11th APCTP-BLTP JINR-PINP NRC KI-SPbSU Joint Workshop
"Modern problems in nuclear and elementary particle physics"
Hotel "New Petergof", Petergof, St. Petersburg, Russia, July 24-28, 2017

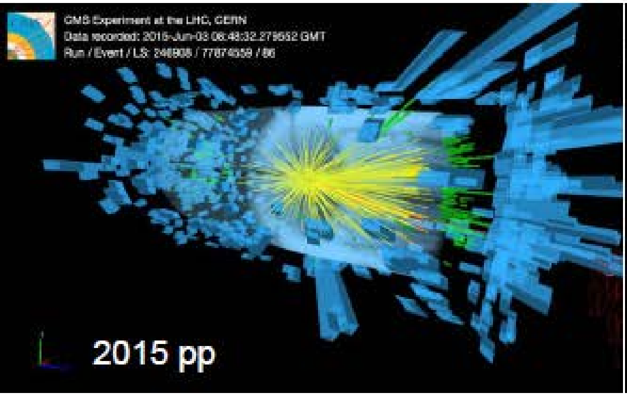
Overview of Recent pPb Results from CMS at LHC

Byungsik Hong
(Korea University)

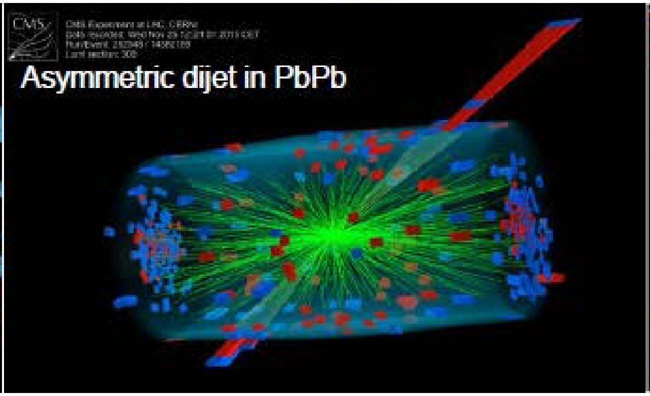
for the CMS Collaboration

Exciting New Results from RUN II Data

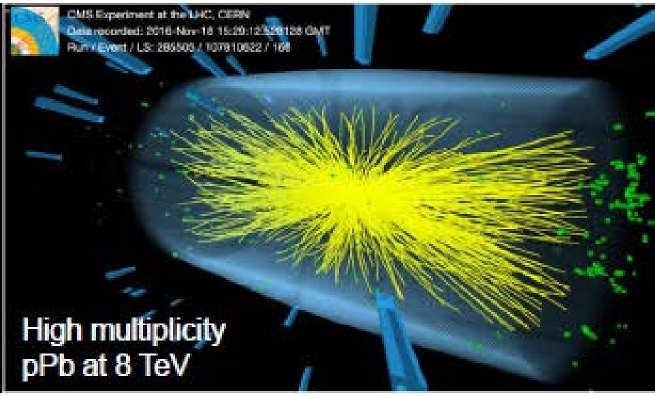
2015+2016 13 TeV pp



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
- ☐ Flavor dependence of heavy-flavored jets

CMS detector

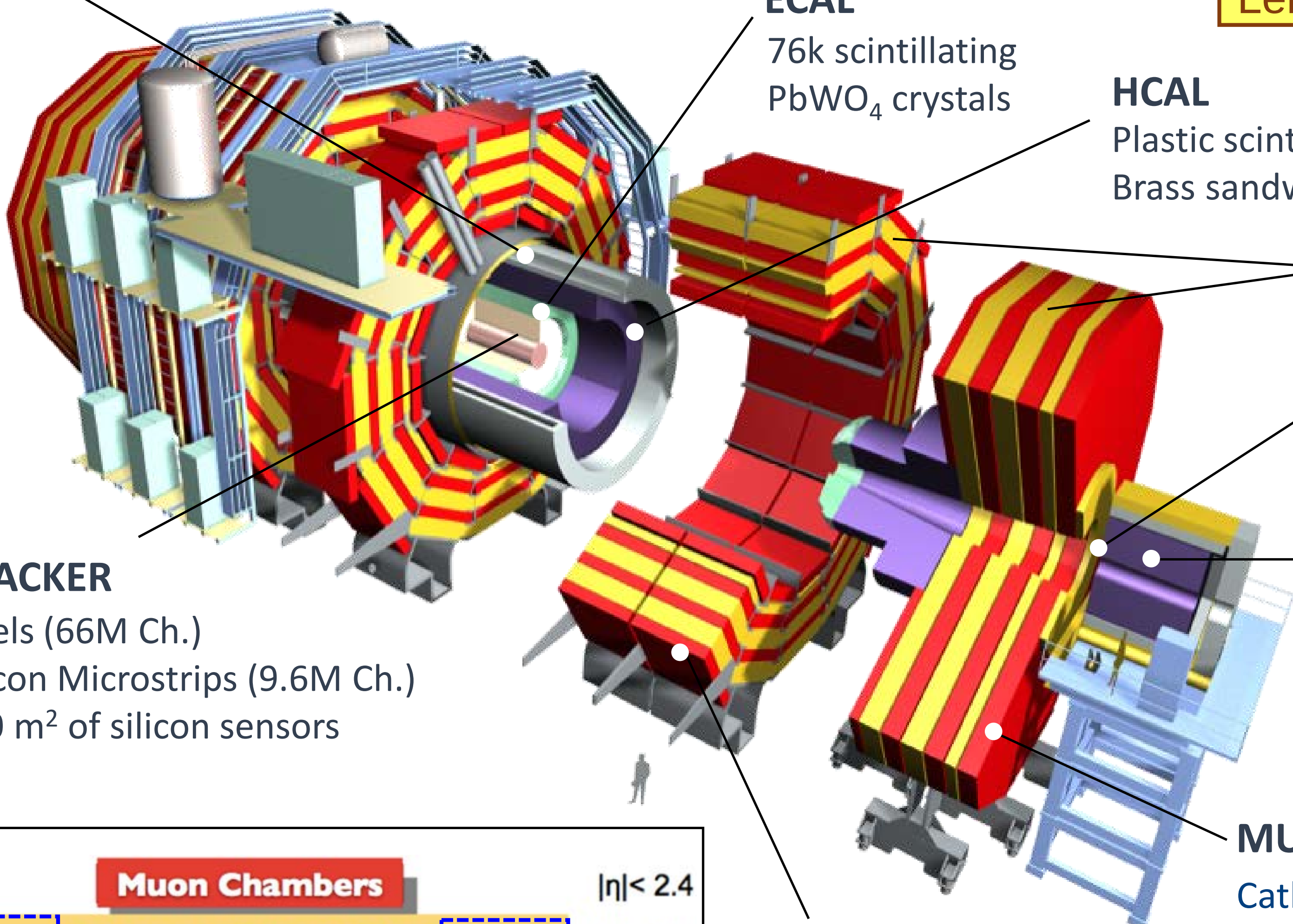
Weight: 12,500 tons
Diameter: 15 m
Length: 22 m

Superconducting Coil (3.8 T)

CALORIMETERS

ECAL
76k scintillating
$PbWO_4$ crystals

HCAL
Plastic scintillator/
Brass sandwich

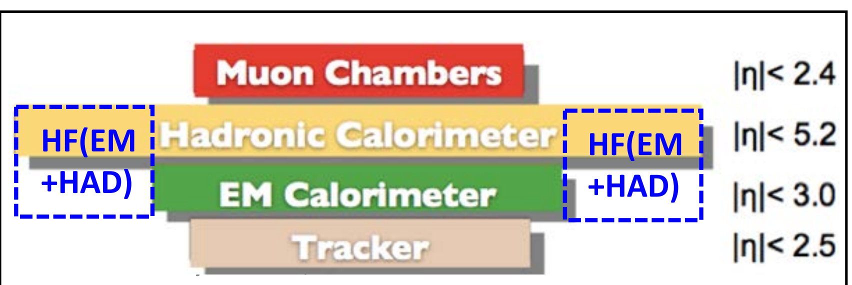


Steel YOKE

BSC
MB trigger

HF
MB trigger
Centrality in HI

TRACKER
Pixels (66M Ch.)
Silicon Microstrips (9.6M Ch.)
220 m^2 of silicon sensors

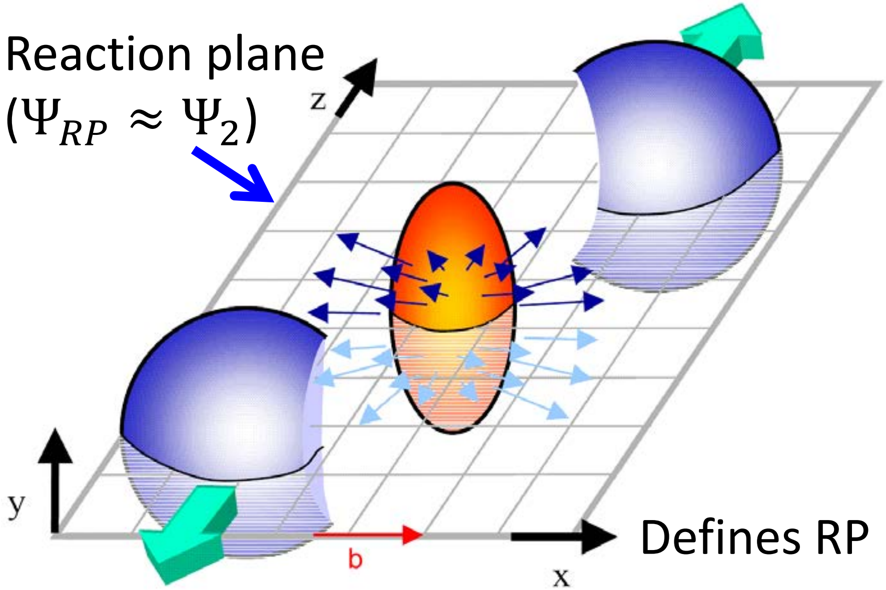


MUON BARREL
Drift Tube Chambers
Resistive Plate Chambers

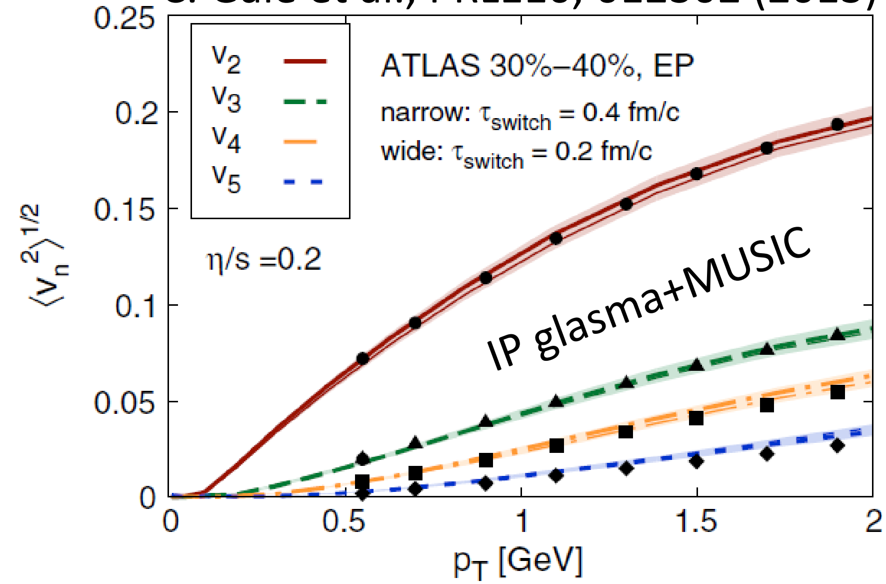
MUON ENDCAPS
Cathode Strip Chambers
Resistive Plate Chambers

pA for
Azimuthal Anisotropy

Hydrodynamics Flow in AA

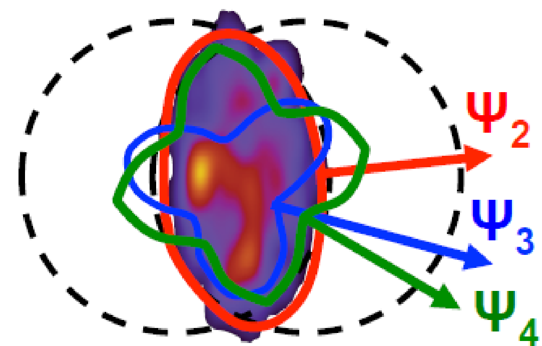


C. Gale et al., PRL110, 012302 (2013)



- □ Azimuthal angle distribution is fitted by:

