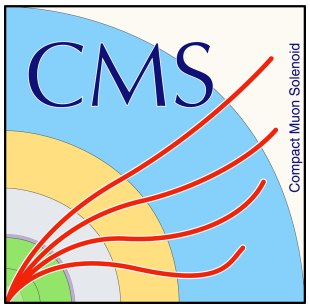


New studies of CME using charge-dependent azimuthal correlations at the LHC

Submitted to PRC and arXiv:1708.01602

Zhoudunming (Kong) Tu

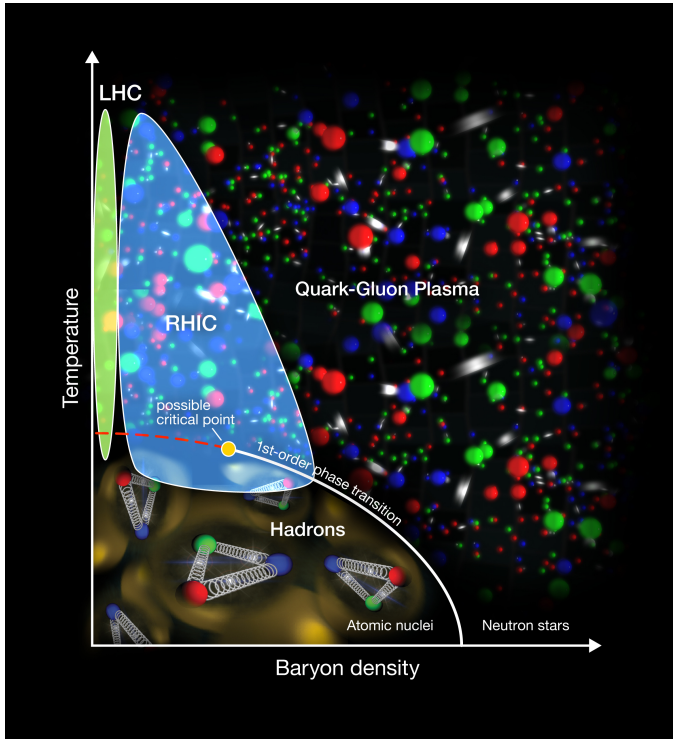
Rice University

On behalf of CMS collaboration

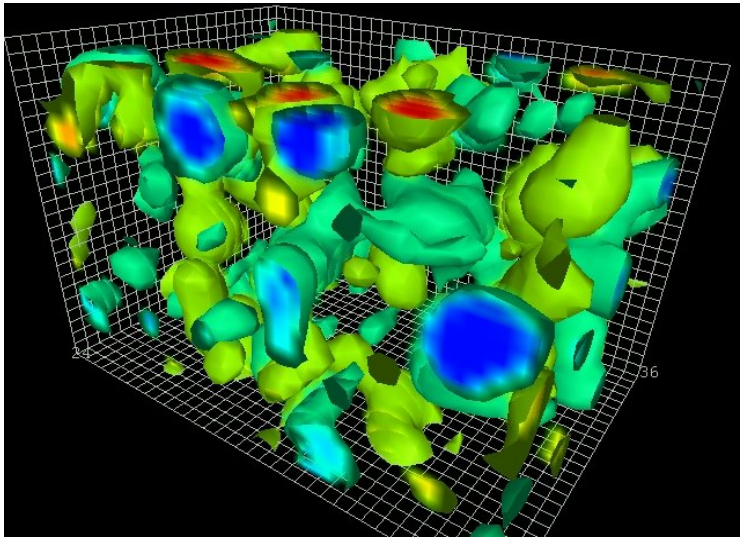
ISMD, TLaxcala 2017

Chiral magnetic effect (CME) in HIC

Deconfinement + Chiral symmetry restoration



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



Derek Leinweber, University of Adelaide

Chiral magnetic effect (CME) in HIC

$\mu_5 \propto$ N (right-handed) – N (left-handed) ≠ 0

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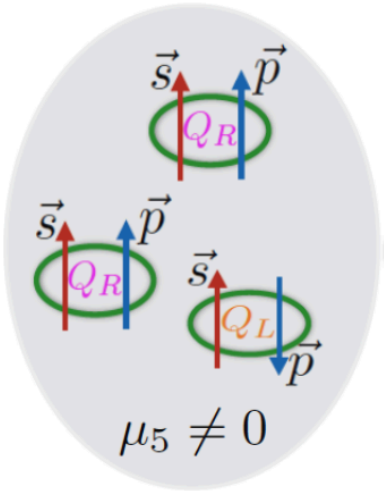

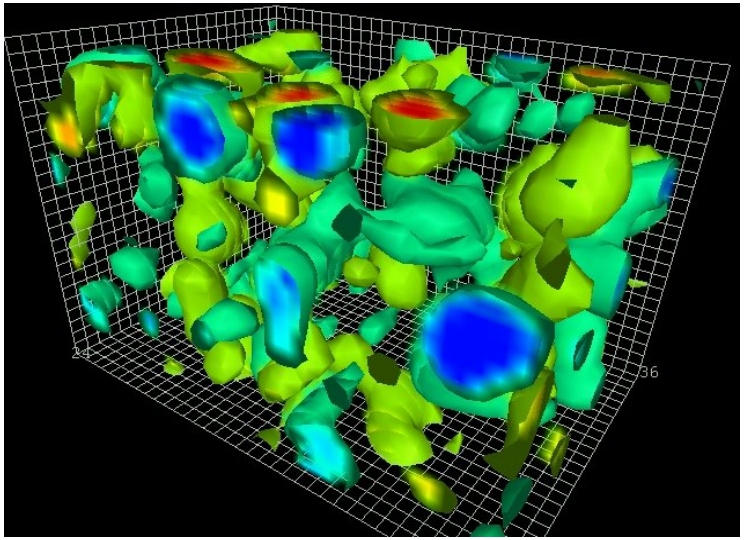

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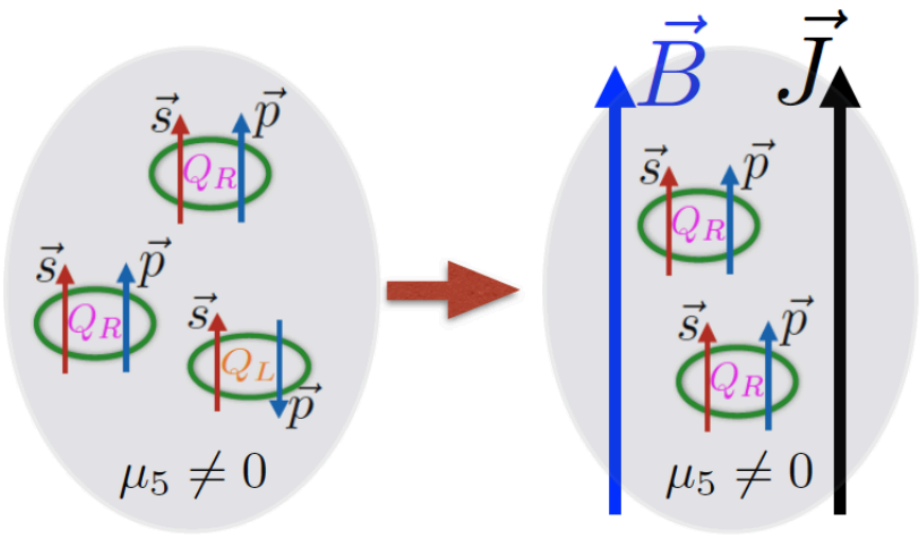
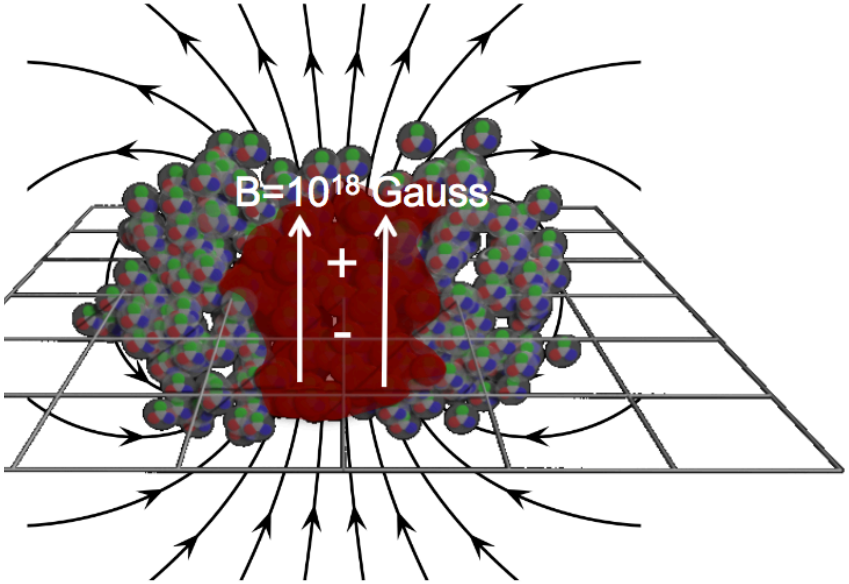
Strong magnetic field





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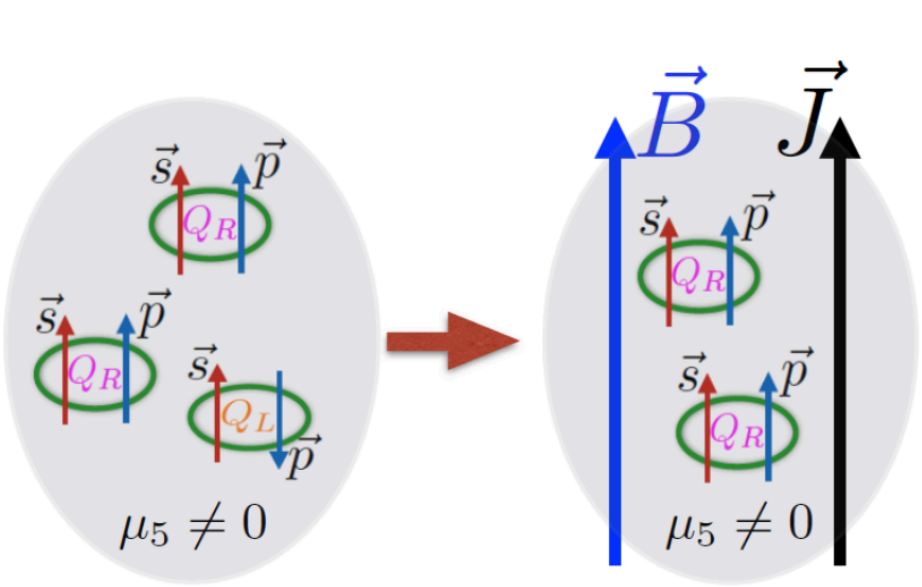
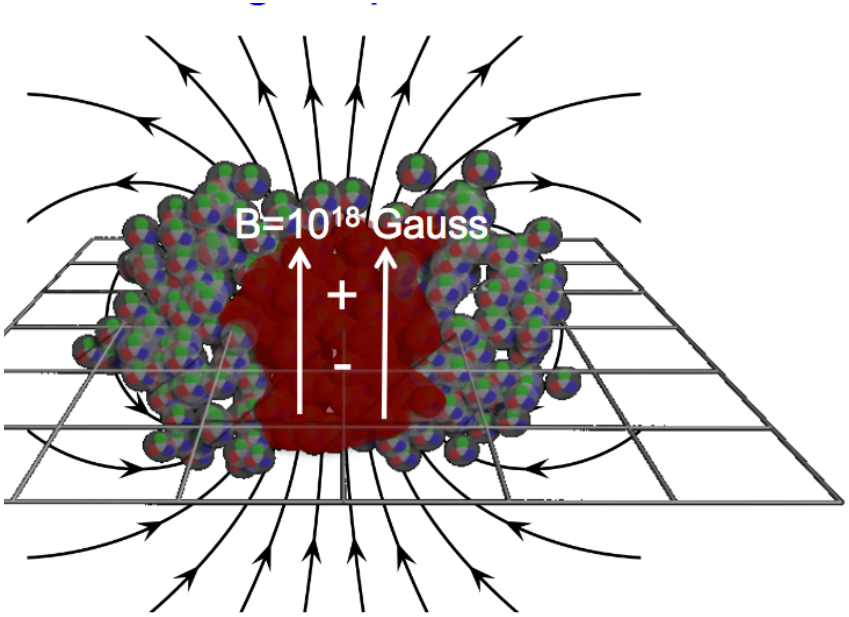




❖ Chirality imbalance inside of the QGP phase with **a strong magnetic field** can generate charge separation, known as the CME

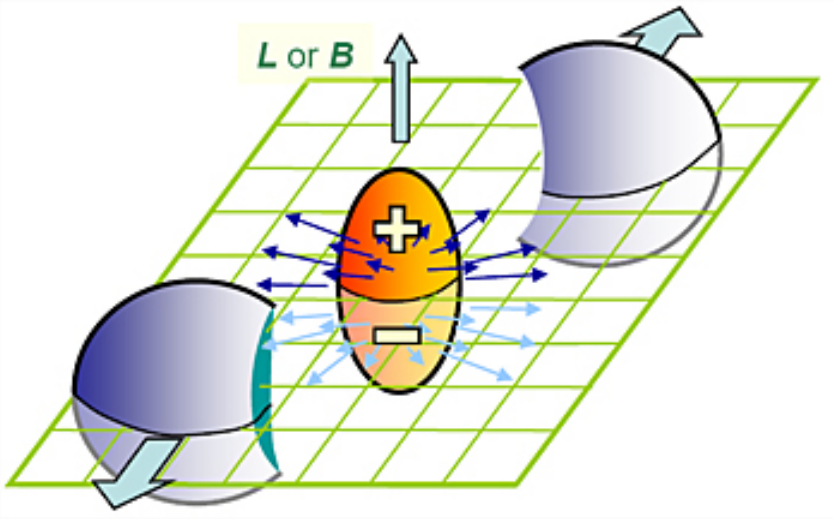
If CME is observed, evidence for chiral symmetry restoration!

Status of CME in previous studies

Same-sign: α = β
Opposite sign: α ≠ β

with $\gamma \equiv \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{RP}\right)\right\rangle$ *arXiv: hep-ph/0406311*

😱**Jargon: γ-correlator**



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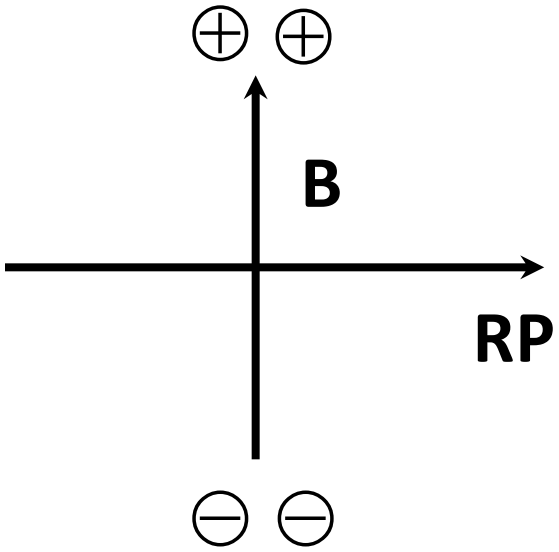

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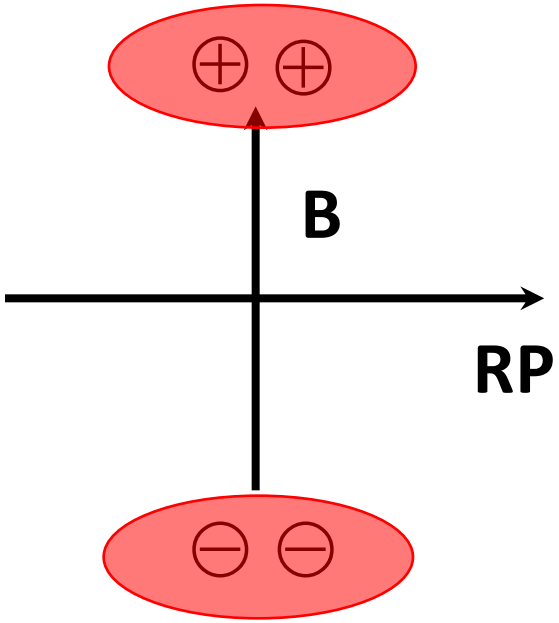

✓ Same-sign (SS):
- cos(π/2 + π/2 - 0) = **-1**
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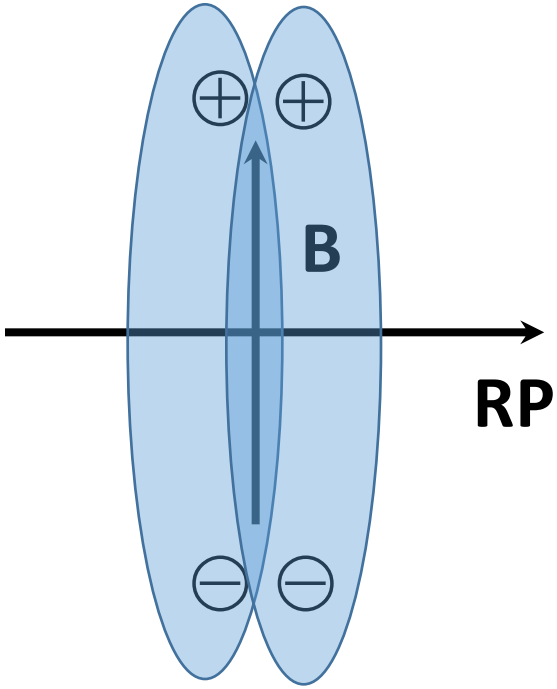

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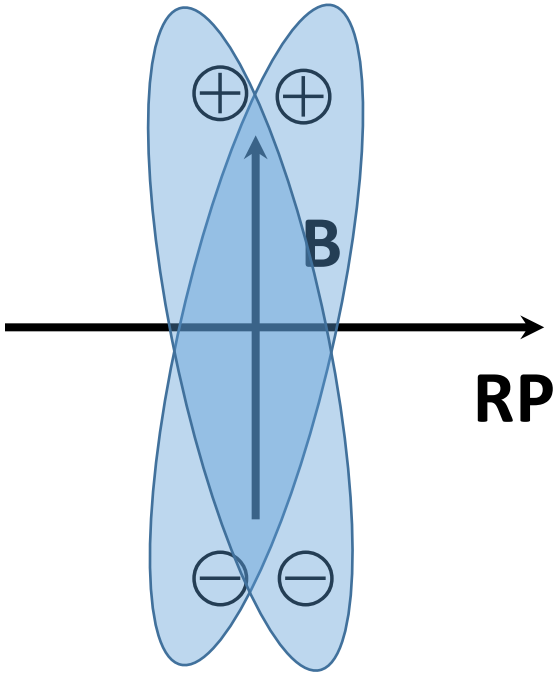

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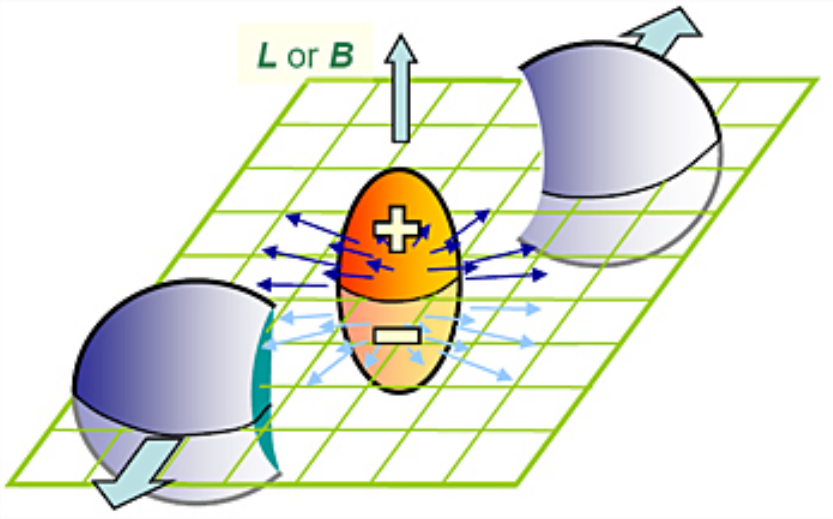

< 0 for same-sign pairs

> 0 for opposite-sign pairs

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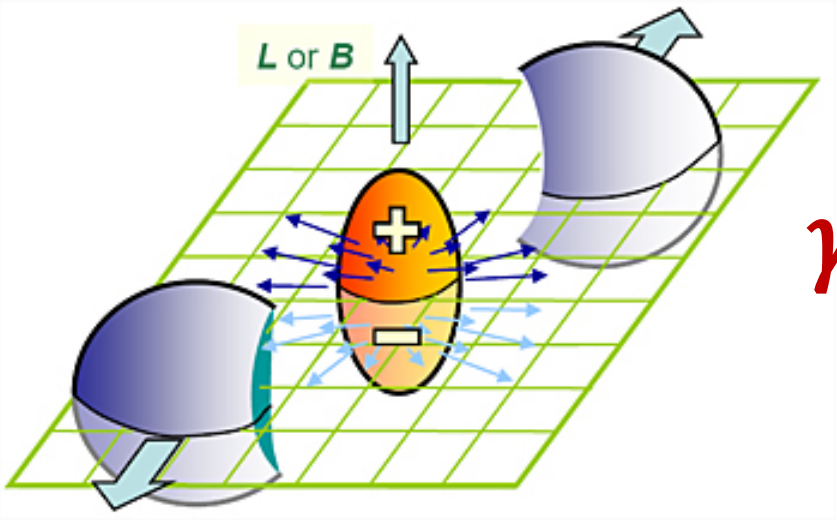
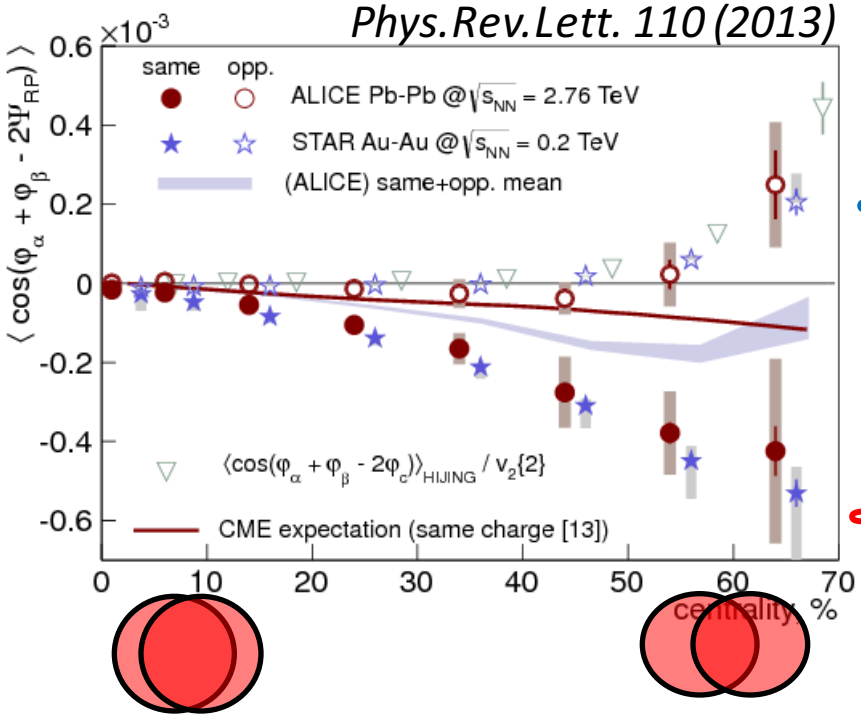


