



THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

www.ifj.edu.pl

Quo Vadis European Particle Physics ?

Tadeusz Lesiak





The Call for a Higgs Factory



2020 European Strategy for Particle Physics:

An **electron-positron Higgs factory** is the highest-priority next collider.

For the longer term, the European particle physics community has the ambition to **operate a proton-proton collider at the highest achievable energy.**



→ Approval of a **Feasibility Study for the Future Circular Collider at CERN**



2022 Snowmass: **e⁺e⁻ Higgs factory** as highest priority next collider

2023 P5: (i) endorses an **off-shore Higgs factory**, located in either Europe or Japan, to advance studies of the Higgs boson

(ii) recommends **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**



2023 China: **CEPC Technical Design Report released (accelerator)** → engineering design
→ reference detector design

the Reference Detector published TDR (Oct. 2025)



2023 Japan: **Setting up of the ILC Technology Network** to foster more global collaboration

Similar processes: NuPPEC – Long Range Plan 2024 ; APPEC – Roadmap 2027-2036



The European Strategy for Particle Physics: 2026 Update

- Strategy process was initiated by the CERN Council in 2024

Motivation:

- Large progress towards future colliders at CERN (FCC feasibility study) and beyond
- International landscape of the field (CEPC, ILC, P5 in the US)
- Accomplishments in physics (LHC, HL-LHC and elsewhere)
- Long timescales (community engagement)



- *Aim: develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN.** This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field.***
- *The Strategy update should include the **preferred option for the next collider at CERN** and **prioritised alternative options** to be pursued if the chosen preferred plan turns out not to be feasible or competitive.*
- *The Strategy update should also **indicate areas of priority for exploration complementary to colliders** and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.*



Timeline for the Update of the ESPP



More details on ESPP web page: <https://europeanstrategyupdate.web.cern.ch/>



The Strategy Secretariat and European Strategy Group (ESG)

Strategy Secretariat:

Karl Jakobs (Strategy Secretary, Chair)
 Hugh Montgomery (SPC Chair)
 Dave Newbold (LDG Chair)
 Paris Spicas (ECFA Chair)

Organising and running the ESPP process

European Strategy Group (ESG)

- The Strategy Secretary (acting as Chair)
- One representative appointed by each CERN Member State
- One representative appointed by each of the laboratories represented in the Large Particle Physics Laboratory Directors Group (LDG), including its Chair
- The CERN Director-General
- The CERN Director-General elect
- The SPC Chair
- The ECFA Chair
- Invitees: President of CERN Council, one representative from each of the Associate Member and Observer States, one representative from the European Commission, the Chairs of APPEC, NuPECC and ESFRI, the members of the Physics Preparatory Group.

Preparation of the Strategy Document



Physics Preparatory Group (PPG)

collects input from the community, organises the Open Symposium, prepares the Briefing Book

PPG:
Physics + Technology working groups

PPG Working Groups

Electroweak Physics

Conveners: M. Dunford, JB

Strong Interactions

Conveners: C. Diaconu, A. Dainese

Flavour Physics

Conveners: G. Isidori, M-H. Schune

Neutrino Physics and Cosmic Messengers

Conveners: P. Hernandez, S. Bolognesi

BSM Physics

Conveners: F. Maltoni, R. Gonzalez-Suarez

Dark Matter and Dark Sectors

Conveners: J. Monroe, M. McCullough

Accelerator Science and Technology

Conveners: G. Arduini, P. Burrows

Detector instrumentation

Conveners: T. Bergauer, U. Husemann

Computing

Conveners: T. Boccali, B. Kersevan

Organisation of the Open Symposium

(see the next slide)

Physics Briefing Book

CERN-ESU-2025-001
30 September 2025

Input for the 2026 update of the European Strategy for Particle Physics

[Physics Briefing Book](#) text
319 pages; issued Sept. 30. 2025

arXiv version: early Nov. 2025:
<https://arxiv.org/abs/2511.03883>



Open ESPP Symposium in Venice



<https://agenda.infn.it/event/44943/overview>

Very clear message: FCC as the first option



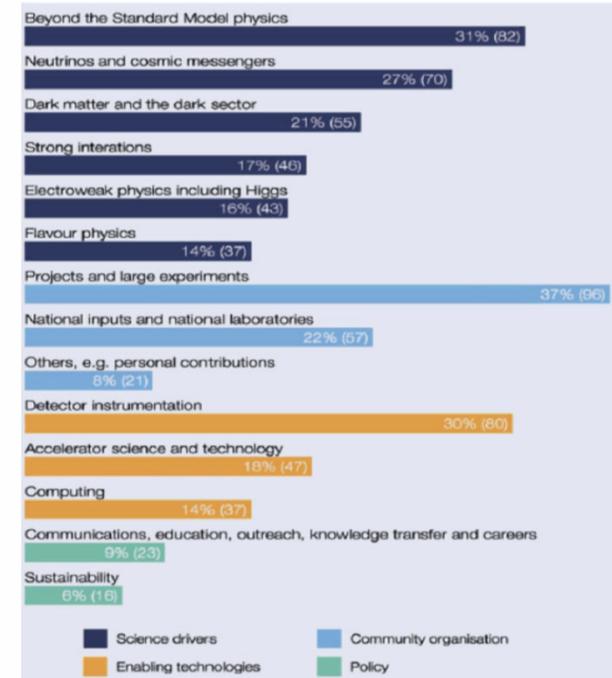


ESG: Overarching topics

- National input / roadmaps (→ strategic)
- **Projects (FCC, LC, LE-FCC-hh, MC, ..)**
(timeline, costs, (physics → PPG))
- Comparisons across proposed projects
- Relations with other fields of physics
- Implementation of the Strategy
(role of CERN and National Labs, coordination of European participation in projects sited outside Europe, ...)
- Knowledge and Technology transfer
- Sustainability, environmental impact
- Public engagement, education, communication
- ...



Draft of the strategy
and its submission to the CERN Council



266 submissions received

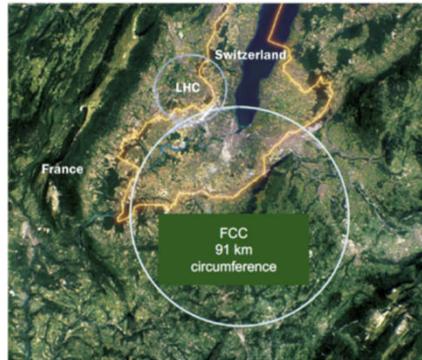
- Major flagship projects
- Many projects in other physics areas
- Input from national HEP communities
- National labs
- Early career researchers
- ...



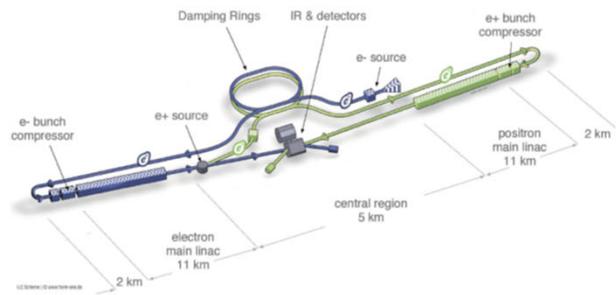
Proposed Large Scale Projects at CERN ~2045

e^+e^- colliders
("Higgs factories")

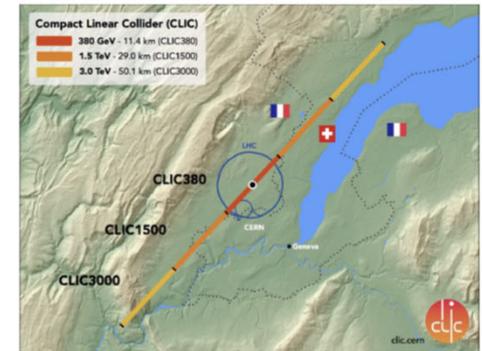
FCC-ee (e^+e^- , circular, 91 – 365 GeV)



LCF (e^+e^- , linear, 91 – 240, 550 GeV)



CLIC (e^+e^- , linear, 380 GeV, 1.5 TeV)



„Bridge Projects“

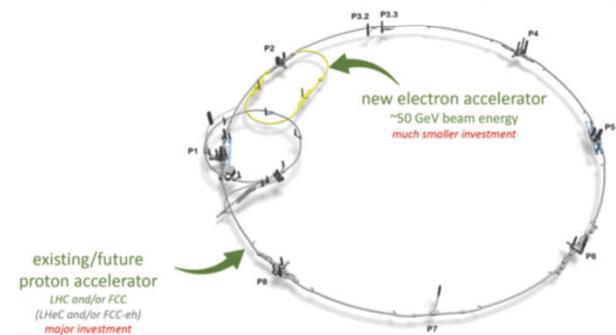
Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LEP3 (e^+e^- , circular, 91 – 230 GeV)



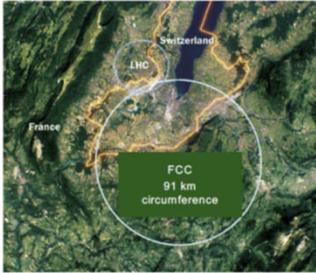
LHeC (ep , circular, electron ERL, 50 GeV e^- , > 1 TeV ep collisions)





Potential for Development: Future 10 TeV Parton-Scale Collider Options

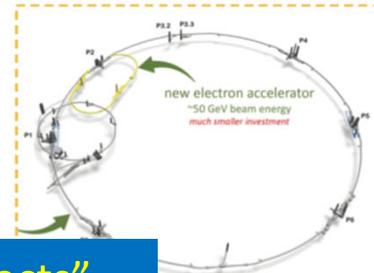
FCC-ee



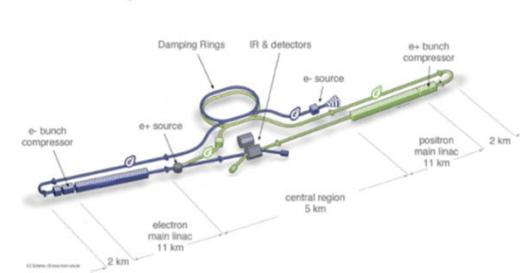
LEP3



LHeC



LCF, CLIC



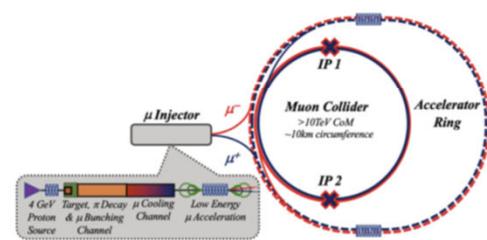
„Bridge Projects”

PERLE

Potential for development: future 10 TeV parton-scale collider options



FCC-hh,
baseline 85 TeV (\rightarrow 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

R&D



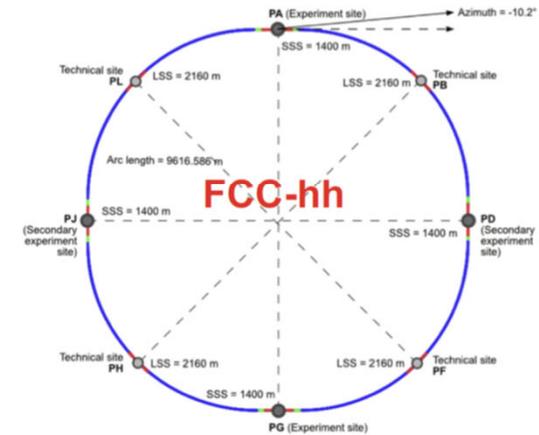
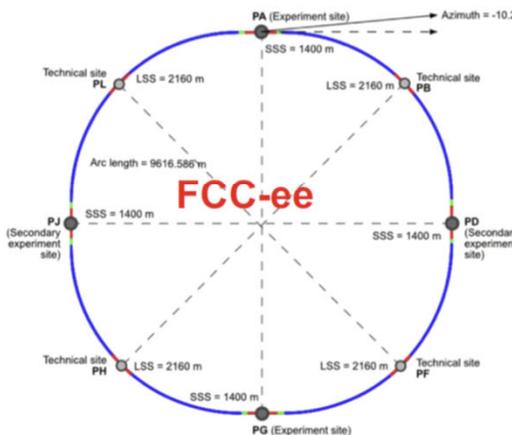
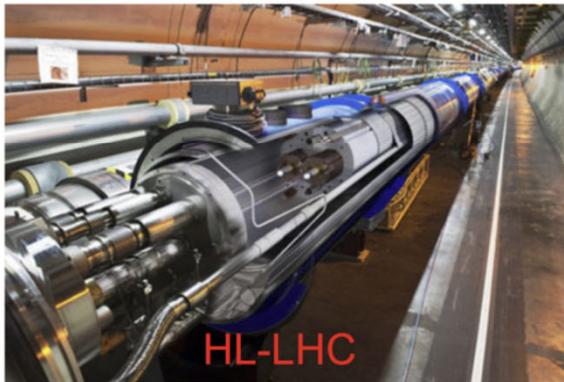
e^+e^- with improved acceleration technologies
LCF, C³ (\rightarrow 1 TeV), CLIC (1.5 TeV), HALHF, ...
 \rightarrow plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)



FCC Integrated Programme

Comprehensive long-term programme maximising physics opportunities:

- **Stage 1: FCC-ee :** e^+e^- Higgs, electroweak & top factory at highest luminosities [91 GeV \rightarrow 365 GeV]
Build on large progress made at circular e^+e^- colliders over the past decades \rightarrow reach luminosities beyond $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- **Stage 2: FCC-hh :** 100 TeV pp collider, energy frontier machine (in addition: eh and ion options)
- **Common civil engineering and technical infrastructures**
- **FCC project start is coupled to HL-LHC programme \rightarrow start operation of FCC-ee around 2048;
can be accelerated if more resources available**



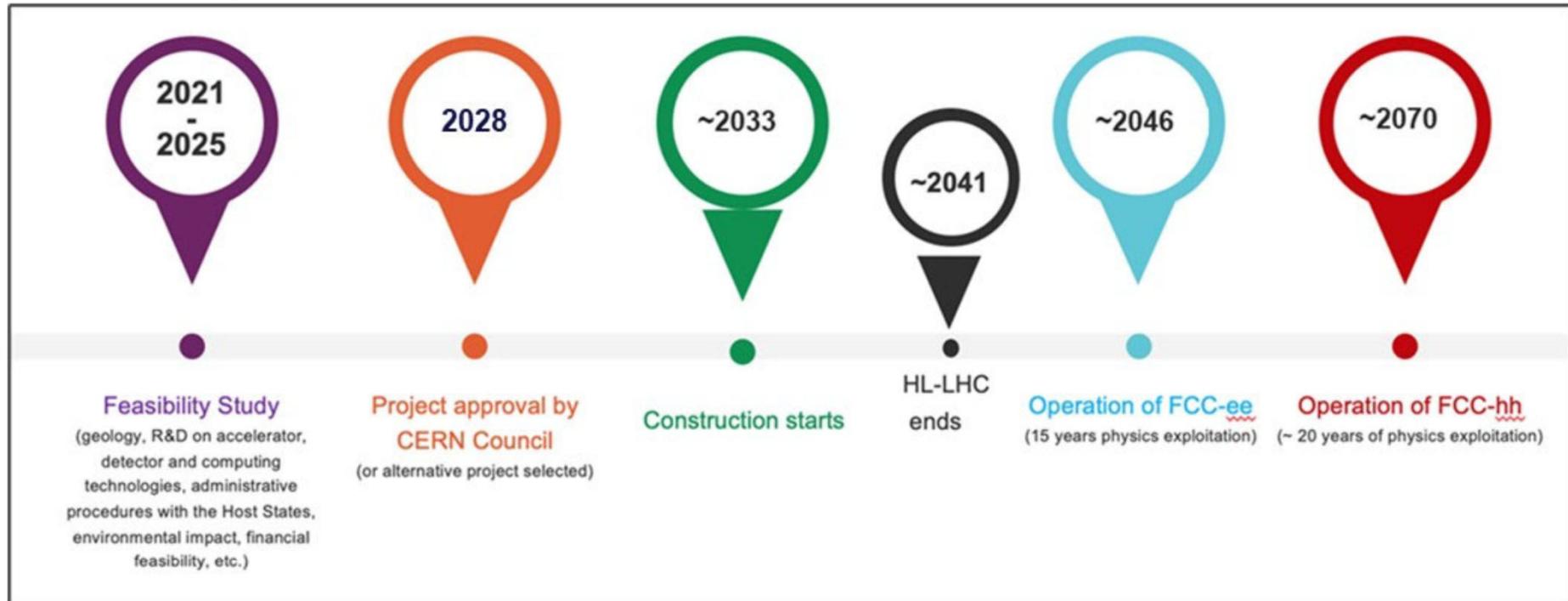
2029 - 2041

2048 - 2063

2074 -



FCC Integrated Programme: Timeline



Ambitious schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- project preparatory phase with adequate resources immediately after Feasibility Study**

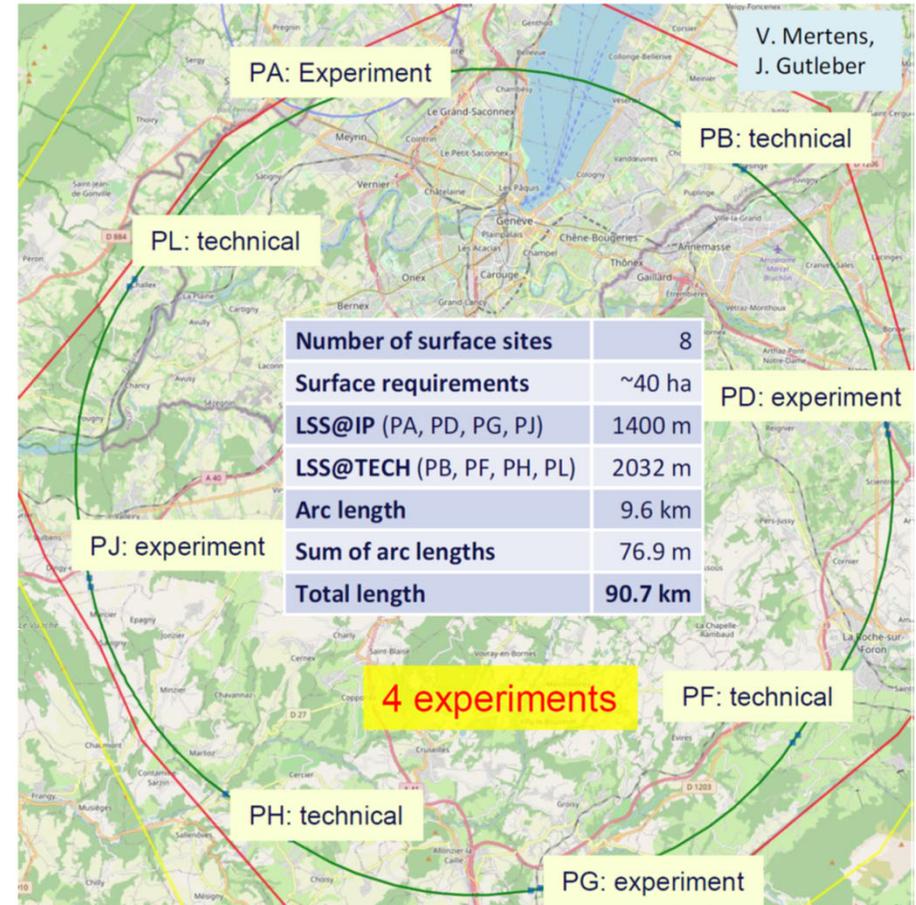


FCC Integrated Programme: Layout

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment**, (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“**Avoid-reduce-compensate**” principle of EU and French regulations

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry
 (Reduction from the 97.7 km and the 12 surface sites in 2019)



V. Mertens,
J. Gutleber

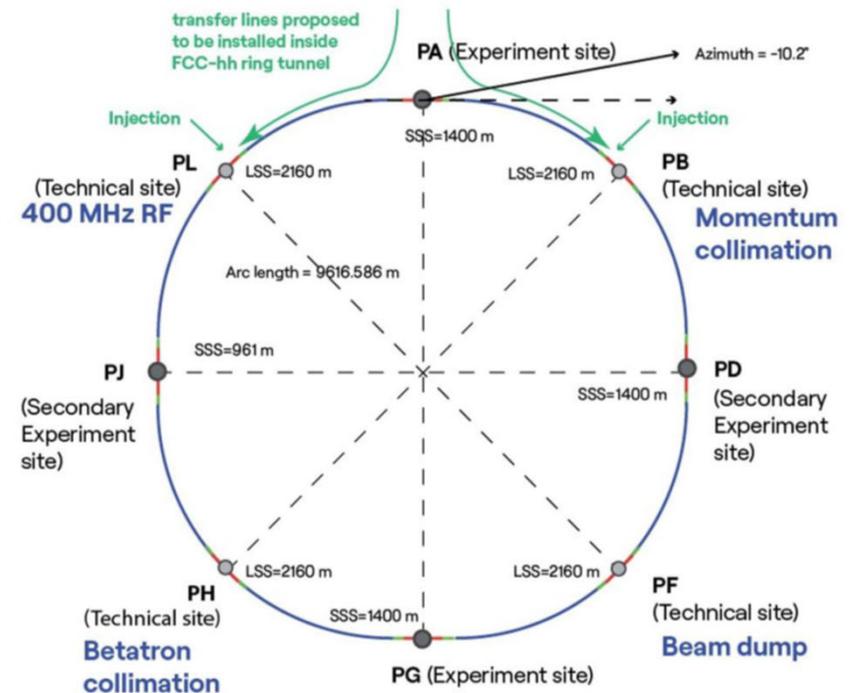


FCC Integrated Programme: Stage 2 Hadron Collider

Main parameters

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout



- Parameter optimization towards “acceptable power consumption” (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today’s technologies (Nb_3Sn , ~14T)



Linear Collider Facility (LCF)

- High level of technology readiness (based on ILC developments)

- Aim for $\sqrt{s} = 250 - 550$ GeV
(can be realised in a 33.5 km tunnel)

- Luminosity: $(2.7 - 7.7) \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
(shared between two experiments)

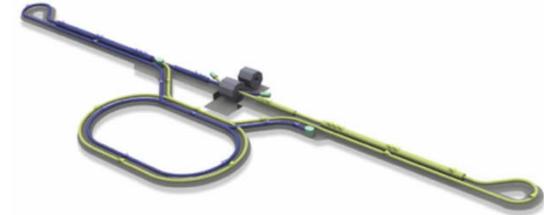
Polarisation possible (→ table)

Power consumption: 143 – 322 MW

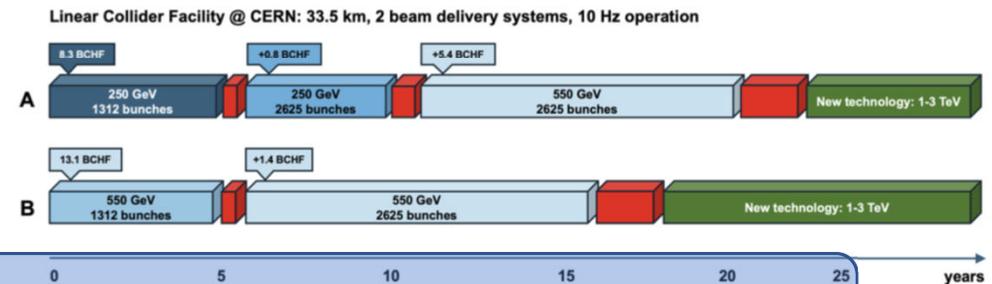
- Upgrade possibilities to reach higher energies, beyond 550 GeV
 - Extension of the tunnel
 - Use of advanced accelerator technologies
(Cold copper C^3 , HALHF, plasma acceleration)

- Accelerator challenges:
 - High acceleration gradients
 - Beamstrahlung constrains beam parameters at IP

- Positron production: $\sim 4-8 \cdot 10^{14} \text{ e}^+/\text{s}$
(SLC: $\sim 6 \cdot 10^{12} \text{ e}^+/\text{s}$)



Quantity	Symbol	Unit	Initial-250	Upgrades		Initial-550	Upgrade
Centre-of-mass energy	\sqrt{s}	GeV	250	250	550	550	550
Inst. Luminosity	\mathcal{L}	$(10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$ P(e^-) / P(e^+) $	(%)	80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Site AC power	P_{site}	MW	143	182	322	250	322
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Operation & maintenance		MCHF/y	170	196	342	291	342
Electricity		MCHF/y	66	77	142	115	142
Operating Personnel		FTE	640	640	850	850	850



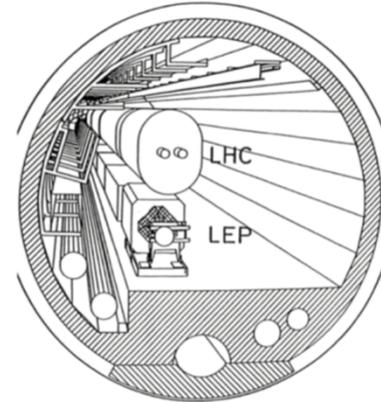


LEP3 as a „Bridge Project”

Possible machine parameters:

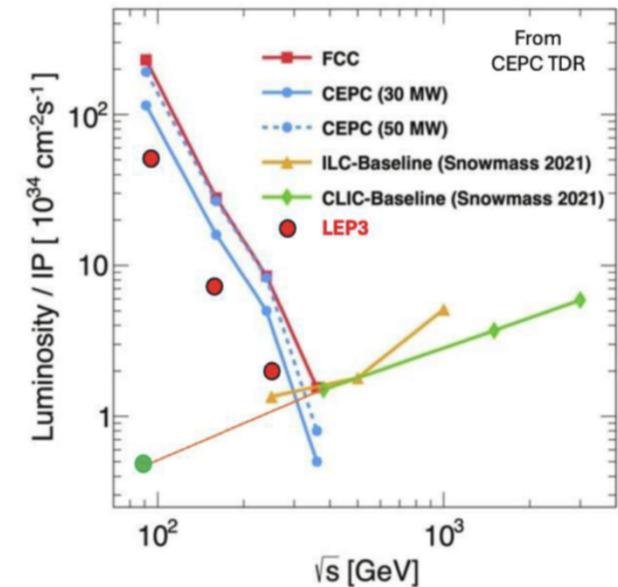
(t.b.c., some technical details still need to be worked out)

- Luminosity: $(1.5 - 2.5) \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 230 GeV
- Number of interaction regions: 2
- Synchrotron radiation power loss: 50 MW
→ ZH run at 230 GeV
- LEP3 would also run at the Z and WW threshold
(→ $2 \cdot 10^{12}$ Z decays, $4 \cdot 10^7$ WW events)



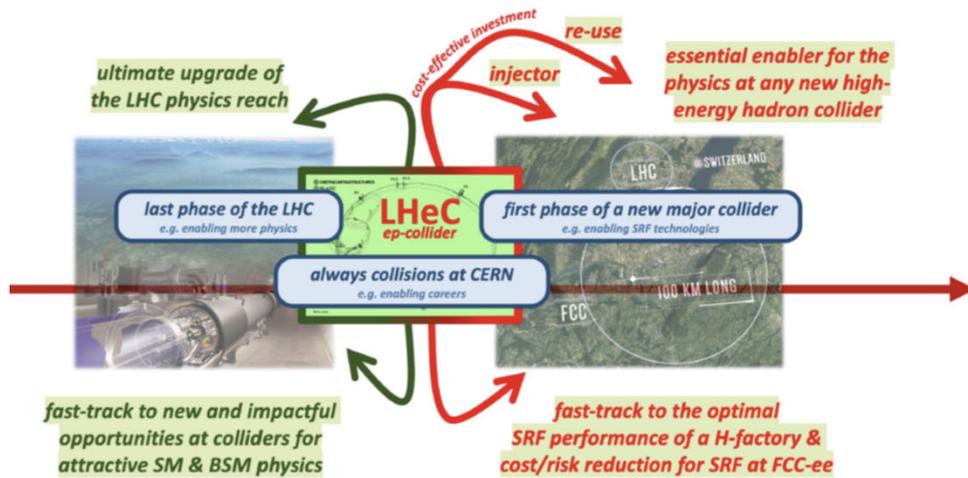
LEP3 is not competitive with FCC-ee or CEPC, but still has an interesting Higgs and el.weak physics programme

(Larger number of Z and WW events than Linear Colliders)



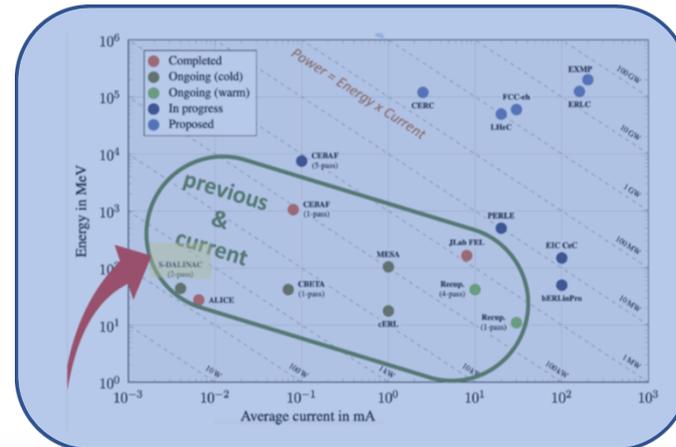


LHeC as a „Bridge Project”



- Propose an LHeC programme extending the regular HL-LHC program with only a standalone electron-hadron operation phase
 - impactful bridge between colliders
QCD studies, structure functions, viable Higgs programme e.g. $H \rightarrow c\bar{c}$
- Accelerator challenges:
Very high currents; recirculation efficiency is critical
(25 mA@ 50GeV → 1.25 GW circulating power)

Parameter	Unit	ep	eA
E_e	GeV	50	50
$N_{p,A}$	10^{11}	2.2	0.0018
$\epsilon_{p,A}$	μm	2.5	1.5
I_e	mA	(20) 50	20
N_e	10^9	(3.1) 7.8	6.2
$\beta_{p,A}^*$	cm	(7) 7	10
Luminosity	$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	(9) 23	0.7





Muon Collider

- Muon colliders provide a **path towards high energy lepton collisions**, but are not at the level of maturity of the other proposals at present

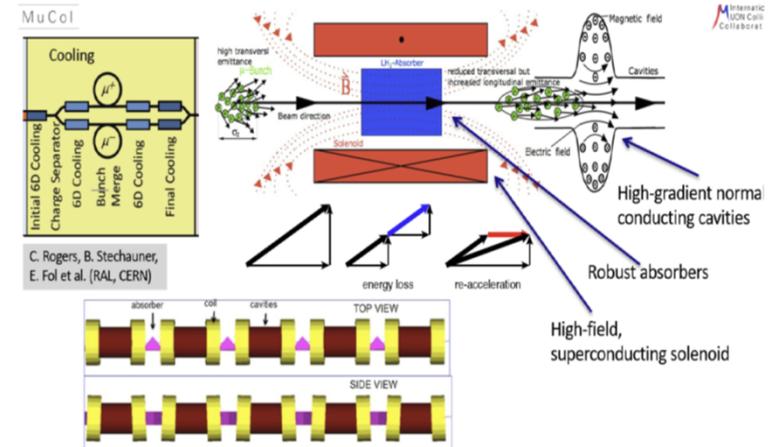
- Accelerator challenges:

- Demonstration of the **6D-cooling technology** is critical

- **Technological challenges are associated with the various acceleration steps**, in particular s.c. magnets, RF systems, fast cycling magnets

- Reliable start-to-end simulation tools need to be further developed to validate and optimize the overall performance

→ **Demonstrator planned (mid 2030s)**



Muon Collider	
Item	Parameters
C.M. Energy	3.2 ... 7.6 ..10 TeV
Length	4.5-11 km
Luminosity @ ZH	1.5...8 x10 ³⁴ cm ⁻² s ⁻¹ (Ni ³ Sn)
Interaction regions	2
Annual energy consumption	0.7 ... 1.0 TWh 113 / 173 / 188 MW
Cost	~10 BCHF
Advantages	Compact accelerator, reuse of existing infrastructure, high energy reach
Challenges	Needs powerful "proton driver" Neutrino flux mitigation Needs vigorous R&D



How Much Would it Cost? (in BCHF)

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

FCC-ee

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	14,020
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	15,320

15.3

16.6

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

LCF

CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	8492	5464	7341	7116

14.0

14.4

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	3870	3800
Experiments non-CERN part	900	270

3.9

Cost summary table in 2024 MCHF for the construction of FCC-hh.

