Forward Physics with ALICE FoCal detector

Takahiro Fusayasu
Saga University

1. Introduction to ALICE experiment
2. QGP discovery and measurements
3. CGC: how the QGP generated?
4. FoCal development

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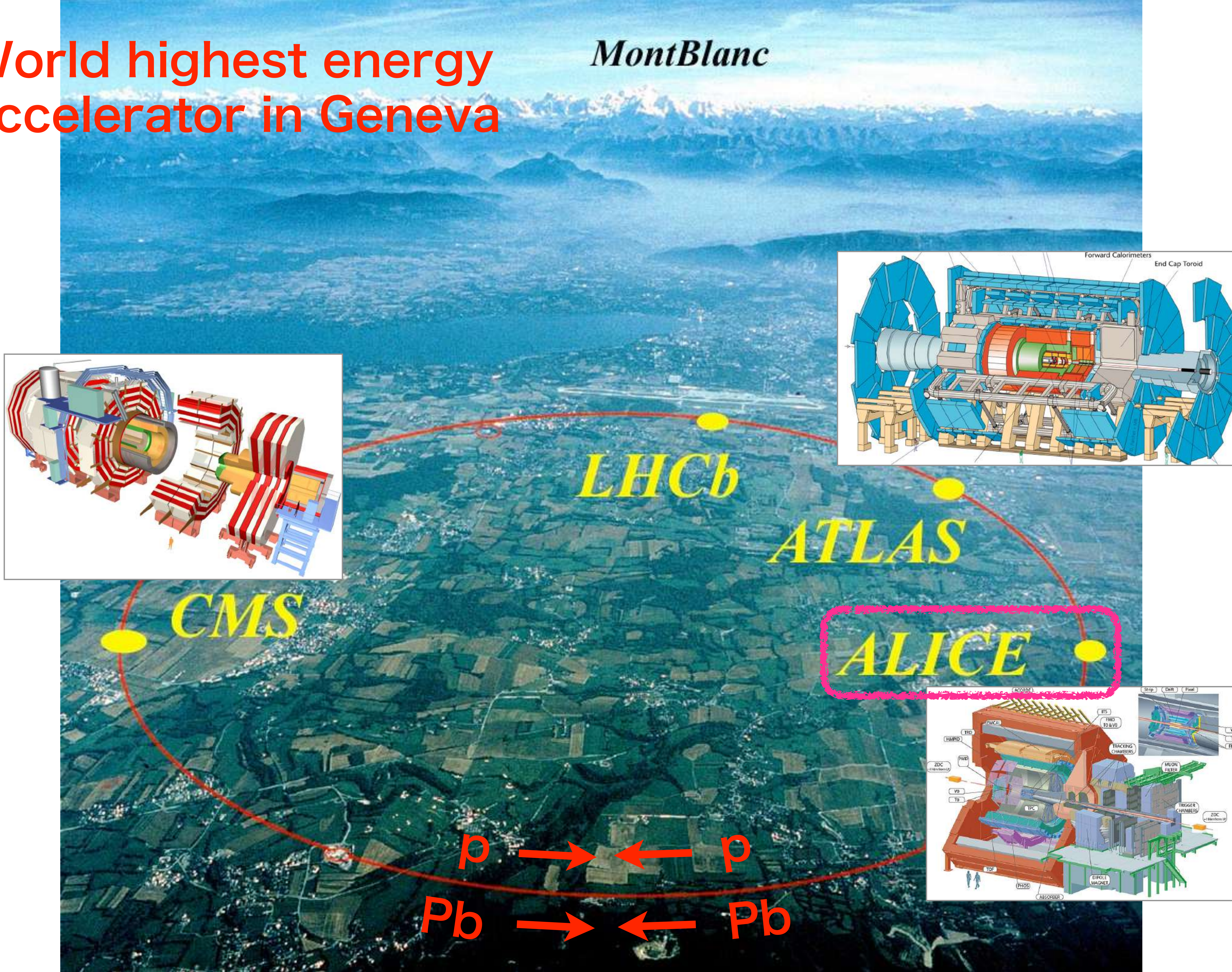
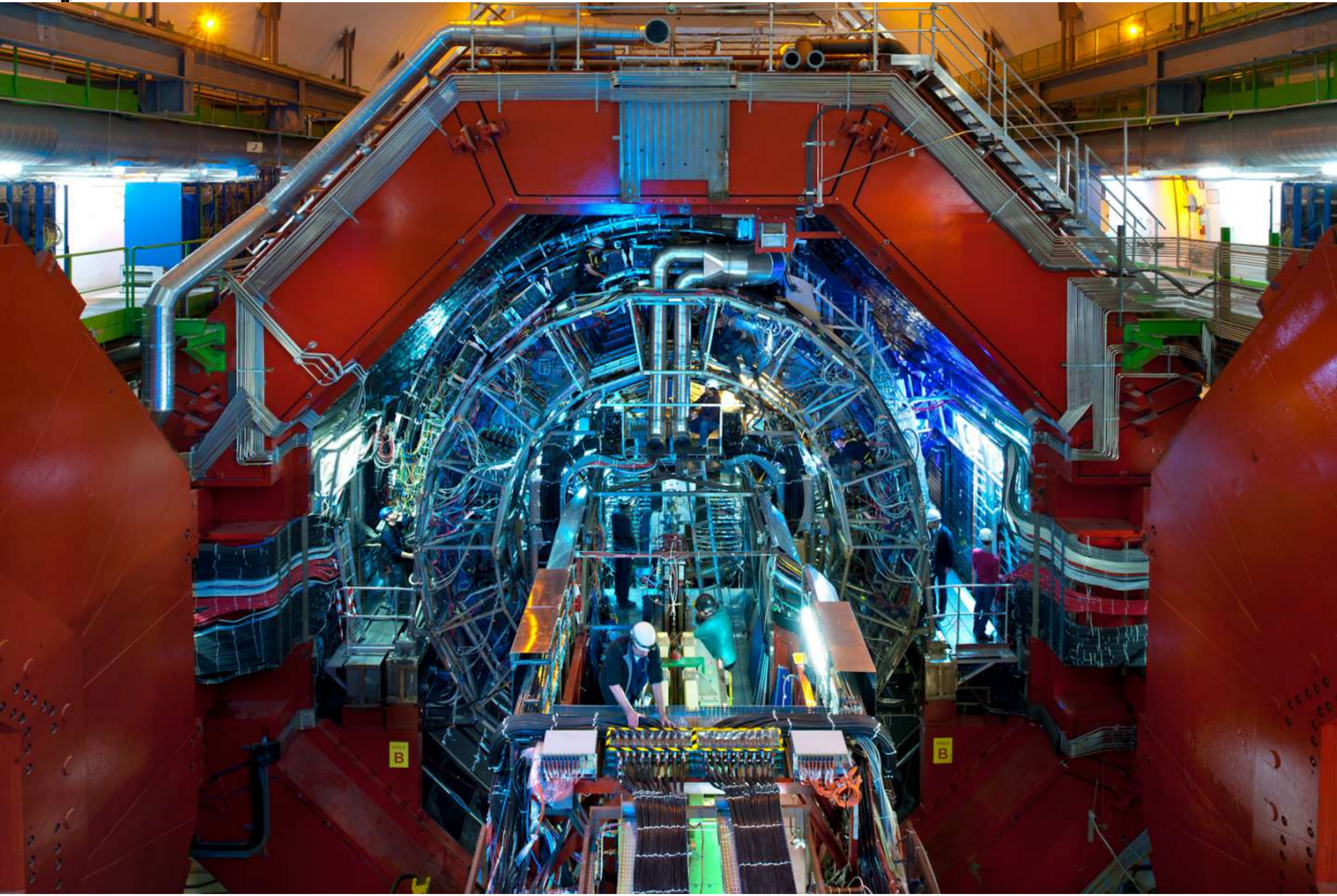
World highest energy accelerator in Geneva

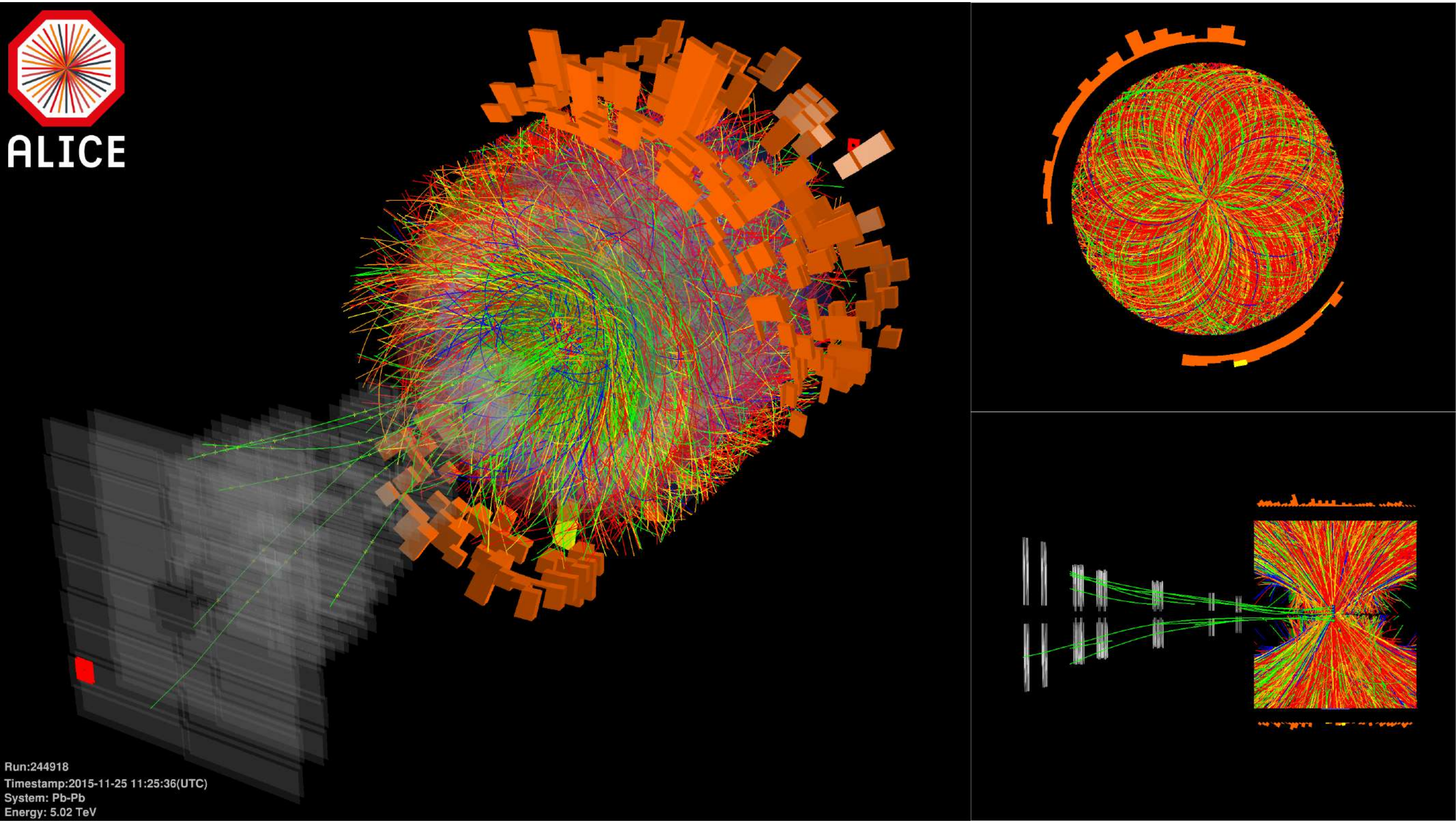


LHC accelerator underground

ALICE detector photo



Pb-Pb collision data by ALICE



- ALICE detector is designed for heavy ion studies with Pb-Pb, p-Pb, pp collisions.
- Multiplicity ranges up to ~3000 for $|\eta|<0.8$

Pb-Pb collision data by ALICE

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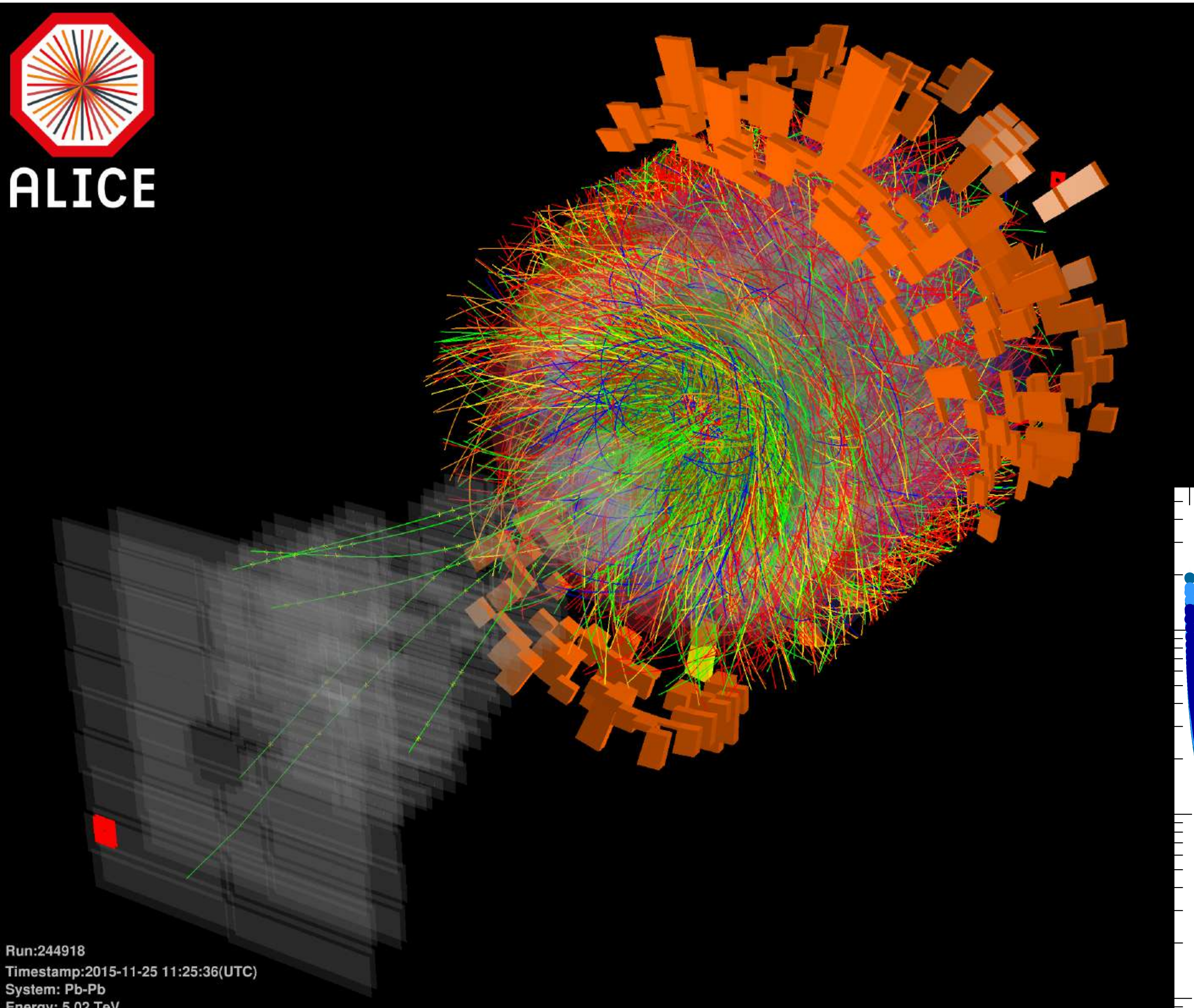

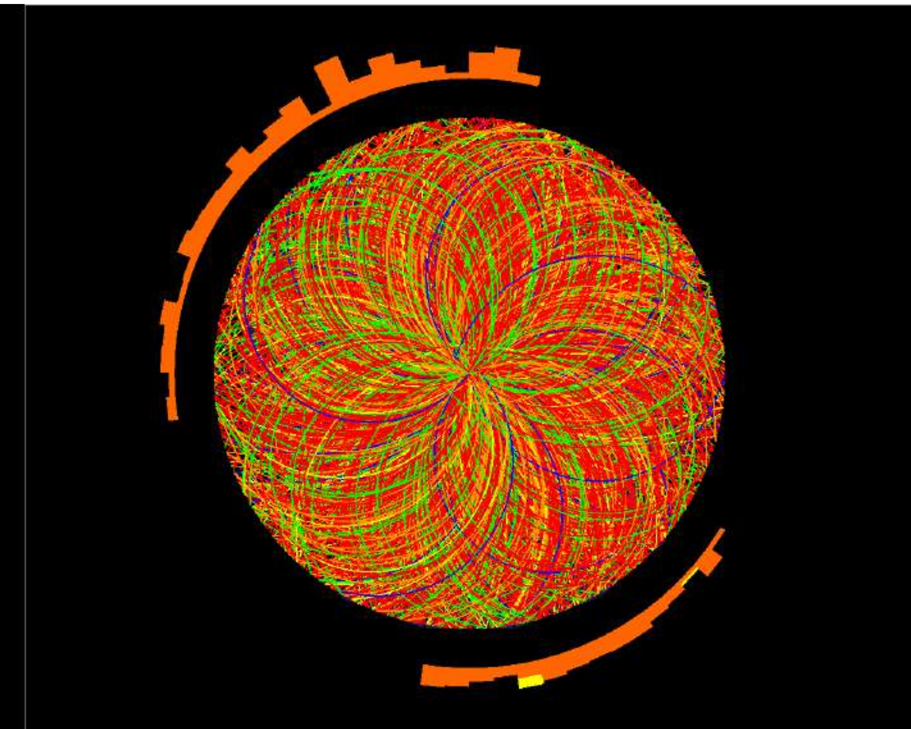

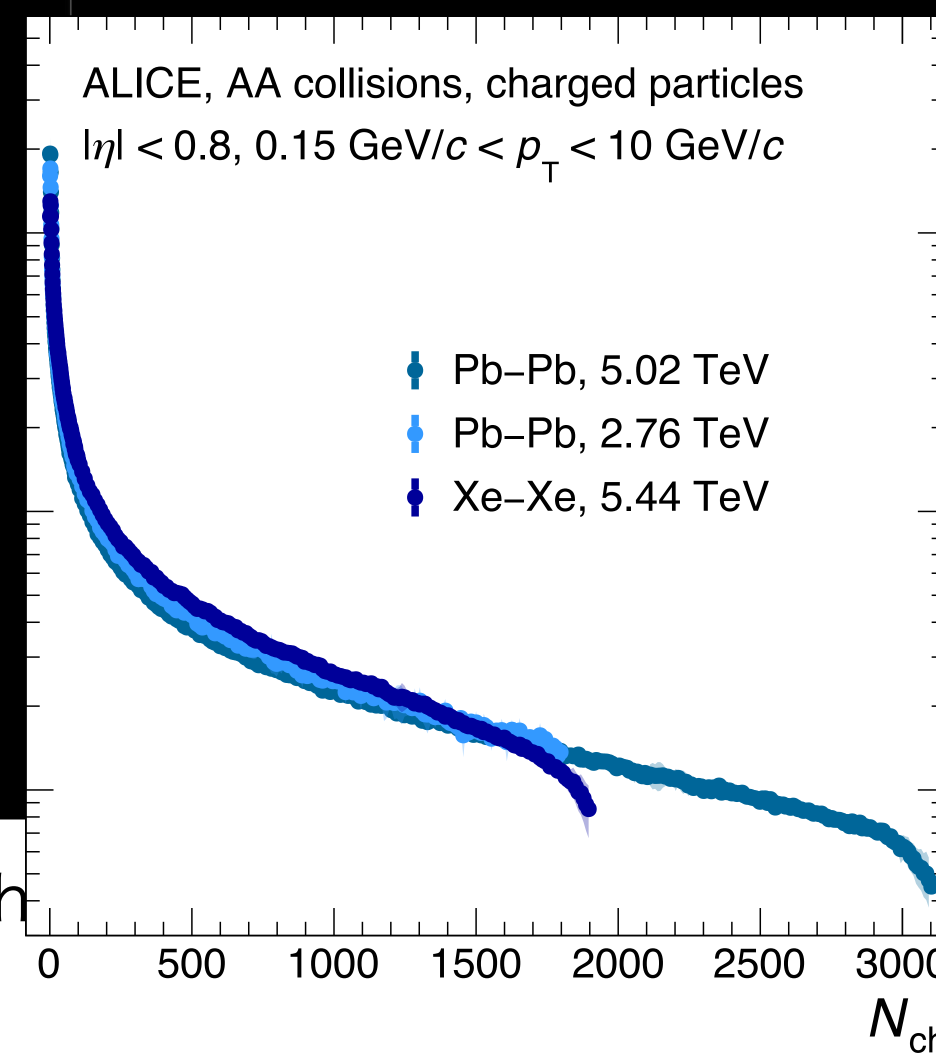

- ALICE detector is designed for heavy ion studies with
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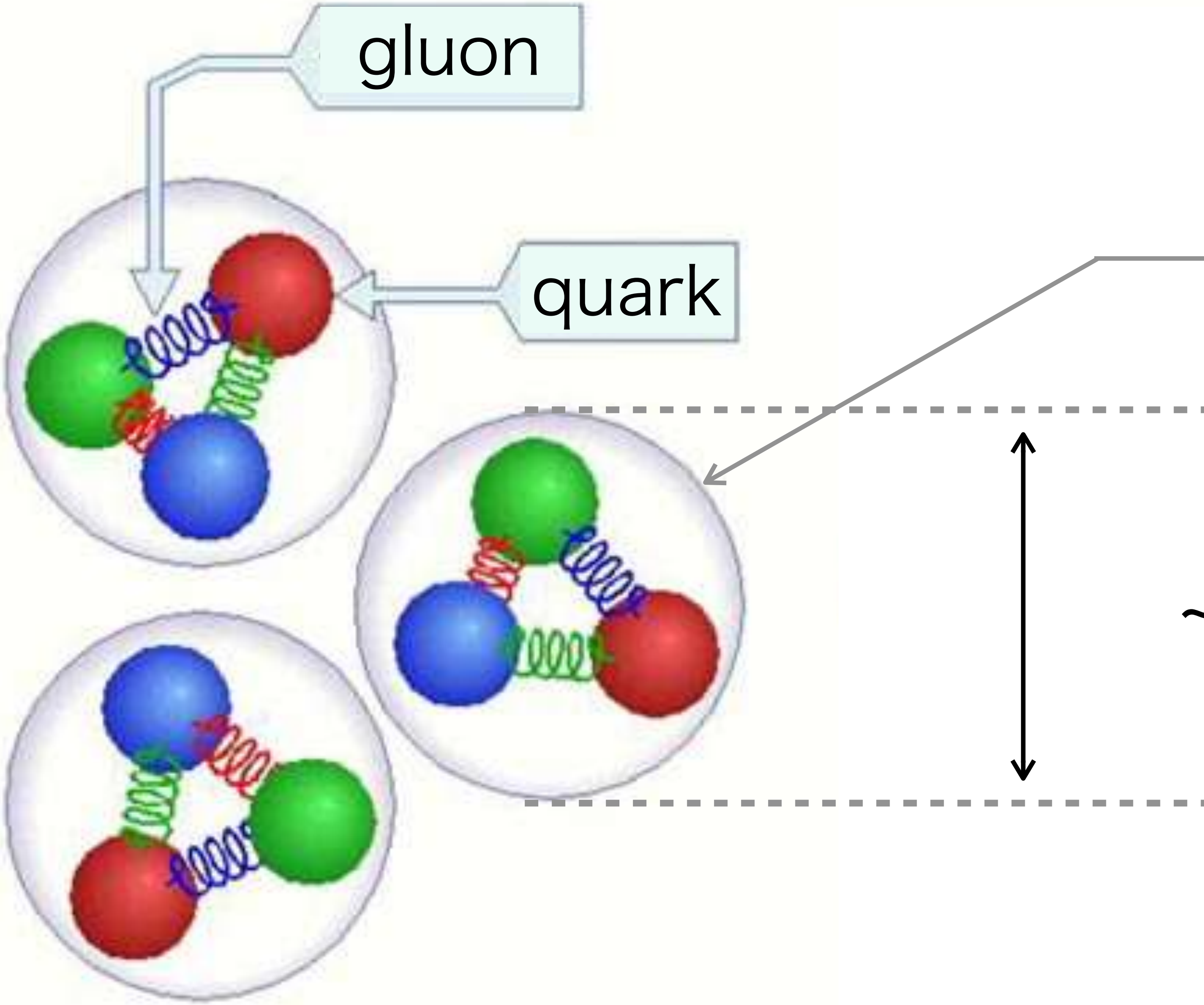
Quark-Gluon Plasma



Mass ~ 1 GeV

~1fm (1×10^{-15} m)

Proton, neutron, other hadrons

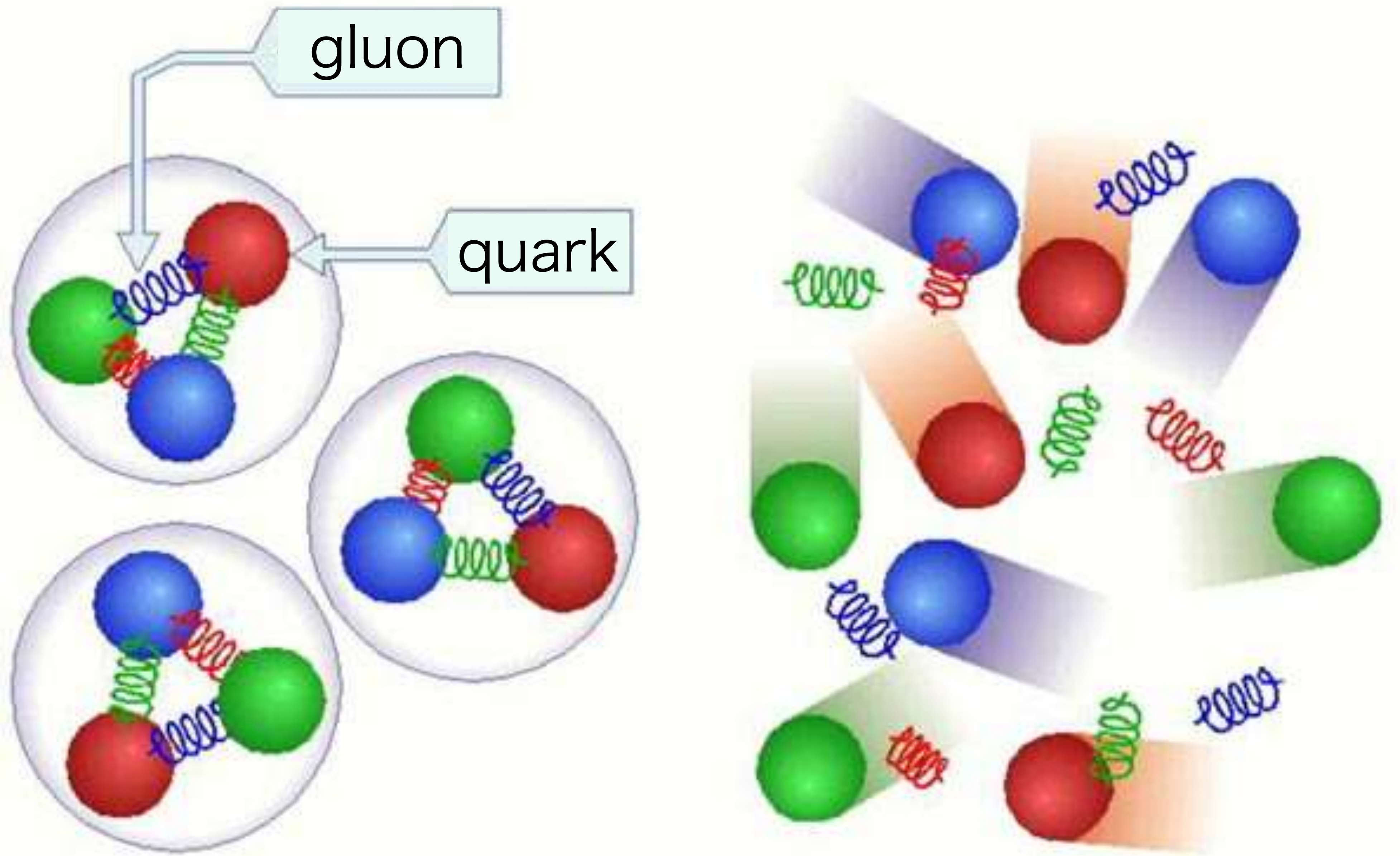
Quarks are bound by gluons,
which mediate strong interactions

Inside hadrons

$$V \propto \frac{A}{r} + Br$$

Huge force if large r.
Cannot extract a quark.

