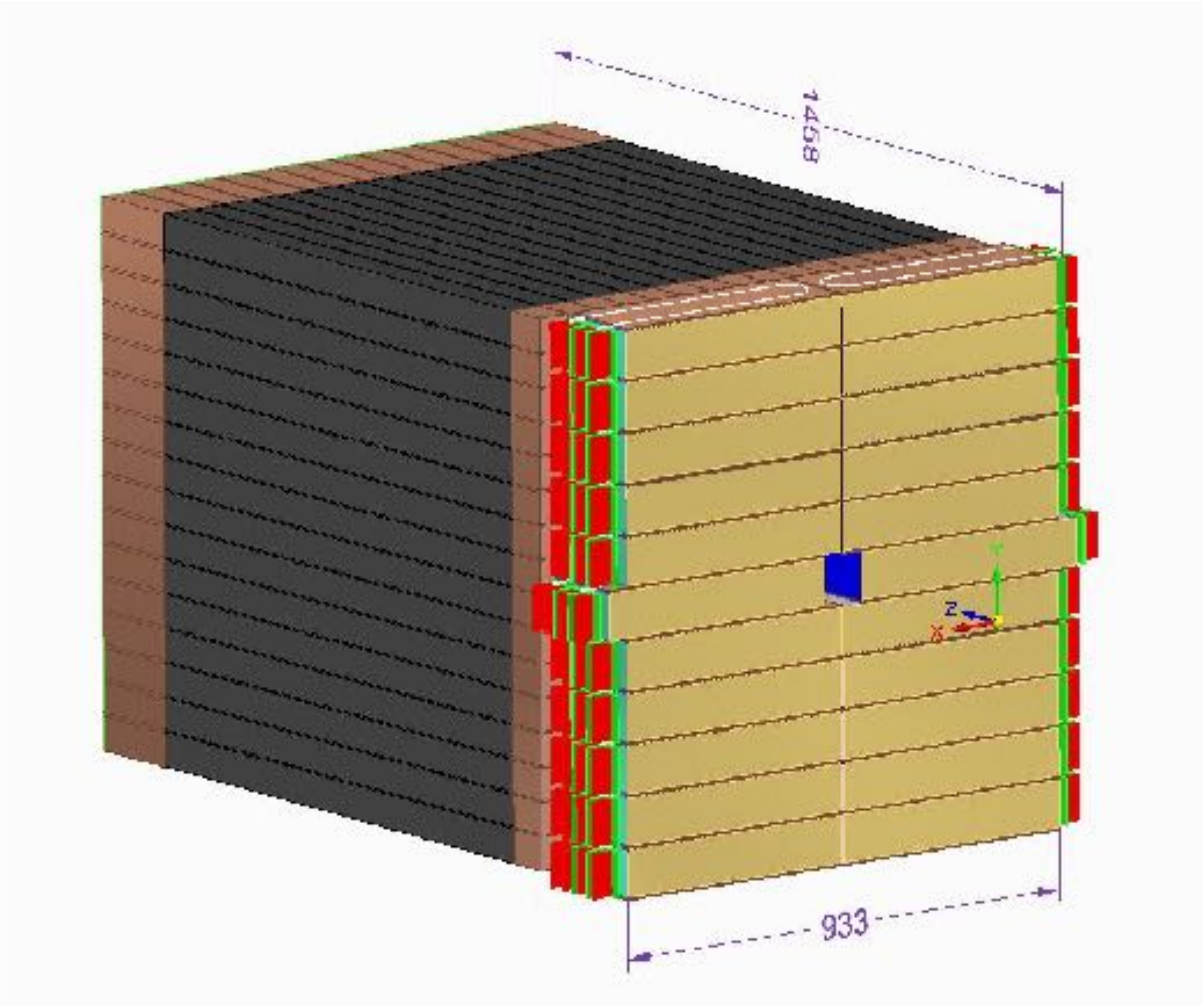
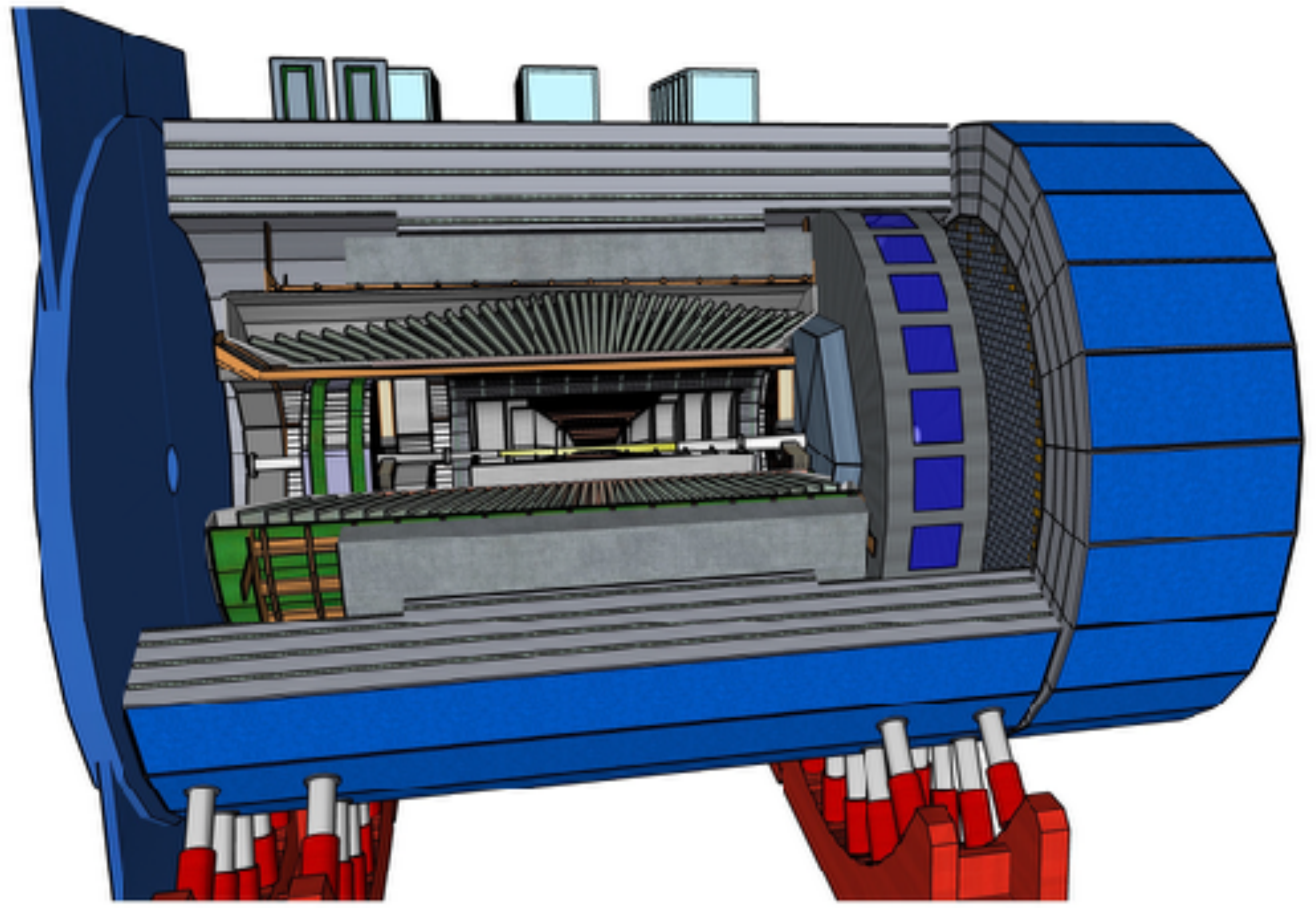
LHCでのグルーオン飽和探索、
QGPの物理との関連性
(Gluon saturation at LHC and QGP to physics)



Tatsuya Chujo

筑波大学
University of Tsukuba



EIC workshop, May 28, 2024, University of Tokyo, Japan

1） Introduction:

Physics of Quark-Gluon Plasma (QGP)

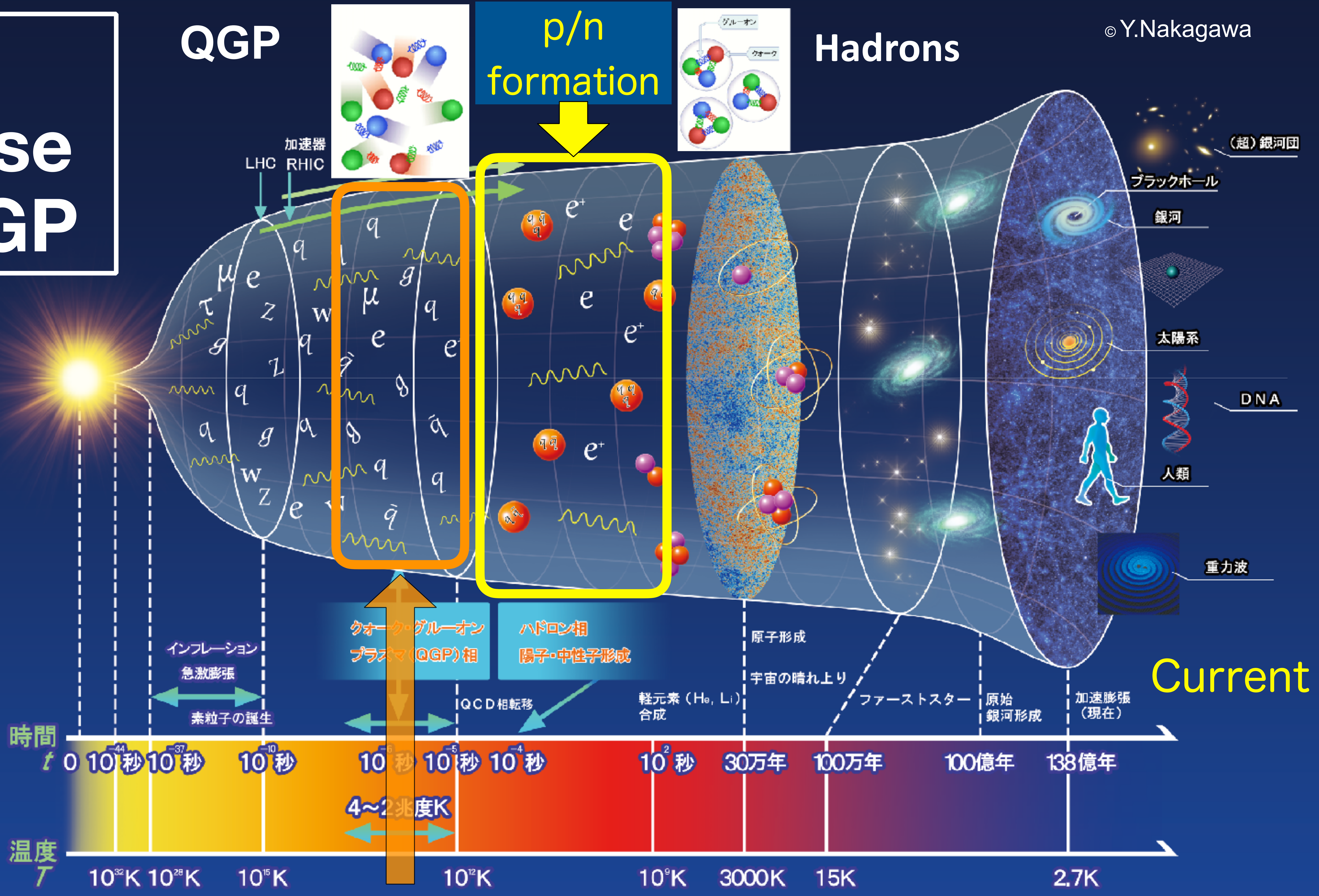
Early Universe and QGP

QGP

p/n formation

Hadrons

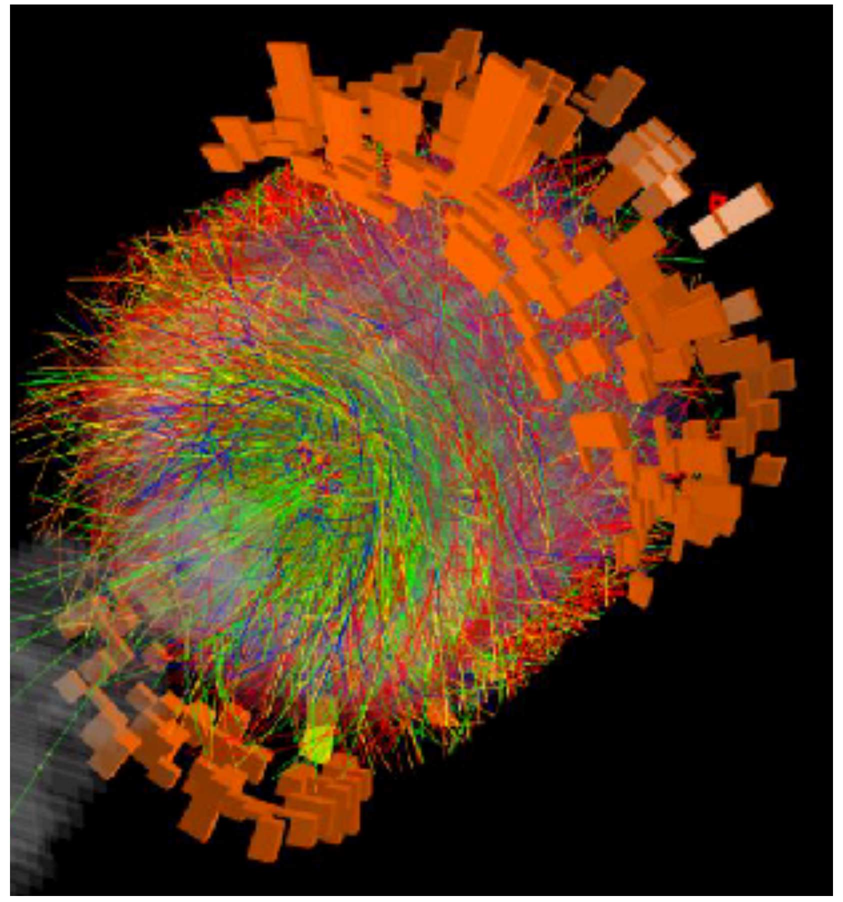
Big Bang



Current universe

A matter of early universe: Quark Gluon Plasma (QGP)

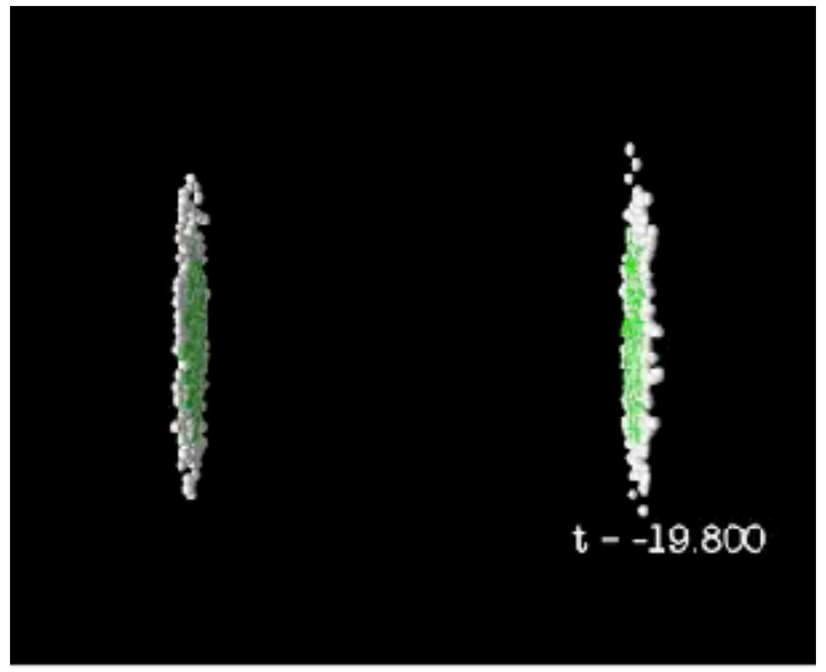
=10μ sec. after the big bang, high temp. ~ 4 trillion K

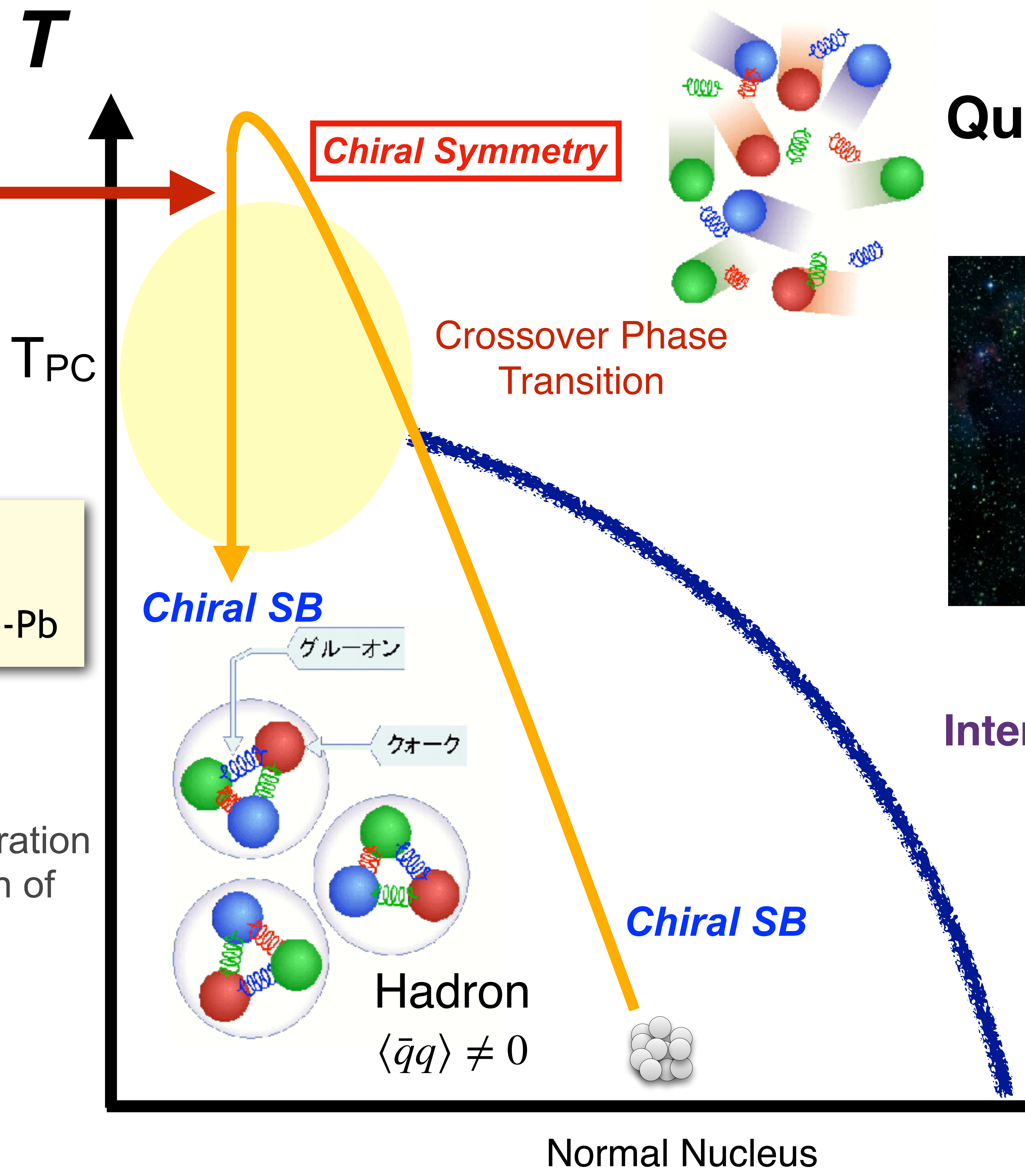


High Energy Nucleus-Nucleus Collisions

CERN (Switzerland)
LHC (2009-), 27 km
$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV Pb-Pb

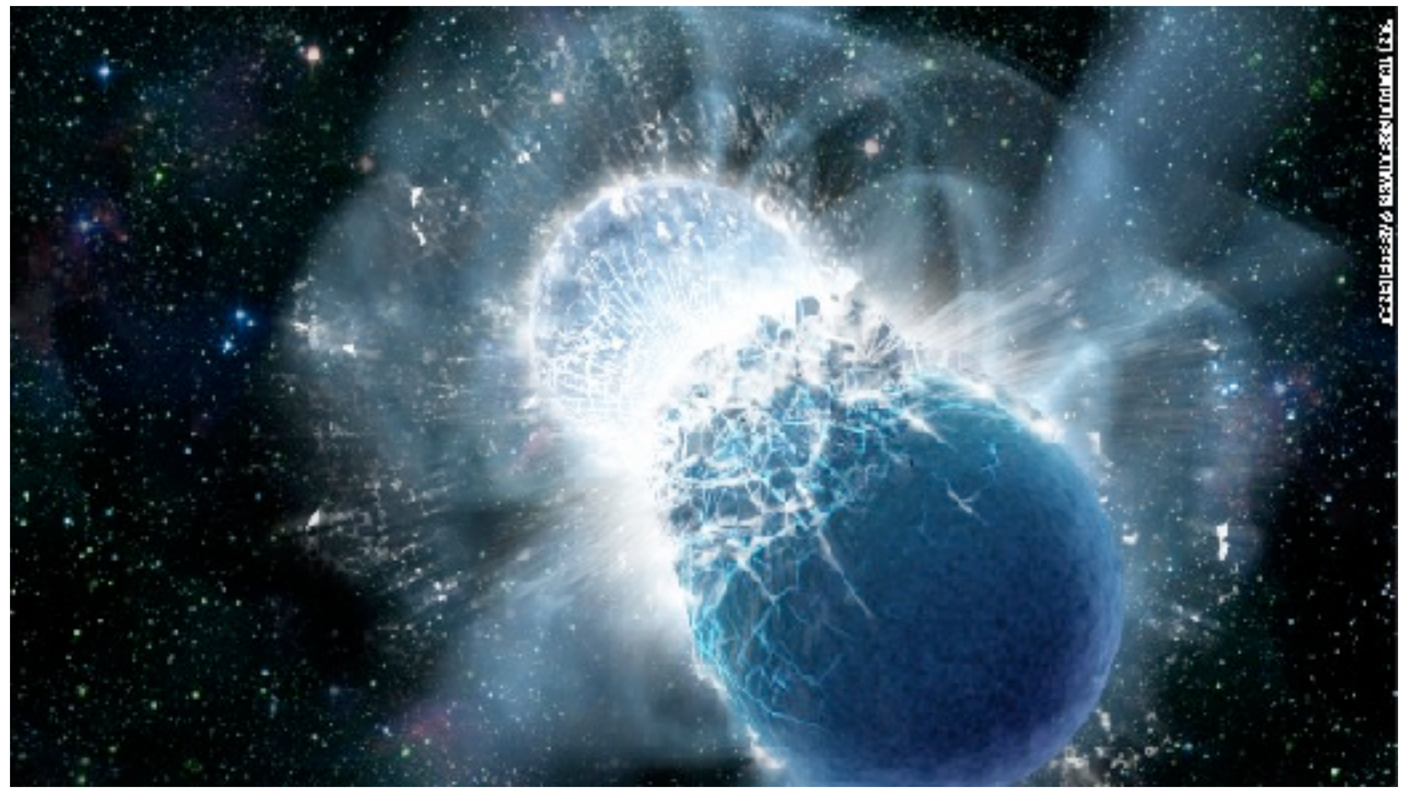
- Creation of QGP in the laboratory
- Properties of QGP, Restoration of Chiral Symmetry, Origin of nucleon mass





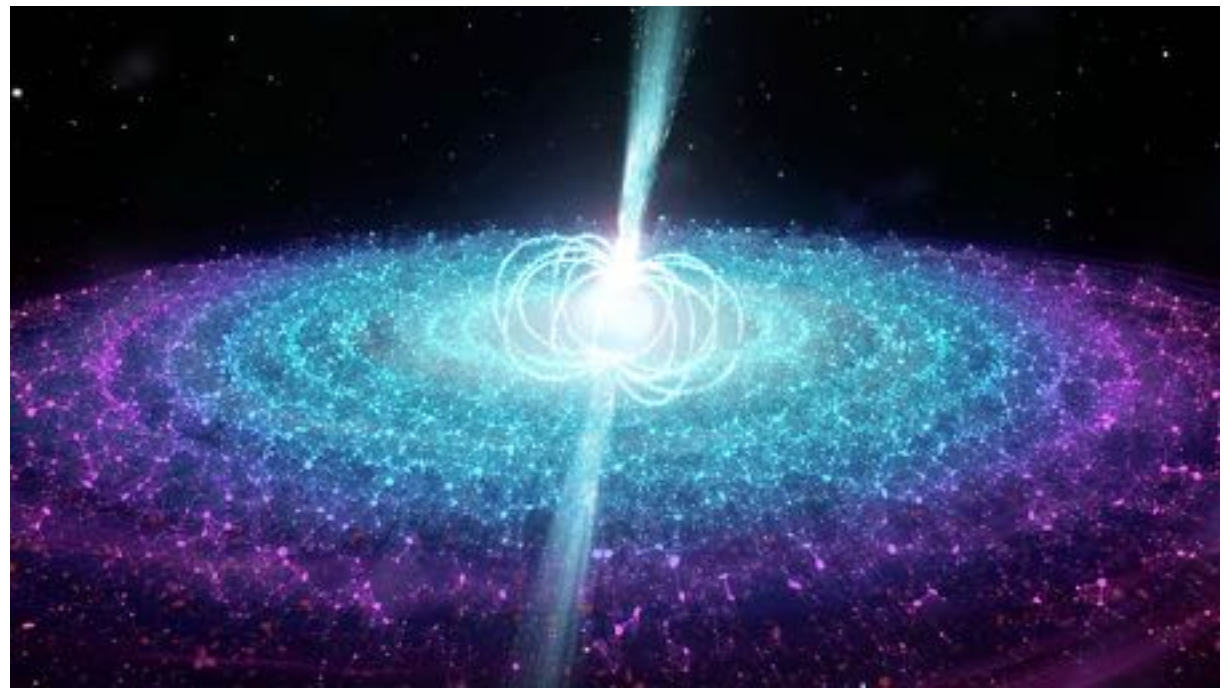
Baryon density

Quark Gluon Plasma (QGP)



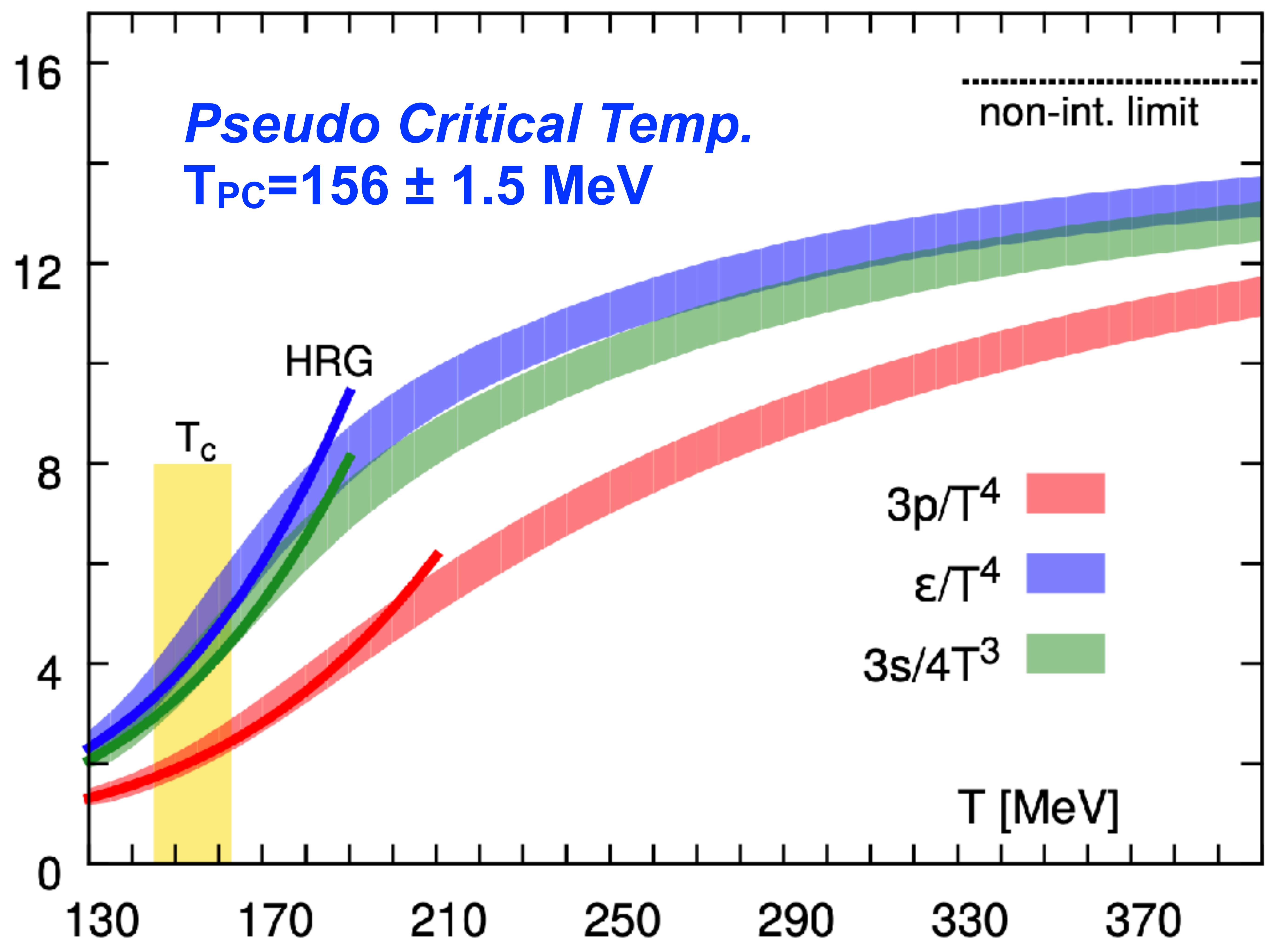
Neutron Star Merger

Interior of Neutron Star



* Neutron star image: https://phys.org/news/2018-09-neutron-star-jets-theory.html

Lattice QCD prediction



HotQCD Collaboration, PRD 90 (2014) 094503, arXiv:1407.6387 [hep-lat]

Crossover phase transition from hadronic phase to partonic phase

$$\epsilon = g\frac{\pi^2}{30}T^4$$

Ideal Stephan-Boltzmann Eq.

ε: energy density
T: temperature
g: degrees of freedom
(3: hadrons, 37: u, d quarks & gluon (spin, color, flavor))

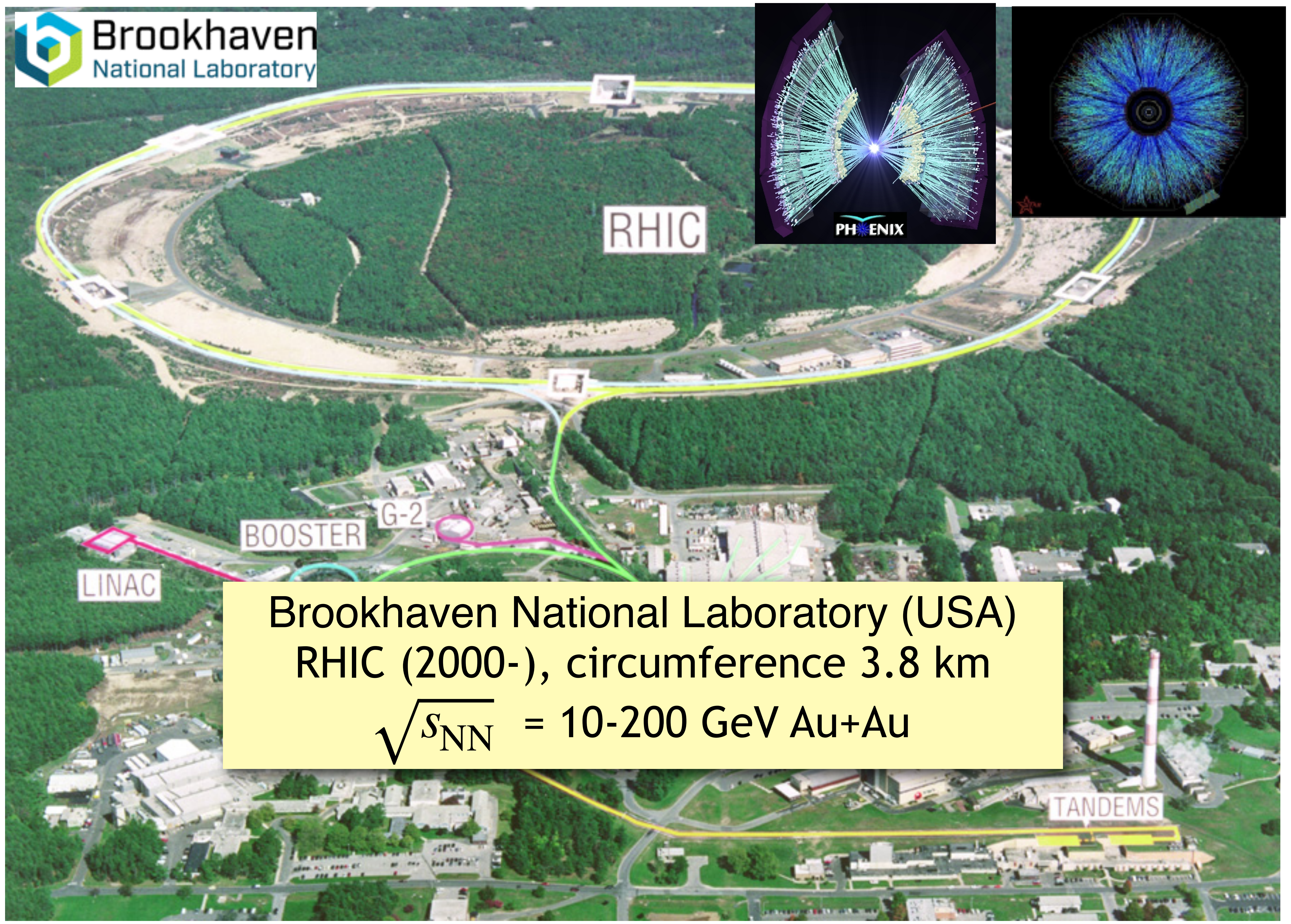
To produce QGP, we need:

T_{pc} ~ 160 MeV

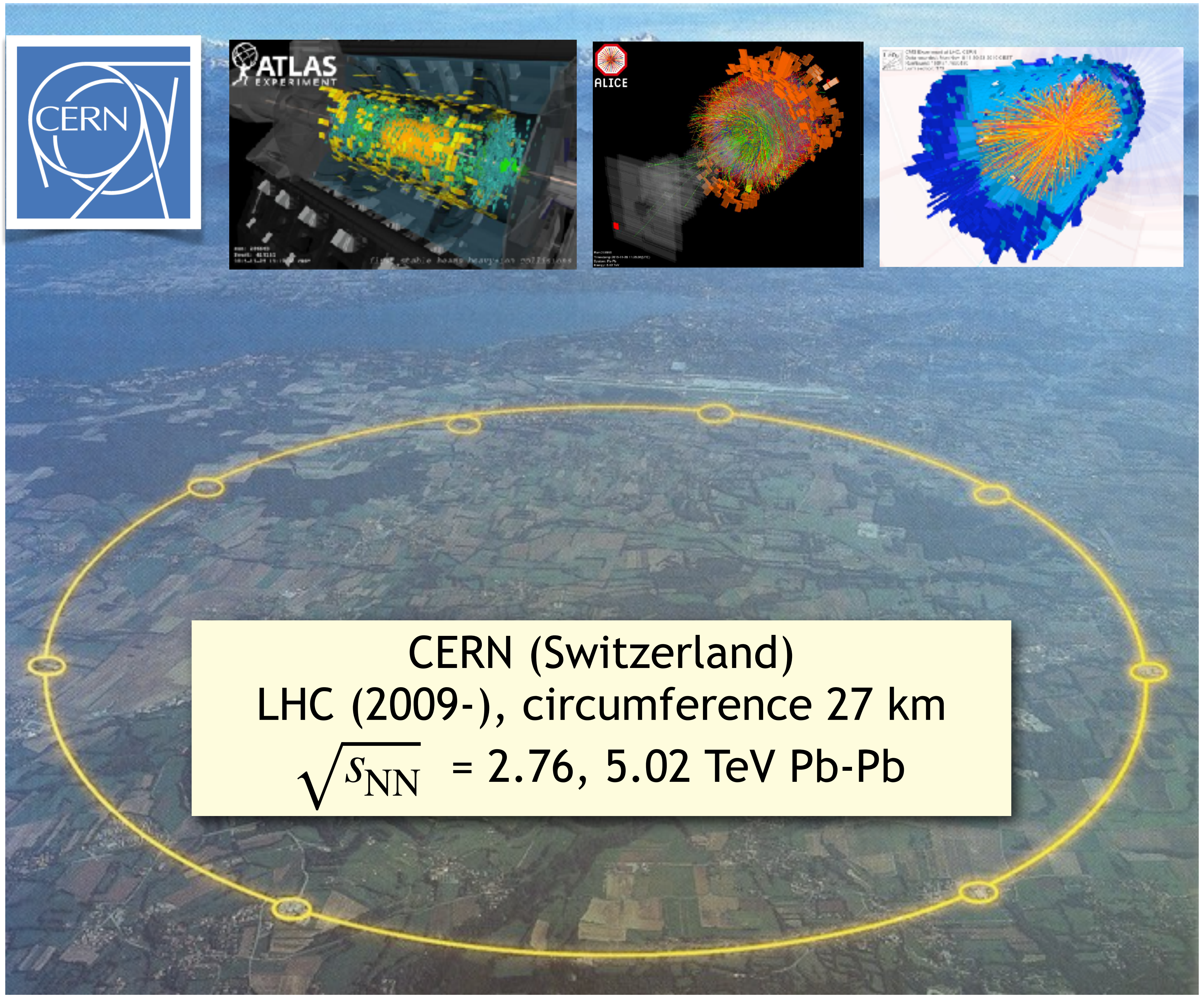
ε ~ 1 GeV/fm^3

Manifestation of dof for quarks and gluons

Creation of QGP at RHIC and LHC



Brookhaven National Laboratory (USA)
RHIC (2000-), circumference 3.8 km
$\sqrt{s_{NN}}$ = 10-200 GeV Au+Au



CERN (Switzerland)
LHC (2009-), circumference 27 km
$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV Pb-Pb

High Energy Heavy Ion Experiments：Quark Gluon Plasma (QGP), a state of early universe = properties of QGP

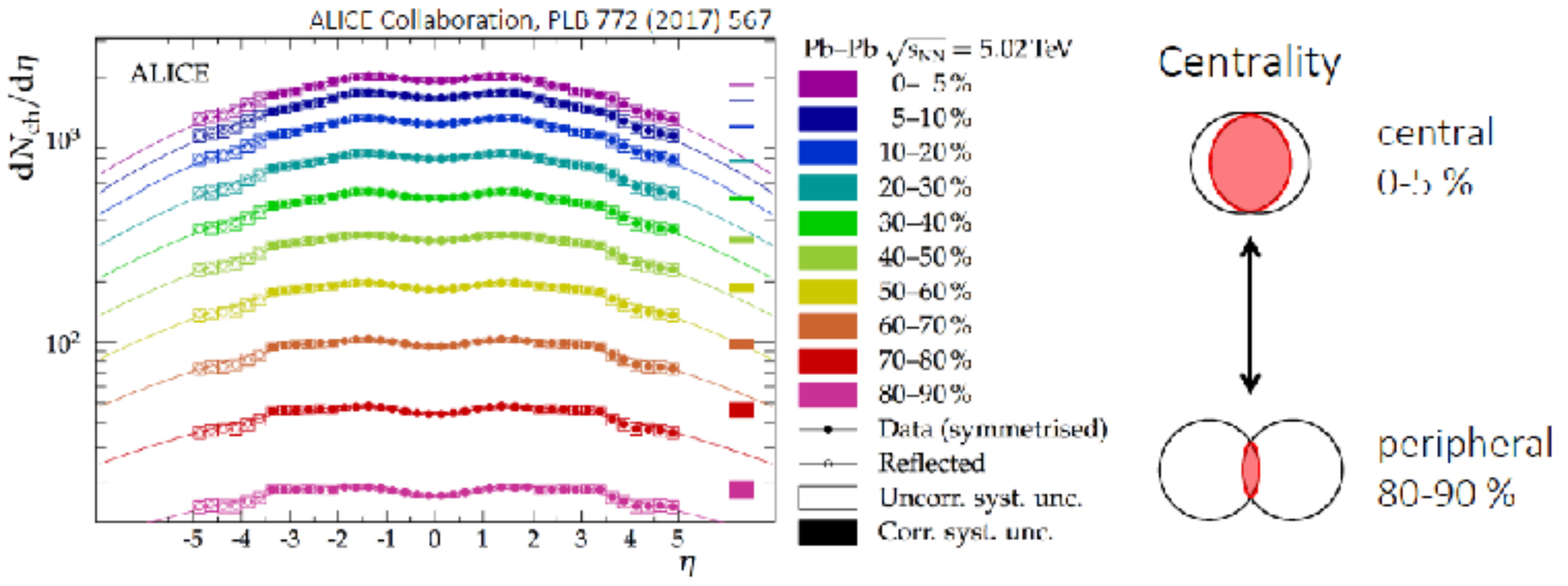
Accelerators: RHIC and LHC

After 2025, RHIC → EIC (physics data taking will start in 2032), After 2035 ALICE3 @ LHC

25 years of QGP research; (1) Bulk properties

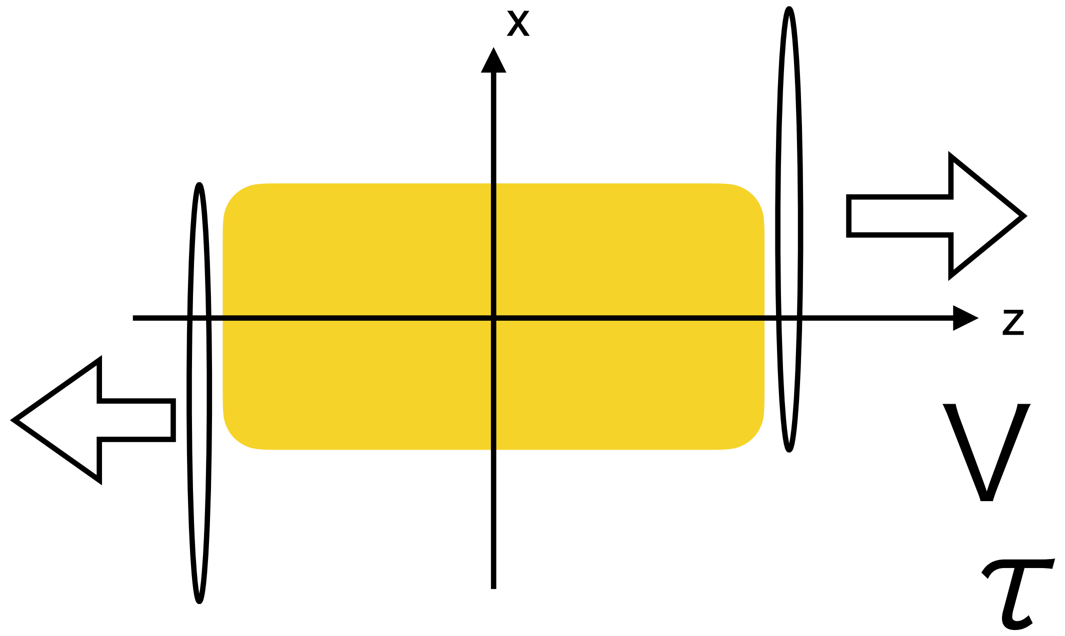
Energy density

$$\langle\epsilon(t)\rangle = \frac{\text{Energy}}{\text{Volume}} = \frac{\langle E\rangle dN}{V} = \frac{1}{tA}\frac{dN(t)}{dy}\langle m_T\rangle(t)$$



ε ~ 16 GeV/fm³

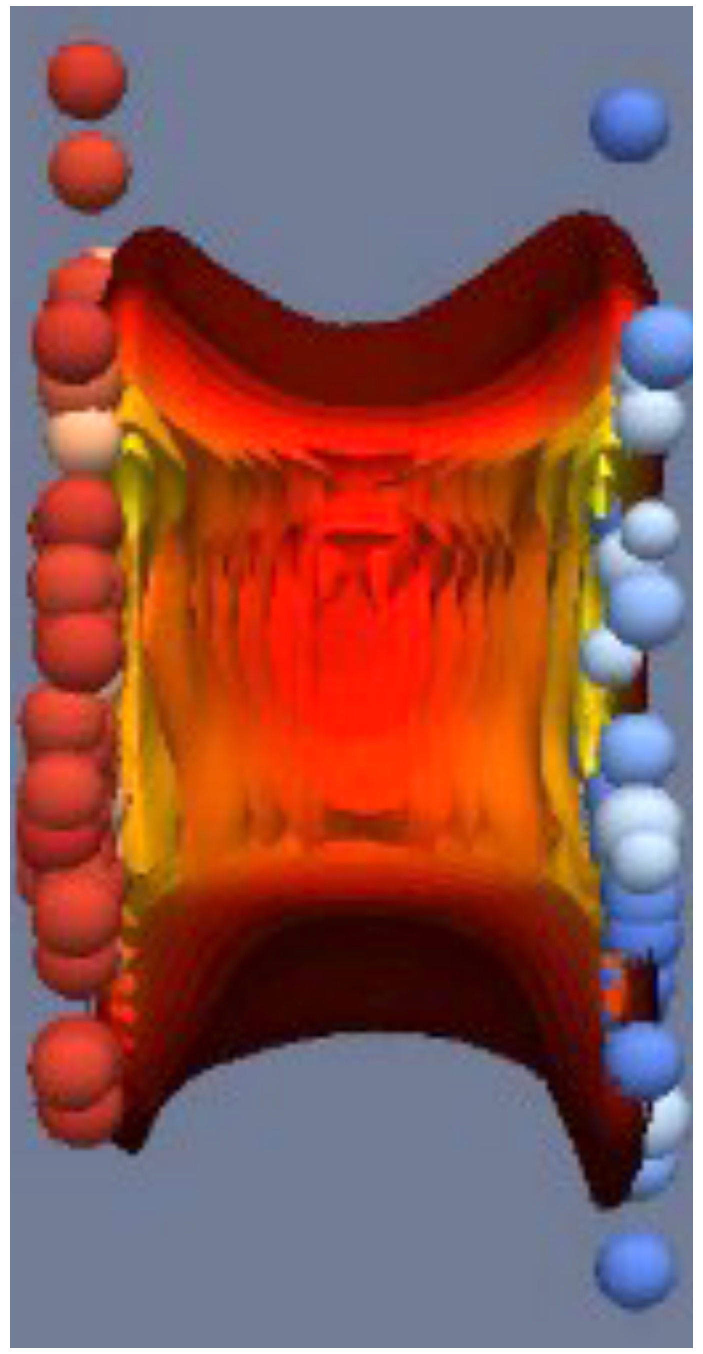
Volume, duration time



V ~ 300 fm³

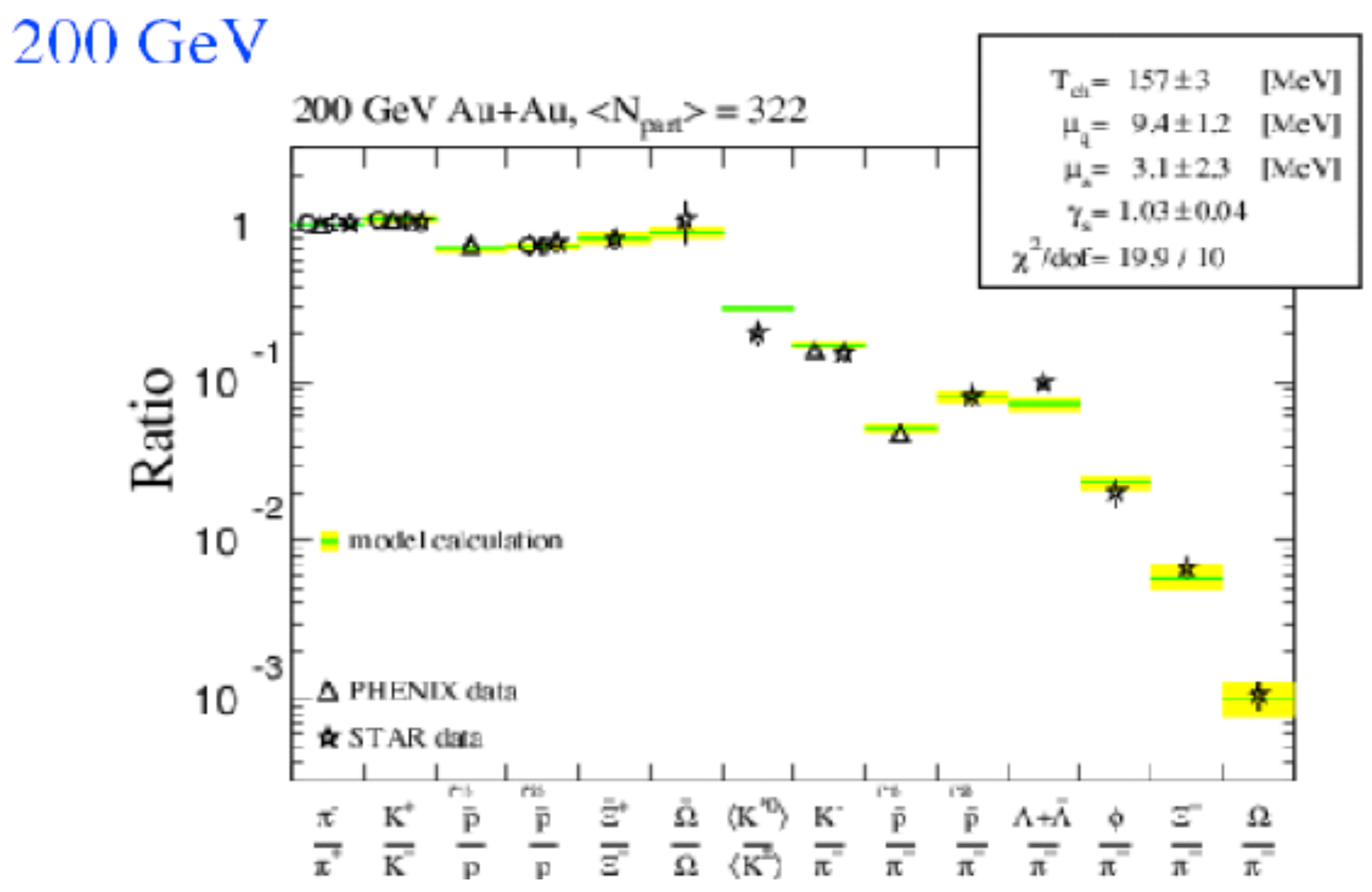
τ ~ 10 fm/c

Thermo-statistical mechanics for quarks and gluons



Hadron production～Bose, Fermi dis.

