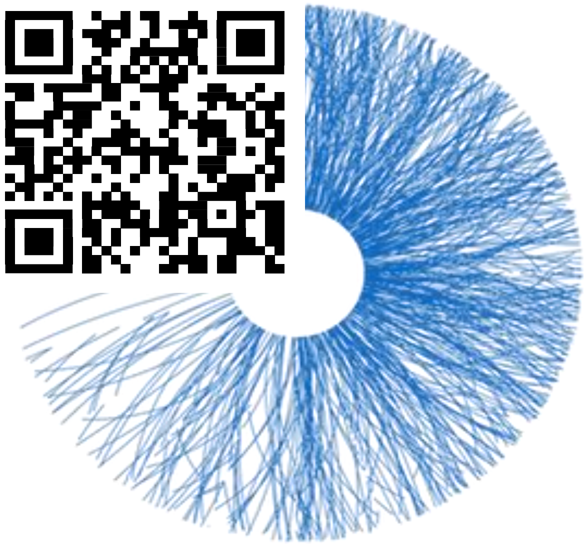


ALICE Upgrade Status and Plans

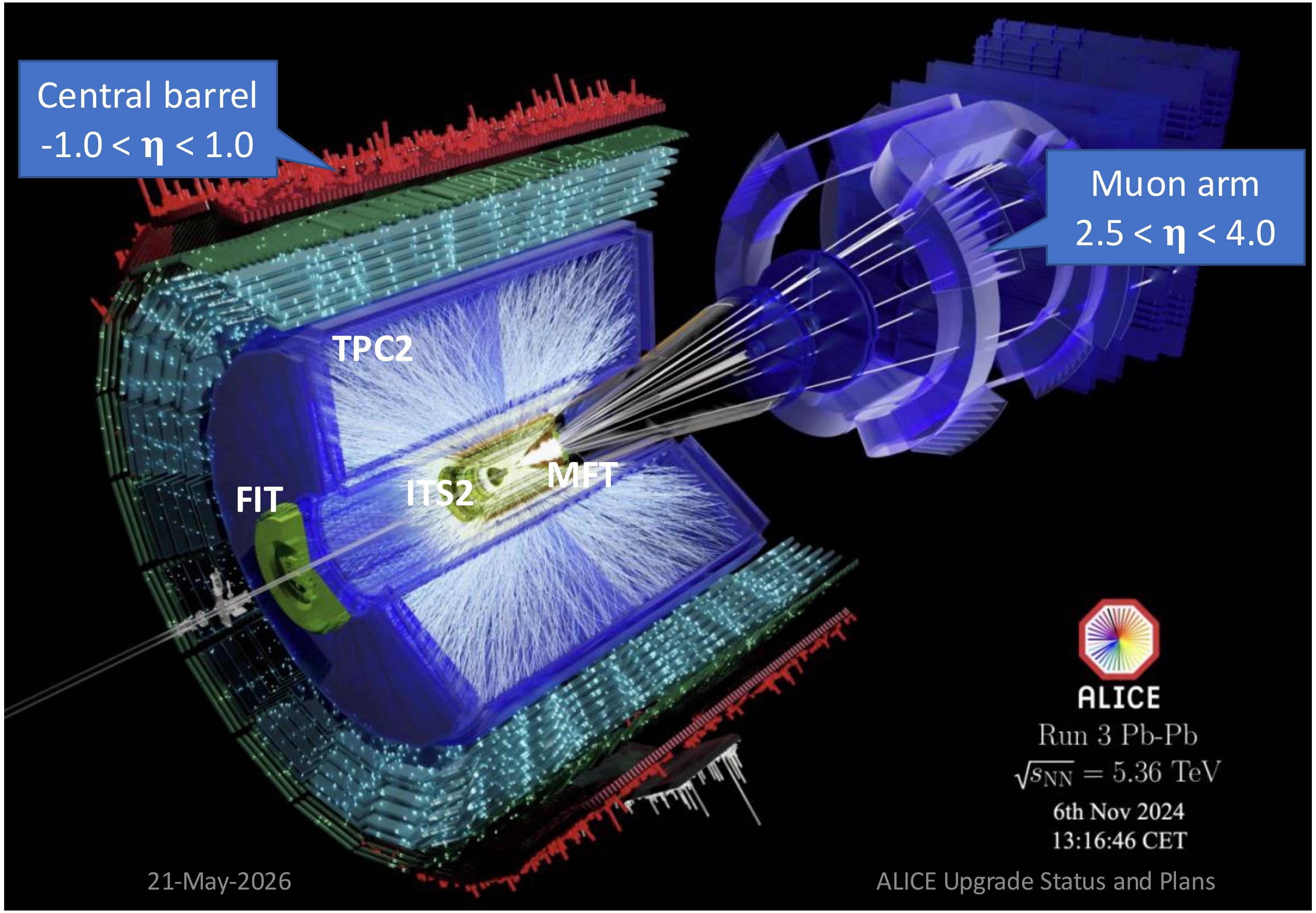
Jacek Otwinowski

Institute of Nuclear Physics (Polish Academy of Sciences)

on behalf of the ALICE Collaboration

A Large Ion Collider Experiment (ALICE)

Excellent particle identification and tracking in the broad momentum range!



LHC Run 1 (2009-2013), Run 2 (2015-2018) and Run 3 (2022-2026)

Collision systems:
pp, p-Pb, pO, OO, Ne-Ne, Xe-Xe and Pb-Pb

Massive upgrade during LS2 (2019-2021):
ITS2, TPC2, MFT, FIT …

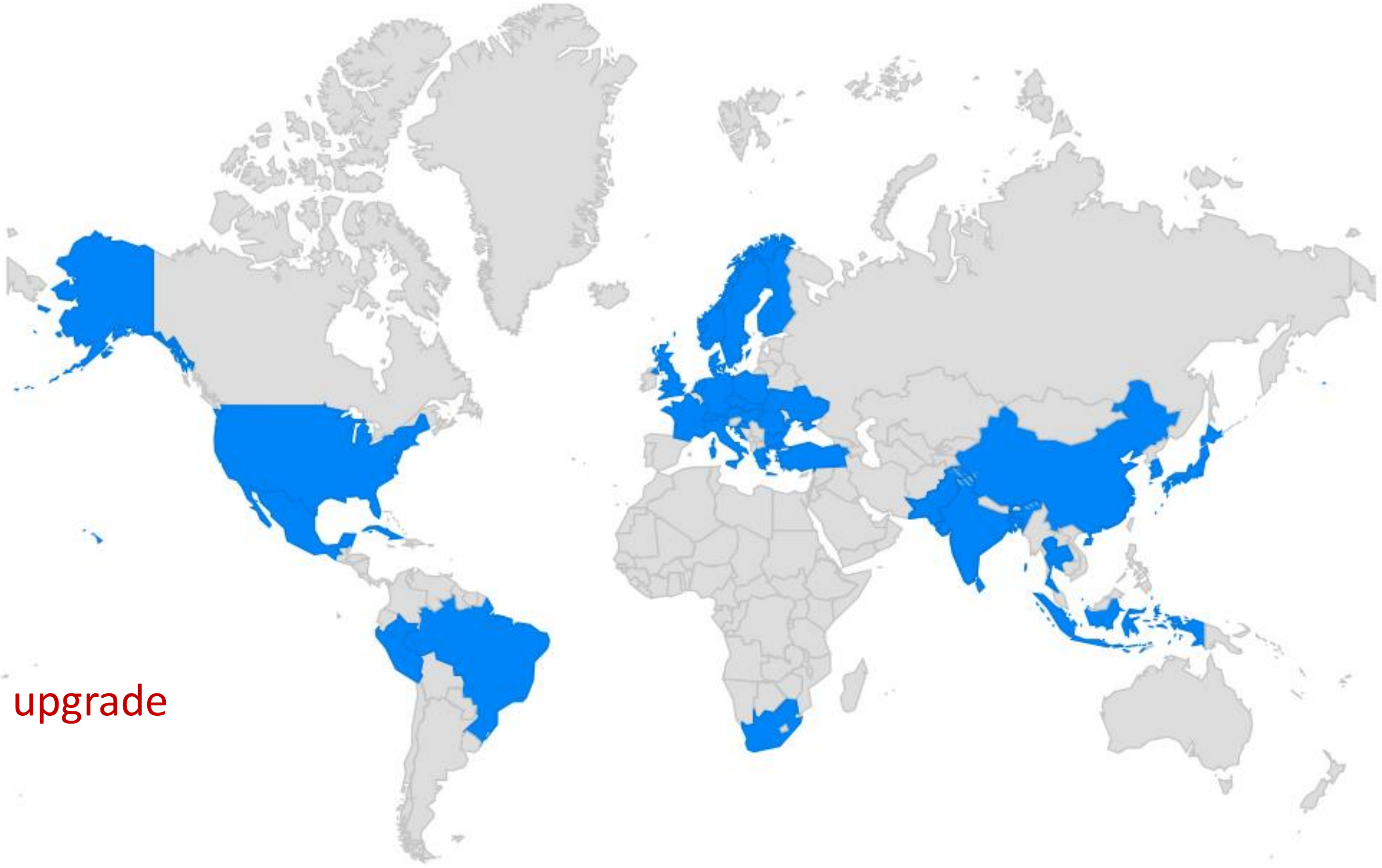
x1000 (x50) more pp (Pb-Pb) events already recorded in Run 3 than in Run 1 & Run 2 (analyses are ongoing)

More than 500 ALICE *papers* so far…

Eur. Phys. J. C 84 (2024) 813
JINST 19 (2024) P05062

ALICE Collaboration

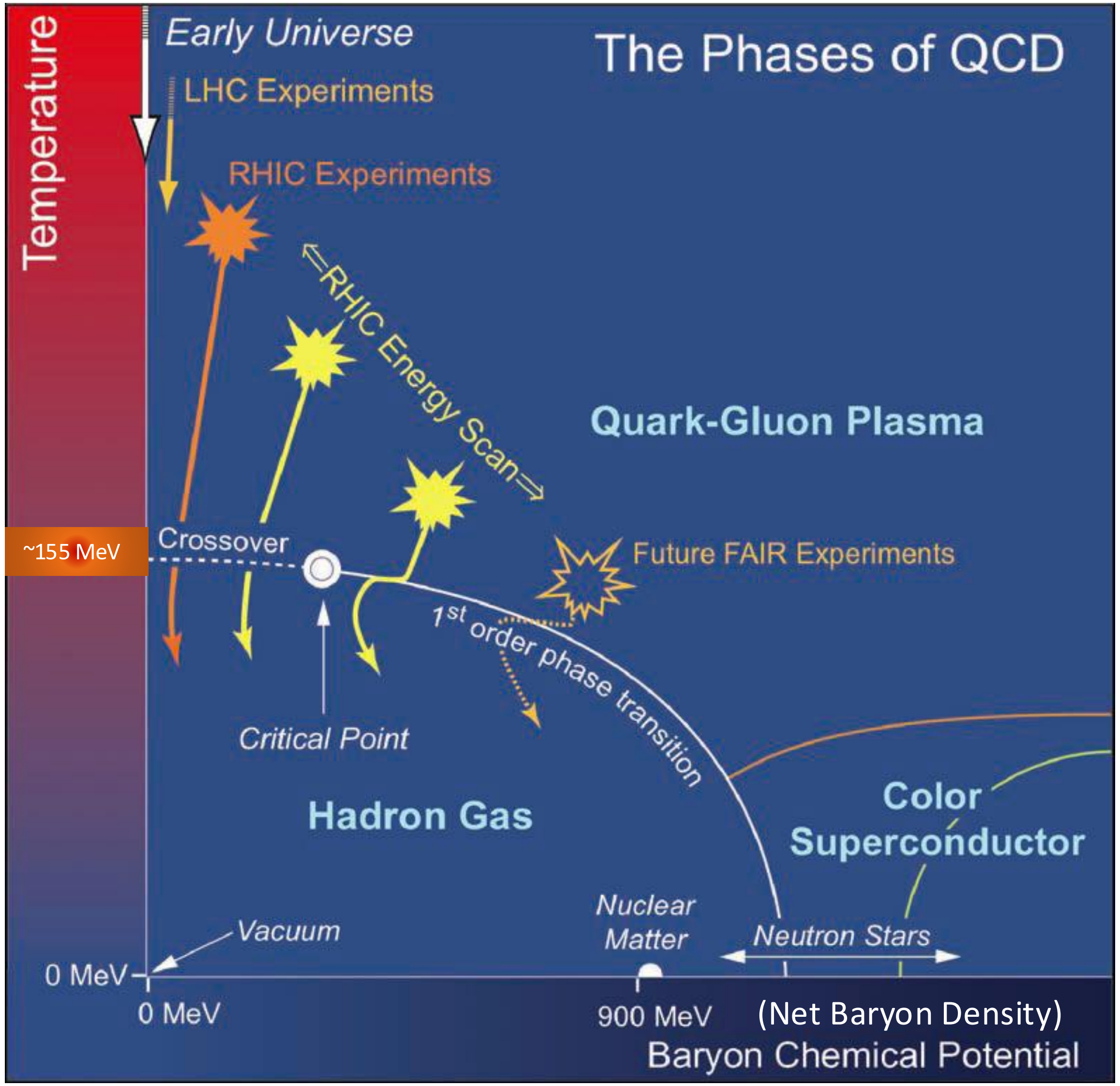
38 countries, 167 institutes, 1873 members



ALICE-PL Consortium:
IFJ PAN, NCBJ, WUT, AGH and UŚ
~6% ALICE members

Involved in critical operations and upgrade projects: FIT, FoCal, ALICE 3 FD…

ALICE purpose



- Properties of QCD matter at extreme conditions
- Characterization of quark-gluon plasma (QGP)
- … also dark matter searches

Deconfinement predicted by Lattice QCD at ~155 MeV (μ_B = 0)

A. Bazavov et al. Phys. Lett. B 795 (2019) 15

Probing QCD Phase Diagram in Laboratory

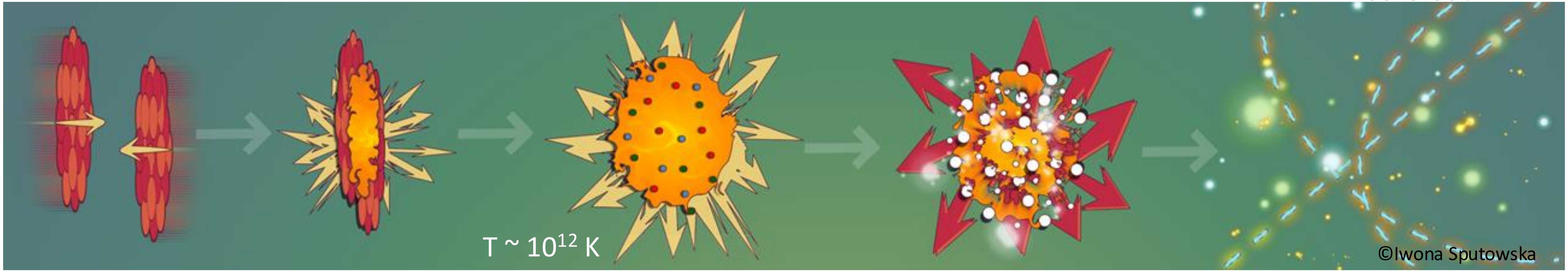
ALICE

Measurements in A-A and reference p-p and p-A collisions

→ Influence of initial- and final-state effects on particle production

Stages of A-A collision (very challenging for modeling)

Initial PDFs | Little Big Bang | Quark-Gluon Plasma | Collective expansion & hadronization | Chemical & kinematic Freeze-out

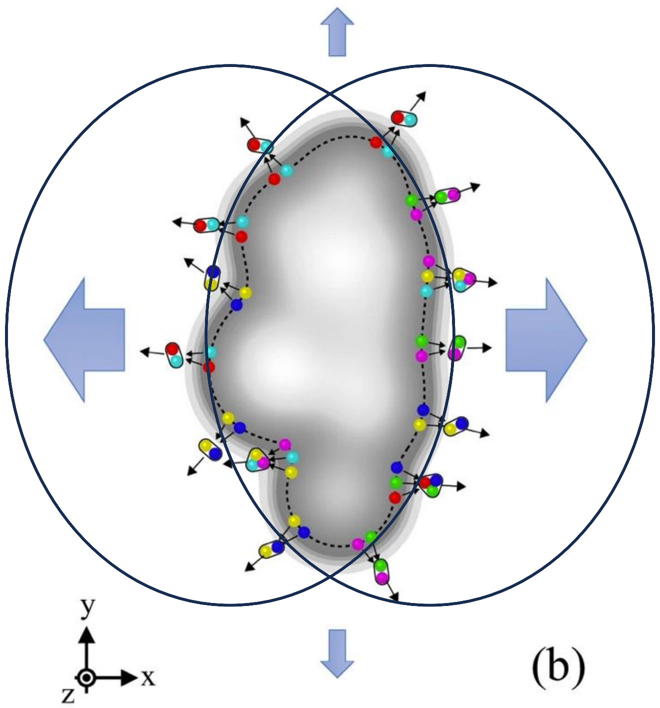


Time

Observation of partonic flow

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + \sum_n 2v_n(p_\mathrm{T})\cos(n\varphi - n\Psi_n)$$

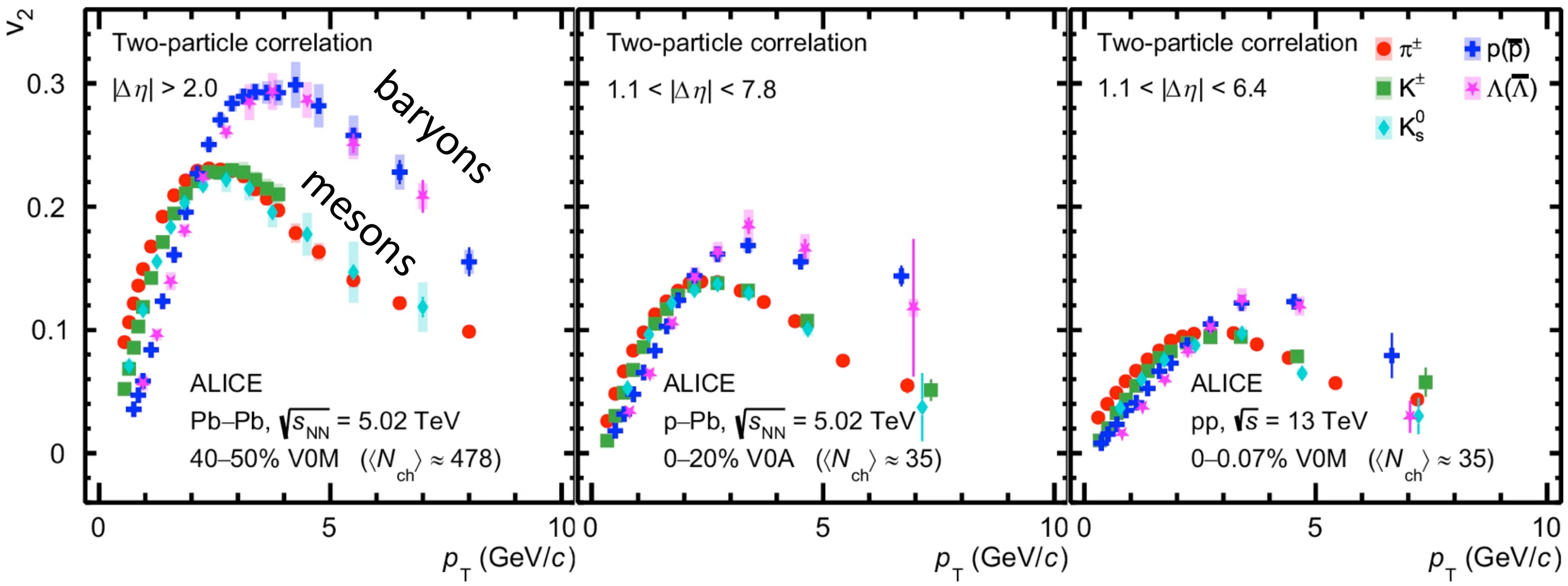
pressure gradient → azimuthal anisotropy in particle distribution



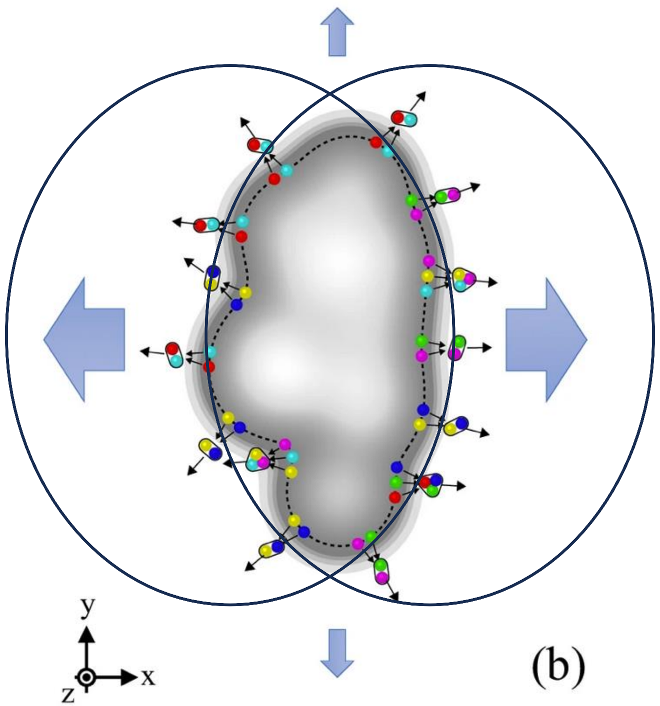
Observation of partonic flow

ALICE, Nature Commun. 17 (2026) 2585

$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2v_n(p_T)\cos(n\varphi - n\Psi_n)$$



pressure gradient → azimuthal anisotropy in particle distribution



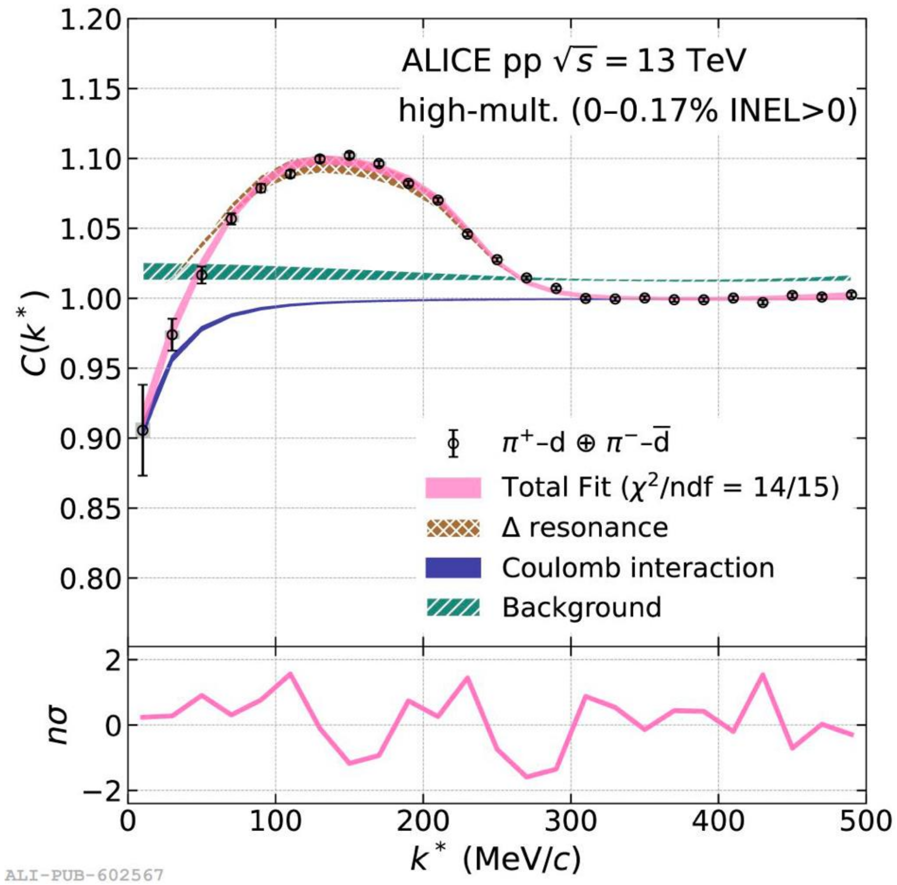
Low p_T: mass ordering

Intermediate p_T: baryon-meson grouping and splitting

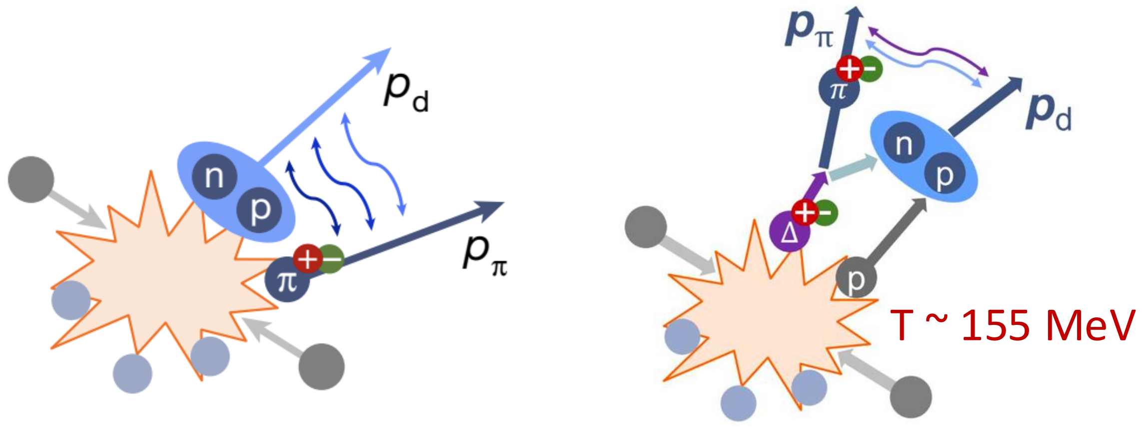
→ quark coalescence and partonic flow

Production of (anti)deuterons in hot plasma

ALICE, Nature 648 (2025) 306



How can weakly bound nuclei emerge from the hot QGP?



