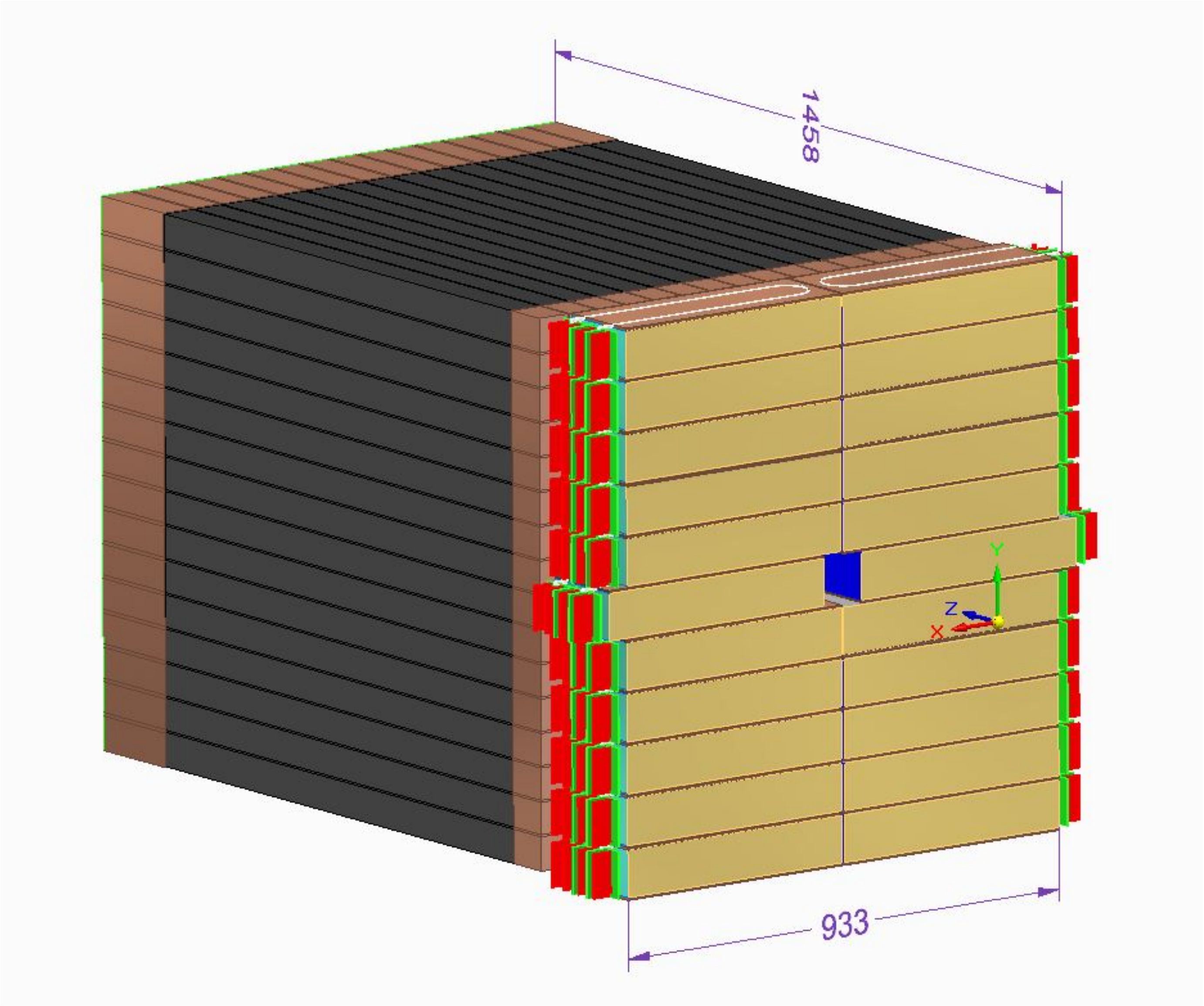
ALICE FoCal and EIC

~ Complementary and similarity on QCD study ~



Tatsuya Chujo

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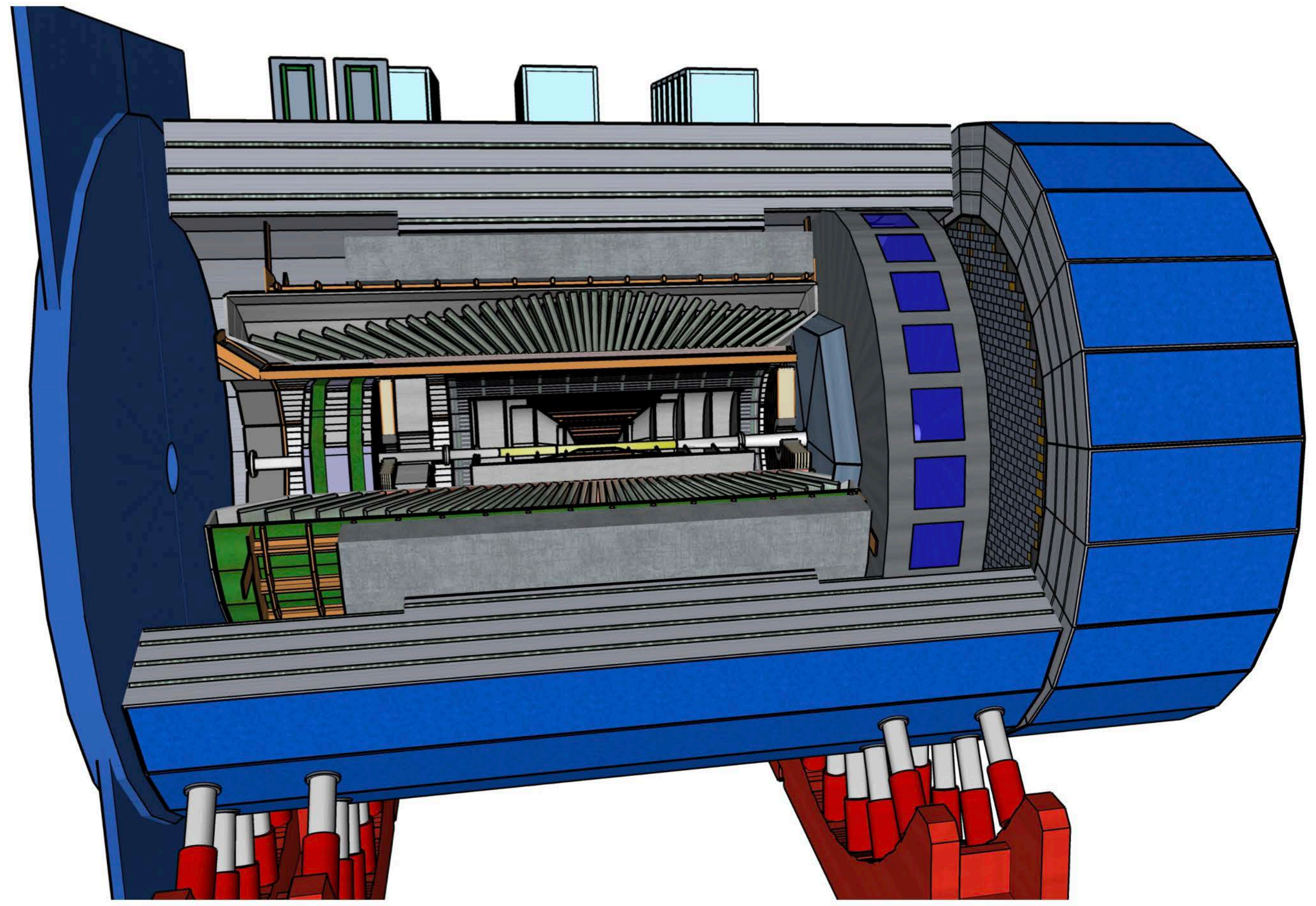
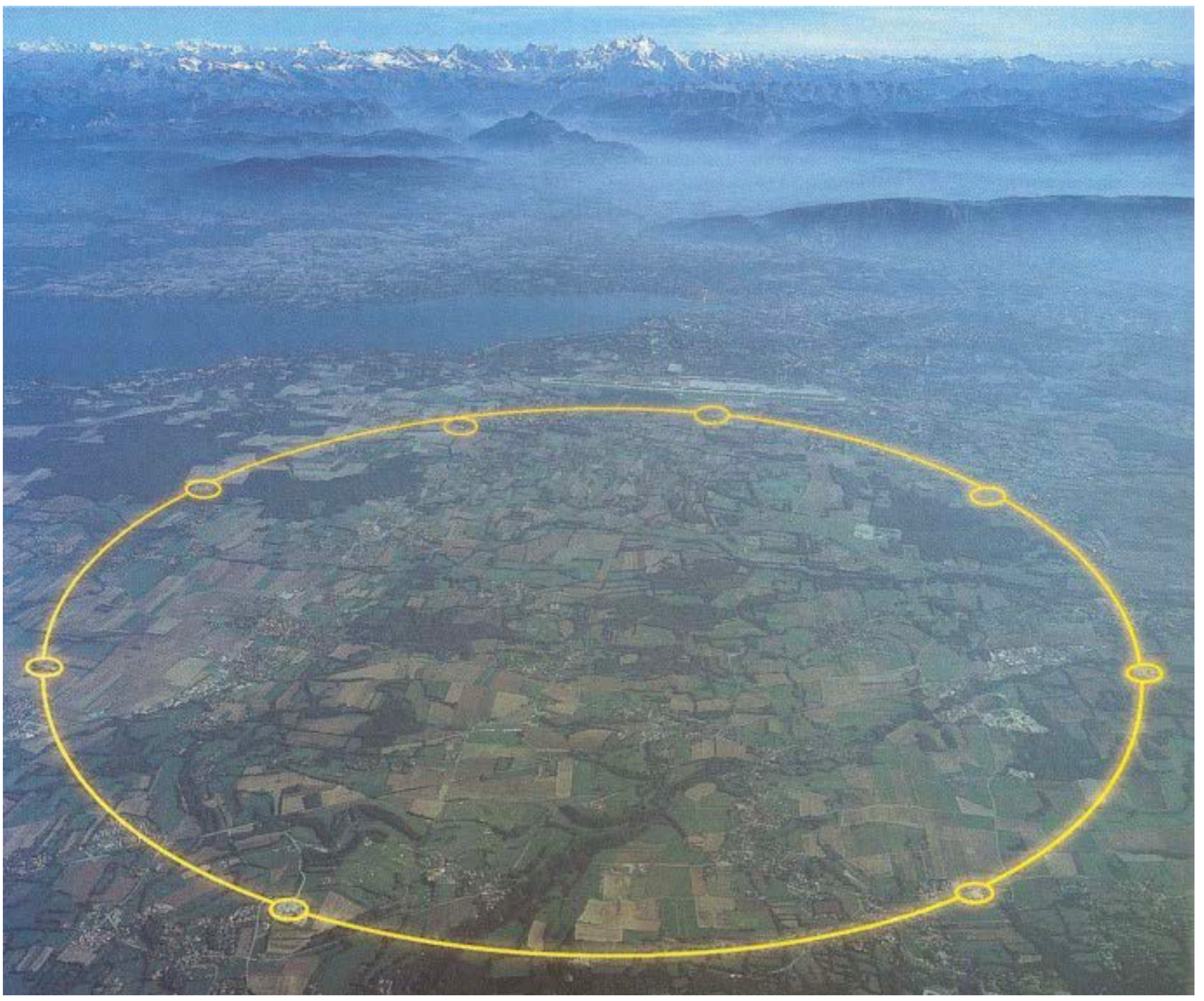
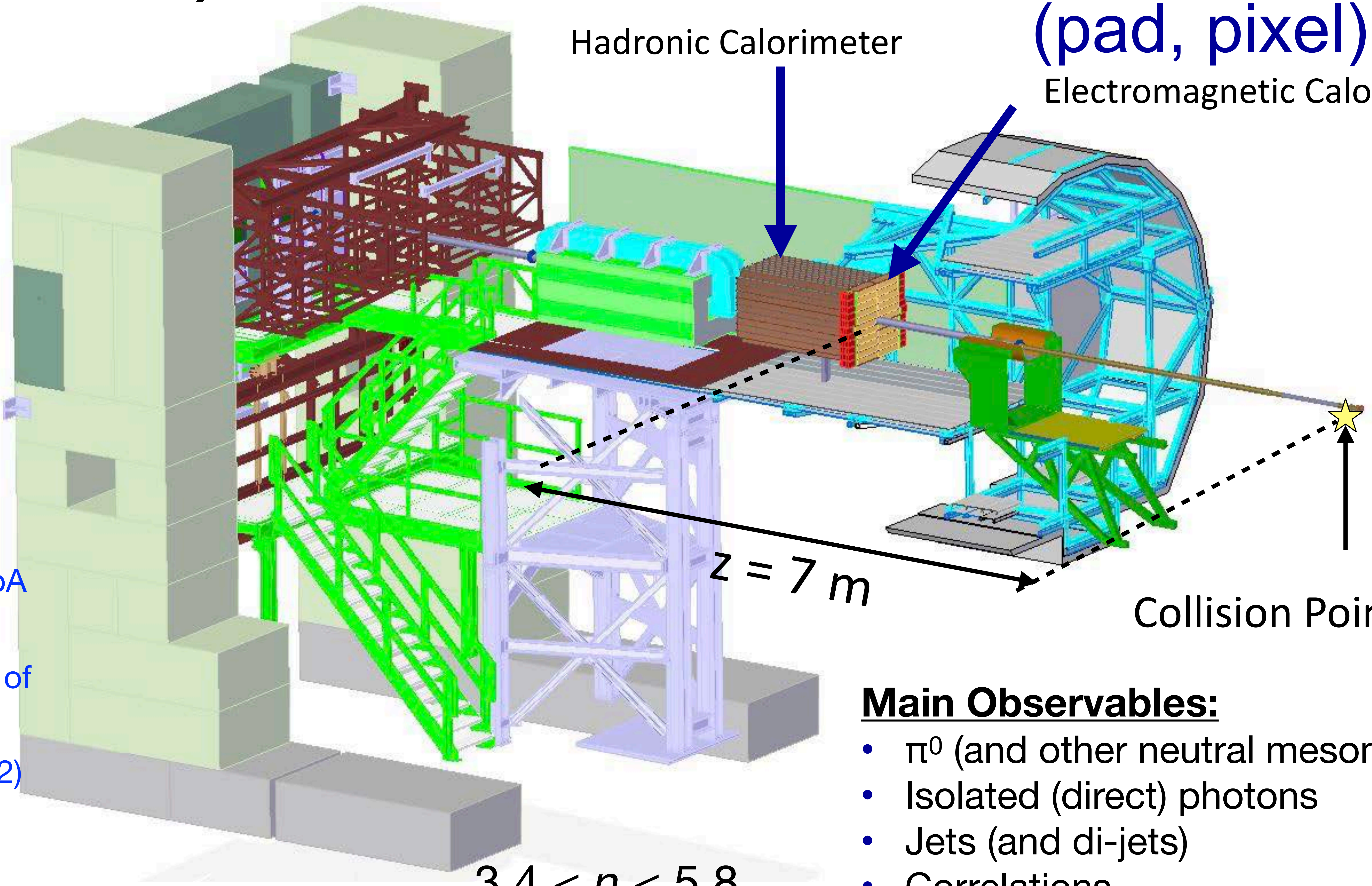


TCHoU workshop, March 29, 2024, Tsukuba, Japan

Forward LHC (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**

$3.4 < \eta < 5.8$

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

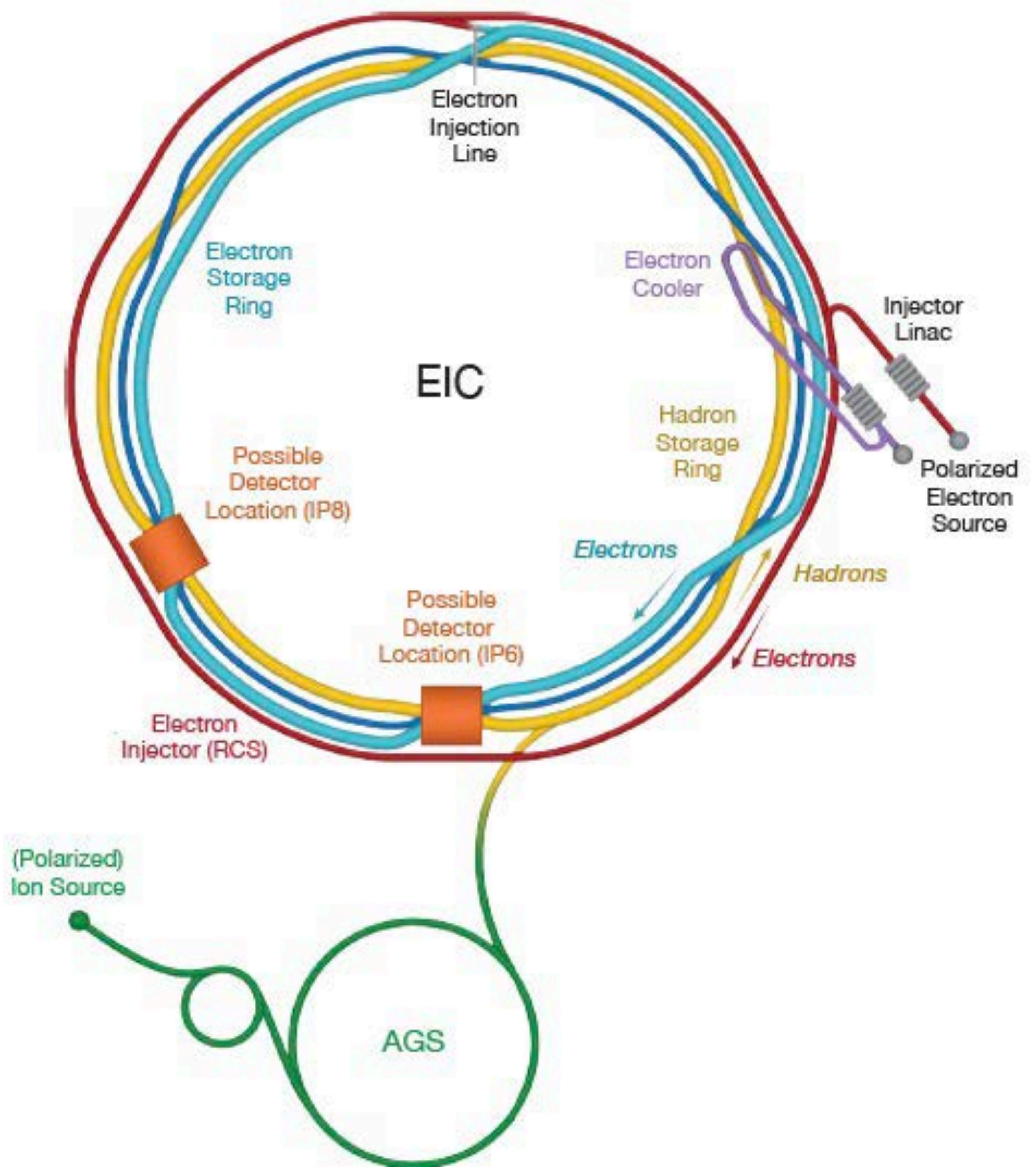
Main Observables:

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

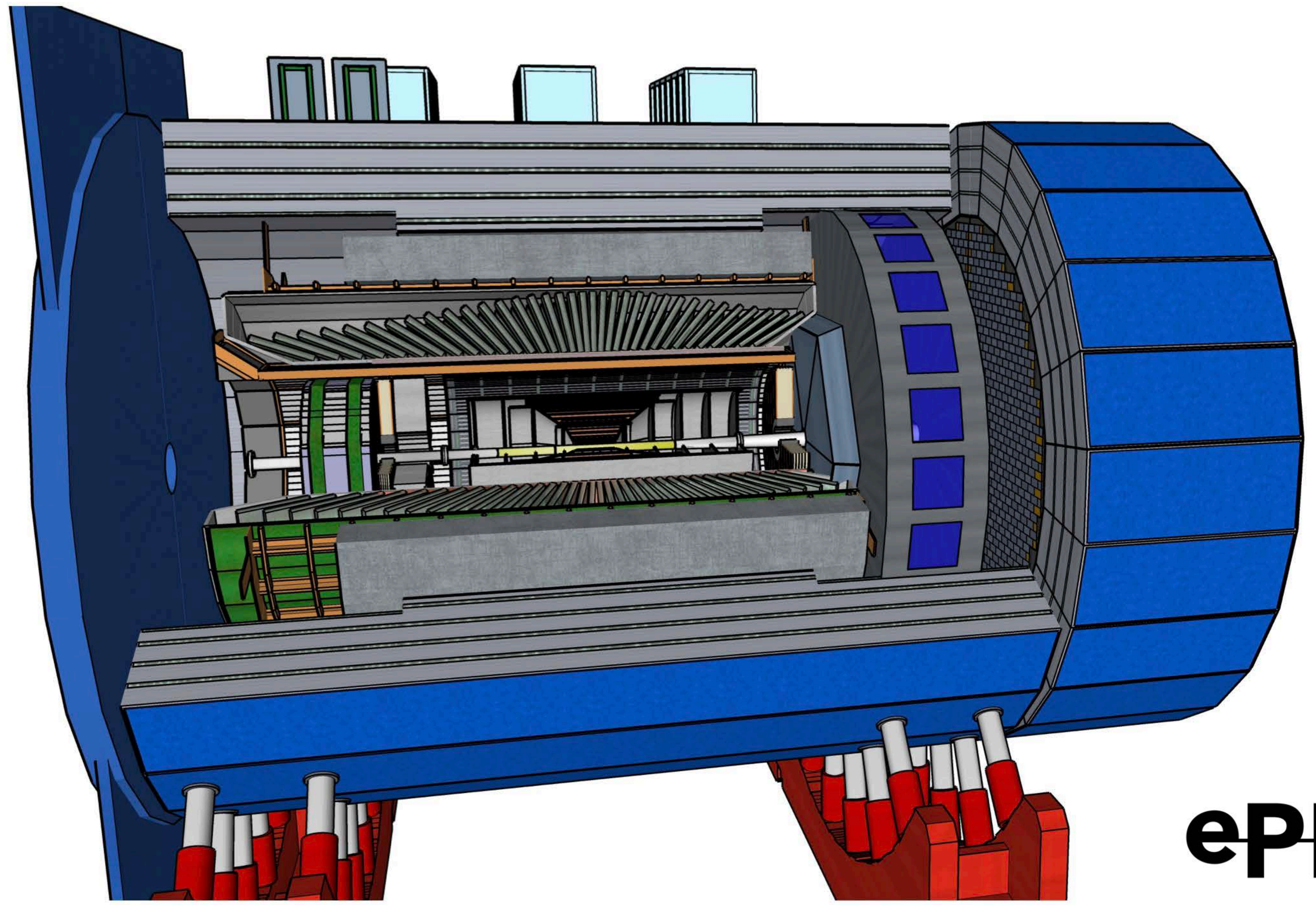
FoCal (LoI) : CERN-LHCC-2020-009

* T. Chujo (FoCal co-project leader, E-pad rep.)

EIC eA



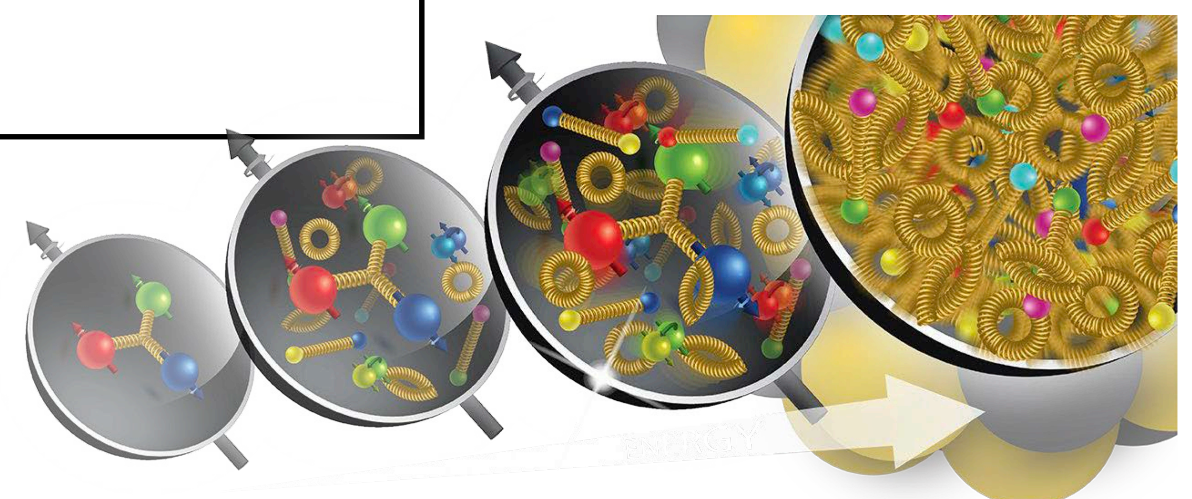
- Brookhaven National Lab. (BNL, USA)
- Will start operation in 2032
- High luminosity polarized e, p / Ion collider at $\sqrt{s}$ = 28-140 GeV
- Luminosity: x100 ~ 1000 higher higher than HERA
- 1st detector: ePIC collaboration



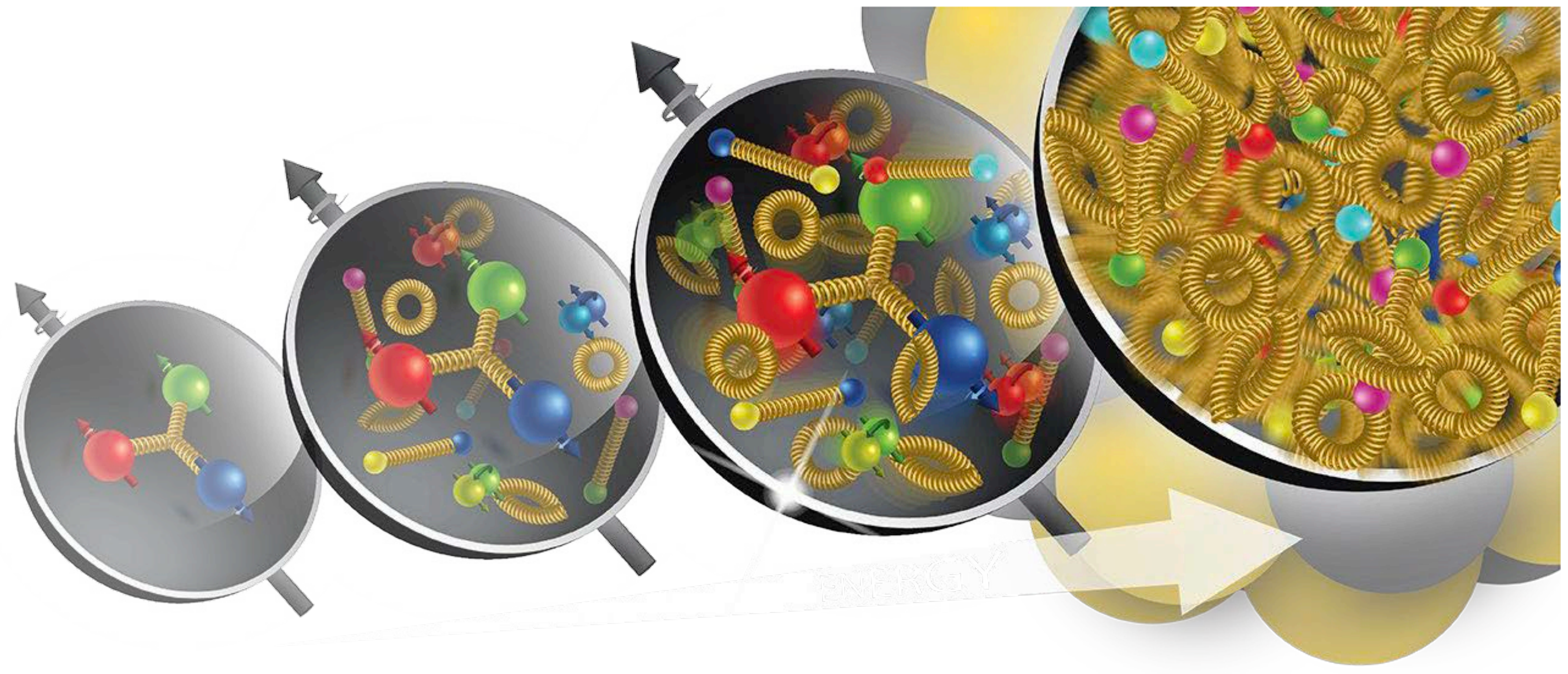
Physics at Electron-Ion Collider (EIC)

- Origin of nucleon mass and spin
- 3D structure of the nucleon and nucleus
- **Gluon saturation (Color Glass Condensate)**
- Hadronization

ePIC



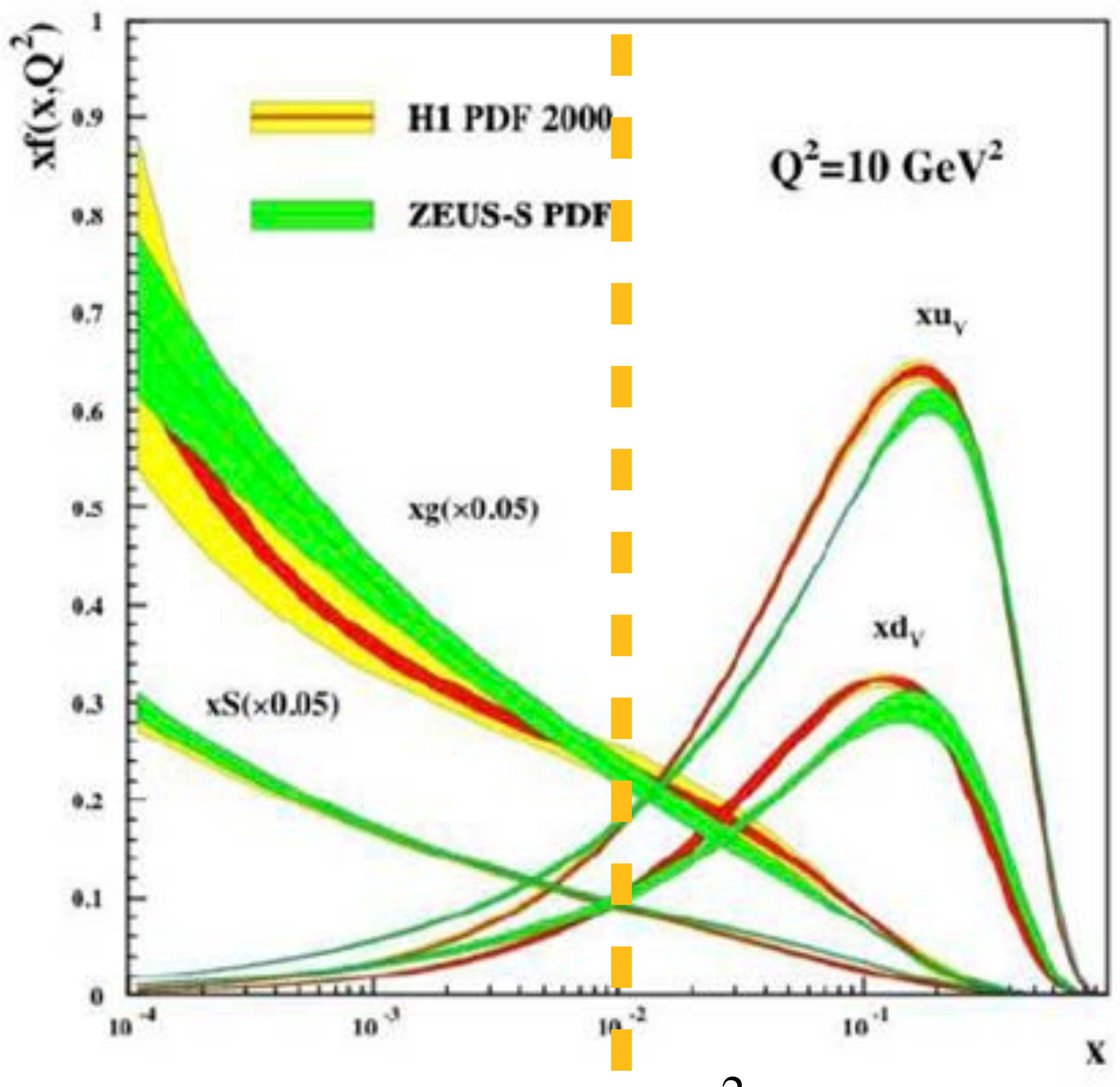
What is the Color Glass Condensate (CGC)?