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$



Baryon chemical potential μ_B ~ 0

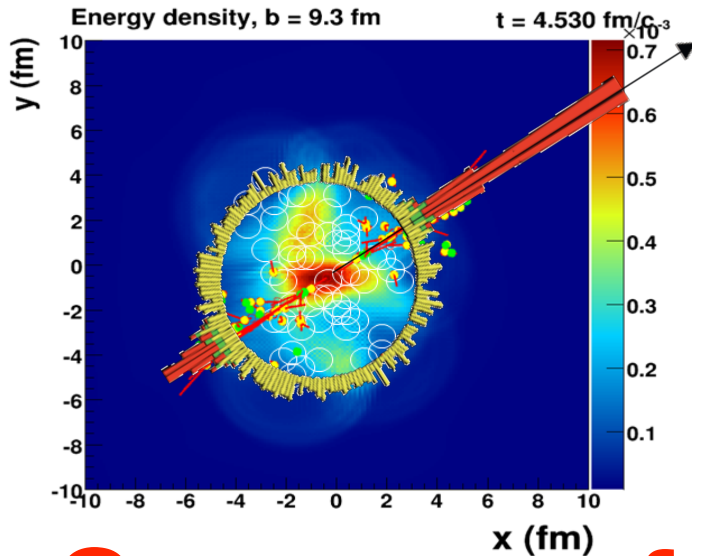
Chemical freeze-out temp. T_{ch} ~ 160 MeV

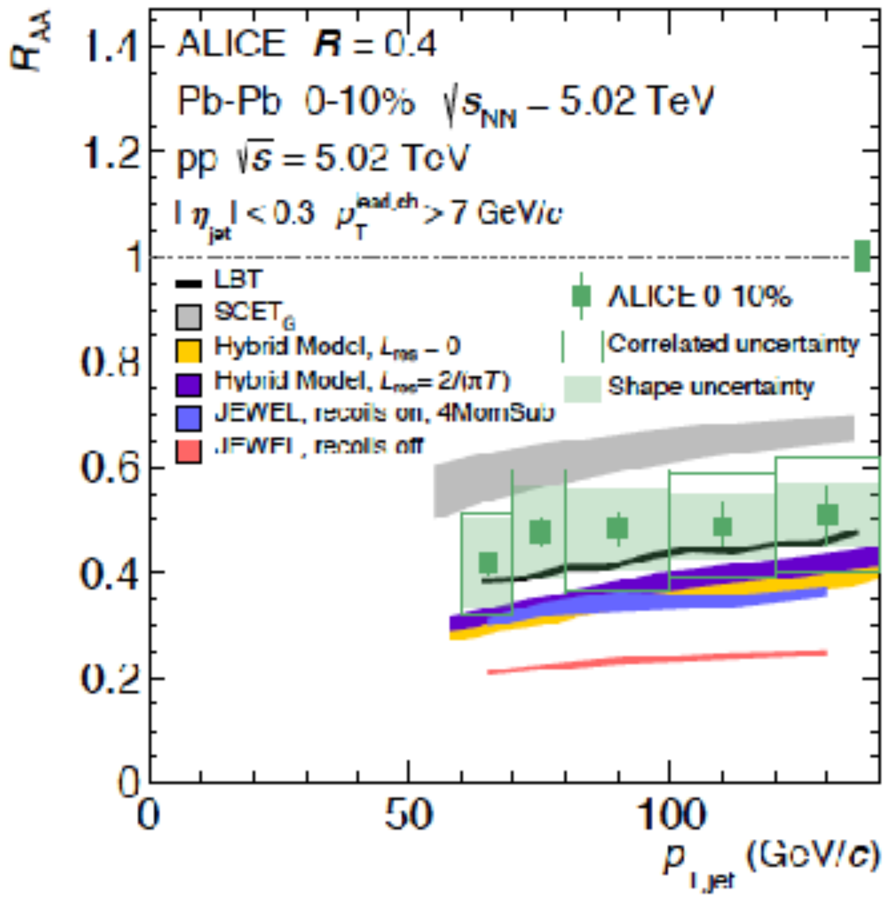
Phys. Rev. C69, 034909 (2004), PHENIX

Nucl. Phys. A 757 (2005) 184

25 years of QGP research; (2) strongly coupled QGP

1. Jet Quenching

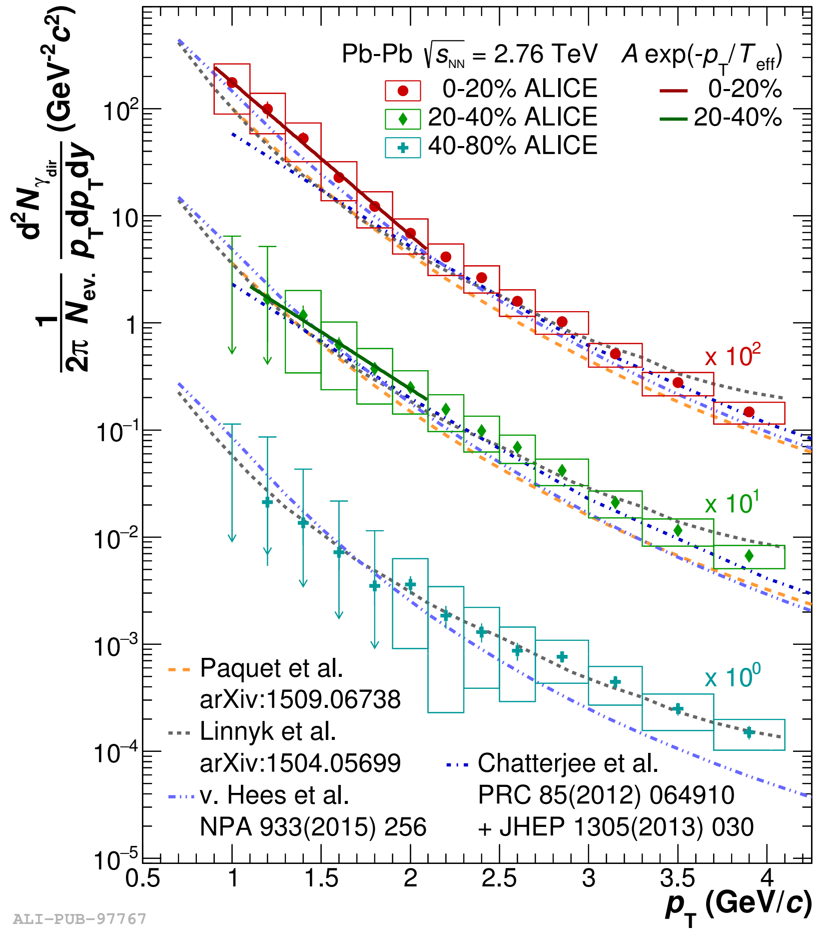




Phys. Rev. C 101, 034911 (2020), ALICE

2. Thermal photons

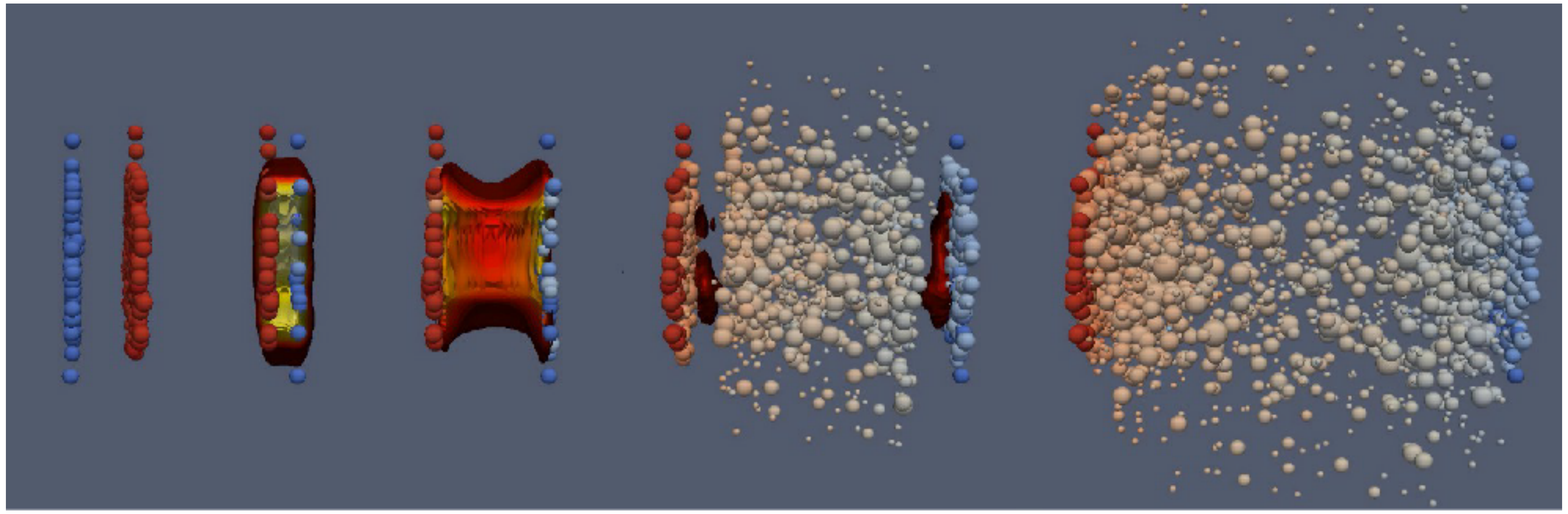
$T_{init.}$ ~300 MeV



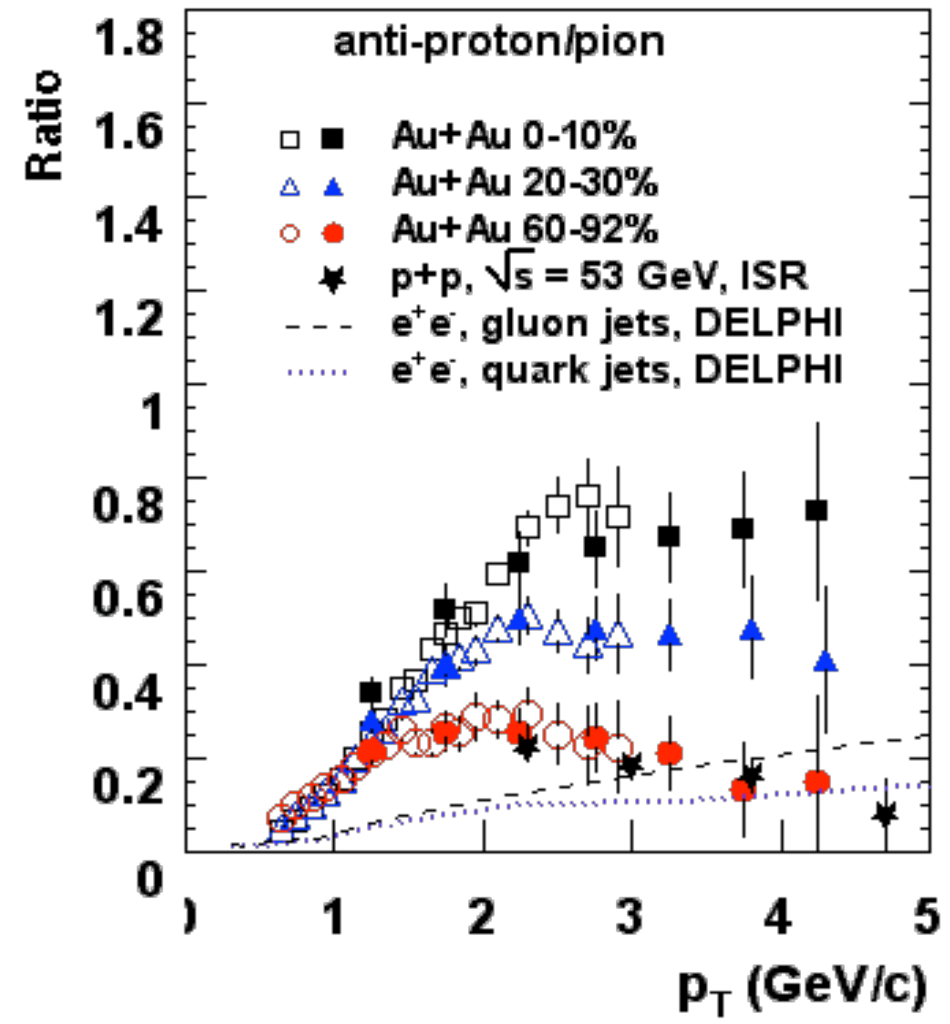
PLB754(2016)235 (ALICE)

Success of hydrodynamic models,

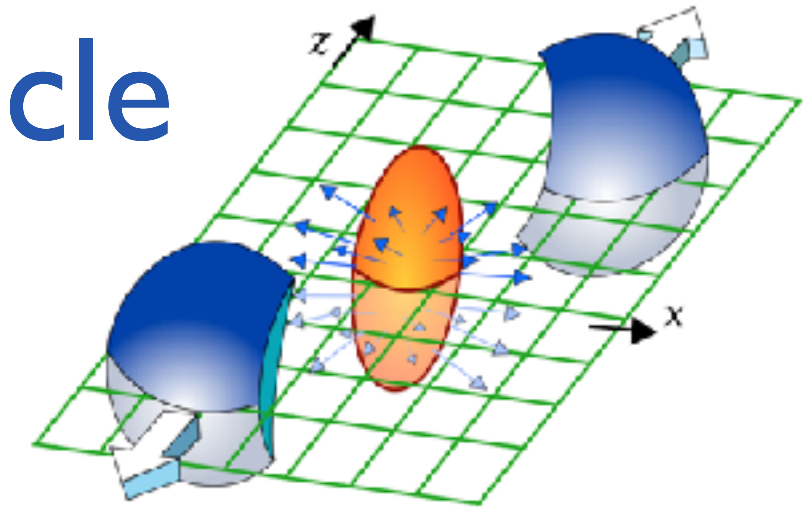
strongly coupled QGP (sQGP)

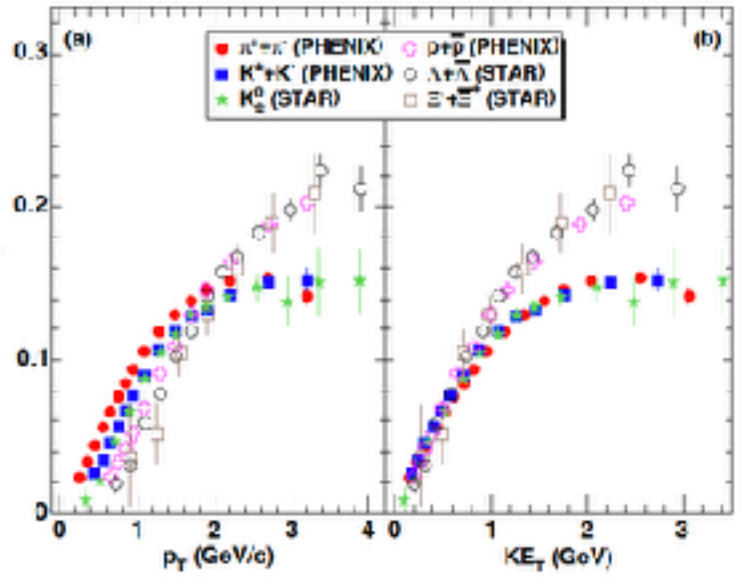


Phys. Rev. C69, 034909 (2004), PHENIX



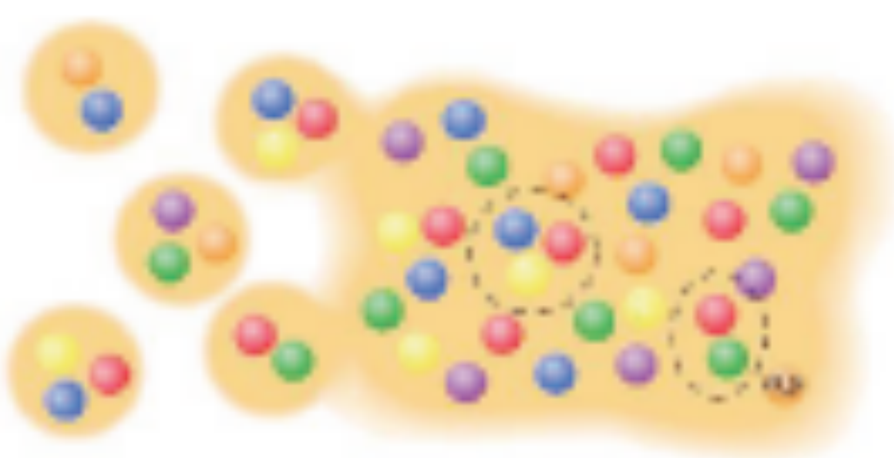
3. Large azimuthal anisotropy of particle emission (v_2)





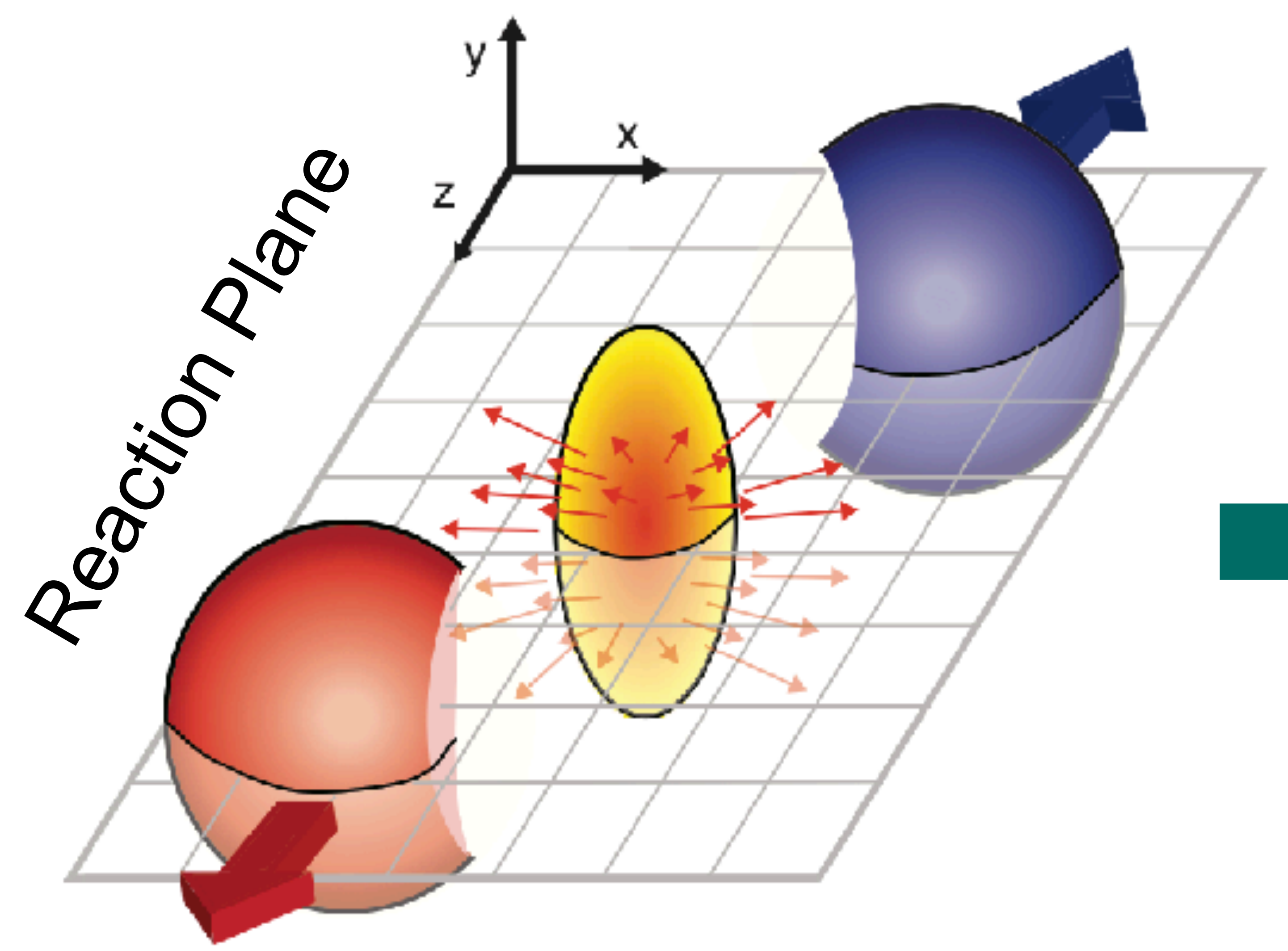
Phys. Rev. Lett.98, 162301 (2007), PHENIX

4. Quark recombination

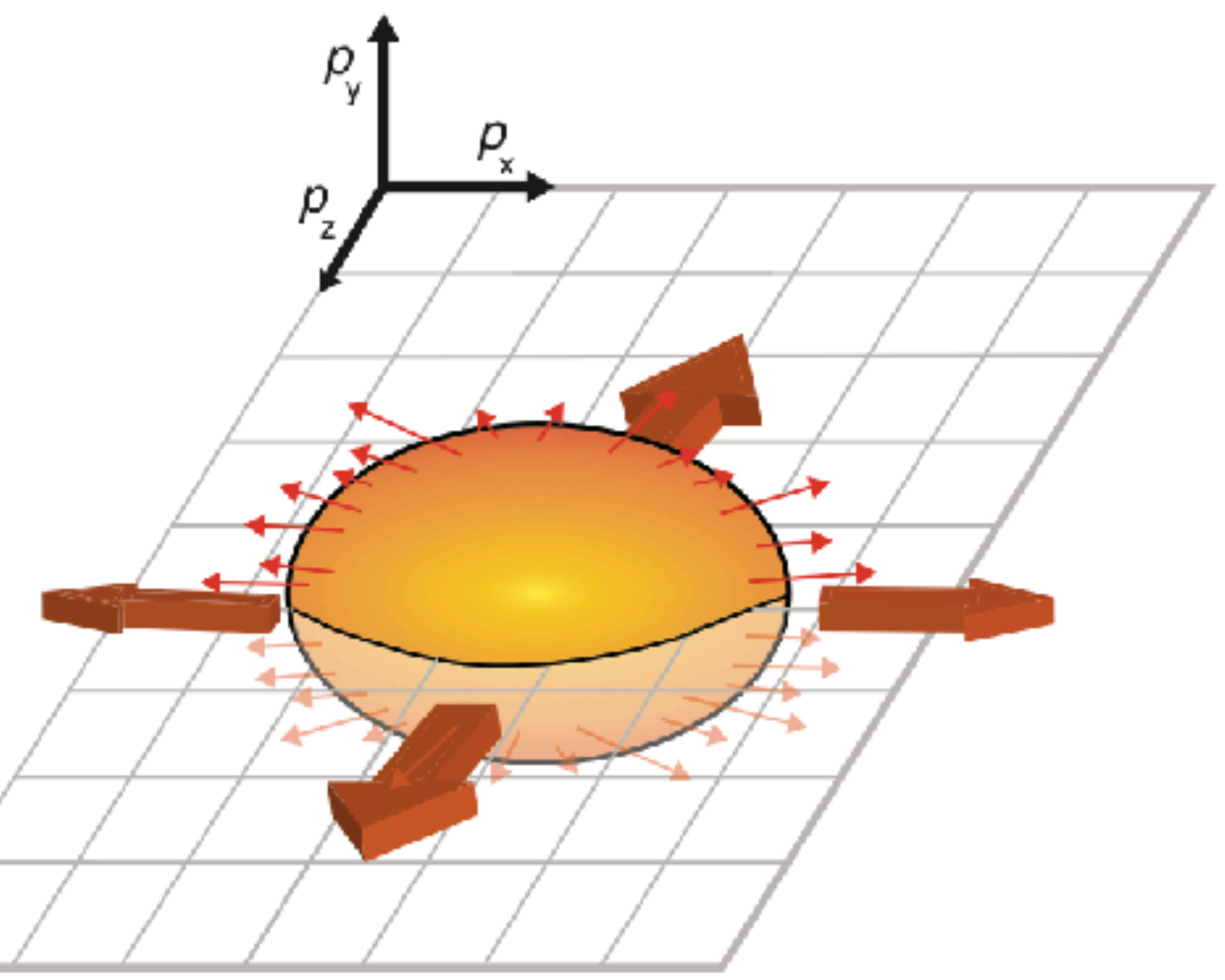


Collectivity of QGP

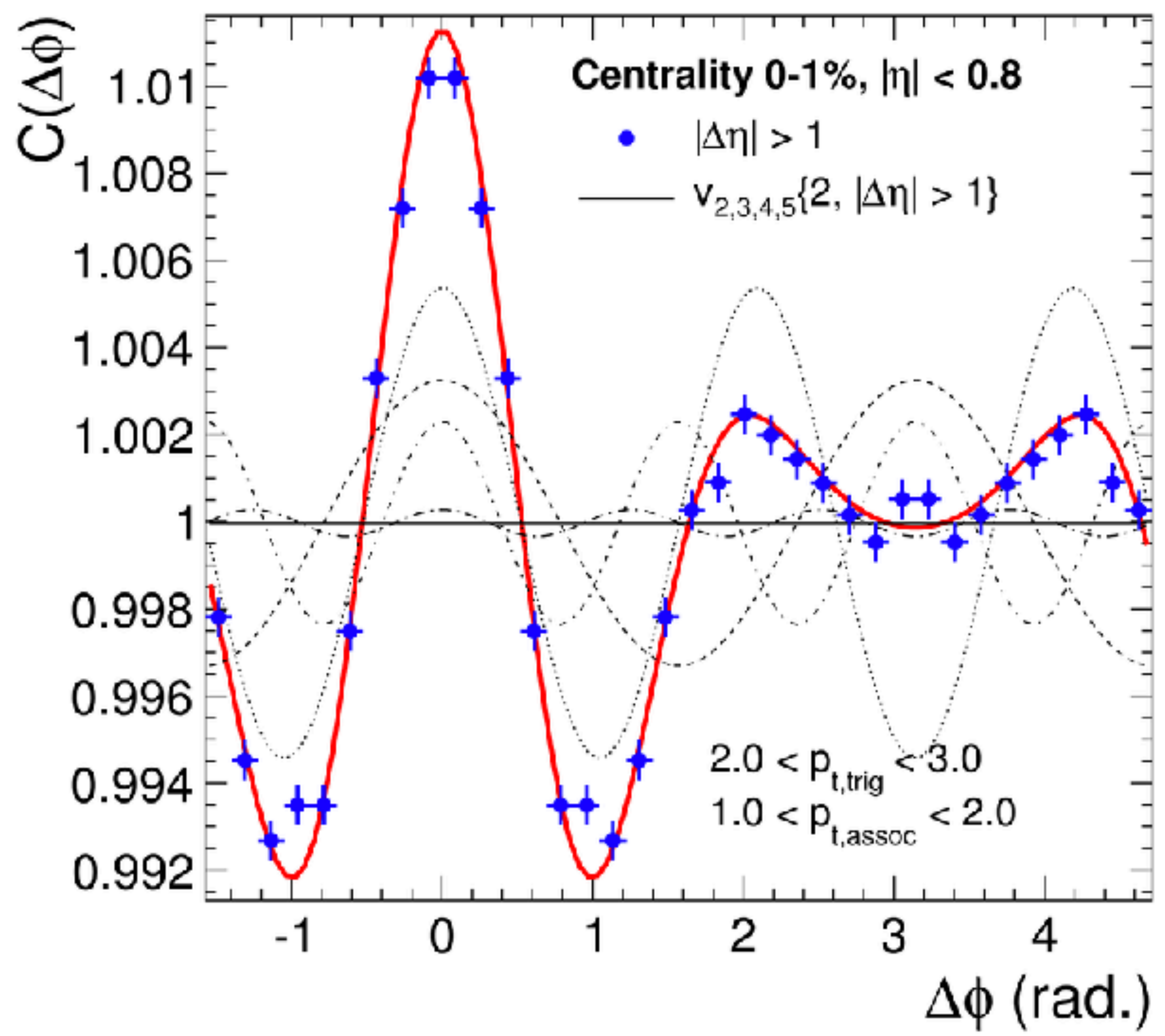
ALICE, Phys. Rev. Lett. 107 (2011) 032301

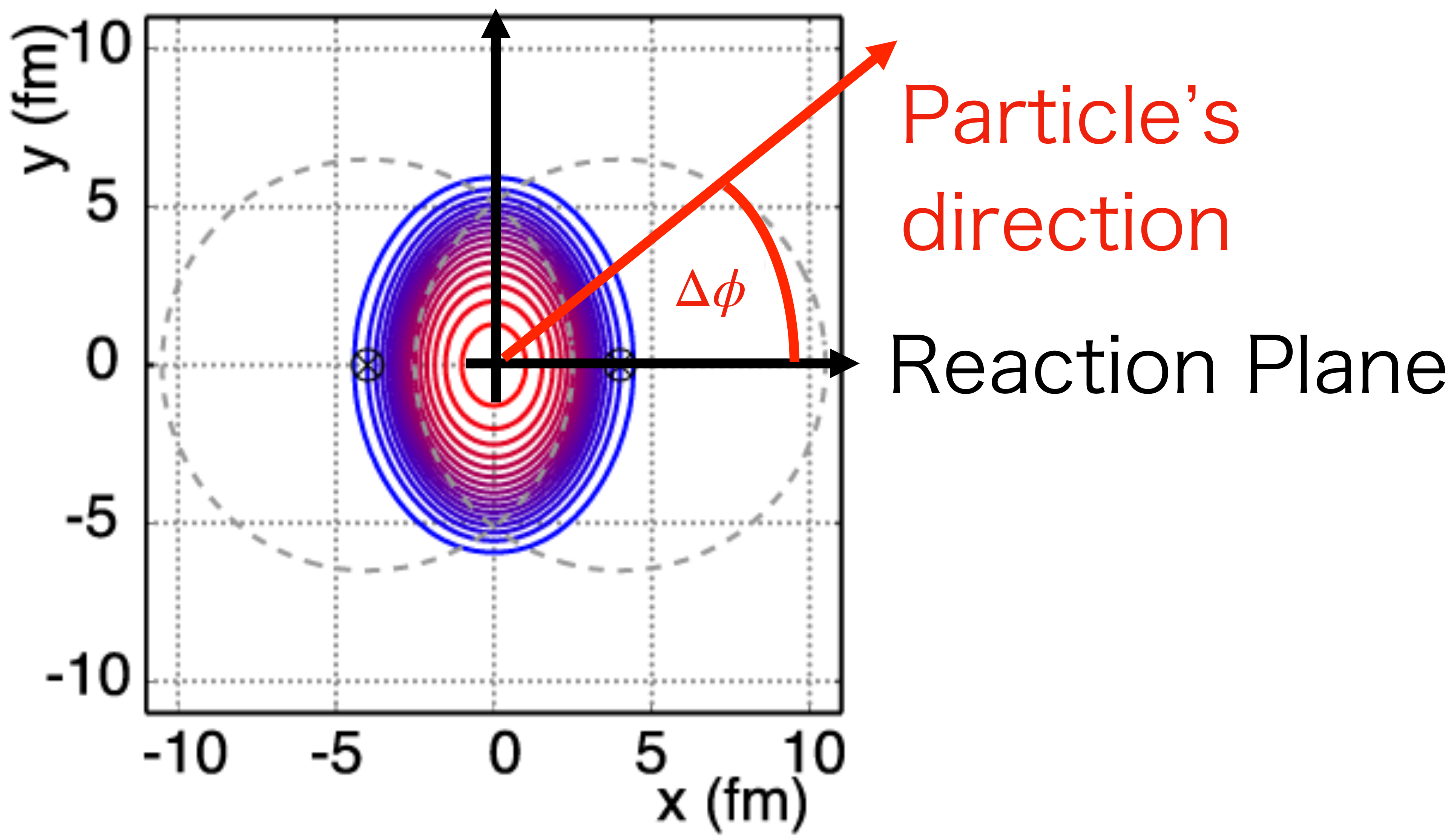


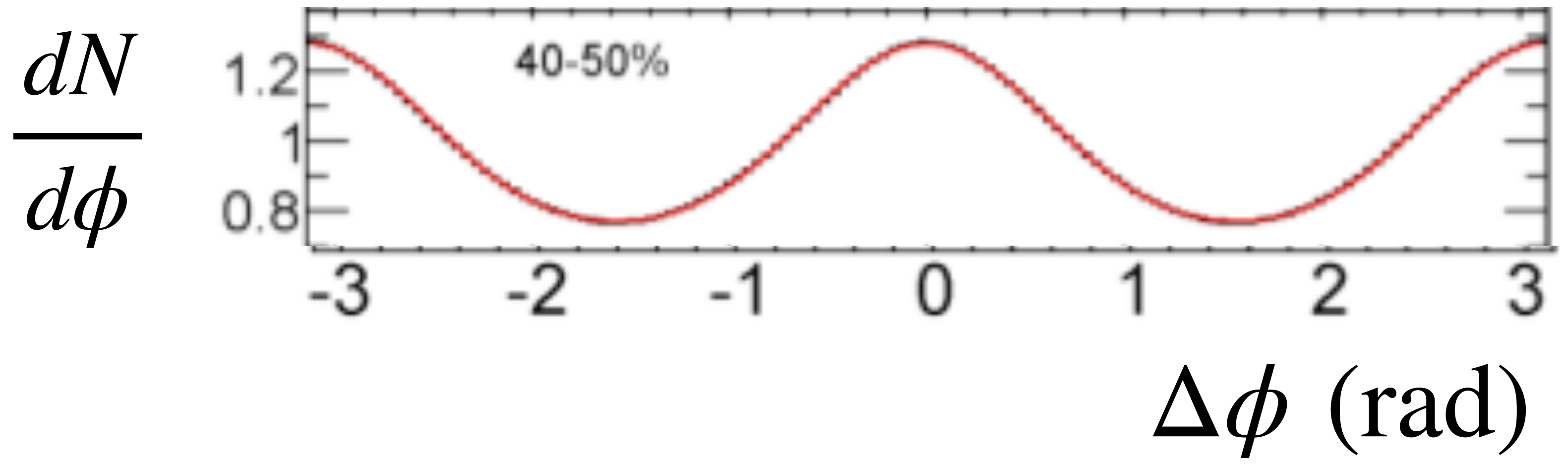
Geometrical Anisotropy



Momentum Anisotropy



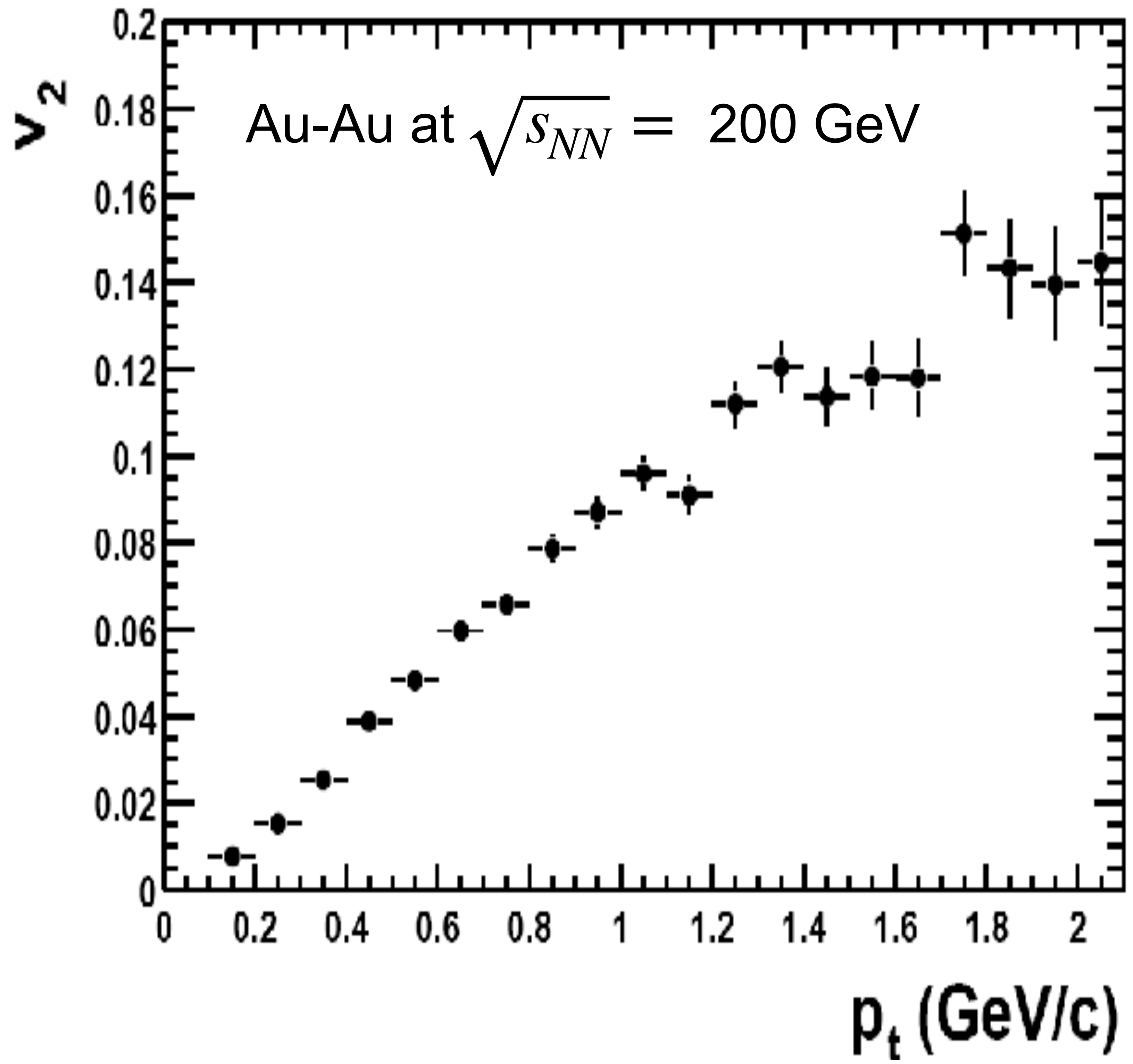




$$\frac{dN}{d\phi} \propto (1 + 2\underline{v_2}\cos(2\Delta\phi) + \ldots)$$

2nd coefficient of Fourier expansion : v_2 （elliptic flow）

STAR PRL86,402 (2001)



- **Large v_2 at RHIC and LHC**
- **To produce large v_2, it needs two conditions in Hydro cal.**
  - (1) Early thermalization ～ 0.6 fm/c
  - (2) Very small η/s

Because at early stage of collisions:

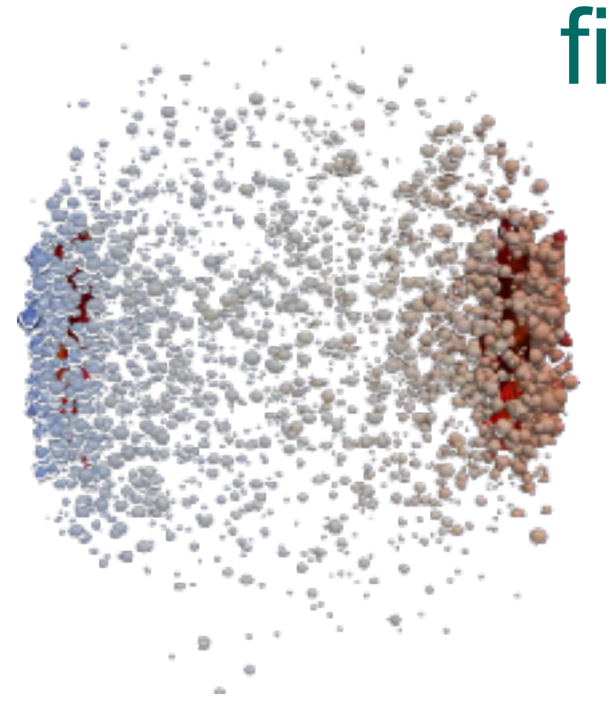
１）Reaction zone is elliptic

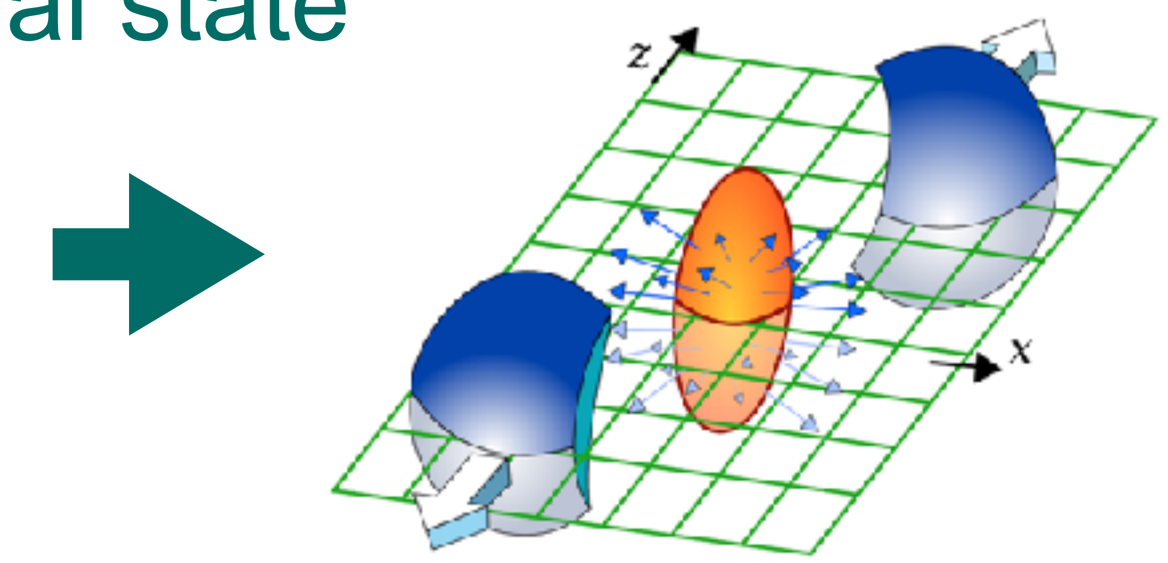
→ Different pressure gradient between short and long axis

