Parton energy loss mechanism in Quark-Gluon Plasma with jet quenching using LHC-ALICE data

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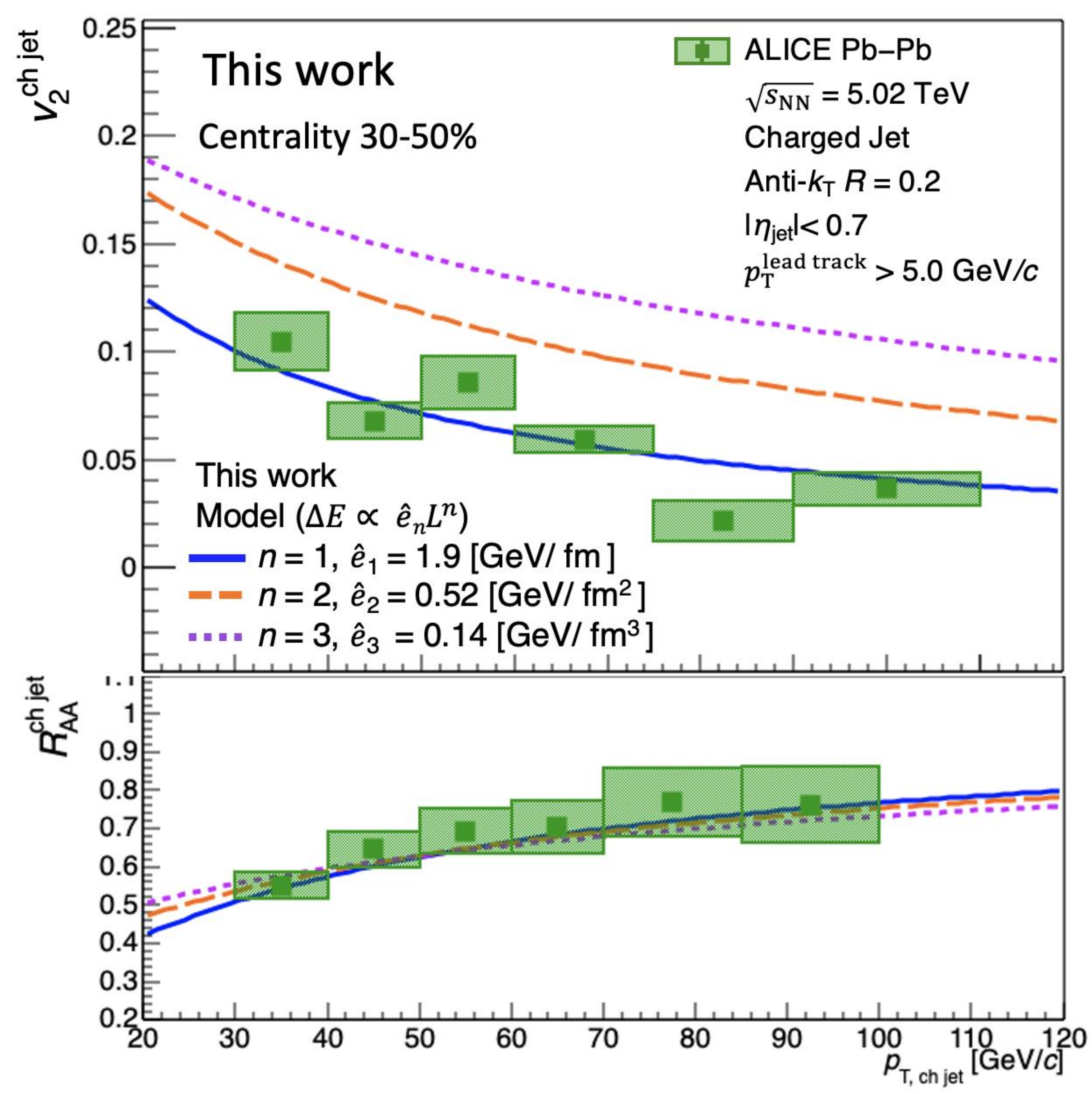
My work

Main work

- **First measurements** of the jet nuclear modification factor (R_{AA}^{jet}) and azimuthal anisotropy (v_2^{jet}) within the same condition.
- **Developed a toy model simulation** which can describe the data results and quantify the parton energy loss parameters.



Service work for ALICE collaboration

- Evaluate direct photon triggers performance for the FoCal-E detector

Conference

- PANIC2020, online, poster (2020)
- EPS2023, Hamburg, talk (2023)
- QM2023, Houston, poster, (2023)
- HP2024, Nagasaki, poster, (2024)

Outline

1. Introduction
2. Experimental Setup
3. Measurement of the jet nuclear modification factor (R_{AA}^{jet}) and azimuthal anisotropy (v_2^{jet})
4. Toy model simulation to quantify the parton energy loss parameters ($\hat{\boldsymbol{e}}_{\boldsymbol{n}}, \boldsymbol{n}$)
5. Summary and Outlook

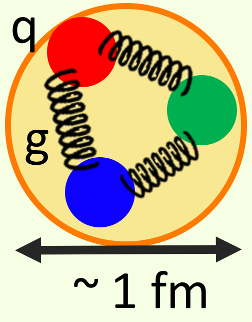
Introduction

The Standard Model of Elementary Particle Physics

Standard model describes 3 types of interactions between particles (**strong**, electromagnetic, weak)

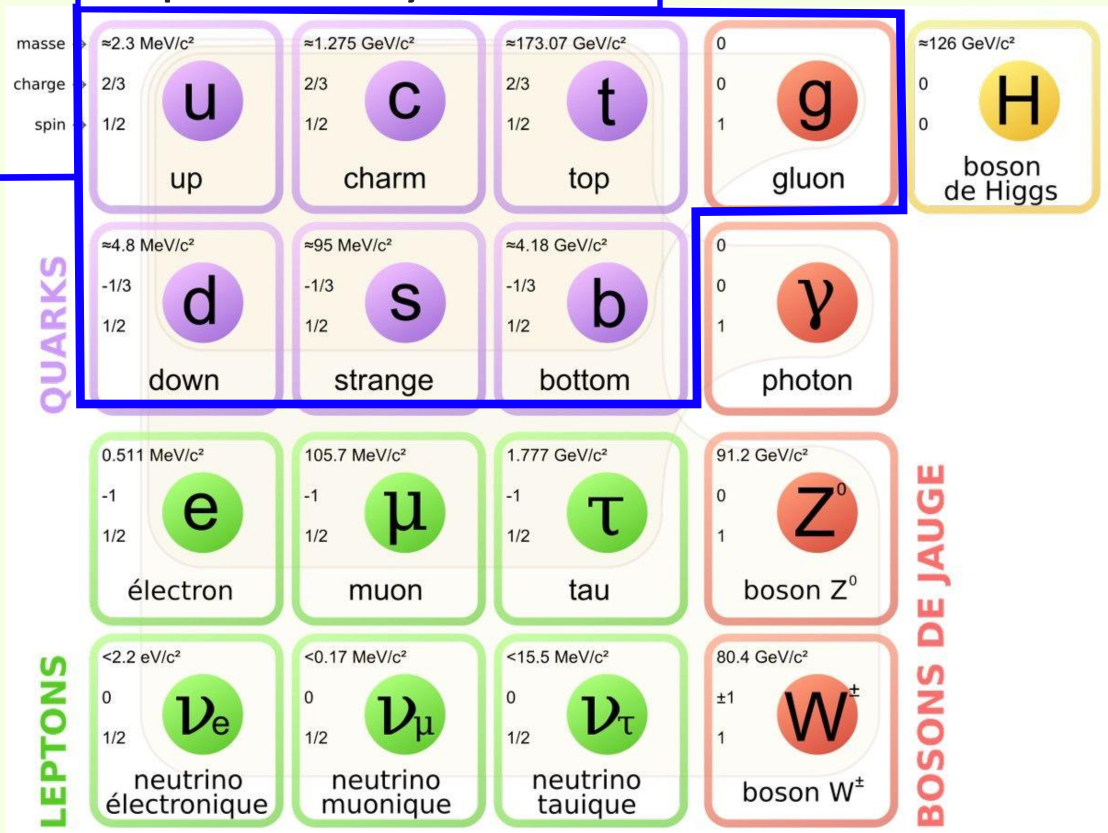
Quantum chromodynamics (QCD):
strong interactions → gluons

In the QCD, gluons can couple themselves.
→ Coupling strength logarithmically changes with energy scale.



Quarks and gluons are confined in hadrons under standard conditions of temperature and pressure .

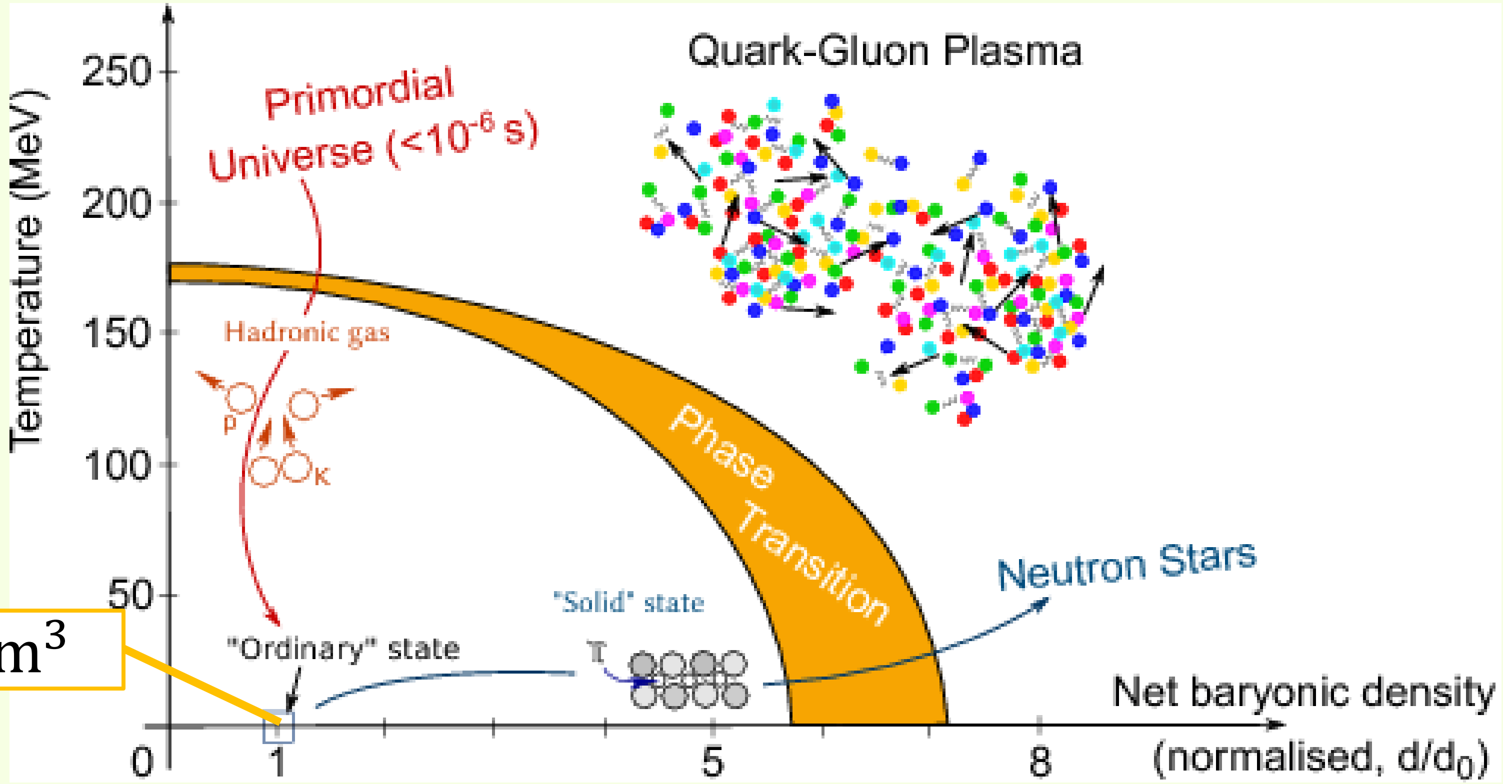
Explained by QCD



Quark-Gluon Plasma

Quark-Gluon Plasma (QGP) is a state of matter made of deconfined quarks and gluons

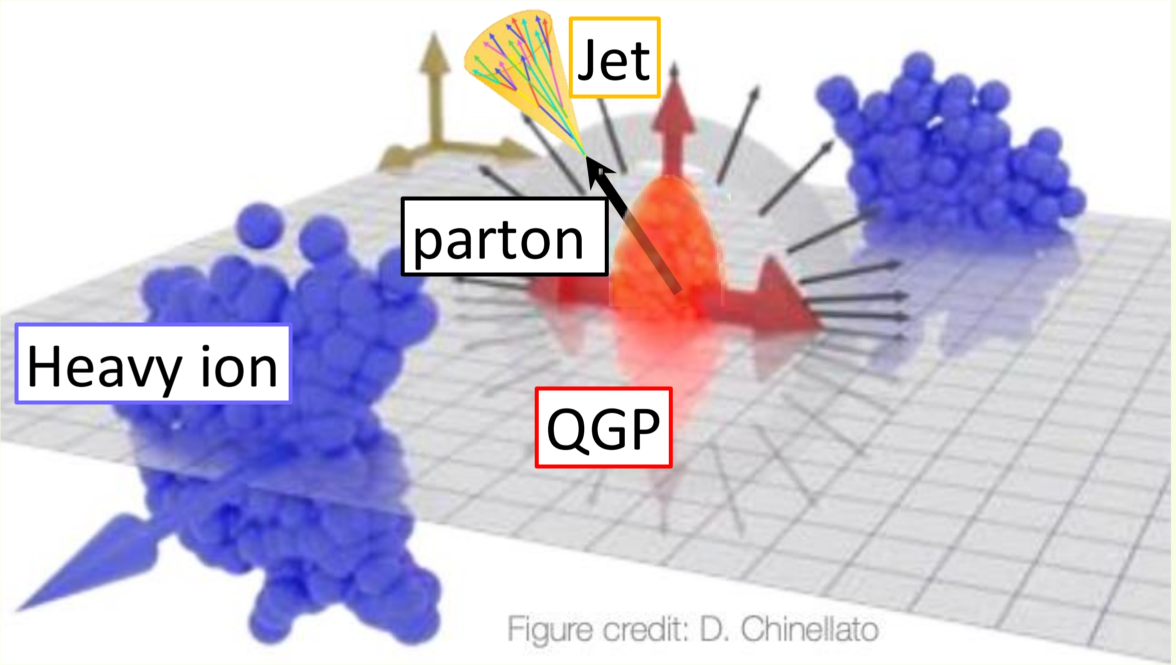
- Predicted by QCD theory
- Formed at high temperature and/or density
- QGP has existed in the *early Universe* ($\approx 10^{-6}$ s after the Big Bang)

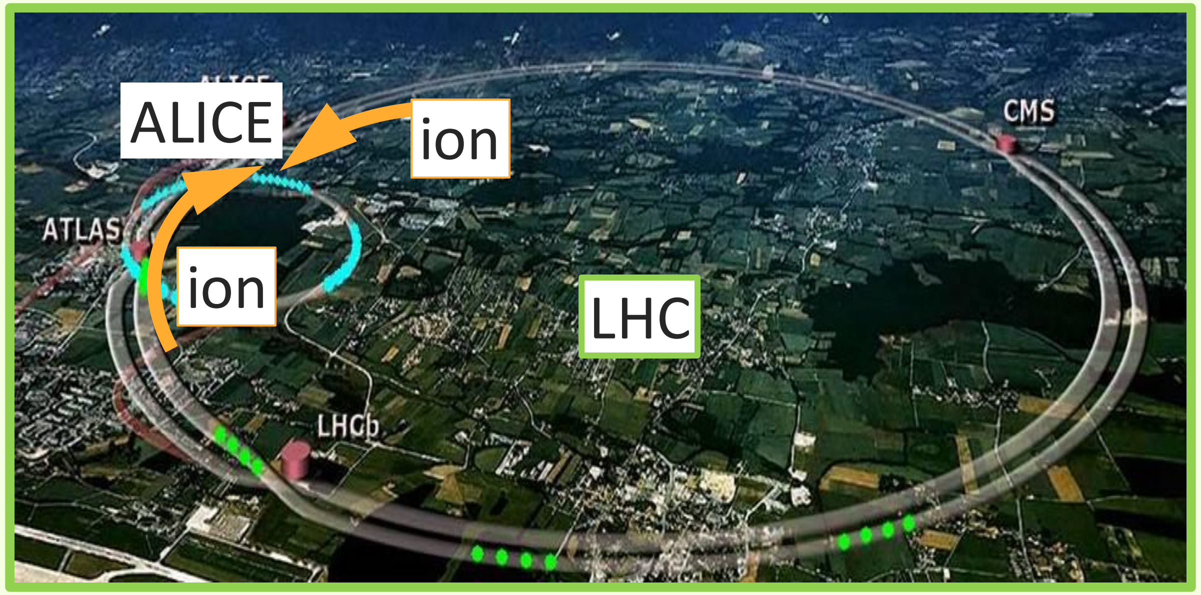


$\rho_0 \approx 0.15\ \mathrm{GeV/fm^3}$

The Physics of Heavy Ion Collisions

QGP is produced by **Heavy Ion Collisions (HIC)** with the large collider (LHC/RHIC).





