Heavy-Ion Meeting (HIM)
IBS, Daejeon, Korea, April 21-22, 2017

Recent pPb Results from CMS

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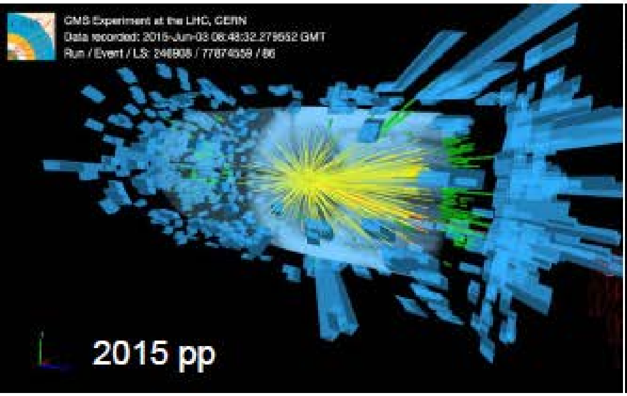
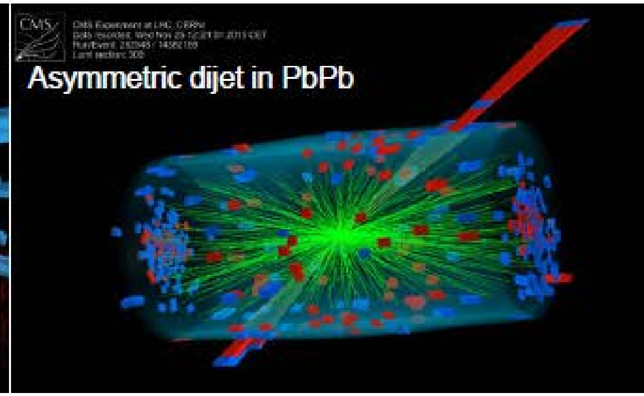
for the CMS Collaboration

Exciting New Results from RUN II Data

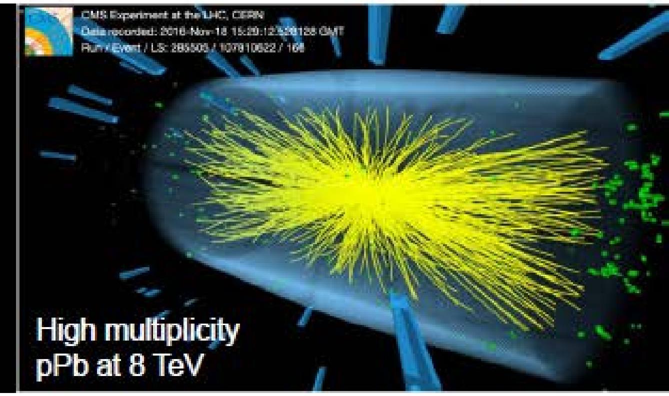
2015+2016 13 TeV pp



2015 5 TeV pp & PbPb



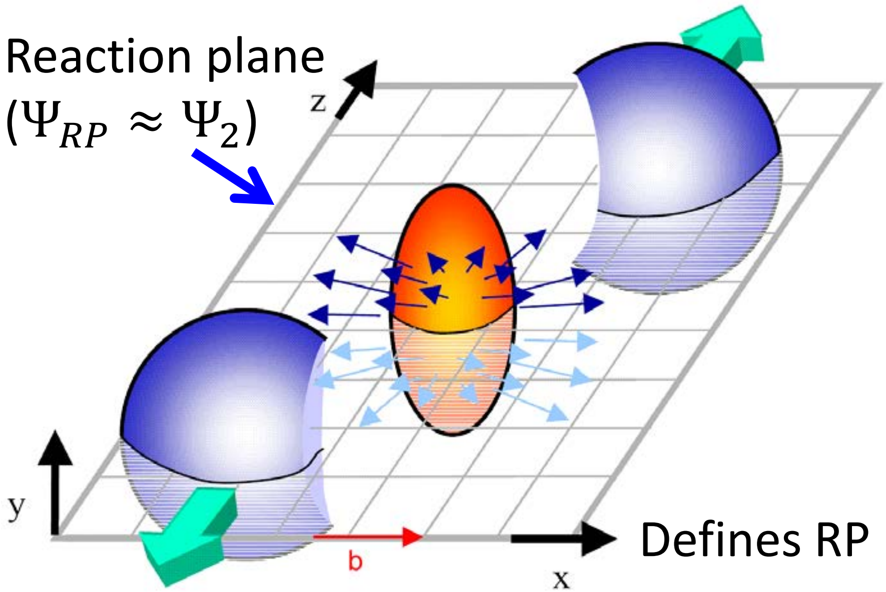
2016 5 & 8 TeV pPb



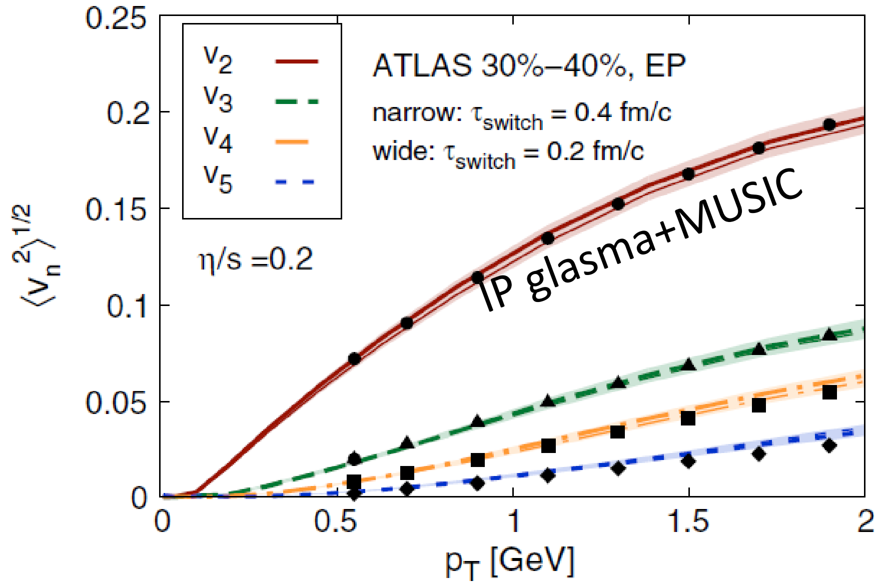
- □ Azimuthal anisotropy in pp, pPb, and PbPb
- □ Charge separation signals from pPb
- □ Gluon parton distribution function in Pb nucleus

pA for Azimuthal Anisotropy

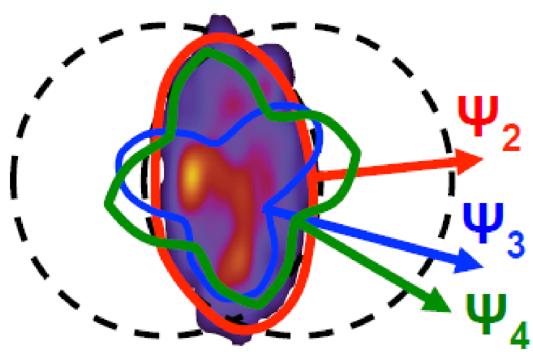
Hydrodynamics Flow in AA



C. Gale et al., PRL110, 012302 (2013)

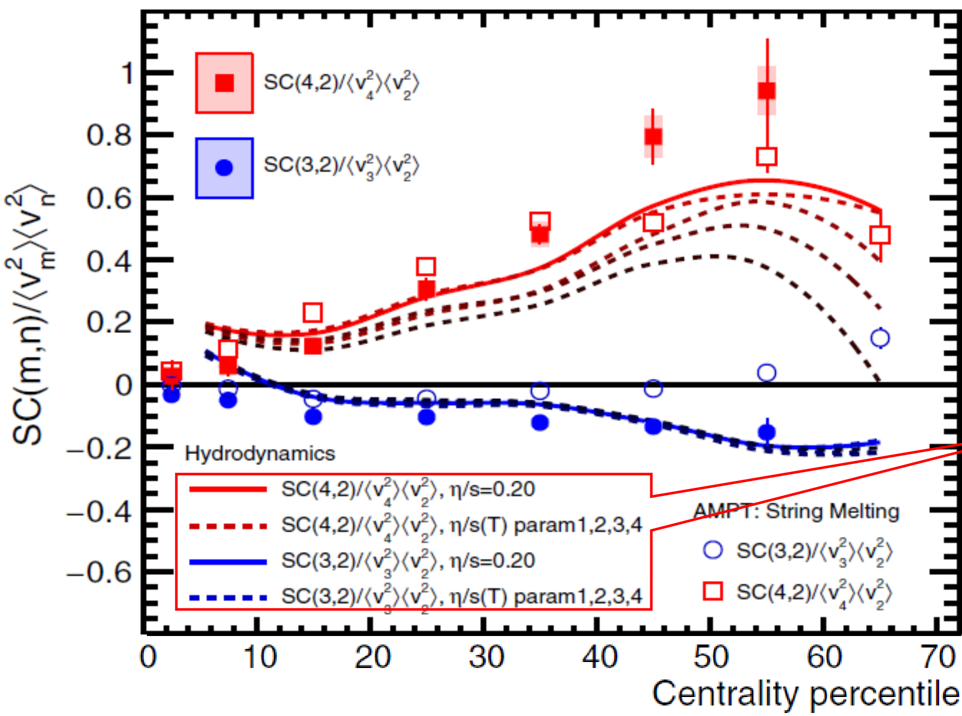


- □ Azimuthal angle distribution is fitted by:
  $dN/d\phi \propto 1 + 2\sum_n [v_n(p_T, \eta)\cos(n(\phi - \Psi_n))]$
- □ Coefficients, v_n, depends on
  - Initial-state geometry and its fluctuation
  - Medium transport coefficients (e.g., $\eta/s, \cdots$)