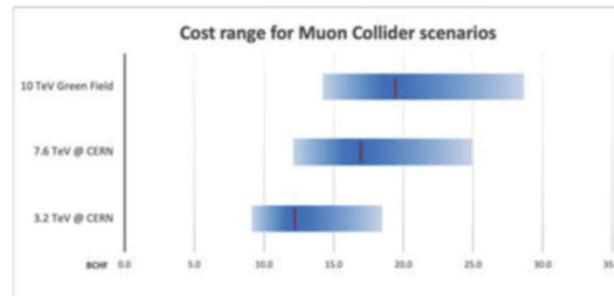
FCC-hh
(after FCC-ee)

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	19080

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

19.1

Muon Collider



9-28

LHeC (cost estimate 2018, 60 GeV e-)

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~ 2.0



(1) National Input, Diversity in European Particle Physics

(Chairperson Calin Alexa)

- Analyse and summarise the input that will be submitted by the national HEP communities.
- Discuss constraints imposed by a large accelerator project at CERN. What fraction of the CERN and European research budget should be put on a single flagship project?

Will also analyse final input by the national HEP communities to be submitted by 14 Nov 2025

(2) Project Comparison Group (a) Project Assessment Group

(Chairpersons: Gianluigi Arduini, Phil Burrows)

For projects to be considered for realisation as the next flagship project at CERN, several aspects need to be thoroughly evaluated and compared:

- Technical feasibility, R&D requirements
- Risks
- Timeline
- Cost and human resources (including estimates for the associated detectors)
- Environmental impact

External experts:
R. Brinkmann, F. Bordry,
N. Holtkamp, L. Rivkin

(b) Physics potential

(Chairperson: Monica Dunford)

- Discussion and the comparison of the physics potential in the different physics areas is carried out by the physics working groups in the Physics Briefing Book
- A more **global comparison across various physics areas** is the responsibility of the ESG



(3) Implementation of the Strategy / Deliverability of larger projects

(Chairperson: Achille Stocchi)

Main purpose: assess how European National Laboratories and institutes can best work together with CERN to deliver large scale accelerator and detector projects.

“Distributed delivery model” for CERN’s next major infrastructure? New management practices and tools?

What lessons can be learnt from the recent major projects (e.g. ATLAS and CMS upgrades)?

What could be a model for international participation (beyond CERN Member and Associate Member States)?)

(4) Relations with other fields of physics

(Chairperson: Marek Karliner)

(5) Sustainability and environmental impact

(Chairperson: Tadeusz Lesiak)

(6) Public Engagement, Education, Communication, Social and career aspects for the next generation

(Chairperson: Pierre van Mechelen)

(7) Knowledge and Technology Transfer

(Chairperson: Beate Heinemann)



What is the preferred large-scale post LHC accelerator at CERN?

Member States (MS)	Preferred Collider
Austria	FCC-ee
Belgium	FCC-ee
Bulgaria	Muon Collider
Czech Republic	FCC-ee
Denmark	FCC-ee
Estonia	FCC-ee *
Finland	FCC-ee
France	FCC-ee *
Germany	FCC-ee
Greece	FCC-ee
Hungary	FCC-ee
Israel	FCC-ee
Italy	FCC-ee
Netherlands	FCC-ee
Norway	FCC-ee
Poland	FCC-ee
Portugal	FCC-ee
Romania	FCC-ee
Serbia	FCC-ee
Slovakia	FCC-ee
Slovenia	FCC-ee
Spain	FCC-ee
Sweden	FCC-ee
Switzerland	FCC-ee
United Kingdom	FCC-ee/FCC-hh

Associate Member States (AMS)

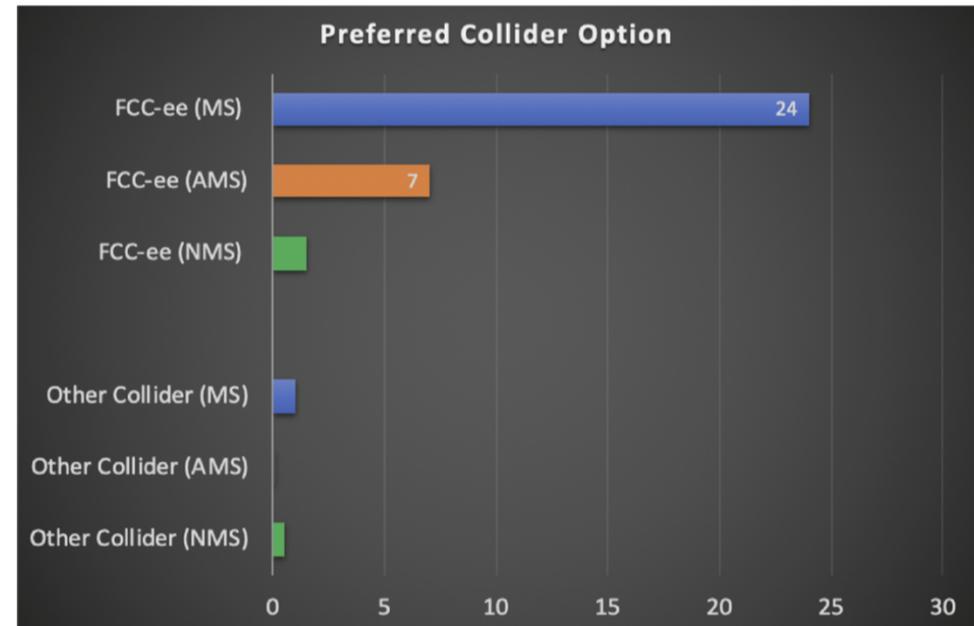
Brazil	FCC-ee
Croatia	FCC
Cyprus	
India	
Ireland	
Latvia	FCC-ee
Lithuania	FCC-ee
Pakistan	FCC-ee
Turkey	FCC-ee
Ukraine	FCC-ee

Non-Member States (NMS)

Japan	FCC-ee or LCF
USA	FCC-ee

* No updated input received, preference expressed in the previous submission taken

Update by France (30 Nov): FCC-ee / hh
(integrated programme)

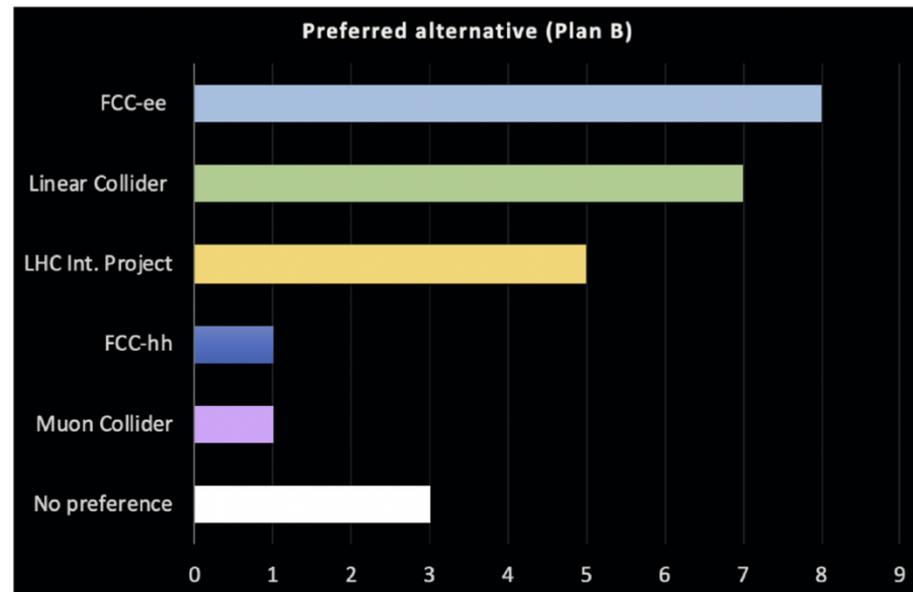


- Overwhelming support (24/25 CERN Member States HEP communities) in favour of the FCC-ee programme
- Support as well from Associate Member States (AMS) and Non-Member States (NMS)



What is the preferred alternative if the preferred option would not be feasible?

Member State	Preferred Alternative (Plan B)
Austria	Linear Collider (LCF, CLIC)
Belgium	LEP3 or LHeC
Bulgaria	Muon Collider
Czech Republic	FCC-hh (FCC-ee)
Denmark	FCC-ee
Estonia	Linear Collider (LCF, CLIC)
Finland	LCF
France	
Germany	LCF
Greece	FCC-ee
Hungary	FCC-ee
Israel	
Italy	FCC-ee
Netherlands	LHeC or LEP3
Norway	Linear Collider (CLIC (LCF))
Poland	FCC-ee
Portugal	
Romania	FCC-ee
Serbia	LEP3 (LHeC)
Slovakia	LHeC
Slovenia	FCC-ee
Spain	Linear Collider (LCF, CLIC)
Sweden	LCF
Switzerland	FCC-ee
United Kingdom	LHC extension, LHeC



France (30 Nov): - staged FCC (if financially not feasible);
 - LHC Intermediate Project (if tunnel cannot be realised)

- No consensus
- Three main axes:
 - FCC (stretched in time, descoped, ...)
 - Linear Collider
 - Intermediate project in LHC tunnel as bridge towards FCC-hh (10++ TeV scale)



The CEPC is NOT included in the next 5-year plan

CERN COURIER

POLICY | NEWS

CEPC matures, but approval is on hold

26 October 2025

Yifang Wang:

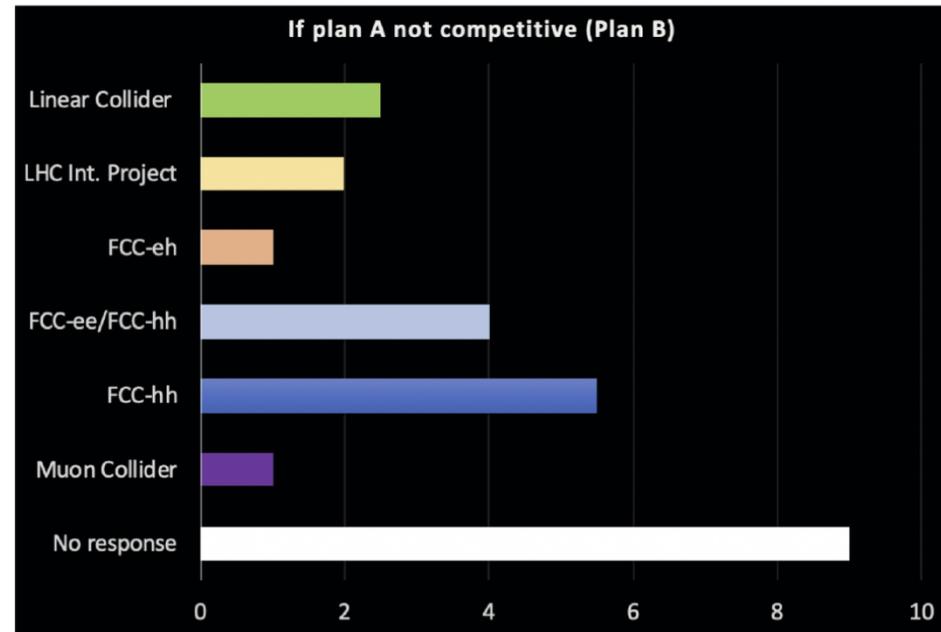
„Although our proposal that CEPC be included in the next five-year plan was not successful, IHEP will continue this effort, which an international collaboration has developed for the past 10 years”

„We plan to submit CEPC for consideration again in 2030, unless FCC is officially approved before then, in which case we will seek to join FCC, and give up CEPC”



What is the preferred alternative if the preferred option would not be competitive?

Member State	Alternative (not competitive)
Austria	FCC-hh
Belgium	LHeC
Bulgaria	
Czech Republic	
Denmark	FCC-ee/hh
Estonia	
Finland	FCC-hh
France	
Germany	FCC-hh or LCF550
Greece	
Hungary	FCC-ee/hh
Israel	
Italy	FCC-hh
Netherlands	Muon Collider
Norway	CLIC
Poland	FCC-ee/hh
Portugal	LCF
Romania	
Serbia	LHC, LEP3, LHeC
Slovakia	FCC-eh
Slovenia	FCC-ee/hh
Spain	
Sweden	
Switzerland	FCC-hh
United Kingdom	FCC-hh



- No consensus
- Main axes:
 - FCC-hh
 - Stick to the FCC-ee/hh integrated programme



Evaluation by the European Strategy Group

Assessment of large-scale accelerator projects at CERN Report of ESG WG2a

31 October 2025

G. Arduini^{1,a} (convener), F. Bordry¹ (co-opted accelerator expert), R. Brinkmann² (co-opted accelerator expert), P. Burrows^{3,b} (convener), K. Desch⁴, S. Farrington^{5,6}, F. Gianotti¹, K. Hanagaki⁷, N. Holtkamp^{8,9} (co-opted accelerator expert), J. Keintzel^{1,c} (scientific secretary), B. Kilminster¹⁰, T. Lesiak¹¹, L. Rivkin^{12,13} (co-opted accelerator expert), F. Sabatié¹⁴, M. Tuts¹⁵, A. Zoccoli¹⁶.

Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
CLIC 380 GeV, 1.5 TeV		4 - 6 / 5.2							
FCC-ee 91-365 GeV		4 - 7 / 6.0							
FCC-hh 85 TeV		4 - 7 (Nb ₃ Sn) / 4.3							
		2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb ₃ Sn) / 5					Nb ₃ Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							



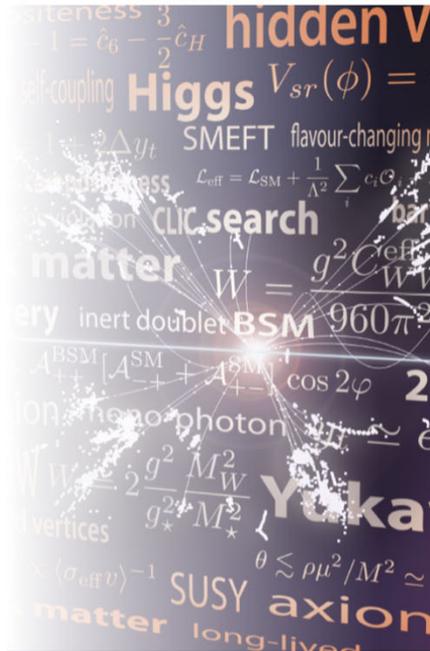
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		2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb ₃ Sn) / 5					Nb ₃ Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

- Muon Collider: The technologies underpinning the MC design are in the early phases of exploration; Comprehensive R&D programme defined (300 MCHF, 1800 FTEy); Demonstrator need to be built.
- FCC-hh: Further R&D and industrialisation of high-field magnets (Nb₃Sn 15 - 20 y); Costs of HFM, further developments of high-temperature superconducting (HTS) magnets
- LEP3: Absence of a detailed lattice design and full-scale simulation → uncertainties on projected luminosity; Proposed baseline HTS nested quadrupoles/sextupoles represent the lowest TRL (luminosity, power)
- LHeC: Performance critically depends on a very high-current Energy-Recovery Linac (ERL); Uncertainty on luminosity of an order of magnitude; Successful demonstration of the PERLE programme at IJCLab is vital

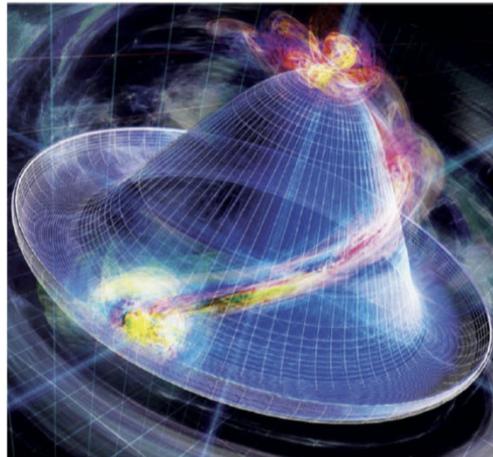


WG2b: Physics Potential



<https://cds.cern.ch/record/2944678>

<https://arxiv.org/abs/2511.03883>



CERN-ESU-2025-001
30 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

Electroweak Physics: Jorge de Blas¹, Monica Dunford² (Convenors), Emanuele Bagnachi³ (Scientific Secretary), Ayres Freitas⁴, Pier Paolo Giardino⁵, Christian Grieff⁶, Michele Schiappi⁷, Angela Talavera⁸ (Contributors)

Strong Interaction Physics: Andrea Dainese⁹, Cristinel Diaconu¹⁰ (Convenors), Chiara Signorile-Signorile¹¹ (Scientific Secretary), Nester Amato¹², Roberta Araldi¹³, Andy Buckley¹⁴, David d'Enterria¹⁵, Antoine Gérardin¹⁶, Valentina Mantovani Sari¹⁷, Sven-Olaf Meck¹⁸, Marco Pappalardo¹⁹, Raimond Stöckli^{20,21}, Urs Achim Wiedemann²² (Contributors)

Flavour Physics: Gino Isidor²³, Marie-Hélène Schune²⁴ (Convenors), Maria Laura Piscopo²⁵ (Scientific Secretary), Marta Cabi²⁶, Yiyai Grossman²⁷, Thibaud Hamat²⁸, Andreas Jäger²⁹, Jesse J. Kamenik^{30,31}, Matthew Kenzie³², Patrick Koppenburg³³, Radoslav Matčevski³⁴, Angela Papp³⁵, Guillaume Pigard³⁶, Justine Serrano³⁷ (Contributors)

Neutrino Physics & Cosmic Messengers: Pilar Hernandez³⁸, Sara Hodelmeier³⁹ (Convenors), Ivan Esteban⁴⁰ (Scientific Secretary), Stepha Delam, Valérie Domcke, Joseph Formaggio⁴¹, M. C. Gonzalez-Garcia^{42,43}, Aari Heijboer⁴⁴, Aldo Ianni⁴⁵, Joachim Kopp⁴⁶, Elisa Resconi⁴⁷, Mark Scott⁴⁸, Viola Seidlmayr⁴⁹ (Contributors)

Beyond the Standard Model Physics: Fabio Maltoni⁵⁰, Rebecca Gonzalez Suarez⁵¹ (Convenors), Benedikt Meier⁵² (Scientific Secretary), Timothy Cohen^{53,54}, Annapaula de Costa⁵⁵, Nathaniel Craig⁵⁶, Roberto Franceschini⁵⁷, Loukas Goussok⁵⁸, Aurelio Juste⁵⁹, Sophie Renner⁶⁰, Lanya Shekhter⁶¹ (Contributors)

Dark Matter and Dark Sector: Jocelyn Monson^{62,63}, Matthew McCullough⁶⁴ (Convenors), Yohel Imz⁶⁵ (Scientific Secretary), Paolo Agnes⁶⁶, Francesca Calore⁶⁷, Emanuele Castorina⁶⁸, Aaron Chou⁶⁹, Monica D'Onofrio⁷⁰, Maksym Ochyniuk⁷¹, Tina Pollmann⁷², Josef Pradler^{73,74}, Yoram Soreq⁷⁵, Julia Katharina Vogel⁷⁶ (Contributors)

Accelerator Science and Technology: Gianluigi Avduin⁷⁷, Philip Barrow⁷⁸ (Convenors), Jacqueline Konradi⁷⁹ (Scientific Secretary), Deepa Anjali-Kalish, Bernhard Auchmann⁸⁰, Massimo Ferrara⁸¹, Angeles Fani Goffe⁸², Roberto Louco, Anke-Susanne Mueller⁸³, Tor Raabsteiner⁸⁴, Marlene Turner, Pierre Vedrine⁸⁵, Hans Weise⁸⁶, Walter Wuerneck⁸⁷, Chenghui Yu⁸⁸ (Contributors)

Detector Instrumentation: Thomas Bergauer⁸⁹, Ulrich Husemann⁹⁰ (Convenors), Dorothea von Bruch⁹¹ (Scientific Secretary), Theo Aarrestad⁹², Daniela Borovikova⁹³, Shikha Bressler⁹⁴, Marcel Demarteau⁹⁵, Michael Doser⁹⁶, Gabriella Gaudin⁹⁷, Inés Gil-Botella⁹⁸, Andrea Giuliani⁹⁹, Fabrizio Palazzi¹⁰⁰, Rok Pevenšek¹⁰¹, Felix Selkow¹⁰², Frank Simon¹⁰³, Maksym Tluch¹⁰⁴ (Contributors)

Computing: Tommaso Boccali¹⁰⁵, Borut Kersevan^{106,107} (Convenors), Daniel Murnane¹⁰⁸ (Scientific Secretary), Gozalo Merino Arcevalo¹⁰⁹, John Derek Chapman¹¹⁰, Frank-Dieter Gade¹¹¹, Stefano Giagu¹¹², Maria Giromi¹¹³, Heather M. Gray¹¹⁴, Giovanni Iadonata, Stéphane Jorquera¹¹⁵, Gregor Kaniuk¹¹⁶, David Lang¹¹⁷, Soledad M. Ryan¹¹⁸, Nicole Skidmore¹¹⁹, Sofia Vallecora¹²⁰ (Contributors)

Theoretical Overview: Eric Laenen^{121,122}

Reviewers: Angharad Cannell¹²³, Xinshou Lou¹²⁴, Roger Rosenfeld¹²⁵, Yiji Yamazaki¹²⁶

Editors: Roger Forry¹²⁷, Karl Jakobs¹²⁸, Hugh Montgomery¹²⁹, Mike Seidel¹³⁰, Paris Spiliotis¹³¹

i

Beyond the **Technical Readiness**, the **physics potential** and the **long-term prospects** of reaching the 10++ TeV energy scale are the driving arguments for the choice of the next collider;

Precision and energy are required



Overall Physics Assessment (Precision Physics)

Project	Circular Linear	Higgs	EWPO	Top	Flavour	QCD (precision)	QCD (Partonic Struct. + HIs)
		Start-of-the-art starting point at the end of HL-LHC					
Lepton and <i>ep</i> Colliders							
FCC-ee		4	5	3	5	5	1
FCC-ee no-top		2	5	2	5	5	1
LEP3		2	4	2	4	2	1
	LCF-250	2	3	2	1	2	1
	CLIC-380	2	2	3	1	2	1
LHeC		1	2	1	1	3	5
Mid-Energy Lepton Colliders							
	LCF-550	4	4	4	1	2	1
	LCF-1000	4	4	4	1	2	1
	CLIC-1500	4	3	4	1	2	1
	CLIC-3000	4	3	4	1	2	1
Energy frontier							
FCC-hh		3	No information		3	2	5
muC-10TeV		4	3	5	3	1	1
Precision w/ energy							
LHeC + FCC-hh		3	2	2	3	4	5
LEP3 + FCC-hh		4	4	3	4	3	5
LEP3 + muC		4	5	5	4	3	2
	LCF-1000 + muC	4	5	5	3	3	2
FCC-ee + FCC-hh		5	5	5	5	5	5

ESG WG 2b report



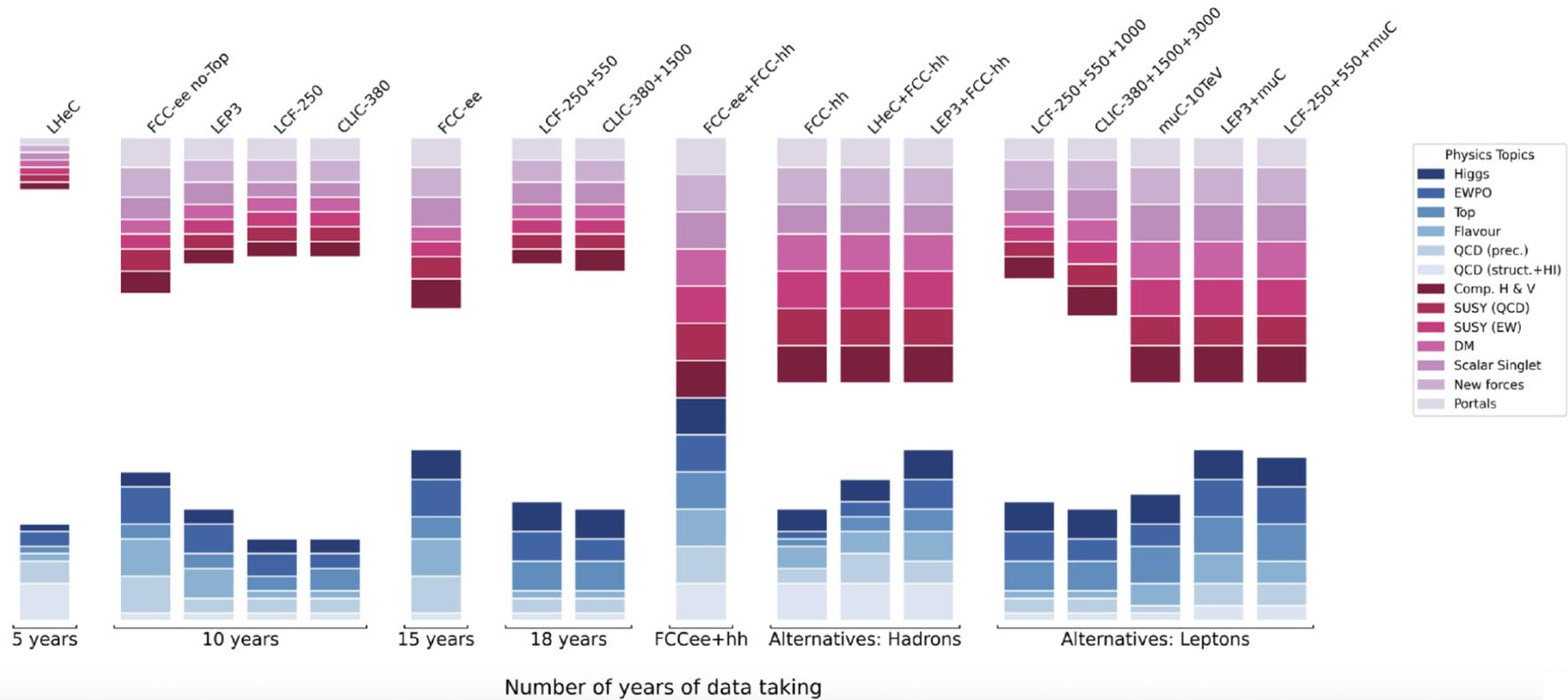
Overall Physics Assessment (BSM Physics)

Project		Comp. H & V	SUSY (QCD)	SUSY (EW)	DM	Scalar Singlet	New forces	Portals
Circular	Linear	State-of-the-art starting point at the end of HL-LHC						
HL-LHC		State-of-the-art starting point at the end of HL-LHC						
Lepton and <i>ep</i> Colliders								
FCC-ee		4	3	2	2	4	4	4
FCC-ee no-top		3	3	2	2	3	4	4
LEP3		2	2	2	2	3	3	3
	LCF-250	2	2	2	2	2	3	3
	CLIC-380	2	2	2	2	2	3	3
LHeC		1	1	1	1	1	1	1
Mid-Energy Lepton colliders								
	LCF-550	2	2	2	2	3	3	3
	CLIC-1.5TeV	3	2	2	2	3	3	3
	LCF-1TeV	3	2	2	2	3	4	3
	CLIC-3TeV	4	3	3	3	4	4	3
Energy frontier								
FCC-hh		5	5	5	5	4	5	4
muC		5	4	5	5	5	5	4
Precision w/ energy								
LHeC+ FCC-hh		5	5	5	5	4	5	4
LEP3 + FCC-hh		5	5	5	5	4	5	4
LEP3 + muC		5	4	5	5	5	5	4
	LCF + muC	5	4	5	5	5	5	4
FCC-ee + FCC-hh		5	5	5	5	5	5	5

ESG WG 2b report



Overall Physics Assessment (Precision and BSM Physics)





ESG: Strategy Drafting Session, Ascona (CH), Dec. 1-5, 2025





Intermediate Conclusions (1)

- The **FCC-ee** would deliver the world's **broadest high-precision particle physics programme**

- Outstanding discovery potential through the Higgs, electroweak, flavour and top sectors, as well as advances in QCD
- Its technical feasibility is demonstrated via the FCC feasibility study
- Scope and costs are well defined, plausible funding models exist

- The FCC-ee would maintain **European leadership in high-energy particle physics**, also advancing technology and providing societal benefits

- **FCC-ee** would also **pave the way towards a hadron collider** reusing the tunnel and much of the infrastructure, providing a direct **discovery reach well beyond the 10 TeV parton energy scale**

→ Flagship project at CERN, which will allow Europe to play a leading role in the field



Intermediate Conclusions (2)

LEP3 and LHeC as alternative options:

- Proposed as **intermediate colliders**; they offer an intermediate physics programme at **significantly lower construction cost**
- Substantially reduced precision physics programme
 - LEP3: - strong electroweak and flavour physics programmes
 - no top-quark programme
 - improvements in Higgs physics w.r.t. HL-LHC
 - LHeC: - strong QCD programme
 - significantly extended knowledge of the proton structure
 - overall precision programme limited, although some improvement in Higgs physics (w.r.t. HL-LHC)
- Not competitive** with an FCC-ee-like collider
- To provide a long-term physics programme, they would **need to be complemented by an energy-frontier machine**, such as a hadron collider

→ No flagship colliders!



