Electroweak, Top, Higgs, and BSM Physics with the LHeC/FCC-he

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

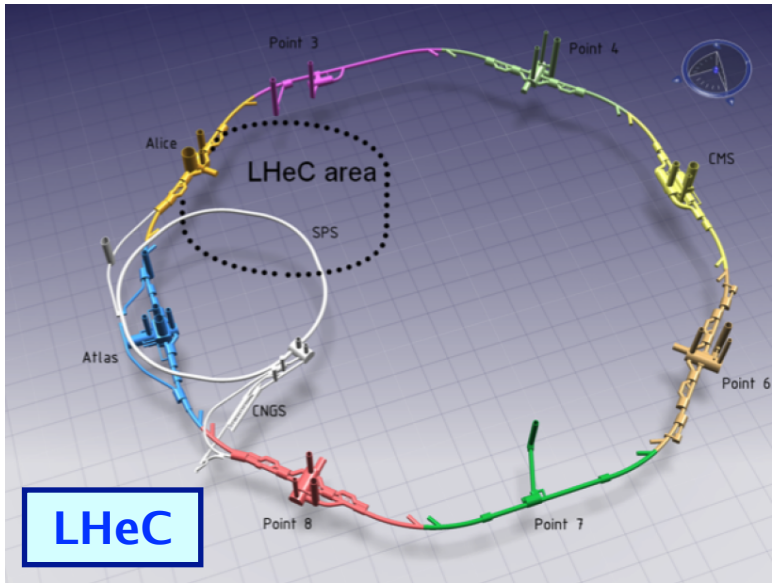
Christian Schwanenberger
DESY & University of Hamburg
for the LHeC/FCC-eh Study Group

XXIX Cracow EPIPHANY Confrence on Phyics at the EIC and Future Facilities

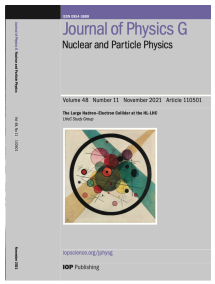
Cracow

19 January 2023

Linac-Ring Collider, LHeC and FCC-eh



LHeC CDRs:
arXiv:1206.2913,
J. Phys. G 39
075001 (2012)
arXiv:2007.14491
(J. Phys. G 48
(2021) 11)



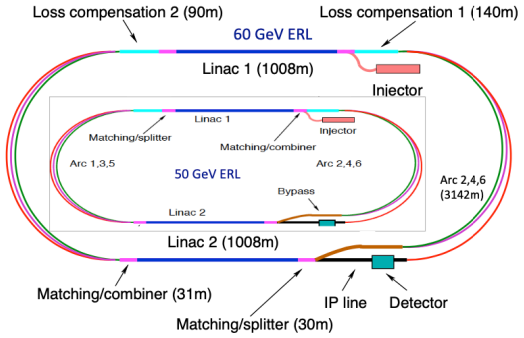
FCC CDR:
Eur. Phys. J. C 79,
no. 6, 474 (2019) -
Physics
Eur. Phys. J. ST
228, no. 4, 755
(2019) - FCC-hh/eh

- operated synchronously with FCC-hh: e beam: 60 GeV × p beam: 50 TeV: $\sqrt{s}$=3.5 TeV
- operation: 2050+
- cost: O(1-2) BCHF

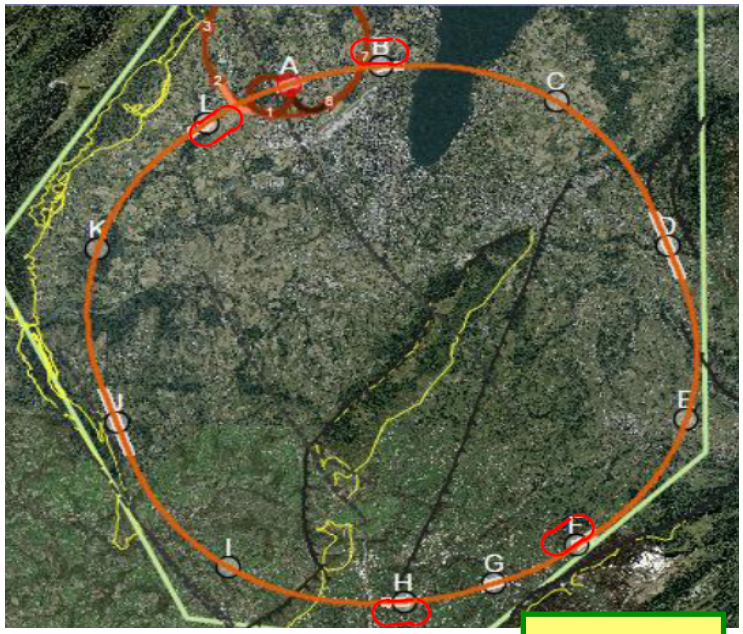
- operated synchronously with HL-LHC: e beam: 50 GeV × p beam: 7 TeV: $\sqrt{s}$=1.2 TeV
- operation: 2035+
- cost: O(1) BCHF
- luminosity of 10^{34} $cm^{-2}s^{-1}$

Energy Recovering Linac

$e^{\pm}$ beam: 50, 60 GeV



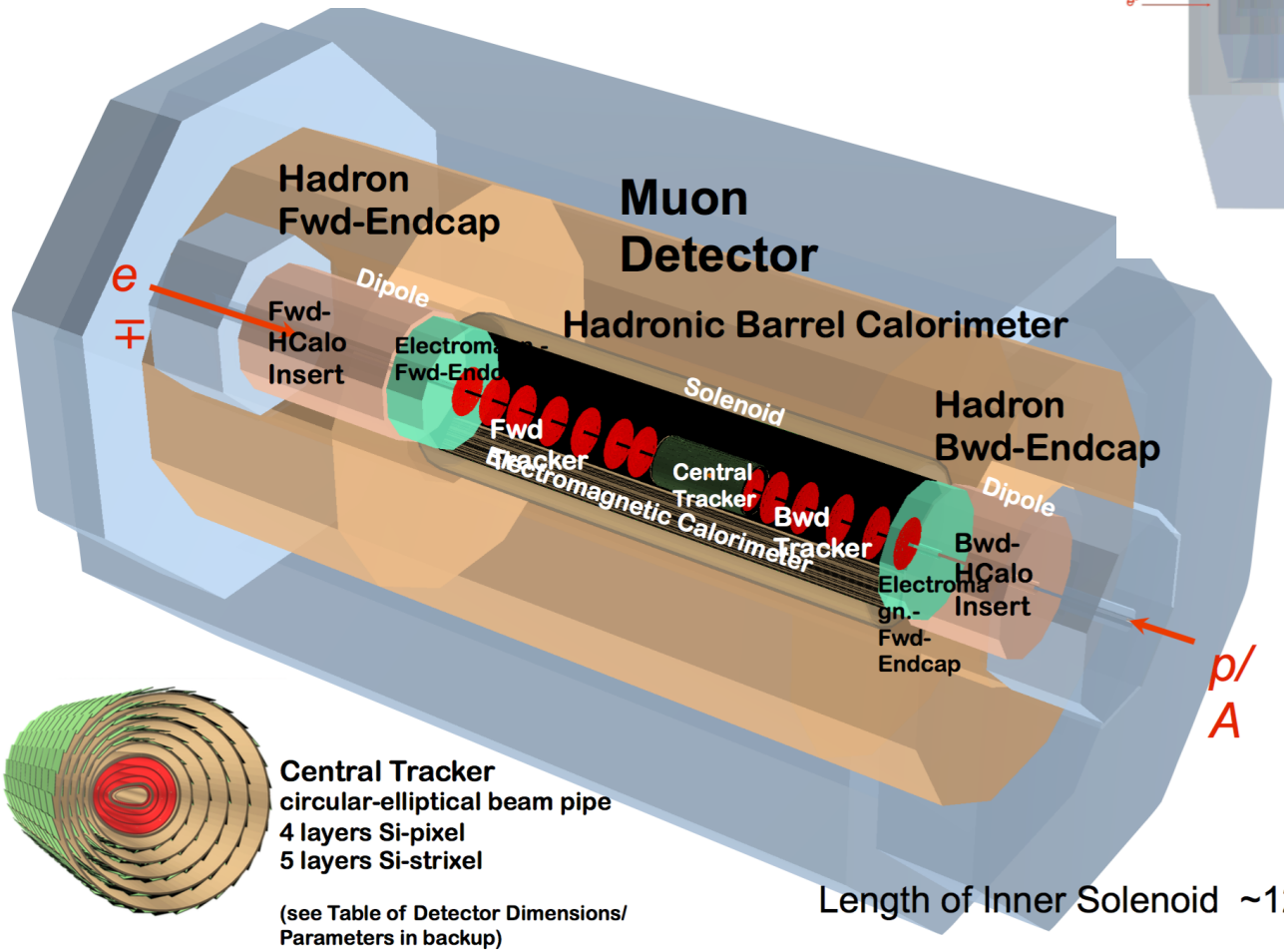
L_{int} = 1-3 ab^{-1} (1000×HERA!)



LHeC and FCC-eh Detector Layout

FCC-eh

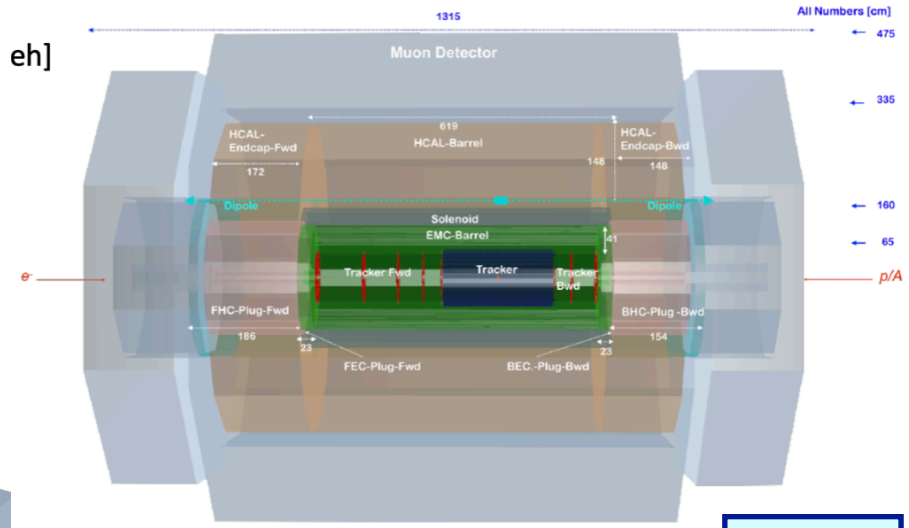
L=19.3m
(about CMS size)



Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/ Parameters in backup)

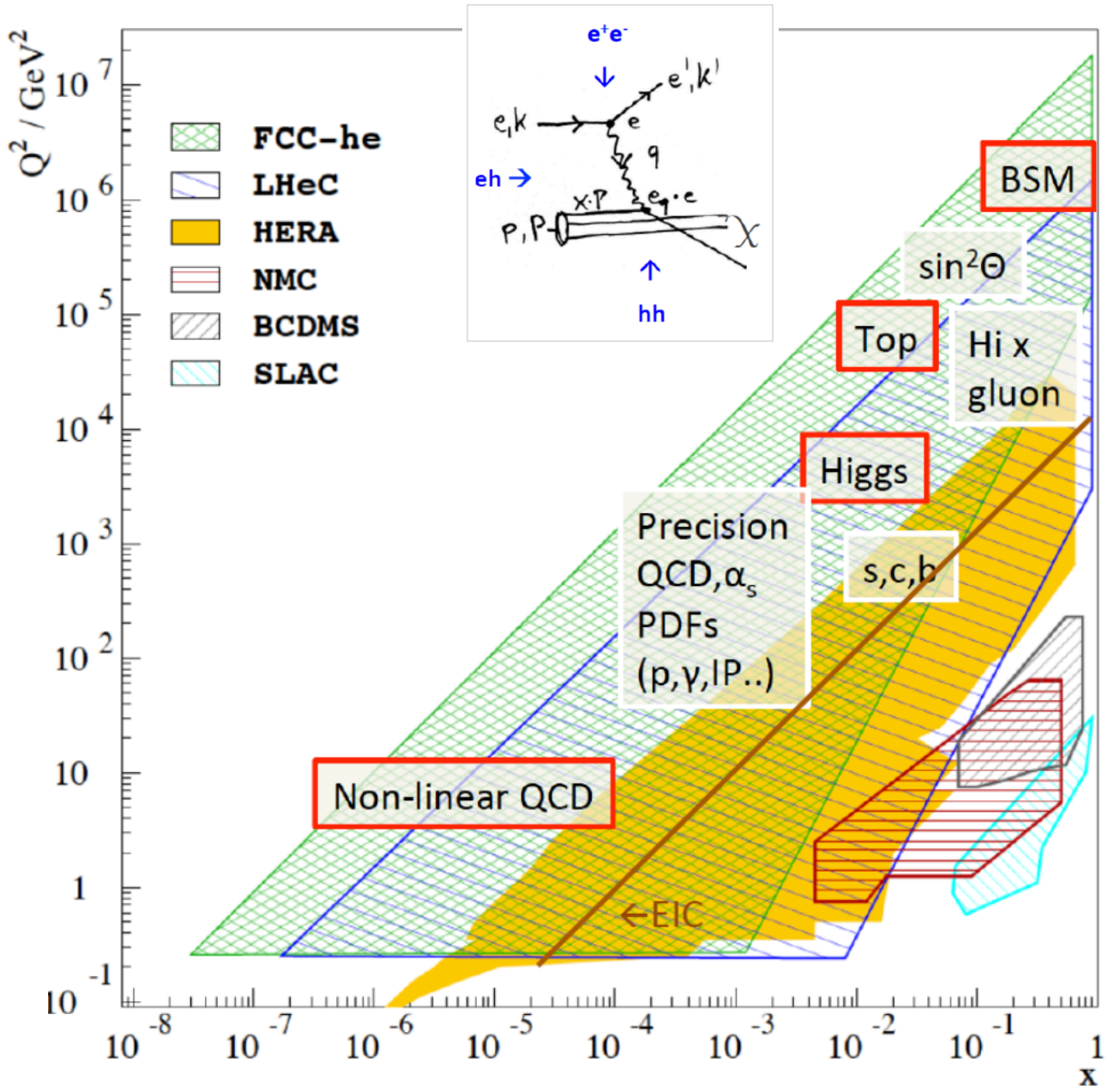
Length of Inner Solenoid ~12m



L=13.2m

LHeC

High energy frontier eh physics

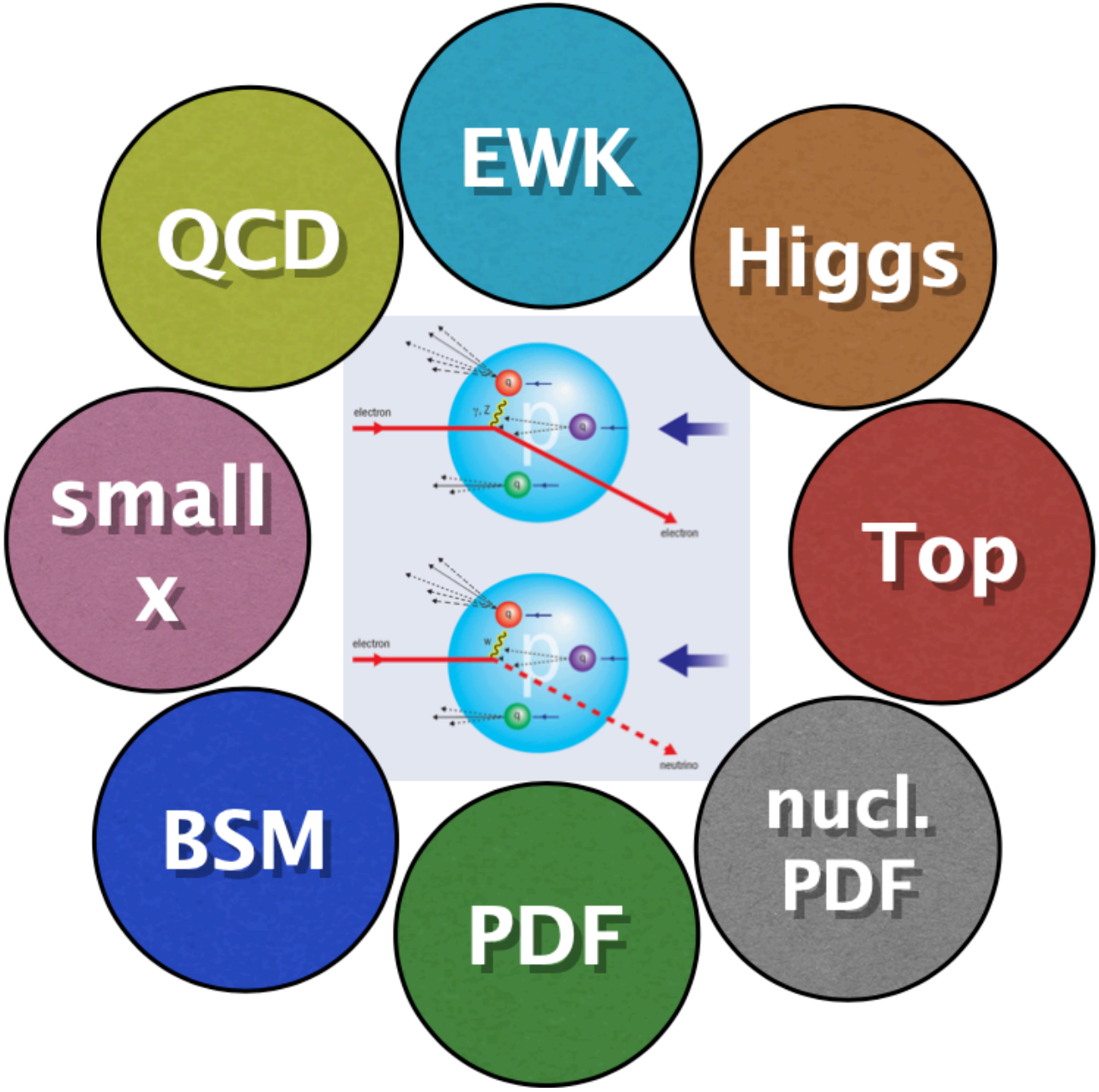


deliveries of ep/eA at the energy frontier

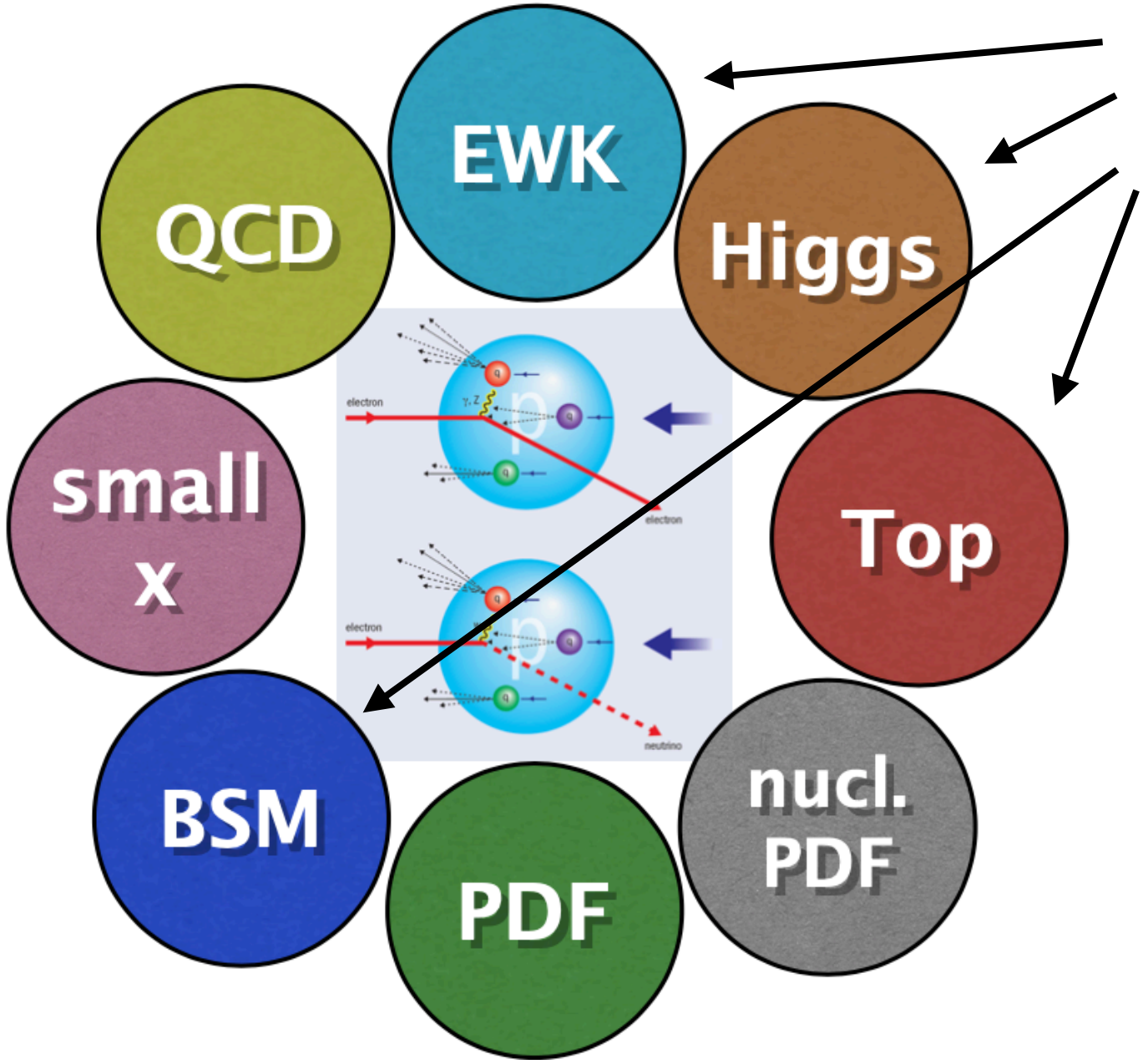
- cleanest high resolution microscope: QCD discovery
- empowering the LHC/FCC search program
- precision Higgs facility together with LHC/FCC-hh
- precision and discovery facility (top, EWK, BSM)
- unique nuclear physics facility

→ diversity

High energy frontier eh physics



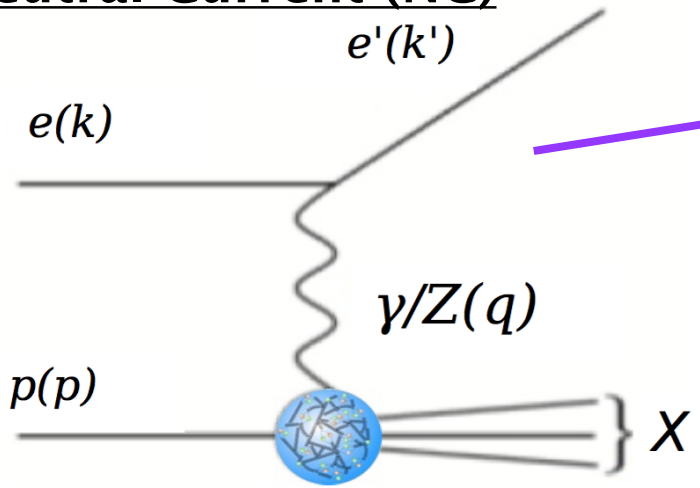
Outline


EWK
QCD
Higgs
small x
Top
BSM
PDF
nucl. PDF
this talk
electron
electron
electron
neutrino

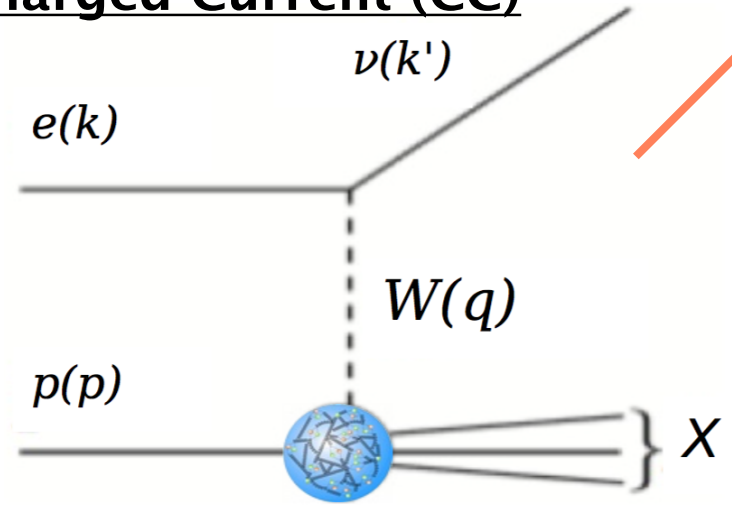
Deep Inelastic Scattering

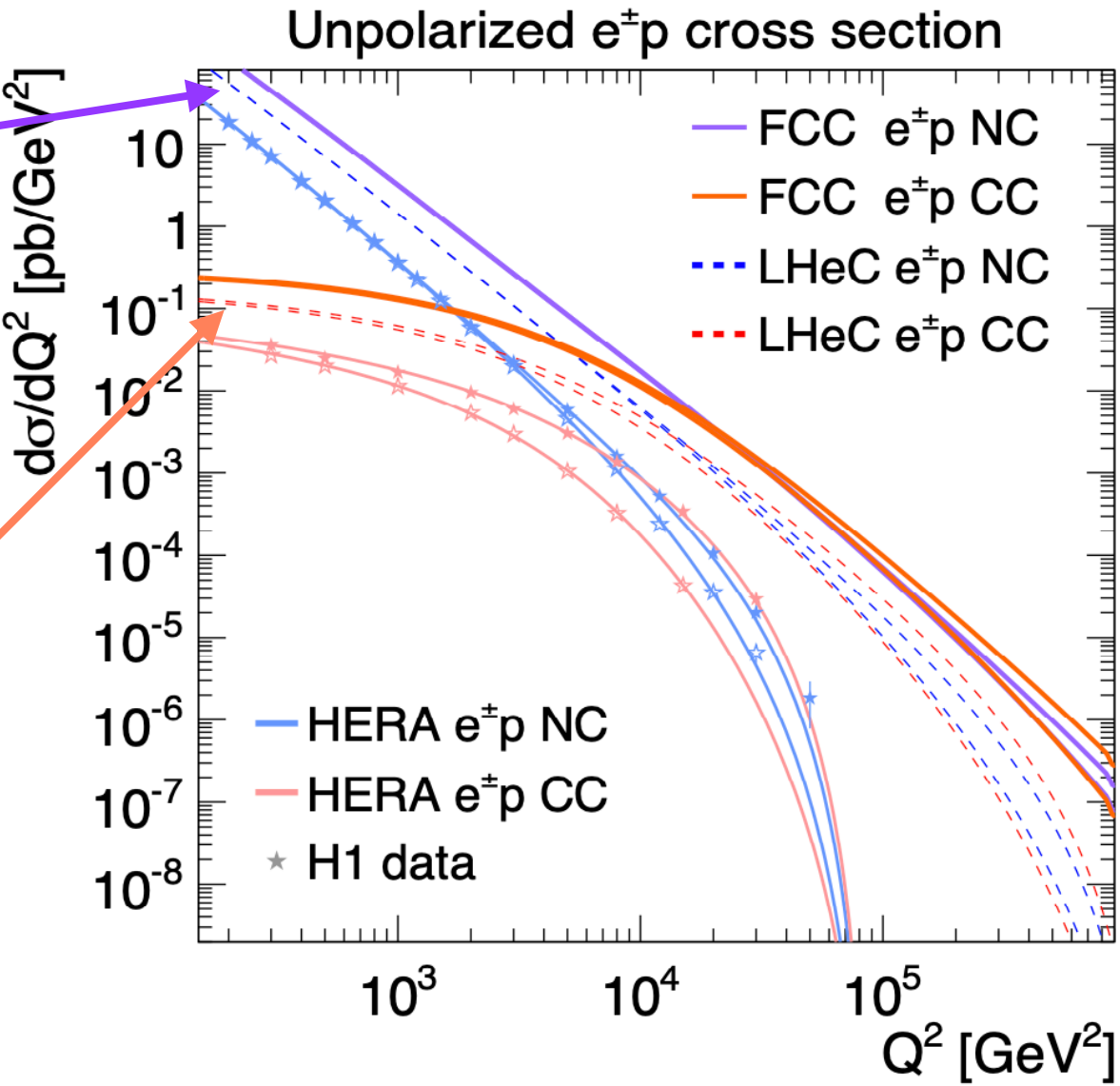
EWK

Neutral Current (NC)



Charged Current (CC)



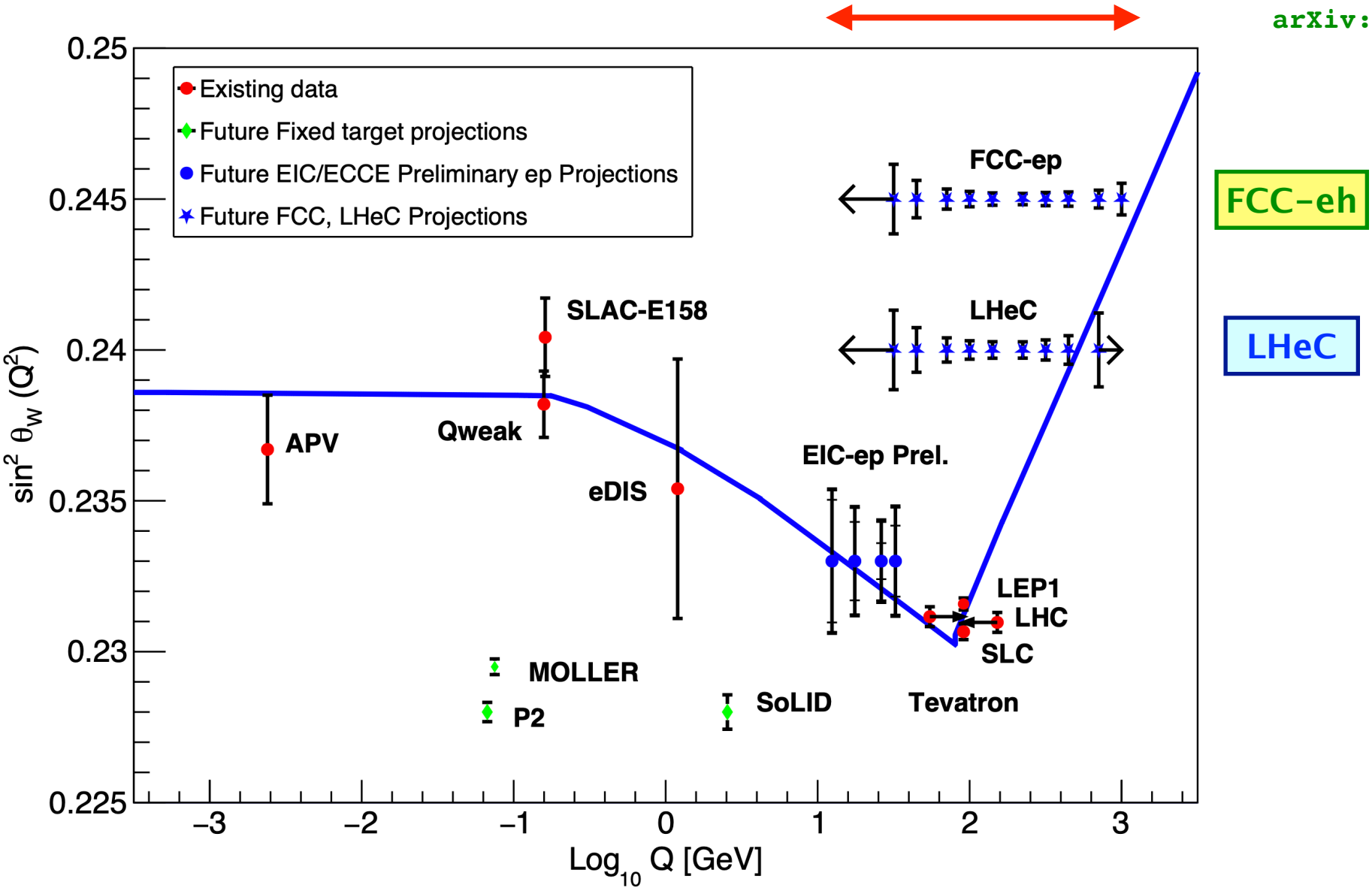


→ **LHeC/FCC-eh are unique facilities for testing EW theory:**
NC+CC, two e-beam charge and polarisation states, p or isoscalar targets

Scale Dependence of $\sin^2\theta_W$

EWK

arXiv:2203.06237



FCC-eh

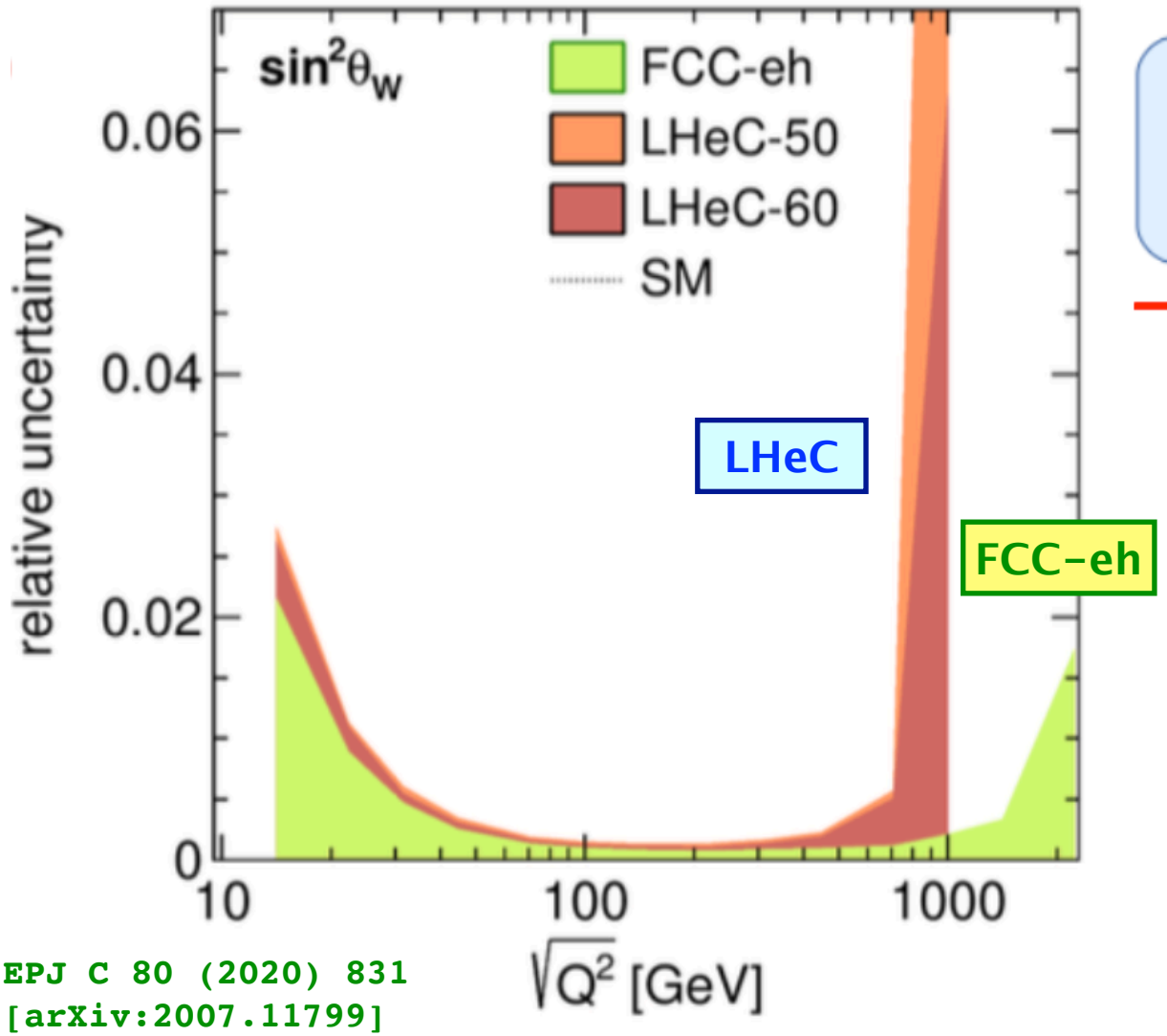
LHeC

→ probe large range of scale dependence

Scale Dependence of $\sin^2\theta_W$

EWK

NC+CC DIS ⟷



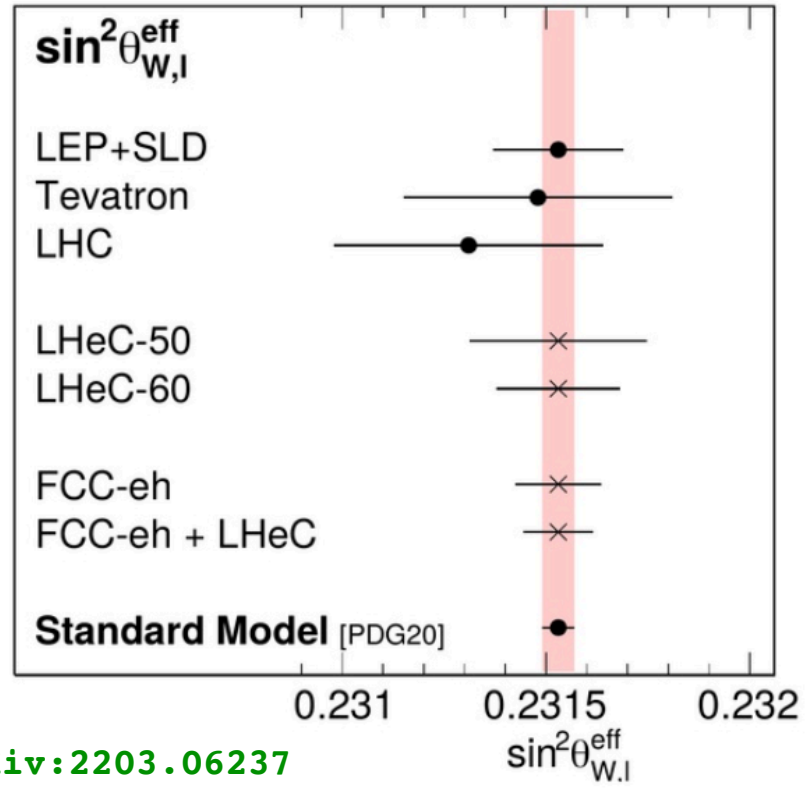
EPJ C 80 (2020) 831
[arXiv:2007.11799]

→ **probe large range of scale dependence**

on-shell definition $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$

$\Delta\sin^2\theta_W$ (FCC-eh) = ±0.00011
= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

→ **precision per mille level**



arXiv:2203.06237

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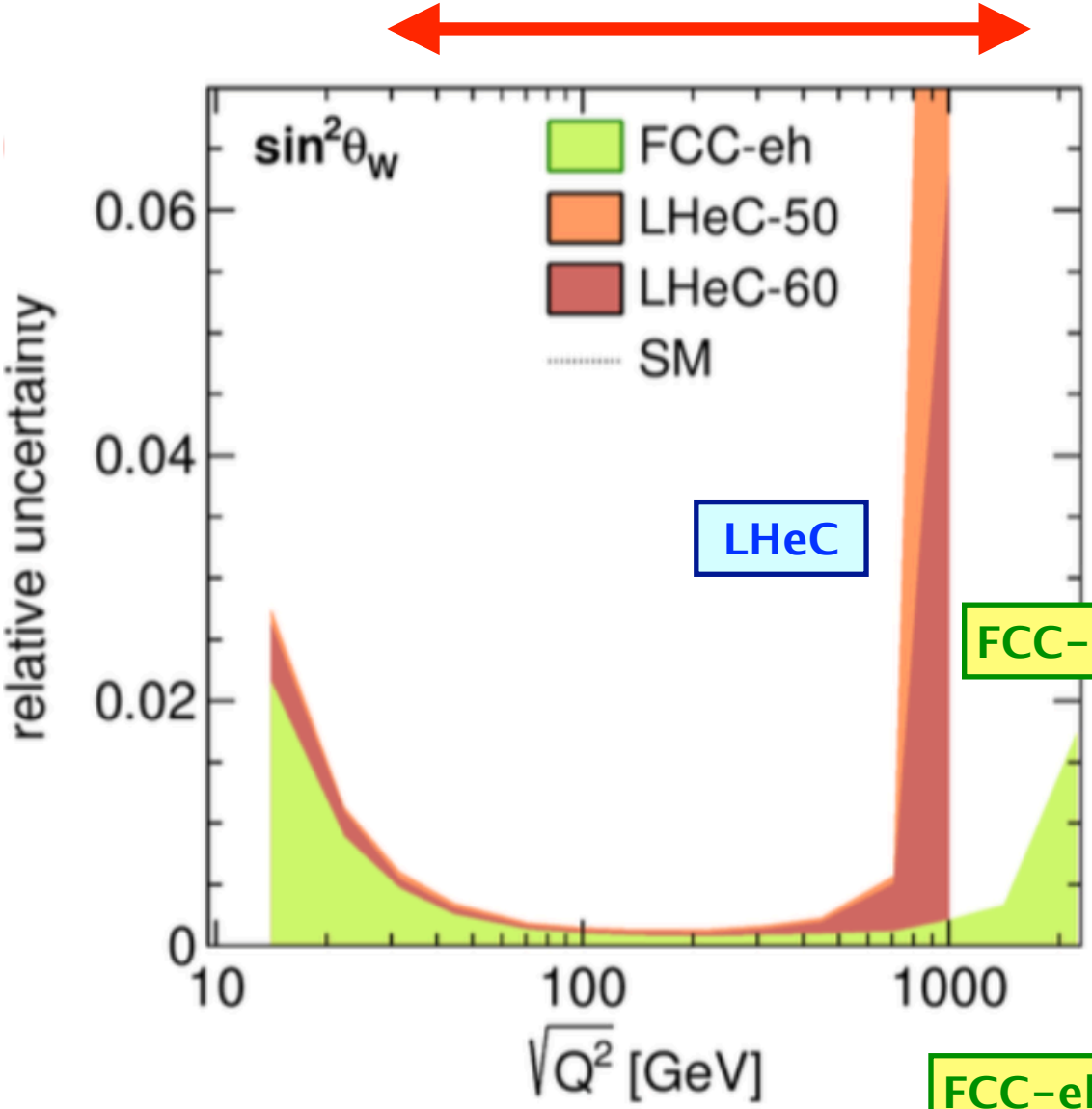

