Jet Physics in Heavy Ion Collision

- with My Ph.D work -

RIKEN
Takuya Kumaoka

Self Introduction

Index of this presentation

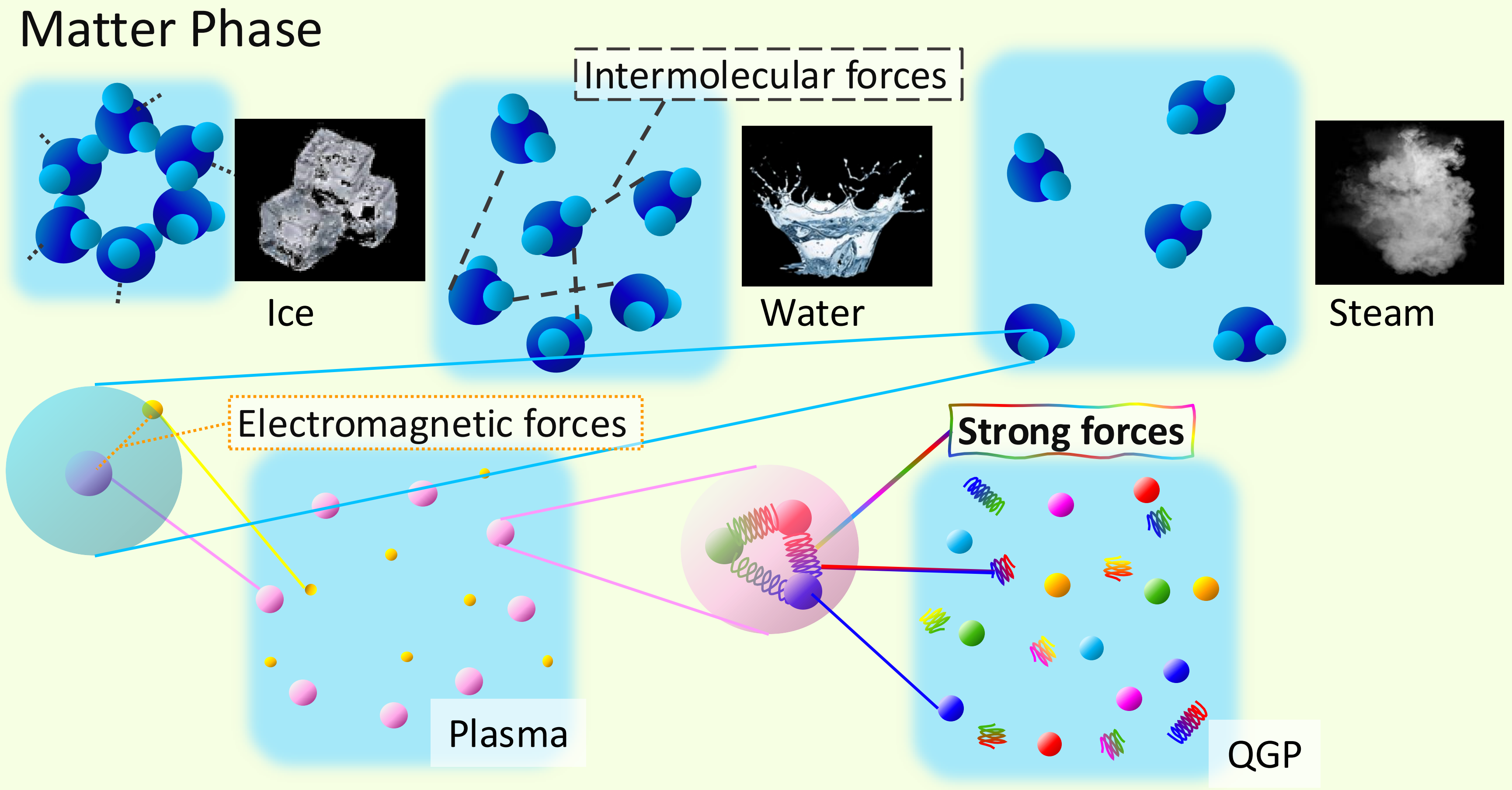
1. Introduction of the Jet Physics for the QGP study (15 min)
2. Experimental technic [ALICE det + centrality + jet reco] (10 min)
3. My Ph.D work (8 min)
4. What can we do using sPHENIX. [advantage of sPHENIX] (7 min)

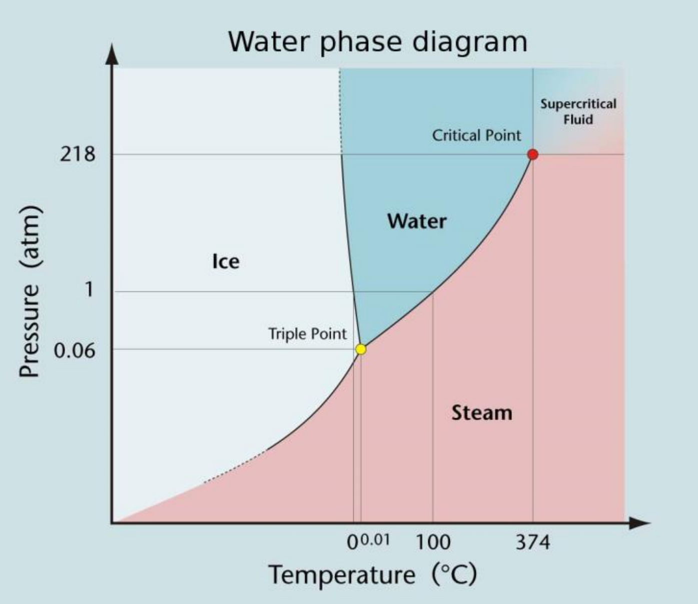
Ex: Details of jet reconstruction (Parameters of jet reconstruction, main cuts, backgrounds, unfolding, systematic uncertainties, and etc...)

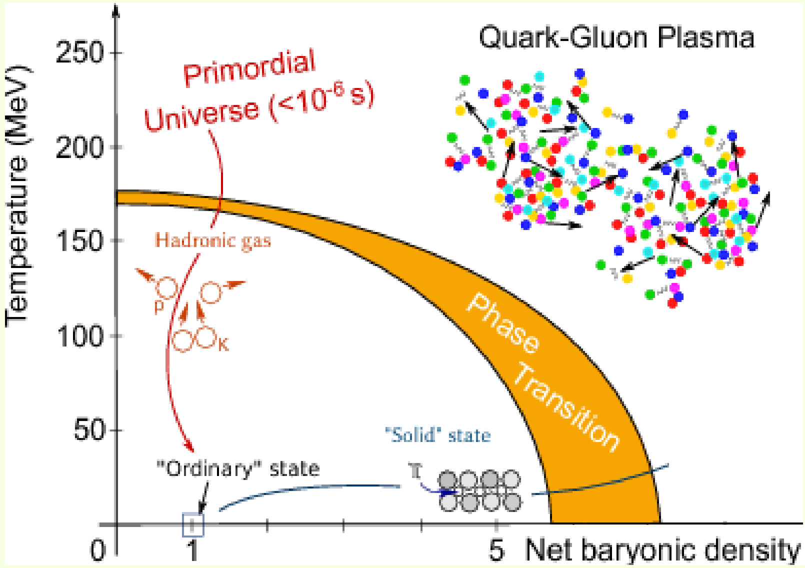
1. Introduction of the Jet Physics for the QGP study

What is Quark-Gluon Plasma (QGP)

QGP: A phase of matter at *extremely* high temperatures or densities.



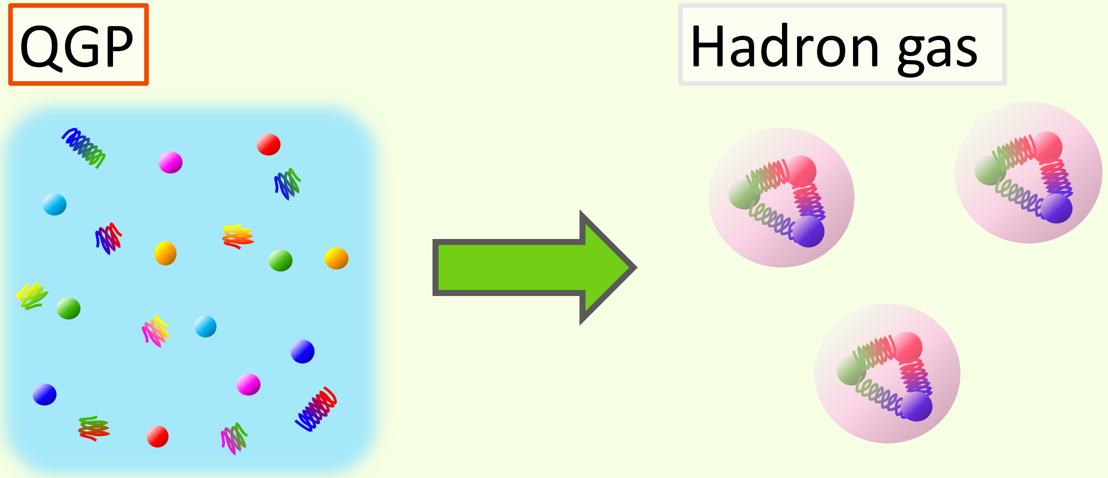




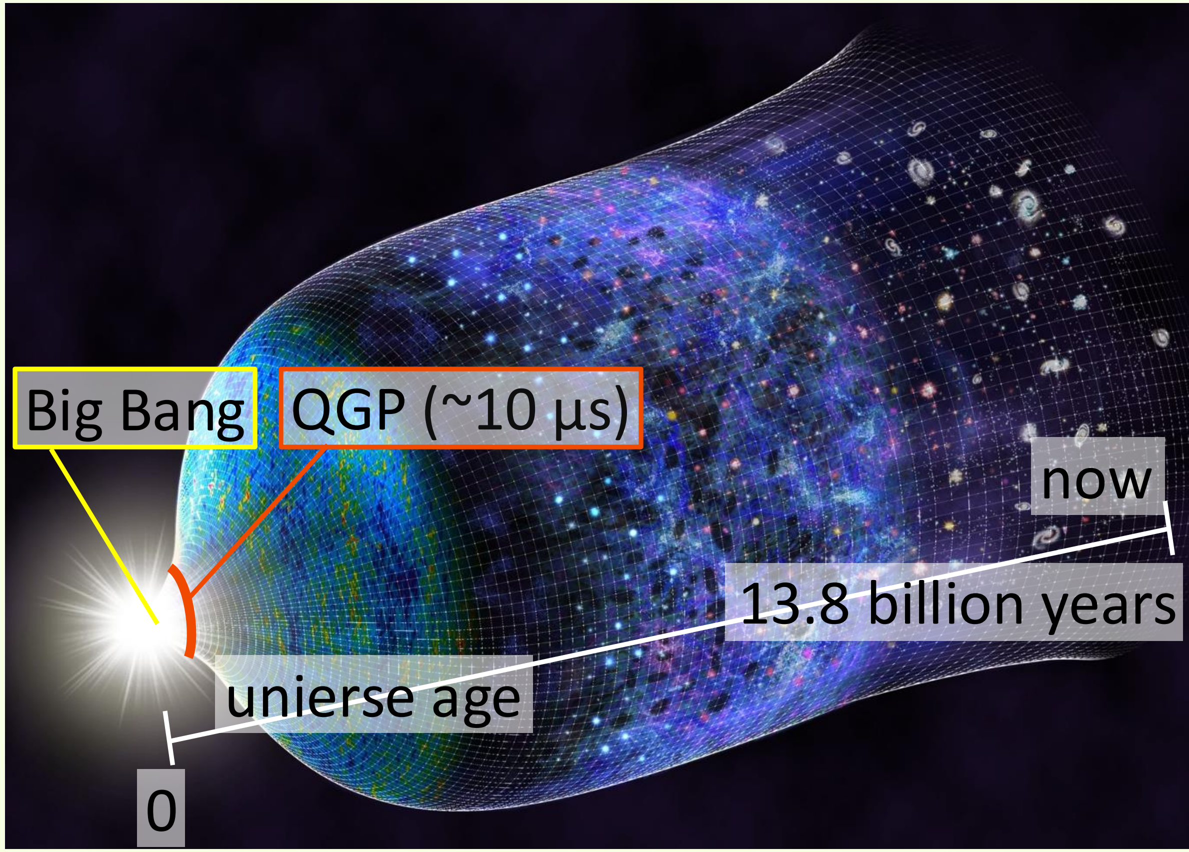
In QGP, the quarks and gluons behave as free particles.
Strong (quantum chromodynamics: QCD) interaction dominates.

QGP in the early Universe

In the early universe (~10 μs), the QGP is expected to have formed.



The QGP becomes a hadron gas state soon.



The QGP studies

→ Clarify this universe evolution.

→ Elucidate the process from elementary particles to hadrons.

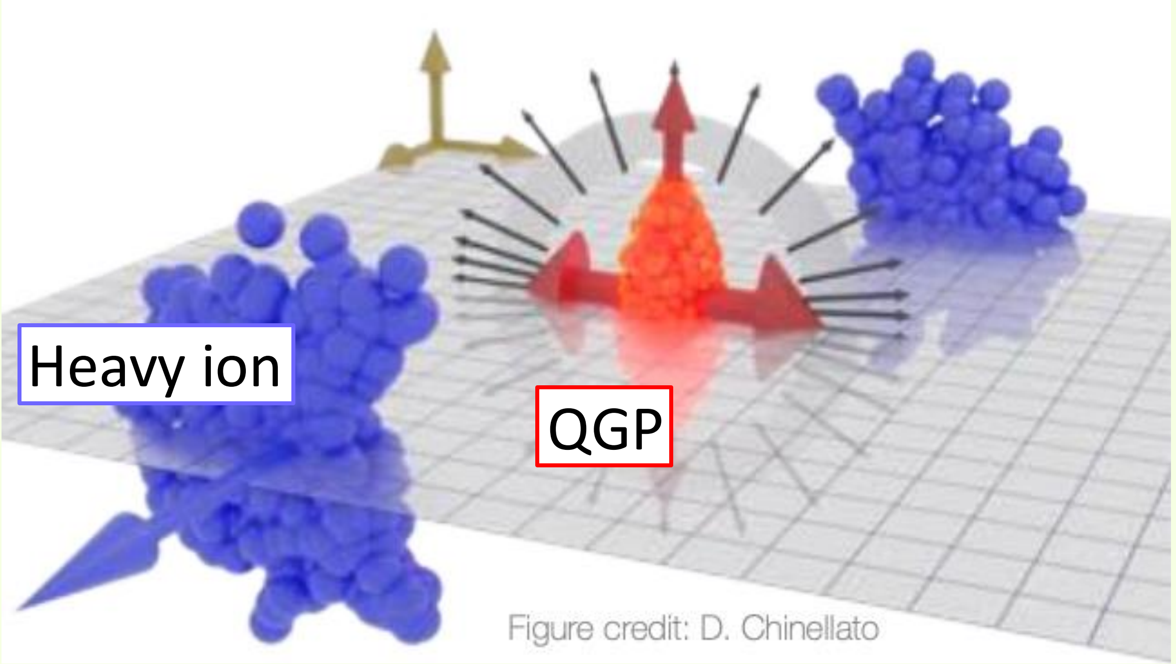
QGP Creation by Heavy Ion Collisions

We want to clarify ***QGP properties***, temperature, density, interactions, and etc...

