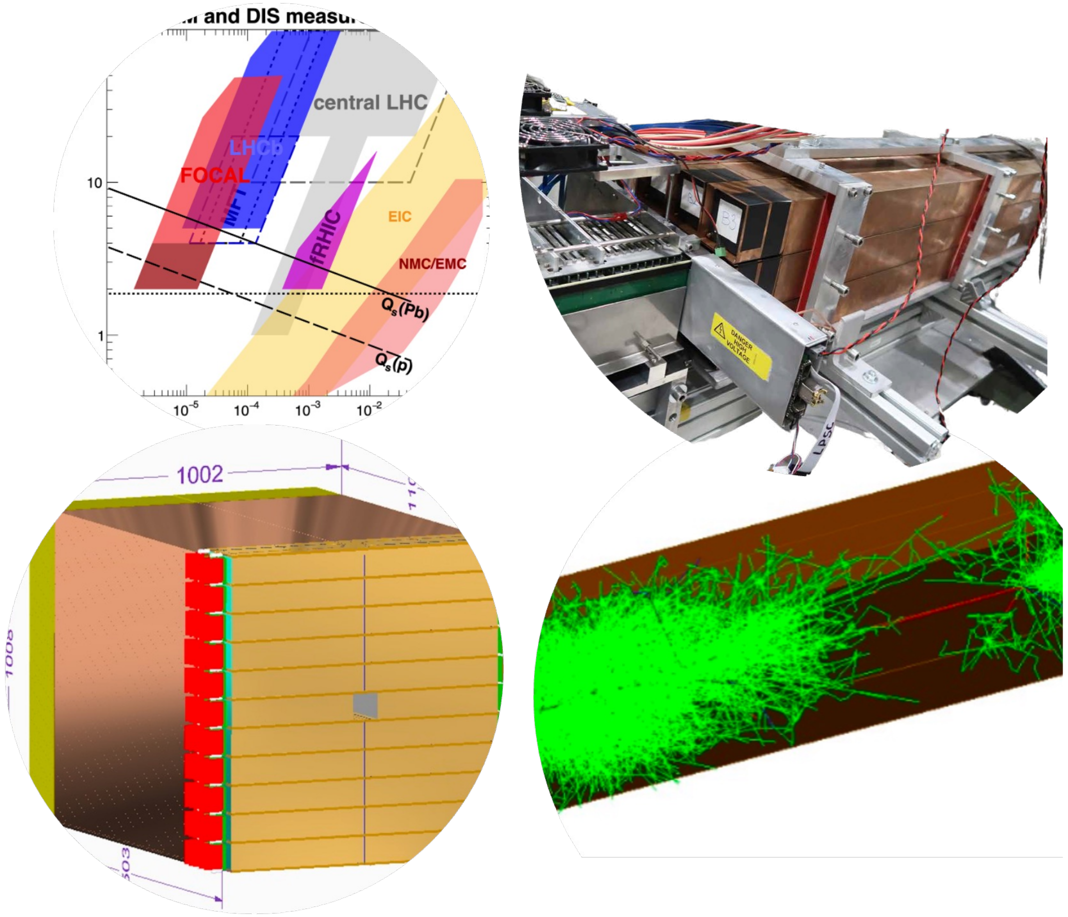
ALICE Forward Calorimeter (FoCal) upgrade: physics program and expected performance

Jacek Otwinowski (IFJ PAN Krakow)

(on behalf of the ALICE Collaboration)

Outline

- FoCal purpose
- Detector design
- Expected performance



FoCal upgrade officially approved as CERN project in April 2024

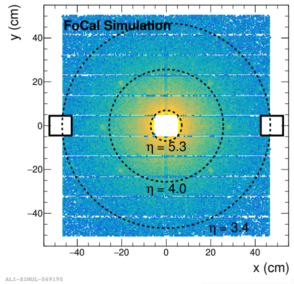
FoCal Letter of Intent: *CERN-LHCC-2020-009*
Physics of the ALICE FoCal upgrade: *ALICE-PUBLIC-2023-001*, *ALICE-PUBLIC-2023-004*
Technical Design Report: *CERN-LHCC-2024-004*
Performance of the FoCal prototype: M.Aehle et al. *JINST 19 P07006 2024*

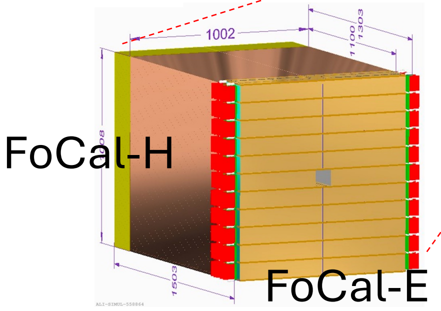
ALICE Forward Calorimeter (FoCal)

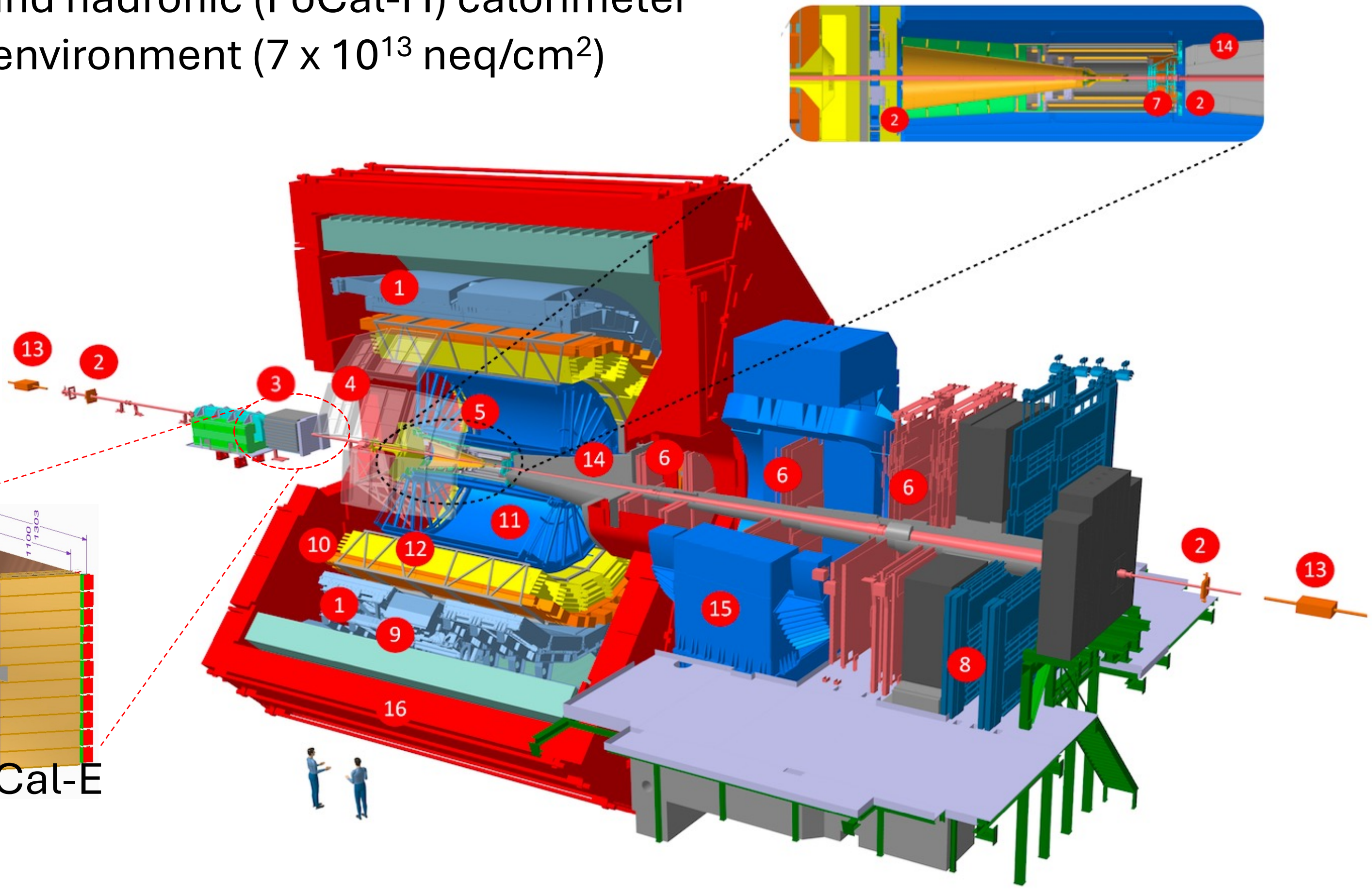
FoCal calorimeter for LHC Run 4 measurements (2029-2032)

CERN-LHCC-2024-004

- FoCal geom. acceptance: $3.2 < \eta < 5.8$
- EM (FoCal-E) and hadronic (FoCal-H) calorimeter
- High radiation environment (7×10^{13} neq/cm^2)





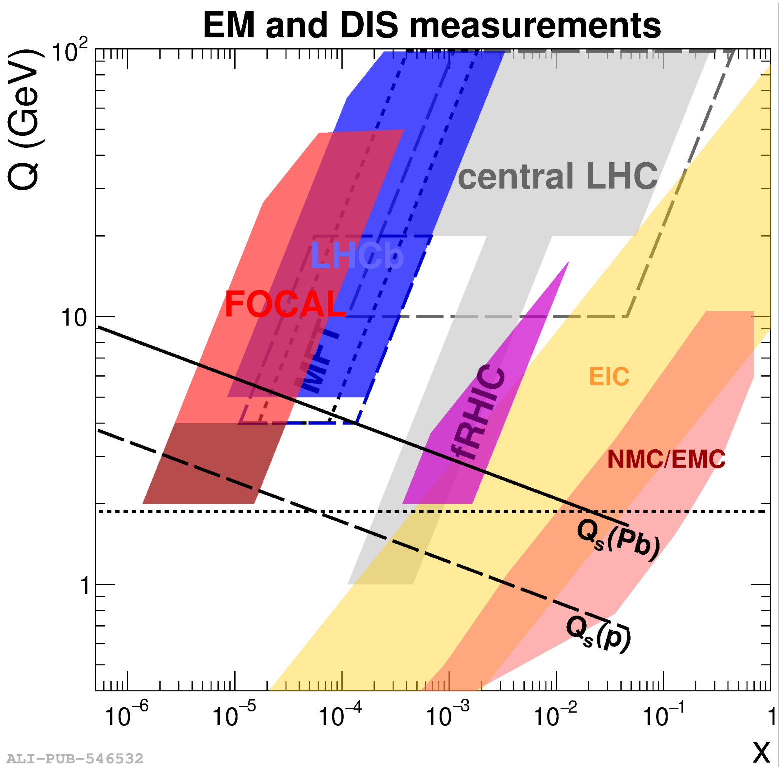


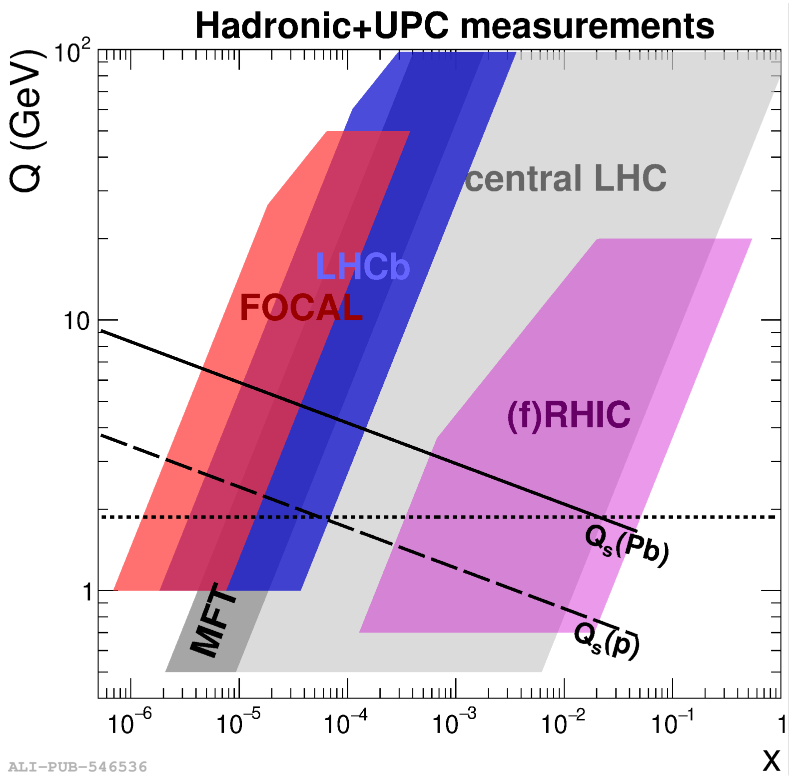
1 **EMCAL |** Electromagnetic Calorimeter
2 **FIT |** Fast Interaction Trigger
3 **FoCal |** Forward Calorimeter (in front of compensator magnet)
4 **HMPID|** High Momentum Particle Identification Detector
5 **ITS|** Inner Tracking System
6 **MCH|** Muon Tracking Chambers
7 **MFT|** Muon Forward Tracker
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**

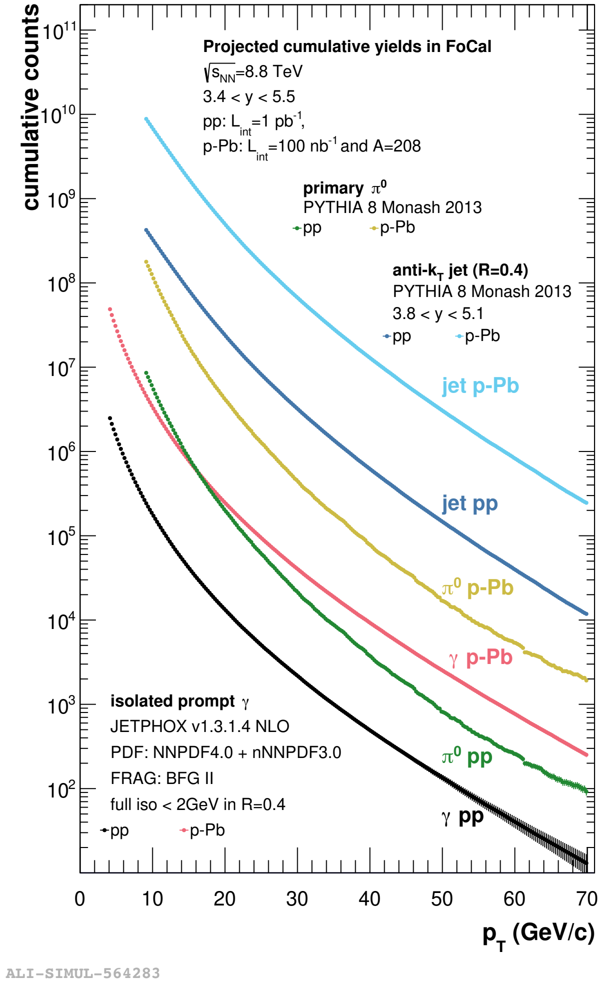
FoCal Purpose

FoCal unique capabilities

Direct γ, neutral hadrons, vector mesons and jets measurements in pp, p-Pb and UPC collisions at the LHC

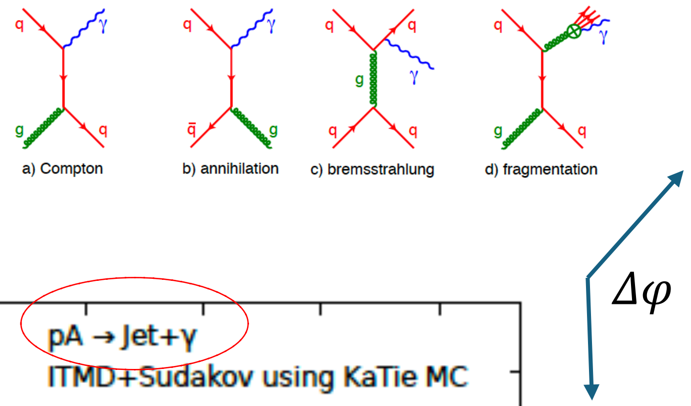






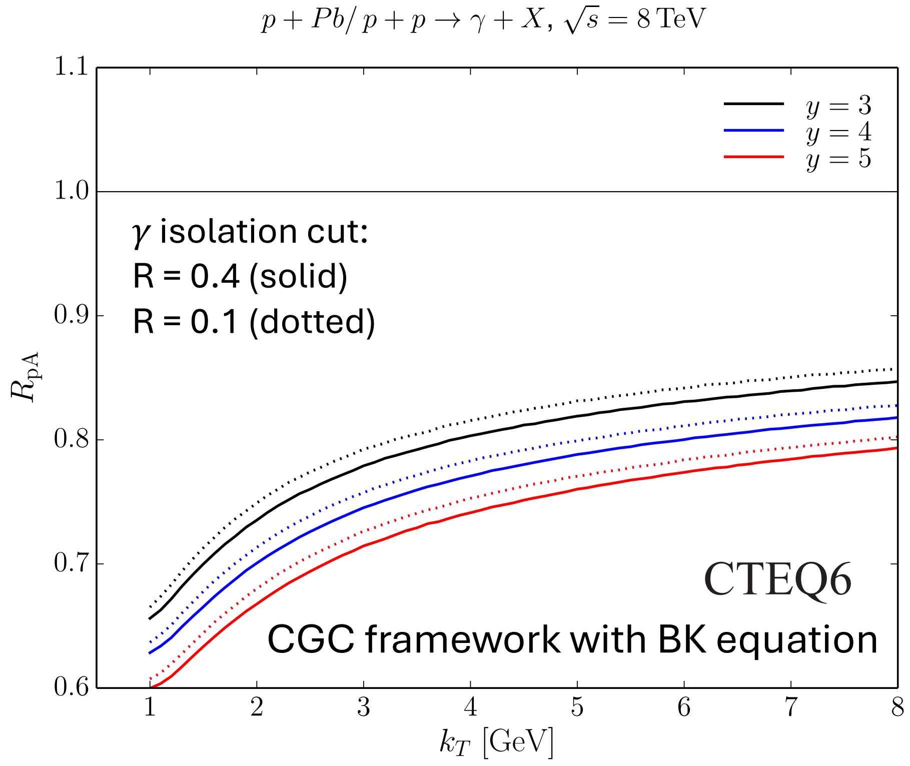
ALICE-PUBLIC-2023-001

Direct γ and γ-jet measurements

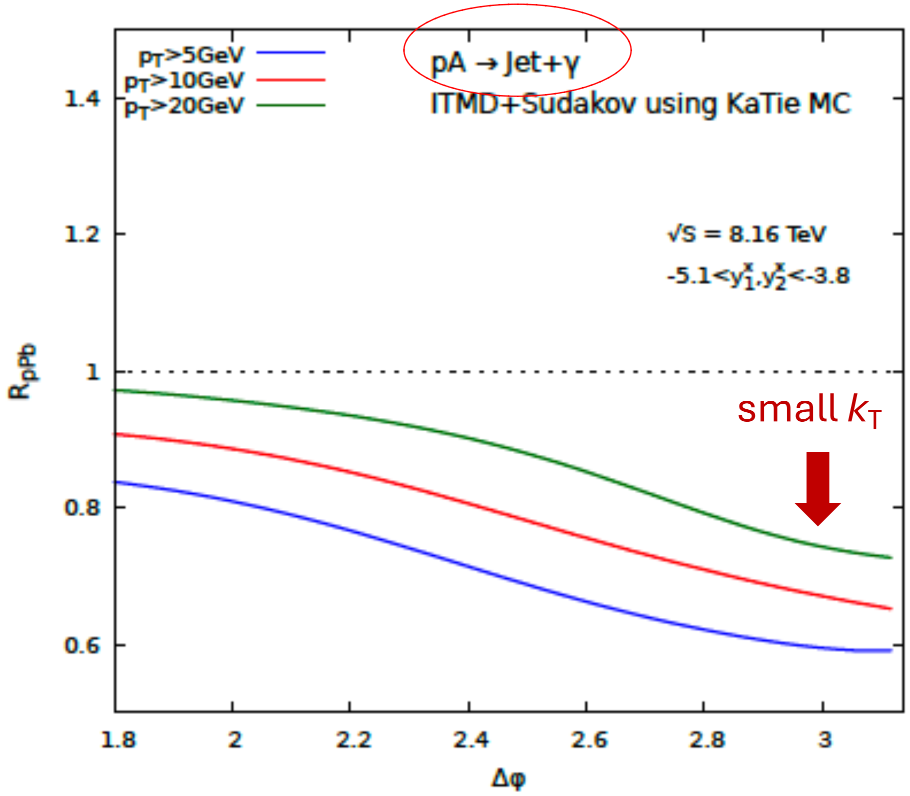


Nuclear modification factors $R_{\mathrm{pPb}} = Y_{\mathrm{pA}} / N_{\mathrm{bin}} Y_{\mathrm{pp}}$

