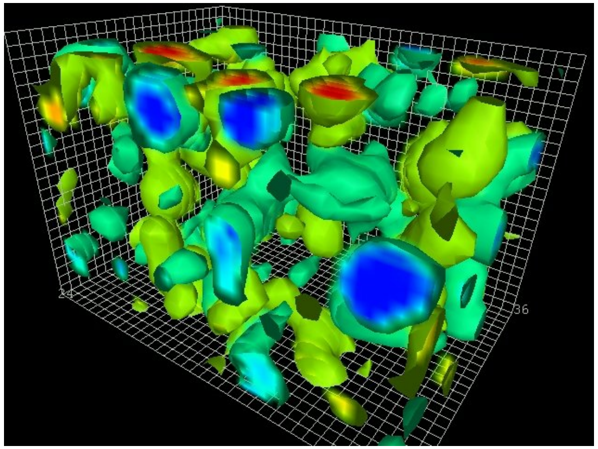
New insights into the search for the CME and CMW in heavy ion collisions

Zhoudunming Tu (Kong)
Rice University
BNL, US 2017

Chiral magnetic effect (CME)

- Formation of QGP in heavy ion collisions with restored chiral symmetry

Fluctuations of topological charge in QCD vacuum → P and CP odd domains



Derek Leinweber, University of Adelaide

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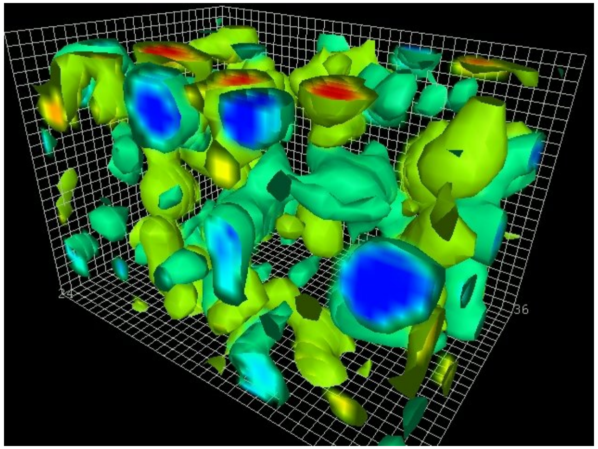

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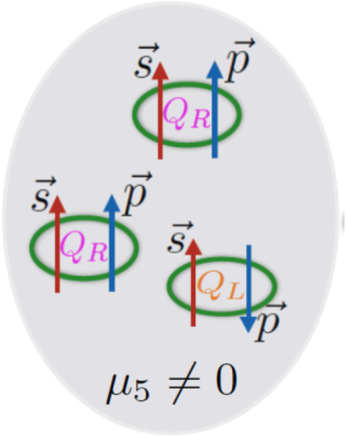
With nonzero chiral chemical potential



Prog.Part.Nucl.Phys. 88 (2016)

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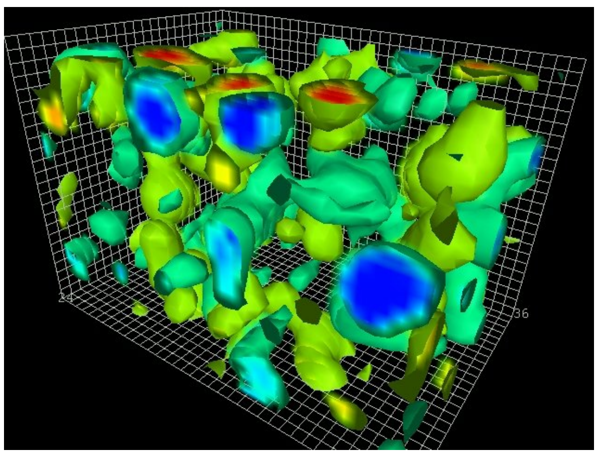

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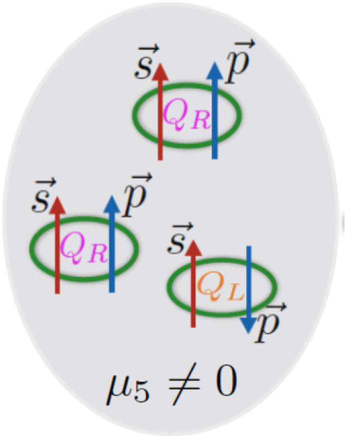

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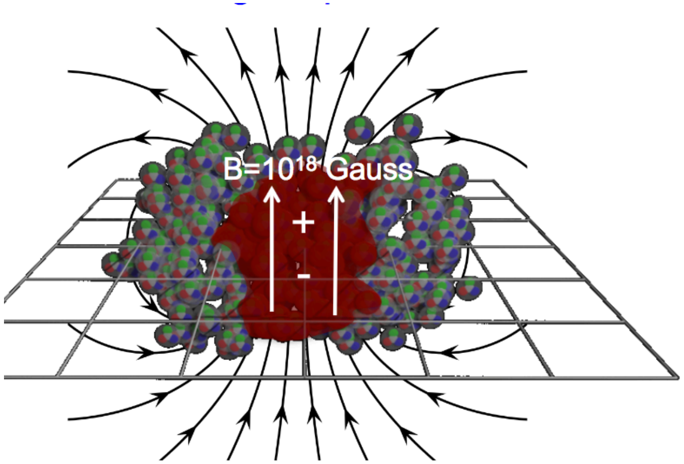
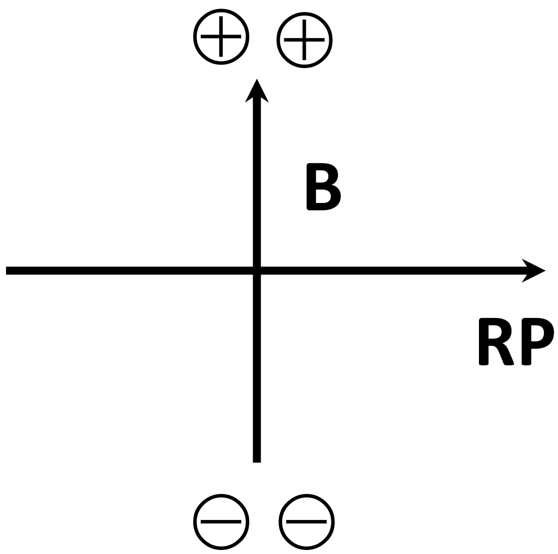
Strong magnetic field



A current →

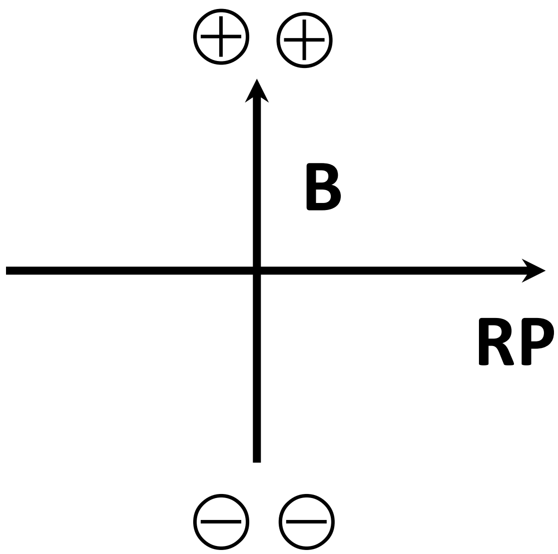
$$\vec{J} = \sigma_5 \vec{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \vec{B}$$

How to measure CME?



How to measure CME?

Same-sign: α = β
Opposite sign: α ≠ β



Charged-dependent correlator γ:

arXiv: hep-ph/0406311

$$\gamma \equiv \left\langle \cos\left(\phi_{\alpha} + \phi_{\beta} - 2\psi_{RP}\right)\right\rangle$$

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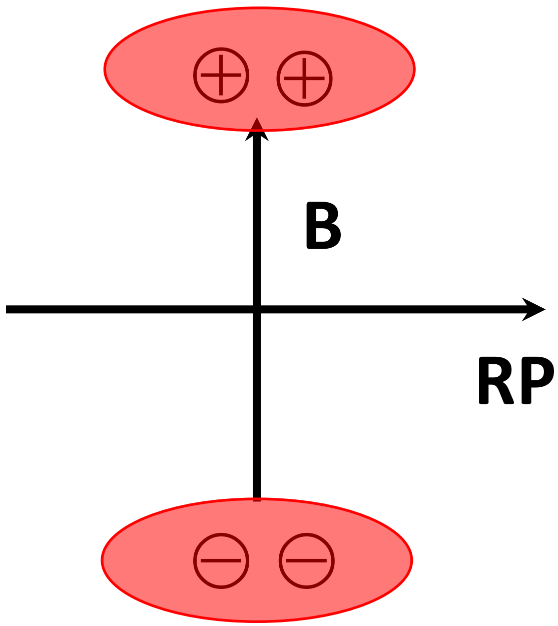

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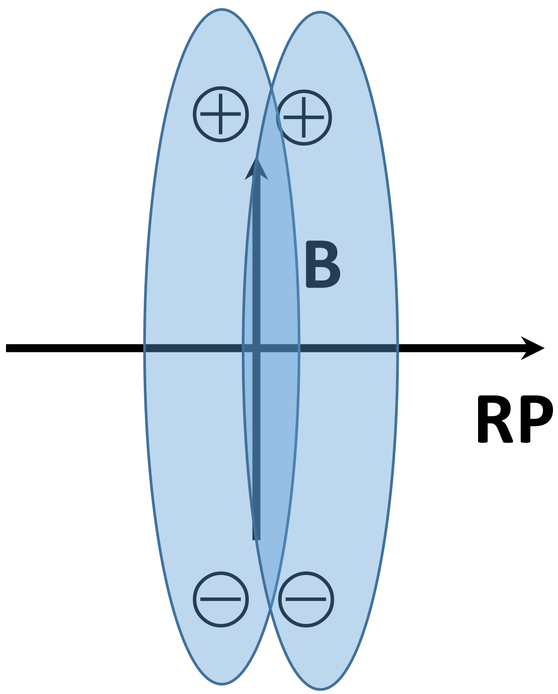

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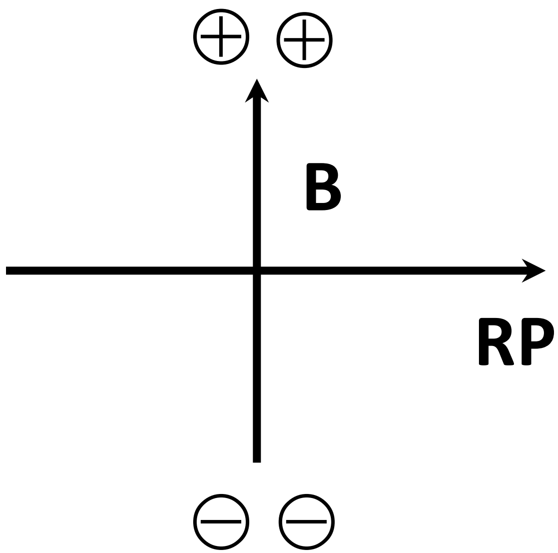

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$$\gamma \equiv \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{RP}\right)\right\rangle = \left\langle \cos\left(\Delta\phi_\alpha\right)\cos\left(\Delta\phi_\beta\right)\right\rangle - \left\langle \sin\left(\Delta\phi_\alpha\right)\sin\left(\Delta\phi_\beta\right)\right\rangle$$

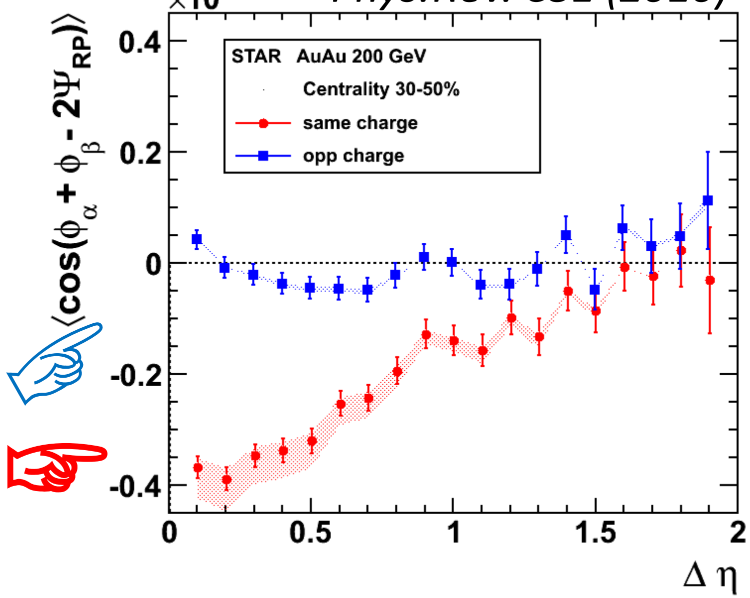
$$= \left[\left\langle v_{1,\alpha} v_{1,\beta}\right\rangle + B_{in}\right] - \left[\left\langle a_\alpha a_\beta\right\rangle + B_{out}\right]$$

< 0 for same-sign pairs
> 0 for opposite-sign pairs

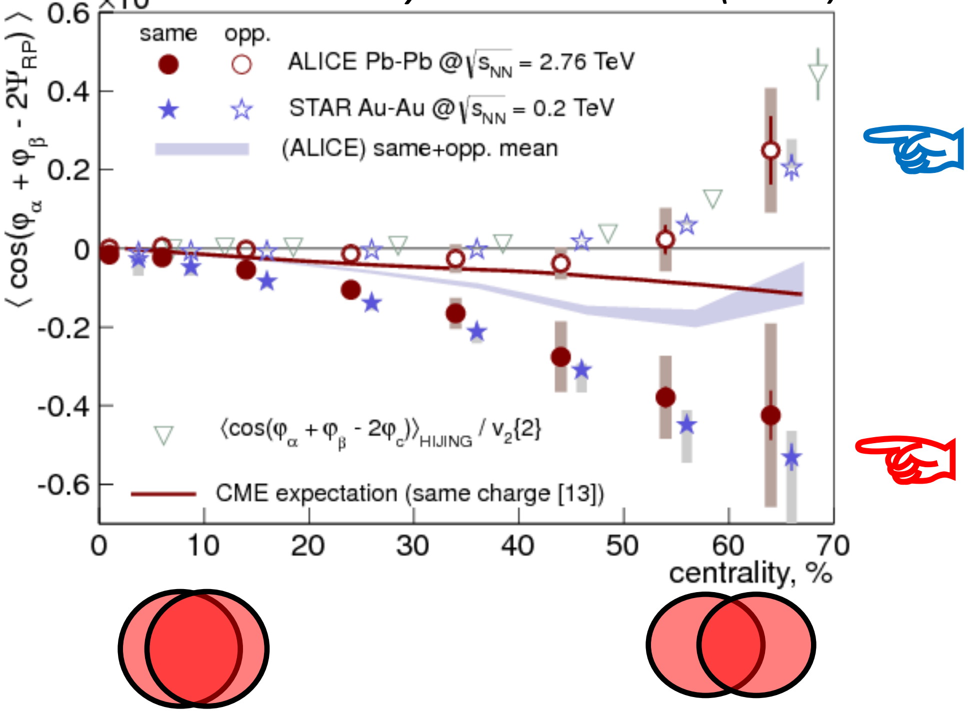
→ a measure of how much the charges separated wrt RP

Experimental evidence

Phys.Rev. C81 (2010)



Phys.Rev.Lett. 110 (2013)



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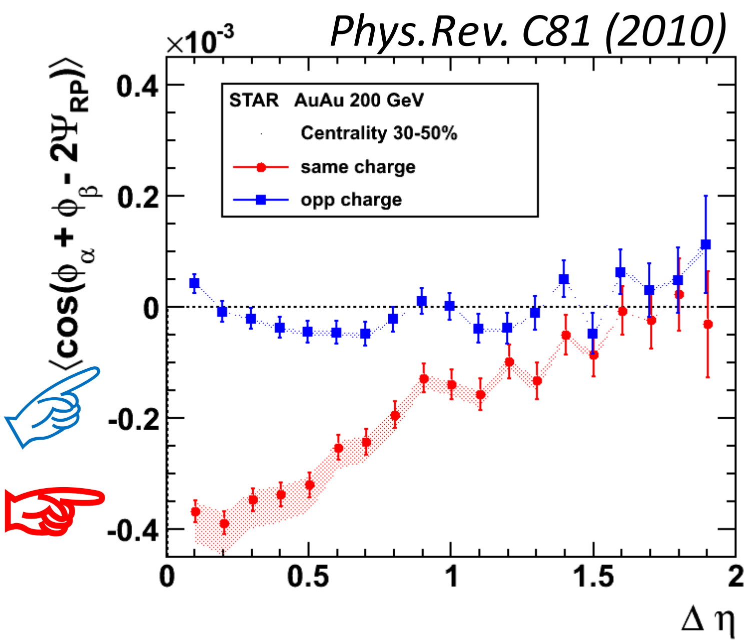

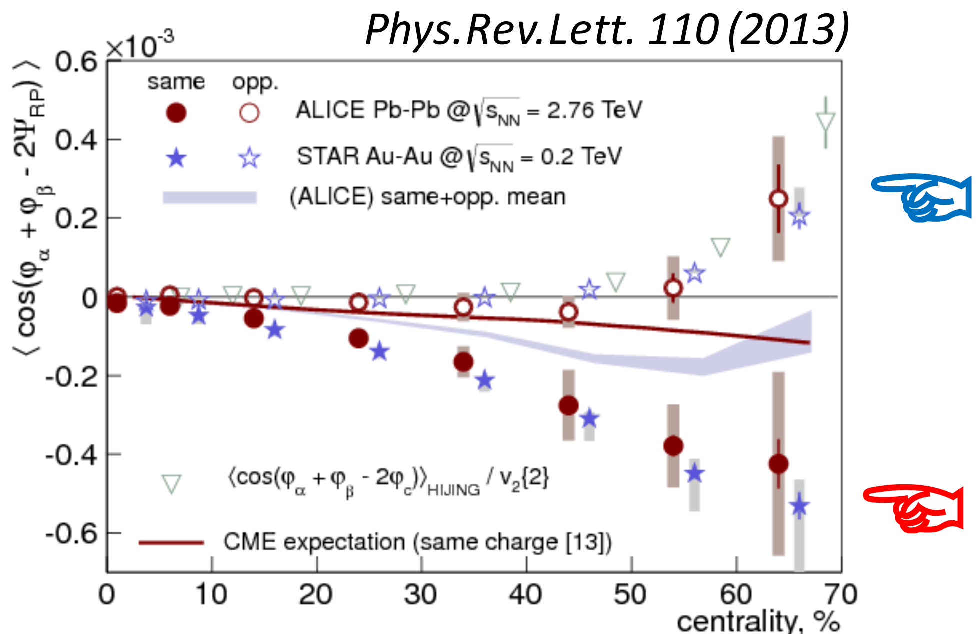

Charged-dependent correlation observed!