LHC: pp at $\sqrt{s} = 7, 2.76, 5.02, 13, 13.5$ TeV,
PbPb at $\sqrt{s_{\mathrm{NN}}} = 2.76, 5.02$ TeV

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

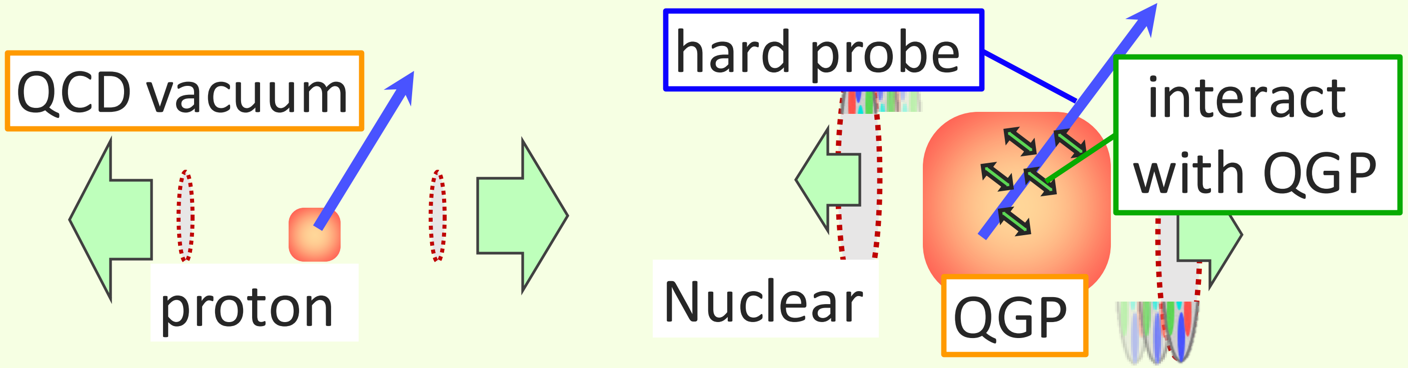
→ **Use high-momentum partons (→ jets) that traverse the QGP medium.**

Hard Probes for the QGP

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

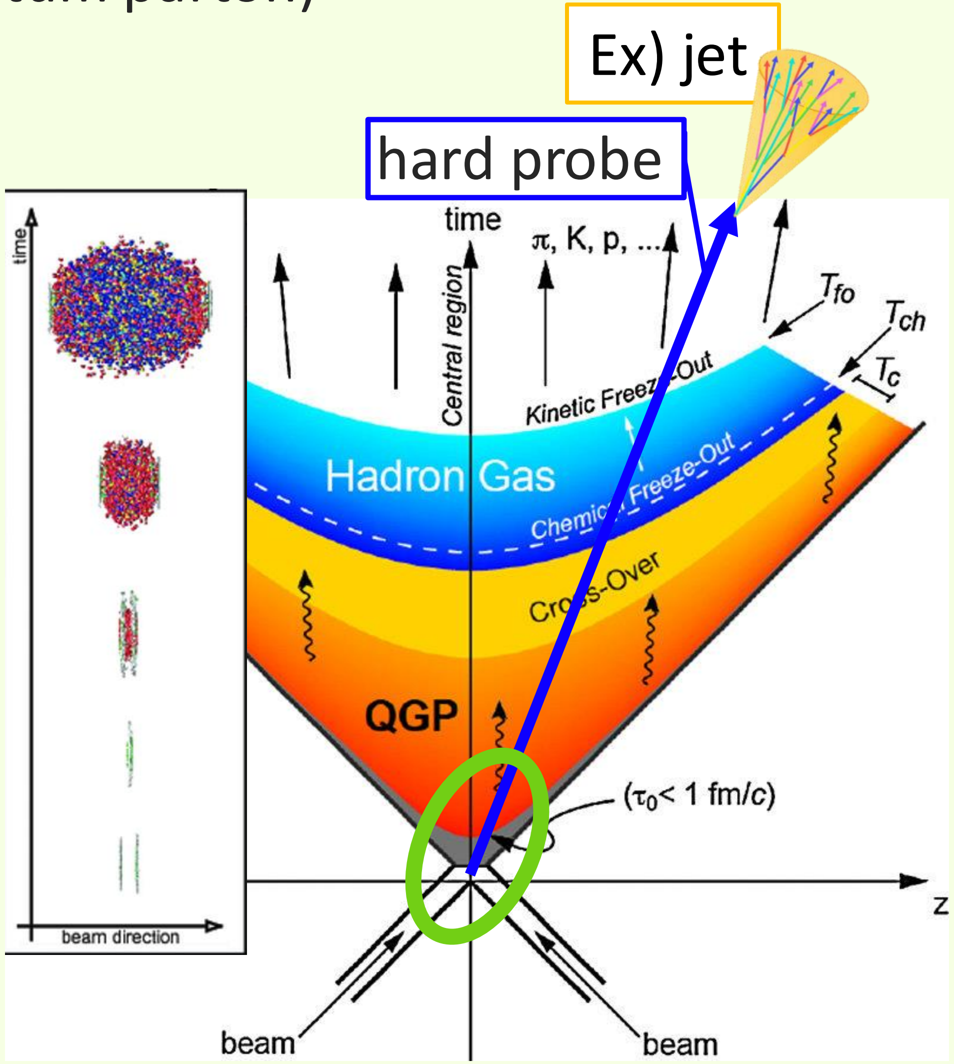
- The rates are calculable within perturbative QCD (pQCD)
  →The hard probes, which are measured in the pp collisions, used as *the reference* for the one measured in the Pb−Pb collisions.

pp collision: reference A − A collision: jet suppression



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

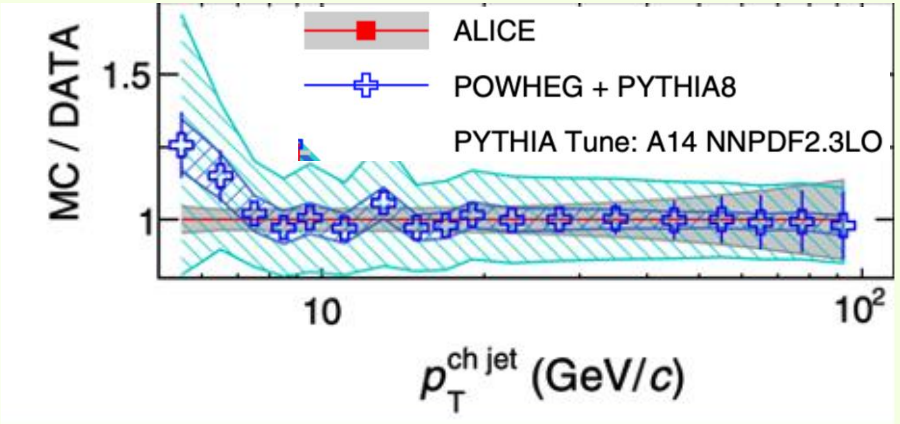
→ The experimental signals of the hard probes contains the history of its interaction with the QGP.



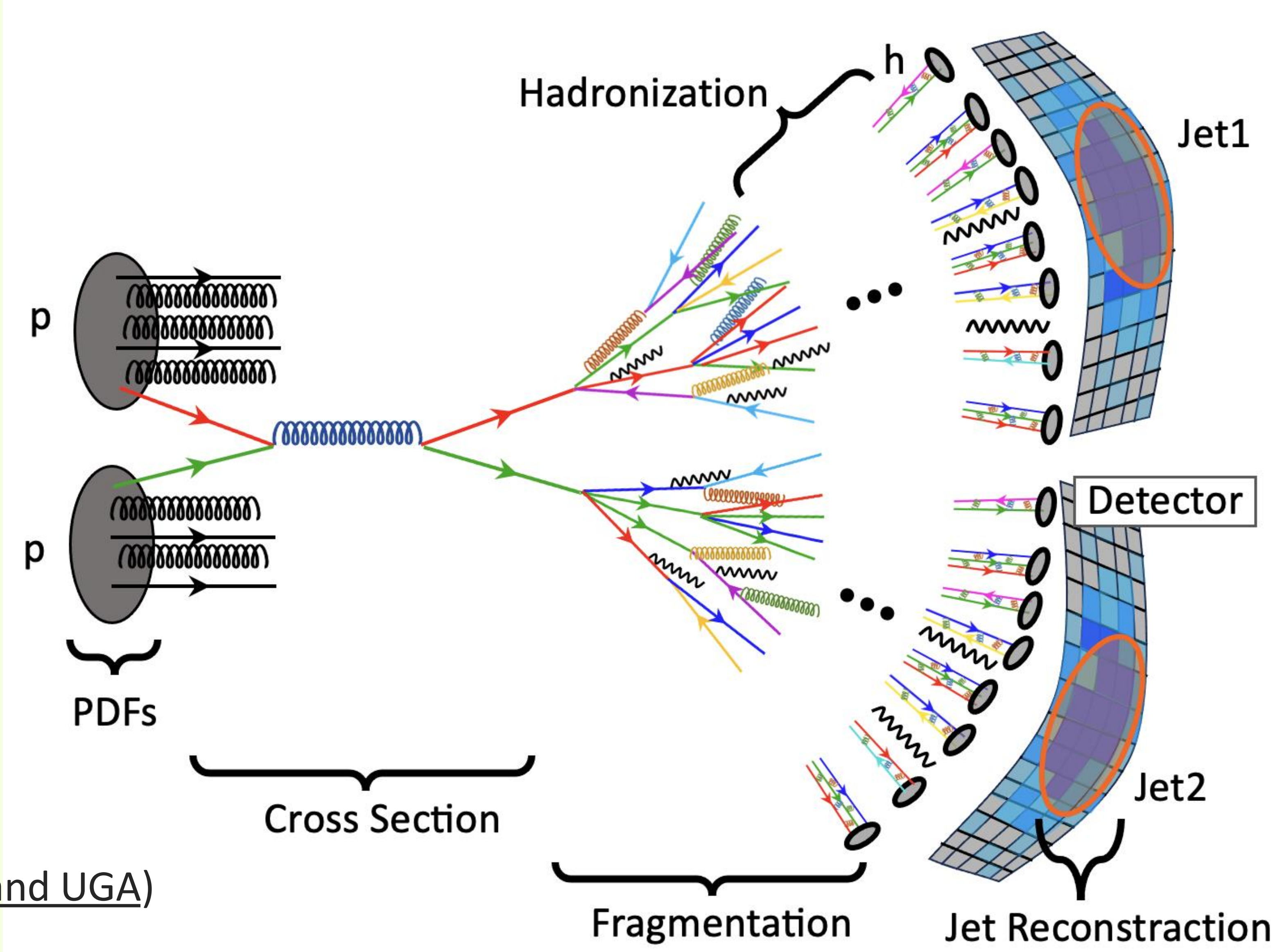
What is a jet?

A **parton** (quarks or gluons) 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



Measured by Ritsuya Hosokawa (Tsukuba and UGA)
PHYSICAL REVIEW D 100, 092004 (2019)



Physics target: Parton Energy Loss Mechanism Models

Partons deposit energy in the QGP medium within different mechanisms.

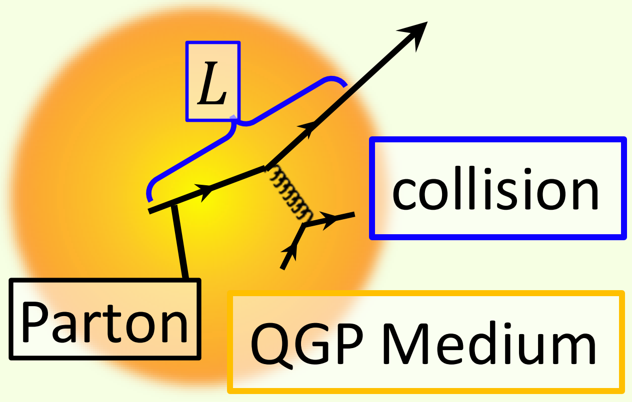
Energy loss

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

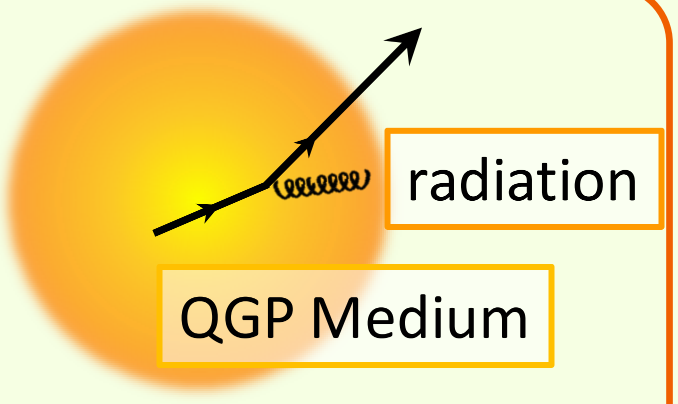
→ **Includes QGP properties**:

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

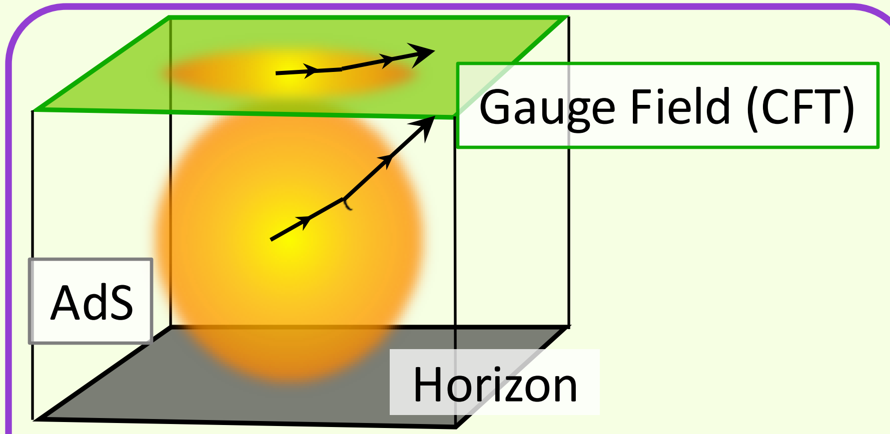
Jet suppression mechanisms: (These model suggest different n)



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



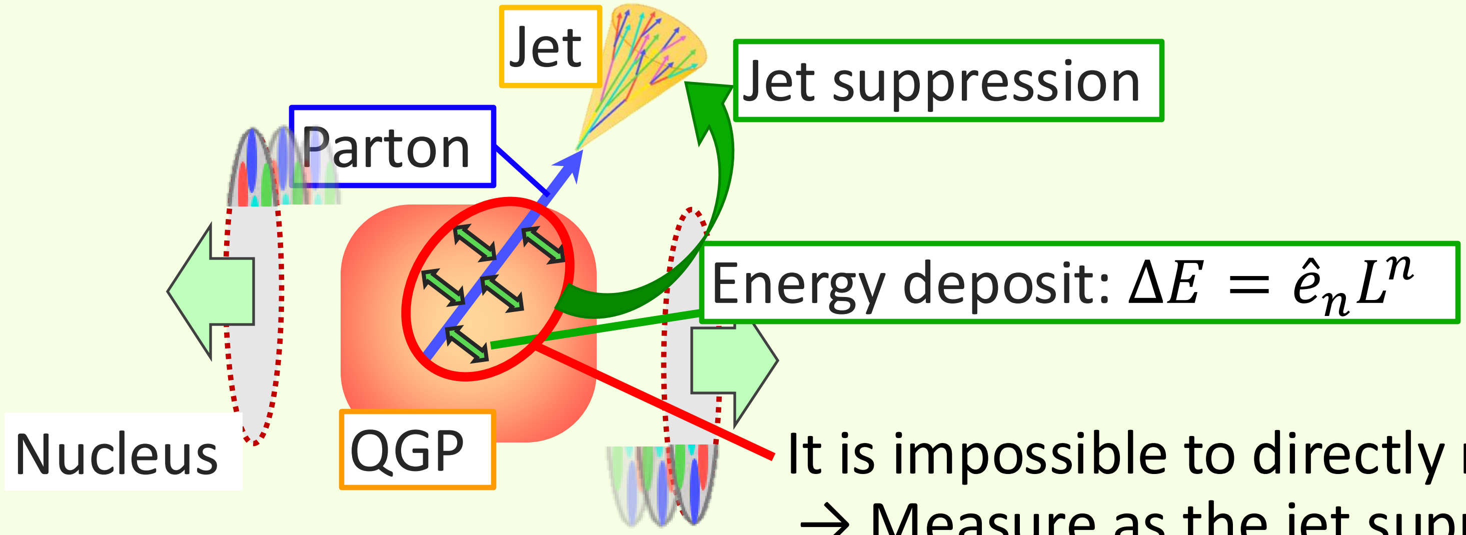
Radiative ($\Delta E \propto L^2, n = 2$)



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

The mechanism have not been clarified yet.
The parameters have not been quantified yet.

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})

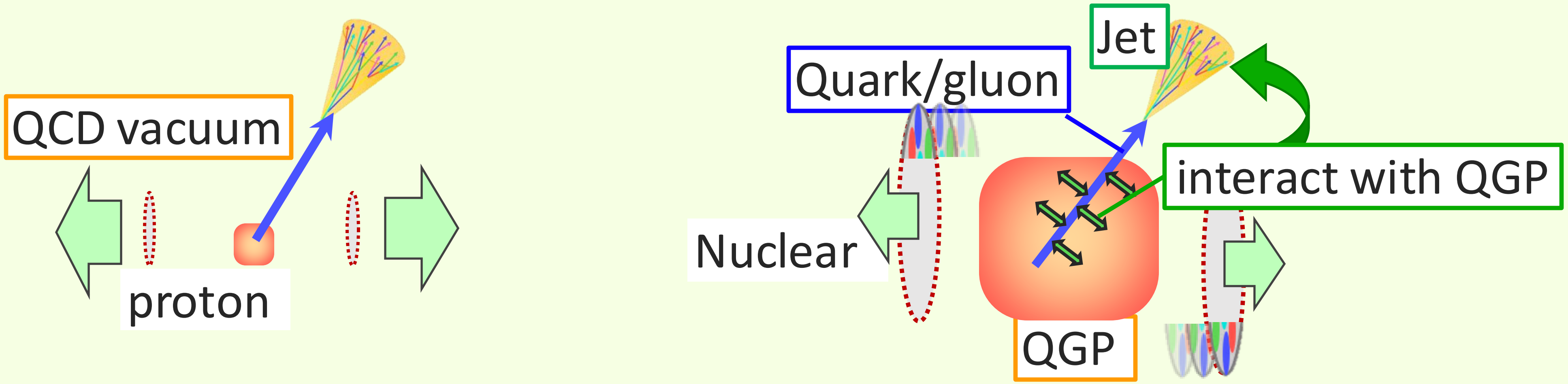
(2) Jet azimuthal anisotropy (v_2^{jet})

Nuclear Modification Factor (R_{AA})

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

pp collision: reference

AA collision: jet suppression



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

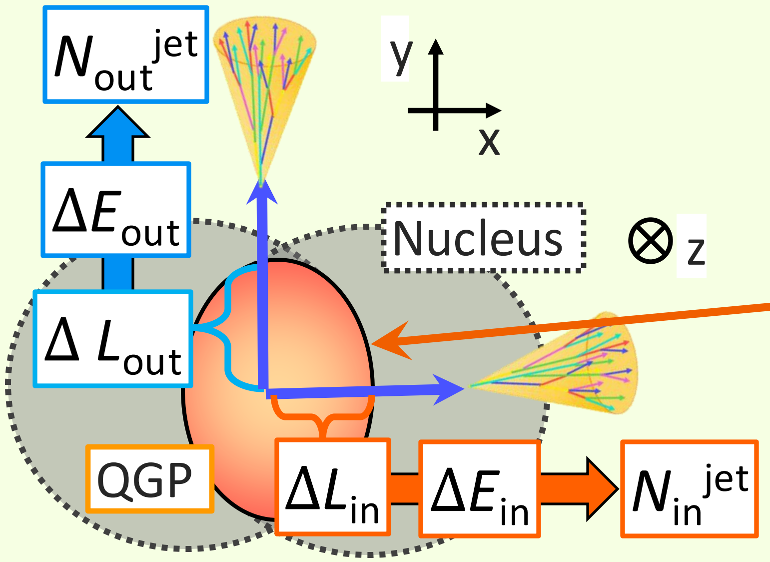
Use the difference between with and without suppression

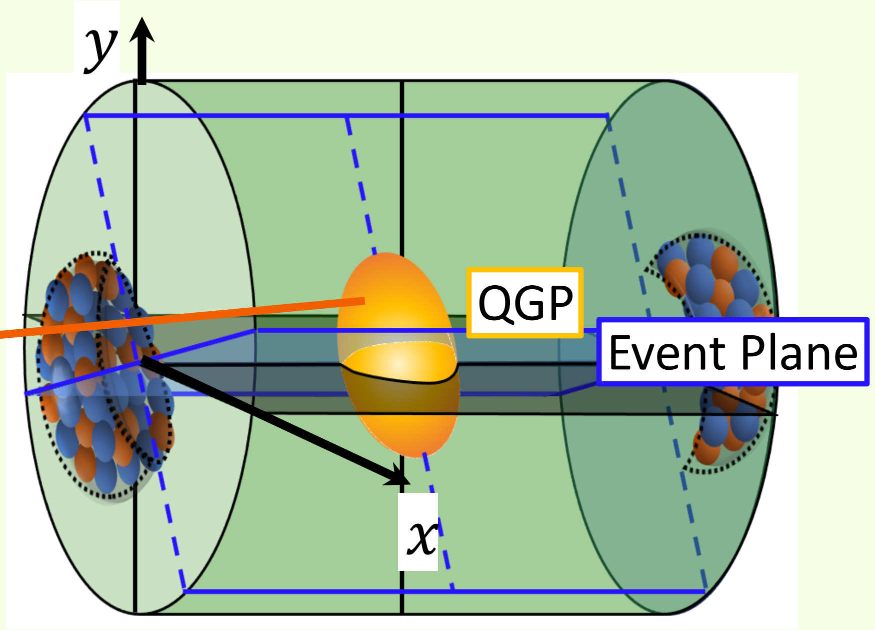
→ **Sensitive to magnitude of suppression**.