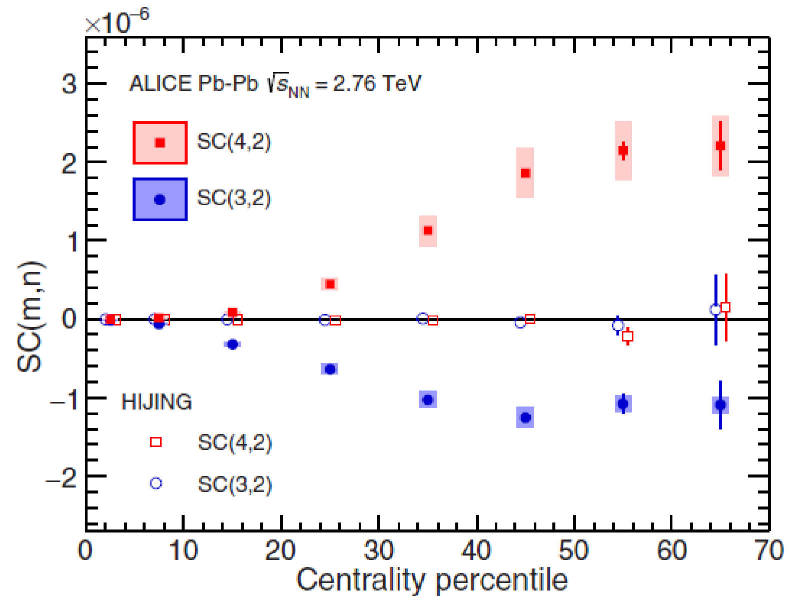
  $dN/d\phi \propto 1 + 2\sum_n [v_n(p_T, \eta)\cos(n(\phi - \Psi_n))]$
- □ Coefficients, v_n, depends on
  - Initial-state geometry and its fluctuation
  - Medium transport coefficients (e.g., $\eta/s, \cdots$)
- □ Diagonal terms (v_n^2) understood well in AA with hydrodynamics
- □ **How to study non-diagonal terms?**

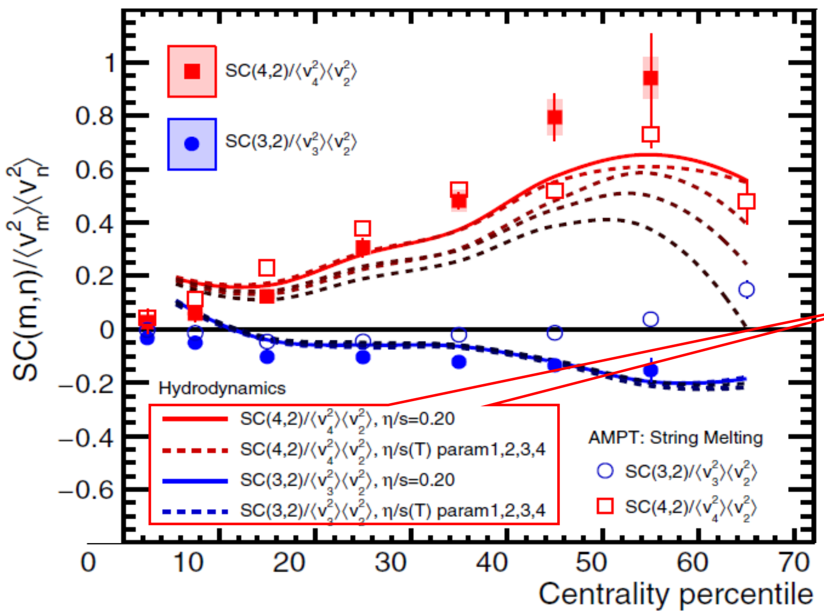


Symmetric Cumulants (SC)

- Correlation between harmonics based on 4-particle cumulant method $SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$ developed by ALICE
- Non-flow free in first order
- $SC(2,3) < 0$: v_2 & v_3 anti-correlated
- $SC(2,4) > 0$: v_2 & v_4 correlated

ALICE, PRL117, 182301 (2016)

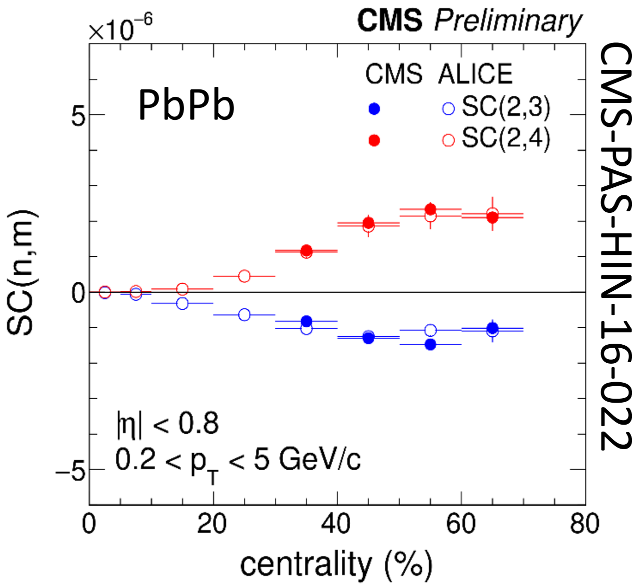




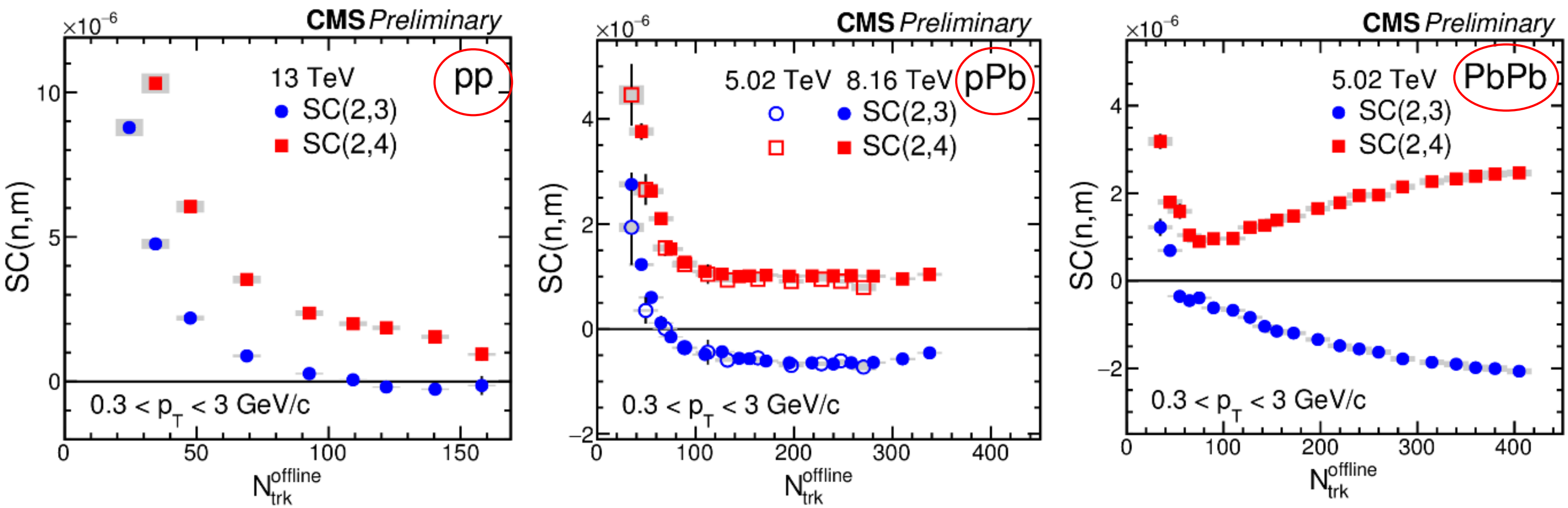
- Model calculations Indicate that
  - Odd-even: IS fluctuation
  - Even-even: Medium response ⊗ IS fluctuation

SC Results from CMS

→ Nice agreement between CMS and ALICE in PbPb

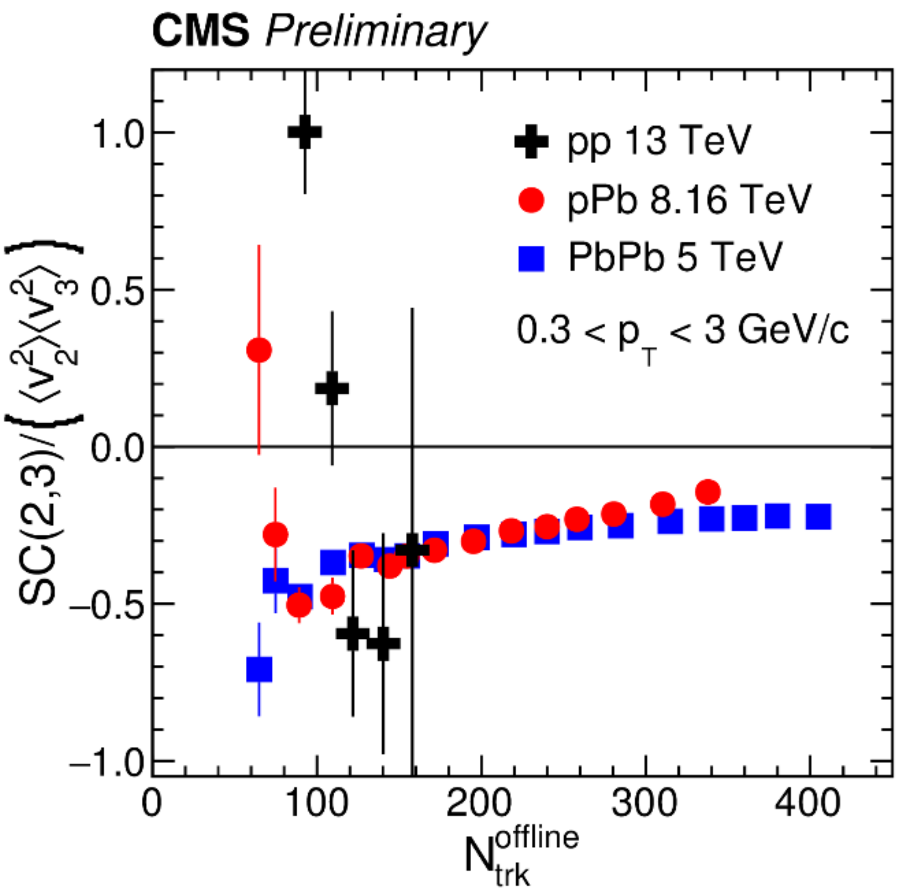


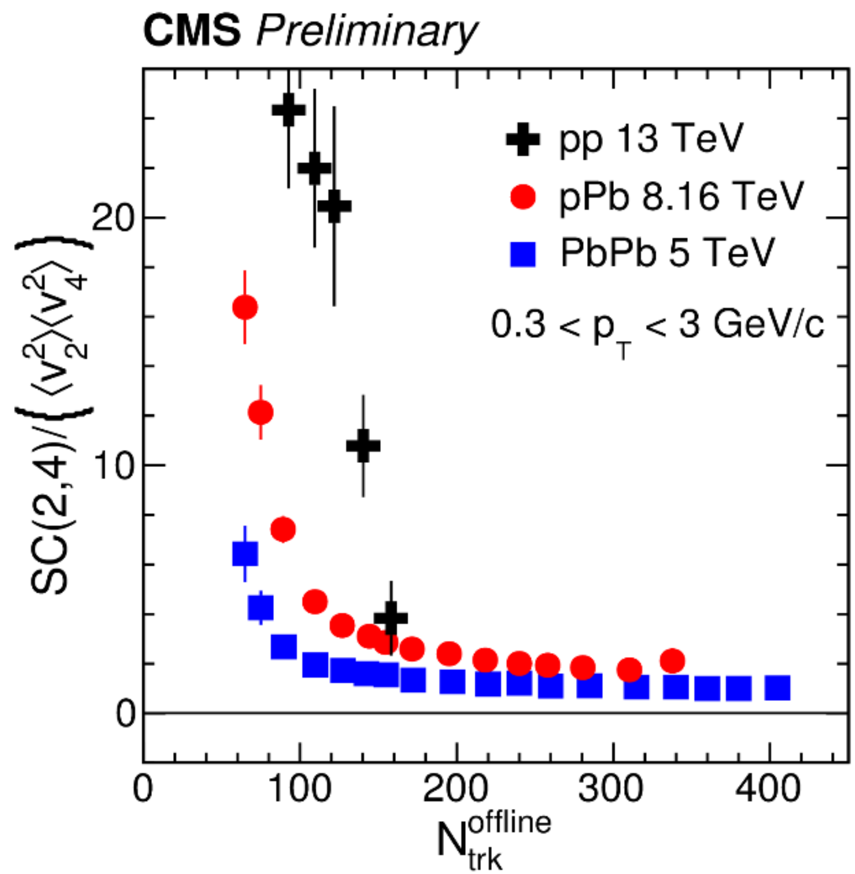
- ☐ Similar pattern for SC in all systems (pp, pPb and PbPb)
- ☐ No energy dependence in pPb
- ☐ Normalization needed for the comparison across collision systems from pp to PbPb