- Short-range effect, OS and SS start to merge after Δη > 1.5 ~ 1.6
- Stronger in peripheral than in central events

Experimental evidence

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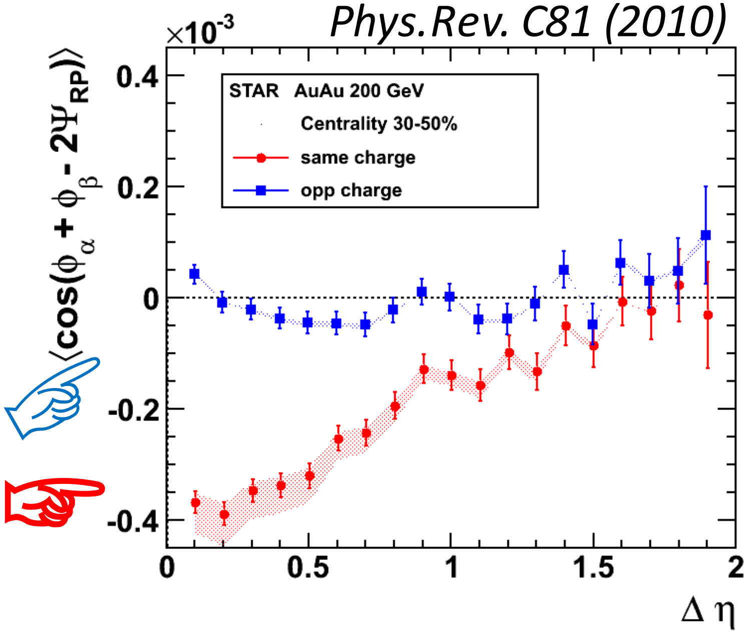

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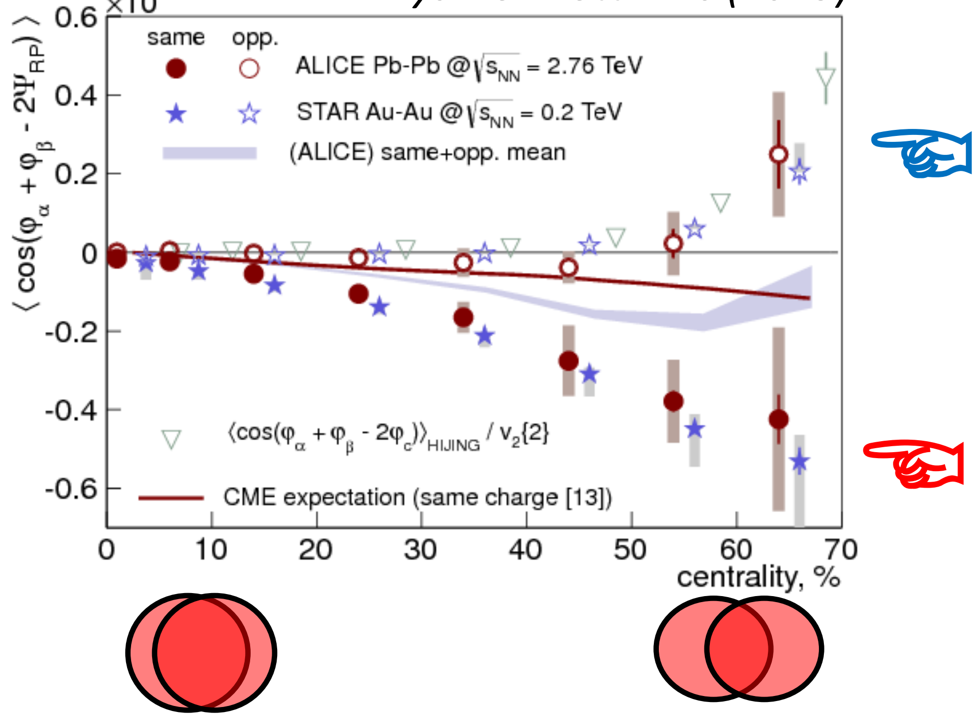


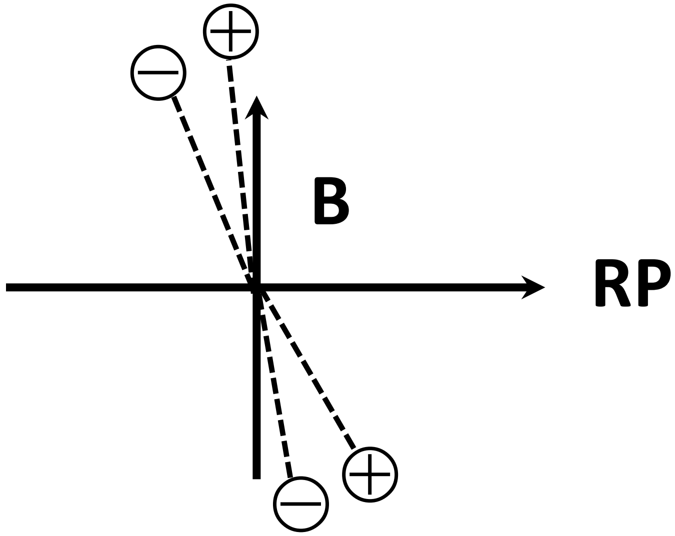
Charged-dependent correlation observed!

- Short-range effect, OS and SS start to merge after $\Delta\eta > 1.5 \sim 1.6$
- Stronger in peripheral than in central events

All in line with CME prediction qualitatively

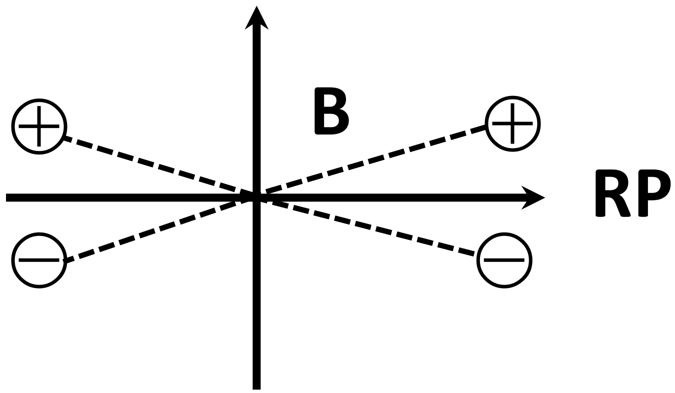
However, story not end!

Local charge conservation



However, story not end!

Local charge conservation + flow



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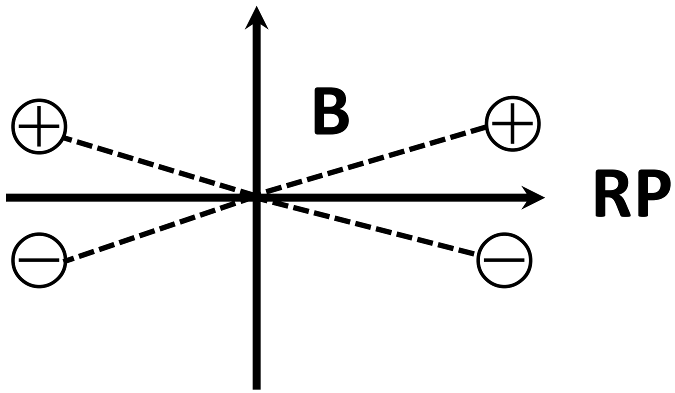
Local charge conservation + flow → charged-dependent correlation



$$\gamma \equiv \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{RP}\right)\right\rangle$$

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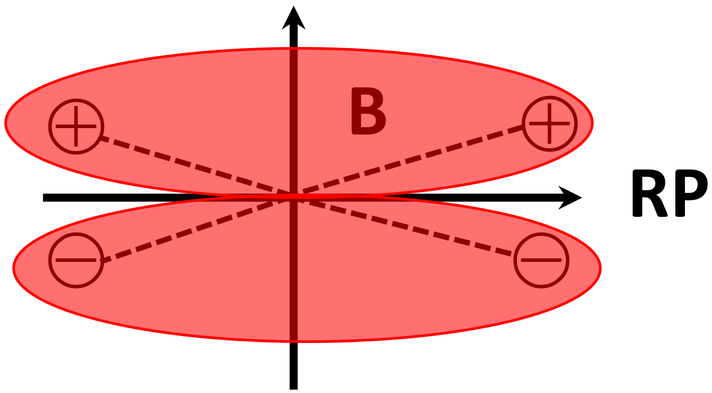

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- cos(0 - π - 0) = **-1**

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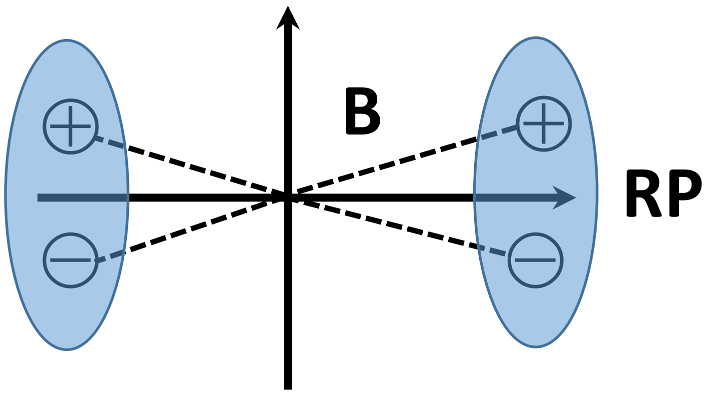

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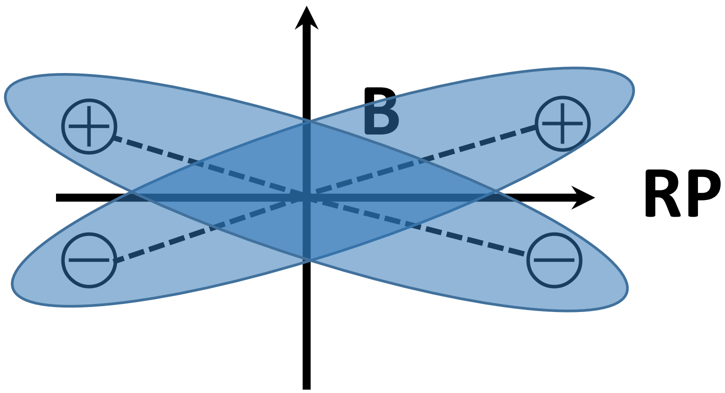
- ○ cos(π - π – 0) = **+1**

However, story not end!

Local charge conservation + flow → charged-dependent correlation



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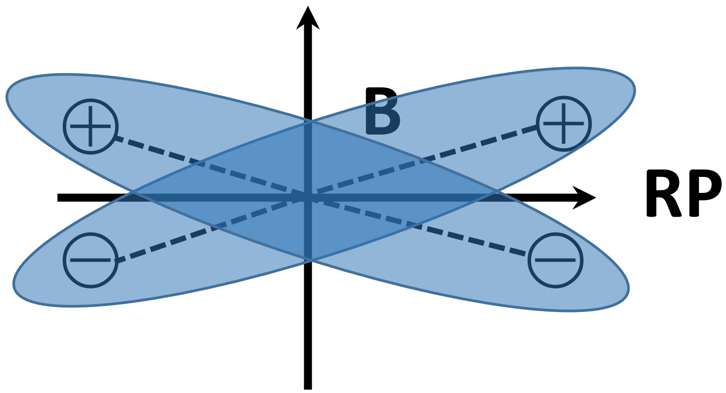
  →-1
- ✓ Opposite-sign (OS):
  - ○ cos(0 + 0 – 0) = **+1**
  - ○ cos(π - π – 0) = **+1**
  - ○ cos(0 - π – 0) = **-1**
  - ○ cos(0 + π – 0) = **-1**

  →0

However, story not end!

Local charge conservation + flow → charged-dependent correlation

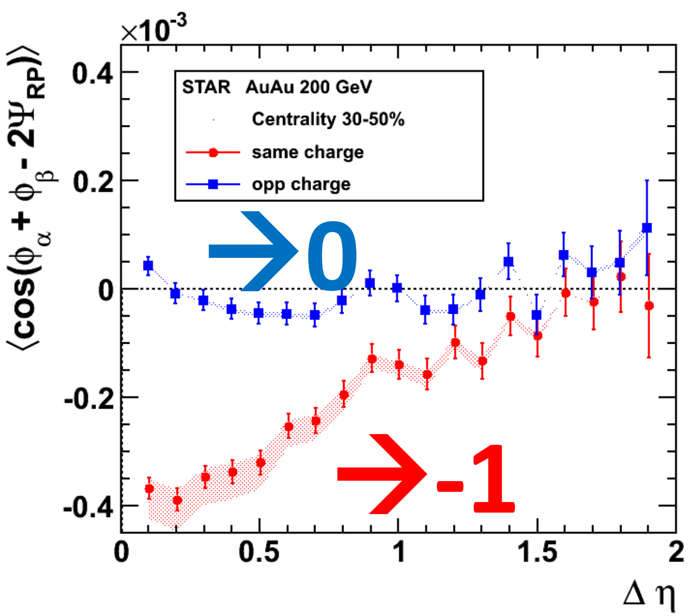


$$\gamma \equiv \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{RP}\right)\right\rangle$$

- ✓ Same-sign (SS):
  - $\cos(0+\pi-0) = -1$
  - $\cos(0-\pi-0) = -1$

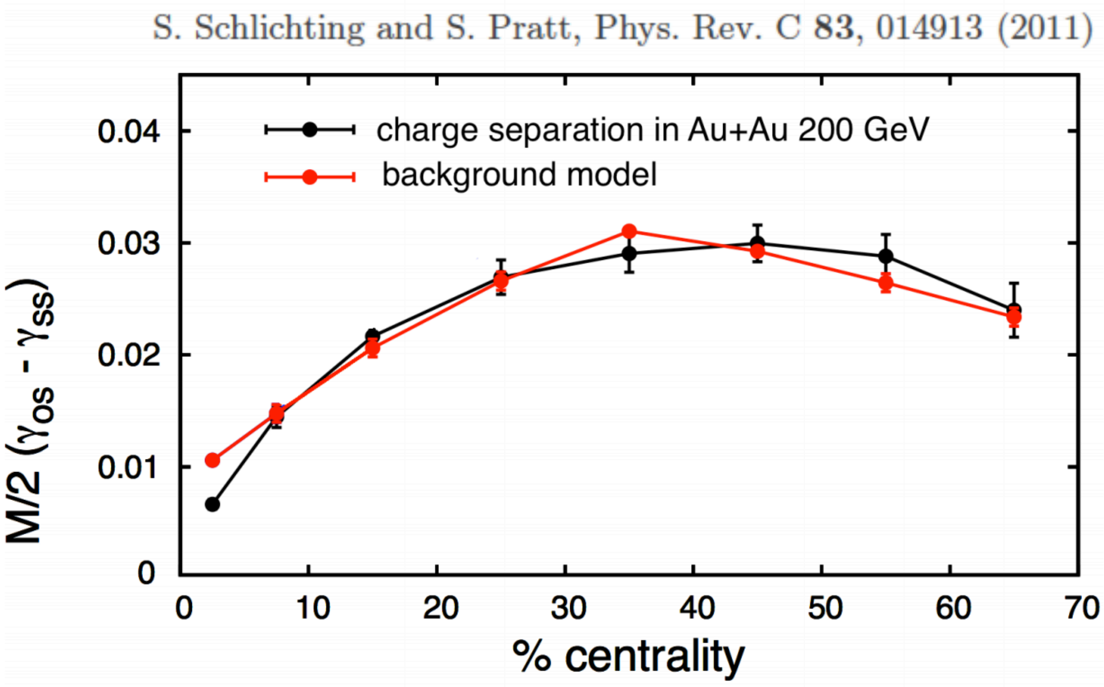
  → -1
- ✓ Opposite-sign (OS):
  - $\cos(0+0-0) = +1$
  - $\cos(\pi-\pi-0) = +1$
  - $\cos(0-\pi-0) = -1$
  - $\cos(0+\pi-0) = -1$

  → 0



Consistent with experimental data as well

Local charge conservation + v2



- γ_{os} - γ_{ss} agrees with data very well for all centralities
- OS and SS individually don't agree with data
  → Charged-independent correlation could be different.

Signal or Background?

$\Delta\gamma$ (γ^{os} - γ^{ss}) = SIGNAL + BKG

How to kill Background?

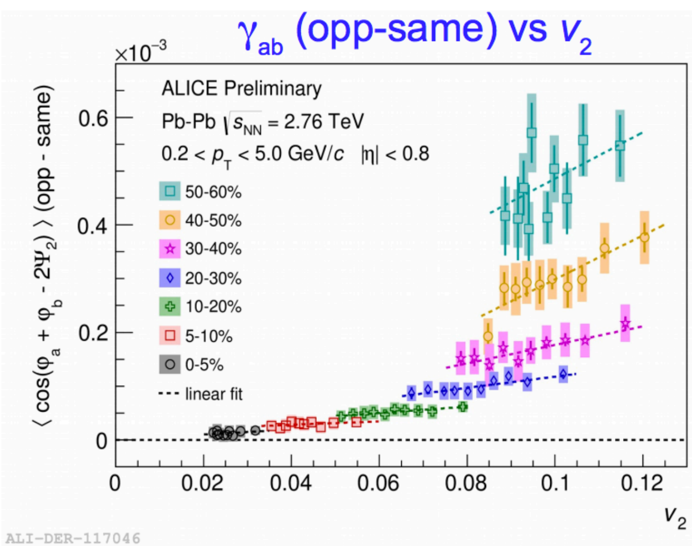
$\Delta\gamma$ $(\gamma^{OS} - \gamma^{SS})$ = ? + ~~BKG~~

How to kill Background?

