Workshop on Electromagnetic Effects in Strongly Interacting Matter
ICTP-SAIFR, São Paulo, Brazil

Searches for EM Fields & CME in Heavy-Ion Collisions with the CMS Detector

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IF-UFRGS, SPRACE

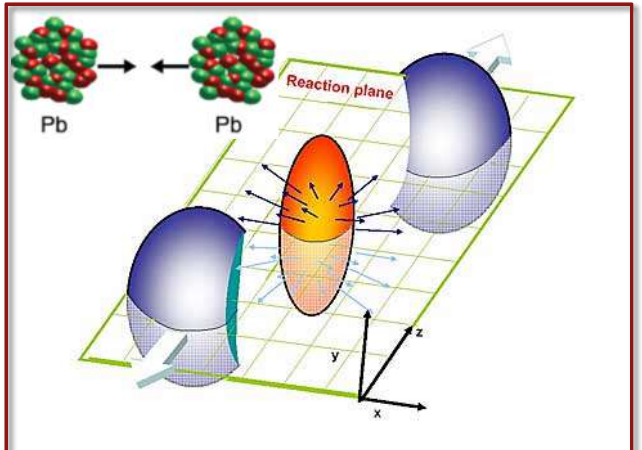
Outlook

Describe studies performed in

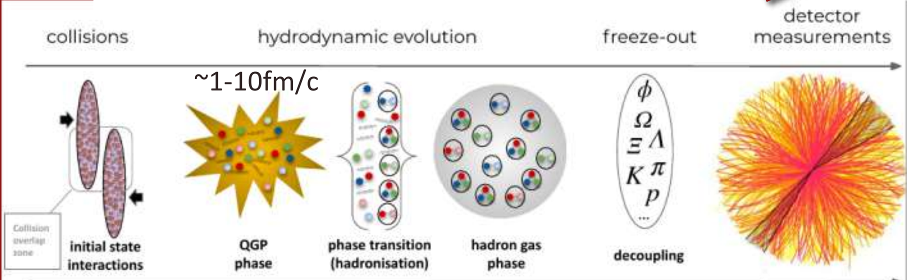
- Search for EM fields using elliptic flow of D^0 mesons
  - Phys. Lett. B **816**, 136253 (2021)

- Studies of CME using charge-dependent correlations in pPb and PbPb
  - Phys. Rev. C **97**, 044912 (2018); Phys. Rev. Lett. **118**, 122301 (2017)

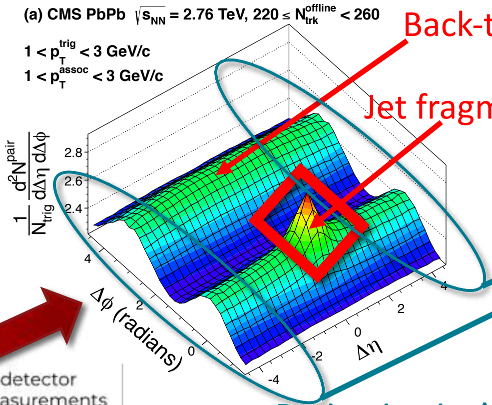
QGP & Azimuthal Correlations



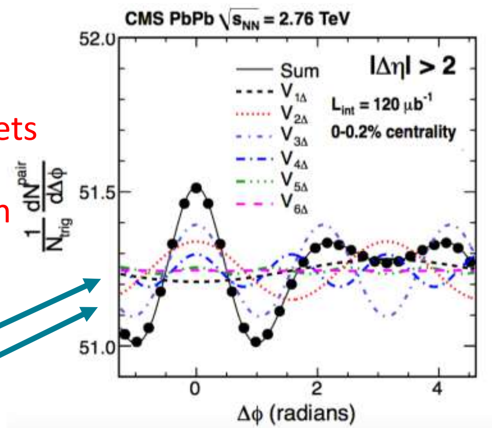
Fluctuating initial geometry + pressure



Two-particle correlations



Projecting in Δϕ the long-range correlations



$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1 + \sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

$V_{n\Delta} = v_n^2$

In Hydrodynamic models : v_2 (elliptic flow) and v_3 (triangular flow)

Related to medium response to initial collision geometry and its fluctuations

Electromagnetic (EM) Fields in AA Collisions

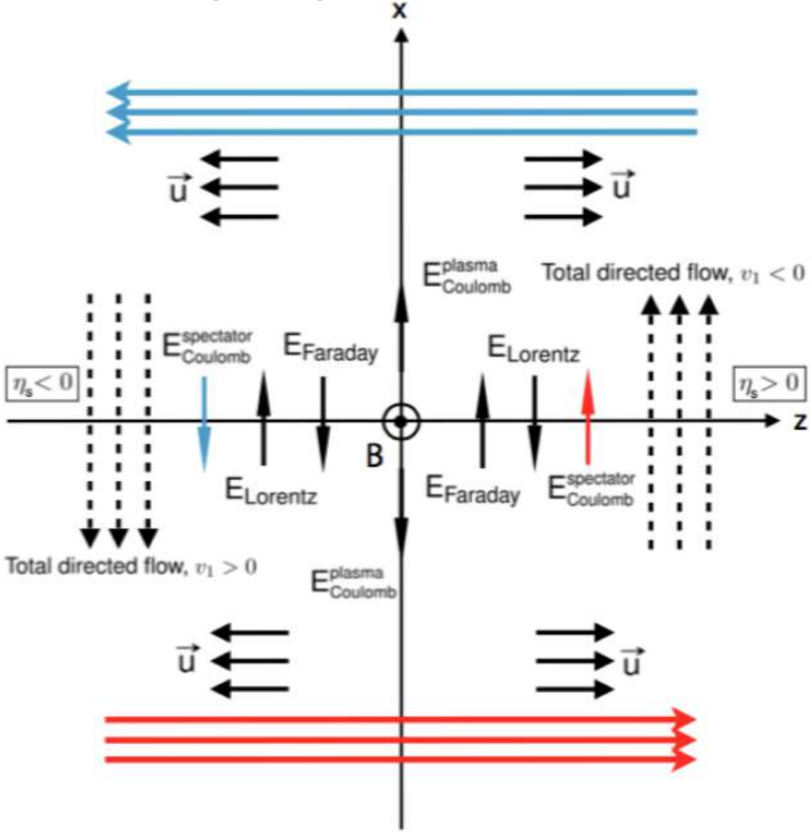
Strong and short lived EM fields expected to be created

- Contributions from spectators and participants
  - Produce significant charge-odd contributions to flow coefficients

Measurements would help to constraint medium parameters

- Drag coefficient
- Electrical conductivity

Collision impact parameter in x direction



Phys. Rev. C **98**, 055201 (2018)

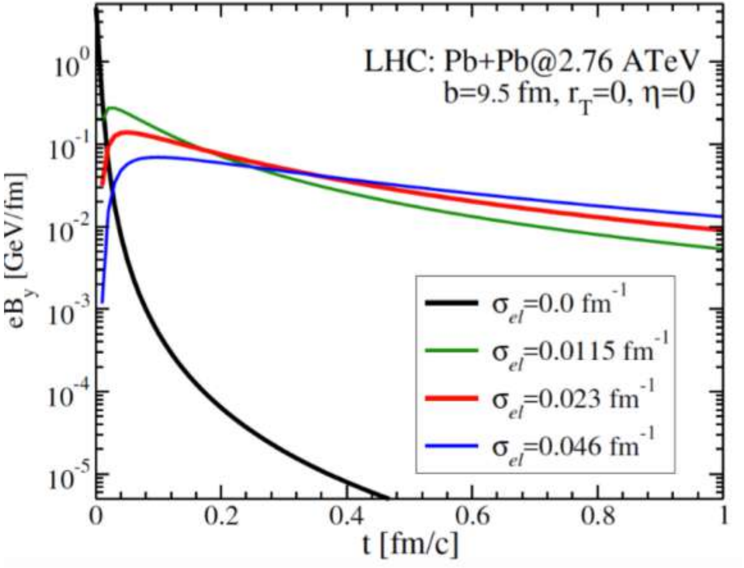
Effect in Flow Coefficients Measurements

QGP can increase lifetime of EM fields

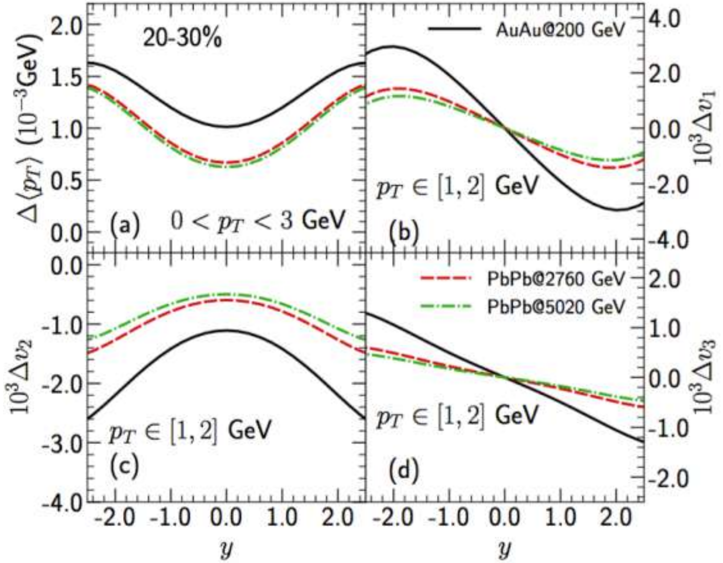
EM fields can introduce

- Rapidity odd (even) contributions to v_n , with n odd (even)

