中国科学技术大学博士学位论文开题报告

J/ψ azimuthal anisotropy measurement in pp collisions at $\sqrt{s}$=13.6 TeV with ALICE

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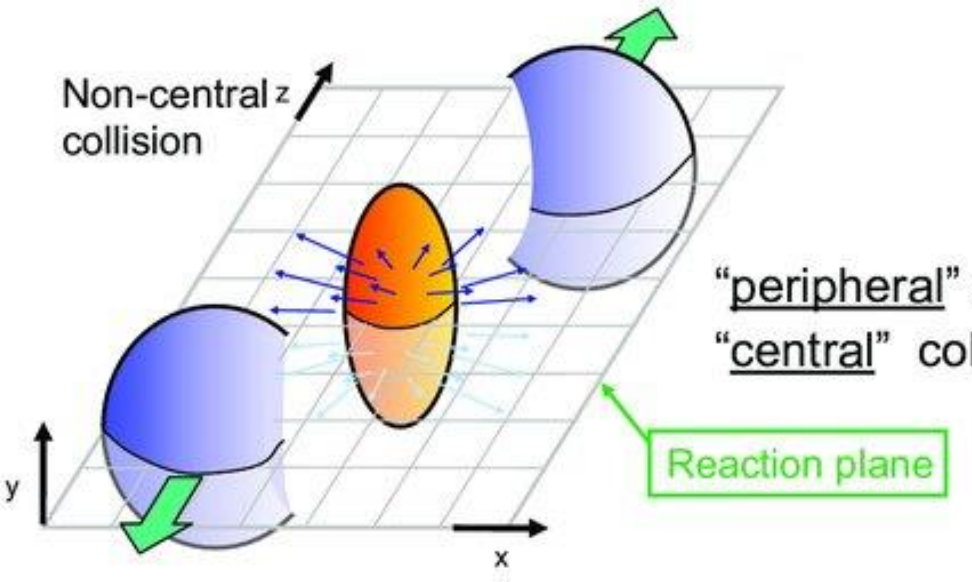
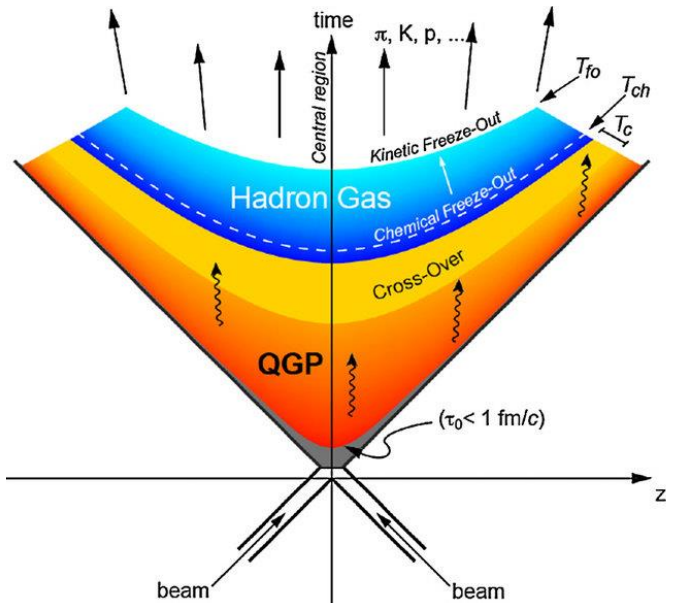
Azimuthal anisotropy at peripheral heavy ion collisions



"peripheral" collision ($b \sim b_{max}$)
"central" collision ($b \sim 0$)

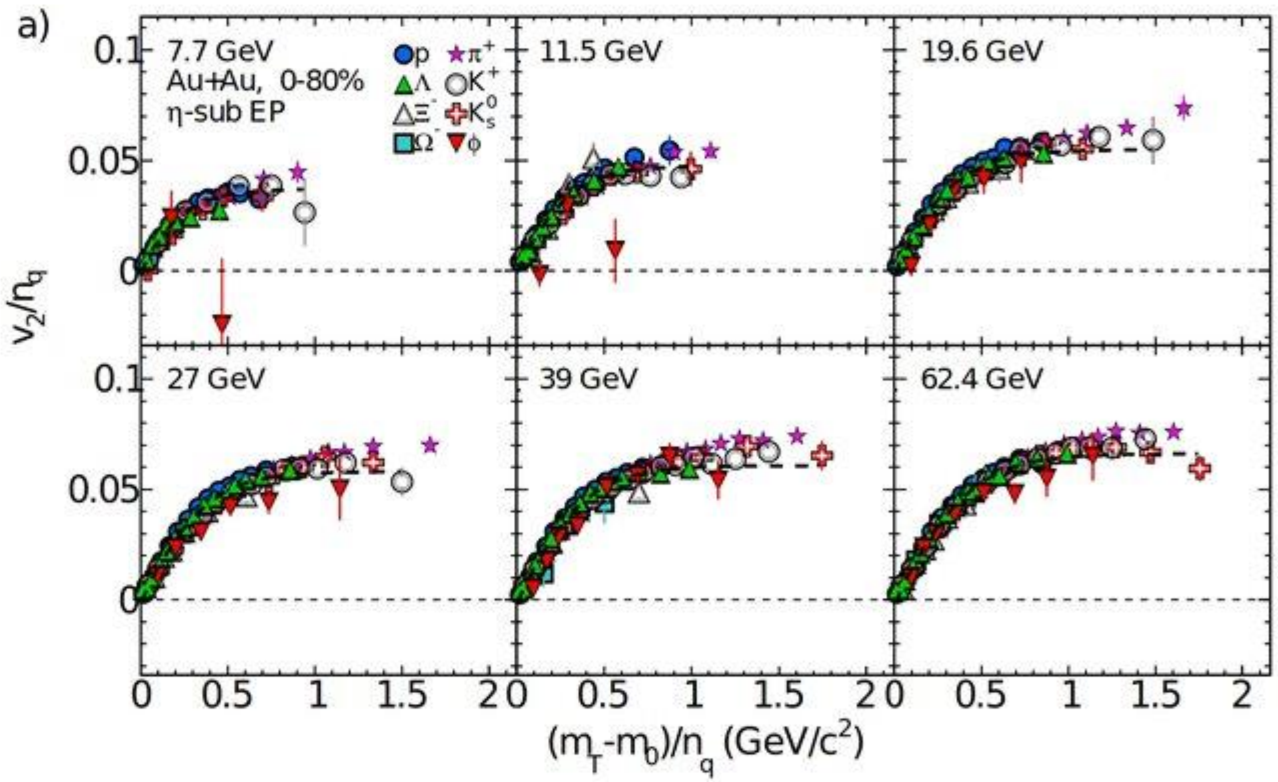


- Peripheral heavy ion collisions
  1. Large energy is deposited in a system with initial space azimuthal anisotropy.
  2. Created medium are heated and **finally thermalized.**
     → Quark gluon plasma is formed. Quarks and gluons are deconfined. **Parton freedom degree is released.**
     → Initial space azimuthal anisotropy is transferred to **momentum azimuthal anisotropy** via strong coupling.
  3. System cools down and deconfined partons hadronized and fragmented into hadrons.
     → Final states, hadrons from partons, inherit **momentum azimuthal anisotropy** from thermalized partons.

Observation

$$f(\phi) = \frac{1}{2\pi}(1 + 2\Sigma_{n=1}^{\infty} v_n cos(n(\phi - \Psi_{EP})))$$

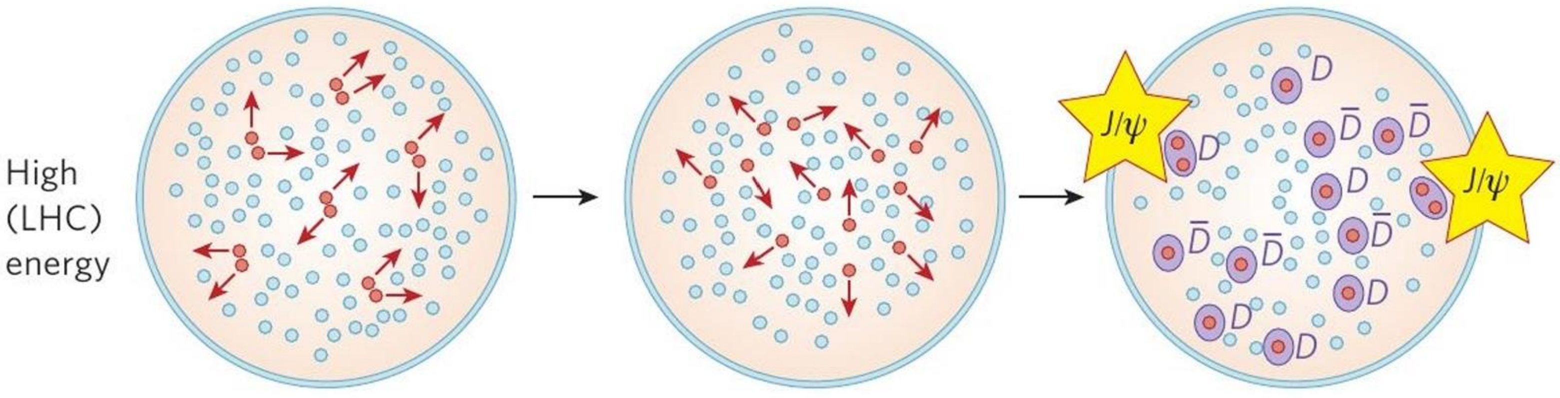
- Evaluation of momentum azimuthal anisotropy
  - Fourier coefficient of azimuthal distribution with respect to event plane

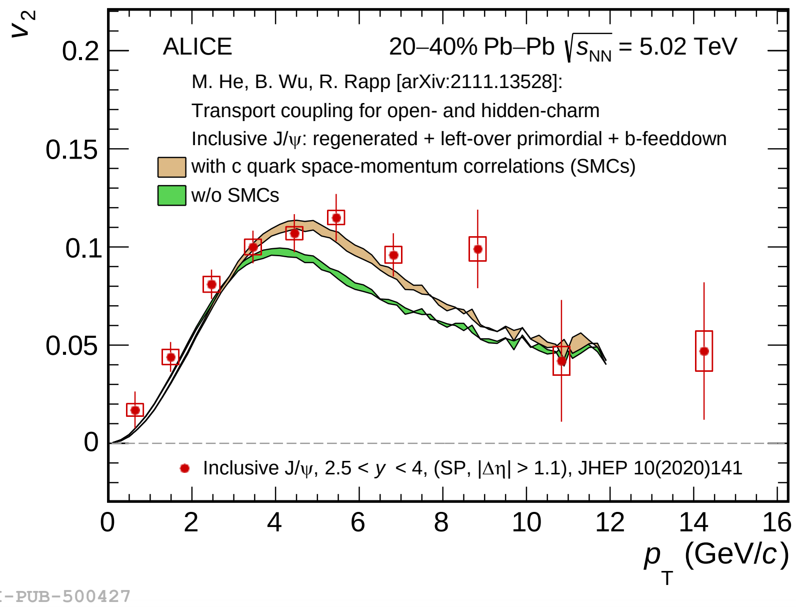


- Strong evidence of thermalization at parton freedom degree (NCQ scaling)
  - v_2/n_q of different particle species agree with each other quite well. (n_q is the number of the constituent quarks)

  → the parton freedom degree is released and the system is thermalized.

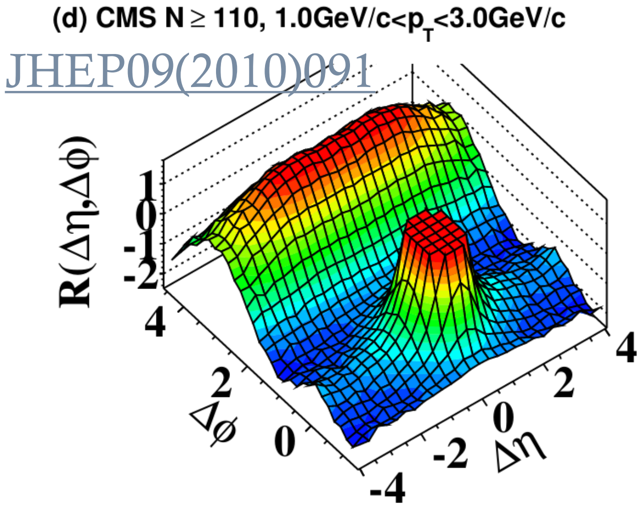
Flow of heavy quarks at heavy ion collisions



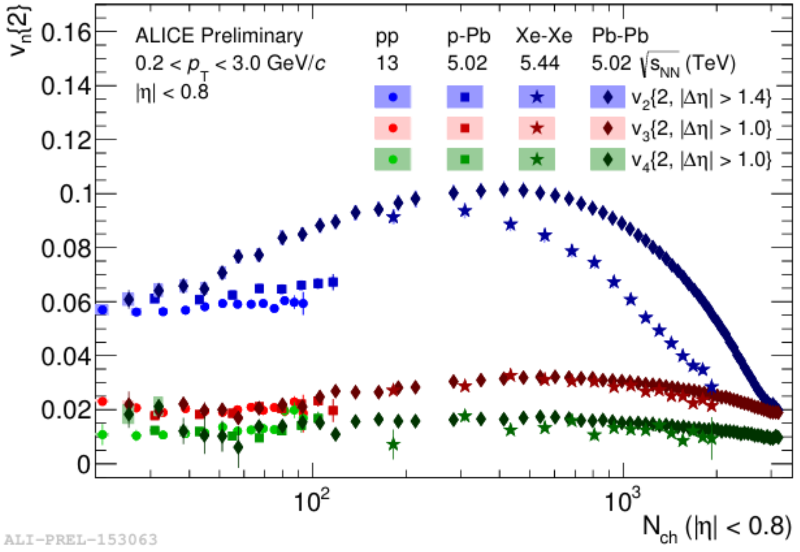


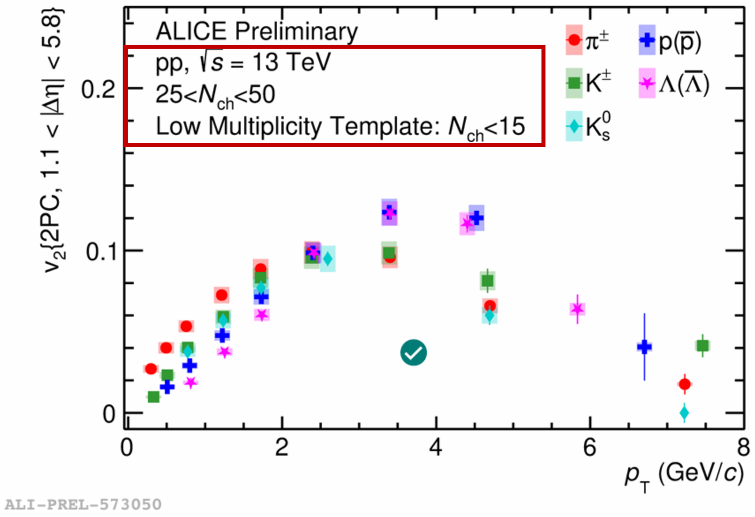
- At LHC, charm quark density in the created medium is high enough to couple together and form J/ψ.
- J/ψ v_2 at heavy ion collisions
  - Charm quarks are pushed by medium and thermalized. → J/ψ from recombination inheriting collective motion of charm quark will have significant v_2.