→ Produce the QGP by **Heavy Ion Collisions (HIC)** with a large collider (LHC/RHIC).

Collision system: pp, pPb, PbPb, XeXe

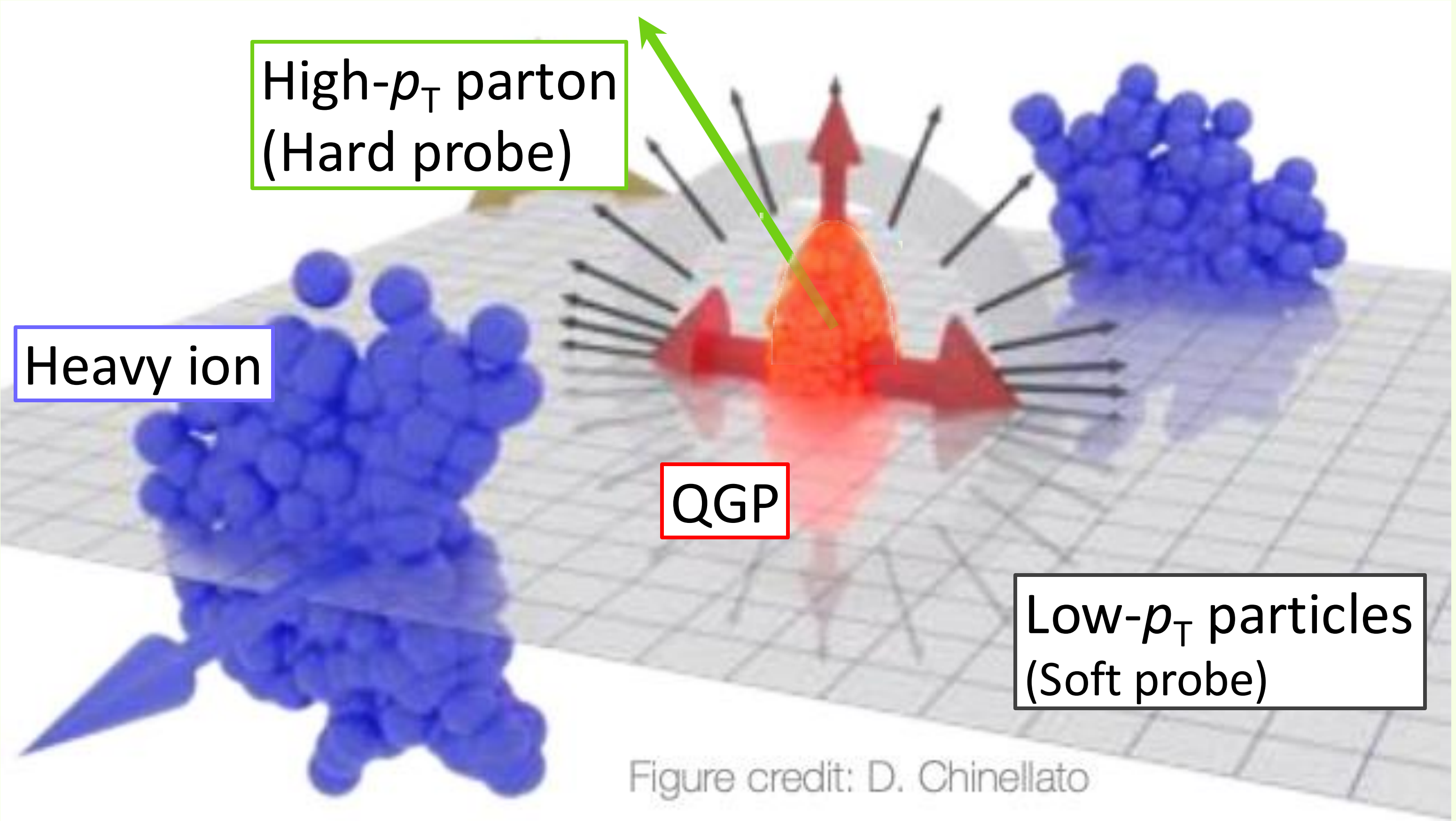
Collisional energy: $\sqrt{s}, \sqrt{s_{\rm NN}} = 2.76 - 14$ TeV



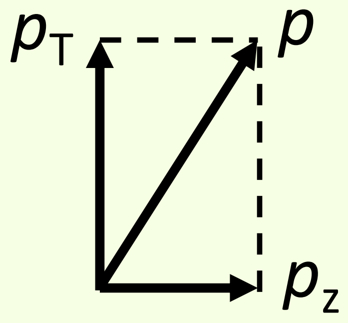
https://www.youtube.com/watch?v=pQhbhpU9Wrg

Methods to Study the QGP properties

<u>Direct observation of the QGP is mostly impossible</u> because of its tiny size and short life time.

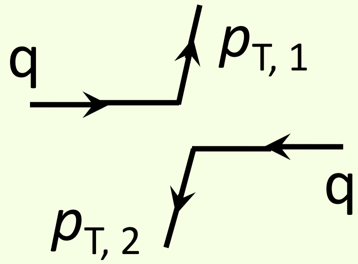


p_T : transverse momentum



beam direction →

A high momentum transfer event makes high momentum particles.



$p_{T,1} = p_{T,2}$

rare ≅ clear signal

→ **Use high-momentum partons (quark/gluon) that traverse the QGP medium.**

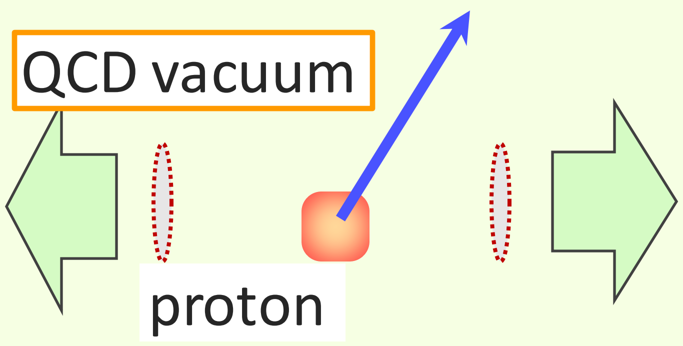
Hard Probes for the QGP: Advantage (1)

Hard probes: High momentum rare transfer events (High momentum parton)

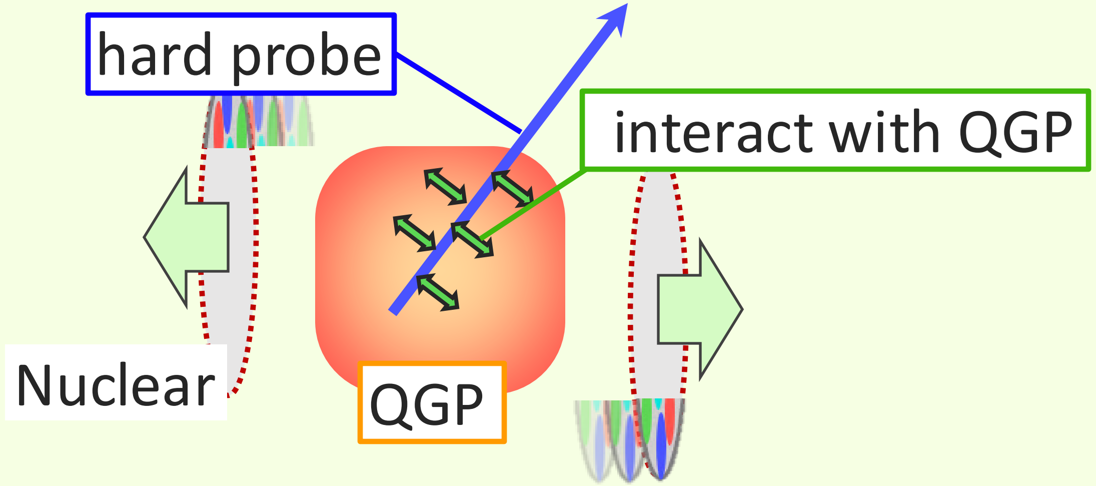
- The production rates are calculable within **perturbative** QCD (pQCD)

  →The hard probes, which are measured in the pp collisions, are used as *the reference* for the one measured in the Pb–Pb collisions.

pp collision: reference



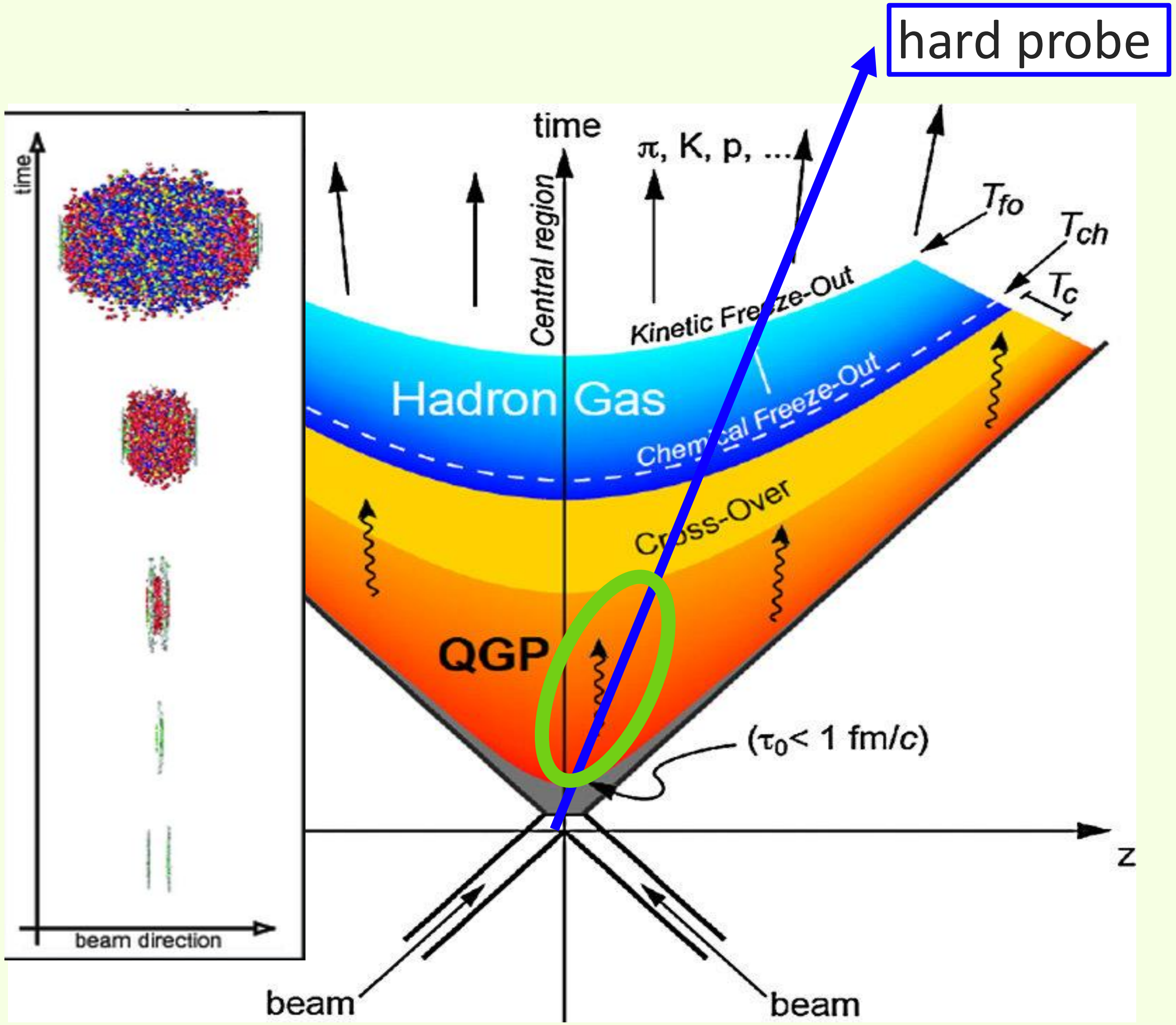
A–A collision: jet suppression



Hard Probes for the QGP: Advantage (2)

- Hard probes are created in the initial collision of the same event of the QGP creation

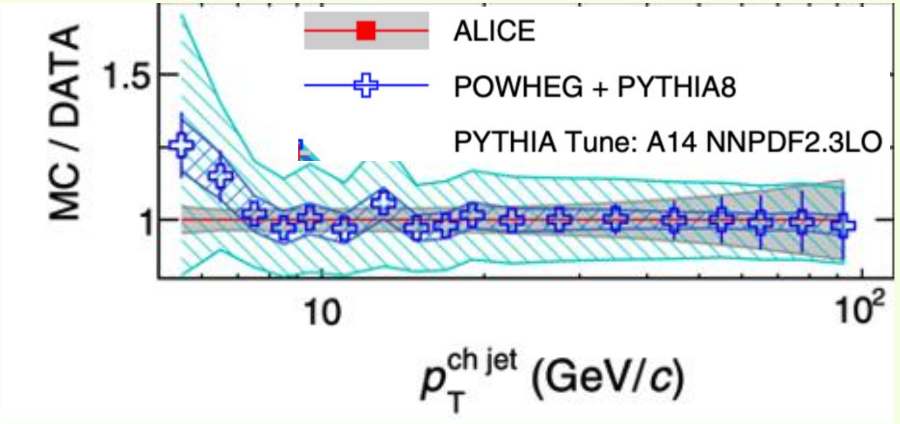
→ The experimental signals of the hard probes contains the history of its interaction with the QGP.