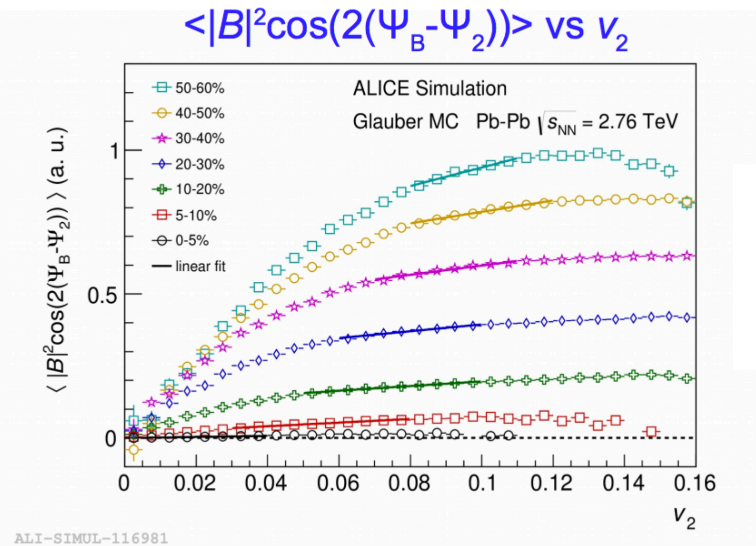
$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) =$ **?** + ~~BKG~~

Event-Shape-Engineering

- Statistically independent "handle" to control the initial geometry
- γ vs v_2 can be explicitly tested out



$$\gamma_{ab} = \langle \cos(\varphi_a + \varphi_b - 2\Psi_2) \rangle$$



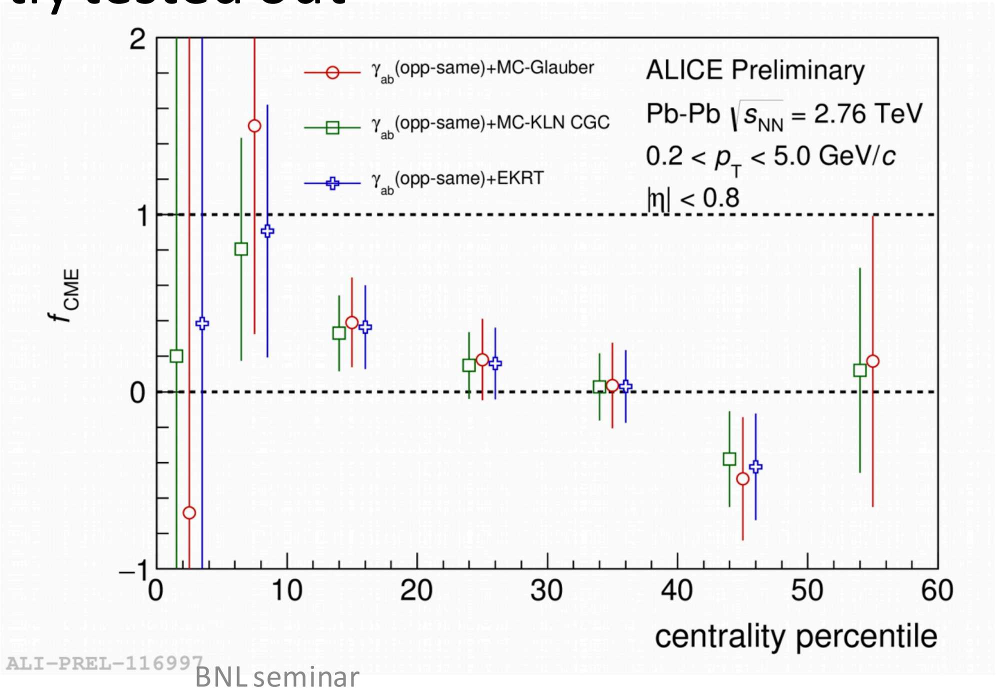
Glauber: M. Miller et al, ARNPS 57, 205 (2007)

How to kill Background?

$\Delta\gamma\ (\gamma^{os} - \gamma^{ss}) =$? + ~~BKG~~

Event-Shape-Engineering

- Statistically independent "handle" to control the initial geometry
- γ vs v_2 can be explicitly tested out
- Less than 20% signal
- Precision is needed!



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arXiv:1607.04697

Charge separation signal: $\Delta\gamma \sim B^2 \left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle$

How does the B-field in pPb compare to PbPb?

Magnetic field

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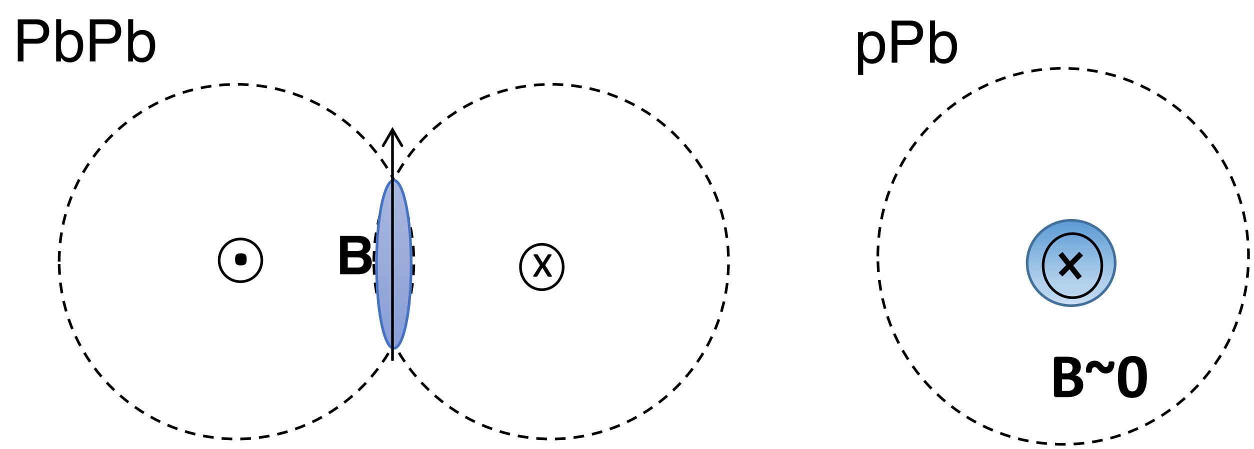

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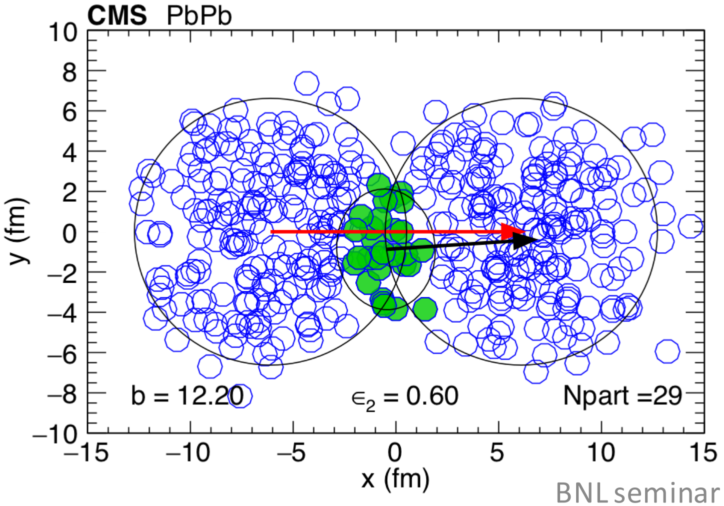

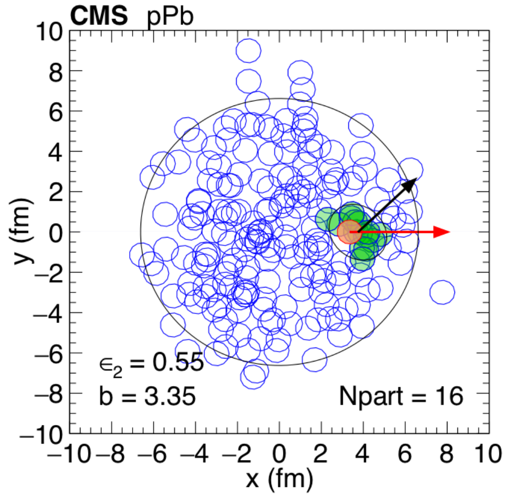

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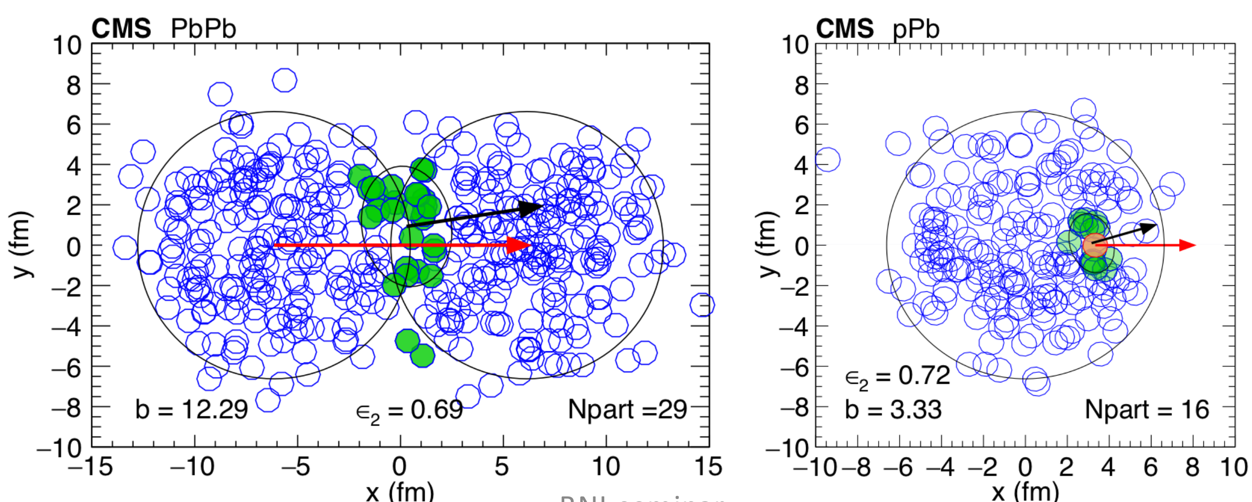

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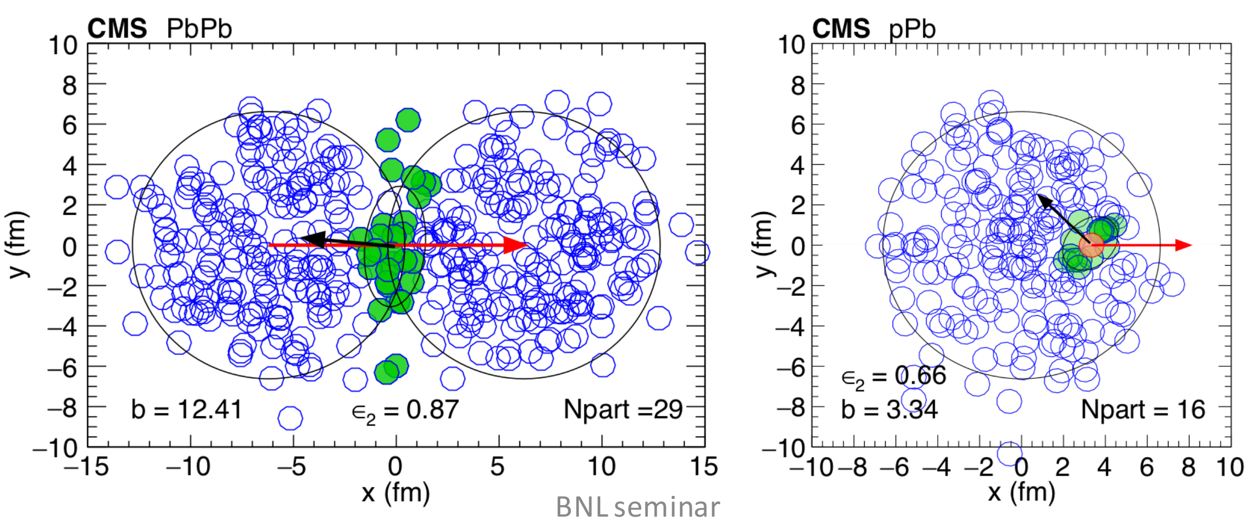
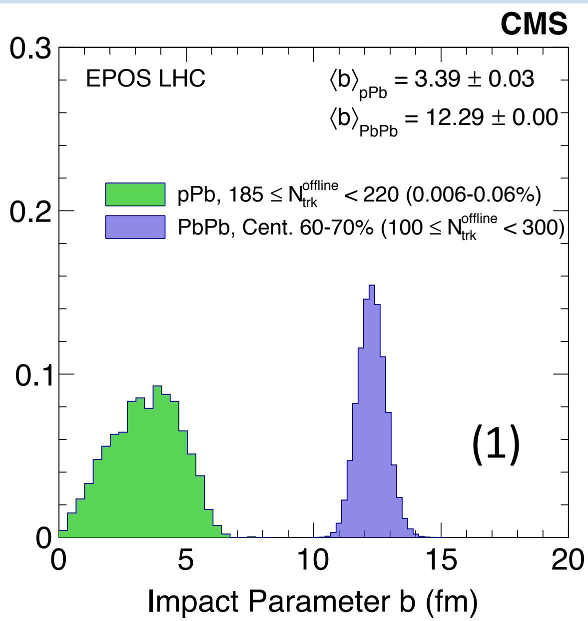
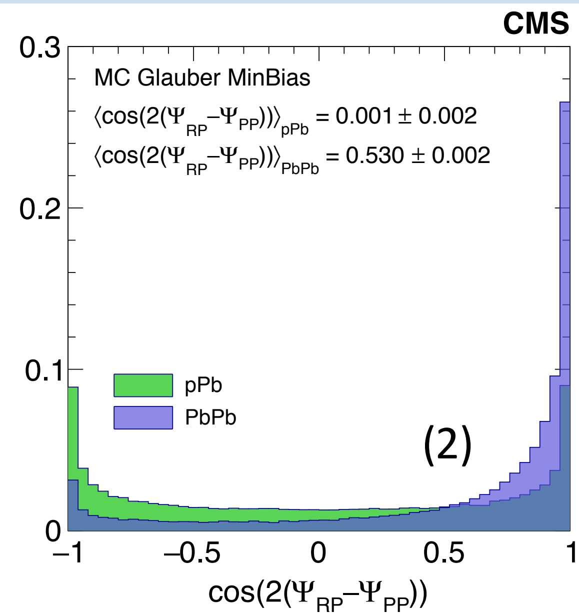


pPb vs PbPb

arXiv:1607.04697

- **Charge separation signal:** $\Delta\gamma \sim B^2 \left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle$
  - B (PbPb) > B (pPb) for the magnitude
  - De-correlation between ψ_B (~ψ_{RP}) and ψ_{EP} (~ψ_{PP})





(1) $\left(\frac{B_{pPb}}{B_{PbPb}}\right)^2 \sim \left(\frac{b_{pPb}}{b_{PbPb}}\right)^2 \leq \frac{1}{16}$

(2) $\frac{\left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle_{pPb}}{\left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle_{PbPb}} \ll 1$

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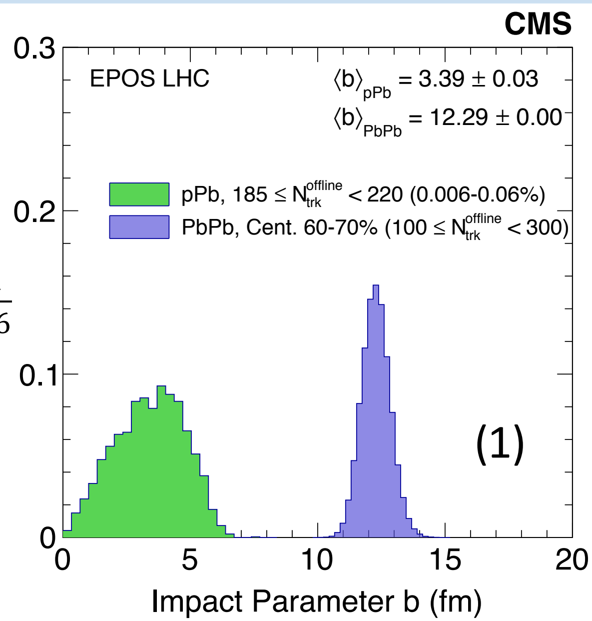
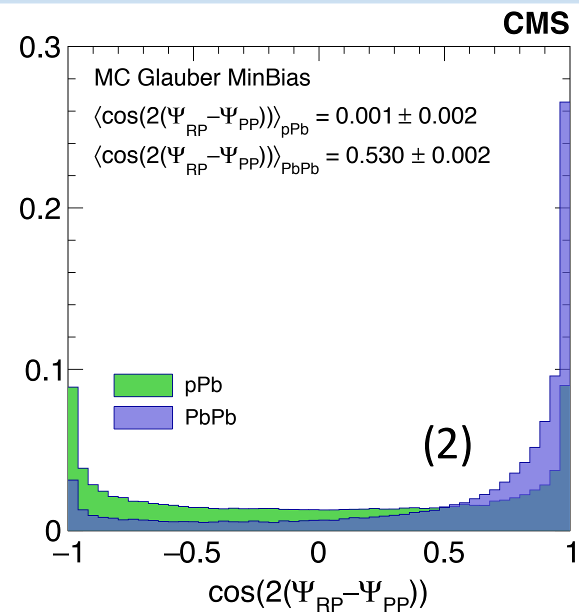
(1)

$$\left(\frac{B_{pPb}}{B_{PbPb}}\right)^2 \sim \left(\frac{b_{pPb}}{b_{PbPb}}\right)^2 \le \frac{1}{16}$$



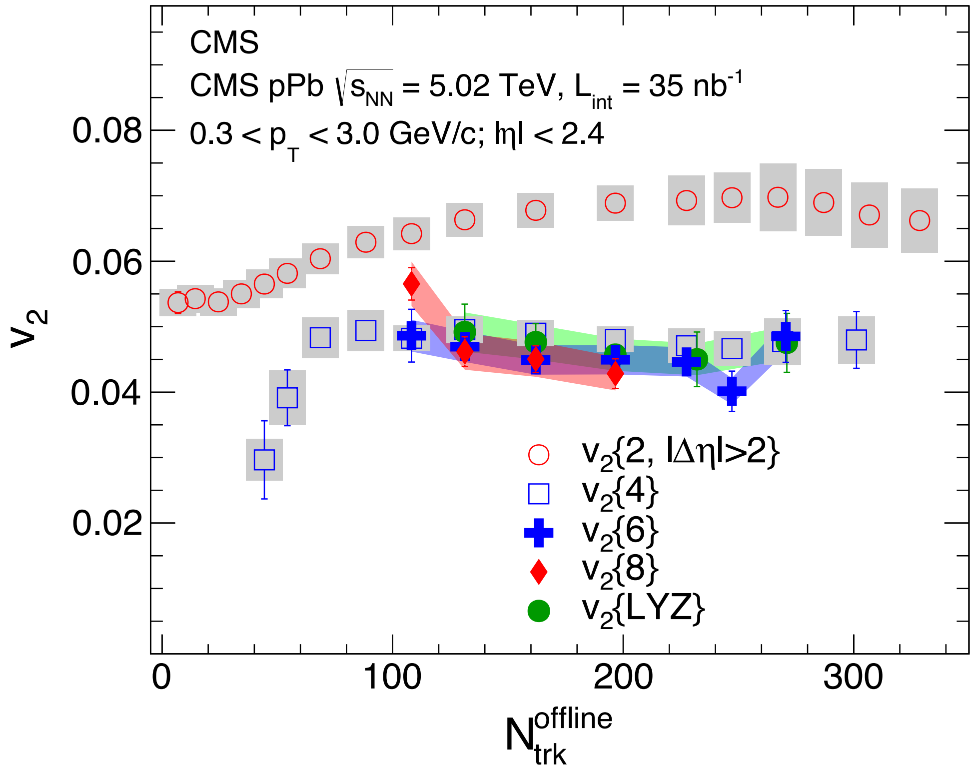


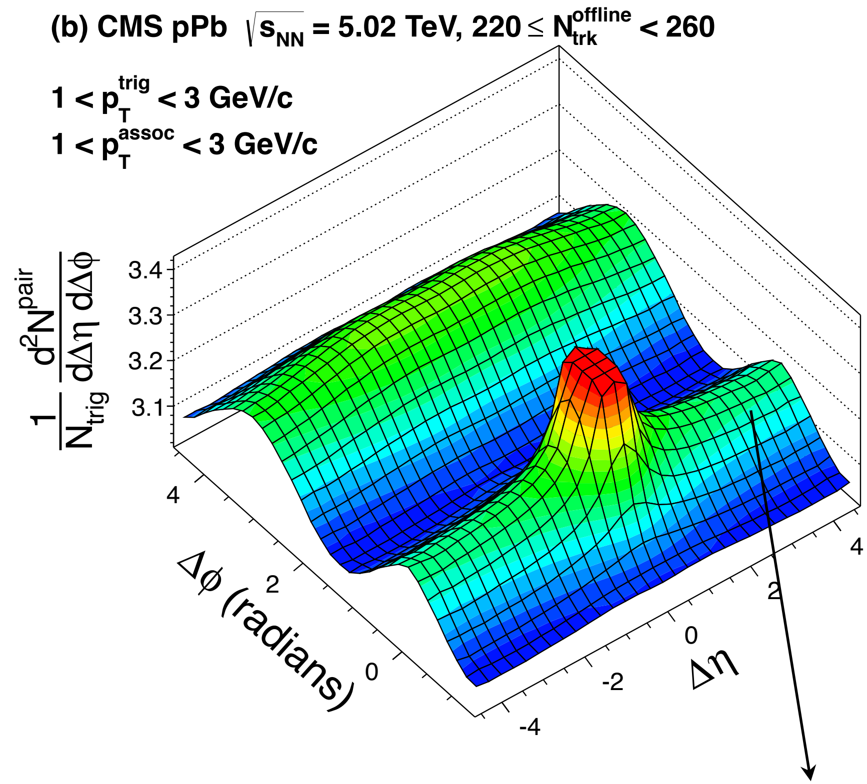
(2)

$$\frac{\left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle_{pPb}}{\left\langle \cos\left(2\Psi_B - 2\Psi_{EP}\right)\right\rangle_{PbPb}} \ll 1$$