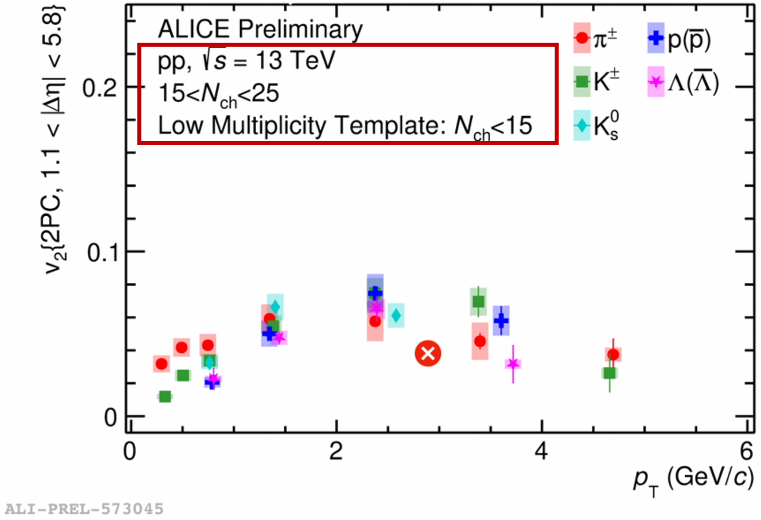
Flow(-like) phenomena in small systems



First observation of long-range correlation ridge in pp







- Flow(-like) phenomena exist in small systems, even when multiplicity is low.
- What is the origin of flow(-like) phenomena in smaller systems?

System-size dependent flow(-like) phenomena

u, d, s (π, p, K), c ($D, J/\psi$), b (B, Υ)

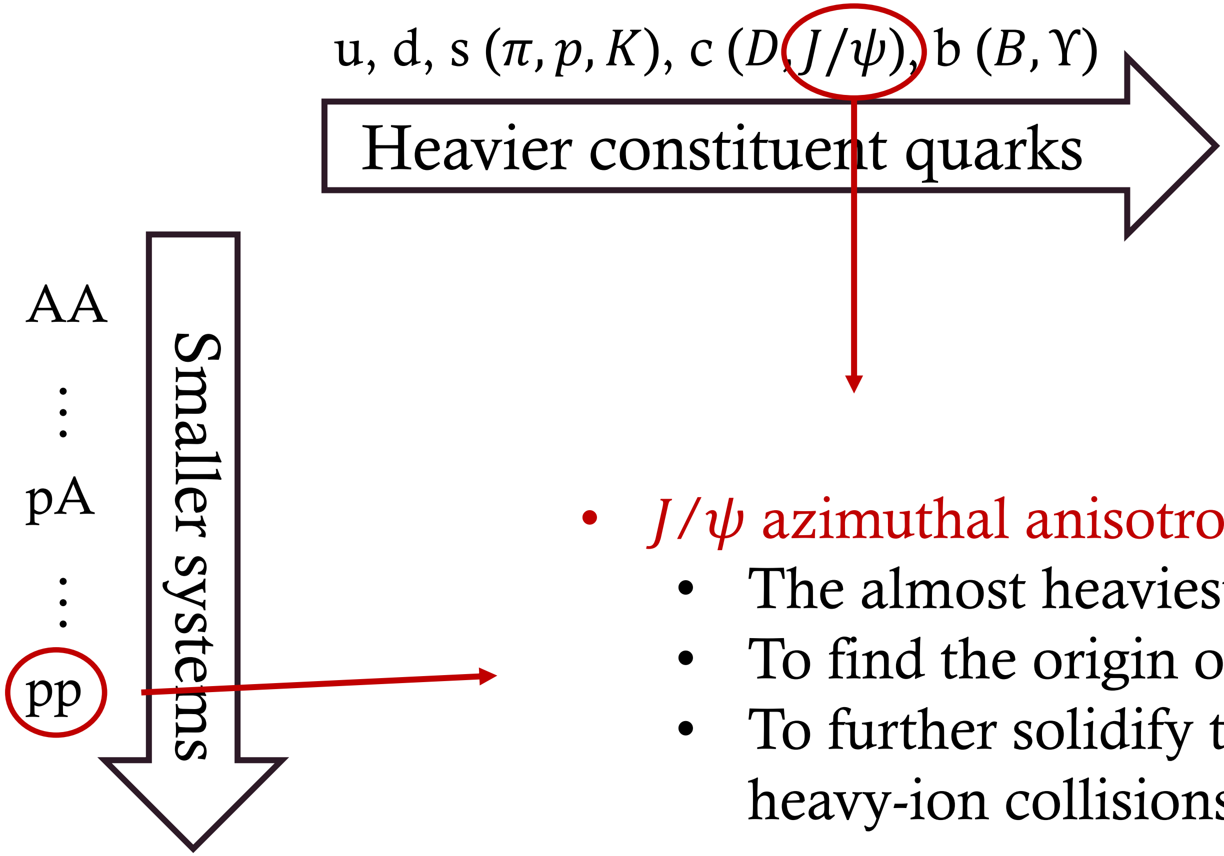
Heavier constituent quarks

AA
⋮
pA
⋮
pp

Smaller systems

- How is going when systems get smaller?
  - Flow(-like) phenomena should be study at different systems (different collisions with different multiplicities).
  - How is the system? Is that system in equilibrium?
    - How does the quark interact with the medium? Are the quark species thermalized?

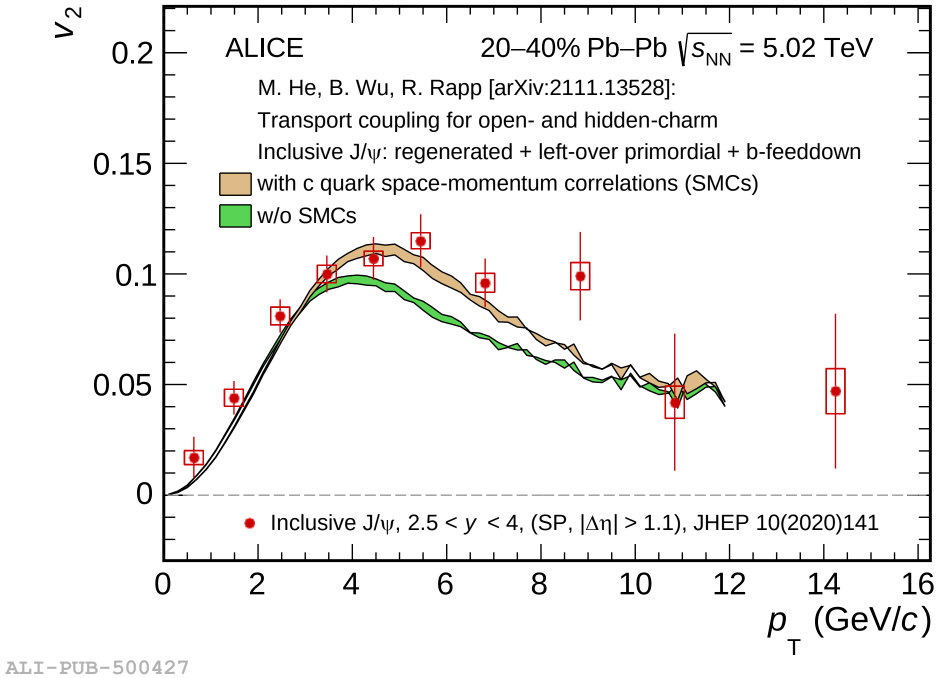
System-size dependent flow(-like) phenomena

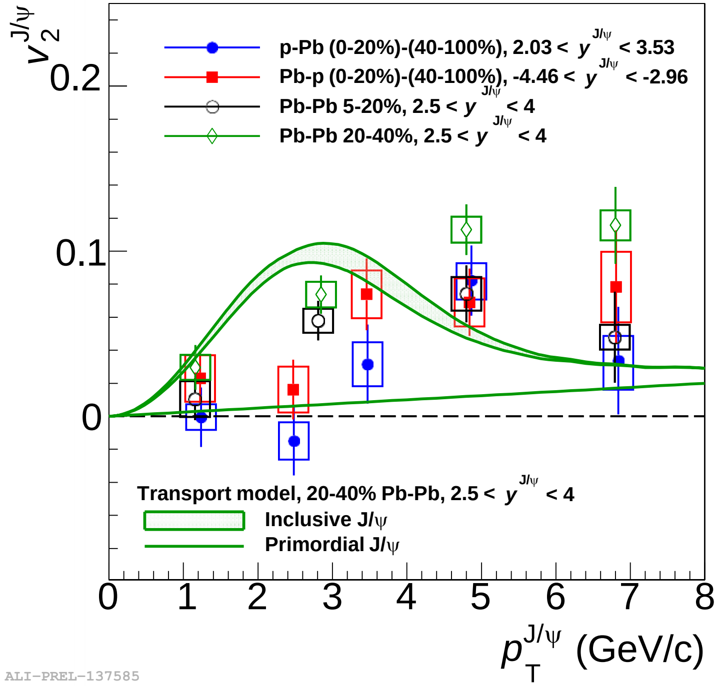


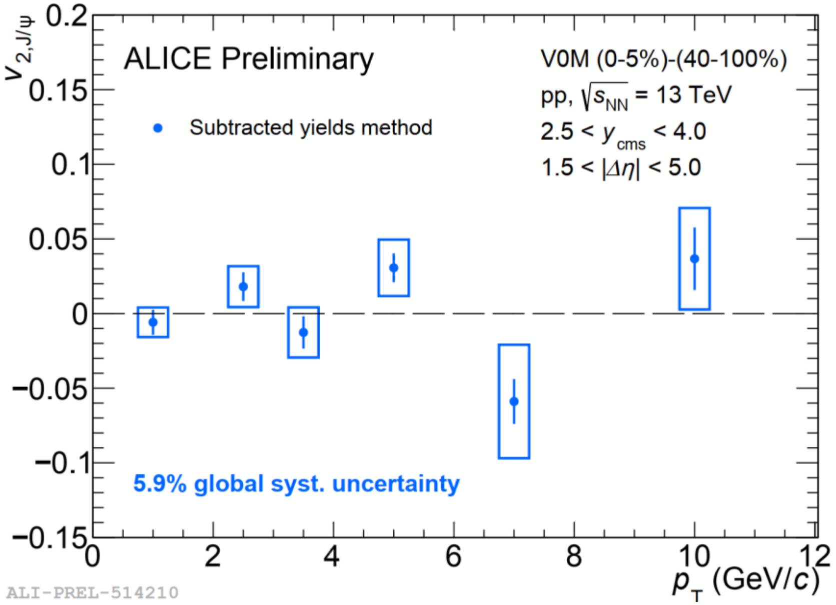
- J/ψ azimuthal anisotropy measurement in pp collisions
  - The almost heaviest hardon in the smallest system.
  - To find the origin of flow(-like) phenomena in small systems
  - To further solidify the mechanism of QGP flow generation in heavy-ion collisions

System dependent $J/\psi\ v_2$

- Pb-Pb
- p-Pb
- pp





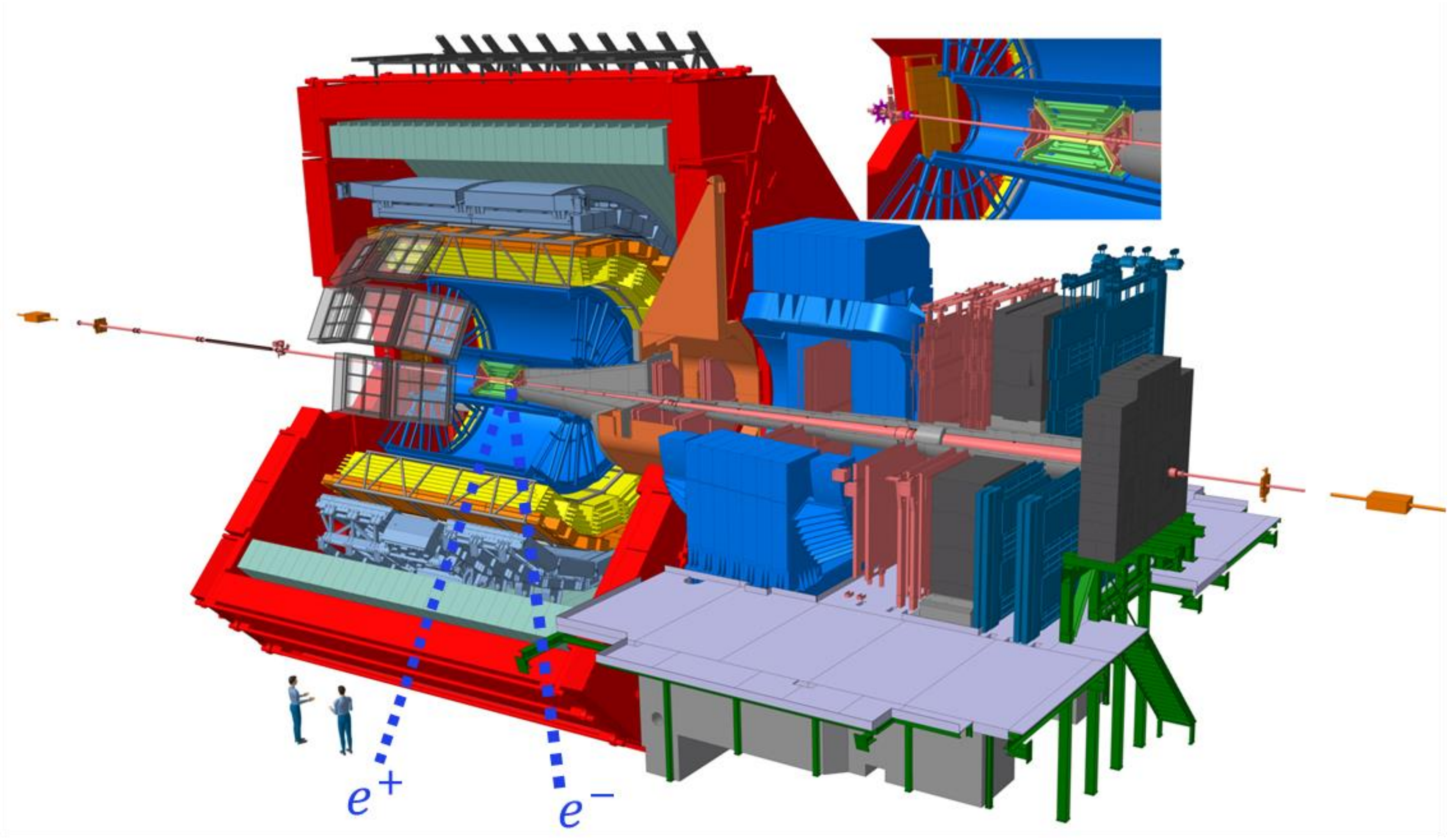


- A significant J/ψ v_2 is observed in Pb-Pb collisions.
- J/ψ v_2 described well by a coalescence model where charm thermalized

- J/ψ v_2 in p-Pb collisions is consistent with 0 at the low p_T,
- but increases to the similar values to Pb-Pb at high p_T.