Normalized SC from CMS

CMS-PAS-HIN-16-022





- □ Similar behavior in pPb and PbPb

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

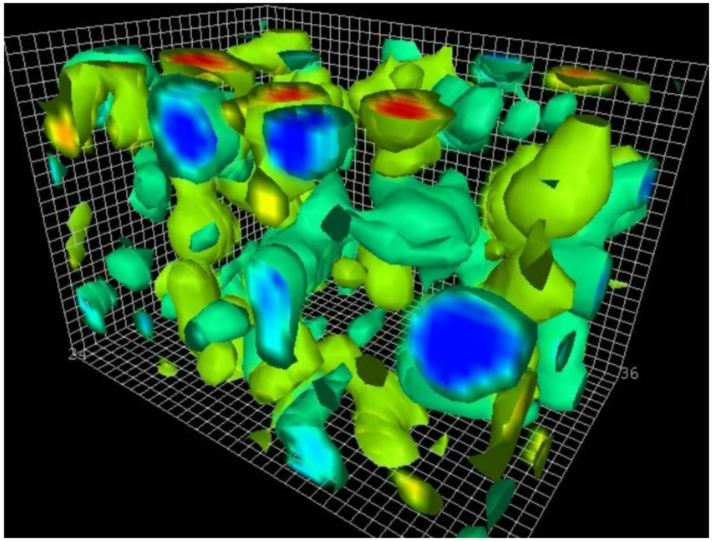
- □ Ordering in normalized SC

pp > pPb > PbPb

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

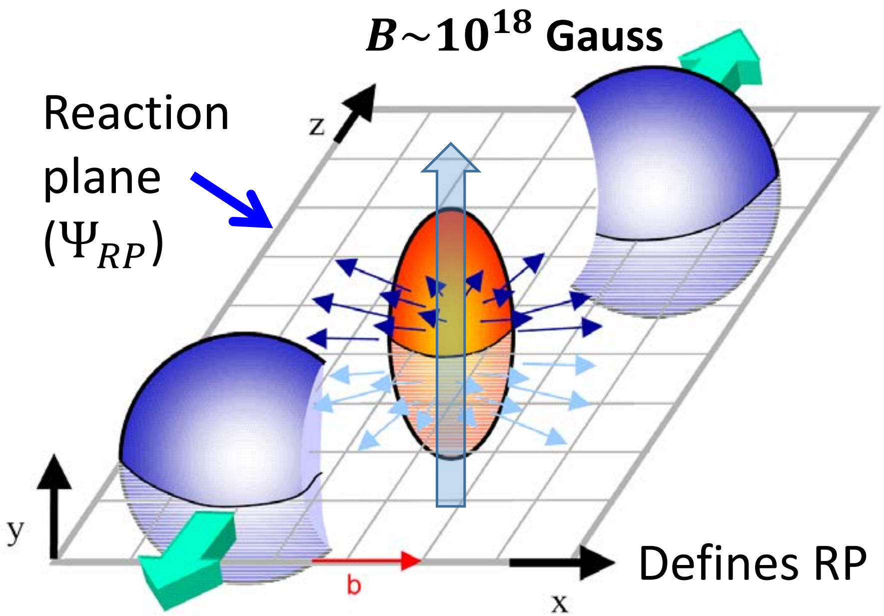
pA for Chiral Anomalies

Anomalous Chiral Effects



- □ Topological fluctuation of the QCD vacuum generates
  (cf. Prof. Andrianov's talk yesterday)
  - 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

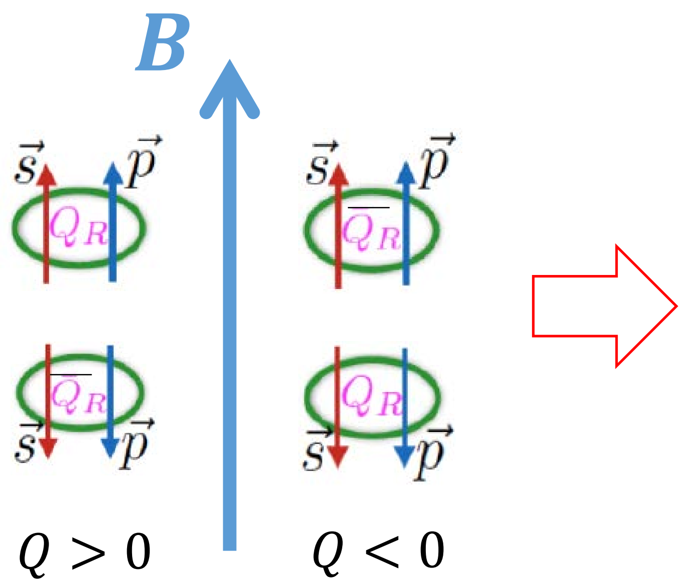
  [Ref.] Derek Leinweber (Univ. of Adelaide)

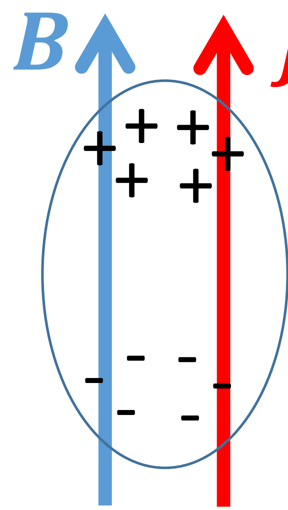


- □ High-energy heavy-ion collisions
  - Formation of strong B-field
  - Chiral anomalies may manifest themselves in such B-field
- □ How do we measure them in experiments at LHC & RHIC?

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 $\mu_5 > 0$





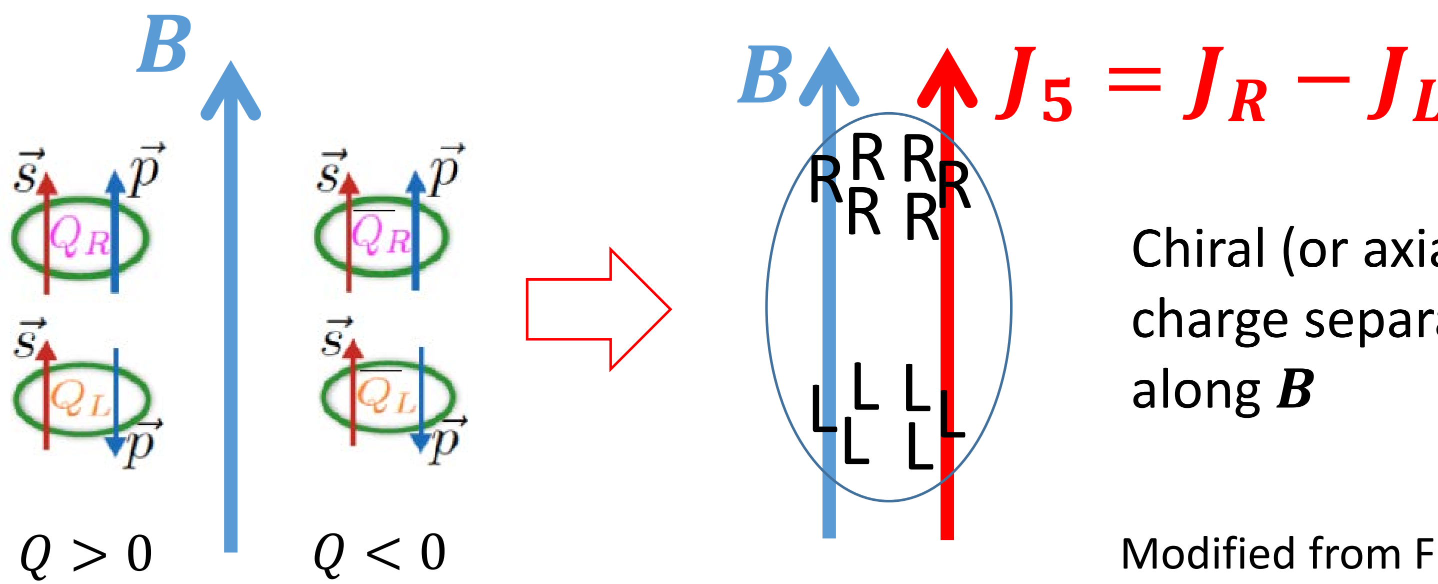
$\boldsymbol{J} = \boldsymbol{J_R} + \boldsymbol{J_L}$

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 $\mu > 0$



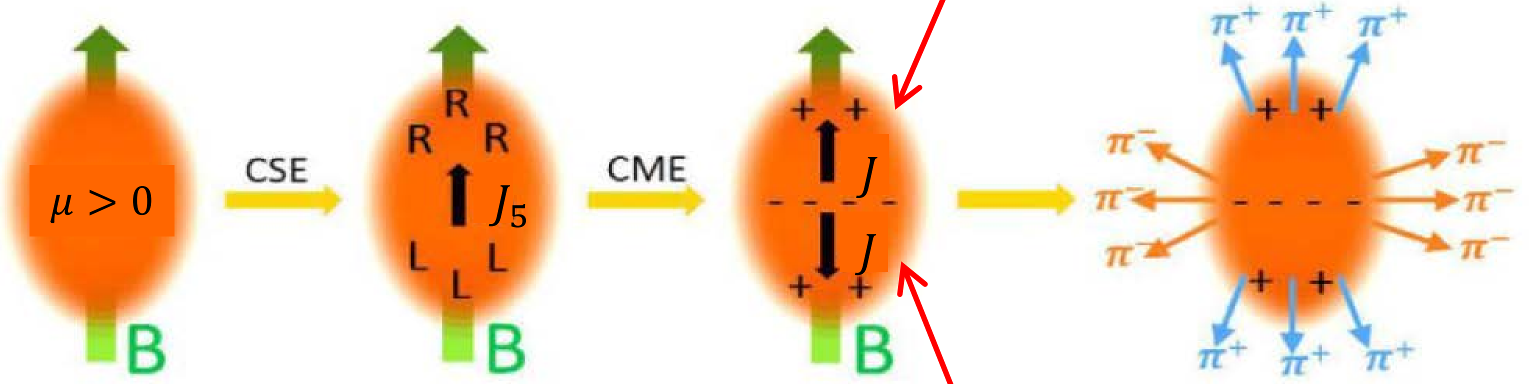
Chiral (or axial) charge separation along $\boldsymbol{B}$

Modified from Fig. 2 of arXiv:1511.04050

Chiral Magnetic Wave (CMW)