- $\Delta\gamma$(PbPb) >> $\Delta\gamma$ (pPb) ➔ support CME in AA
- $\Delta\gamma$(PbPb) ≈ $\Delta\gamma$ (pPb) ➔ challenge to CME

High-multiplicity pPb collisions

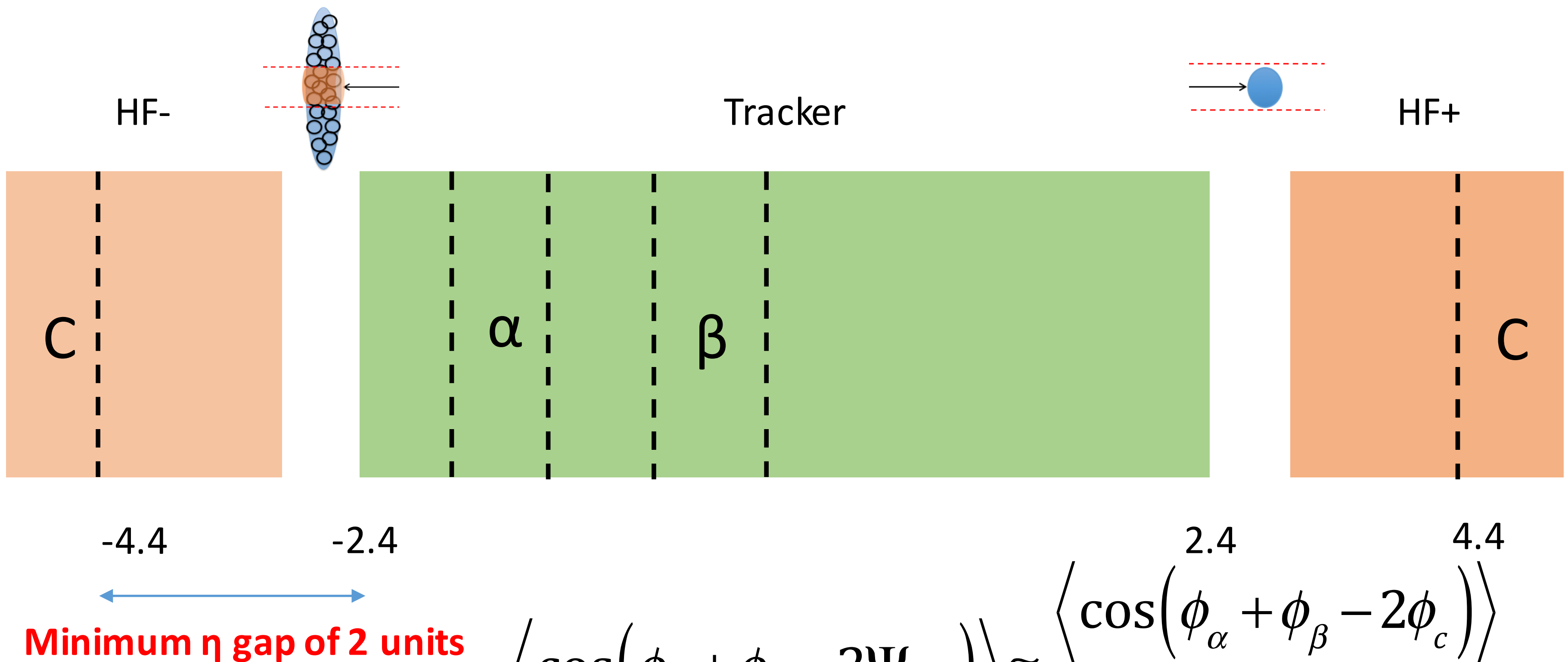




"Ridge in pPb"

Collective nature in pPb gives us a perfect testing ground for magnetic field related analysis.

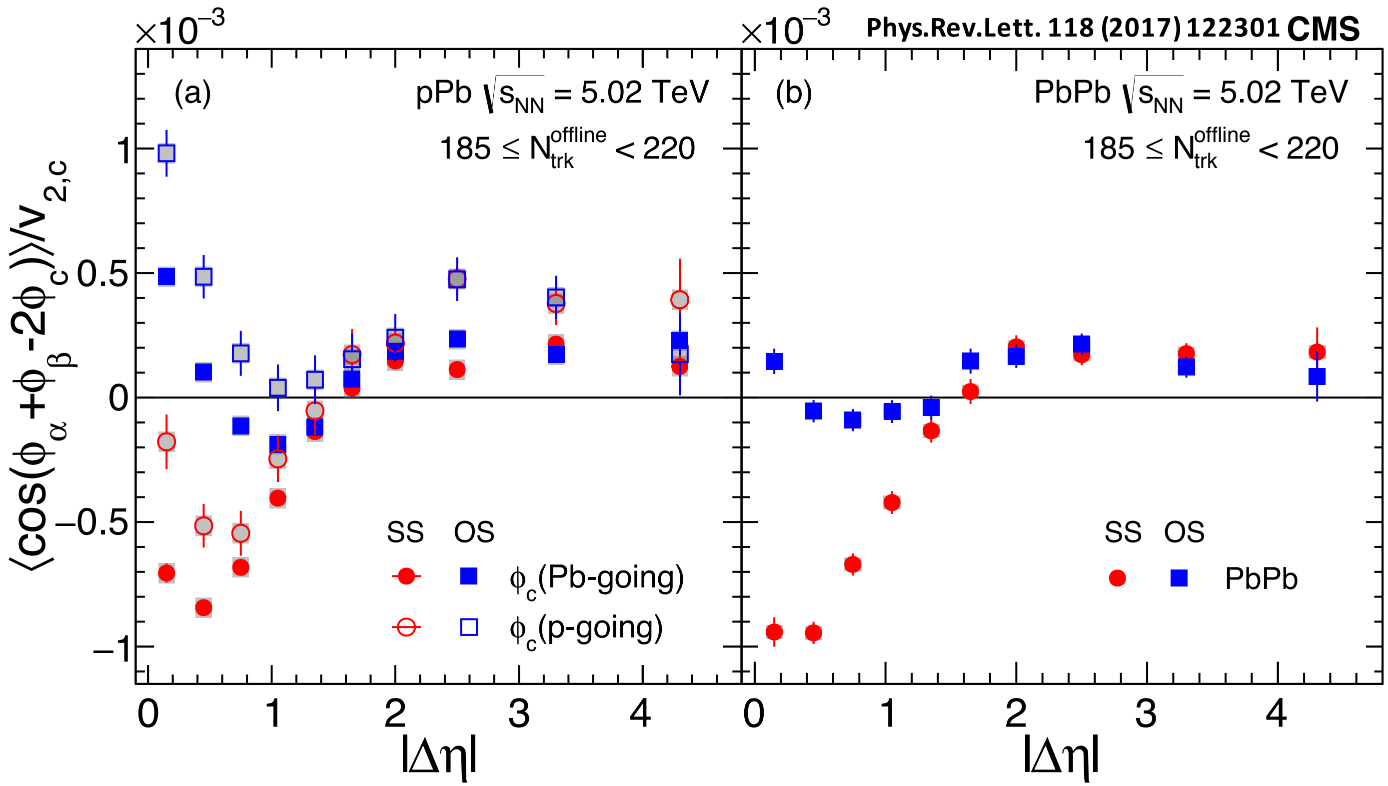
How do we measure with CMS?



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

- Large acceptance (~ 5 units in pseudorapidity) in CMS
- Large gap between particle α,β and c, to reduce short range correlation. Valid for factorization.

γ as function of $|\Delta\eta|$

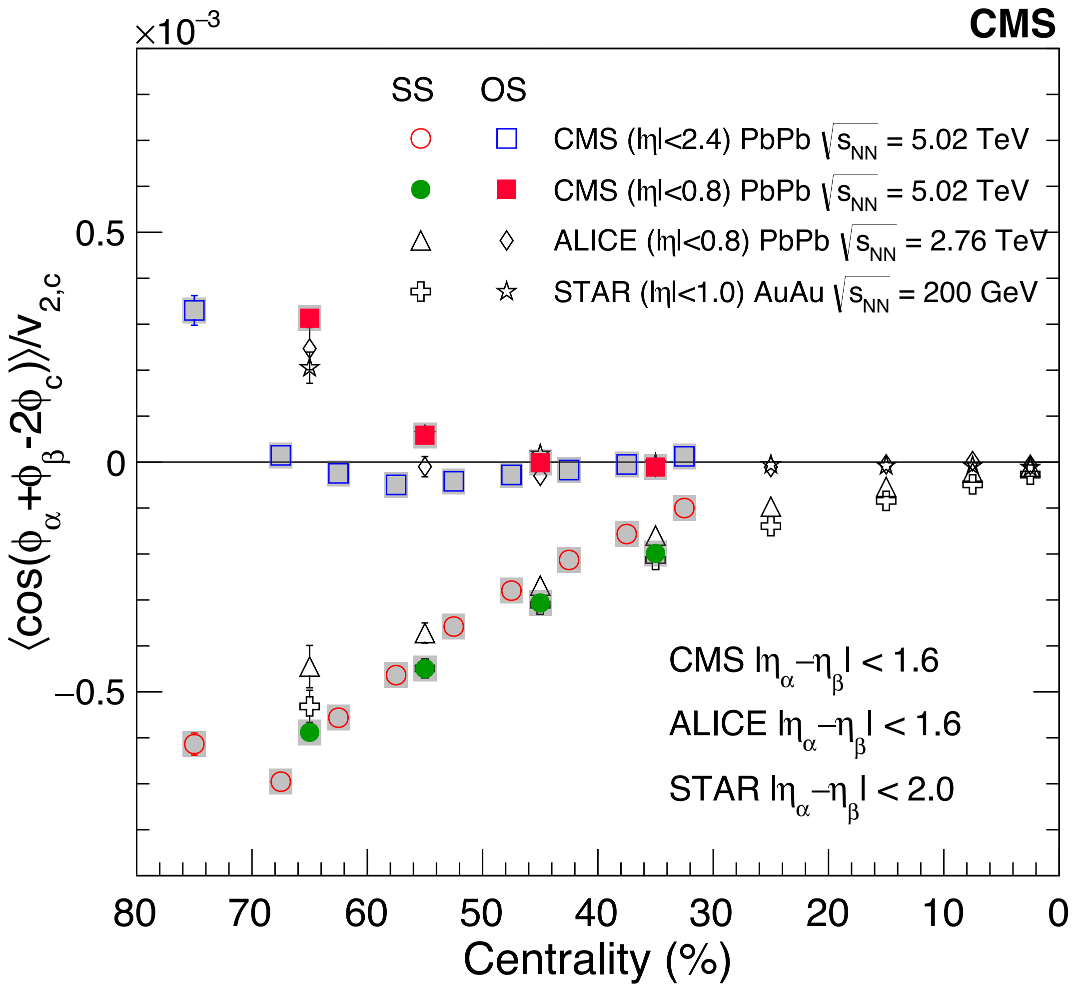


- Clear splitting btw SS and OS; similarity observed in pPb and PbPb at the same multiplicity → **same physics mechanism?**
- **p- and Pb-going may have different charged-independent correlation that could arise from various sources**
- **NOT** in favor of CME interpretation.

γ as a function of centrality

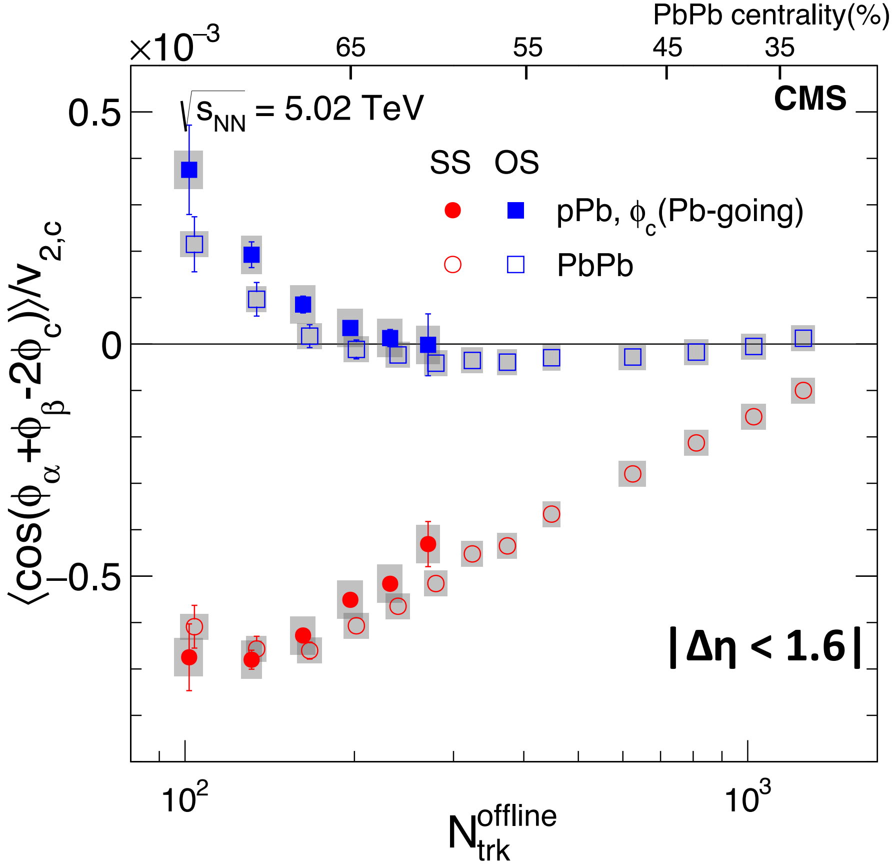
- Integrated results as a function of centrality in AA collisions.
- Almost identical for both SS and OS for **different energies**
- **No strong energy dependence observed**

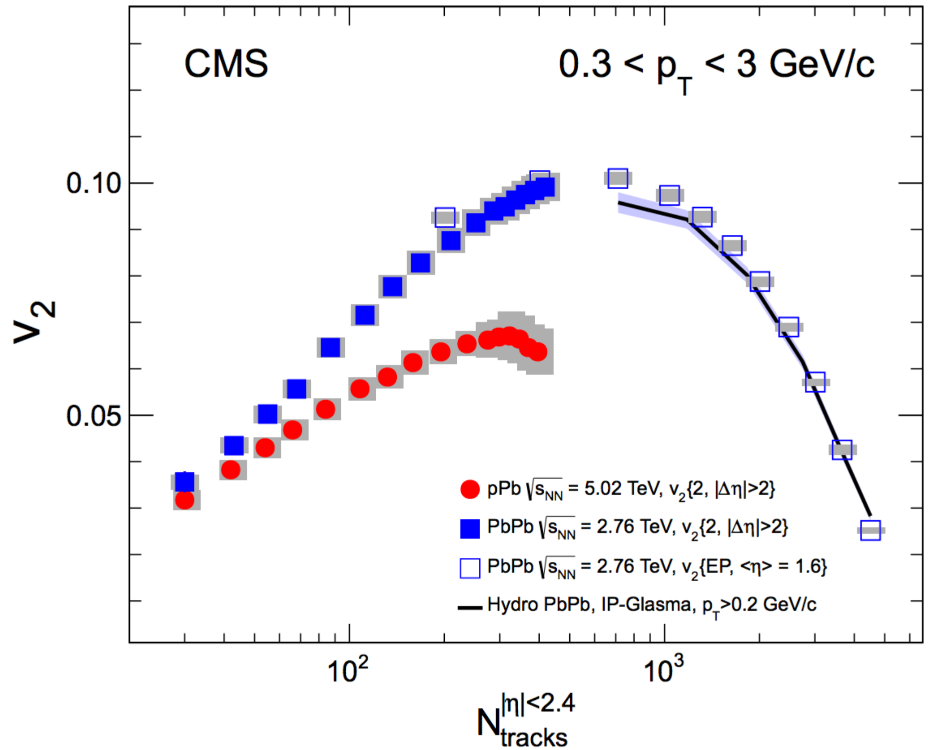
→ similar background contributed? This is not trivial!