Quark-Gluon Plasma



Protons, neutrons → **Quark-Gluon Plasma (QGP)**

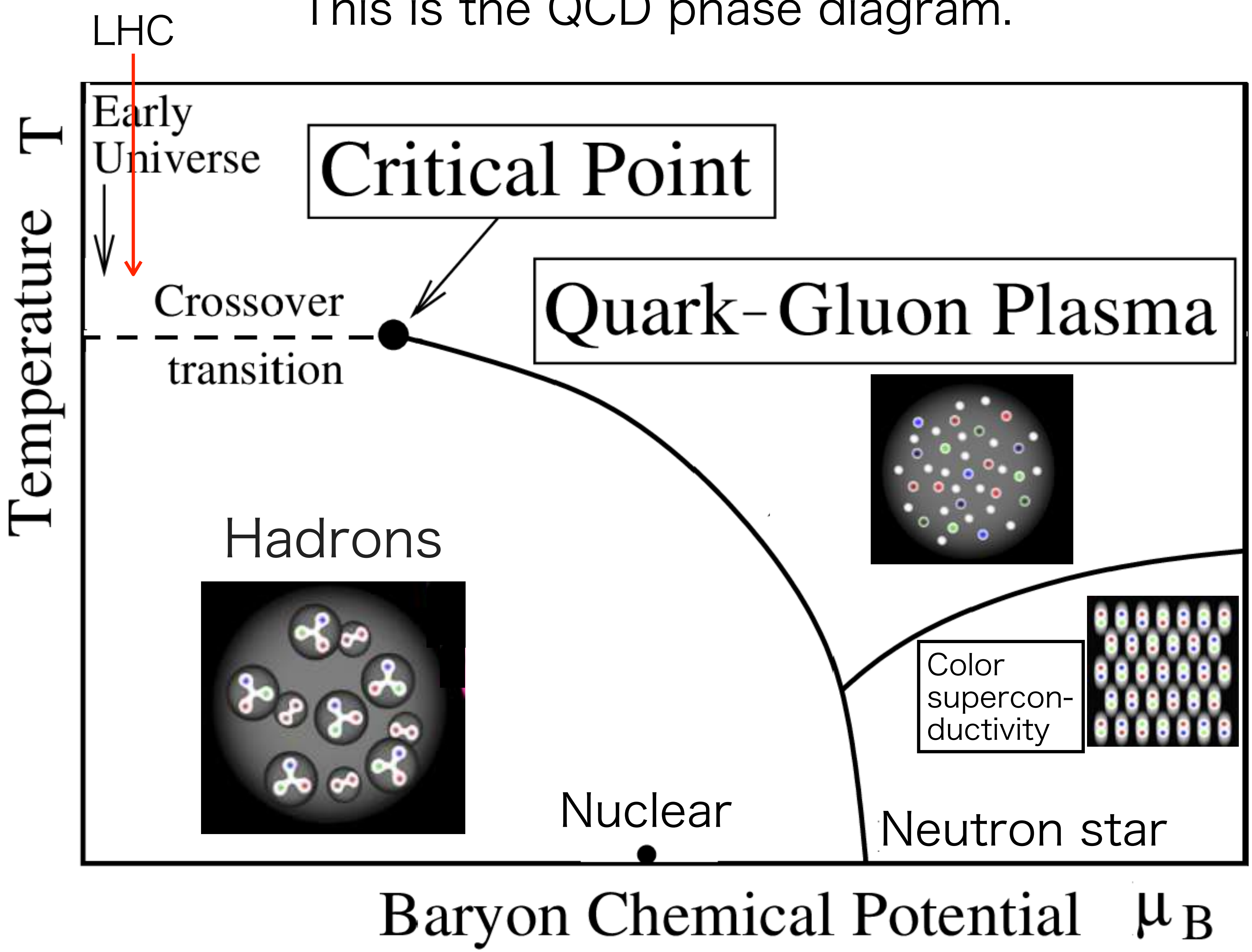
High T, high P

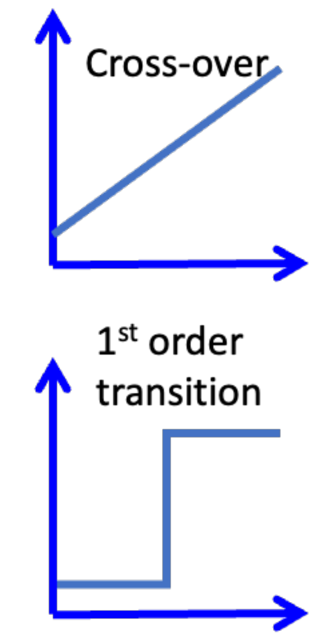
No boundary between p, n.
Quarks and gluons are free.

Phases of Quark matter (QCD)

Compared to water phase diagram (QED).

This is the QCD phase diagram.





History of the Universe

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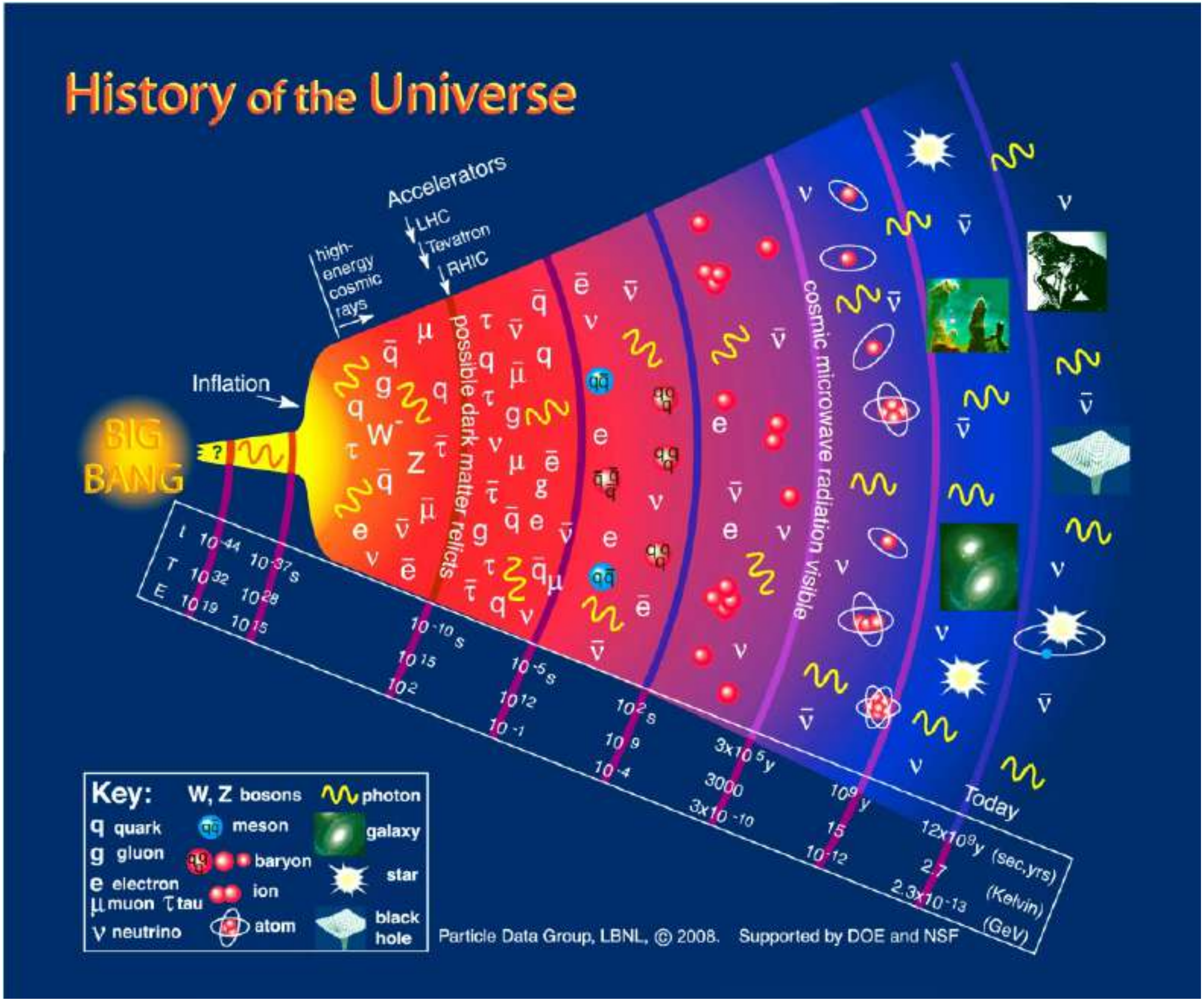
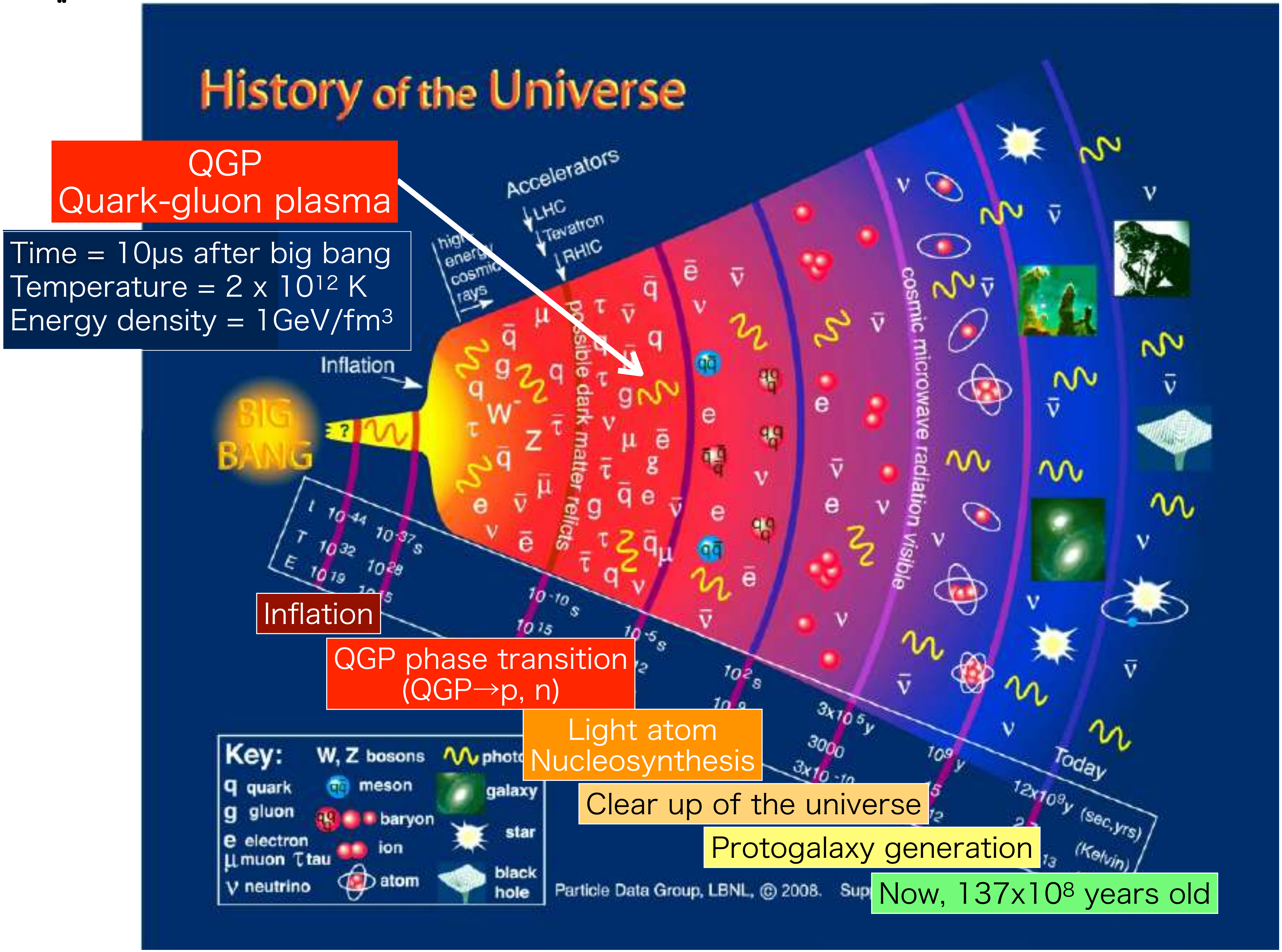


History of the Universe



History of the Universe

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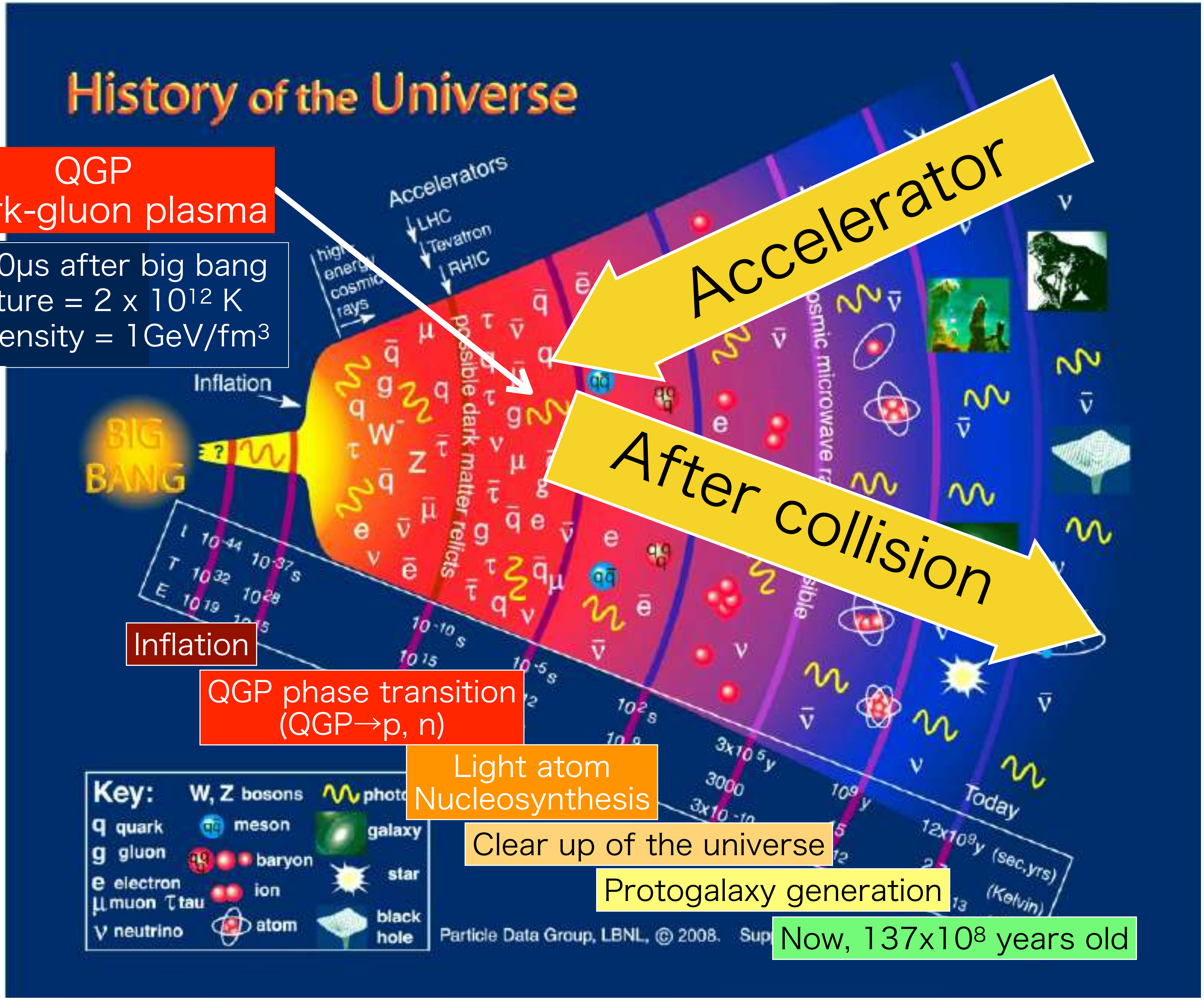
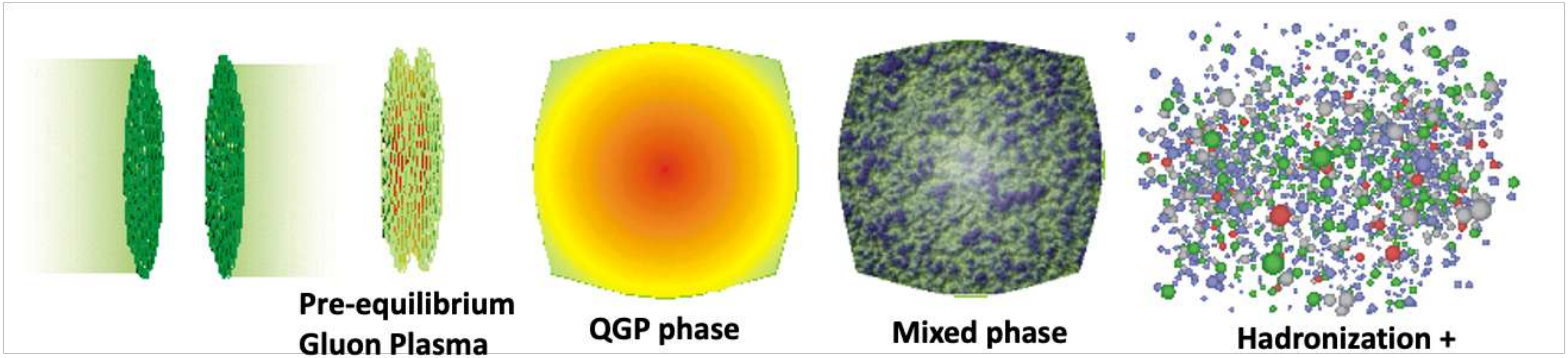


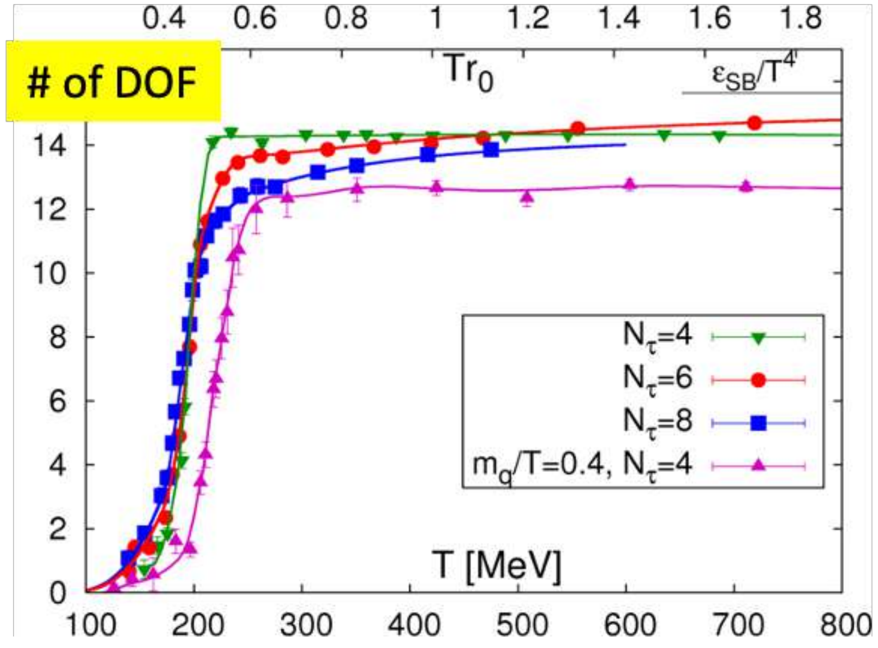
System development after collisions



- Gold ions pass through each other
  - High momentum (high-x) partons fly away
  - Low momentum (low-x) gluons remain in the mid-rapidity (y=0), and create "gluon matter"

- (Pre-equilibrium) Gluon plasma → QGP → Hadronization

- Transition temperature (quark to hadron)： T=~180MeV
- Energy density: >2GeV/fm^3
  - Estimate from Lattice QCD calculation