- J/ψ v_2 in pp collisions compatible with 0 with large uncertainties

ALICE RUN 3 upgrade



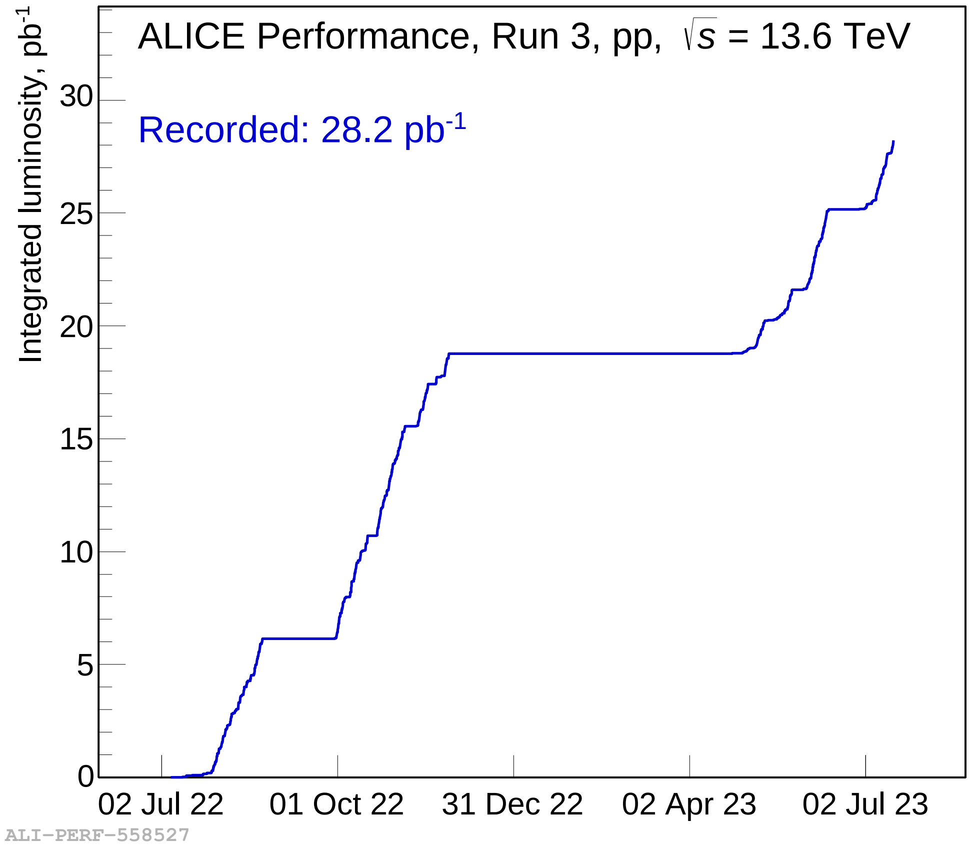
Time Projection Chamber
Tracking, particle identification

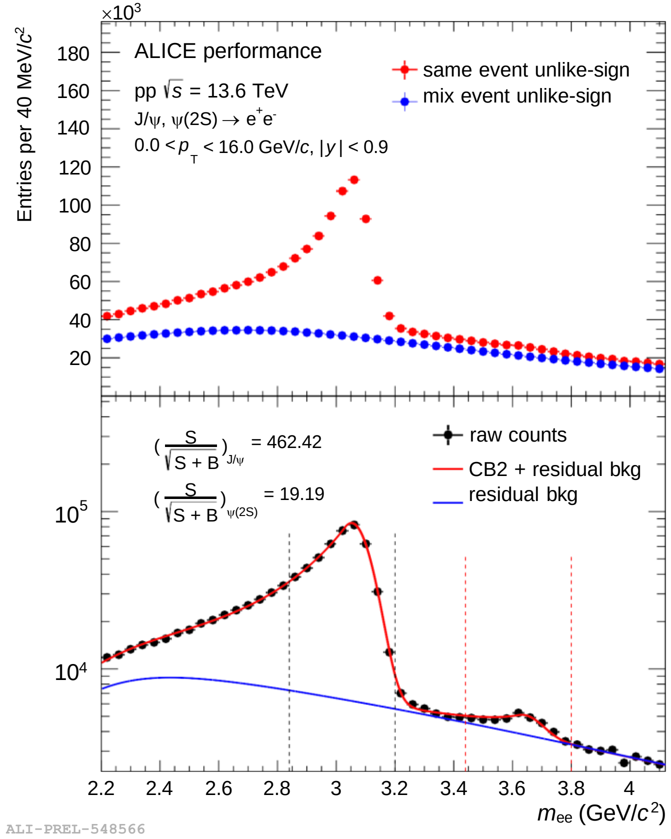
Inner Tracking System
Tracking, vertex reconstruction

V0 Detector
Centrality determination triggering, and reaction plane measurement

$J/\psi \rightarrow e^+e^-$

ALICE RUN 3 Upgrade





- Statistic has been increased a lot in RUN 3.
- Plentiful J/ψ counts has already been seen.
- Measurement of J/ψ v_2 in pp is possible.

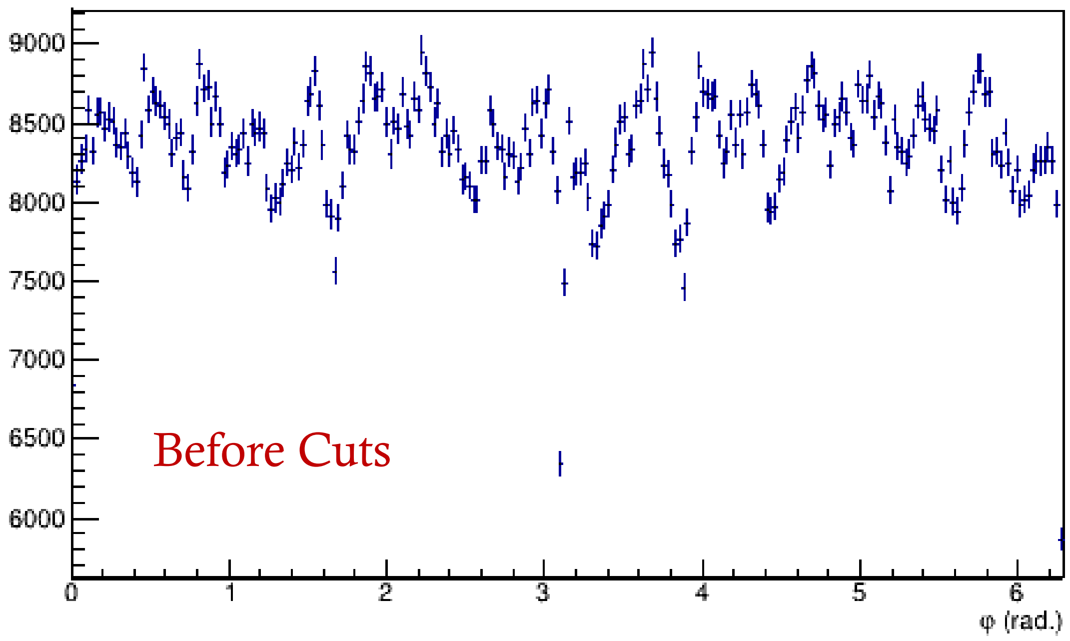
Contents

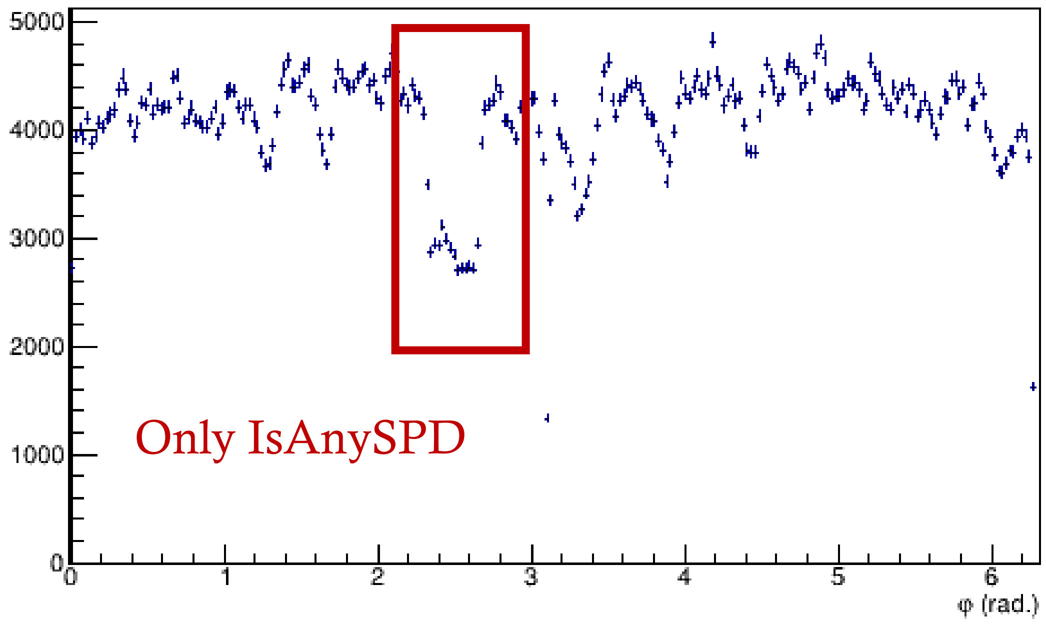
Datasets and Analysis Cuts

- Dataset
  - DQ_Skimmed: LHC22_HighIR_pass4_electron
    AliHyperloop (cern.ch)
  - Including:
    - 22moprt
  - Offline trigger:
    - Events should contain two $p_T > 1$ GeV electrons

- Track Quality Cuts:
  - $0 < \chi^2_{TPC} < 4$
  - $Ncls_{TPC} > 90$
  - $Ncls_{ITS} > 2$
  - IsSPDany (have at least one hit at the innermost two ITS layers)
  - $-1 < DCA_{xy} < 1$
  - $-3 < DCA_z < 3$
- Kinematic Cuts for electrons from J/ψ:
  - $-0.9 < \eta < 0.9$
  - $p_T > 1$ GeV/c
- Kinematic Cuts for reference flow:
  - $-0.9 < \eta < 0.9$
  - $0.2 < p_T < 3$ GeV/c

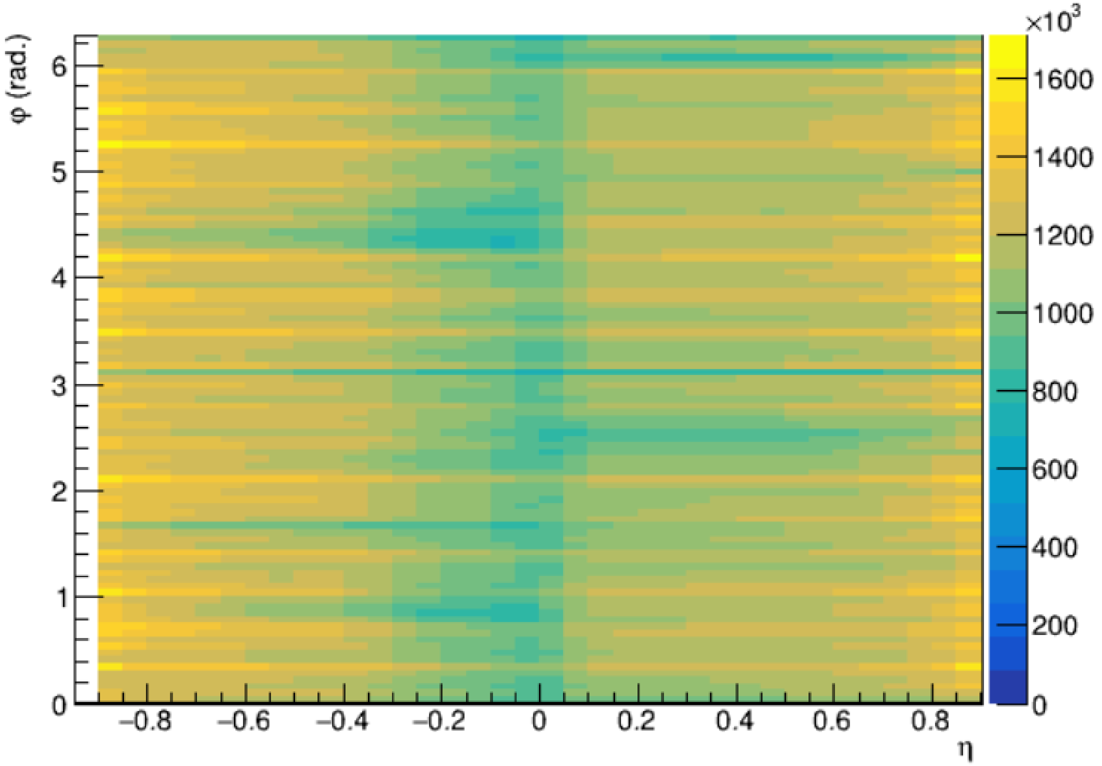
Detailed ϕ acceptance check

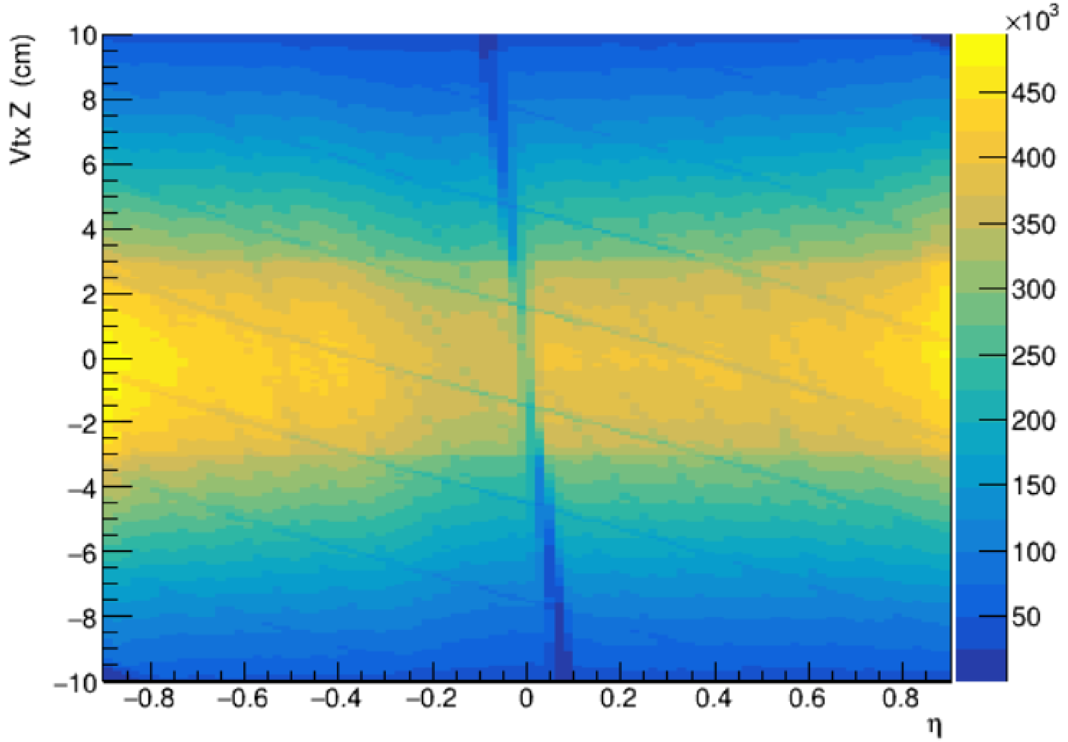




- Efficiency loss at the coverage in the red box
- No acceptance is lost but the efficiencies are low at specific $\eta-\phi$ region for SPD.
- If there's no IsAnySPD cut, a large fluctuation of ϕ distribution will be observed.
- Non-uniform Acceptance should be done from run to run.

