Introduction to the ALICE experiment

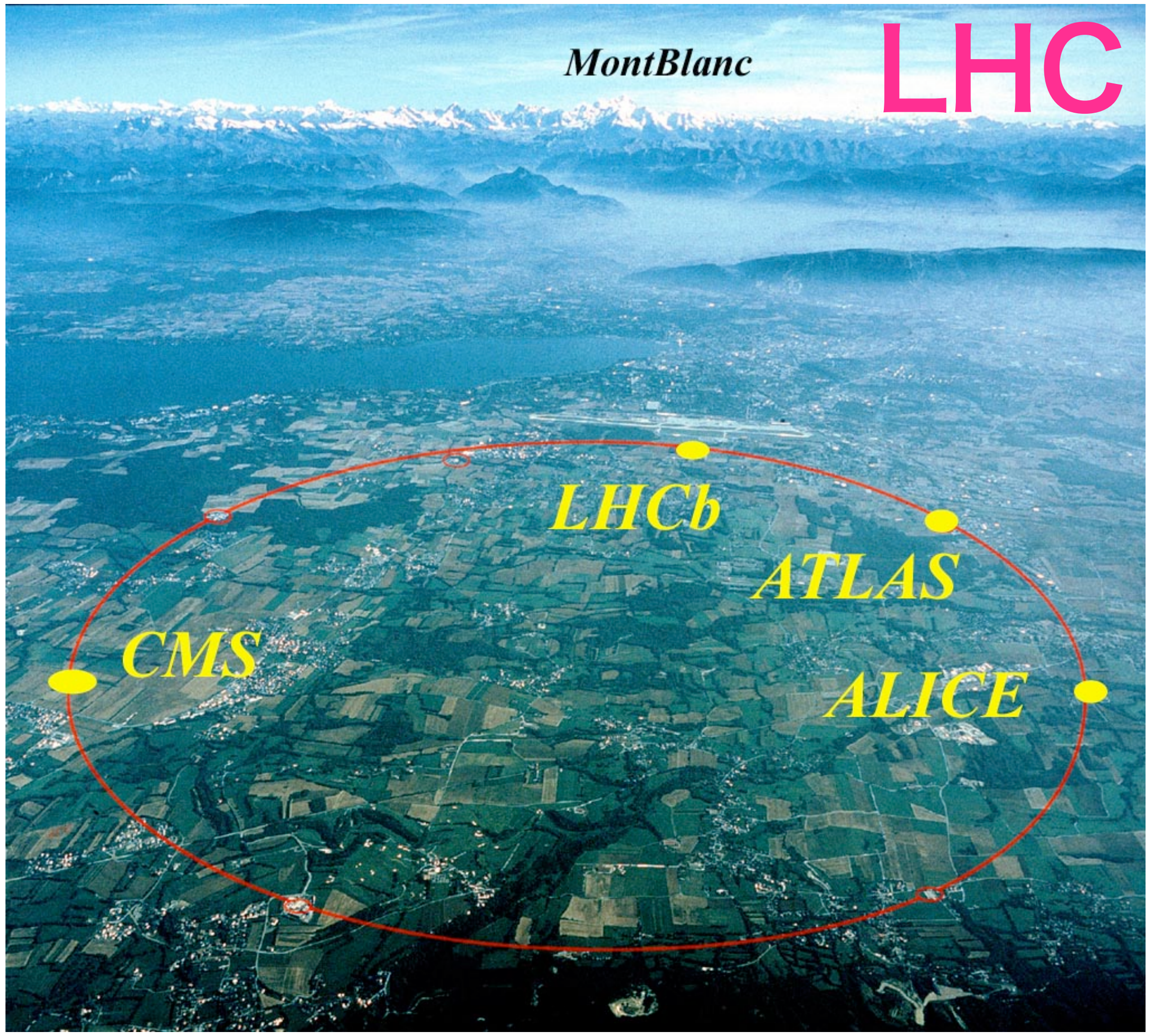
Takahiro Fusayasu
Saga University

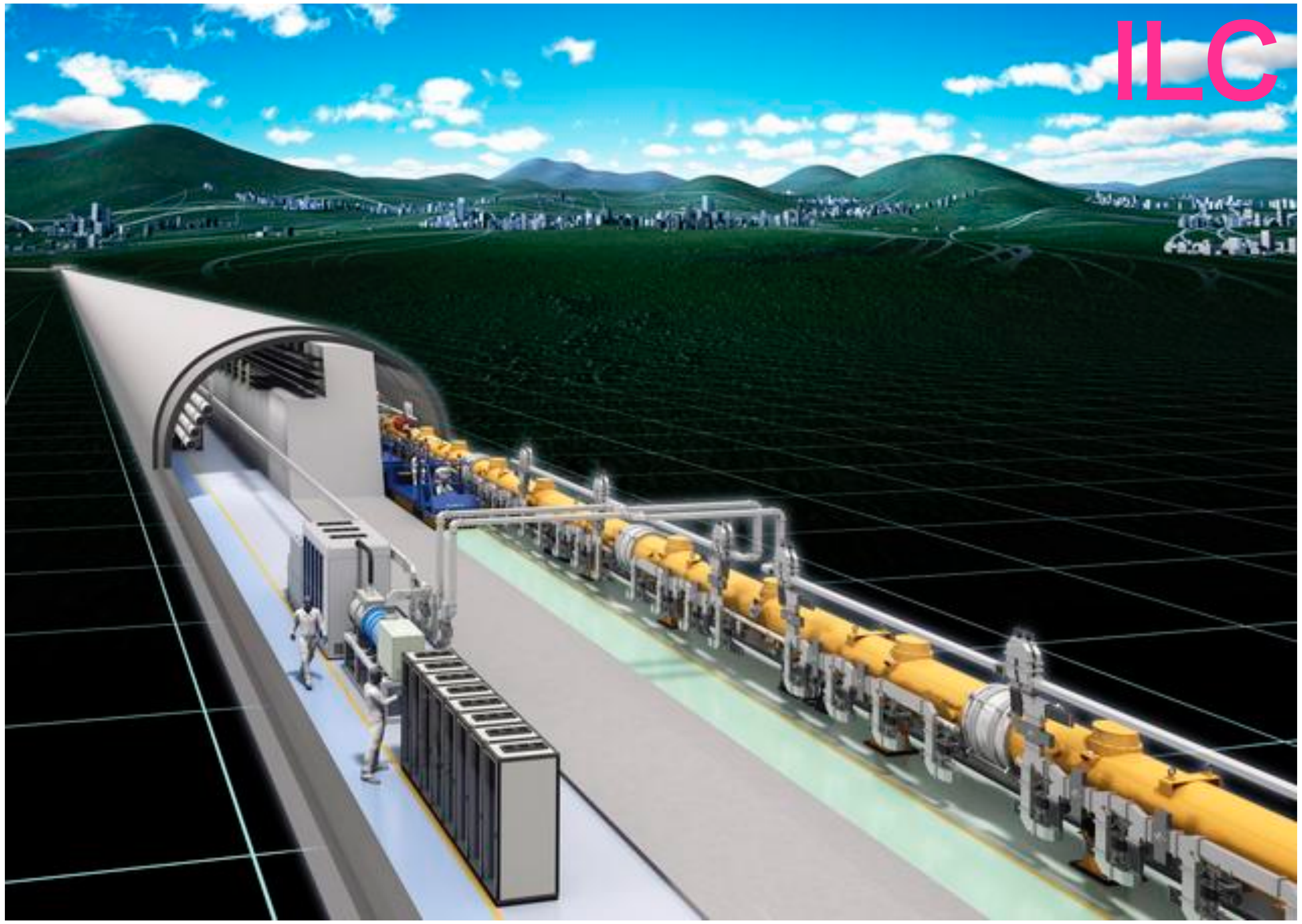
1. Introduction
2. Basics of Heavy Ion Collisions
3. Results from RHIC/LHC

High Energy Physics Group @ Saga U.

Attends two experiments

- The ALICE collaboration @ LHC. Joined in 2021.
  Study of quark-gluon plasma.
- International Linear Collider (ILC).
  Higgs factory for precise Higgs measurements.





High Energy Physics Group @ Saga U.

Members

Prof. Akira Sugiyama (retiring Mar/2023)
Assoc. Prof. Takahiro Fusayasu → Join the WS ☆

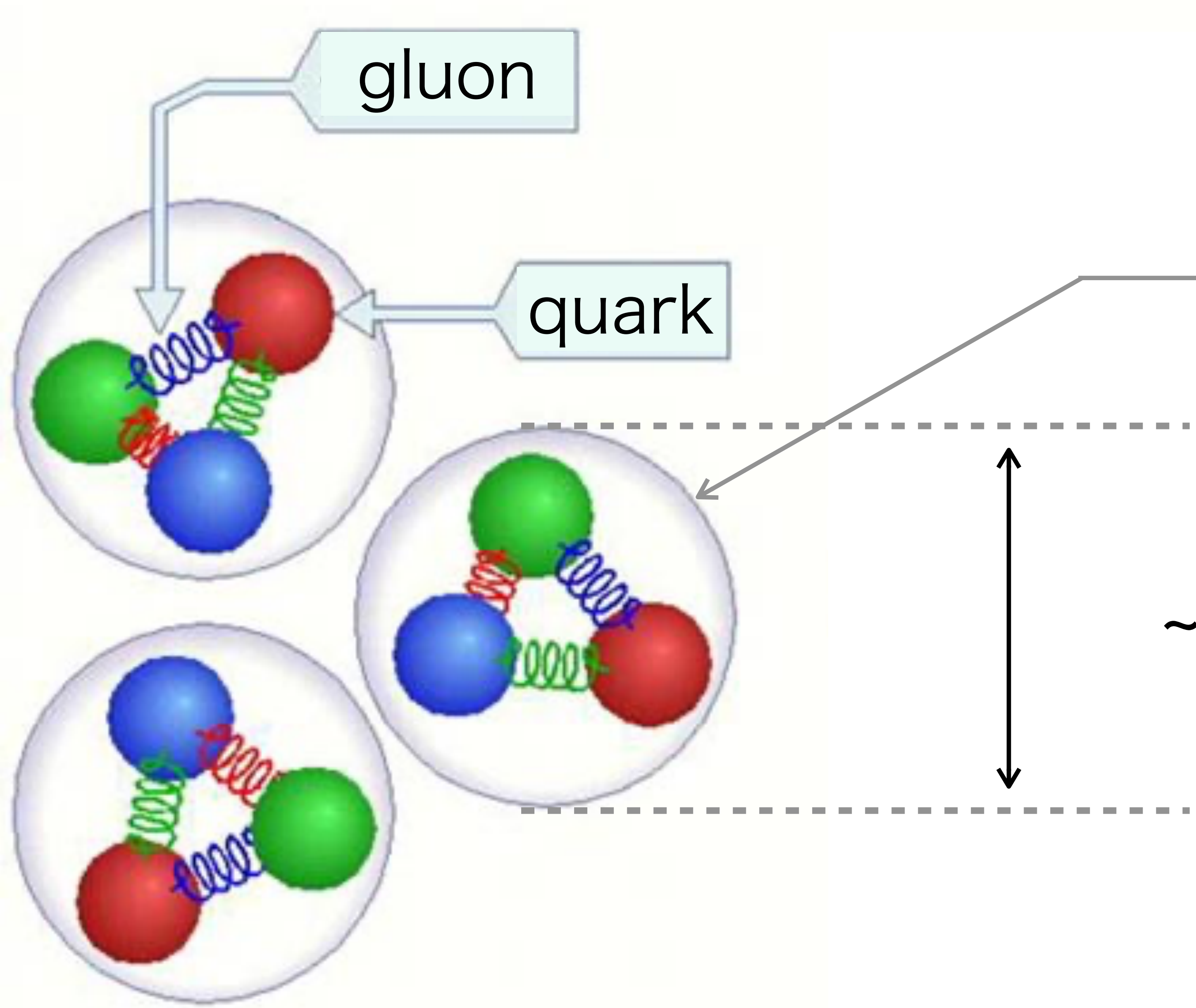
Mr. Tomoki Ishida (M2) ALICE electronics
Mr. Yu Tsukigawa (M2) Gas detector
Mr. Kamei Kazuma (M2) Gas detector

Mr. Haruki Kanemitsu (M1) ALICE electronics → Join the WS ☆
Mr. Keiichiro Higuchi (M1) ILC TPC electronics → Join the WS ☆

Mr. Kai Ishizuka (B4) → Join the WS ☆
Mr. Ryota Iwanaga (B4)
Mr. Toshiyuki Ono (B4)
Mr. Yuta Shimazaki (B4)
Mr. Kaito Mine (B4)

Introduction

Quark-Gluon Plasma



Mass ~ 1 GeV

~1fm (1×10^{-15} m)

Inside hadrons

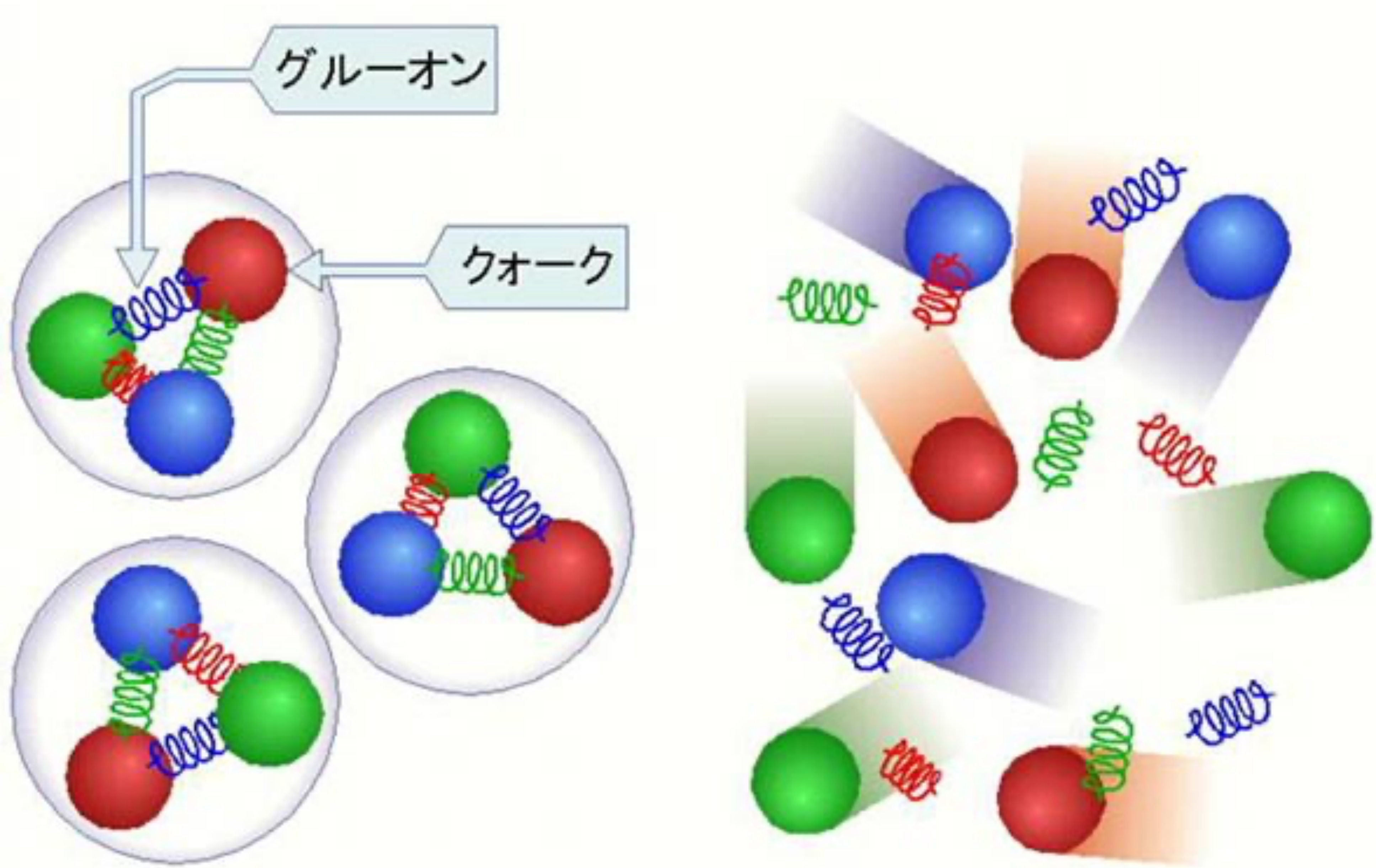
$$V \propto \frac{A}{r} + Br$$

Huge force if large r.
Cannot extract a quark.

Proton, neutron, other hadrons

Quarks are bound by gluons,
which mediate strong interactions

Quark-Gluon Plasma

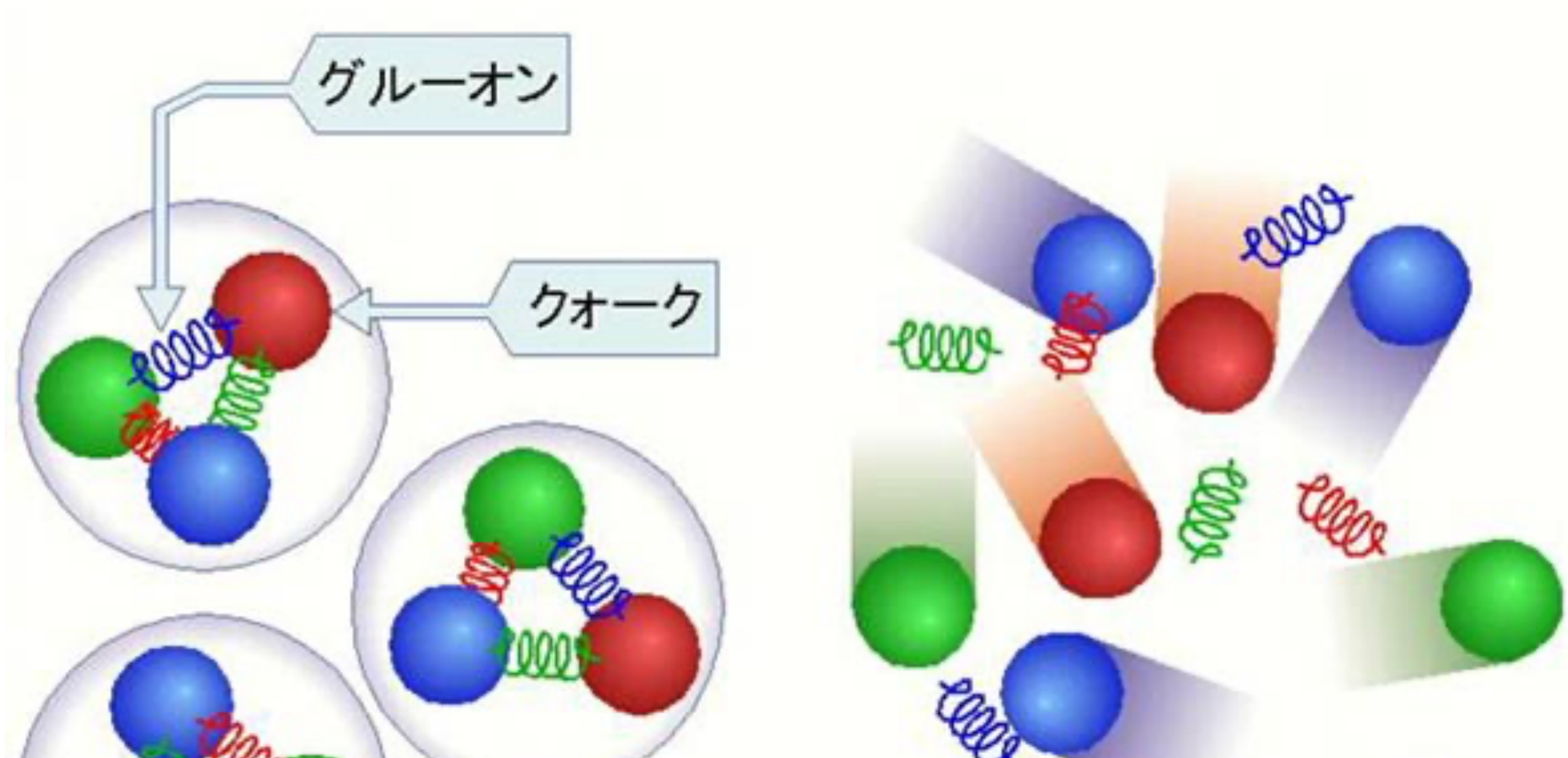


Protons, neutrons → **Quark-Gluon Plasma (QGP)**

High T, high P

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

Quark-Gluon Plasma



Quarks carry only 1% of p, n mass. Other 99% is thought to be because of the mechanism “chiral symmetry breaking.”

Chiral symmetry is restored. Important knowledge for the origin of p, n mass, i.e. nuclear mass.

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

High T, high P

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

Water Phase Transition (QED)

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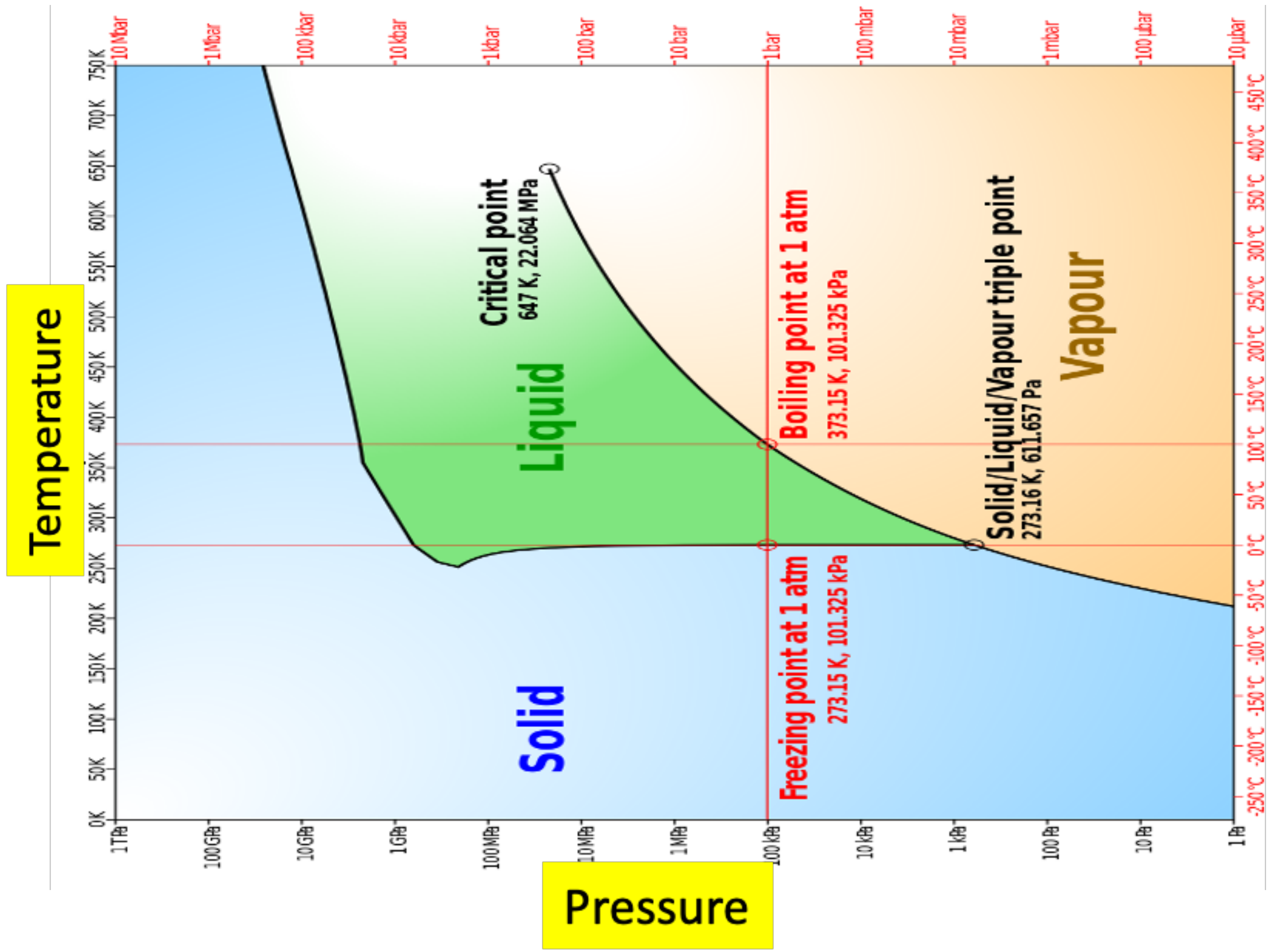
Water phase diagram.