CMW = CSE $\otimes$ CME

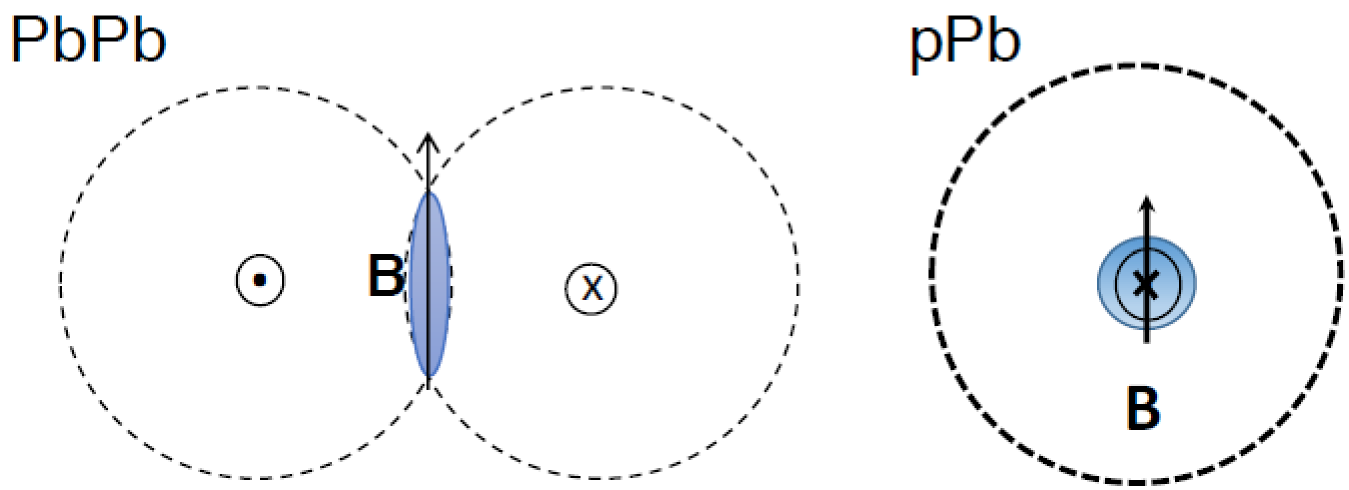
$\mu_5 > 0$: $\begin{pmatrix} Q_R \\ \bar{Q}_R \end{pmatrix}$ for $Q > 0$ or $\begin{pmatrix} \bar{Q}_R \\ Q_R \end{pmatrix}$ for $Q < 0$



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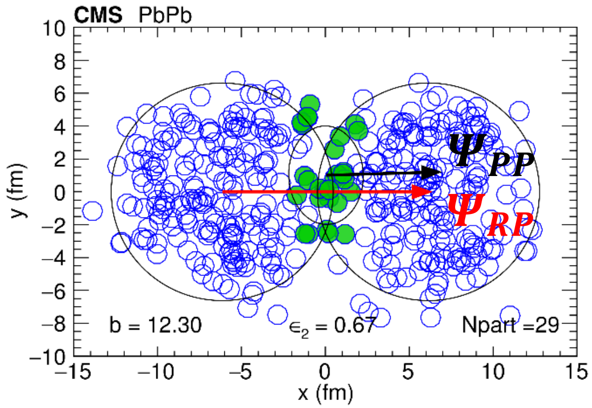
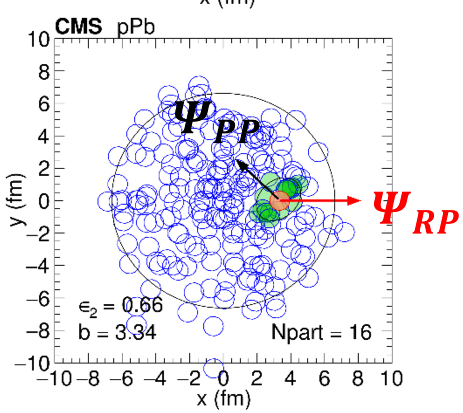
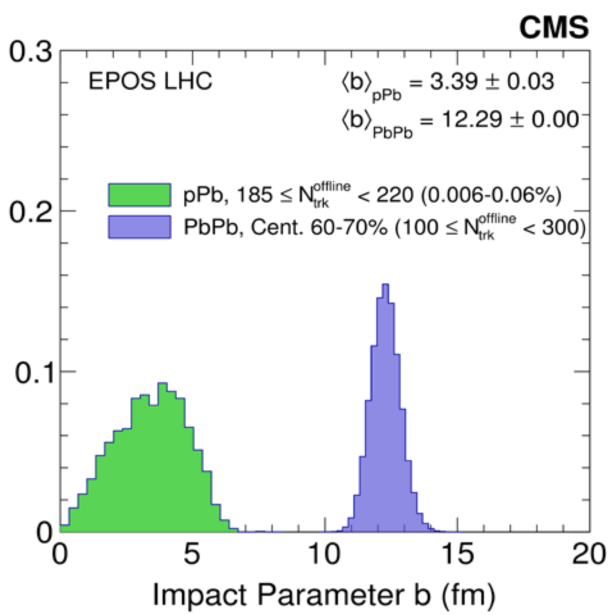
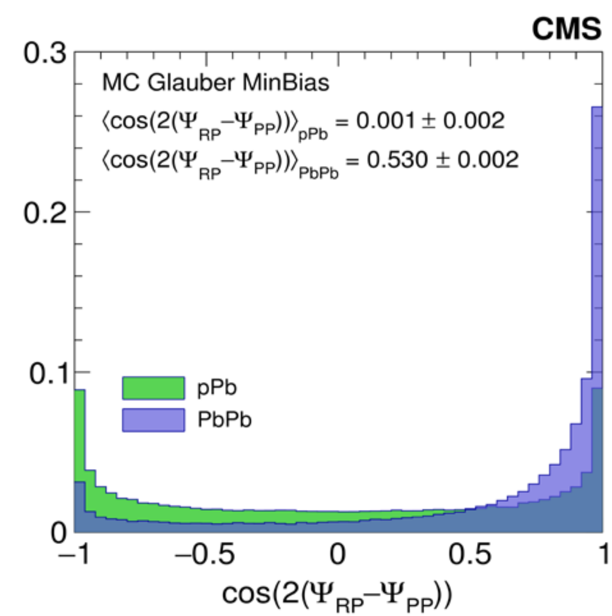








- Various chiral anomalies are expected to be much weaker in pPb!

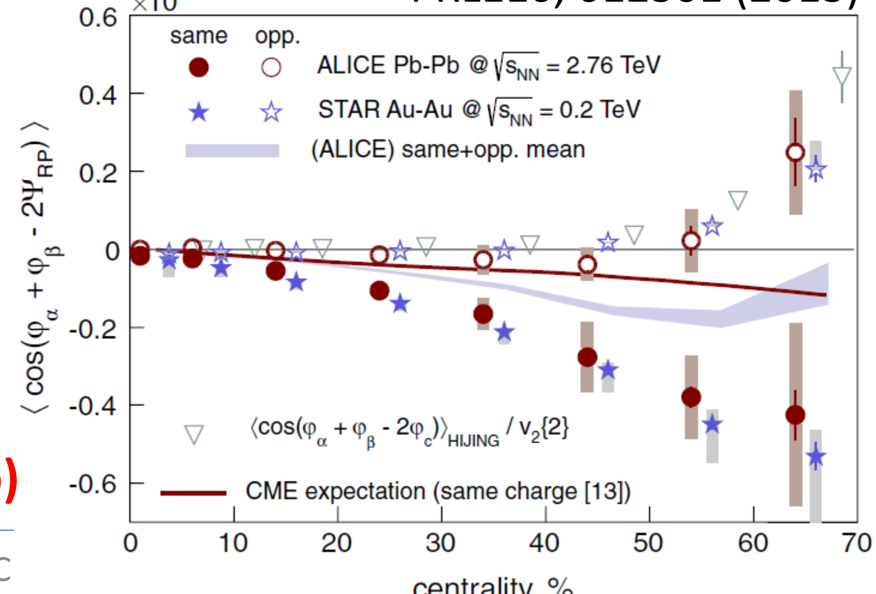
Analysis of CME

- 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

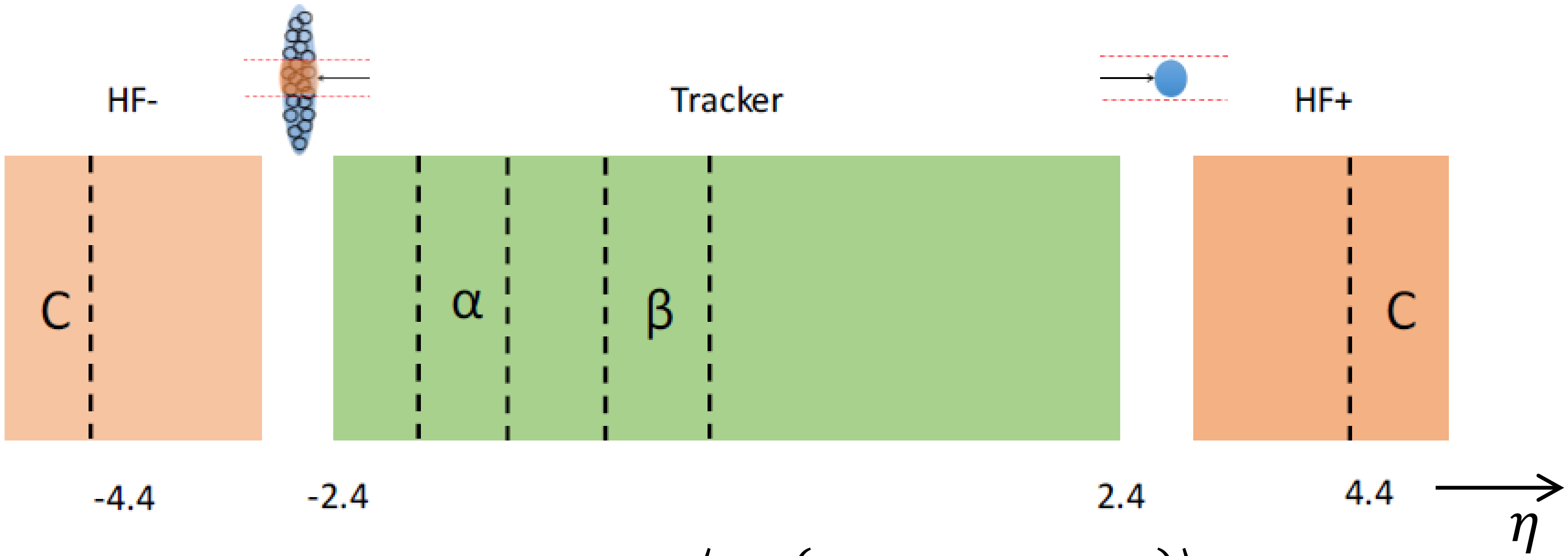
- **Charge separation relative to RP observed in AA**
- **Is this really due to CME?**
  Crucial check: the B dependence of the correlation strength (PbPb vs. pPb)

PRL110, 012301 (2013)



Analysis of CME

CMS utilized the three-particle correlation method

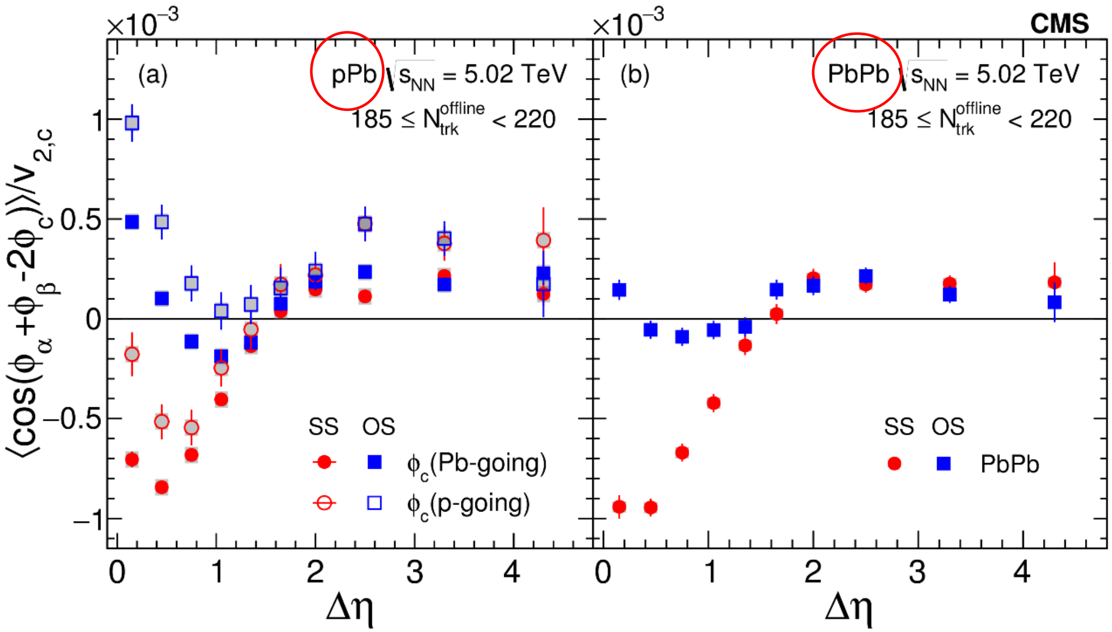


$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle \cong \frac{\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle}{v_{2,c}}$$

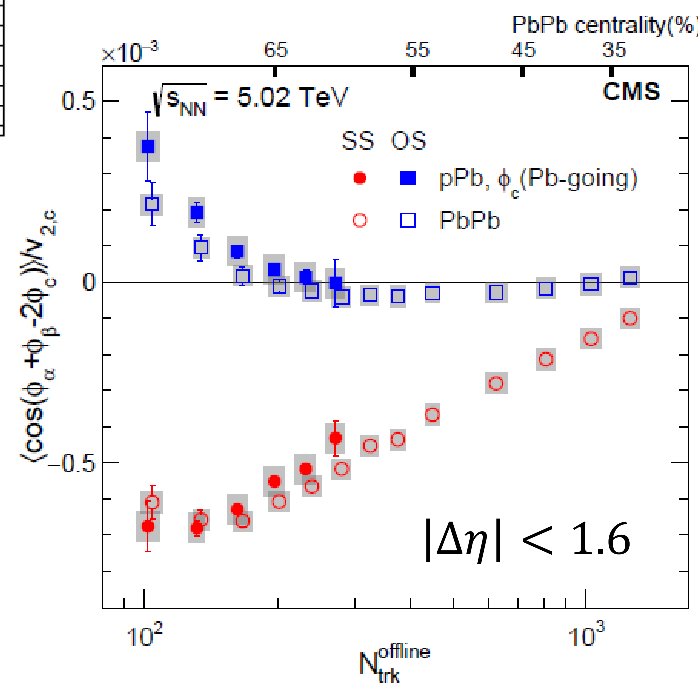
- Large acceptance ($\sim$5 units of pseudorapidity) of CMS
- Large η gap between particles α, β and c is advantageous to reduce the short-range correlation.

