Forward Physics at LHC-ALICE

Tatsuya Chujo

筑波大学
University of Tsukuba

ATHIC 2025, Mayfair Palm Beach Resort, Gopalpur, India, Jan. 13-16, 2025

Our field is growing!

1st ATHIC (2006), Seoul, Korea

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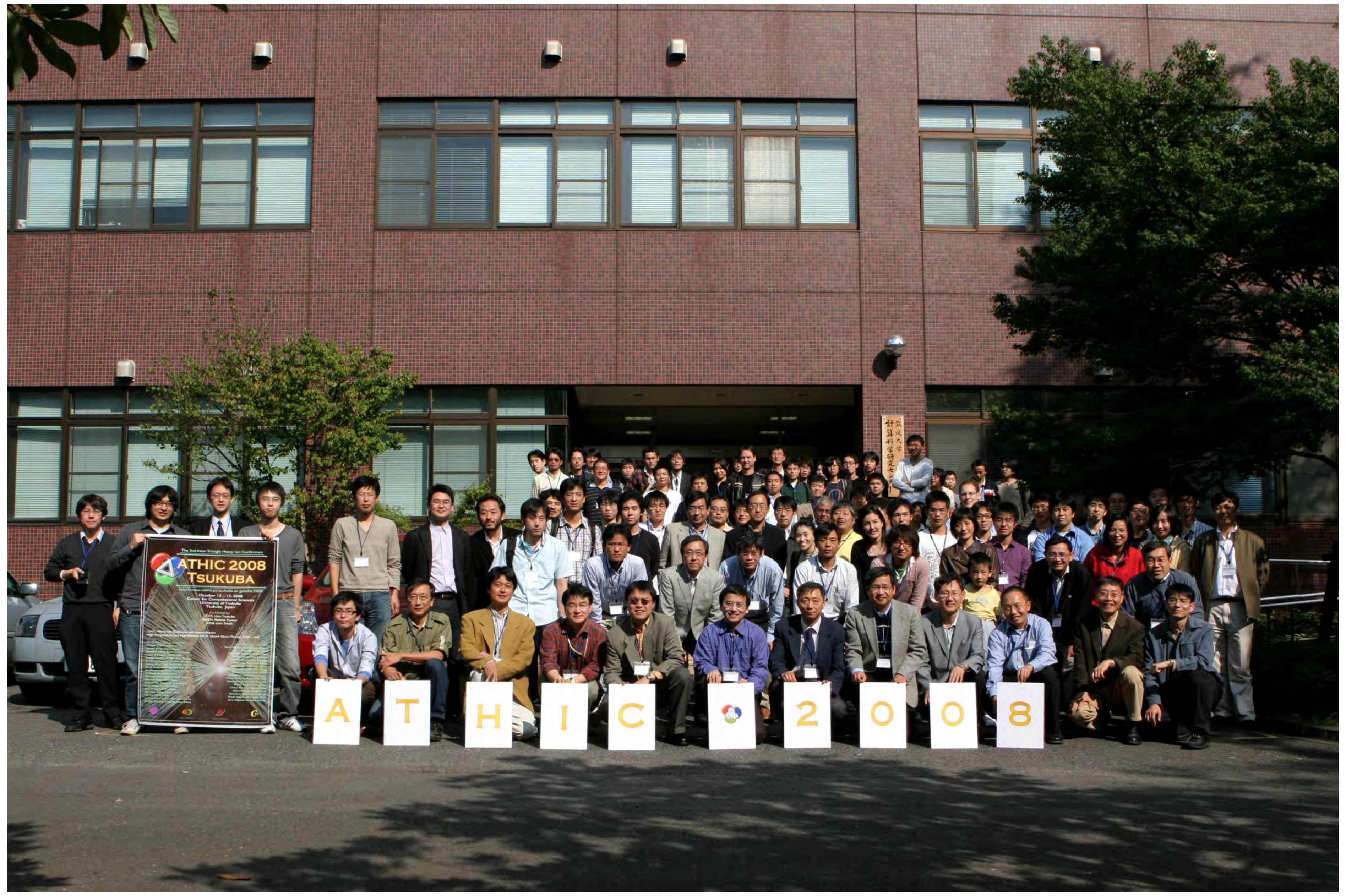


	Japanese	Korean	Chinese	Other	Sum
Senior Staff	12	7	9	1	29
Junior Staff	9	2	1	1	13
Post Doc	9	1	4	0	14
Student	25	4	4	1	34
Sum	55	14	18	3	90

2nd ATHIC (2008), Tsukuba, Japan

90 participants

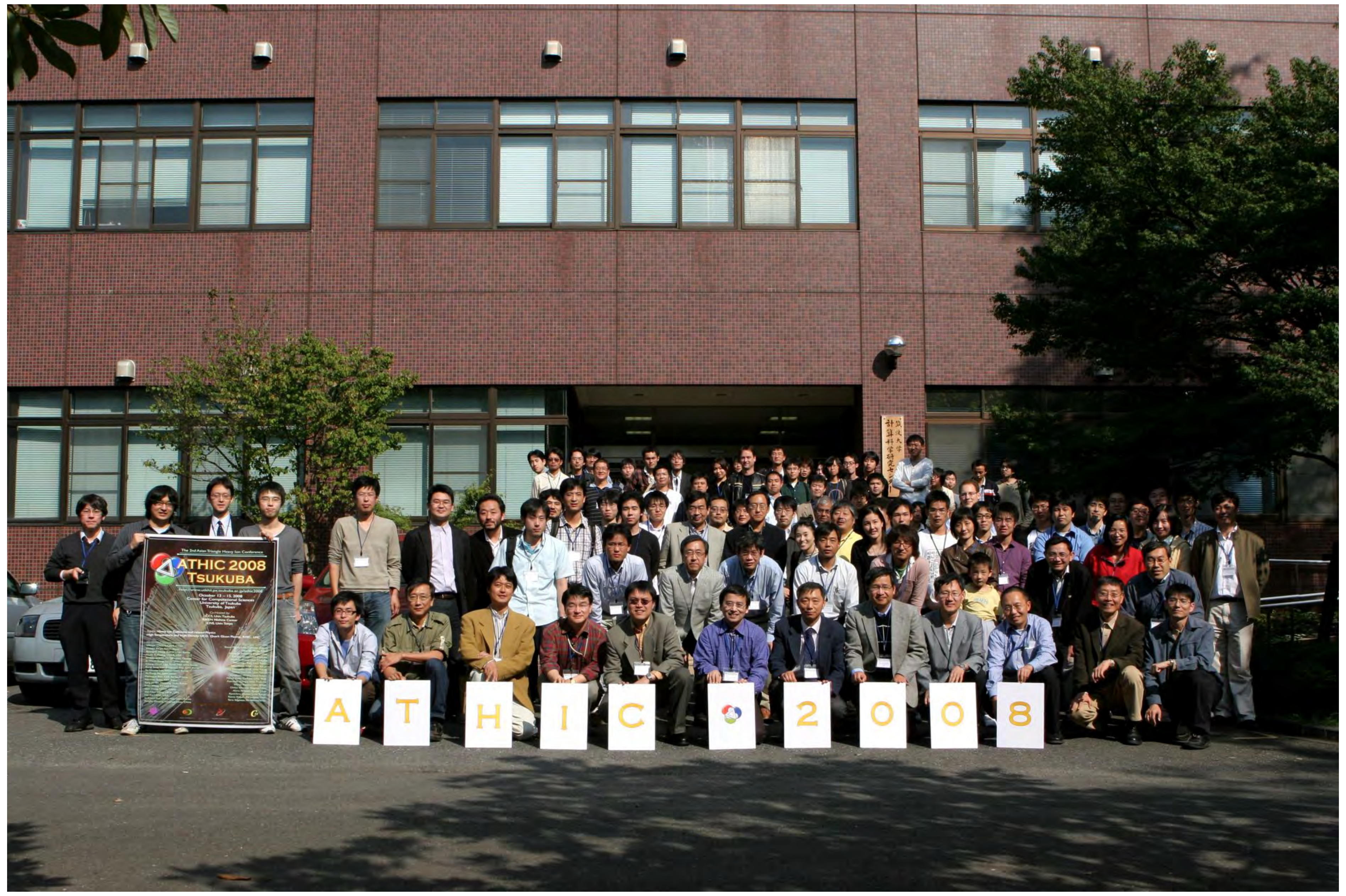
Our field is growing!

1st ATHIC (2006), Seoul, Korea

10th ATHIC (2025), Gopalpur, India

<u>258 participants!</u>

x3 larger than that in 2008



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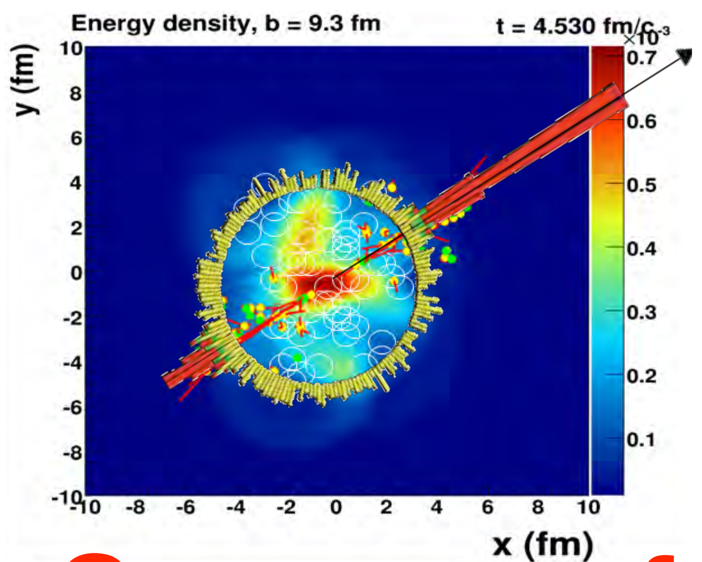
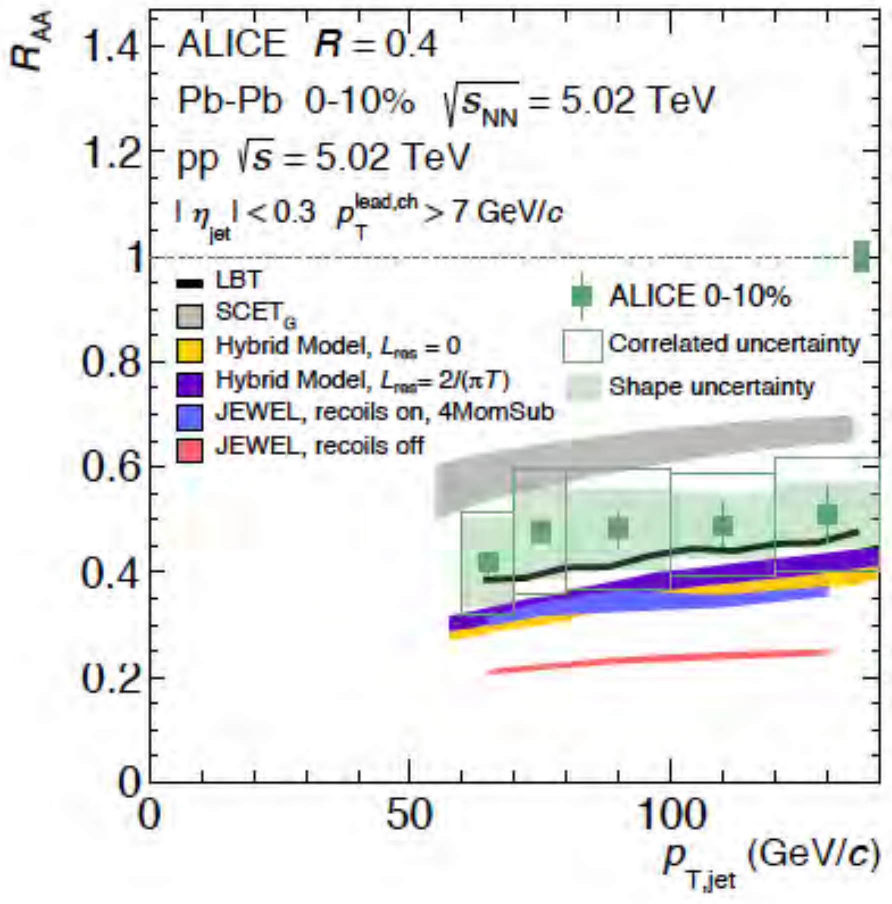
2nd ATHIC (2008), Tsukuba, Japan

90 participants

25 years of QGP research; strongly coupled QGP

1. Jet Quenching

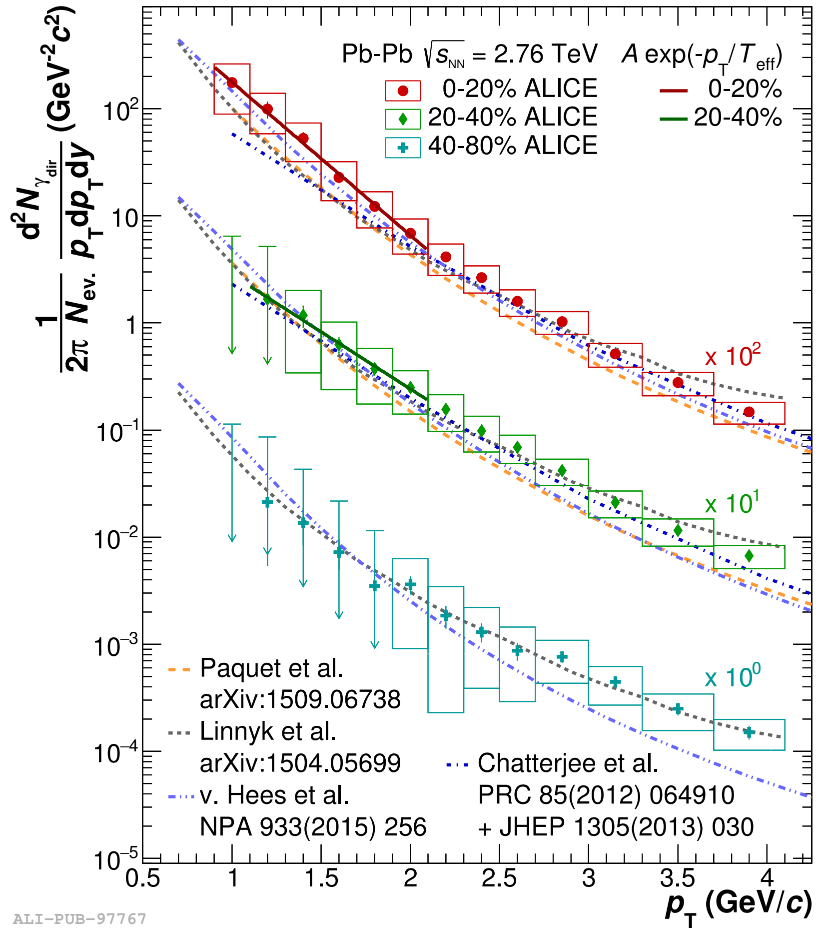




Phys. Rev. C 101, 034911 (2020), ALICE

2. Thermal photons

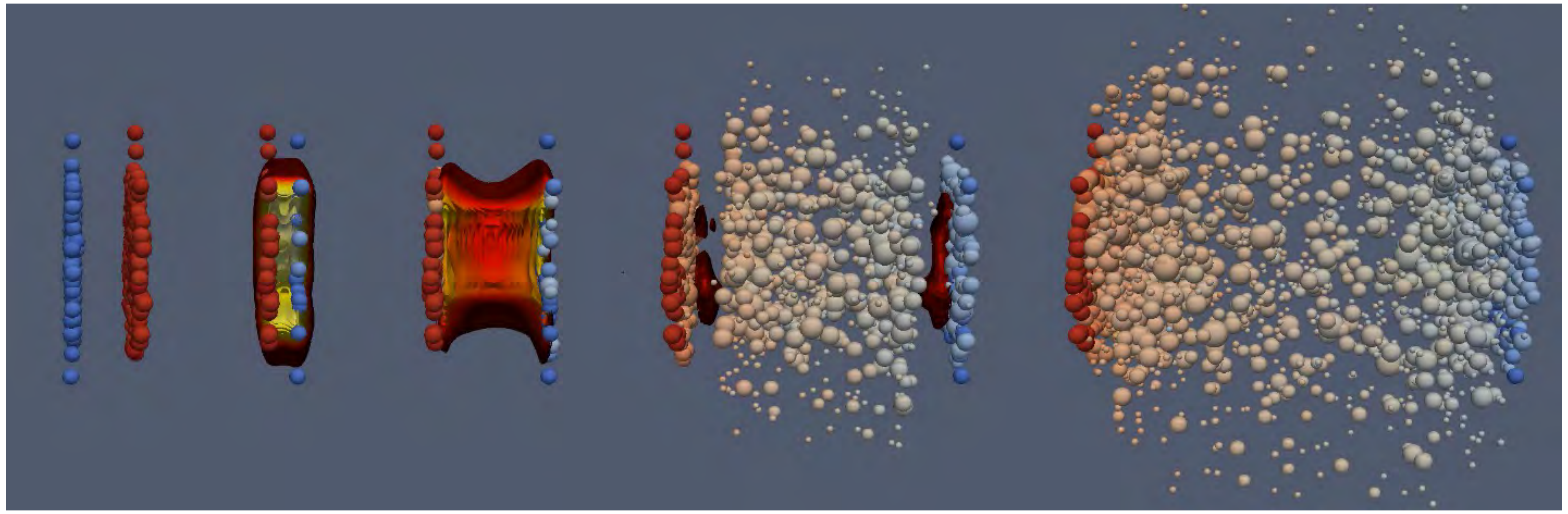
$T_{init.}$ ~300 MeV



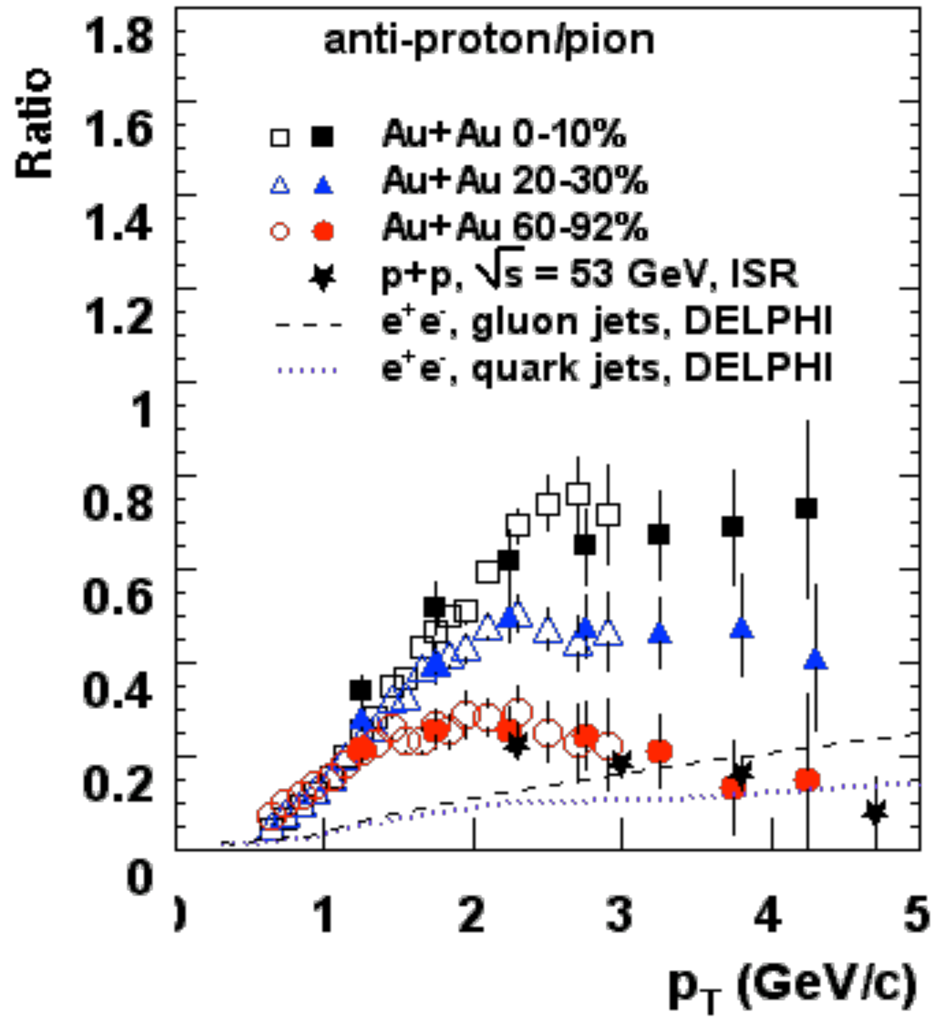
PLB754(2016)235 (ALICE)

Success of hydrodynamic models,

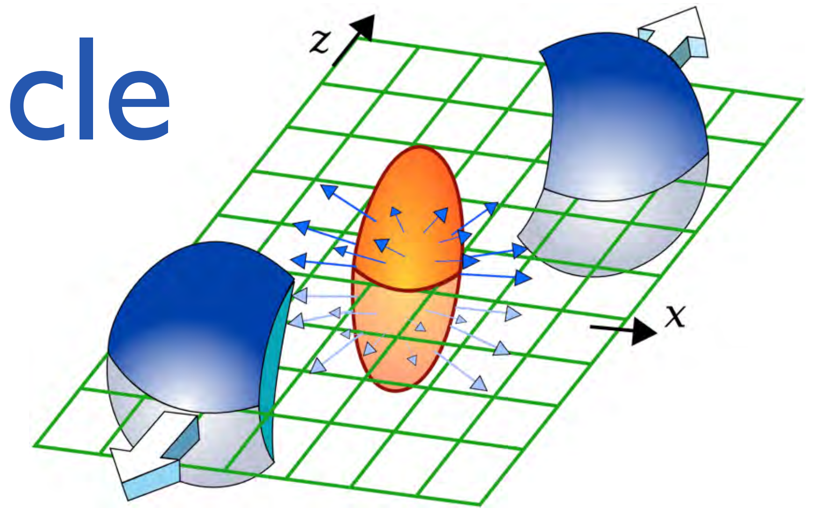
strongly coupled QGP (sQGP)