$\Delta \equiv (\pi^+ - \pi^-)$



Mod. Phys. Lett. A **35**, 2050324 (2020)

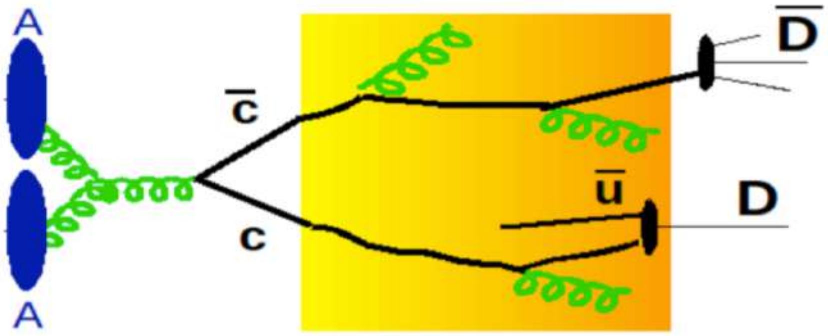


Phys. Rev. C **98**, 055201 (2018)

Studies using D^0 mesons

Why use D^0 ($\bar{u}c$) mesons?

- Heavy-flavor quarks mostly produced in primordial stages of collision (~0.1 fm/c)
  - $M_{c/b}$ >> typical medium temperatures
    - Low probability of annihilation



Phys.Rev.C 90 (2014) 2, 024911

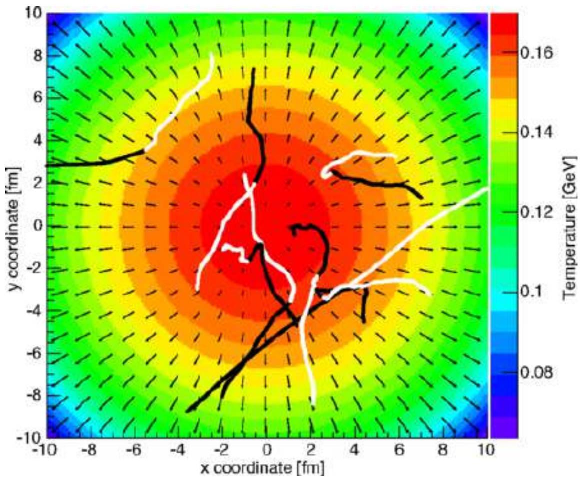


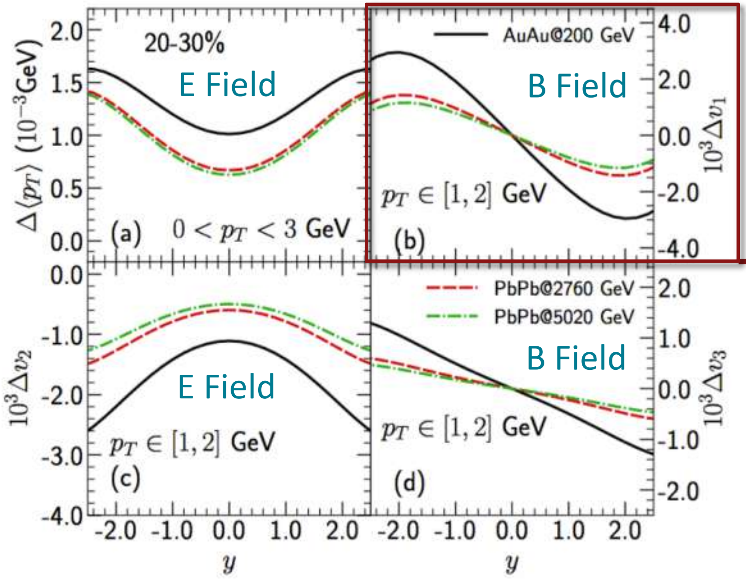
Illustration of few $c\bar{c}$ pair trajectories in the expanding medium after 10 fm/c

- EM fields expected to vanish relatively fast
  - Peak magnitude at around 0.1 - 0.2 fm/c

Effect on Δv_1 between $D^0(\bar{u}c)$ and $\bar{D}^0(u\bar{c})$

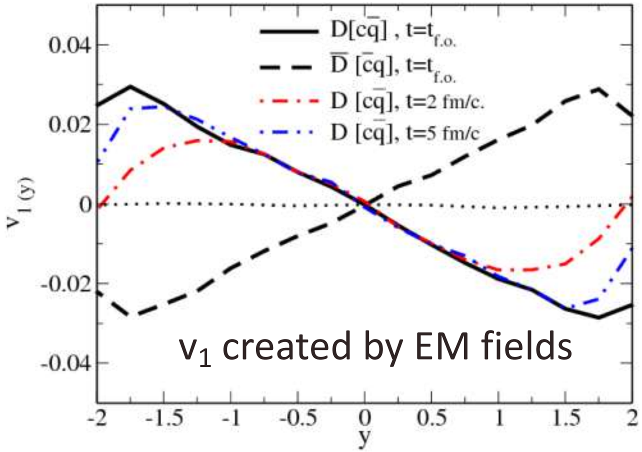
Non-zero Δv_1 mainly due to magnetic field from spectators

$\Delta \equiv (\pi^+ - \pi^-)$



Phys. Rev. C **98**, 055201 (2018)

Larger effect on D^0 mesons



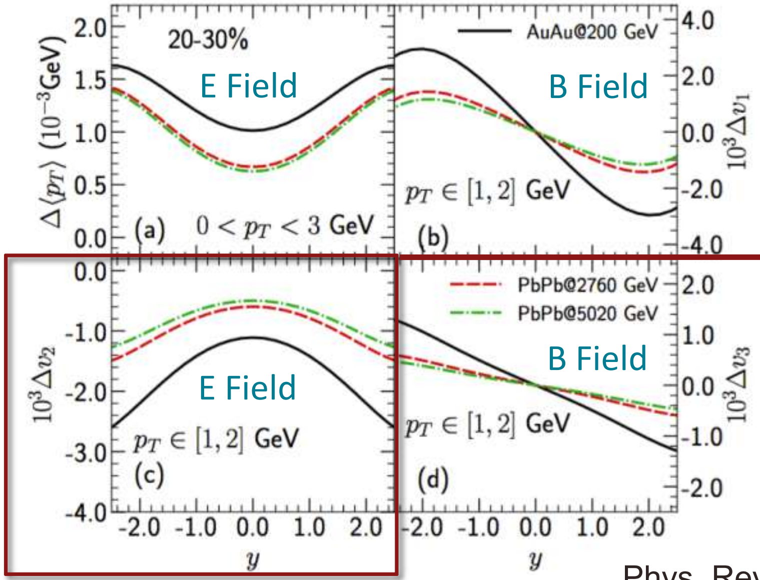
Phys. Lett. B **768**, 260 (2017)