Direct production

Δ resonance assisted fusion

pion-deuteron fetoscopy correlations

$$C(k^*) = \mathcal{N}\,[N_{\mathrm{same}}(k^*)/N_{\mathrm{mixed}}(k^*)].$$

~90% (anti)deuterons produced in nuclear reactions following the decays of short-lived resonances

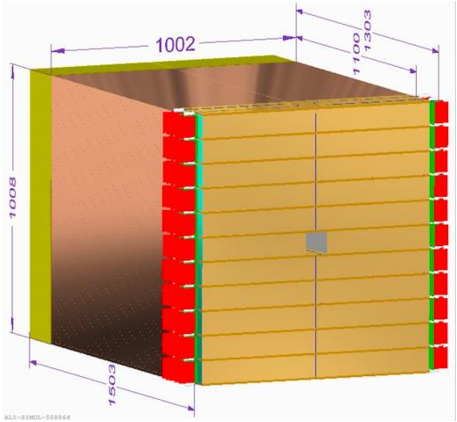
→ Modeling of (anti)nuclei production hadronic collisions, cosmic rays or dark-matter decays

ALICE Detector Upgrades

LS3: Forward Calorimeter (FoCal) & Inner Tracking System 3 (ITS3)

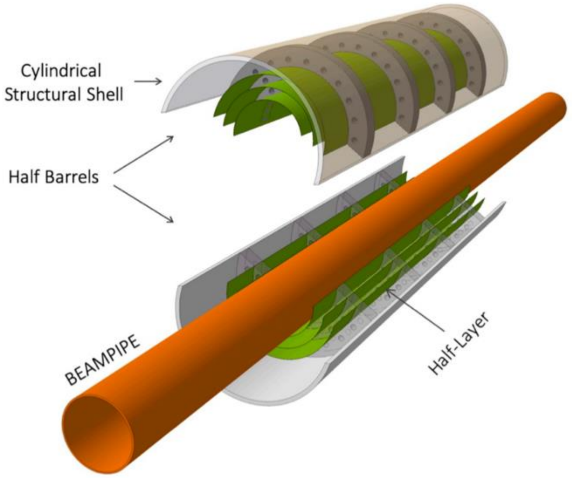
LS4: New heavy-ion detector (ALICE 3)

FoCal

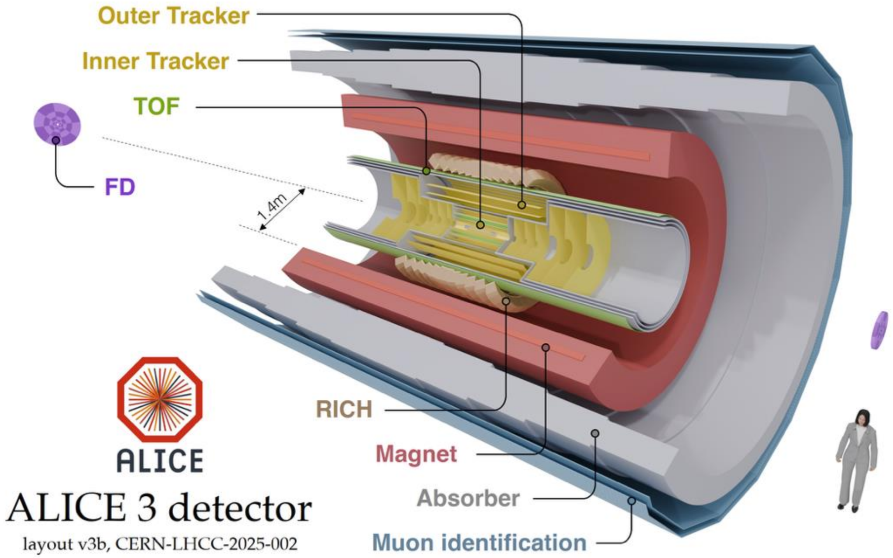


TDR: CERN-LHCC-2024-004

ITS3



TDR: CERN-LHCC-2024-003



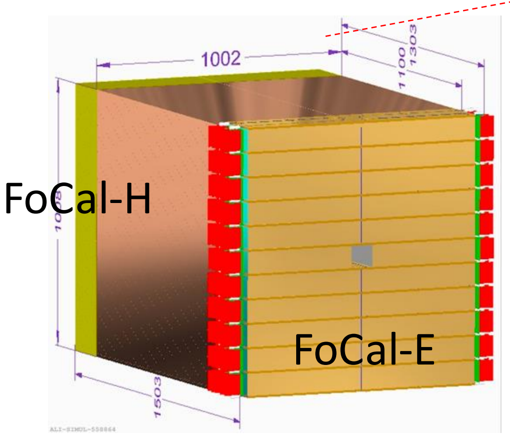
ALICE3 LoI: CERN-LHCC-2022-009
Scoping document: CERN-LHCC-2025-002

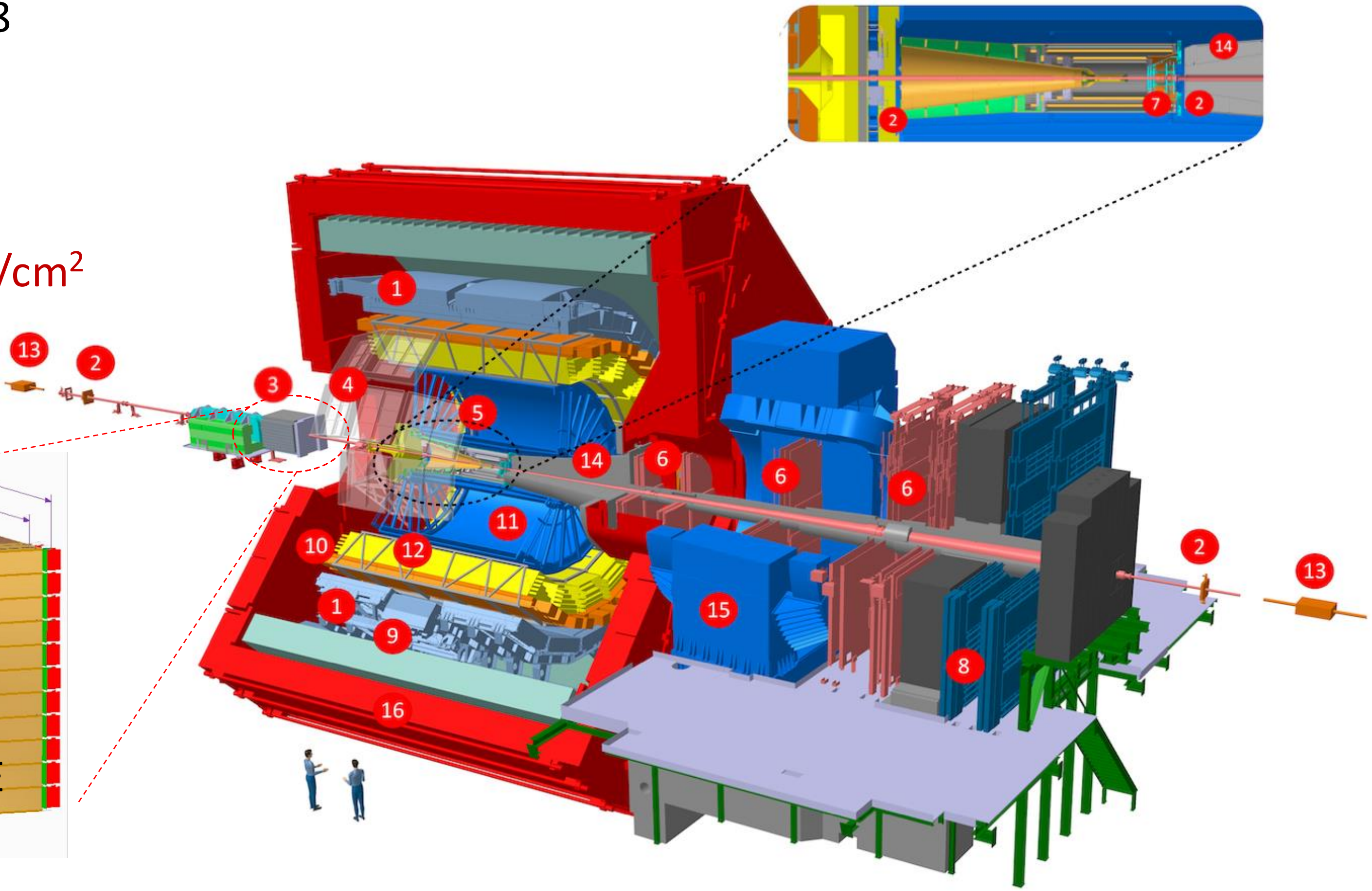
Forward Calorimeter (FoCal)

IFJ PAN & WUT key players!

Electromagnetic (FoCal-E) and hadronic (FoCal-H) calorimeter
Acceptance: $3.2 < \eta < 5.8$

TID ~ 3.5 Mrad
NIEL ~ 7×10^{13} 1-MeV n_{eq}/cm^2





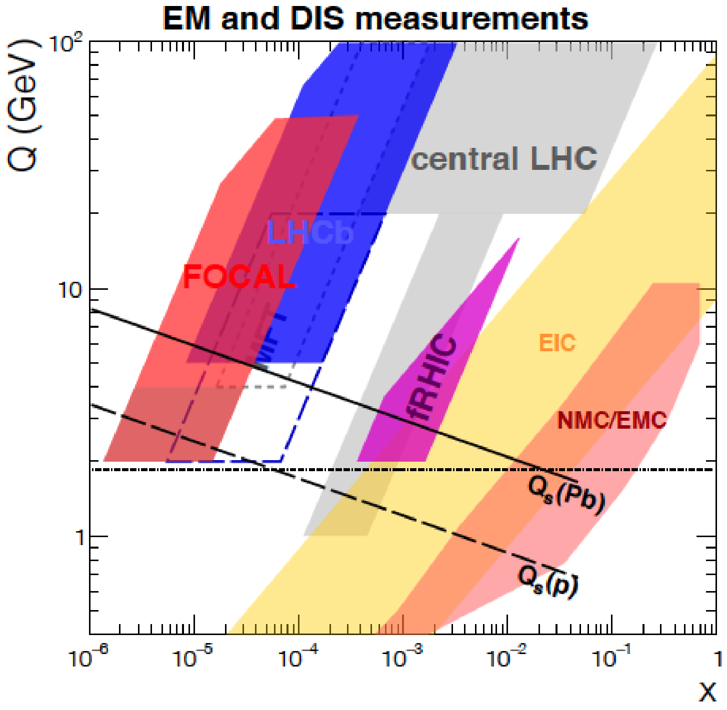
1. **EMCAL** | Electromagnetic Calorimeter
2. **FIT** | Fast Interaction Trigger
3. **FoCal** | Forward Calorimeter (in front of compensator magnet)
4. **HMPID** | High Momentum Particle Identification Detector
5. **ITS** | Inner Tracking System
6. **MCH** | Muon Tracking Chambers
7. **MFT** | Muon Forward Tracker
8. **MID** | Muon Identifier
9. **PHOS/CPV** | Photon Spectrometer
10. **TOF** | Time Of Flight
11. **TPC** | Time Projection Chamber
12. **TRD** | Transition Radiation Detector
13. **ZDC** | Zero Degree Calorimeter
14. **Absorber**
15. **Dipole Magnet**
16. **L3 Magnet**

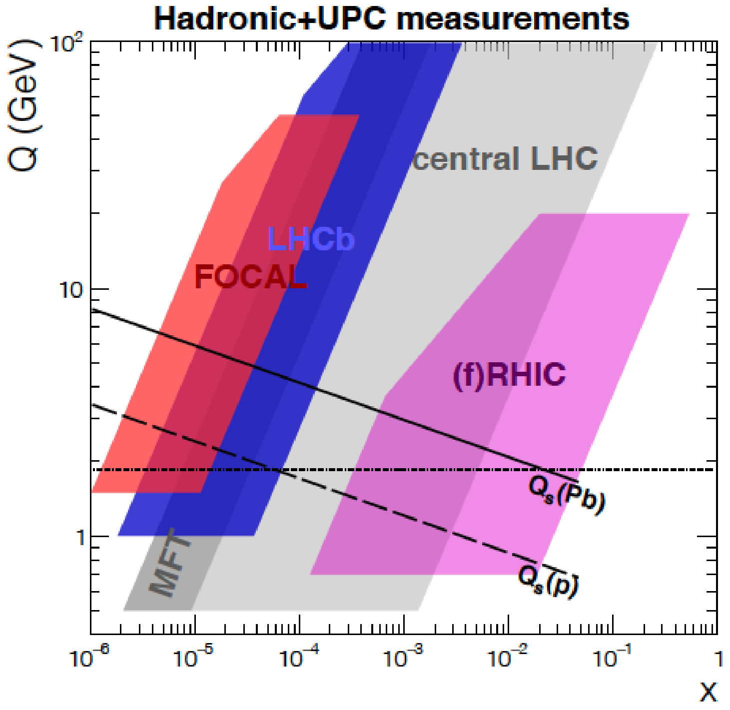
CERN-LHCC-2024-004

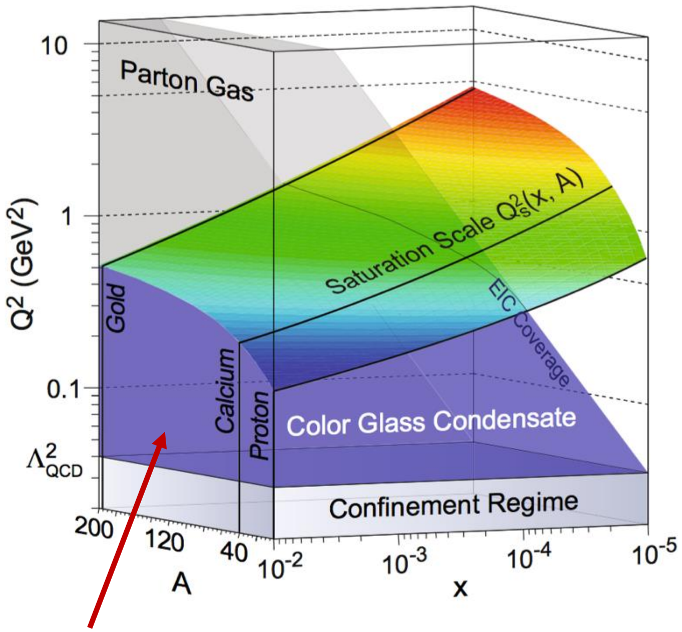
FoCal physics motivation

Constrain PDFs in the unique kinematic range (gluon saturation?)

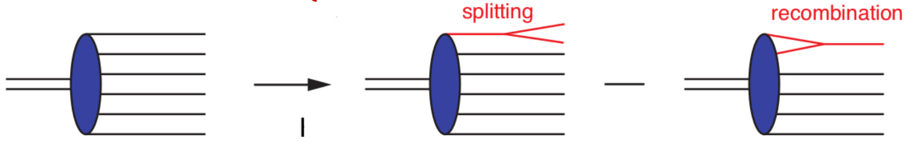
Measurements of isolated-γ, DY, neutral mesons, quarkonia, and jets







non-linear QCD evolution

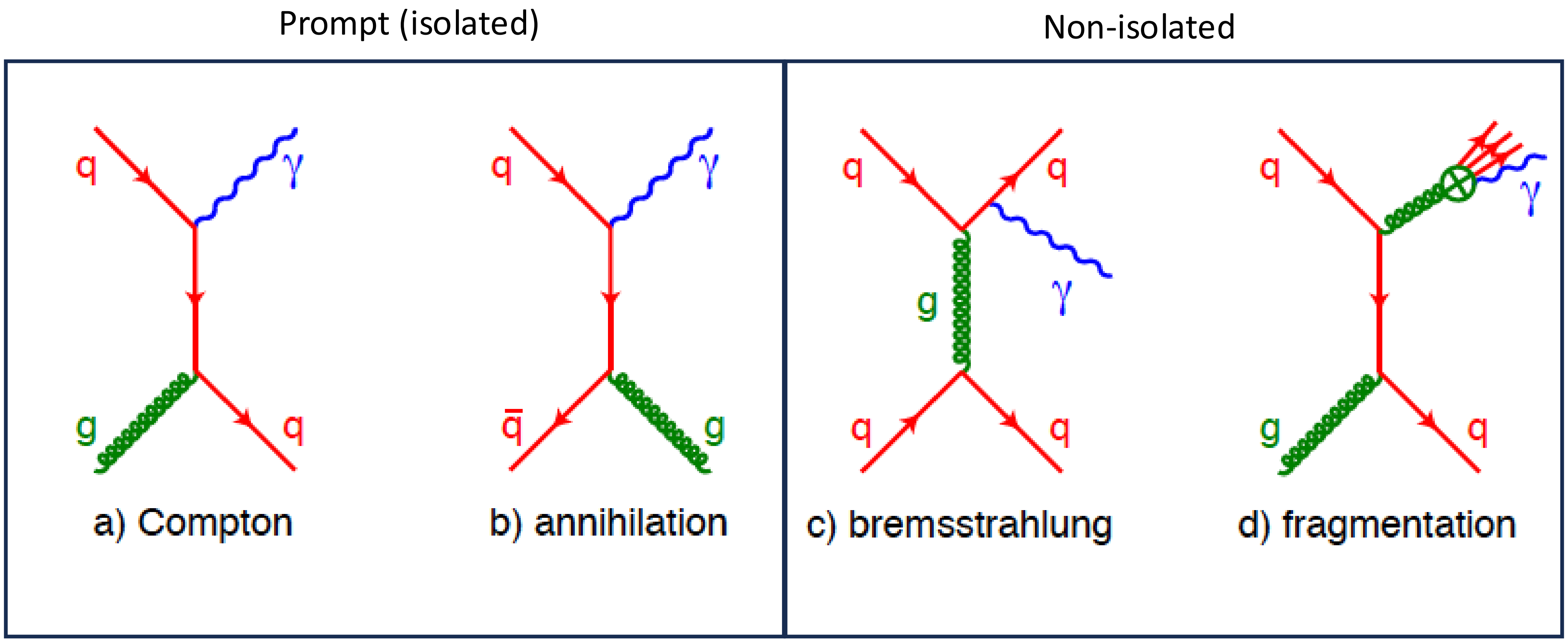


$$x = \frac{p_T}{\sqrt{s}} e^{\pm\eta}$$

$$Q^2_{s,A}(x) \propto A^{1/3} x^{-\lambda}$$

[ALICE-PUBLIC-2023-001]()

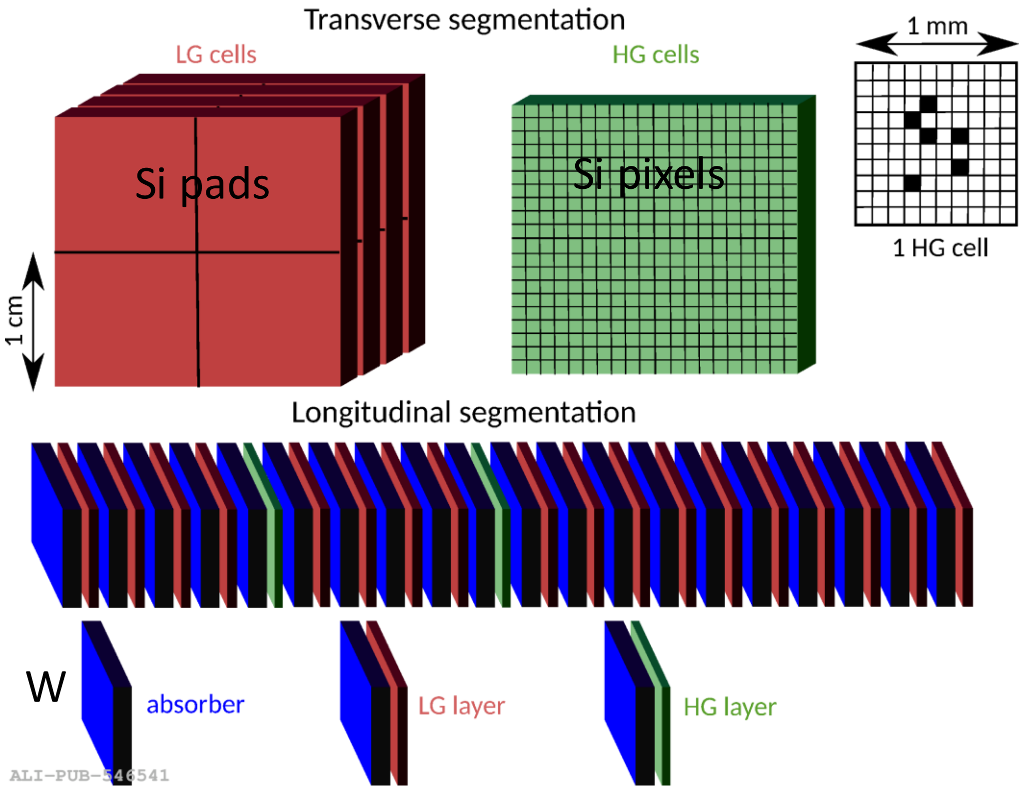
Isolated photon measurement challenges

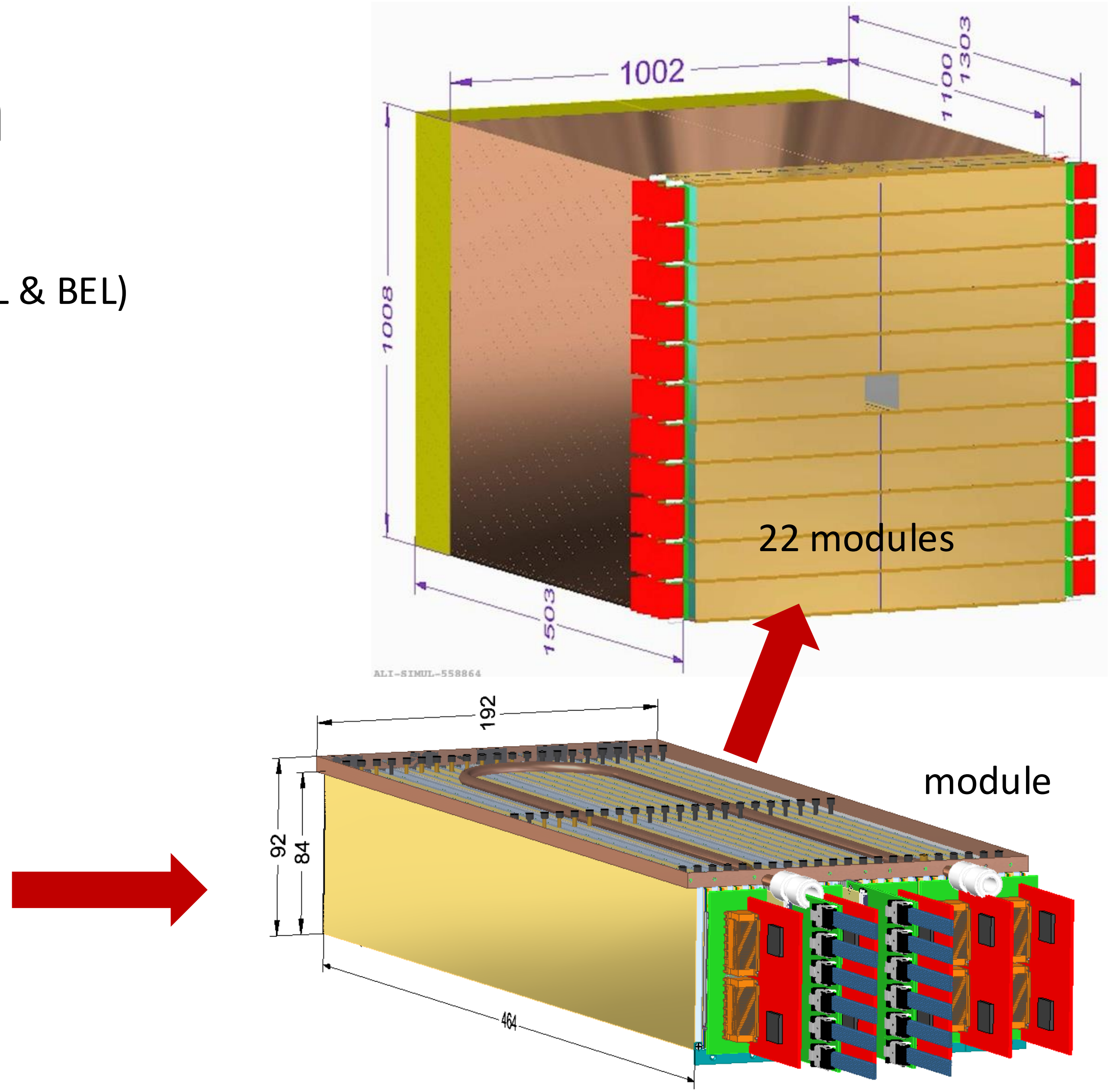


FoCal-E: Discrimination of prompt and decay photon showers
FoCal-H: Suppression of bremsstrahlung and fragmentation γ