Intermediate Conclusions (3)

Linear Collider: CLIC and LCF as alternative options

- **Substantially reduced precision physics programme**

(less strong electroweak programme, non-competitive flavour programme due to lower luminosities at lower energies)

- **Operation at 550 GeV or higher would offer competitive programmes in Higgs and top-quark physics, however, overall not competitive with an FCC-ee-like collider**

- Both colliders require a new tunnel of about 33 km to reach their ultimate energies

* CLIC: 550 GeV collider: 60% of construction cost of FCC-ee
 1500 GeV collider: construction costs at the same level as FCC-ee
 CLIC technology is well developed, but less mature than the LCF technology

* LCF: 550 GeV collider: construction costs at the same level as FCC-ee
 LCF technology is mature

- **The path towards 10 TeV collisions would require plasma wakefield acceleration, which is not yet proven to be a viable technology.**

→ - Reduced physics
 - Not competitive with an FCC-ee-like collider
 - Currently no path exists to 10 TeV collisions



Other alternative options

A descoped FCC-ee (to improve the financial feasibility)

- Descoping scenarios include:

- removing the top-quark run	-1.26 BCHF
- constructing two rather than four interaction regions and experiments	- 0.80 BCHF
- decreasing RF system power	- 0.35 BCHF

- These measures would reduce the construction cost by approximately 15%.

- **Although this would have a significant impact on the breadth of the physics programme and the precision achieved, the descoped FCC-ee would still provide a very strong physics programme and a viable path towards high energies, compared to the alternative collider options.**

- Should additional resources become available, these descoping scenarios would be reversible.



ESG: Strategy Drafting Session, Ascona (CH), Dec. 1-5, 2025

Overall Summary

Machine	Precision Physics	BSM physics	Phys vs CEPC	Tech readiness	Const. cost (GCHF)	Path to ≥ 10 TeV
FCC-ee	22	23			15.3	
LCF250/ LCF550	15	17			14.8	
CLIC380/ CLIC1500	14	18			14.6	
LCF250	10	16			9.4	
CLIC380	10	16			7.5	
LEP3	14	17			4.1	
LHeC	8	7			2.1	

Physics: from WG2b: sum of precision/BSM physics
 Phys vs CEPC: competitiveness, assuming CEPC is running in parallel
 Tech readiness: from WG2a
 Construction cost: from proponents + exp. (CERN part)

CERN Press Release 12.12.2025 (excerpts)

PR11.25
12.12.2025

The European Strategy for Particle Physics reaches an important milestone

Geneva, 12 December 2025. At its 225th session, the CERN Council received the recommendations for the update of the European Strategy for Particle Physics, the aim of which is to develop a common vision for the future of the field. The recommendations will be reviewed by the Council in the coming months. A final decision is expected at a dedicated Council Session in Budapest in May 2026.

The recommendations address a broad range of topics and goals related to research in high-energy physics in Europe and beyond.

The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

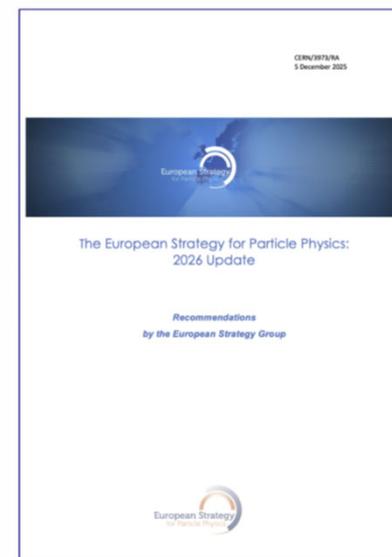
The ESG presents a descoped FCC-ee as the preferred alternative option for the next flagship collider at CERN.

The full set of recommendations is available at this [link](#).

[The recently completed FCC Feasibility Study provides the basis](#) for continued work on multiple aspects of the project.

<https://cds.cern.ch/record/2950671>

A decision by the CERN Council on the possible construction of the FCC is expected around 2028.





General Recommendations

- i. *The **full exploitation of the physics potential of the LHC and the HL-LHC and the completion of the high-luminosity upgrade remain the highest priorities** of European particle physics. Every effort must be made to complete the HL-LHC upgrade within the current schedule.*
- ii. *The unique ecosystem of particle physics research centres and universities in Europe should be further strengthened in order to address the objectives set out in this Strategy.*
- iii. *The implementation of the Strategy should be pursued in strong collaboration with global partners and neighbouring fields.*
- iv. *The relationship between the particle physics community and the European Commission should be further strengthened, exploring funding opportunities for the realisation of infrastructure projects and R&D programmes in cooperation with other fields of science and industry.*



I. *The next CERN flagship collider project*

- i. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.*
- ii. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN*

At this stage, without knowing the reasons for which the FCC-ee would not be feasible, other alternative options are not ranked.



II. Technology

To ensure that Europe remains at the forefront of technologies for particle physics, R&D in collaboration with international partners and industry must continue to be supported with high priority, thereby enhancing sustainability and societal impact.

Accelerator Technology:

- i. In order to realise the visionary plan presented, the **highest priority** must be the **development and industrialisation of key technologies: advanced superconducting and normal-conducting RF structures, efficient RF power sources and accelerator-quality magnets in the 14 - 20 T range**, including those based on **high-temperature superconductors**.*
- ii. Demonstration of **high-current multi-turn energy recovery** in linacs constitutes an important step towards power-efficient lepton accelerators for a broad range of applications and should be pursued.*
- iii. The **longer-term** development of advanced technologies, such as **high-gradient wakefield acceleration and those underpinning bright muon beams**, should be supported at an appropriate level. Synergies with the US initiative on muon collider R&D should be exploited.*



Detector Technology:

- i. For the **DRD collaborations** to address the requirements of future flagship projects, they **must receive adequate funding**. New R&D topics and initiatives should be integrated in the DRD scheme. The General Strategic Recommendations in the roadmap must be fully addressed by dedicated initiatives coordinated across the DRD collaborations.*
- ii. A coherent, strategic approach and sufficient resources to support **close cooperation with industry are required to address the rising costs and growing complexity in engineering, particularly in microelectronics**.*
- iii. To enhance efficiency and align developments with global technology trends in other fields, standardised, off-the-shelf solutions should be prioritised over custom designs, where applicable*



Computing:

- i. Adequate and sustained support for and coordination of software and computing must be provided to achieve the goals of future particle physics projects, starting with the HL-LHC. **Planning of future projects should include software and computing from the outset**, addressing energy efficiency and sustainability.*
- ii. In order to address theoretical and experimental needs such as in lattice QCD, data intensive workflows through WLCG, long-term data preservation and reinterpretation, the particle physics community should further engage with, and **help shape the evolution of EuroHPC, AI factories, and other global initiatives**.*
- iii. The European particle physics community must further **intensify its activities in AI** and sustain them with adequate resources. A **roadmap**, coordinated among CERN and national laboratories, institutes and universities, should be developed **to prioritise AI activities** taking into account synergies with international partners and other communities.*



III. Other research directions in particle physics:

- i. European contributions to both accelerator-based and non-accelerator neutrino and dark matter experiments are essential and should be supported.***
- ii. CERN should continue to provide support to the global long-baseline neutrino programme via the Neutrino Platform. The collaboration between CERN and non-accelerator-based experiments on technologies of mutual benefit should be continued.***
- iii. The ecosystem of European particle physics laboratories should continue to support a broad, diverse spectrum of key precision experiments in particle physics.***



IV. Theory

- i. *Europe should maintain a strong and diverse particle theory landscape, from formal to phenomenological aspects, while further strengthening and leveraging connections to neighbouring fields.*
- ii. *Collaborative efforts to improve the precision of theoretical predictions should be recognised and supported. Europe is world-leading in these areas and should strive to remain so by attracting, fostering and retaining early-career global talent. CERN should continue to be an integral part of all these efforts.*



V. Project Implementation, cooperation with large Particle Physics Laboratories (PPLs) in Europe

- i. The next flagship collider at CERN should be developed under CERN's leadership, with coordinated in-kind contributions from the PPLs. **Collaboration between CERN and PPLs should be strengthened for strategic technology developments.***
- ii. The large particle physics **Laboratory Directors Group (LDG)** should explore the possibility for a new initiative to enable and strengthen the implementation and promotion of scientific diversity in particle physics with a shared European vision.*
- iii. LDG must continue the coordination of the accelerator R&D roadmap by integrating strategic priorities, by enhancing collaboration across PPLs and CERN, and by optimising usage of laboratory resources. In addition, R&D efforts to enhance the sustainability and energy efficiency of accelerators from design to operation and decommissioning should be supported.*



VI. Synergies with Neighbouring Fields

- i. The European particle physics community, in coordination with APPEC and NuPECC, should maintain its scientific diversity via strong collaboration with nuclear and astroparticle laboratories and research infrastructures in Europe and beyond, including the Einstein Telescope in Europe and the Electron-Ion Collider in the US.*
- ii. CERN should continue its involvement in experimental nuclear physics and astroparticle physics at the current level. Consideration of additional experimental activities outside of CERN's accelerator-based particle physics programmes should be subject to adequate resources being available for CERN's primary mission.*



VII. Sustainability

- i. For every new proposed project, a detailed Life Cycle Assessment should be carried out at each stage from concept, design and implementation to quantify and minimise environmental impact.*
- ii. The particle physics community should continue and intensify its efforts to develop and adopt sustainable solutions.*
- iii. An effective balance between in-person and online meetings should be considered, in order to mitigate the environmental impact of travel.*



VIII. *Public engagement, education, communication, social and career aspects*

- i. Education, communication and engagement in particle physics should target a broad range of stakeholders, with a dedicated effort to reach diverse and underrepresented audiences.*
- ii. The many education, communication and outreach initiatives in the various European national communities, EPPCN, IPPOG and the Teacher and Student Forum should be further encouraged, integrated and supported by European institutions and CERN.*
- iii. **Dedicated European training programmes in accelerator science, computing and detector instrumentation**, including sustainability aspects as well as first-hand exposure to the latest technologies, should be further developed at the master and doctoral levels. The existing international schools in these areas should be strengthened to offer an expanded, coherent training programme.*
- iv. The community should actively promote the creation of **long-term positions for engineers and technicians**, as well as **physicists with technological expertise** in accelerators, detectors and computing. Two-way transfer of knowledge via mobility between industry and academia should also be encouraged.*
- v. The particle physics community should continue its unwavering commitment to place the principles of Equity, Diversity, and Inclusion (EDI) at the heart of all its activities.*
- vi. Current efforts for mentoring, easing mobility across institutions and promoting well-being of early-career researchers should be reinforced. In addition to scientific achievements, career evaluation should also consider technological, outreach and knowledge transfer activities.*





ESG: Future Steps



The recommendations will be reviewed by the Council in the coming months.

A final decision is expected at a dedicated Council Session in Budapest in May 2026.

A decision by the CERN Council on the possible construction of the FCC is expected around 2028.

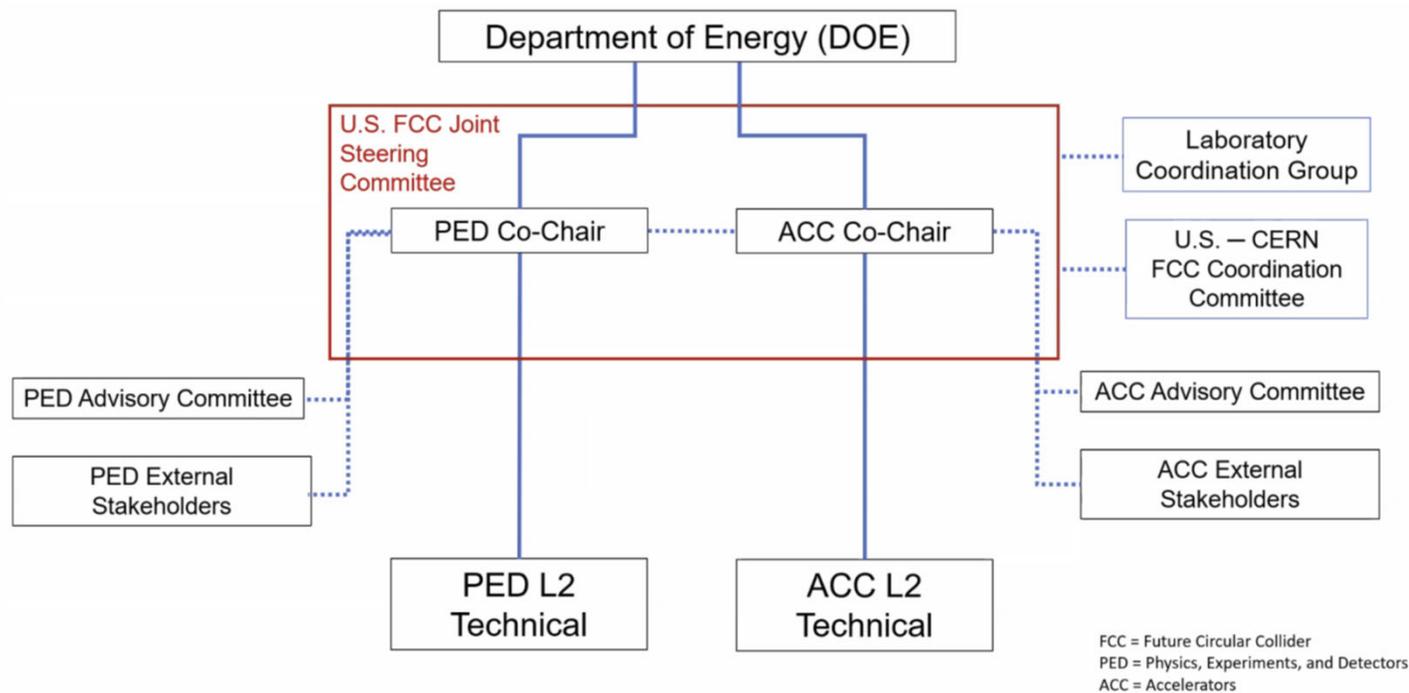


U.S. – an important step by the DOE: Focus on the „preferred option”

Remarkable rebranding: „Higgs Factory Coordination Consortia” (both linear and circular) →
→ U.S. „Higgs Factory Circular Collider”

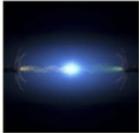
U.S. Higgs Factory Circular Collider Organization

<https://indico.global/event/14674/>





European Commission proposal for 2028-2034 MFF released in July

Moonshots					
 <p>Future Circular Collider</p> <p>What: Sustain Europe's leadership in particle physics by investing in CERN's next-generation collider.</p> <p>How: Co-invest with other CERN countries, leveraging Horizon Europe funding.</p>	 <p>Clean Aviation</p> <p>What: Lead the world in developing the next generation of CO₂-free aircraft.</p> <p>How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens.</p>	 <p>Quantum Computing</p> <p>What: Make Europe the first continent with fully integrated quantum computing in daily life.</p> <p>How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens.</p>	 <p>Next Generation AI</p> <p>What: Model the new AI on the laws of nature and grounded in physics and biology.</p> <p>How: AI developed by, with, and for European scientists and industry, drawing to Europe the world's best minds.</p>	 <p>Data Sovereignty</p> <p>What: Make Europe the global leader and safest hub for critical research data.</p> <p>How: Provide access to critical data for researchers, universities and companies, offering competitive advantage in tackling global challenges.</p>	
 <p>Automated Transport and Mobility</p> <p>What: Advance safe, inclusive, and emission-reducing automated transport and mobility in Europe.</p> <p>How: Invest in smart transport systems to improve traffic, reduce emissions, and enhance access.</p>	 <p>Regenerative Therapies</p> <p>What: Deliver breakthrough therapies to improve people's health and lives.</p> <p>How: Harness Europe's scientific strengths to treat incurable diseases and personalise medicine.</p>	 <p>Fusion Energy</p> <p>What: The first commercial nuclear fusion power plant, generating safe, consistent, and reliable electricity.</p> <p>How: Overcome the scientific and technological challenges necessary to put fusion on the grid in Europe by 2034.</p>	 <p>Space Economy</p> <p>What: Make Europe the leader in the space economy.</p> <p>How: Develop the next generation launch vehicles such as reusable rockets, able to deploy massive cargo by 2040.</p>	 <p>Zero Water Pollution</p> <p>What: Move towards zero pollution of water in the EU.</p> <p>How: Stimulate innovation to build a true water-smart economy which secures sufficient, clean and affordable water and sanitation to all at all times.</p>	 <p>Ocean Observation</p> <p>What: Achieving strategic autonomy in ocean observation infrastructure, data and information services.</p> <p>How: Developing, connecting, governing and securing the next generation of European ocean observing technologies.</p>

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FCC is the first of 11 “Moonshots” examples, with a proposed budget line of 3 billion Euros.

FCC is also the **only research infrastructure** among current Moonshots.

First time that the European Commission proposes to support the construction of a (flagship) project at CERN

This is **draft MFF** → not yet approved by the European Council (timescale: end 2027)
→ support of CERN Member and Associate Member States that are also EU members will be crucial to keep this budget line for FCC.

And sponsors...

Fabiola Gianotti, SPC, 22 September 2025



CERN Press Release 12.12.2025 (excerpt)

PR12.25
18.12.2025

Private donors pledge 860 million euros for CERN's Future Circular Collider

Geneva, 18 December 2025. For the first time in CERN's history, private donors (individuals and philanthropic foundations) have agreed to support a CERN flagship research project. Recently, a group of friends of CERN, including the Breakthrough Prize Foundation, The Eric and Wendy Schmidt Fund for Strategic Innovation, and the entrepreneurs John Elkann and Xavier Niel, have pledged significant funds towards the construction of the Future Circular Collider (FCC), the potential successor of the Large Hadron Collider (LHC). These potential contributions, totalling some 860 million euros and corresponding to 1 billion US dollars, would represent a major private sector investment in the advancement of research in fundamental physics.



- **FCC funding scenario ?**
- **FCC governance model ?**
- **FCC acceptance by the local community → public dialogue**
- **FCC: preparations for the pre-TDR**

Work programme for the pre-TDR phase is being defined around the following key dates and milestones:

- **2026:** Lattice selection; project baseline freeze; public debate
- **2026–27:** Environmental impact assessment; prototypes; integration
- **mid-end 2027:** CE tender-design maturity; updated costs; full risk register, implementation plan; funding model; pledges



Thanks for your attention

- Some slides were taken from presentations of

Karl Jakobs

<https://agenda.infn.it/event/44943/overview>

and Guy Wilkinson

FCC Physics, Experiments and Detectors
Guy Wilkinson

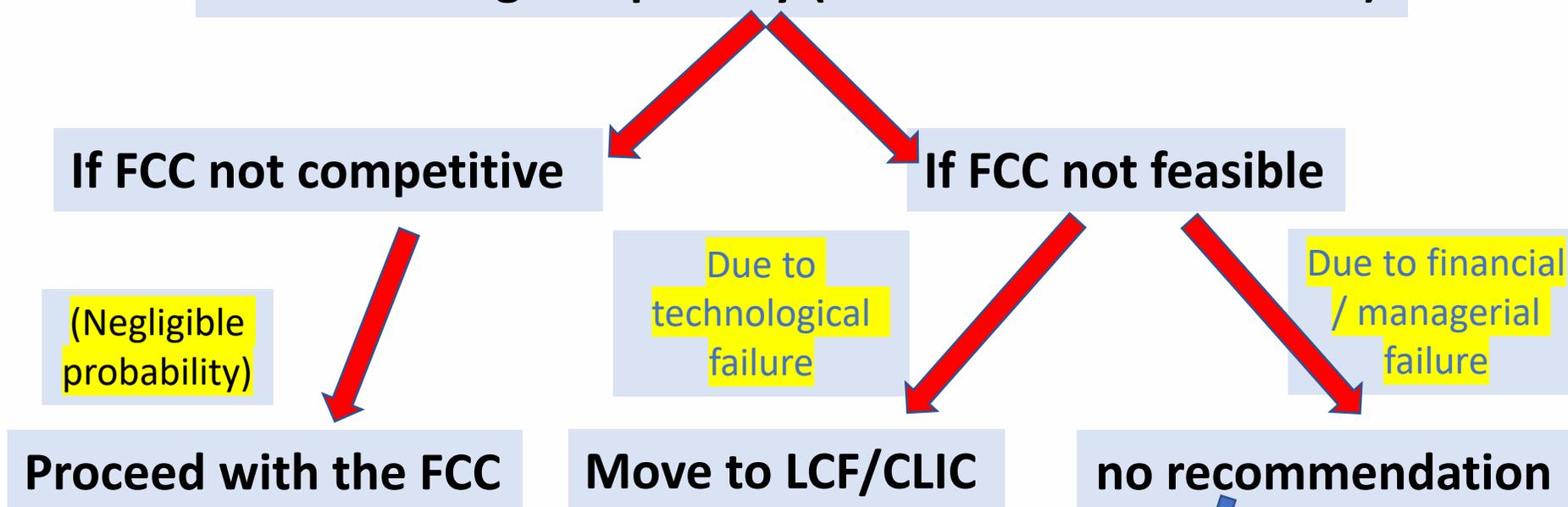
8/9/25



National Strategy of our community

<https://indico.cern.ch/event/1439855/contributions/6461412/>

FCC as the highest priority (both FCC-ee and FCC-hh)



If the preferred option were to turn out not to be feasible, we have, after thorough discussion, decided to refrain from providing a direct recommendation. In our view, especially if financial feasibility were to become an issue, the most appropriate solution would be to reconsider the FCC programme — particularly its timeline — in order to adapt it to the available resources.



FCCFS Finances

in MCHF	2021-2023	2024	2025	2026	2027	Total
FCC feasibility phase	44.2	29.7	9.3			83.2
<i>Material</i>	21.4	18.0	6.1			45.5
<i>Staff</i>	22.8	11.7	3.2			37.7
FCC study continuation			41.0	54.7	58.9	154.5
<i>Material</i>			24.5	27.9	29.9	82.4
<i>Staff</i>			16.4	26.8	29.0	72.1
Total	44.2	29.7	50.2	54.7	58.9	237.7



FCC Project: Prospects and Physics Programme



FCC Feasibility Study: Accomplished with Success

The recent meetings (Sept, 8-10) of the SPC and FC subjected the FCC FS project to the detailed scrutiny, based also the evaluations of the SAC and the CRP

- **SPC (Scientific Policy Committee of CERN Council):**

„The baseline physics program (FCC-ee → FCC-hh) is coherent and convincing”

- **FC (Finance Committee of CERN Council):**

„The FC is reassured to see that the SAC and the CRP have not identified any major showstoppers from the perspective of technical and scientific feasibility”

- **SAC (Scientific Advisory Committee of the FCC FS):**

„The SAC has concluded that, insofar as can be determined at this stage, the project is feasible and provides an excellent opportunity for CERN’s next flagship project and its long-term future”

- **CRP (Cost Review Panel of the FCC FS):**

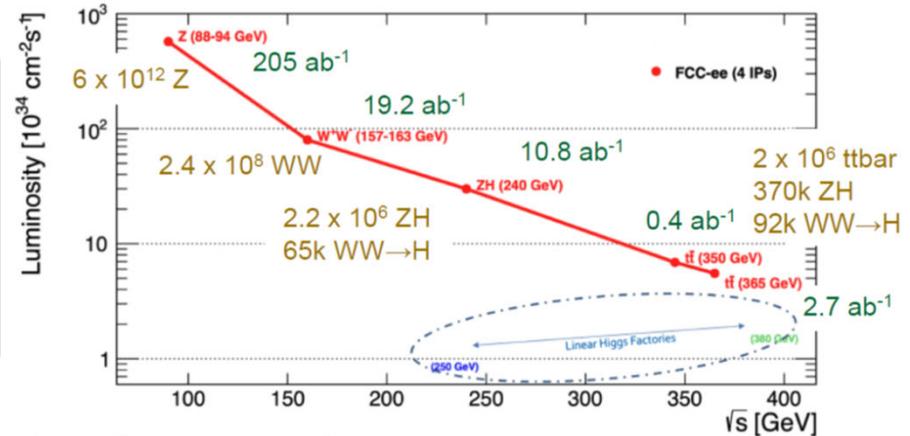
„The CRP has not found missing elements in the costing”



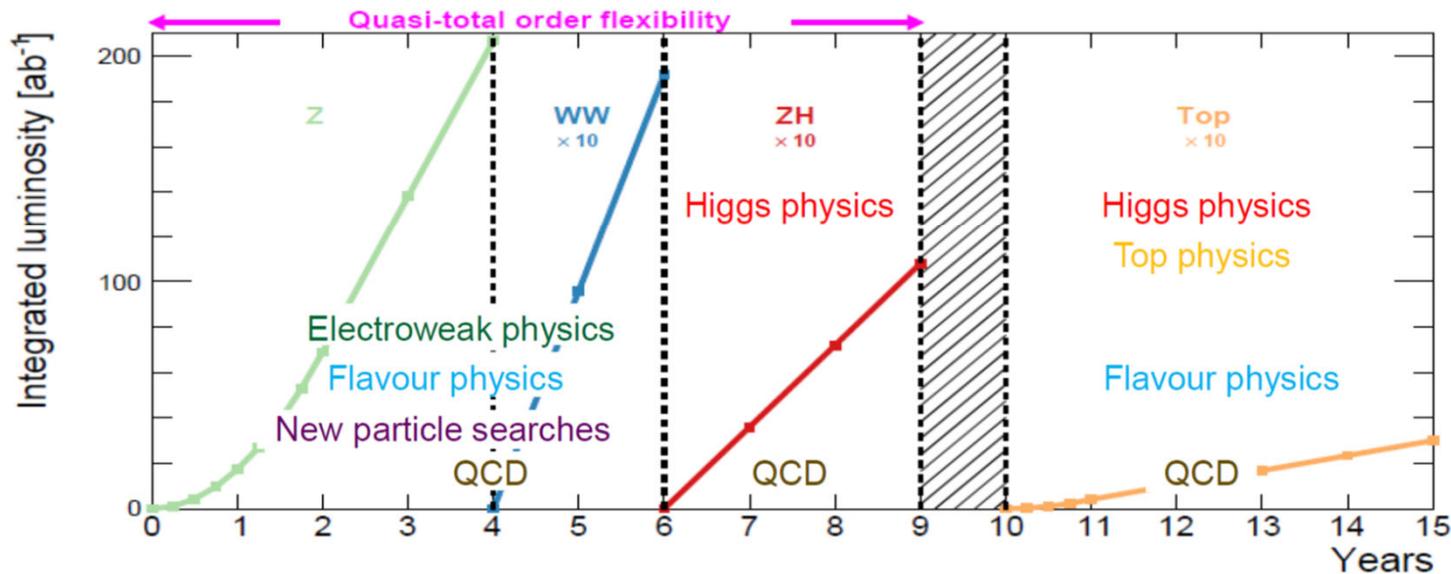
FCC-ee Essentials and Enabling Characteristics

FCC-ee enabling characteristics:

- Huge samples → extreme precision;
- Four (+) energy points, explored in a compact 15-year programme;
- With exciting options for extension (e.g. Higgs-pole run [backups]).