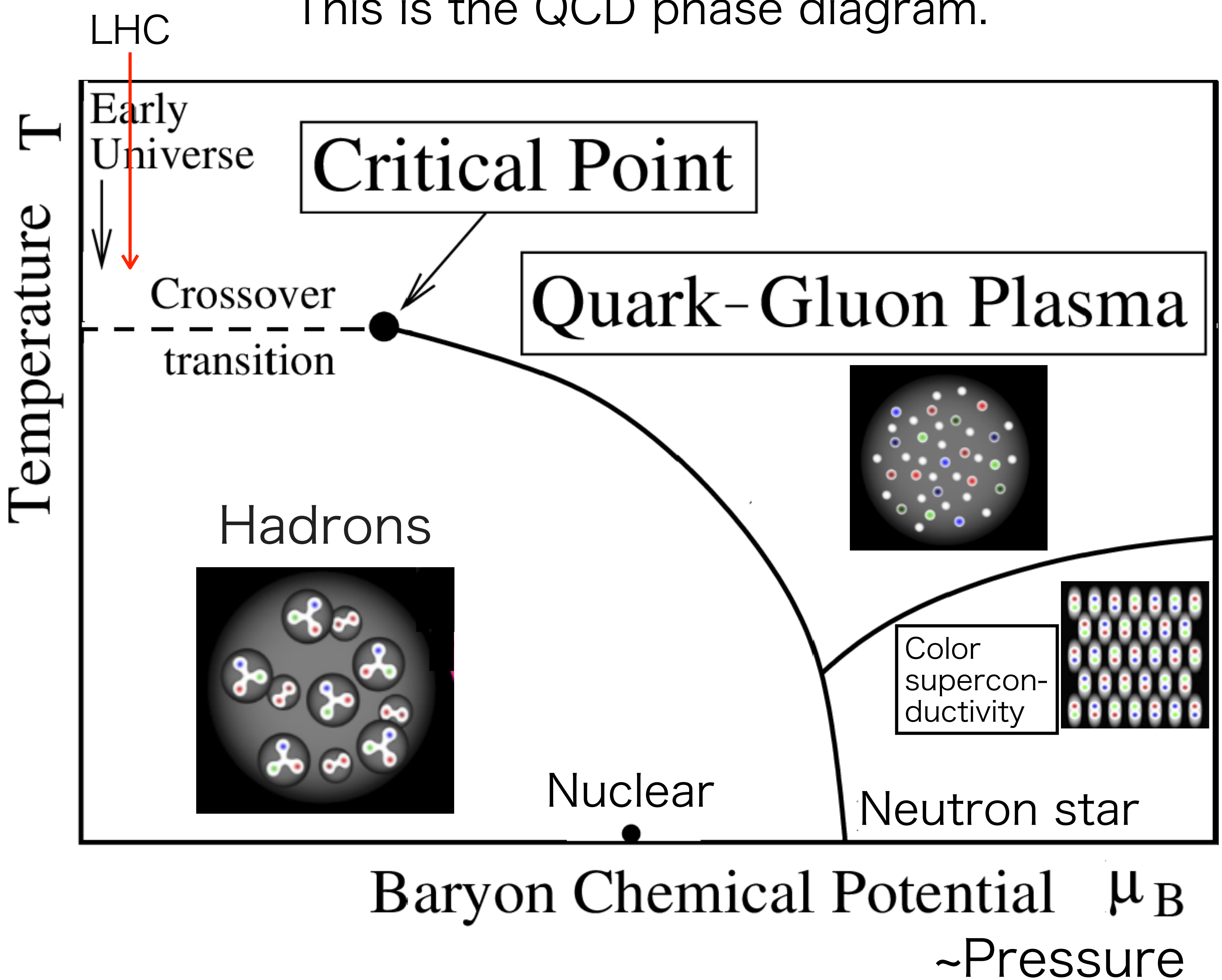
It's based on electromagnetic interactions, i.e. QED.

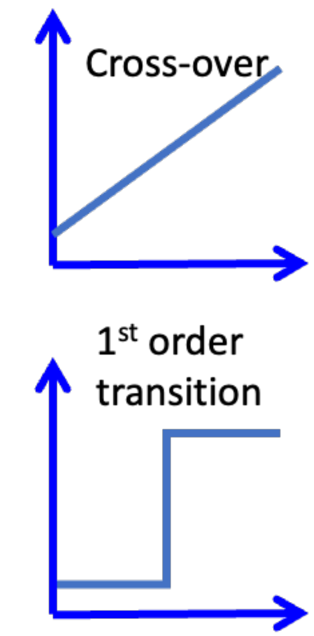


Phases of Quark matter (QCD)

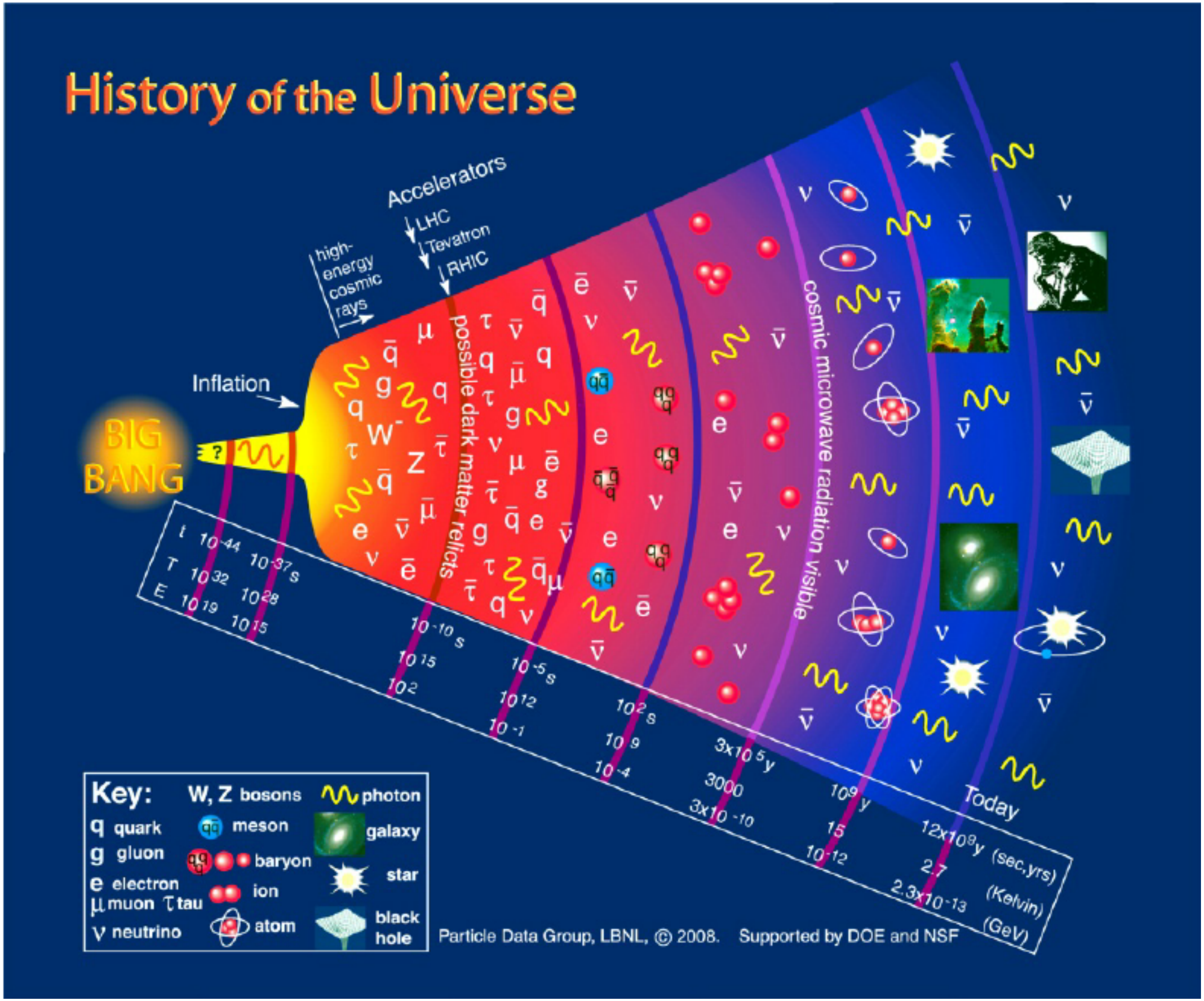
Compared to water phase diagram.

This is the QCD phase diagram.





History of the Universe



History of the Universe

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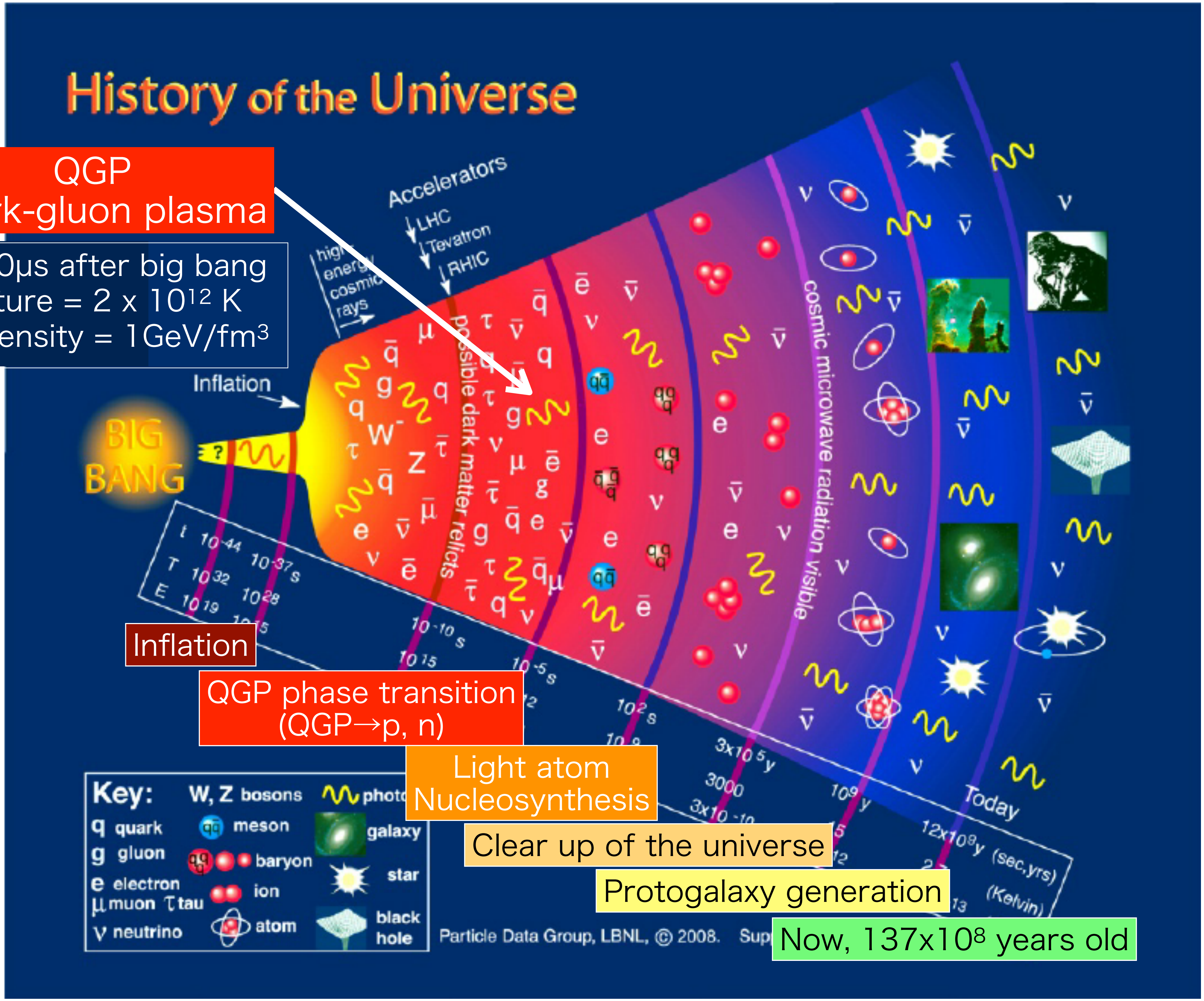

History of the Universe

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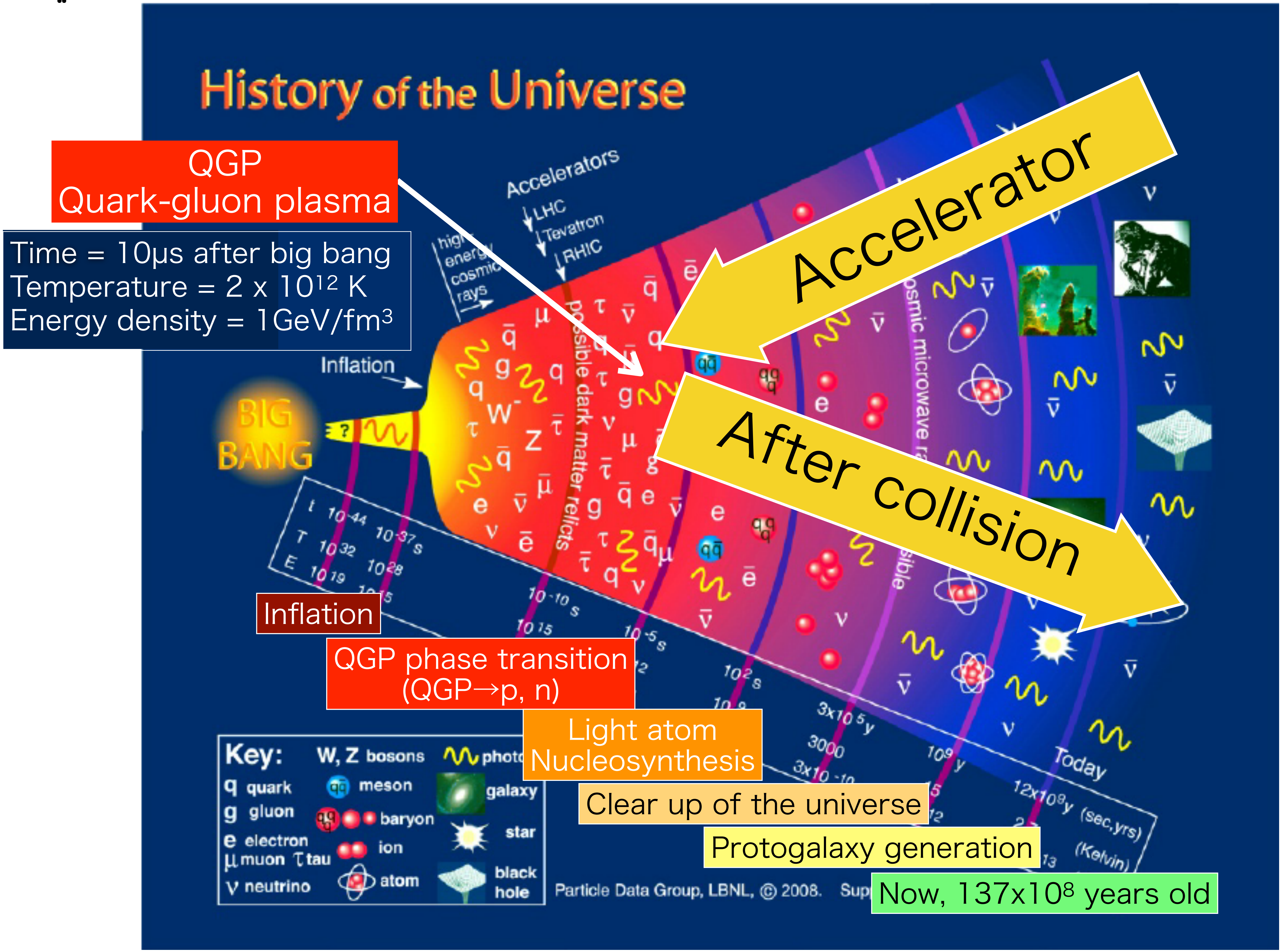

Big bang emulated by little bang

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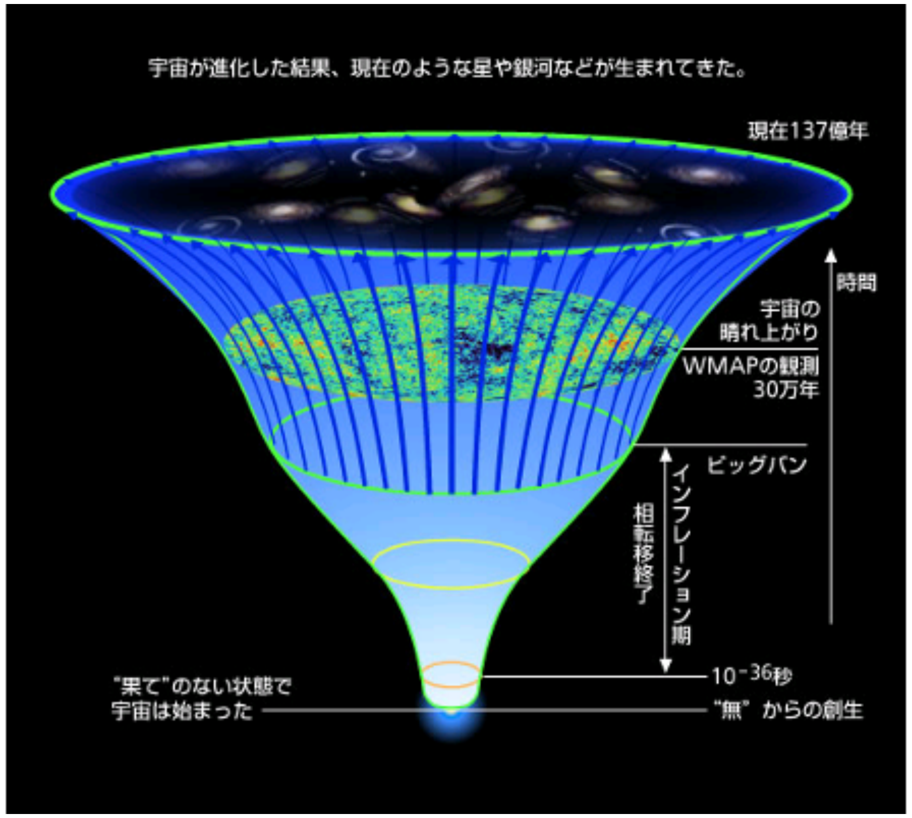
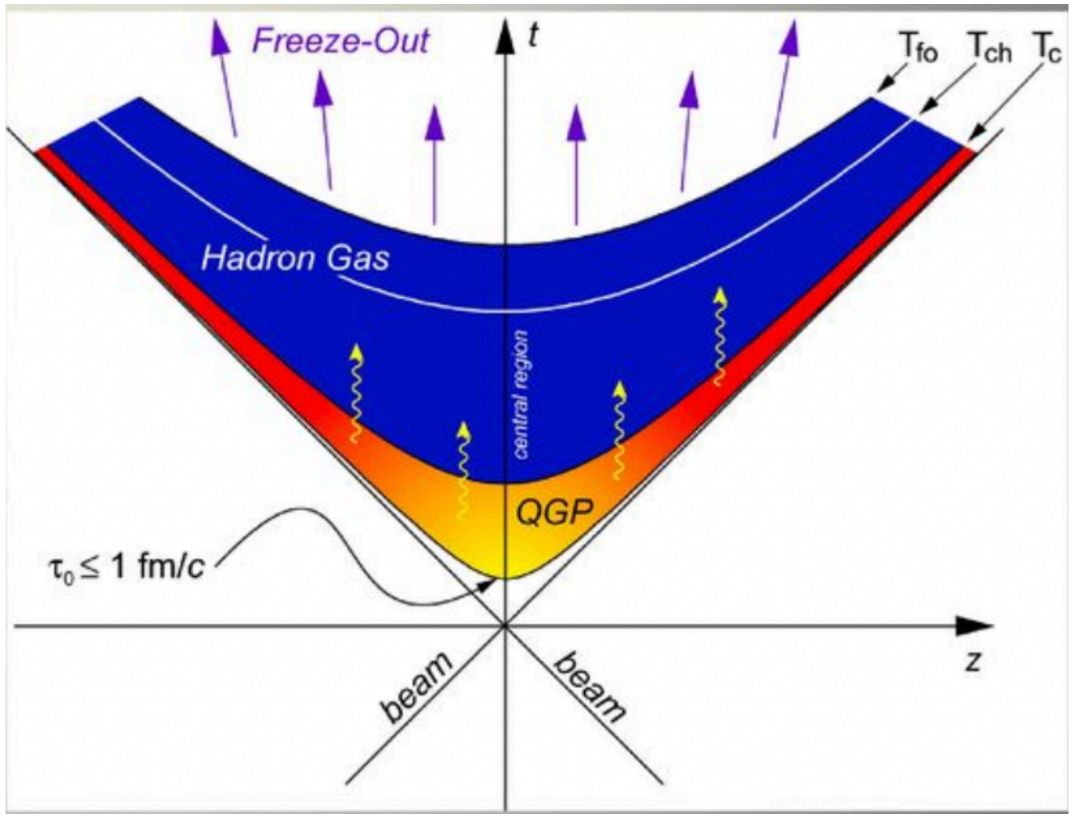
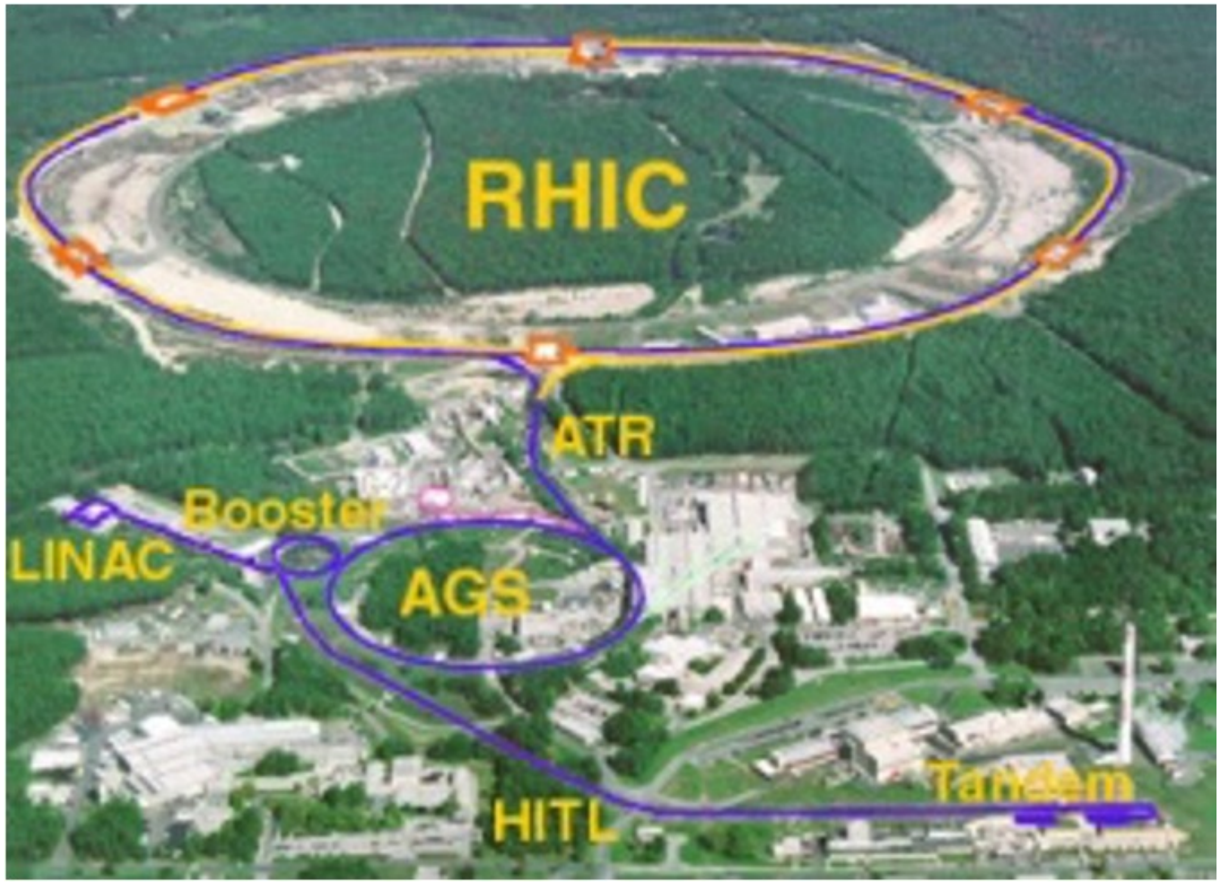