Non-uniform Correction





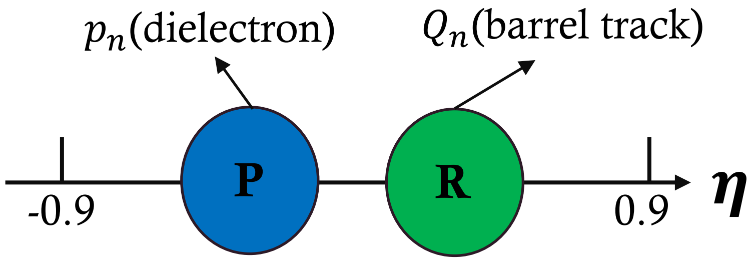
- The dimension of non-uniform correction for reference flow should also include $Vtx_z,\ \eta$ from run to run.
- And for non-uniform correction for J/ψ, p_T of J/ψ should also be included.

Contents

Observable

$$v_n v'_n = \langle \cos n(\phi - \psi) \rangle$$
$$v_n^2 = \langle \cos n(\phi_1 - \phi_2) \rangle$$

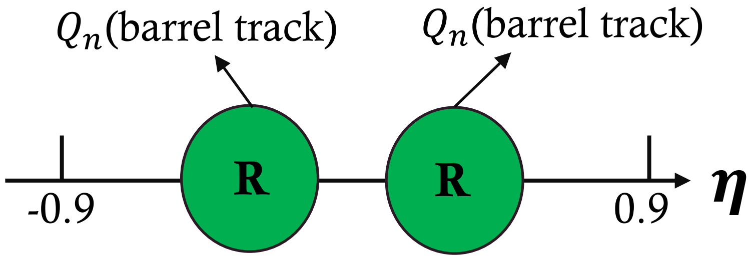
- v_n: the n-th harmonic coefficient of REF
- v'_n: the n-th harmonic coefficient of POI
- ϕ: azimuthal angle of reference flow
- ψ: azimuthal angle of J/ψ



- Barrel Q-vector → $Q_n = \Sigma_{i=1}^{M} e^{in\phi_i} = Q_n^X + iQ_n^Y$
- Dielectron Q-vector → $p_n = \Sigma_{i=1}^{m} e^{in\psi_i} = p_n^X + ip_n^Y$

M: multiplicity barrel, m: multiplicity dielectron

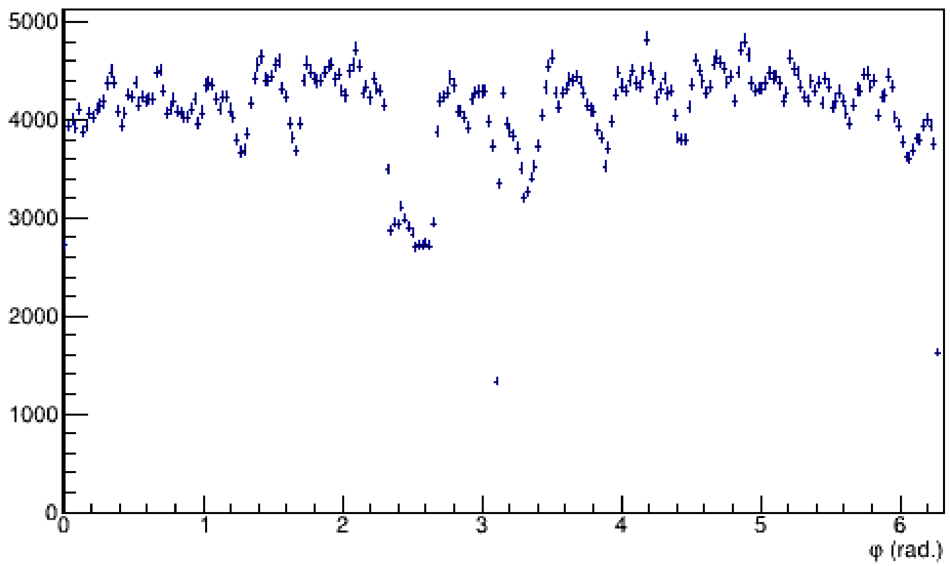
PARTICLE OF INTEREST (**POI**): $V'_{n,2} = v_n v'_n = \frac{p_n Q_n^*}{mM}$

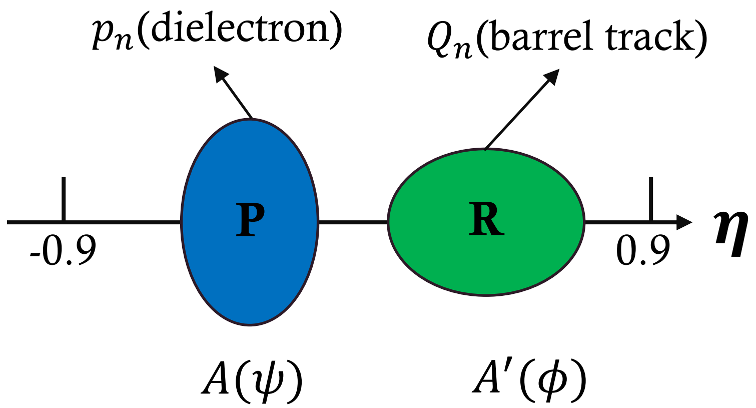


REFERENCE (**REF**): $V_{n,2} = v_n^2 = \frac{|Q_n|^2 - M}{M(M-1)}$

Dielectron harmonic coefficient: $v_2^{ee} = \frac{V'_{2,2}}{\sqrt{V_{2,2}}}$

Non-uniform Correction





- Acceptance function J/ψ: $A(\psi)$
- Acceptance function barrel: $A'(\phi)$
- $\int A(\phi)\frac{d\phi}{2\pi} = \int A'(\psi)\frac{d\psi}{2\pi} = 1$

- Non-uniform effect of detector acceptance should be corrected.

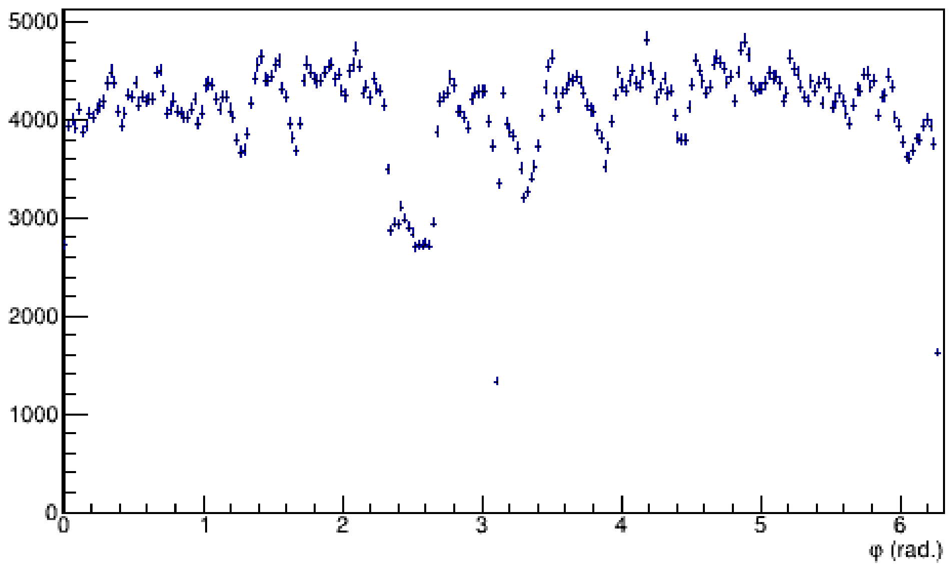
- With uniform acceptance:

$$\langle \cos n(\phi-\psi) \rangle = \iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} f(\phi) f'(\psi) \cos n(\phi-\psi)$$

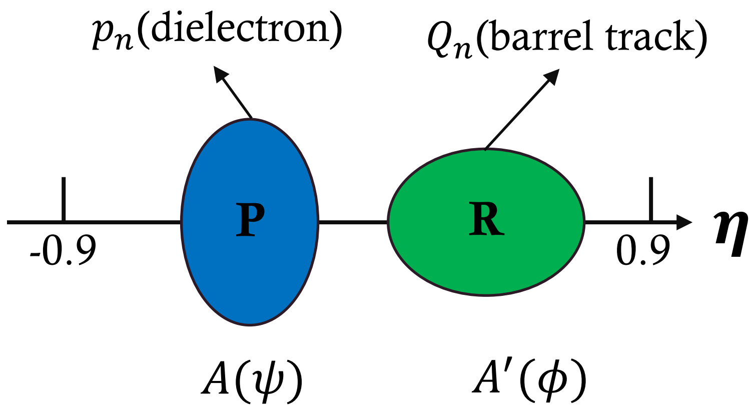
- With non-uniform acceptance:

$$\langle \cos n(\phi-\psi) \rangle = \iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} \boxed{A(\phi)A'(\psi)} f(\phi,\Psi_{EP}) f'(\psi,\Psi_{EP}) \cos n(\phi-\psi)$$

Non-uniform Correction



- Non-uniform effect of detector acceptance should be corrected.



- Acceptance function J/ψ: $A(\psi)$
- Acceptance function barrel: $A'(\phi)$
- $\int A(\phi)\frac{d\phi}{2\pi} = \int A'(\psi)\frac{d\psi}{2\pi} = 1$

Shifting part

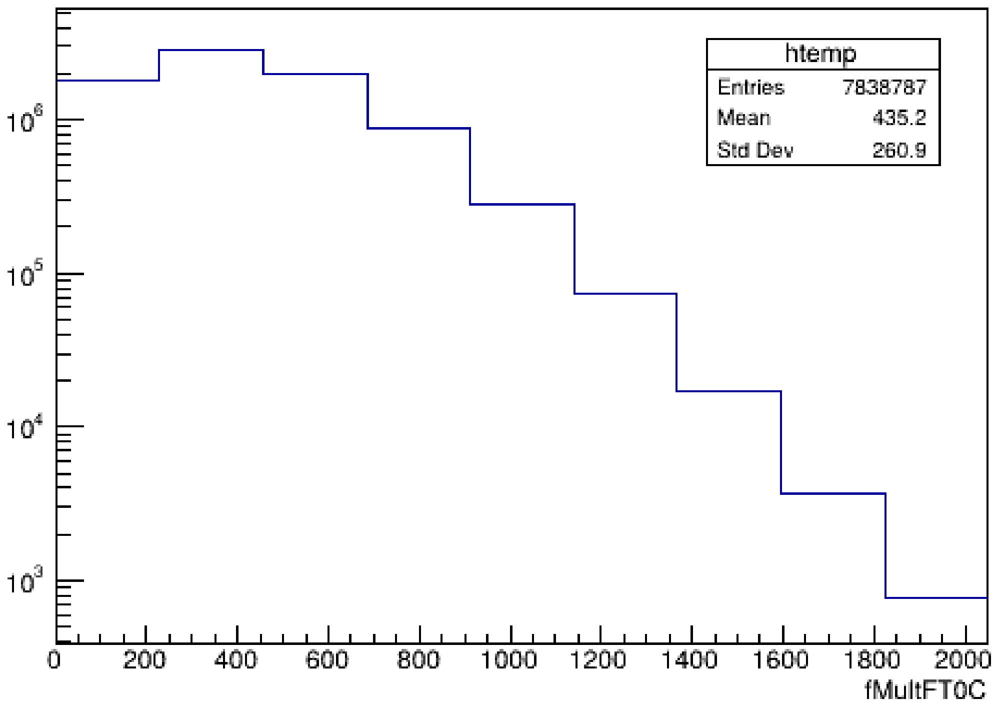
$$v_n v_n' = \frac{\langle \cos n(\psi - \phi)\rangle - \langle \cos n\psi\rangle\langle \cos n\phi\rangle - \langle \sin n\psi\rangle\langle \sin n\phi\rangle}{1 + \langle \cos 2n\psi\rangle\langle \cos 2n\phi\rangle + \langle \sin 2n\psi\rangle\langle \sin 2n\phi\rangle}$$

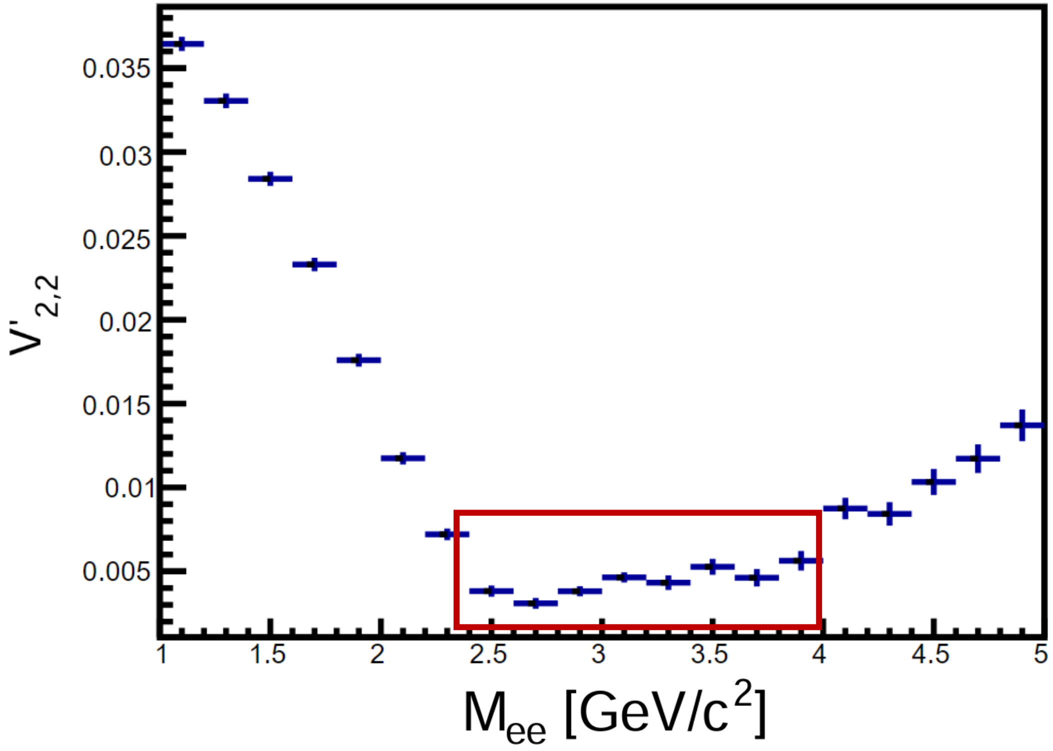
Scaling part

Dimension of correction	
REF	η, V_z
POI	$M, \eta_{J/\psi}, V_z, p_T$

Contents

$V_{2,2}(J/\psi - track\ barrel)$ Measurements





- FT0C multiplicity is used as the multiplicity indicator.
- $V'_{2,2}$ without any p_T or multFT0C cuts
- A peak-like structure has been observed.