Effect on Δv_2 of D^0 Mesons

Mostly produced by Electric field from collision participants

- Coulomb interaction

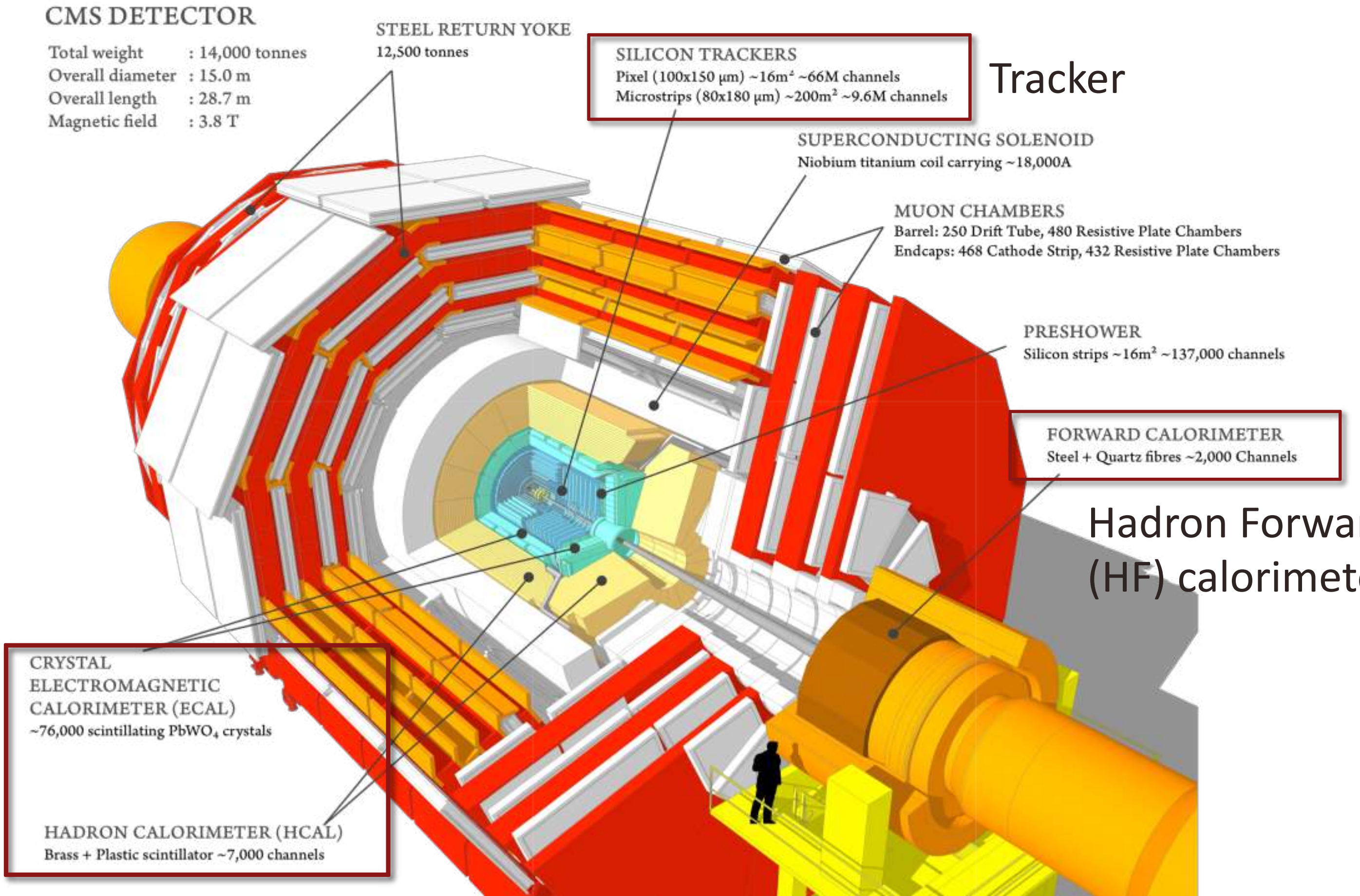
$\Delta \equiv (\pi^+ - \pi^-)$



Bigger effect on D^0 meson Δv_2?

Phys. Rev. C **98**, 055201 (2018)

The CMS Detector



Tracker

Hadron Forward (HF) calorimeters

ECAL/HCAL

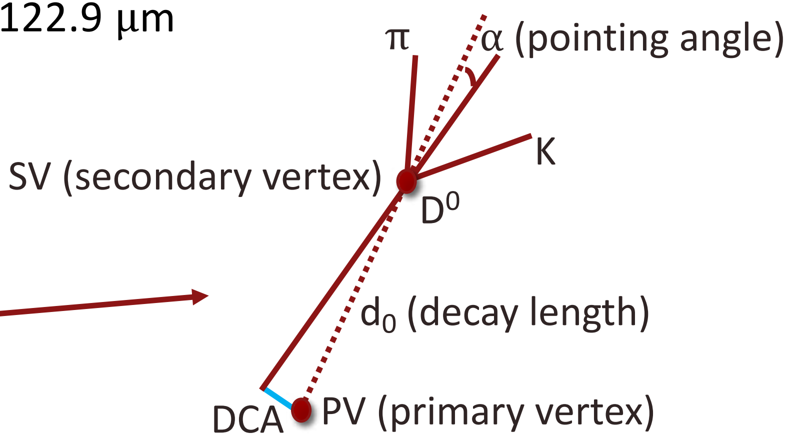
D^0 Reconstruction & Selection

Minimum Bias events from PbPb collisions at 5.02 TeV

$D^0(\bar{u}c) \rightarrow K\pi$, BR = 3.88 $\pm$ 0.05 %, $c\tau(D^0)$ = 122.9 μm

D^0 Reconstruction

- ❑ Pairing oppositely charged tracks (no PID)
- ❑ Secondary vertex reconstruction



Prompt D^0 candidate selection

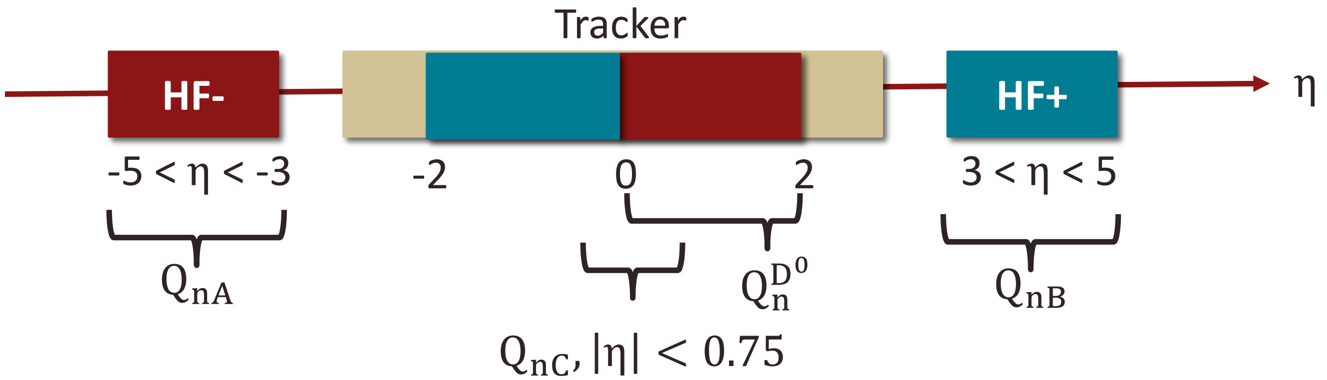
- ❑ MVA Boosted Decision Tree (BDT)
  - D^0 variables
    - $d_0/\sigma(d_0)$, α, SV probability
  - Tracks ($K\pi$)
    - Distance of closest approach significance, error on p_T, number of hits

Nonprompt D^0 (from B hadron decay) contamination (as systematic uncertainty)

- ❑ Estimate contribution using DCA variable (nonprompt D^0 enriched region for DCA > 0.012 cm)

Flow Measurement: Scalar Product Method

v_2, v_3, $\Delta v_2(D^0 - \overline{D^0})$ as functions of centrality, rapidity and p_T



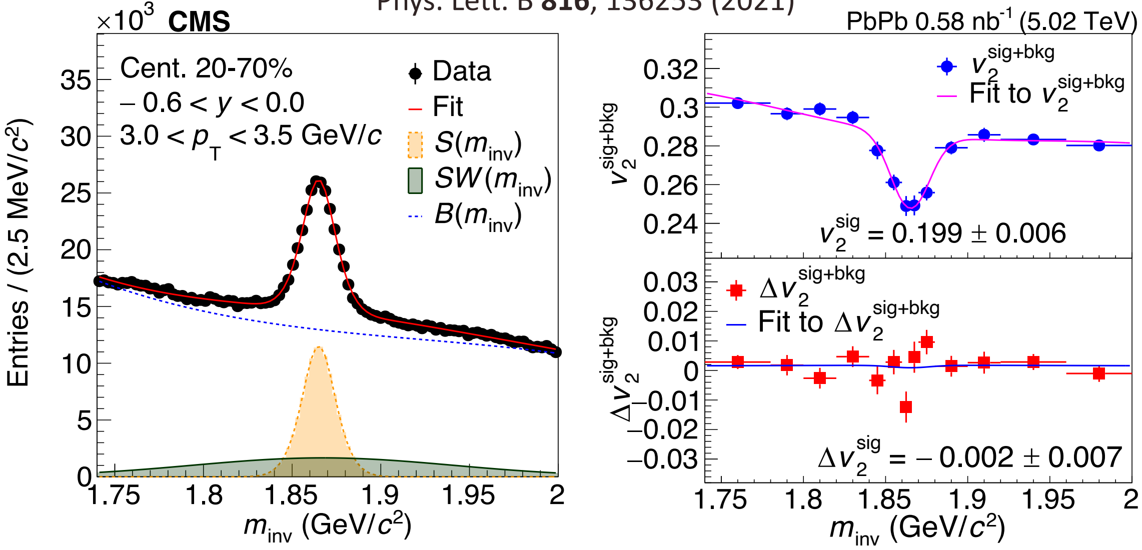
- $Q_n = \sum_j w_j e^{in\phi_j}$ (w_j = tower E_T for HF, w_j = track p_T for tracker, w_j = 1 for $D^0, \overline{D^0}$)

- $v_n\{SP\} = \dfrac{\langle Q_n^{D^0/\overline{D^0}} Q_{nA}^* \rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ $\quad \Delta v_n\{SP\} = \dfrac{\langle Q_n^{D^0} Q_{nA}^* \rangle - \langle Q_n^{\overline{D^0}} Q_{nA}^* \rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ Average over all events

Signal Extraction: Simultaneous Fit on Mass

Simultaneous fit on mass distribution and v_n (Δv_n) versus mass

Phys. Lett. B **816**, 136253 (2021)