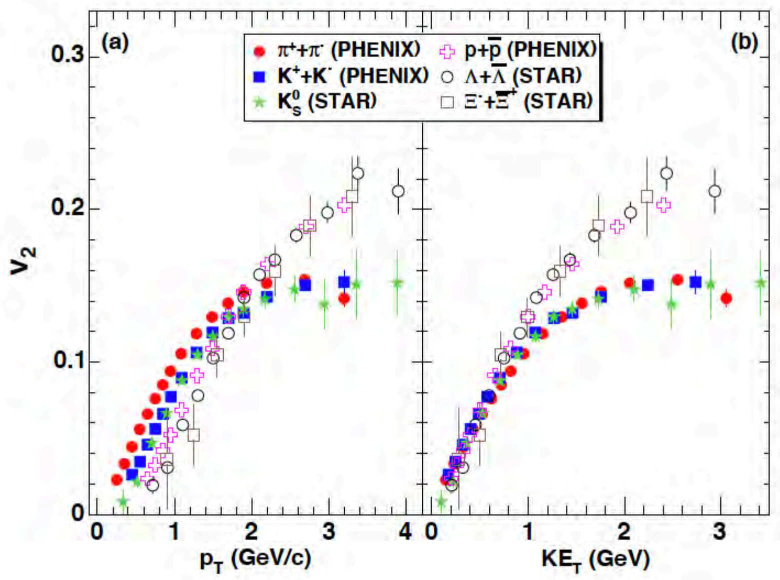


Phys. Rev. C69, 034909 (2004), PHENIX



3. Large azimuthal anisotropy of particle emission (v_2)

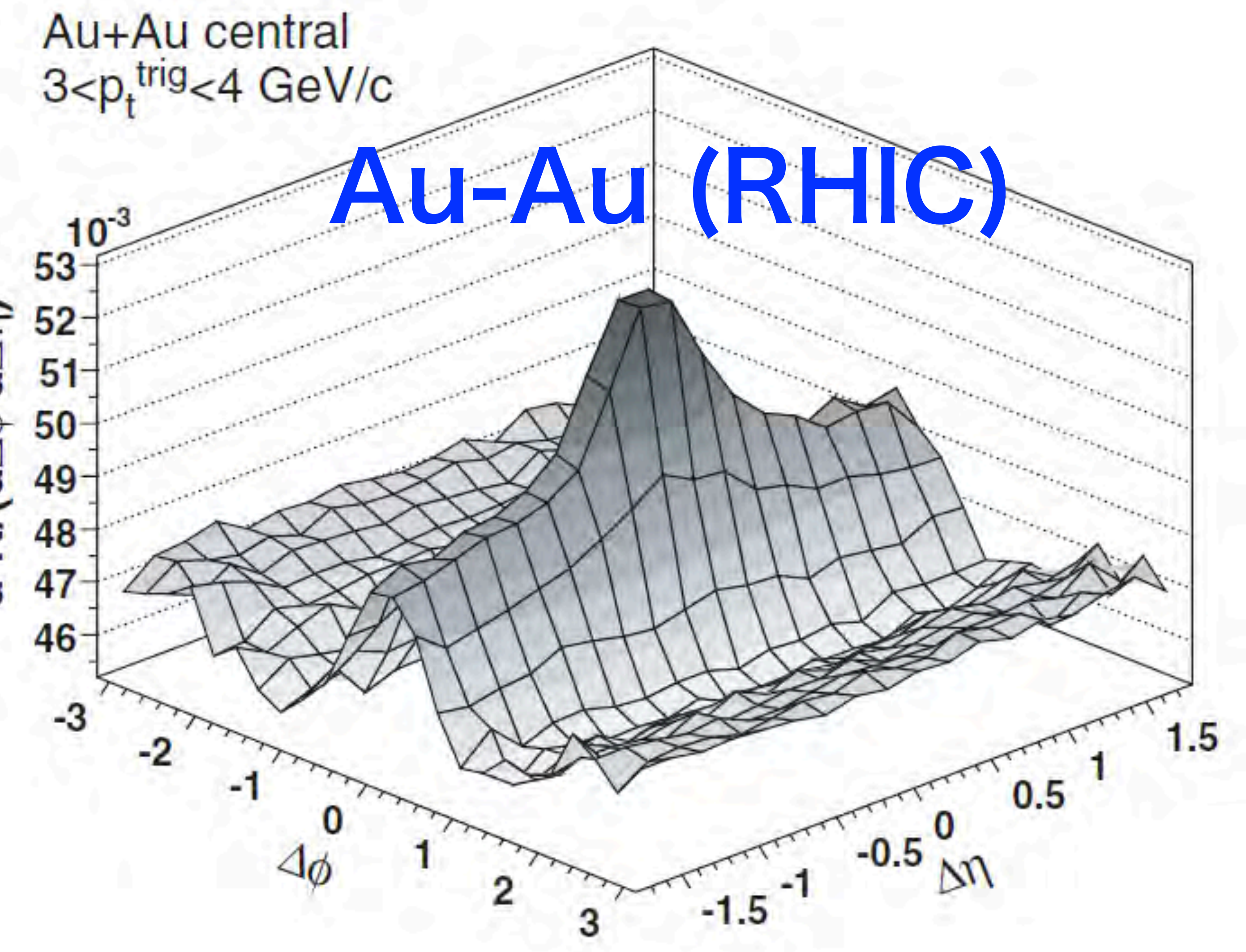




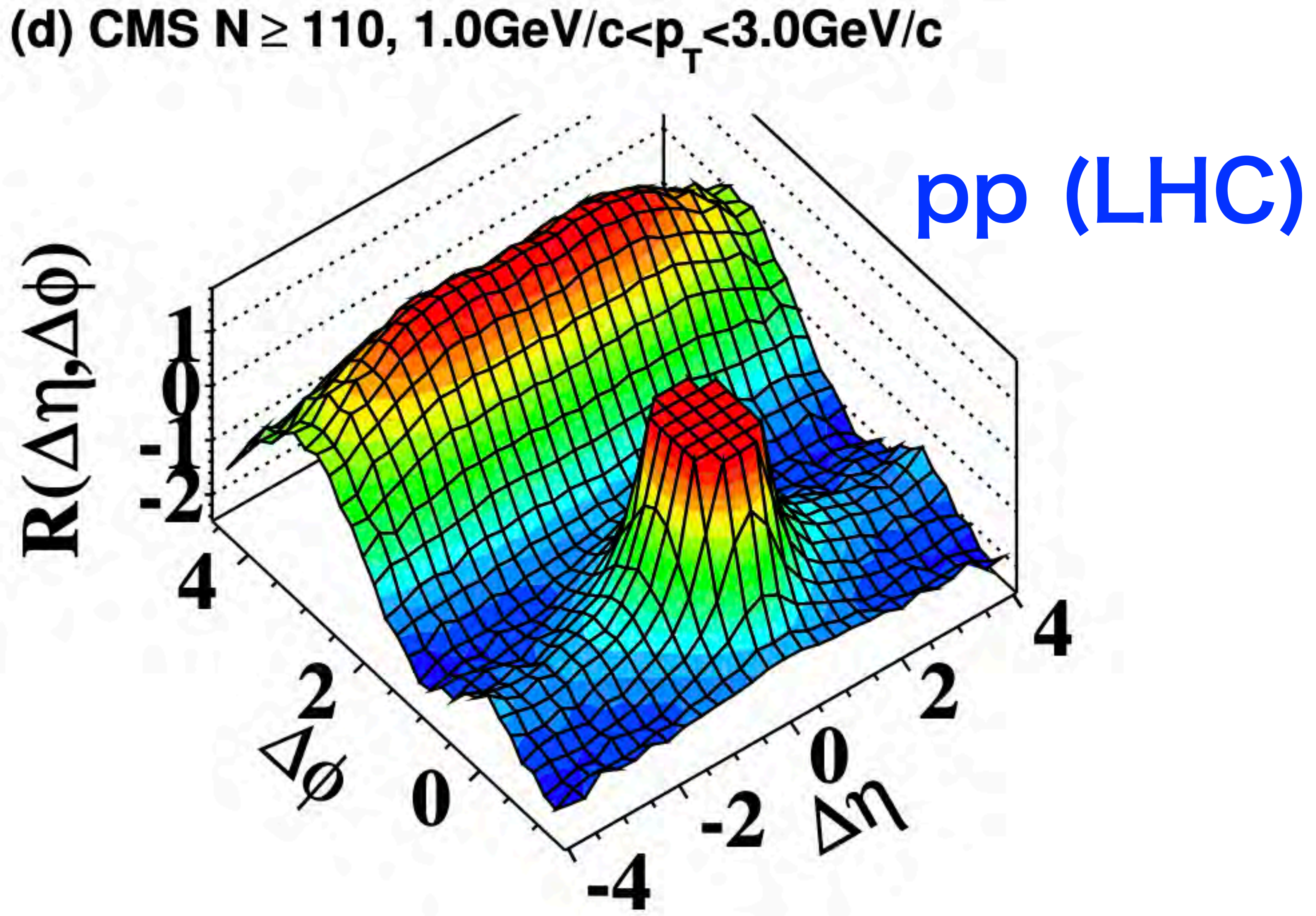
Phys. Rev. Lett.98, 162301 (2007), PHENIX

4. Quark recombination

【Turning point】 High multiplicity events in small systems (2010)



STAR, PRC 80 (2009) 064912



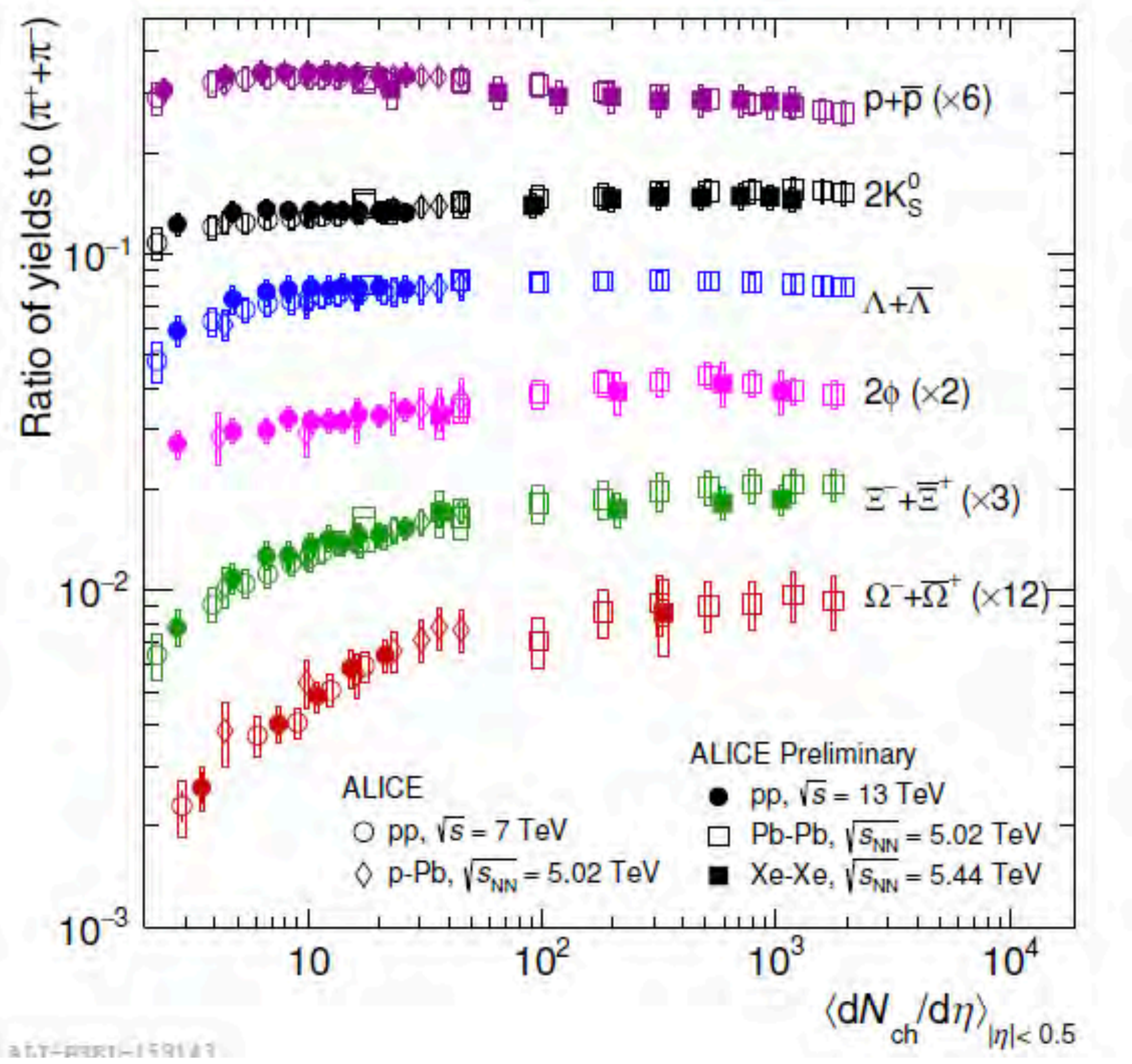
CMS, JHEP 1009 (2010) 91

1. Two particle correlations ($\Delta\varphi$, $\Delta\eta$)

- **LHC pp, p-Pb, high multiplicity events**
  - **Observed “Ridge” structure**

→ v_2 in pp, p-Pb !

2. Strangeness production is scaled by particle multiplicity (pp → p-Pb → Pb-Pb)



ALICE overview, talk at QM2018

pp → p-Pb → Pb-Pb

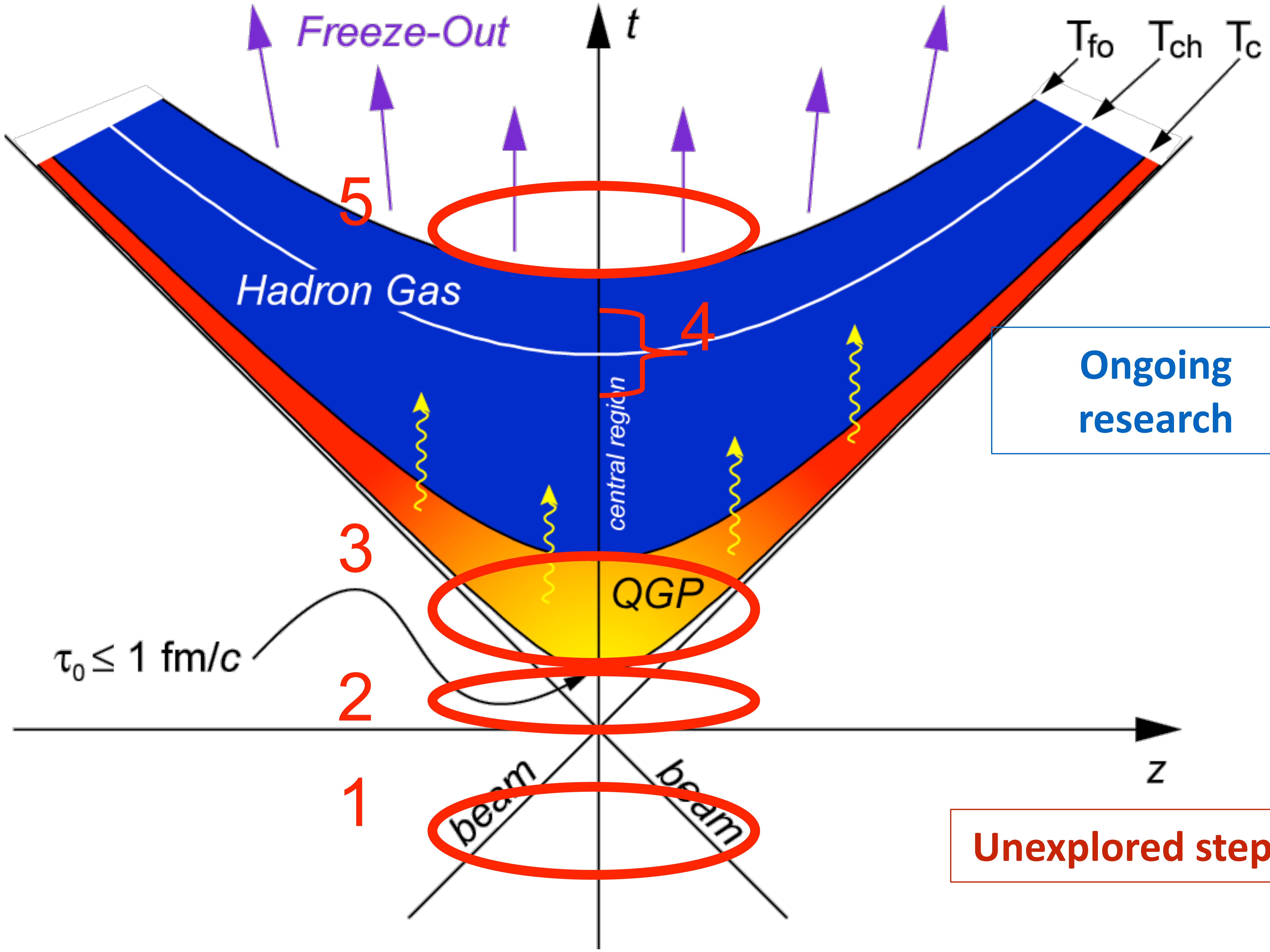
New questions

- Small droplet of QGP?
- Information of initial stages?
- Multi-parton interaction (MPI)?

<u>Still not well understood those phenomena</u>

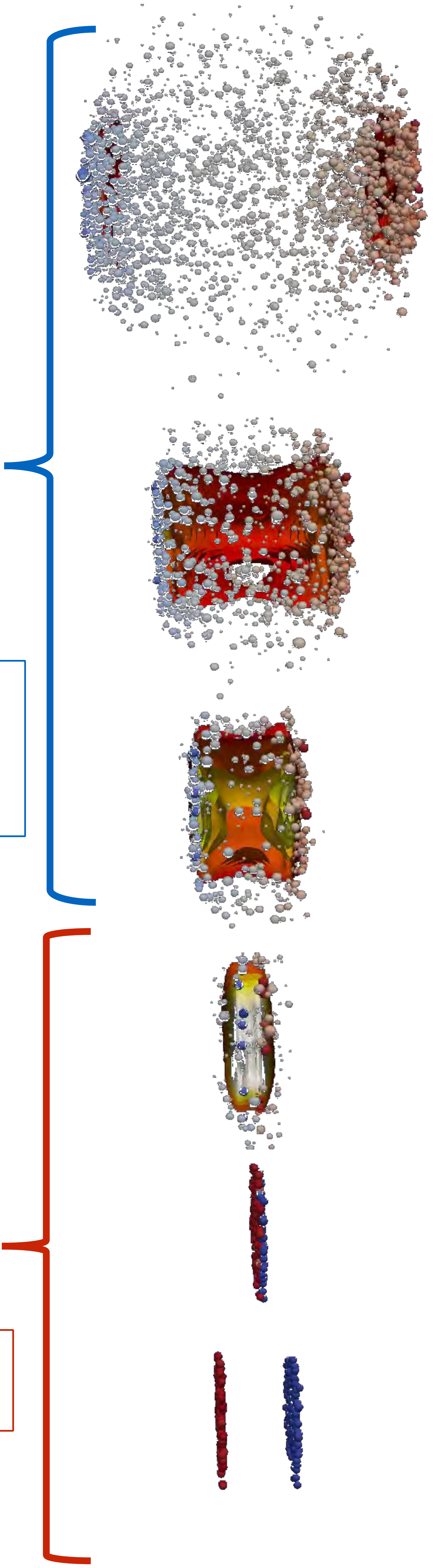
→ because of the missing steps in QGP formation→Early dynamics, non-linear, non-equilibrium physics!

Understanding of initial condition is crucial !



Ongoing research

Unexplored steps



5. Kinetic freeze-out

4. Chemical freeze-out

3. QGP (local thermal equilibrium)

2. Glasma

Collision!

1. Initial condition (CGC)

Undiscovered

arXiv:1804.06469v1, Jonah E. Bernhard

CGC and Glasma

Two unexplored steps

(1) Color Glass Condensate (CGC)

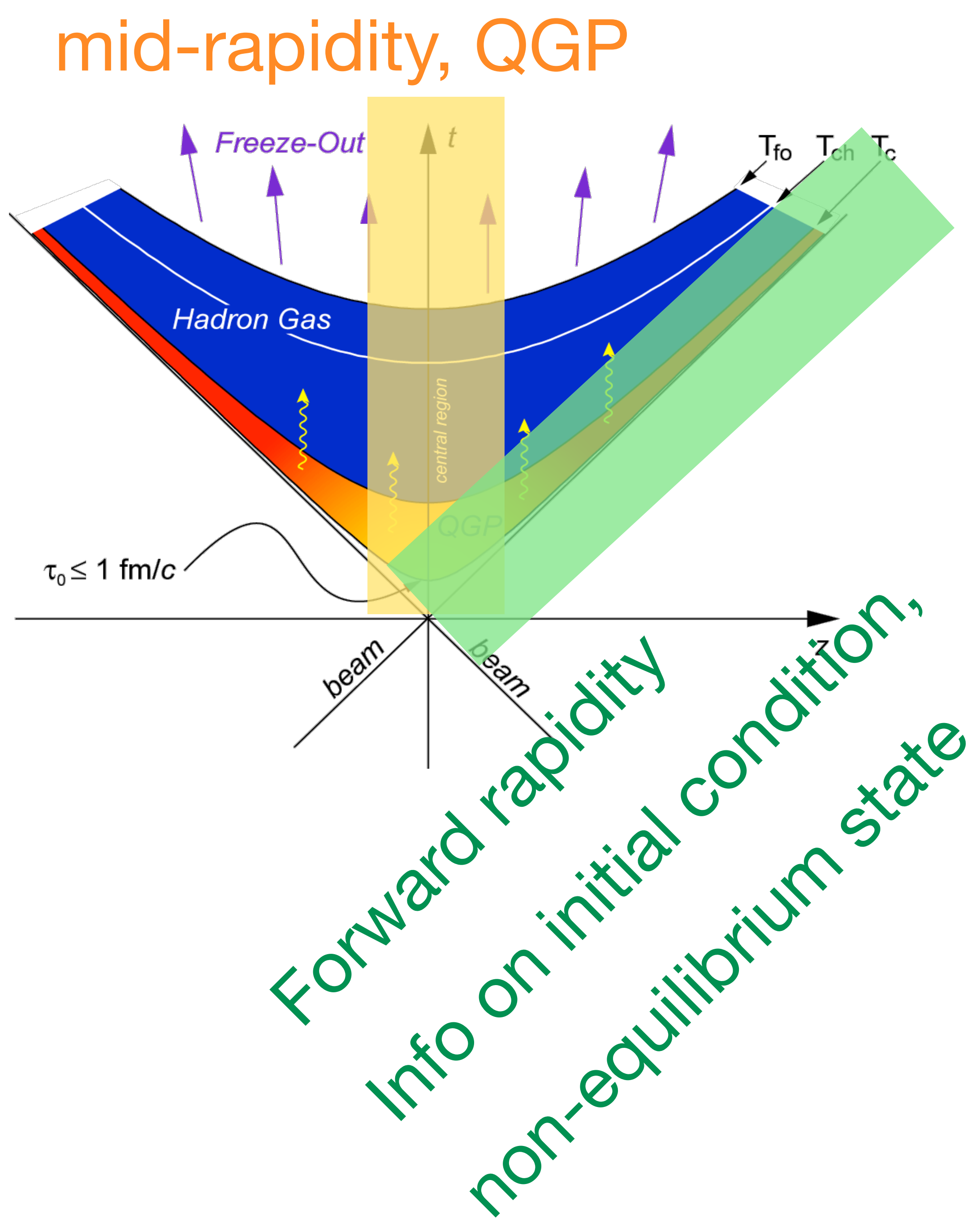
- **nonlinear** QCD evolution (gluons)
- Initial condition of QGP formation
- Undiscovered, properties are not known
- Directory connected to gluon density

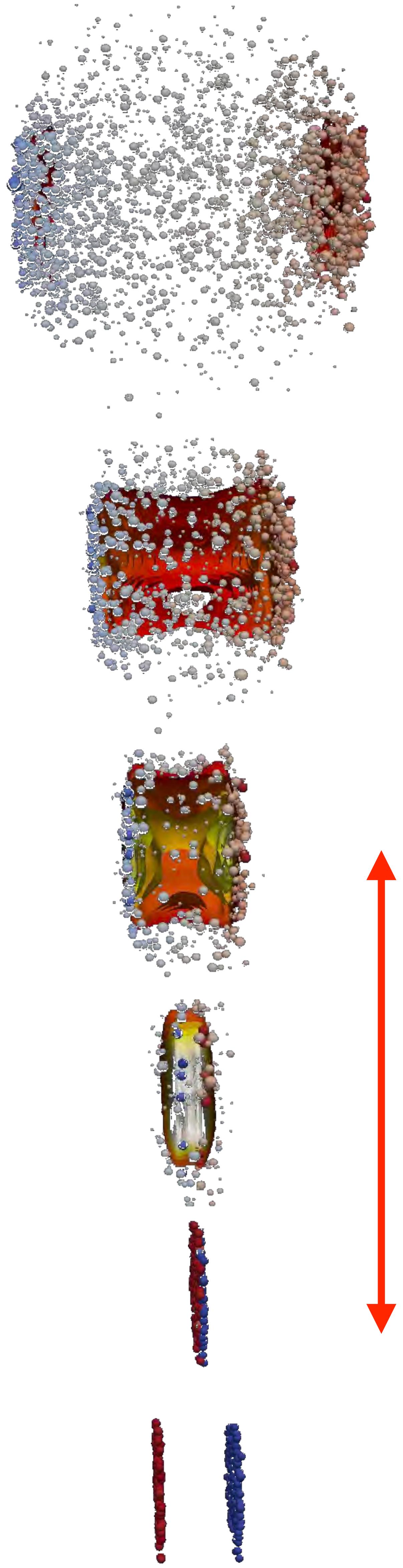
(2) Glasma

- **non-equilibrated state**
- a state between CGC and QGP
- Very short time (0.4 - 0.6 fm/c), from CGC to QGP

→Rapid thermalization problem

"Very Forward Rapidity Region"
→Access to CGC and Glasma





5. Kinetic freeze-out
4. Chemical freeze-out
3. QGP (local thermal equilibrium)

rapid thermalization: ~0.6 fm/c

2. Glasma

Non-equilibrated state for q/g

Collision!

1. Initial condition (CGC)

Nonlinear QCD evolution

arXiv:1804.06469v1, Jonah E. Bernhard

Color Glass Condensate (CGC)

proton

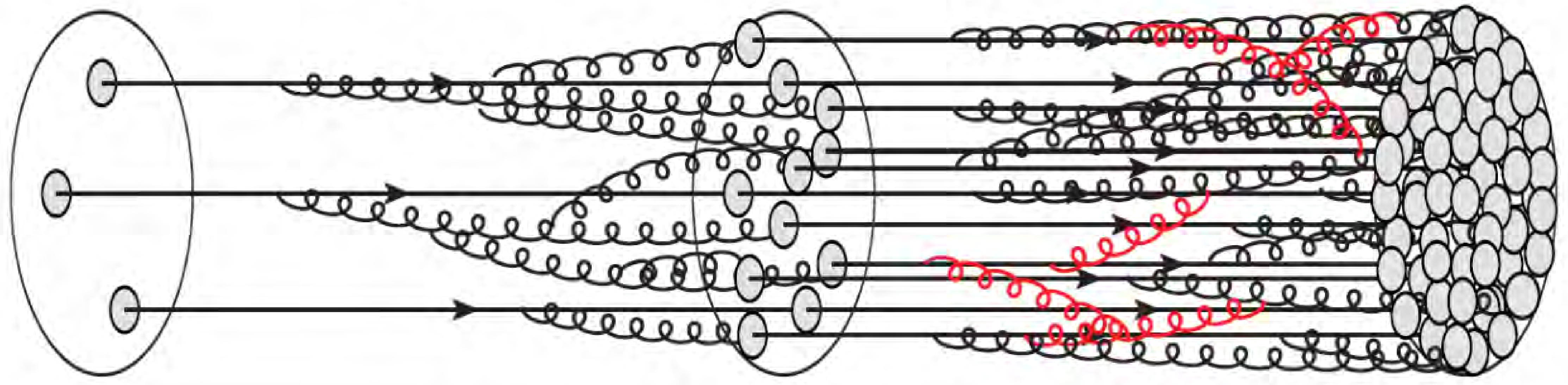
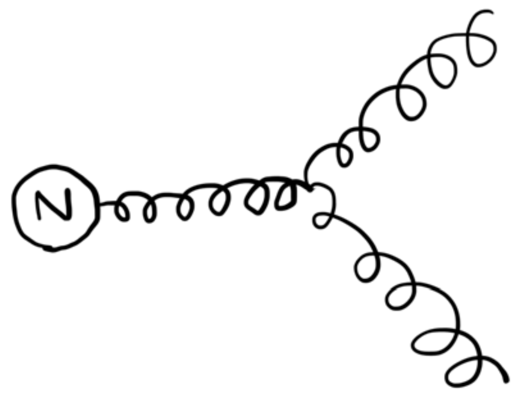


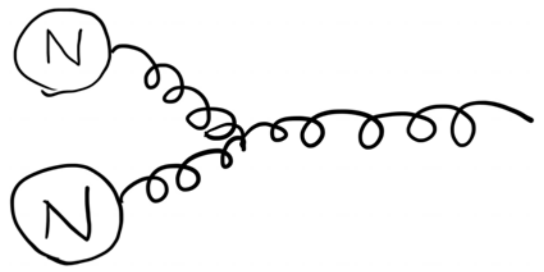
Fig. by K. Watanabe



g →gg

gluon splitting

$\propto N_g$



gg →g

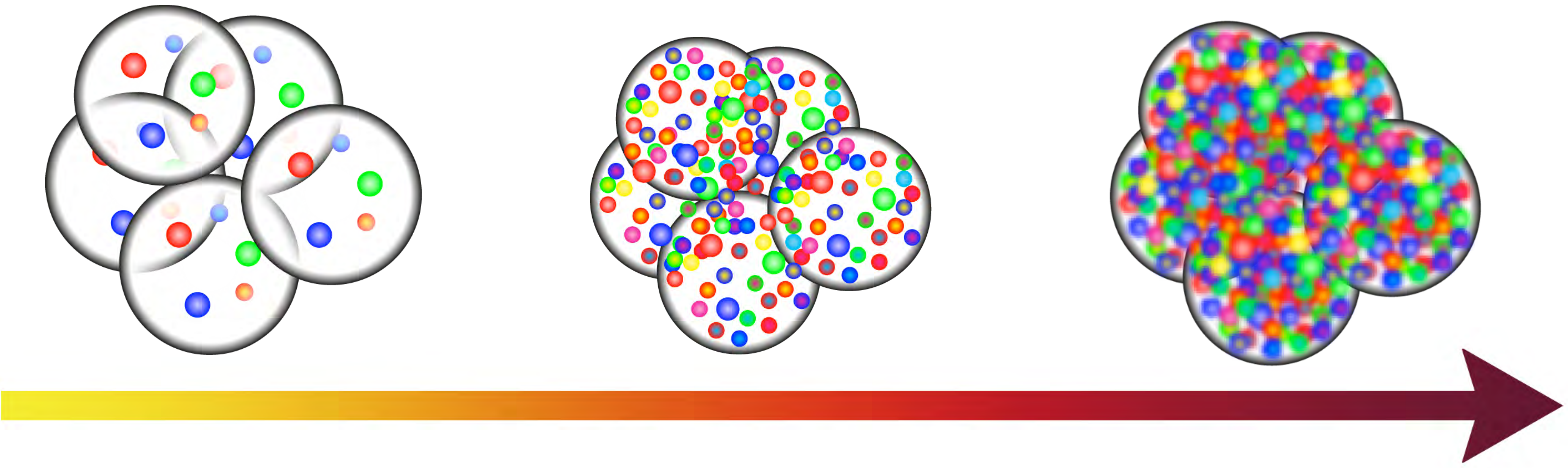
gluon merge

(non-linear effect)

$\propto N_g^2$

nucleus

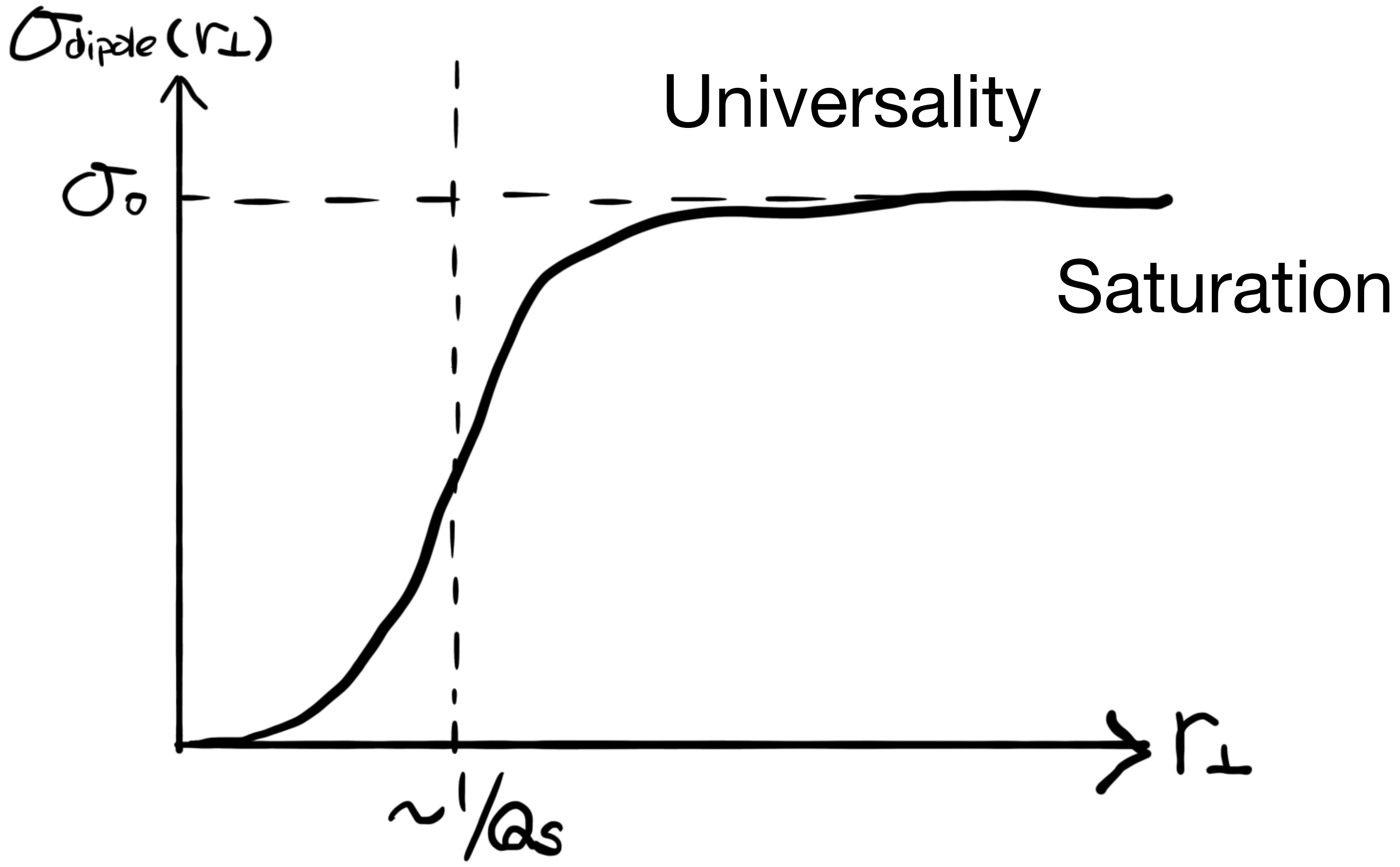
CGC!



e.g.) Logistic Eq.

$$\frac{d}{dt}N(t) = \kappa\left((N(t) - N(t)^2\right)$$

⇄ Balitsky-Kovchegov (BK) e.q.