Correlation signal extraction

- $N_{total} = N_{signal} + N_{background}$
  - N_{signal}: Crystal ball function
  - $N_{background}$: Scaled mix event, residual background
- $V(ee - track\ barrel) = \frac{N_{signal}}{N_{total}} V(J/\psi - track\ barrel) + \frac{N_{background}}{N_{total}} V(bkg - track\ barrel)$
  - V(bkg-track barrel): polynomial function

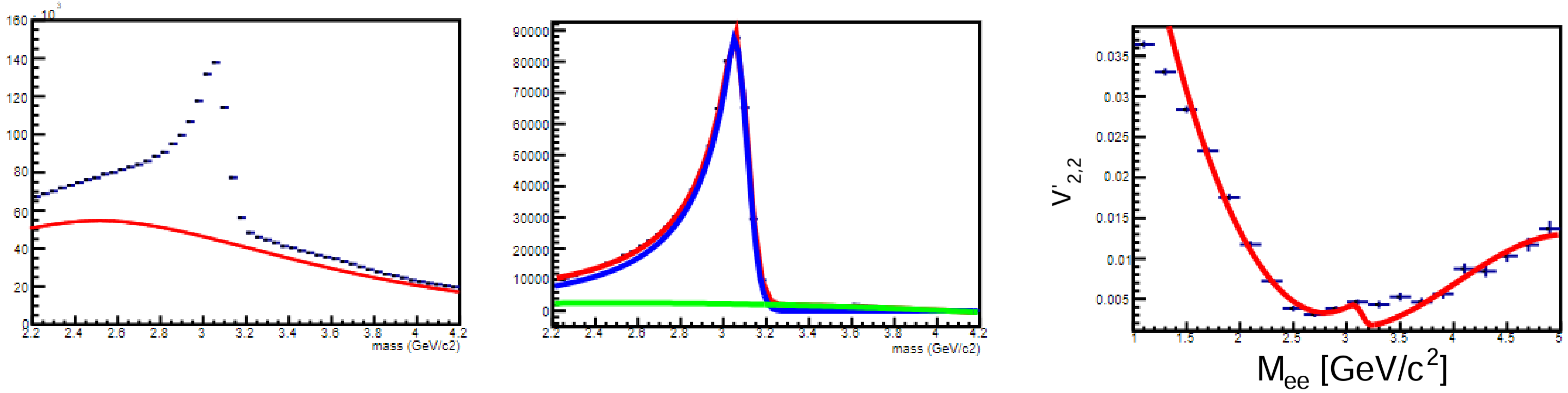
Fit simultaneously:

- Calculate the χ^2 of the two function above
- Minimize the χ^2 with Minuit

Correlation signal extraction

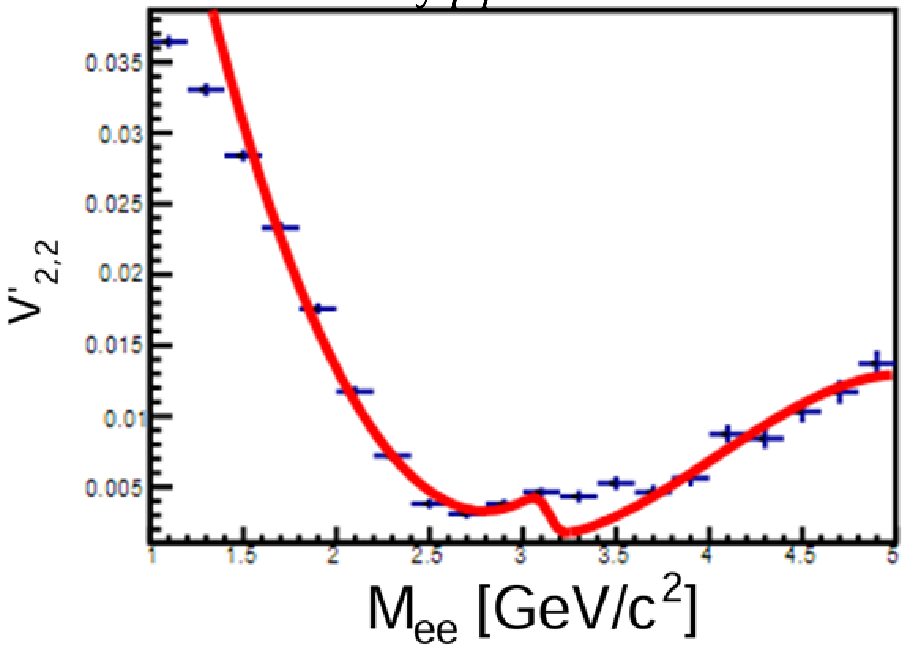
- $N_{total} = N_{signal} + N_{background}$
  - N_{signal}: Crystal ball function
  - $N_{background}$: Scaled mix event, residual background

- $V(ee - track\ barrel) = \frac{N_{signal}}{N_{total}} V(J/\psi - track\ barrel) + \frac{N_{background}}{N_{total}} V(bkg - track\ barrel)$
  - V(bkg-track barrel): polynomial function



Correlation signal extraction

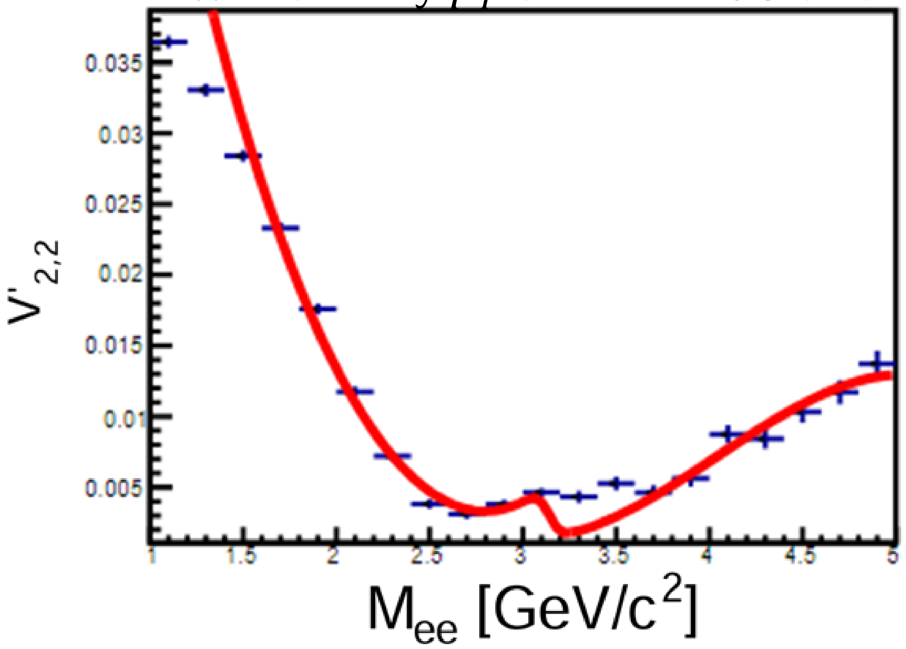
Without any p_T or multFT0C cuts

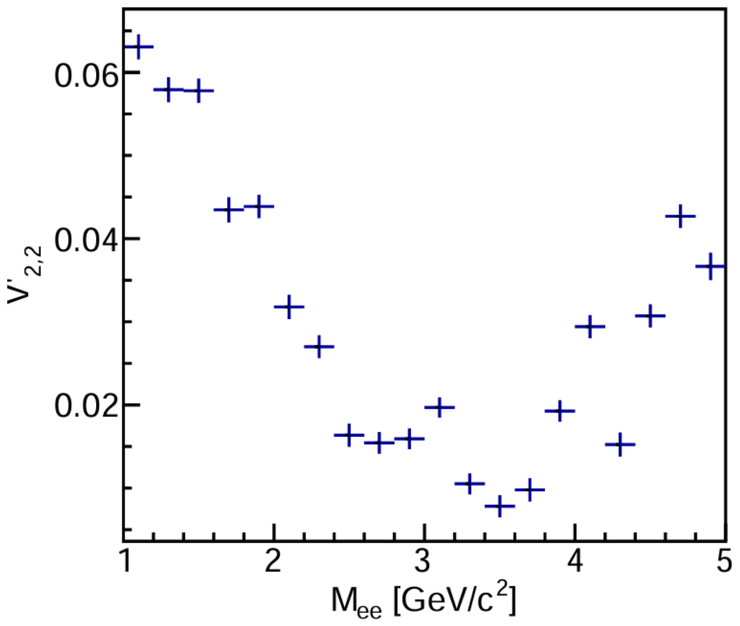


- Fit can't describe data well.

Correlation signal extraction

Without any p_T or multFT0C cuts

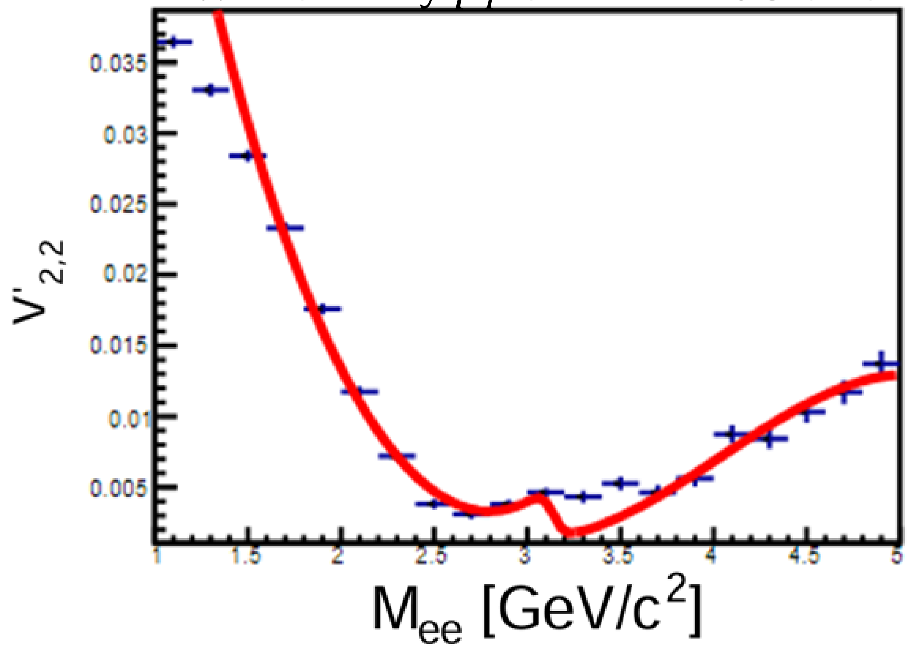




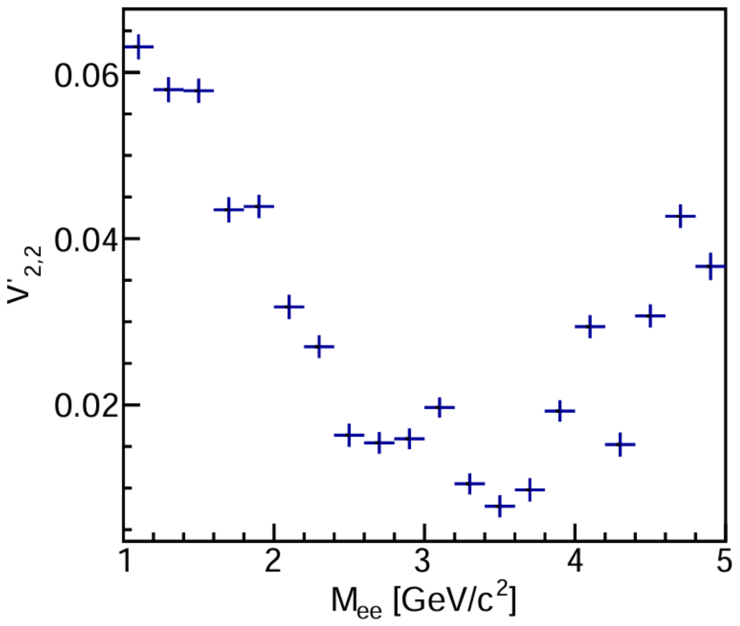
- Fit can't describe data well.
- Apply $\Delta\eta > 0.1, p_T > 1$ GeV/c to get larger signal and flatter background. Background is still strange.

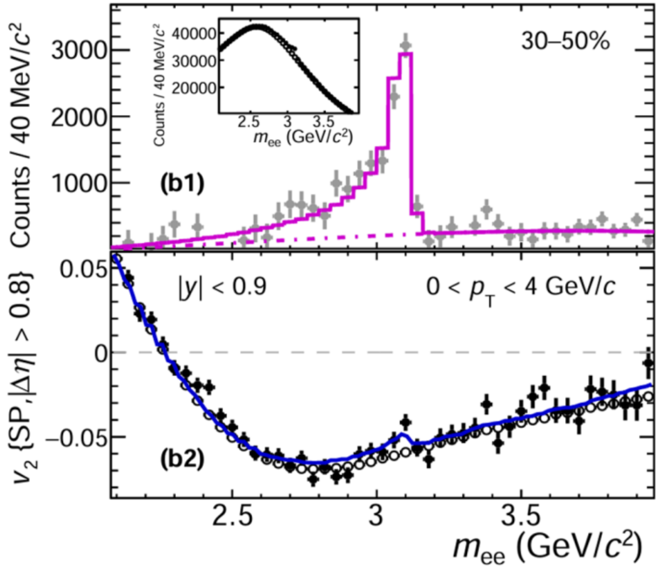
Correlation signal extraction

Without any p_T or multFT0C cuts



0<MultFT0C<400;pT>1GeV/c





- Fit can't describe data well.
- Apply $\Delta\eta > 0.1, p_T > 1$ GeV/c to get larger signal and flatter background. Background is still strange.
- RUN2 published results with a larger η gap also has a strange background shape.
- A smaller mass region and finer mass bin width should be used.

Low statistic condition

- When statistic is low, TProfile will bias the mean value and underestimate the uncertainty.