→ **Sensitive $\hat{e}_n$**

Jet azimuthal anisotropy (v_2)

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





$v_2^{jet} \propto N_{in}^{jet} - N_{out}^{jet}$ N_{in}, N_{out}: Jet yield in the in-/out-of-plane, respectively

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

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

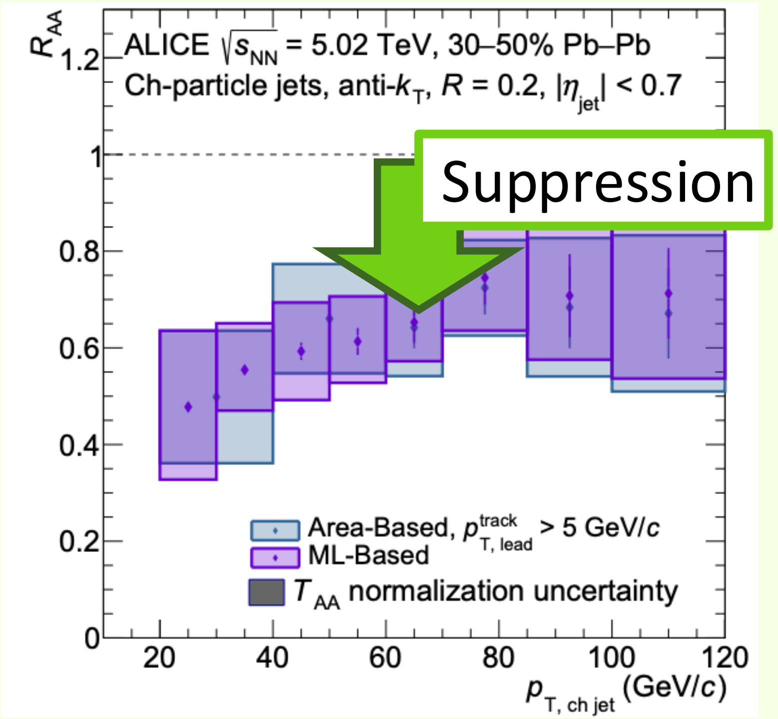
→ Sensitive L **dependency** of ΔE.

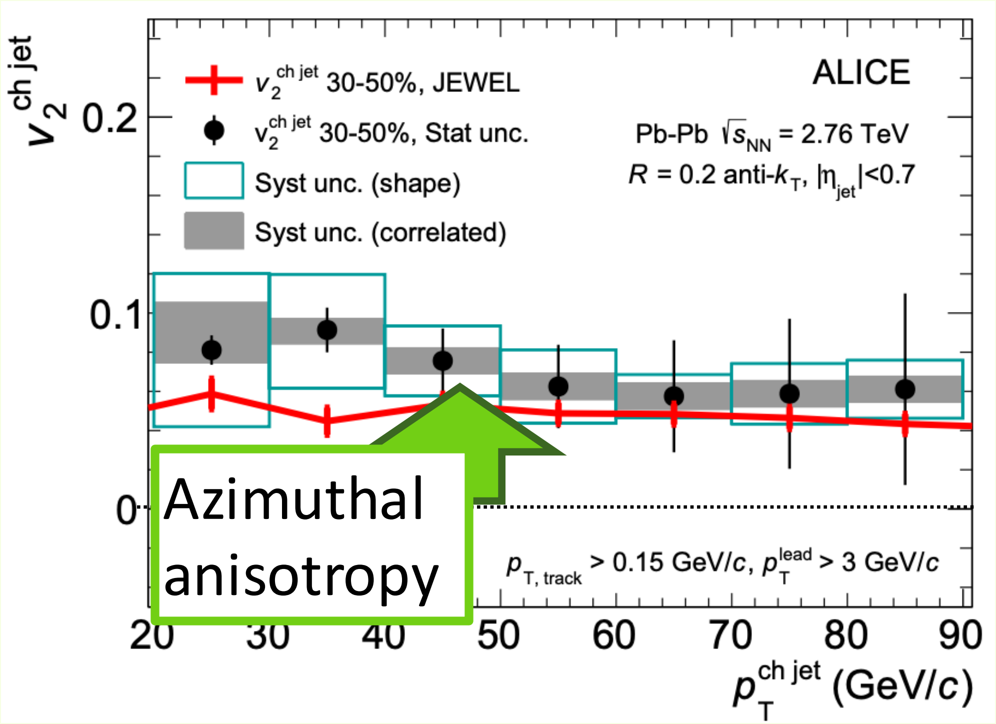
→ **Sensitive the power of n**

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

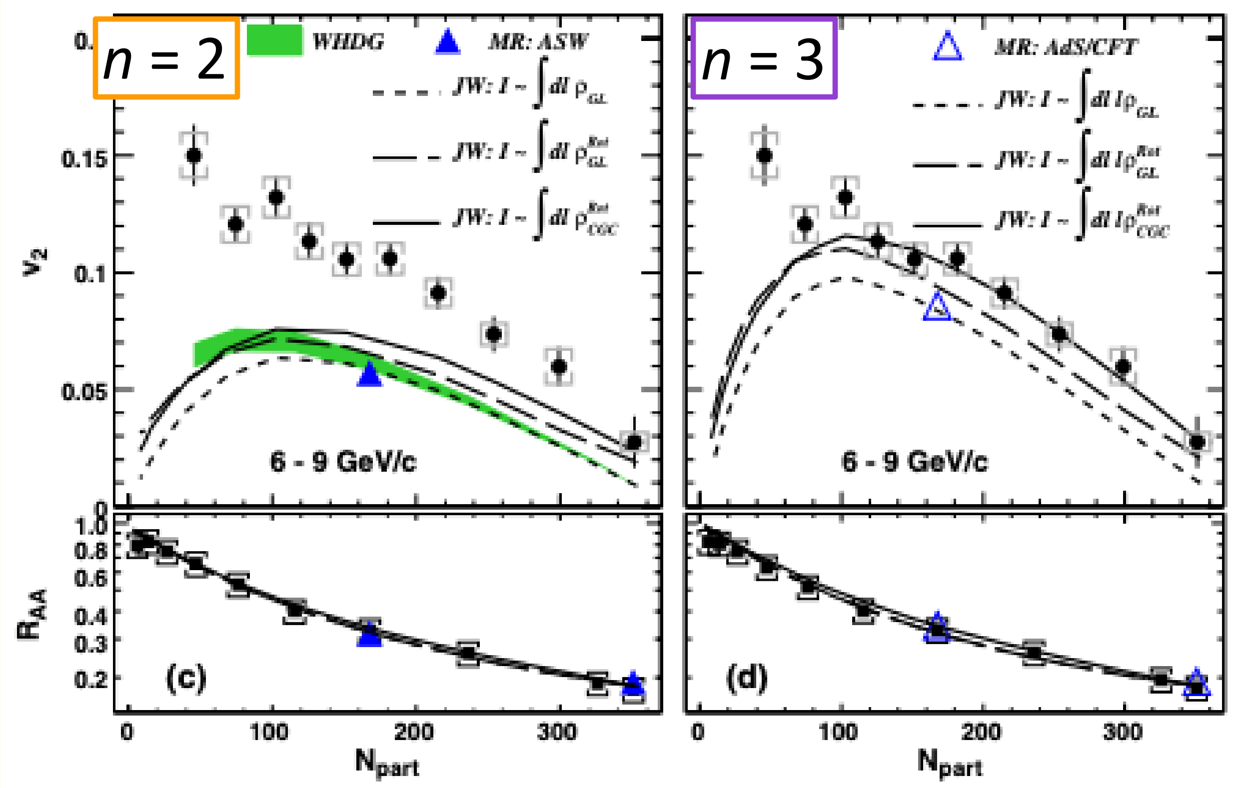


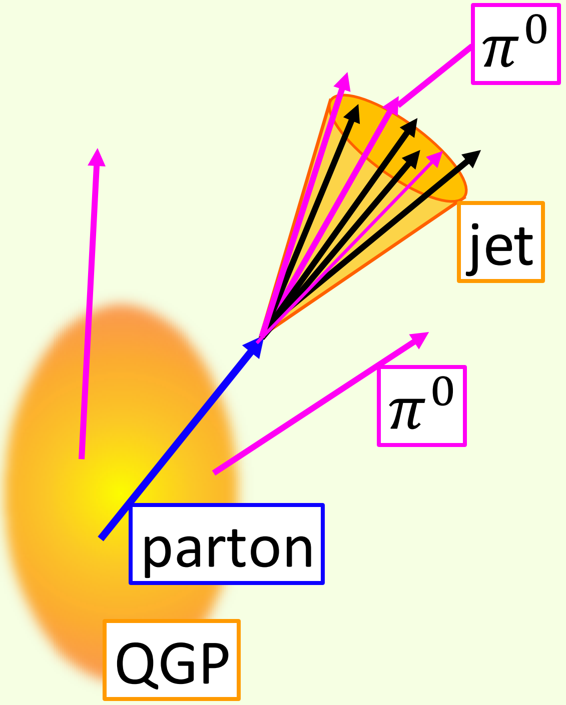


These results indicates the jet suppression and azimuthal anisotropy exist ($R_{AA}^{jet} < 1$, $v_2^{jet} > 0$).
→ However, they do not still clarify the energy loss mechanisms and quantify their parameters.

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 <u>only partial information</u> of the original parton.

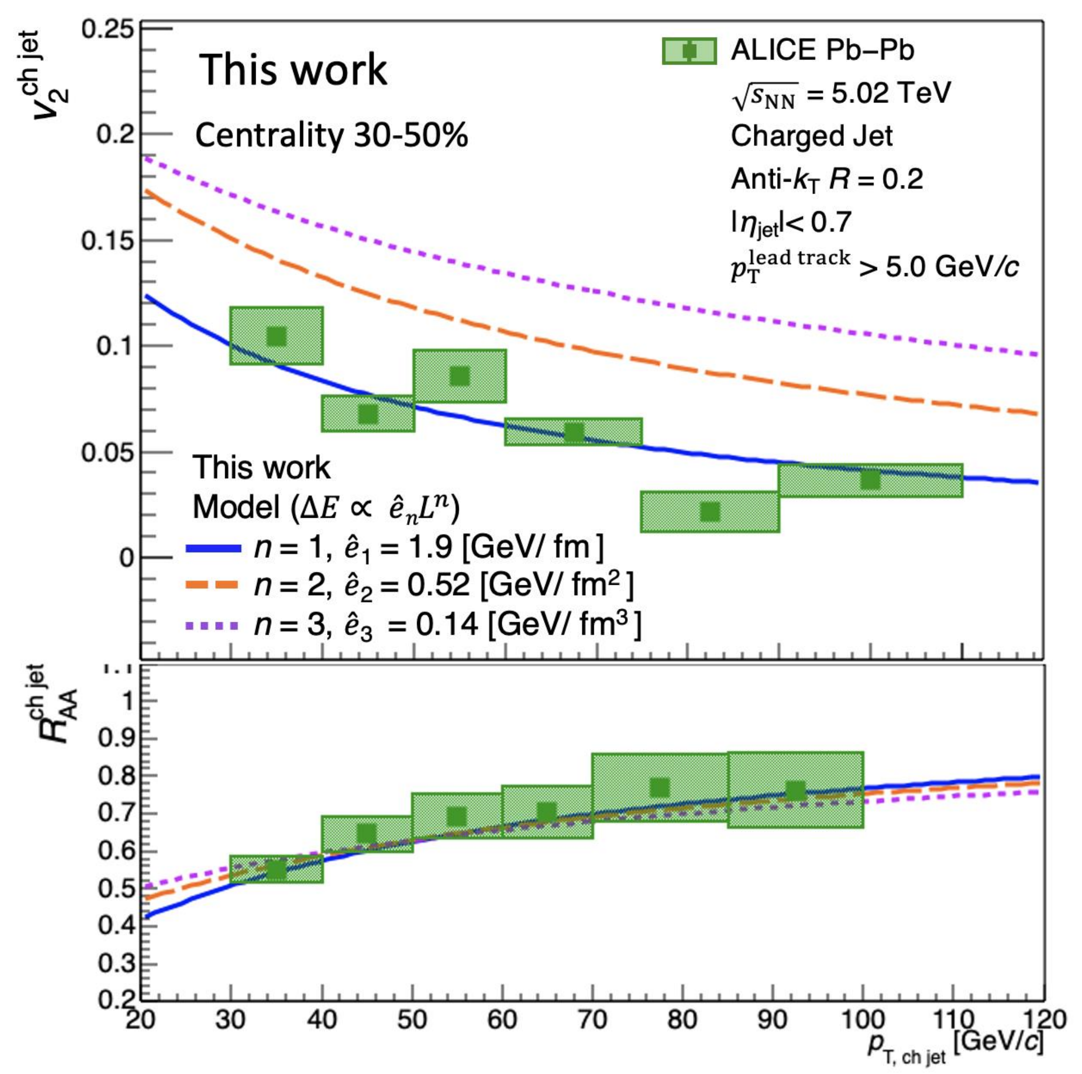
New points of my study for Energy loss

- **First measurements within the same experimental conditions of the charged jet v_2 and R_{AA}**

→ Expect strong model constraints and acquire accurate suppression parameter values.

- **Develop a toy model simulation of the parton energy loss considering the path-length dependency ($\Delta E \propto \hat{e}_n L^n$).**

The simulation results matched the data results very well, and quantified the parton energy loss parameters!



Experimental Setup

ALICE Detector

The ALICE detector is desined to study the QGP.

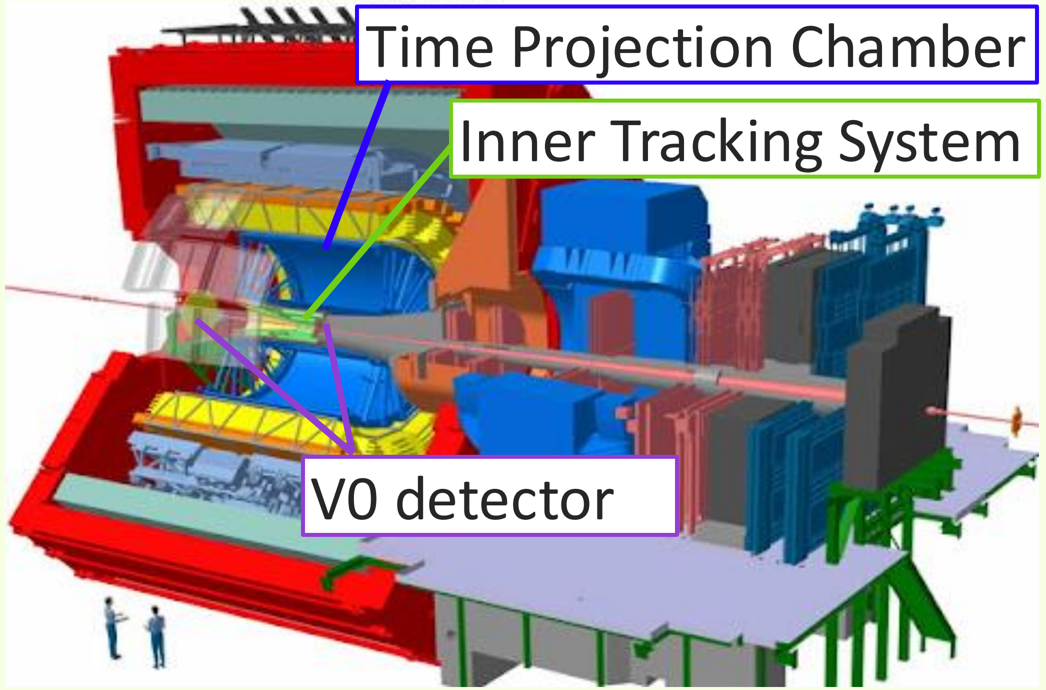
It is a general detector containing many detectors.

Roughly categorized three parts

(1) The central barrel covering the collision point ($-0.9 < \eta < 0.9$)

(2) The muon arm to detect forward-direction muons ($-4 < \eta < 2.5$)

(3) The global detector for selecting collision events



Property

Height/Width: 18 m

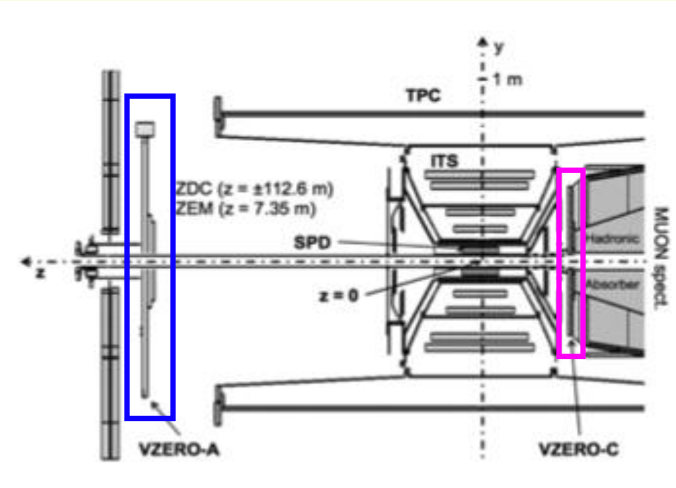
Length: 26 m

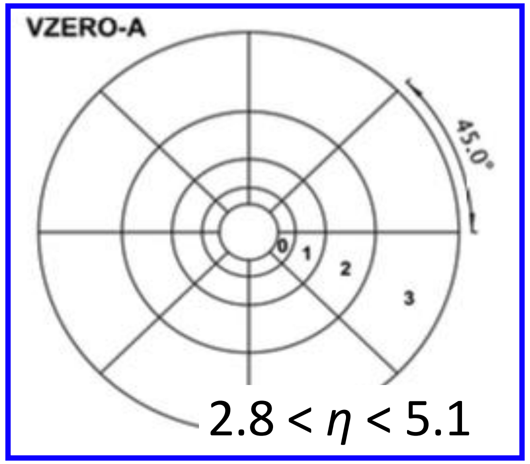
Weight: 10,000 t

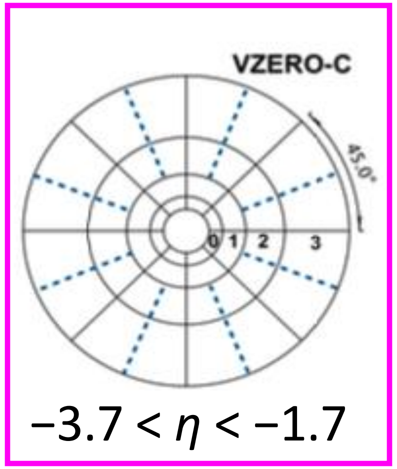
Magnet: 0.5 T

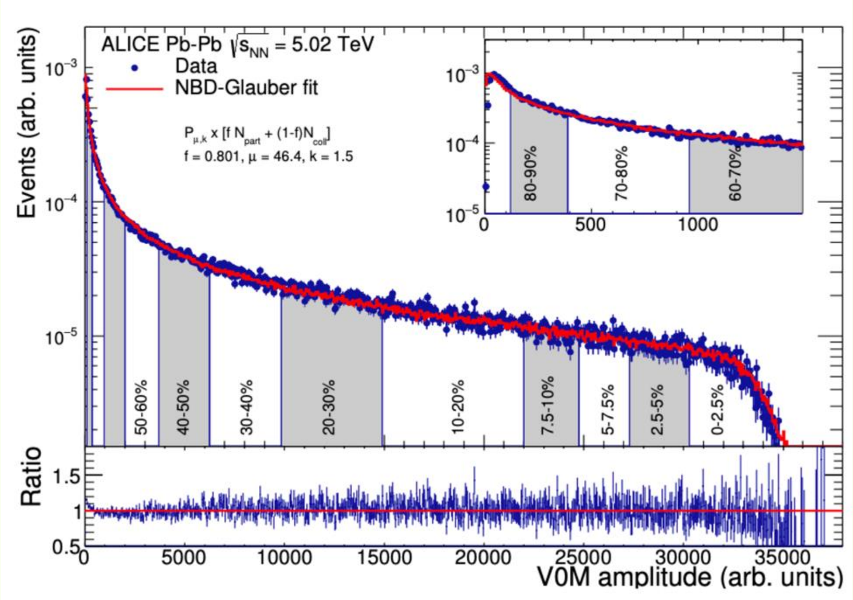
V0 Detector

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

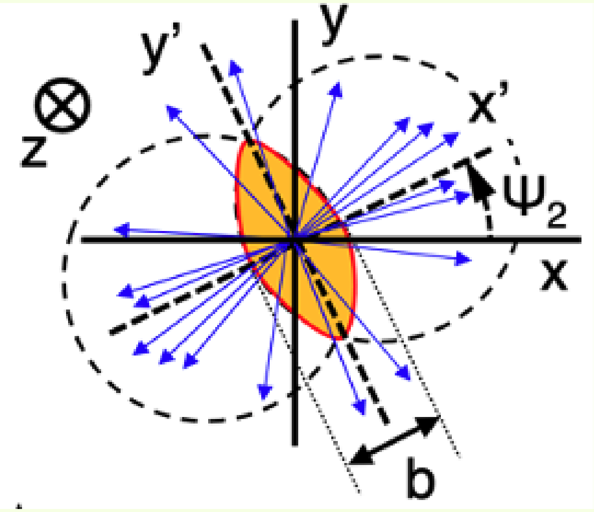








Using NBD-Glauber fit for V0M amplitude, the event centrality is determined



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

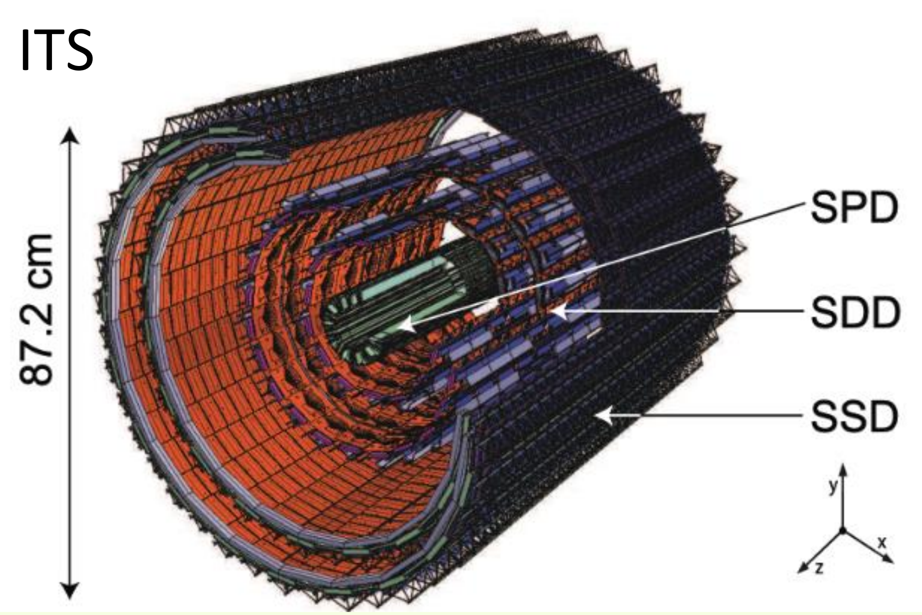
Inner Tracking System / Time Projection Chamber

In this analysis, the only charged tracks were used to reconstruct jets.