γ

Phys.Rev.Lett. 110 (2013)



- Charged-dependent correlation observed

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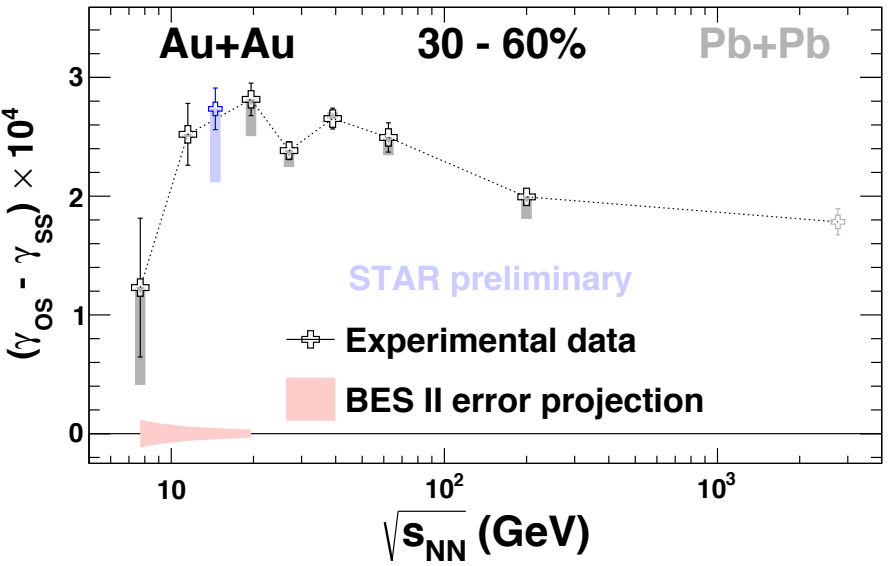

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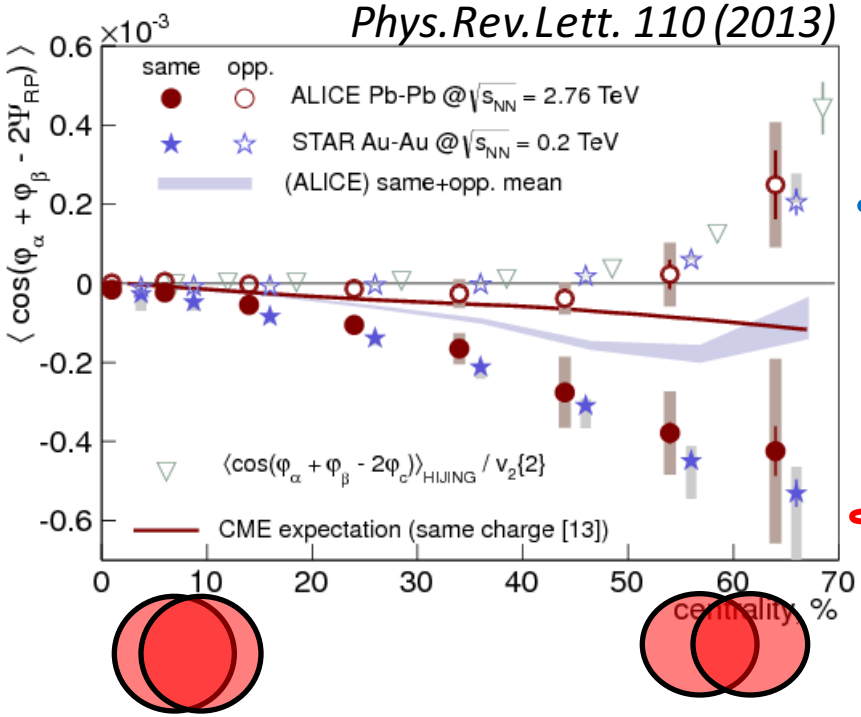

- $\gamma_{os\text{-}ss}$ drops at low energy (?)
- Important for BES program

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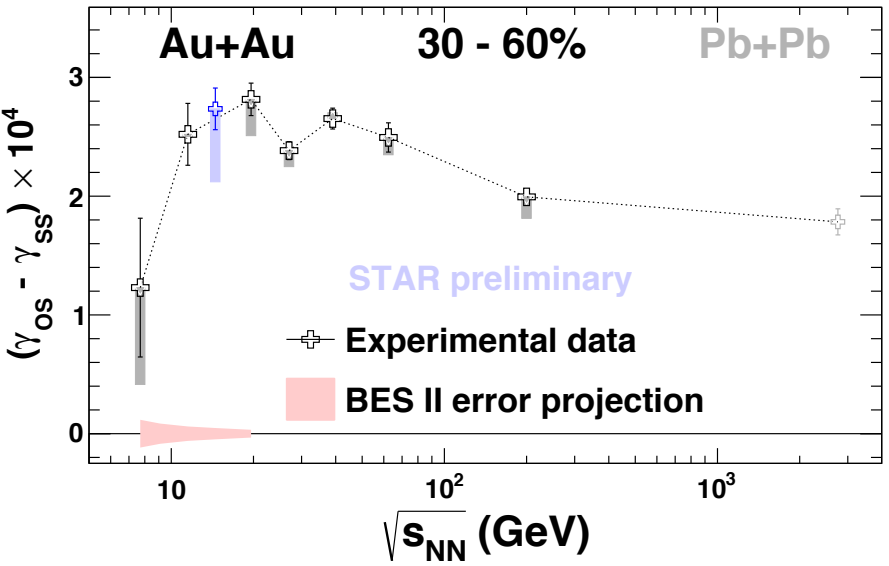

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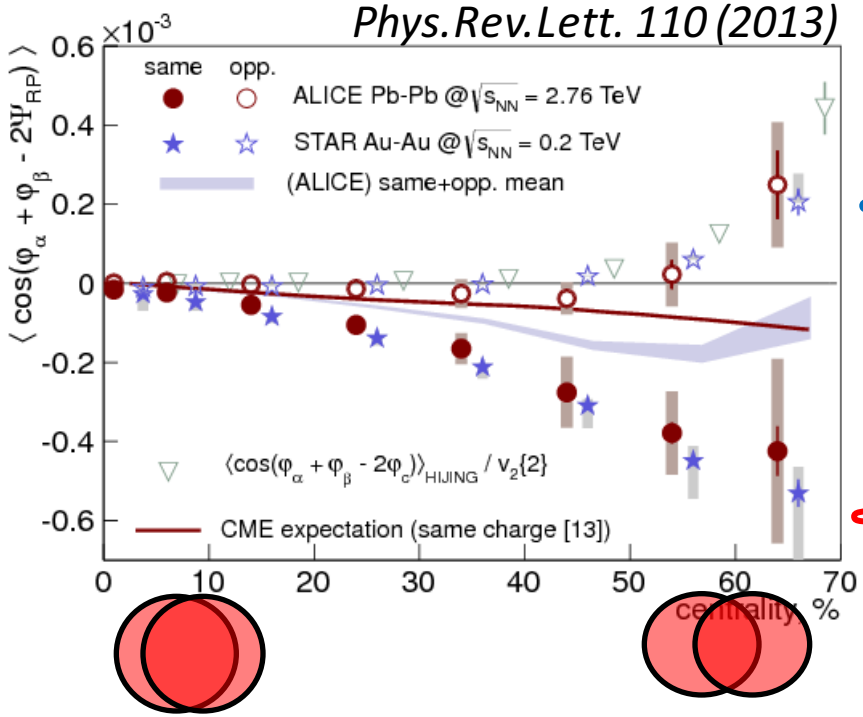

- $\gamma_{os\text{-}ss}$ drops at low energy (?)
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- Charged-dependent correlation observed

Agree with CME expectation

Status of CME in recent studies

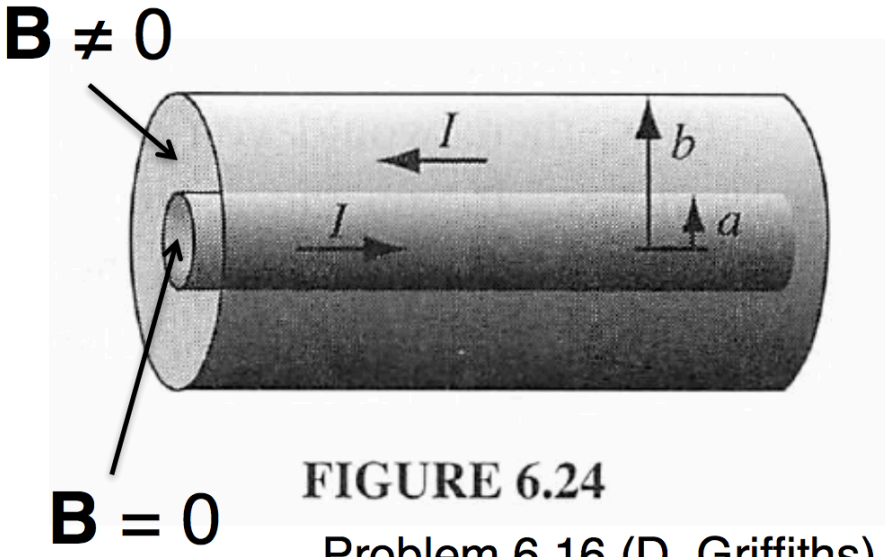
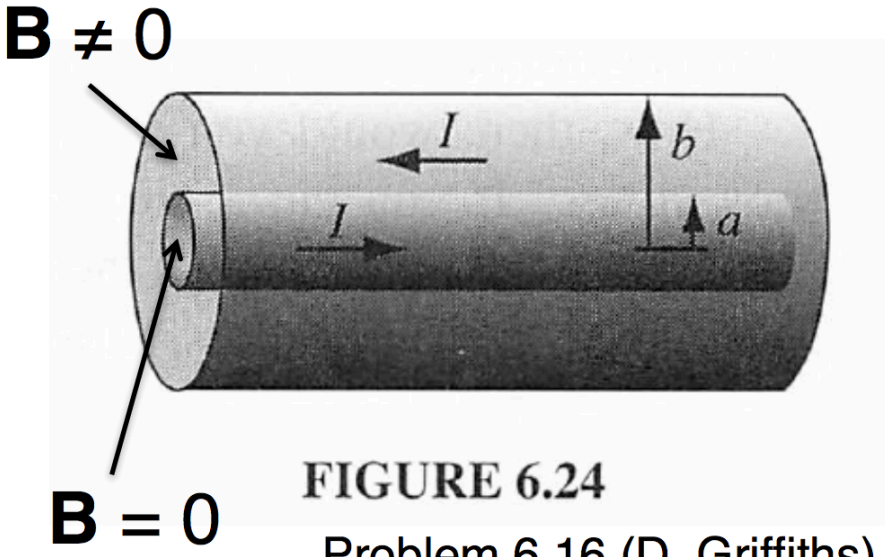


FIGURE 6.24

Problem 6.16 (D. Griffiths)

Wei.Li, Chirality workshop at UCLA 2017

Status of CME in recent studies



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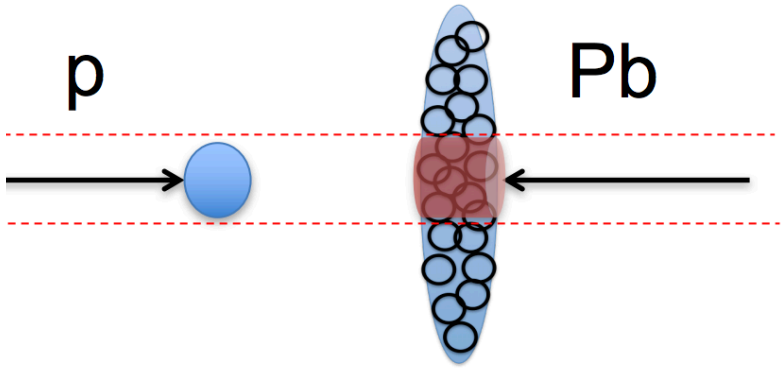

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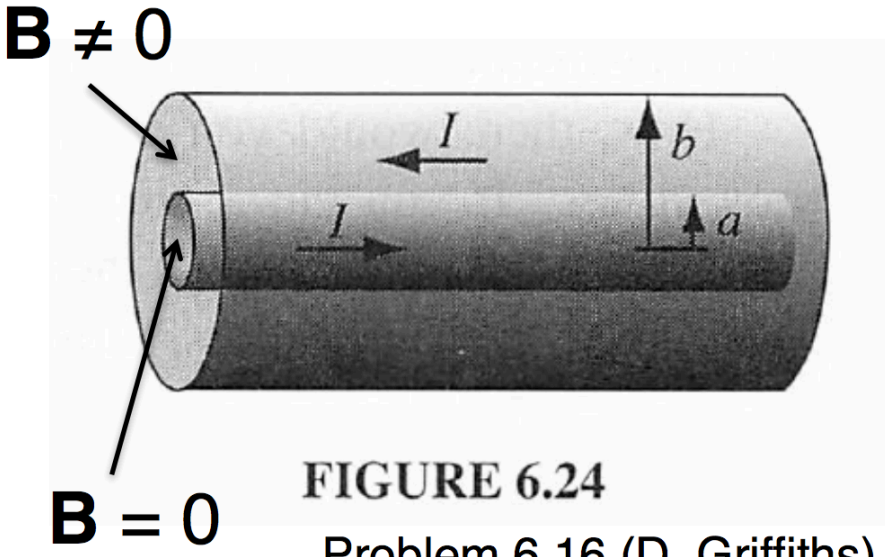

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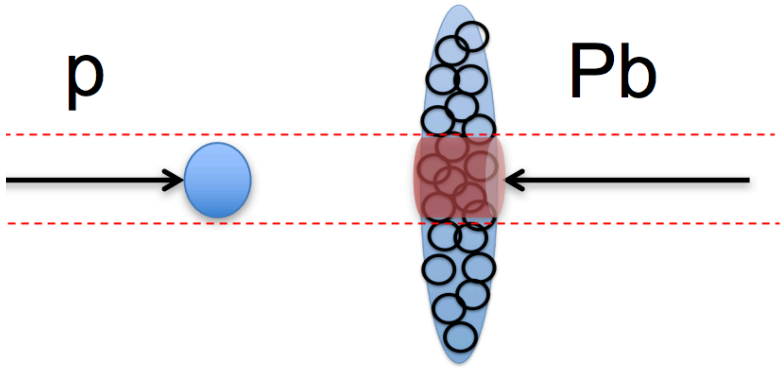

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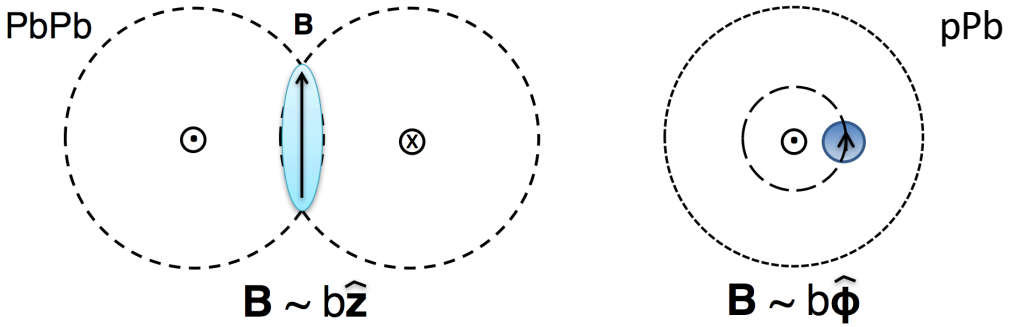
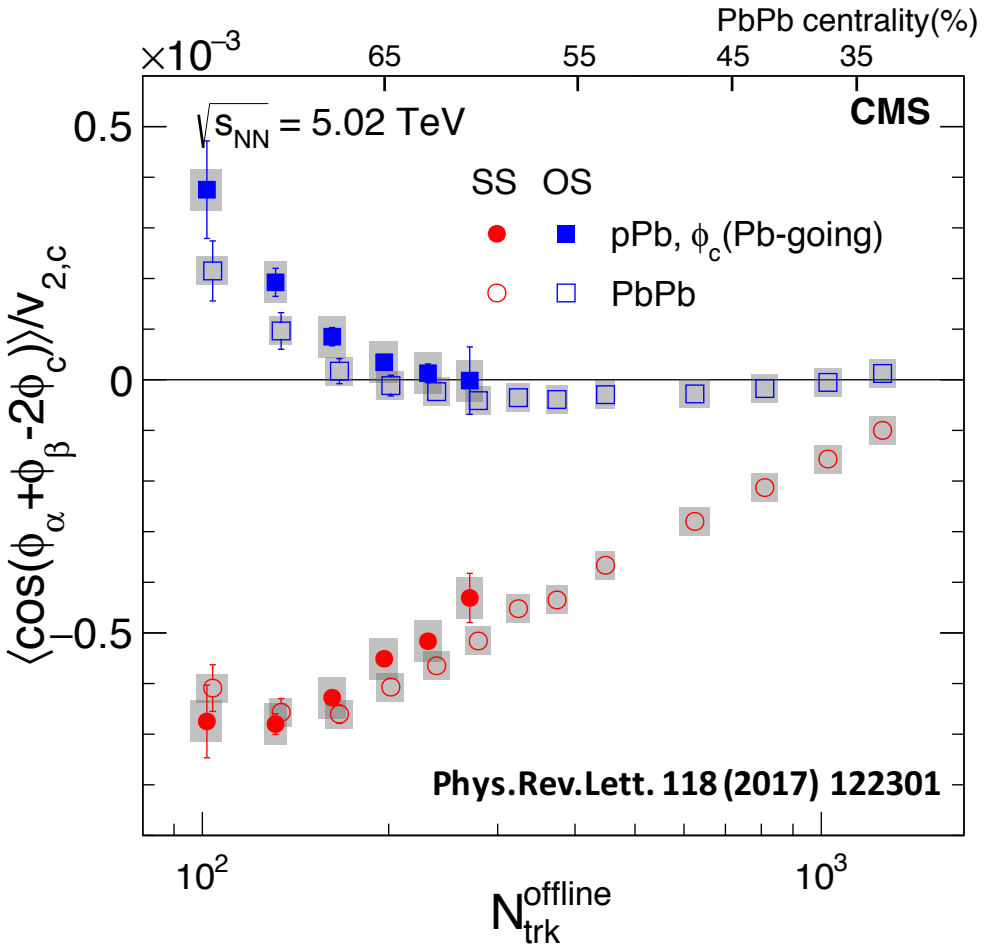


B and 2nd order EP decorrelates in pA
--Phys.Rev.Lett. 118 (2017) 122301

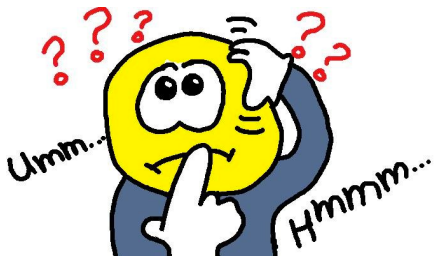
pA can be a baseline for CME measurement

Status of CME in recent studies



Non negligible background has been long speculated.

Question is about "how much"?



❖ **Why is pPb and PbPb so similar? Background dominated**

❖ The fact that γ(pPb) ≈ γ(PbPb) not only challenges the CME but also the background mechanism (e.g., ~v2/N)

Motivation of a detail analysis

- **Two major questions to be answered:**
  i. What is the background exactly?
  ii. Is there any real CME signal, if BKG is removed?

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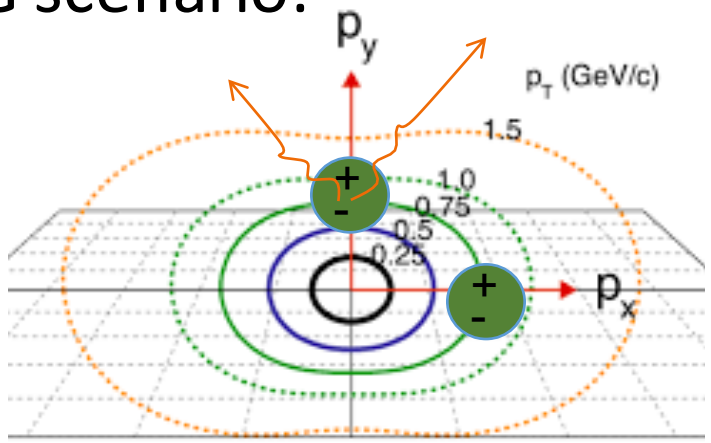
Commonly suspected BKG scenario:

Lect.Notes Phys. 871 (2013) 503-536

$$\gamma = \kappa \cdot v_2 \cdot \delta - H$$

where $\delta \equiv \left\langle \cos\left(\phi_\alpha - \phi_\beta\right) \right\rangle$



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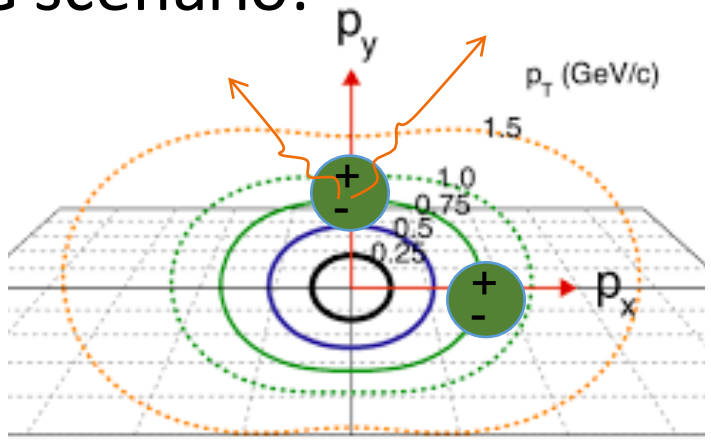

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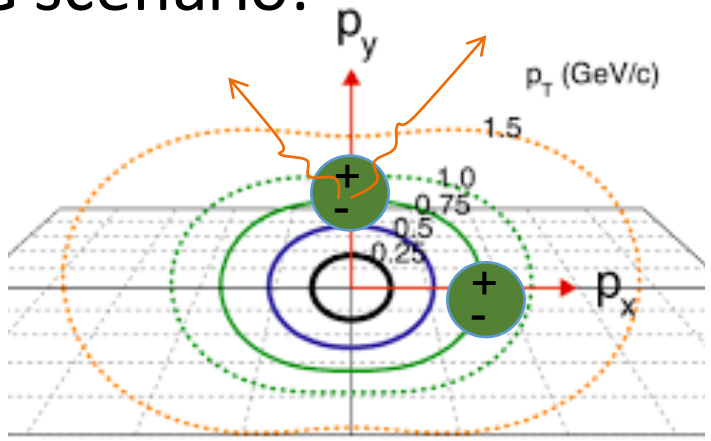

i.e., local charge conservation + v2

- **Two major difficulties:**
  - i. κ parameter is hard to constrain
  - ii. BKG is hard to control, need an independent handle on v_2 without changing the B field

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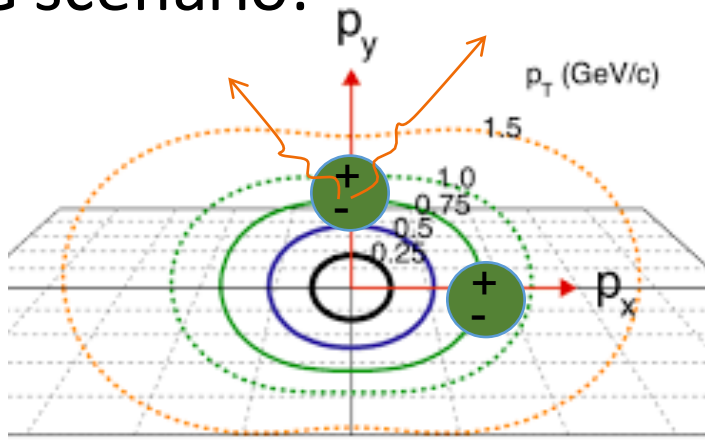

i.e., local charge conservation + v2

New experimental strategy is needed!