Physics goals encompass Higgs studies, and very much more:



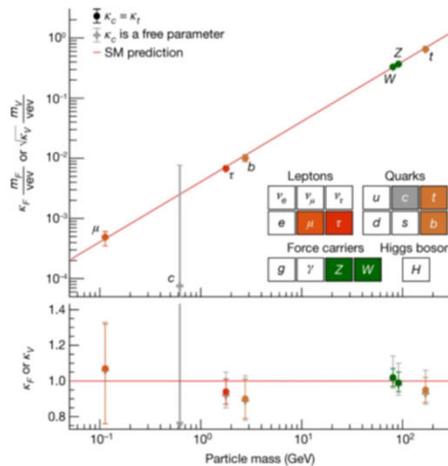
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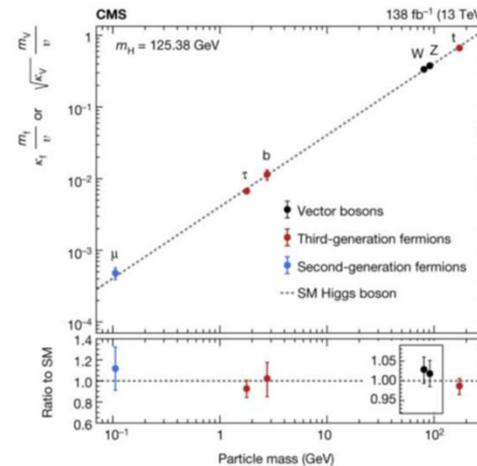
Higgs Physics at the End of the HL LHC

Higgs is a uniquely odd particle, which is connected to many of the open questions of the Standard Model (SM), and possibly also to cosmology.

Great work of LHC, ATLAS and CMS → Higgs superficially behaving as in SM.



[ATLAS, Nature 607 (2022) 52]



[CMS, Nature 607 (2022) 60]

However, much too early to declare ‘mission accomplished’:

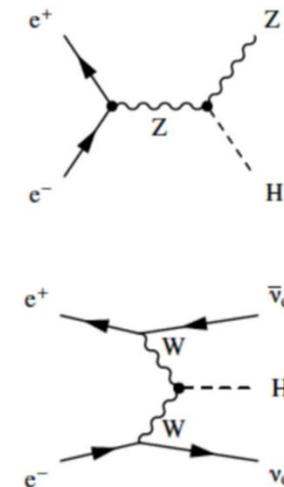
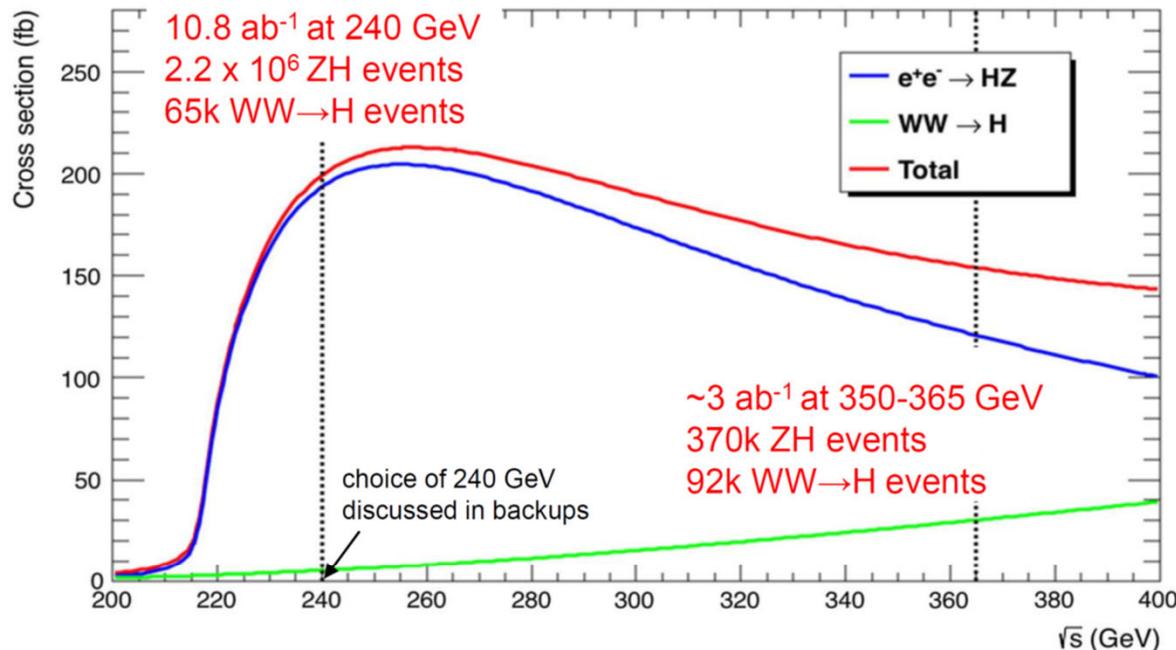
- Precision on couplings ($\sim 5\%$ in best case) not yet in ‘interesting regime’;
- Very limited information on second generation quarks;
- Nothing known about how Higgs couples to ‘everyday’ matter (first generation);
- All results model dependent, as Higgs width is badly known;
- Essentially no knowledge on how the Higgs couples to itself.

HL-LHC will make progress (e.g. self-coupling), but picture will not change much.

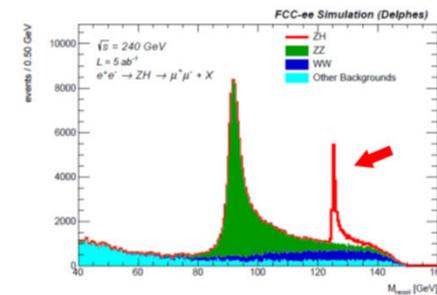


Higgs Studies at FCC-ee

Central goal of FCC-ee: *model-independent* measurement of Higgs width and couplings with (<) % precision. Achieved through operation at two energy points.



Why model independent? e.g. in $e^+e^- \rightarrow Z^*H$ events, presence of Higgs can be inferred independent of its decay mode by reconstructing recoiling Z decay.





Higgs Coupling Measurements at FCC-ee

Sensitivity of HL-LHC and FCC-ee projections, as ratio of measured coupling to SM expectation ('κ'):

- FCC-ee reaches 0.1-0.5% precision on many of the most interesting couplings;
- Accesses, for the first time, second-generation quarks;
- Results are model independent;
- Achieved in a compact period of eight-years operation.

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.49
κ_g (%)	2*	0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	–	+29 –67
Γ_H (%)	–	0.78
\mathcal{B}_{inv} (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
\mathcal{B}_{unt} (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

* next to HL-LHC numbers → not model independent

But can this not be also done at other e^+e^- machines ? To an extent... but takes much longer to reach this precision at e.g. the ILC [see backups and [arXiv:1412.13130](https://arxiv.org/abs/1412.13130)].

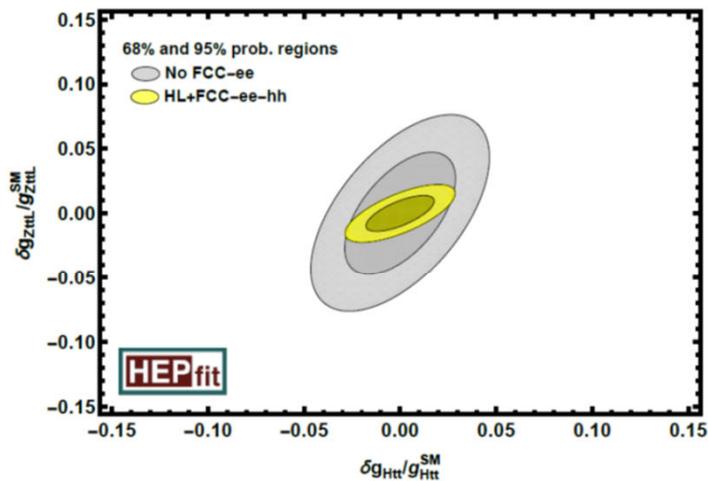
All e^+e^- Higgs factories are equal, but some are more equal than others !



Higgs Coupling Measurements at FCC-hh

FCC-hh completes the job. The dataset of 20 billion Higgs bosons allows for precise measurements of the rare decay modes with high p_T events. Normalisation provided by FCC-ee measurements allows for full model independence, and higher precision.

e.g. normalise $H\bar{t}\bar{t}$ to $Z\bar{t}\bar{t}$, benefitting from FCC-ee results at 365 GeV to constrain κ_t .



Great complementarity and synergy between -ee and -hh !

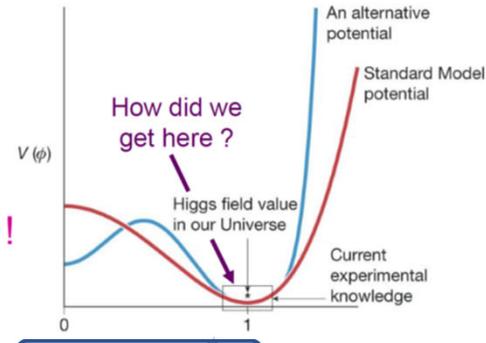
Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.49	0.49
κ_g (%)	2*	0.54	0.54
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.87	0.87
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	–	+29 –67	+29 –67
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

* next to HL-LHC numbers → not model independent

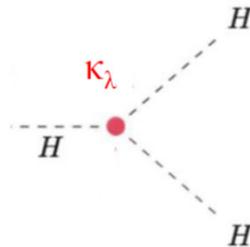


Higgs Self-Coupling at FCC-hh

A central contribution of FCC-hh to Higgs physics, will be to tell us the shape of the Higgs potential, which is linked to critical questions at the dawn of the universe !

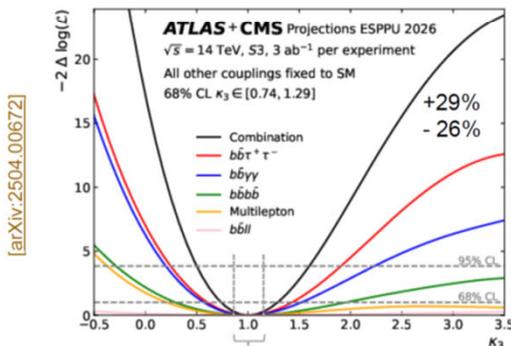


[Salam, Wang, Zanderighi, Nature 607 (2022) 411]

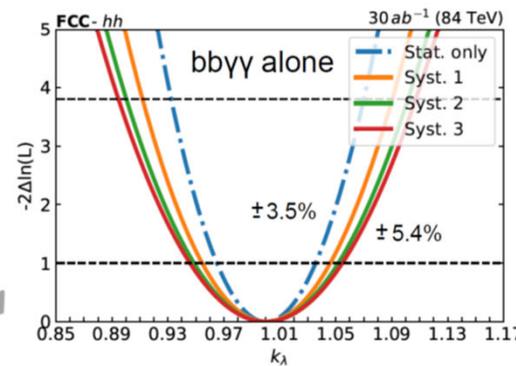


Expressed through the parameter κ_λ ($=1$ in SM), which should be measured with $O(\%)$ precision. Can be accessed through self-coupling, *ie.* di-Higgs production

HL-LHC + loop-sensitive measurements at FCC-ee [backups] will reach $\sim 18\%$ precision. FCC-hh, with 30 million Higgs pairs, can reach $2-3\%$ (final Feasibility Study projection, with $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ combination, ready later this month).



[arXiv:2504.00672]

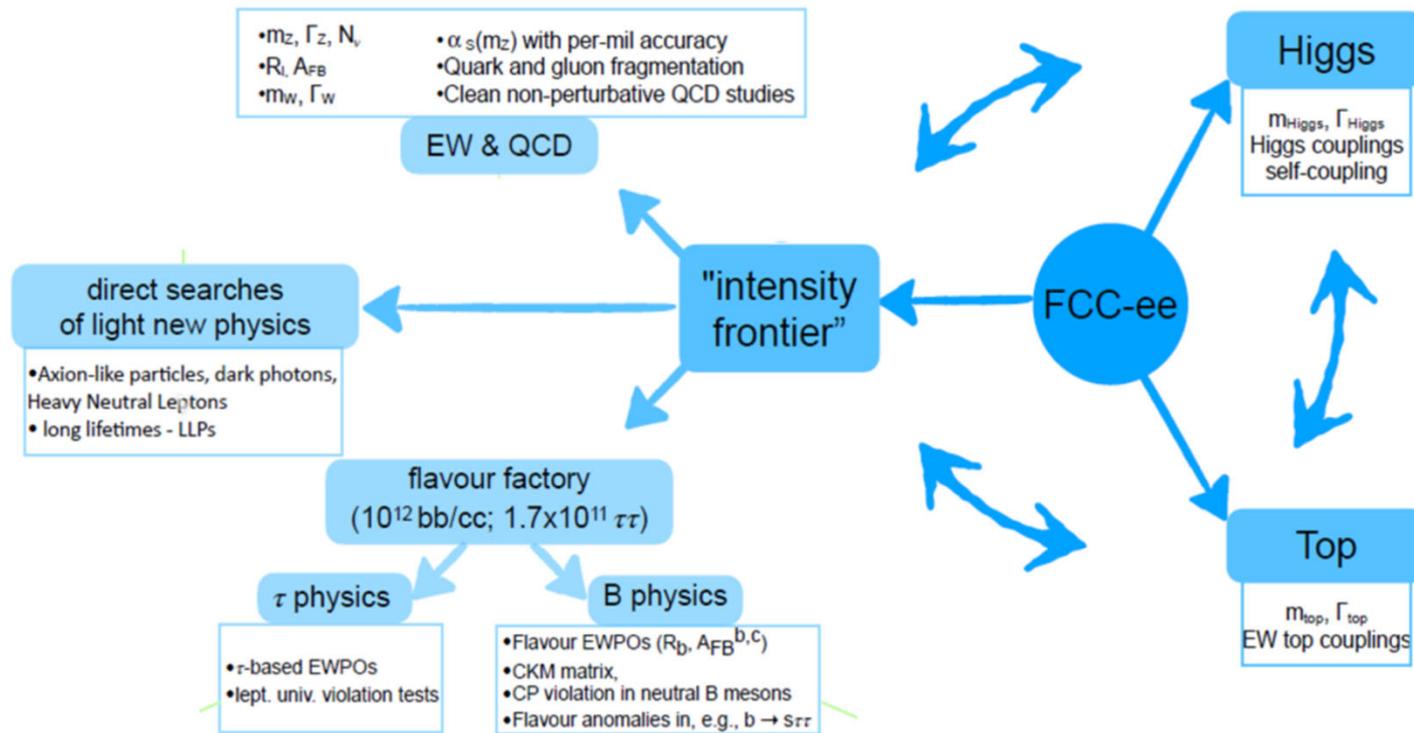


[https://doi.org/10.17181/5mqfv-xnd34]



The FCC is Much More than a Higgs Factory...

The FCC-ee is much, much more than a Higgs factory. Its very high luminosity across a range of energies gives it an immensely broad physics programme.



[Christophe Grojean]

This diversity is unique to FCC-ee, and is a point of contrast with a linear collider. Invaluable in providing the highest possible reach for new physics (NP) discovery.



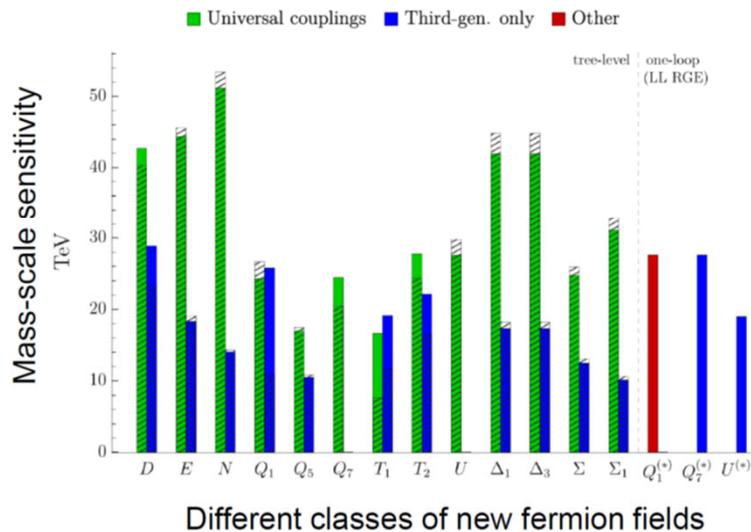
Discovery through Precision: EW@FCC-ee

The Tera-Z programme is not just 'LEP revisited'. The 10^5 increase in sample sizes will enable a *giant* leap in sensitivity, and open up many new measurements.

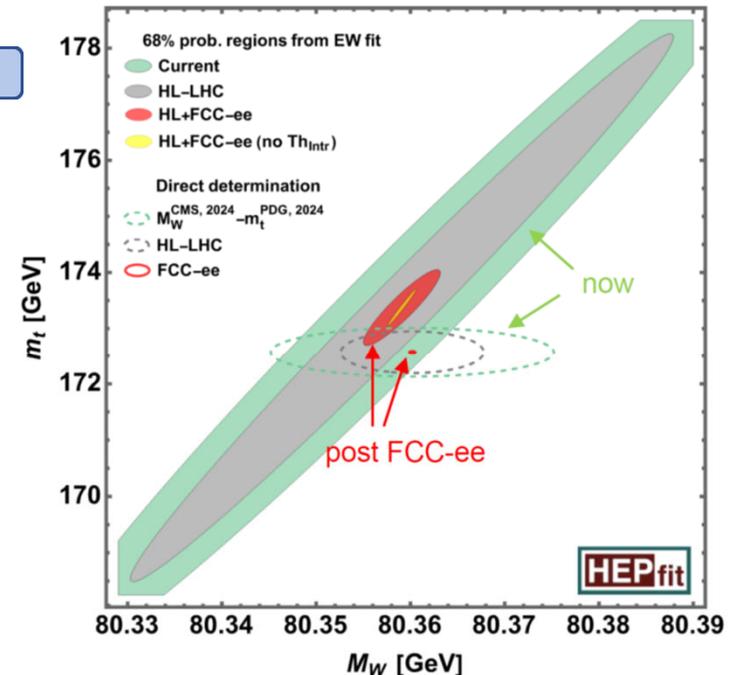
Improvements of e.g. ~ 200 on Γ_Z precision give great sensitivity to NP contributions

Up to $O(\text{TeV})$ masses "Tera-Z provides an almost inescapable probe of heavy NP", with sensitivity in some cases to many 10s of TeV.

Similar story applies in WW and $t\bar{t}$ energy regimes – both essential for complete picture.



[Allwicher, McCullough, Renner, arXiv:2408.0399]



Δm_W : 13.3 MeV (PDG) \rightarrow 0.5 MeV (FCC - ee)

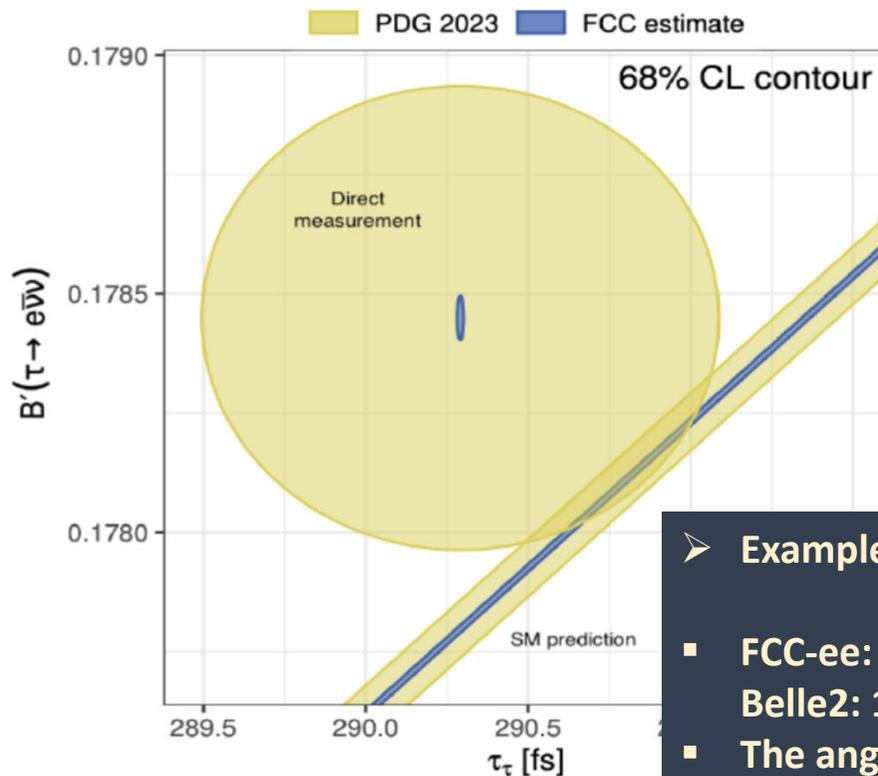
Δm_t : 310 MeV (PDG) \rightarrow 10 MeV (FCC - ee)



Flavour Physics at FCC-ee

Tera-Z will produce a huge number of beauty hadrons in a very clean environment. Many measurement opportunities that are highly complementary to LHCb Upgrade I
FCC-ee will also provide world's largest sample of 'background free' tau decays.

e.g. lepton universality tests with taus.

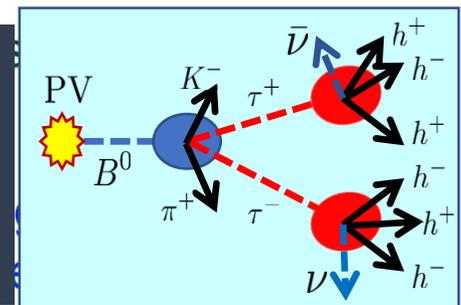


- Example: $B \rightarrow K^*(892)\tau^+\tau^-$ decay:
 - FCC-ee: 1000 signal events expected
 - Belle2: 10 events expected
 - The angular analysis feasible

FCC is the **only** planned collider where b, c and τ physics can be advanced in the post HL-LHC /

Belle II era – another blessing of the Tera-Z programme !

(Also great opportunities to measure 'on-shell' CKM elements in W and top decays).

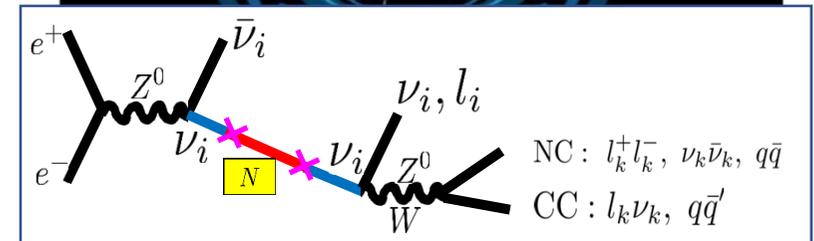
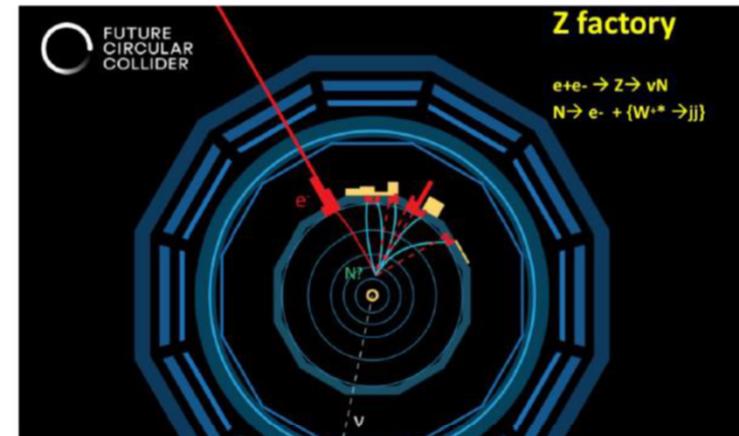
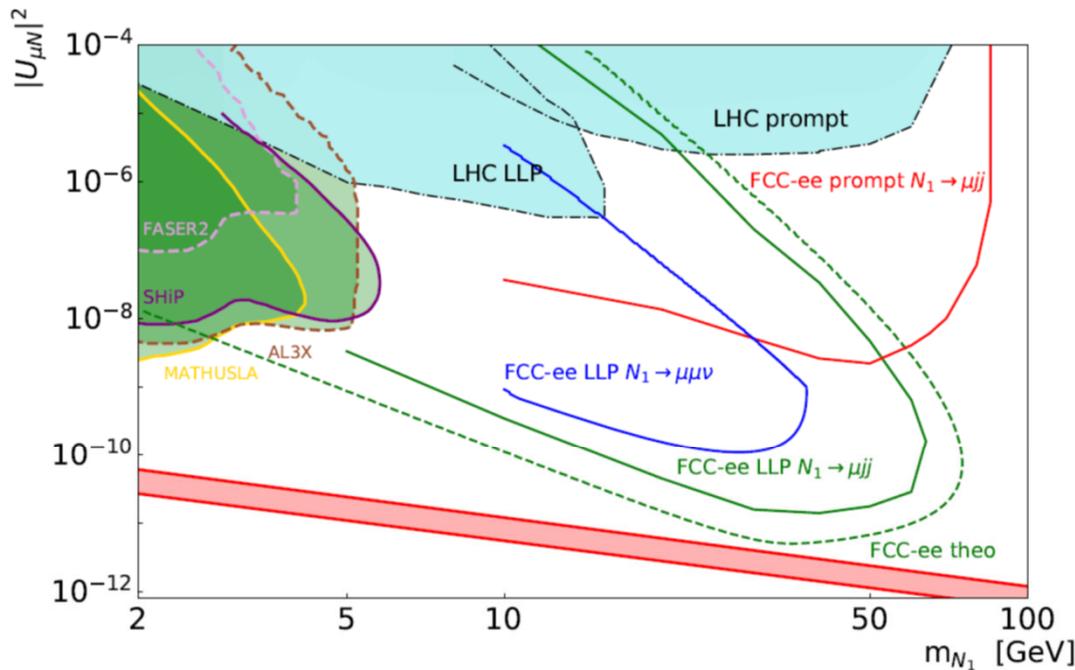




Direct Searches for New Particles at FCC-ee

FCC-ee have remarkable prospects in direct searches, again profiting from the huge samples at Tera-Z. The search for 'low' mass, feebly coupling new particles is a vital endeavour, complementary to searches at the 'energy frontier' (i.e. FCC-hh).

e.g. heavy-neutral lepton searches – sensitivity complementary to SHiP and LHC



Similarly, high sensitivity in ALP searches from $e^+e^- \rightarrow a\gamma \rightarrow \gamma\gamma\gamma$ and $\gamma\gamma \rightarrow a \rightarrow 2\gamma$.



High Mass Searches at FCC-hh

FCC-hh main purposes are Higgs studies (discussed) & as energy-frontier machine
 High parton centre-of-mass energies will allow for discoveries up to very high masses, e.g. in searches for Higgs compositeness or Supersymmetry, e.g. :

	84 TeV	
BSM object (%)	FSR baseline	
$Z'_{SSM} \rightarrow \ell\ell$	37	[TeV]
$Z'_{SSM} \rightarrow \tau\tau, tt$	16	
$Z'_{TC} \rightarrow tt$	20	
$G_{RS} \rightarrow WW$	19	
$Q^* \rightarrow jj$	35	
\tilde{W}^0	4.0	
\tilde{h}^0	1.1	

Impressive and very significant – for example. \tilde{W}^0 and \tilde{h}^0 are the wino and higgsino WIMP DM candidates, searched for by disappearing track signature, which are constrained by cosmology to lie below ~ 3.5 TeV and ~ 1 TeV, respectively. Can also discover new Higgs bosons in the range 5-20 TeV.

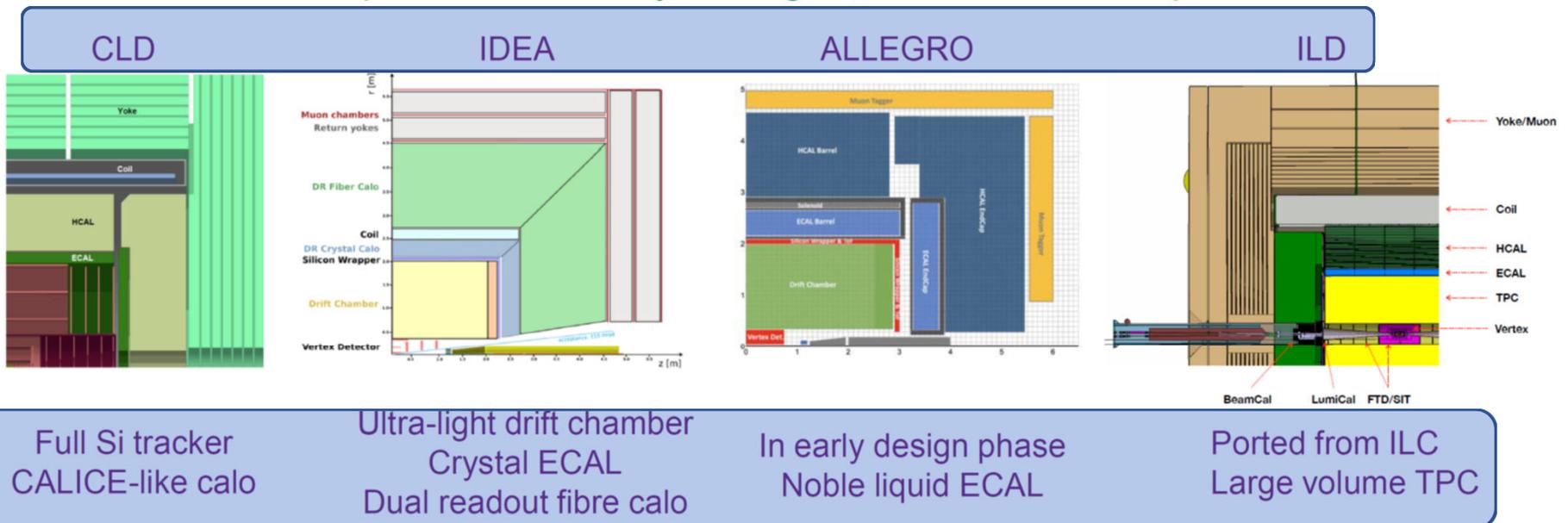


Detectors Developments

Work progressing to understand detector requirements for *full* physics programme.