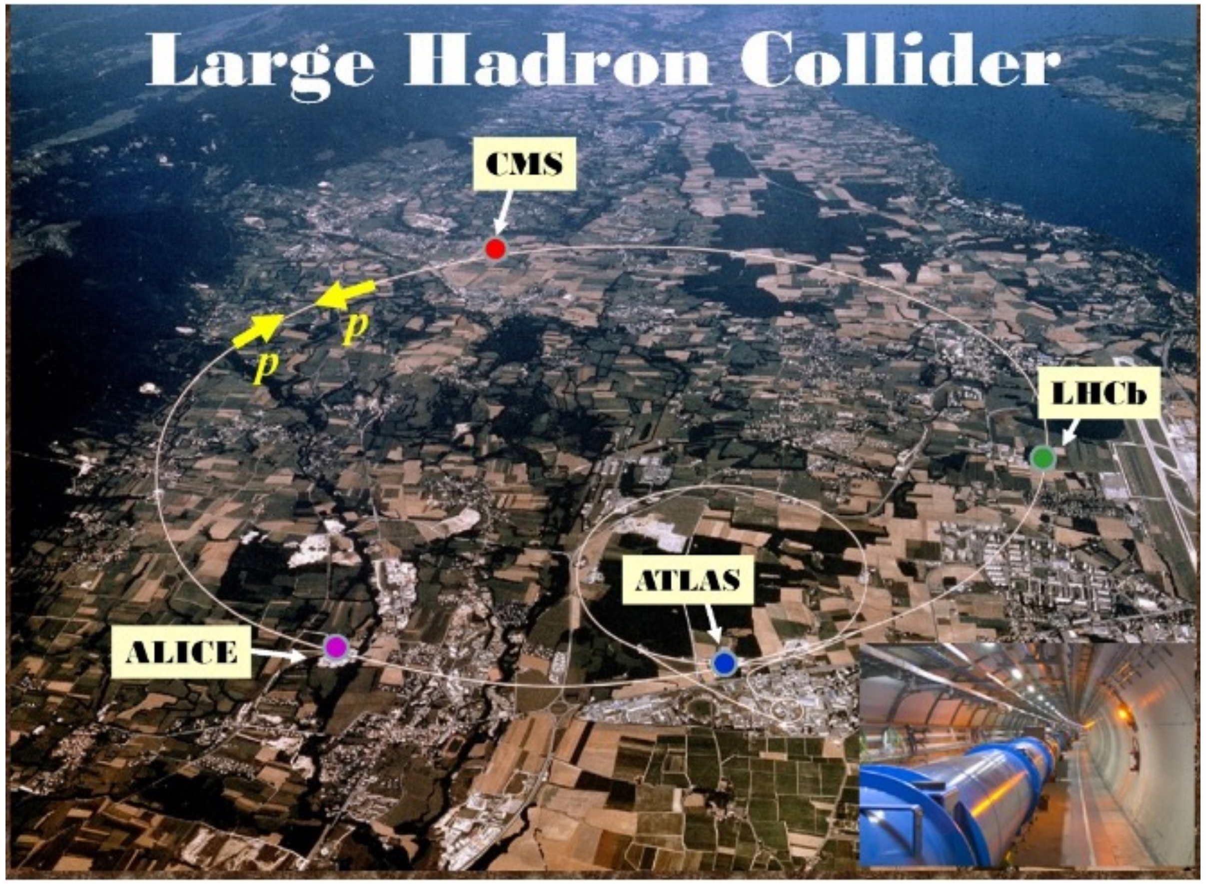
http://www-utap.phys.s.u-tokyo.ac.jp/~sato/index-j.htm



	Big Bang	Little Bang
Time scale	10^{-5} sec	10^{-23} sec
Expansion rate	$10^{5\sim6}$ /sec	$10^{22\sim23}$ /sec
Spectrum	Red shift (CMB)	Blue shift (hadrons)

Heavy Ion Colliders





$\sqrt{s_{NN}}$ = 200 GeV $\sqrt{s_{NN}}$ = 5.02 TeV

5.02 TeV per nucleon collision corresponds to ~1000 TeV per Pb-Pb !!

< Just a very simple question >

$\sqrt{s}$ of pp collision at LHC before the previous shutdown (2018-2022) was 13 TeV.

Why does it decrease to 5.02 TeV for heavy ion collisions?

Heavy Ion Collider Experiments

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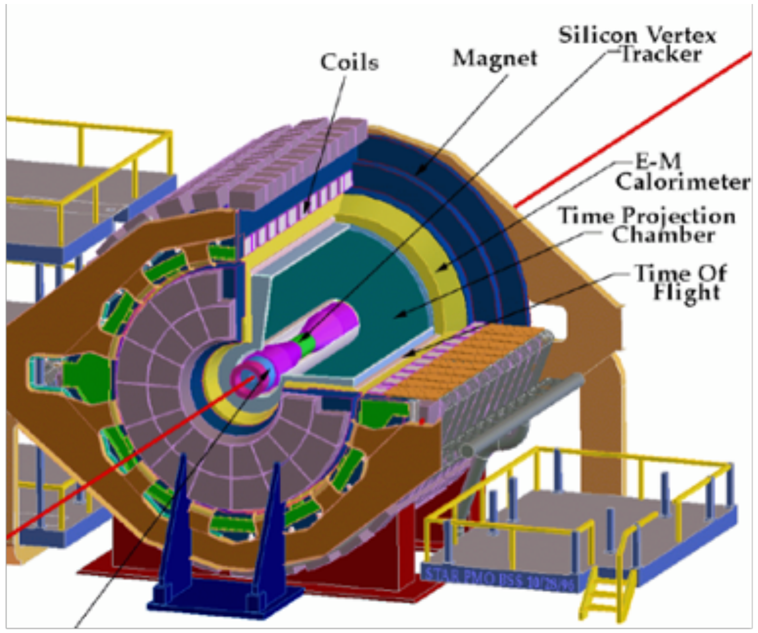
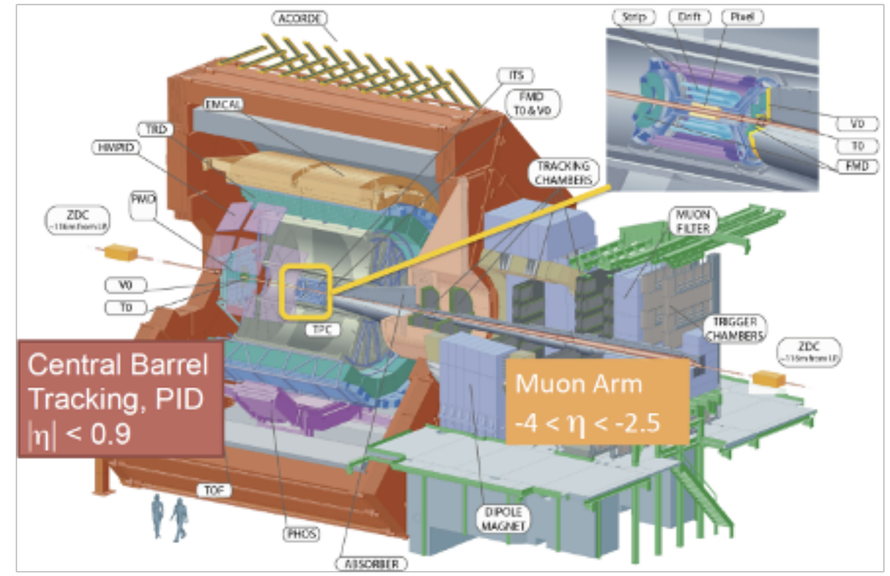
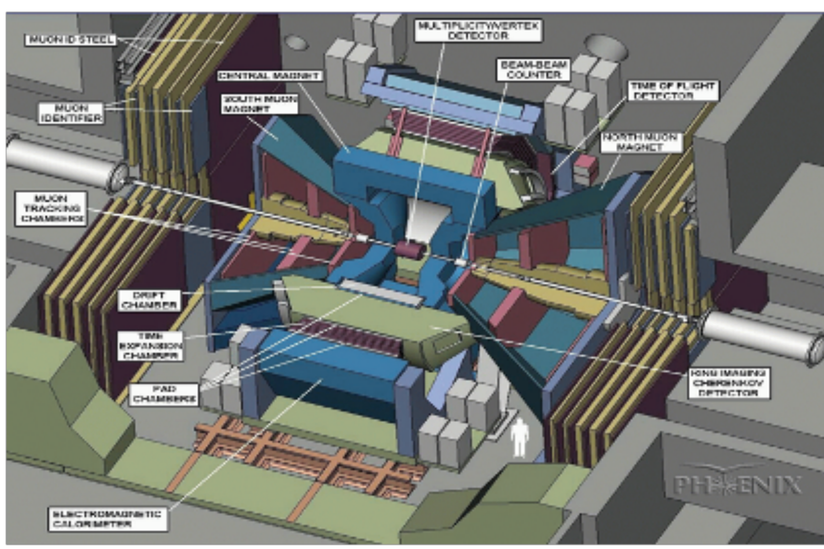
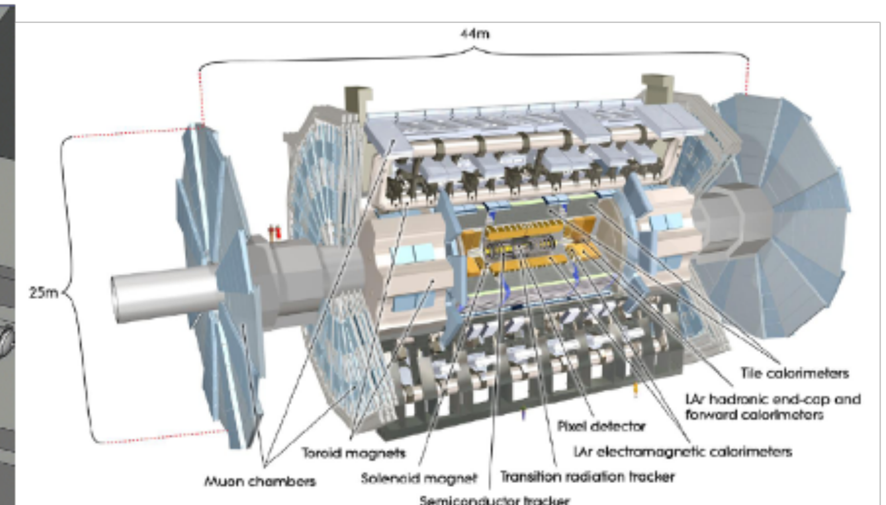




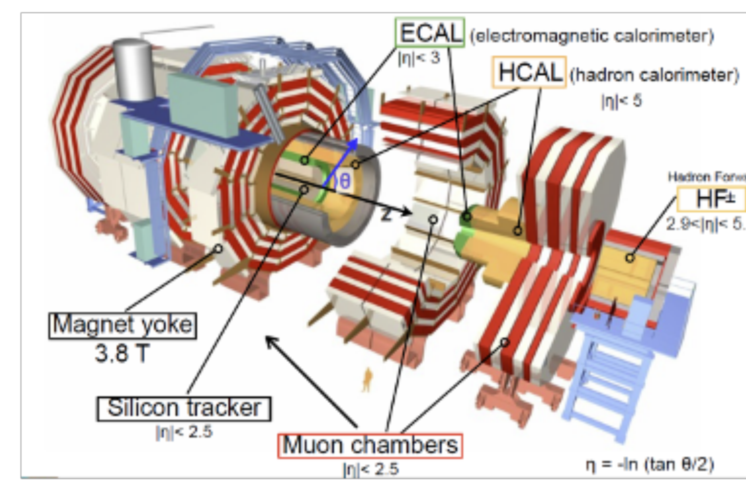
ALICE

PHENIX





ATLAS



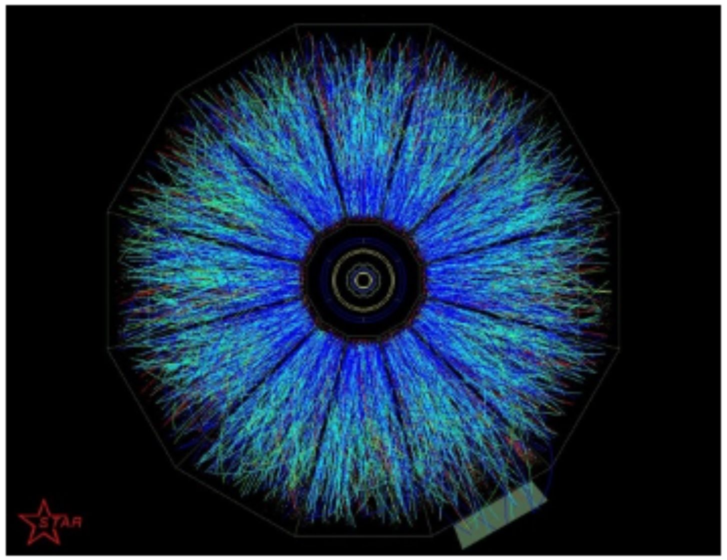
CMS

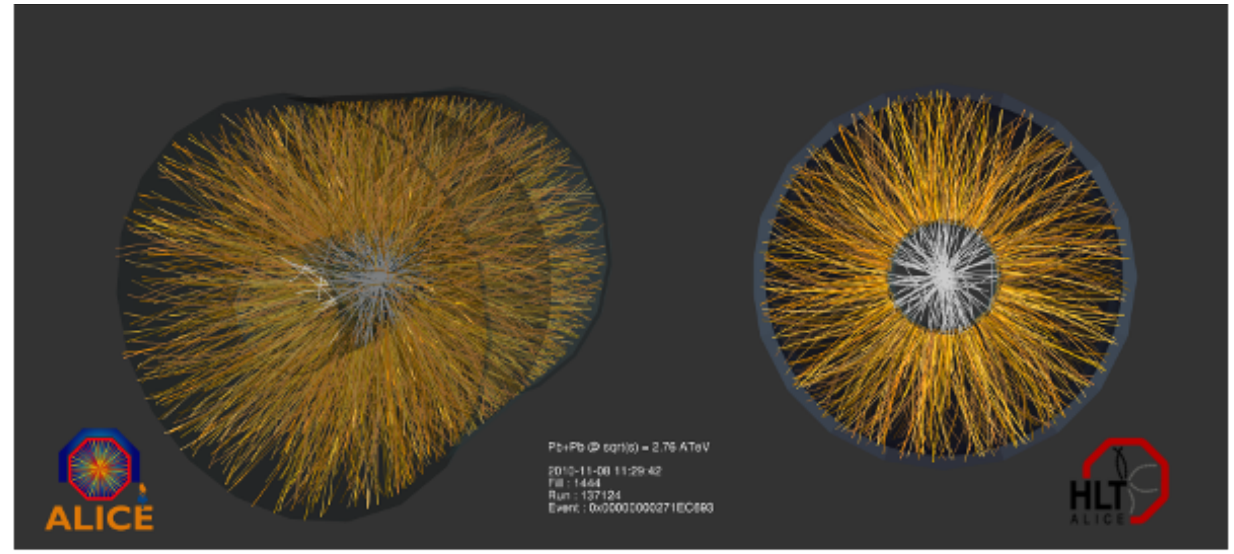
RHIC

LHC

Heavy Ion Collider Experiments

STAR





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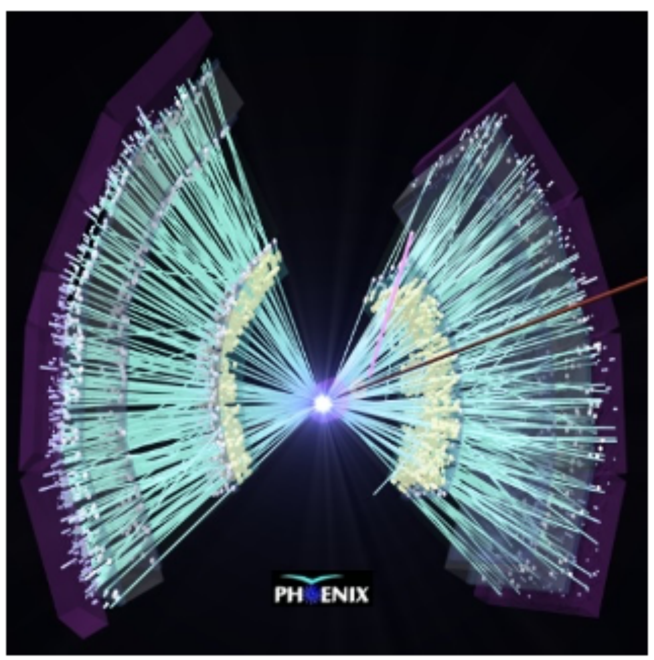