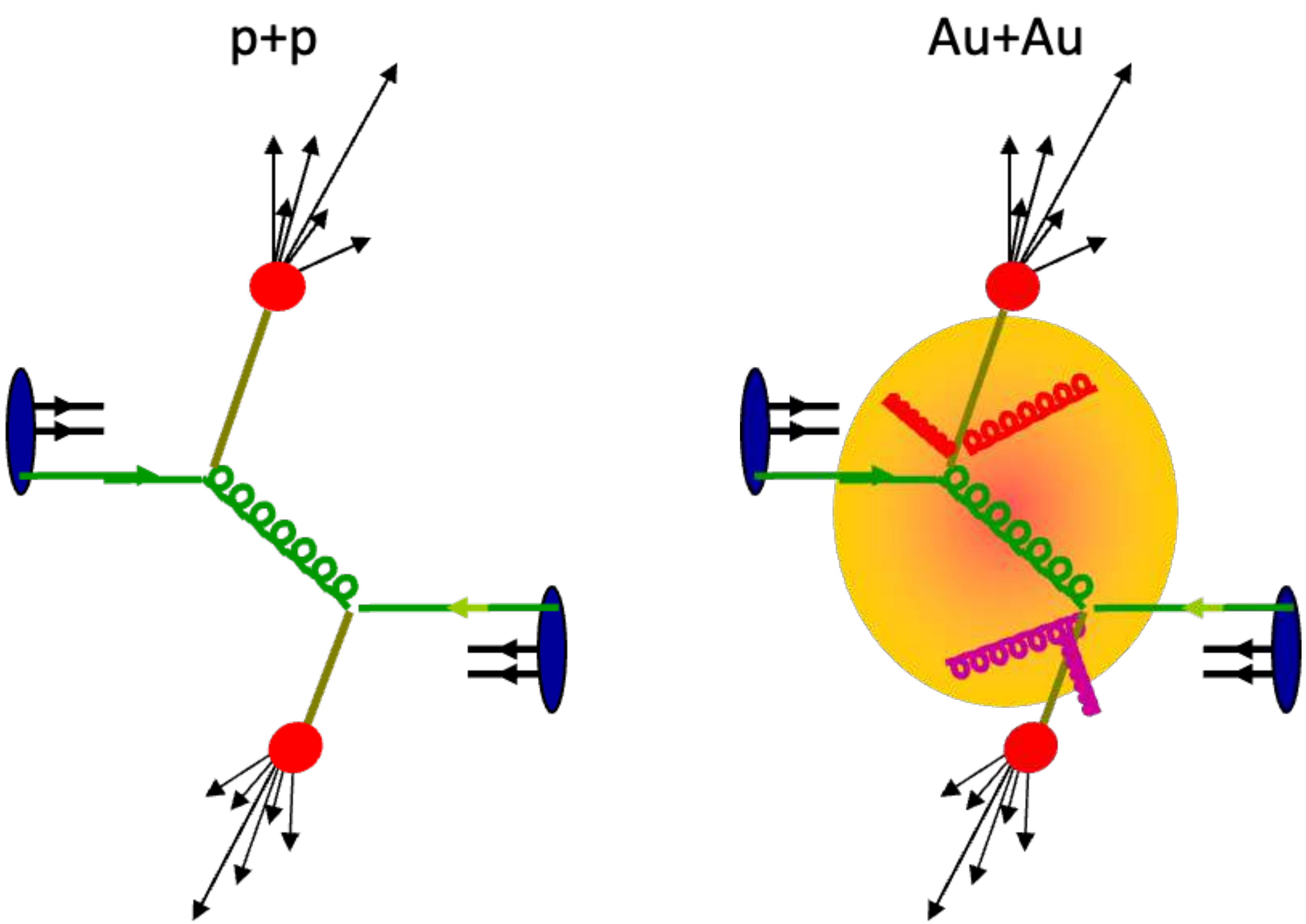


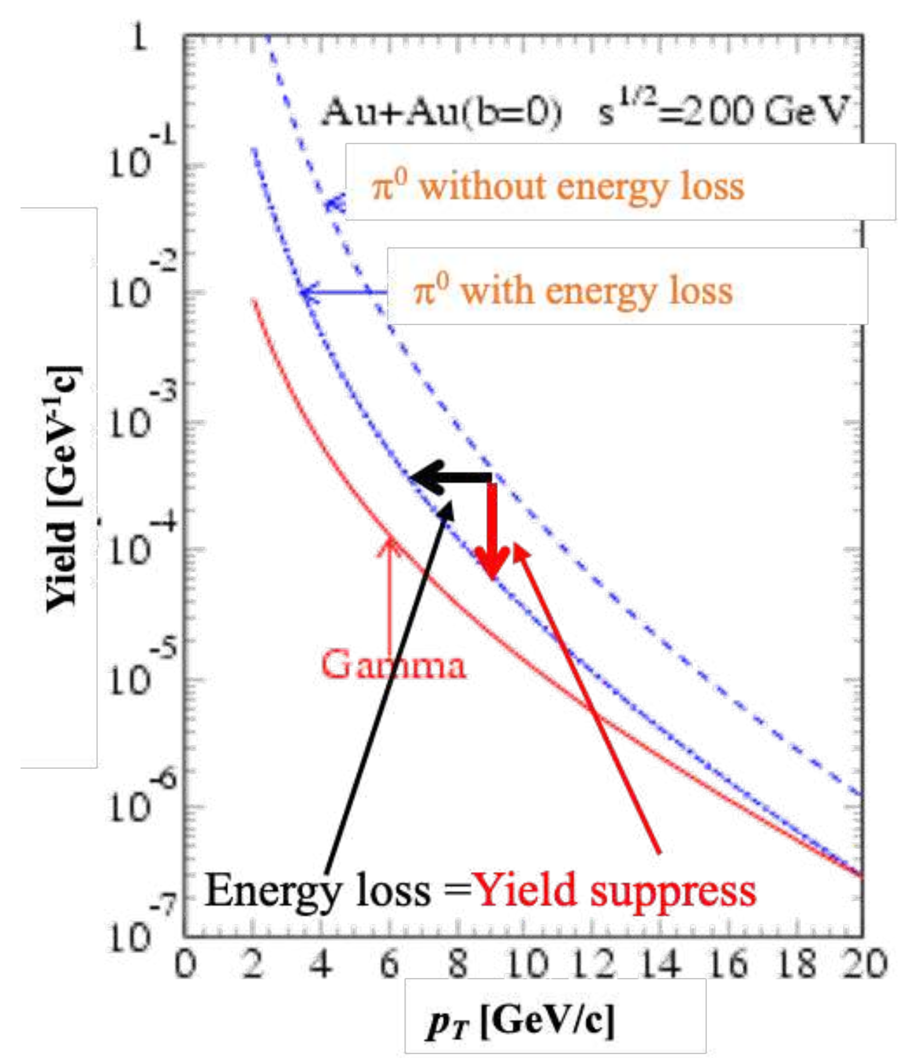
What's known briefly

- In 2005, RHIC experiments discovered generation of the QGP state, which is high-T, high-density material.
- QGP had been expected to be a gas-like state, but the discovered QGP was almost perfect fluid, i.e. fluid with very low viscosity.
- LHC (2009~) measurements follow the RHIC results.

QGP sign: Yield suppression of leading particles

- Hard scattered partons lose their energies in the QGP via gluon radiation or parton collisions.
- However, jet reconstruction was difficult in heavy ion collision experiments.
- Instead, high P_T hadrons (π^0 etc.) are observed, which are leading particles from jets and carry a large fraction of jet momentum.
- Energy loss of the partons at RHIC are initially observed by high-p_T π^0.





X.-N., Wang, PRC **58** (1998)2321

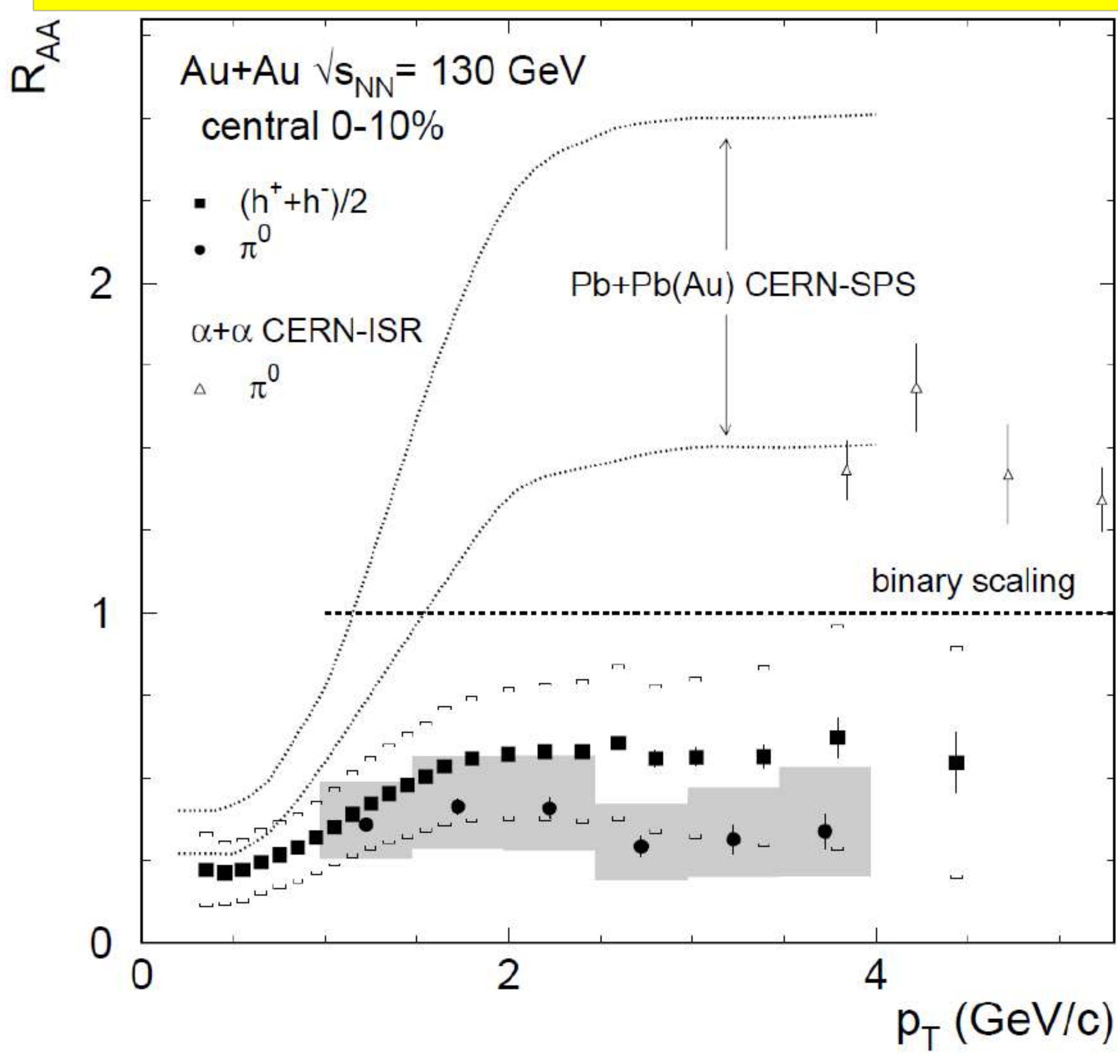
QGP sign: Yield suppression of leading particles

- Nuclear Modification Factor (R_{AA})
  - (Yield in A+A collision)/(Yield in p+p collision × Ncoll)
  - R_{AA} =1: No nuclear effect
  - R_{AA} <1: Suppression due to energy loss, etc.
  - R_{AA} >1: multiple scattering, etc.
- R_{AA} <1 for RHIC and LHC, >1 for SPS ($\sqrt{s_{NN}}$=17GeV)

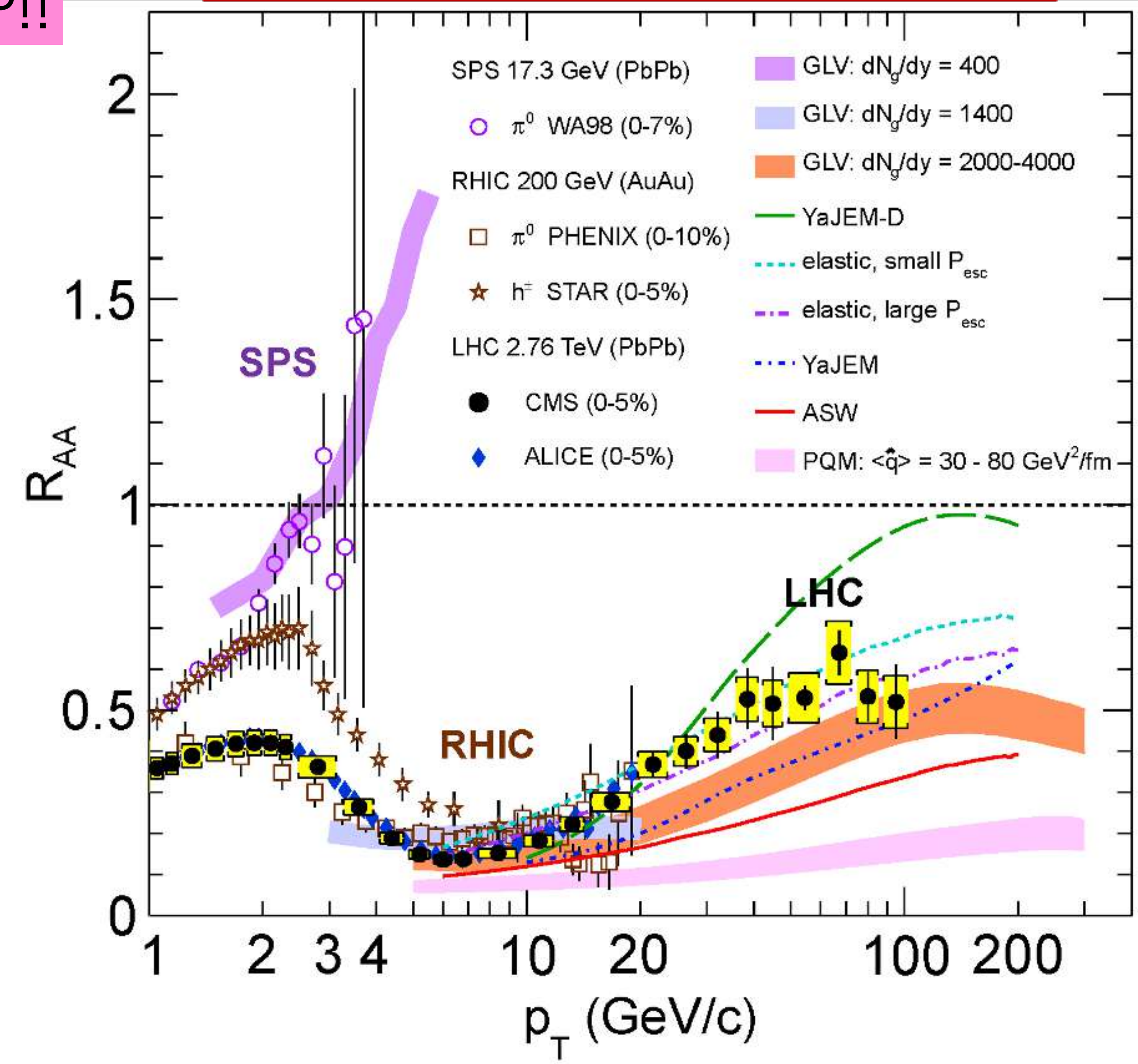
$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}}\cdot\left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

Sign of hot and dense matter, i.e. QGP!!

π^0 and $h^{+/-}$, PHENIX, PRL 88, 022301 (2002)



R_{AA} = 0.2 at LHC: 30% loss of original p_T

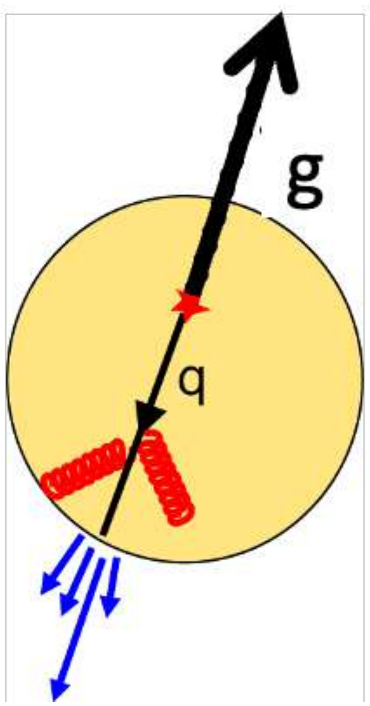


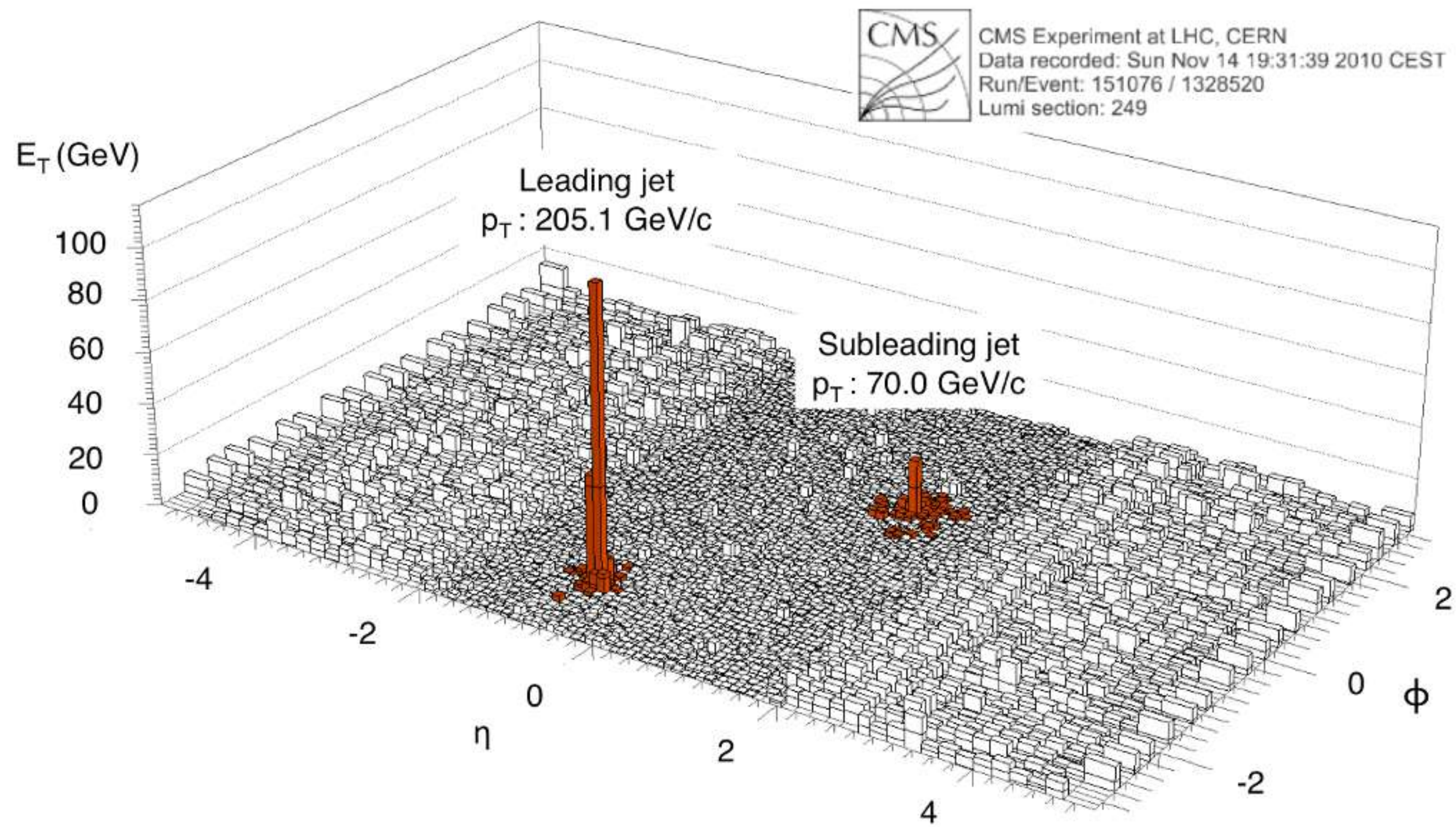
Jet reconstruction became possible at LHC

- Hard scattering probability is so large at LHC that the observation of reconstructed jets and their energy loss became possible.
- Back-to-back jets are observed. Energy of sub-leading jets is significantly lower than that of leading jets.

CMS, PRC84, 024906(2011)

Jet Production: **Yield** $\propto \alpha_s^2$





Jet reconstruction became possible at LHC

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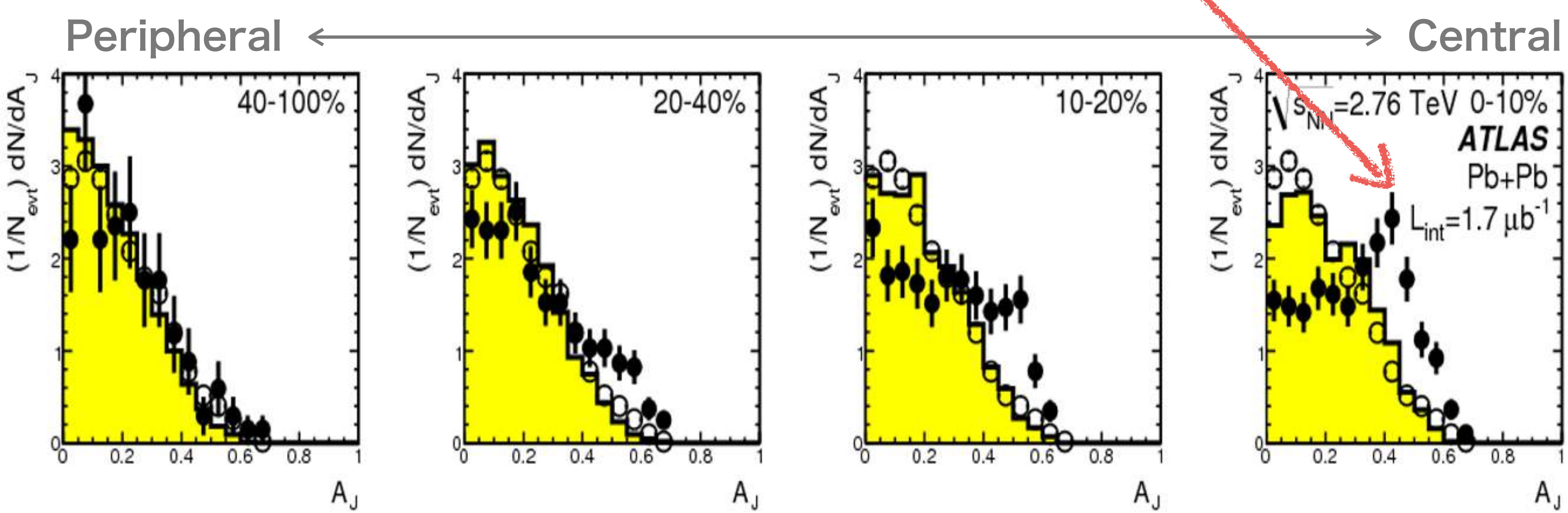
- ATLAS has successfully measured asymmetry of energies of back-to-back jets.

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \qquad \Delta\phi > \frac{\pi}{2},$$

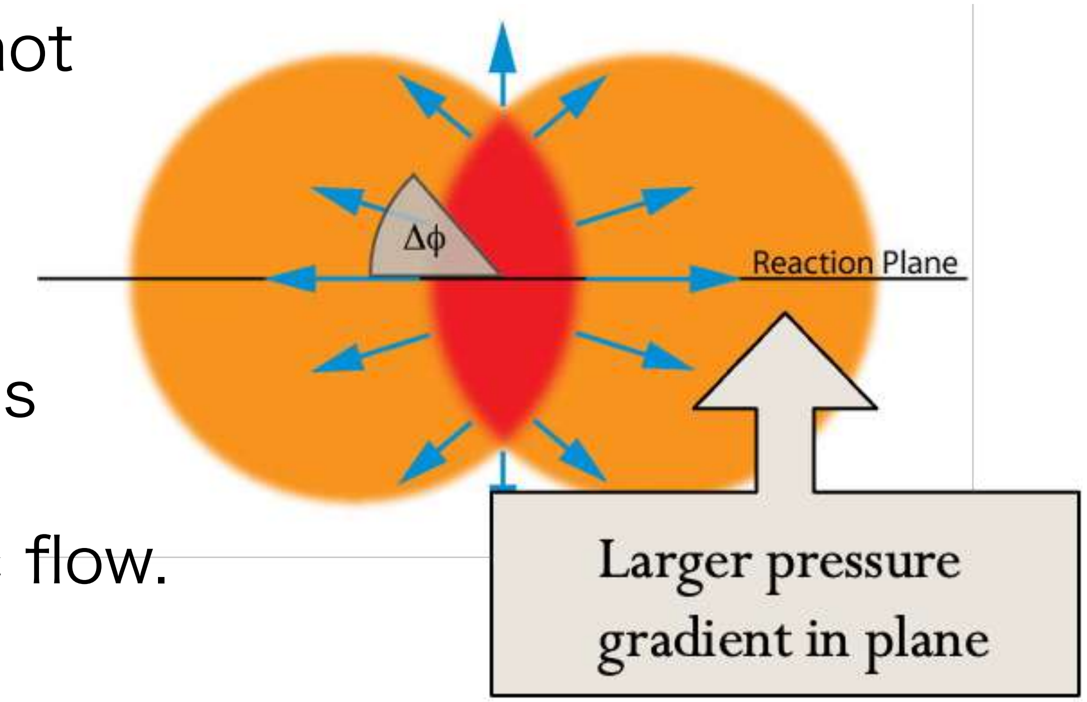
- Central Pb+Pb points deviate from p+p and estimated Pb+Pb distribution without energy loss.
  → The deviation corresponds to 30-40% loss of jet energy.