Symmetric Cumulant (SC)

- Diagonal terms (v_n^2) understood well in AA with hydrodynamics
- **How to study non-diagonal terms?**
- Symmetric cumulant
  - Correlation between harmonics based on the 4-particle cumulant method: $SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$

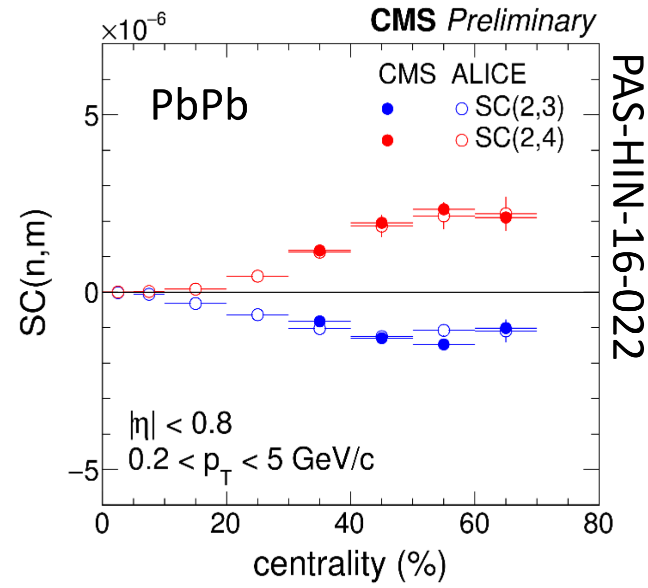


- Non-flow free in first order
  - $SC(2,3) < 0$: v_2 and v_3 are anti-correlated.
  - $SC(2,4) > 0$: v_2 and v_4 are correlated.
- Model calculations show that
  - Odd-even: IS fluctuation
  - Even-even: Medium response ⊗ IS fluctuation

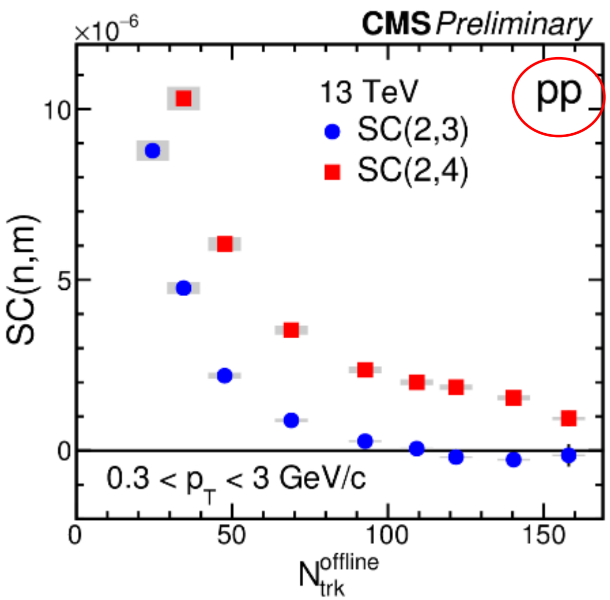
[Ref.] ALICE, PRL117, 182301 (2016)

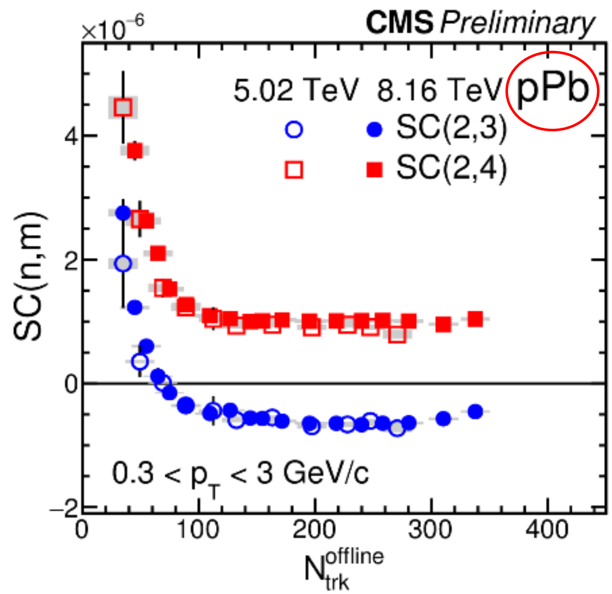
SC Results from CMS

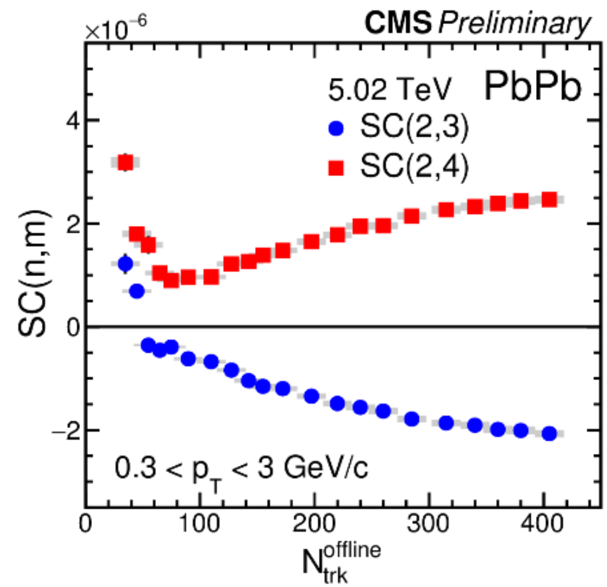
→ Nice agreement between CMS and ALICE in PbPb



- ☐ Similar pattern for SC in all systems (pp, pPb and PbPb)
- ☐ No energy dependence in pPb
- ☐ Normalization needed for the comparison across collision systems from pp to PbPb