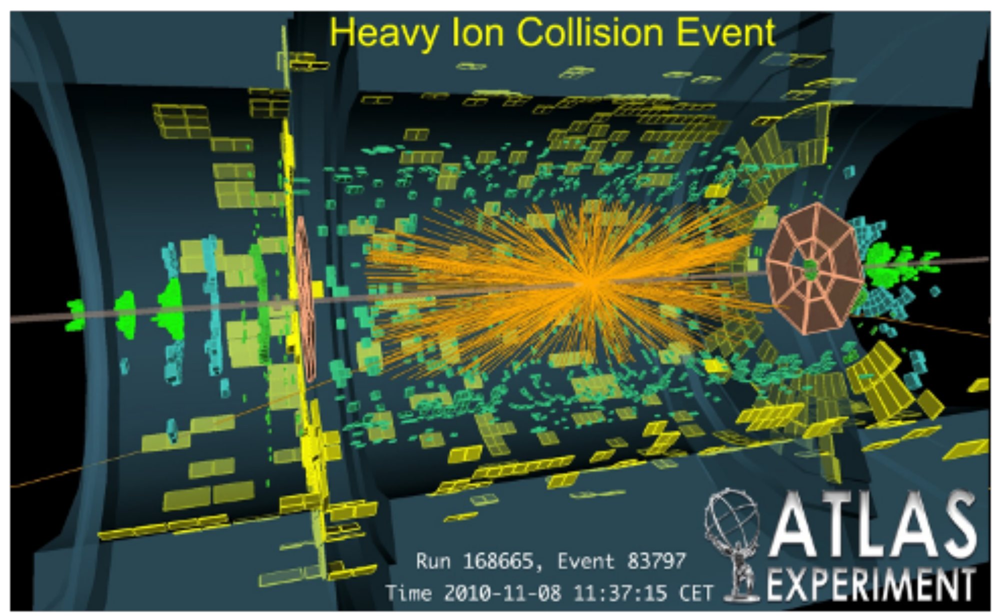

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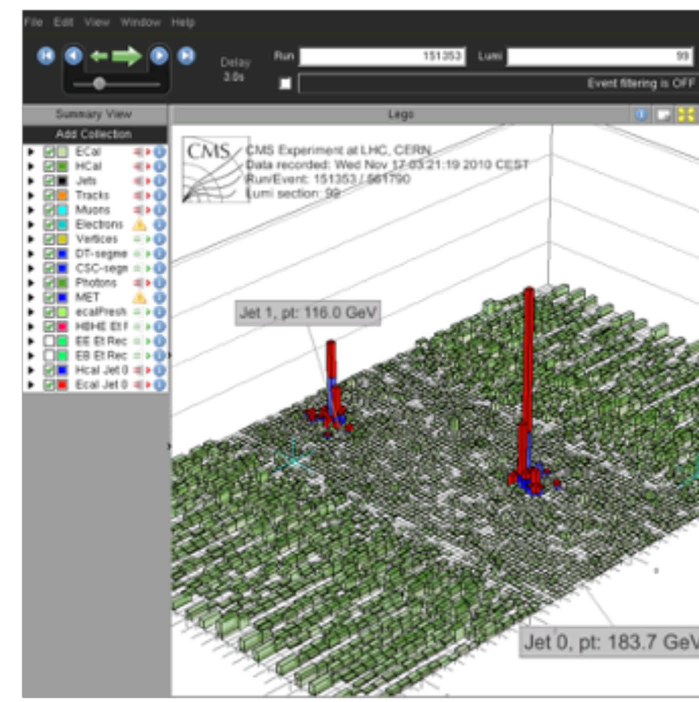
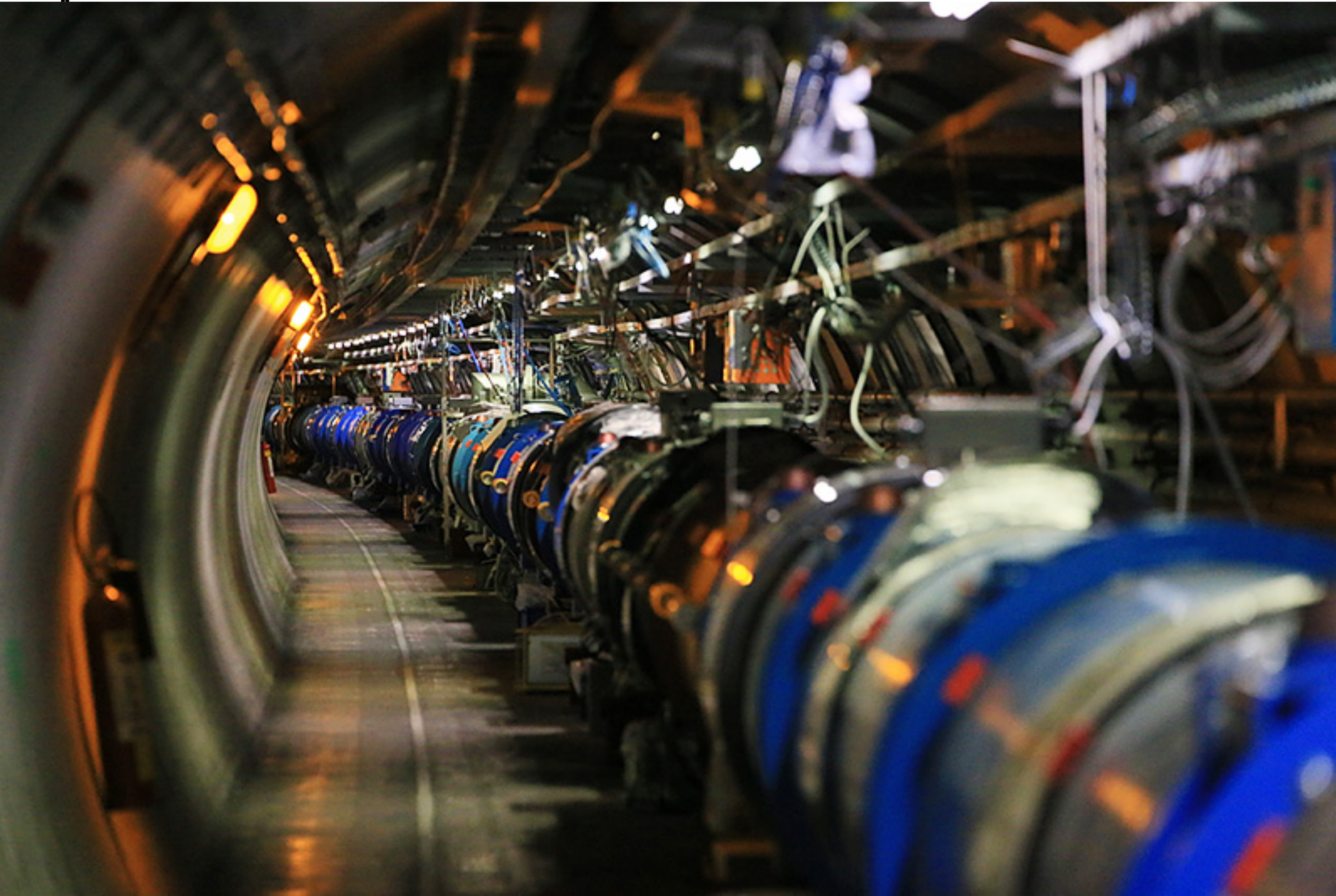


CMS

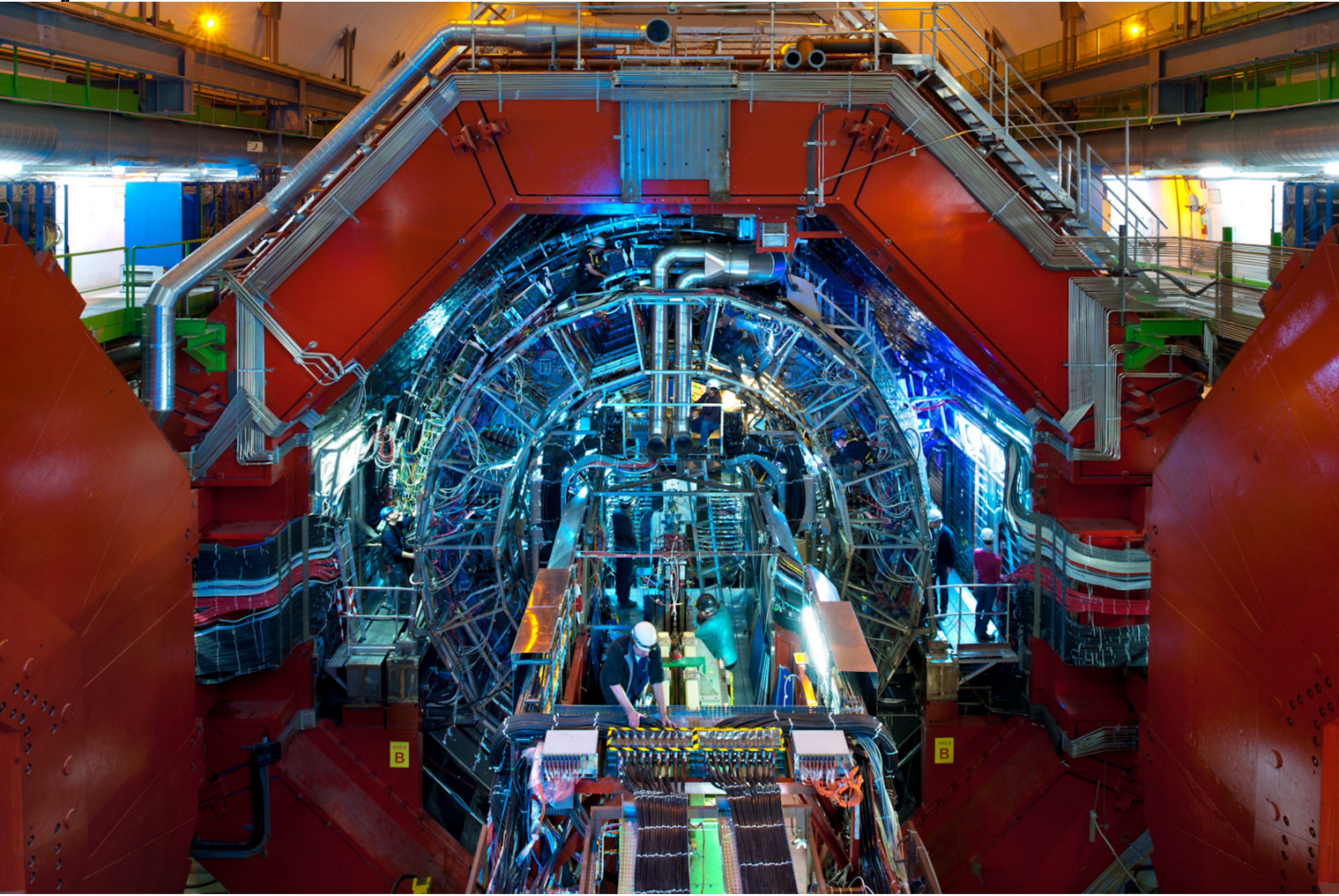
RHIC

LHC

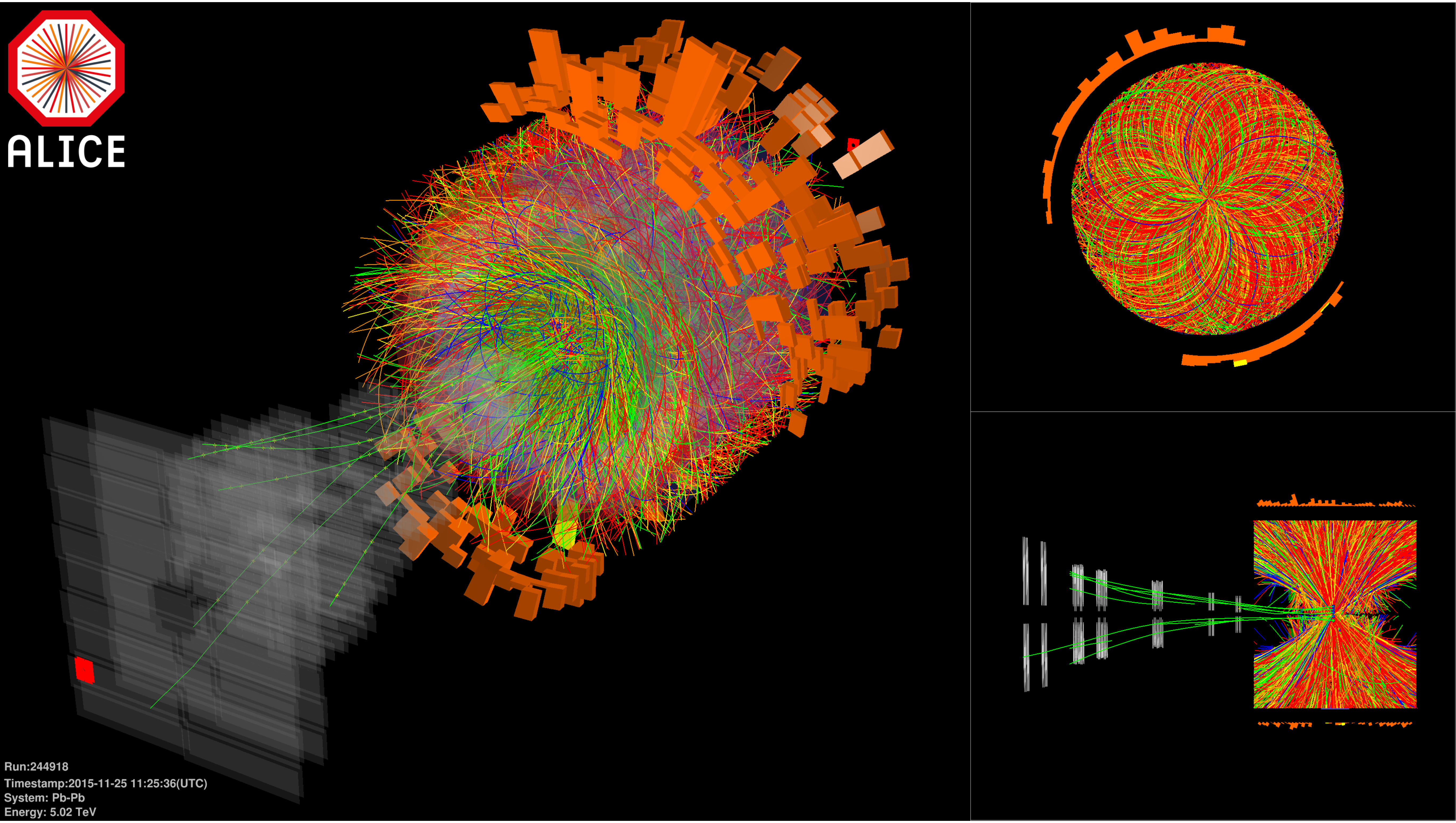
LHC accelerator underground



ALICE detector photo



Pb-Pb collision data by ALICE

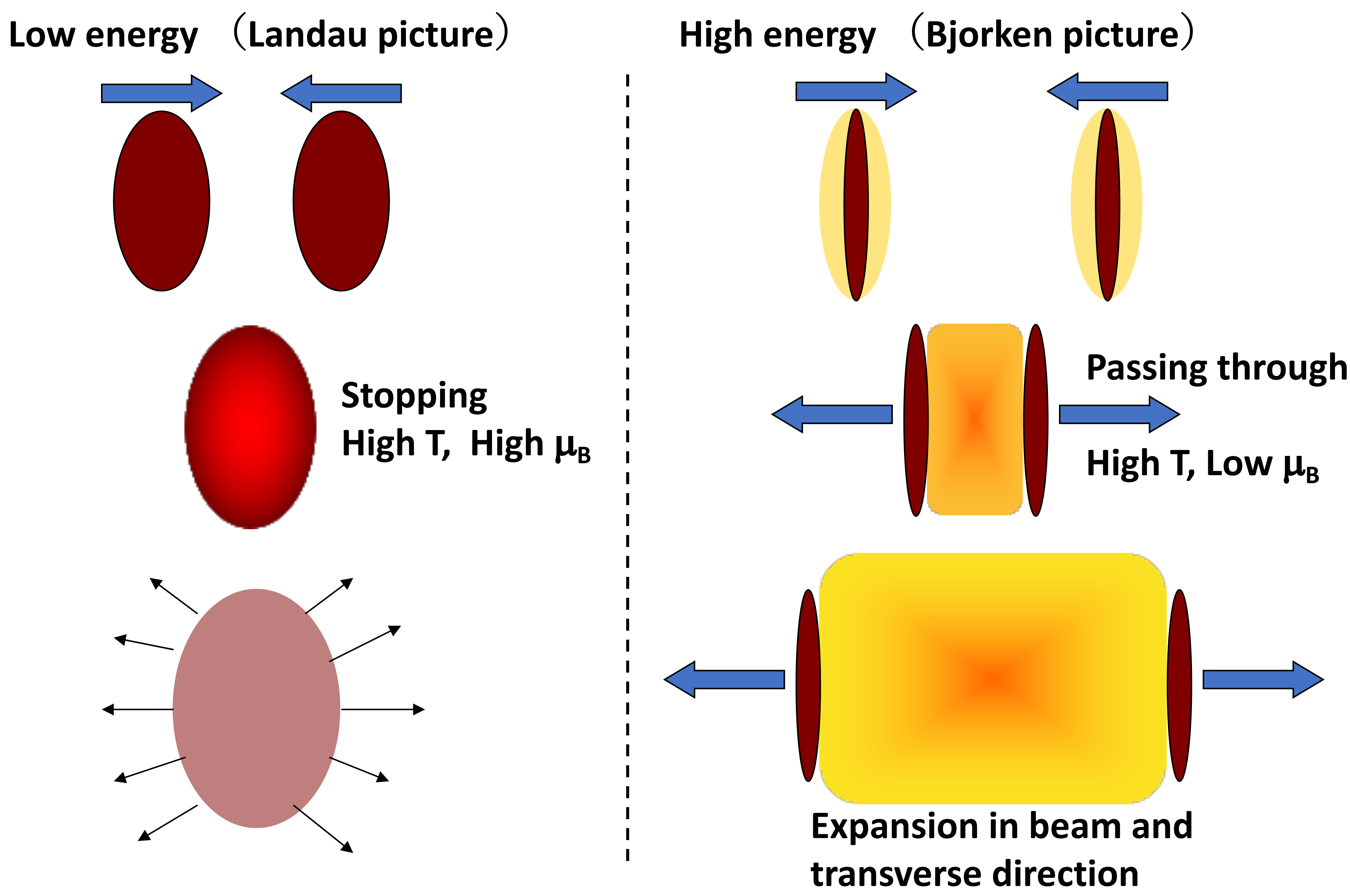


Basics of Heavy Ion Collisions

(Helped by Prof. T. Sakaguchi's slides at YSJW 2020)

Reality of collisions

Rather different collision profile at low and high energies.



Reality of collisions

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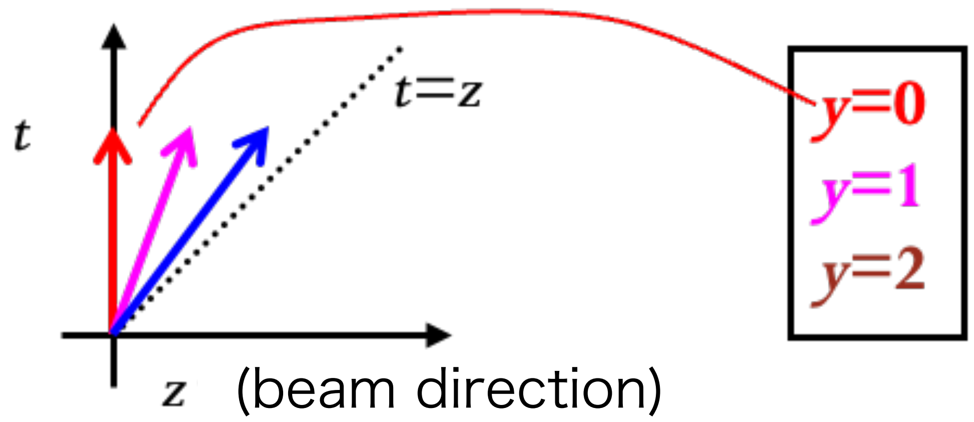
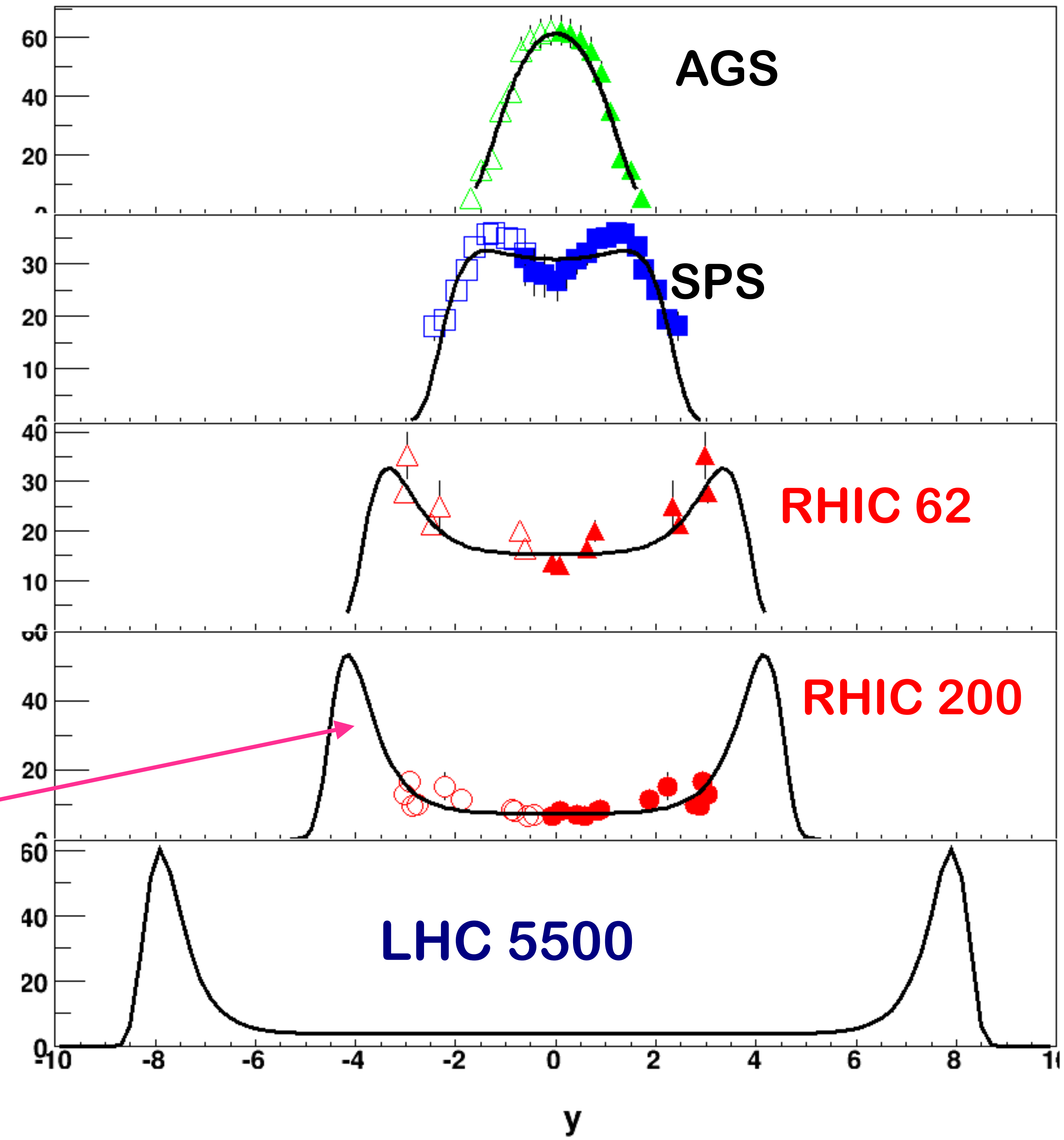
Rapidity: $y = ½ \ln\{(t+z)/(t-z)\}$

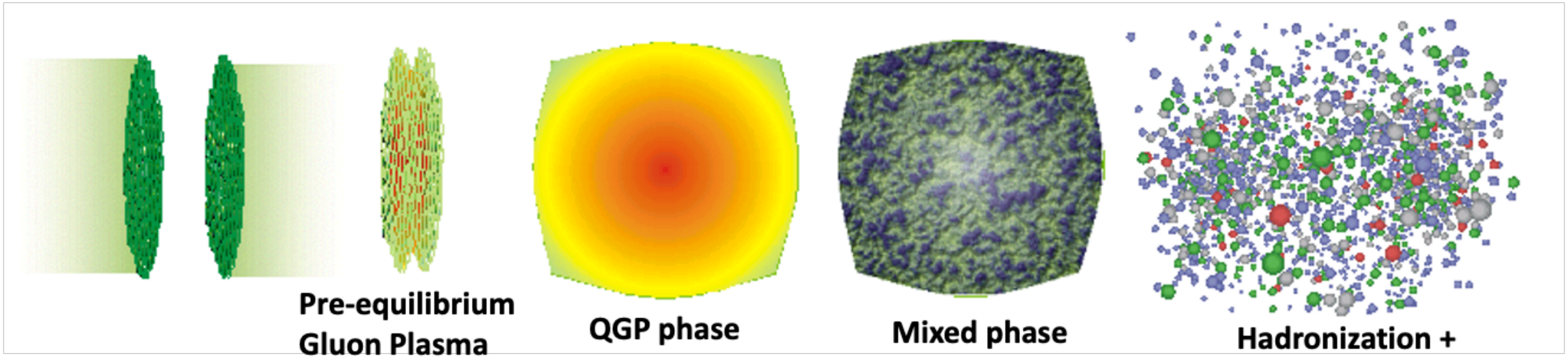


y=0 : stay near collision point
Large |y| : go forward/backward

Large loss of beam energy, 25TeV



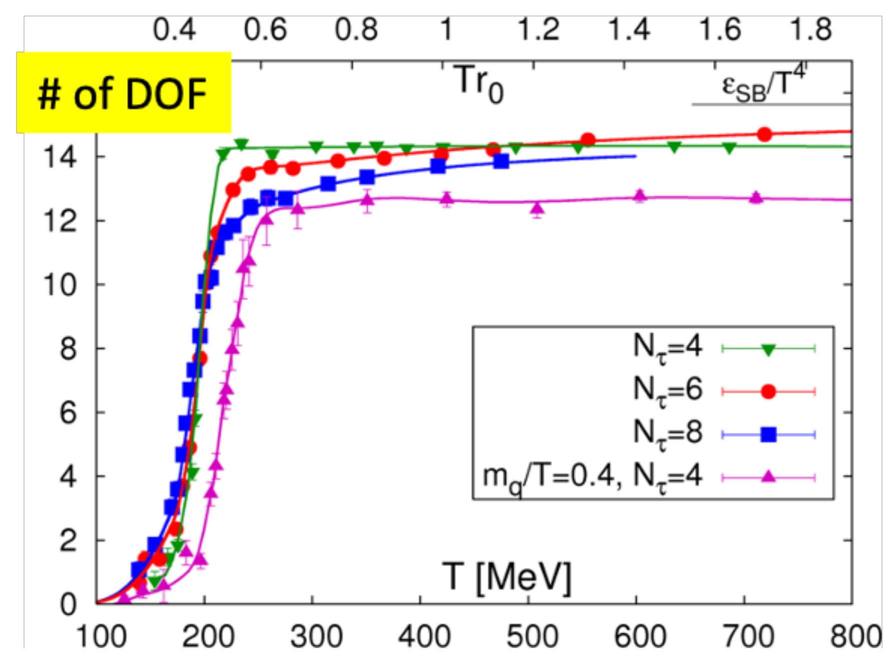
System development after collisions



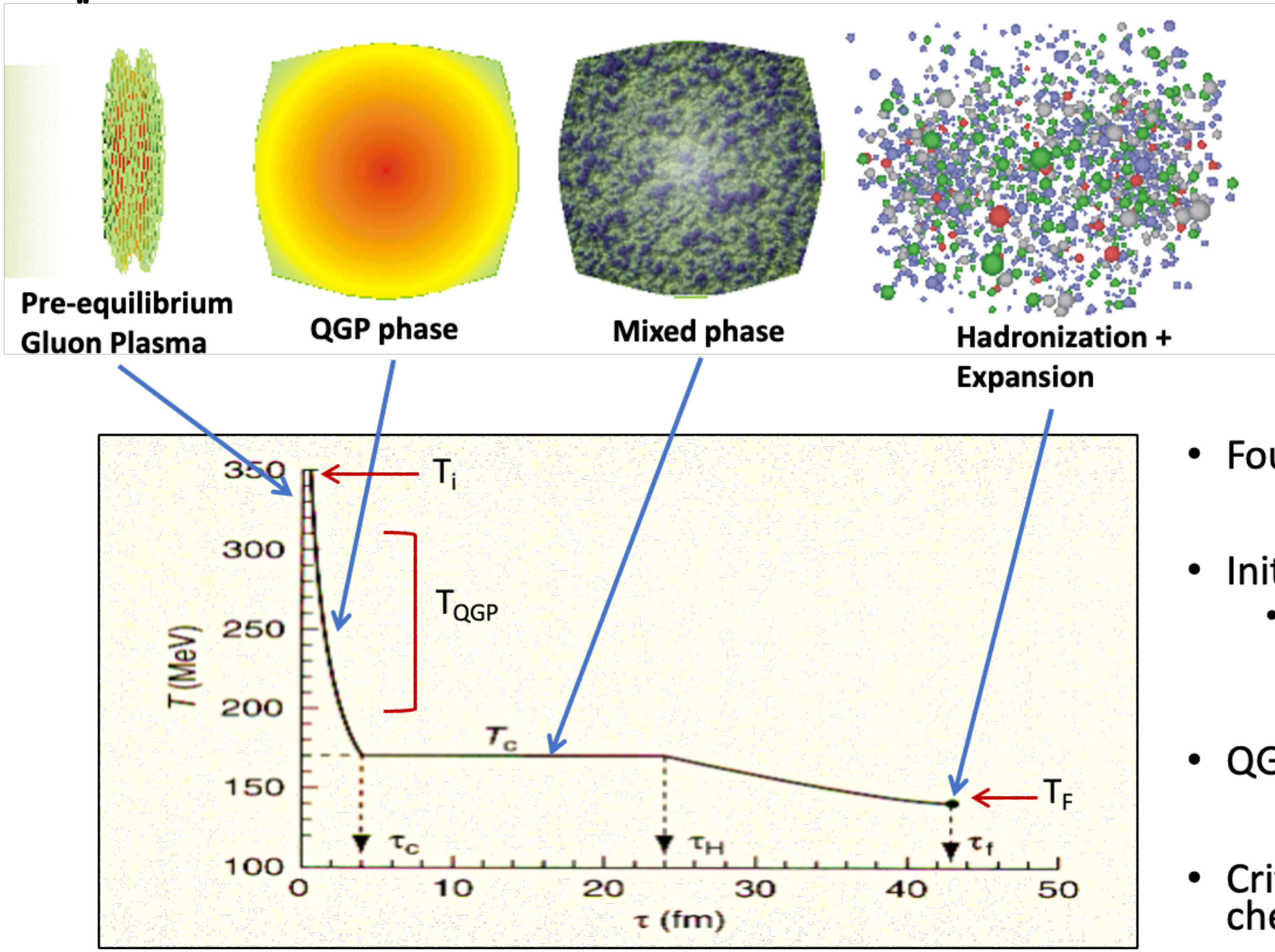
- Gold ions pass through each other
  - High momentum (high-x) partons fly away
  - Low momentum (low-x) gluons remain in the mid-rapidity (y=0), and create "gluon matter"

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

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



Time and Temperature profile after collisions



- Four characteristic temperatures
- Initial (T_i ~300-600MeV)
  - As going to higher collision energy, this temperature goes higher.
- QGP (T_{QGP} ~200-300MeV)
- Critical (phase transition) or chemical freezeout (T_C ~170MeV)
  - Particle composition (μ_b) is fixed
- Thermal freezeout (T_F~100MeV)
  - Momenta of particles are fixed
  - System expansion velocity (β) is fixed

Physics quantities in H.I. collisions

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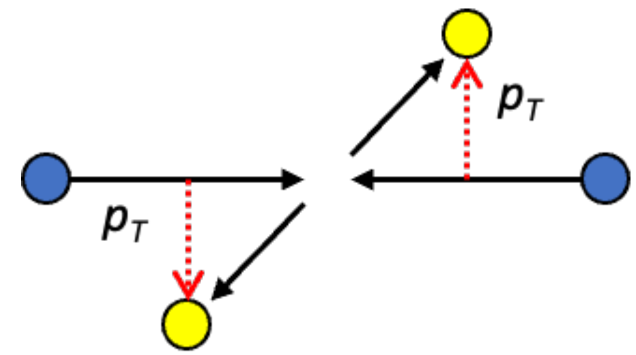
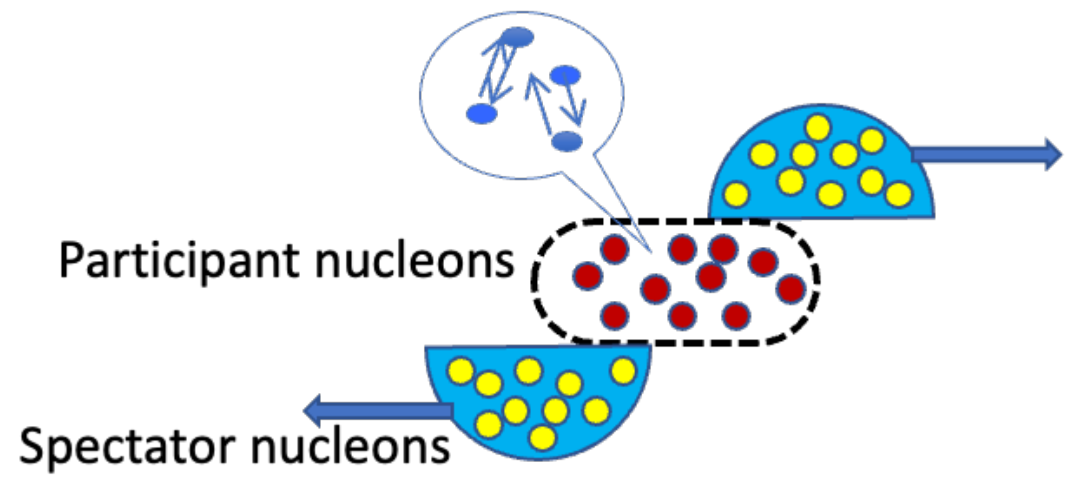
Transverse momentum (p_T)

- Momentum component normal to the beam direction in centre-of-mass frame



Number of participant nucleons (N_{part})

- Calculable from impact parameters
- A measure of energy density

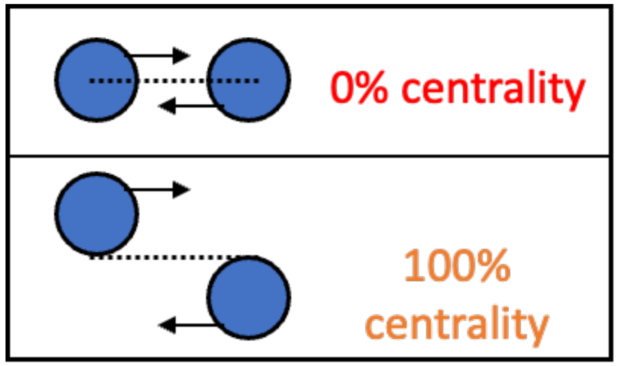


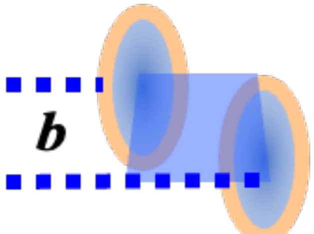
Number of nucleon collisions (Ncoll)

- Number of nucleon collisions in an event
- Nucleons are considered to collide individually in high energy collisions.

Centrality

- Proportional to impact parameters
- 0%: b=0, central collisions
- 100%: b=b_{max}, peripheral collisions

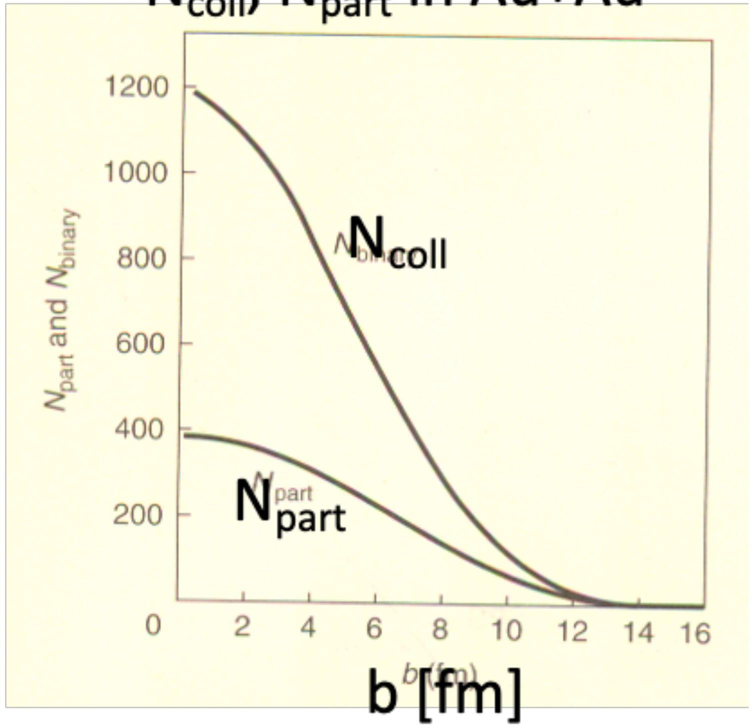




$$T_{AB}(b)=\int T_A(\vec{s}+\frac{\vec{b}}{2})T_B(\vec{s}-\frac{\vec{b}}{2})d\vec{s}$$

Overlap Function

N_{coll}, N_{part} in Au+Au



Results from RHIC/LHC

(Helped by Prof. T. Sakaguchi’s slides at YSJW 2020)

Whats' 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.

pQCD predicts photons and jets precisely

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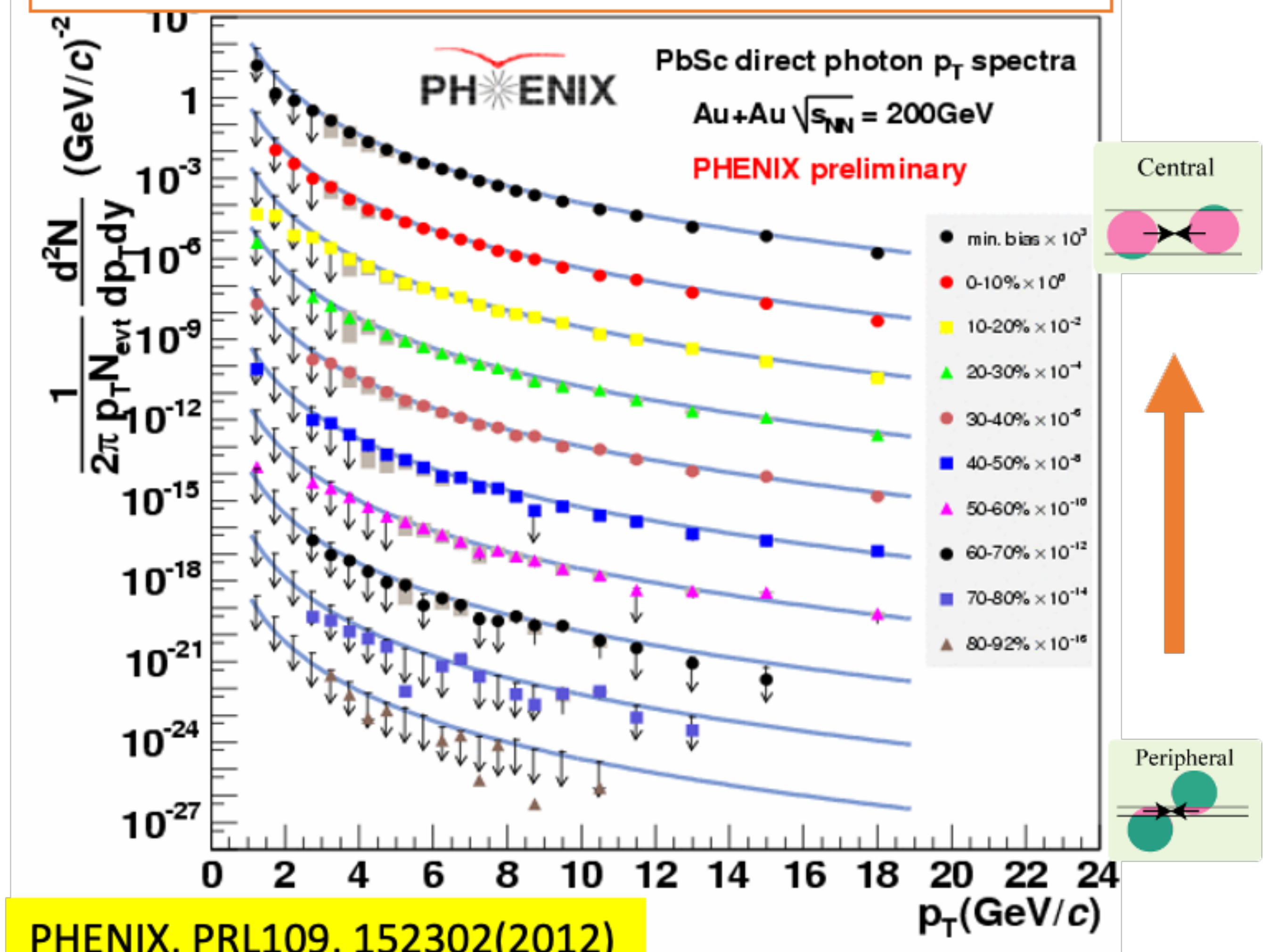
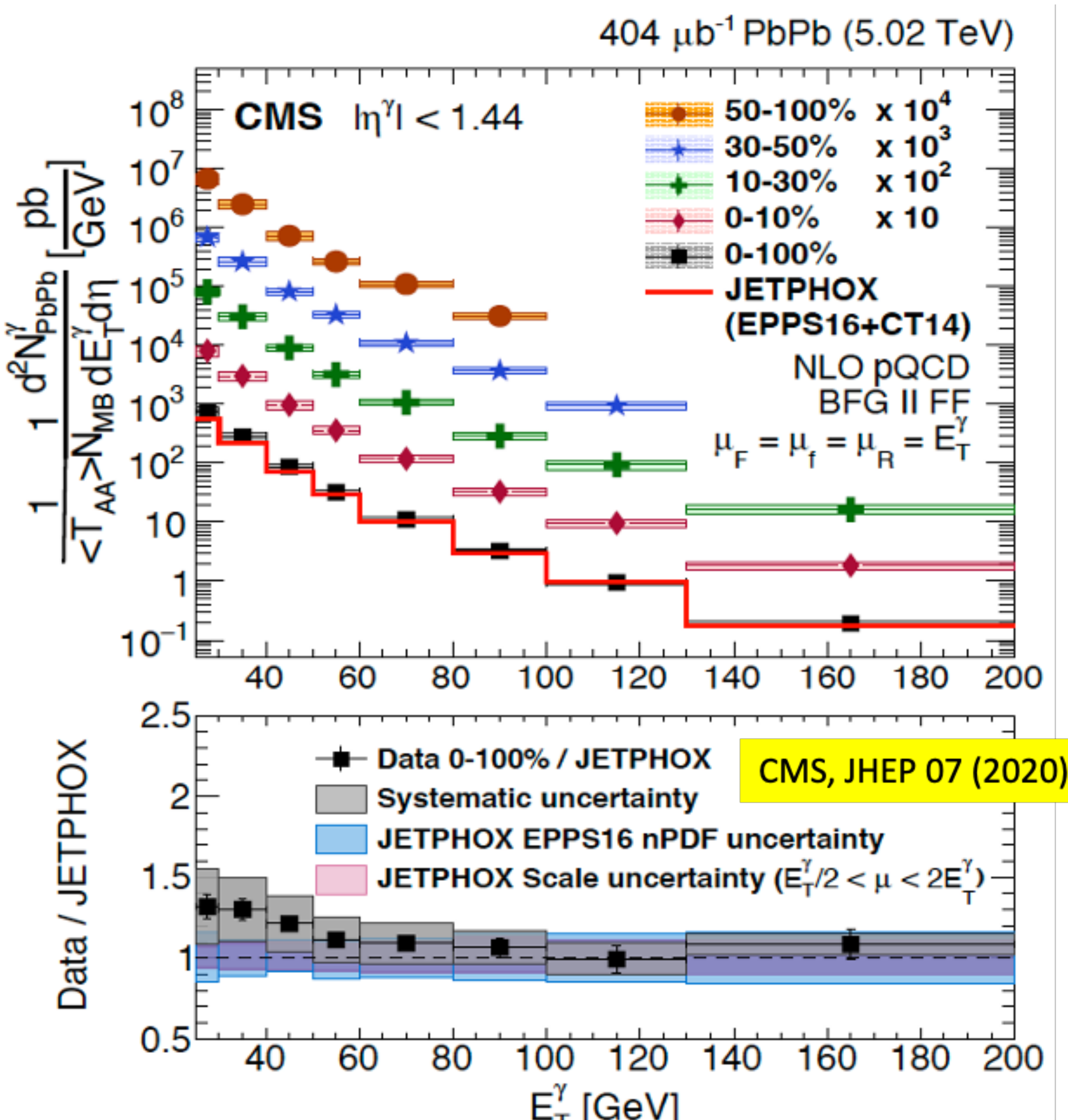
- Yields of jets and photons are well-reproduced by perturbative QCD (pQCD) calculation.
- Yields in Au-Au and Pb+Pb scale with number of binary-nucleon collisions (N_{coll}). This goes very well as shown below for the photon yields.

Blue line: N_{coll} scaled p+p cross-section



PHENIX, PRL109, 152302(2012)

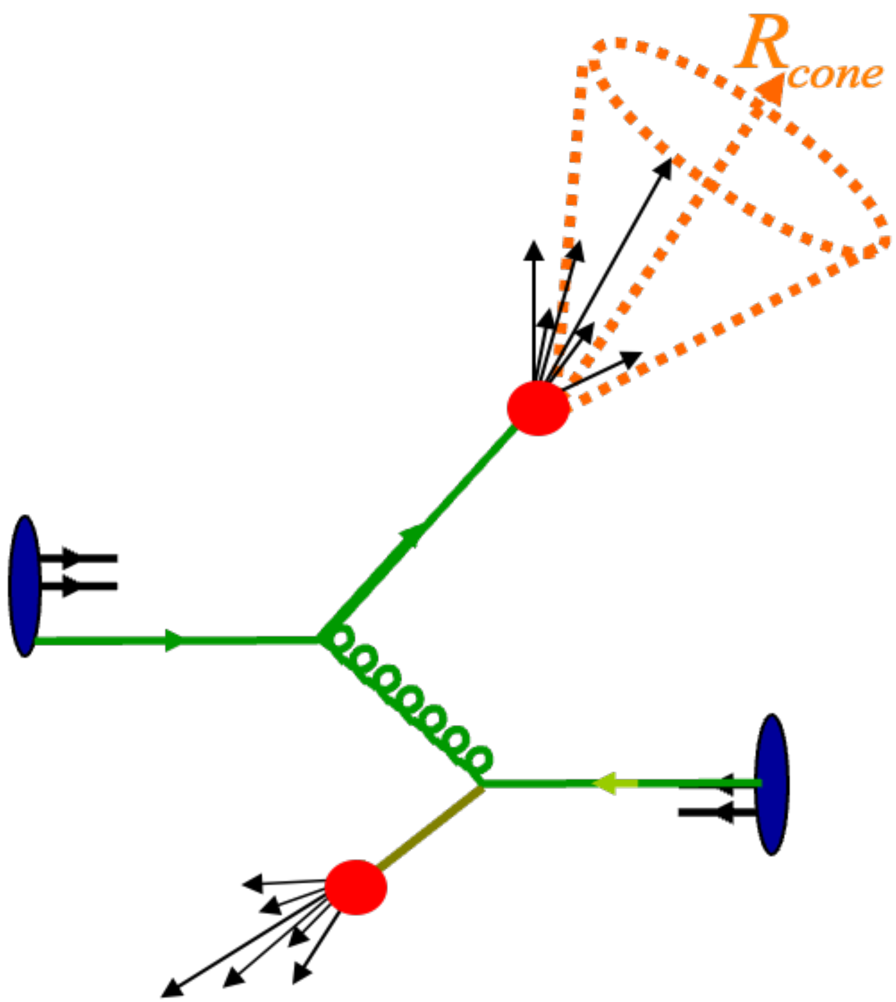


CMS, JHEP 07 (2020) 116

The case of jets

Jets in p+p (primordial hard scattering)

Yield in A+A collisions ∝ Ncoll × p+p collisions

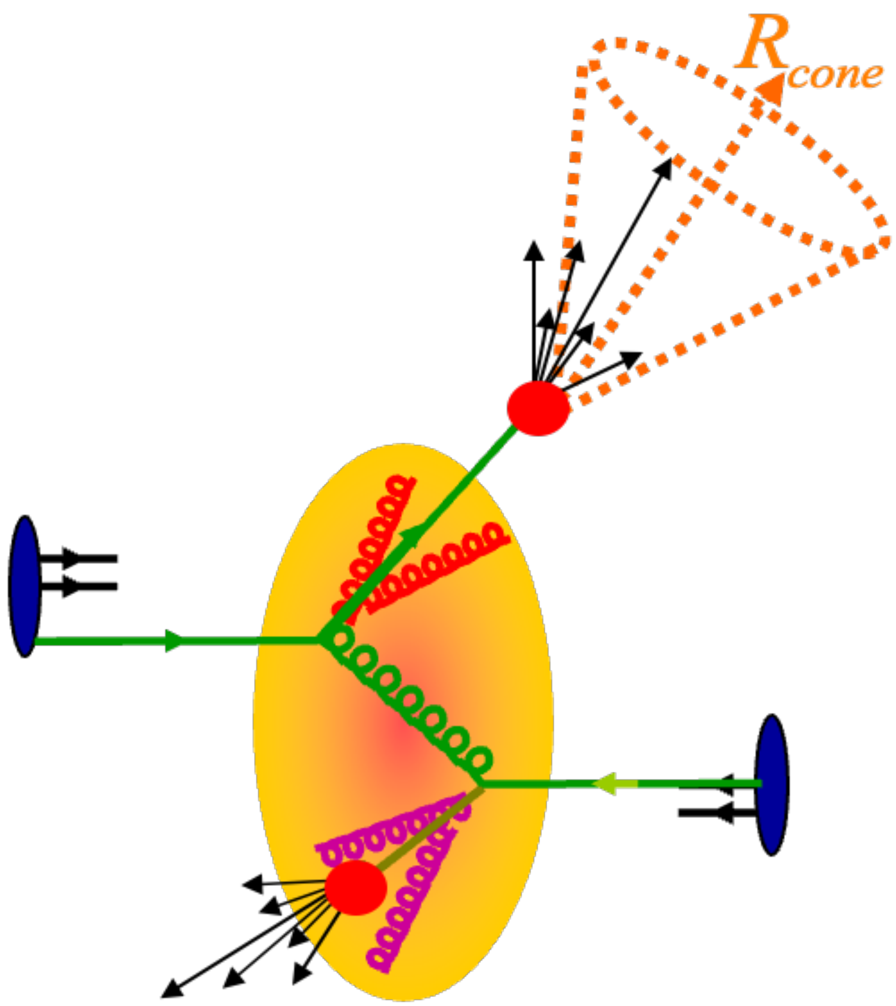


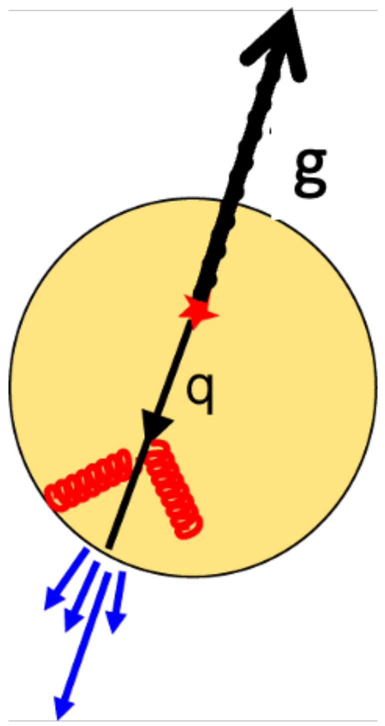
The case of jets

Jets in QGP

- Hard scattered partons lose their energies in the QGP via gluon radiation or parton collisions.
- Jets that are fragment of the partons accordingly reduce their energies.

Yield in A+A collisions ∝ Ncoll × p+p collisions





The case of jets

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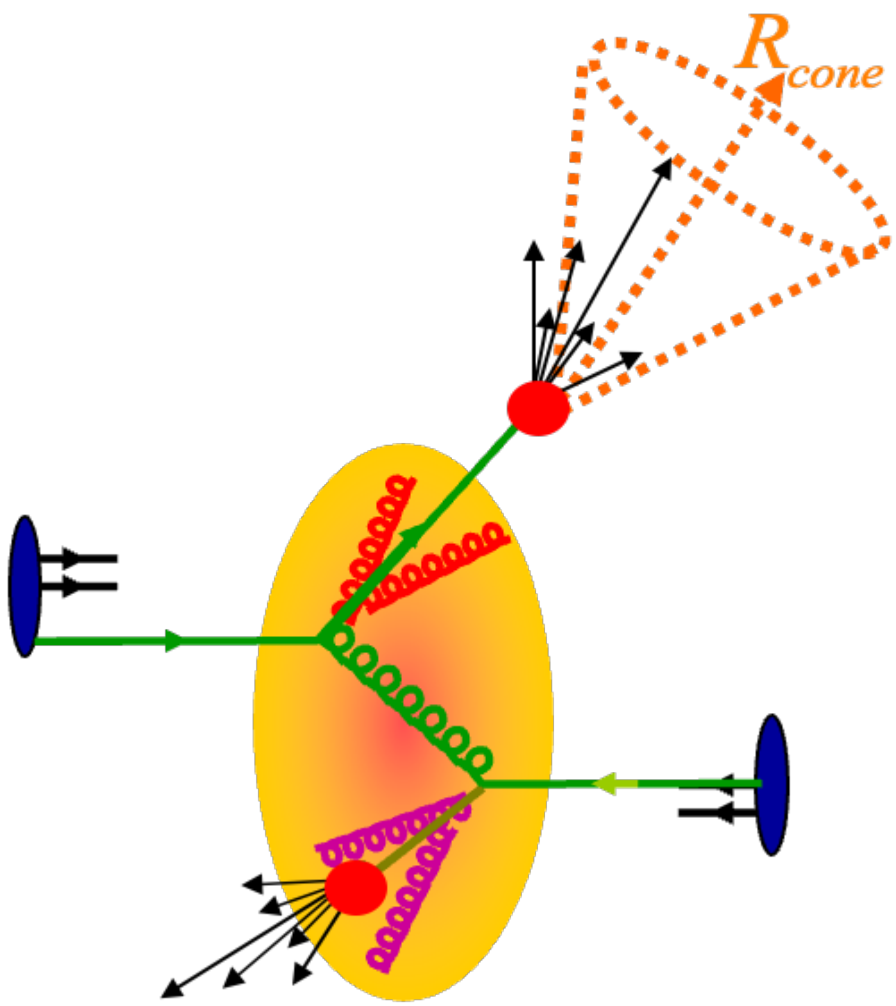
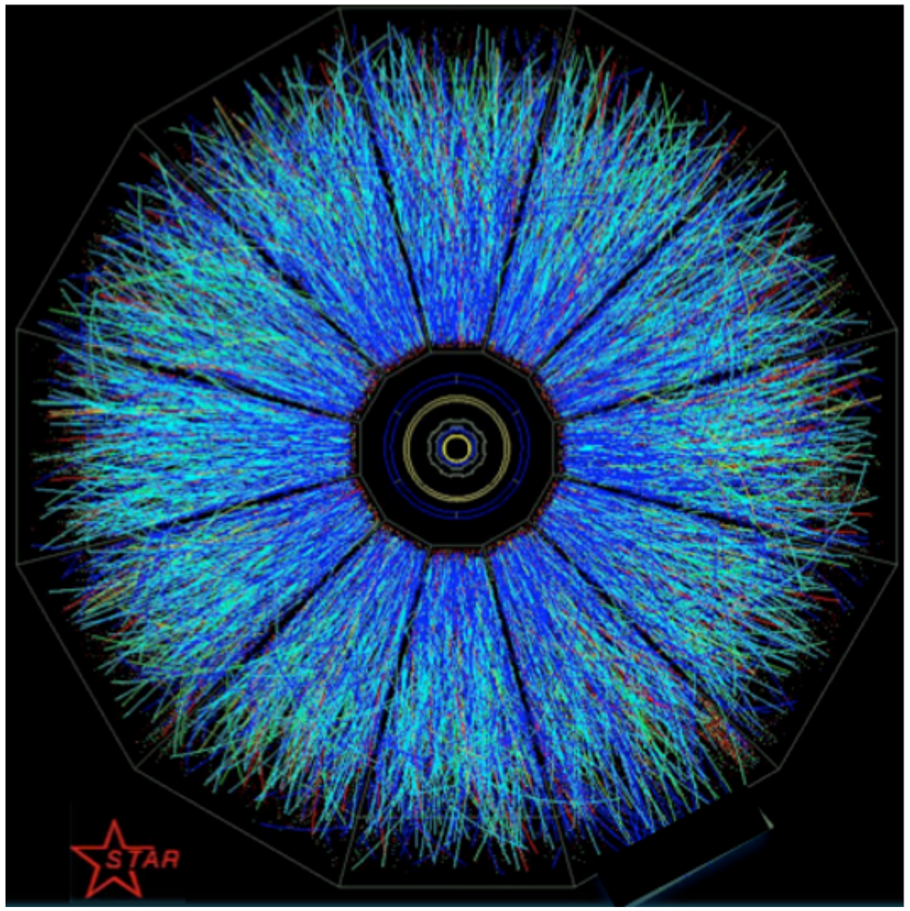
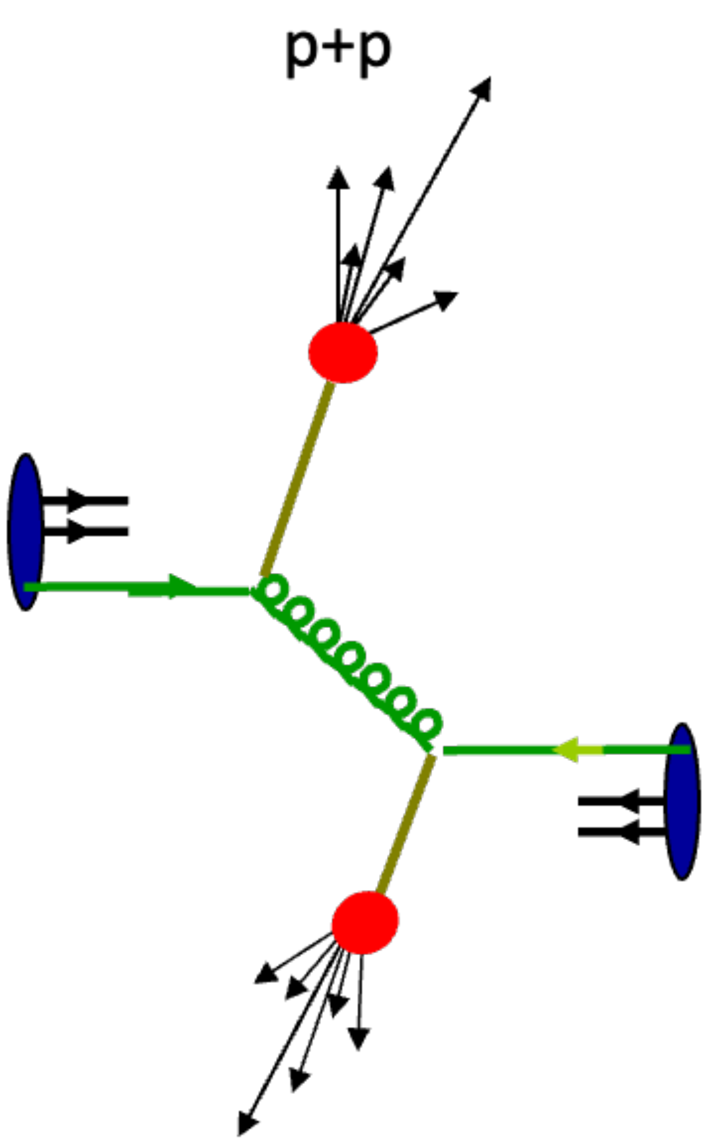


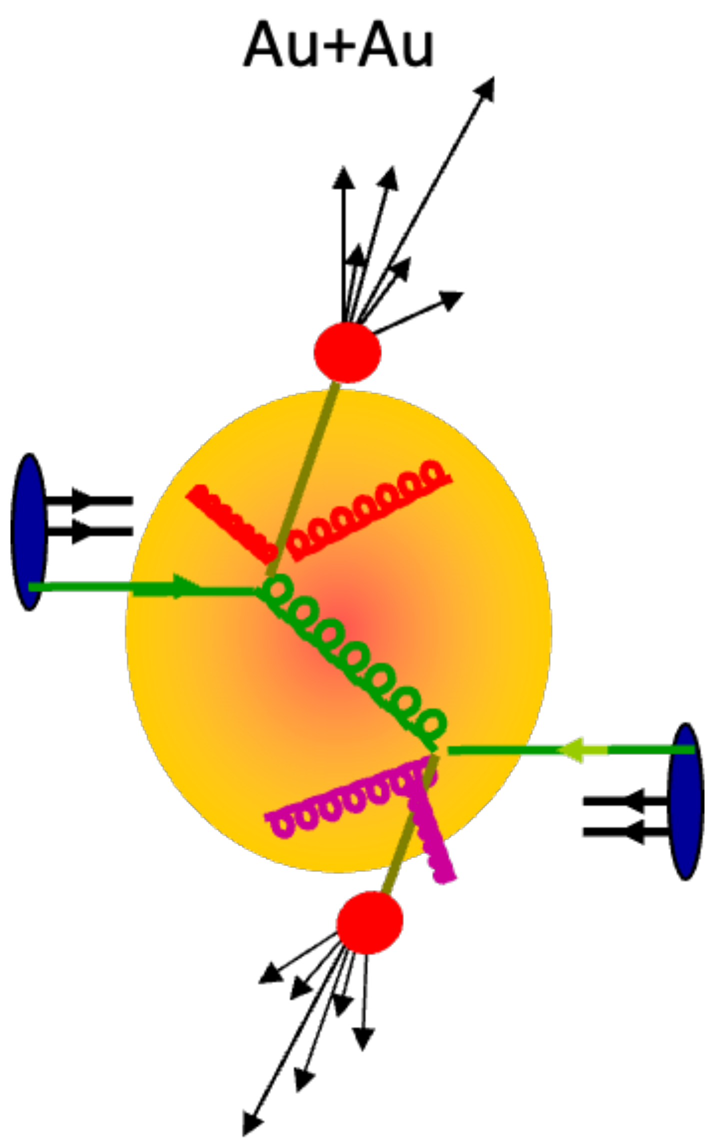
However, extreme difficulties in jet reconstruction in heavy-ion collisions!!

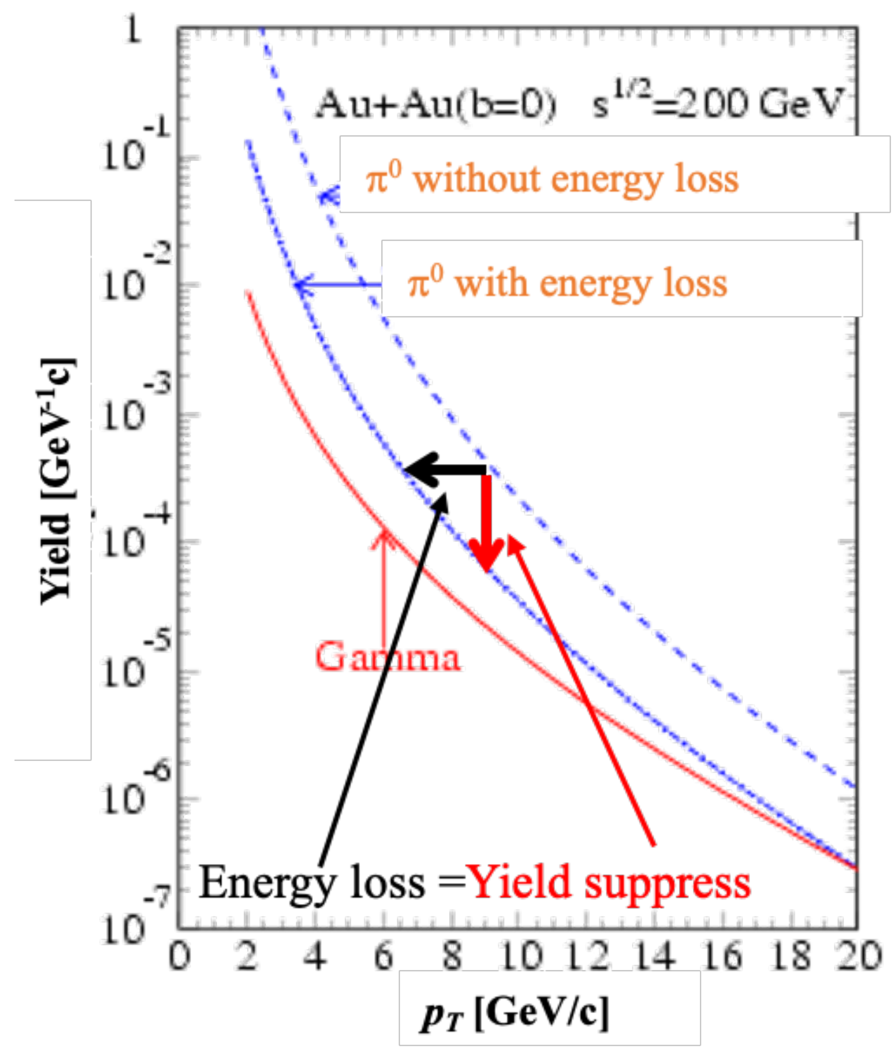


Instead, observe leading particles from jets

- High P_T hadrons (π^0 etc.) are leading particles from jets and a large fraction of jet momentum are carried by them.
- 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

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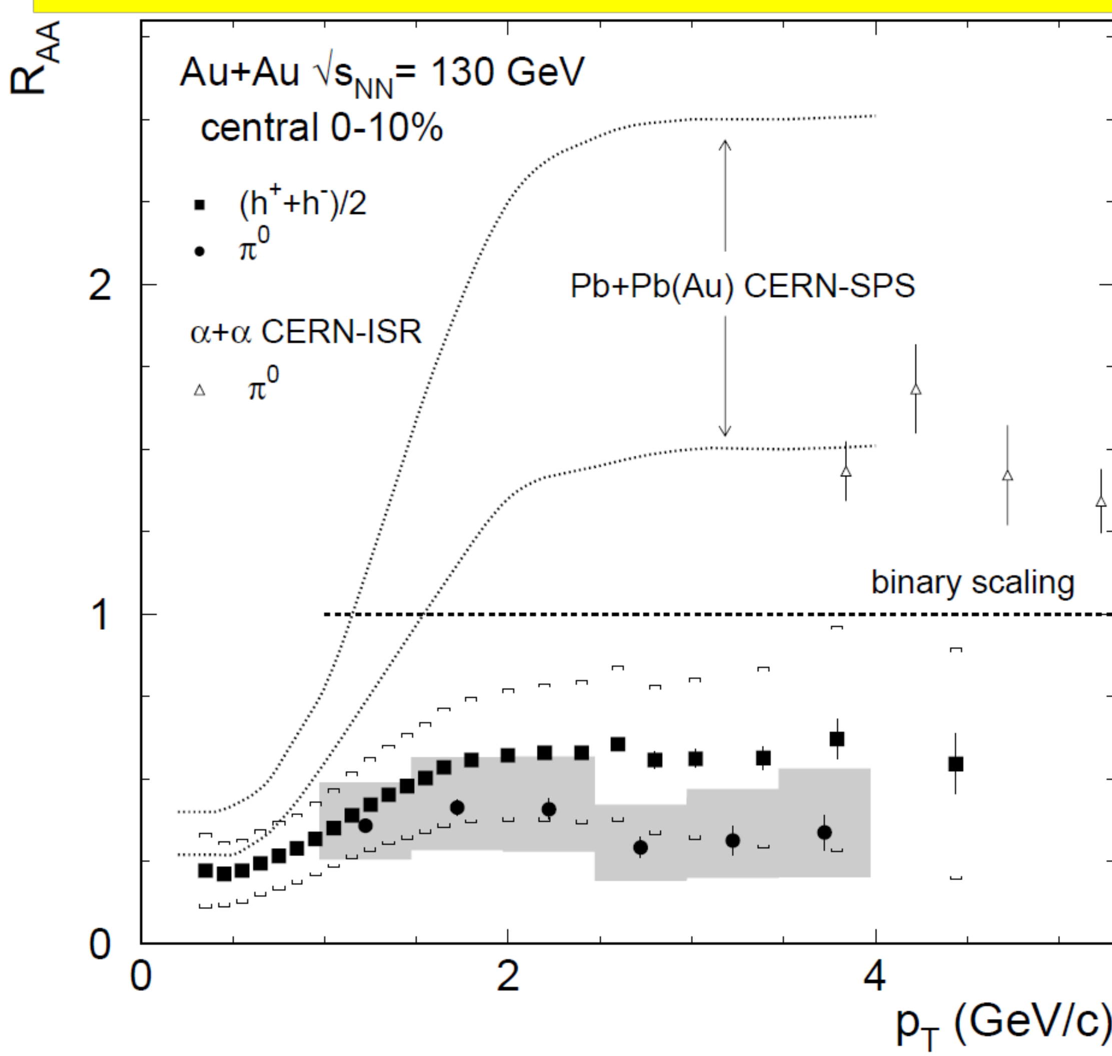
- Nuclear Modification Factor (R_{AA})
  - (Yield in A+A collision)/(Yield in p+p collision × Ncoll)
  - R_{AA} =1: No nuclear effect
  - R_{AA} <1: Suppression due to energy loss, etc.
  - R_{AA} >1: multiple scattering, etc.
- R_{AA} <1 for RHIC and LHC, >1 for SPS ($\sqrt{s_{NN}}$=17GeV)

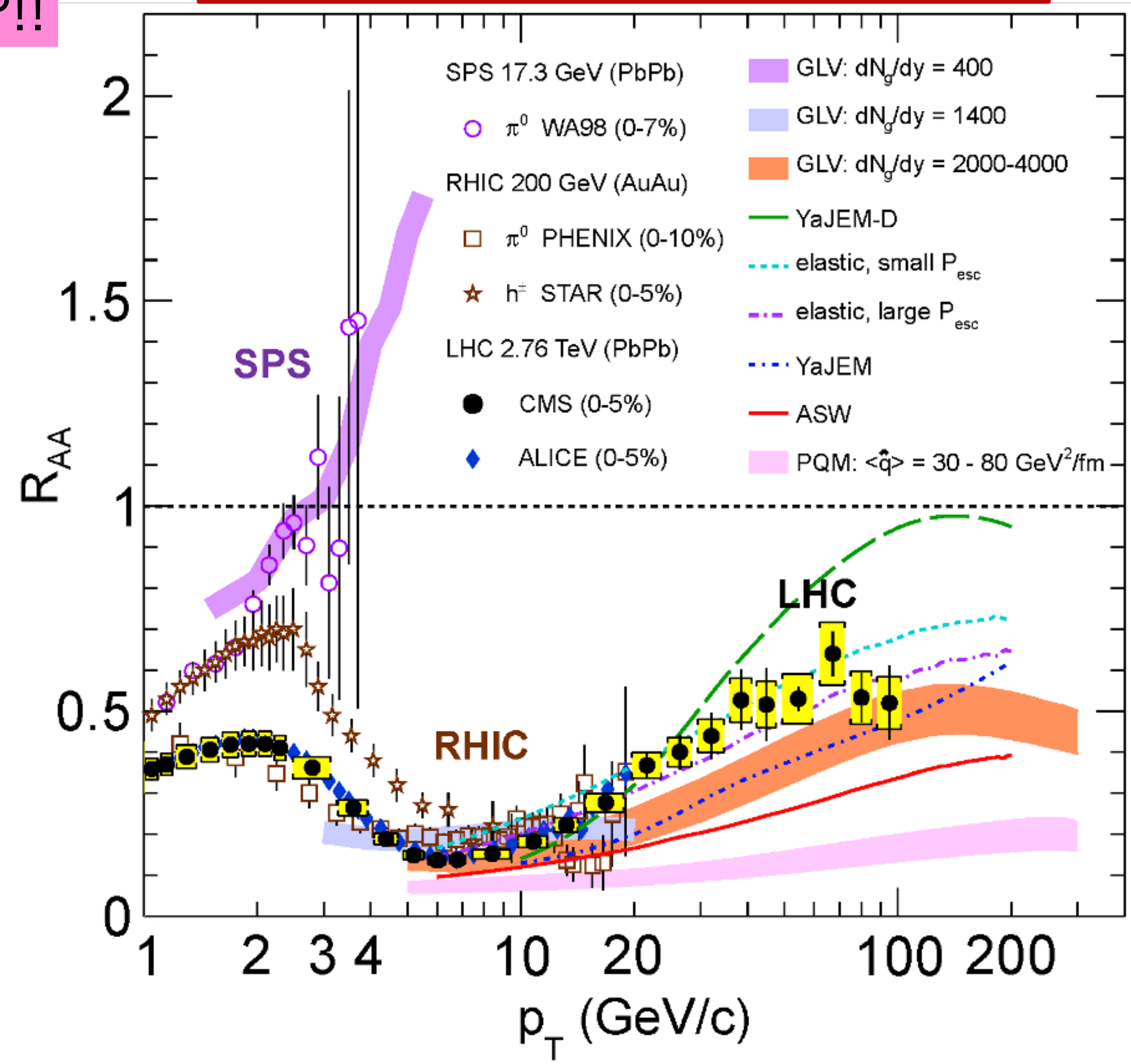
$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

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

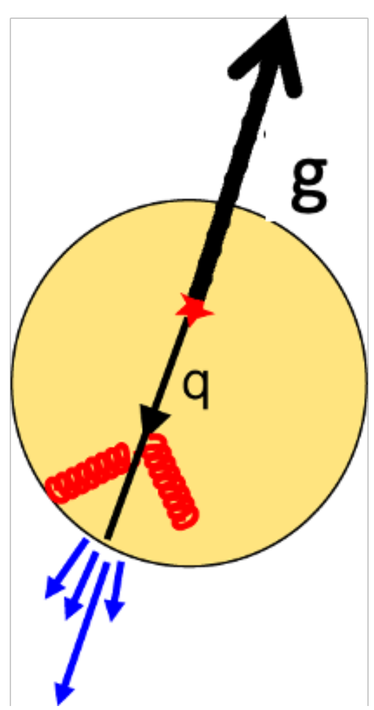


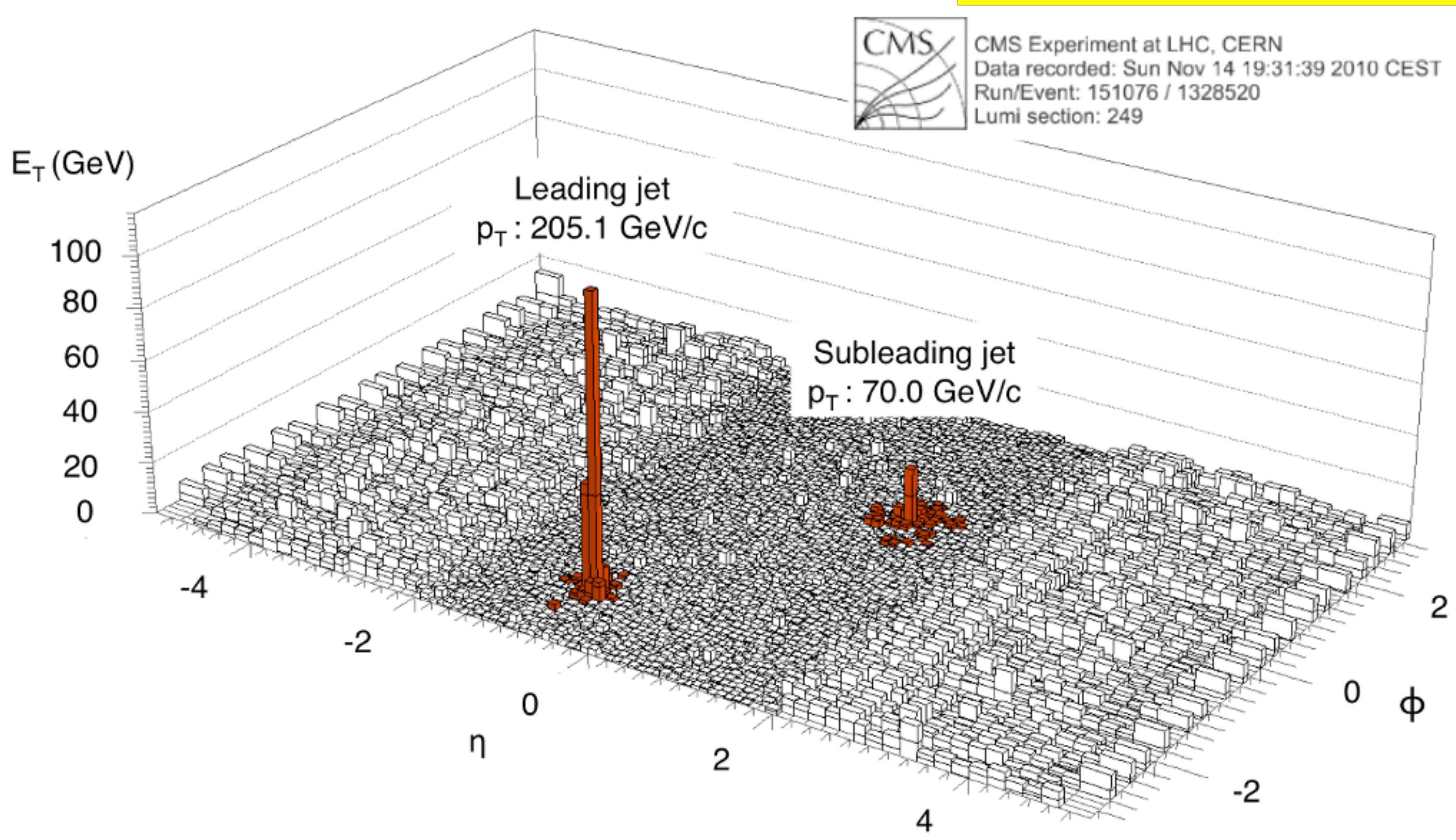
Jet reconstruction became possible at LHC

- 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 ∝ α_s^2**



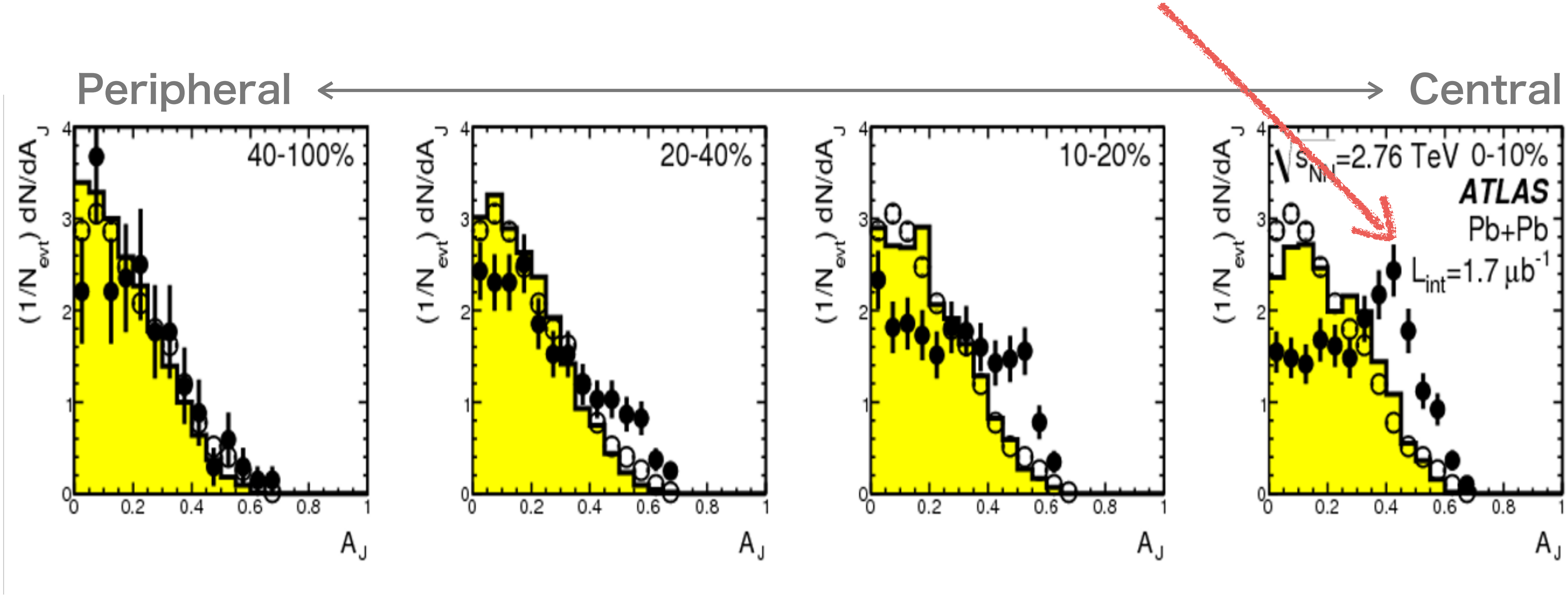


Jet reconstruction became possible at LHC

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

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

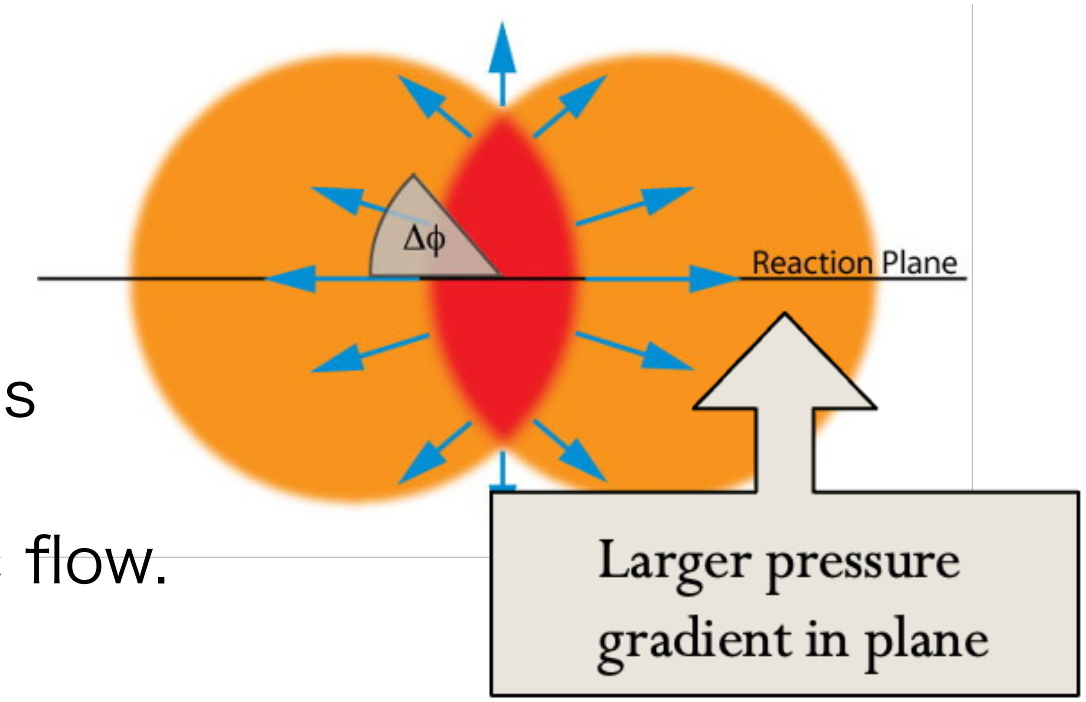
- Central Pb+Pb points deviate from p+p and estimated Pb+Pb distribution without energy loss.
  → The deviation corresponds to 30-40% loss of jet energy.



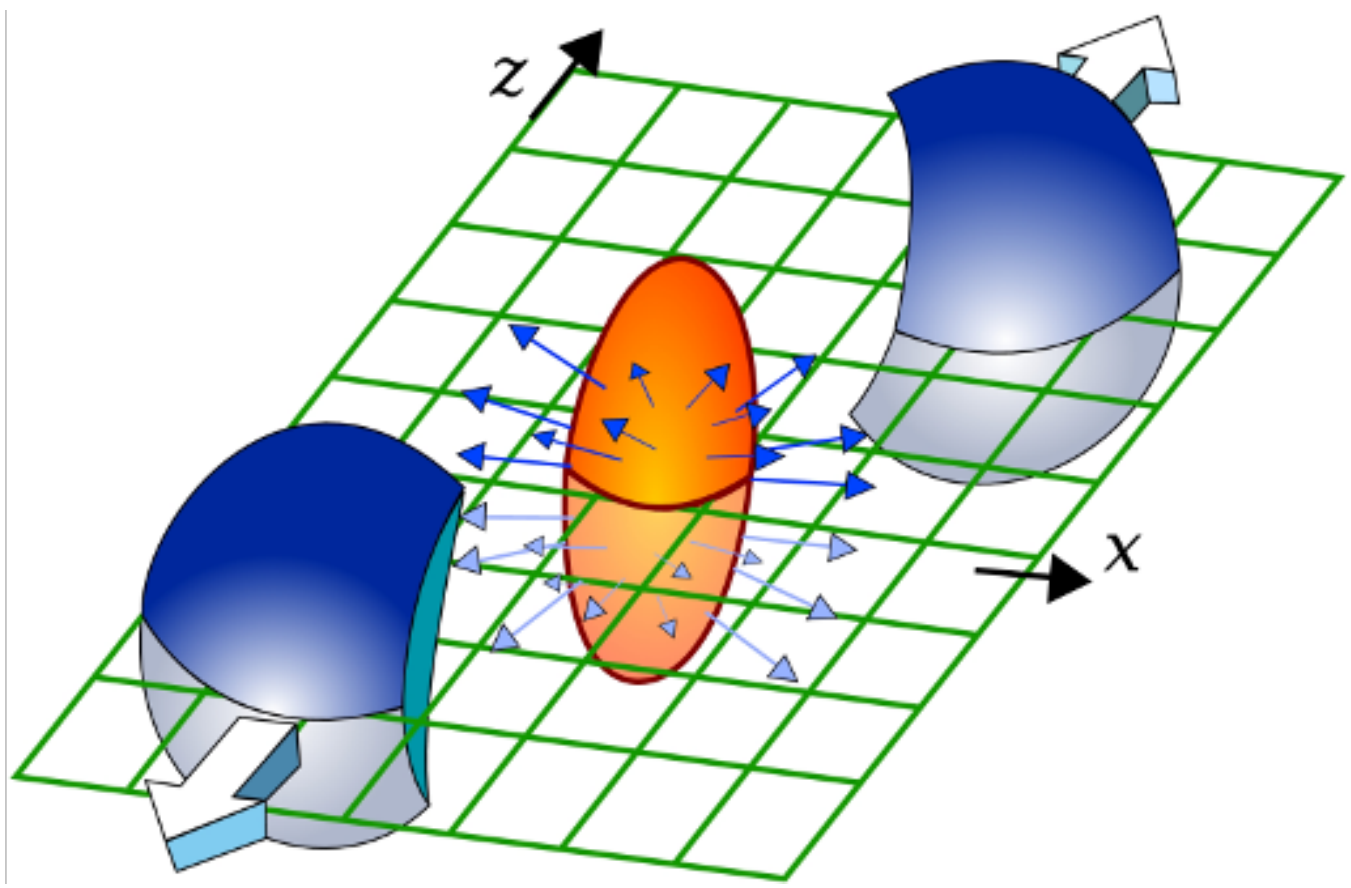
○ p+p data ● Pb+Pb data ▭ Estimated Pb+Pb distribution without energy loss

QGP property: Collective flow of particles

- In non-central collisions, the collision are 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)



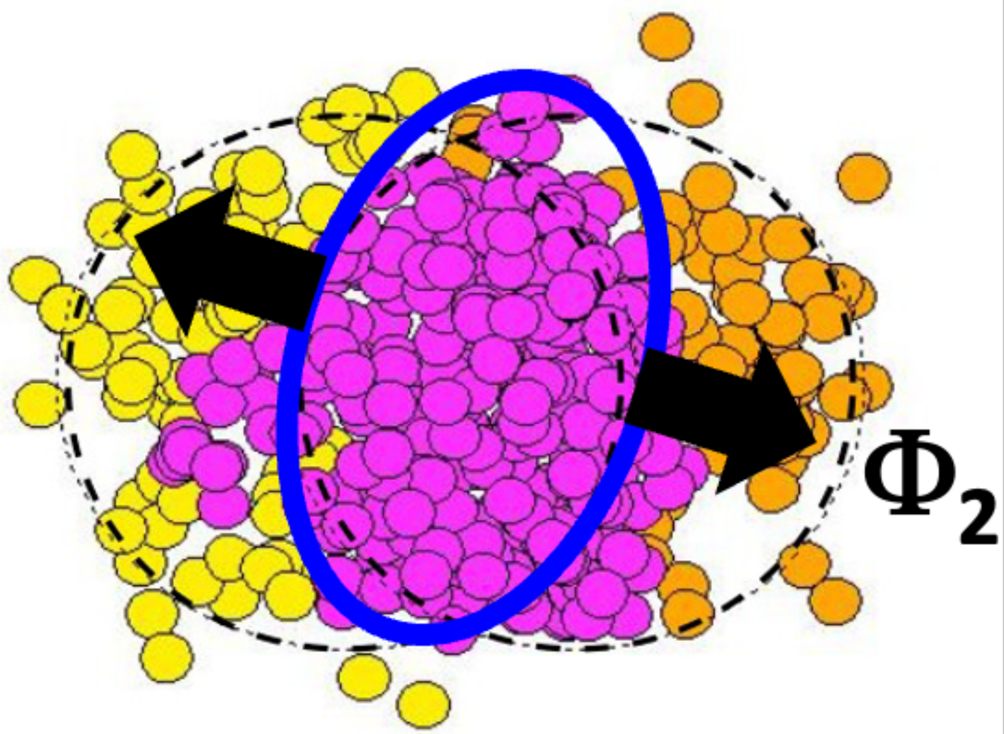
$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$



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 $v_2 = \frac{\langle p_y^2 \rangle - \langle p_x^2 \rangle}{\langle p_y^2 \rangle + \langle p_x^2 \rangle}$

The flow is not completely elliptic

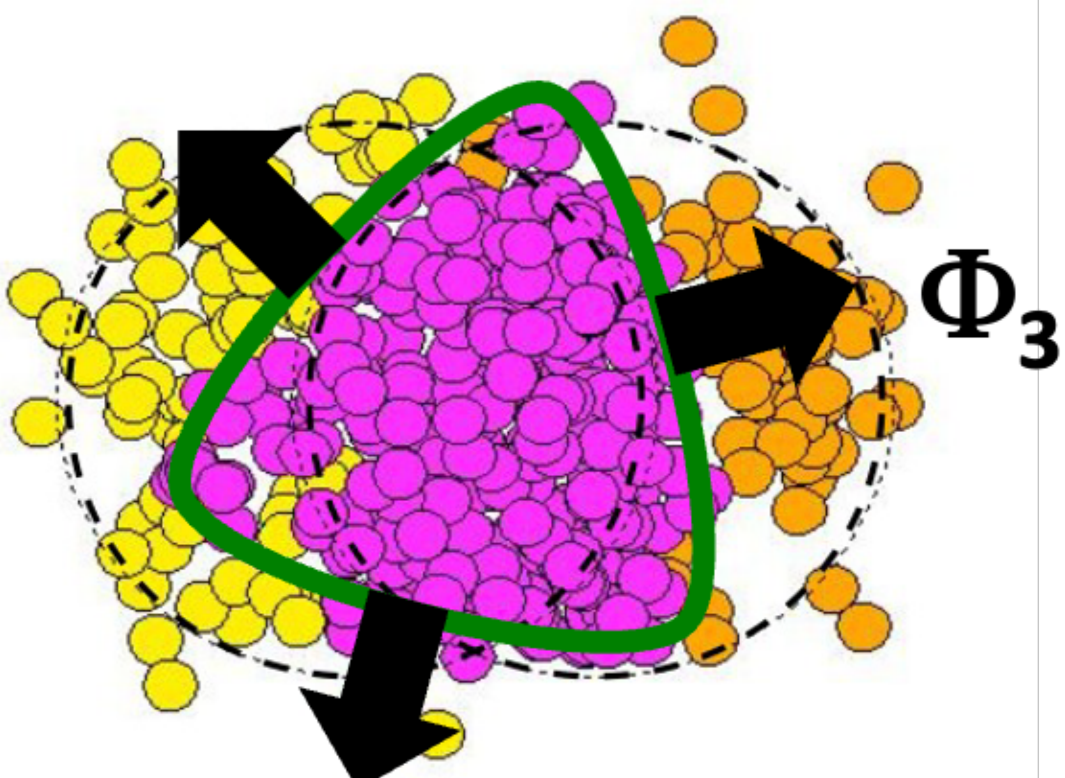


- Fluctuation of nucleon position yields higher order anisotropy of particles.
  → higher order flow v_3, v_4, ···, v_n

$$\frac{dN}{d(\phi - \Psi_n)} = N_0[1 + 2\sum_{n=1}^{\infty} v_n cos\{n(\phi - \Phi_n)\}]$$