Phys.Rev.Lett. 118 (2017) 122301

γ as function of multiplicity





Phys.Rev.Lett. 118 (2017) 122301

Int.J.Mod.Phys. E25 (2016) no.01, 1630002

- Almost identical for both SS and OS btw two systems.
- **The fact that γ(pPb) ≈ γ(PbPb) not only challenge the CME but also the background with only v2/N.**

$\Delta\gamma$ (γ^{OS} - γ^{SS})

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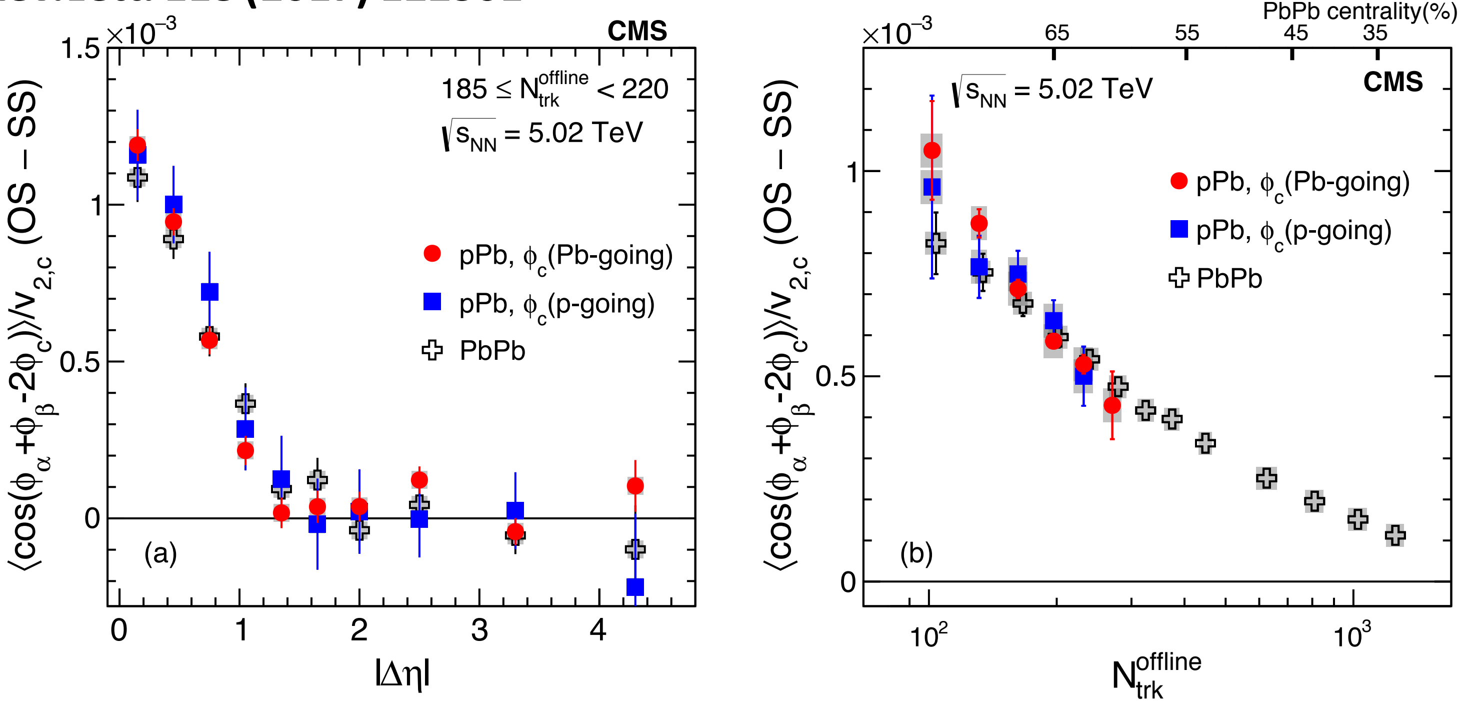


- ➢ All $\Delta\gamma$ (OS-SS) agree with each other in both Δη and multiplicity.
- ➢ The γ seems not sensitive to the CME signal.

Personal thoughts on what's next

- ✓ High precision measurement is necessary
  - *no clear picture can be drawn with BIG error bar*
- ✓ Confusing model-dependent technique should be avoided
  - *more info might be misleading and confusing*
- ✓ LHC energies, small systems, might be able to narrow down what exactly the background is
  - provides guidance on lower energy search.
- ✓ i.e.,

$$\gamma = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{EP}\right)\right\rangle = \gamma_c + \left\langle \cos\left(\phi_\alpha - \phi_\beta + 2\phi_\beta - 2\Psi_{EP}\right)\right\rangle$$

$$\gamma_c + \left\langle \cos\left(\phi_\alpha - \phi_\beta\right)\right\rangle \left\langle \cos\left(2\phi_\beta - 2\Psi_{EP}\right)\right\rangle$$

This can be directly tested experimentally → δv_2

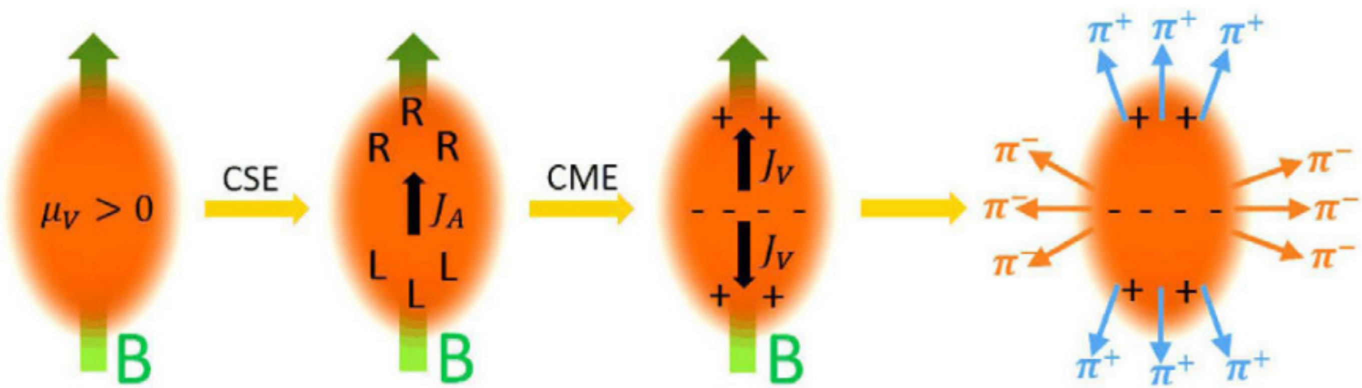
CMW in small systems

CMW in small systems

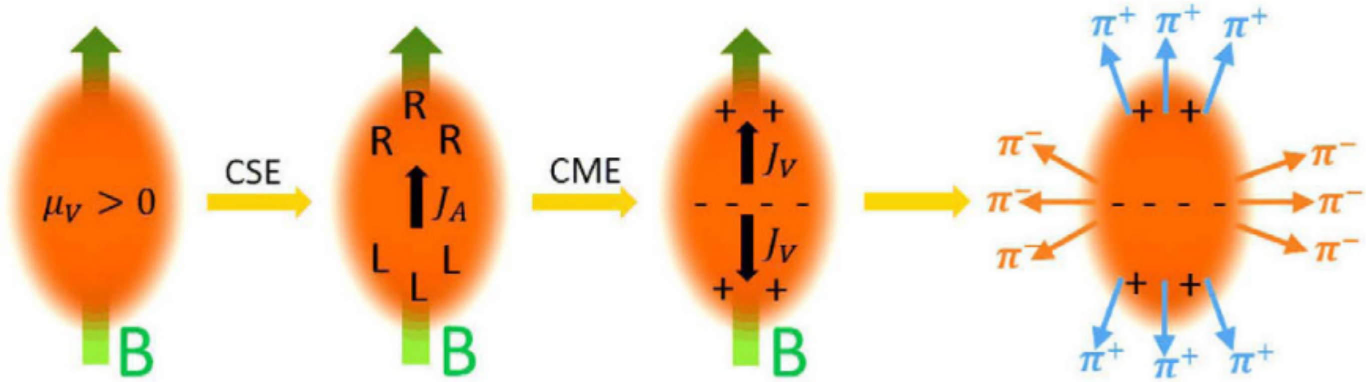
$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Coupling of electric and axial charge densities

CME + CSE = CMW



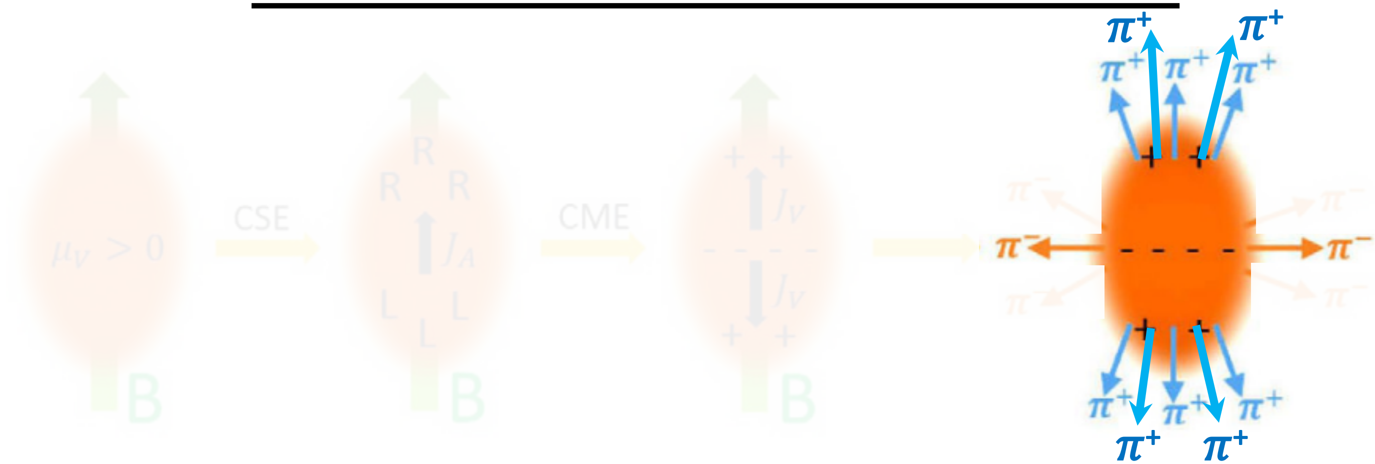
How to measure CMW?



How to measure CMW?

- If the CMW induces such charge distribution event-by-event
  - Charged-dependent v_2 measurement
  - Charge asymmetry (A_{ch}) can "amplify" the $\Delta v_{2,+/-}$

How to measure CMW?



- If the CMW induces such charge distribution event-by-event
  - Charged-dependent v_2 measurement
  - Charge asymmetry (A_{ch}) can "amplify" the $\Delta v_{2,+/-}$
    - If more ⊕ at "poles", less ⊖ at "equators"

    A_{ch} ⇑, $v_{2,+}$ ⇓ $v_{2,-}$ ⇑

How to measure CMW?

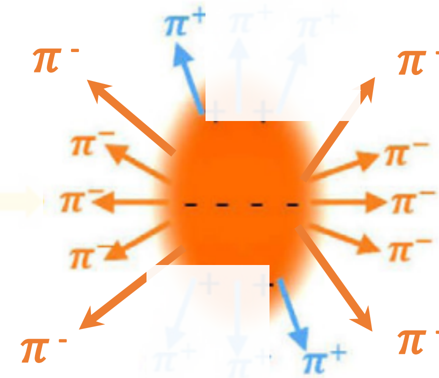
- If the CMW induces such charge distribution event-by-event
  - Charged-dependent v_2 measurement
  - Charge asymmetry (A_{ch}) can "amplify" the $\Delta v_{2,+/-}$
    - If more $\oplus$ at "poles", less $\ominus$ at "equators"

      $A_{ch} \Uparrow$, $v_{2,+} \Downarrow$ $v_{2,-} \Uparrow$
    - If more $\ominus$ at "equators", less $\oplus$ at "poles"

      $A_{ch} \Downarrow$, $v_{2,+} \Uparrow$ $v_{2,-} \Downarrow$

How to measure CMW?

$$v_2^{\pm} \simeq v_{2,\pm}^{base} \mp r_e A_{ch}/2$$



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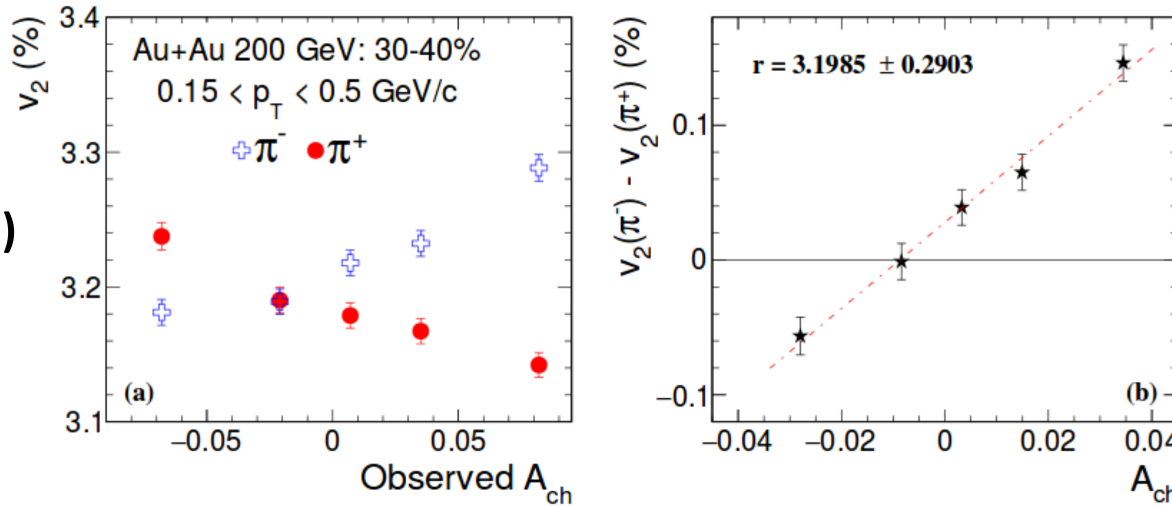
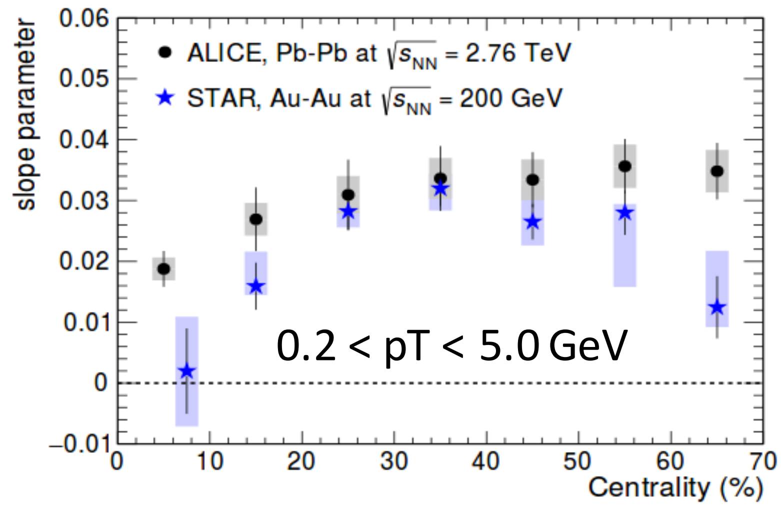
      A_{ch} ⇓, $v_{2,+}$ ⇑ $v_{2,-}$ ⇓

Previous measurements

STAR
(Phys.Rev.Lett. 114 (2015))



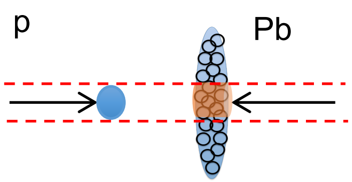
ALICE
(Phys.Rev. C93 (2016))

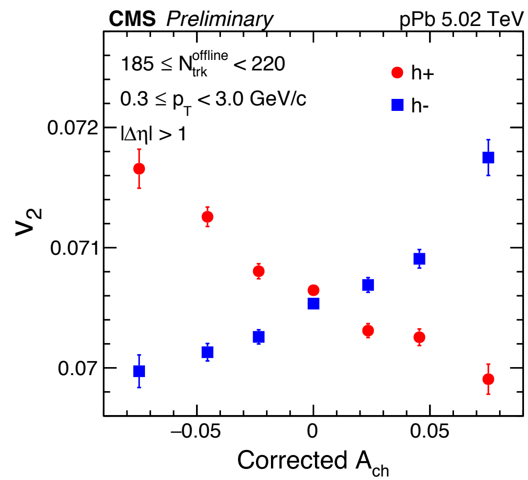


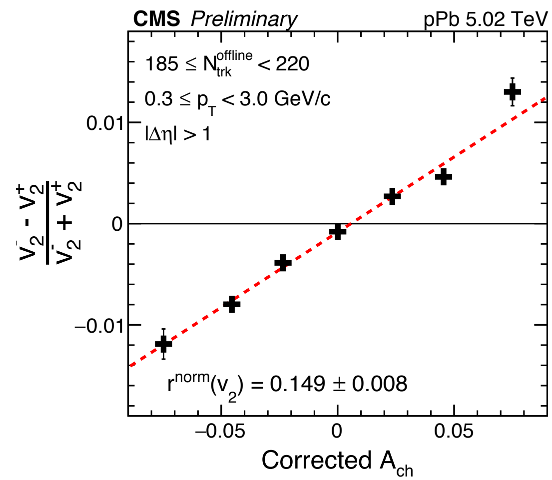
➢ **Very different p_T ranges are used**