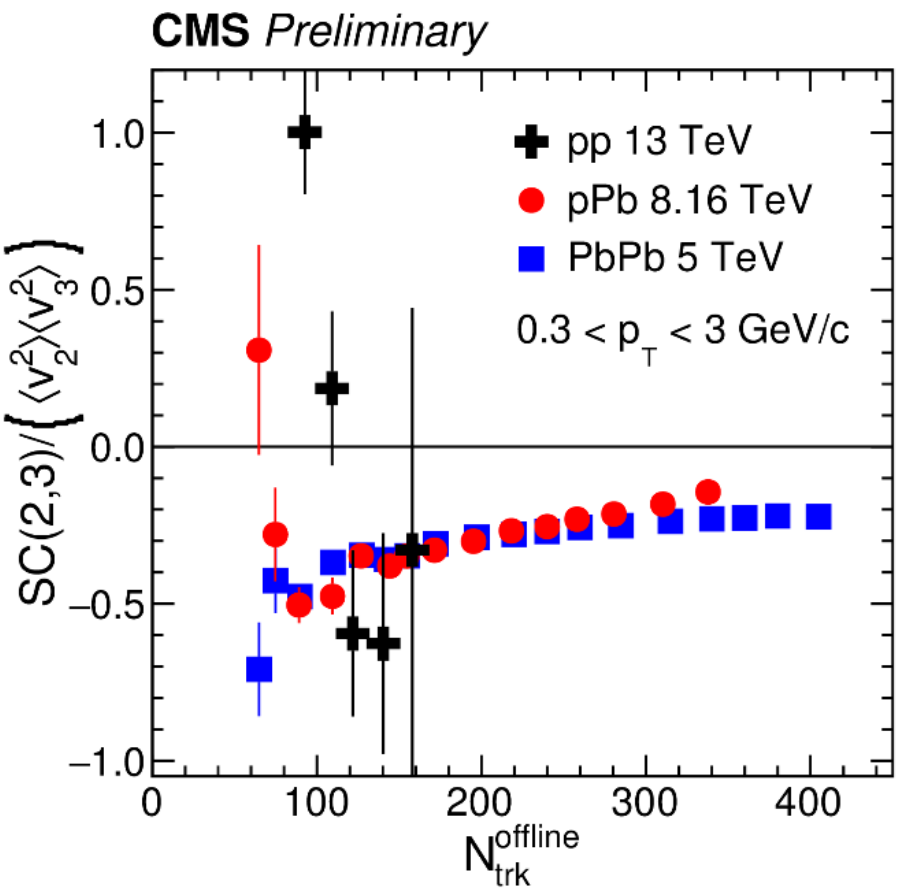


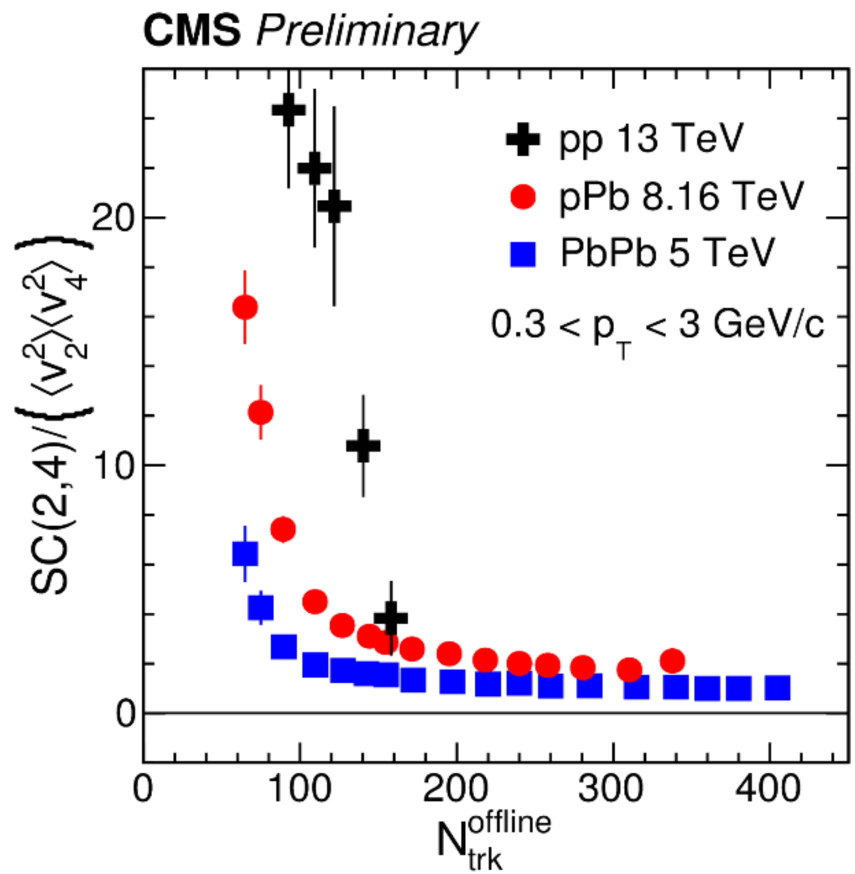




Normalized SC from CMS

PAS-HIN-16-022





- Similar behavior in pPb and PbPb

→ ***Similar IS fluctuation: Common origin of the observed anisotropy***

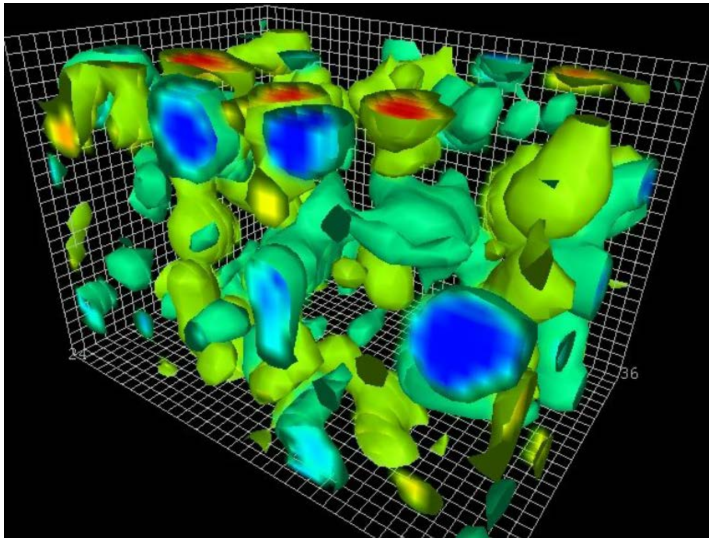
- Ordering in normalized SC

pp > pPb > PbPb

→ ***This may point to the different transport properties.***

pA for
Chiral Anomalies

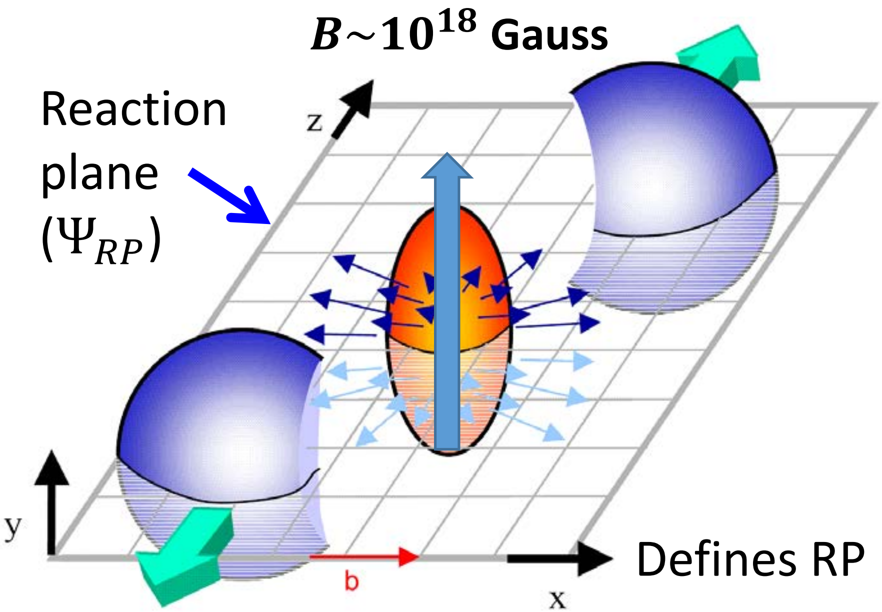
Anomalous Chiral Effects



□ Topological fluctuation of the QCD vacuum generates

- Vector chemical potential $\mu \neq 0$: More positive or negative charges $\Rightarrow$ Local P and CP-odd domains
- Chiral chemical potential $\mu_5 \neq 0$: More R- or L-handed particles $\Rightarrow$ Local net charge domains

[Ref.] Derek Leinweber (Univ. of Adelaide)



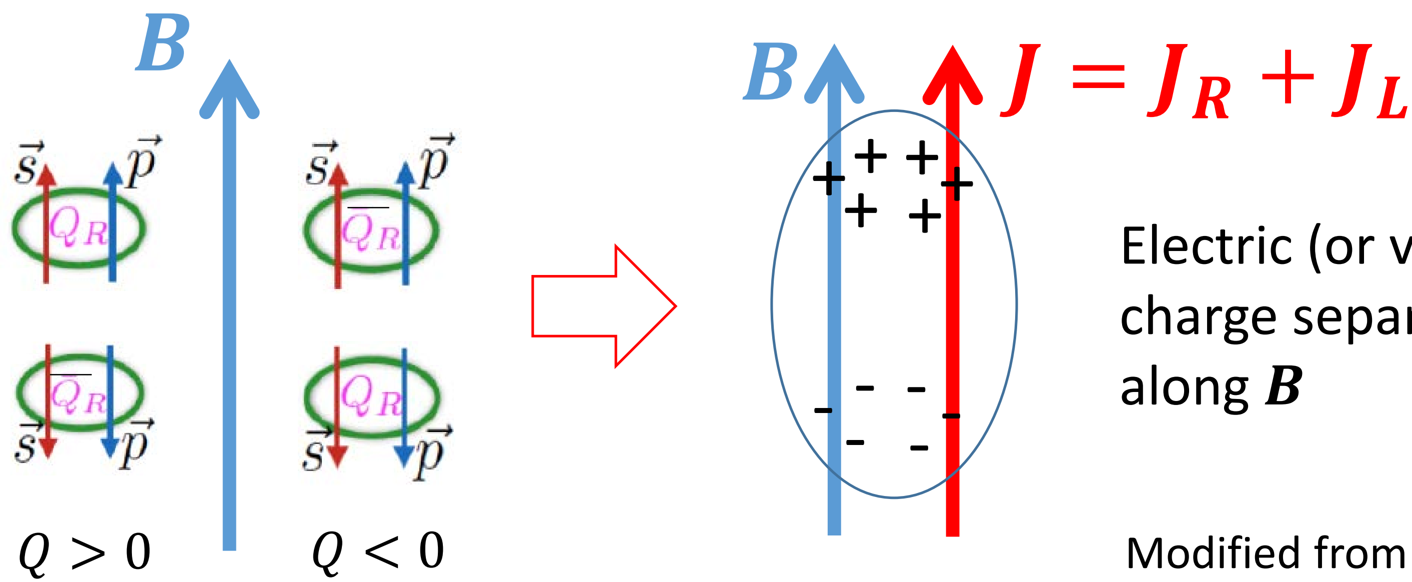
□ High-energy heavy-ion collisions

- Formation of strong B-field
- Chiral anomalies may manifest themselves in such B-field

□ How do we measure them in experiments at LHC & RHIC?