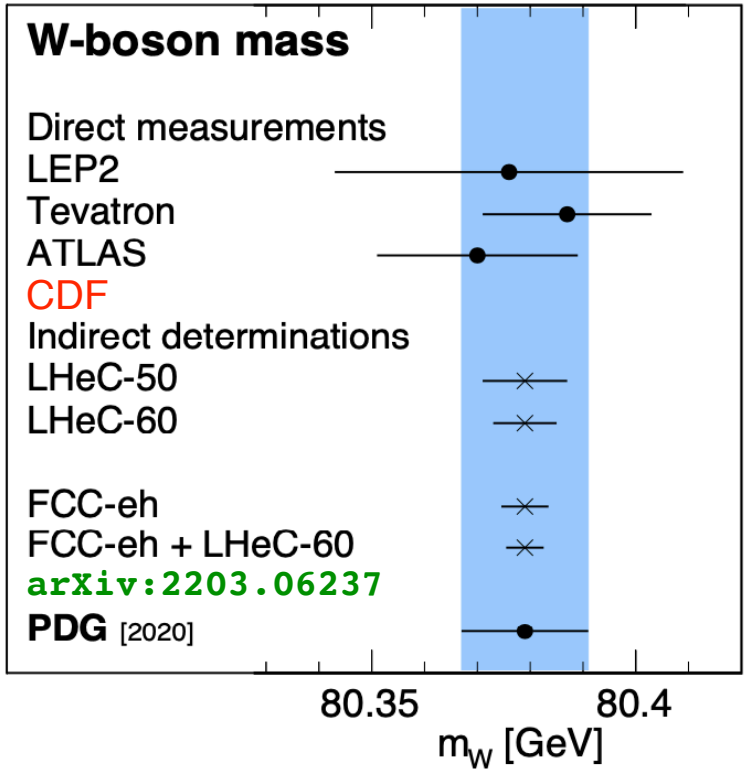

$\Delta m_W = \pm 4.5$ MeV

(includes PDF uncertainty of about ±3.6 MeV)

→ **probe large range of scale dependence**

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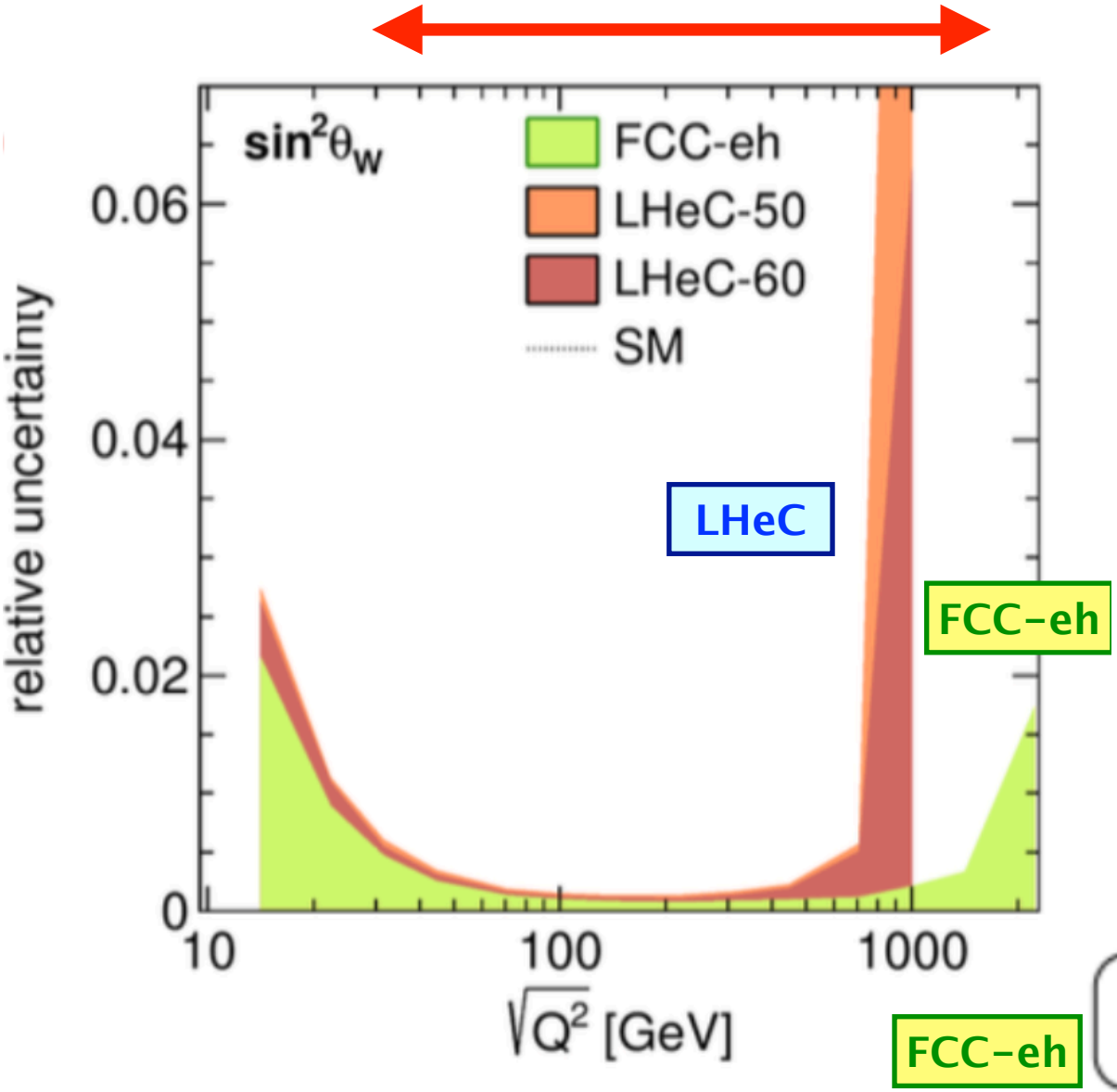

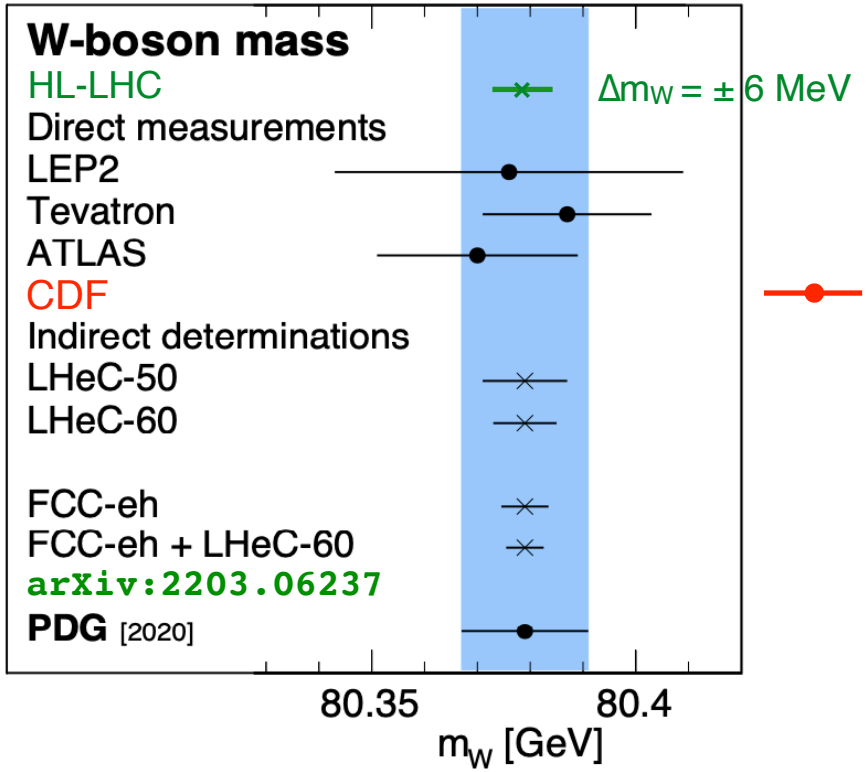

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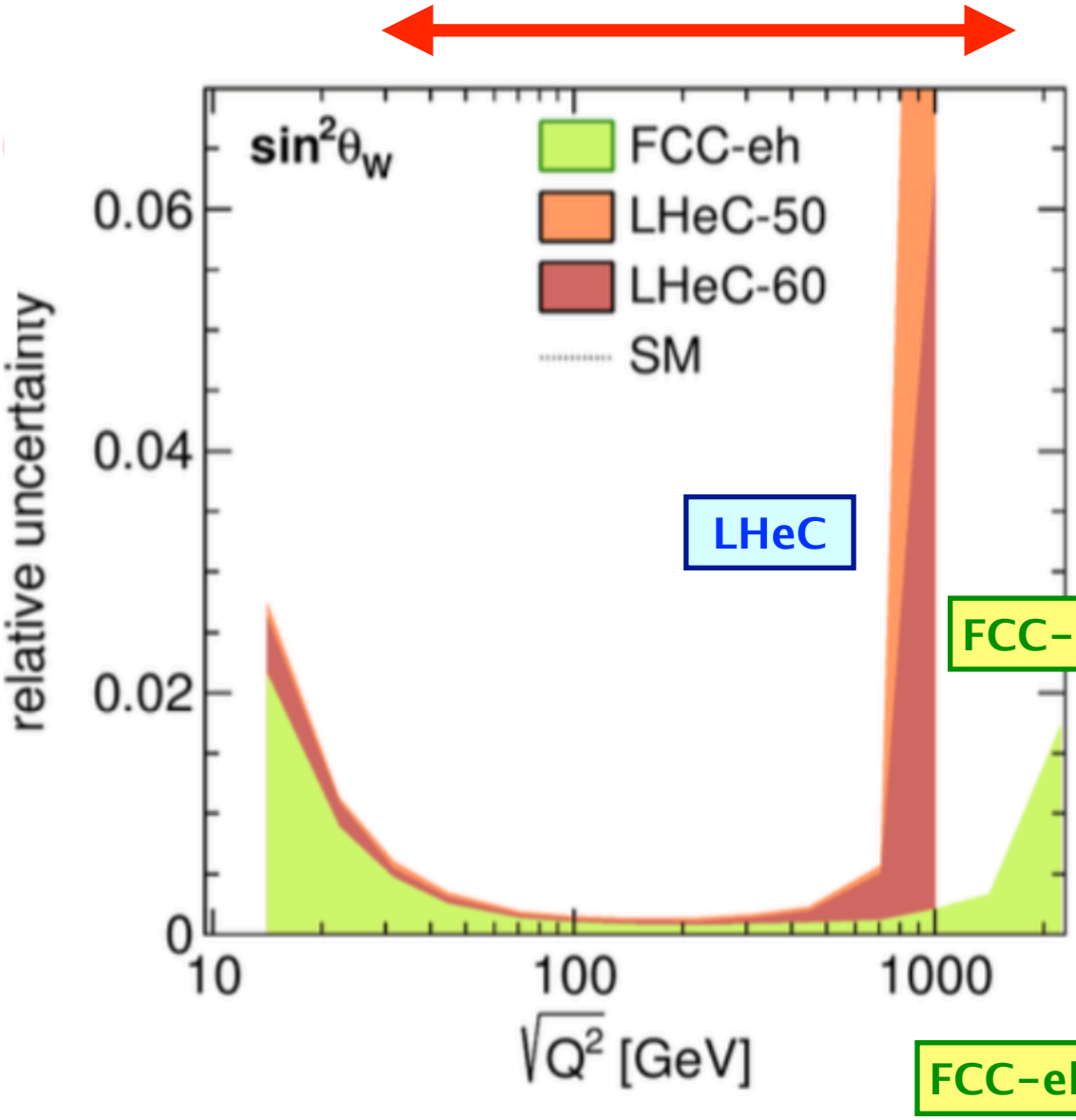

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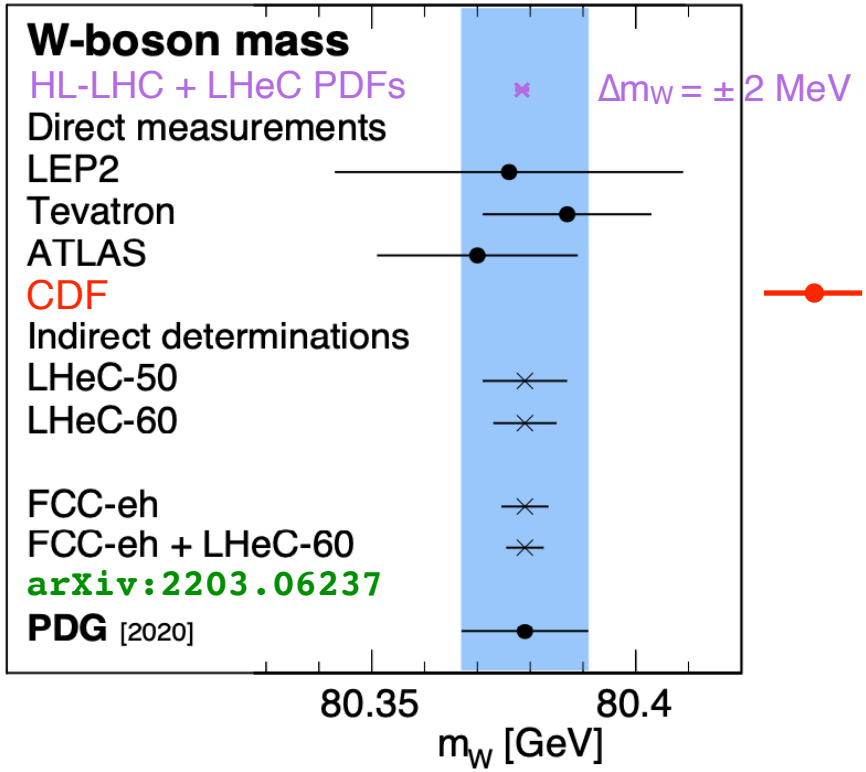

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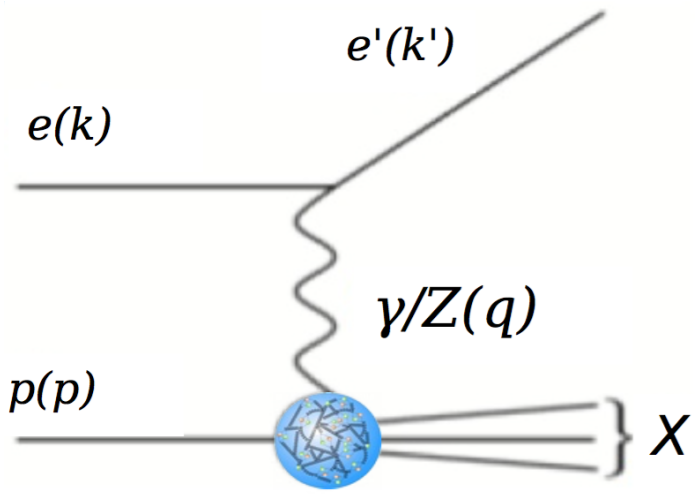
→ **probe large range of scale dependence**

Electroweak Fermion Couplings EWK



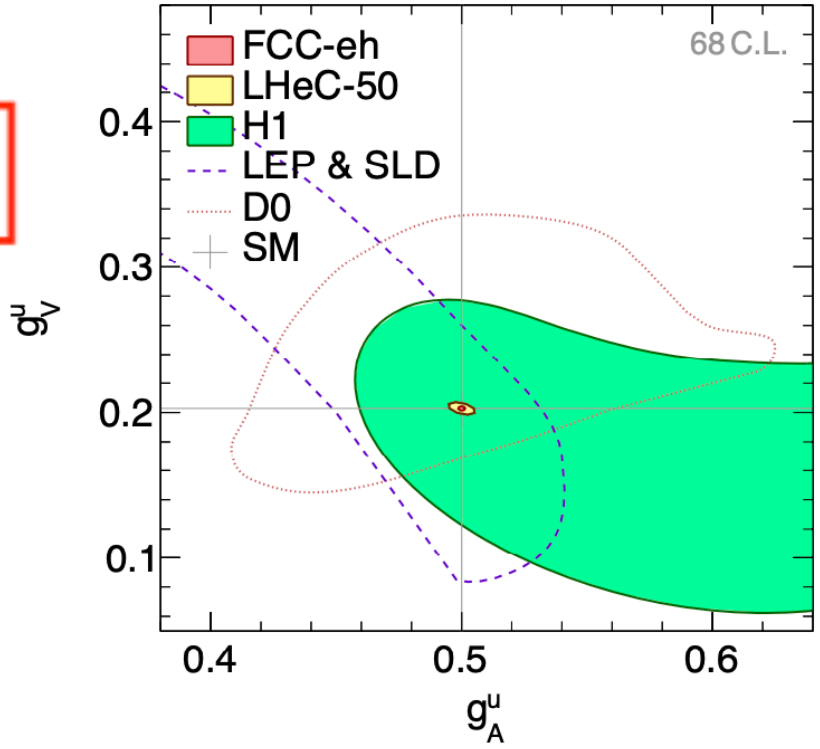
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$

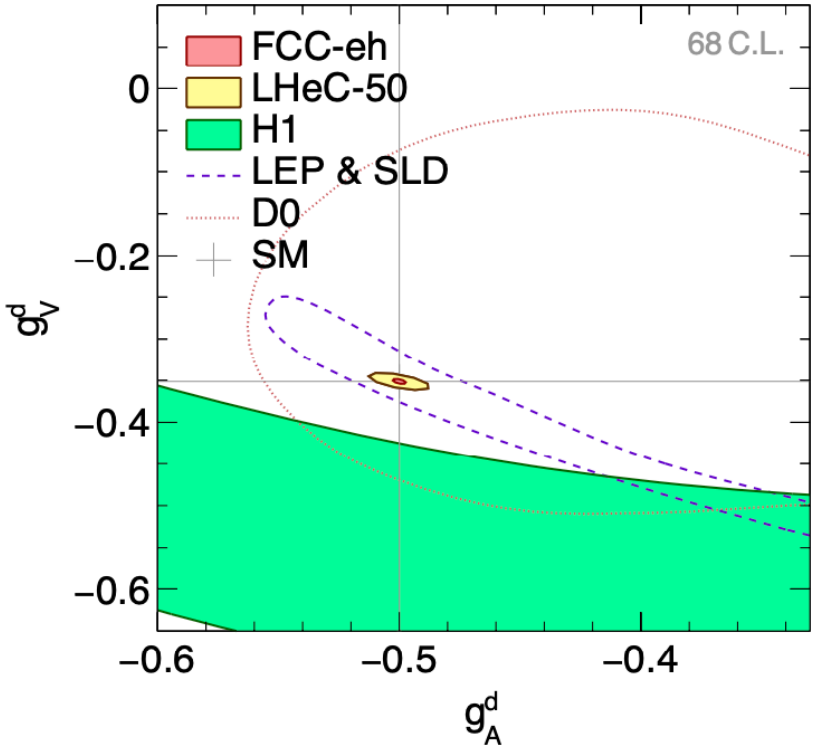
$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\kappa'_{\mathrm{NC},f}\sin^2\theta_W\right)$$

→ **precision on per mille level**

(largely unaccessible in e^+e^-)

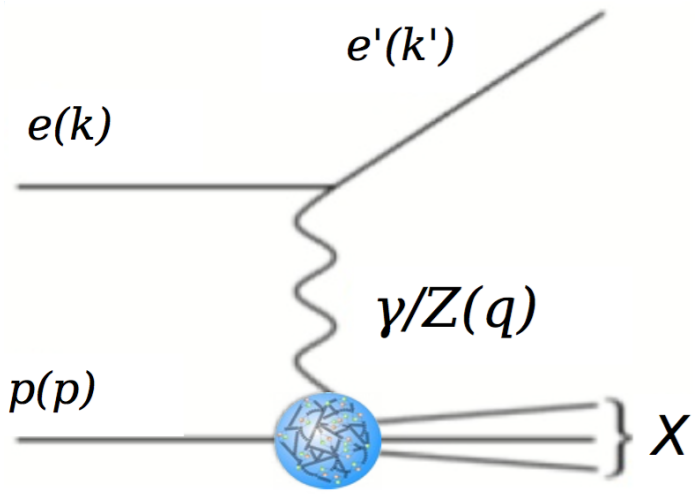
u





d

Electroweak Fermion Couplings EWK



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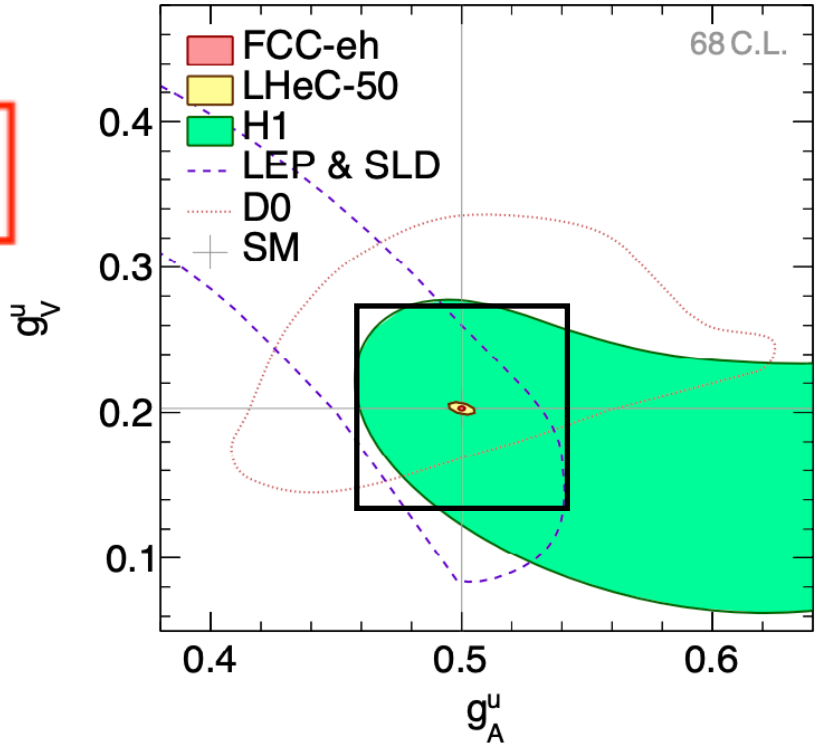
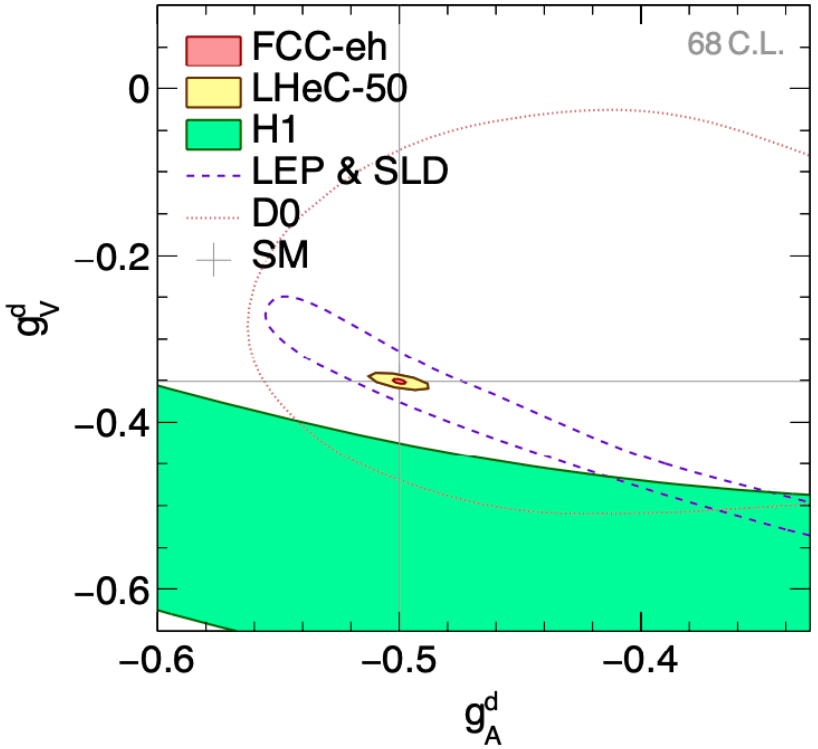
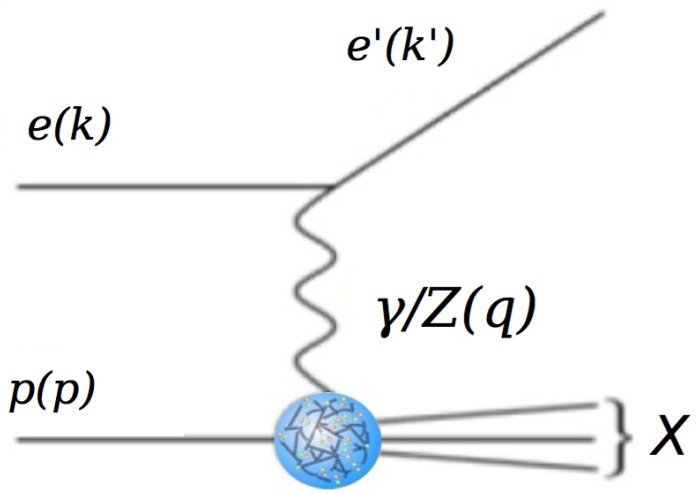




d

Electroweak Fermion Couplings EWK



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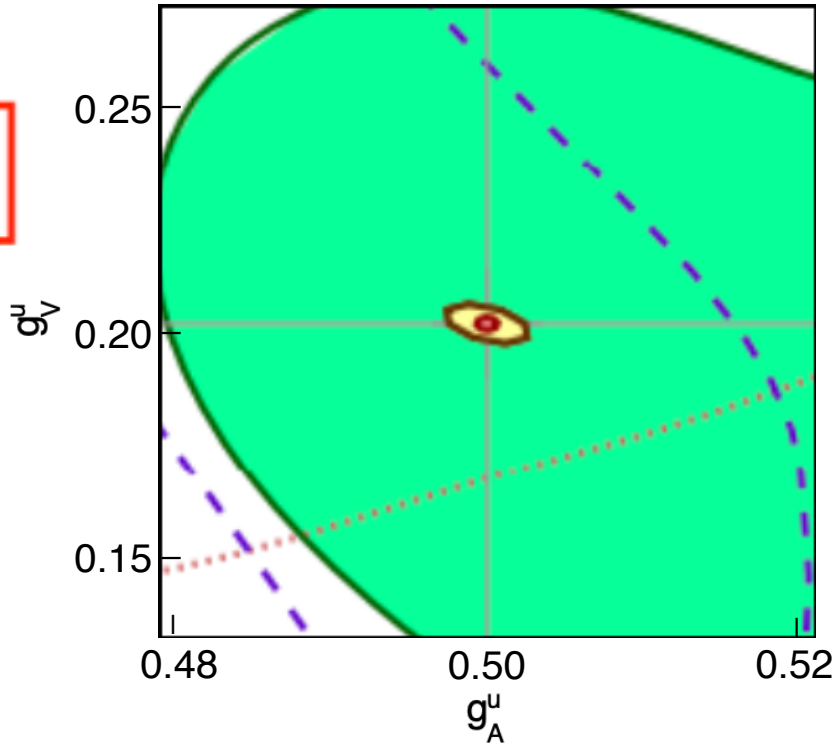
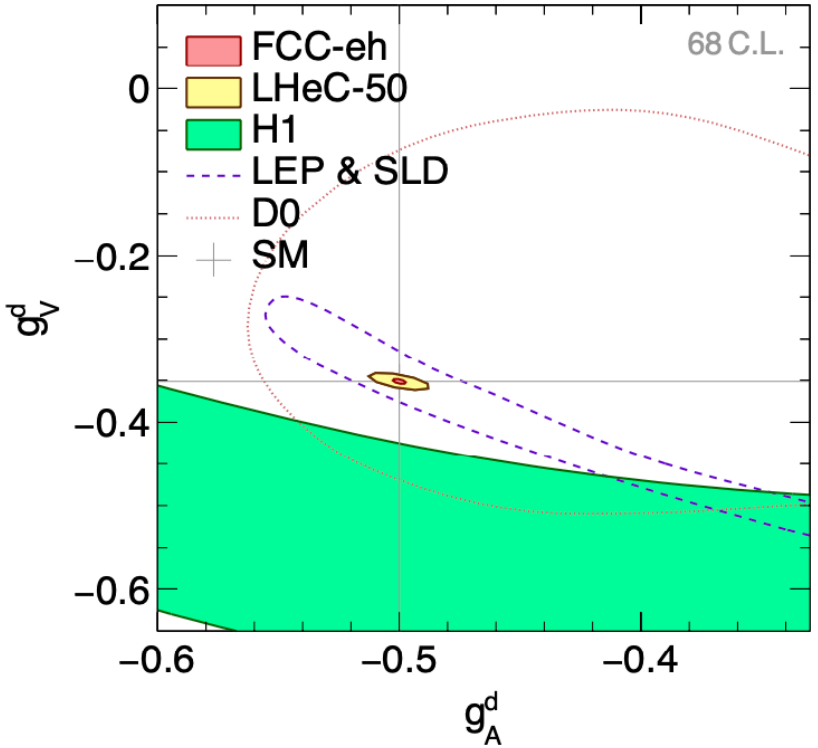
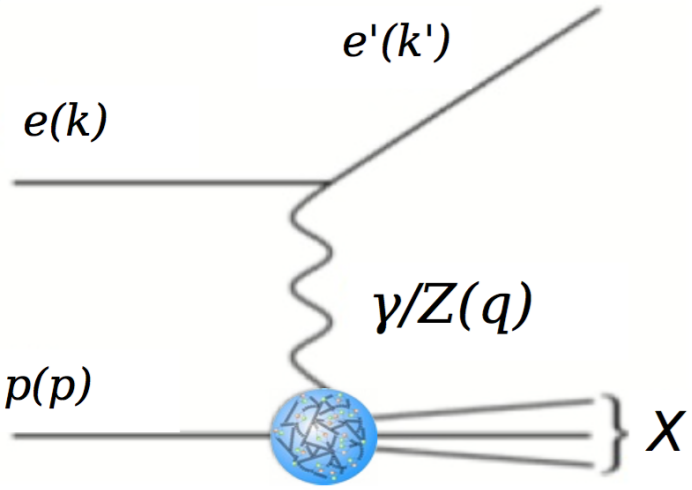




d

BSM Electroweak Fermion Couplings EWK



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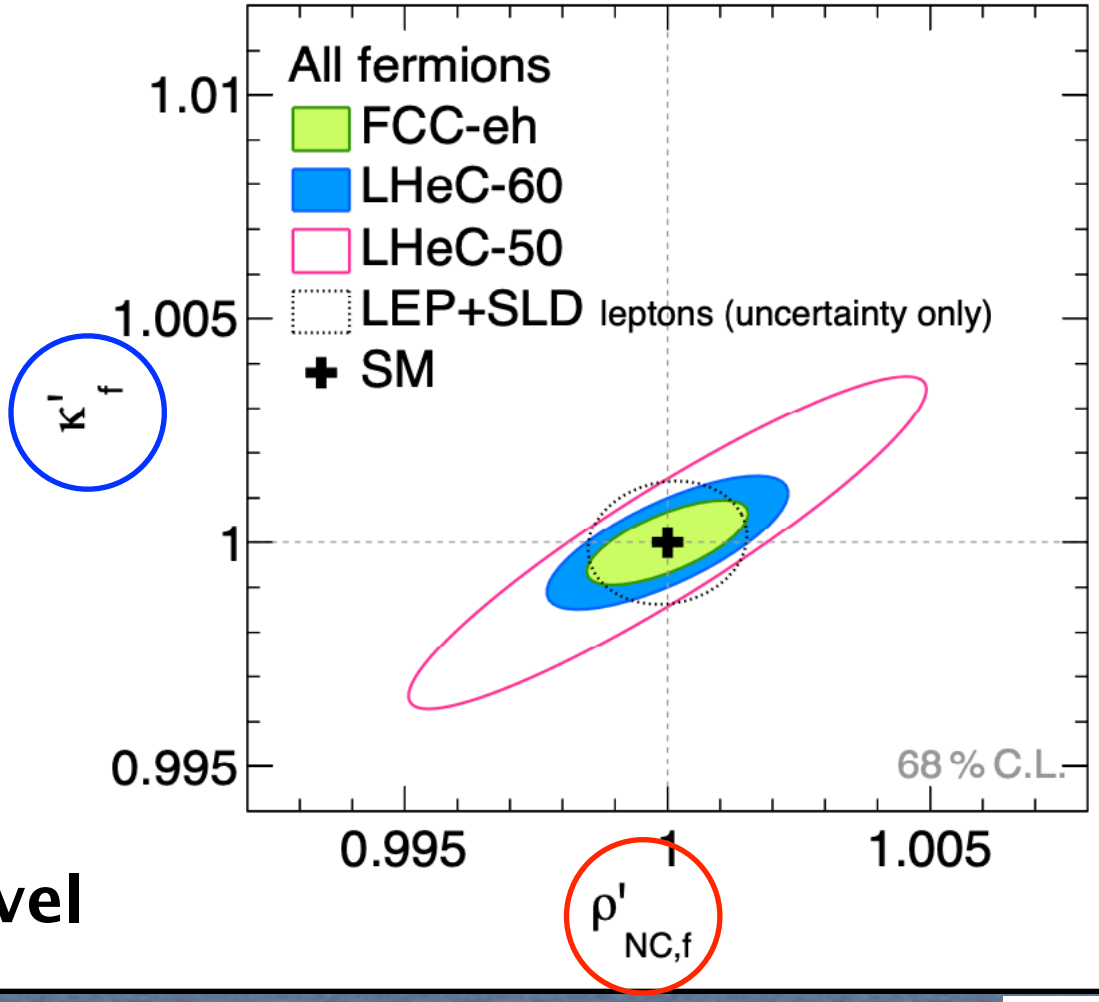
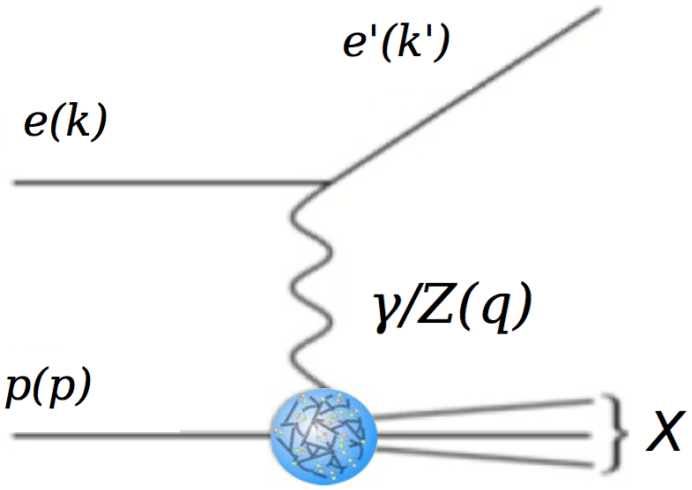
f = fermions



→ **precision on per mille level**

BSM Electroweak Fermion Couplings EWK



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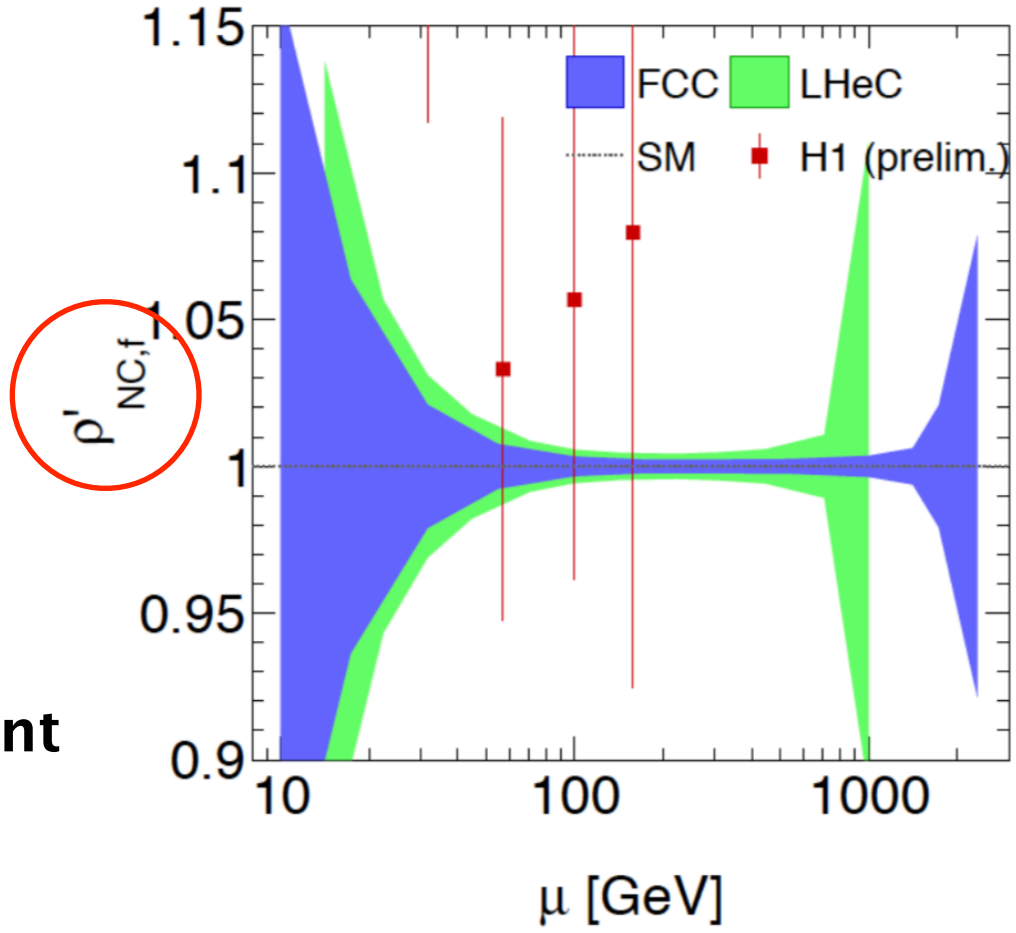


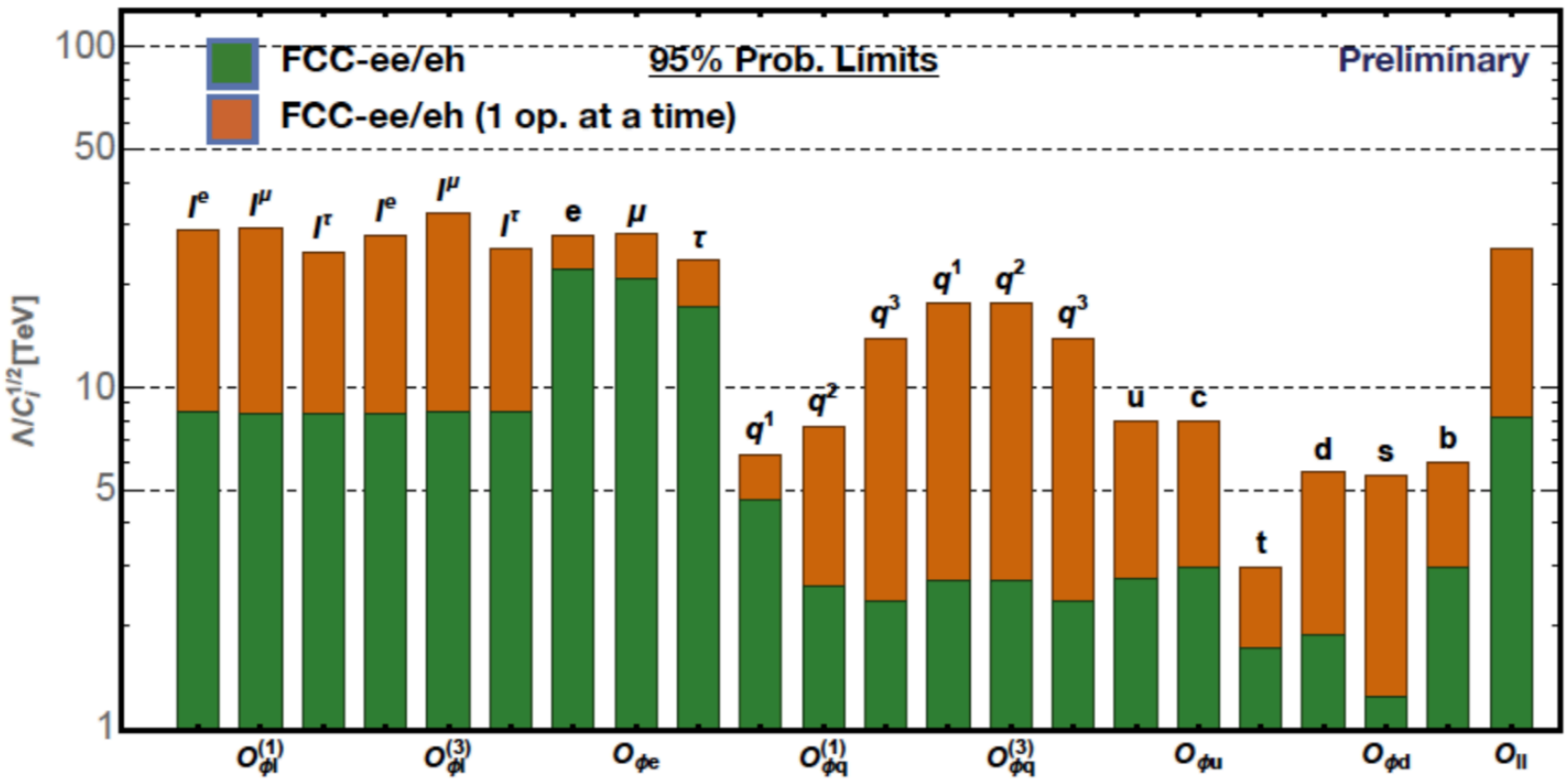
→ scale dependence on per cent level (mostly per mille level) between 20 < μ < 2000 GeV