→ strong suppression due to gluon saturation in Pb nuclei



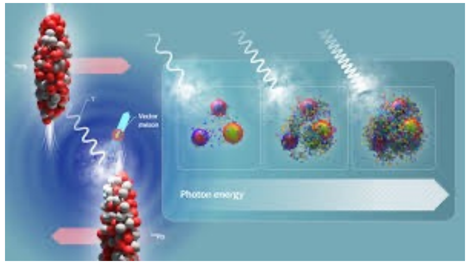
B. Ducloué, T. Lappi, H. Mäntysaari *Phys. Rev. D 97, 054023 (2018)*

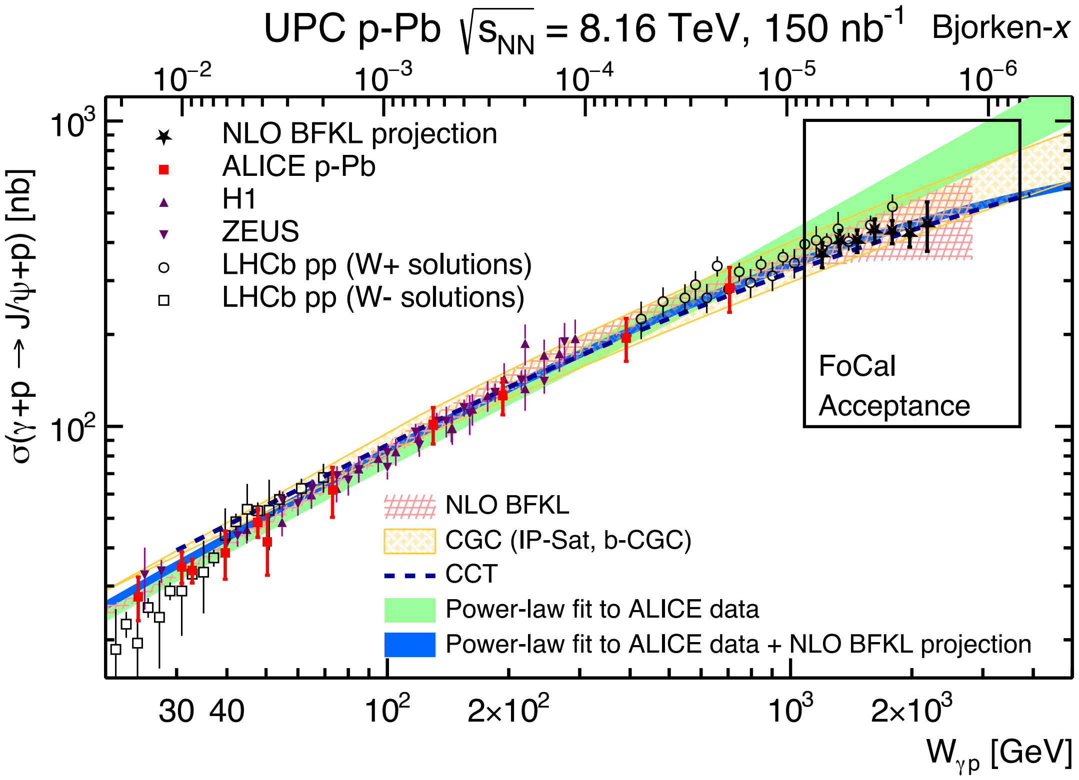


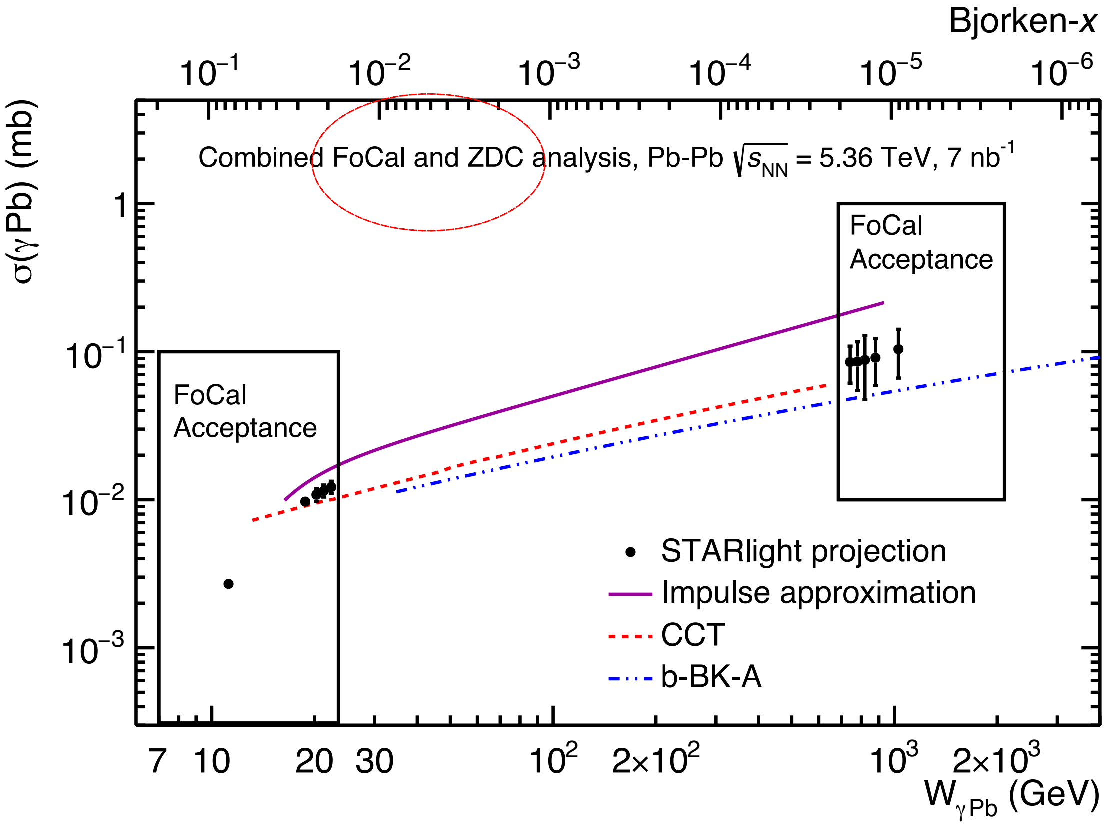
*M. Abdullah Al-Mashad, A. van Hameren, H. Kakkad, **P. Kotko**, K. Kutak, P. van Mechelen S. Sapeta arXiv.2210.06613*

J/ψ production in p-Pb and Pb-Pb UPC

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





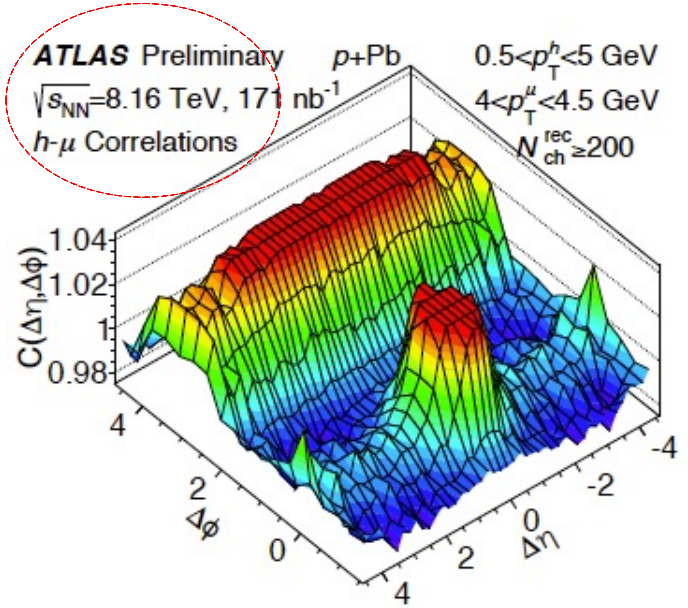


A. Bylinkin, J. Nystrand, D. Tapia Takaki arXiv:2211.16107

Initial vs final state momentum anisotropies

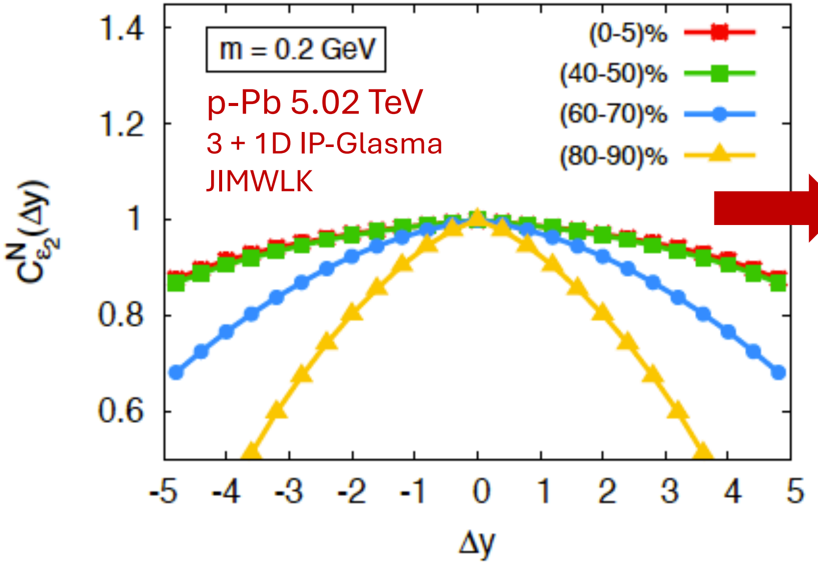
Initial vs final state momentum anisotropies in small colliding systems → origin of long-range correlations?

Long-range correlations

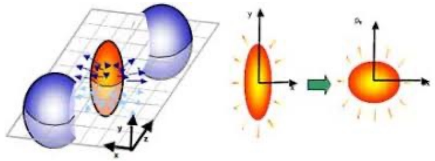


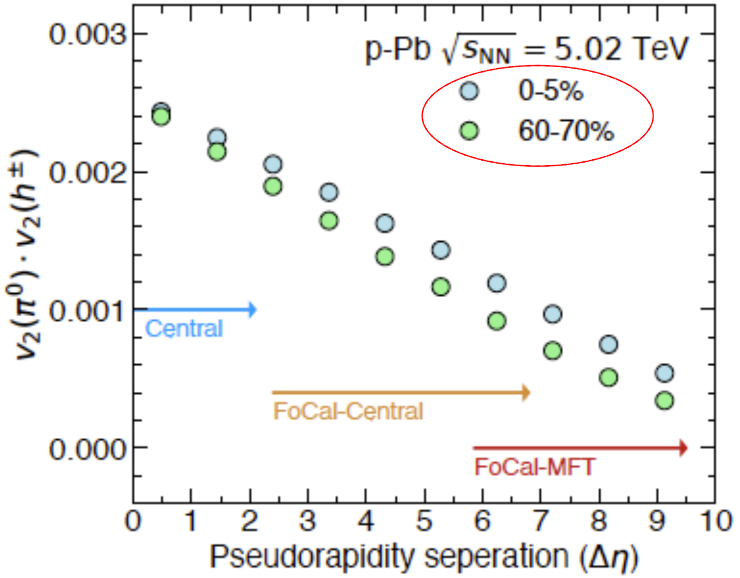
ATLAS-CONF-2017-006

$$C^N_{\varepsilon_2}(\Delta y) = \frac{\langle \varepsilon_2(y_1)\varepsilon_2(y_2)\rangle}{\sqrt{\langle \varepsilon_2(y_1)^2\rangle\langle \varepsilon_2(y_2)^2\rangle}}$$



B. Schenke, S. Schlichting, and P. Singh
Phys. Rev. D105 (2022) 094023



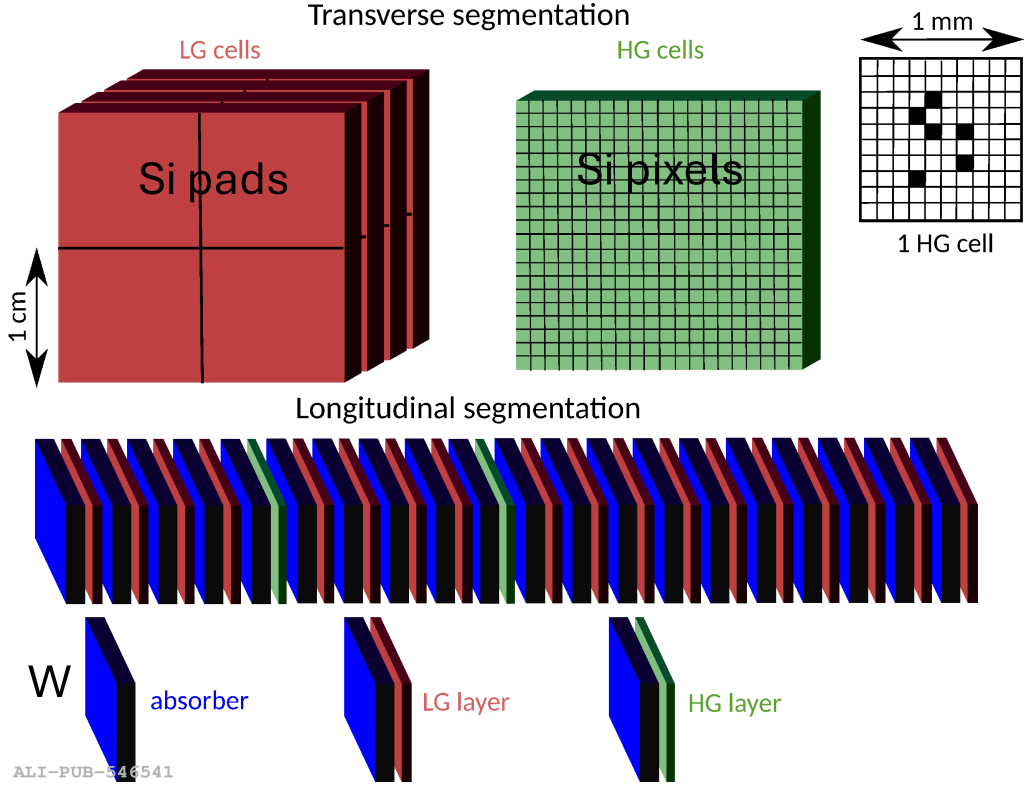


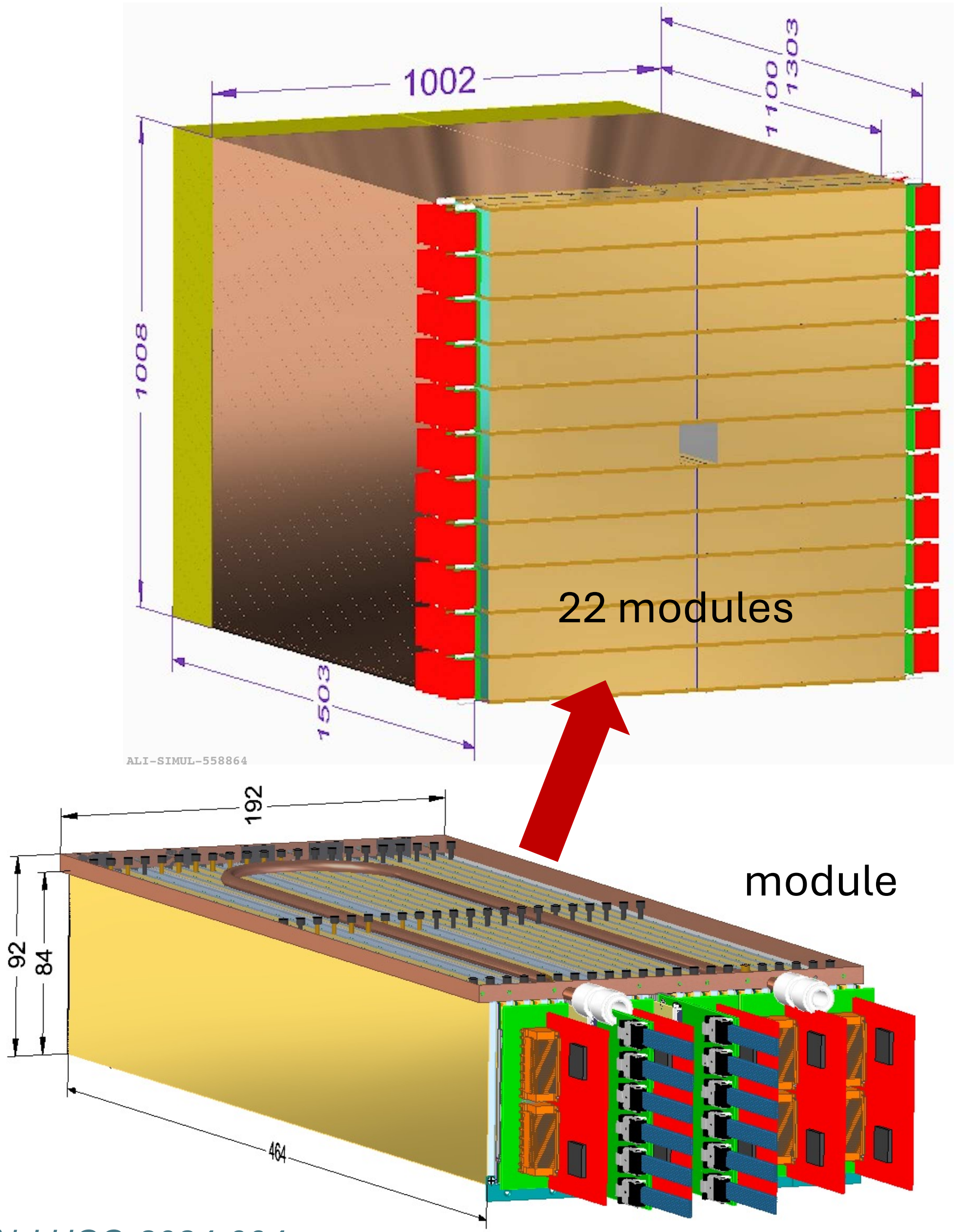
ALICE-PUBLIC-2023-001

Detector design

FoCal-E design

- Si+W electromagnetic calorimeter (~20 X_0)
- 18 Si pad (LG)+ 2 Si pixel (HG) sensor layers
- Si pad ~ 1 x 1 x 0.03 cm^3 (p-type, Hamamatsu Photonics)
- Si pixel ~ 30 x 30 x 100 μm^3 (ALPIDE/MAPS)

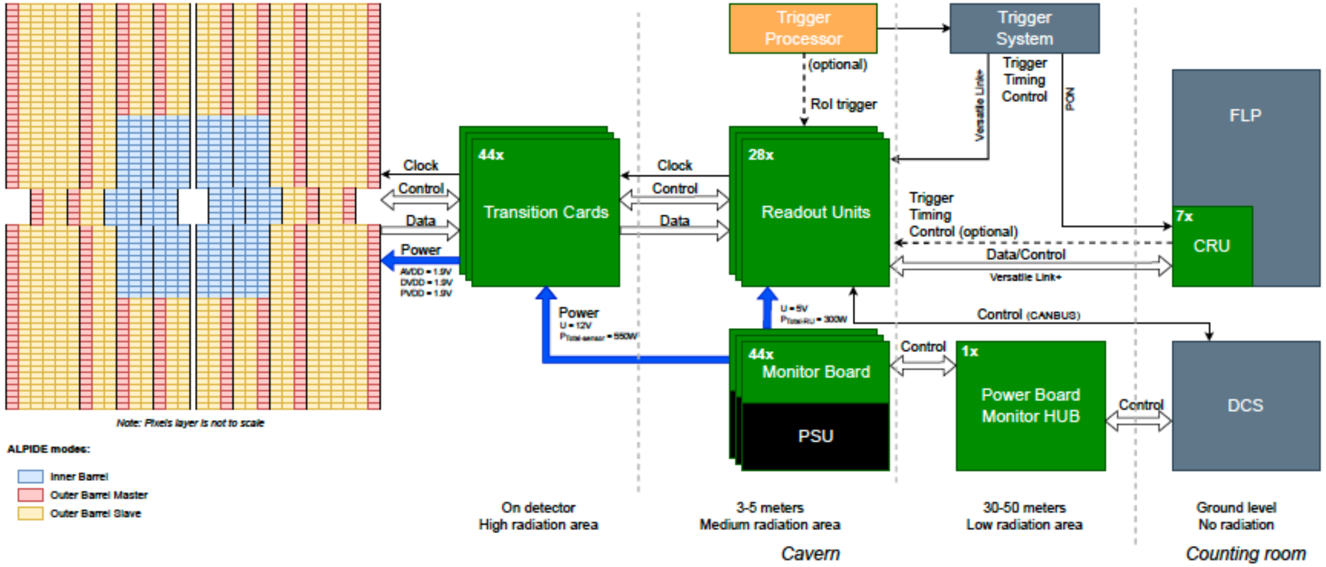




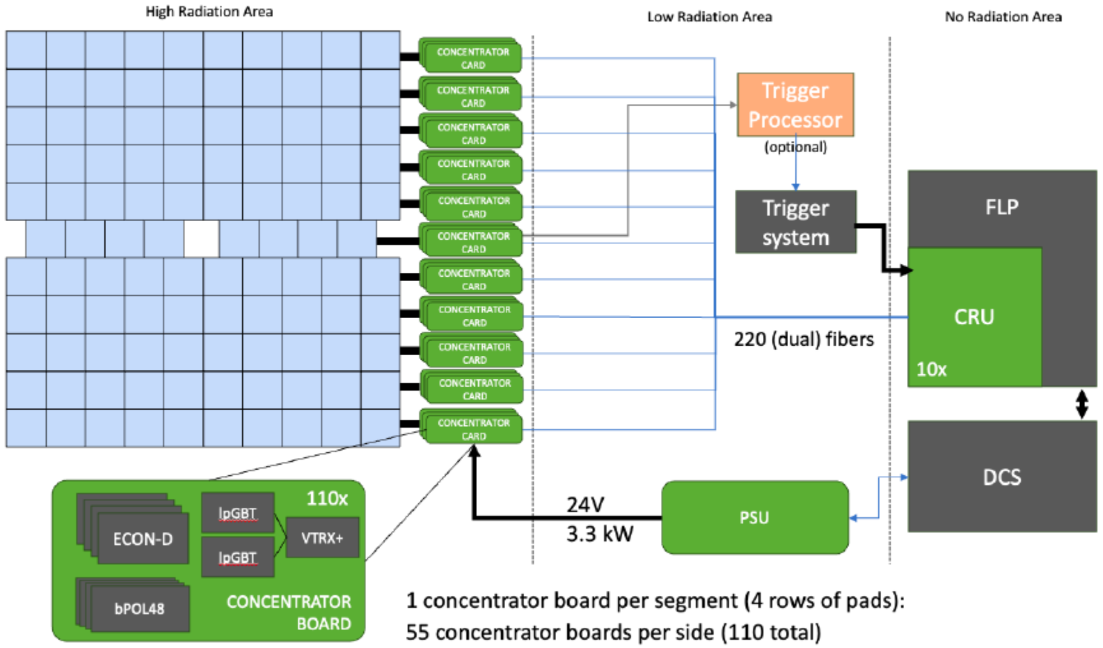
CERN-LHCC-2024-004

FoCal-E readout

Si Pixel Layers



Si Pad Layers



- 3888 ALPIDE chips (ADC)
- Data rate (2 pixel layers): 65 - 320 Gbps

- 1944 HGCROC chips (ToA, ADC and ToT)
- Data rate (18 pad layers): 110 – 170 Gbps

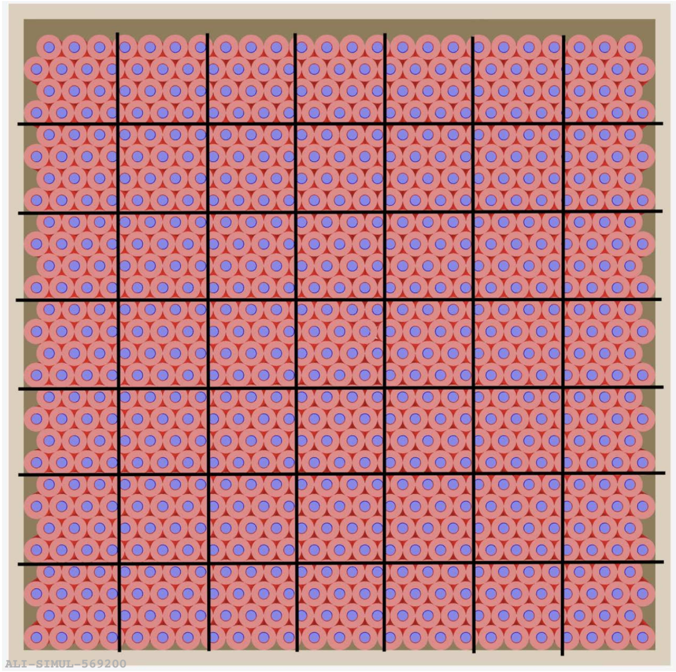
G. A. Rinella, ALICE Coll., [Nucl. Instrum. Meth. A845 (2017) 583]

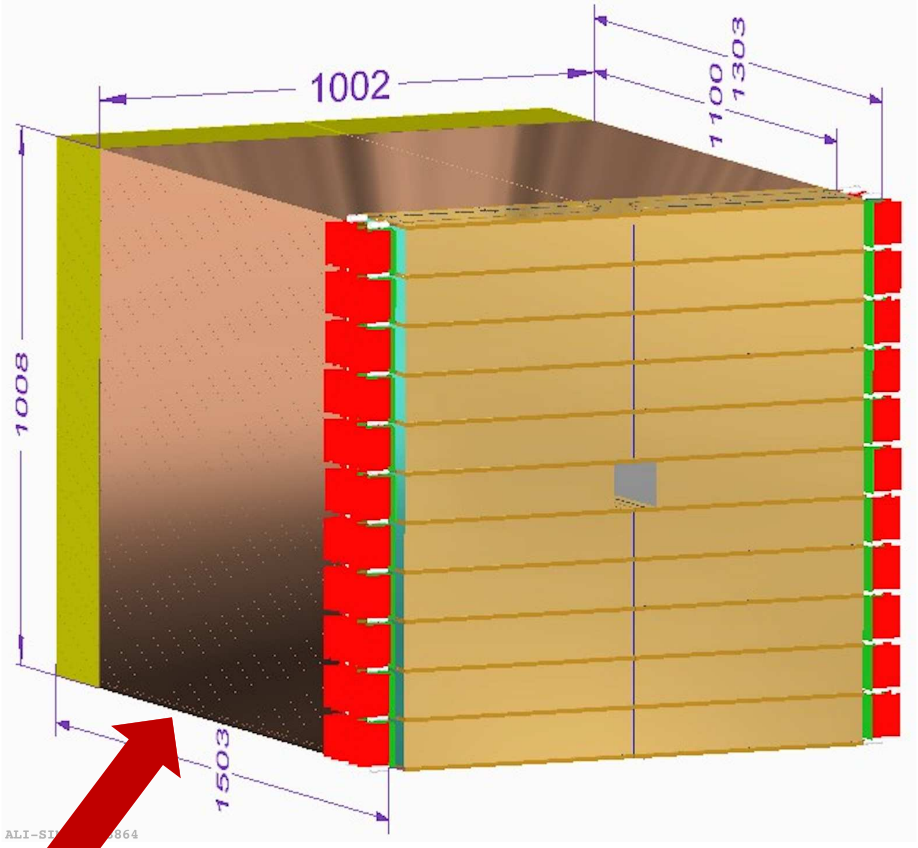
F. Bouyjou et al. [JINST 17 (2022) C03015]

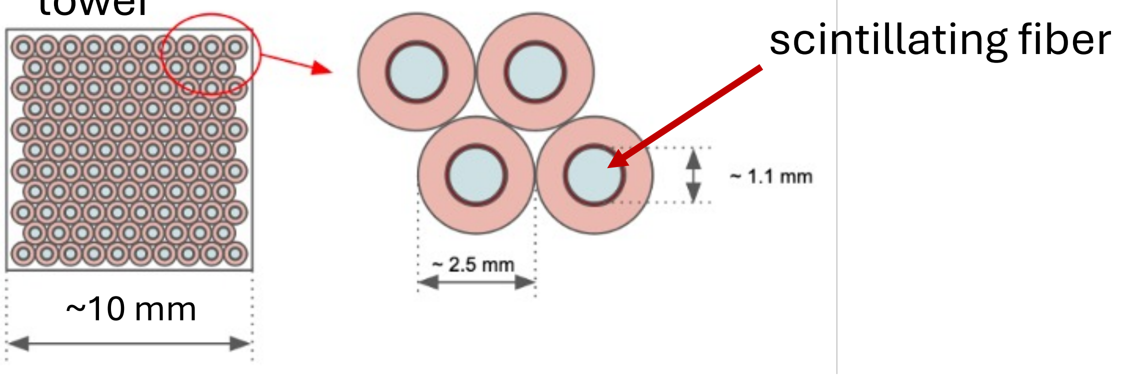
[CERN-LHCC-2024-004]

FoCal-H design

- Cu capillary tubes + scintillation fibers
- 1 x 1 cm^2 towers with SIPM readout (~10000 ch.)
- Thickness ~ 1m (~5 x λ_{int})

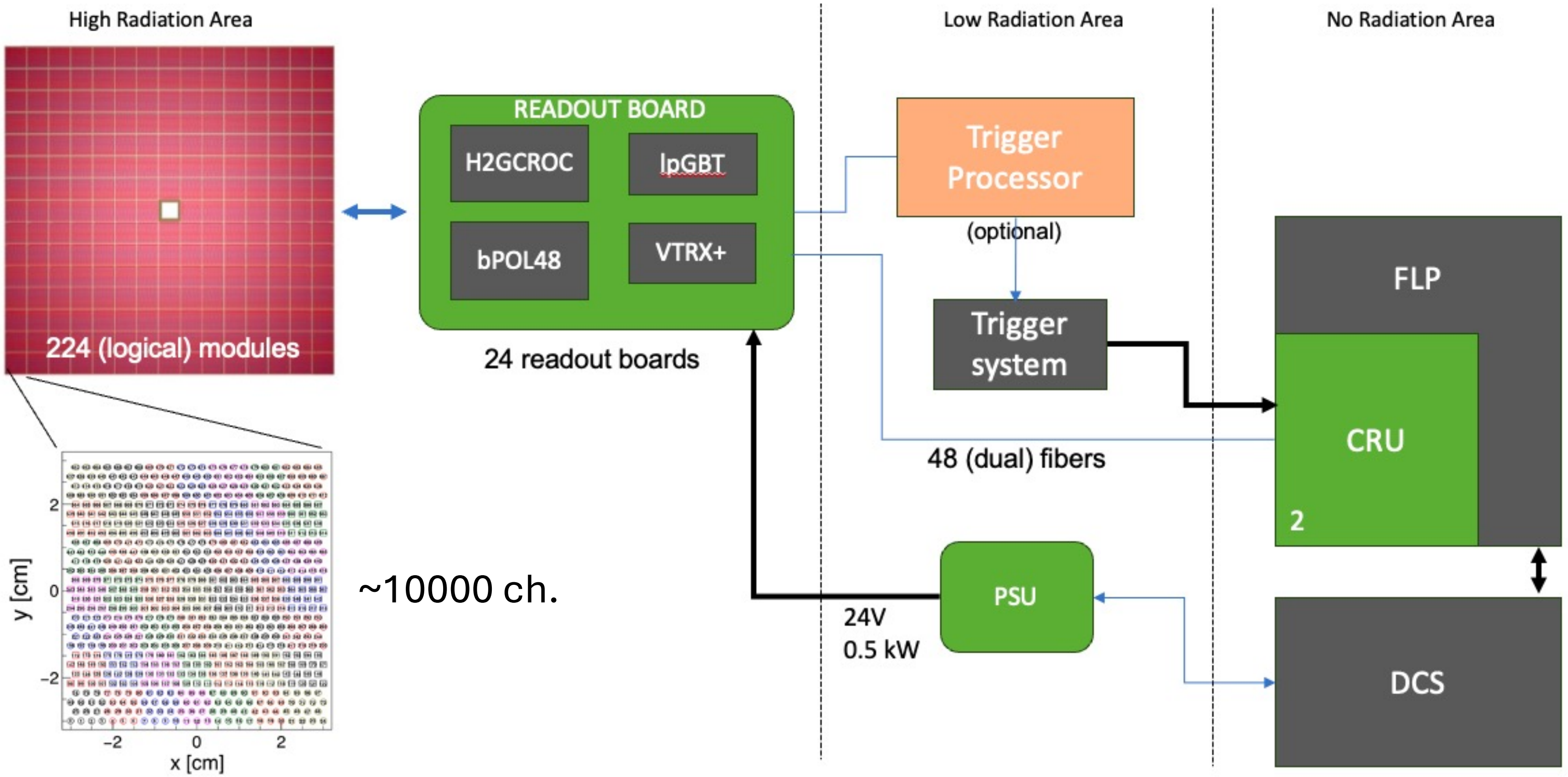






CERN-LHCC-2024-004

FoCal-H readout



- H2GCROC chips for SiPM readout with programmable gain (ToA, ADC and ToT)
- Data rate: 13 – 21 Gbps

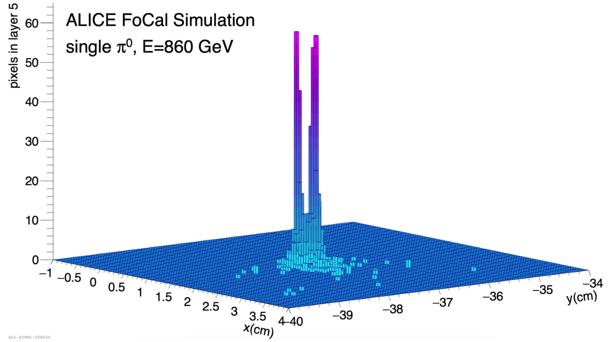
F. Bouyjou et al. *JINST 17 (2022) C03015*

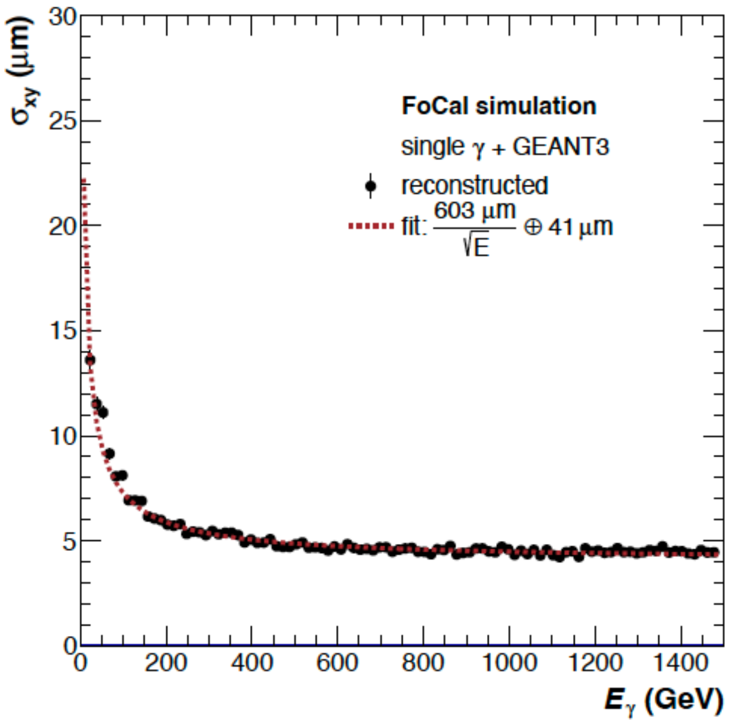
CERN-LHCC-2024-004

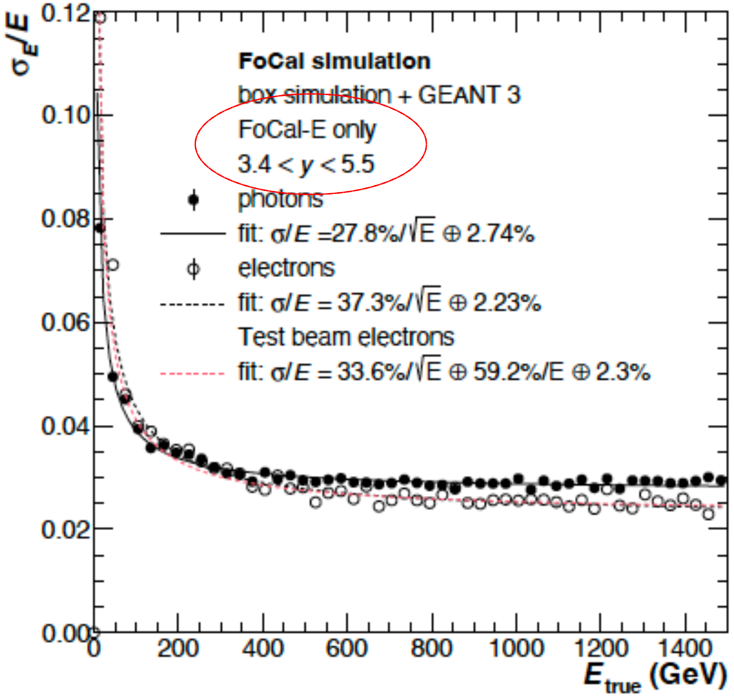
Expected performance

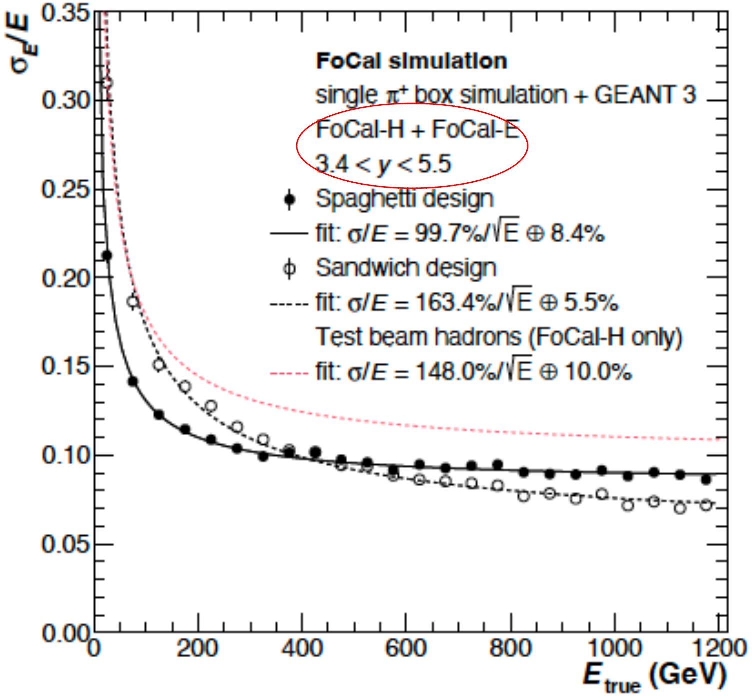
Position and energy resolution

- Good position resolution required for direct γ and π^0 measurements
- Reasonably good energy resolution for γ isolation and jet reconstruction



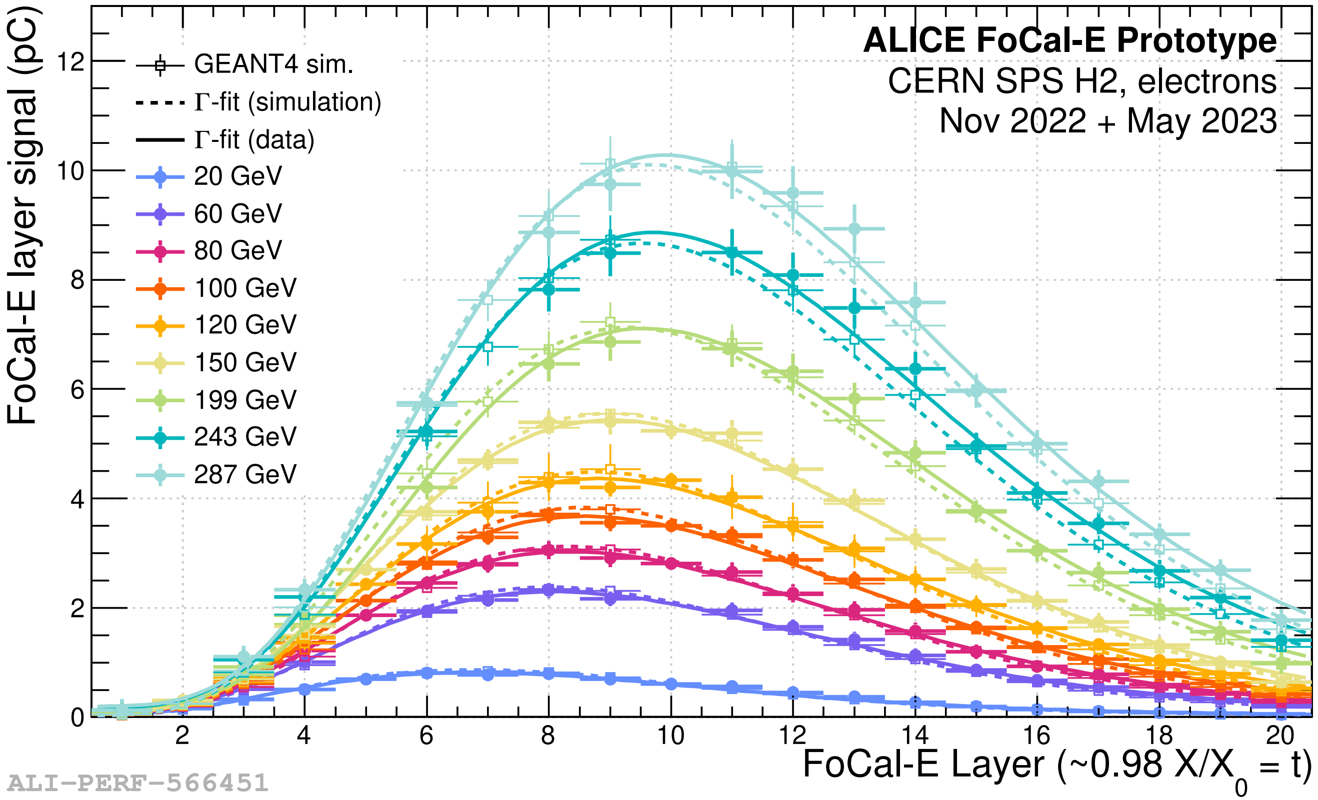






ALICE-PUBLIC-2023-004

FoCal-E longitudinal shower profile



- Good agreement between data and simulations
- Parametrized with Γ function

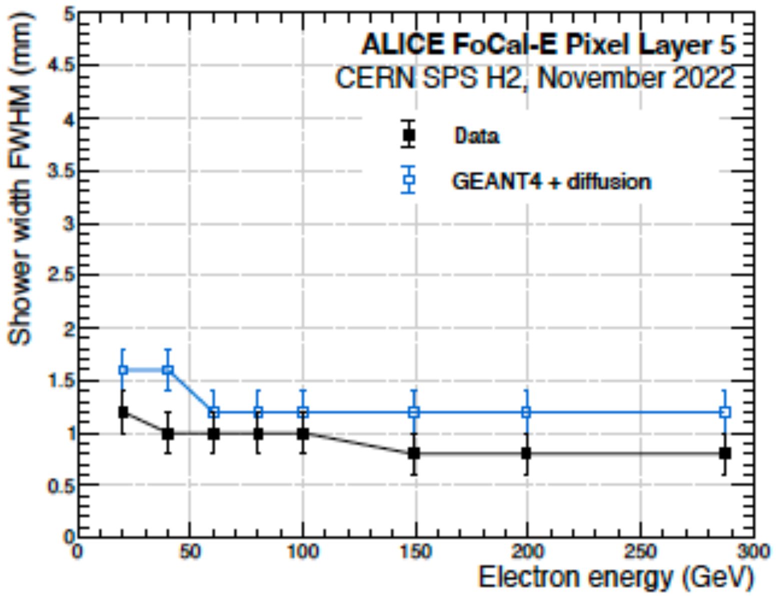
$$\frac{dQ}{dt} = Q_E\,\beta\,\frac{(\beta t)^{\alpha-1}e^{-\beta t}}{\Gamma(\alpha)} + Q_0$$

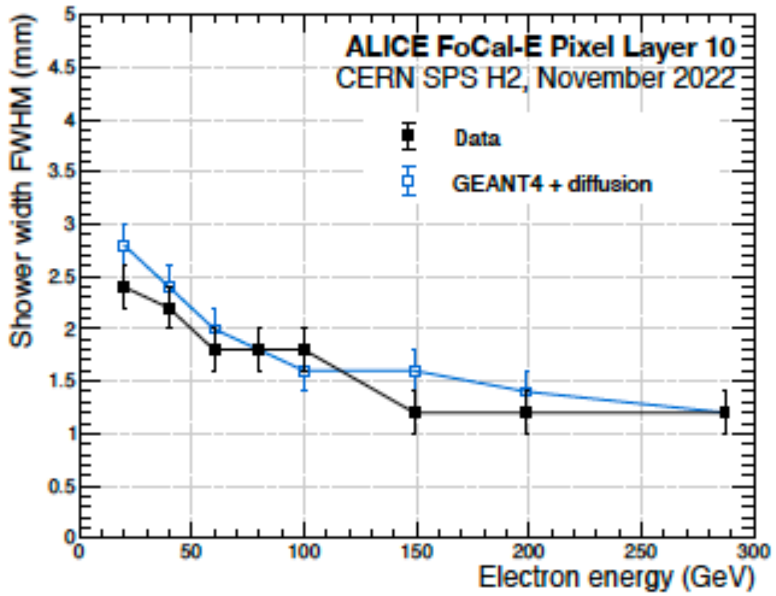
$$\Gamma(\alpha) = \int_0^\infty e^{-z} z^{\alpha-1}\,dz$$

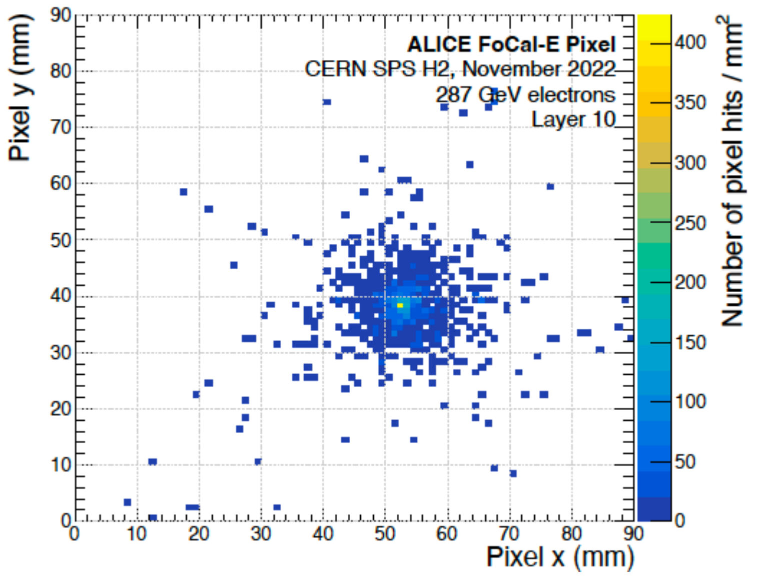
M.Aehle et al. JINST 19 P07006 2024

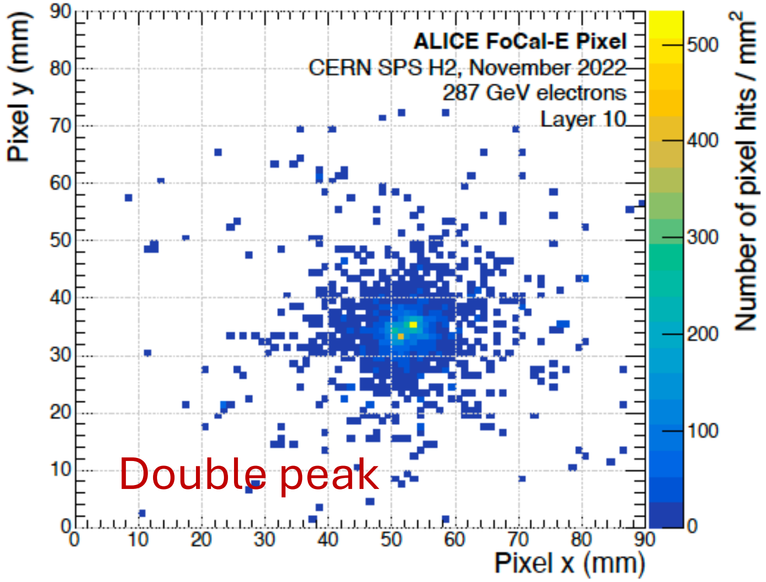
FoCal-E pixel transverse profiles

Good agreement between data and simulations





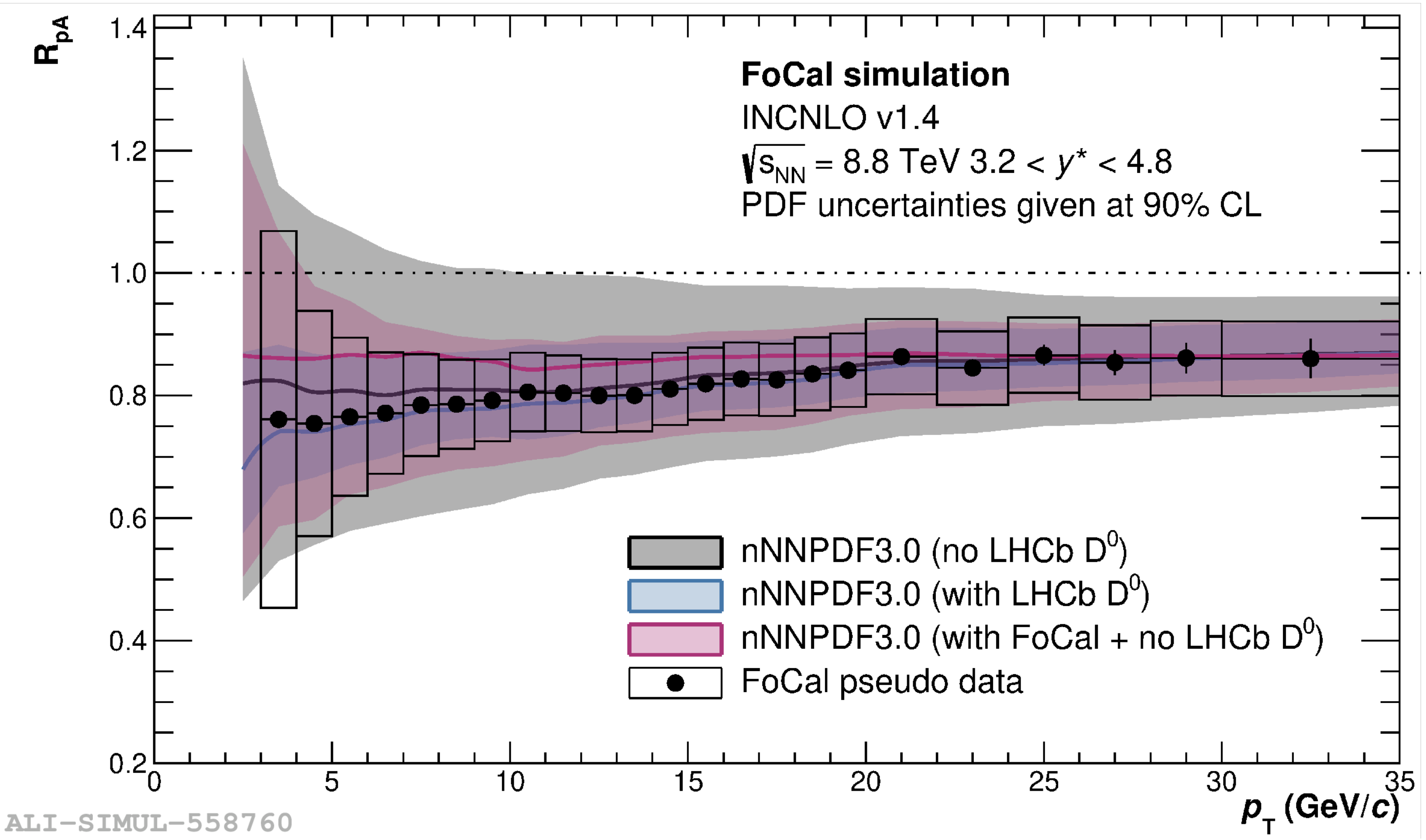




M.Aehle et al. [JINST 19 P07006 2024]

R_{pPb} of prompt γ in simulations

FoCal pseudo-data for constraining nPDFs



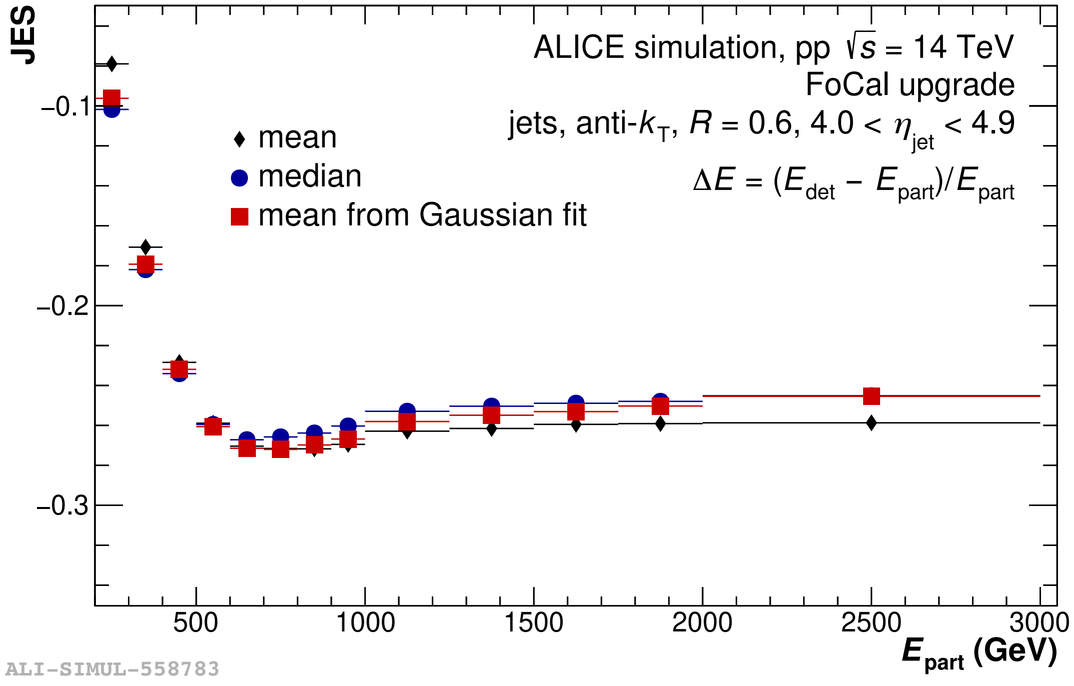
- R_{pPb} obtained with INCNLO including stat. and syst. uncertainties
- No correlation between syst. uncertainties in pp and p-Pb collisions
- Comparison to nNNPDFs calculations including FoCal pseudo-data
- Prompt γ not affected by the FS effects and fragmentation

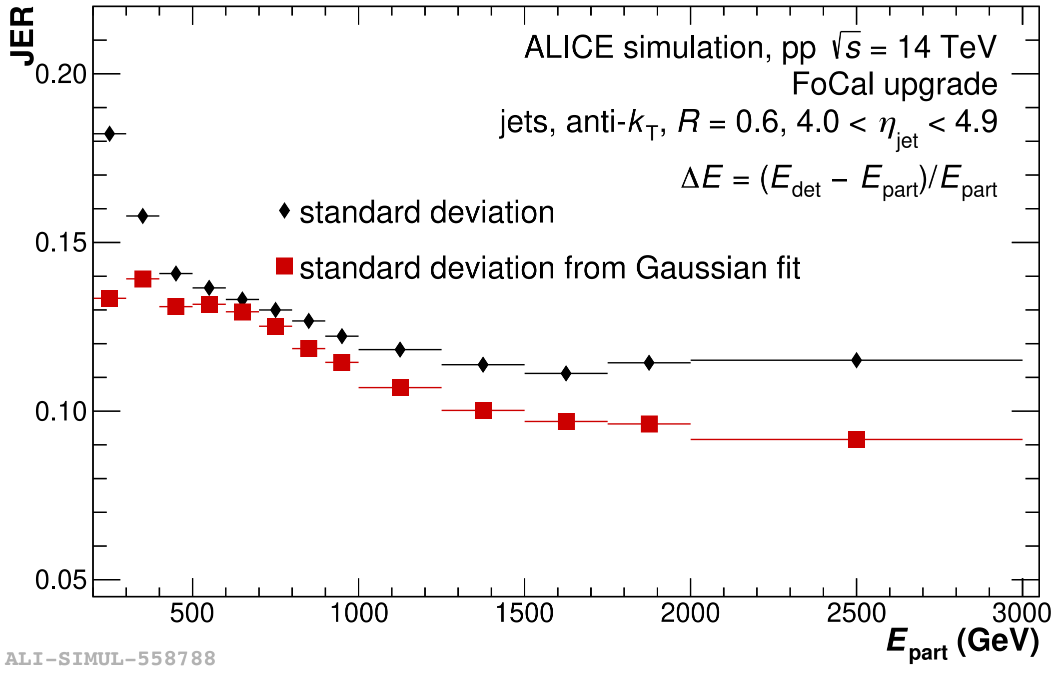
ALICE-PUBLIC-2023-004

P. Aurenche et al. Eur. Phys. J. C 9 (1999)107

Jet reconstruction performance

Jet energy scale (JES) and resolution (JER)





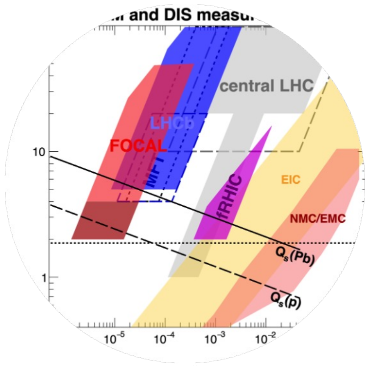
- Jet reconstruction bias < 25%
- Non-Gaussian tails at small energy jets

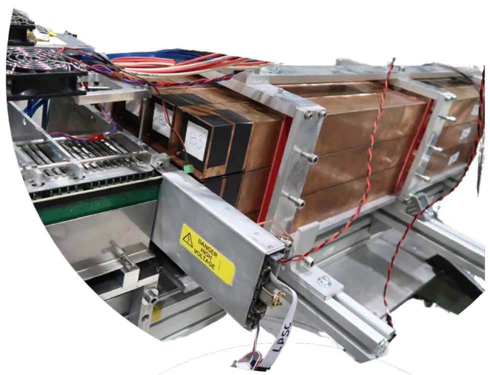
ALICE-PUBLIC-2023-004

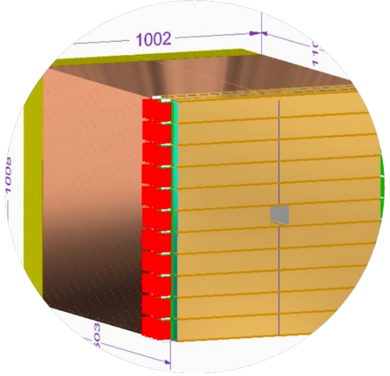
Summary and Outlook

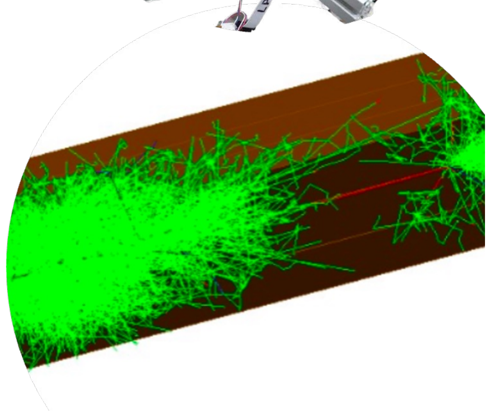
- FoCal upgrade officially approved as CERN project
- FoCal has unique capabilities to study low-x physics
- FoCal performance in test measurements as expected

- FoCal R&D is still ongoing (mechanics, cooling system and FEE)
- Detector installation at CERN in 2028 for Run 4 data taking
- Discussions about FoCal impact on ALICE 3 for Run 5 – 6
    - Precision measurements over 10 units in η









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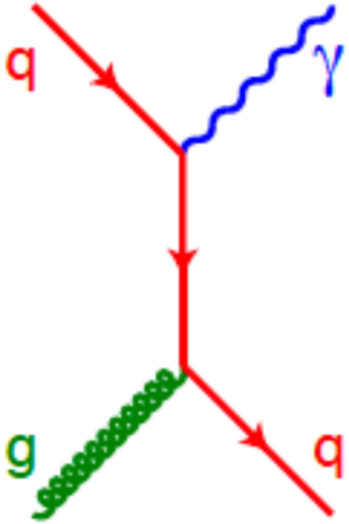
Performance of the FoCal prototype: M.Aehle et al. *JINST 19 P07006 2024*

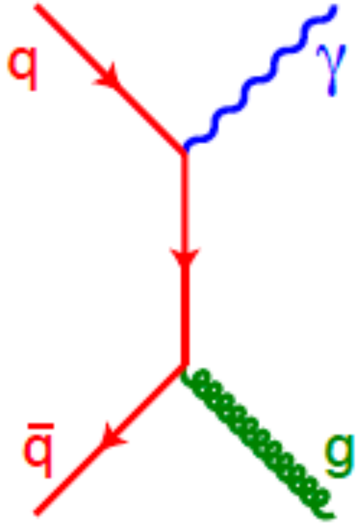
ALICE 3 Letter of Intent: CERN-LHCC-2022-009

Backup

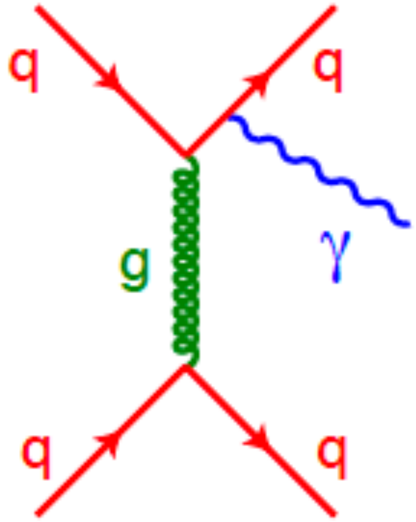
Direct photons



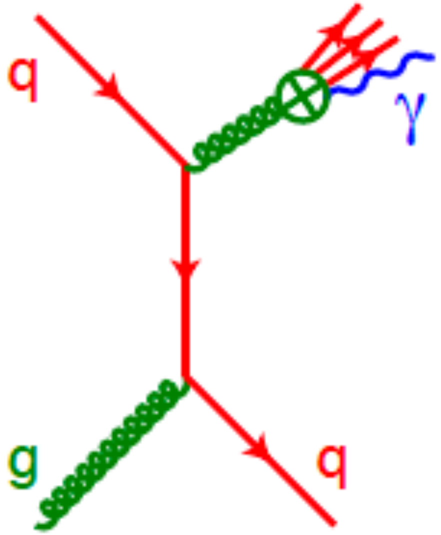
a) Compton



b) annihilation



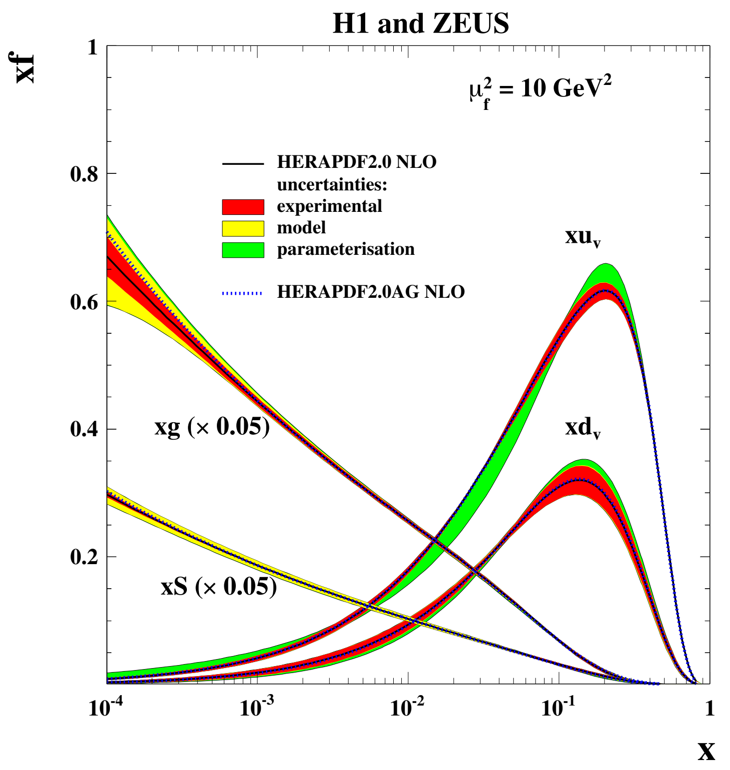
c) bremsstrahlung



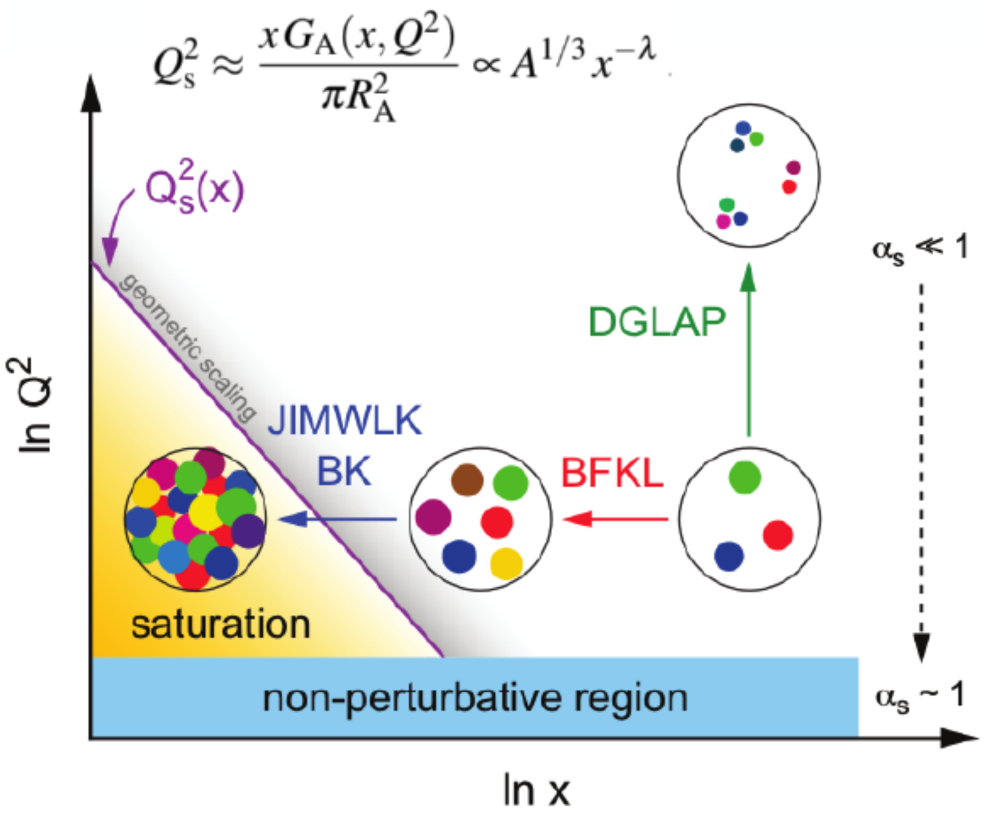
d) fragmentation

Explore QCD matter at the smallest Bjorken-*x*

- Partonic structure at small *x* and gluon saturation
- Non-linear QCD evolution
- Transition to Color Glass Condensate (CGC)



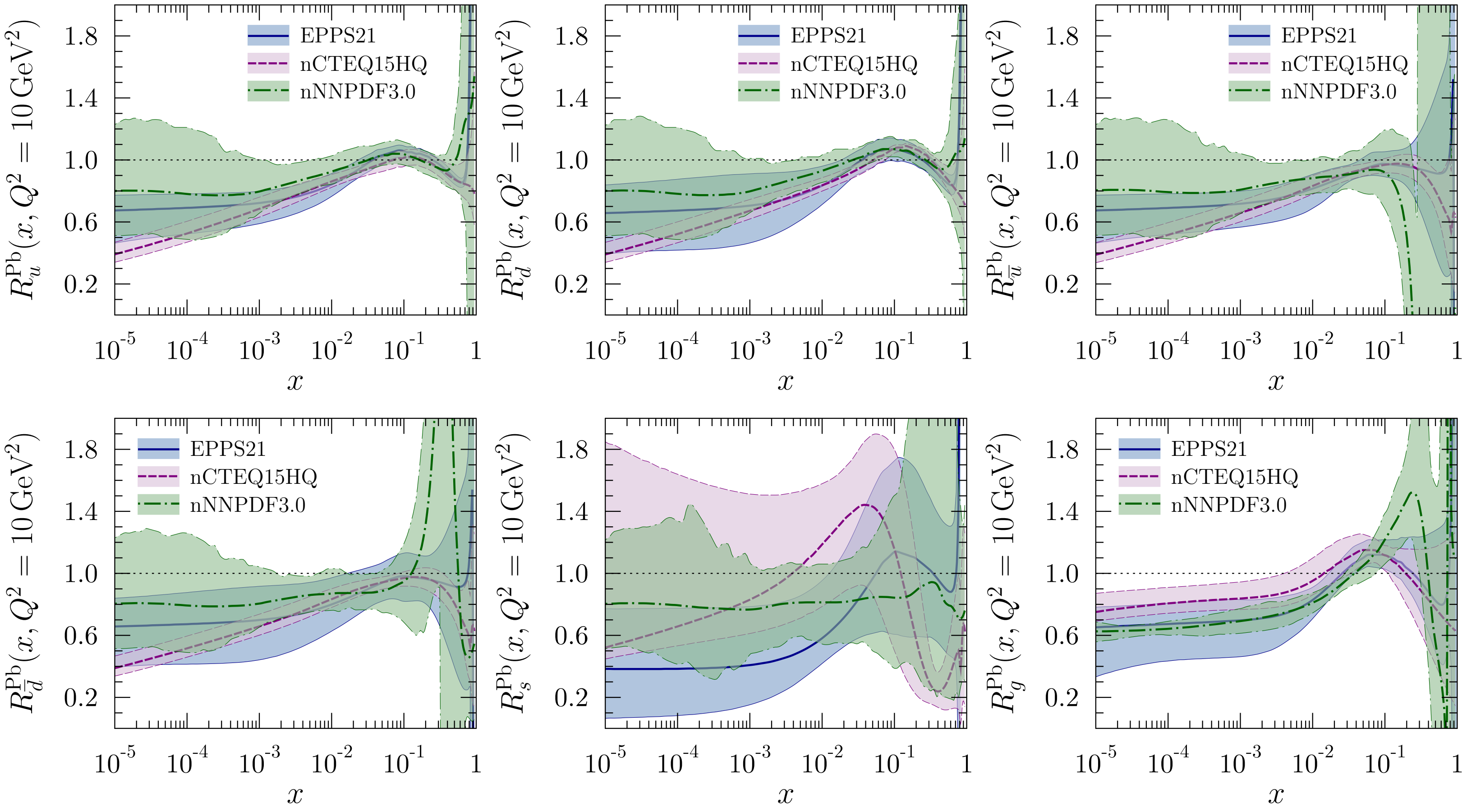
H. Abramovicz et al. Eur.Phys.J.C75 (2015) 580



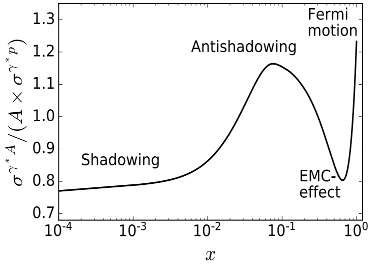
E. Iancu et al. Nucl. Phys. A692 (2001) 583

Nuclear PDFs

State-of-the-art analyses including electroweak-boson, jet, light-hadron, and heavy-flavor observables

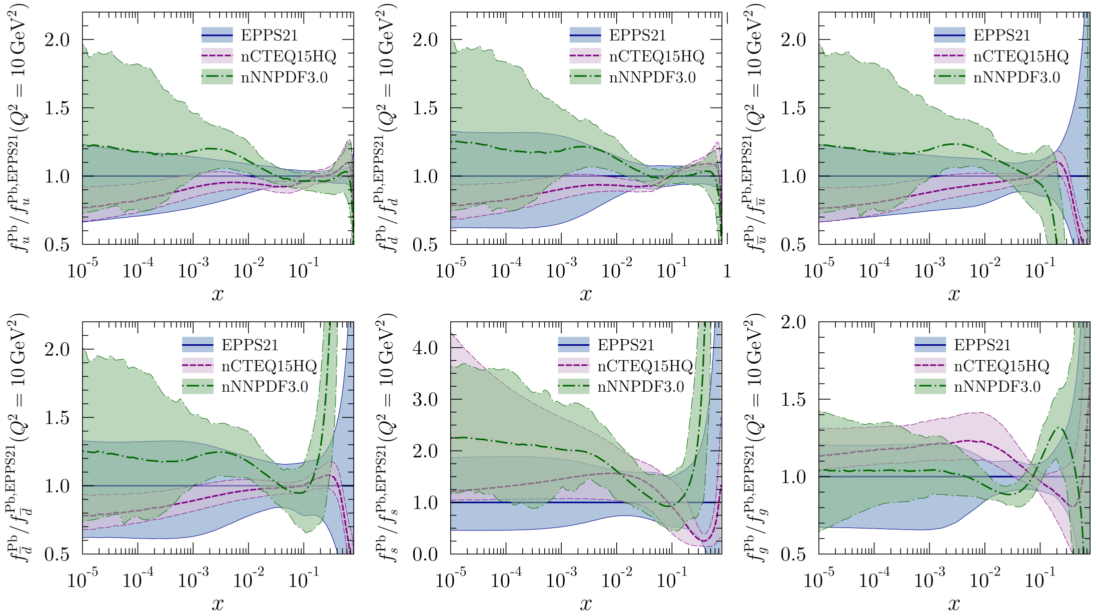


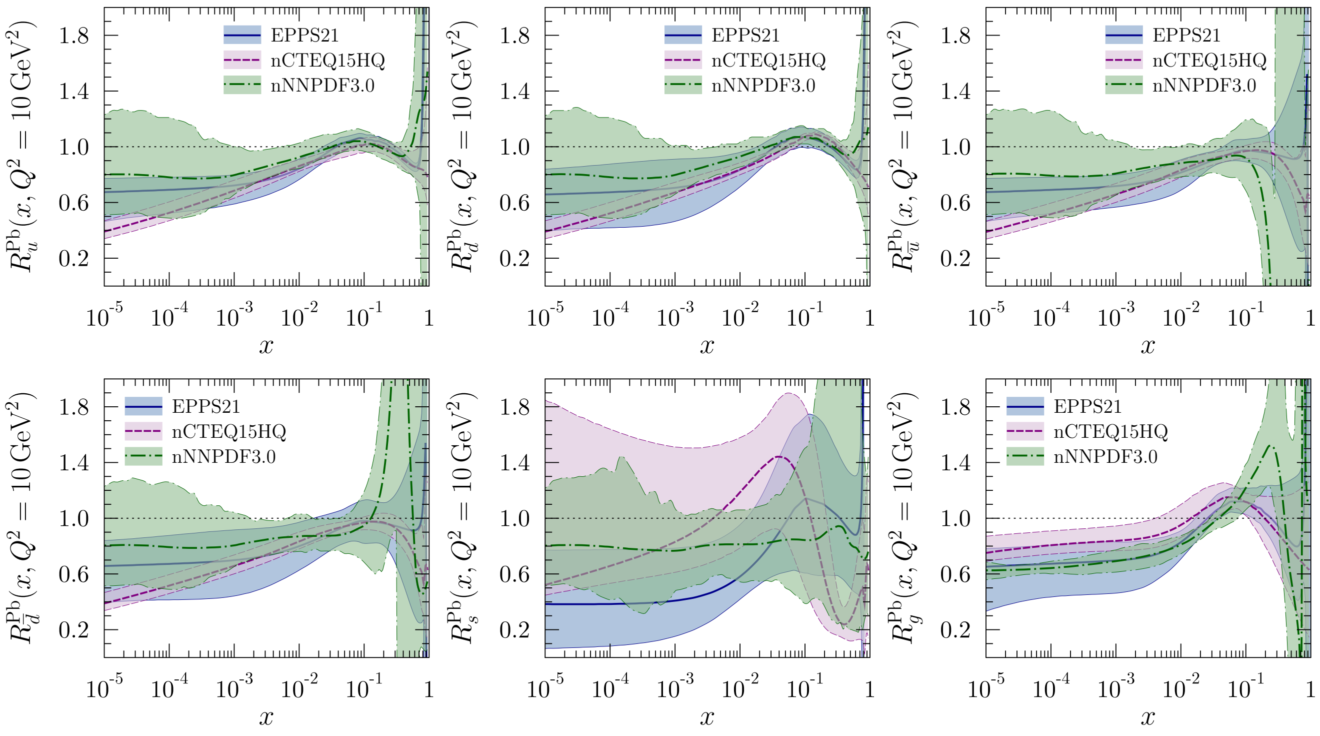
$f_A = R \cdot f_N$

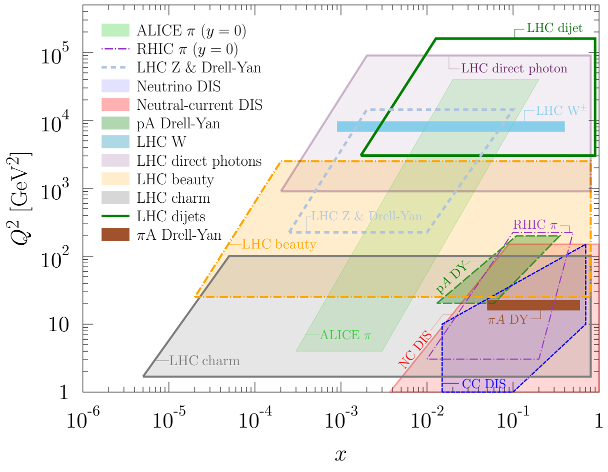


M. Kalssen & H Pakkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024)1–41

FoCal Purpose





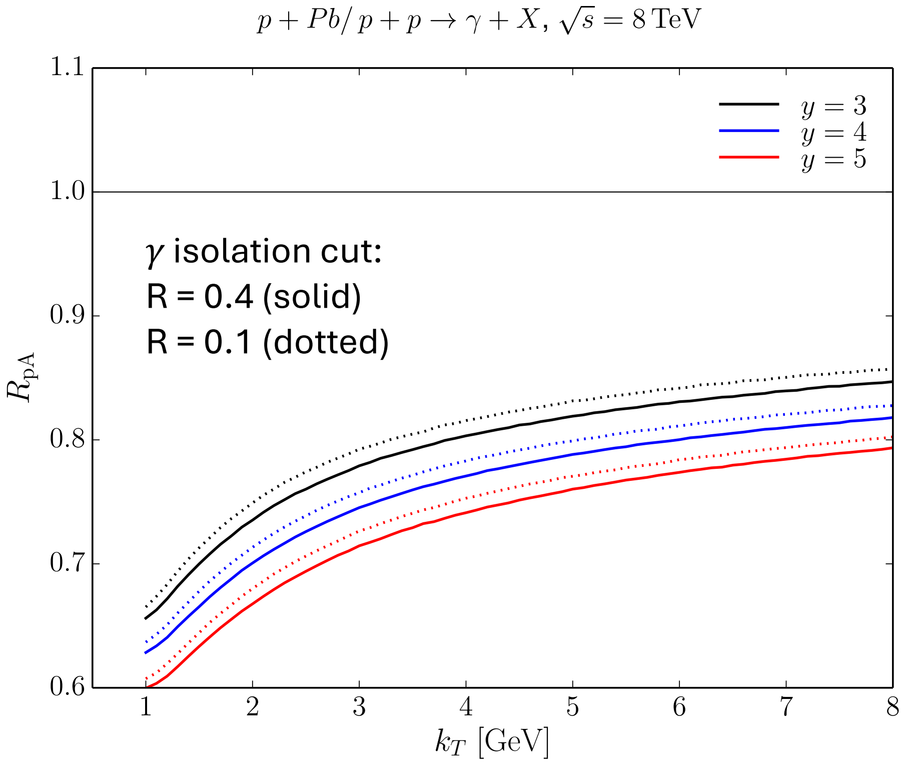


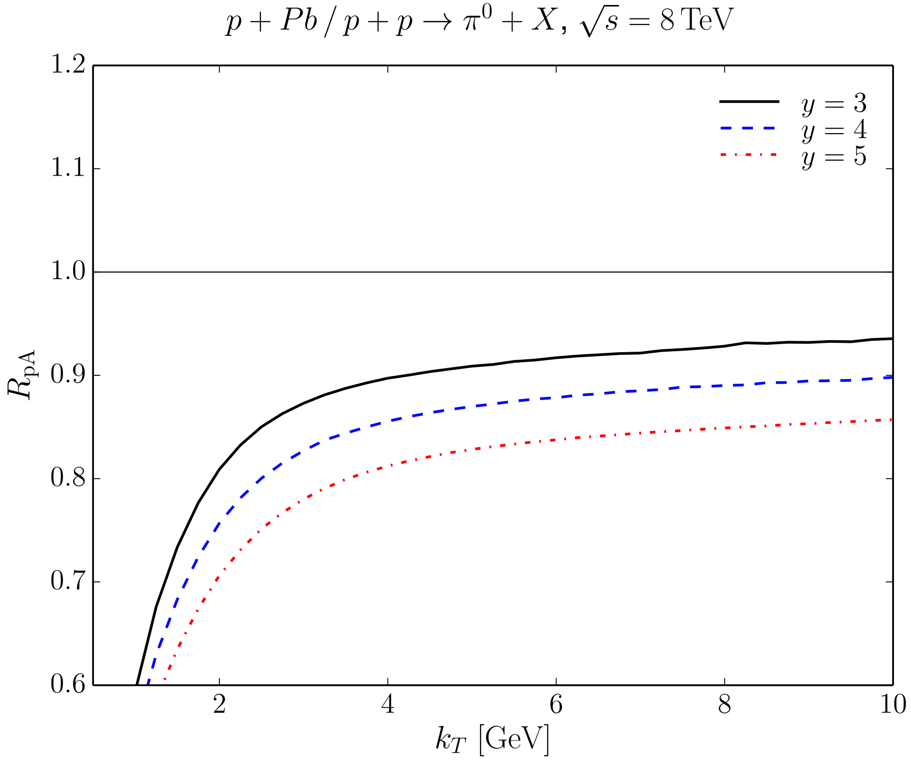
[M. Klasen & H. Paukkunen arXiv:2311.00450]

Direct γ and π^0 measurements

Nuclear modification factors $R_{pPb} = Y_{pA} / N_{bin} Y_{pp}$ calculated in CGC framework with BK equation

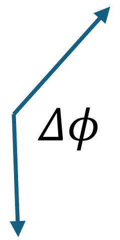
→ strong suppression due to gluon saturation in Pb nuclei





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

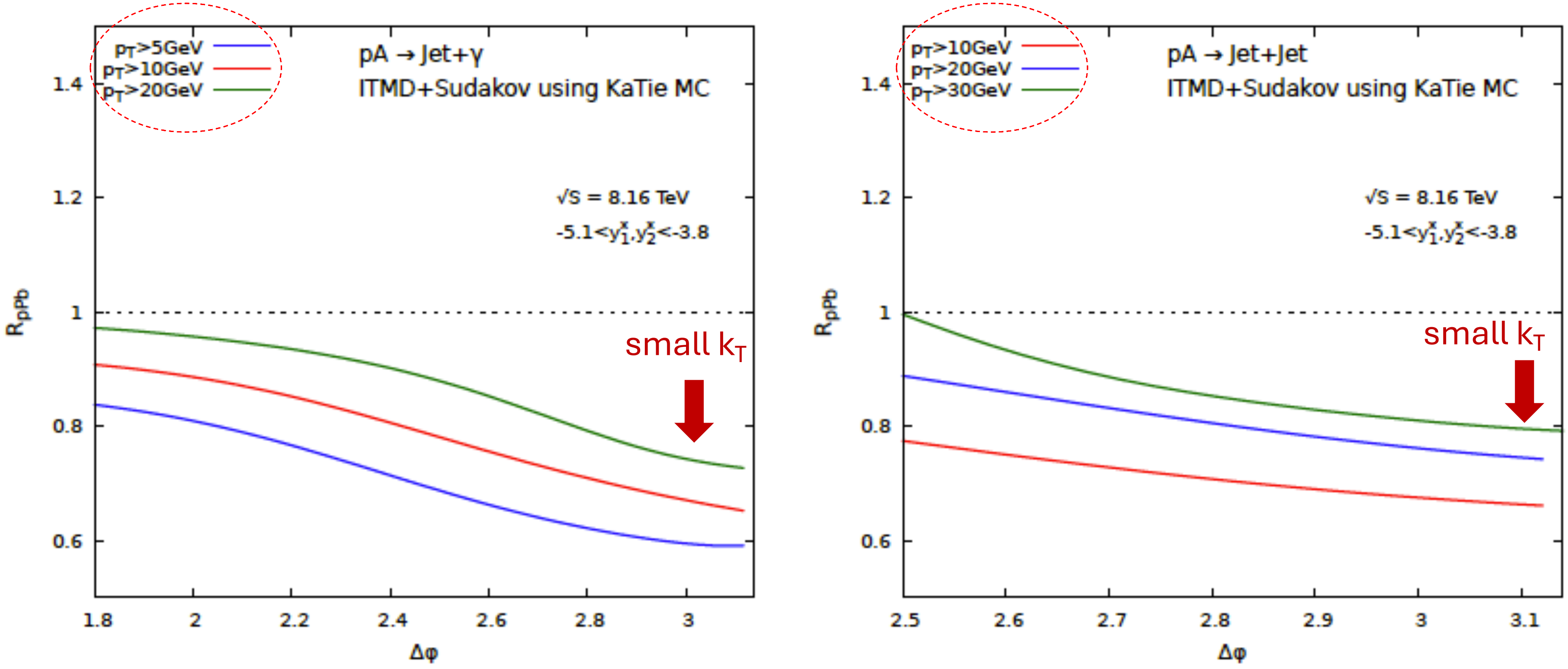
γ-jet and jet-jet $\Delta\phi$ correlation



$\Delta\phi$ dependence of R_{pPb} at forward rapidity in ITMD framework

→ excellent probe of saturation

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

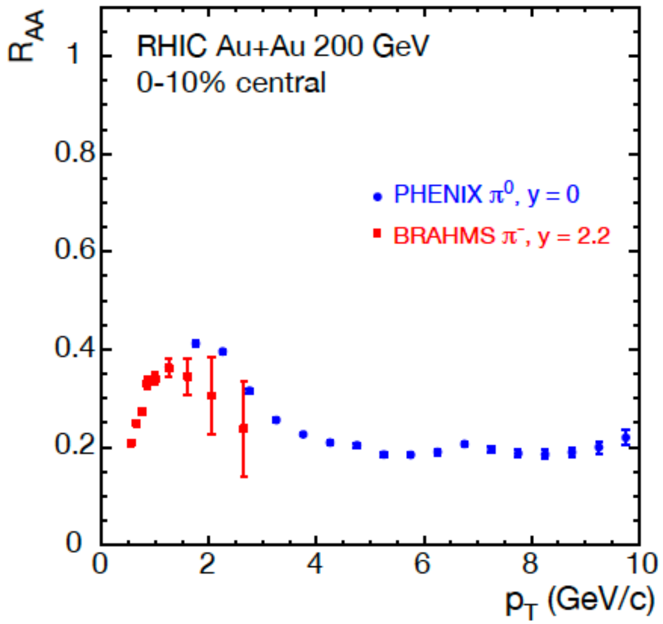


ALICE-PUBLIC-2023-001

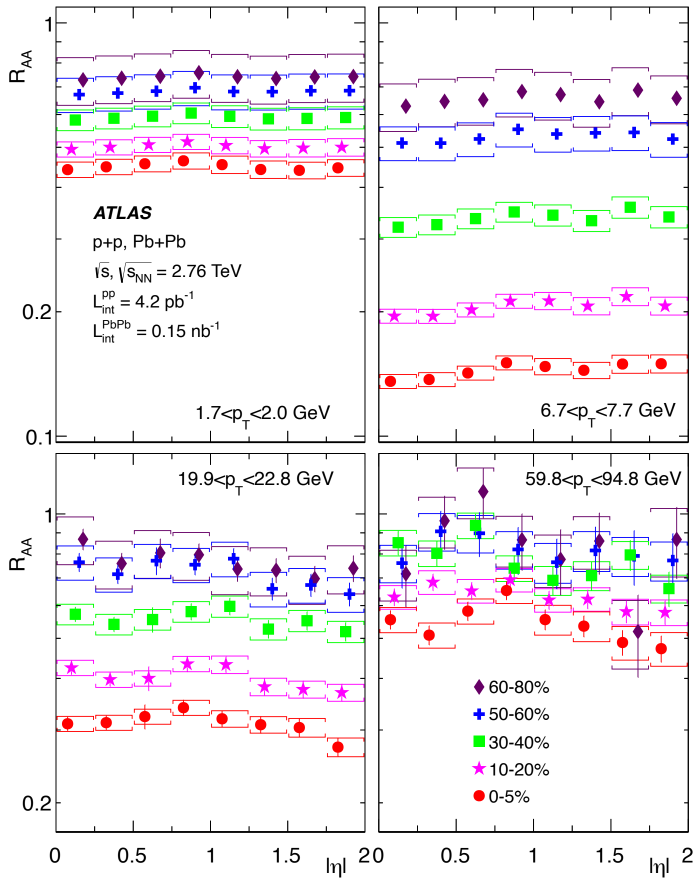
Jet quenching in A-A collisions at large rapidity

FoCal significantly extends the rapidity range for R_{AA} measurements!

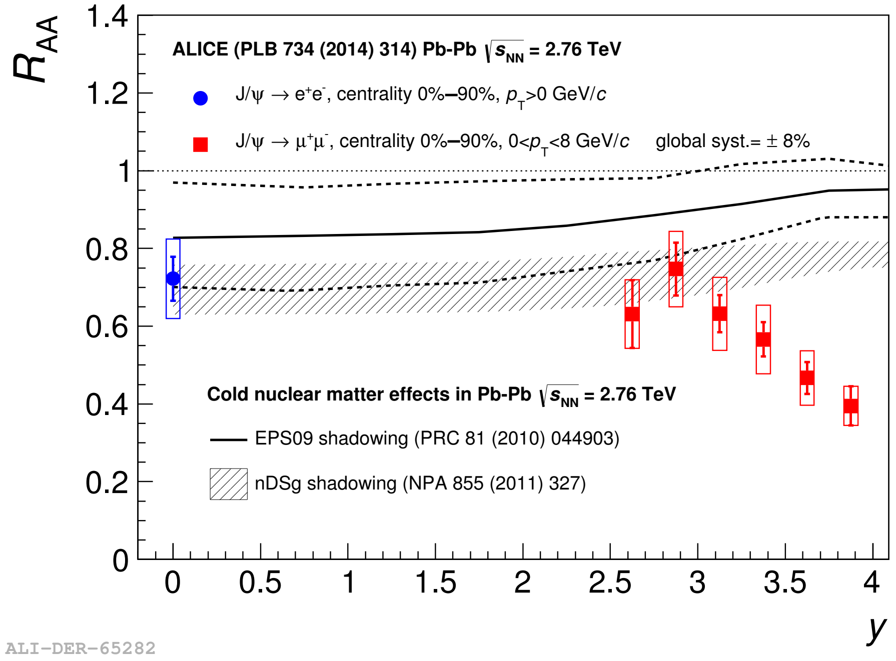
$$R_{AA} = Y_{AA} / \langle N_{coll} \rangle Y_{pp}$$



BRAHMS, Phys.Lett.B650:219-223,2007
PHENIX, Phys.Rev.Lett.101:232301,2008

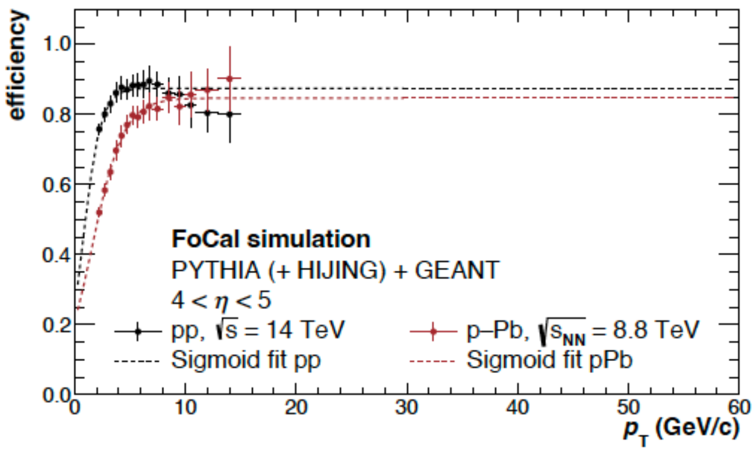


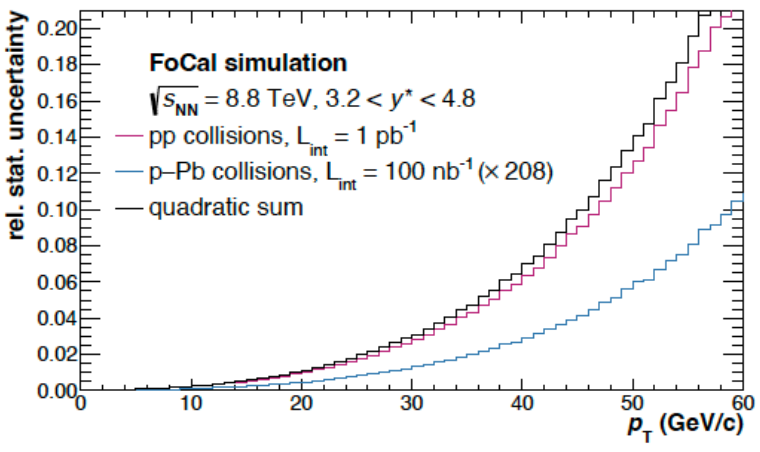
ATLAS, JHEP09(2015)050

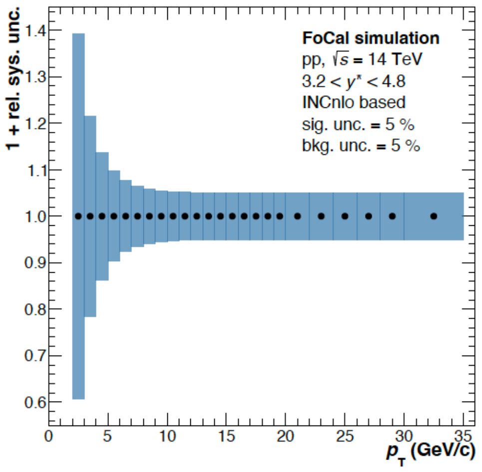


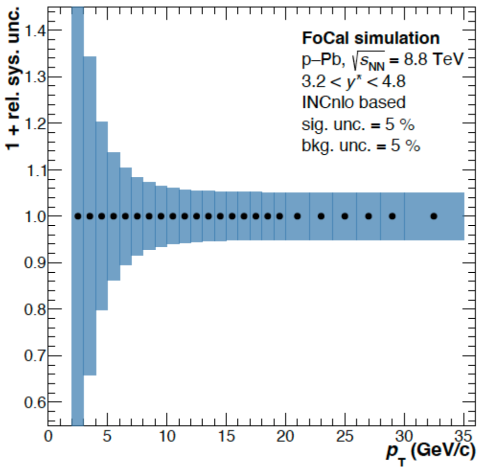
Isolated prompt γ reconstruction

- Efficiency above 80% for p_T > 5 GeV/c in pp and p-Pb collisions
- Statistical uncertainties projections based on JETPHOX NLO and expected luminosity in LHC Run 4
- Systematic uncertainties estimation with INCNLO including signal and background sources









P. Aurenche et al. Eur. Phys. J. C 9 (1999)107

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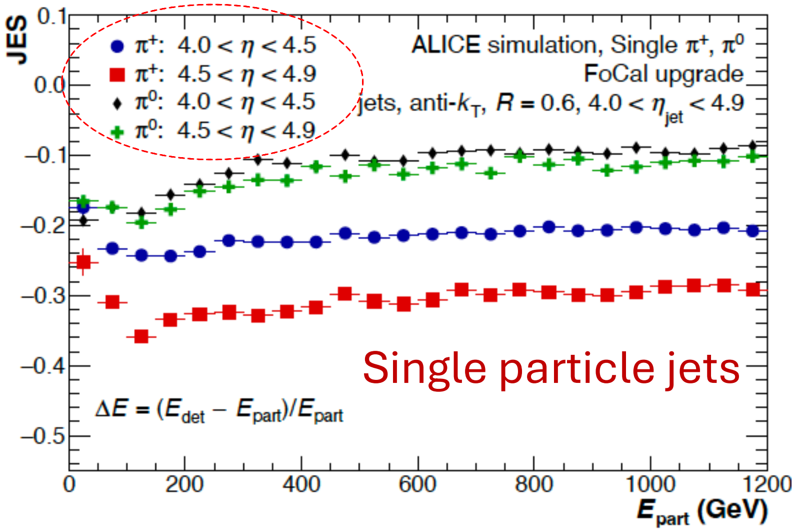
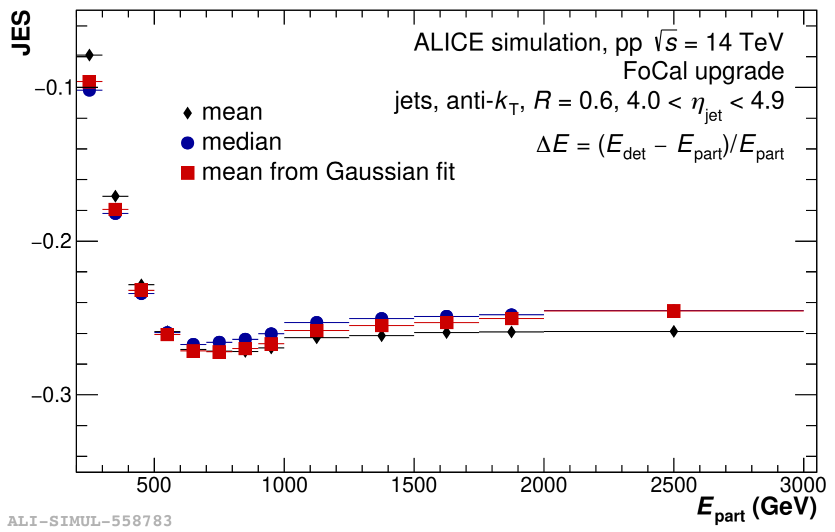
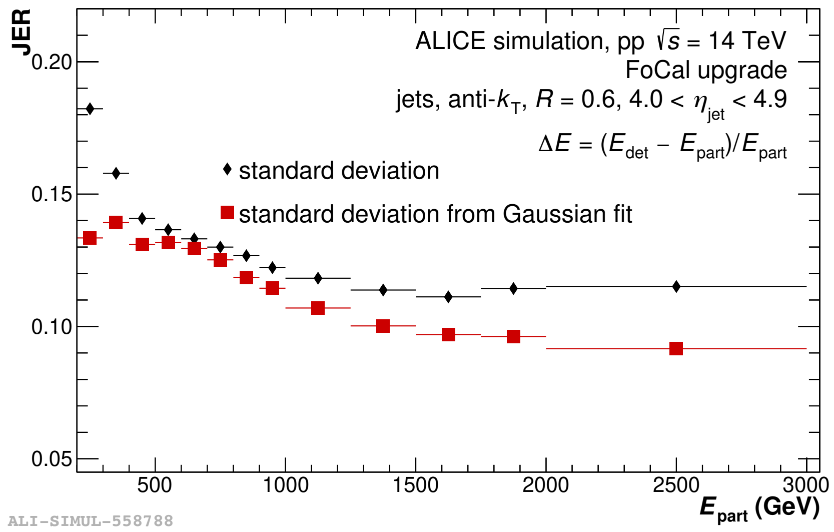
Jet reconstruction performance

Jet energy scale (JES) and resolution (JER)







- EM showers (π^0) miss less jet energy than hadronic showers (π^+)
- Non-Gaussian tails at small energy jets

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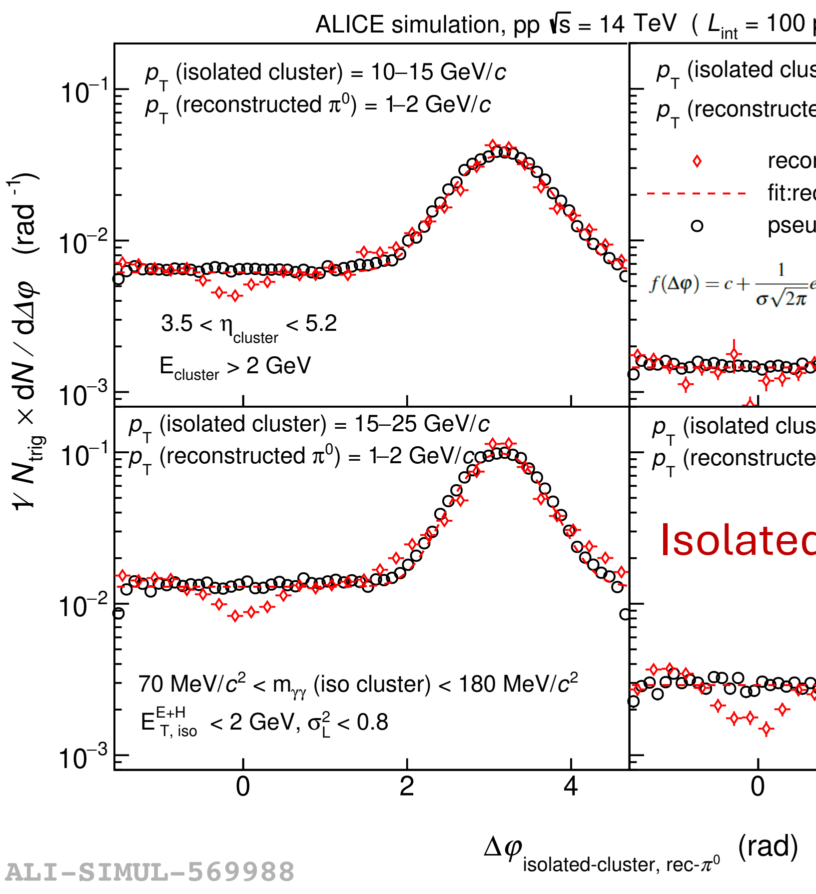
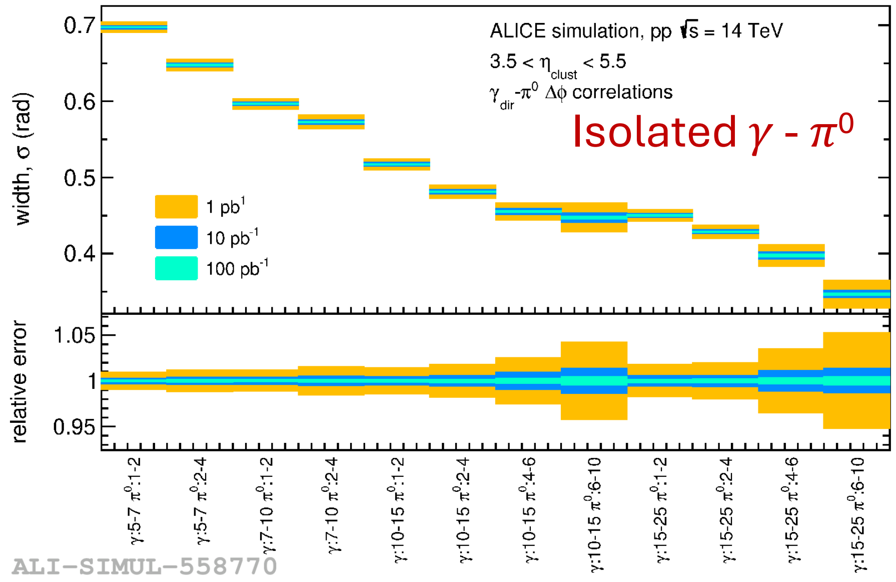
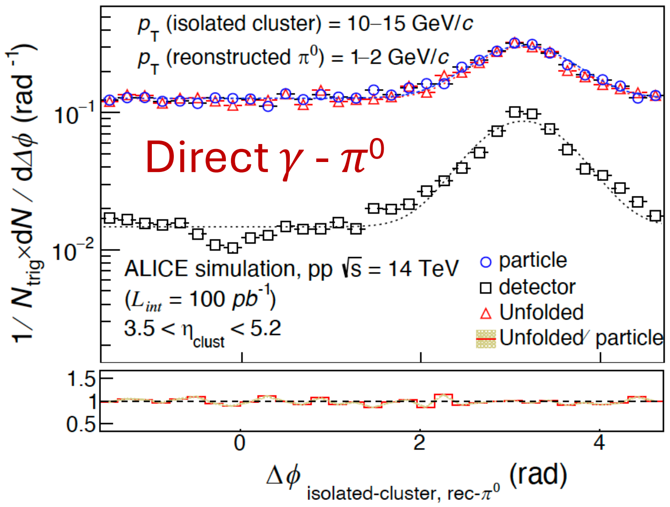
Isolated/direct γ and π^0 correlations

Isolated γ - π^0 correlations unfolded to direct γ - π^0







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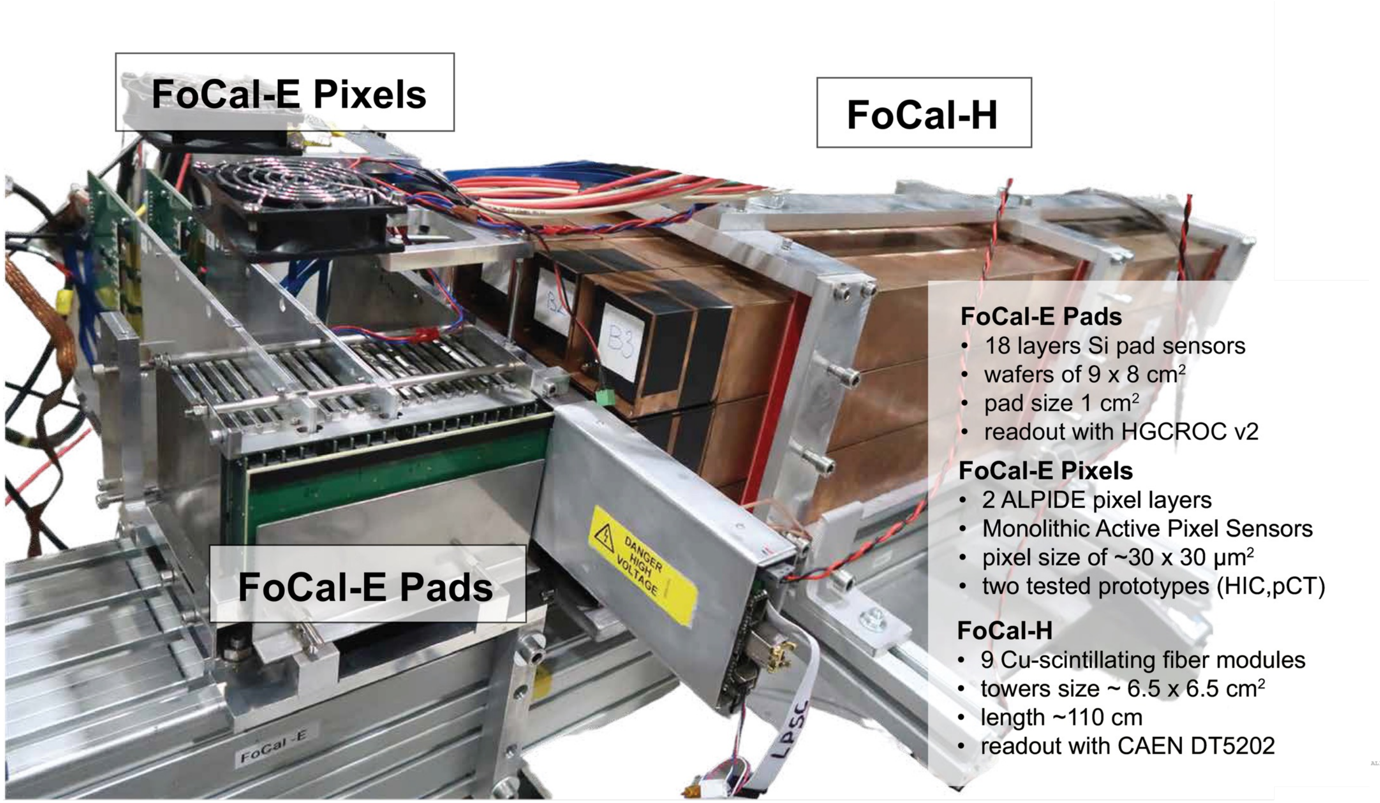
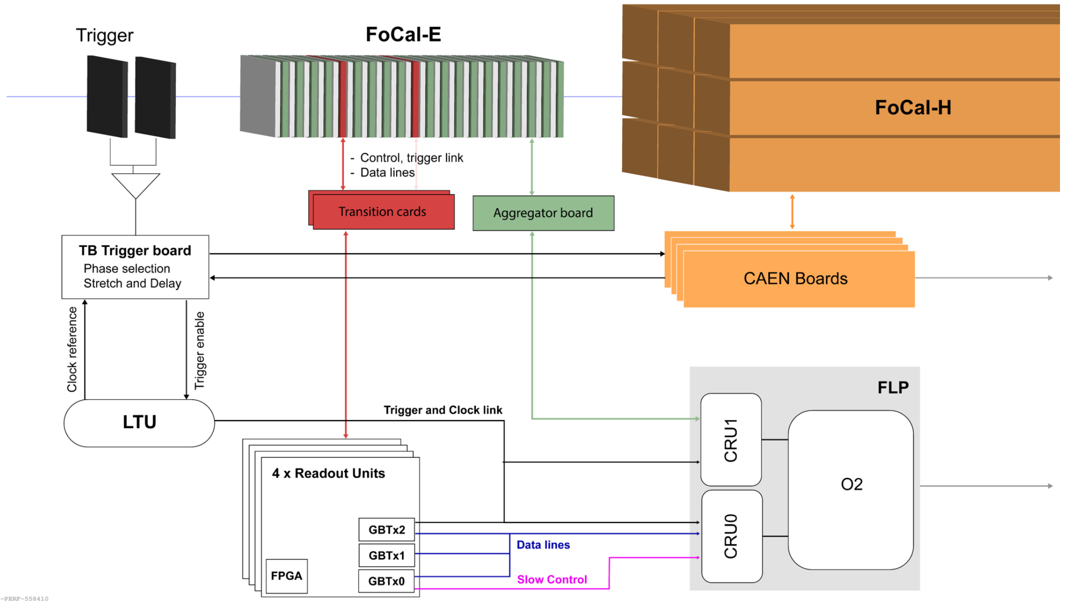
Performance of the FoCal prototype

Measurements performed in 2021 - 2023 with CERN PS and SPS with electron and hadron beams



ALI-PERF-569144



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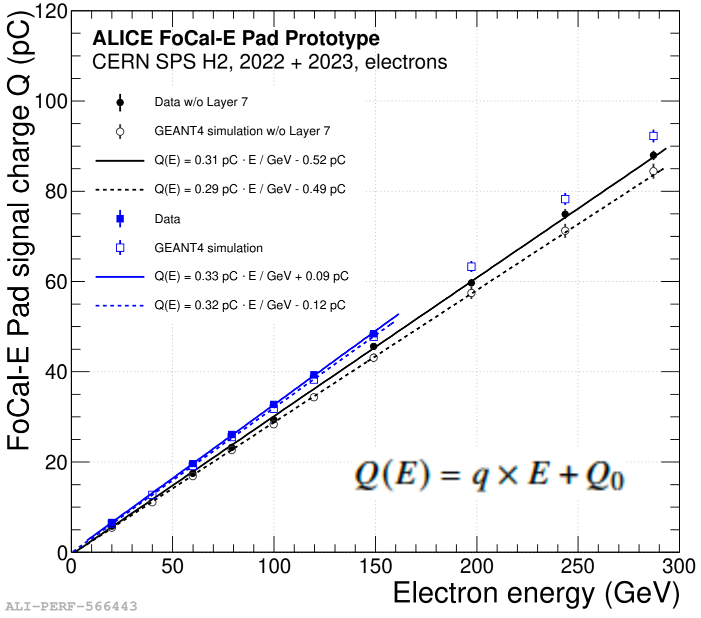
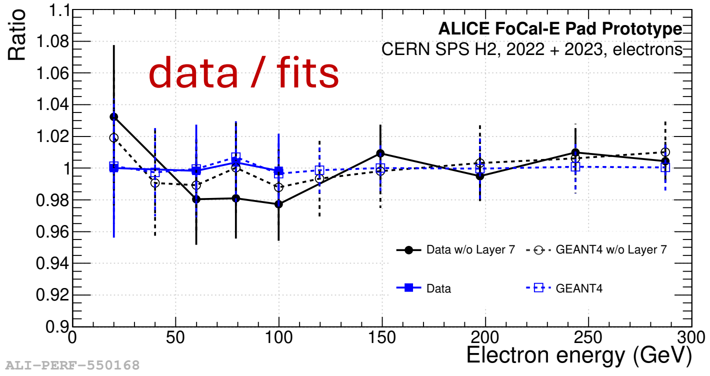
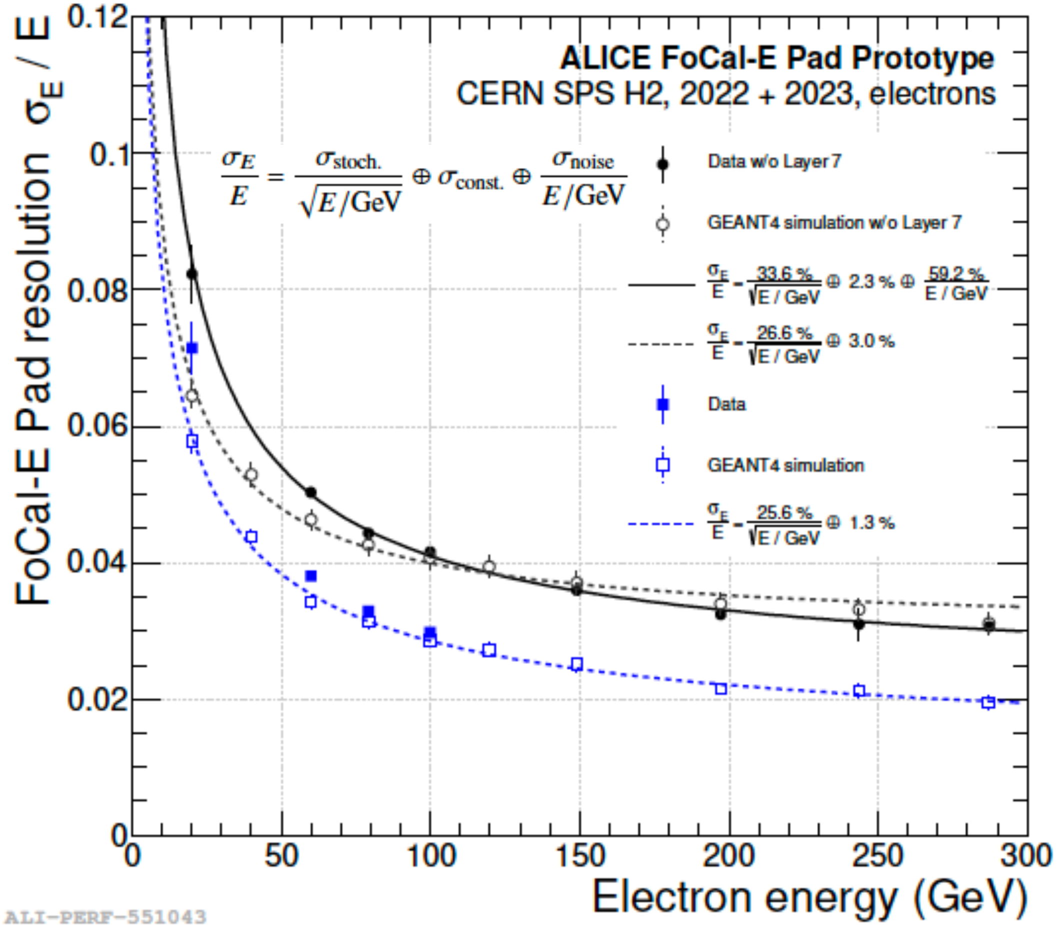
FoCal-E pad layer linearity and resolution

Good agreement between data and simulations







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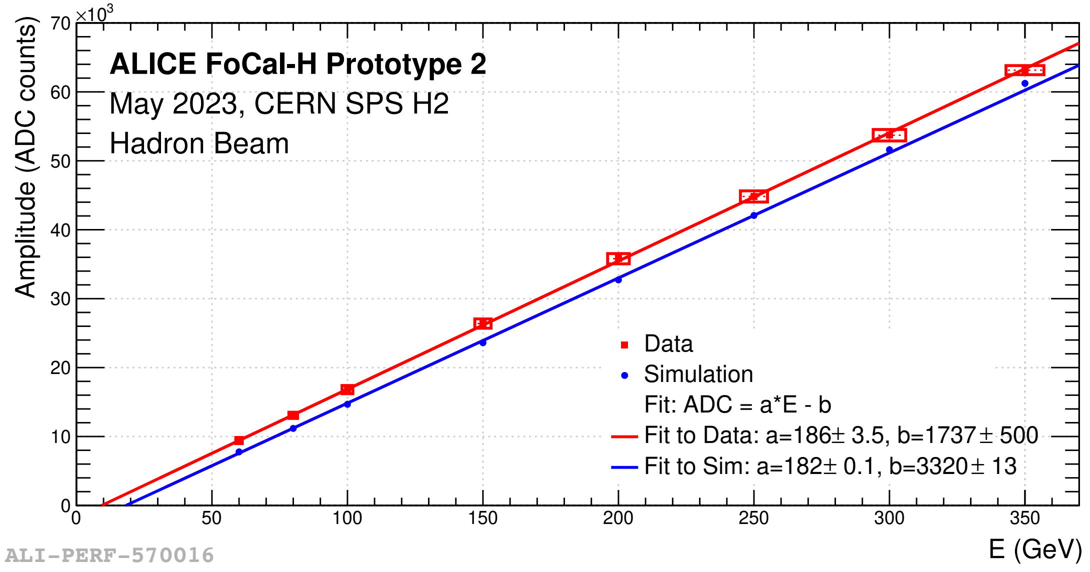
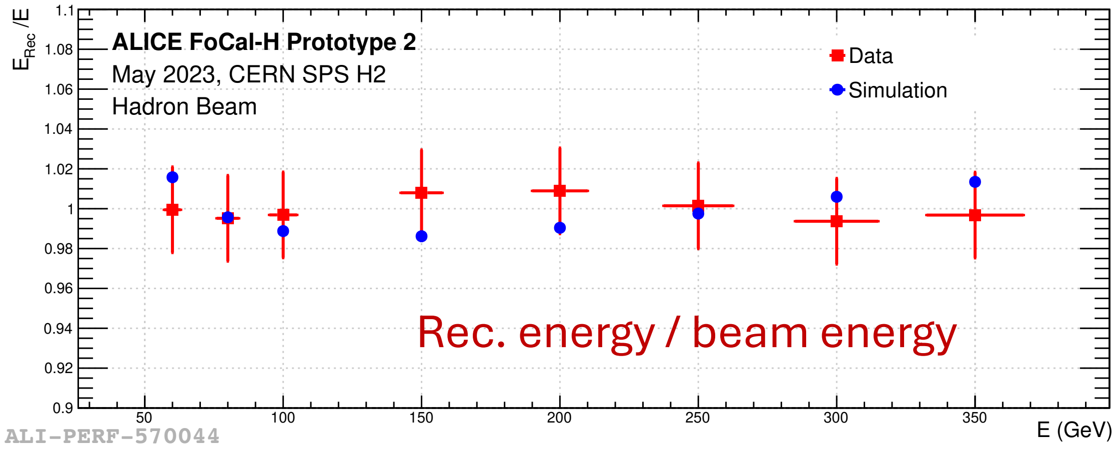
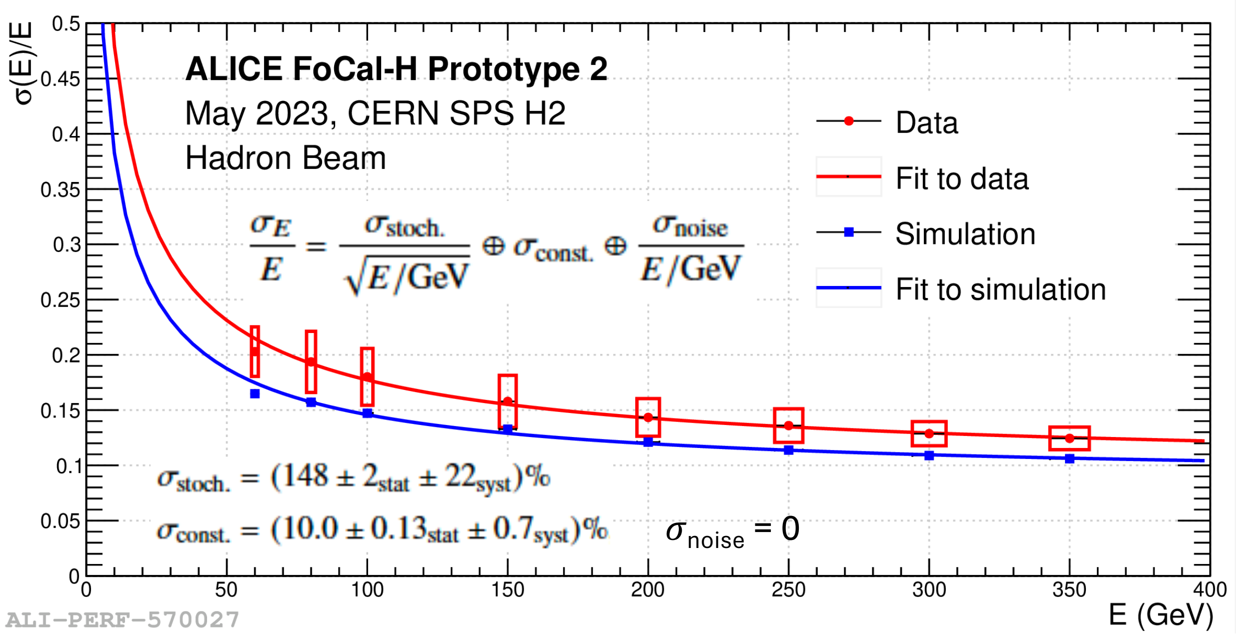
FoCal-H linearity and resolution





Rec. energy / beam energy

Data vs simulation differences investigated



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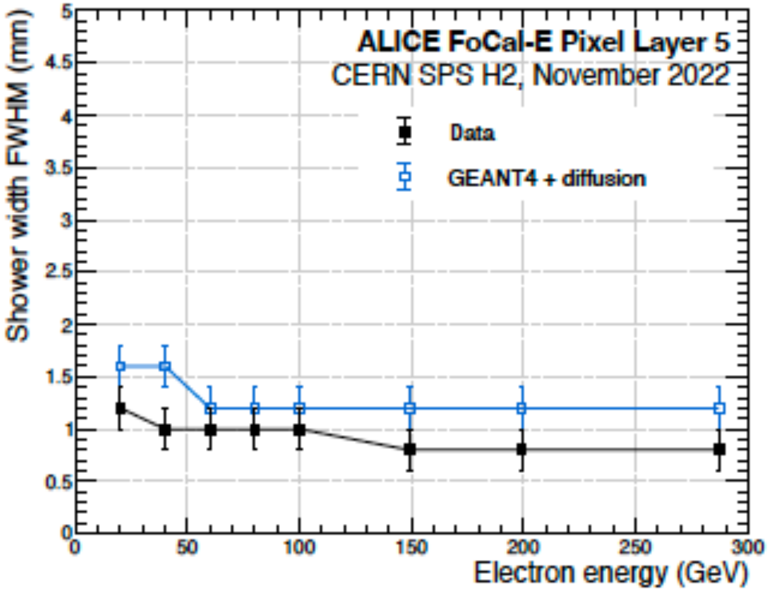
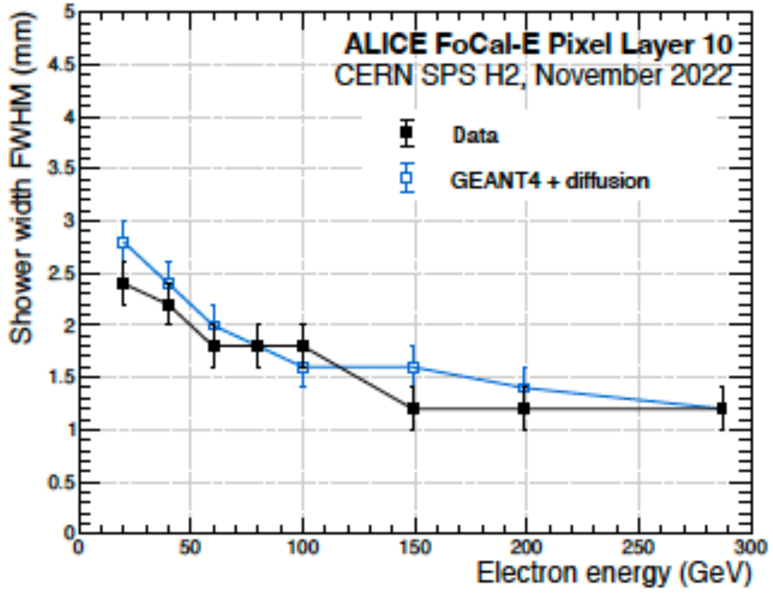
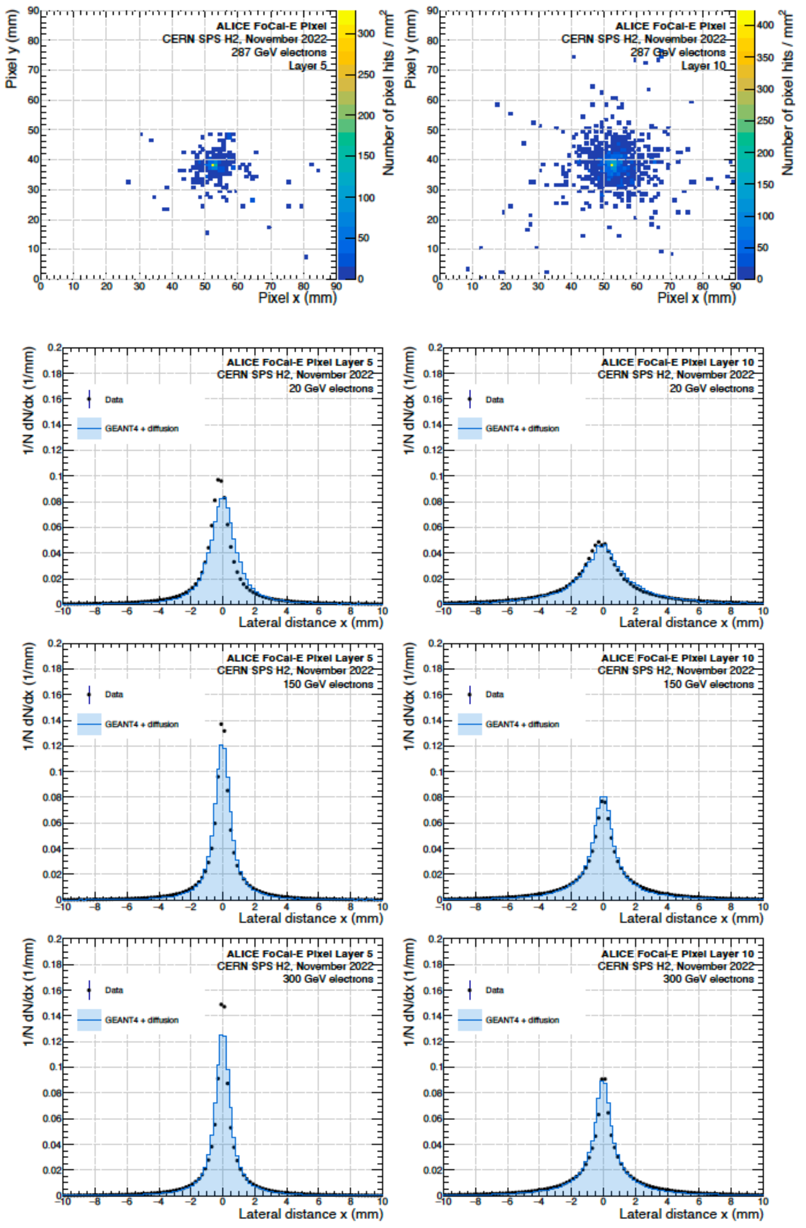
FoCal-E pixel transverse profiles

Good agreement between data and simulations







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$$f(\Delta x) = \frac{1}{N_{\text{hits}}} \frac{d}{dx} N_{\text{hits}}(x - x_0)$$