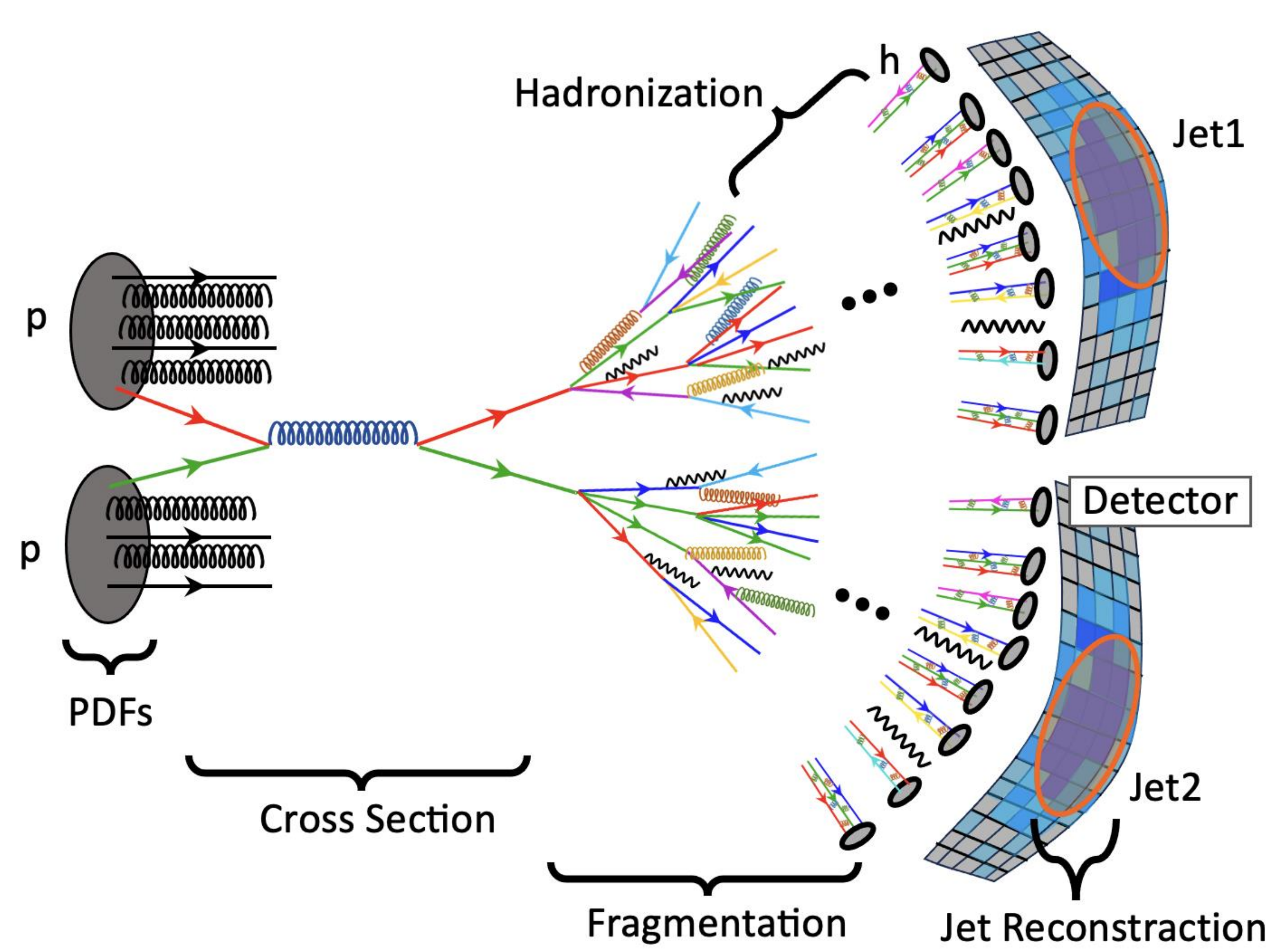
What is a jet?

A **parton** is fragmented into a hadron collimated shower.
→ Detect as a **jet** of hadrons
→ Experimental signatures of quarks or gluons

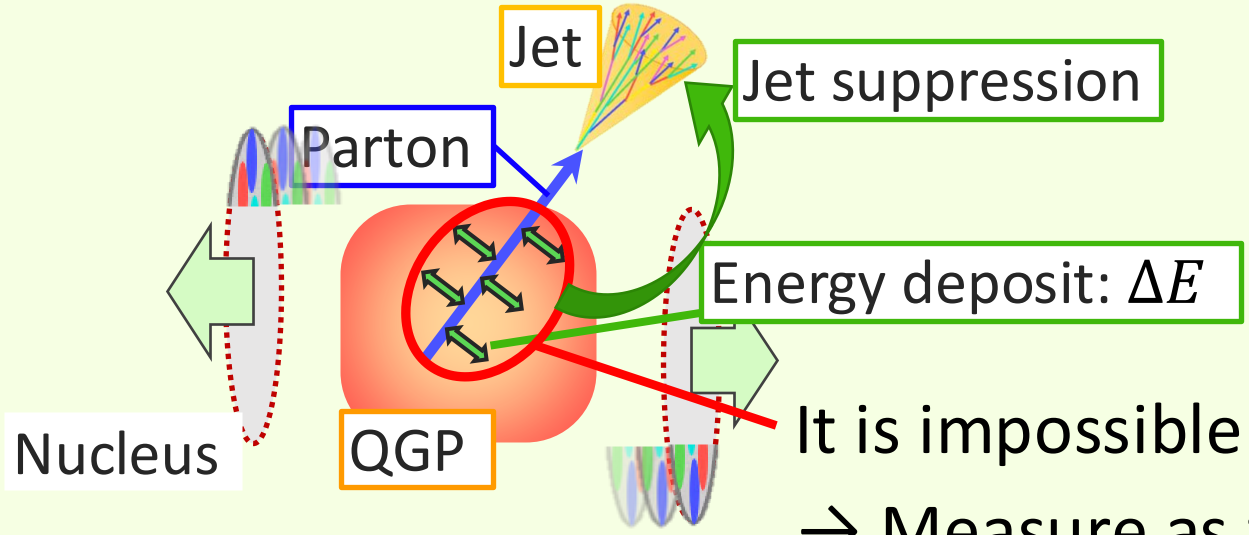
p−p measurements match pQCD theoretical predictions



PHYSICAL REVIEW D 100, 092004 (2019)



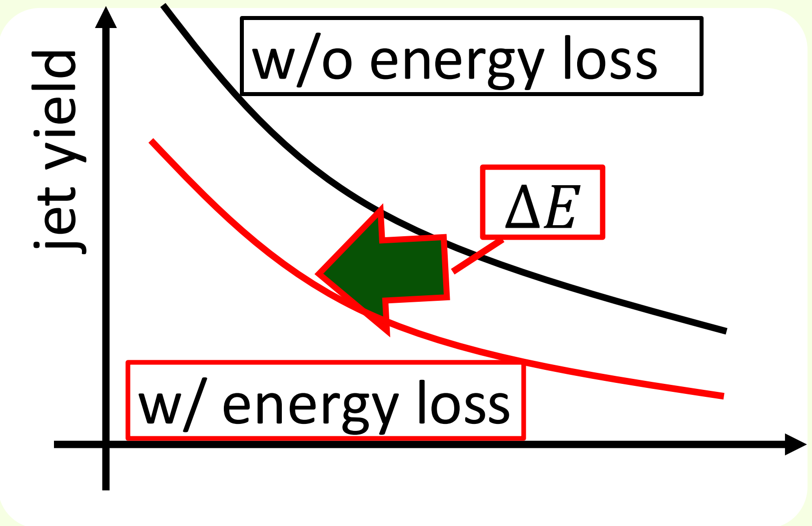
Parton Energy Loss Measurement



It is impossible to directly measure the energy loss.

→ Measure as the jet suppression

→ Require comparisons



Two major measurements for the jet quenching

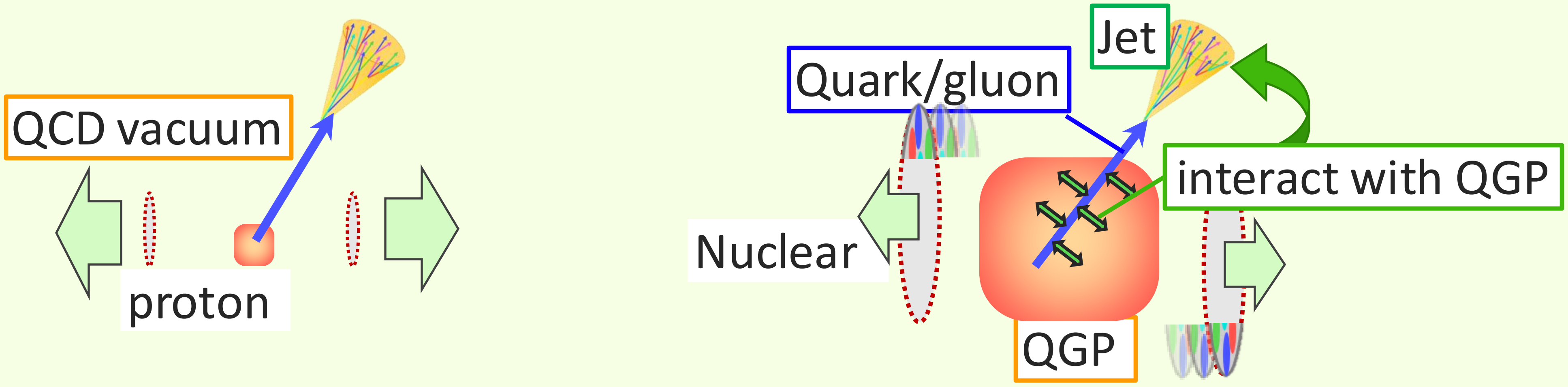
(1) Nuclear modification factor (R_{AA}^{jet})

(2) Jet azimuthal anisotropy (v_2^{jet})

Nuclear Modification Factor (R_{AA})

pp collision: reference

AA collision: jet suppression



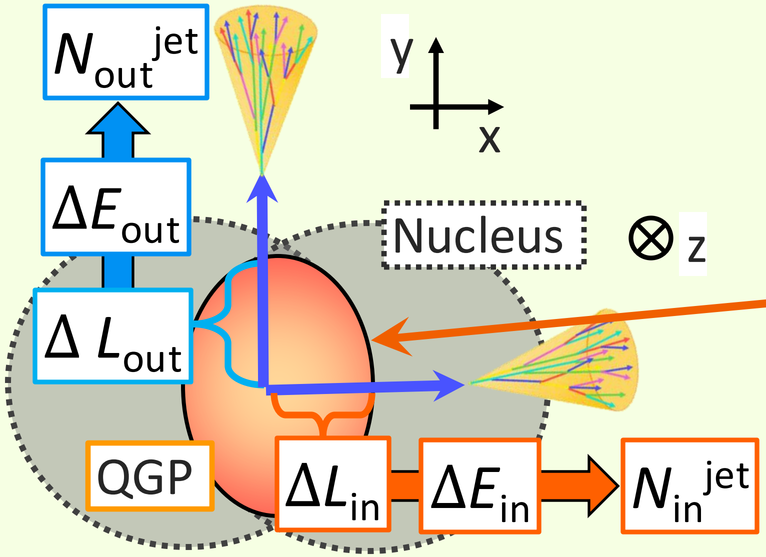
$$R_{AA}^{jet} = \frac{\text{Jet yield of the Pb-Pb collisions scaled as binomial collision}}{\text{Jet yield of the p-p collision}}$$

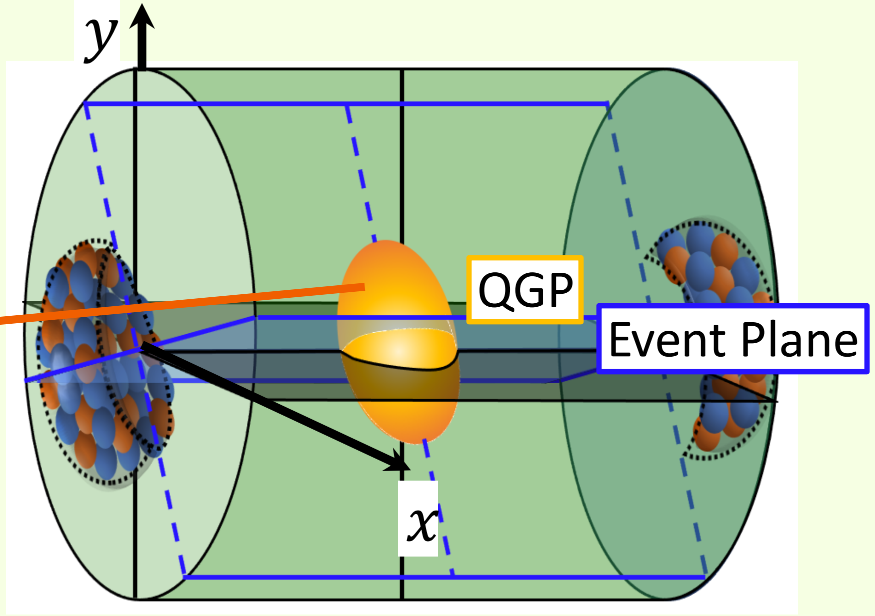
Use the difference between with and without suppression

→ **Sensitive to magnitude of suppression**.