Analysis strategy

$Update$: $\gamma_{112} = \gamma$

❖ **1: Higher-harmonic correlator**

$$\gamma_{123} \equiv \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right) \right\rangle$$

- CME free as no charge separation w.r.t. Ψ_3
- For BKG-only source,

$$\gamma_{123} = \kappa \cdot v_3 \cdot \delta \quad \cancel{= H}$$

An independent constraint to κ!

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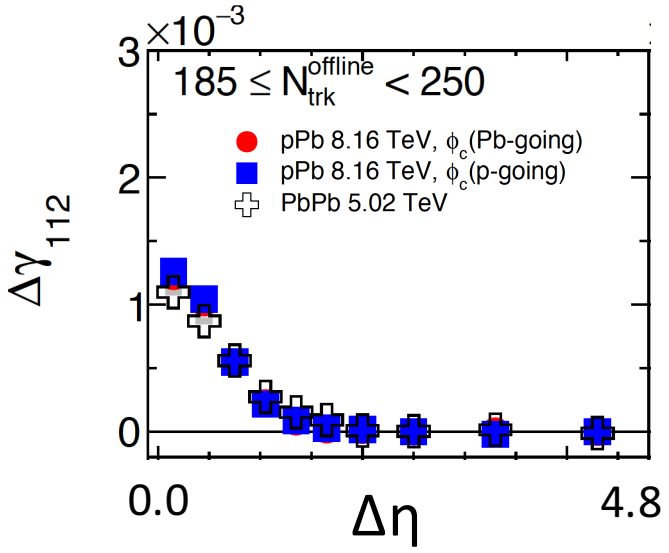
❖ 2: Event Shape Engineering (ESE) arXiv:1608.03205v2

To directly observe the relation between γ_{112} and v_2

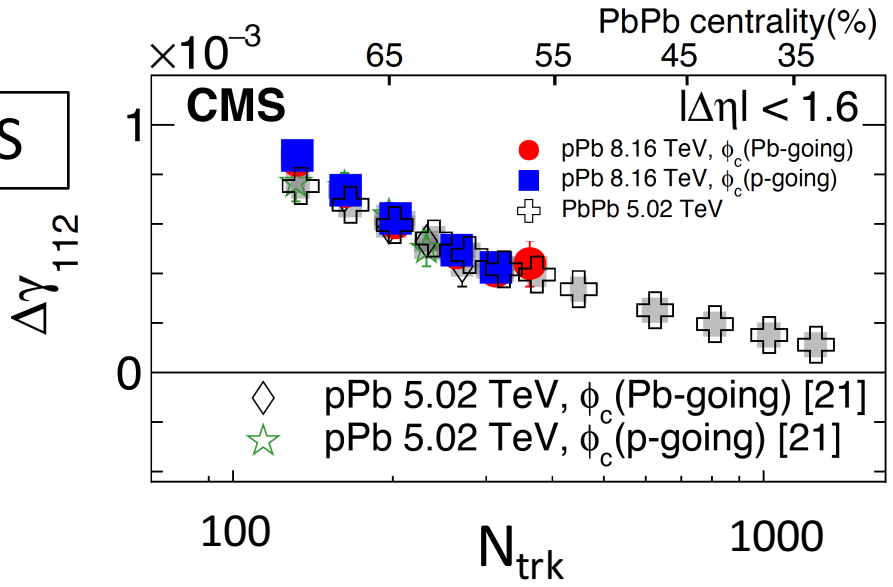
(Is it consistent with a v_2-linear BKG-only scenario?)

Results: (OS-SS)

arXiv:1708.01602



Δ = OS-SS



Results: (OS-SS)

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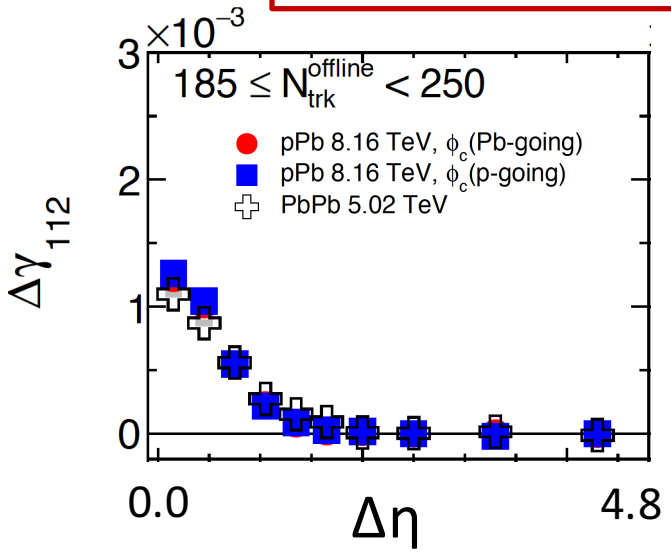
❖ **Why is γ_{112} pPb and PbPb so similar?**



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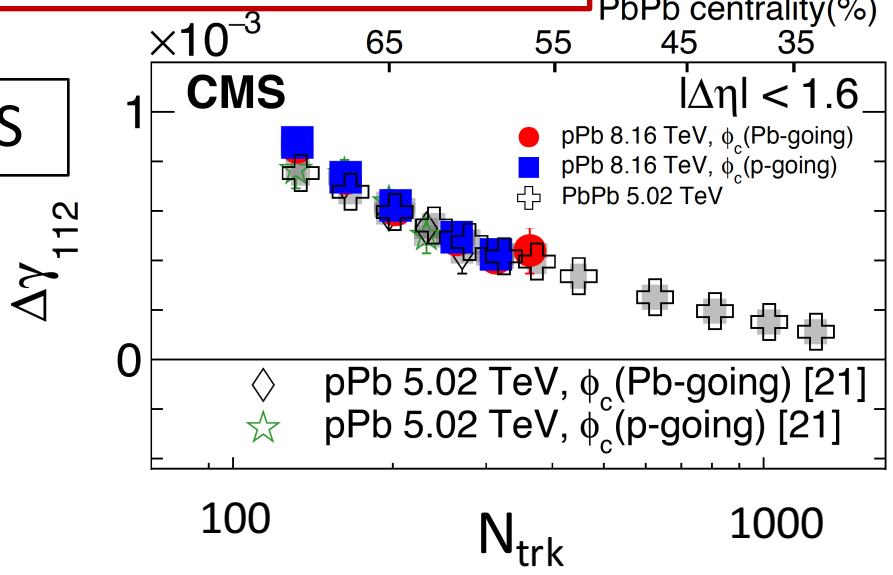

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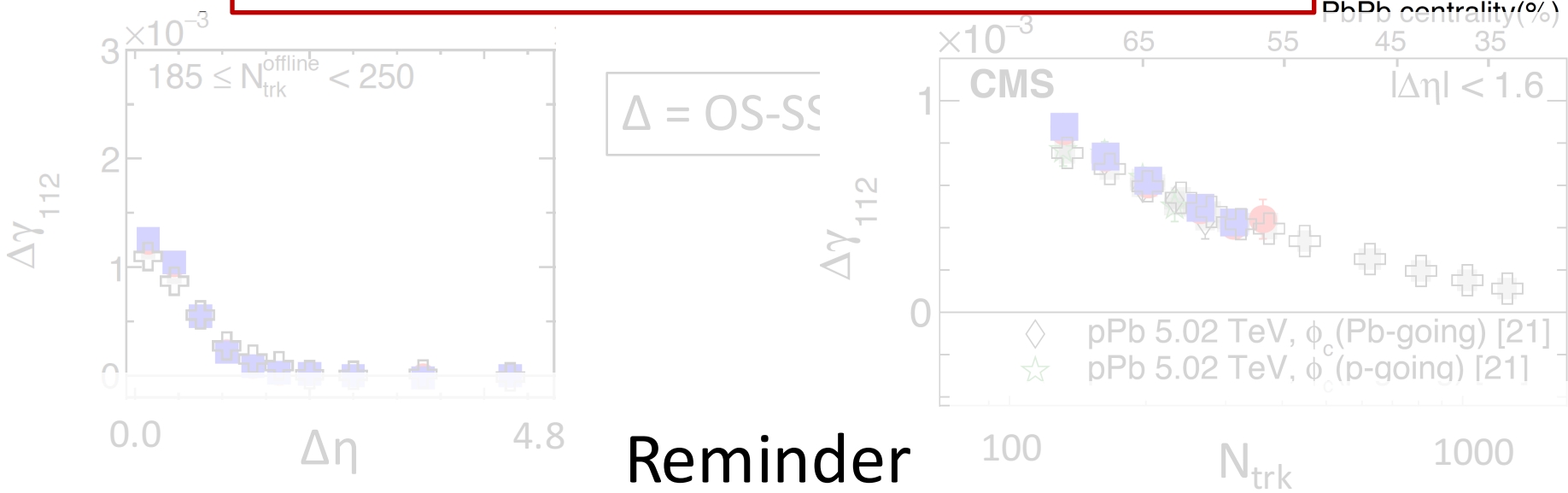
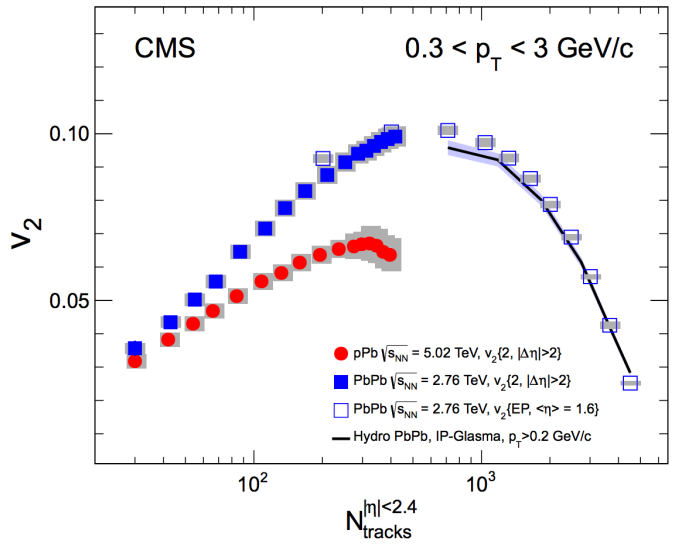


Reminder

V_2 (pPb) < V_2 (PbPb)



BKG scenario:

$$\gamma_{112} = \kappa \cdot v_2 \cdot \delta$$

How about δ btw pPb and PbPb?

Results: (OS-SS)

arXiv:1708.01602

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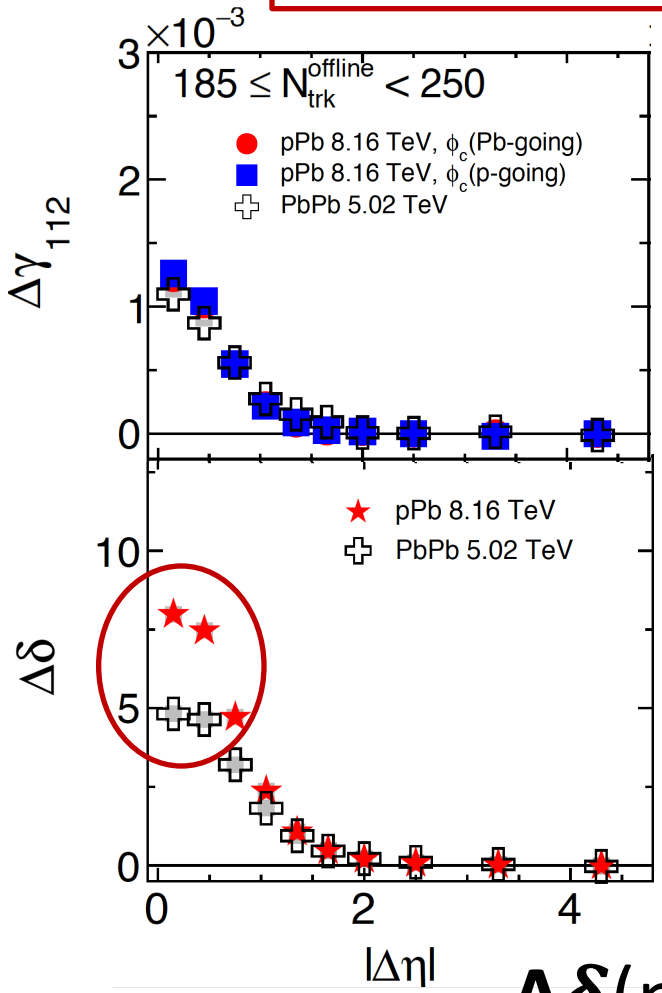
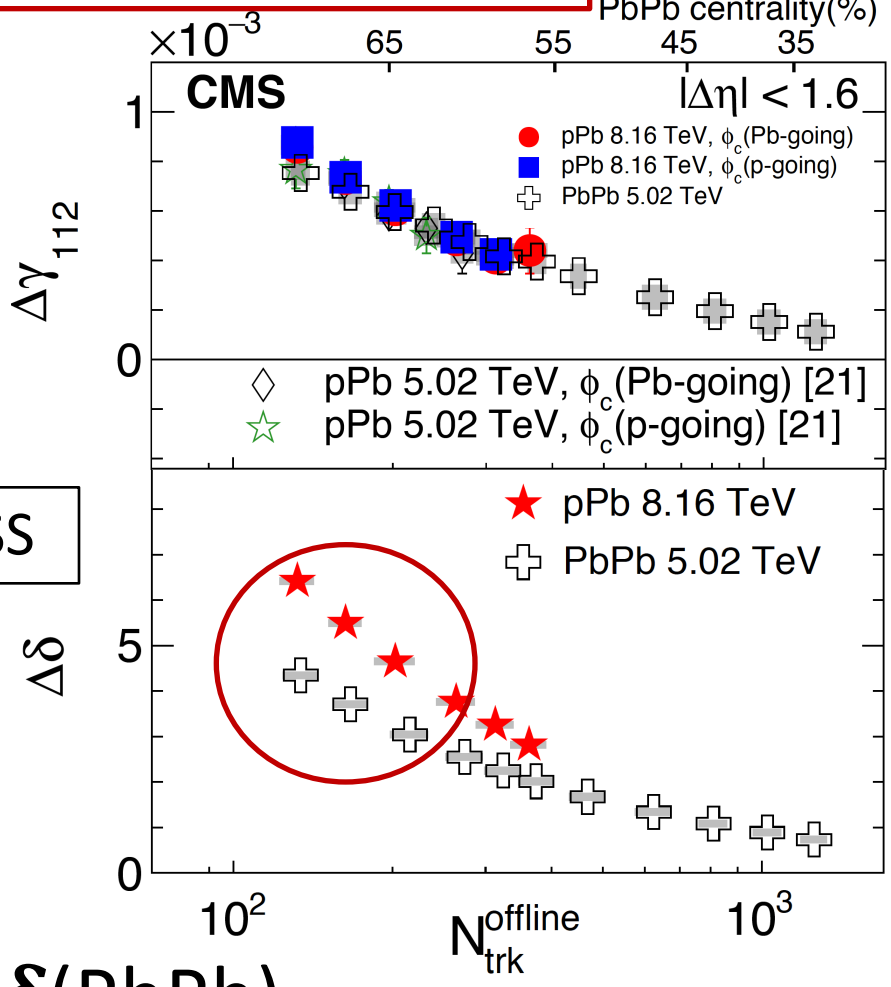


Δ = OS-SS

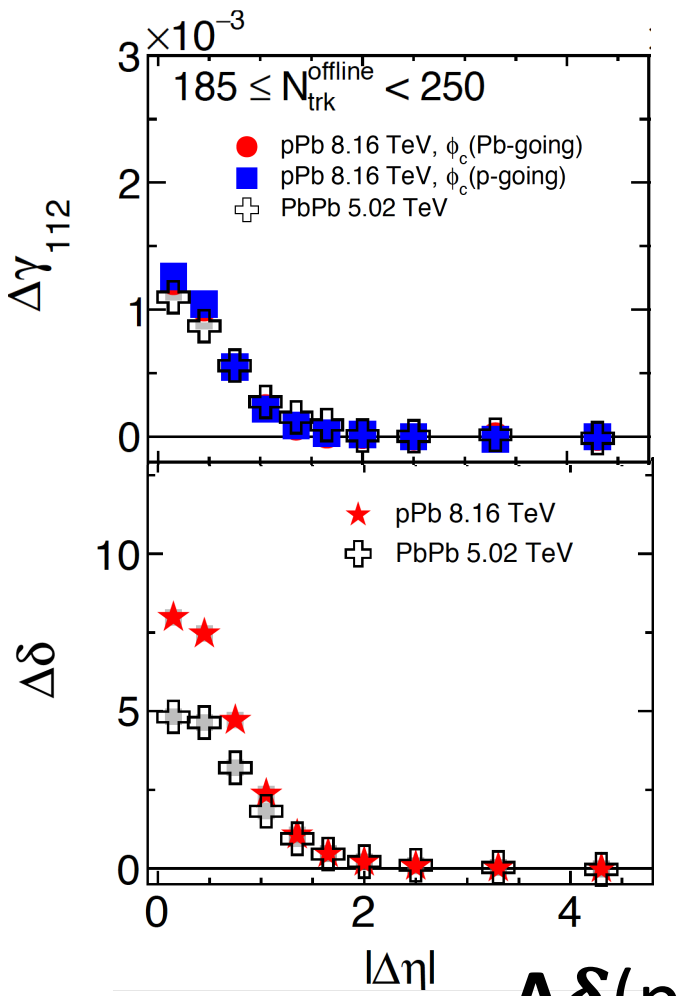


$\Delta\delta$(pPb) > $\Delta\delta$(PbPb)

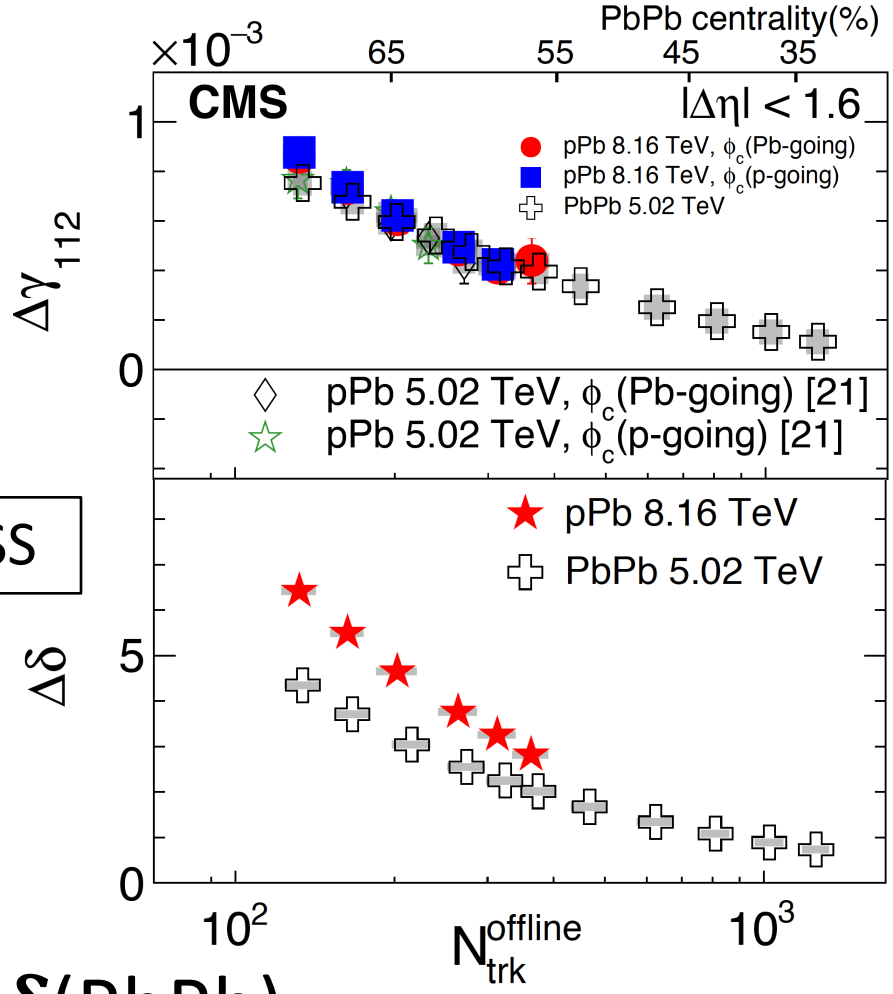
This can explain γ(pPb) ≈ γ(PbPb), if $\gamma = \kappa \cdot v_2 \cdot \delta$

Results: (OS-SS)

arXiv:1708.01602



Δ = OS-SS



$\boldsymbol{\Delta\delta}$(pPb) > $\boldsymbol{\Delta\delta}$(PbPb)

Still unconstrained

This can explain γ(pPb) ≈ γ(PbPb), if $\gamma = \boxed{\kappa} \cdot v_2 \cdot \delta$

Results: higher-order correlator

- CME free correlator

$$\gamma_{123} \equiv \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right) \right\rangle$$

Charge-dependent signal has to be BKG

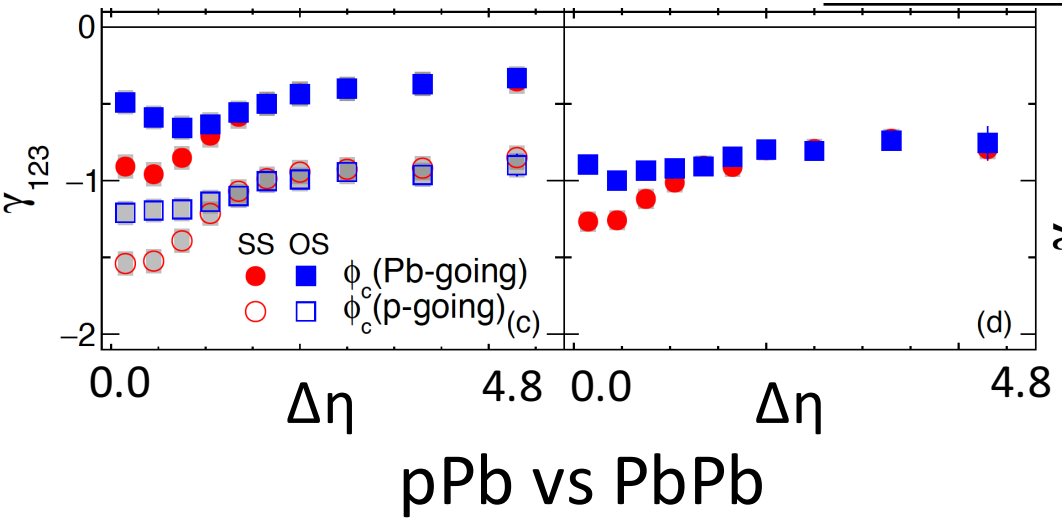
Results: higher-order correlator

❖ CME free correlator

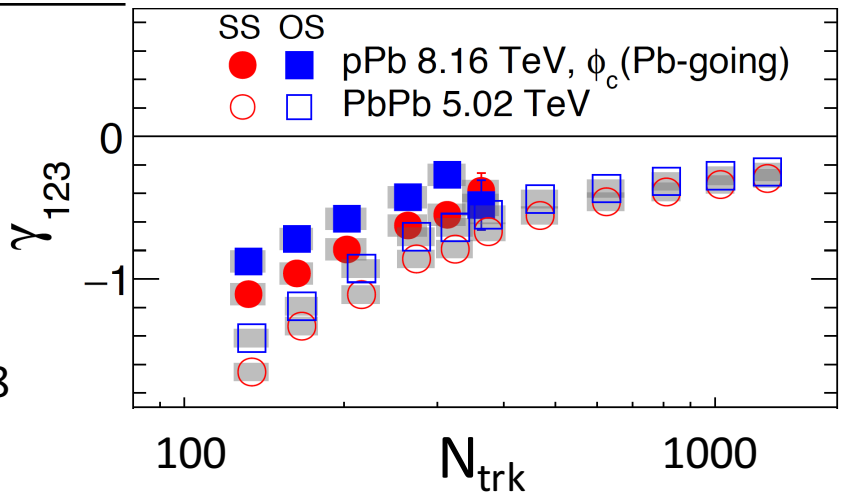
$$\gamma_{123} \equiv \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right)\right\rangle$$

Charge-dependent signal has to be BKG

arXiv:1708.01602



pPb vs PbPb



➢ Correlation is still short-range and charge-dependent.