FoCal-E unique design

- Si+W electromagnetic calorimeter (~20 X_0)
- Si pads: 18 layers, 1 cm pitch (Japan - HPK, India - SCL & BEL)
- Si pixel: 2 layers, ~ 30 μm (CMOS MAPS/ALPIDE)





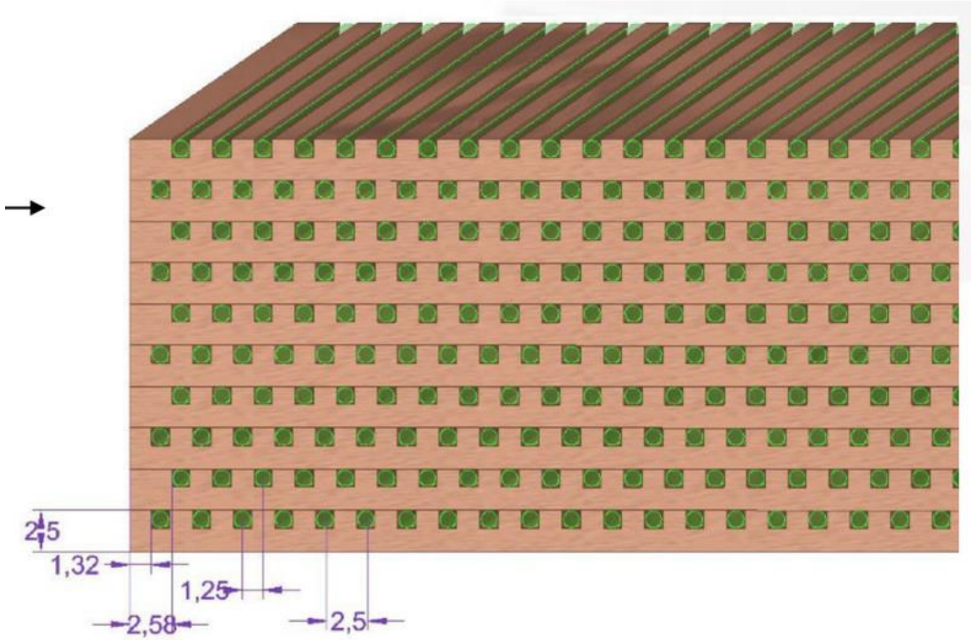
CERN-LHCC-2024-004

FoCal-H design

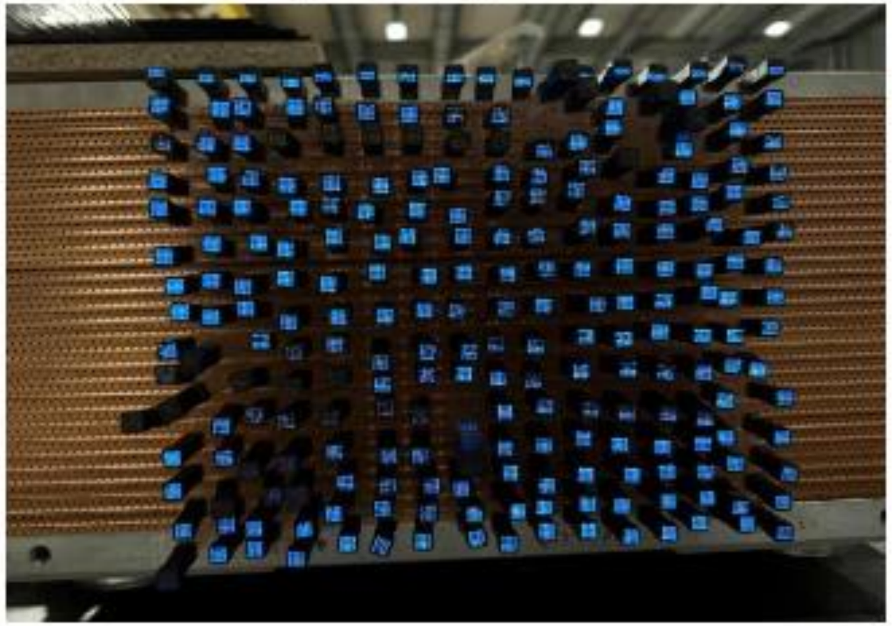
- Spaghetti calorimeter: Cu + scintillation fibers
- SiPMs readout (~10000 ch.)
- Thickness ~1 m (~5 x λ_{int})

SiPM (6x6mm^2) readout

grooved Cu plates



Prototype with final design



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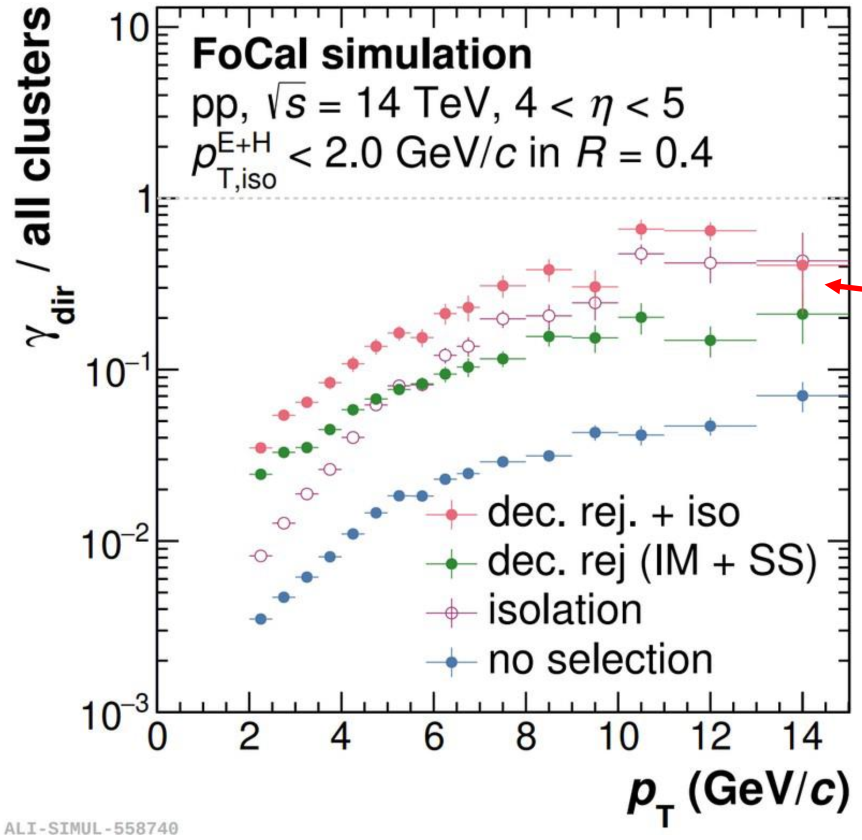
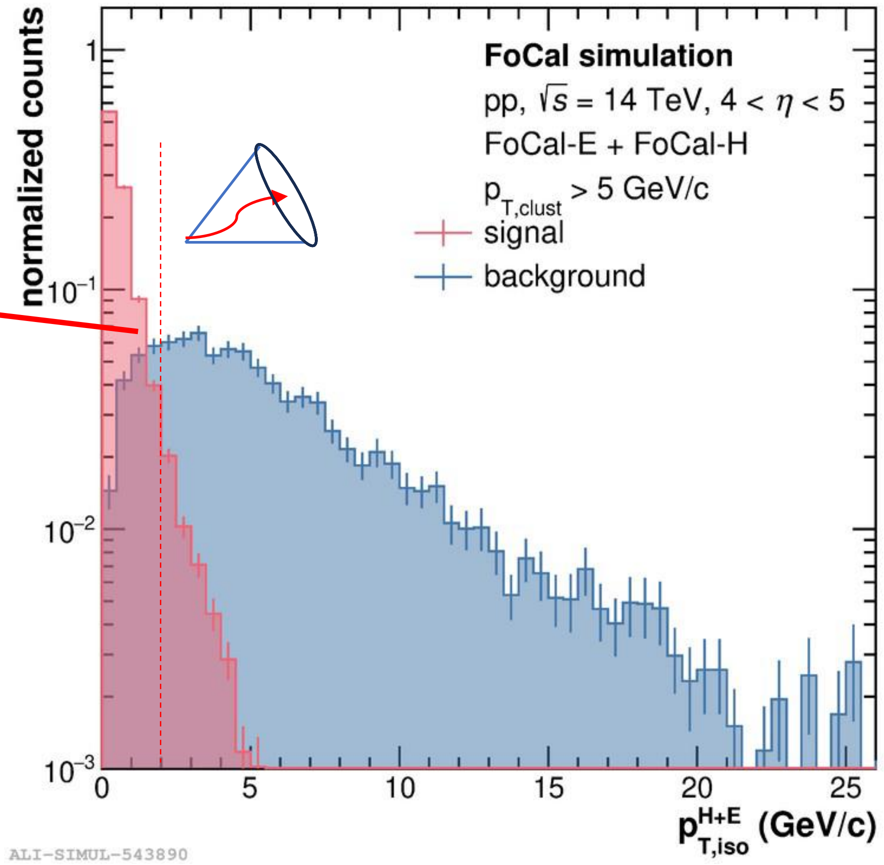
Prompt γ in simulations

Prompt γ isolation performance





ALICE-PUBLIC-2023-004

FoCal status

FoCal-E Pixels
- 7 chip string mass production
- 15 chip strings prototyping

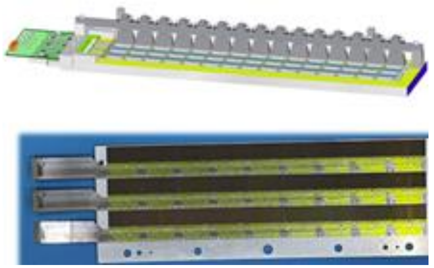
FoCal-E Pads
- Final HPK sensors production (end 2026)
- SCL & BEL sensors prototyping

FoCal-E mechanics and cooling
- Tungsten plates Q1/2027
- FoCal-E cooling approved for production

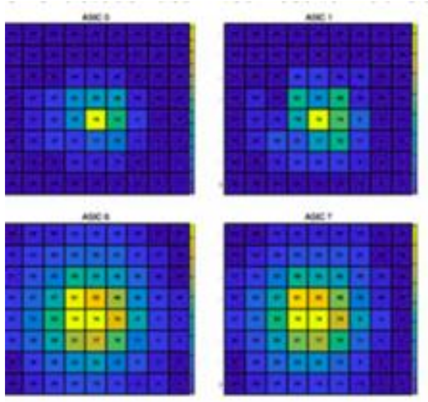
FoCal-H
- SiPM Peltier cooling prototyping
- Grooved plate prototype testing

Final electronics (middle 2026)

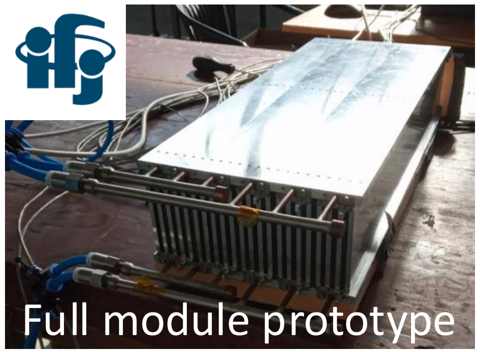
FoCal-E: Pixel string assembly

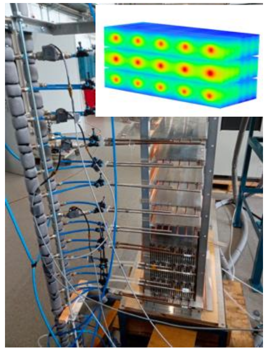


SCL Si-pads sensor testing

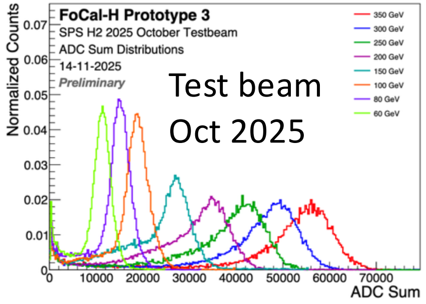


FoCal-E: cooling system





FoCal-H testing



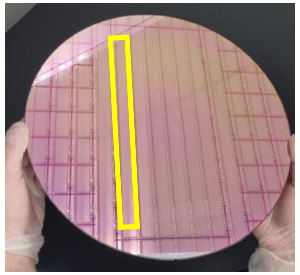
FoCal-E integration in IFJ PAN (June 2027 – March 2028)

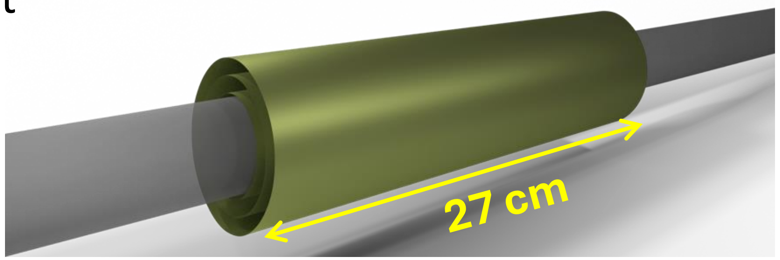
ITS3 design

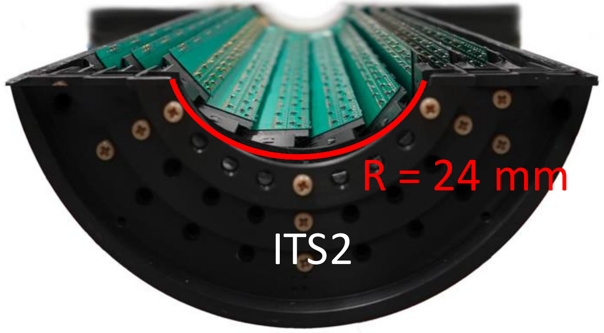
Cutting edge technology for the future Higgs/EW/Top Factories (*Physics Briefing Book* [*arXiv.2511.03883*](https://arxiv.org/abs/2511.03883))

Wafer-scale cylindrical stitched 65 nm CMOS Monolithic Active Pixel Sensors (MAPS)

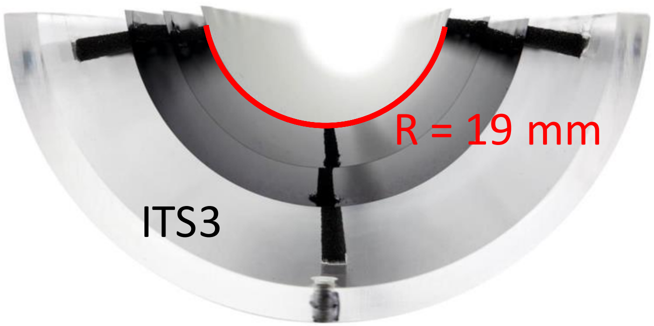
- 50 μm thin, 20.8 x 22.8 μm pitch
- Very low material budget



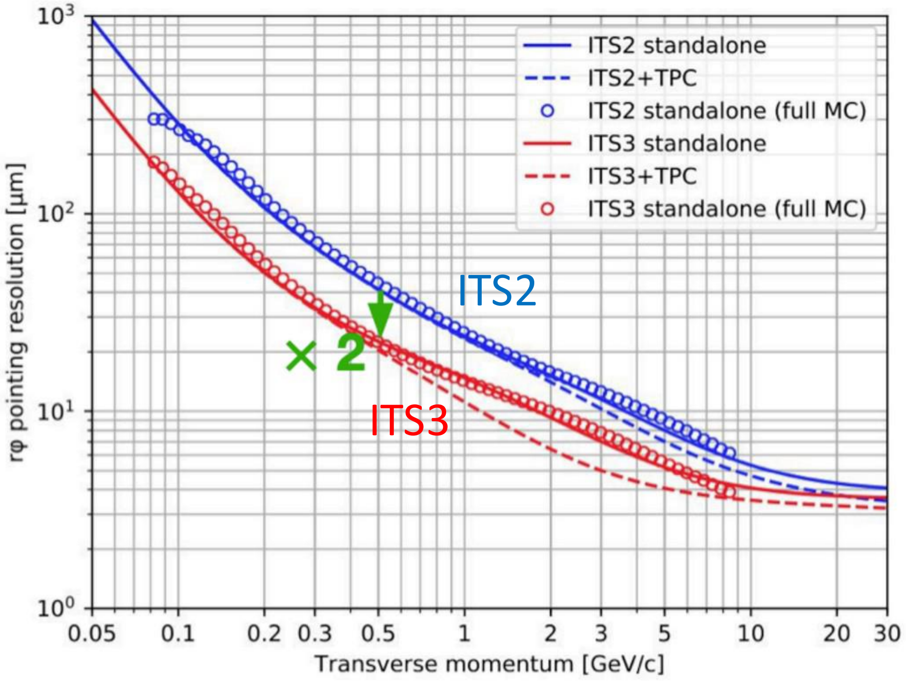




0.36% X_0/layer



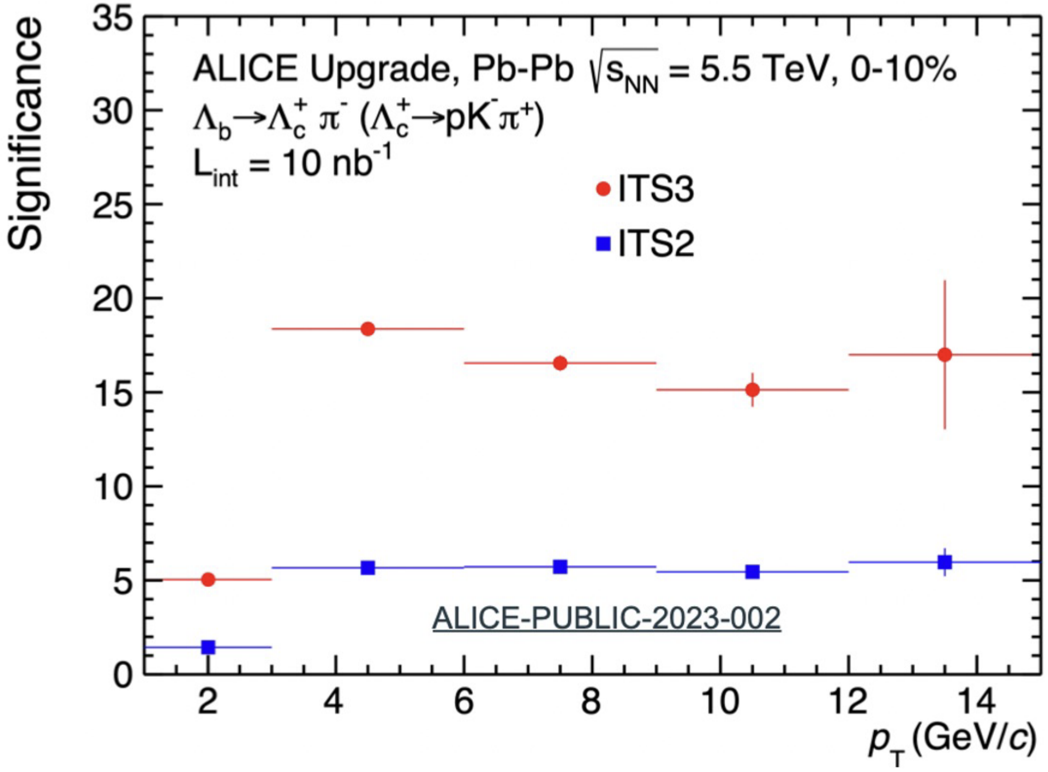
0.09% X_0 /layer



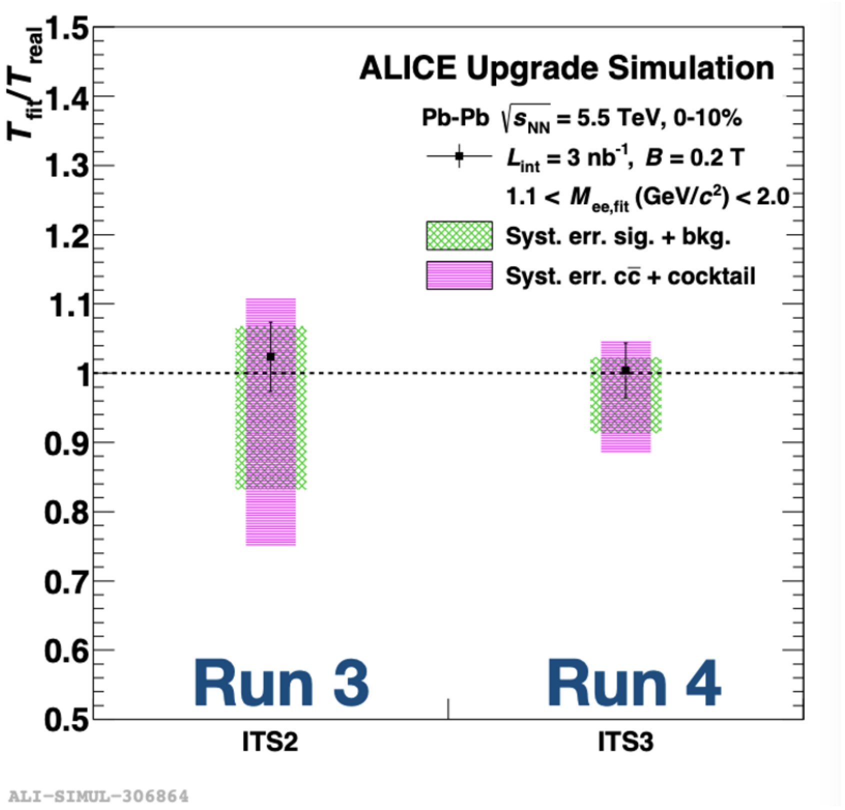
ALICE-PUBLIC-2023-002

Physics projections

Significance of Λ_b



Inv. slope T from thermal dN/dM_{ee}



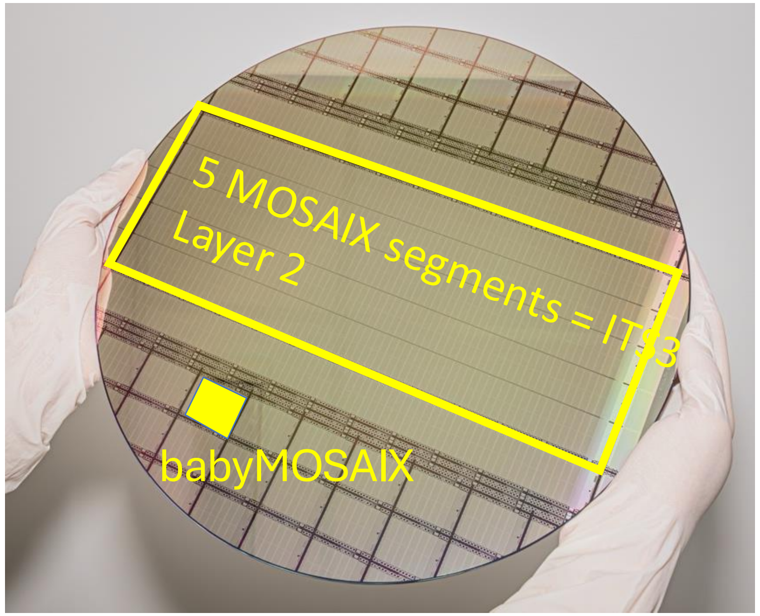
Improved performance for heavy flavour and dielectron measurements

