Physics prospects from FoCal

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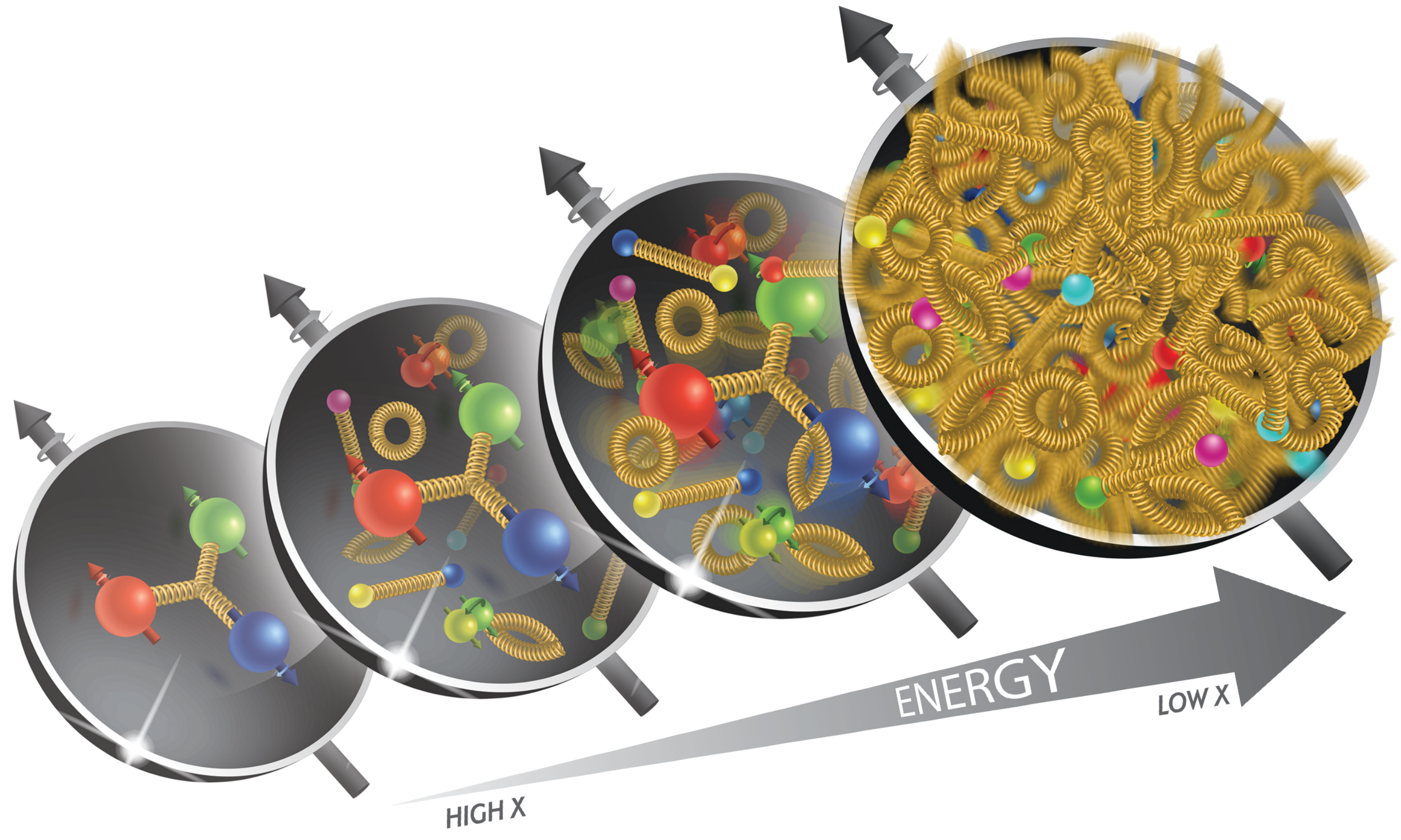
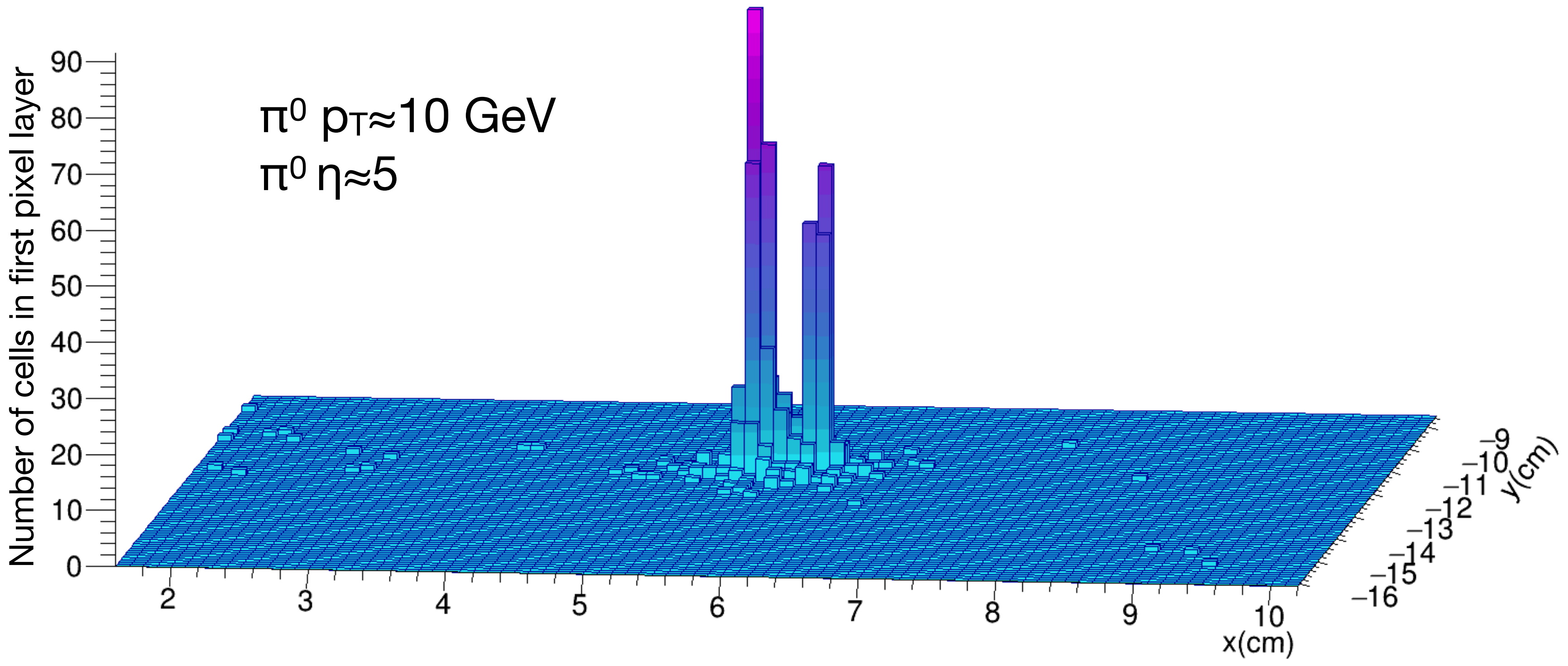
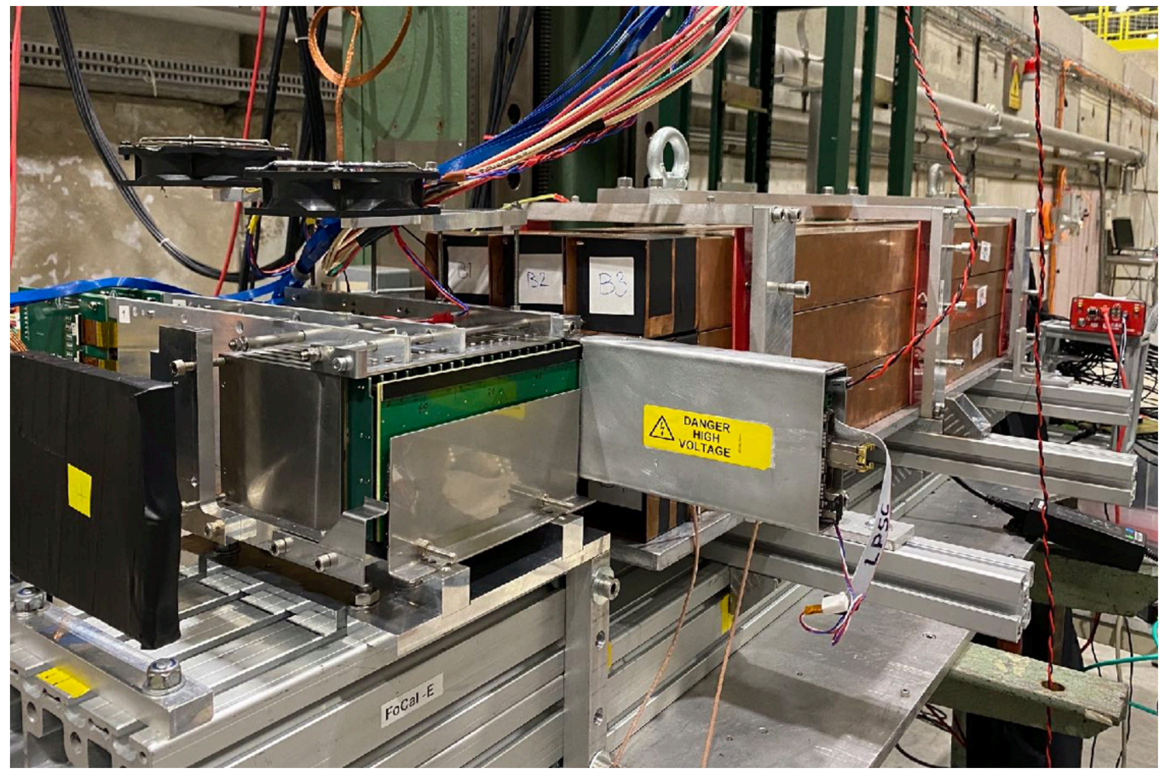
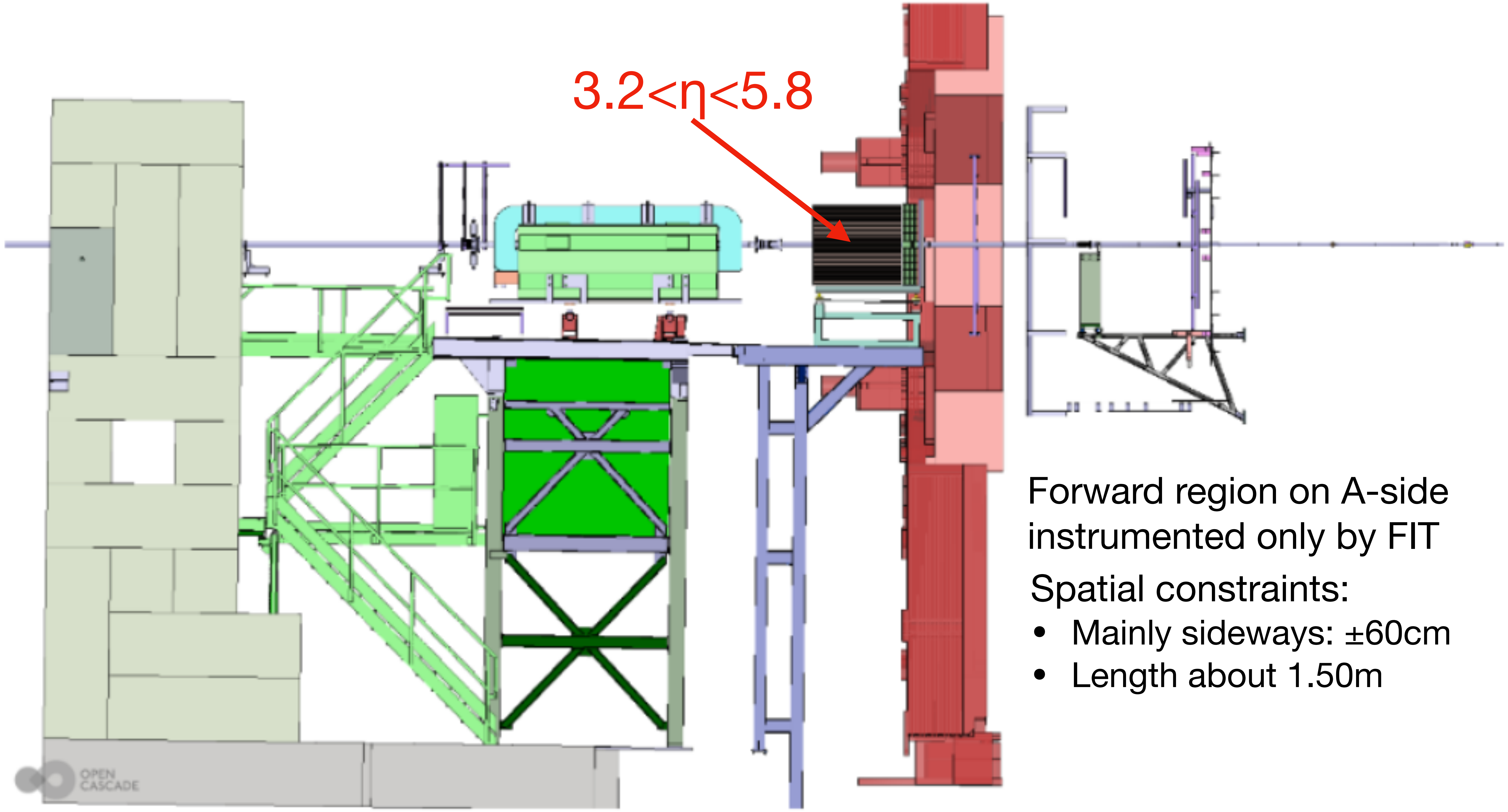
05/31/2024







The FoCal project in ALICE for Run 4



Forward region on A-side instrumented only by FIT

Spatial constraints:
- Mainly sideways: ±60cm
- Length about 1.50m

FoCal-E: high-granularity Si-W sampling calorimeter with longitudinal segmentation for identification of decay photons from π^0

FoCal-H: conventional Cu/SciFi sampling calorimeter for photon isolation and jets

Main physics goal:
Saturation/non-linear evolution at small-x

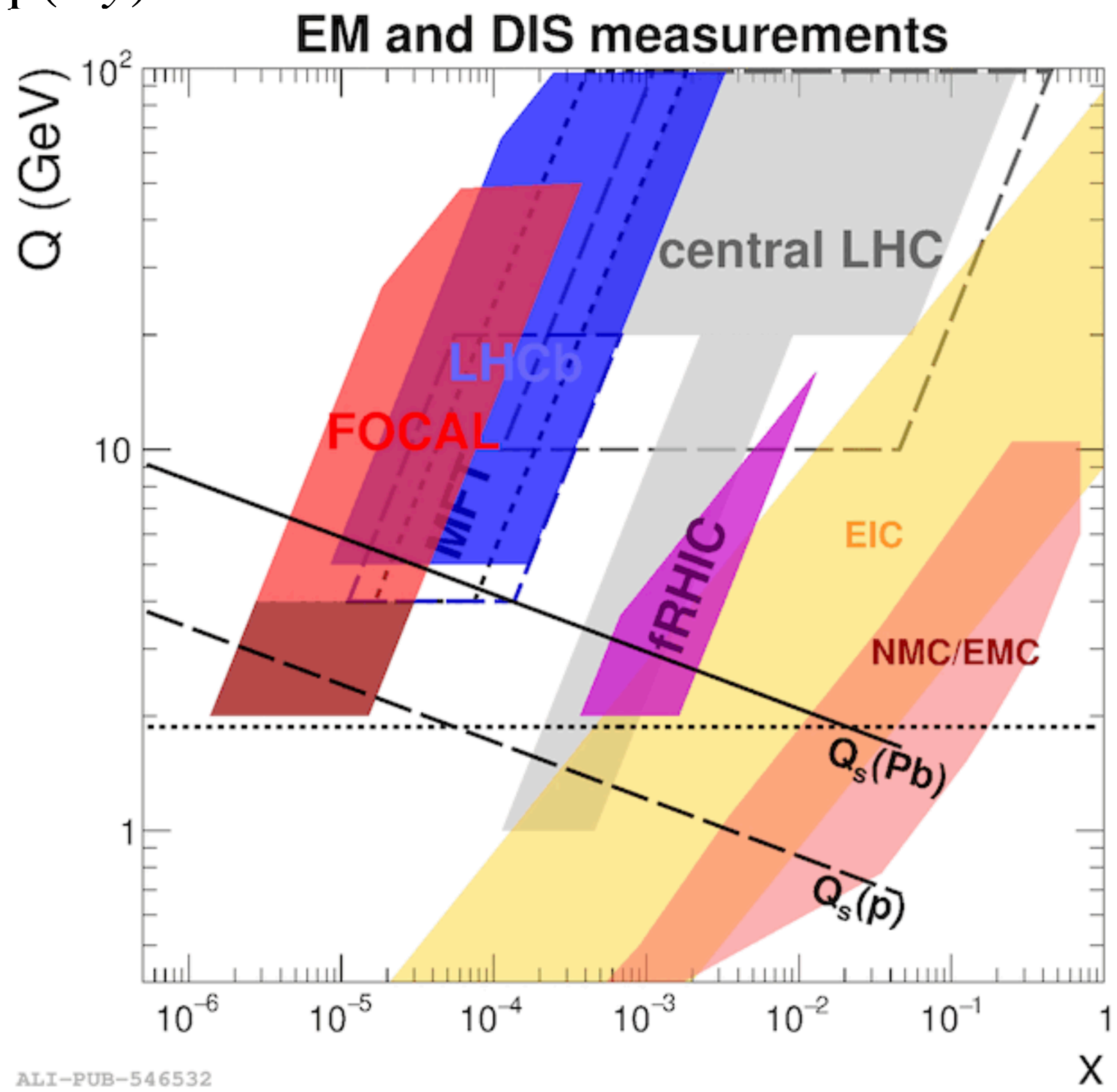
Observables
- π^0 and other neutral mesons
- Isolated (prompt) photons
- Jets
- J/ψ, Υ (in UPC)
- Z, W
- Correlations

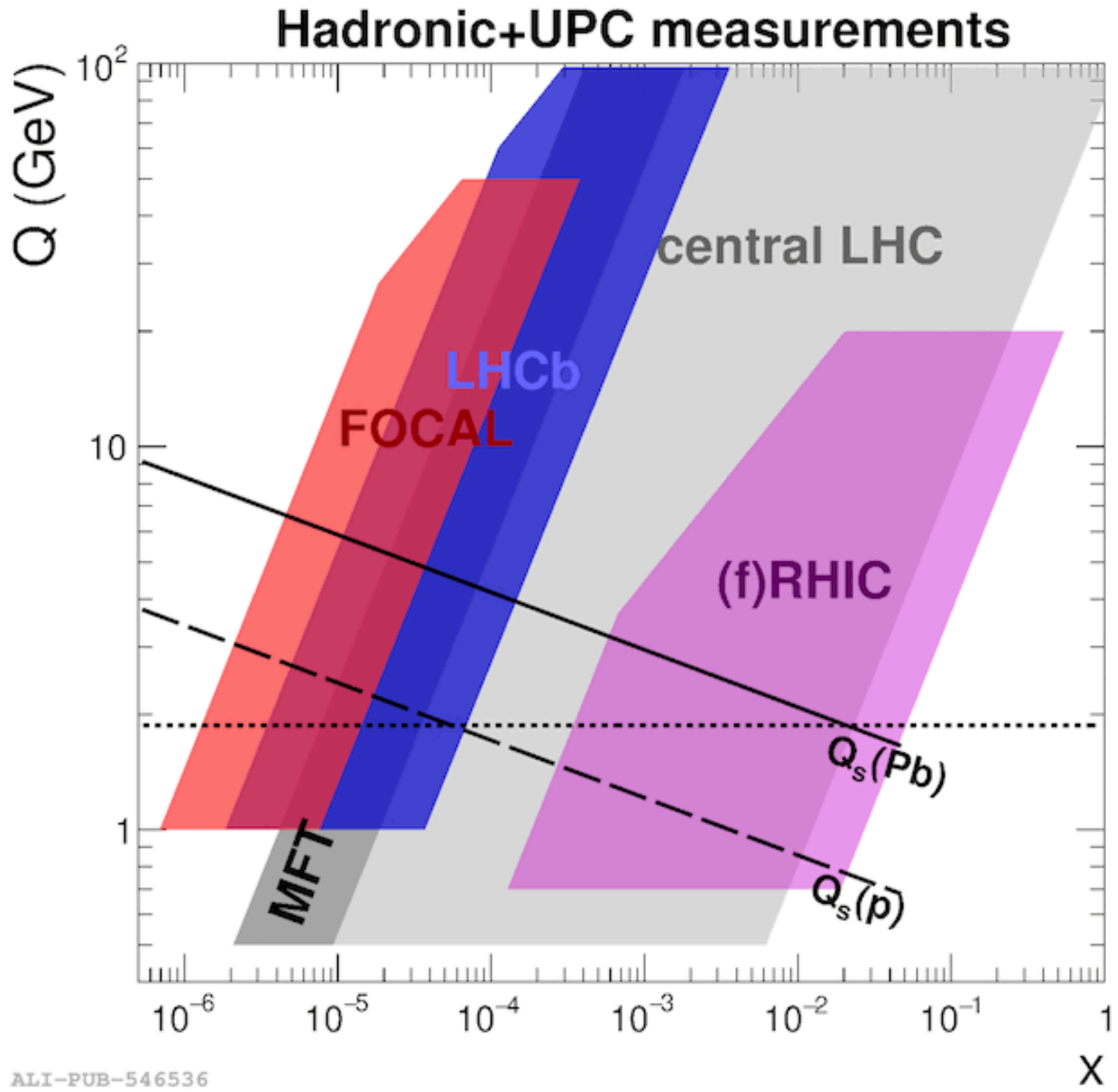
Letter-of-Intent: CERN-LHCC-2020-009

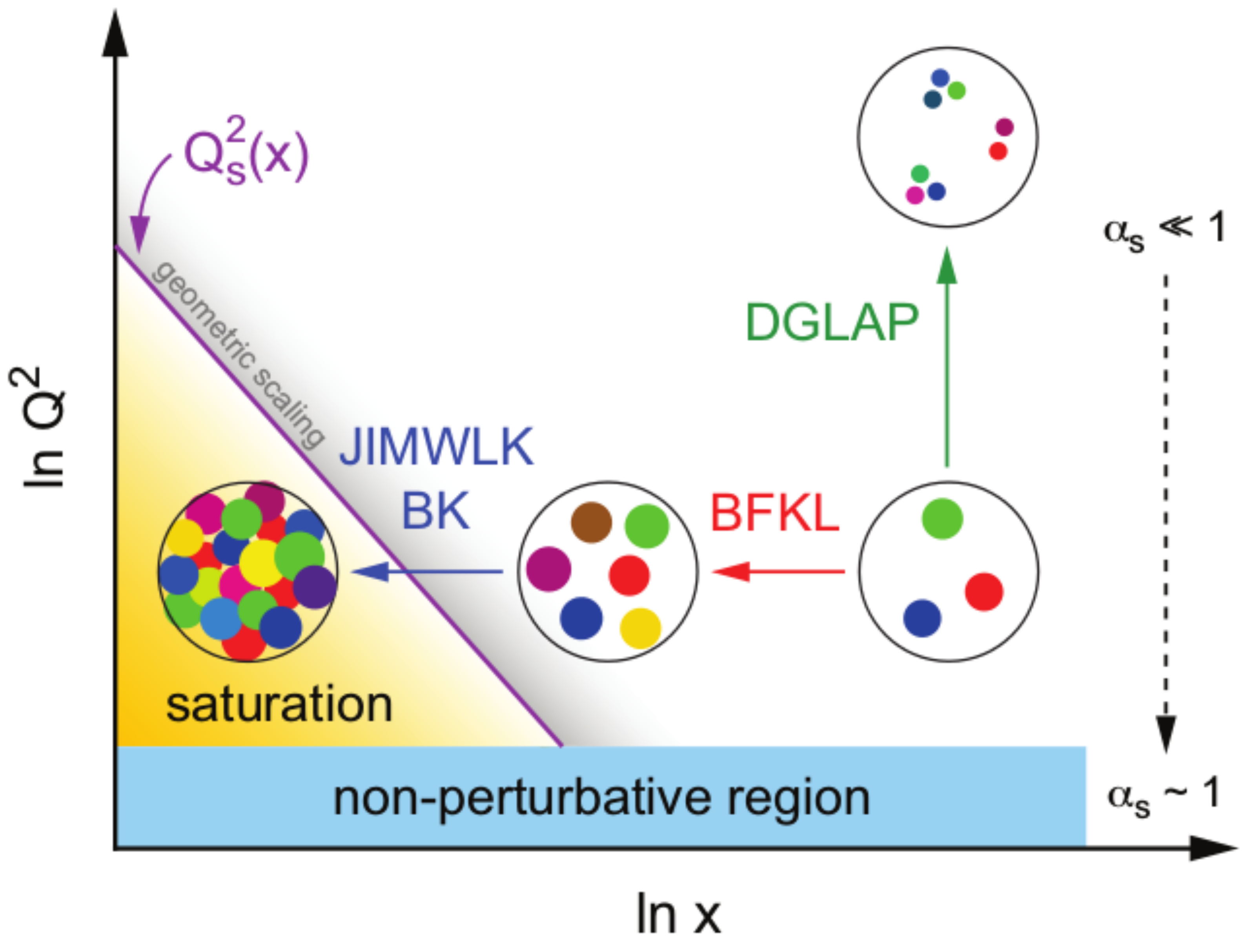
Technical Design Report: CERN-LHCC-2024-004

Probing gluon saturation: Current and future measurements

$$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$$





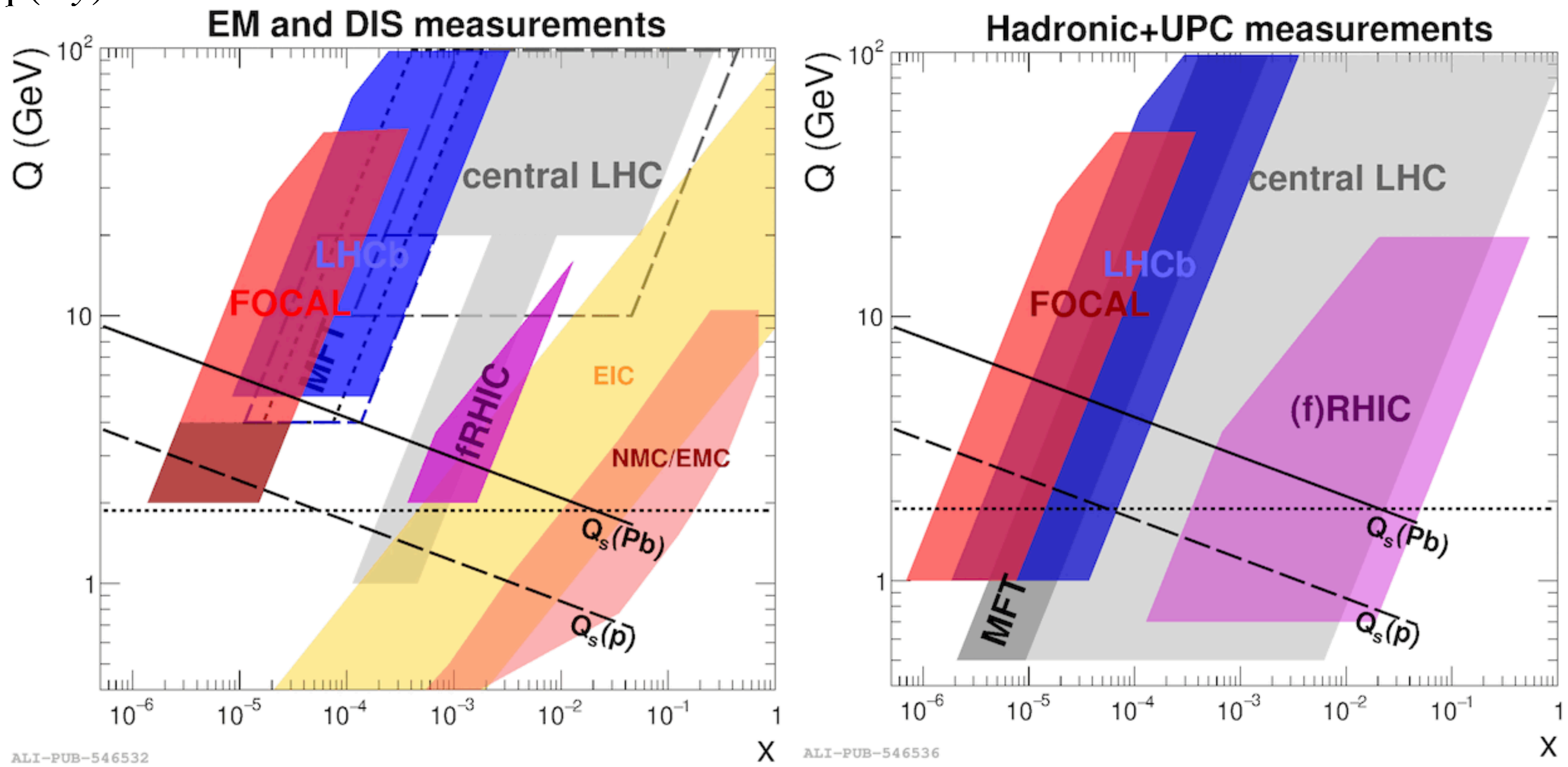


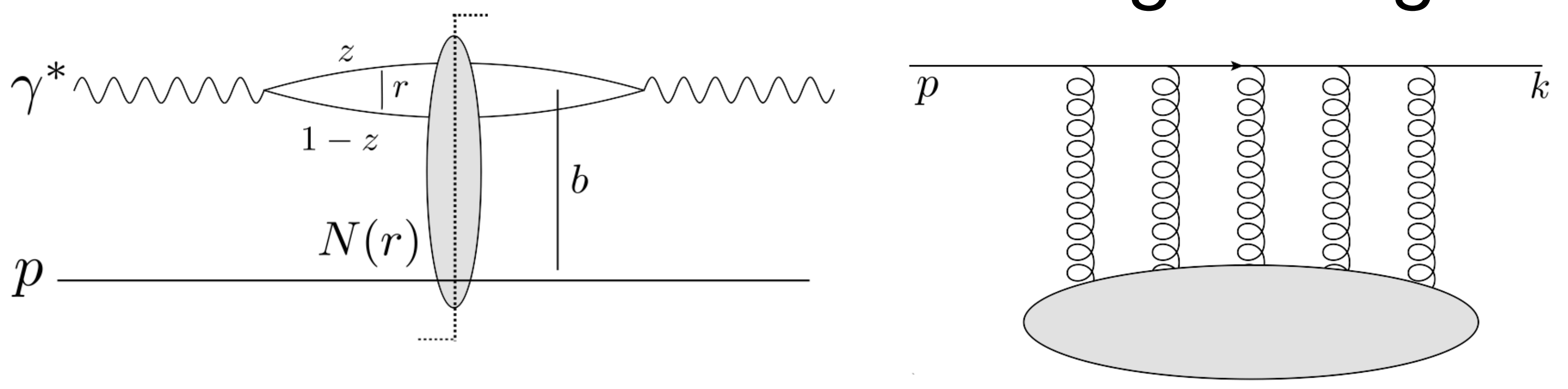
- Study of saturation requires to study evolution of observables over large range in x at low Q^2
- Multi-messenger approach: measure multiple probes at various experimental facilities
- Forward LHC (+RHIC) and EIC are complementary: together they provide a huge lever arm in x
  - EIC: Precision control of kinematics, A-dependence + polarisation
  - Forward LHC: Significantly lower x
    - Observables: isolated γ, jets, open charm, DY, W/Z, hadrons, UPC

ALICE-PUBLIC-2023-001

Probing gluon saturation: Current and future measurements

$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$





$$\text{Dipole}\, N = 1 - \frac{1}{N_C} \mathrm{tr} V(x) V^{\dagger}(y)$$

e.g. see p232ff in the EIC YR

- Study of saturation requires to study evolution of observables over large range in x at low Q^2
- Multi-messenger approach: measure multiple probes at various experimental facilities
- Forward LHC (+RHIC) and EIC are complementary: together they provide a huge lever arm in x
  - EIC: Precision control of kinematics, A-dependence + polarisation
  - Forward LHC: Significantly lower x
    - Observables: isolated γ, jets, open charm, DY, W/Z, hadrons, UPC
- Observables in **DIS and forward LHC are fundamentally connected via same underlying dipole operator**

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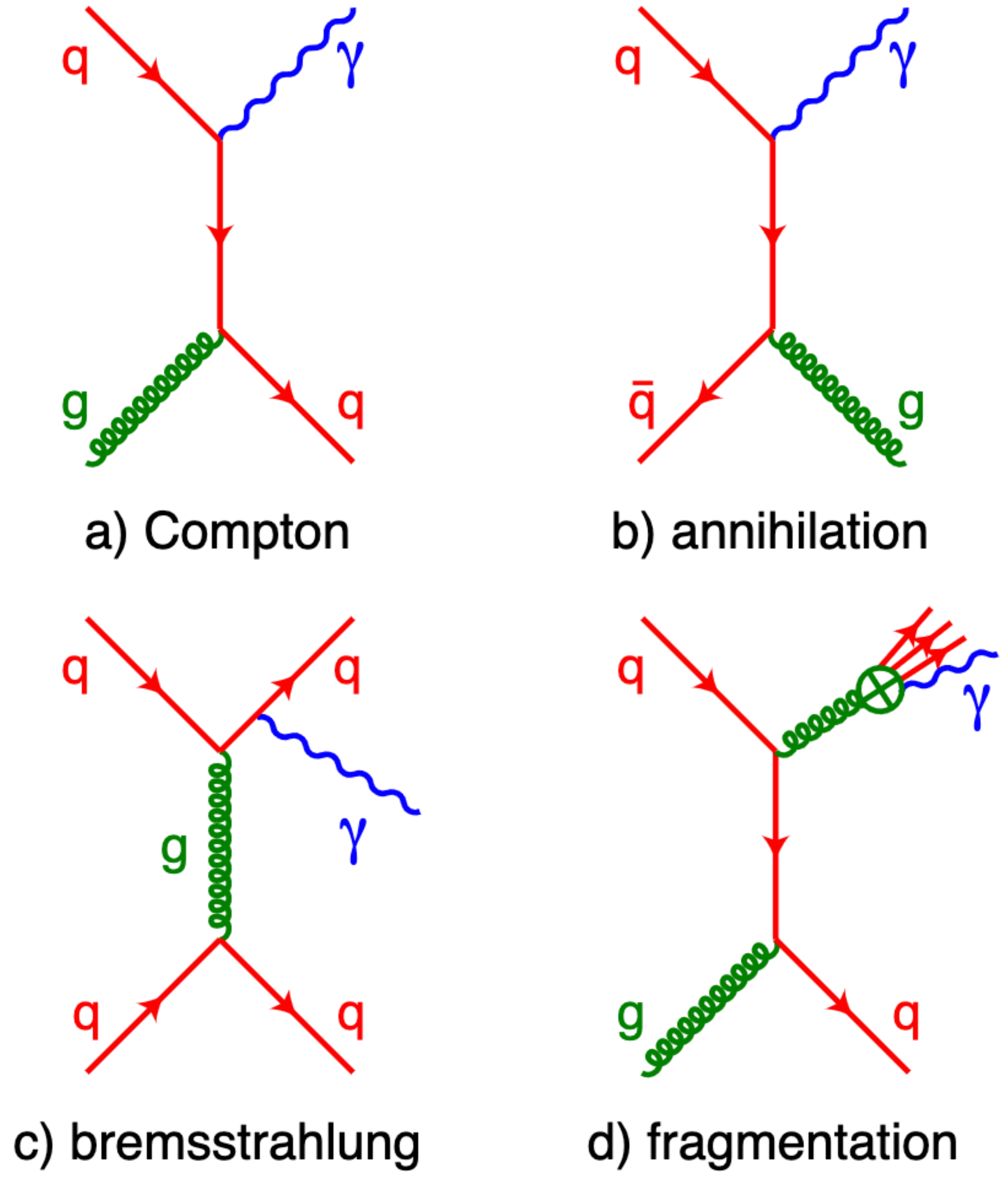
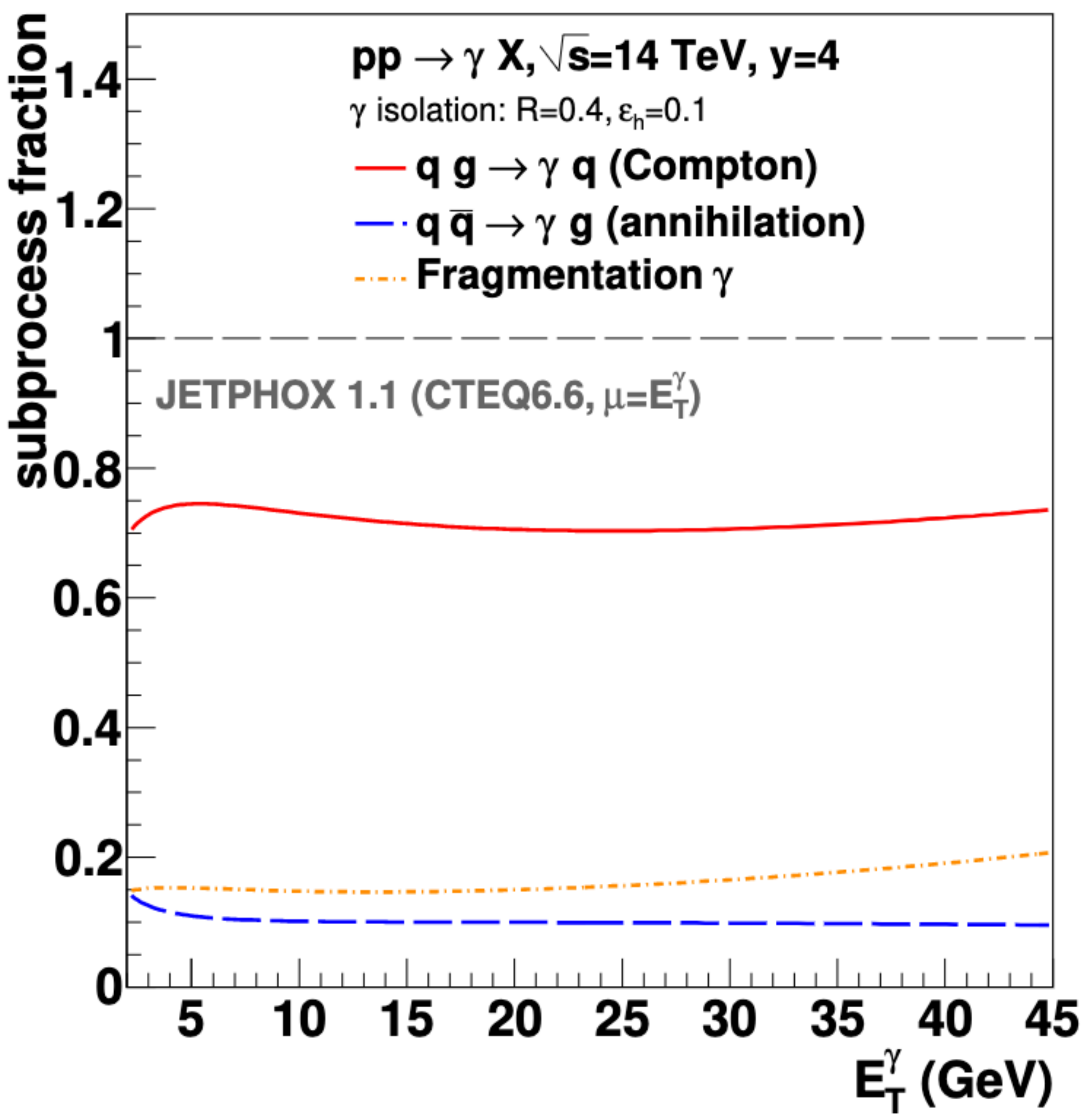
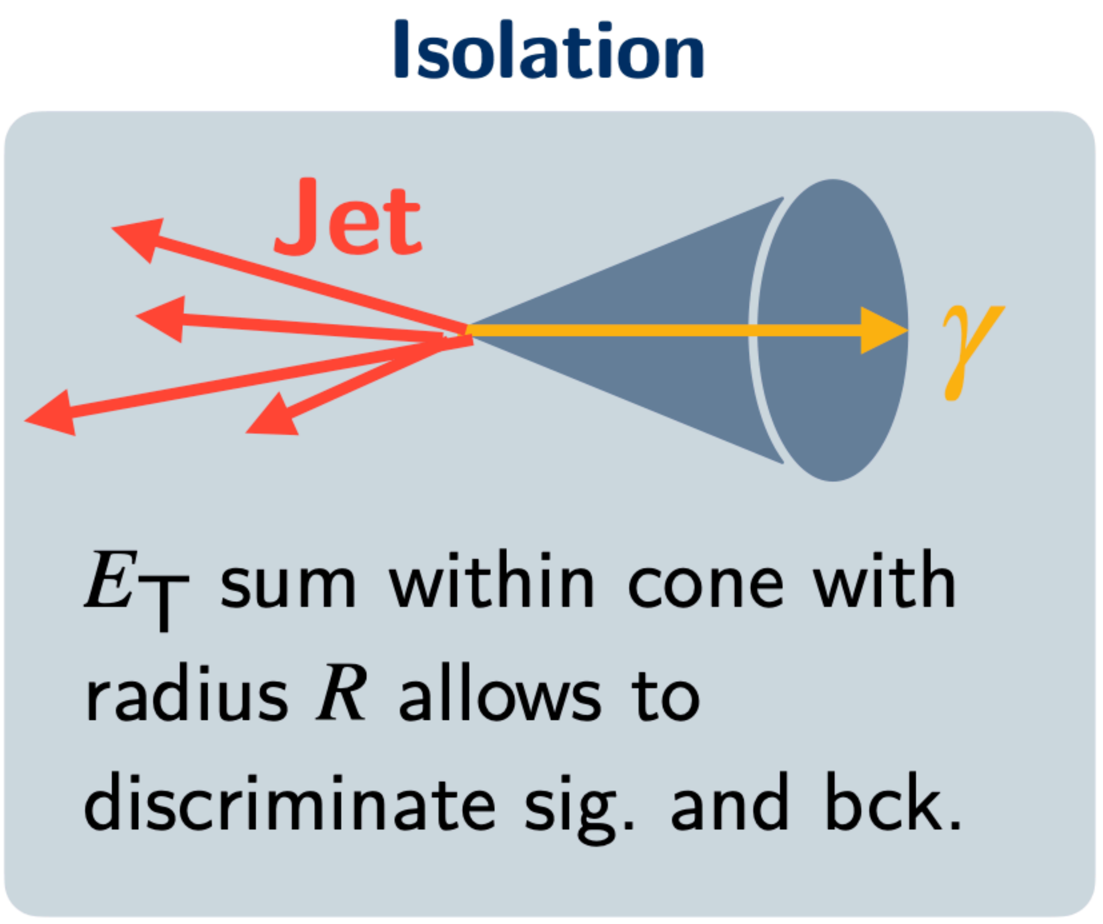
Prompt isolated photons







(1) **Direct production** (direct access to incoming parton, e.g. gluon)

(2) **Bremstrahlung & fragmentation** of outgoing parton (requires inclusion of non-perturbative objects)

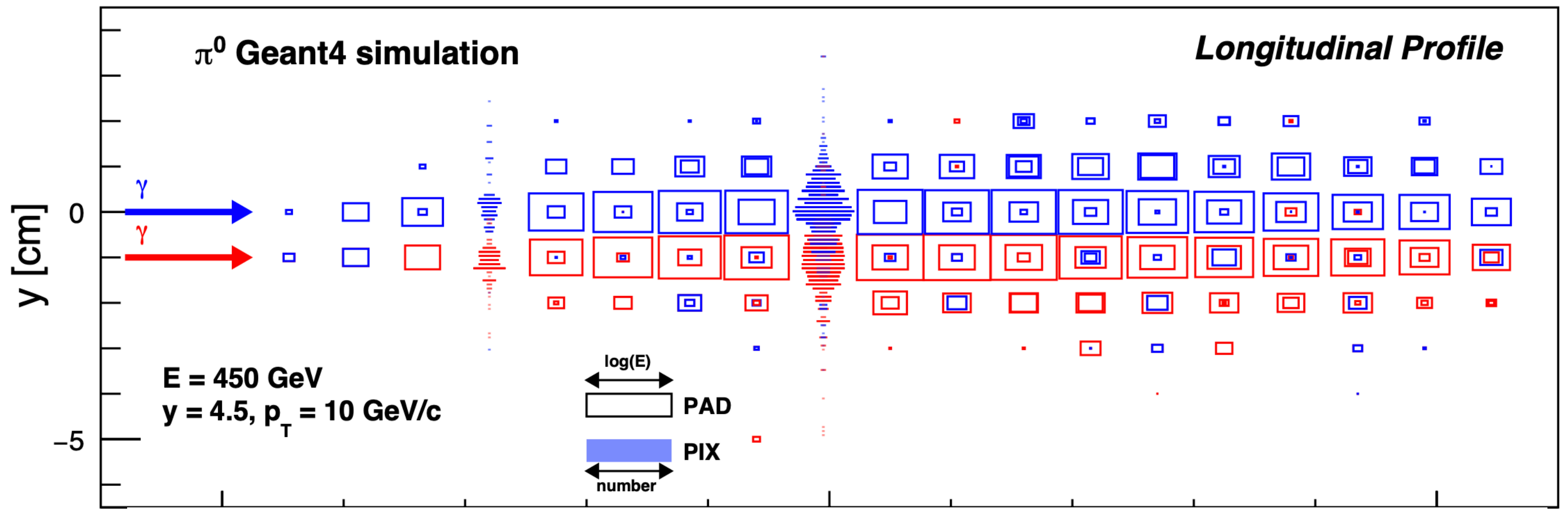
- The sum of both contributions is the physical observable
- Use isolation to suppress contribution from (2)

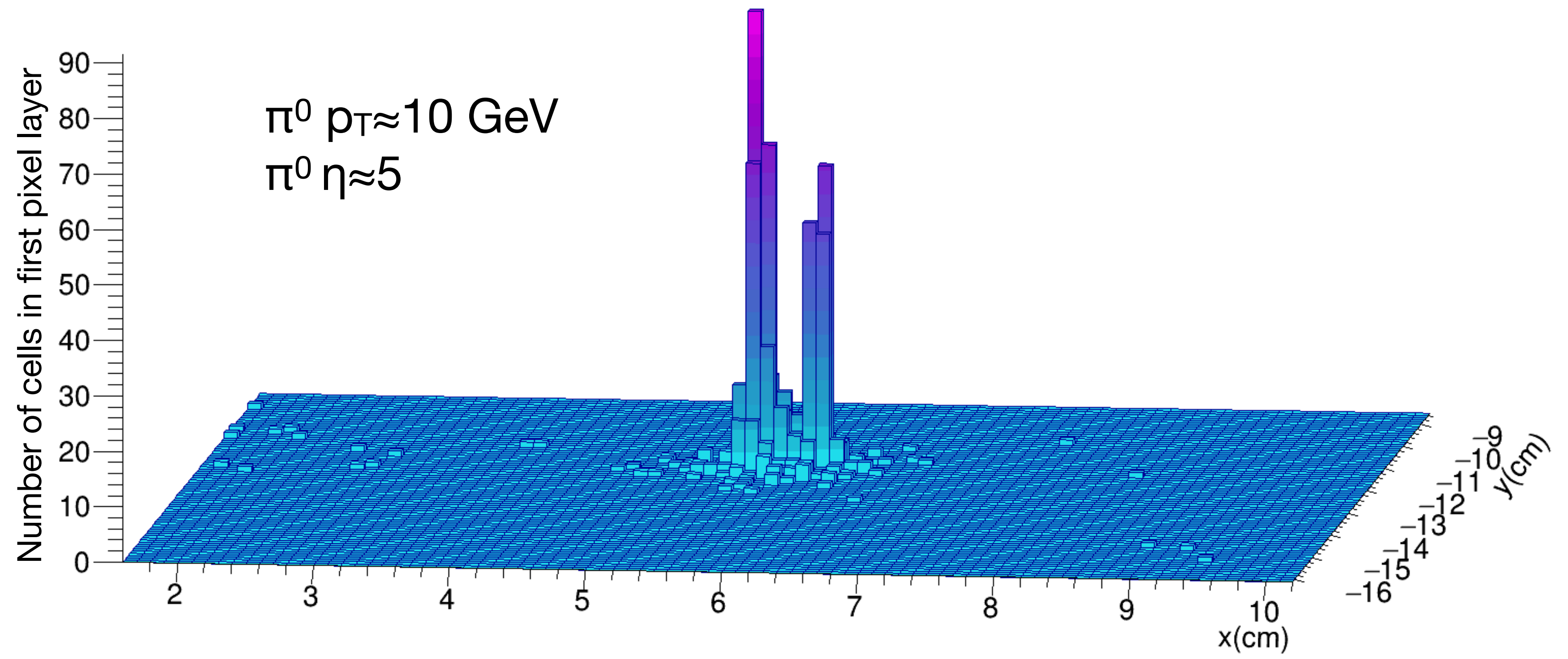
Prompt isolated photons key observable for FoCal

- Prompt photons sensitive to gluon (n)PDF
- No strong interaction in final state
- Exploration of low-x gluons
  - Shadowing?
  - Non-linear QCD effects (saturation)
- Validity of factorisation?

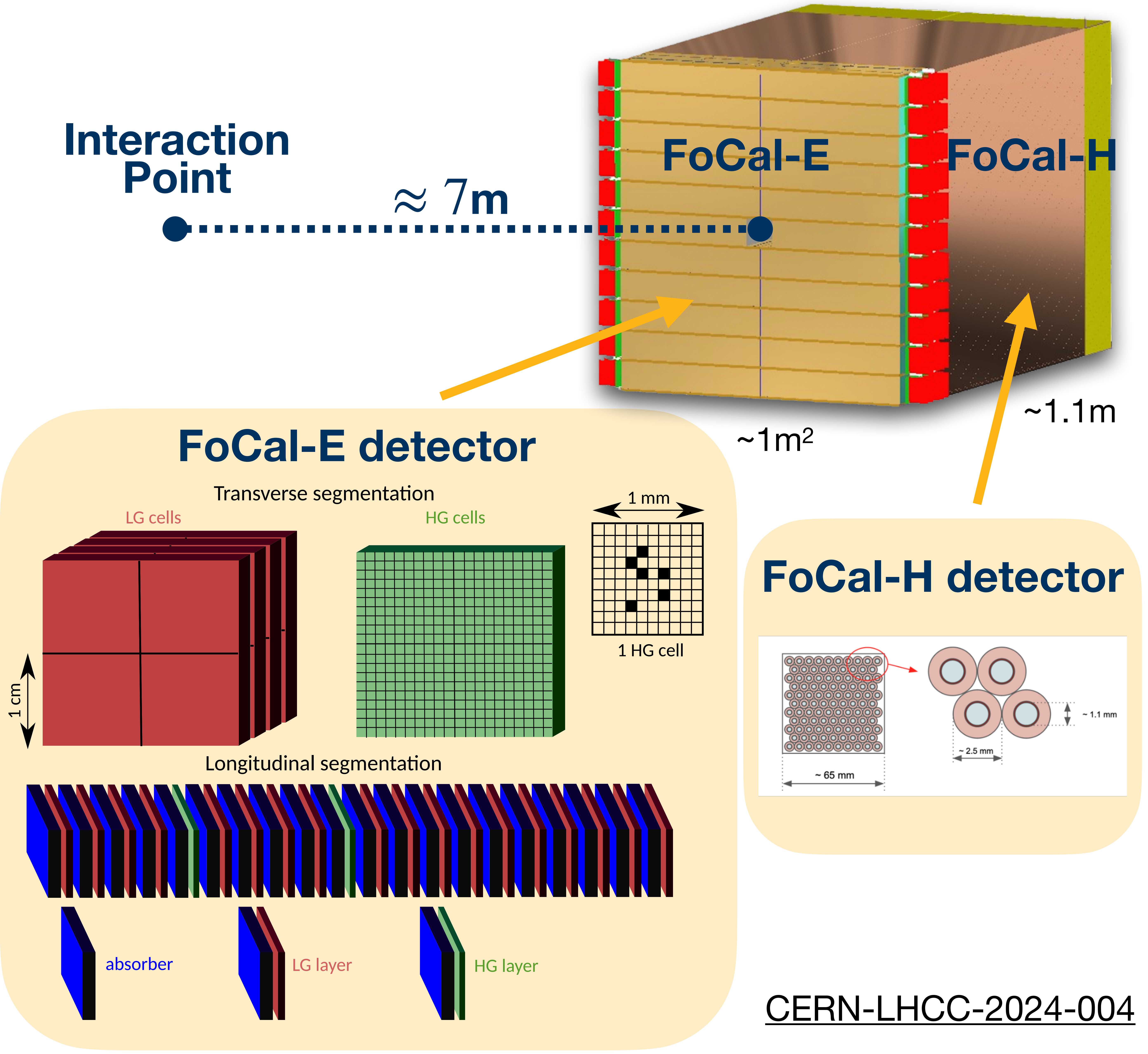
FoCal detector concept

- **FoCal-E** is a highly granular Si-W calorimeter combining two sensor technologies ($20X_0$):
  - 18 silicon pad layers ($1x1cm^2$)
  - two pixel layers ($30x30\mu m^2$)



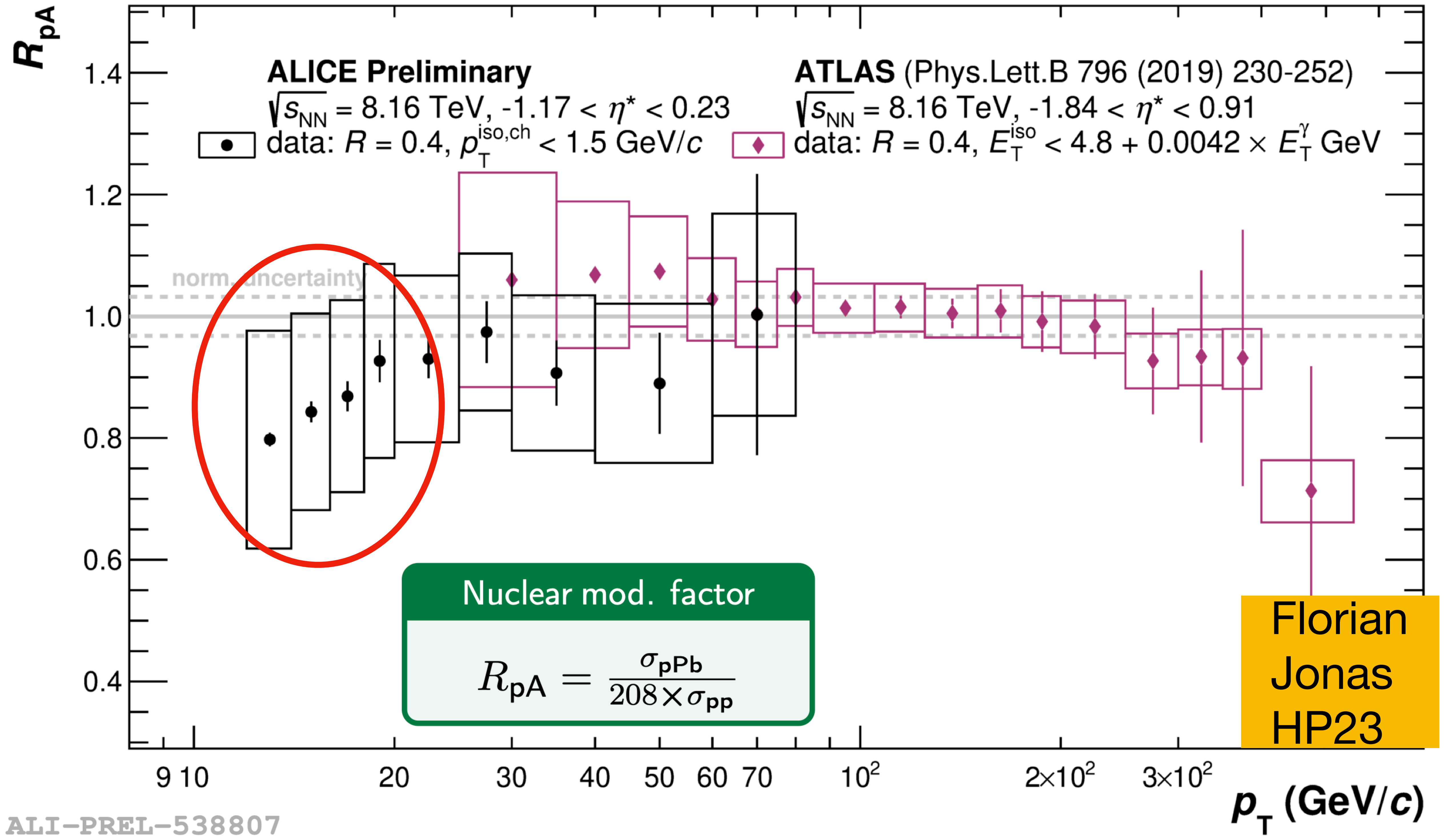


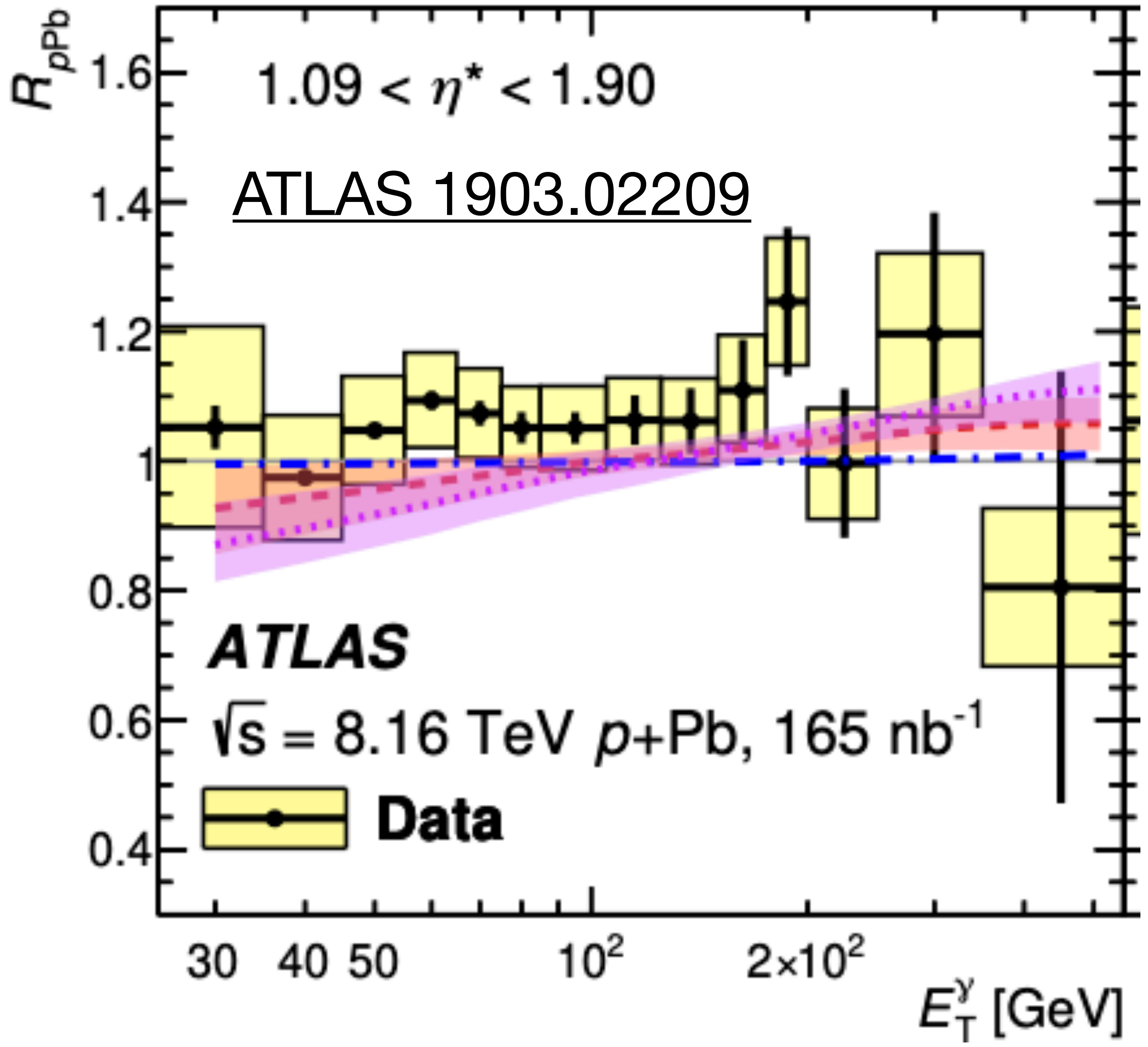
- **FoCal-H** uses scintillation fibres embedded into Cu tubes ($\sim 5\lambda_{int}$)



CERN-LHCC-2024-004

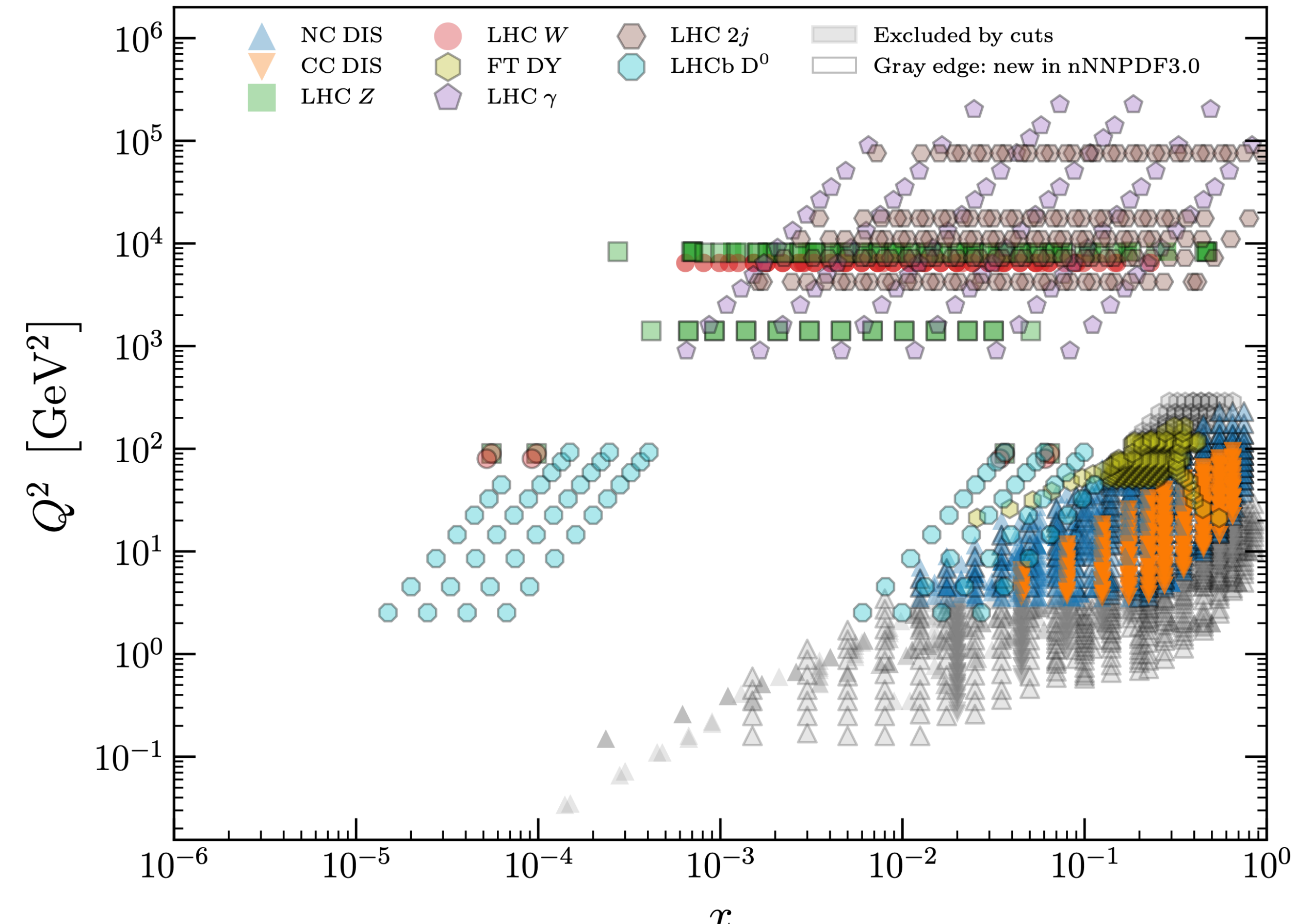
State of the art photon R_{pPb} measurements at LHC



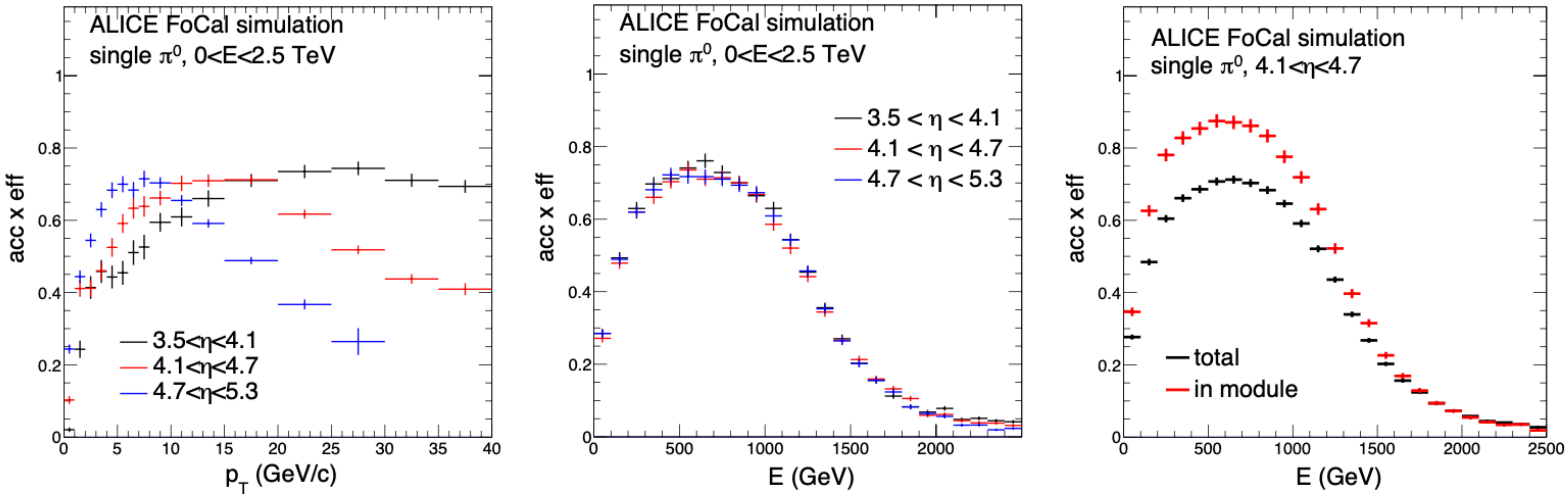


- No modification visible above 20 GeV
- In ALICE prel data, hint for suppression at low p_T
- Paper in progress
- Difficult to push to sign. lower p_T with this dataset

Included in nNNPDF3.0



Key feature of FoCal: High neutral pion efficiency



- High efficiencies of ~70% for most part of the phase space
- Inefficiencies mainly from gaps and/or very asymmetric decays
  - Cluster finder settings and algorithm are not yet optimized

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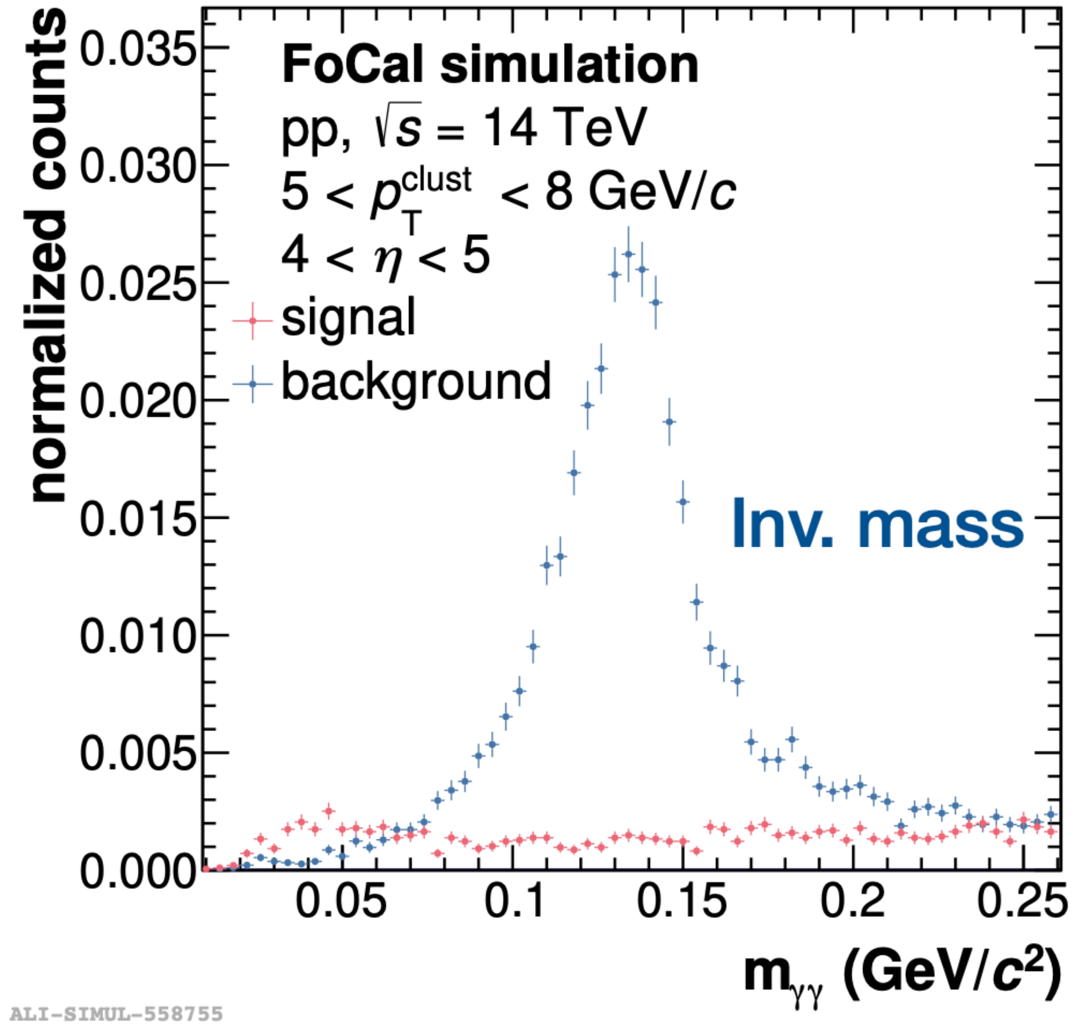
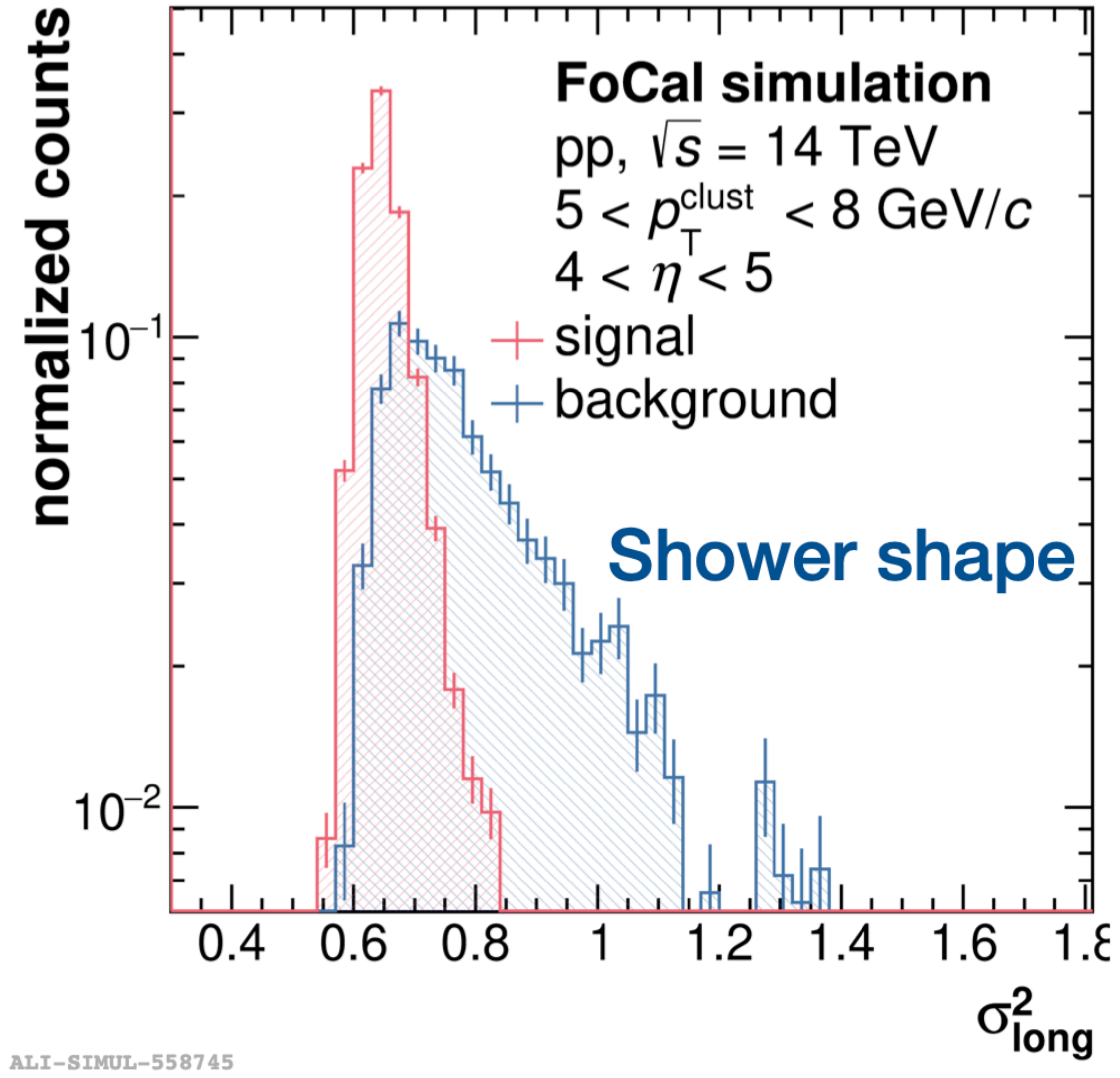
Isolated photon performance

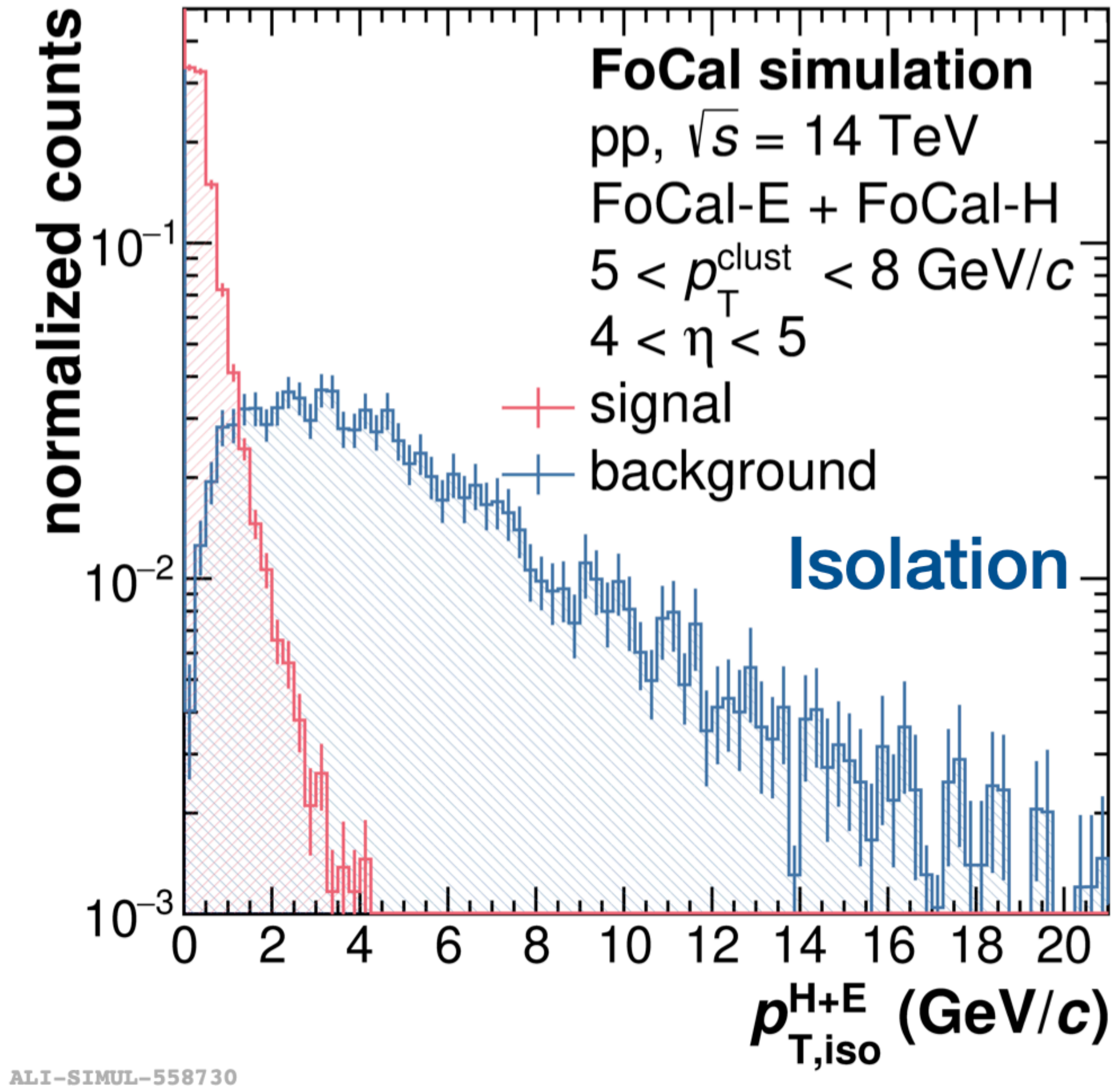
Tagging



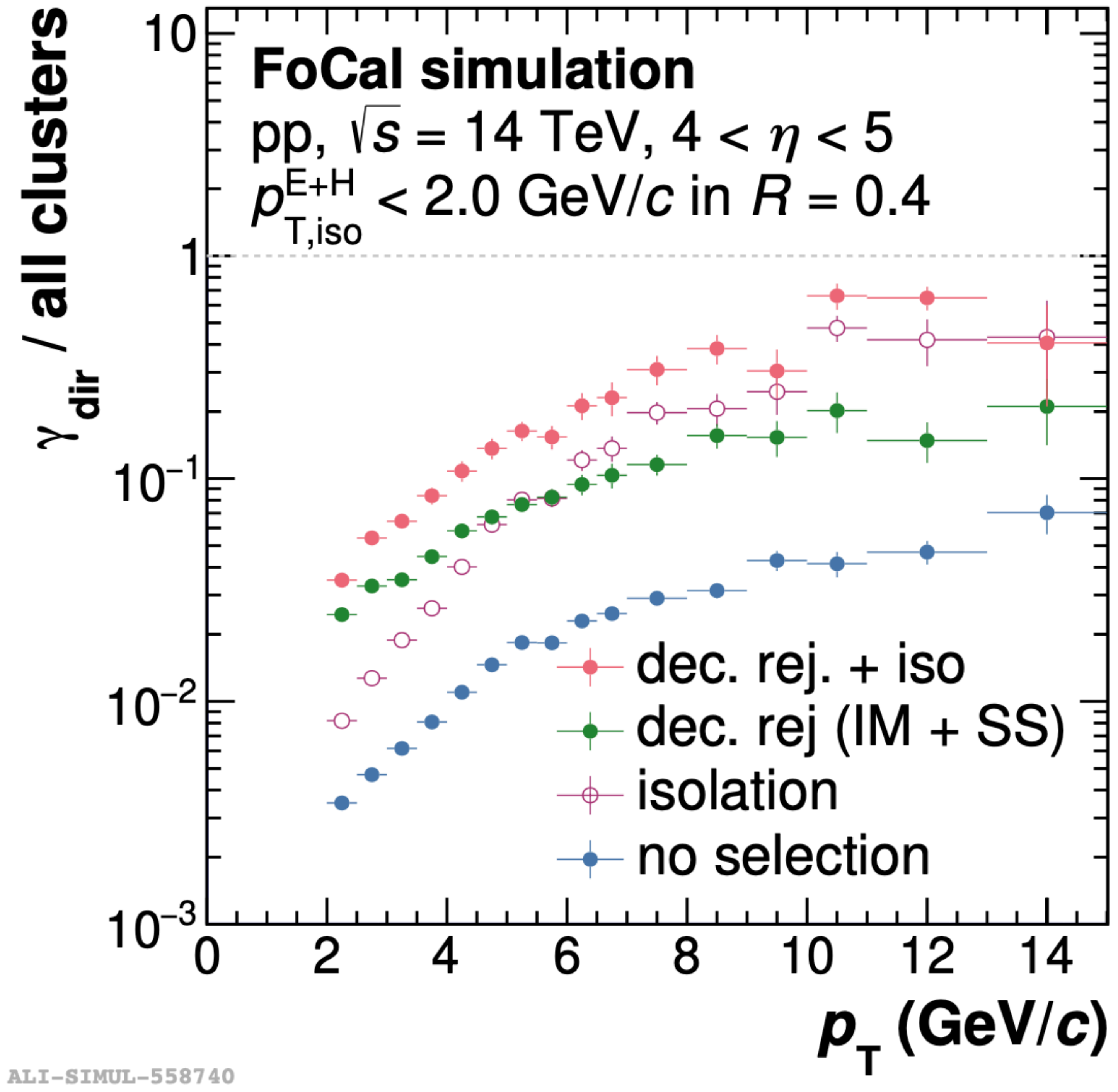
Shower shape



Isolation



Signal fraction



Main ingredients for direct photon identification

- π^0 tagging: remove photons candidates in inv. mass window
- Shower shape selection
- Isolation cut (EmCal + HCal)

Improvement in signal fraction by factor ~10 to ~0.1-0.6

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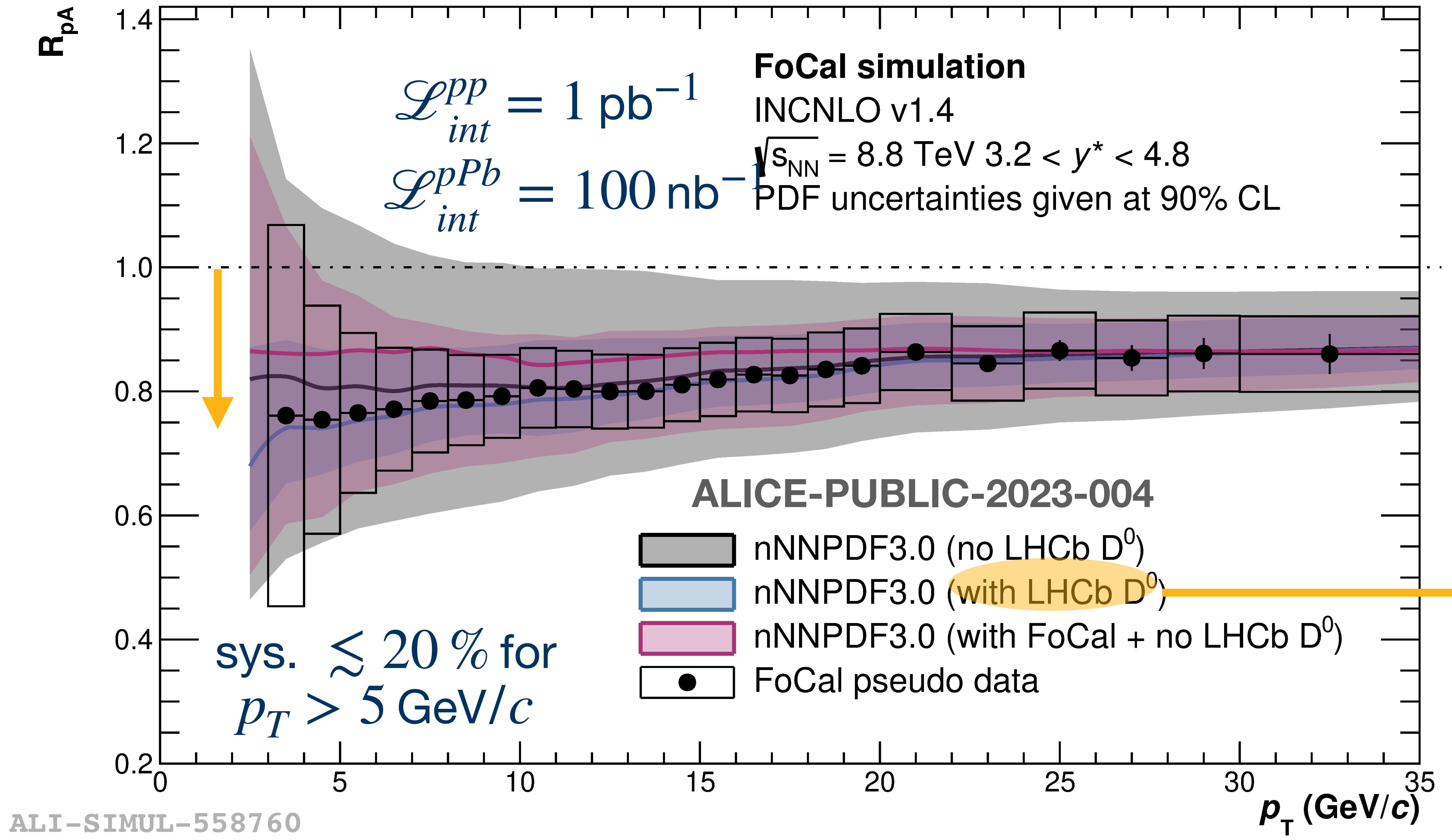
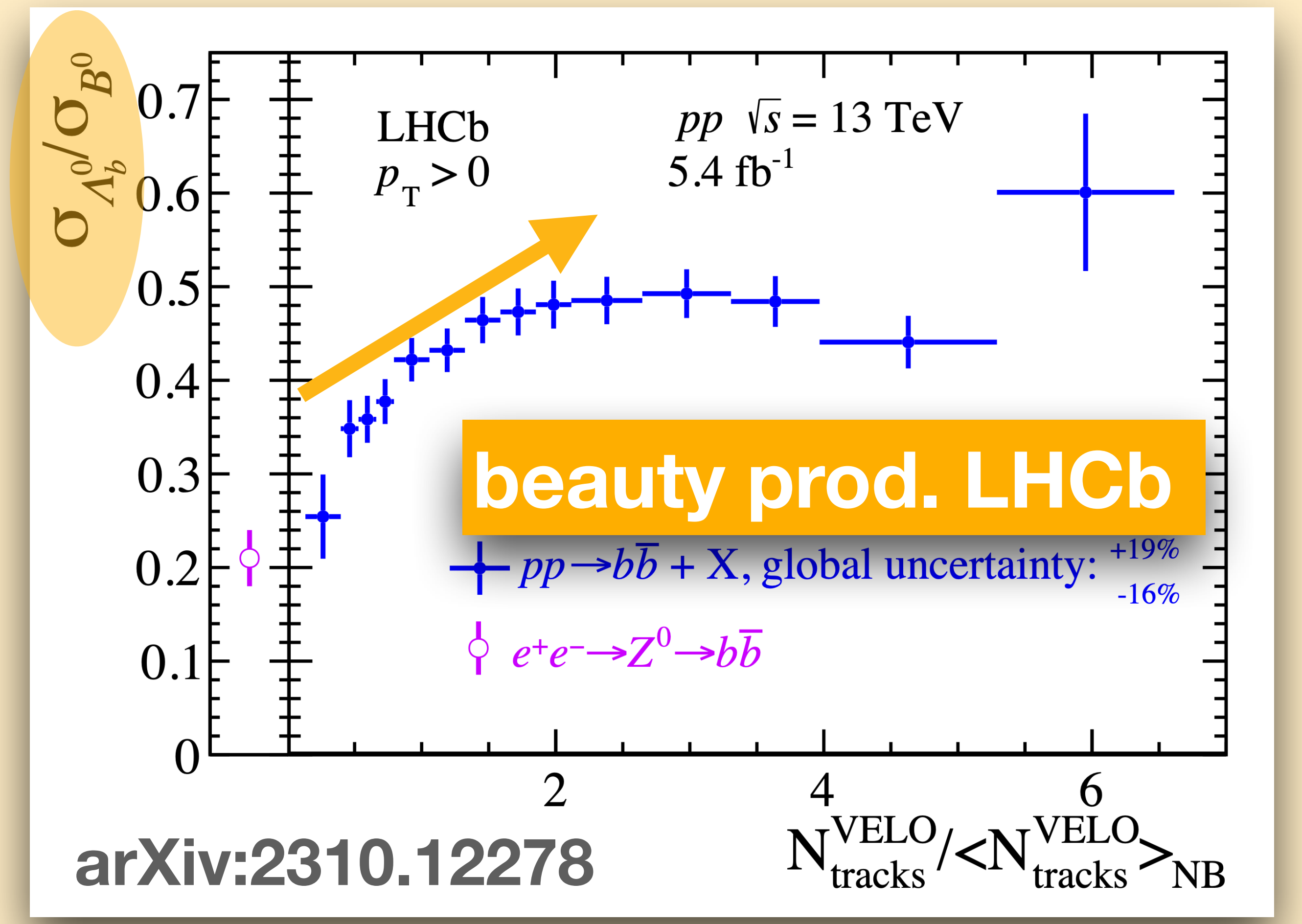
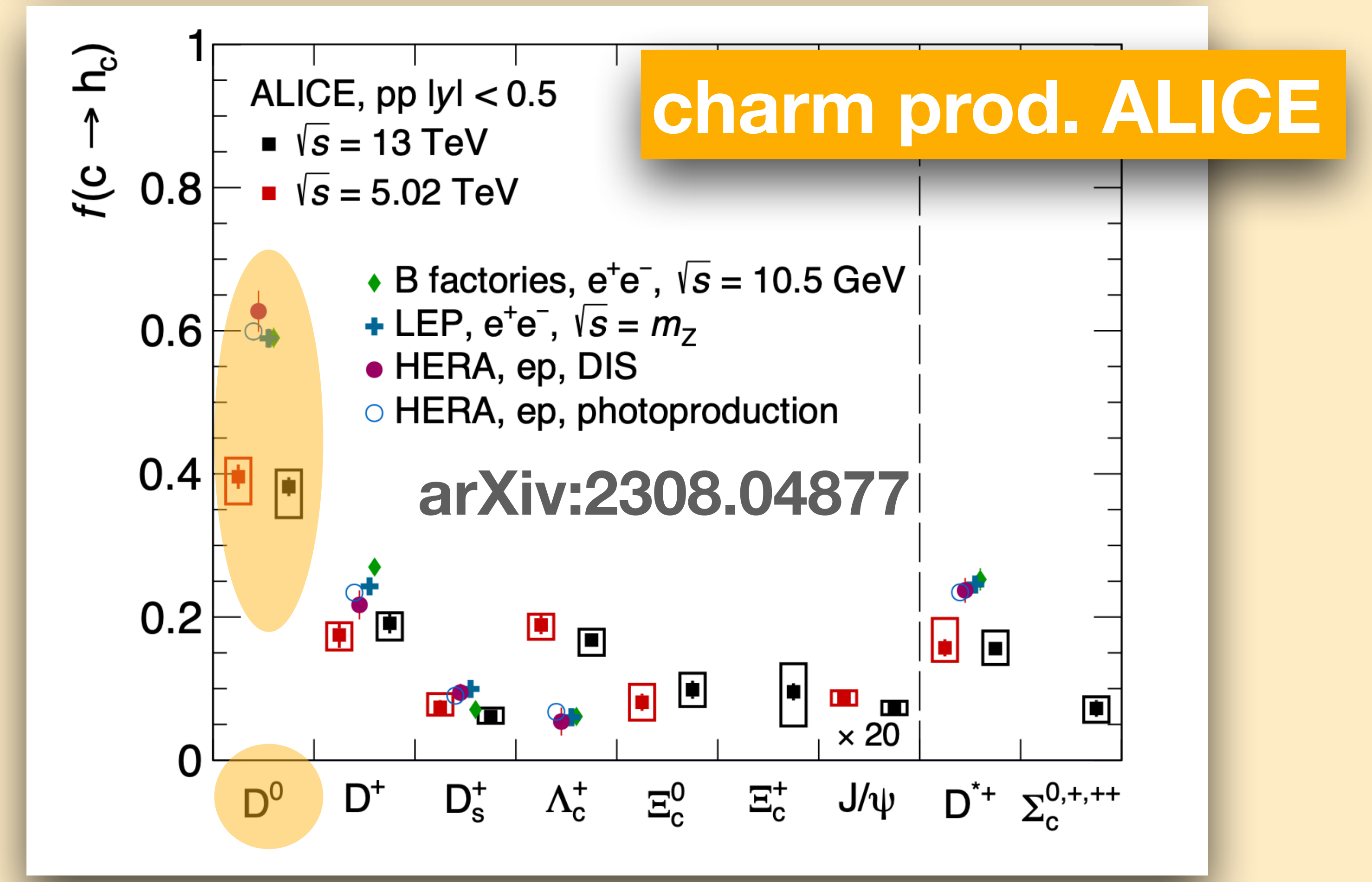
Universality test with the prompt photon data



FF are not universal





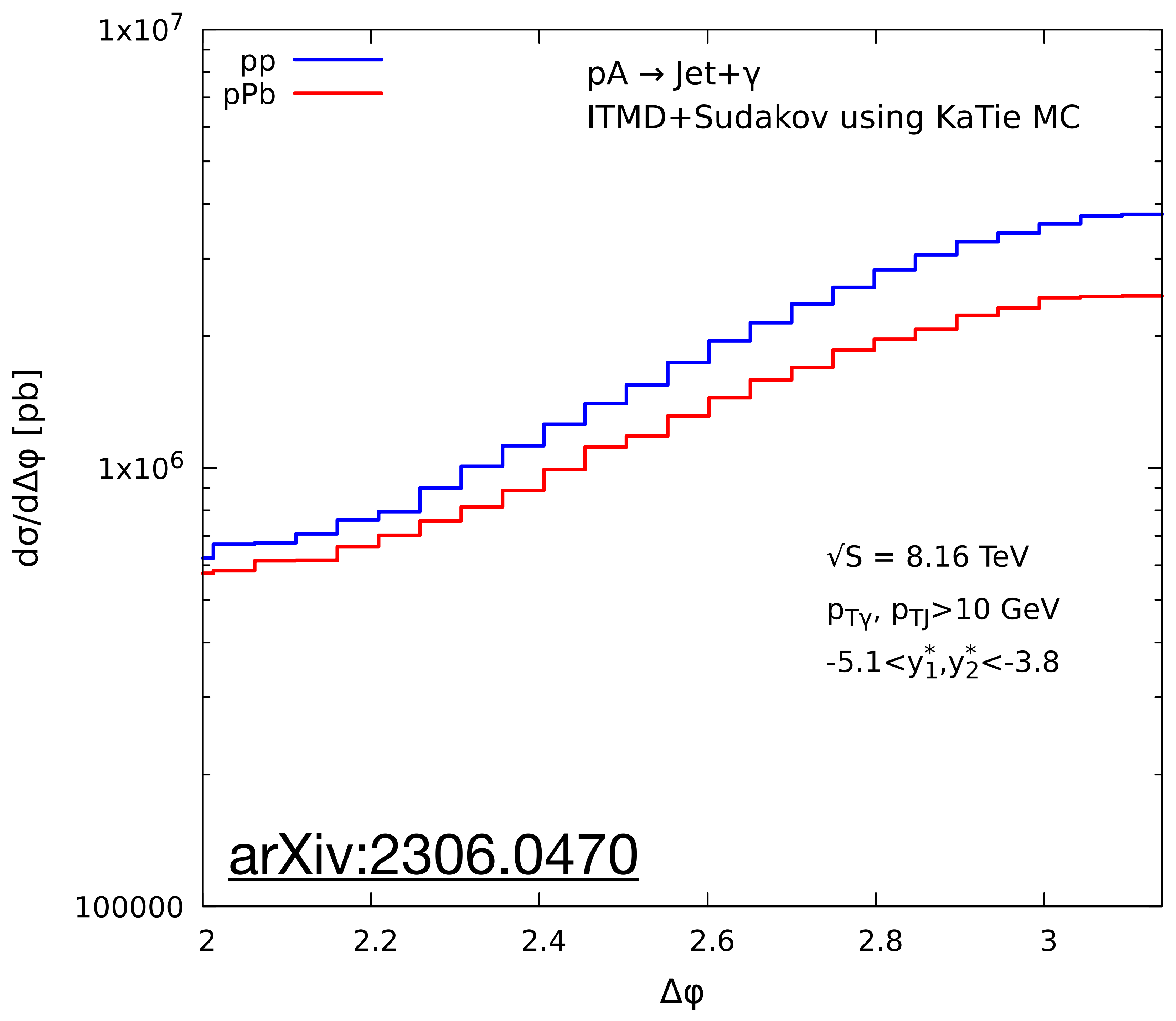
- **FoCal pseudo-data** of nuclear modification factor R_{pA}constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

Prompt photons → no final state and hadronisation effects → universality test of low-x formalism

Isolated photon - neutral pion correlations

Theory:

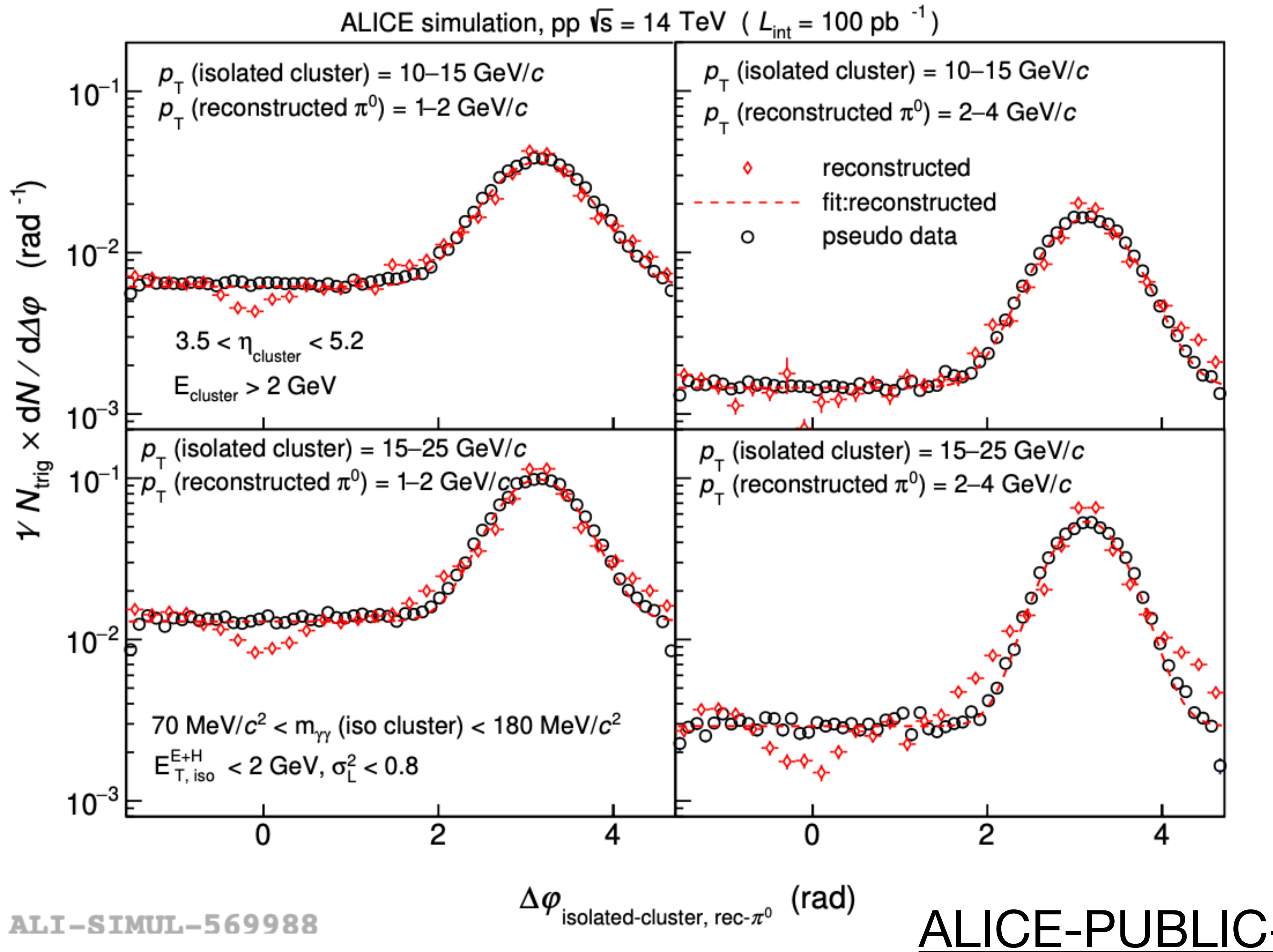
- Study of γ-hadron correlations offers additional sensitivity to low-x gluon dynamics
- Expectation of **yield suppression** and **de-correlation** due to saturation effects



arXiv:2306.0470

FoCal performance:

- Analysis of γ-π^0 corr. in simulated pp collision events + detector smearing
- Correlation peak can be measured precisely: stat. unc. of peak width $\sim$ 0.1% for expected Run 4 luminosities



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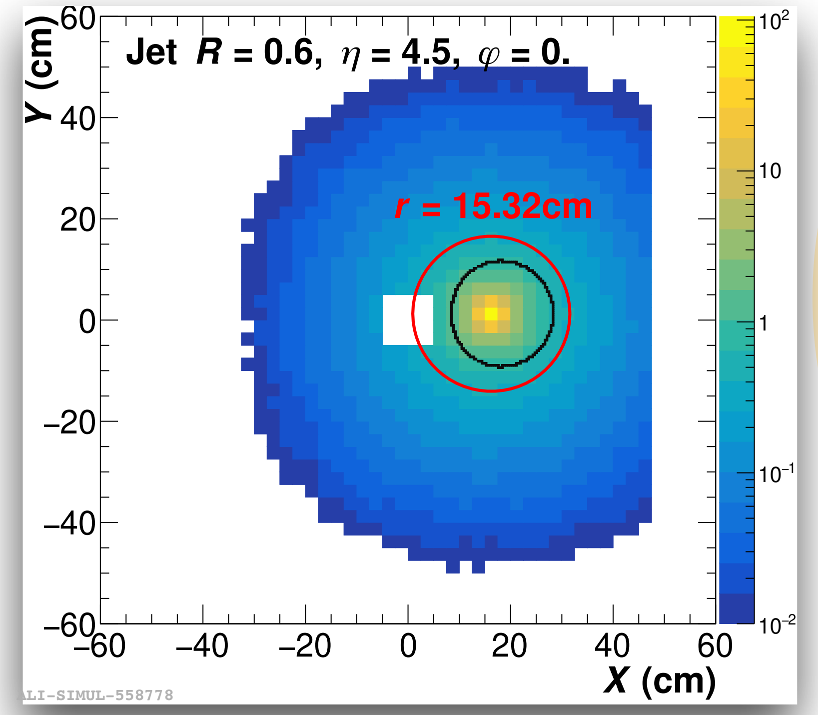
Jet measurements

- Forward inc. jet, γ-jet and dijet production sensitive to gluon saturation
- Performance of FoCal quantified using Pythia + GEANT for $R = 0.6$ anti-k_T jets

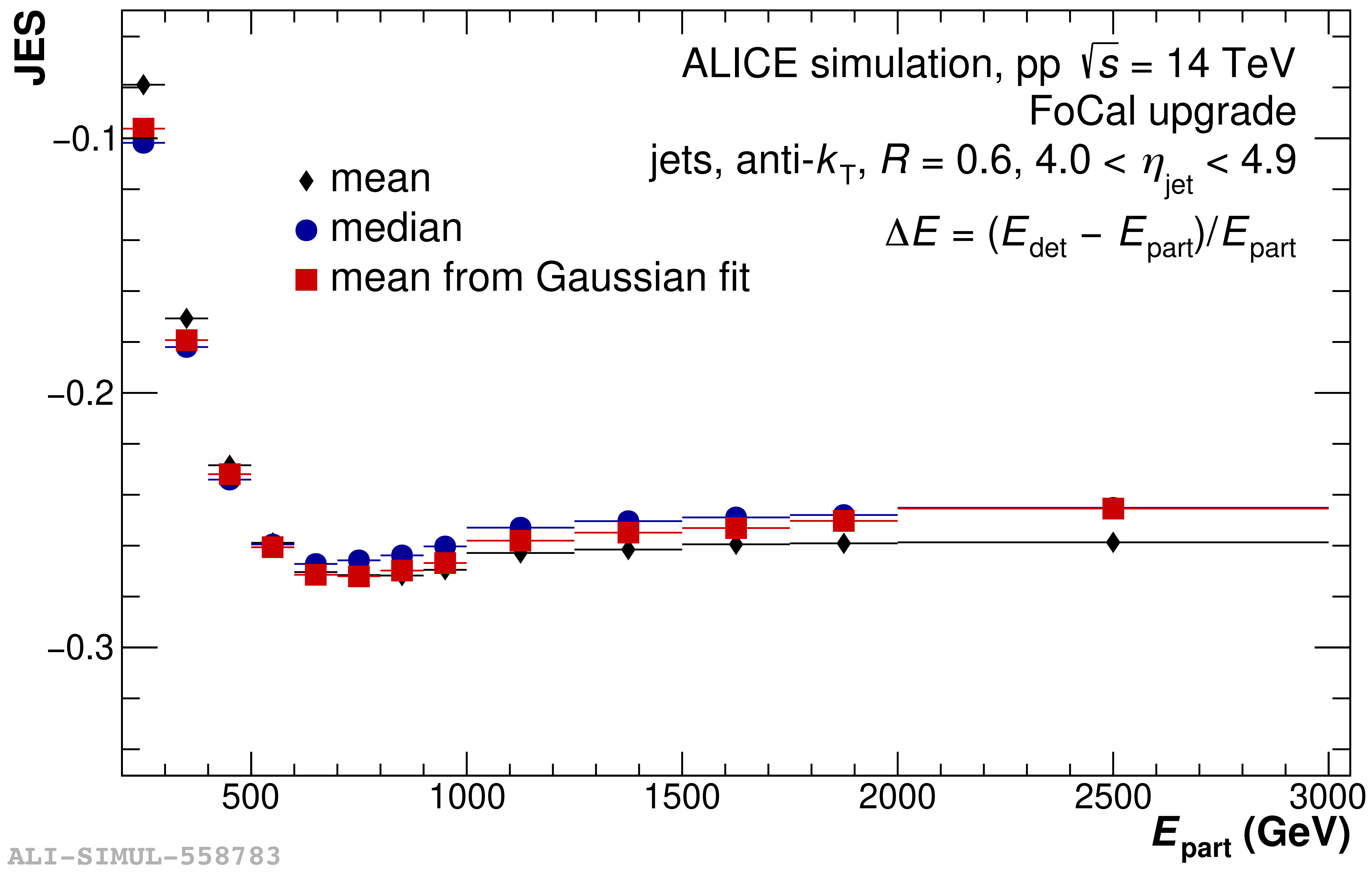
FoCal-H shower



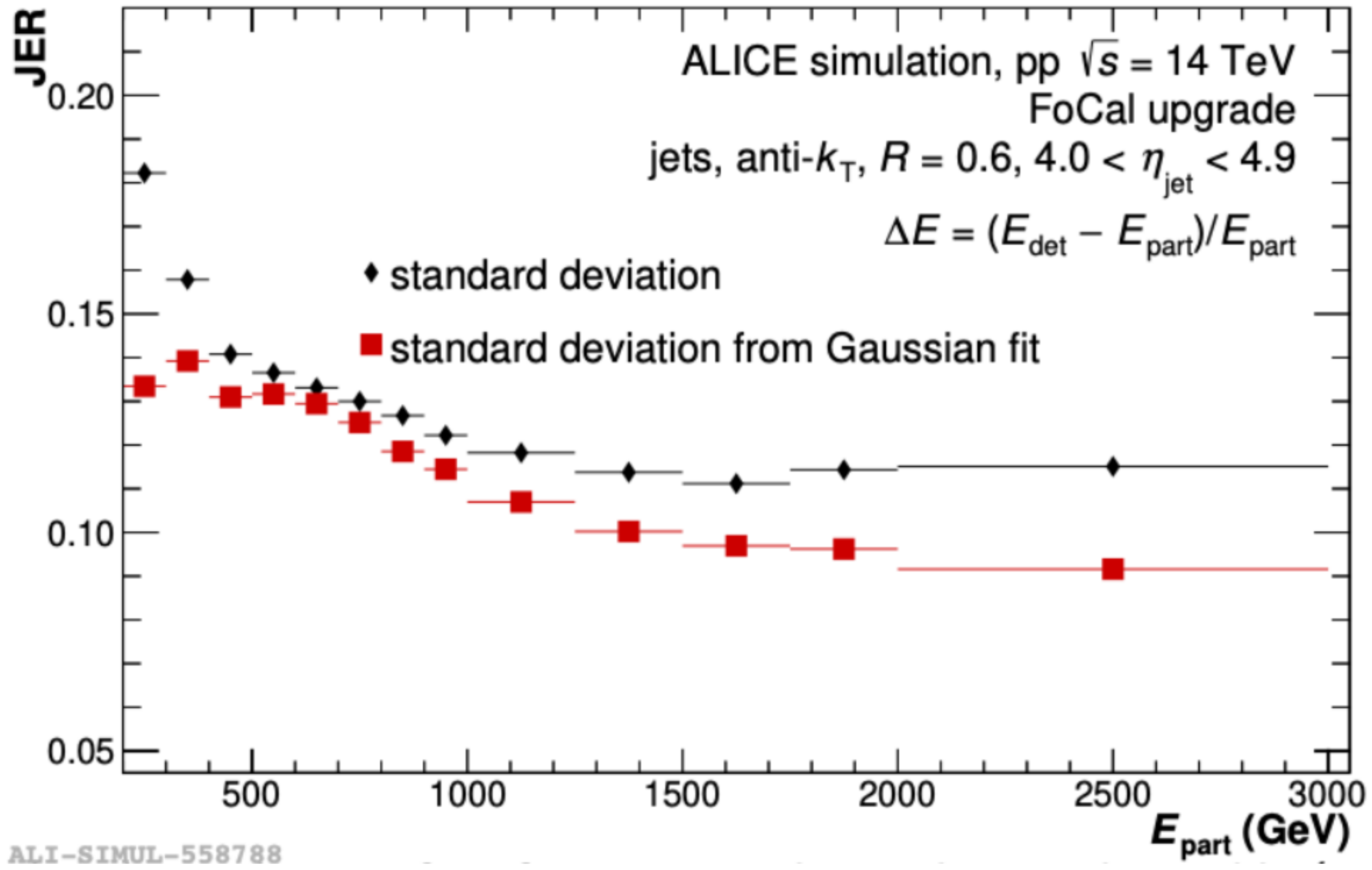
Effective Moliere radius FoCal-E ≈ 1-2cm

Interaction length FoCal-H ≈ 15-20 cm

Jet Energy Scale

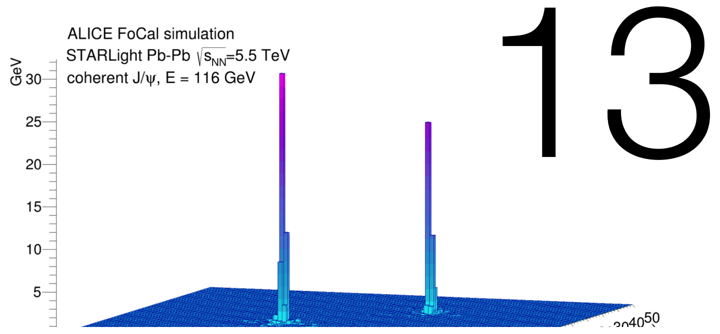


Jet Energy Resolution



Achieve good energy scale and resolution, however performance depends on NEF (not shown)

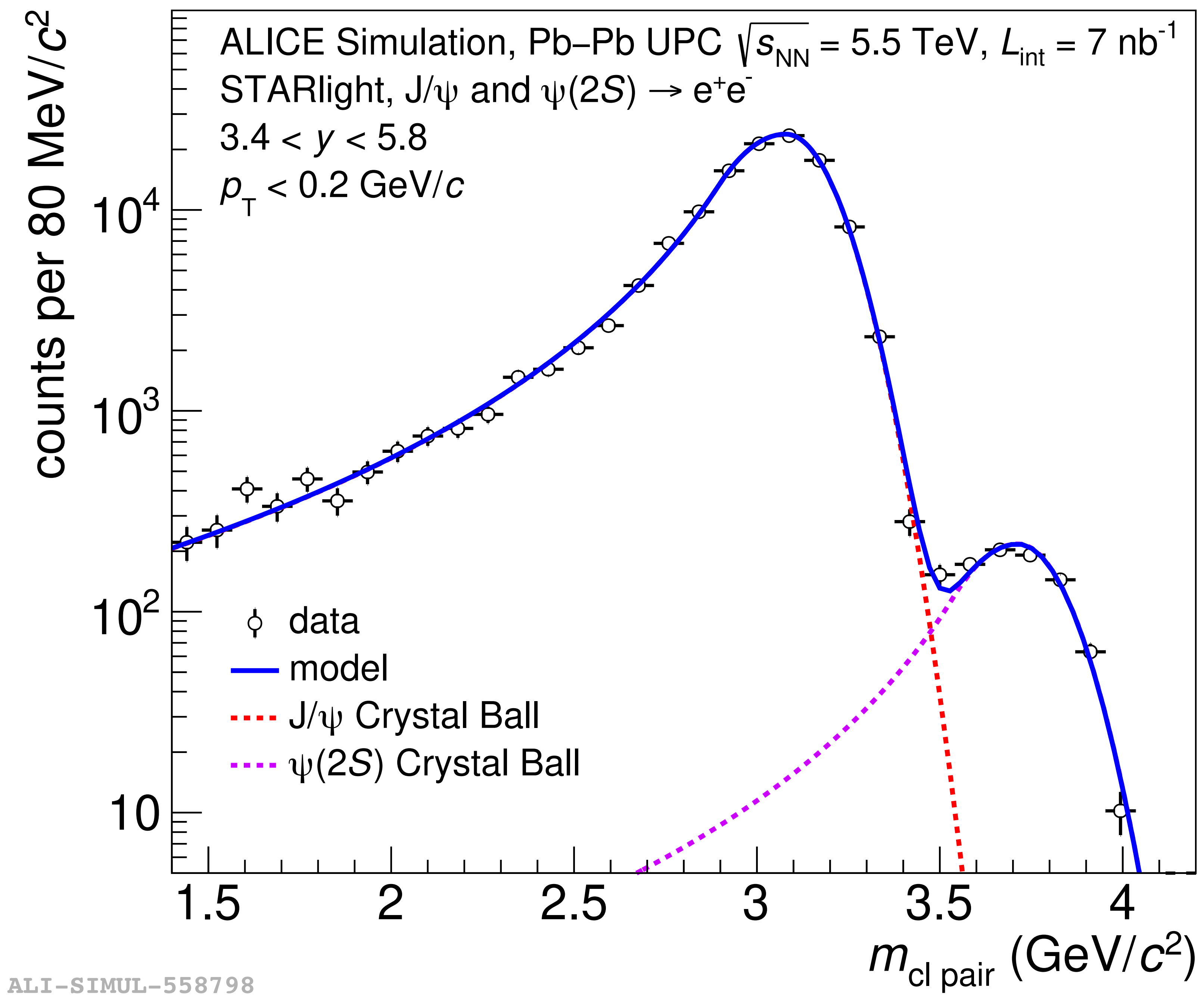
Vector meson photoproduction in UPC

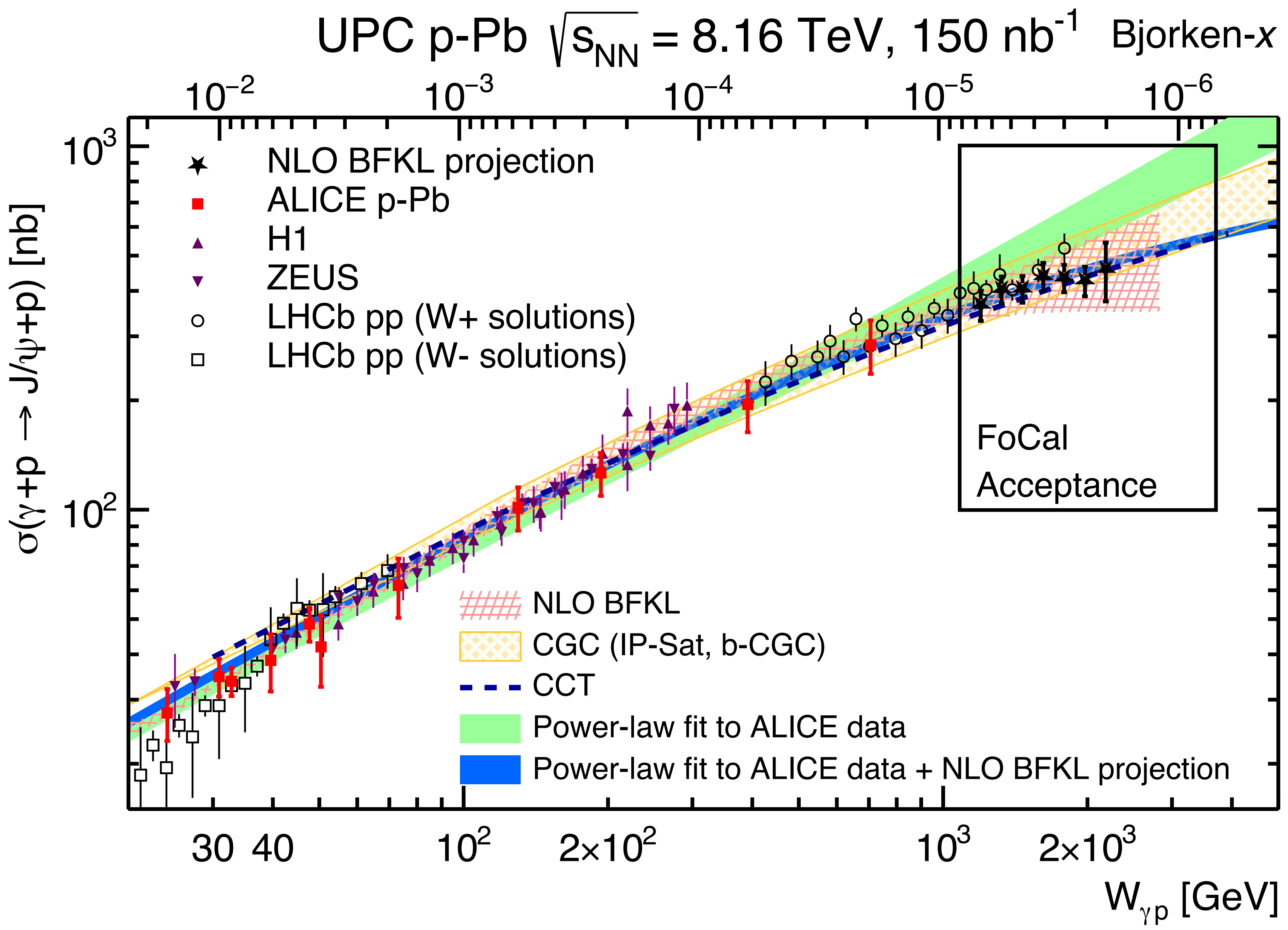


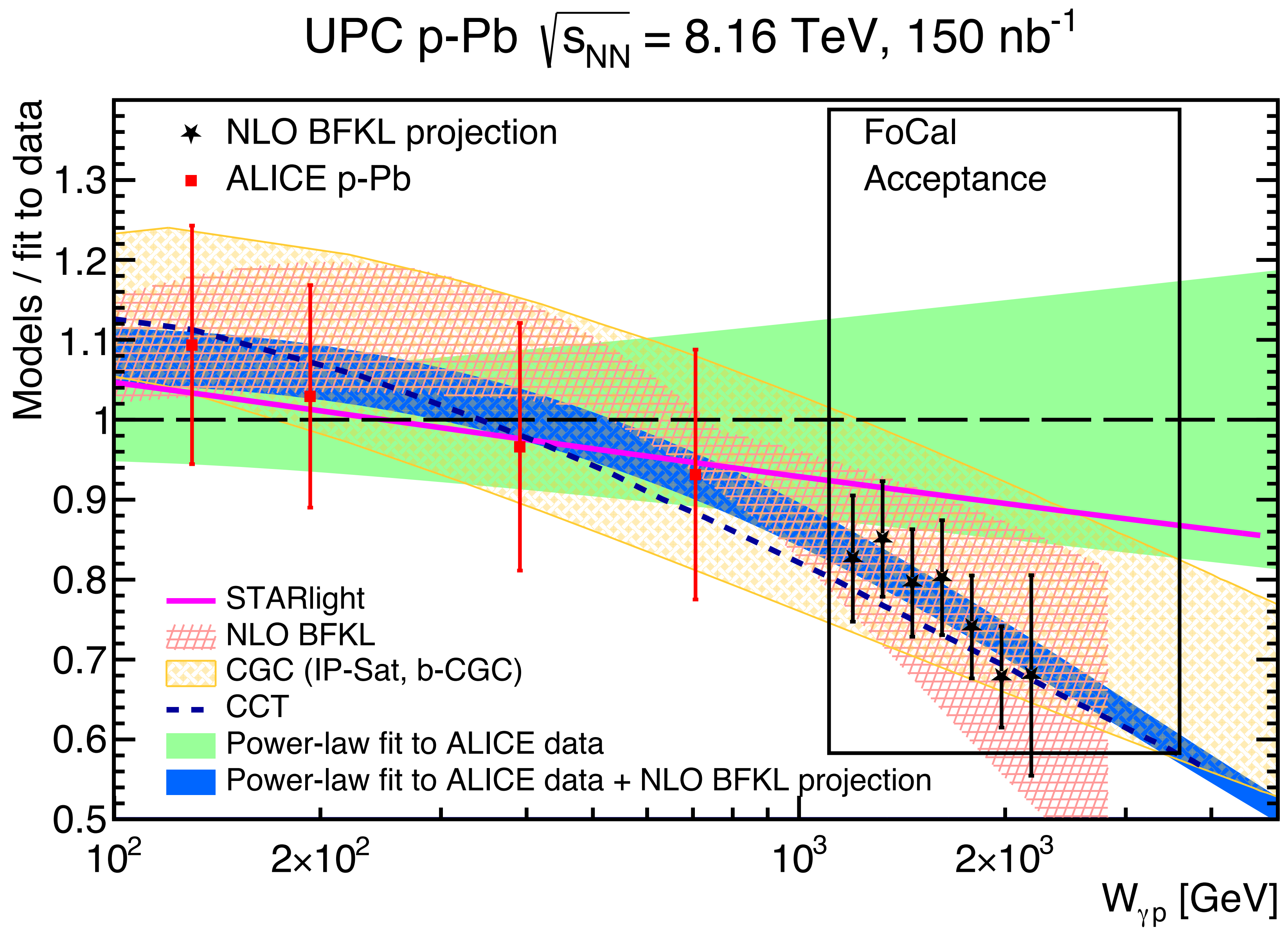
Theory:

- Photoproduction cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions (UPCs) **proportional to gluon density squared** at LO
- **Deviation from power-law** growth of cross section with increasing $W_{\gamma p}$ expected due to **saturation effects**

FoCal perf.:







- FoCal allows to access unprecedented low-x, extending existing measurements to $W_{\gamma p} \approx 2$ TeV (10 GeV) in p-Pb (Pb-p) collisions + Pb-Pb collisions
- Studies with STARlight + GEANT show successful reconstruction of J/ψ and $\psi(2S)$

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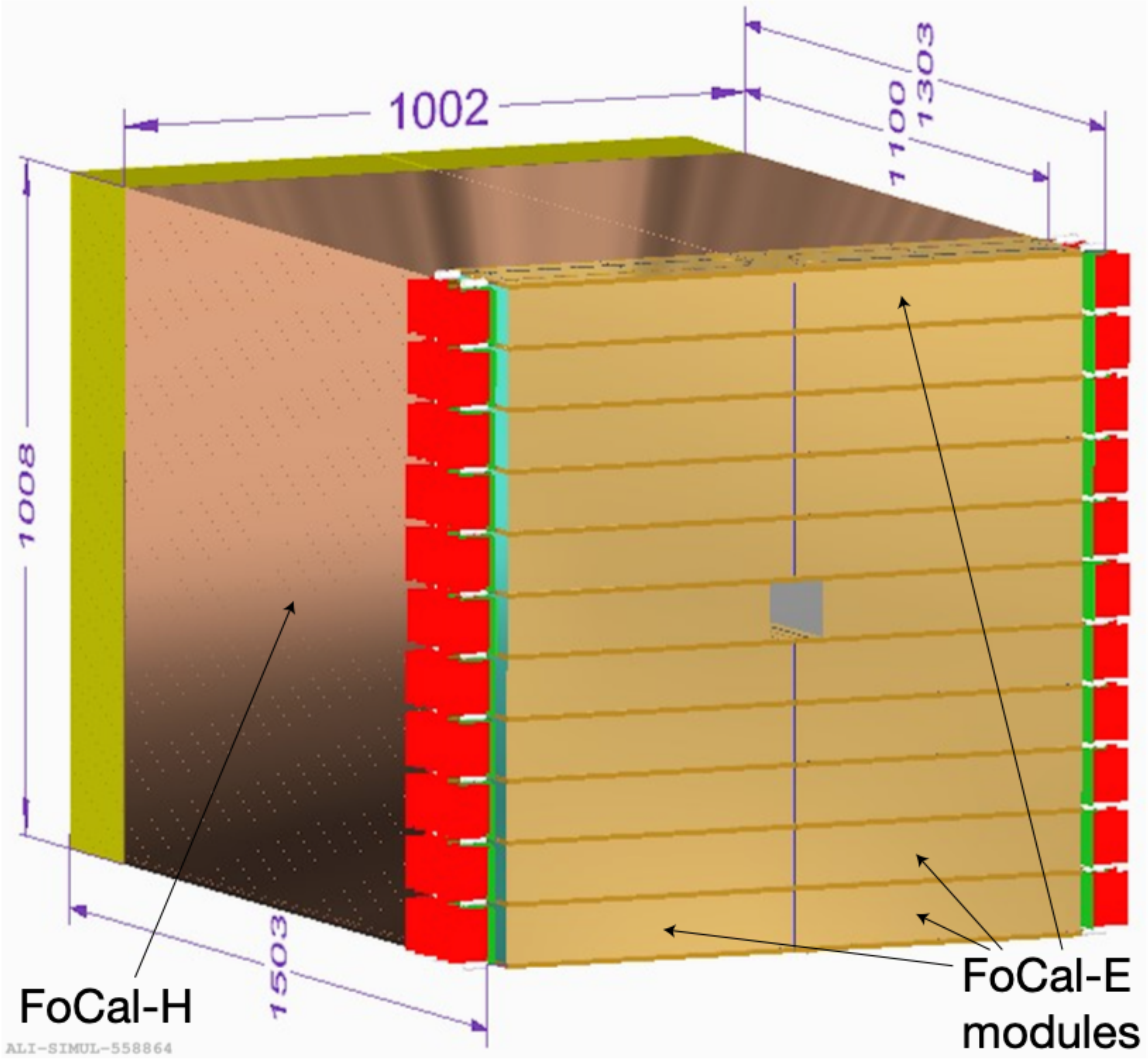
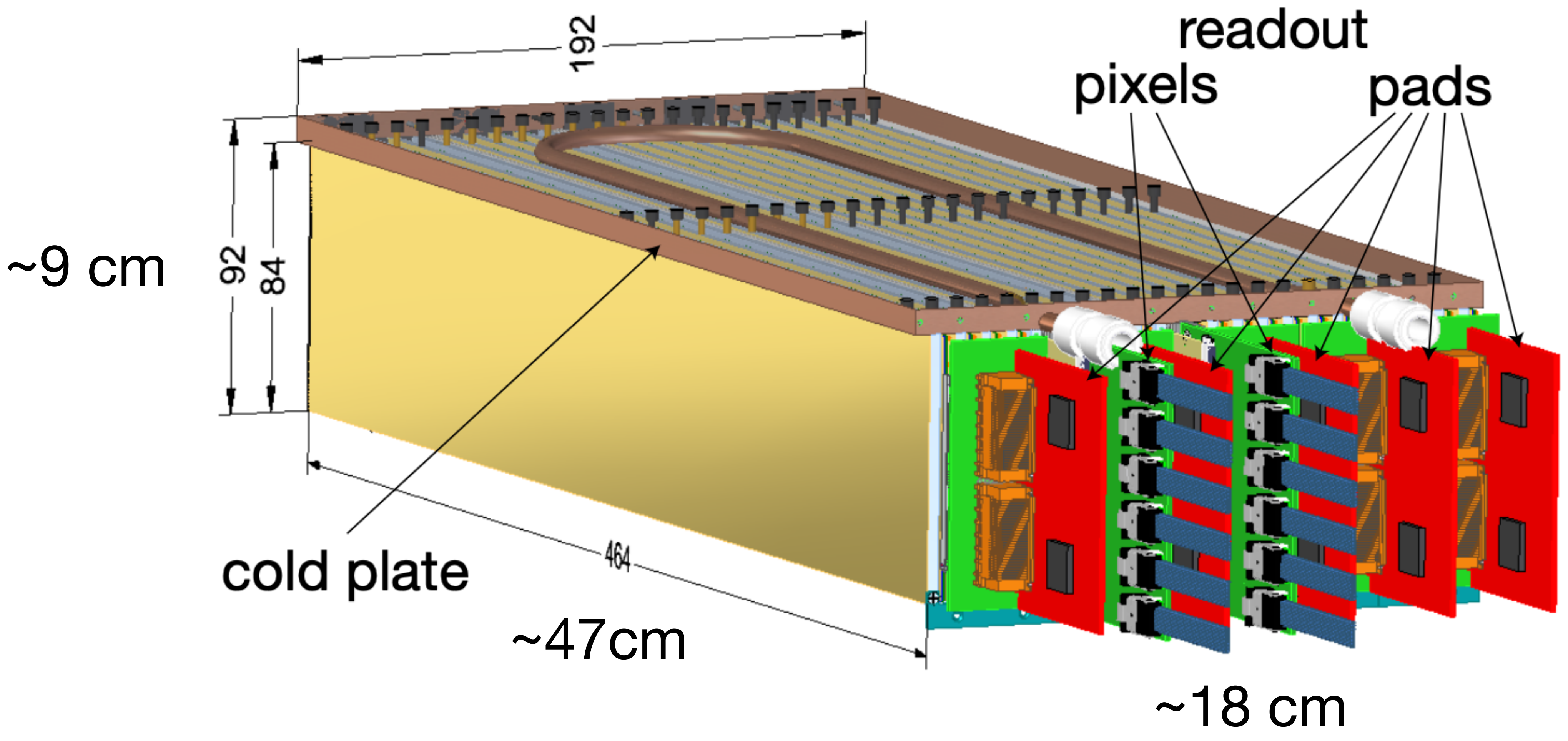
The FoCal detector





- **FoCal-E pad layers**:
  - Silicon pad sensor (Hamamatsu), 72 pads, each 1x1cm^2
  - HGCROC chip (ADC/TOT/TOA@40Mhz, large dynamic range, trigger), 1944 chips
  - aggregated readout of layers in groups (concentrator board)
- **FoCal-E pixel layers**:
  - ALPIDE MAPS (3x1.5cm^2, 1024x512 pixels, 30x30μm^2), 3888 chips
  - adapted ITS2-readout; compared to pads slow, i.e. about ~5μs pulse

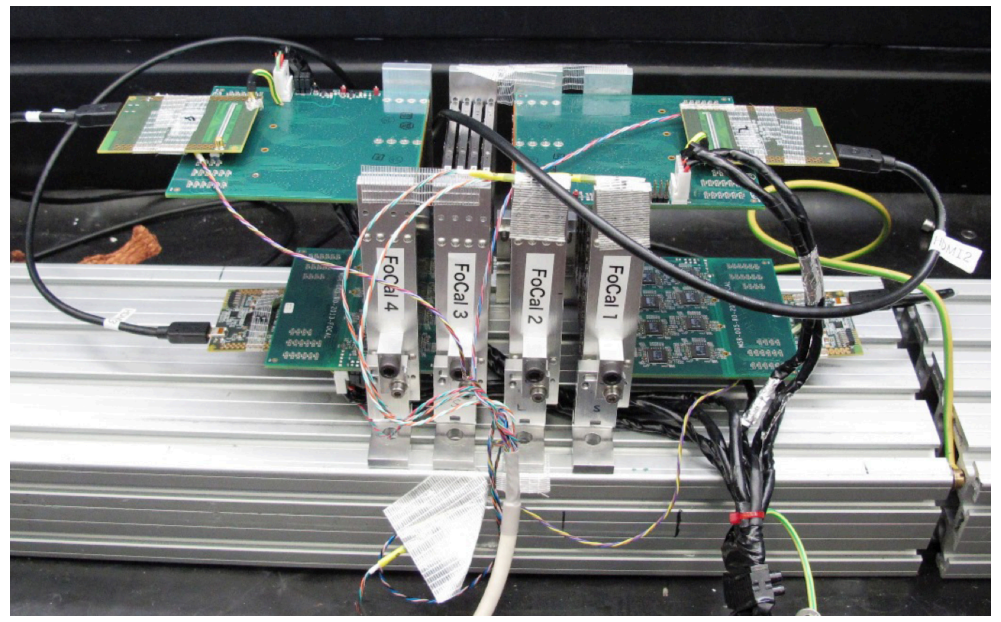
FoCal-H: Cu capillary-tubes filled with scintillating fibers

- 100cm x 100cm x110cm (~5 λ_{int})
- Tubes outer diameter: 2.5mm, inner diameter 1.1mm
- ~7t of tubes, and 200km of fiber
- Group fibers to make **towers of ~1x1cm²**
- ~8000 channels with SiPM and H2GCROC

Technical Design Report: CERN-LHCC-2024-004

FoCal R&D and prototypes

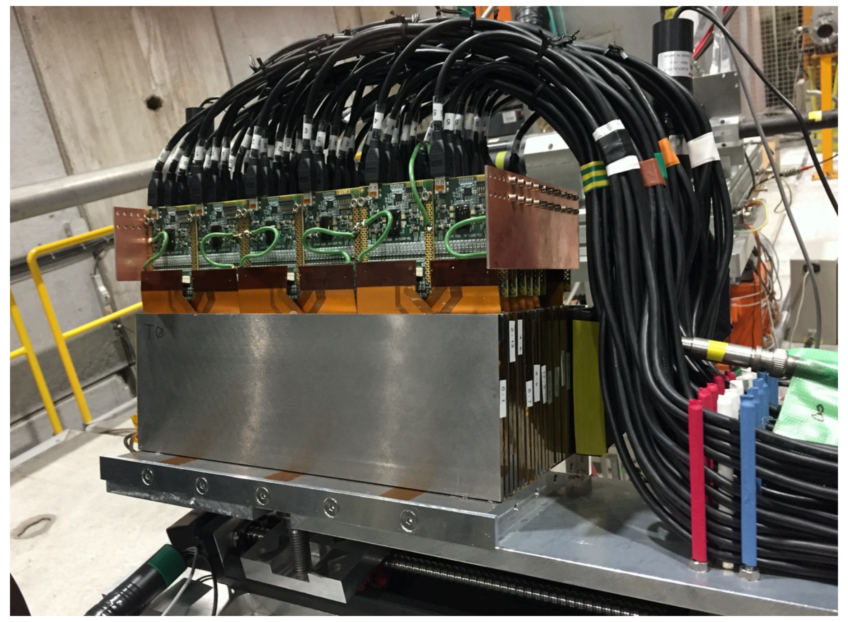
2010-2015



ORNL / Japan prototype:
- NIM A 988 (2021) 164796

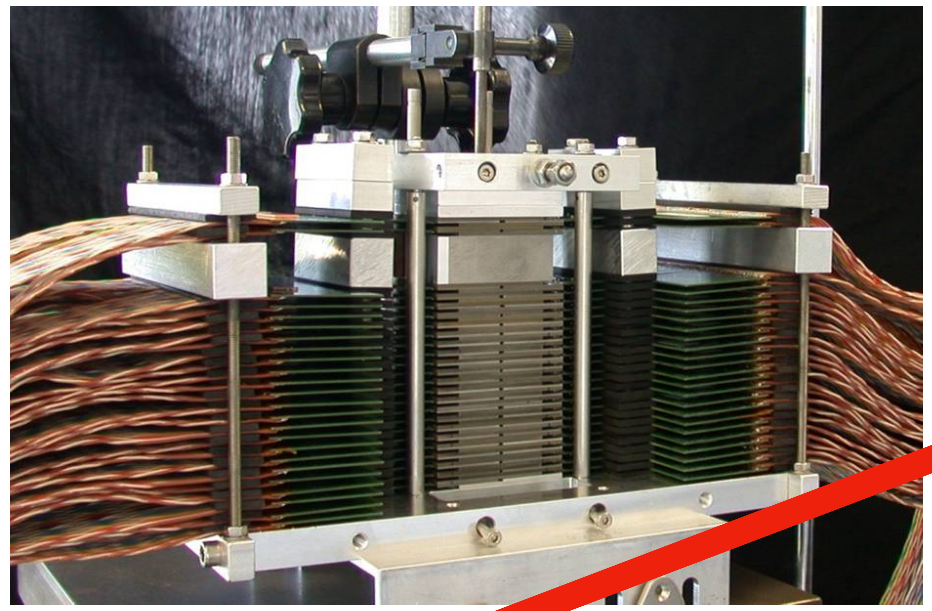
Indian prototypes:
- NIM A 764 (2014) 24
- JINST 15 (2020) 03, P03015

2014-2018



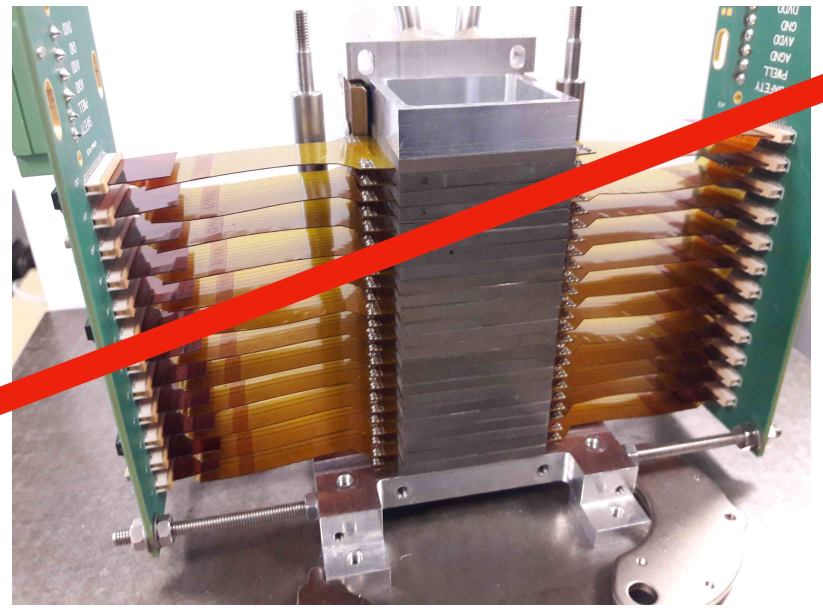
Mini-FoCal (PADs only) in beam at P2
arXiv:2306.06153

2014-2016



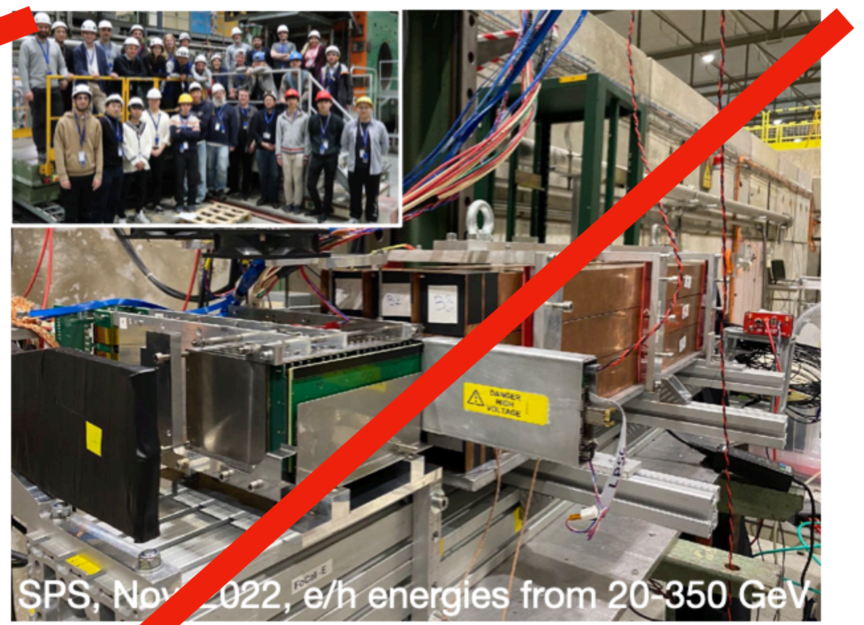
MIMOSA pixel tower (EPICAL)
JINST 13 (2018) P01014

2018-2021



ALPIDE pixel tower (EPICAL-2)
NIM A1045 (2023) 167539
JINST 18 (2023) 01, P01038

2021-2023

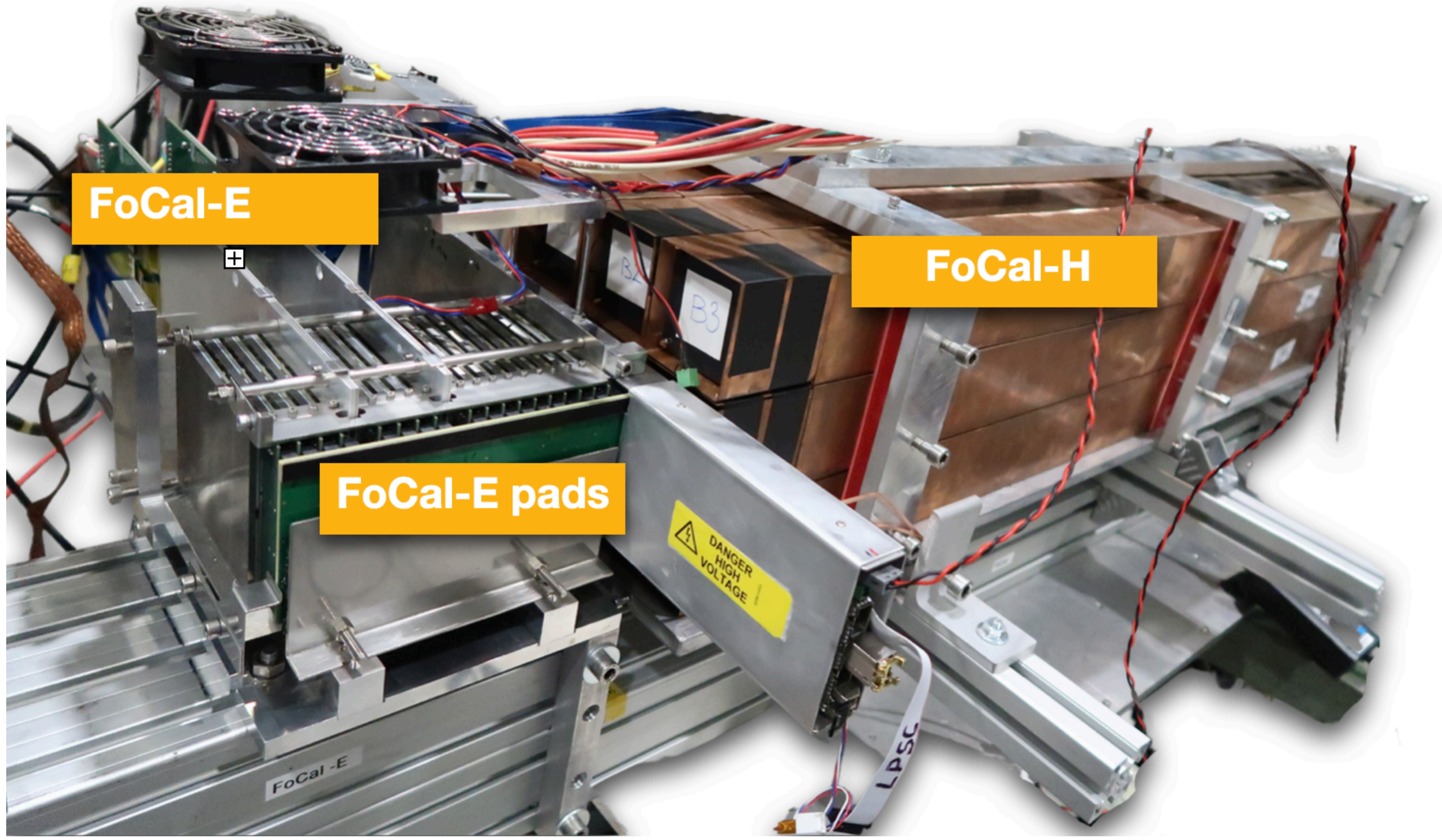


FoCal-E and H prototypes
- final sensors and chips
- close-to-final readout

arXiv:2311.07413

FoCal-E: prototype

- One tower ($9 \times 8 \times 17$ cm^3) of 18 silicon pad and 2 silicon pixel layers
- **Pad layers:** Si p-type sensors by Hamamatsu; readout using HGCROC (v2) developed for CMS HGCal
- **Pixel layers**: ALPIDE sensors using IB and OB readout modes



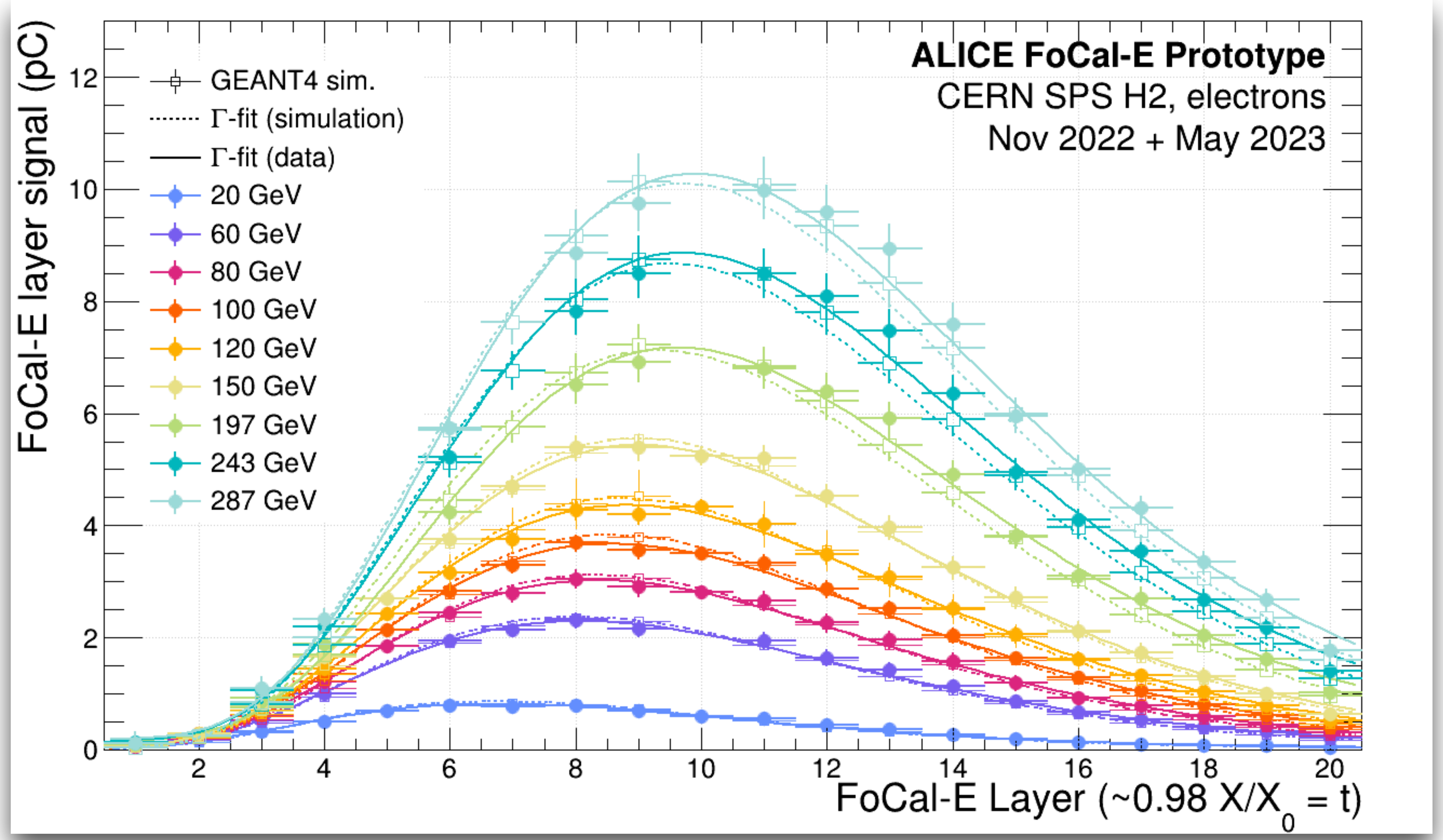
FoCal-H: prototype

- 9 modules arranged in stack
- Scintillation fibres inserted into Cu tubes (668 per module) and readout using SiPMs
- CAEN readout (not yet H2GCROC)

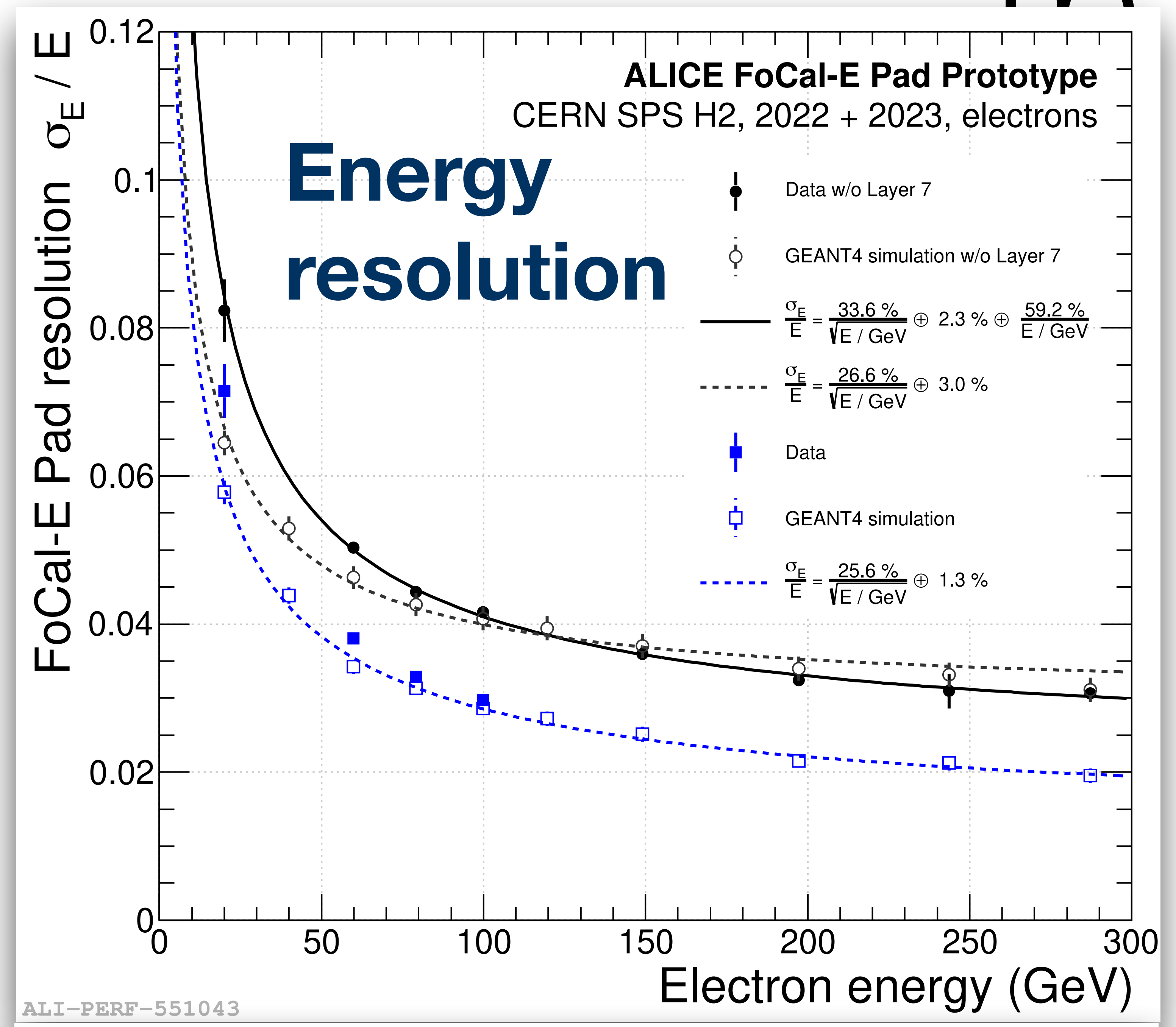
arXiv:2311.07413

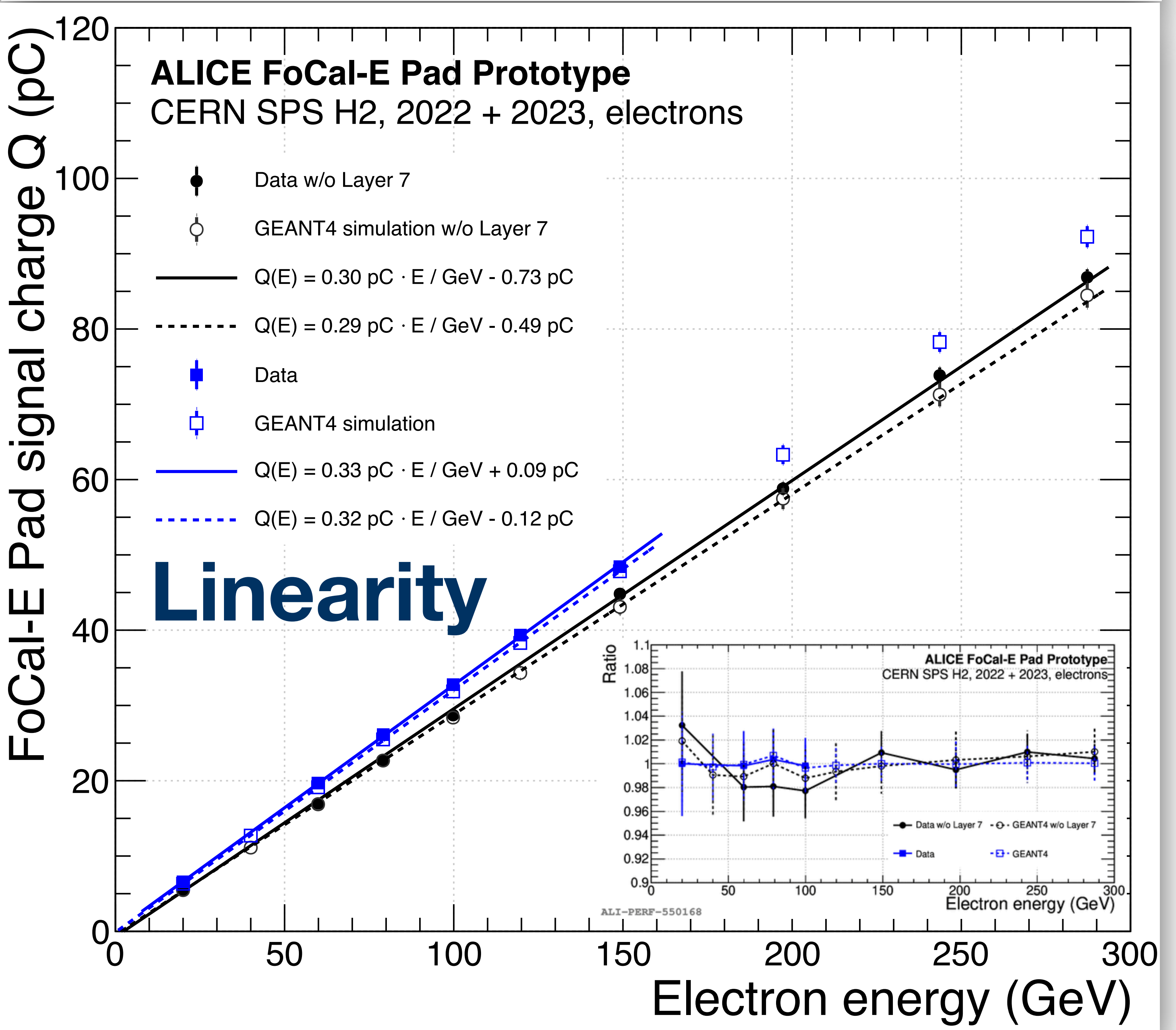
FoCal-E (pad) results

- All key metrics of calorimeter quantified using electron beams at SPS → meets physics requirements
- Energy resolution $< 4\,\%$ for $E > 100$ GeV



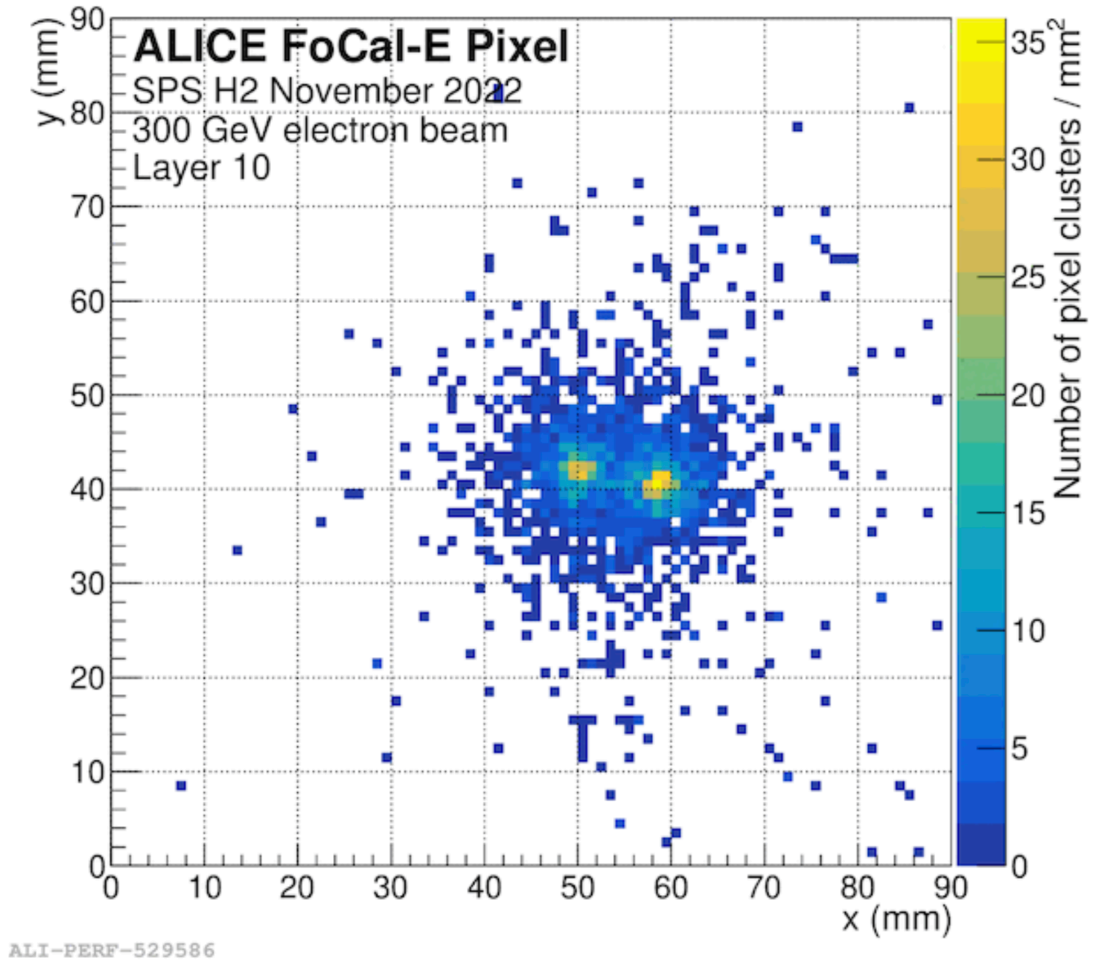
Longitudinal Shower Profile



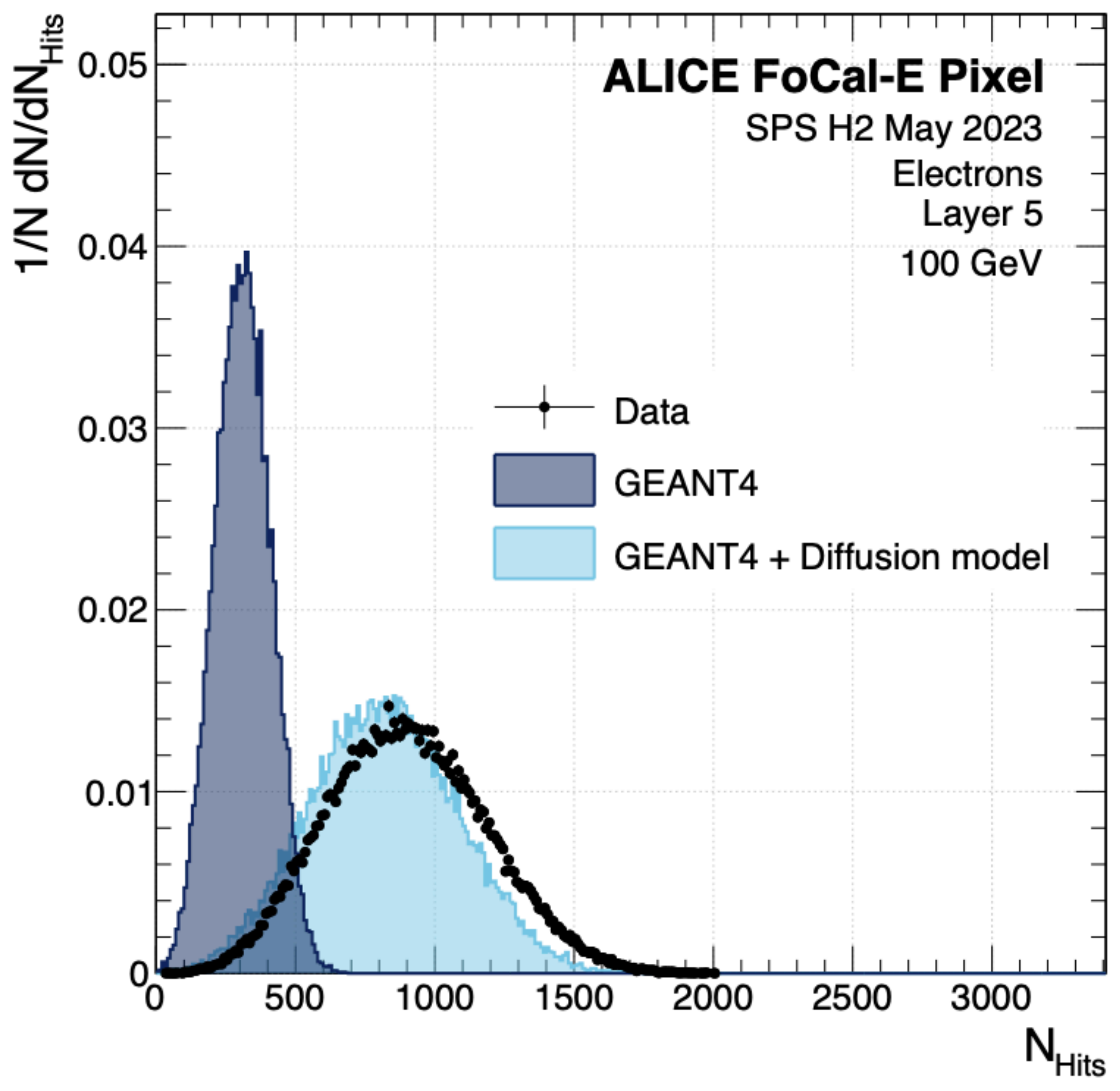


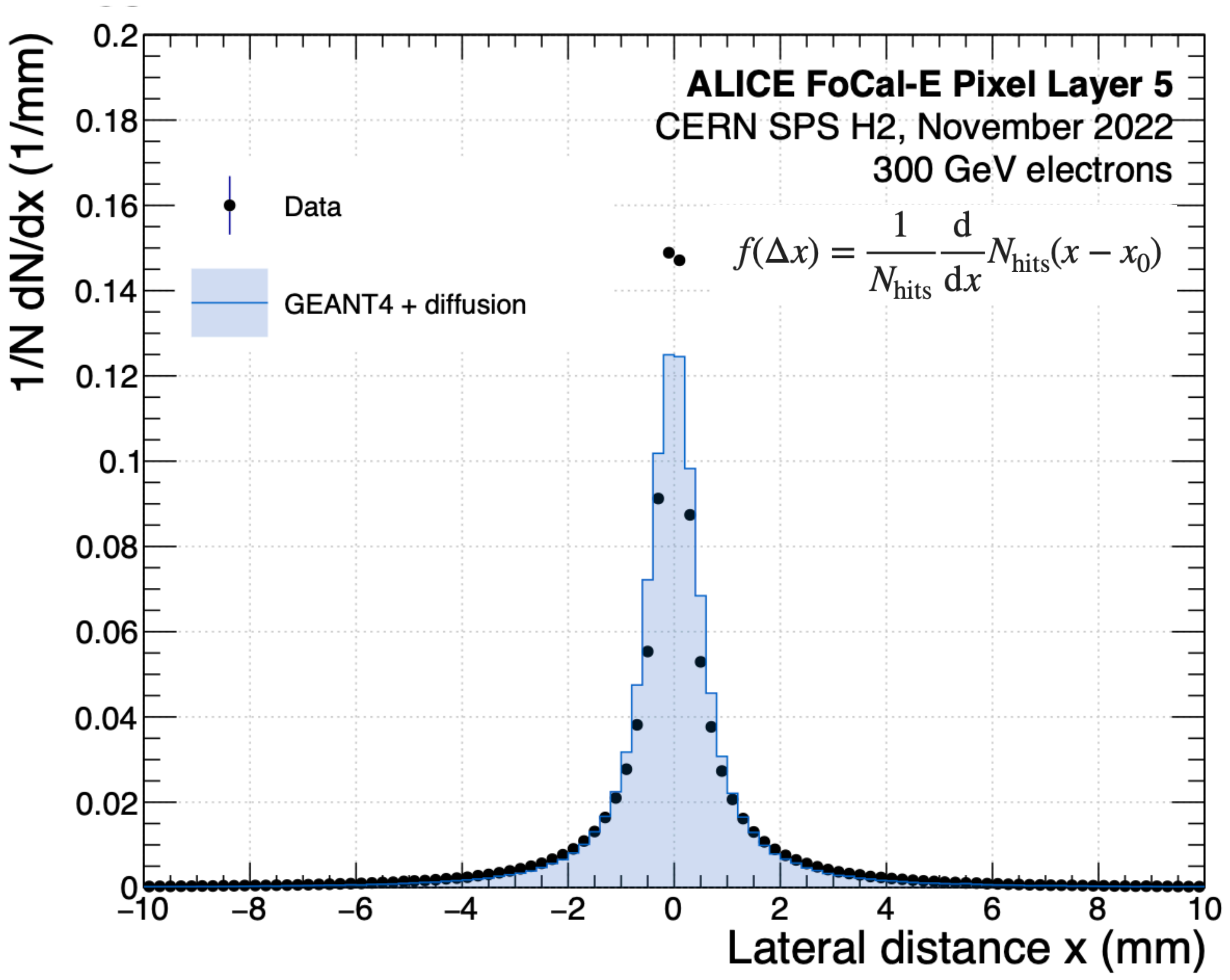
FoCal-E pixel layer results

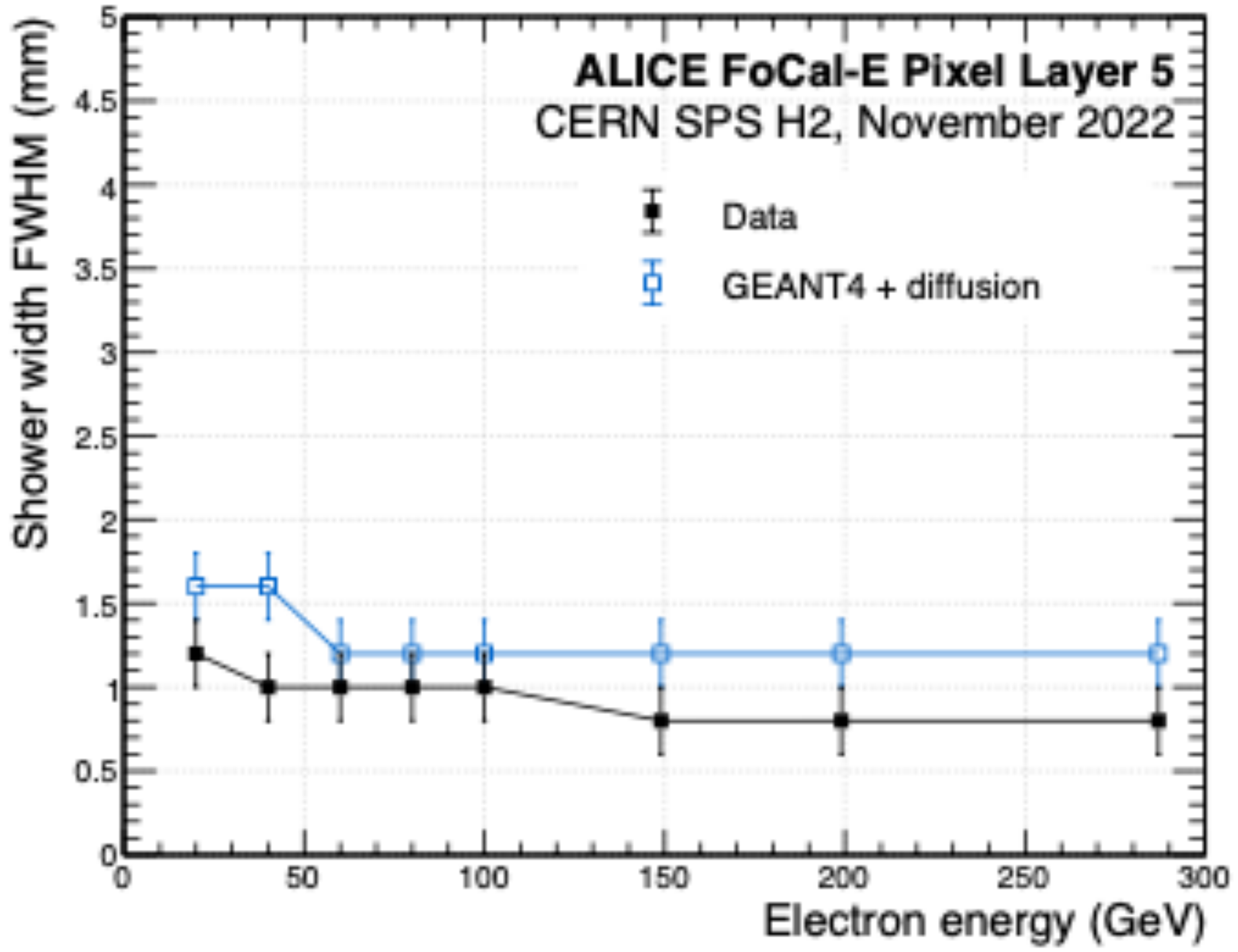
Shower separation
in 2-electron events



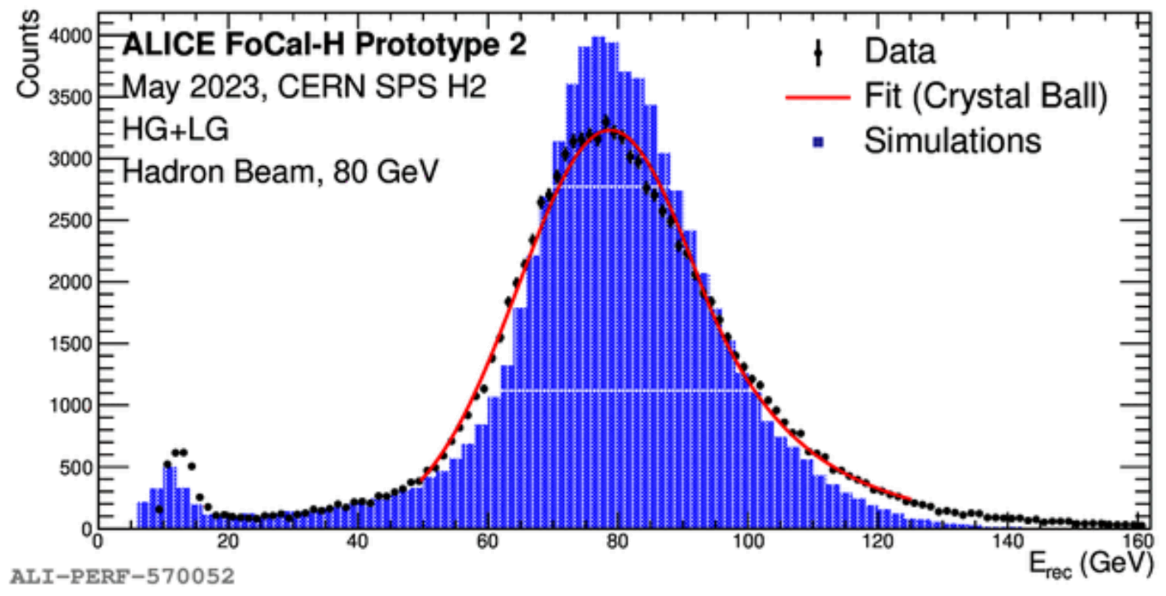
- The two high granularity pixel layers enable **excellent shower separation!**
  - Important for example to measure highly boosted $\pi^0 \to \gamma\gamma$
- Detector response well reproduced by GEANT4 + diffusion model
- Characterisation of shower width indicates FWHM on mm scale
  - Result affected by uncertainty on shower origin x_0
- For layer 5 simulations slightly over-estimate the measured width

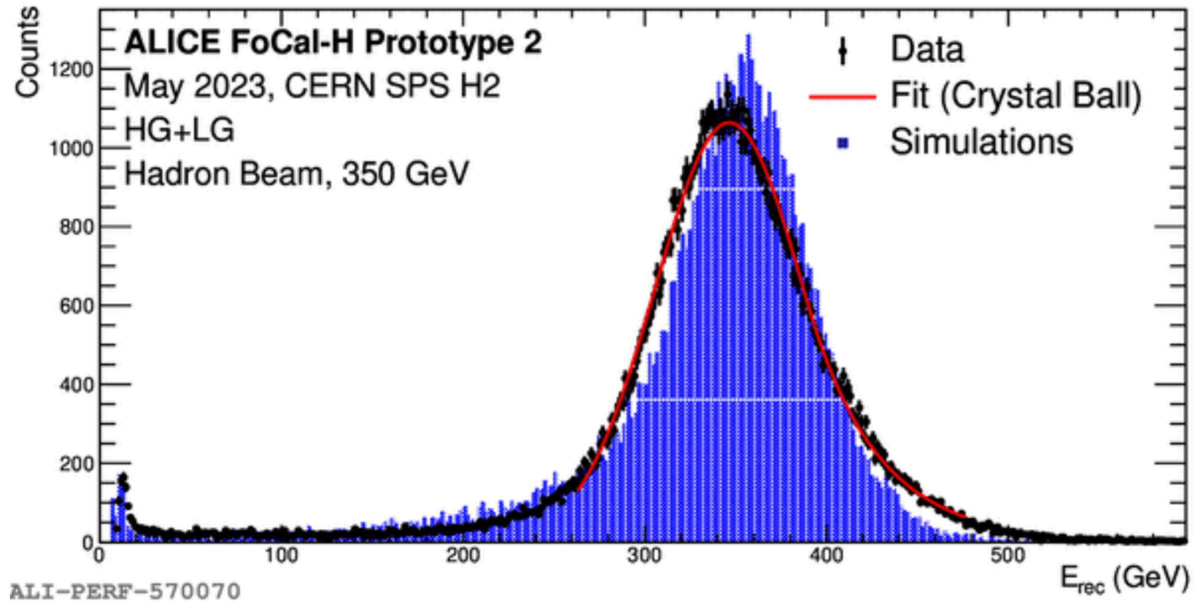




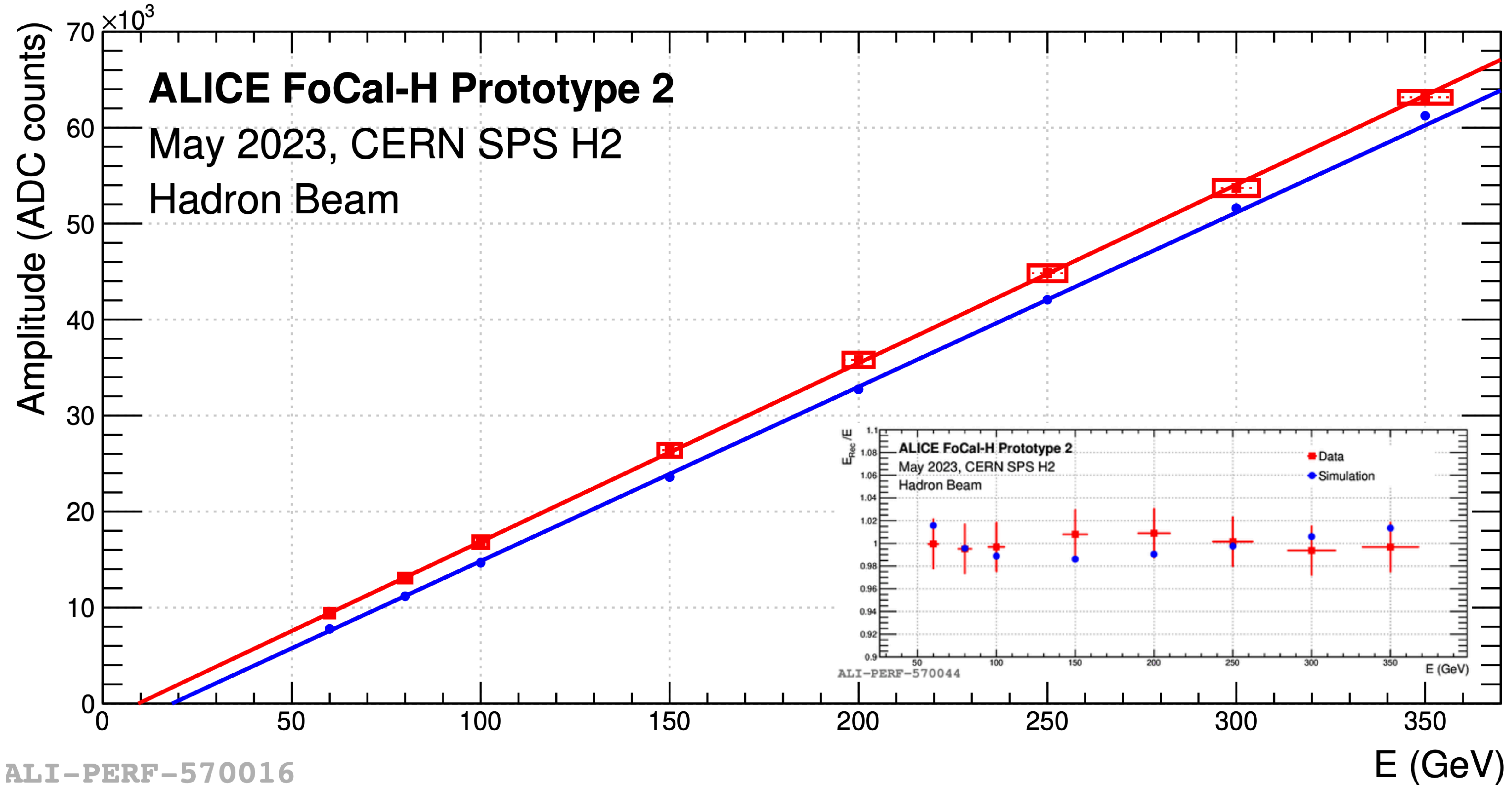


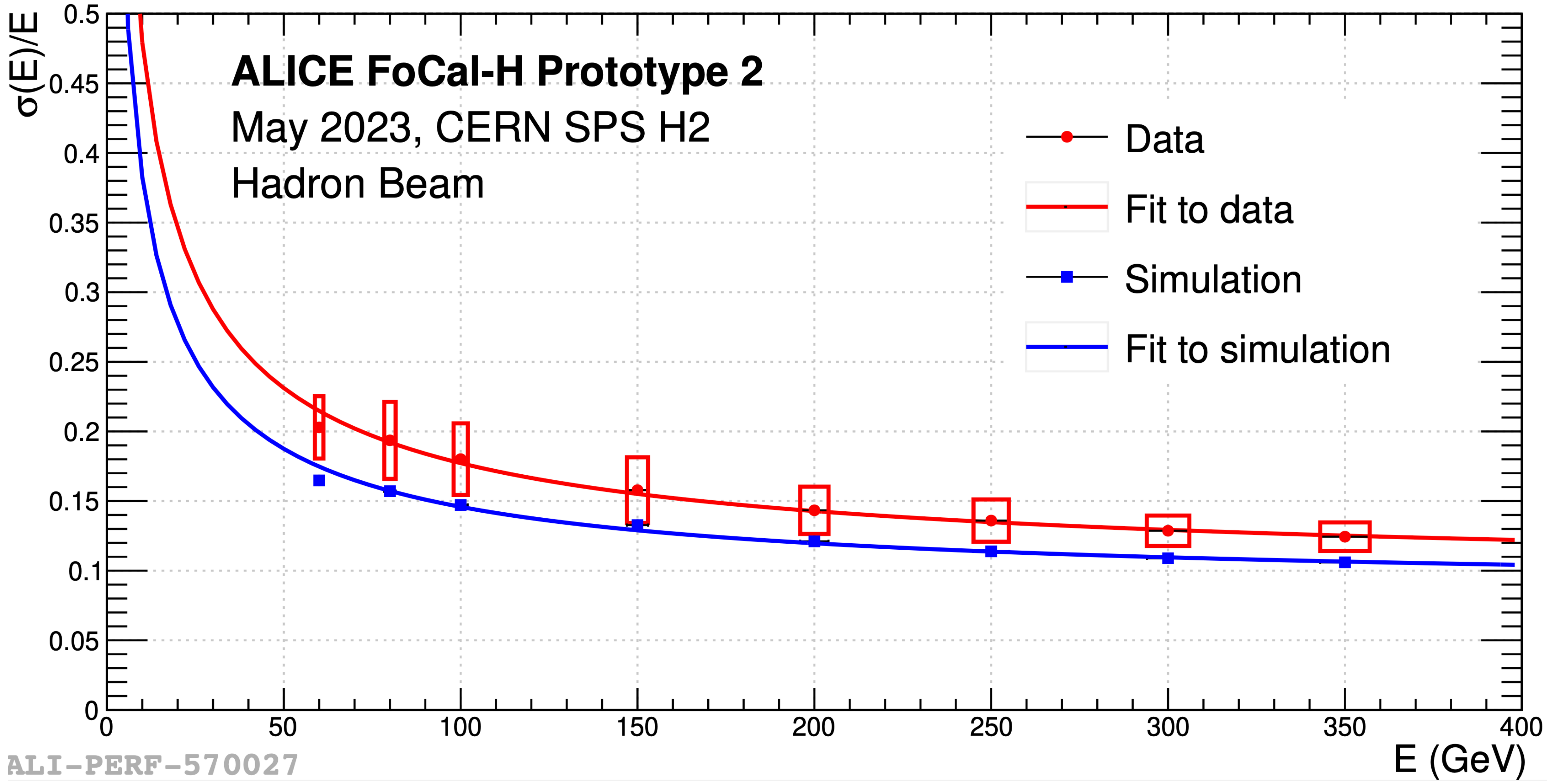
FoCal-H results





- FoCal-H performance tested at SPS in hadron beams from 60 to 350 GeV
- Response linear (rel. to fit) but different offset in data and MC
- Energy resolution of ~12% at high energies
- Disagreement with description in GEANT4 under investigation
- Response with final readout to be tested in 2025
  - including results combined with FoCal-E

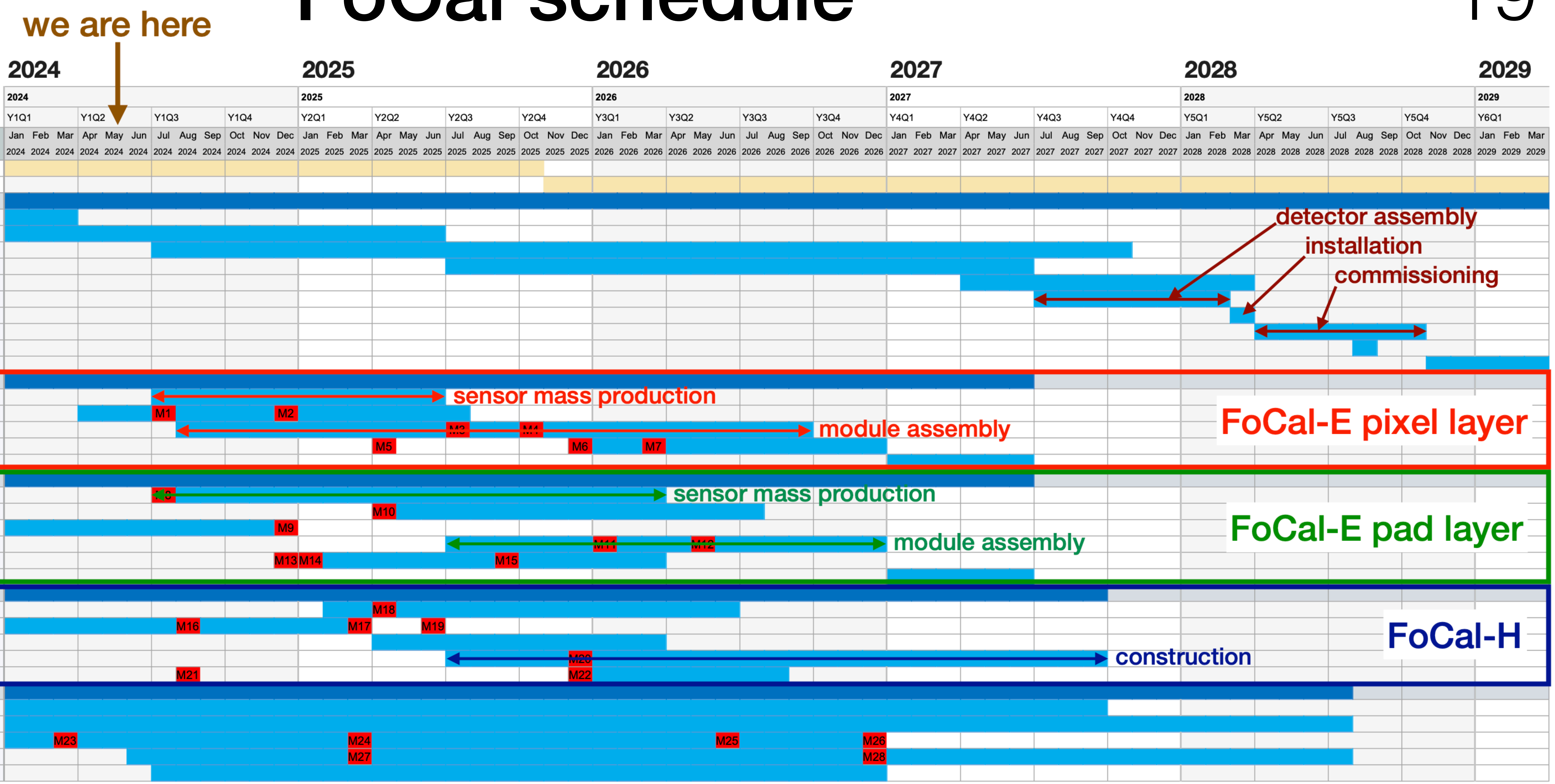




FoCal schedule

FoCal schedule overview

PROJECT NAMES + TASK TITLES	START DATE	END DATE	# of Days
LHC Run 3	**03/01/22**	**10/31/25**	**959**
LHC Long Shutdown 3	**11/01/25**	**03/31/29**	**890**
FoCal Global	**01/01/23**	**03/31/29**	**1630**
TDR	01/01/23	03/31/24	325
Final design	07/01/23	06/01/25	500
Production	07/01/24	10/31/27	870
Assembly decentralized	07/01/25	06/30/27	522
Racks and services at IP2 (pit)	04/01/27	3/31/28	262
Assembly at IP2 (upstairs)	07/31/27	02/28/28	151
Installation at IP2 (pit)	03/01/28	3/31/28	23
Commissioning	04/01/28	10/31/28	152
SPS test beam (calibration)	08/01/28	08/31/28	23
Contingency	11/01/28	03/31/29	108
FoCal-E pixel layers	**01/01/24**	**06/30/27**	**913**
ALPIDE production	07/01/24	06/30/25	261
Components production	04/01/24	07/31/25	349
Assembly	08/01/24	09/30/26	565
Readout production	01/01/26	12/31/26	261
Contingency	01/01/27	06/30/27	129
FoCal-E pad layers	**11/01/23**	**06/30/27**	**956**
Sensors	07/01/24	03/31/26	457
W plates	04/01/25	07/31/26	349
Module design	11/01/23	12/31/24	305
Assembly segments	07/01/25	12/31/26	393
Readout production	01/01/25	03/31/26	325
Contingency	01/01/27	06/30/27	129
FoCal-H	**01/01/24**	**09/30/27**	**979**
SIPM + fiber procurement	02/01/25	06/01/26	346
Design decision	01/01/24	03/30/25	325
Cu procurement	04/01/25	03/31/26	261
Construction	07/01/25	09/30/27	588
Readout production	01/01/26	08/31/26	173
Infrastructure	**01/01/24**	**07/31/28**	**1196**
Support for mini frame	01/01/24	09/30/27	979
Beam pipe	01/01/24	07/31/28	1196
Platform	01/01/24	12/31/26	784
Cooling	06/01/24	7/31/28	1086
O2 (CRU firmware)	07/01/24	12/31/26	654



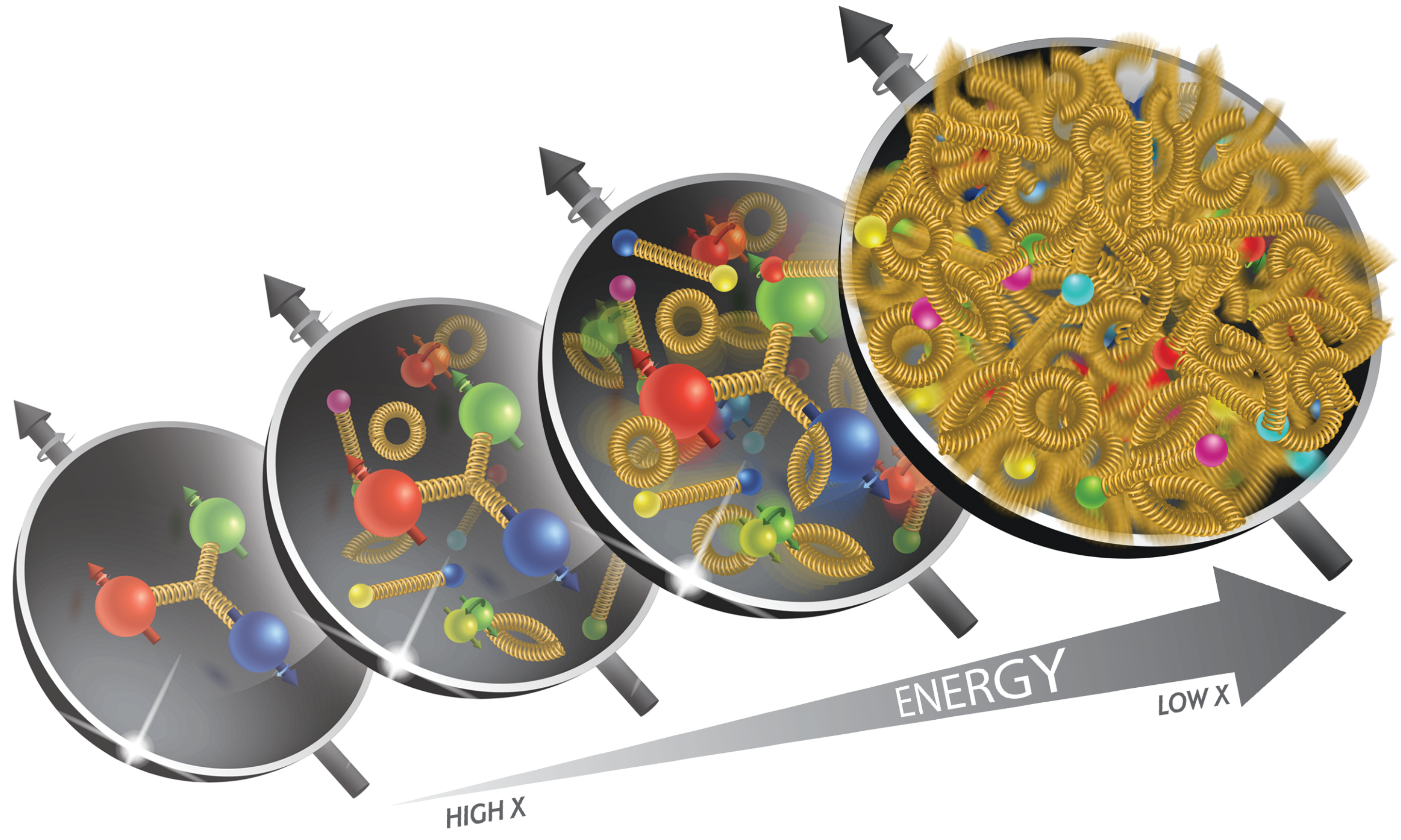
- Tense schedule; installation foreseen for 2028
- Mass production for 50% of sensors of FoCal-E started
- Ongoing FoCal-H readout development and tests

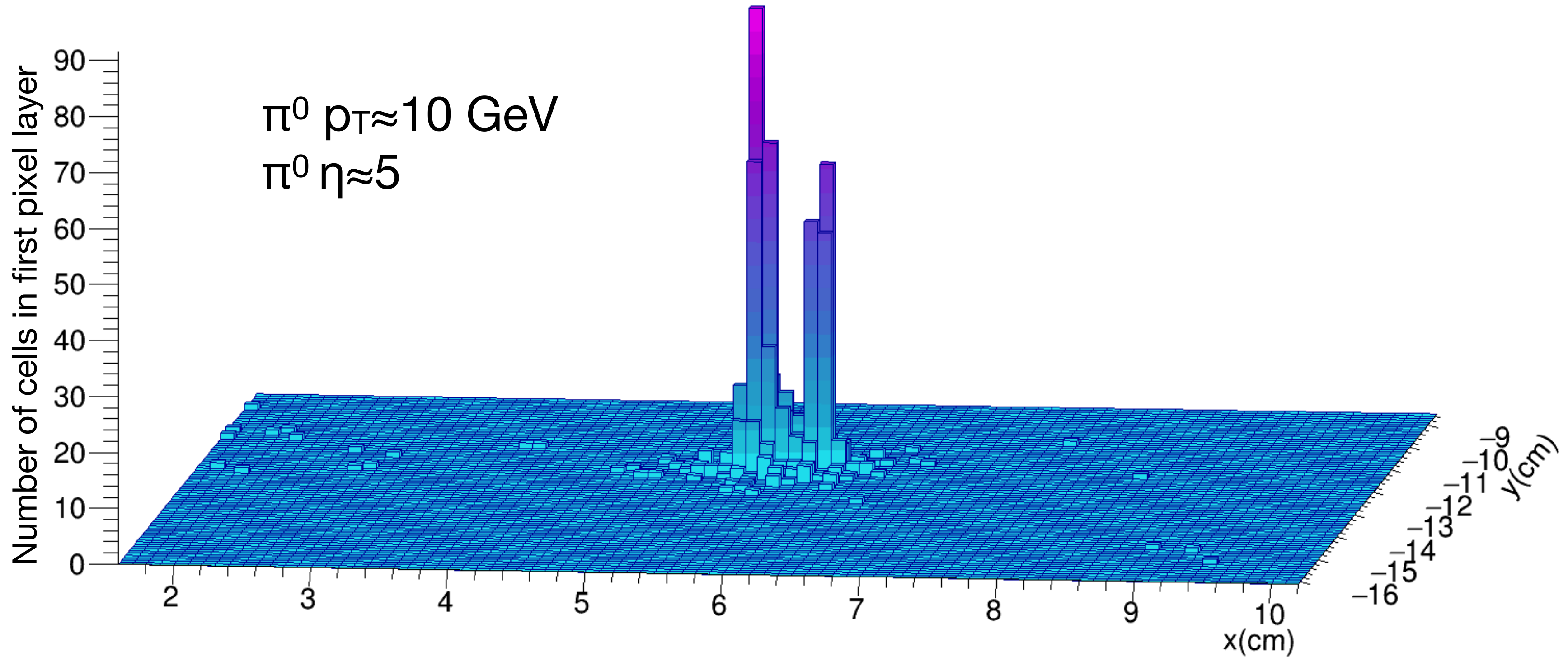
Summary

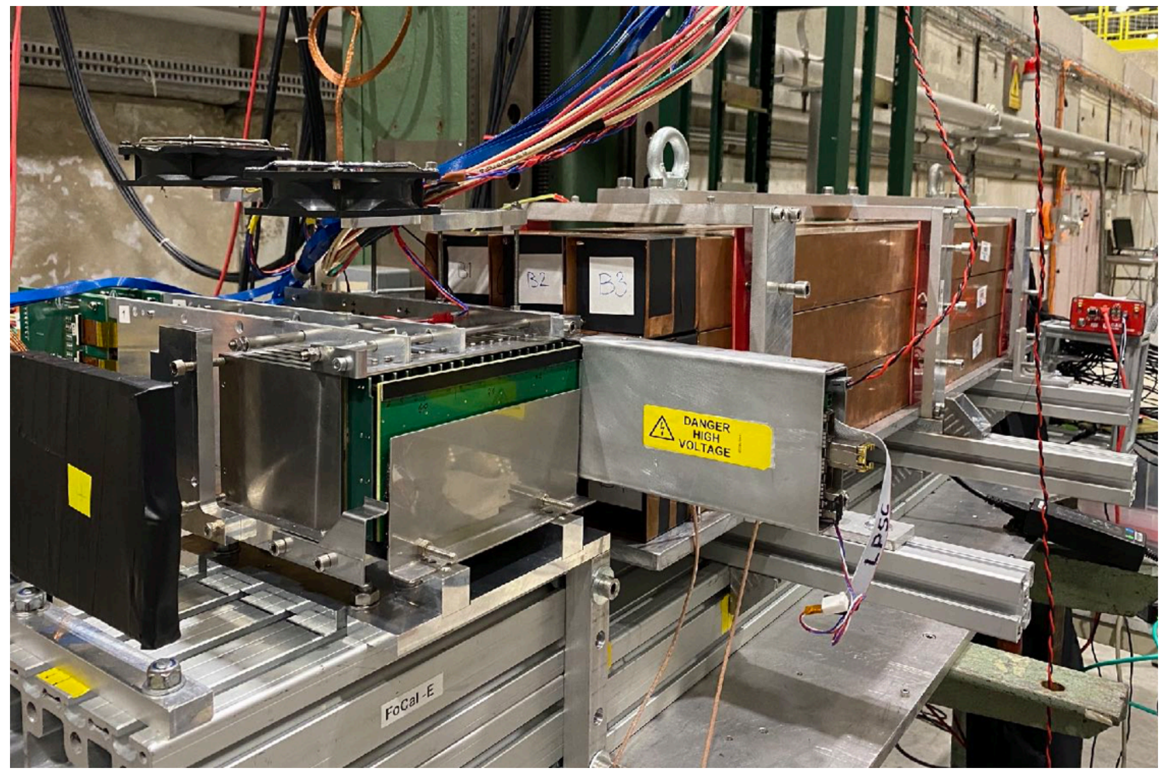
- FoCaL very forward, highly-granular Si+W "shower tracking" ECal with HCal
  - Fore-front calorimeter concept and technology
  - Technology synergy (ALPIDE, HGCROC)
  - Approved CERN project since 03/24
- Main physics goal to explore QCD saturation and the non-linear QCD evolution regime
  - Isolated photons, jets and correlations and photo-production in UPC at uniquely low x
  - Strong small-x program together with LHCb complementary to EIC
  - Enables precision multi-messenger program to test QCD universality
  - Discovery potential before the EIC era
  - Perfectly suited for any group interested in EIC physics at LHC

References

- Letter-of-Intent CERN-LHCC-2020-009
- Physics of the FoCal ALICE-PUBLIC-2023-001
- Physics performance of the FoCal ALICE-PUBLIC-2023-004
- Prototype electronics for FoCal 2023 JINST 18 P04031
- Performance of FoCal prototypes arXiv:2311.07413 (sub. to JINST)
- Technical Design Report CERN-LHCC-2024-004



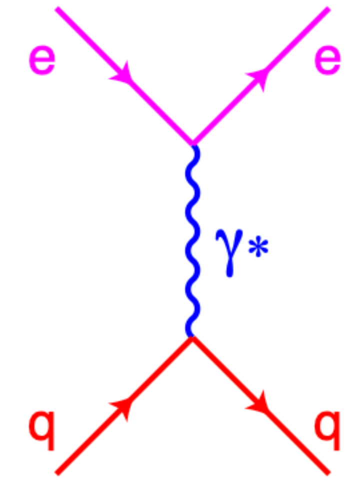




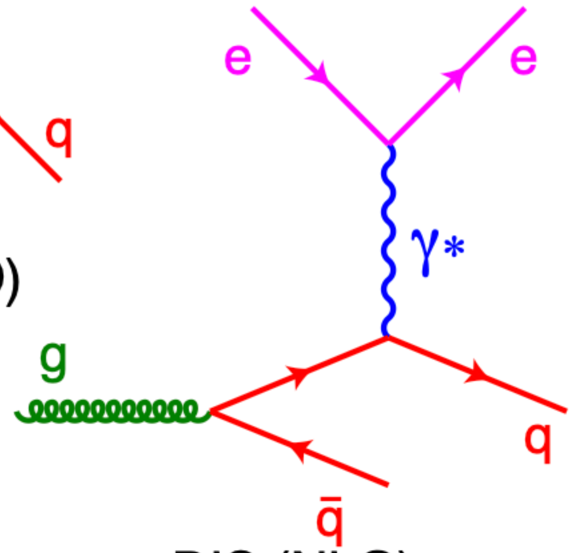
Extra

Processes sensitive to the gluon density

DIS



DIS (LO)

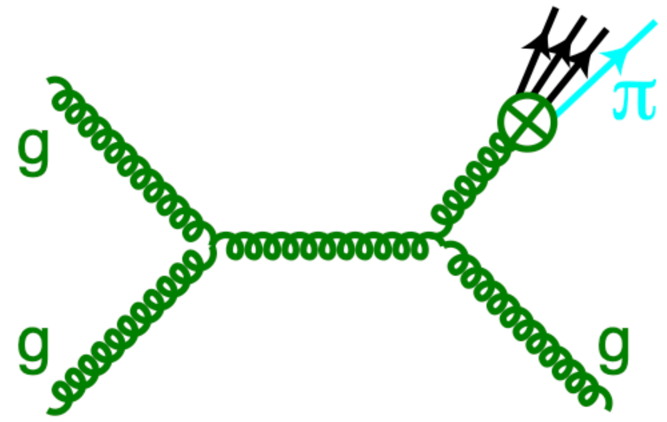


DIS (NLO)

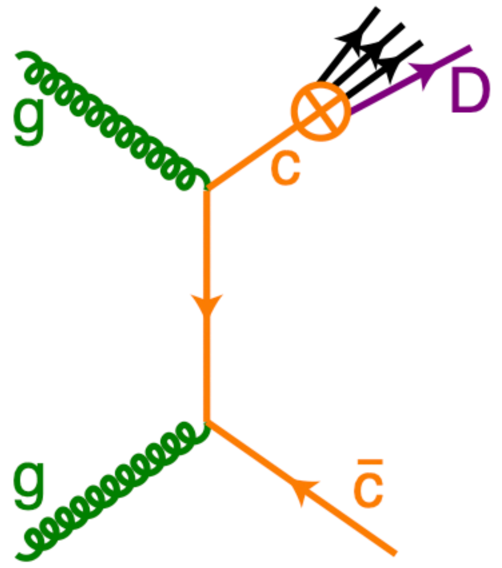
Classical DIS sensitive to gluons only at NLO or via evolution

Advantage: Full control of kinematics (x, Q^2)

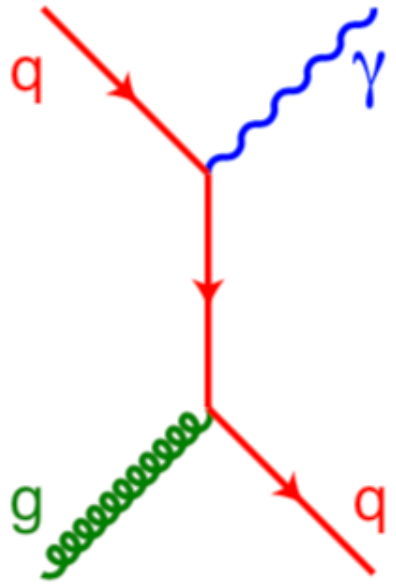
pA collisions



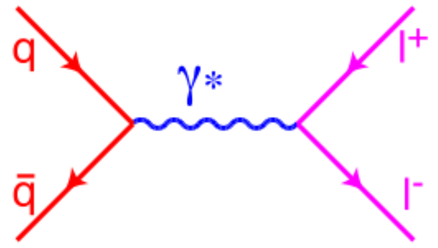
light hadron



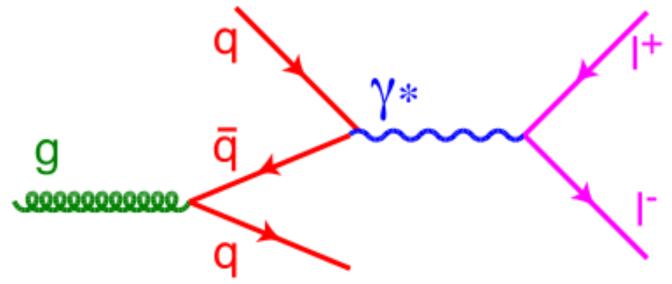
heavy hadron



Compton



DY (LO)



DY, virtual Compton (NLO)

Production of light and heavy hadrons

- HQ dominated by gluon fusion and tags the hard scattering
- Affected by fragmentation and possibly other final state effects

Direct photon production

- Sensitive at LO via Compton scattering
- Not affected by FF nor final state effects

Drell-Yan only at NLO (small cross sections)

PbPb UPC

LO

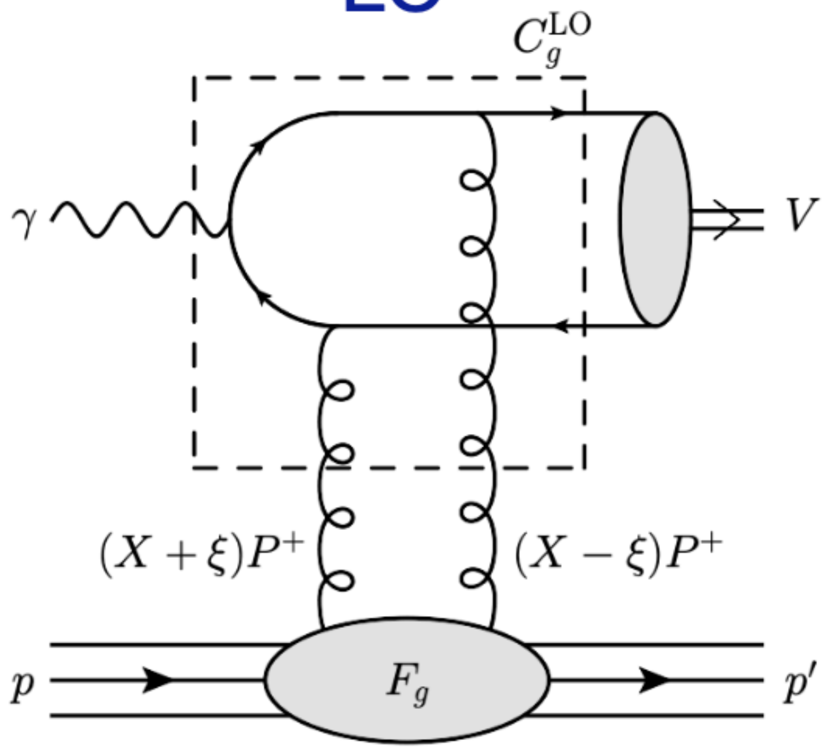
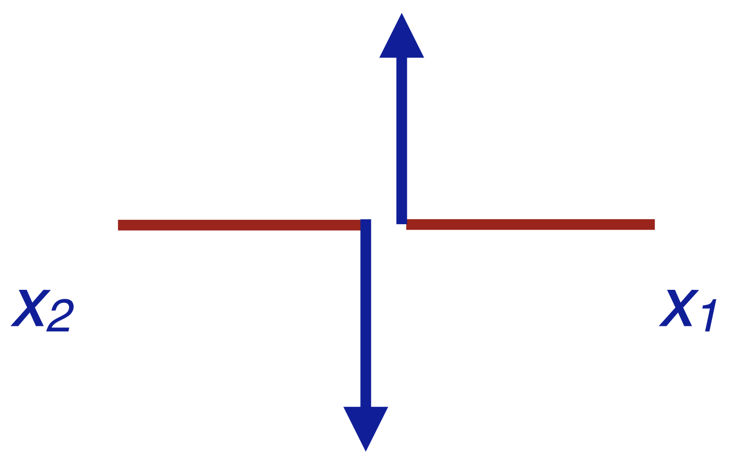


Photo-nuclear production of J/ψ (or dijets)

- sensitive at LO
  (but to product of densities at different x)

Two-parton kinematics in hadronic collisions

Both outgoing partons at mid-rapidity



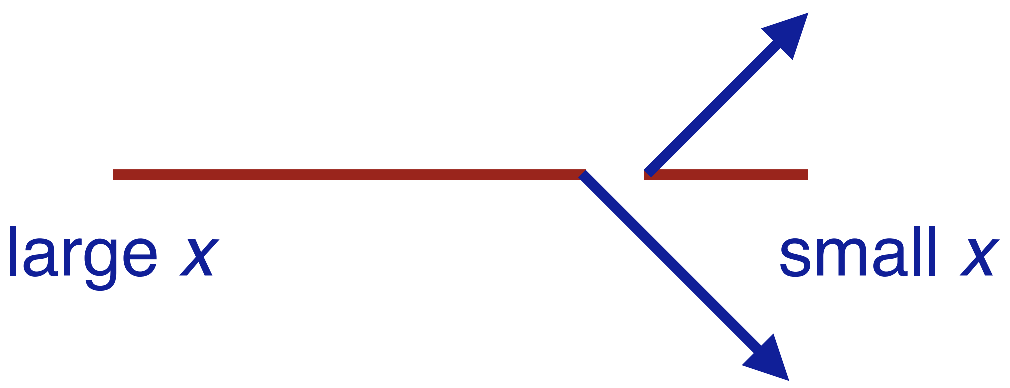
Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2\, p_\mathrm{T})^2$$

$$x_1 \approx x_2 \approx \frac{2p_T}{\sqrt{s}}$$

RHIC: x~0.01
LHC: x~0.001

Both outgoing partons at forward rapidity



Boosted configuration:
One small-x, one large-x parton

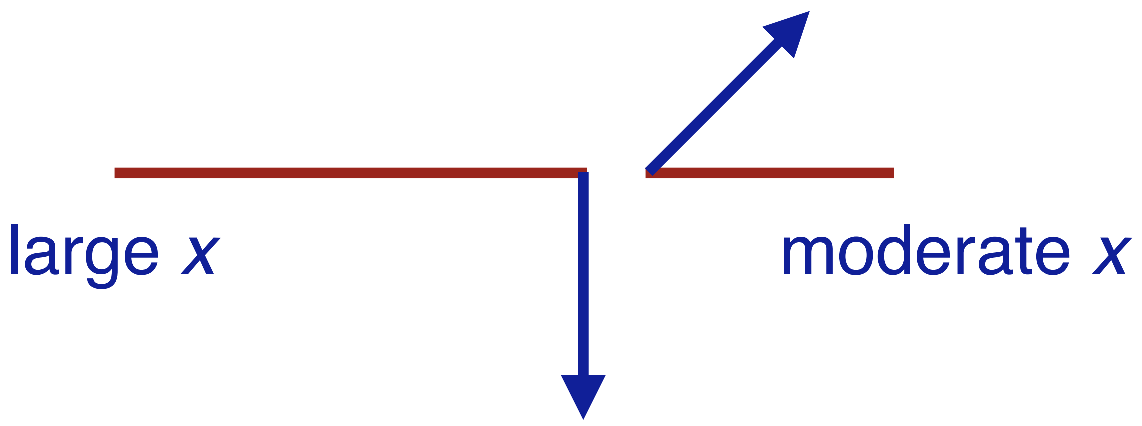
$$\hat{s} = x_1 x_2 s \approx (2\, p_\mathrm{T})^2$$

$$x_1 \approx \frac{2p_T}{\sqrt{s}}\, e^{-y}$$

RHIC: x~0.001
LHC: x~0.0001

Mid-rapidity at LHC ≈ forward rapidity at RHIC

One parton forward, one closer to mid-rap



Large mass final state

$$Q^2 = \hat{s} > (2\, p_\mathrm{T})^2$$

small probability

Note: NLO processes add additional freedom/smearing

Theoretical connection between EIC and forward pA

EIC Yellow Report Sec. 7.5.4:

*"Meanwhile, **pA collisions can serve as a gateway to the EIC** as far as saturation physics is concerned, and it also plays an **important and complementary role** in the study of these two fundamental gluon distributions."*

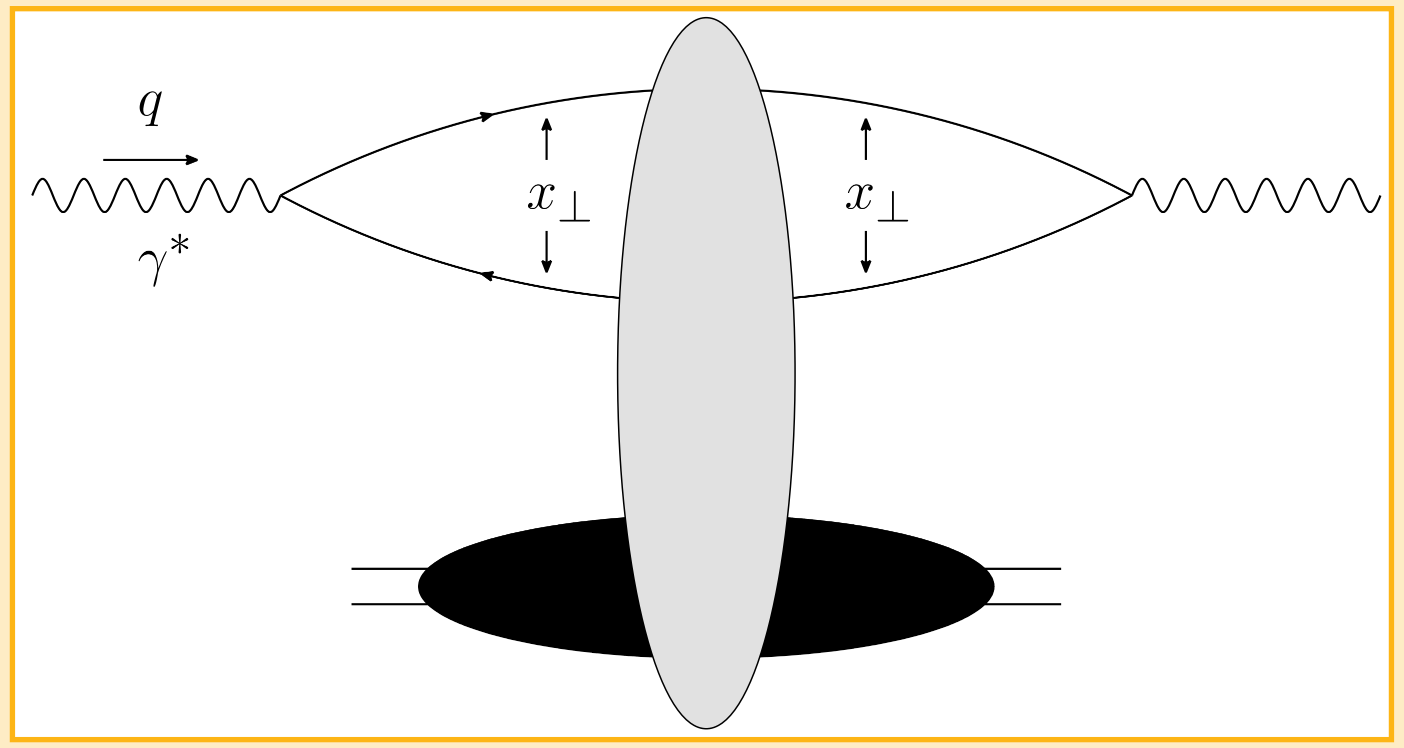
Nucl.Phys.A 1026 (2022) 122447

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	−	−	+	−	−	+
xG_{DP}	+	+	−	+	+	+

- Multiple processes in **e-A DIS** and **forward p-A** collisions are theoretically described using the **same dipole/ quadrupole scattering amplitudes!**

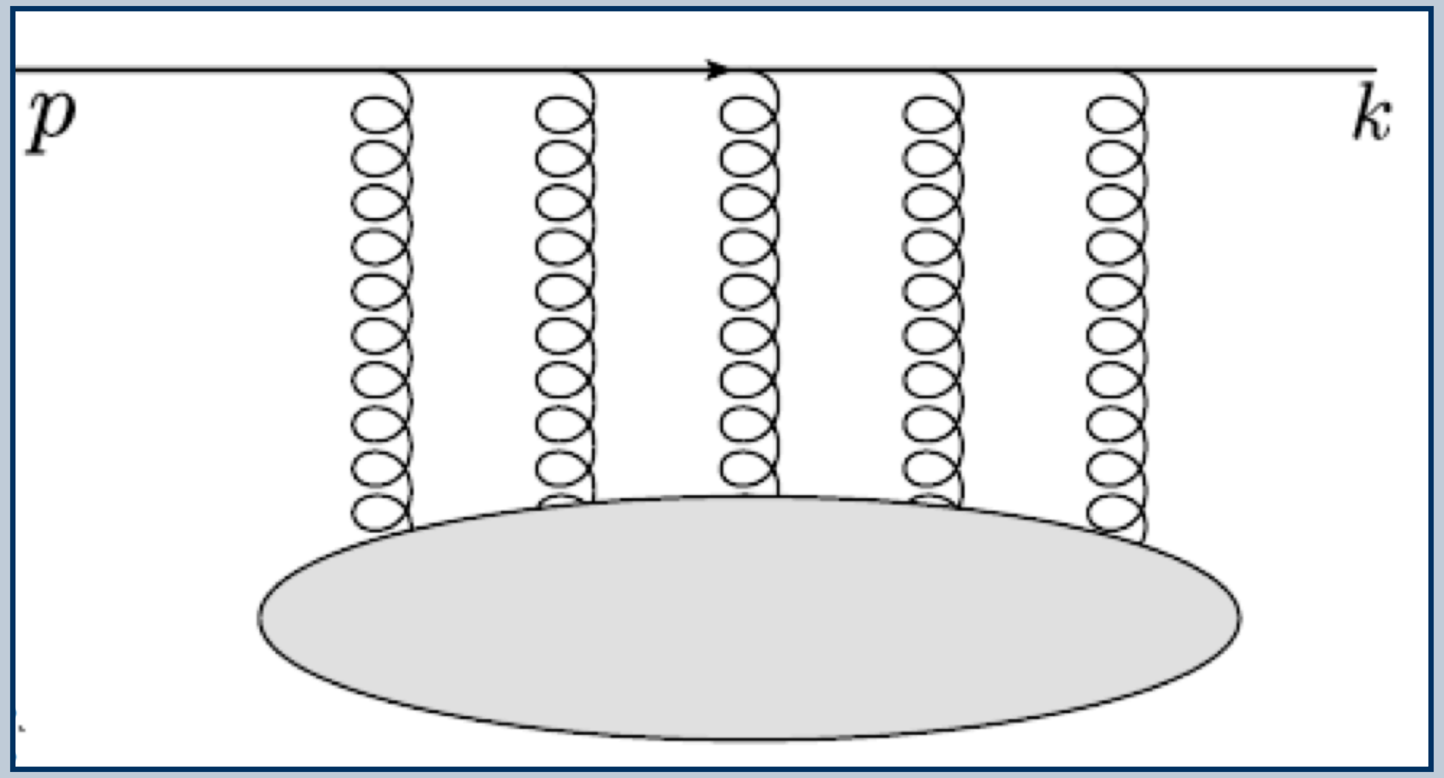
measurements in e-A DIS and forward p-A collisions
→ **test universal description of gluon saturated matter**

e+A Deep Inelastic Scattering (DIS)



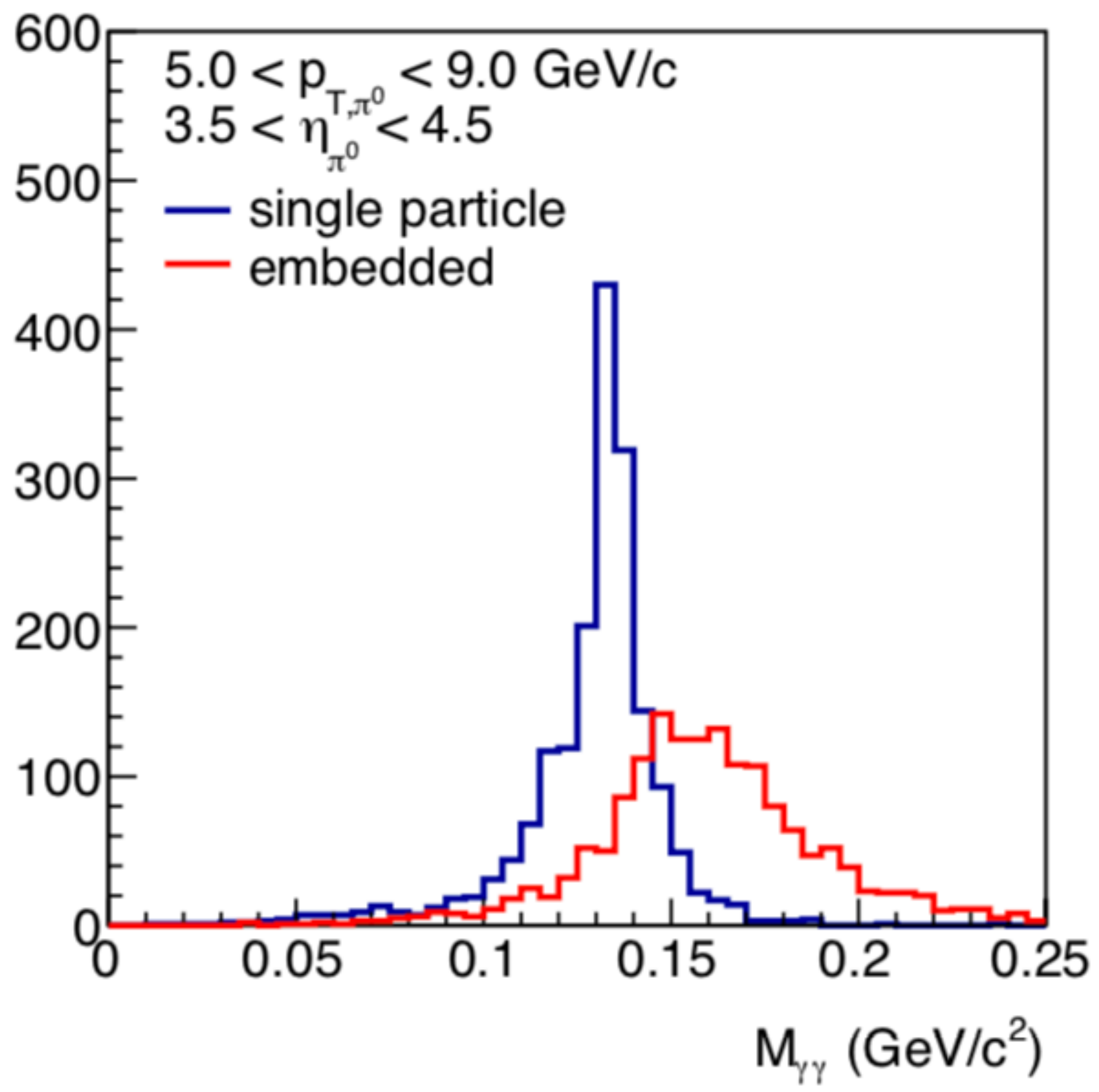
JETP 30 (1970) 709-717, Phys. Rev. D 8 (1973) 1341, Nucl. Phys. B 335 (1990) 115

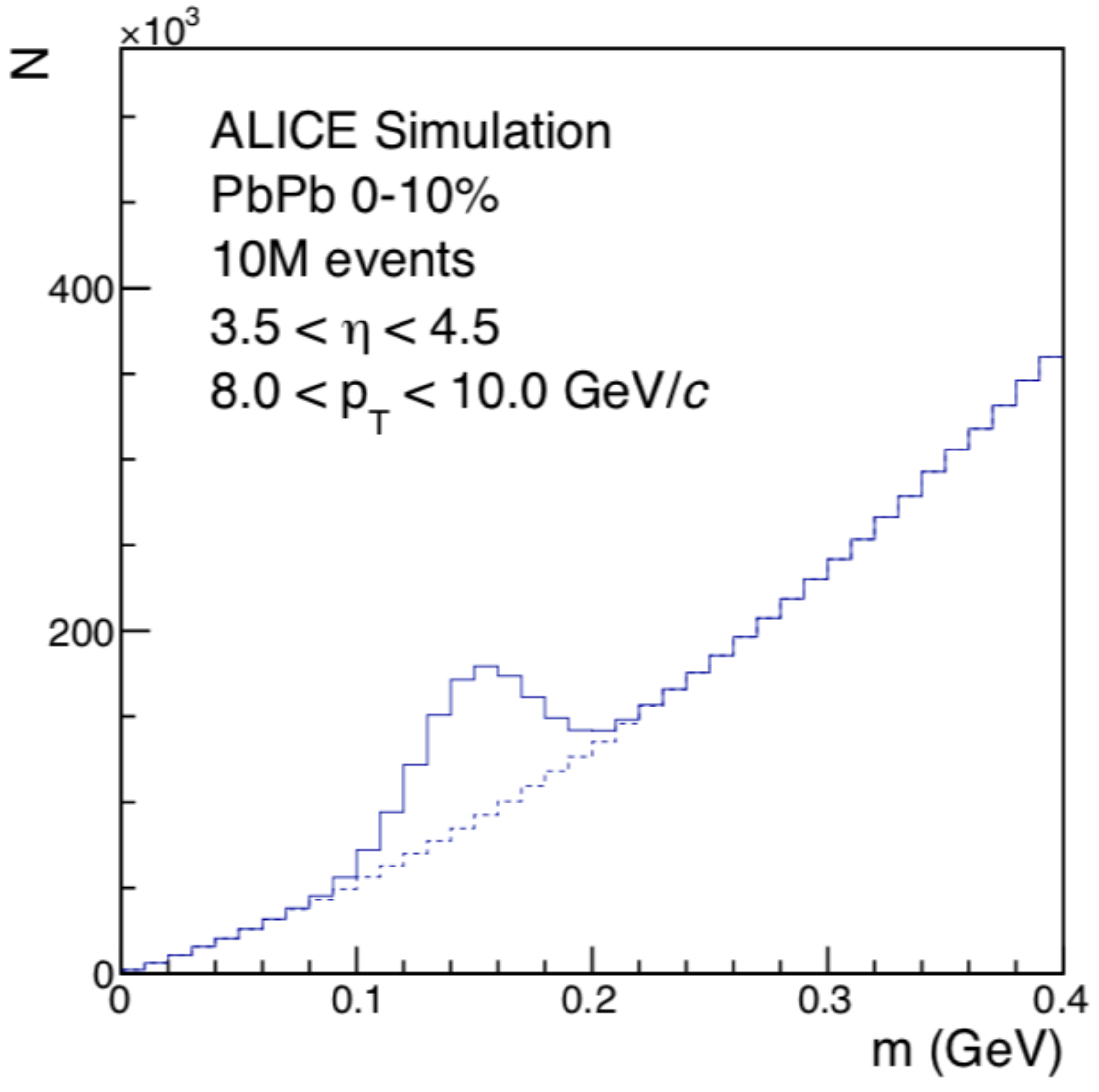
Forward p+A collisions

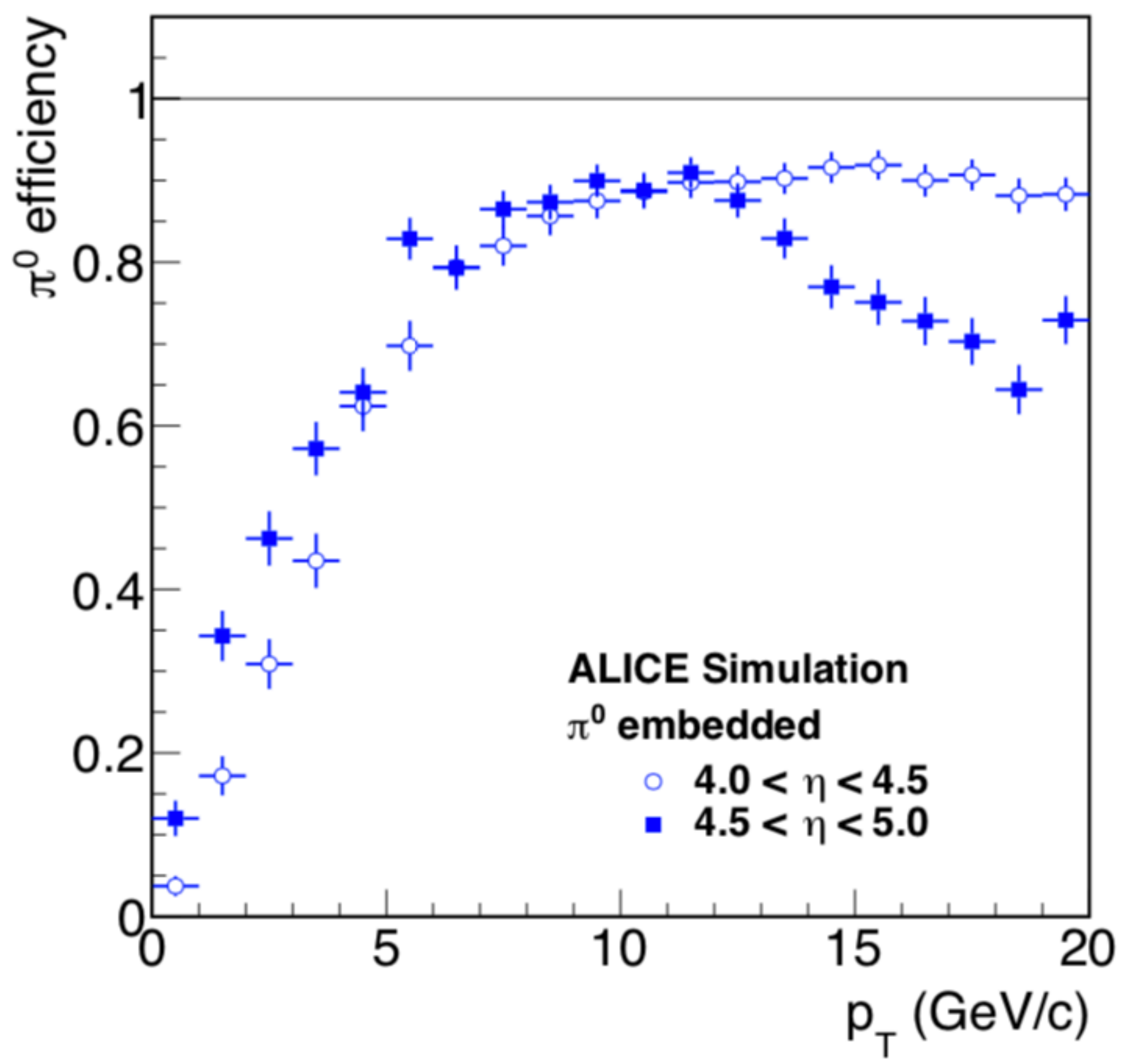


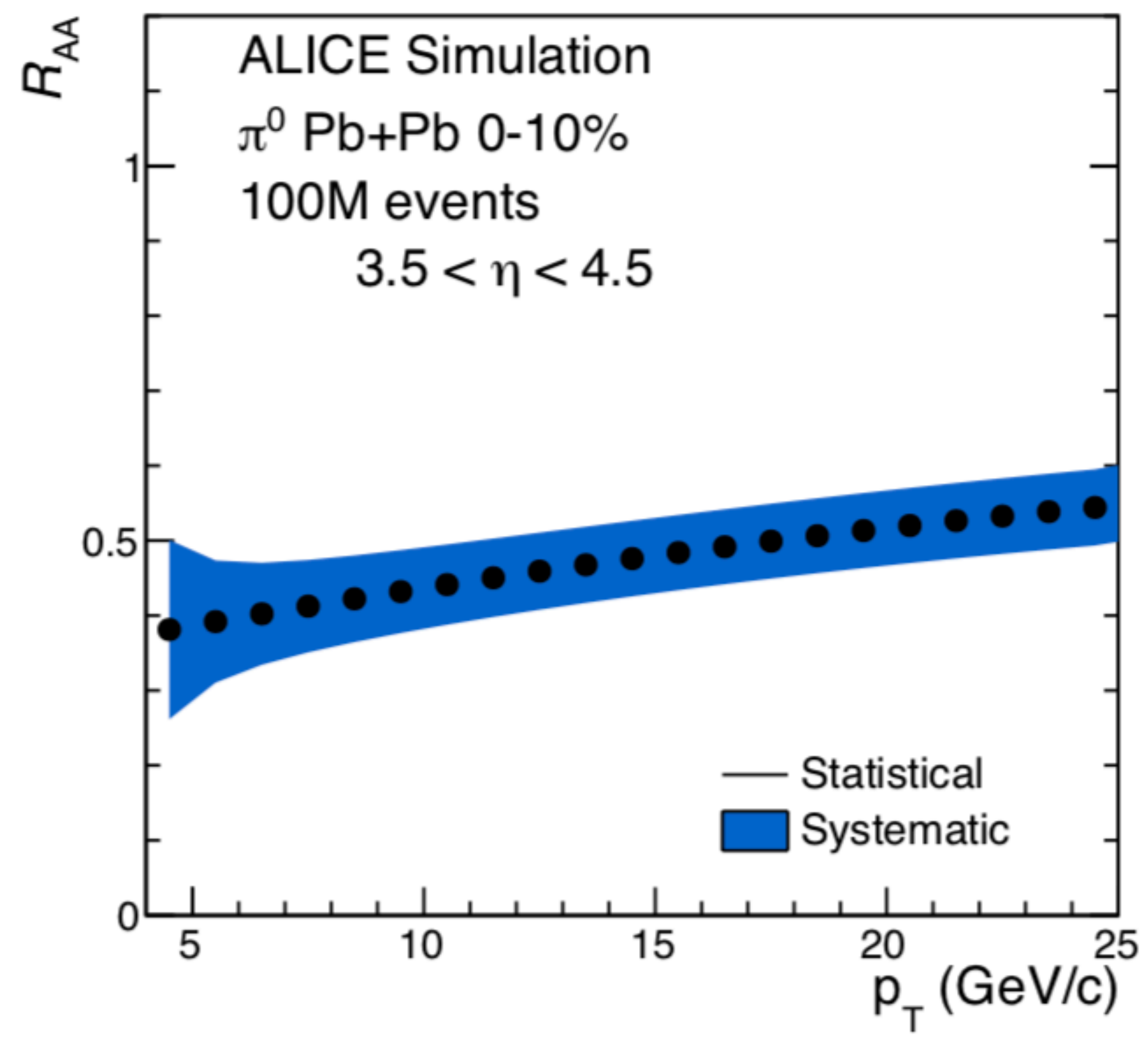
Phys. Rev. C 59 (1999) 1609, Phys. Rev. D66 (2002) 014021, Phys. Lett. B 503 (2001) 91

FoCal: Performance in PbPb



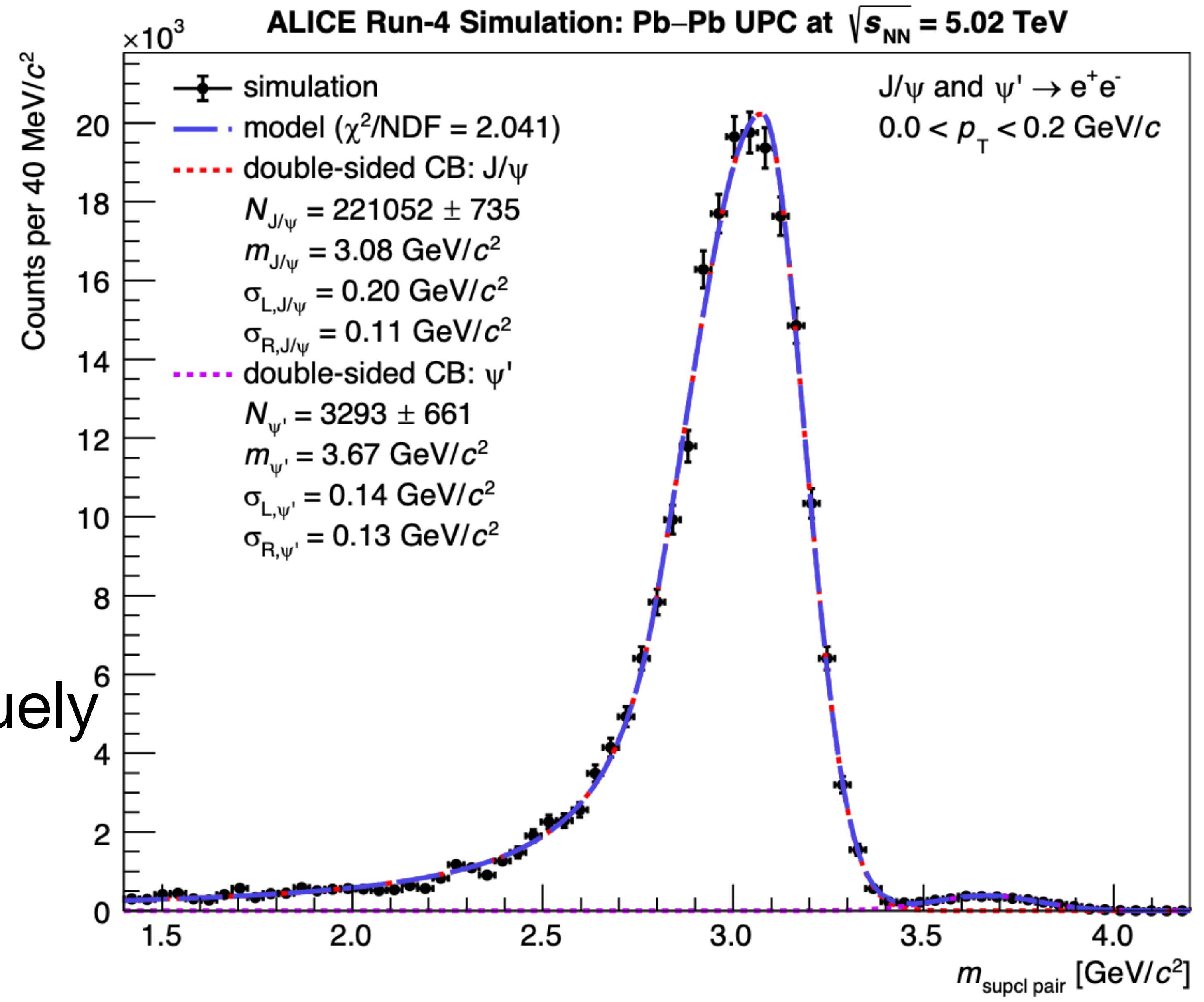






- Performance in PbPb affected by shower overlaps and combinatorial background
- Efficiency for high energy neutral pions nevertheless quite good
- Combinatorial background may prohibit very low p_T reconstruction, but above 5 GeV expect a precise R_{AA} measurement

In UPC, detailed studies of J/ψ and ψ(2s) at uniquely small x (⇒S.Klein)



CERN-LHCC-2020-009