Jet azimuthal anisotropy (v_2^{jet})

Use non-central heavy ion collisions





$v_2^{jet} \propto N_{in}^{jet} - N_{out}^{jet}$

N_{in}, N_{out}: Jet yield in the in-/out-of-plane, respectively

$\Delta E_{out} > \Delta E_{in} \Rightarrow v_2^{jet} > 0$

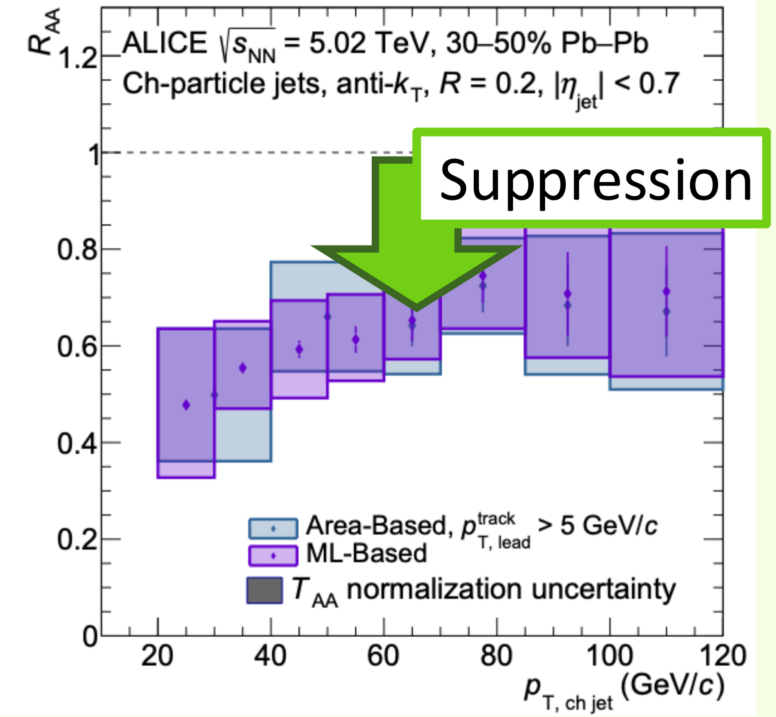
Use difference of the path length between in-plane and out-of plane

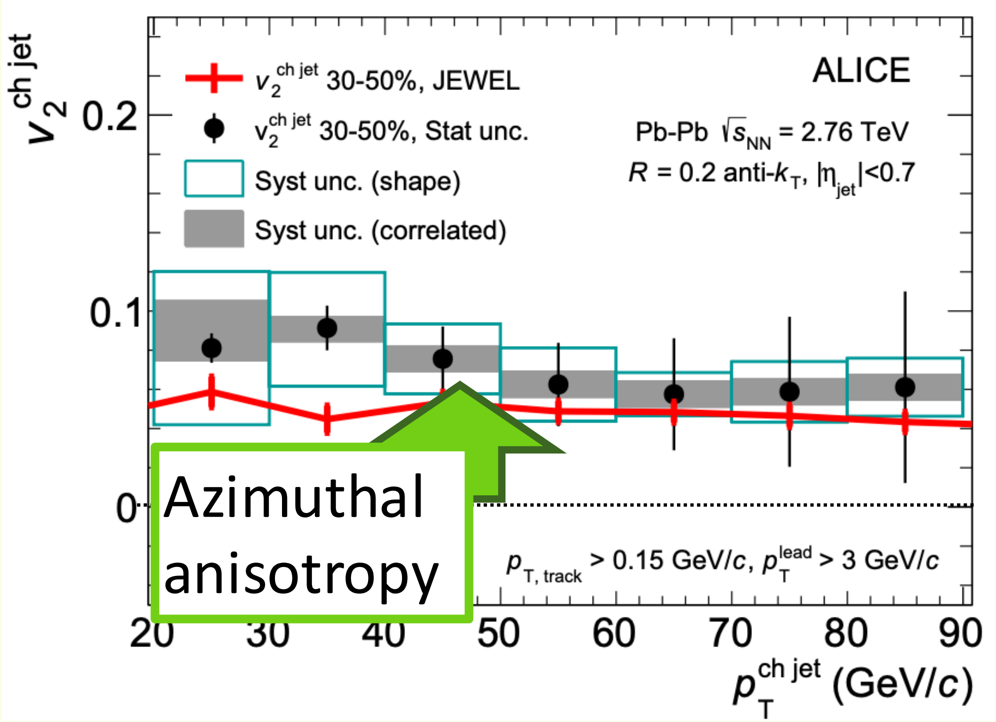
→ Sensitive $\boldsymbol{L}$ **dependency** of ΔE.

Current status on the study of the parton energy loss

- LHC-ALICE jet R_{AA} ($\sqrt{s_{NN}} = 2.76,\ 5.02$ TeV) and v_2 ($\sqrt{s_{NN}} = 2.76$ TeV) https://arxiv.org/pdf/2303.00592.pdf https://doi.org/10.1016/j.nuclphysa.2016.03.006

- LHC-ATLAS jet R_{AA} and v_2 ($\sqrt{s_{NN}} = 2.76, 5.02$ TeV) https://cds.cern.ch/record/2853755/files/ATL-PHYS-PUB-2023-009.pdf https://journals.aps.org/prc/pdf/10.1103/PhysRevC.105.064903





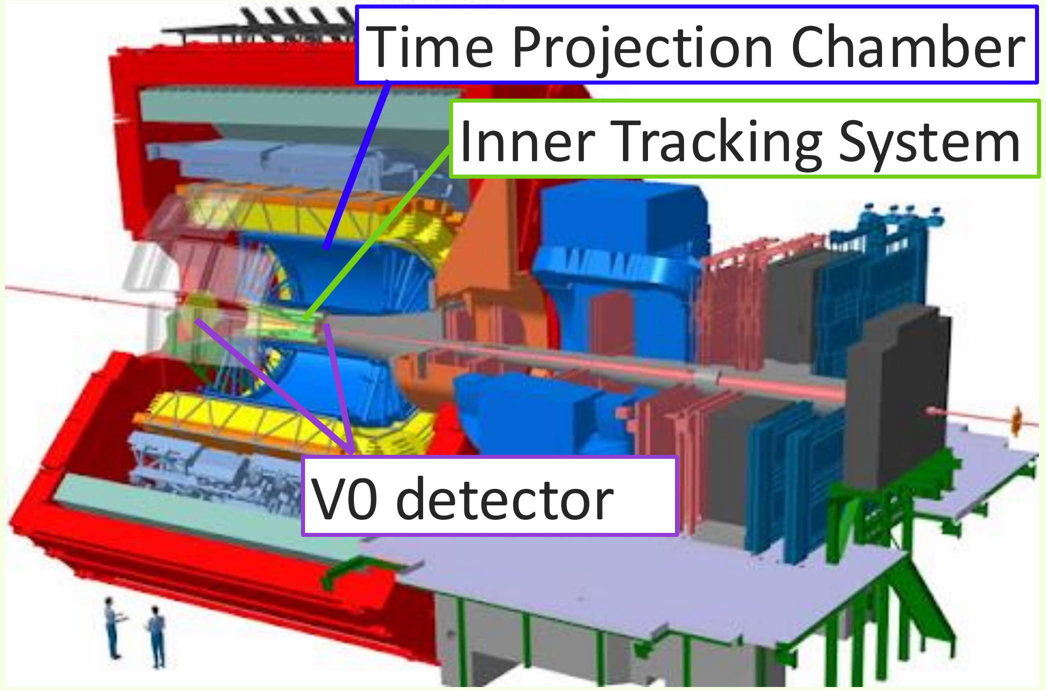
These results indicates the jet suppression and azimuthal anisotropy exist ($R_{AA}^{jet} < 1$, $v_2^{jet} > 0$).
→ However, they do not still clarify the energy loss mechanisms and quantify their parameters.

2. Experimental technic

～ALICE det + centrality + jet reco～

ALICE Detector in Run-2

The ALICE detector is designed to study the QGP properties.
The experimental setup is divided in mainly three parts:
(1) The central barrel covering the collision point ($-0.9 < \eta < 0.9$) [ITS, TPC]
(2) The muon arm to detect forward-direction muons ($-4 < \eta < 2.5$)
(3) The global detector for selecting collision events [V0 detector]



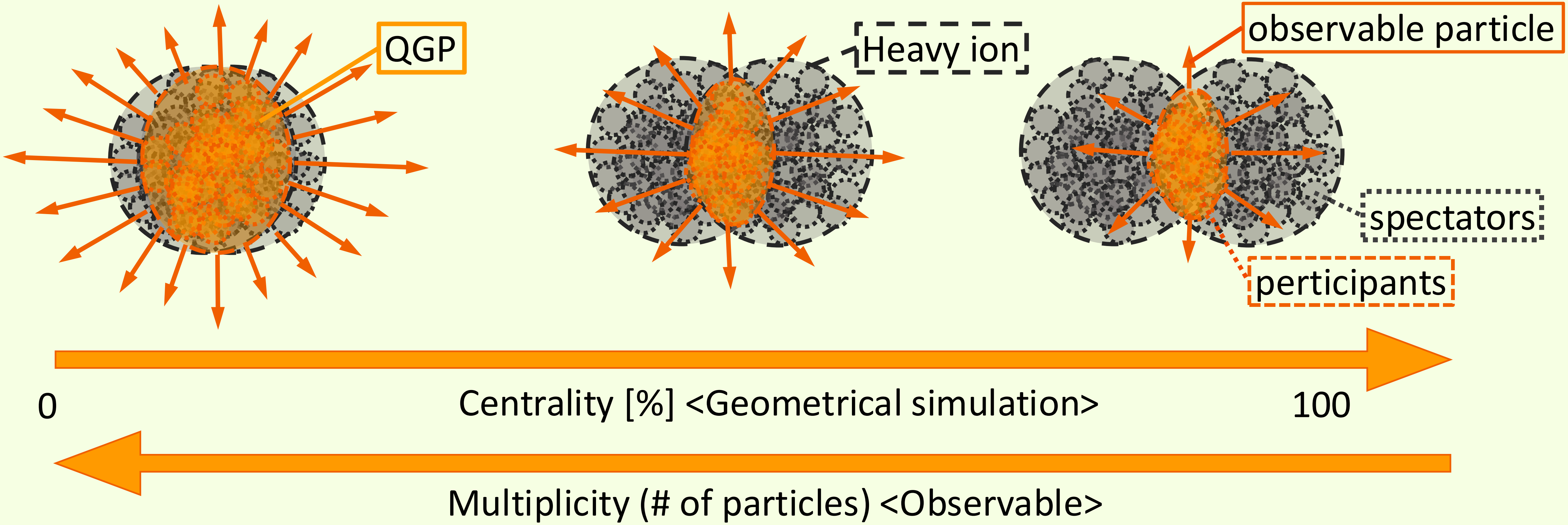
Property

Height/Width: 18 m
Length: 26 m
Weight: 10,000 t

Magnet: 0.5 T

Centrality

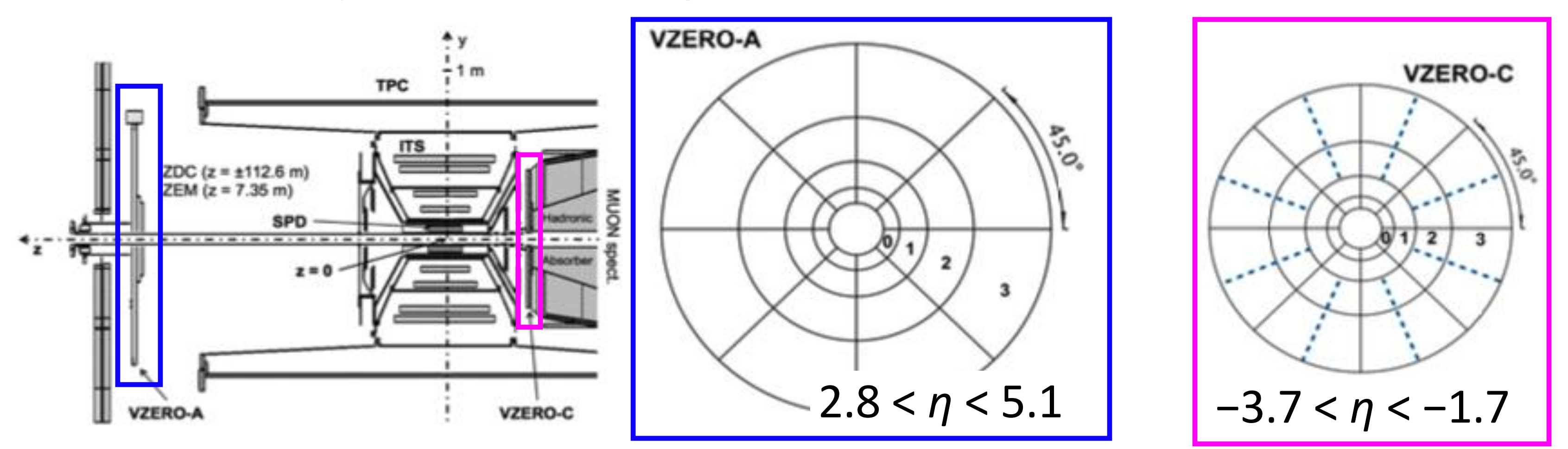
Centrality: Degree of a geometrical overlap between the collision two nucleon.
→ It gives a geometrical information of the QGP medium, size and shape.



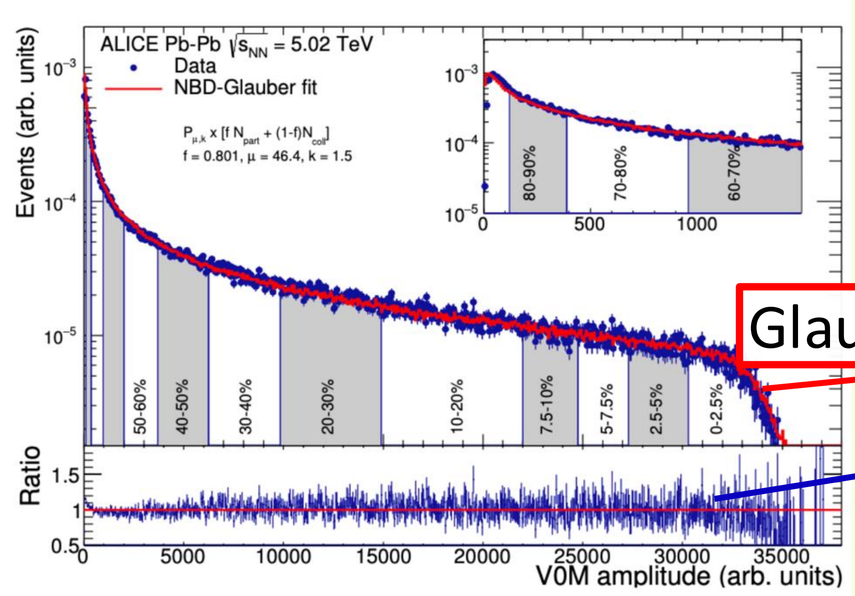
It is impossible to see the medium geometry.
→ Estimate the centrality by connecting the multiplicity. (Data – Simulation w/ Glauber model)

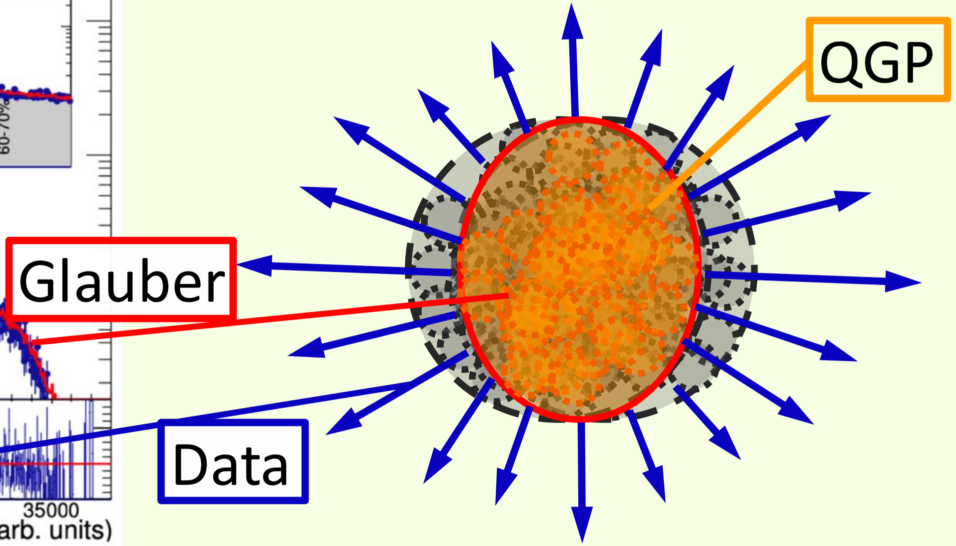
V0 Detector

Two end cap scintillating detector (V0A, V0C), **V0M**: V0A+V0C



Using NBD-Glauber fit for V0M amplitude, the event centrality is determined.