Internal structure of proton and high energy limit

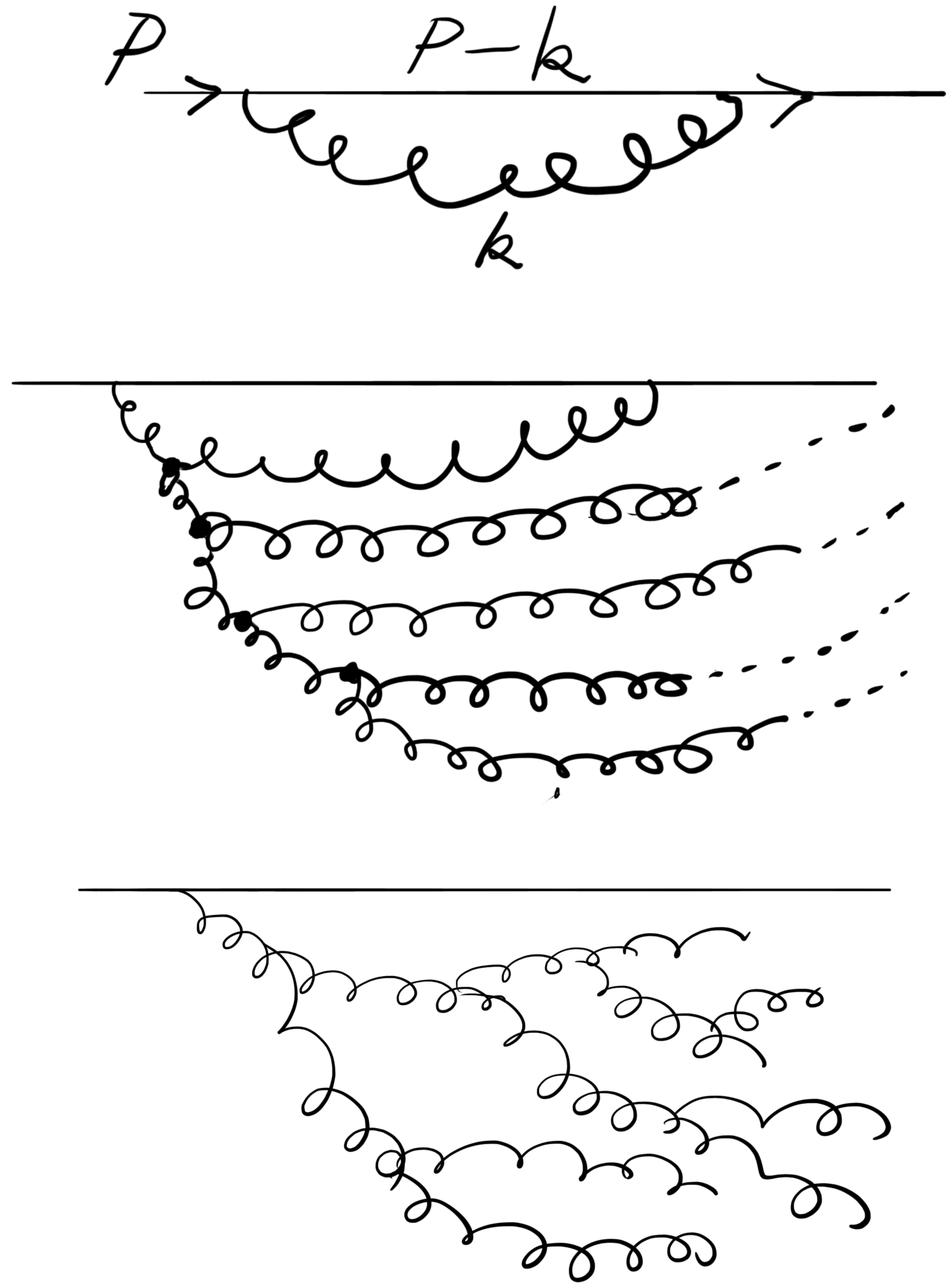
Structure of proton

small x | large x



$x = 10^{-2}$

$x = p_{q,g} / p$



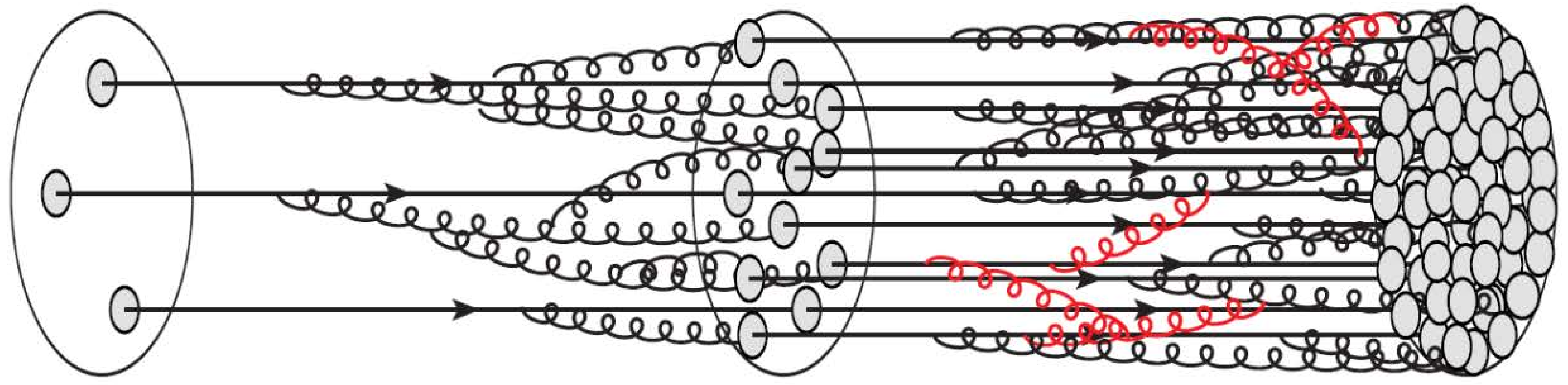
Mechanism of multipole gluon creations

- Lifetime of parton's fluctuations: p → Larger, Lifetime → Longer
- Probability of fluctuation generation: x → smaller, Prob. → Larger

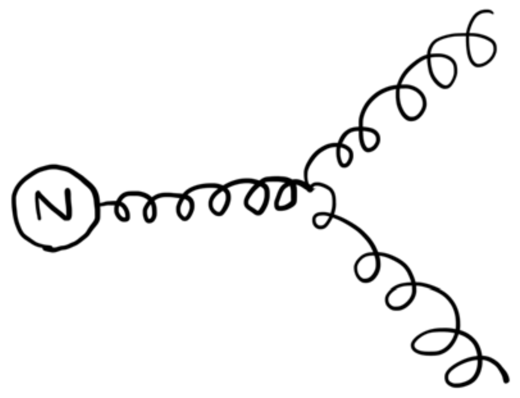
→ At high energy, increased small fluctuations exponentially !

Color Glass Condensate (CGC)

proton



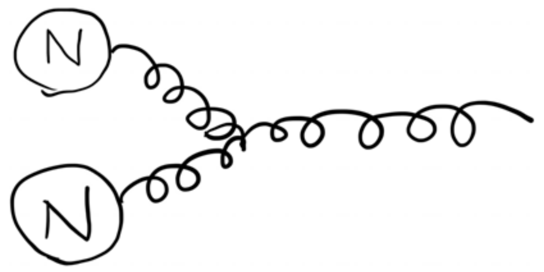
K. Watanabe



$g \to gg$

gluon splitting

$\propto N_g$



$gg \to g$

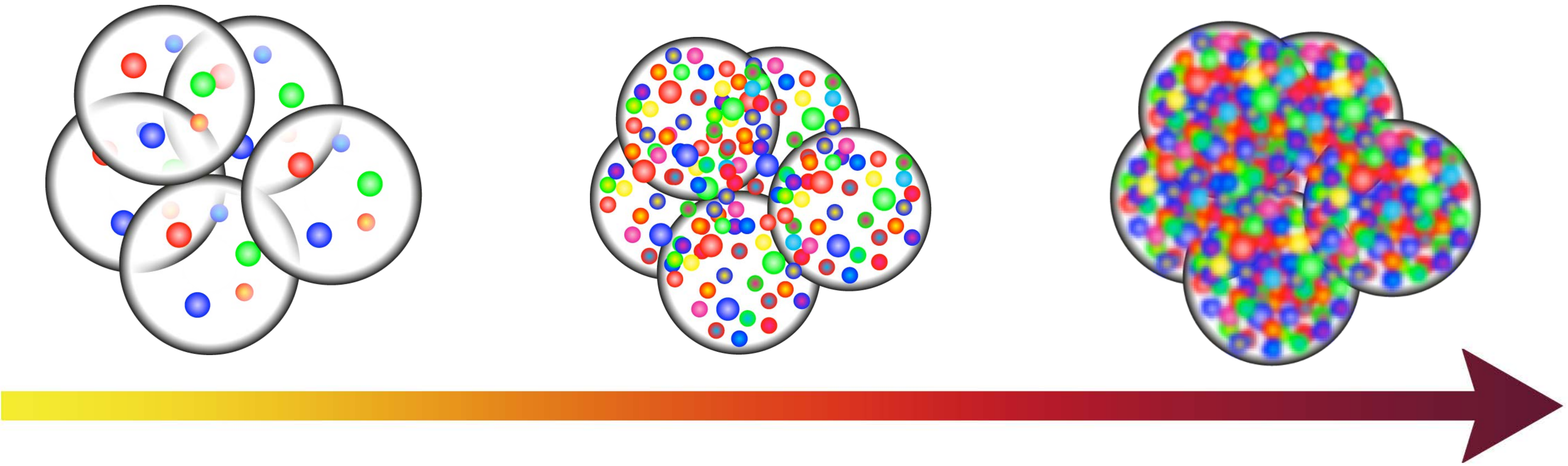
gluon merge

(non-linear effect)

$\propto N_g^2$

nucleus

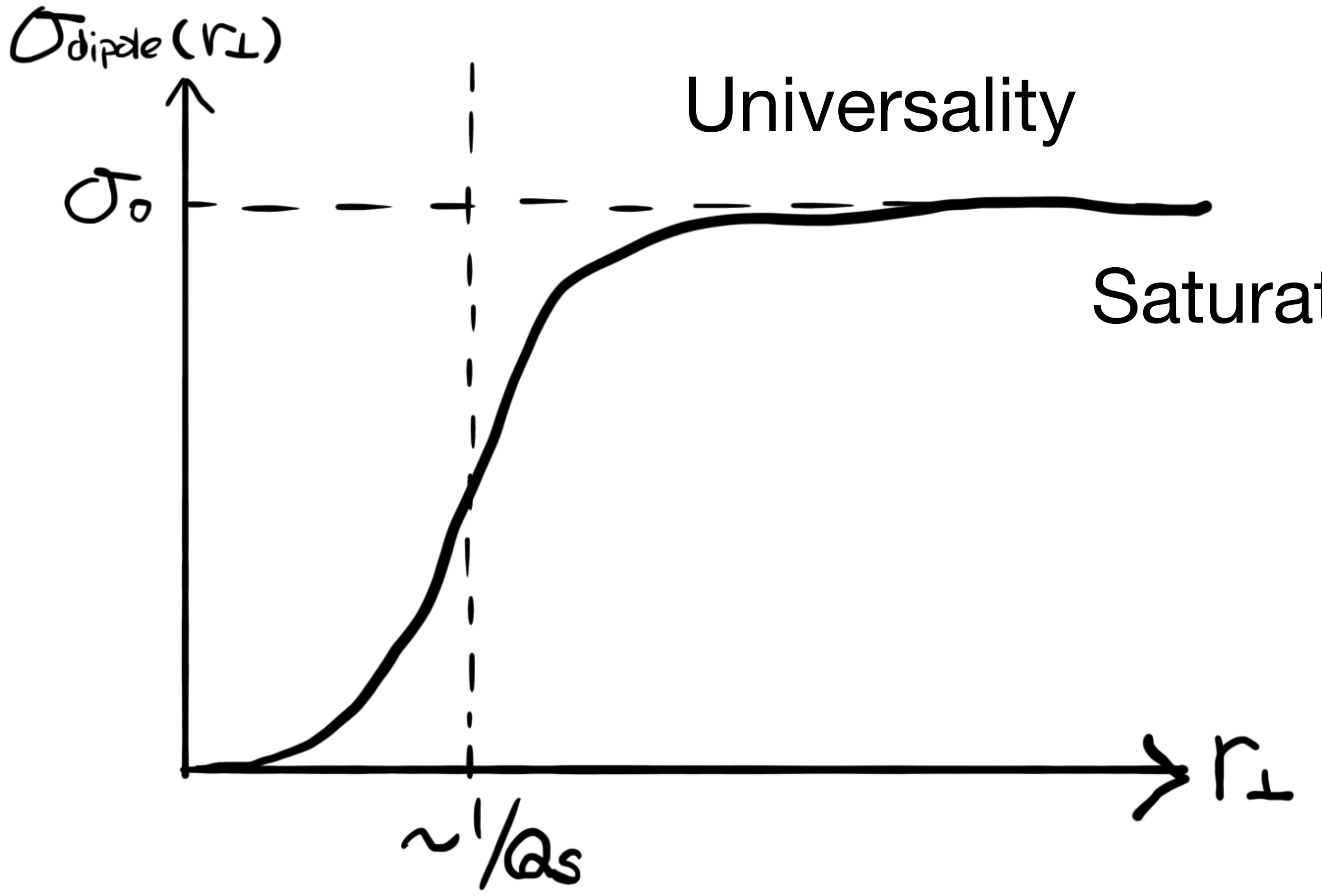
CGC!



e.g.) Logistic Eq.

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

⇄ Balitsky-Kovchegov (BK) e.q.

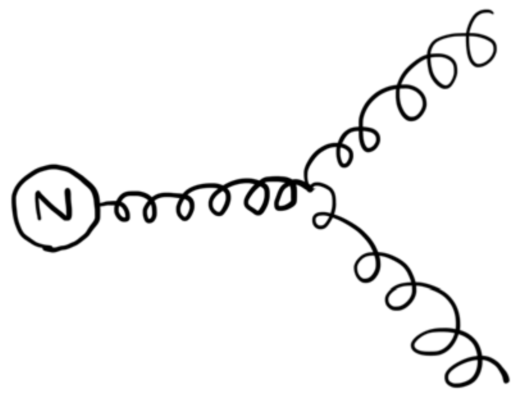


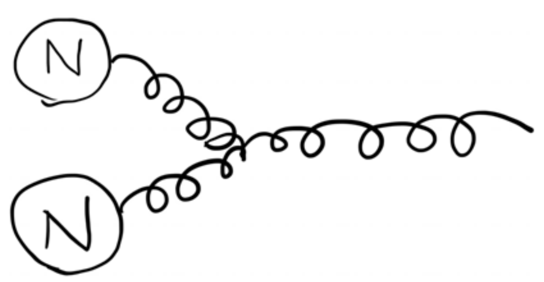
Large x
mid-rapidity
Low energy scattering

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

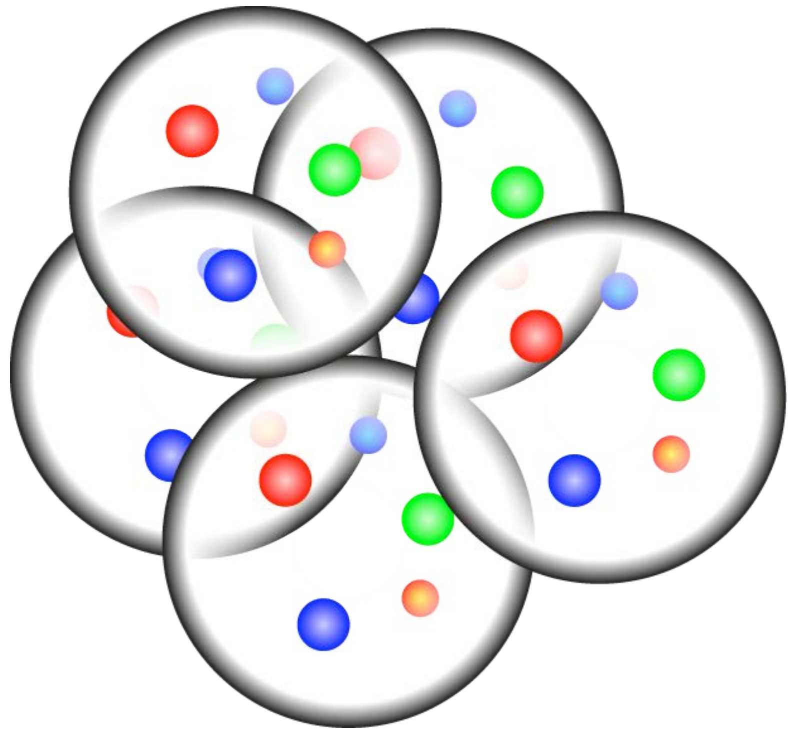
Small x
forward rapidity
High energy scattering

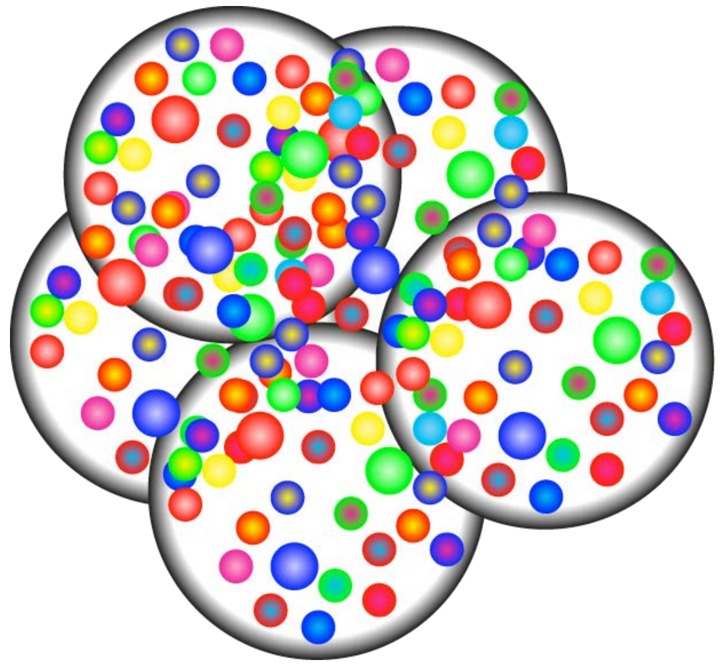
Color Glass Condensate (CGC)

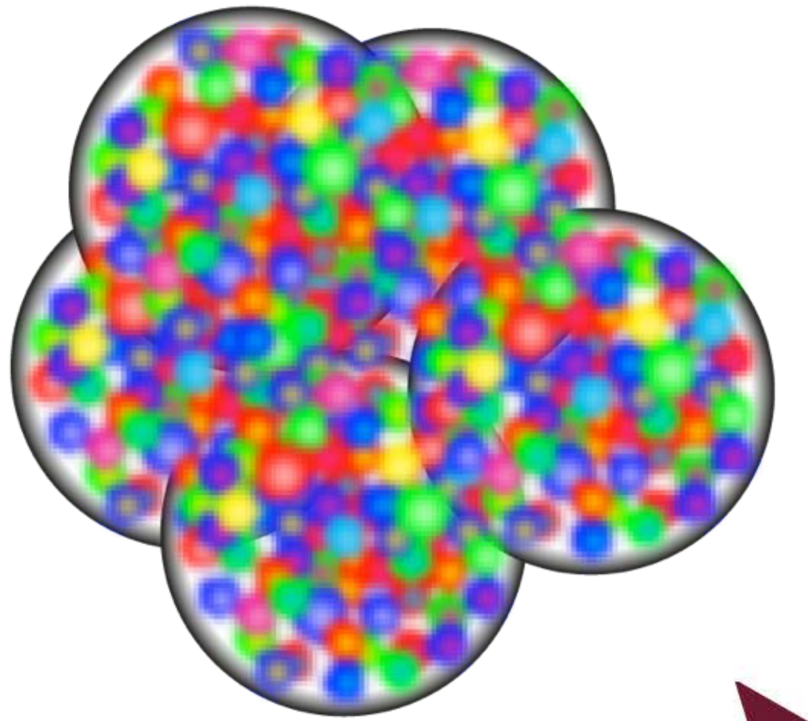




CGC!







g →gg

gluon splitting

$\propto N_g$

gg →g

gluon merge

(non-linear effect)

$\propto N_g^2$

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Large x

mid-rapidity

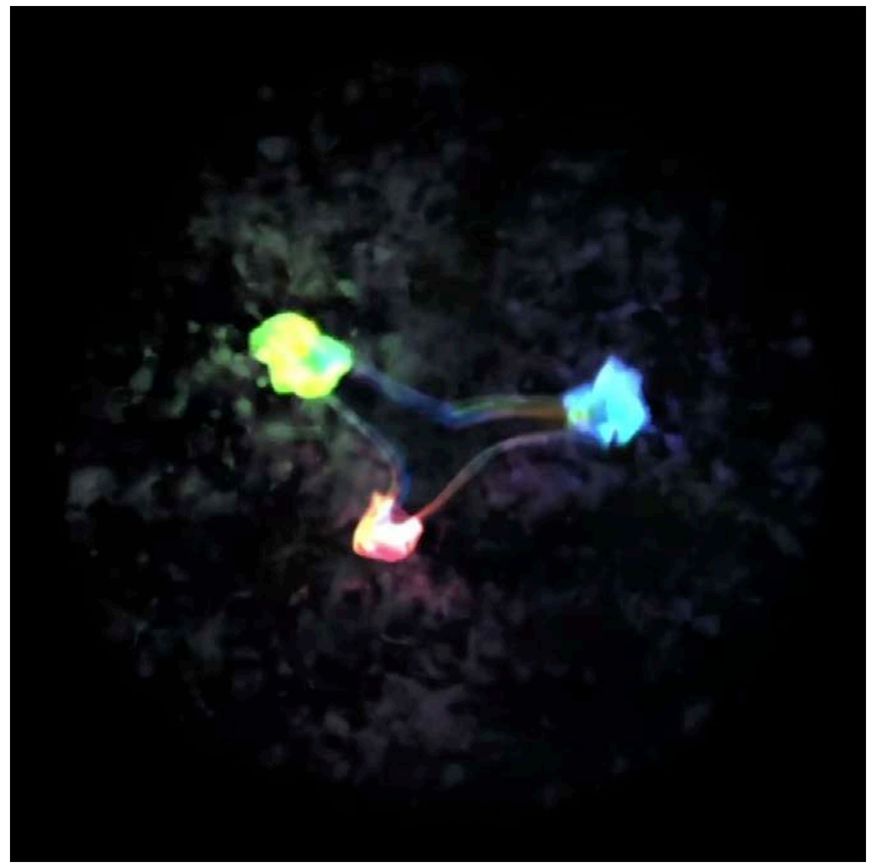
Low energy scattering

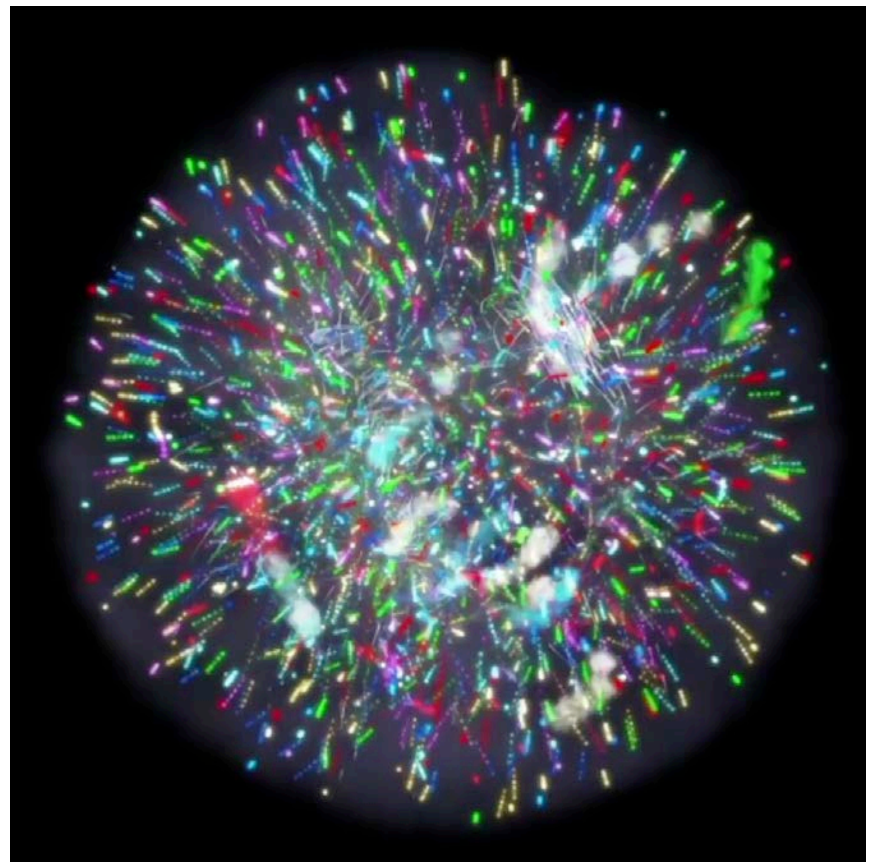
$$x \approx \frac{2p_T}{\sqrt{s}}\exp^{-\eta}$$