Call opened late 2024 for Expressions of Interest for detector studies and for 'detector concepts'. Enthusiastic response from community (39 joint submissions – see [here](#)). In parallel, close ongoing communication with DRD collaborations.

Four 'detector concepts' have already emerged, as test beds for possible solutions.

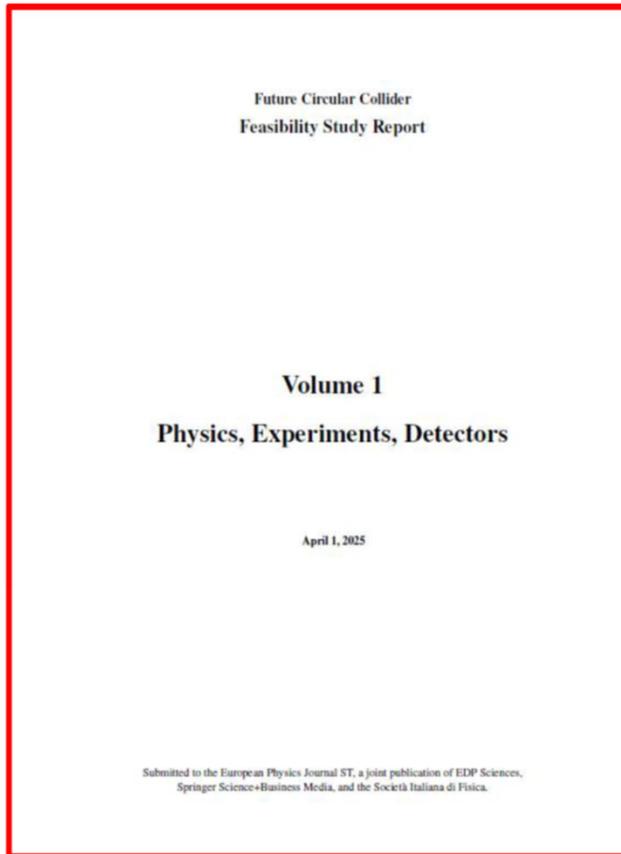


...these are NOT yet collaborations or locked-in designs. Full participation of community, and close collaboration with DRDs, needed to progress in next phase.



FCC Physics Programme: Source Materials

Intense physics, experiment and detector studies have been conducted since launch of Feasibility Study (FS) in 2021, summarised in Volume 1 of FS Report (FSR).



[CDS, [arXiv:2505.00272](https://arxiv.org/abs/2505.00272),
submitted to EPJC]

In addition, focused 10-page documents have been prepared for the ESPPU:

The FCC integrated programme:
a physics manifesto [CDS, [ESPPU #241](#),
[arXiv:2504.02634](#)]

Prospects in EW, Higgs and top
physics at FCC [CDS, [ESPPU #217](#)]

Prospects in BSM physics at FCC [CDS, [ESPPU #242](#)]

FCC: QCD physics [CDS, [ESPPU #209](#)]

Prospects for flavour physics at FCC [CDS, [ESPPU #196](#)]

Prospects for physics at FCC-hh [CDS, [ESPPU #227](#)]

Expressions of interest for the
development of detector concepts and
sub-detector systems for the FCC [CDS, [ESPPU #95](#)]

What follows is a summary of the key points.



Take-Away Message

- **Update of the European Strategy for Particle physics is in full swing with the final outcome next March and May**
- **The FCC programme is extremely attractive, gains momentum, and passes (with flying colors) the subsequent milestones on the path of its approval**



Accelerator Challenges

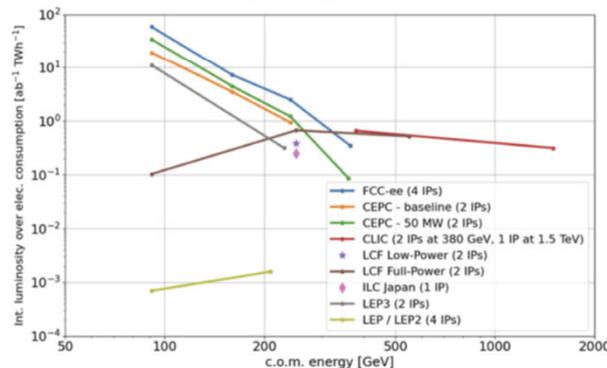
Circular Colliders (e^+/e^-)

Beam is recirculated, enabling high luminosity, but **synchrotron radiation (SR) losses constrain the energy**

- High luminosity is achieved with **advanced but challenging schemes (e.g. crab waist)**
- High-luminosity goals may be constrained by **beam-beam and intensity effects**

Lumi / bunch pair (different machines: E, # bunches)
(SuperKEKB²⁰²⁴: $2.2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} \rightarrow \text{FCC-ee Z: } 1.3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$)

- Smaller circumference imply **strong quadrupoles / sextupoles** to maintain luminosity (e.g. LEP3)



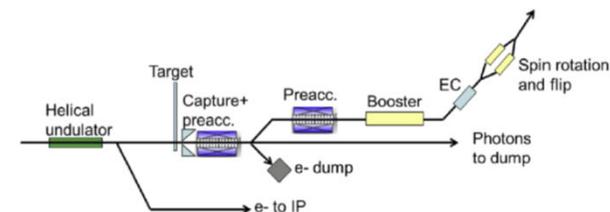
Linear Colliders

No SR but beam energy dumped after a single collision

- High acceleration gradients** needed for cost efficient accelerators with reasonable length
- Beamstrahlung** constrains beam parameters at IP
- The small beams needed for high luminosity require stabilisation and extremely tight optics control and correction capabilities
- Positron production** and capture at high intensity is critical

(SLC: $\sim 6 \times 10^{12} \text{ e}^+/\text{s}$)

LCF: $\sim 4\text{-}8 \times 10^{14} \text{ e}^+/\text{s} \rightarrow \text{R\&D needed}$



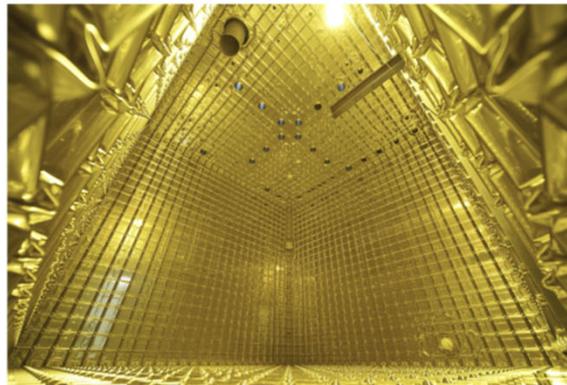
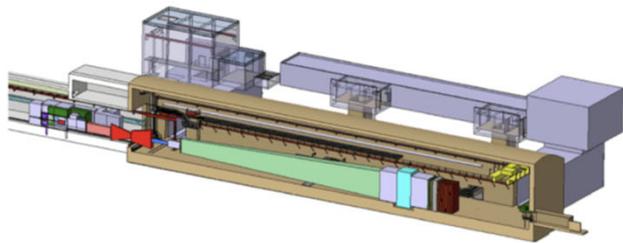


Diversity in the Physics Programme

Keeping **diversity in the particle physics** programme is essential: the next collider project should not come at the expense of a diverse scientific programme in Europe in terms of resources

Ensuring a diverse and comprehensive physics programme is crucial for addressing fundamental physics questions, including fixed-target, neutrino, flavour, astroparticle and nuclear physics experiments

We do not know where new physics might be hiding → potential for groundbreaking discoveries



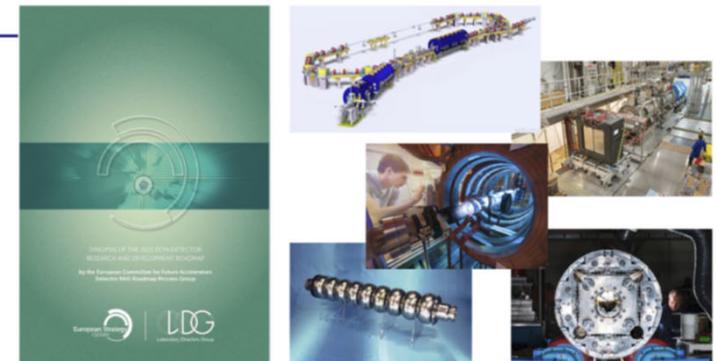


R&D on Accelerator Technologies

2020 Strategy Update:

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include **high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.**

- Accelerator R&D on **technologies** (magnets, RF systems, ...) remains a **high priority** and appropriate investments have to be made; the developments on **advanced concepts** should continue with adequate effort to prepare future projects
- The European Accelerator Roadmap of LDG should be continued with an updated program; **future R&D lines must be aligned with the needs of the highest priority projects** defined in the 2026 strategy
- It is essential to set up a **coherent programme between CERN, the Large National Laboratories in Europe and with international partners** to address the major topics.
- Industry needs to be involved **as early as possible** and production be industrialised wherever possible
- Besides of key performance parameters also **energy efficiency and sustainability aspects** must be optimized with high priority





R&D on Detector Technologies

2020 Strategy Update:

The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large.

- Eight **Detector R&D Collaborations** (DRDs) have been set up, following the ECFA Detector R&D Roadmap, **focussing on strategic R&D**
- Still in infancy, but expected to grow, once HL-LHC is built
- **General Strategic recommendations** have not yet all been implemented

<p>DRD1: Gaseous Detectors Large · Fast · eco-friendly gases · MPGD, e.g. GEMs</p> <p>PICOSEC: NIMA903 (2018) 317</p>	<p>DRD3: Semiconductor Det. Monolithic CMOS · LGADs · radiation hardness · interconn.</p>	<p>DRD6: Calorimetry Energy resolution · High granularity · dual readout · particle flow · sandwich · optical</p>	<p>DRD7: Electronics ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access</p>						
<p>DRD2: Liquid Detectors for Neutrinos · Dark Matter · Ovbb</p> <table border="1"> <thead> <tr> <th>Noble Elements</th> <th>Liquid Scintillators</th> <th>Water Cherenkov</th> </tr> </thead> <tbody> <tr> <td> <ul style="list-style-type: none"> Argon & Xenon Ionization chamber & nanopill UV Scintillation, light propagation & detection </td> <td> <ul style="list-style-type: none"> Visible scintillation, light propagation Scintillator properties Optical coupling </td> <td> <ul style="list-style-type: none"> Cherenkov light, light propagation Cladding for light capture </td> </tr> </tbody> </table>	Noble Elements	Liquid Scintillators	Water Cherenkov	<ul style="list-style-type: none"> Argon & Xenon Ionization chamber & nanopill UV Scintillation, light propagation & detection 	<ul style="list-style-type: none"> Visible scintillation, light propagation Scintillator properties Optical coupling 	<ul style="list-style-type: none"> Cherenkov light, light propagation Cladding for light capture 	<p>DRD4: Photon detectors vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID and RICH</p>	<p>DRD5: Quantum Sensors Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks Applications in LEPP, first projects in HEPP happening</p>	<p>DRD8: Mechanics Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality</p>
Noble Elements	Liquid Scintillators	Water Cherenkov							
<ul style="list-style-type: none"> Argon & Xenon Ionization chamber & nanopill UV Scintillation, light propagation & detection 	<ul style="list-style-type: none"> Visible scintillation, light propagation Scintillator properties Optical coupling 	<ul style="list-style-type: none"> Cherenkov light, light propagation Cladding for light capture 							



Future HEP Computing

The goal of the ongoing software and computing development is to facilitate the successful and timely delivery of the best possible physics results

- HL-LHC computing is not an easy journey, but it should be feasible, provided an **intense and uninterrupted R&D** is carried out.
- Likewise, for any future project chosen, the required software and computing should be feasible, **provided adequate person power and funding are available**
- **Successful projects and collaborations** such as WLCG, GEANT, ROOT, KEY4HEP, ... and their deliverables and services **need to be sustained**
- Make sure not to miss the opportunities to **adopt new new technologies**, particularly GPUs and AI, as well as Quantum Computing on a longer timeframe.
- We may not have a clear picture what our computing environment will look like 40 years from now, **but we have an excellent record to adapt and use whatever is available to its full potential.**

A collaborator setting up the event display, showing an HL-LHC event in 1955

4.5 megabytes of data in 62,500 punched cards (1955) = 1 HL-LHC RAW event (collected at 10 kHz)

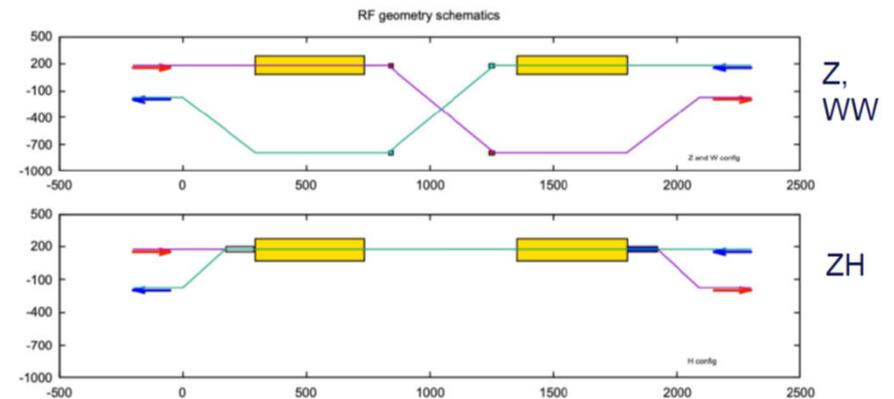
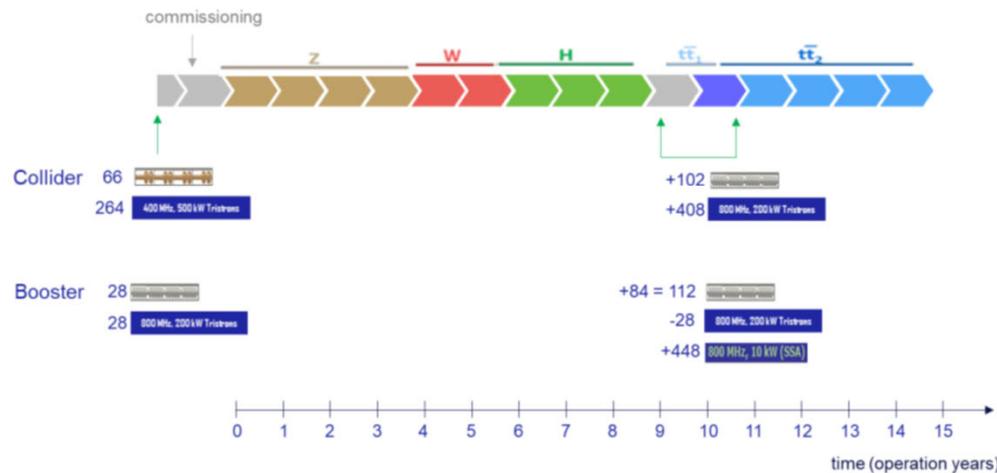


From T. Boccali & B. Kersevan



FCC Integrated Programme: FCC-ee Operation Sequence and SRF Concept

- 2-cell 400 MHz SRF system for Z, W and ZH, entire system installed at operation start of FCC-ee
- Constant cavity coupling thanks to reversed phase operation at Z
- Full installation prior operation, incl. cryogenic system (vs staging with shutdown requirements)
 - Allows flexibility and switching between Z, WW, ZH operation modes.
 - Suppression of the single-cell 400 MHz system (reduced R&D, installation, commissioning, etc...)
- 800 MHz SRF system real estate gradient increases by ~ 20% by using 6 cells cavities instead of 5 cell.



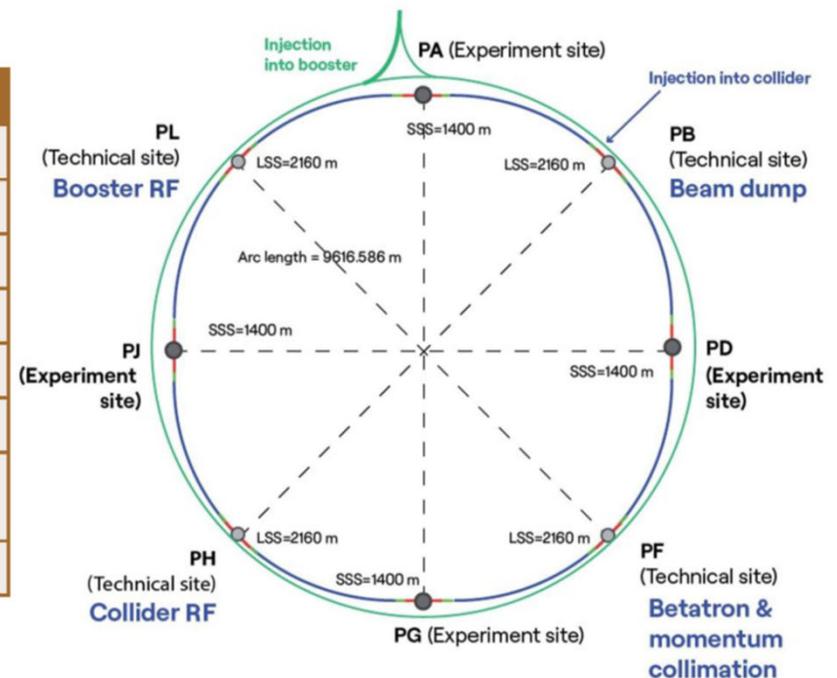


FCC Integrated Programme: Stage 1 e^+e^- Collider

Main parameters

parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1283	135	26.8	5.0
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	140	20	7.5	1.4
total integrated luminosity / IP / year [$\text{ab}^{-1} / \text{yr}$]	17	2.4	0.9	0.17
beam lifetime [min]	15	12	12	11

FCC-ee functional layout

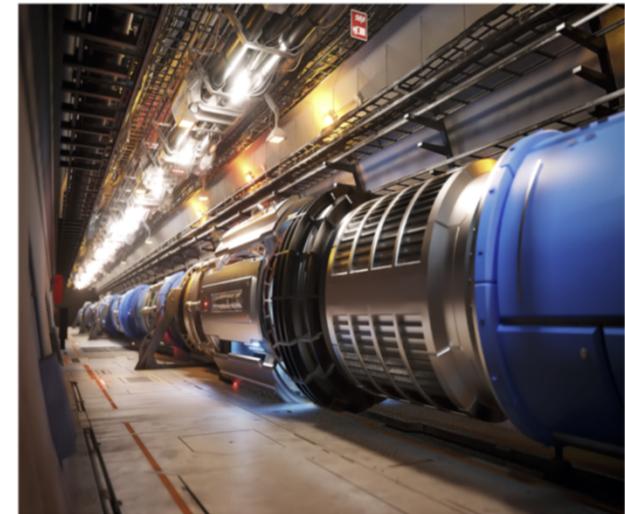




FCC Stage Two: FCC-hh

- Parameter optimization towards “acceptable power consumption” → $\sqrt{s} = 85 \text{ TeV}$
- Magnetic field considered realistic with today’s technologies (Nb_3Sn , 14 T)
- Optimized accelerator optics design to increase arc dipole filling factor to maximise beam energy
- Increase cryo-magnet operation temperature

Parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000



	FCC-hh 90.7km 14T	FCC-hh 90.7km 14T
Magnet temperature	1.9 K	4.5 K
Power consumption @ 85 TeV c.m.	< 430 MW	< 330 MW
Yearly electricity consumption	< 2.8 TWh	< 2.2 TWh

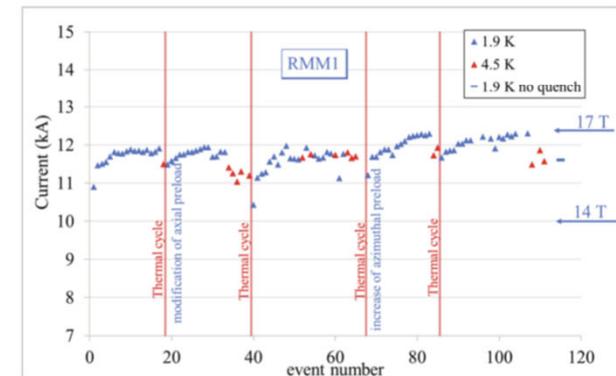
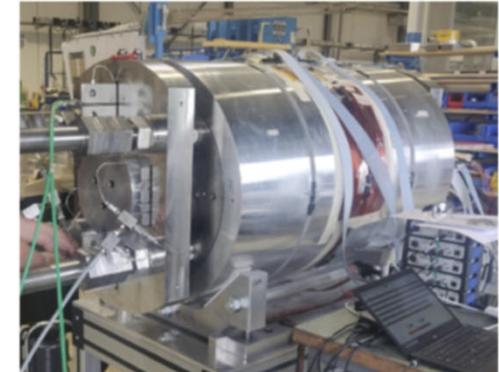


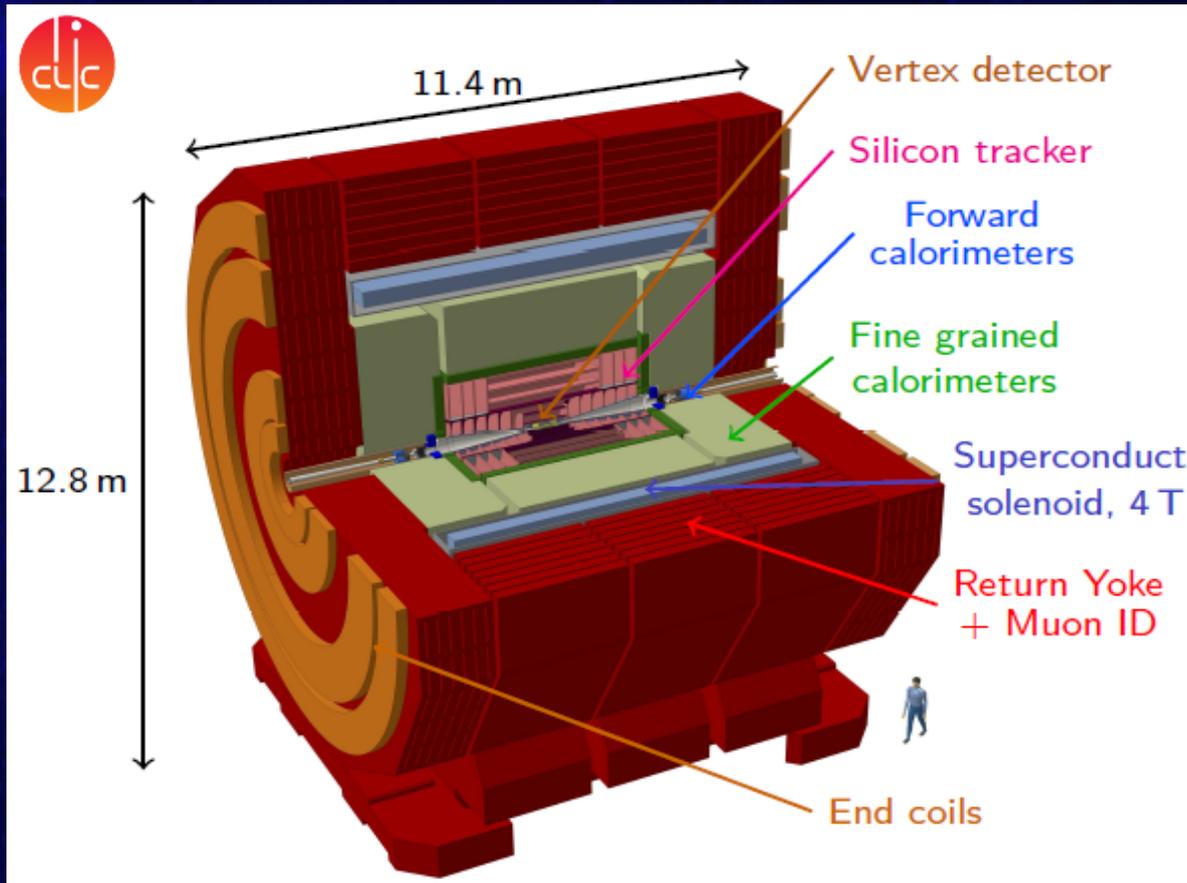
Highest energy hadron collider

- Parameter optimization towards “acceptable power consumption”
→ $\sqrt{s} = 85 \text{ TeV}$
- Magnetic field considered realistic with today’s technologies (Nb_3Sn , 14 T)

High priority **R&D on High- and Low-Temperature Superconductors** to identify the best solution

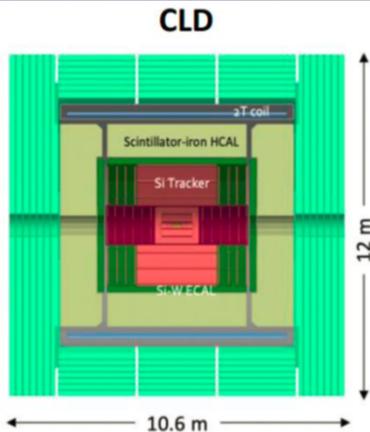
- **Superconductor supply and cost are critical**
- Magnets need sophisticated system integration to ensure high field strength and acceptable field errors, but also efficient heat removal from SR deposition, good vacuum conditions for beam
- Increase of circulating beam energy an order of magnitude compared to LHC challenges the machine protection and collimation





- Low material budget
- Hermeticity (forward region)
- Precision vertex and tracking detectors
- High granularity calorimeters (Particle Flow Algorithm PFA)
- Cost 500-700 MEUR
- Technology fully mature

- Number of electronic channels: $>10^9$
- Most of the machine induced limitations are imposed by the Z pole run (large collision rates (33 MHz) and continuous beams, large event rates (100 kHz), beamstrahlung)



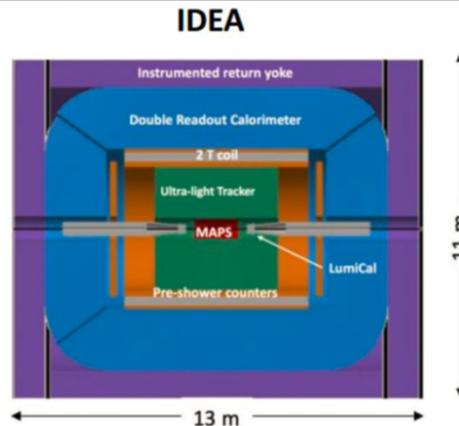
- Well established design
 - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
 - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
 - σ_p/p , σ_E/E
 - PID ($\mathcal{O}(10\text{ ps})$ timing and/or RICH)?
 - ...

FCC-ee CDR: <https://link.springer.com/article/10.1140/epjst/e2019-900045-4>

<https://arxiv.org/abs/1911.12230>

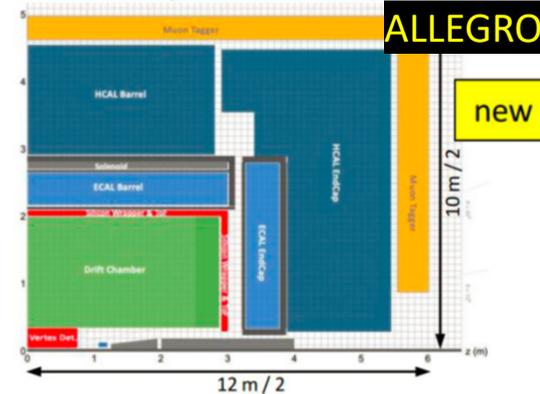
<https://arxiv.org/abs/1905.02520>

<https://pos.sissa.it/390/>



- A bit less established design
 - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
 - Possibly augmented by crystal ECAL
- Muon system
- Very active community
 - Prototype designs, test beam campaigns, ...

Noble Liquid ECAL based



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
 - Pb/W+LAR (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAR, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
 - Readout electrodes, feed-throughs, electronics, light cryostat, ...
 - Software & performance studies

Full Si vtx

&

tracker

Si vtx

&

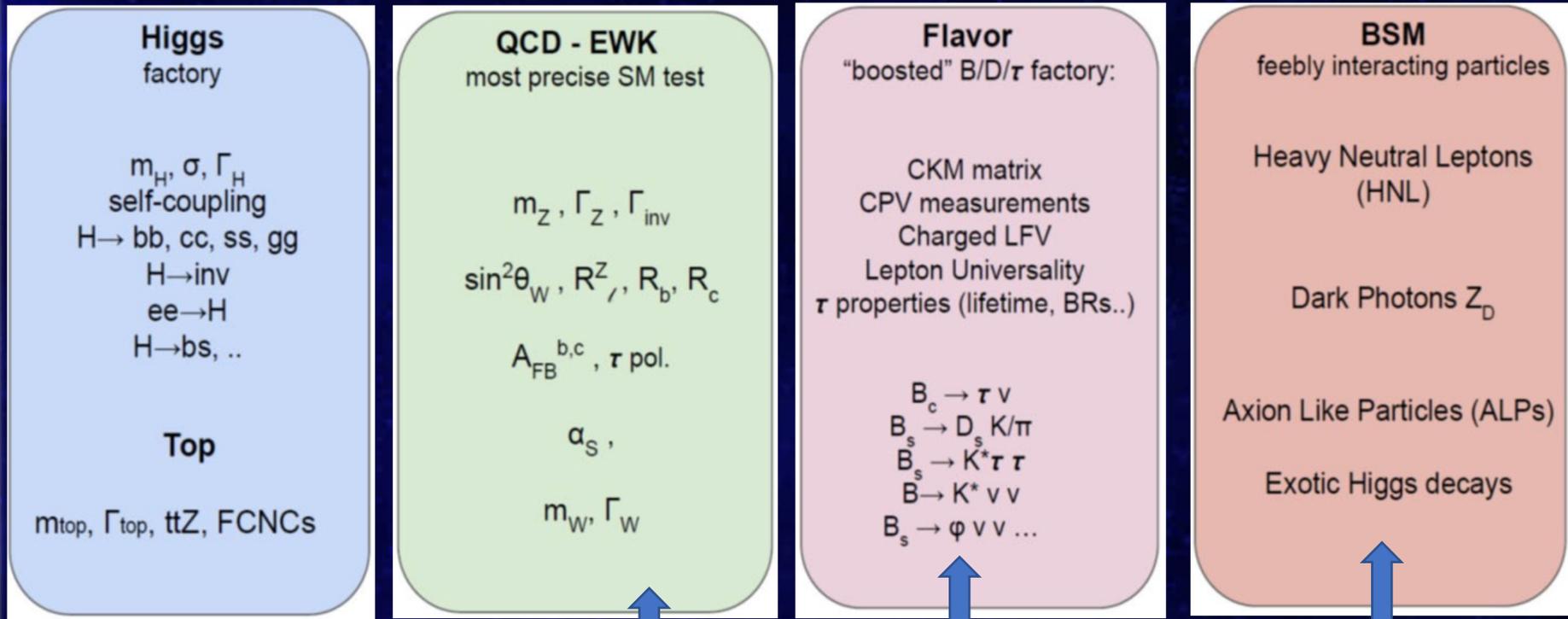
ultra light drift chamber

Si vtx &

ultra light drift chamber (or Si)

High granularity noble Liquid ECAL

Quo Vadis European HEP?