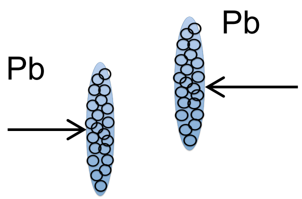
“search” for CMW in pPb

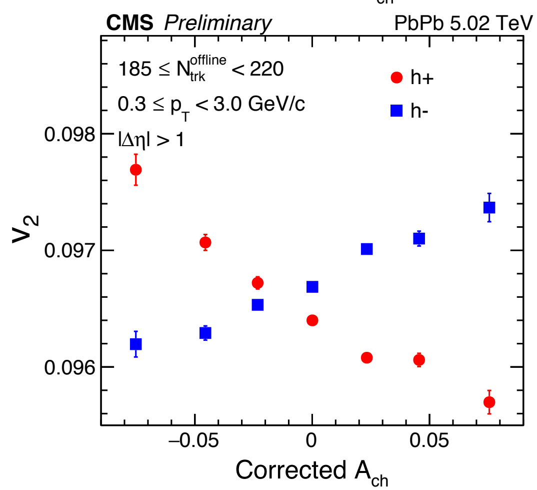
“search” for CMW in pPb

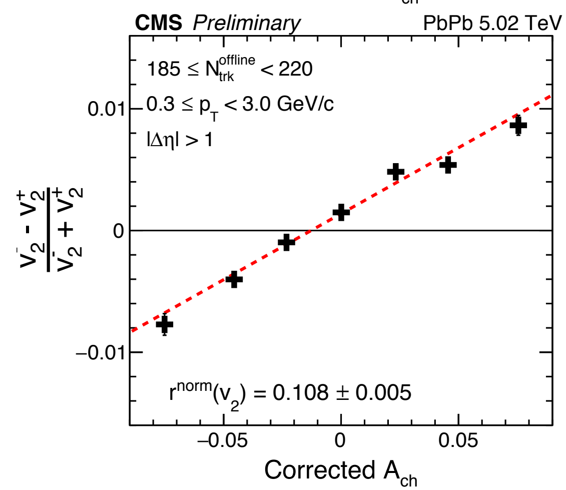






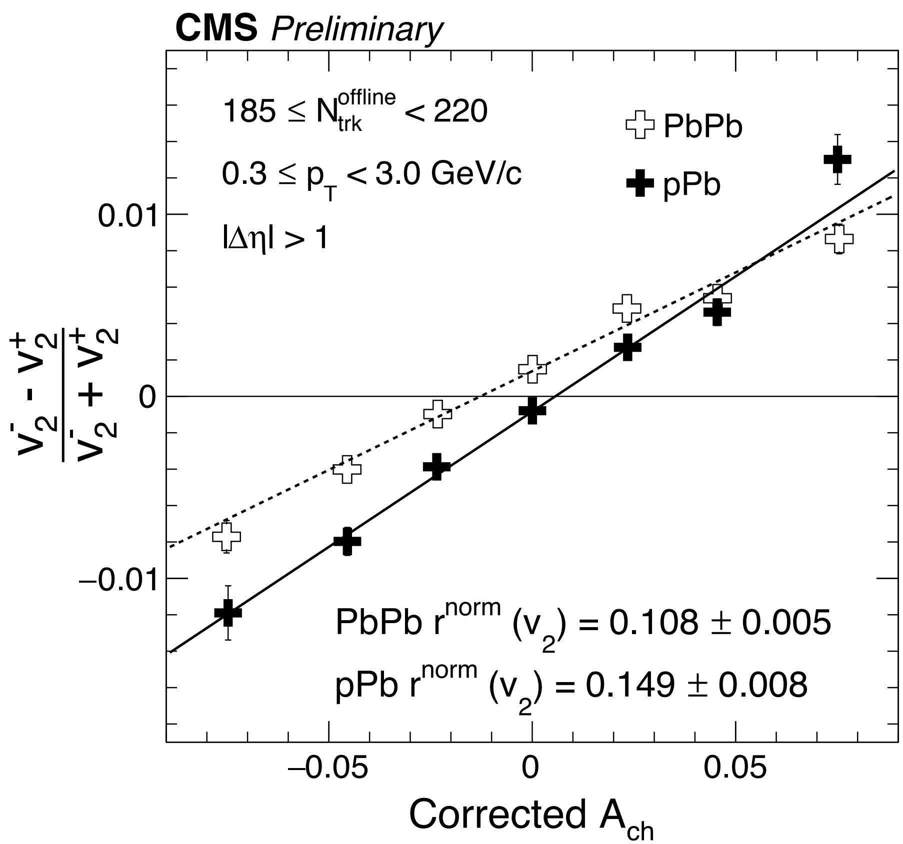






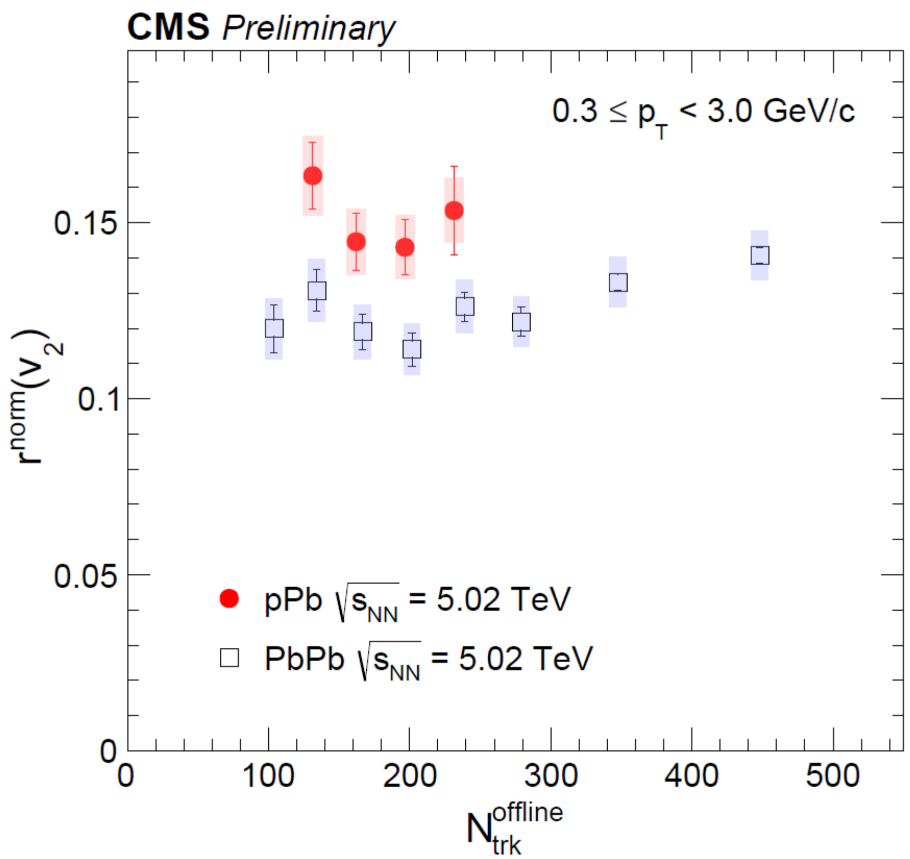
- Relative slope removes v_2 magnitude dependence

“search” for CMW in pPb



- Significant nonzero slope in pPb has been observed
- Slope is even **larger** than in PbPb

Relative slope (v_2) vs Ntrk



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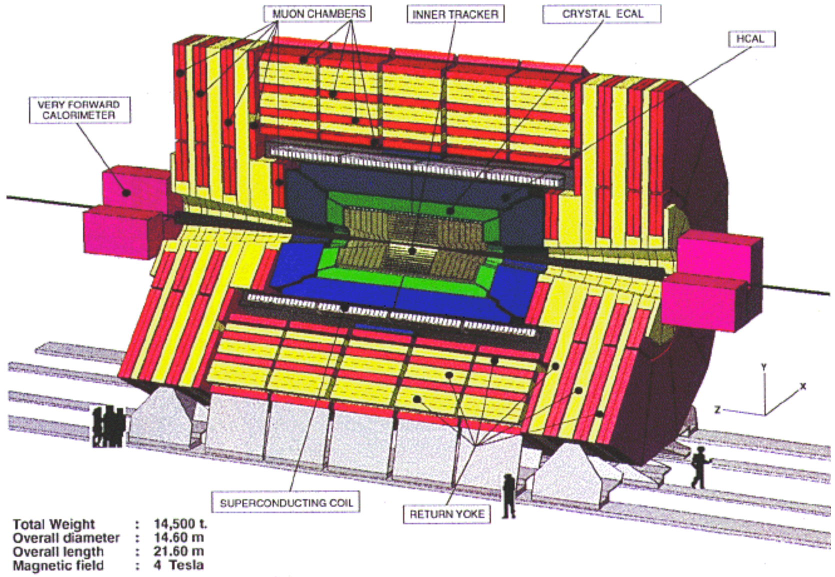
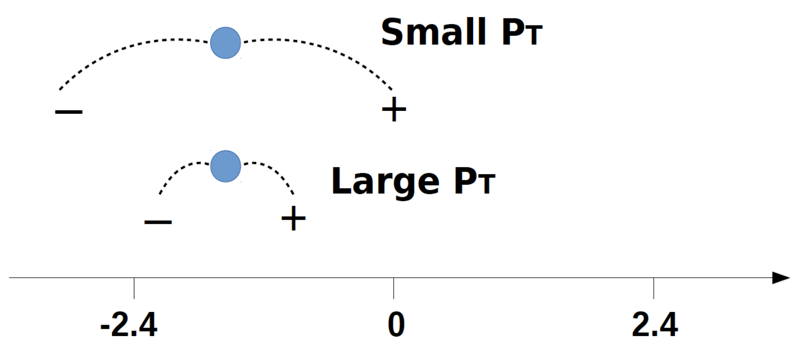
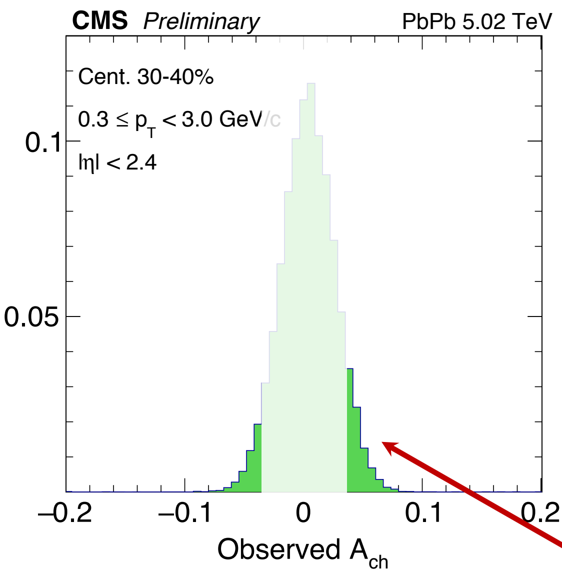
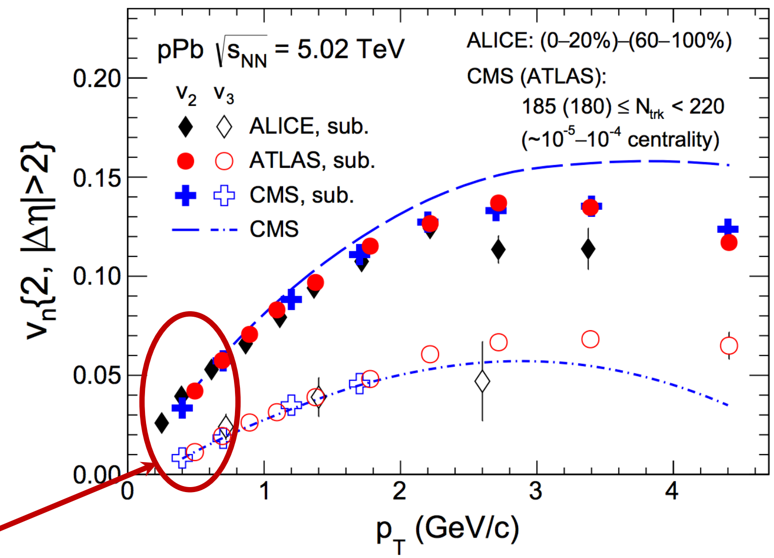
Local charge conservation (again)



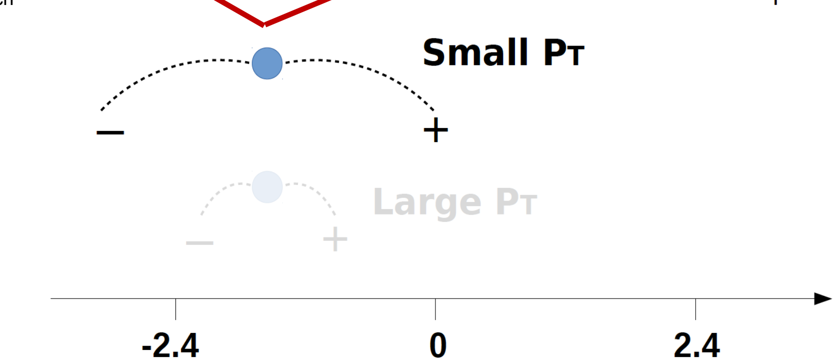


Local charge conservation (again)



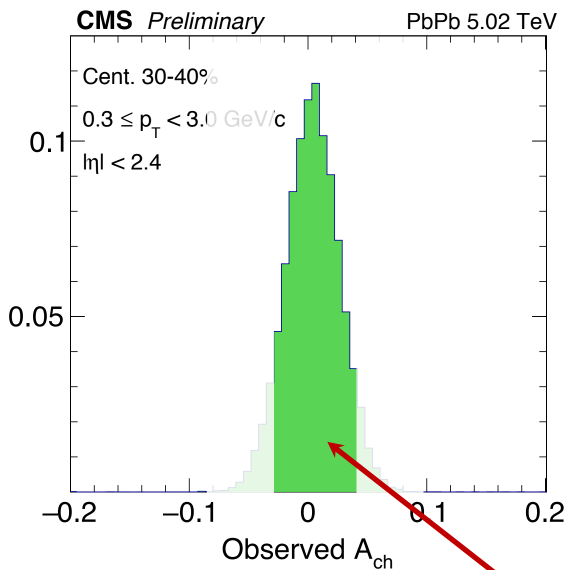


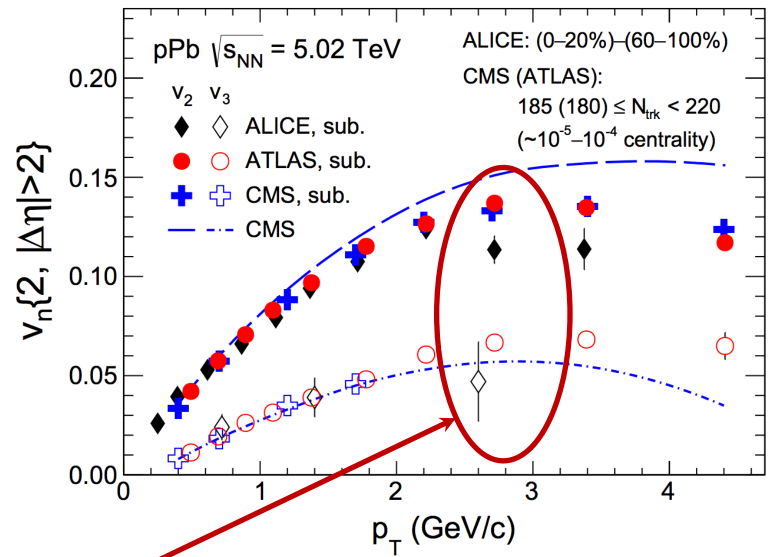
- Low-pT → high Ach

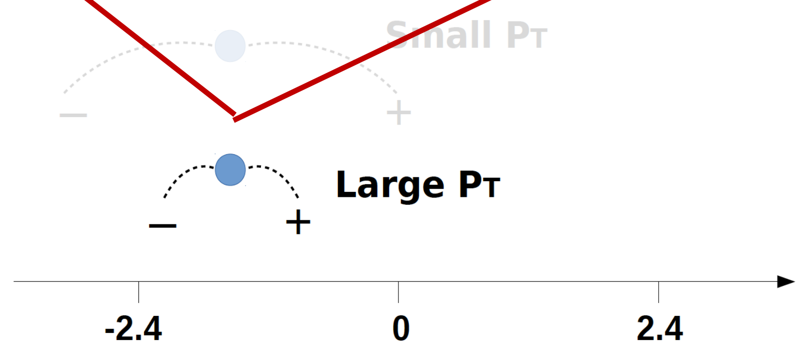


- Low-pT → low v_2

Local charge conservation (again)



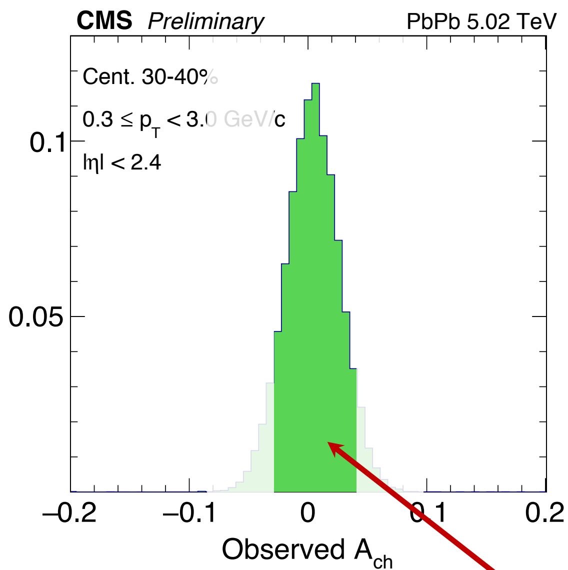


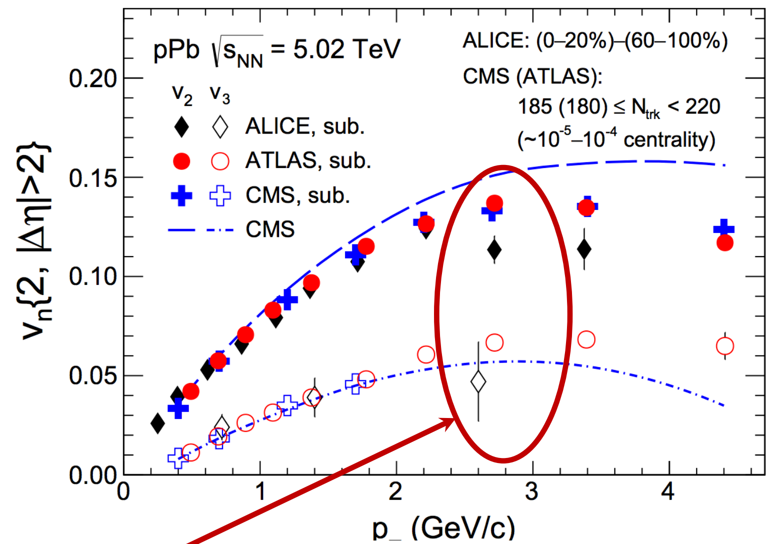


- Low-pT → high Ach
- High-pT → low Ach

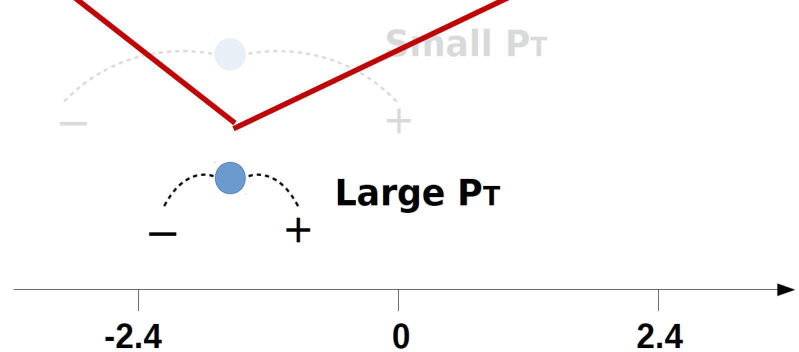
- Low-pT → low v_2
- High-pT → high v_2

Local charge conservation (again)





- Low-pT → high Ach
- High-pT → low Ach

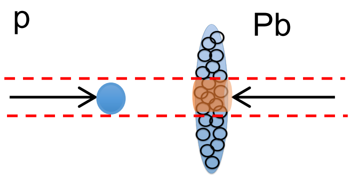


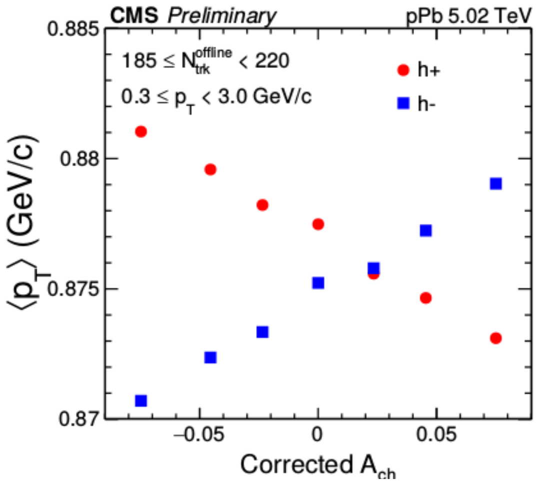
- Low-pT → low v_2
- High-pT → high v_2

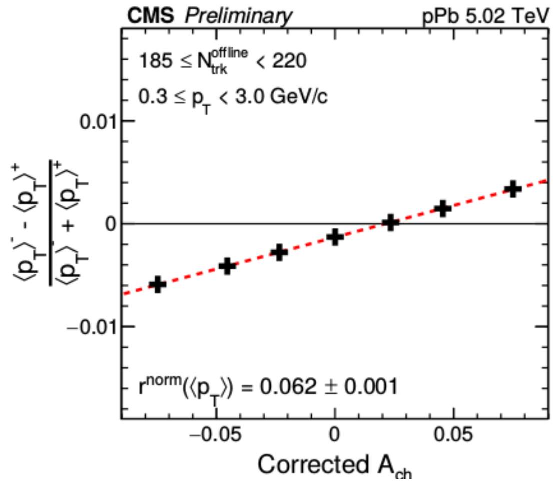
high Ach → low v_2(+) **Low Ach → high v_2(+)**