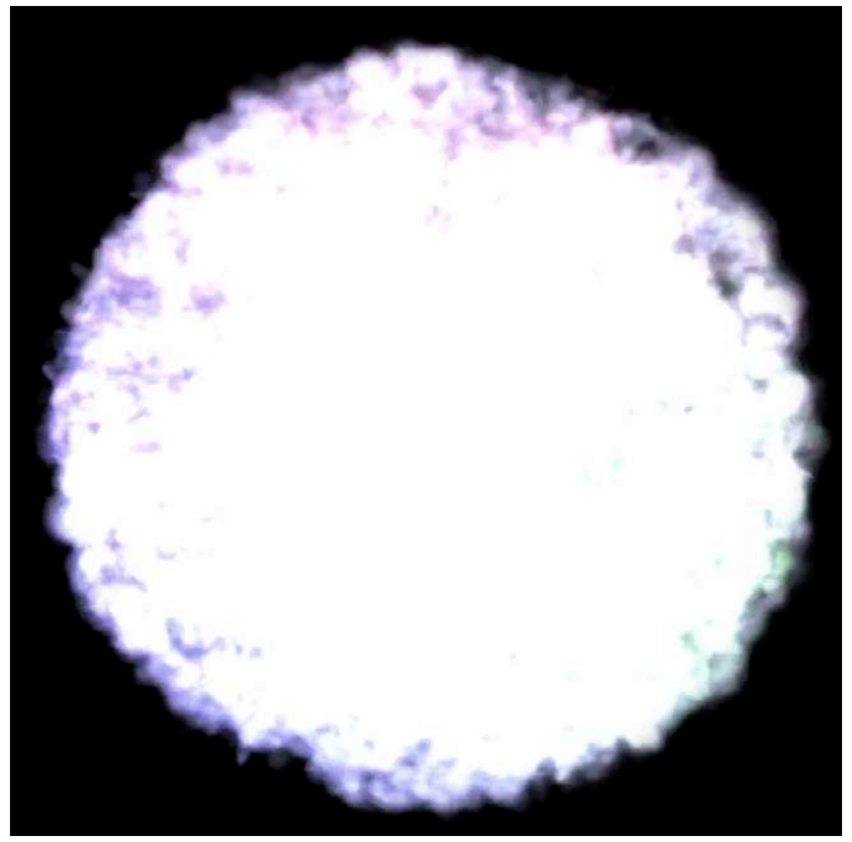
Small x

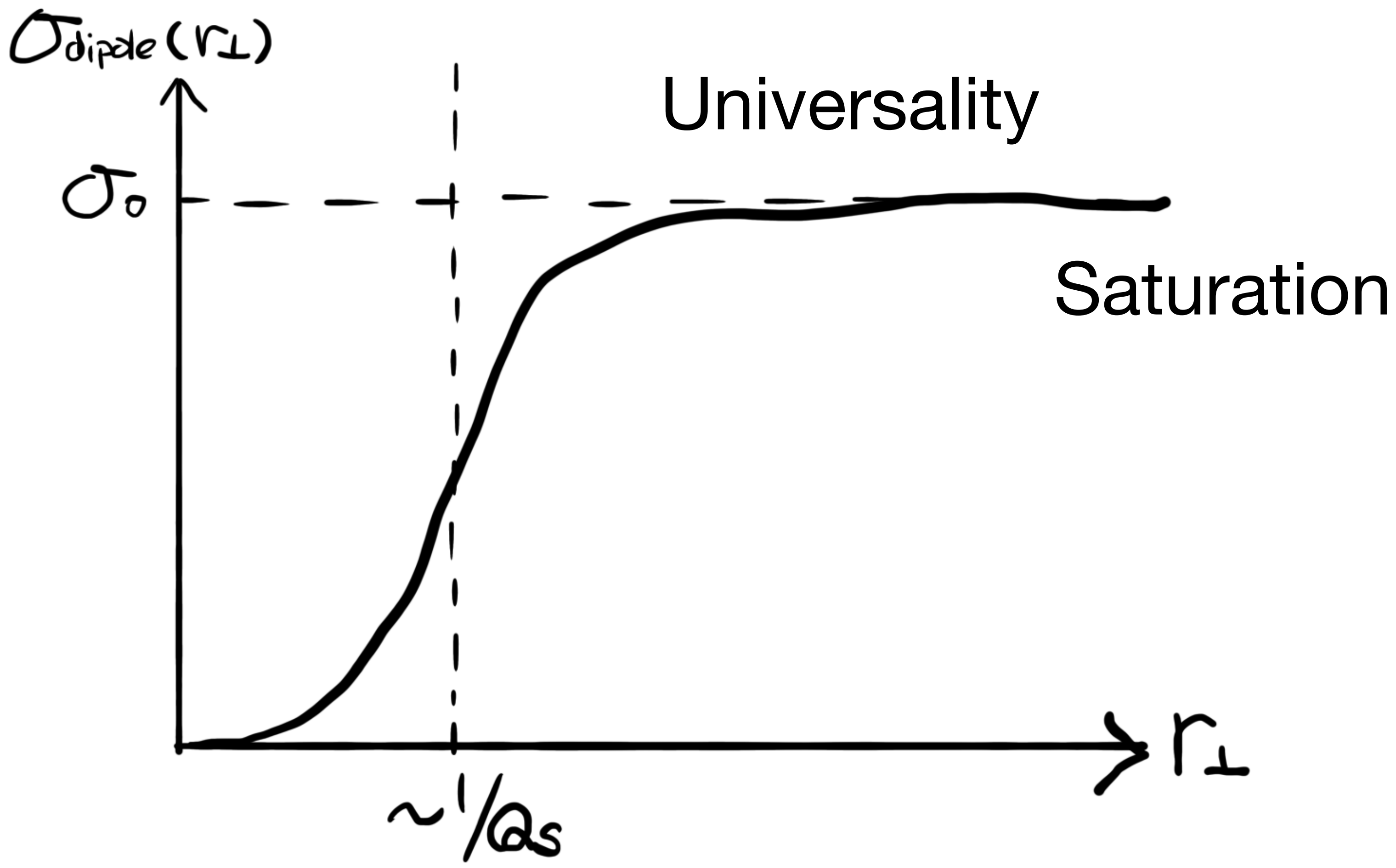
forward rapidity

High energy scattering

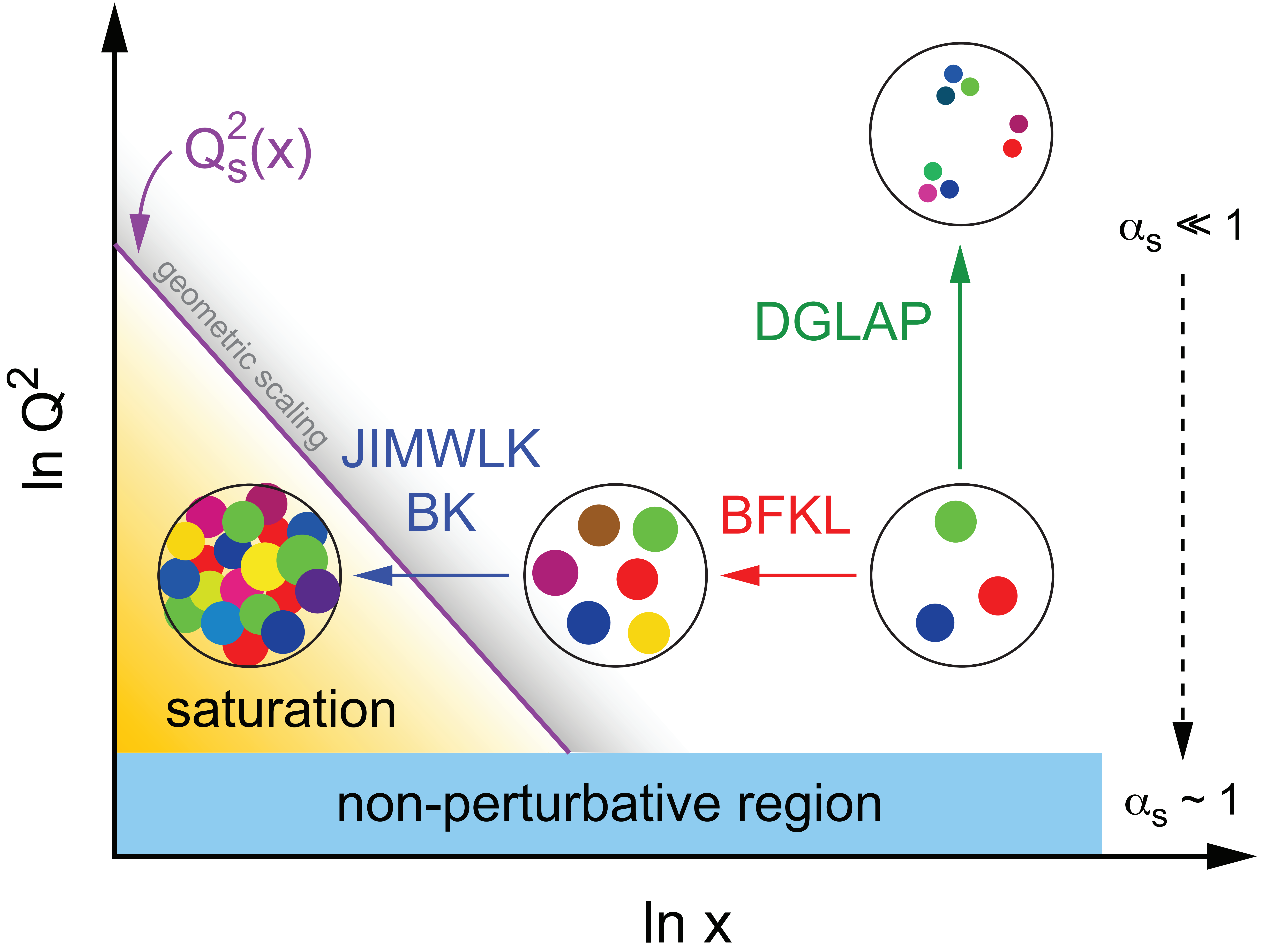








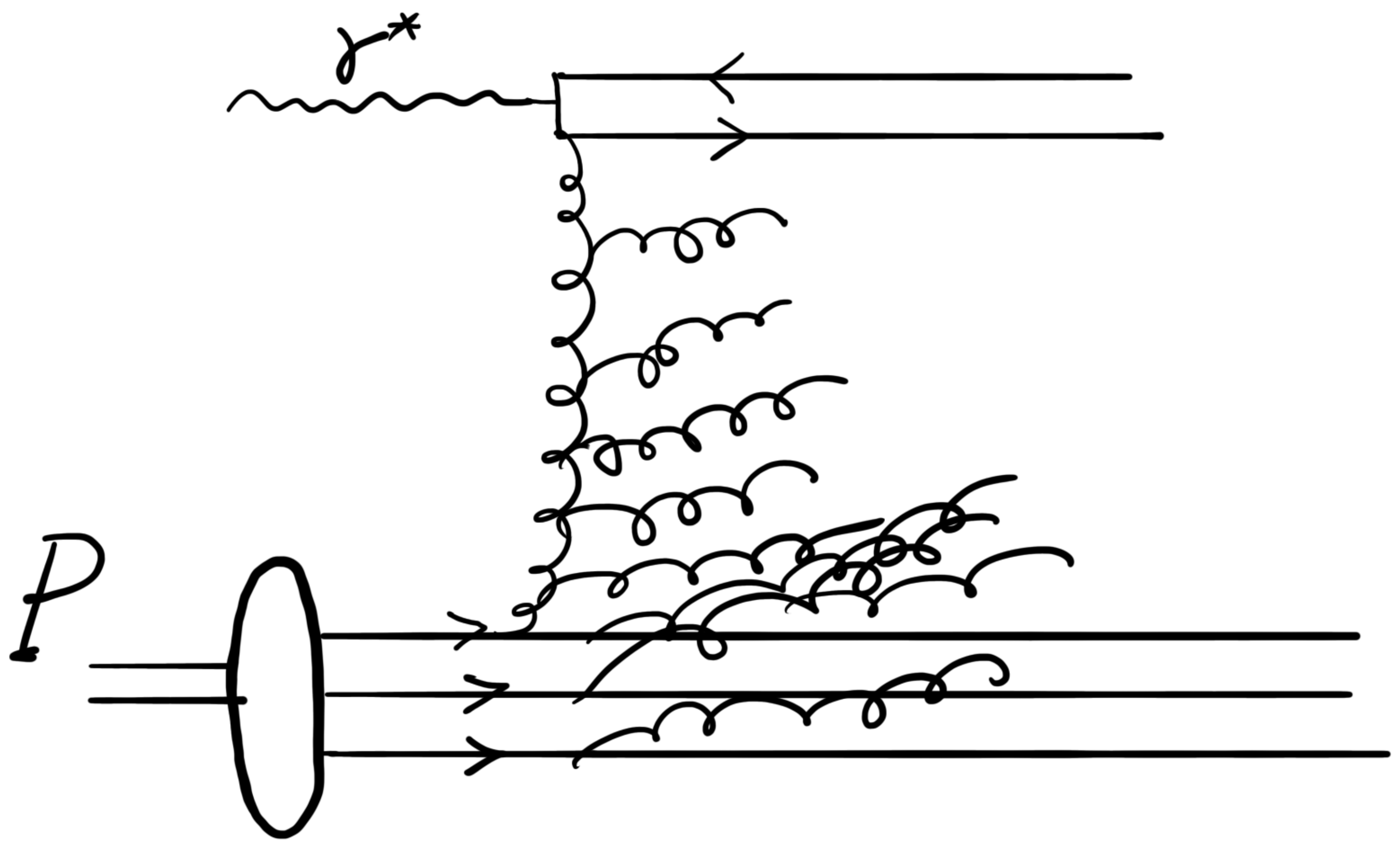
Where we can see CGC?

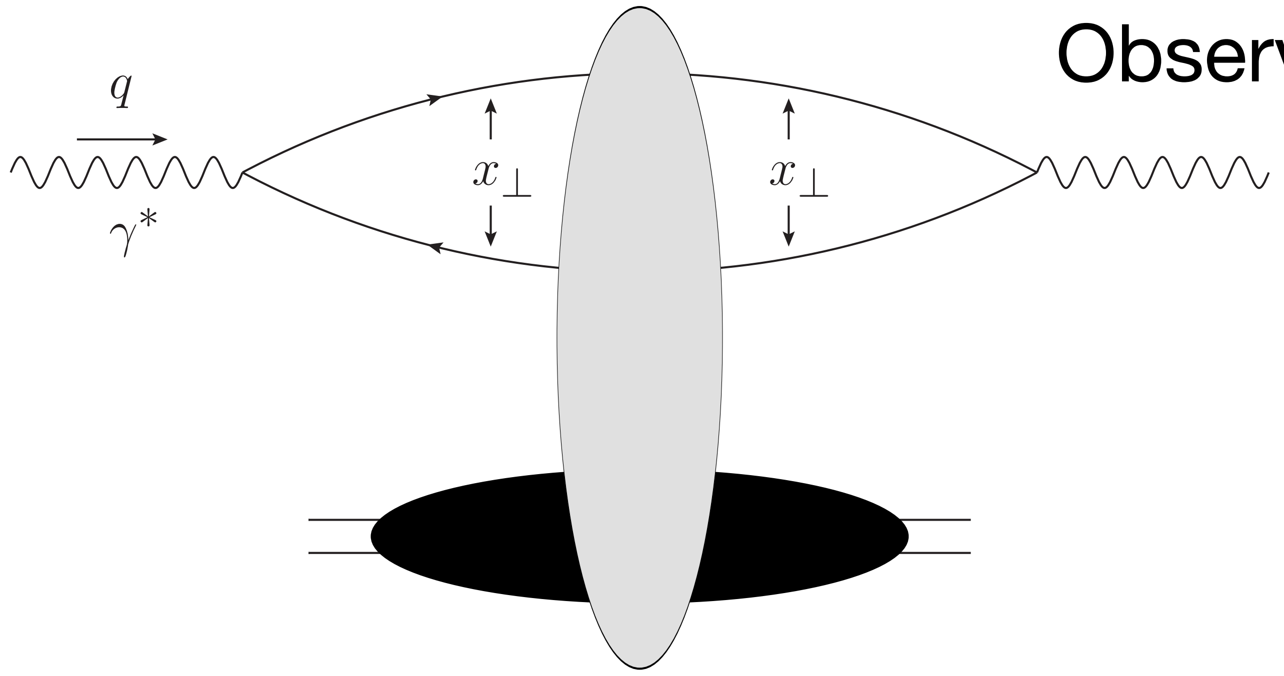


- **Small x and low Q** region (but $Q >> \Lambda_{QCD}$)
- **Universal picture** of internal structure of high energy hadron (universality)
- Log-Log plot !

  → **Essential to explore a wide x-Q^2 space**
- Non-linear QCD evolution
- Find CGC signal → Gluon density

How we probe gluon density (dipole formalism)



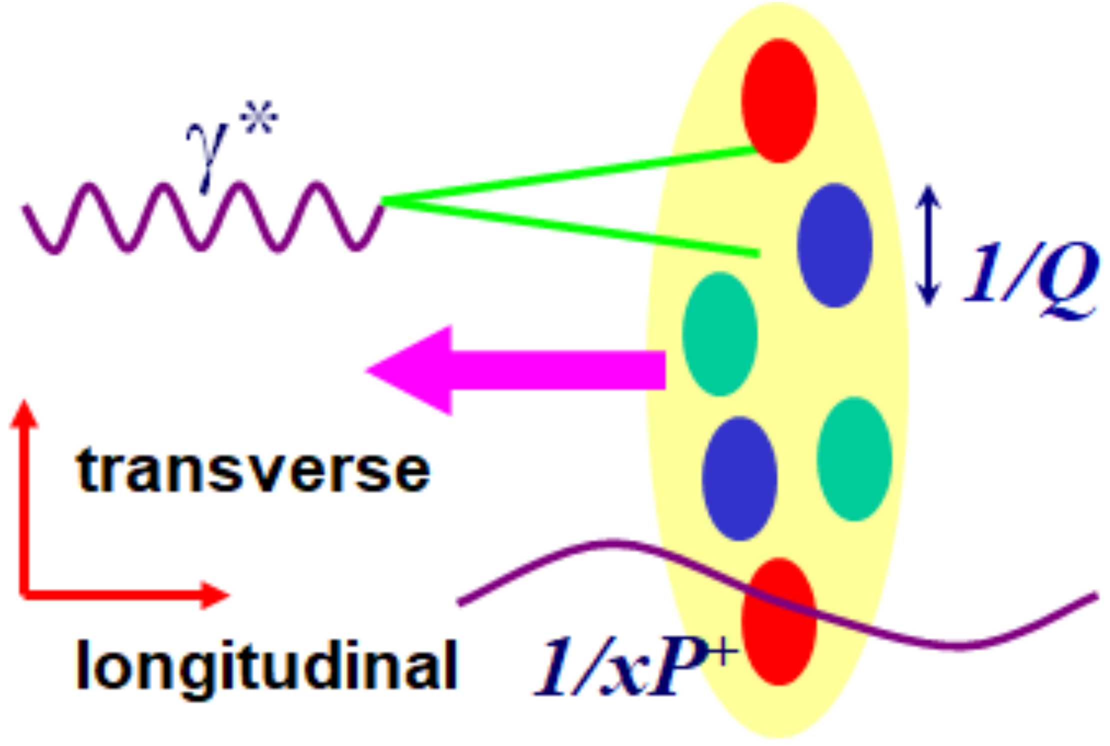


e+A DIS

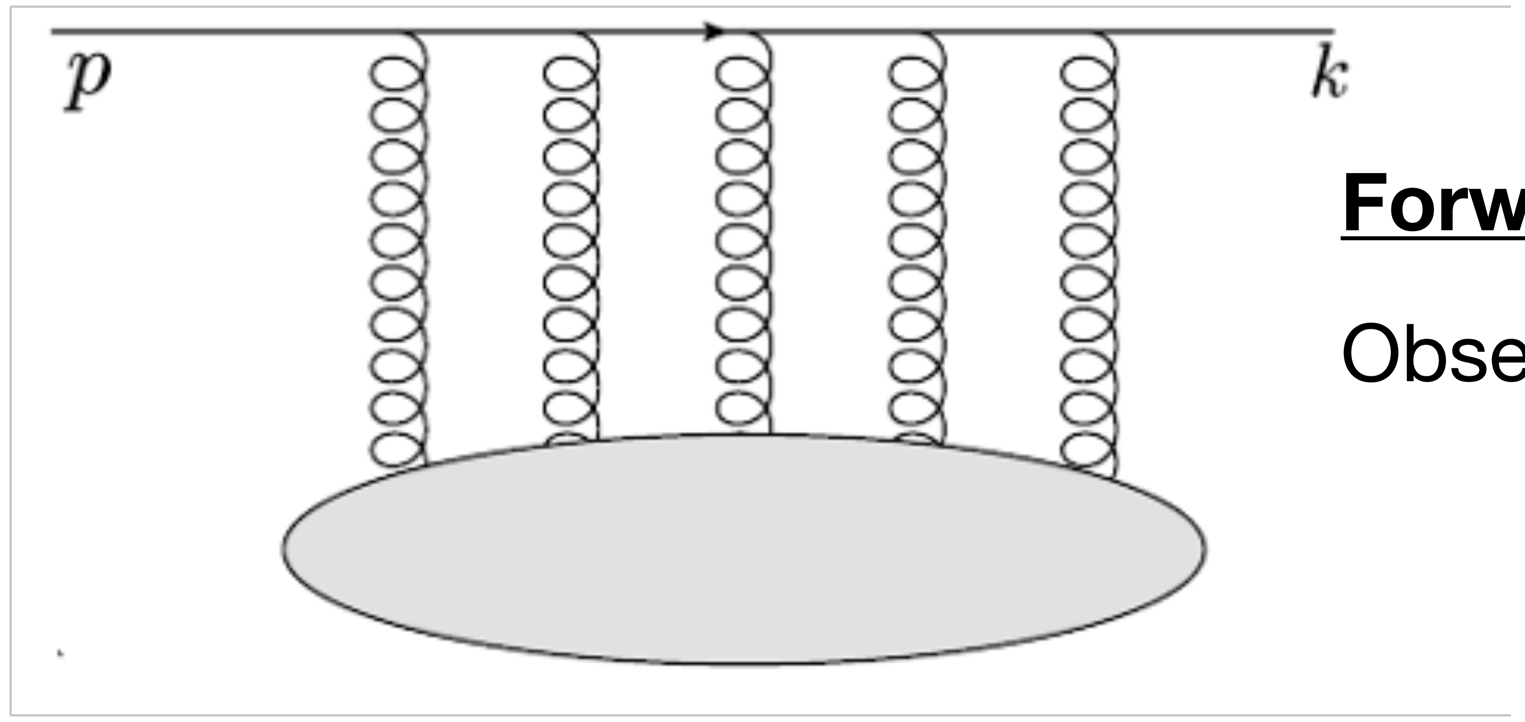
Observables : int. cross section, Structure func. (F_2, F_L)

$$\sigma_{\gamma^* T} = \int_0^1 dz \int d^2\mathbf{r}_\perp |\psi^{\gamma^* \to q\bar{q}}(z, \mathbf{r}_\perp)|^2 \sigma_{\text{dipole}}(x, \mathbf{r}_\perp)$$

$$\sigma^{\text{LO}}_{\text{dipole}}(x, \mathbf{r}_\perp) = 2 \int d^2\mathbf{b}\, T_{\text{LO}}(\mathbf{b} + \frac{\mathbf{r}_\perp}{2}, \mathbf{b} - \frac{\mathbf{r}_\perp}{2})$$



K. Itakura



Forward p+A

Observables: Inclusive π^0, jet, direct γ, γ-jet, di-jet

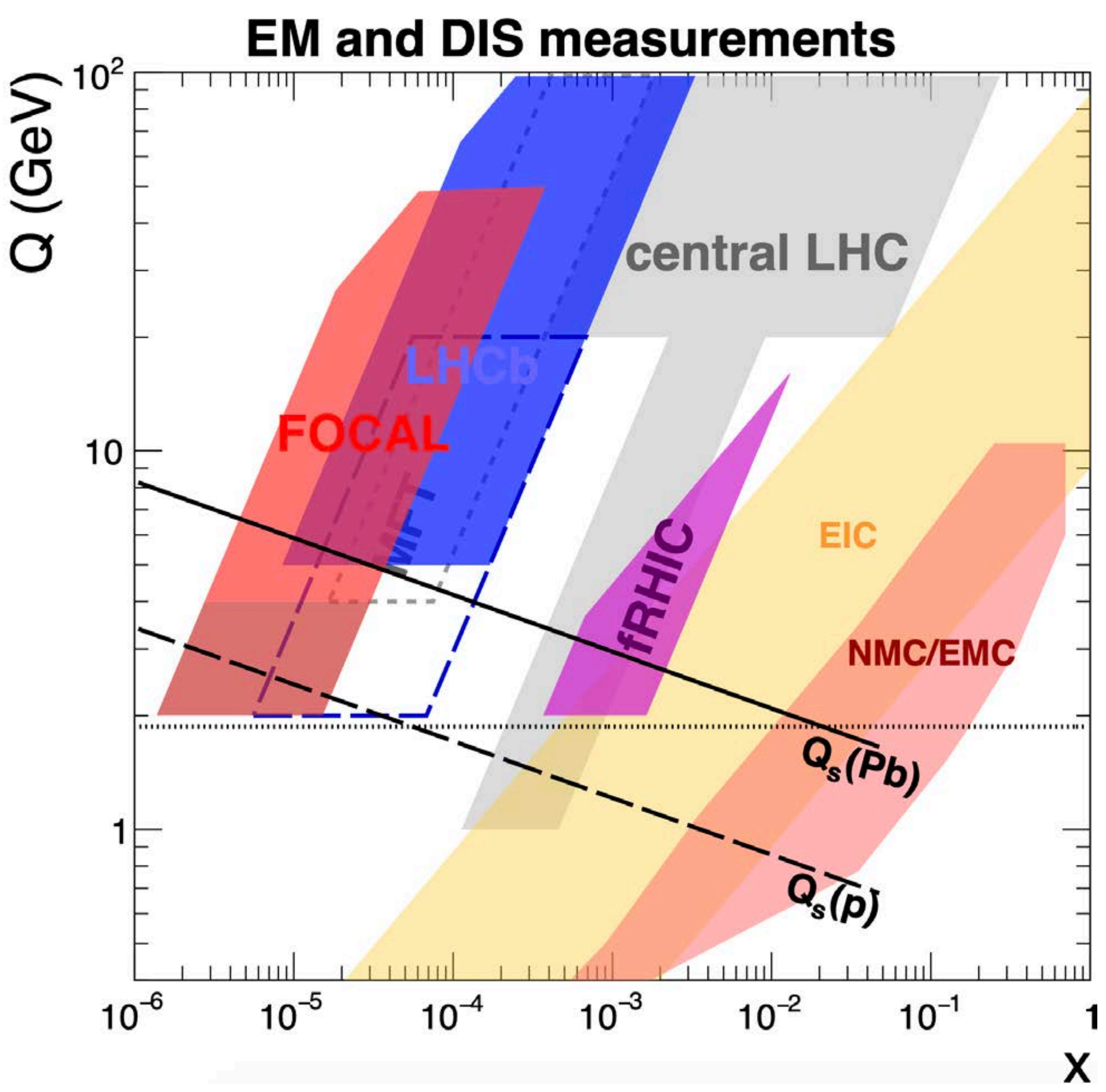
$$|M|^2_{\text{LO}} \propto \int d^2\mathbf{b}\, d^2\mathbf{r}_\perp e^{i\mathbf{p}_\perp \cdot \mathbf{r}_\perp} T_{\text{LO}}(\mathbf{b} + \frac{\mathbf{r}_\perp}{2}, \mathbf{b} - \frac{\mathbf{r}_\perp}{2})$$

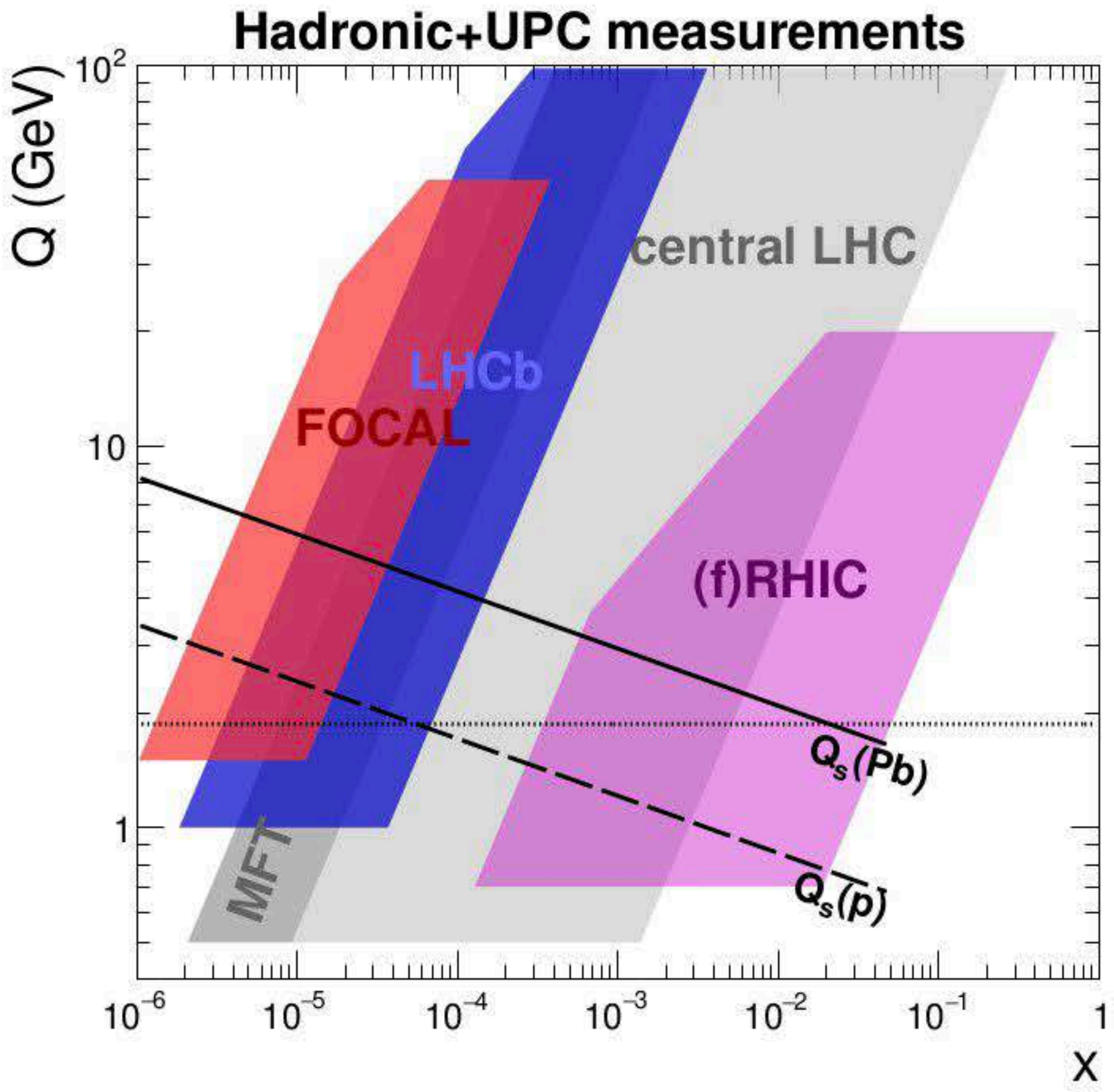
e+A DIS & p+A forward observables: same theoretical Framework **"Color Dipole (Quadrupole) Formalism"**

→ NLO cal. is possible

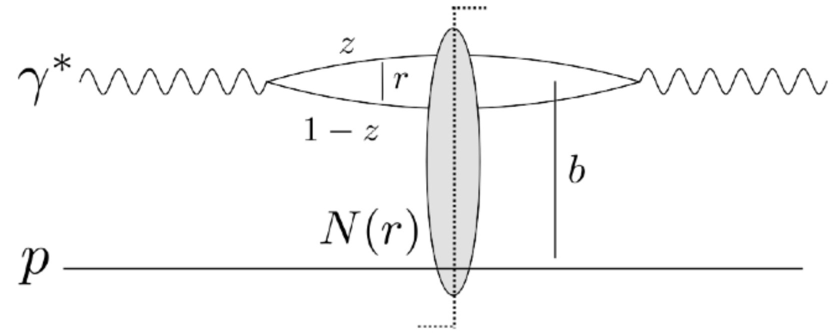
→Comparison e+A DIS with forward p+A：**Universality of QCD can be tested**

EIC vs. forward LHC

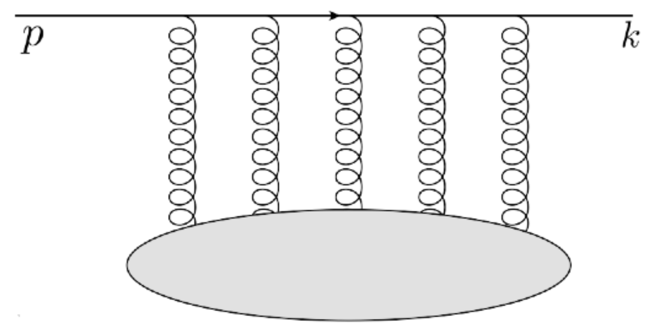




DIS (EIC) eA



Forward pA
at high energies



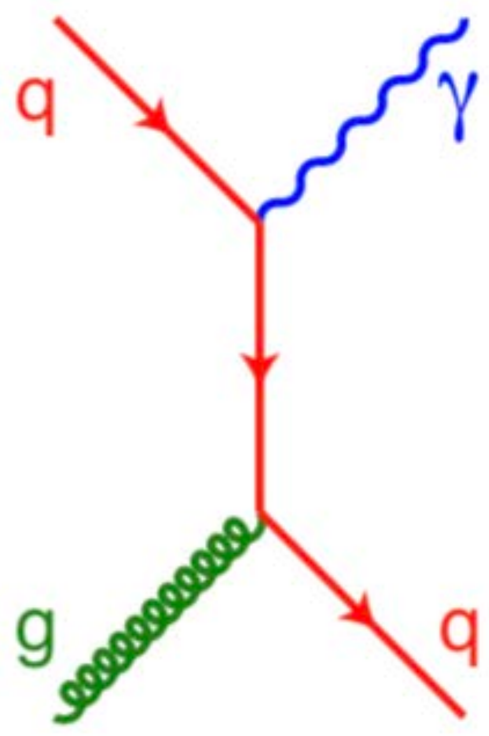
$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

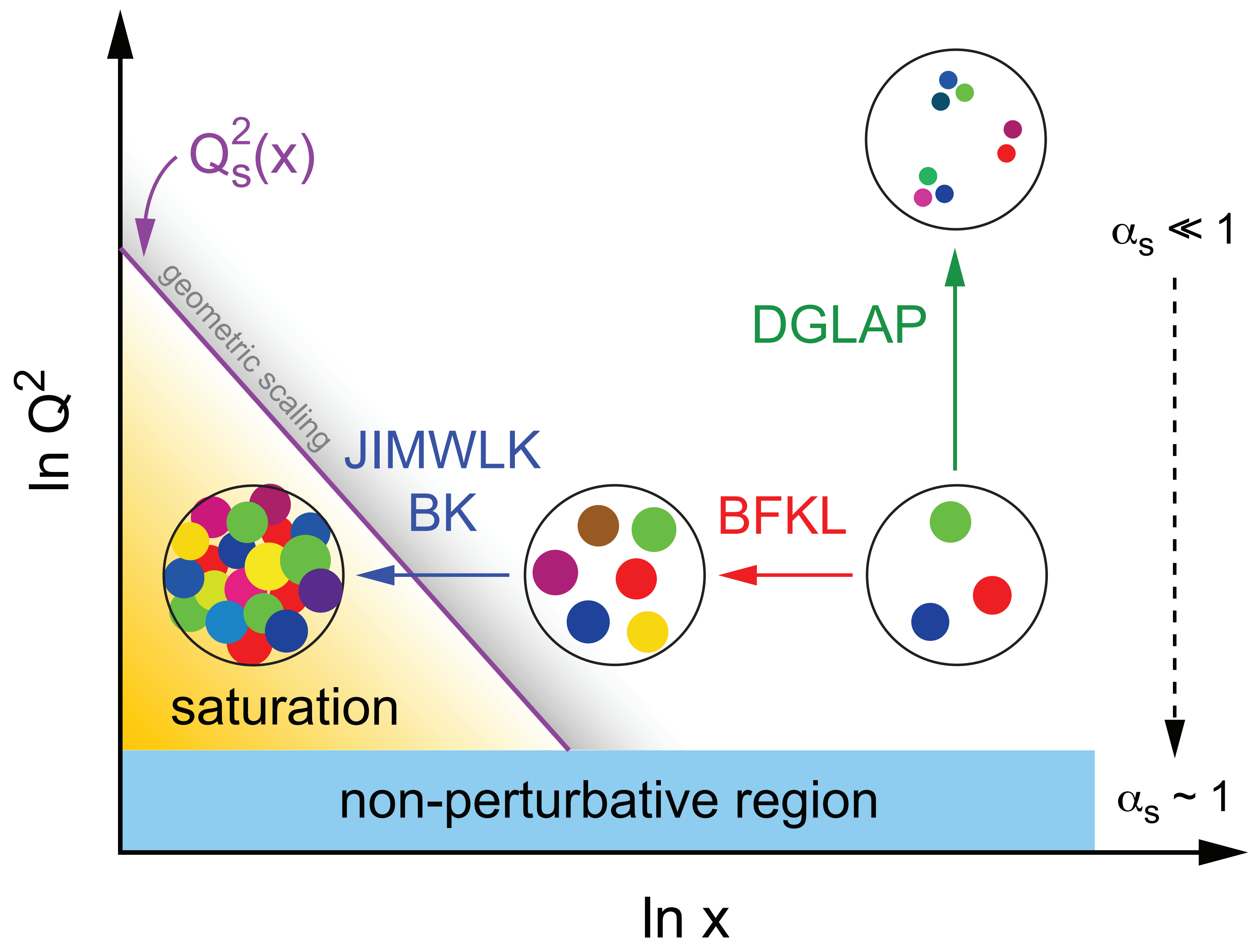
$$\text{Dipole } N = 1 - \frac{1}{N_C} \mathrm{tr} V(x) V^\dagger(y)$$

- 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?

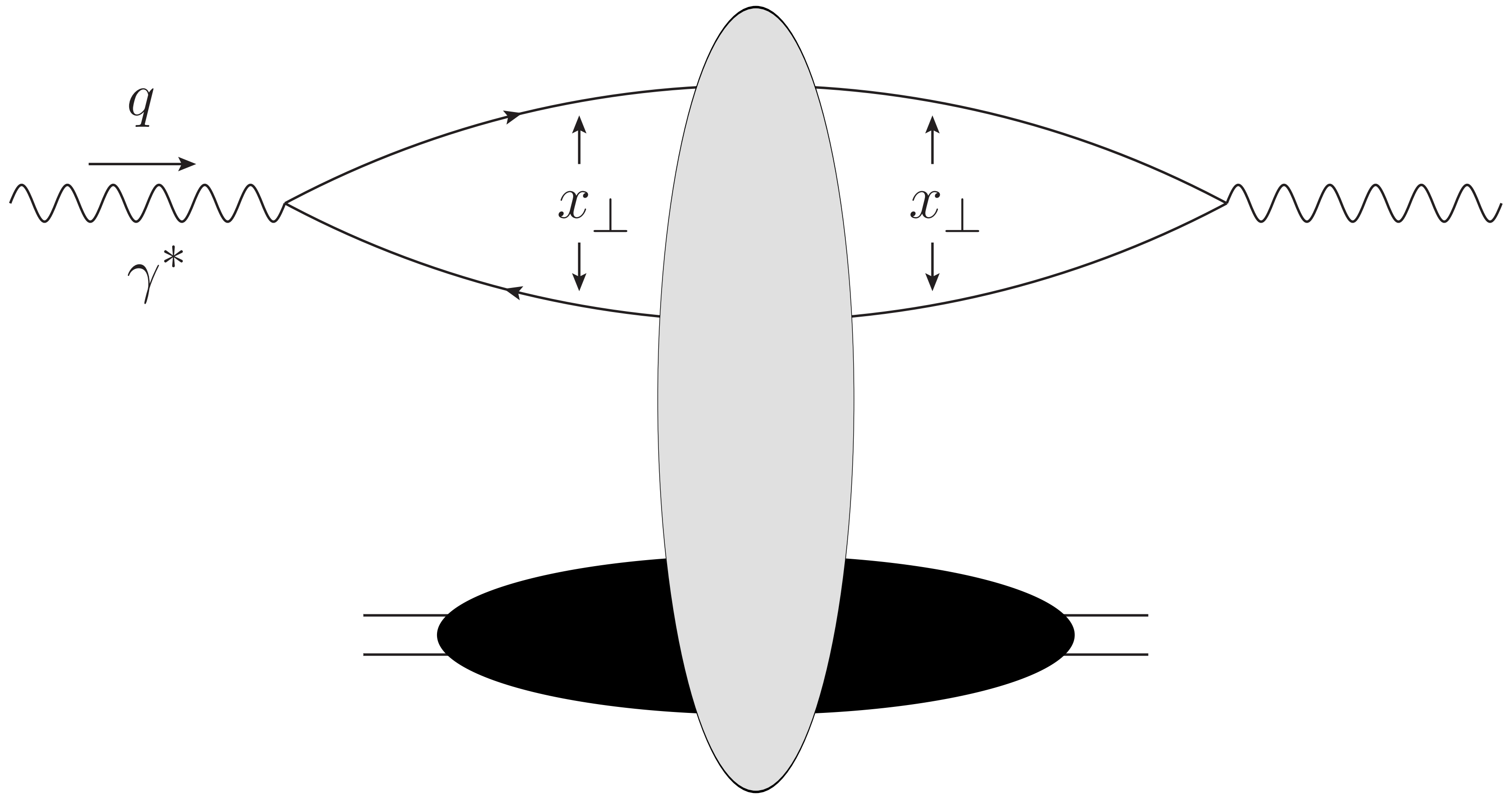
Key points to understand CGC and QCD

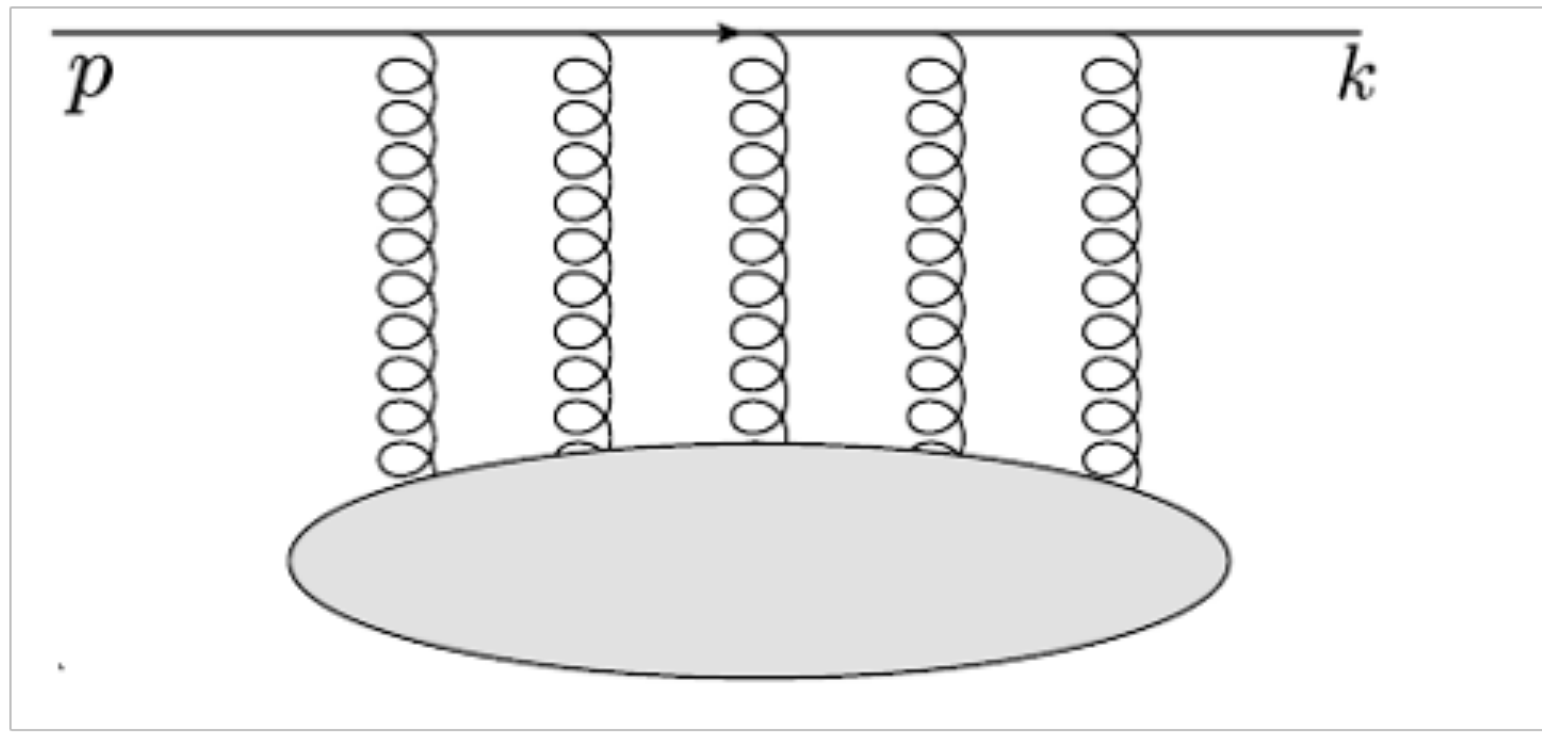
- **Need a clear CGC signal**
  - Hadron measurement →Uncertainty by fragmentation
  - Need a clean probe (e.g) q + g -> γ + q
- **Need to see non-linear evolution of QCD**
  - Explore wide rage of x-Q^2 space
- Theoretically calculable and compare with data (CGC weakly coupled physics) → color dipole
- High precision measurements (statistic, systematic)



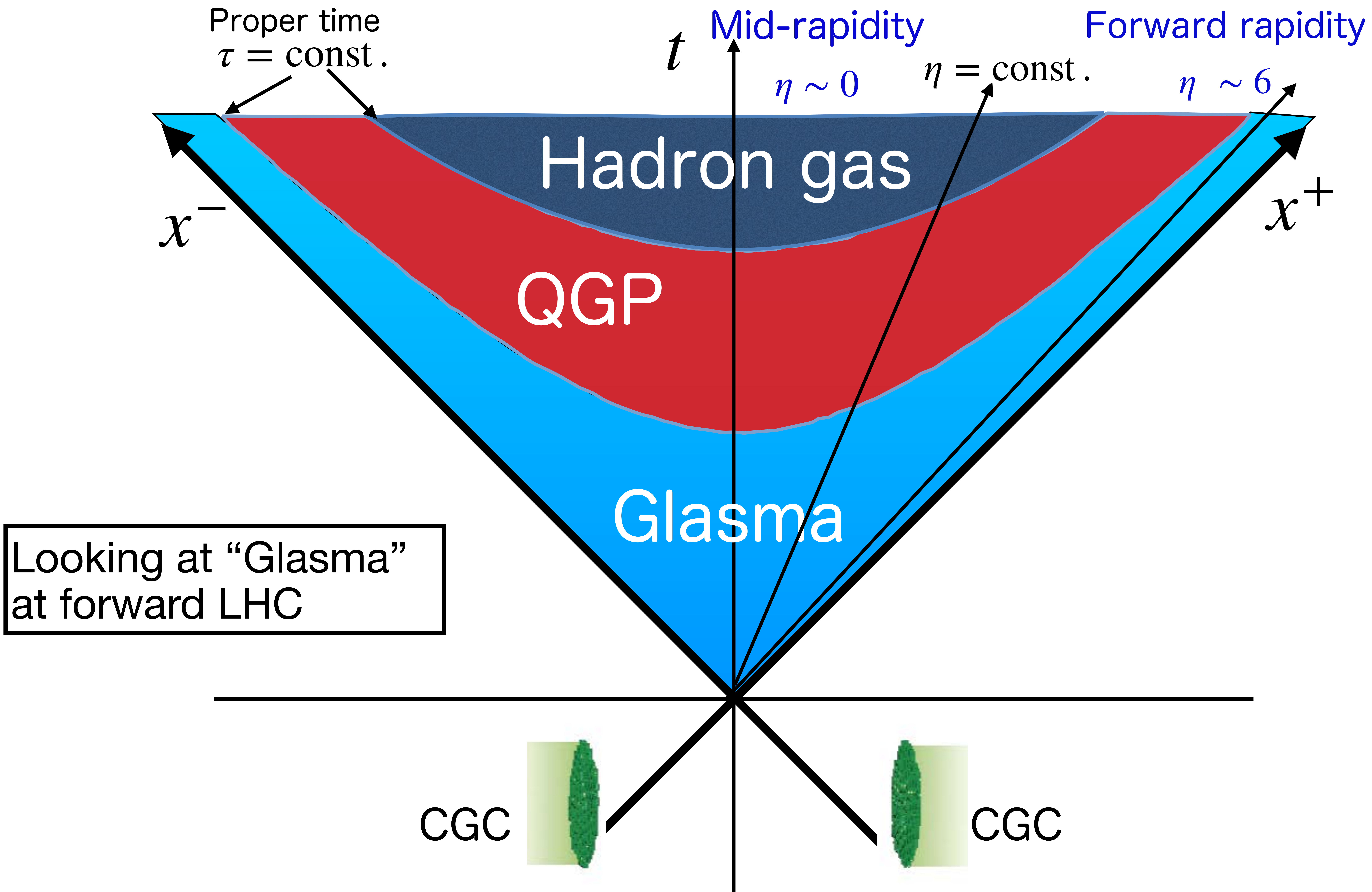


Next generation experiments (LHC forward pA, EIC eA)

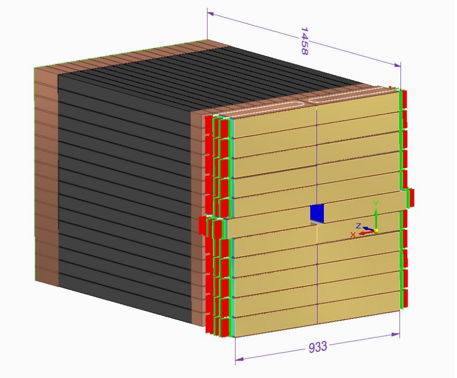




Ultimate question:How is QGP created by HIC?

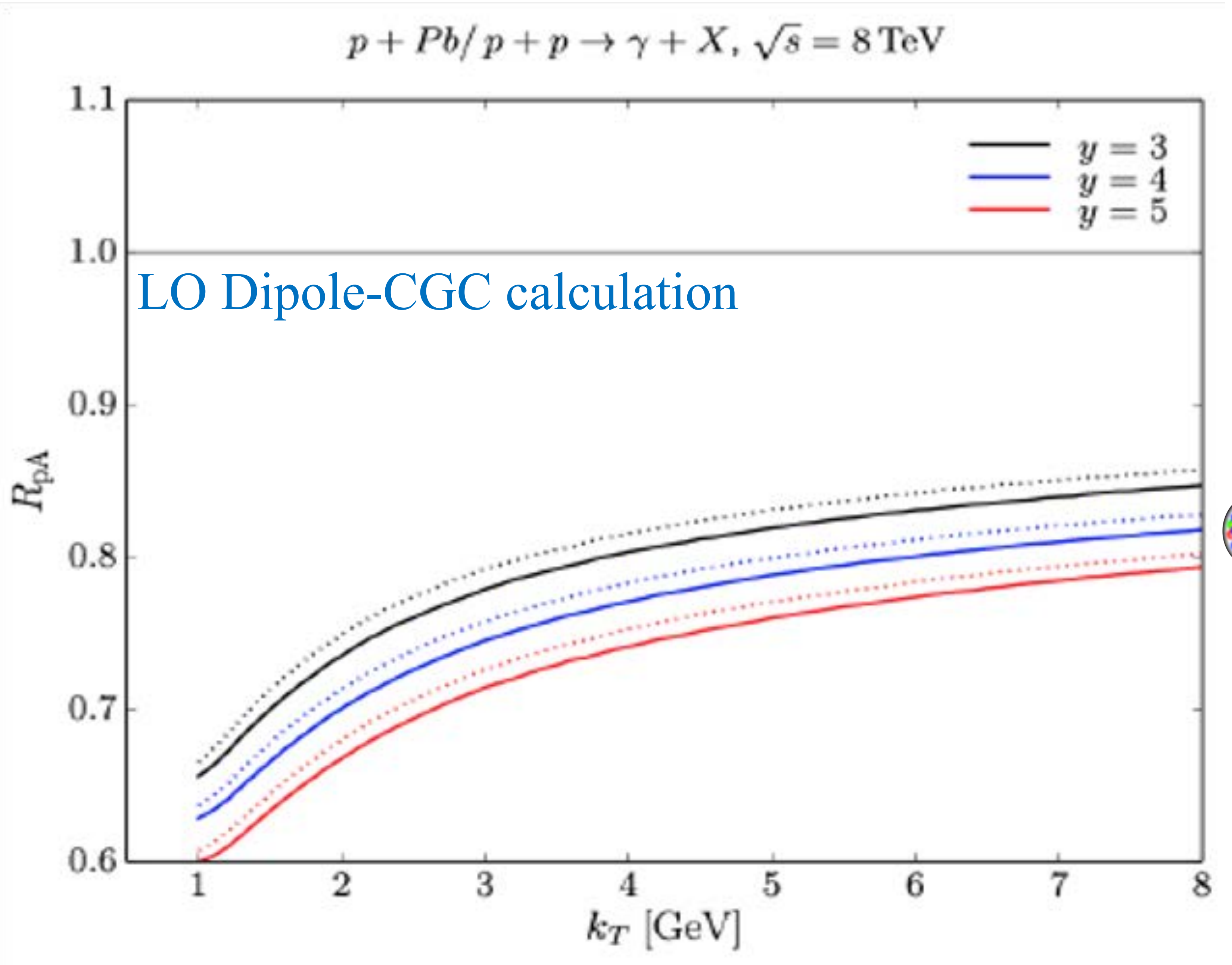

Proper time
$\tau = \mathrm{const.}$
t
Mid-rapidity
Forward rapidity
$\eta = \mathrm{const.}$
$\eta \sim 0$
$\eta \sim 6$
Hadron gas
x^-
x^+
QGP
Glasma
Looking at "Glasma" at forward LHC
CGC
CGC

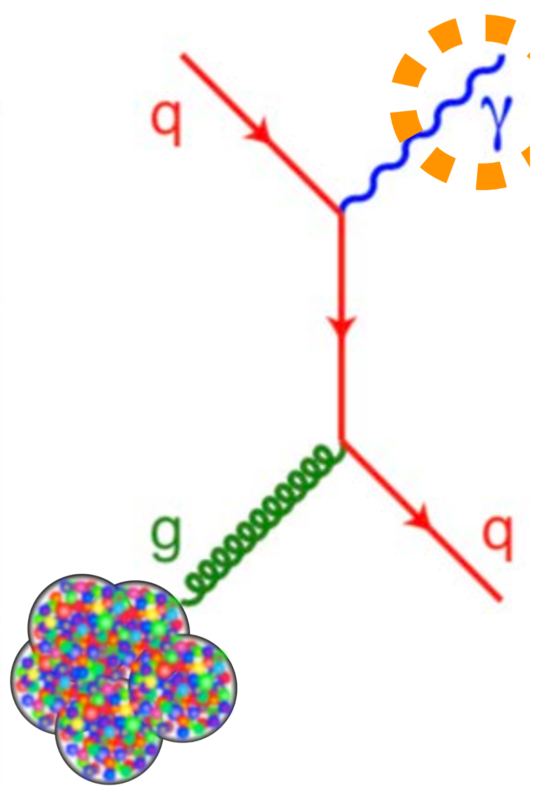
FoCal/EIC and CGC

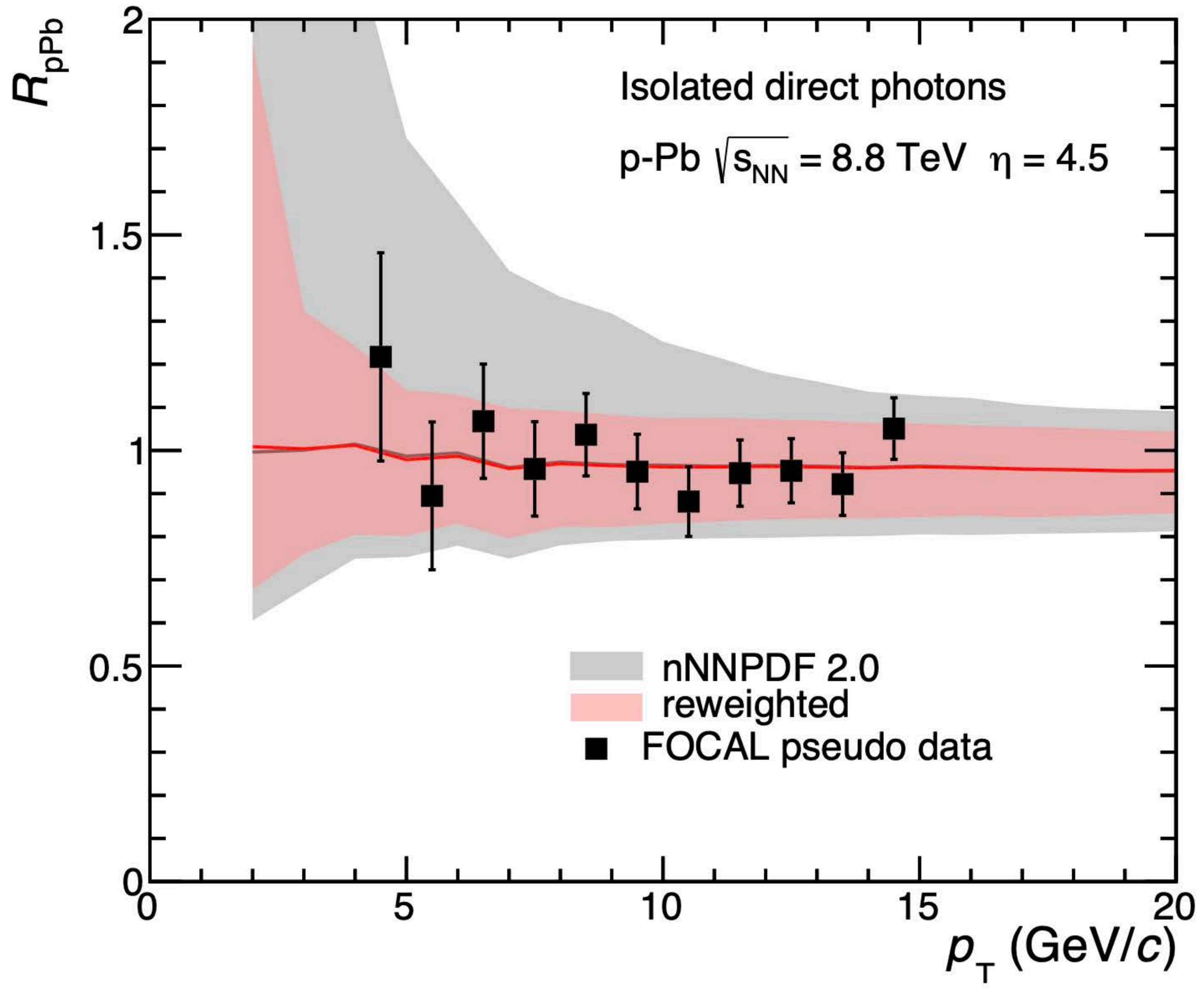


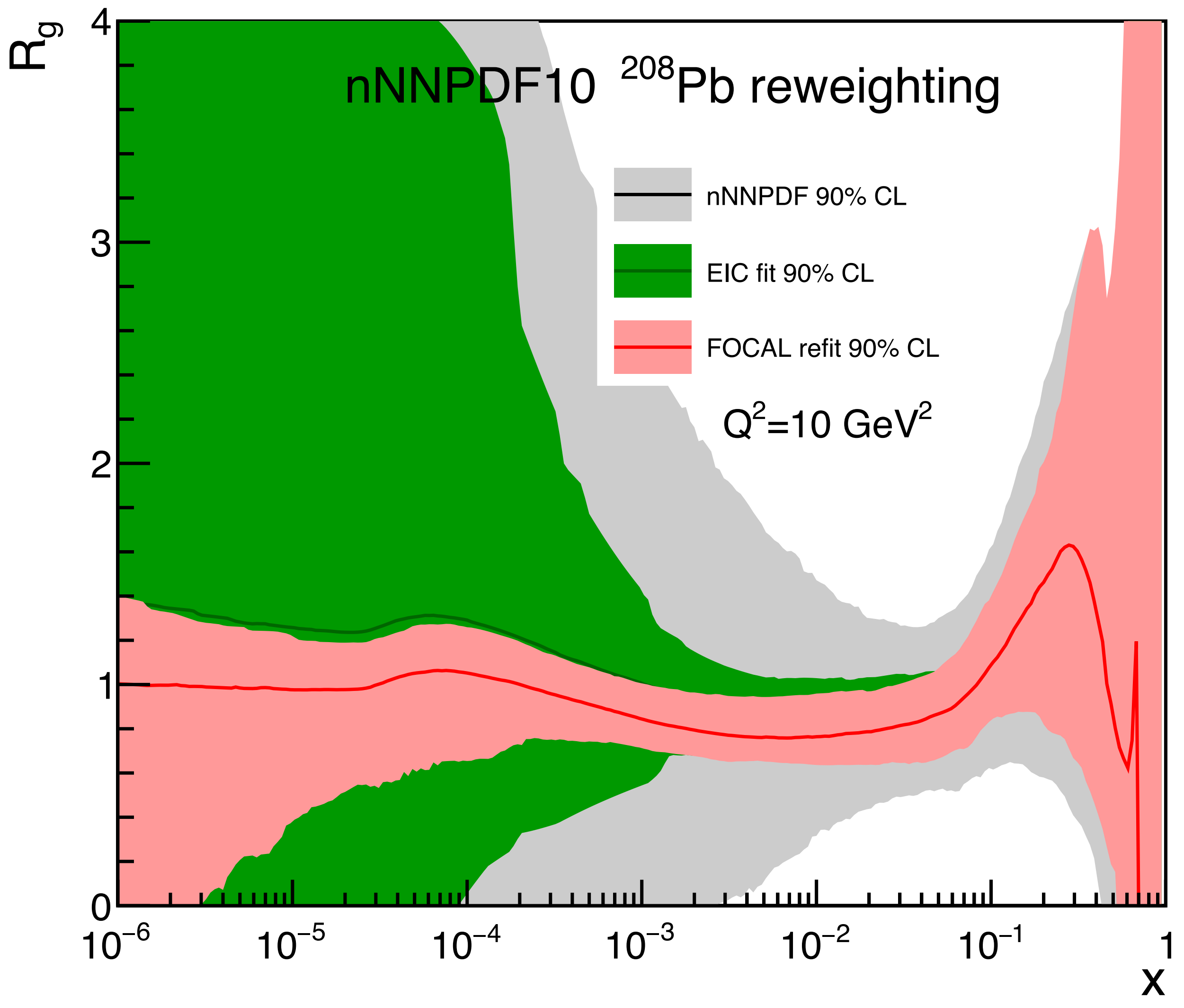
Saturation signal in FoCal (1)

R_{pPb}: forward γ

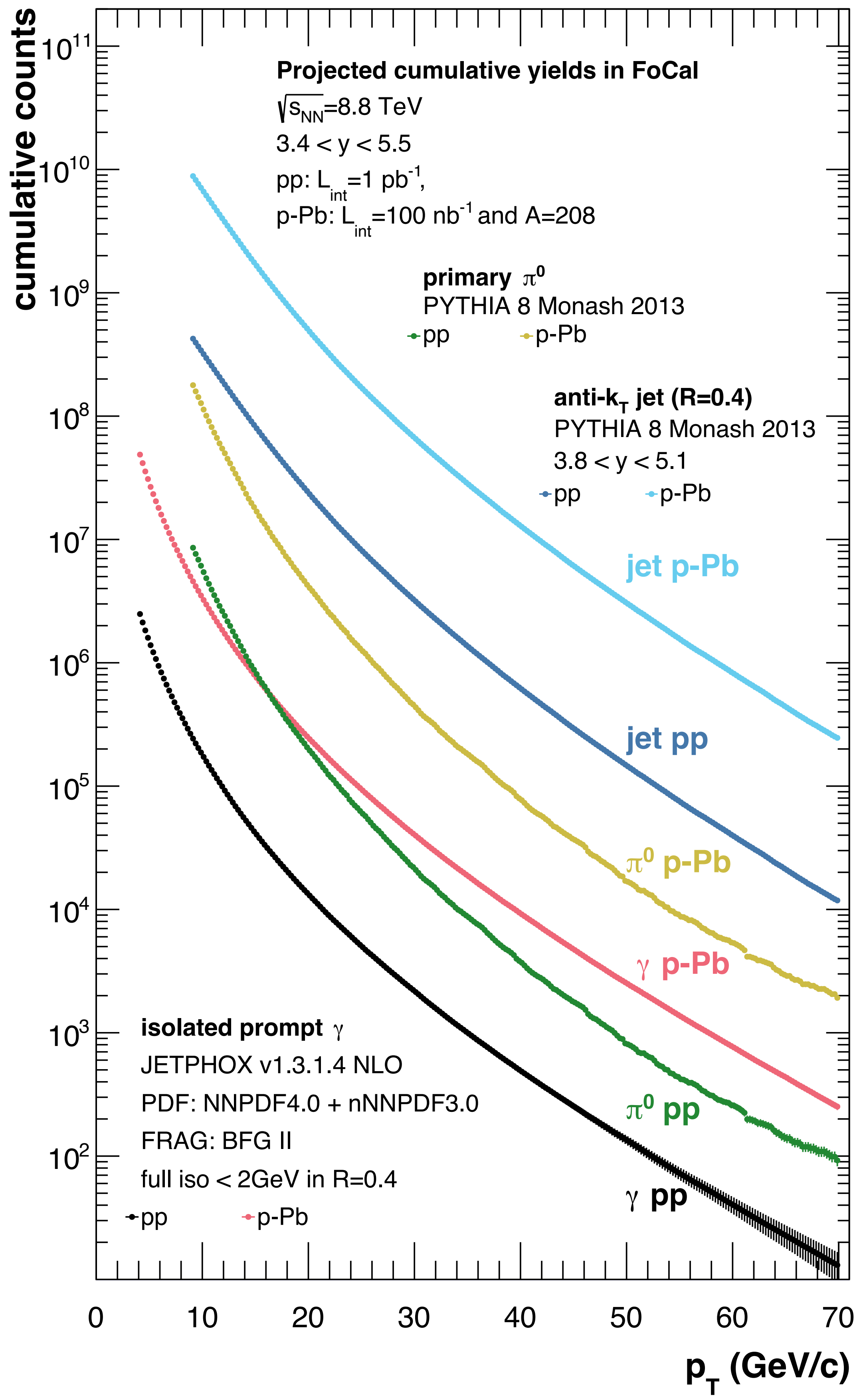








Expected yields in FoCal (Run-4)



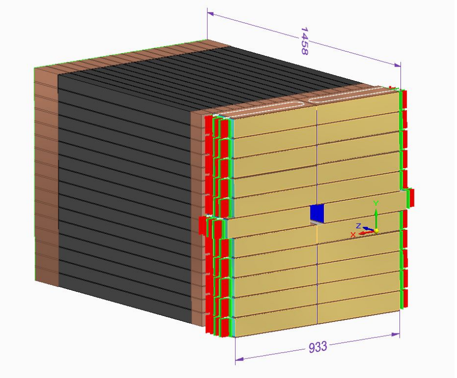
- Large suppression at low p_T for isolated γ

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

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

- 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};

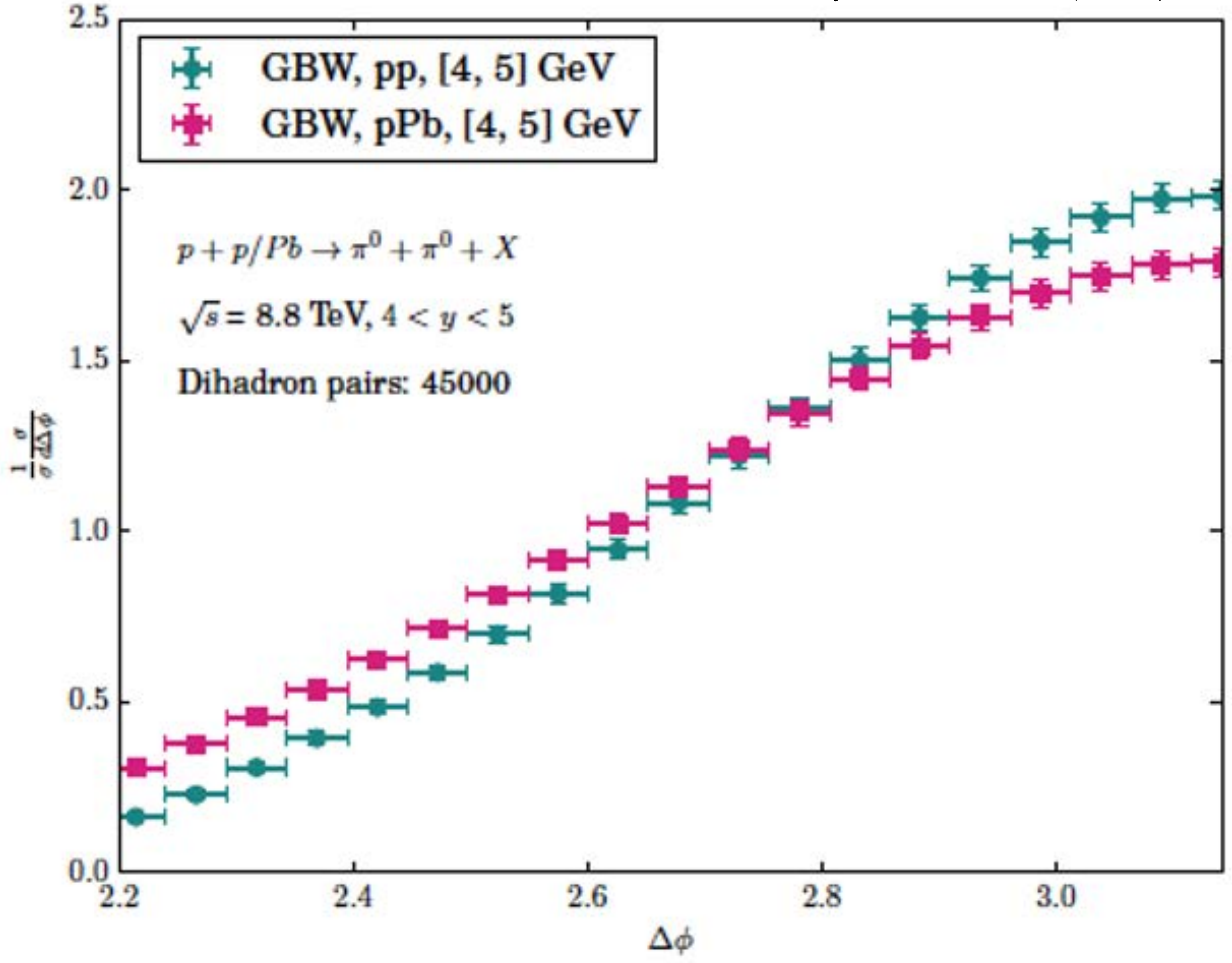
- Expected gluon saturation (CGC) in small-x, not yet clear evidence
- Excellent probe: isolated photons from quark-gluon Compton scattering



Saturation signal in FoCal (2)

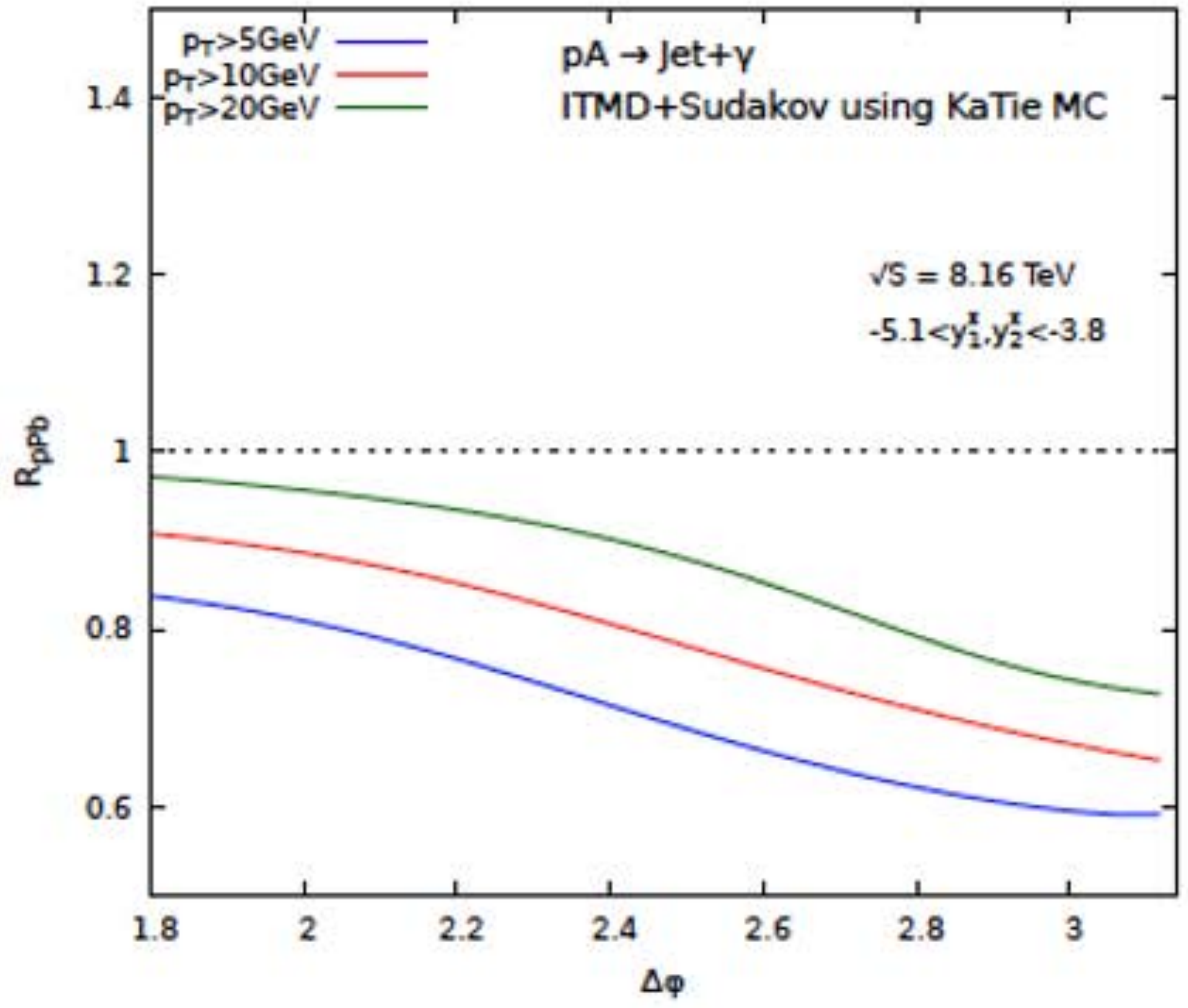
Di-hadron Correlations

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

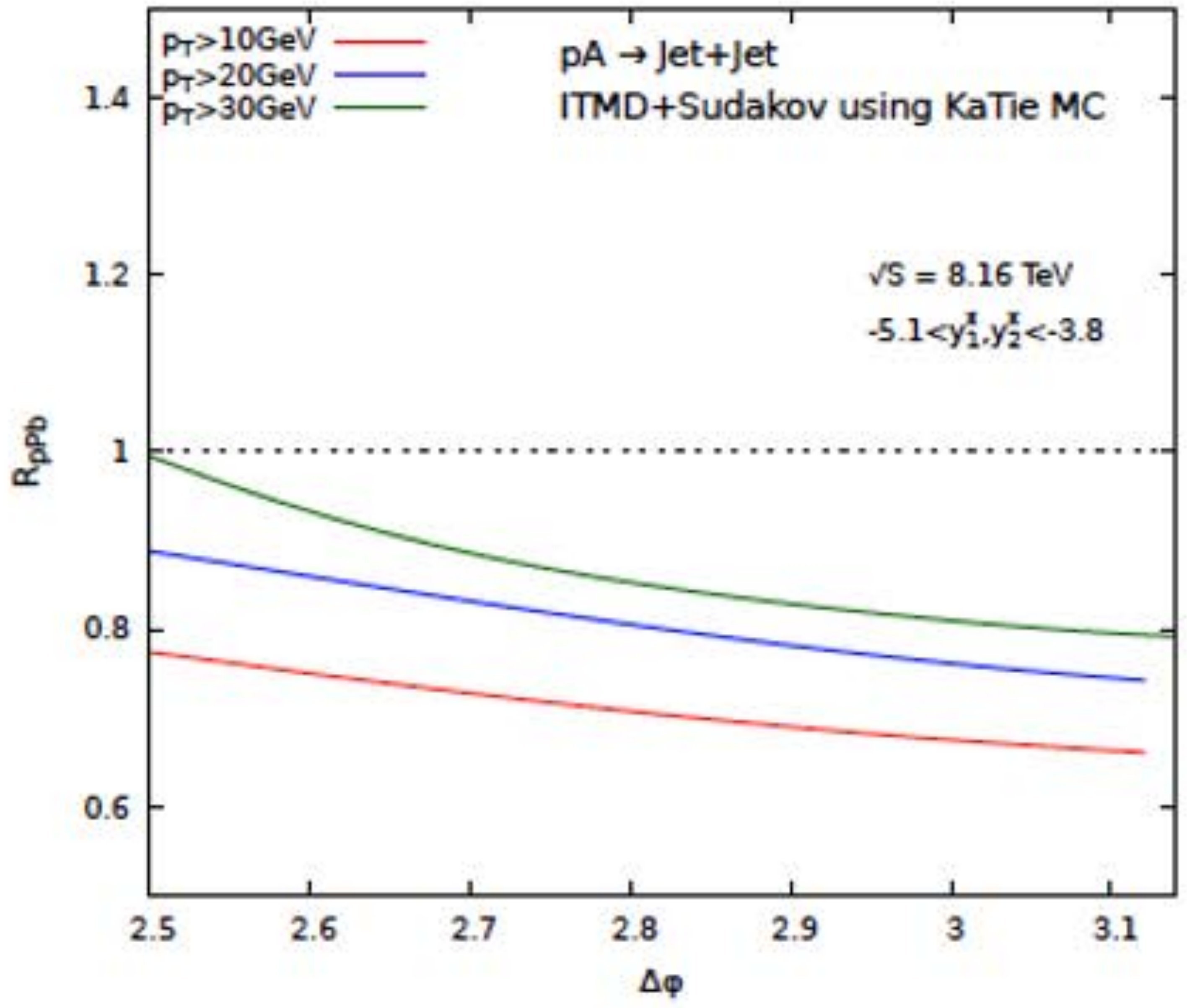


Dilute-dense LO + Sudakov probes quadrupole operator

Forward γ+jet



Forward di-jet

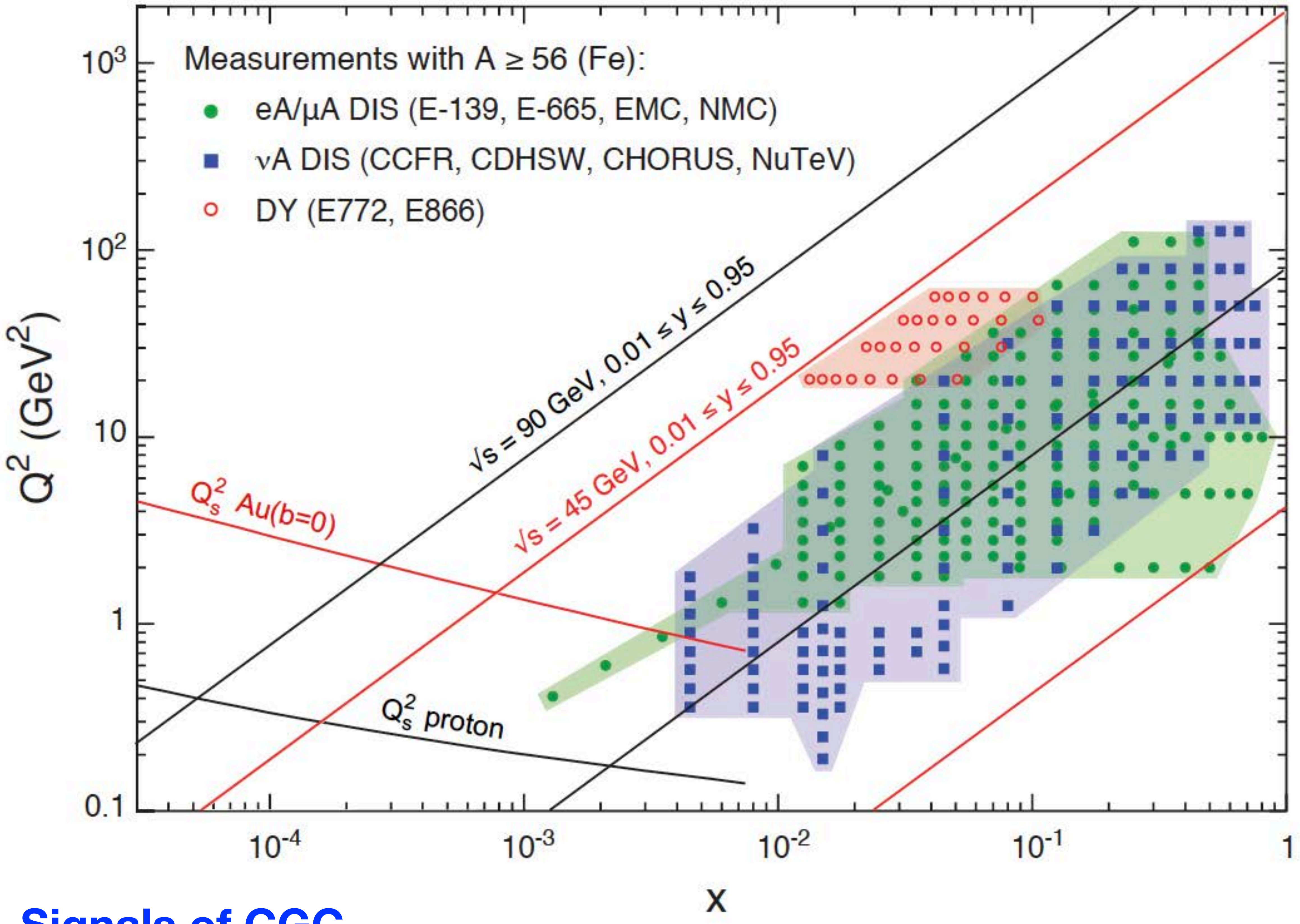


- γ+jet: dipole TMD gluon distribution
- di-jet: multiple TMD distributions

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

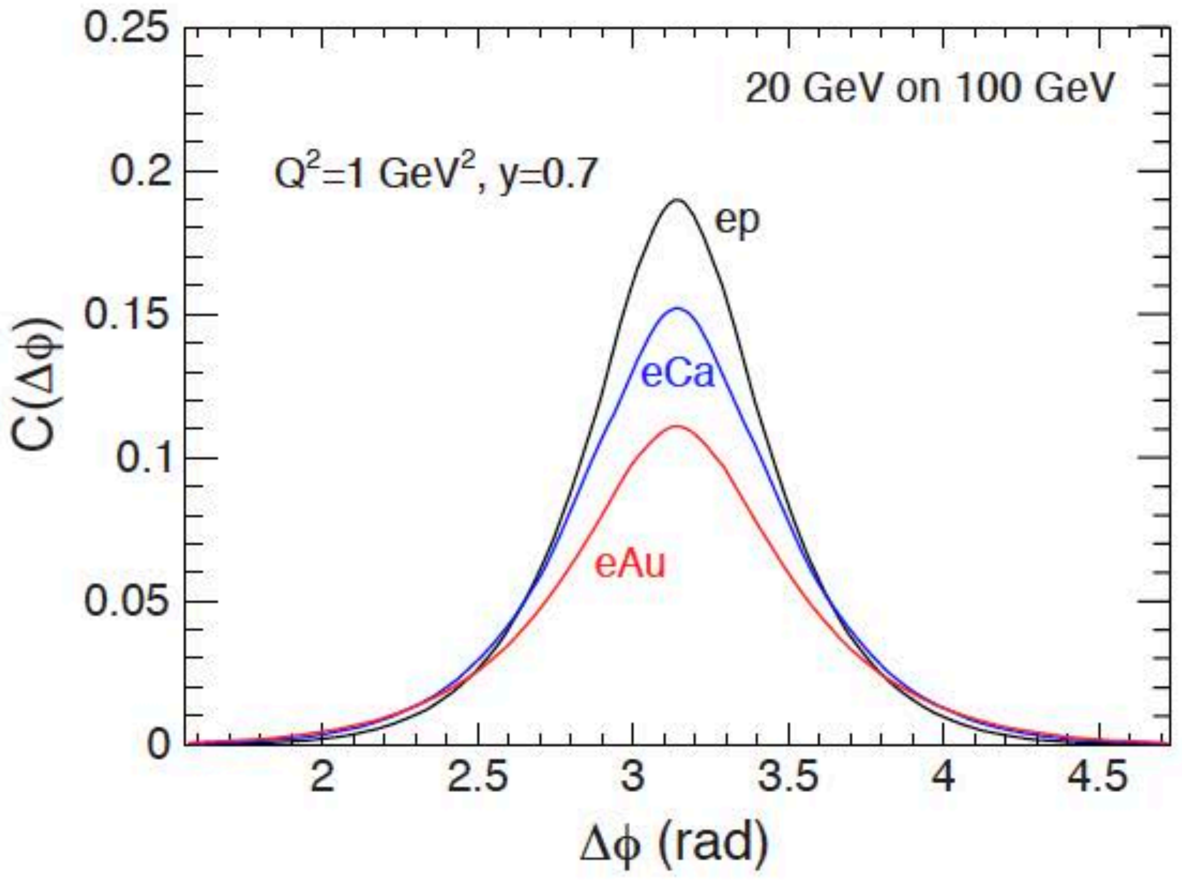
- γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$ (sensitive to saturation)
- changing k_T (p_T) → exploring non-linear QCD evolution in wide kinematic coverage of x-Q^2 by FoCal

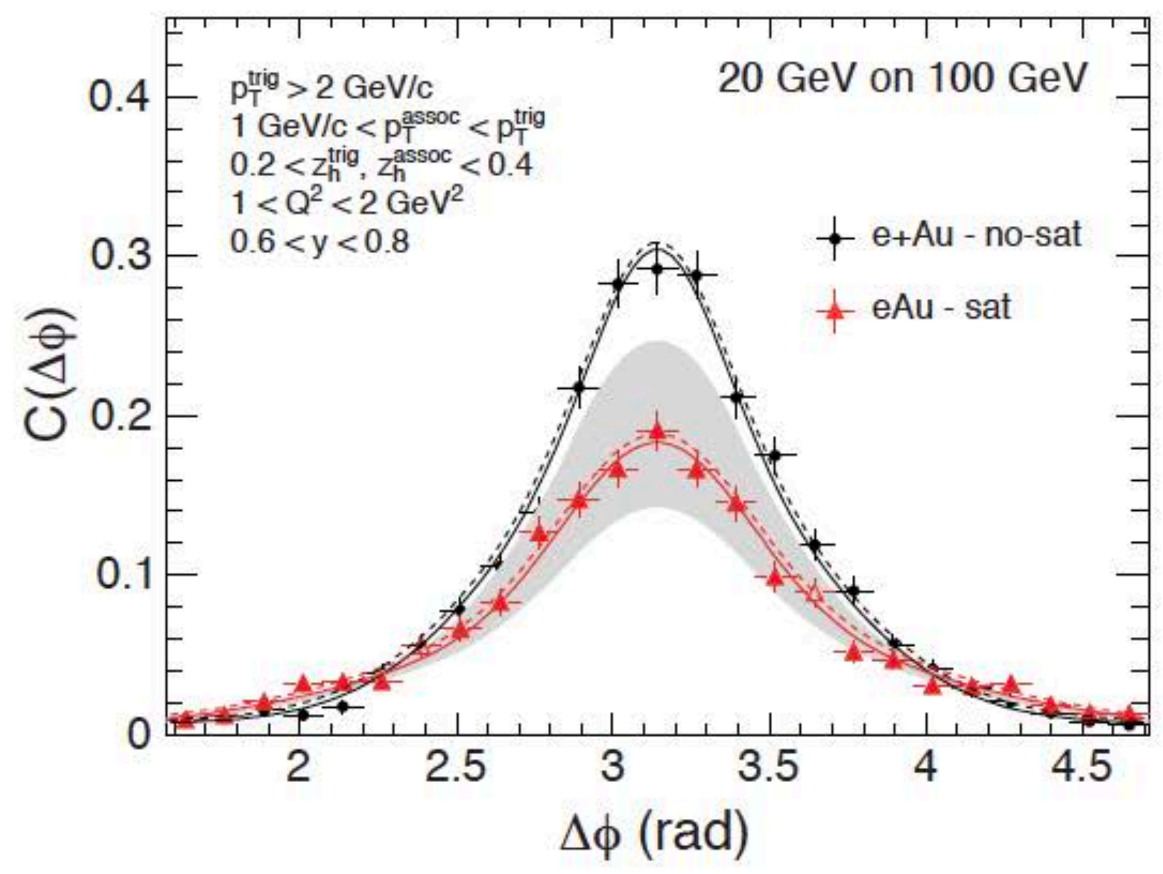
Saturation signal @ EIC eA



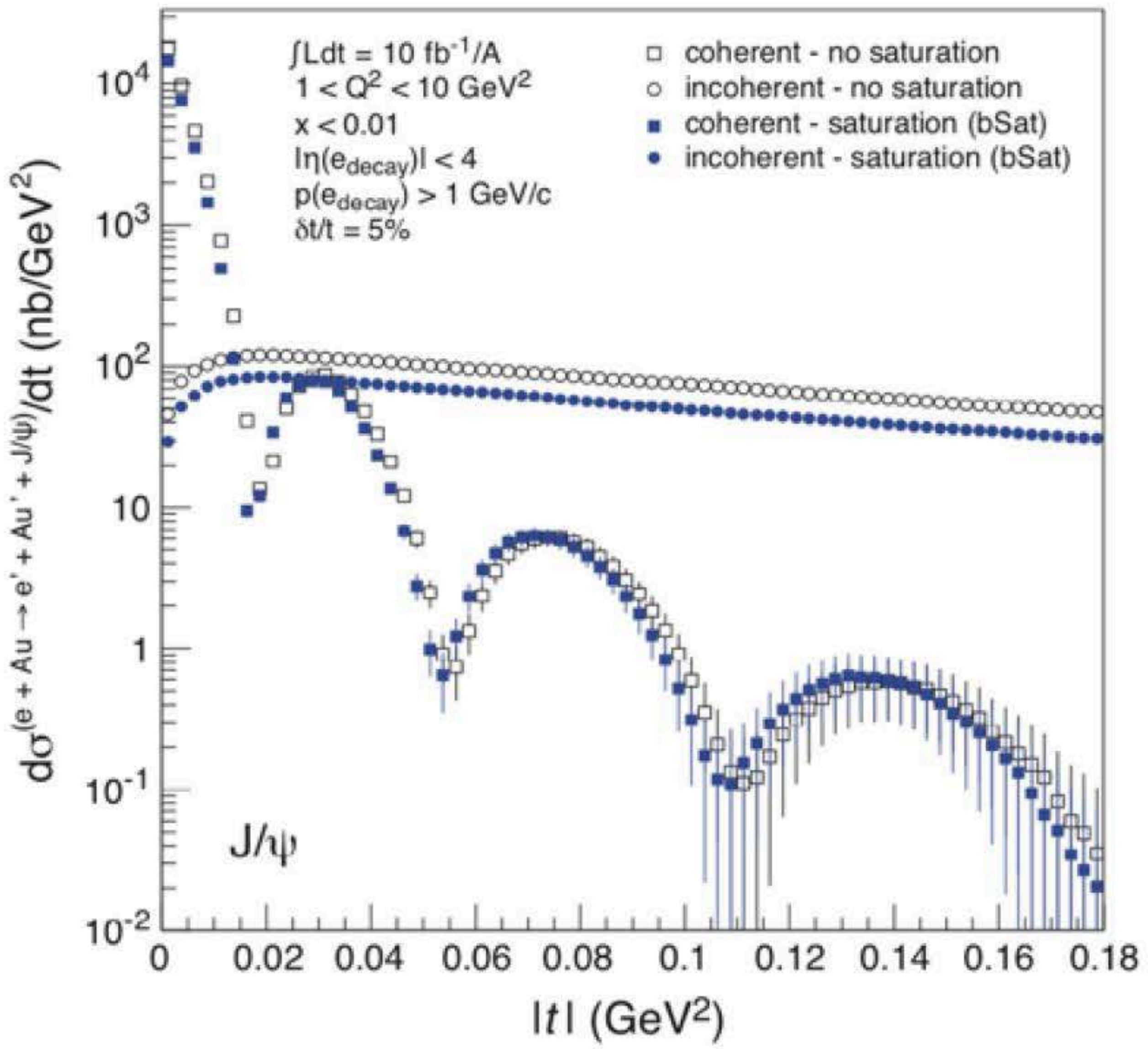
EIC White Paper, '12, '14 (2nd ed).

Depletion of di-hadron in e+A as compared to e+p
(Domingues et al '11; Zheng et al '14).

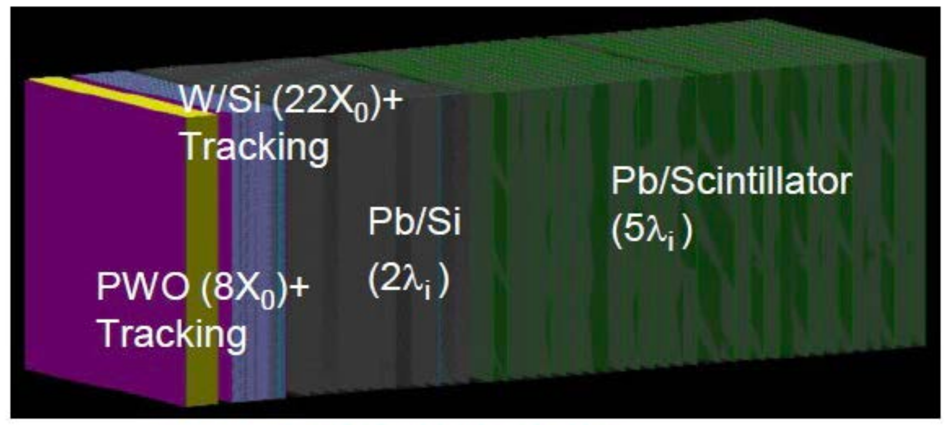




J/ψ, t distribution



FoCal technology



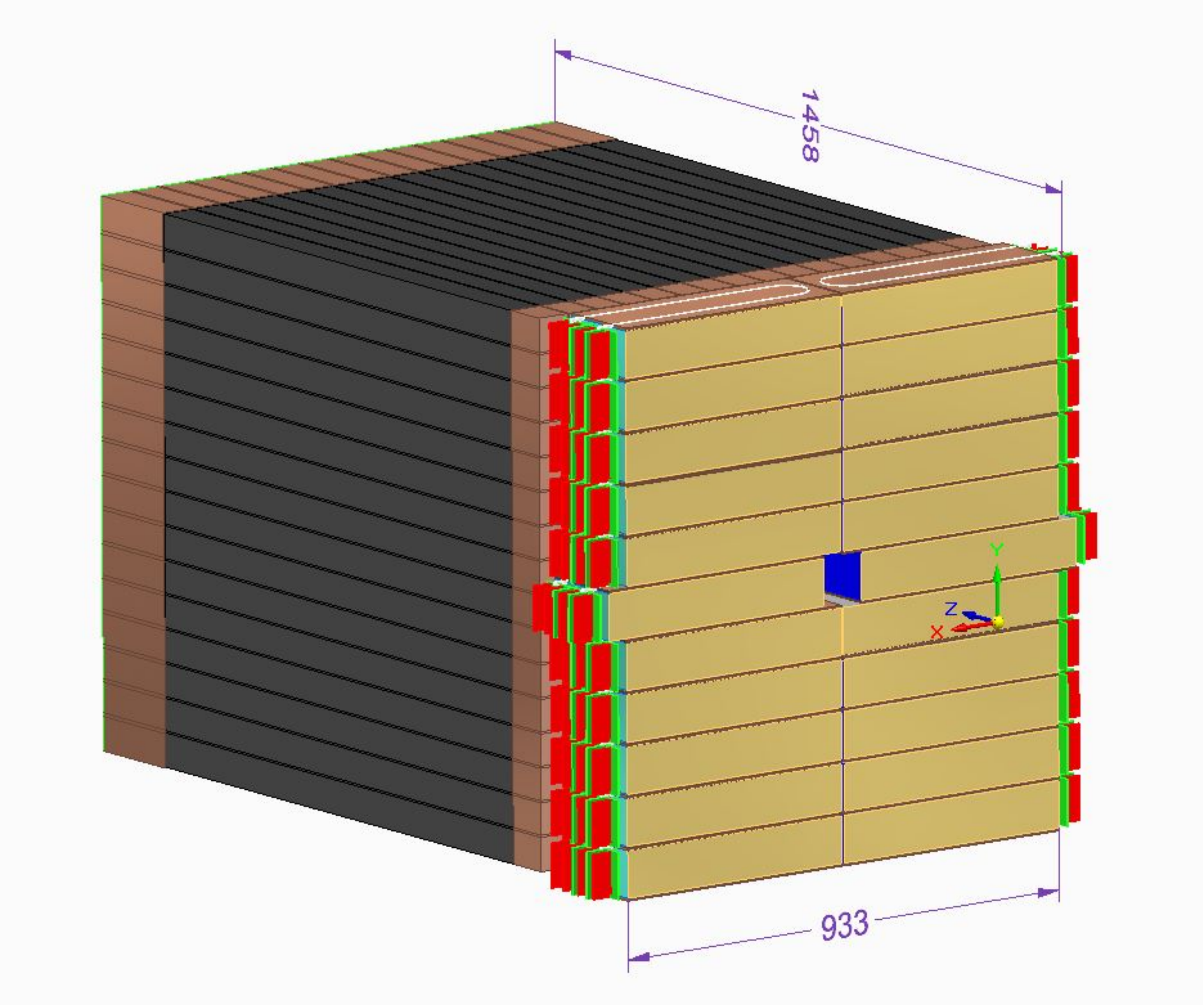
A ZDC design for EIC

Signals of CGC

- di-hadron correlation (e-A vs. ep), broadening of width
- Quasi-elastic coherent J/ψ production (eliminate de-excitation photons ~300 MeV)

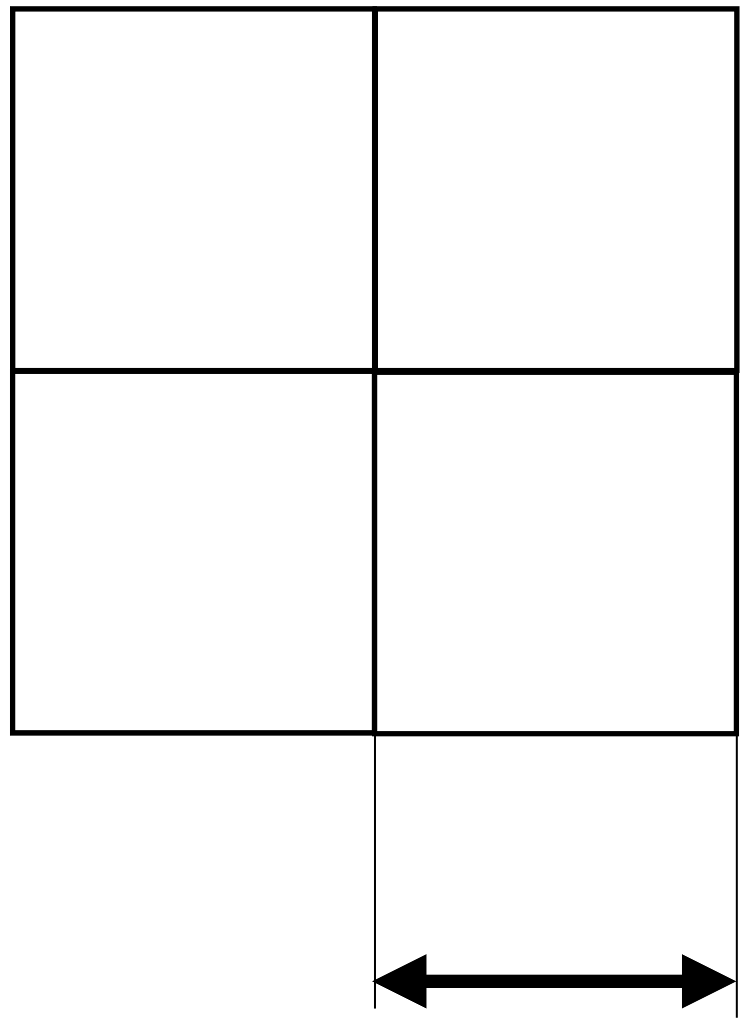
  →ZDC is essential !
- shifted t-distribution by CGC

FoCal detector
(design and current status)

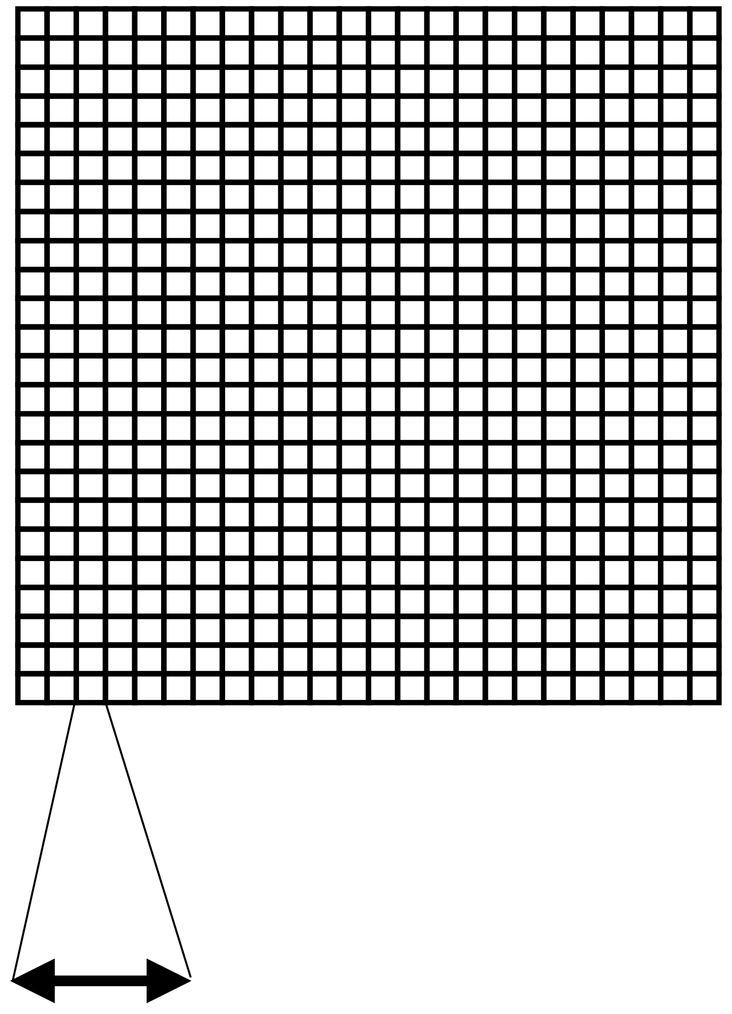


Detector design

E-Pad



E-Pixel



FoCal-E (pad, pixel)

20 layers of W(3.5 mm ≈ $1X_0$) + silicon sensors:

Two types: **Pad (1×1 cm^2)** and **Pixel (30×30 μm^2)**

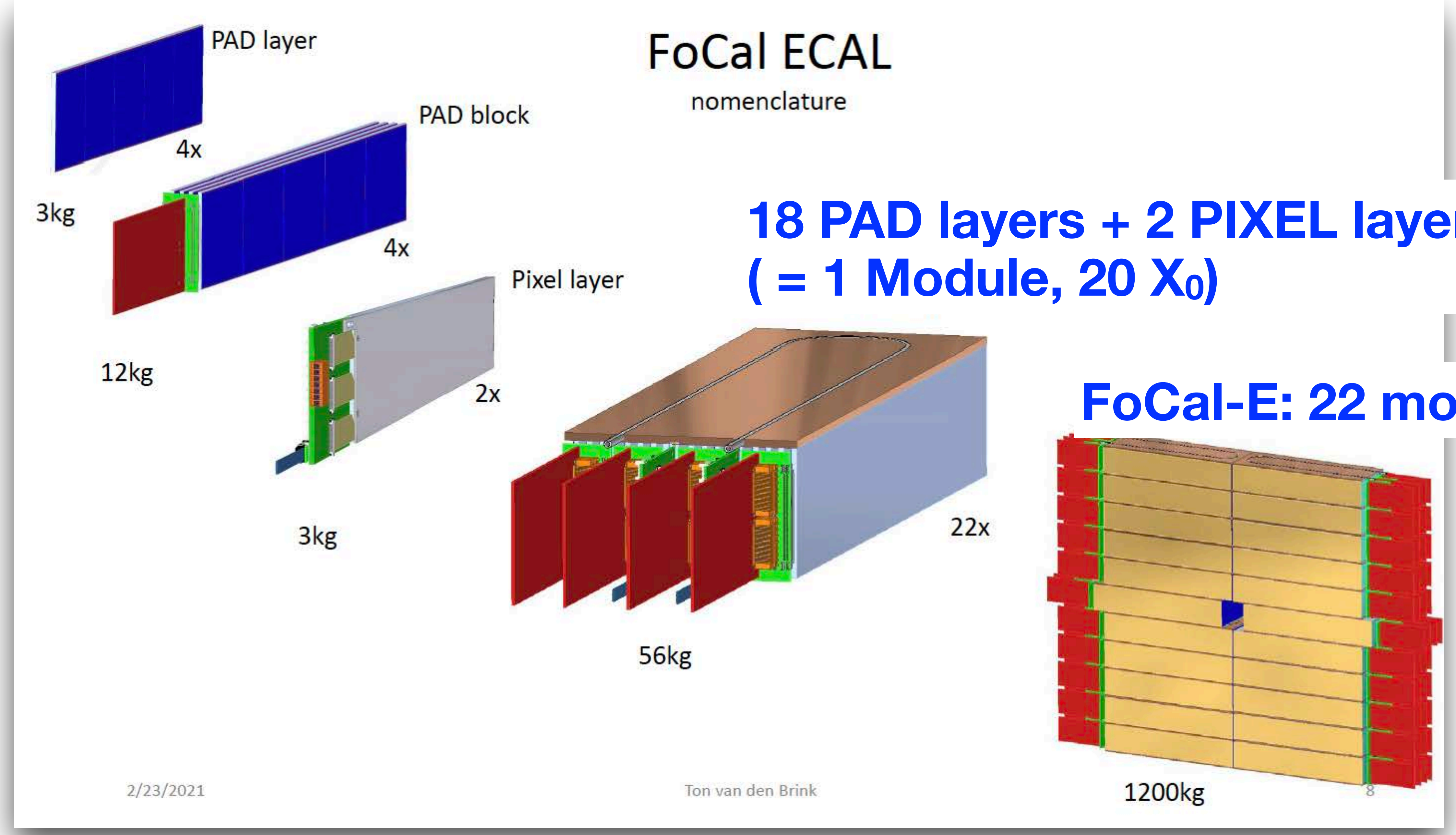
- Pad: shower profile and total energy
  - Si PAD sensor
- Pixel: position resolution to resolve overlapping showers
  - CMOS MAPS technology (ALPIDE)

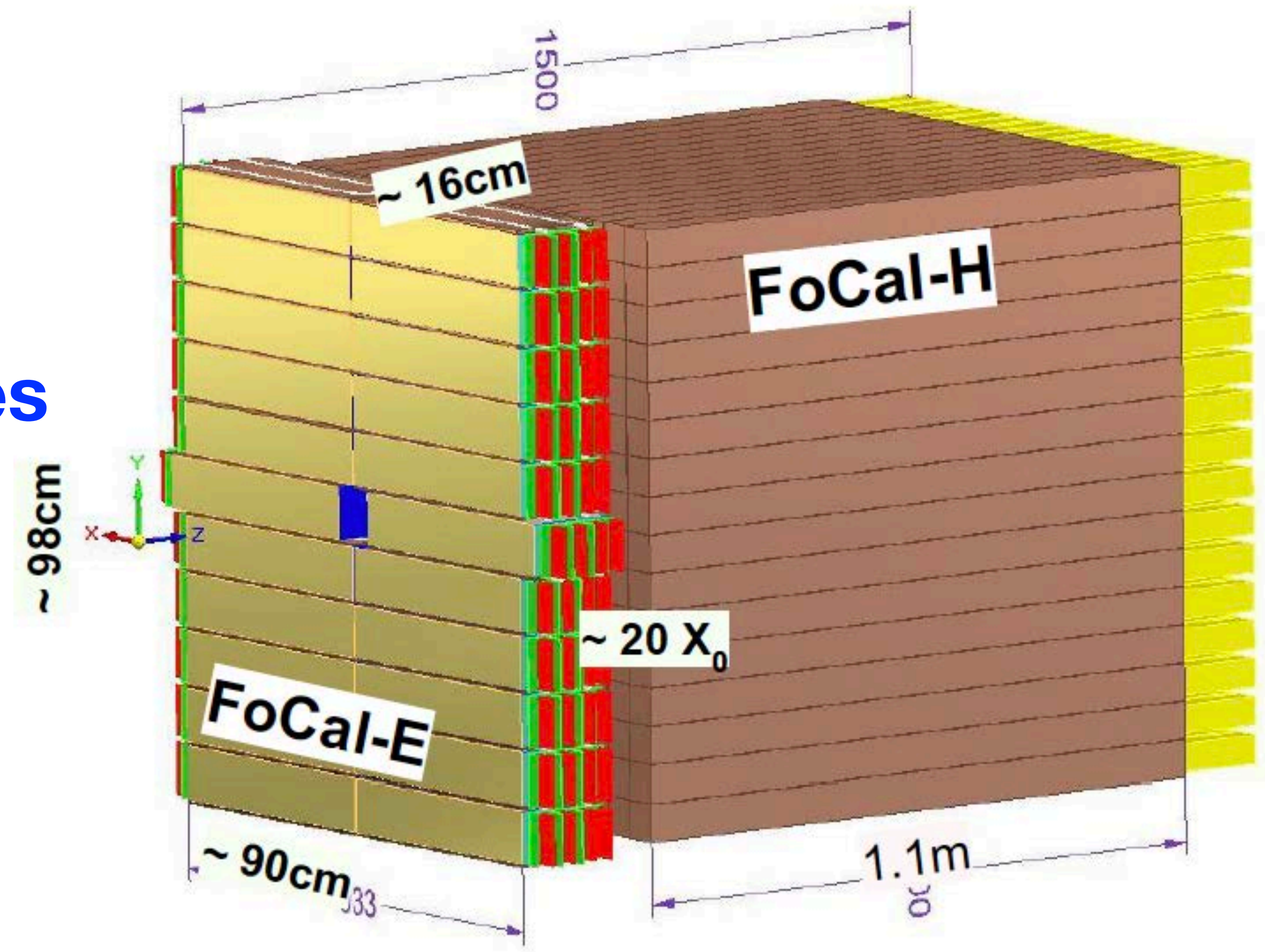
FoCal-H

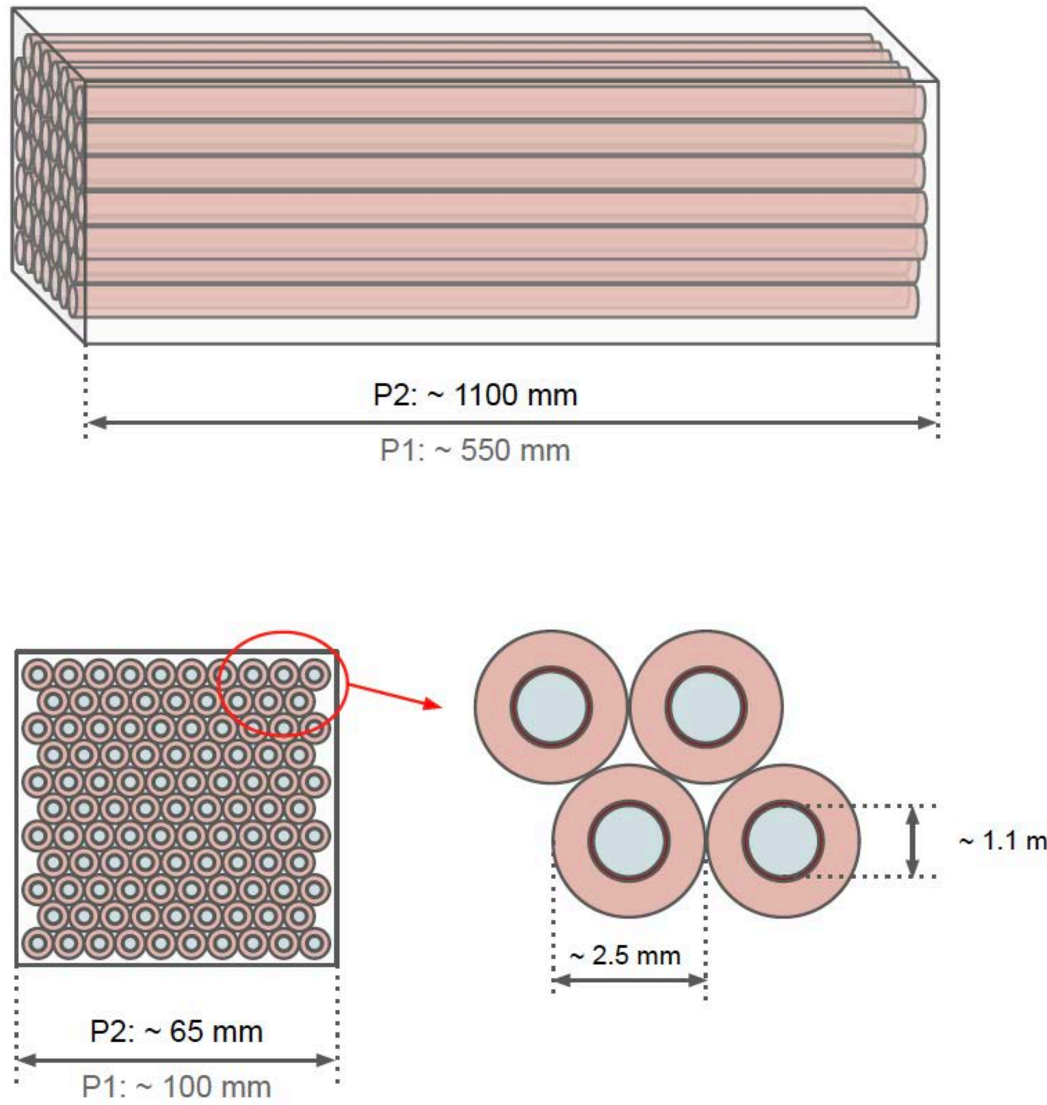
Conventional metal-scintillator design

Cu capillary-tubes enclosing BCF scintillating fibers

SiPM readout







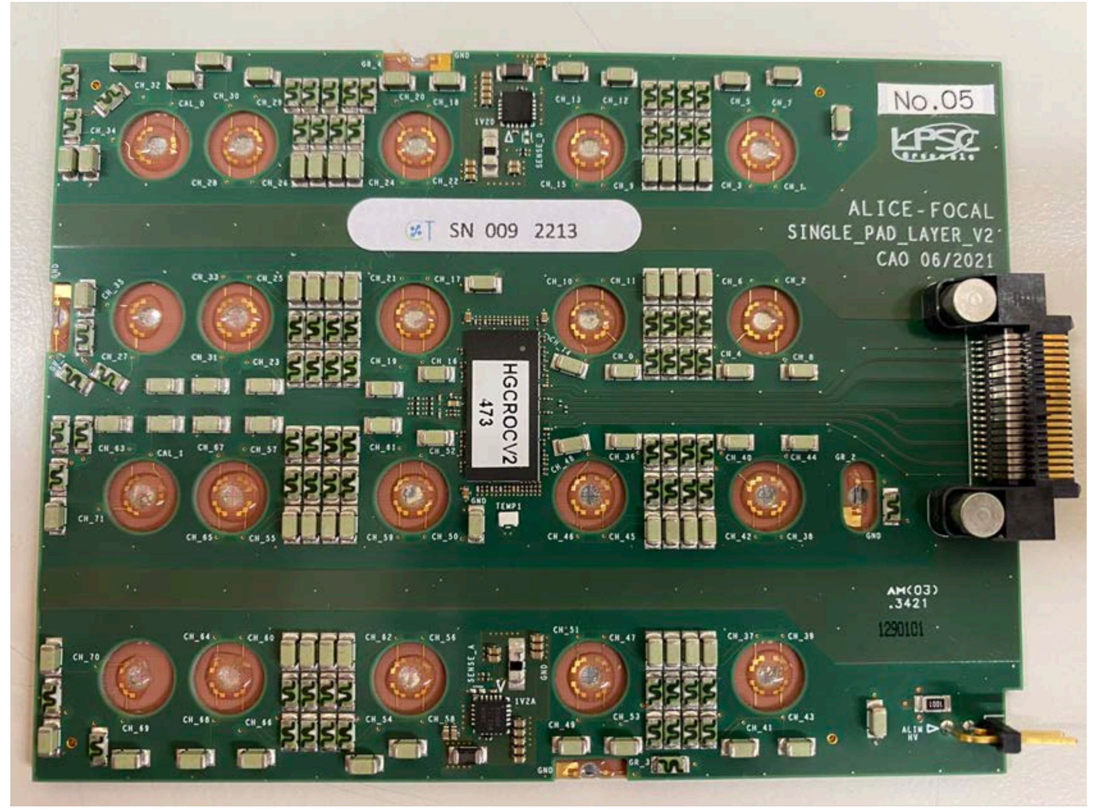
FoCal Japan

Responsibilities:

(1) FoCal-E pad, (2)readout and trigger

8 institute, 25 members

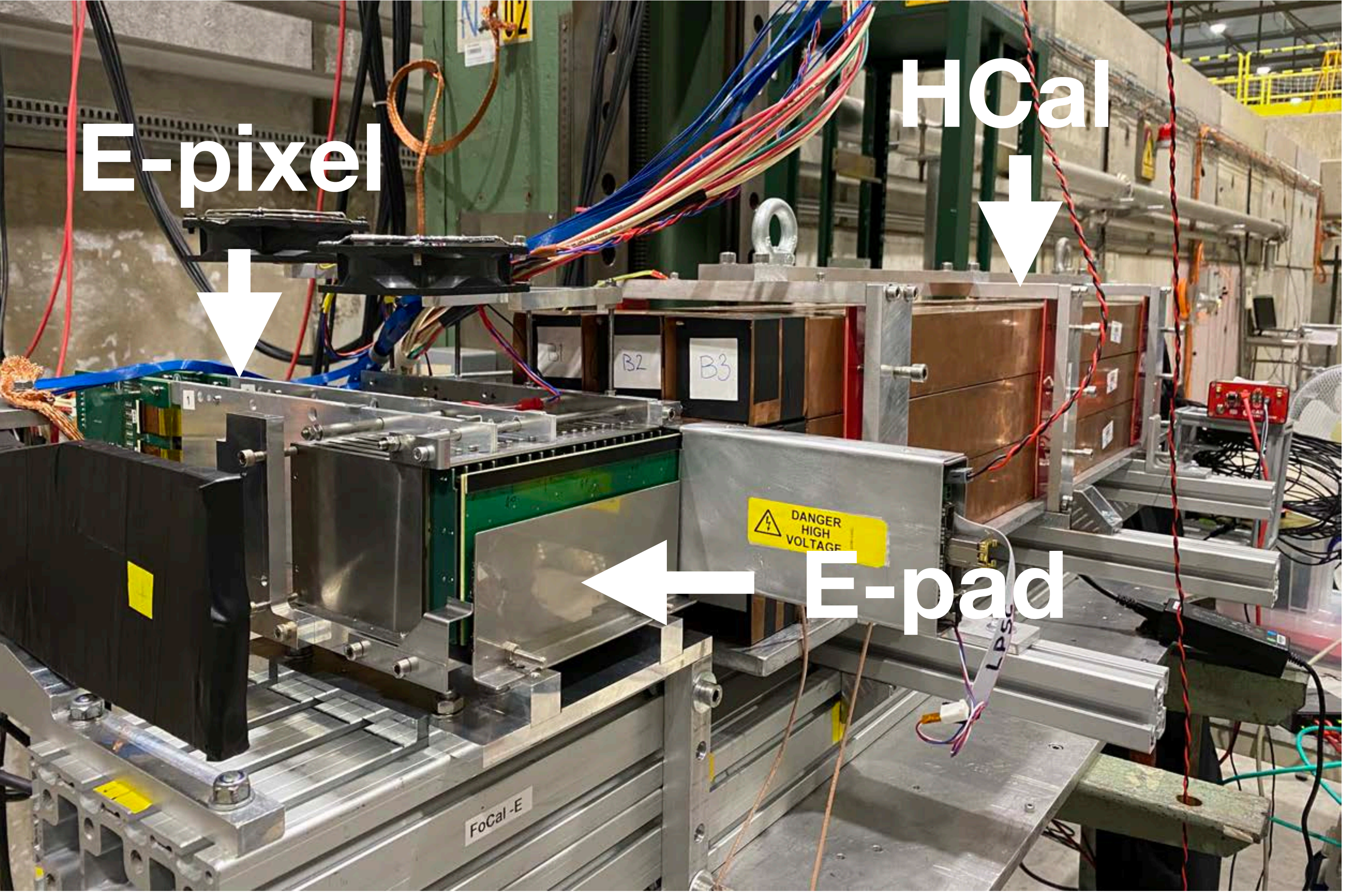
- Univ. of Tsukuba
- Tsukuba Univ. of Tech
- RIKEN
- Hiroshima Univ.
- Nara Women's Univ.
- Saga Univ.
- Nagasaki Inst. of App. Sciences
- Kumamoto Univ.



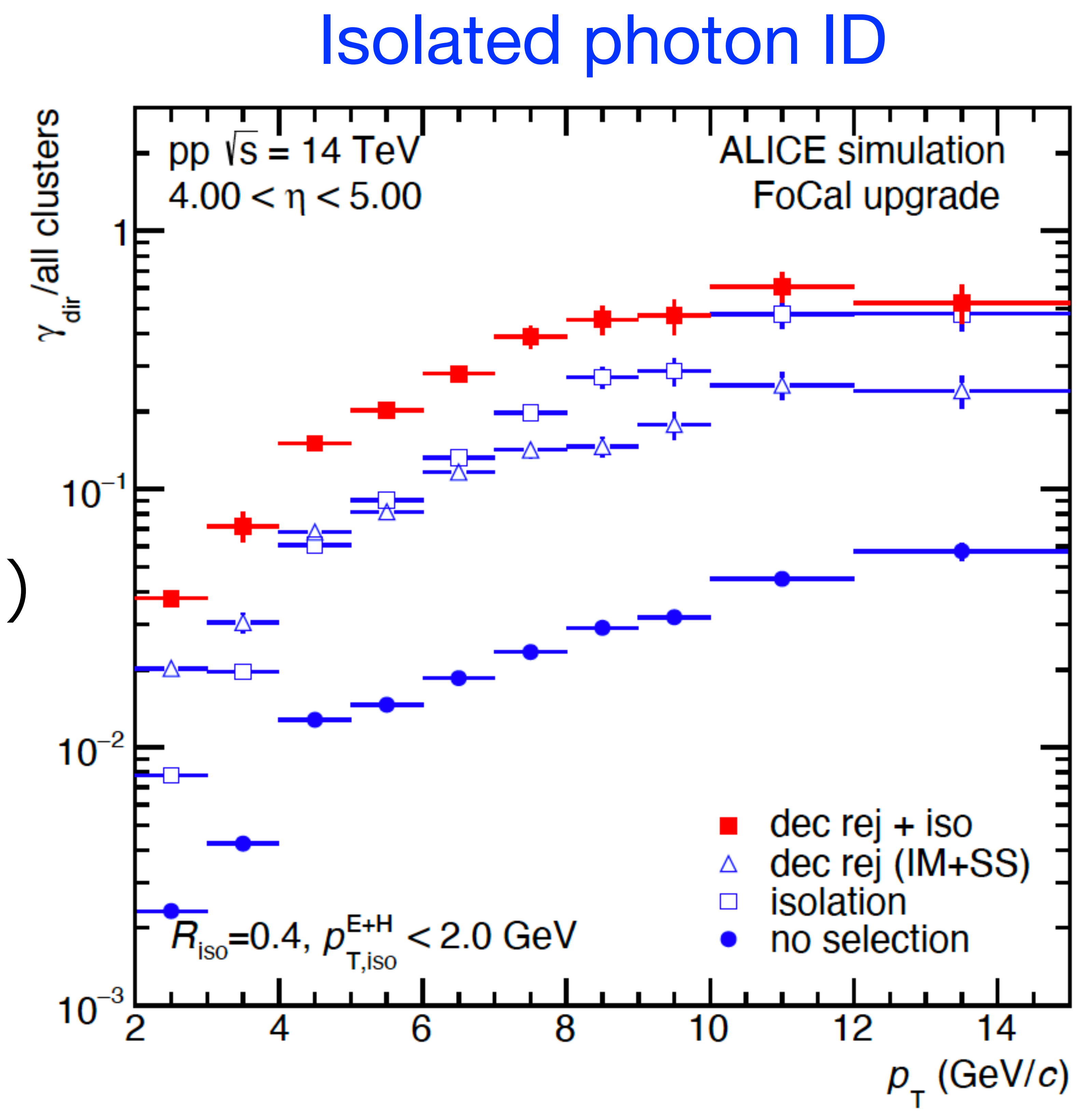
科研費 KAKENHI

JSPS KAKENHI Grant Number JP20H05638 基盤 (S) (2020-2024, PI 中條)
「LHC 超前方光子測定によるグルーオン飽和とQGP生成起源 」

Uniqueness of FoCal detector



PS/SPS test beam in 2022



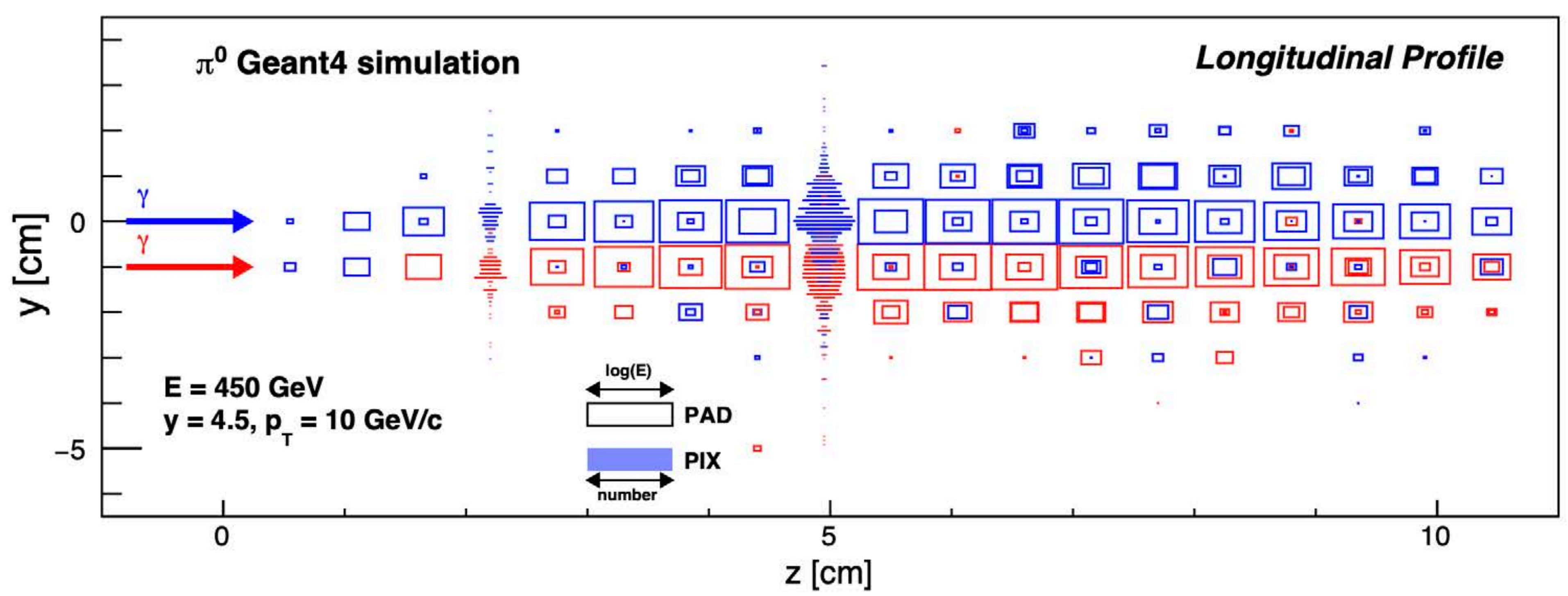
1） **High two photon separation power**（<~5mm, energy resolution ~3%）

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

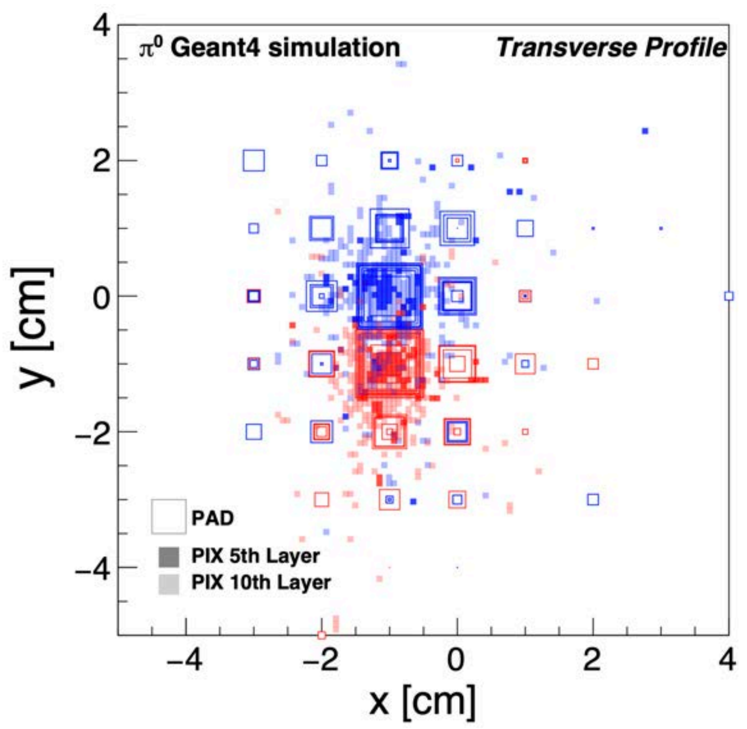
3） **High radiation tolerance**（10^{13} (1MeV neutrons) / cm^2)

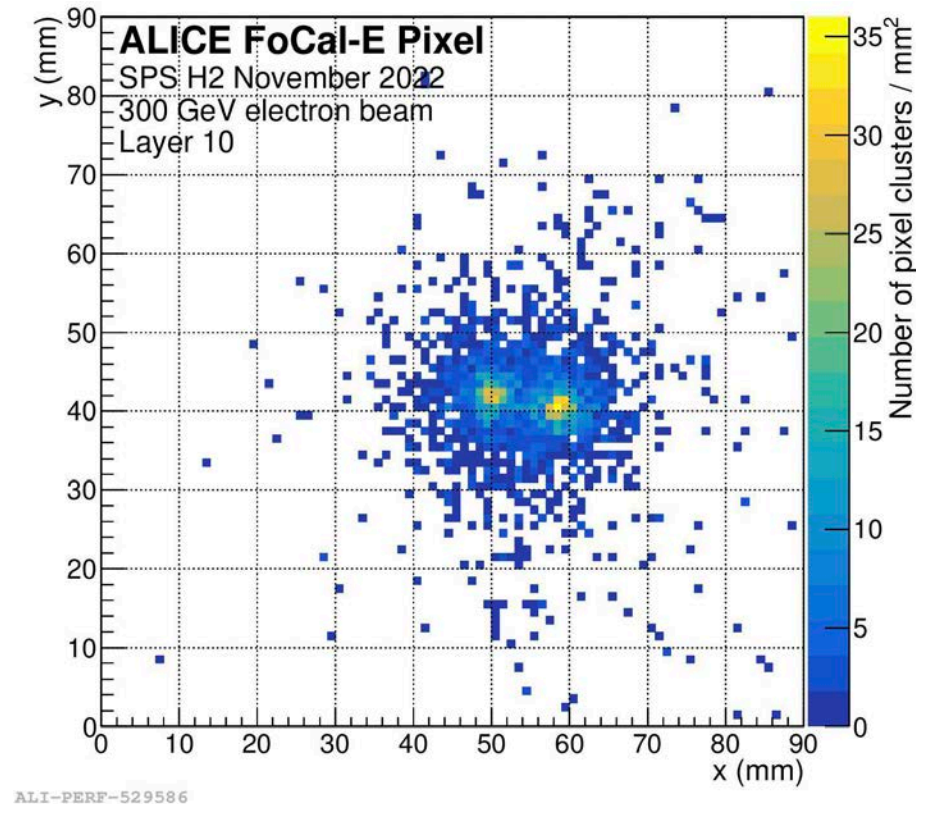
→FoCal-E pad: mainly developed by FoCal-Japan group

Longitudinal profile (2γ showers)



Trans. profile

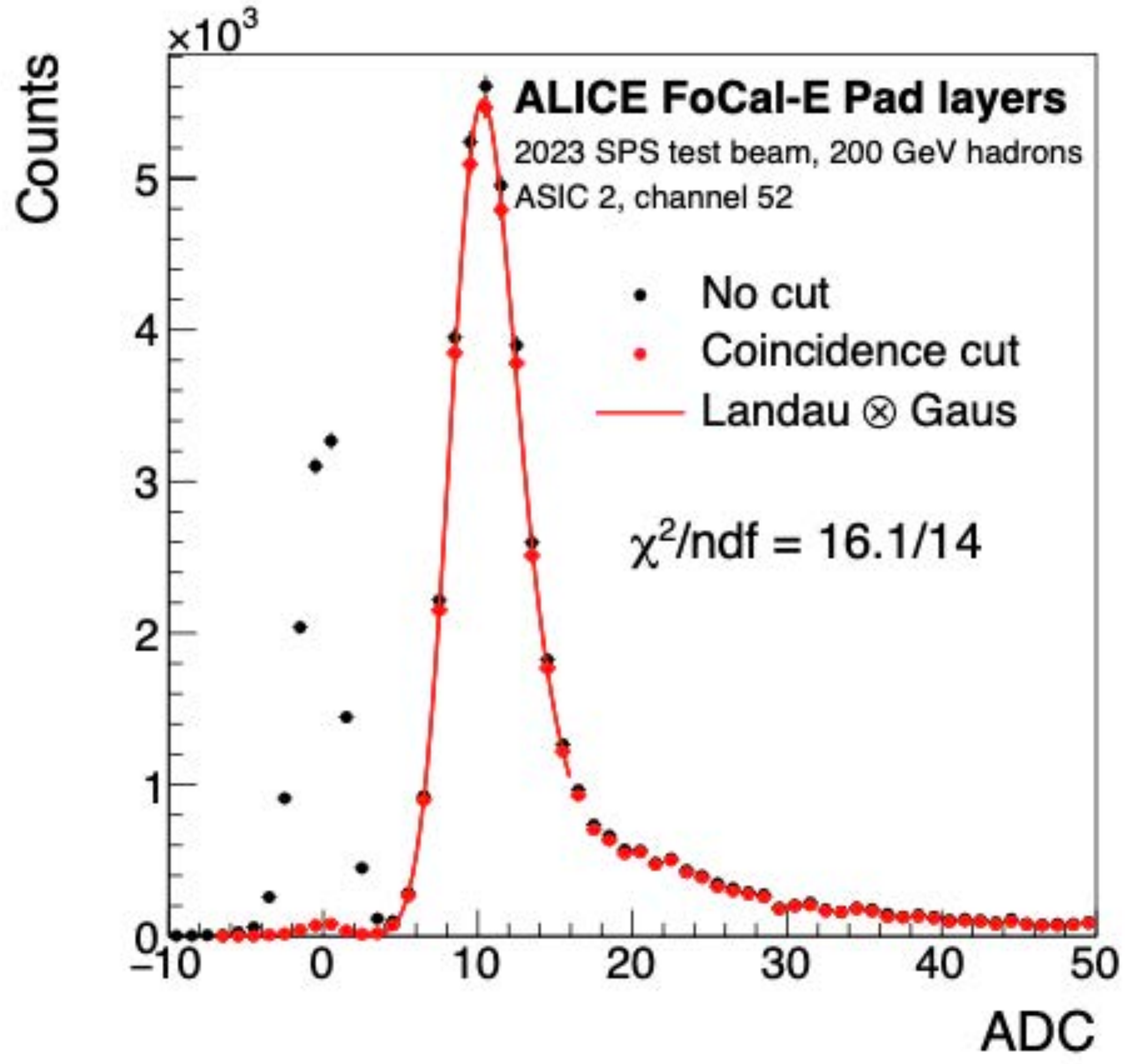


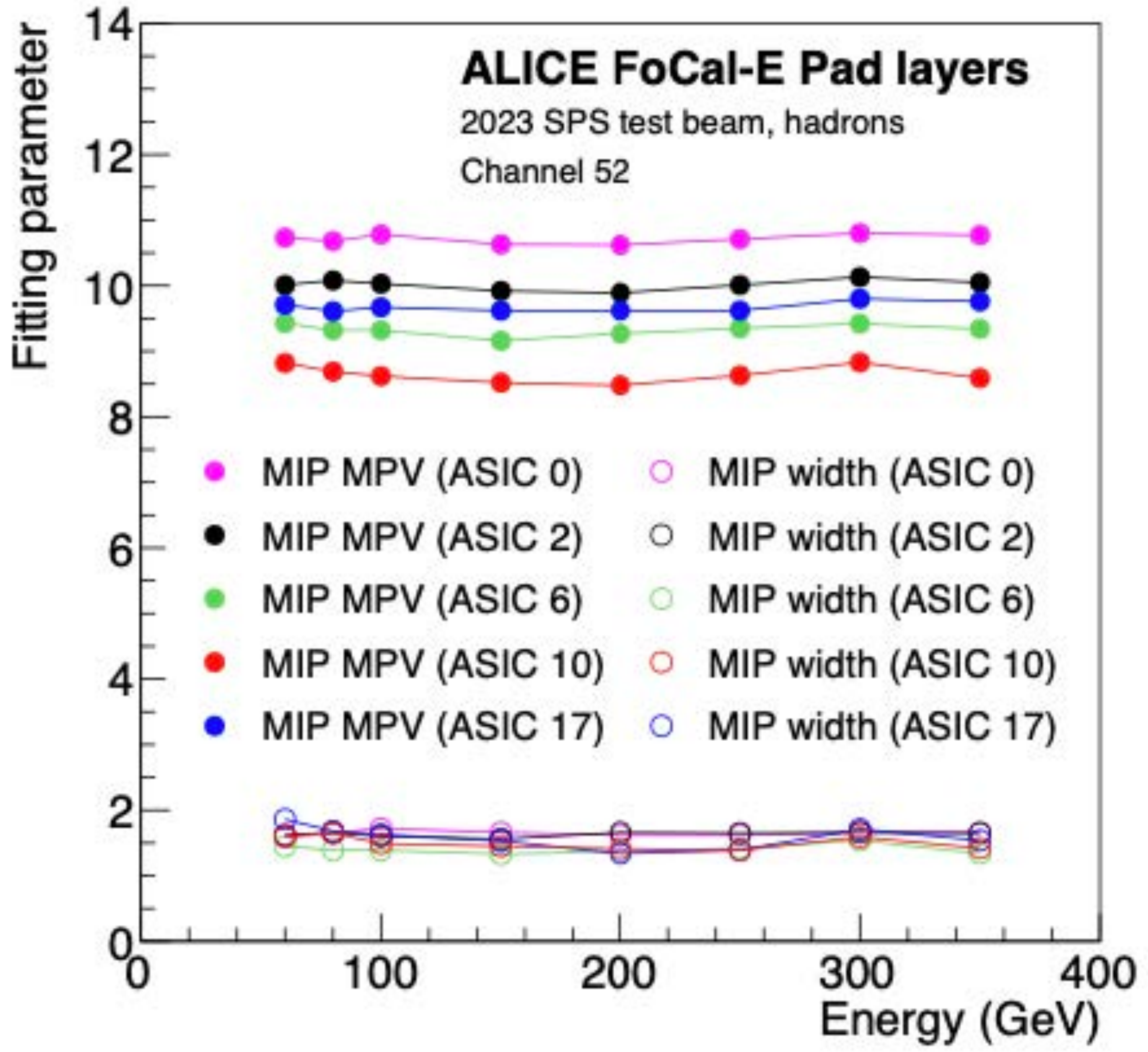


FoCal-E pad performance

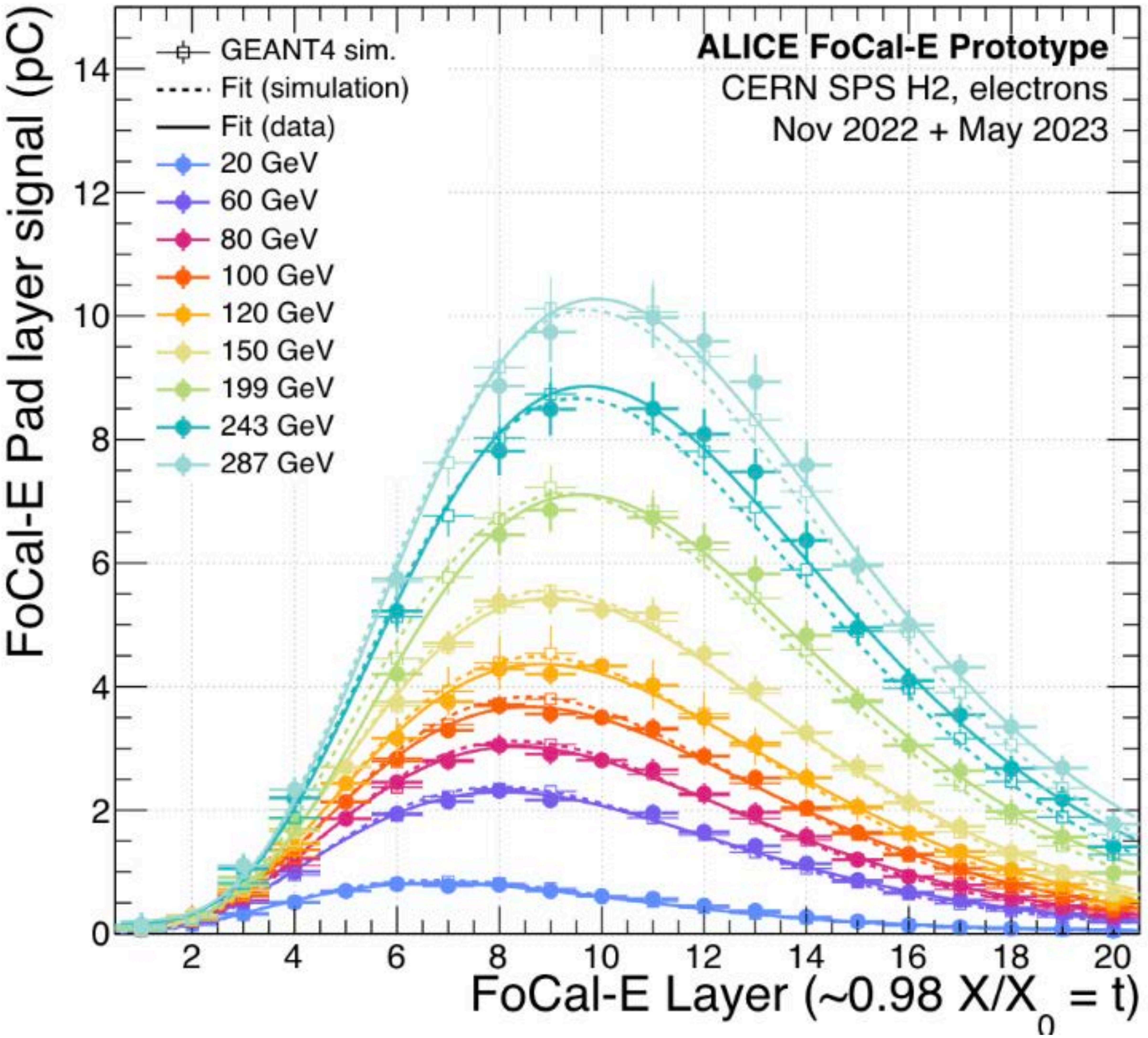
arXiv:2311.07413

MIP responce





Longitudinal shower profiles



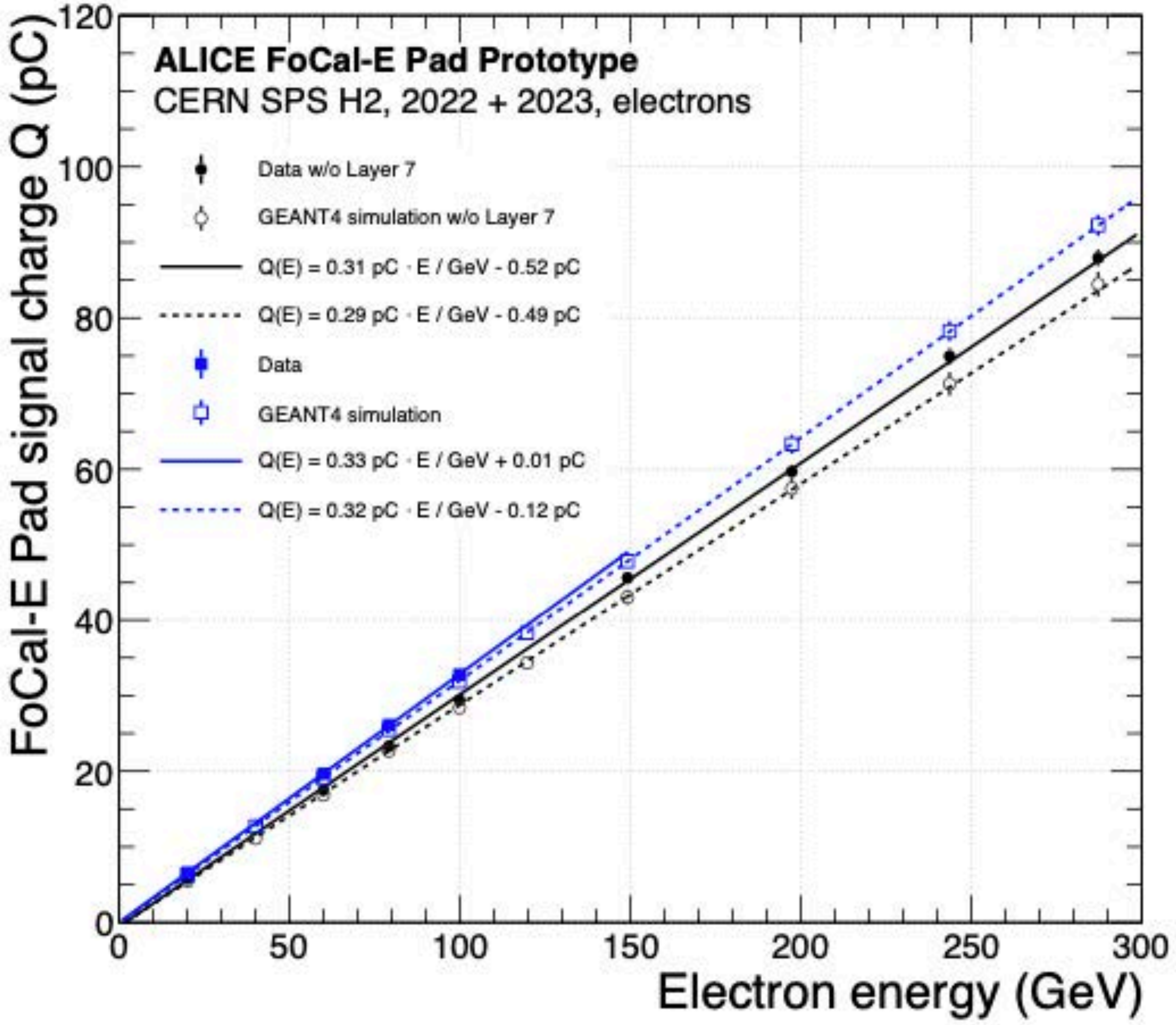
Excellent performance of prototype

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

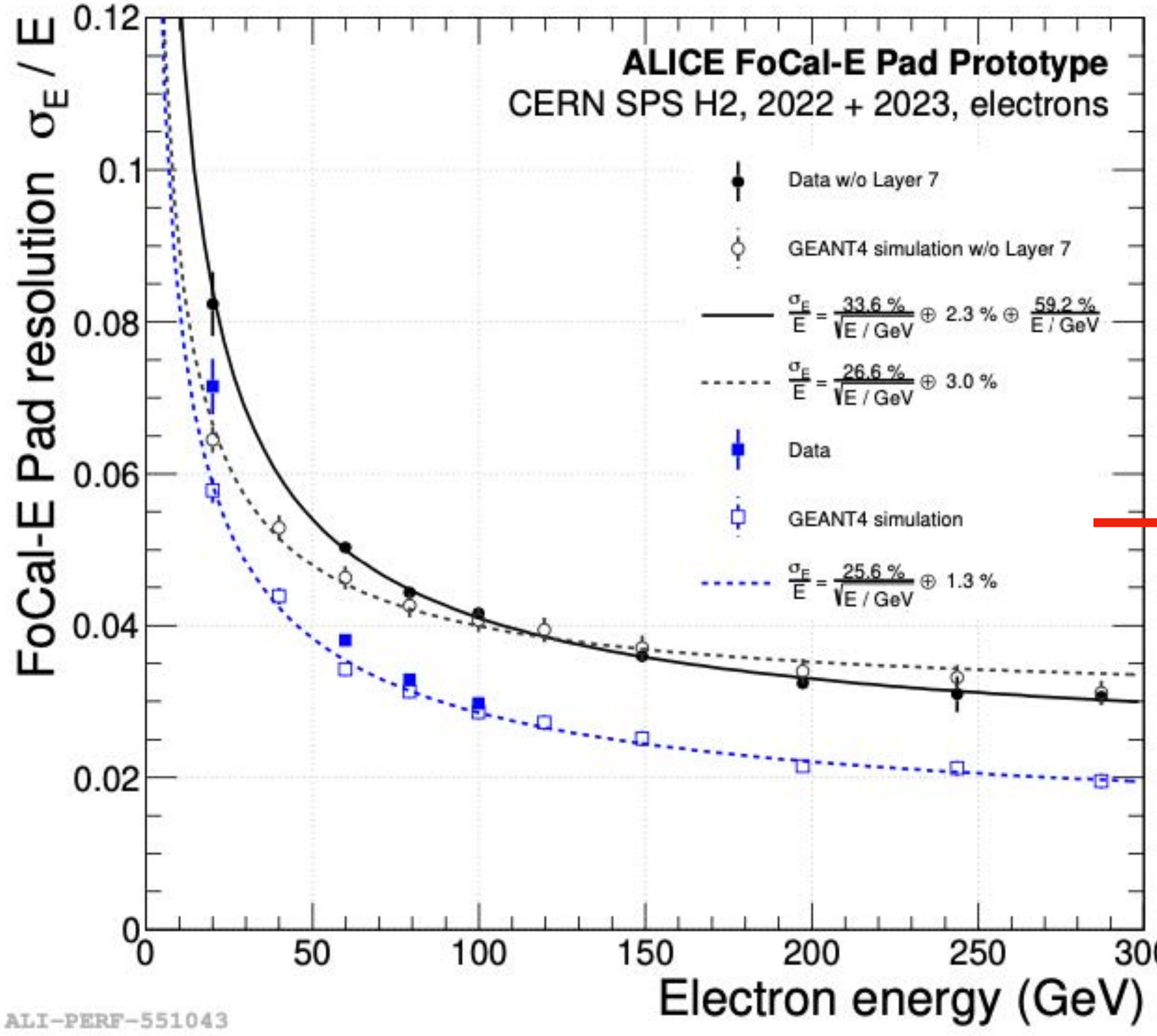
FoCal-E pad performance

arXiv:2311.07413

Linearity



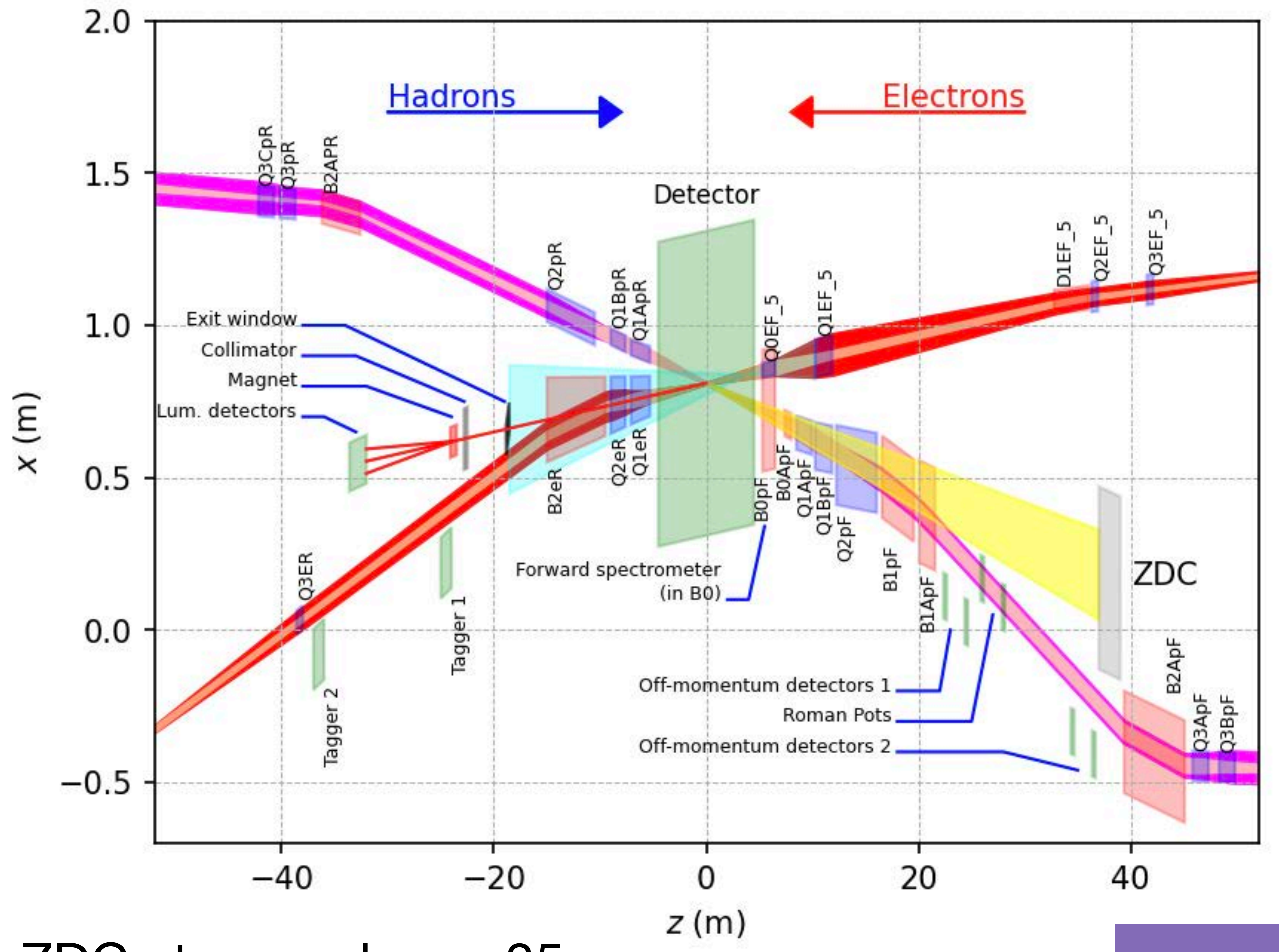
Energy resolution



5%

Results show expected behavior

EIC-ZDC design



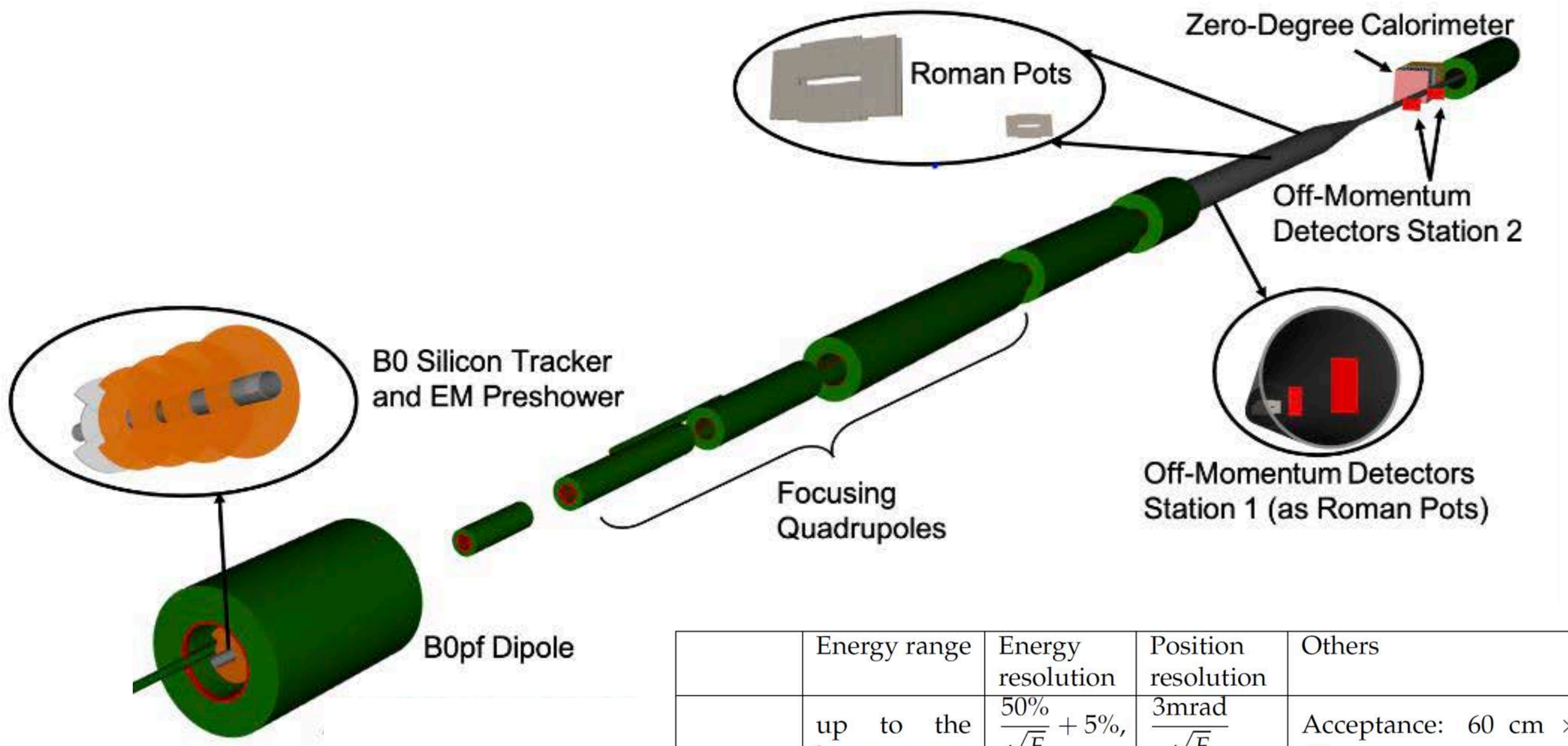
ZDC at around z = +35 m

Aperture: ~ 4 mrad

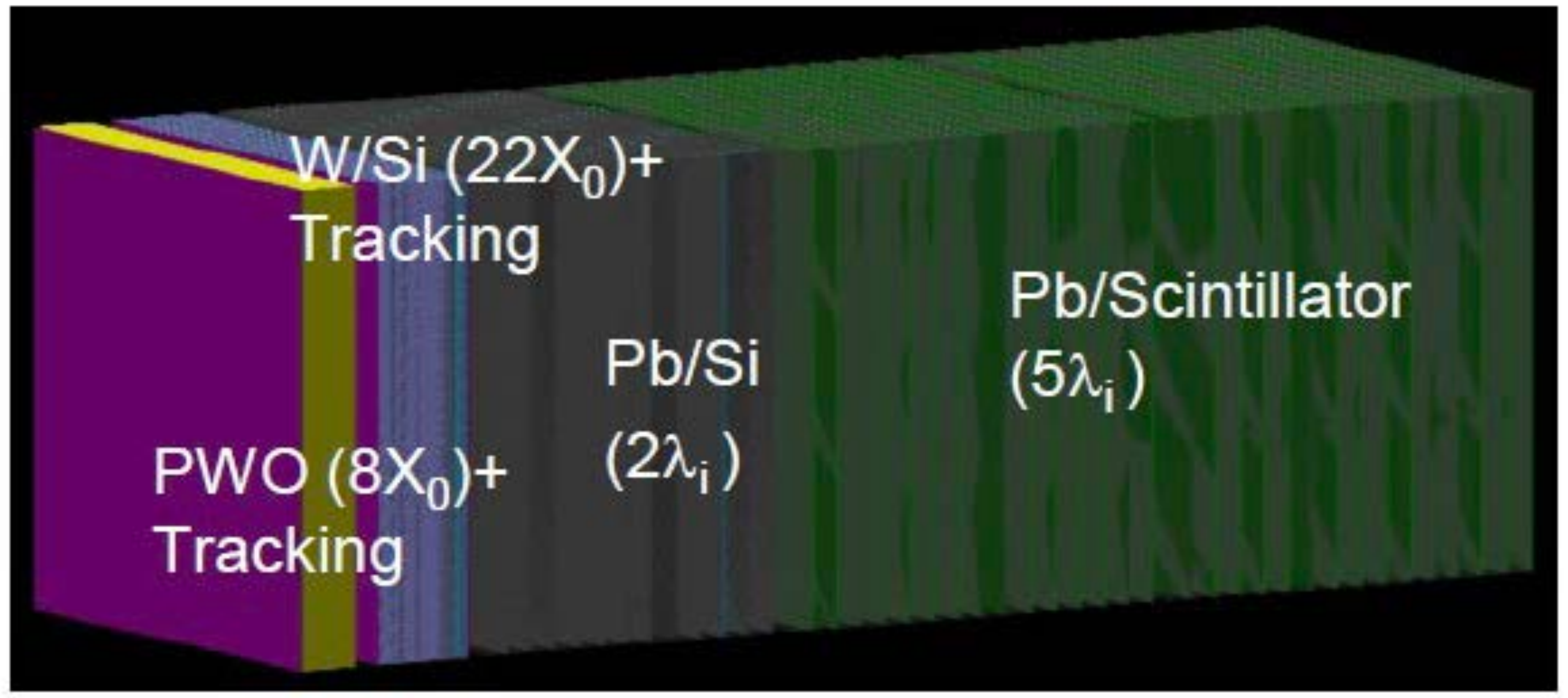
Available space: 60 x 60 x 200 cm

ePIC-ZDC collaboration in Japan

- RIKEN, Tsukuba, Tsukuba Tech, Shinshu, Kobe
- First test beam with Taiwan group at ELPH, Tohoku Univ. on March 2024.



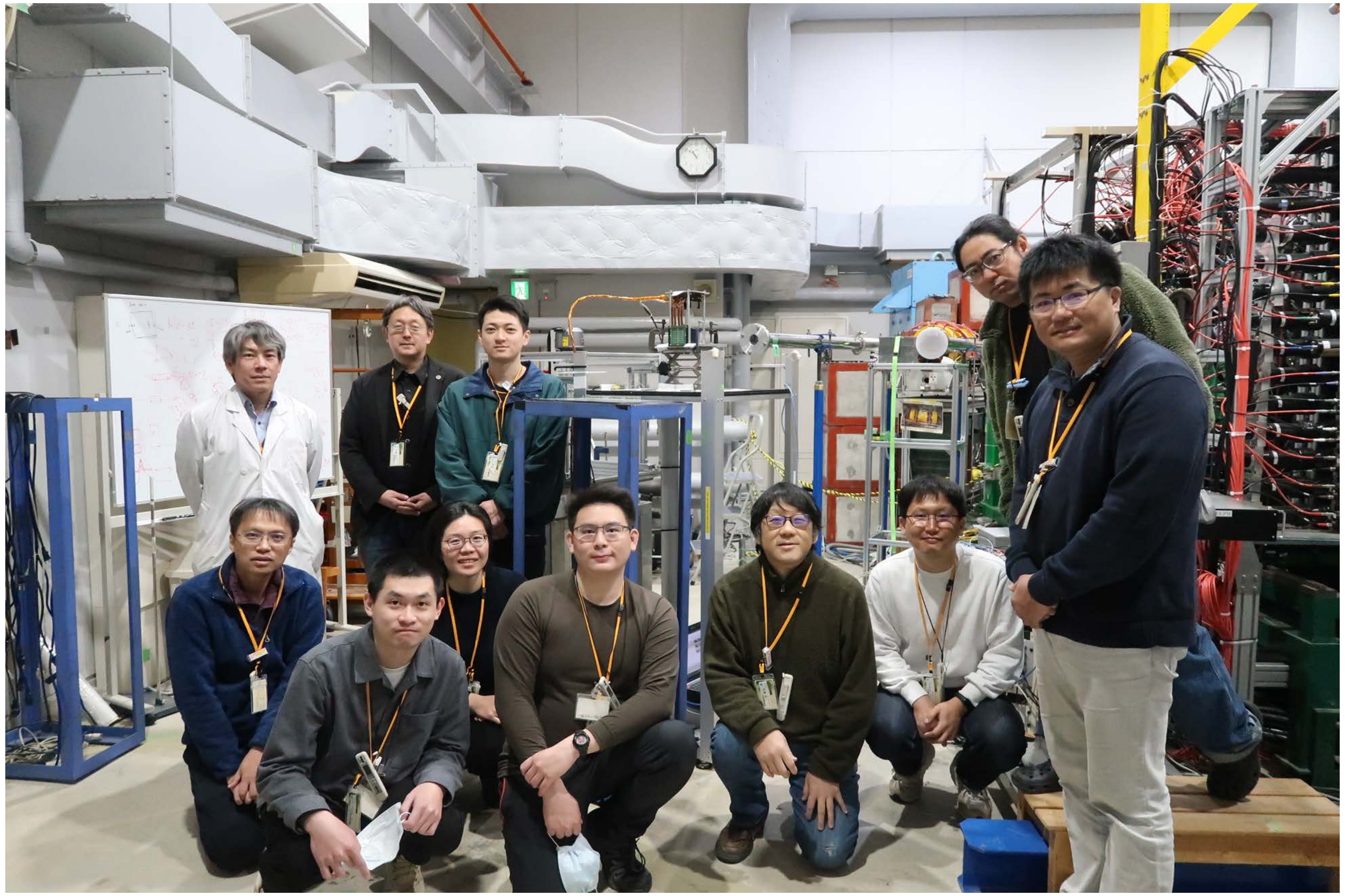
FoCal technology

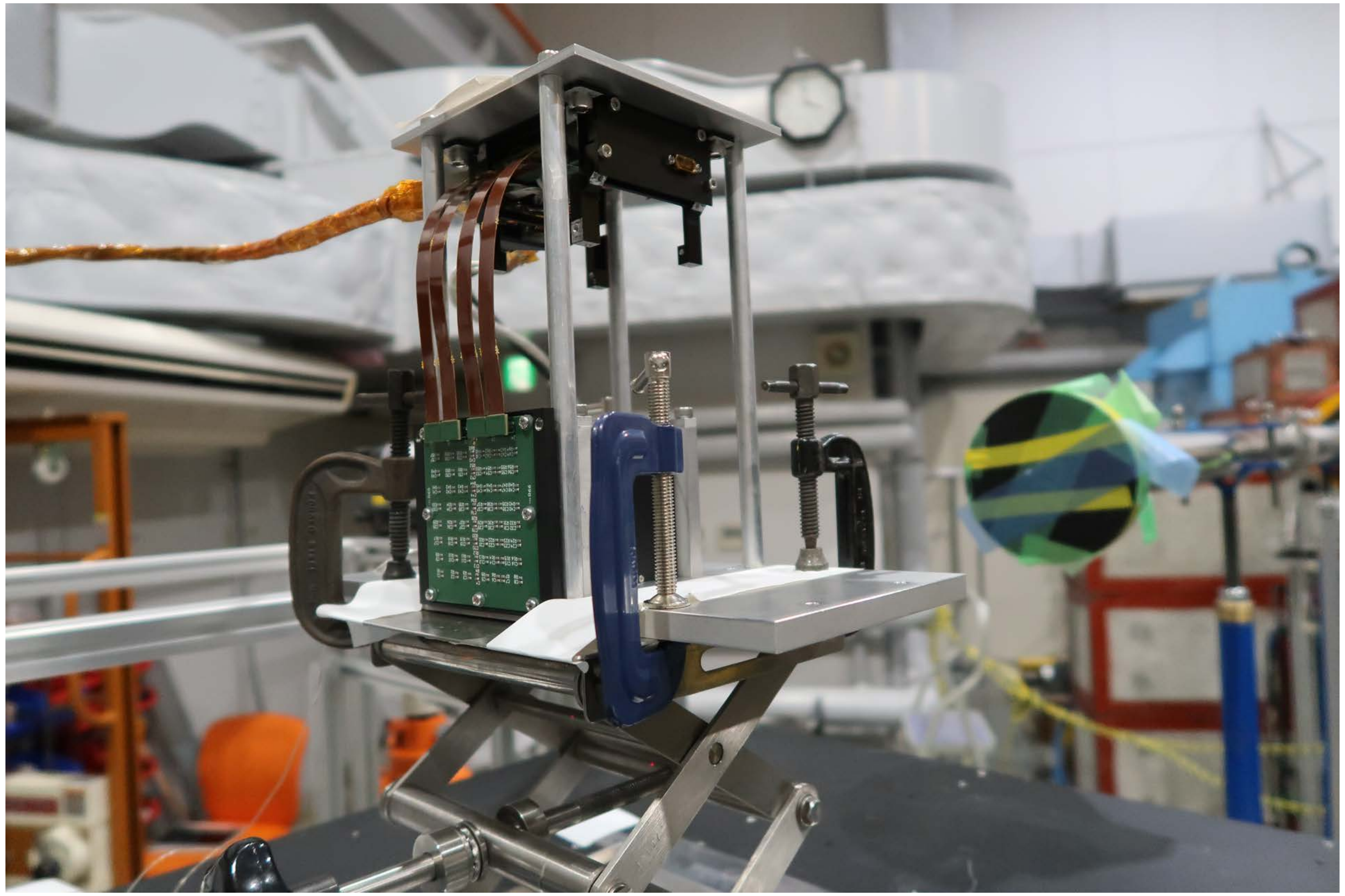


	Energy range	Energy resolution	Position resolution	Others
Neutron	up to the beam energy	$\frac{50\%}{\sqrt{E}}+5\%$, ideally $\frac{35\%}{\sqrt{E}}+2\%$	$\frac{3mrad}{\sqrt{E}}$	Acceptance: 60 cm × 60 cm
		Note: The acceptance is required from meson structure measurement. Pion structure measurement may require a position resoultion of 1 mm.		
Photon	0.1 – 1 GeV	20 – 30%		Efficiency: 90 – 99%
		Note: Used as a veto in e+Pb exclusive J/ψ production		
	20 – 40 GeV	$\frac{35\%}{\sqrt{E}}$	0.5–1 mm	
		Note: u-channel exclusive electromagnetic π^0 production has a milder requirement of $\frac{45\%}{\sqrt{E}}+7\%$ and 2 cm, respectively. Events will have two photons, but a single-photon tagging is also useful. Kaon structure measurement requires to tag a neutron and 2 or 3 photons, as decay products of Λ or Σ.		

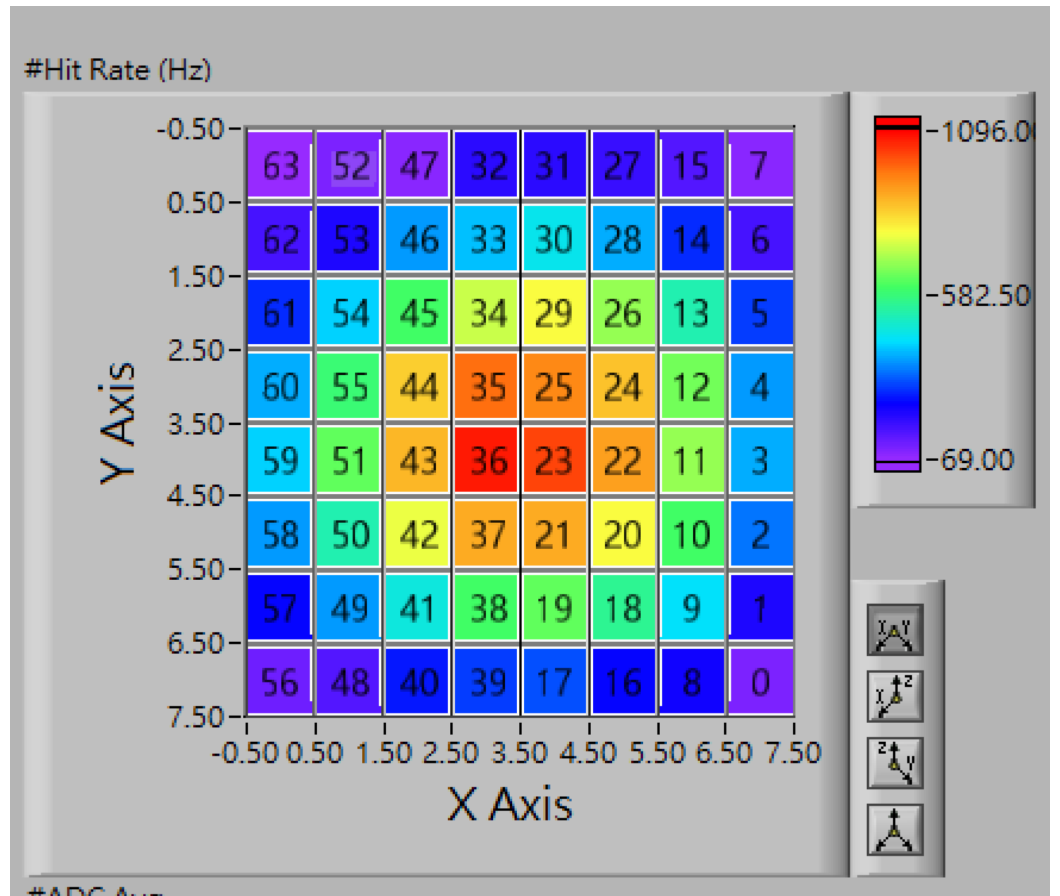
Table 2: Physics requirement for ZDC

ePIC ZDC prototype test @ ELPH (2024.03)





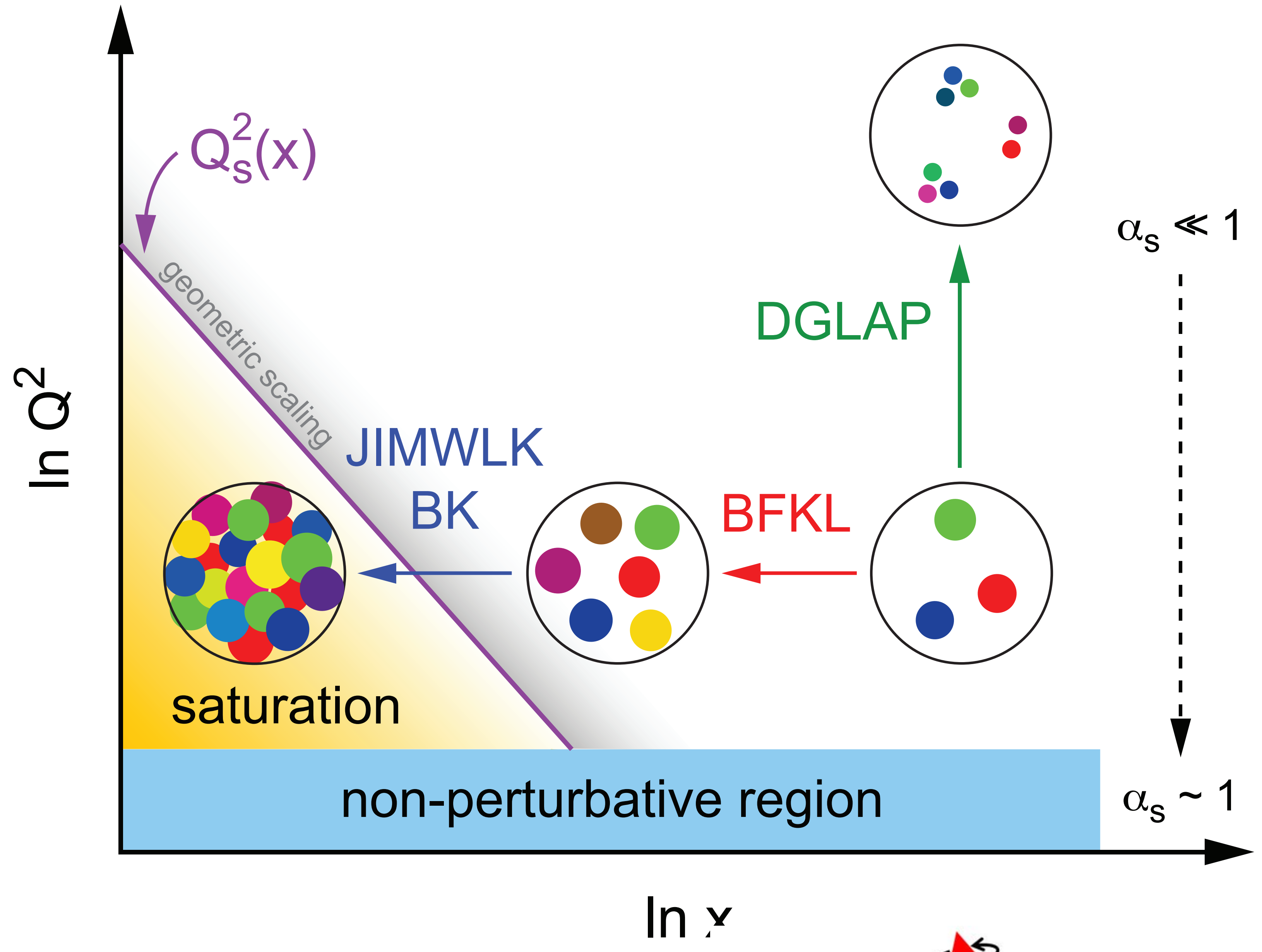
LYSO crystal with SiPM readout



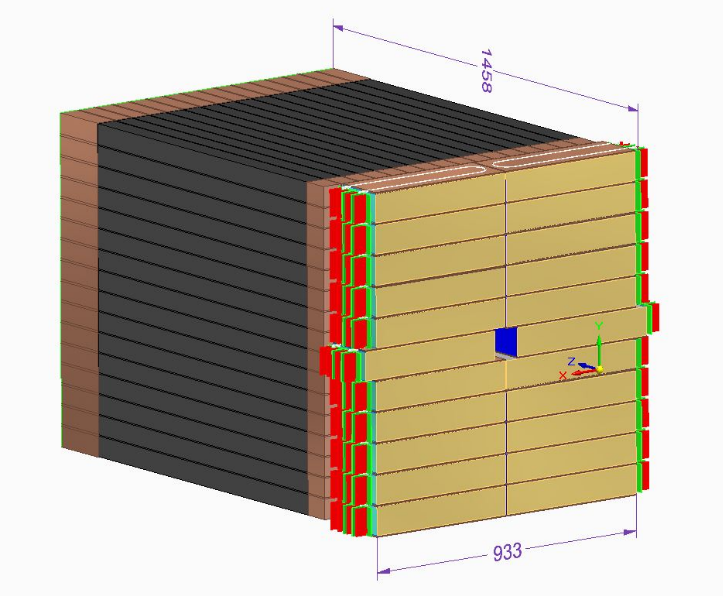
Hit map of LYSO crystal calorimeter from online monitoring

Summary

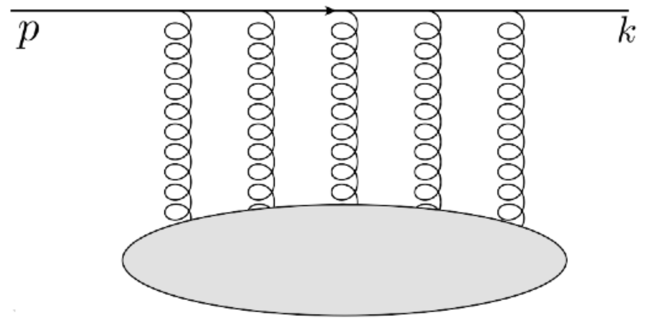
- Strong synergies between EIC and LHC forward
- To understand QCD and find a clear signal of CGC, exploring a wide kinematic coverage in x-Q^2 is crucial
- Universality test of QCD (color dipole formalism) at both EIC and forward LHC
- FoCal: Common detector technologies at forward LHC and EIC (ZDC)
- We will start FoCal production in Japan from 2024, and do physics from 2029-2032 (LHC Run-4) and maybe beyond in ALICE3)



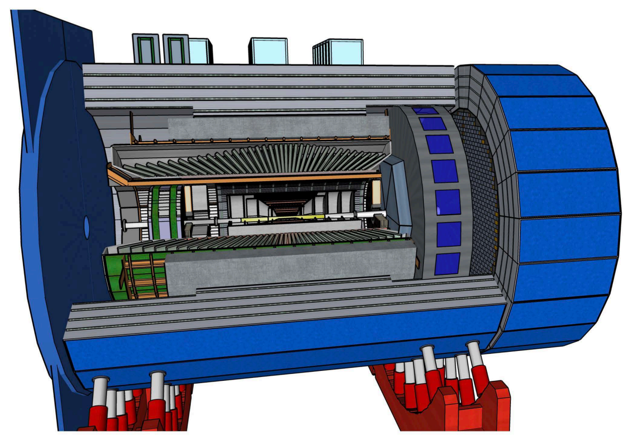
ALICE



Forward pA
at high energies



ePIC



DIS (EIC) eA