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

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

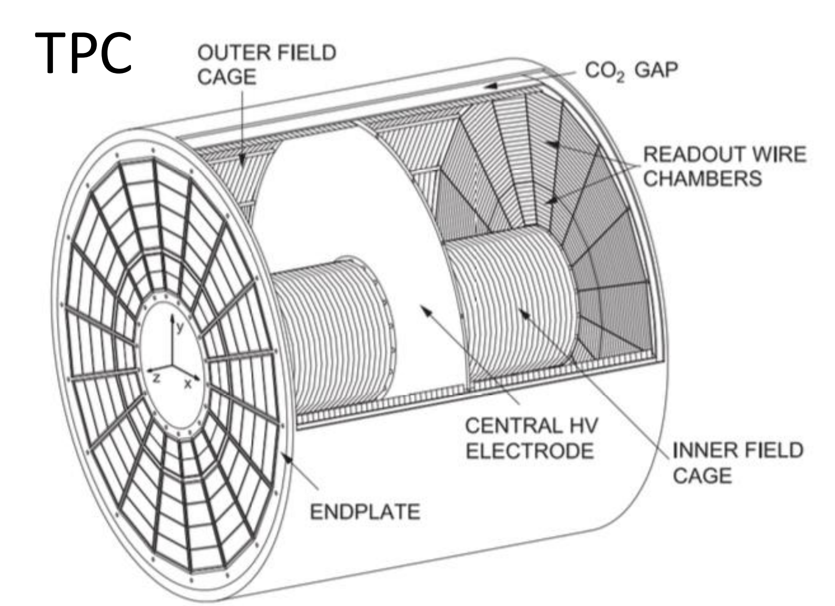
ITS



Silicon Pixel Detectors (SPD)
Silicon Drift Detectors (SDD)
Silicon micro-Strip Detectors (SSD)

Six silicon pixel layers detector

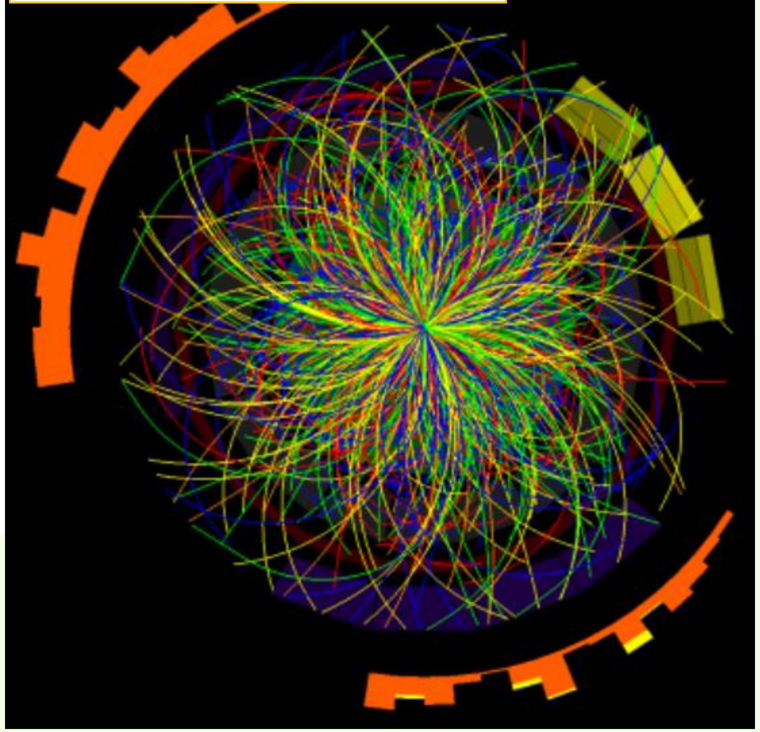
TPC



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

Gas chamber detector

Reconstructed tracks



Data Set

Data set

- p−p 2018 (Run 2), $\sqrt{s} = 5.02$ TeV, Minimum Bias (MB), 103×10^6 events
  (doi:10. 1103/PhysRevC.105.064903)

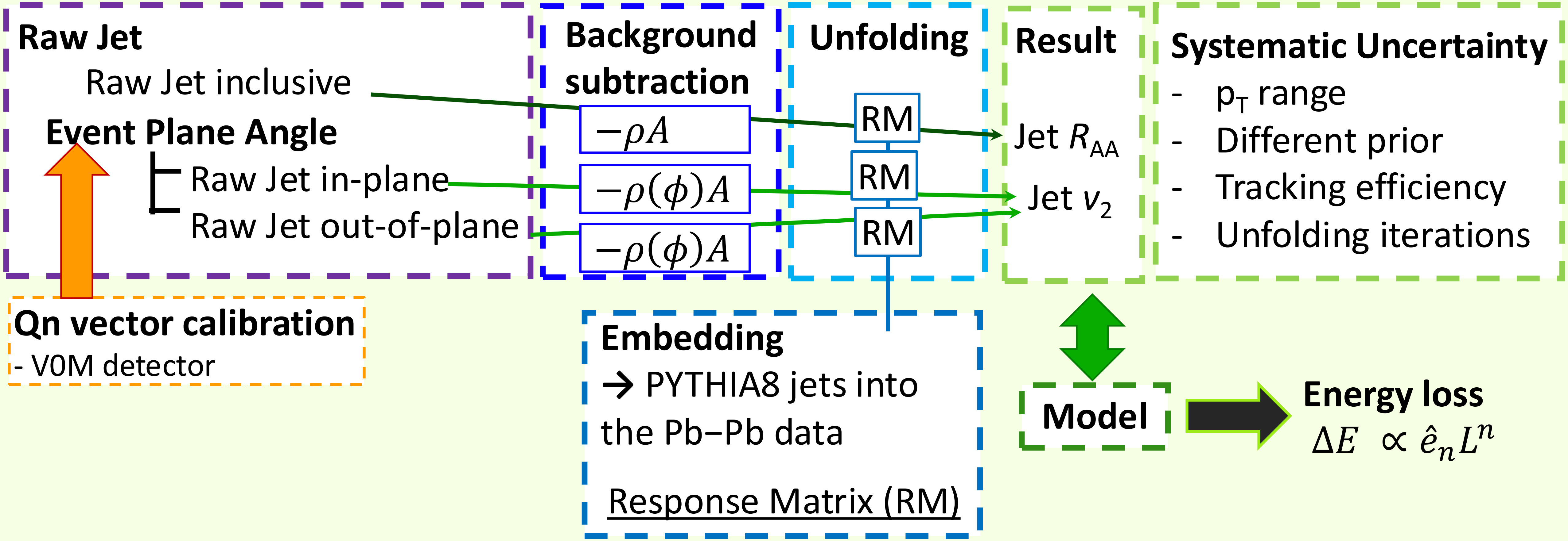
- Pb−Pb 2018 (Run 2), $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (This measurement)
  Trigger: Minimum Bias (MB) + Semi-Central trigger for centrality 30−50% data
  - MB requires simultaneous signals in the V0A, V0C, and ITS detectors.
  - Semi-central trigger is obtained using the V0 detector amplitude.

  Event cut
  - Primary vertex within $|z| < 10$ cm.
  - Pileup cut: Correlation between the hits in the ITS and TPC.

  → 38×10^6 events (centrality 30−50%)

Measurement of the jet nuclear modification factor (R_{AA}) and azimuthal anisotropy (v_2)

Analysis Flow

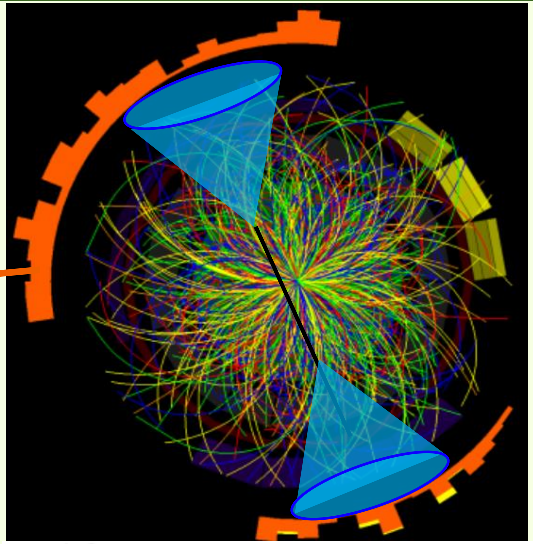


Two types of the Jet in LHC-ALICE Experiment

There are two kinds of jets in the LHC-ALICE experiment

(1) Full jet: Includes the energy of the neutral particles (EMCal) and the momentum of the charged tracks (ITS and TPC)

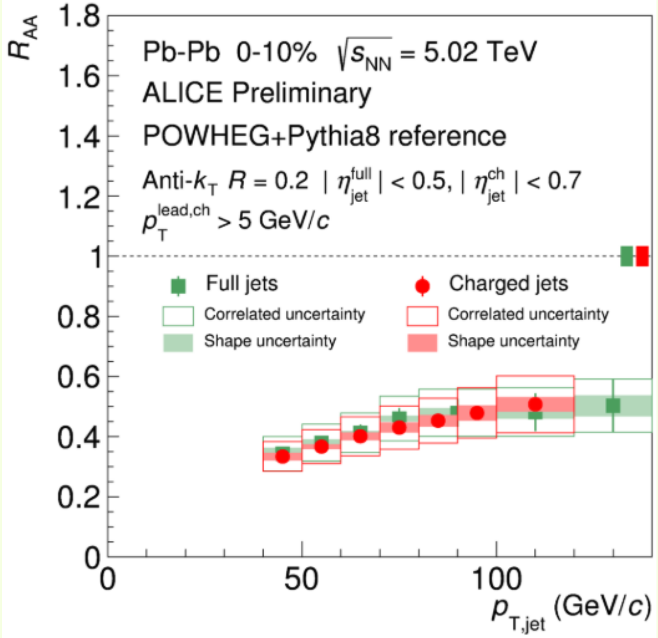
- Includes most particles of the jet.
- Does not covered full azimuthal angle (EMCal reduced acceptance).



(2) **Charged jet**: Includes the only charged tracks (ITS and TPC)

- The quality of the charged jets is ensured by previous studies (PHYSICAL REVIEW D 100, 092004 (2019)) .
- Covered full azimuthal angle

→ <u>It is essential for the measurements of the jet azimuthal anisotropy.</u>

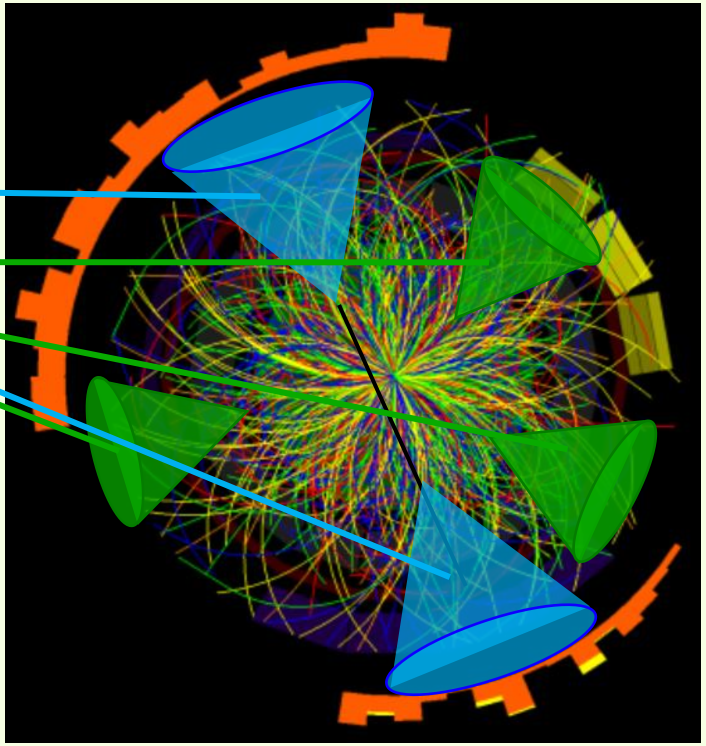


Jet Reconstruction Methods

Jet reconstruction algorithm

Fast jet package [Phys Lett B 641 (2006) 57]

- Signal Jet→ anti-k_T algorithm
- Background density→ k_T algorithm



Requirements for jet reconstruction

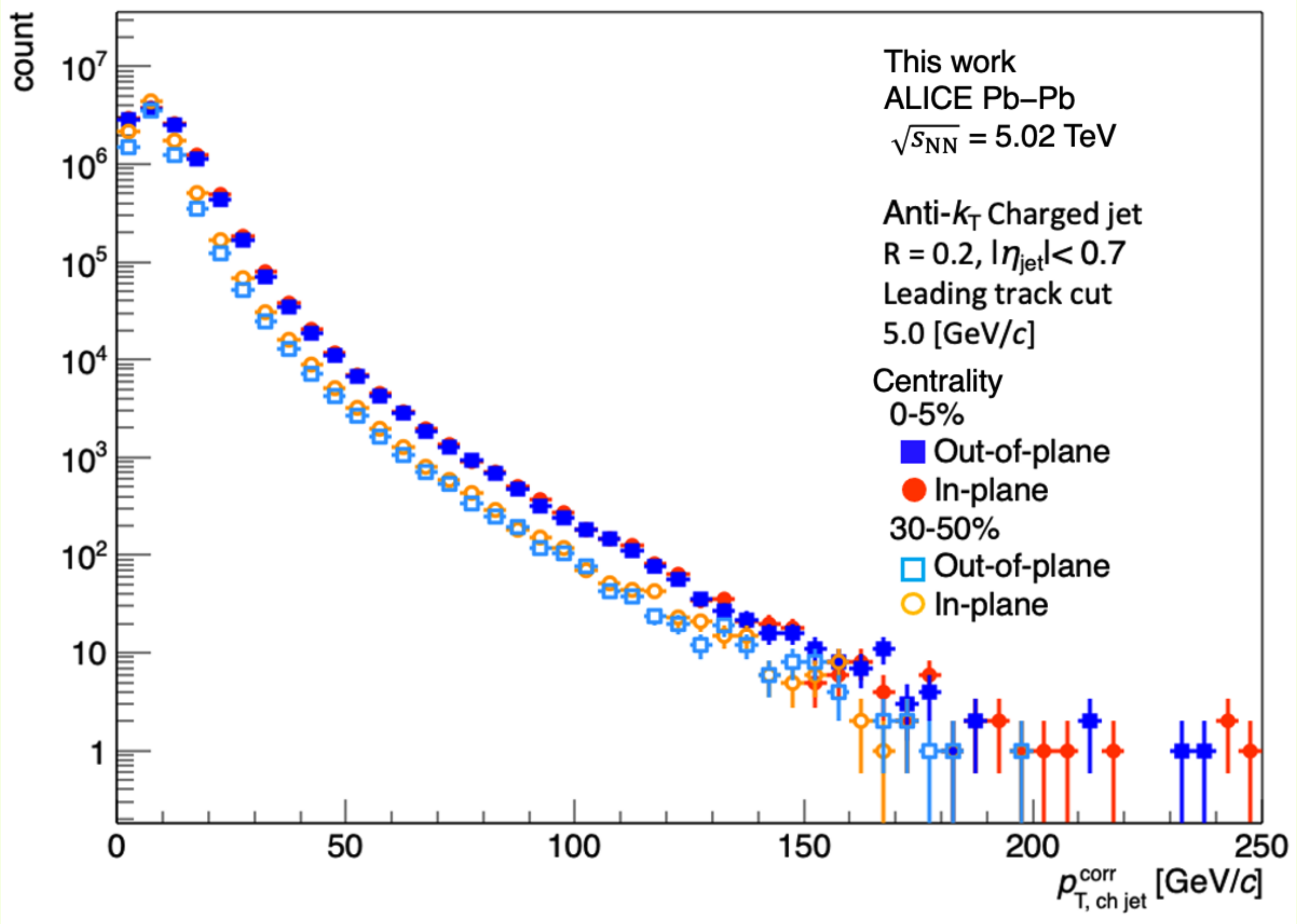
- Jet resolution parameter (R): 0.2
- Track cut: $0.15 < p_T < 100$ GeV/c
- Leading track cut: > 5.0 GeV/c
- Acceptance: $|\eta| < 0.7$, $0 < \phi < 2\pi$

Raw Charged Jet Spectrum for each Event Plane

Corrected Raw jet p_T distribution (w/o unfolding): $p_T^{corr} = p_T^{raw} - \rho(\phi)A$

Anti-k_T jet p_T

Background transverse momentum

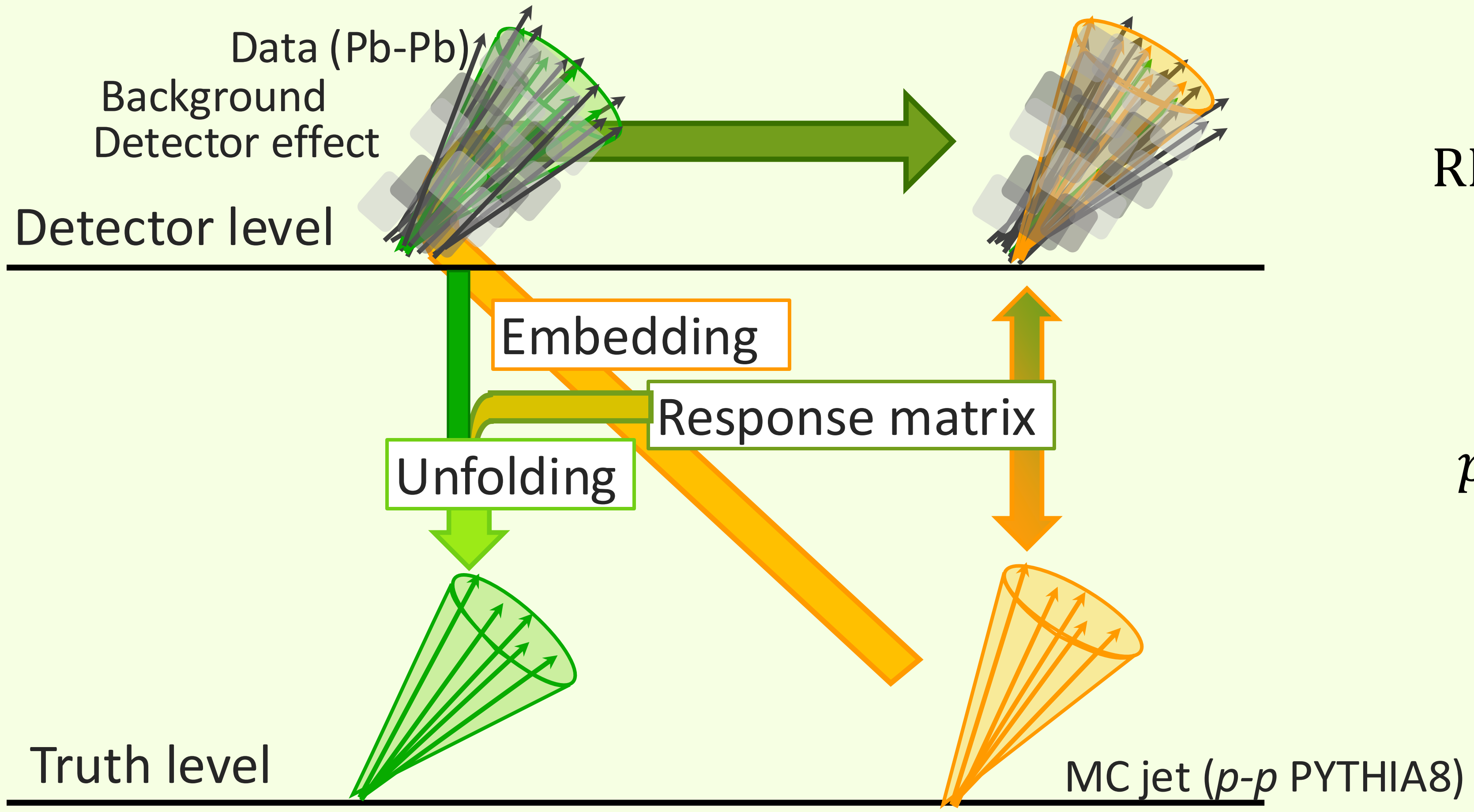


Out-Plane jets are more suppressed than in-plane ones for each centrality.