➢ Can this be compatible with the suspected BKG?

Results: Test BKG

(Δ = OS-SS)

To test this background only scenario, we compare $\boldsymbol{\kappa}_2$ and $\boldsymbol{\kappa}_3$

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$
$$\Delta\gamma_{123} = \kappa_3 \cdot v_3 \cdot \Delta\delta$$

If $\boldsymbol{\kappa}_2 = \boldsymbol{\kappa}_3$, the data is compatible with ~100% background

Results: Test BKG

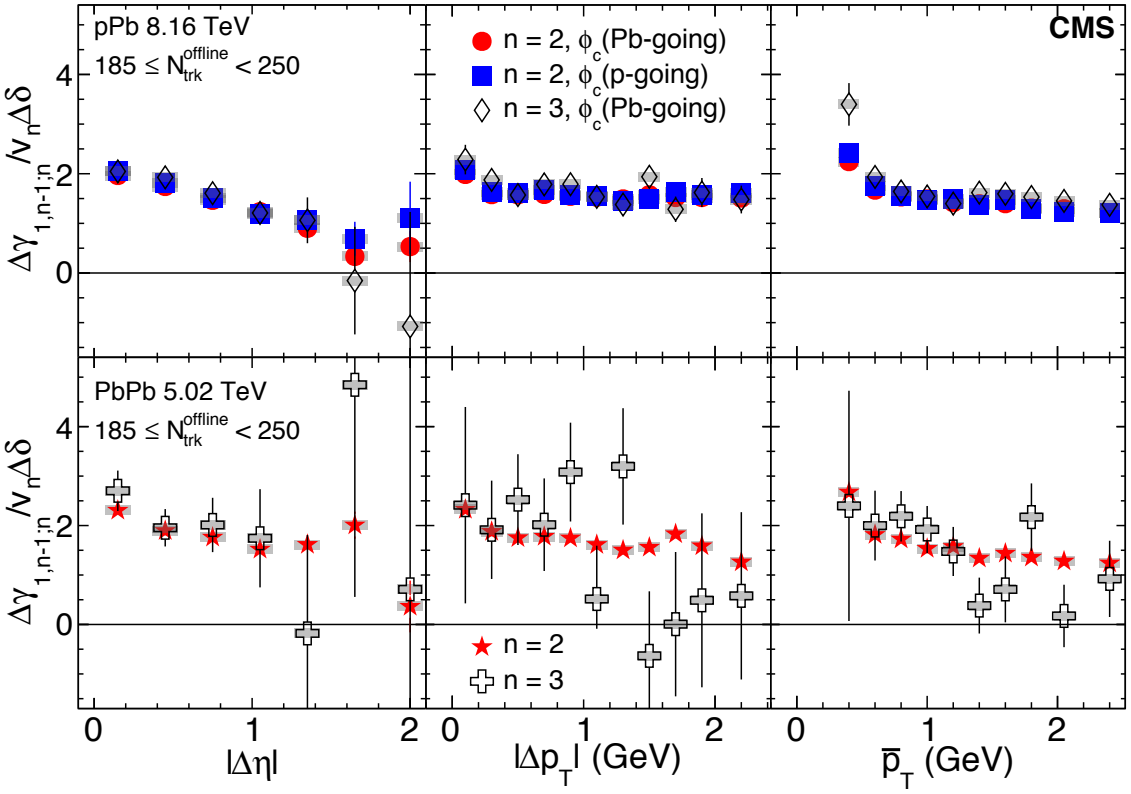
(Δ = OS-SS)

To test this background only scenario, we compare κ_2 and κ_3

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$
$$\Delta\gamma_{123} = \kappa_3 \cdot v_3 \cdot \Delta\delta$$

✓ $\kappa_2 = \kappa_3$, the data is compatible with ~100% background

κ_n



κ_n

pPb

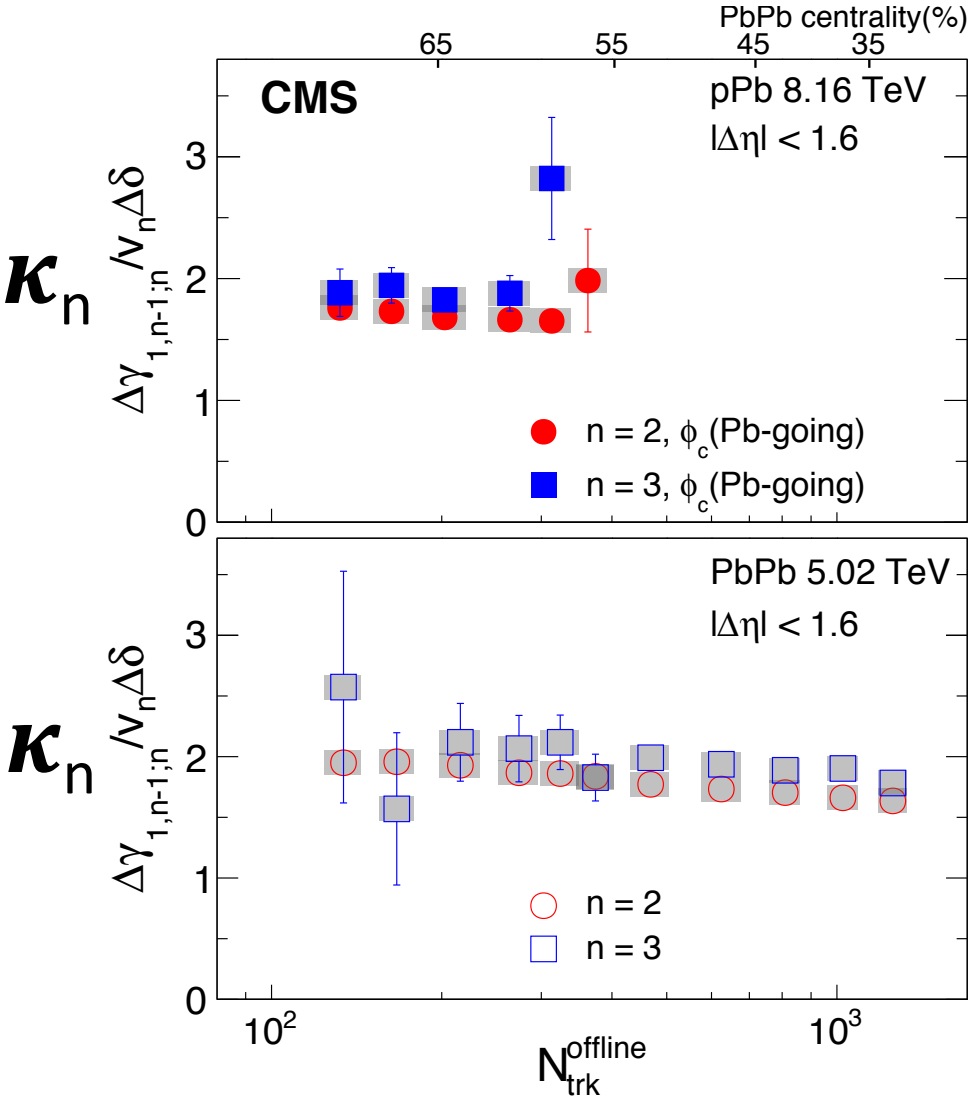
PbPb

arXiv:1708.01602

Results: Test BKG

arXiv:1708.01602

✓ $\kappa_2 = \kappa_3$, the data is compatible with ~100% background scenario throughout **the entire multiplicity or centrality range**

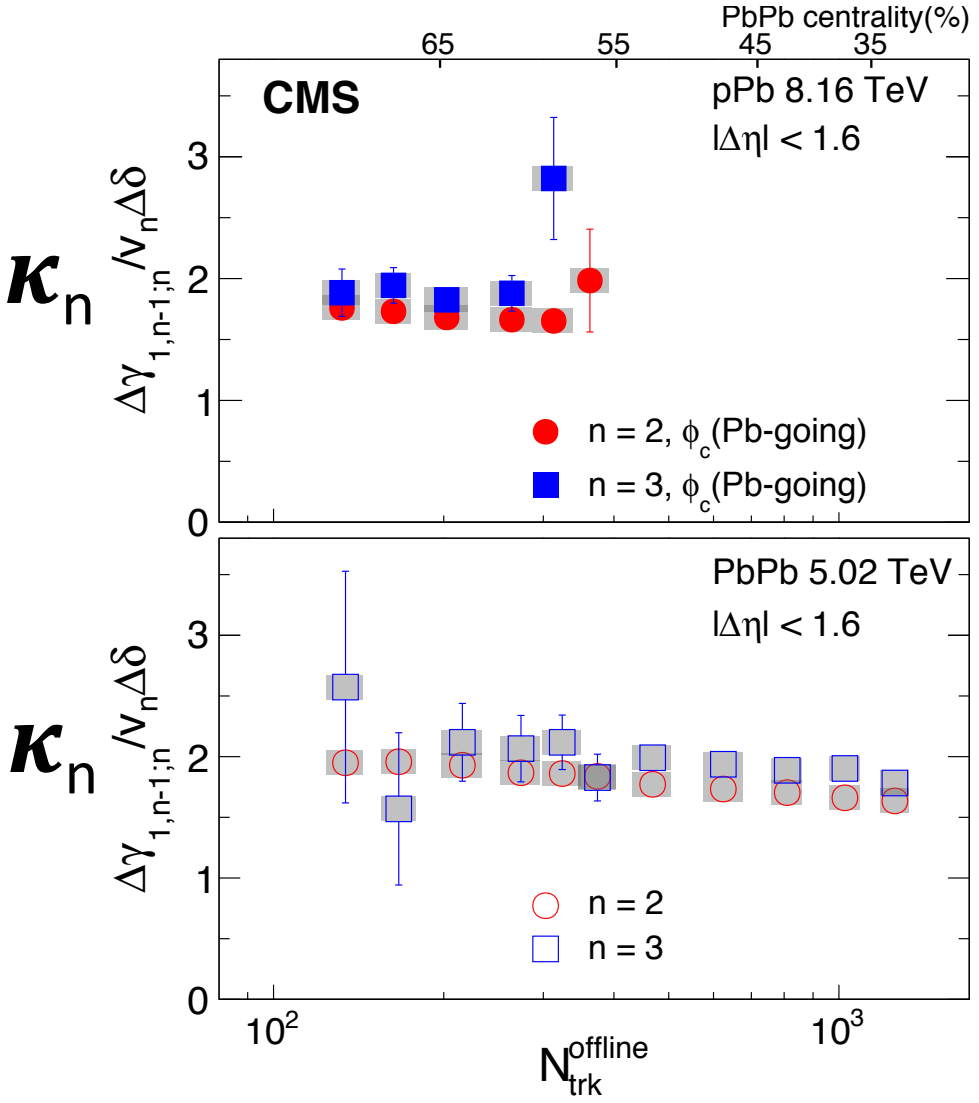


Results: Test BKG

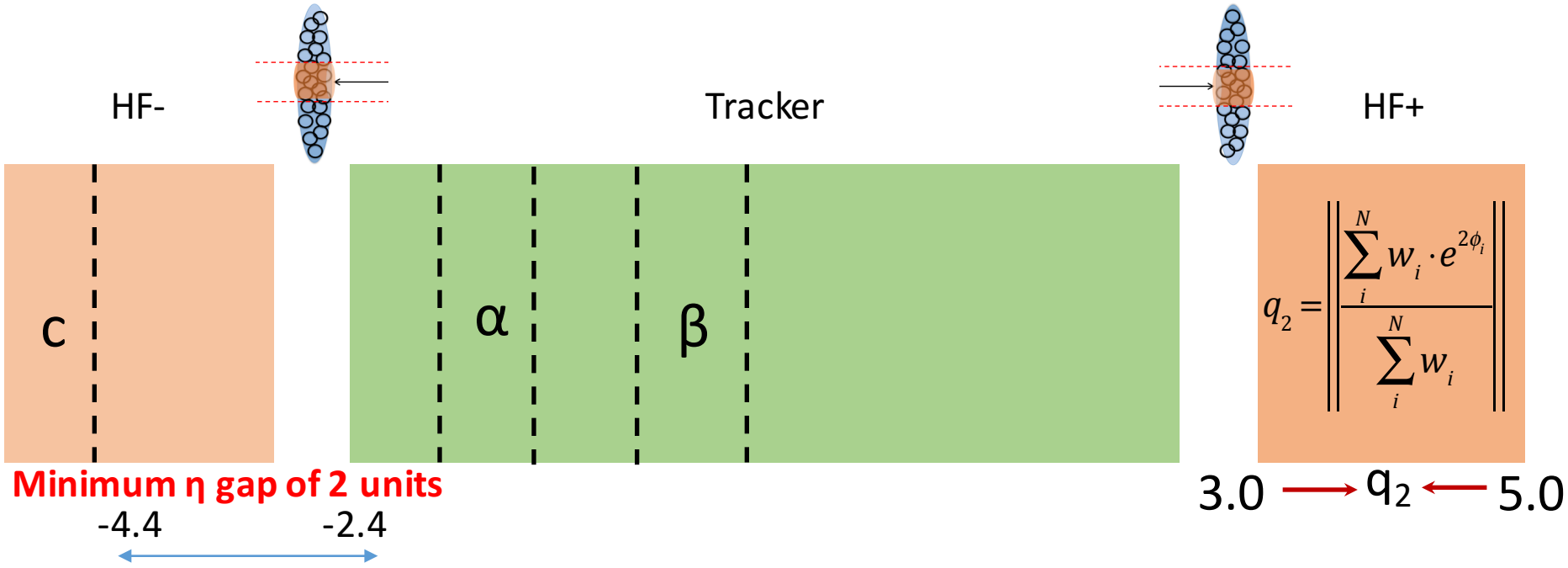
arXiv:1708.01602

✓ $\kappa_2 = \kappa_3$, the data is compatible with ~100% background scenario throughout **the entire multiplicity or centrality range**

❖ Now, can we observe the linear dependence on v2 and see if there is any room for CME?



ESE with CMS detectors

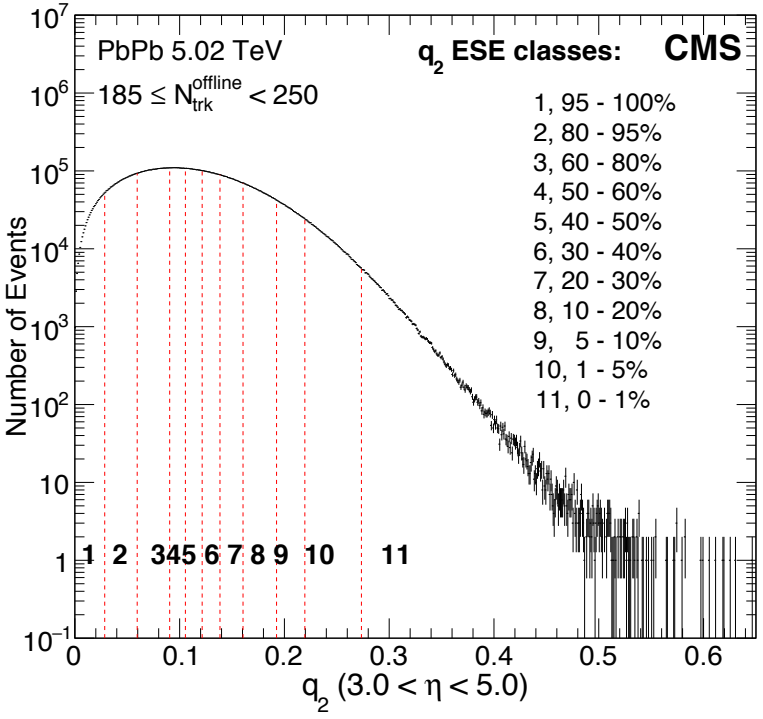


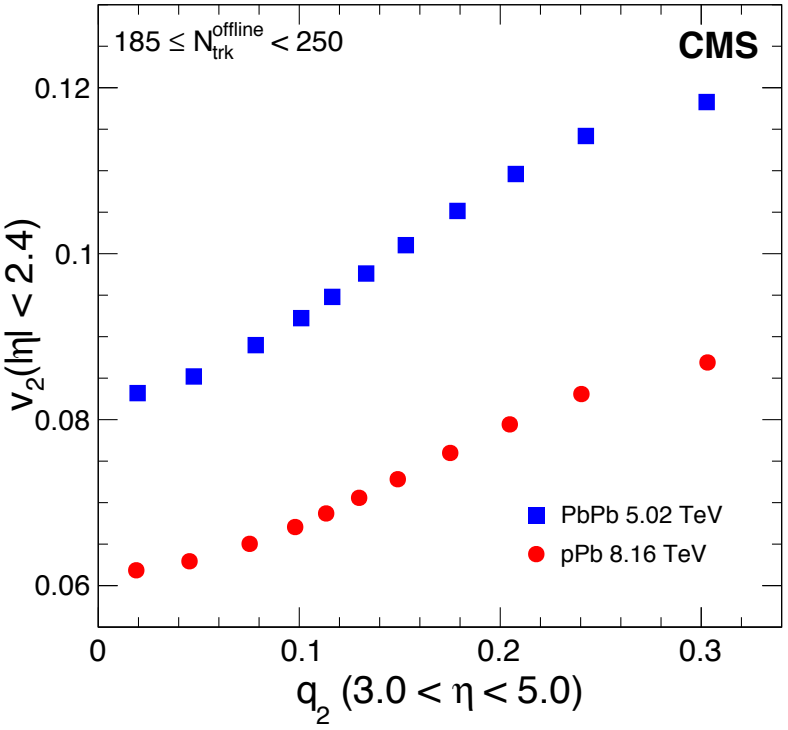
- The ESE uses q_2, magnitude of q vector, in one side of the HF (3-5 units) to select events with very different v2
- In pPb collision, q_2 is calculated from the Pb-going side. Particle c from both p- and Pb-going side are studied.

- Particle c in γ_{112} is from the other side of the q_2 region in PbPb.

ESE with CMS detectors

arXiv:1708.01602

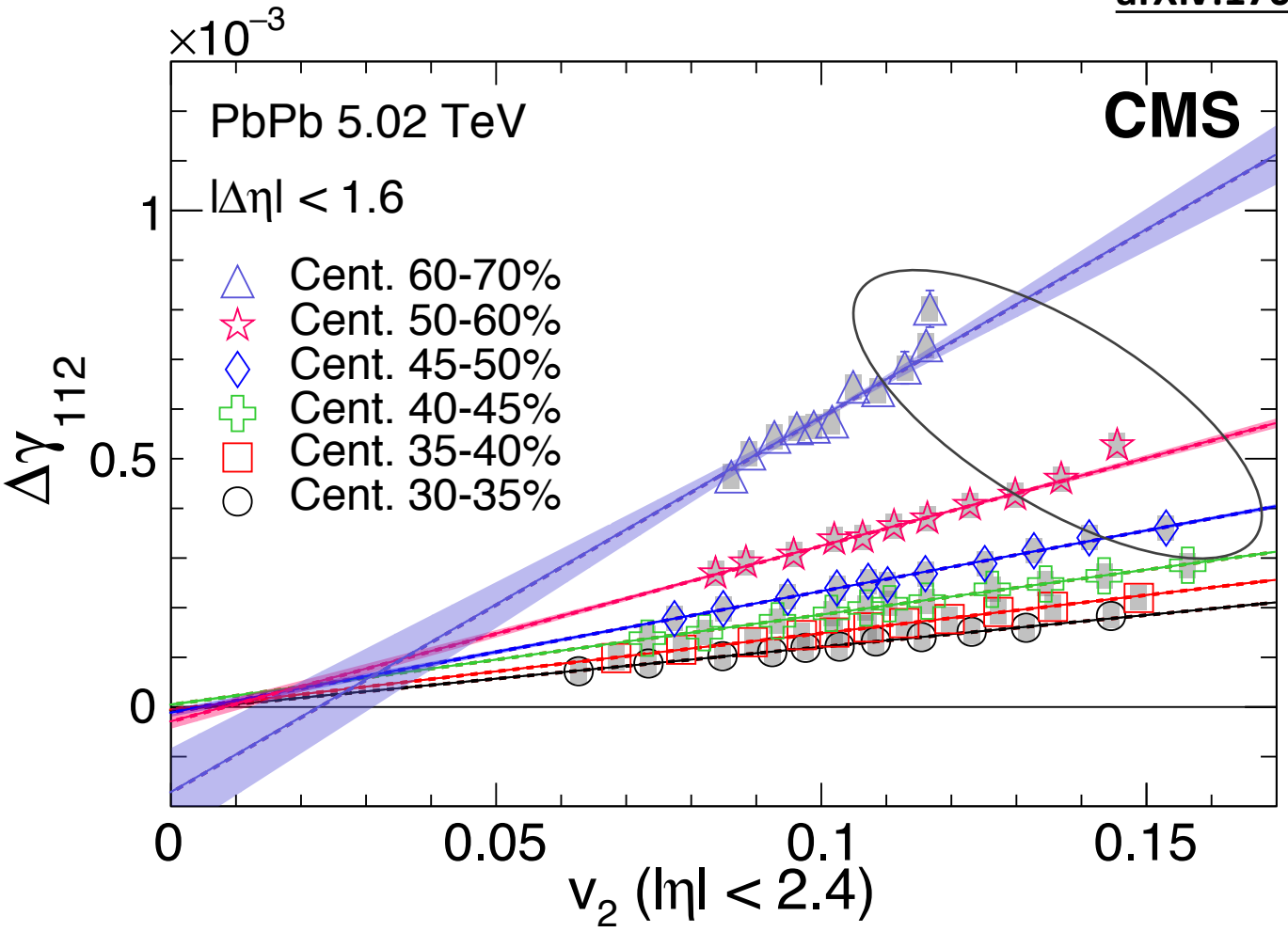




- q_2 is monotonically correlated with v2, expected from the initial-state geometry;
- γ_{112} can be studied as a function of v2 within a single multiplicity or centrality class.