○ p+p data ● Pb+Pb data ▭ Estimated Pb+Pb distribution without energy loss

QGP property: Collective flow of particles

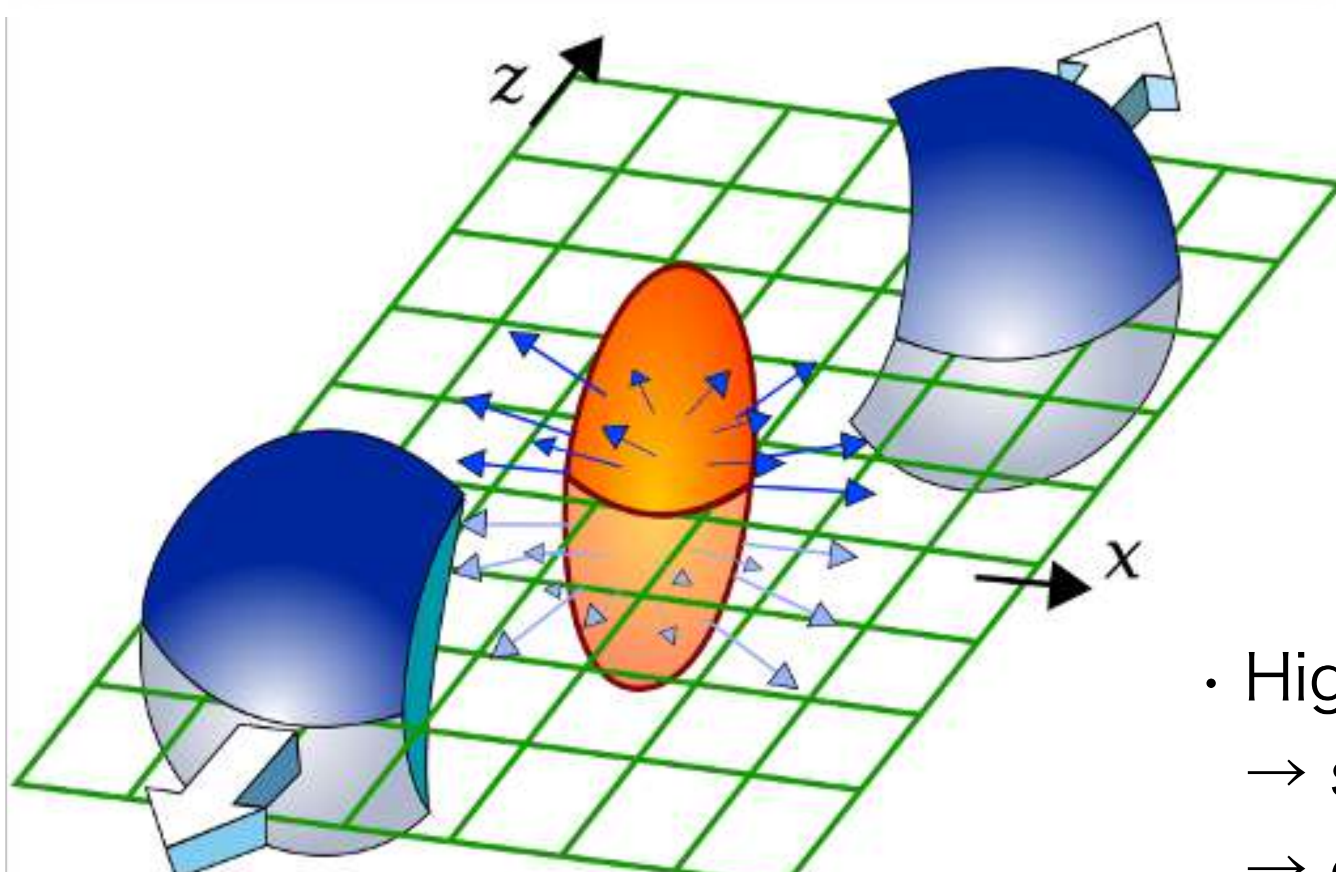
- In non-central collisions, the collision region is not isotropic but almond-like shape.
  → Different pressure gradient produces momentum anisotropy of emitted particles.
- Measure the angular distribution of the particles with respect to the reaction plane.
  → 2nd order Fourier coefficient show the elliptic flow. (楕円)



$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$

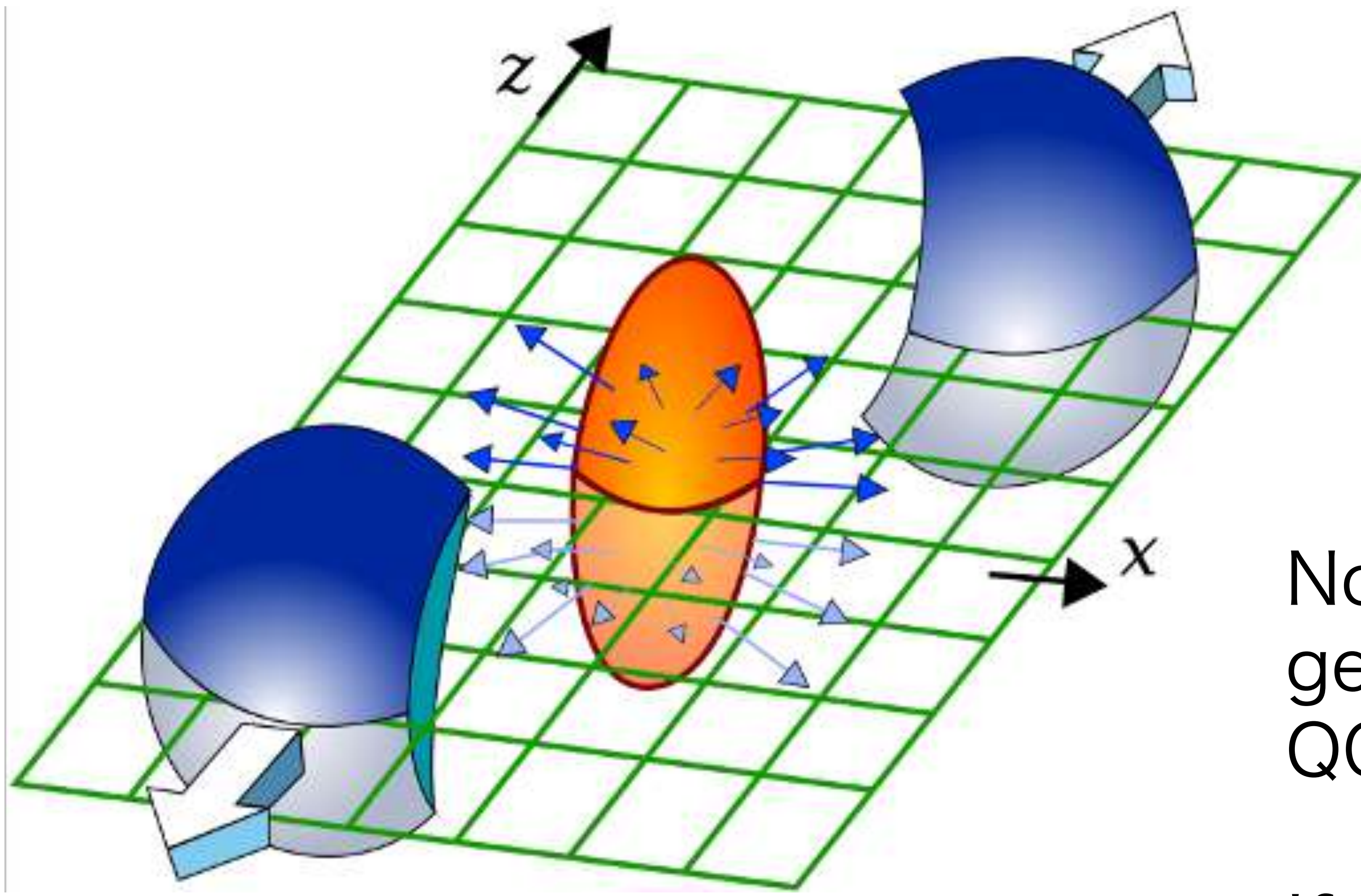
Spatial asymmetry
eccentricity $\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$

Mom. Asymmetry
elliptic flow $v_2 = \frac{\langle p_y^2 \rangle - \langle p_x^2 \rangle}{\langle p_y^2 \rangle + \langle p_x^2 \rangle}$



- Higher order flows v_n
  → sensitive to the properties of the matter.
  → compared to the hydrodynamics model.

QGP is found to be almost perfect fluid



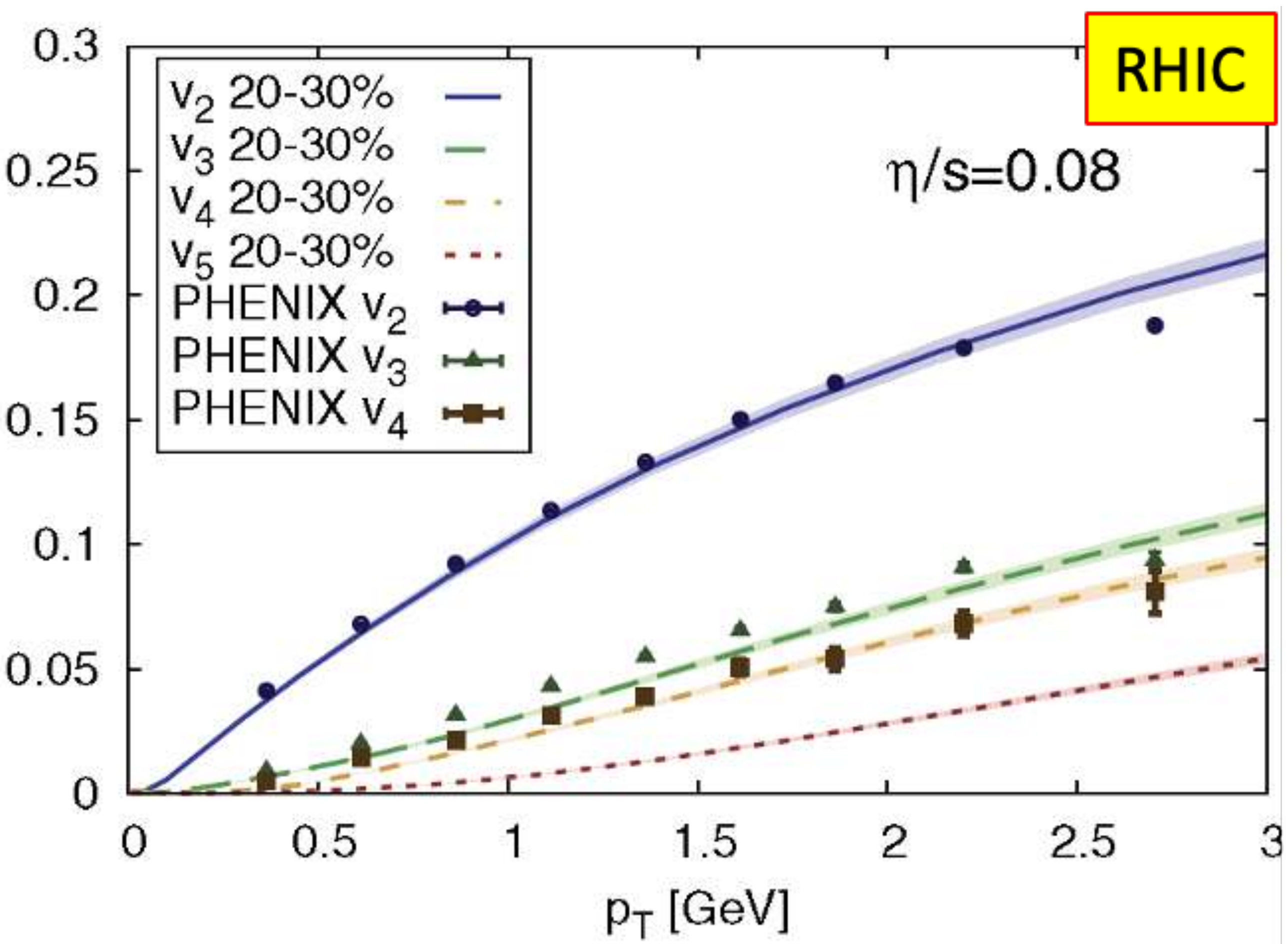
Non-central collision generates almond-shaped QGP.

✕ If the QGP is gas, particles flow isotropically regardless of the QGP shape.

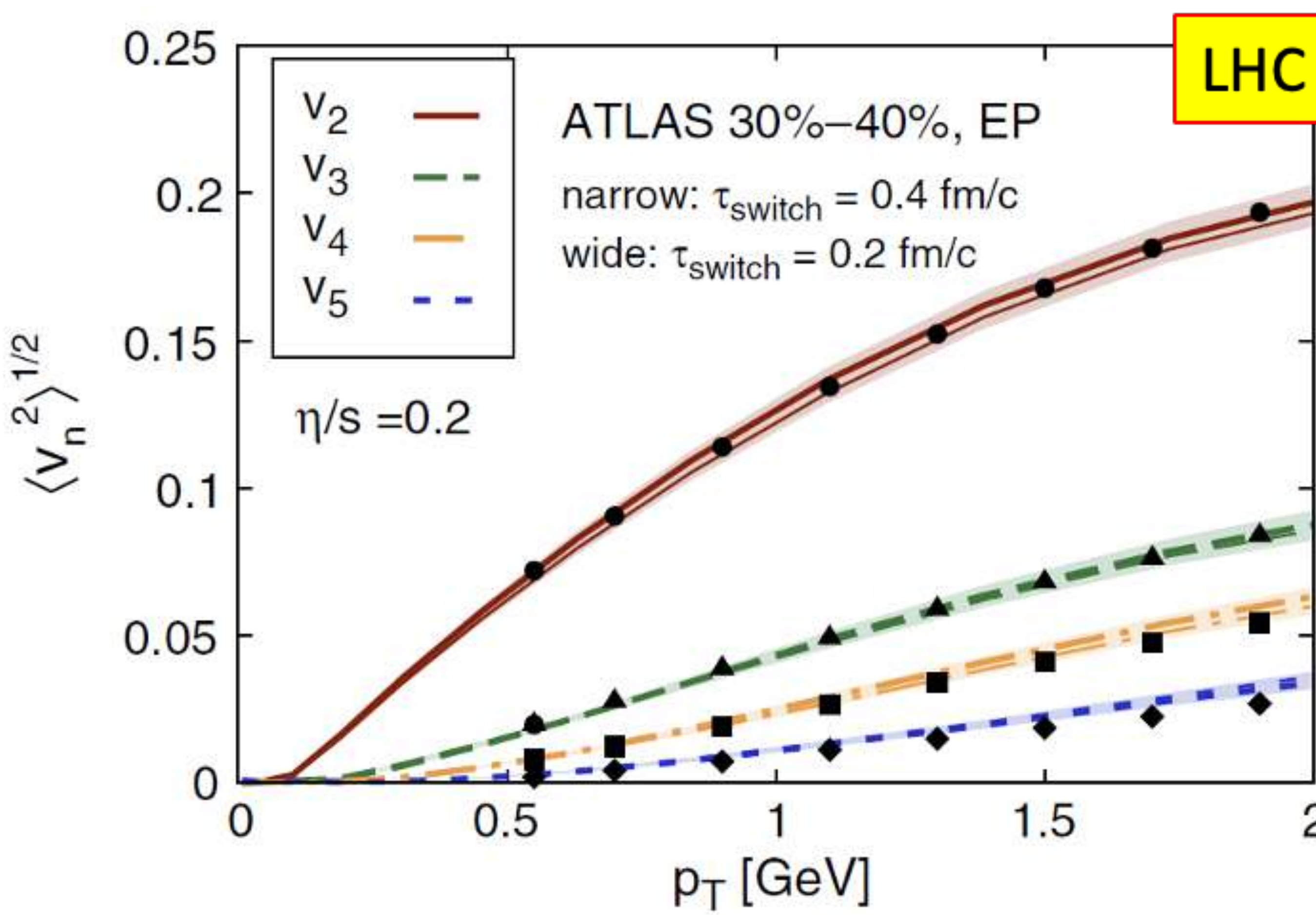
○ If the QGP is fluid, the scattered particles reflect the shape of the QGP.

v_n results compared with hydrodynamics model

- PHENIX (RHIC) and ATLAS (LHC) v_n analysis results are compared with a hydrodynamics model → QGP is modeled as fluid consisting of partons.
- The model reproduces the higher order flow at RHIC and LHC very well.
- **Almost perfect fluid** is realized at RHIC (η/s from quantum limit ~ $1/4\pi$ ~ 0.08)

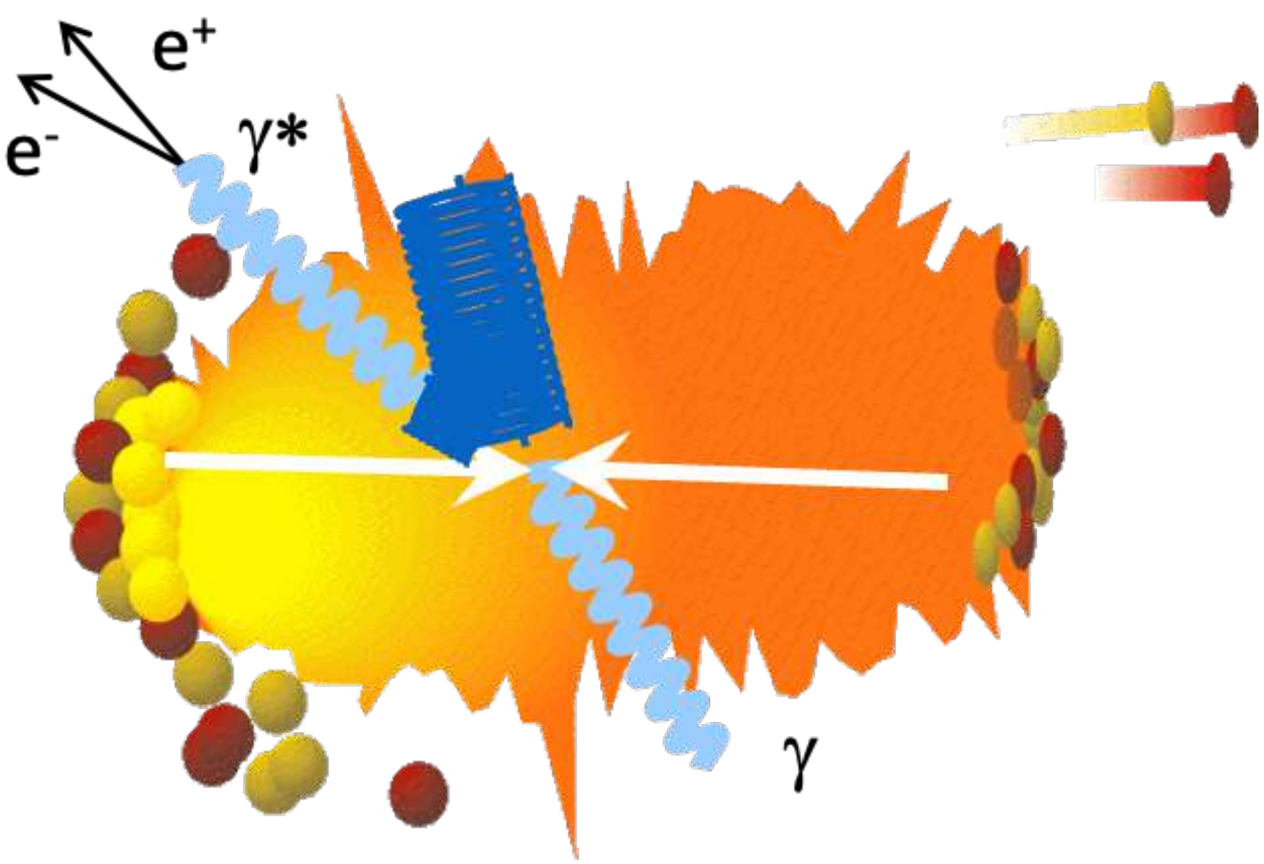


B. Schenke, S. Jeon and C. Gale, PRC 85, 024901 (2012)



C. Gale et al., PRL110, 012302(2013)

QGP measurement: temperature from thermal photons



- Thermal photons are emitted from all the stages after collisions.
- Penetrate the system unscattered after emission, because "no strong interaction".
  → carry out QGP information such as temperature.
- Photons are produced by Compton scattering or q-qbar annihilation at LO.

$$E\frac{dR_\gamma}{d^3p} = -\frac{\alpha_{em}}{\pi^2}\mathrm{Im}\Pi_{em}(\omega,k)\frac{1}{e^{E/T}-1}$$

Π_{em}: photon self energy

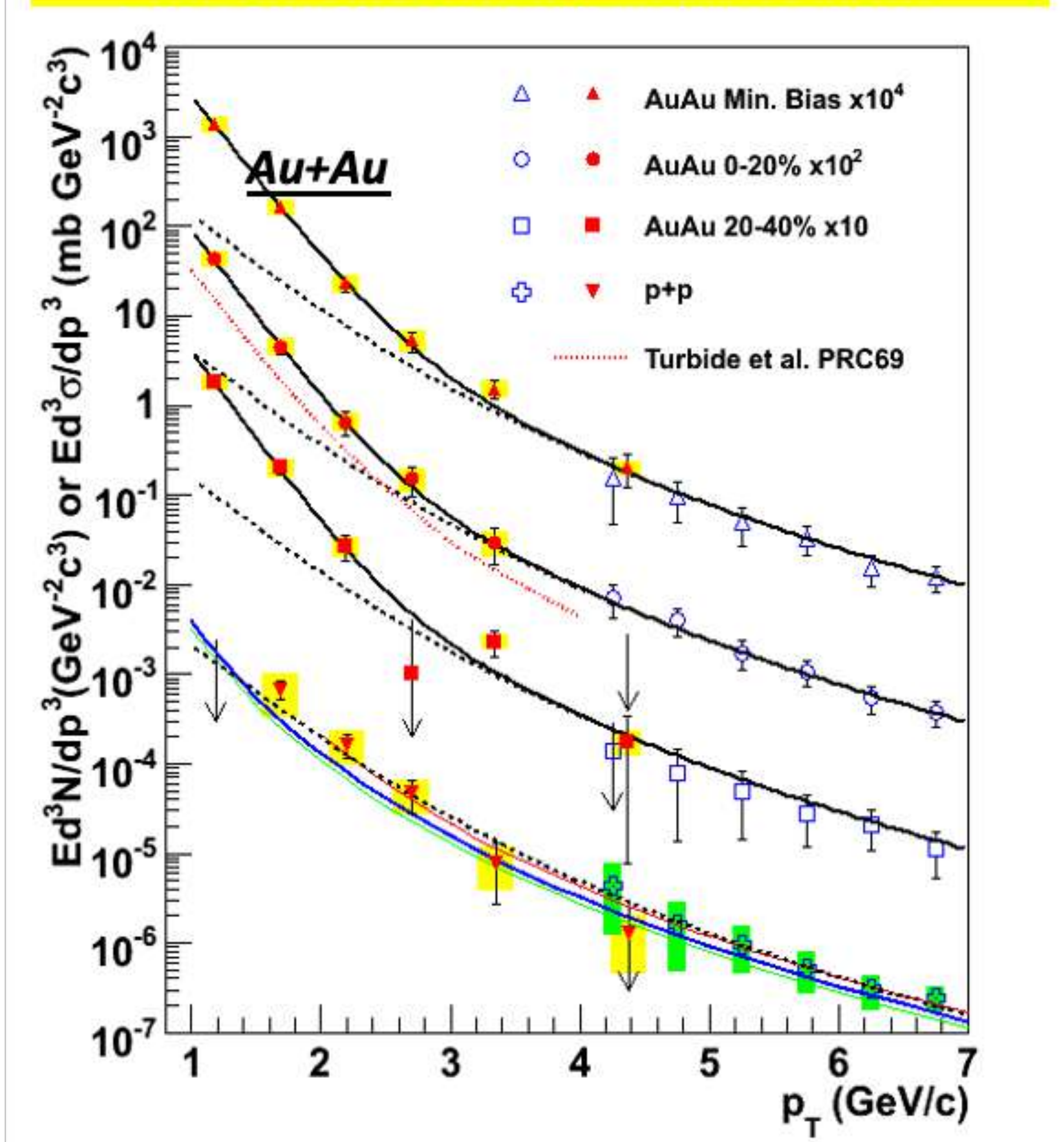
$$\mathrm{Im}\Pi_{em}(\omega,k) \approx \ln\left(\frac{\omega T}{(m_{th}(\approx gT))^2}\right)$$

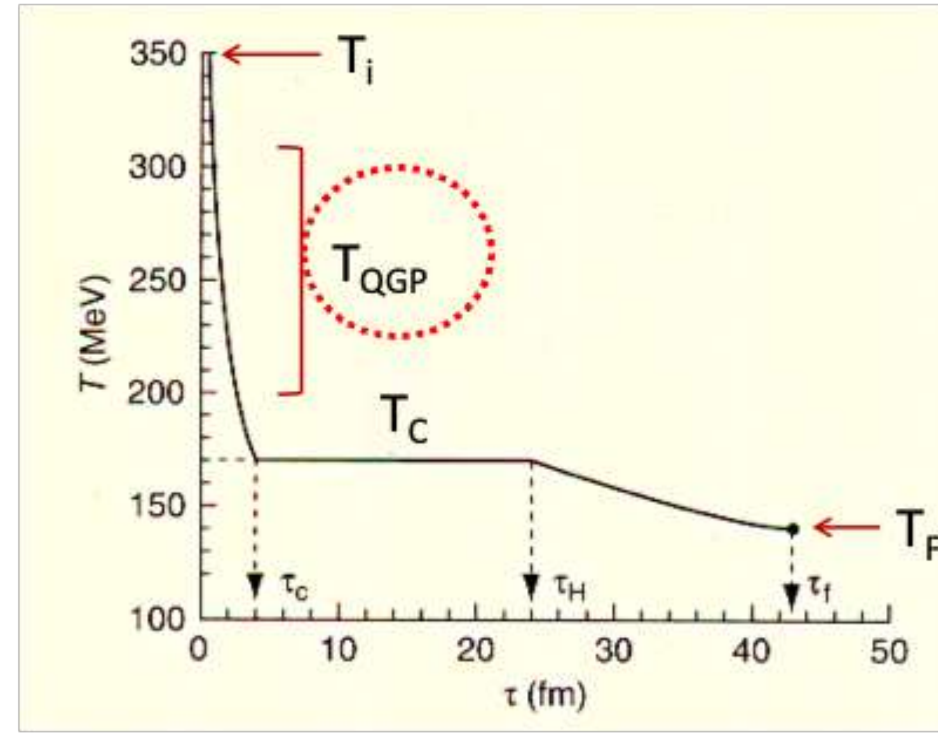
- Thermal photon distribution will be expressed by the product of
  - Bose distribution, and
  - transition probability of QGP
- Fitting the model to the experiment data gives QGP temperature.