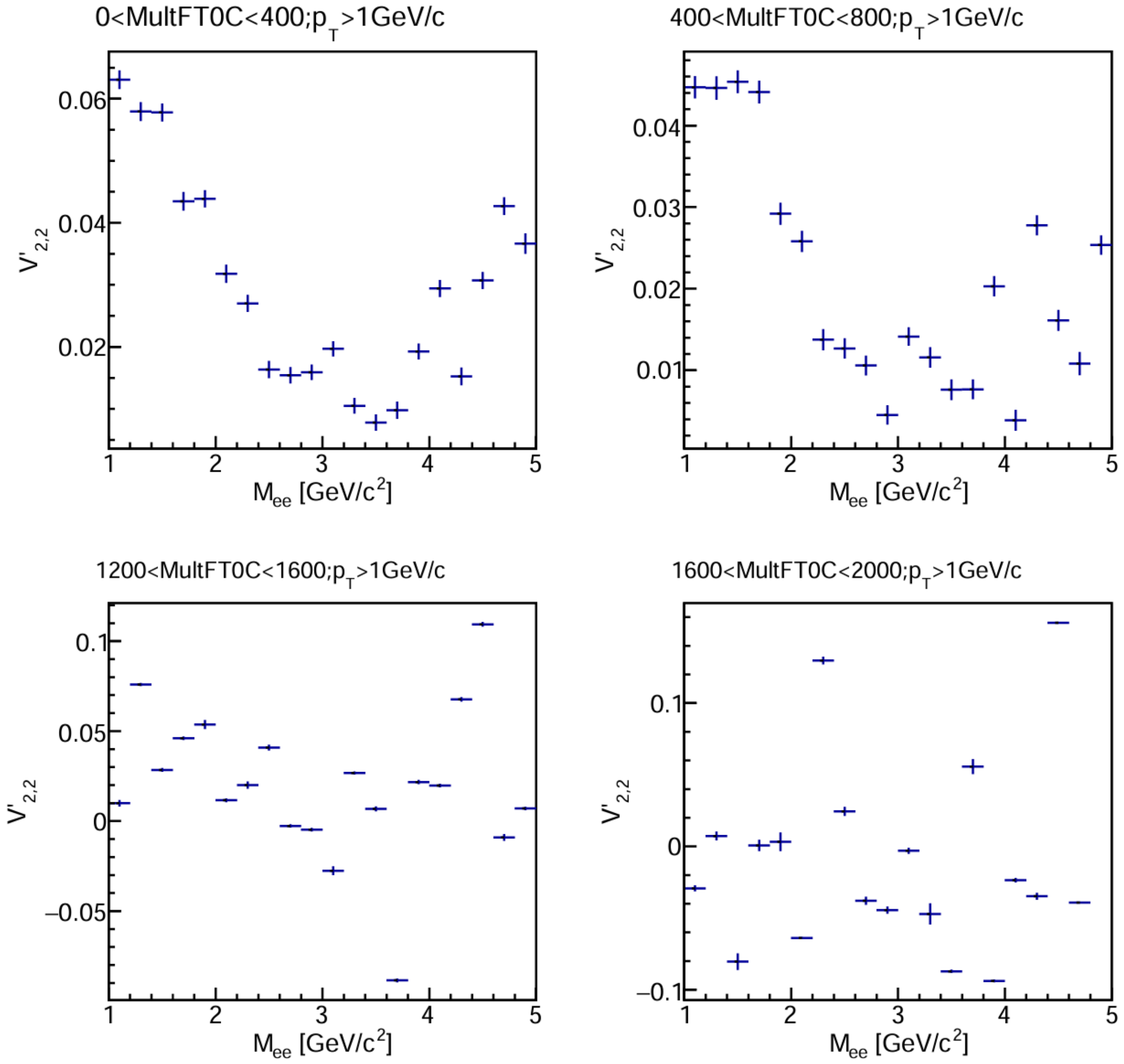
Shifting part

$$v_n v_n' = \frac{\langle \cos n(\psi - \phi) \rangle - \langle \cos n\psi \rangle \langle \cos n\phi \rangle - \langle \sin n\psi \rangle \langle \sin n\phi \rangle}{1 + \langle \cos 2n\psi \rangle \langle \cos 2n\phi \rangle + \langle \sin 2n\psi \rangle \langle \sin 2n\phi \rangle}$$

Scaling part

- The NUE correction and uncertainty propagation are unreliable.

Low statistic condition



- Bootstrap should be applied.
- NUE grouping should be done.
- NUE should be corrected with Monte-Carlo data.

Contents

Summary

- The framework has been set up.
- 2 papers published

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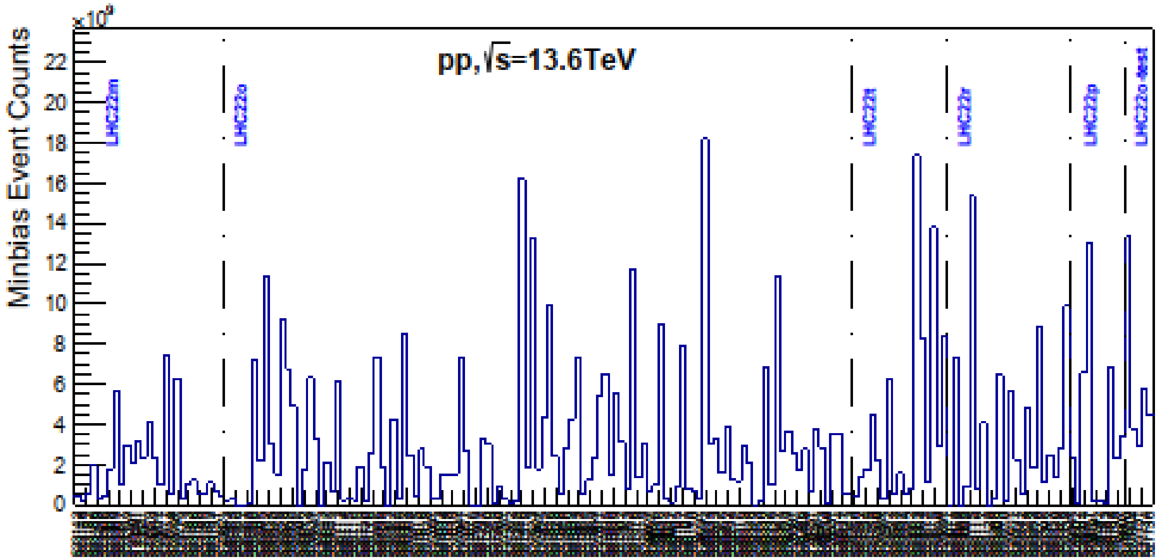
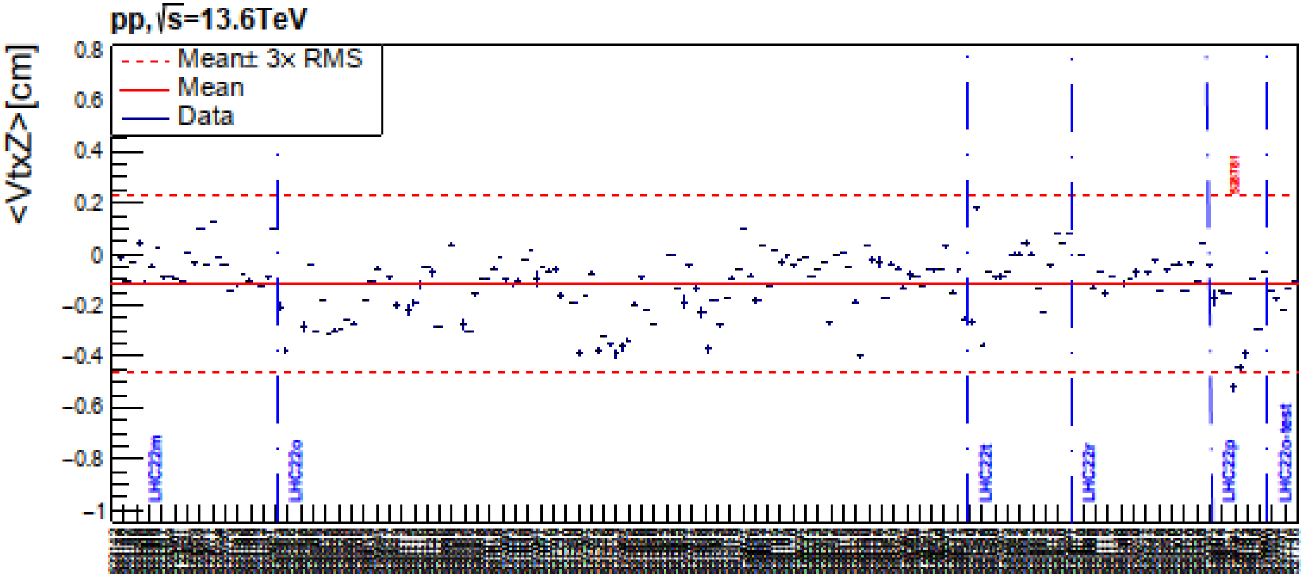
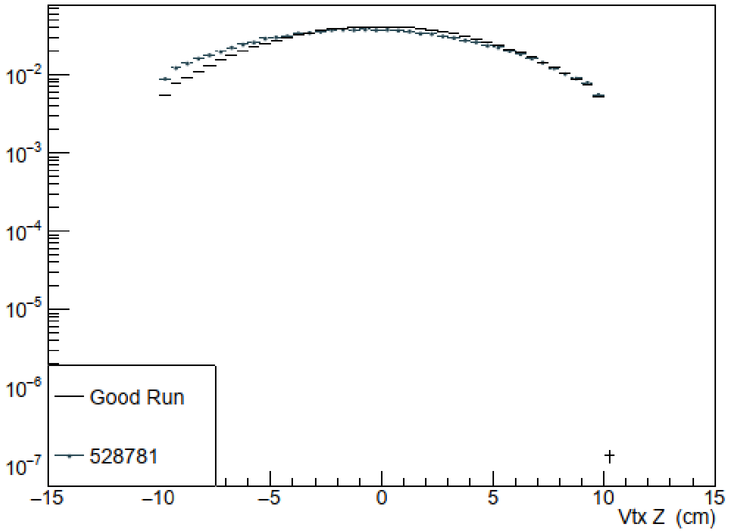
Research Plans