Results: ESE

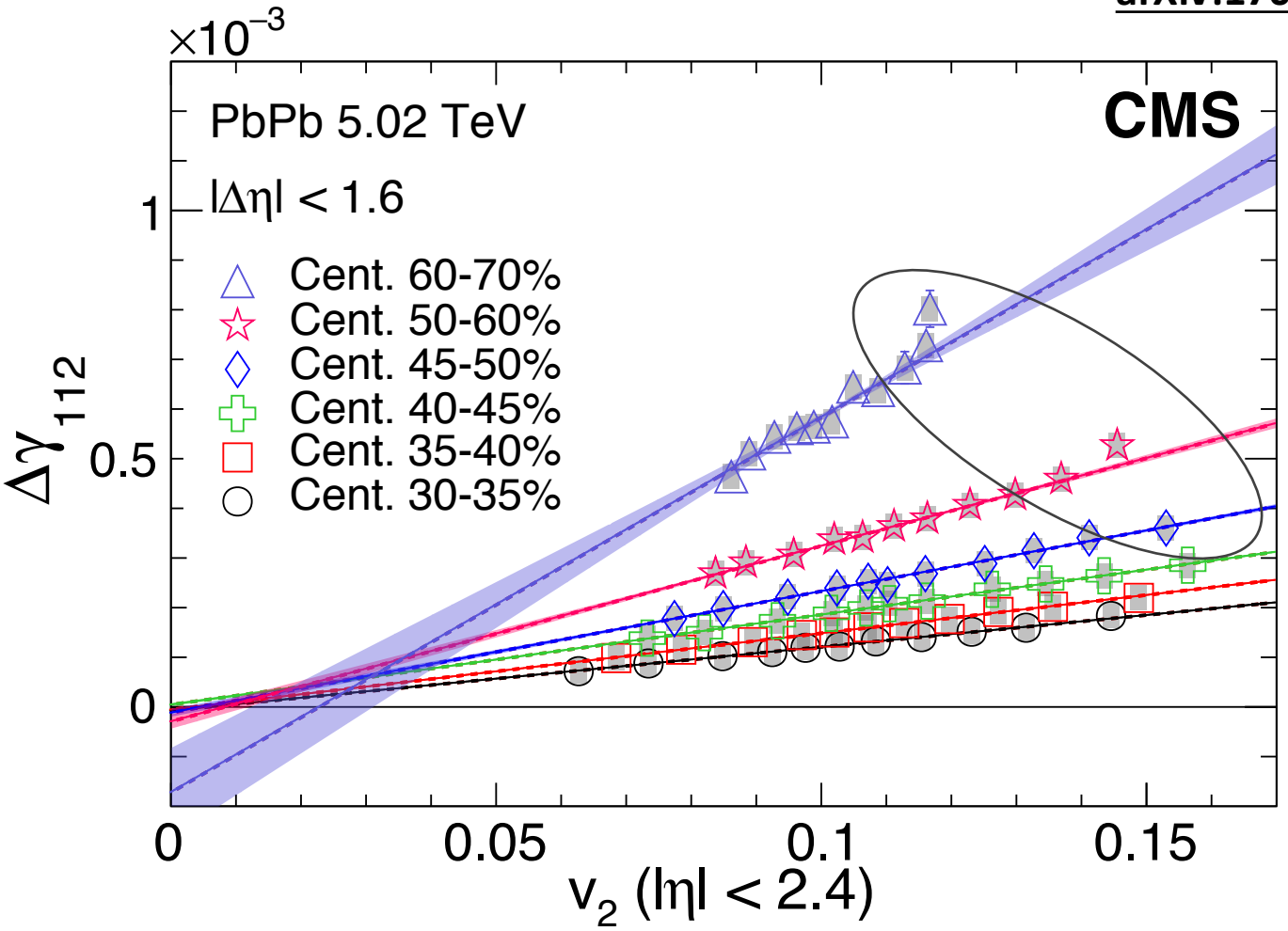
arXiv:1708.01602



- OS-SS vs v2, when v2 = 0 → finite intercept?
- Some nonlinear trend at high v2. Anything else other than CME?

Results: ESE

arXiv:1708.01602

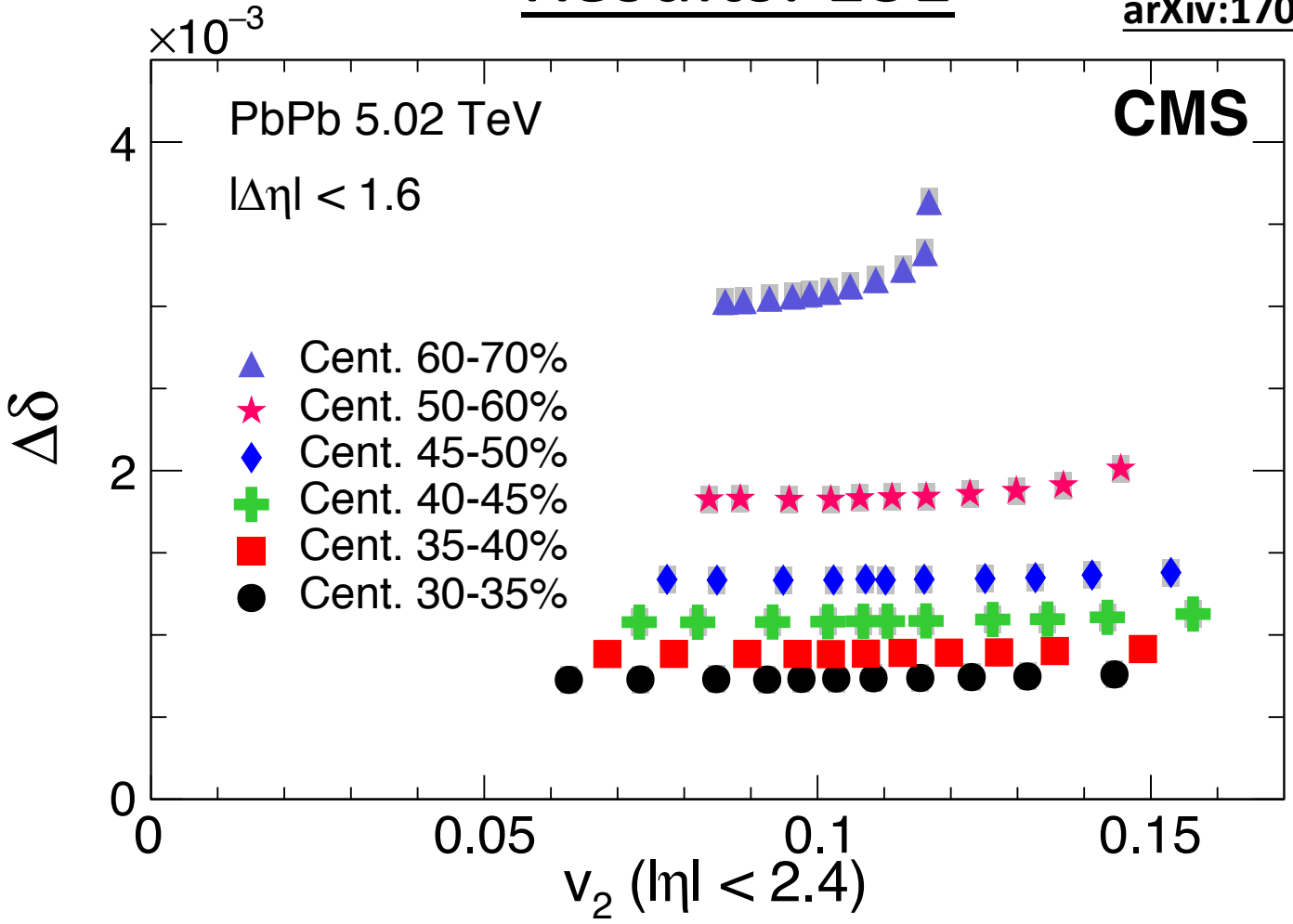


- OS-SS vs v2, when v2 = 0 → finite intercept?
- Some nonlinear trend at high v2. Anything else other than CME?

δ-correlator? Is δ independent of v2?

Results: ESE

arXiv:1708.01602



- Indeed, the Δδ is not flat vs v2, esp at low multiplicity.
- Two effects:
  1. Multiplicity dilution, multiplicity bias from q_2 selection
  2. Nonflow, η-gap is not optimal.

Results: ESE

- Background-only scenario:

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$

➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2$$

→ Goes thru ZERO!

Results: ESE

- Background-only scenario:

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$

➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2$$

→ Goes thru ZERO!

- Background + signal scenario:

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta - b$$

➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2 - b/\Delta\delta$$

→ Finite intercept!

Results: ESE

arXiv:1708.01602

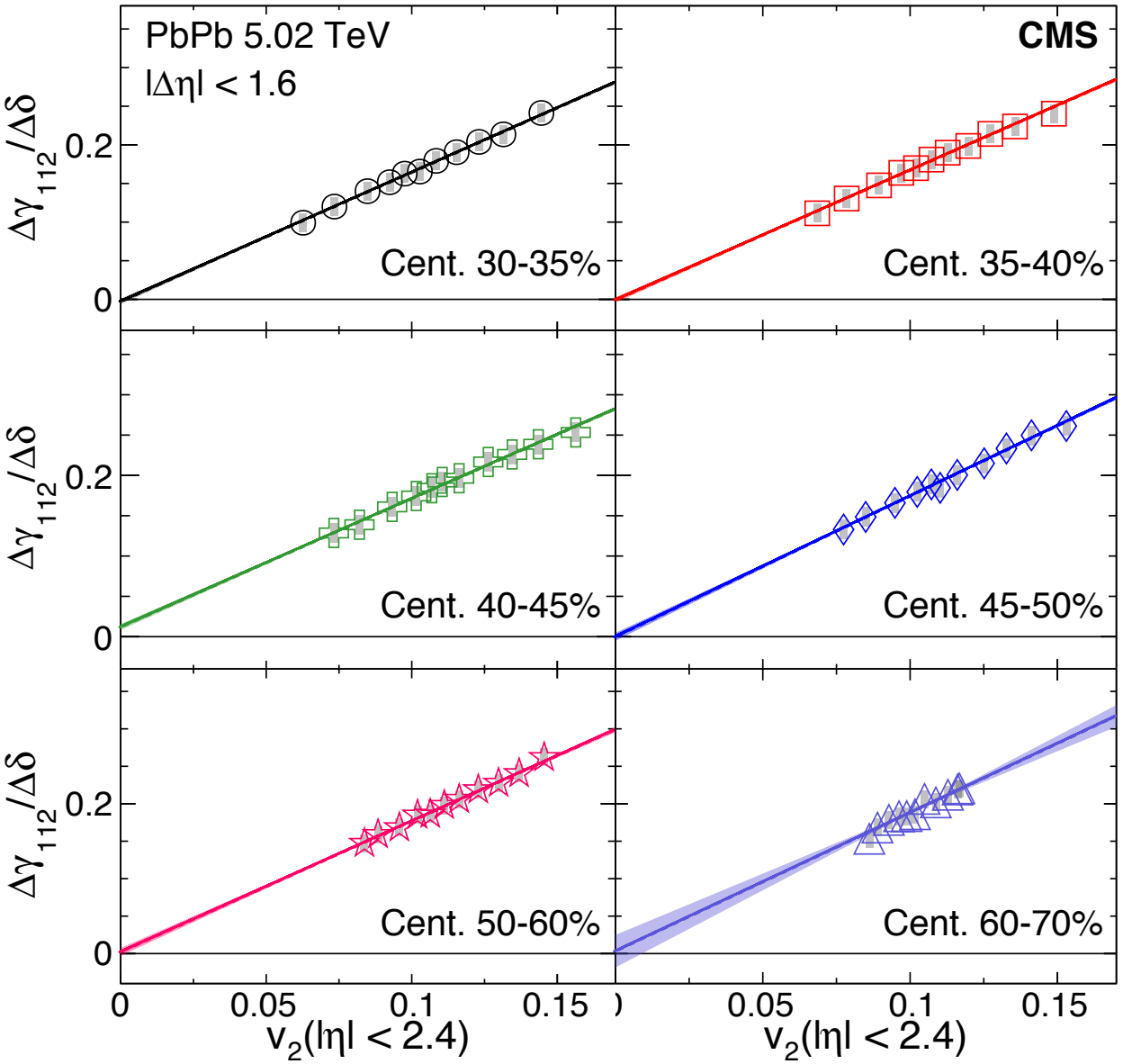
- Background-only scenario:

$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$

➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2$$

→ Goes thru ZERO! ✓



Results: ESE

pPb vs PbPb

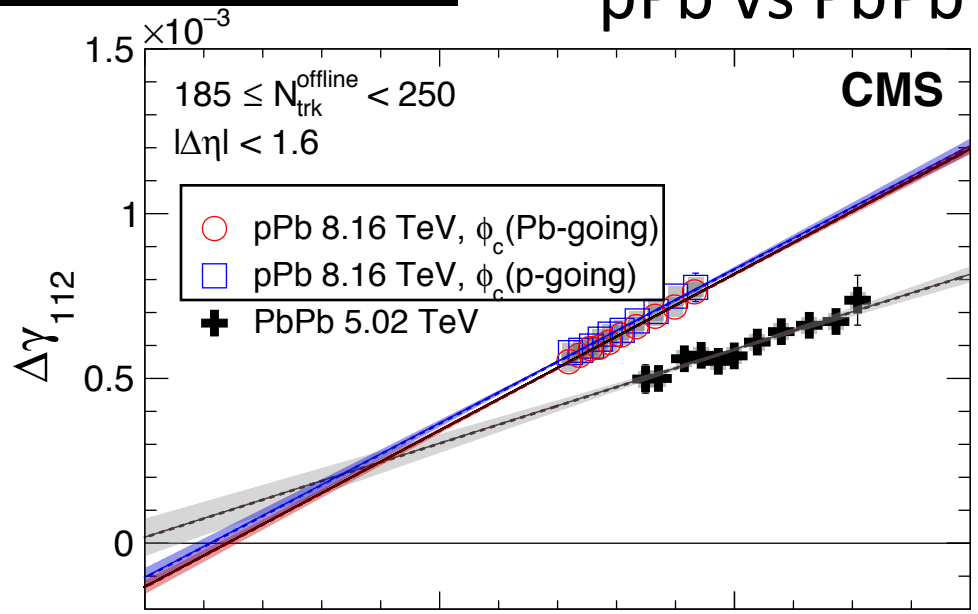
- Background-only scenario:

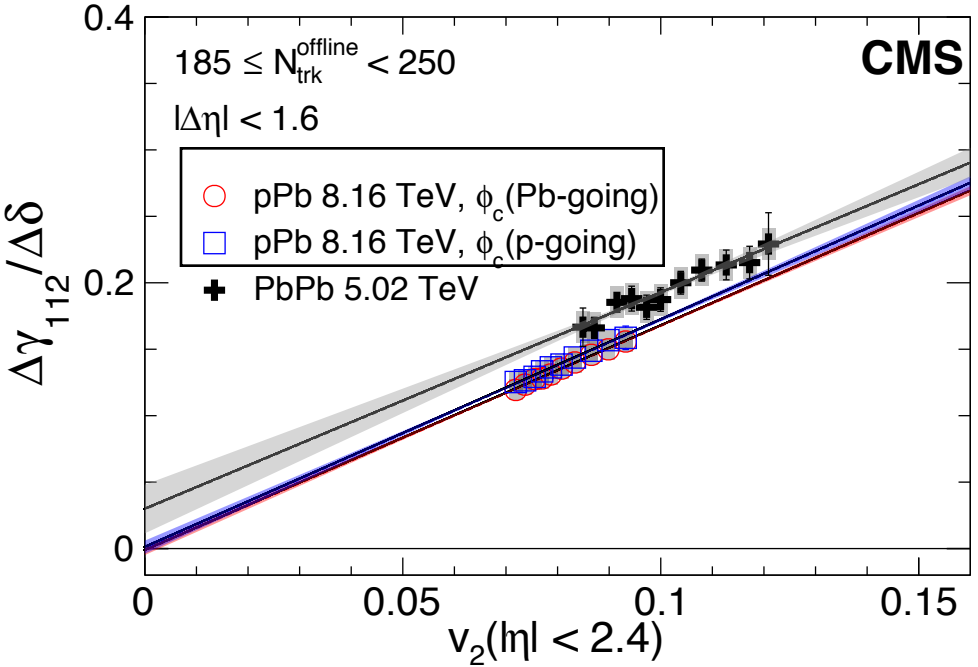
$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$

➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2$$

→ Goes thru ZERO! ✓





arXiv:1708.01602

Results: ESE

pPb vs PbPb

- Background-only scenario:

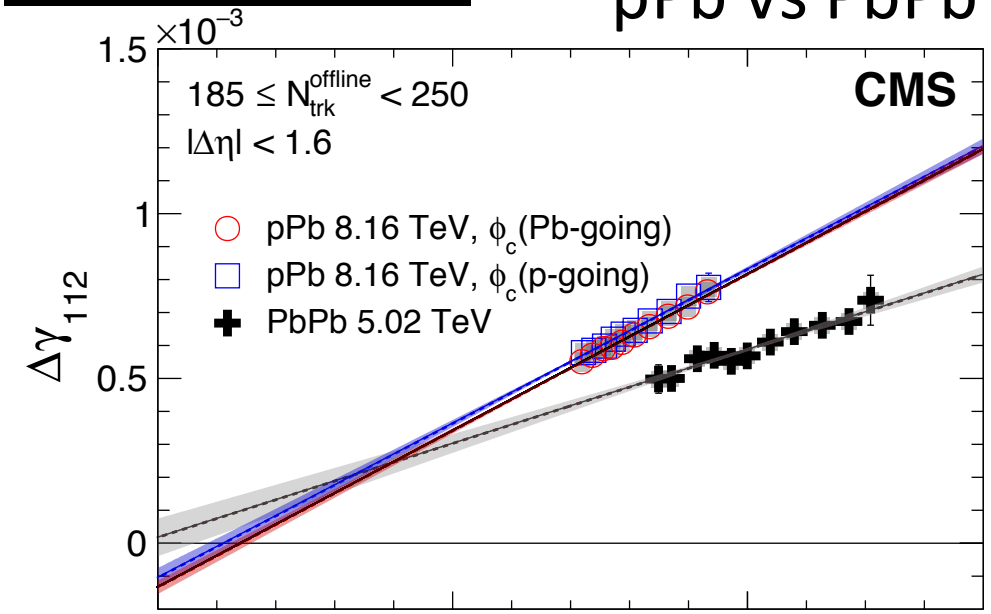
$$\Delta\gamma_{112} = \kappa_2 \cdot v_2 \cdot \Delta\delta$$

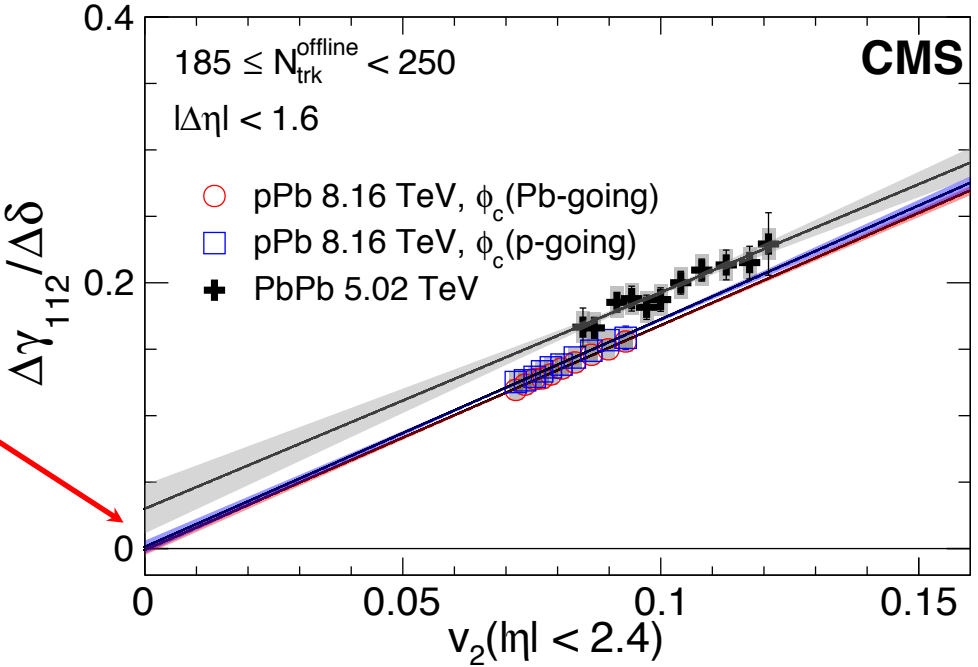
➡

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2$$

→ Goes thru ZERO! ✓

- The remaining intercept can be quantitatively constrained with uncertainty



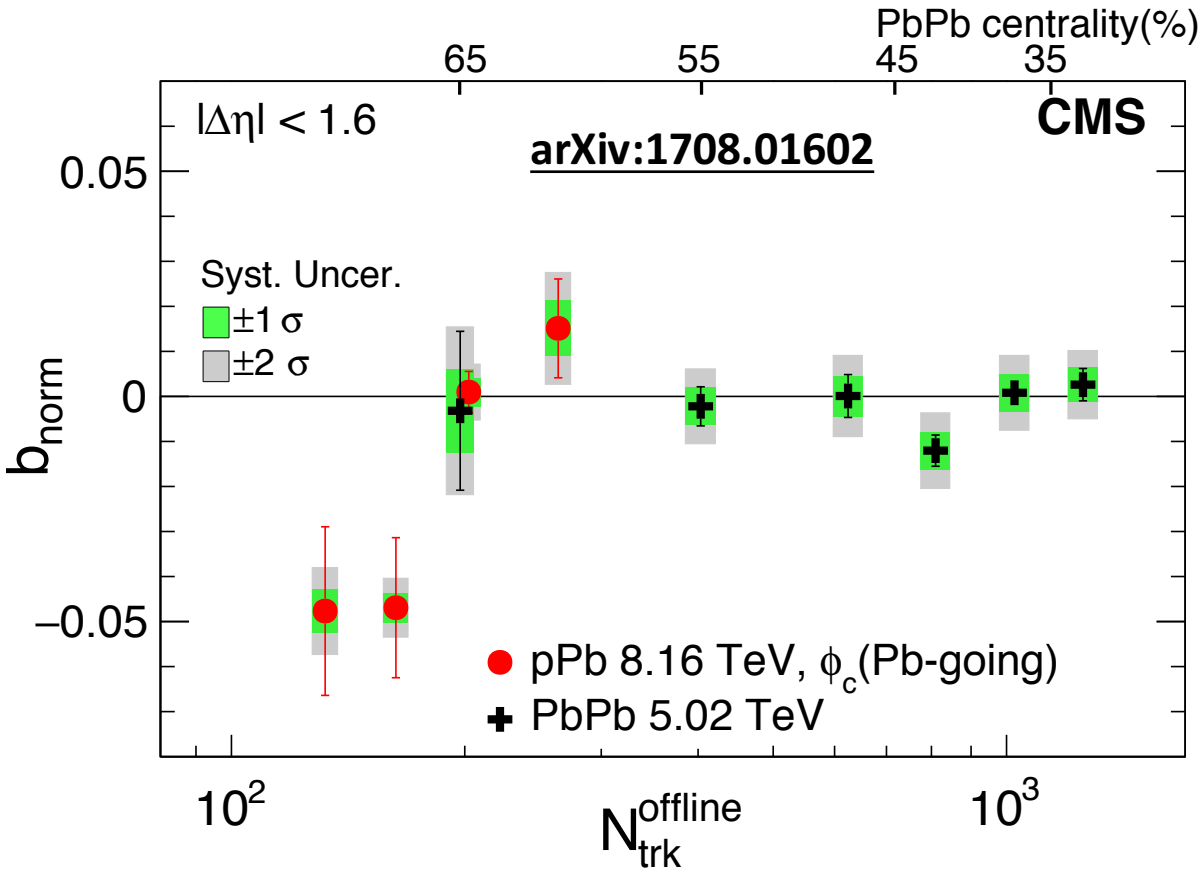


arXiv:1708.01602

Results: ESE

- Normalized intercept vs multiplicity:

$$\Delta\gamma_{112}/\Delta\delta = \kappa_2 \cdot v_2 - \mathrm{b}/\Delta\delta \quad (\mathrm{b_{norm}})$$



No significant positive intercept!