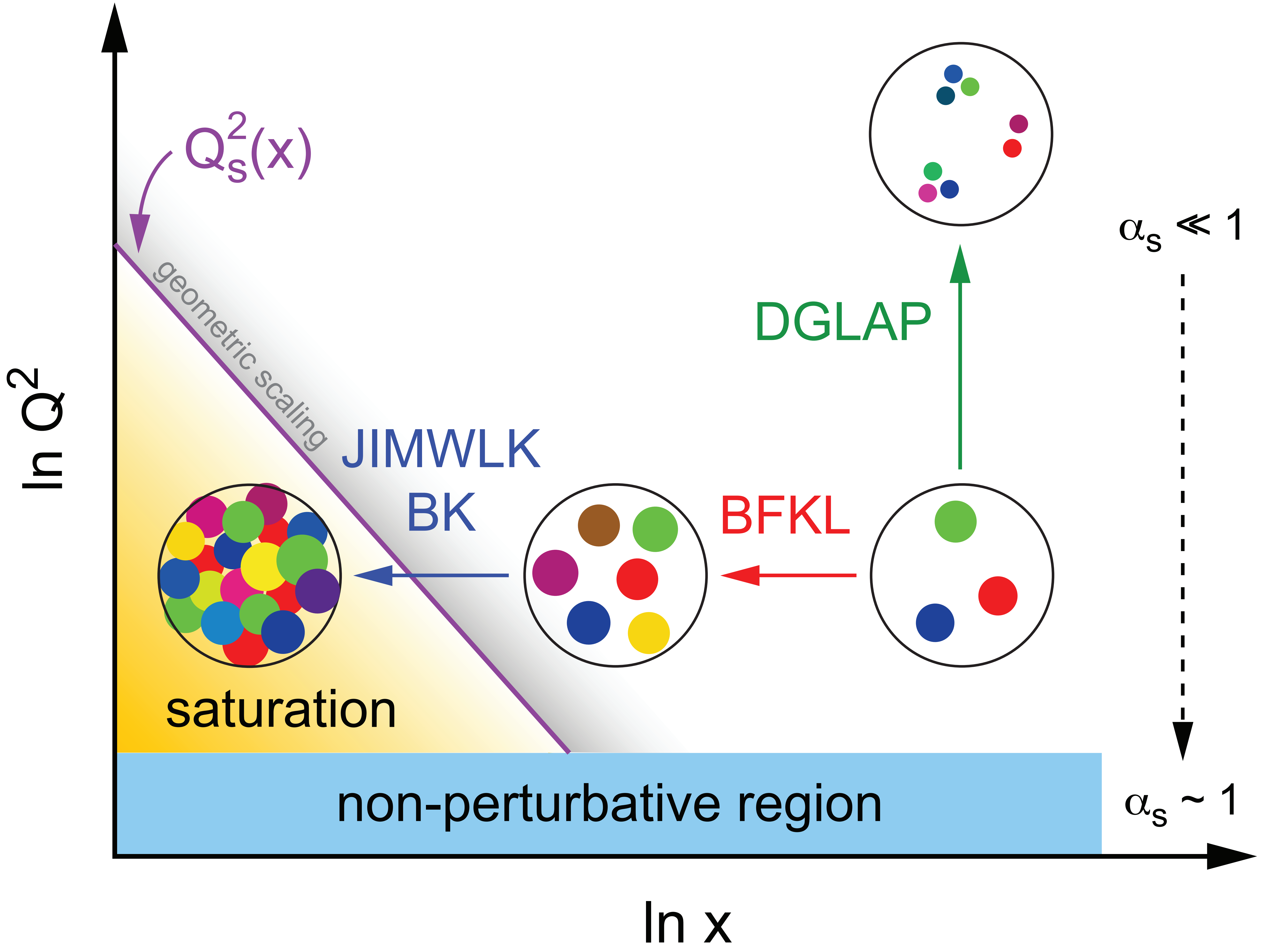


Large x
mid-rapidity
Low energy scattering

$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

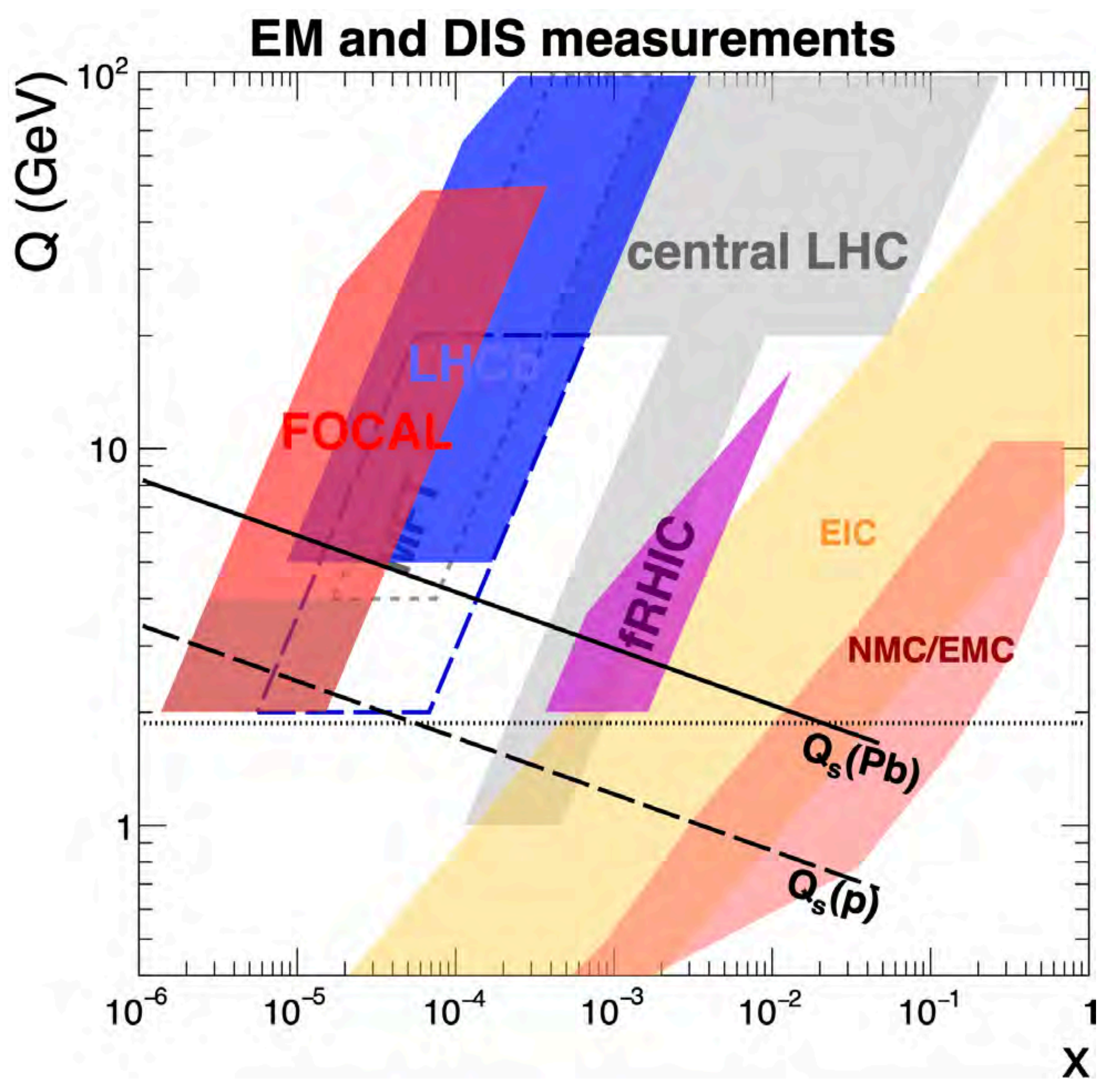
Small x
forward rapidity
High energy scattering

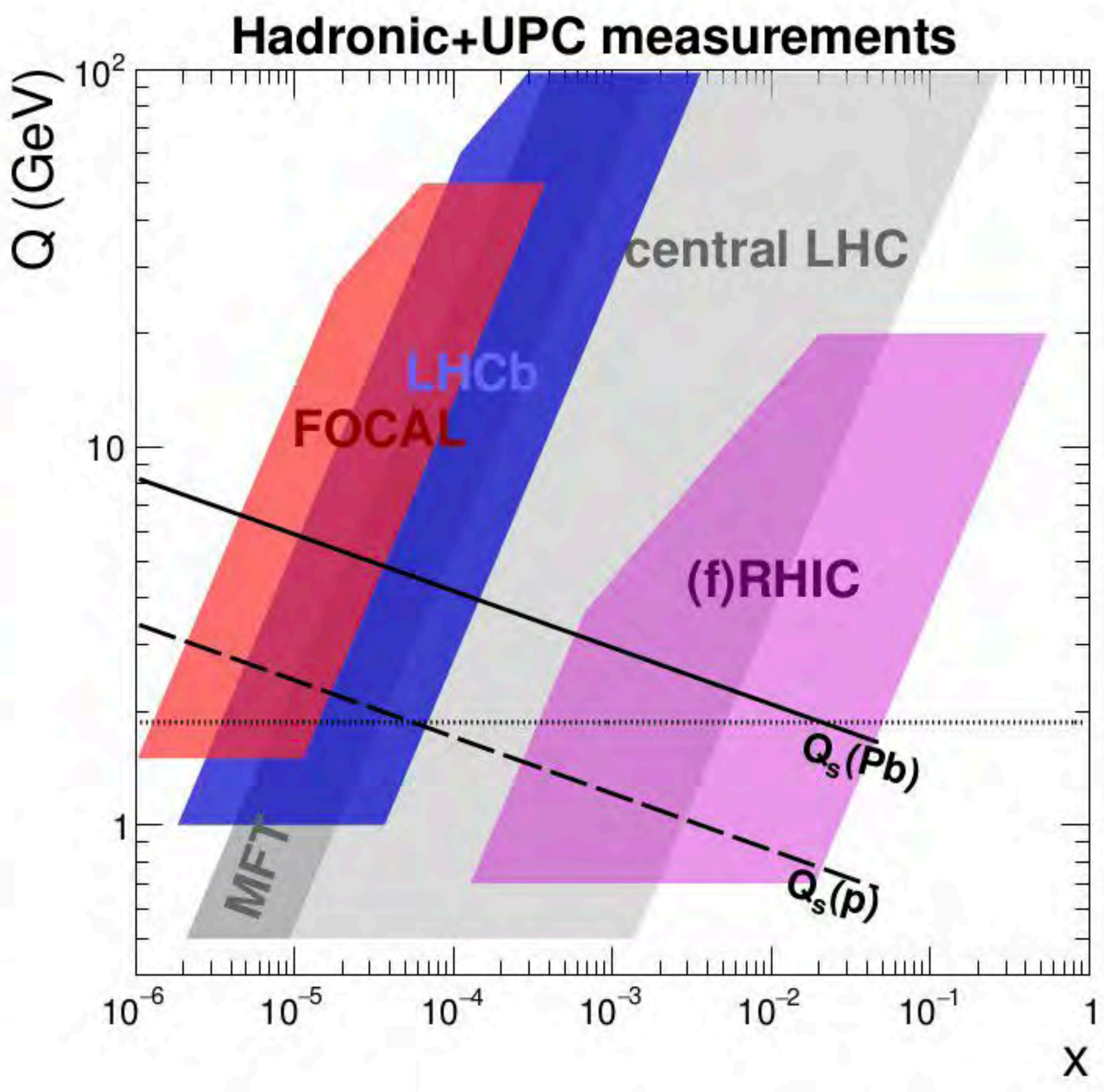
Where we can see CGC?



- **Small x and low Q** region (but $Q >> \Lambda_{QCD}$)
- **Universal picture** of internal structure of high energy hadron (universality)
- Log-Log plot !
  → **Essential to explore a wide x-Q^2 space**
- Non-linear QCD evolution
- Find CGC signal → Gluon density

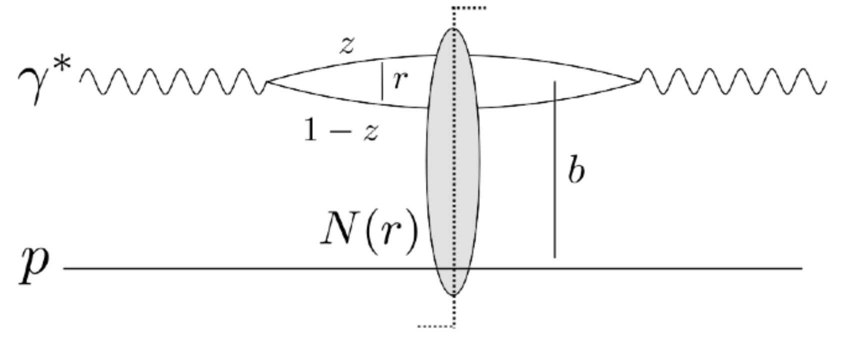
Forward LHC vs. EIC



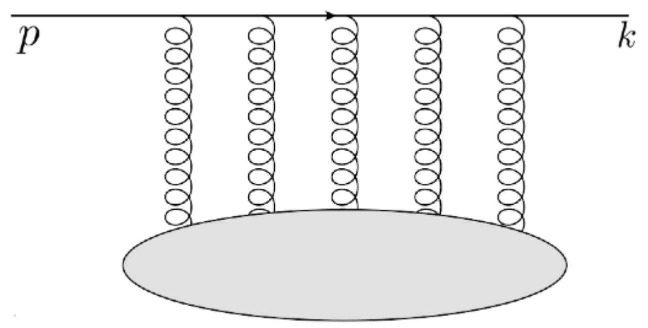


ALICE

DIS (EIC) eA



Forward pA
at high energies

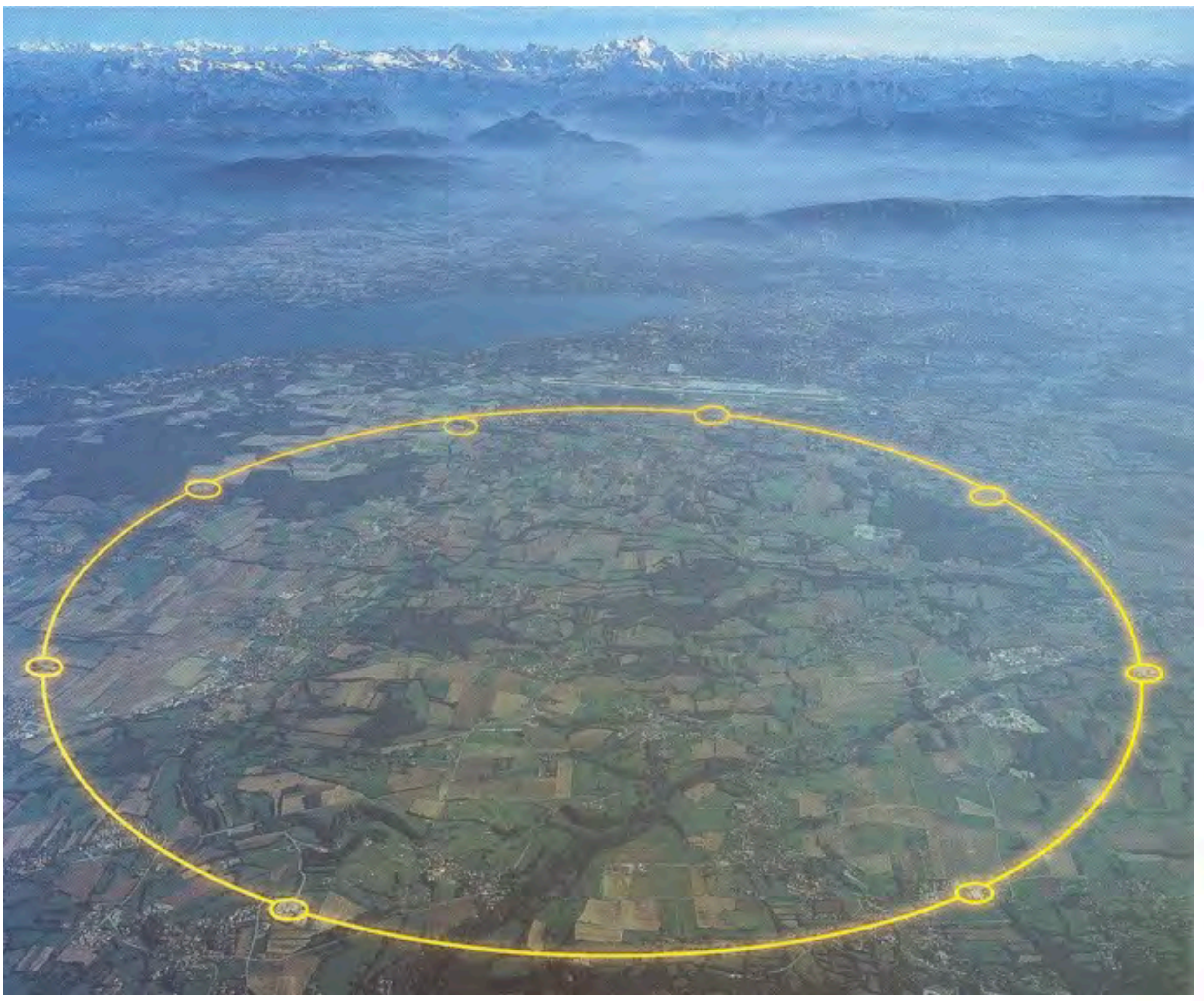


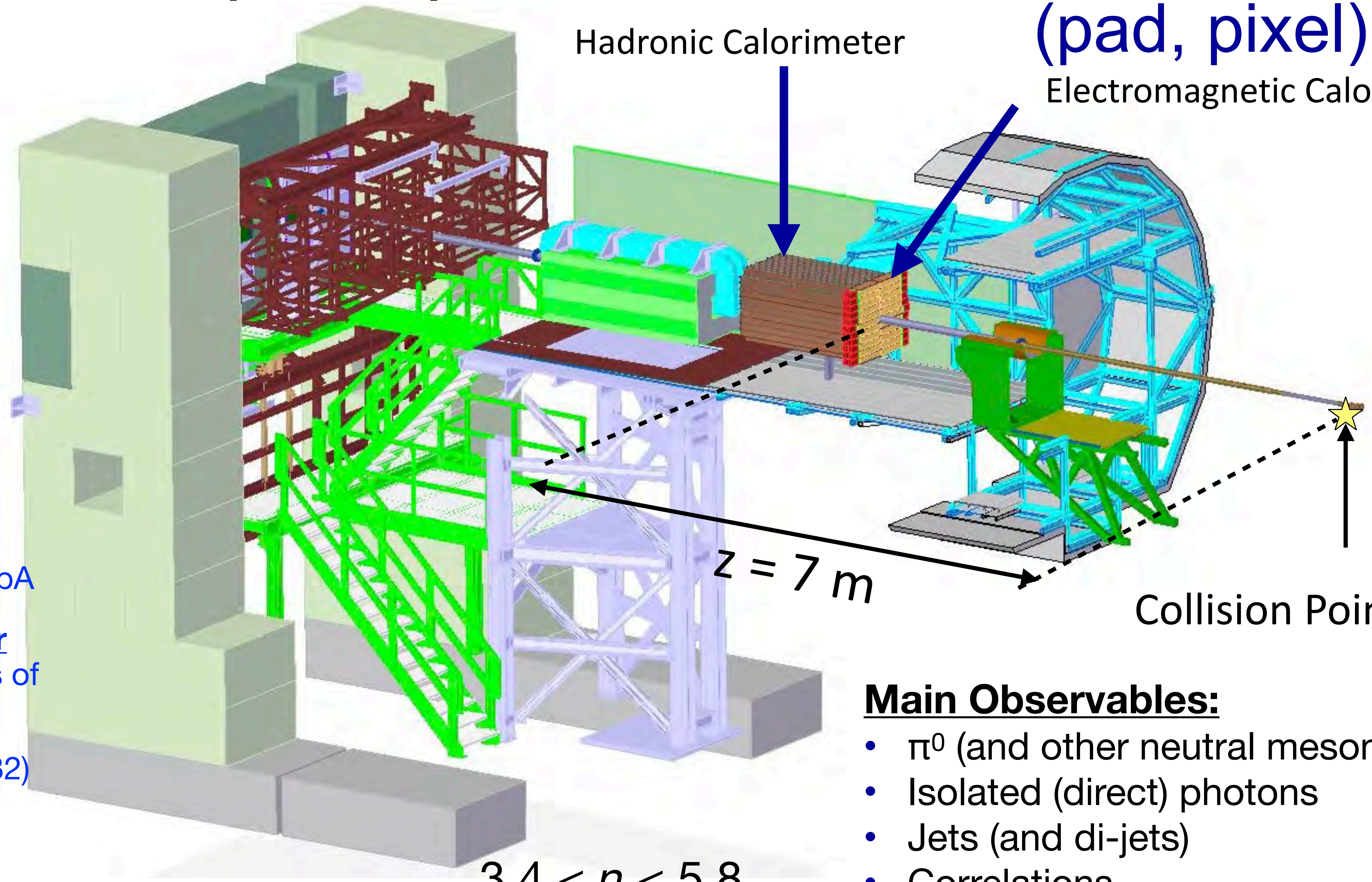
$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

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

- Study of saturation requires to study evolution of observables over large range in x at low Q^2
- Forward LHC (+RHIC) and EIC are complementary: together they provide a huge lever arm in x
- EIC: **Precision control of kinematics + polarization**
- 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
- **Multi-messenger program to test QCD universality**: does saturation provide a coherent description of all observables, and is therefore a universal description of the high gluon density regime?