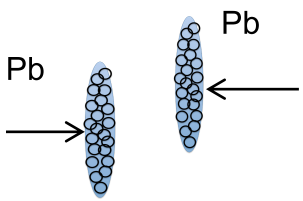
Correlation btw **Ach and v_n** doesn't necessarily need CMW

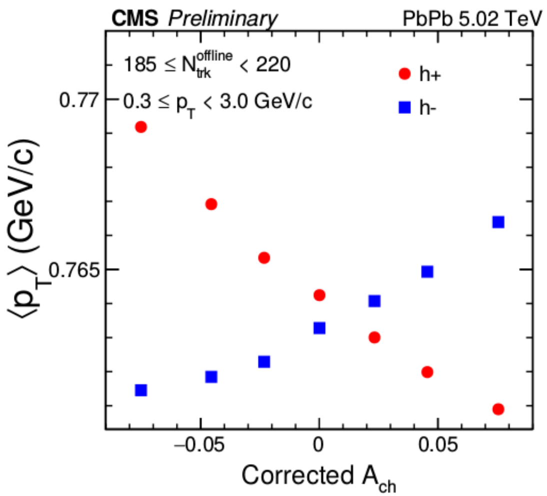
p_T vs A_{ch}

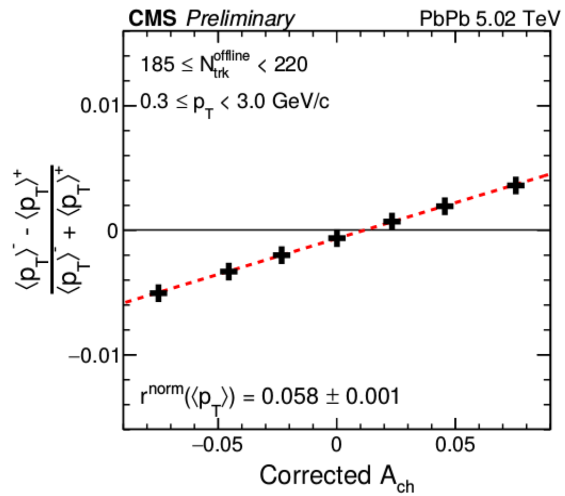






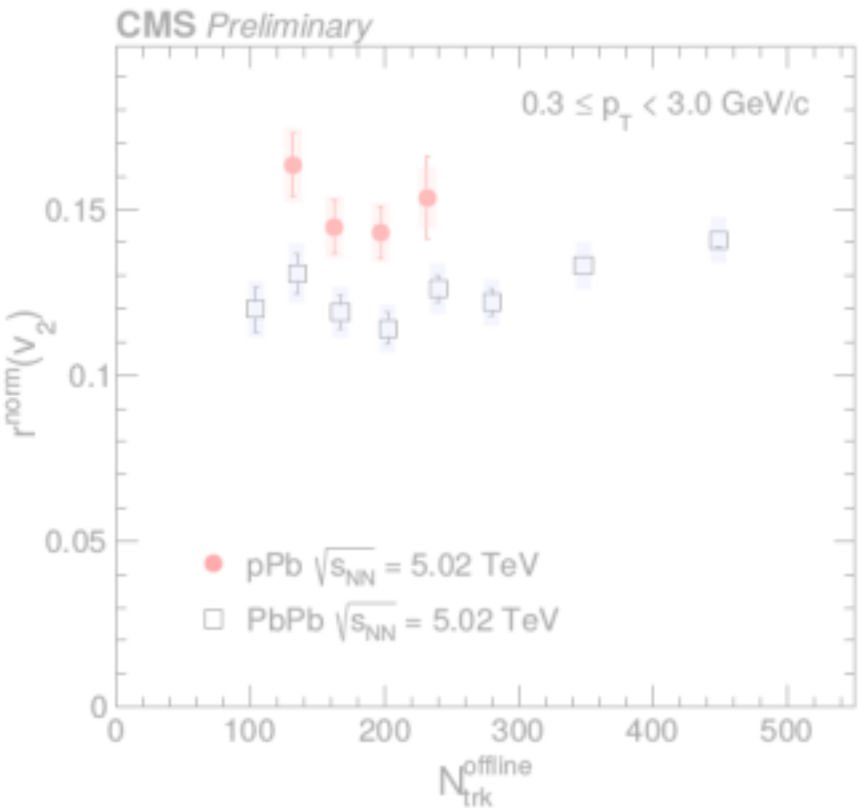


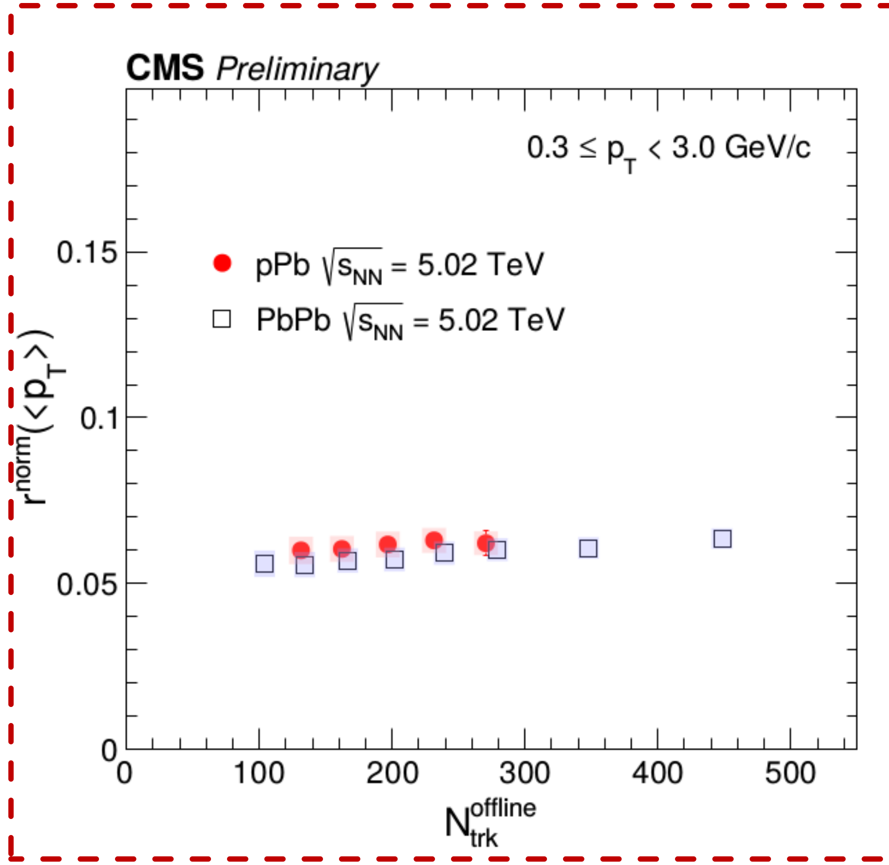




- Similar pattern seen in <p_T> vs A_{ch} in pPb and PbPb

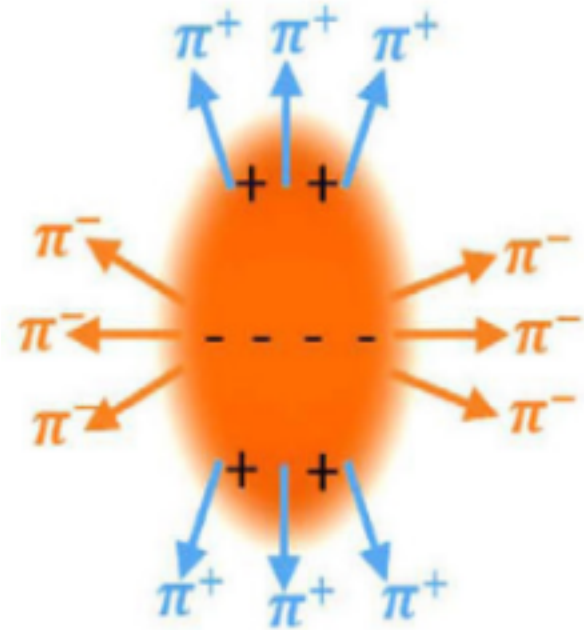
Relative slope (p_T) vs Ntrk





- At least 50% of slope comes from $<p_T>$
- Qualitatively in line with LCC

Triangular flow (v3) can be useful



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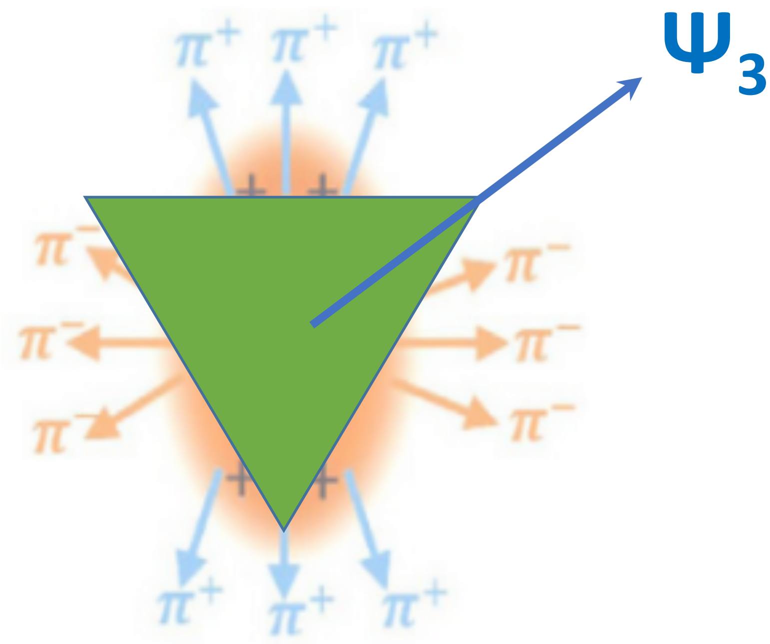
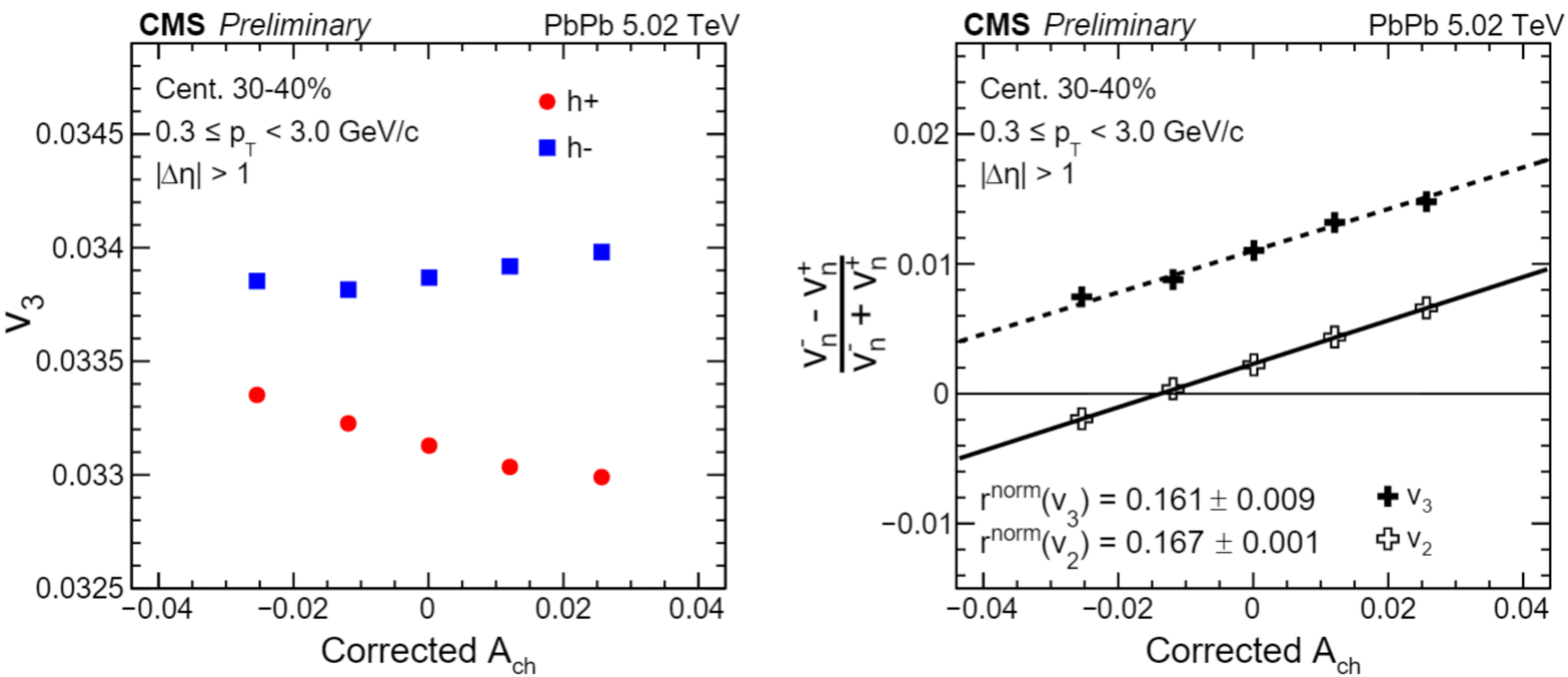


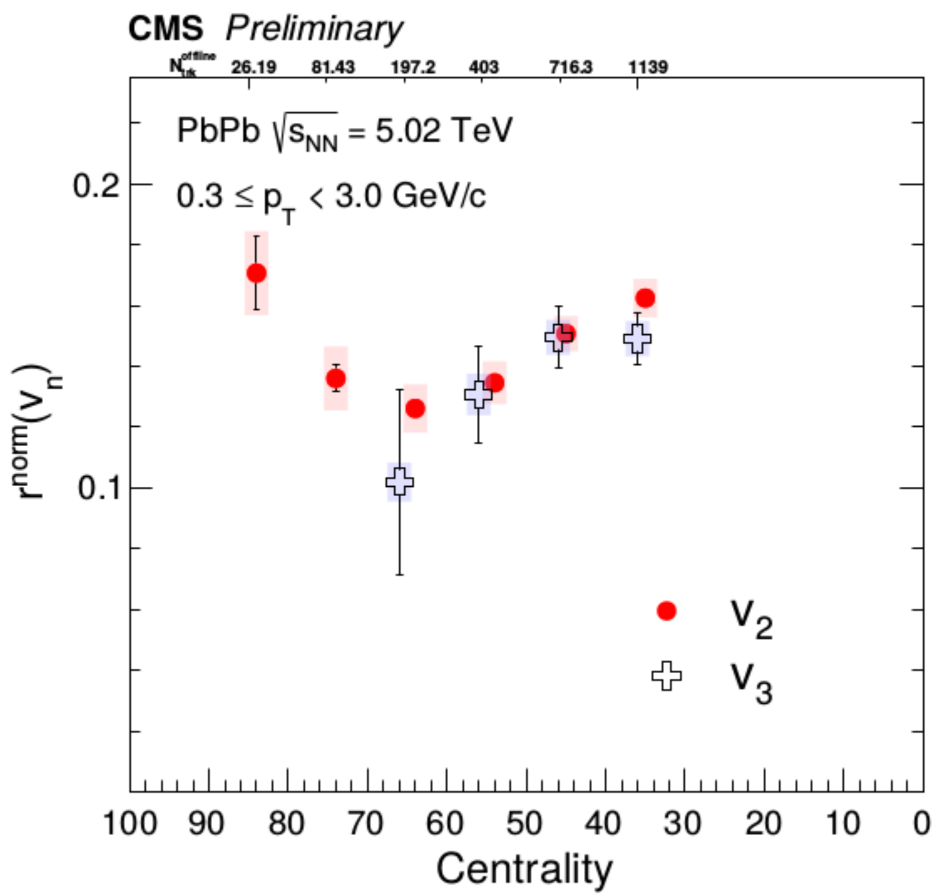
- CMW should expect no A_{ch} dependence on v_3
- Any v_3 slope has to come from something else

Relative slope (v_3) vs A_{ch}



- Almost identical slope between v_2 and v_3
- **LCC can, but CMW cannot**

Relative slope (v_3) vs Ntrk



- Almost identical slope between v_2 and v_3
- **LCC can, but CMW cannot**

Summary

High-multiplicity pPb results are powerful and useful

- @LHC energy, little room for CME/CMW.
- Similar data shown comparing with RHIC energy.
- CME/CMW at RHIC is the final question.

Background models are in great need of

- Correctly modeling the physics (i.e., LCC)
- Quantitative prediction/description

outlook

Event-Shape-Engineering?

- Precisely extract the CME signal term/flow-independent part
- **Fully understand the background is equivalently important**

δ, v_2, mixed harmonics

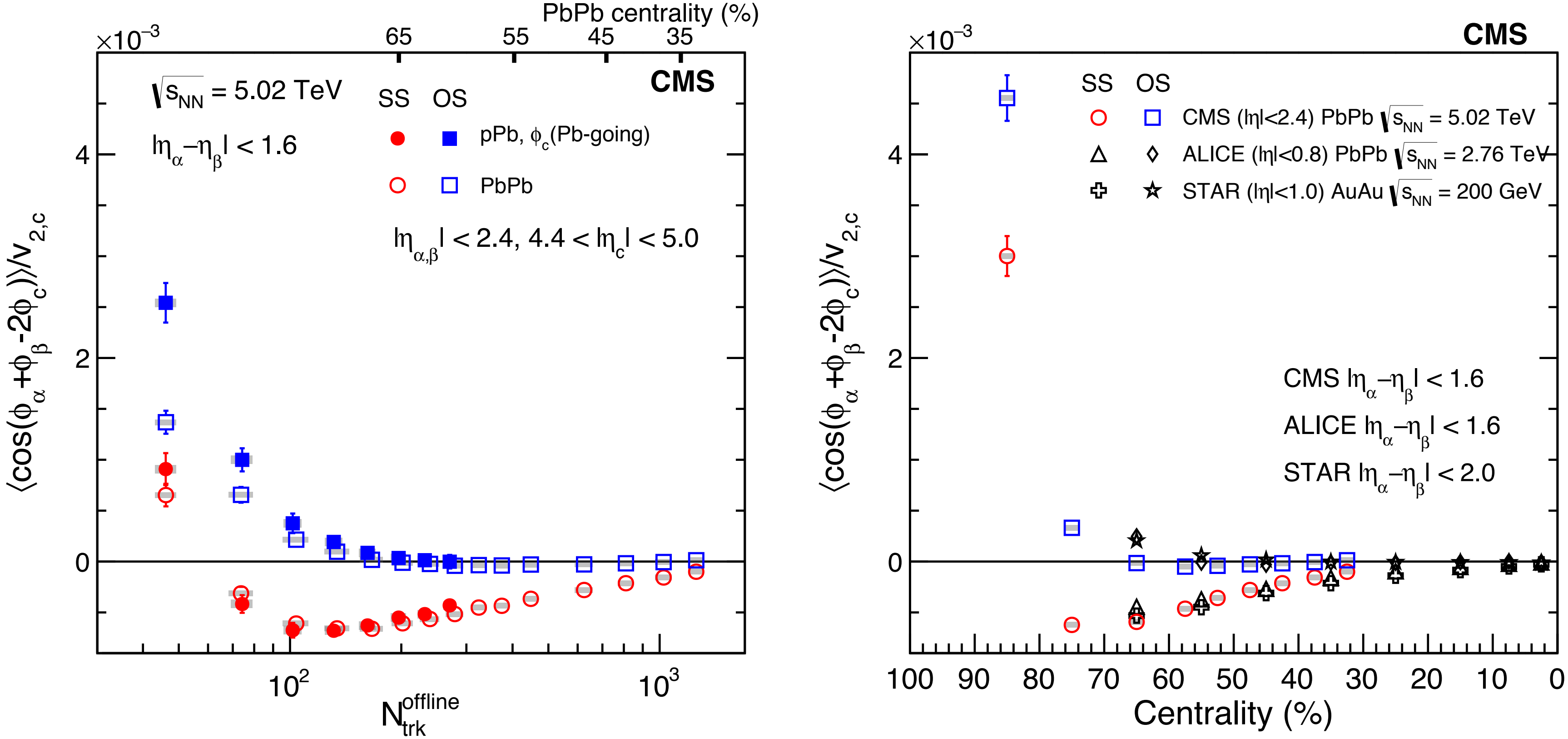
- **How γ is related to** δ, v_2, N, and etc...