Constraints on New Physics

BSM

EWK

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh



No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

→ high sensitivity to NP

Top Quark Production

Top

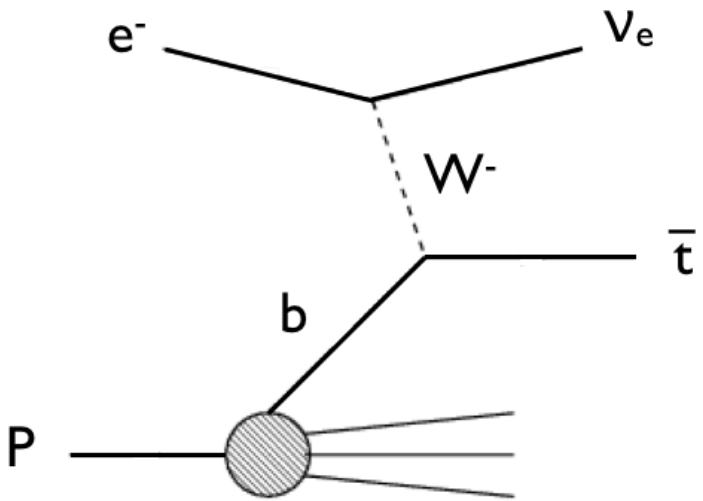
σ=1.89pb @ LHeC

σ=15.3pb @ FCC-eh

E_e=60 GeV

NLO calculation: Gao & Gao, arXiv:2103.15846

CC DIS top production



Direct Measurement of $|V_{tb}|$

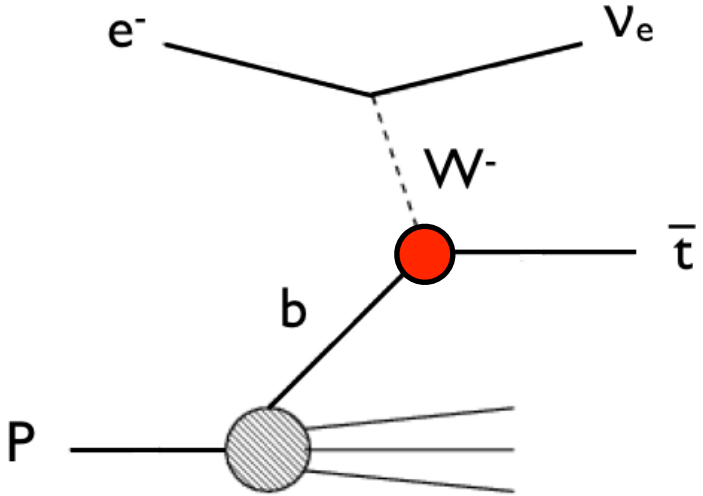
Top

σ=1.89pb @ LHeC

σ=15.3pb @ FCC-eh

E_e=60 GeV

CC DIS top production



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Anomalous Wtb Couplings

BSM

Top

= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

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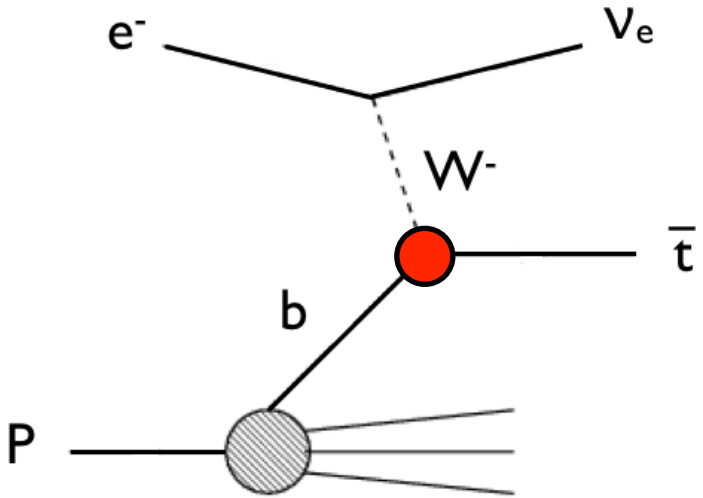

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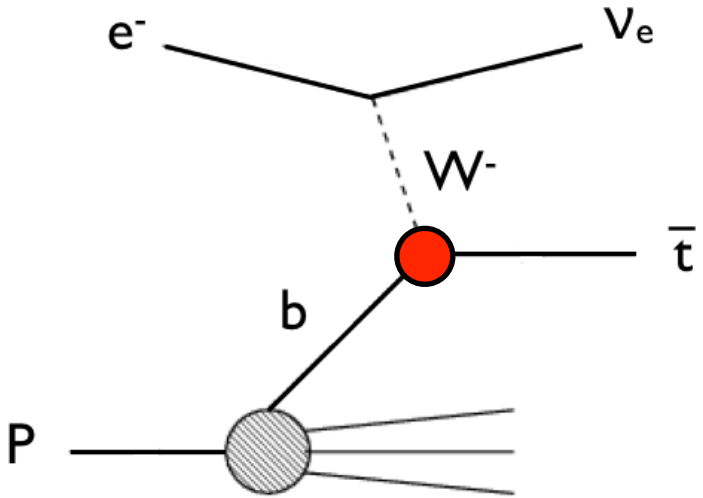

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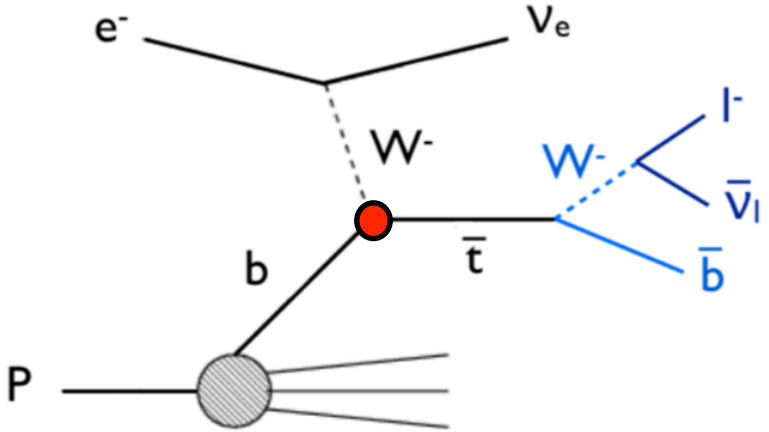
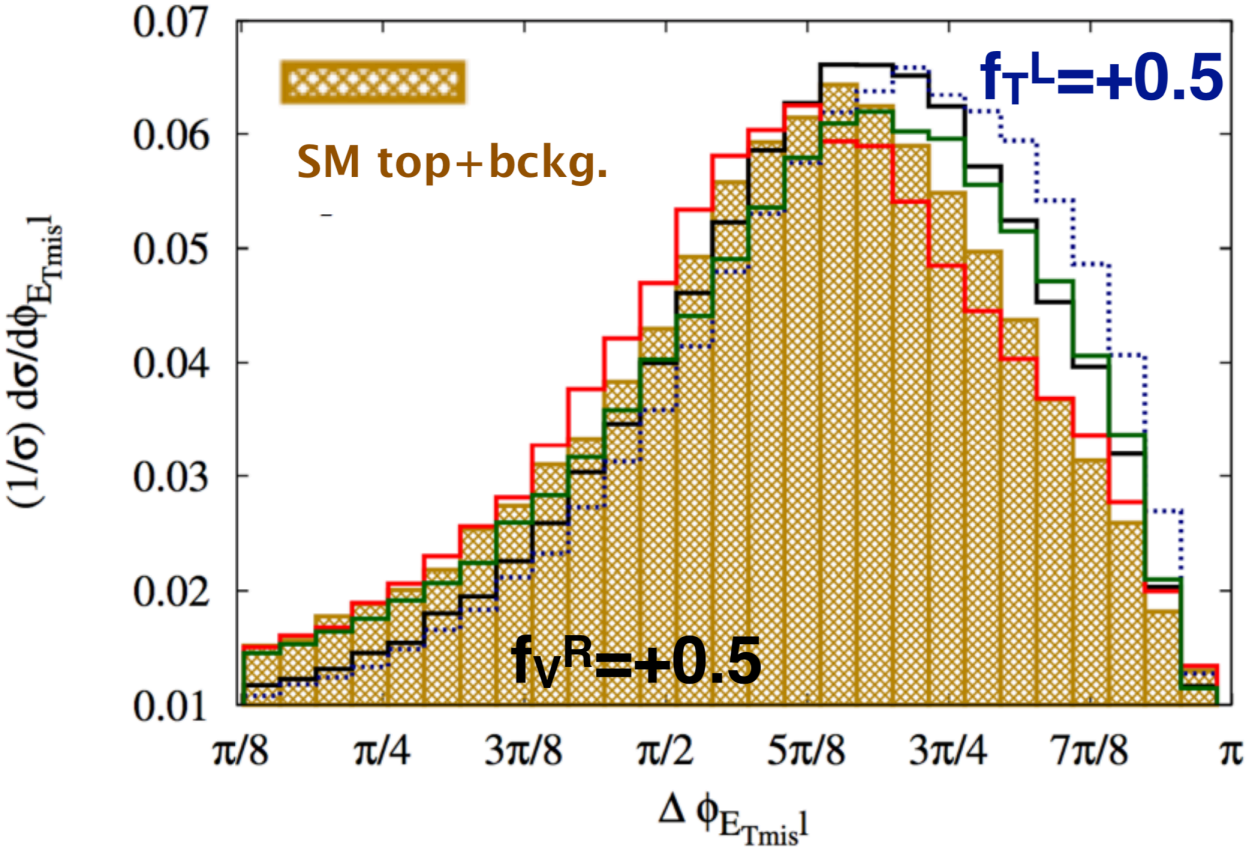
CC DIS top production



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



+ other variables sensitive on W helicity

Anomalous Wtb Couplings

BSM

Top

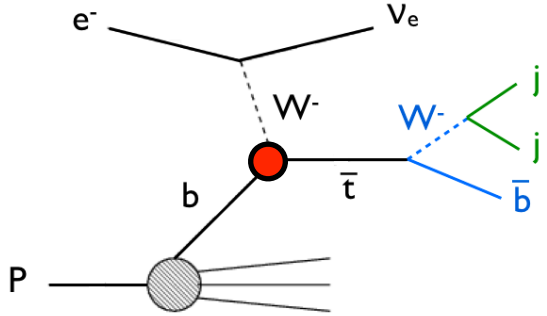
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

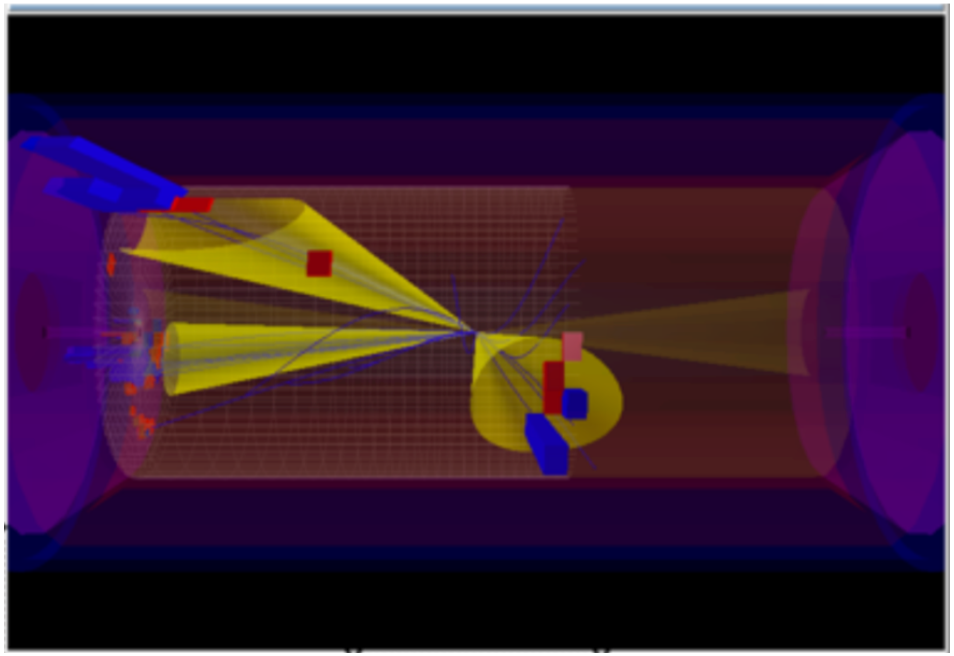
= 1 in SM

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.

95% C.L.



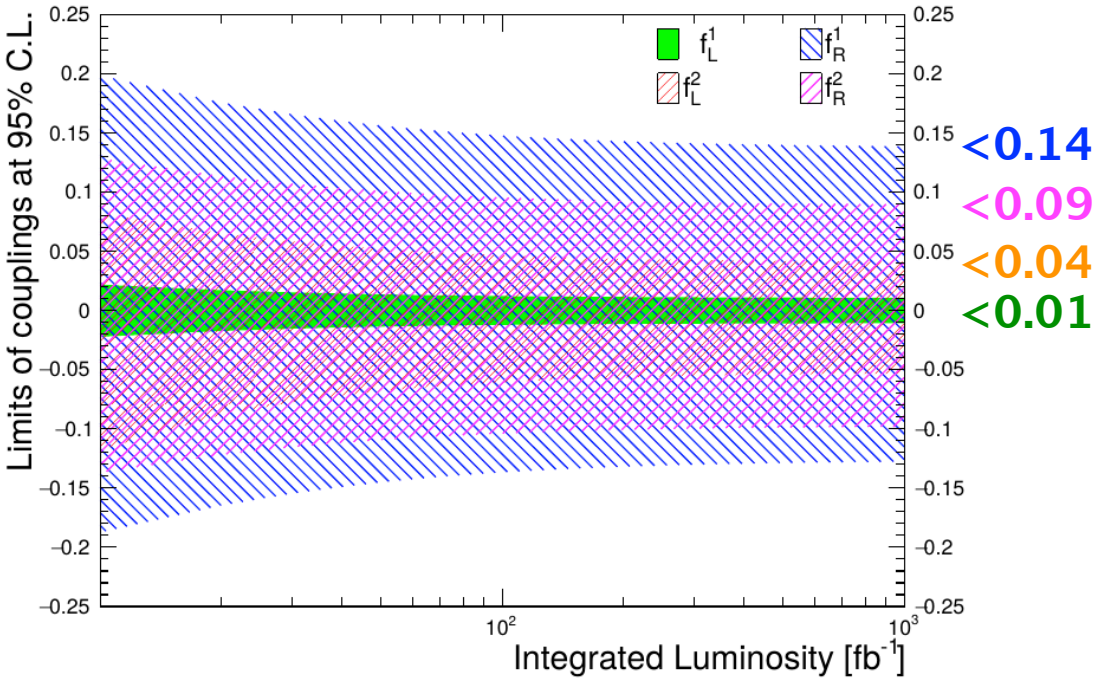
DELPHES



including detector simulation (Delphes)

LHeC

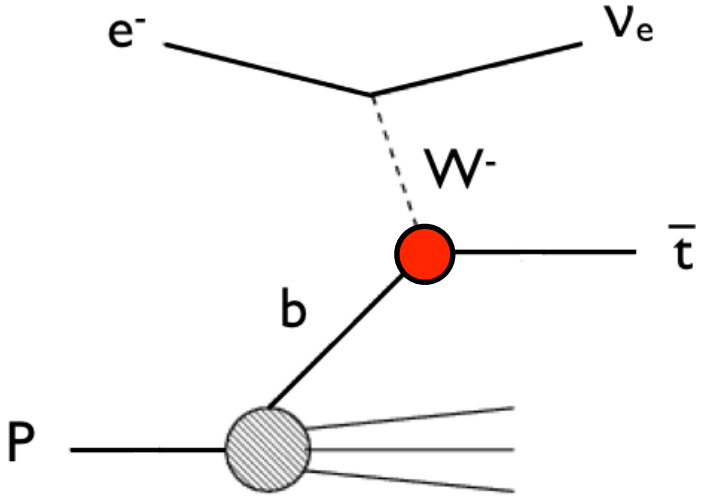
hadronic channel:



<0.14
<0.09
<0.04
<0.01

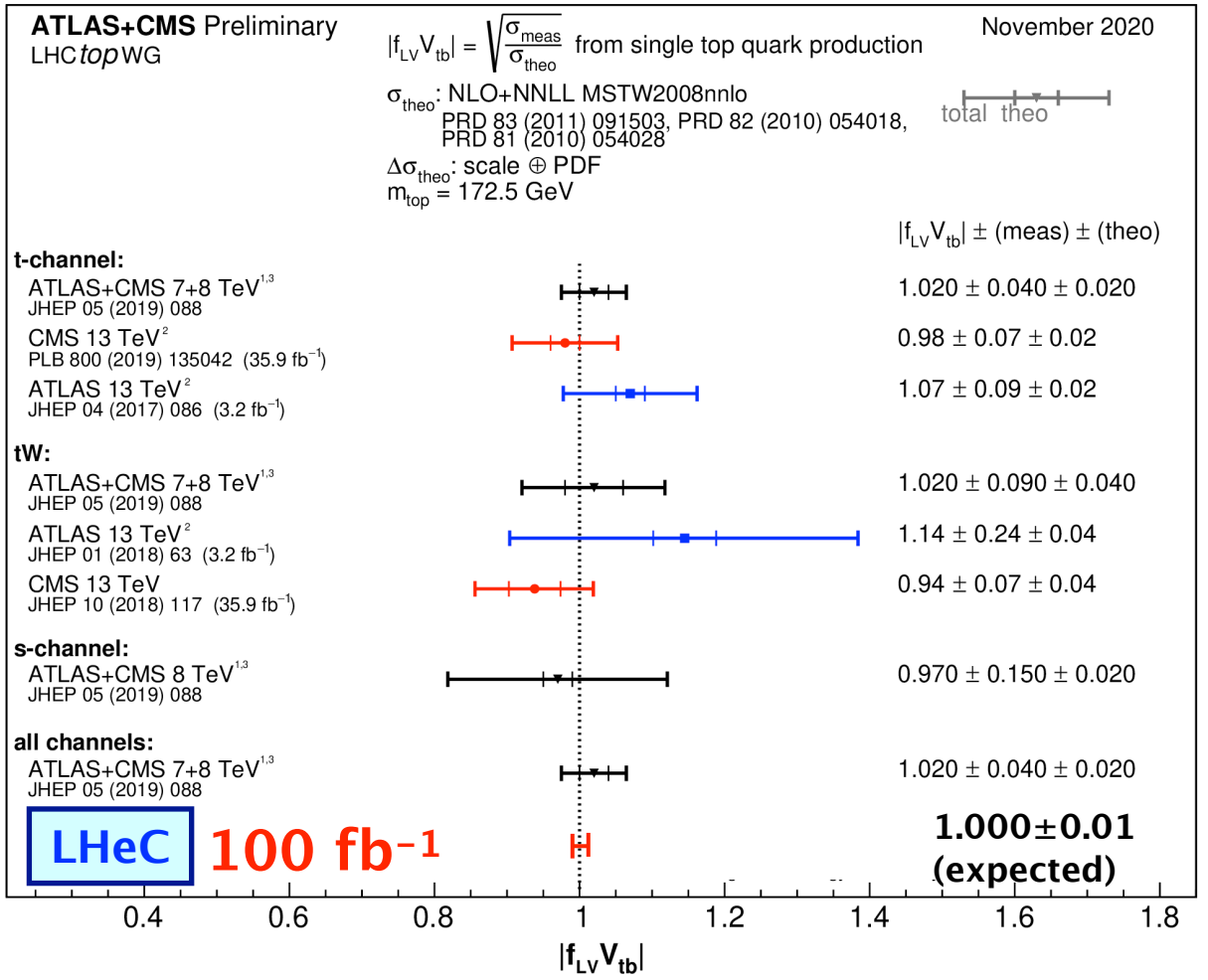
Direct Measurement of $|V_{tb}|$

Top



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11
[3] NPPS205 (2010) 10, CPC191 (2015) 74 including beam energy uncertainty



Measurement of $|V_{ts}|$

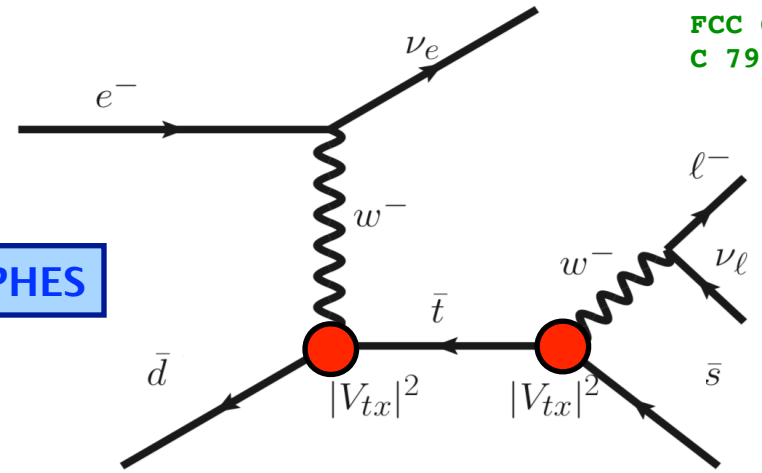
Top

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

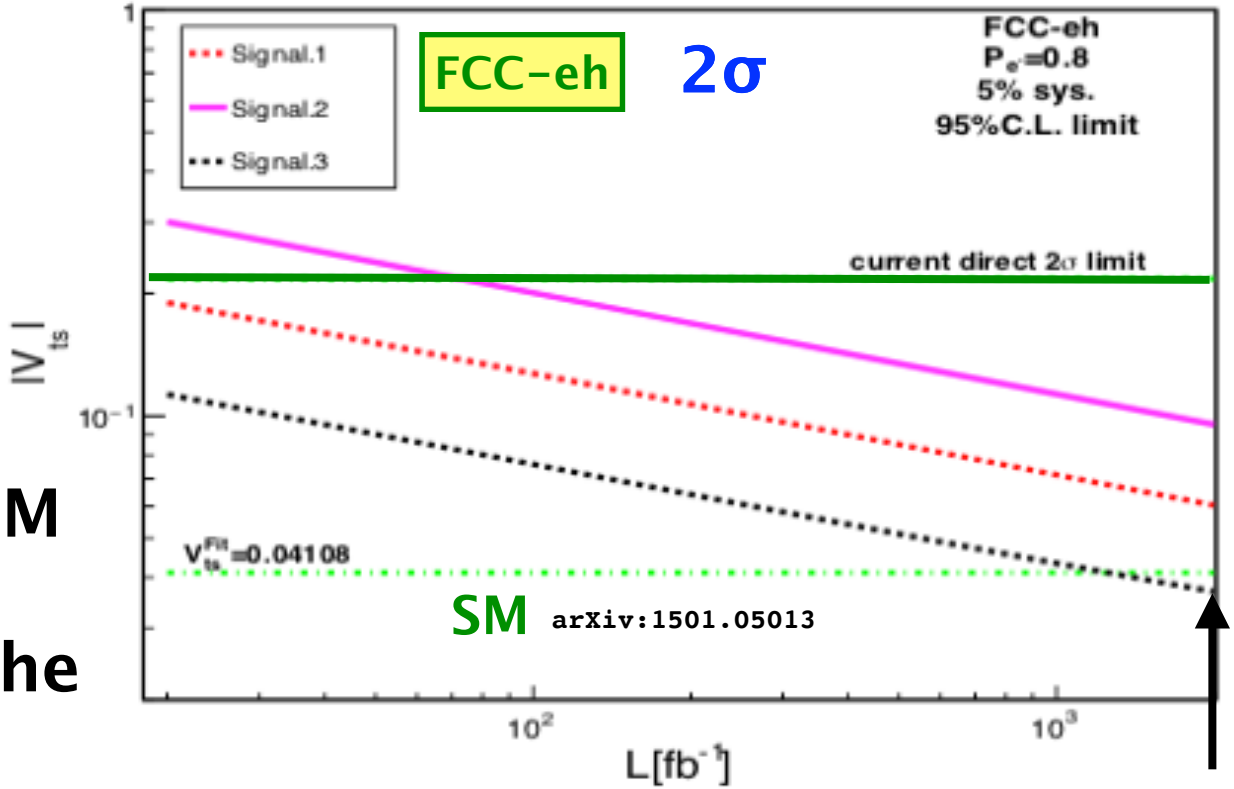
arXiv:1709.07887

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

DELPHES



H. Sun PoS DIS 2018, 167 (2018)



arXiv:1709.07887

LHC

→ probing SM prediction directly for the first time

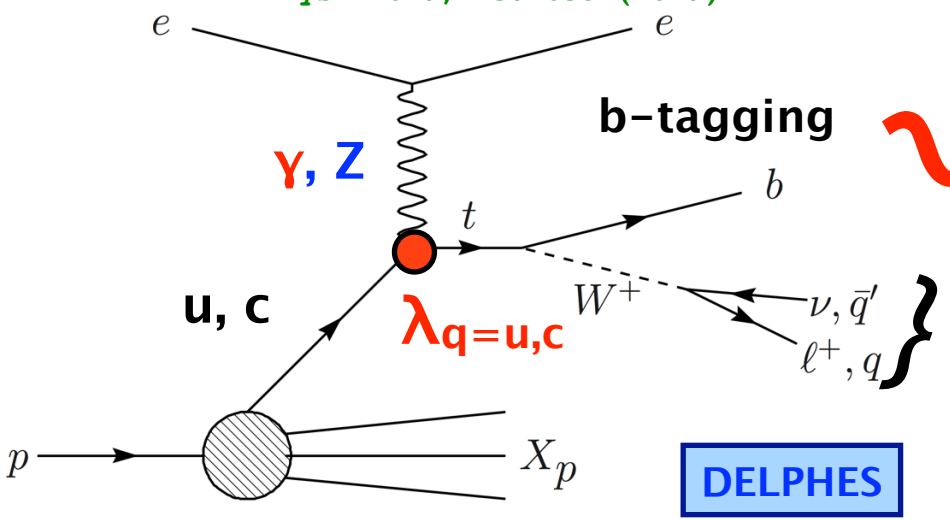
→ $|V_{ts}|<0.037$

BSM Anomalous FCNC tuγ, tuZ Couplings Top

signal

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

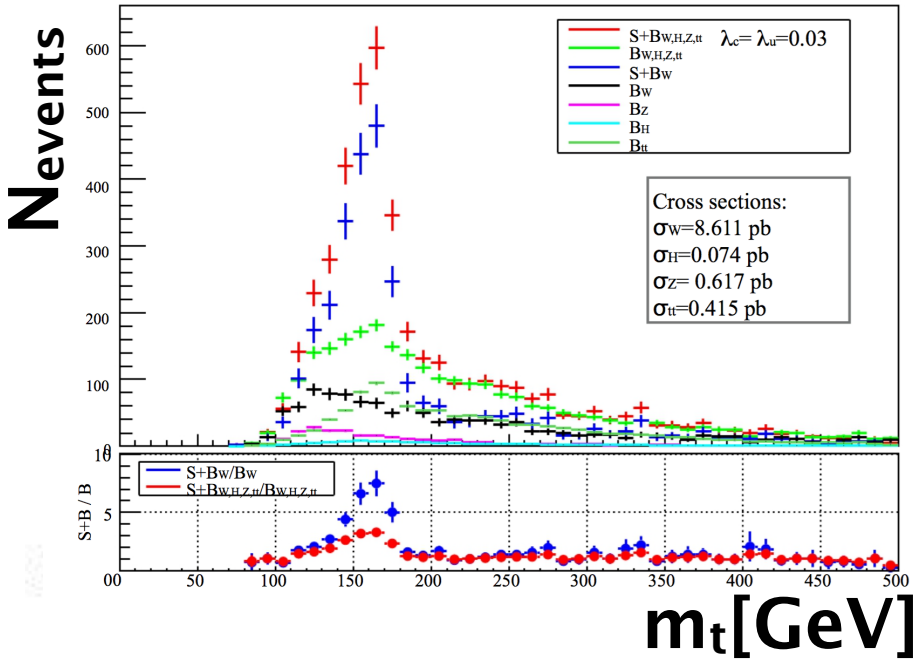
$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$



130<MWb<190 GeV

50<Mjj<100 GeV

DELPHES



BSM Anomalous FCNC tuγ, tuZ Couplings Top

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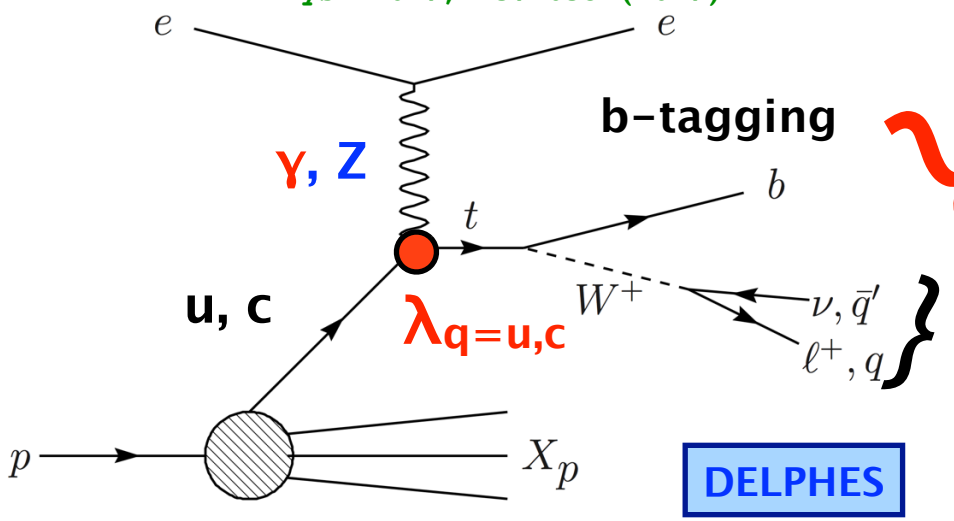
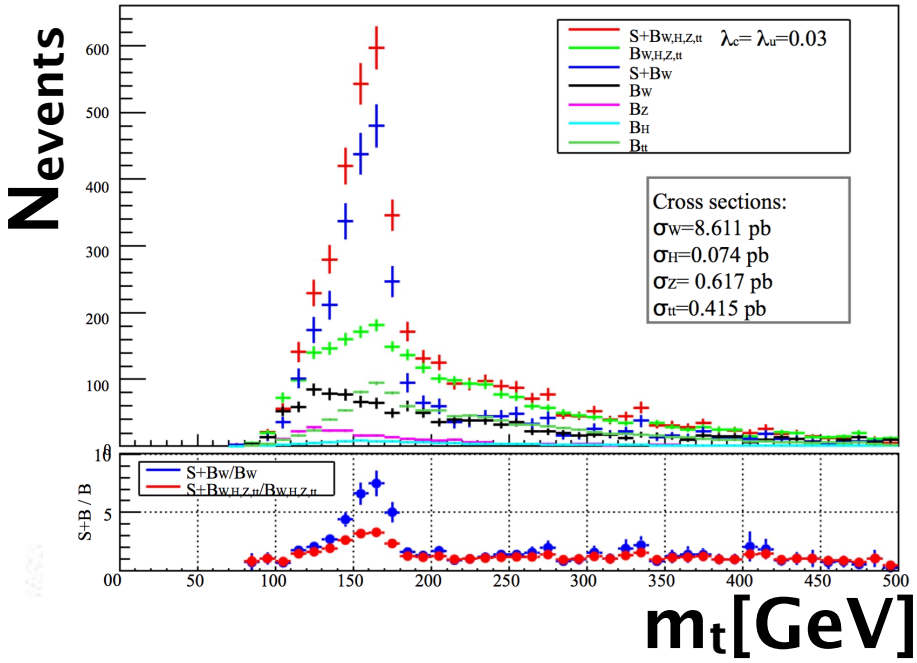


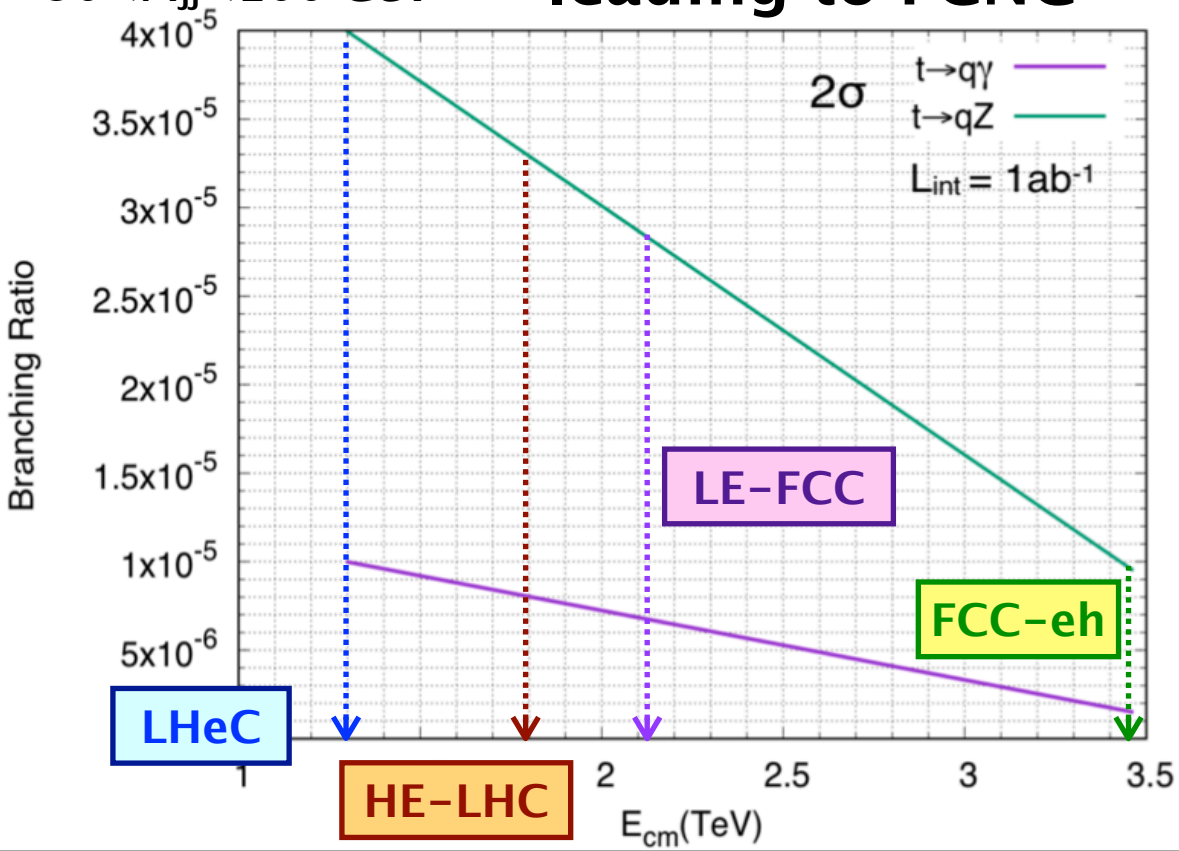
130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

→ test exotic models leading to FCNC

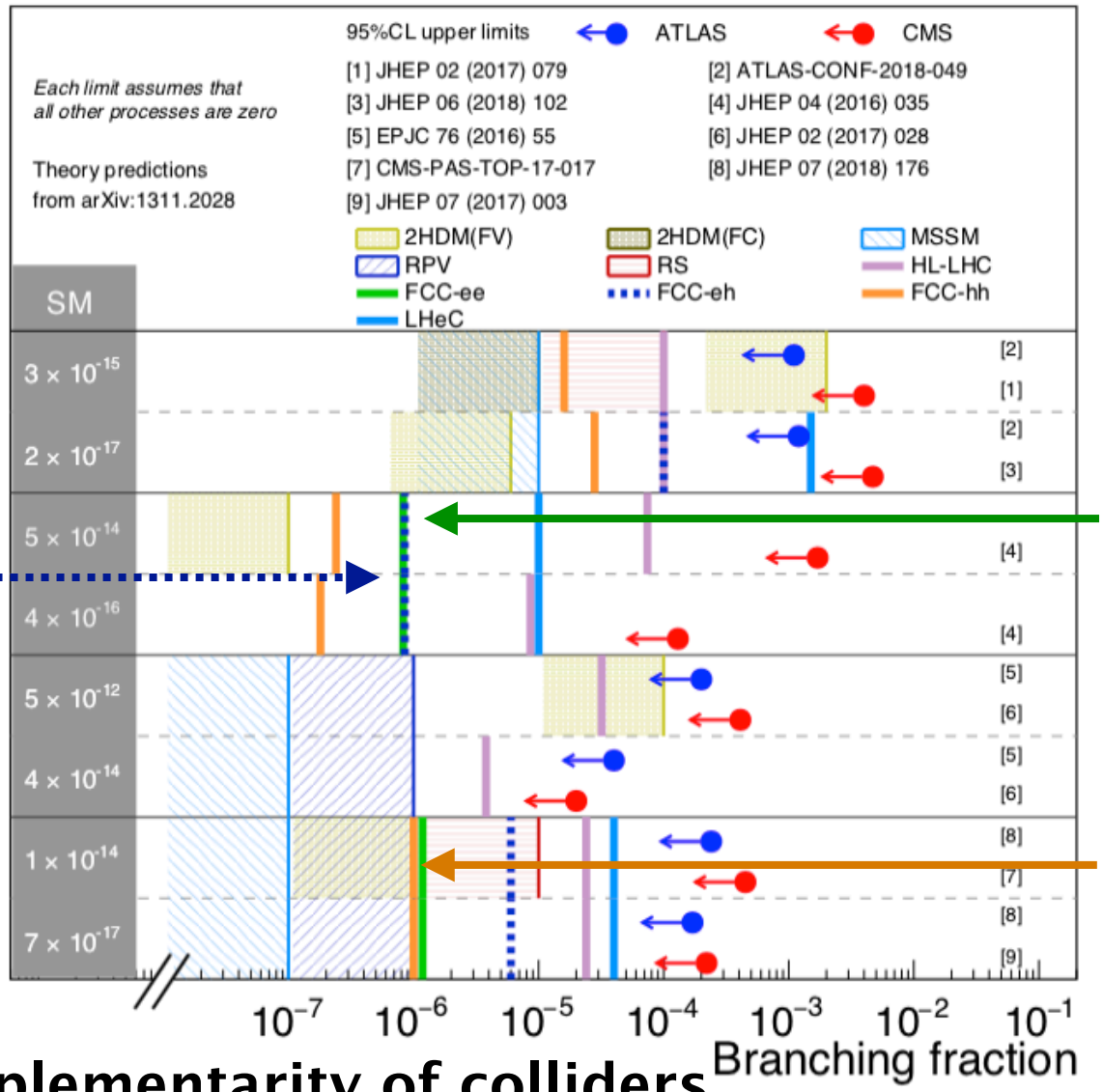
DELPHES



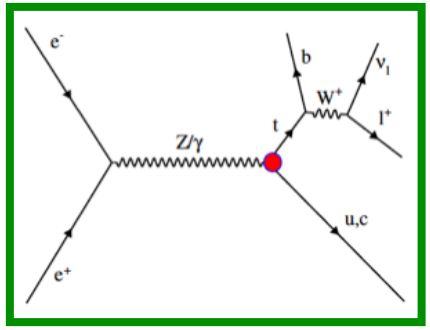


FCNC Top Quark Couplings

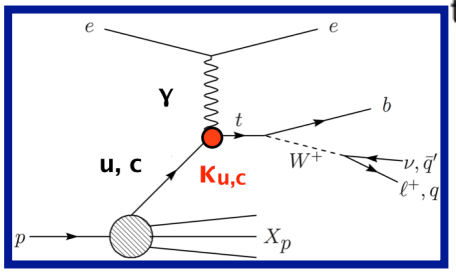
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)