Physics performance: ALICE-PUBLIC-2023-002

ITS3 status

Final sensor: MOnolithic Stitched Active pIXel (MOSAIX)

- 25.9 cm x 10.5 cm x 50 µm
- Engineering run 2 (ER2) delivered in Feb 2026
- Testing ongoing



ITS3 (engineering model 4)

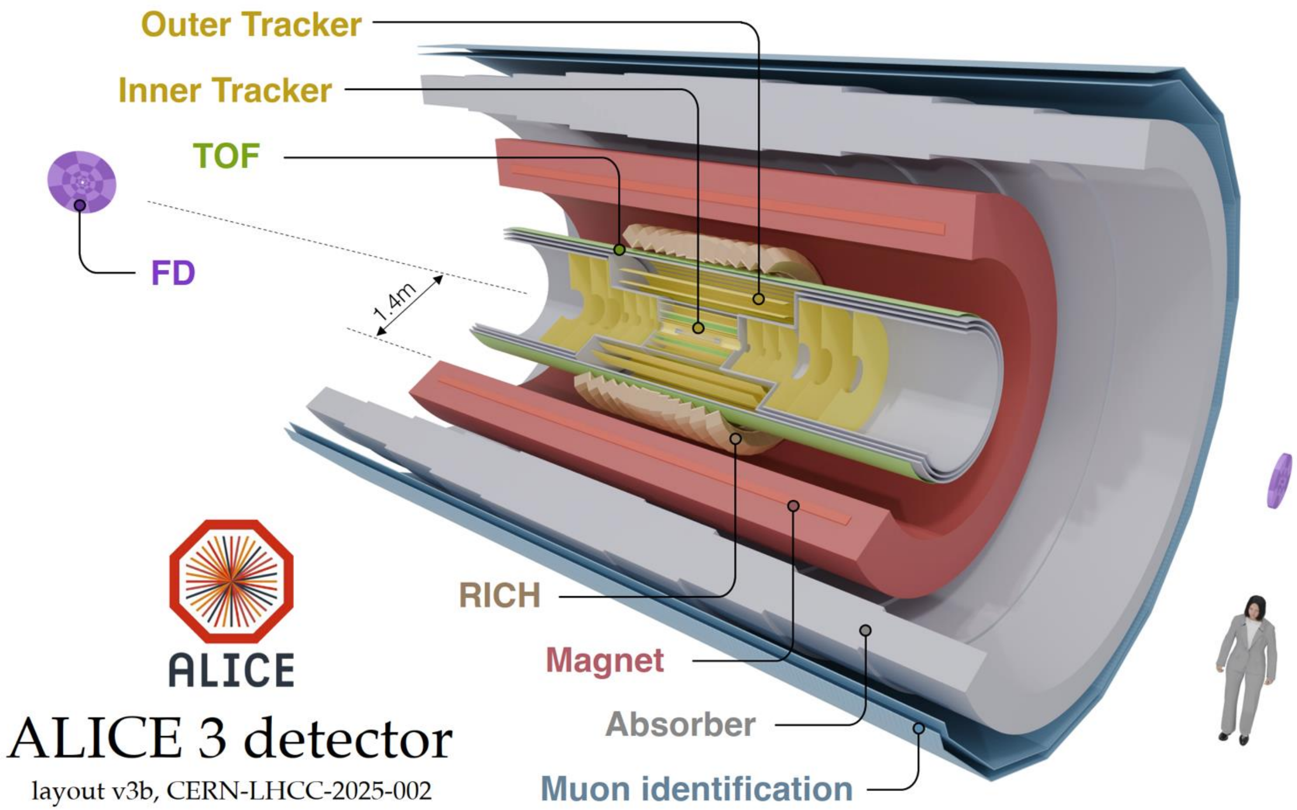
- Dummy silicon with nominal dimensions
- Long-term stability tests with air-cooling

ALICE 3 concept

Novel and innovative detector concept

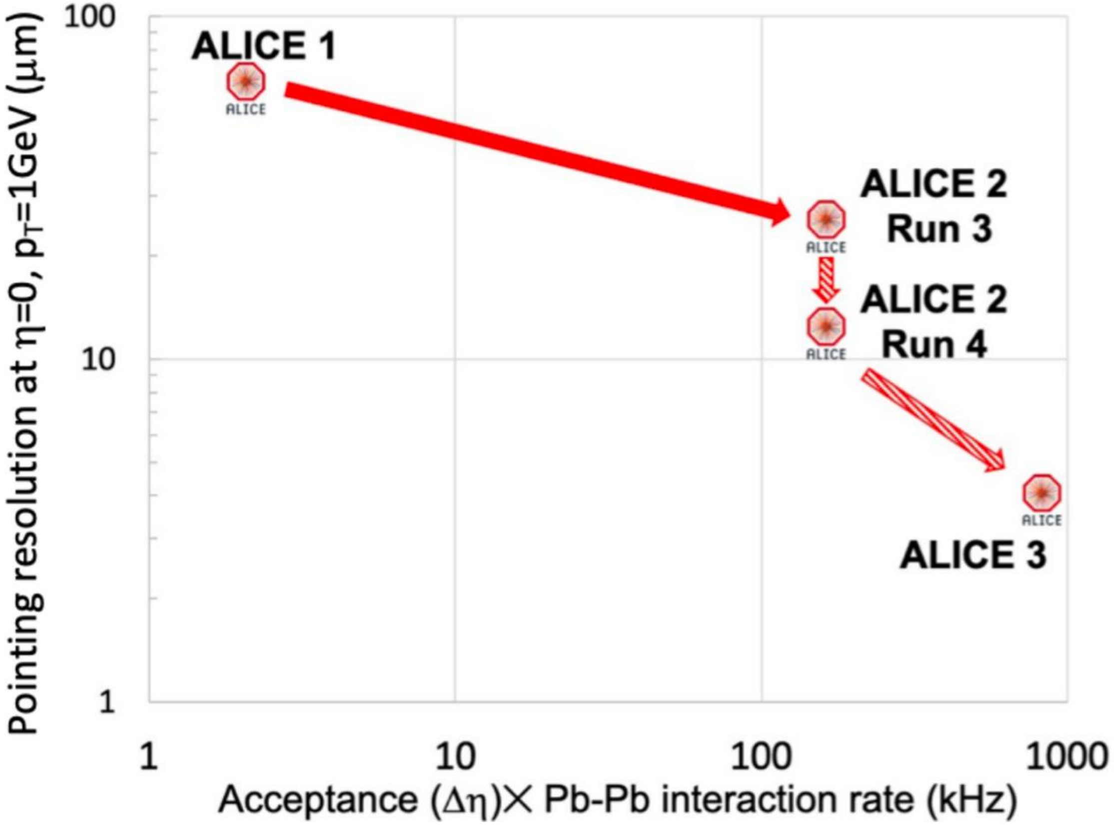
- Compact and ultra-light silicon pixel trackers
- Retractable vertex detector (IRIS)
- Extensive particle identification TOF, RICH, MID
- Forward Detector (luminosity and centrality)
- Large acceptance
- Superconducting magnet system, B = 2T
- Continuous readout and online processing

Detector layout still under discussion!

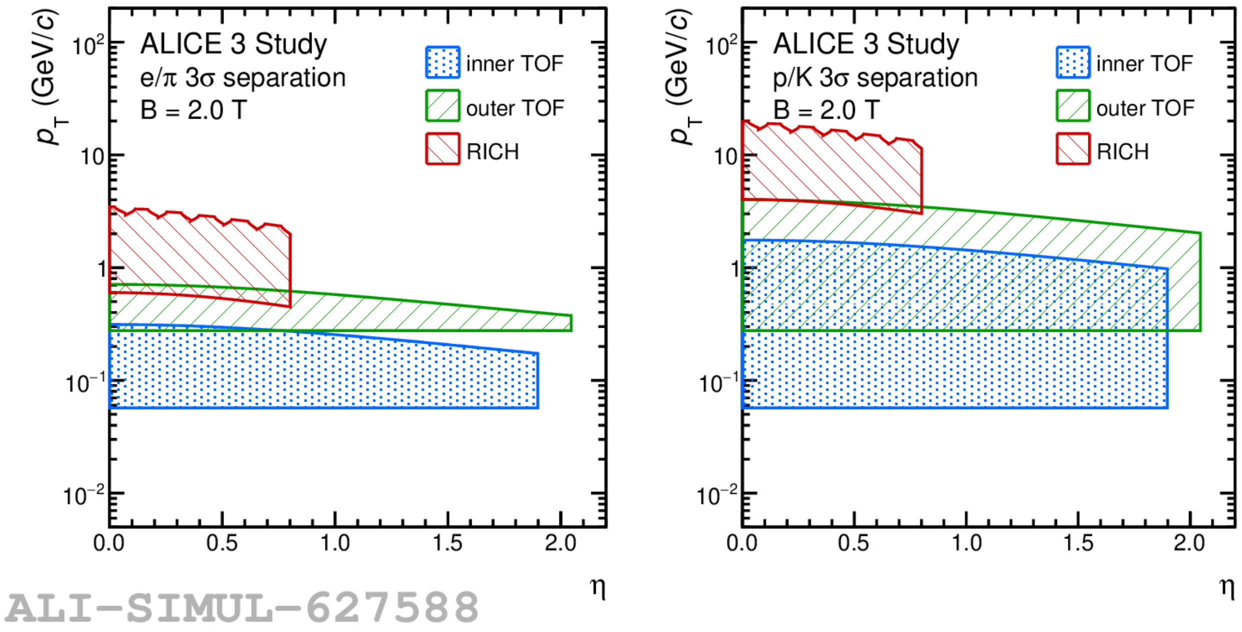


ALICE3 LoI: CERN-LHCC-2022-009
Scoping document: CERN-LHCC-2025-002

ALICE 3 Performance



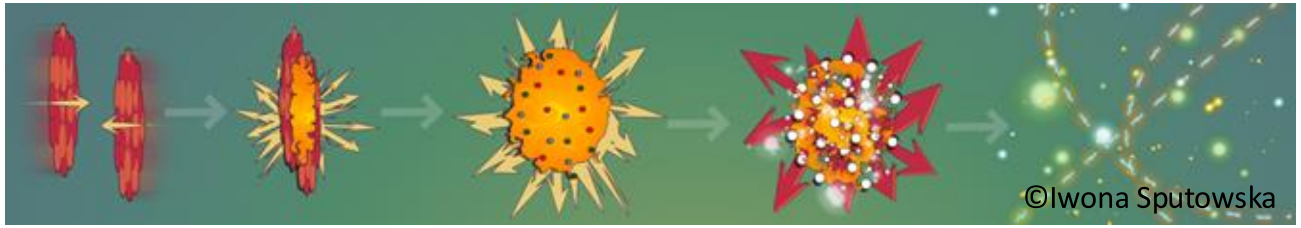
3σ separation power



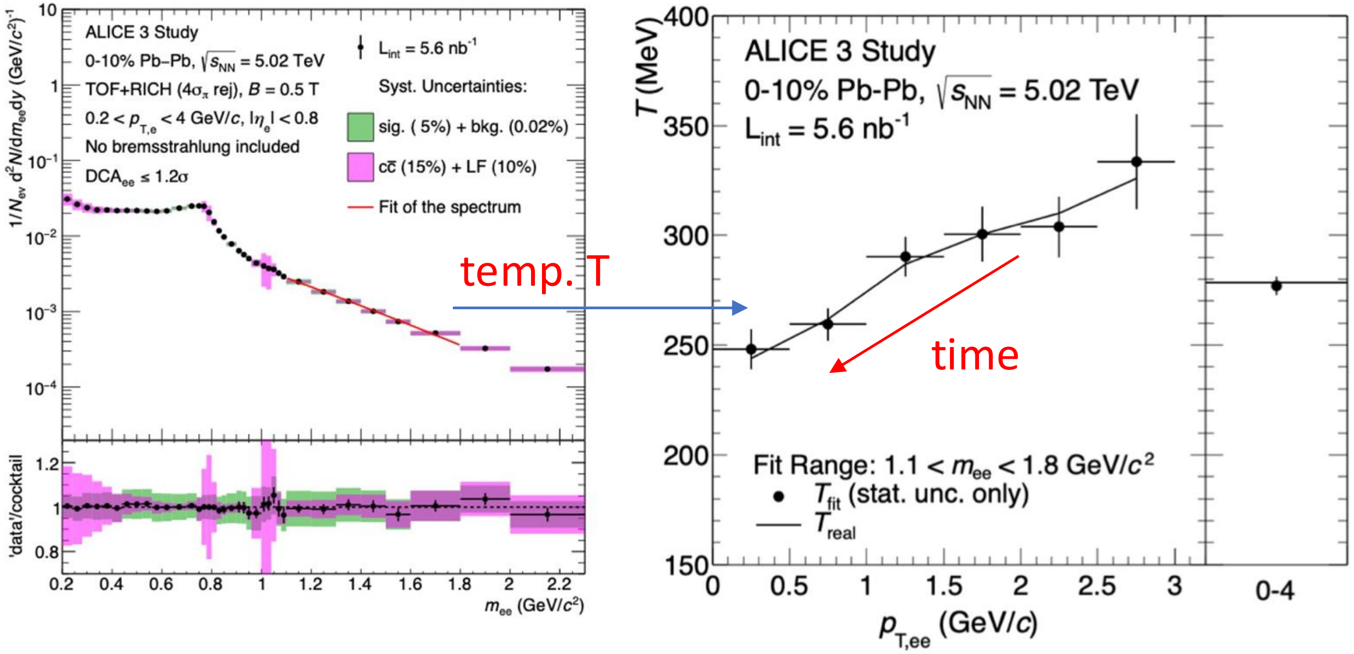
ALICE3 LoI: CERN-LHCC-2022-009
Scoping document: CERN-LHCC-2025-002

Main ALICE 3 Physics Goals

- Early stages: QGP temperature and chiral symmetry restoration
  - Photon and dilepton measurements



- Heavy flavour diffusion and thermalization in the QGP
  - Precise beauty flow at low p_T, D-Dbar correlations
- Hadronization mechanisms of charm and beauty hadrons, and nuclei
- …



CERN-LHCC-2022-009

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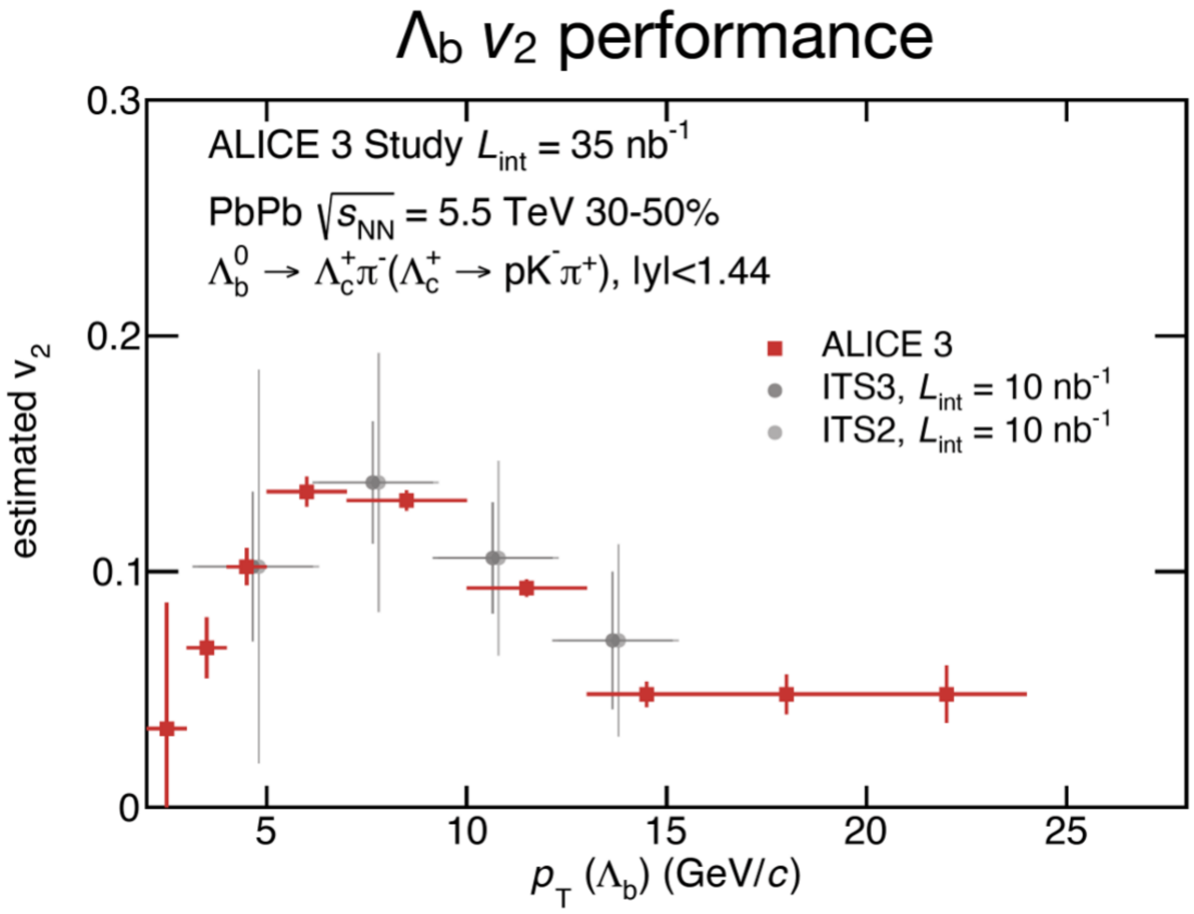

CERN-LHCC-2022-009

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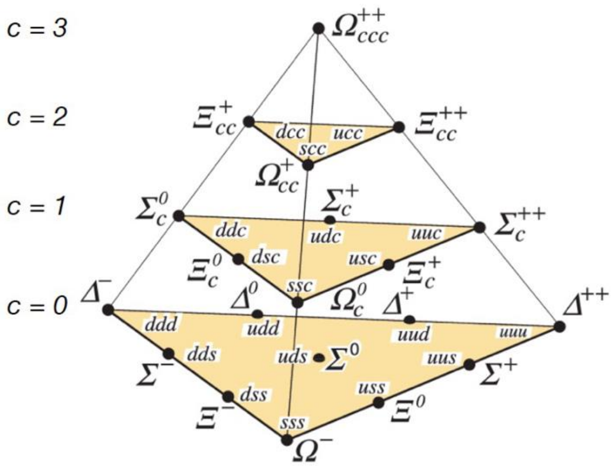
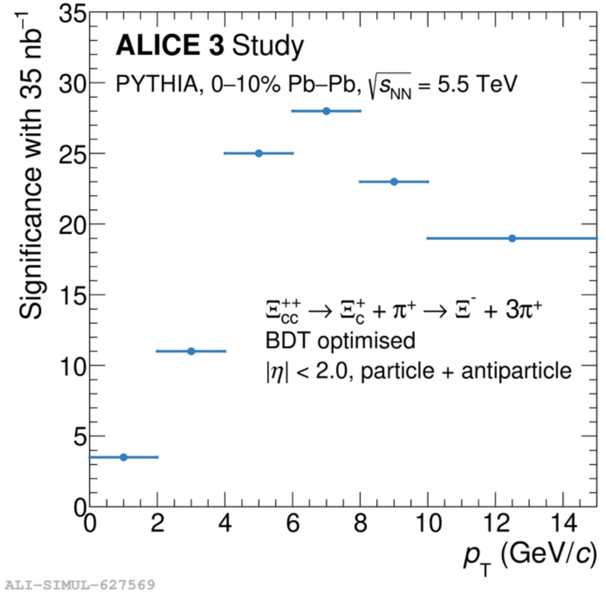
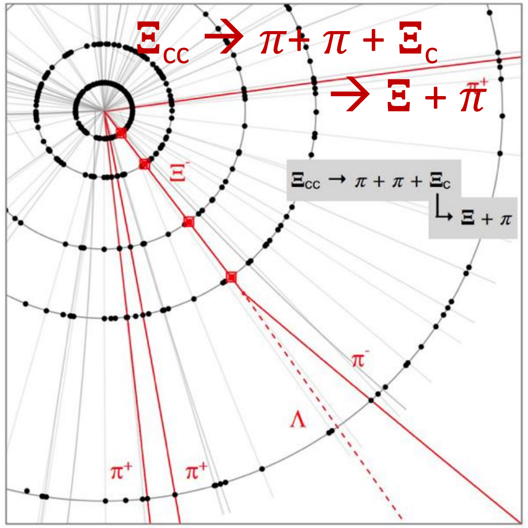


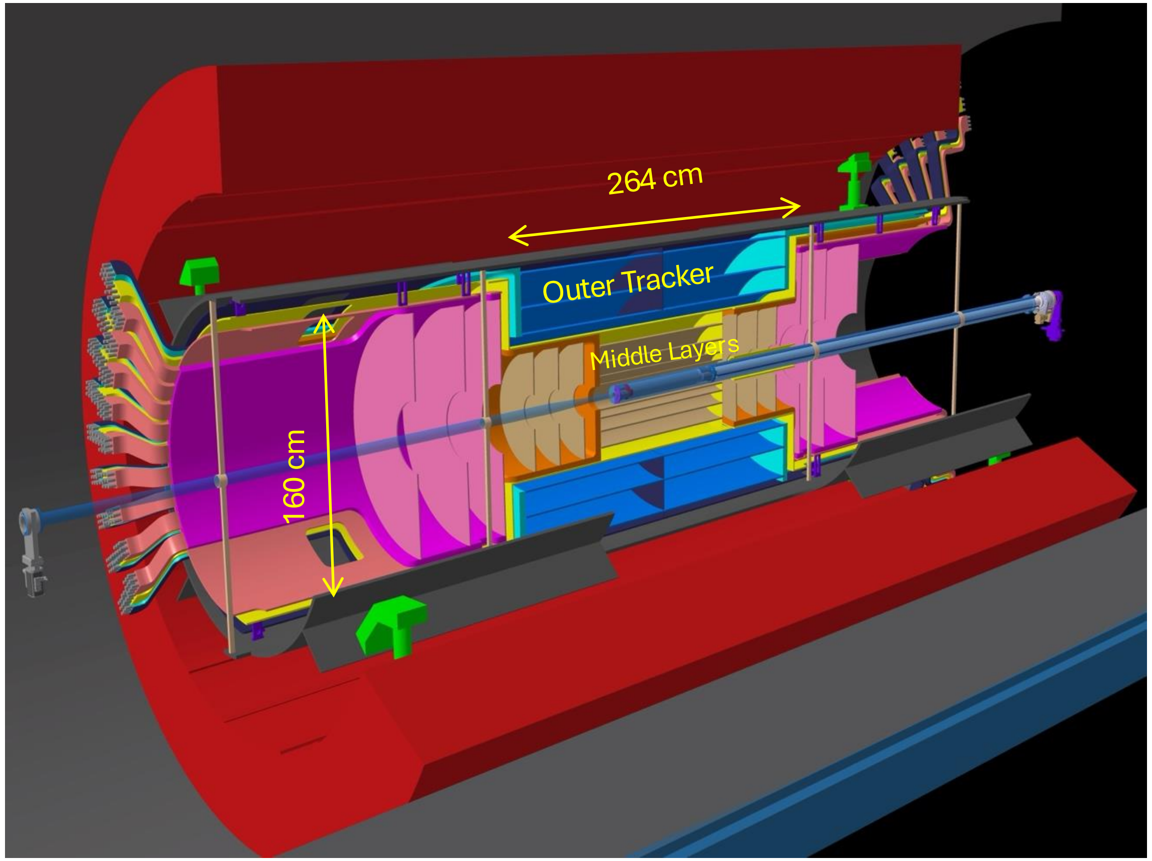




Multi-charm baryons production mostly via coalescence?