→ Elliptic flow (v_2) generation

２）Hydrodynamic equation works for QGP at a very early time (~0.6 fm/c) and also needs a small η/s (= strong coupling)

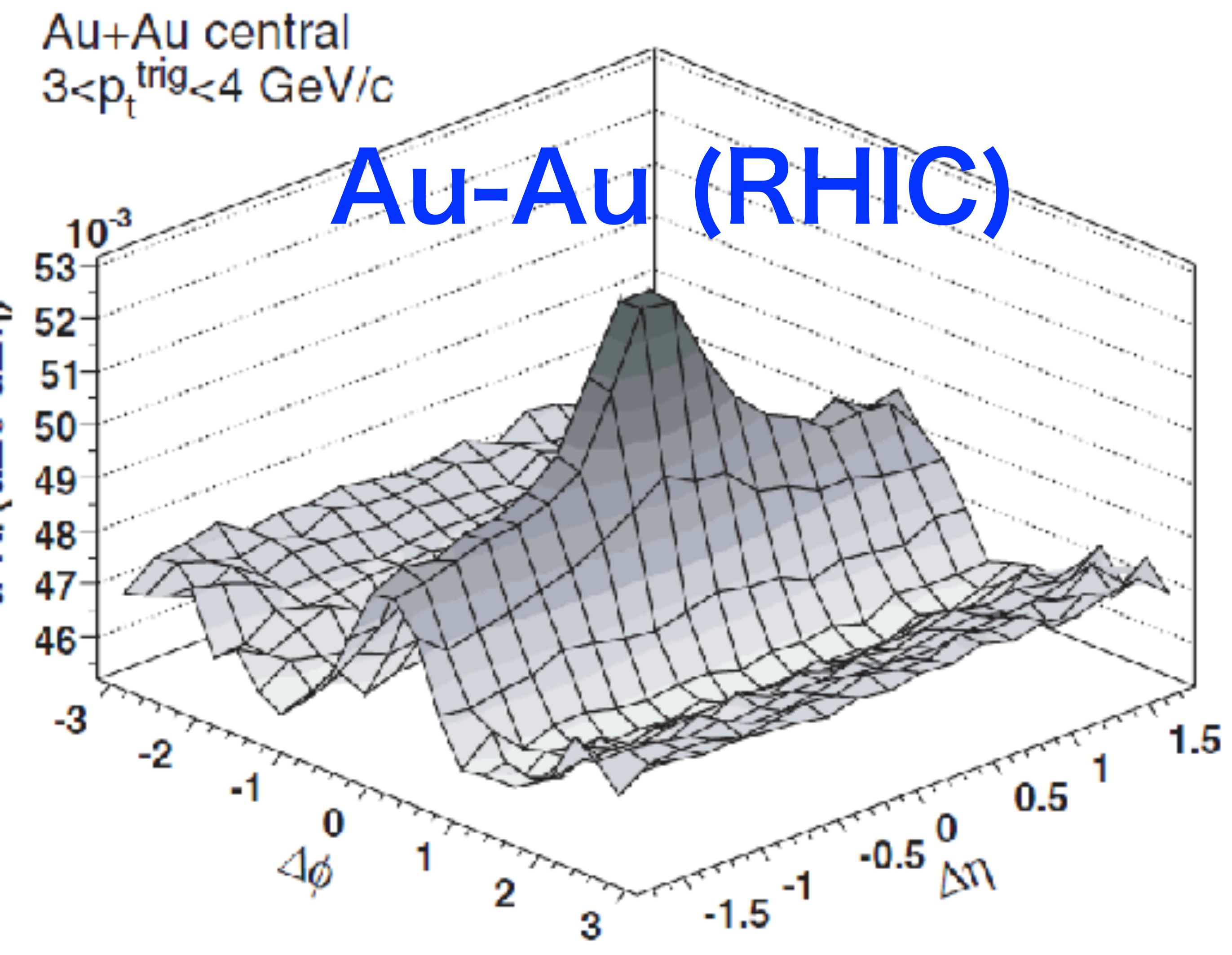
Extraction of properties from the final state



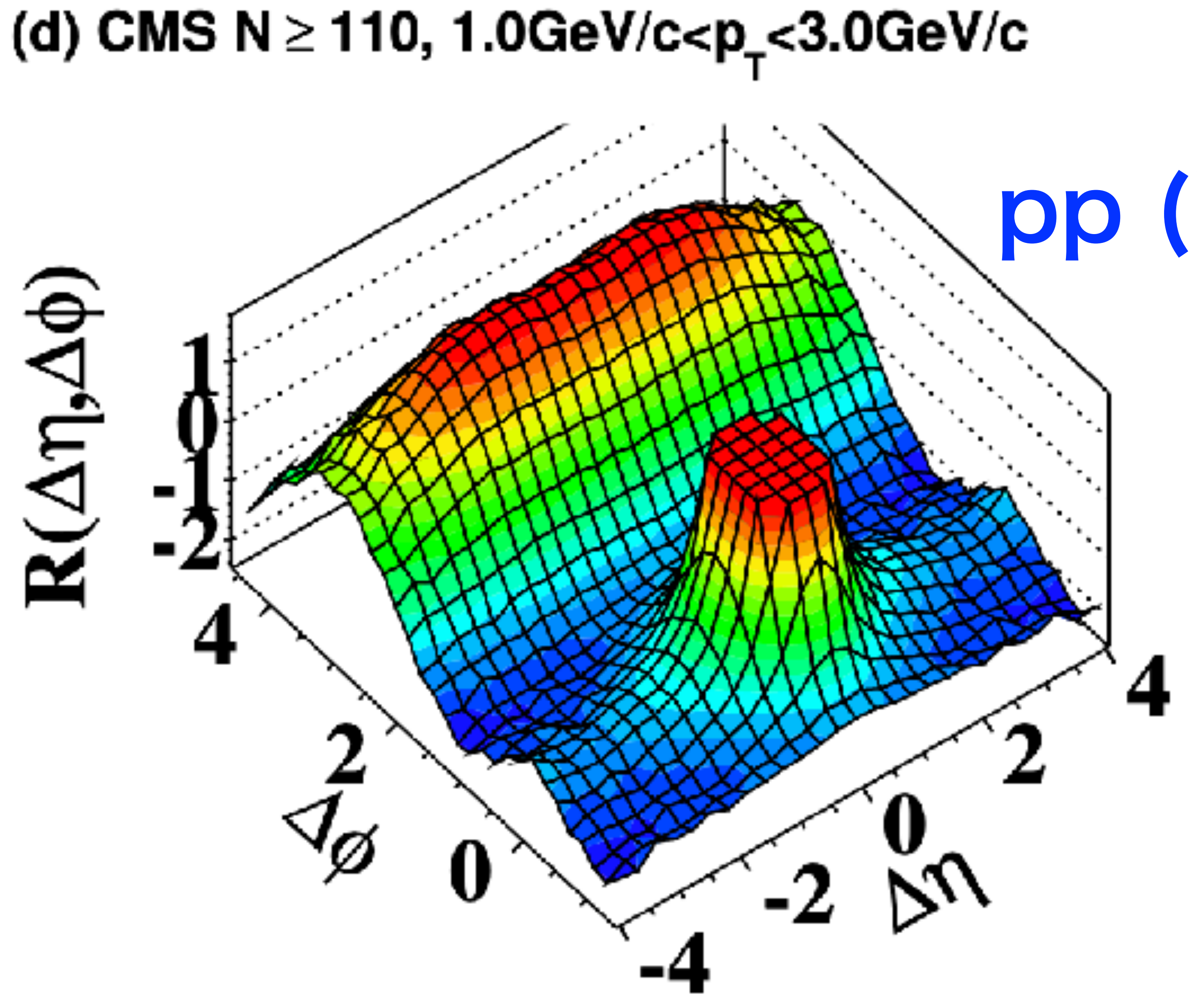


“strongly” coupled QGP (sQGP) with early thermalization

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



STAR, PRC 80 (2009) 064912



pp (LHC)

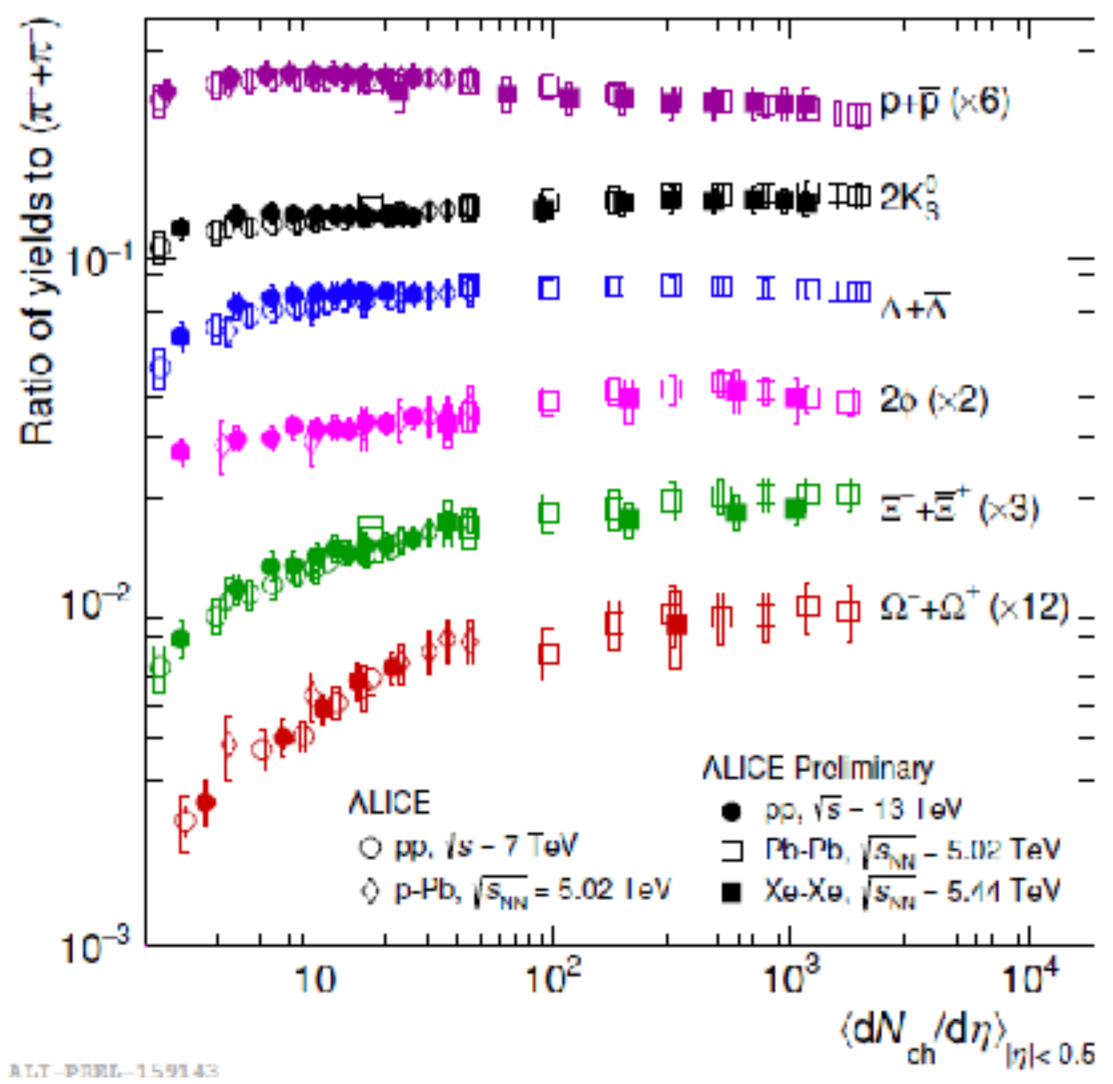
CMS, JHEP 1009 (2010) 91

1. Two particle correlations (Δφ, Δη)

- **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

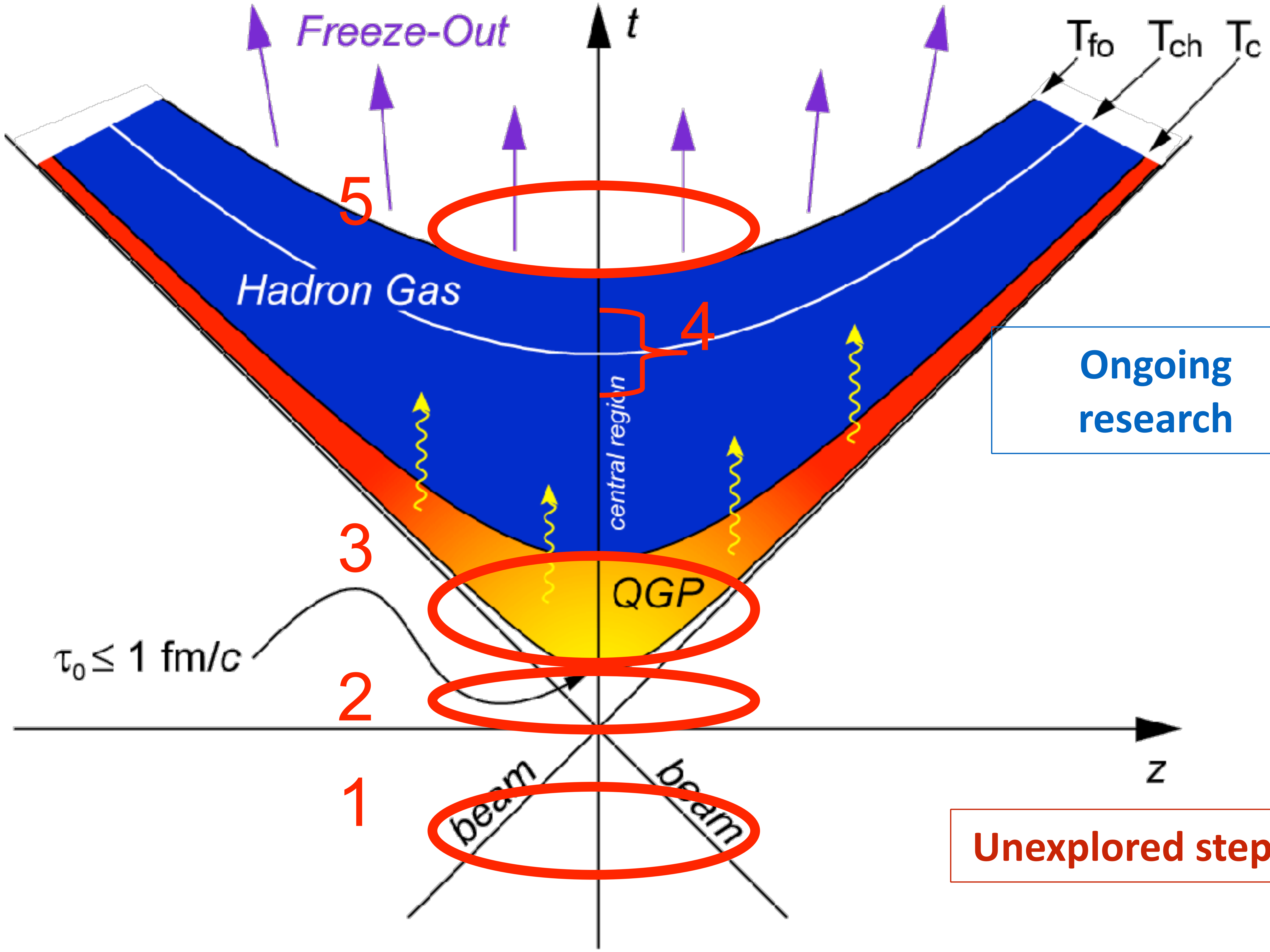
- Small droplet of QGP?
- Information of initial stages?
- Multi-parton interaction (MPI)?

Still not well understood those phenomena

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

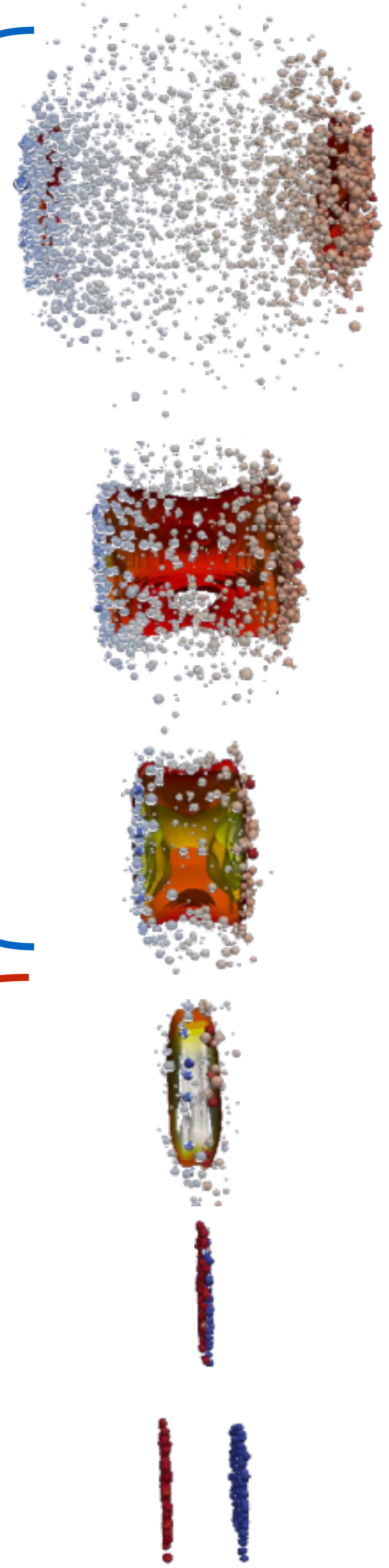
2） What is nonlinear, non-equilibrium processes in QGP formation?

Non-equilibrium and nonlinear phenomena in high-energy HIC



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

Non-equilibrium and nonlinear phenomena in high-energy HIC

Two unexplored steps

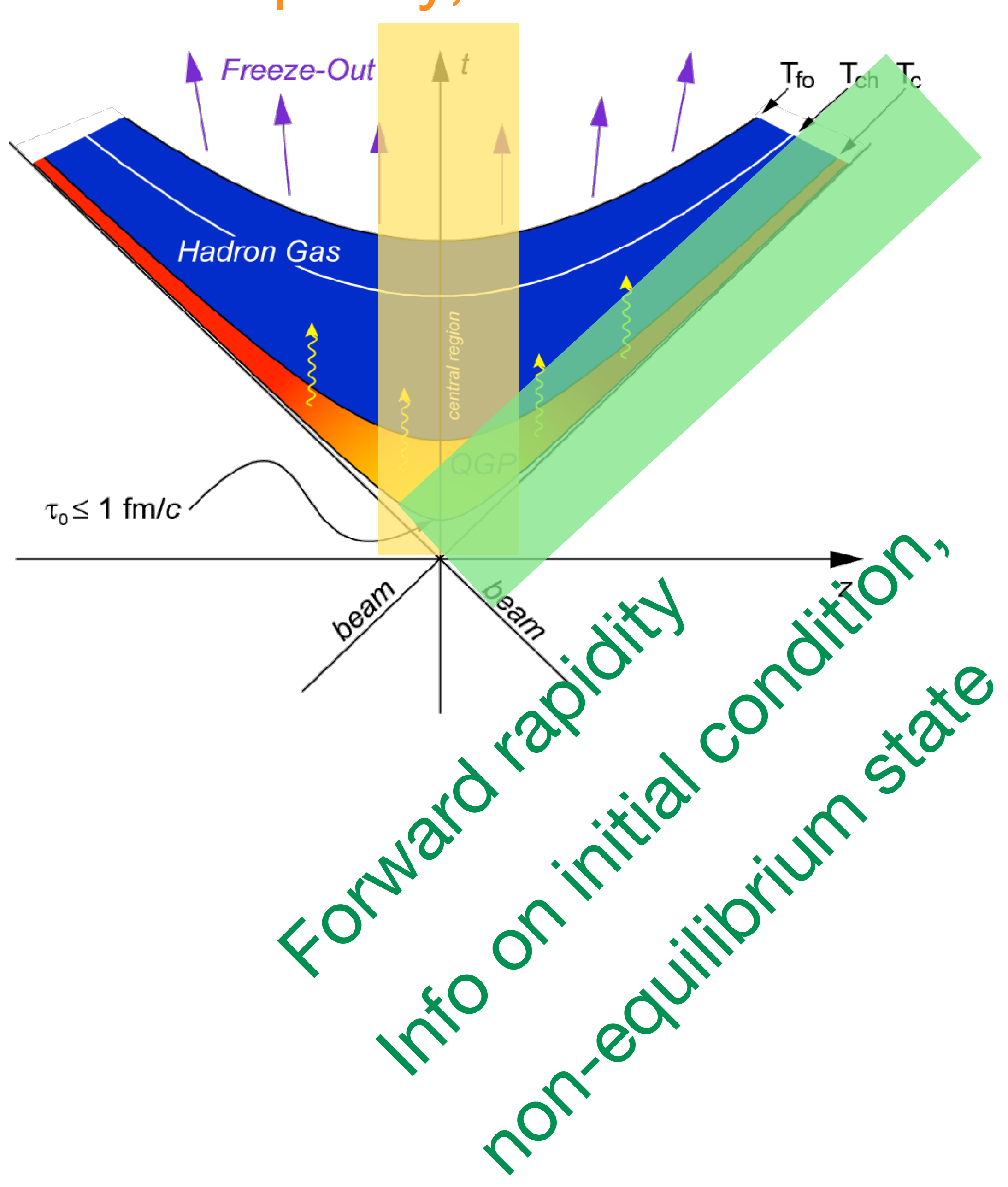
(1) Color Glass Condensate (CGC)

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

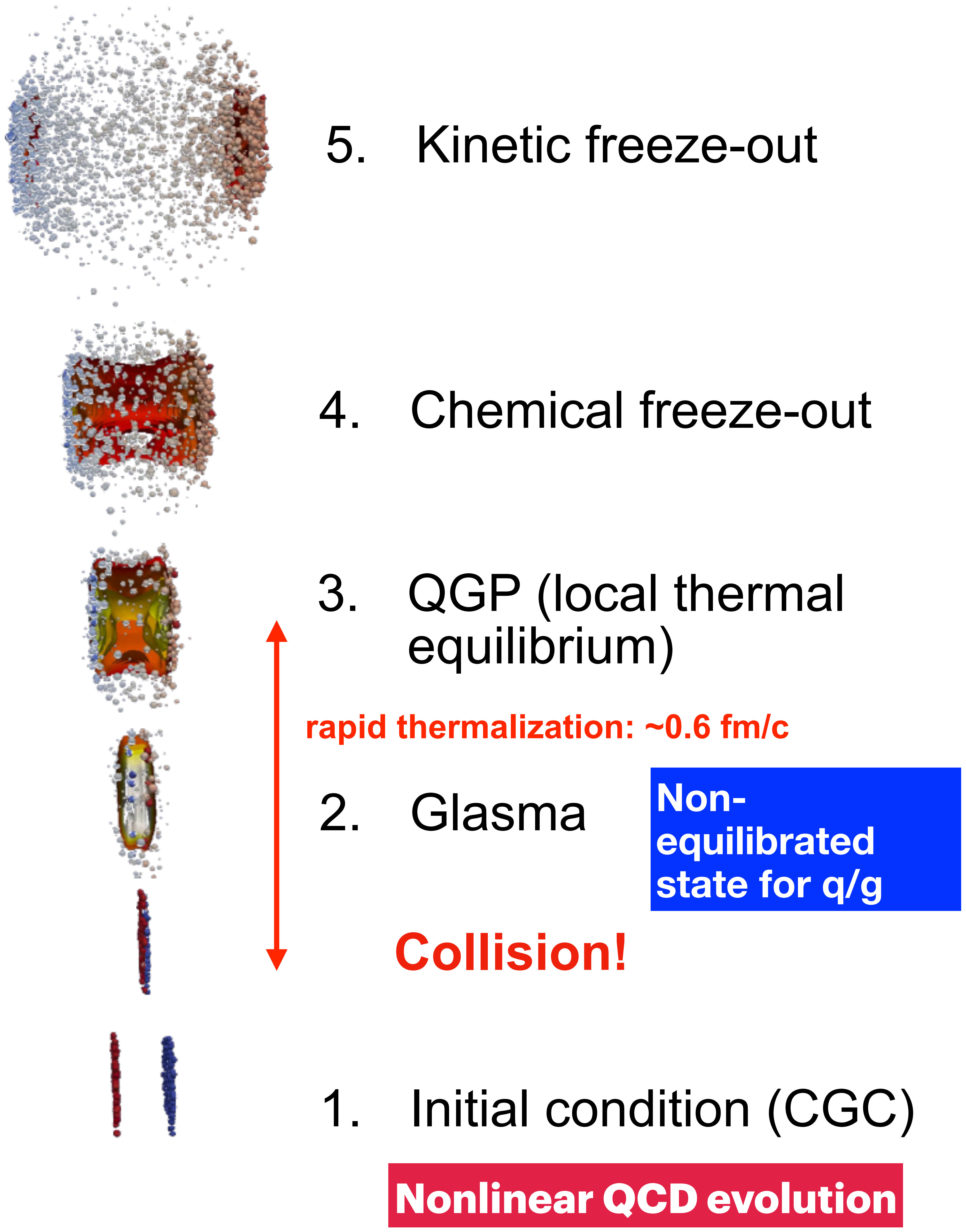
(2) Glasma

- **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

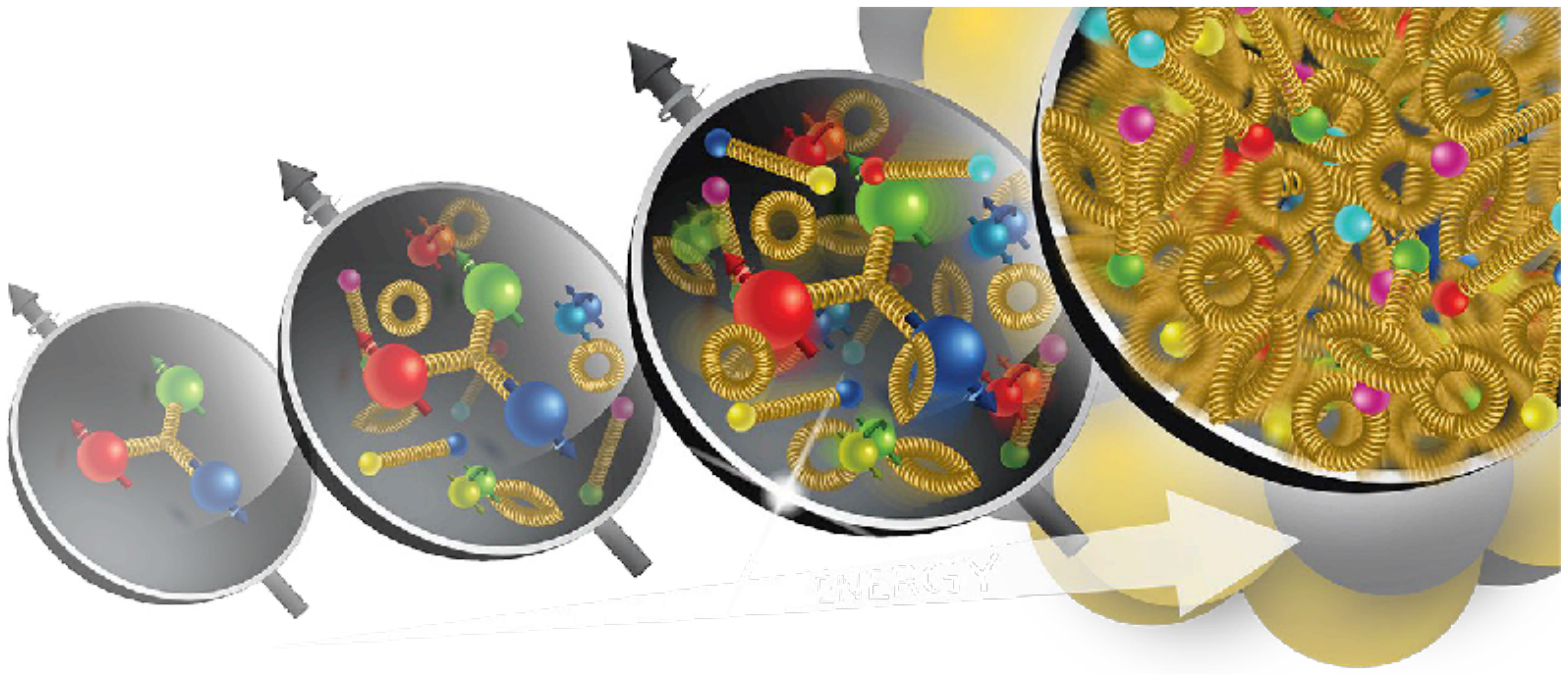


"Very Forward Rapidity Region"
→Access to CGC and Glasma for the first time!

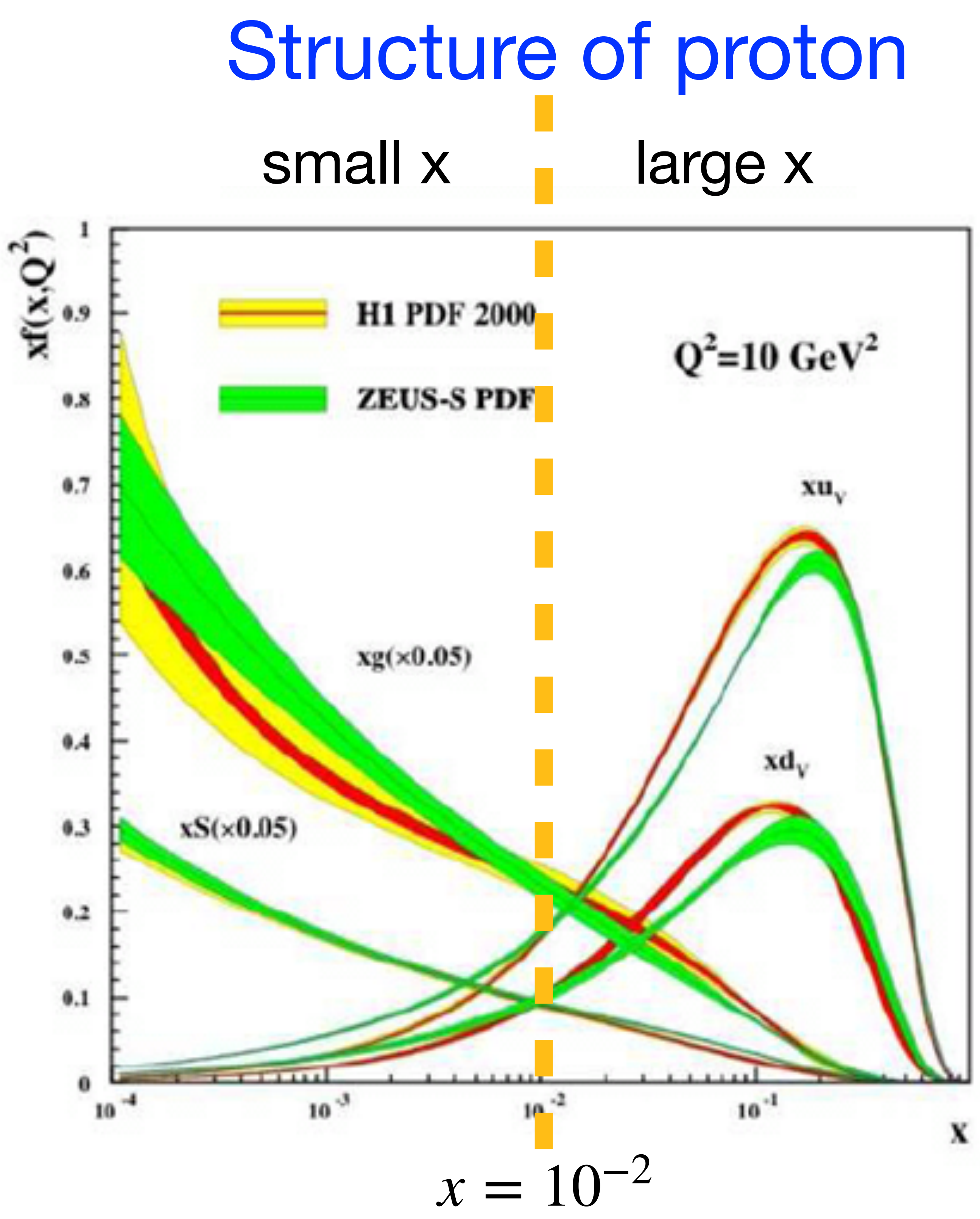


arXiv:1804.06469v1, Jonah E. Bernhard

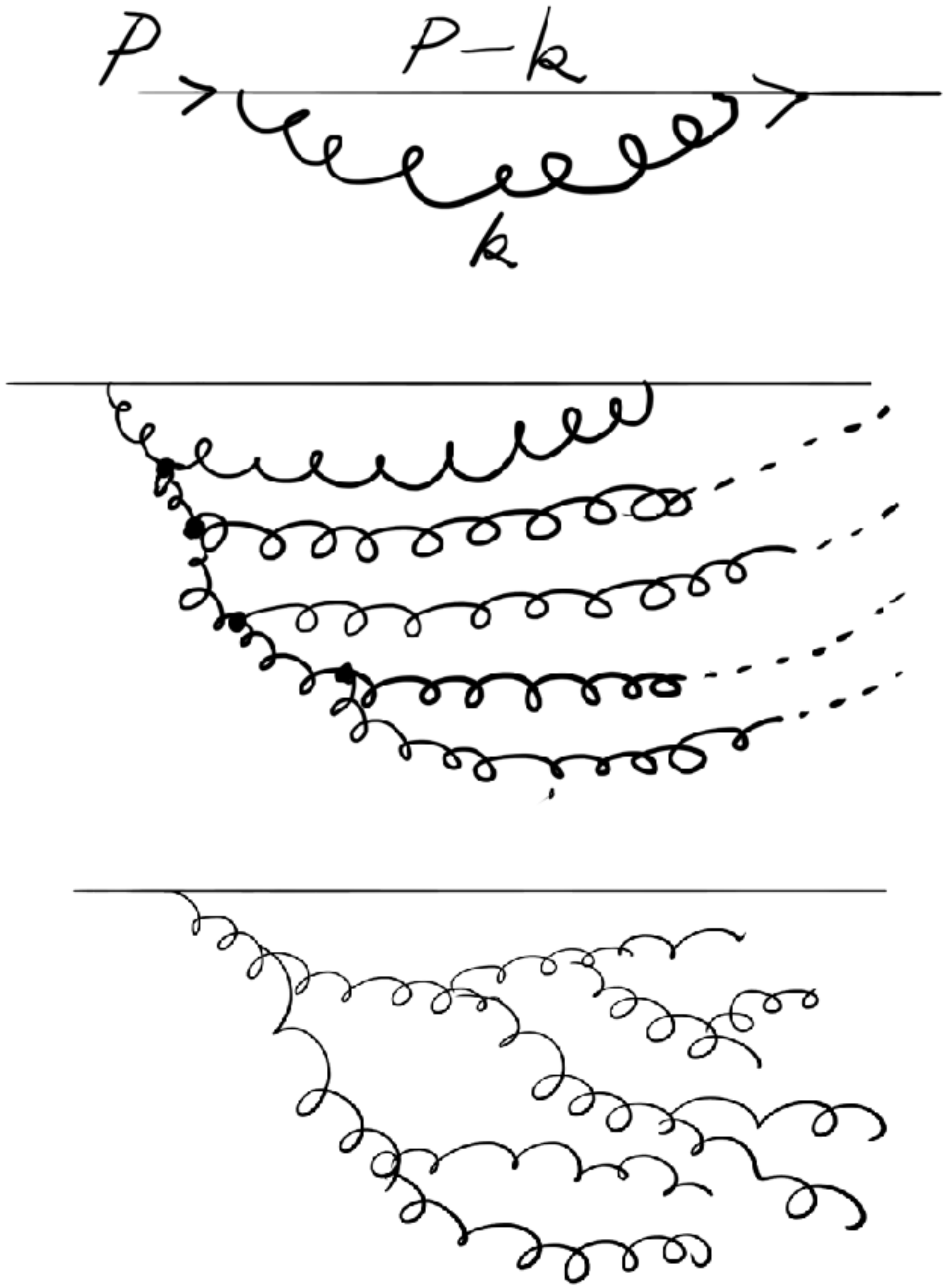
3) What is the Color Glass Condensate (CGC)?



Internal structure of proton and high energy limit



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



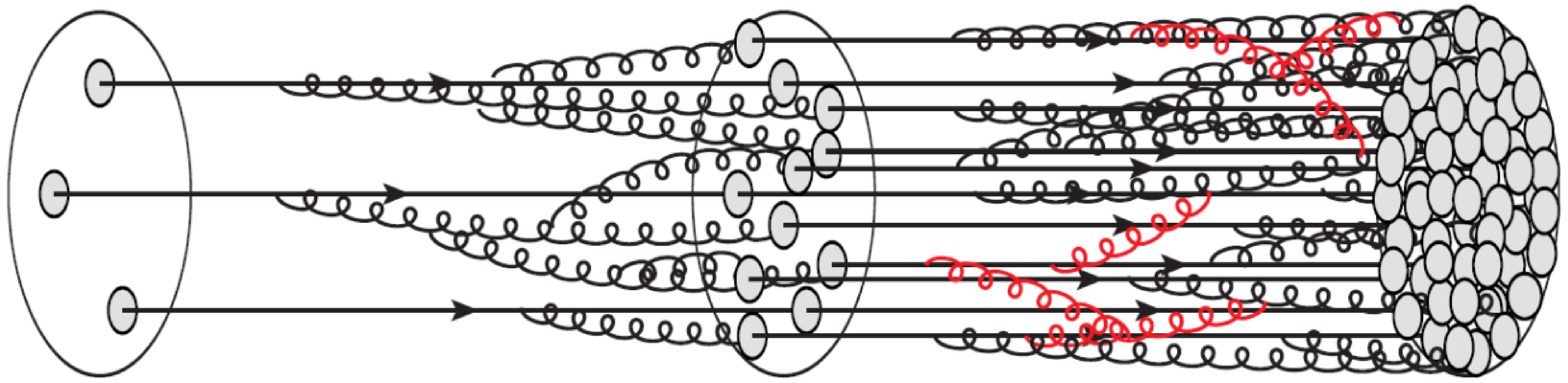
Mechanism of multipole gluon creations

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

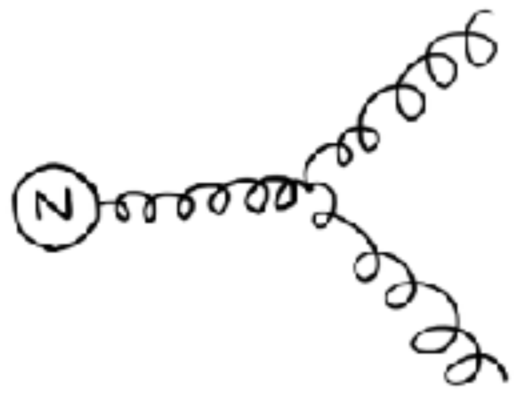
→ At high energy, increased small fluctuations exponentially !

Color Glass Condensate (CGC)

proton



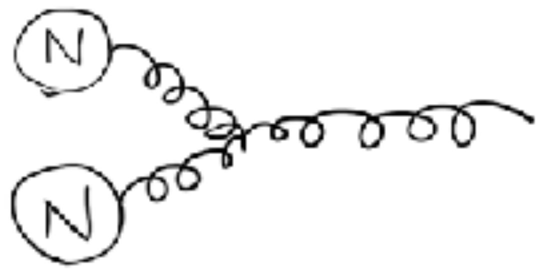
K. Watanabe



g →gg

gluon splitting

$\propto N_g$



gg →g

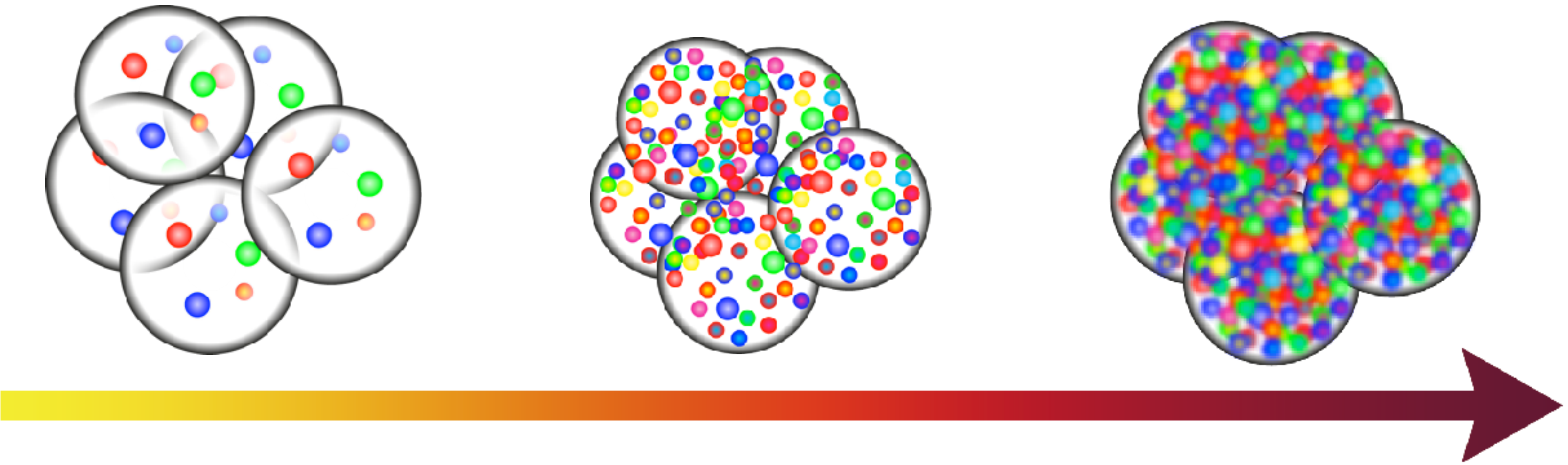
gluon merge

(non-linear effect)

$\propto N_g^2$

nucleus

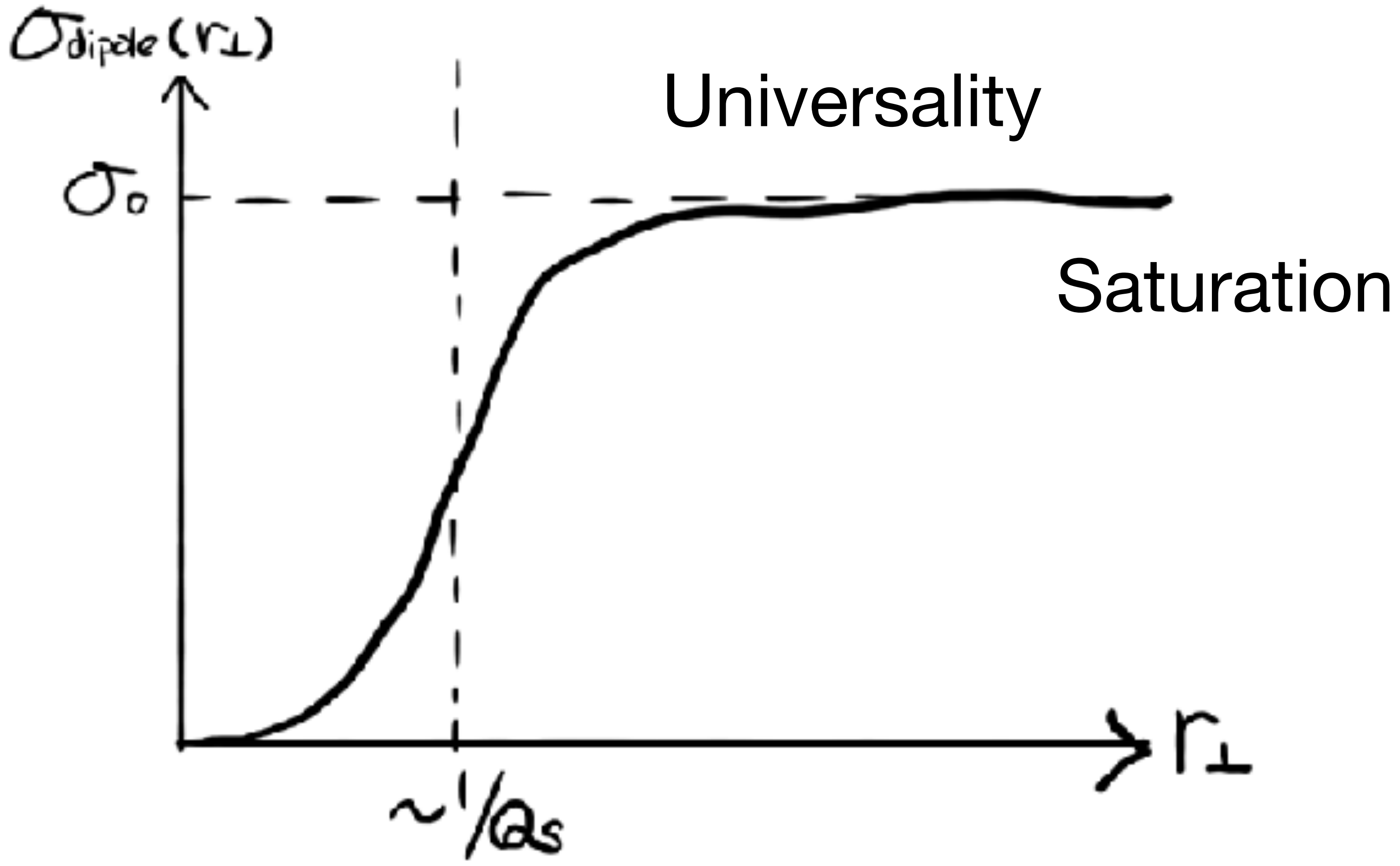
CGC!



e.g.) Logistic Eq.