Analysis of CME

CMS, PRL 118, 122301 (2017)



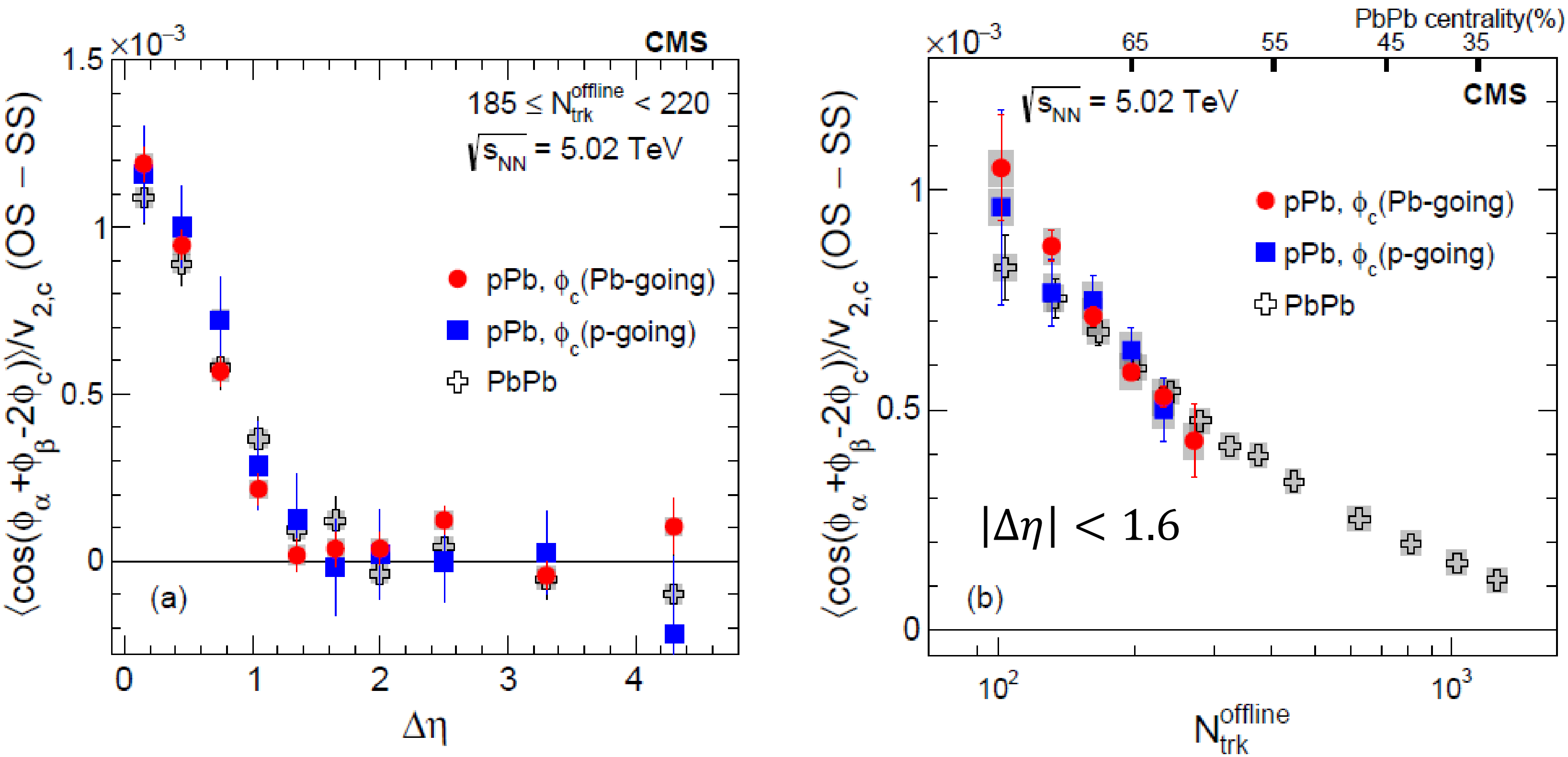
- Clear splitting between SS and OS
- Similarity observed between pPb (Pb-going) and PbPb at the same multiplicity bin.



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

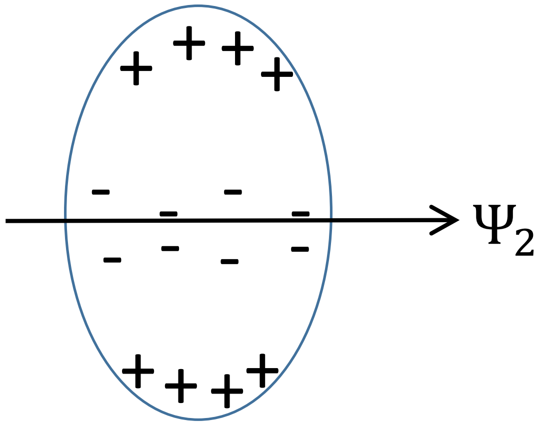
Analysis of CME

CMS, PRL 118, 122301 (2017)



- 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:

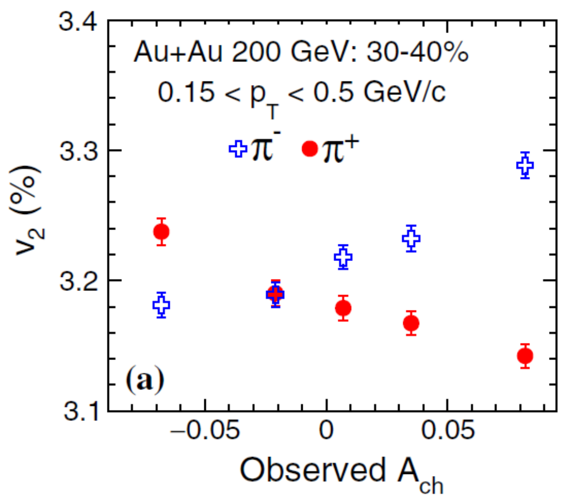
$$dN_\pm/d\phi \propto 1 \pm A_{ch}\boxed{[1-(r_e/2)\cos(2\phi-2\Psi_2)]} \times \left[1+2v_{2,\pm}^{base}\cos(2\phi-2\Psi_2)\right]$$

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

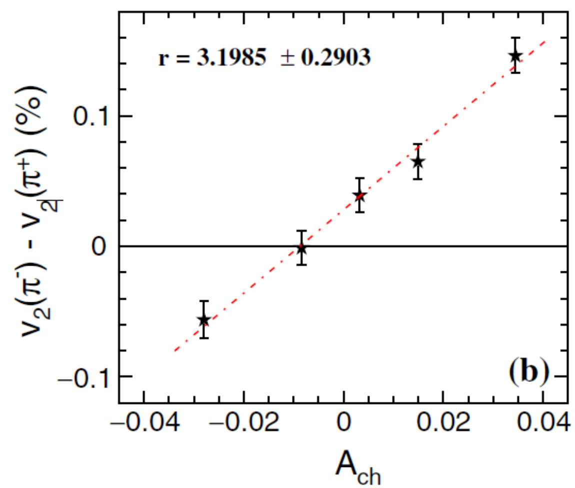
$$\boxed{\begin{aligned} v_{2,\pm} &= v_{2,\pm}^{base} \mp r_e A_{ch}/2 \\ v_{2,-} - v_{2,+} &= r_e A_{ch} \end{aligned}}$$

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

STAR

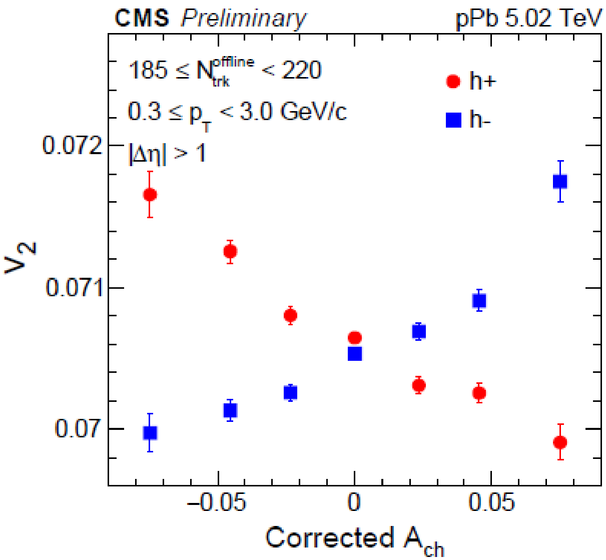


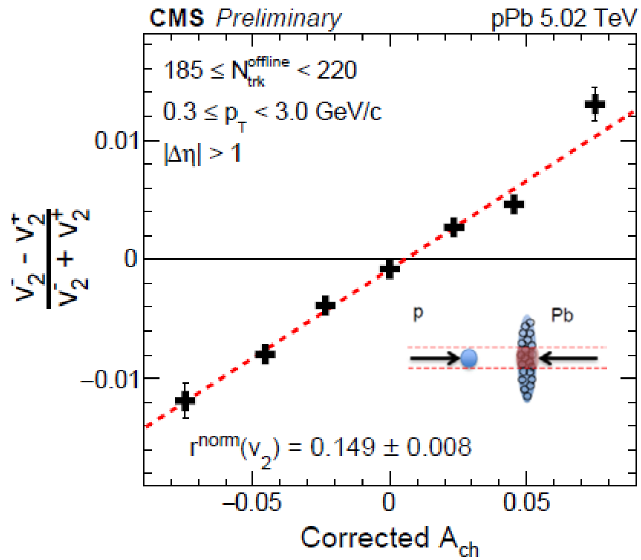
PRL114, 252302 (2015)