Forward Calorimeter (FoCal)





- **Fo**rward **Cal**orimeter
- LHC ALICE, $\sqrt{s_{NN}}$ = 8.8 TeV, pp, pA
- Non-linear QCD evolution, **Color glass condensate**, initial stages of Quark Gluon Plasma (QGP)
- Physics in LHC Run 4 (2029-2032)
- **TDR approved by LHCC on March 2024**

$3.4 < \eta < 5.8$

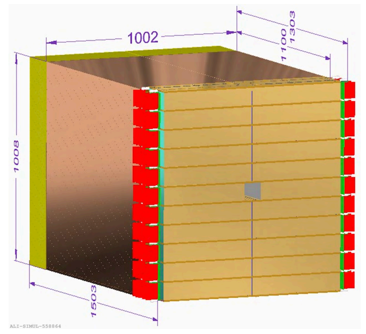
$$\eta = -\ln(\tan(\theta/2))$$

Main Observables:

- π^0 (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- Correlations
- J/Ψ in UPC

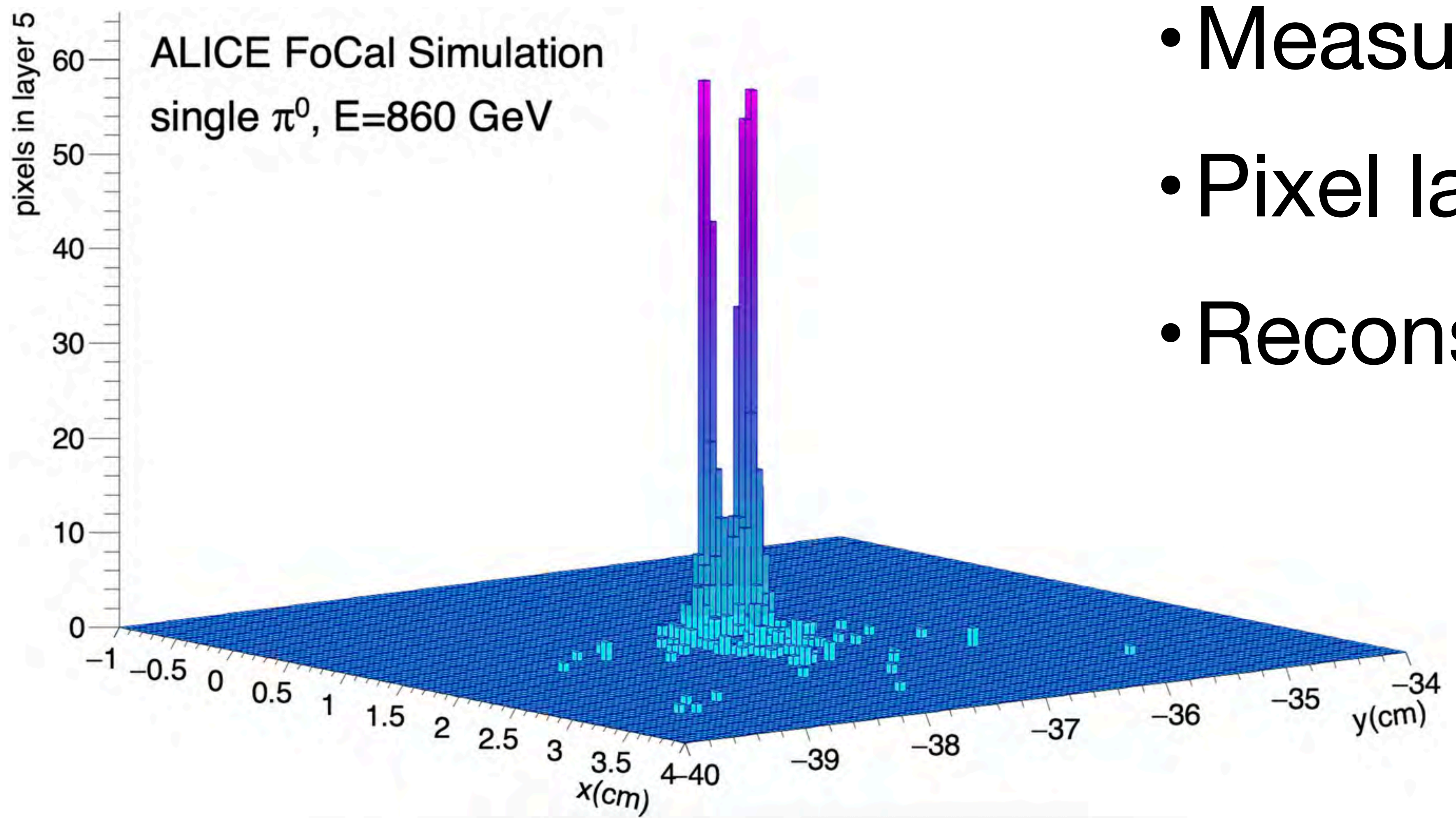
FoCal (LoI) : CERN-LHCC-2020-009

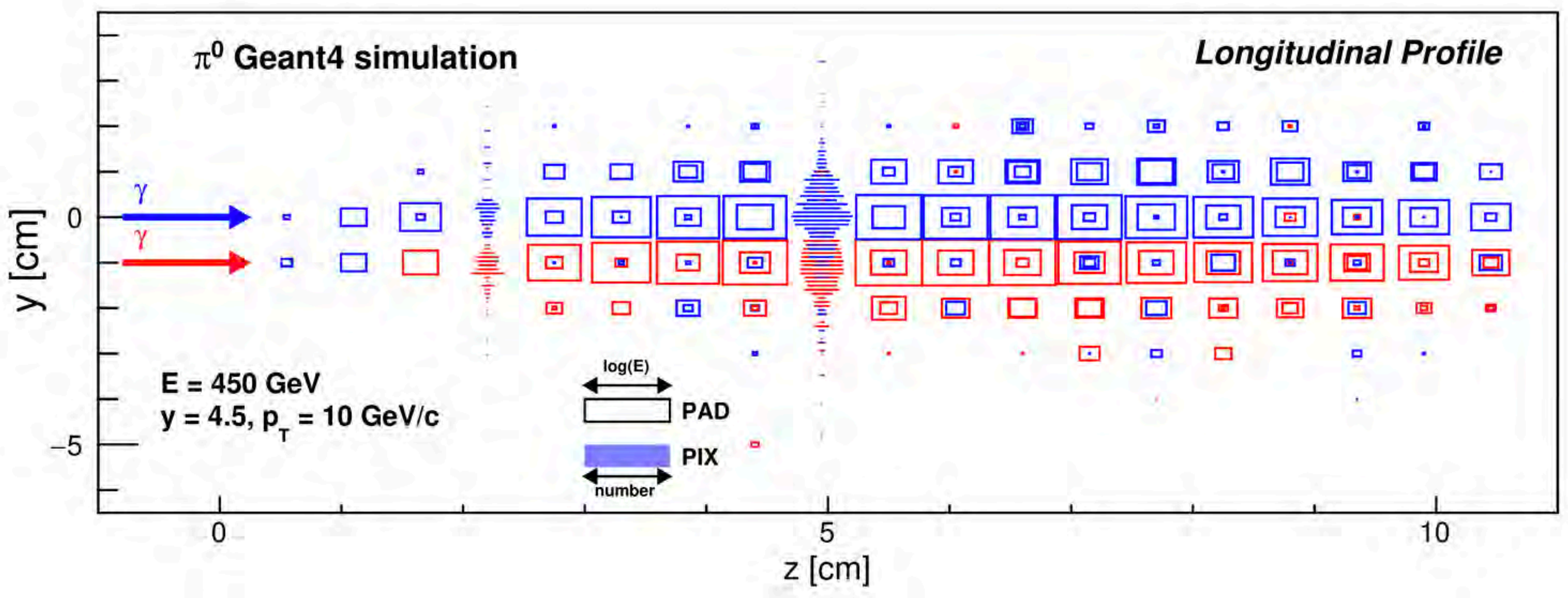
FoCal (TDR) : CERN-LHCC-2024-004

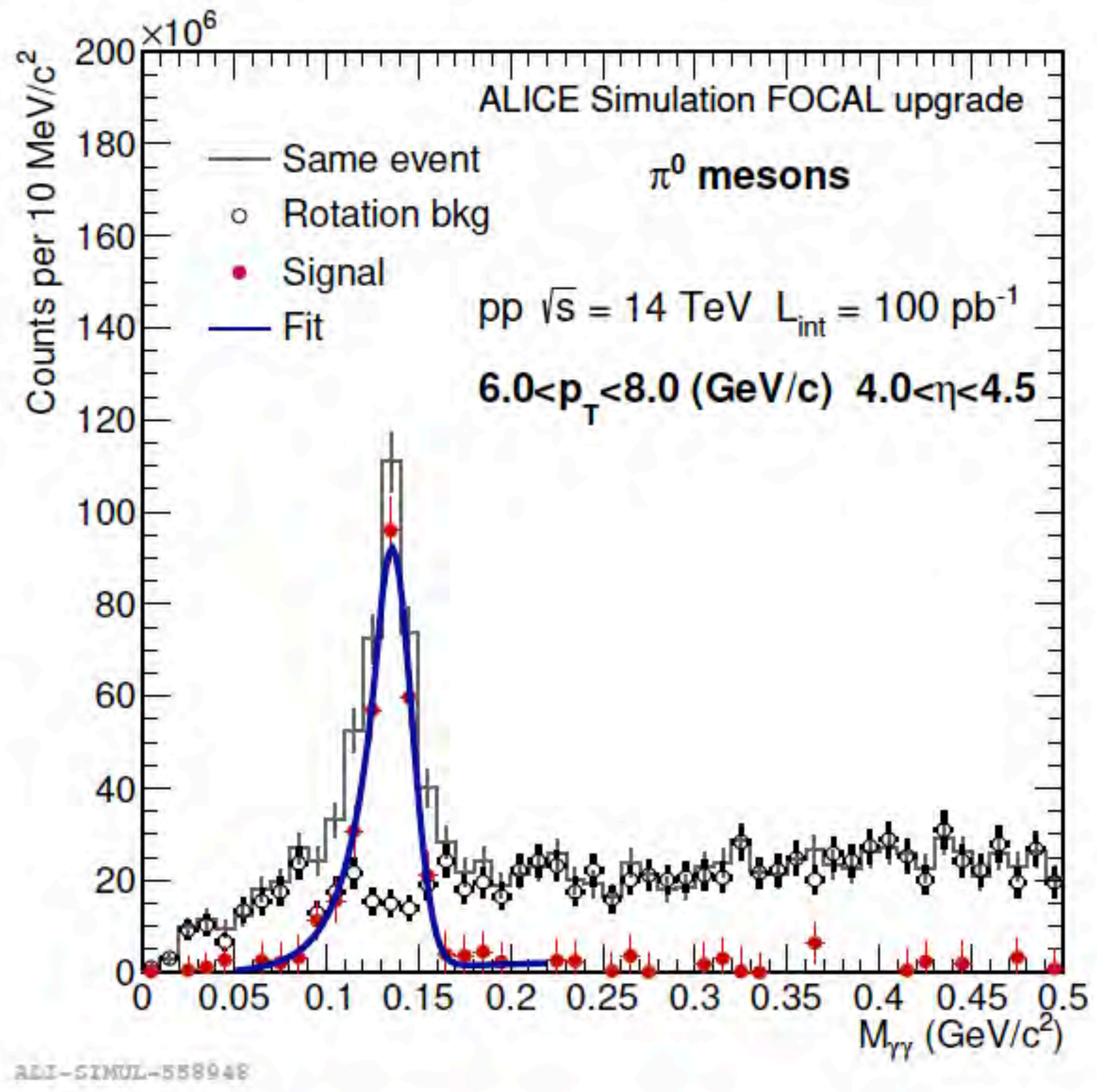


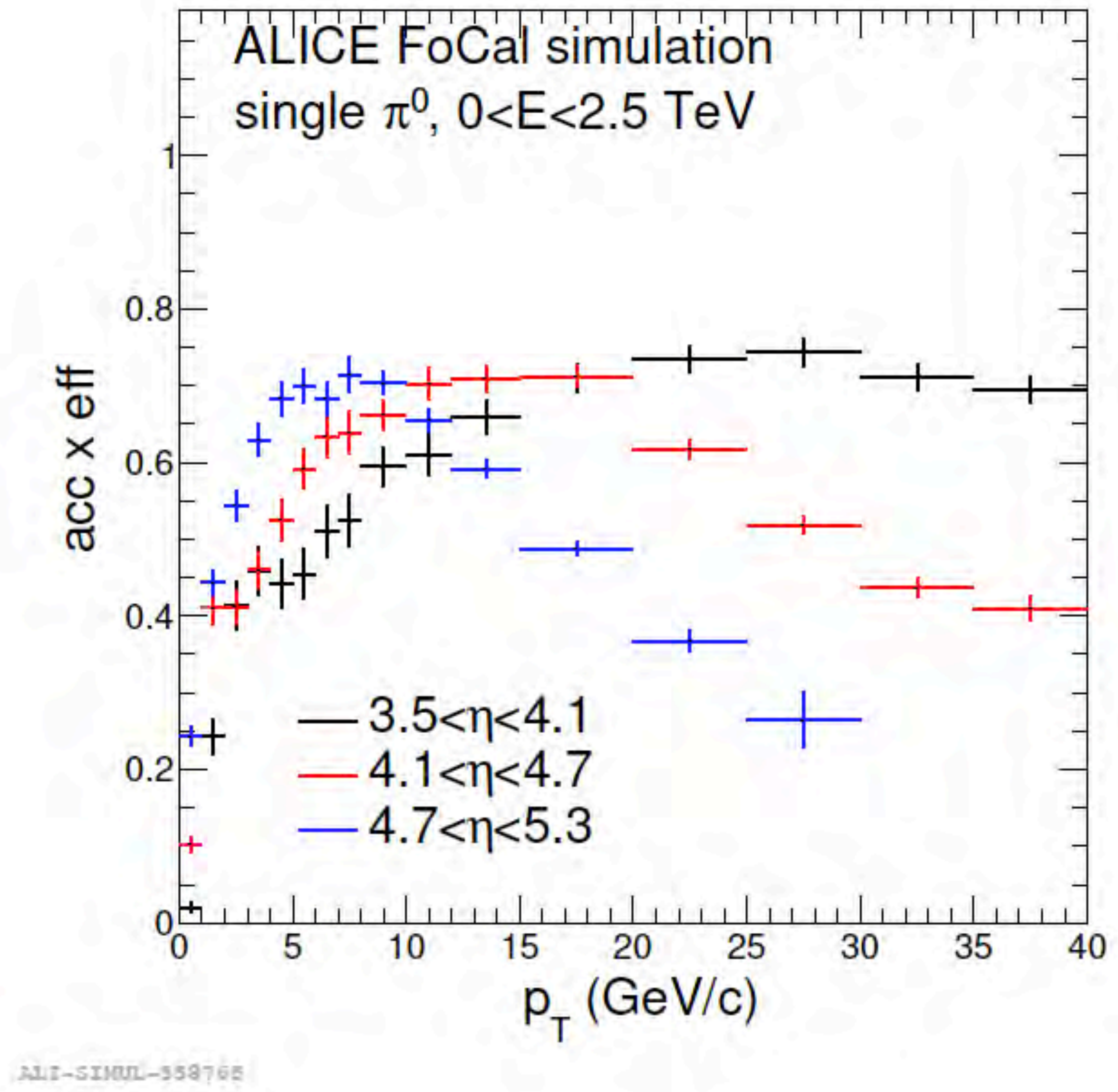
Neutral mesons in FoCal

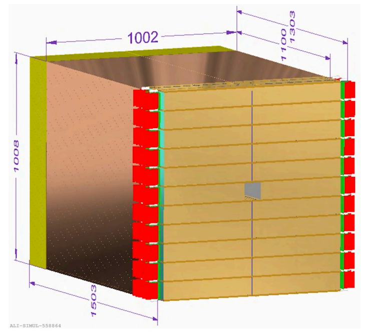
- Measurement of neutral mesons, e.g. π^0, η and ω up to E = 2 TeV
- Pixel layers allow measuring photons with less than d = 5 mm separation
- Reconstruction efficiency of up to 75%











Prompt photon identification

Isolation
Restrict p_T within cone of $R = 0.4$

+

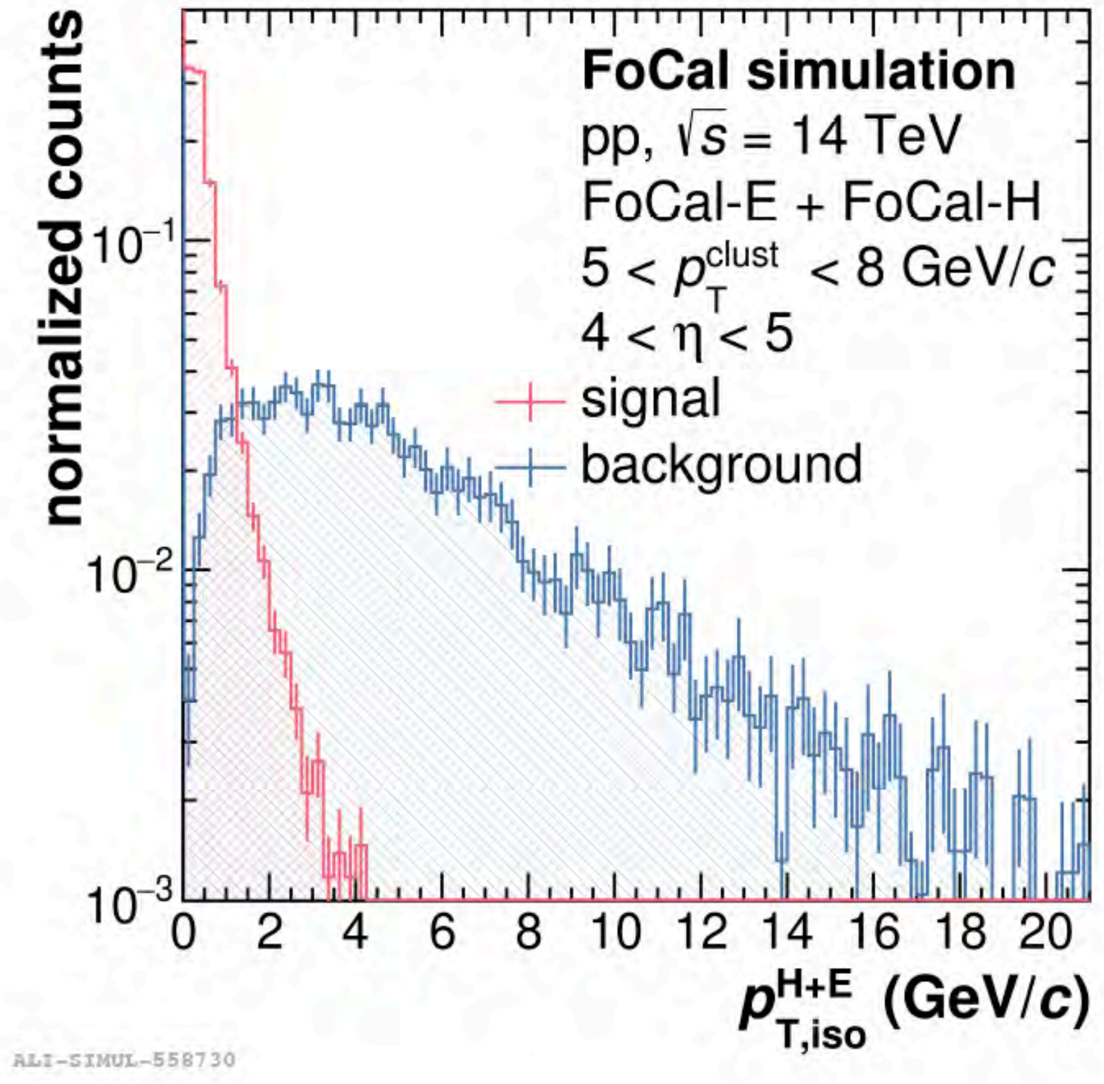
Shower shape
Restrict shower ellipse elongation to reduce merged π^0 clusters

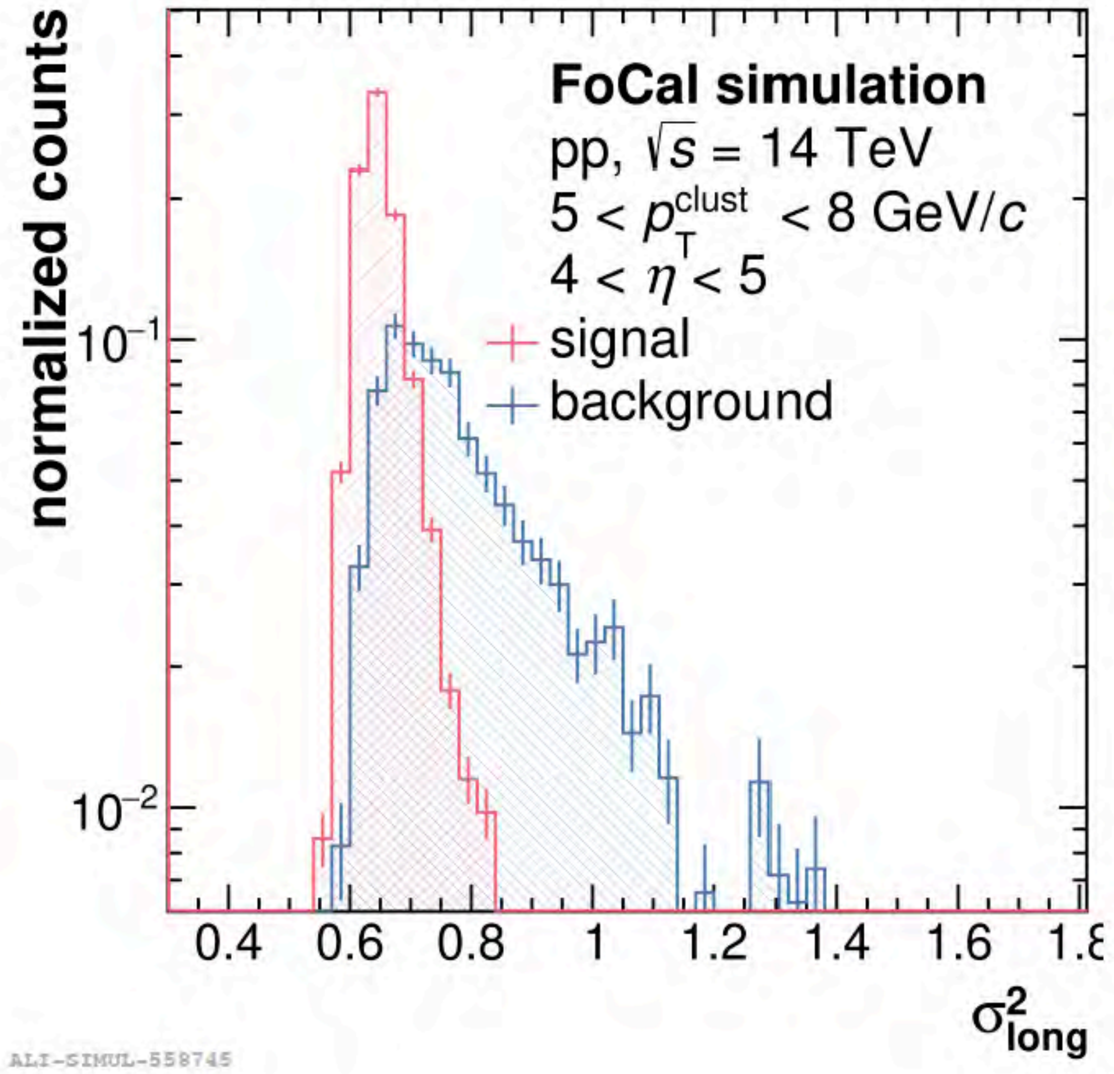
+

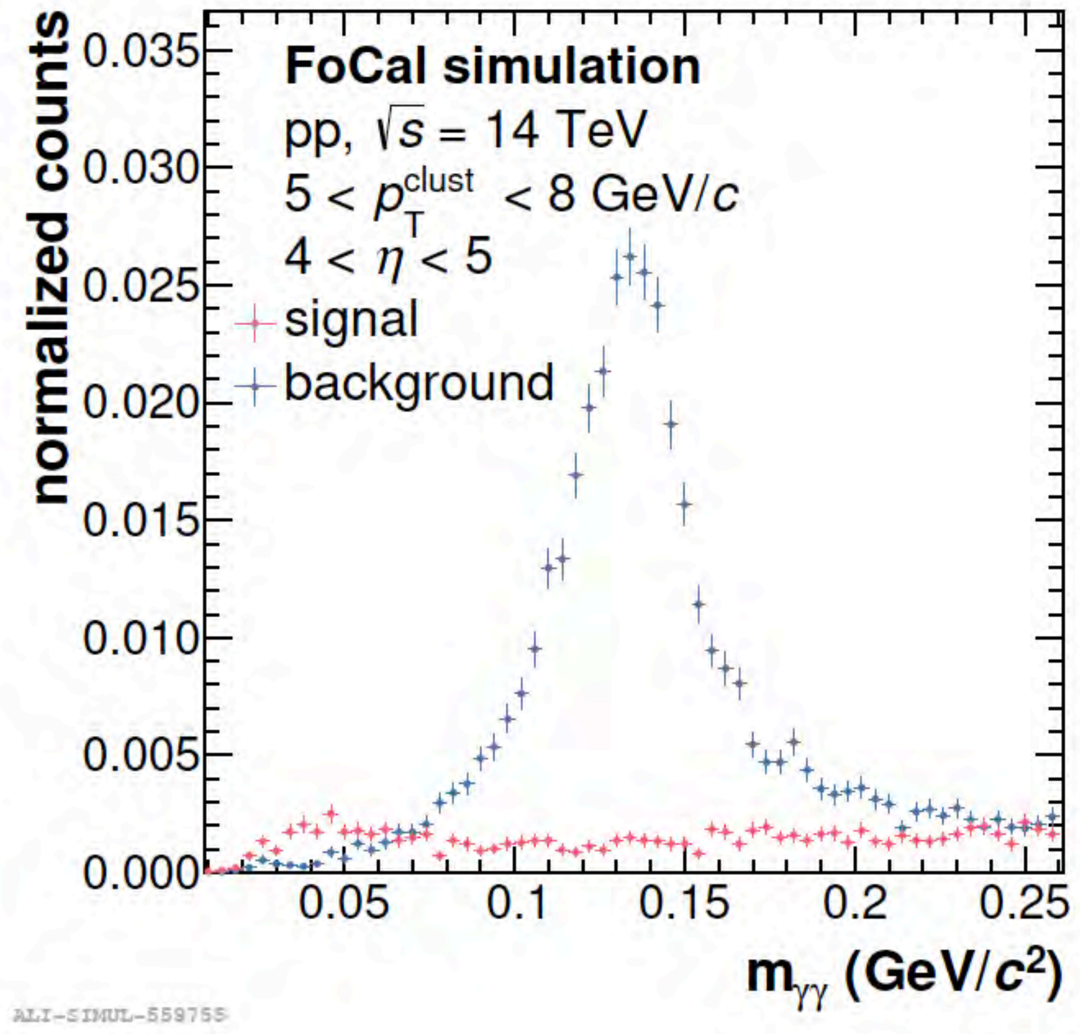
π^0 tagging
Tag decay photons according to inv. mass of cluster pairs