Unfolding Process

The measured jet p_T distribution is affected by the background fluctuations and the finite resolution / efficiency of the detector

→ Correcting p_T distribution distortions by using the **unfolding** procedure.

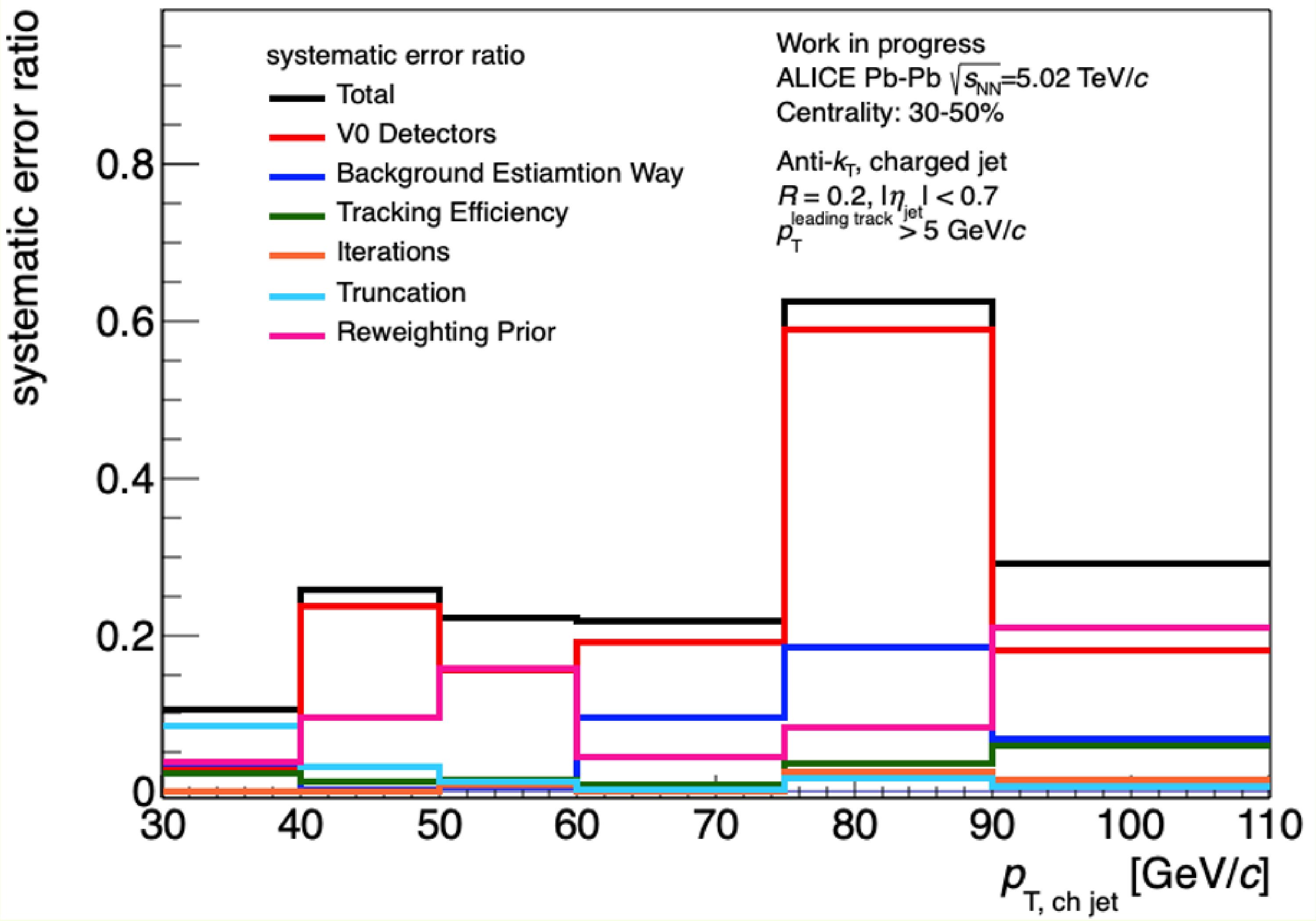


$$\mathrm{RM}\, p_{\mathrm{T,MC}}^{\mathrm{tru}} = p_{\mathrm{T,MC}}^{\mathrm{hyb}}$$

Unfolding

$$p_{\mathrm{T,data}}^{\mathrm{tru}} = \mathrm{RM}^{-1}\, p_{\mathrm{T,data}}^{\mathrm{meas}}$$

Systematic Error Ratio (v2)



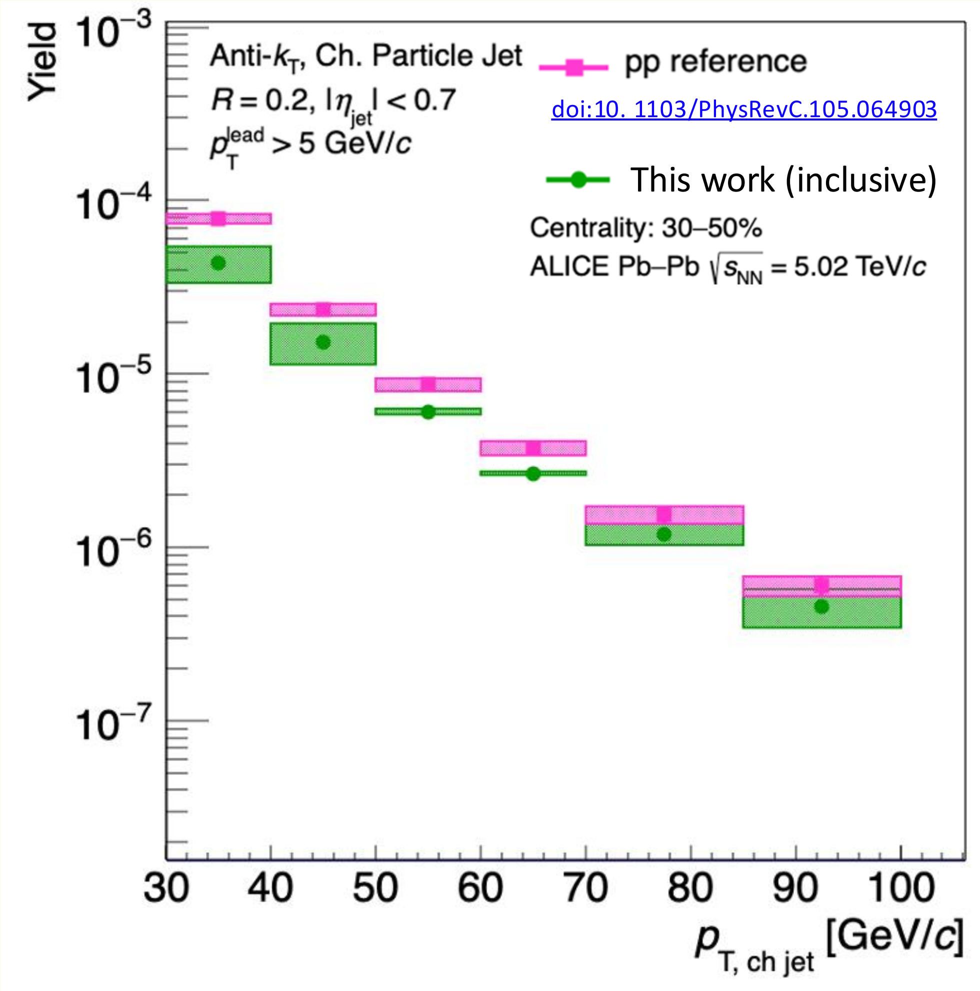
- $\delta_{sys} = \frac{|obs^{com} - obs^{Nomi}|}{obs^{Nomi}}$
- For all p_T range, the systematic error is lower than 1.
- The reason of the large error on 80-90 GeV/*c* is the observable value is very small.

Kinds of Systematic Uncertainties

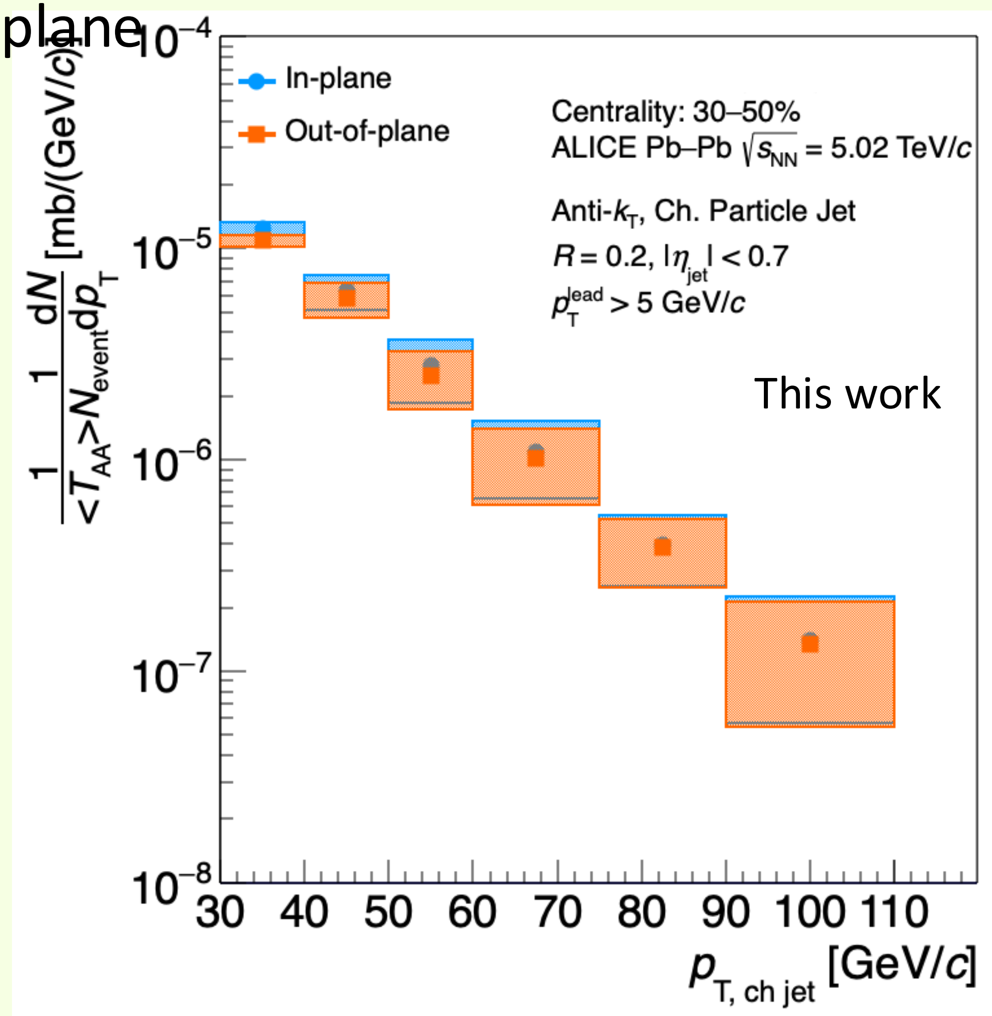
- Detector level p_{T} range in the response matrix ($\pm 5\ \mathrm{GeV}/c$)
- Unfolding iterations (± 1)
- Unfolding different prior (Modify input MC simulation)
- Tracking efficiency (98%, 94%)
- Different event plane angle determination detector (V0M, V0A, V0C)
- Different background fitting function (Two type functions)

Jet Yield Distributions

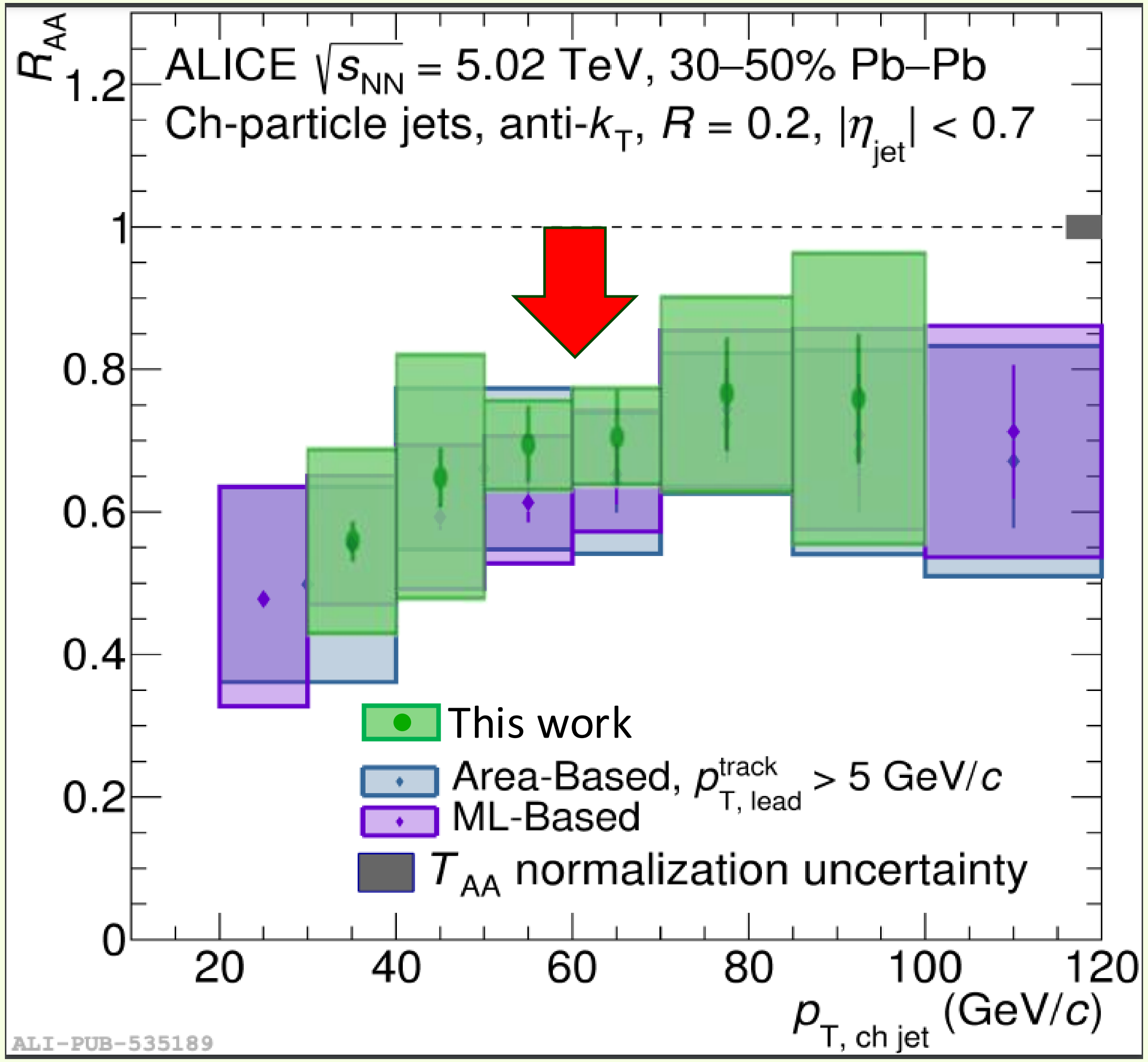
Inclusive charged jet yield for the p-p and Pb-Pb collision



Charged jet yield for the in- and out-of-plane



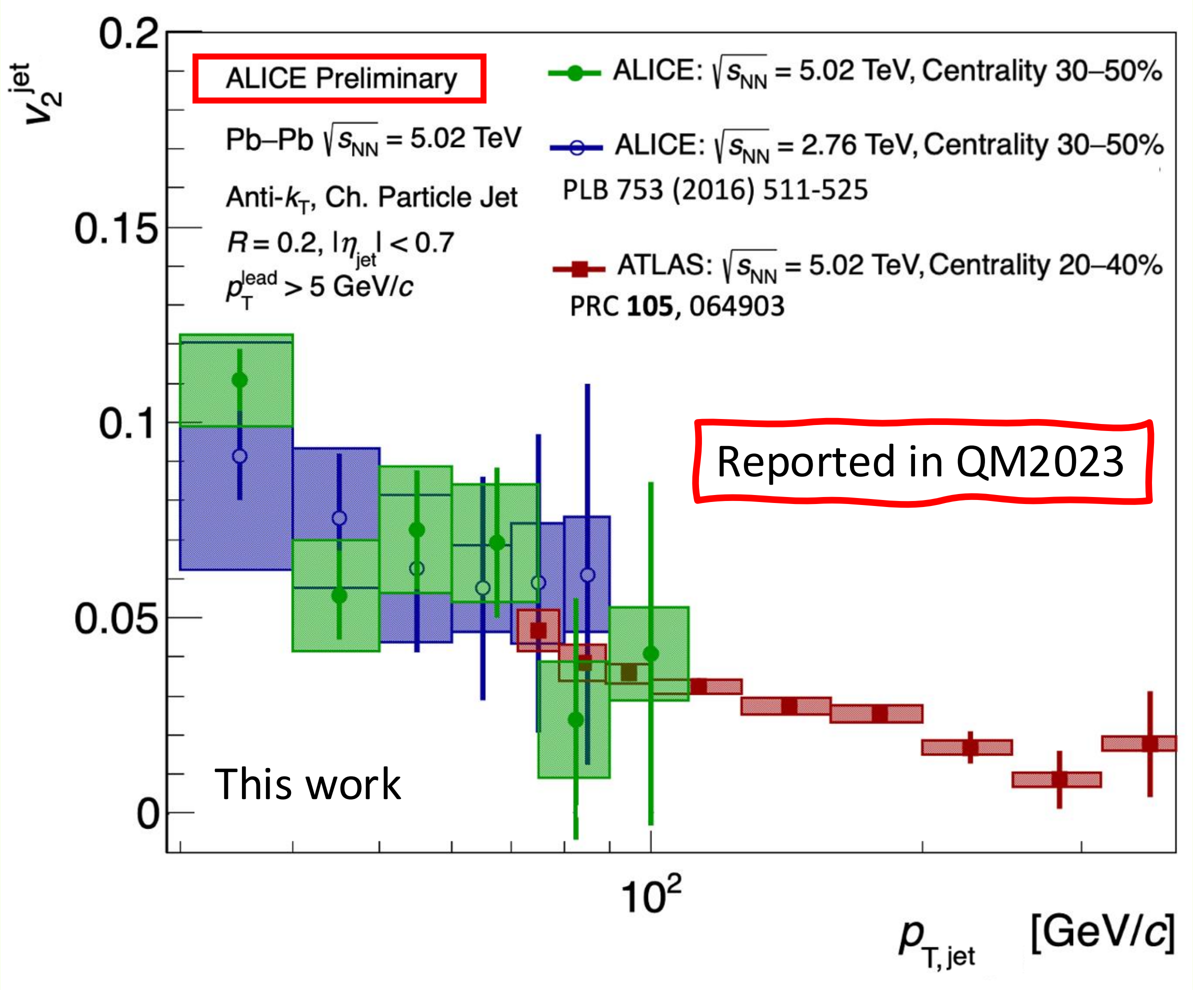
Jet Nuclear Modification Factor (R_{AA}^{jet})



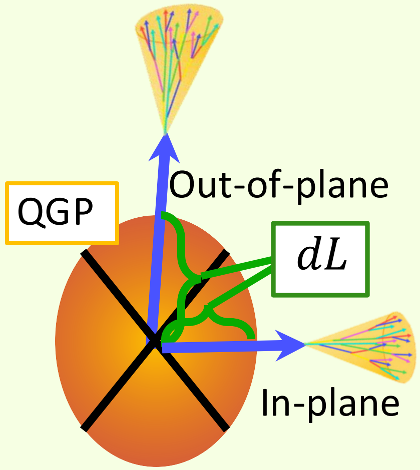
- It indicates that there is the value of the R_{AA} is smaller than 1 over all p_T range
→ This indicates the jets suppression due to the parton energy loss.