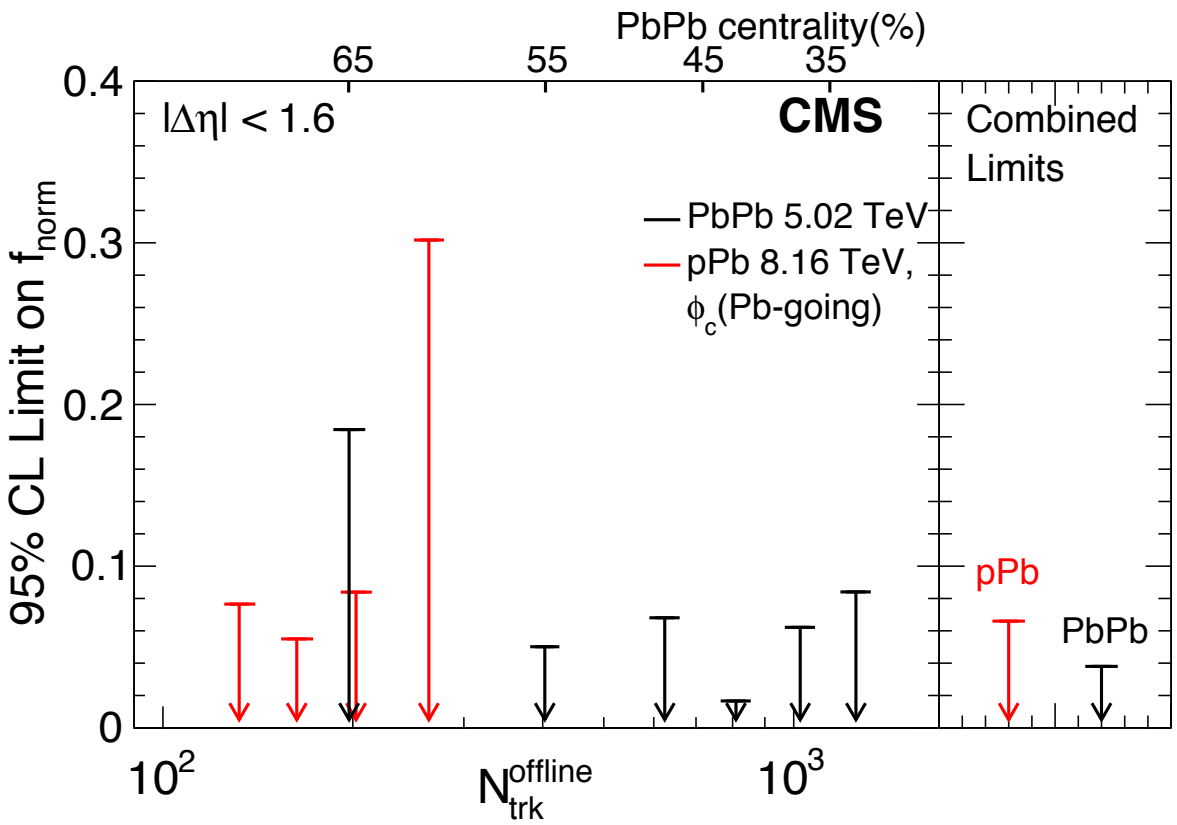
Results: ESE

$f_{norm} = b_{norm} / (\Delta\gamma_{112}/\Delta\delta) \approx b/\Delta\gamma_{112}$ (v2-indep-comp)

Upper limit @ 95% Confidence level

6.6% and **3.8%** for pPb and PbPb, if combined all multiplicities

arXiv:1708.01602



Summary and outlook

❖ Experimental achievements:

- ✓ First time measurement of γ_{123}, and δ in pA collisions
- ✓ First time Event-Shape-Engineering in pA collisions

❖ Major conclusions and implications:

- ✓ γ dominated by background, i.e., $\gamma = \kappa \cdot v_n \cdot \delta$
- ✓ Possible CME signal (at LHC energies) is less than 6.6% for pPb and 3.8% for PbPb collisions @95% CL.

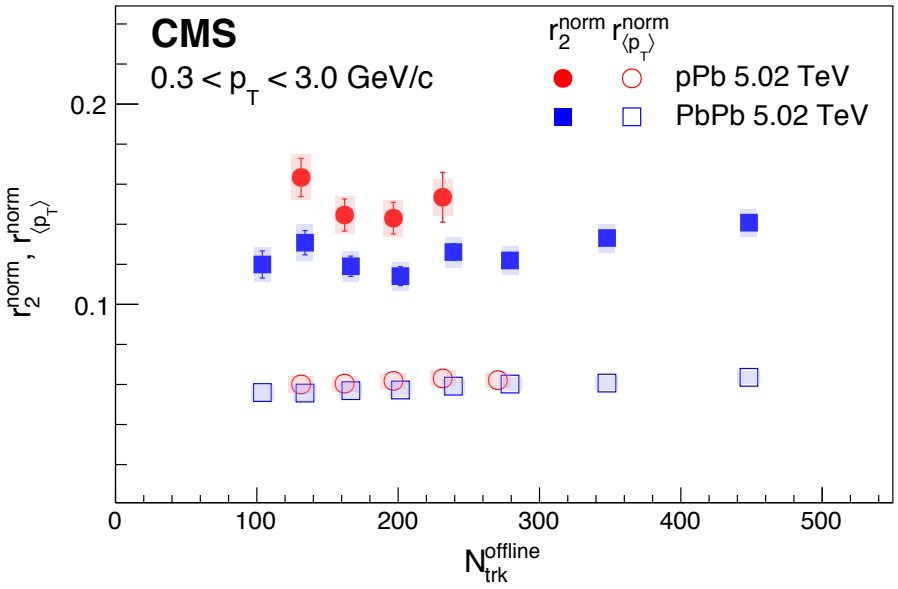
✓ Significant improvement on constraining the CME signal.

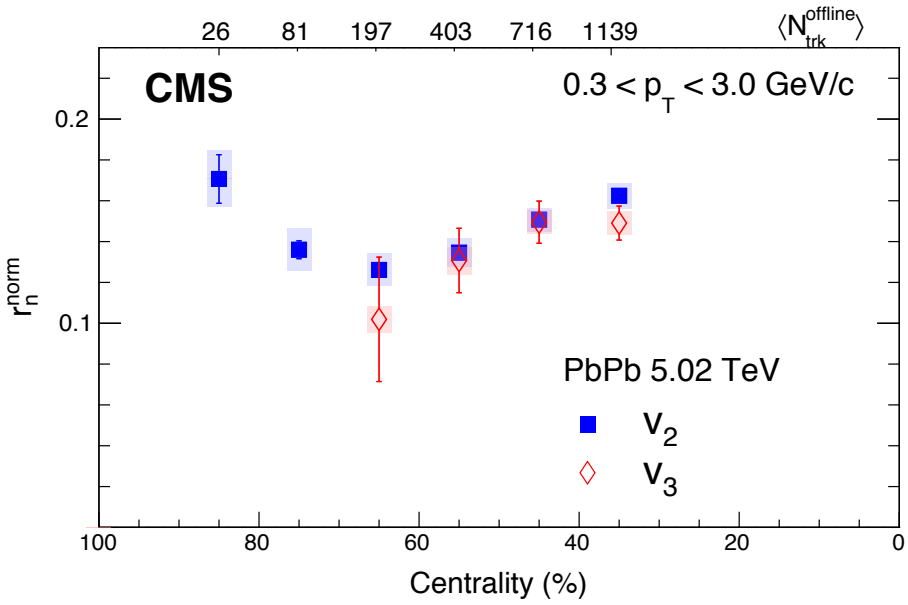
Provide more insights for lower energy CME search

New results on CMW

Shown in QM17

Submitted to PRL and arXiv:1708.08901

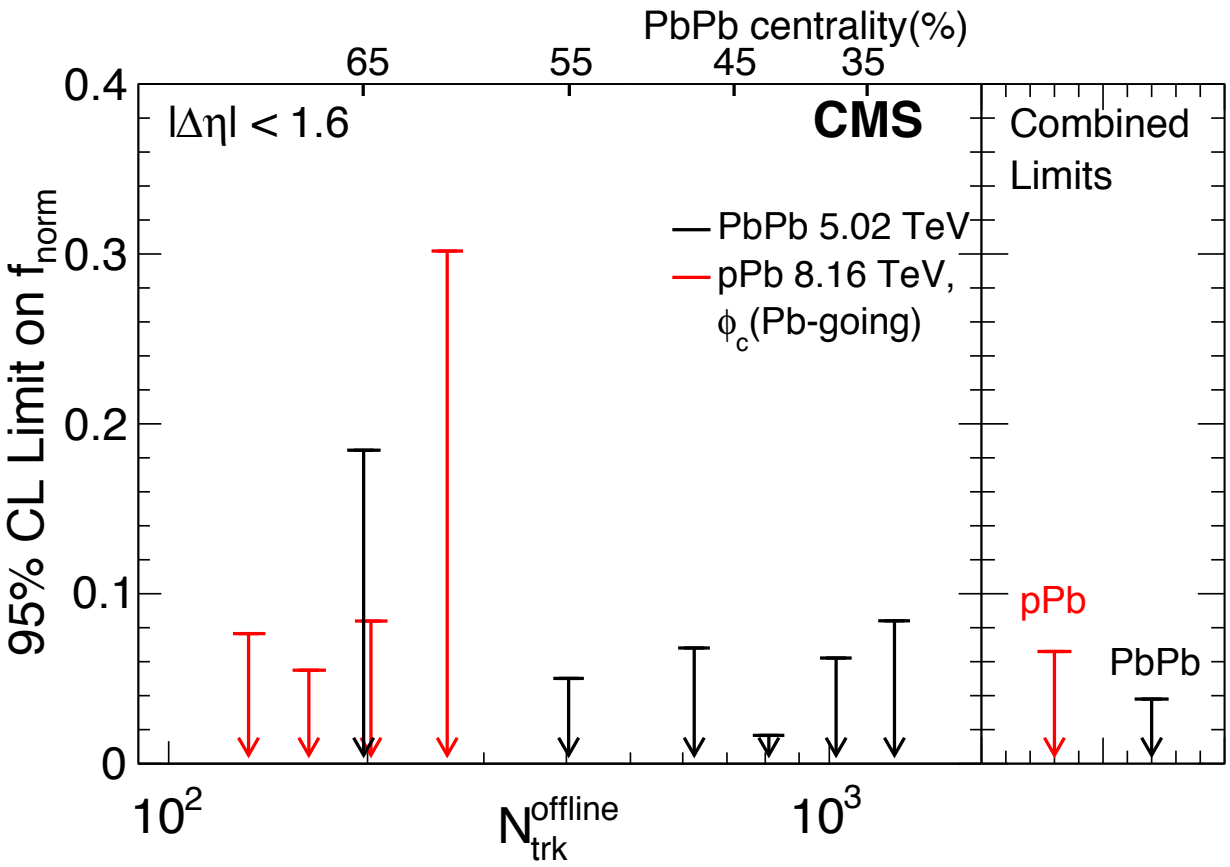




- pPb shows significant slope parameters btw v2 and charge asymmetry
- In PbPb collisions, v2 and v3 show identical slope parameters

Challenges to the Chiral Magnetic Wave interpretations

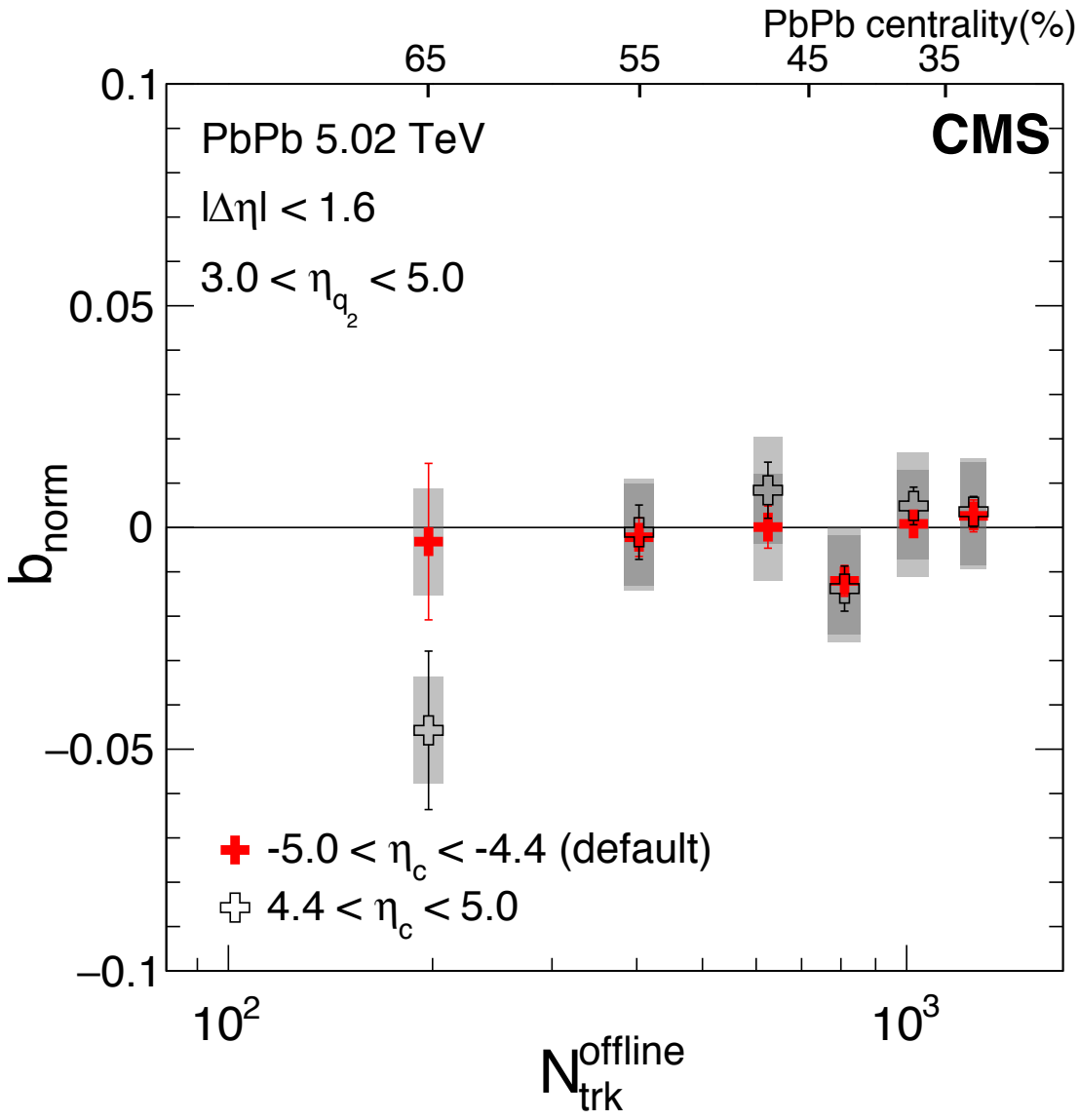
Thank you!



arXiv:1708.01602

Backup

arXiv:1708.01602



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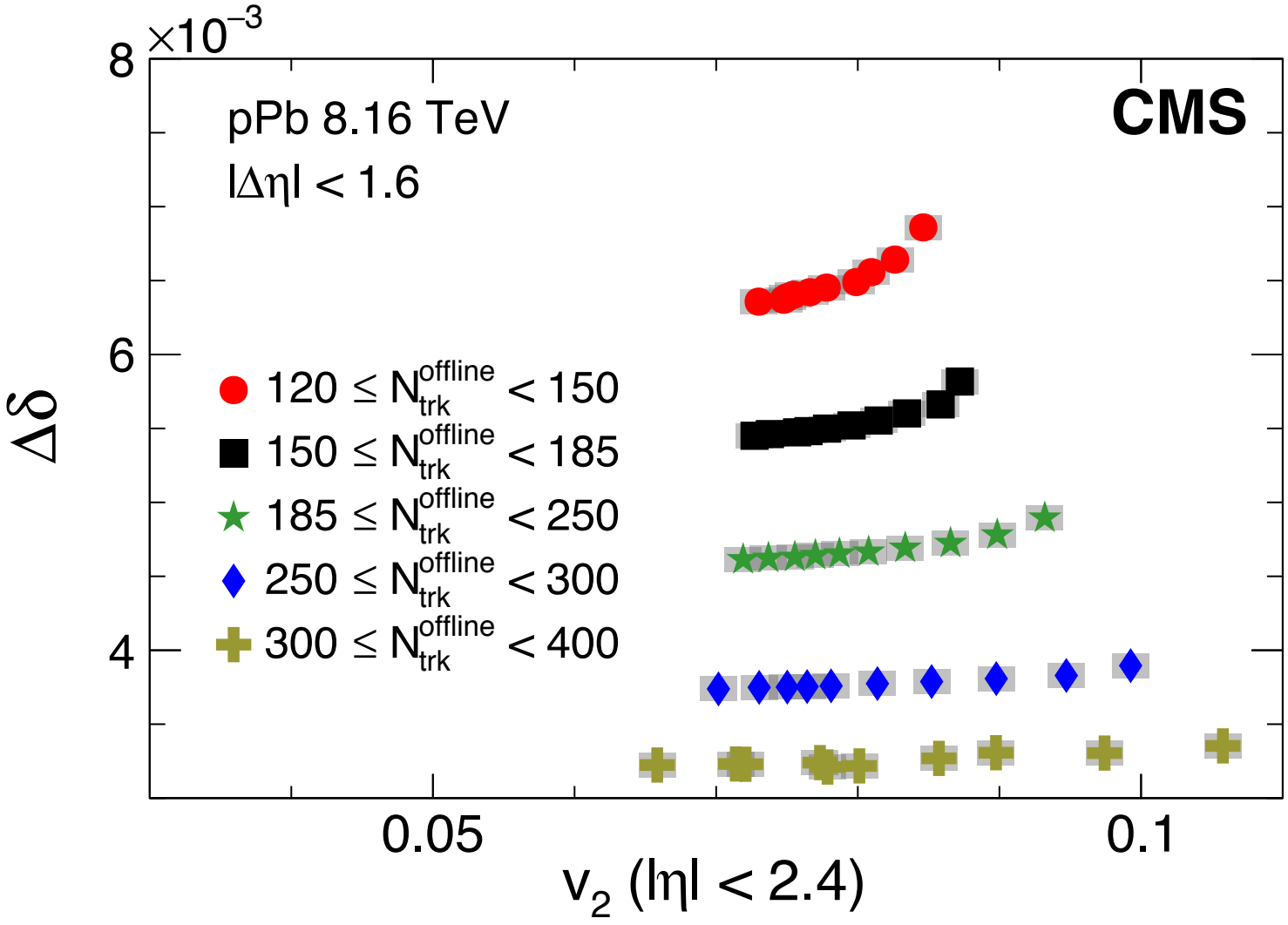
arXiv:1708.01602



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arXiv:1708.01602

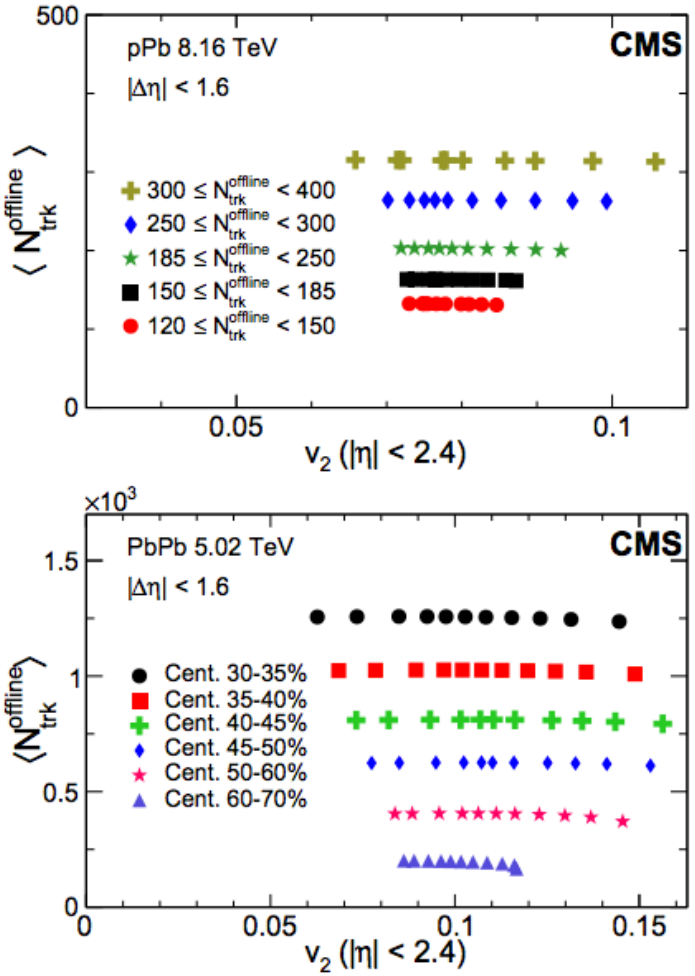
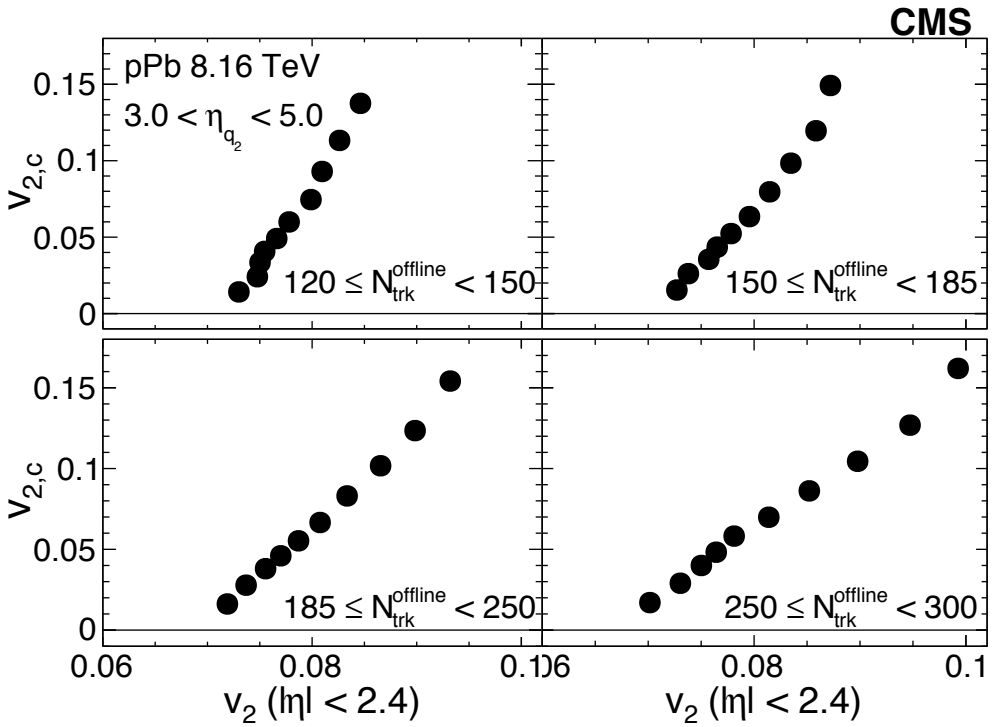
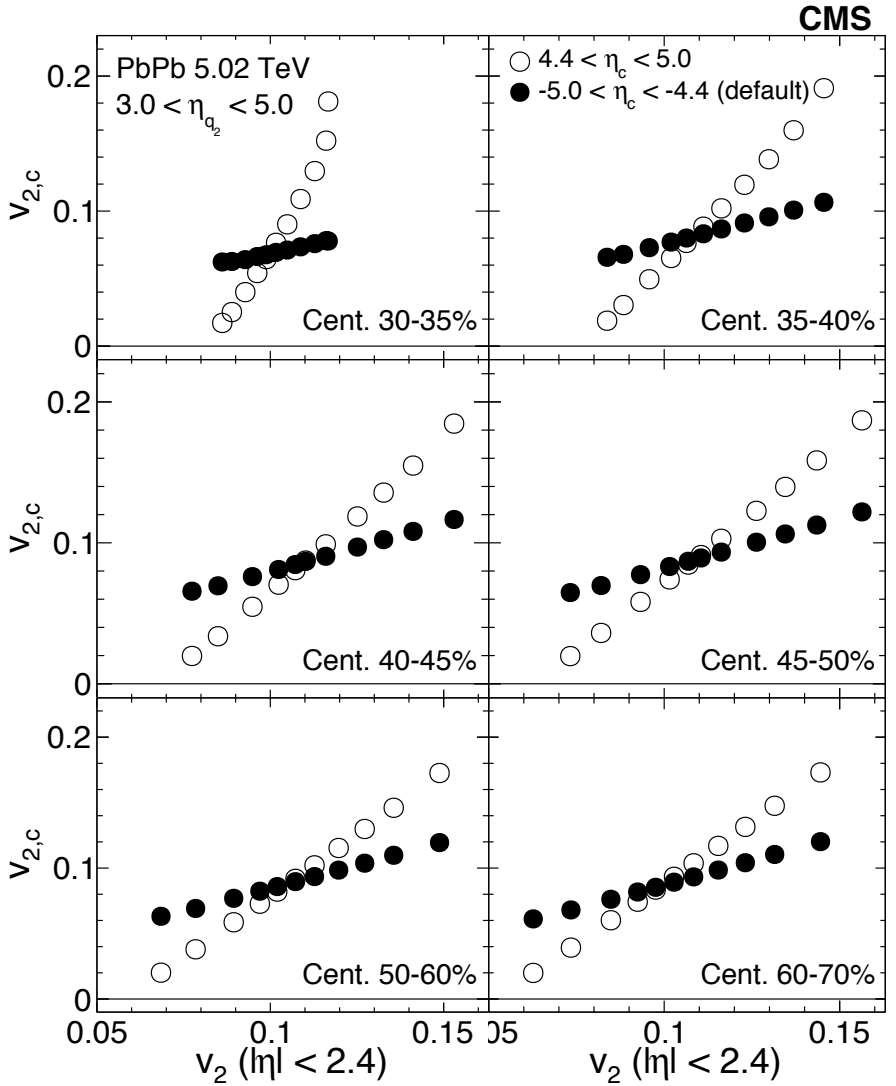


Figure 19: The average multiplicity $N_{trk}^{offline}$ as a function of v_2 evaluated in each q_2 class, for different multiplicity ranges in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV (upper), and for different centrality classes in PbPb collisions at 5.02 TeV (lower). Statistical uncertainties are invisible on the current scale.