- Mass fit: background (3[rd] order polynomial), signal (double Gaussian), swap (single Gaussian)
- v_n background (linear function), Δv_n (background is canceled)

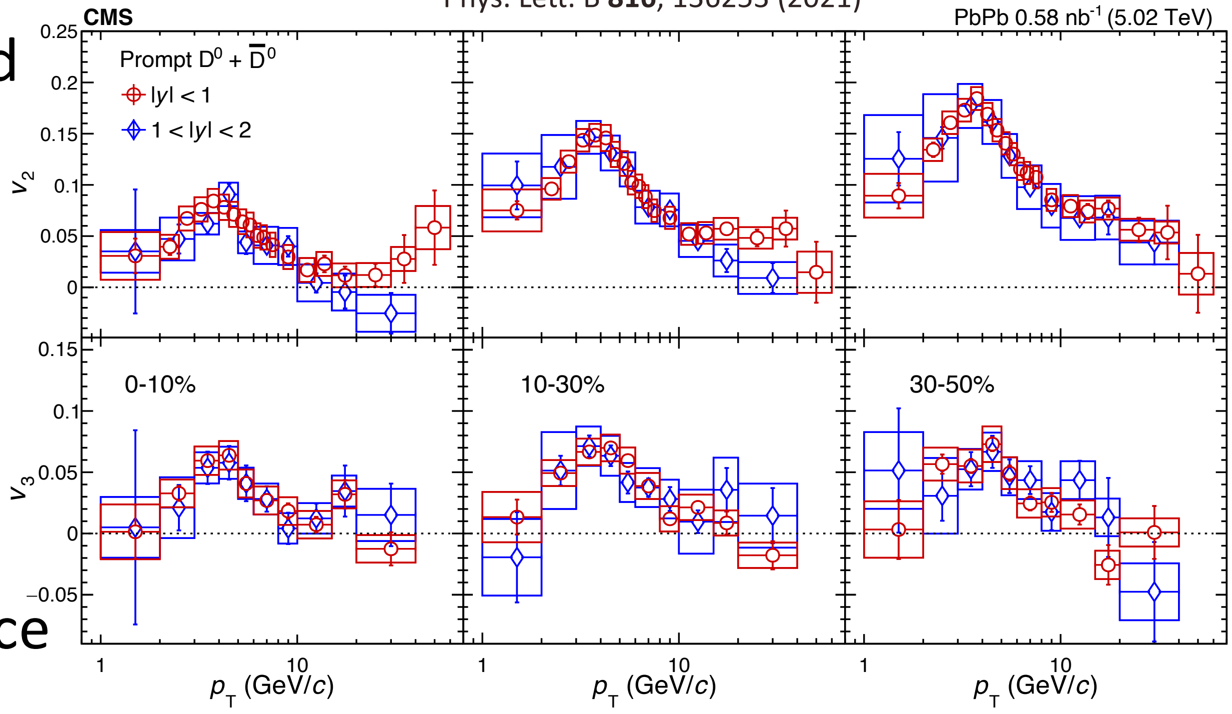
Flow Coefficients (v_2 & v_3) as Functions of p_T

Mid-rapidity Region (|y|<1) & forward region (1<|y|<2)

v_2 : considerable dependence on centrality

v_3 : small dependence on centrality

Phys. Lett. B **816**, 136253 (2021)



$\Delta v_2(D^0 - \overline{D^0})$ as Function of Rapidity

Electric field can generate non-zero Δv_2

- Currently, no theoretical predictions for D^0 mesons
  - Predictions for charged hadrons at LHC energies: $\Delta v_2 \sim -0.001$ [Phys. Rev. C **98**, 055201 (2018)]
  - Expected bigger values for D^0 [Phys. Rev. C **98**, 055201 (2018)]

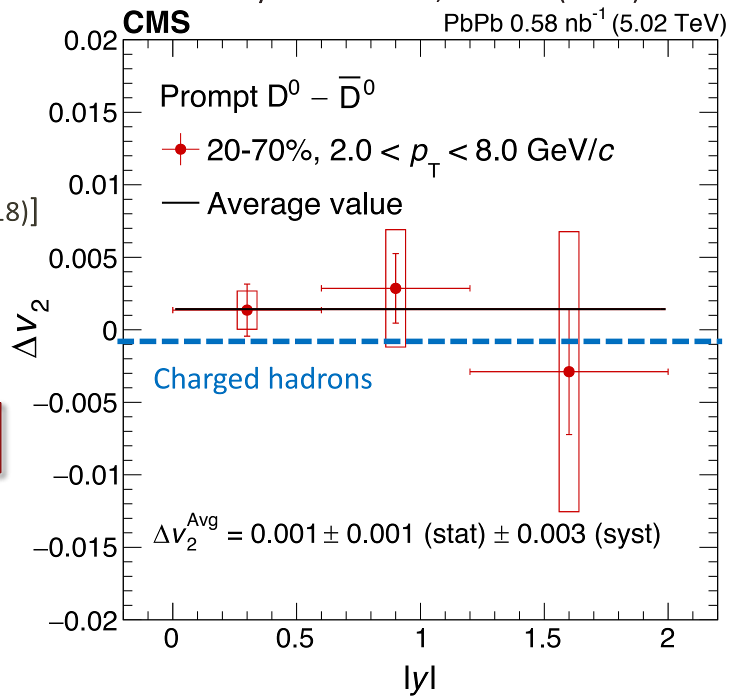
Average value extracted with a fit to data

- $\Delta v_2^{\text{Fit}} = 0.001 \pm 0.001\ (\text{stat}) \pm 0.003\ (\text{syst})$

Comparable to the values for charged hadrons

- Constrain medium properties: electric conductivity

Phys. Lett. B **816**, 136253 (2021)



What can we try next in the CMS experiment?

Need to improve precision of the measurements

- Statistical uncertainties: more data collected in the next LHC runs
- Systematics uncertainties: improving methods to measure heavy-flavor v_n

Reaction Plane Detector (RPD) in future runs → Spectator plane

- Directed flow of
  - Charged particles, V^0 particles & D^0 mesons
  - Leptons from Z^0 boson decay [Phys. Lett. B **816**, 136271 (2021)]

More ideas???

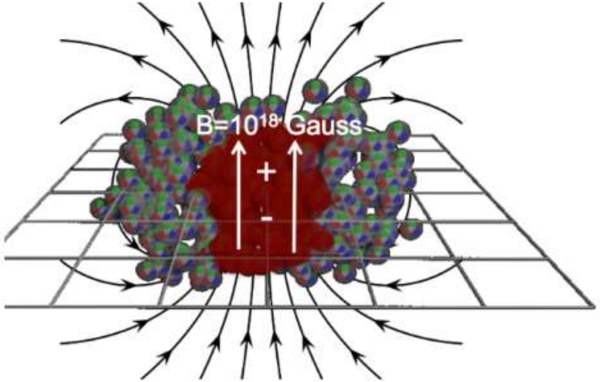
Chiral Magnetic Effect (CME) Studies

USING UNIDENTIFIED CHARGED PARTICLES

Chiral Magnetic Effect in AA Collisions

In peripheral ultrarelativistic nucleus-nucleus collisions

- Possible domains of chirality imbalance + strong magnetic field
  - Expected to lead to an electric current perpendicular to the reaction plane
    - Final-state charge separation phenomenon: chiral magnetic effect (CME)



    - A signature
      - Back-to-back emissions of opposite-sign (OS) charged hadrons
      - Collimated emissions of same-sign (SS) charged hadrons

Searches for CME in AA Collisions

3-particle correlators (contain P-odd term)

- $\gamma \equiv \frac{\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle}{v_{2,c}} = \frac{\langle Q_{112} Q^*_{2,HF\pm} \rangle}{\sqrt{\frac{\langle Q_{2,HF\pm} Q^*_{2,HF\mp} \rangle \langle Q_{2,HF\pm} Q^*_{2,trk} \rangle}{\langle Q_{2,HF\mp} Q^*_{2,trk} \rangle}}}$

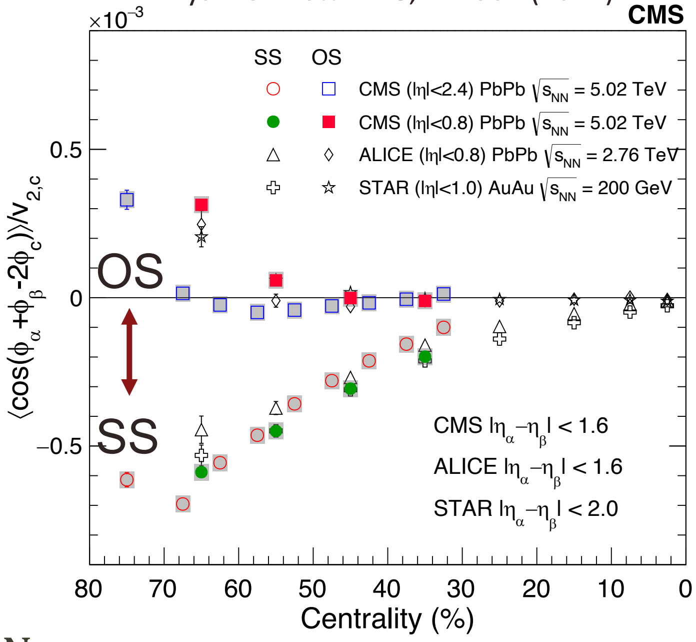
  Phys. Rev. C **70**, 057901 (2004)