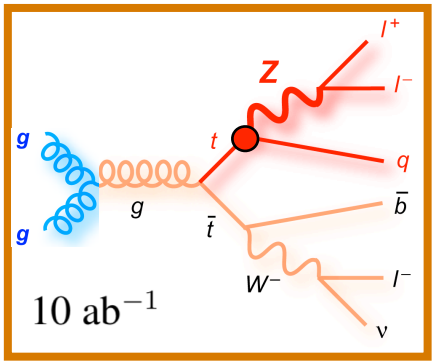
FCC-ee



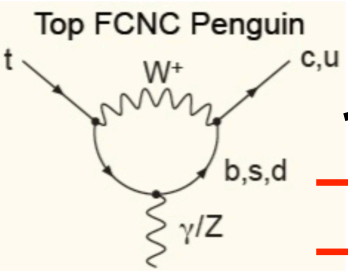
FCC-eh



FCC-pp



Top FCNC Penguin



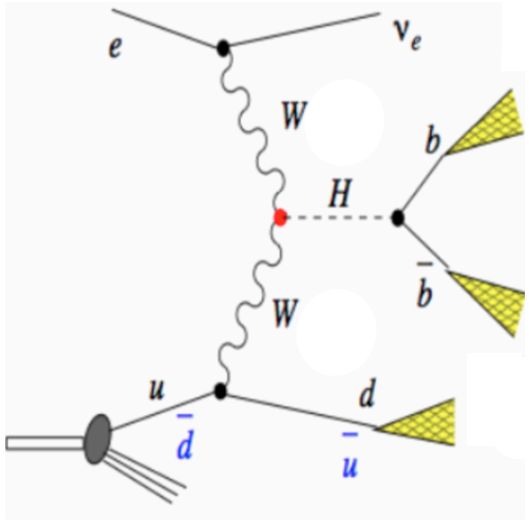
→ complementarity of colliders

→ test little Higgs, SUSY, technicolor, …

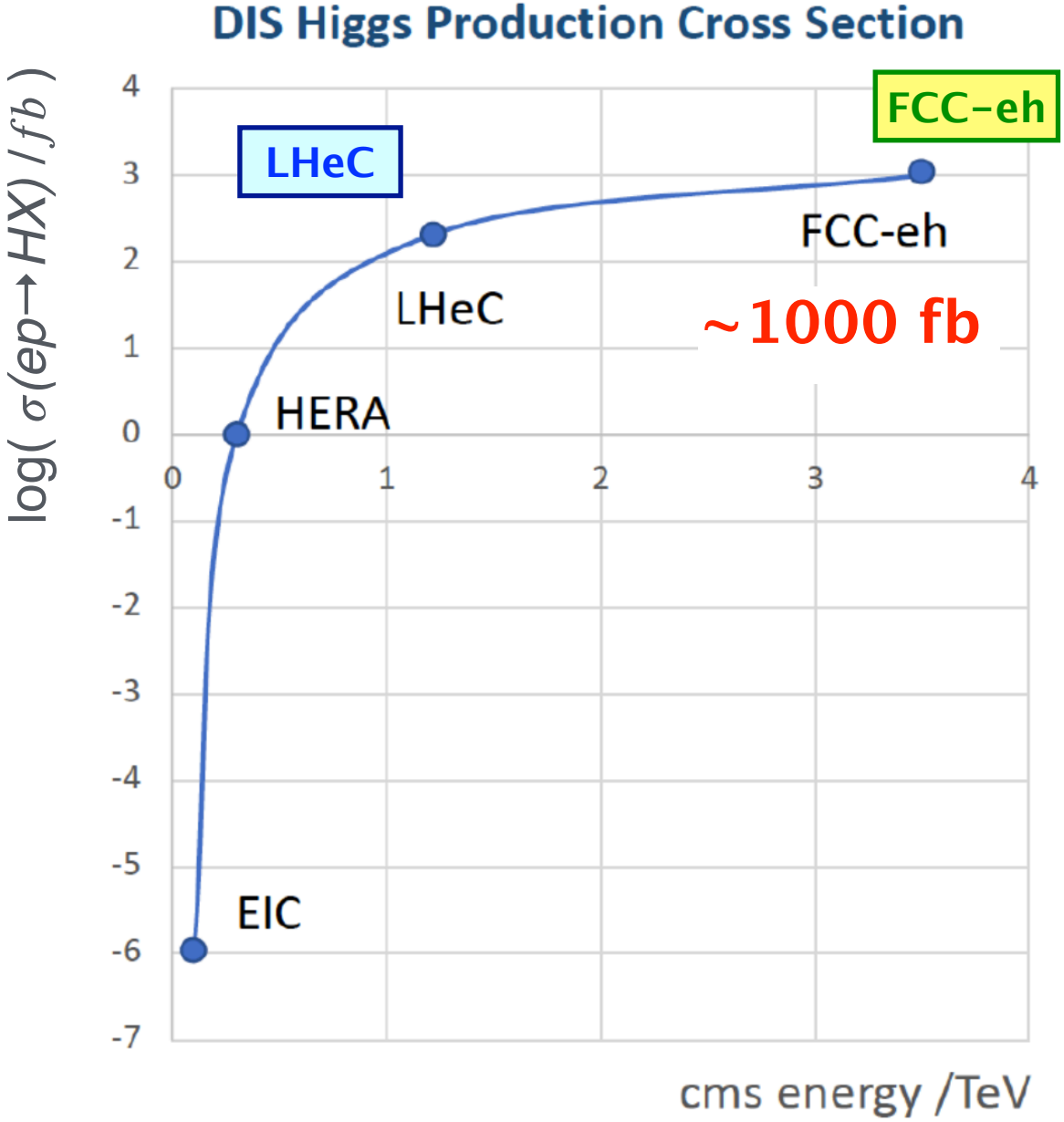
Higgs Production Cross Section

Higgs

CC(e^-p): 196 fb (LHeC)



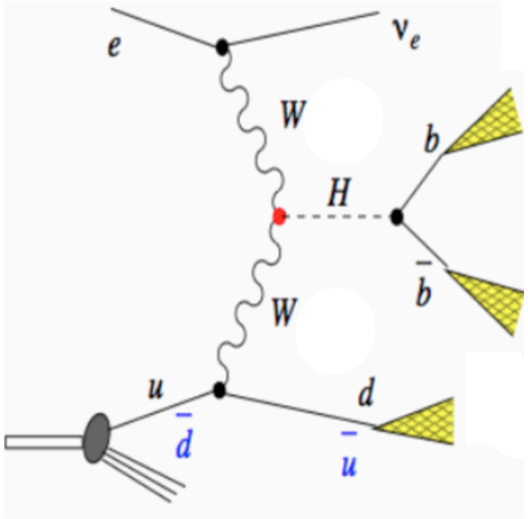
- no pile-up
- clean final state
- small systematic uncertainties



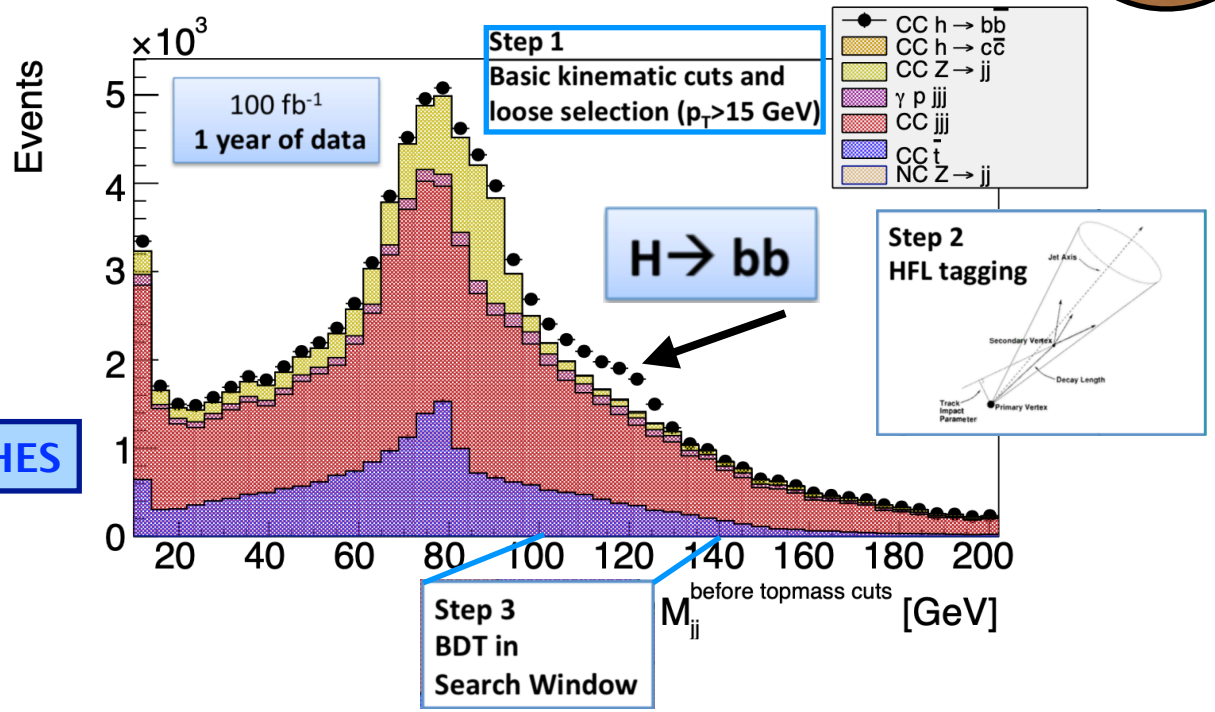
Higgs Analyses

Higgs

CC(e⁻p): 196 fb (LHeC)



DELPHES

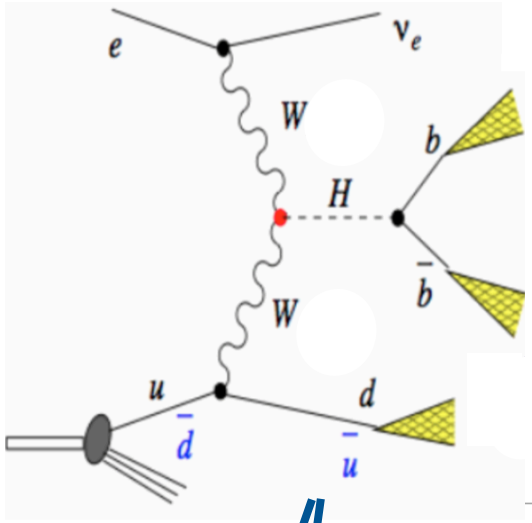


- no pile-up
- clean final state
- small systematic uncertainties

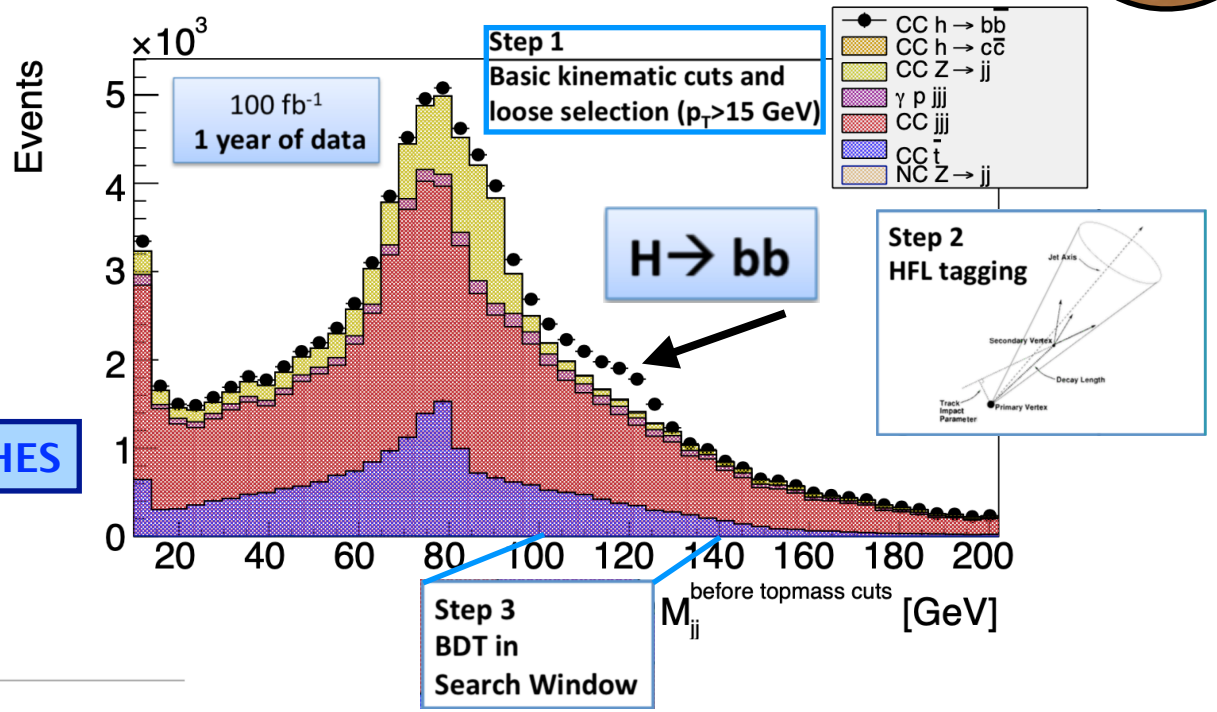
Higgs Couplings (κ-framework)

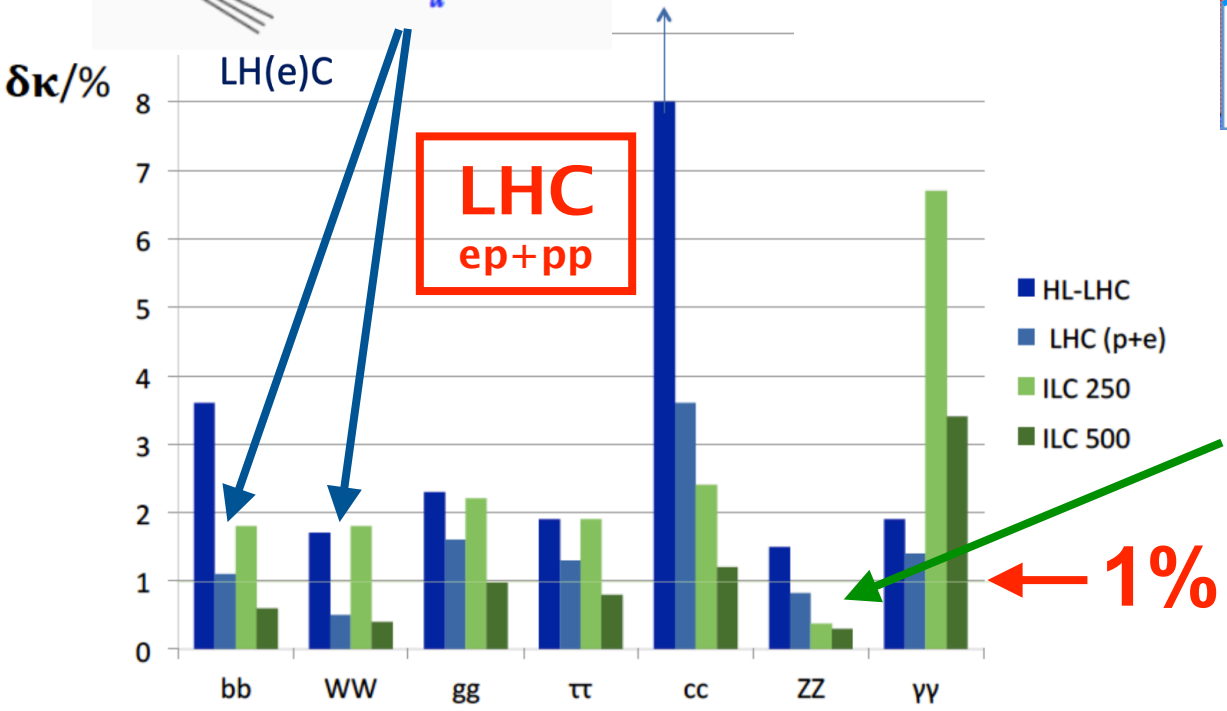
Higgs

CC(e⁻p): 196 fb (LHeC)

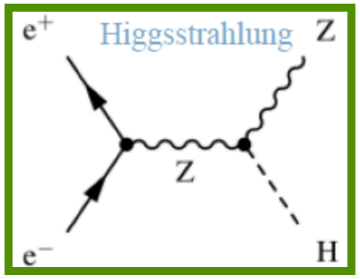


DELPHES





1%



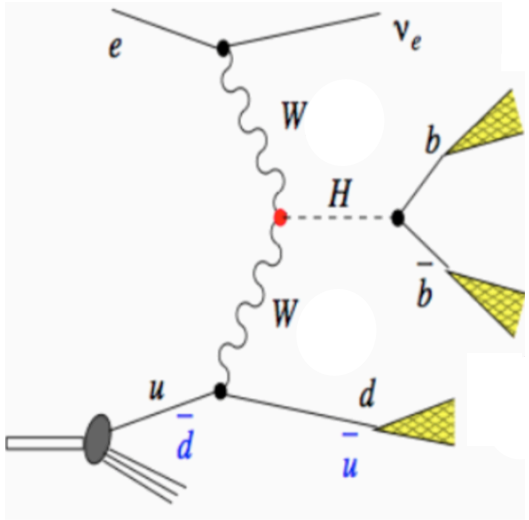
we profit from diversity through complementarity

→ **adding electrons makes the LHC a Higgs precision facility**

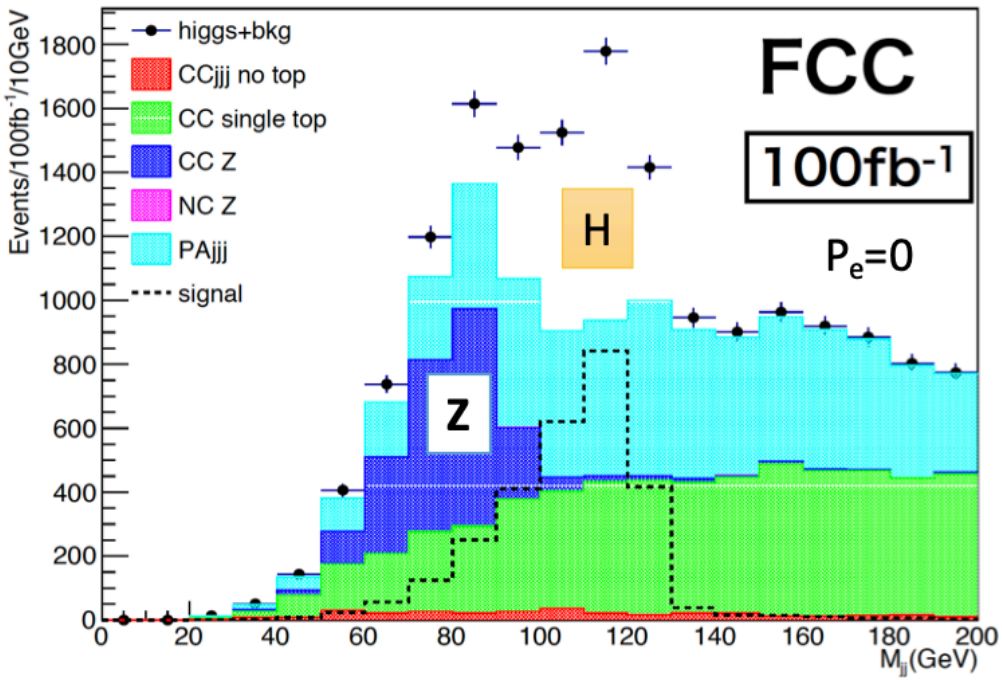
SM Higgs Signal Strengths

Higgs

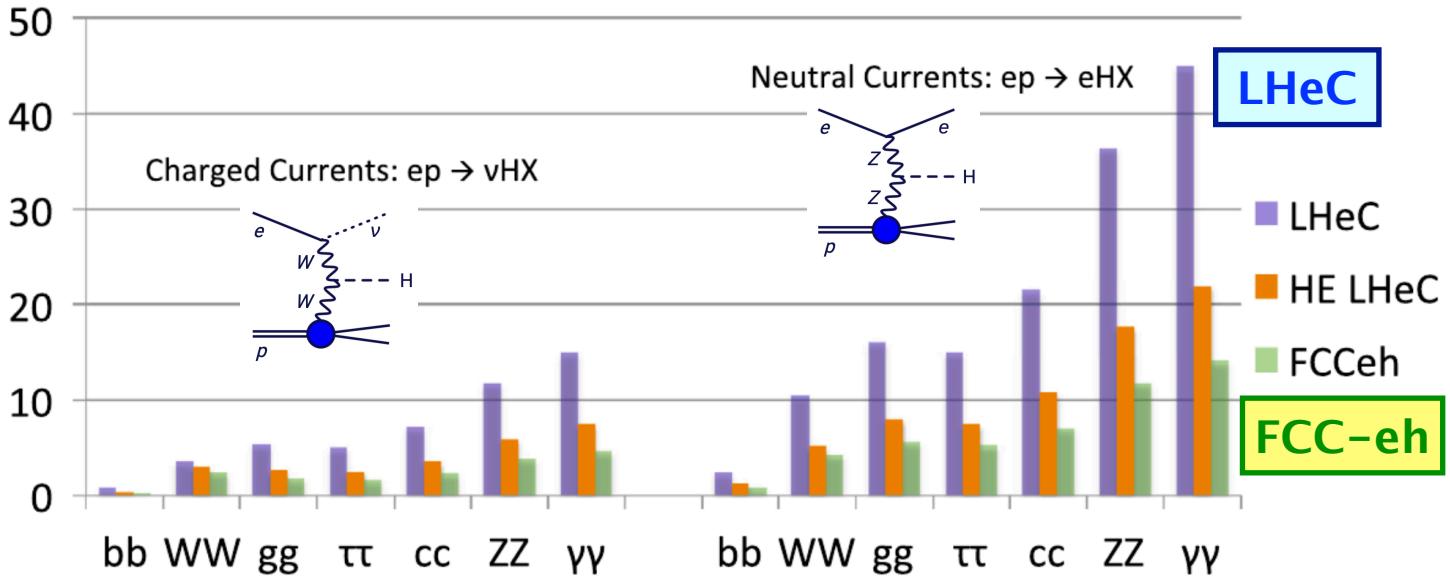
CC(e⁻p): 196 fb (LHeC)



DELPHES



$\delta\mu/\mu$ [%]



→ improvement for FCC-eh compared to LHeC by factor ~3-3.5

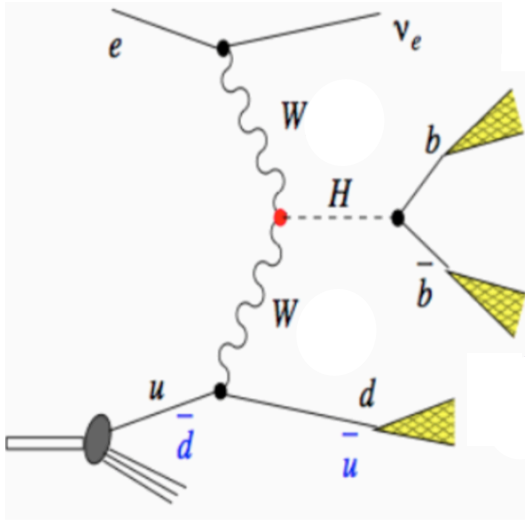
→ good sensitivity to many decay channels

→ NC+CC DIS over-constrain Higgs couplings in combined SM fit

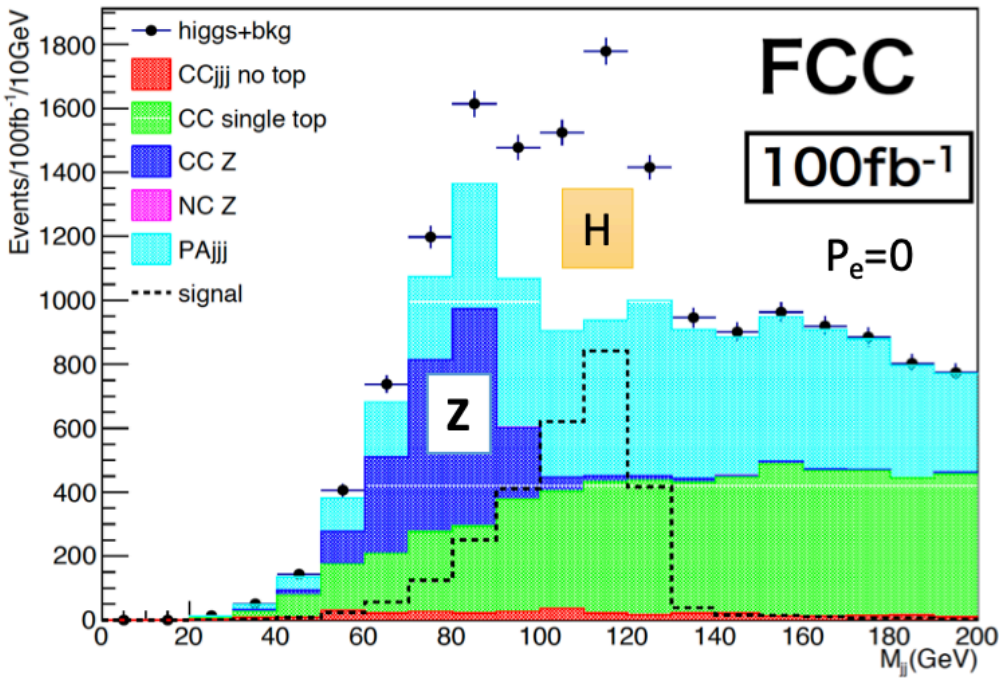
Higgs Couplings (κ-framework)

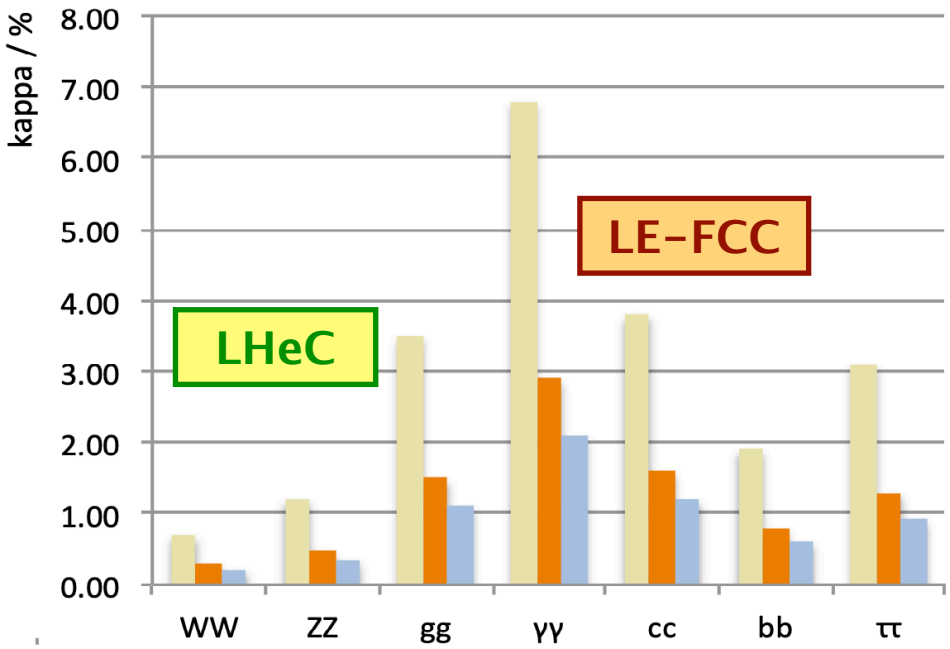
Higgs

CC(e⁻p): 196 fb (LHeC)



DELPHES





	E_p=
LHeC	7 TeV
FCC-eh (2.2)	20 TeV
FCC-eh (3.5)	50 TeV

FCC-eh

→ improvement for FCC-eh compared to LHeC by factor ~3-3.5

→ high precision to many decay channels by CC+NC DIS

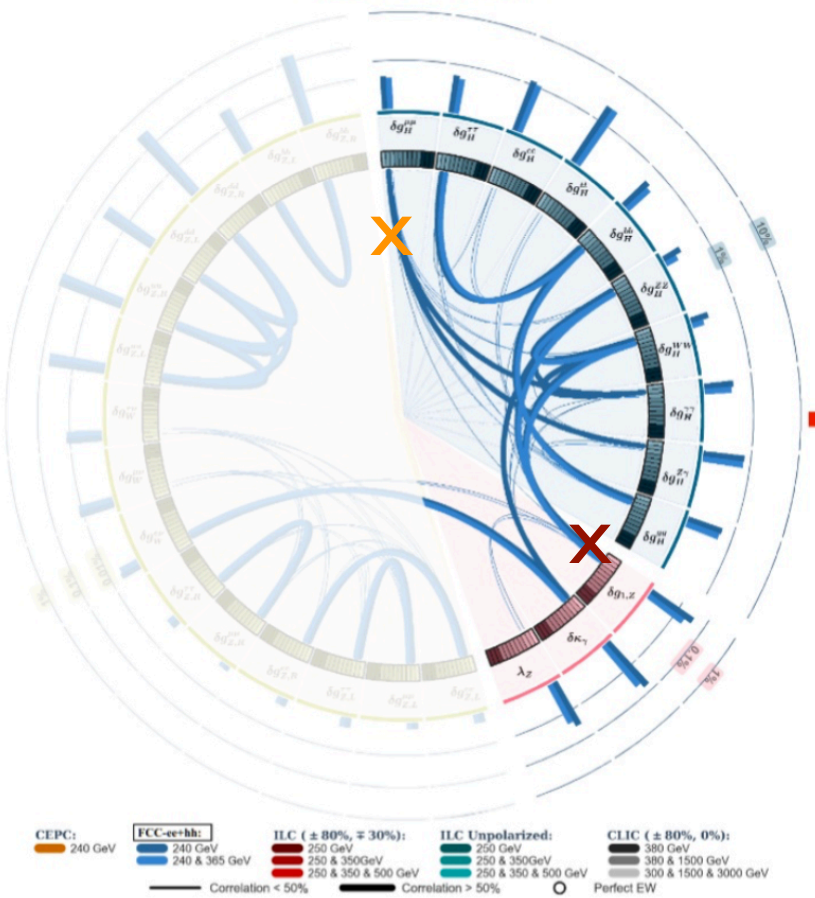
SMEFT fit results after FCC era

BSM

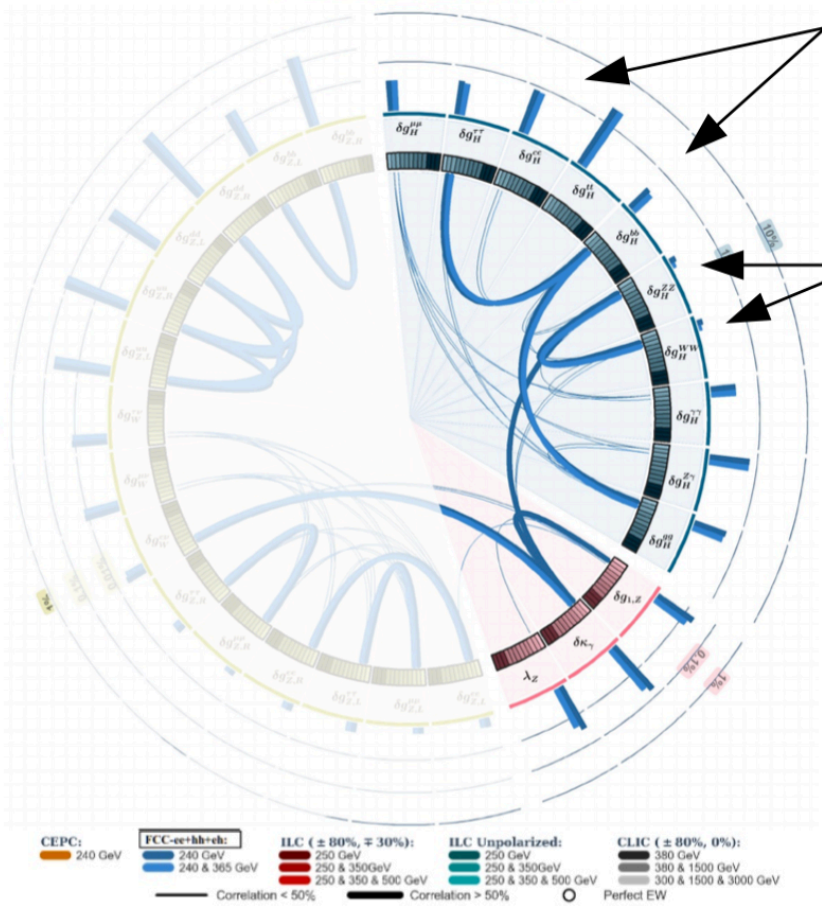
Higgs

Couplings and correlations

FCCee+hh



FCCee+eh+hh



reduction for Hcc and Hbb

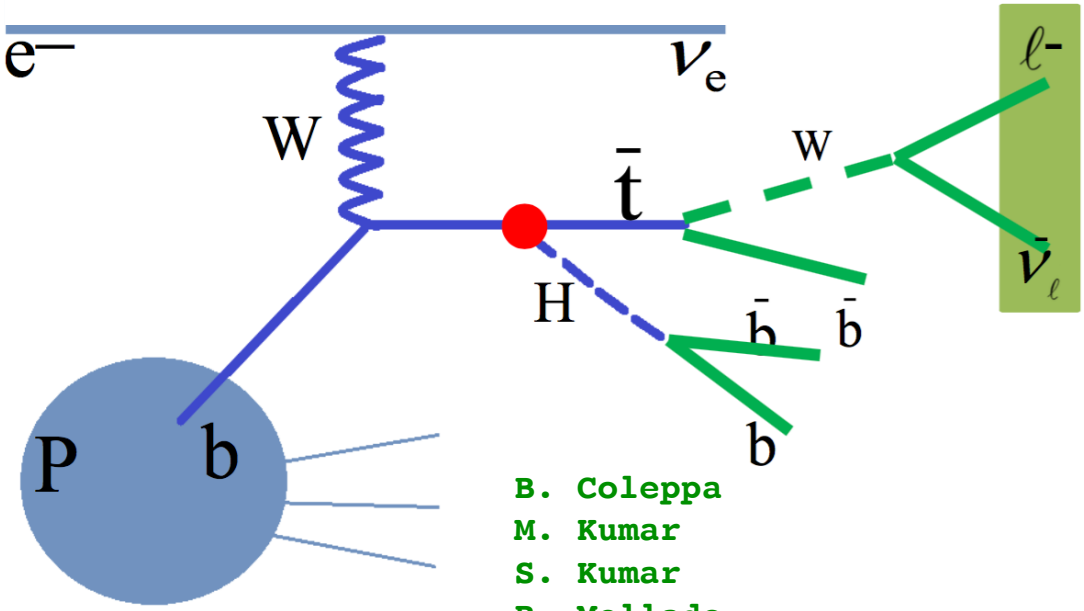
eh contributes to the HWW and HZZ couplings and resolves their correlation X

reduces further correlations X

theory profits from diversity (ee, ep, pp)

PRELIMINARY

Top CP Nature of Top-Higgs Coupling Higgs

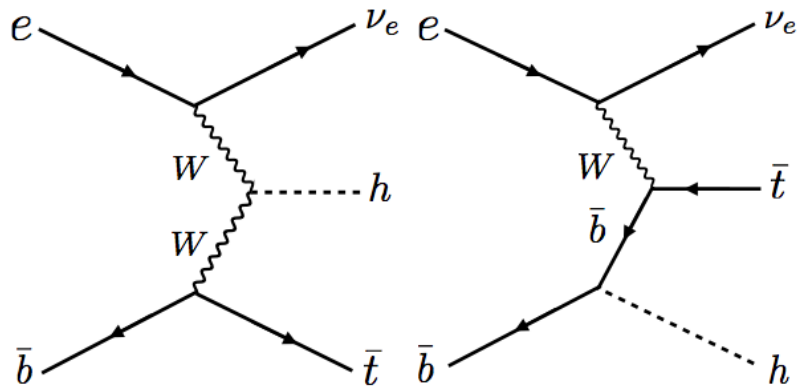


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

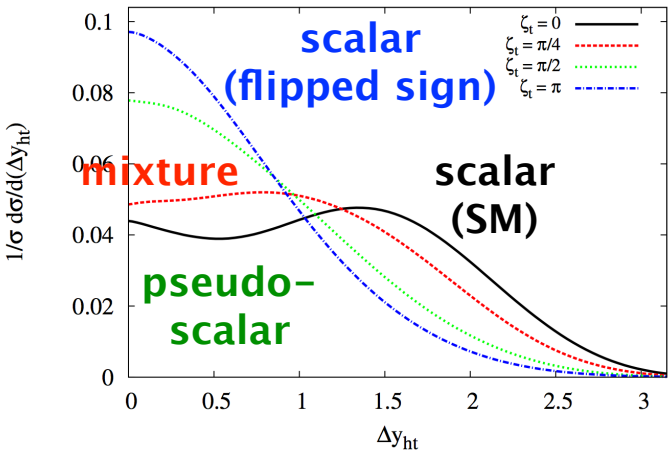
Phys. Lett. B770 (2017) 335

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

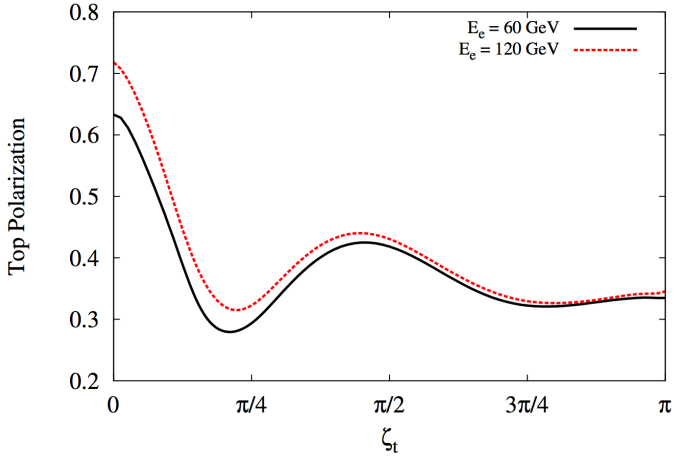


LHeC

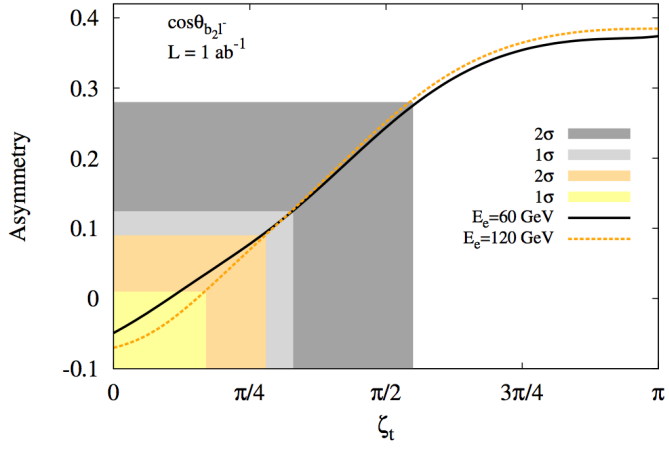
rapidity difference (H,$\bar{t}$)



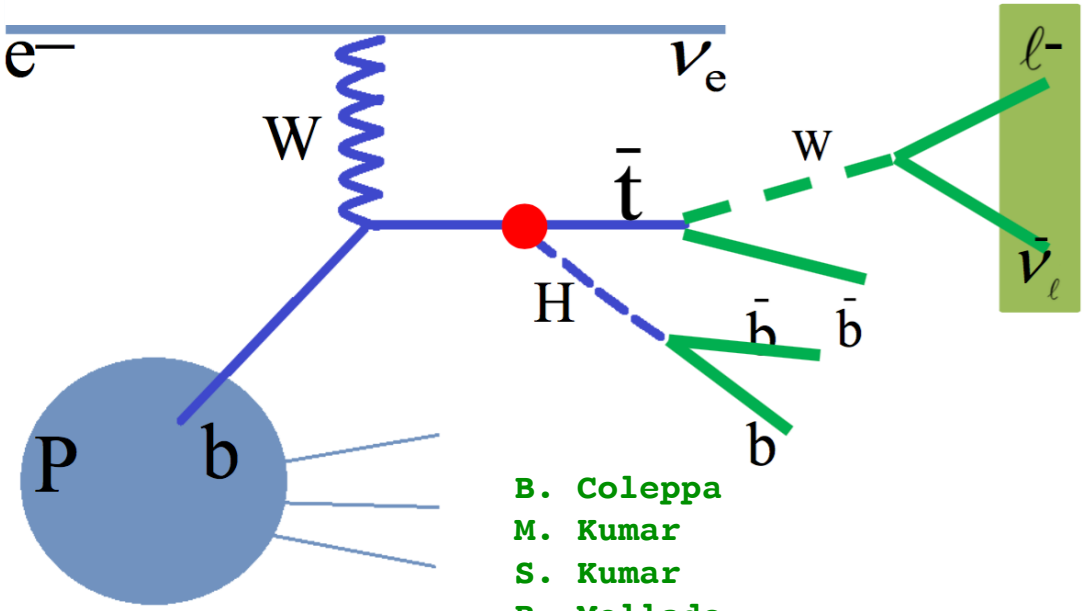
top polarisation



angular asymmetries (b_2,l^-)