V0 Detector for Event Plane

Determine the event plane angle (Ψ_2) using the V0 amplitude distribution for azimuthal angle.

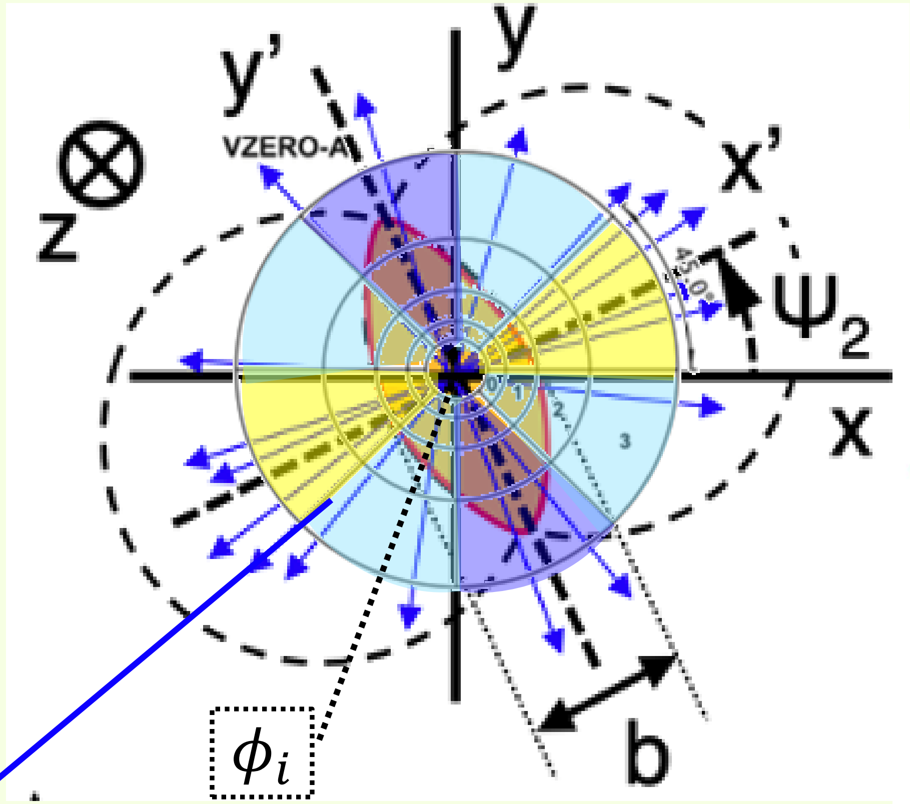
Event plane angle

$$\Psi_{\mathrm{EP}\,n} = \frac{1}{n}\arctan\frac{Q_{n,y}}{Q_{n,x}}$$

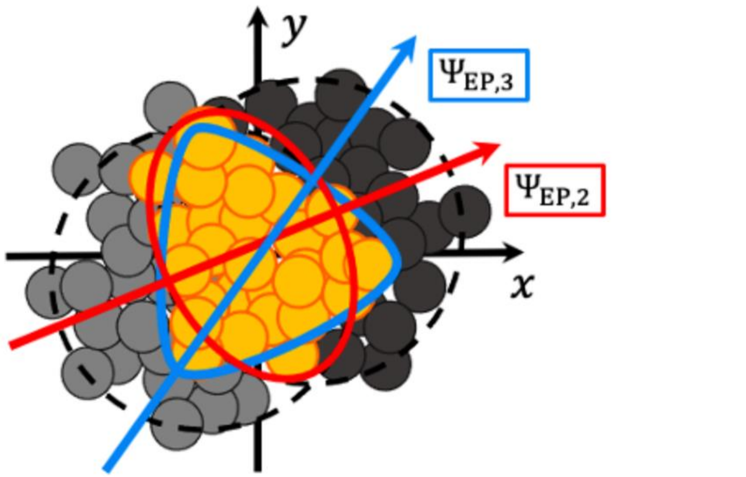
Flow Vector compornet

$$Q_{n,x} = \sum_i \omega_i \cos n\phi_i$$

$$Q_{n,y} = \sum_i \omega_i \sin n\phi_i$$



(ϕ_i : detector sector angle, ω_i :multiplicity weight,
n: Fourier order)



$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos 2(\phi - \Psi_{\mathrm{EP},2}) + 2v_3\cos 3(\phi - \Psi_{\mathrm{EP},3}) + \cdots$$

$$v_n = \langle \cos n(\phi - \Psi_{\mathrm{EP},n}) \rangle$$

$\Psi_{\mathrm{EP},n}$: Higher harmonic event plane
ϕ: Azimuthal angle of emitted particles

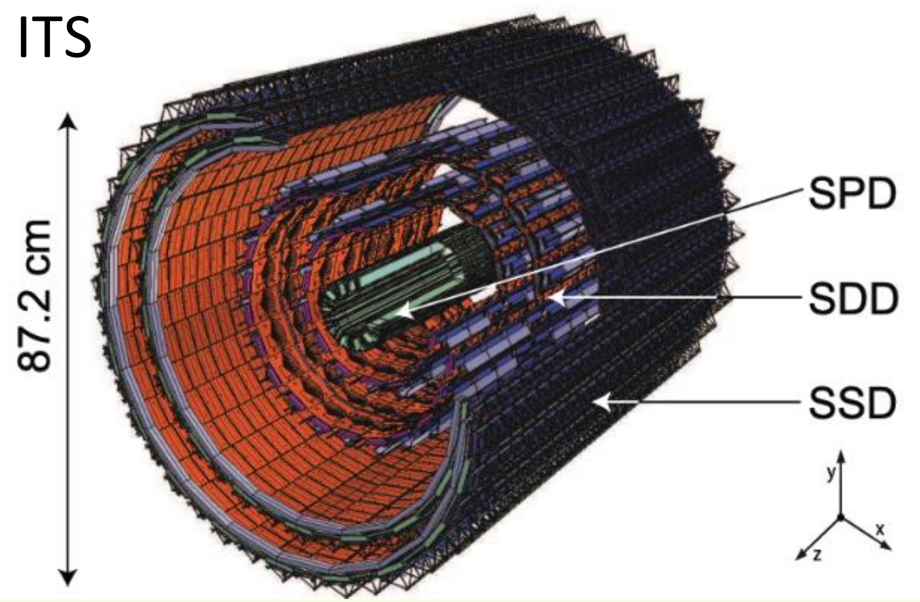
Inner Tracking System / Time Projection Chamber

In my analysis, <u>the only charged tracks were used to reconstruct jets</u>.

→ Detector: Inner Tracking System (ITS) and Time Projection Chamber (TPC)

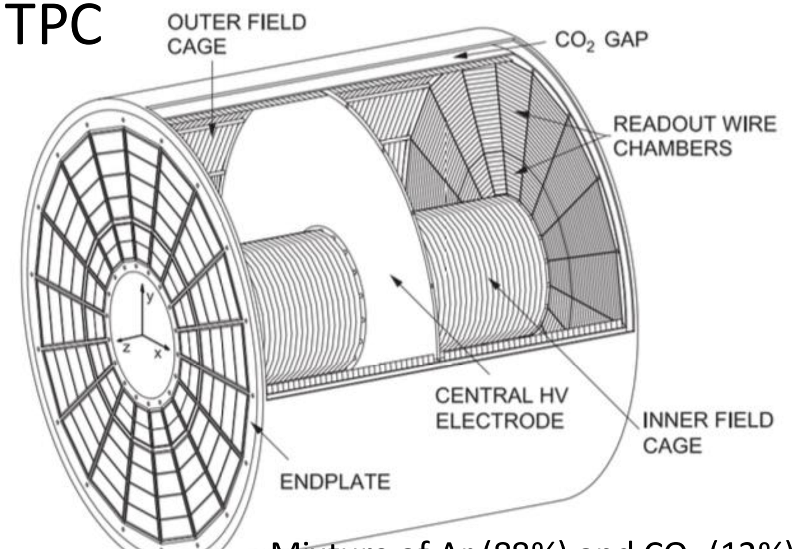
Acceptance: $|\eta| < 0.9$, $0 < \phi < 2\pi$

ITS



Six silicon pixel layers detector

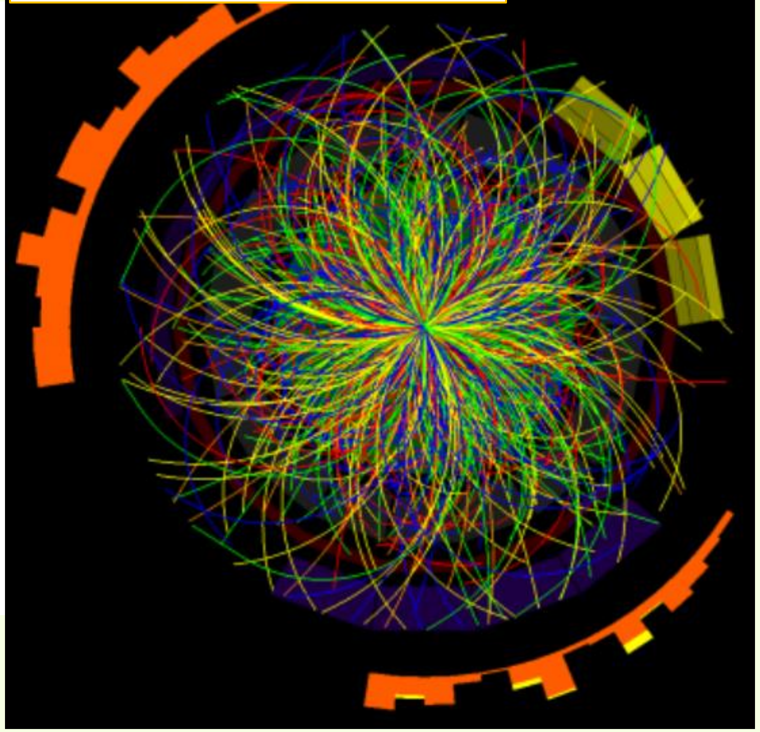
TPC



Mixture of Ar (88%) and CO_2 (12%)

Gas chamber detector

Reconstructed tracks

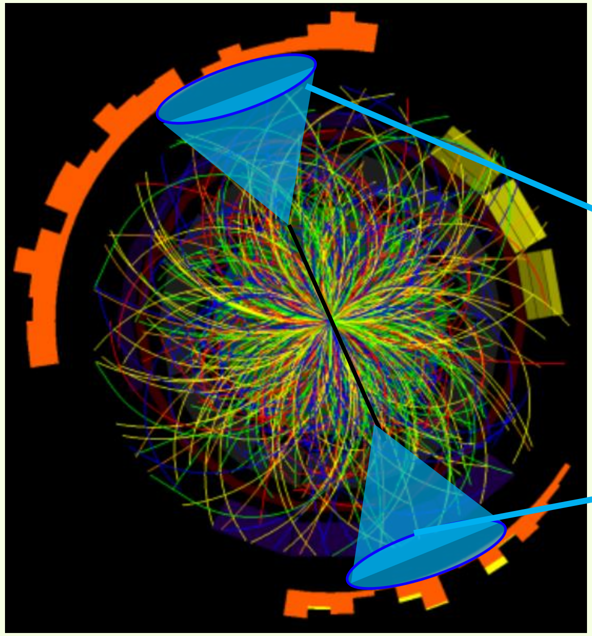


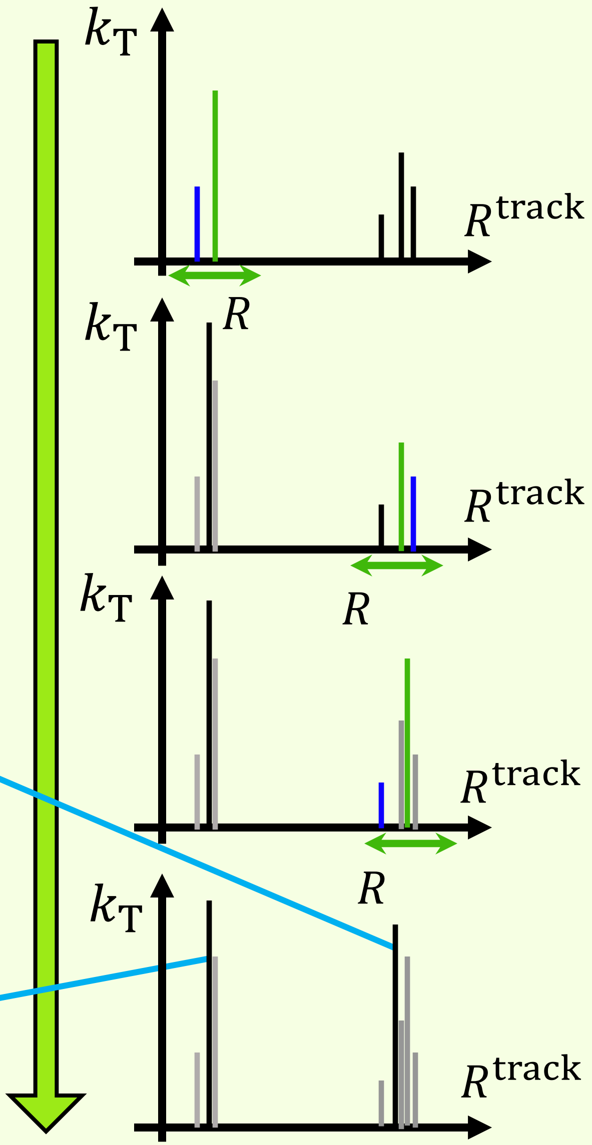
Anti-k_T signal jet reconstraction

Merge track transverse momentum (k_T) from the track having highest k_T to minimize d_{ij} in resolution paramter (R) range.