In this way, the obtained temperatures are:

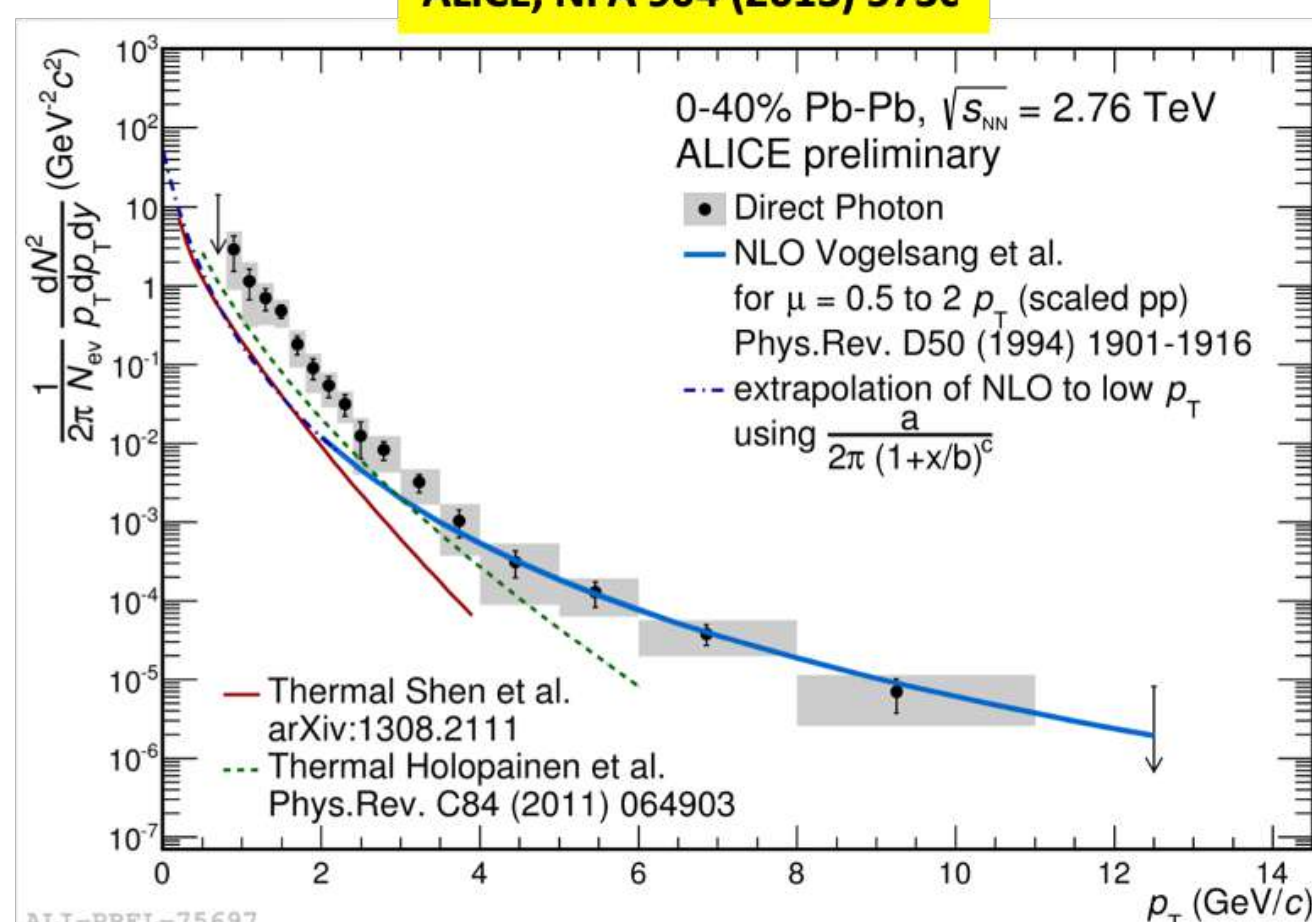
- RHIC, Au+Au 200GeV: T_{ave} = ~220 MeV = 2.5 trillion K
- LHC, Pb+Pb 2.76TeV: T_{ave} = ~304 MeV = 3.5 trillion K

PRL104,132301(2010), arXiv:0804.4168





ALICE, NPA 904 (2013) 573c



QGP discovery and its properties: summary

- Quark gluon plasma (QGP), which is the state of very early universe (10us after bigbang), can be investigated by heavy-ion collider experiments.
- As a sign of QGP, **jet quench** phenomena were observed.
- From particle flow study, QGP was found to be **almost complete fluid**.
- These studies were first performed at RHIC experiments and more precisely performed at LHC experiments.
- QGP **temperature was measured** from thermal photons and the results are consistent with expected QGP temperature.

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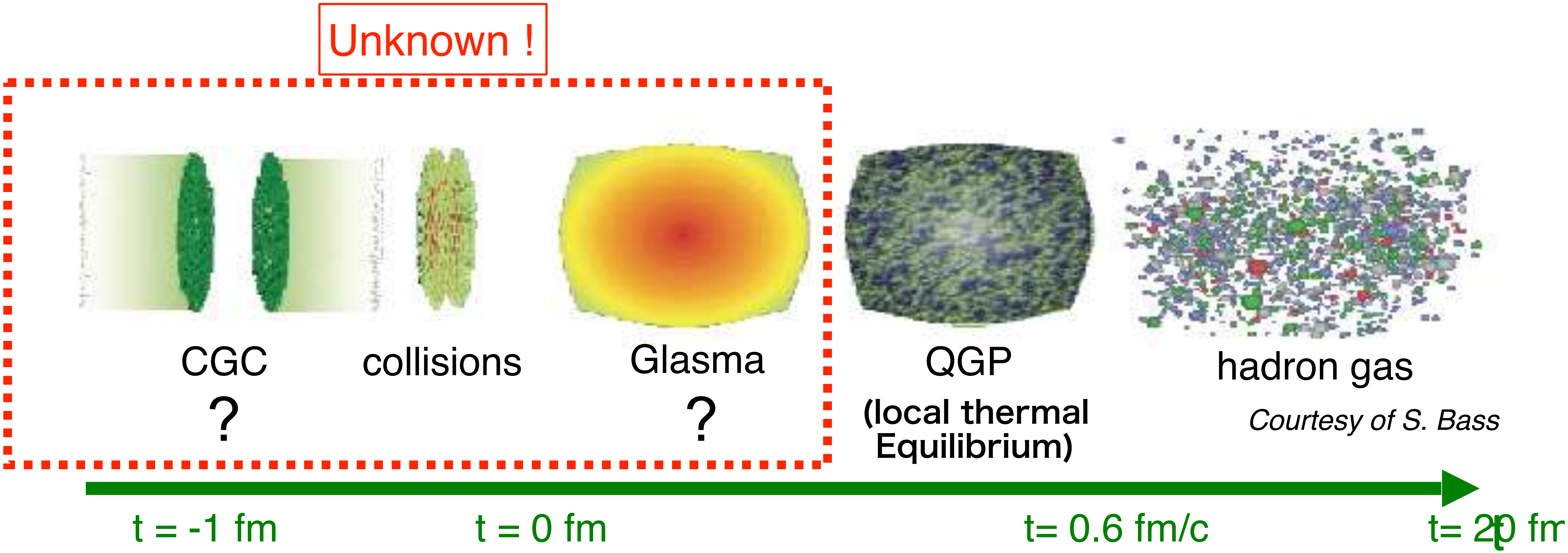
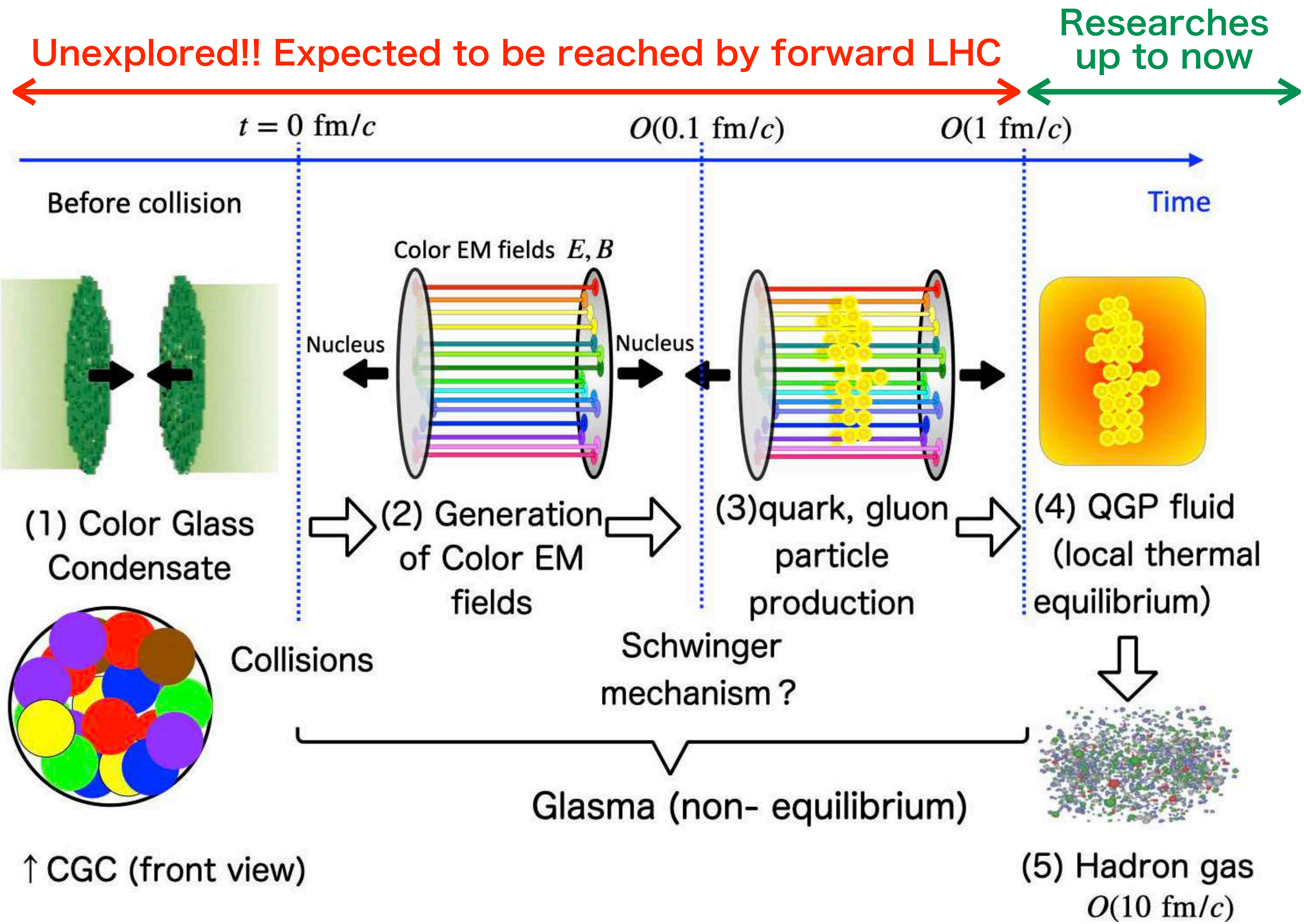
QGP generation processes are unknown

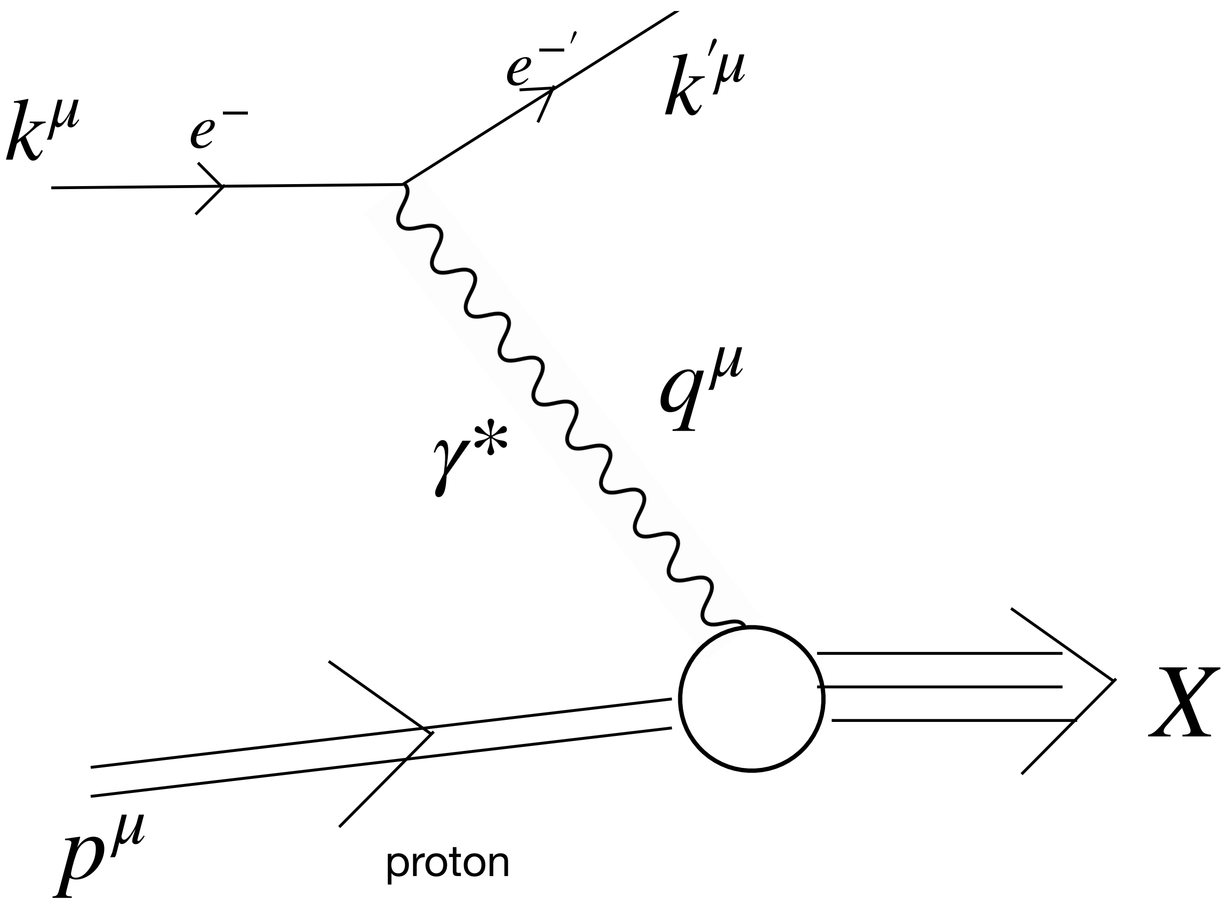


- What is the initial condition?
  So called Color Glass Condensate (CGC)?
  → No clear evidence for the CGC yet.
- Why so rapidly (~0.6fm/c) thermalized?
  → Instability of strong color field?
- Initial condition ↔ CGC strong color fields ↔ thermalized QGP

Glasma thermalized process — not observed yet



Deep Inelastic Scattering (DIS) basics



Lorentz invariant variables

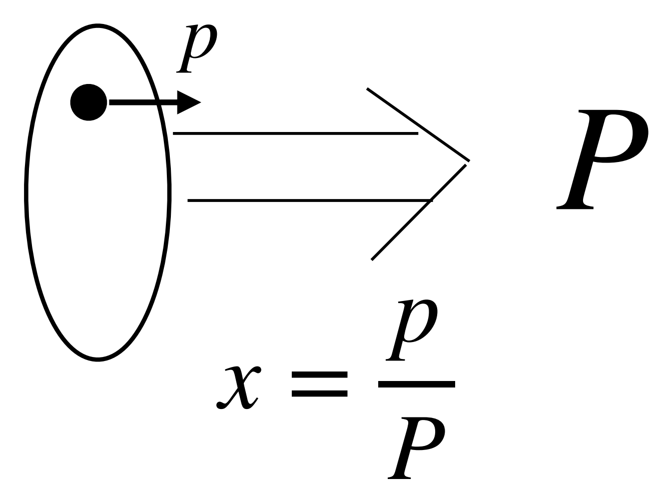
$Q^2 \equiv -q^2$: photon's virtuality

$x \equiv \dfrac{Q^2}{2\,p \cdot q}$: Bjorken variable

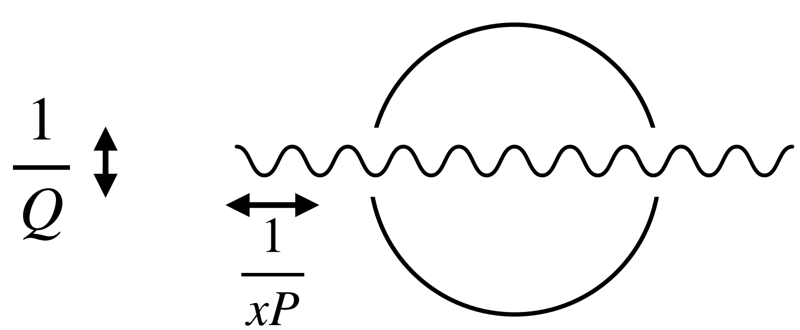
Physics meanings

Q^2: Transverse resolution

x: Longitudinal momentum fraction of parton

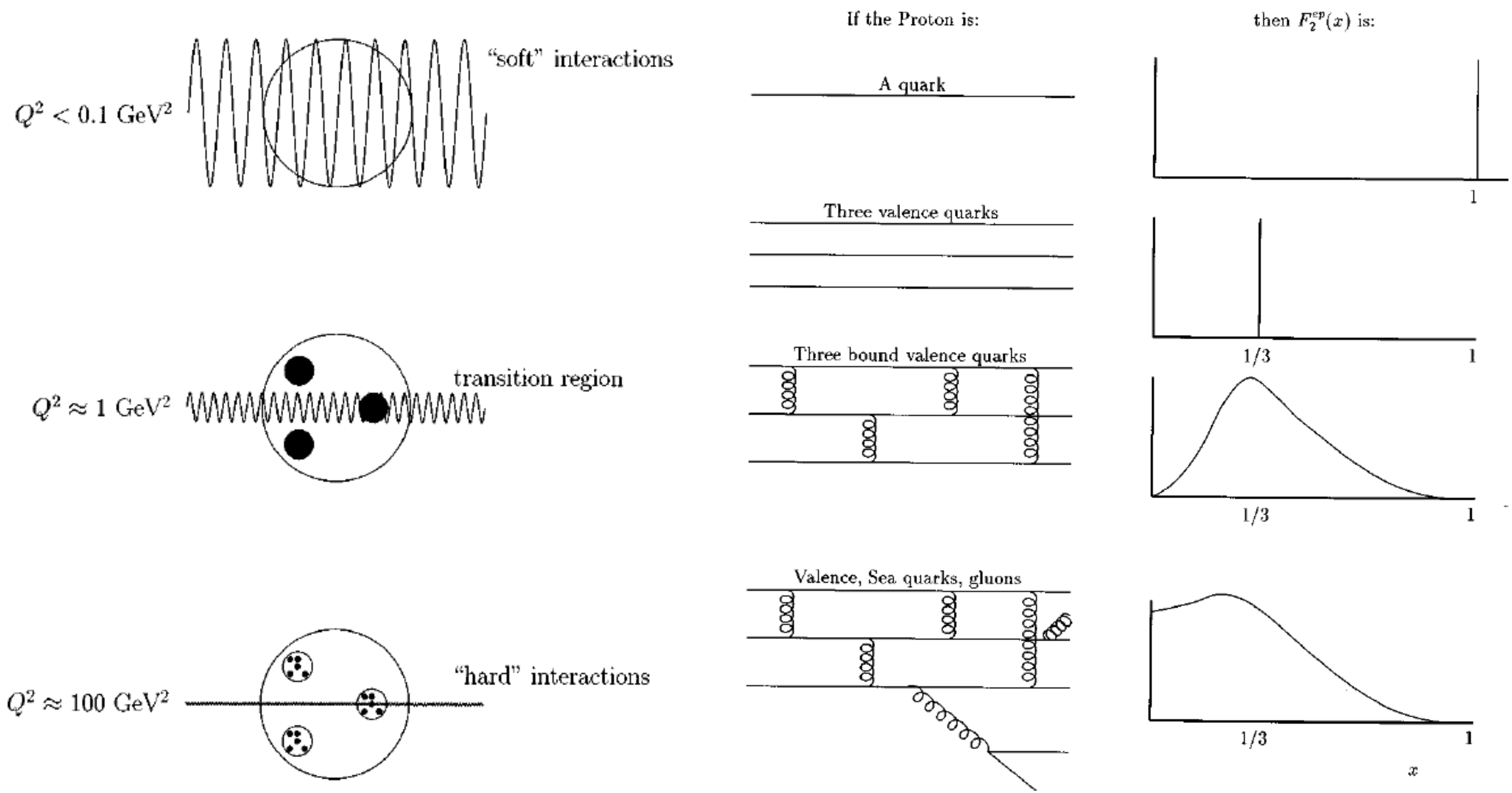


DIS resolves the target proton in vertical and horizontal scales.