Top CP Nature of Top-Higgs Coupling Higgs

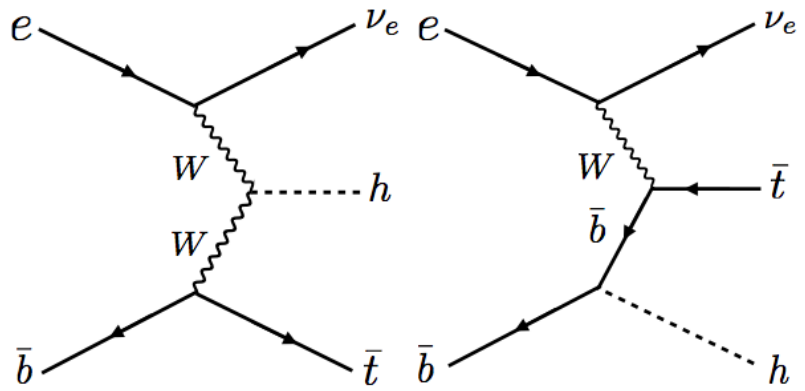


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

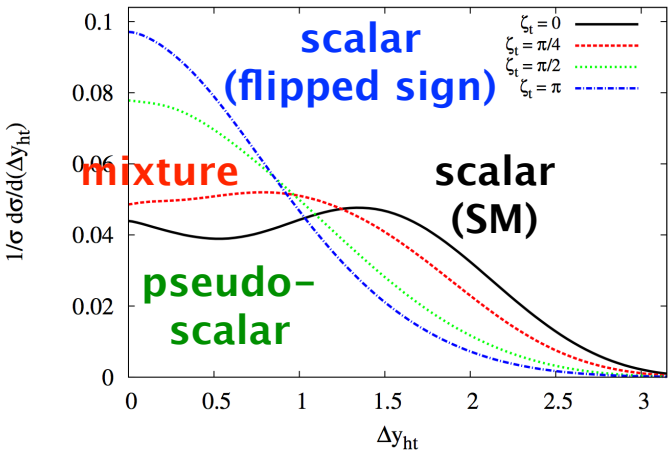
Phys. Lett. B770 (2017) 335

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

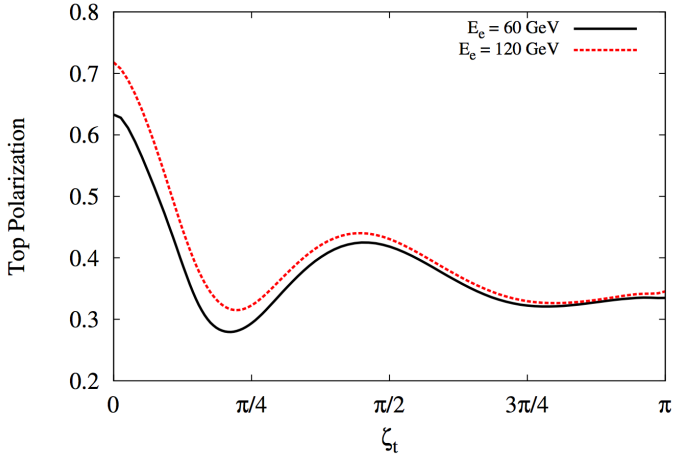


LHeC

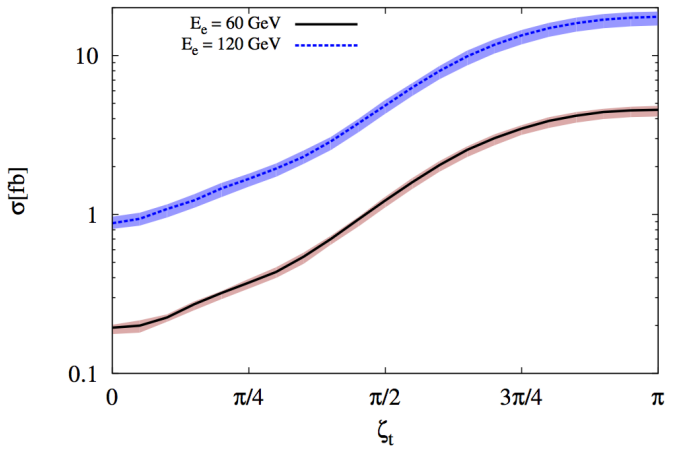
rapidity difference (H,$\bar{t}$)



top polarisation



fiducial incl. cross-section



Top Exclusion Contours (fiducial cross section) Higgs

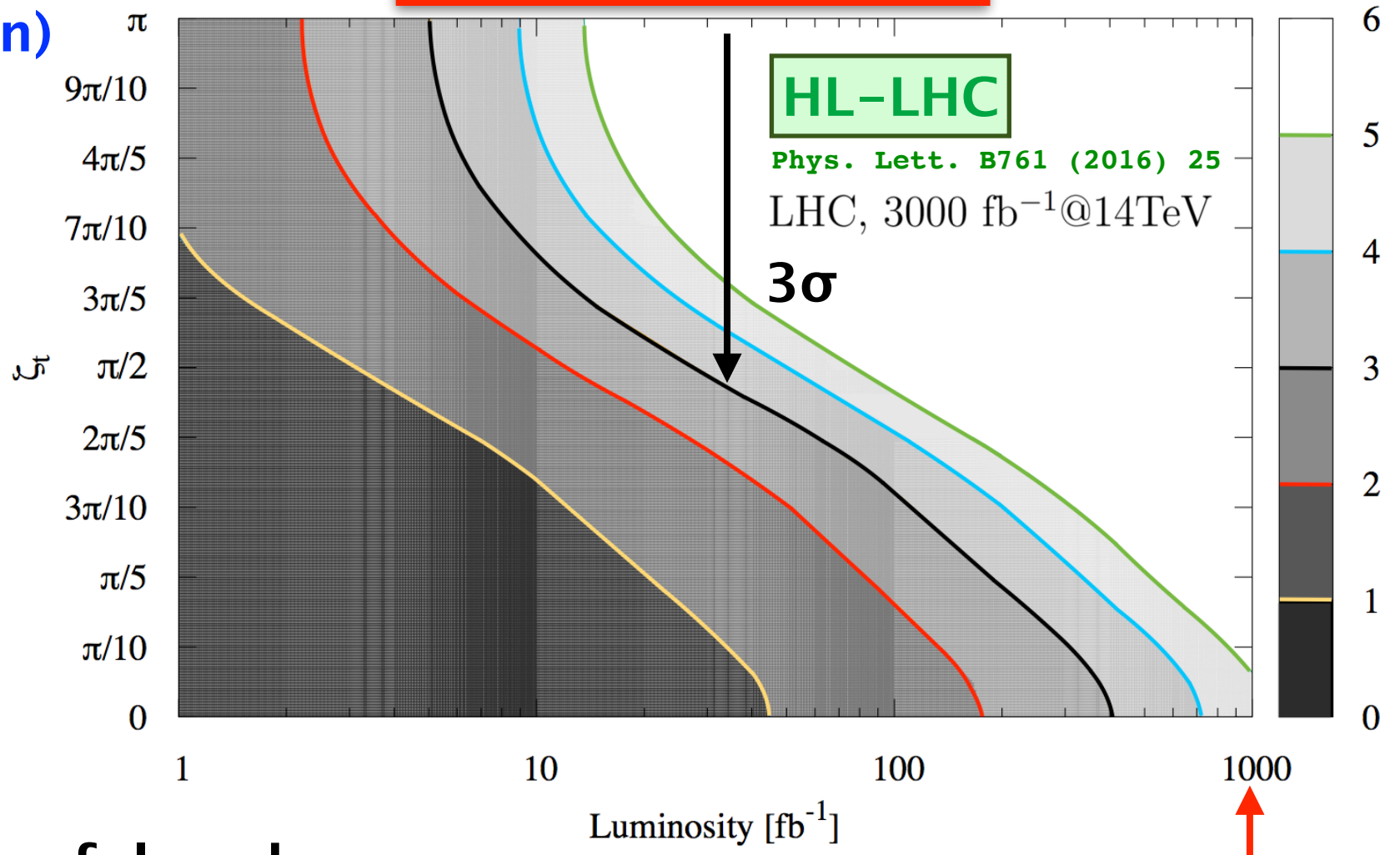
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

LHeC

CP-even (flipped sign)

CP-odd

CP-even (SM)



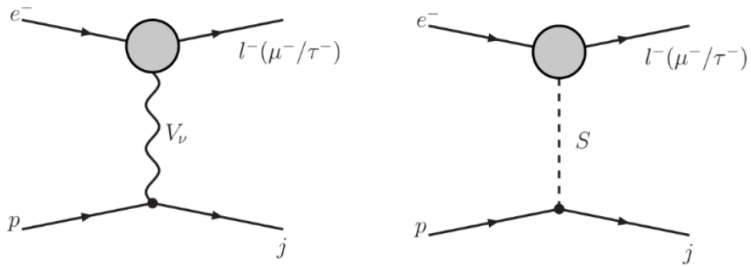
→ powerful probe of ttH coupling

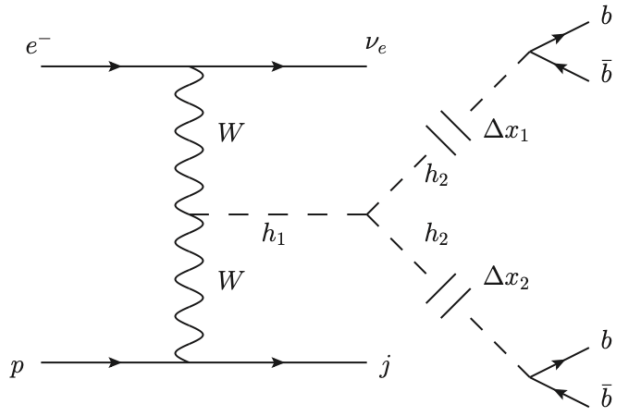
10% uncertainty on background yields

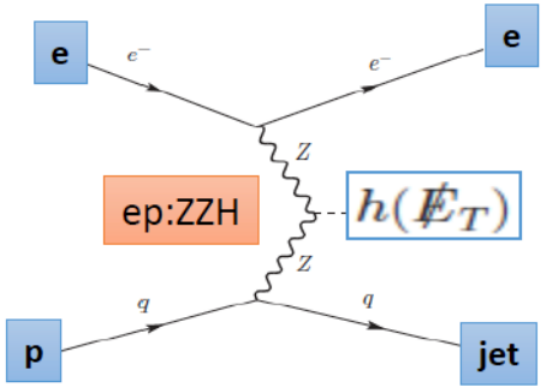
$\kappa = 1.00 \pm 0.17$

Searches for New Phenomena

BSM







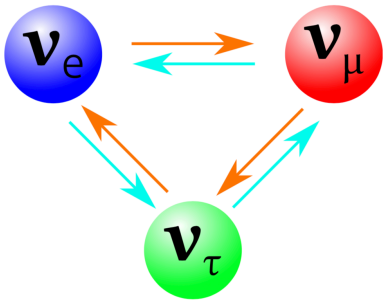
LHeC CDRs:
arXiv:1206.2913, J. Phys. G 39 075001 (2012)
arXiv:2007.14491 (J. Phys. G 48 (2021) 11)

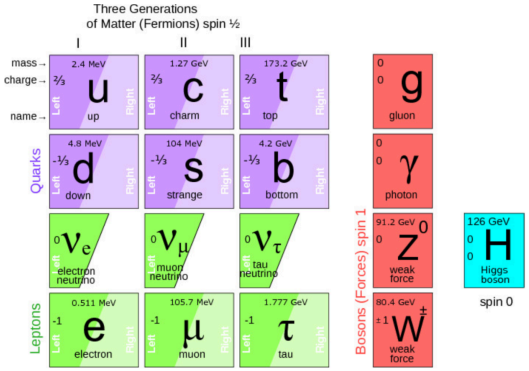
FCC CDR:
Eur. Phys. J. C 79, no. 6, 474 (2019) - Physics
Eur. Phys. J. ST 228, no. 4, 755 (2019) - FCC-hh/eh

… and much more

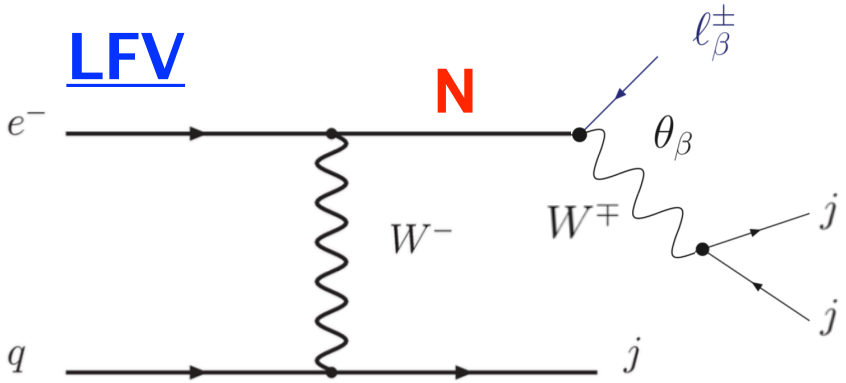
Heavy Sterile Neutrinos

BSM





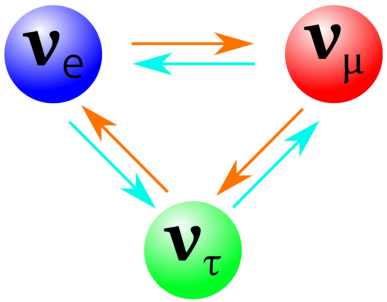
LFV

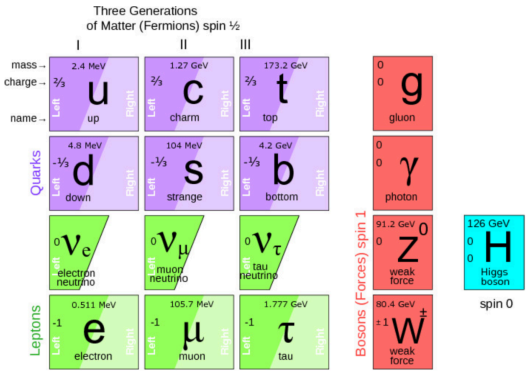


+ many backgrounds included

Heavy Sterile Neutrinos

BSM





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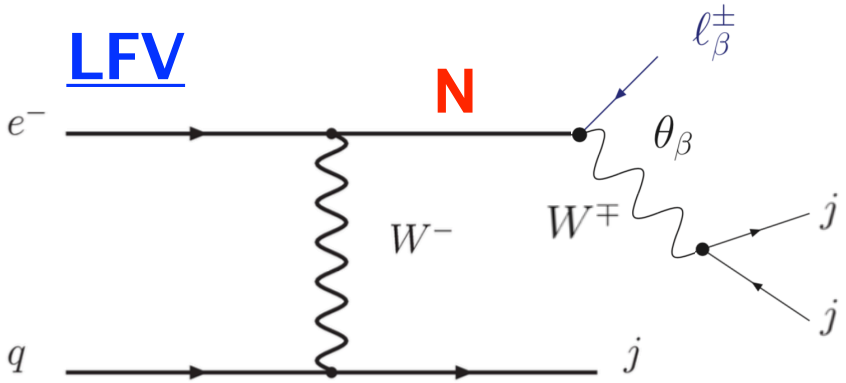
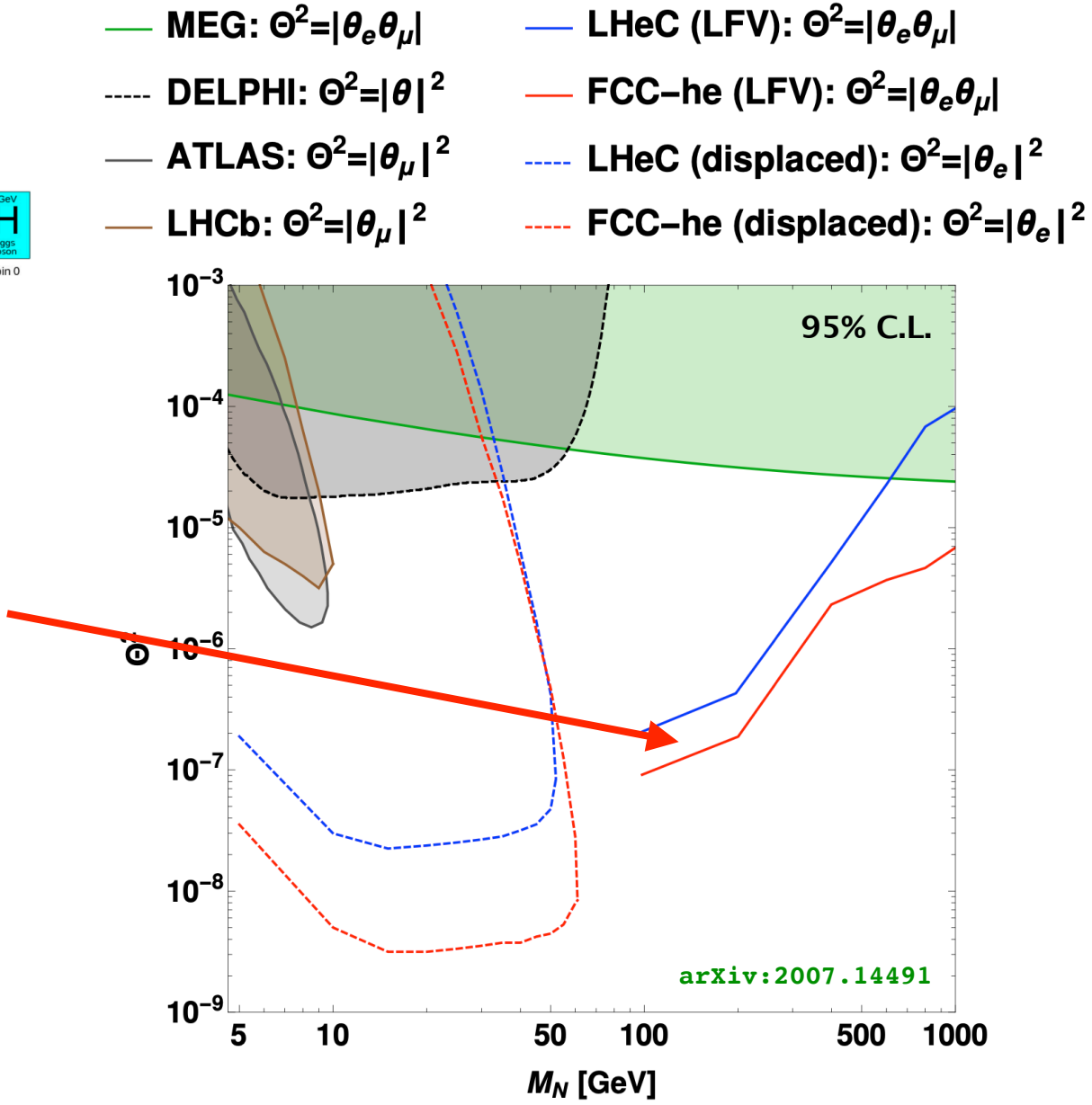
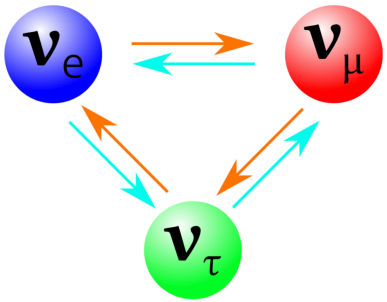


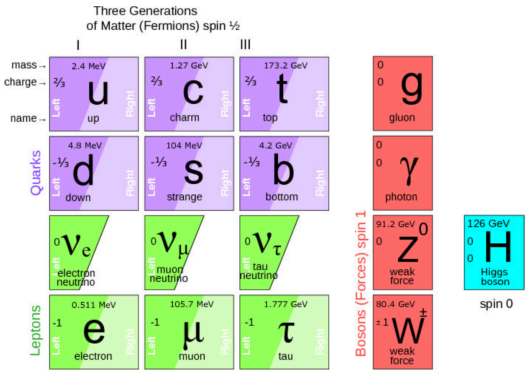
+ many backgrounds included



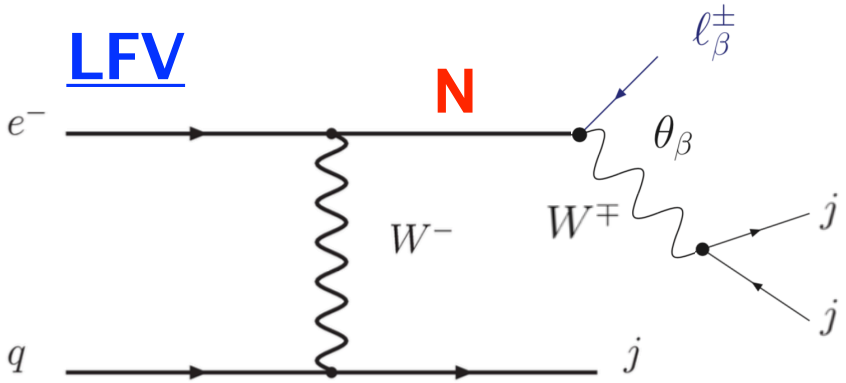
Heavy Sterile Neutrinos

BSM

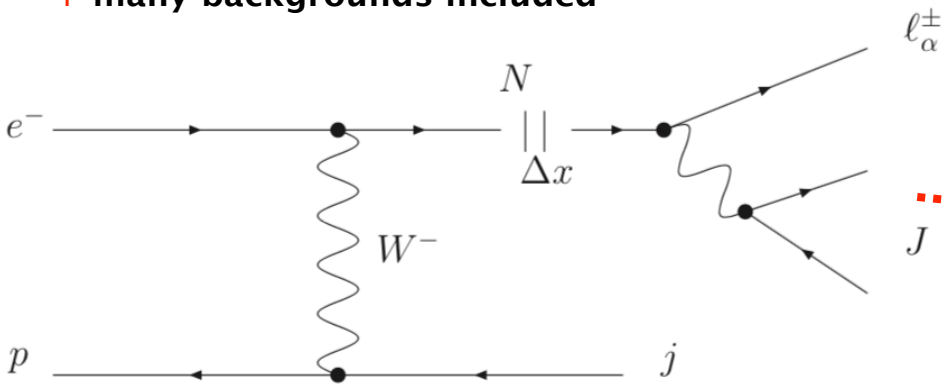




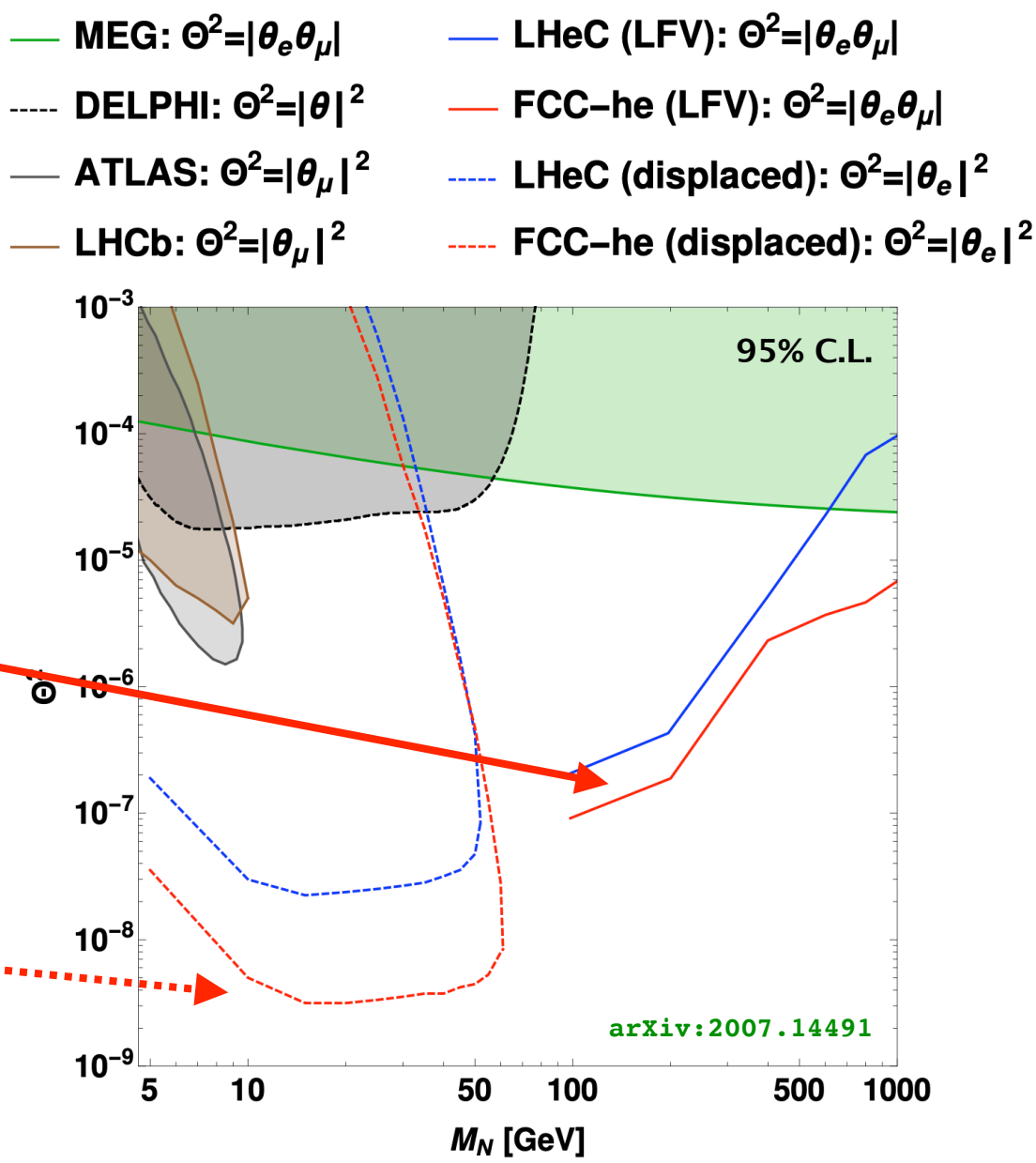
LFV



+ many backgrounds included



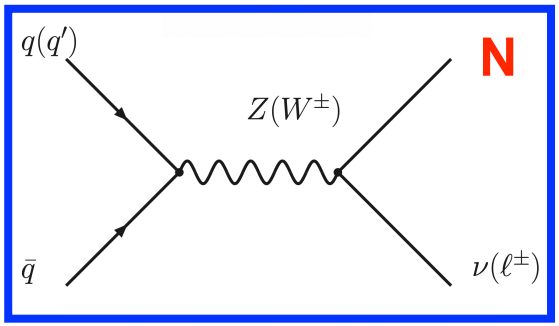
arXiv:1908.02852

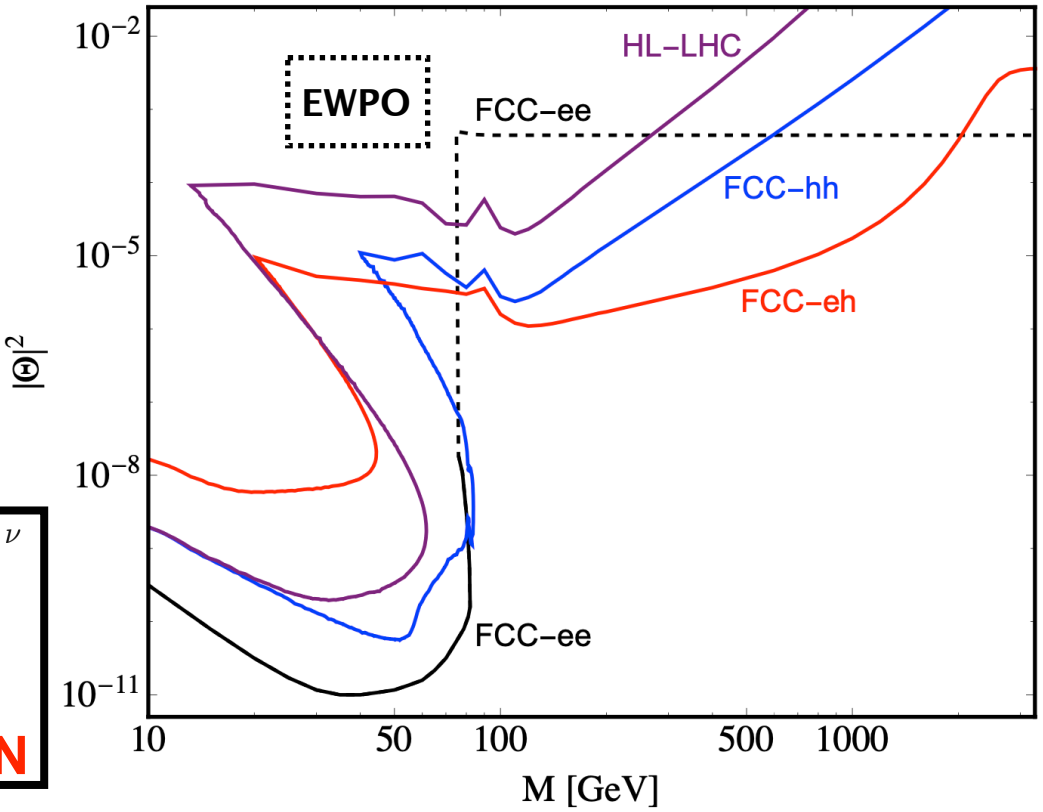


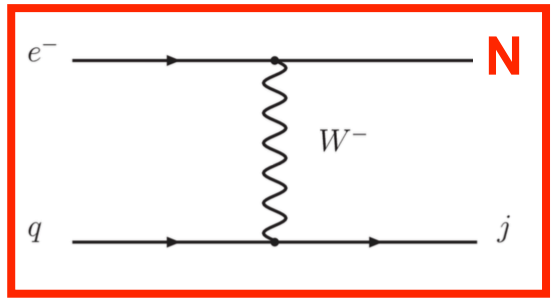
Heavy Sterile Neutrinos

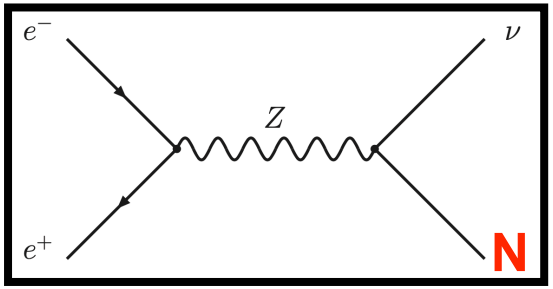
BSM

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)
arXiv:1612.02728 [hep-ph]



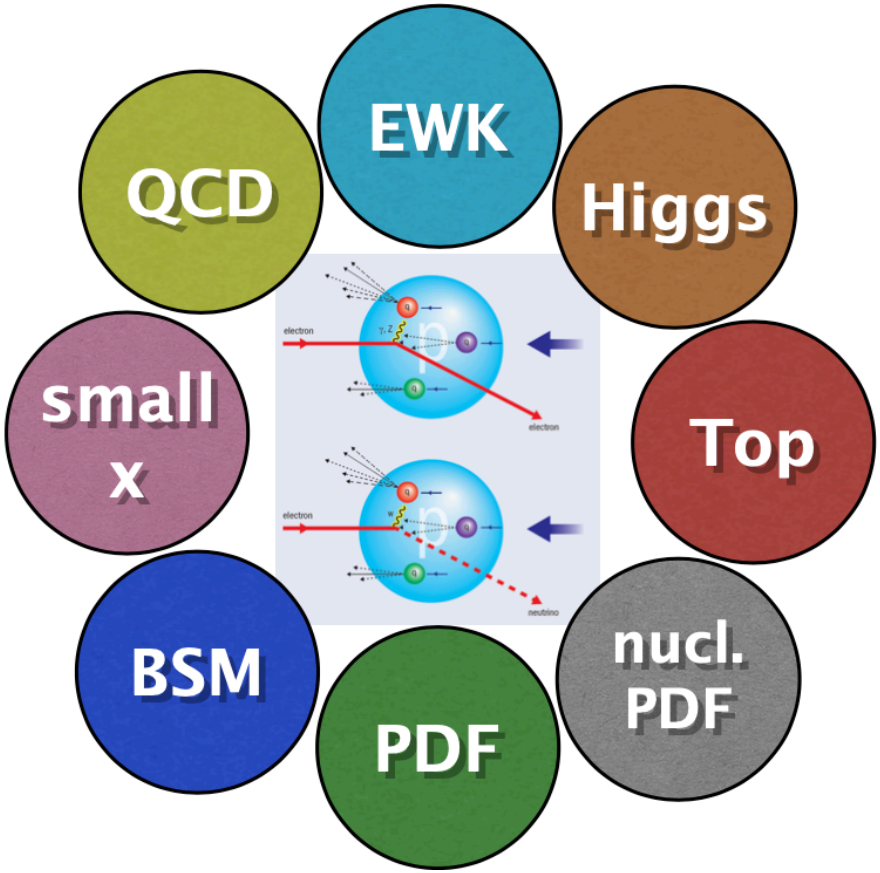






→ complementary prospects for discovery in ee, ep and pp

Conclusions



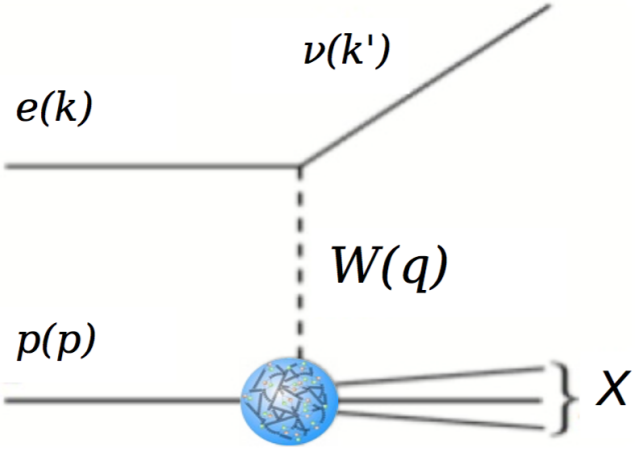
we profit from diversity through complementarity (ee, ep, pp)

- future ep collider has a rich physics programme that substantially strengthens the HL-LHC in particular for electroweak interactions of light and heavy quarks, Higgs physics, and searches for BSM – besides the QCD and PDF proton and ion physics, which makes the LHeC indeed a new general purpose experiment!
- FCC-eh is a crucial part of the FCC program through kinematic range and unprecedented precision

Backup

Weak Couplings of W boson

EWK



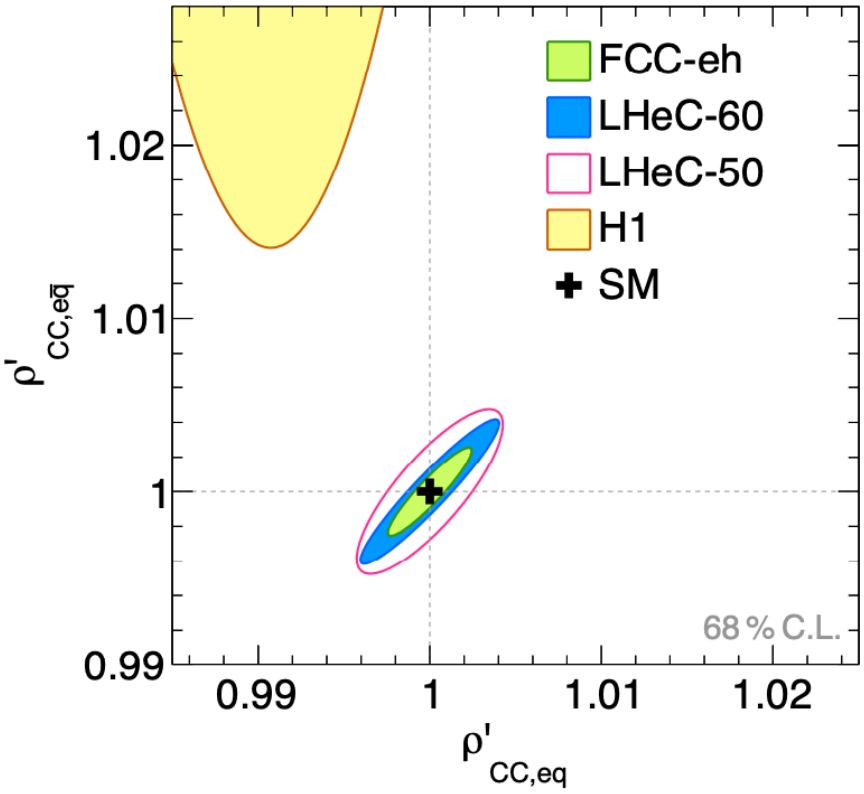
kinematics of CC DIS is completely measured from final state and incoming electron (despite ν)

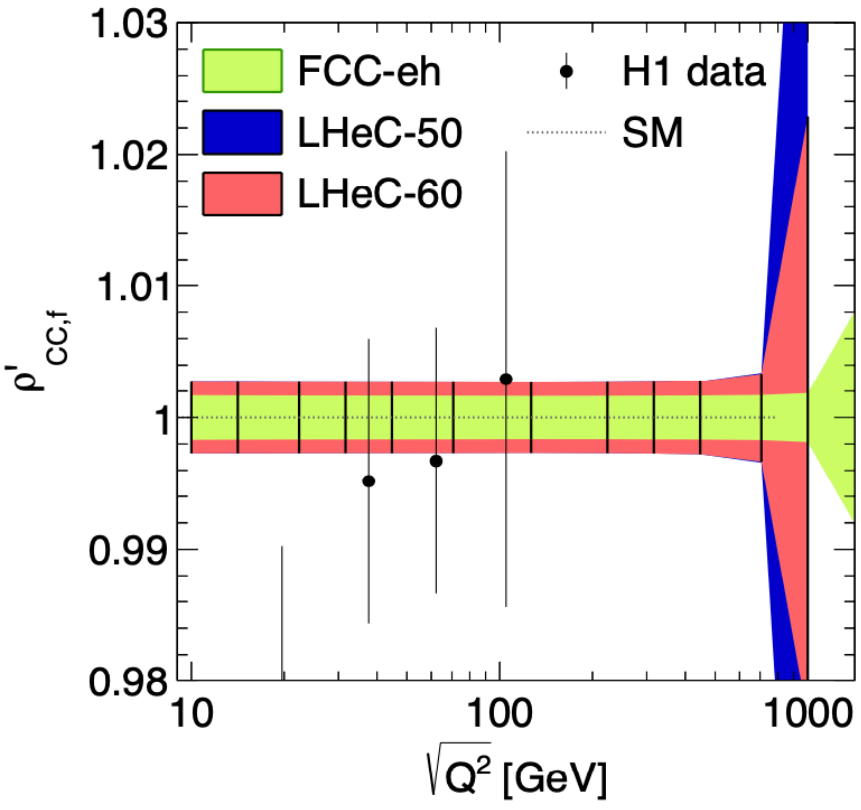
→ **scale dependence of a few per mille level**

→ **large range of Q^2, up to the TeV regime**

→ **very unique measurement**

$\rho'_{CC,eq} = \rho'_{CC,e\bar{q}} = \rho'_{CC,f}$

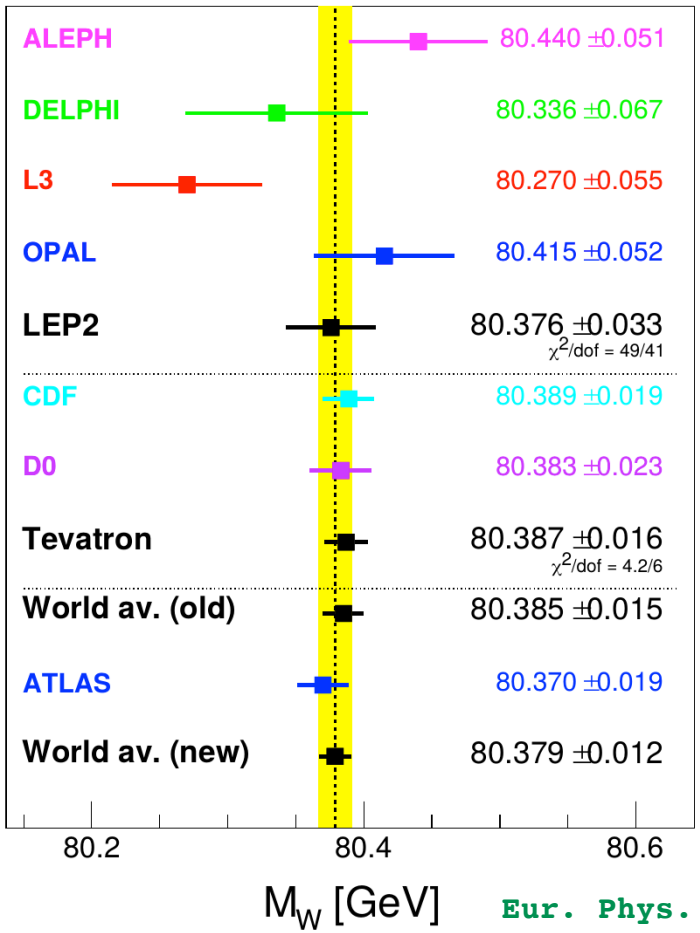




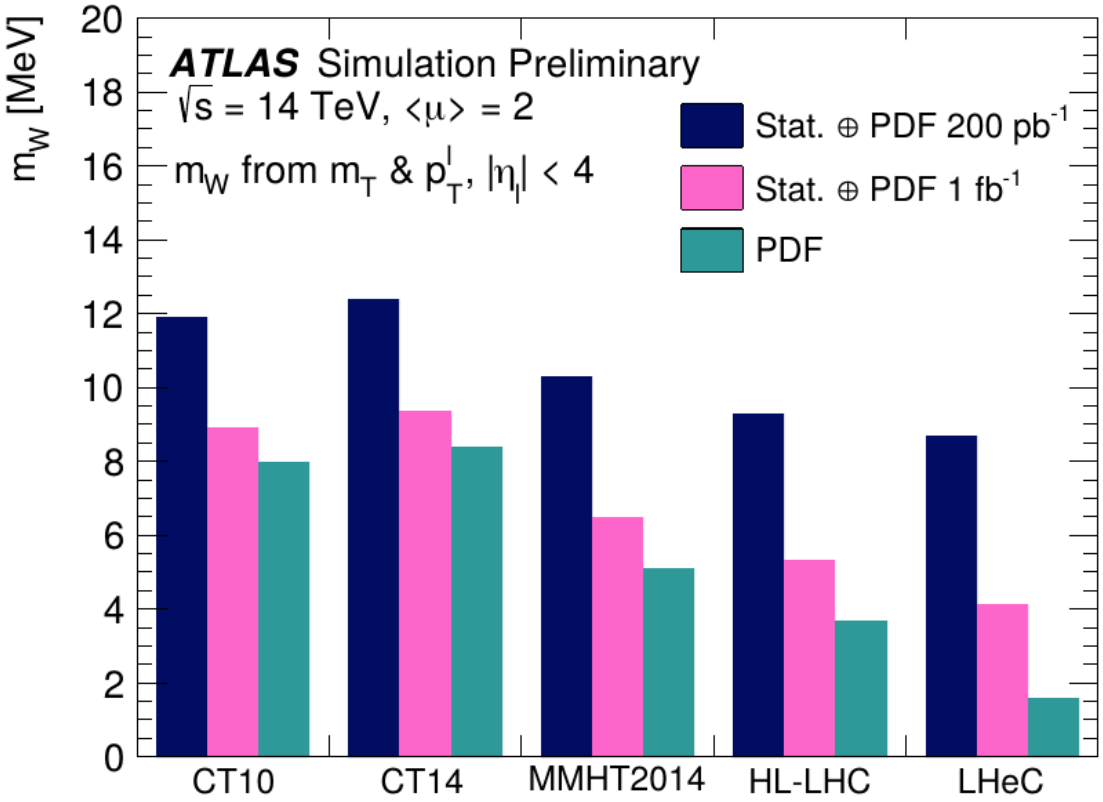
W mass measurements at HL-LHC

EWK

- @LHC: precision limited by PDFs ($\Delta m_W^{PDF} \sim 9.2$ MeV)



