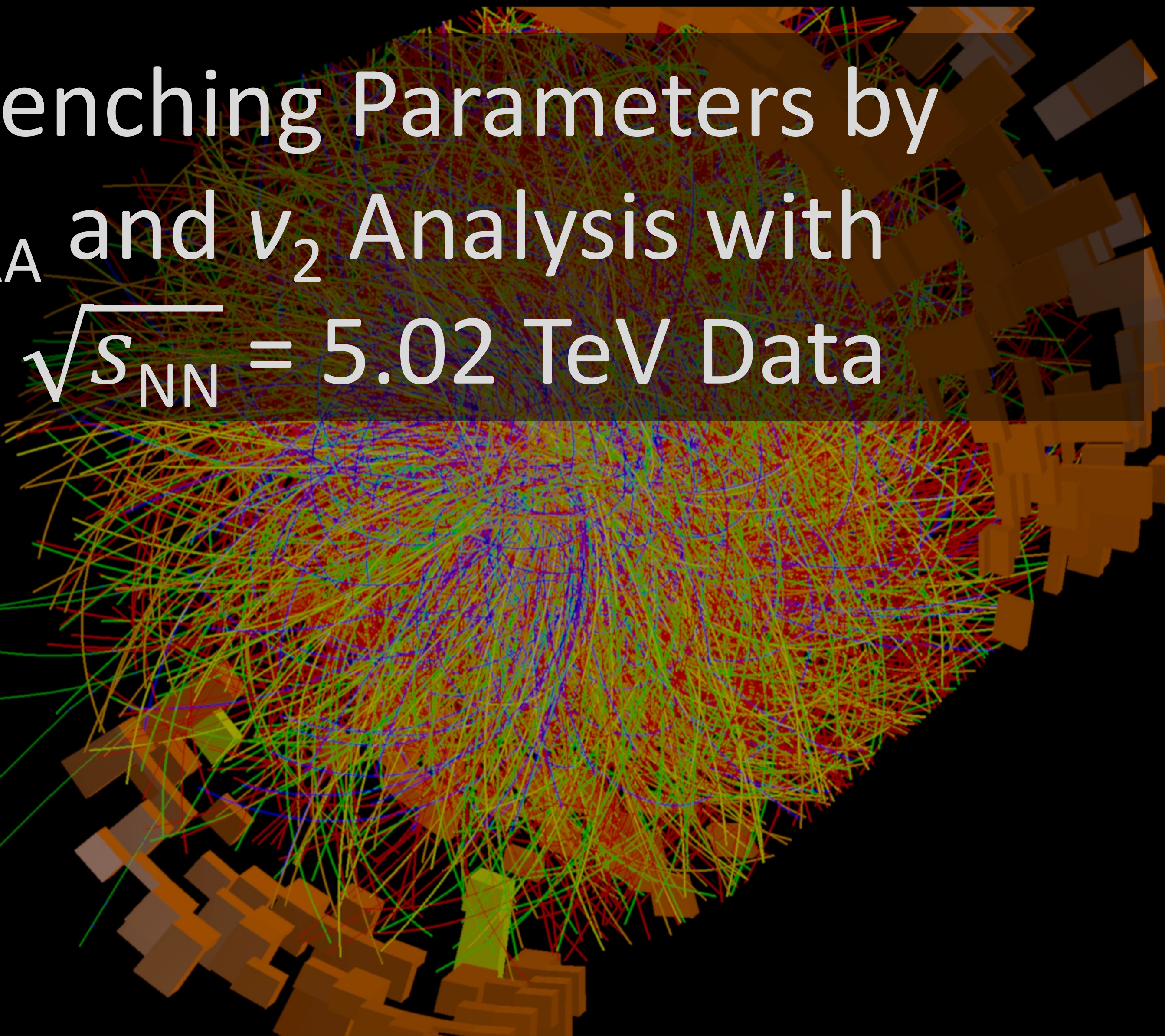
Measurement of Jet Quenching Parameters by Inclusive Charged Jet R_{AA} and v_2 Analysis with ALICE Pb-Pb Collision at $\sqrt{s_{NN}} = 5.02$ TeV Data

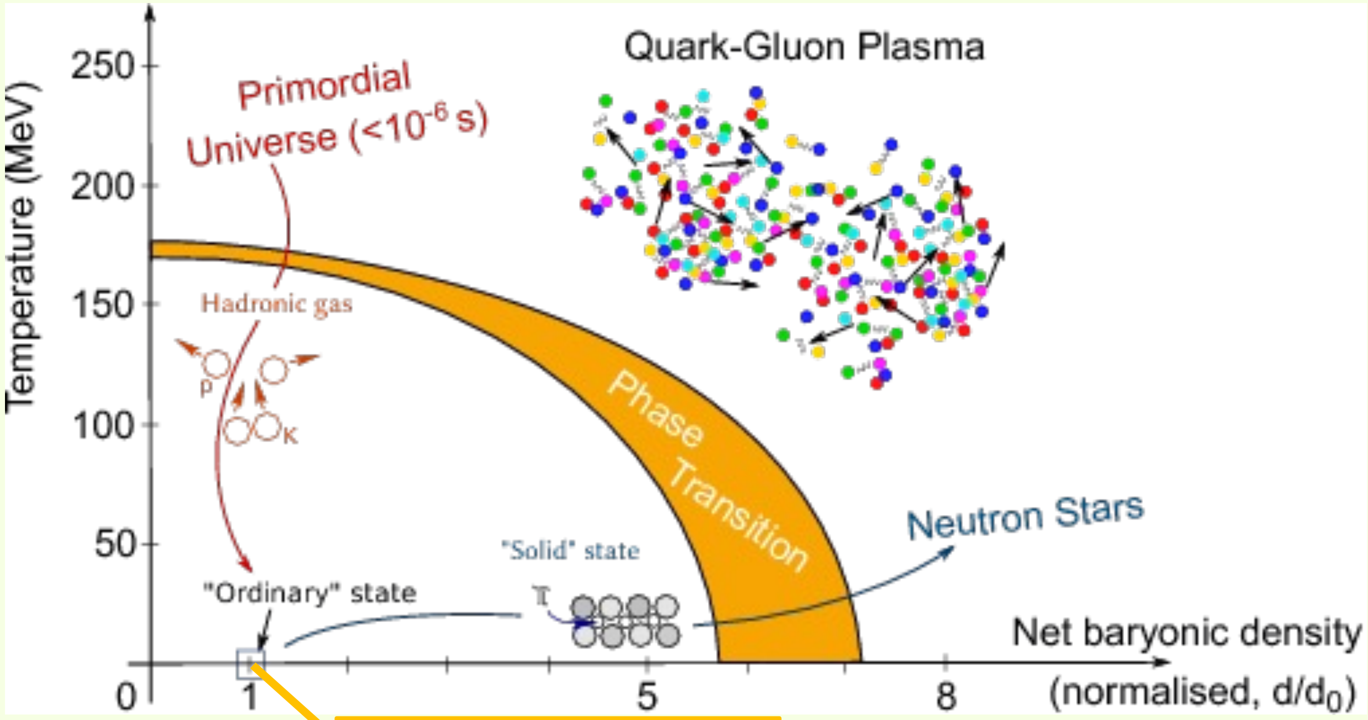


RIKEN (JRA)
Takuya Kumaoka

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)

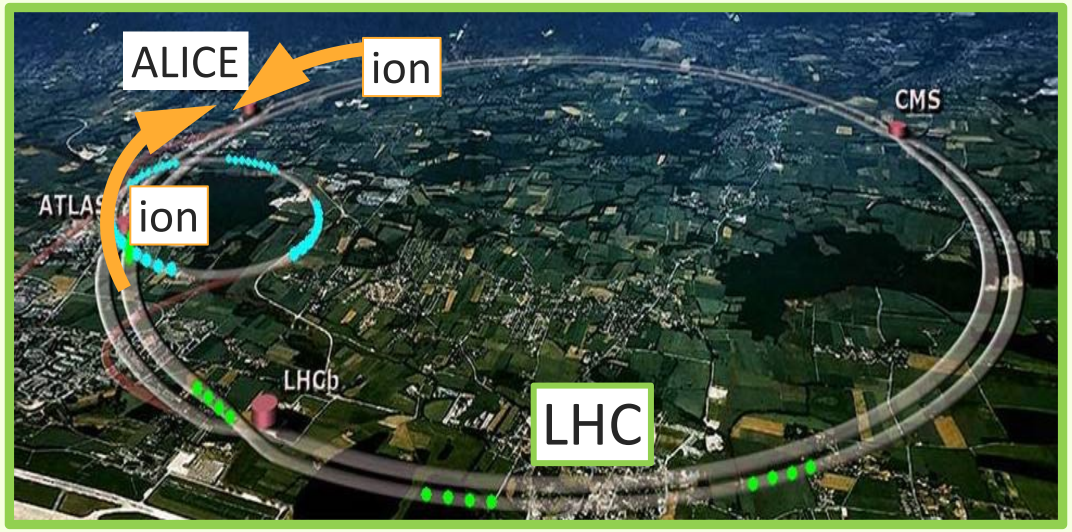


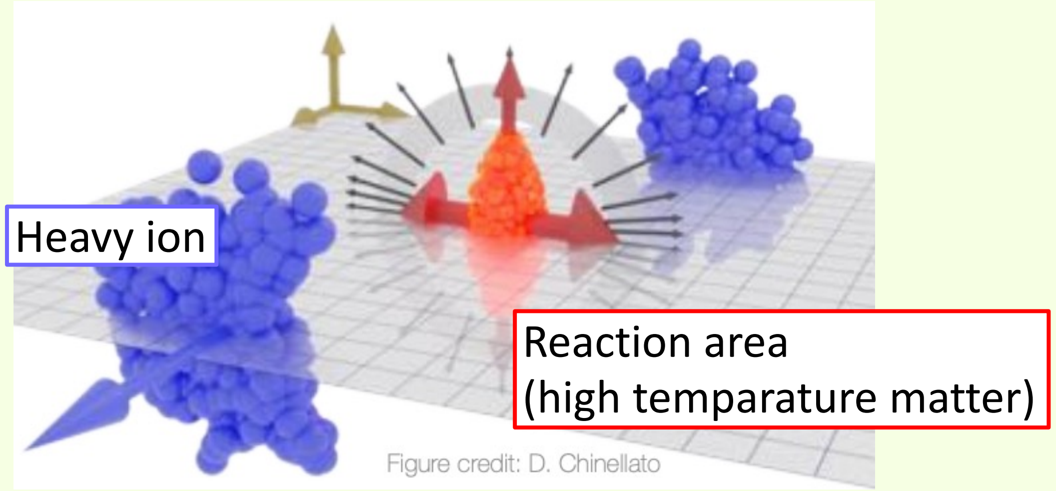
$\rho_0 \approx 0.15\ \mathrm{GeV}/fm^3$

The Physics of Heavy Ion Collisions

Create QGP by **Heavy Ion Collisions (HIC)**

- Product the high energy matter state by colliding accelerated heavy ions with the large collider (LHC/RHIC).





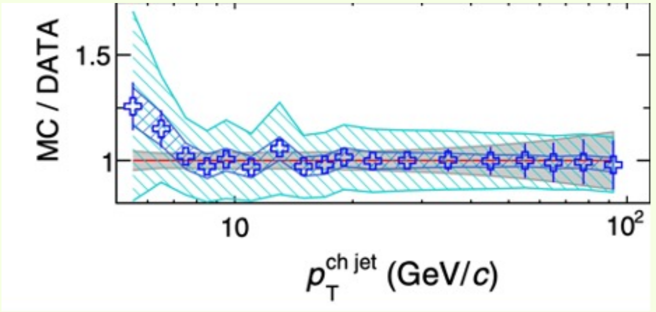
LHC: pp at $\sqrt{s} = 7, 2.76, 5.02, 13$ TeV,
PbPb at $\sqrt{s_{\mathrm{NN}}} = 2.76, 5.02$ TeV

Evidence of QGP formation in HIC : **jet quenching,** elliptic flow

Hard Probes of the QGP

Hard probes: High momentum transfer event

- The rates are calculable within perturbative QCD (pQCD)



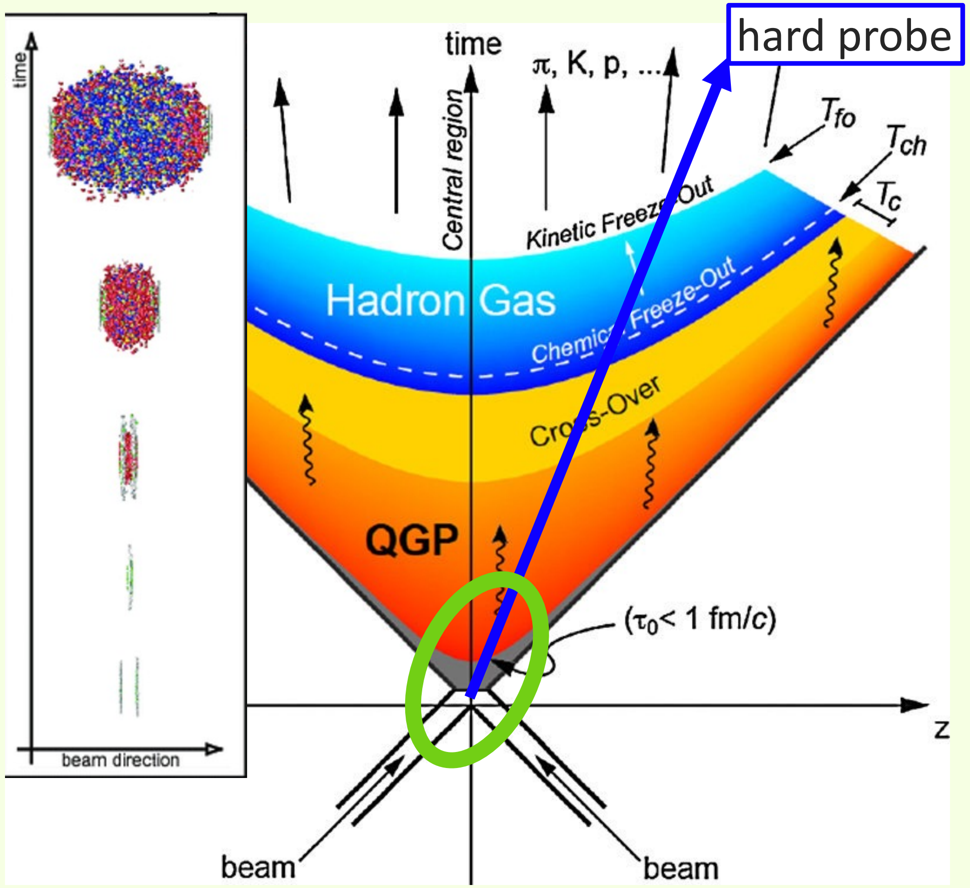
Jet yield measurement [PHYSICAL REVIEW D 100, 092004 (2019)]: The data match the calculation results based on pQCD

Measured by Ritsuya Hosokawa (UGA)

→The hard probes measured in *pp* collisions used as *the reference* for the one measured in PbPb collisions.

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

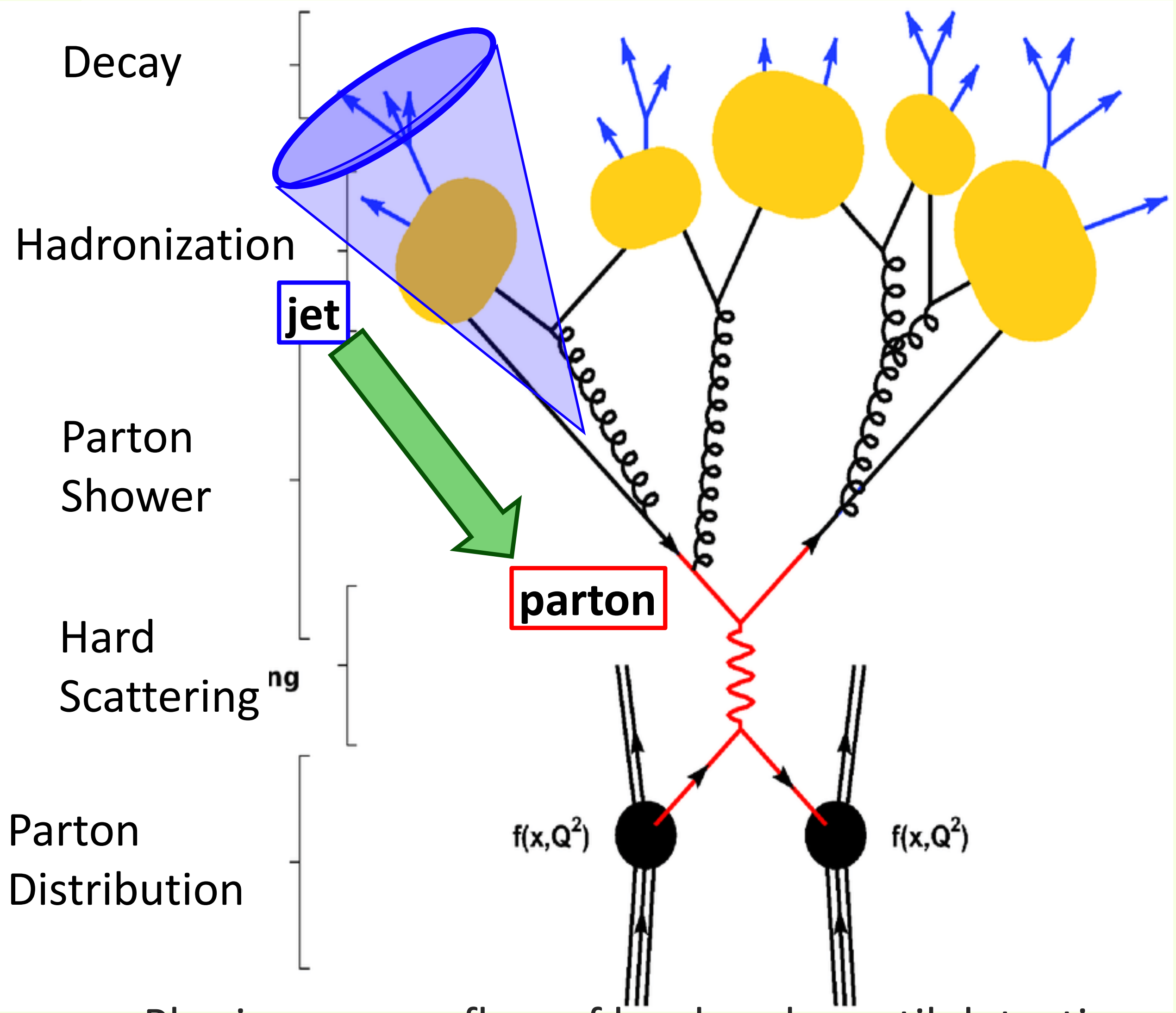
→ The experimental signals of the hard probes have the record of the interaction with the QGP.



What are Jets?

Jets are **hard probes**
<u>- experimental signatures</u> of **quarks or gluons**
→ detected as <u>collimated sprays</u> of hadrons

Reconstruct jets by clustering the hadrons and regarded them as the signal of quarks or gluons.



Physics process flow of hard probe until detection

Physics target: Parton Energy loss mechanism

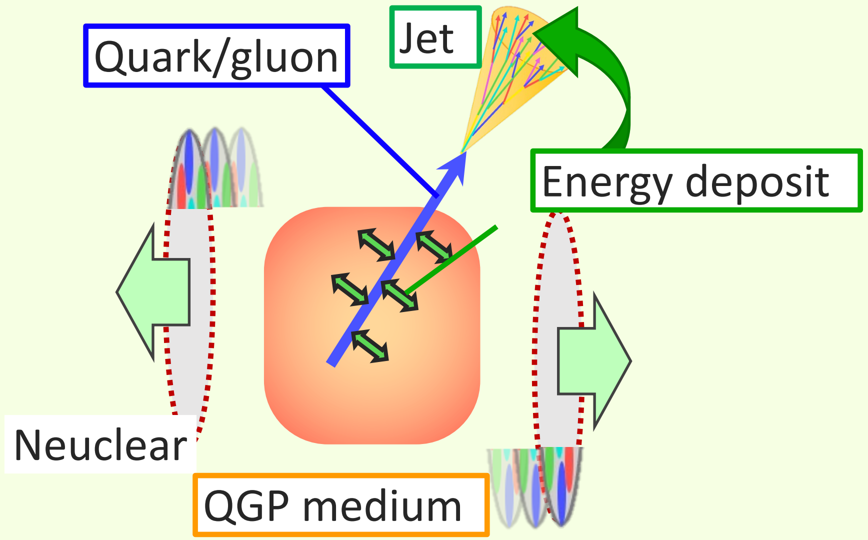
Partons deposit energy in the QGP medium.

Energy loss

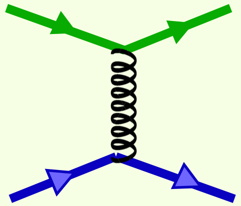
$$\Delta E \propto \hat{q}\boxed{L^n}$$

$\hat{q}$: transport coefficient

L: path length in QGP

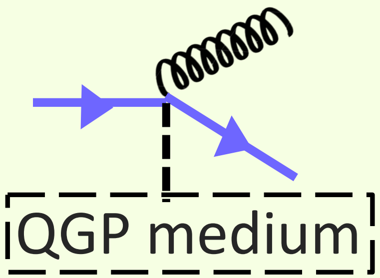


Jet suppression mechanism



Collisional

$\Delta E \propto L$



Radiative

$\Delta E \propto L^2$

AdS/CFT

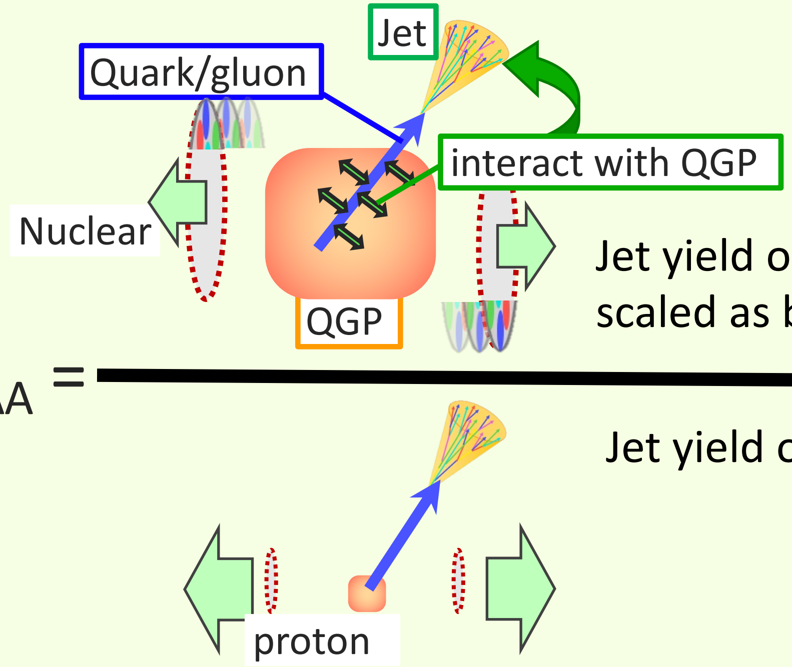
$\Delta E \propto L^3$

There are some jet suppression mechanisms, but the detail ratio of suppression or correct model are not clarified.

Parton Energy Loss Analysis

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

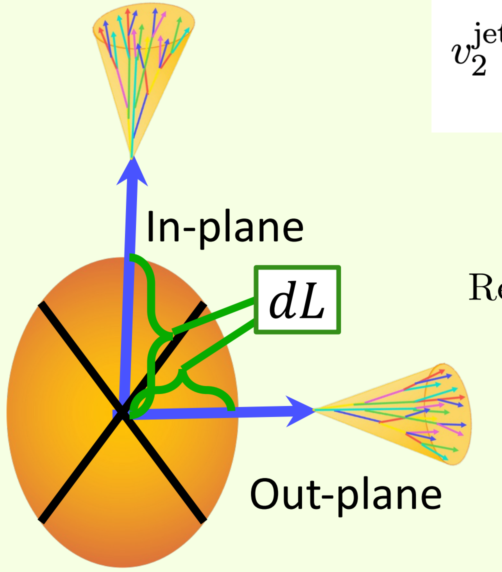
Nuclear modification factor (R_{AA}) is built by comparing *heavy-ion* collisions and *proton* collisitions.



$R_{AA} = \dfrac{\text{Jet yield of Pb-Pb collisions scaled as binomial collision}}{\text{Jet yield of p-p collision}}$

Using the difference between with or without suppression allow to measure the magnitude of suppression.
→ Quantify $\hat{q}$

Jet v_2 is built by comparing in-plane jets and out-of-plane jets.



$$v_2^{\text{jet}} = \frac{1}{\mathrm{Res}\left\{\psi_2^{meas}\right\}} \frac{\pi}{4} \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$

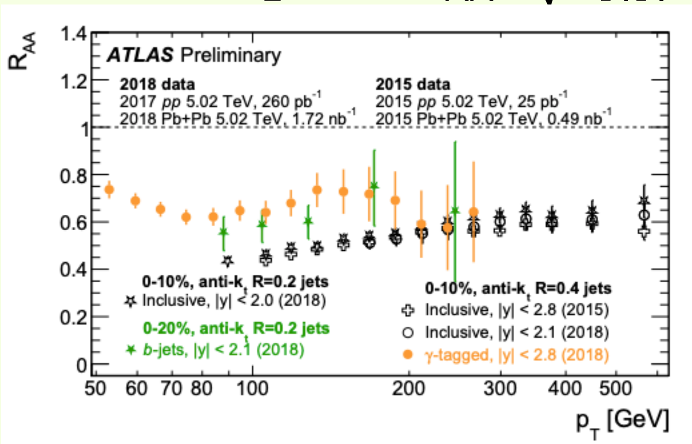
$N_{in},\ N_{out}$: Jet yield at in-plane and at out-of-plane

$\mathrm{Res}\left\{\psi_2^{meas}\right\}$: Event plane resolution

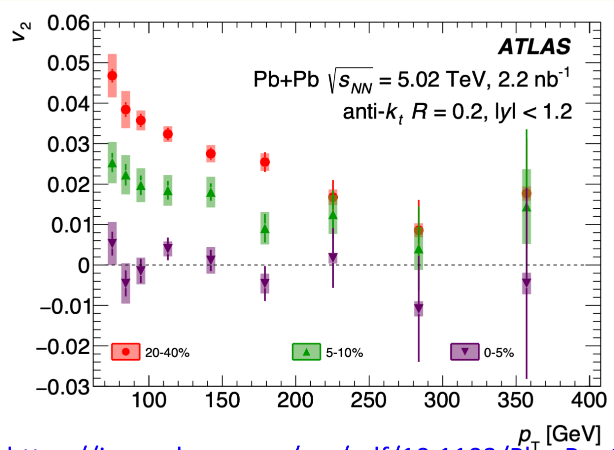
Using difference of the path length between in-plane and out-of plane allows to study L dependency of ΔE.
→ Quantify the power of n

Current study about the energy loss mechanithm

- ALICE jet v_2 ($\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV) and jet R_{AA} ($\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV)
- ATLAS jet v_2 and R_{AA} ($\sqrt{s_{\mathrm{NN}}} = 2.76, 5.02$ TeV)



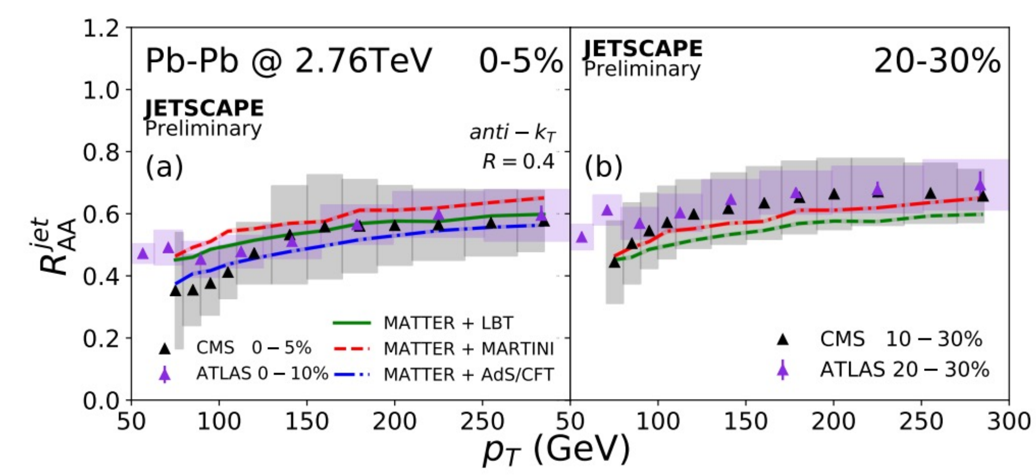
https://cds.cern.ch/record/2853755/files/ATL-PHYS-PUB-2023-009.pdf

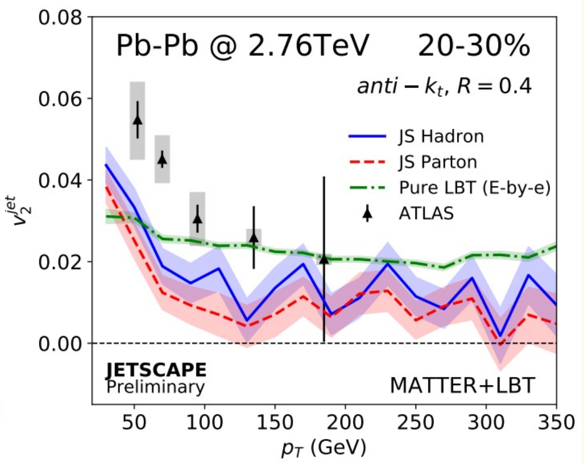


https://journals.aps.org/prc/pdf/10.1103/PhysRevC.105.064903

- JETSCAPE

(Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope):
Model simulation framework





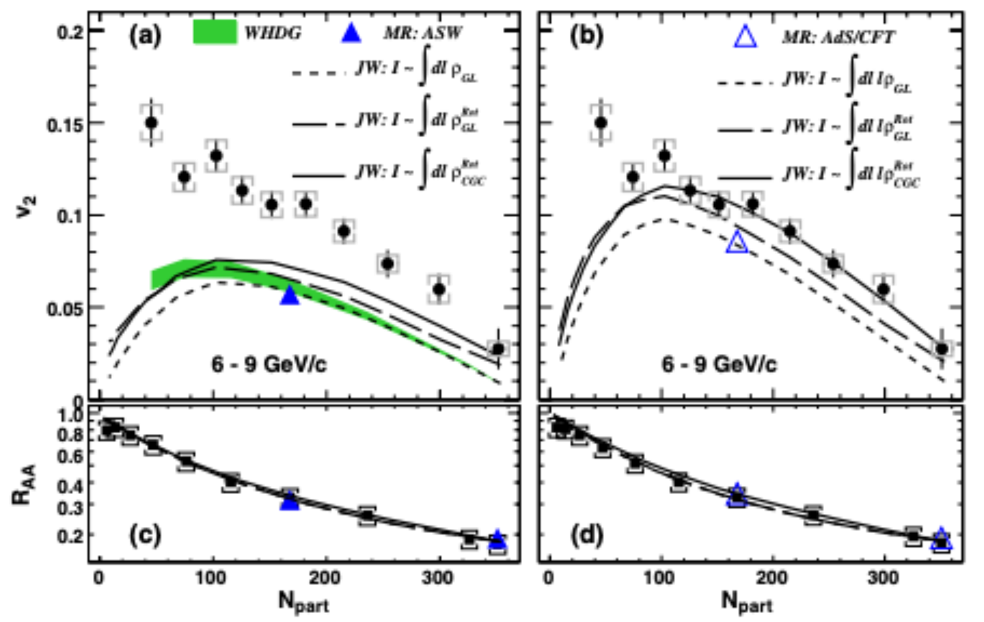
New points of my study for Energy loss ($\Delta E \propto \hat{q}\, L^n$)

- Simultaneous measurement of charged jet v_2 and R_{AA} → Expect strong model constraints and acquire accurate suppression parameter values.
- New collisional energy data ($\sqrt{s_{\rm NN}} = 5.02$ TeV) as ALICE measurement
- Use JETSCAPE model simulation framwork

→ It has $\hat{q}$ as a variable parameter.

→ It has some models having different the power of n for L.

v_2 and R_{AA} of π^0 measurement using PHENIX $\sqrt{s_{\rm NN}} = 200$ GeV data (2010)



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

Analysis Flow

Raw Jet task

Raw Jet inclusive

Event Plane

- Raw Jet in-plane
- Raw Jet out-of-plane

Qn vector calibration

- V0A, V0C, V0M
- TPC ($\eta<0$), TPC ($\eta>0$)

Unfolding

RM

RM

RM

Embedding

Response Matrix (RM)

Jet energy scale shift

Kinematic efficiency

Result

Jet R_{AA}

Jet v_2

Systematic Uncertainty

- p_T cut / p_T range
- Unfolding way
- Background Estimation way

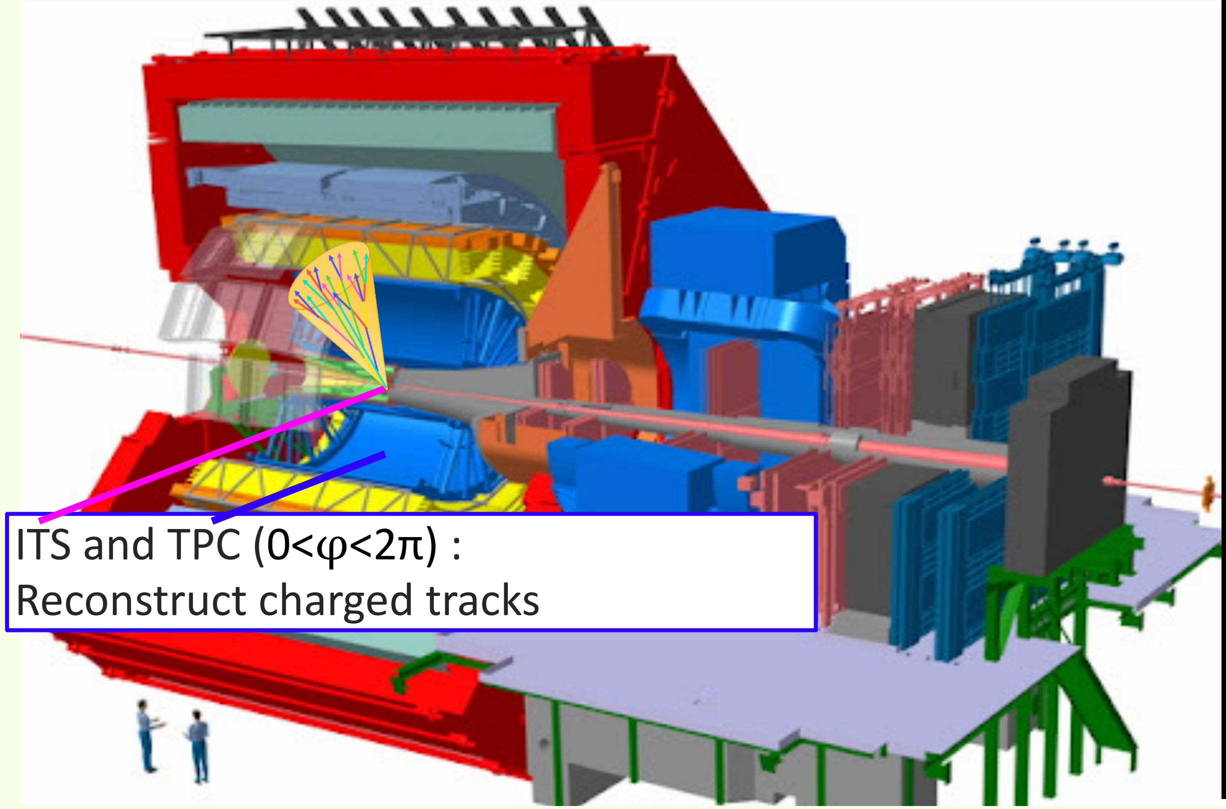
Model

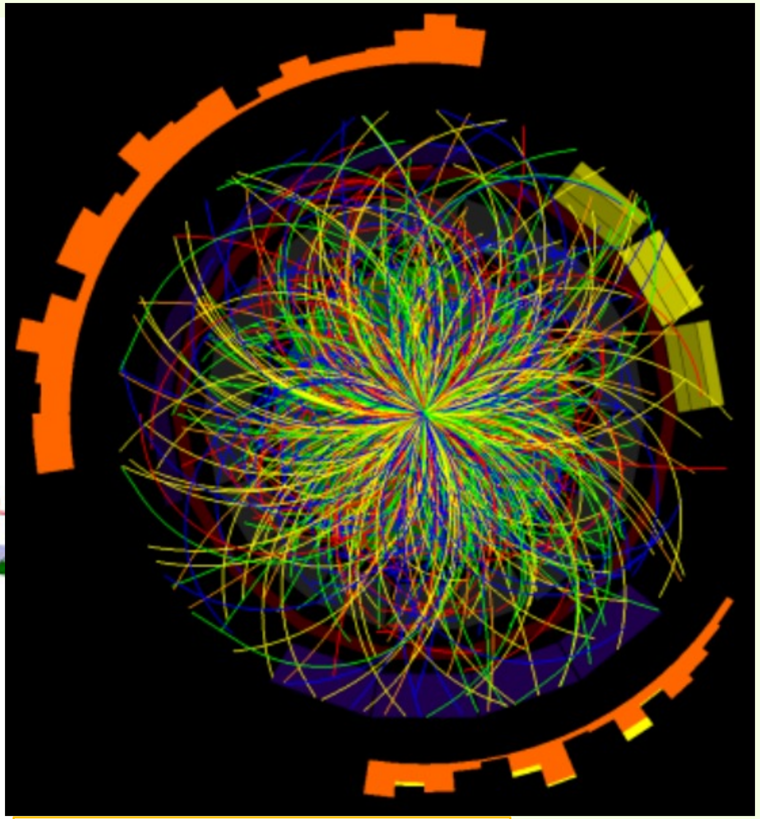
- JETSCAP

Energy loss

$$\Delta E \propto \hat{q} L^n$$

Charged jet





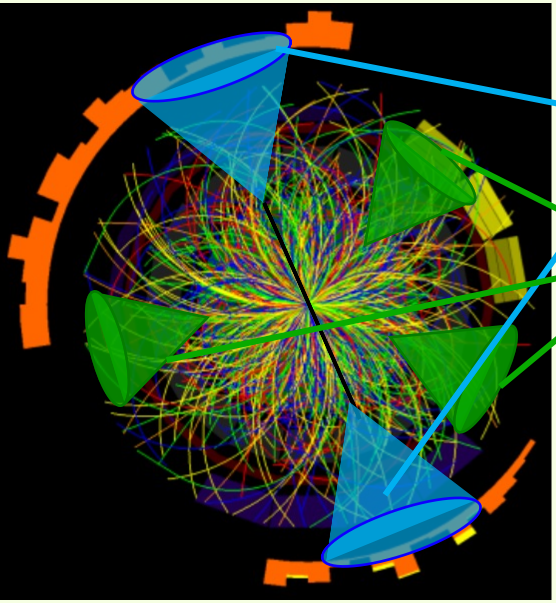
Reconstructed tracks

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

Clustering track p_T in resolution pamareter (R) range.

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

Background p_T distribution (ordinary inclusive jet way)



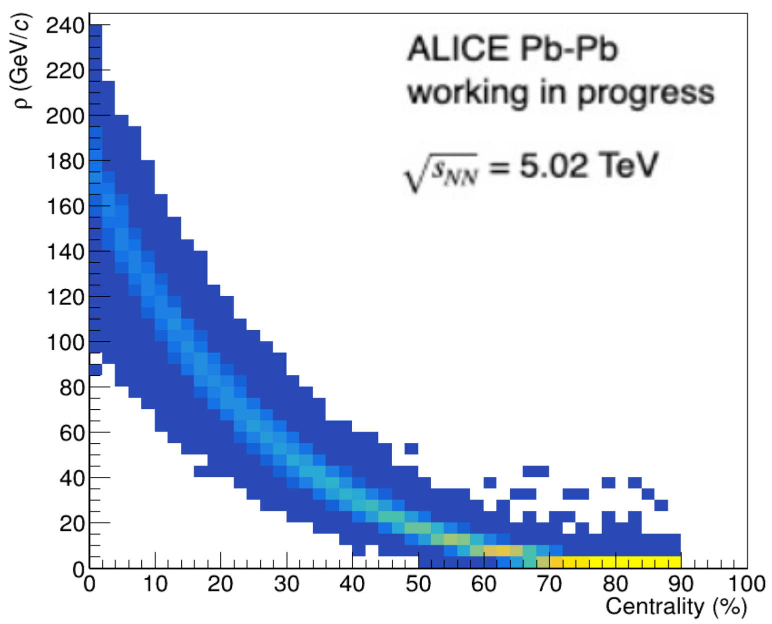
In HIC, a huge number of particles are produced.

→ Signal jets are reconstructed with the background particles.

→Estimate background p_T density (ρ) except for jet area to subtract the background from the signal jets

$$\rho = \mathrm{median}(p_{\mathrm{T},i}/A_i)$$ A : cluster area, i: cluster id

background p_T for centrality



ρ is considered uniform and determined event by event

→ subtract the background from each jet

$$\boxed{p_{\mathrm{T,corr}}^{\mathrm{jet}} = p_{\mathrm{T}}^{\mathrm{jet}} - \rho A}$$

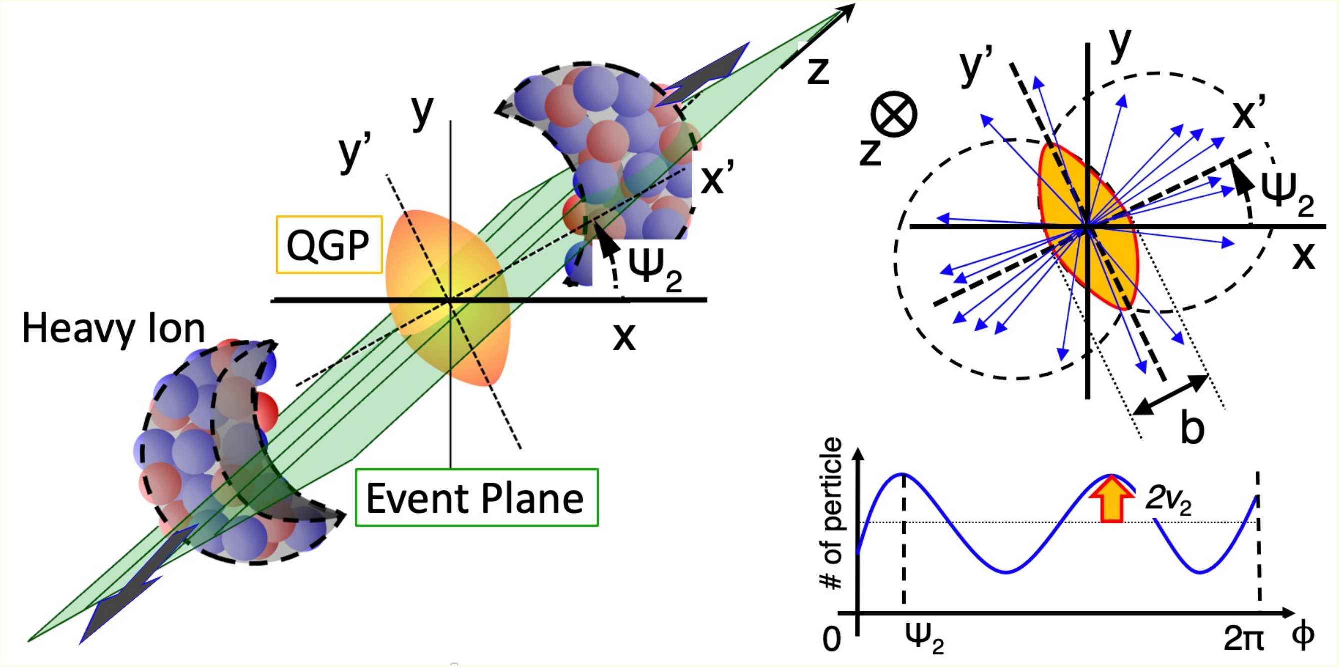
A : jet area

Flow vector from detector measurement

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

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

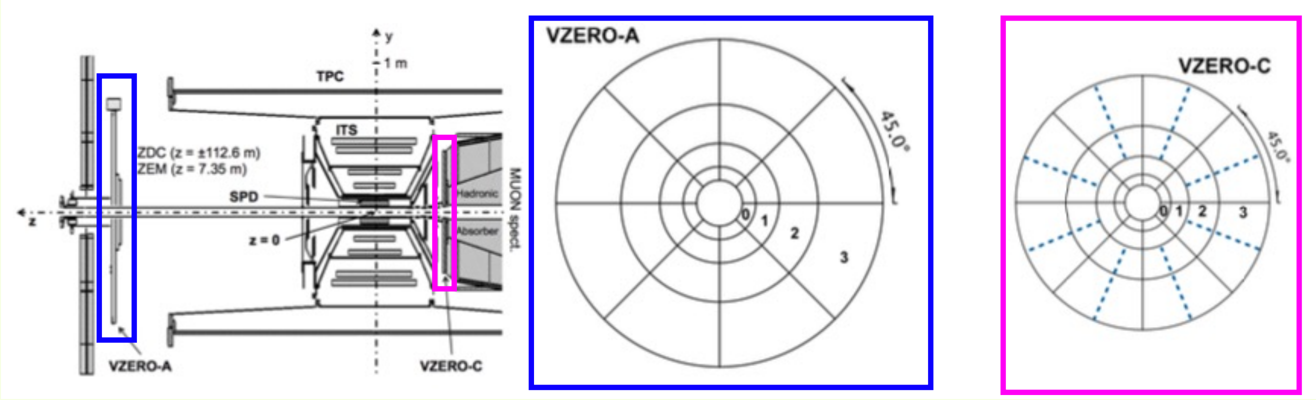
(ϕ_i : Track angle, ω_i :multiplicity weight, n: Fourier order)



Event Plane

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

Qn vector calibration

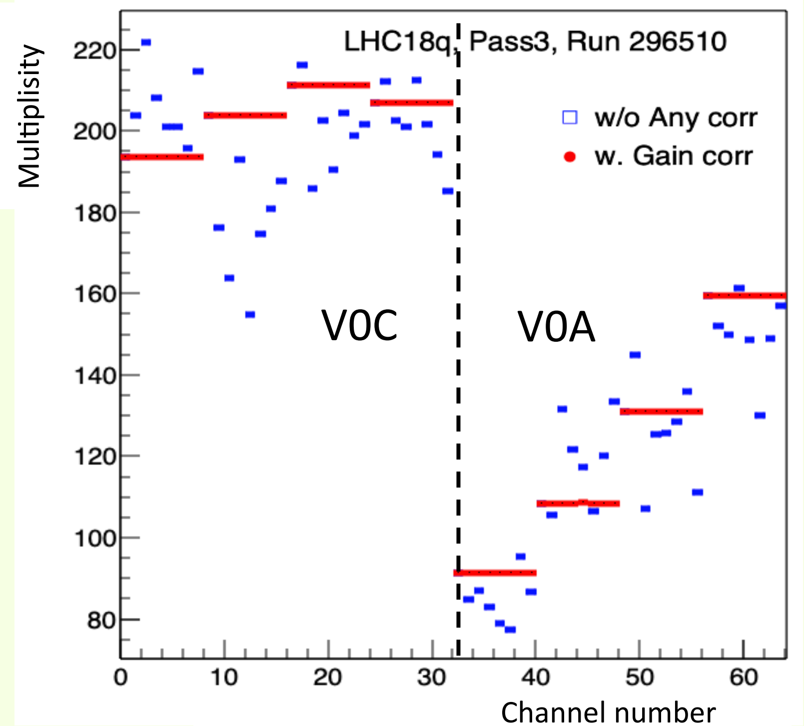


esimated for run-by-run.
Average means the run average.

Gain equalization

$$\omega_{\mathrm{ch}} = M_{\mathrm{i}} \boxed{\frac{\langle M_{\mathrm{ref}} \rangle}{\langle M_{\mathrm{i}} \rangle}}$$

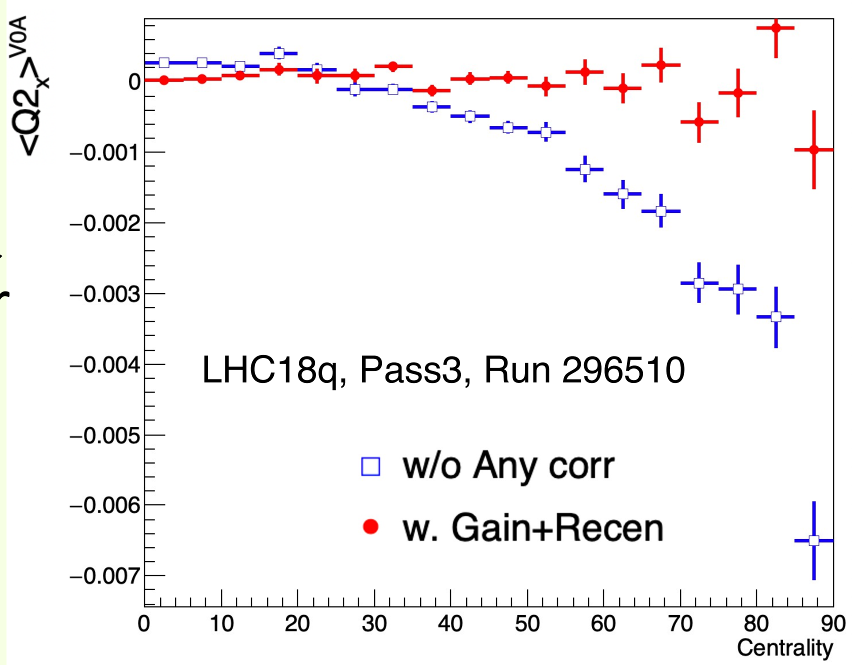
Equalizate gain to uniform the each channel value on the same ring.



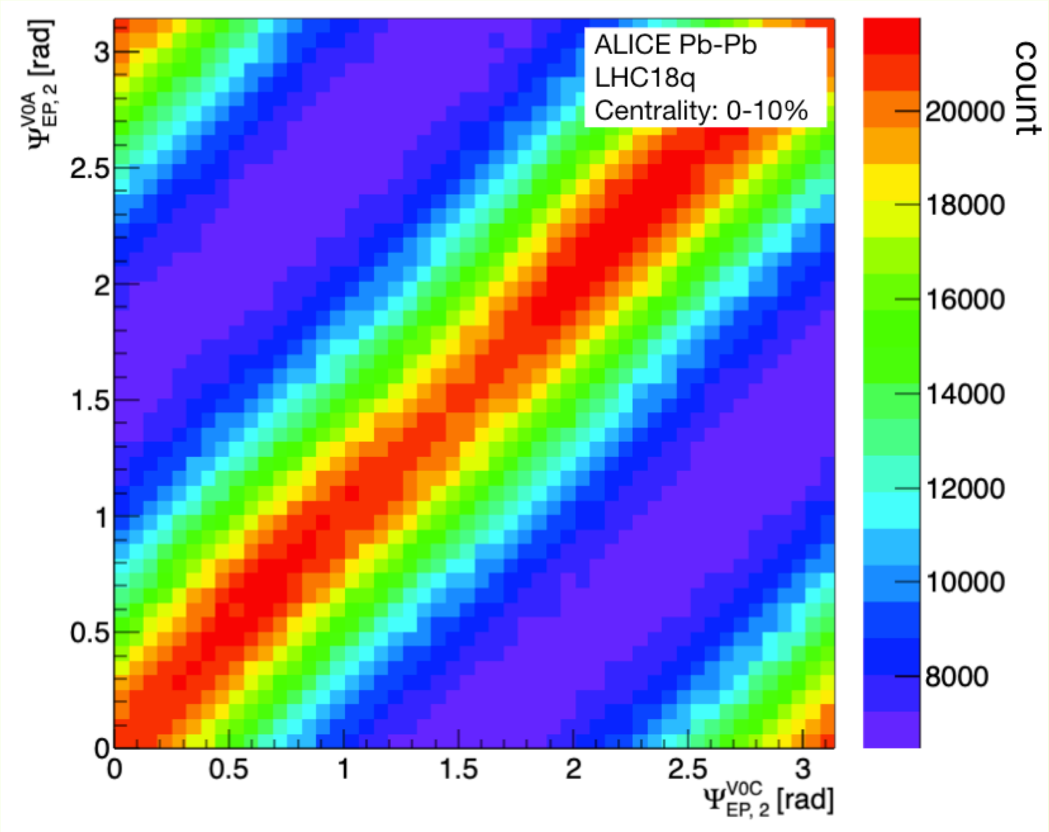
Recentring

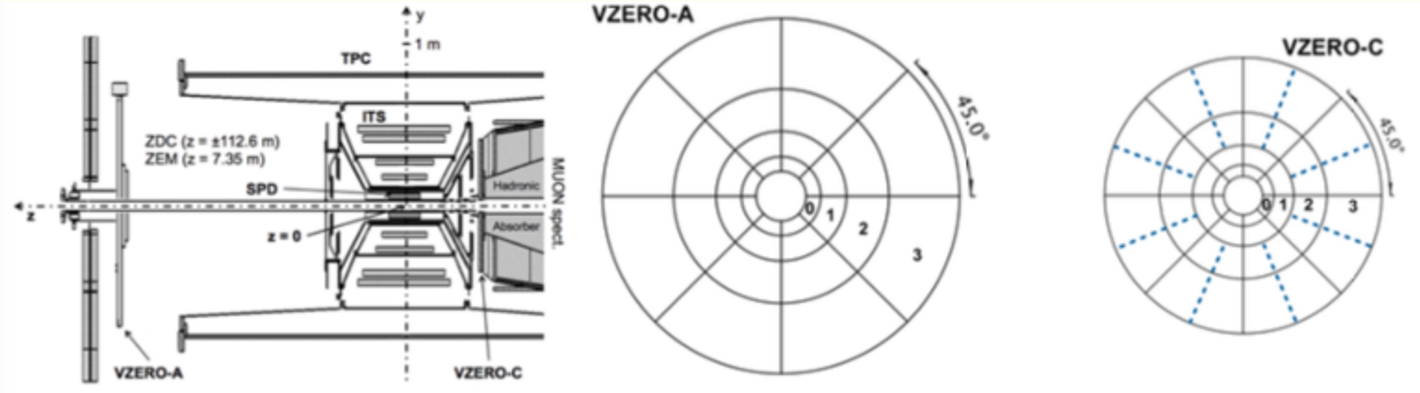
$$\boldsymbol{Q'}_n = \boldsymbol{Q}_n - \boxed{\langle \boldsymbol{Q}_n \rangle}$$

Equalizate $\boldsymbol{Q}_n$ to uniform for centrality



Calibration of estimated event plane anlgle between V0C and V0A





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

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

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

The correlation seems correct.

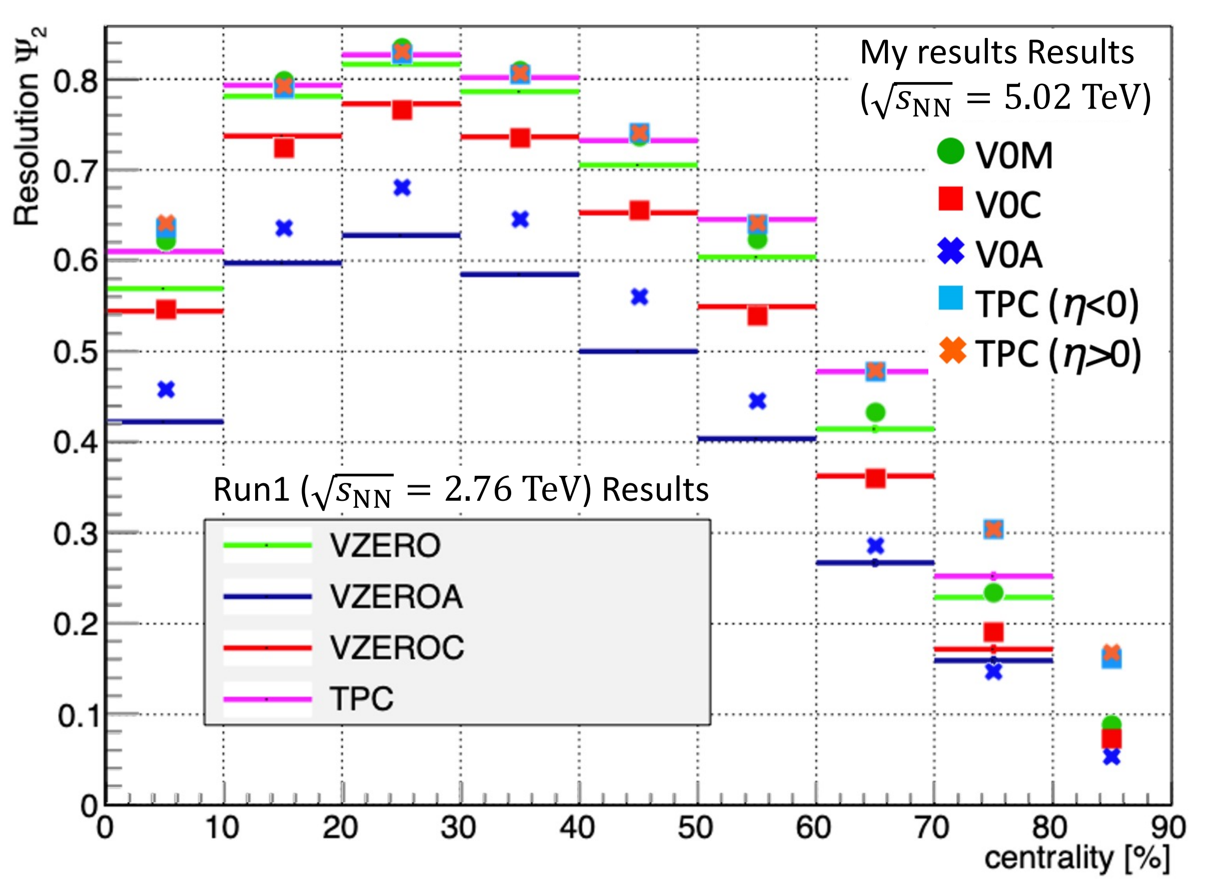
Event plane angle resolution

$$\mathrm{Res}\{\Psi_{\mathrm{EP},2}^{\mathrm{meas}}\} = \langle\cos(n[\Psi_{\mathrm{EP},n}^{\mathrm{a}} - \Psi_n])\rangle = \sqrt{\frac{\langle\cos(n[\Psi_{\mathrm{EP},n}^{\mathrm{a}} - \Psi_{\mathrm{EP},n}^{\mathrm{b}}])\rangle\langle\cos(n[\Psi_{\mathrm{EP},n}^{\mathrm{a}} - \Psi_{\mathrm{EP},n}^{\mathrm{c}}])\rangle}{\langle\cos(n[\Psi_{\mathrm{EP},n}^{\mathrm{b}} - \Psi_{\mathrm{EP},n}^{\mathrm{c}}])\rangle}}$$

$$v_2^{\mathrm{jet}} = \frac{1}{\boxed{\mathrm{Res}\{\Psi_{\mathrm{EP},2}^{\mathrm{meas}}\}}}\frac{\pi}{4}\frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$

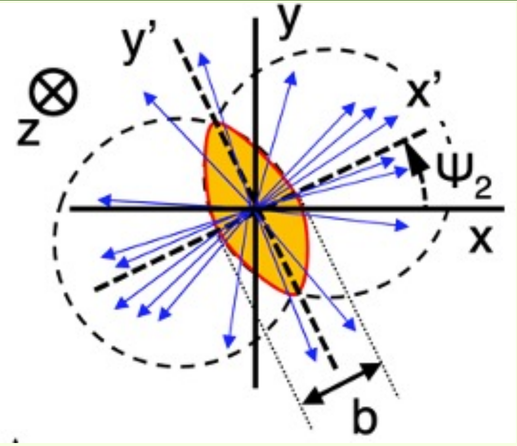
Ideally, $\Psi_{\mathrm{EP},n}^{\mathrm{a}} - \Psi_{\mathrm{EP},n}^{\mathrm{truth}}$ close to 0.
In that case, $\mathrm{Res}\{\Psi_{\mathrm{EP},2}^{\mathrm{meas}}\}$ close to 1.

V0 sub-detector
(b: TPC $\eta<0$, c: TPC $\eta>0$)
TPC sub-detector
(b: V0C, c: V0A)

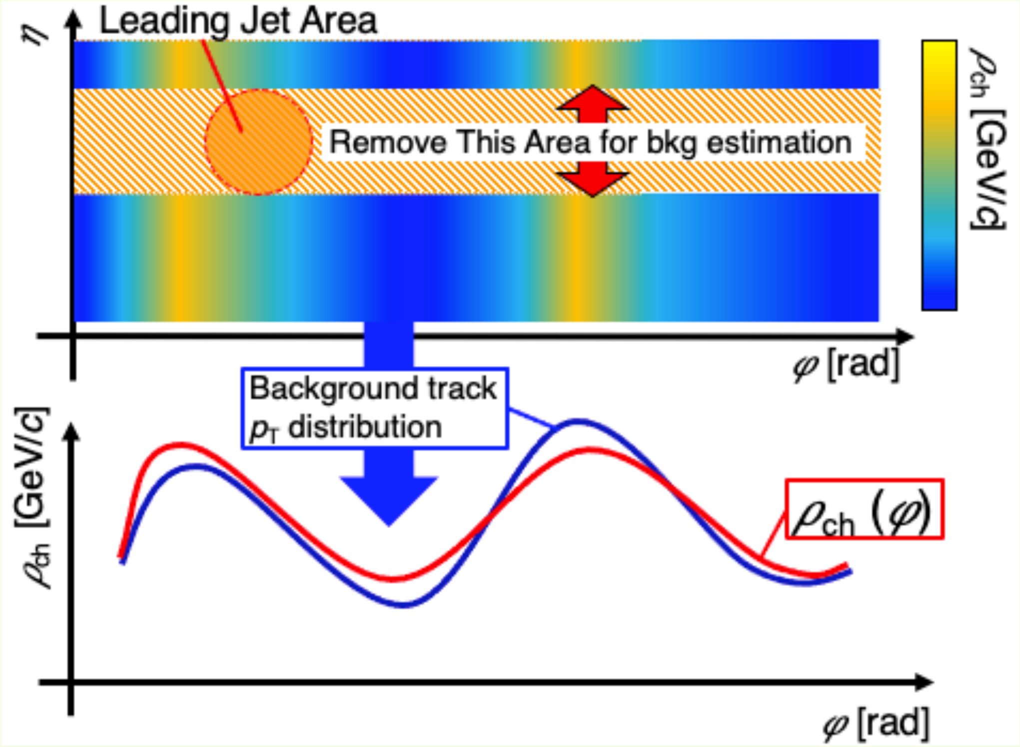


Both side TPC resolutions are matched. → It is reasonable.

The soft particle background is **not uniform** for azimuthal angle (φ).
→The background calculation should take the φ dependency into account.



The local rho is estimated using tracks except the leading jet η region. (Because of the statistic problem, it includes the sub-leading jet region.)



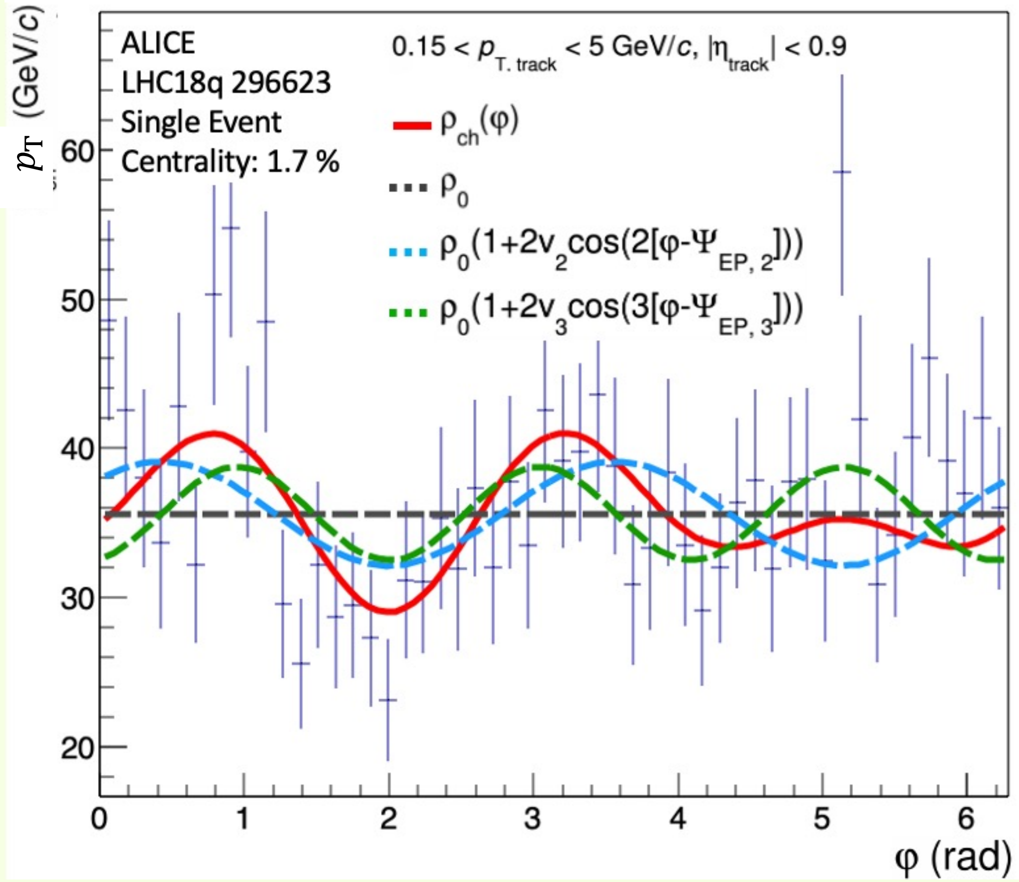
In this analysis, a following equation is used.

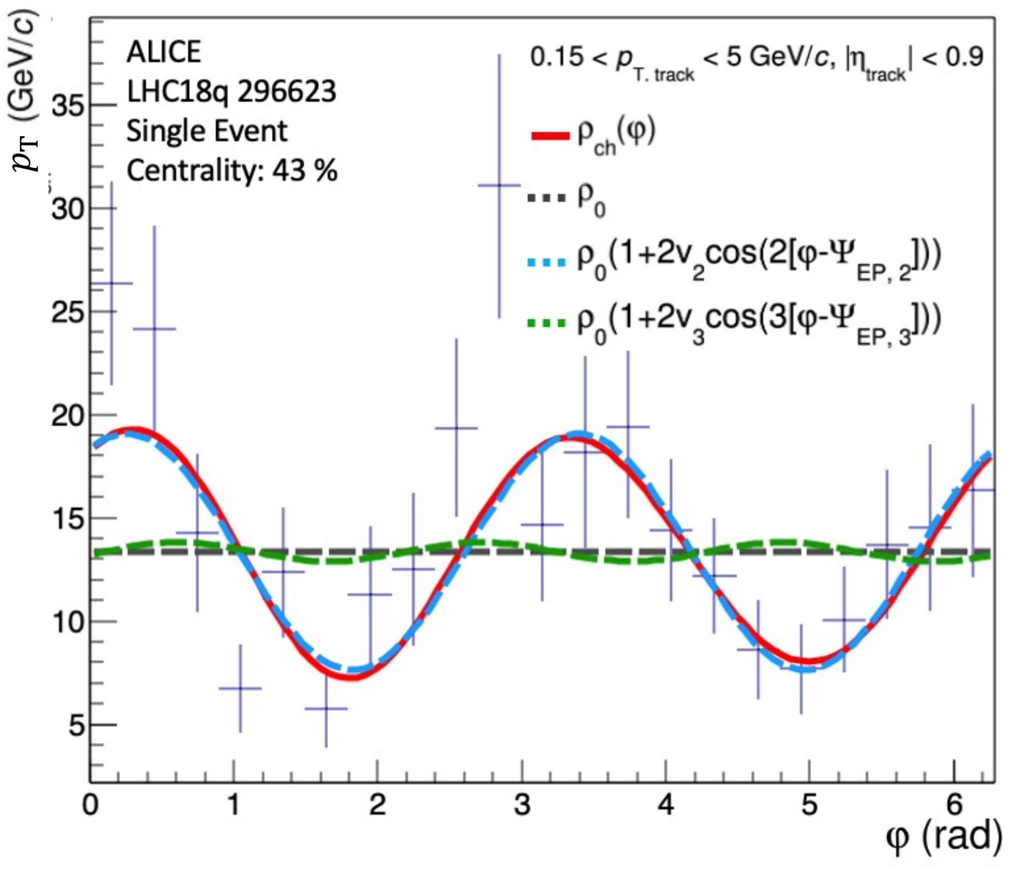
$$\rho_{ch}(\varphi) = \rho_0 \times \left(1 + 2\left\{v_2^{obs}\cos(2[\varphi - \Psi_{EP,2}]) + v_3^{obs}\cos(3[\varphi - \Psi_{EP,3}])\right\}\right)$$

$\Psi_{EP,2}$ and $\Psi_{EP,3}$ are calculated by the Qn vectors.
And ρ_0, v_2^{obs}, and v_3^{obs} are fitting value.

Local background p_T results

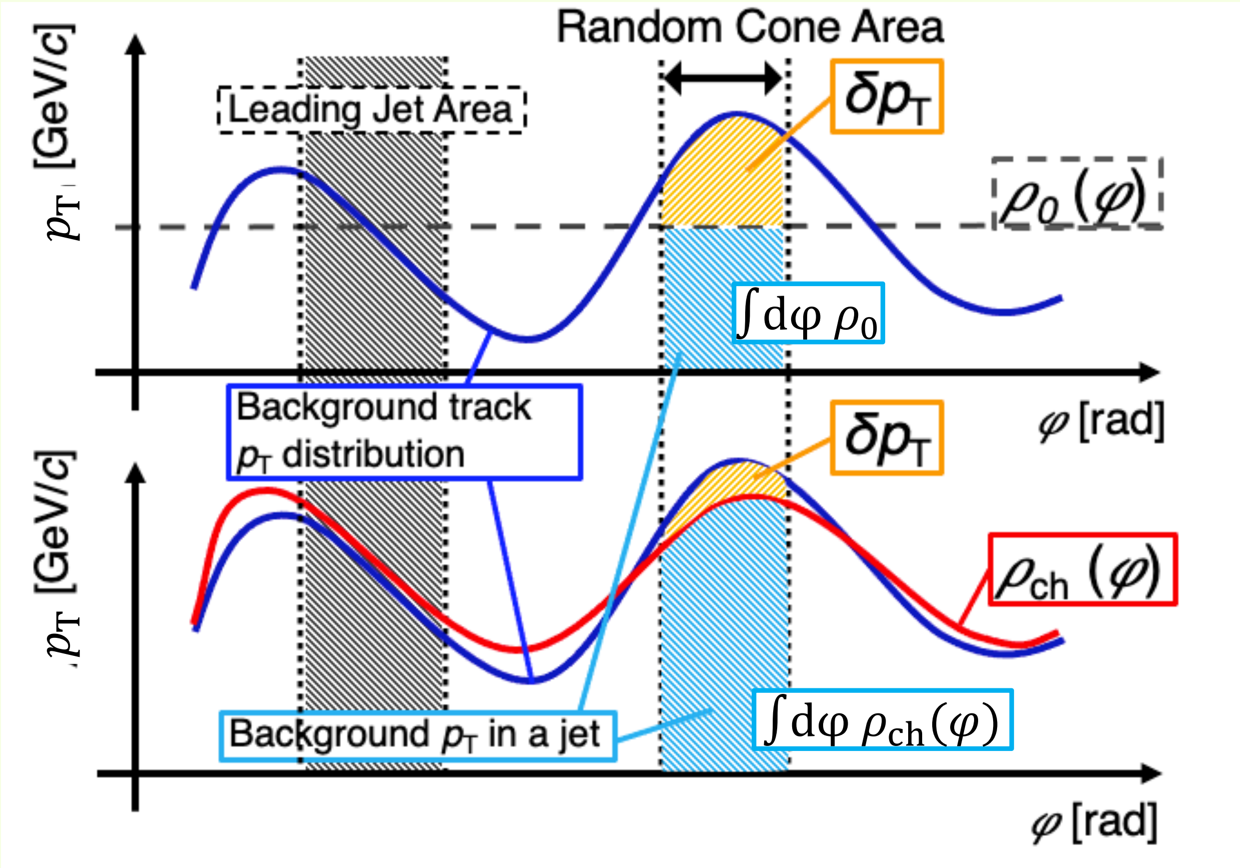
$$\rho_{ch}(\varphi) = \rho_0 \times \left(1 + 2\left\{v_2^{obs}\cos(2[\varphi - \Psi_{EP,2}]) + v_3^{obs}\cos(3[\varphi - \Psi_{EP,3}])\right\}\right)$$





# of bins = $\sqrt{N_{\mathrm{track}}}$

Evaluation of background fit (δp_T)

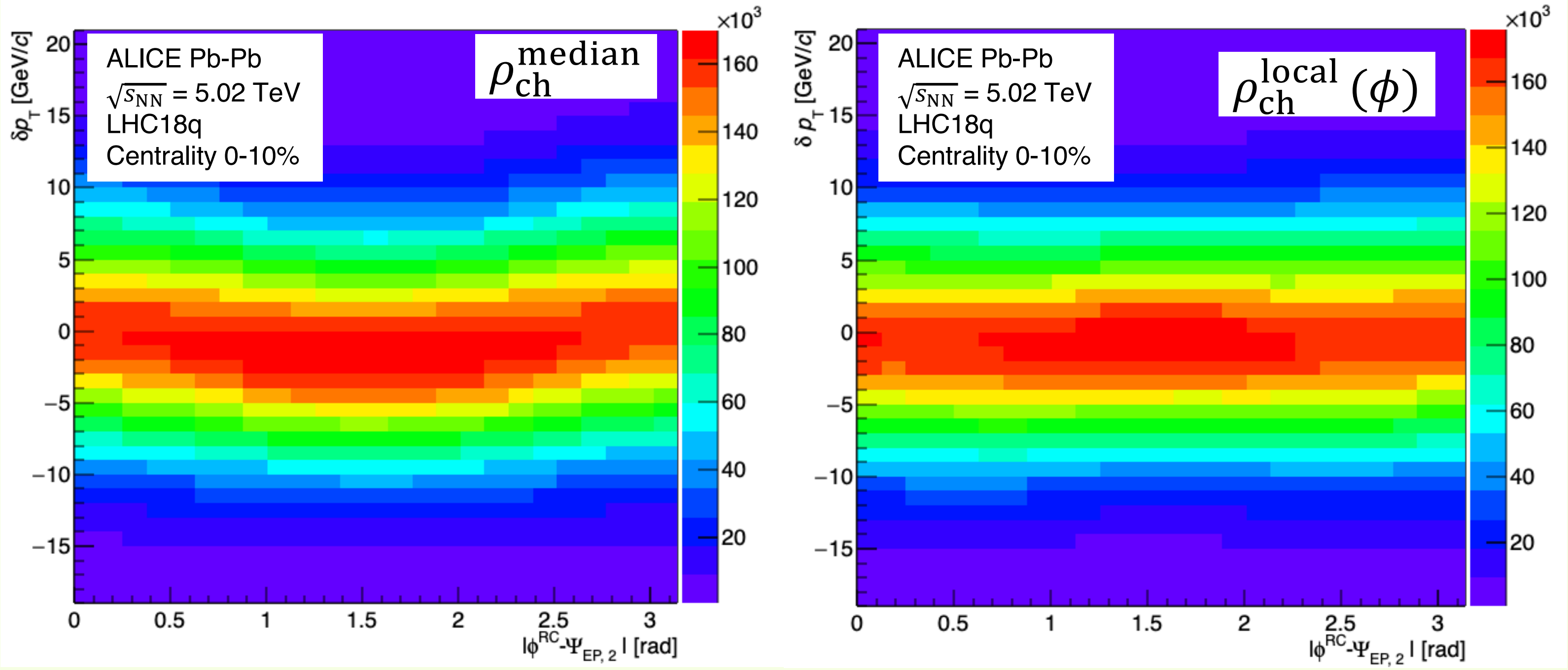


δp_T is a gap between integration of background tracks p_T and integration of background function in a random cone area.

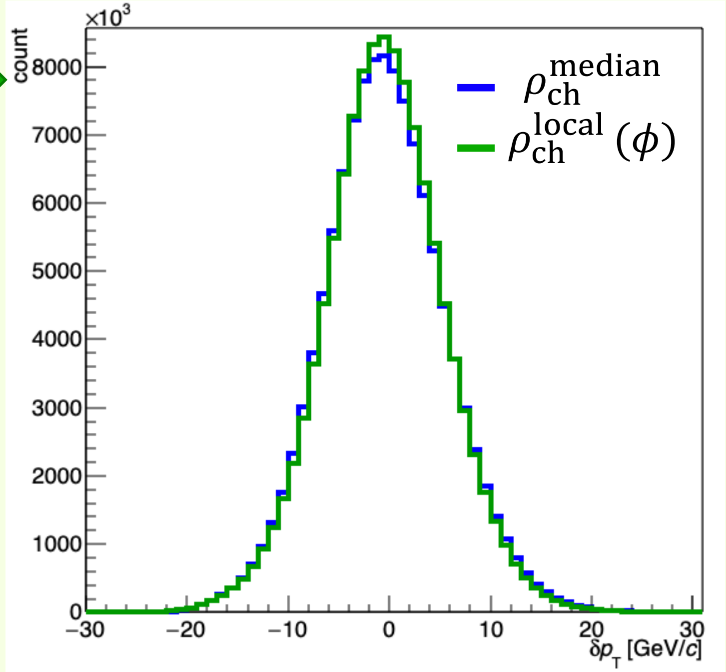
We expect the local rho's δp_T should be smaller than the median one.
And in the local rho case, δp_T phi dependency is expected to make small.

The Random cone is created once per event except the leading jet region.

The background δpT distribution

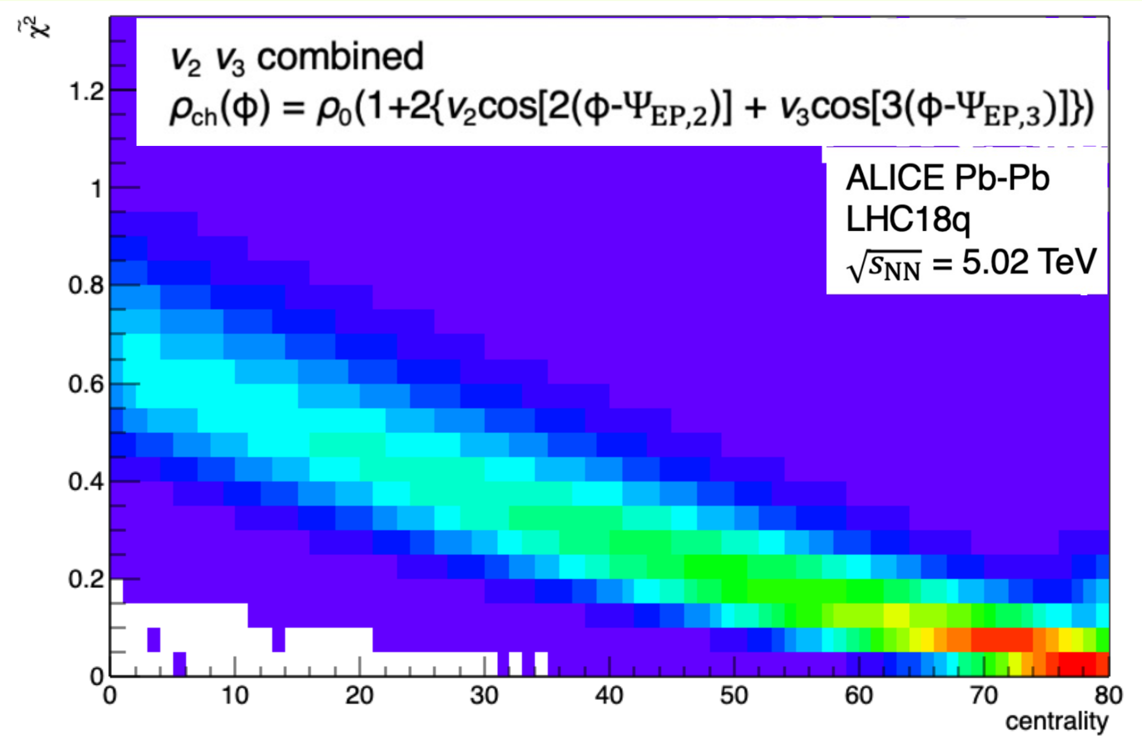


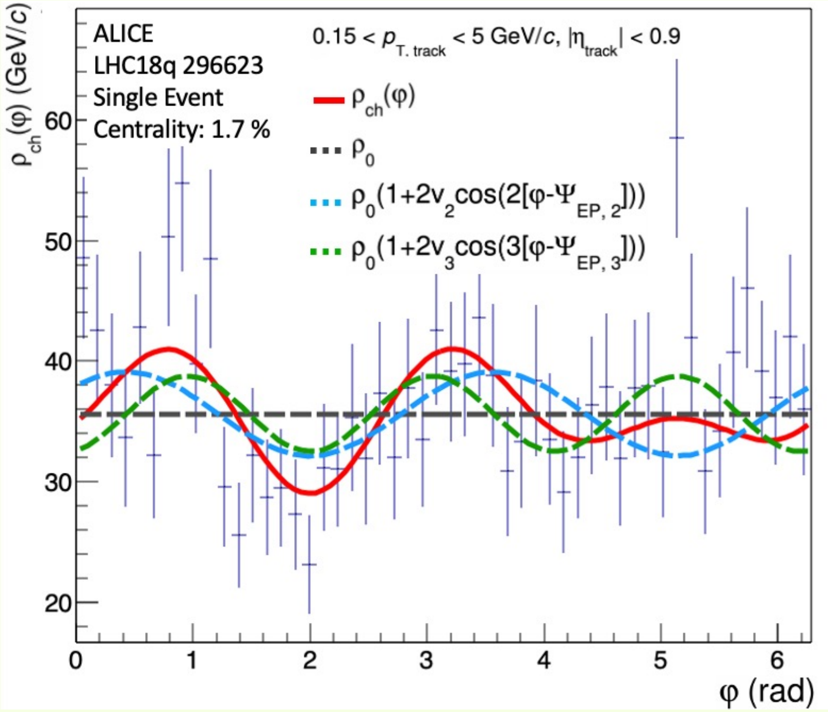
Projection on y axis



As expected, the median rho has ϕ dependency and the local rho makes smaller the ϕ dependency. Furthermore, the dispersion of local rho background is more narrow than median rho. And these same tendency is seen in the all centrality regions.

Background pT function fit quality





$$\tilde{\chi}^2 = \left(\sum_{n=0}^{i} \frac{\left(p_T^{\mathrm{track}} - p_T^{\mathrm{function}}\right)^2}{p_T^{\mathrm{track}}}\right) \Big/ (\#\ \mathrm{of\ bins} - 3)$$

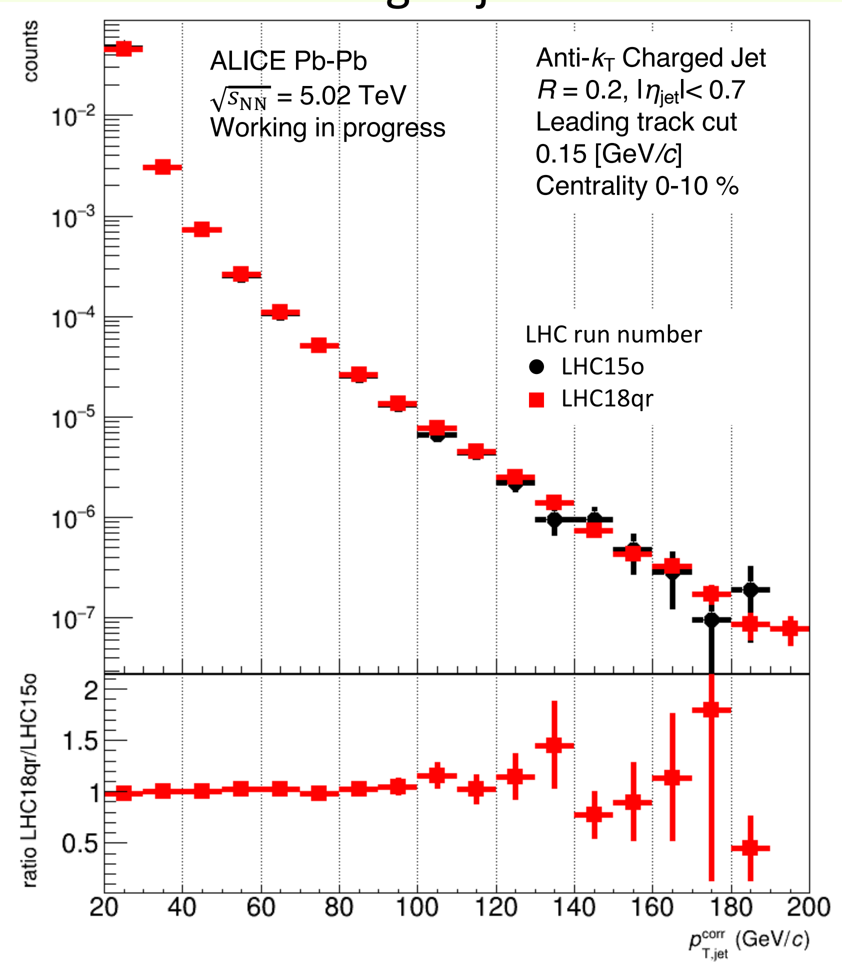
\# of free parameters (ρ_0, v_2, v_3)

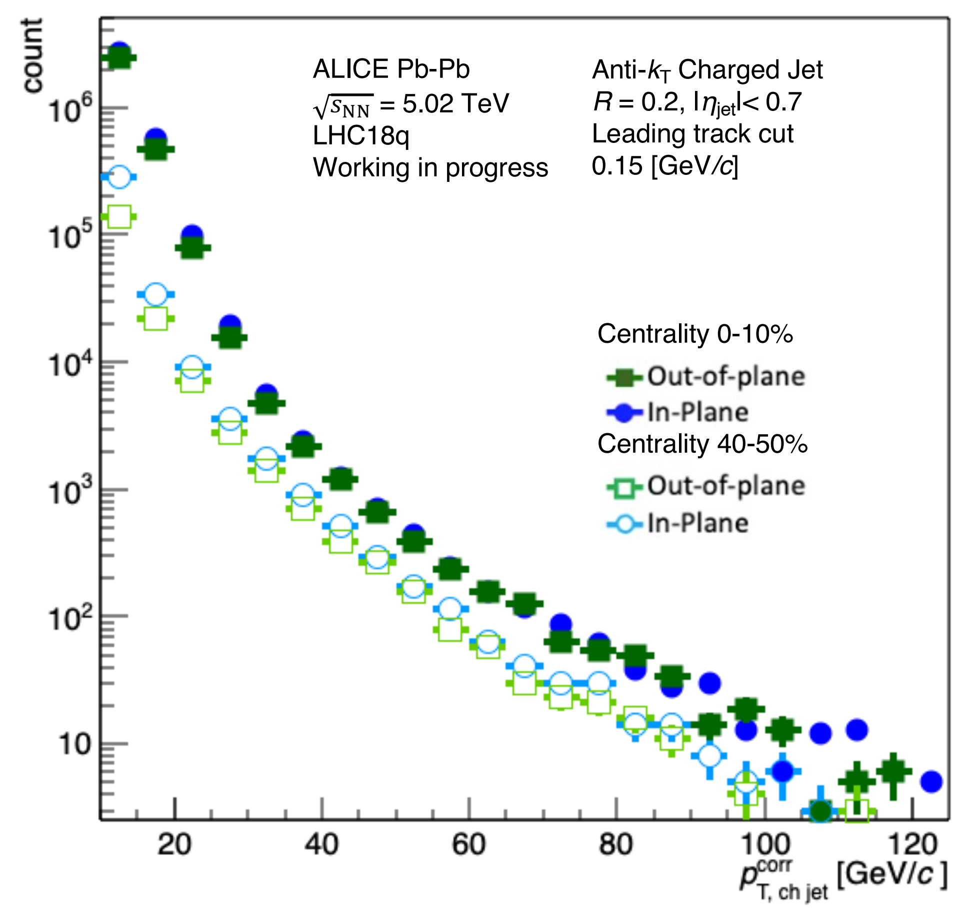
$\tilde{\chi}^2$ is smaller than 1. → Fitting quality is good.

Raw Jet Spectrum

Corrected Raw jet pT distribution (w/o unfolding): $p_{\mathrm{T}}^{raw} - \rho(\phi)A$

Different run periods comparison
for inclusive charged jet

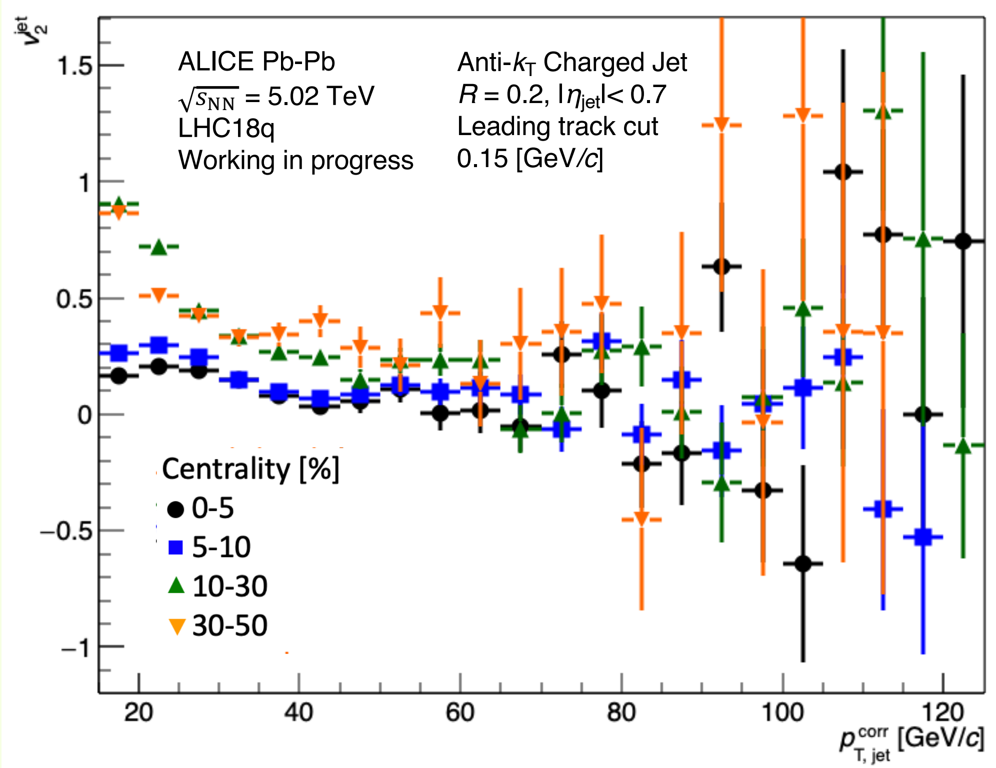




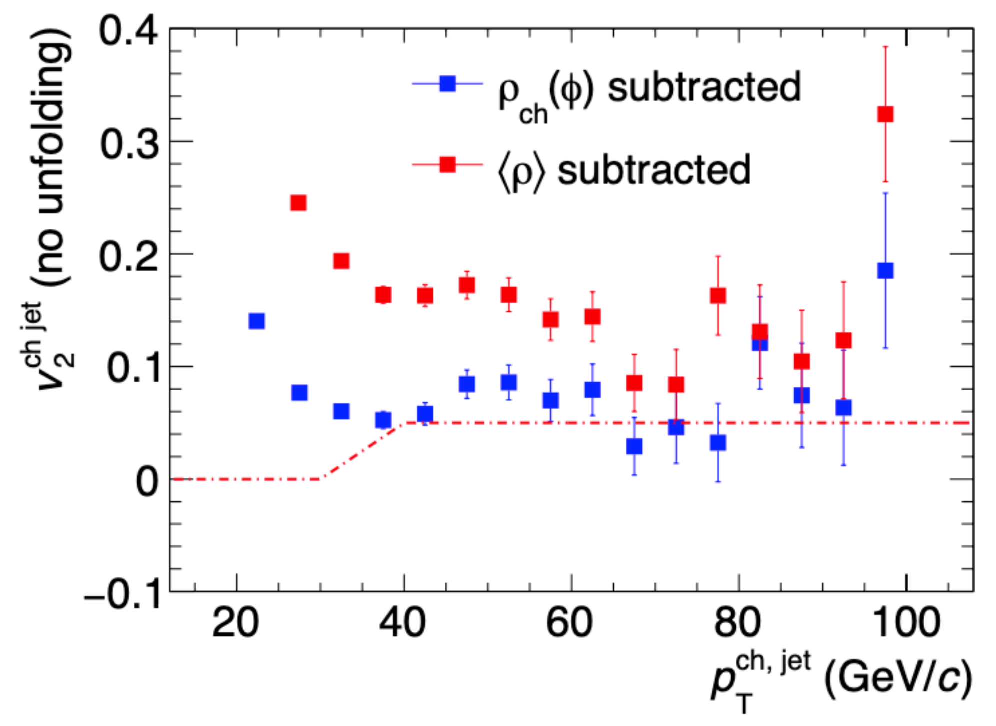
Out-Plane jets are more suppressed than In-plane ones for each centrality.

Raw charged jet v_2 (R=0.2)

$$v_2^{\rm jet} = \frac{1}{{\rm Res}\{\psi_2^{meas}\}} \frac{\pi}{4} \frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$



Run1 ($\sqrt{s_{\rm NN}} = 2.76$ TeV) Result (centrality ?)



Value of jet v2 is close to Run1 ($\sqrt{s_{\rm NN}} = 2.76$ TeV) results.
And the shape around 20 – 60 GeV/c is also similar with Run1 results.

Study Plan

Raw Jet task

Raw Jet inclusive

Event Plane

- Raw Jet in-plane
- Raw Jet out-of-plane

Qn vector calibration

- V0A, V0C, V0M
- TPC ($\eta<0$), TPC ($\eta>0$)

Unfolding

RM

RM

RM

Result

Jet R_{AA}

Jet v_2

Systematic Uncertainty

- p_T cut / p_T range
- Unfolding way
- Background Estimation way

May - Jun

Embedding

<u>Response Matrix (RM)</u>

Jet energy scale shift

Kinematic efficiency

Already prepare code

- Middle May

Model

- JETSCAP

Jun - Sep

Energy loss

$\Delta E \ \propto \hat{q}L^n$

Already started to write thesis. I target the date of the defence is middle of March.