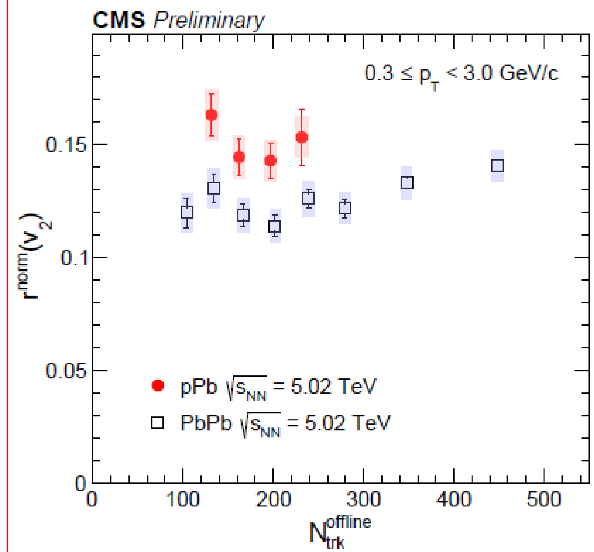


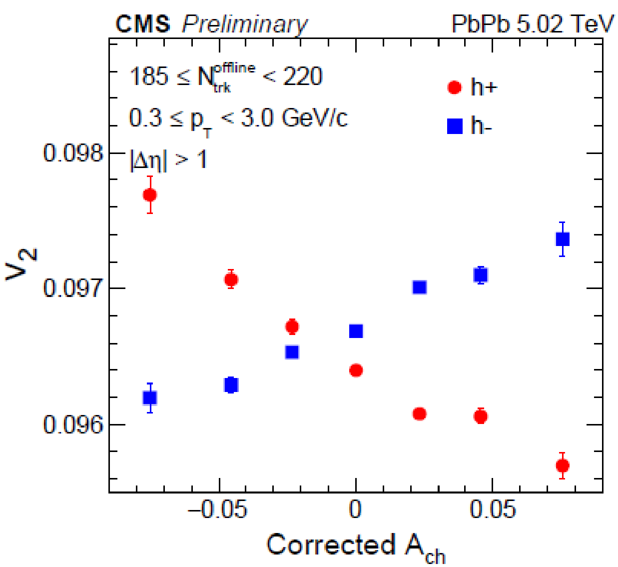
Analysis of CMW

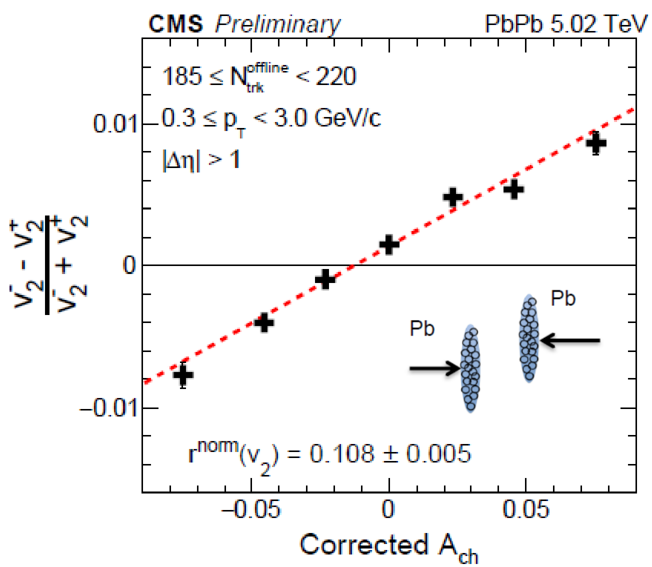
CMS-PAS-HIN-16-017











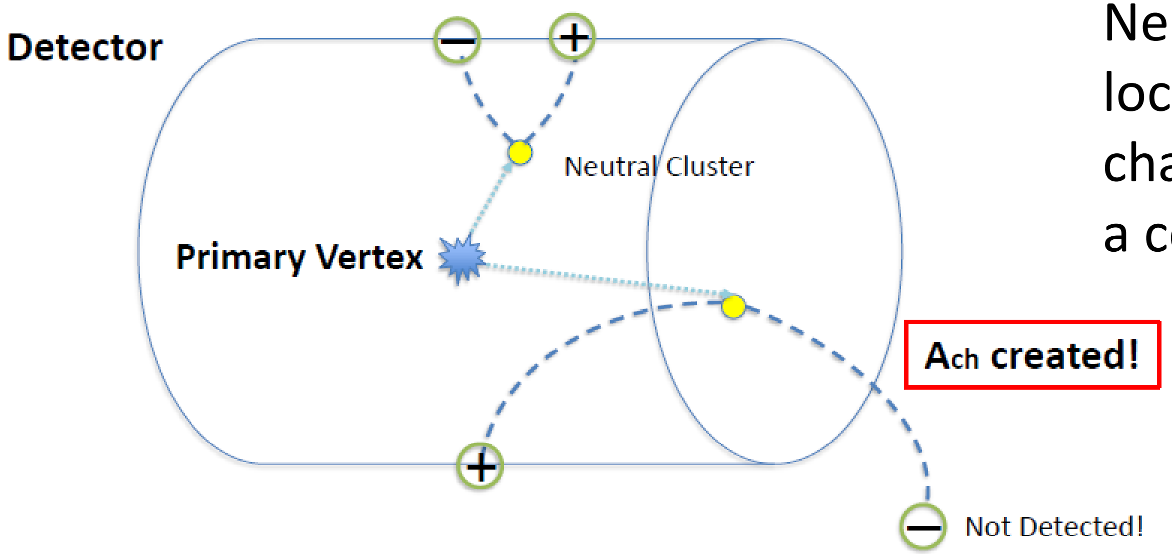
- **Significant slopes for pPb that is not expected in CMW**

$\Rightarrow$ **Challenges to CMW**

Analysis of CMW

CMS-PAS-HIN-16-017

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

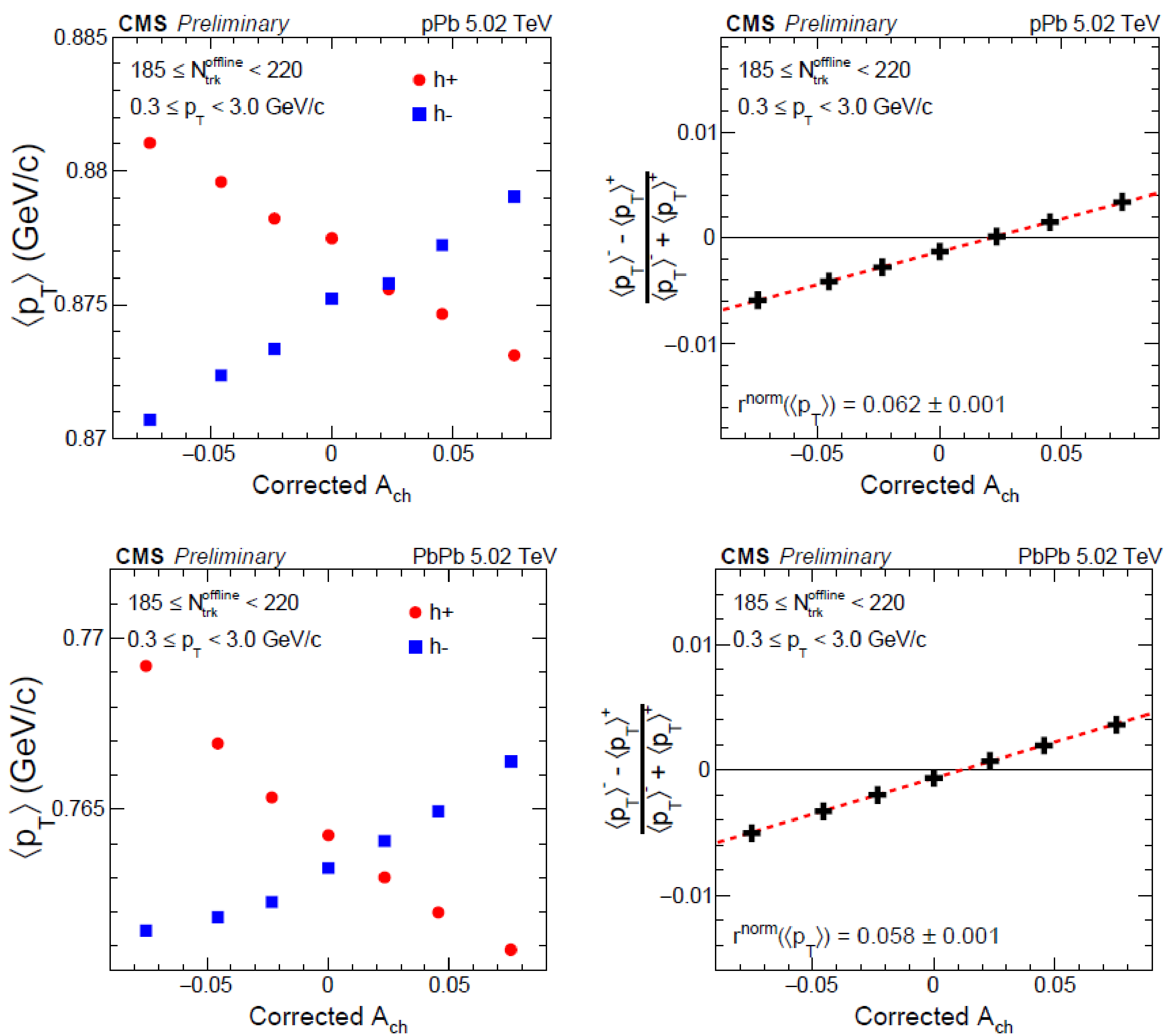


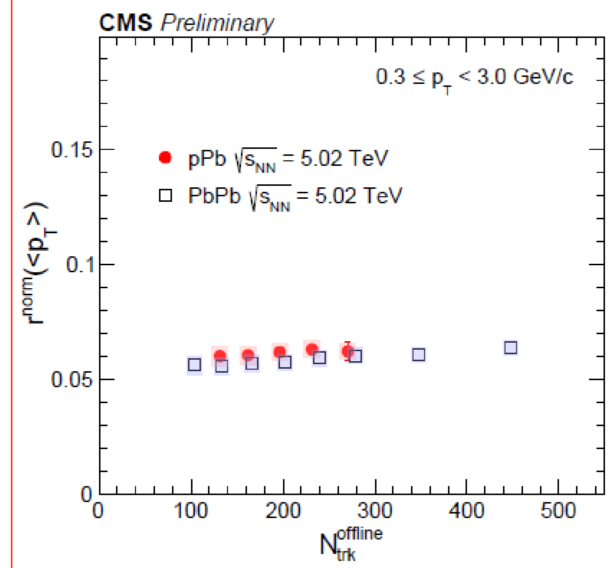
Neutral cluster decays locally into the pair of charged particles with a certain η separation.

- 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 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

CMS-PAS-HIN-16-017



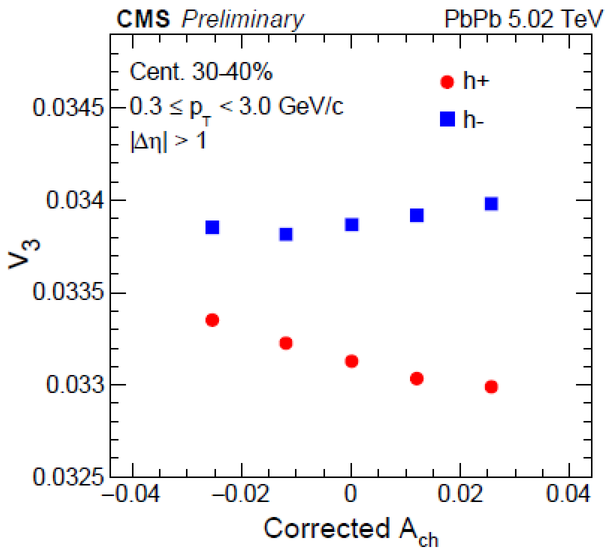


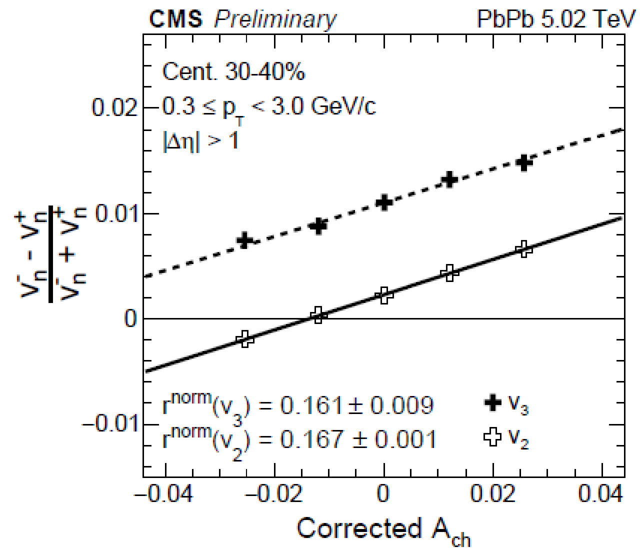
- **Very similar slopes for pPb and PbPb**