  - $Q_{112} \equiv \frac{\left(\sum_{j=1} w_j e^{i\phi_j}\right)^2 - \sum_{j=1} w_j^2 e^{i2\phi_j}}{\left(\sum_{j=1} w_j\right)^2 - \sum_{j=1} w_j^2}$

Experiments observed CME-like charge dependent correlations

- But background expected to be of same order of $\Delta\gamma(OS - SS)$ [mainly charge-dependent ones $\propto 1/N$ (N event multiplicity)]

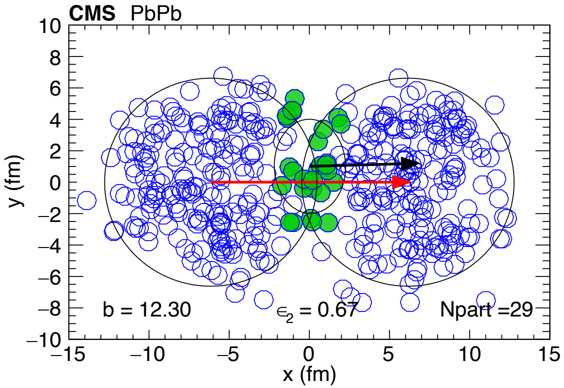
Phys. Rev. Lett. **118**, 122301 (2017)

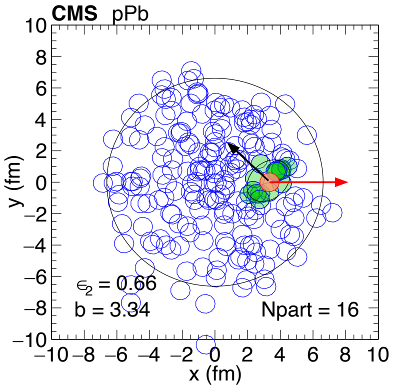


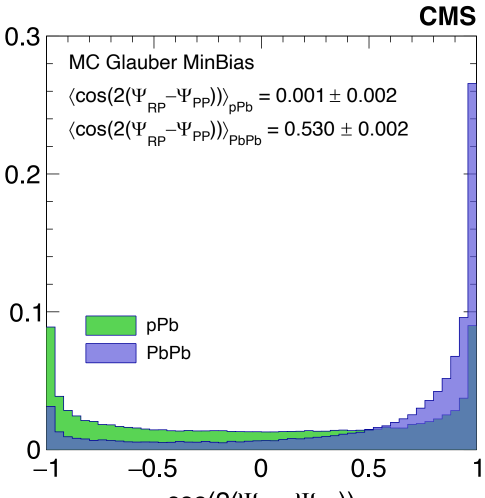
CME Studies in the CMS Experiment

Strategy

- The CME effect is expected to be negligible in pPb collisions
  - Angle between the direction of $\vec{B}$ and the event plane expected to be randomly distributed







Phys. Rev. Lett. **118**, 122301 (2017), Phys. Rev. C **96**, 024901 (2017)

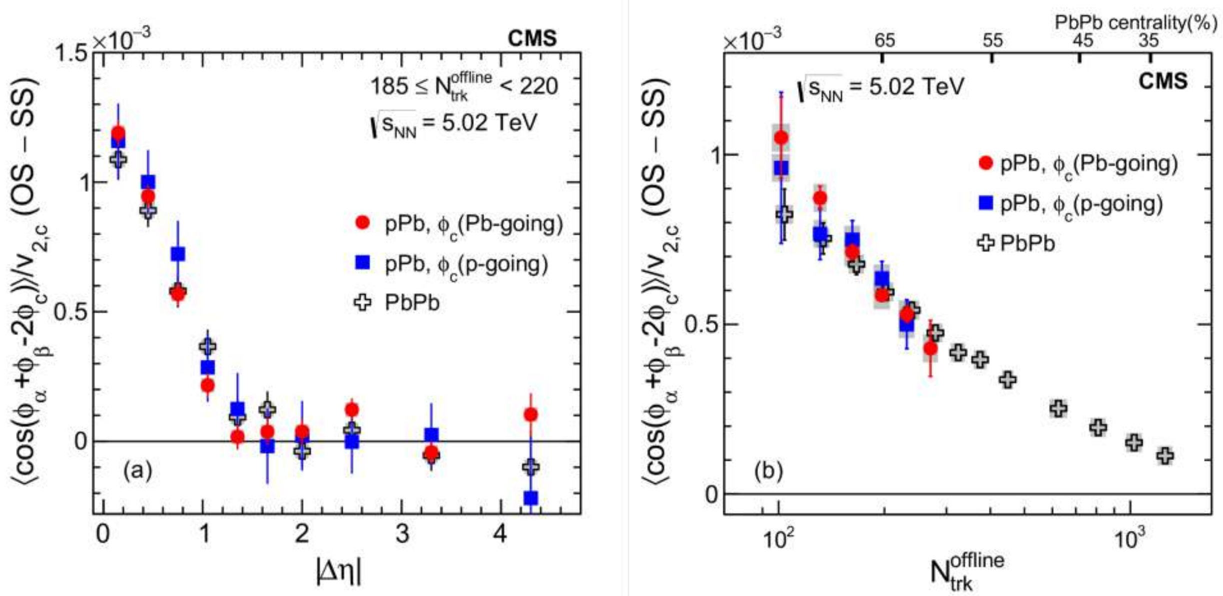
Comparison of pPb & PbPb for $\Delta\gamma$ (OS - SS)

Compatible within uncertainties

Why background is identical in pPb and PbPb?

- ❑ What is the origin of background in $\Delta\gamma$?

Phys. Rev. Lett. **118**, 122301 (2017)



Observables & Strategy (I)

To minimize Ψ_2-independent background (non-flow)

- Use rapidity gap of 2 units
  - Particles α e β in the Tracker ($|\eta| < 2.4$)
  - Particles c in the HF detector ($4.4 < |\eta| < 5$)

The Ψ_2-dependent background is modeled using
(from local charge conservation coupled to elliptic flow)

- $\Delta\gamma^{BKG} = \kappa_2 \cdot v_2 \cdot \Delta\delta$ Lect. Notes Phys. **871**, 503 (2013)
  - $\delta \equiv \langle\cos(\phi_\alpha - \phi_\beta)\rangle$ is the two-particle correlator
  - κ is a constant independent of v_2 (undetermined)

How much of the observed charge-dependent correlations come from this source?

Observables & Strategy (II)

Weak correlation between Ψ_2 and Ψ_3 → negligible charge separation effect w.r.t. Ψ_3

- ❑ CME signal free 3rd-order harmonic charge-dependent correlator
  - $\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$
  - Similar to $\Delta\gamma^{BKG}$: $\Delta\gamma_{123} = \kappa_3 \cdot v_3 \cdot \Delta\delta$

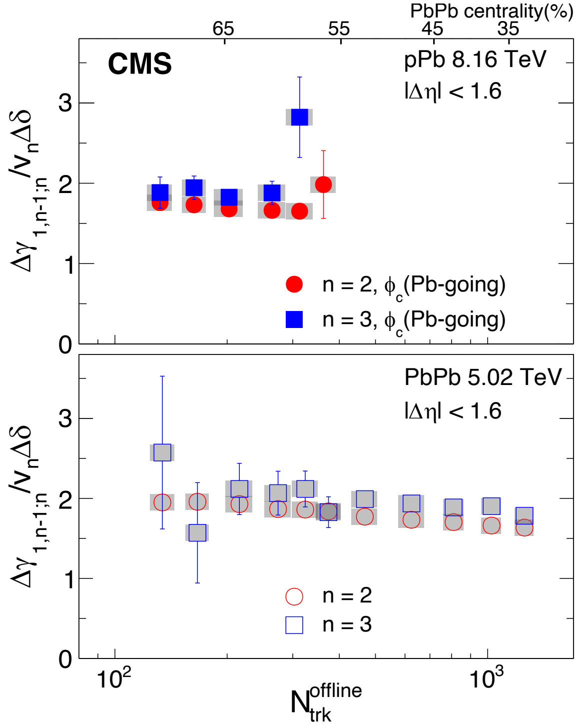
Assumption to check

- ❑ If charge dependence of the 3-particle correlators is dominated by the effect of local charge conservation coupled with the anisotropic flow (defining $\gamma \equiv \gamma_{112}$)
  - Expected to have: $\frac{\Delta\gamma_{112}}{v_2\Delta\delta} \approx \frac{\Delta\gamma_{123}}{v_3\Delta\delta}$

Results

$$\left(\Delta\delta^{pPb} > \Delta\delta^{PbPb}\ \&\ v_2^{pPb} < v_2^{PbPb}\right) \rightarrow \Delta\gamma^{pPb} \approx \Delta\gamma^{PbPb}$$