Chiral Vortical Effect (CVE)? Chiral Vortical Wave (CVW)?

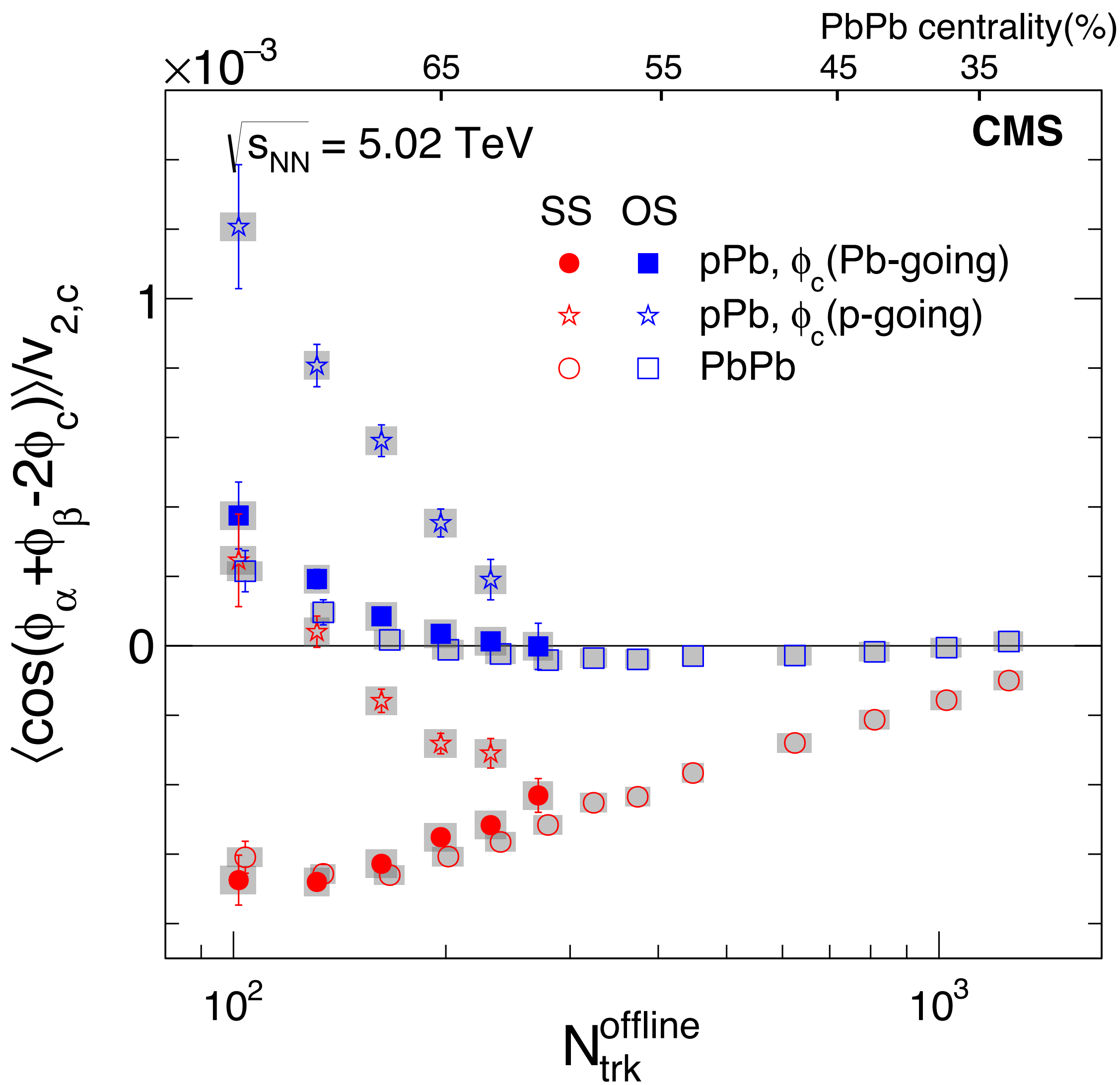
- Baryon number separation
- Baryon v2 vs A_{ch}
- pA system to observe it?

Thank you!

Backup

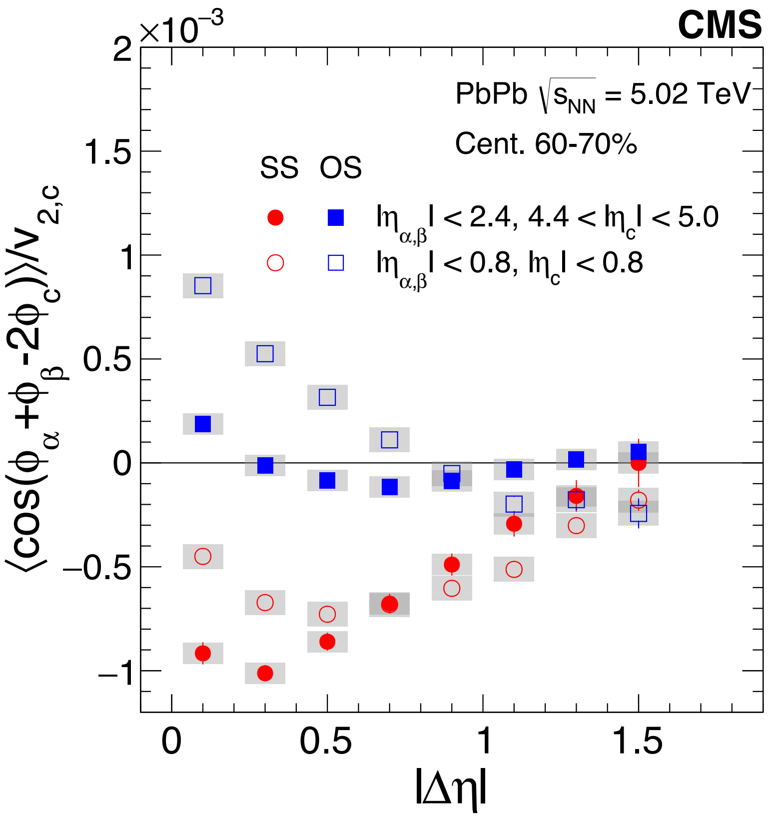

PbPb centrality (%)
65 55 45 35
×10⁻³
CMS
√sNN = 5.02 TeV
|ηα−ηβ| < 1.6
SS OS
pPb, φc(Pb-going)
PbPb
|ηα,β| < 2.4, 4.4 < |ηc| < 5.0
⟨cos(φα+φβ-2φc)⟩/v2,c
N_trk^offline
SS OS
CMS (|η|<2.4) PbPb √sNN = 5.02 TeV
ALICE (|η|<0.8) PbPb √sNN = 2.76 TeV
STAR (|η|<1.0) AuAu √sNN = 200 GeV
CMS |ηα−ηβ| < 1.6
ALICE |ηα−ηβ| < 1.6
STAR |ηα−ηβ| < 2.0
Centrality (%)

Backup

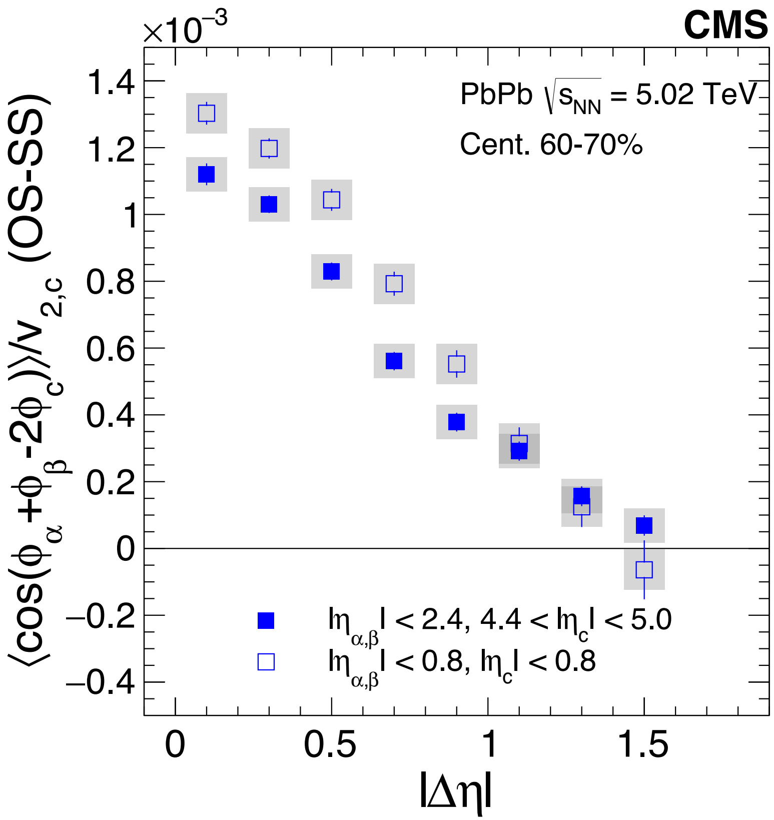


PbPb centrality(%)
65
55
45
35
$\times 10^{-3}$
$\sqrt{s_{NN}}$ = 5.02 TeV
CMS
SS OS
pPb, ϕ_c(Pb-going)
pPb, ϕ_c(p-going)
PbPb
1
0
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$
10^2
10^3
$N_{trk}^{offline}$

Backup

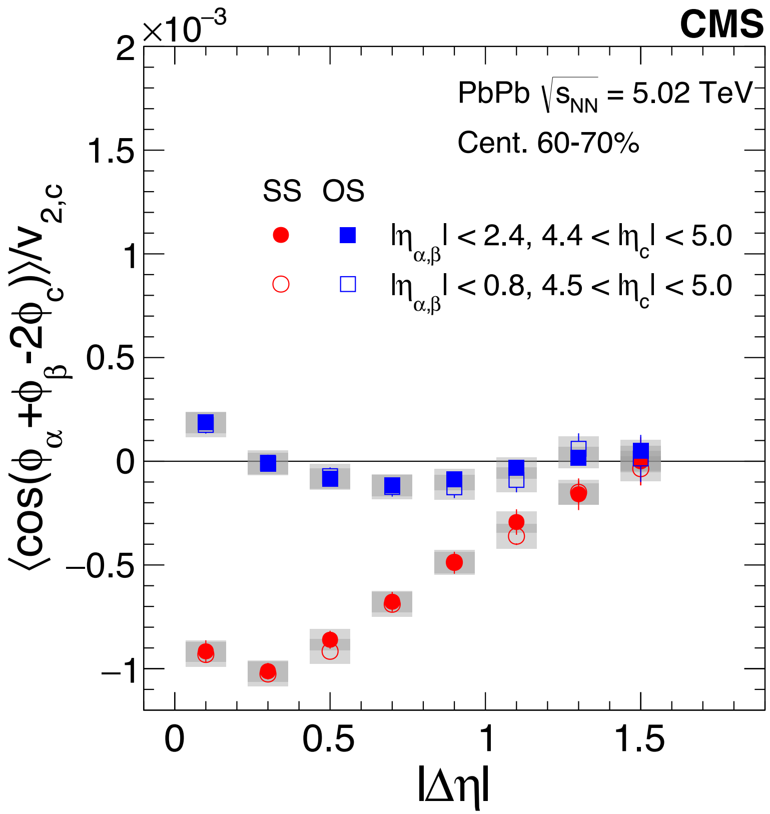


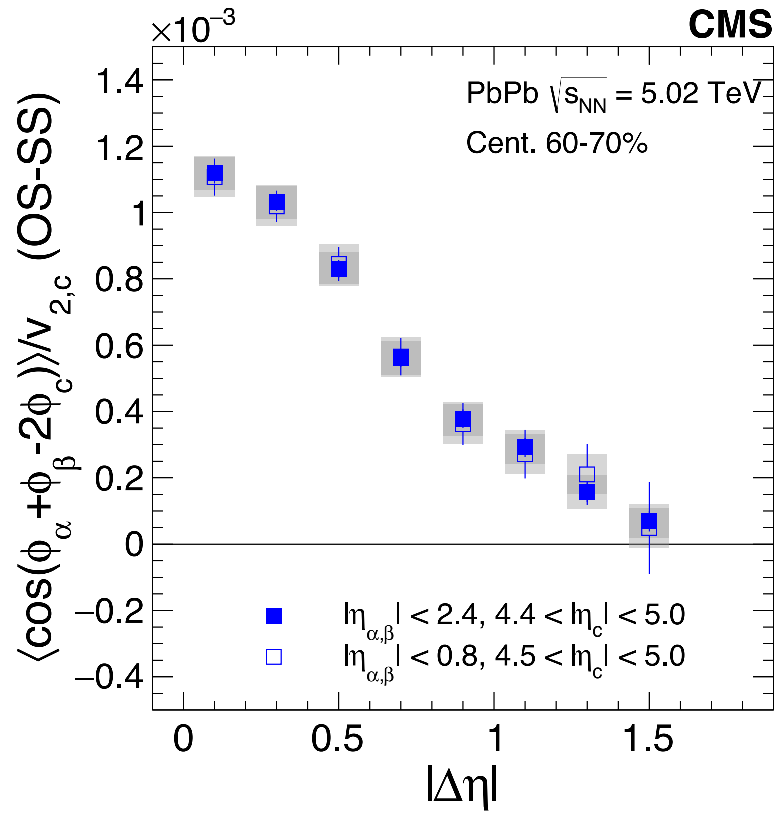
CMS
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Cent. 60-70%
SS OS
$|\eta_{\alpha,\beta}| < 2.4$, $4.4 < |\eta_c| < 5.0$
$|\eta_{\alpha,\beta}| < 0.8$, $|\eta_c| < 0.8$
$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle/v_{2,c}$
$\times10^{-3}$
$|\Delta\eta|$



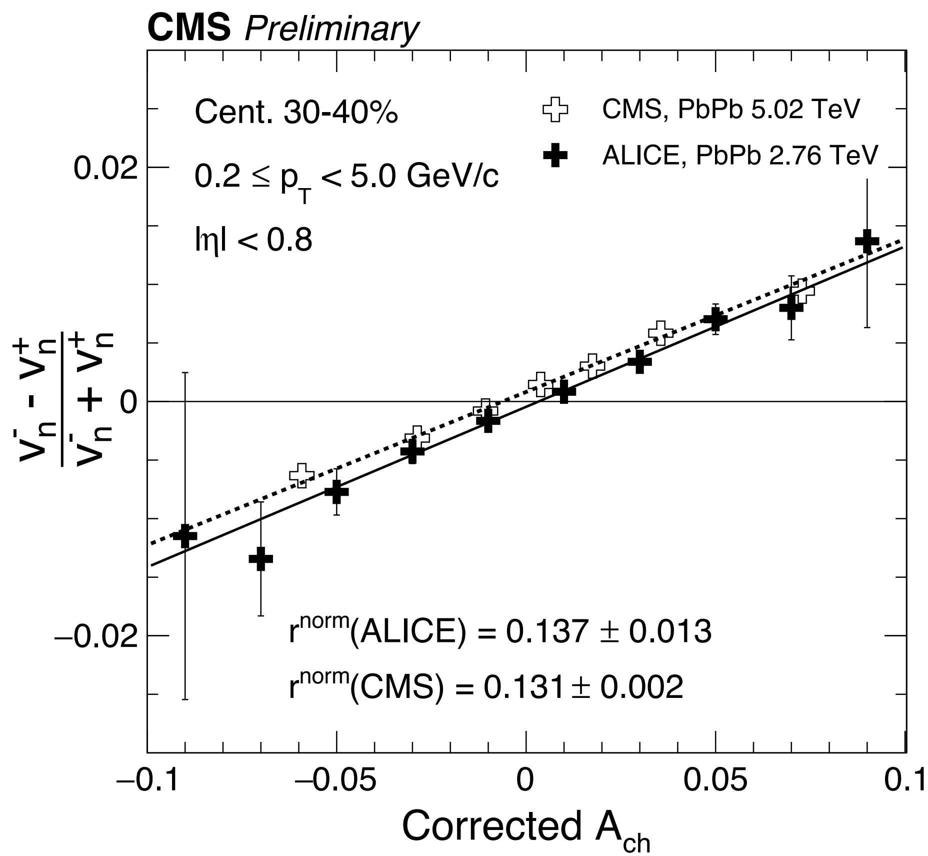
CMS
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Cent. 60-70%
$|\eta_{\alpha,\beta}| < 2.4$, $4.4 < |\eta_c| < 5.0$
$|\eta_{\alpha,\beta}| < 0.8$, $|\eta_c| < 0.8$
$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle/v_{2,c}$ (OS-SS)
$\times10^{-3}$
$|\Delta\eta|$

Backup


CMS
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Cent. 60-70%
SS OS
$|\eta_{\alpha,\beta}| < 2.4,\ 4.4 < |\eta_c| < 5.0$
$|\eta_{\alpha,\beta}| < 0.8,\ 4.5 < |\eta_c| < 5.0$
$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle/v_{2,c}$
$\times10^{-3}$
$|\Delta\eta|$


CMS
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Cent. 60-70%
$|\eta_{\alpha,\beta}| < 2.4,\ 4.4 < |\eta_c| < 5.0$
$|\eta_{\alpha,\beta}| < 0.8,\ 4.5 < |\eta_c| < 5.0$
$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle/v_{2,c}$ (OS-SS)
$\times10^{-3}$
$|\Delta\eta|$

Backup



CMS Preliminary
Cent. 30-40%
0.2 ≤ p_T < 5.0 GeV/c
|η| < 0.8
CMS, PbPb 5.02 TeV
ALICE, PbPb 2.76 TeV
r^norm(ALICE) = 0.137 ± 0.013
r^norm(CMS) = 0.131 ± 0.002
0.02
0
−0.02
−0.1
−0.05
0
0.05
0.1
Corrected A_ch
(v_n^- - v_n^+)/(v_n^- + v_n^+)