- My result consistents with the same measurements which already published (using different p−p reference).
[Phys Lett. B 849, (2024) 138412]

Inclusive charged jet v_2



$$v_2^{\text{ch jet}}(p_T^{\text{jet}}) = \frac{\pi}{4}\frac{1}{\mathscr{R}_2}\frac{N_{\text{in}(p_T^{\text{jet}})} - N_{\text{out}(p_T^{\text{jet}})}}{N_{\text{in}(p_T^{\text{jet}})} + N_{\text{out}(p_T^{\text{jet}})}}$$



- At low p_T, the charged jet v_2 show **evidently positive value**. As it becomes high p_T, the charged jet v_2 gets **closer to zero**.
- The charged jet v_2 of this measurement is **consistent with ATLAS result** within uncertainty around 70-110 GeV/c.

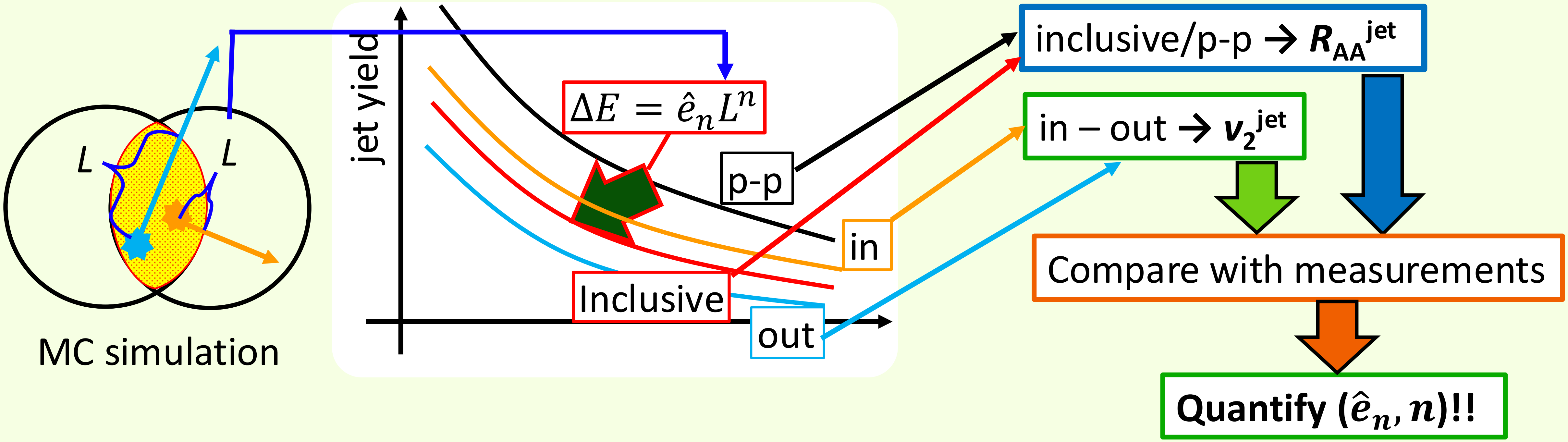
This result got the ALICE Preliminary.
And it was reported in the EPS2023 and QM2023

Toy model simulation to quantify the parton energy loss parameters $(\hat{e}_n, n)$

Concept of my parton energy loss simulation

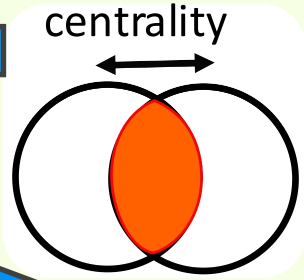
Evaluate the parton energy loss parameters ($\hat{e}_n, n$) and constrain the models using both the measurements R_{AA}^{jet} and v_2^{jet}.

- Estimate R_{AA}^{jet} and v_2^{jet} by applying the pass length(L) using MC simulation and energy loss equation ($\Delta E \propto \hat{e}_n L^n$) to the jet yield in the pp collisions.

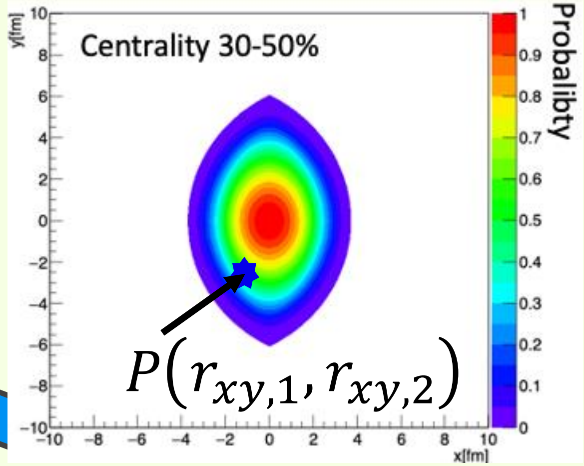


Overview of Simulation Algorithm Flow

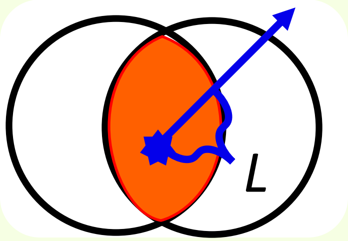
1. Determine Centrality



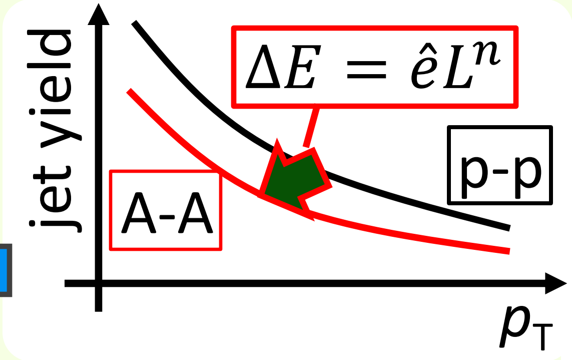
2. MC for creating a parton using $P(r_{xy,1}, r_{xy,2})$



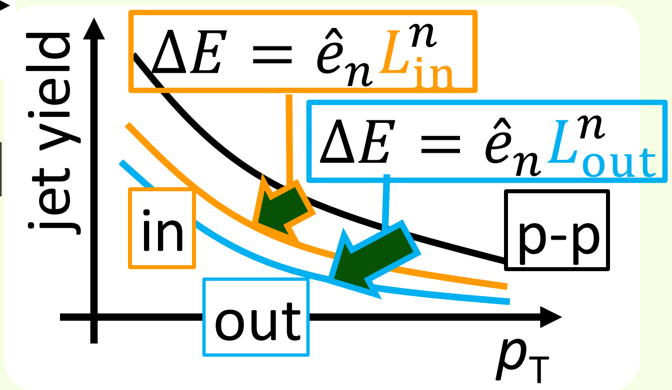
3. Calc pass length (L)



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



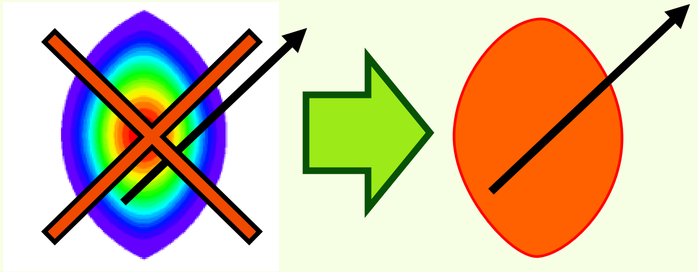
5. Determine $\hat{e}_n$ by fitting the PbPb jet distribution



6. Applying $\hat{e}_n$ to path-length in the in- and out-of-plane
7. Estimate jet R_{AA} and v_2

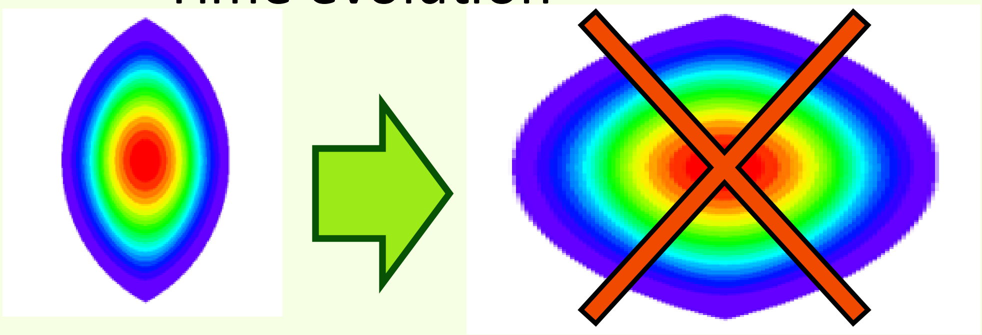
Assumption

<1> Do not consider a dependency of the QGP density profile dependency



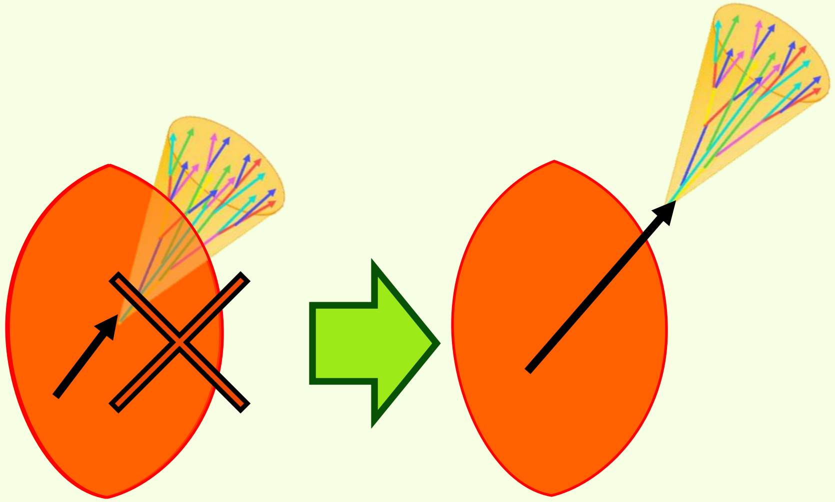
<2> Do not consider the time evolution of the QGP medium.

Time evolution

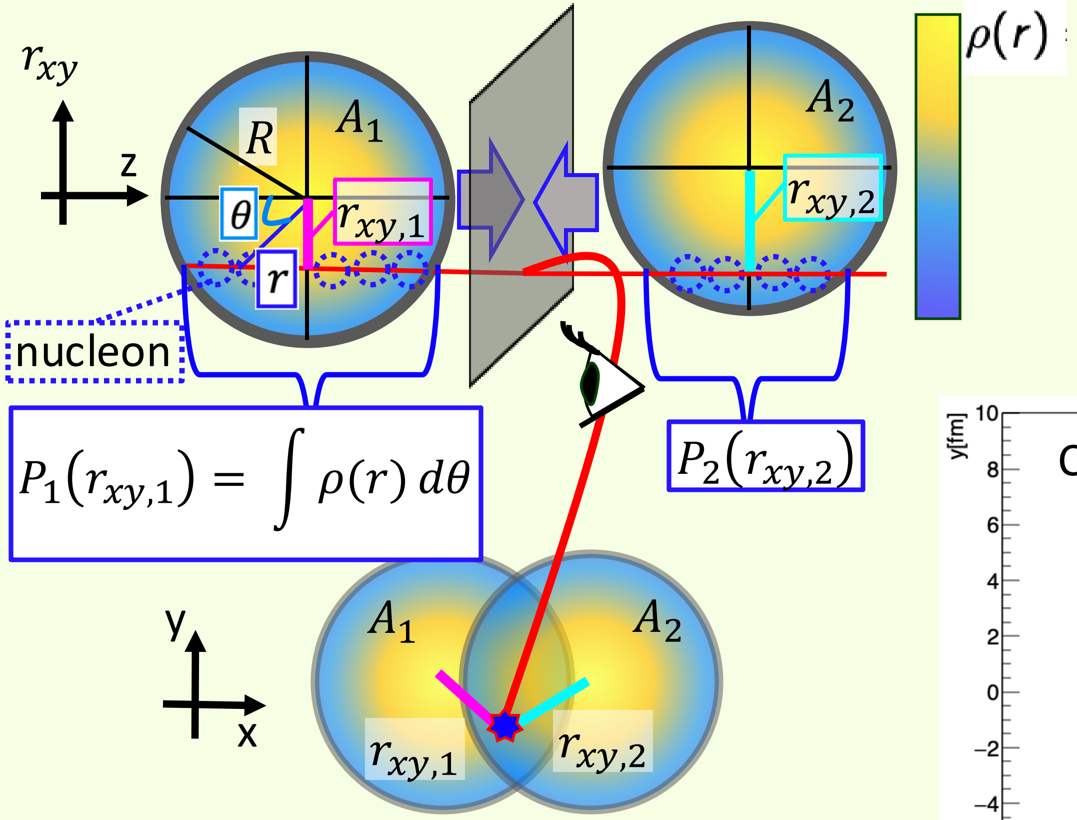


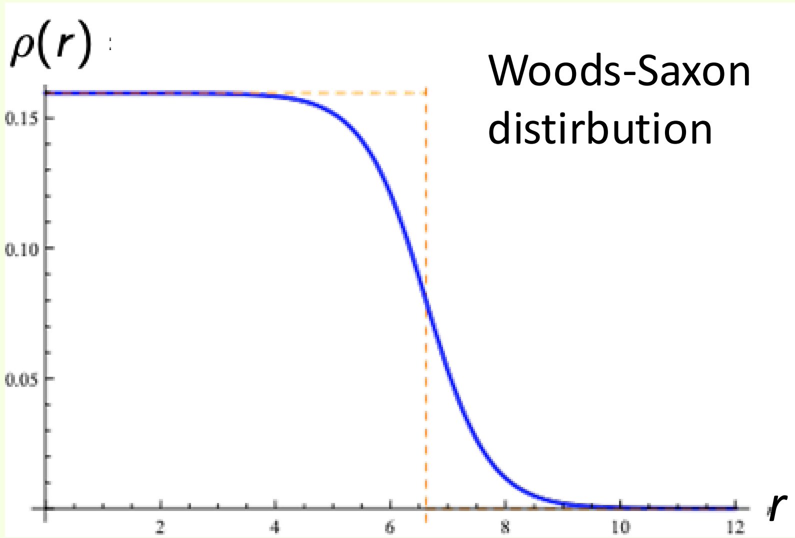
<3> Do not consider a dependency of parton p_T.

<4> Do not consider parton fragmentation in the QGP medium



Calculate the hard scattering probablity based on the nuclear density





Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1+\exp(\frac{r-R}{t})}$$

$$\rho_0 = 3/\left(4\pi R^3\left(1+\frac{\pi^2 t^2}{R^2}\right)\right)$$

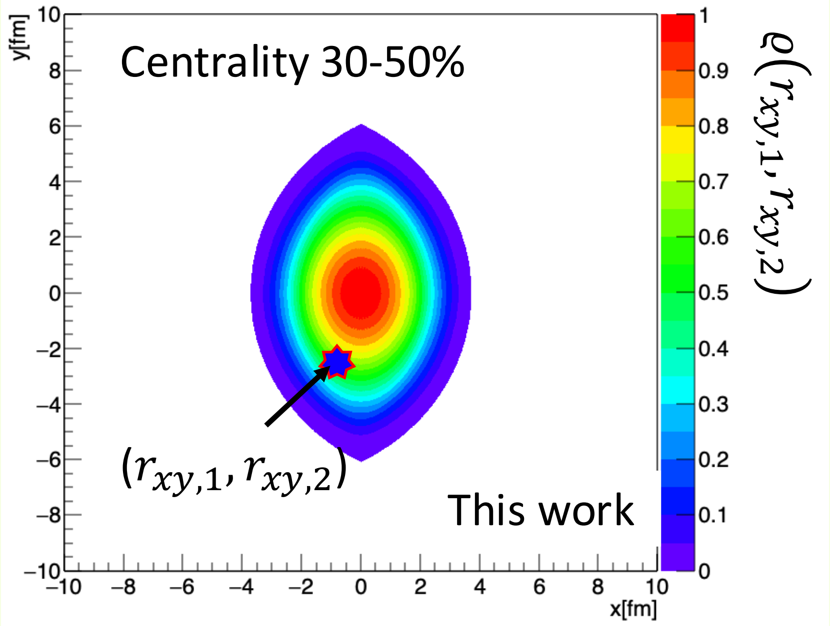
Pb

t = 0.55 fm

R = 6.8 fm

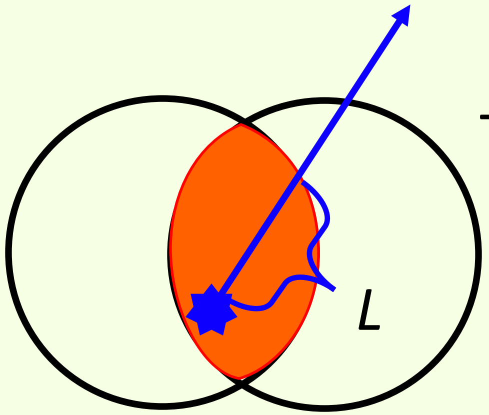
$$\mathrm{P}(r_{xy,1}, r_{xy,2}) = P_1(r_{xy,1}) \times P_2(r_{xy,2})$$

$$\varrho(r_{xy,1}, r_{xy,2}) = \frac{P(r_{xy,1}, r_{xy,2})}{P_{max}}$$

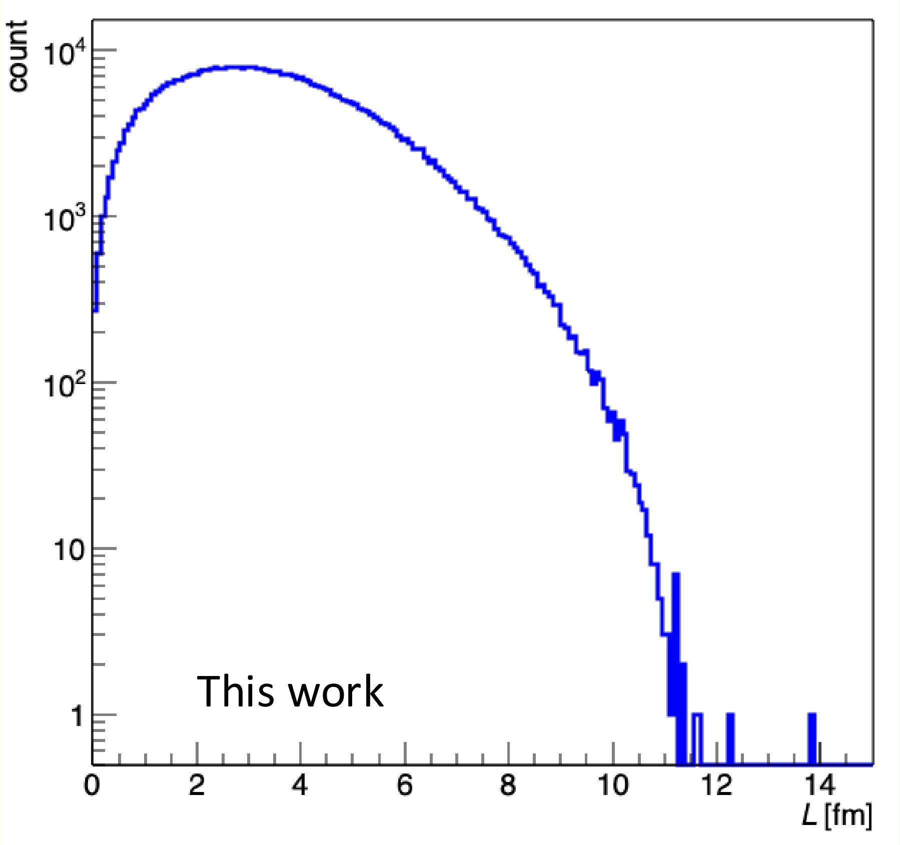


The density profile map ϱ is calculated for each centrality bin 1%.