Chiral Magnetic Effect (CME)

- Electric current along an external $\boldsymbol{B}$ field: $\boldsymbol{J} = \sigma_5 \boldsymbol{B}$
  - $\sigma_5 = \frac{(Qe)^2}{2\pi^2}\mu_5$: chiral magnetic conductivity
  - μ_5: axial chemical potential
    (> 0: more right-handed, < 0: more left-handed quarks)
- Examples for right-handed quarks/antiquarks when $\mu_5 > 0$

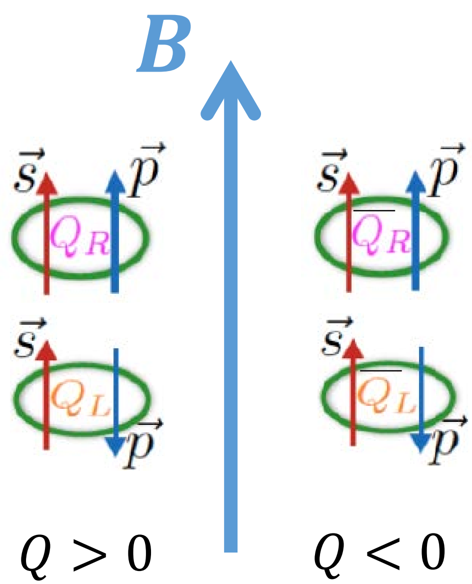


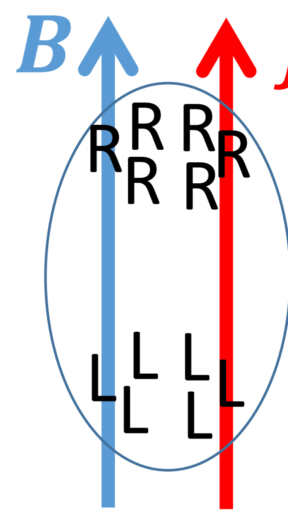
Electric (or vector) charge separation along $\boldsymbol{B}$

Modified from Fig. 1 of arXiv:1511.04050

Chiral Separation Effect (CSE)

- □ Axial current along an external $\boldsymbol{B}$ field: $\boldsymbol{J_5} = \sigma_s \boldsymbol{B}$
  - $\sigma_s = \frac{(Qe)^2}{2\pi^2}\mu$: chiral separation conductivity
  - μ: vector chemical potential
    (> 0: more positive, < 0: more negative particles)
- □ Examples for positive quarks/antiquarks when $\mu > 0$





$\boldsymbol{J_5} = \boldsymbol{J_R} - \boldsymbol{J_L}$

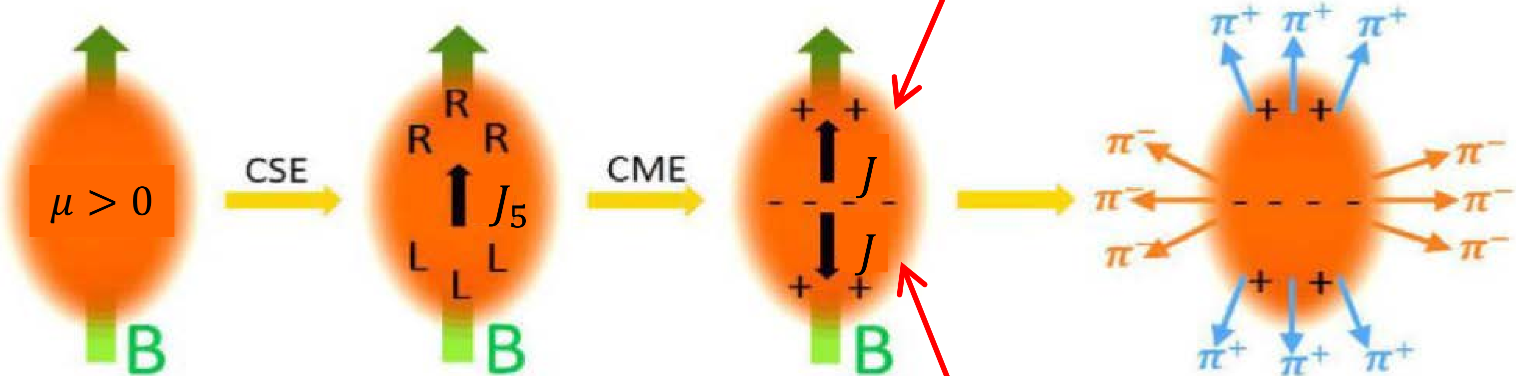
Chiral (or axial) charge separation along $\boldsymbol{B}$

Modified from Fig. 2 of arXiv:1511.04050

Chiral Magnetic Wave (CMW)

CMW = CSE ⊗ CME

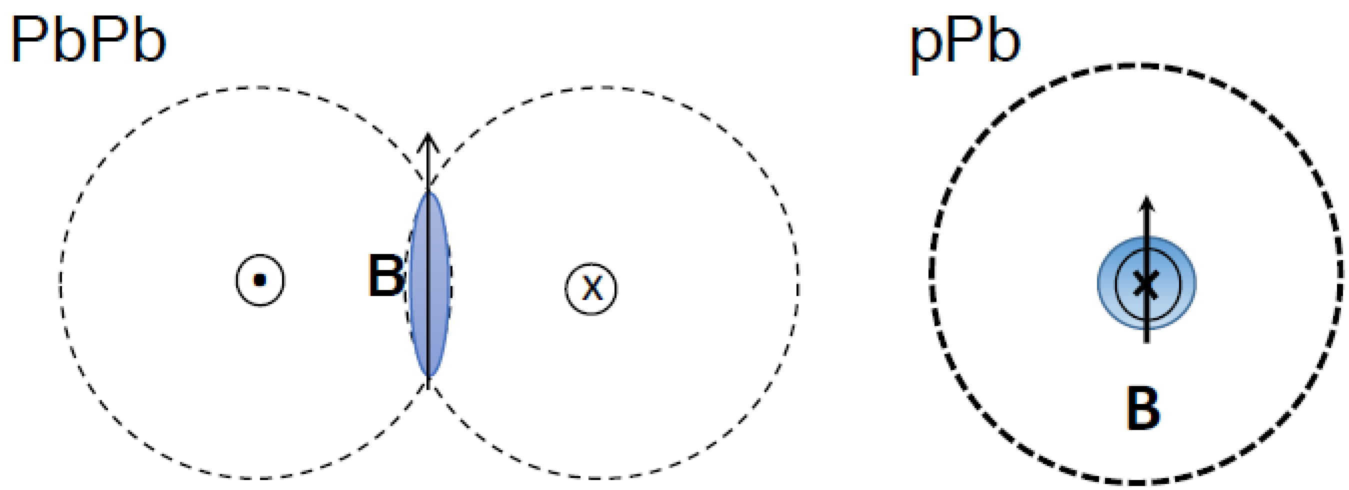
$$\mu_5 > 0: \begin{pmatrix} Q_R \\ \bar{Q}_R \end{pmatrix} \text{ for Q} > 0 \text{ or } \begin{pmatrix} \bar{Q}_R \\ Q_R \end{pmatrix} \text{ for Q} < 0$$



$$\mu_5 < 0: \begin{pmatrix} \bar{Q}_L \\ Q_L \end{pmatrix} \text{ for Q} > 0 \text{ or } \begin{pmatrix} Q_L \\ \bar{Q}_L \end{pmatrix} \text{ for Q} < 0$$

How can pA help to investigate the various chiral anomalies?

- How does the B field in pPb compared to that in PbPb?
  - $B(\mathrm{PbPb}) > B(\mathrm{pPb})$ in a similar multiplicity bin
  - De-correlation between Ψ_B and Ψ_{EP} in pPb



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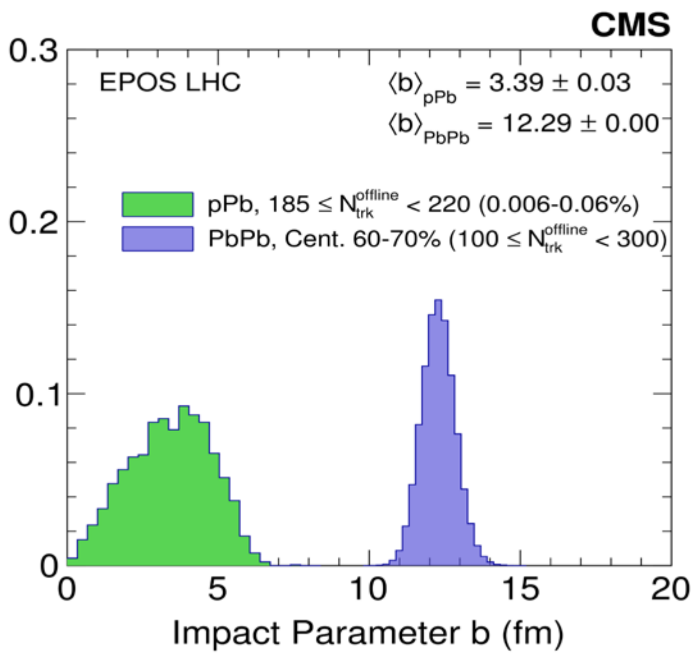
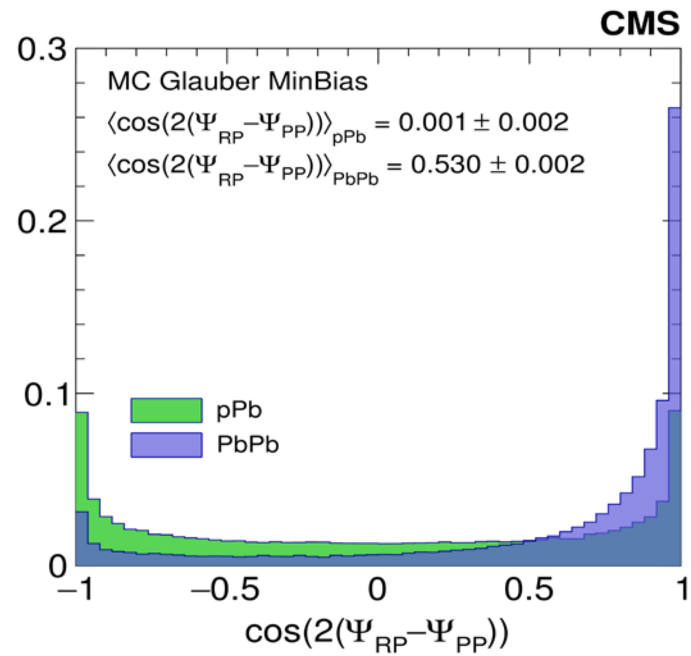




- Various chiral anomalies are expected to be much weaker in pPb!