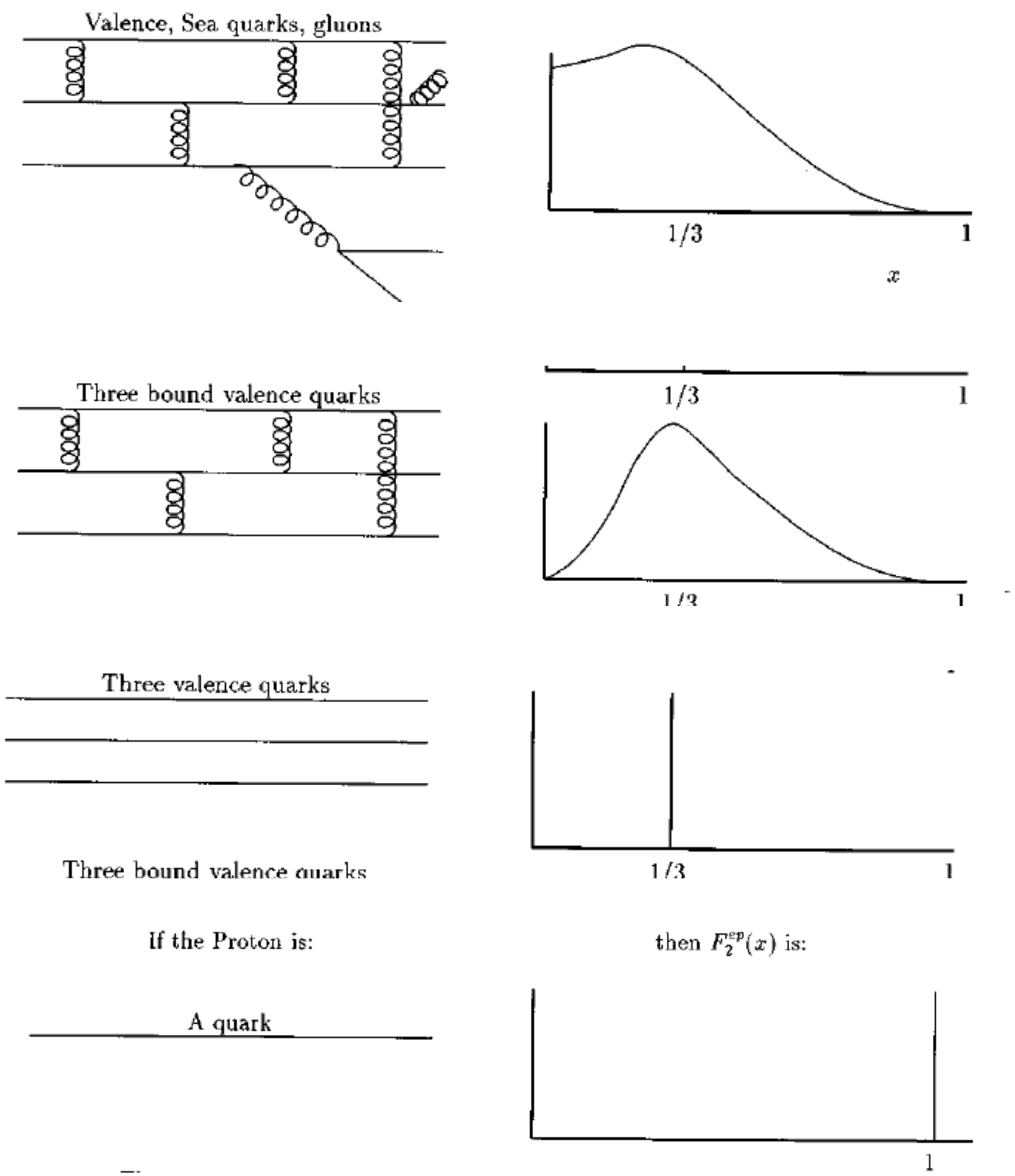
ep / eA DIS works as an electron microscope on proton/nucleus

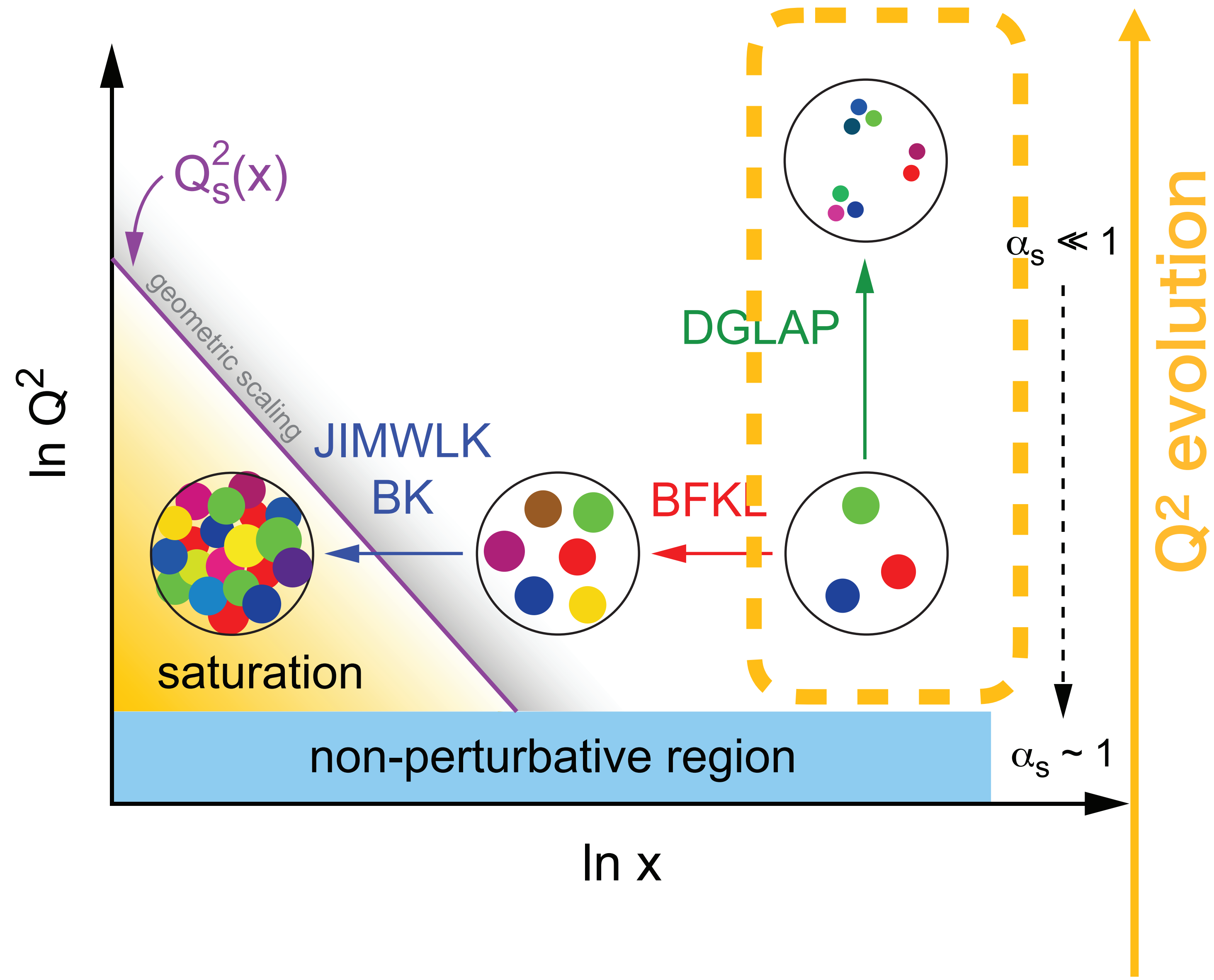
Q^2 evolution



Higher Q^2 dissolves gluon contributions!

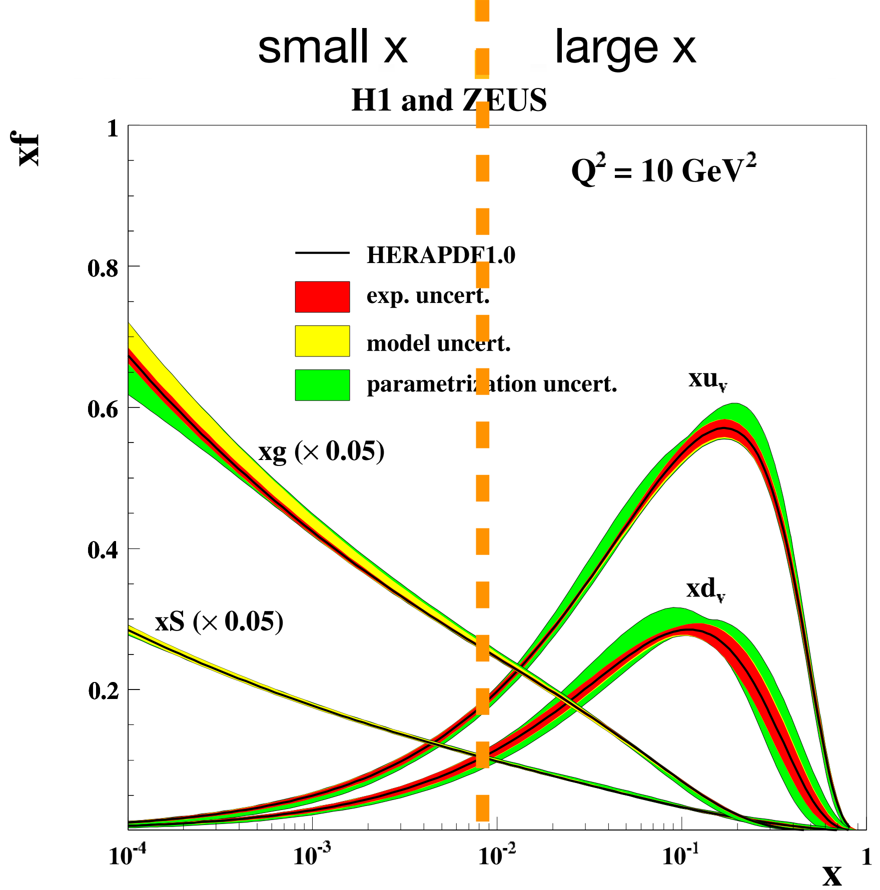
Q^2 evolution: DGLAP evolution equation



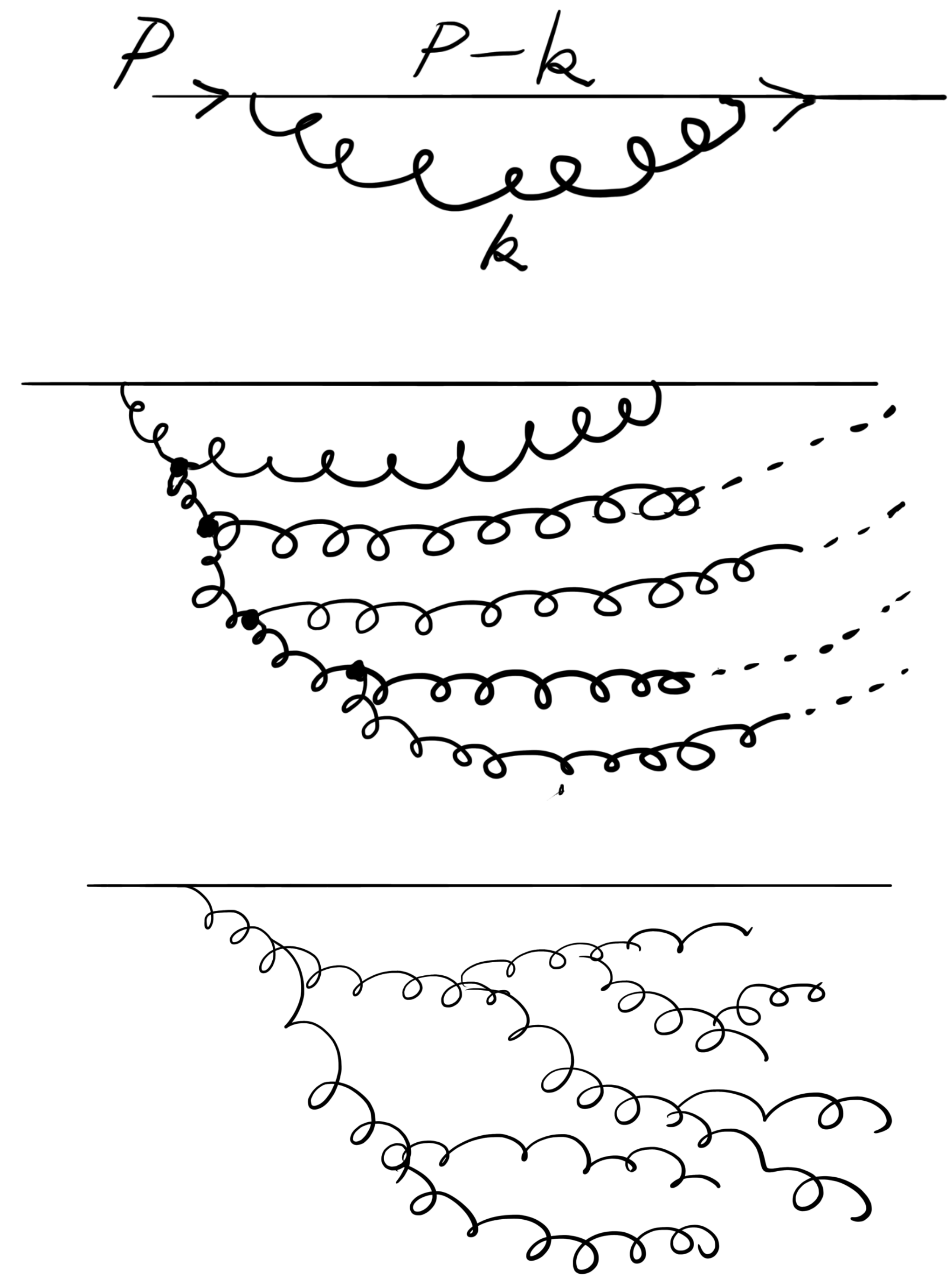


Linear QCD evolution in Q^2 is established by the DGLAP equation.

Structure of proton (PDF)



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



by T. Chujo

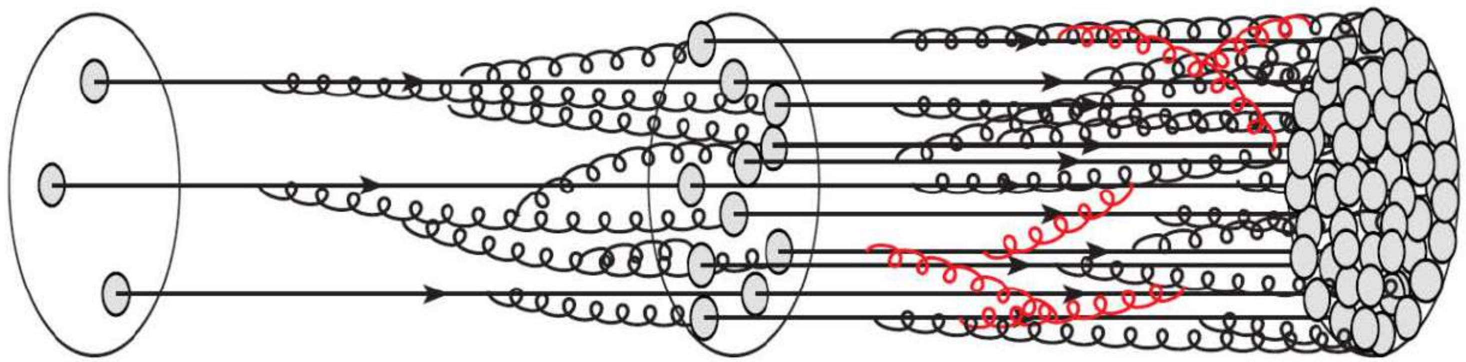
Mechanism of multipole gluon creations

- 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

nucleus

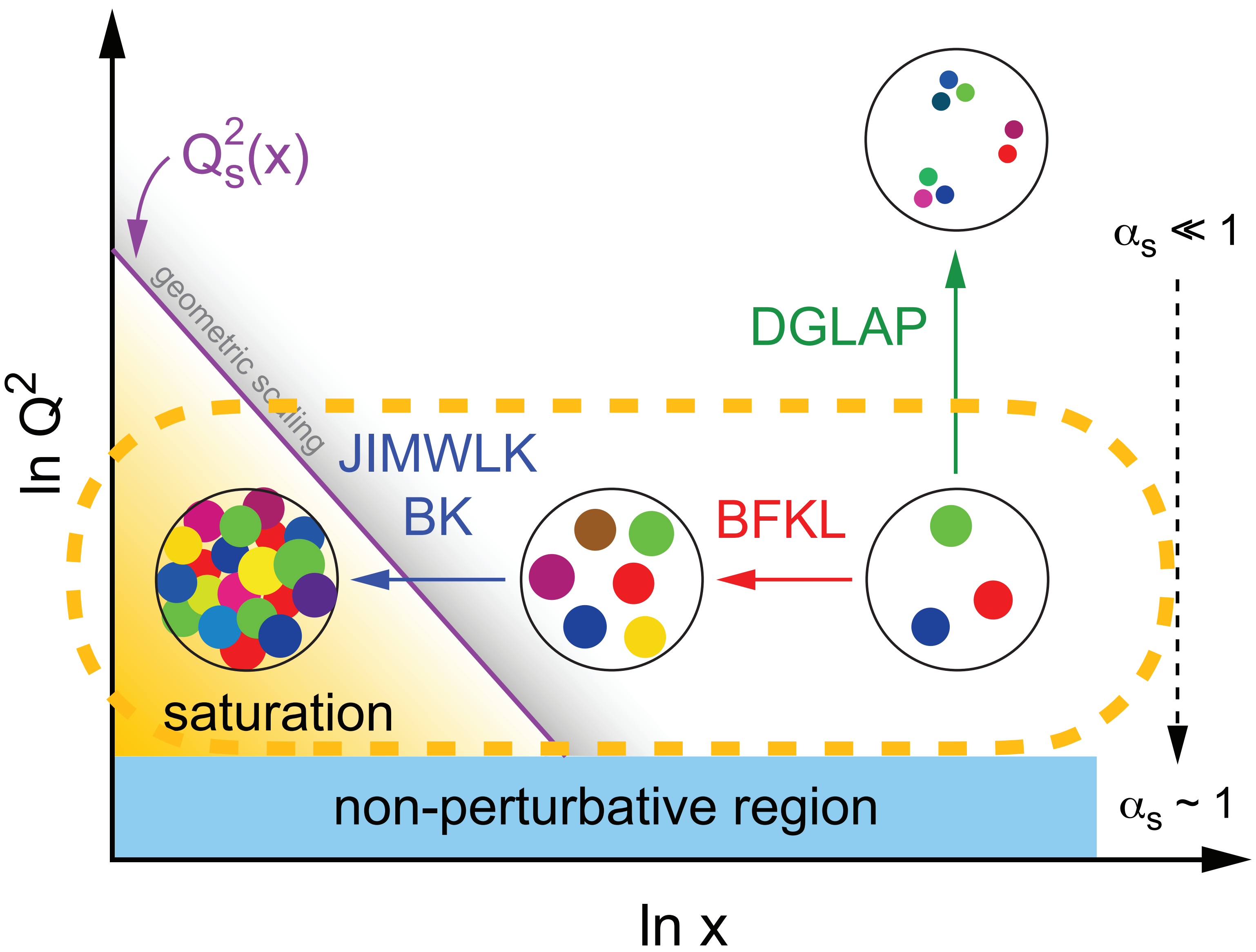
CGC!

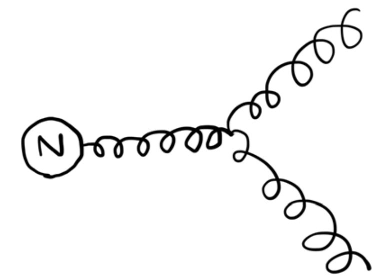
Large x
mid-rapidity
Low energy scattering

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

Small x
forward rapidity
High energy scattering

x evolution: BFKL → BK, JIMWLK

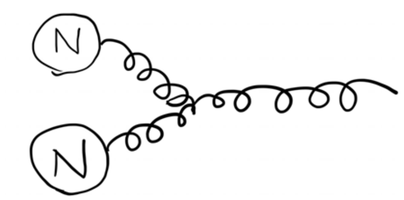




g →gg

gluon splitting

$\propto N_g$



gg →g

gluon merge

(non-linear effect)

$\propto N_g^2$

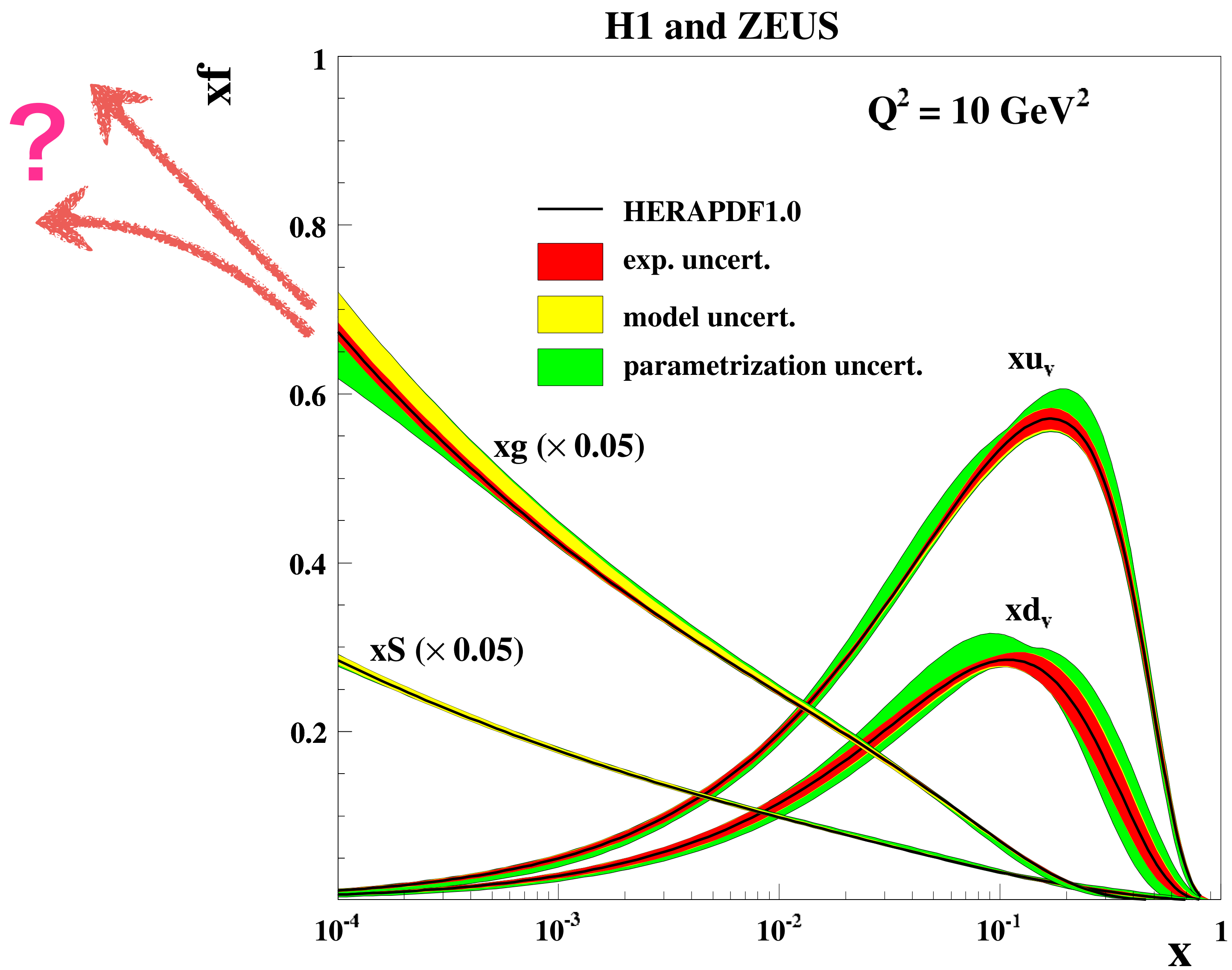
e.g.) Logistic Eq.

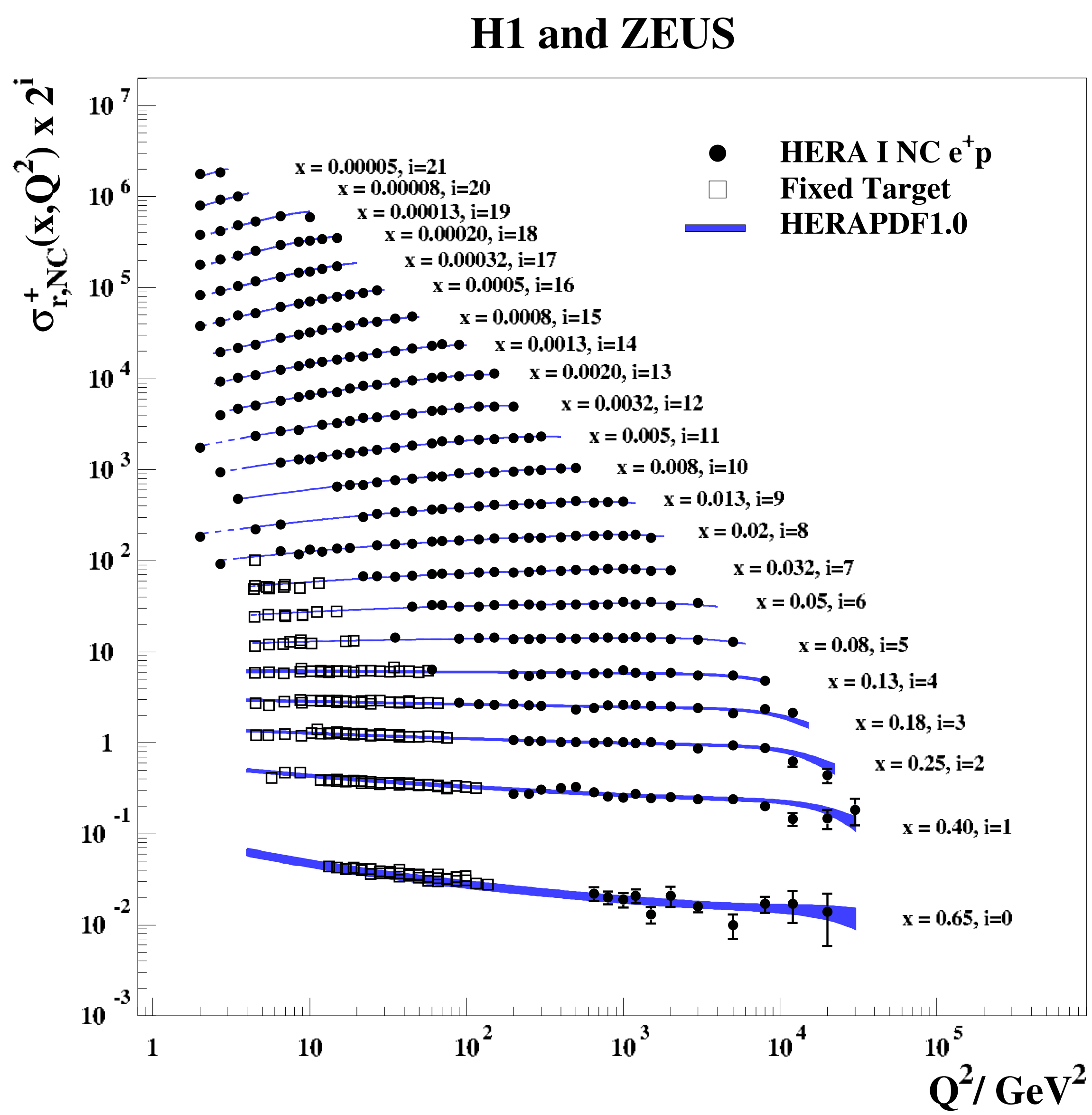
$$\frac{d}{dt}N(t) = \kappa\left((N(t) - N(t)^2\right)$$

⇄ Balitsky-Kovchegov (BK) e.q.