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

⇄ Balitsky-Kovchegov (BK) e.q.

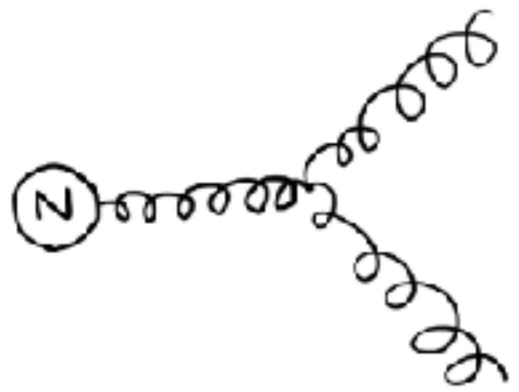


Large x
mid-rapidity
Low energy scattering

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

Small x
forward rapidity
High energy scattering

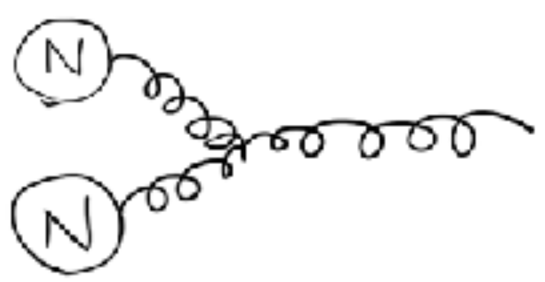
Color Glass Condensate (CGC)



$g \to gg$

gluon splitting

$\propto N_g$



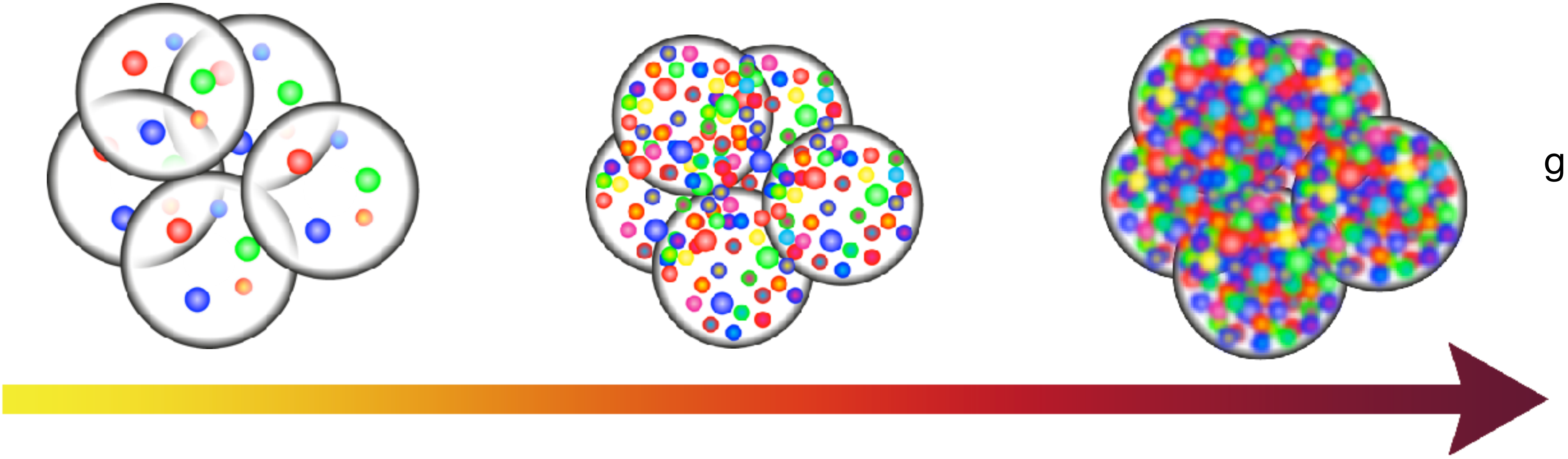
$gg \to g$

gluon merge

(non-linear effect)

$\propto N_g^2$

CGC!



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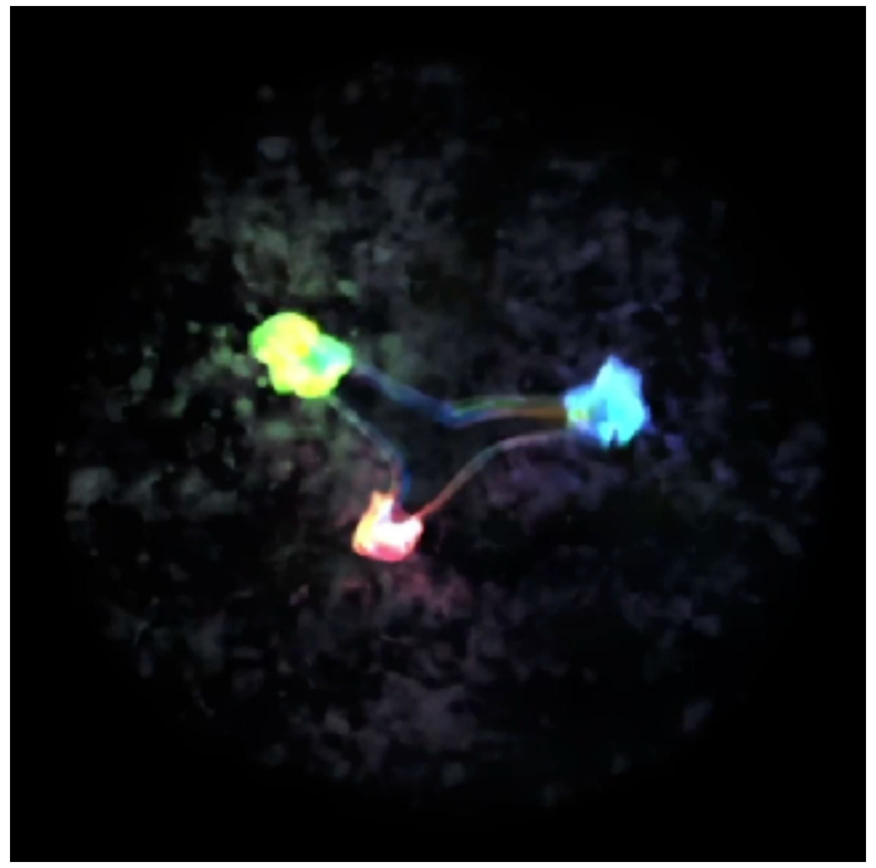
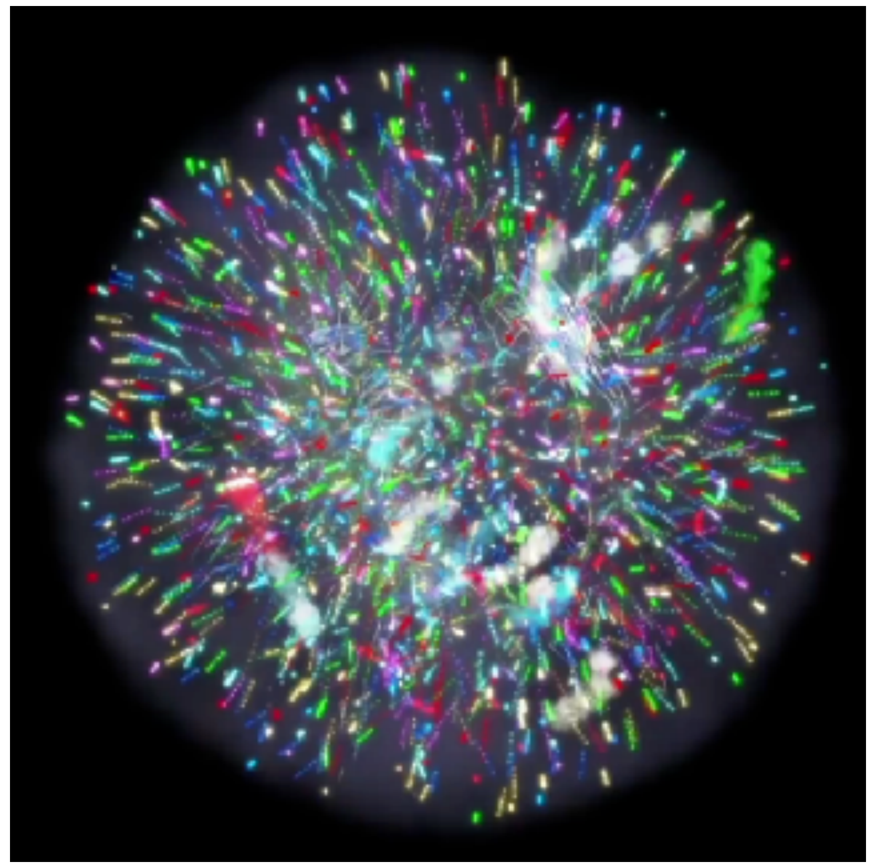
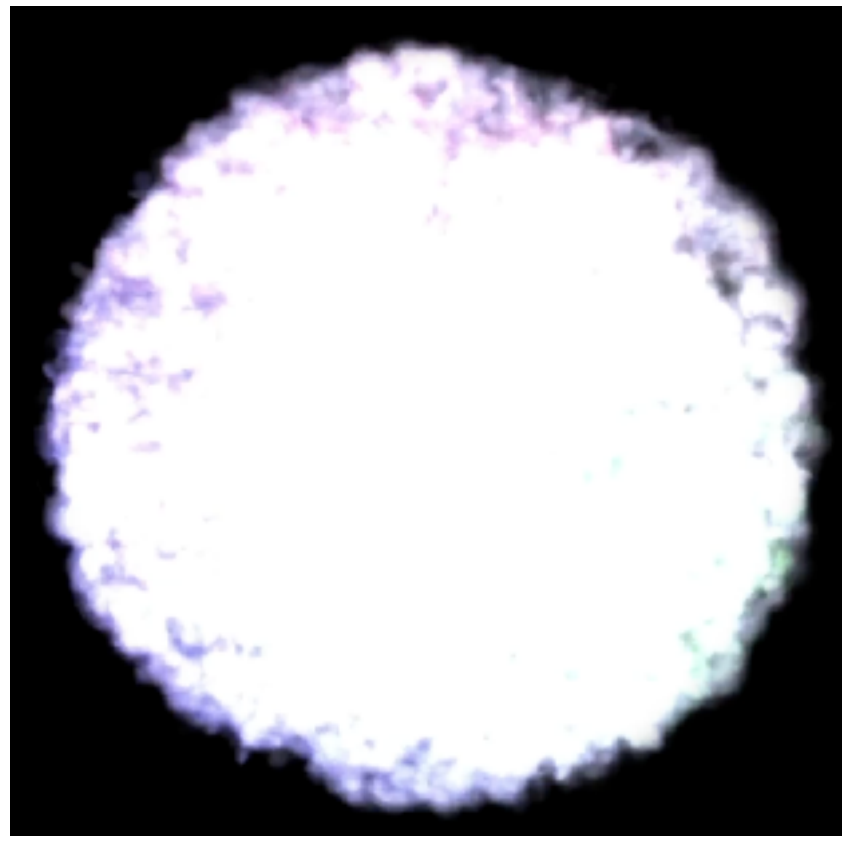
Large x
mid-rapidity
Low energy scattering

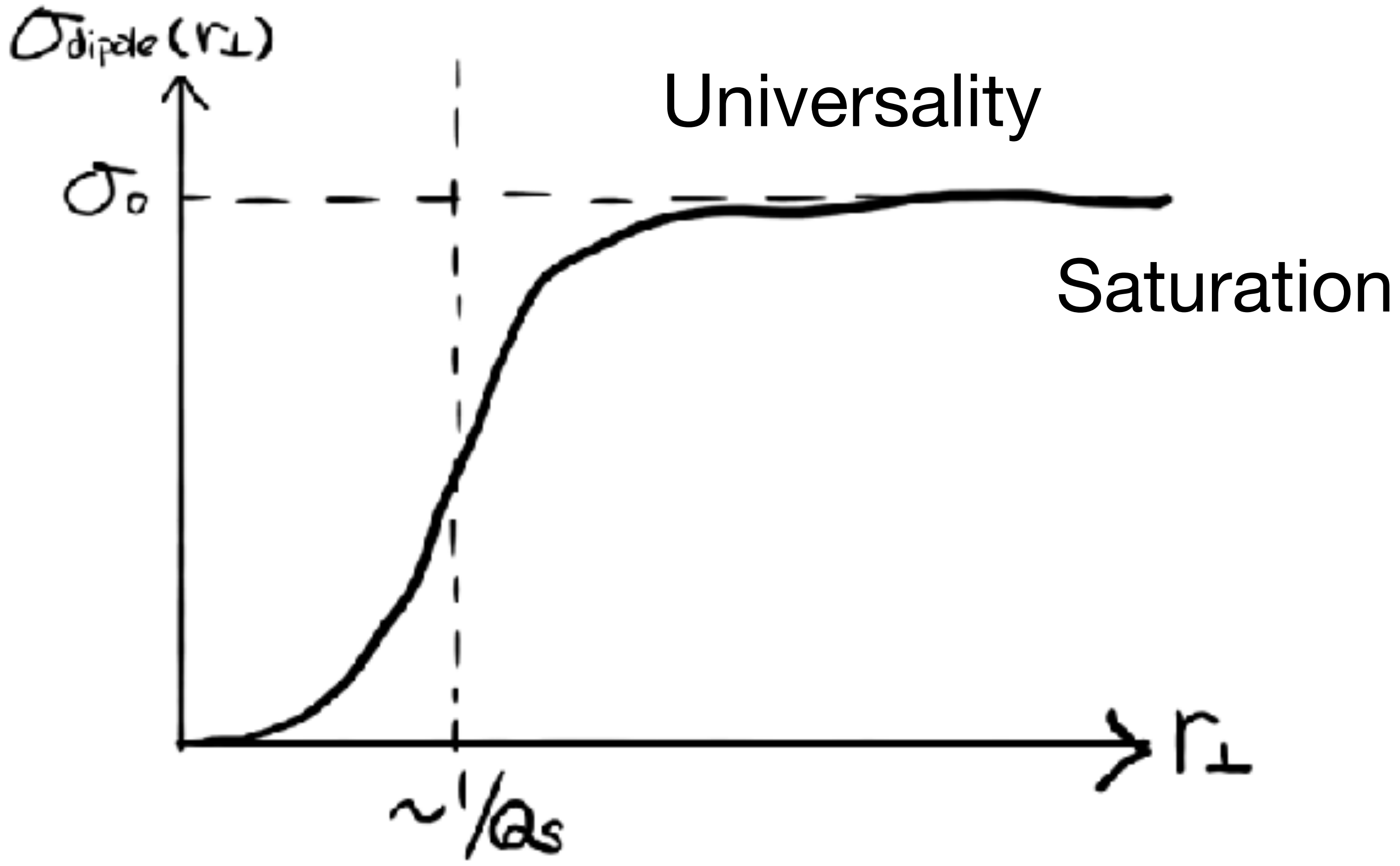
$$x \approx \frac{2p_T}{\sqrt{s}}\exp^{-\eta}$$

Small x
forward rapidity
High energy scattering

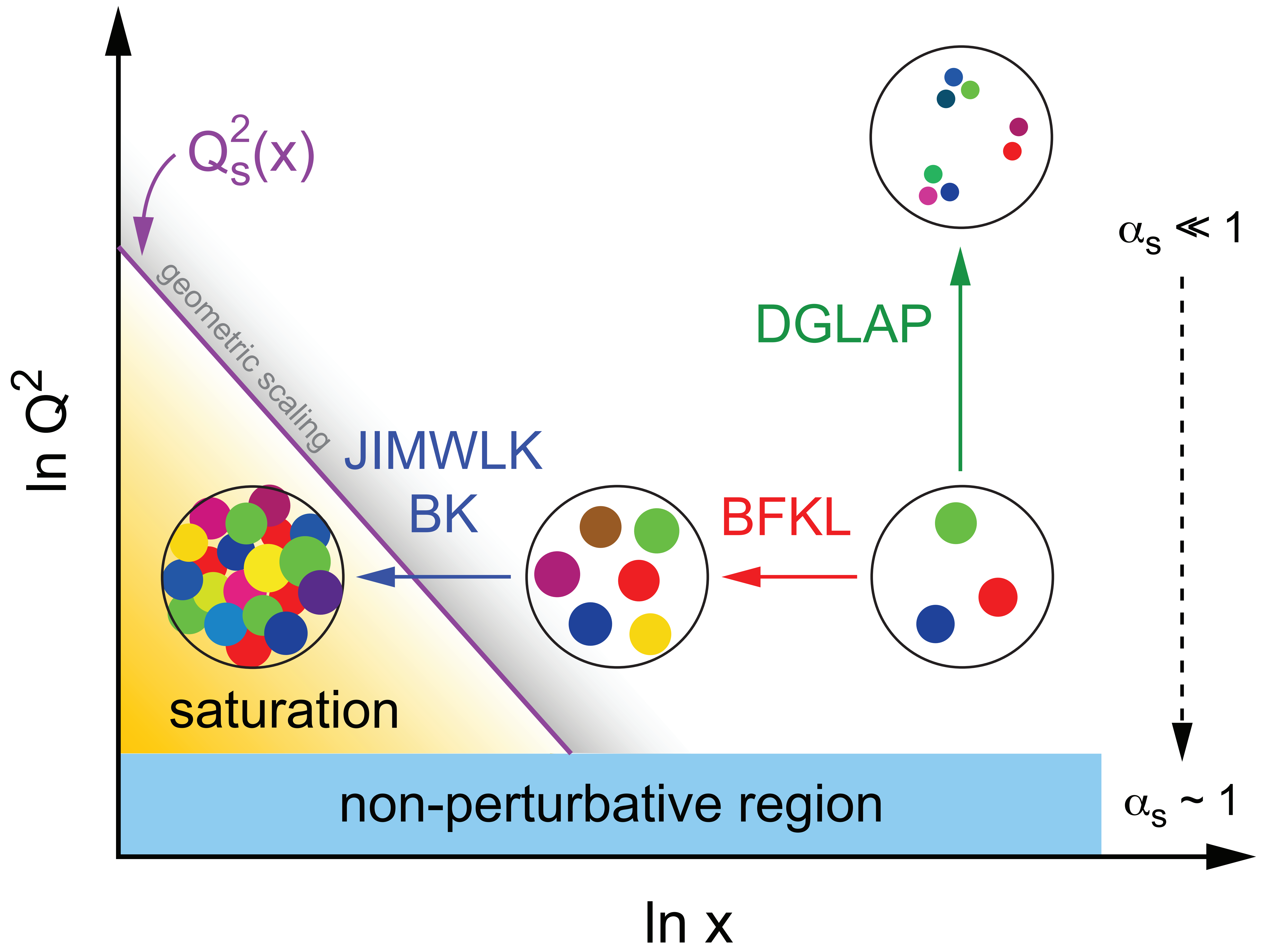








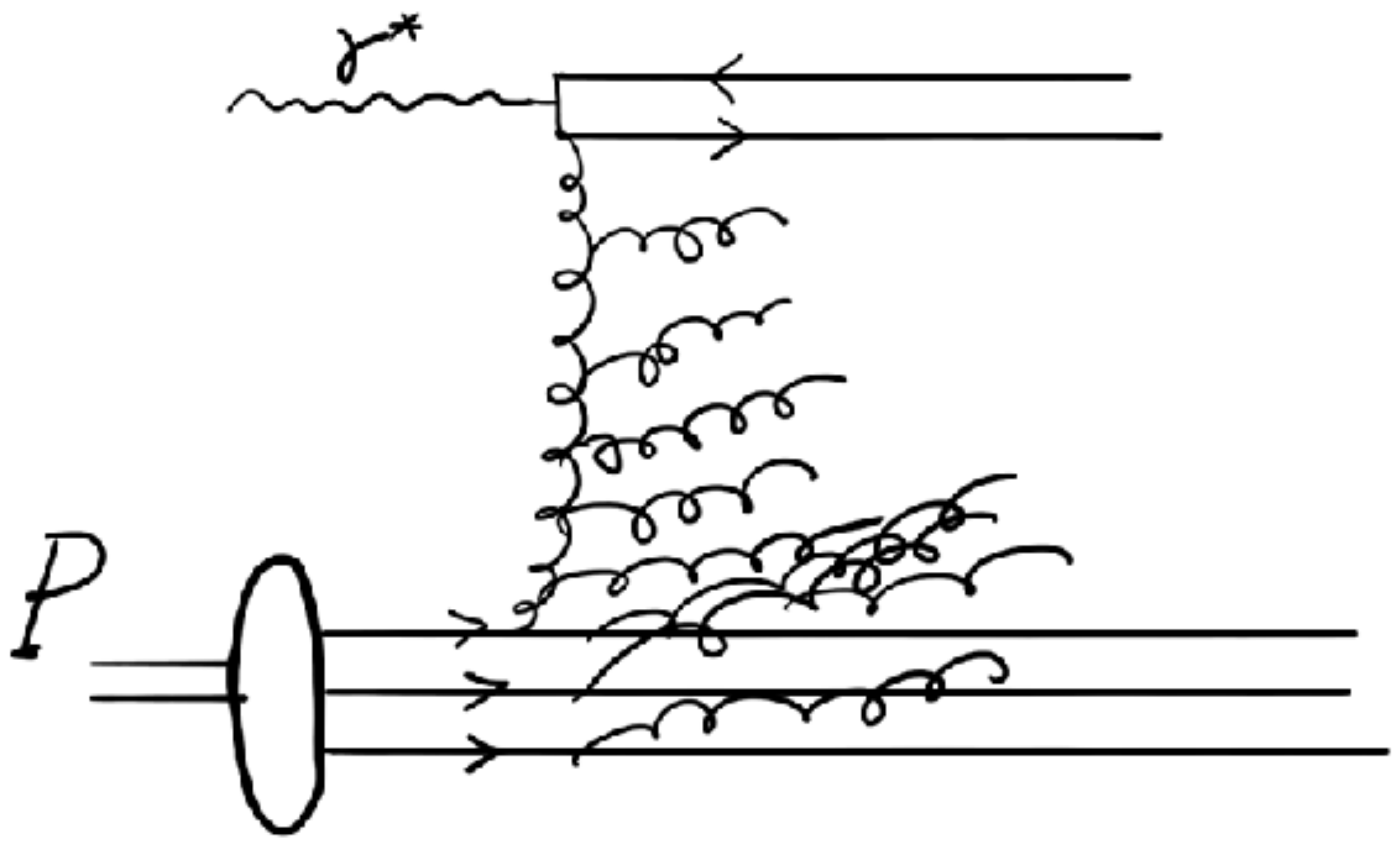
Where we can see CGC?

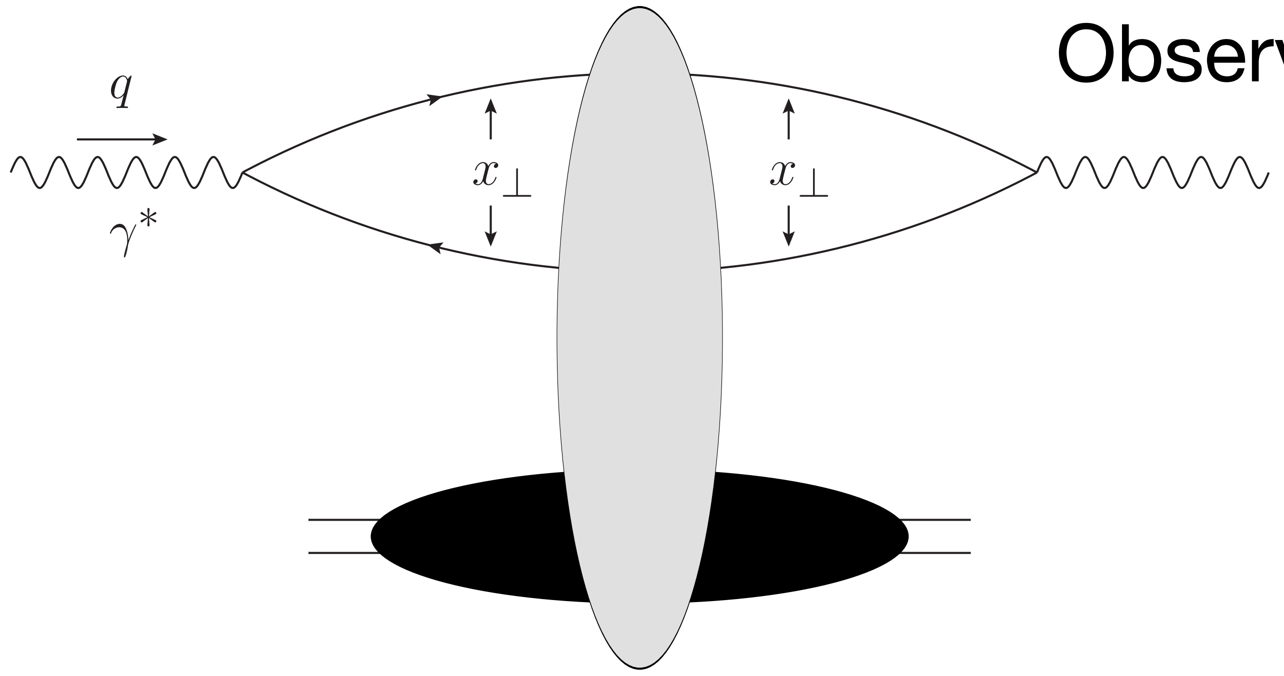


- **Small x and low Q** region (but Q >> Λ_{QCD})
- **Universal picture** of internal structure of high energy hadron (universality)
- Log-Log plot !

  → **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)



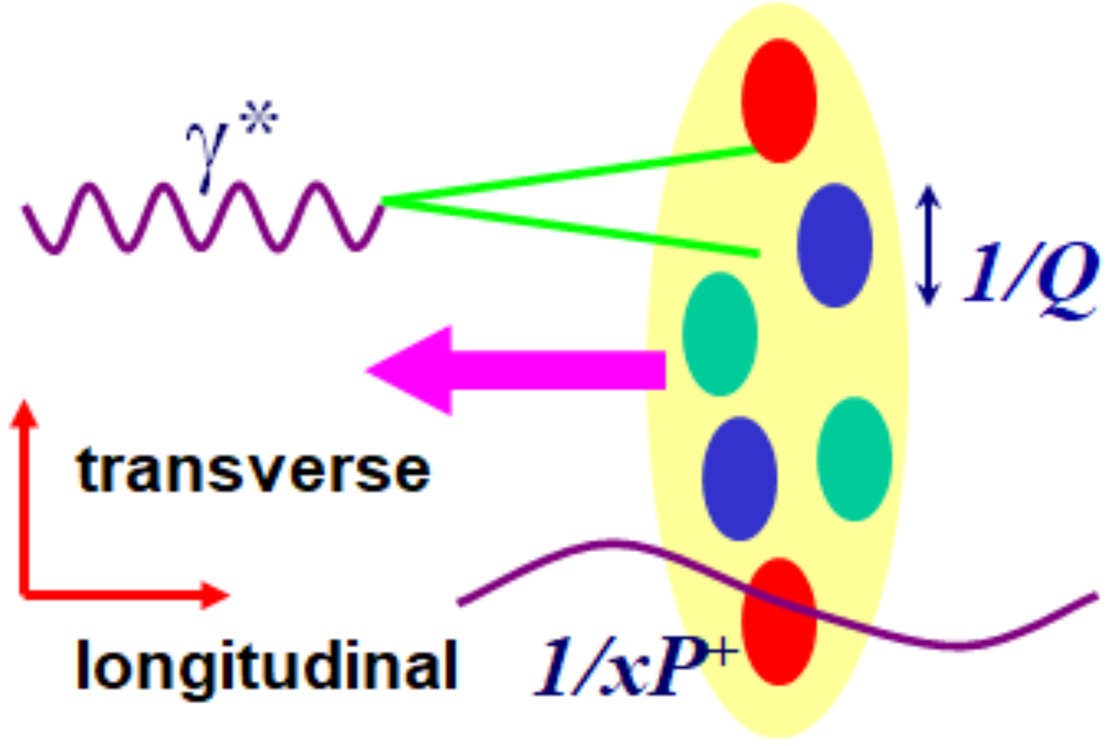


e+A DIS

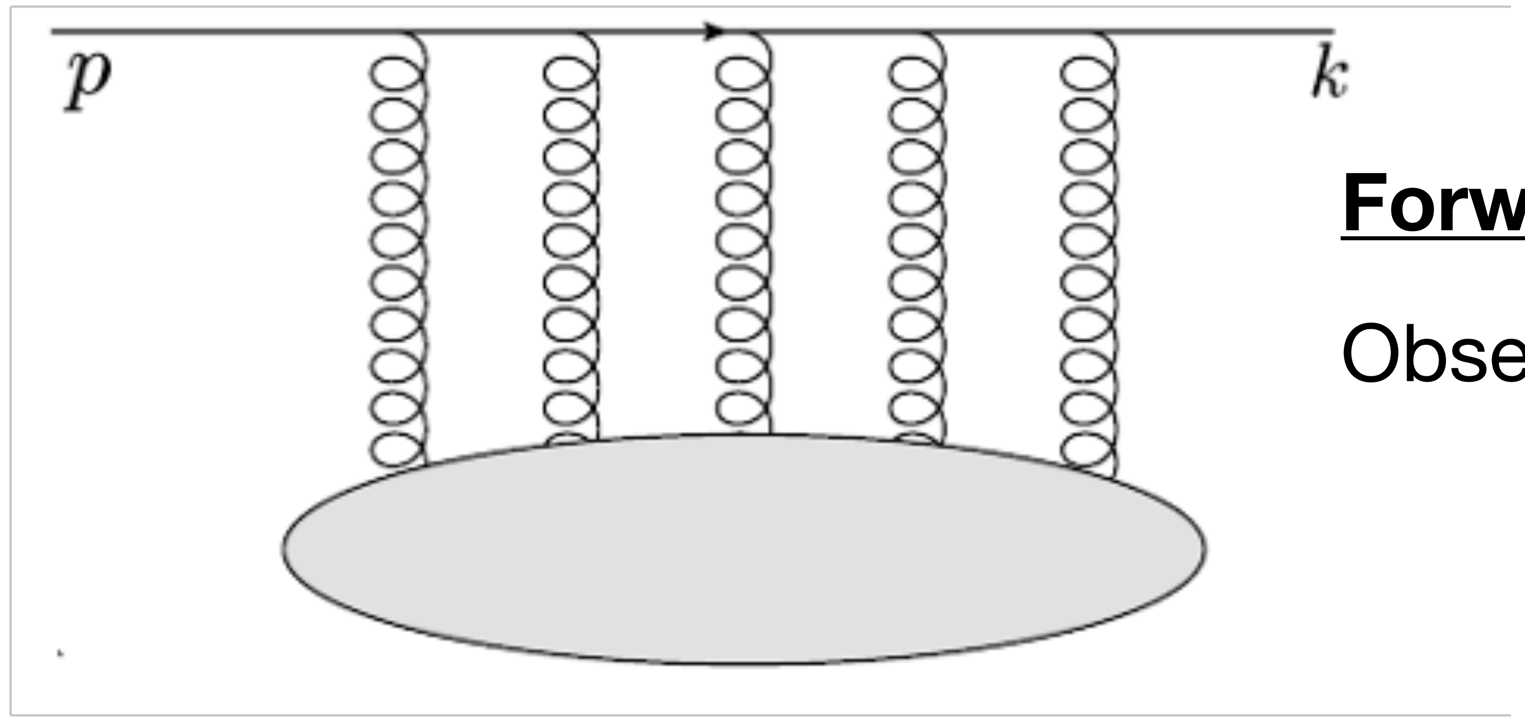
Observables : int. cross section, Structure func. (F_2, F_L)

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

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



K. Itakura



Forward p+A

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

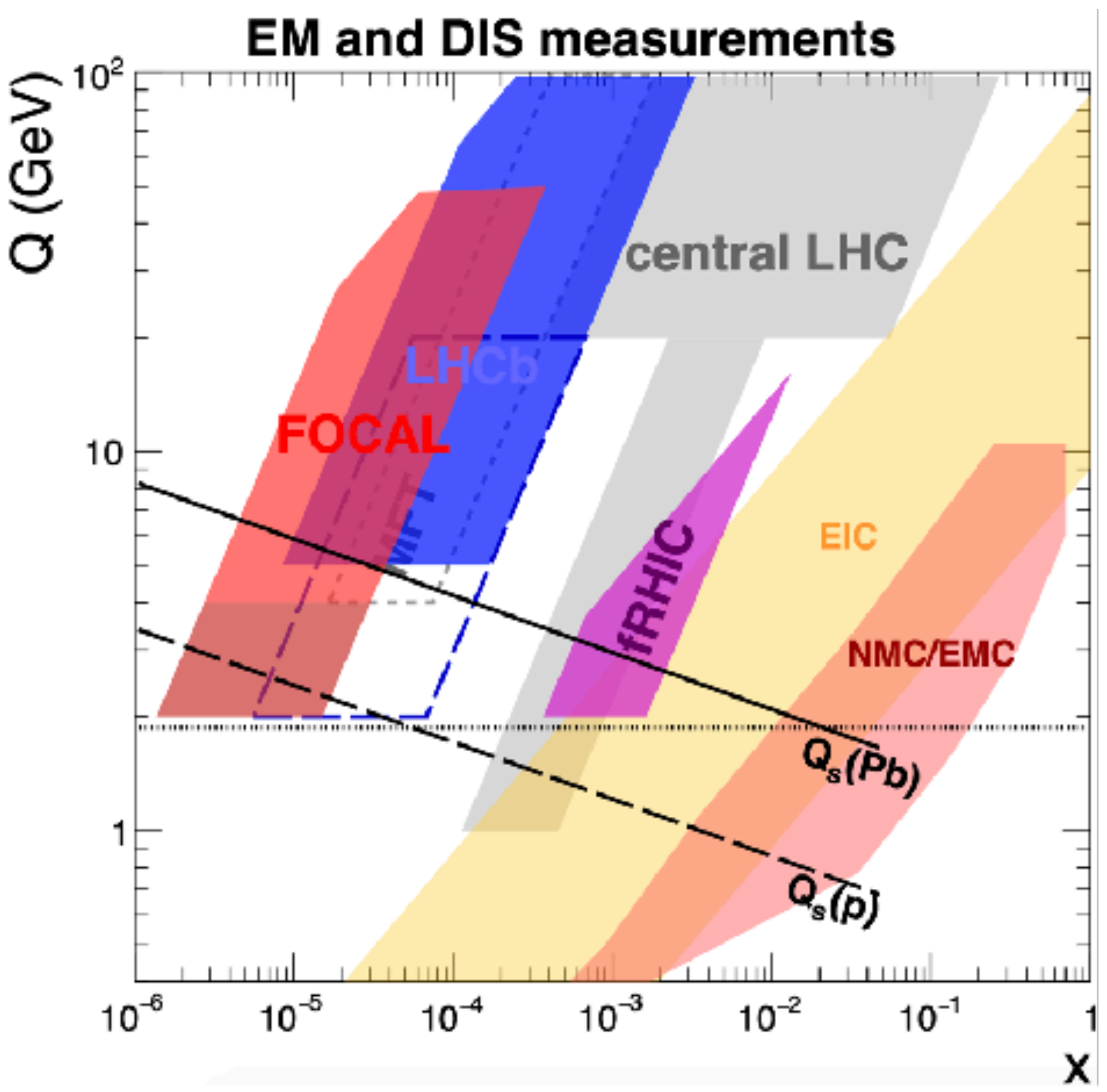
$$|M|^2_{\text{LO}} \propto \int d^2\mathbf{b}\, d^2\mathbf{r}_\perp e^{i\mathbf{p}_\perp\cdot\mathbf{r}_\perp} T_{\text{LO}}(\mathbf{b}+\frac{\mathbf{r}_\perp}{2}, \mathbf{b}-\frac{\mathbf{r}_\perp}{2})$$

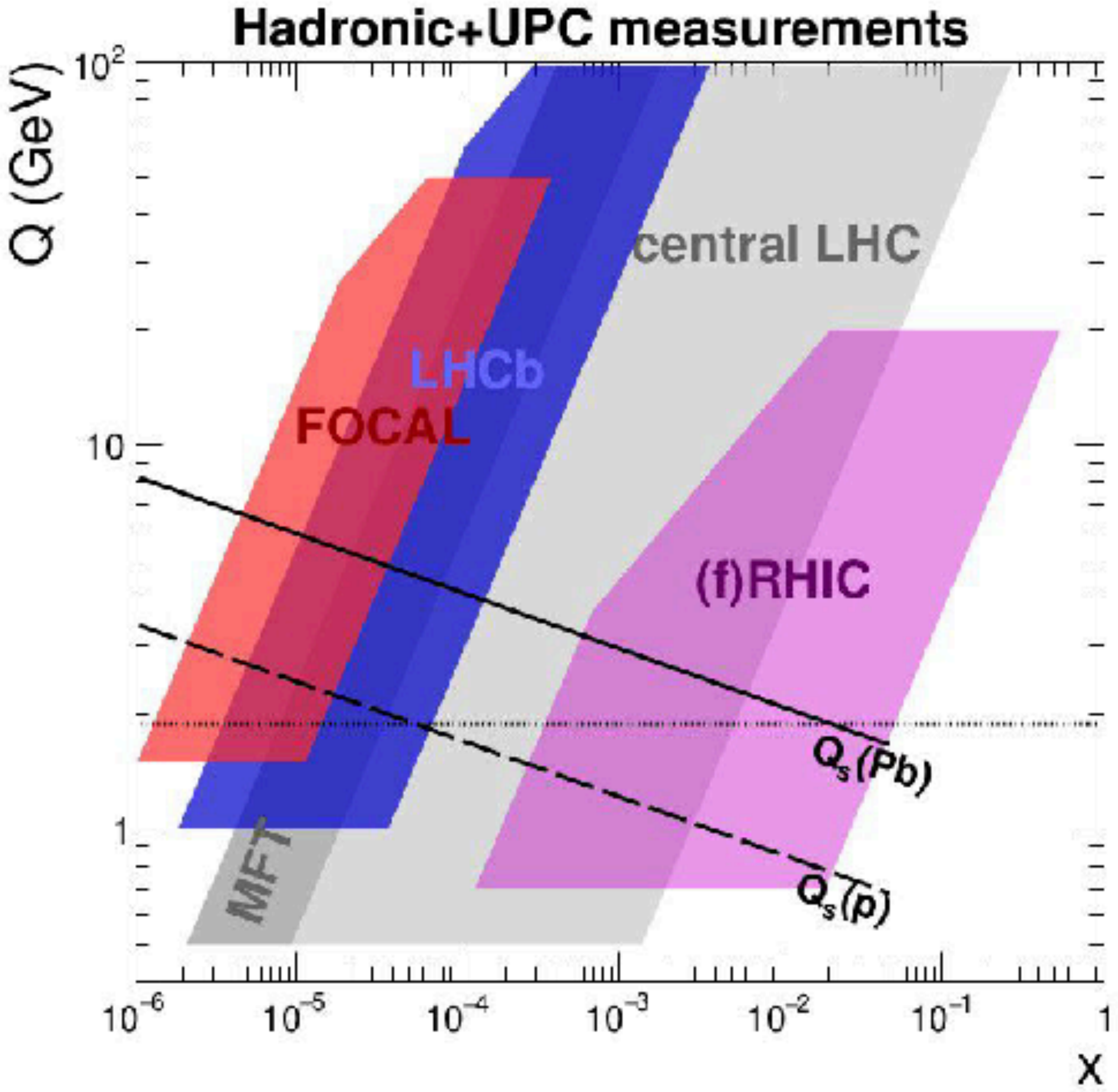
e+A DIS & p+A forward observables: same theoretical Framework **"Color Dipole (Quadrupole) Formalism"**

→ NLO cal. is possible

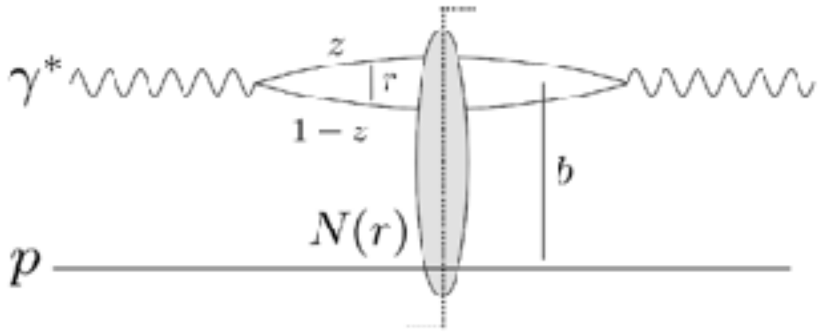
→Comparison e+A DIS with forward p+A : **Universality of QCD can be tested**

EIC vs. forward LHC

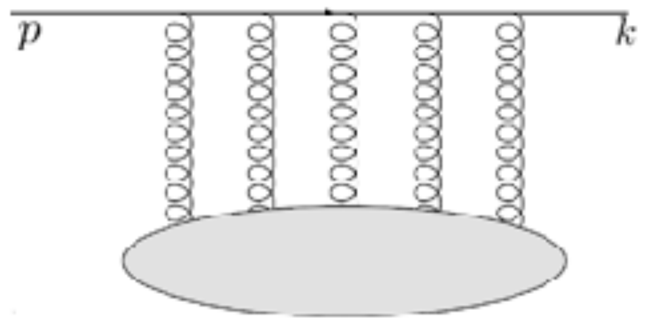




DIS (EIC) eA



Forward pA
at high energies



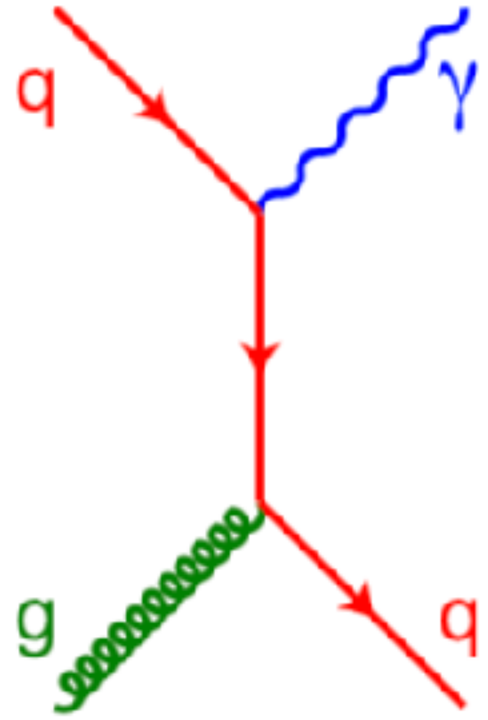
$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