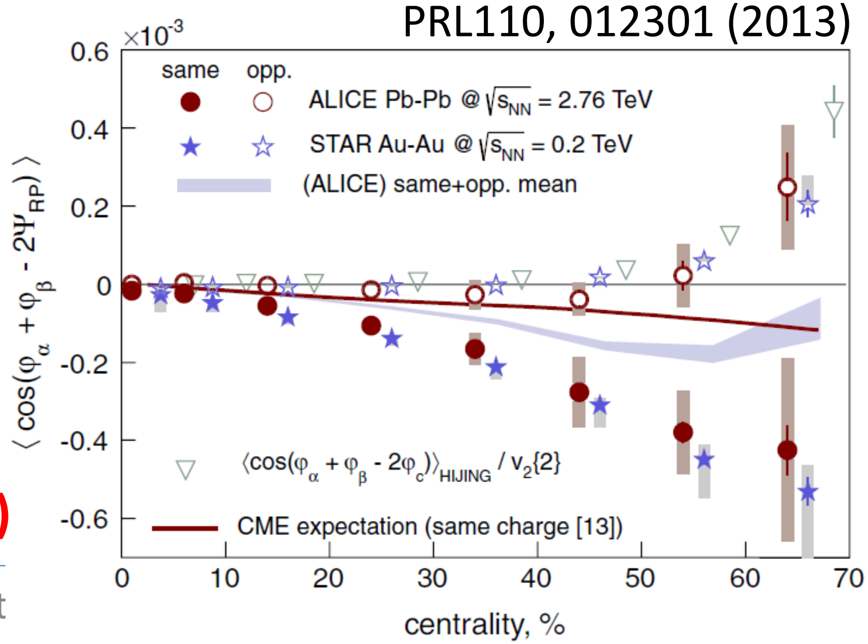
Analysis of CME *(before CSE is considered)*

- Charge separation by the Parity-odd sine terms:
  $dN/d\phi \propto 1 + 2\sum_n [v_n \cos(n(\phi - \Psi_{RP})) + a_n \sin(n(\phi - \Psi_{RP}))]$
- Azimuthal correlator for a_1, proposed by Voloshin [PRC 70, 057901 (2004)]:
  $\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$
  $= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}) - (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{out})$
  where $\Delta\phi_{\alpha(\beta)} = \phi_{\alpha(\beta)} - \Psi_2$,
  $\alpha = \beta$ for same sign and $\alpha \neq \beta$ for opposite sign,
  $\langle v_{1,\alpha} v_{1,\beta} \rangle \cong 0$ in the region symmetric w.r.t. midrapidity,
  $B_{in} - B_{out}$ suppresses correlations not related to RP

- Dominant term to be $-\langle a_{1,\alpha} a_{1,\beta} \rangle$
  < 0 for the same-sign pairs
  > 0 for the opposite-sign pairs

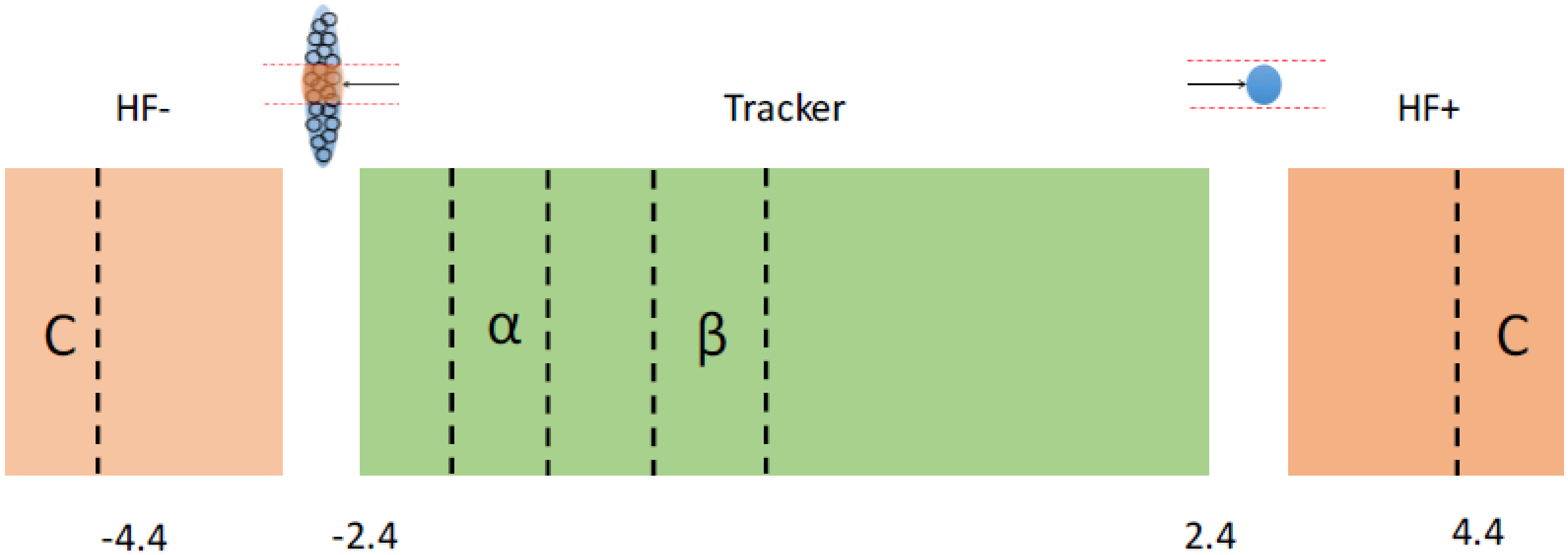
- **Charge separation relative to RP observed in AA**
- **Is this really due to CME?**
  Crucial check: the B dependence of the correlation strength (PbPb vs. pPb)

PRL110, 012301 (2013)



Analysis of CME

CMS utilized the three-particle correlation method

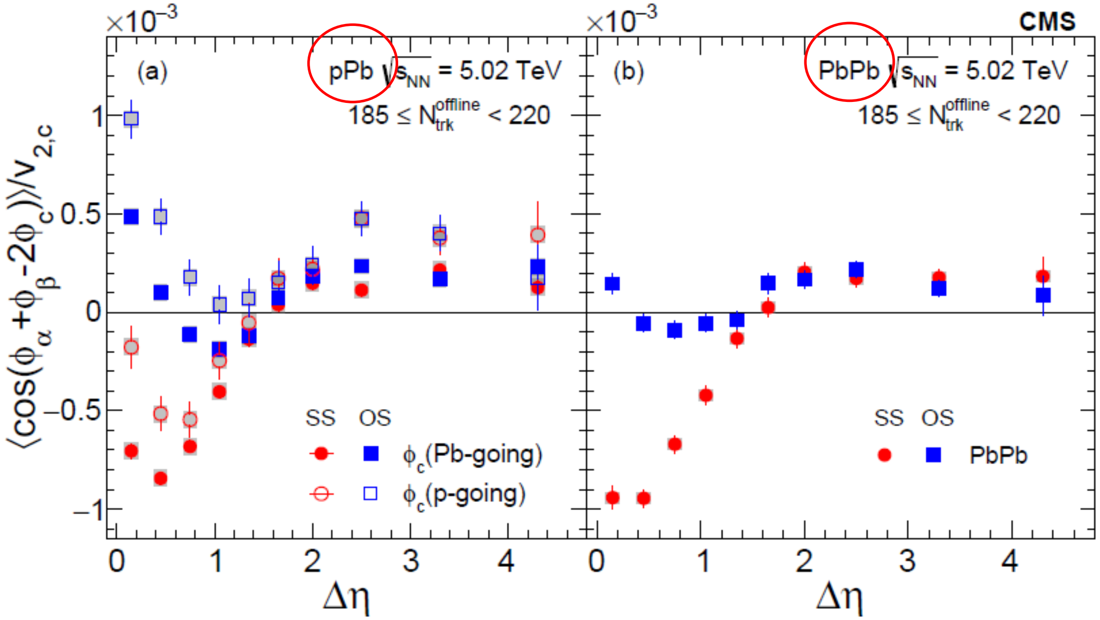


$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle \cong \frac{\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle}{v_{2,c}}$$

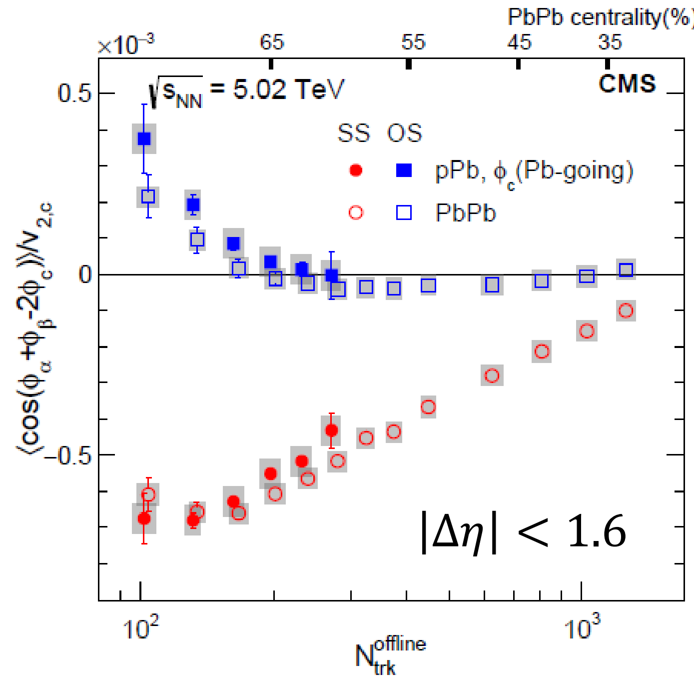
- □ Large acceptance (~5 units of pseudorapidity) of CMS
- □ Large η gap between particles α, β and c is advantageous to reduce the short-range correlation.