Φ_n : Event Plane

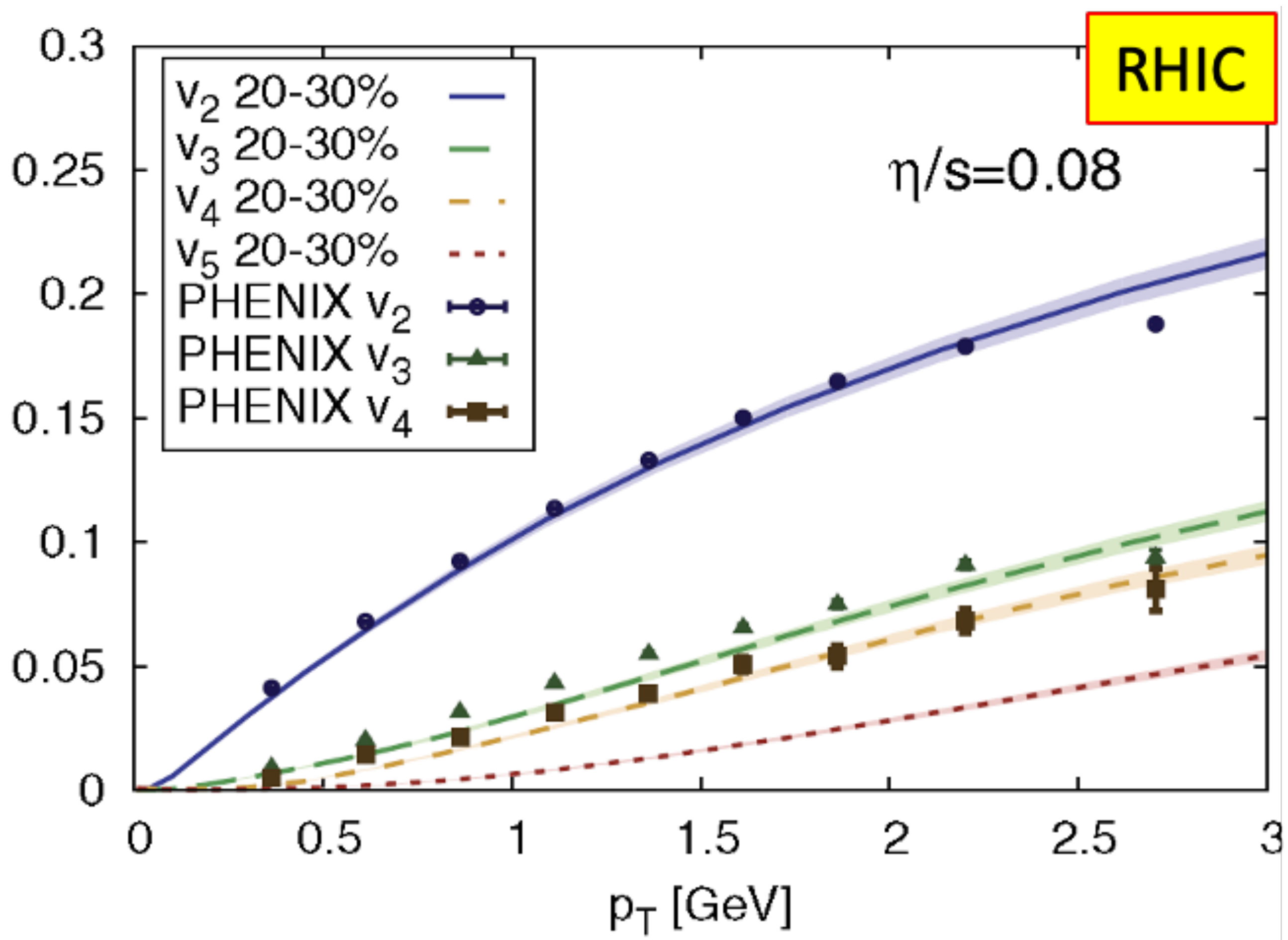
$$\nu_n =< cos\{n(\phi - \Phi_n)\} >$$



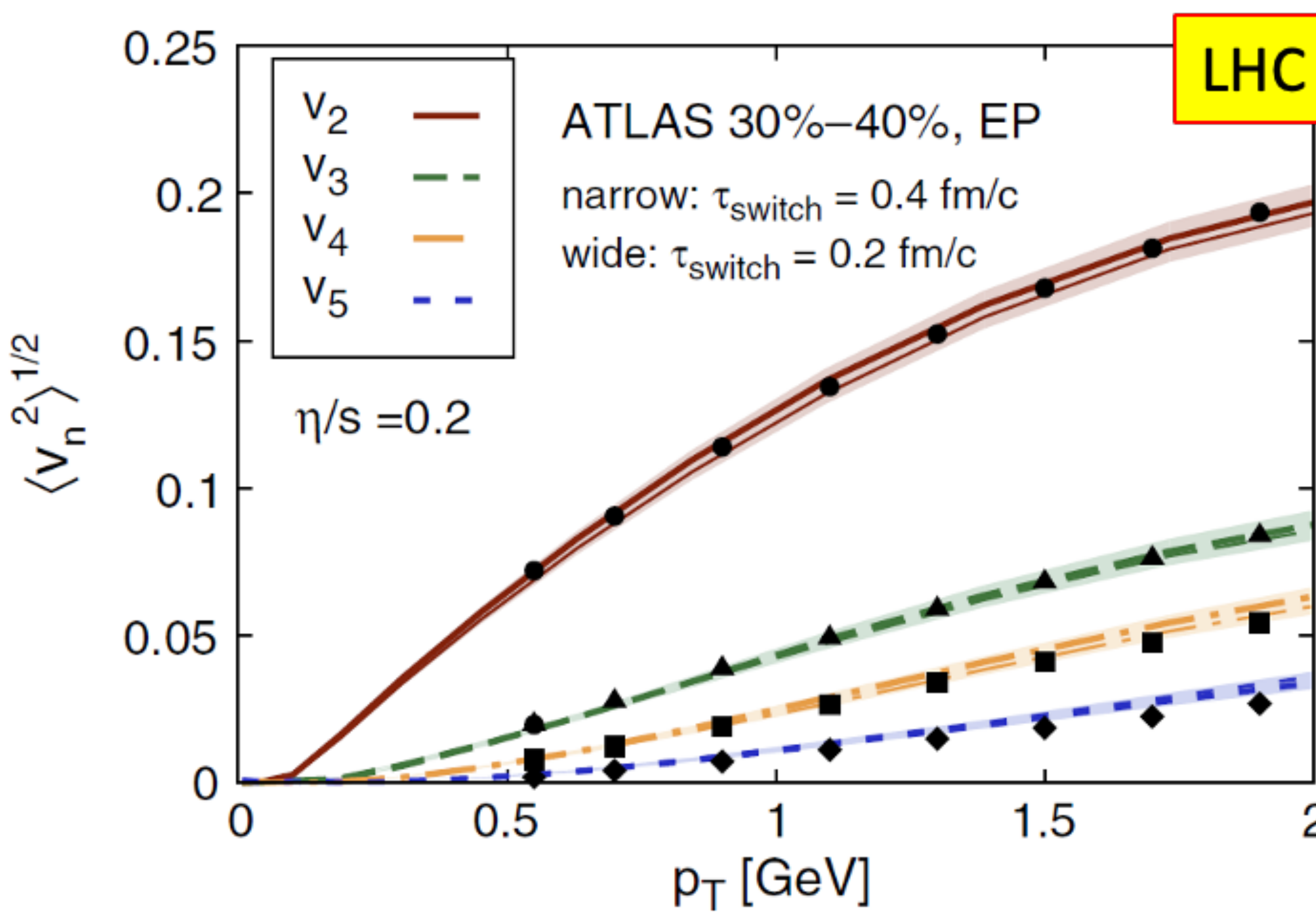
- Higher order flows are sensitive to the properties of the matter. (流体model)
  → comparison to the hydrodynamics model gives state equation E=E(P) and shear viscosity (η) to entropy density (s) ratio (η/s).

v_n results compared with hydrodynamics model

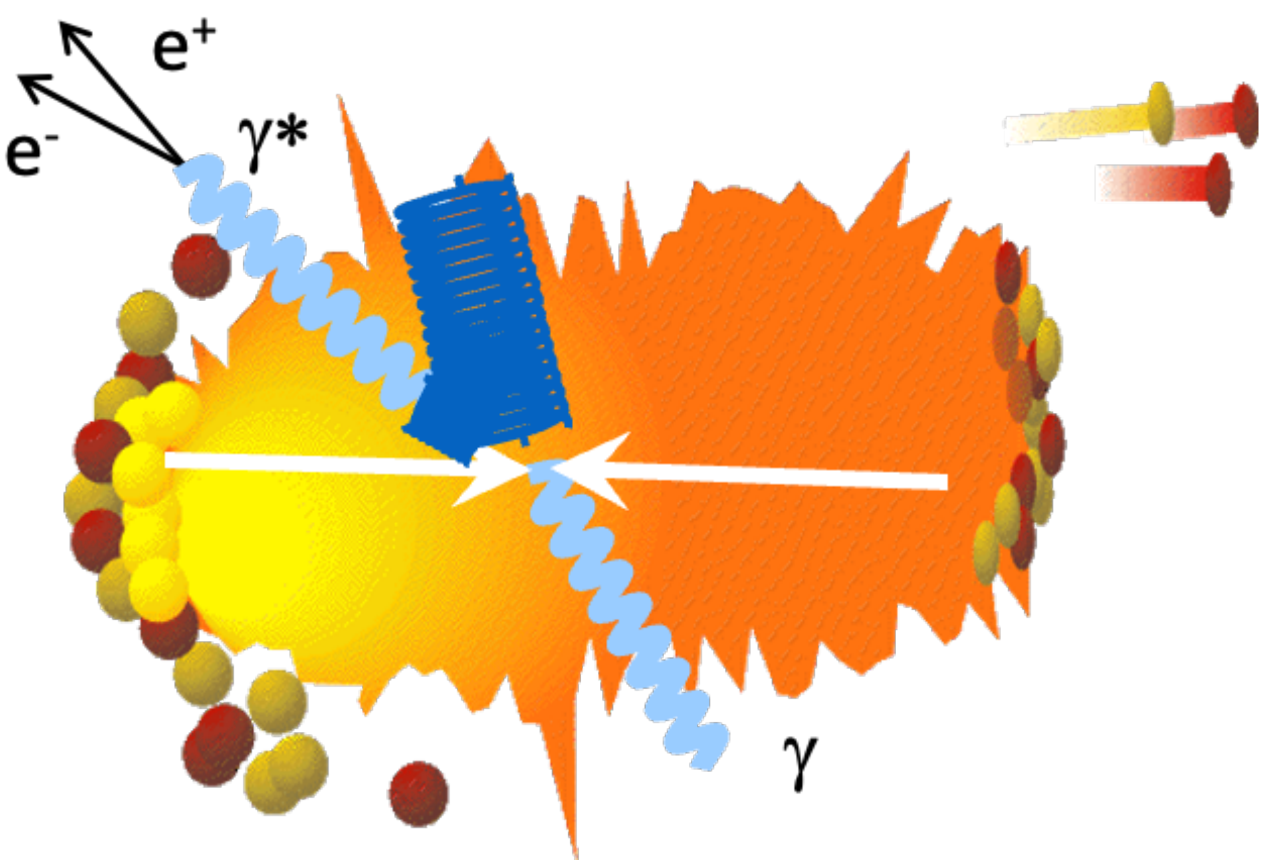
- PHENIX (RHIC) and ATLAS (LHC) v_n analysis results are compared with a hydrodynamics model → QGP is modeled as fluid consisting of partons.
- The model reproduces the higher order flow at RHIC and LHC very well.
- **Almost perfect fluid** is realized at RHIC (η/s from quantum limit ~ 1/4π ~ 0.08)



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



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



- 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

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

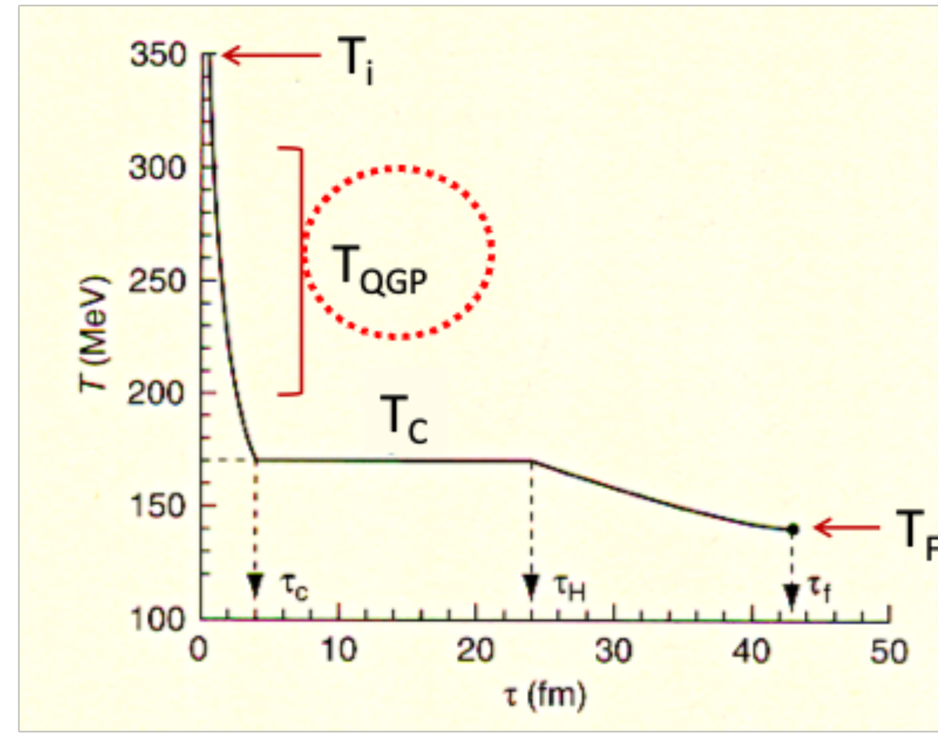
- Thermal photon distribution will be expressed by the product of
  - Bose distribution, and
  - transition probability of QGP
- Fitting the model to the experiment data gives QGP temperature.

QGP measurement: temperature from thermal photons

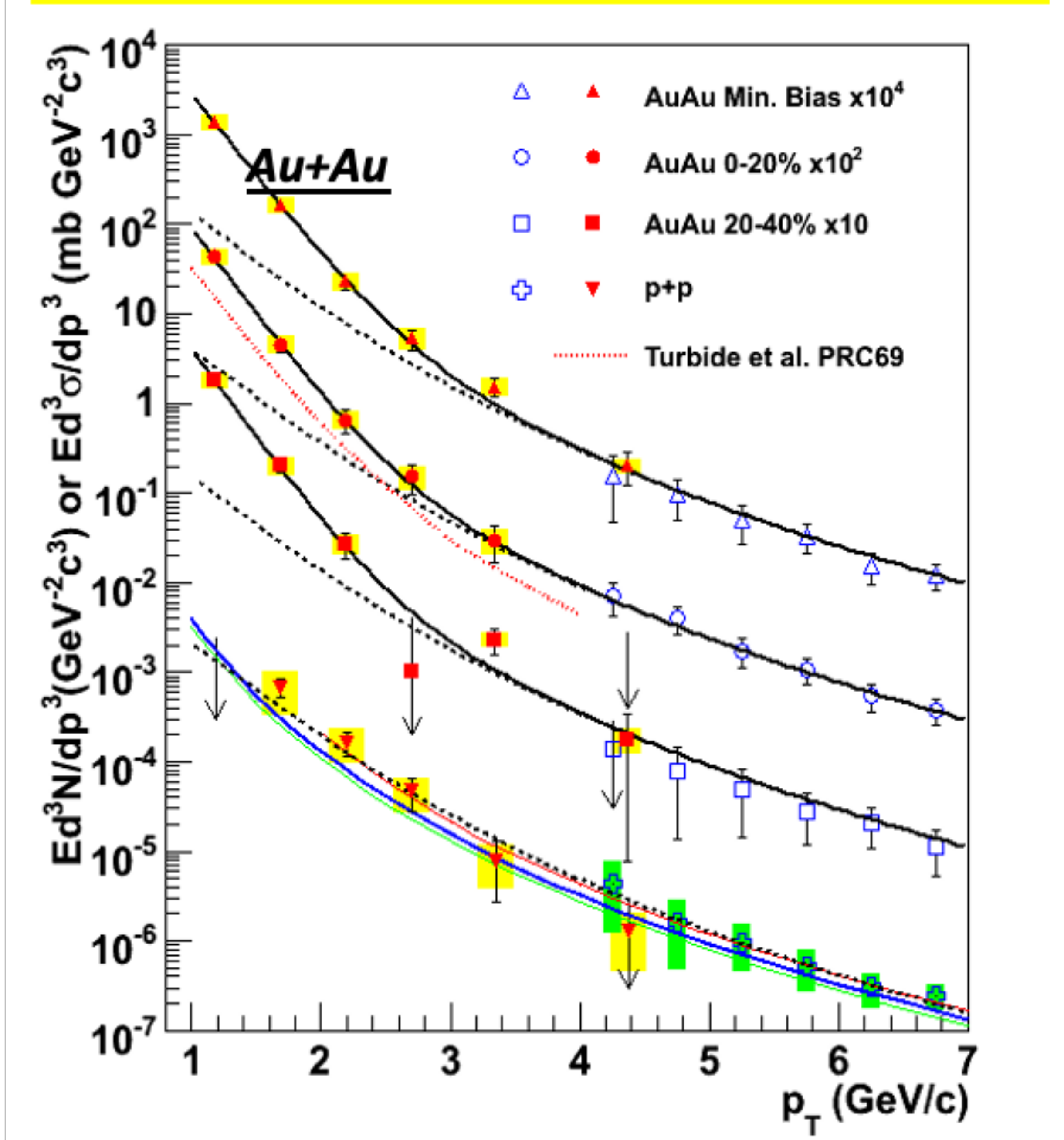
YSWS 18th
T. Fusayasu @ Saga U

In this way, the obtained temperatures are:

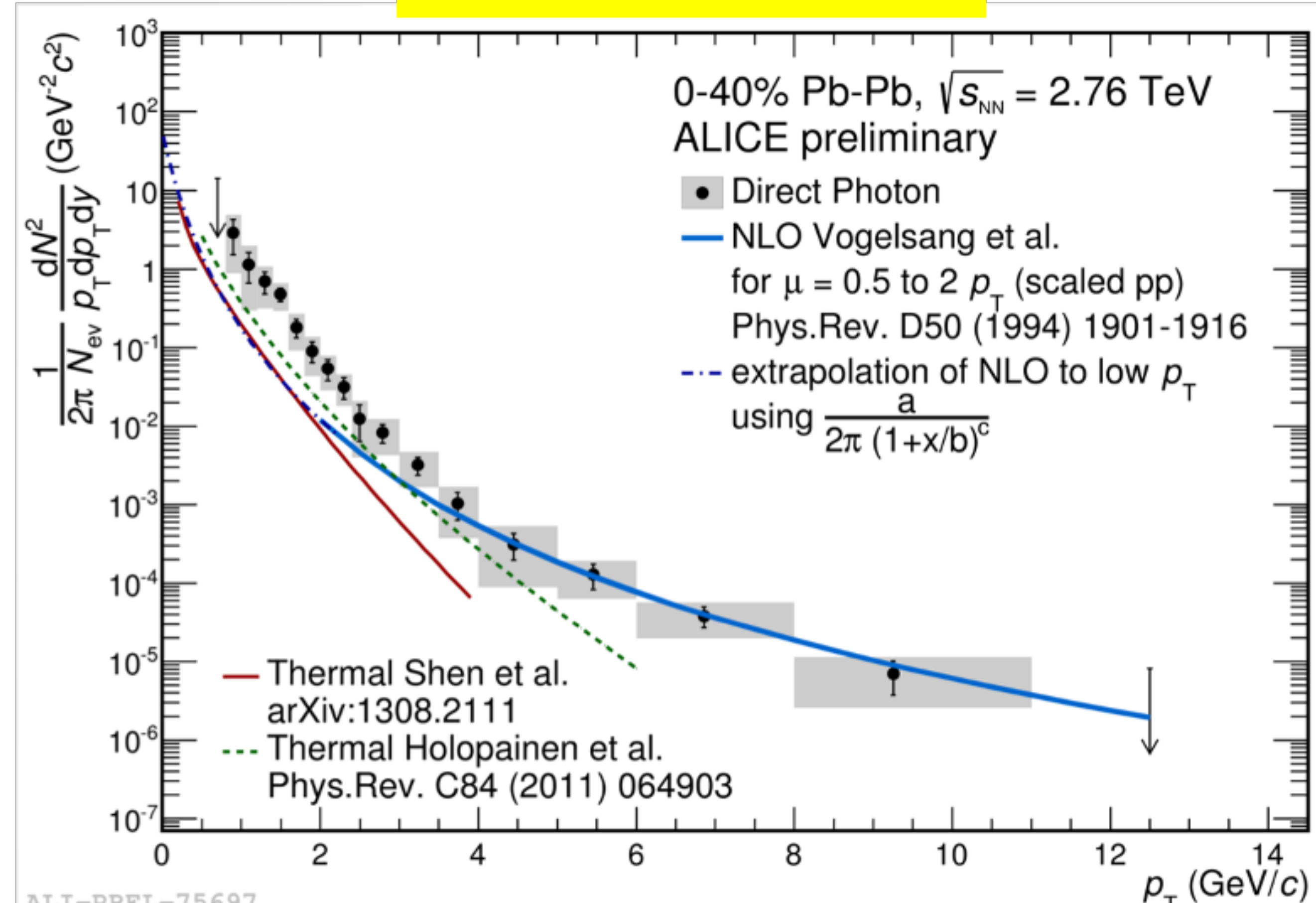
- RHIC, Au+Au 200GeV: T_{ave} = ~220 MeV = 2.5 trillion K
- LHC, Pb+Pb 2.76TeV: T_{ave} = ~304 MeV = 3.5 trillion K



PRL104,132301(2010), arXiv:0804.4168



ALICE, NPA 904 (2013) 573c



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 study was introduced.
- From particle flow study, QGP was found to be almost complete fluid.
- These studies were first performed in RHIC experiments and more precisely performed in LHC experiment.
- QGP temperature was measured from thermal photons and the results are consistent with expected QGP temperature.
- (Future: A very forward detector, FoCal, will help extension of the study, though not included in today's lecture)