- @HL-LHC: major reduction of PDF uncertainty with LHeC PDFs ($\Delta m_W^{PDF} \sim 2$ MeV)



Eur. Phys. J. C 78 (2018) 110; PDG (2017)

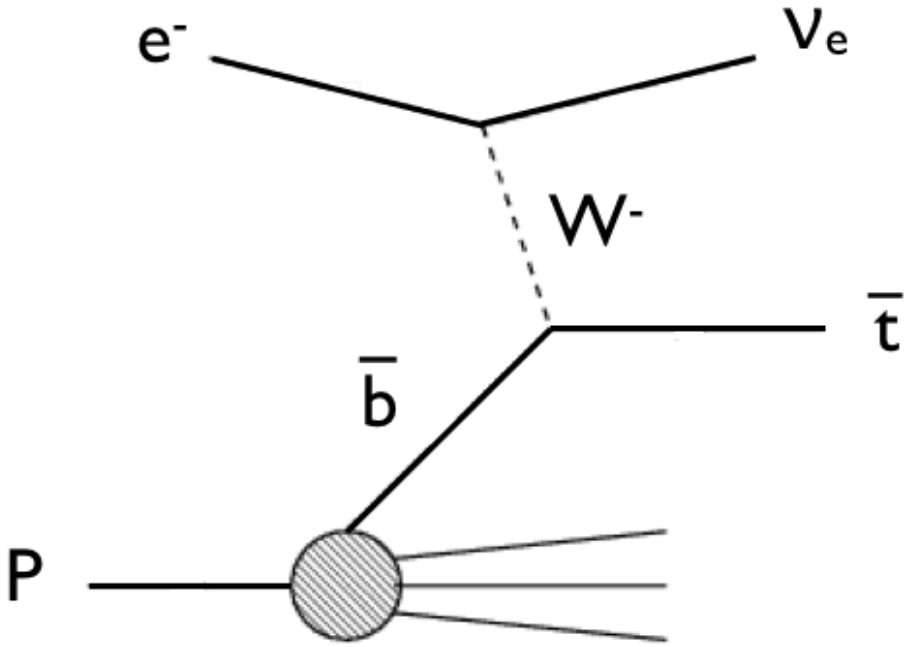
ATL-PHYS-PUB-2018-026

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Electroweak Top Quark Production

Top

CC DIS top production

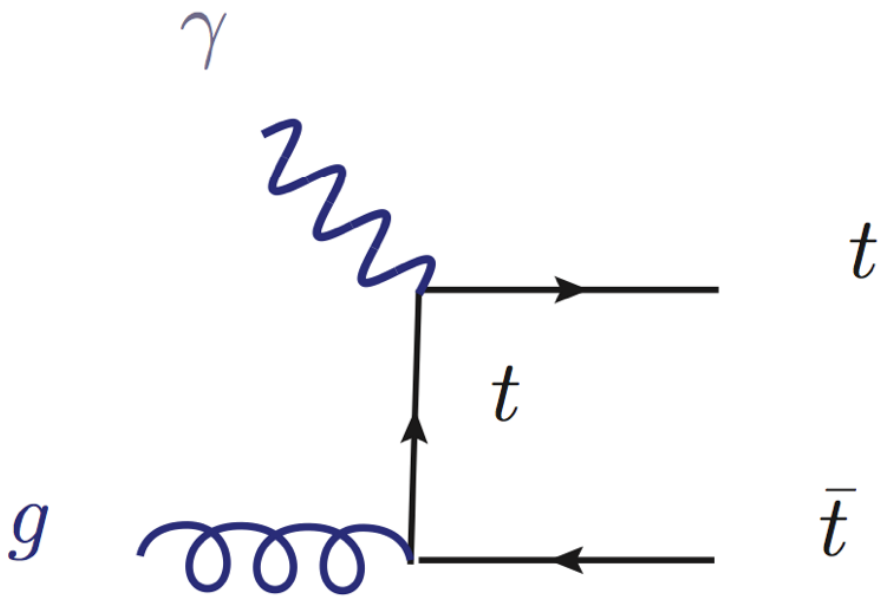


σ=1.89pb @ LHeC

σ=4.46pb @ HE-LHC

σ=15.3pb @ FCC-eh

NC top photoproduction



σ=0.05pb @ LHeC

σ=0.??pb @ HE-LHC

σ=1.14pb @ FCC-eh

E_e=60 GeV

→ future ep collider is ideal to study EWK interactions of the top quark

Signal and Backgrounds

signal

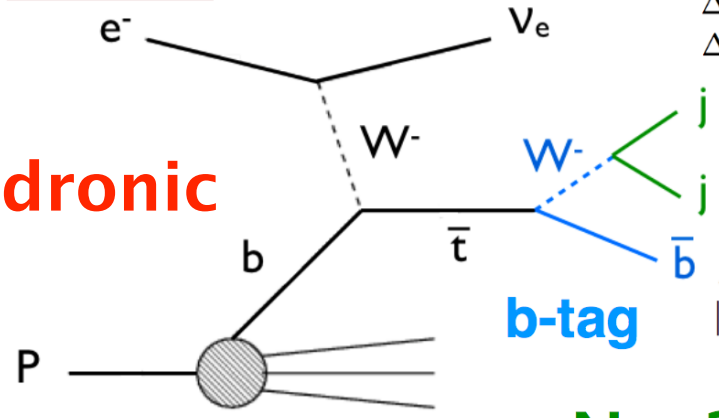
Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577

$\not{E}_T \geq 25\,\text{GeV}$

$\Delta\Phi_{\not{E},j} \geq 0.4$

$\Delta\Phi_{\not{E},b} \geq 0.4$

hadronic



$|m_{j_1 j_2} - m_W| \leq 22\,\text{GeV}$

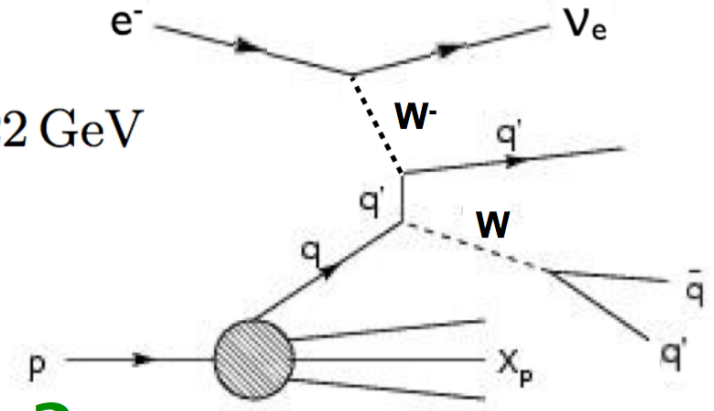
b-tag

$p_{T\,j,b} \geq 20\ \text{GeV}$

$|\eta_j| \leq 5, |\eta_b| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$

background



N_t=220k, s/b=1.2

e beam: 60 GeV
1000 fb^{-1}

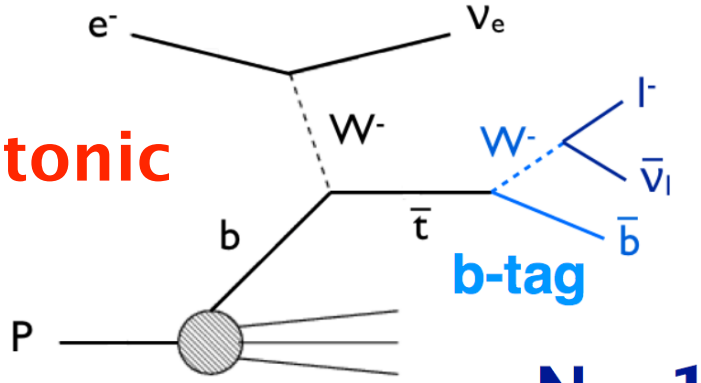
$\not{E}_T \geq 25\,\text{GeV}$

$\Delta\Phi_{\not{E},j} \geq 0.4$

$\Delta\Phi_{\not{E},b} \geq 0.4$

$\Delta\Phi_{\not{E},l} \geq 0.4$

leptonic

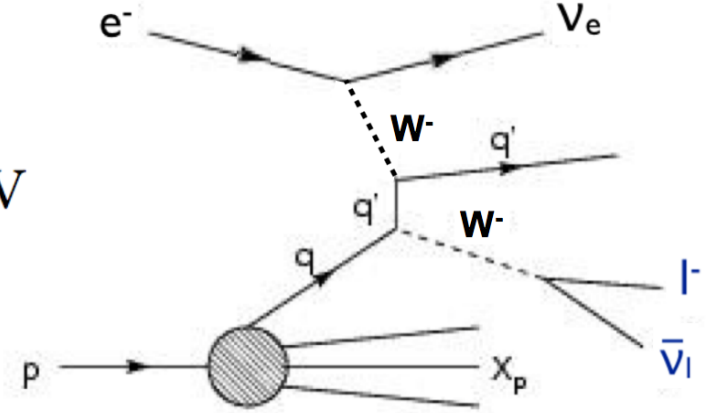


b-tag

$p_{T\,j,b,l} \geq 20\ \text{GeV}$

$|\eta_j| \leq 5,\ |\eta_{b,l}| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$



N_t=110k, s/b=11

→ **top quark factory (with low backgrounds)**

Measurement of $|V_{td}|$

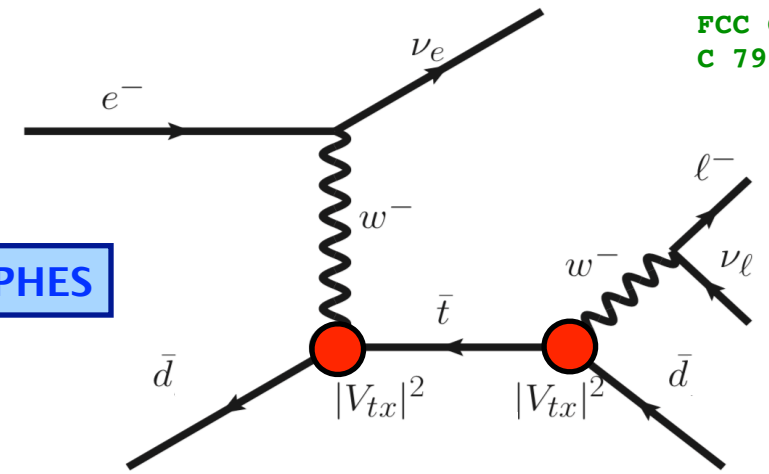
Top

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

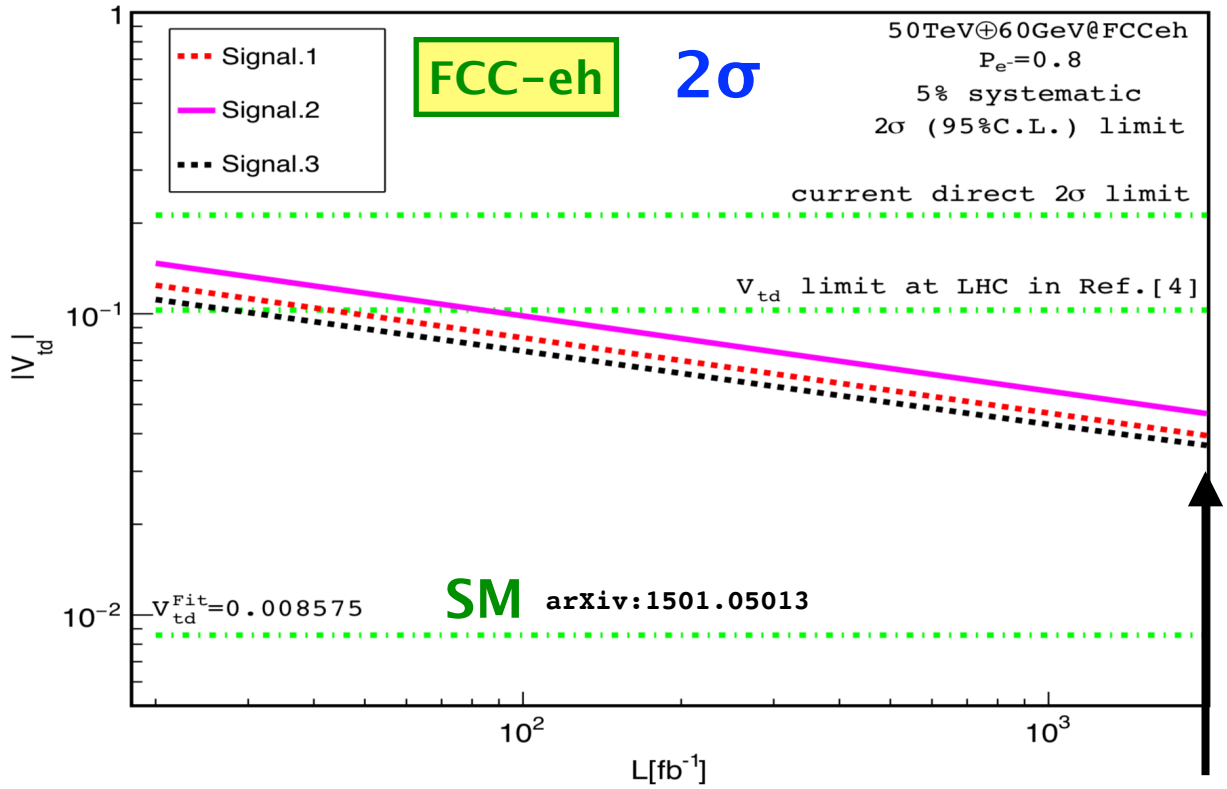
arXiv:1709.07887

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

DELPHES



H. Sun PoS DIS 2018, 167 (2018)



LHC

HL-LHC

LHC, 3000 fb^{-1}@14TeV

→ $|V_{td}|$<0.037

→ extend HL-LHC limits

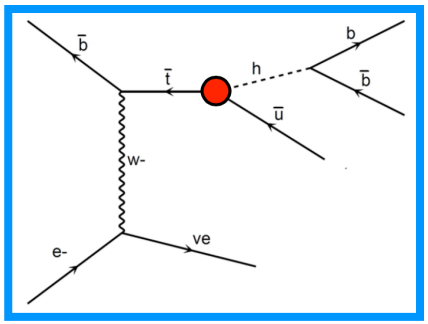
FCNC Top Quark Couplings

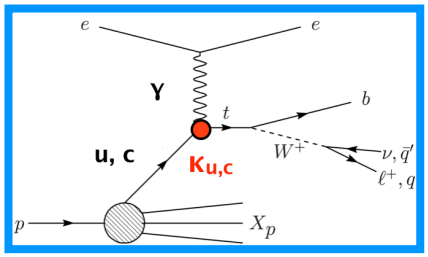
Top

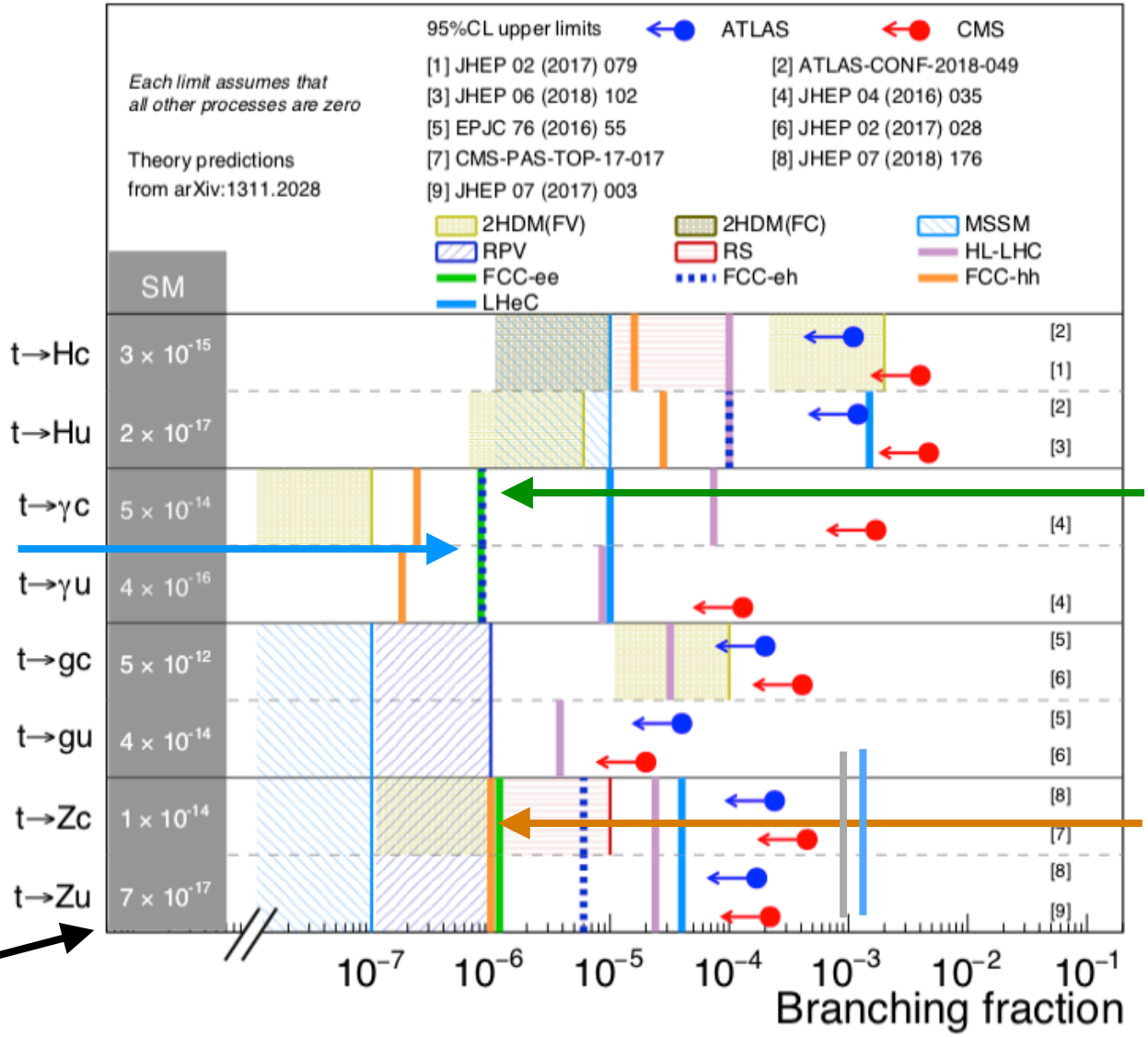
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

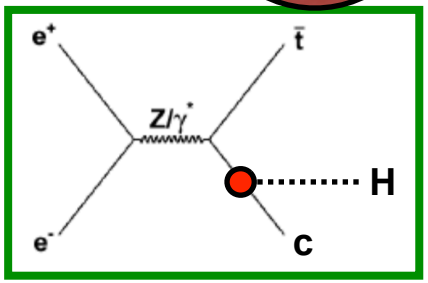
LHeC

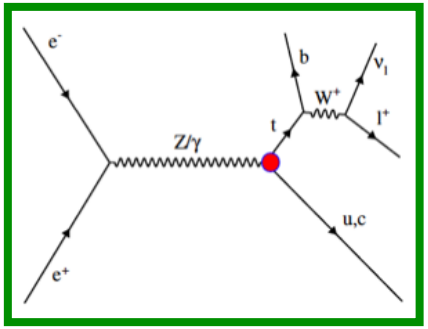
FCC-ep







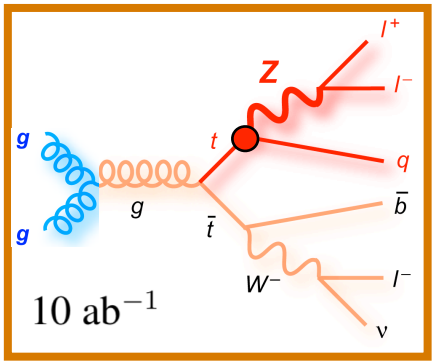




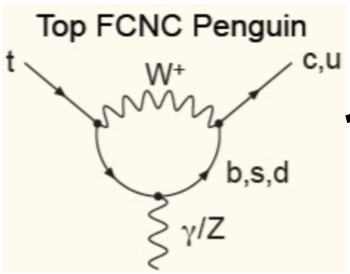
CLIC

FCC-ee

FCC-pp



Top FCNC Penguin

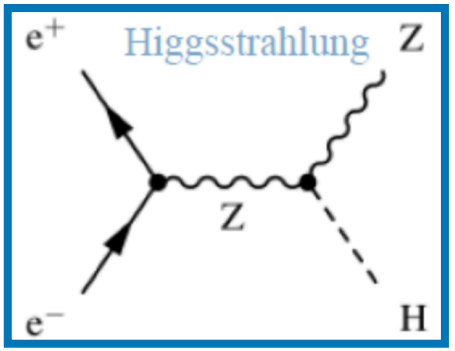


→ complementarity of colliders

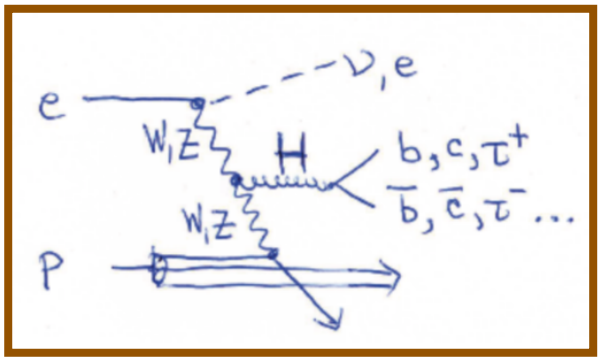
Higgs Couplings at FCC-ee and FCC-eh

Higgs

Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	**1.01**	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	**0.74**	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	**9.0**	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	**3.9**	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	–	1.7
BR_{EXO} (%)	< **1.0**	n.a.



- gets width with Z recoil

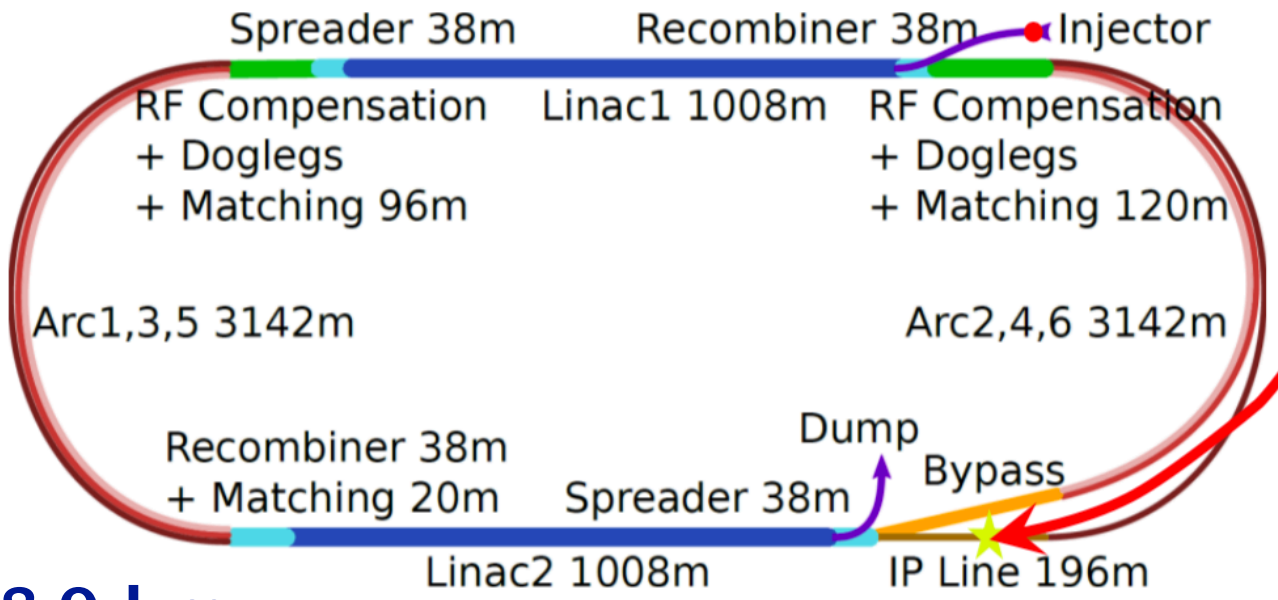


→ **high precision measurements**

Energy Recovering Linac

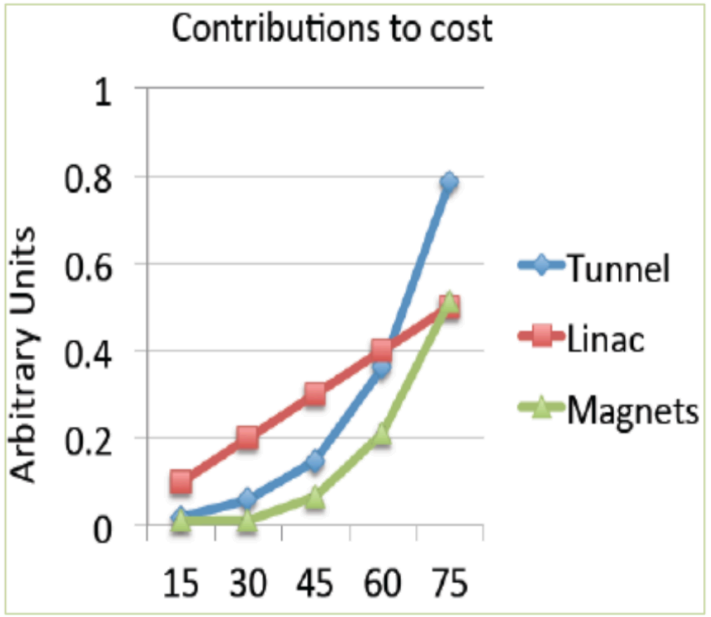
Energy Recovering Linac (ERL):

E_e=60 GeV



8.9 km

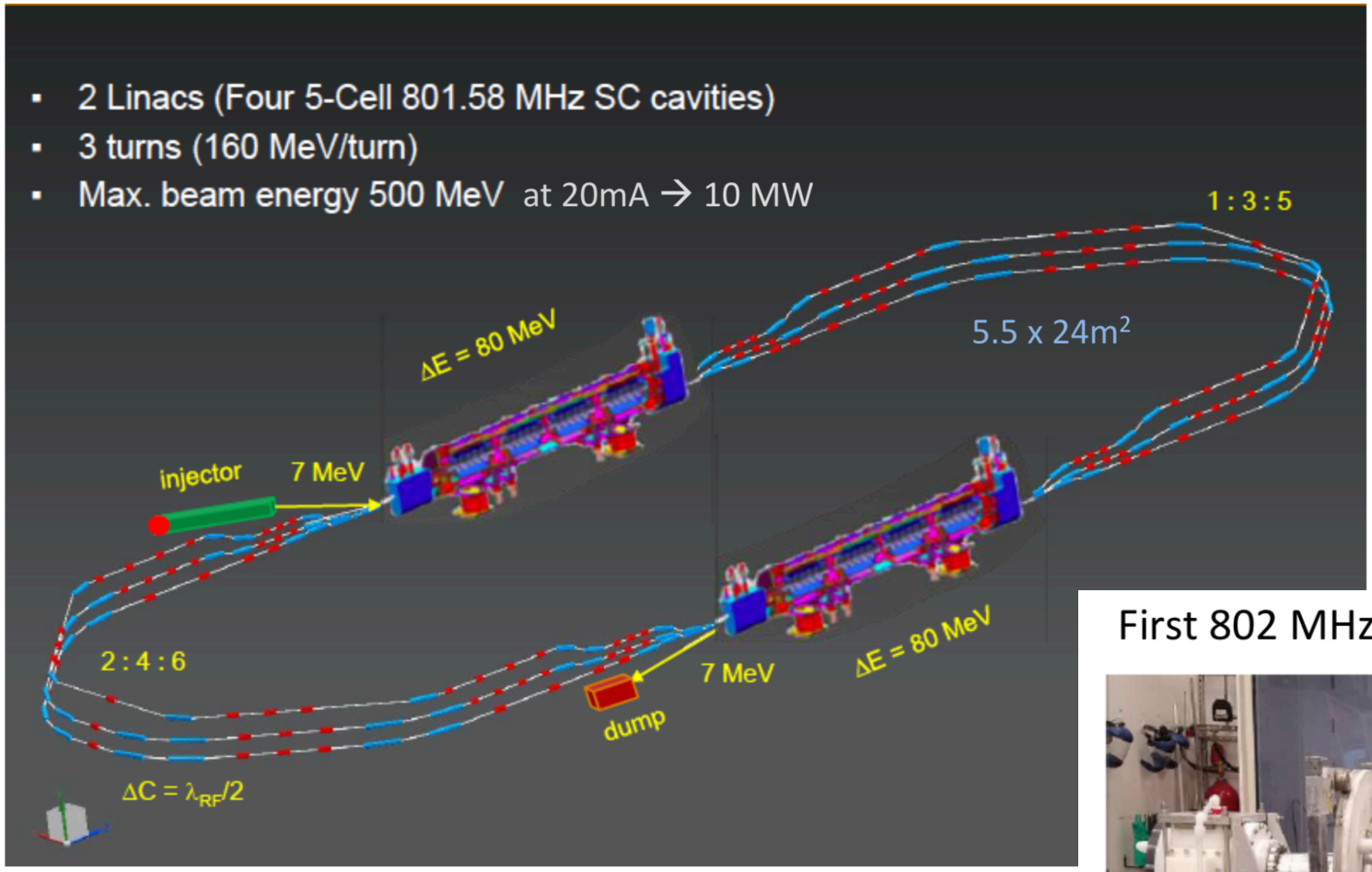
- power limit: 100 MW
- luminosity: 10^{34} cm^{-2} s^{-1}
- factor of 15/120 (LHeC/FCC-eh) extension of Q^2, 1/x reach



M. Klein, F. Zimmermann

Initial, tentative, rough scaling estimate of basic cost (tunnel, linac (XFEL), magnets

Powerful ERL for Experiments (PERLE)



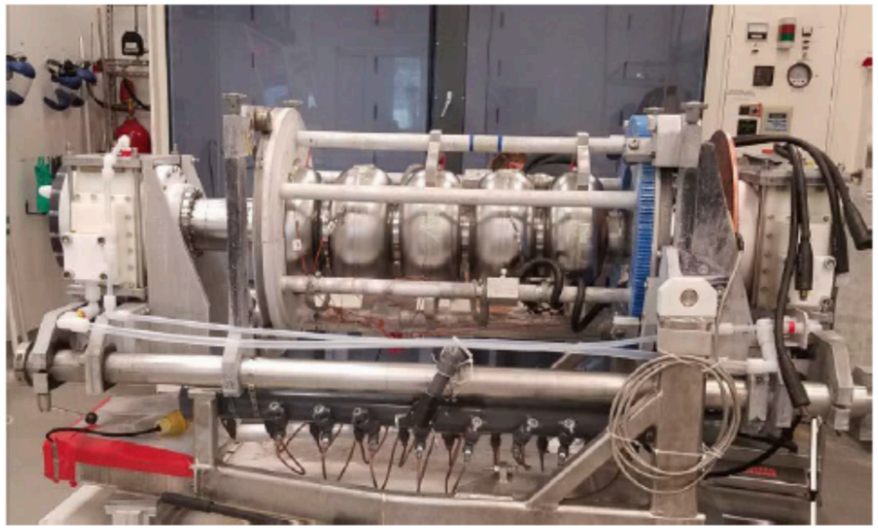
cf Walid Kaabi at Amsterdam FCC

in Orsay

- BINP
- CERN
- Daresbury/Liverpool
- Jlab
- Orsay

→ CDR 1705.08783 [J. Phys G]
→ TDR in 2019

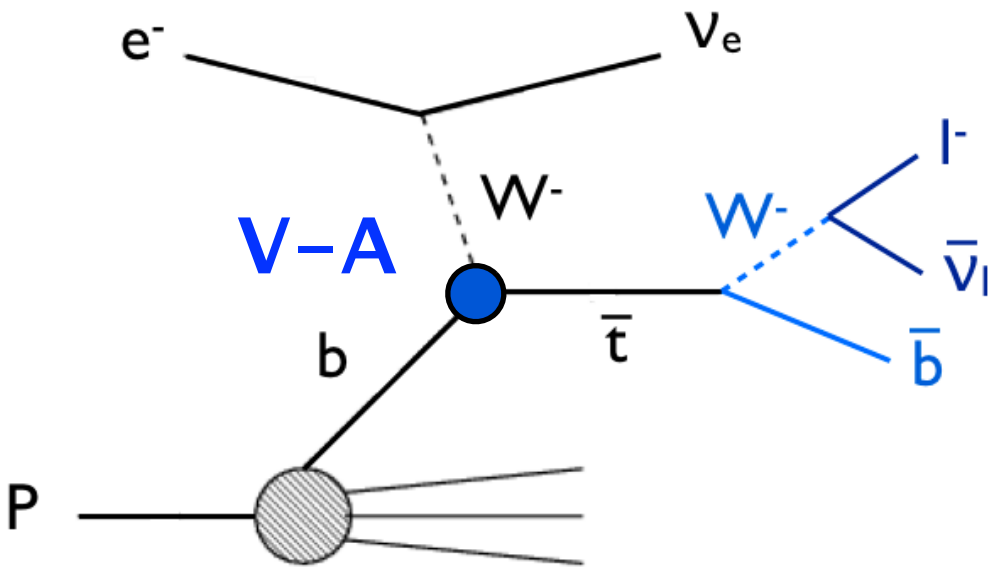
First 802 MHz cavity successfully built (Jlab)



→ ERL demonstrator
→ O(10 MeV) physics

Top Quark Polarisation

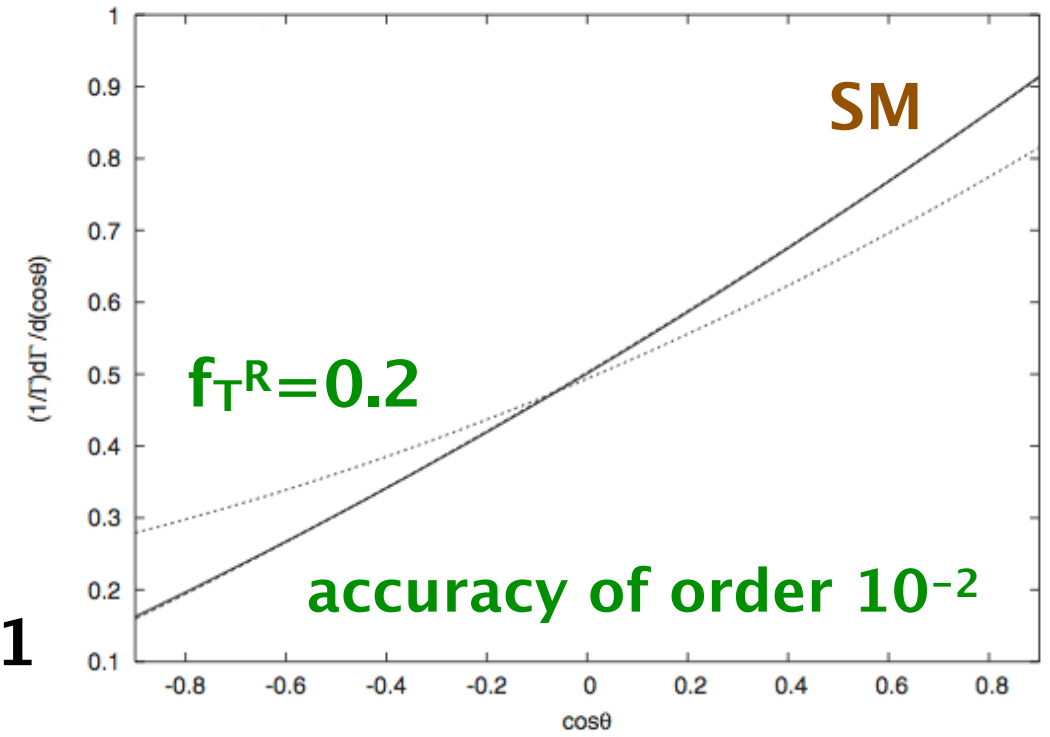
Top



Atag, Sahin,
PRD 73, 074001 (2006)

cosθ: angle between charged lepton and spin quantisation axis in top rest frame

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + A_{\uparrow\downarrow}\alpha\cos\theta) \qquad A_{\uparrow\downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



using simply e-beam axis: polarisation: P_t = 96%

TESLA+HERAp:

$\sqrt{s}$=1.6 TeV
L_{int}=20 fb^{-1}

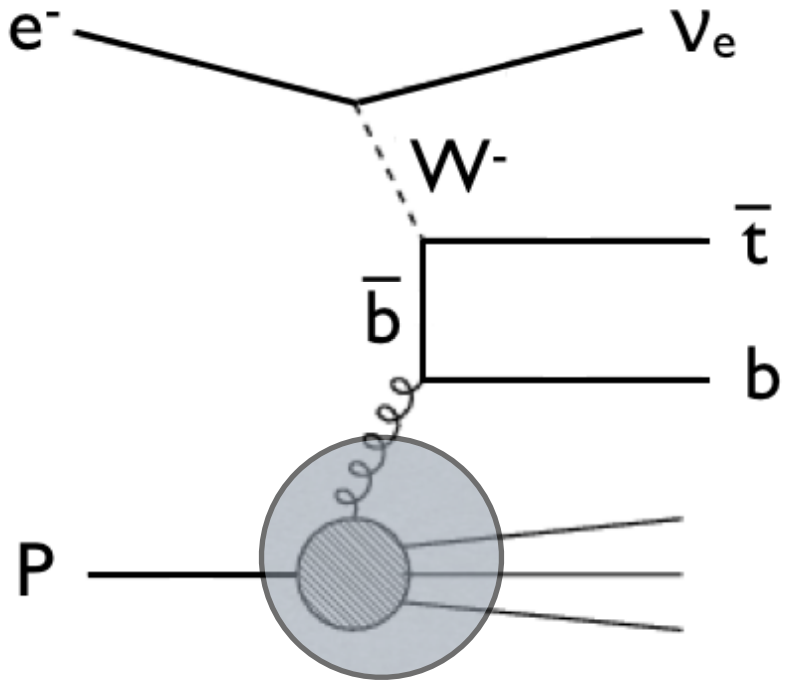
CMS

19.7 fb^{-1}: $A_{\uparrow\downarrow}$ = 0.26±0.11

JHEP 04 (2016) 073

Gluon Parton Density Function

Top



→ **measure gluon density at high x**

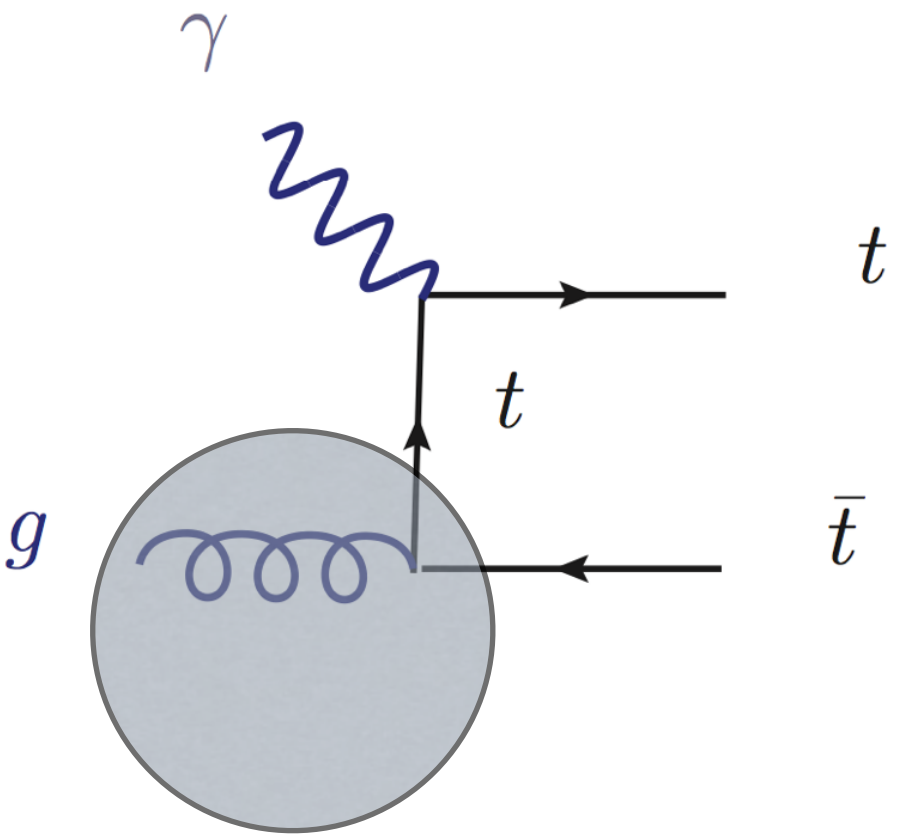
Top Quark Structure Function

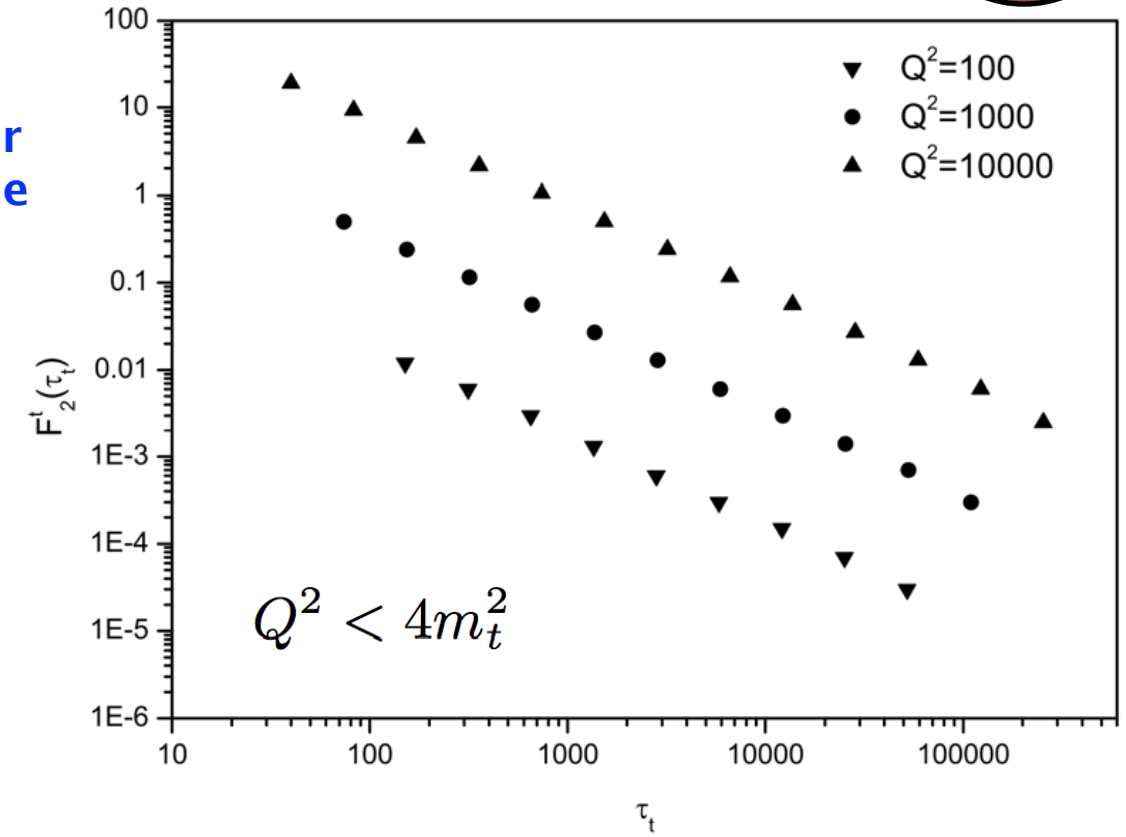
Top

Boroun, Phys. Lett. B744, 142 (2015)