3.1 Calc pass length

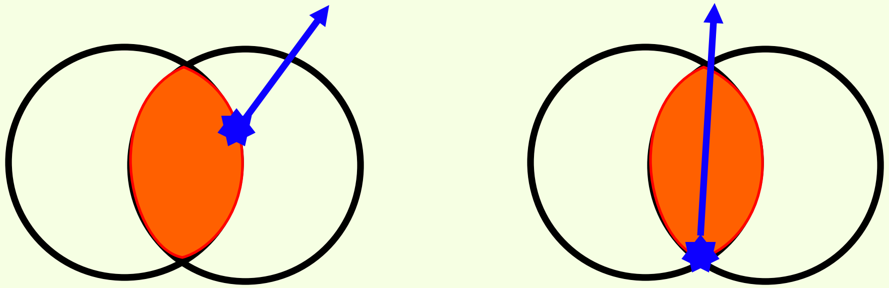


The edge corresponds to Wood-Saxon R



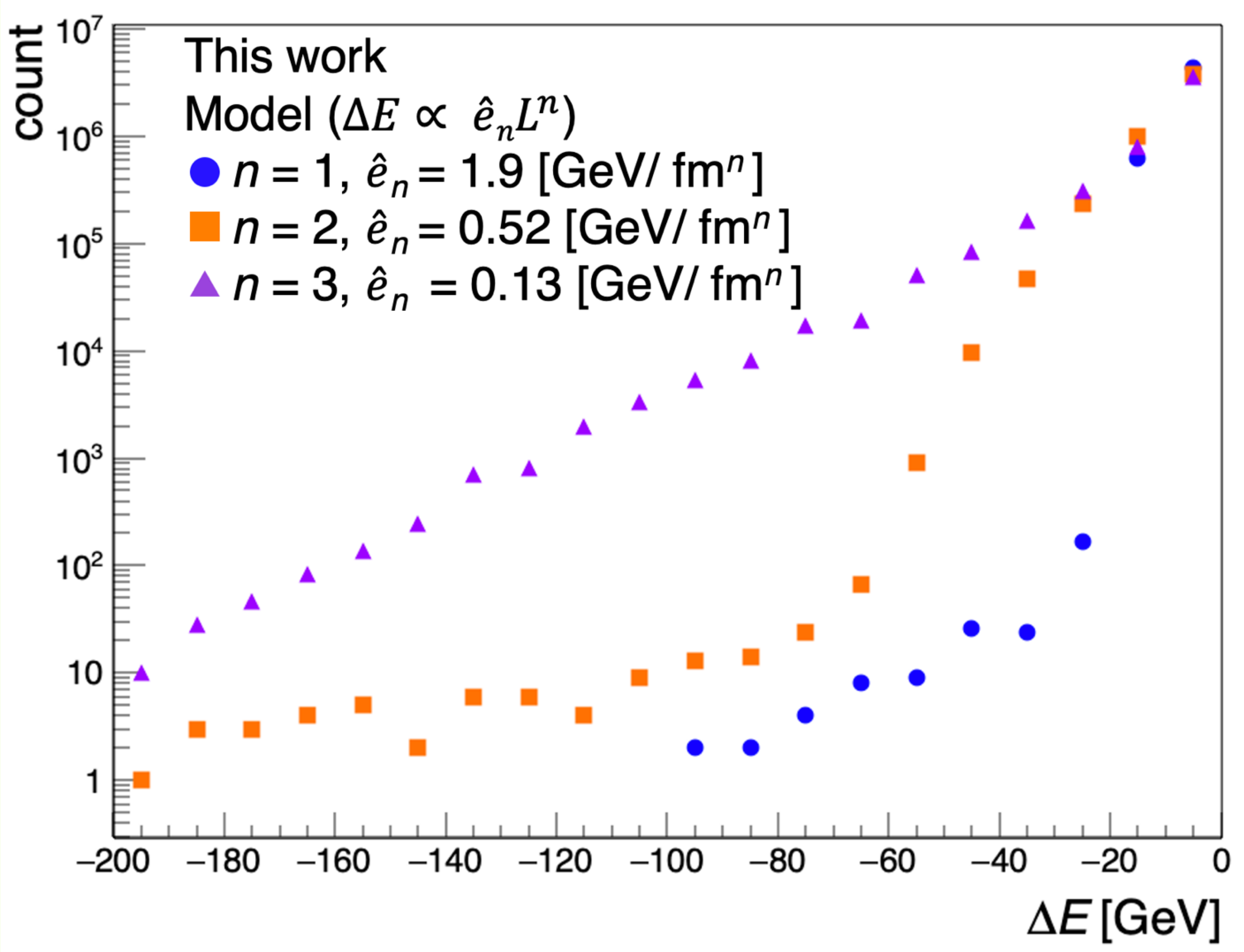
Regard the length from a parton creation point to a cross point of the original atom edge as the pass length using two main hypothesis.

- The original nucleus is supposed as a circle.
- The density of QGP is uniform in the overlapping region



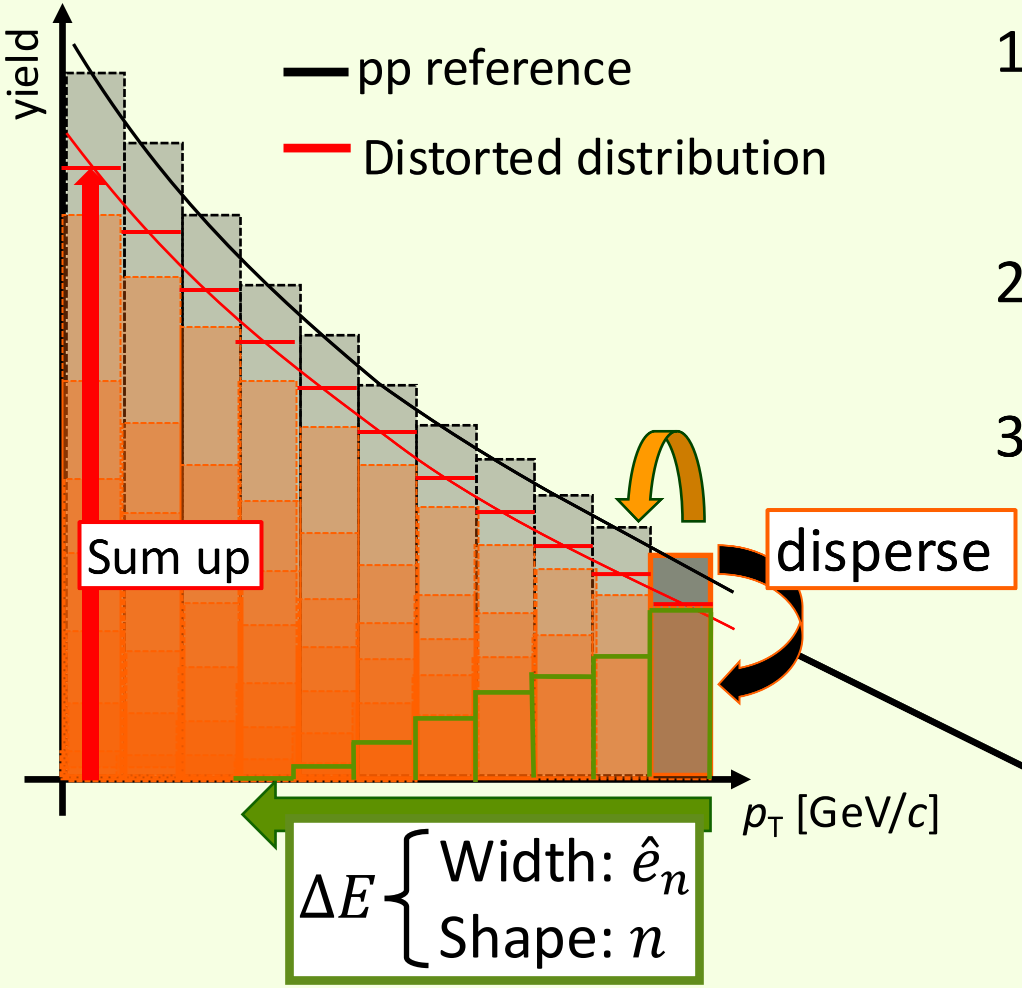
3.2 Energy loss distribution ($dE = \hat{e}_n L^n$)

Disperse histogram (d*E* distribution)

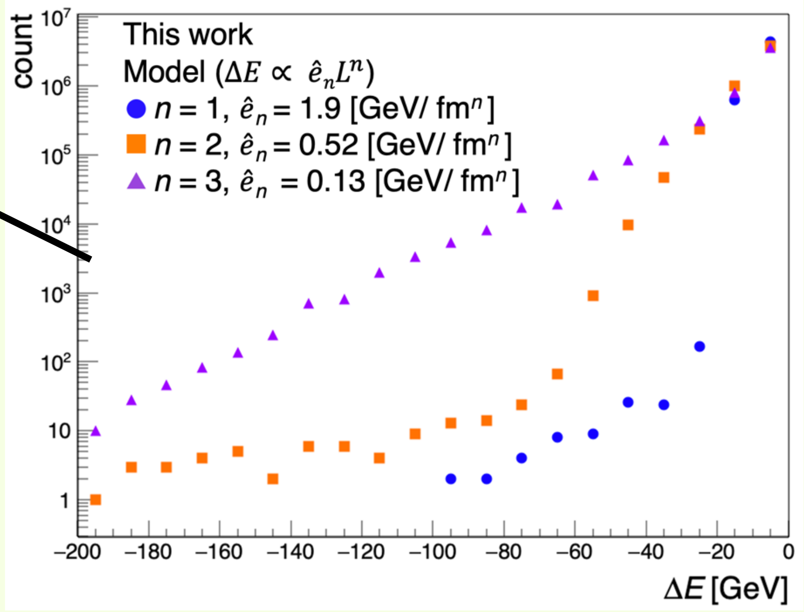


Estimate the energy loss distribution ($dE = \hat{e}_n L^n$) using the path length (L) and an arbitrary value $\hat{e}_n$.
The distribution shape depends on the exponent *n*.

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

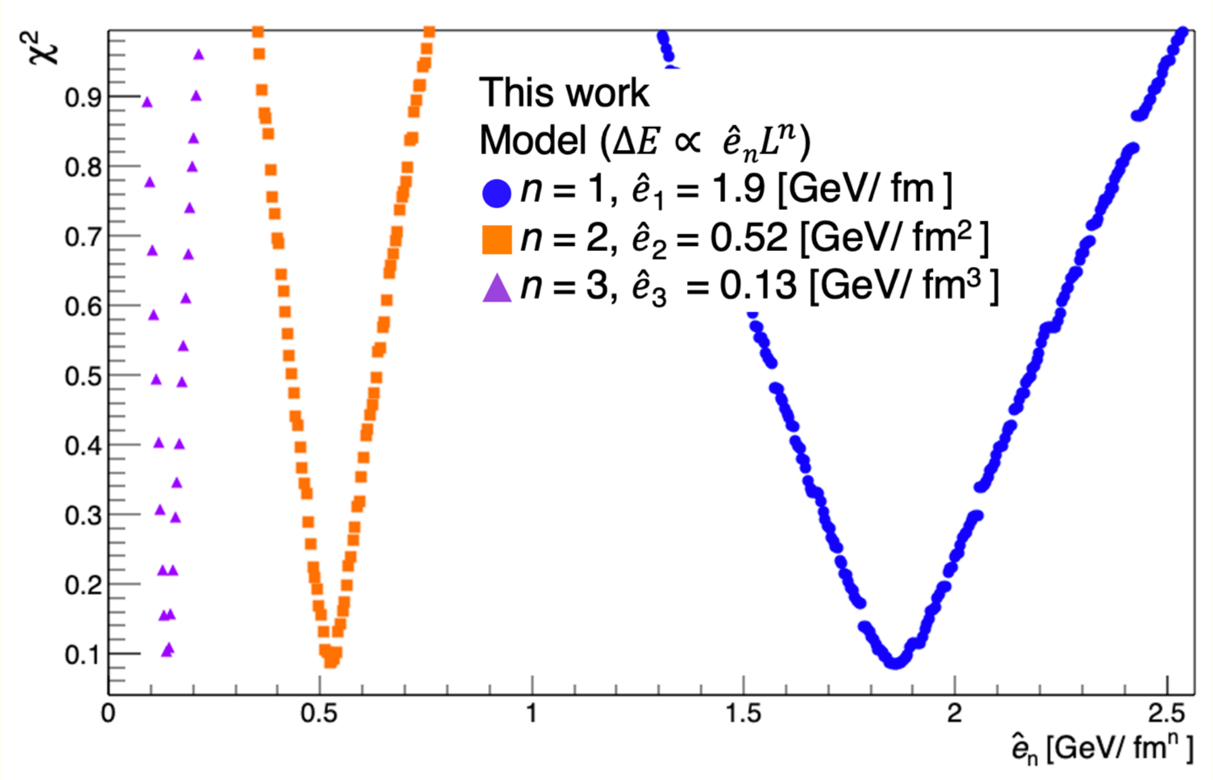


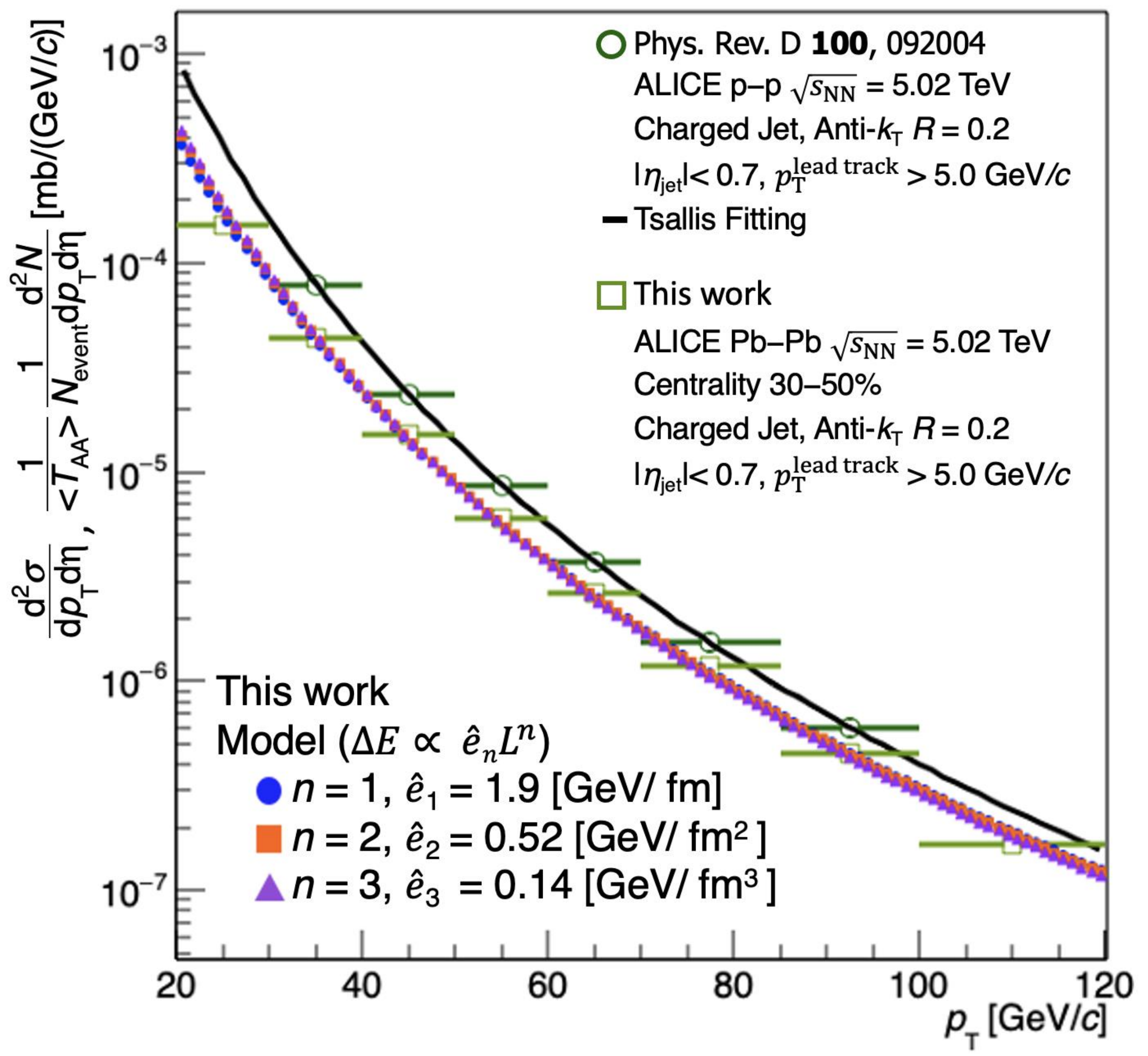
1. Using the dE distribution, disperse each bin of the pp jet p_T distribution (MC/Fitting function). The dE distribution is normalized by each p_T bin counts.
2. Calculate a suppressed jet distribution by summing up distributions comming from each p_T bin.
3. Determine the best $\hat{e}_n$ by fitting the experimental Pb-Pb jet p_T distribution for each n = 1, 2 and 3 value.



5. Determine $\hat{e}_n$

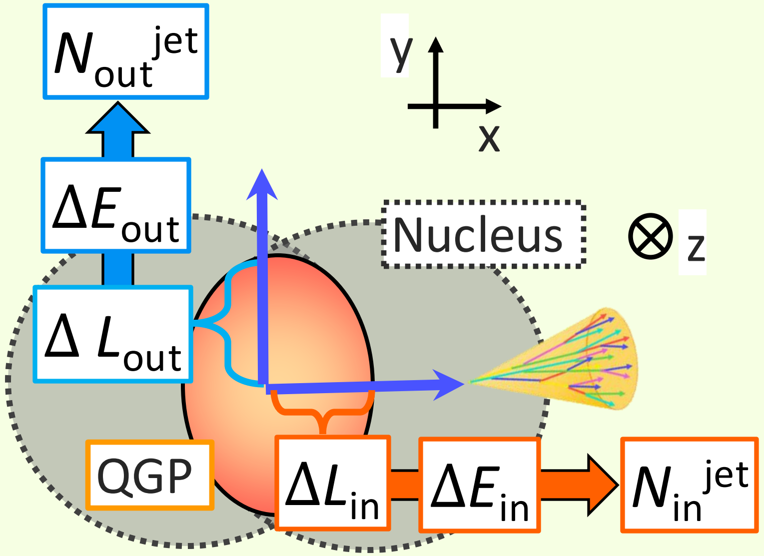
The $\hat{e}_n$ is determiend by adjusting the simulation the p_T distribution to the p_T distribution of the HIC.





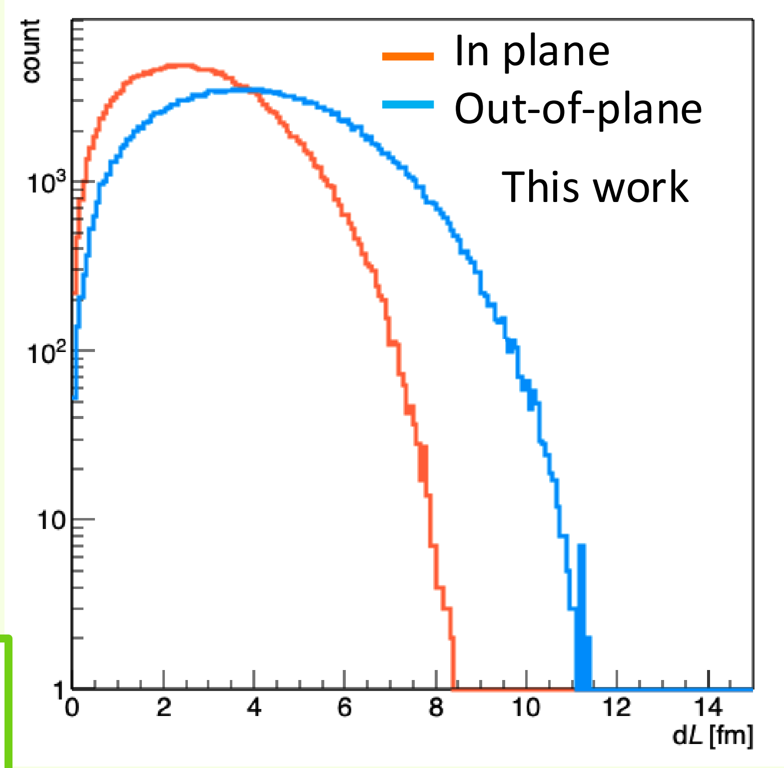
6. Make In/Out of plane jet yield distributions

Calculate the in and out of plane distributions using the $\hat{e}_n$ obtained in the previous step.

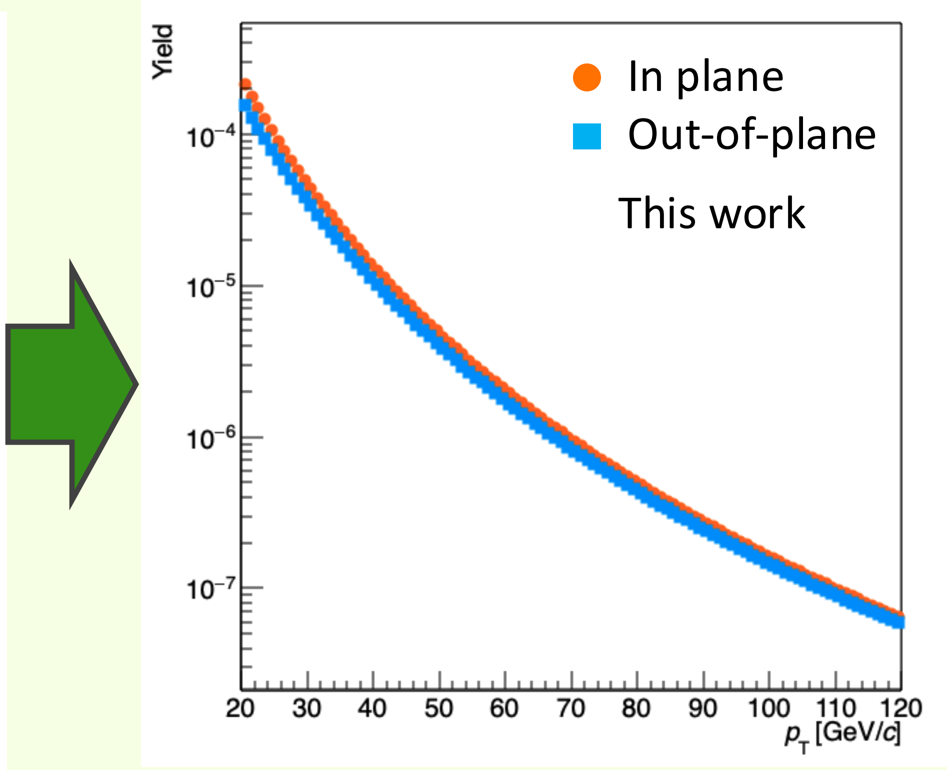


$$v_2^{\mathrm{ch\ jet}}(p_T^{\mathrm{jet}}) = \frac{\pi}{4}\frac{1}{\mathscr{R}_2}\frac{N_{\mathrm{in}(p_T^{\mathrm{jet}})} - N_{\mathrm{out}(p_T^{\mathrm{jet}})}}{N_{\mathrm{in}(p_T^{\mathrm{jet}})} + N_{\mathrm{out}(p_T^{\mathrm{jet}})}}$$

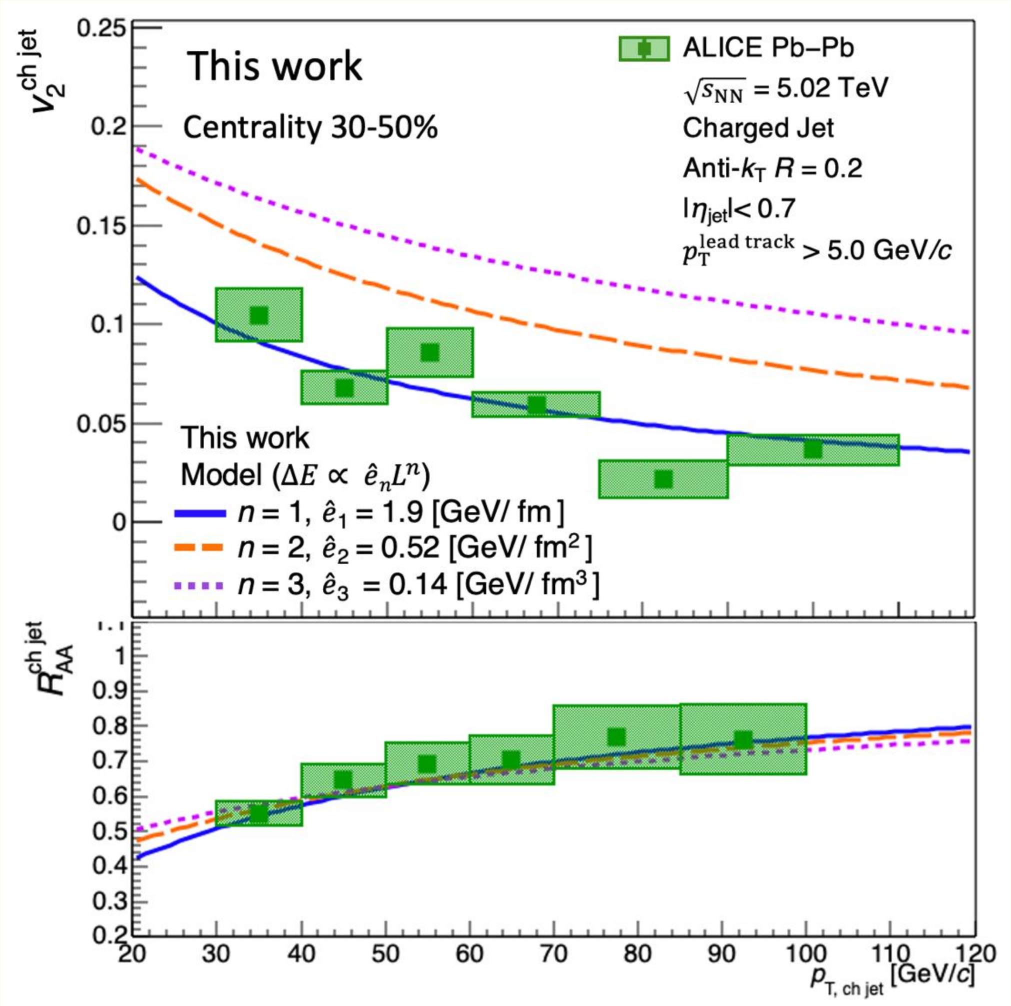
Path length



Jet yield (n=1)



In the simulation, the event plane angle resolution ($\mathcal{R}_2$) is 1.



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

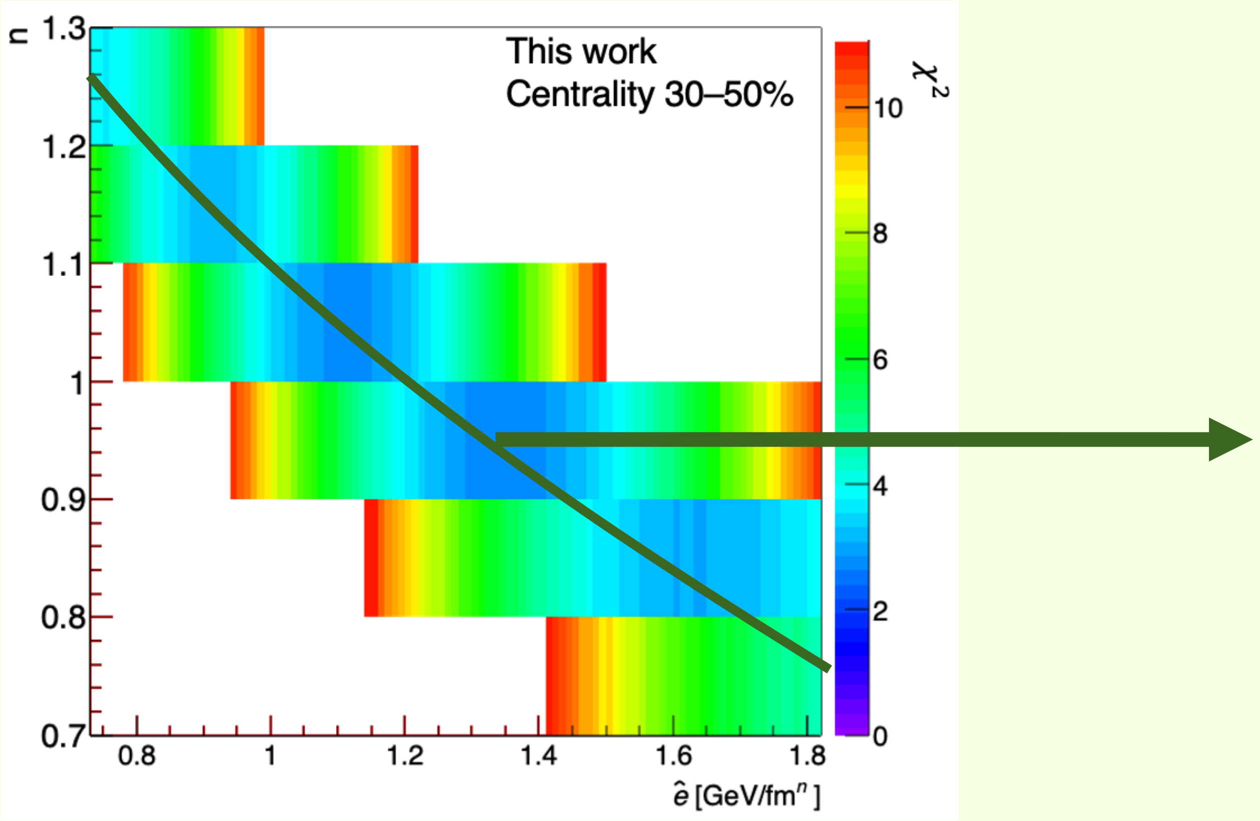
Significance level 0.05: **χ^2(5) < 11**

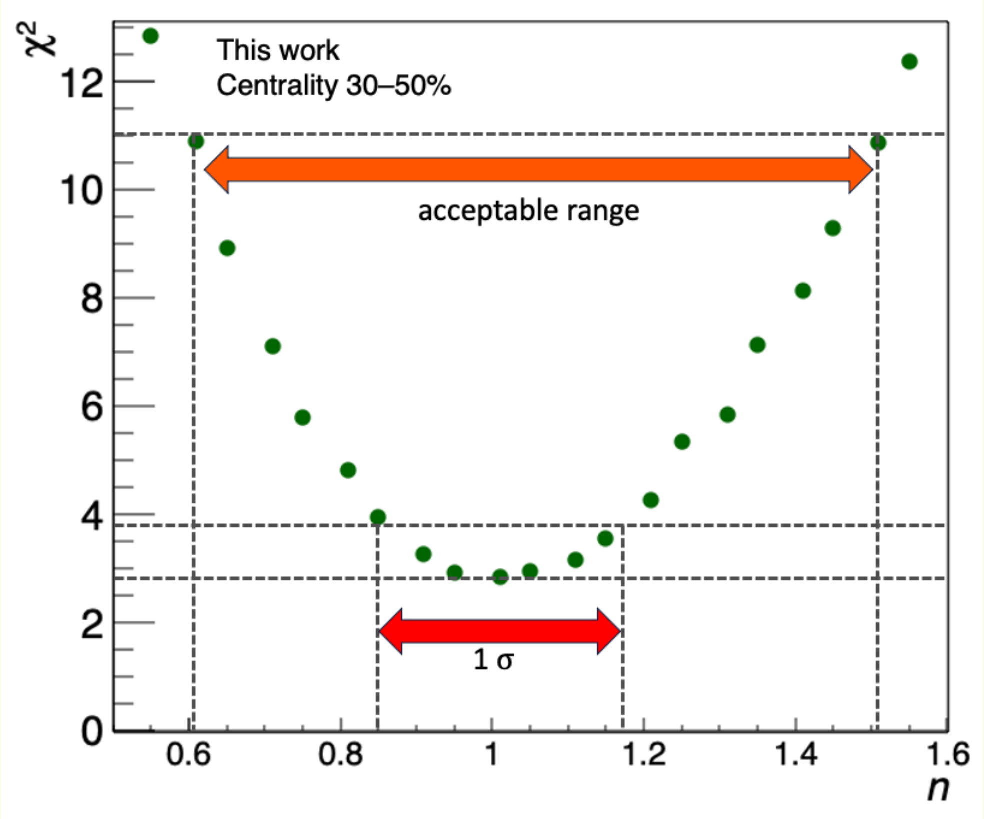
	n = 1	n = 2	n = 3
χ^2 (R_{AA}^{jet})	0.29	0.31	0.52
χ^2 (v_2^{jet})	**2.9**	31	72

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

Best L dependece Search (mixing model case)

If the energy loss models are mixing, the n has not to be an integer.
$(n = p_1 \times 1 + p_2 \times 2 + p_3 \times 3)$

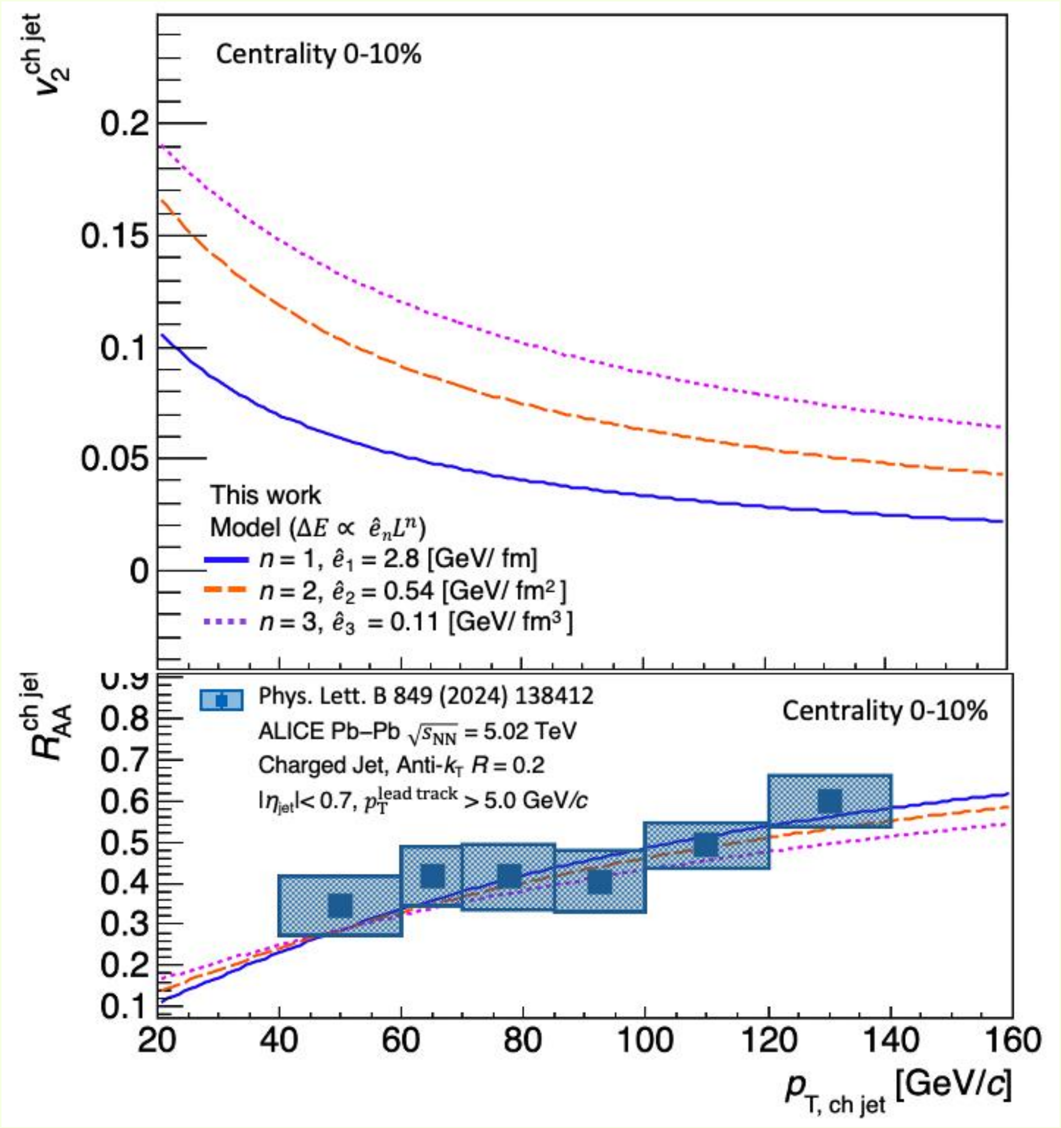




※ The $\hat{e}_n$ is adjusted for each pass length dependency value of the n exponent.

Just n = 1.00 corresponds to the best value for the exponent in the path length power law dependency for parton energy loss.

Central collision comparison



Estimated R_{AA}^{jet} and v_2^{jet} and $\hat{e}_n$ evaluated in the central colllision using the exisiting R_{AA}^{jet} measurement.

Centrality 30−50%	$n = 1$	$n = 2$	$n = 3$
$\hat{e}_n$ [GeV/fm^n]	1.9	0.52	0.14

Centrality 0−10%	$n = 1$	$n = 2$	$n = 3$
$\hat{e}_n$ [GeV/fm^n]	2.8	0.54	0.11
χ^2 (R_{AA}^{jet})	0.29	0.31	0.52

- R_{AA}^{jet}: Every models were consistent with the data.
- v_2^{jet}: The central collision values are smaller than the semi-central ones.

$\hat{e}_n$ was expected not to depoend centrality.
→ $\hat{e}_n$ is larger as centrality.

Simulation Conclusion

- For all models (*n* = 1, 2, and 3), the simulation results of the R_{AA}^{jet} are consistent with the measurement.

- Comparing the v_2^{jet} measurement enable to quantify the exponent ***n* = 1.00±0.15**.

- When the n = 1, the energy loss unit per path length is $\hat{e}_n$ **= 1.9 GeV/fm.**

- To validate the accuracy of this model, further comparison with other experiments is necessary.

Simulation Outlook

Additional comparison

→ Make this toy model simulation more solid.

→ Give the dependency of the parton energy loss parameters($\hat{e}_n$) to the jet and QGP properties.

- Compare with the different **centrality** results

  ⇨ { Give the centrality dependence of the energy loss parameters.
  Enables discussions on the effects of the QGP's density and time evolution.

- Compare with the different **collisional energy** measurements.

  ⇨ Give the temperature and density dependence of this toy model.

- Apply my simulation for the results of **other experiments** (LHC-ATLAS, RHIC-sPHENIX).

  ⇨ Give the jet p_T dependence of the energy loss.

- Compare with the JETSCAPE results (on going)

  ⇨ Give more detail information of the parton interactions.

Summary & Outlook

Summary

- To clarify the parton energy loss mechanism and estimate its parameters, the charged jet R_{AA} and v_2 are measured using the LHC-ALICE data of the Pb–Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV.

- The charged jet v_2 in centrality 30-50% show **positive value** and is **consistent with other experiments**.

- Develop a simulation framework for the parton energy loss dE = $\hat{e}_n L^n$ depending path length in the QGP medium
- The comparison between the data and simulation suggests that the ***n* = 1.00±0.15 case is the best** and the $\boldsymbol{\hat{e}_n = 1.9}$ **GeV/fm**.

Outlook

- Publish the charged jet v_2 result.
- Measure a charged jet v_2 result in different centrality bins.
- Update the toy model simulation.