CERN-LHCC-2022-009

ALICE 3 Middle and Outer Tracker



Middle Tracker: 4 barrel layers at R < 20 cm, 3x2 disks
Outer Tracker: 4 barrel layers at R > 20 cm, 3x2 disks

$|\eta| < 4.0$, area ~ 47 m^2

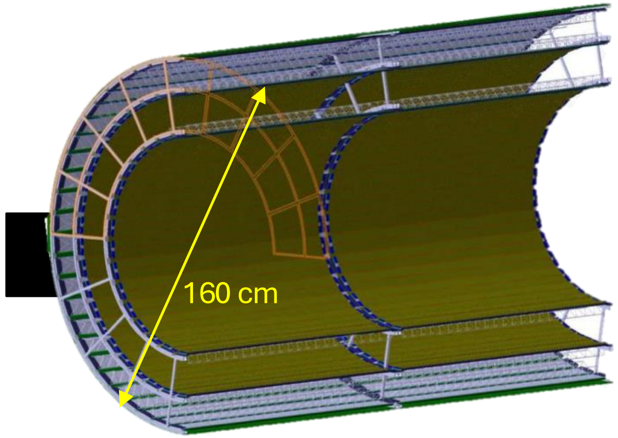
- MAPS detectors (50x50 μm^2)
- High spatial resolution: ~ 10 μm
- low material budget X/X_0 ~ 1% per layer
- Low power: 20 mW/cm^2
- Hit rates up to 0.5 MHz/cm^2

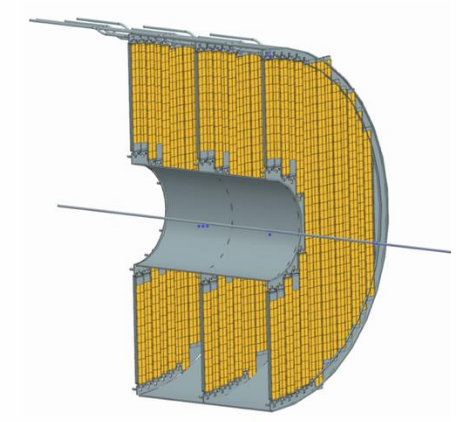
R&D challenges: power consumption and distribution

CERN-LHCC-2025-002

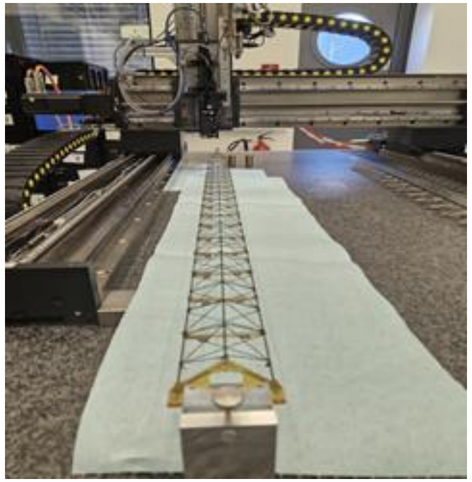
ALICE 3 Outer Tracker R&D

Barrel, disks and stave mechanics studies

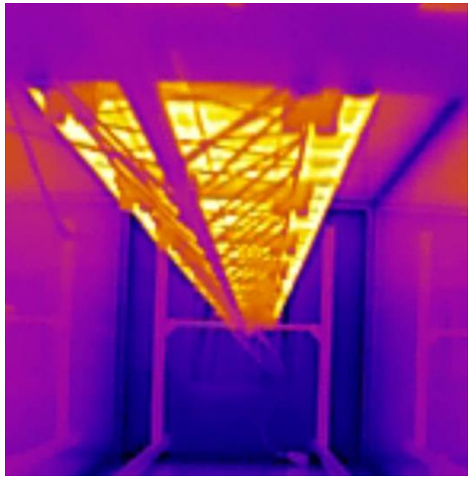




Metrology on space-frame prototypes



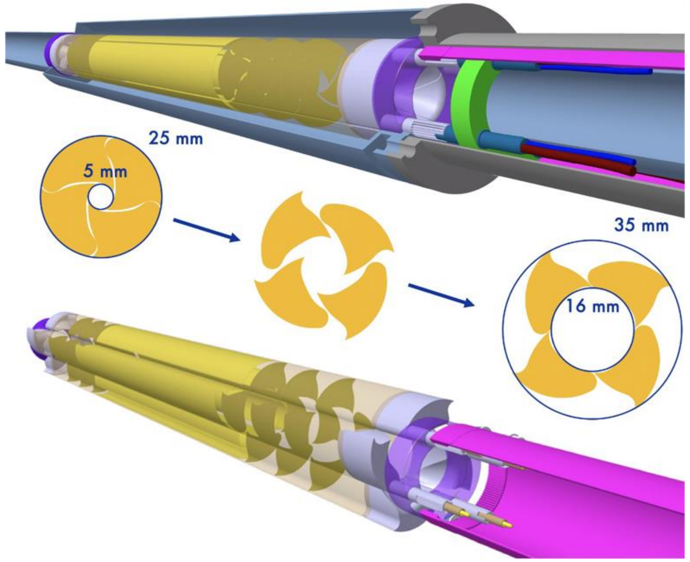
Air cooling studies with dummy staves



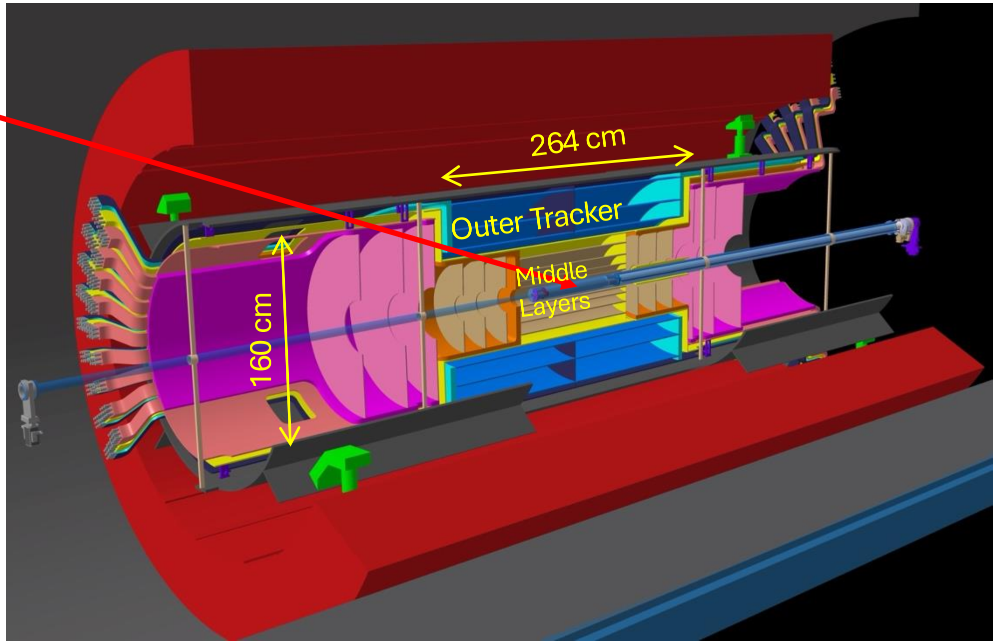
CERN-LHCC-2025-002

ALICE 3 IRIS Vertex Detector

IRIS



IRIS engineering model



IRIS: 3 barrel layers + 3x2 disks
(in secondary vacuum inside the beam pipe)

- Ultra-thin wafer-size MAPS (10x10 μm^2, thickness <50 µm)
- Unprecedented spatial resolution ~ 2.5 µm
- Radiation hardness NIEL ~ 10^{16} 1-MeV n_{eq}/cm^2
- Hit rate up to 94 MHz/cm^2

Intensive R&D on pixel size optimization, mechanics and cooling for the TDR (FCC-ee similar requirements)

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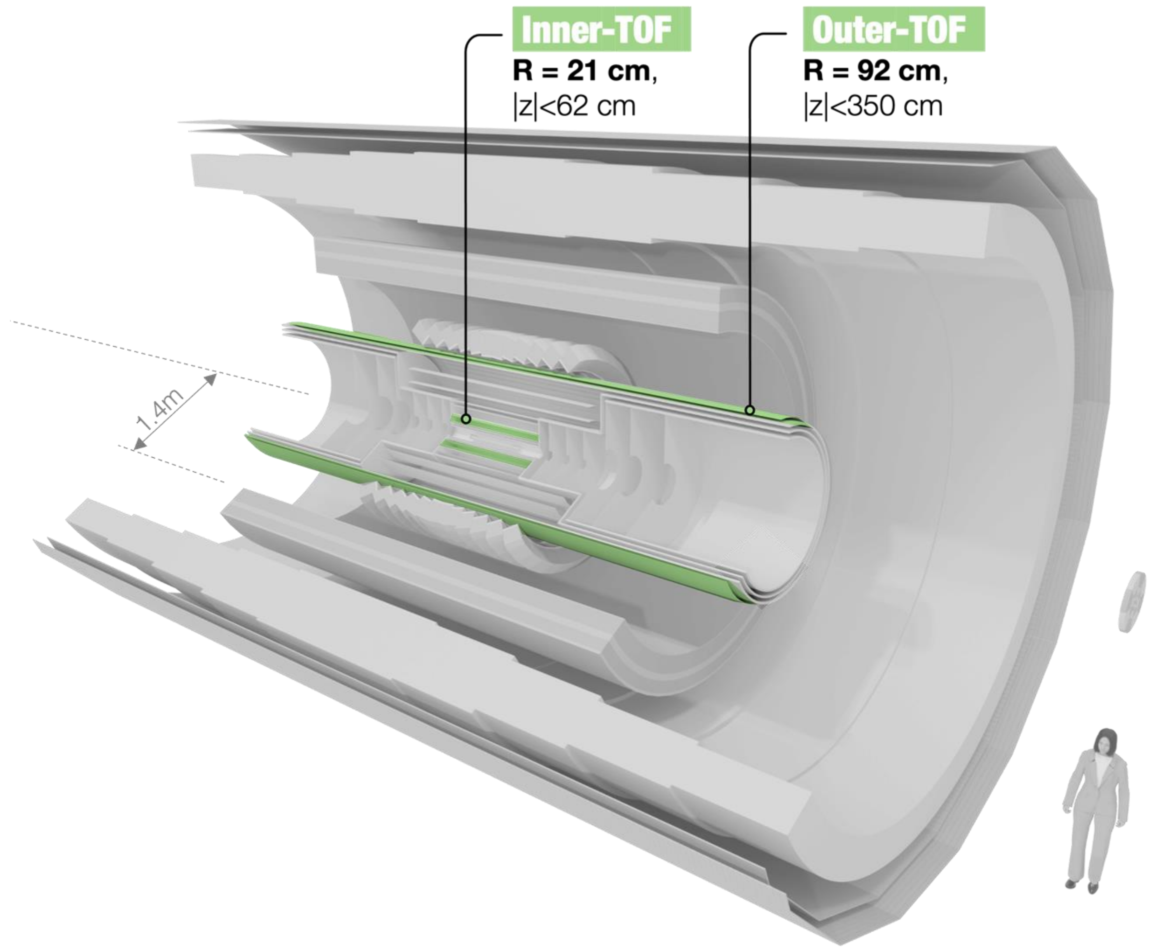
ALICE 3 TOF



$|\eta| < 2.5$, area ~ 39 m^2

- Monolithic CMOS LGAD sensors
- Pitch: 1 x 1 mm^2
- Material budget X/X_0 ~ 1-3%
- Power : 200 mW/cm^2
- Time resolution: 20 ps

R&D challenges: time resolution for CMOS LGADs…

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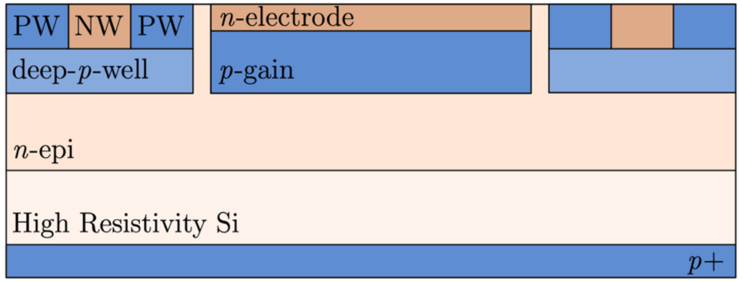
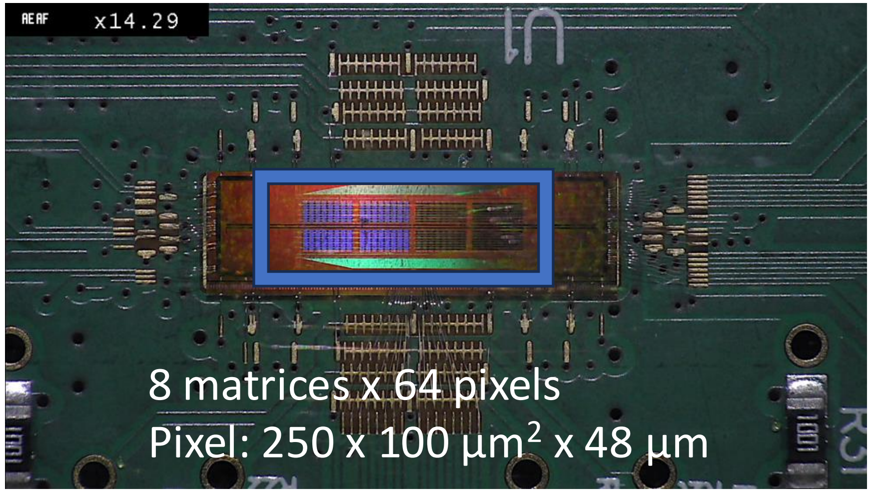
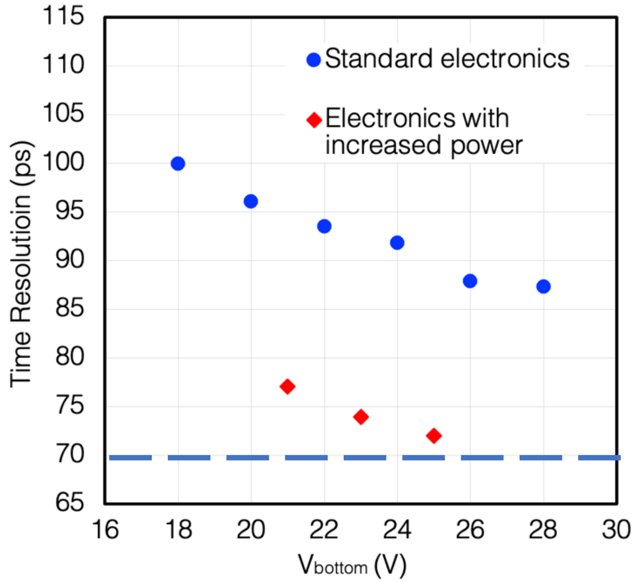
ALICE 3 TOF R&D

CMOS LGAD (Lfoundry/ARCADIA)



MadPix





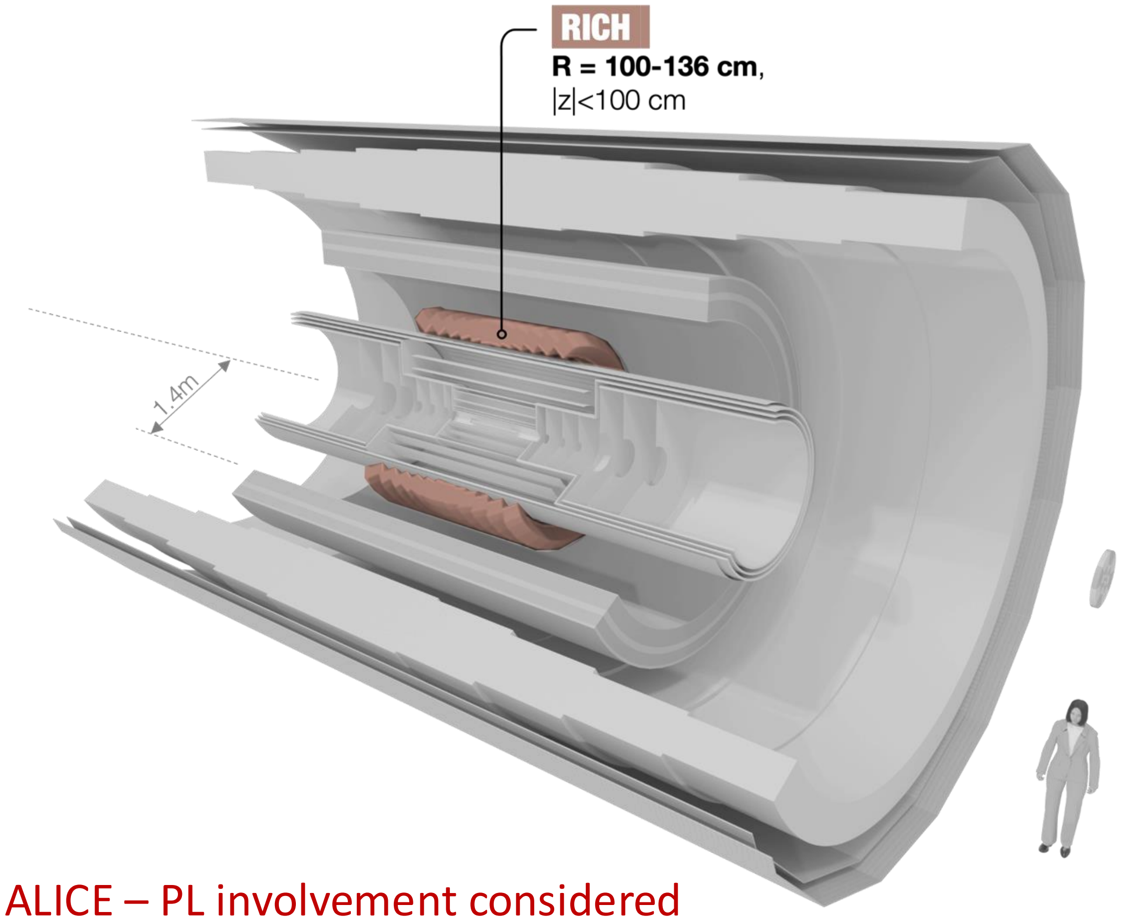
Required time resolution ~20 ps

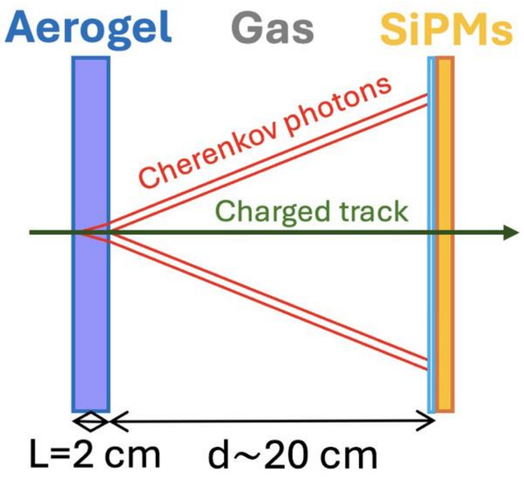
CMOS LGAD (baseline)

- Integrated readout on chip
- First MadPix chip testing (currently resolution ~70 ps)
- 20 ps resolution expected with 15-20 μm sensors

MadPix: C. Ferrero et al. [Nuovo Cim.C 48 (2025) 3, 134]

ALICE 3 RICH





|η| < 0.8, area ~ 10.4 m^2

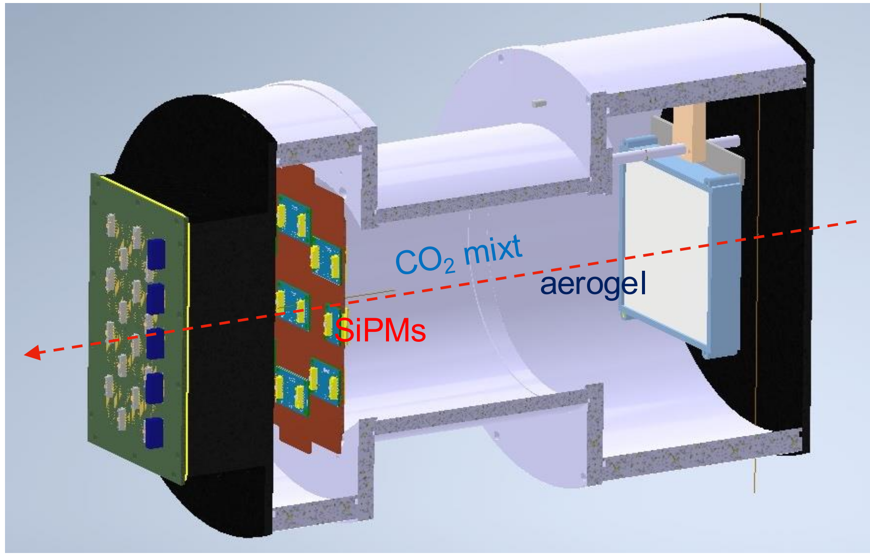
- SiPM readout: pitch 2x2 mm^2
- Cherenkov radiator: aerogel n=1.03, gas n=1.006
- Cherenkov ring angle resolution: σ = 1.5 mrad
- Time resolution < 100 ps
- Radiation load: 8.3 x10^{11} 1 MeV n_{eq}/cm^2

ALICE – PL involvement considered

CERN-LHCC-2025-002

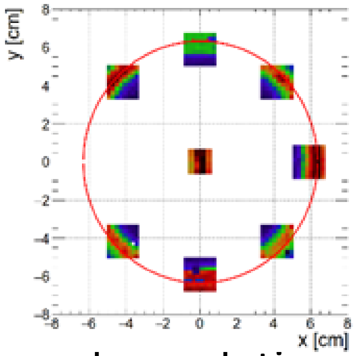
R&D challenges: SiPM radiation tolerance, CO_2 cooling & anneling…

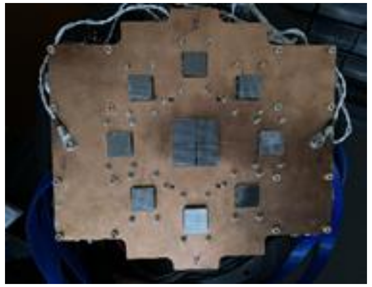
ALICE 3 RICH R&D

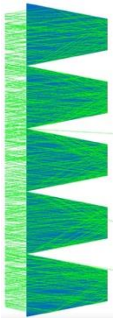


Light concentrator concept

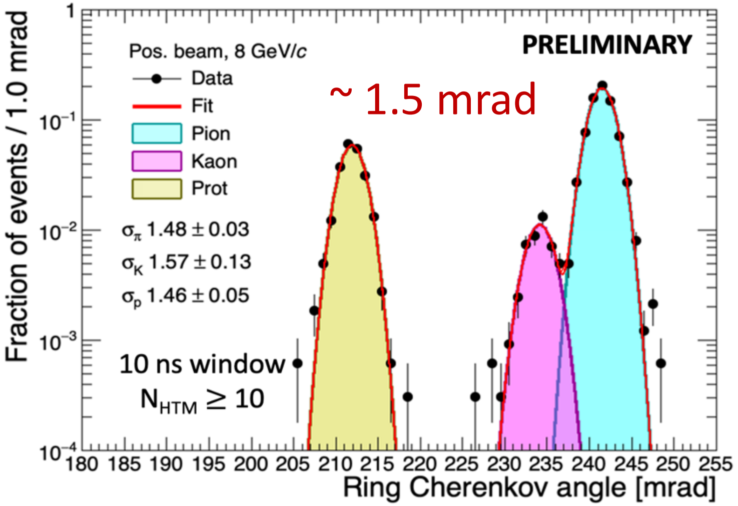
Mini light-guides array allowing reduction of SiPM pixel from 4 to 1 mm^2