- Also observed compatibility in $|\Delta\eta|$, $|\Delta p_T|$ and $\bar{p}_T$



Phys. Rev. C **97**, 044912 (2018)

Event-Shape Engineering Method

Tentative to establish linearity $\Delta\gamma^{\mathrm{BKG}} \sim v_2$

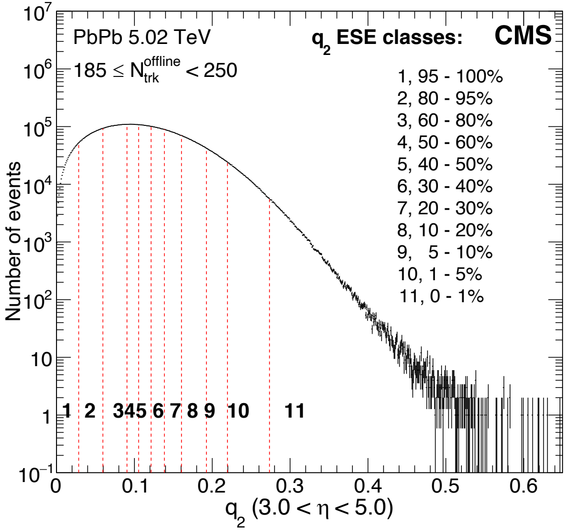
- Trying to quantify the amount of CME signal

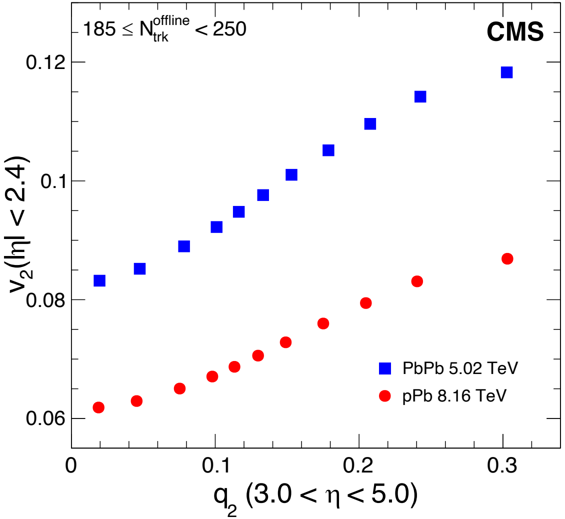
In a narrow centrality or event multiplicity range

- Events are further classified in terms of event ellipticity

In HF detector

$$q_2 = \left\| \frac{\sum_j w_j e^{2i\phi_j}}{\sum_j w_j} \right\|$$





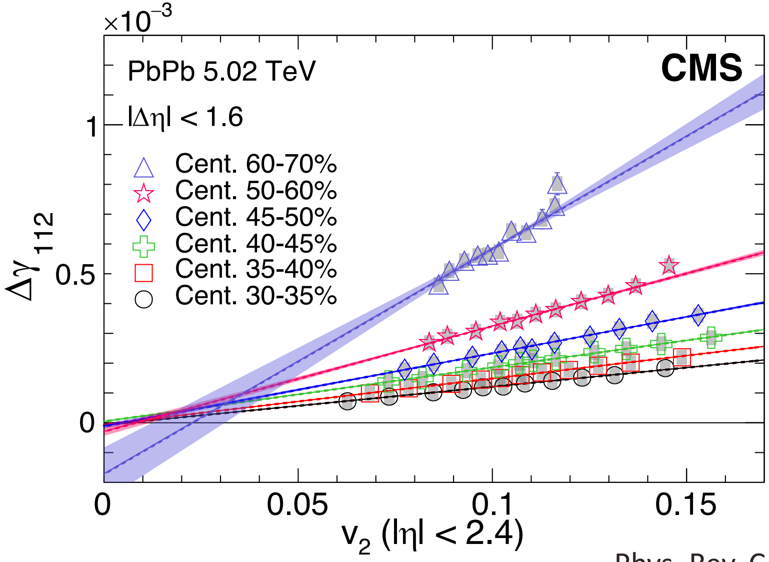
Phys. Rev. C **97**, 044912 (2018)

Results (I)

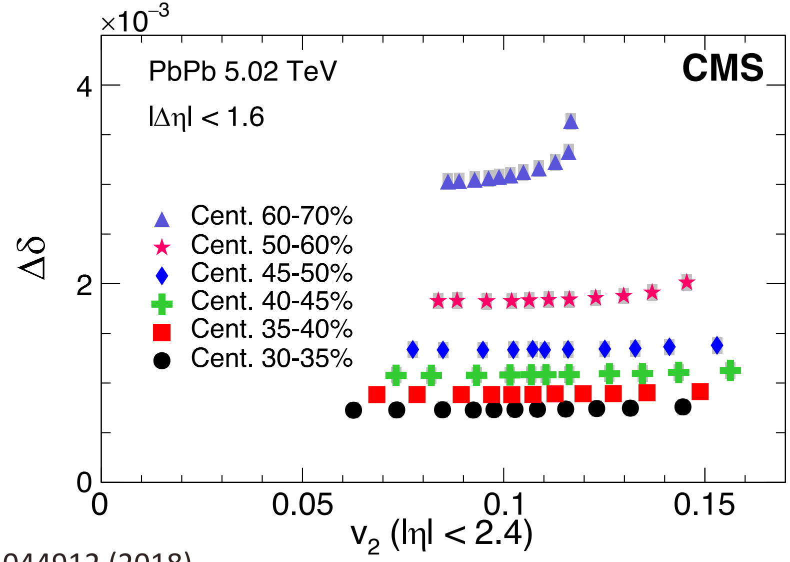
Nonzero intercept value of the γ correlators → strength of the CME

PbPb in centrality bins

Linear, intercepting close to zero



Δδ not really independent of q_2/v_2



Phys. Rev. C **97**, 044912 (2018)

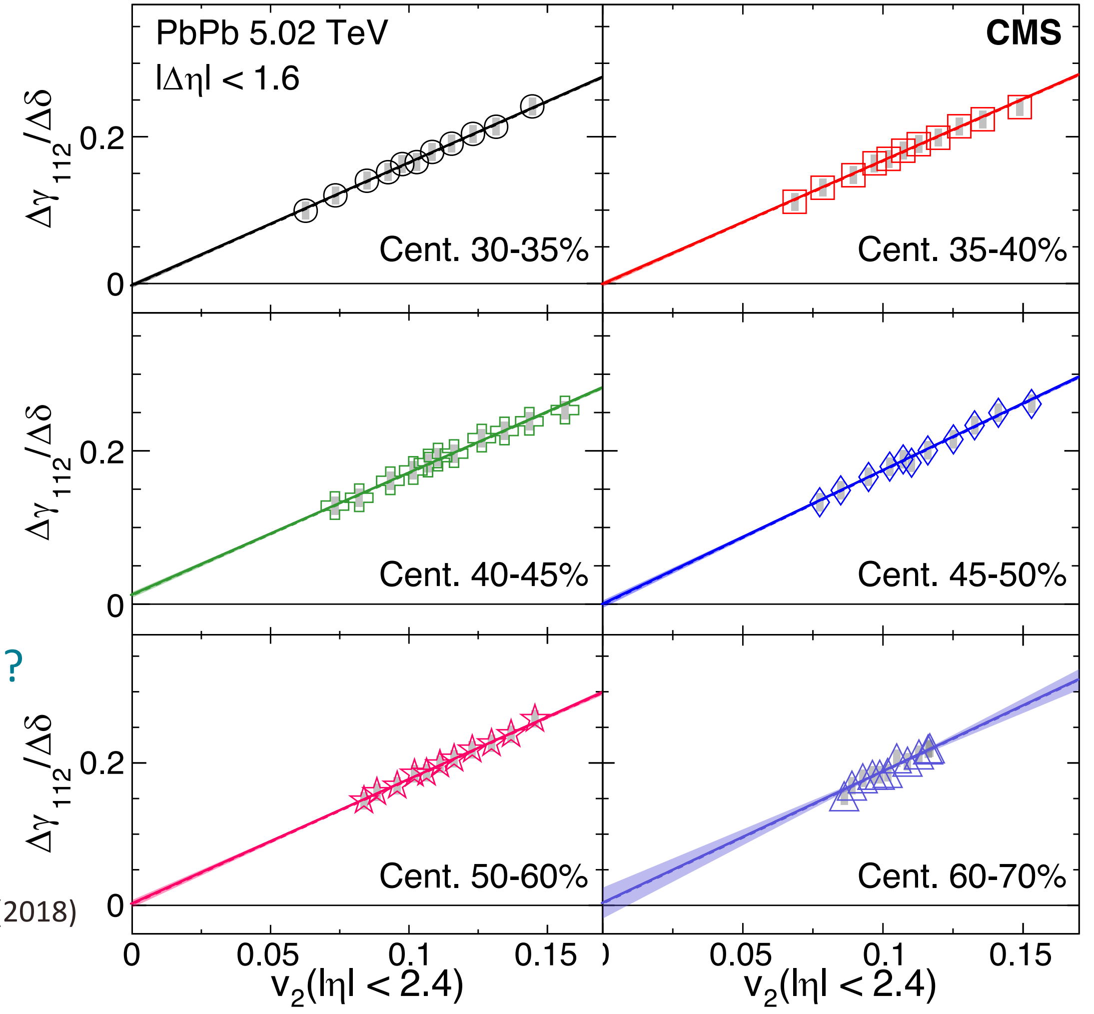
Results (II)

PbPb in centrality bins

- Use the ratio

$$\frac{\Delta\gamma}{\Delta\delta} = \kappa v_2 + \frac{\Delta\gamma^{\text{CME}}}{\Delta\delta}$$

What is the effect from non-flow???