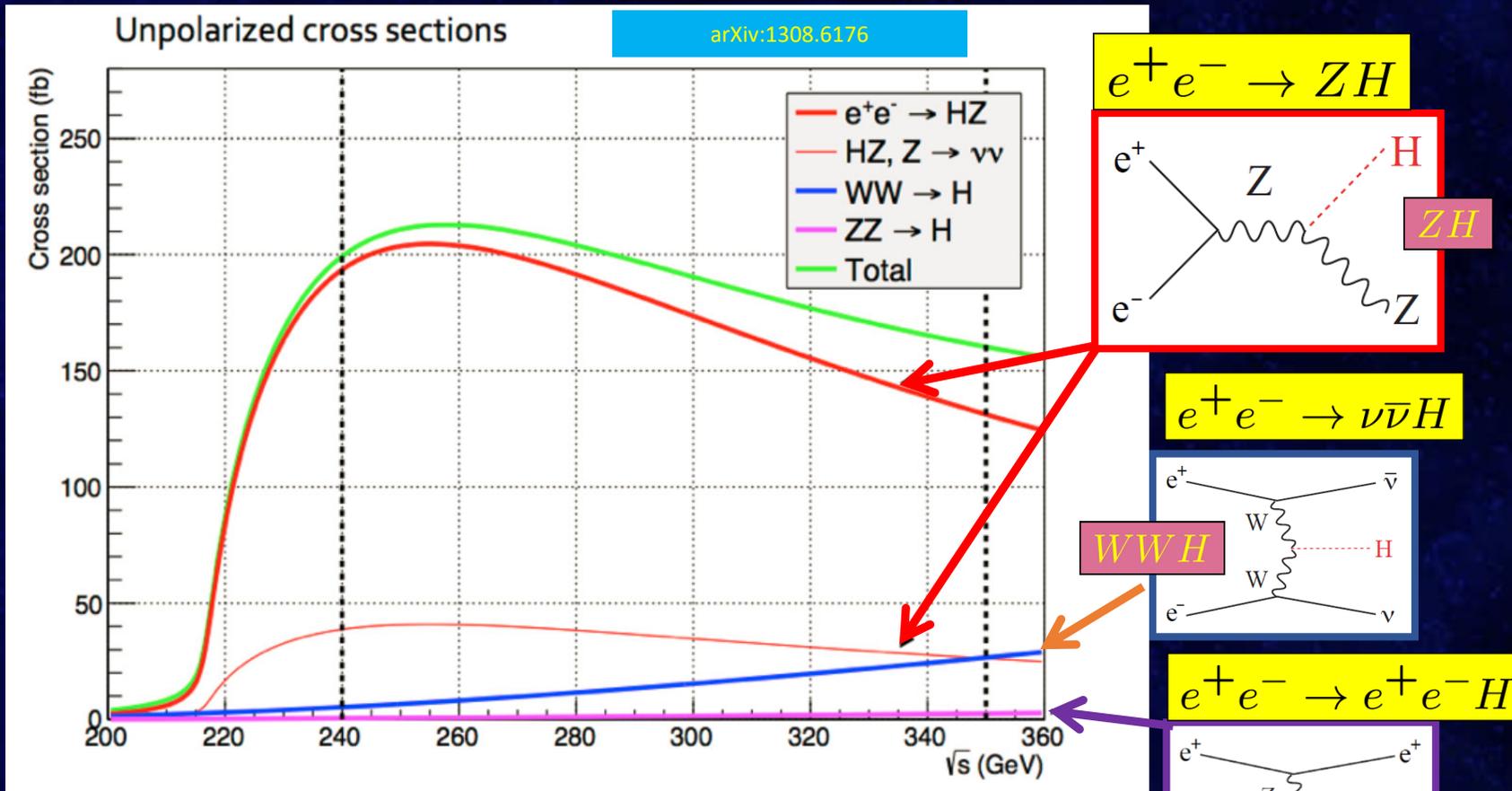
up to **x 10** improvement on Higgs coupling (model-indep.) measurements over HL-LHC

x 10-50 improvements on all EW observables

x 10 Belle II statistics for b, c, τ

Indirect discovery potential up to **~ 70 TeV**

Direct discovery potential for feebly-interacting particles over **(5-100) GeV** mass range



With 2 IPs:

Phase / threshold	\sqrt{s} [GeV]	int. lumi. [ab^{-1}]	Run duration [years]	No. of Higgs bosons
ZH	240	5.0	3	10^6
$t\bar{t}$	345-365	1.5	5	2×10^5 ZH 5×10^4 VBF

$VBF = WWH + ZZH$

With 4 IPs:

- Total integrated luminosity x 1.7
- Statistical precision increase x 1.3

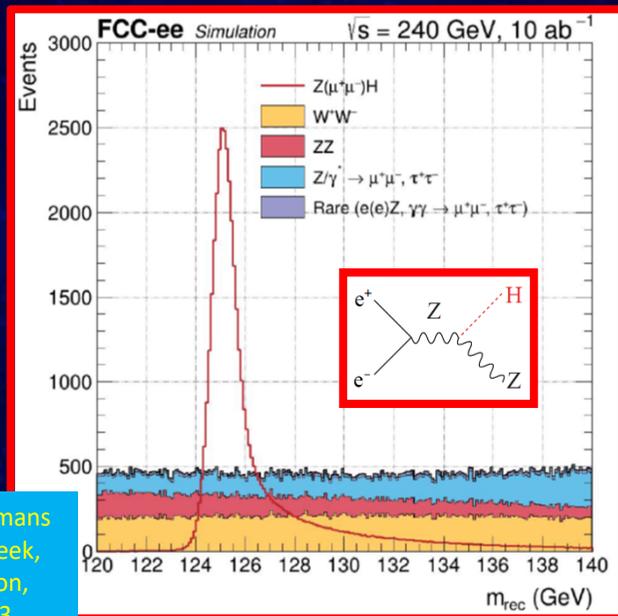


➤ The recoil technique in $e^+e^- \rightarrow ZH$ - unique for lepton colliders:

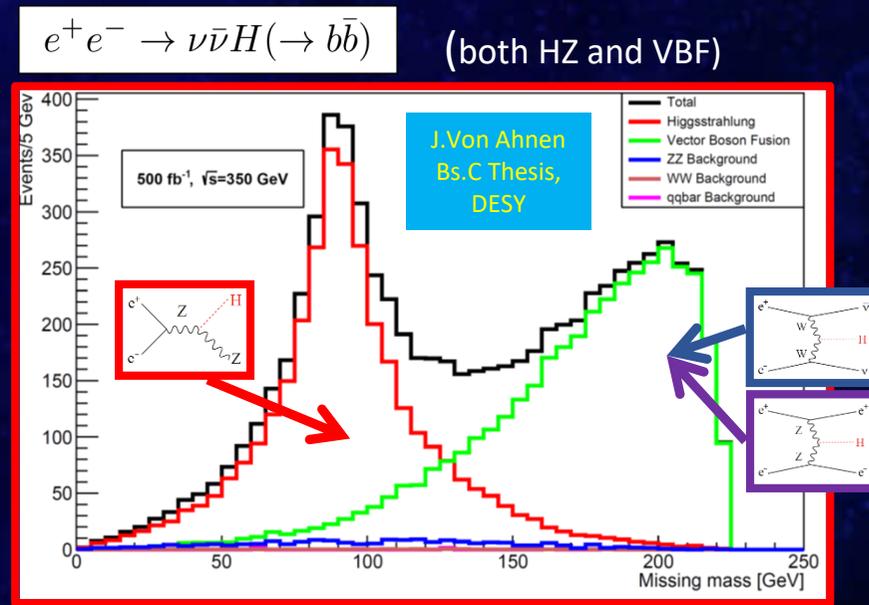
- Look just at the Z and reconstruct its decay products
- ZH events are tagged independently of Higgs decay mode (include invisible decay modes)

• Very clean Higgs mass determination: $m_{\text{recoil}}^2 = (\sqrt{s} - E_Z)^2 - |p_Z|^2$ $\Delta m_H \sim 10 \text{ MeV}$

• Precise determination of the ZH cross-section: $\Delta\sigma(ZH)/\sigma(ZH) \sim 0.5\%$



J.Eysemans
FCC week,
London,
2023





$$\sqrt{s} = 240 \text{ GeV}$$

$$\sigma(HZ) \propto g_{HZZ}^2$$

g_{HZZ}
measured
(0.1%)

$$\sqrt{s} = 240 \text{ GeV}$$

$$\sqrt{s} = 365 \text{ GeV}$$

$$\frac{\sigma(e^+e^- \rightarrow H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow HZ) \times BR(H \rightarrow b\bar{b})} \propto \frac{g_{HWW}^2}{g_{HZZ}^2}$$

g_{HWW} measured

$$\sqrt{s} = 240 \text{ GeV}$$

$$\sigma(e^+e^- \rightarrow HZ) \times BR(H \rightarrow ZZ^*) \propto \frac{g_{HZZ}^4}{\Gamma_H}$$

Γ_H
measured
(1%)

Higgs couplings to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $gg, \gamma\gamma$...

can be determined through the tagging of the respective Higgs decay final states:

$$\sqrt{s} = 240 \text{ GeV}$$

$$\sigma(e^+e^- \rightarrow HZ) \times BR(H \rightarrow X\bar{X}) \propto \frac{g_{HZZ}^2 g_{HXX}^2}{\Gamma_H}$$

$$\sqrt{s} = 365 \text{ GeV}$$

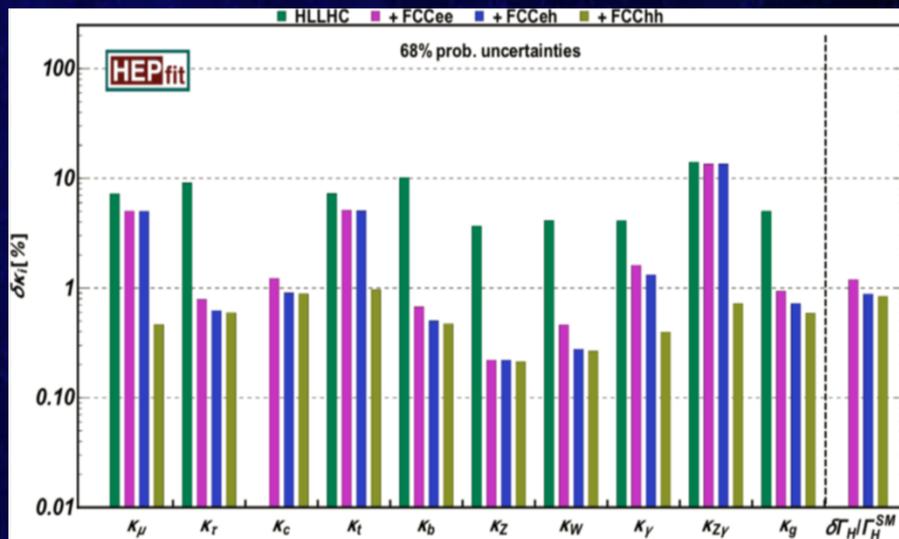
$$\sigma(e^+e^- \rightarrow \nu\bar{\nu}H) \times BR(H \rightarrow X\bar{X}) \propto \frac{g_{HWW}^2 g_{HXX}^2}{\Gamma_H}$$

g_{HXX} measured

- Higgs couplings normalized to the Standard Model predictions:

$$k_f = \frac{g_{Hff}}{g_{Hff}^{SM}}, \quad f = b, c, \tau$$

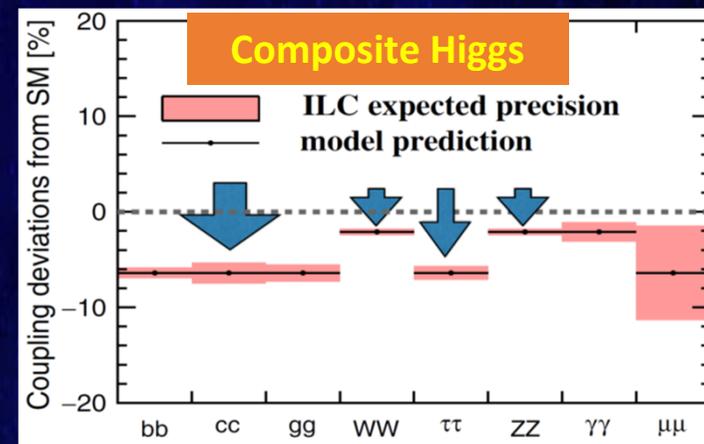
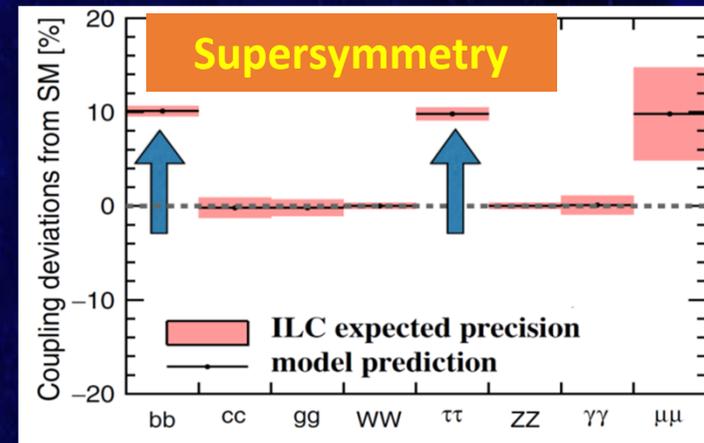
$$k_V = \frac{g_{HVV}}{g_{HVV}^{SM}}, \quad V = W, Z, \gamma, g$$



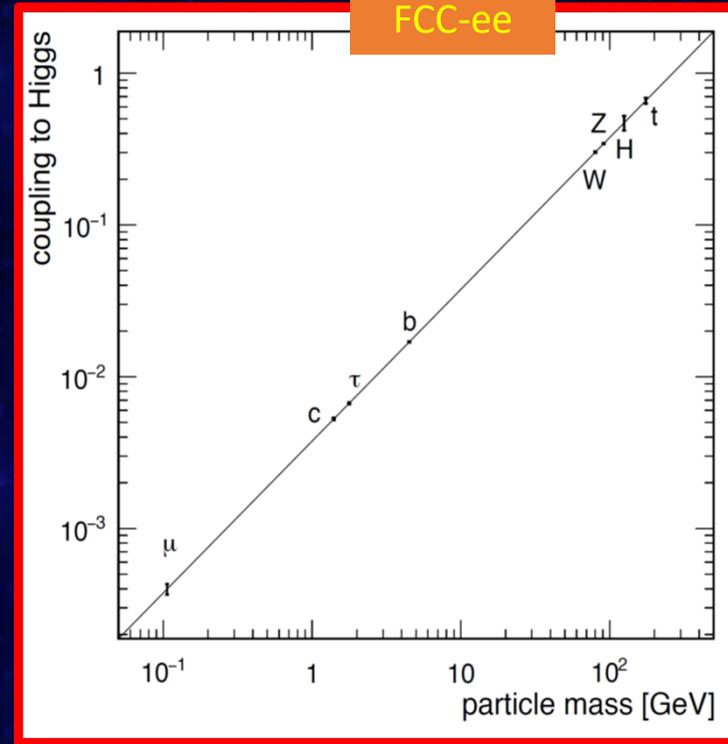
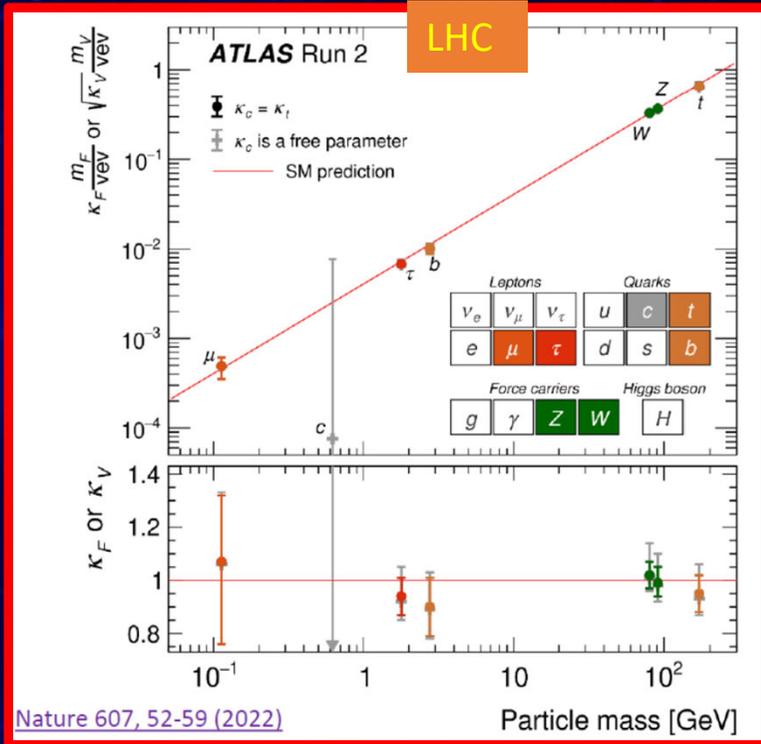
Eur. Phys. J. Plus (2022) 137:92

FCC: Factor of (4-10)x improvement for most couplings (w.r.t. HL-LHC)

- Fingerprinting NP: different BSM models predict different pattern of deviations from the SM:



Phys Rev. D 97, 053003 (2018)



$\Delta k_f \sim 15\%$

$\Delta k_f \sim 1\%$

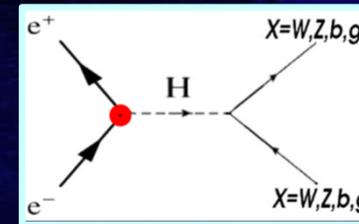
3rd and 2nd fermion generations only (qualitative precision level for the latter)

3rd AND 2nd generations precise measurements

Other Higgs topics: Higgs self-coupling

- FCC-ee: potential for direct measurement of the H-e-e Yukawa coupling $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$

- $\sigma(e^+e^- \rightarrow H) = 1.64 \text{ fb}$ - very small $(m_H = 125 \text{ GeV}, \Gamma_H = 4.2 \text{ MeV})$
(several (≈ 10) final states can be studied)



- Calls for a high-luminosity run precisely at $\sqrt{s} = M_H = 125 \text{ GeV}$

- Since $\Gamma_H = 4.1 \text{ MeV}$, it requires beam energy spread monochromatization from the natural spread of $\sim 46 \text{ MeV}$ down to $\sim 4.1 \text{ MeV}$ (and a prior knowledge of the Higgs mass to a few MeV)
- Other problems: ISR+FSR, big backgrounds

Currently reached monochromatization

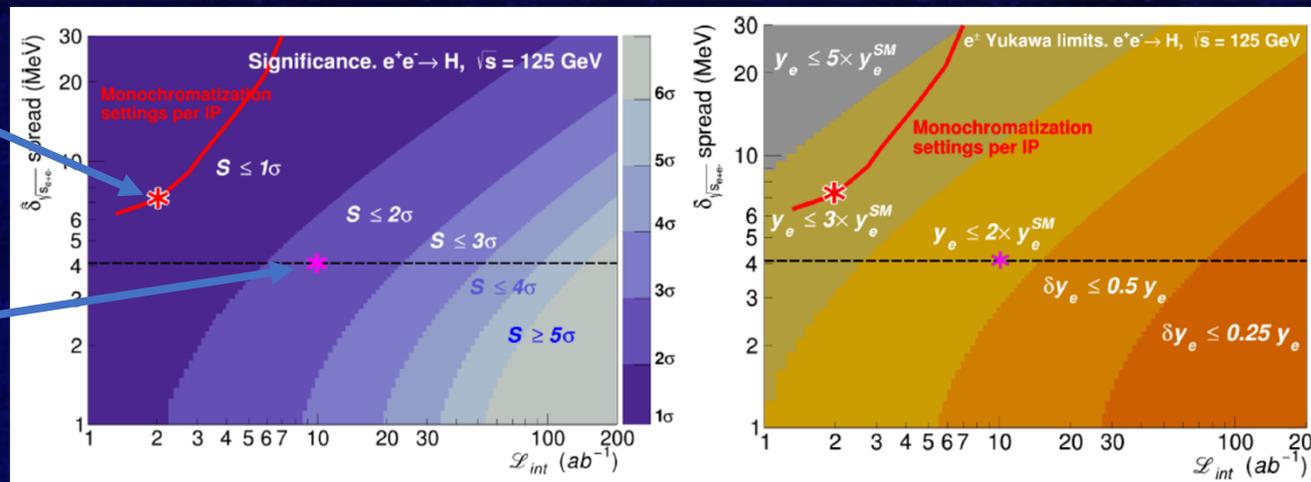
$$C = (\delta_{\sqrt{s}}, \mathcal{L}_{int}) = (7 \text{ MeV}, 2 \text{ ab}^{-1})$$

Best signal strength monochromatization

$$B = (\delta_{\sqrt{s}}, \mathcal{L}_{int}) = (4.1 \text{ MeV}, 10 \text{ ab}^{-1})$$

- The signal significance at C

$$S \approx 0.4\sigma/\text{year}/IP$$



- Assuming B and two years of running with 4 IPs ($\sim 12\text{k eeH events}$)

$$|y_e| < 1.6 |y_e^{SM}| \quad (1.3\sigma)$$

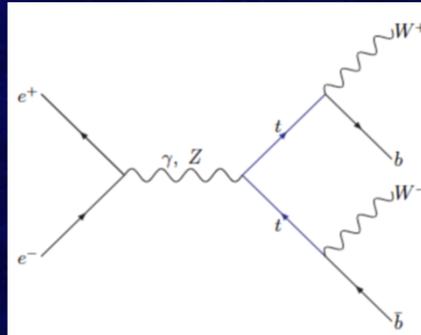
Not yet in the baseline

Quo Vadis European HEP?

arXiv:2107.0268

➤ Any next e^+e^- collider:

for the 1st time the top quark to be studied using a precisely defined leptonic initial state

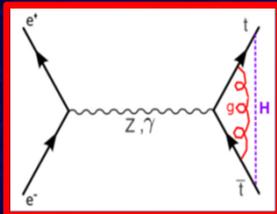


$$e^+e^- \rightarrow Z/\gamma \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-)$$

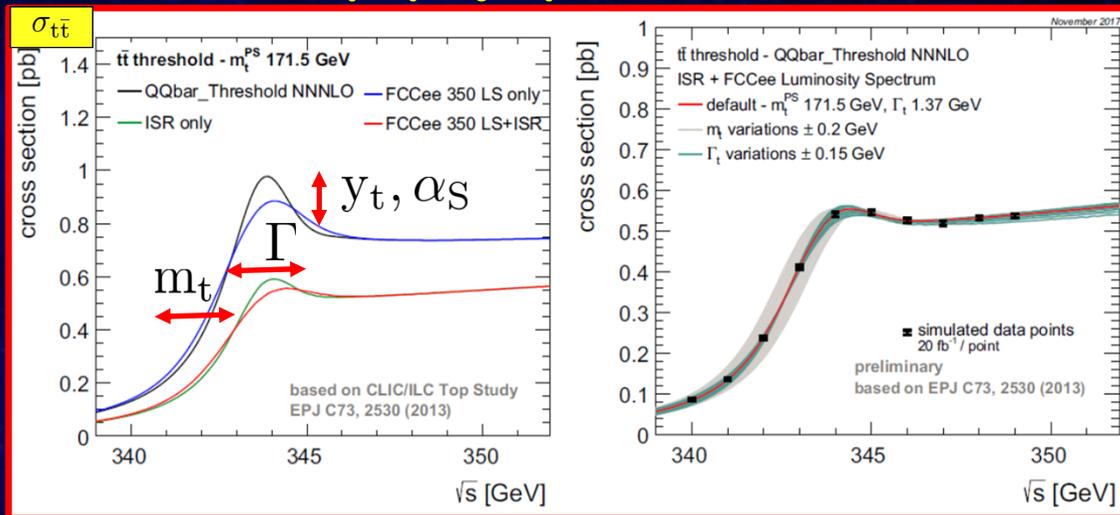
Final state	BR [%]	signature
Fully hadronic	46.2	6 jets
Semi leptonic	43.5	4 jets, 1 l^\pm , 1 ν
Fully leptonic	10.3	2 jets, 2 l^\pm , 2 ν

➤ The shape of the $t\bar{t}$ production cross-section at the threshold is **computable to high precision and depends on $m_t, \Gamma_t, \alpha_s, y_t$, (and luminosity spectrum)**

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PDG:



➤ Other top topics:

Single top production, top quark FCNC, $e^+e^- \rightarrow t\bar{t}\gamma$, top-quark EW couplings

PDG : $m_t = (172.69 \pm 0.30) \text{ GeV}$

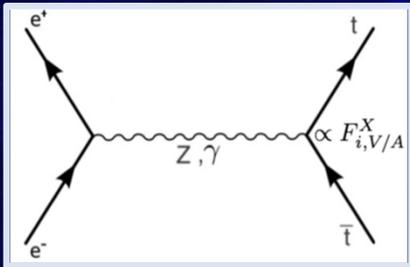


FCC-ee

$\Delta m_t \geq 10 \text{ MeV}$

$$e^+e^- \rightarrow \gamma^*/Z^* \rightarrow t\bar{t}$$

Clean EW process; parametrisation of the current at $t\bar{t}X$, $X = Z, \gamma$ vertex



$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = -ie \left\{ \underbrace{\gamma_{\mu}}_{\text{Vector}} (F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)) + \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^{\nu} \left(iF_{2V}^X(k^2) + \underbrace{\gamma_5 F_{2A}^X(k^2)}_{\text{CPV}} \right) \right\}$$

q (\bar{q}) - four-vector of the t (\bar{t}) quark $k^2 = (q + \bar{q})^2$

Sensitivity of the V and A couplings to NP

Linear Collider: profit from the initial-state longitudinal polarisation of the incoming e^+, e^- beam

- Determination of the cross-section and the A_{FB} of two configurations:

$$\mathcal{P}_{e^-} = \pm 0.8$$

$$\mathcal{P}_{e^+} = \mp 0.3$$



Measure:

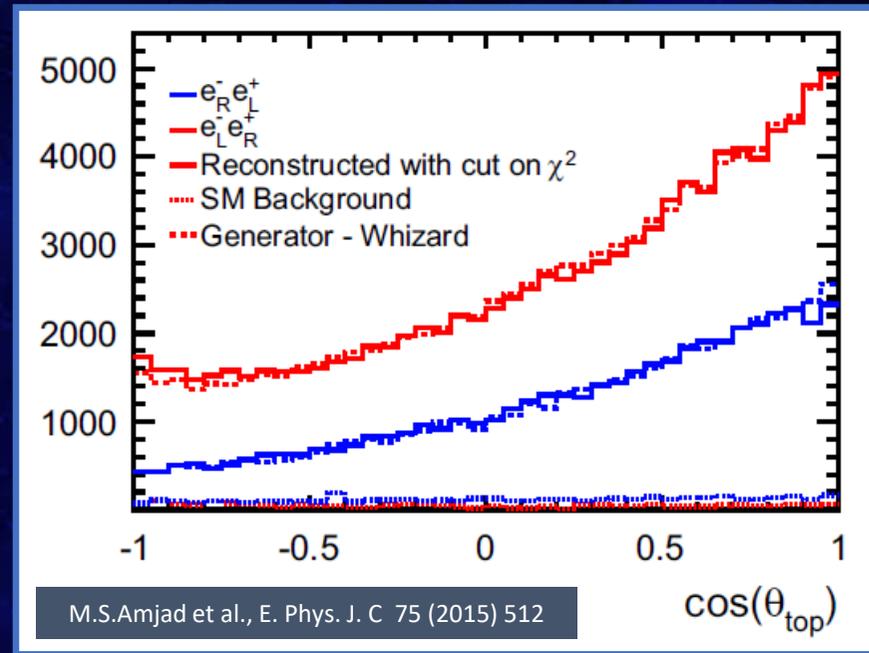
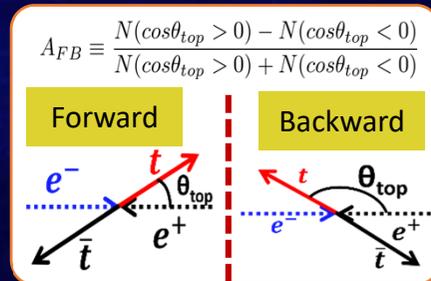
$$\sigma^+, \sigma^-, A_{FB}^+, A_{FB}^-$$

$$\begin{aligned} + &= e_R^- \\ - &= e_L^- \end{aligned}$$

Extract:

$$F_{1V}^Z, F_{2V}^Z, F_A^Z$$

$$F_{1V}^{\gamma}, F_{2V}^{\gamma}, F_A^{\gamma} \equiv 0$$

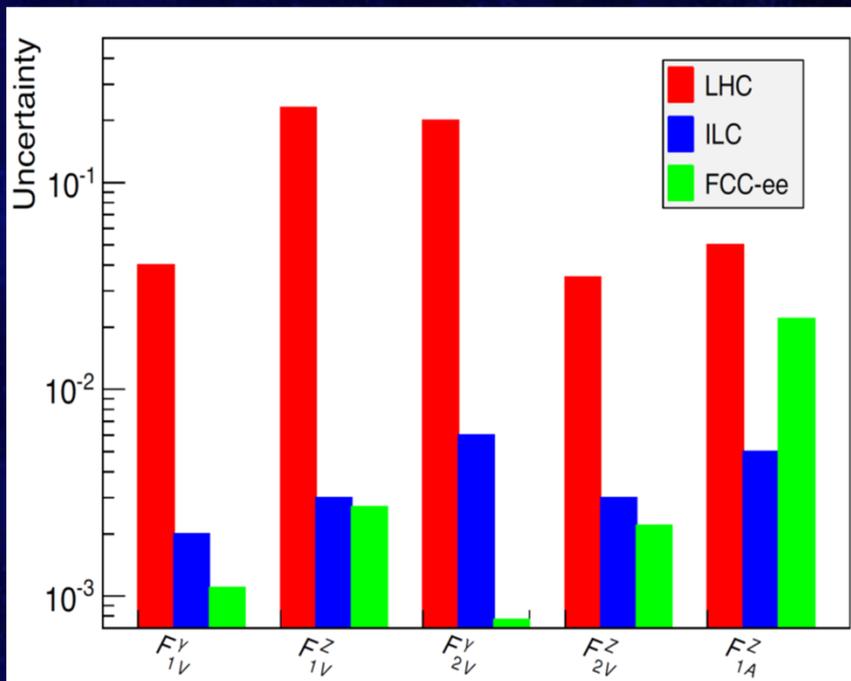


Circular Collider:

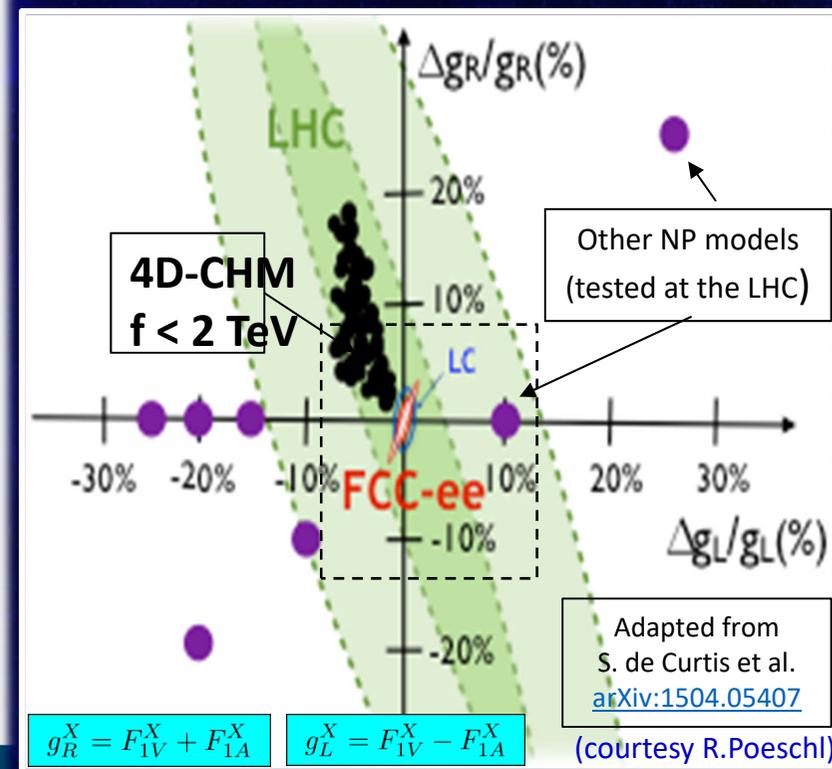
lack of initial-state polarization → profit from the final-state polarisation, which is maximally transferred to the top decay products ($t \rightarrow Wb$)

Any anomalous ttZ , $t\tau\gamma$ coupling would lead to a modification of the final kinematics, in particular of the angular and energy distributions of the leptons from the W decays. (analogy to τ polarisation in $Z \rightarrow \tau\tau$ decays at LEP)

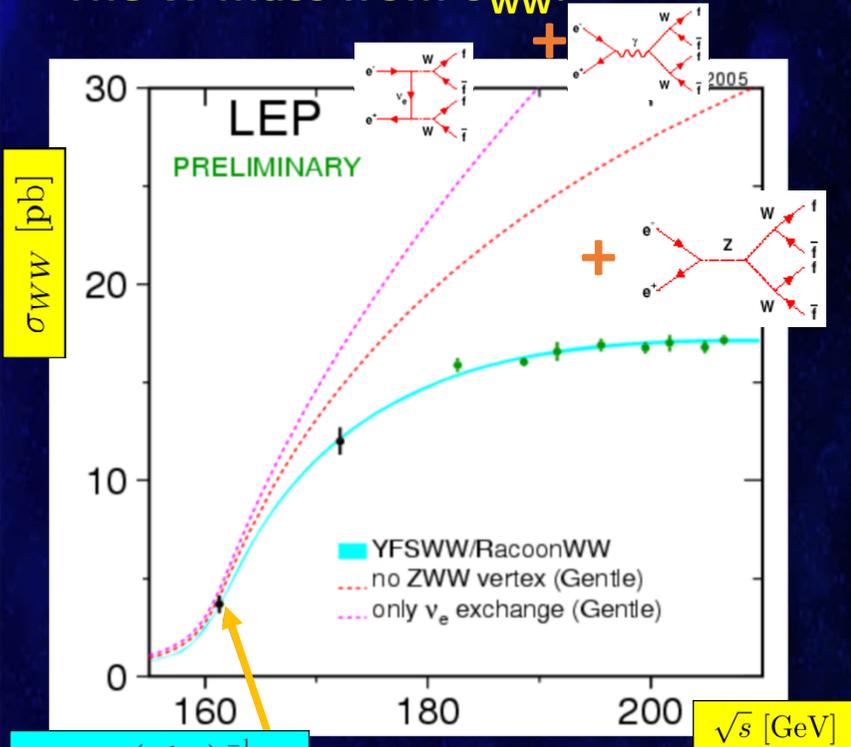
P. Janot JHEP 04 (2015) 182



$\Delta F \sim (10^{-2} - 10^{-3})$



➤ The W mass from σ_{WW} :



$$\Delta m_W = \left(\frac{d\sigma}{dm_W} \right)^{-1} \Delta\sigma$$

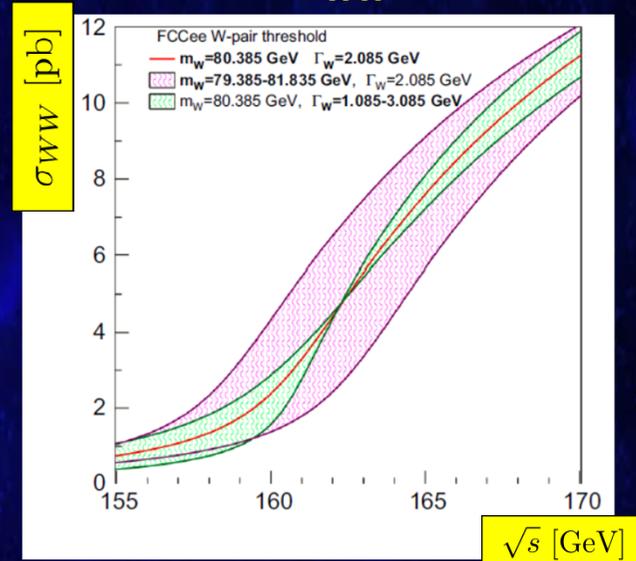
	LEP2 Stat./Prec.	FCC – ee stat (syst)
N_{WW}	4×10^4	3×10^7
M_W [MeV]	$80376 \pm 33 \pm 4$	$0.3 (< \pm 1)$

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Other W topics:

W branching ratios (universality), TGCs, α_s ...

➤ The W width from σ_{WW} :



- Measure σ_{WW} in two energy points E_1 and E_2 , with the fractions of luminosity f and $(1-f)$ → evaluation of both m_W and Γ_W
- Choose the parameters E_1 , E_2 , and f in order to minimize the errors: $\Delta\Gamma_W$ and Δm_W :

$$E_1 = 157.5 \text{ GeV}$$

$$E_2 = 162.5 \text{ GeV}$$

$$f = 0.4$$

$$12 \text{ ab}^{-1}$$

$$\Delta m_W = 0.5 \text{ MeV}$$

$$\Delta\Gamma_W = 1.2 \text{ MeV}$$

➤ **WW samples (FCC-ee)**

\sqrt{s} [GeV]	161	240	350
$N_{WW} [\times 10^6]$	30	80	15

➤ **W Branching ratios (%)**

LEP2

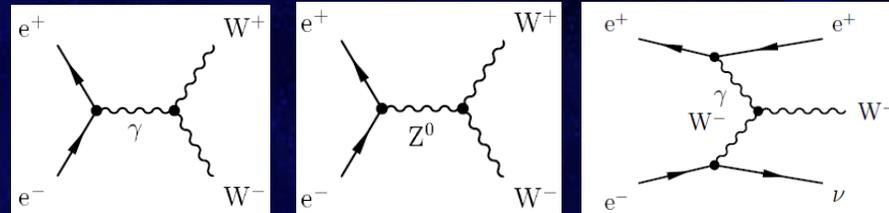
$BR(W \rightarrow e\nu)$	10.65 ± 0.17
$BR(W \rightarrow \mu\nu)$	10.59 ± 0.15
$BR(W \rightarrow \tau\nu)$	11.44 ± 0.22
$BR(W \rightarrow l\nu)$	10.84 ± 0.09
$BR(W \rightarrow \text{hadrons})$	67.48 ± 0.28

- Lepton universality tested at **2%** level (2.7 σ discrepancy between τ and μ/e)
- Quark-lepton universality tested at **0.6%**

FCC-ee

- Lepton universality test at **0.04%** level
- Quark-lepton universality test at **0.01%**
- Flavour tagging $\rightarrow V_{cs} V_{cb} \dots$

➤ **Triple Gauge Couplings**



- Selected LEP limits (95% C.L.)

Δk_γ	$[-9.9, 6.6] \times 10^{-2}$
λ_γ	$[-5.9, 1.7] \times 10^{-2}$
Δk_Z	$[-7.4, 5.1] \times 10^{-2}$
λ_Z	$[-5.9, 1.7] \times 10^{-2}$
Δg_1^Z	$[-5.4, 2.1] \times 10^{-2}$

- FCC-ee: overall improvements by a factor of **50** to compare with LEP

➤ **The strong coupling constant:**

- FCC-ee: $\Delta_{\text{rel}} \alpha_S(m_W^2) = 3 \times 10^{-3}$ from hadronic W decays (Γ_W and $BR_{W,\text{had}}$)
- LEP2 precision: 37%

LEP

$$N_Z = 1.7 \times 10^7$$



FCC-ee

$$N_Z \sim 5 \times 10^{12}$$



Extreme precision of EW observables

Z mass and width (from Z pole scan):

The crucial factor: continuous E_{CM} calibration (resonant depolarization)

$$\Delta E_{CM} \approx (10 \text{ (stat)} + 100 \text{ (syst)}) \text{ keV}$$

	Δ_{rel} (LEP)	Improvement factor
Z mass	1×10^{-6}	~ 20
Z width	5×10^{-5}	~ 20

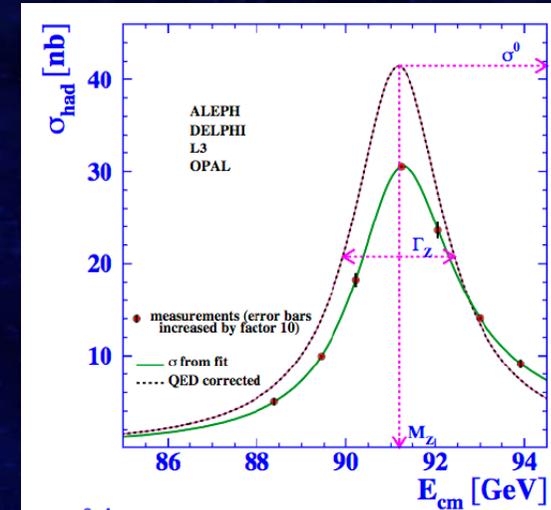
(~ 300 (stat) \oplus ~ 10 (syst))



$$2.1 \text{ MeV} \rightarrow 100 \text{ keV}$$

$$2.3 \text{ MeV} \rightarrow 100 \text{ keV}$$

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Normalized partial widths:

$$R_l = \frac{\Gamma_{had}}{\Gamma_{l\bar{l}}}, \quad l = e, \mu, \tau \quad \Gamma_{f\bar{f}} \propto (g_V^f)^2 + (g_A^f)^2$$

$$R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{had}}, \quad q = b, c \quad f = l, q$$

necessary input for a precise measurement of EW couplings (next slide)

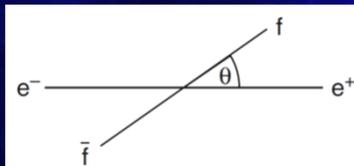
	PDG (LEP) value	PDG (LEP) rel. precision	FCC - ee Improvement factor
R_e	20.804 ± 0.050	2.4×10^{-3}	~ 20
R_μ	20.785 ± 0.033	1.6×10^{-3}	~ 20
R_τ	20.764 ± 0.045	2.2×10^{-3}	~ 20
R_b	0.21629 ± 0.00066	3.1×10^{-3}	~ 10
R_c	0.1721 ± 0.0030	1.7×10^{-2}	~ 10

and $\alpha_S(m_Z^2)$ (from hadronic Z decays). FCC-ee precision: $\Delta_{rel} \alpha_S(m_Z^2) = 2 \times 10^{-3}$ LEP: 2.5%

➤ **Z asymmetries:**

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma_{f\bar{f}}^{\text{tot}} [(1 - \mathcal{P}_e \mathcal{A}_e)(1 + \cos^2\theta) + 2(\mathcal{A}_e - \mathcal{P}_e)\mathcal{A}_f \cos\theta]$$

\mathcal{P}_e - polarization of the initial state e^-



The forward-backward asymmetry:

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e \mathcal{A}_f$$

The left-right asymmetry:

$$A_{LR}^f = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$$

$$\mathcal{A}_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

LEP & SLC: longstanding discrepancies between different asymmetry measurements; uncertainties dominated by statistics

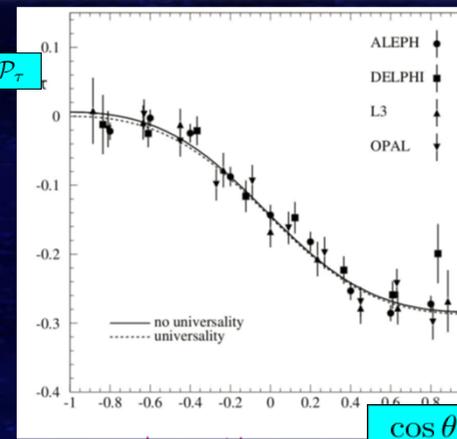
tau lepton case:
the final state helicity can be measured

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1 + \cos^2\theta) + 2\mathcal{A}_e \cos\theta}{(1 + \cos^2\theta) + \mathcal{A}_e \mathcal{A}_\tau \cos\theta}$$

$$\mathcal{P}_\tau(\cos\theta) = \frac{d(\sigma_r - \sigma_l)}{d\cos\theta} \cdot \left(\frac{d(\sigma_r + \sigma_l)}{d\cos\theta}\right)^{-1}$$

$$A_{FB}^\tau = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B}$$

\mathcal{P}_τ



Experimentally accessible observables:

$$\langle \mathcal{P}_\tau \rangle = -\mathcal{A}_\tau$$

$$A_{FB}^\tau = -\frac{3}{4}\mathcal{A}_e$$

\mathcal{A}_f measured
($f = e, \mu, \tau, b, c$)



g_V^f, g_A^f extracted



$$\sin^2 \theta_{W,\text{eff}}^f = \frac{1}{4} \left(1 - \frac{g_V^f}{g_A^f} \right)$$

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	$\Delta_{\text{rel}}^{\text{stat}}$ (FCC - ee)	$\Delta_{\text{rel}}^{\text{syst}}$ (FCC - ee)	Improvement factor w.r.t. LEP
\mathcal{A}_e	5.0×10^{-5}	1.0×10^{-4}	~ 50
\mathcal{A}_μ	2.5×10^{-5}	1.5×10^{-4}	~ 30
\mathcal{A}_τ	4.0×10^{-5}	3.0×10^{-4}	~ 15
\mathcal{A}_b	2.0×10^{-4}	3.0×10^{-3}	~ 5
\mathcal{A}_c	3.0×10^{-4}	8.0×10^{-3}	~ 4

Precision on vector and axial couplings from R_f and A_f :

Improvement w.r.t. LEP: (10-100)x

fermion	Δg_V	Δg_A
e	2.5×10^{-4}	1.5×10^{-4}
μ	2.0×10^{-4}	2.5×10^{-5}
τ	3.5×10^{-4}	0.5×10^{-4}
b	1.0×10^{-2}	1.5×10^{-3}
c	1.0×10^{-2}	2.0×10^{-3}

Systematic uncertainties dominate

Quo Vadis European HEP?

→ $\sin^2 \theta_{W,eff}$ (absolute) uncertainties:

	stat	syst	Improvement w.r.t. LEP
from muon FB	10^{-7}	5.0×10^{-6}	~ 100
from tau pol	10^{-7}	6.6×10^{-6}	~ 75

➤ **Measurement of $\alpha_{QED}(m_Z^2)$ - better precision necessary for future precision SM tests !**

- **Current uncertainty:** $\Delta\alpha_{QED}(m_Z^2) = 10^{-4}$ from running coupling constant formula:

$$\alpha_{QED}(m_Z^2) = \frac{\alpha_{QED}(0)}{1 - \Delta\alpha_l(m_Z^2) - \Delta\alpha_{had}^{(5)}(m_Z^2)}$$

dominated by the experimental determination of the hadronic vacuum polarization, obtained from dispersion integral with expt. input from low energies (KLOE, Belle, BaBar, CLEO, BES CMD-2...)

➤ **Alternative: the direct measurement of $\alpha_{QED}(m_Z^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan) – no need of extrapolation from $\alpha_{QED}(0)$**

- **The $A_{FB}^{\mu\mu}$ - self normalized quantity**

$$A_{FB}^{\mu\mu} = \frac{\sigma_{\mu\mu}^F - \sigma_{\mu\mu}^B}{\sigma_{\mu\mu}^F + \sigma_{\mu\mu}^B}$$

(no need for measurement of L_{int} ;

most uncertainties (sel. efficiency, det. acceptance) cancel in the ratio

$$\frac{\Delta\alpha_{QED}}{\alpha_{QED}} \simeq \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu}} \times \frac{\mathcal{Z} + \mathcal{G}}{\mathcal{Z} - \mathcal{G}}$$

2x 6 months of FCC-ee running:

$\mathcal{Z}(\mathcal{G})$ - Z(photon)-exchange terms

Optimal CMS energies:

$$\sqrt{s_-} = 87.9 \text{ GeV}$$

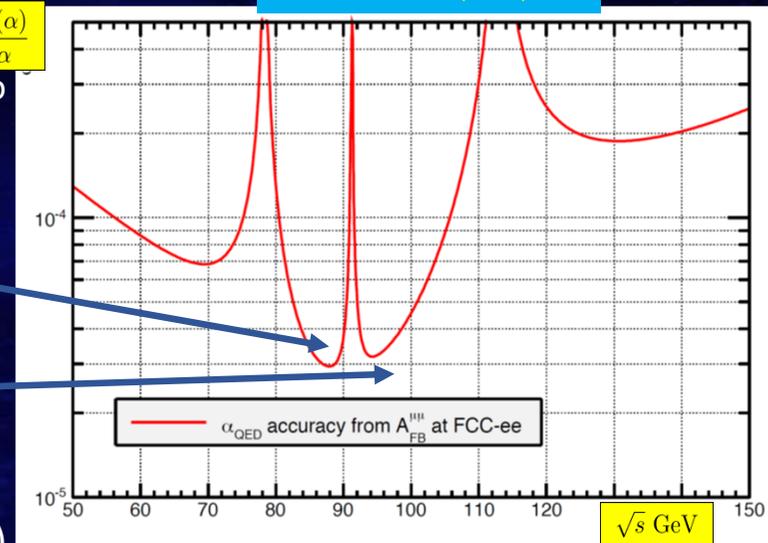
$$\sqrt{s_+} = 94.3 \text{ GeV}$$

$$\frac{1}{\alpha_{QED}(m_Z^2)} = \frac{1}{\alpha_{\pm}} + \beta_{QED} \log \frac{s_{\pm}}{m_Z^2}$$

$$\Delta\alpha_{QED}(m_Z^2) = 3 \times 10^{-5}$$

(adequate for future precision EW fits)

$$\frac{\sigma(\alpha)}{\alpha}$$



The Z Invisible Width – Number of Light Neutrino Species



1) N_ν determined at LEP1 from the Z line-shape scan:

$$N_\nu = 2.991 \pm 0.007$$

$$N_\nu \cdot \Gamma_\nu = \Gamma_Z - \Gamma_h - 3\Gamma_l$$

$$N_\nu = \left(\frac{\Gamma_l}{\Gamma_\nu} \right)_{SM} \cdot \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_{had}^{peak,0}}} - R_l - 3 \right)$$

theory

all measured at the peak

Only small room for improvements:

precision limited mainly by the theoretical uncertainty on luminosity determination

i.e. on small angle Bhabha cross section

(LEP1: $\Delta L/L = 0.00061$, $\Delta N_\nu^{lumi} = 0.0046 \rightarrow \Delta N_\nu^{lumi} = 0.0001$ @FCC-ee).

$$\Delta N_\nu^{FCC-ee} = 0.00008(stat) \pm 0.0001(syst)$$

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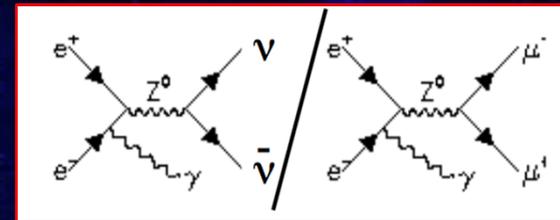
2) N_ν from the radiative return process

$$e^+e^- \rightarrow Z\gamma, Z \rightarrow \nu\bar{\nu}$$

from the higher masses than the Z resonance

Monophoton events (normalized to photon-lepton-lepton events):

$$N_\nu = \frac{\left(e^+e^- \rightarrow \gamma Z_{inv} \right)^{meas}}{\left(e^+e^- \rightarrow \gamma Z_{lept} \right)} \cdot \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{lept}} \right)^{SM}$$



- LEP1: $N_\nu = 2.92 \pm 0.05$ (statistics too scarce).

- Photon selection common for both final states \rightarrow cancellations of systematics.
- N_ν can be measured vs sqrt(s) \rightarrow sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

\sqrt{s} [GeV]	years of running	ΔN_ν (stat)
161	1	0.0011
240 & 340	5	0.0008
125	1	0.0004

$3 \times 10^7 \gamma Z(inv)$ ev.
(running parasitically)

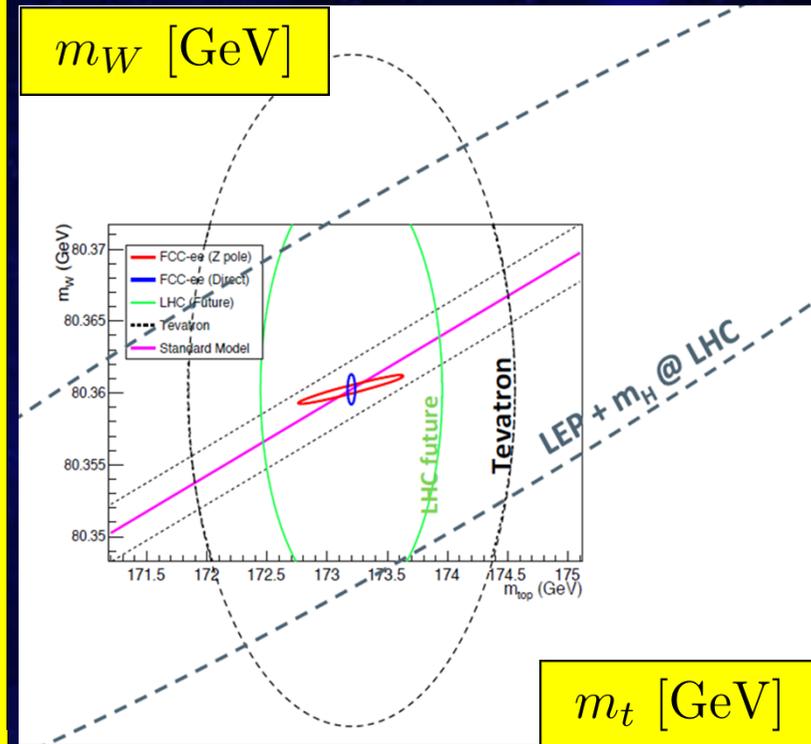
$$\Delta N_\nu \leq 4 \times 10^{-4}$$





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Observable	unit	Present value	± error	FCC-ee	
				(stat.)	(syst.)
m_Z	[keV/c ²]	91 186 700	2 200	4	100
Γ_Z	[keV]	2 495 200	2 300	4	25
$\sin^2 \theta_W^{\text{eff}}$	[×10 ⁶]	231 480	160	2	2.4
$1/\alpha_{\text{QED}}(m_Z^2)$	[×10 ³]	128 952	14	3	small
R_i^Z	[×10 ³]	20 767	25	0.06	0.2-1
$\alpha_S(m_Z^2)$	[×10 ⁴]	1 196	30	0.1	0.4-1.6
σ_{had}^0	[×10 ³ nb]	41 541	37	0.1	4
N_ν	[×10 ³]	2 996	7	0.005	1
R_b	[×10 ⁶]	216 290	660	0.3	< 60
$A_{\text{FB}}^{b,0}$	[×10 ⁴]	992	16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$	[×10 ⁴]	1498	49	0.15	< 2
τ lifetime	[fs]	290.3	0.5	0.001	0.04
τ mass	[MeV/c ²]	1776.86	0.12	0.004	0.04
τ leptonic BR	[%]	17.38	0.04	0.0001	0.003
m_W	[MeV/c ²]	80 350	15	0.25	0.3
Γ_W	[MeV]	2 085	42	1.2	0.3



➤ **The sheer power of statistics:**

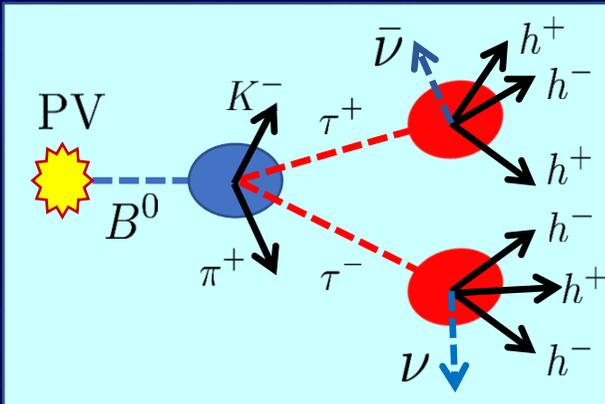
Particles	B^0/B^+	B_s^0	Λ_b	B_c	$Z \rightarrow \tau^+\tau^-$
Yields (FCC-ee 150 ab^{-1})	10^{12}	$2.5 \cdot 10^{11}$	$2.5 \cdot 10^{11}$	$2.5 \cdot 10^9$	$5 \cdot 10^{11}$
Yields (Belle II 50 ab^{-1})	10^{11}	10^{7-8}	—	—	$5 \cdot 10^{10}$

LEP : $\sim 6 \times 10^6$

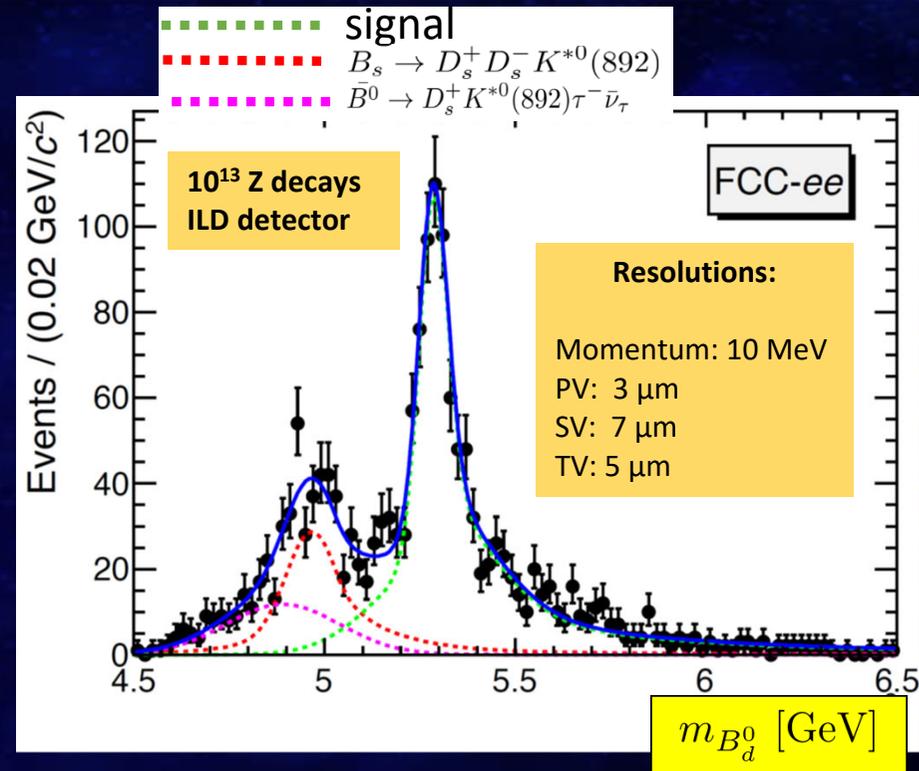
S.Monteil, 2nd FCC Physics Workshop

➤ **Example: $B \rightarrow K^*(892)\tau^+\tau^-$ decay**

- Excellent vtx reconstruction ($\tau \rightarrow 3$ prongs)



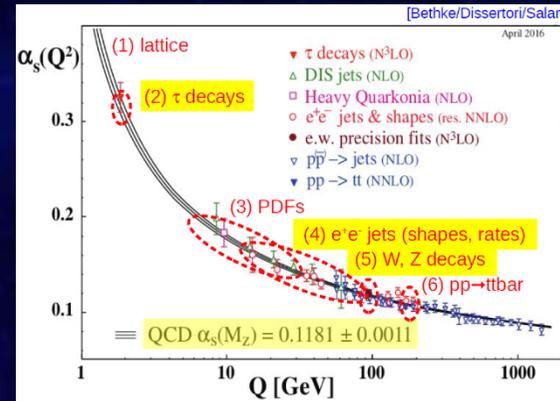
- **FCC-ee: 1000 signal events expected, Belle2: 10 events expected**
- **The angular analysis feasible**



Other flavour topics: CKM parameters, UT angles, tau physics, lepton universality, heavy quark spectroscopy, rare decays...