Analysis of CME

arXiv:1610.00263



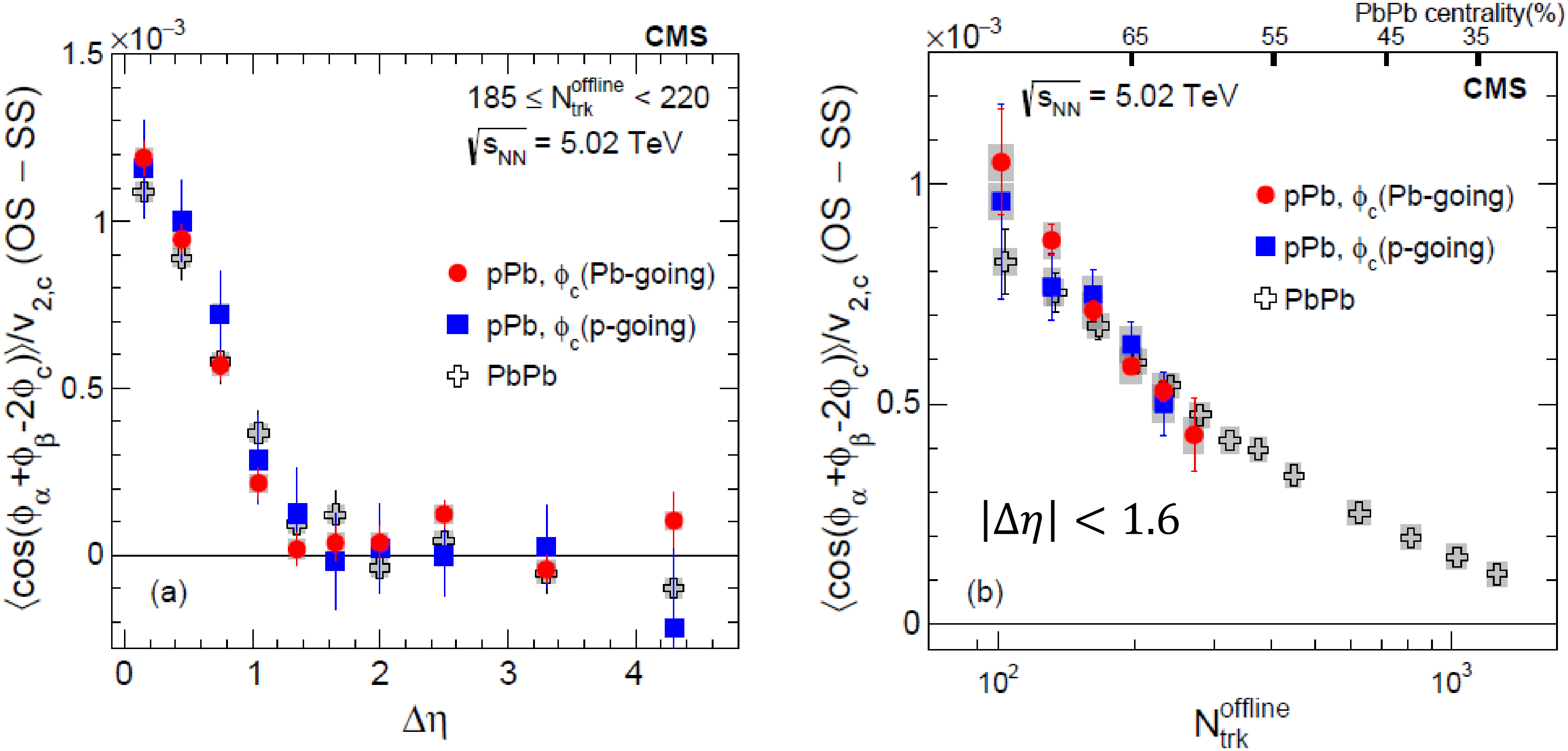
- Clear splitting between SS and OS in pPb
- Similarity observed between Pb-going data in pPb and PbPb at the same multiplicity bin



- **Almost identical for SS and OS between pPb (Pb-going side) and PbPb**
- **Not in favor of CME**

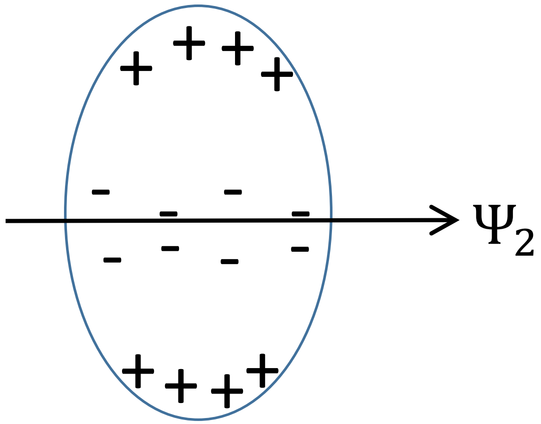
Analysis of CME

arXiv:1610.00263



- All $\Delta\gamma(OS - SS)$'s agree each other as functions of $\Delta\eta$ and multiplicity.
  In the CMW model, $\Delta\gamma \sim B^2\langle\cos(2\Psi_B - 2\Psi_2)\rangle$
- **Charge separation seems not related to the B field.**

Analysis of CMW



- Charge asymmetry parameter fluctuating e-b-e: $A_{ch} \equiv (N^+ - N^-)/(N^+ + N^-)$
- Expectation for the ϕ distribution due to electric quadrupole deformation in addition to elliptic flow:

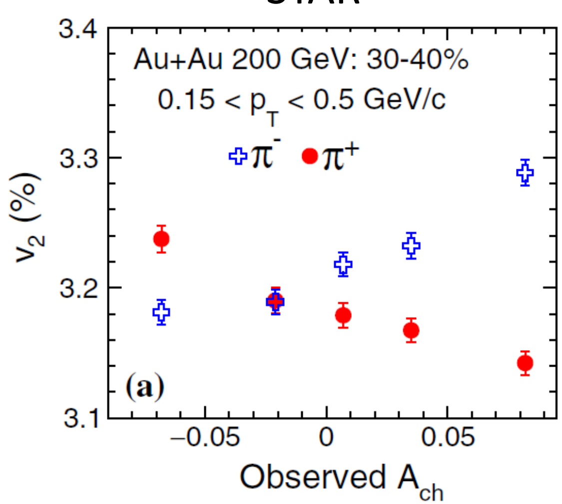
$$dN_\pm/d\phi \propto 1 \pm A_{ch}\left[1 - (r_e/2)\cos(2\phi - 2\Psi_2)\right] \times \left[1 + 2v_{2,\pm}^{base}\cos(2\phi - 2\Psi_2)\right]$$

$$dN_\pm/d\phi \simeq (1 \pm A_{ch})\left[1 + 2\left(v_{2,\pm}^{base} \mp r_e A_{ch}/2\right)\cos(2\phi - 2\Psi_2)\right]$$

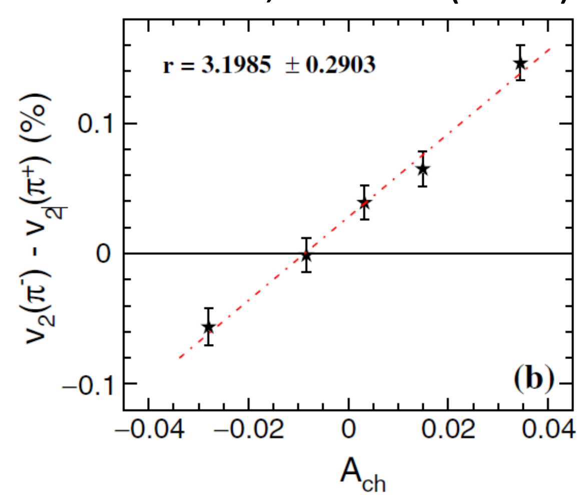
$$v_{2,\pm} = v_{2,\pm}^{base} \mp r_e A_{ch}/2$$
$$v_{2,-} - v_{2,+} = r_e A_{ch}$$

- **STAR/ALICE observed what expected by CMW.**
- **Is this really due to CMW?**
  Check the *B* dependence using PbPb and pPb