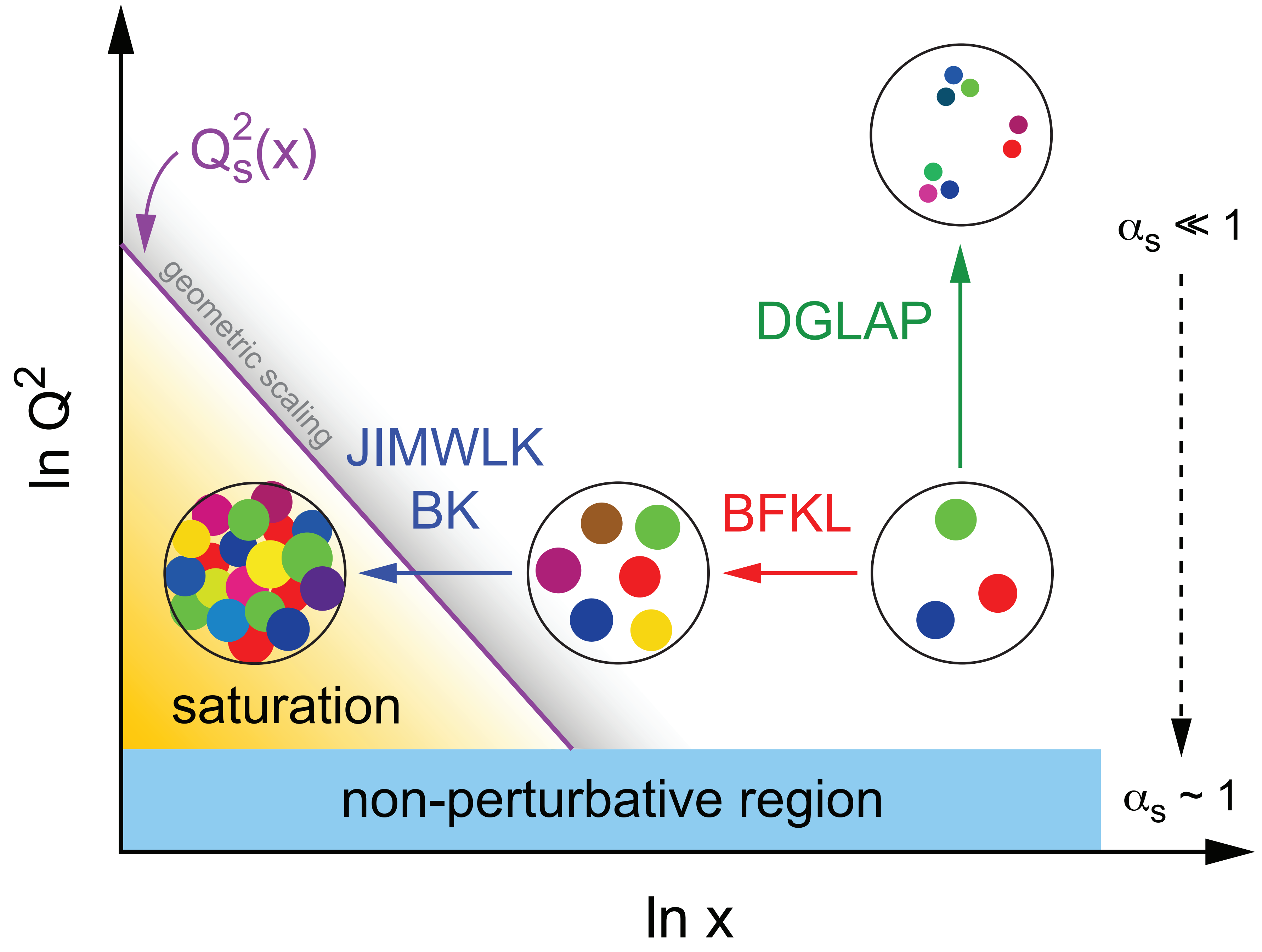
$$\text{Dipole } N = 1 - \frac{1}{N_C} \mathrm{tr} V(x) V^\dagger(y)$$

- 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

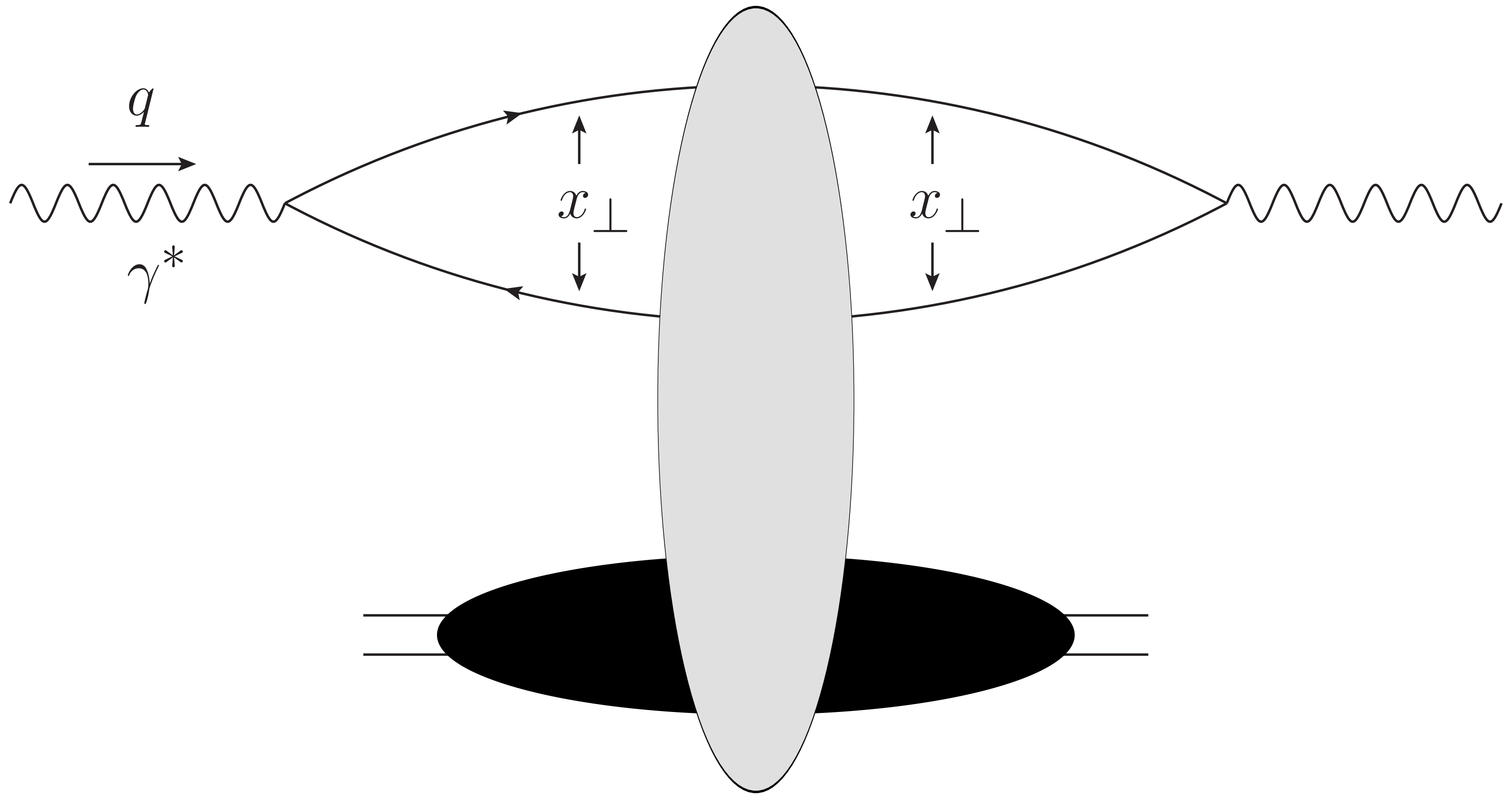
- **Need a clear CGC signal**
  - Hadron measurement →Uncertainty by fragmentation
  - Need a clean probe (e.g) q + g -> γ + q

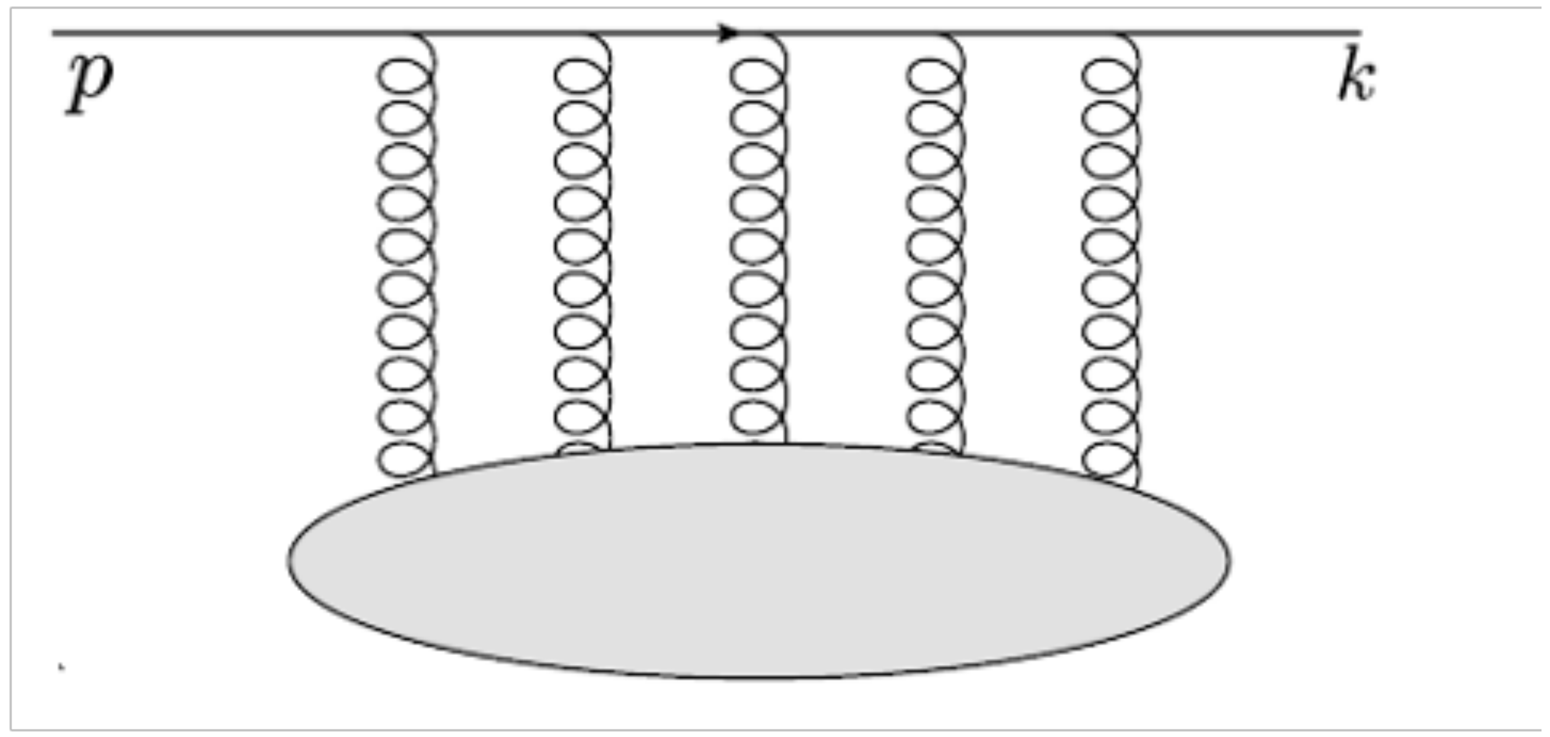




- **Need to see non-linear evolution of QCD**
  - Explore wide rage of x-Q^2 space
- Theoretically calculable and compare with data (CGC weakly coupled physics) → color dipole
- High precision measurements (statistic, systematic)

Next generation experiments (LHC forward pA, EIC eA)





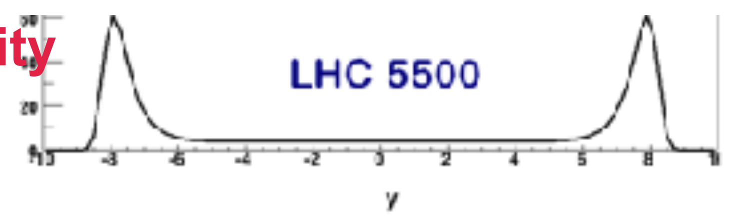
4) Importance of CGC and Glasma to understand QGP formation

Ultimate question:How is QGP created by HIC?

Physics of Glasma: How to create QGP

Before collision **τ ~ 0 fm/c** After collision

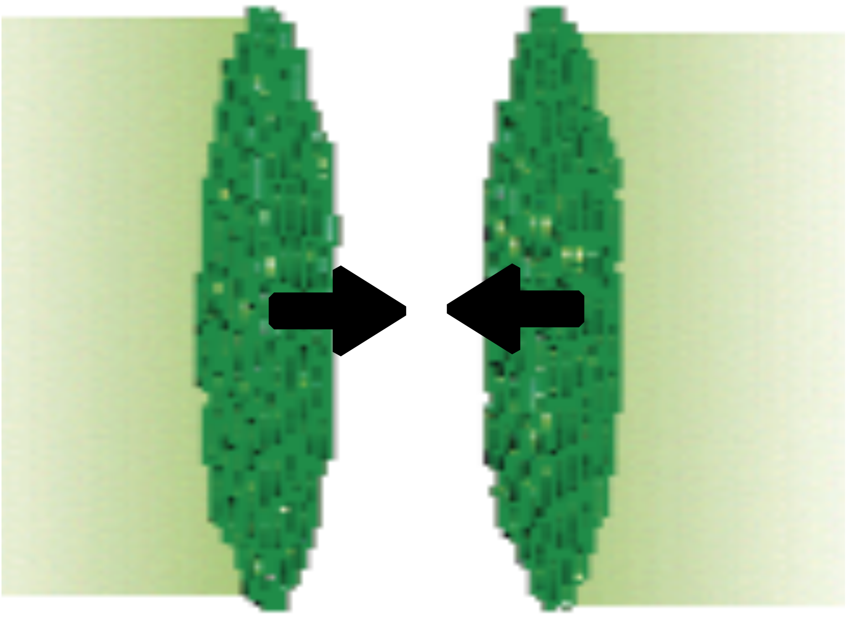
Baryon stopping ~
Energy deposit in Mid-rapidity

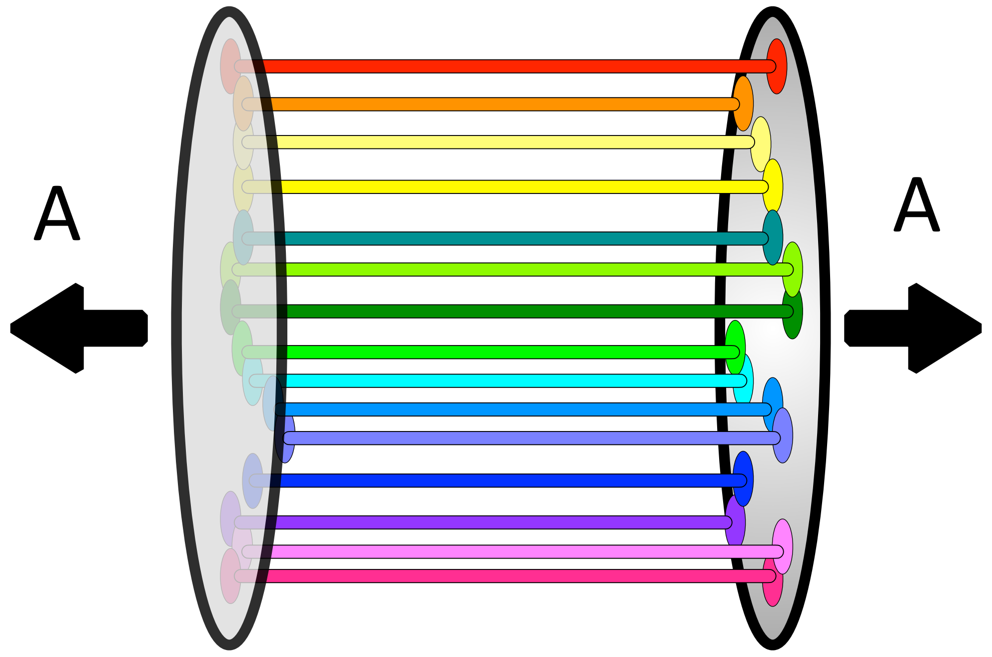


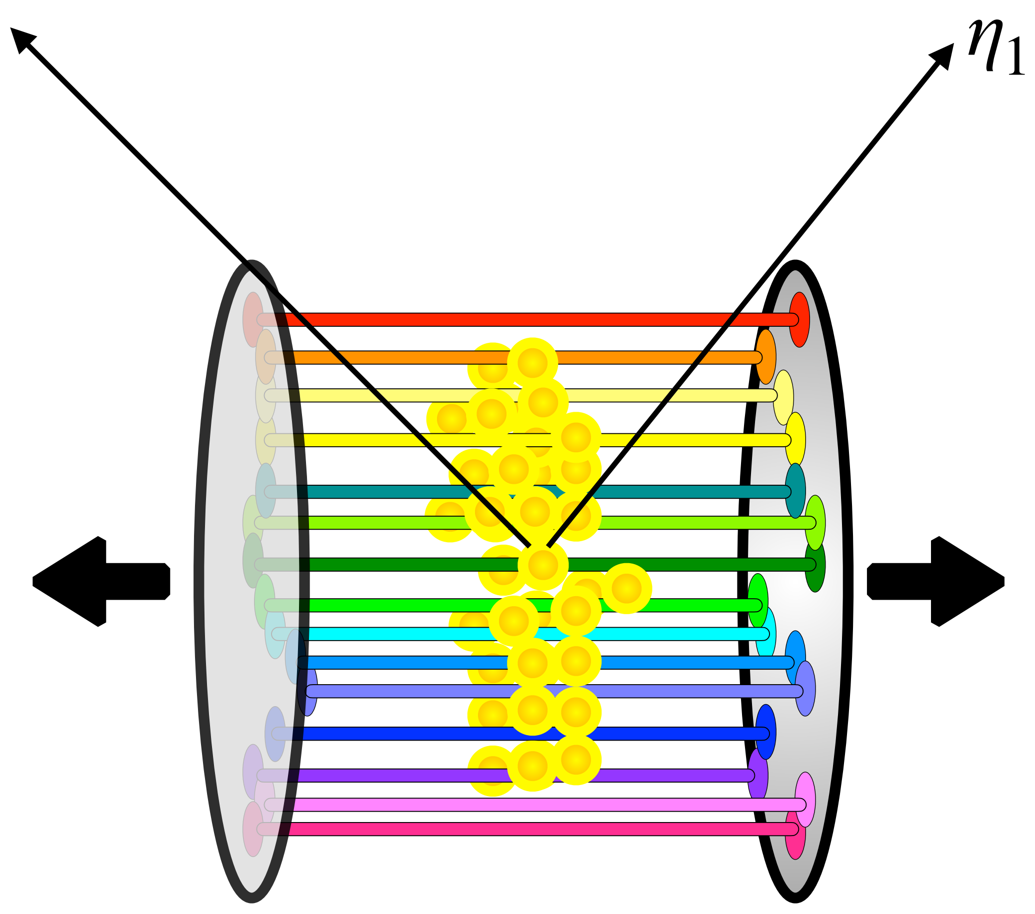
Rapid thermalization
τ ~0.6 fm/c

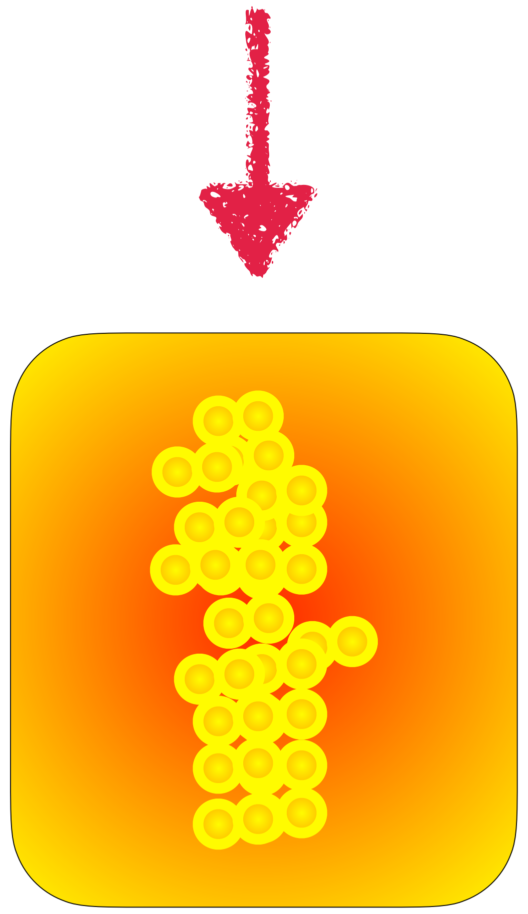
τ ~ 20 fm/c

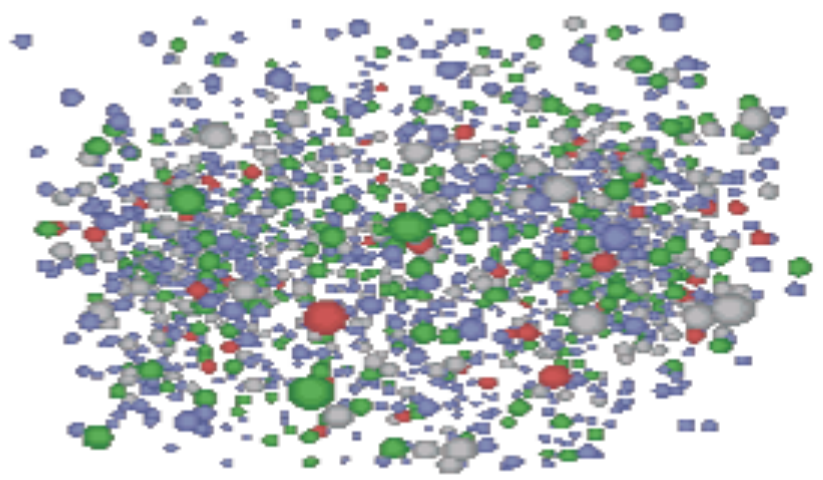
Color Electric/Magnetic
Fields: E, B











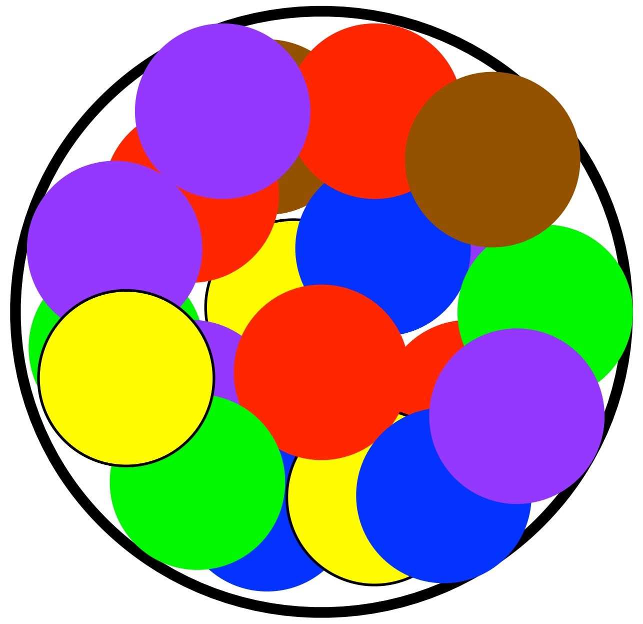
(1) Color Glass Condensate (CGC)

(2) Color E/B fields generation

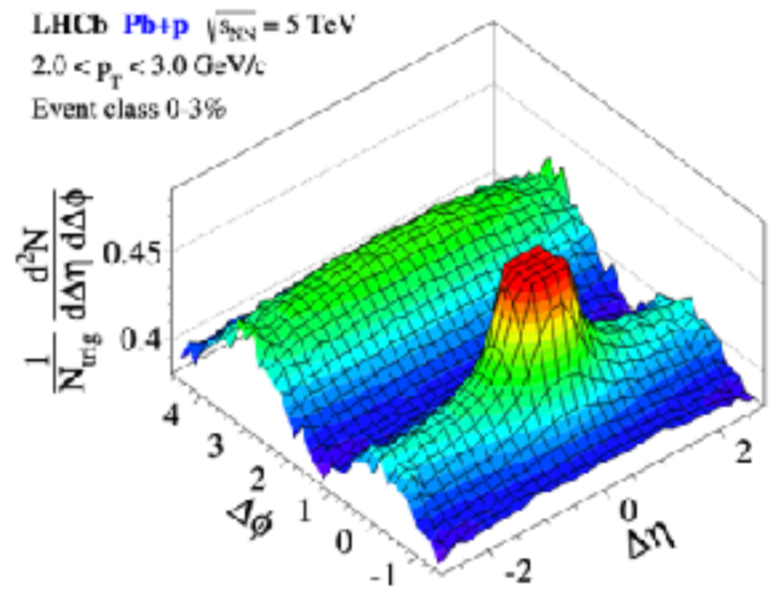
(3) quark, gluon particle produciton

(4) Parton thermalization

(5) Hadronization

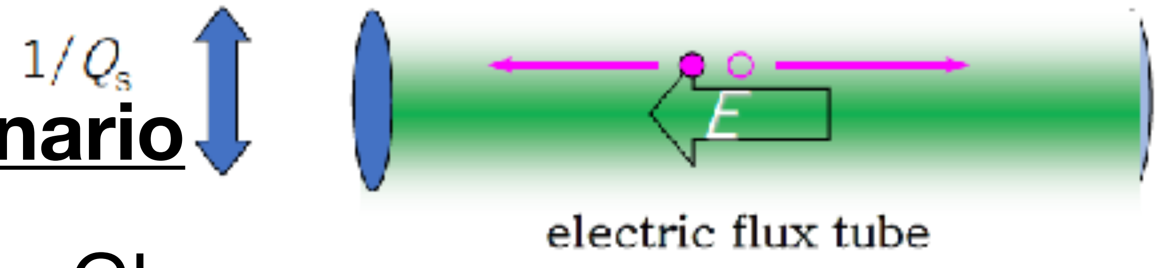


Ridge formed?



$\Delta\eta = (\eta_1 - \eta_2)$

Tanji, Itakura (2012)



A rapid thermalization scenario

Very strong E/B color fields in Glasma

$\sqrt{gB} \approx \sqrt{gE} \approx Q_s \approx 1$ GeV (RHIC) – a few GeV (LHC)

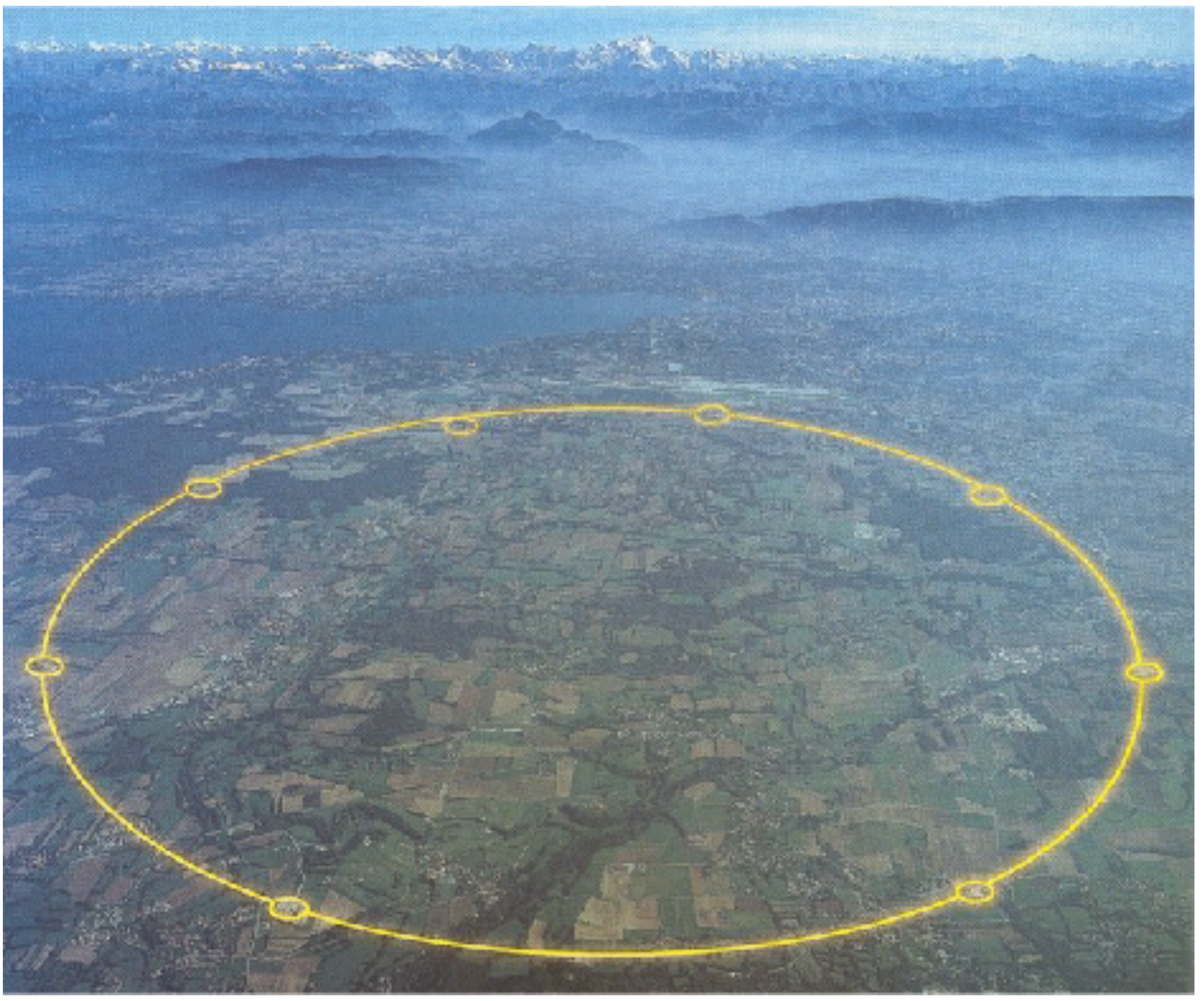
Field to particle prod. by Schwinger mechanisms rapidly?

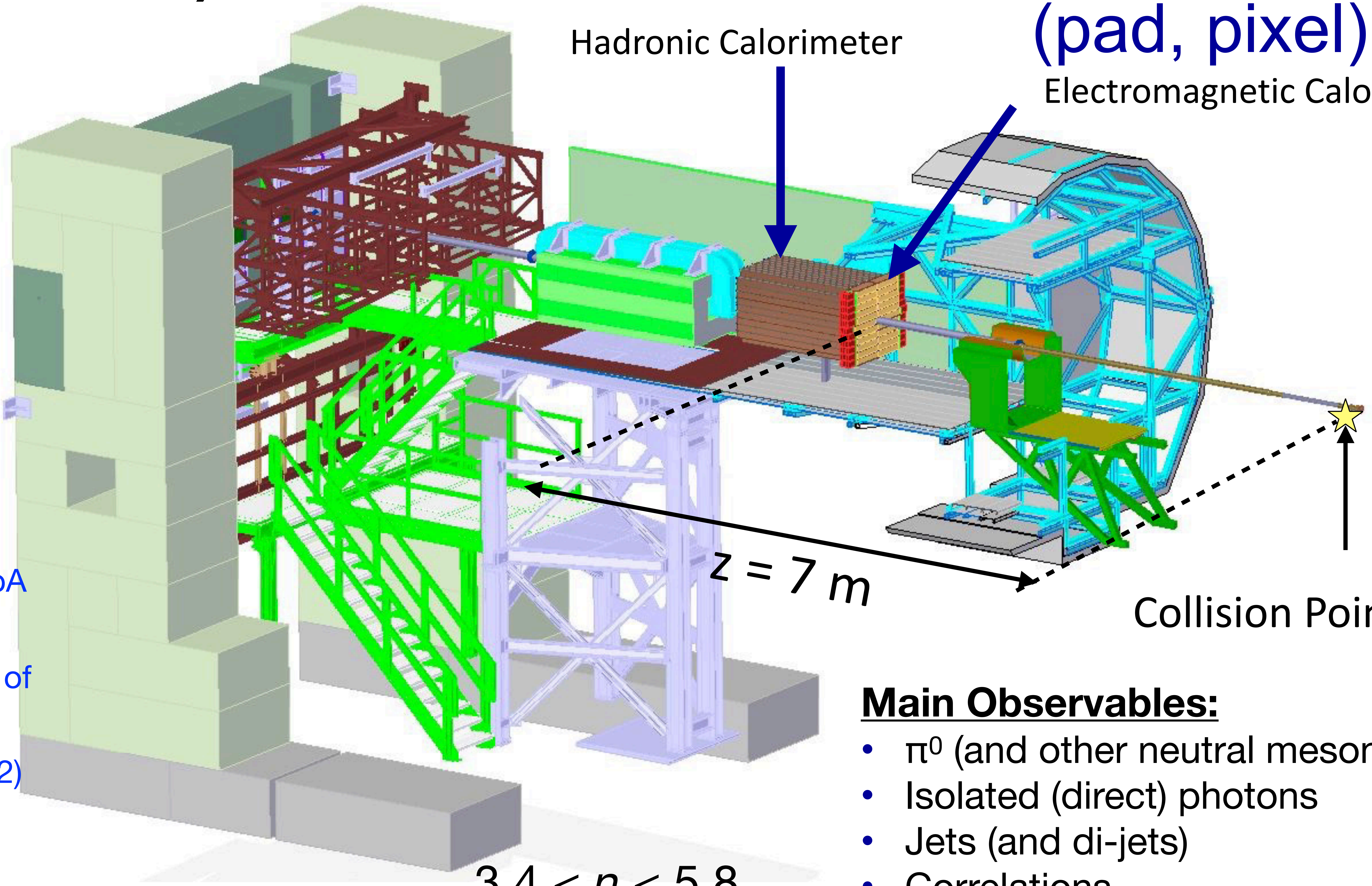
Furthermore, unsuitability of fields → amplified by Schwinger mech.

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

5) Go forward!
“FoCal, EIC and CGC”

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**

$3.4 < \eta < 5.8$

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

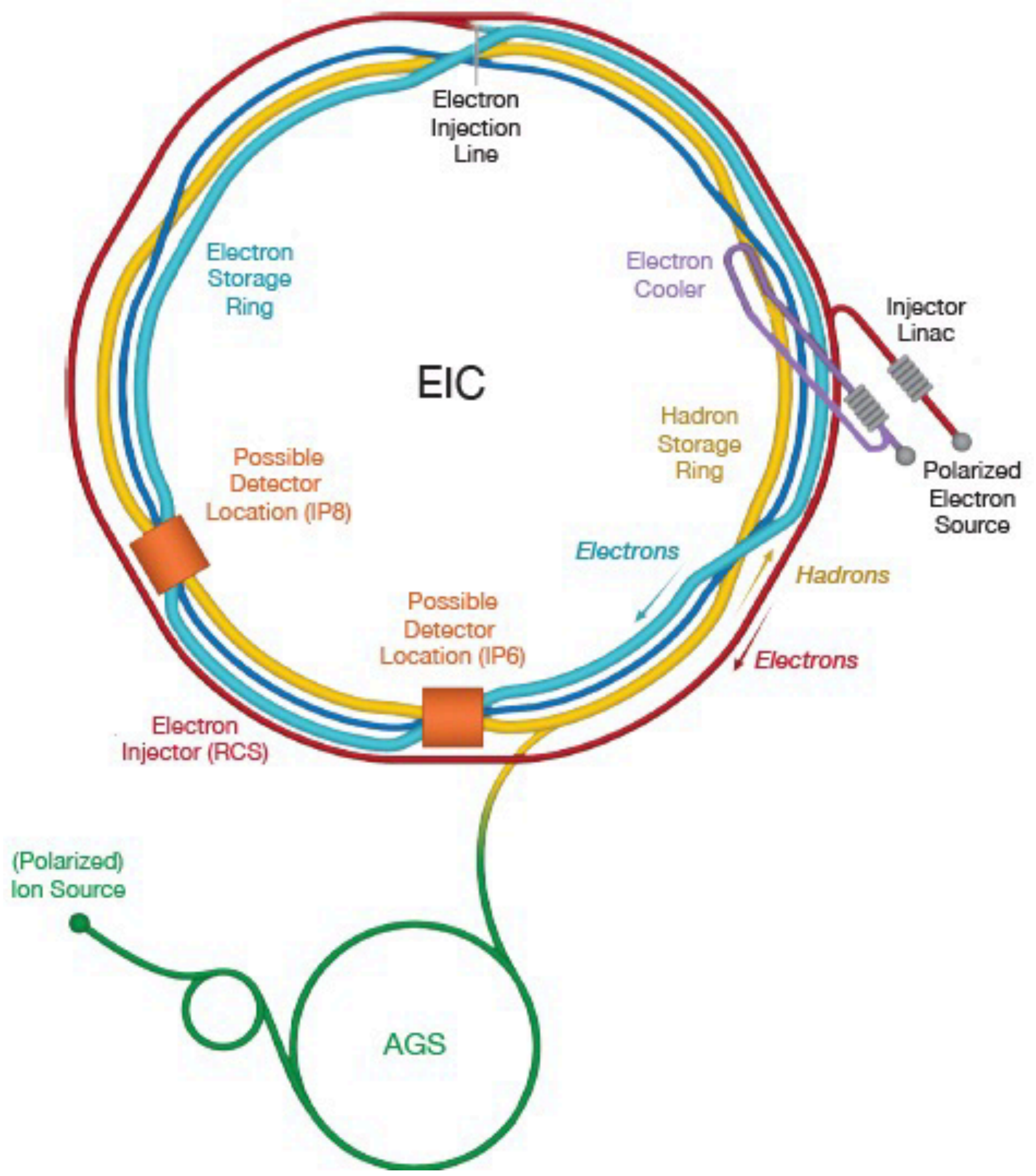
Main Observables:

- 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

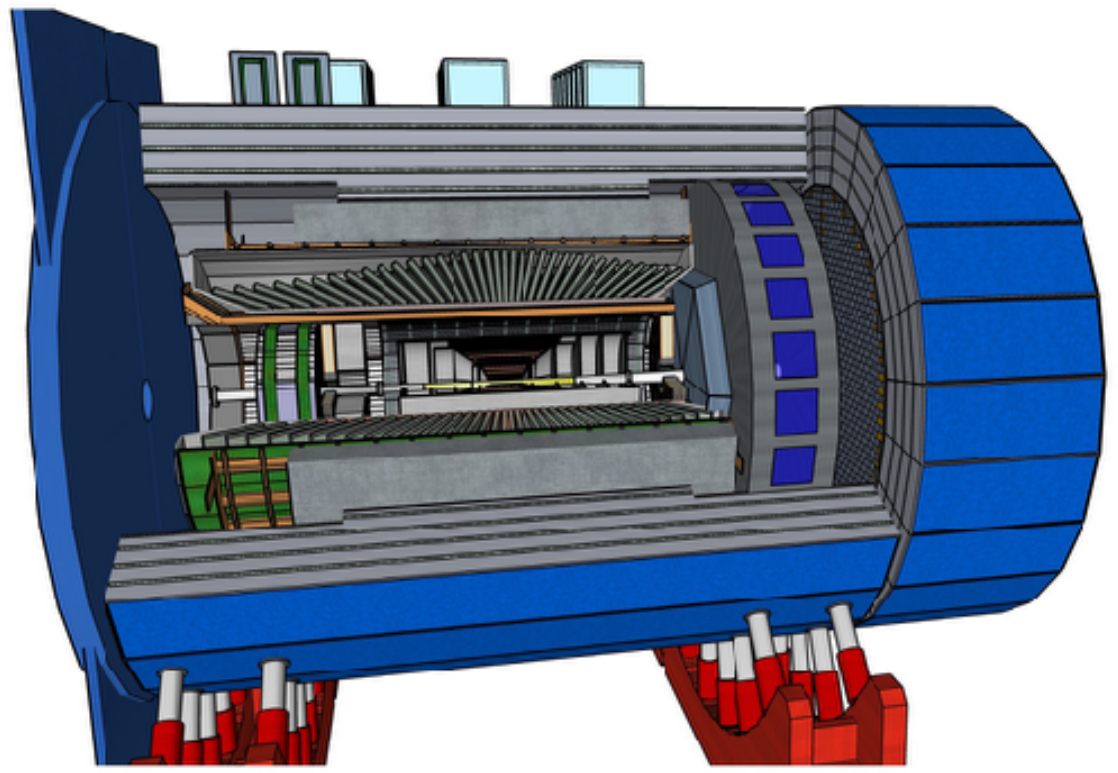


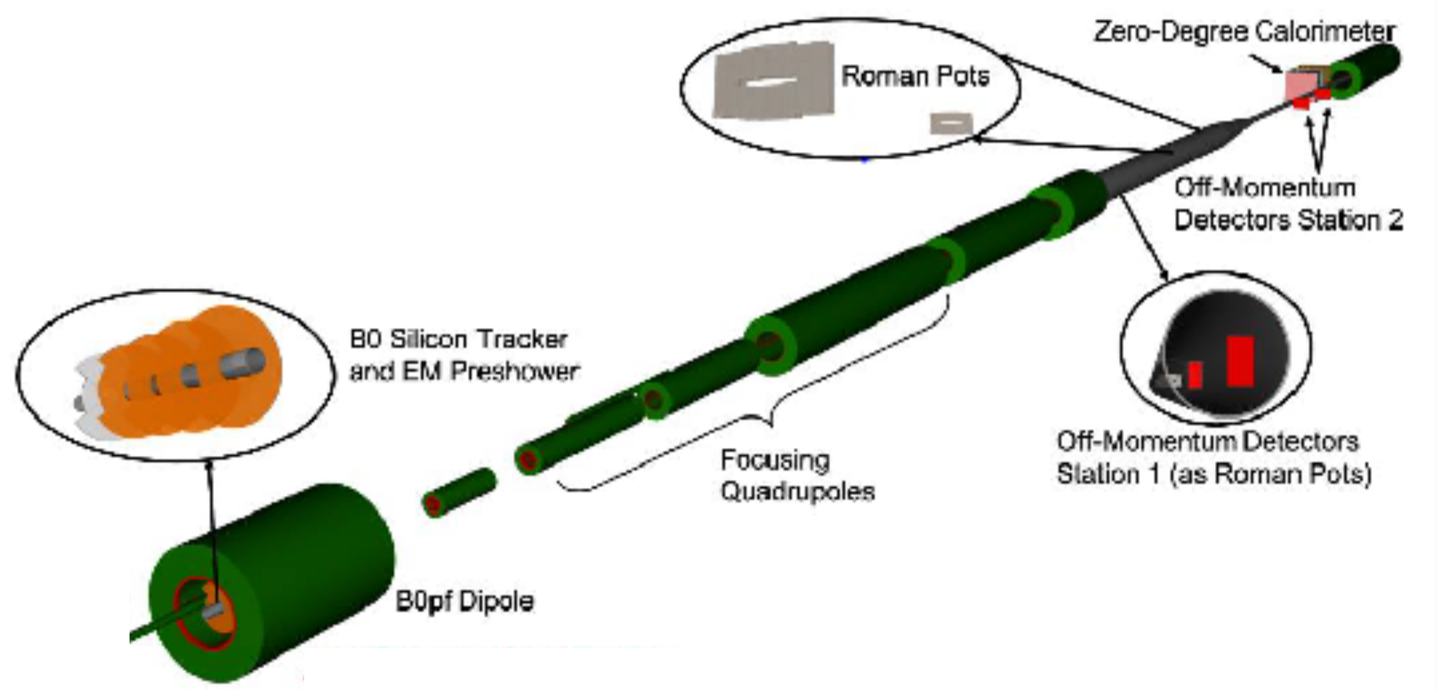
- Brookhaven National Lab. (BNL, USA)
- Will start operation in 2032
- High luminosity polarized e, p / Ion collider at $\sqrt{s}$ = 28-140 GeV
- Luminosity: x100 ~ 1000 higher higher than HERA
- 1st detector: ePIC collaboration

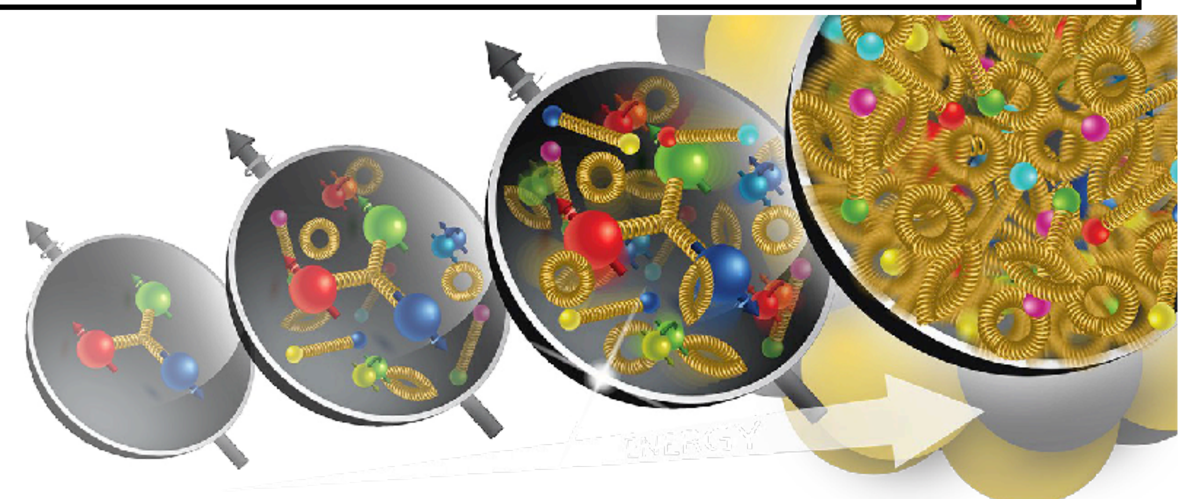
ePIC

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



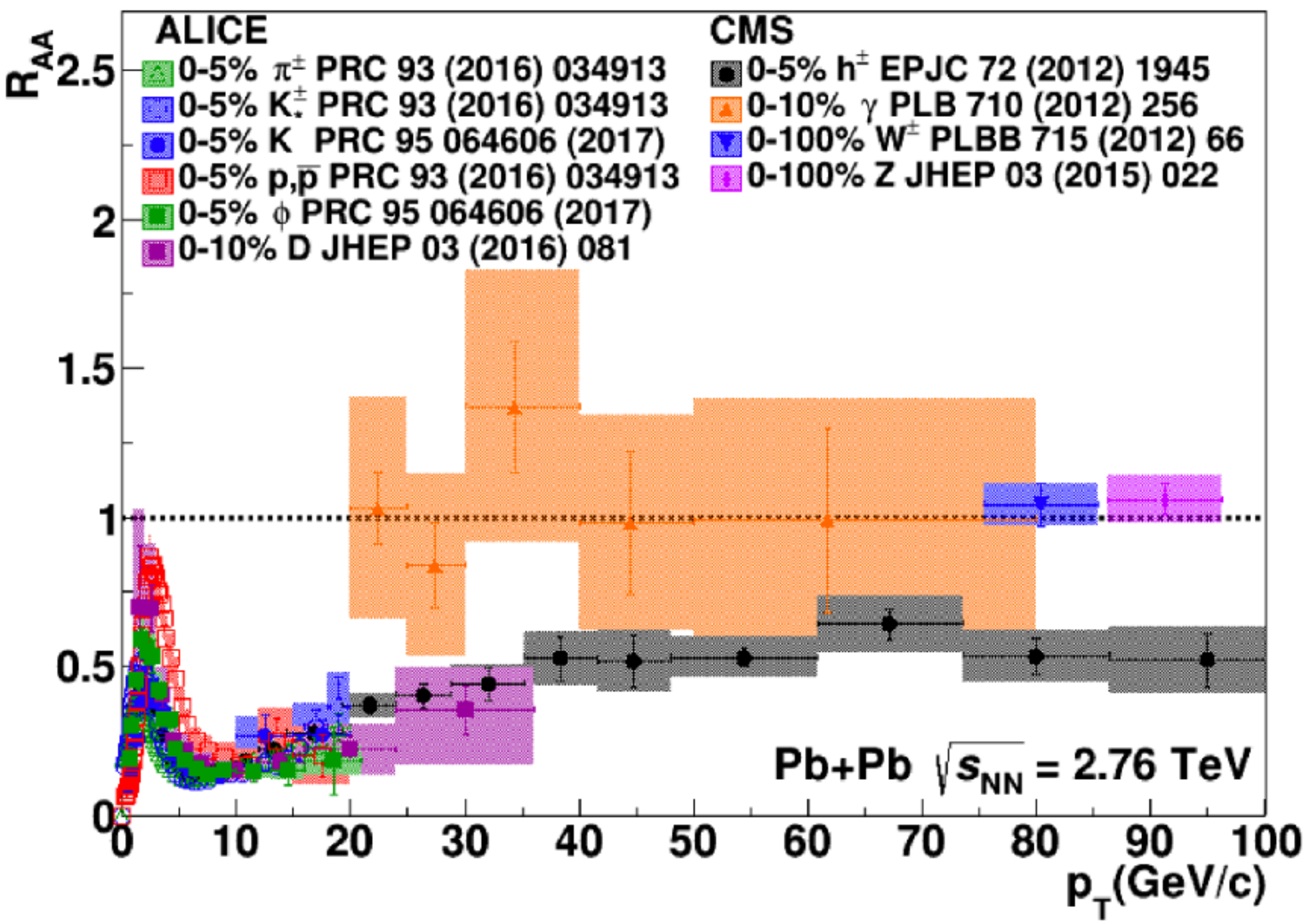




Energy loss in QGP

$$R_{AA} = \frac{\text{Hot Dense QGP in Pb} - \text{Pb}}{\text{Vacumme in pp}}$$

- **Significant suppression of jet in AA**
- **Large energy loss is possible by QGP only**
- **Extract stopping power from model comparison**



If CGC exists…

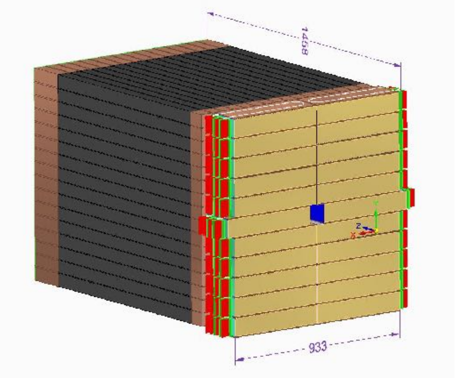
$$R_{pA} = \frac{\text{Yields in p} - \text{Pb}}{\text{Yields in pp}}$$

← Slowly increased compared to p-p due to saturation

← Increased faster

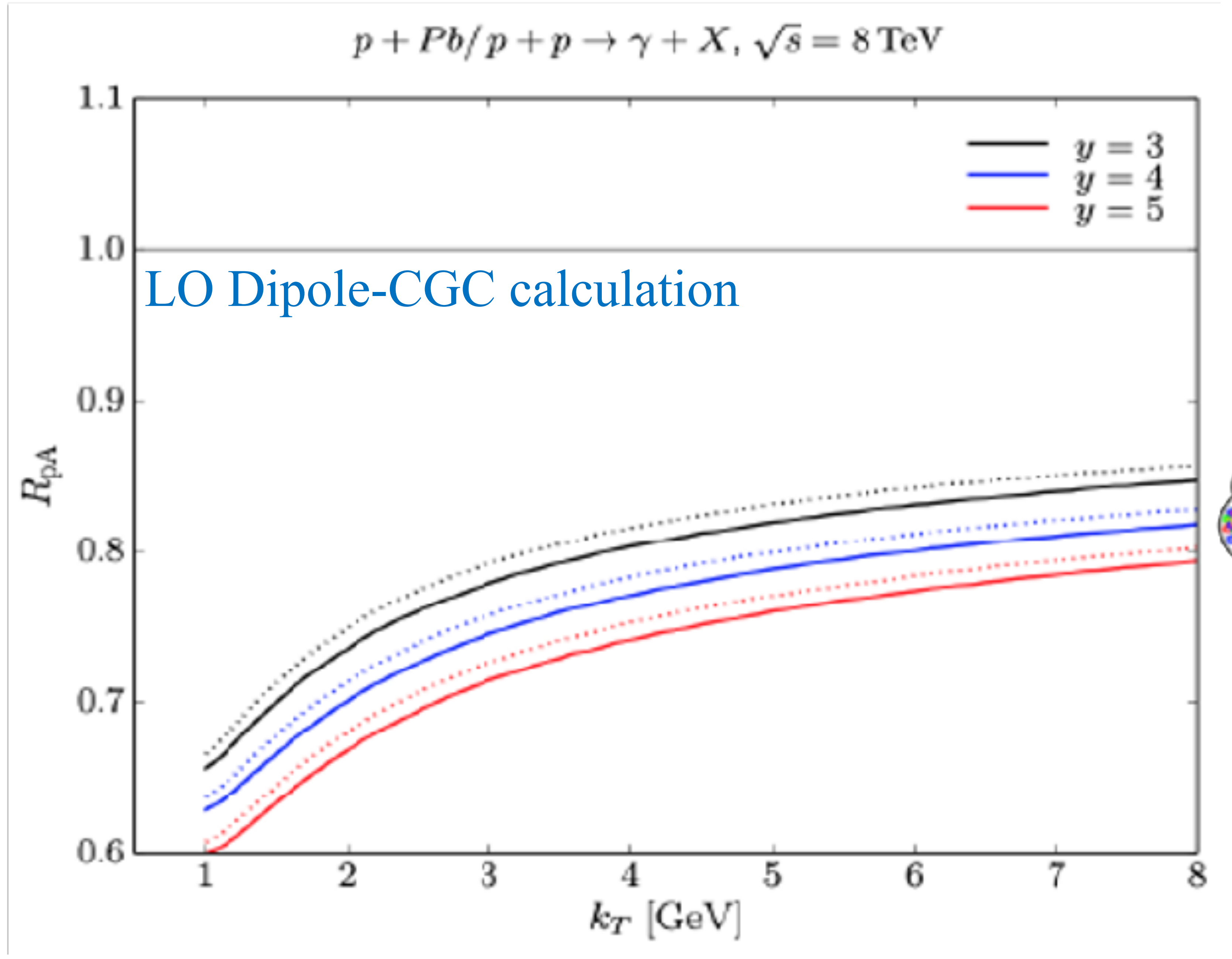
RpA decreases

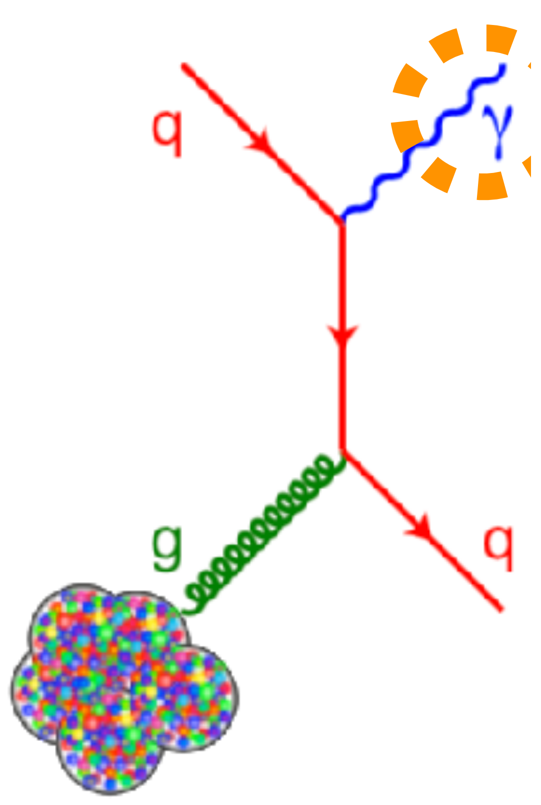
+ Δφ broadened



Saturation signal in FoCal (1)

R_{pPb}: forward γ

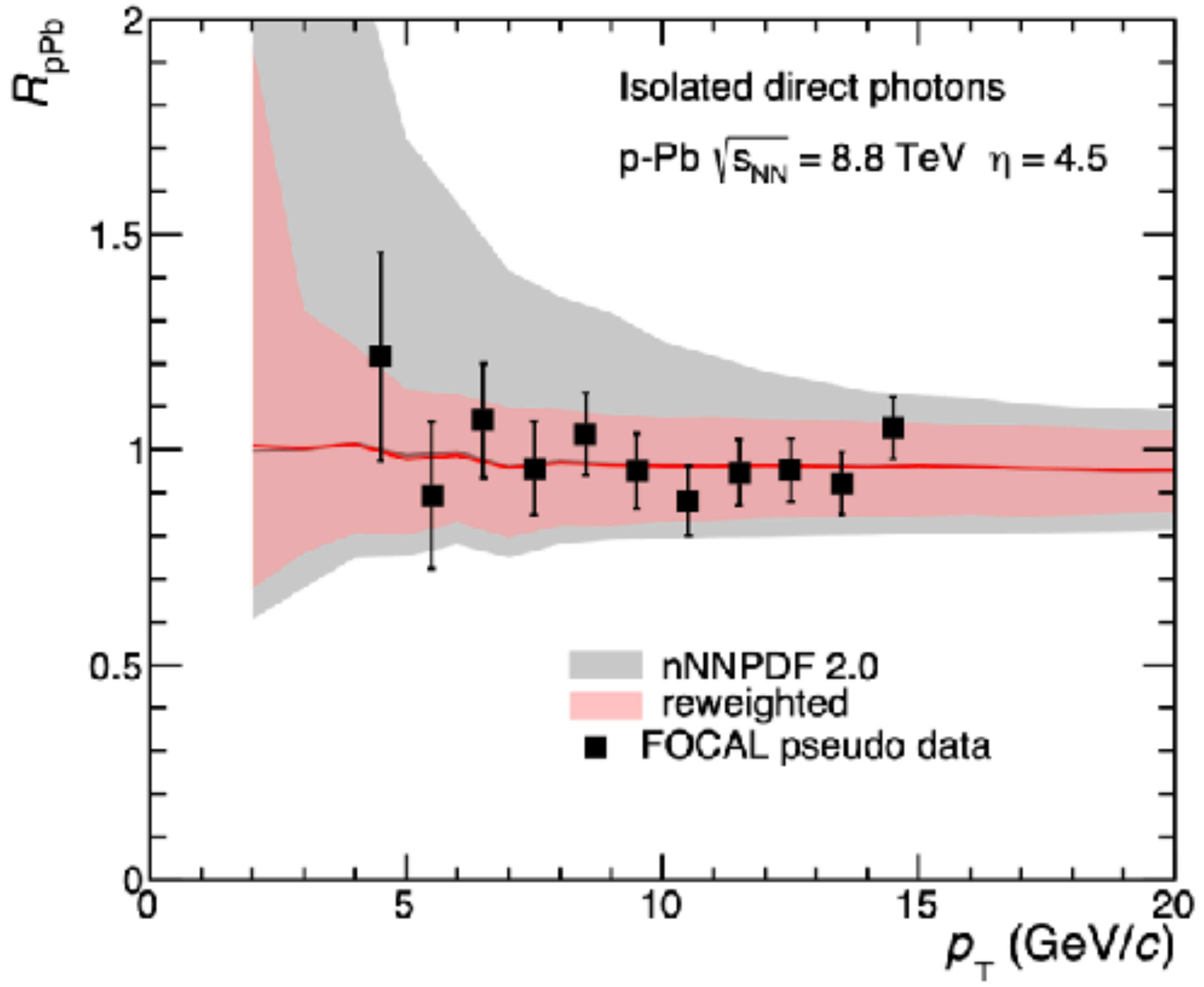


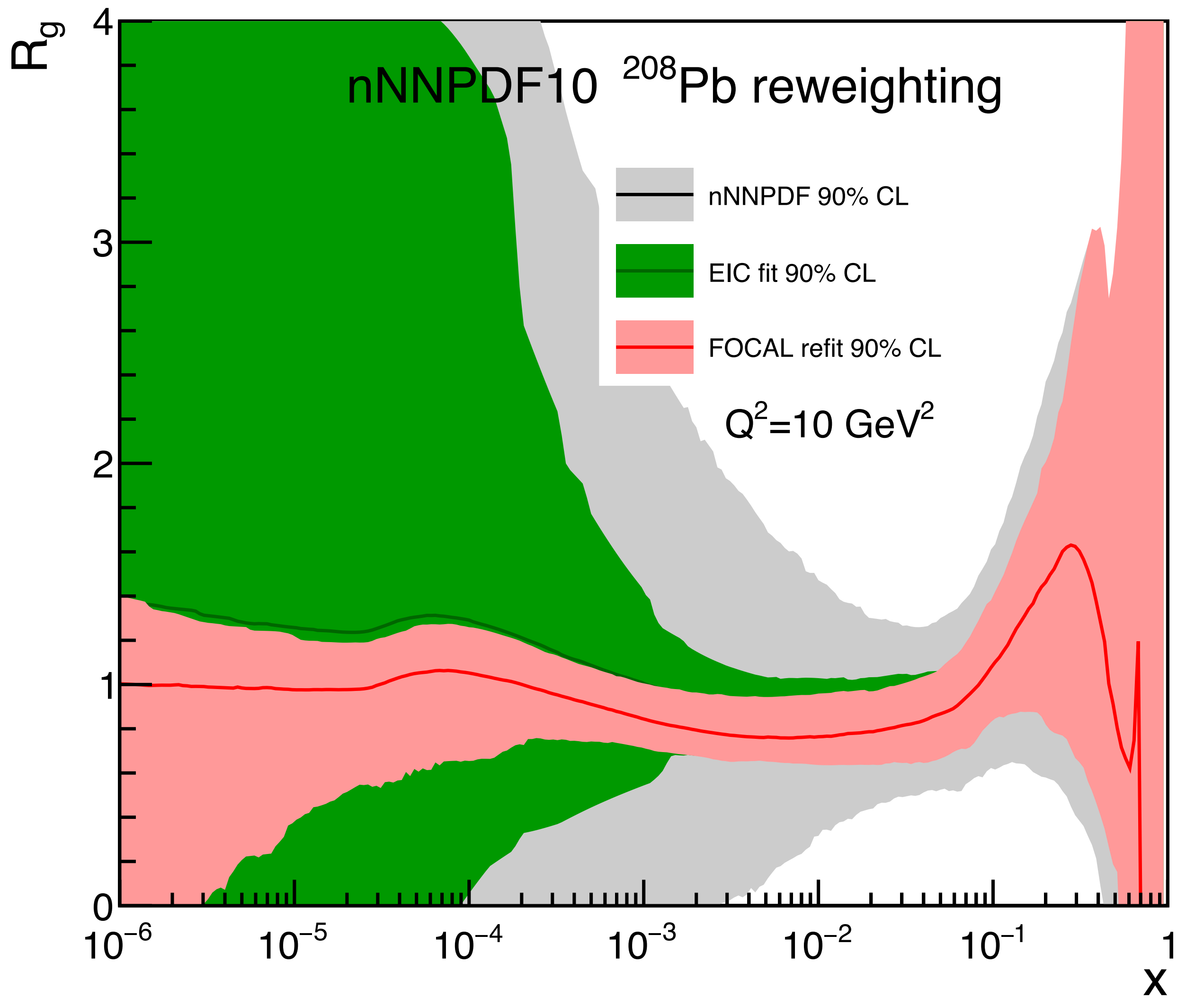


- Large suppression at low p_T for isolated γ

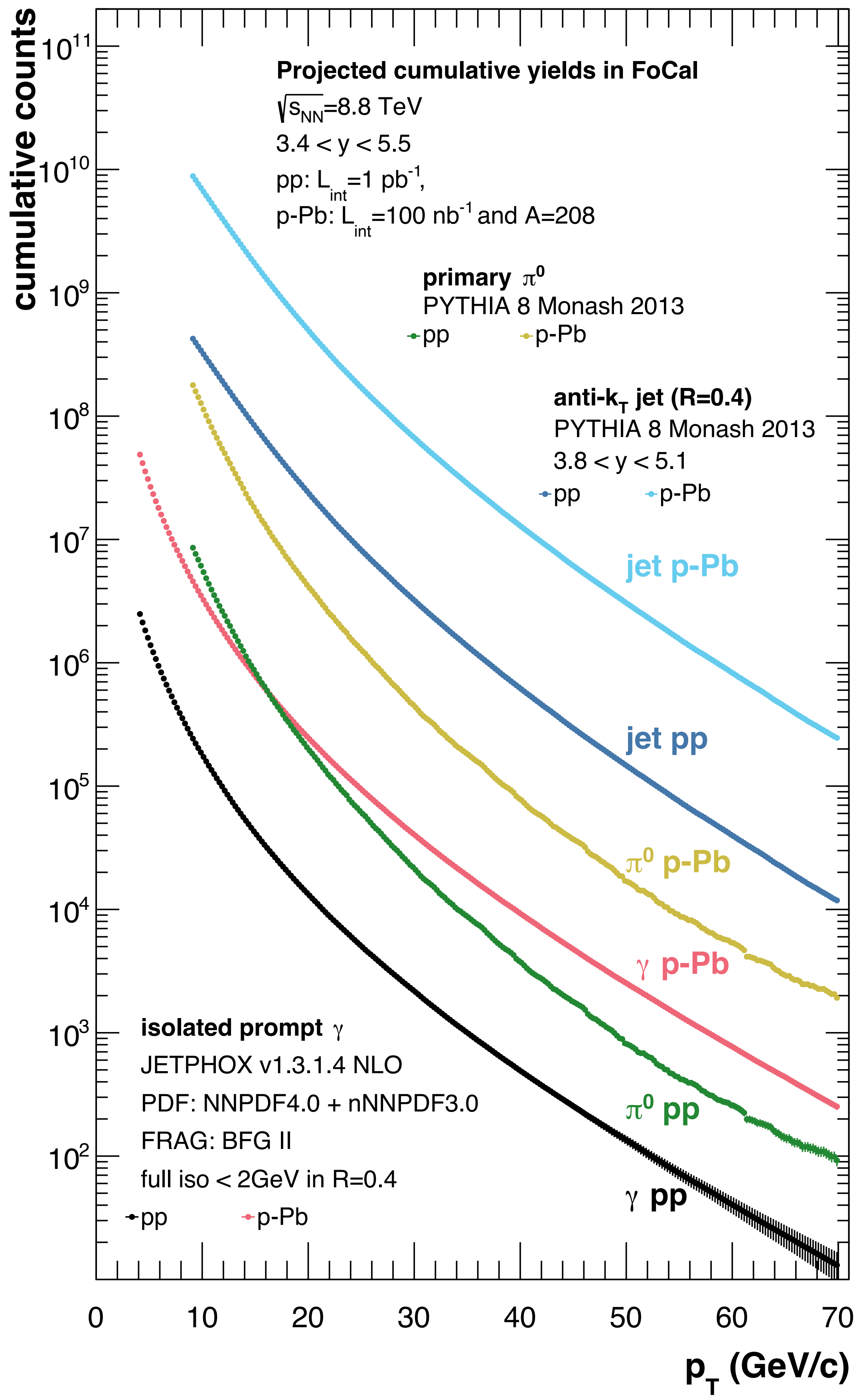
  Isolated γ: qg → qγ ; $k_T \sim Q_{sat}$

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



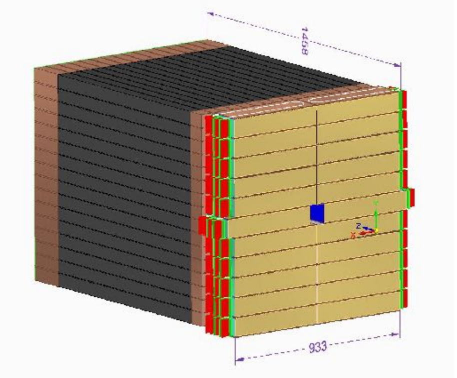


Expected yields in FoCal (Run-4)



- 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};

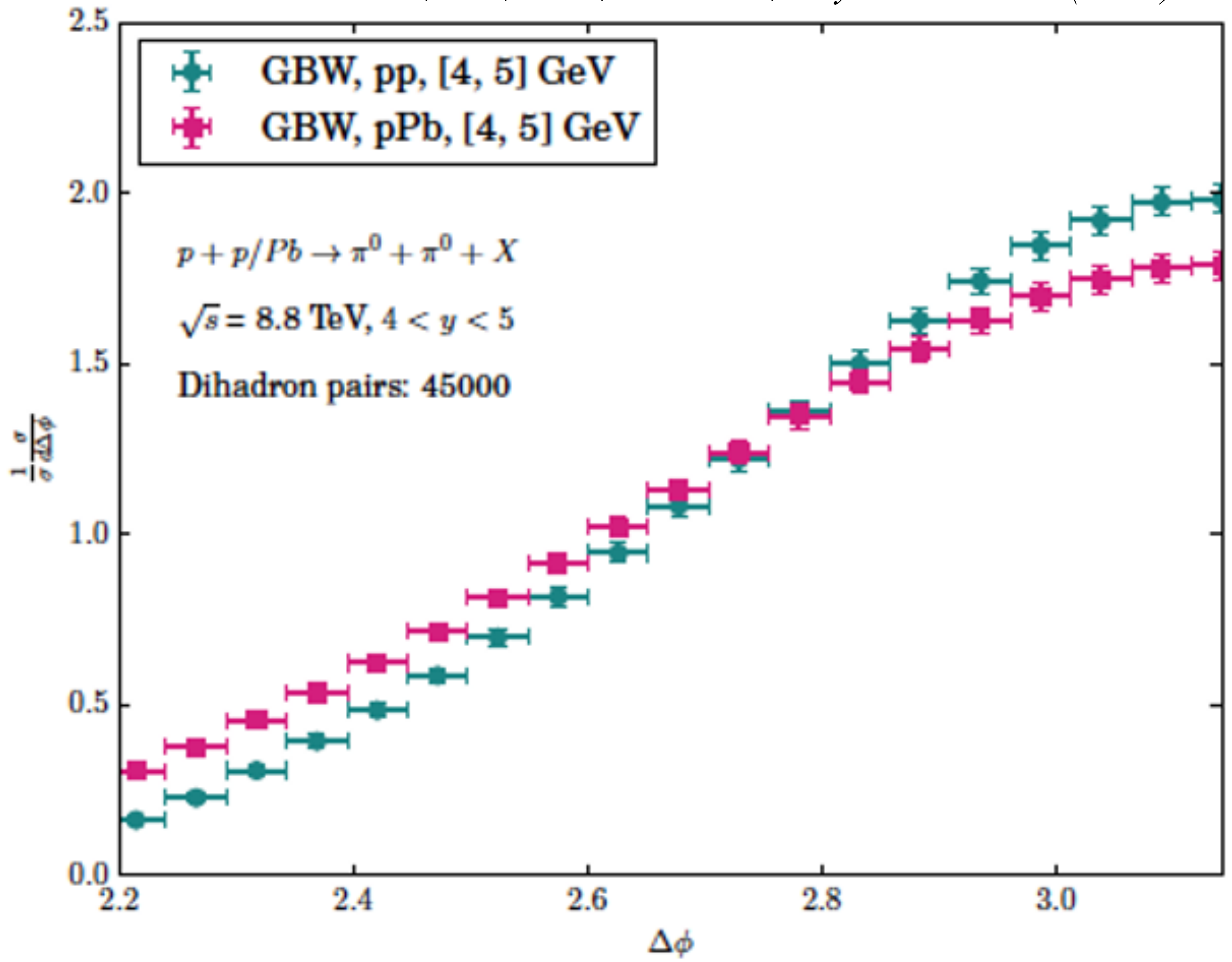
- Expected gluon saturation (CGC) in small-x, not yet clear evidence
- Excellent probe: isolated photons from quark-gluon Compton scattering



Saturation signal in FoCal (2)

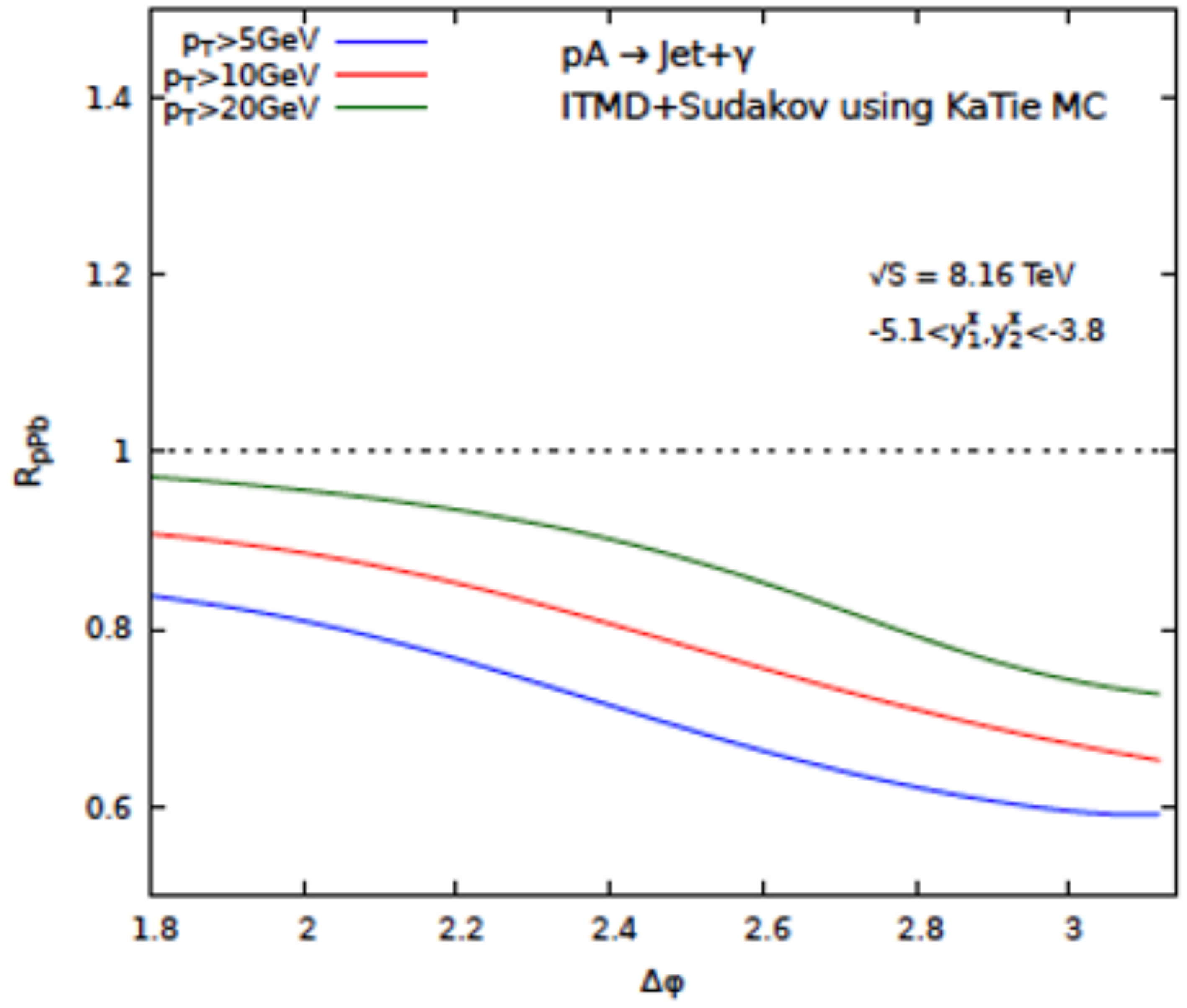
Di-hadron Correlations

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

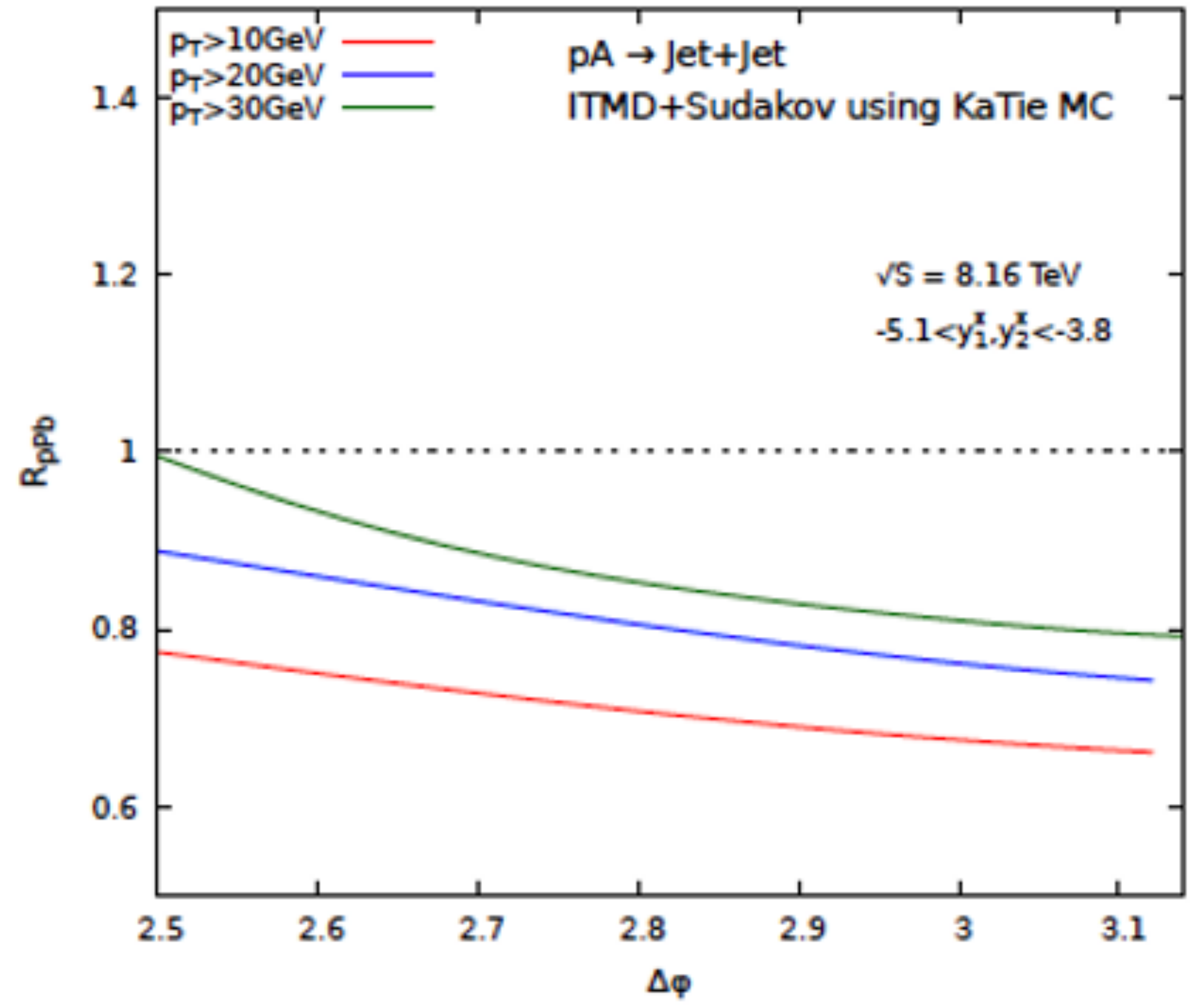


Dilute-dense LO + Sudakov
probes quadrupole operator

Forward γ+jet



Forward di-jet

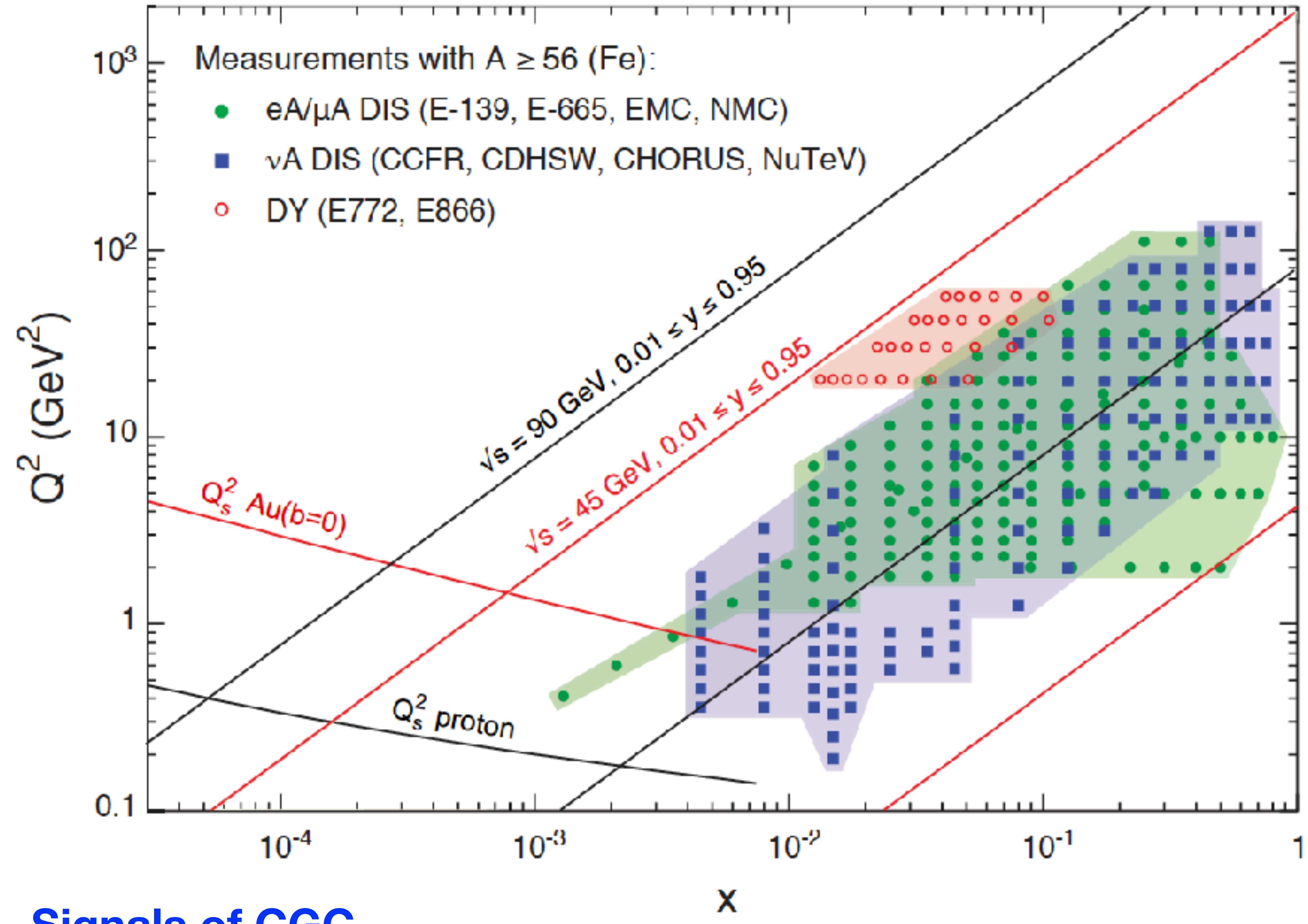


- γ+jet: dipole TMD gluon distribution
- di-jet: multiple TMD distributions

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

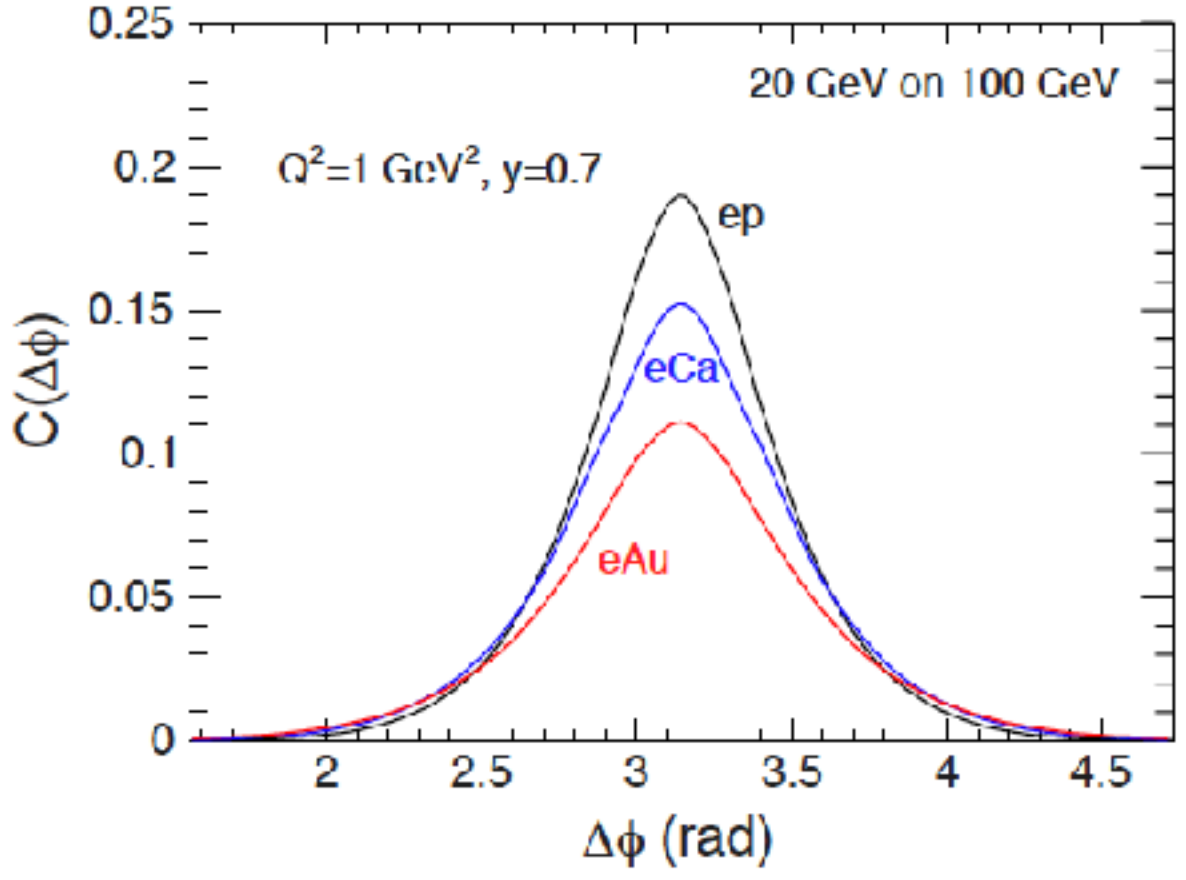
- γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$ (sensitive to saturation)
- changing k_T (p_T) → exploring non-linear QCD evolution in wide kinematic coverage of x-Q^2 by FoCal

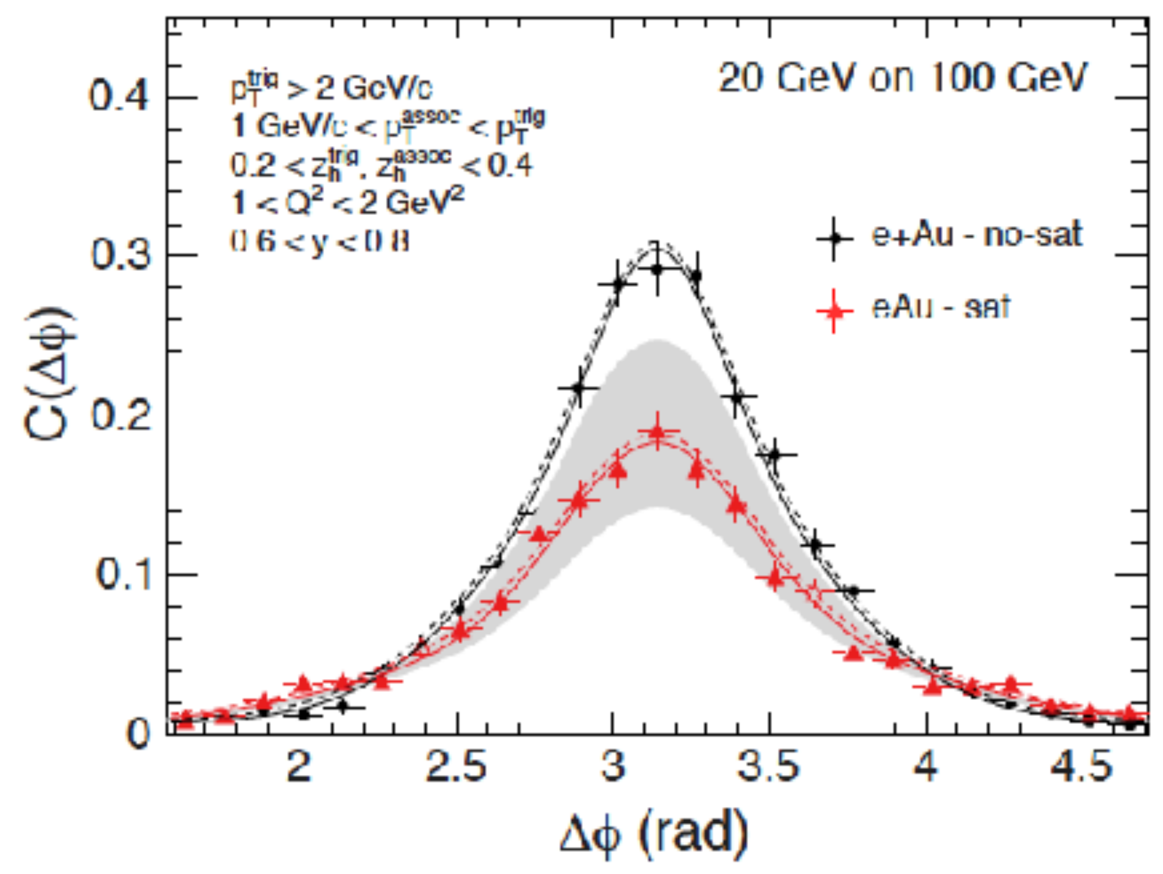
Saturation signal @ EIC eA



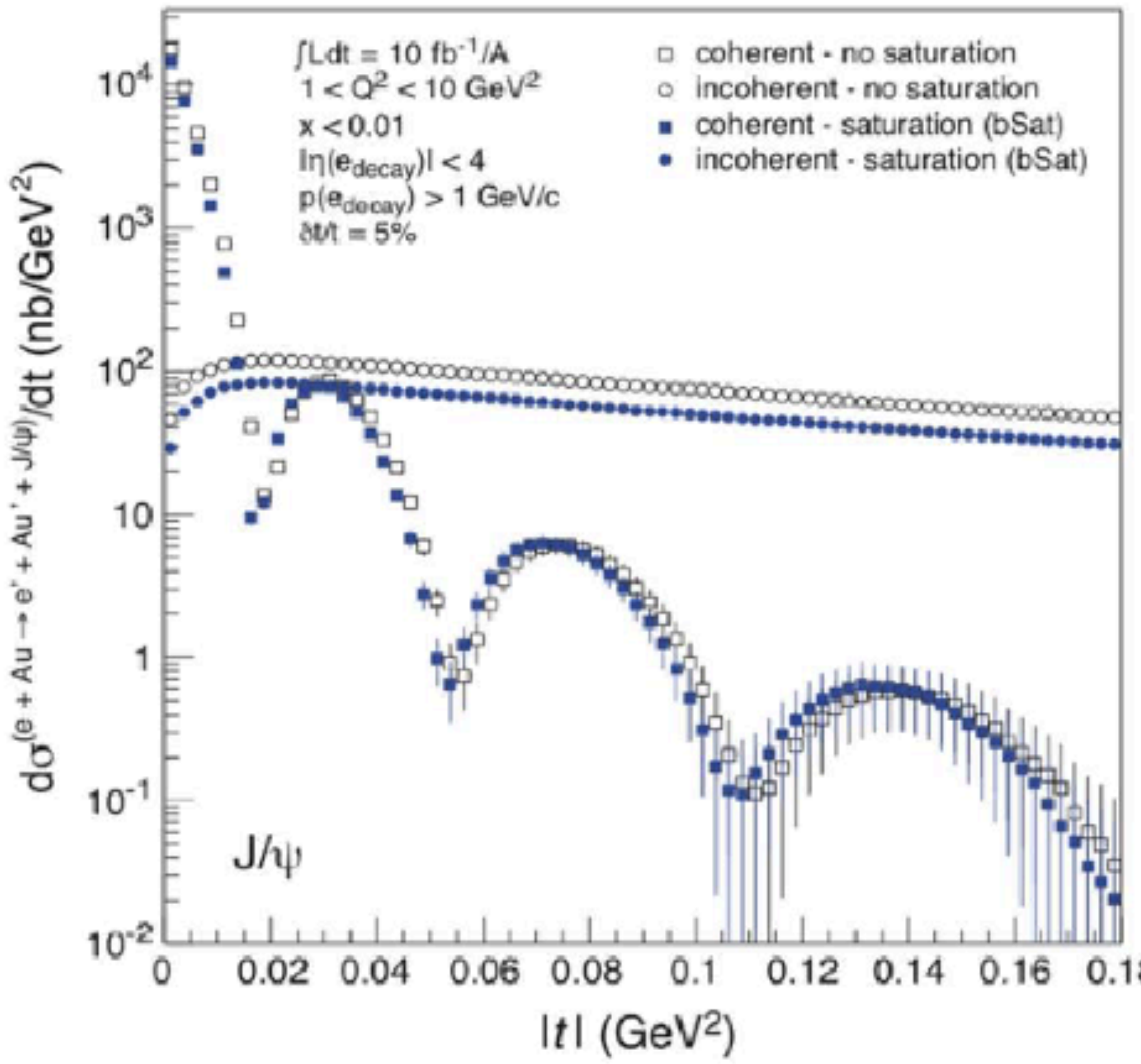
EIC White Paper, '12, '14 (2nd ed).