BACKUP

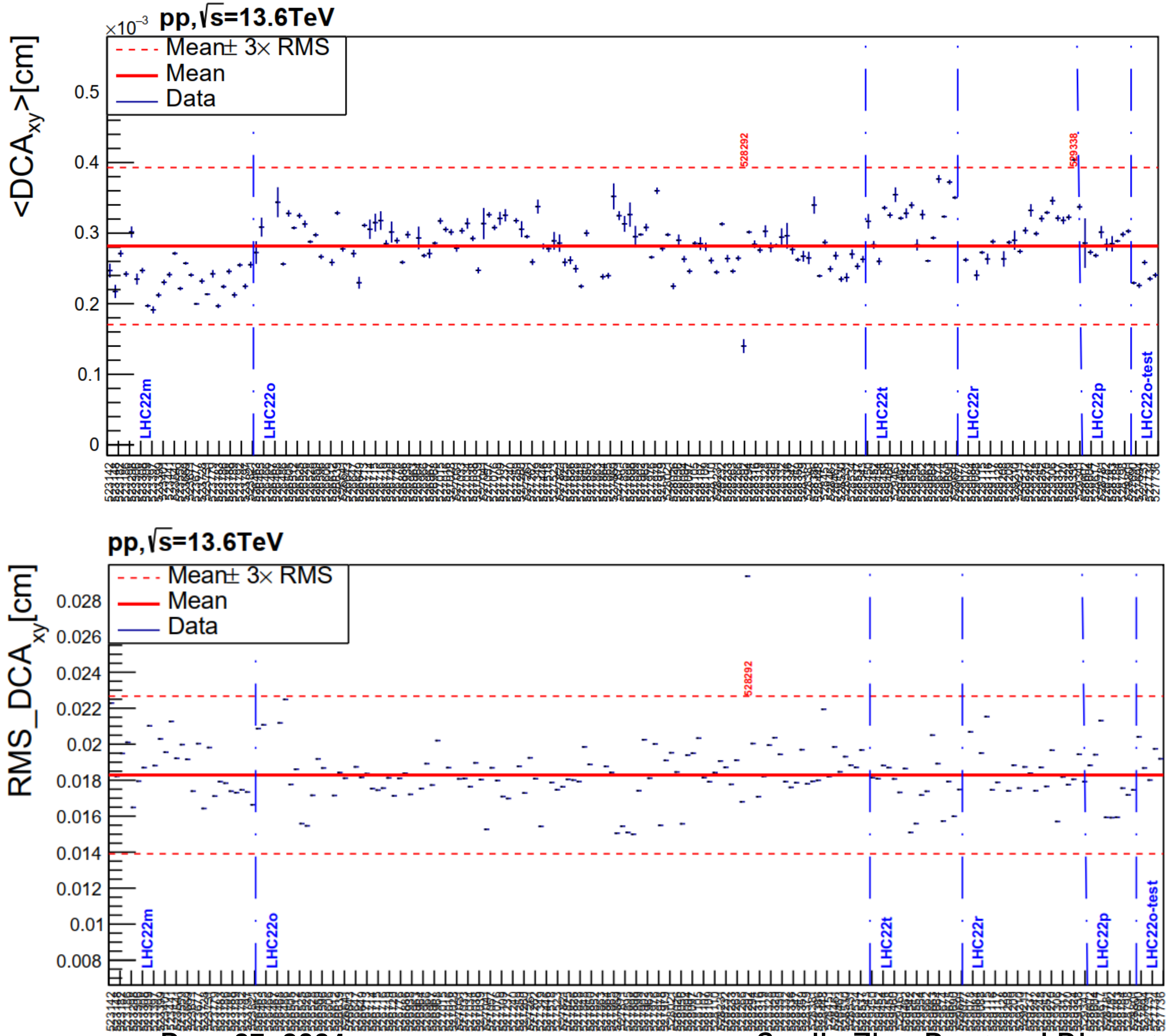
Event Information

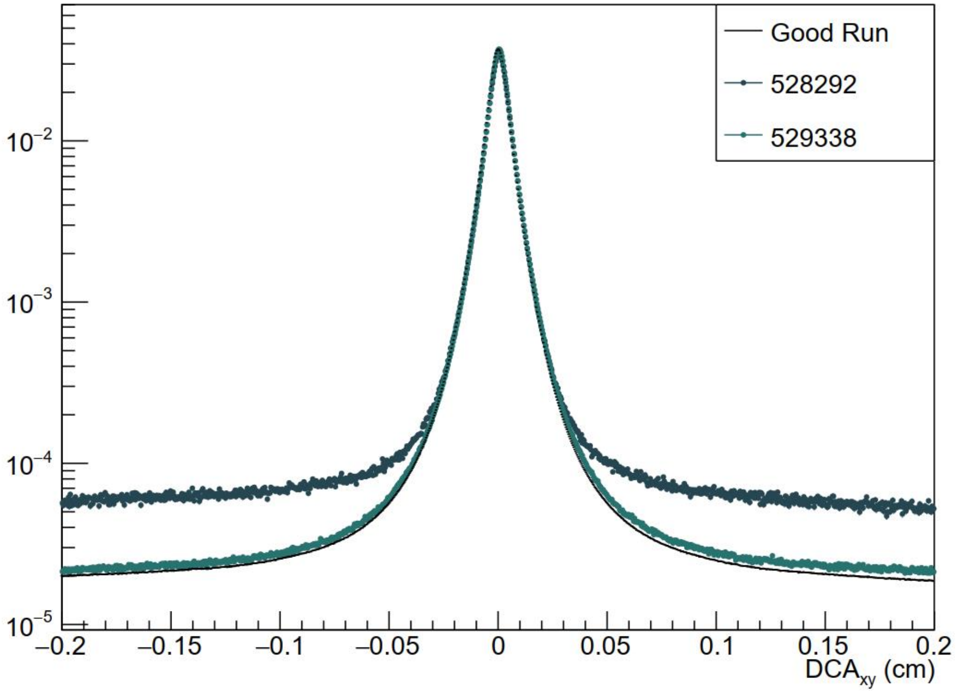






Data quality check





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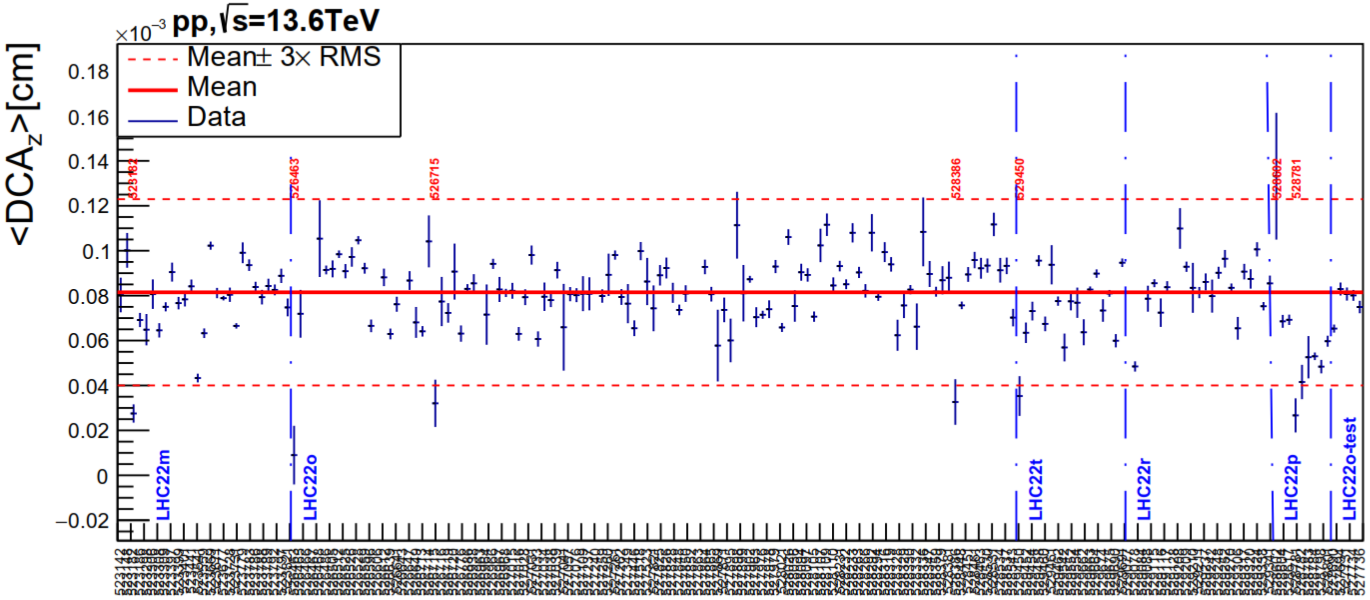

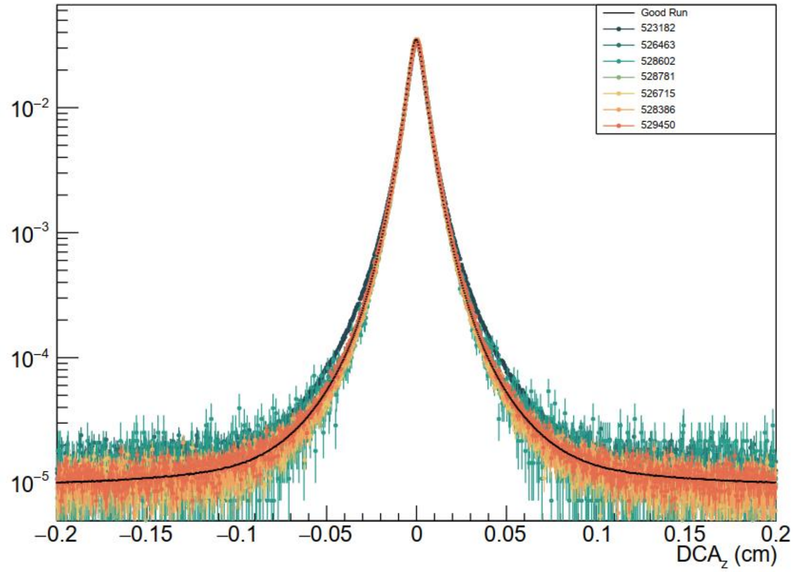

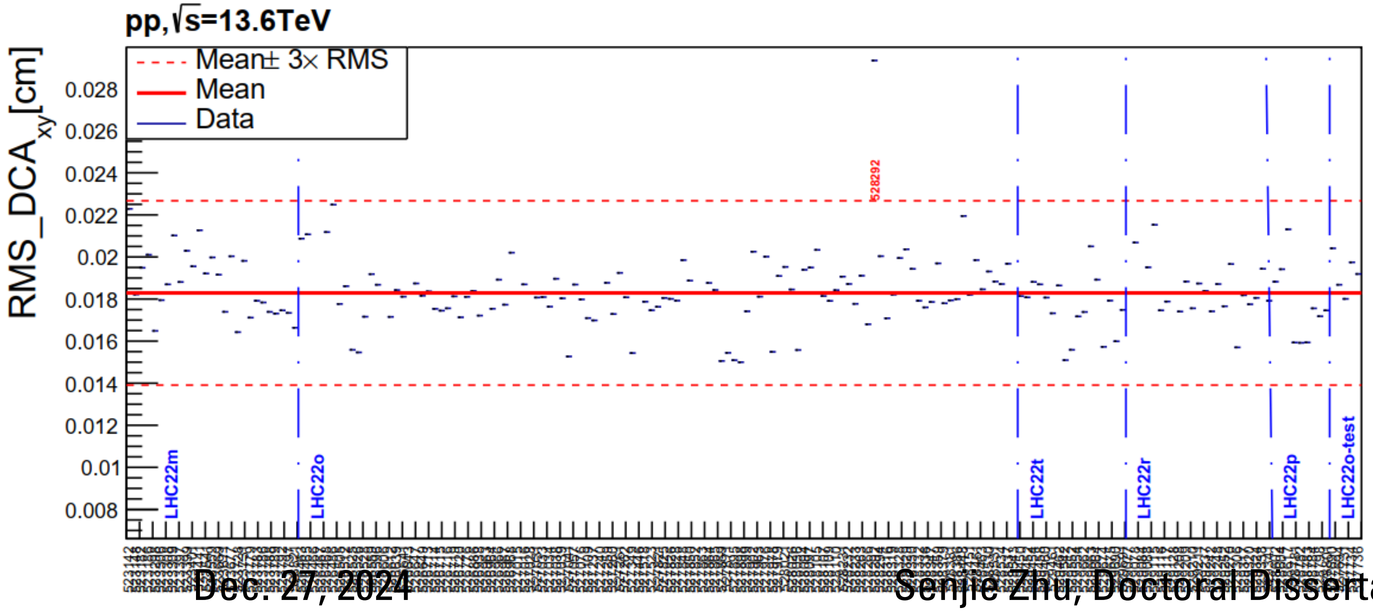

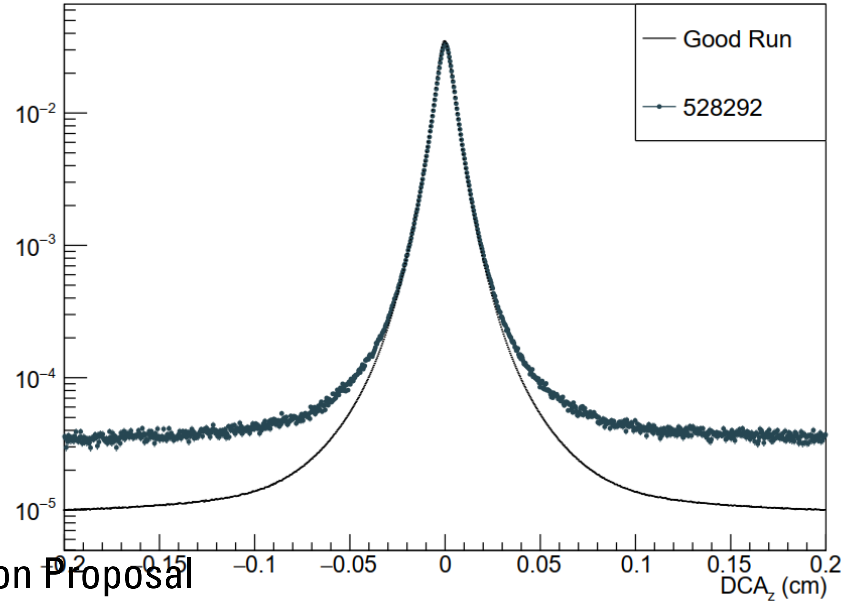

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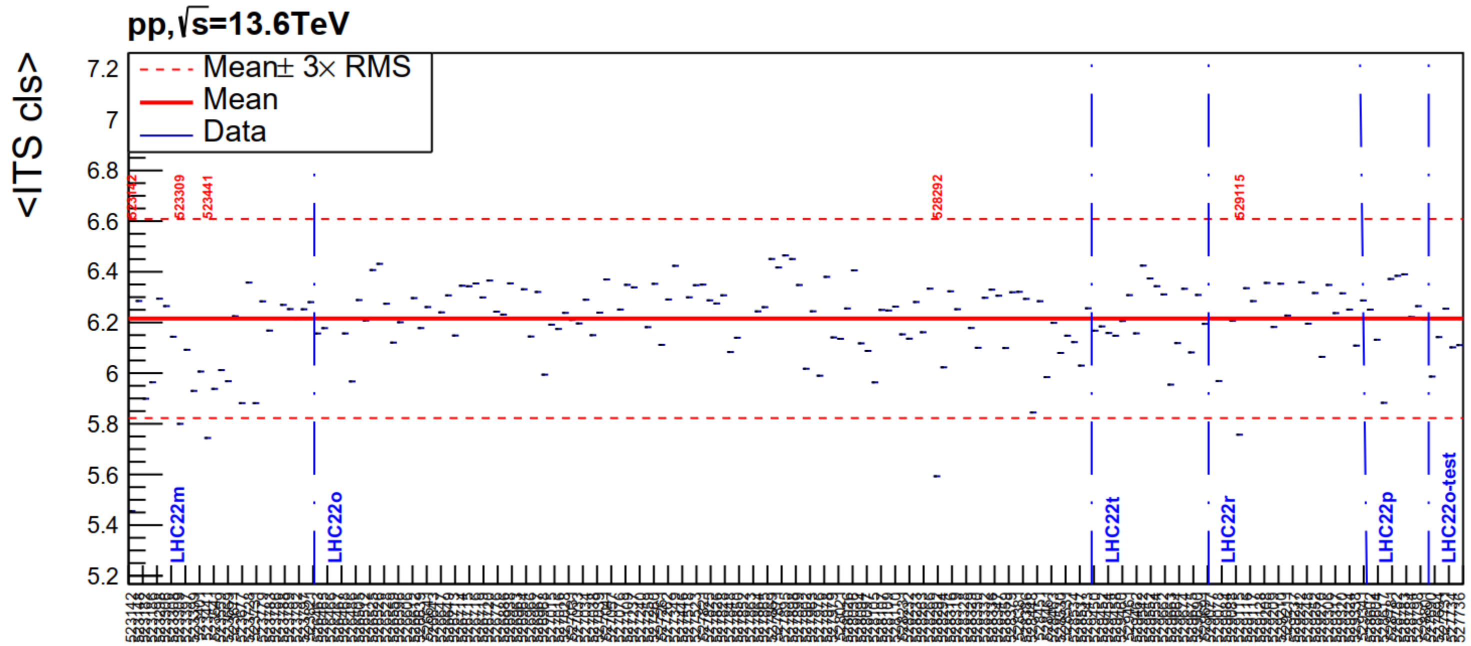
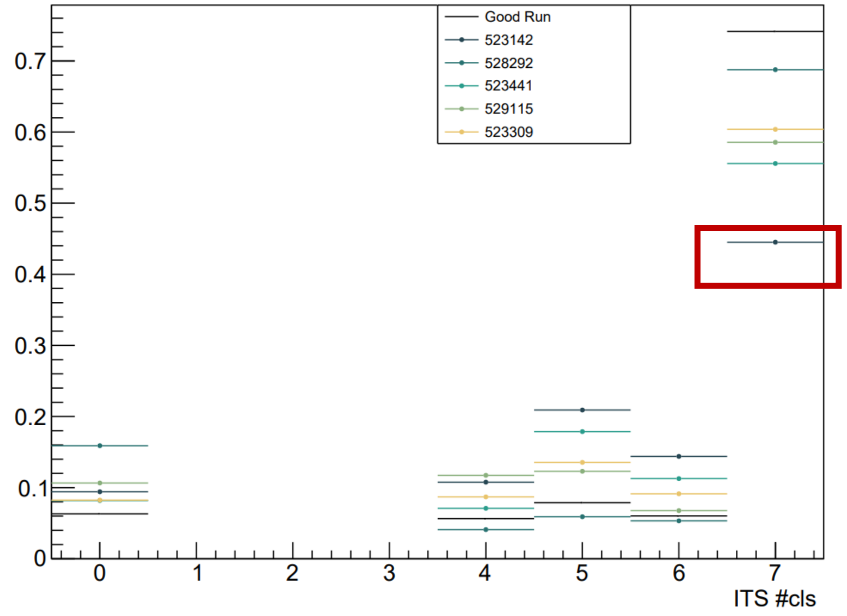
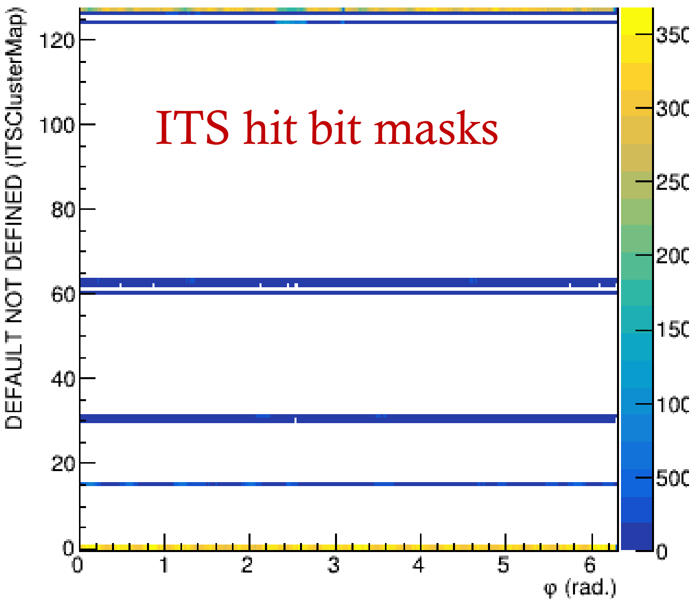