STAR

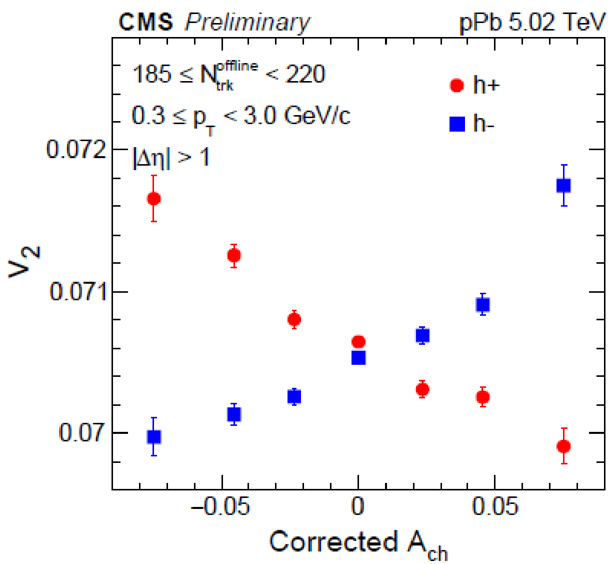


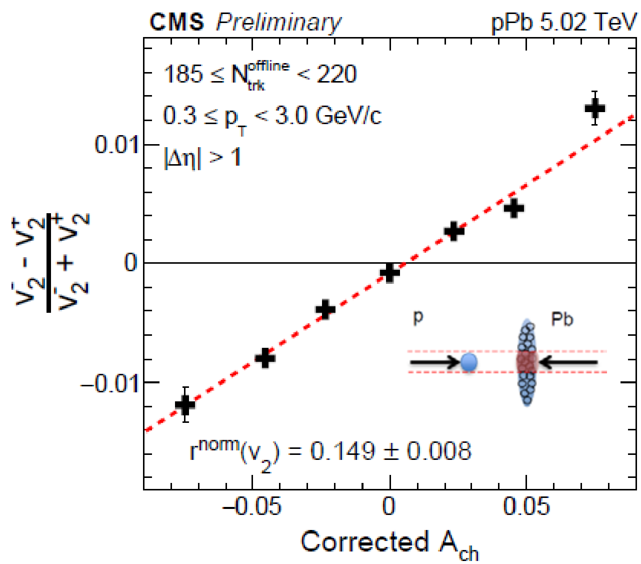
PRL114, 252302 (2015)

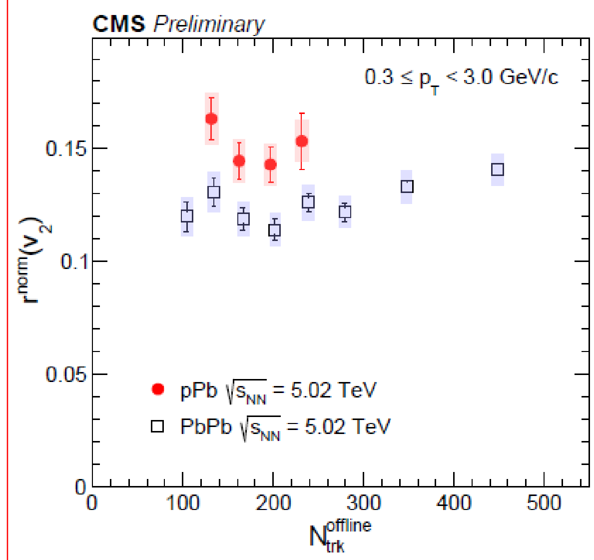


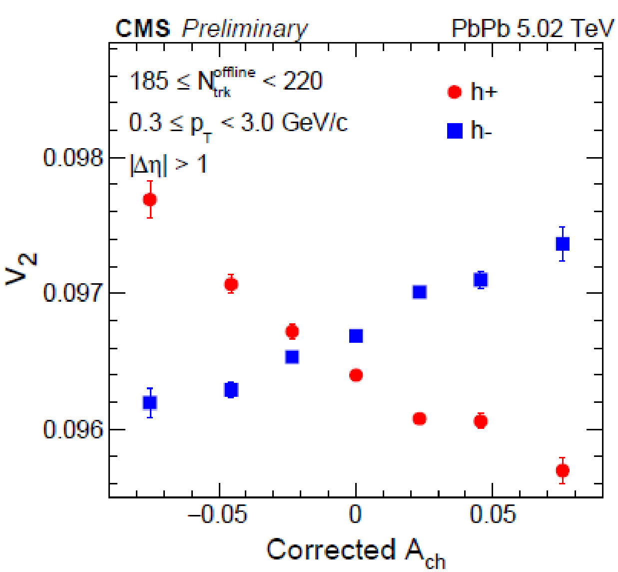
Analysis of CMW

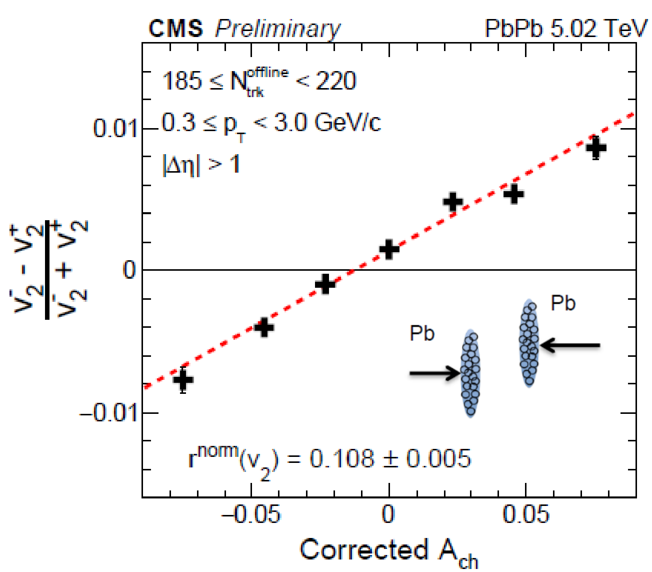
PAS-HIN-16-017











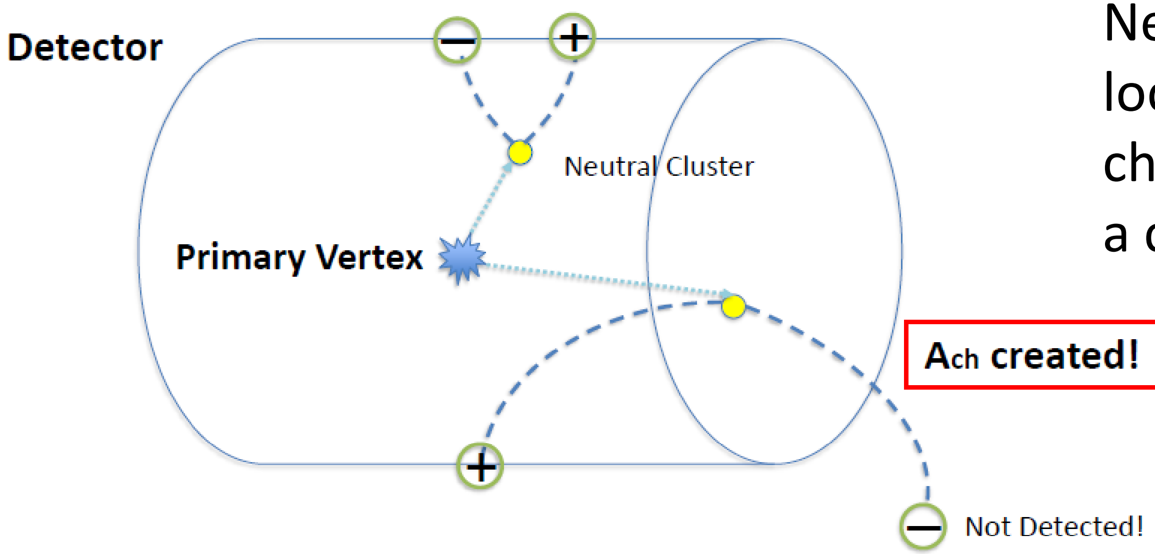
- □ **Significant slopes for pPb that is not expected in CMW**

⇒ **Challenges to CMW**

Analysis of CMW

PAS-HIN-16-017

- **Alternative interpretation: Local Charge Conservation (LCC)**
  [Bzdak & Bozek, PLB726, 239 (2013)]