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

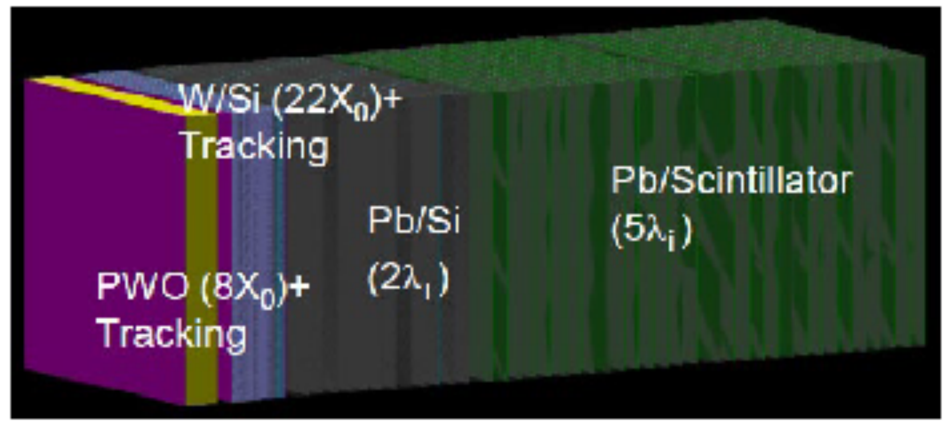




J/ψ, t distribution



FoCal technology



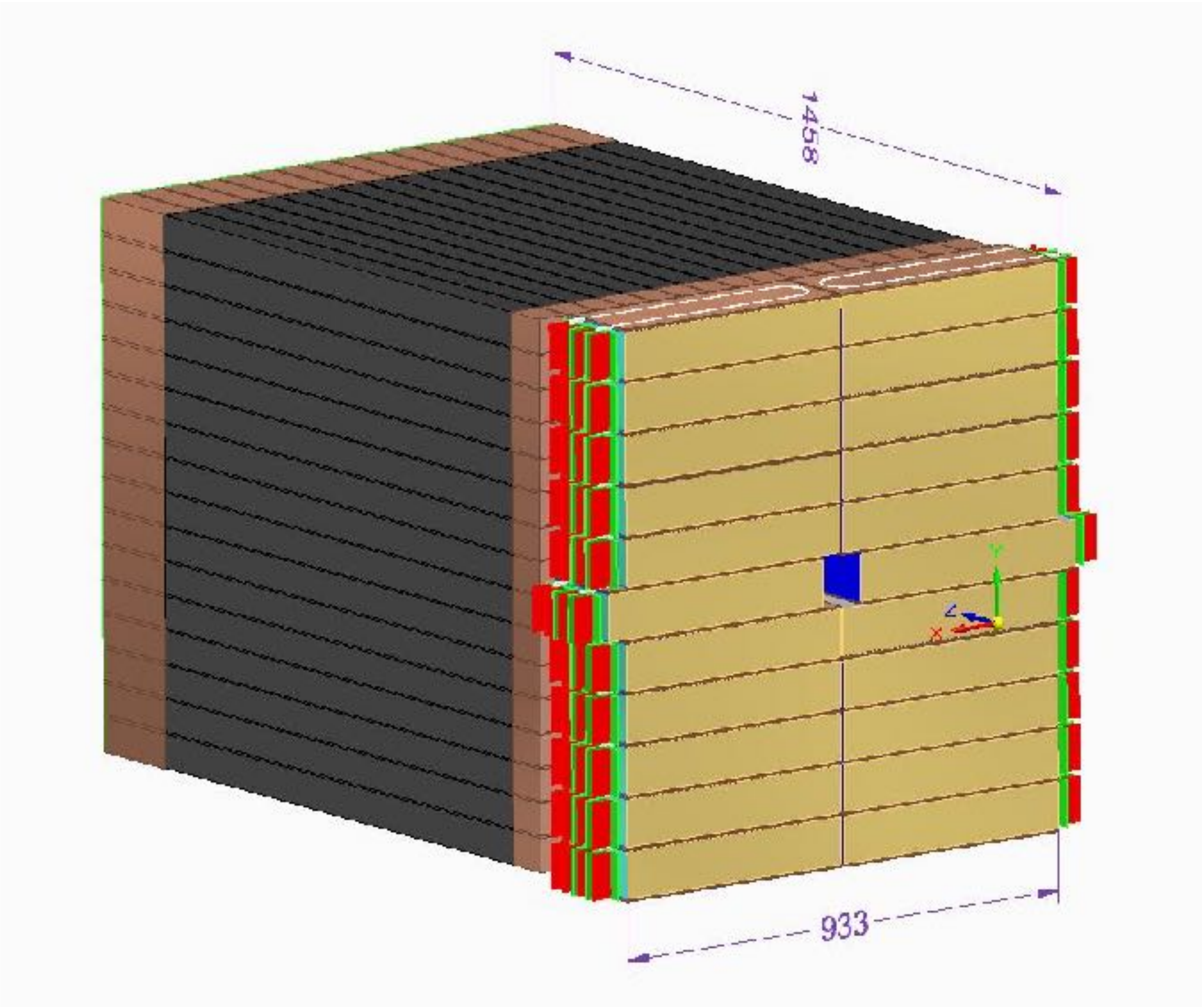
A ZDC design for EIC

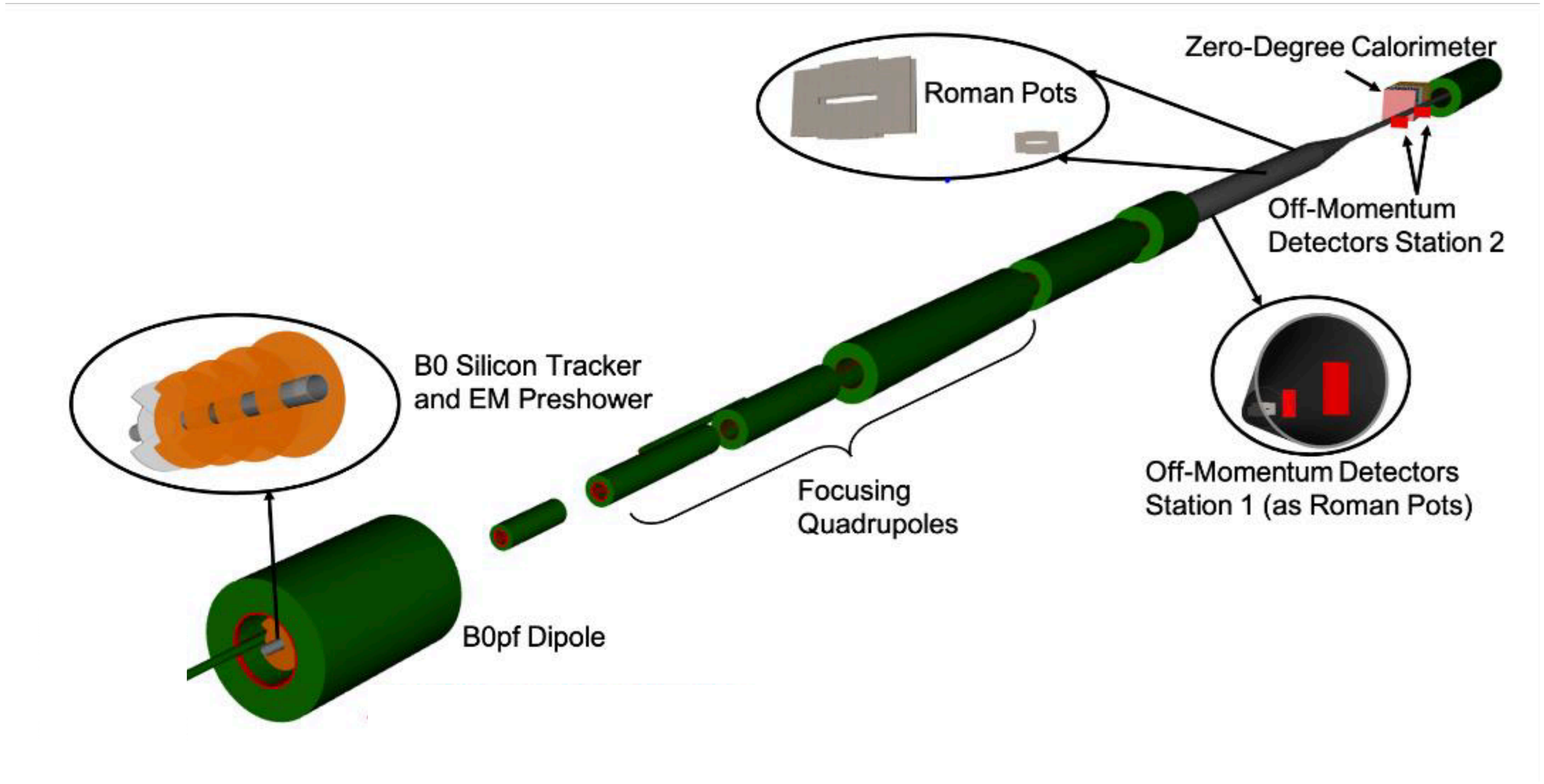
Signals of CGC

- 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

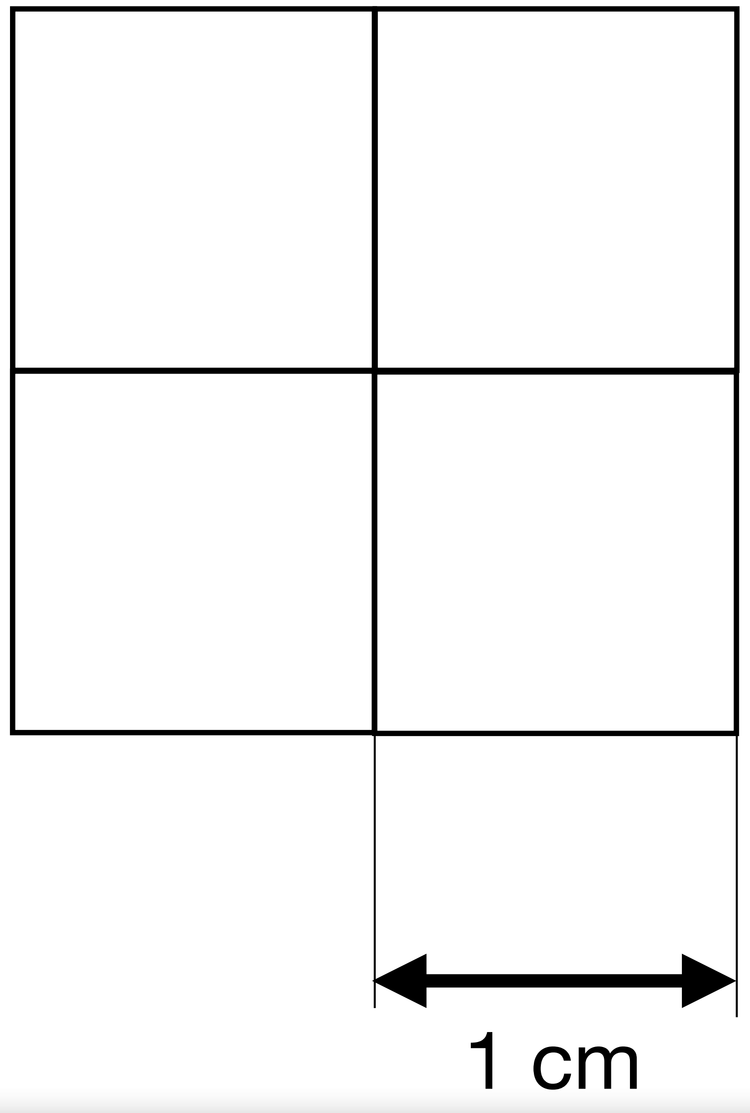
6) Forward detector at LHC and EIC



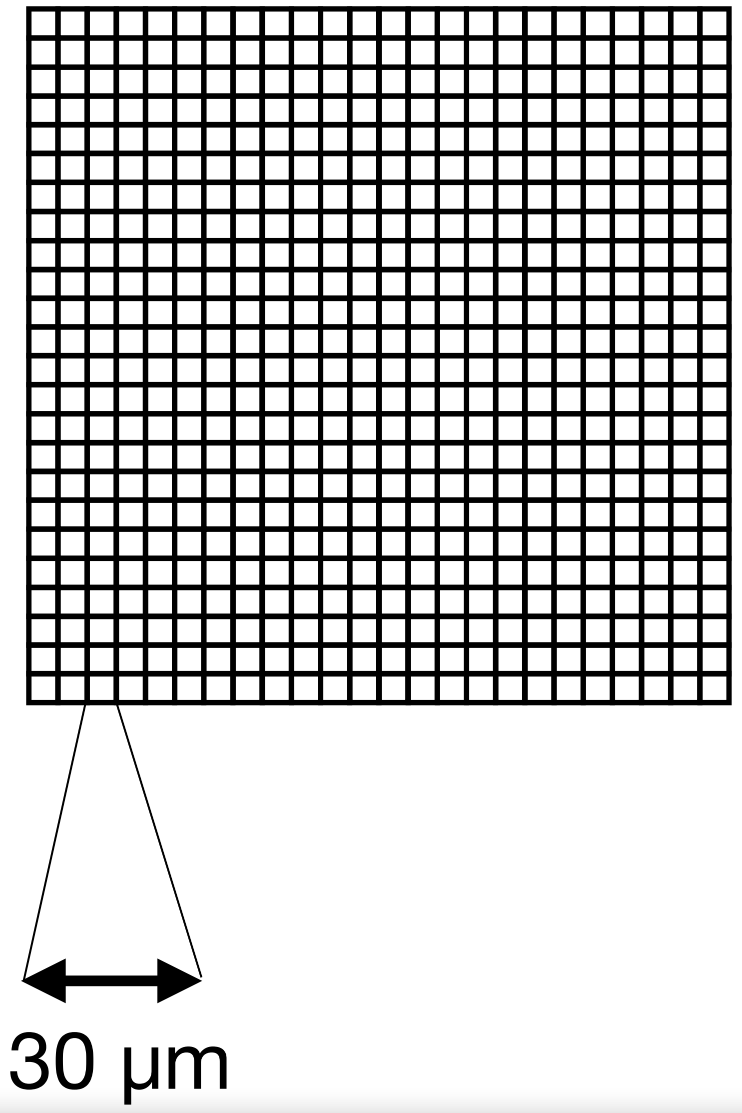


Detector design

E-Pad



E-Pixel



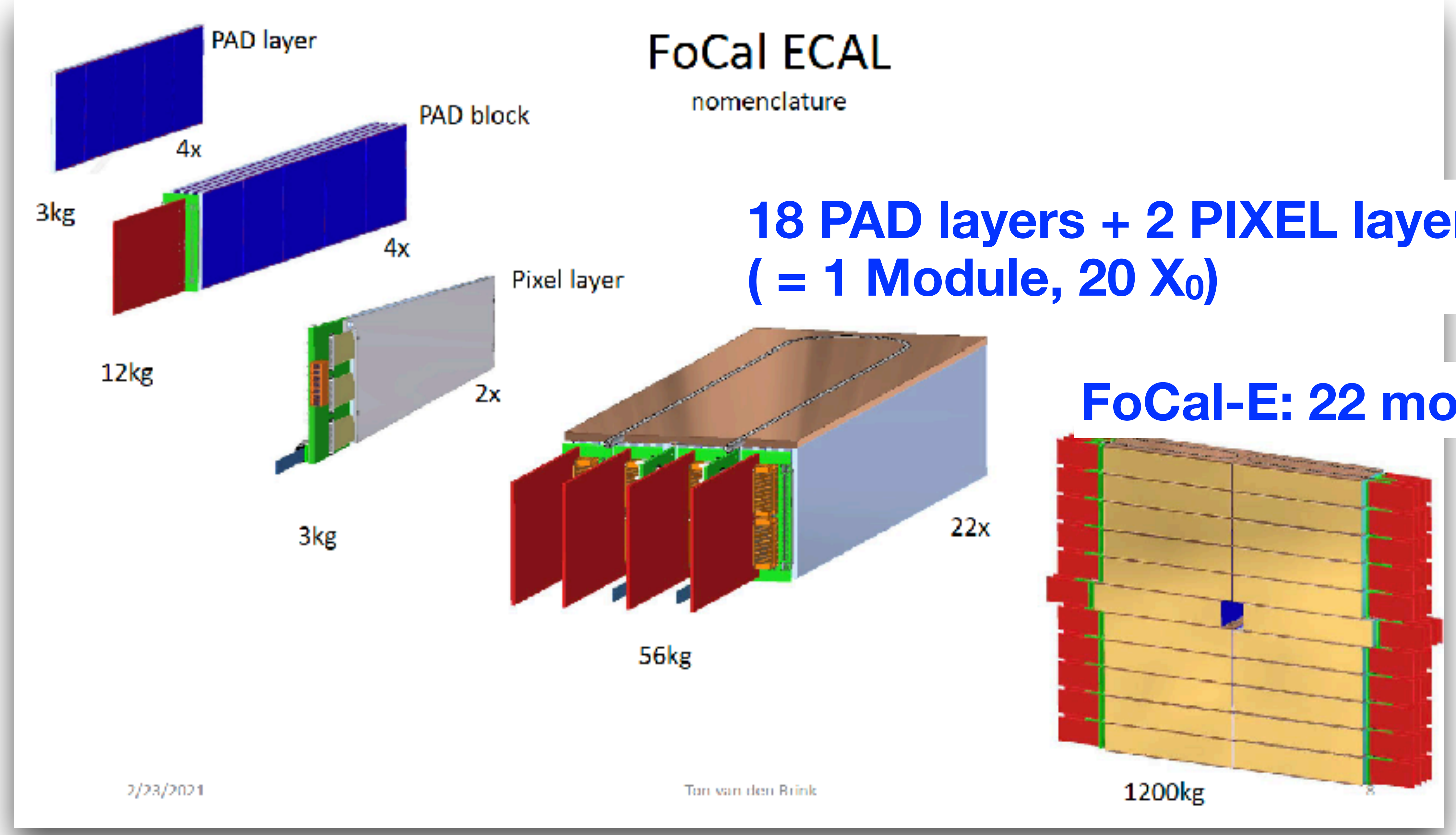
FoCal-E (pad, pixel)

20 layers of W(3.5 mm ≈ $1X_0$) + silicon sensors:
Two types: **Pad (1x1 cm²)** and **Pixel (30 x 30 μm²)**

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

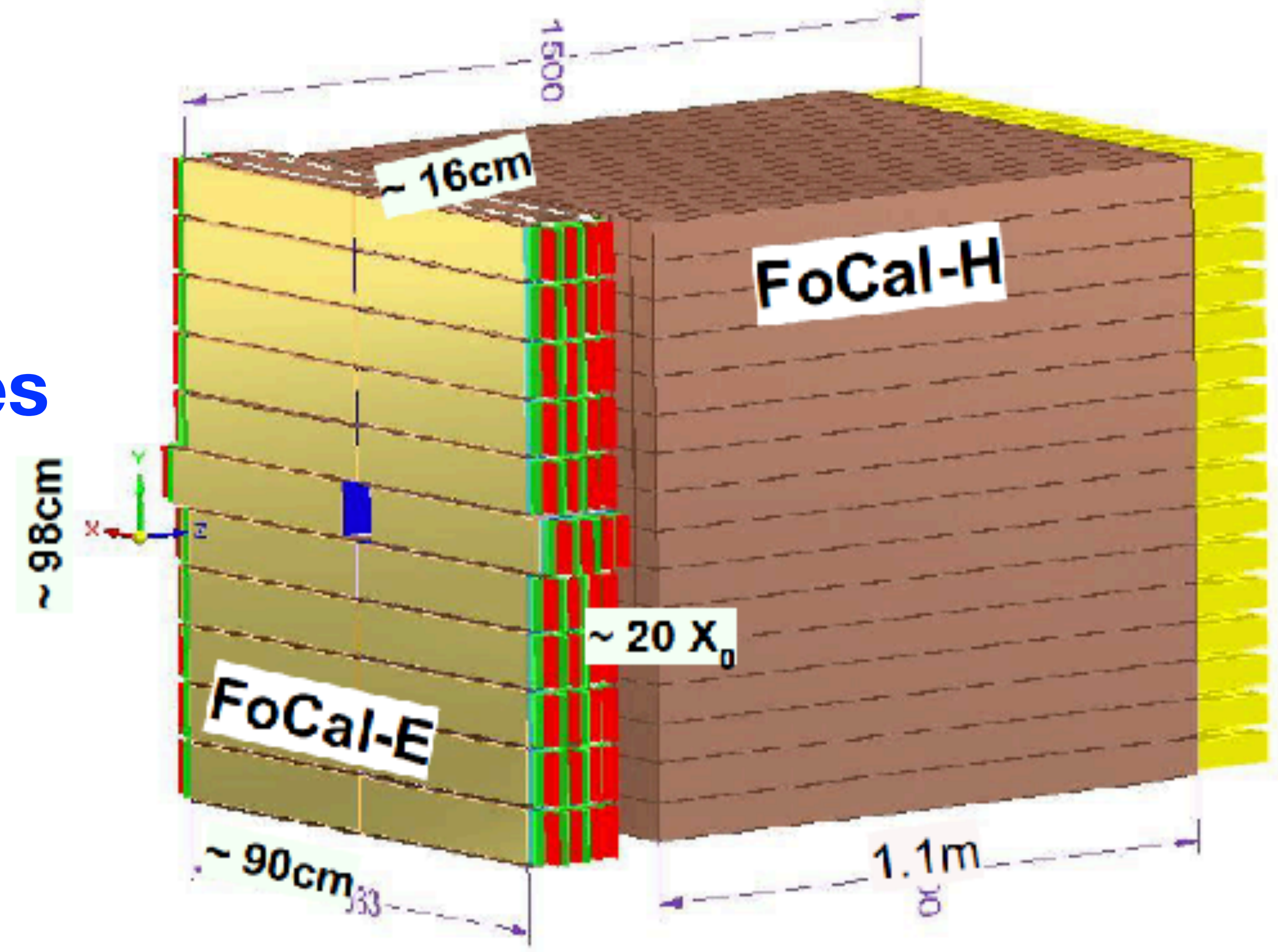
FoCal-H

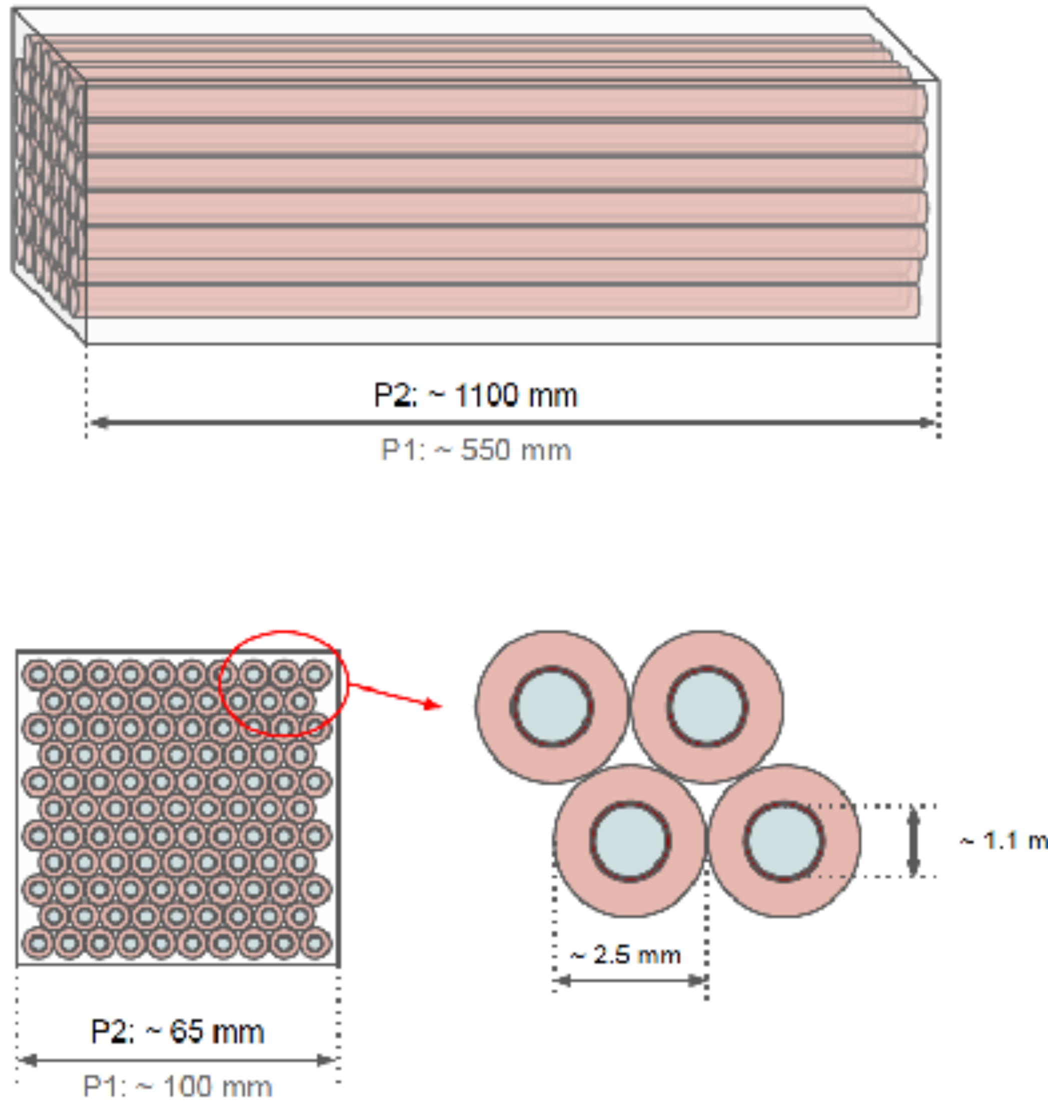
Conventional metal-scintillator design
Cu capillary-tubes enclosing BCF scintillating fibers
SiPM readout



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

FoCal-E: 22 modules





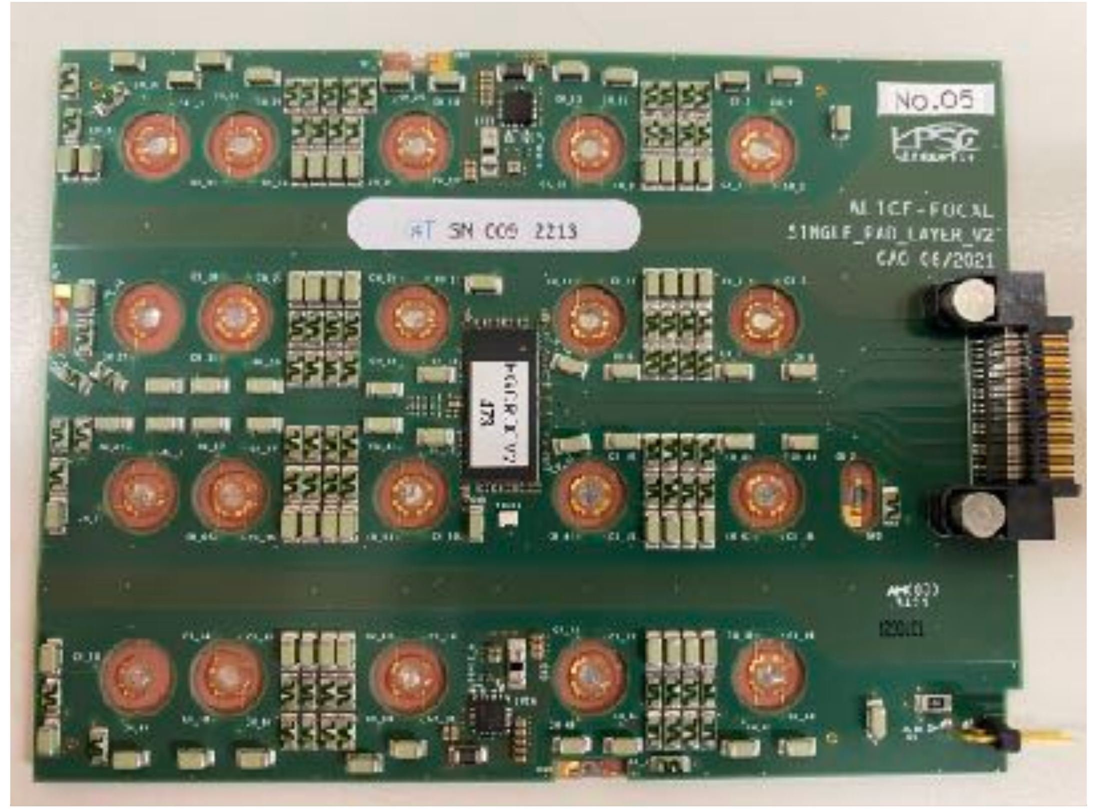
FoCal Japan

Responsibilities:

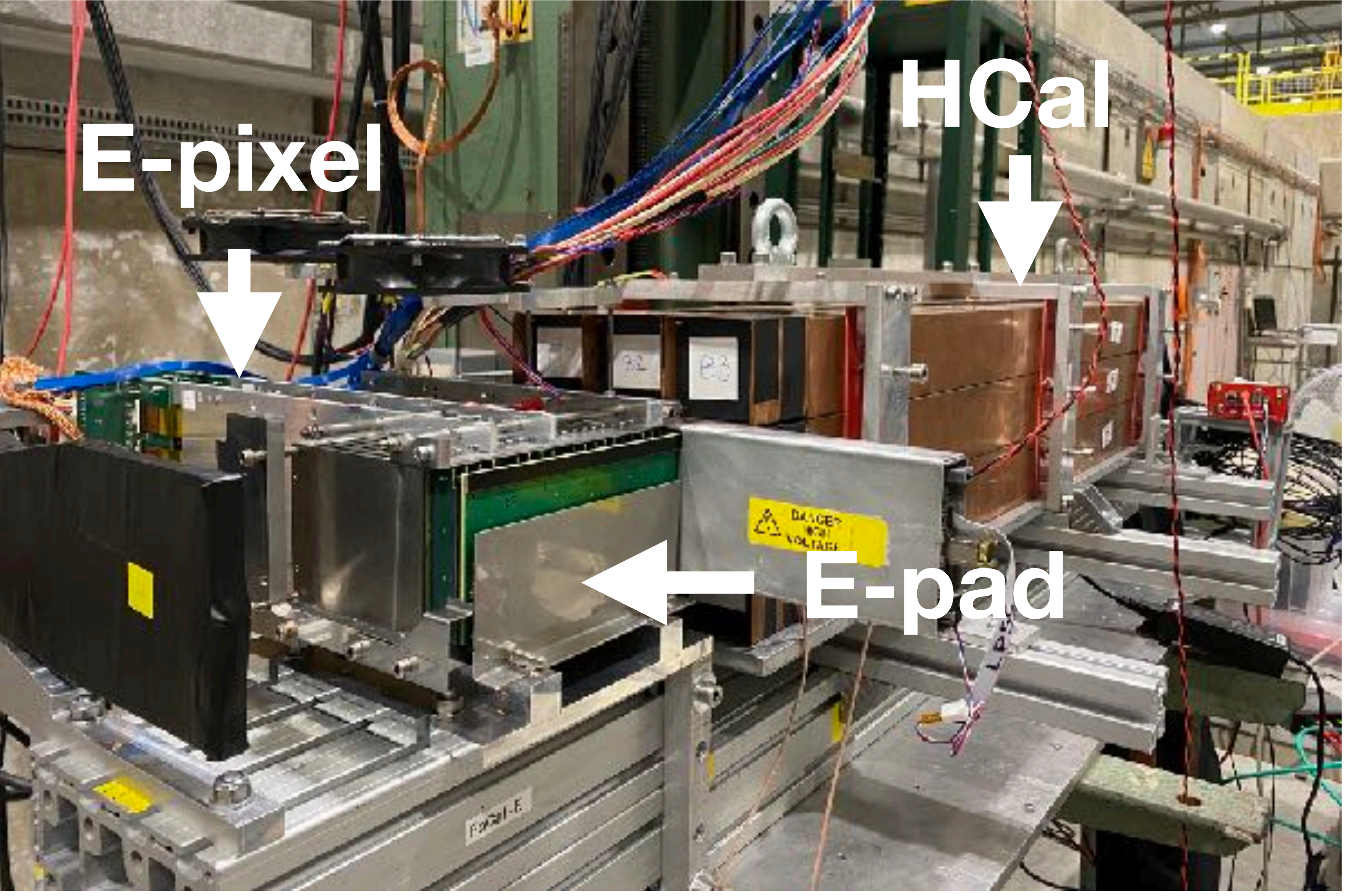
(1) FoCal-E pad, (2)readout and trigger

9 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.
- Univ. of Tokyo CNS

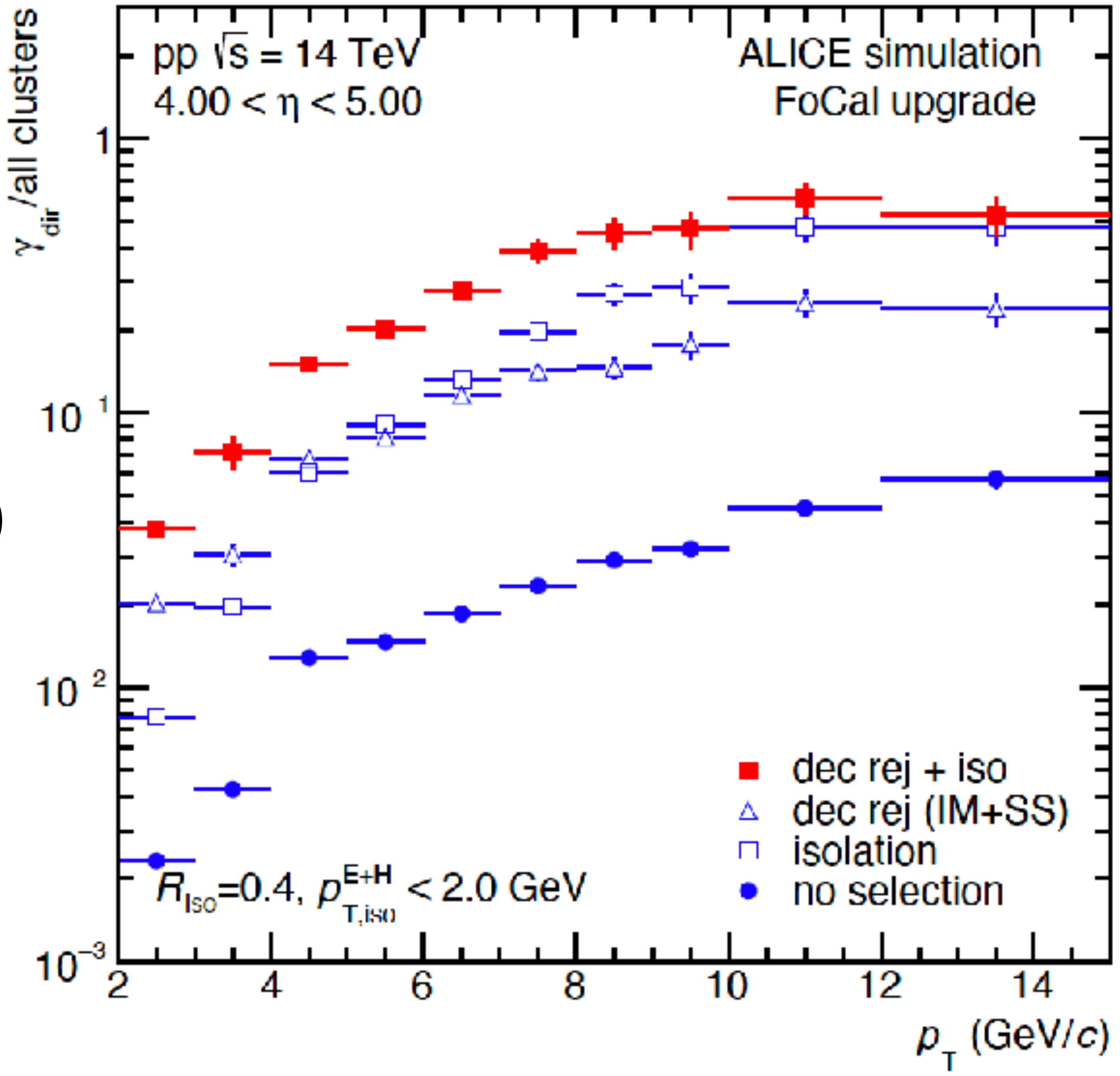


Uniqueness of FoCal detector



PS/SPS test beam in 2022

Isolated photon ID



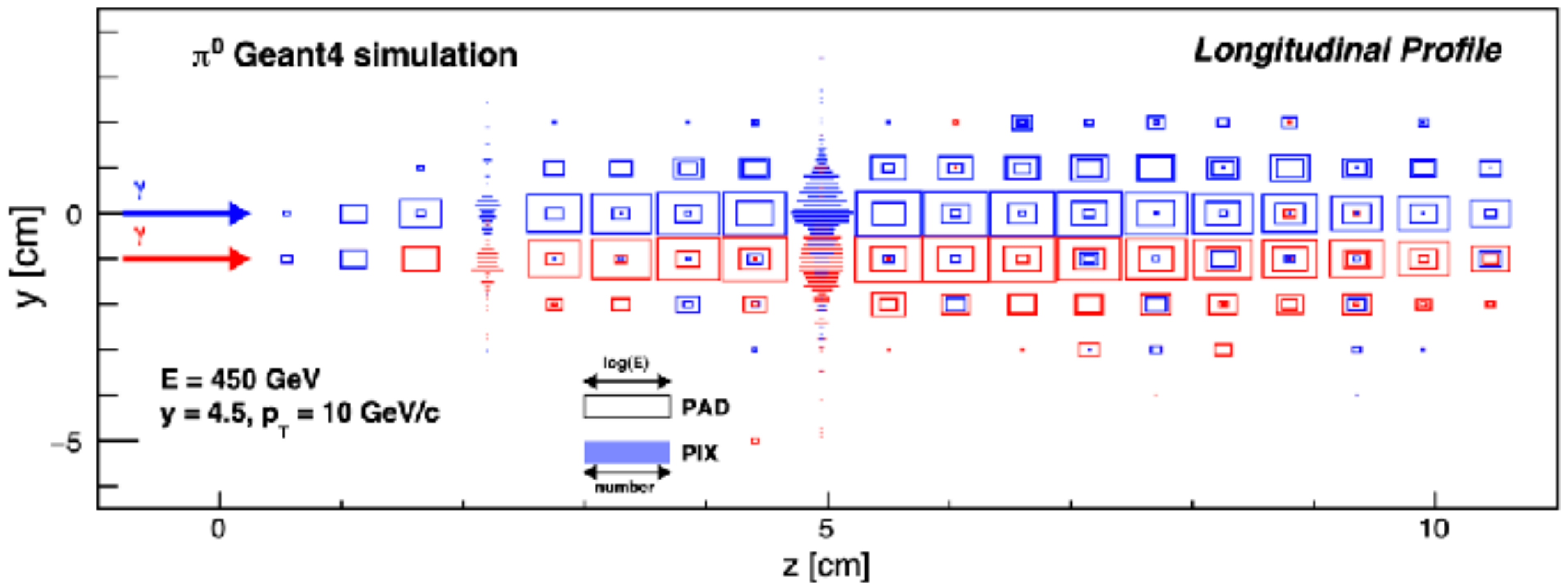
1） **High two photon separation power**（<~5mm, energy resolution ~3%）

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

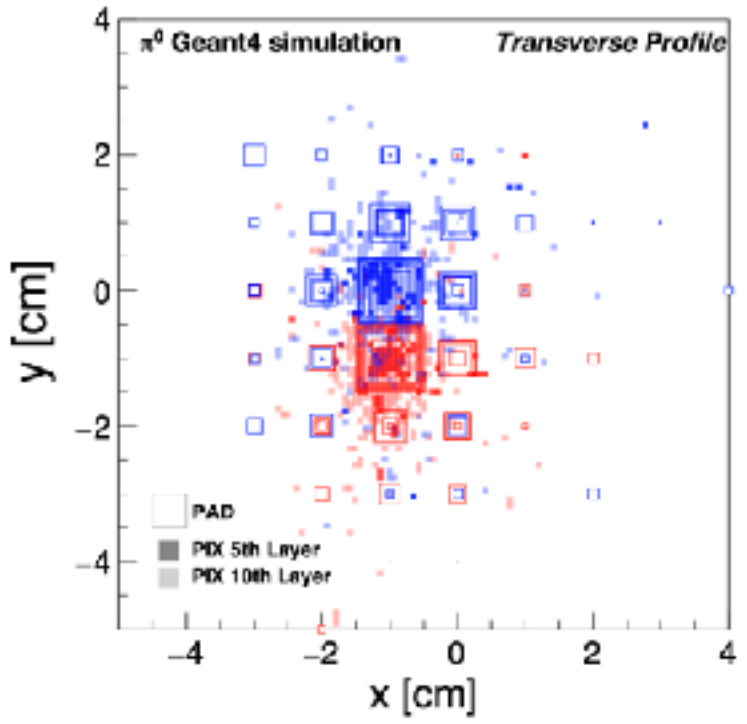
3） **High radiation tolerance**（10^{13} (1MeV neutrons) / cm^2）

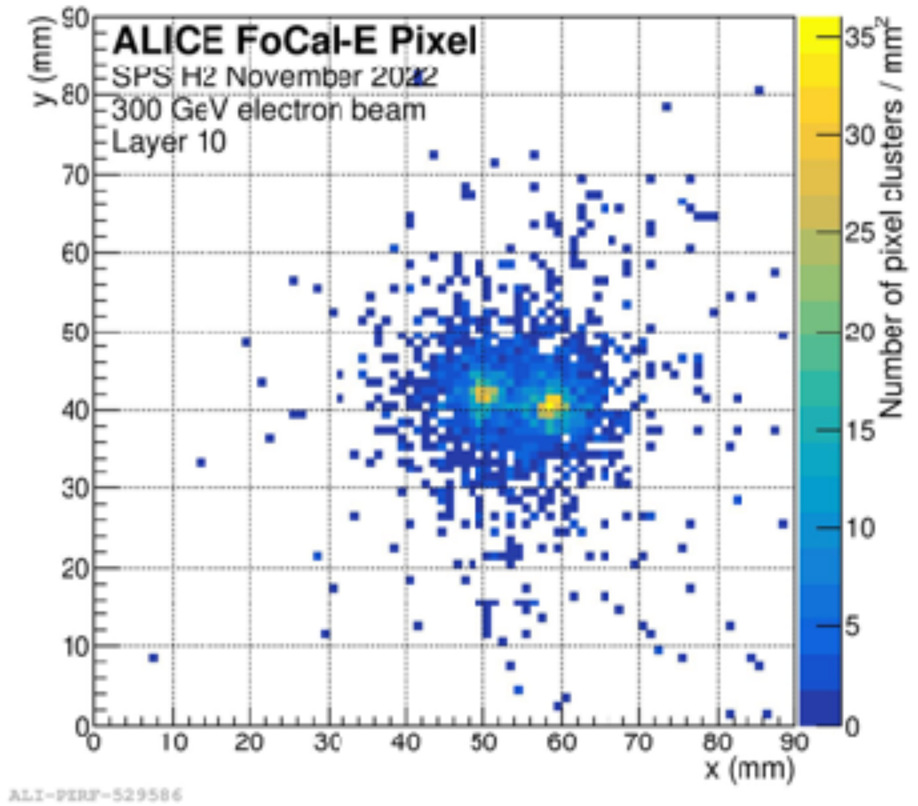
→FoCal-E pad: mainly developed by FoCal-Japan group

Longitudinal profile (2γ showers)