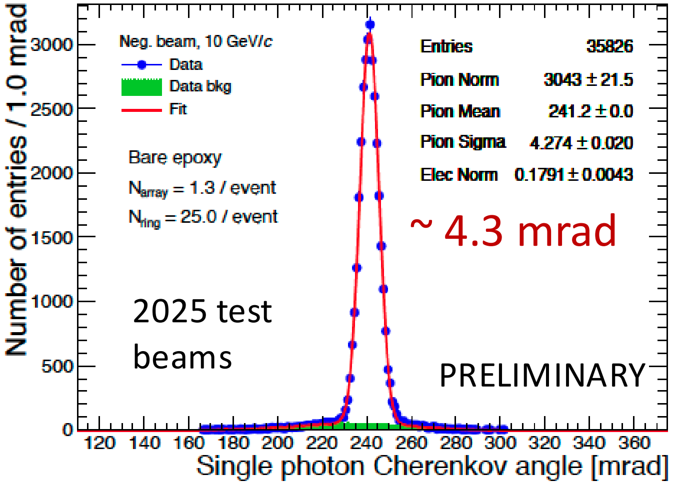




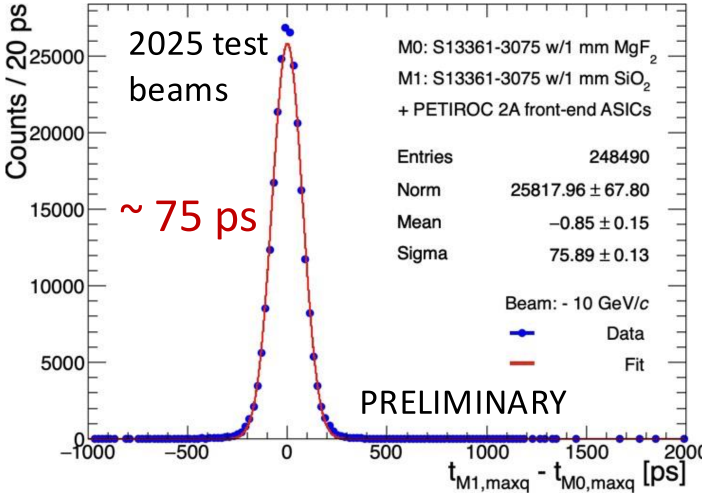


Cherenkov angle resolution



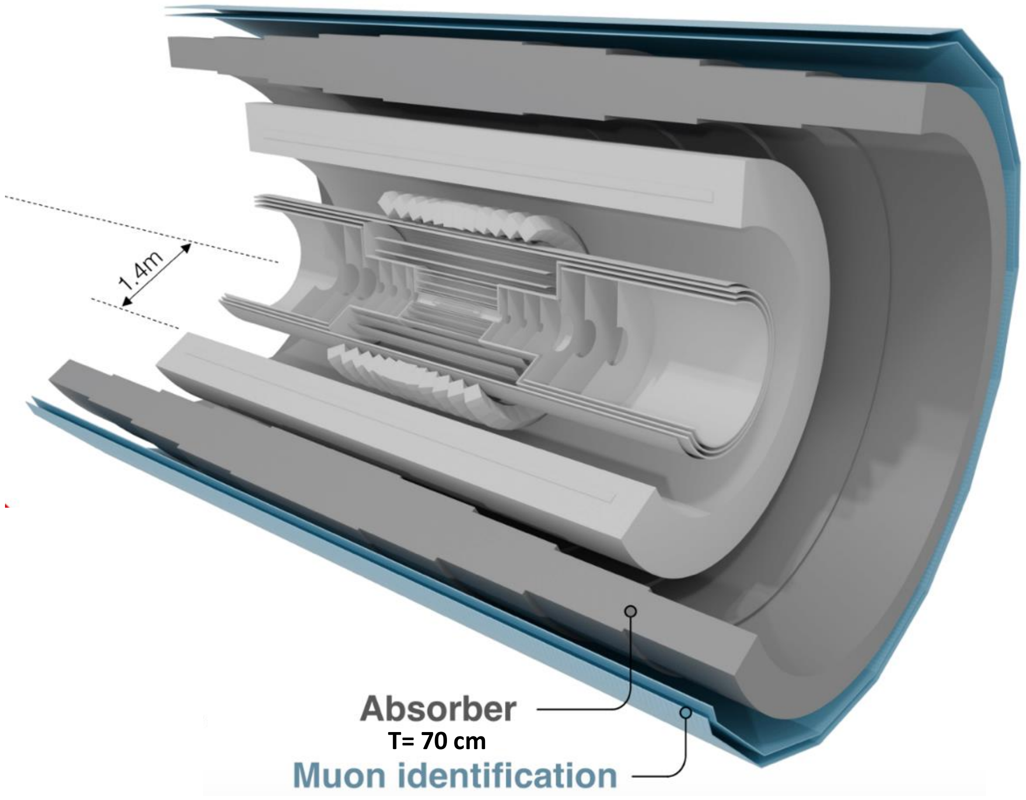


Time resolution



ALICE 3 MID

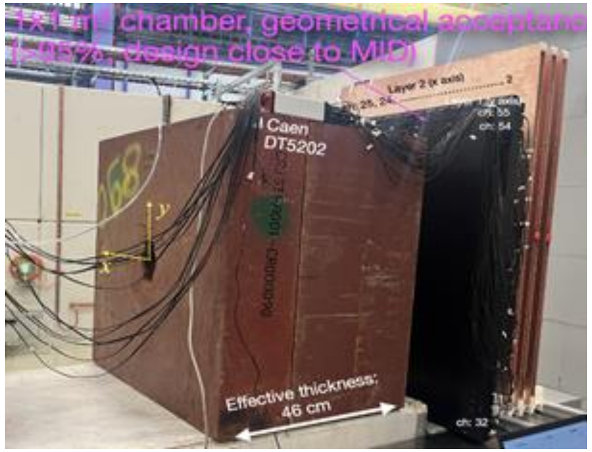
J/ψ down to p_T ~0
Charm exotics and excited states decaying to J/ψ

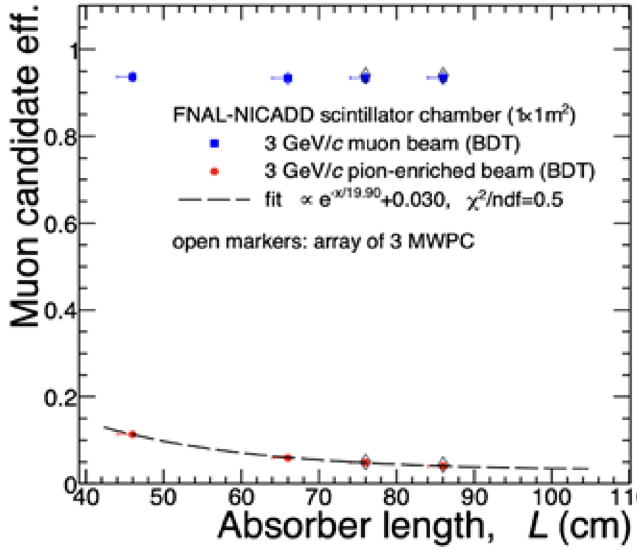


~ 190 m^2 area coverage

- Standard magnetic still absorber
- Double layer of crossed scintillator bars (100 x 20 x 5 cm^3) coupled to SiPM via WLS fibers (alternative MWPC)

R&D focus on absorber geometry optimization





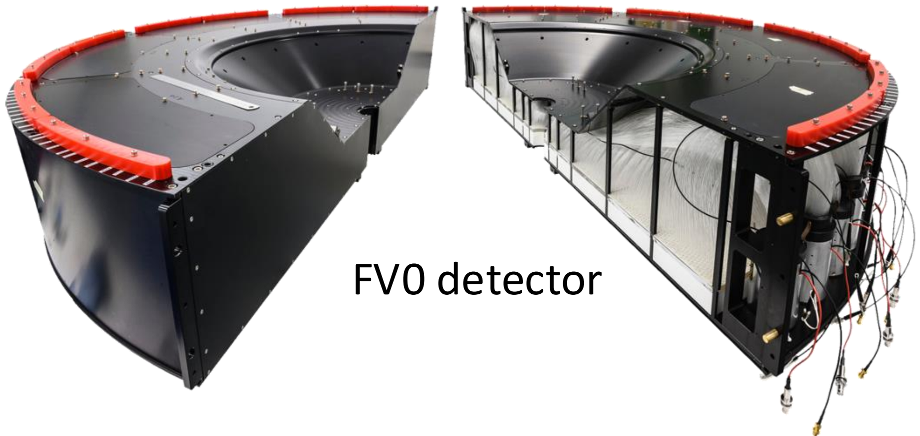
A. Ortiz et al. [JINST 20 (2025) P09015]

ALICE 3 FD Design

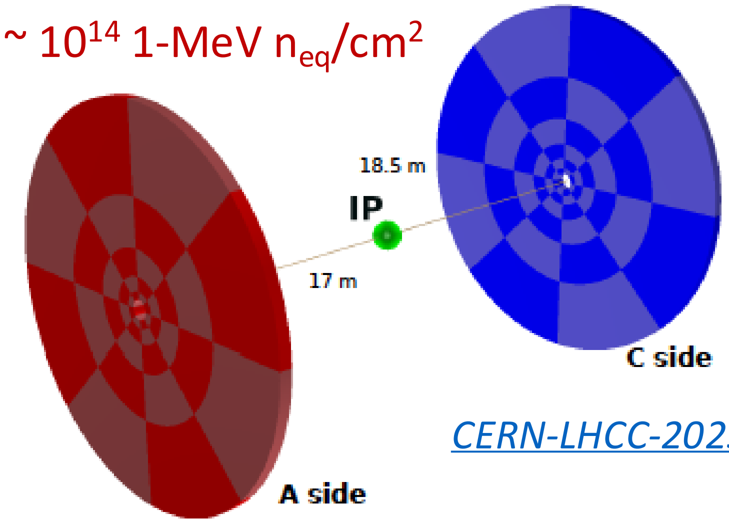
V. Grabski arXiv:1909.01184

ALICE-PL leadership!

- Two segmented scintillator
- Light collections with clear fibers
- Fast metal channel PMTs (good ageing properties)
- Fast FEE (<25 ns/event, large dynamic range)

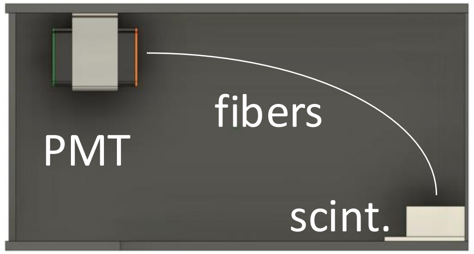


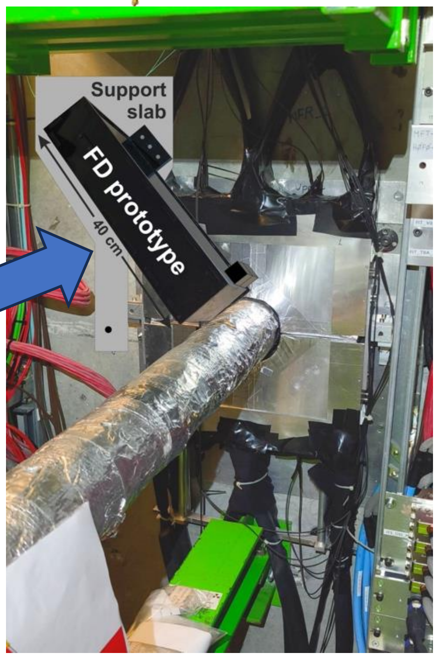
TID ~ 1 Mrad
NIEL ~ 10^{14} 1-MeV n_{eq}/cm^2



CERN-LHCC-2025-002

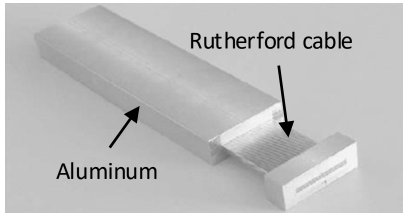
One channel FD prototype installed at LHC for 2026 tests

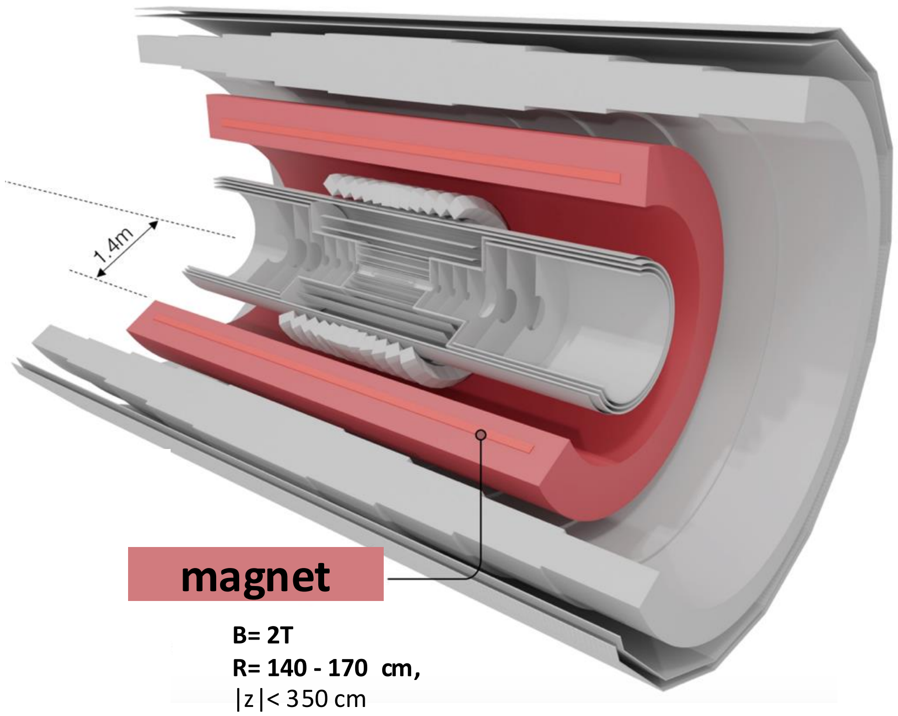




Key detector for ALICE 3 operations (luminosity & background monitoring)

Superconducting magnet

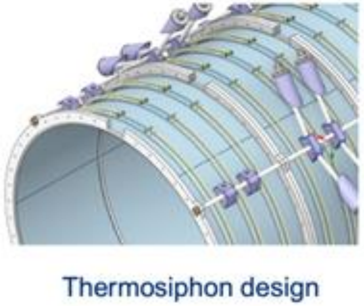




Baseline conductor: Aluminum-cladded Nb-Ti

CNPEM Institute (Brasil) leading the design of the magnet in collaboration with ALICE Techn. Coord., CERN EP R&D Magnet group, CEA-Saclay, and INFN Genova

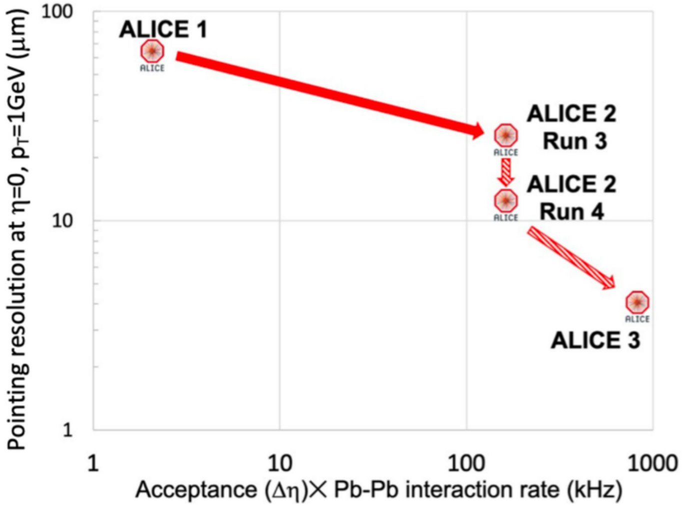
Conceptual Design Report and final cable specifications in Q3 2026

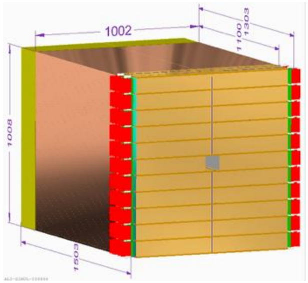


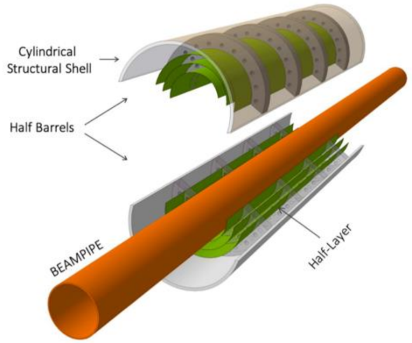
Summary & Outlook

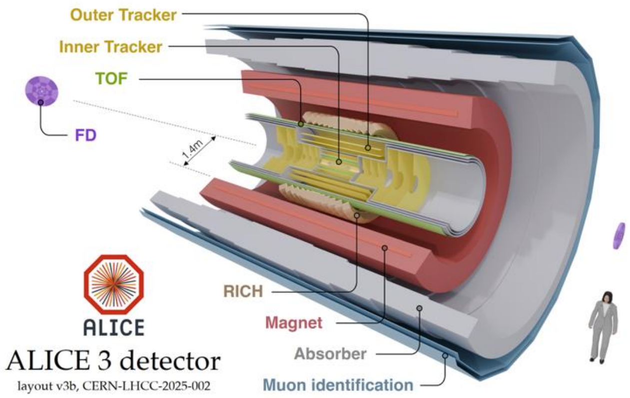
Fully exploit LHC potential for heavy-ion physics in Run 4 and beyond

- ALICE is a top tier experiment at the LHC
- Catching edge technology for FoCal, ITS3 and ALICE 3 detectors
- CMOS MAPS and LGADs, and SiPMs for particle detection in high radiation environments
- FoCal and ITS3 Run 4 upgrades advanced (production reviews)
- Intensive ALICE 3 R&D ongoing for TDR preparation
- ALICE 3 scoping options are under discussion (stay tunned in 2026)









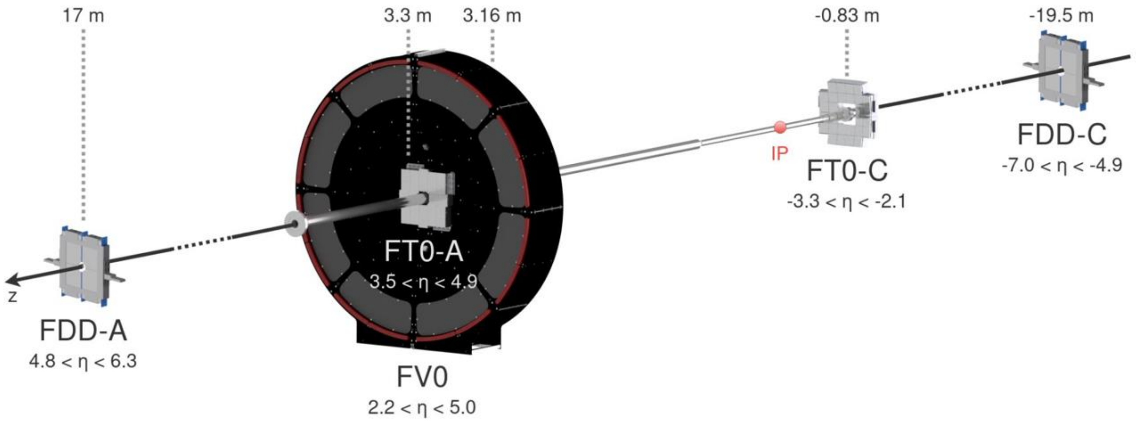
ALICE Week July 2025 (CERN LHC Point 2)

backup

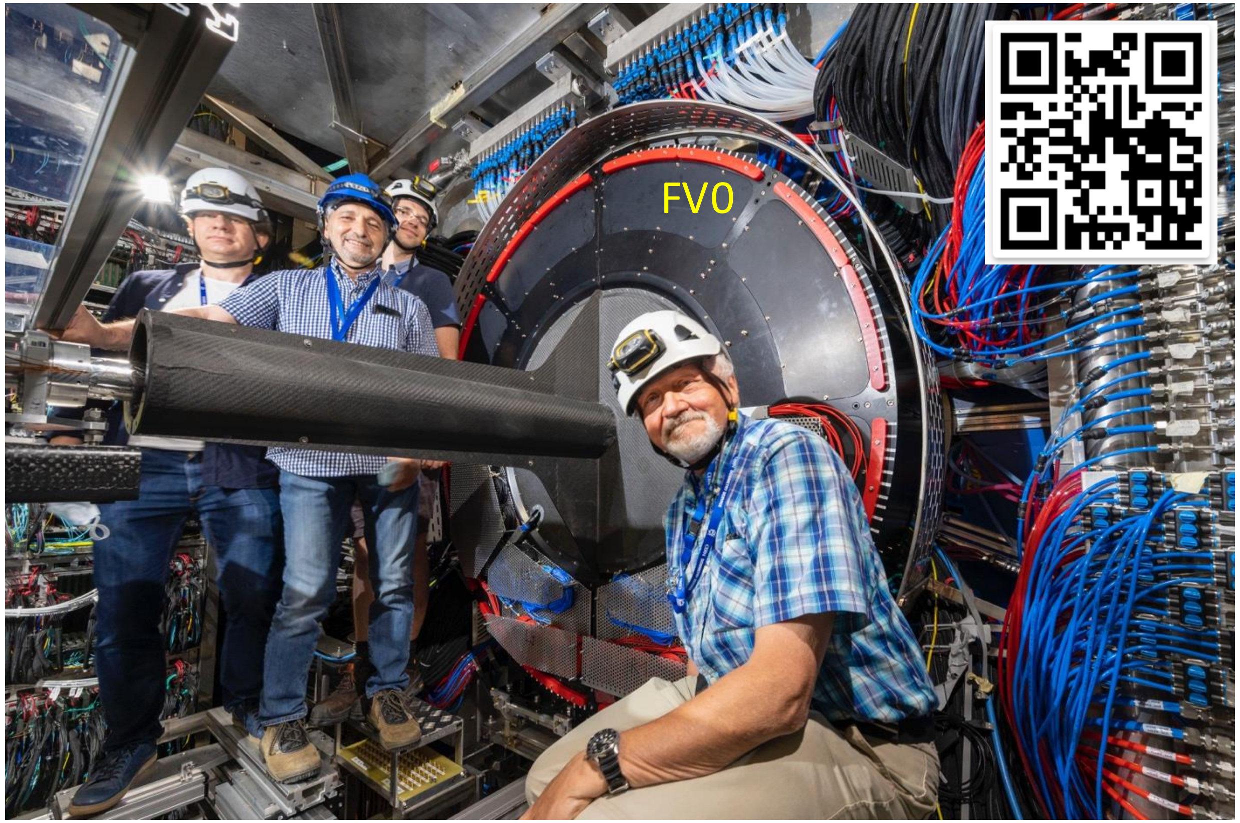
Fast Interaction Trigger (FIT)

ALICE-PL leadership!