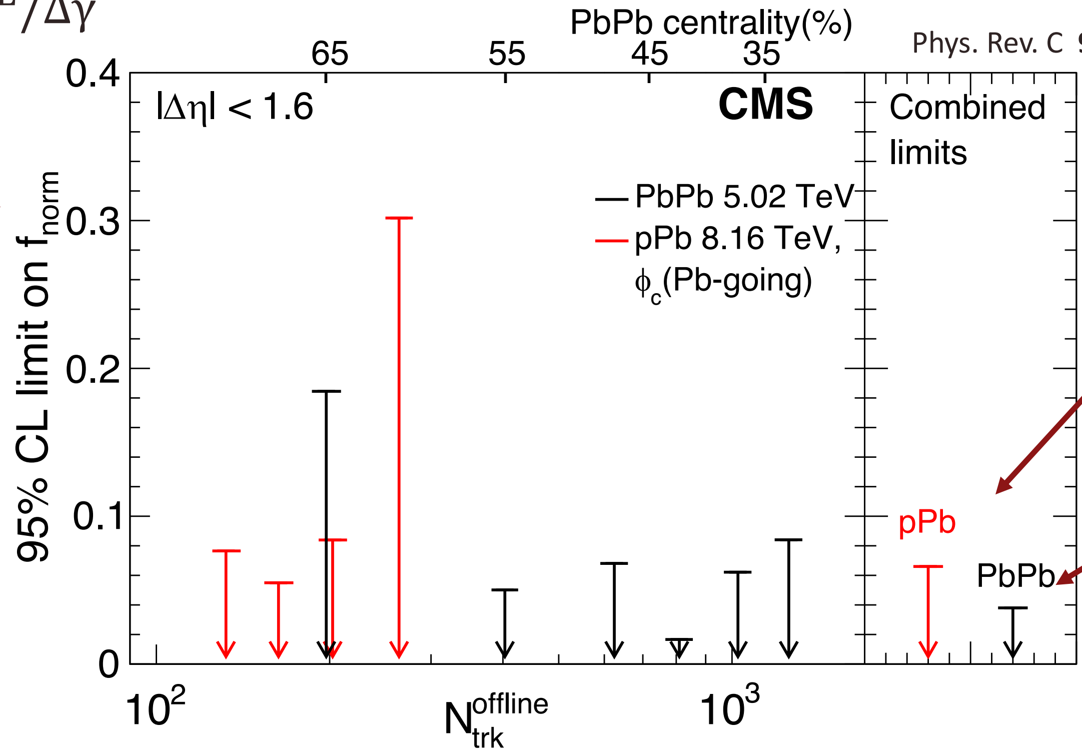
Phys. Rev. C **97**, 044912 (2018)

Upper Limits @ 95% C.L. in PbPb Collisions

Suppose a non-negative CME signal

$f_{norm} = \Delta\gamma^{CME}/\Delta\gamma$

Phys. Rev. C **97**, 044912 (2018)



PbPb cent.: 30 -70%

pPb mult.: 120-300

$\Delta\gamma^{CME}/\Delta\gamma$ < 7%

What can we try next in the CMS experiment?

Some methods have been tried in the RHIC and LHC experiments

- 1) Event-shape engineering
  [Phys. Rev. C 89, 044908 (2014); Phys. Rev. C 97, 044912 (2018); Phys. Lett. B 777, 151 (2018)]
- 2) Isobar collisions [Phys. Rev. C **105**, 014901 (2022)]
- 3) Measurements w.r.t. spectator and participant plane [Phys. Rev. Lett. **128** (2022) 092301]

Method "3)" showed a hint of possible CME in AuAu collisions

- ~2σ significance

Reaction Plane Detector (RPD) in future runs → Spectator plane

- Can try also method "3)"?

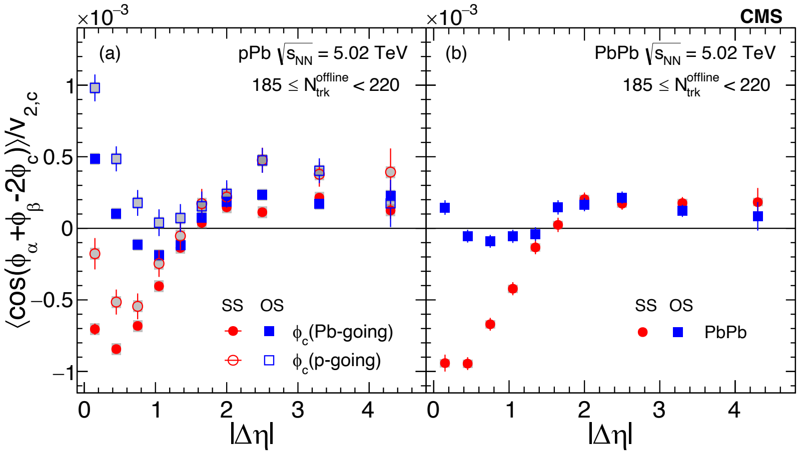
More ideas???

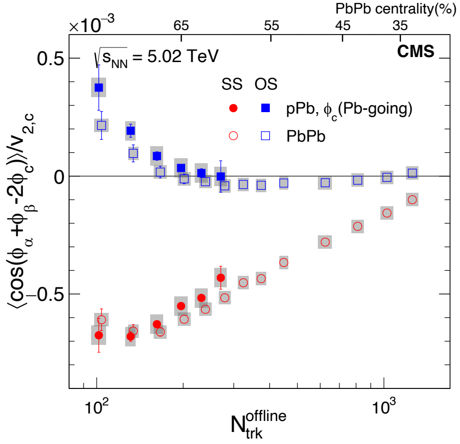
Thank You!

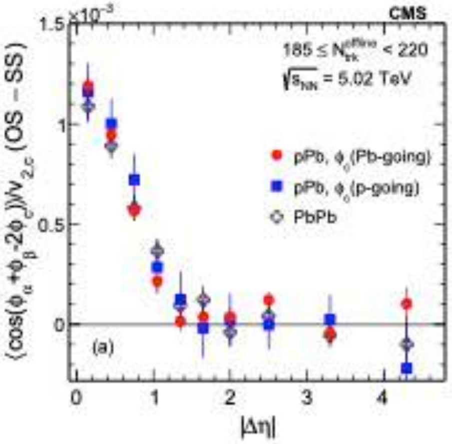
THIS MATERIAL IS BASED UPON WORK SUPPORTED BY THE SÃO PAULO RESEARCH FOUNDATION (FAPESP) GRANTS NO. 2018/01398-1. ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS EXPRESSED IN THIS MATERIAL ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF FAPESP.

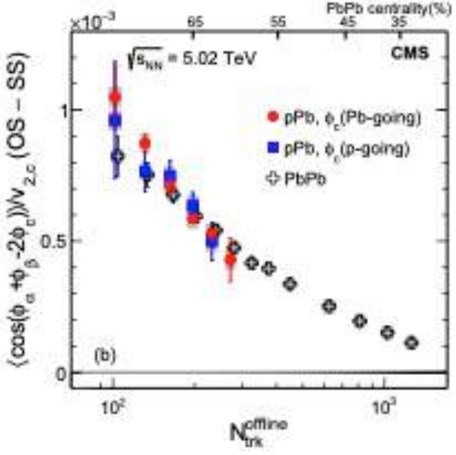
FAPERGS GRANT NO. 22/2551-0000595-0, CNPQ GRANT NO. 407174/2021-4.