Trans. profile

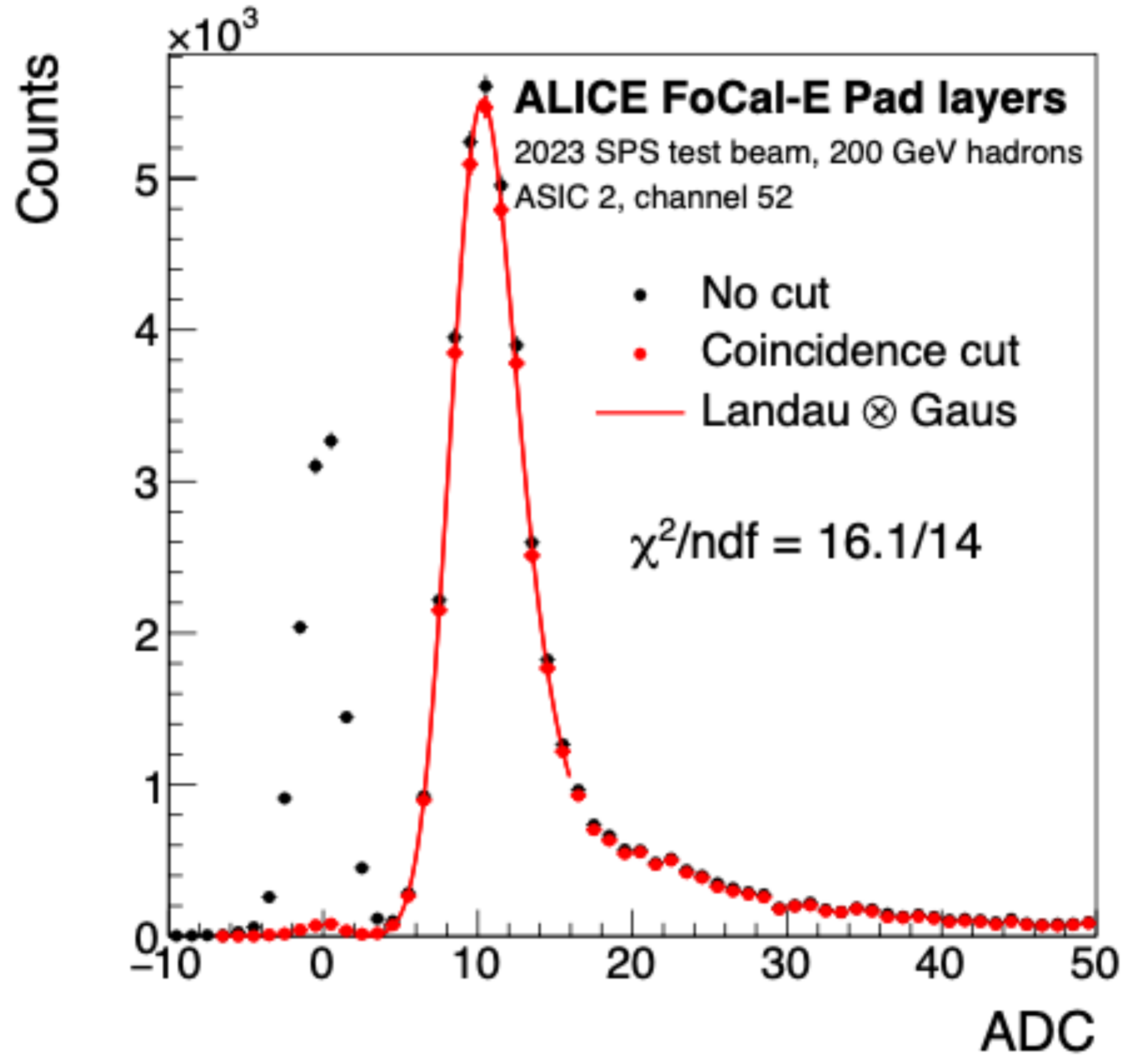


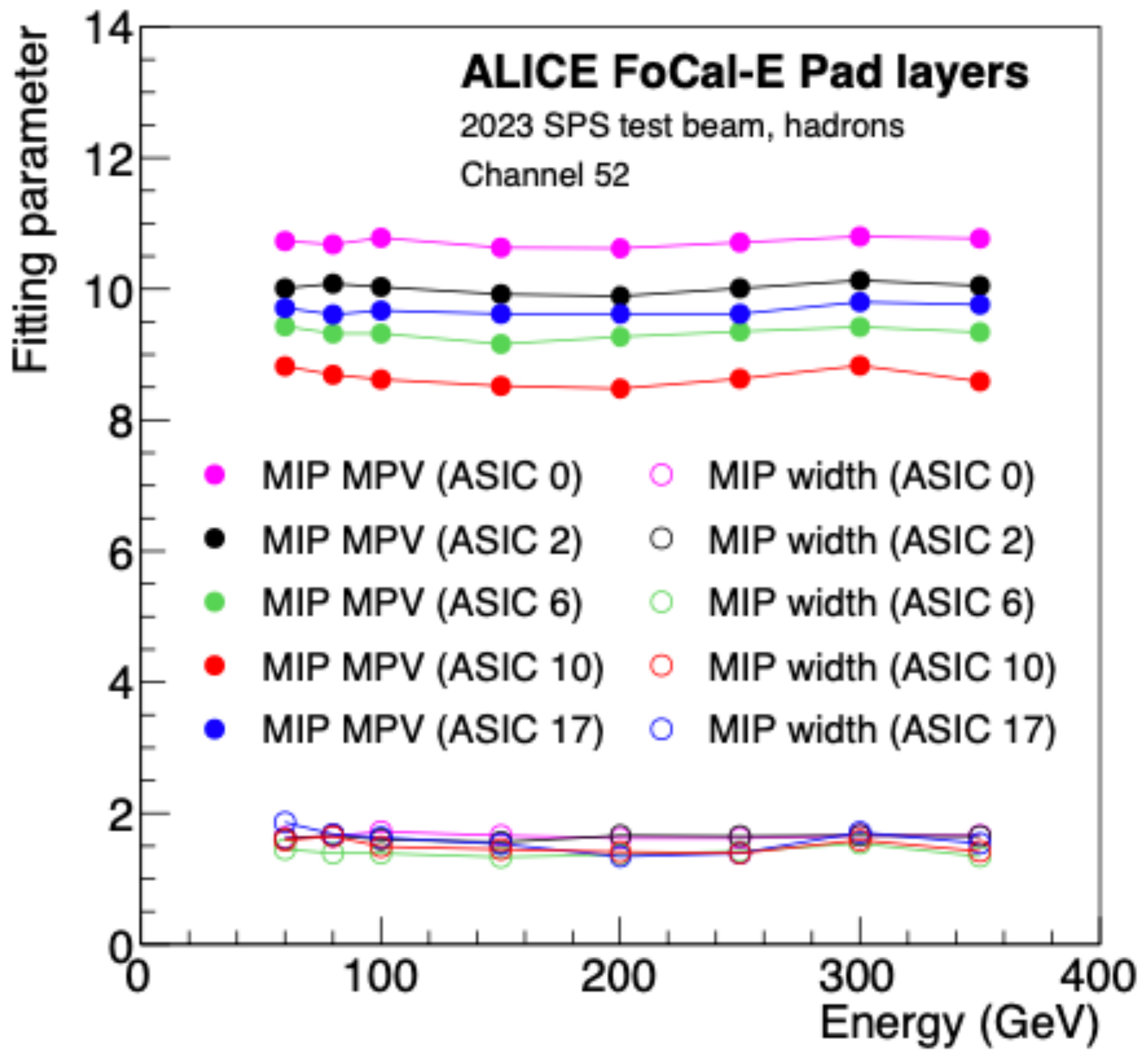


arXiv:2311.07413

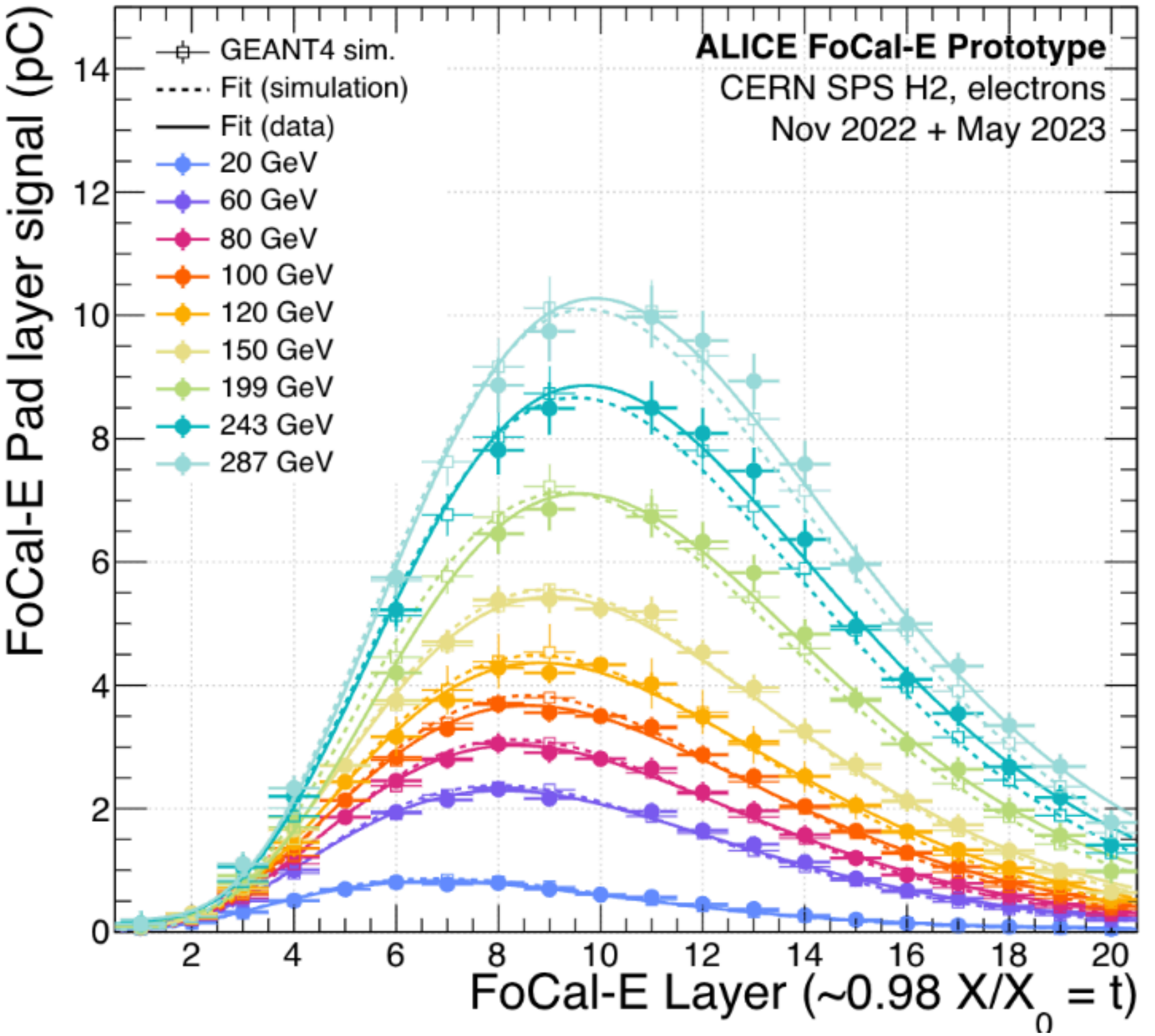
FoCal-E pad performance

MIP responce





Longitudinal shower profiles



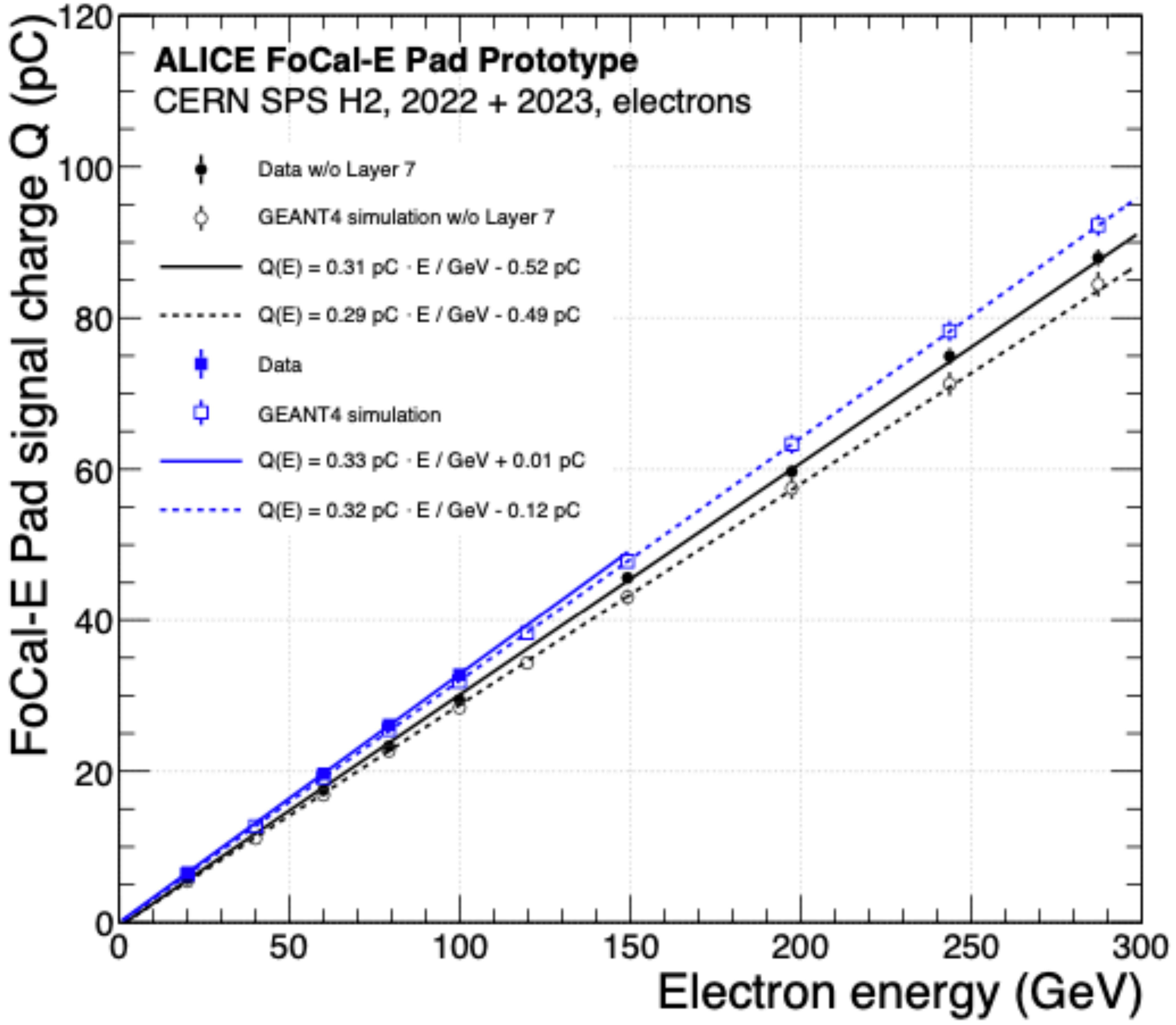
Excellent performance of prototype

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

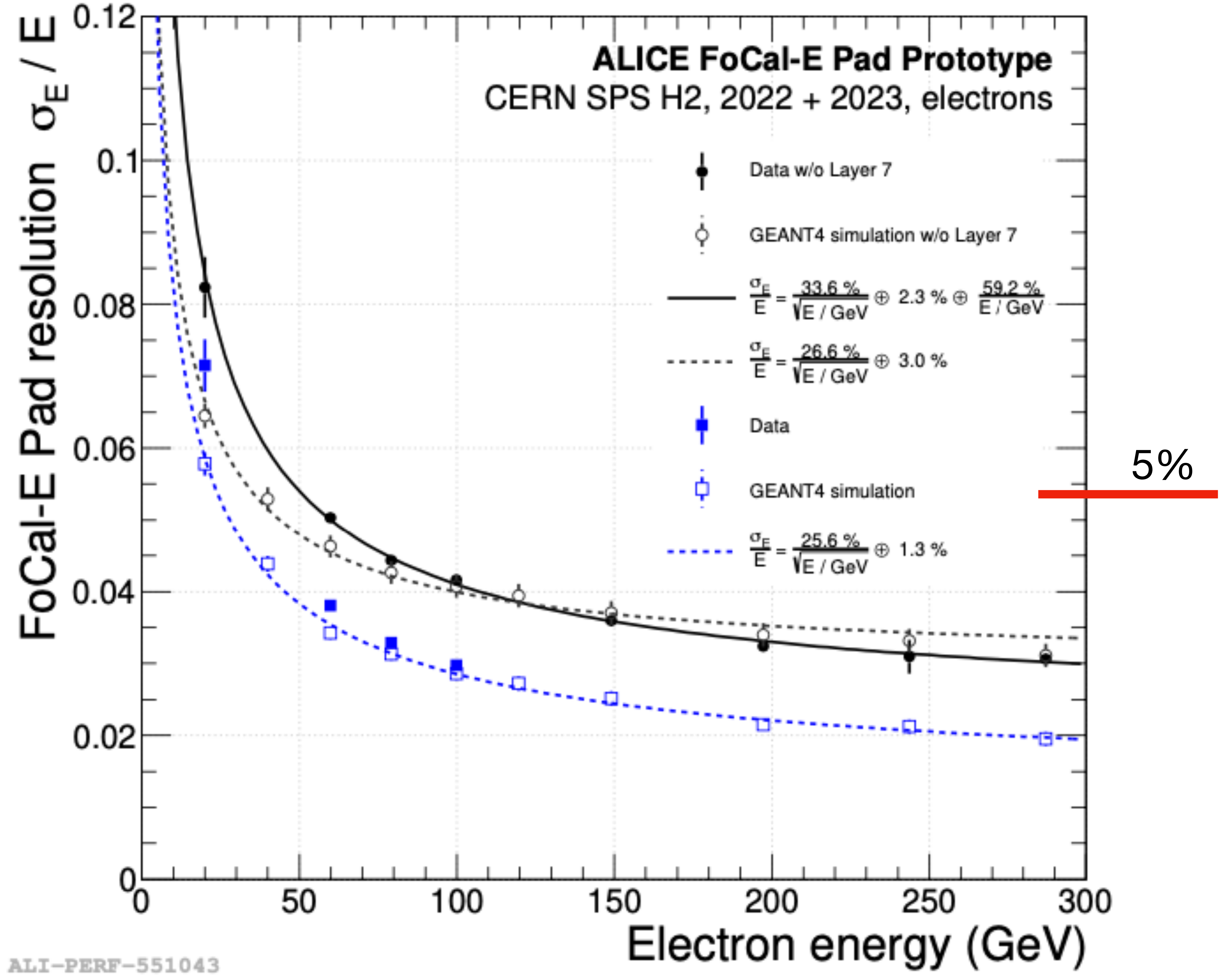
FoCal-E pad performance

arXiv:2311.07413

Linearity

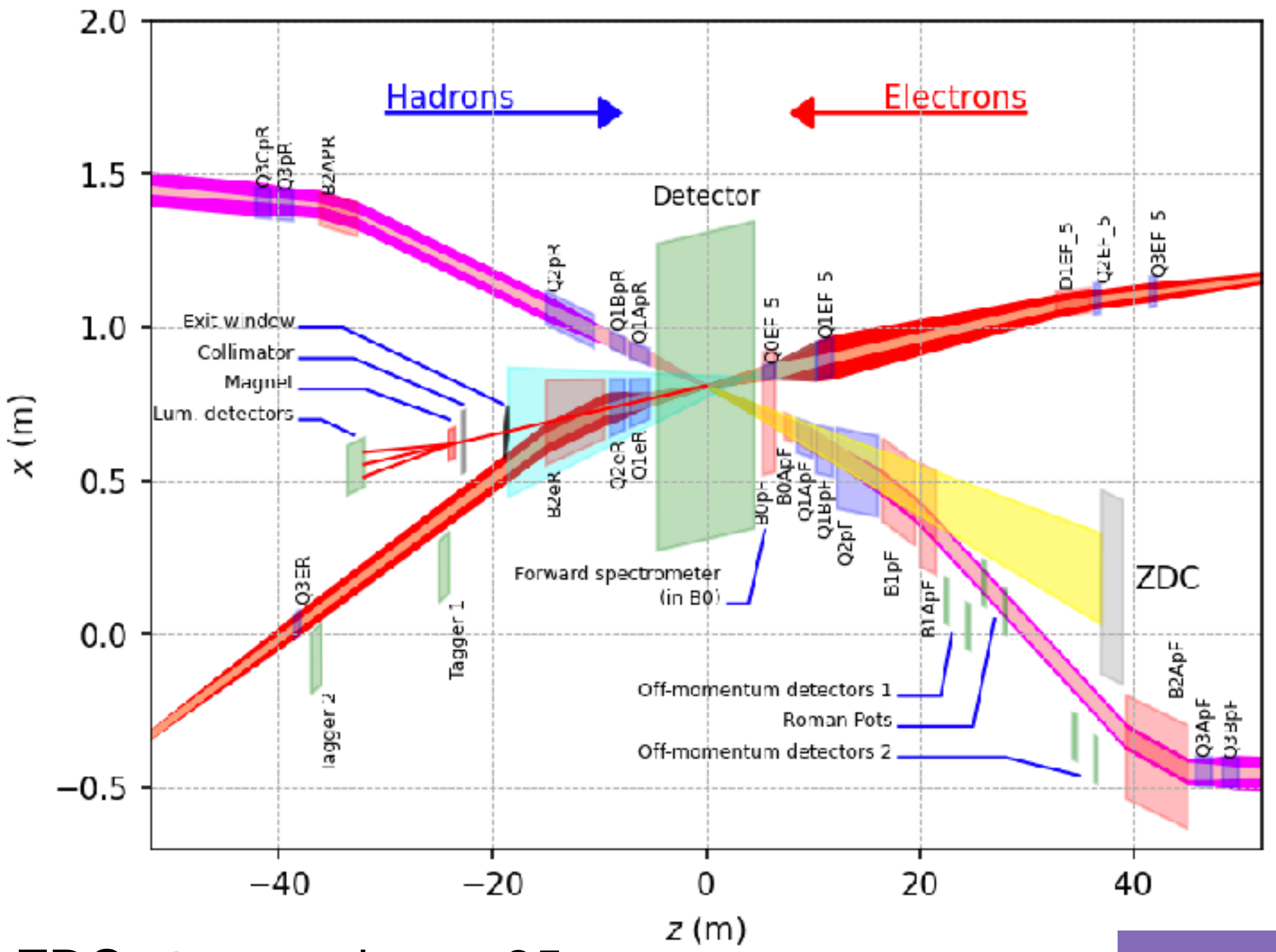


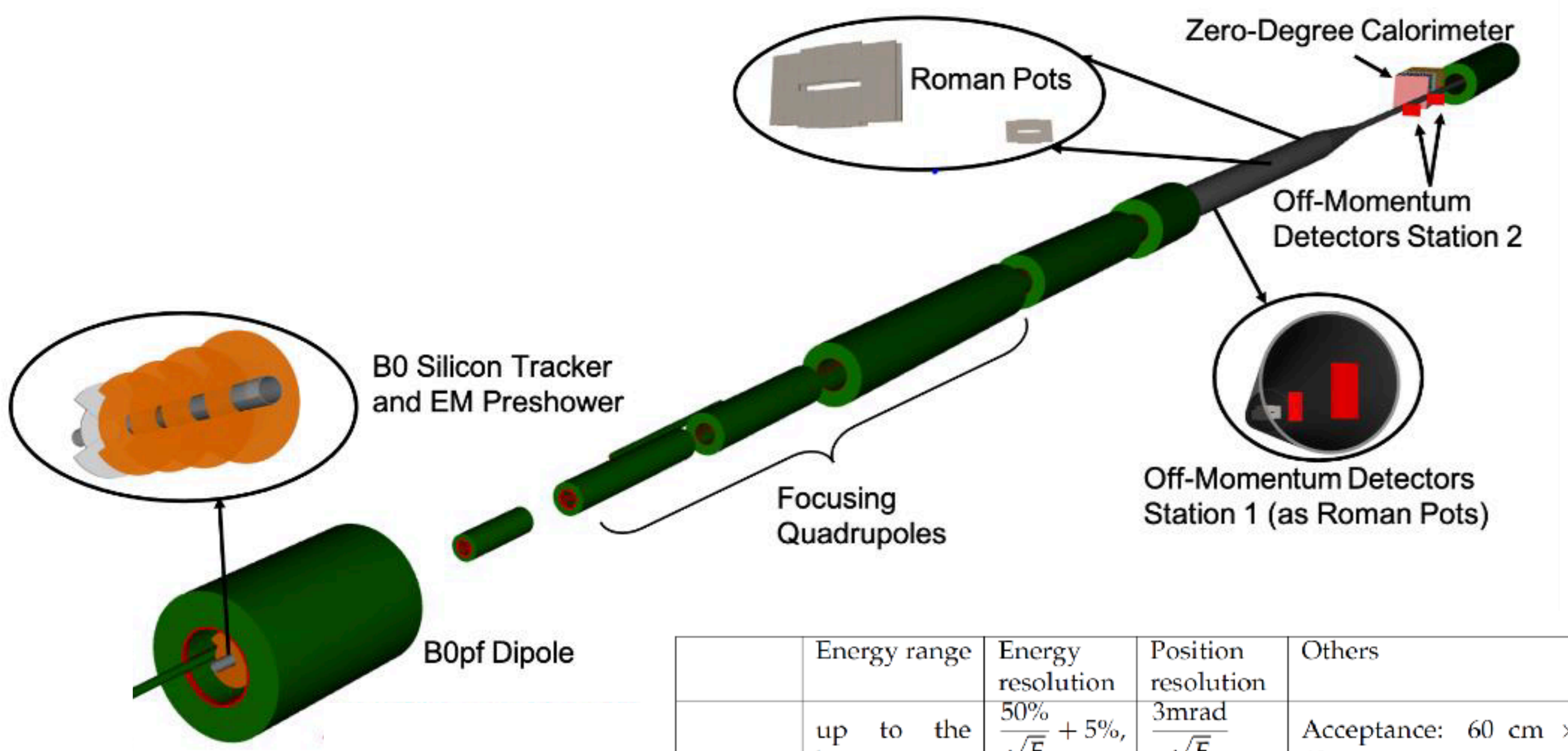
Energy resolution



Results show expected behavior

EIC-ZDC design





ZDC at around z = +35 m

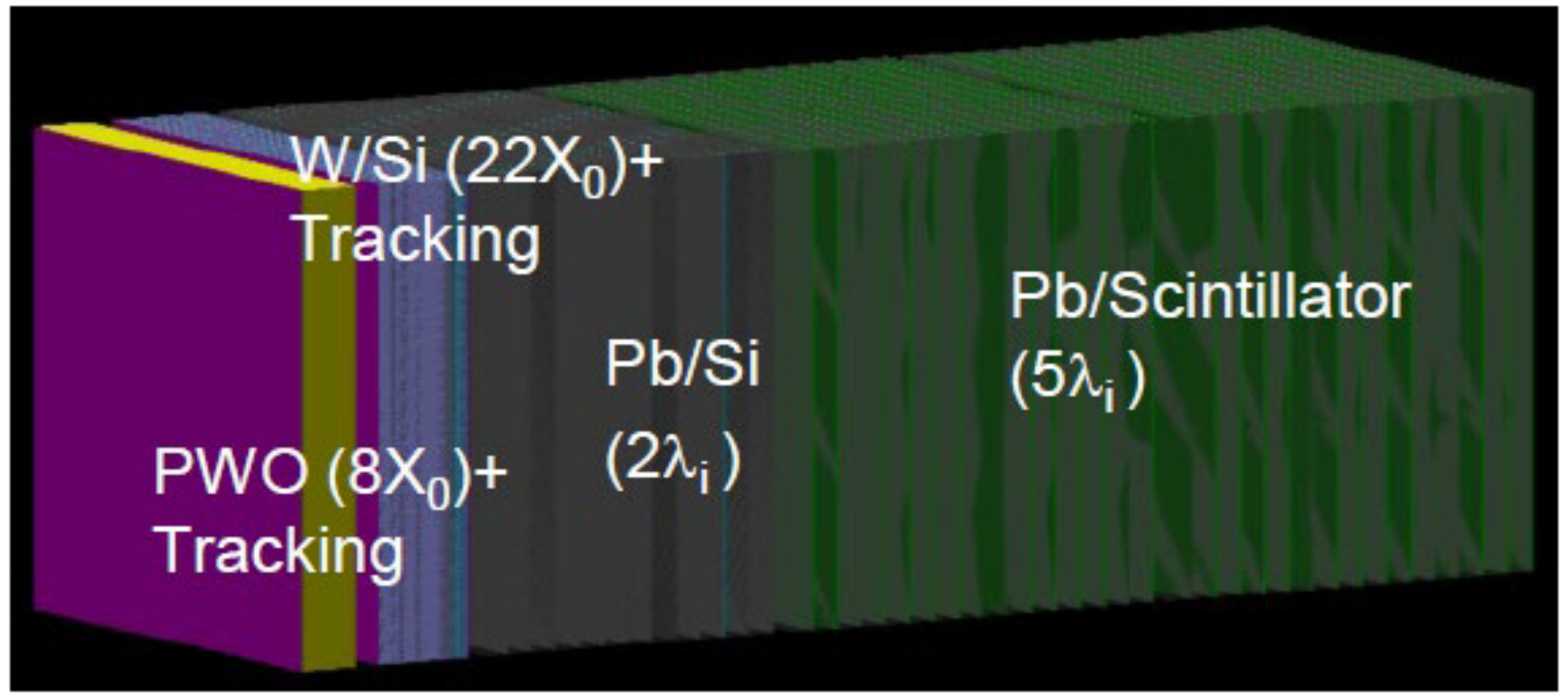
Aperture: ~ 4 mrad

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.

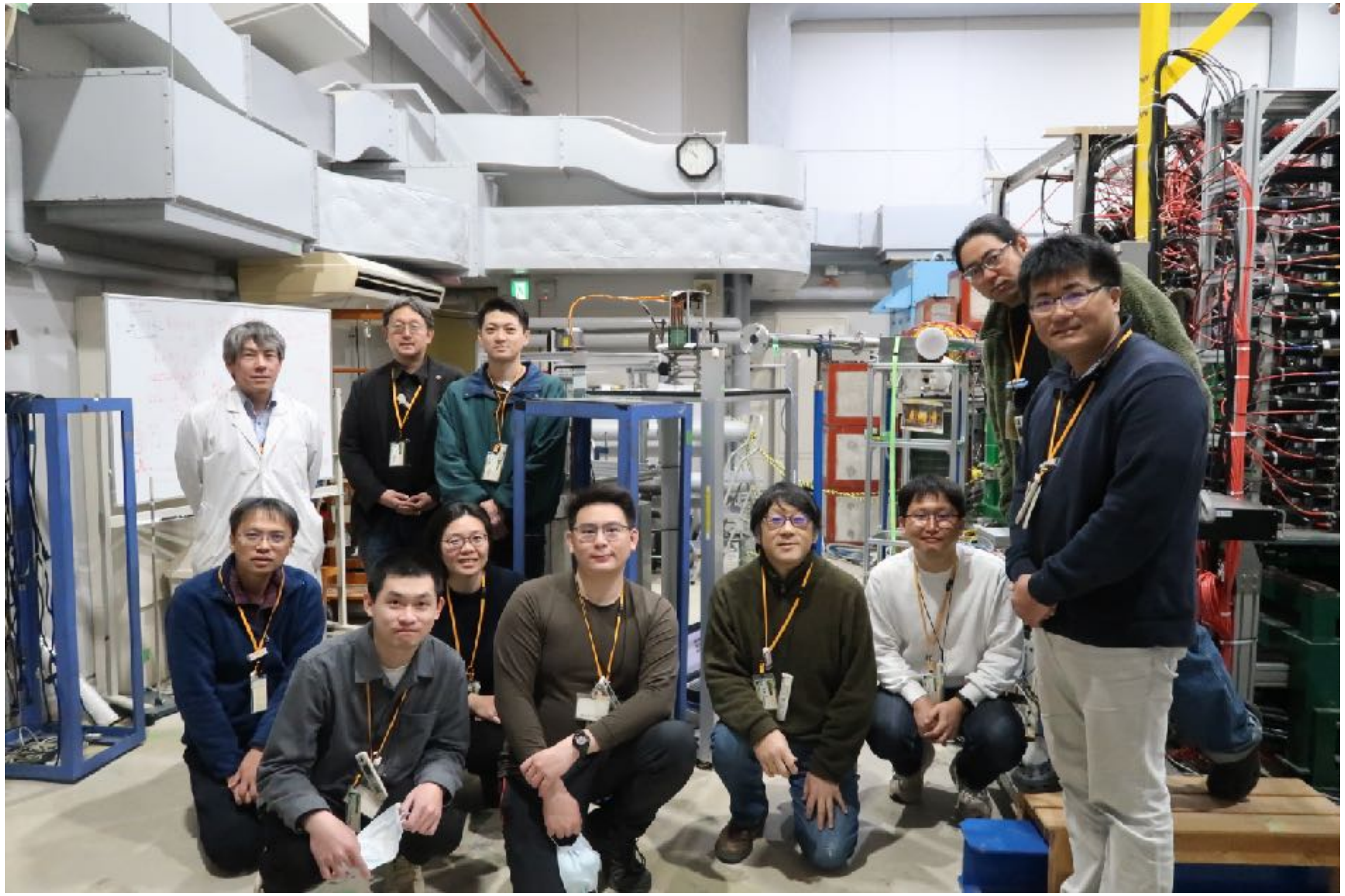
FoCal technology

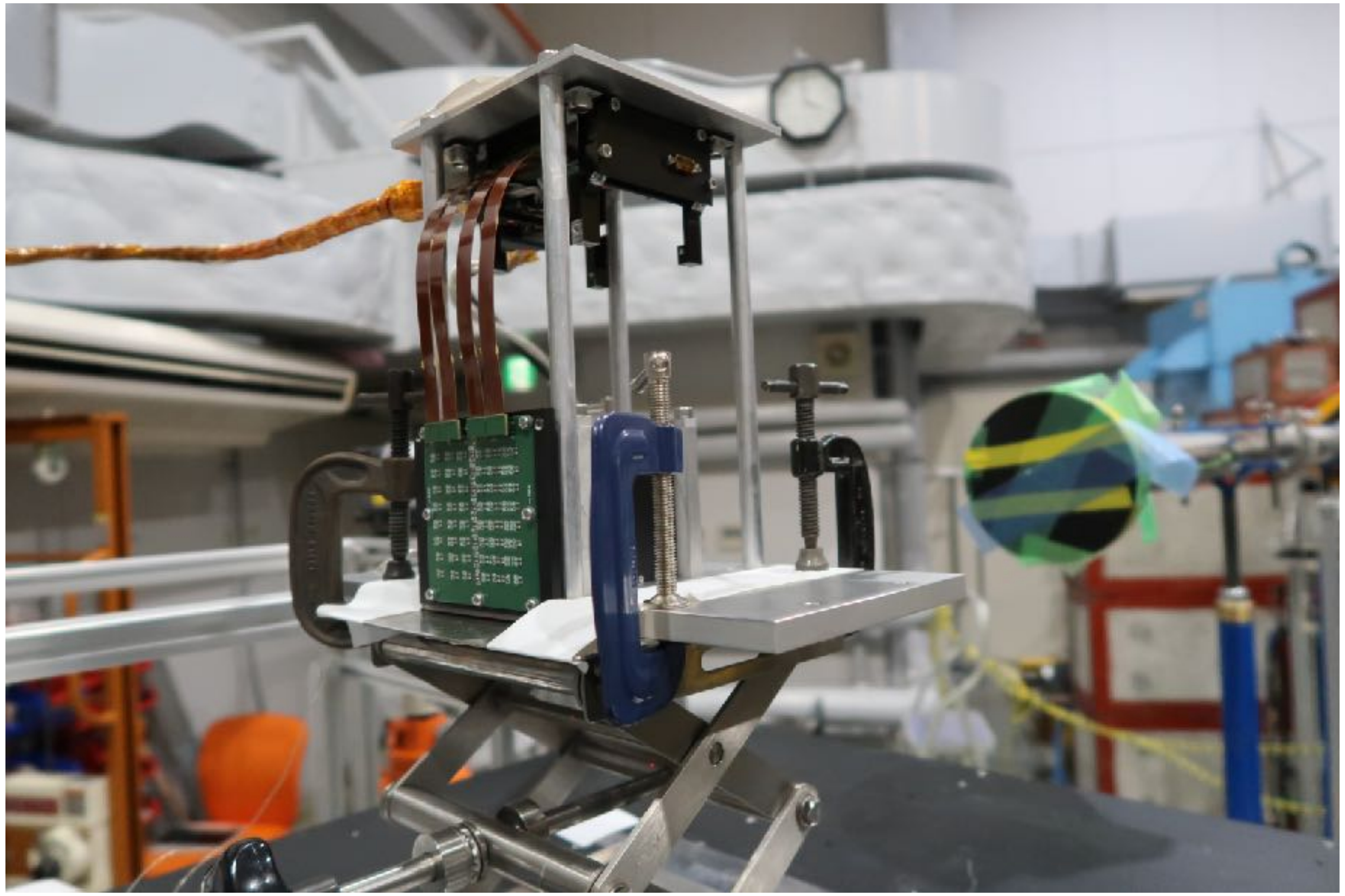


	Energy range	Energy resolution	Position resolution	Others
Neutron	up to the beam energy	$\frac{50\%}{\sqrt{E}}+5\%$, ideally $\frac{35\%}{\sqrt{E}}+2\%$	$\frac{3\text{mrad}}{\sqrt{E}}$	Acceptance: 60 cm × 60 cm
		Note: The acceptance is required from meson structure measurement. Pion structure measurement 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.		

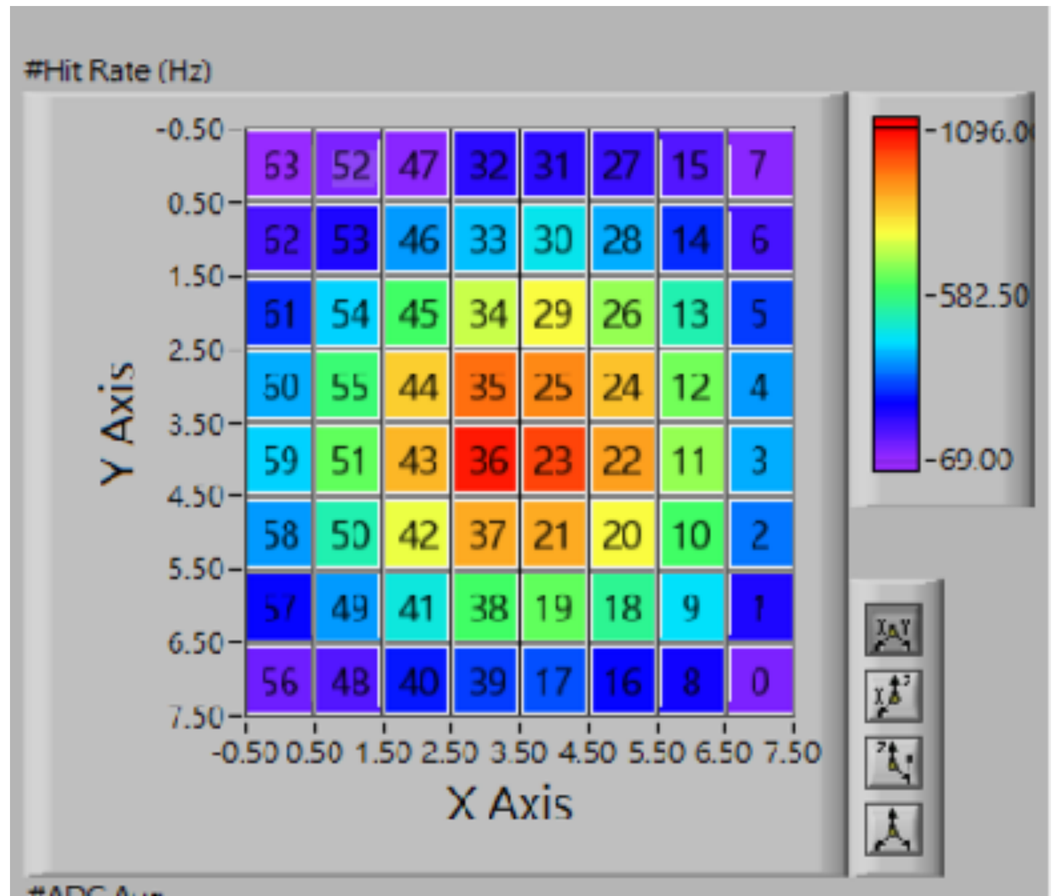
Table 2: Physics requirement for ZDC

ePIC ZDC prototype test @ ELPH (2024.03)





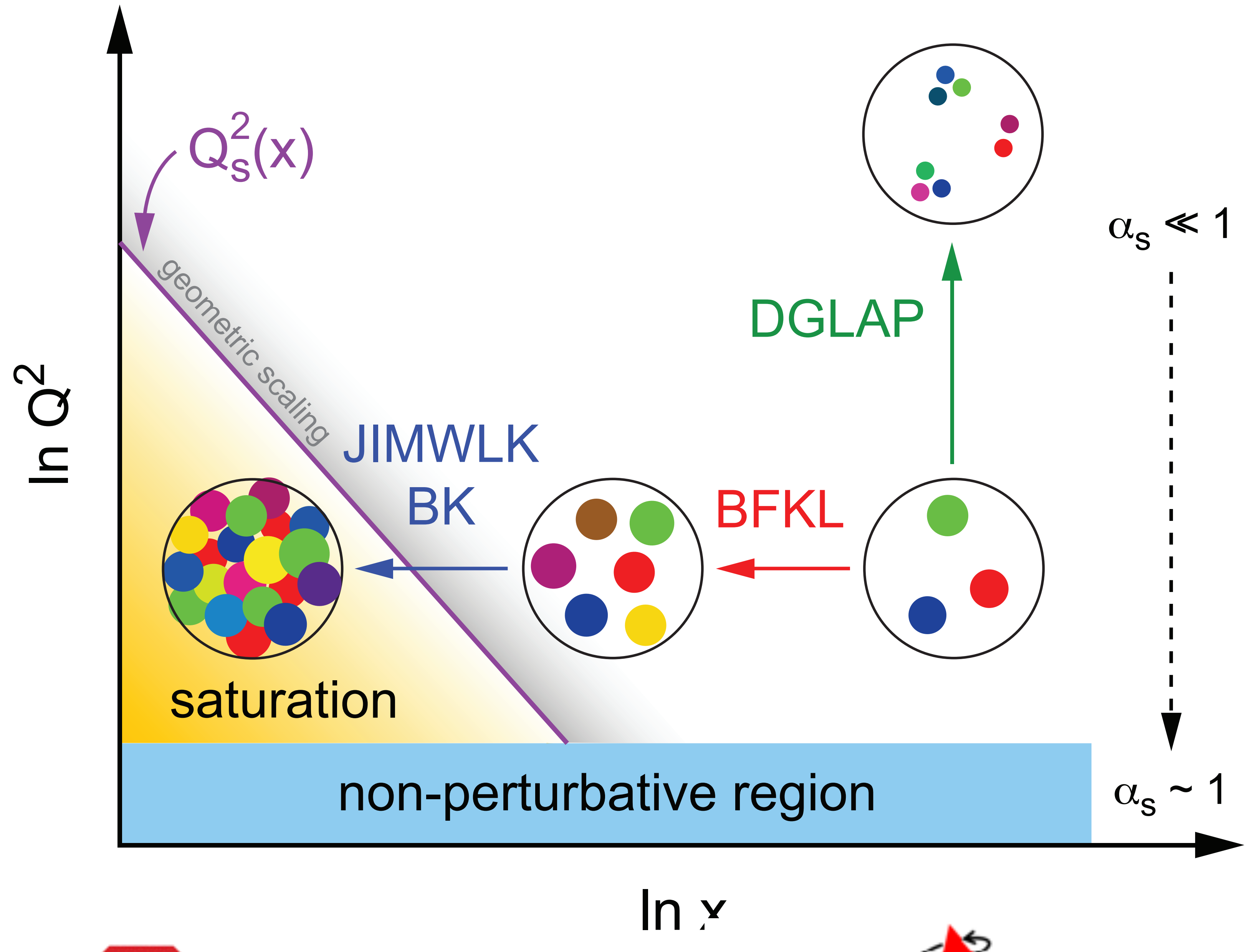
LYSO crystal with SiPM readout



Hit map of LYSO crystal calorimeter from online monitoring

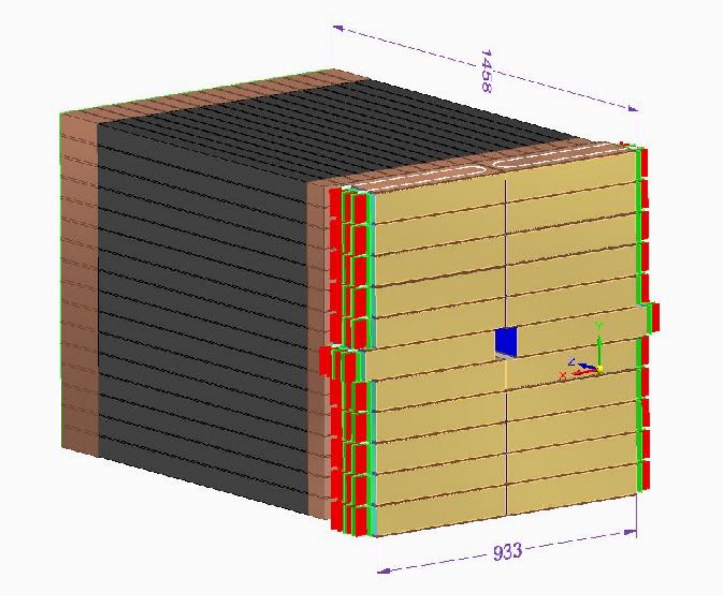
Summary

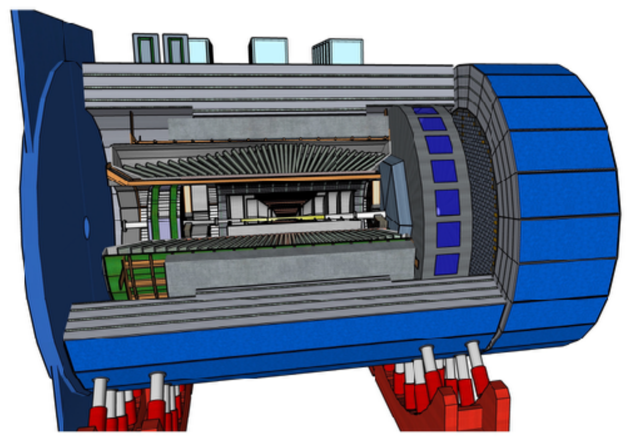
- Strong synergies between EIC and LHC forward
- To understand QCD and find a clear signal of CGC, exploring a wide kinematic coverage in x-Q^2 is crucial
- Universality test of QCD (color dipole formalism) at both EIC and forward LHC
- FoCal: Common detector technologies at forward LHC and EIC (ZDC)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



ALICE

ePIC





Forward pA
at high energies

DIS (EIC) eA