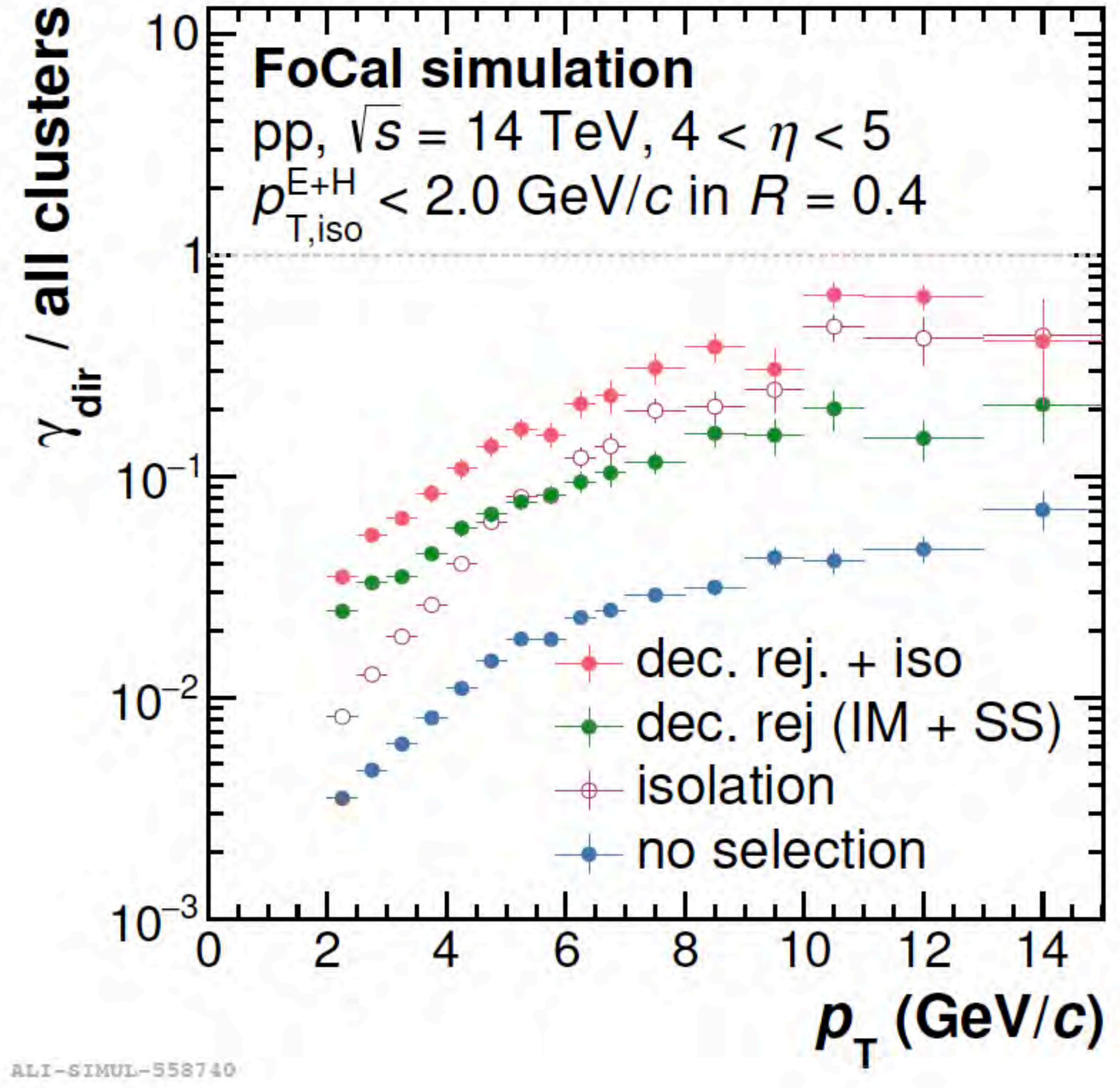
=

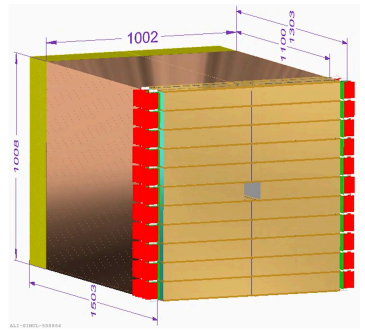
Signal fraction
Selections increase signal fraction $\times 11$





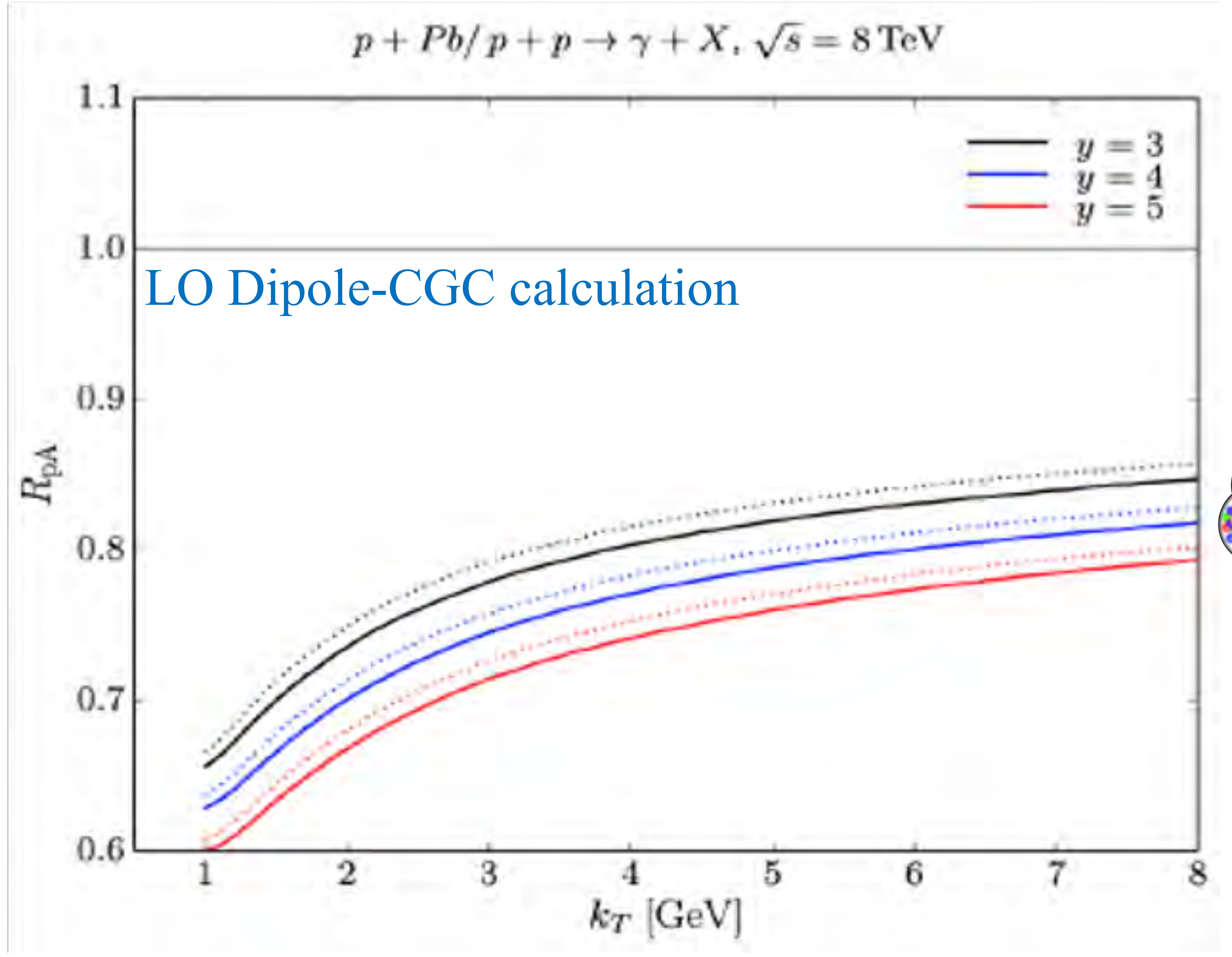


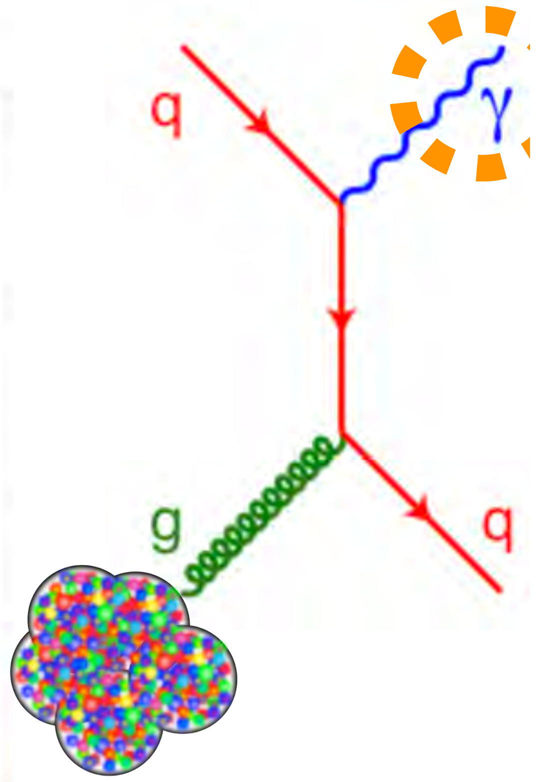




Saturation signal in FoCal (1)

R_{pPb}: forward γ

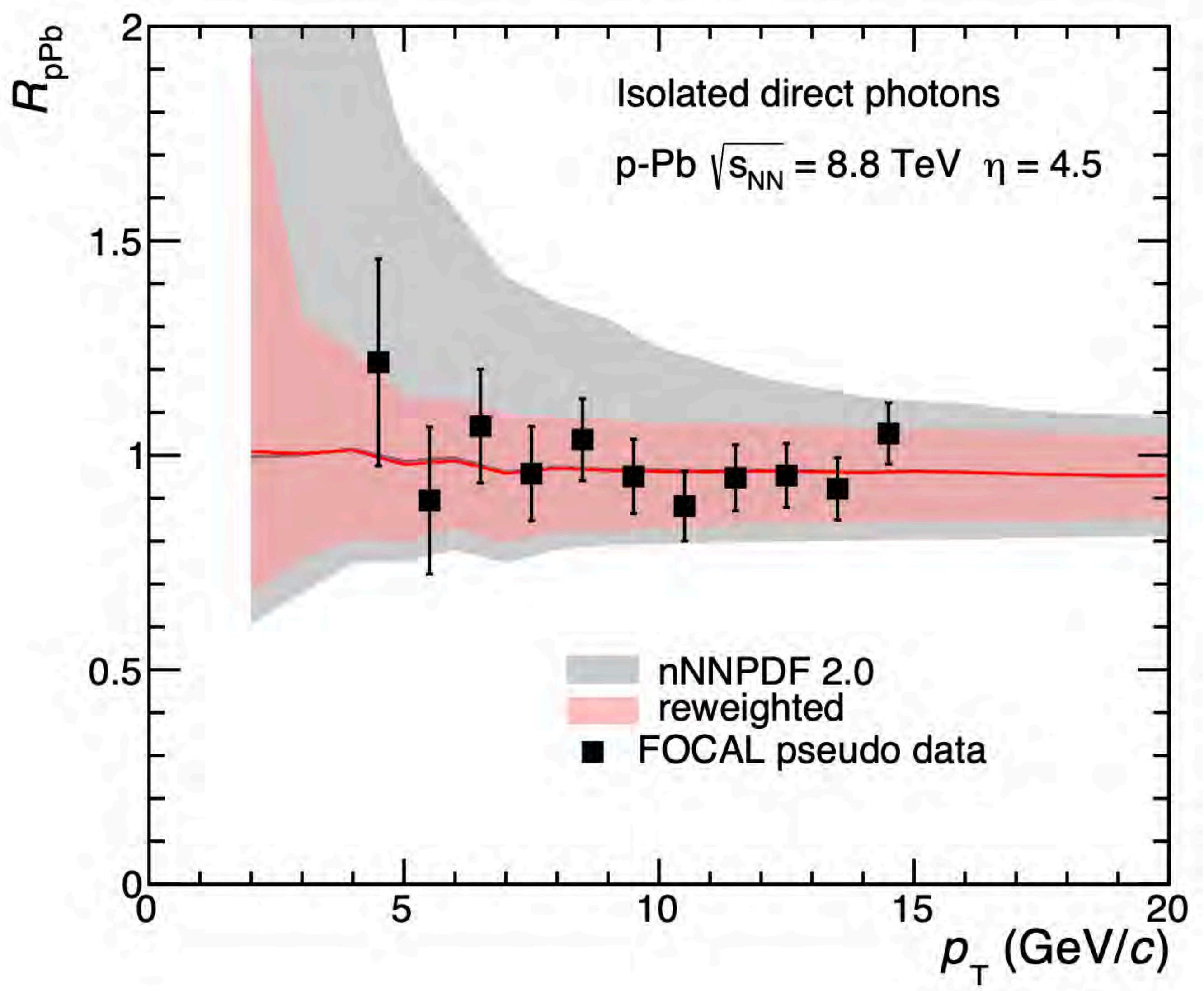


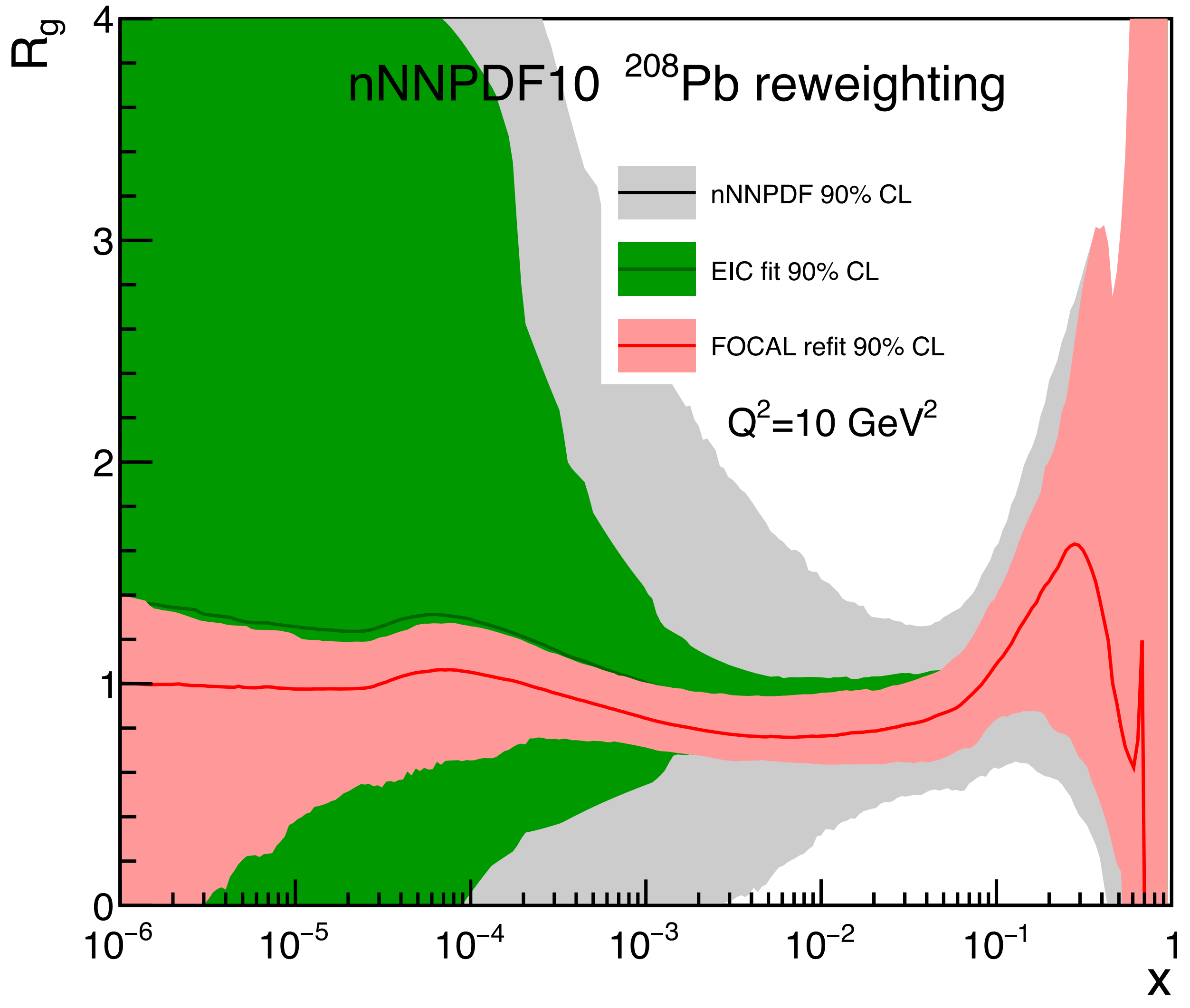


- Large suppression at low p_T for isolated γ

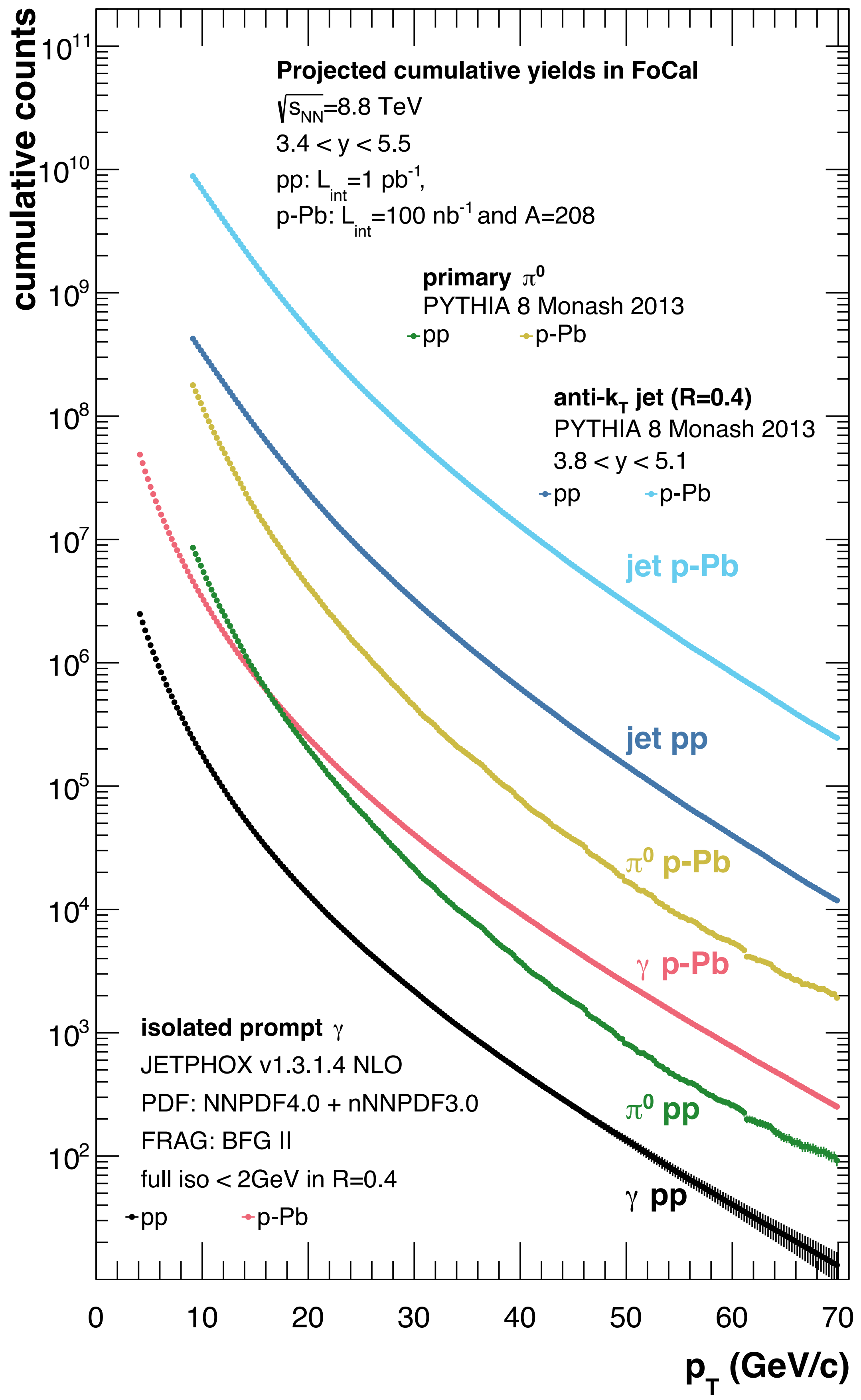
  Isolated γ: qg → qγ ; $k_T \sim Q_{sat}$

Ducloué, Lappi, and Mäntysaari, Phys. Rev. D97 (2018) 054023



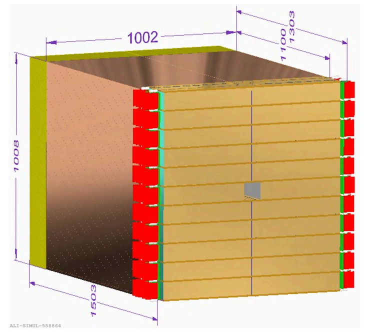


Expected yields in FoCal (Run-4)



- pp at $\sqrt{s}$=8.8 TeV: 1 week, $\mathcal{L}$=4 pb^{-1};
- p–Pb at $\sqrt{s}$=8.8 TeV: 3 weeks, $\mathcal{L}$=300 nb^{-1};
- Pb–Pb at $\sqrt{s_{NN}}$=5.02 TeV: 3 months; $\mathcal{L}$=7 nb^{-1};
- pp at $\sqrt{s}$=14 TeV: ≈ 18 months, $\mathcal{L}$=150 pb^{-1};

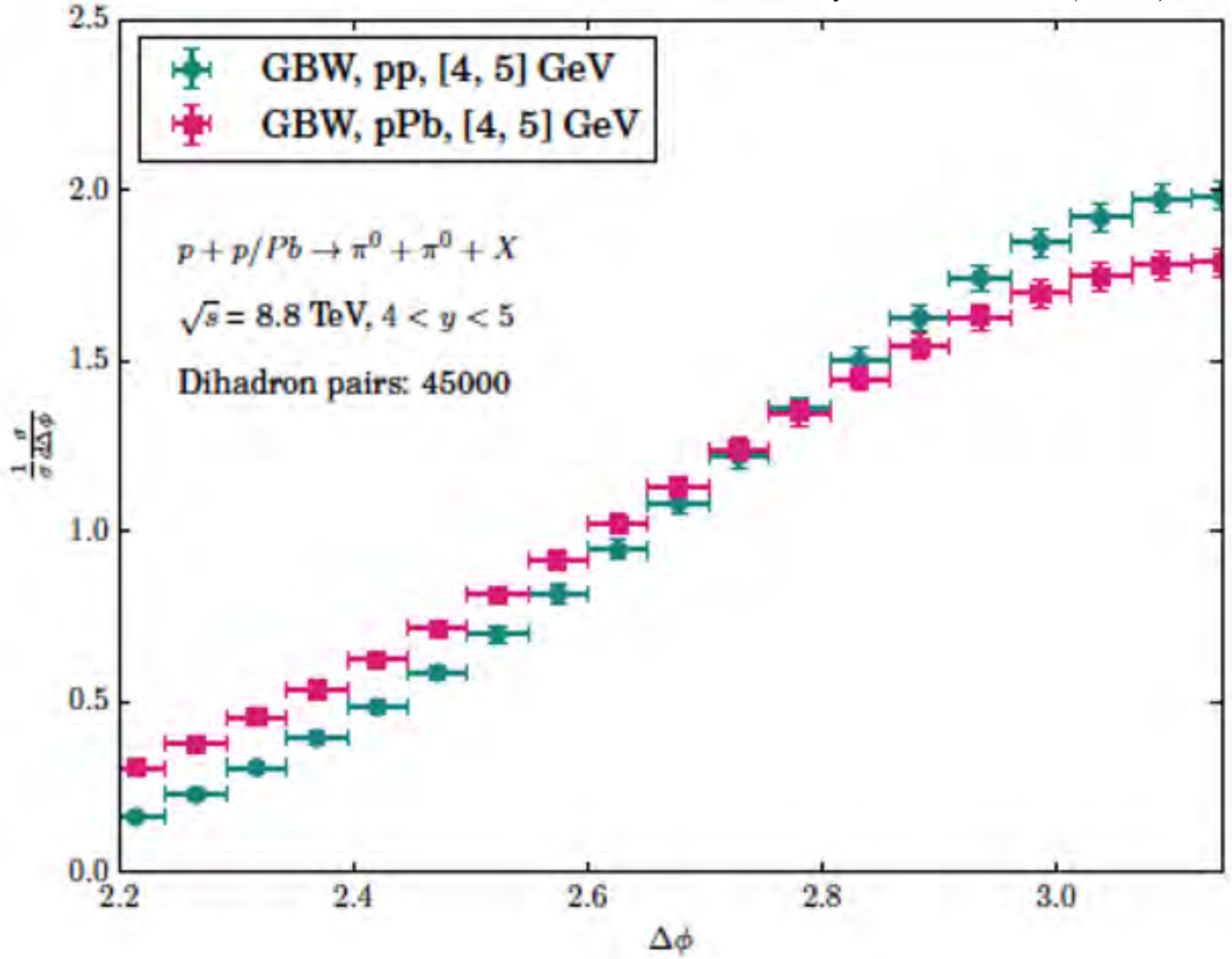
- Expected gluon saturation (CGC) in small-x, not yet clear evidence
- Excellent probe: isolated photons from quark-gluon Compton scattering



Saturation signal in FoCal (2)

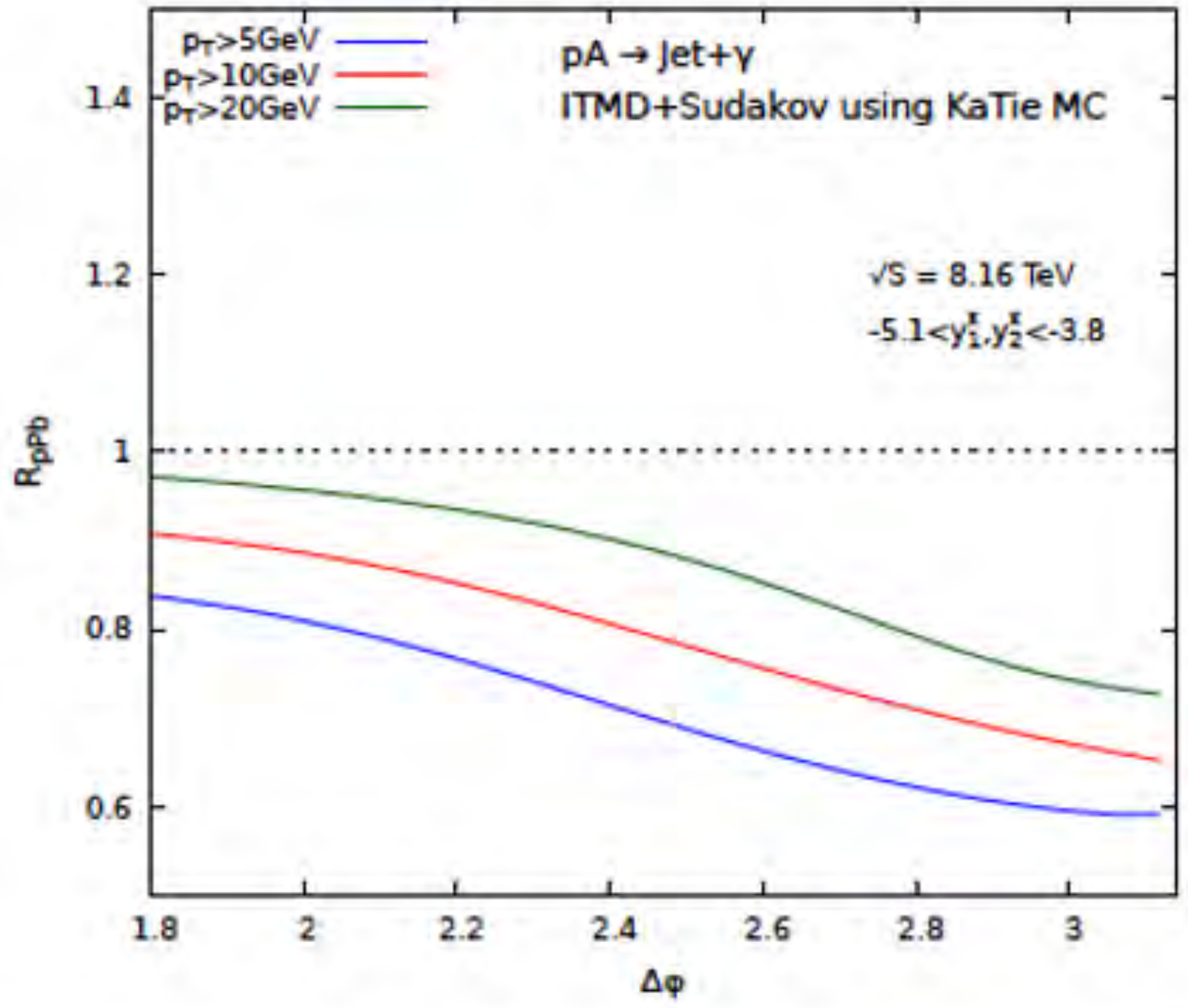
Di-hadron Correlations

Stasto, Wei, Xiao, and Yuan, Phys. Lett. B784 (2018) 301

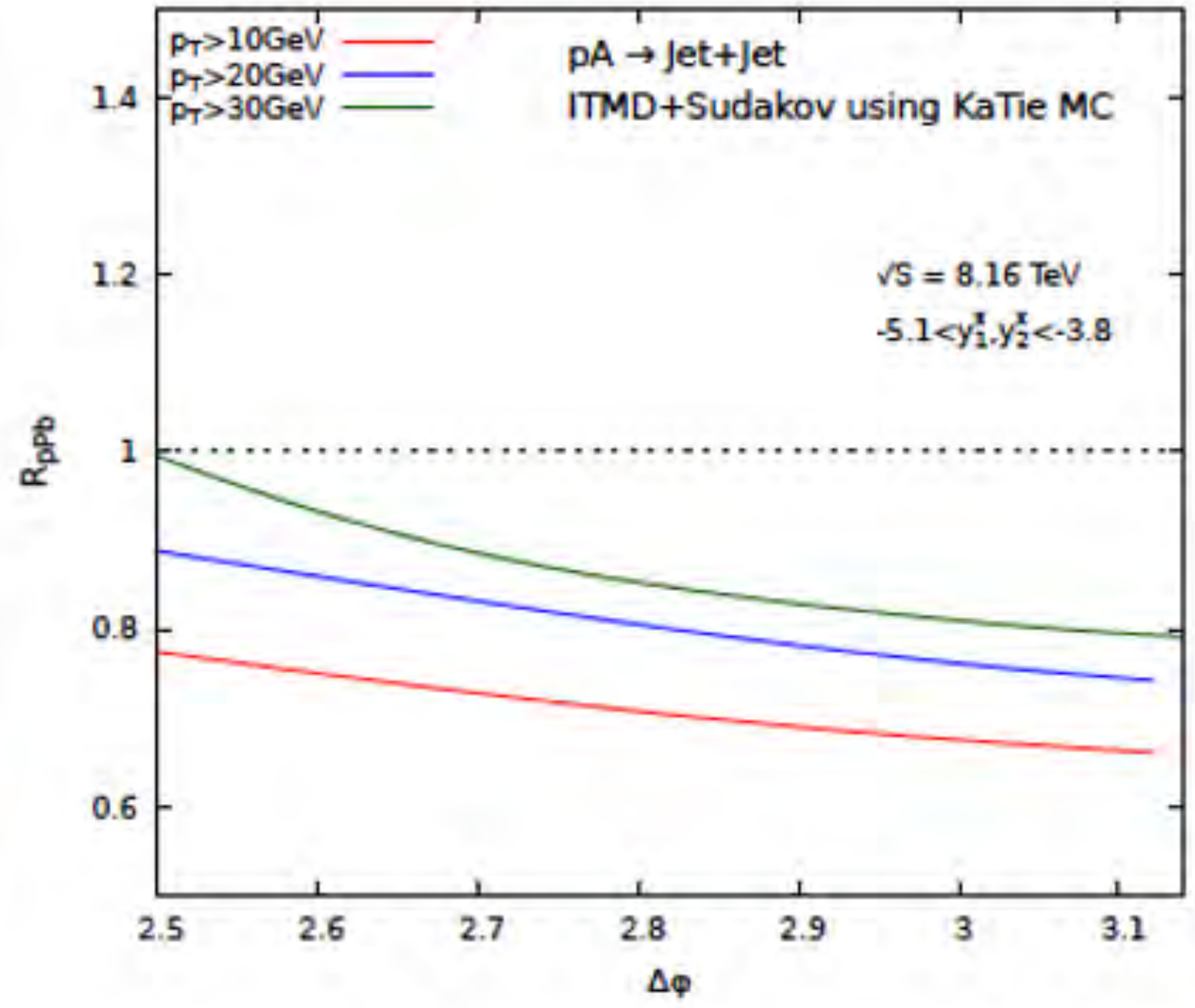


Dilute-dense LO + Sudakov
probes quadrupole operator

Forward γ+jet



Forward di-jet

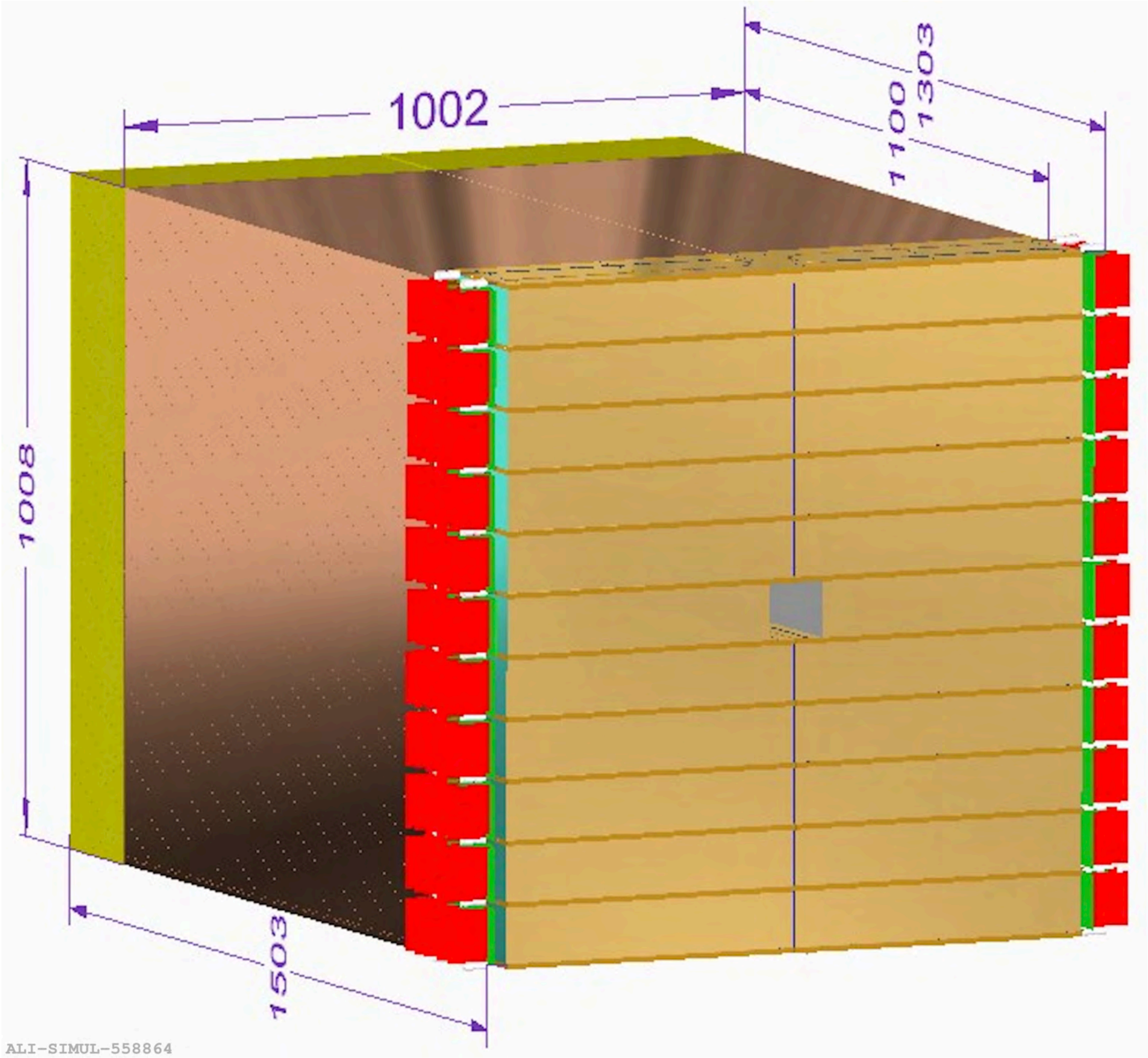


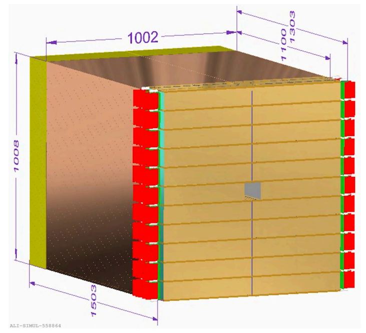
- γ+jet: dipole TMD gluon distribution
- di-jet: multiple TMD distributions

- Experimental challenge to see an effect of CGC in Δϕ width?
- Theory: NLO cal. is needed

- γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$ (sensitive to saturation)
- changing k_T (p_T) → exploring non-linear QCD evolution in wide kinematic coverage of x-Q^2 by FoCal

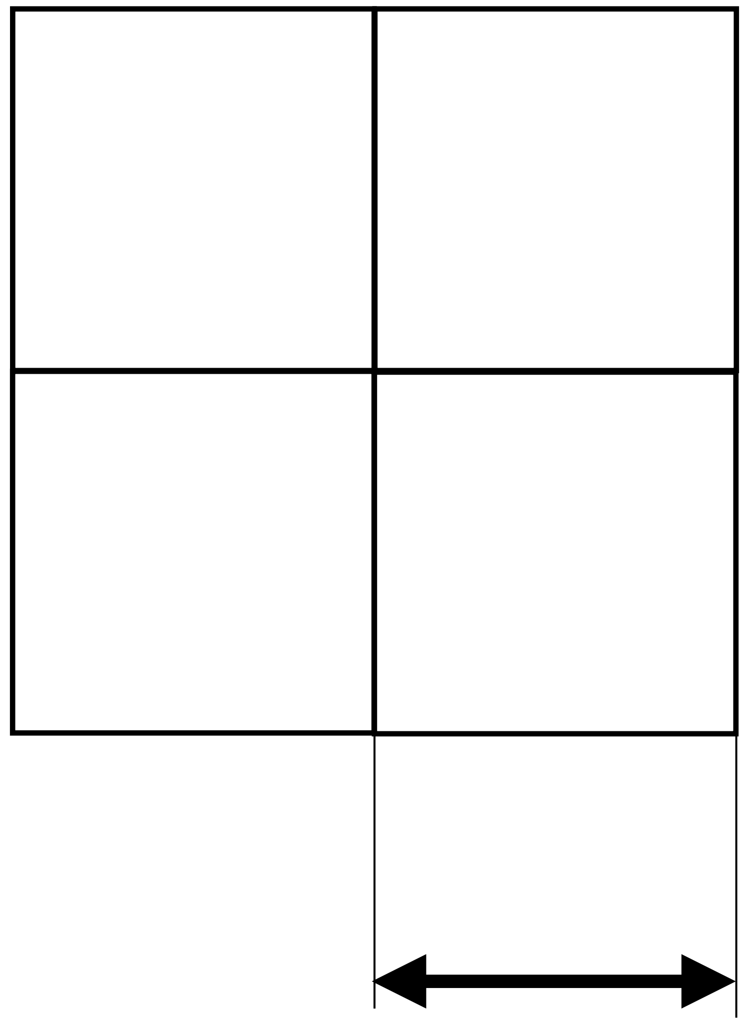
ALICE FoCal detector





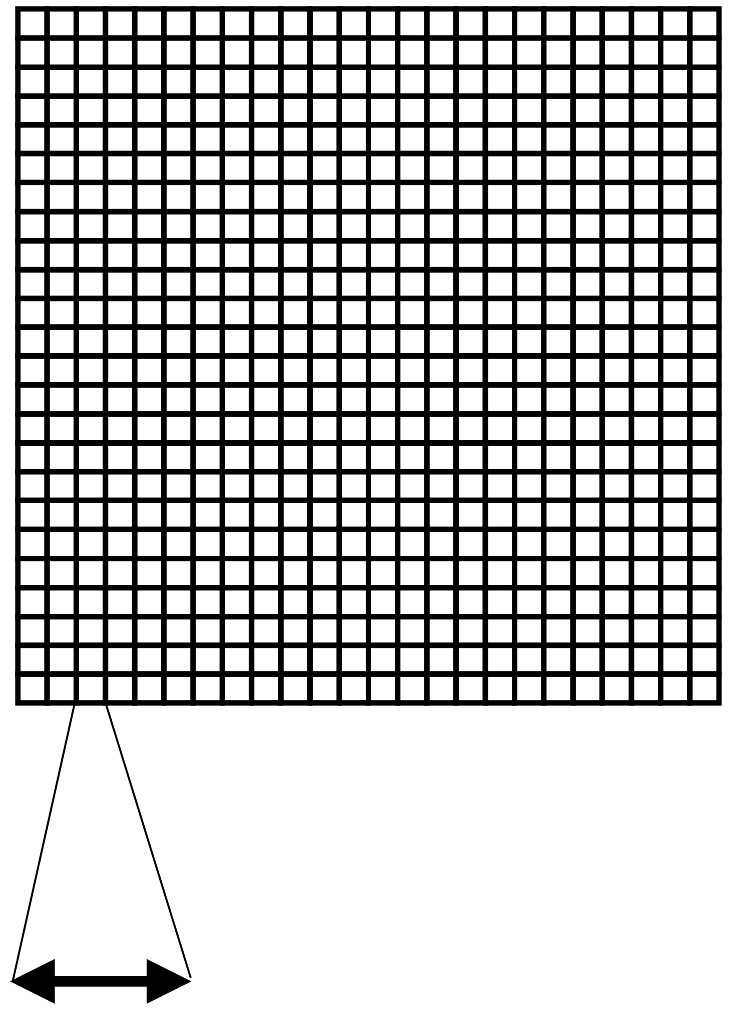
Detector design

E-Pad



1 cm

E-Pixel



30 µm

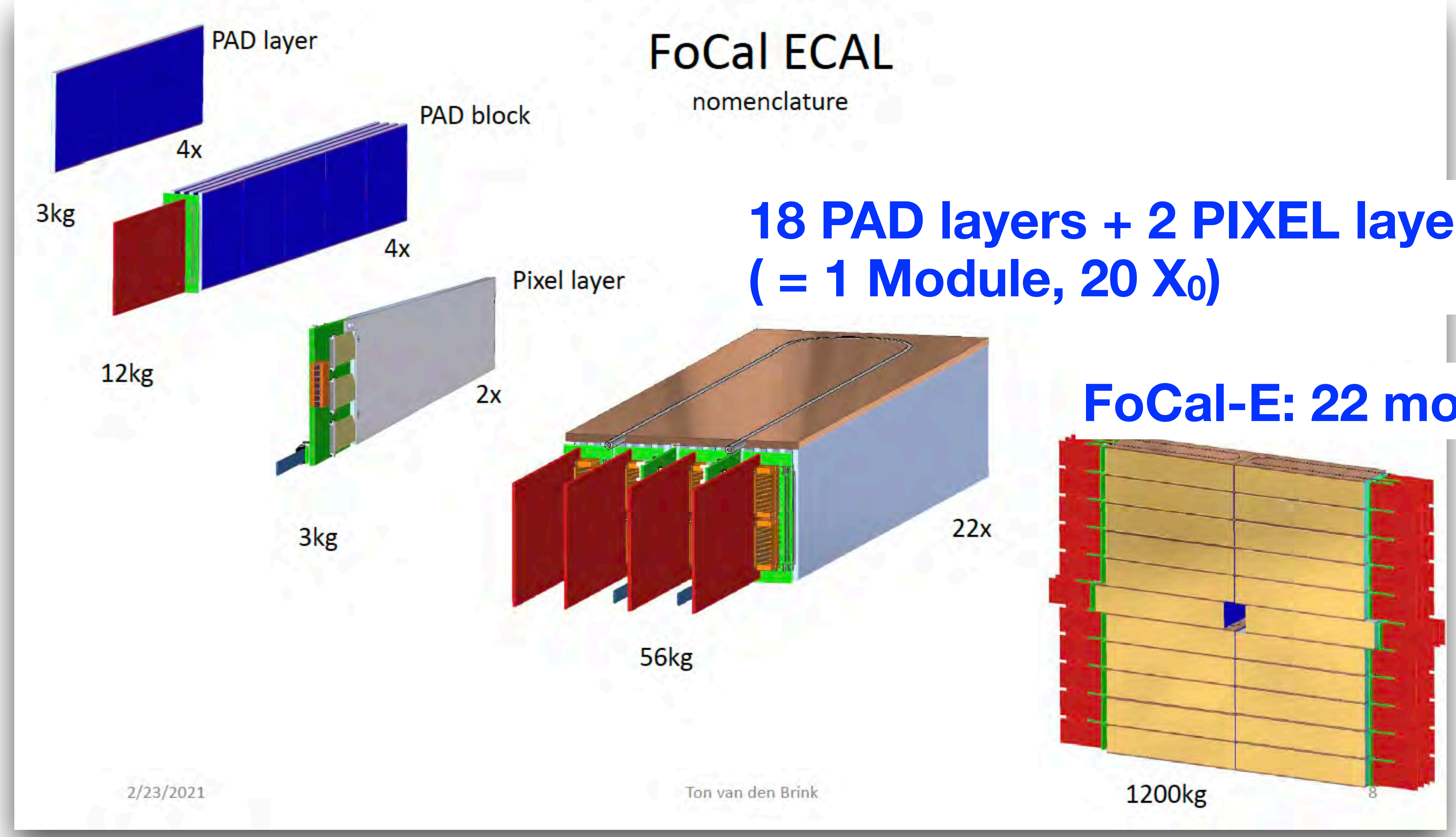
FoCal-E (pad, pixel)

20 layers of W(3.5 mm ≈ $1X_0$) + silicon sensors:
Two types: **Pad ($1x1\ cm^2$)** and **Pixel ($30 \times 30\ \mu m^2$)**

- Pad: shower profile and total energy
  - Si PAD sensor
- Pixel: position resolution to resolve overlapping showers
  - CMOS MAPS technology (ALPIDE)

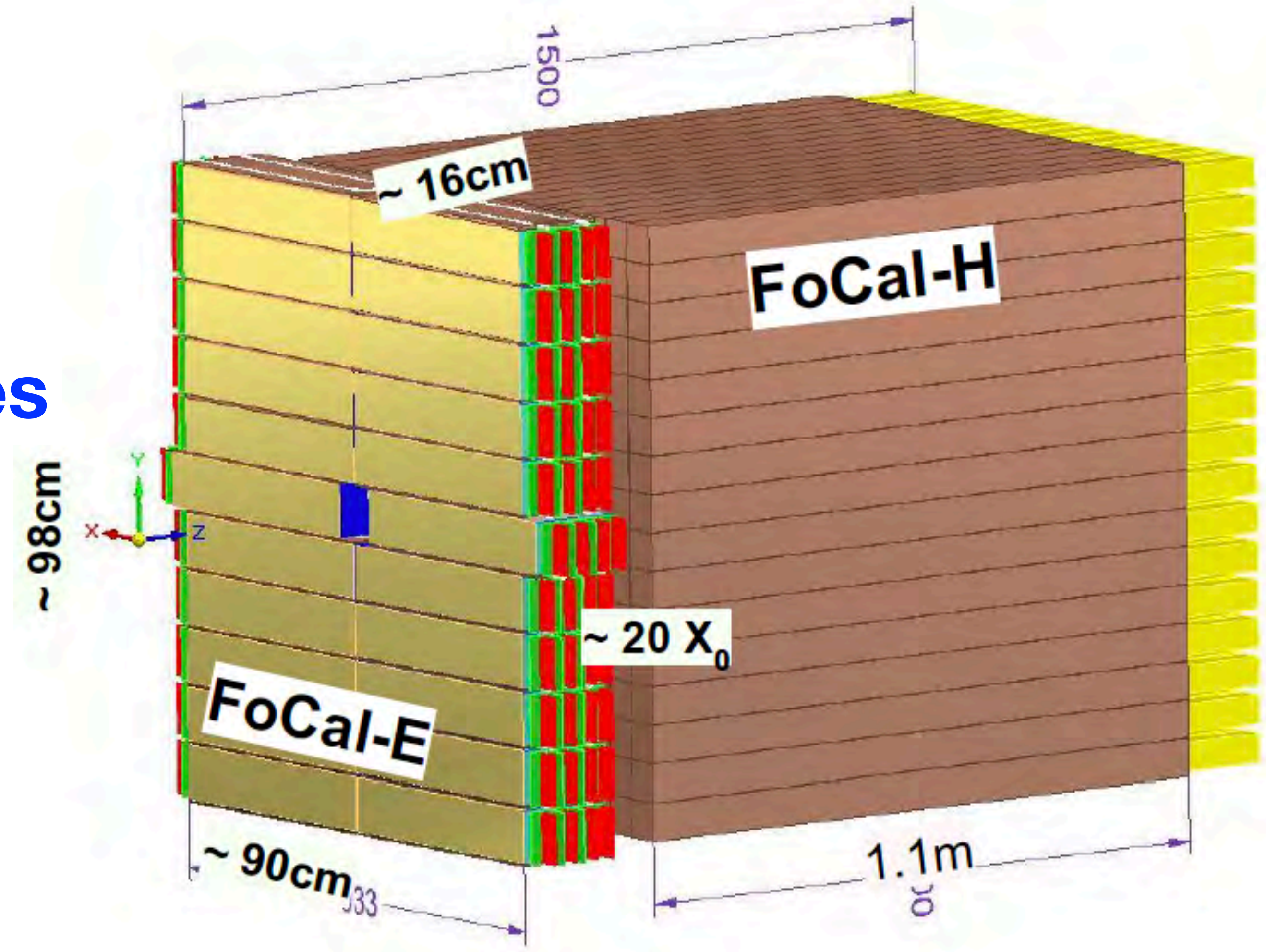
FoCal-H

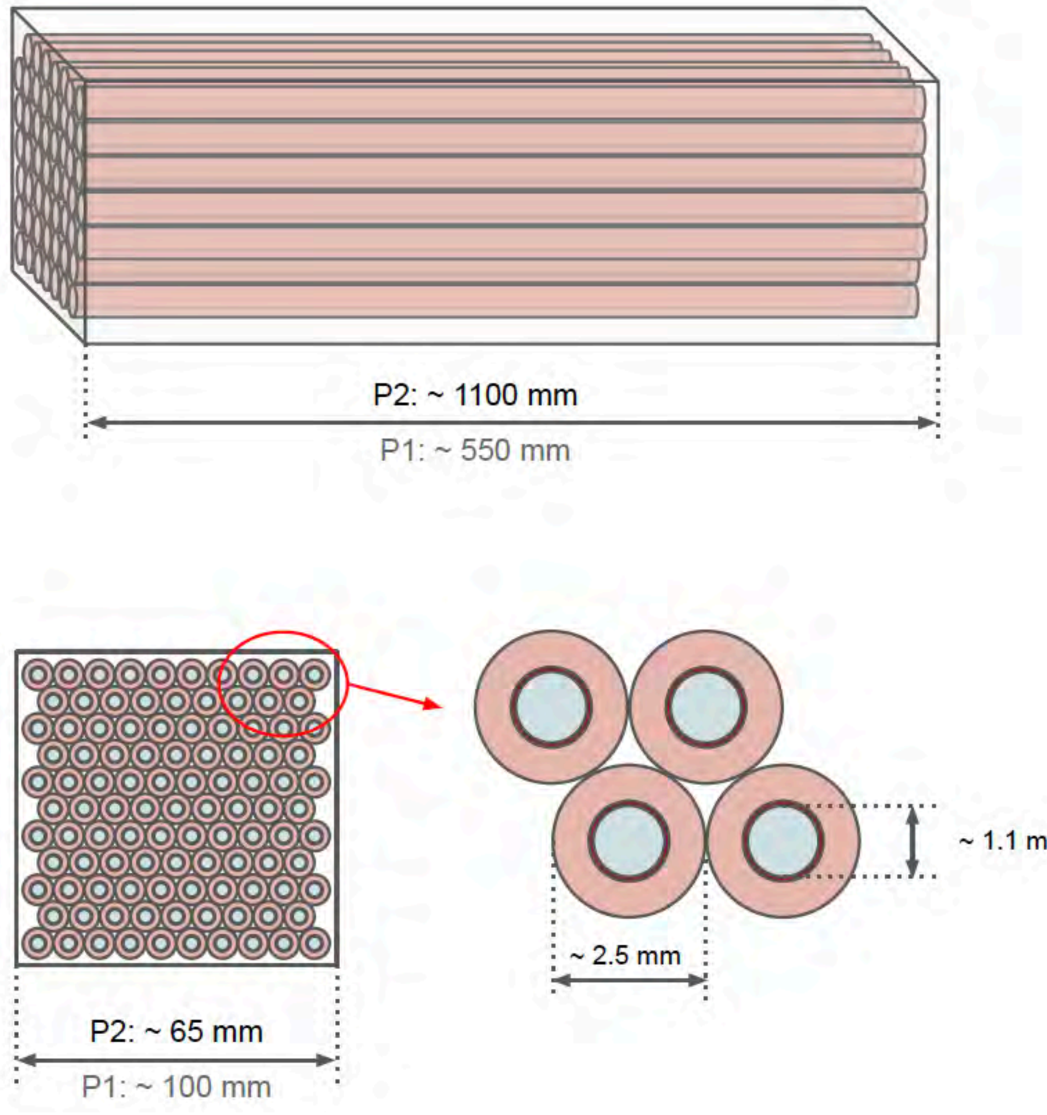
Conventional metal-scintillator design
Cu capillary-tubes enclosing BCF scintillating fibers
SiPM readout



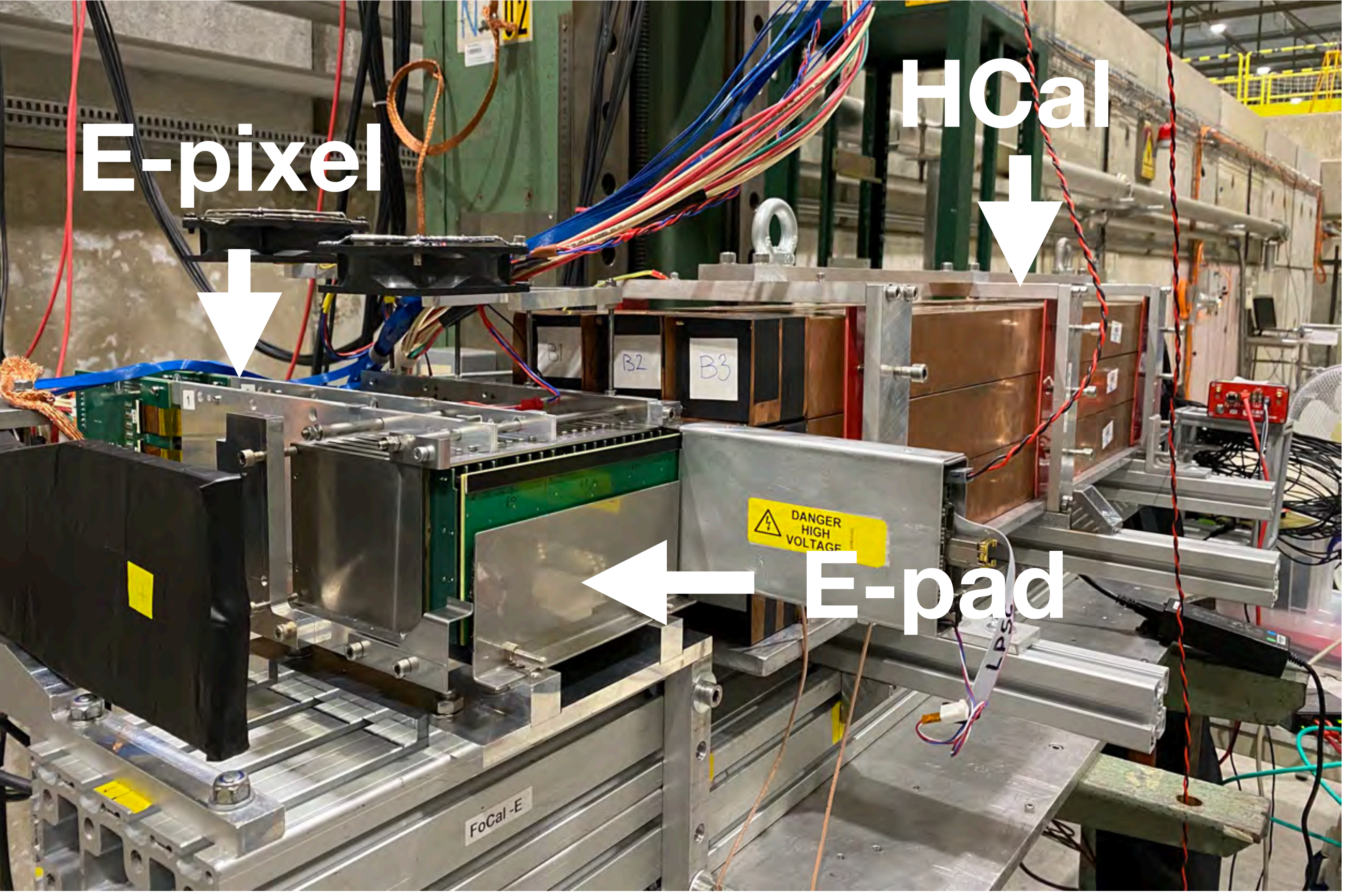
18 PAD layers + 2 PIXEL layers (= 1 Module, 20 X_0)

FoCal-E: 22 modules



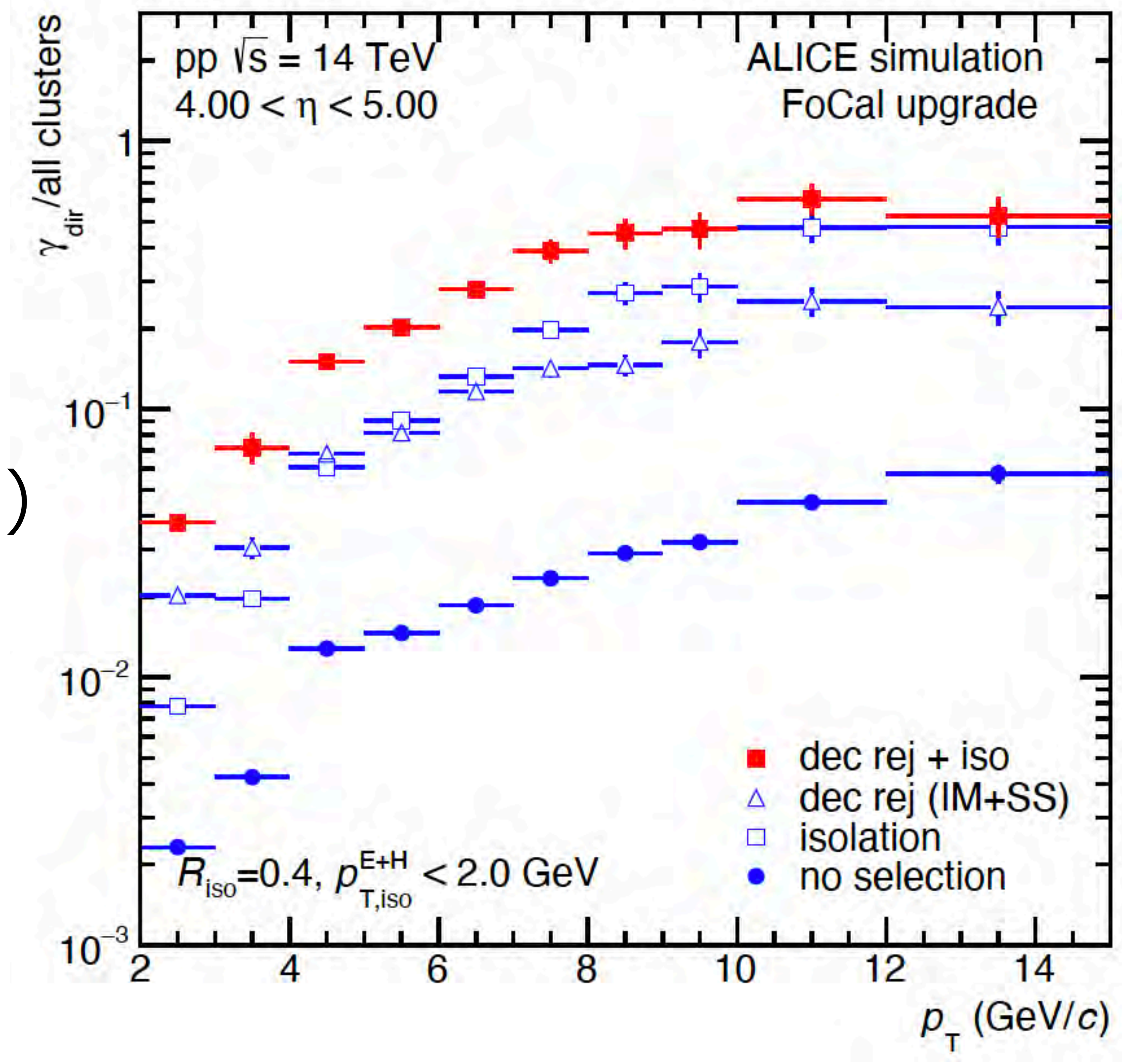


Uniqueness of FoCal detector



PS/SPS test beam in 2022

Isolated photon ID



1）**High two photon separation power**（<~5mm, energy resolution ~3%）

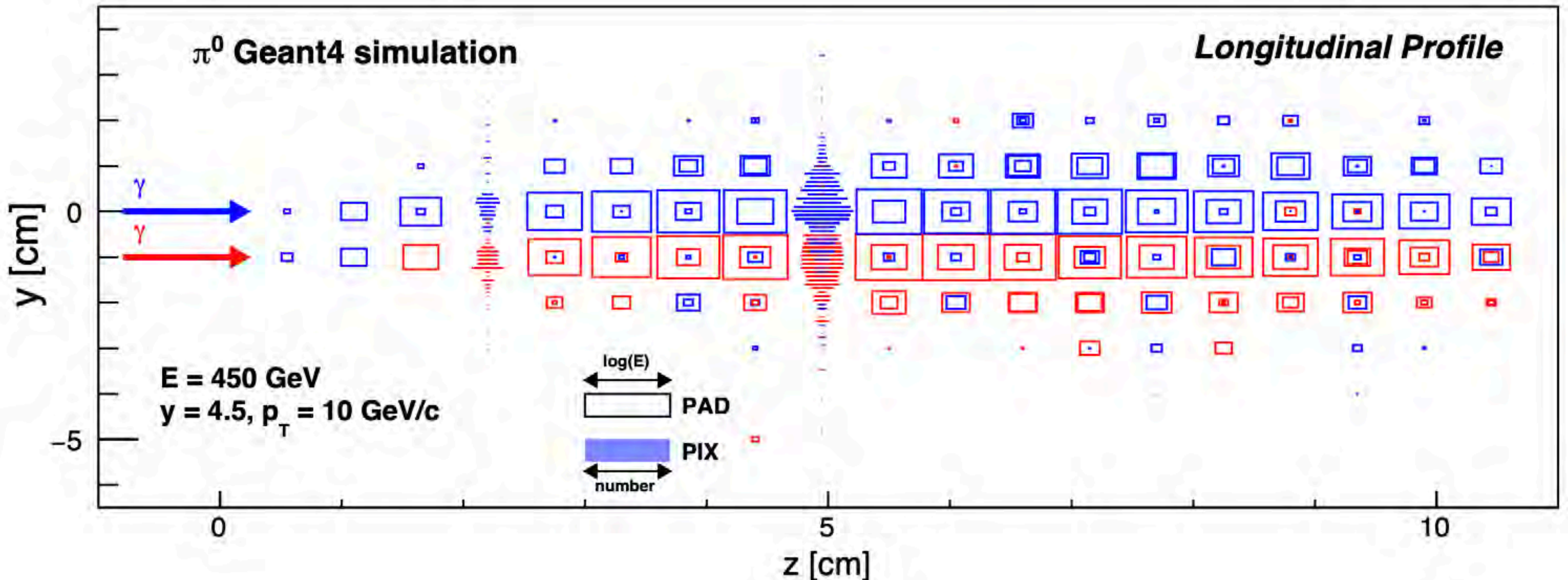
2）**Wide energy dynamic rage** (from 1 MIP to TeV EM showers）

3）**High radiation tolerance**（10^{13} (1MeV neutrons) / cm^2）

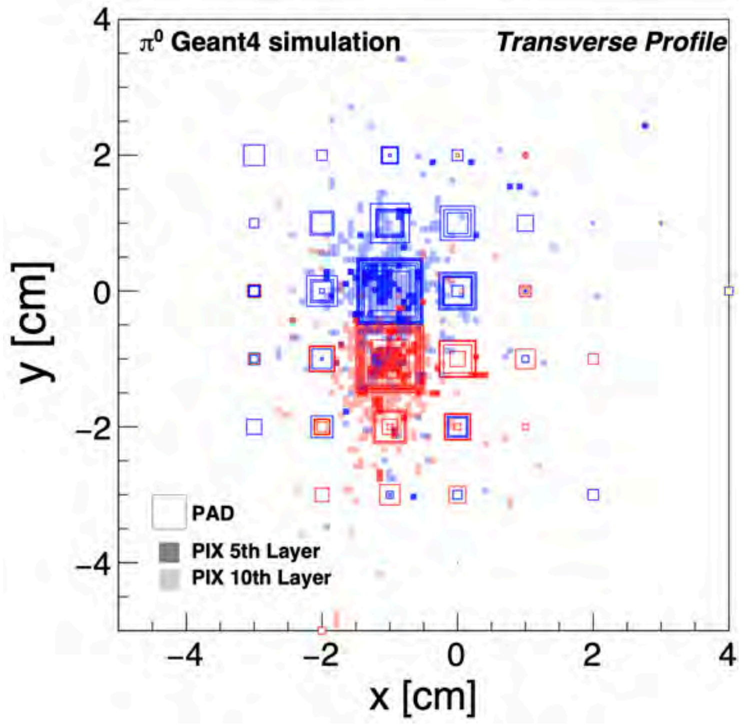
→FoCal-E pad: major contributions from Japan and India

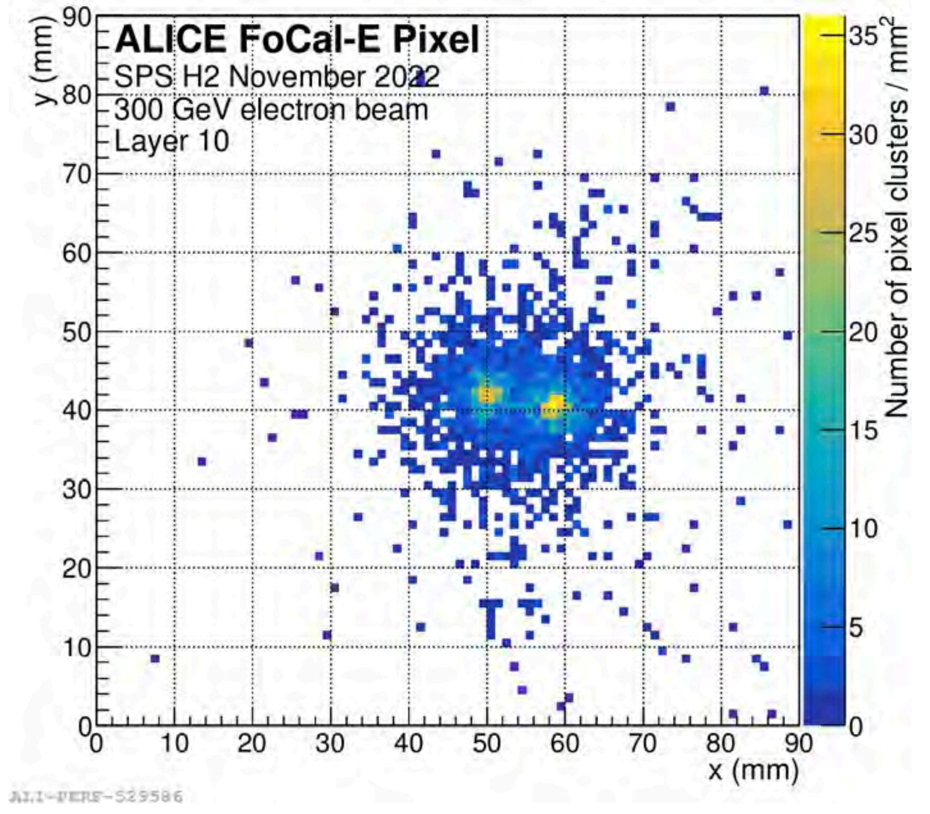
FoCal-E pixel: China

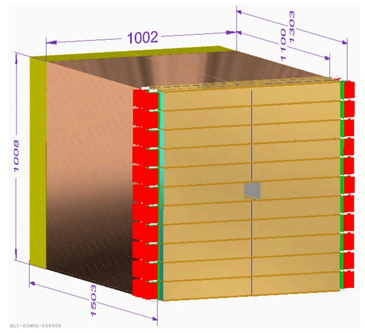
Longitudinal profile (2γ showers)



Trans. profile



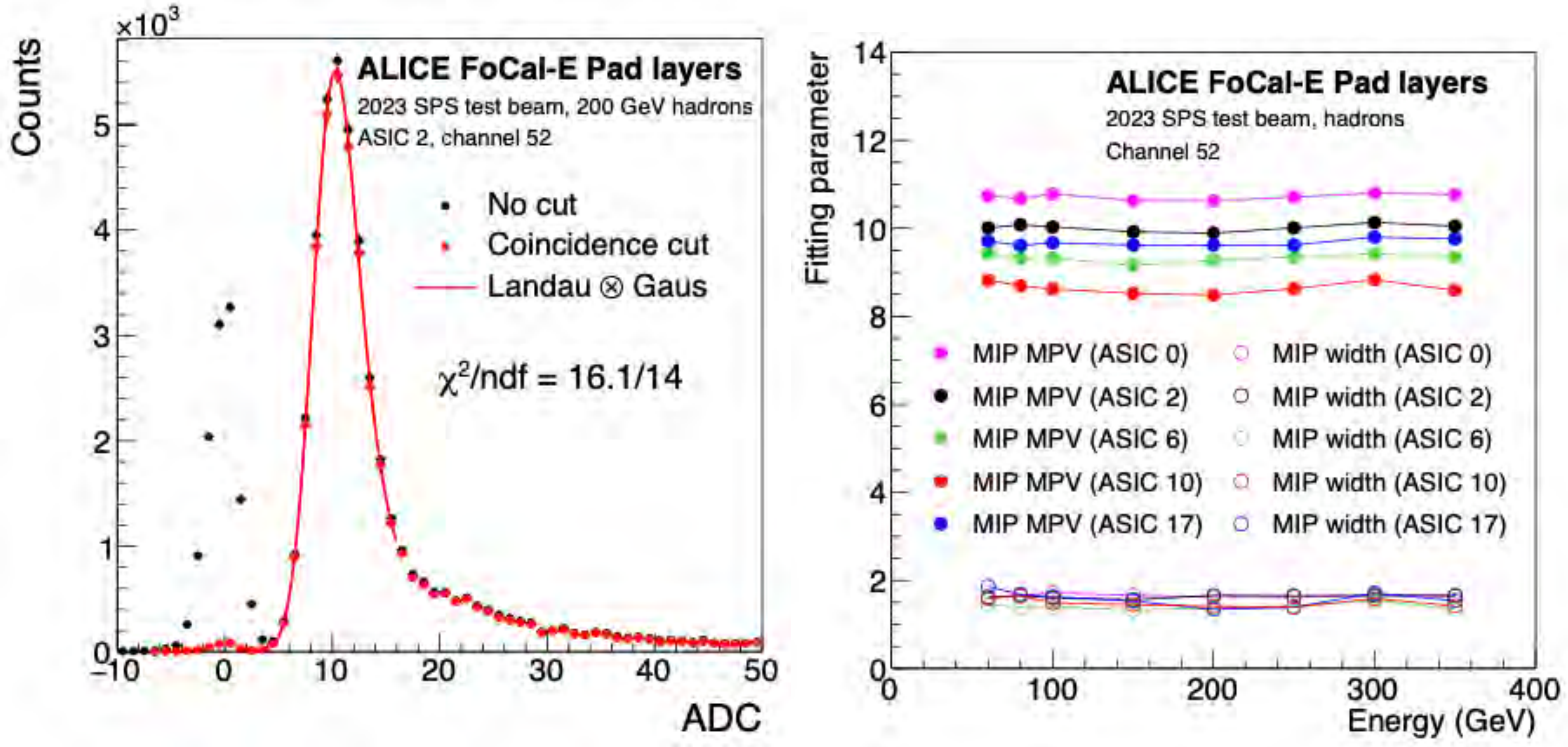




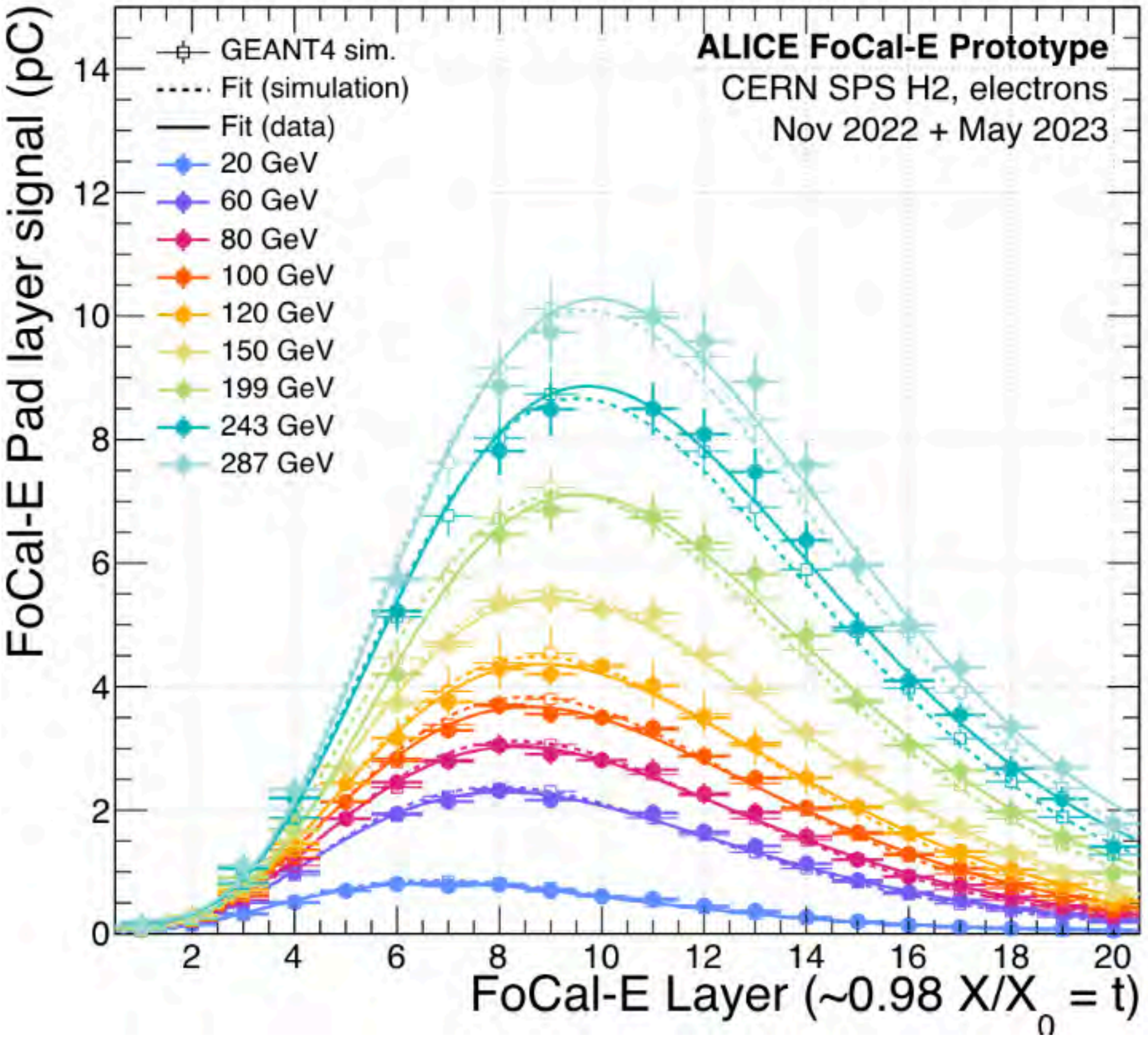
FoCal-E pad performance

JINST 19 P07006 (2024)

MIP responce

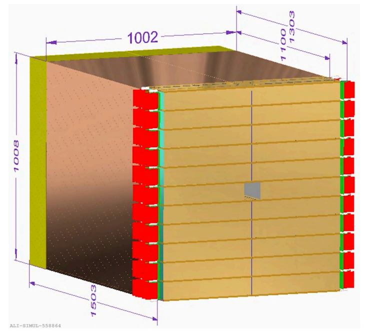


Longitudinal shower profiles



Excellent performance of prototype

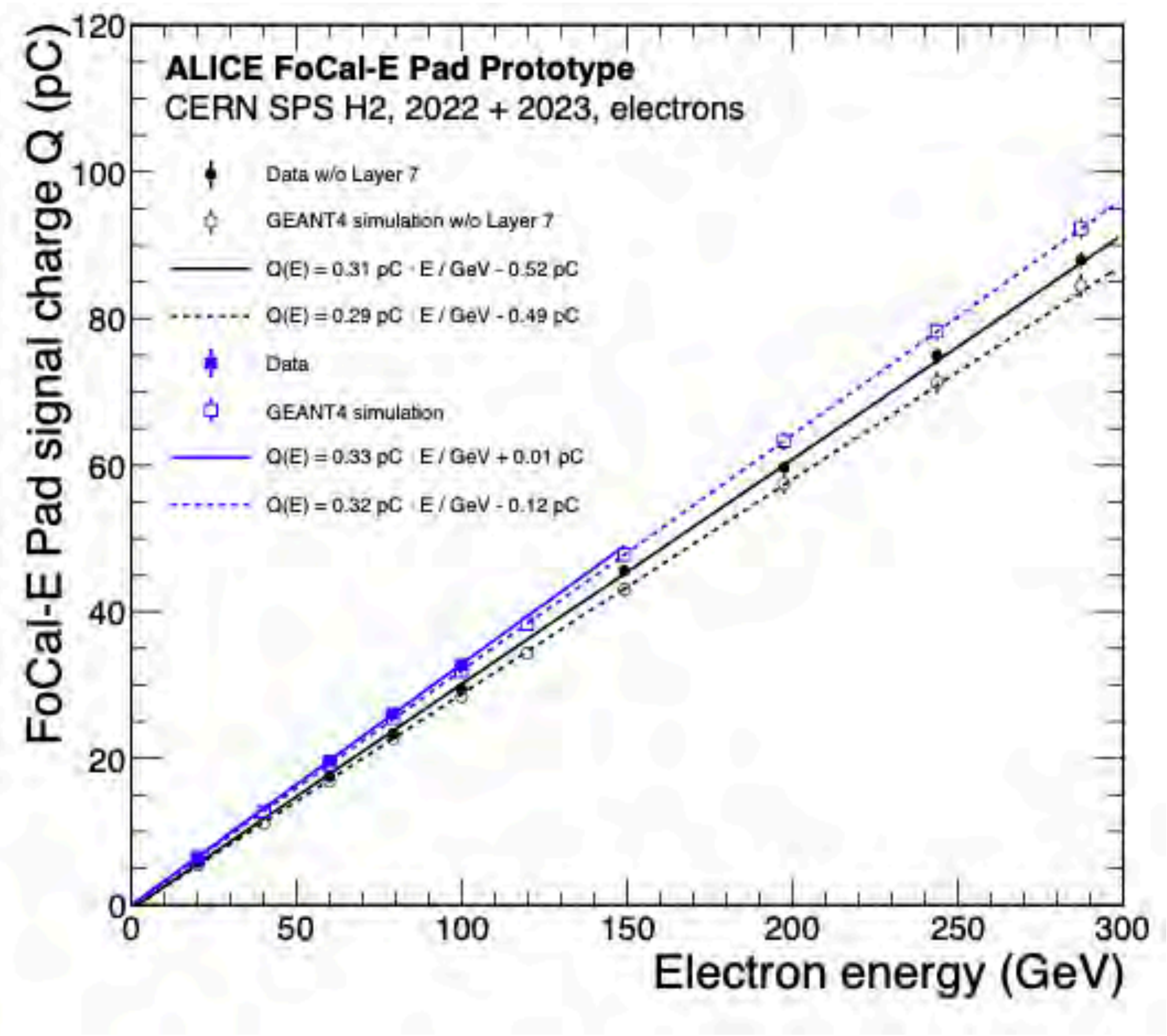
- Pad MIP single channel distribution and stability
- Longitudinal shower profile



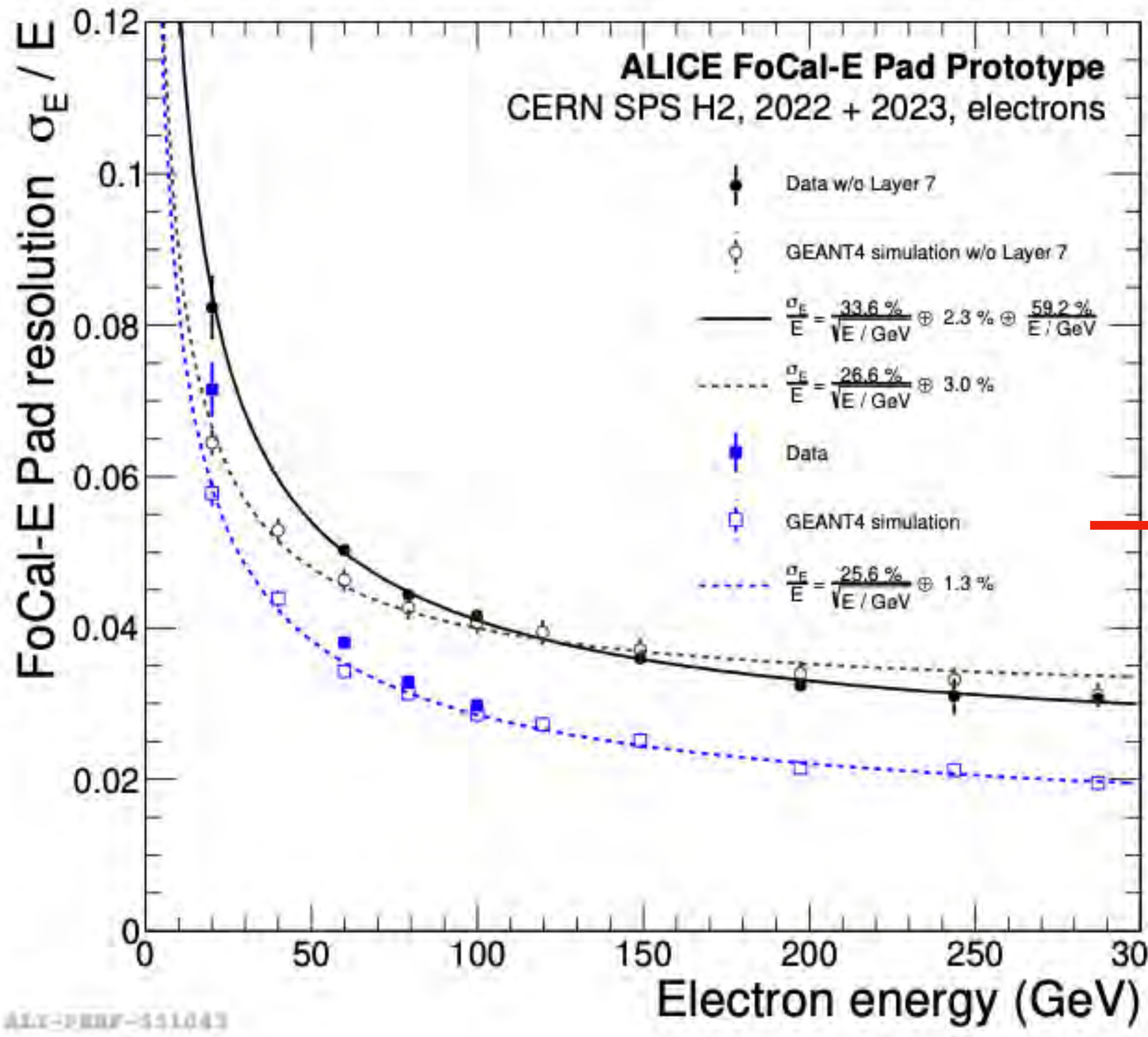
FoCal-E pad performance

JINST 19 P07006 (2024)

Linearity

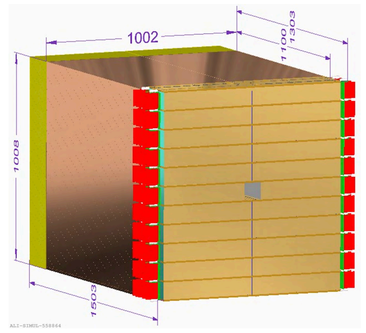


Energy resolution



5%

Results show expected behavior

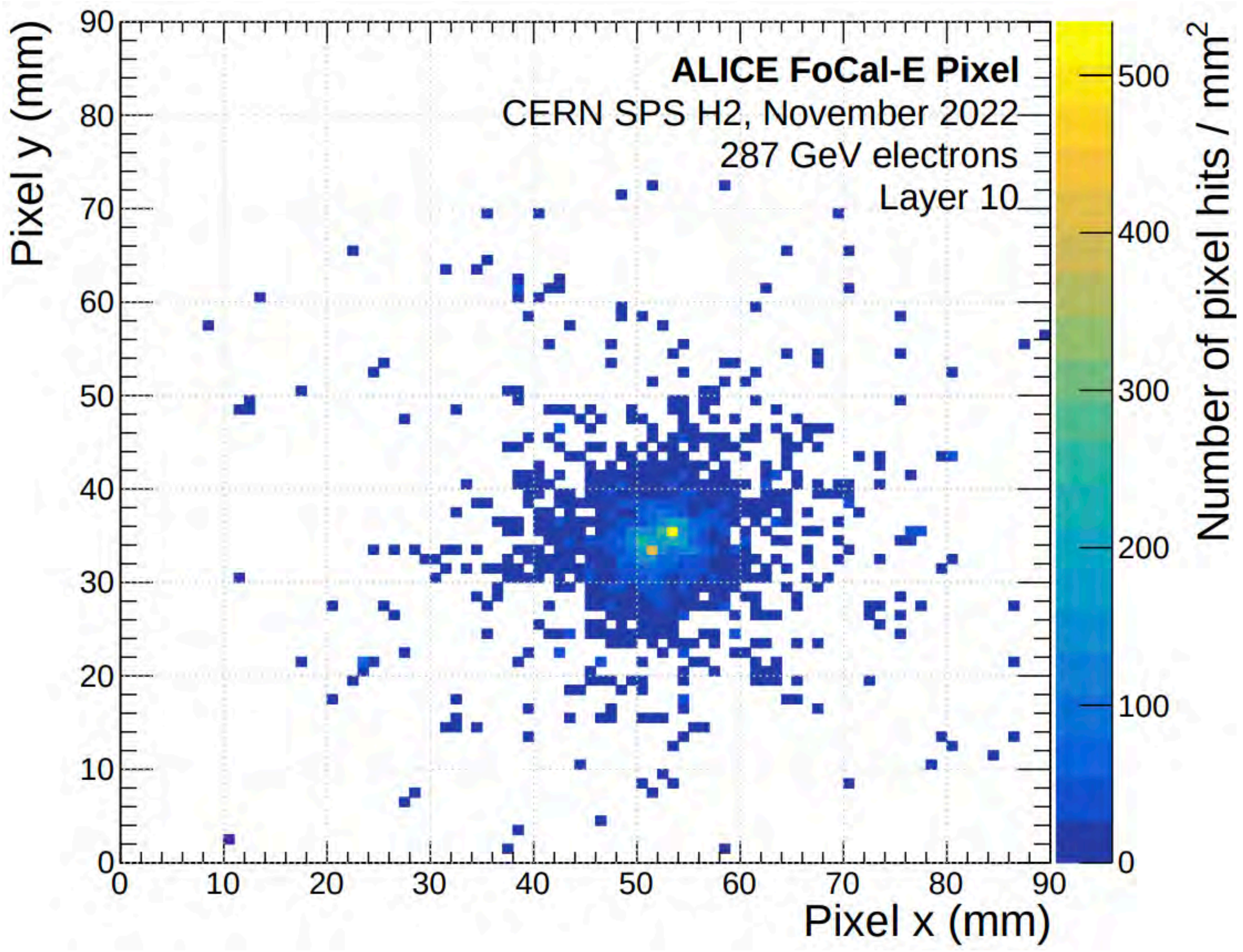


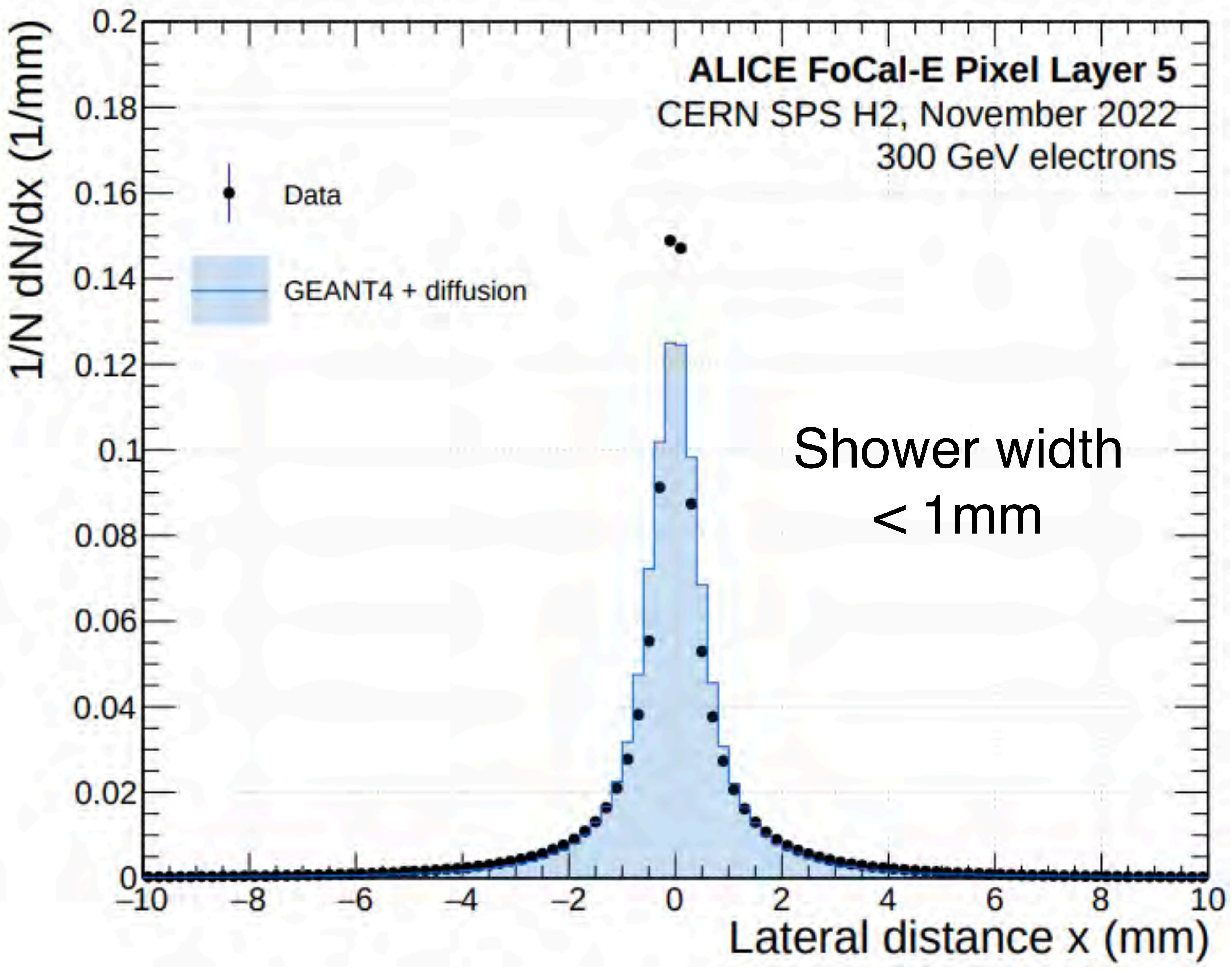
FoCal-E PIXEL @ SPS test beam in 2022

JINST 19 P07006 (2024)

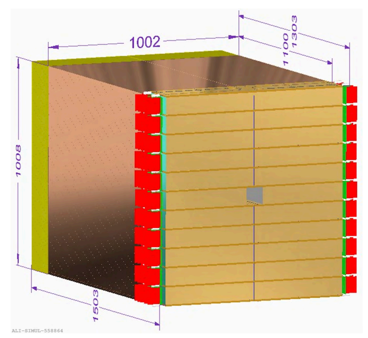
- Successful commissioning of FoCal-E PIXEL (ALPIDE)
- Distance between electrons here <5 mm, demonstration of a good two gamma separation
- Detector response well described by GEANT4 + diffusion model

Layer 10, 2 e⁻ event





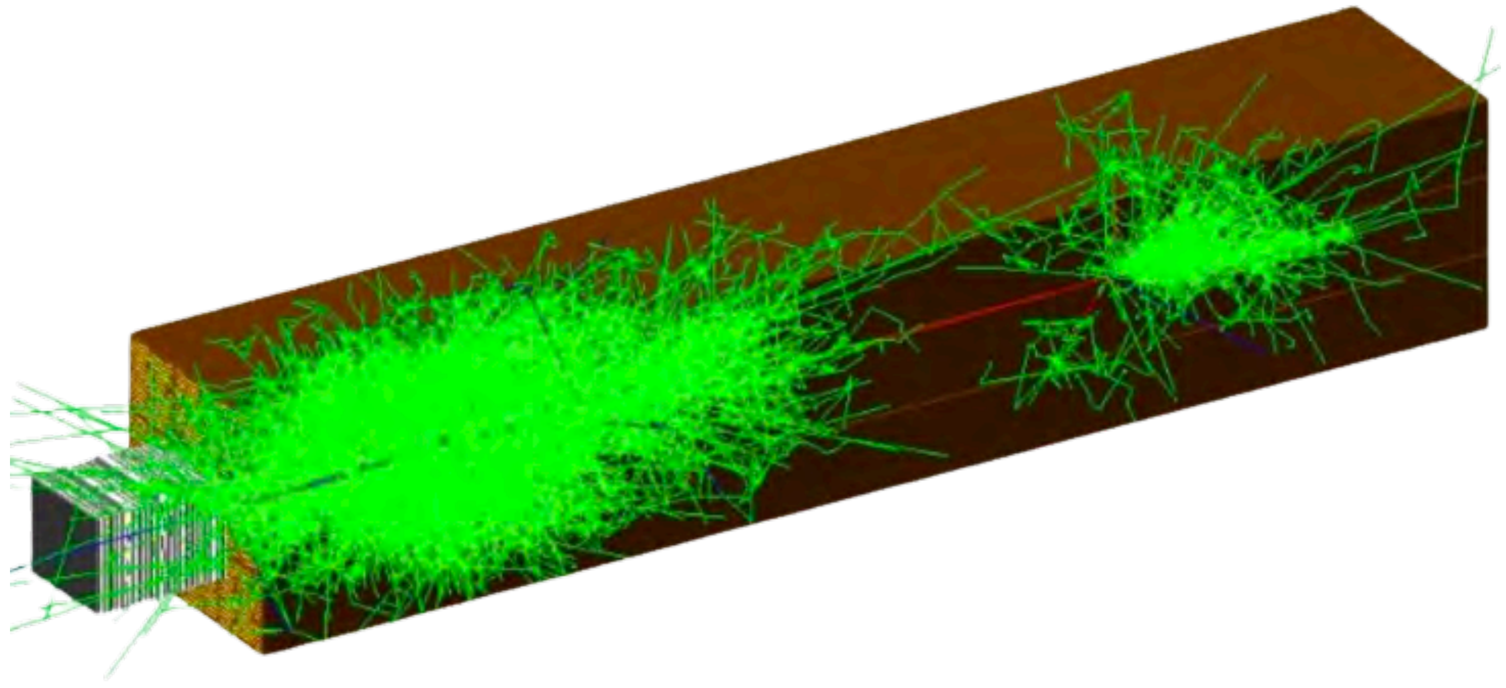
Shower width
< 1mm

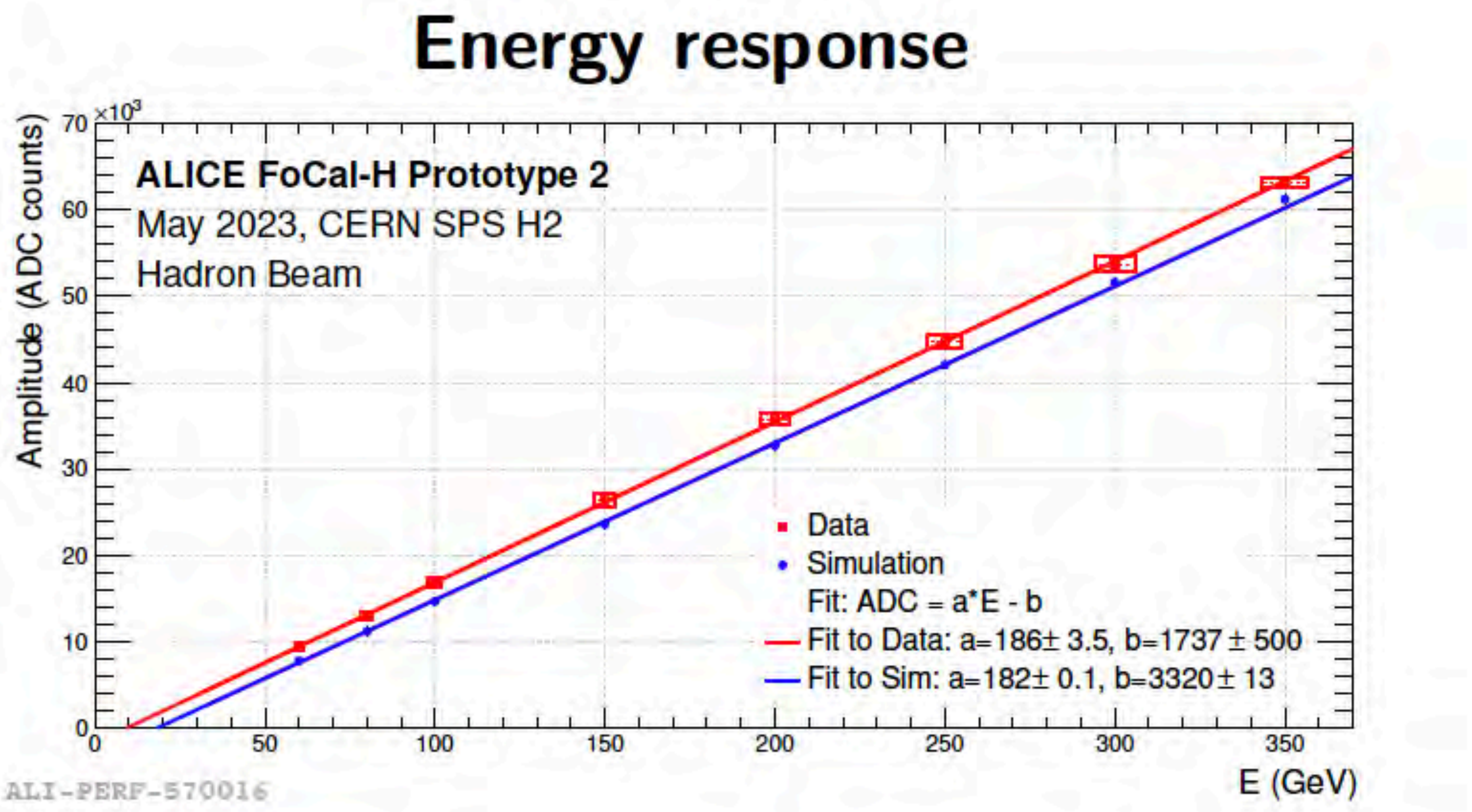


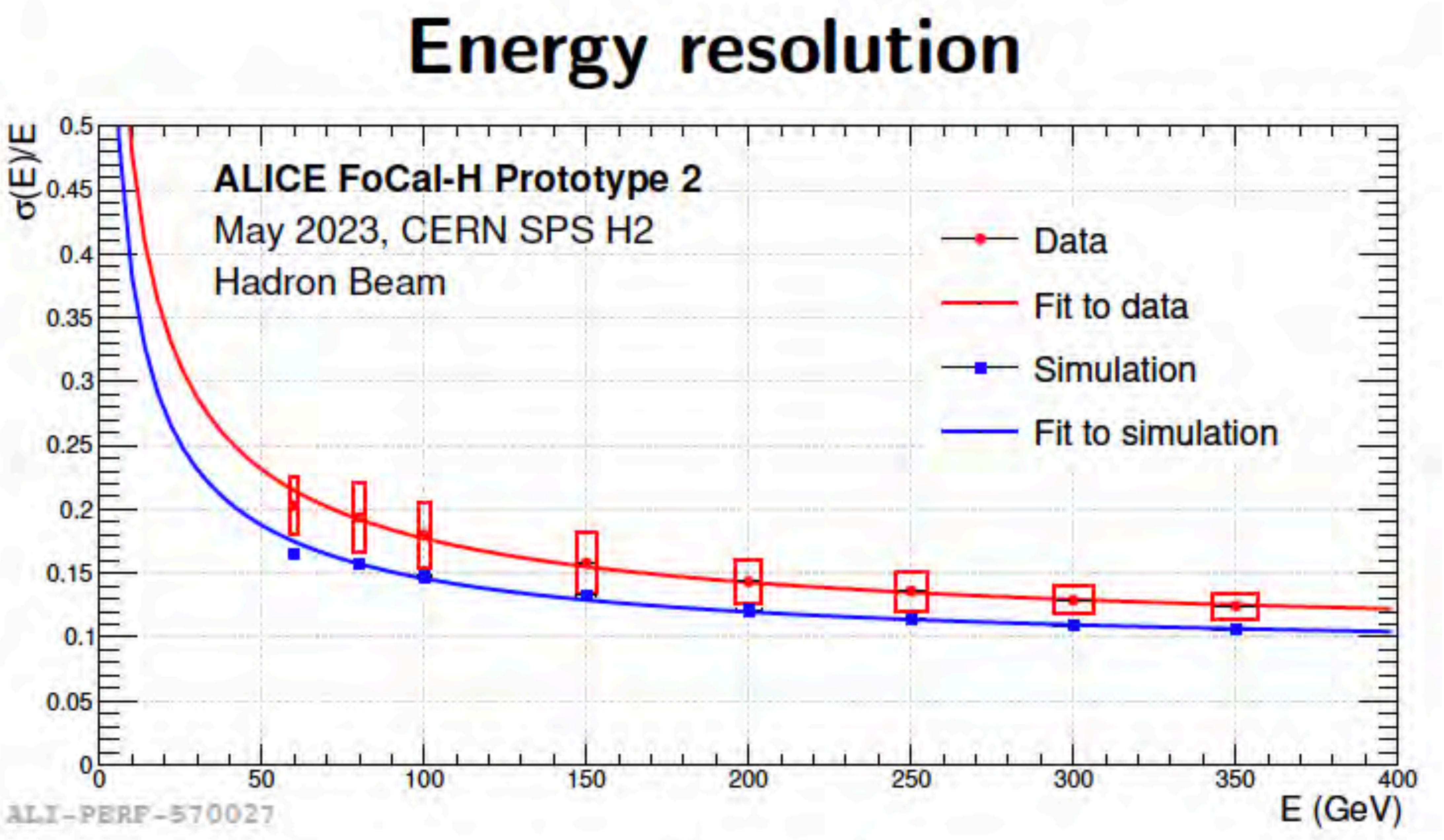
FoCal-H

JINST 19 P07006 (2024)

- Performance tested in hadron beam at SPS
- Energy response slope agreement between data and MC
- Energy resolution saturates at ≈ 12%
- Slight disagreement with simulation (GEANT4) under investigation







Summary

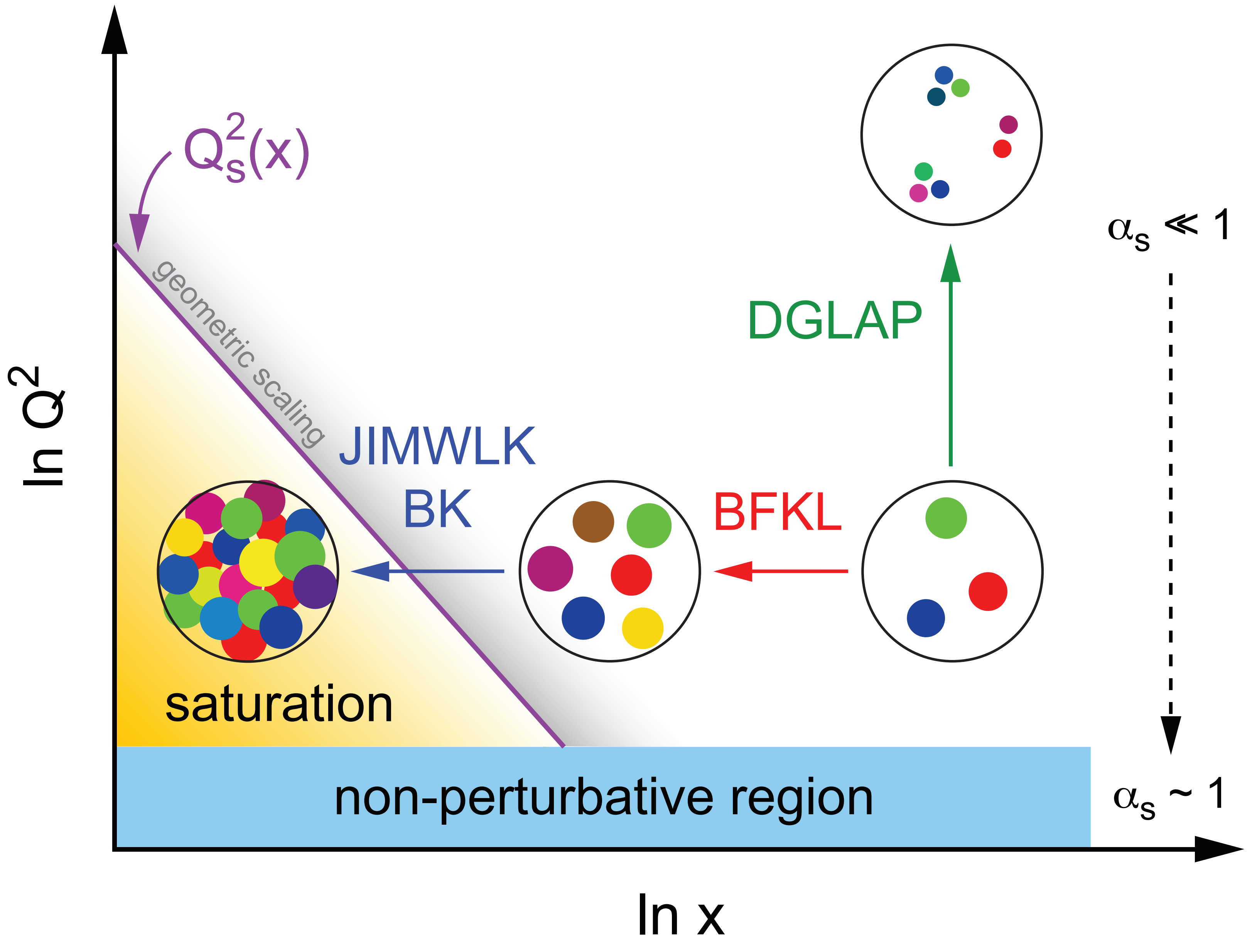
- FoCal is a crucial new detector to understand QCD and find a clear signal of CGC, exploring a wide kinematic coverage in x-Q^2 is crucial

- FoCal TDR has been approved, moving towards the construction

- Mass production has started in 2024, and physics in LHC Run-4 (2030-2033)

- Major contribution from Japan, India for FoCal

- FoCal provides the lowest x down to x ~10^{-6} to detect CGC signal clearly in LHC Run-4!



ALICE