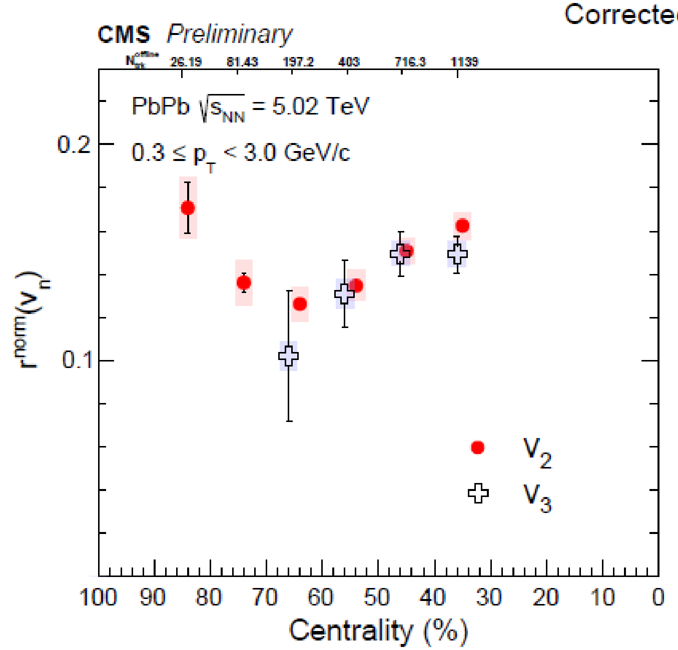
⇒ **Supports LCC, Challenges to CMW**

Analysis of CMW

CMS-PAS-HIN-16-017







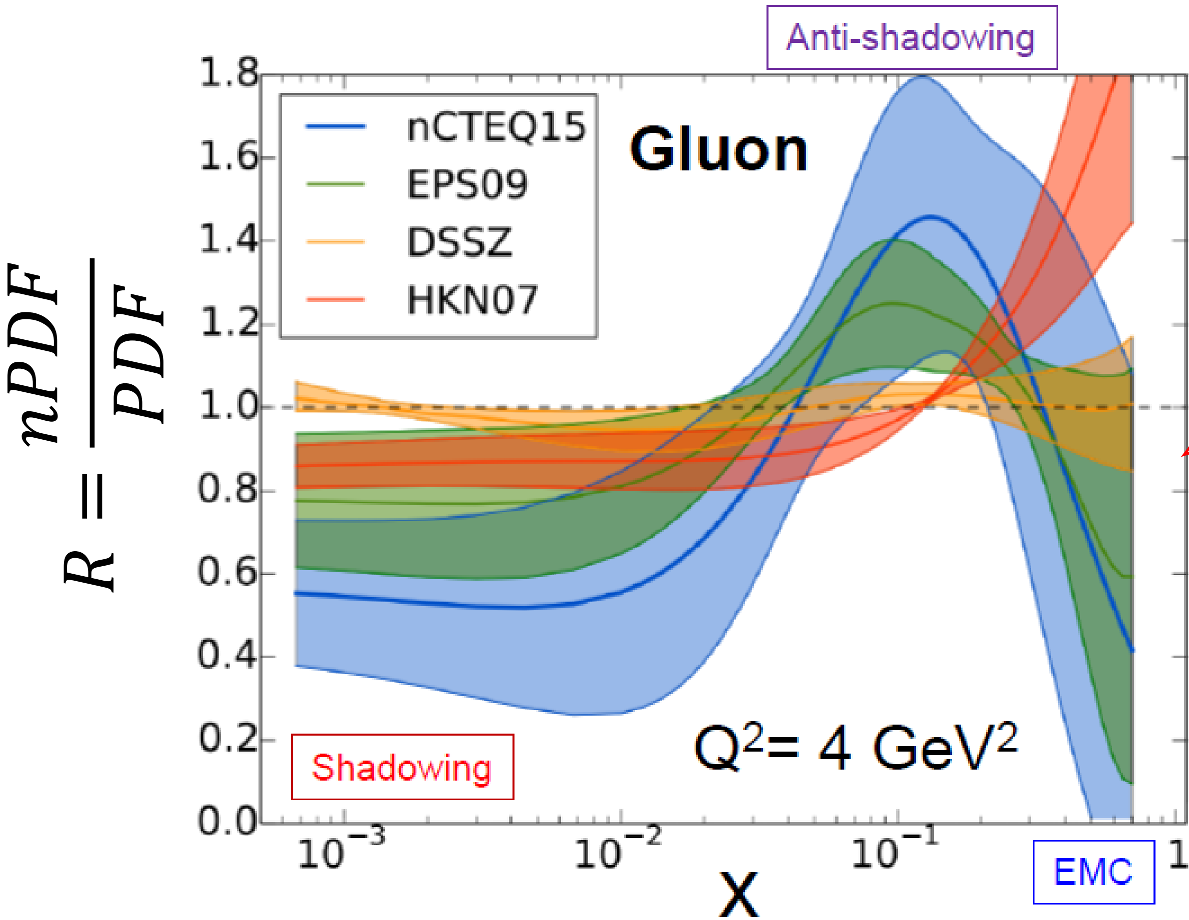
- **Normalized v_2 and v_3 slopes are very similar in all centrality ranges in PbPb**

⇒ **Supports LCC, Challenges to CMW**

- No interpretation yet for larger intercept for v_3

pA for nPDF

Nuclear Parton Distribution Function (nPDF)



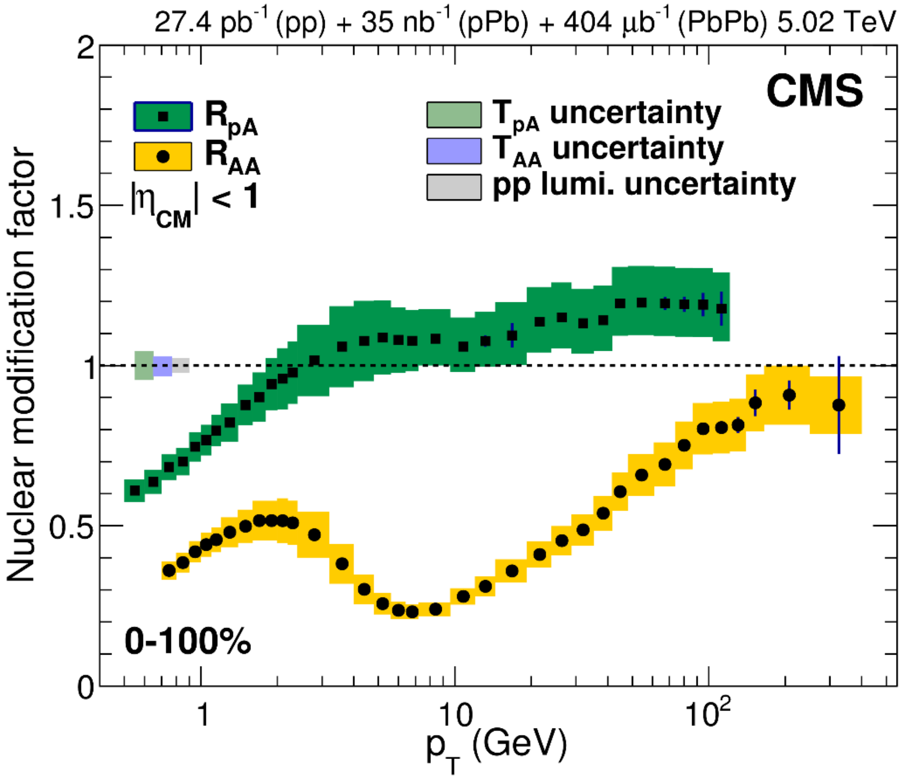
arXiv:1605.01389

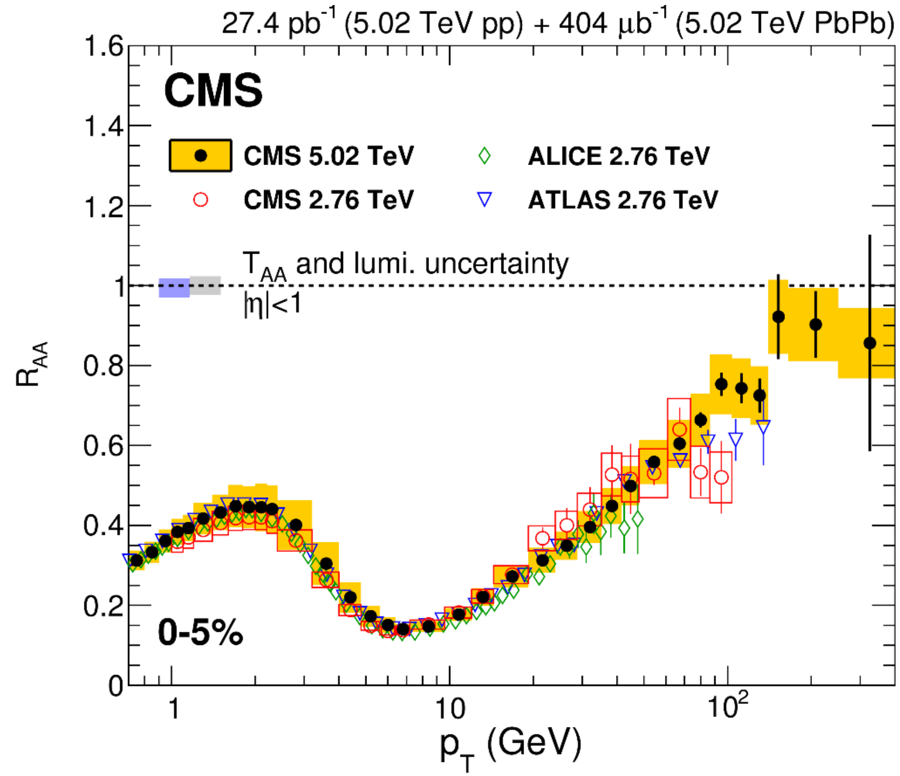
- Deep Inelastic Data
- Drell-Yan Data
- RHIC Pion Data in dAu

- EPS09 & nCTEQ15: Gluon (anti-)shadowing
- DSSZ: Modified parton to pion fragmentation (vacuum-like gluon PDF)

R_{pA} of Charged Particles at 5 TeV

CMS, JHEP 04, 039 (2017)

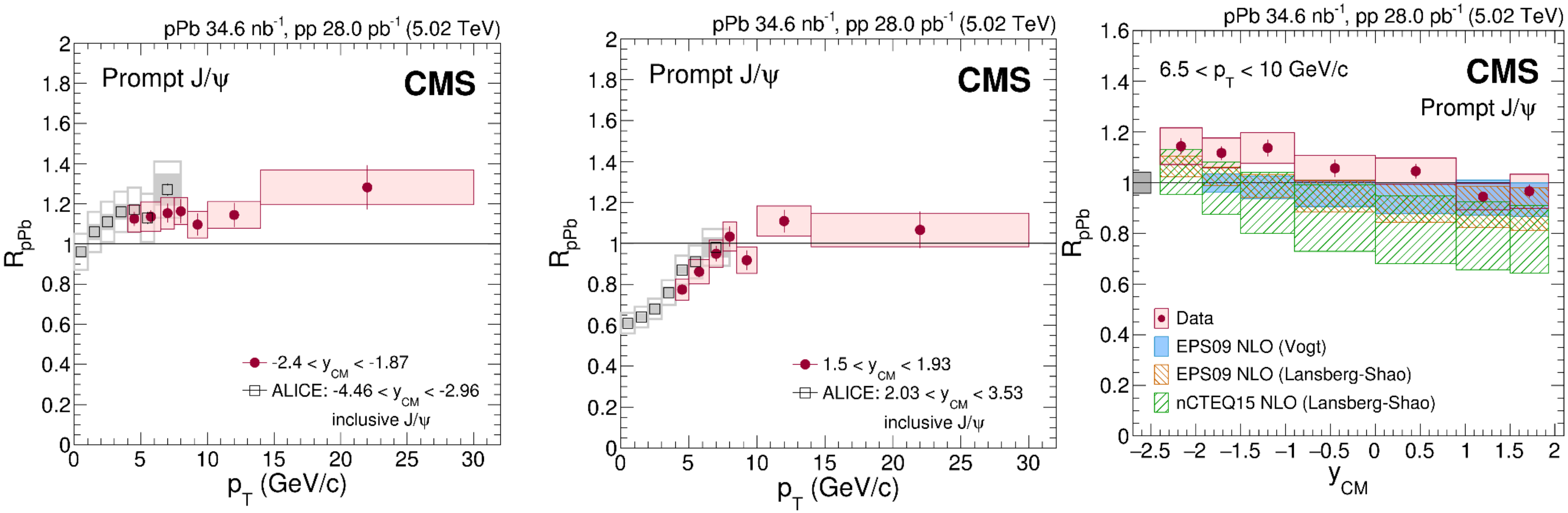


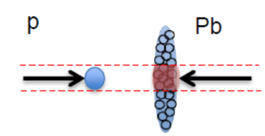


- R_{pA} and R_{AA} analyzed with **high statistics pp reference data**.
- **pPb data imply possible anti-shadowing and hadronization effects**
- Similar suppression at 2.76 and 5 TeV in PbPb