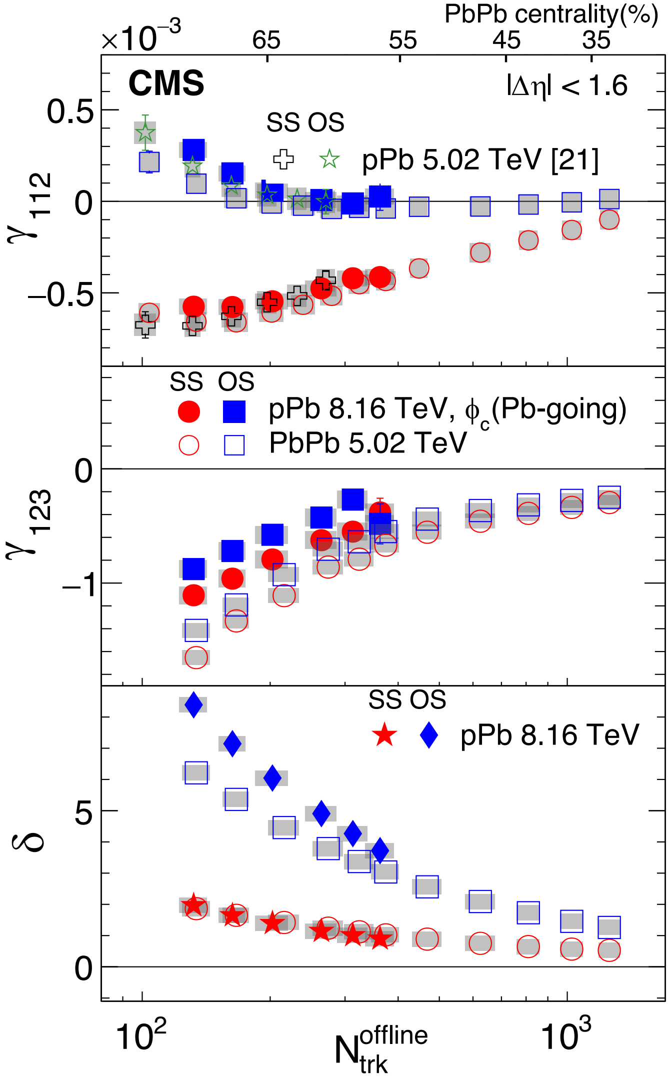
BACKUP

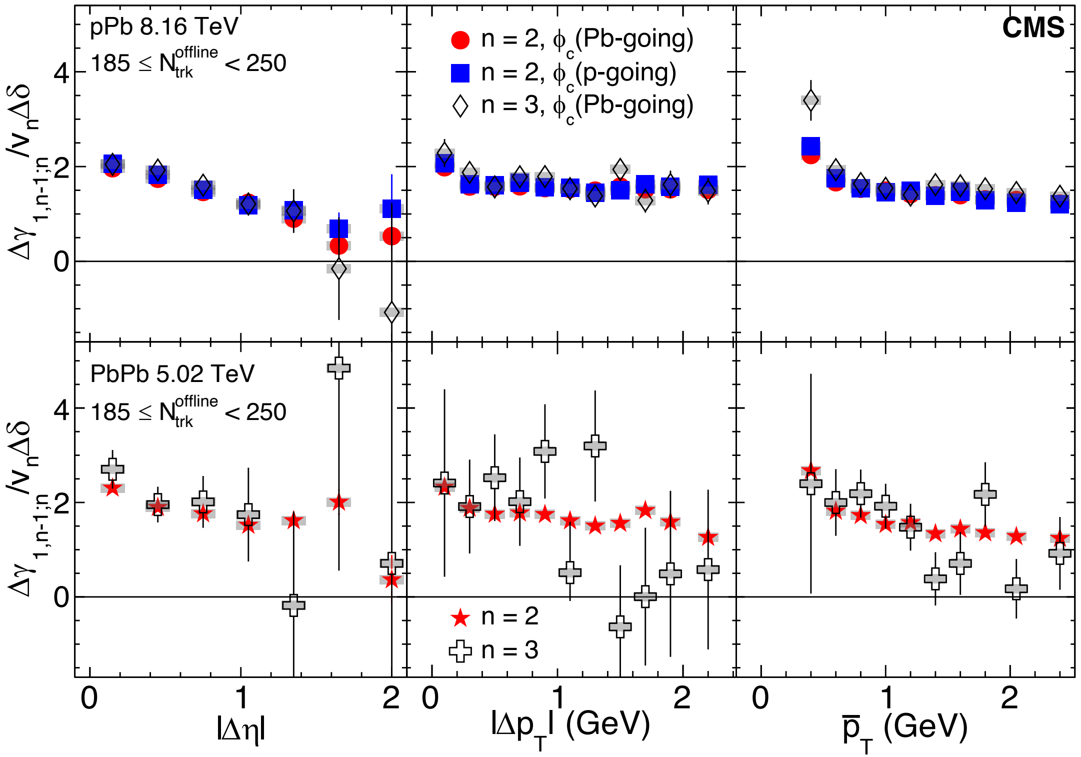

CMS
(a)
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
$185 \le N_{trk}^{offline} < 220$
(b)
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
$185 \le N_{trk}^{offline} < 220$
SS OS
ϕ_c(Pb-going)
ϕ_c(p-going)
PbPb
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$
$\times 10^{-3}$
$|\Delta\eta|$


PbPb centrality(%)
65
55
45
35
$\sqrt{s_{NN}}$ = 5.02 TeV
CMS
SS OS
pPb, ϕ_c(Pb-going)
PbPb
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$
$\times 10^{-3}$
$N_{trk}^{offline}$


CMS
$185 \le N_{trk}^{offline} < 220$
$\sqrt{s_{NN}}$ = 5.02 TeV
pPb, ϕ_c(Pb-going)
pPb, ϕ_c(p-going)
PbPb
(a)
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$ (OS − SS)
$\times 10^{-3}$
$|\Delta\eta|$

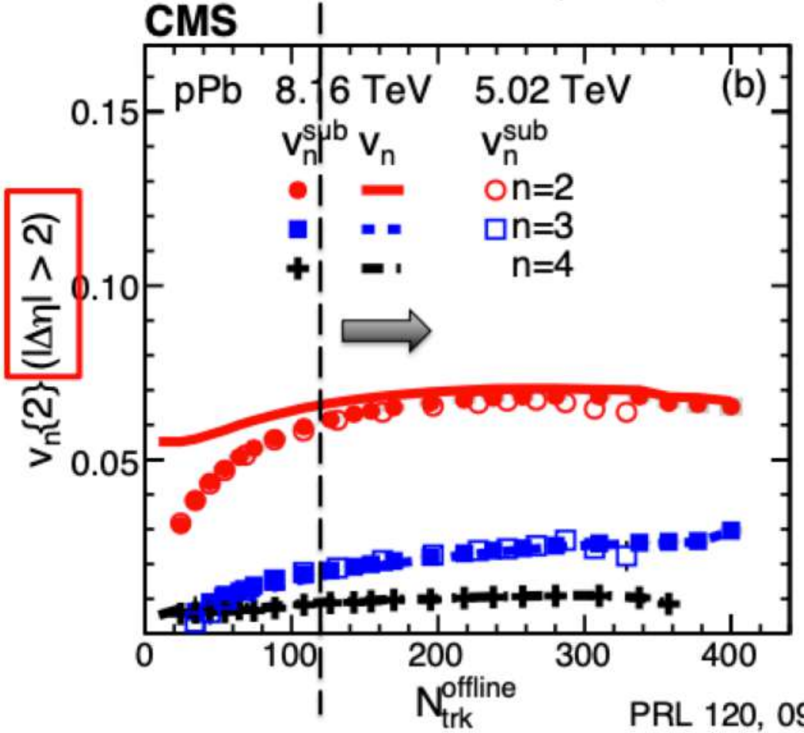

PbPb centrality(%)
65
55
45
35
$\sqrt{s_{NN}}$ = 5.02 TeV
CMS
pPb, ϕ_c(Pb-going)
pPb, ϕ_c(p-going)
PbPb
(b)
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$ (OS − SS)
$\times 10^{-3}$
$N_{trk}^{offline}$


CMS
PbPb centrality(%)
65
55
45
35
$\times 10^{-3}$
$|\Delta\eta| < 1.6$
SS OS
pPb 5.02 TeV [21]
γ_{112}
0.5
0
−0.5
SS OS
pPb 8.16 TeV, ϕ_c(Pb-going)
PbPb 5.02 TeV
γ_{123}
0
−1
SS OS
pPb 8.16 TeV
δ
5
0
10^2
10^3
$N_{trk}^{offline}$


pPb 8.16 TeV
$185 \leq N_{trk}^{offline} < 250$
$n = 2, \phi_c$(Pb-going)
$n = 2, \phi_c$(p-going)
$n = 3, \phi_c$(Pb-going)
CMS
$\Delta\gamma_{1,n-1;n}/v_n\Delta\delta$
4
2
0
PbPb 5.02 TeV
$185 \leq N_{trk}^{offline} < 250$
n = 2
n = 3
0
1
2
$|\Delta\eta|$
$|\Delta p_T|$ (GeV)
$\bar{p}_T$ (GeV)

Ψ_{EP}-independent BKG

$$\langle \cos 2(\phi_\alpha - \Psi_{EP}) \rangle \cong \frac{\langle \cos 2(\phi_\alpha - \phi_c) \rangle}{v_{2,c}}$$



Slides
From Z.Tu QM2018

Negligible with (1) large $|\Delta\eta|$ and (2) high multiplicities

Slides
From Z.Tu QM2018

Origin of background in Δγ?

$$\gamma = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{EP}\right)\right\rangle \cong \frac{\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\phi_c\right)\right\rangle}{v_{2,c}}$$

Ψ_{EP}-independent

between **α** (**β**) and **c**

short-range correlations
(jets, clusters etc.)

"Nonflow"

Ψ_{EP}-dependent

between **α** and **β**
(jet, clusters etc.)

⊗

both correlate to Ψ_{EP}
(elliptic flow)

Charge-dep. due to charge conservation, ordering etc.