Backup

arXiv:1708.01602





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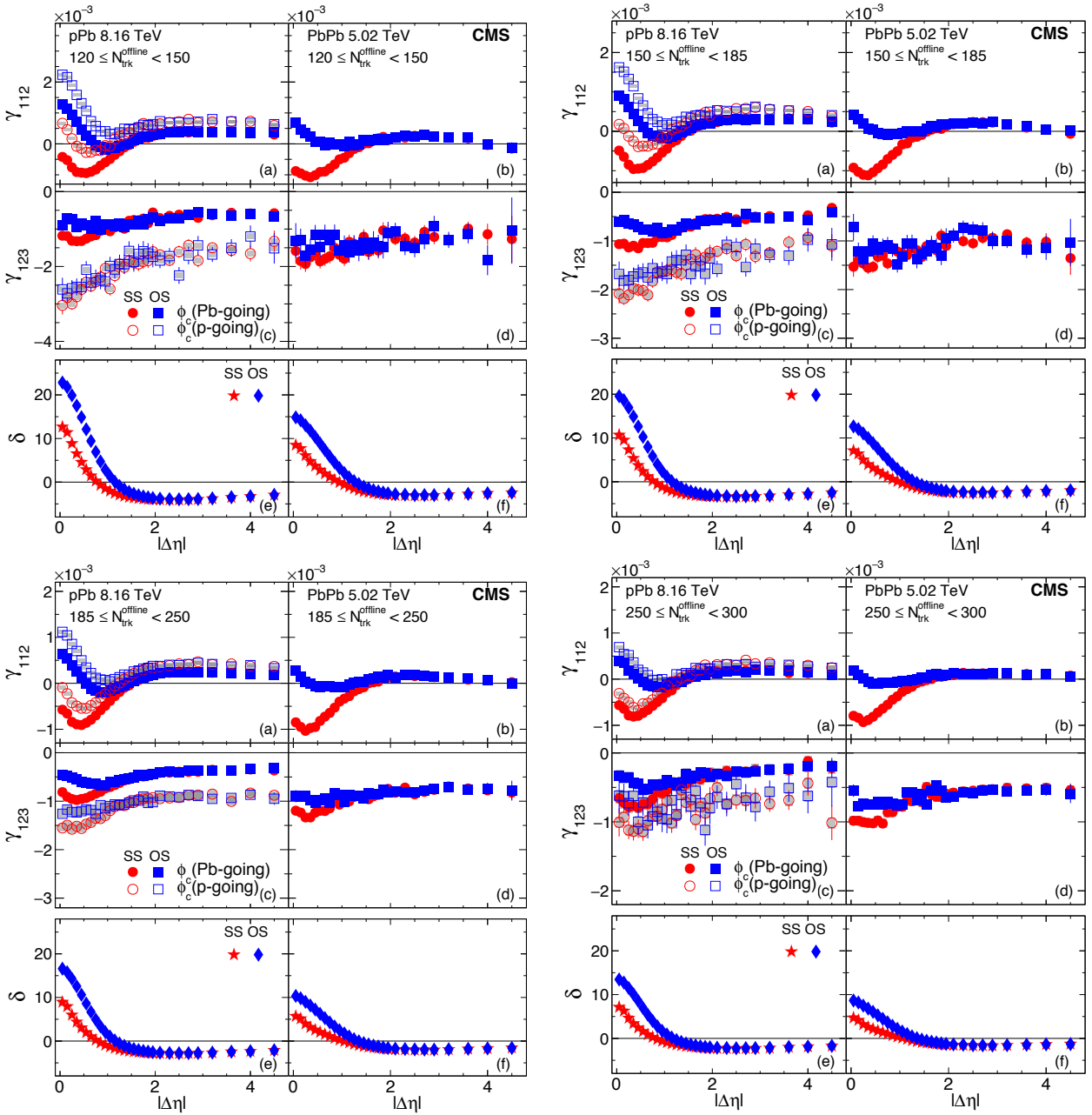
arXiv:1708.01602



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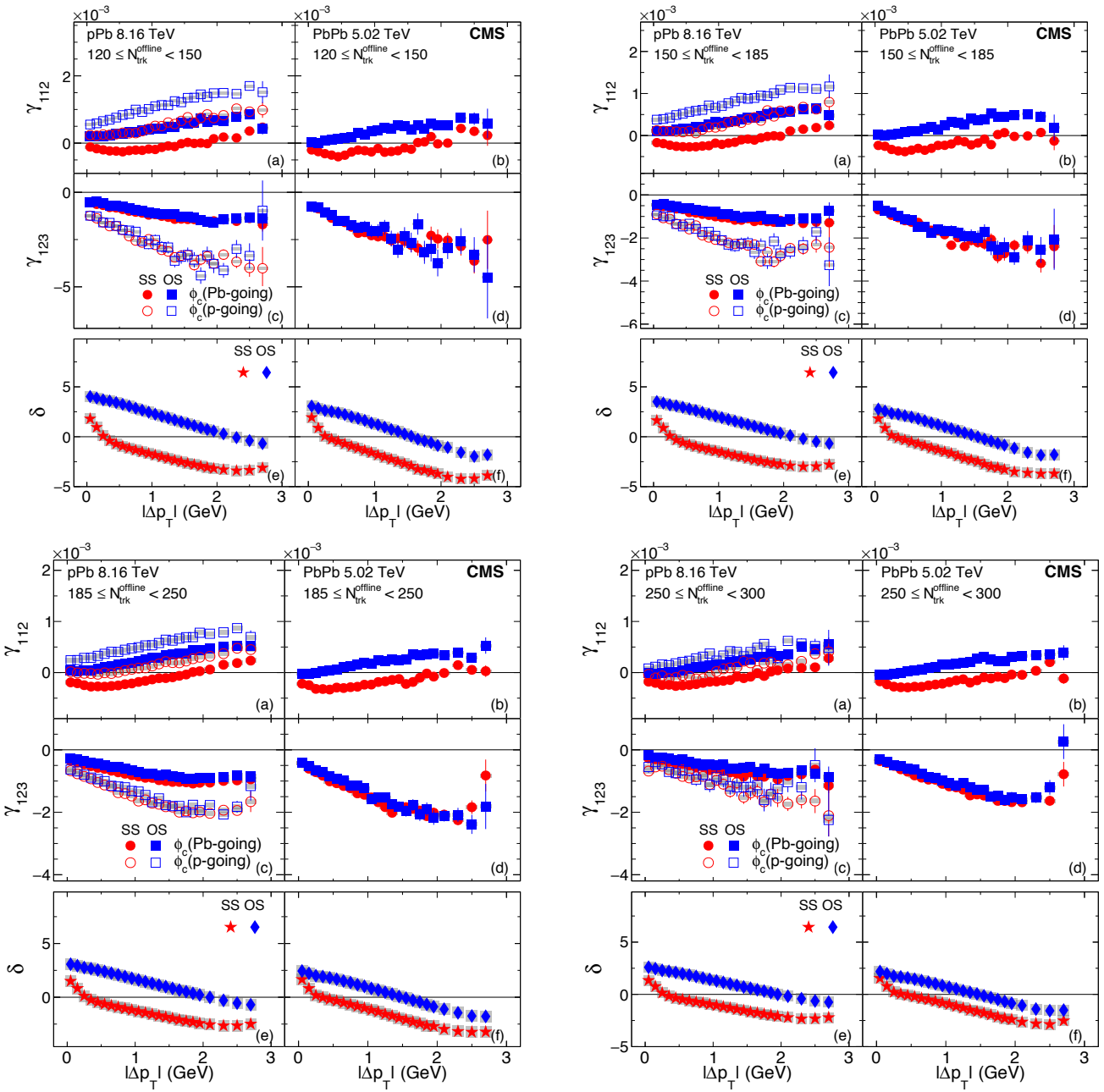
arXiv:1708.01602



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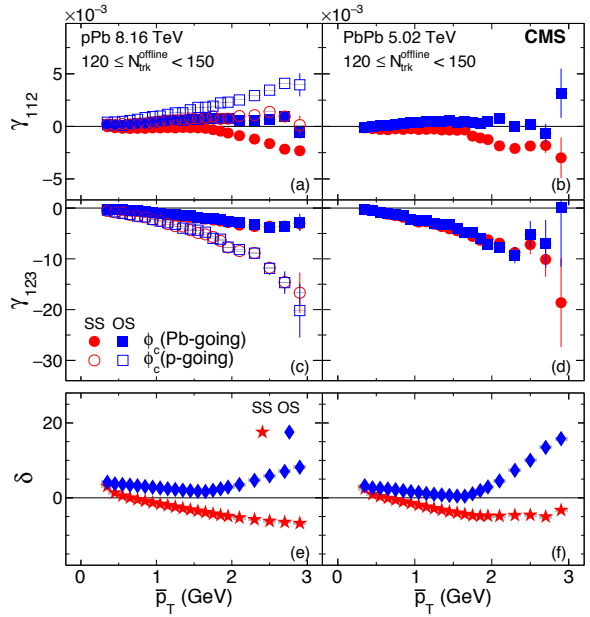
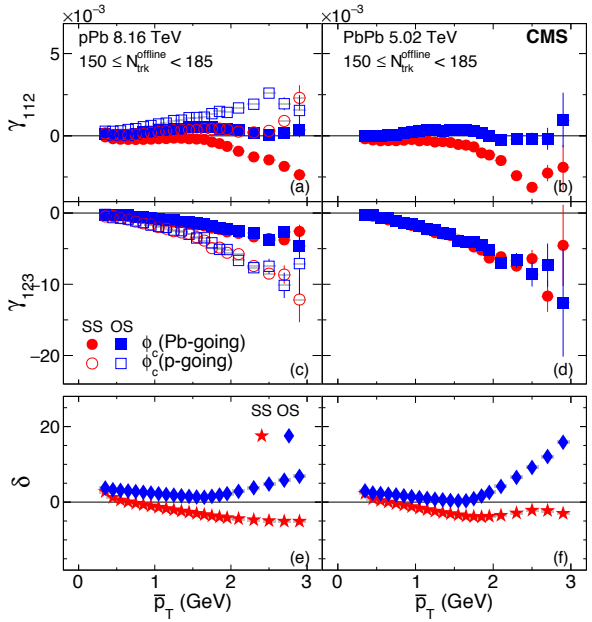
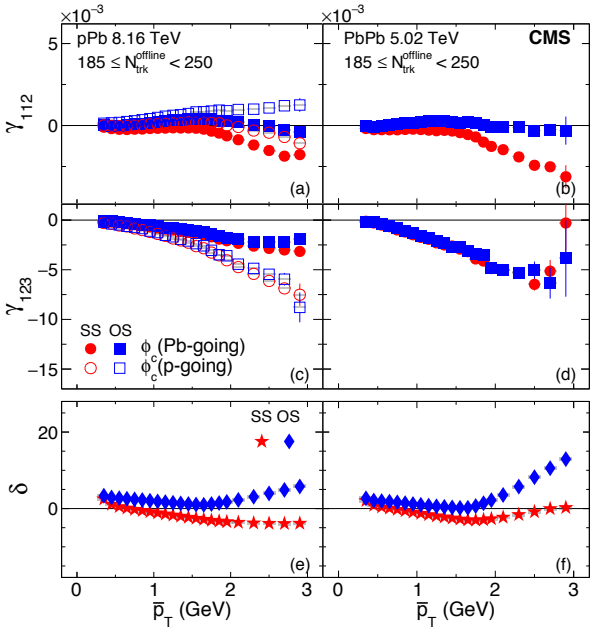
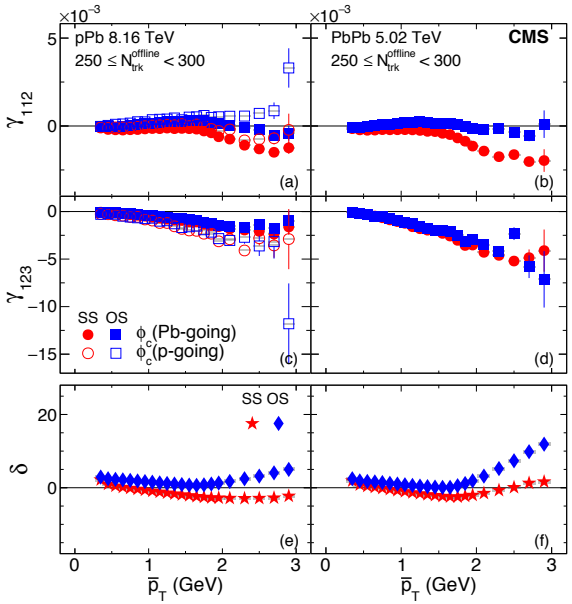
arXiv:1708.01602









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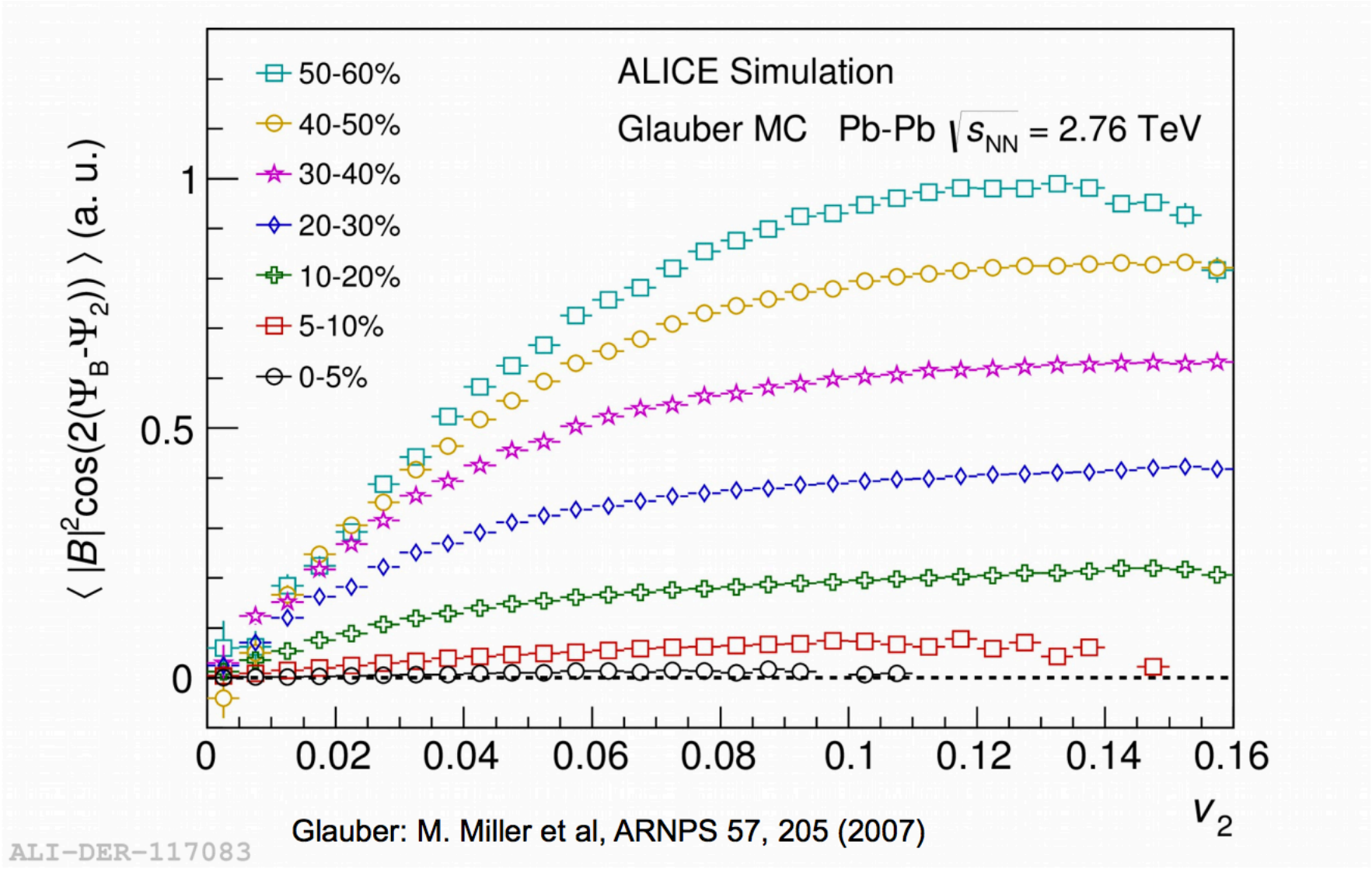
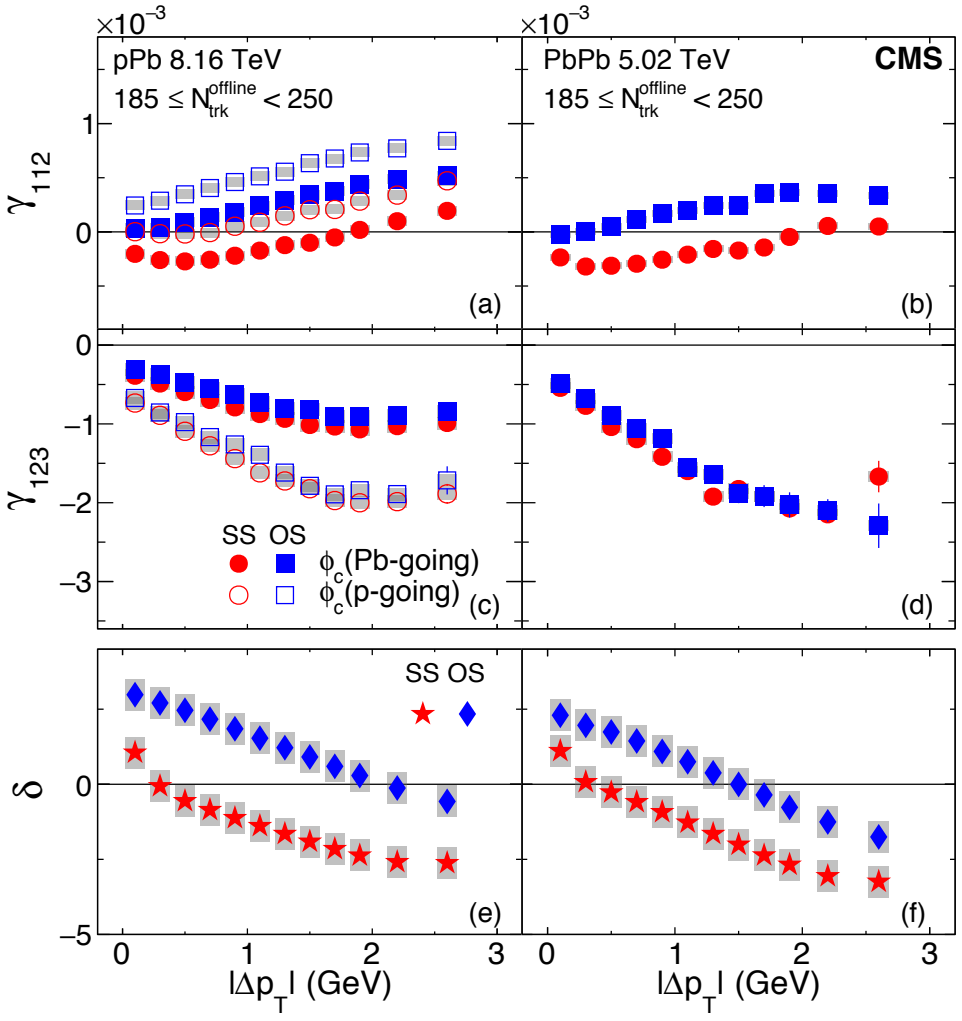

ALICE Simulation
Glauber MC Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
50-60%
40-50%
30-40%
20-30%
10-20%
5-10%
0-5%
$\langle |B|^2 \cos(2(\Psi_B - \Psi_2)) \rangle$ (a. u.)
v_2
0
0.5
1
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Glauber: M. Miller et al, ARNPS 57, 205 (2007)
ALI-DER-117083

Backup

arXiv:1708.01602

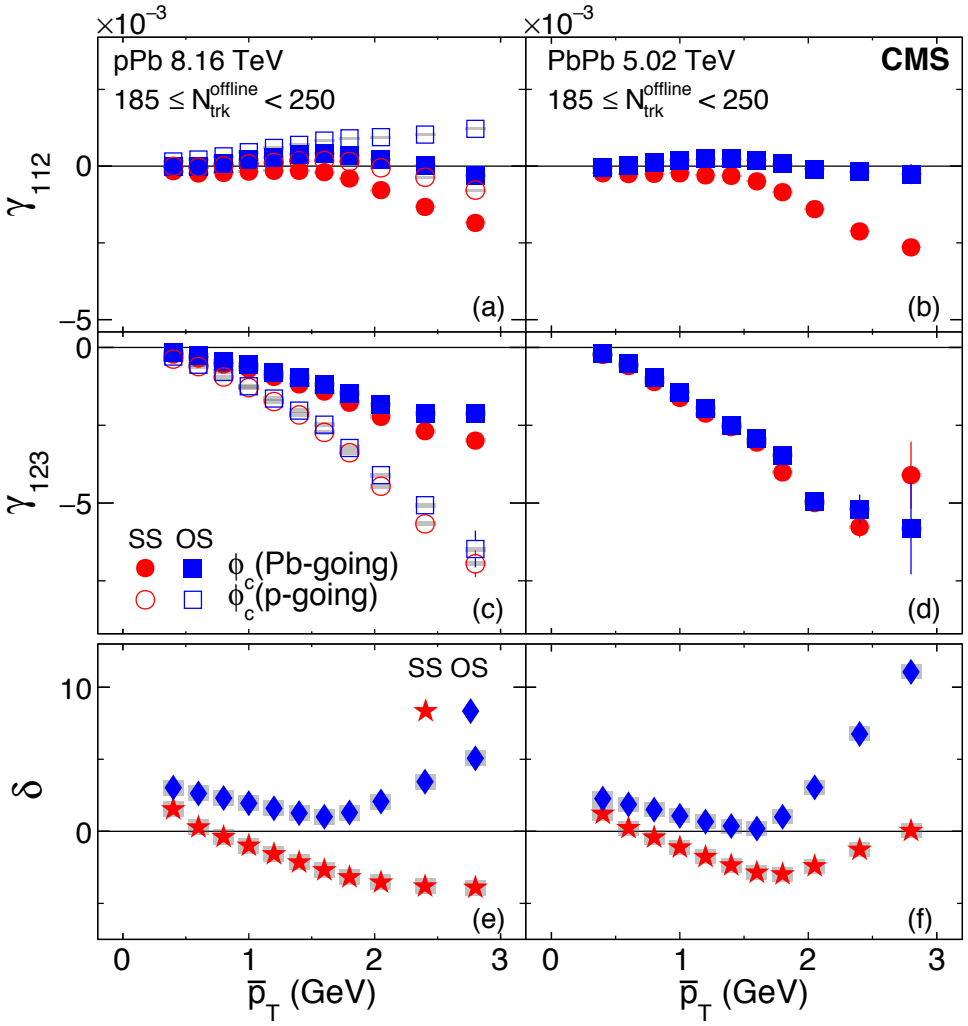
- First time measurement of γ_{123} as function of $|\Delta p_T| \equiv |p_{T,\alpha} - p_{T,\beta}|$
- Similar trend and magnitude observed between pPb and PbPb
- Not only in $|\Delta\eta|$, the similarity extends to $|\Delta p_T|$
- Observation: δ and γ_{123} are different between pPb and PbPb collisions.