$L_{int}=10\ fb^{-1}$

variable flavour number scheme for top quark





$$\tau_t = (1+\frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^{\lambda}$$

$$x = x_B(1+\frac{4m_t^2}{Q^2})$$

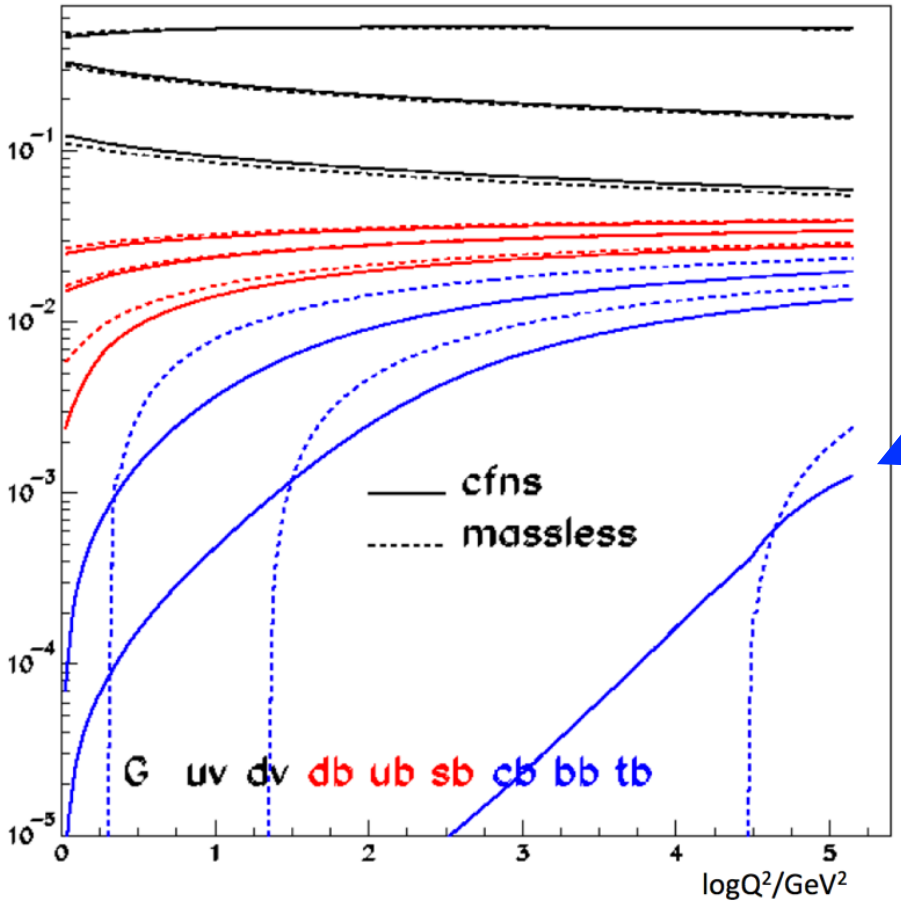
→ LHeC opens up a new field of top quark PDFs

Top Quark Parton Density Functio

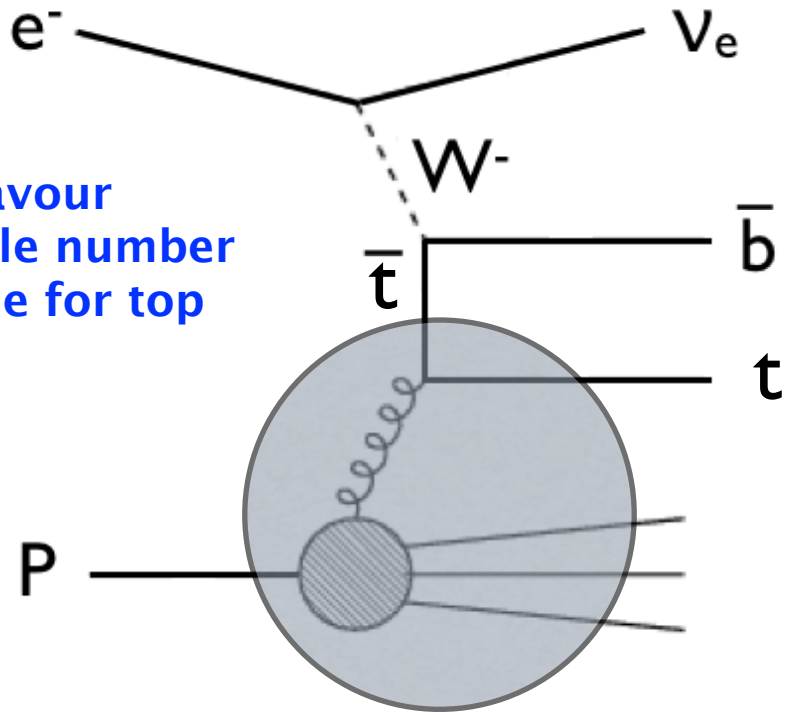
Top

LHeC CDR, J.Phys. G39, 075001 (2012)

parton momentum fraction



six-flavour variable number scheme for top quark



→ LHeC offers new field of research for top quark PDF

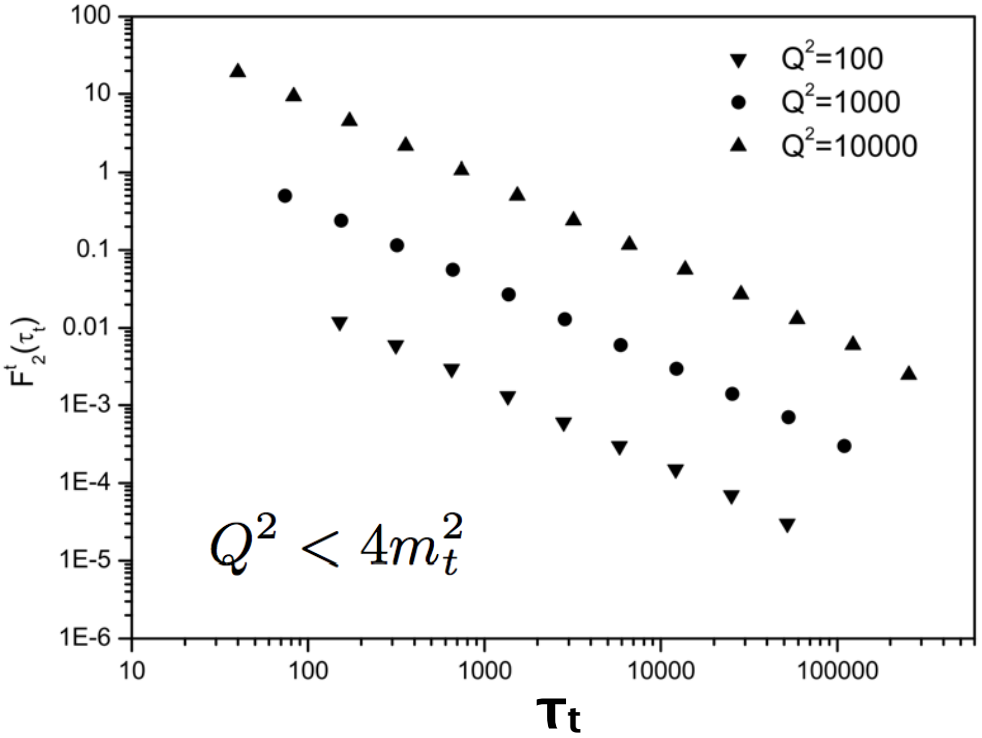
Top Quark Structure Function

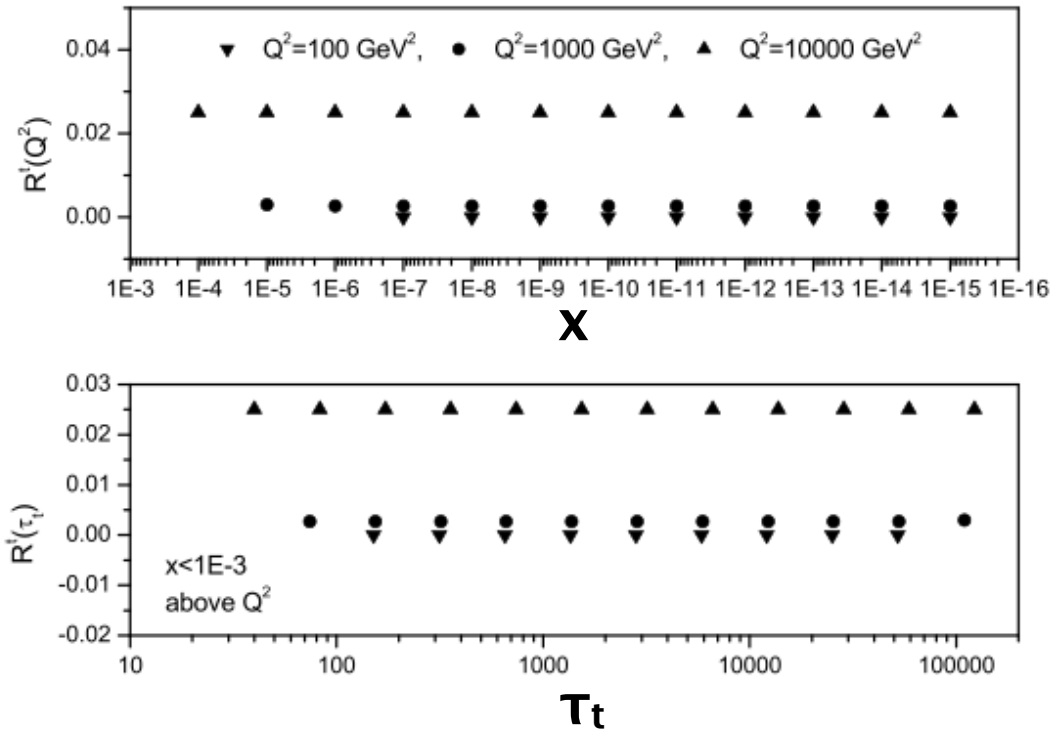
Top

Boroun, Phys. Lett. B744, 142 (2015)

$$\tilde{\sigma}^{t\bar{t}}(\tau_t) \rightarrow F_2^t(\tau_t)[1 - R^t(\tau_t)]$$

variable flavour number scheme for top quark





→ approximately: $1/\tau_t$

→ independent of x and τ_t

→ longitudinal top structure function component could be good to probe top quark density in proton at $Q^2 \simeq 4m_t^2$

NC Top Quark Production

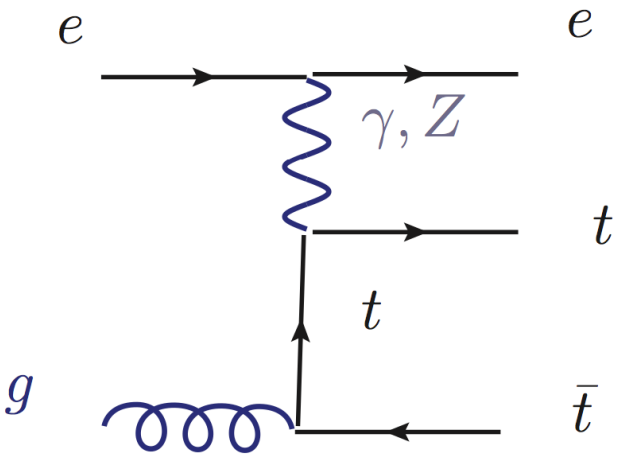
Top

Bouzas, Larios,
Physical Review D 88, 094007 (2013)

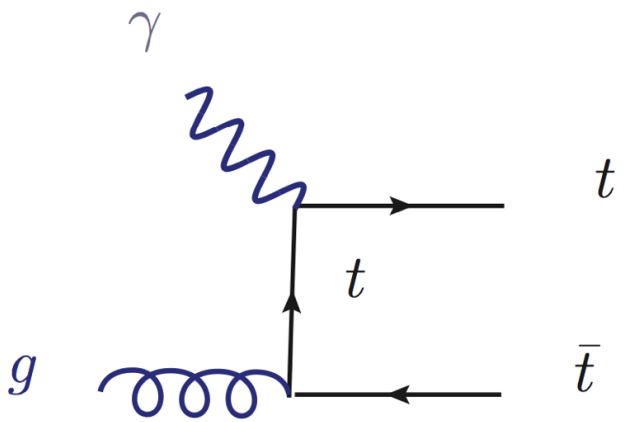
top pair production

single top production

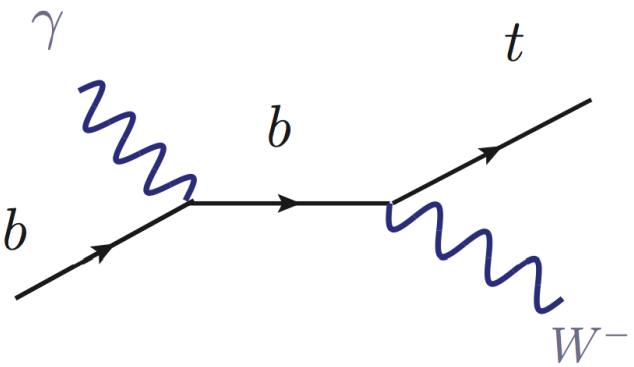
DIS



photoproduction



photoproduction



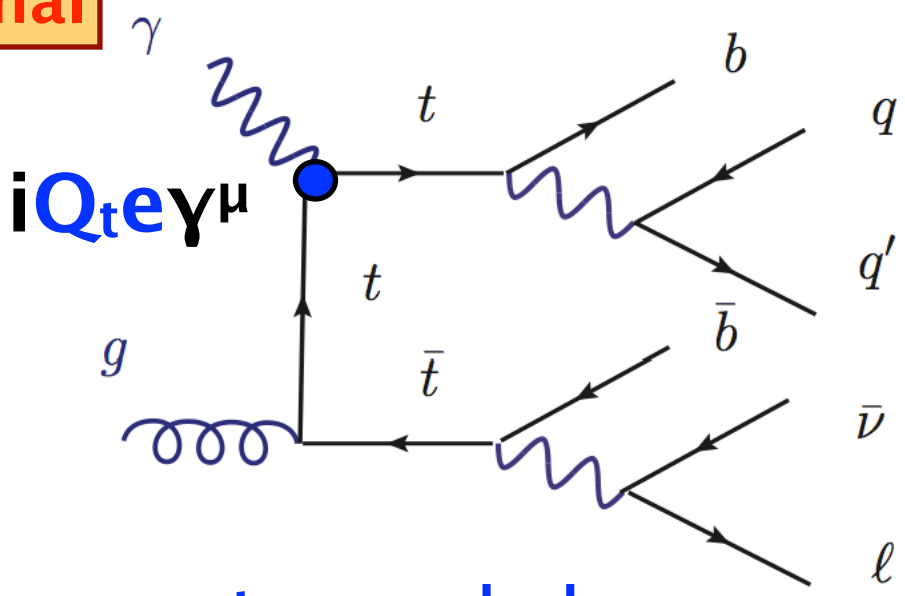
e-beam 60 GeV, 100 fb^{-1}:

0.023 pb	0.70 pb	0.031 pb
$N_{t\bar{t}}$=2,300	$N_{t\bar{t}}$=70,000	N_t=3,100

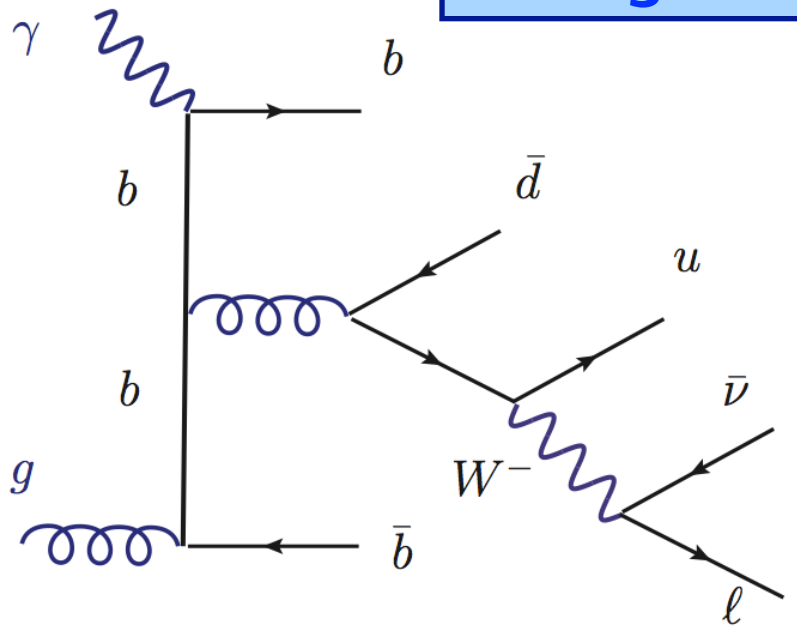
Analysis of the $t\bar{t}\gamma$ Vertex

Top

signal

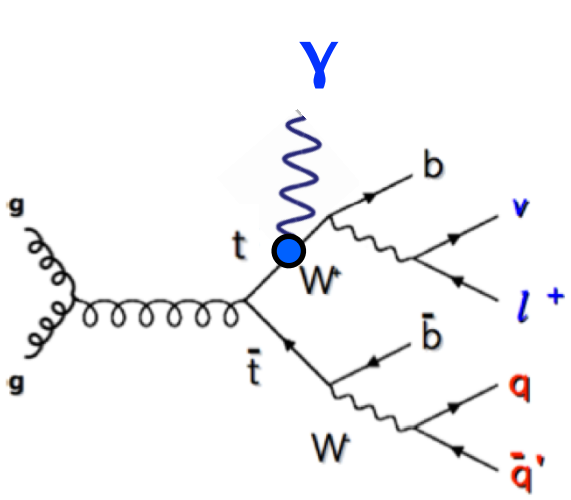


background

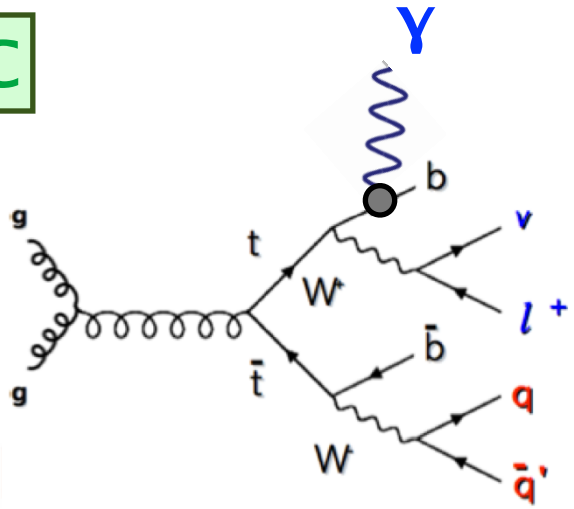


→ measure top quark charge

LHC



OR

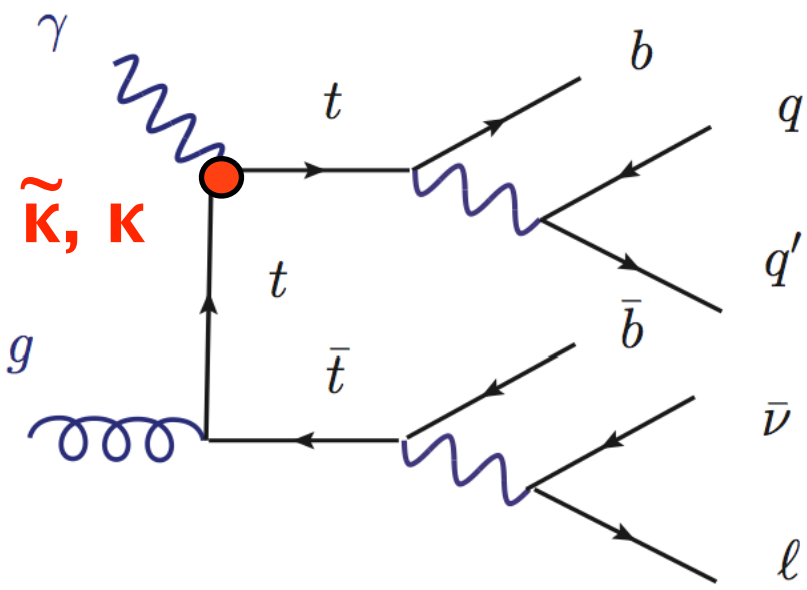


?

→ difficult at the LHC

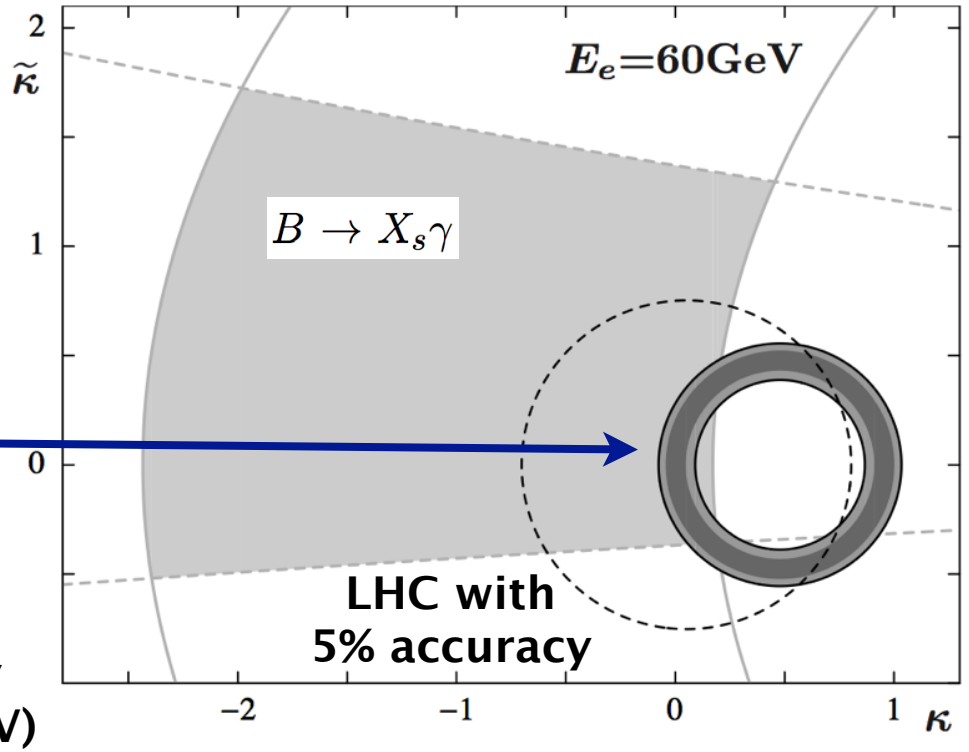
Search for Anomalous $t\bar{t}\gamma$ Coupling

Top



$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

electric dipole moment: $\tilde{\kappa}$



LHeC:
10% and 18% accuracy

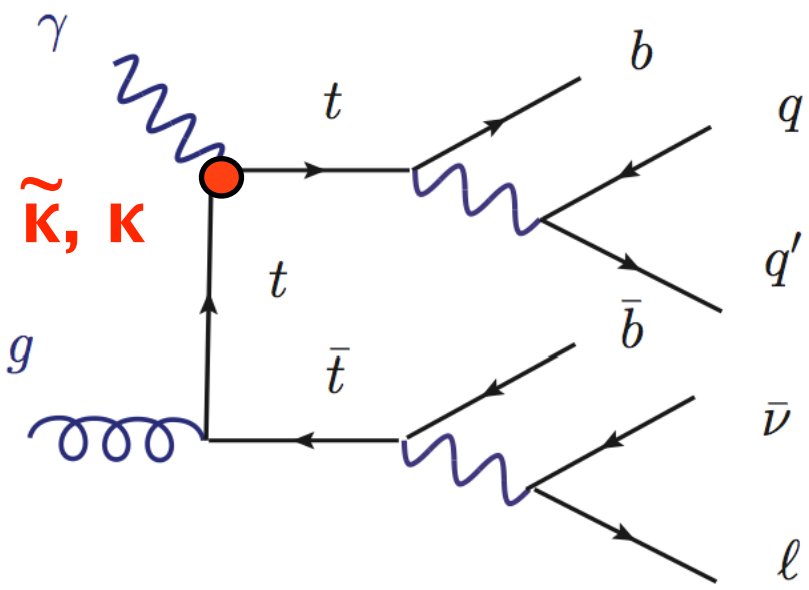
27% accuracy
(4.59fb^{-1}, 7 TeV)

magnetic dipole moment: κ

Bouzas, Larios,
Physical Review D 88, 094007 (2013)

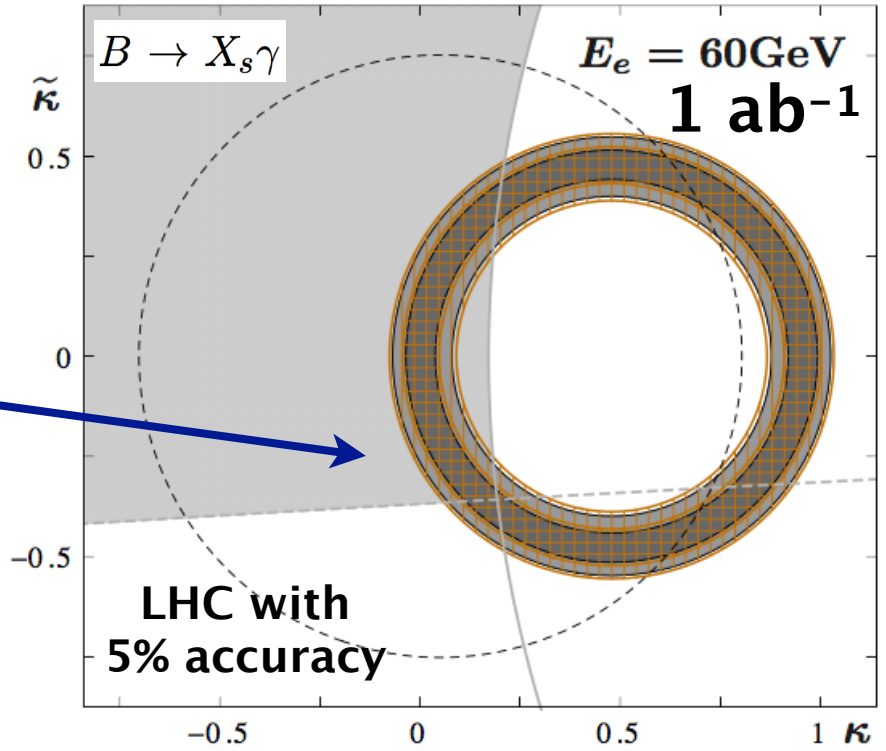
Search for Anomalous $t\bar{t}\gamma$ Coupling

Top



$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

electric dipole moment: $\tilde{\kappa}$



magnetic dipole moment: κ

LHeC:

8% and 16% accuracy

10% 18%

→ systematically limited

27% accuracy (4.59fb⁻¹, 7 TeV)

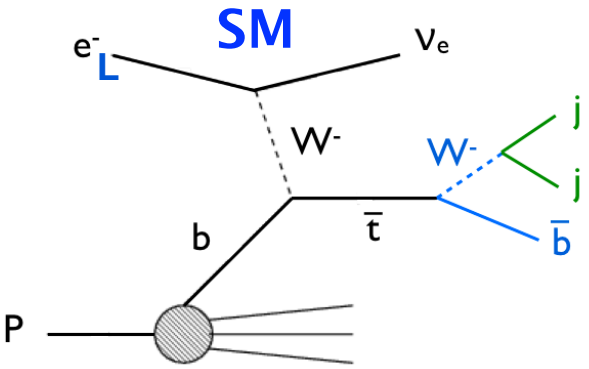
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

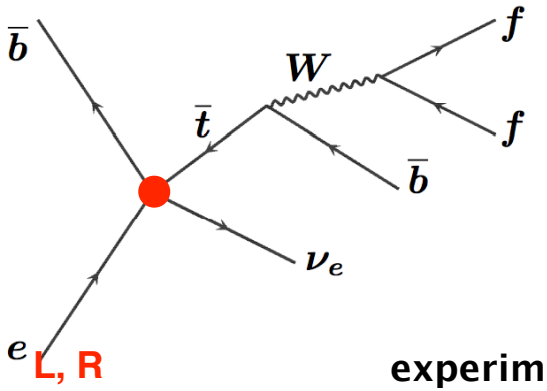
Top Quark Dimension 6 Operators

Top

$$\Lambda^2 \mathcal{L}_{4f} = C_1(\bar{\nu}_L \gamma^\mu t_L \bar{b}_L \gamma_\mu e_L + h.c.) + [C_2 \bar{\nu}_L e_R \bar{b}_R t_L + C_3 \bar{b}_L e_R \bar{\nu}_L t_R + C_4 \bar{\nu}_L e_R \bar{b}_L t_R + h.c.]$$

Λ=1TeV





property	precision
C_1	0.50–0.85
C_2^r	2.2–5.0
C_3^r	1.4–2.9
C_4^r	2.2–4.9

Sarmiento-Alvarado, Bouzas, Larios, arXiv:1412.6679

$\mathcal{P}_e = 0$

$\mathcal{P}_e = 0.4$

$\mathcal{P}_e = 0.7$

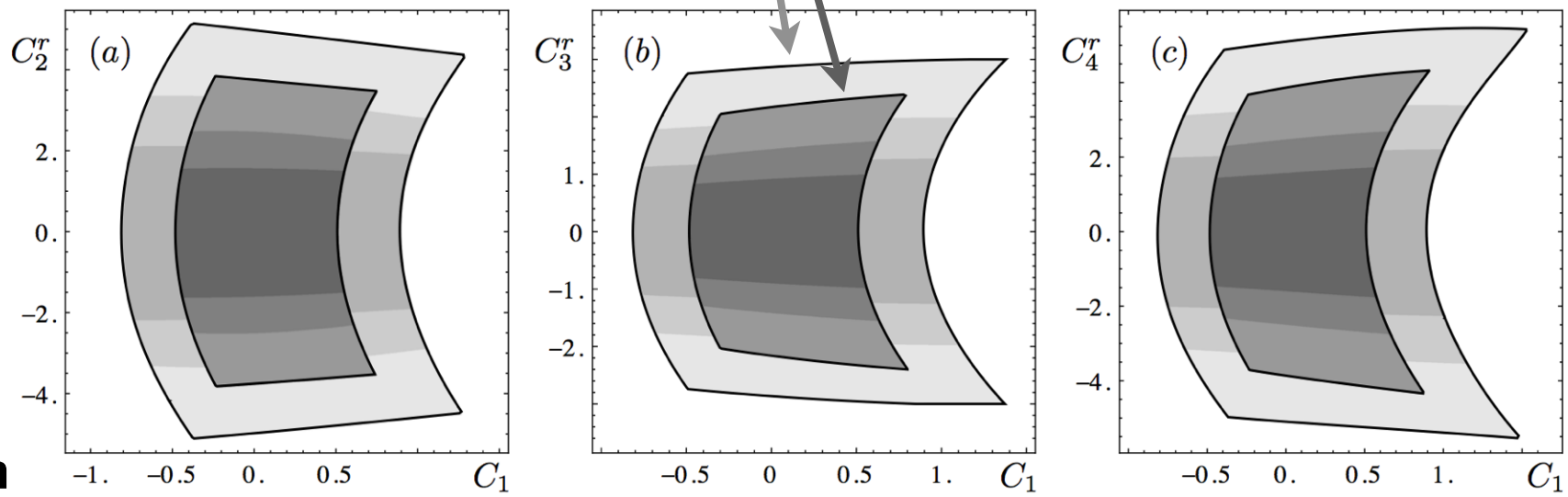
cross section

experimental error

15% 7%

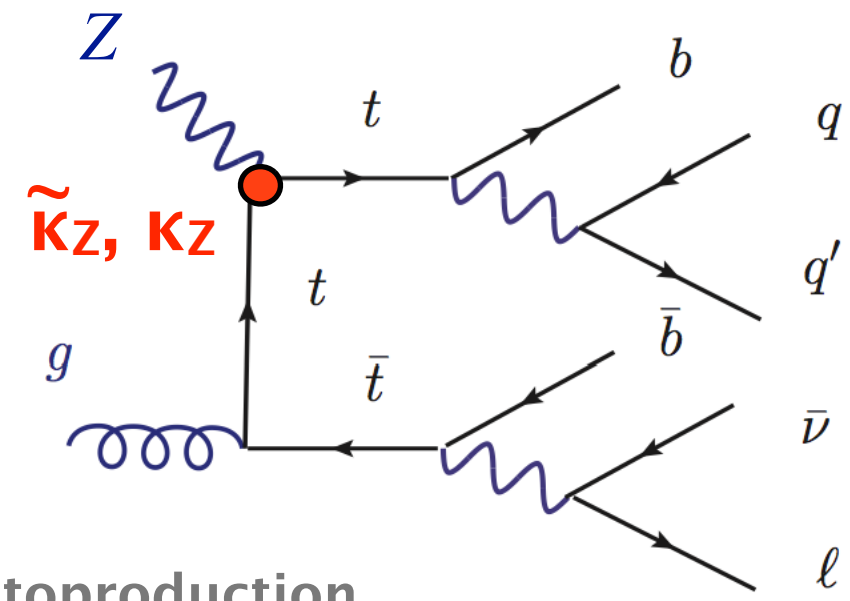
68% C.L.

$A(\Delta\eta(\bar{b}, j_1))$ $A(\Delta\varphi(j_2, \not{E}_T))$



Search for Anomalous $t\bar{t}Z$ Coupling

Top

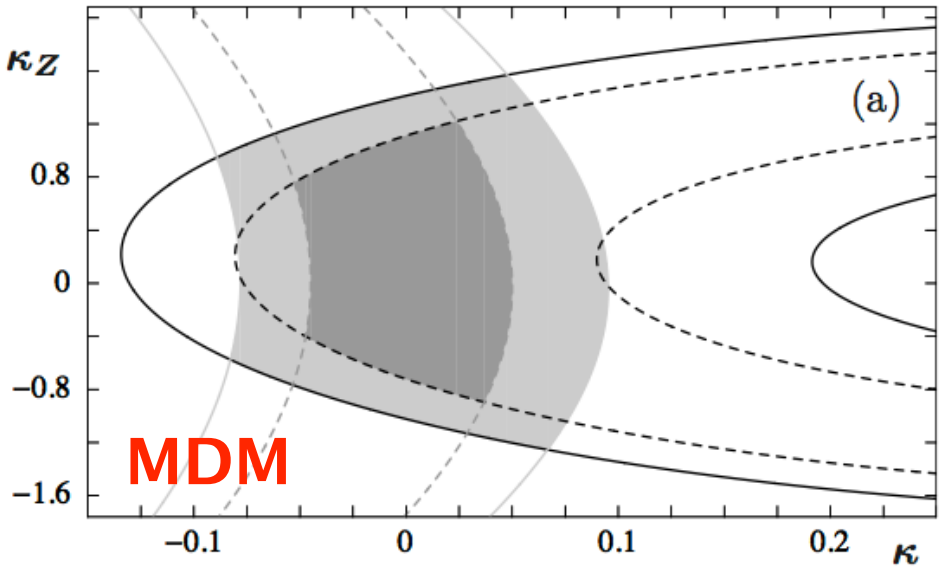


$t\bar{t}$ photoproduction

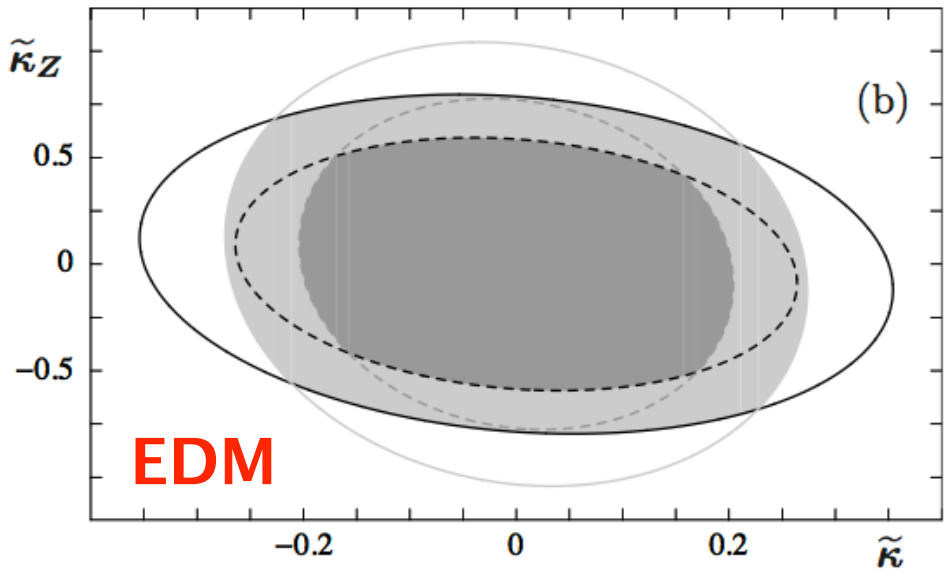
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

property	precision
EDM: $\tilde{\kappa}$ / $\tilde{\kappa}_Z$	0.20–0.28/0.6–0.8
MDM: κ / κ_Z	0.05–0.09/0.9–1.3

LHeC:
10% and 18% accuracy



$t\bar{t}$ DIS

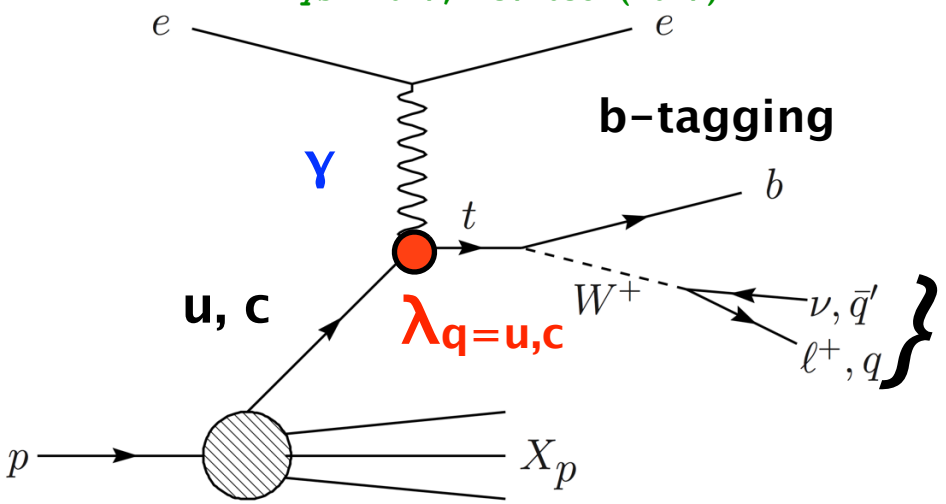


Search for Anomalous FCNC tuγ Coupling

signal

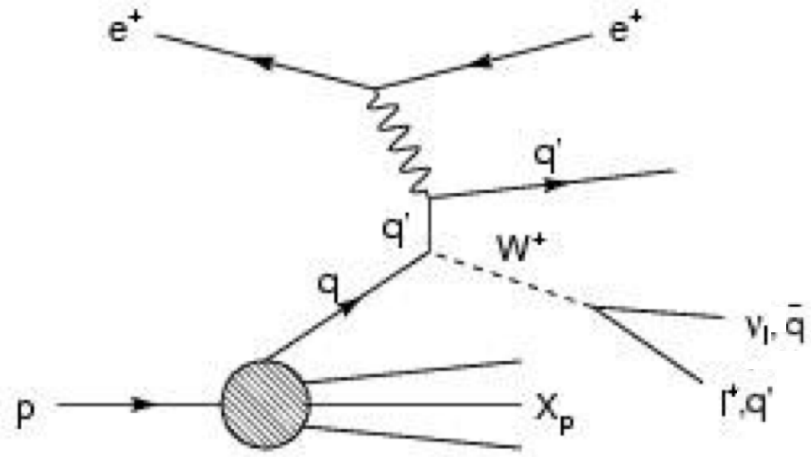
I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$



50<Mjj<100 GeV

background



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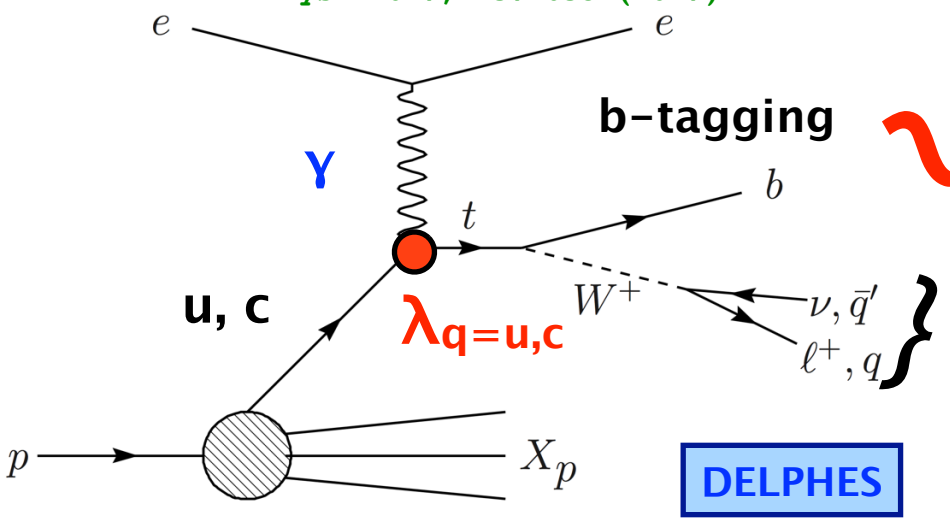
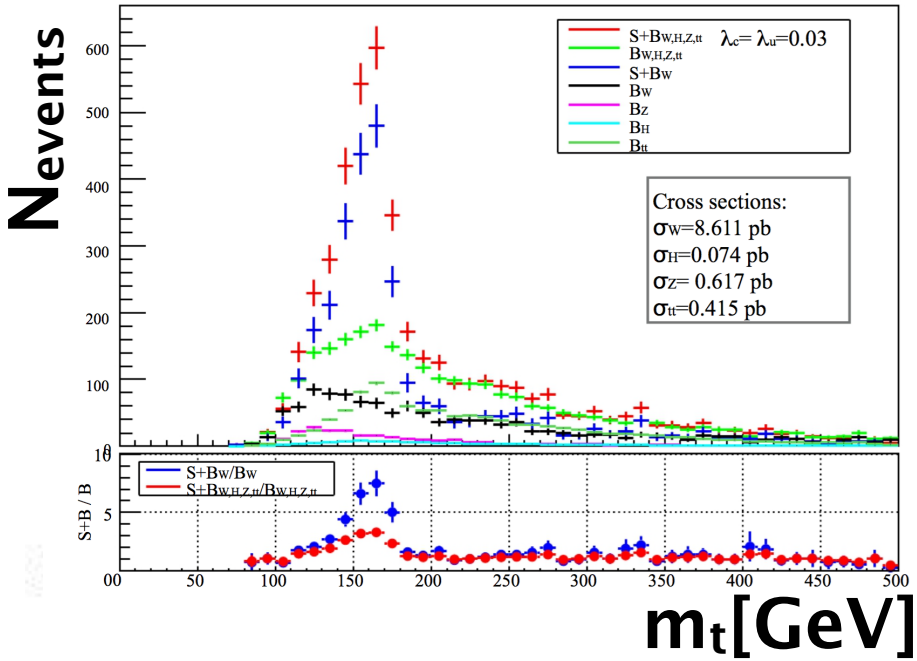


$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

130<M_{Wb}<190 GeV

50<M_{jj}<100 GeV

DELPHES



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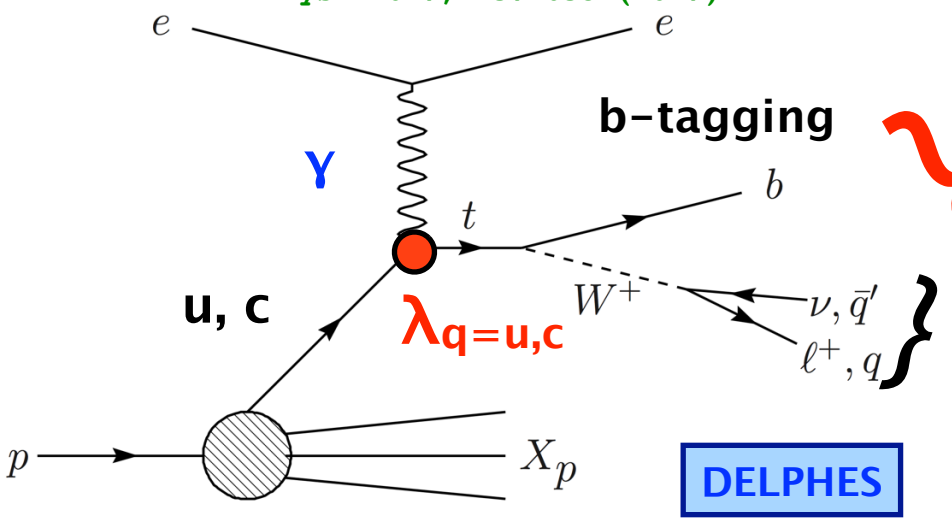
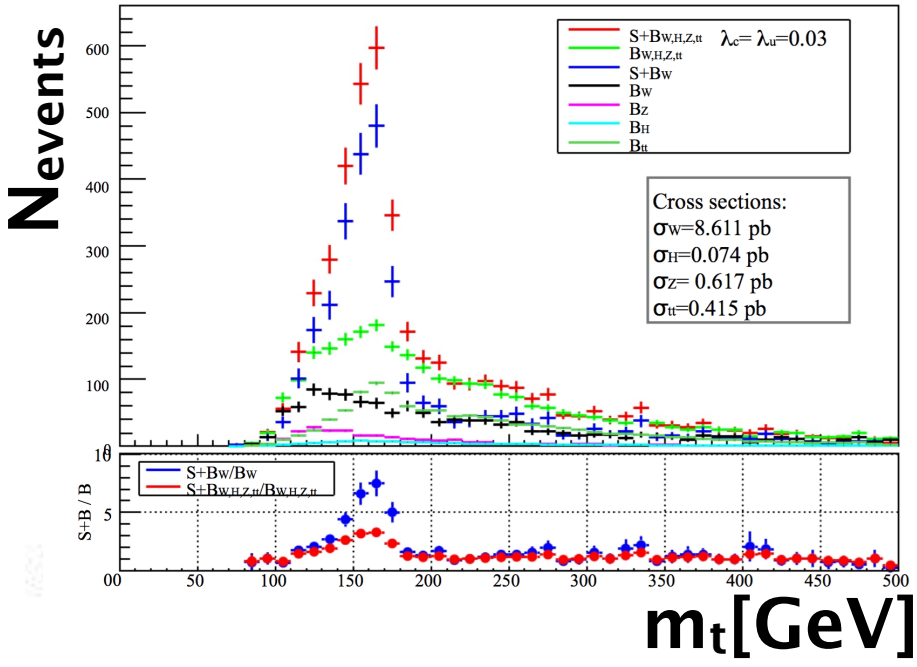


130<M_{Wb}<190 GeV

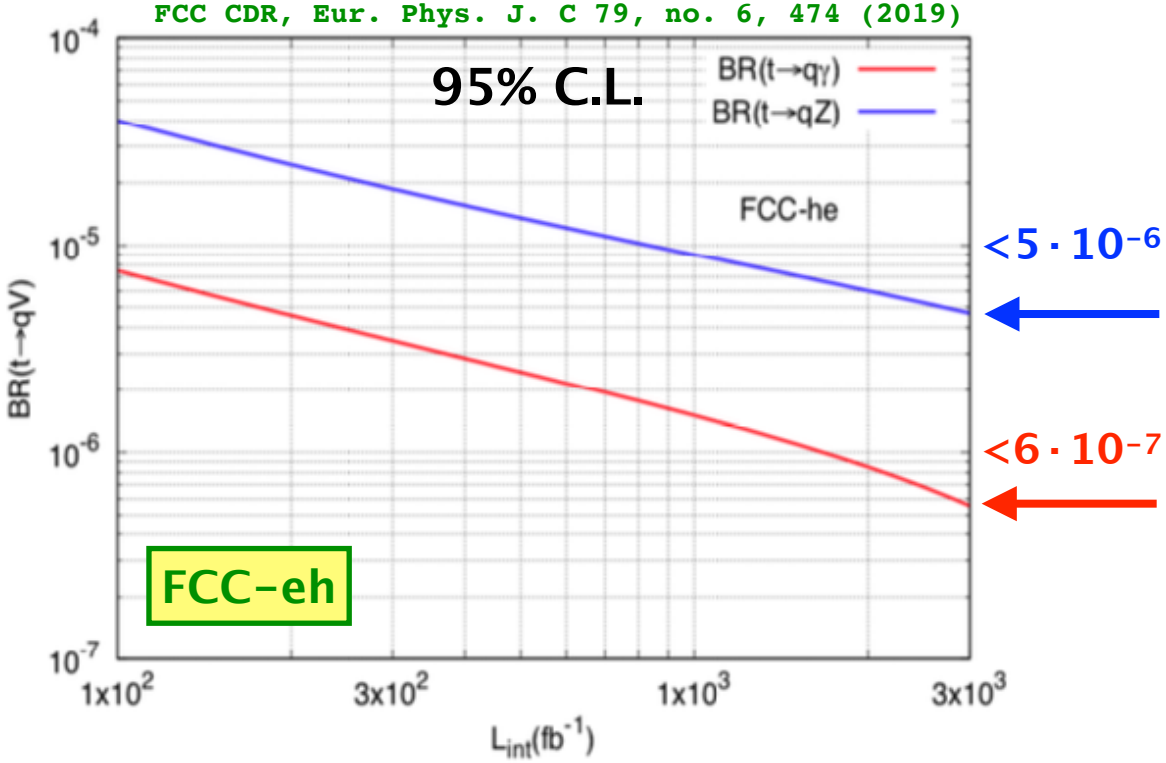
50<M_{jj}<100 GeV

→ test exotic models leading to FCNC

DELPHES



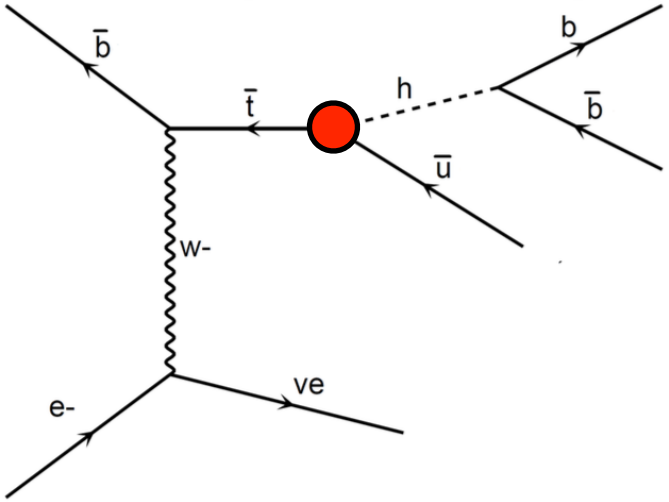
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)



Search for Anomalous FCNC tHu Coupling

signal

Sun, Wang,
arXiv:1602.04670 [hep-ph]



$$e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} \to \nu_e b \bar{b} \bar{q}, \quad q = u, c$$

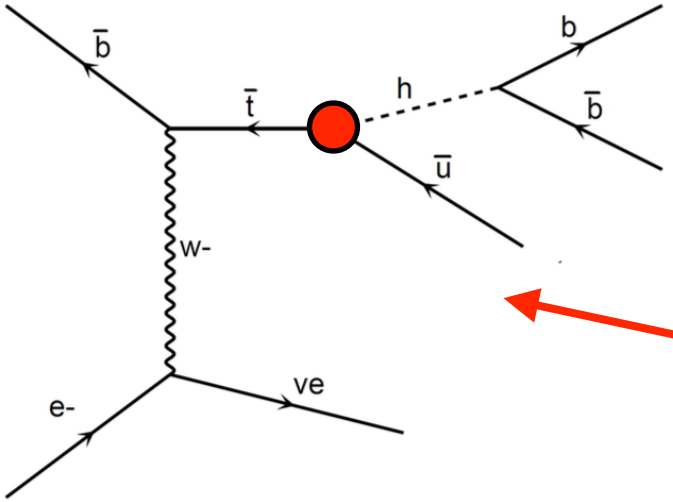
$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + h.c.$$

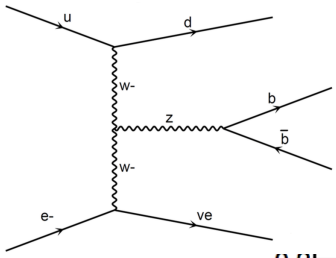
Search for Anomalous FCNC tHu Coupling

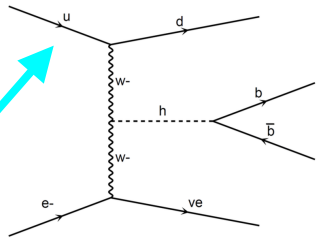
signal

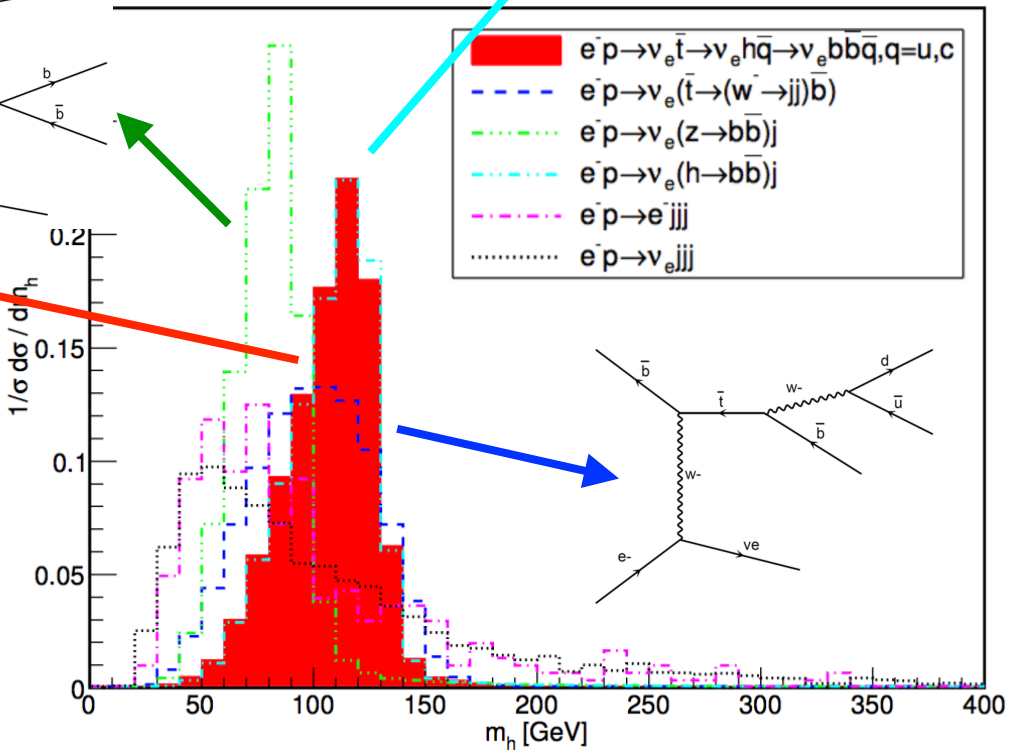
Sun, Wang,
arXiv:1602.04670 [hep-ph]

background









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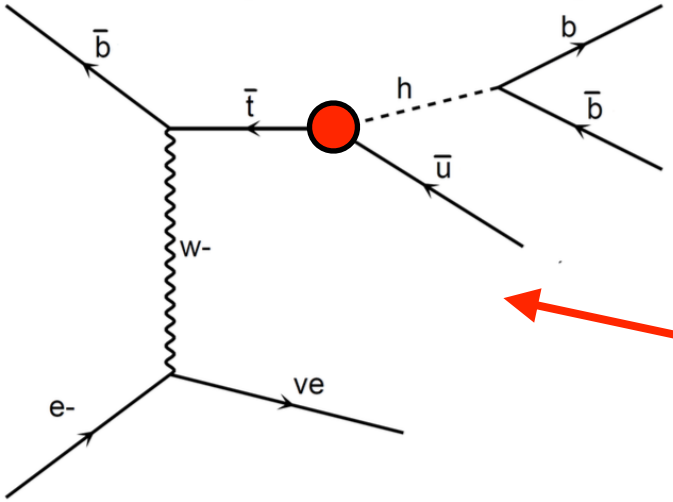
$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + \text{h.c.}$$

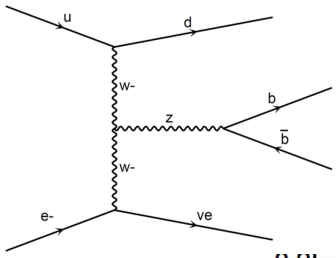
Search for Anomalous FCNC tHu Coupling

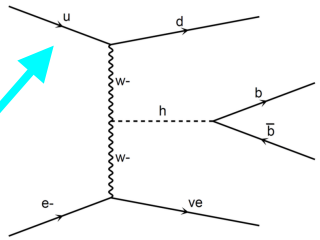
signal

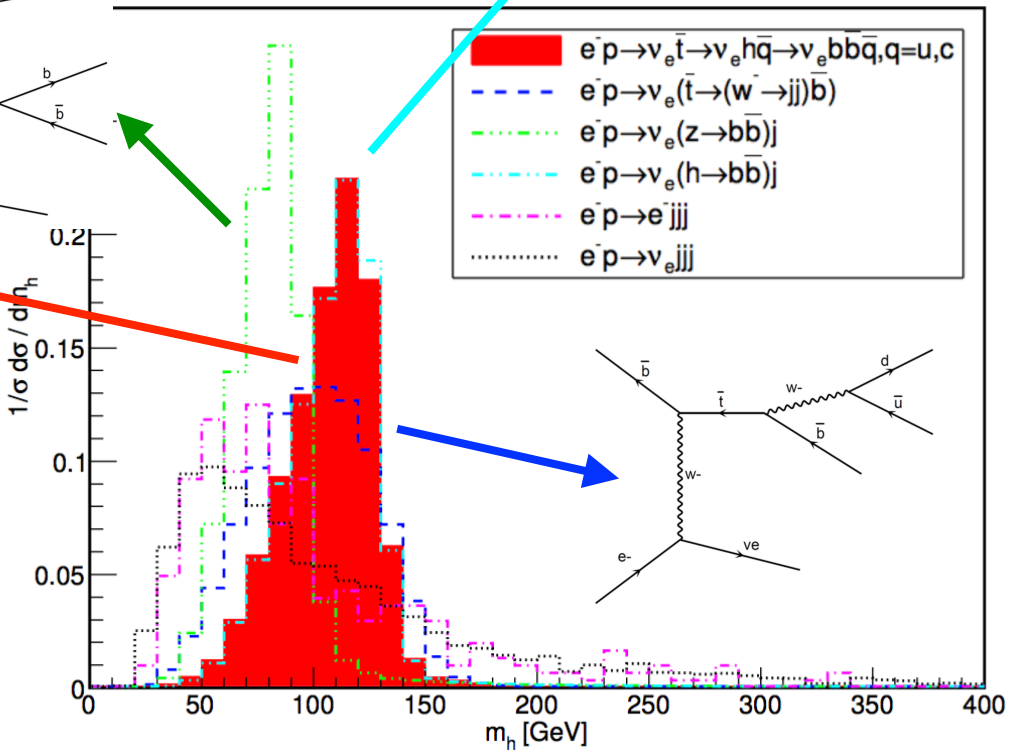
Sun, Wang,
arXiv:1602.04670 [hep-ph]

background









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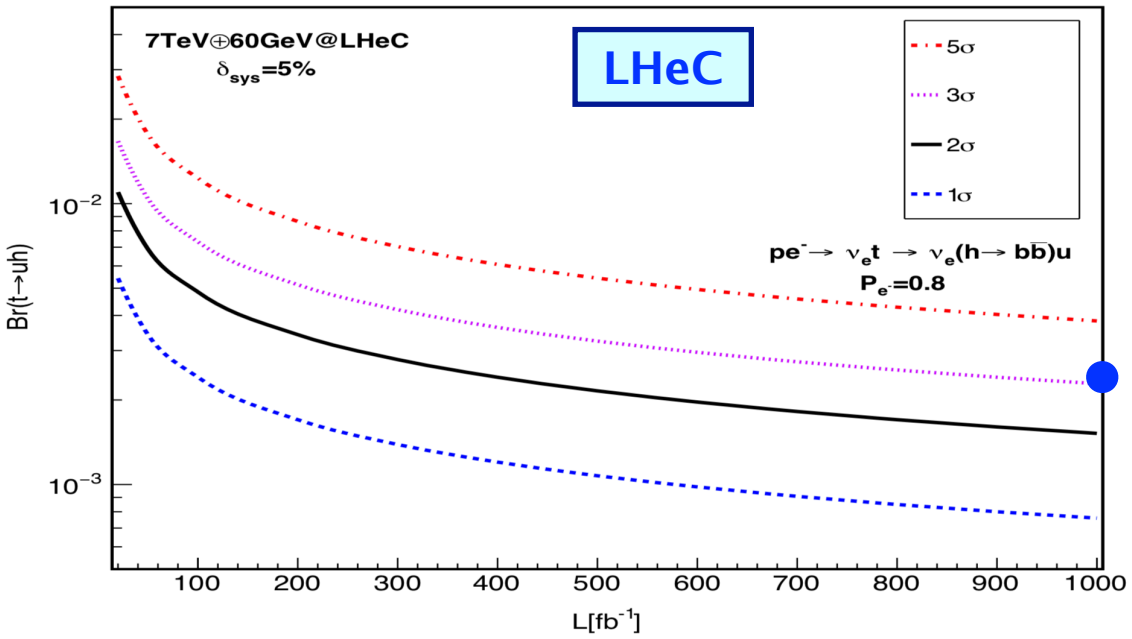
$$\mathcal{L} = \kappa_{tuh} \bar{t} u h + \kappa_{tch} \bar{t} c h + \text{h.c.}$$

- parametrised assumed resolutions for electrons/photons, muons, jets and unclustered energy using ATLAS values
- b-tag rate of 60%, c-jet fake rate of 10%, light-jet fake rate of 1%
- selections optimized for LHeC and FCC-ep scenarios (s/√(S+B))
- cut-based and MVA-based analyses

Upper Limit on Br(t→uH) in MVA analysis



Sun, Wang,
arXiv:1602.04670 [hep-ph]

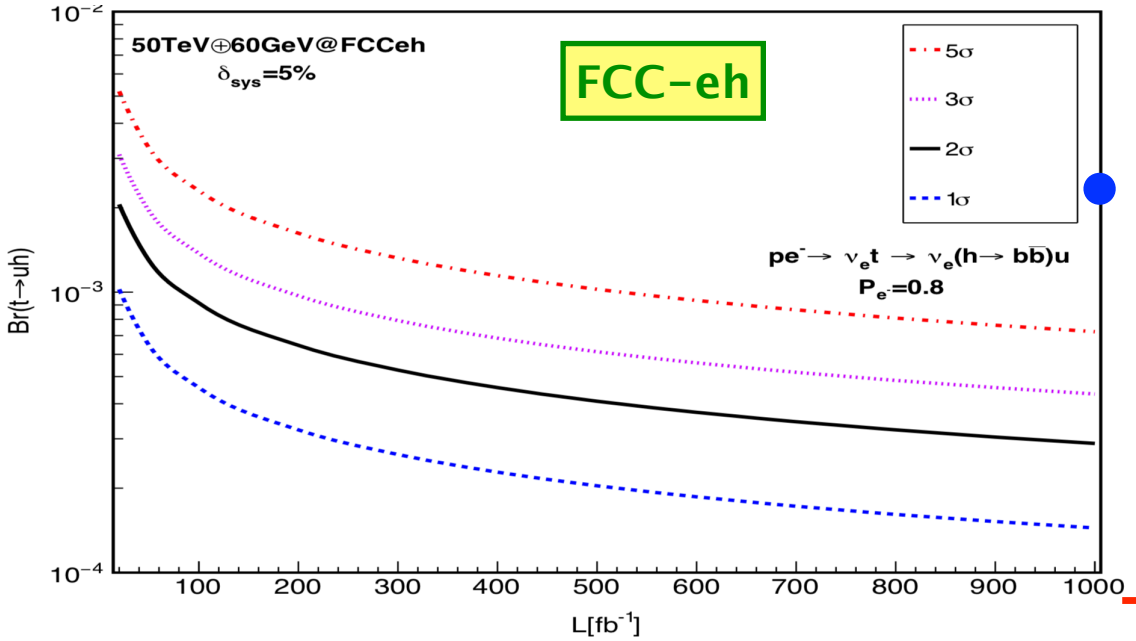
parametrisation

HL-LHC

LHC, 3000 fb^{-1}@14TeV

<0.0015 (1ab^{-1})

2σ



HL-LHC

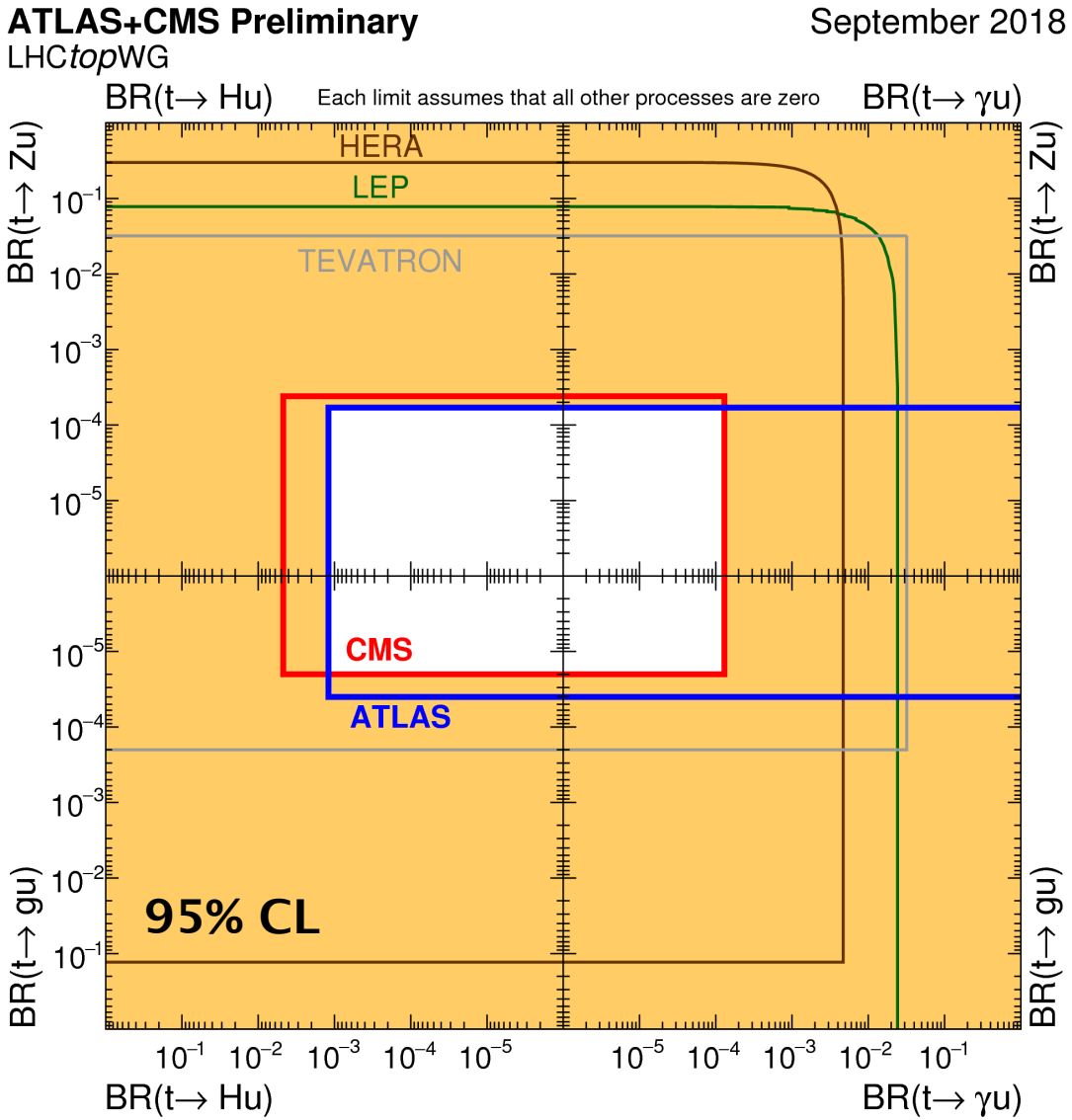
LHC, 3000 fb^{-1}@14TeV

2σ

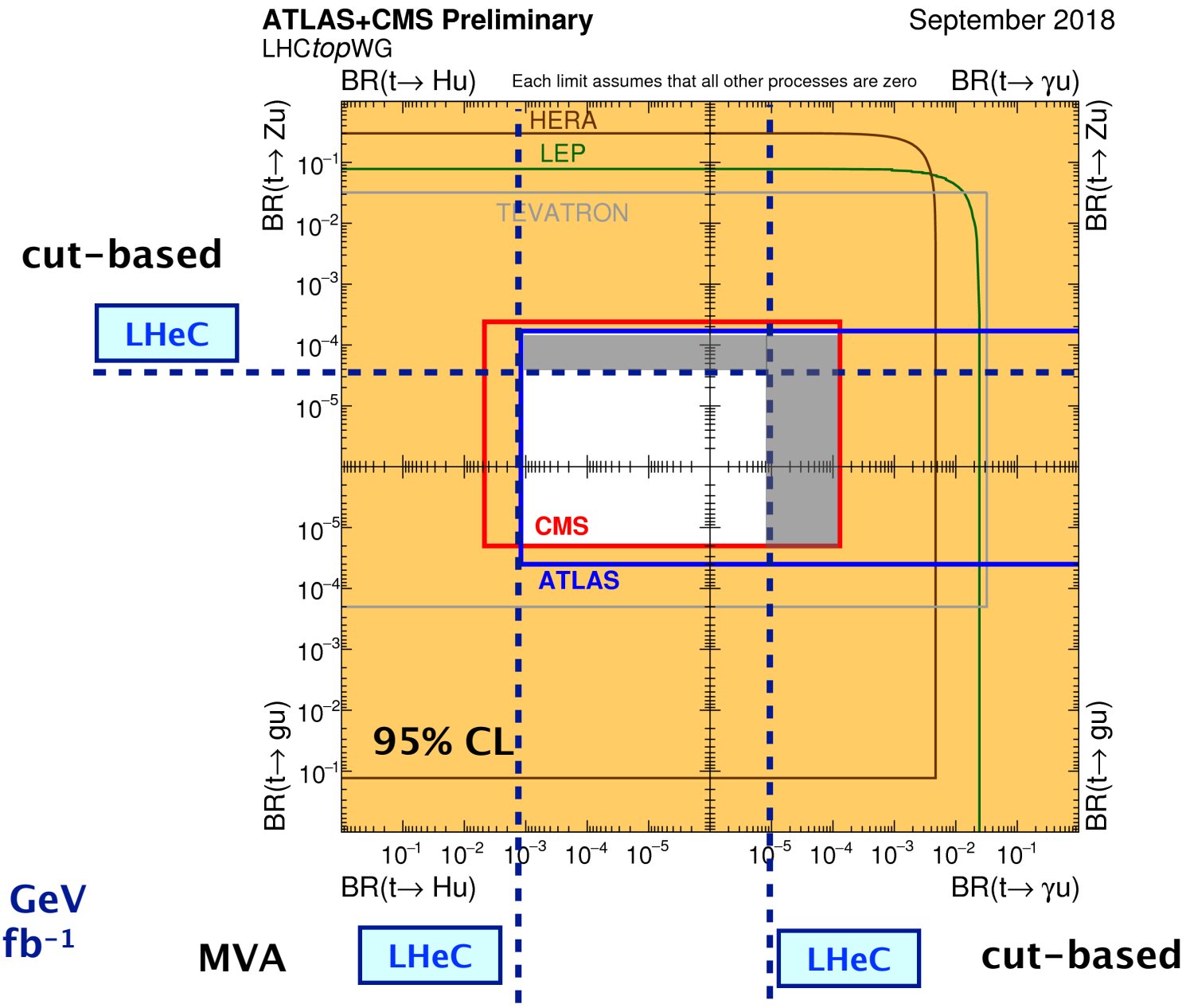
<0.0002 (2ab^{-1})

→ improves HL-LHC sensitivity

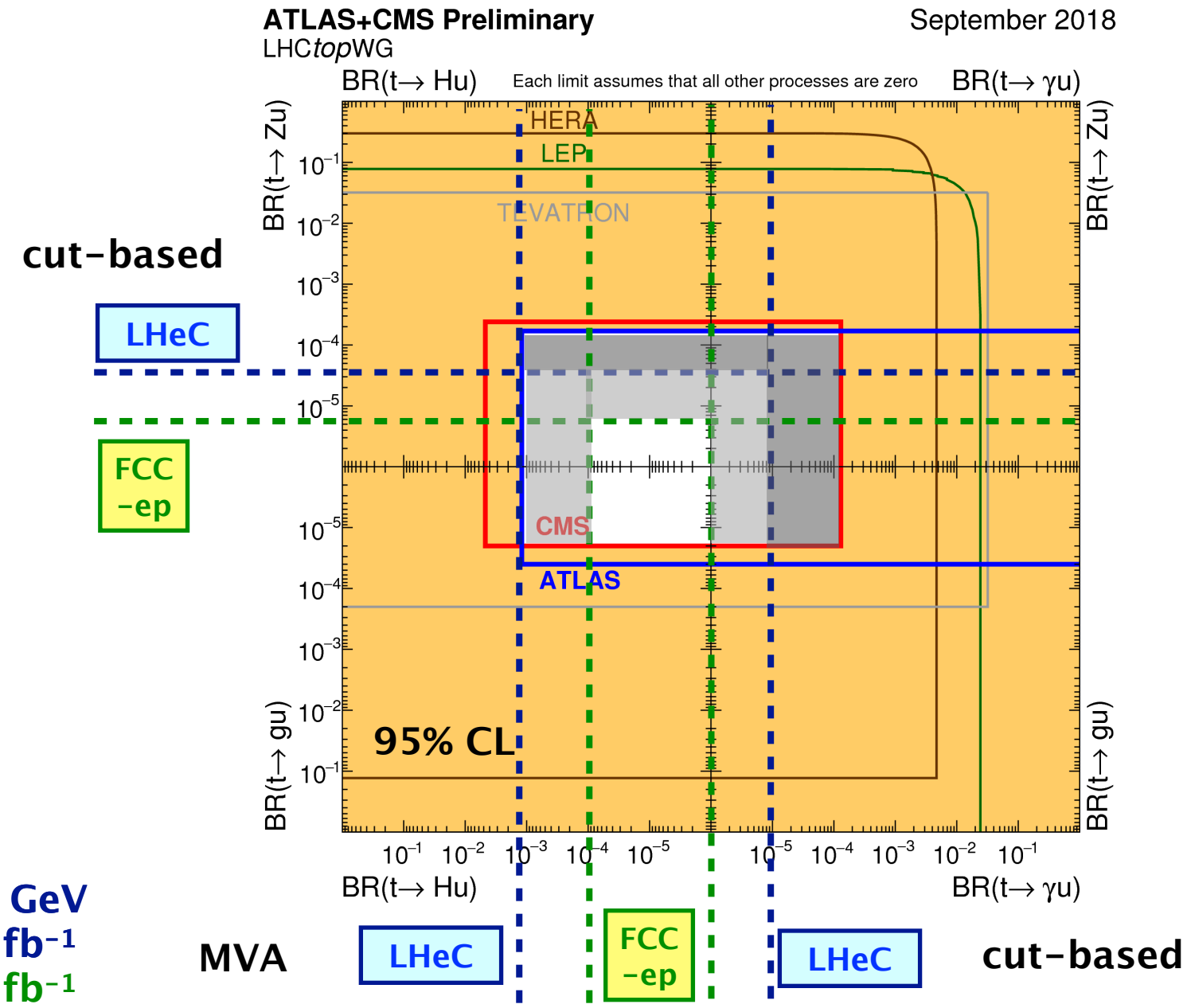
FCNC Branching Ratios at Colliders



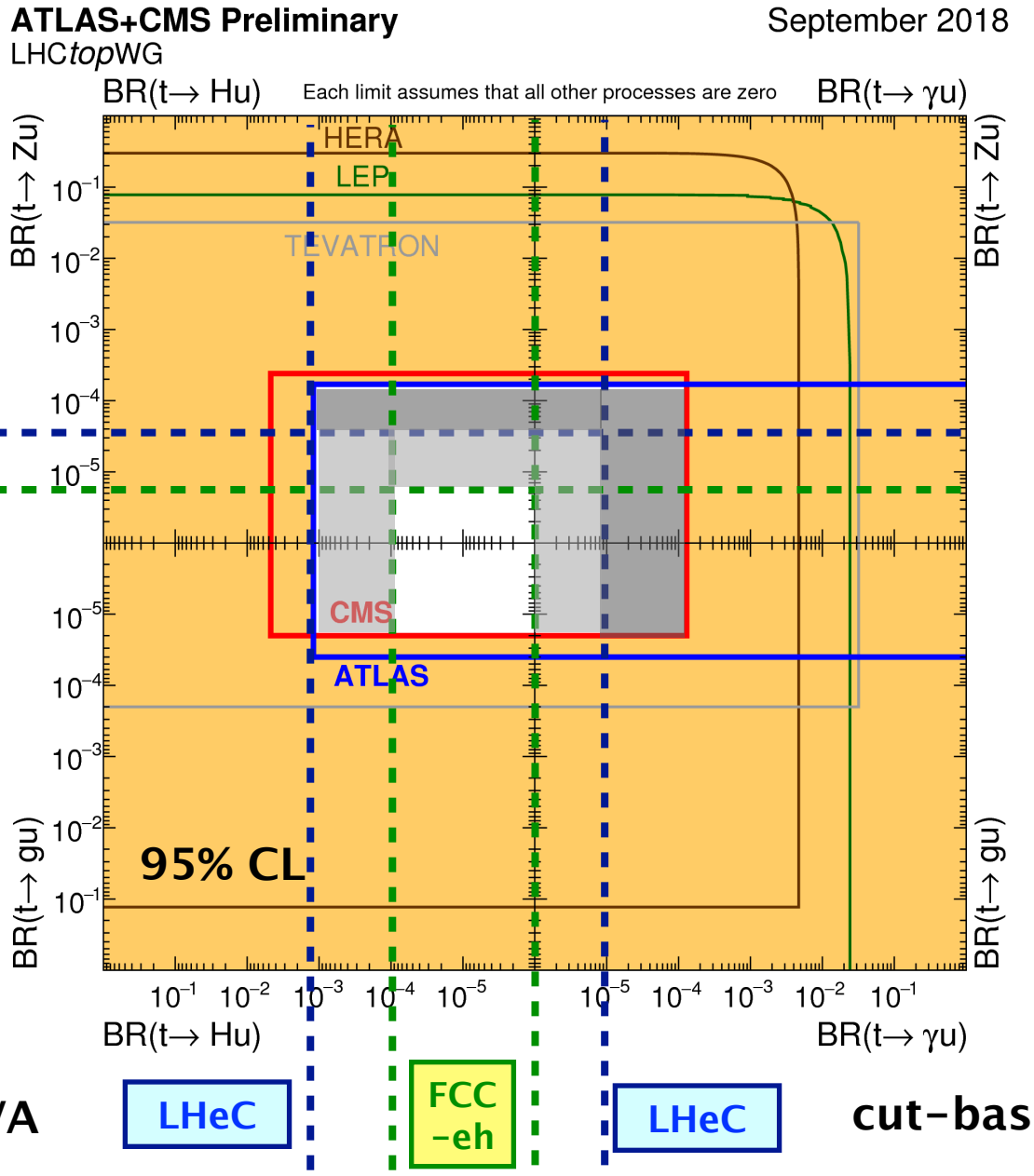
FCNC Branching Ratios at Colliders



FCNC Branching Ratios at Colliders



FCNC Branching Ratios at Colliders



- improve limits on BR(t→γu), BR(t→Zu), BR(t→Hu) considerably

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}
2000 fb^{-1}