➤ **High precision α_s determination**
(with the accuracy at the % level) from:

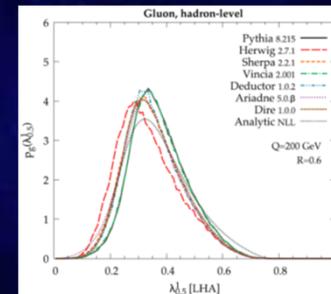
- hadronic τ decays
- Jet rates, event shapes
- hadronic Z decays
- hadronic W decays



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➤ **High precision studies of perturbative parton radiation including:**

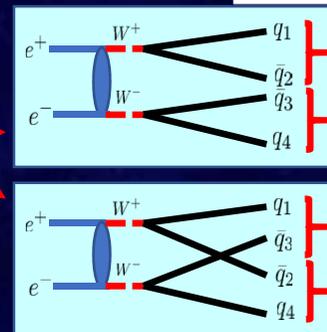
- jet rates and event shapes
- jet substructure
- quark/gluon/heavy-quark discrimination
- g,q,b,c parton-to-hadron fragmentation functions



Gluon radiation & fragmentation poorly known

➤ **High precision non-perturbative QCD studies including:**

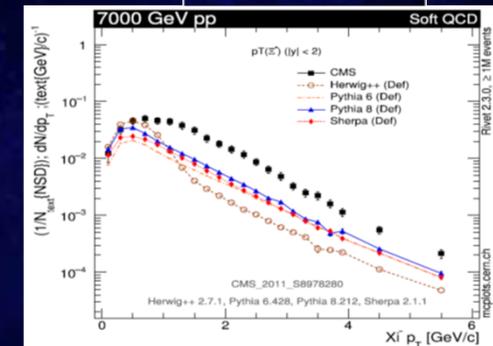
- colour reconnection (<1% control)
- final-state multiparticle correlations



➤ **High precision hadronization studies**

- very rare hadron production and decays

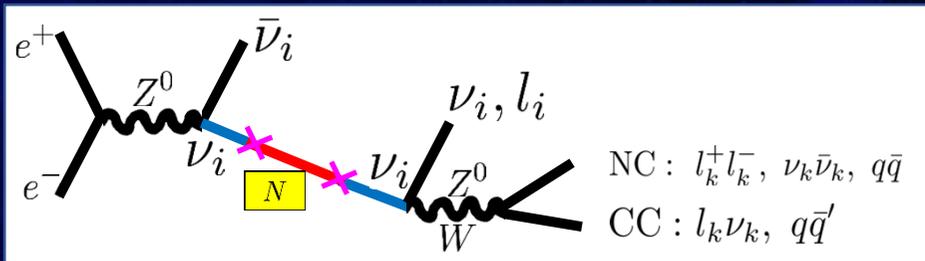
Ξ^- spectrum





- Sterile, right-handed neutrinos (N) are common in extensions of the SM; they couple to Higgs and SM ν
- Substantial part of them are HNLs: very massive and characterised by macroscopic decay length

➤ The HNL production and decay at the $\sqrt{s} = M_Z$



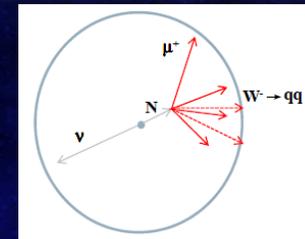
$$\nu_L = \nu \cos \theta + N \sin \theta$$

$$\theta \approx m_\nu / m_N$$

➤ Experimental signatures

NC: 2 leptons/jets + E_{miss}

CC: 2 jets + lepton/ E_{miss}

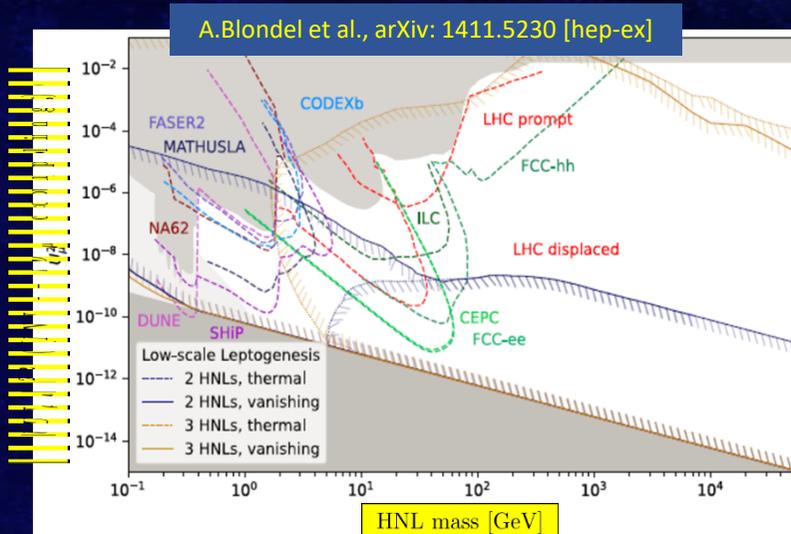


Search for (highly) displaced vertices;
 very clean events



➤ FCC-ee sensitivity
 to HNLs up to 10^{-11}

- Complementary to beam dump facilities
- The upper limits of LEP searches: 10^{-4}



Other topics:

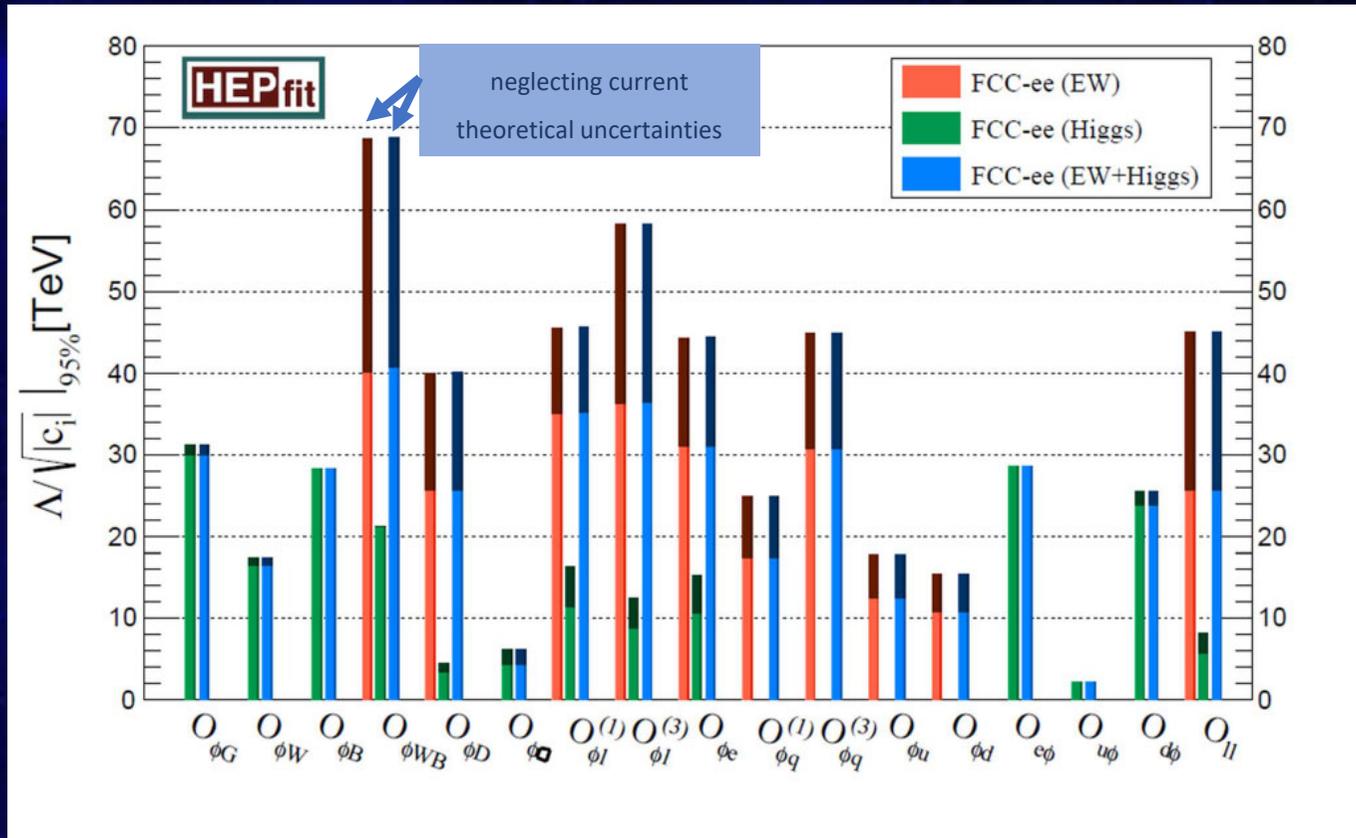
axion-like particles, exotic Higgs decays,...

➤ **New Physics** → **new interactions of SM particles:**

$$\mathcal{L}_{\text{rmEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + o(\Lambda^{-4})$$

Λ - mass scale
 $C_i^{(6)}$ - dimensionless coefficients
 $O_i^{(6)}$ - operators of dimension d

95% probability bounds on the interaction scale $\Lambda/(c_i)^{1/2}$



- Nucl. Phys. B268 (1986) 621
- arXiv 1008.4884
- Eur Phys. J. C. (2019) 79, 474

Sensitivity exceeding 50 TeV for several EFTs

T.Lesiak

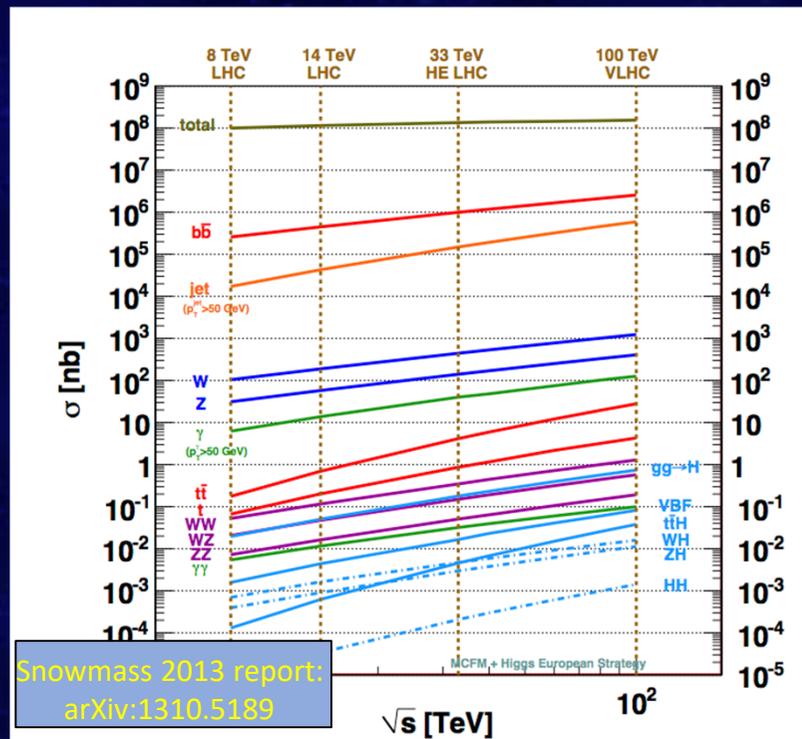
➤ **Opportunities of ~100 TeV pp collider:**

- Exploration of scenarios that could emerge from a FCC-ee
- The next qualitative leap in precision of crucial measurements, providing hope to answer nagging questions (shortages of SM, BSM...)

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➤ **Big gain (x10) in production cross sections of many relevant processes**

- Impressive precision of the SM measurements
- Reach of terra incognita in the energy frontier



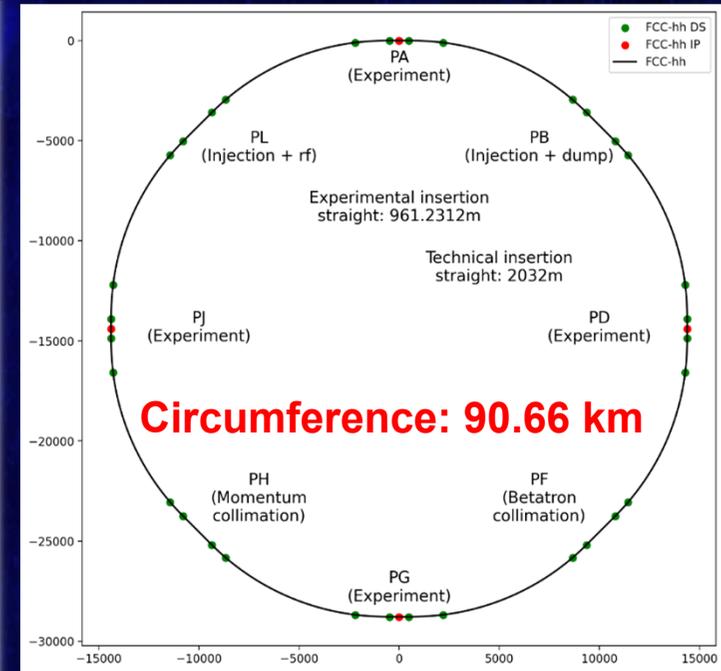
Snowmass 2013 report:
arXiv:1310.5189

Process	$\sigma (100 \text{ TeV}) / \sigma (14 \text{ TeV})$
Total pp cross-section	1.25
W, Z production	7
WW, ZZ production	10
tt	30
H	15
ttH	60
HH	40
stop-stop production m=1 TeV	10^3

With 20 ab^{-1} at $\sqrt{s}=100 \text{ TeV}$ expect:

- $\sim 10^{13}$ W
- $\sim 10^{12}$ Z
- $\sim 10^{11}$ tt
- $\sim 10^{10}$ H
- $\sim 10^9$ ttH
- $\sim 10^7$ HH
- $\sim 10^5$ gluino pairs m=8 TeV

Parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	80-116	14	14
dipole field [T]	14 (Nb ₃ Sn) – 20 (HTS/Hybrid)	8.33	8.33
circumference [km]	90.7	26.7	26.7
beam current [A]	0.5	1.1	0.58
bunch intensity [10 ¹¹]	1	2.2	1.15
bunch spacing [ns]	25	25	25
synchr. rad. power / ring [kW]	1020-4250	7.3	3.6
SR power / length [W/m/ap.]	13-54	0.33	0.17
long. emit. damping time [h]	0.77-0.26	12.9	12.9
beta* [m]	1.1	0.15 (min.)	0.55
normalized emittance [μm]	2.2	2.5	3.75
peak luminosity [10 ³⁴ cm ⁻² s ⁻¹]	5	5 (lev.)	1
events/bunch crossing	170	132	27
stored energy/beam [GJ]	6.1-8.9	0.7	0.36
integrated luminosity [fb ⁻¹]	20000	3000	300



➤ Formidable challenges:

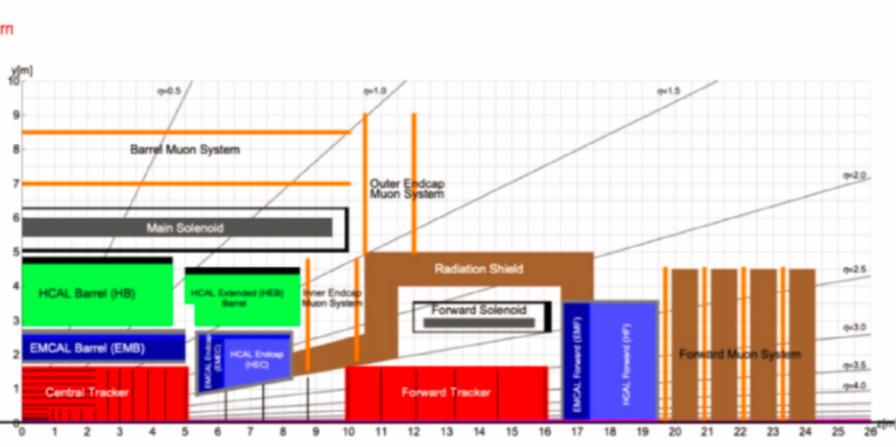
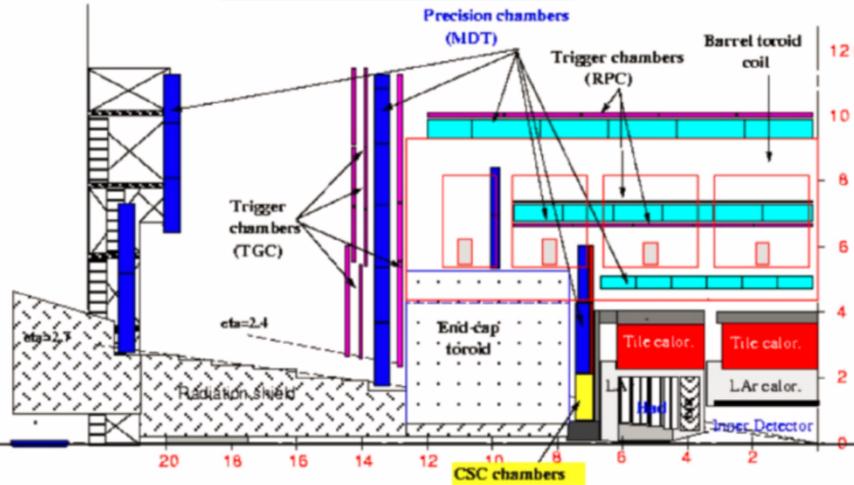
arXiv:2203.07804

- High-field SC magnets: (14 – 20) T; current setup with 16T dipoles → beam energy 48GeV
- Power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- Stored beam energy: ~ 9 GJ → machine protection
- Pile-up in the detectors: ~1000 events/crossing
- Energy consumption: 4 TWh/year
- ...

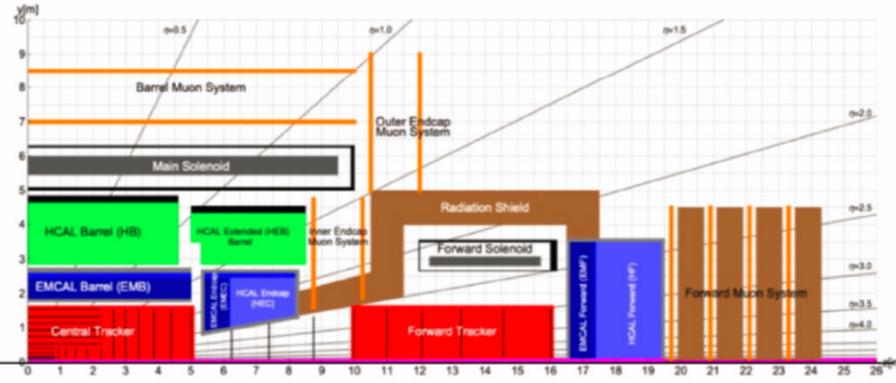
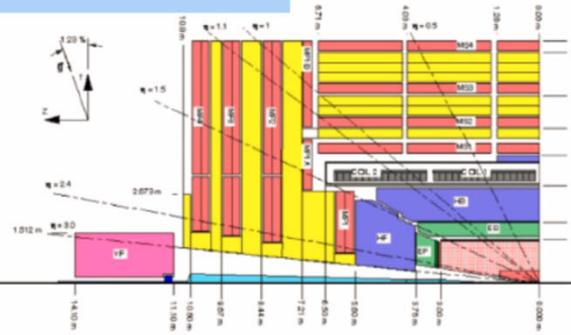
→ R&D on cryogenics, HTS, beam current...

ATLAS

FCC-hh



CMS

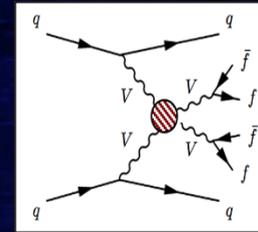


➤ **Direct discovery potential up to ~40 TeV**

➤ **Conclusive elucidation of EWSB by probing SM in regime where EW symmetry is restored ($\sqrt{s} \gg v=246 \text{ GeV}$)**

Without H: $V_L V_L$ scattering violates unitarity at $m_{VV} \sim \text{TeV}$

- H regularizes the theory fully → a crucial “closure test” of the SM
- Else: new physics: anomalous quartic couplings ($VVVV, VVhh$) and/or new heavy resonances
- FCC-hh: direct discovery potential of new resonances in the $\mathcal{O}(10 \text{ TeV})$ range

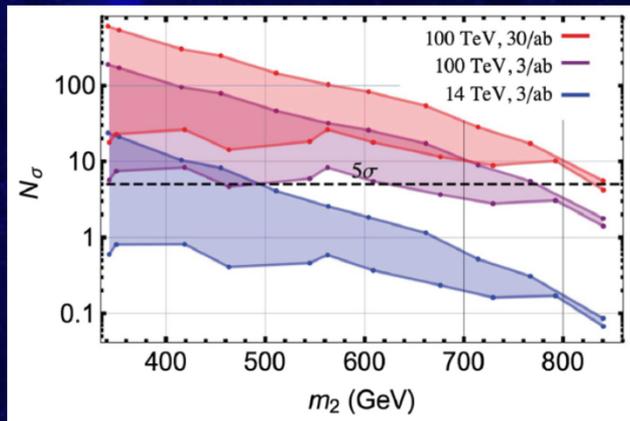


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➤ **Determination of nature of EW phase transition**

(is it 1st order transition, faster than in SM, as required for EW baryogenesis? → modification to Higgs potential)



Additional Higgs singlet with mass m_2 decaying into HH

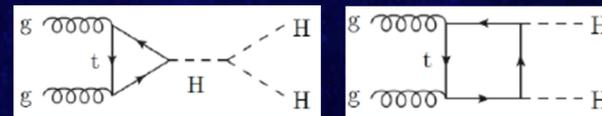
Constraints also from self-coupling (5% precision of FCC-hh, 50% @HL-LHC), and from HZZ at FCC-ee.

➤ **Higgs Self Coupling (HSC λ_{3H})**

$$V(h) = \frac{m_H^2}{2} h^2 + \lambda_{3H} \nu h^3 + \lambda_{4H} \nu h^4$$

$$\nu = 246 \text{ GeV}$$

- Issues of EWPT and HSC are tightly connected – their answer depends on the parameters of $V(h)$
- Di-Higgs production (destructive interference of the box and triangle diagrams):



$$\sigma_{HH}^{\text{LHC}} \approx 37 \text{ fb}$$

$$\sigma_{HH}^{\text{FCC-hh}} \approx 50 \times \sigma_{HH}^{\text{LHC}}$$

- Main decay channels: $b\bar{b}\gamma\gamma, b\bar{b}\tau\tau, b\bar{b}b\bar{b}$
- Expected precision:

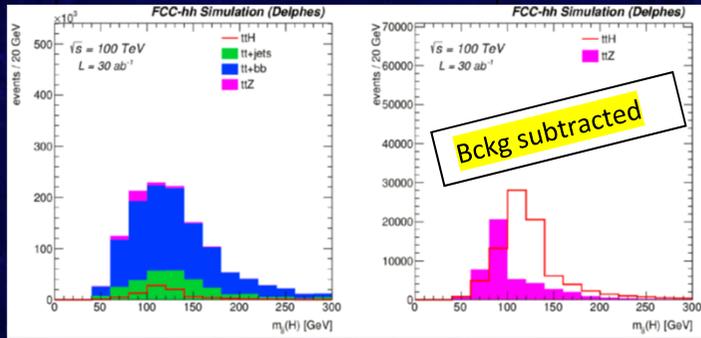
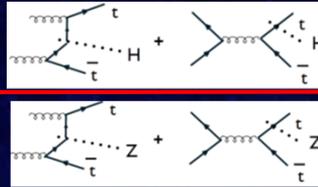
$$\delta\lambda_{3H}/\lambda_{3H} \sim 5 \%$$

arXiv:2203.08042

➤ Top - Higgs Yukawa Coupling (k_t)

- Measurement of $\sigma_{ttH}/\sigma_{ttZ}$

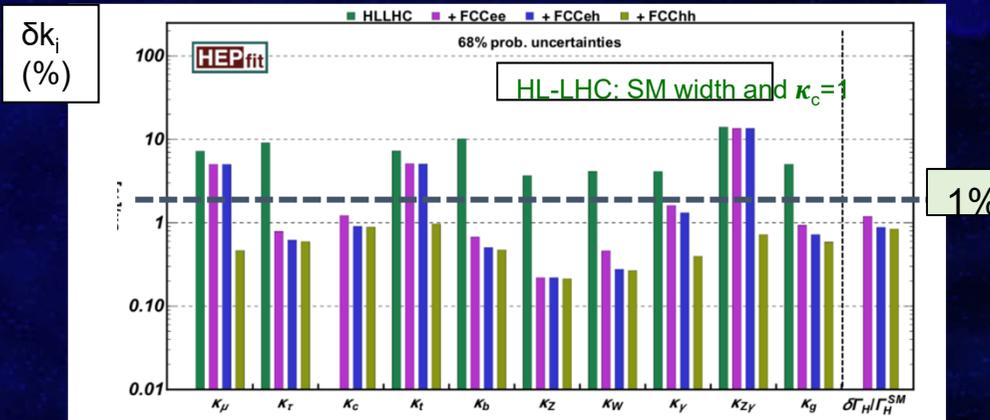
- identical production dynamics
- substantial reduction of theoretical uncertainties)



arXiv:1507.08169

$\delta k_t/k_t \sim 1\%$

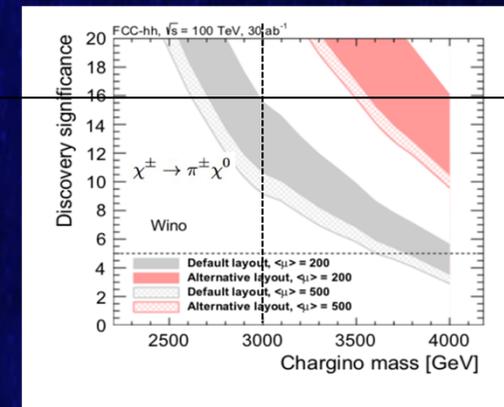
➤ Precise measurement of SM couplings with precision $\sim 1\%$



Quo Vadis European HEP?

➤ Final word about thermal WIMP dark matter (DM)

- Thermal WIMP dark cannot be too heavy: (1- 3) TeV upper mass limit from observed relic abundance
- The conclusive affirmation/rejection of WIMPs by accelerator expts is of paramount importance
- LHC: can exclude only a fraction of the range (1-3) TeV
- FCC-hh is necessary and just sufficient with this respect



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FCC-ee in a Nutshell

Running mode	Z	WW	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1283	135	26.8	5.1
Luminosity/IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	144	20	7.5	1.45
Energy loss / turn [GeV]	0.039	0.369	1.86	9.94
Synchrotron Radiation Power [MW]	100	100	100	100

- Luminosity: $144 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at $\sqrt{s} = 91 \text{ GeV}$
 (per IP) $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at $\sqrt{s} = 240 \text{ GeV}$
 (4 experiments)

Power consumption: 222, 247, 273, 357 MW
 at Z, WW, ZH, $t\bar{t}$

Accelerator challenge: **High luminosity**

 - advanced but challenging schemes (e.g. crab waist);
 - may be constrained by beam-beam and intensity effects

Lumi/bunch pair (different machines: E, # bunches):
 SuperKEKB²⁰²⁴: $2.2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
 → FCC-ee Z: $1.3 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