- **Small x and low Q** region (but Q >> Λ_{QCD} (~ 0.2GeV) for perturbative 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

Evolution examined by experiments up to now





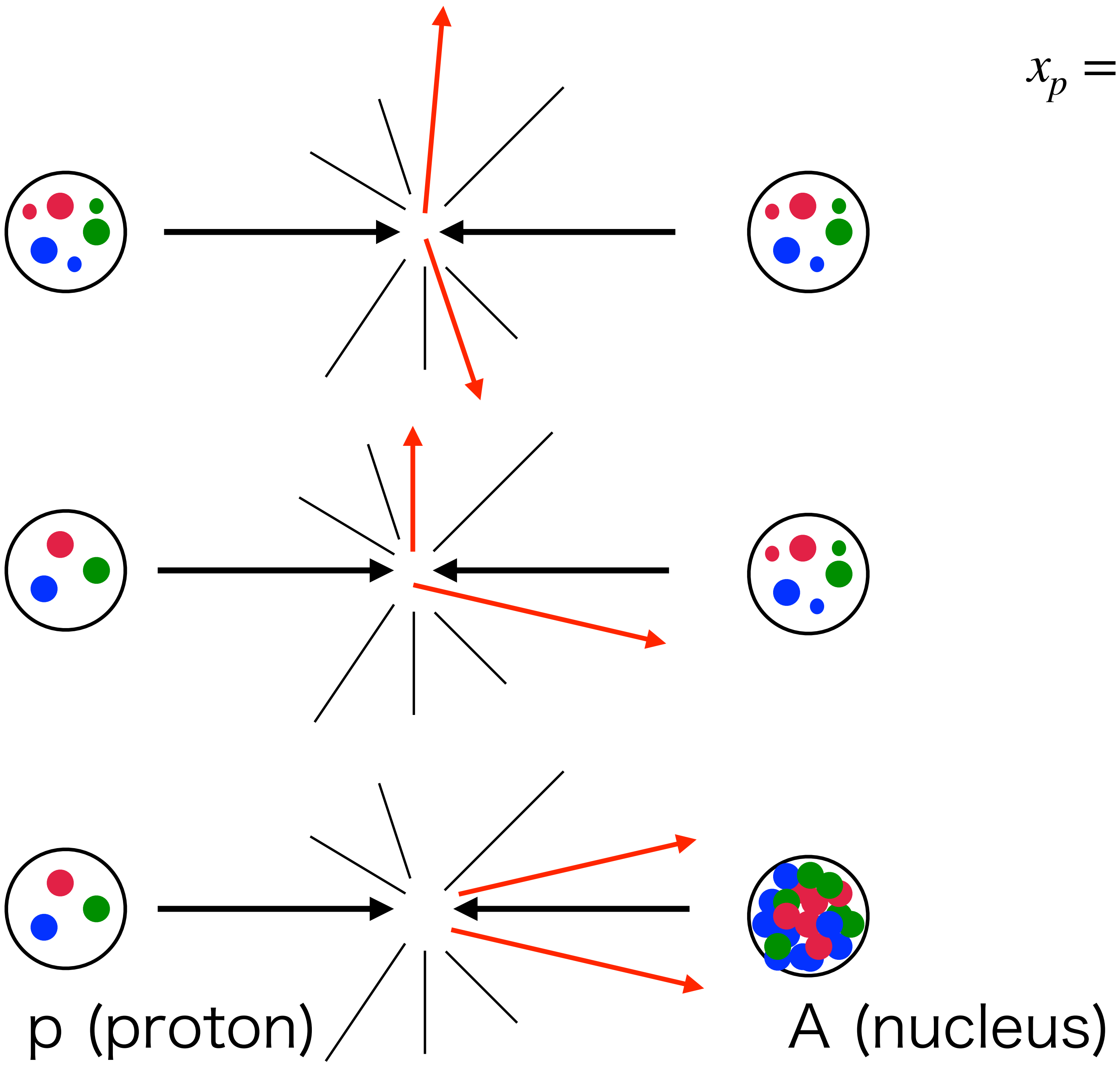
Up to now, evolution was successfully examined by measurements.

(expected to be) Saturation region is not explored yet.

Forward pA collision makes $x_A \ll 1$

Final state: $p_{T,1}, y_1 \quad p_{T,2}, y_2$

$$x_p = \frac{p_{T,1}e^{y_1} + p_{T,2}e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{p_{T,1}e^{-y_1} + p_{T,2}e^{-y_2}}{\sqrt{s}}$$



Central rapidities probe moderate x

$$x_p \sim x_A < 1$$

forward/central doesn't probe smaller x

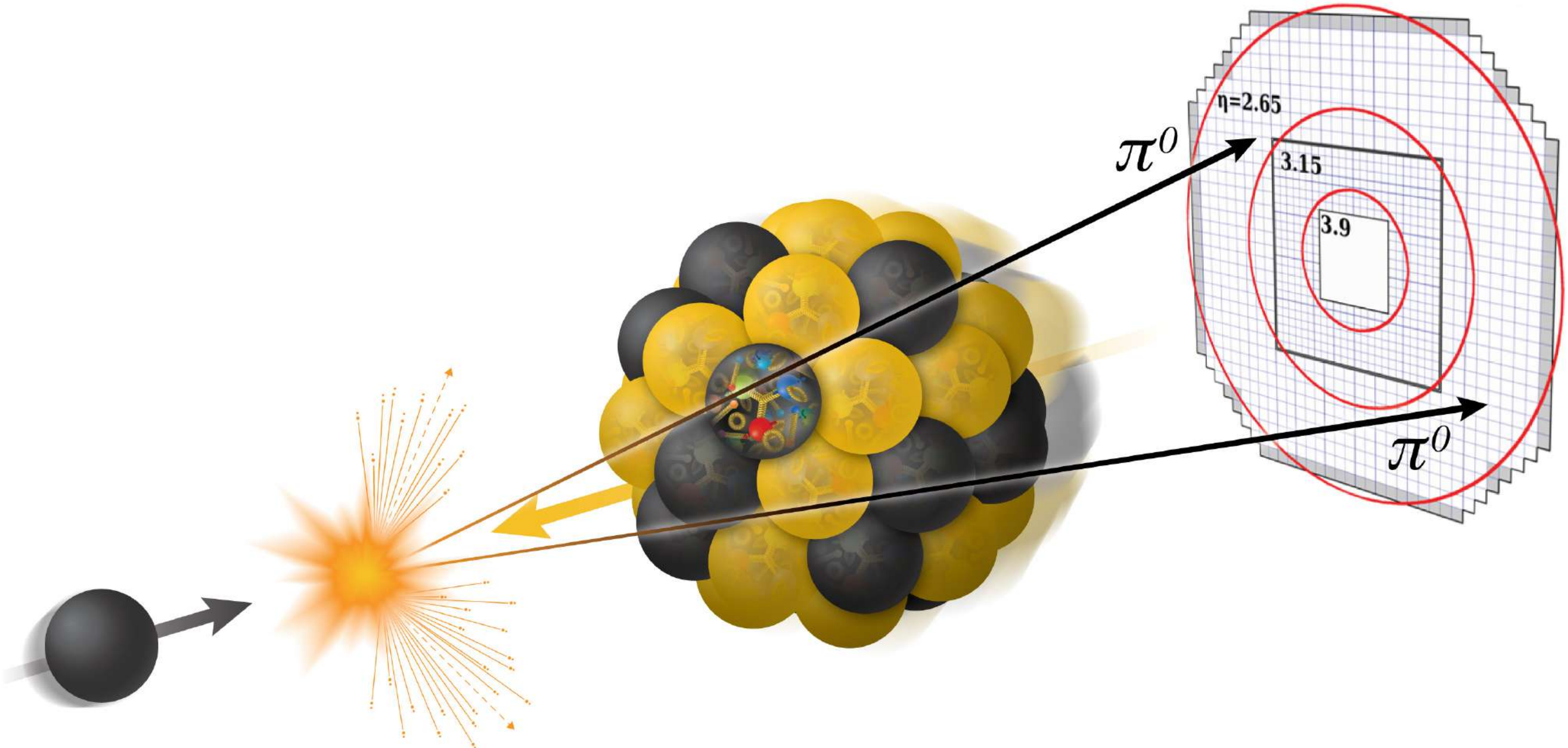
$$x_p \sim 1,\ x_A < 1$$

forward rapidities probe small x

$$x_p \sim 1,\ x_A \ll 1$$

Why nucleus?
→ gluon saturates faster than p by ³√A ~ 6 (Pb case)

Forward pA collision makes x_A << 1



https://www.bnl.gov/today/body_pics/2022/08/proton-collision-hr.jpg

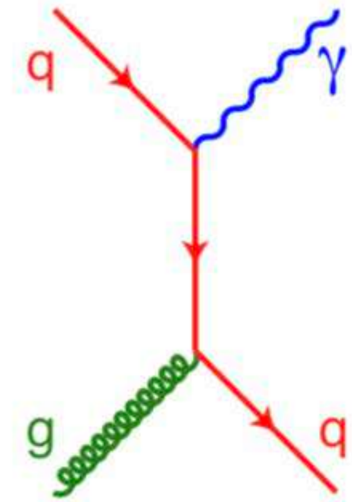
Forward measurements so far

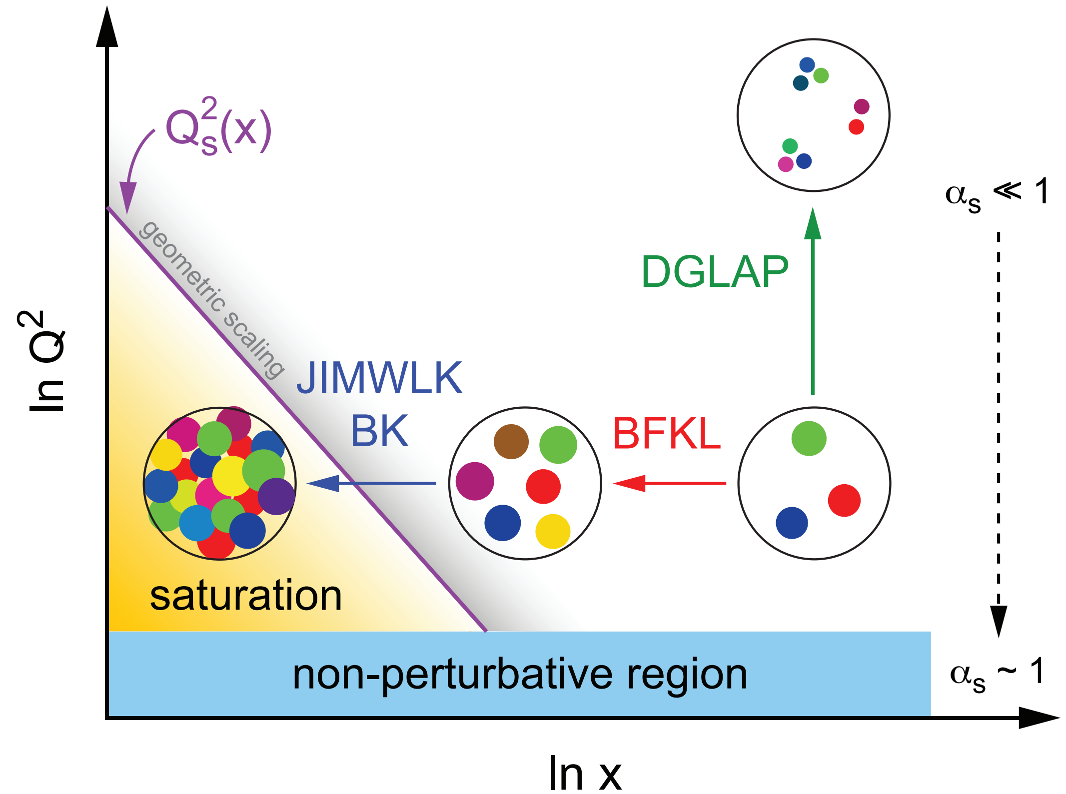
- There are several indications of gluon saturation from data vs. theory by RHIC experiments and LHC experiments.
- However, both CGC and linear QCD evolution can describe the data most of the cases.
- **Uncertainties on probe**: Hadron → final state interactions.

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

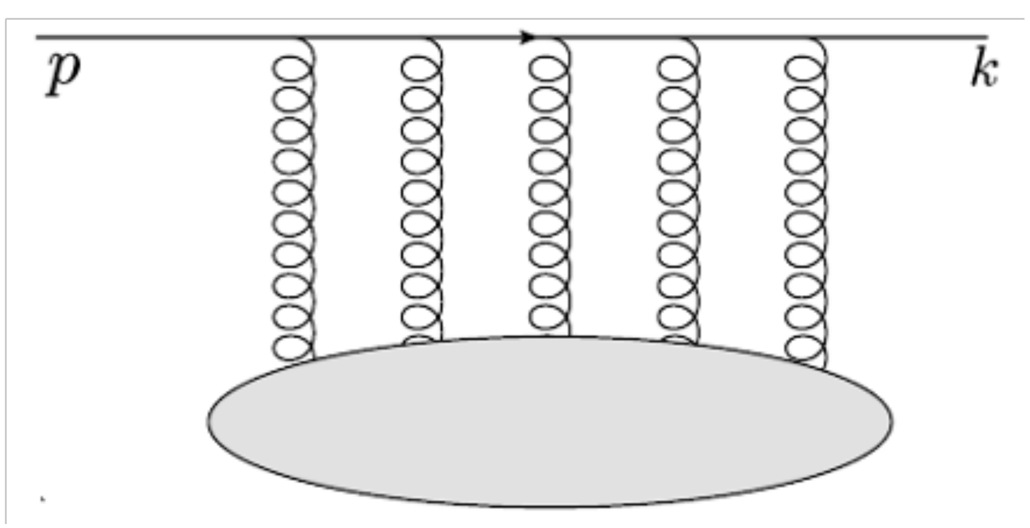


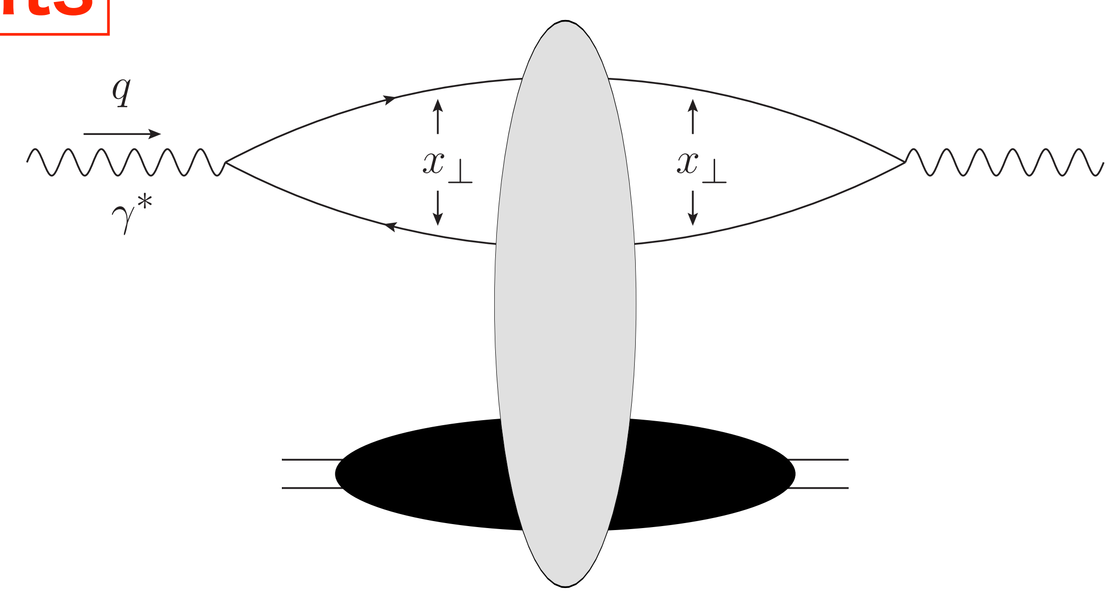


Need to see non-linear evolution of QCD

- Explore wide rage of x-Q2 space
- High precision measurements

Next generation experiments

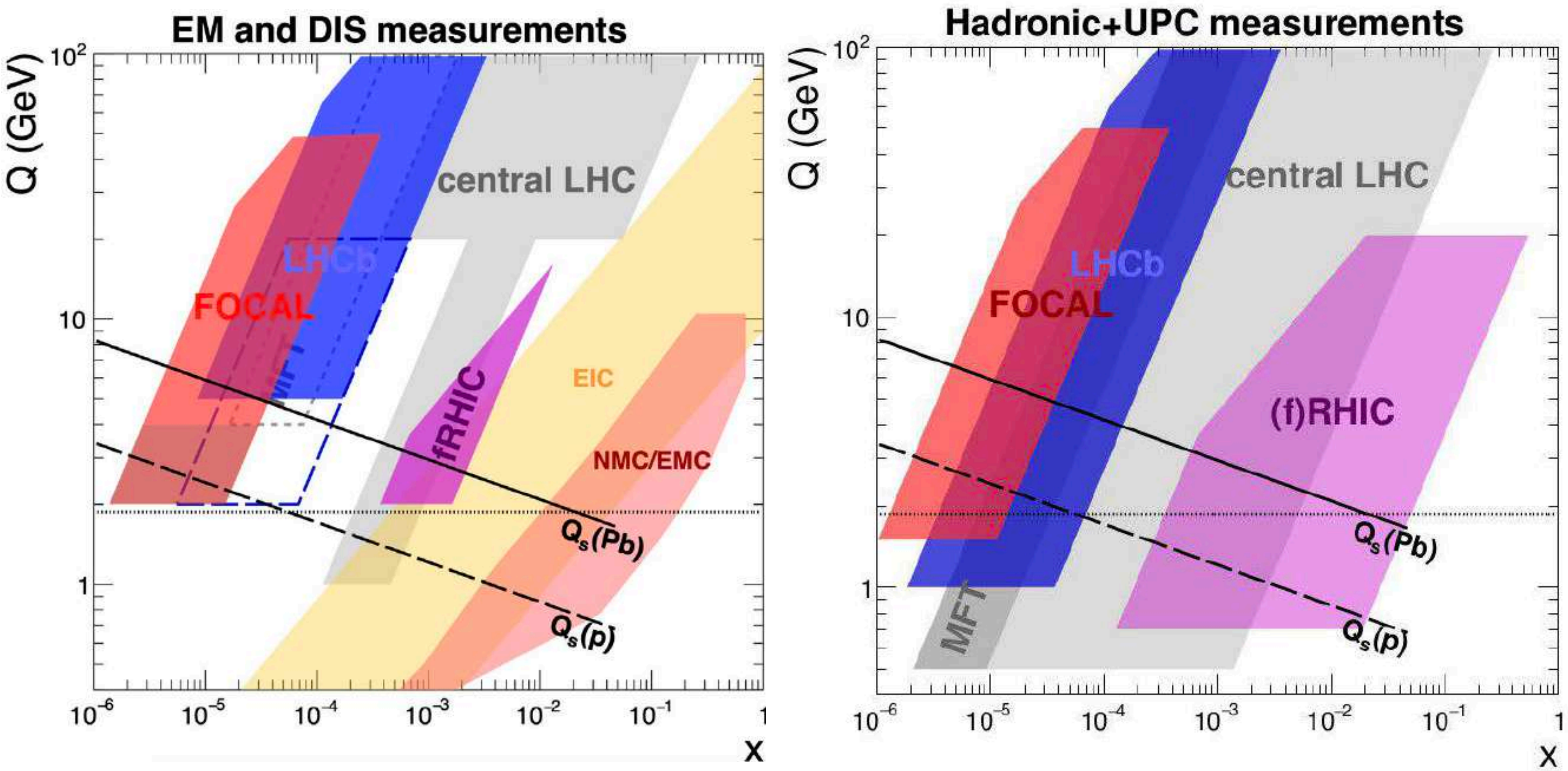




LHC forward p+A: observables are inclusive π^0, jet, direct γ, γ-jet, di-jet

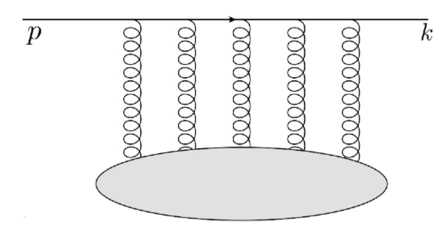
e+A DIS: observables are integrated σ, structure functions (F_2, F_L)

Forward LHC (pA) vs. EIC (eA)



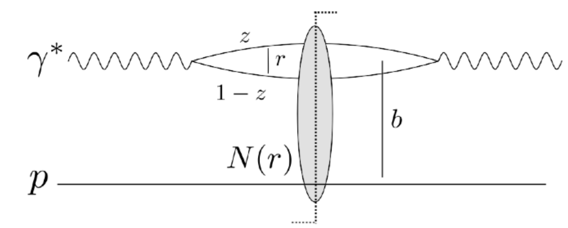
ALICE

Forward pA
at high energies



ePIC

DIS (EIC) eA



- 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
- Forward LHC: **Significantly lower x**
- EIC: **Precision control of kinematics + polarization**
- **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 Physics with ALICE FoCal detector

Takahiro Fusayasu
Saga University

1. Introduction to ALICE experiment
2. QGP discovery and measurements
3. CGC: how the QGP generated?
4. FoCal development

FoCal installation for LHC Run4

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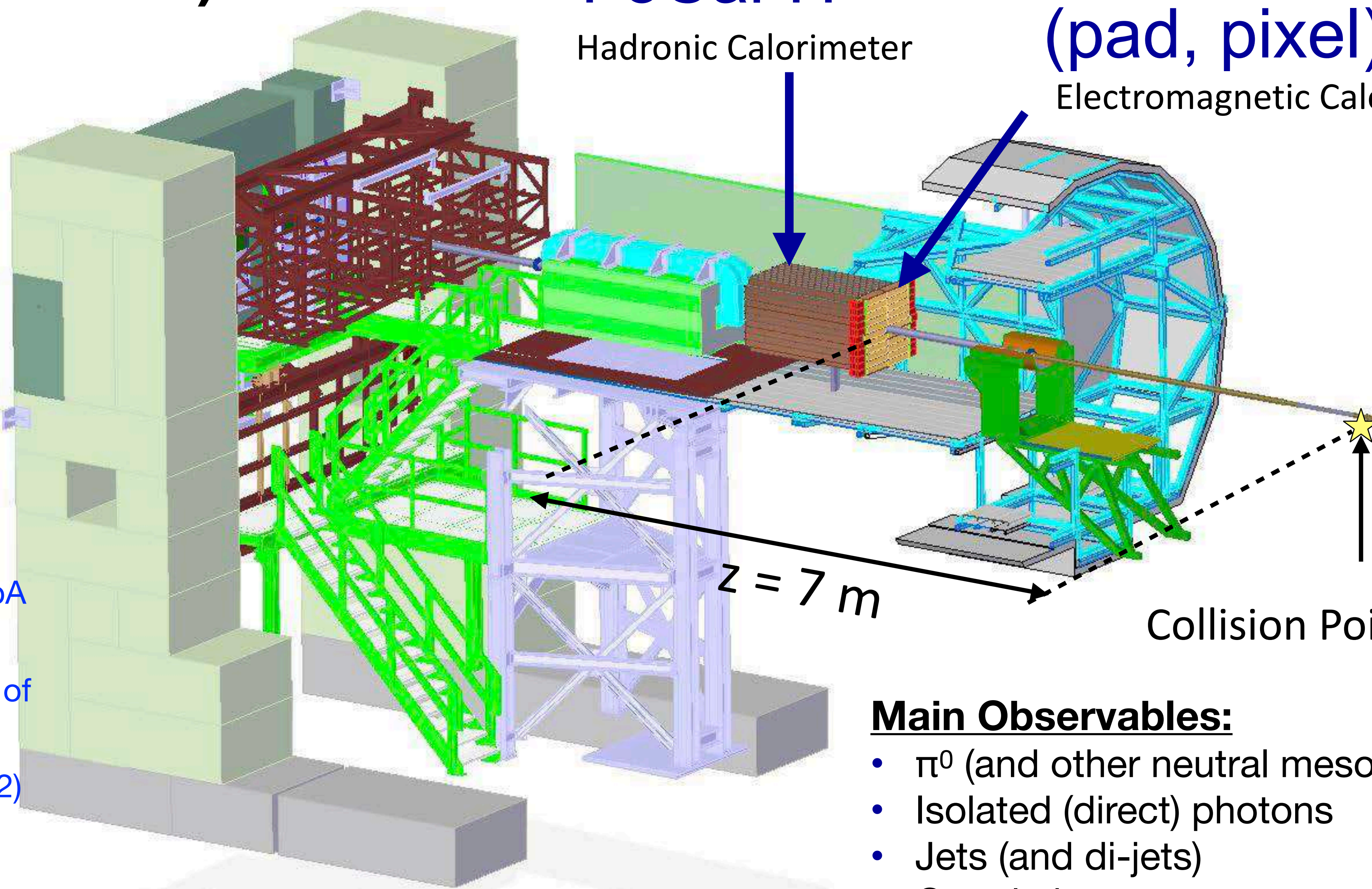
Forward LHC (FoCal)



- **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 (LINK)**

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

$3.4 < \eta < 5.8$

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

Main Observables:

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

by T. Chujo

FoCal installation for LHC Run4

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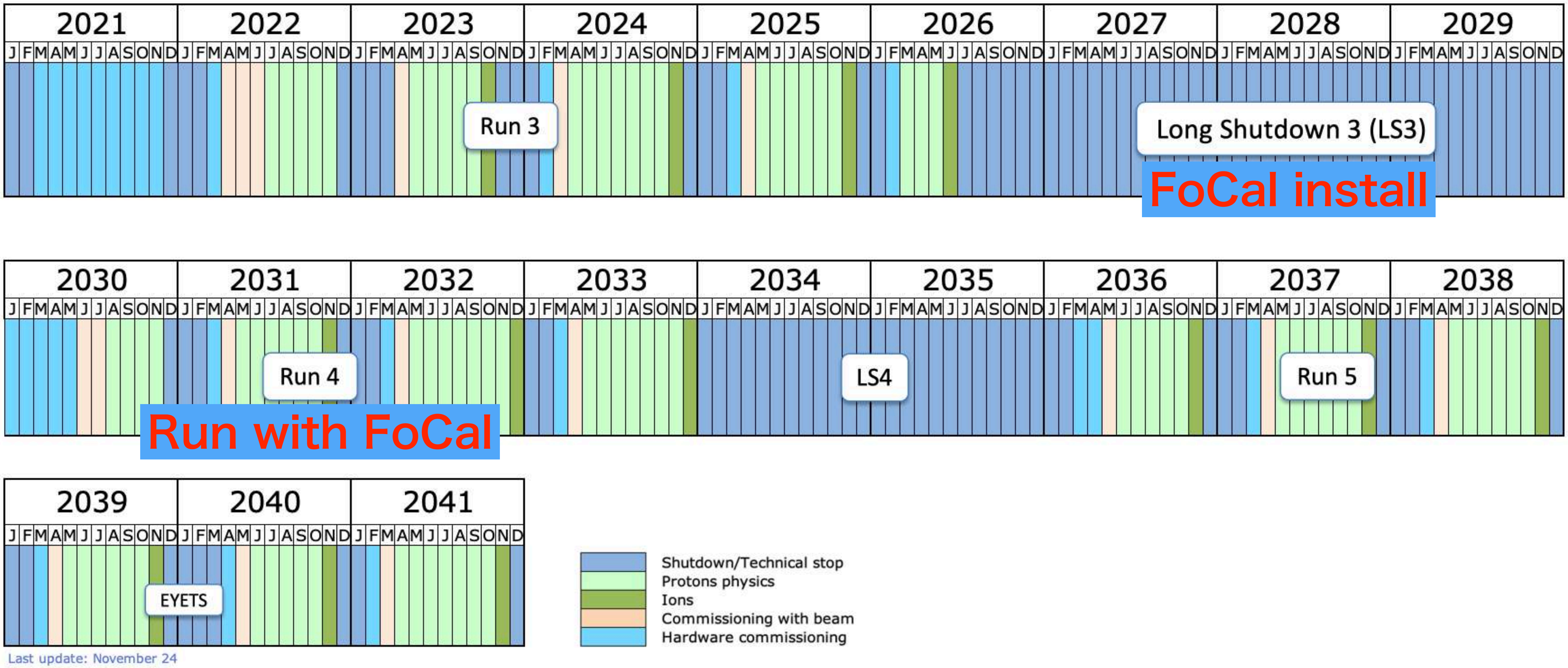

FoCal Japan

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**

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広島大学
RIKEN
国立大学法人奈良女子大学 Nara Women's University
NiAS 長崎総合科学大学 Nagasaki Institute of Applied Science
SAGA UNIVERSITY 国立大学法人 佐賀大学
熊本大学 Kumamoto University

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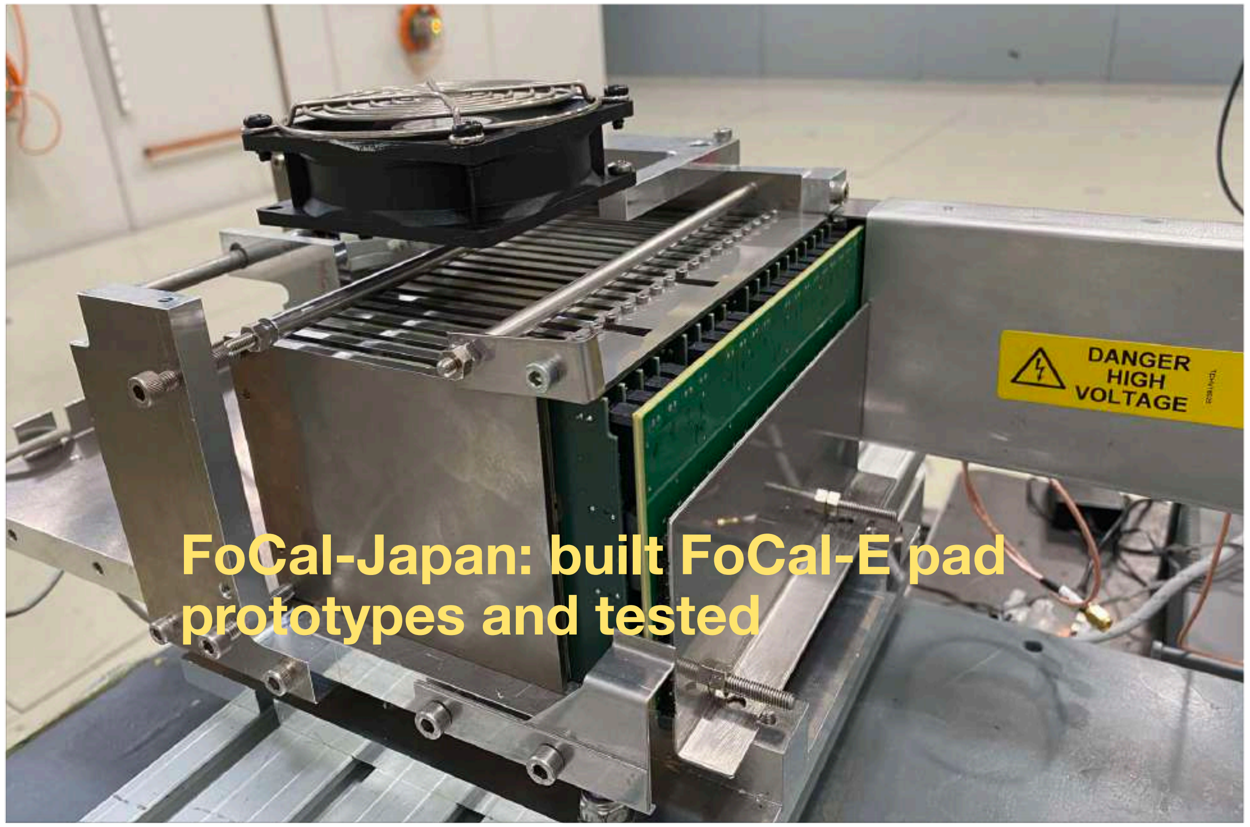

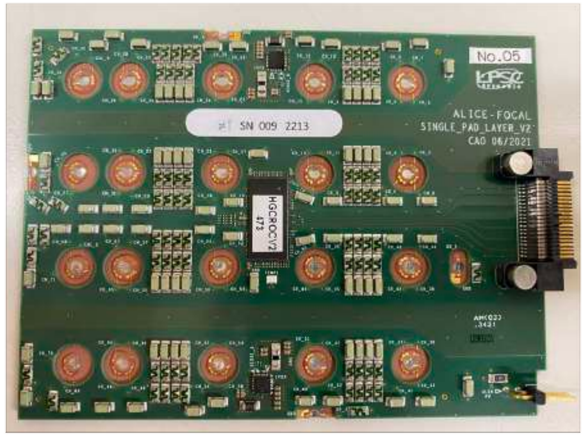

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Uniqueness of FoCal detector

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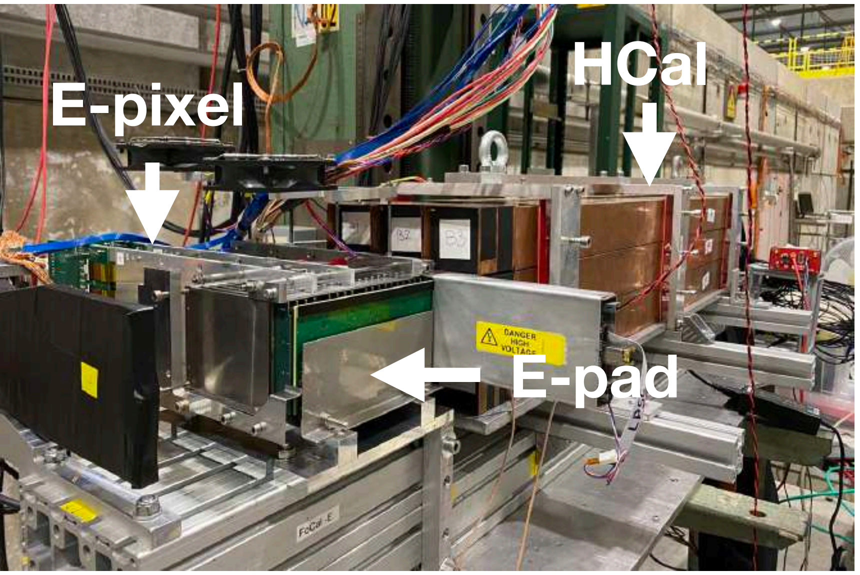
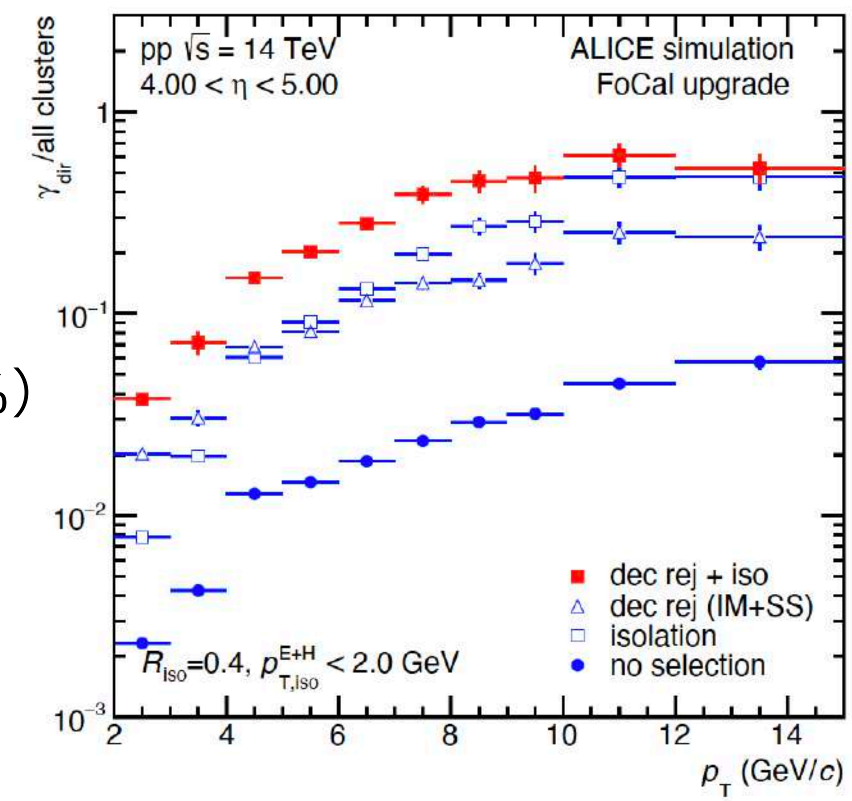
Uniqueness of FoCal detector



PS/SPS test beam in 2022

Isolated photon ID



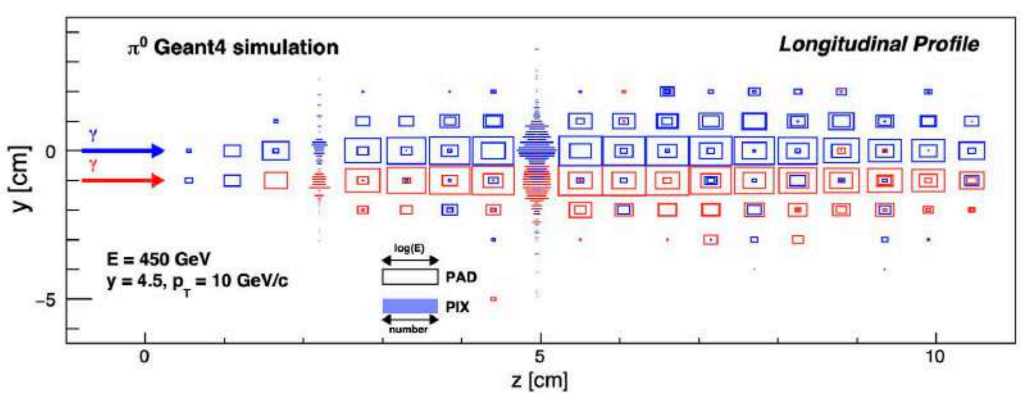
1） **High two photon separation power**（<~5mm, energy resolution ~3%）

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

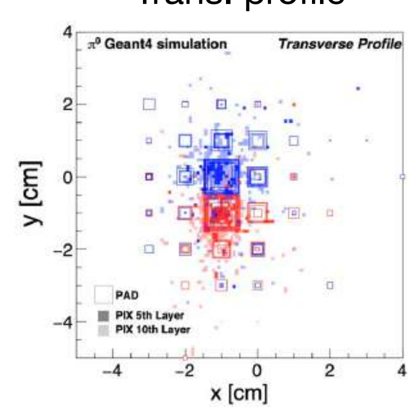
3） **High radiation tolerance**（10^{13} (1MeV neutrons) / cm^2）

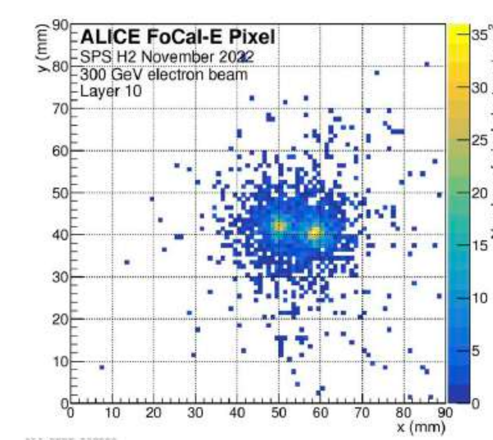
→FoCal-E pad: mainly developed by FoCal-Japan group

Longitudinal profile (2γ showers)



Trans. profile





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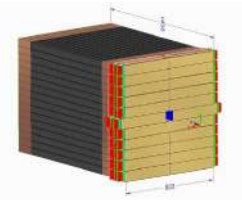
Saga U. → Mass evaluation of HGCROCv3 readout chips

Look at the slides by M. Yokoyama

Saturation signal in FoCal



Saturation signal in FoCal (1)

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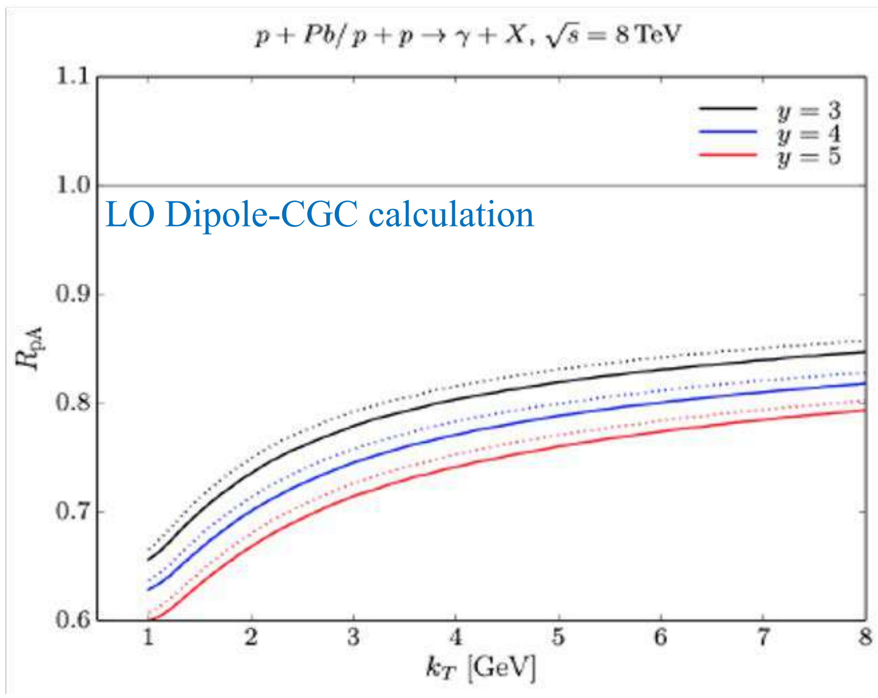
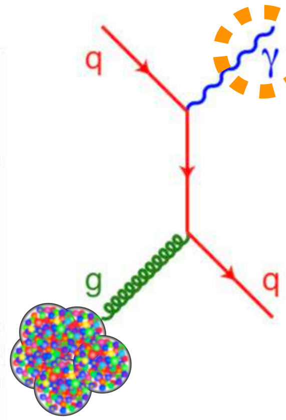
R_{pPb}: forward γ

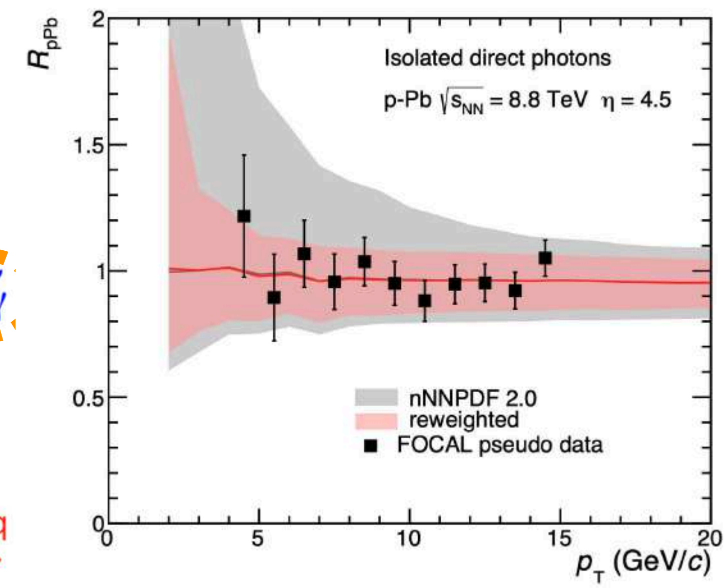


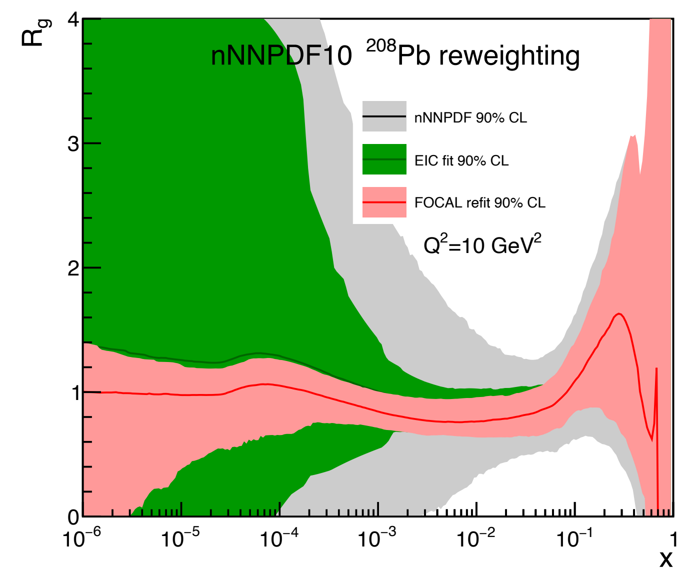


- Large suppression at low p_T for isolated γ

  Isolated γ: qg → qγ ; k_T~ Q_{sat}

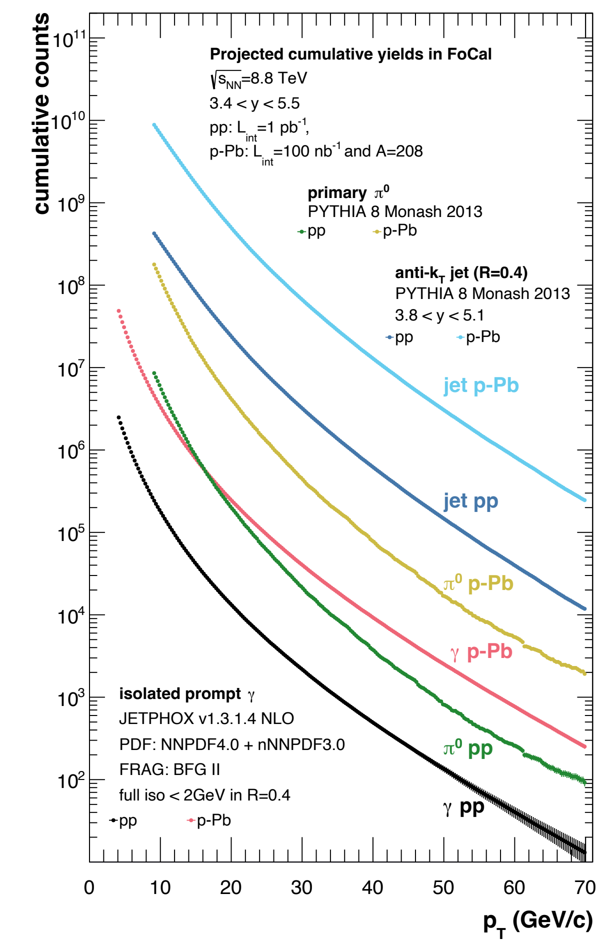
Ducloué, Lappi, and Mäntysaari, Phys. Rev. D97 (2018) 054023





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

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};

by T. Chujo

FoCal PIXEL trigger development

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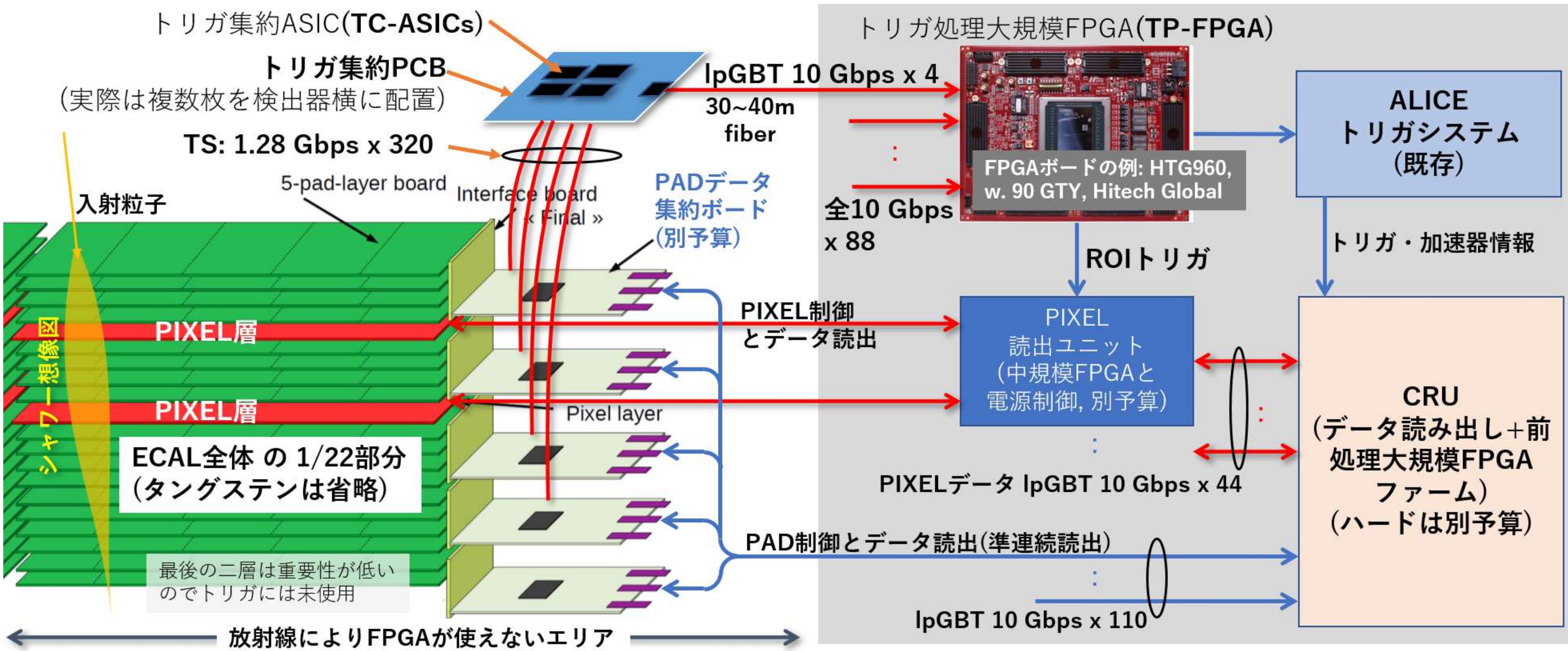

- ALICE readout rate: 1MHz (pp), 500kHz (p-Pb)
- PIXEL readout (ALPIDE) is not fast enough! ~100kHz
- PIXEL trigger should delay by 1.2us → Physics triggering of PIXEL is difficult.
- Our plan: For the tower with important signals, ROI (Region Of Interest) trigger is issued. PIXELs with ROI and neighboring PIXELs are chosen to be readout.
  → Japanese group's important task!

Summary

- QGP was discovered and its characteristics were measured by RHIC and LHC experiments. The QGP was found to be almost perfect fluid.
- Pre-QGP state is not identified and generation process of the QGP is unknown.
- CGC is a candidate of pre-QGP state. ALICE FoCal is appropriate for low-Q^2, very low-x studies and being prepared for LHC LS3 installation. Combined with future EIC experiment results, wide range of x evolution is expected to be established, together with discovery of gluon saturation modeled by CGC.