Key detector for ALICE operations
(luminosity, background, collision time, centrality, …)



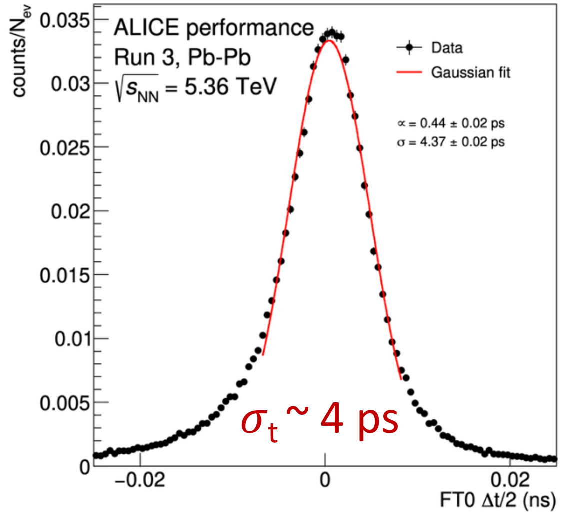
- FT0 Cherenkov (quartz) detector
- FV0 and FDD Scintillators

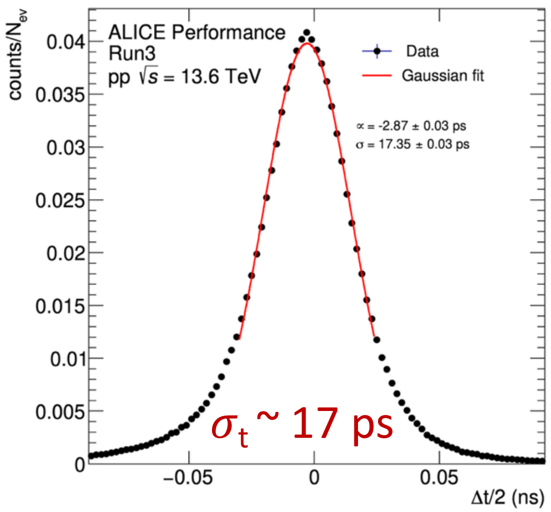


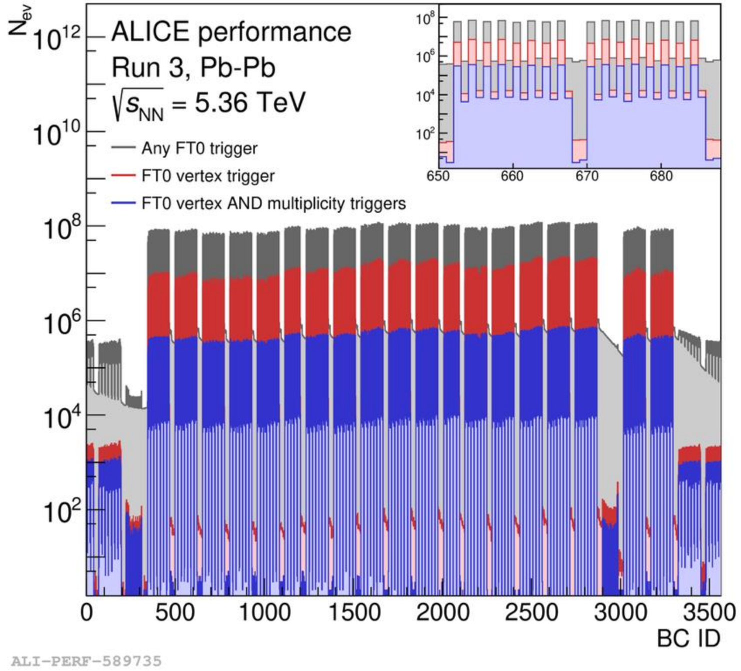
ALICE-PL involved since 2018

- Detector operations, DCS, QC and maintenance
- FEE and DCS upgrades for Run 4

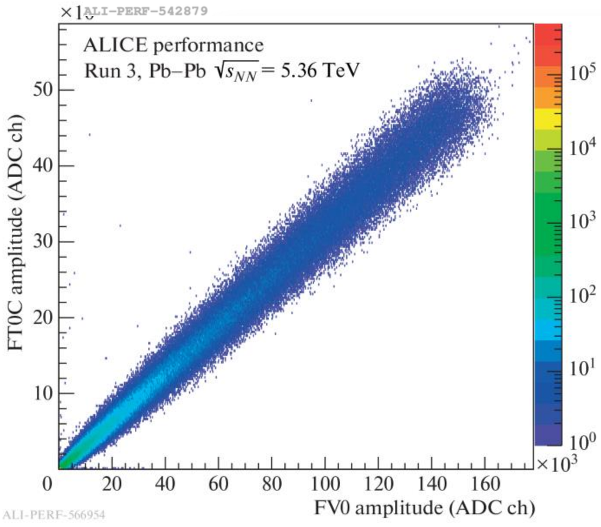
FIT Performance in Run 3

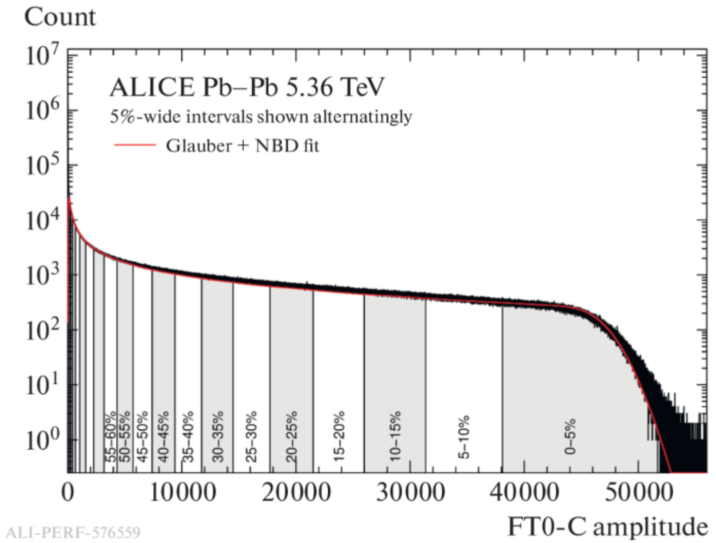




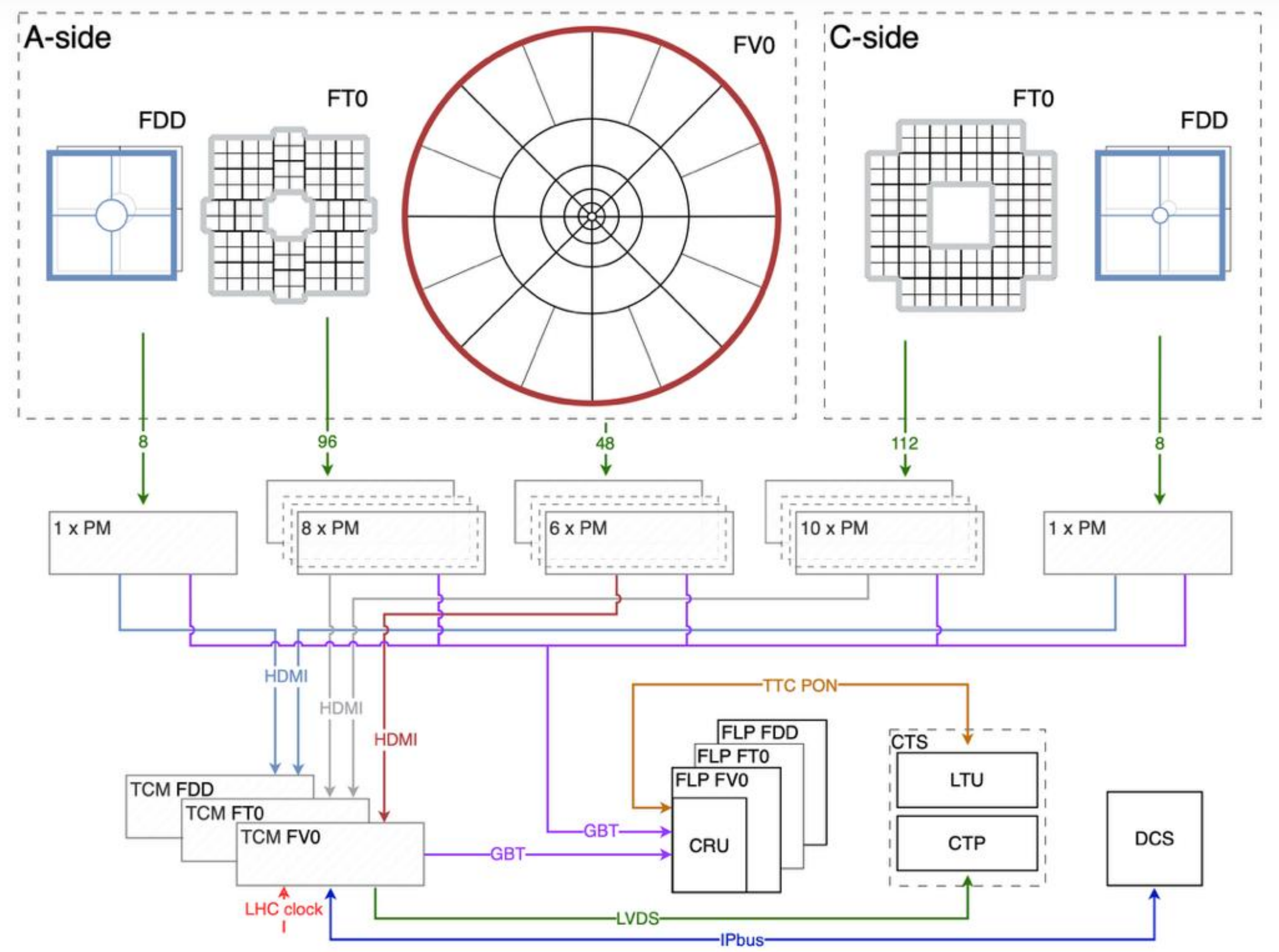


Excellent FT0 time resolution!





FIT Front-End Electronics upgrade for Run 4



WUT & AGH key players!

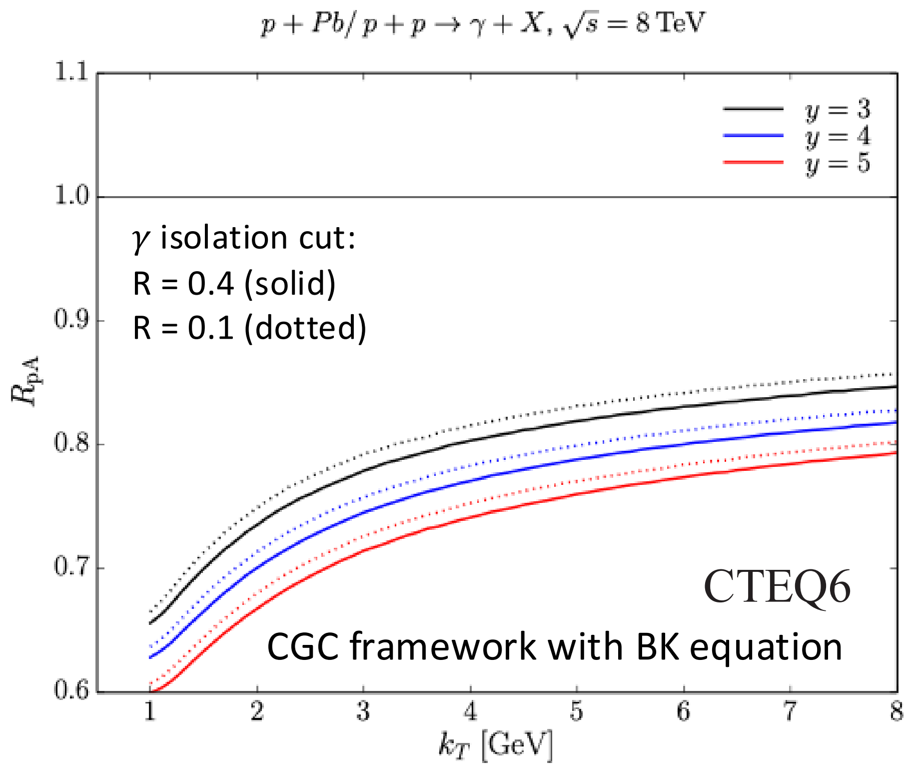
Fast FEE (<200 ns event processing)
- Processing modules (PM)
- Time & Clock Modules (TCM)

FEE upgrades
- Larger dynamic range (1 mV – 5 V)
- Reduce time slewing

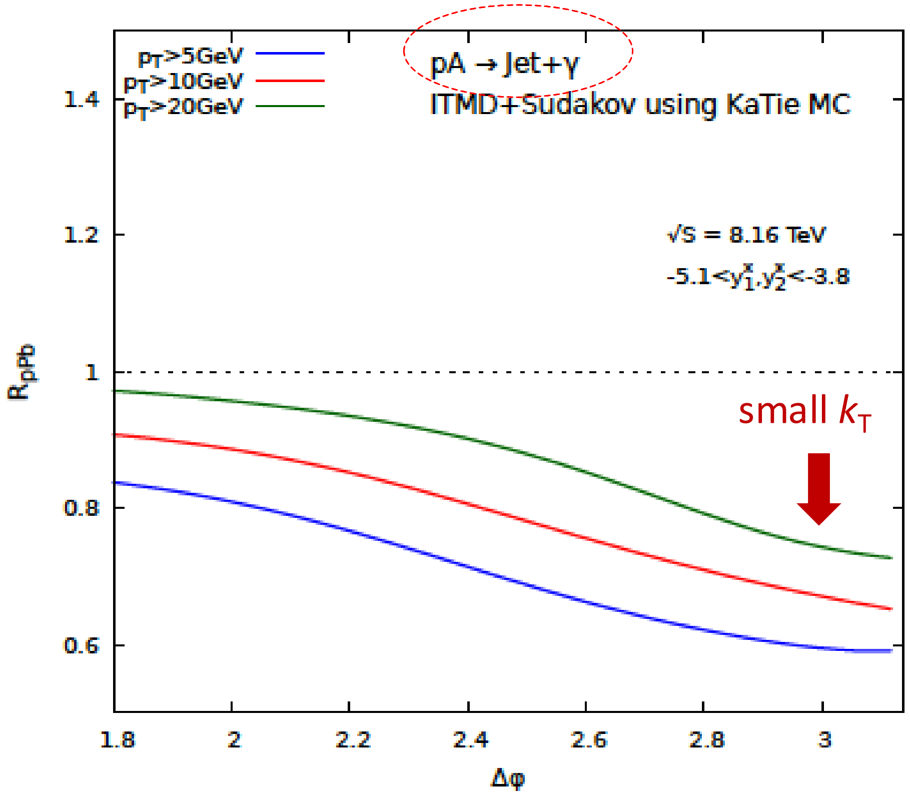
Direct γ and γ-jet predictions

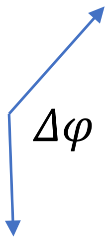
Nuclear modification factors $R_{pPb} = Y_{pA} / N_{bin} Y_{pp}$

→ strong suppression due to gluon saturation in Pb nuclei



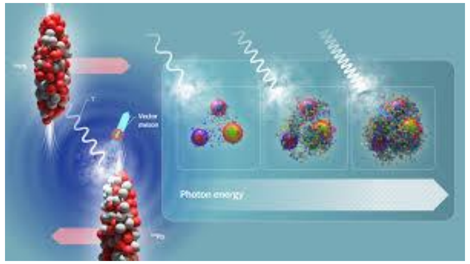
B. Ducloué, T. Lappi, H. Mäntysaari *Phys. Rev. D 97, 054023 (2018)*



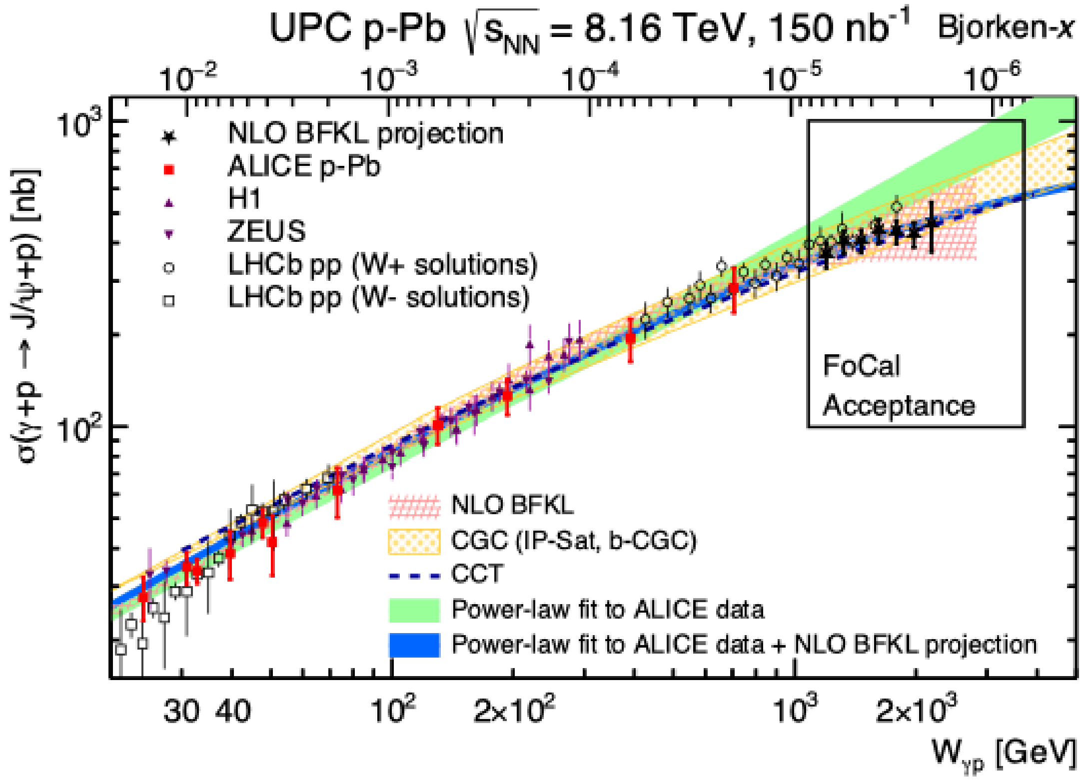


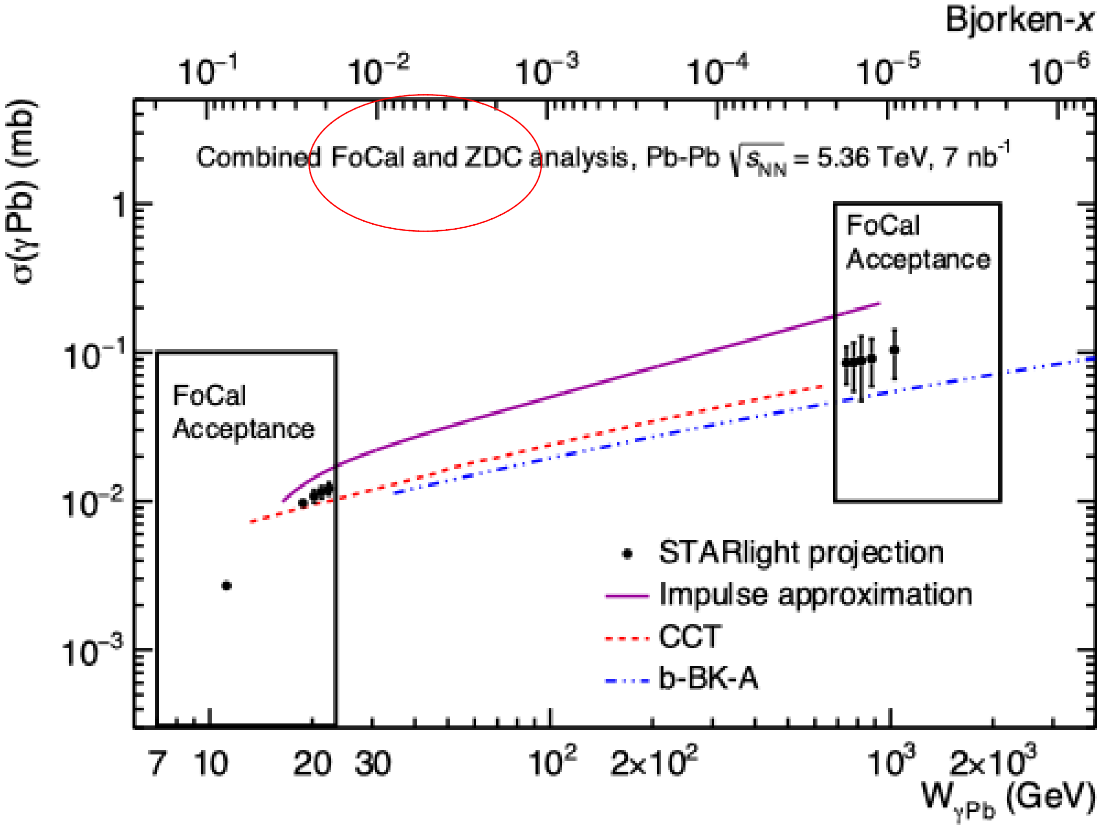
*M. Abdullah Al-Mashad, A. van Hameren, H. Kakkad, **P. Kotko**, K. Kutak, P. van Mechelen S. Sapeta* arXiv.2210.06613

J/ψ production in p-Pb and Pb-Pb UPC



Probing small-x with charmonium production in UPC at the LHC

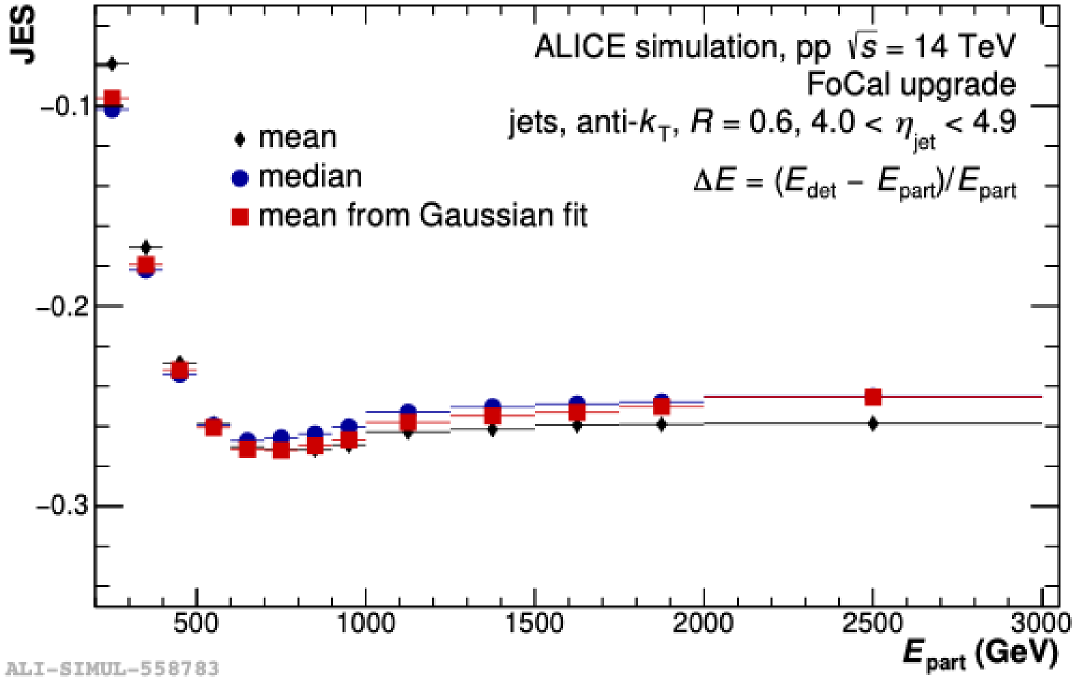


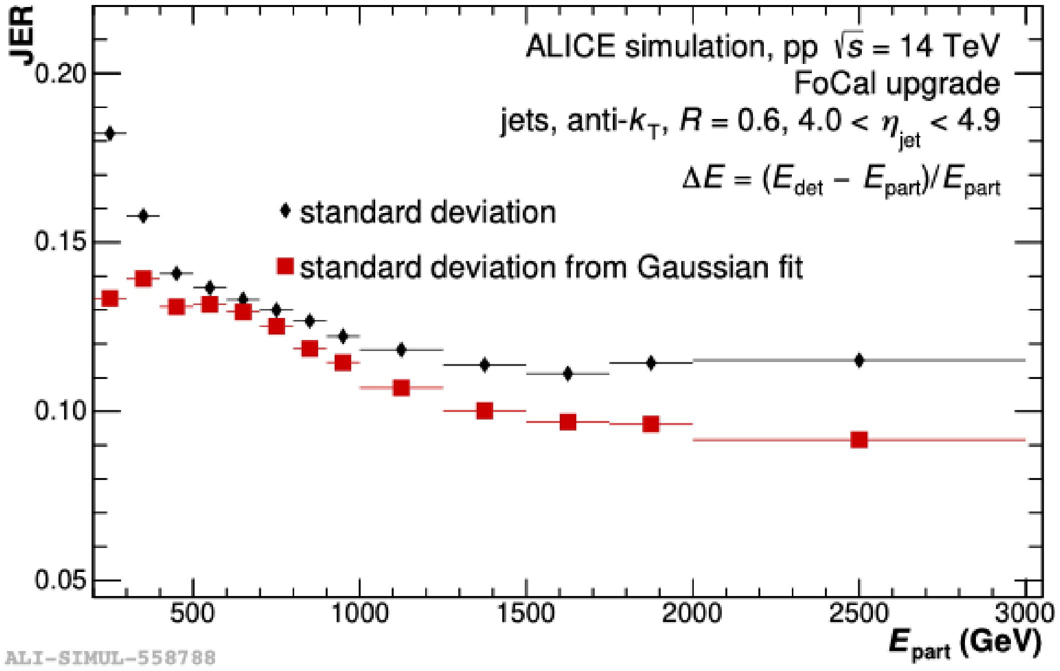


A. Bylinkin, J. Nystrand, D. Tapia Takaki arXiv:2211.16107

Jet reconstruction in simulations

Jet energy scale (JES) and resolution (JER) quantified with Pythia + GEANT simulations