R_{pA} of Charmonia at 5 TeV

CMS, EPJC 77, 269 (2017)



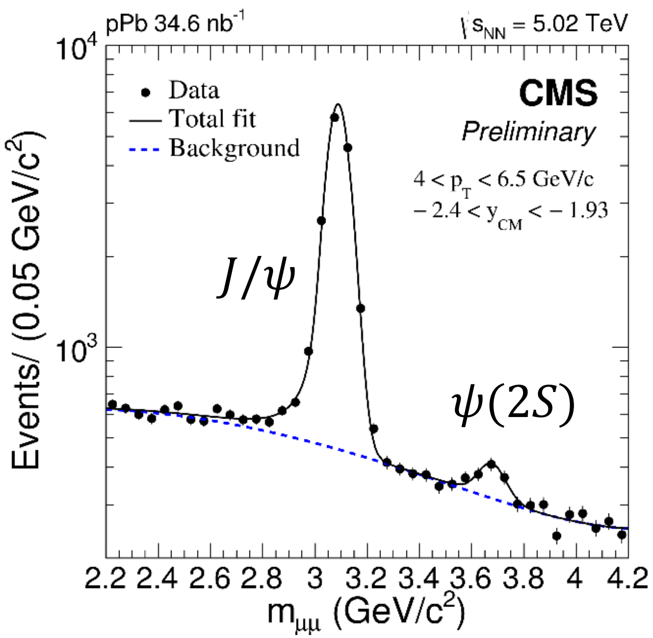


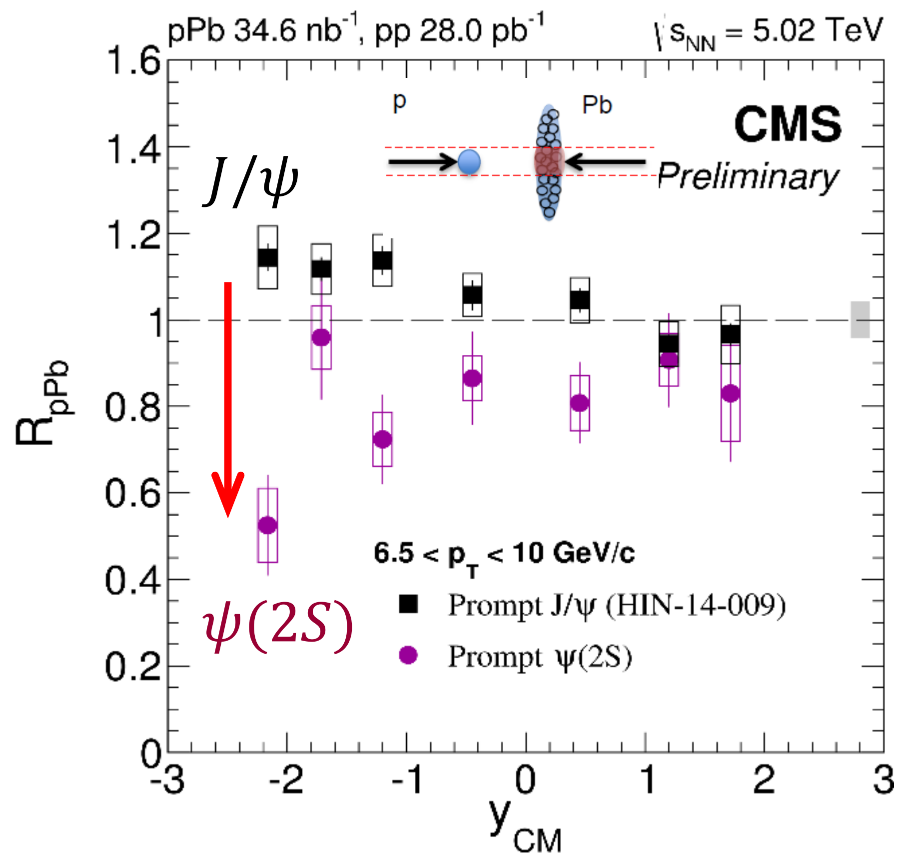
□ Suppression at low p_T in forward rapidities (or the low-x region)

⇒ **Hints some cold nuclear matter effects in Pb**

R_{pA} of Charmonia at 5 TeV

CMS-PAS-HIN-16-015

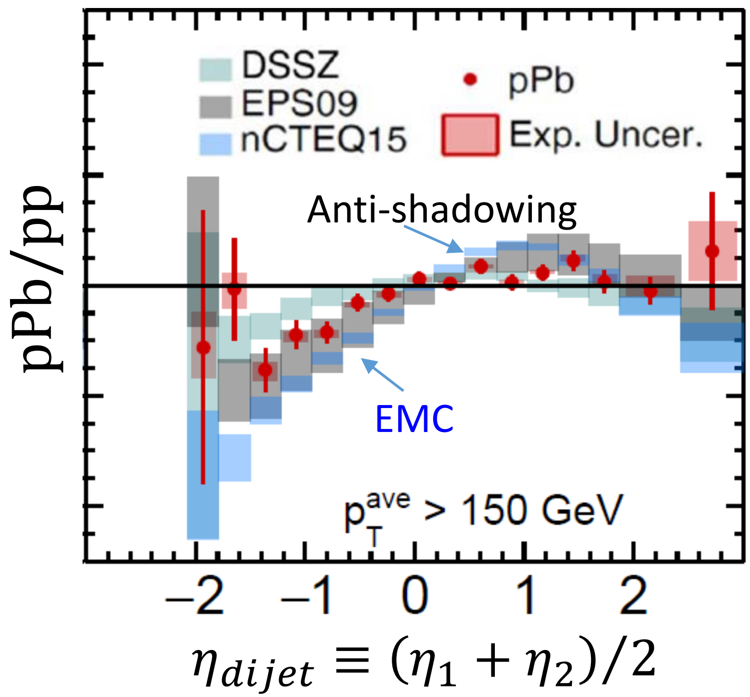




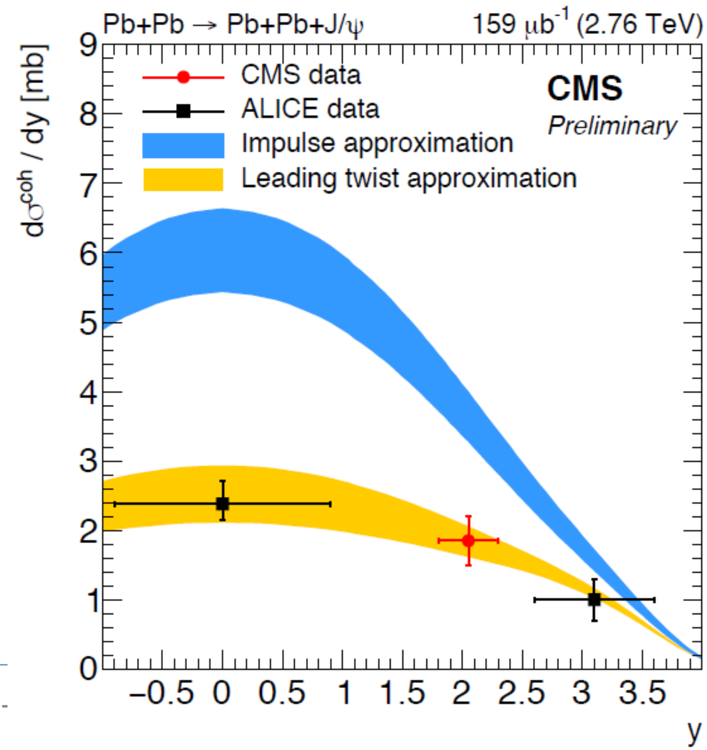
- Larger suppression of $\psi(2S)$ in Pb-going side accompanied with higher dN_{ch}/dy
- **Indicate the final state effects from comover absorption?**

Dijet Pseudorapidity Distribution at 5 TeV

CMS-PAS-HIN-16-003
Accepted by PLB



- Dijet's average-η distribution
- $Q^2 \sim 20{,}000 \text{ GeV}^2$
- Inconsistent between DSSZ and nCTEQ15
- **Evidence of gluon anti-shadowing and modification in the EMC region with $x > 0.3$**

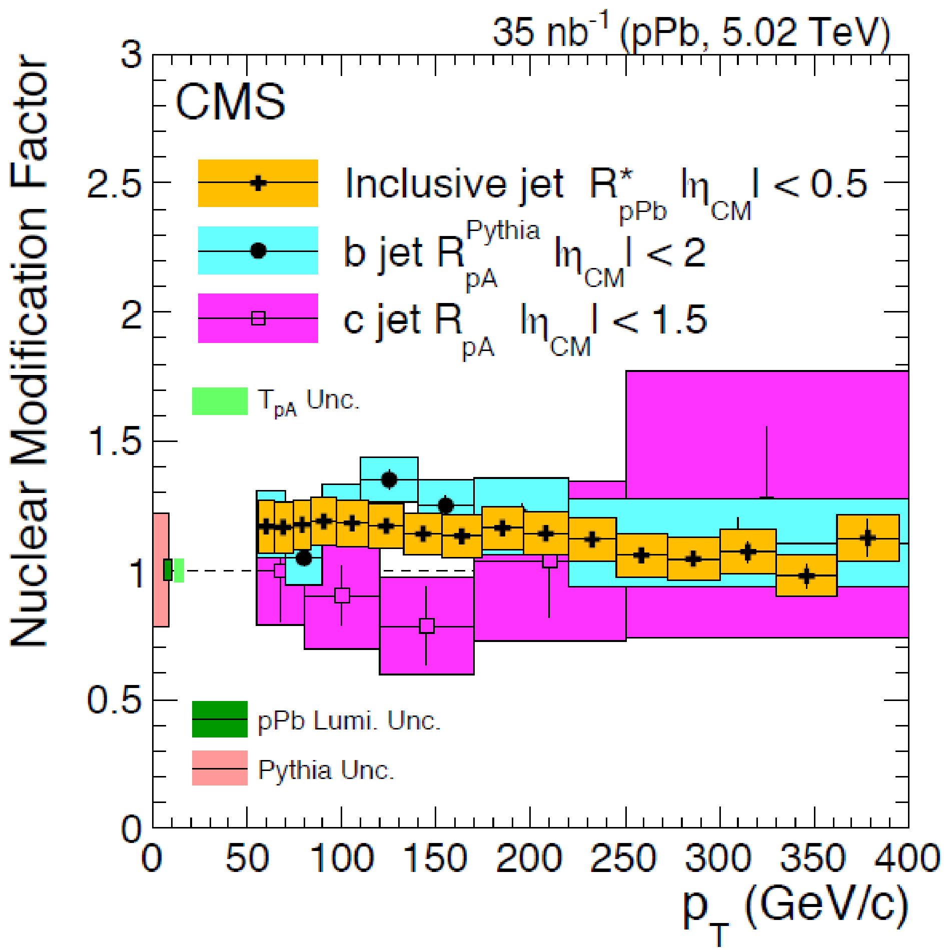


CMS, arXiv:1605.06966, Submitted to PLB

- J/ψ in UPC in PbPb
- $Q^2 \sim 2.4 \text{ GeV}^2$
- **Evidence of nuclear modification of gluon PDF at $x \sim 8 \times 10^{-3}$**

R_{pA} of Heavy-Flavored Jets at 5 TeV

- □ c- and b-jet distributions are dominated by gluon PDF
  ⇔ Inclusive dijet distributions are convoluted by quark PDF



- □ All jet data are consistent with each other in pPb
- □ **No indication of favor dependent nPDF within uncertainties**

[CMS Results]
Incl. jet: EPJC 76, 372 (2016)
b-jet: PLB 754, 59 (2016)
c-jet: Submitted to PLB

Summary

- Symmetric cumulant (SC) analysis indicates 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 exists 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