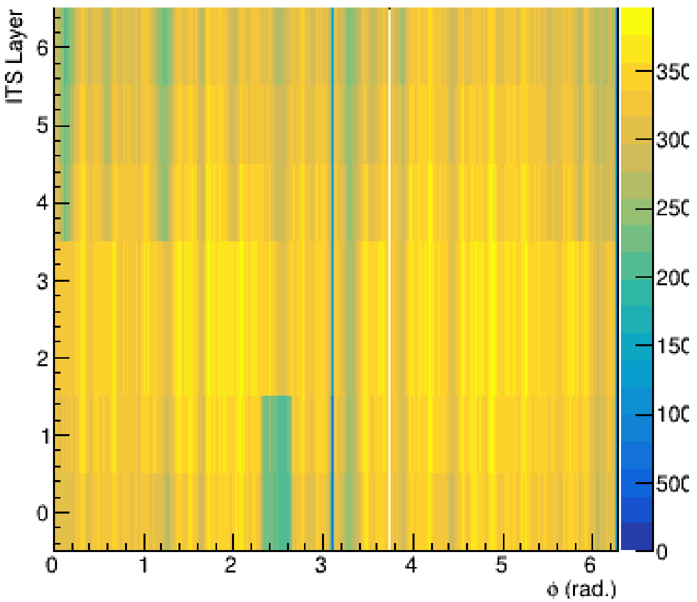


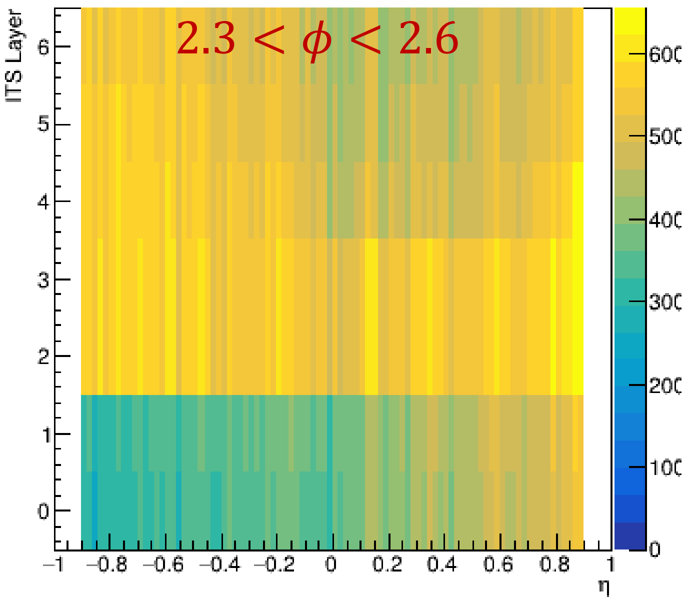
Bad runs: 528781, 528292, 523142

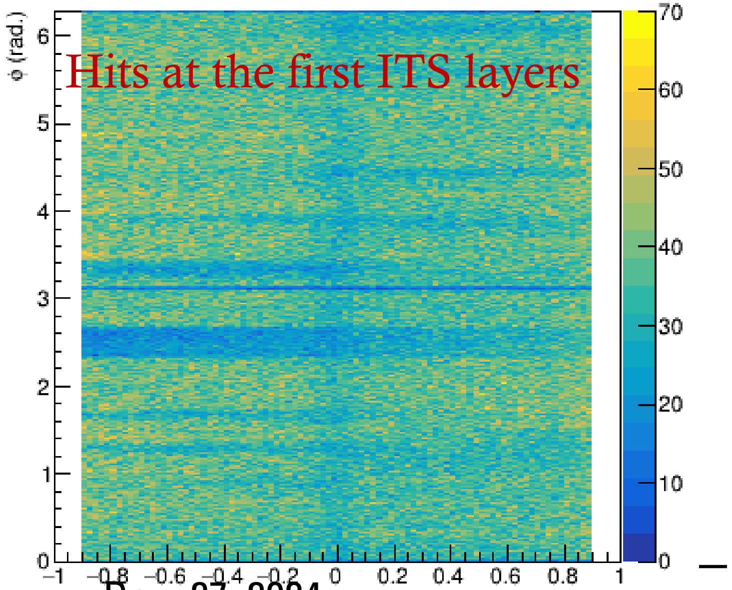
Detail Check

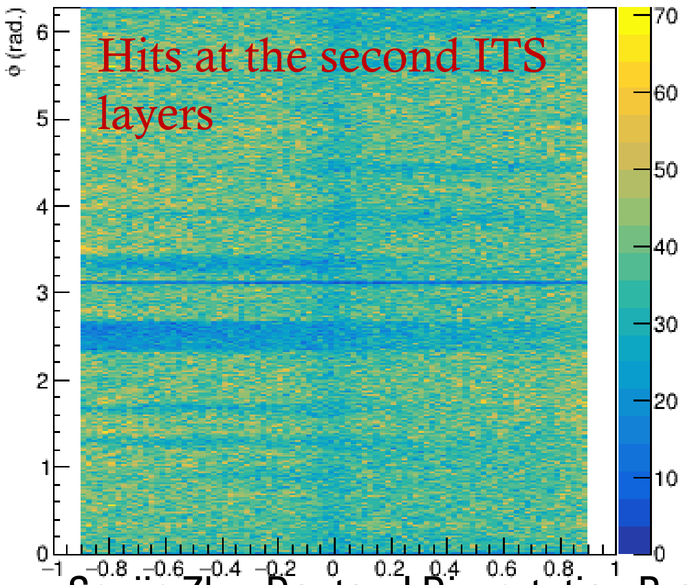
Before Cuts











The innermost two ITS layers have problems at specific ϕ region.

Observable

$$f(\phi) = \frac{1}{2\pi}(1 + 2\Sigma_{n=1}^{\infty} v_n cos(n(\phi - \Psi_{EP})))$$

- Basic idea (in isotropic case)

$$\iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} f(\phi) f'(\psi) \cos m(\phi - \psi) = v_m v'_m.$$

- Practical observable

Define $q_n = \Sigma_\mu e^{in\phi_\mu}$ for REF and $Q_n = \Sigma_\mu e^{in\psi_\mu}$ for POI in for per event.

$$V_{2,2}(J/\psi - tracklet) = Re(\frac{\Sigma_i (V_{2,2})_i W_i}{\Sigma_i W_i}) = v_2 v'_2$$

In the practical code, profiles will be filled to calculated $V_{2,2}$.

$$(V_{2,2})_{single\ event} = Re(\frac{Q_2 \bar{q_2}}{Q_0 q_0})$$

will be filled for each events with weight $W_{single\ event} = Q_0 q_0$.

Uncertainty estimation

- Uncertainty estimation in TProfile

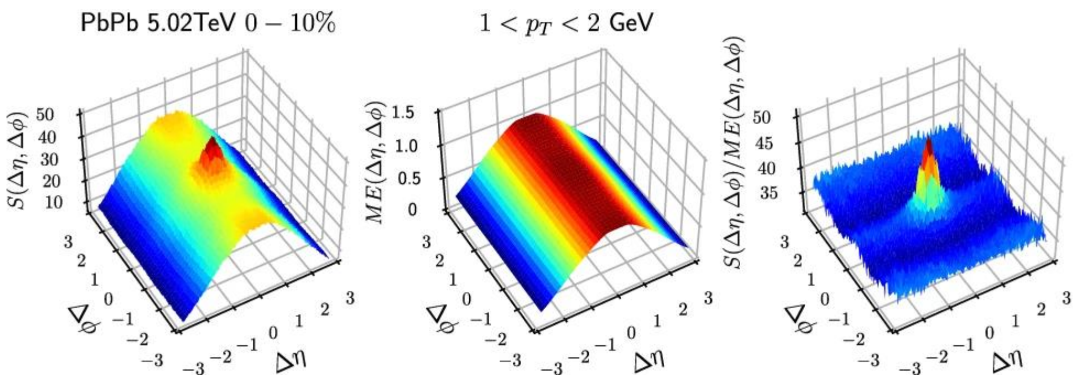
```
Double_t cont = p->fArray[bin];                    // sum of bin w *y
Double_t sum  = p->fBinEntries.fArray[bin];        // sum of bin weights
Double_t err2 = p->fSumw2.fArray[bin];            // sum of bin w * y^2
Double_t neff = p->GetBinEffectiveEntries(bin);  // (sum of w)^2 / (sum of w^2)
...
Double_t contsum = cont/sum;
Double_t eprim2  = TMath::Abs(err2/sum - contsum*contsum);
Double_t eprim   = TMath::Sqrt(eprim2);
...
return eprim/TMath::Sqrt(neff);
```

The proof are as below. The mean estimation is $\bar{x} = \frac{\Sigma_i w_i x_i}{\Sigma_i w_i}$.Thus,

$$\Delta^2(\bar{x}) = \frac{\Sigma_i w_i^2 \Delta^2(x_i)}{\Sigma_i w_i} = \frac{\Sigma_i w_i^2}{\Sigma_i w_i}\sigma^2$$

$$V_{2,2}(J/\psi - tracklet) = Re(\frac{\Sigma_i (V_{2,2})_i W_i}{\Sigma_i W_i}) = v_2 v_2'$$

Event-by-event



Correlation-by-correlation

Uncertainty estimation

Assuming a distribution with mean value μ and variance σ^2,

- In correlation by correlation case,

$$\{(x_i, w_i), 1 < i < N\}.$$

$$\bar{x} = \frac{\Sigma_i w_i x_i}{w_i} = \frac{\Sigma_i w_i \mu}{w_i} = \mu$$

$$\overline{x^2} - \bar{x}^2 = \frac{\Sigma_i w_i x_i^2}{w_i} - (\frac{\Sigma_i w_i x_i}{w_i})^2$$

$$= \frac{\Sigma_i w_i (\mu^2 + \sigma^2)}{\Sigma_i w_i} - \frac{1}{\Sigma_i w_i^2}(\Sigma_i w_i^2 x_i^2 + \Sigma_{i \neq j} w_i w_j x_i x_j)$$

$$= (1 - \frac{\Sigma_i w_i^2}{(\Sigma_i w_i)^2})\sigma^2 + \mu^2 - \frac{1}{\Sigma_i w_i^2}(\Sigma_i w_i^2 + \Sigma_{i \neq j} w_i w_j)\mu^2$$

$$= (1 - \frac{\Sigma_i w_i^2}{(\Sigma_i w_i)^2})\sigma^2$$

$$\{(x_{i,j}, w_{i,j}), 1 < i < n_j, 1 < N < j\},$$

$$W_j = \Sigma_{i=1}^{n_j} w_{i,j} \qquad X_j = \Sigma_{i=1}^{n_j} w_{i,j} x_{i,j} / W_j.$$

$$\bar{X} = \frac{\Sigma_j^N W_j X_j}{\Sigma_j^N W_j} = \mu$$

$$\sigma^2_{measured} = \overline{X^2} - \overline{X}^2 = \frac{\Sigma_j^N W_j X_j^2}{\Sigma_j^N W_j} - (\frac{\Sigma_j^N W_j X_j}{\Sigma_j^N W_j})^2$$

- In the measurement, the even-by-event uncertainty estimation should be corrected to correlation-by-correlation case. This can be done with a scale.

$$\sigma^2_{measured} = (\frac{\Sigma_j \frac{\Sigma_i^{n_j} w_{i,j}^2}{W_j}}{\Sigma_j W_j} - \frac{\Sigma_{i,j} w_{i,j}^2}{(\Sigma_{i,j} w_{i,j})^2})\sigma^2 = \frac{\Sigma_j \frac{\Sigma_i^{n_j} w_{i,j}^2}{W_j}}{\Sigma_j W_j}\sigma^2$$

- Finally $\Delta^2_{corrected} = \Delta^2_{TProfile} \frac{(\Sigma_j W_j)^2}{\Sigma_j W_j^2} \frac{\Sigma_j W_j}{\Sigma_j \frac{\Sigma_i^{n_j} w_{i,j}^2}{W_j}} \frac{\Sigma_{i,j} w_{i,j}^2}{(\Sigma_{i,j} w_{i,j})^2} = \Delta^2_{TProfile} \frac{\Sigma_j W_j}{\Sigma_j W_j^2} \frac{\Sigma_{i,j} w_{i,j}^2}{\Sigma_j \frac{\Sigma_i^{n_j} w_{i,j}^2}{W_j}}$

Non-uniform Correction

- Define acceptance function $A(\phi)$ for the reference track, and $A'(\psi)$ for J/ψ with condition $\int A(\phi)\frac{d\phi}{2\pi} = 1$ and $\int A'(\psi)\frac{d\psi}{2\pi} = 1$
- Now, $\iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} f(\phi) f'(\psi) \cos m(\phi - \psi)$ becomes

$$\iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} f(\phi) f'(\psi) A(\phi) A'(\psi) \cos n(\psi - \phi)$$
$$= \langle\cos(n\psi)\rangle\langle\cos(n\phi)\rangle + \langle\sin(n\psi)\rangle\langle\sin(n\phi)\rangle$$
$$+ \iiint d\phi d\psi A(\phi) A'(\psi) \Sigma_{n'=1}^{\infty} v_n v'_{n'} (\cos(n - n')(\psi - \phi) + cos(n + n')(\psi - \phi))$$

If ignoring all terms where $n \neq n'$,

$$\iiint d\phi d\psi \frac{d\Psi_{EP}}{2\pi} f(\phi) f'(\psi) A(\phi) A'(\psi) \cos n(\psi - \phi)$$
$$= \langle\cos(n\psi)\rangle\langle\cos(n\phi)\rangle + \langle\sin(n\psi)\rangle\langle\sin(n\phi)\rangle + v_n v'_n +$$
$$\iiint d\phi d\psi A(\phi) A'(\psi) v_n v'_n \cos 2n(\psi - \phi)$$
$$= \langle\cos(n\psi)\rangle\langle\cos(n\phi)\rangle + \langle\sin(n\psi)\rangle\langle\sin(n\phi)\rangle$$
$$+ v_n v'_n (1 + \langle\cos(2n\psi)\rangle\langle\cos(2n\phi)\rangle + \langle\sin(2n\psi)\rangle\langle\sin(2n\phi)\rangle)$$

Finally,

$$v_n v'_n = \frac{\langle\cos n(\psi-\phi)\rangle - \langle\cos(n\psi)\rangle\langle\cos(n\phi)\rangle - \langle\sin(n\psi)\rangle\langle\sin(n\phi)\rangle}{1 + \langle\cos(2n\psi)\rangle\langle\cos(2n\phi)\rangle + \langle\sin(2n\psi)\rangle\langle\sin(2n\phi)\rangle}$$

Merge run-by-run measurements

- Mean value

$$\mu_{merge} = \frac{\Sigma_{\text{cases}} \mu_{cases} N_{cases}}{\Sigma_{\text{cases}} N_{cases}}$$

(N_{case} is the number of J/ψ track pairs in one case.)

- In the discussion above, all uncertainties have been corrected into correlation-by-correlation case. So when run-by-run measurements are merged, all the measurement should be considered as correlation-by-correlation measurements.

$$\Delta^2_{merge} = \frac{\Sigma_k \left(\Delta^2_{run} \frac{(\Sigma_{i,j} w_{i,j})^2}{\Sigma_{i,j} w^2_{i,j}} \Sigma_{i,j} w^2_{i,j}\right)_k}{\left(\Sigma_k (\Sigma_{i,j} w_{i,j})_k\right)^2} = \frac{\Sigma_k \left(\Delta^2_{run} (\Sigma_{i,j} w_{i,j})^2\right)_k}{\left(\Sigma_k (\Sigma_{i,j} w_{i,j})_k\right)^2}$$

Scale uncertainty to variance

Get the summation of the scaled variance