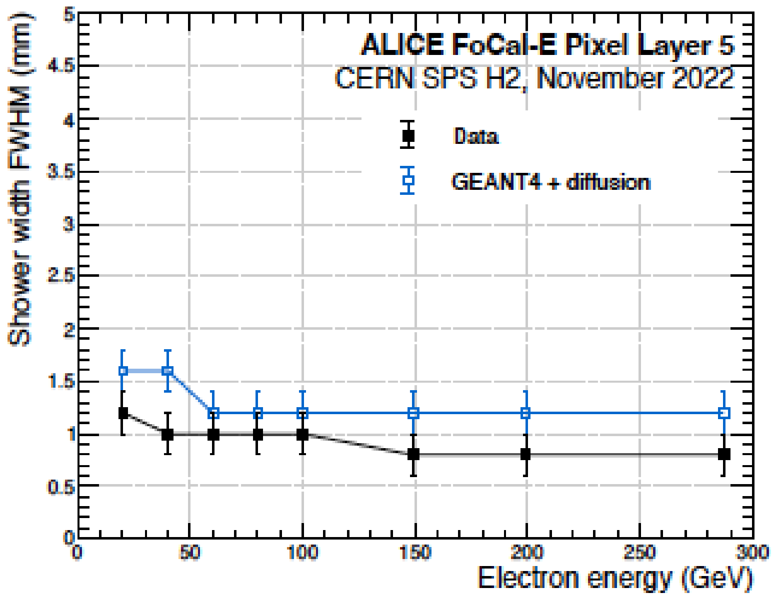


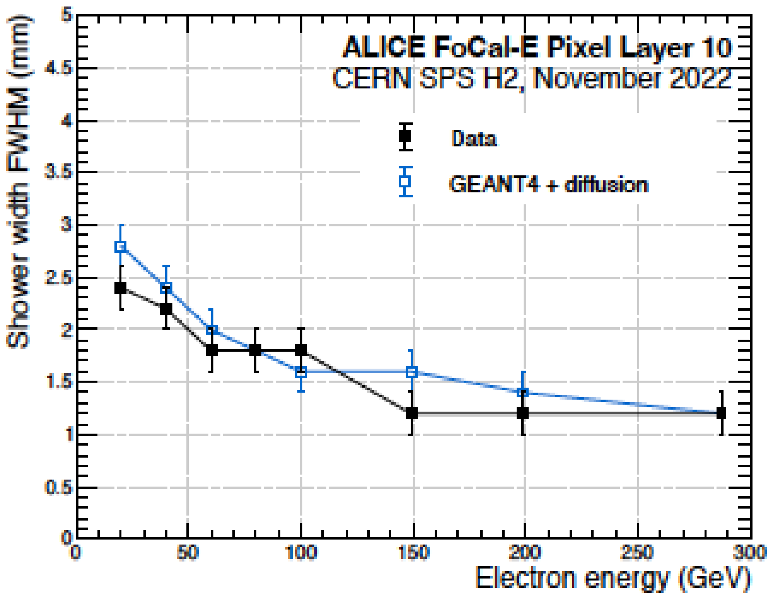
- Jet reconstruction bias < 25%
- Non-Gaussian tails at small energy jets

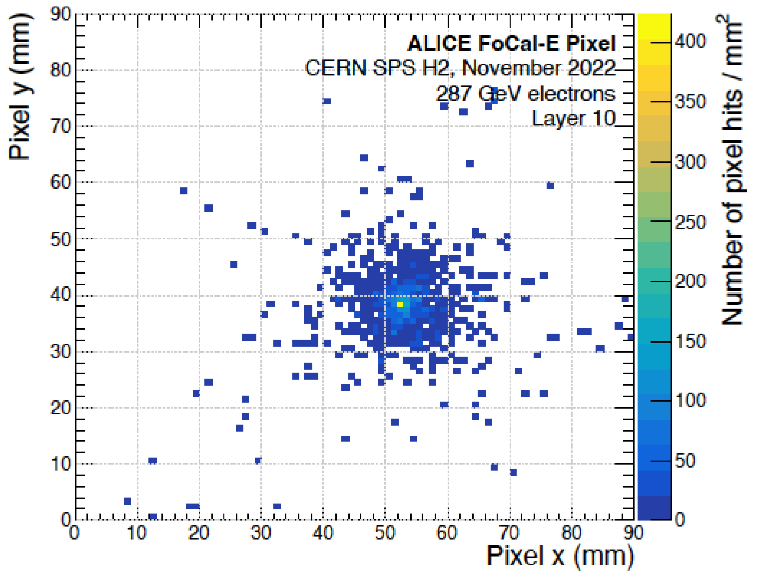
ALICE-PUBLIC-2023-004

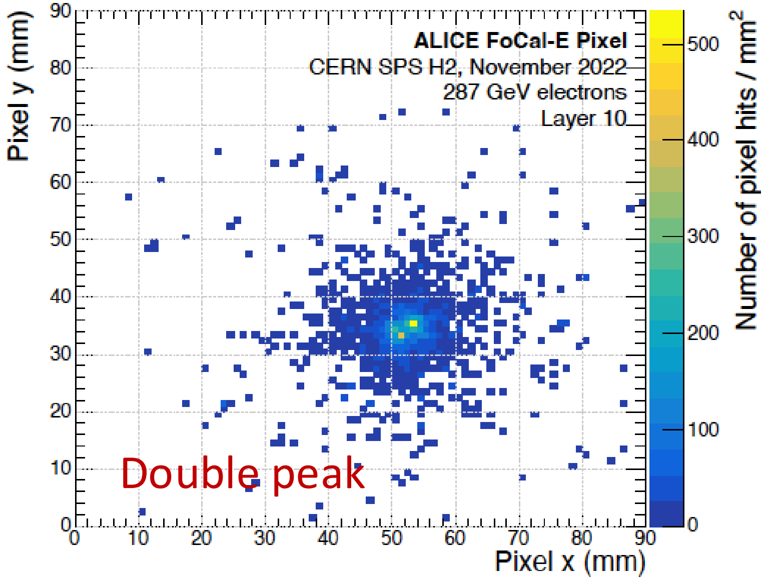
FoCal-E pixel transverse profiles

Good agreement between data and simulations







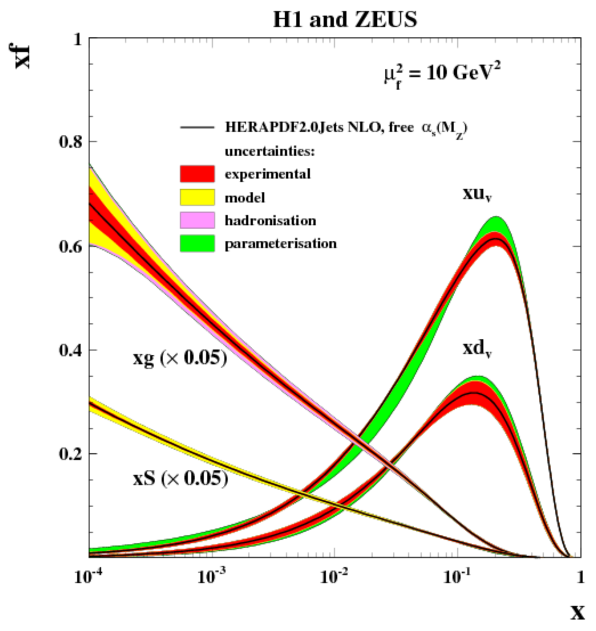


M.Aehle et al. [JINST 19 P07006 2024]

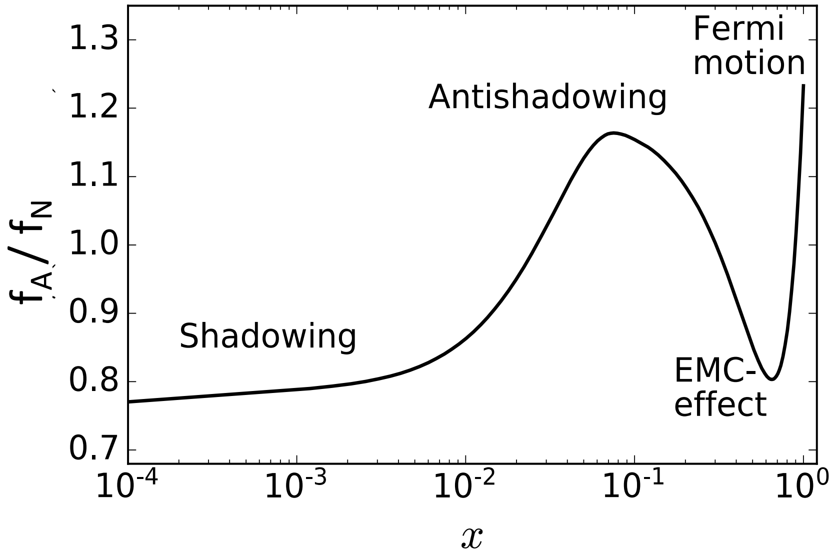
Probing parton distributions

- Hadron and nuclear PDFs at high energy
- Shadowing and gluon saturation at small Bjorken-x?
- Universal state of matter at high energy - Color Glass Condensate (CGC)?

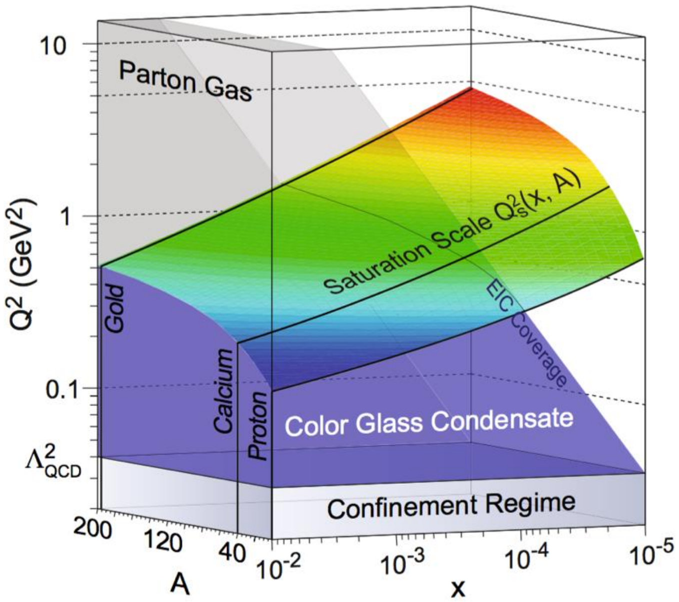
L. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233



H1 and Zeus, EPCJ 75 (2015) 580



EMC, J.J. Aubert et al. Phys. Lett B123 (1983) 275



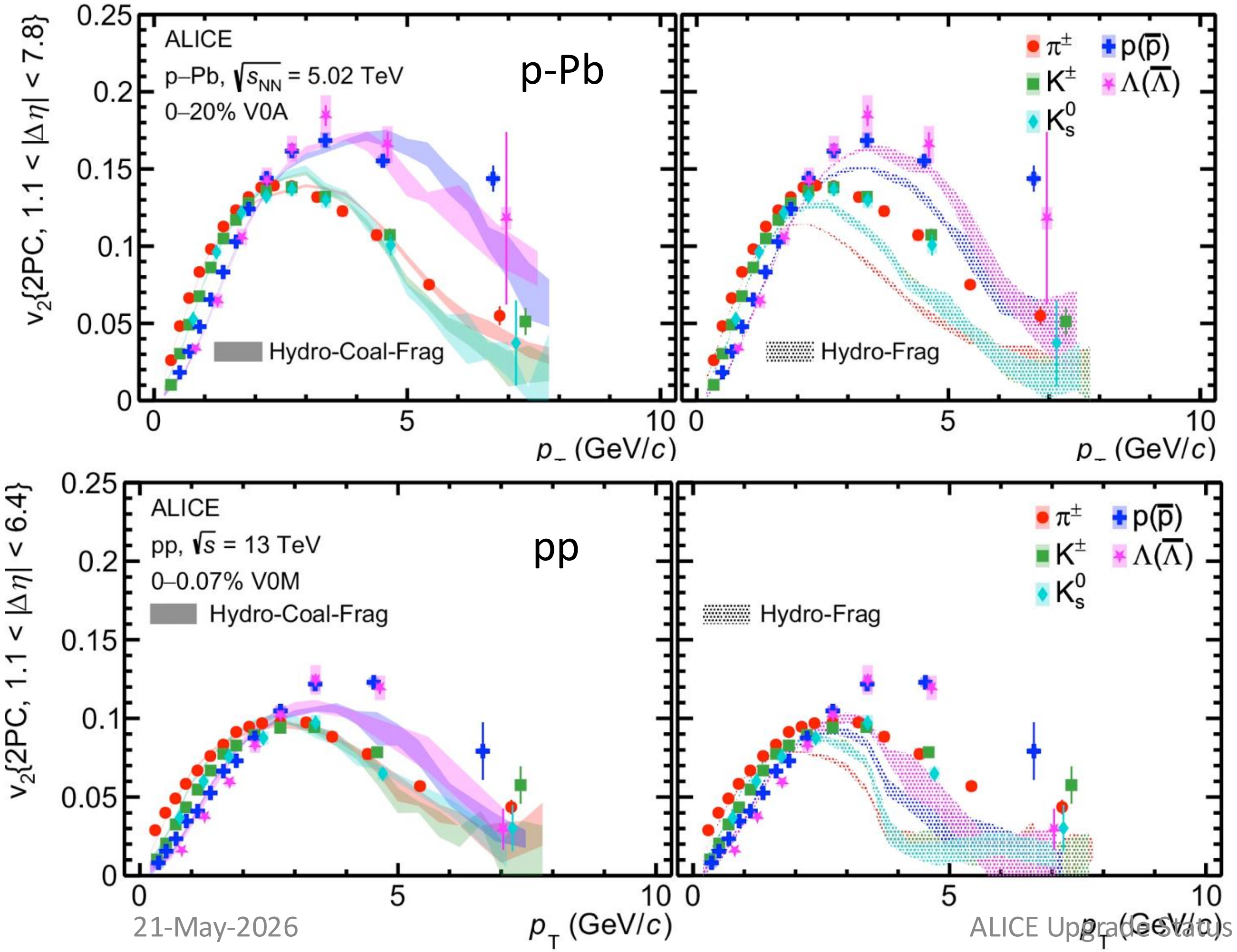
Accardi et al, EPJA 52 (2016) 268

Bjorken - x

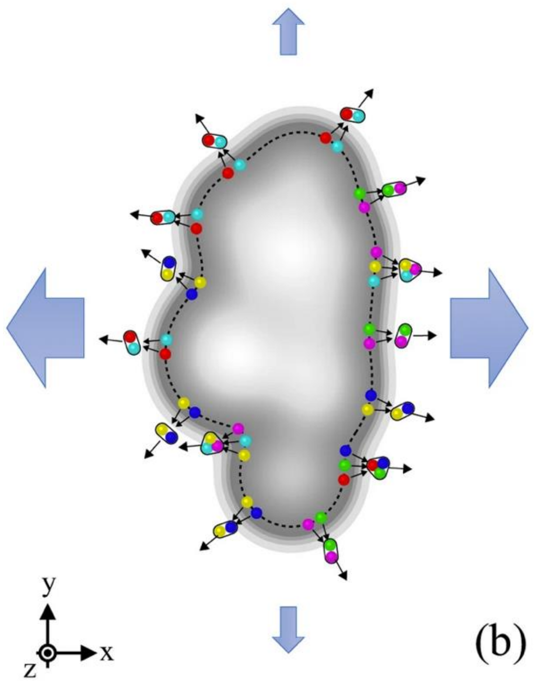
$$x = \frac{p_T}{\sqrt{s}} e^{\pm\eta}$$

Observation of partonic flow in pp and p-Pb

ALICE, Nature Commun. 17 (2026) 2585



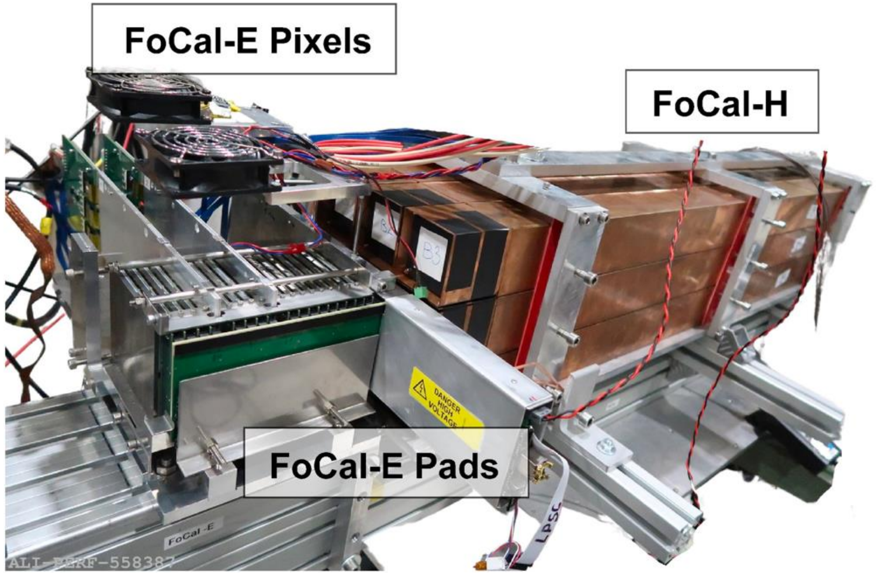
$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2v_n(p_T)\cos(n\varphi - n\Psi_n)$$

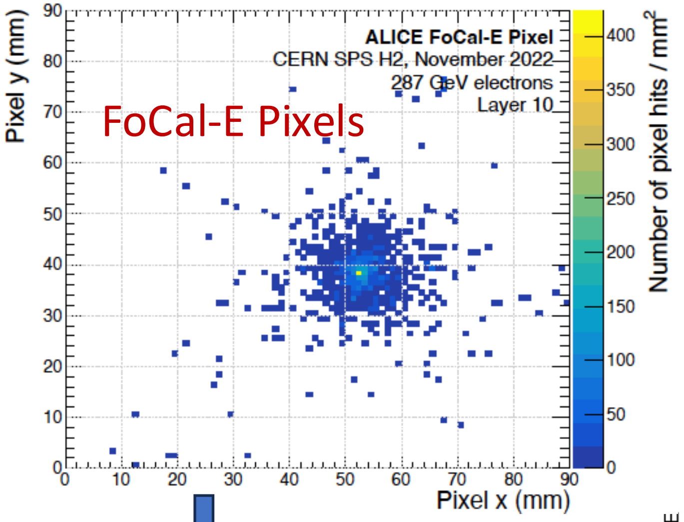


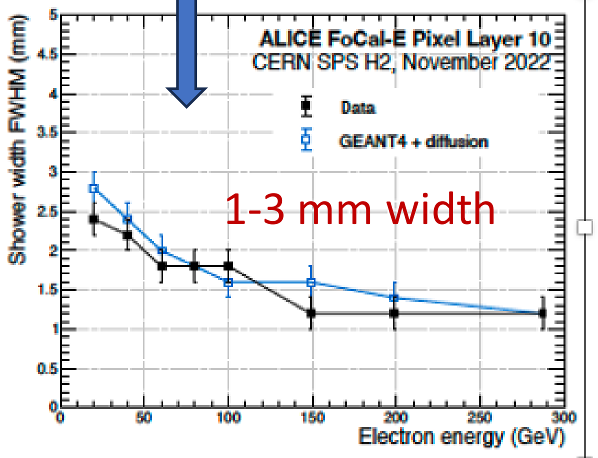
→ quark coalescence and partonic flow

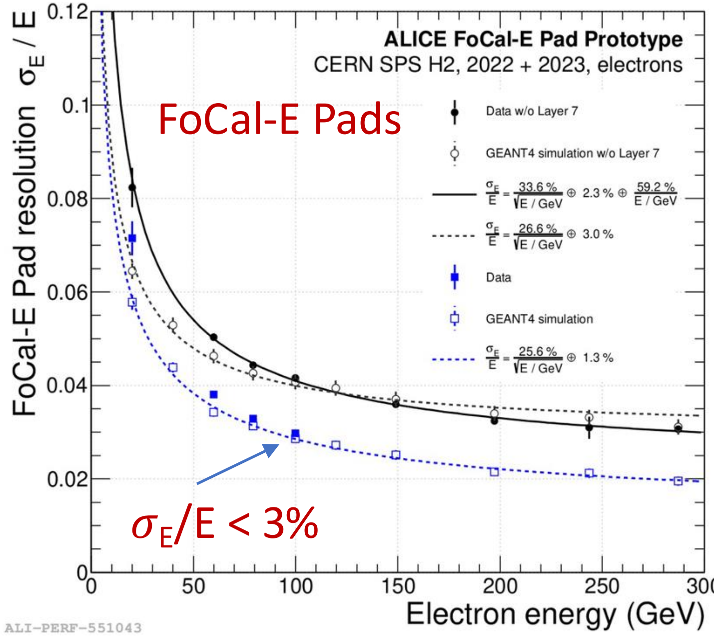
FoCal small prototype setup

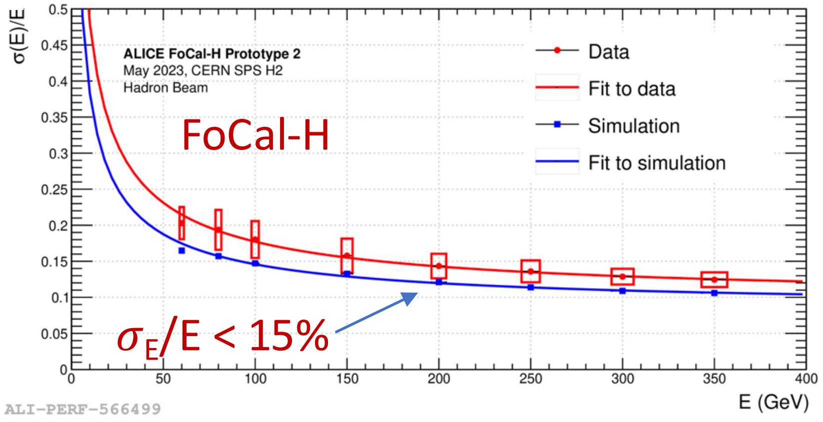
Several tests performed with electron and proton beams











FoCal-E

- ~ 9 x 8 cm^2 transverse size
- 18 pad + 2 pixel layers

FoCal-H

- 9 Cu-scintillator towers
- ~ 20 x 20 cm^2 transverse size

M.Aehle et al. JINST 19 P07006 2024