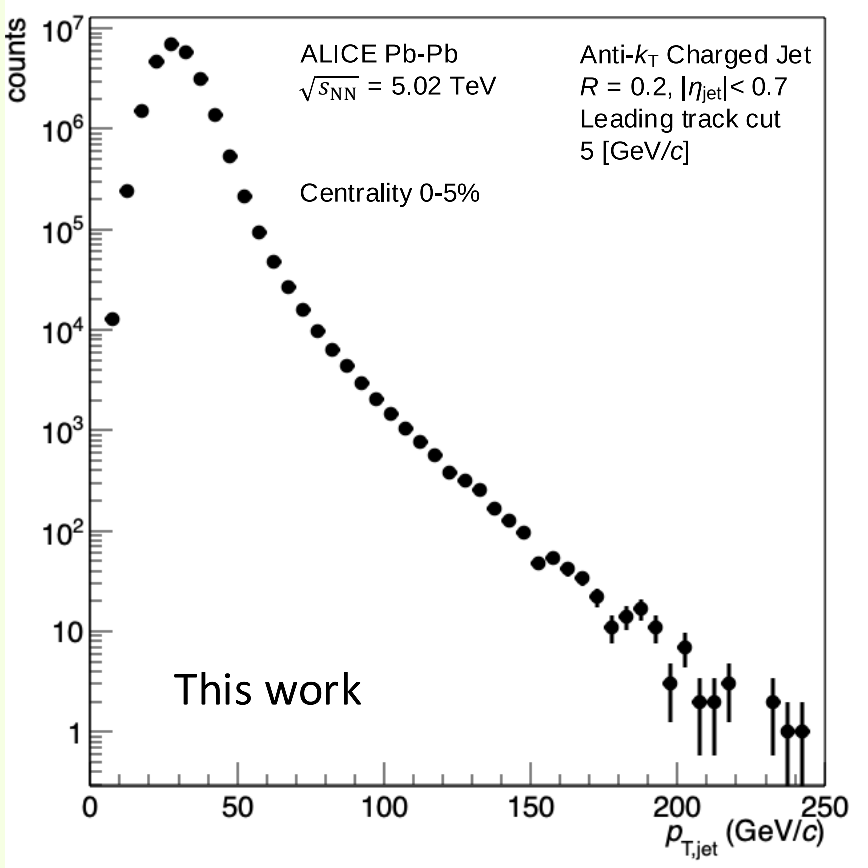
$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$$

(anti-k_T)





anti-k_T jet yield distribution for pT

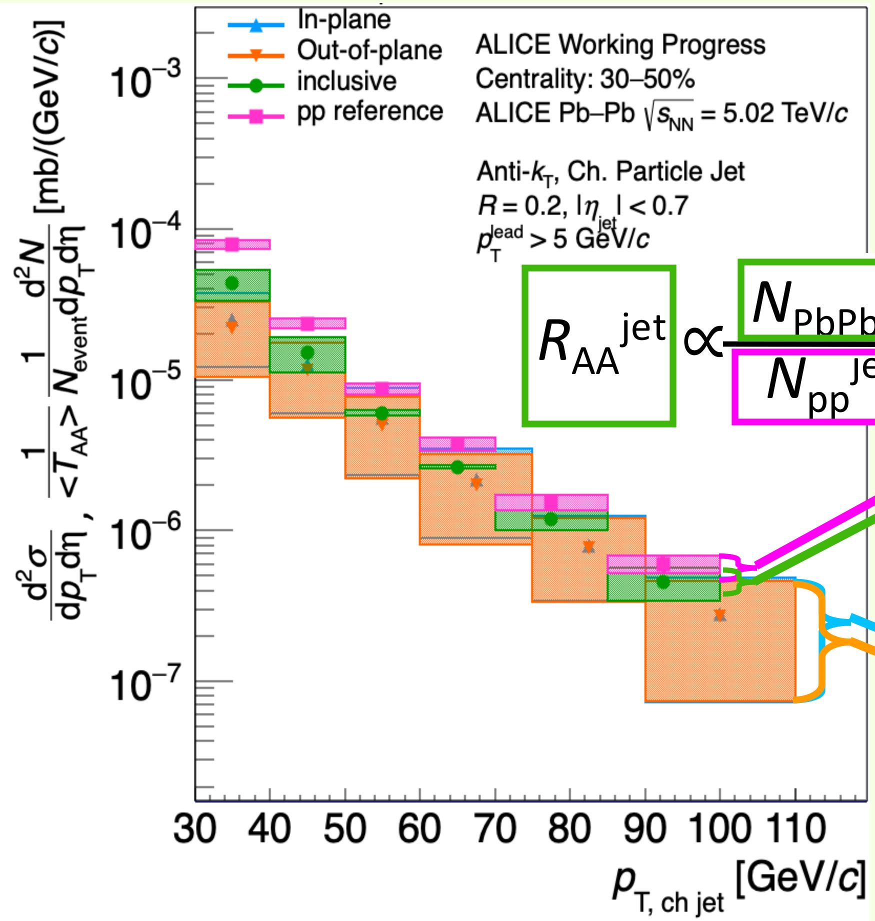


Spectrums inclusvive, and in, out-of-plane

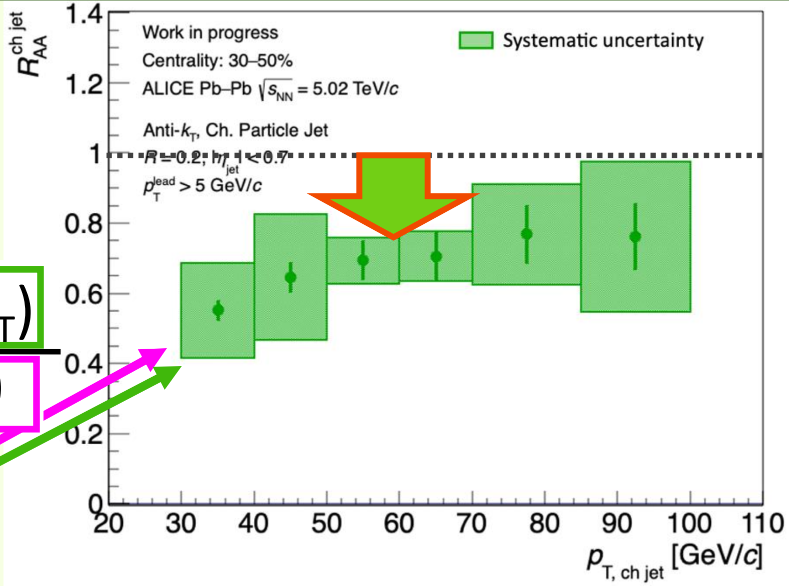
Raw jets (anti-k_T)

→ Correction jet
(BKG subract)

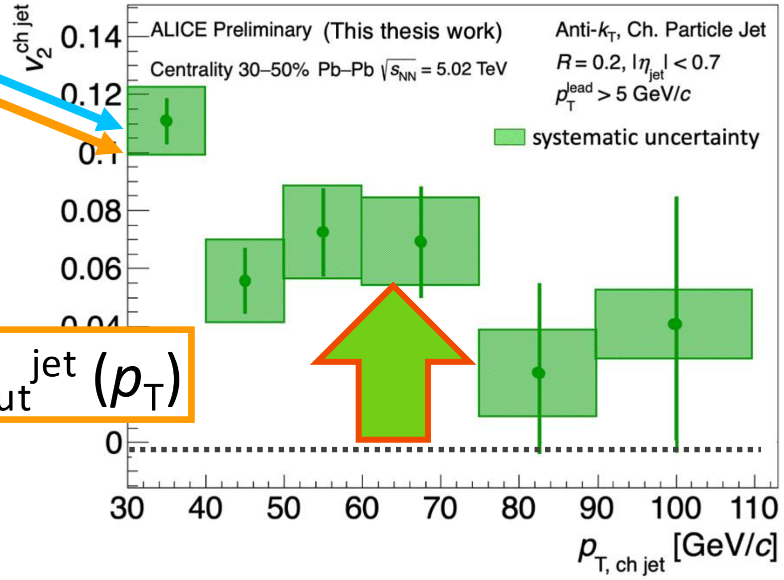
→ Unfolded jet
(BKG and detector effect modification)



$R_{AA}^{jet} \propto \frac{N_{PbPb}^{jet}(p_T)}{N_{pp}^{jet}(p_T)}$



$v_2^{jet} \propto N_{in}^{jet}(p_T) - N_{out}^{jet}(p_T)$



The R_{AA}^{jet} is smaller than 1.
→ **It suggests the jet suppression.**

The v_2^{jet} shows positive value.
→ **It suggests path length dependency of the parton energy loss.**

3. My Ph.D work

～Parton Energy Loss Toy Model Simulaiton～

Physics target: Parton Energy Loss Mechanism Models

Partons deposit energy in the QGP medium within different mechanisms.

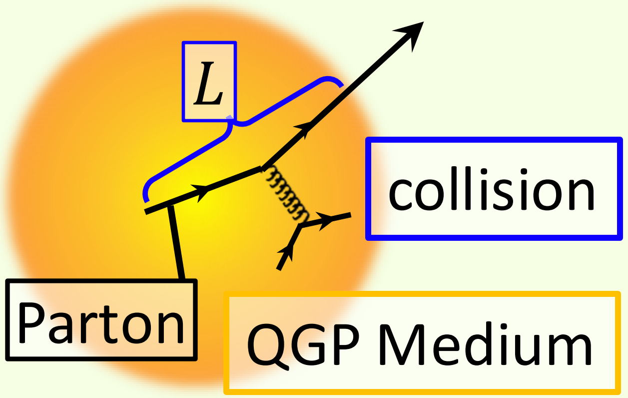
Energy loss

$\Delta E = \hat{e}_n L^n$ ($\hat{e}_n$: energy loss per unit path-length, L: path length in the QGP medium)

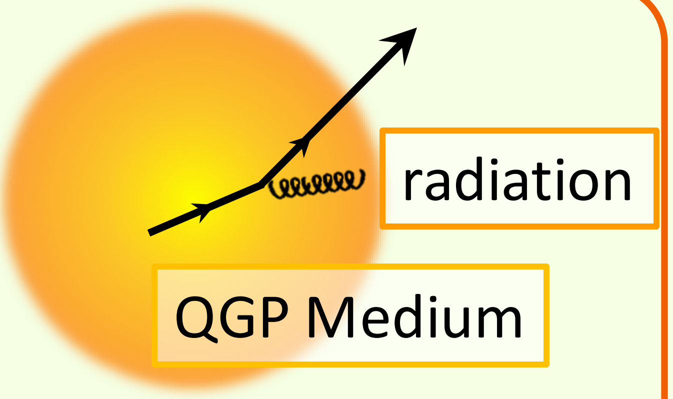
Includes QGP properties:

QGP viscosity (η/s), Temperature (T), Coupling constant (α_s)...

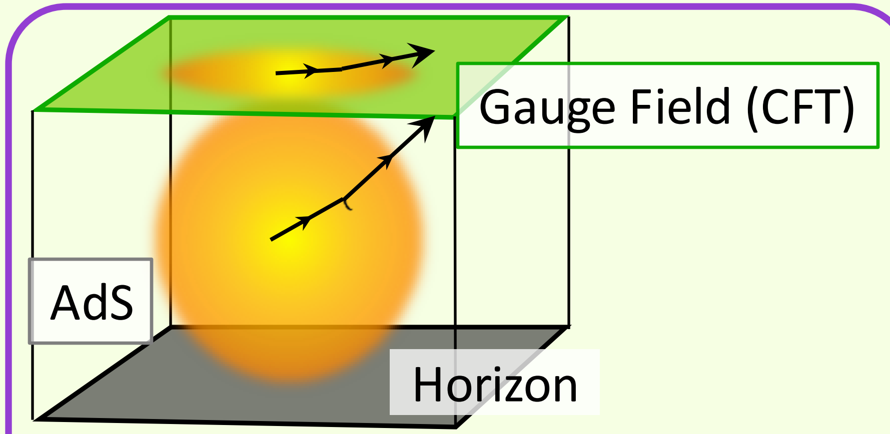
Parton energy loss mechanisms: (These mechanisms suggest different n)



Collisional ($\Delta E \propto L, n = 1$)



Radiative ($\Delta E \propto L^2, n = 2$)



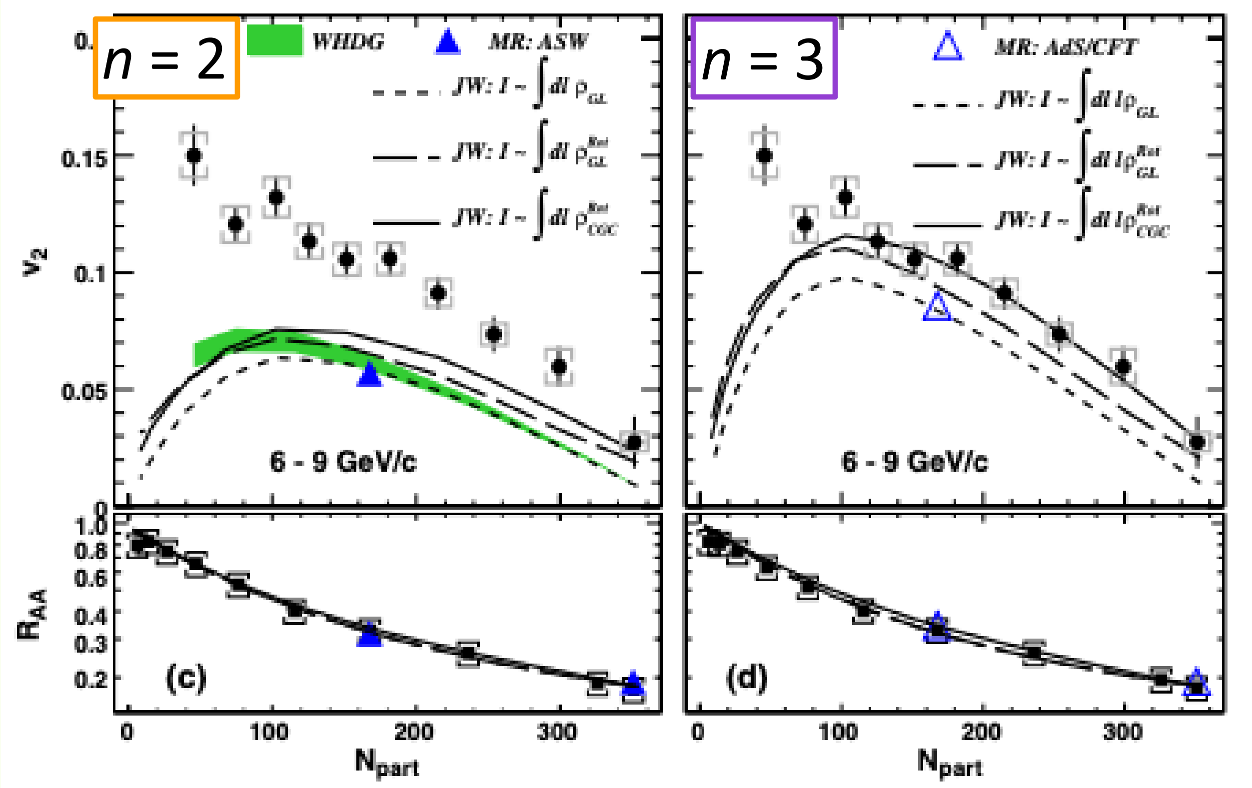
AdS/CFT ($\Delta E \propto L^3, n = 3$)

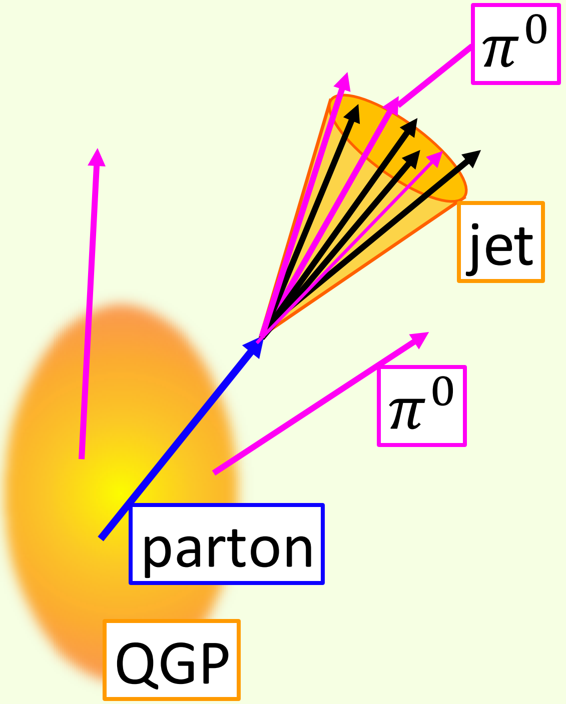
Which of these mechanisms dominates the energy loss is not yet clarified.
The parameters have not been quantified yet.

Previous study of the n detemination

For strong constraints on the parton energy loss models depending on the path length, the v_2 and R_{AA} of π^0 measurement using PHENIX $\sqrt{s_{NN}} = 200$ GeV data (2010) were conducted.

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.105.142301





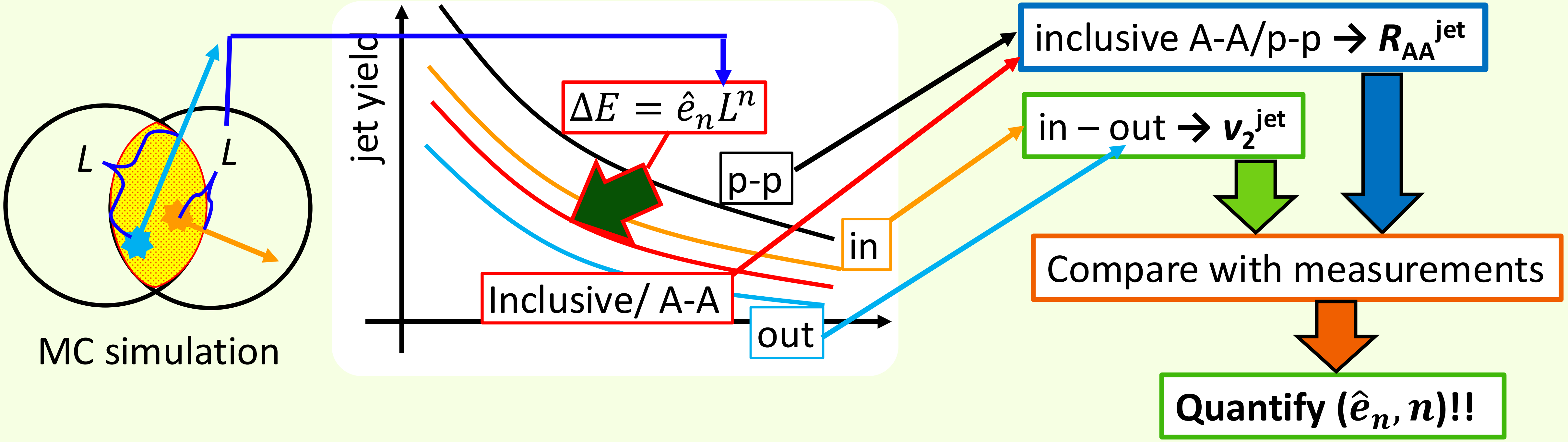
The results indicates the n = 3 model is better than the n = 2 case.

However, a π^0 particle contains only partial information of the original parton.

Concept of my parton energy loss simulation

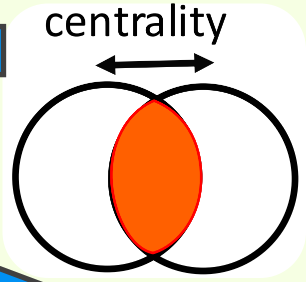
Evaluate the parton energy loss parameters ($\hat{e}_n$, n) and constrain the models using both the measurements R_{AA}^{jet} and v_2^{jet}.

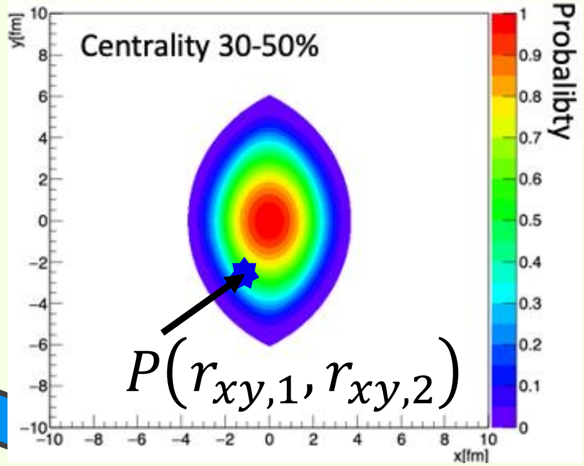
- Connect the path length obtaind by MC simulation to the observables (R_{AA}^{jet} and v_2^{jet}).



Overview of Simulation Algorithm Flow

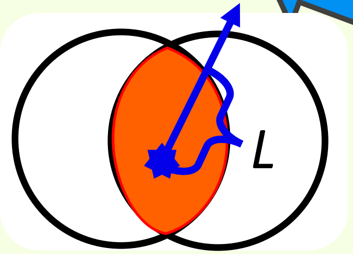
1. Determine Centrality



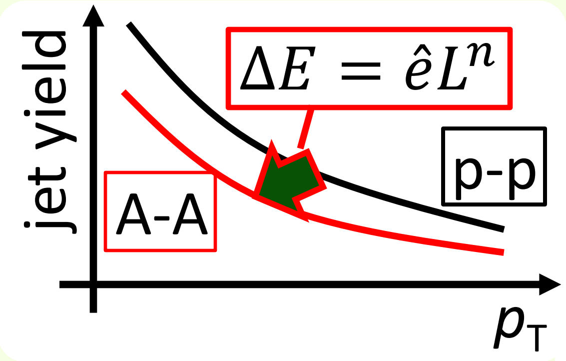


2. MC for creating a parton using $P(r_{xy,1}, r_{xy,2})$

3. Calc pass length (L)

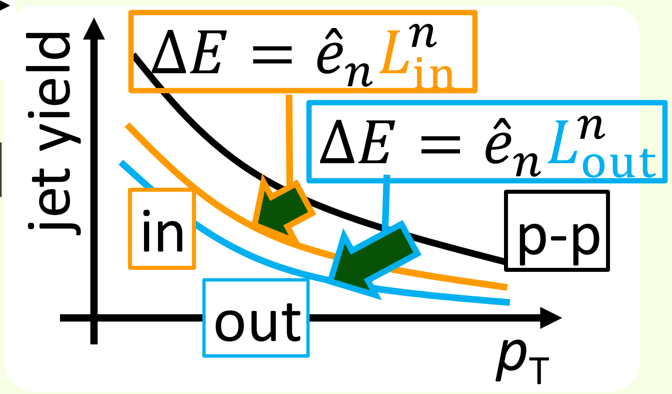


4. Calc Energy Loss ($\Delta E = \hat{e}_n L^n$)



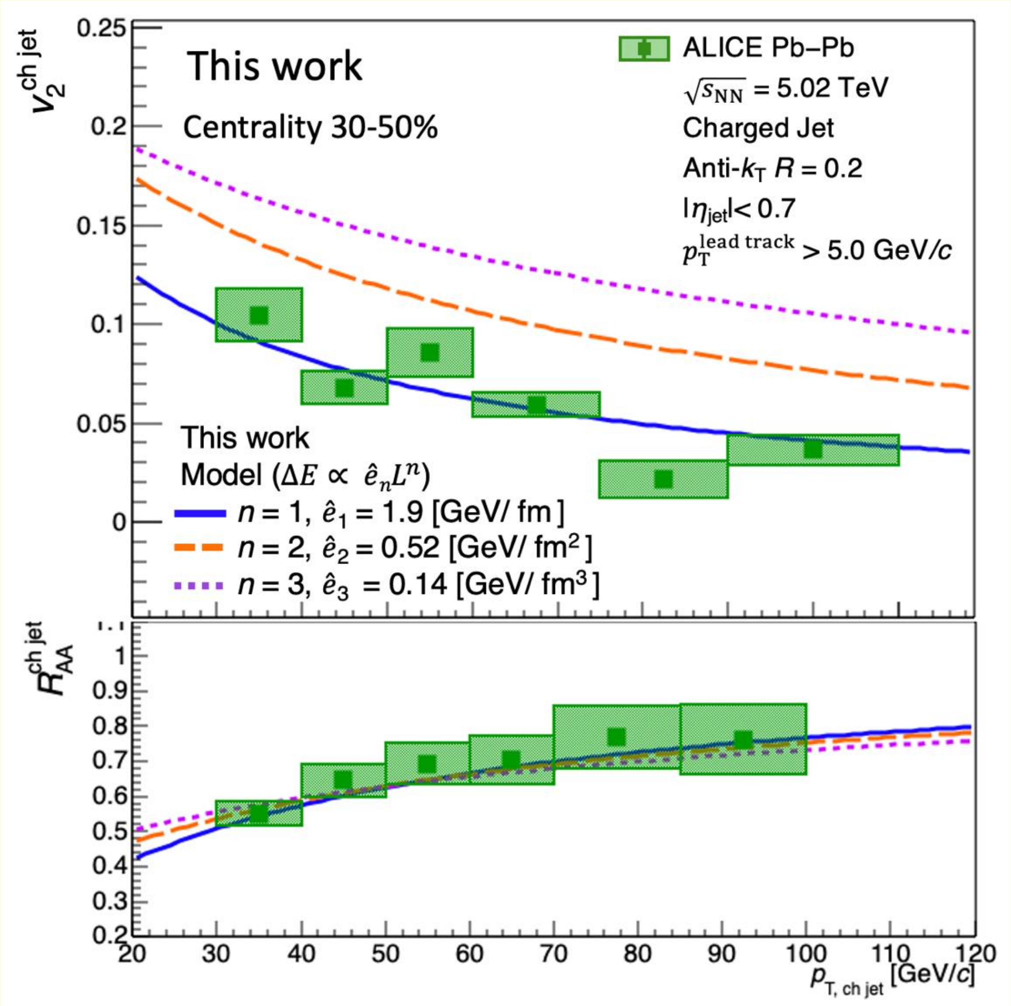
5. Determine $\hat{e}_n$ by fitting the A-A jet distribution with fixed n

6. Applying $\hat{e}_n$ to path-length in the in- and out-of-plane



7. Estimate jet R_{AA} and v_2

Jet R_{AA} and v_2 comparison with the data results



Energy loss: $\Delta E = \hat{e}_n L^n$

	n = 1	n = 2	n = 3
$\hat{e}_n$ [GeV/fm^n]	**1.9**	0.52	0.14

$$\chi^2 = \sum_i \frac{(\mathrm{Obs}_i - \mathrm{Sim})^2}{(\sigma_{\mathrm{data},i})^2} / \mathrm{NDF}$$

Obs_i :Observation, Sim: Simulation,

$\sigma_{\mathrm{data},i}$: Measurement Uncertainty

NDF = # of p_T bins – 1 (Free parameter $\hat{e}_n$) = 5

Significance level 0.05: χ^2**(5) < 11**

	n = 1	n = 2	n = 3
χ^2 (R_{AA}^{jet})	0.29	0.31	0.52
χ^2 (v_2^{jet})	**2.9**	31	72

→ **Only n = 1 simulation result is consistent with both R_{AA}^{jet} and v_2^{jet} measurements very well.**
And energy loss parameter is quantified as $\hat{e}_1$ = 1.9 GeV/fm!!

Summary/Open Issues/Outlooks of my simulation

Summary

We connected the measurements of R_{AA}^{jet} & v_2^{jet} and my developed simulation.

→ Quantified the parton energy loss parameters ($\hat{e}_n$, n)!

Open Issues

- Still do not identify the parton energy loss mechanism.
- Not enough to show soundness of my simulation, which has some strong assumptions.

Outlooks

- Compare with other centrality results
- Compare with other experiments (LHC-ATLAS, RHIC-sPHENIX, and etc...)
- Compare with other simulations (LBT, JETSCAPE, and etc...)

4. What can we do using sPHENIX

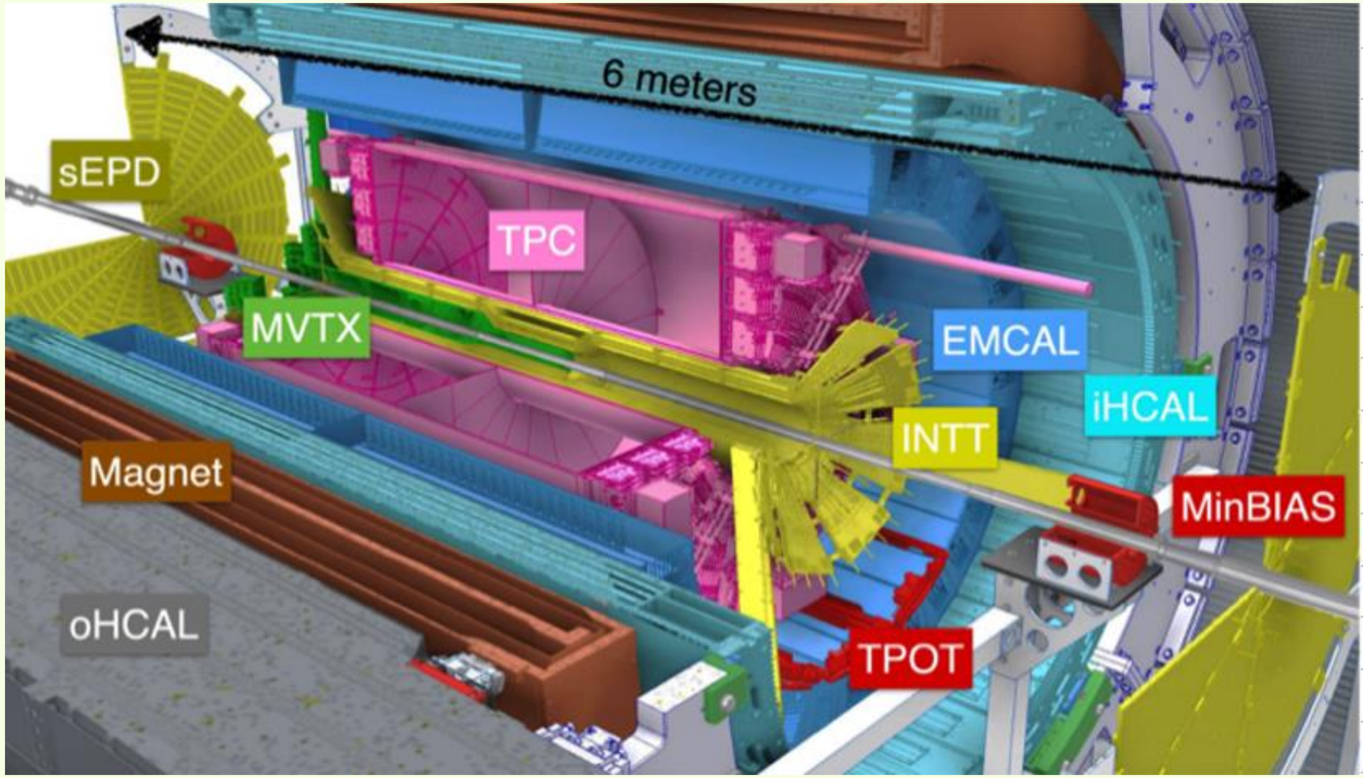
〜Advantages of sPHENIX〜

EMCal+HCal (iHCAL+oHCal)
- Estimate the energy of both **charged and nutral** hadrons
- They cover **full** azimuthal angle (ϕ)

INTT
- Estimate the vertex point

sEPD
- Determine the event plane angle

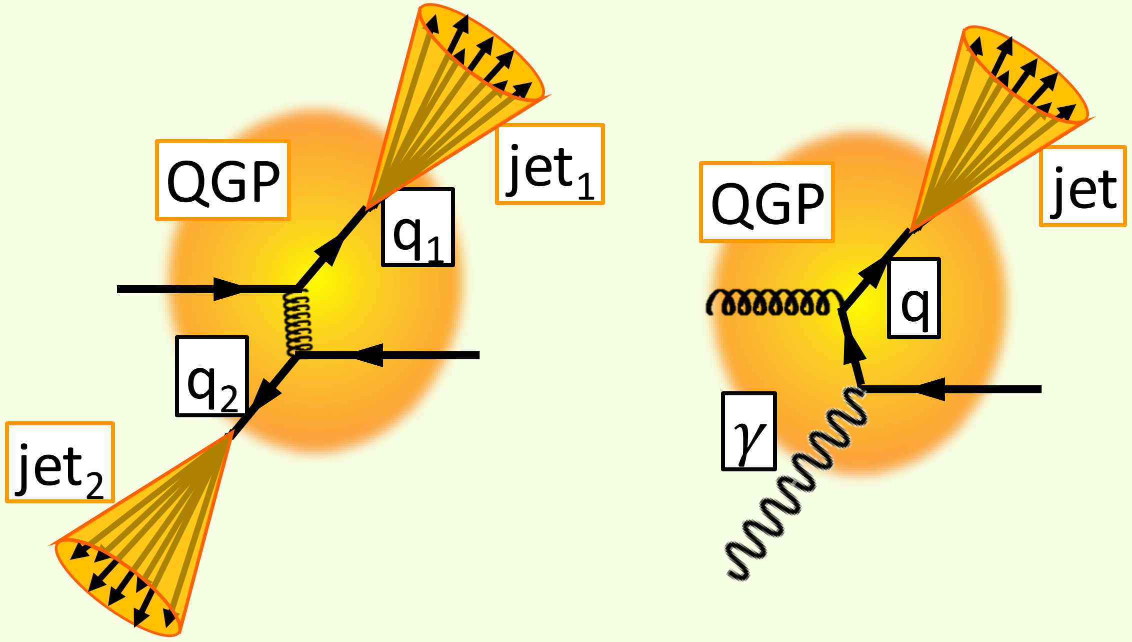
TPC
- Identify kinds of particle in the jet
- Improve the jet p_T resolution



Jet Measurement by EMCal+HCal (iHCAL+oHCal)

- The full ϕ range calorimeter enable to back-to-back event study.
→ Enable to study the energy loss difference between back-to-back particle.

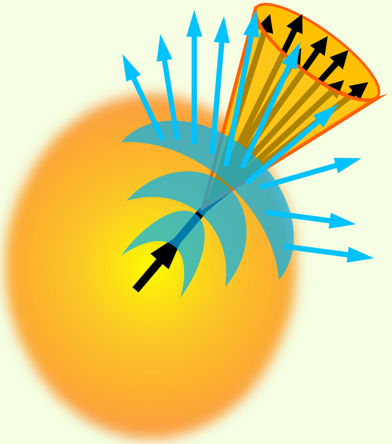
- jet-jet (di jet): path length difference.
- γ-jet: γ does not QCD interaction with the QGP.
→ The difference is obvious energy loss of the parton.

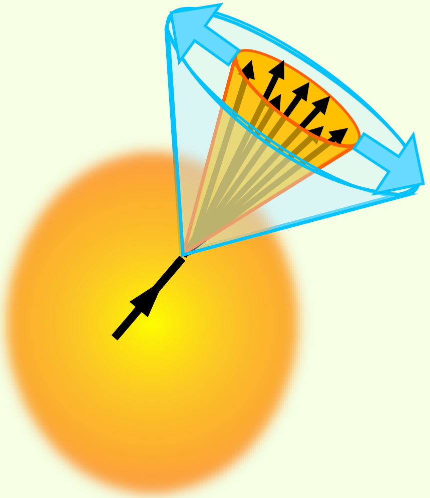


- The jet modification is expected for not only momentum but also the QGP shape.

1. Recoiled and fluid particles.
→ It is expected to make shock-wave.

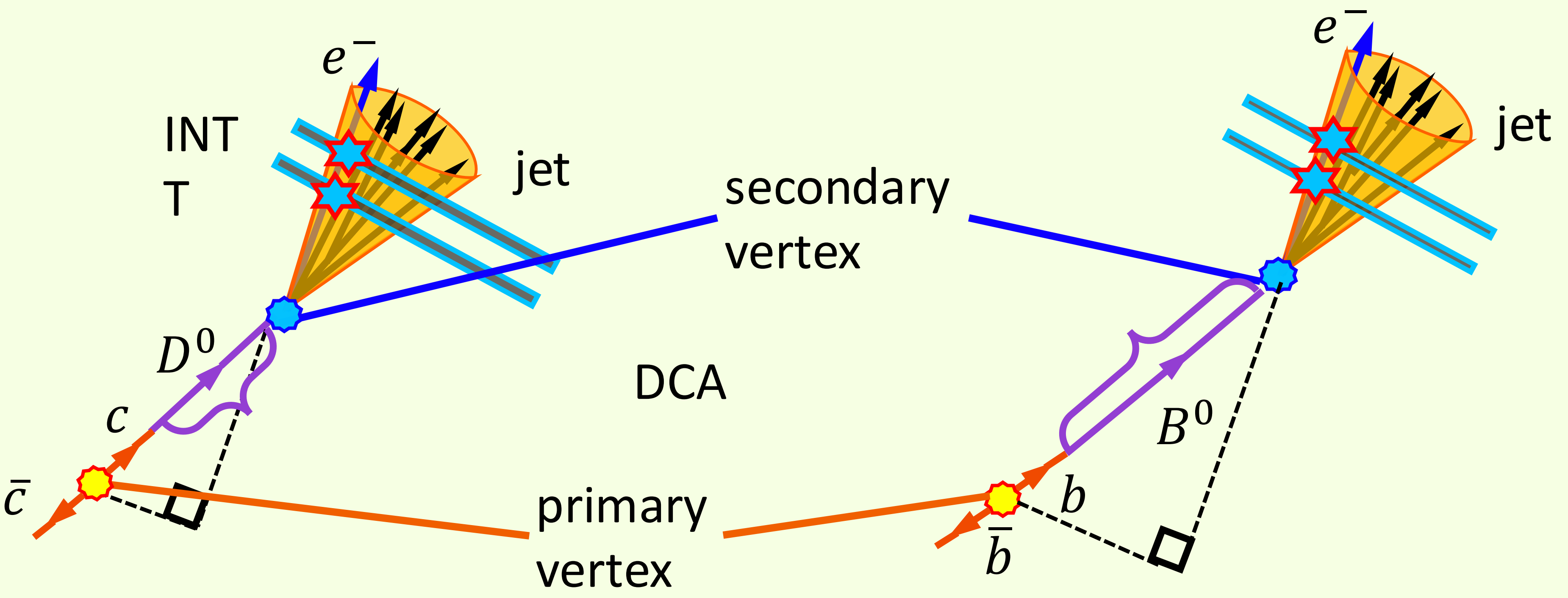
2. QGP makes jet broadening.
→ Jet shape is also expected to be modified the shape.





Jet Measurement by INTT

Heavy fravor(HF) quark has secondary vertex (HF hadron flight and decay).
The b hadron flight longer than c hadron.
INTT detector can estimate secondary vertex and distinguish b and c.

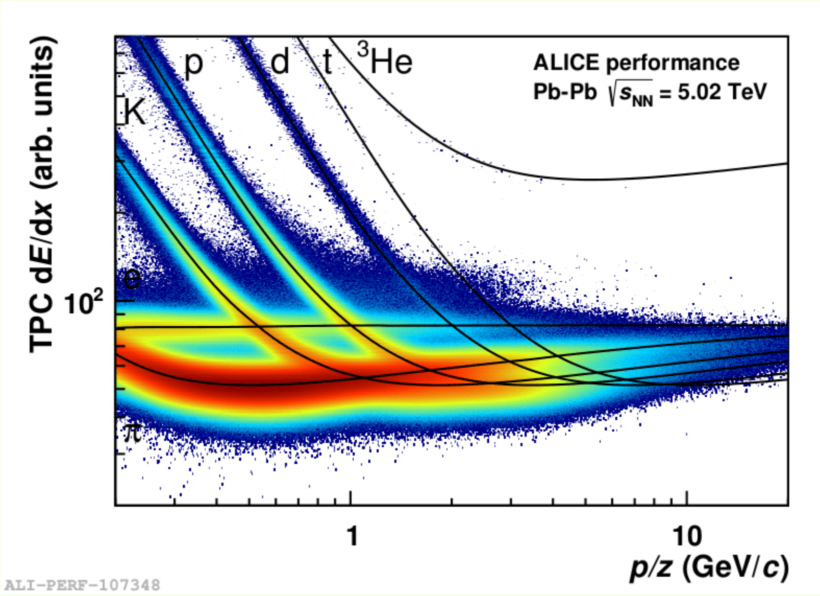


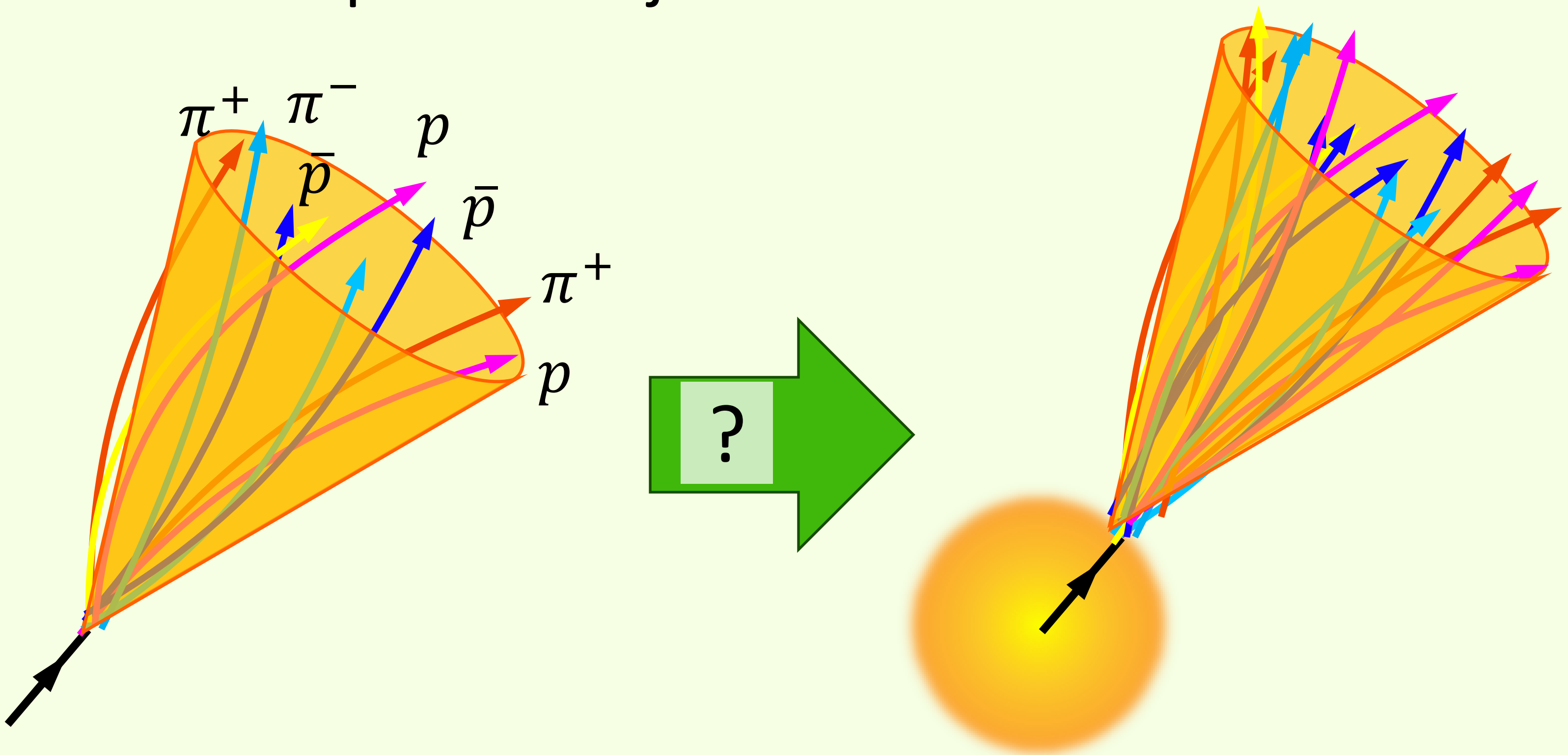
- Seach for the suppression difference between flavors.
- Evaluate the HF components in the QGP medium.

Jet Measurement by TPC

- TPC can identify kinds of charged hadrons.
- Estimation of pT of charged hadrons improve the jet momentum.

TPC identify particles





→ Clarify the QGP effect for jet components.

→ Identify g/q jets.

We have still not understhand the QGP properies, jets, and jet modification.

sPHENIX experiment has a lot of potencials!!

Let us to study QGP properties using jets!!!