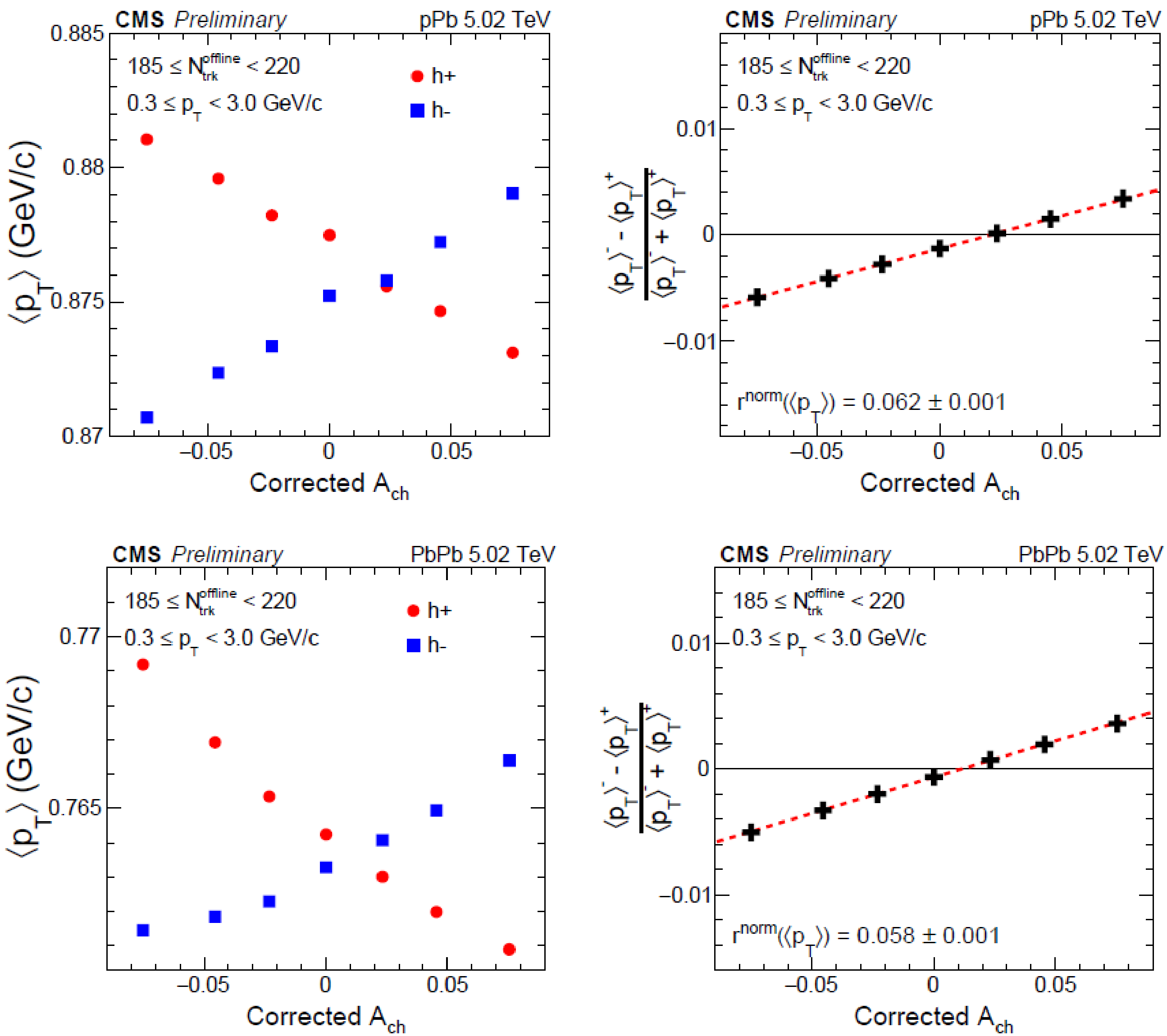
Neutral cluster decays locally into the pair of charged particles with a certain η separation.

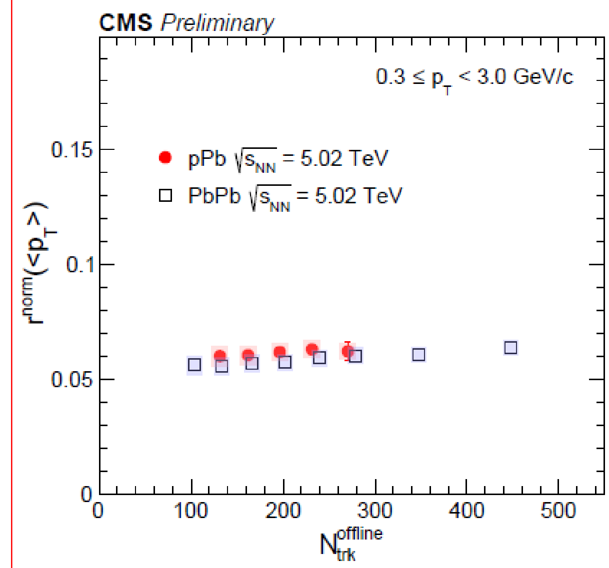
$$A_{ch} \equiv \frac{(N^+ - N^-)}{(N^+ + N^-)}$$

- Limited detector acceptance creates A_{ch}, especially, at low p_T region.
  If A_{ch} becomes large (negatives are out of acceptance at small p_T),
  - More h^+ at small $\langle p_T \rangle \Rightarrow$ Smaller v_2 for h^+
  - Less h^- at small $\langle p_T \rangle \Rightarrow$ Larger v_2 for h^-
- The data indicate that both v_2 & v_3 are proportional to p_T at small p_T.
  - Same p_T dependence for v_2 and v_3 in LCC $\Leftrightarrow$ Flat for v_3 in CMW

Analysis of CMW

PAS-HIN-16-017



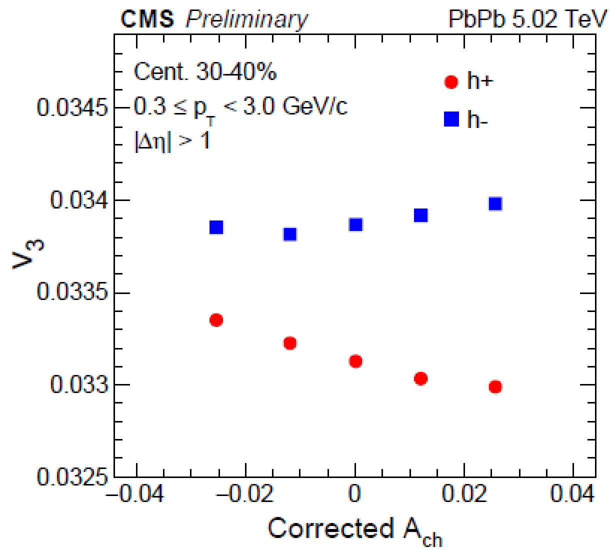


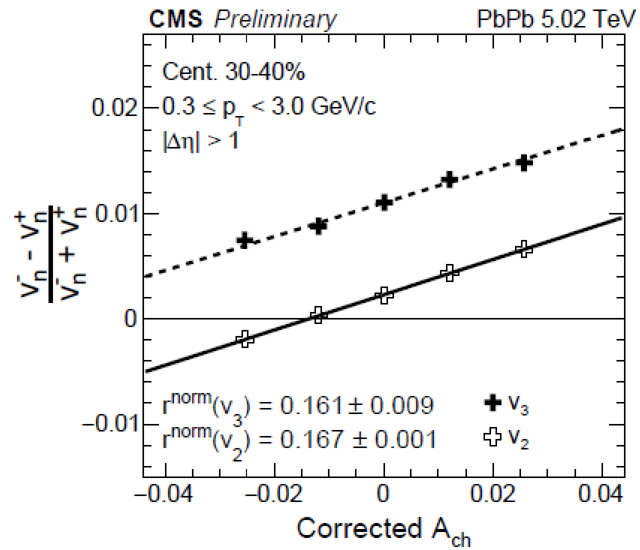
- □ **Very similar slopes for pPb and PbPb**

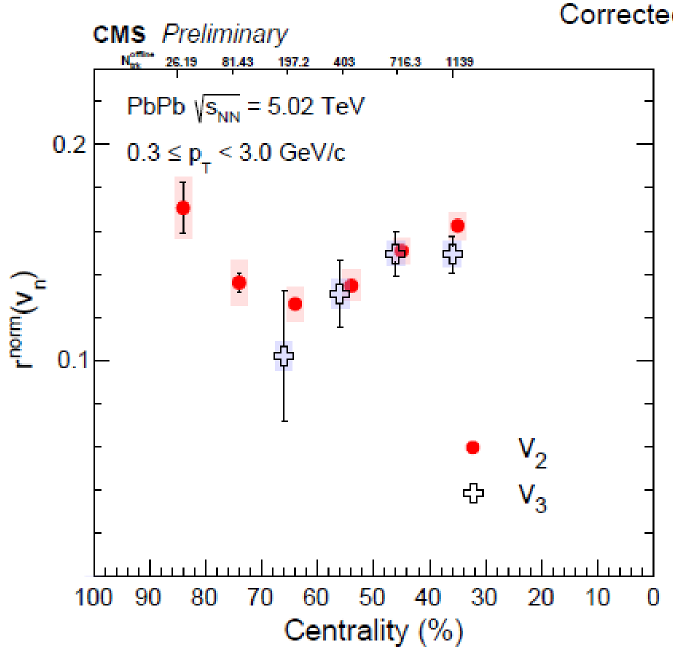
⇒ **Supports LCC, Challenges to CMW**

Analysis of CMW

PAS-HIN-16-017







- □ **Normalized v_2 and v_3 slopes are very similar in all centrality ranges in PbPb**

⇒ **Supports LCC, Challenges to CMW**

- □ No interpretation yet for larger intercept for v_3

Summary

- Symmetric cumulant (SC) analysis points to similar initial state fluctuation, but different transport properties among pp, pPb, and PbPb.
- Charge-separation signals in pPb impose a big challenge to the CME and CMW interpretations of AA data.
- Possible influence of commoving hadrons in the $\psi(2S)$ production in pPb
- Dijet data indicate the gluon (anti-)shadowing and EMC effects in the Pb nucleus.
- No indication of favor dependence for nPDF in the jet production
- Public results

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN