Physics program and performance of the ALICE Forward Calorimeter upgrade (FoCal)

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on behalf of the ALICE collaboration

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Centre of Excellence in Quark Matter

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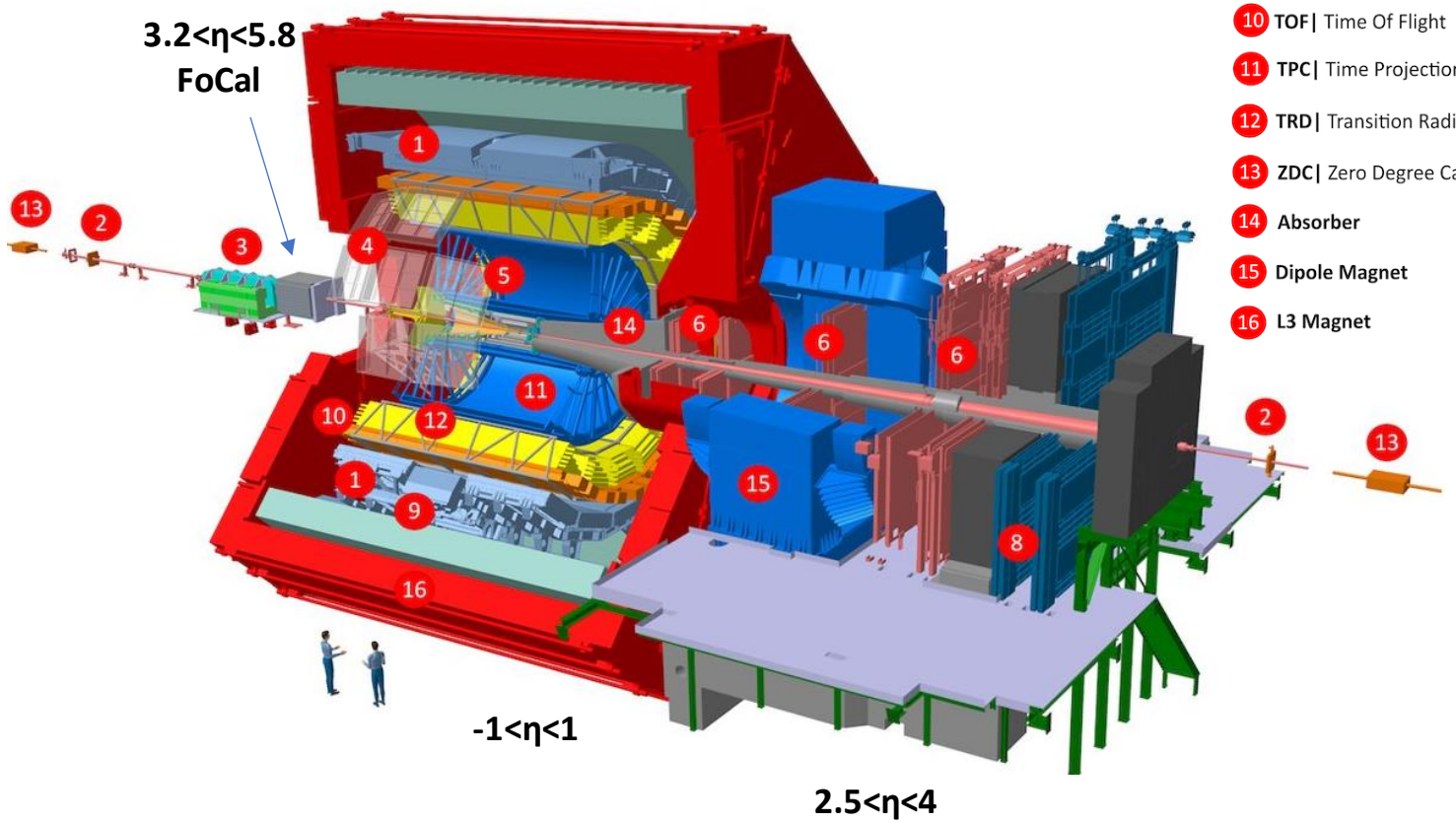
The Forward Calorimeter (FoCal)

A high-granularity forward calorimeter to be installed in ALICE during the LHC Long Shutdown 3 for Run 4 (2029-2032)

Publications

- Letter of Intent CERN-LHCC-2020-009
- Physics of the ALICE FoCal upgrade ALICE-PUBLIC-2023-001
- Performance of the ALICE FoCal upgrade ALICE-PUBLIC-2023-004
- Prototype electronics for the silicon pad layers of FoCal arXiv:2302.13912
- Test beam paper of FoCal prototypes (2021-2023) arXiv:2311.07413
- Technical Design Report CERN-LHCC-2024-004

FoCal is a project approved by the LHCC since March 2024



1 **EMCAL** | Electromagnetic Calorimeter
2 **FIT** | Fast Interaction Trigger
3 **FoCal** | Forward Calorimeter
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**

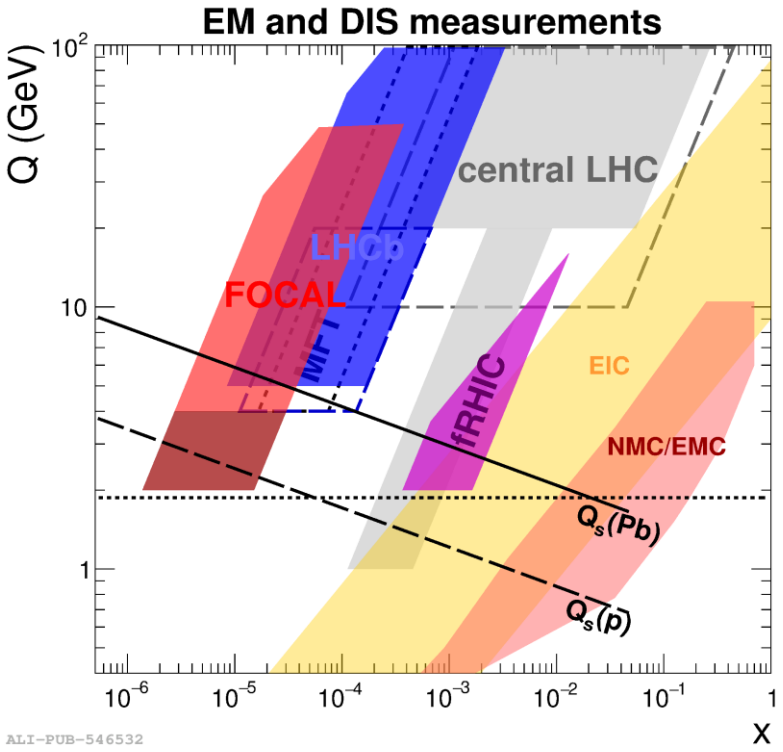
The Forward Calorimeter (FoCal)

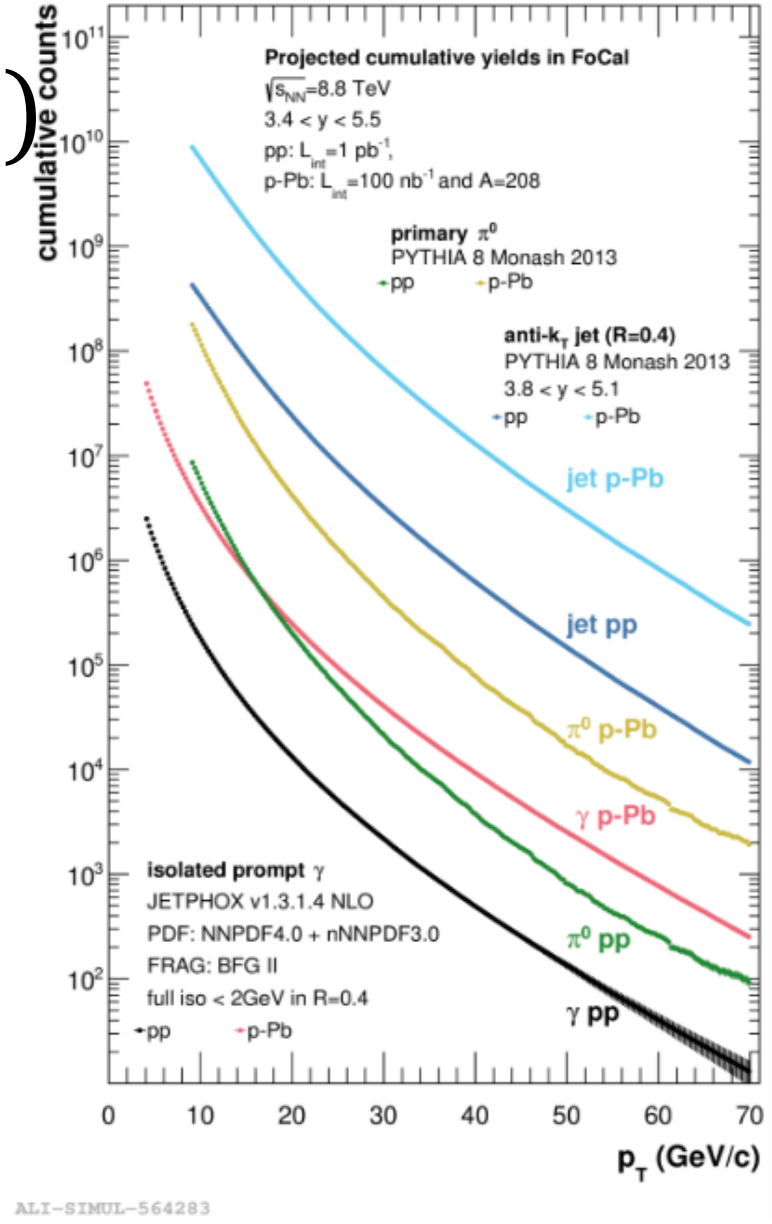
Physics goals of the FoCal:

- Search for evidence of gluon saturation by studying non-linear QCD in nucleons and nuclei at low Bjorken x down to ~10^{-6}
- Constrain nuclear PDFs
- Broad phase-space coverage while providing a multi-messenger approach
  - Comprehensive and complementary exploration of saturation

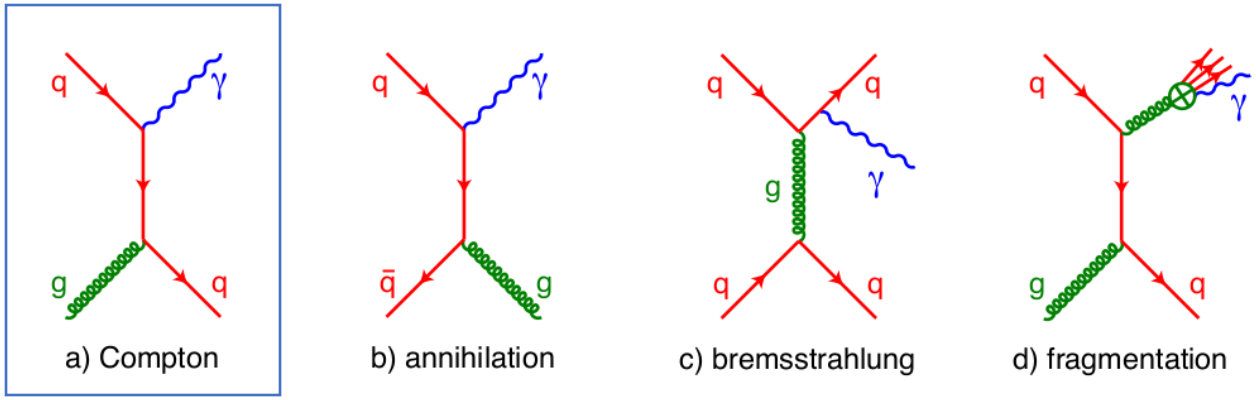
Wide set of experimental observables:

- Isolated (direct) photons
- π^0 and other neutral mesons
- Jets
- Vector mesons in UPC (J/ψ, Υ,…)
- Correlations (γ-hadron, hadron-hadron, …)
- … and more



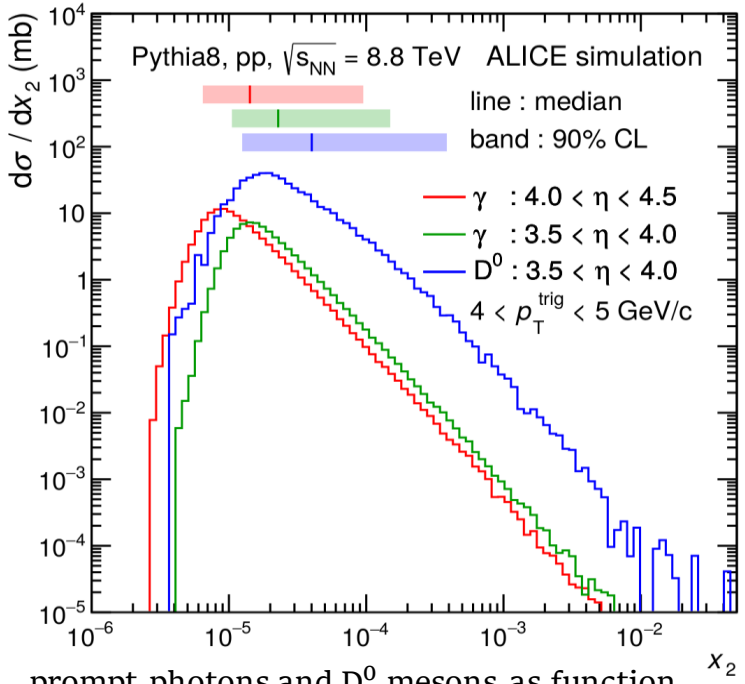


Prompt photons

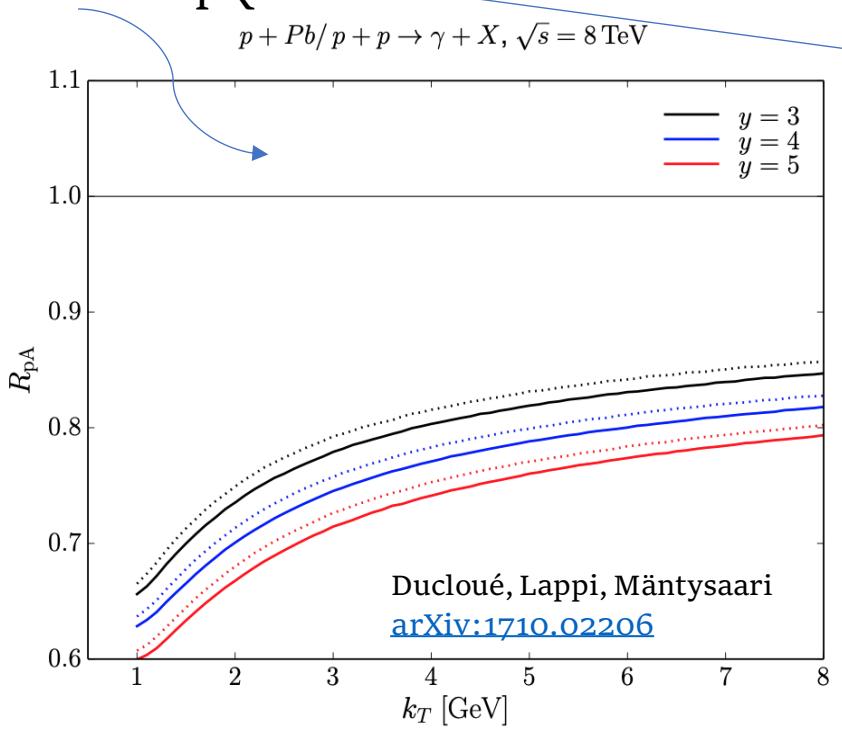


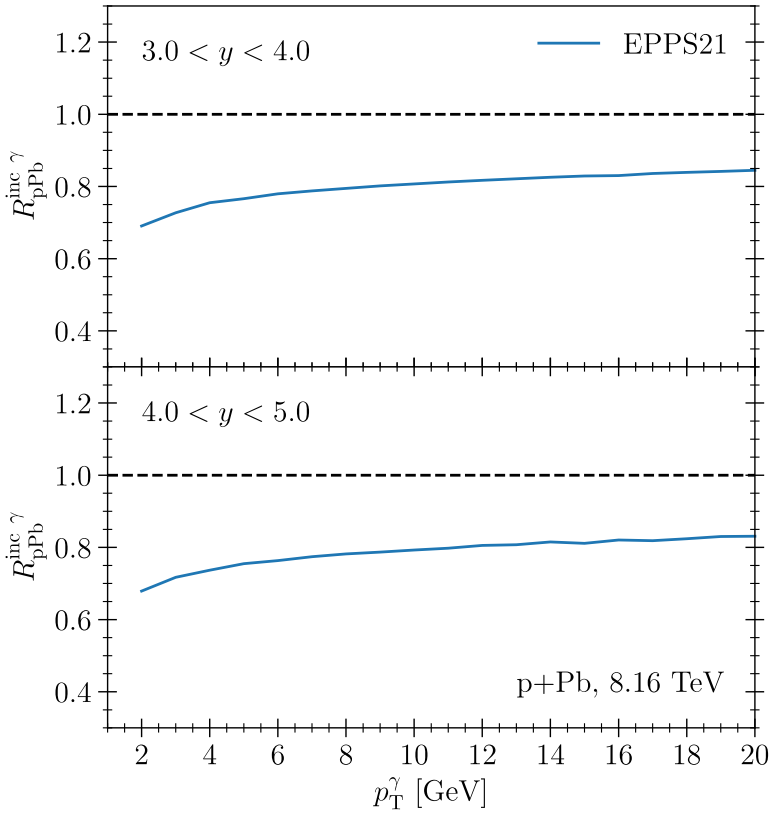
- Compton scattering
  - Directly sensitive to gluons
  - **Isolated** photon with no strong interaction in final state
  - With isolation, at forward rapidity QCD Compton channel **dominates**
- Suppression seen in both CGC and pQCD+nPDF models

CERN-LHCC-2020-009



prompt photons and D^0 mesons as function of gluon momentum fraction x

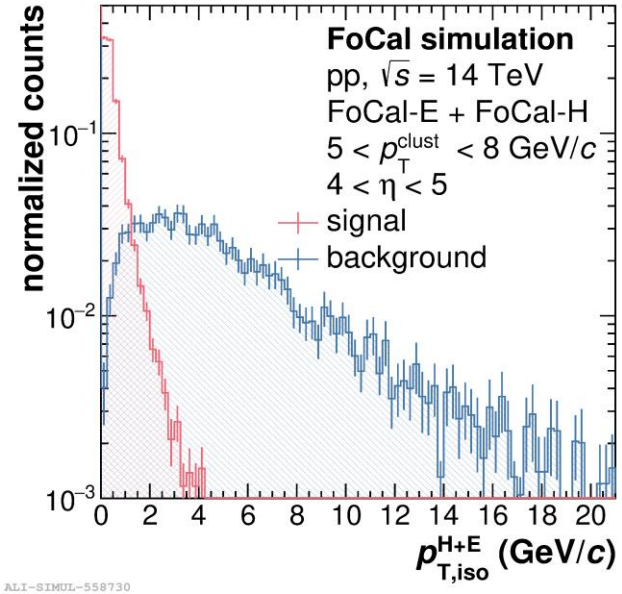


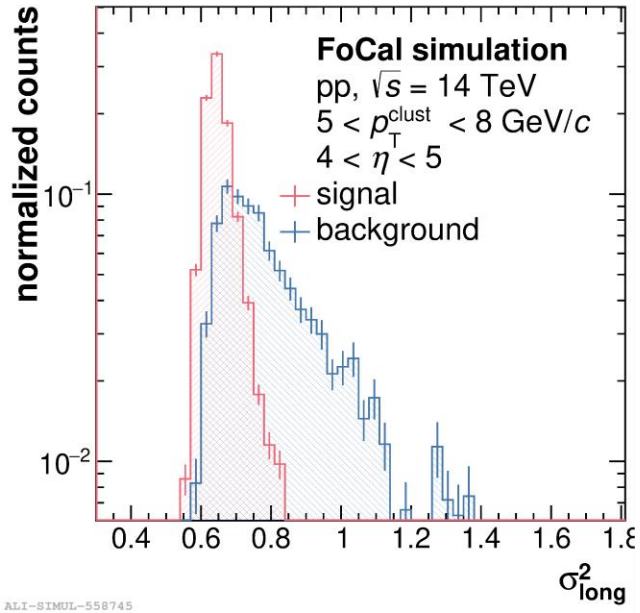


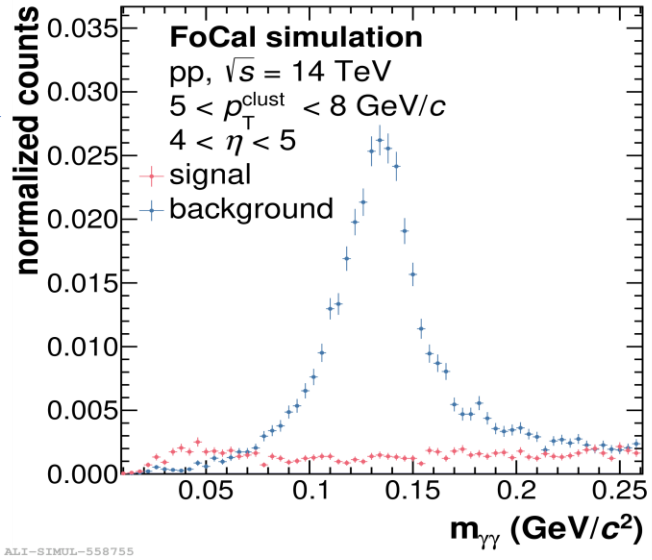
Helenius, et al. JHEP 09 (2014) 138
Updated to EPPS21 (Helenius, private communication)

Prompt photons

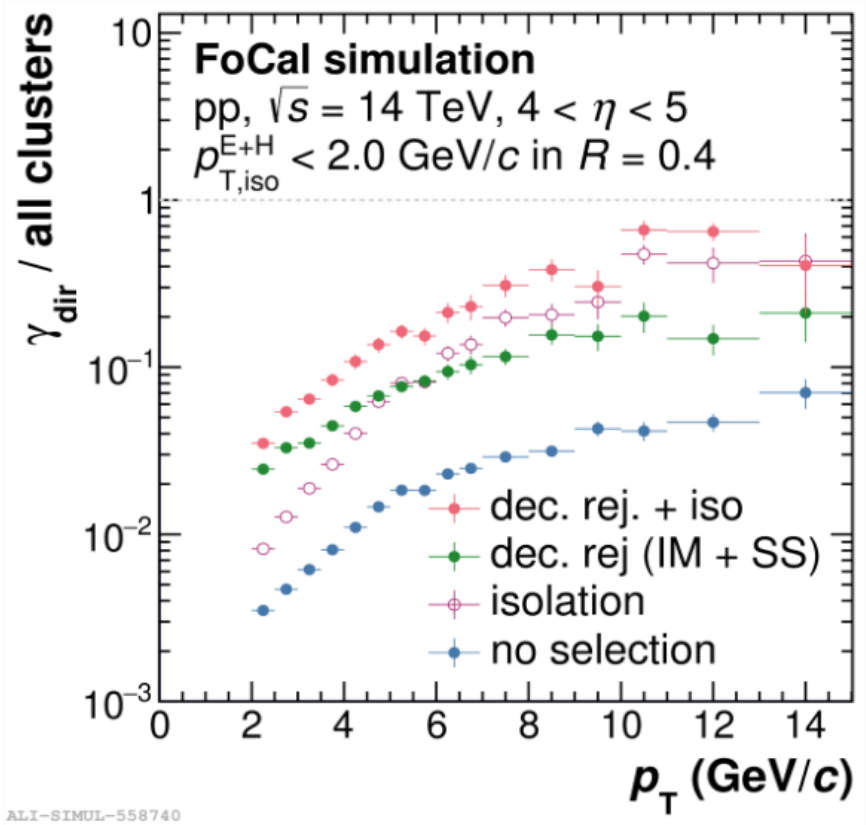
- Selection on isolation energy
- Decay photon rejection based on
  - shower shape
  - invariant mass tagging







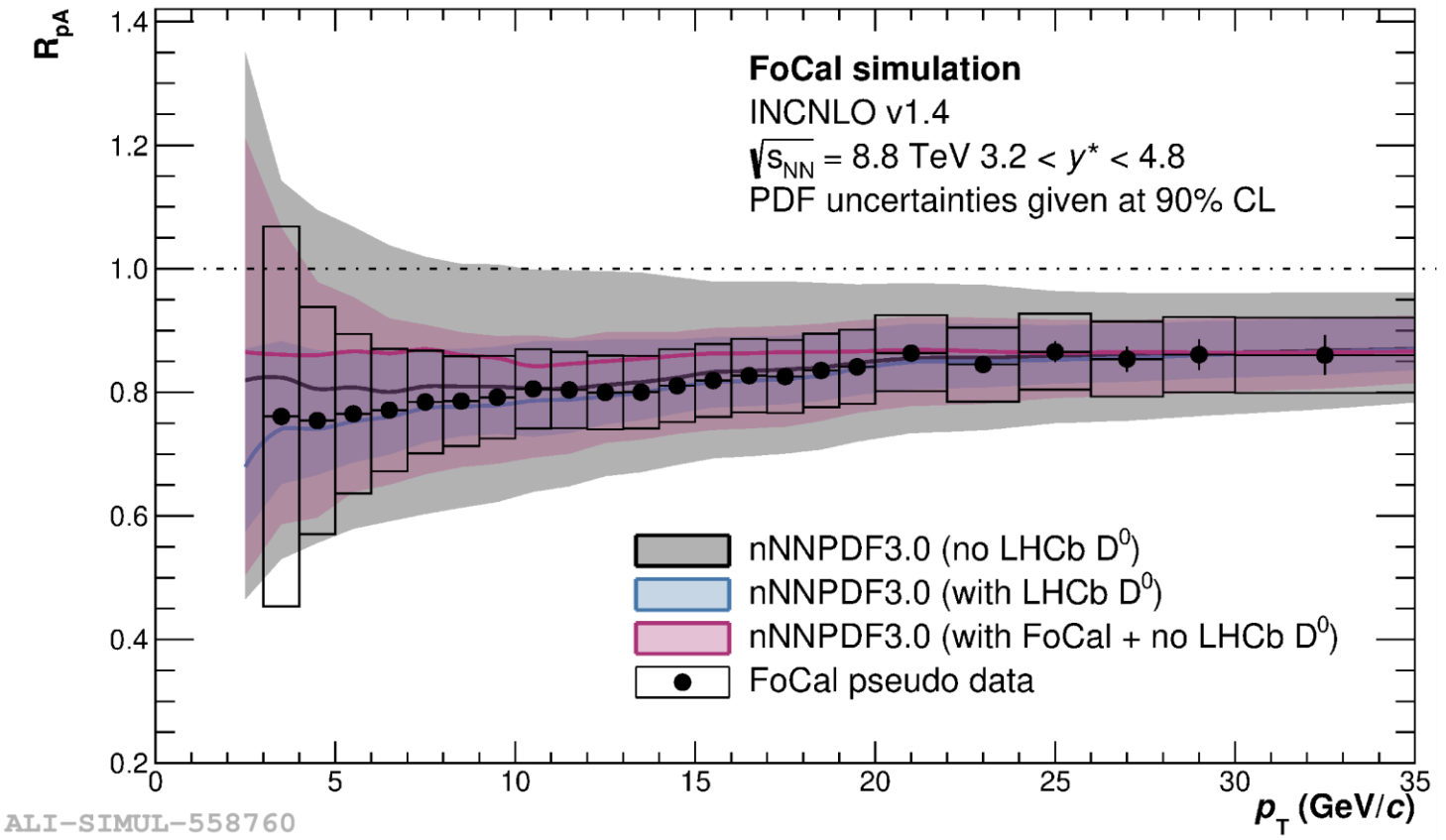
These selections improve signal-to-background fraction by about factor of 10



Prompt photons

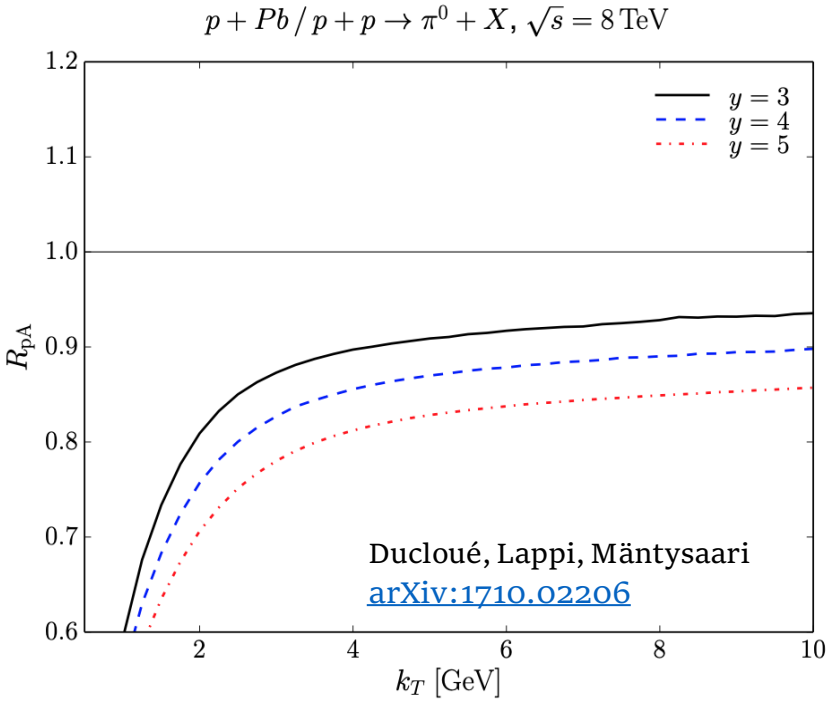
- Isolation **suppresses fragmentation** photon contribution
  → measurement of isolated prompt photons is **theoretically clean probe** of underlying gluon distributions
- Inclusion of FoCal prompt photon data in global PDF fits will provide additional insight into **factorization** and **universality** in nuclear environments.

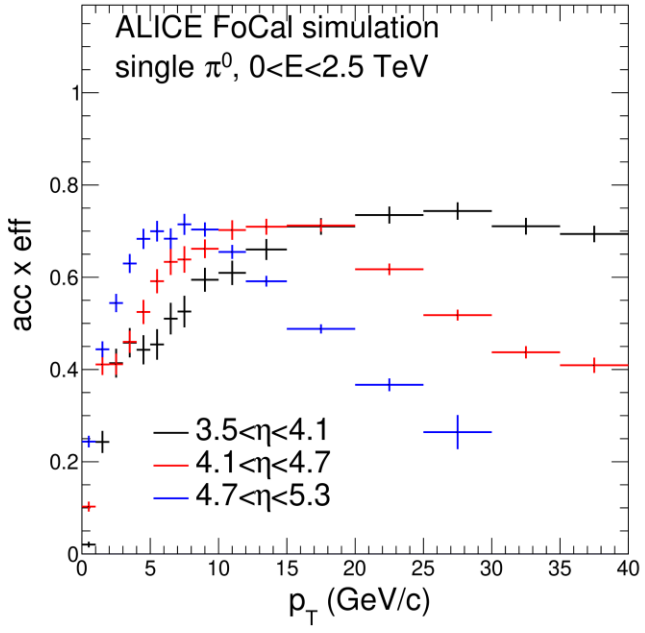
nPDF+NLO R_{pA} reweighted using FoCal pseudo data

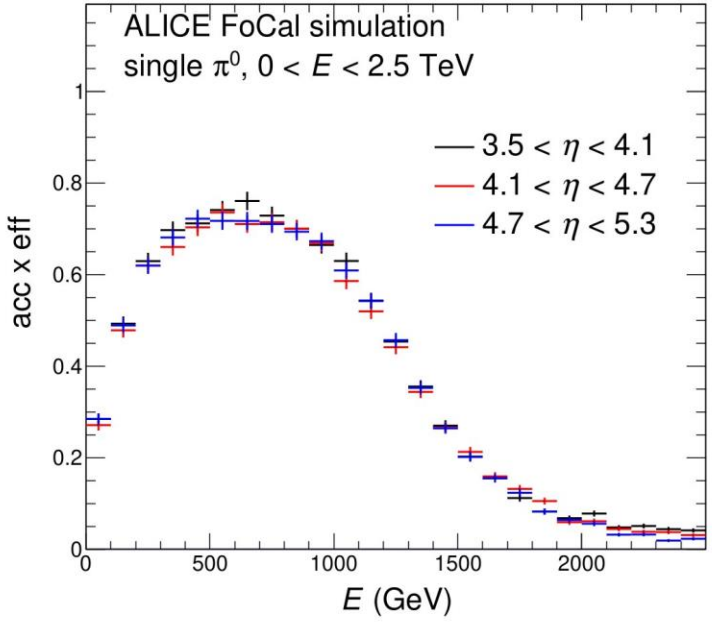


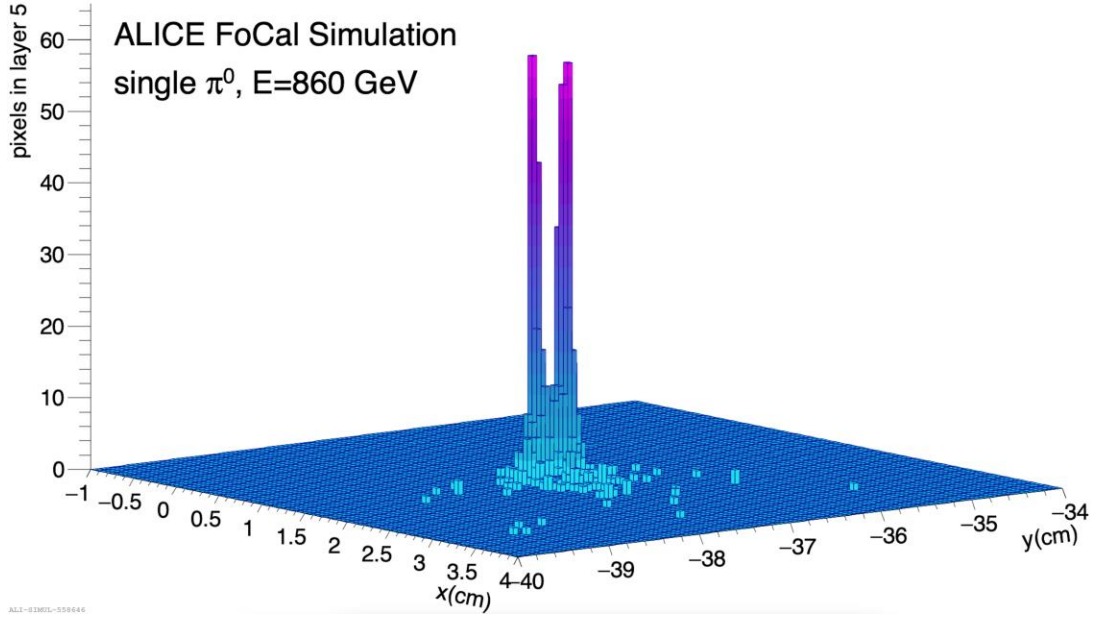
Mesons

- Neutral mesons decaying fully into photons or electrons can be reconstructed using EM showers in FoCal-E.
  - Most abundant: **π^0, η, and ω**
- Vector mesons decaying via di-electrons can also be reconstructed.
- Clusterization parameters can be tuned to obtain better performance in certain kinematical regions, e.g. high π^0 energy.









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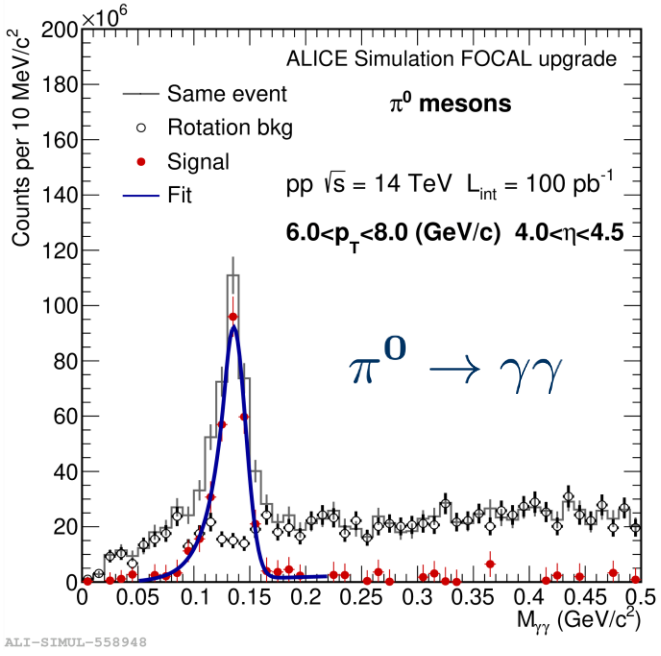
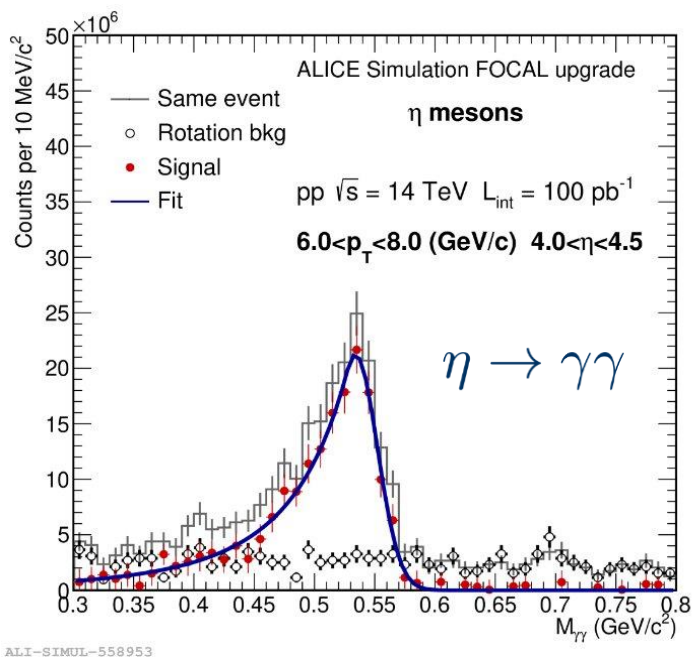
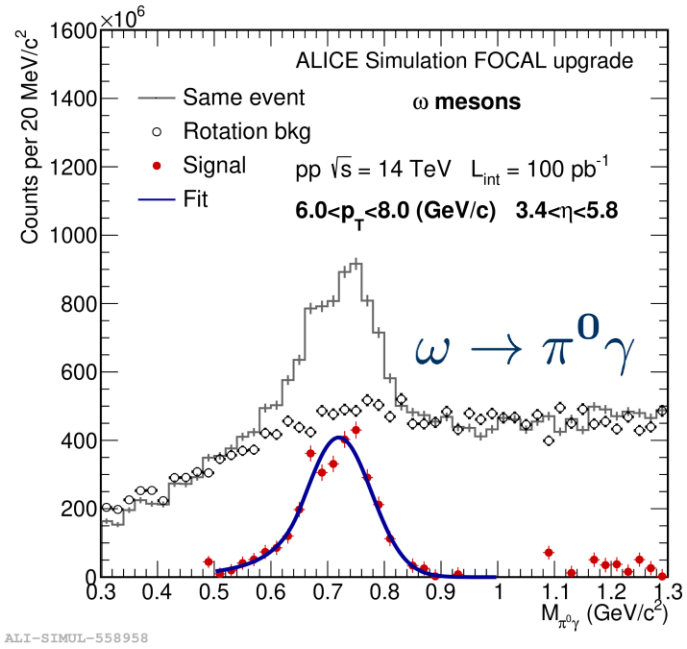


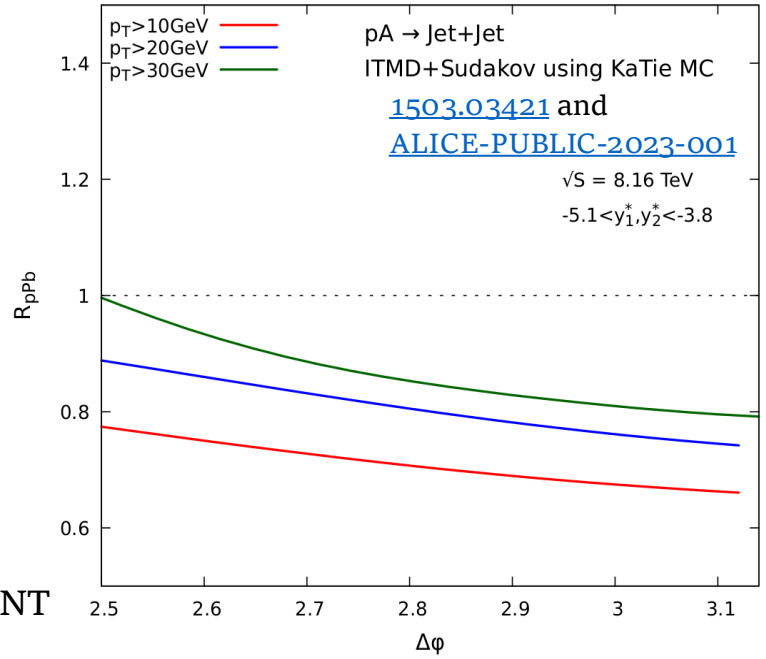




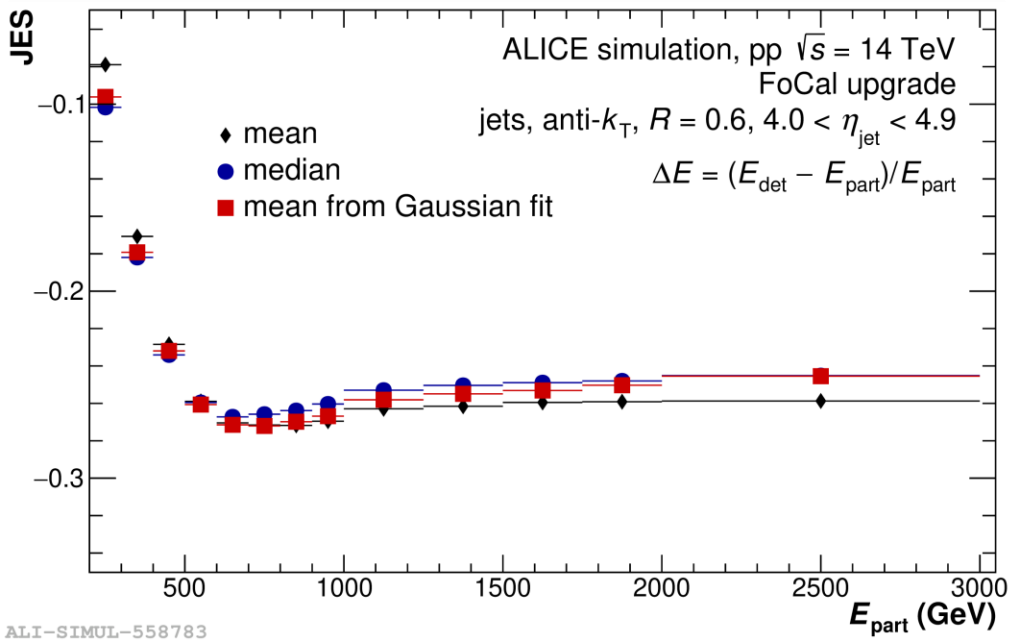
Jets

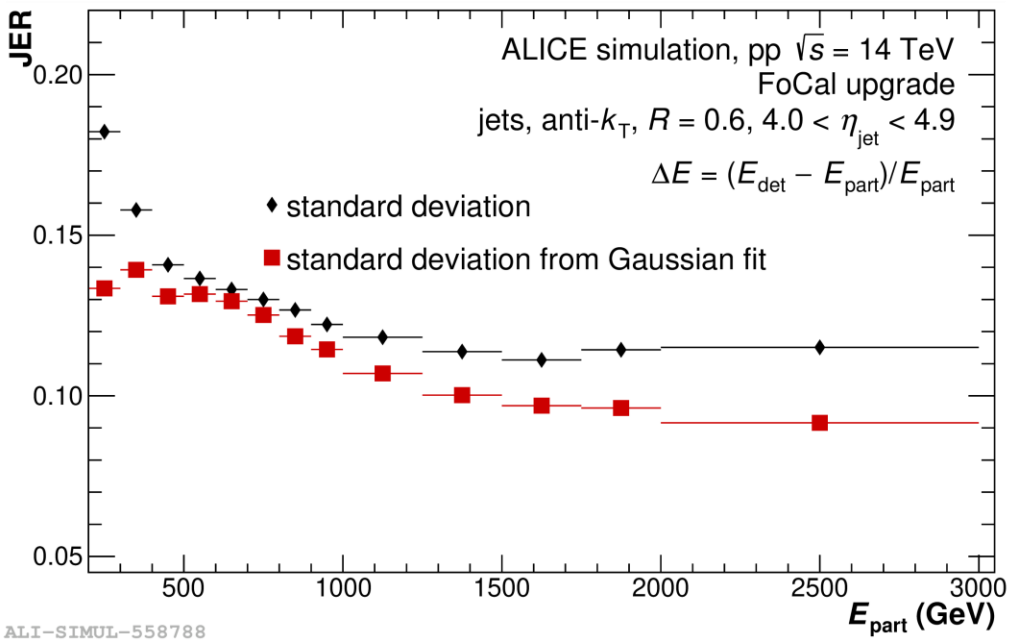
- Forward inclusive jet, γ+jet and dijet production
  - sensitive to gluon saturation
  - dijets especially interesting
    → momentum imbalance k_T probes Q_{sat}

$$\Delta E = (E_{\mathbf{det}} - E_{\mathbf{part}})/E_{\mathbf{part}}$$



- Jet energy spectrum JES and resolution JER are the mean and standard deviation of ΔE
  - Used to quantify performance of R=0.6 jets in FoCal, simulated using PYTHIA + GEANT

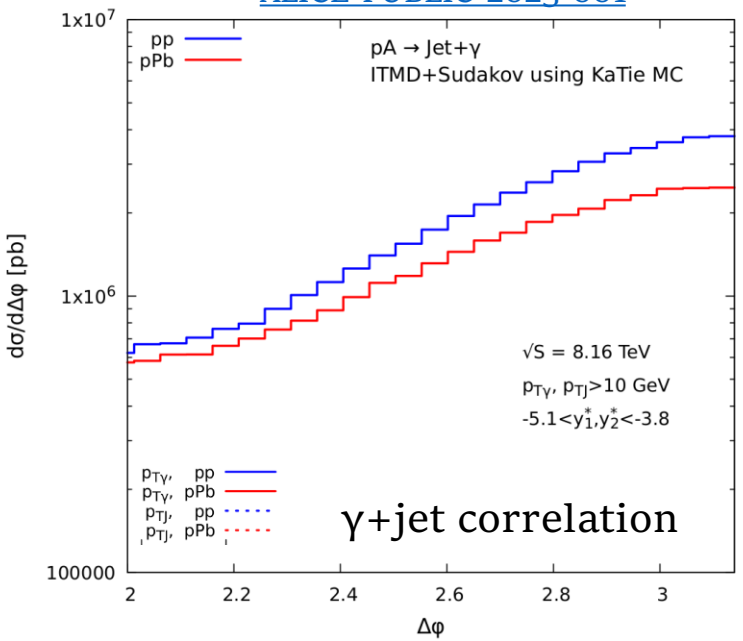




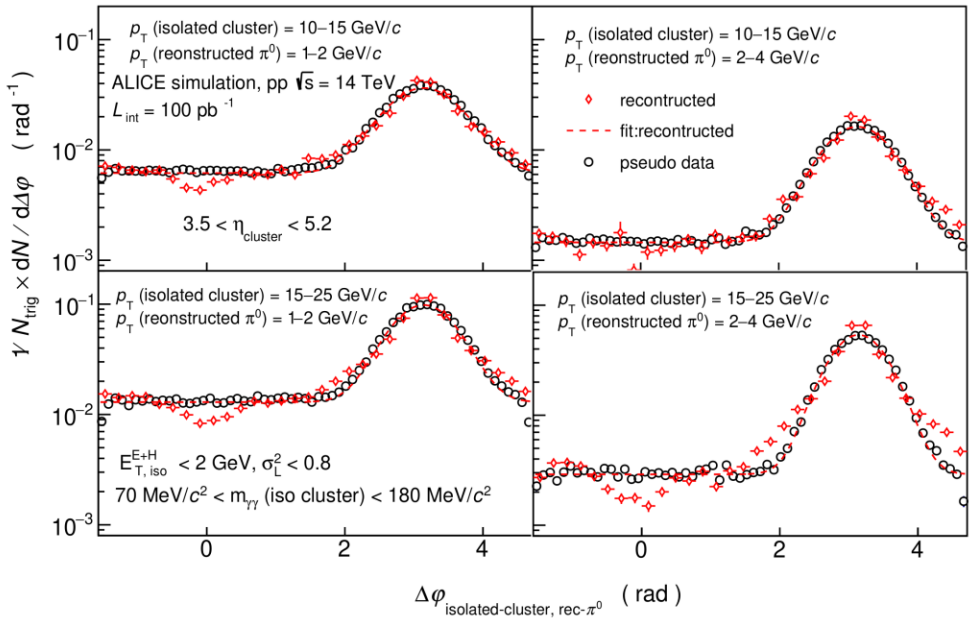
Correlations

- Photon and hadron-triggered correlations in the forward region of pA collisions also probe small-x gluon dynamics, but with different sensitivity than inclusive yields
  - Correlated **yield suppression** probes gluon density, similar to measurements of inclusive production
  - Measurement of **angular decorrelation** is in addition sensitive to the coherence of the gluonic wavefunction.

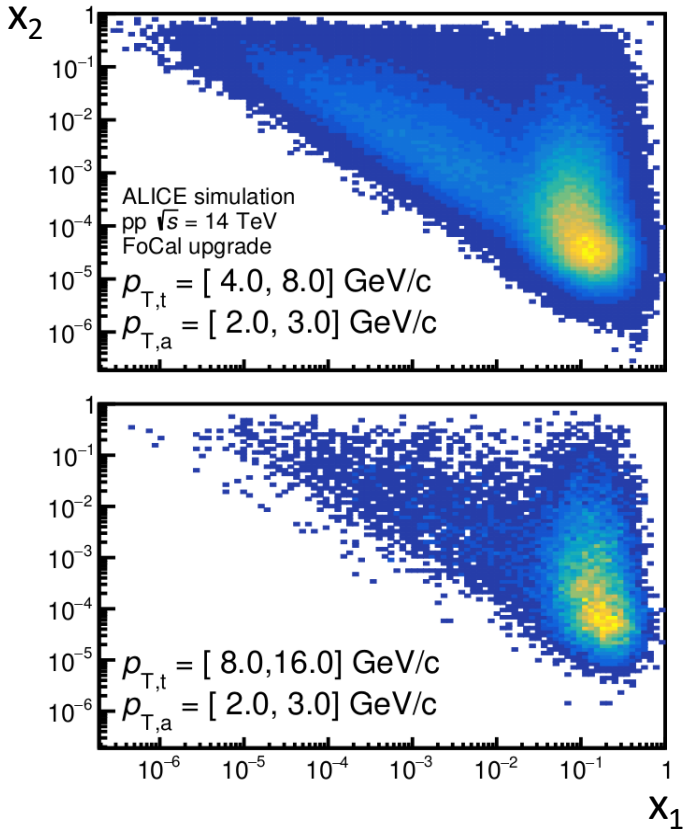
ALICE-PUBLIC-2023-001



γ+jet correlation



π^0-π^0 correlation

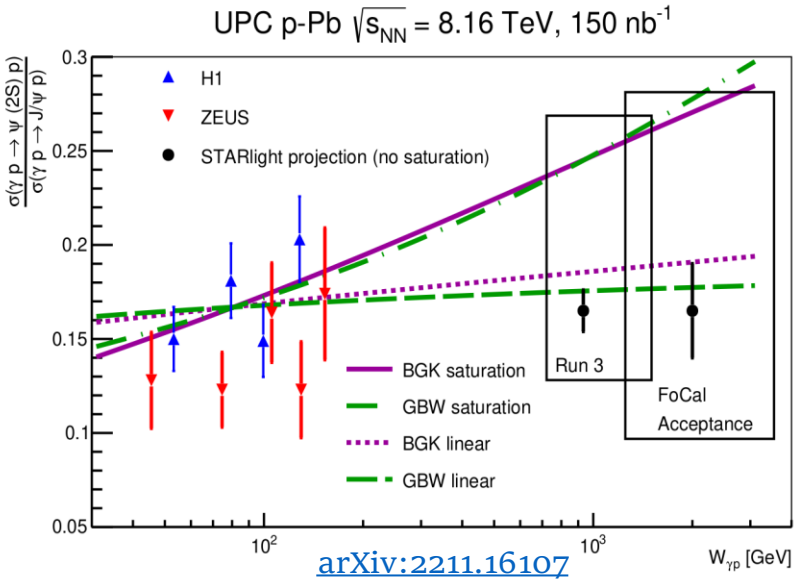


ALICE-PUBLIC-2023-004

analysis of γ-π^0 corr. in simulated pp collision events + detector smearing

UPC vector meson photo-production

- Deviation of σ from power-law growth with increasing $W_{\gamma p}$ expected due to saturation effects
- FoCal allows access to unprecedented low-*x*, extending existing measurements up to $W_{\gamma p} \approx 2$ TeV (and down to 10 GeV) in p-Pb (Pb-p) and Pb-Pb collisions
- Studies with STARLight + GEANT show successful reconstruction of J/ψ and ψ(2S)



arXiv:2211.16107

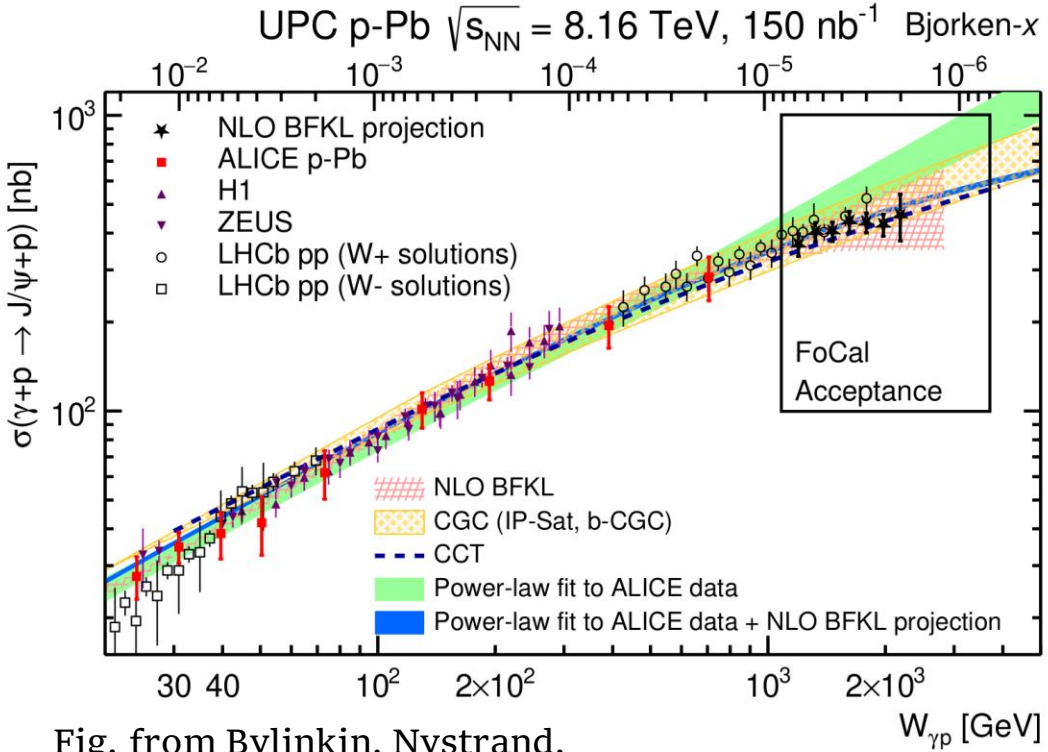
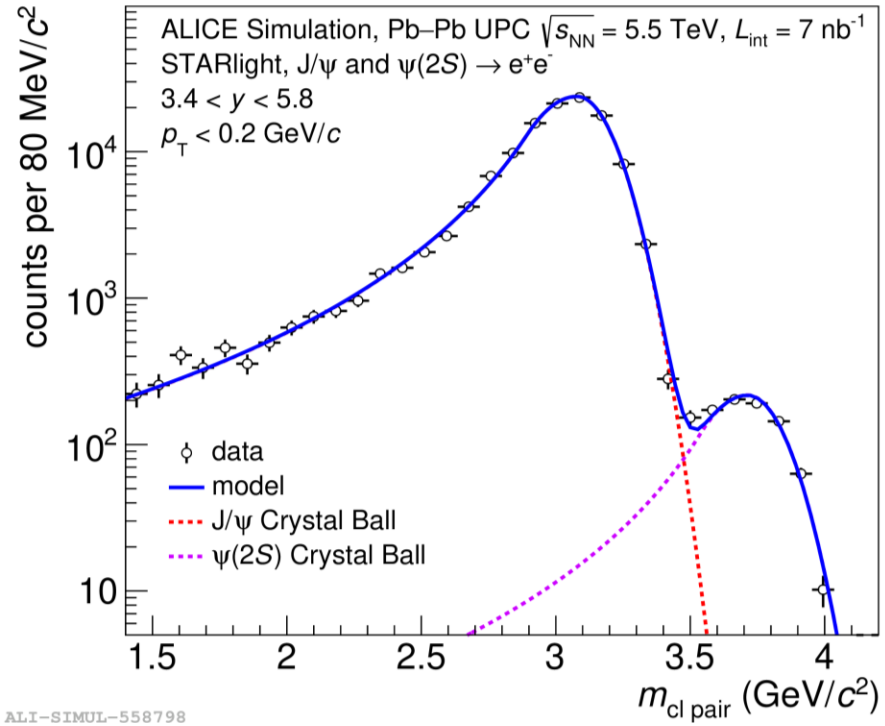


Fig. from Bylinkin, Nystrand, Takaki arXiv:2211.16107



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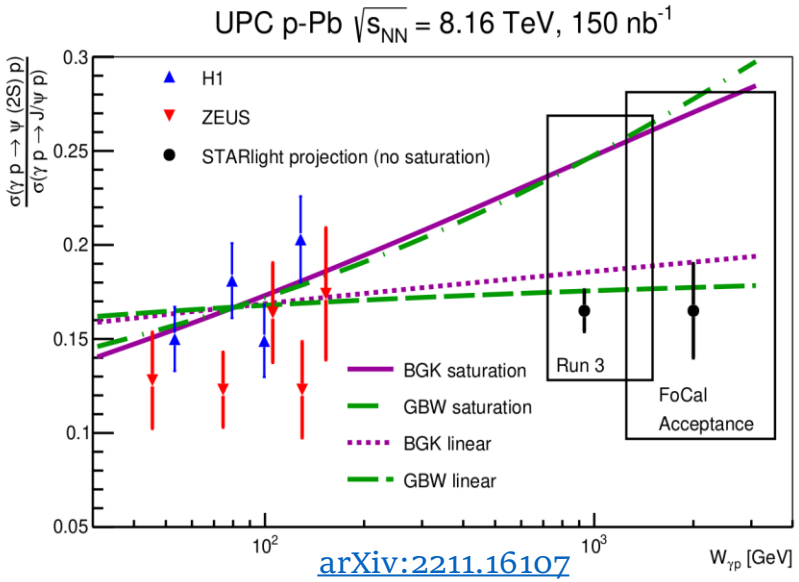

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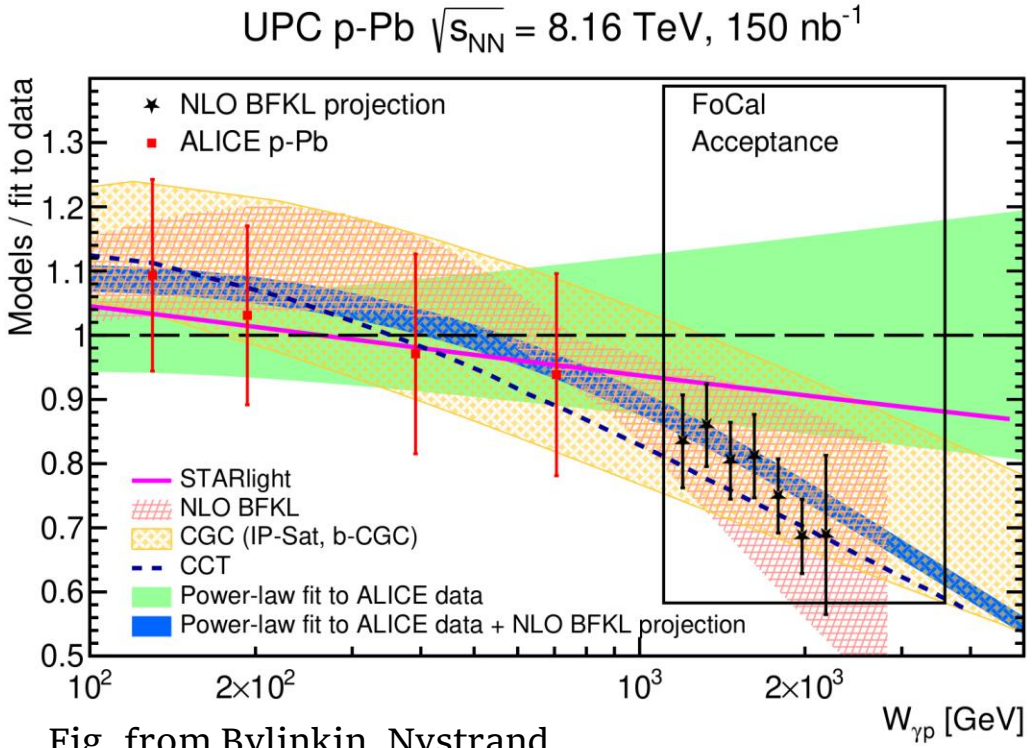

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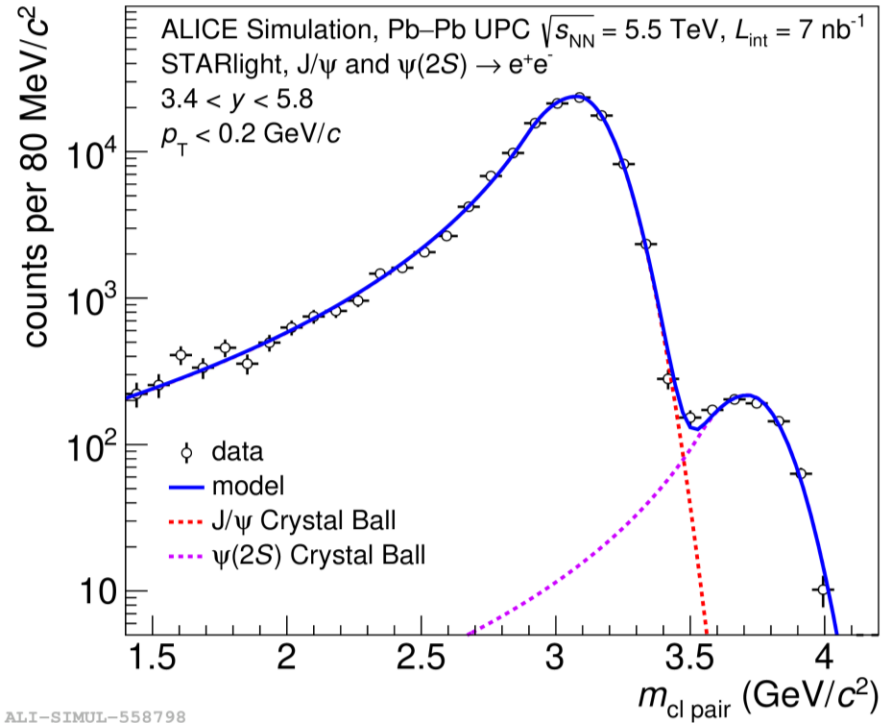
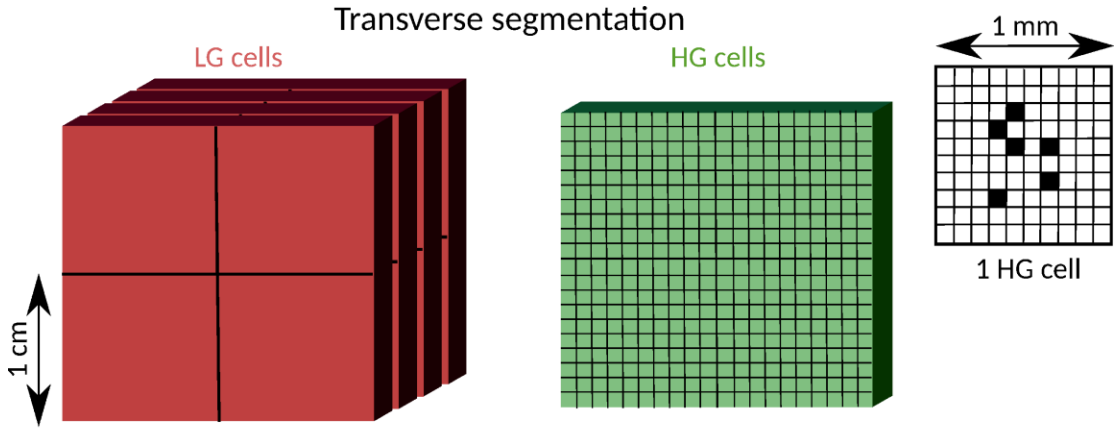
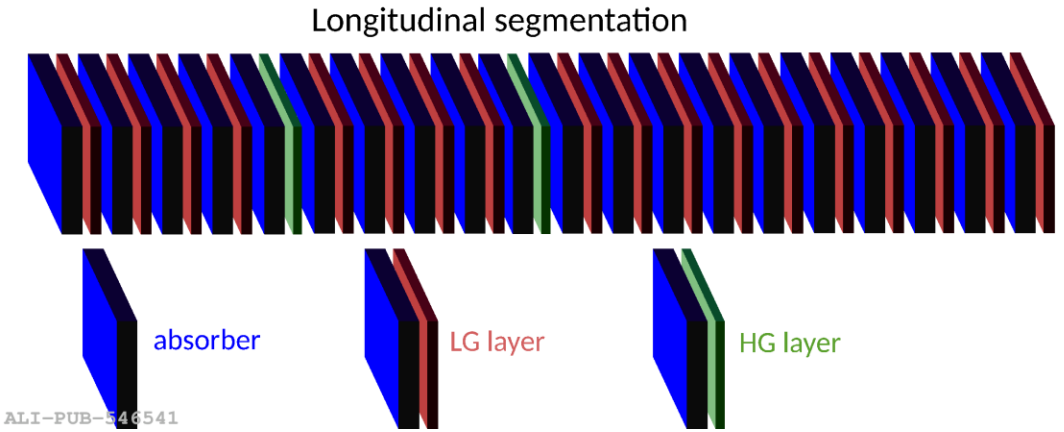
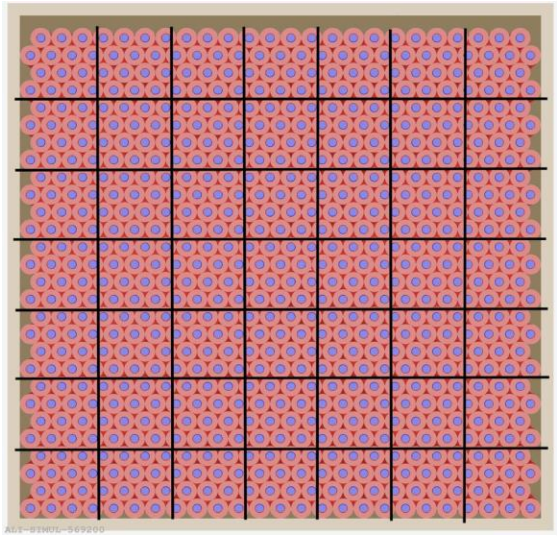


The Forward Calorimeter

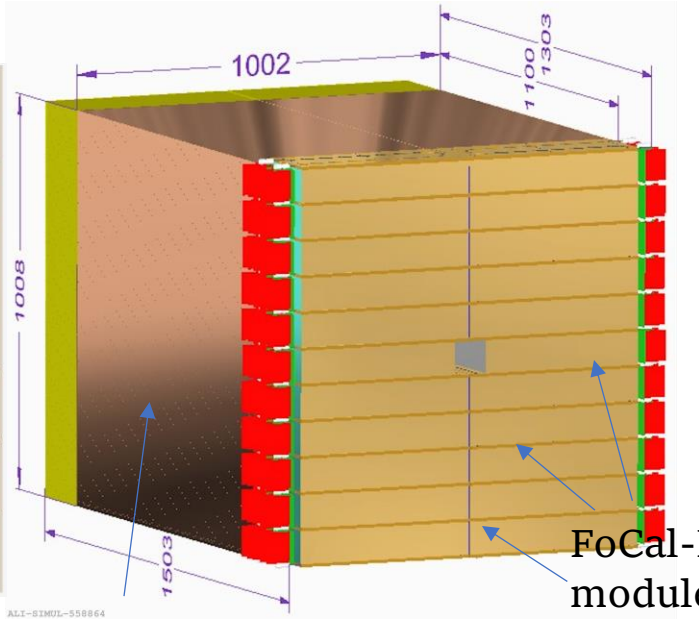
- **FoCal-E:** A compact silicon-tungsten sampling electromagnetic calorimeter with **pad** (1 × 1 cm²) and **pixel** (30 × 30 μm²) segmented readout layers
  - High spatial resolution for discriminating between isolated photons and decay photon pairs
- **FoCal-H:** Hadronic calorimeter constructed from copper capillary tubes filled with scintillator fibers
  - Photon isolation energy and jet measurements

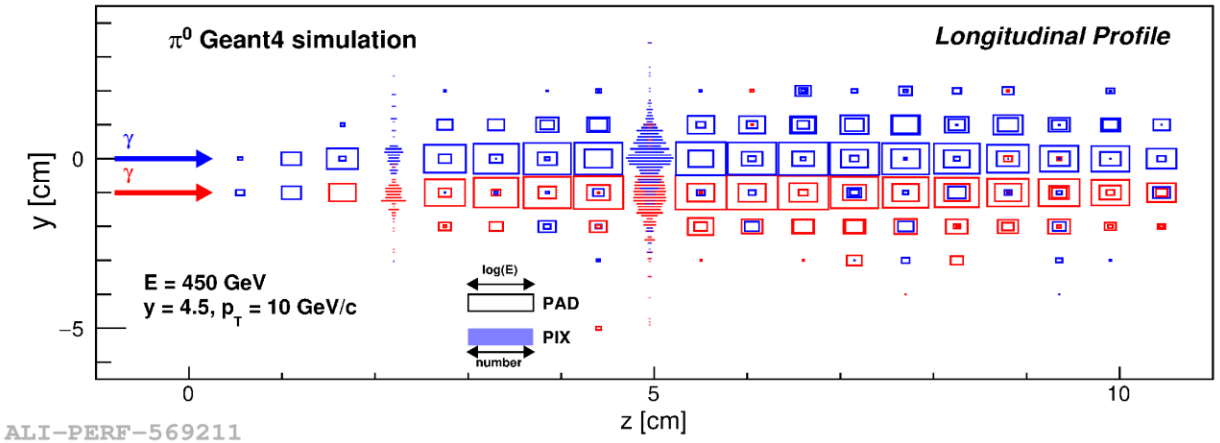






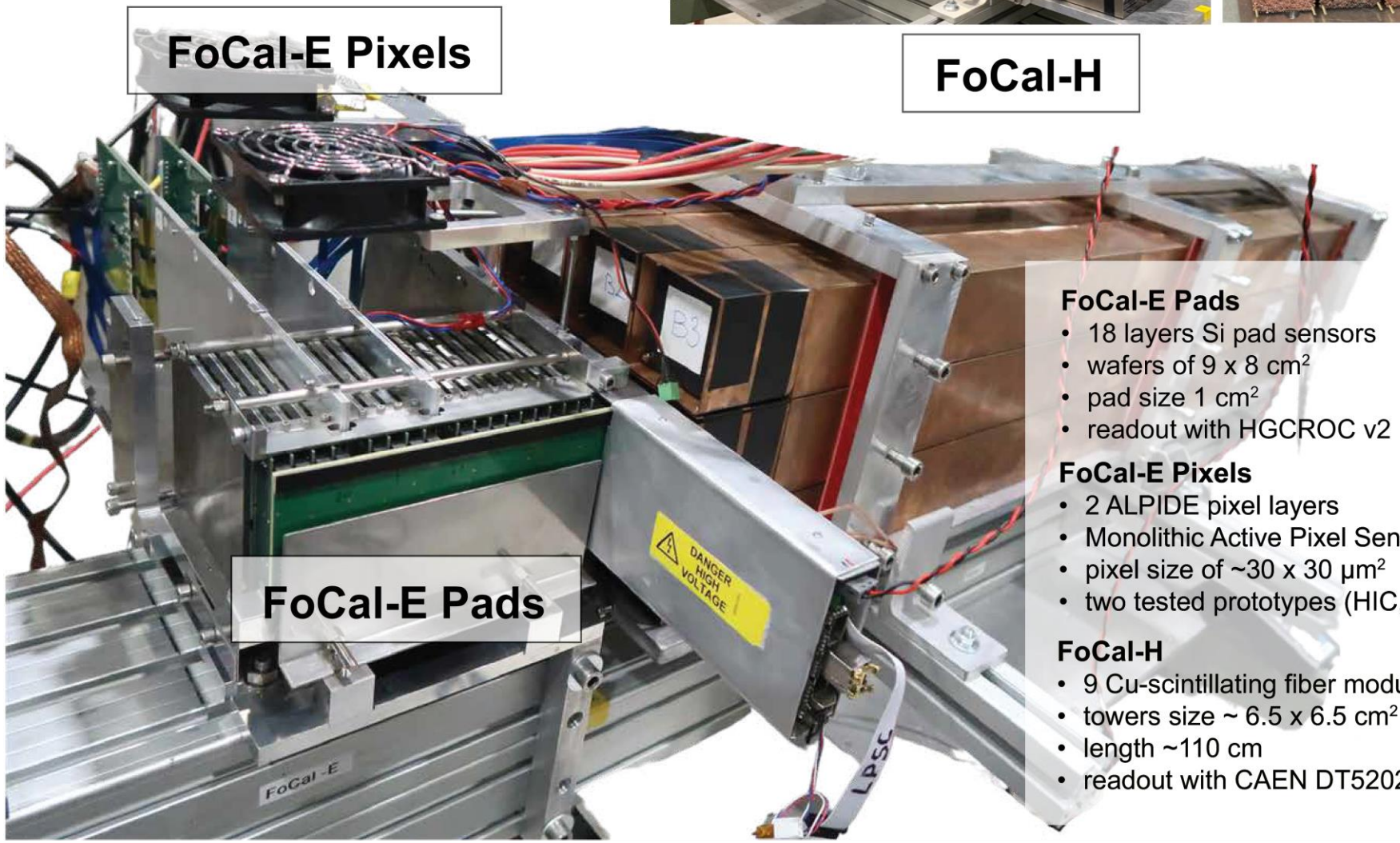
Front view of a FoCal-H module in simulation





FoCal test beams

- Test beam campaigns between 2021 and 2023 at the CERN PS and SPS
  - hadron beams up to energies of 350 GeV
  - electron beams up to 300 GeV
- More test beams are scheduled for 2024



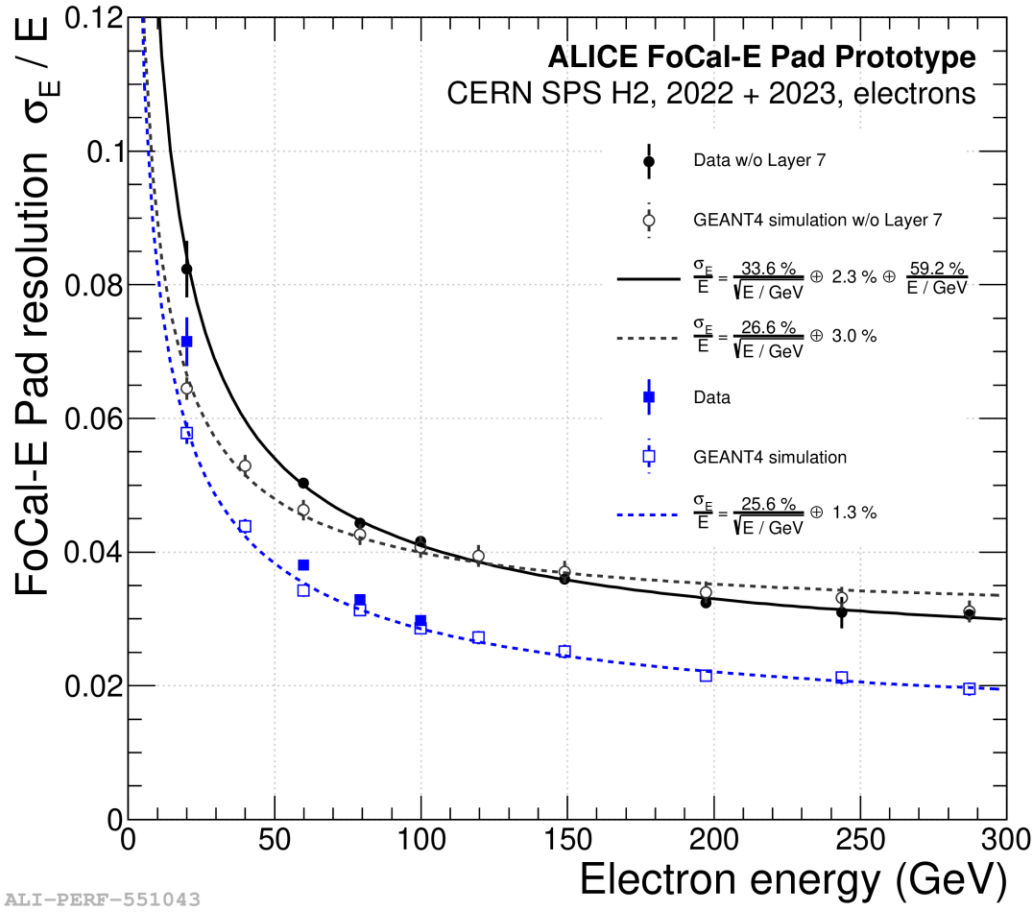
FoCal-E Pads
- 18 layers Si pad sensors
- wafers of 9 x 8 cm^2
- pad size 1 cm^2
- readout with HGCROC v2

FoCal-E Pixels
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm^2
- two tested prototypes (HIC,pCT)

FoCal-H
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm^2
- length ~110 cm
- readout with CAEN DT5202

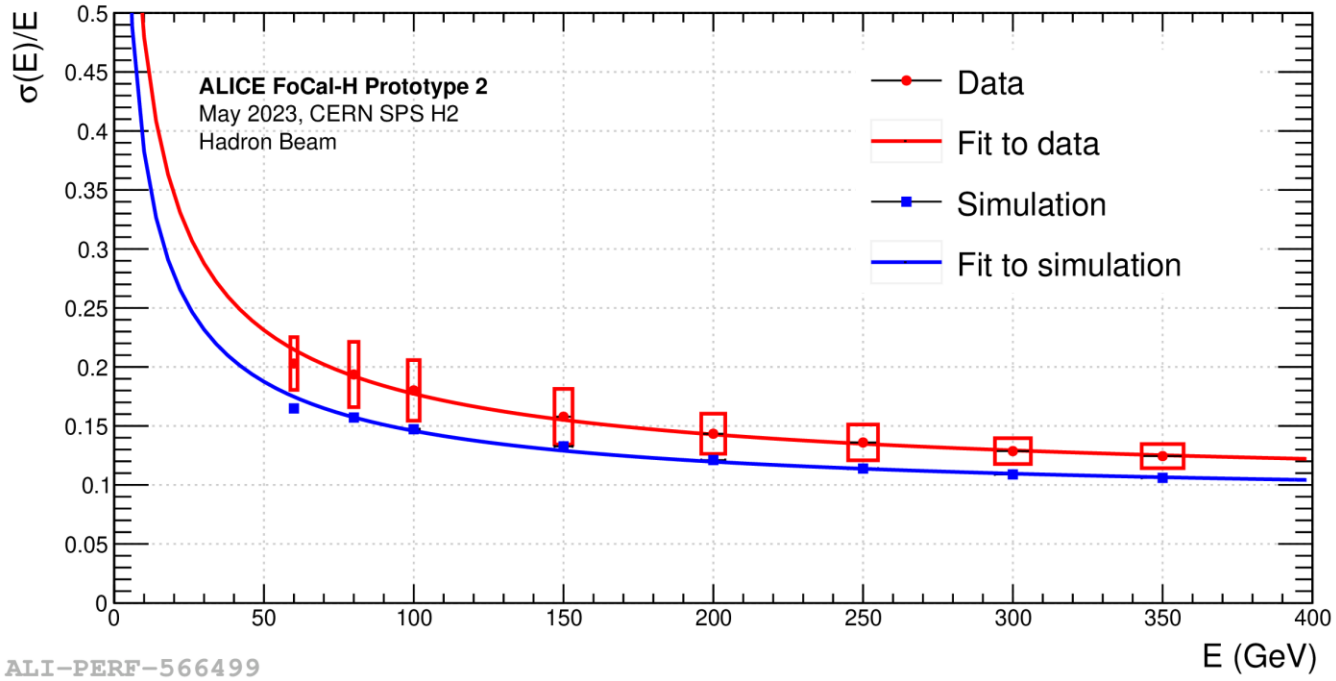
FoCal test beam results

Relative energy resolution of FoCal-E (left) and FoCal-H (right)



ALI-PERF-551043

- Resolution at higher energies below 3-4%
- Well described by simulations

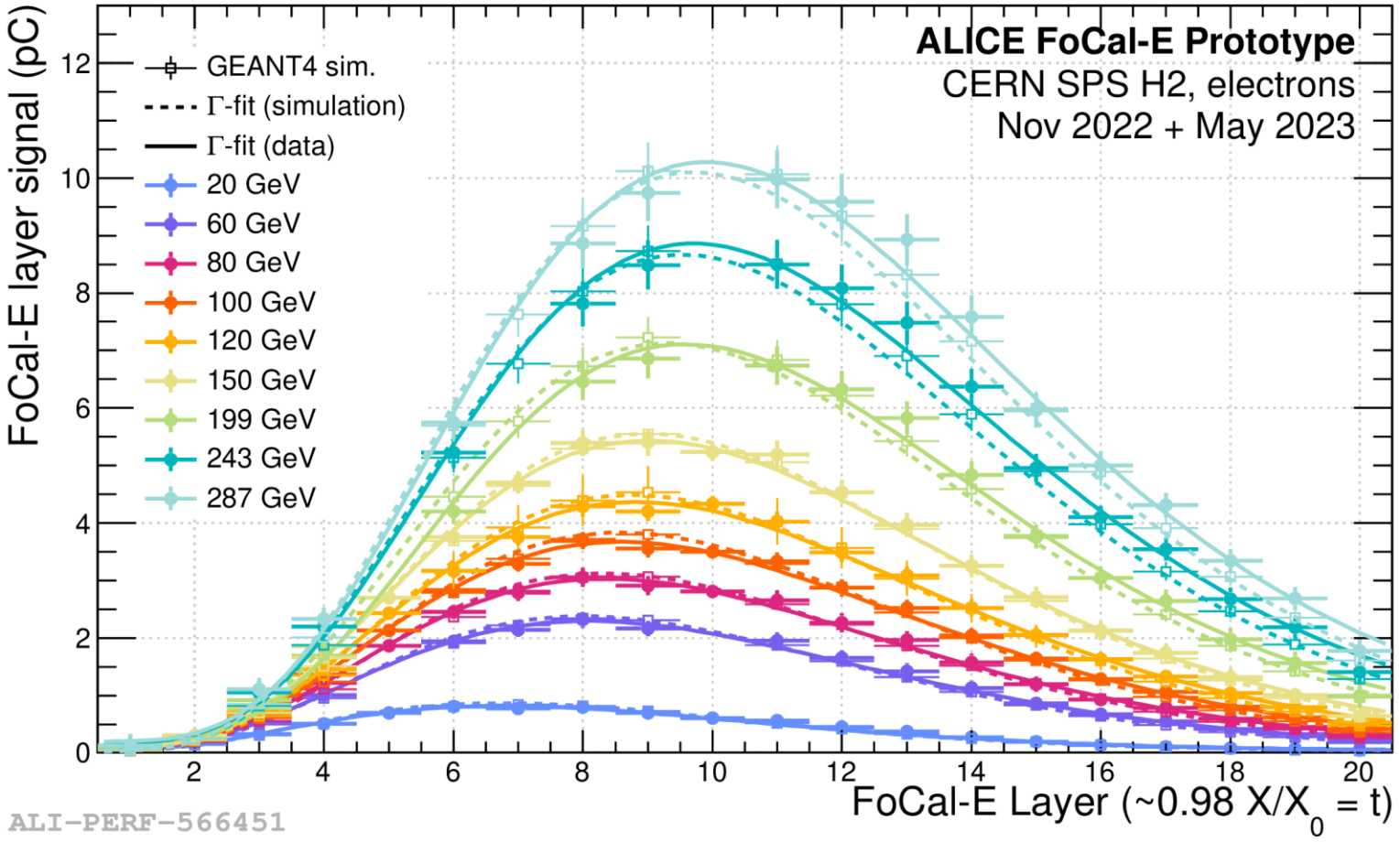


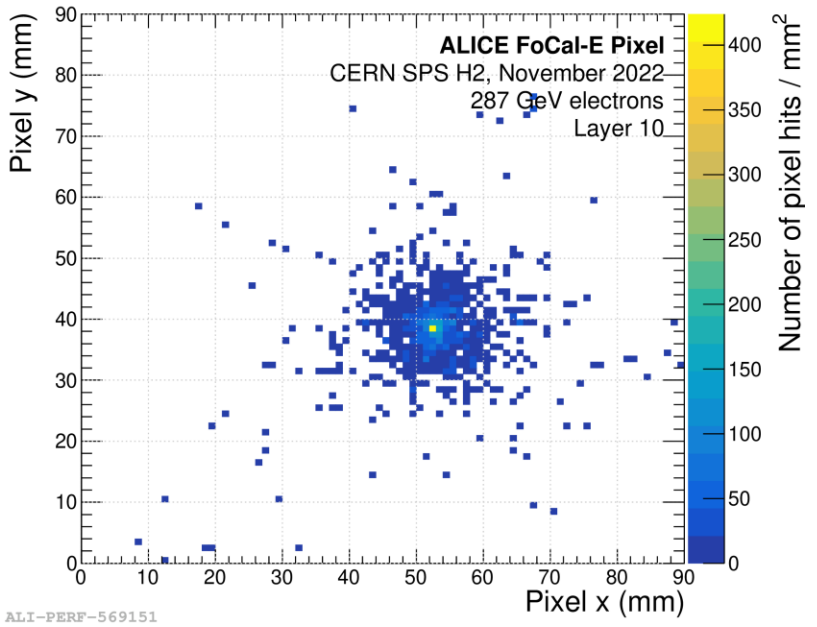
ALI-PERF-566499

- Resolution < 15% at high energies
- Slight discrepancy to simulation under study

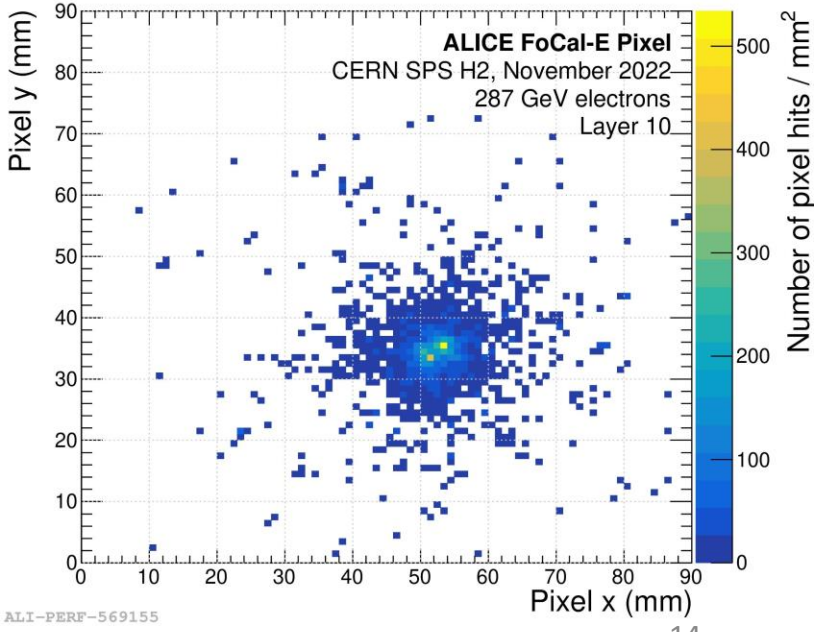
FoCal test beam results

Longitudinal shower profile in FoCal-E





Pixel readout of one- and two-electron showers measured in 2nd pixel layer

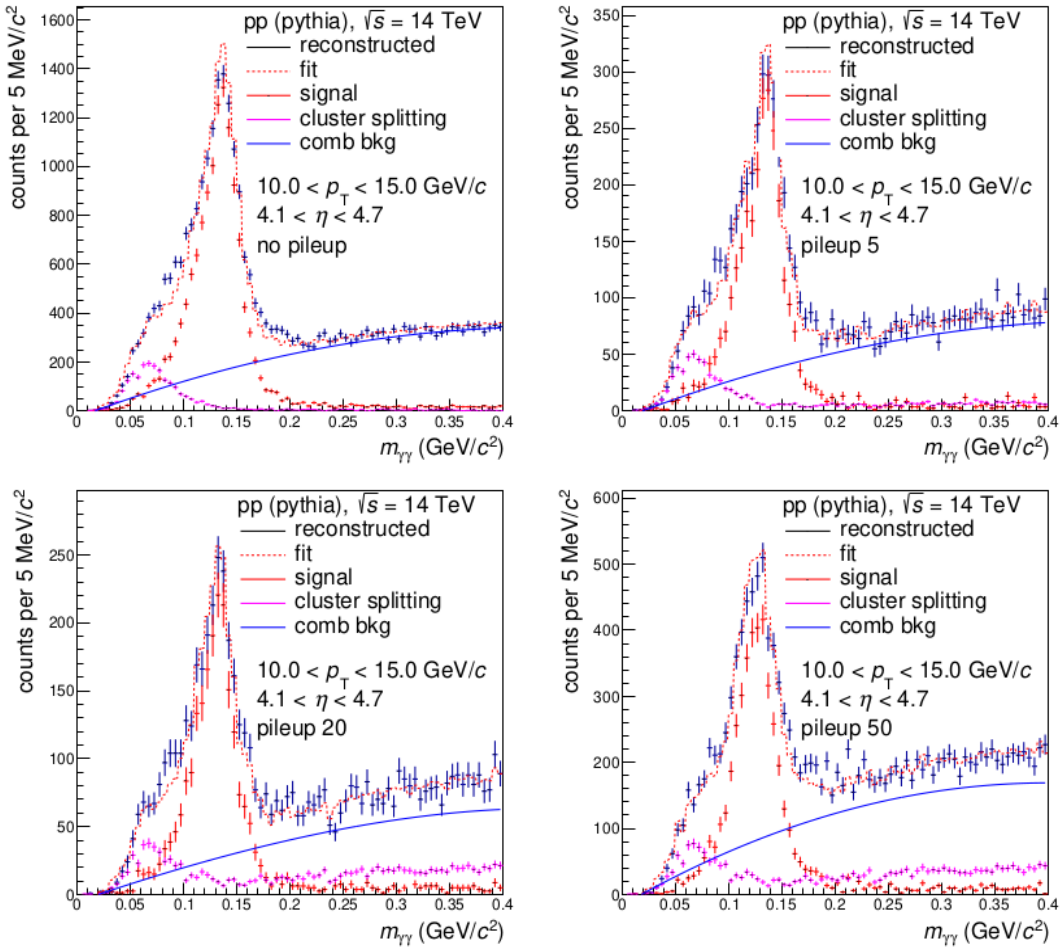


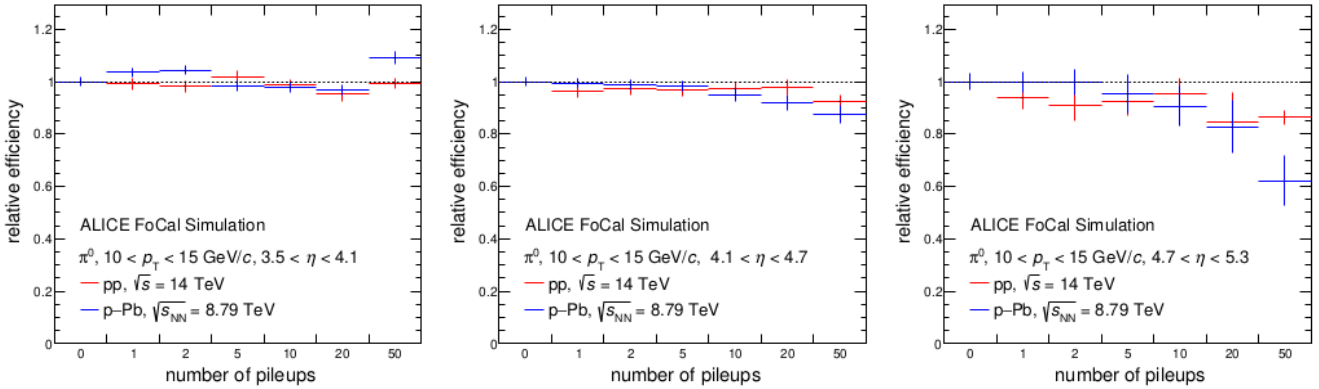
Summary

- FoCal is a calorimeter upgrade for the ALICE experiment for Run 4 (2029-2032), with a pseudorapidity coverage of $3.2<\eta<5.8$
- The goal is to explore gluon saturation at low Bjorken x using a multi-messenger approach
- The prototype of the detector tested in test beams at PS and SPS show good energy resolution and performance
- Performance studies using simulated collision events + detector simulation show FoCal is capable of probing low-x regime with a variety of observables
- Complementarity with LHCb (D^0 mesons in reducing nPDF uncertainties) and EIC (saturation, dipole universality)

Backup slides:

Pileup effects

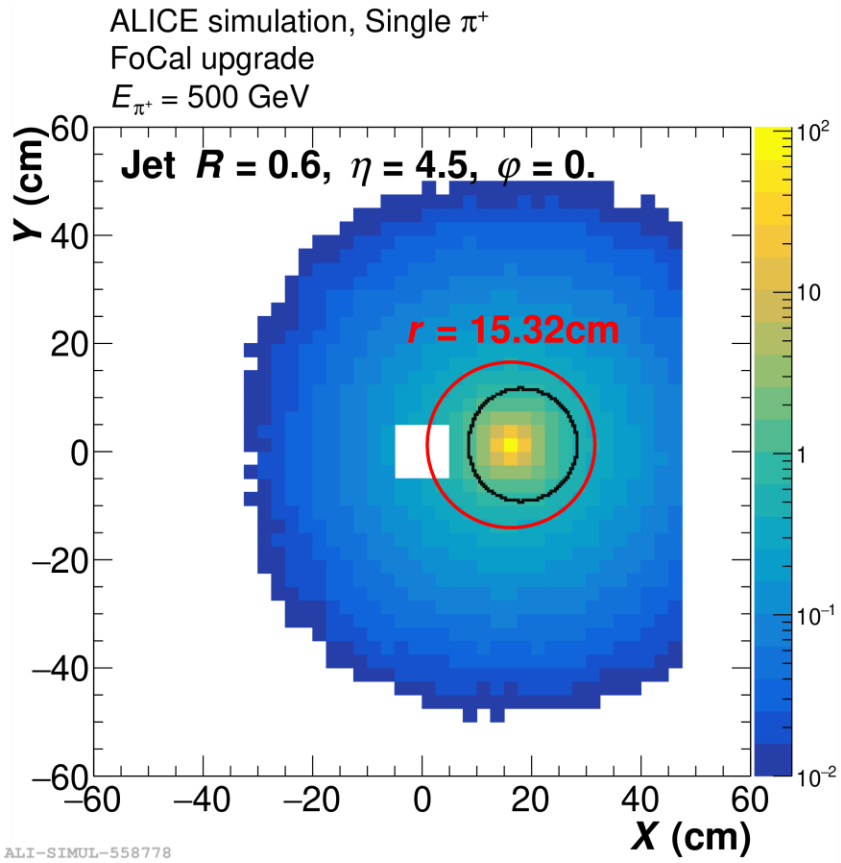




[ALICE-PUBLIC-2023-004]

Jets

- a given jet with resolution parameter R will be squeezed into an increasingly small geometrical space at forward rapidities
- The red circle (which corresponds approximately to the nuclear interaction length of Cu) contains 81% of the shower energy in (x, y) space.
- Black circle is the jet cone, R=0.6.
- A larger jet energy fraction is captured by the R = 0.6 phase space contour for smaller η, and correspondingly smaller shift in JES is expected.



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