Backup

arXiv:1708.01602

- First time measurement of γ_{123} as function of $\bar{p}_T \equiv (p_{T,\alpha} + p_{T,\beta})/2$
- Similar trend and magnitude observed between pPb and PbPb
- δ correlator shows more positive value towards high p_T, indicating jet-like correlation starts to be dominant.

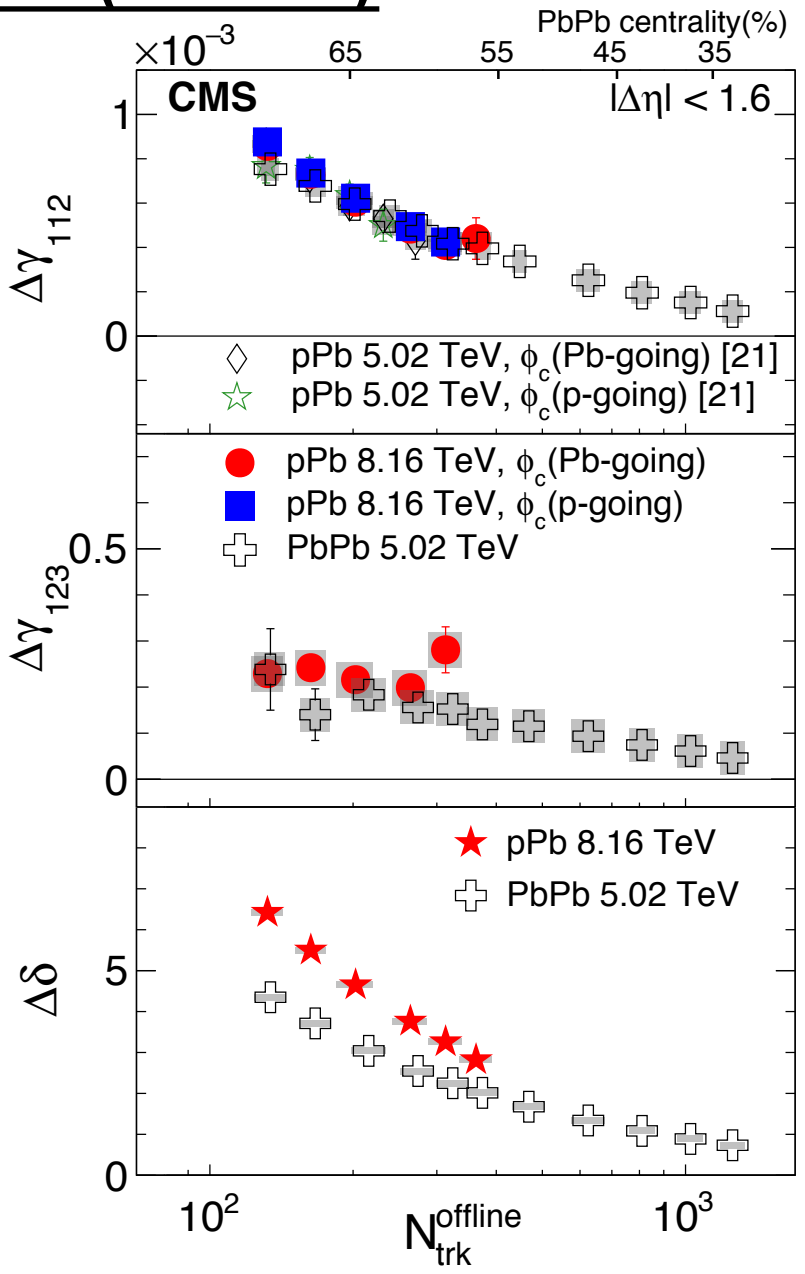


Results: (OS-SS)

arXiv:1708.01602

Δ = OS-SS vs Ntrk

- Is that possible the v2 and δ, these two effects add up to γ_{112}?
- If this is true, can it be compatible with → the 3rd order?
- **Then it should also describe all multiplicity ranges**



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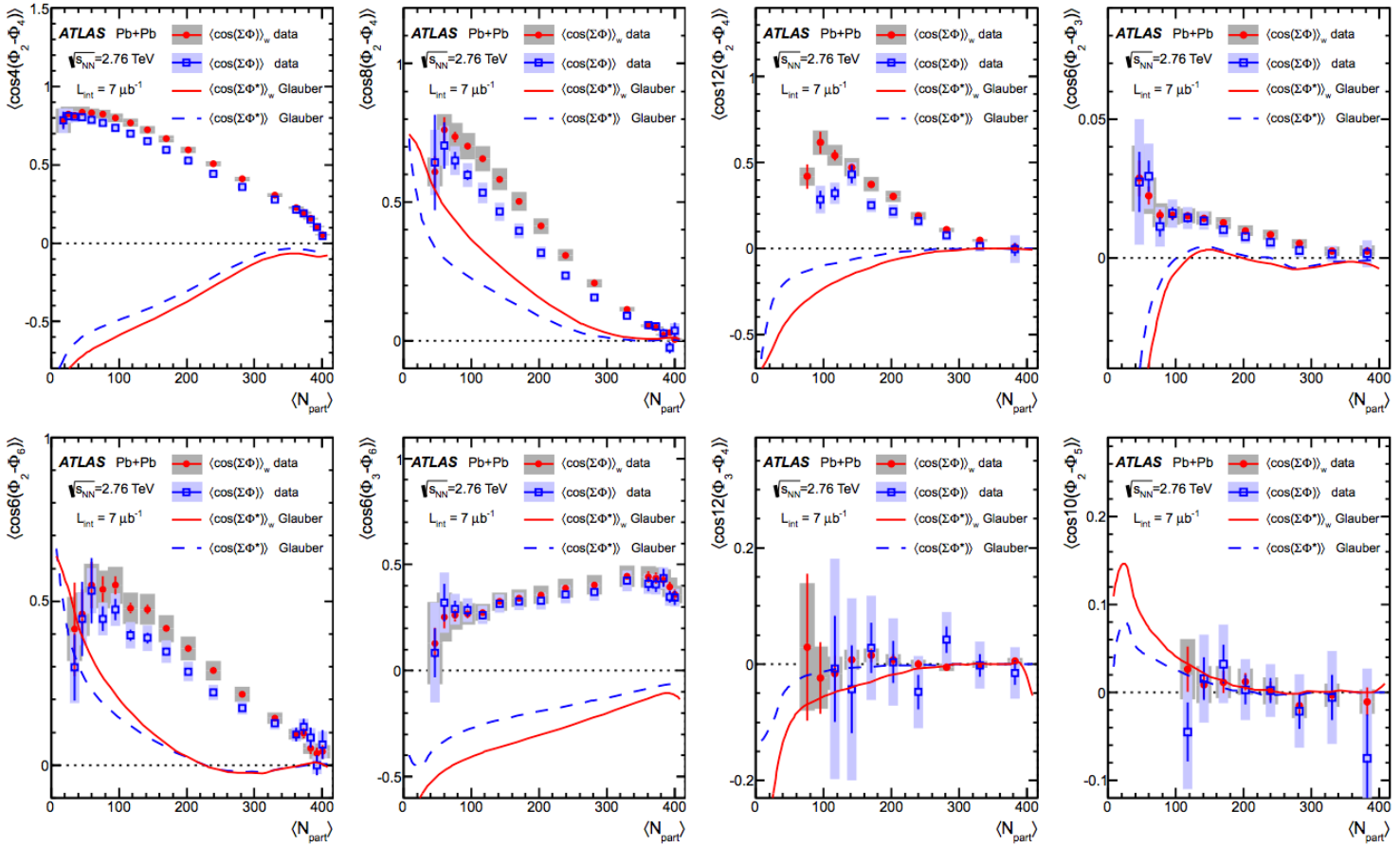
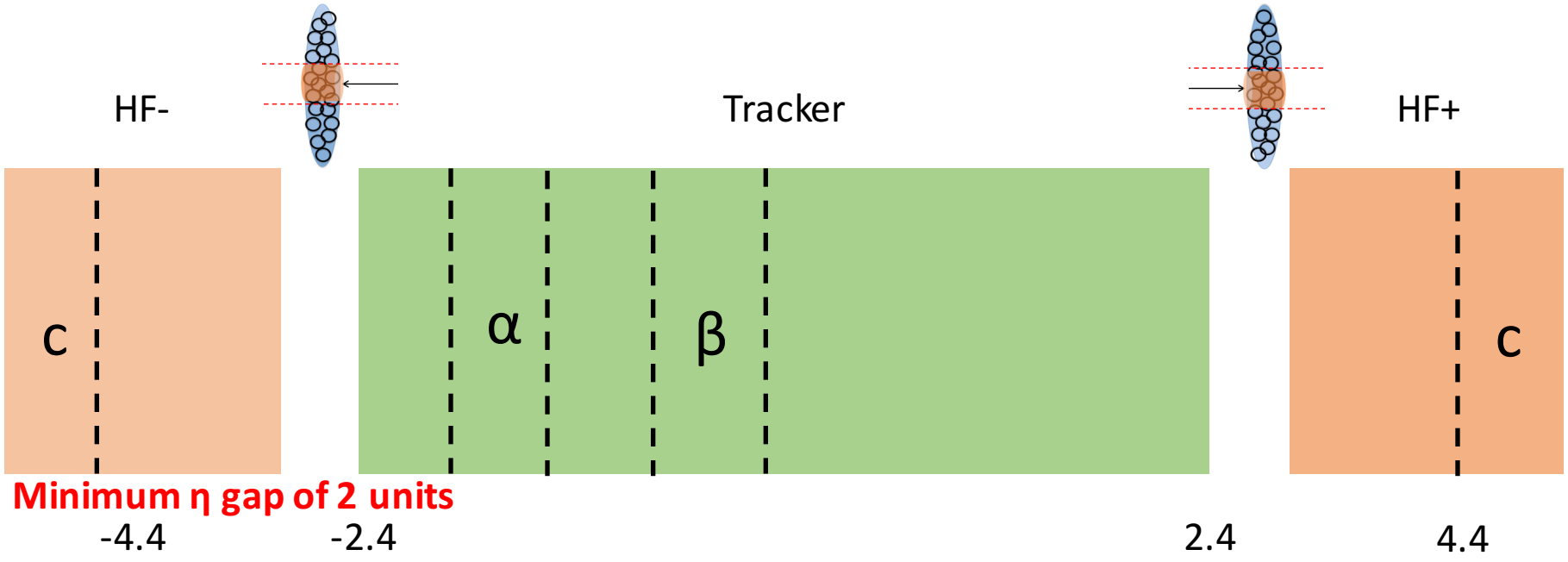


FIG. 6: (Color online) The centrality dependence of eight two-plane correlators, $\langle\cos(\Sigma\Phi)\rangle$ with $\Sigma\Phi = jk(\Phi_n - \Phi_m)$ obtained via the SP method (solid symbols) and the EP method (open symbols). The middle two panels in the top row have $j = 2$ and $j = 3$, respectively, while all other panels have $j = 1$. The error bars and shaded bands indicate the statistical uncertainties and total systematic uncertainties, respectively. The expected correlations among participant-plane angles Φ_n^* from a Glauber model are indicated by the solid curves for weighted case (Eq. (11)) and dashed lines for the unweighted case.

Measurement with CMS detectors



- γ_{112} is γ, measured in the same way as before: Phys.Rev.Lett. 118 (2017) no.12, 122301

$$\gamma_{112} = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{EP}\right)\right\rangle \cong \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\phi_c\right)\right\rangle / v_{2,c}$$

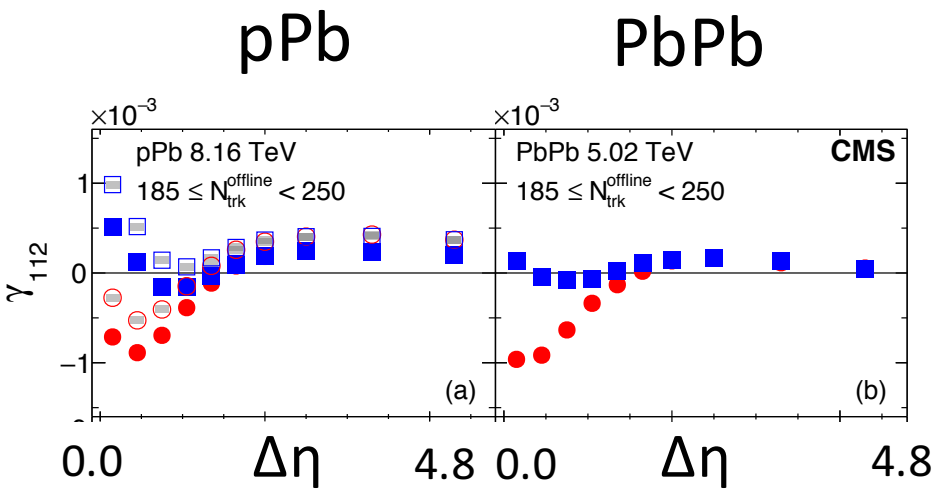
- Similarly, $\gamma_{123} = \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right)\right\rangle \cong \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\phi_c\right)\right\rangle / v_{3,c}$ $\quad \delta \equiv \left\langle \cos\left(\phi_\alpha - \phi_\beta\right)\right\rangle$

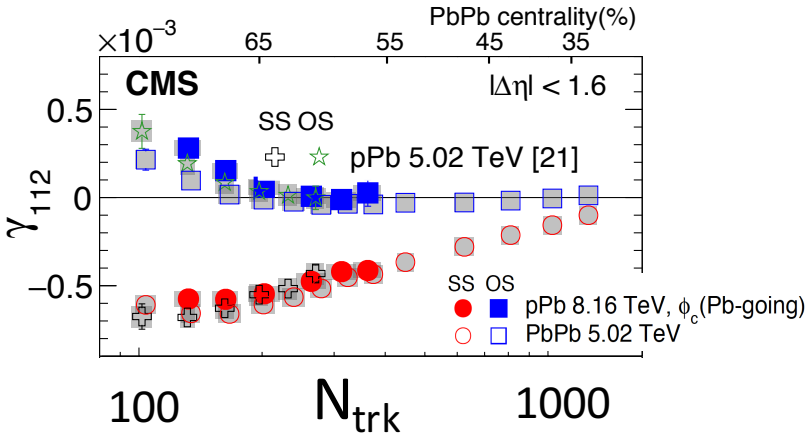
- Large gap between particle α,β and c, to reduce short range correlation. Valid for factorization.

arXiv:1708.01602

Results: OS and SS

Similar data is seen btw 8 and 5 TeV pPb

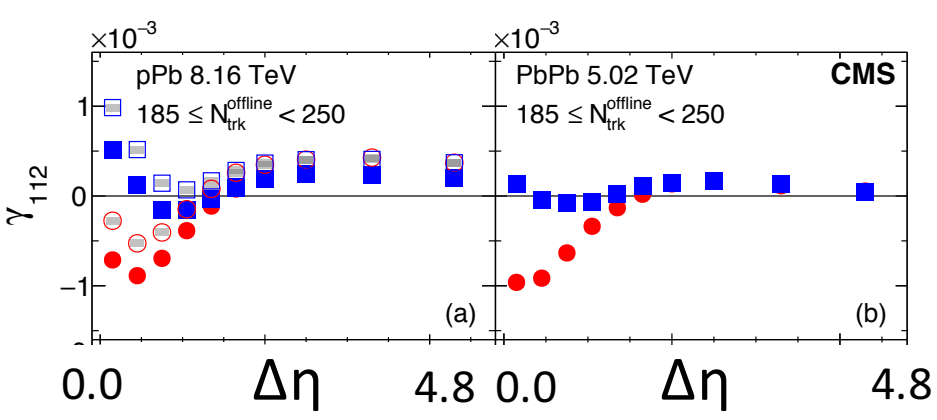


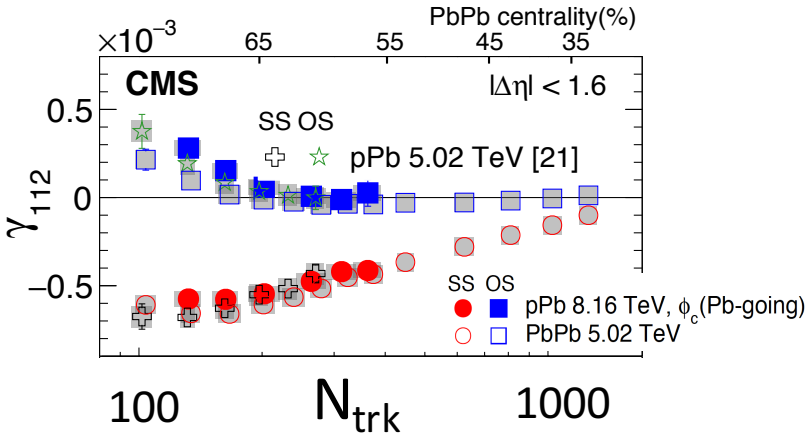


arXiv:1708.01602

Results: OS and SS

Similar data is seen btw 8 and 5 TeV pPb





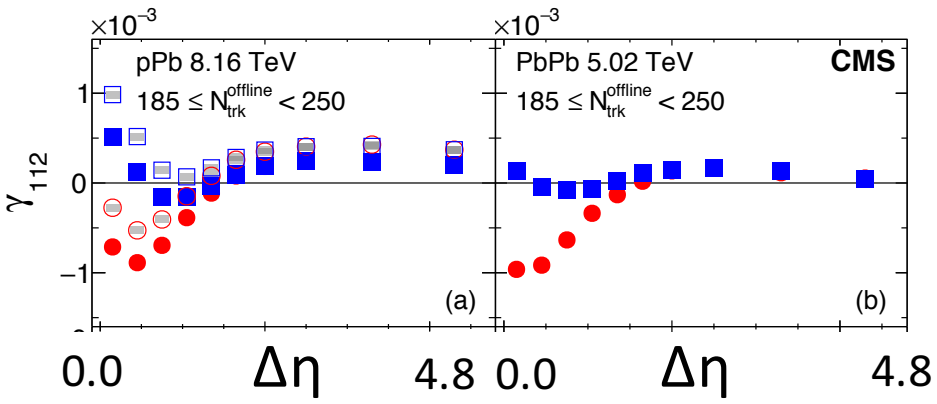
❖ **Why is γ_{112} pPb and PbPb so similar?**

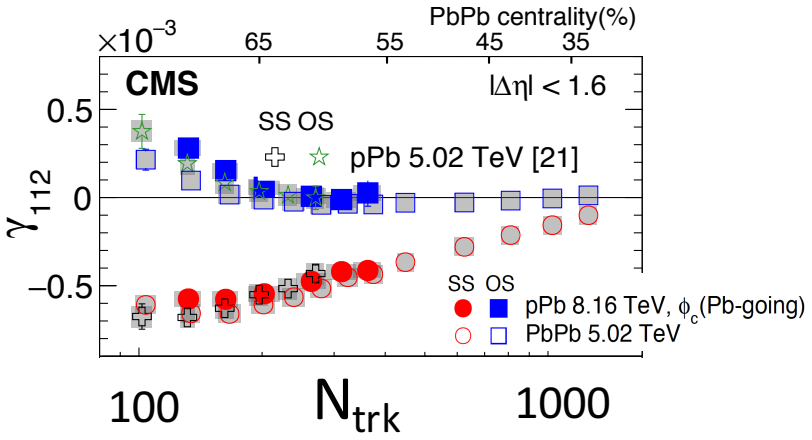
arXiv:1708.01602

Results: OS and SS

Similar data is seen btw 8 and 5 TeV pPb

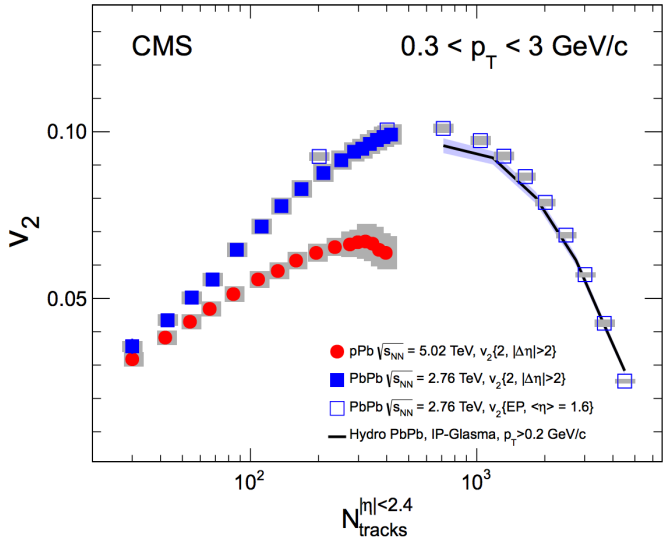
pPb PbPb





❖ **Why is γ_{112} pPb and PbPb so similar?**

V_2 (pPb) < V_2 (PbPb)



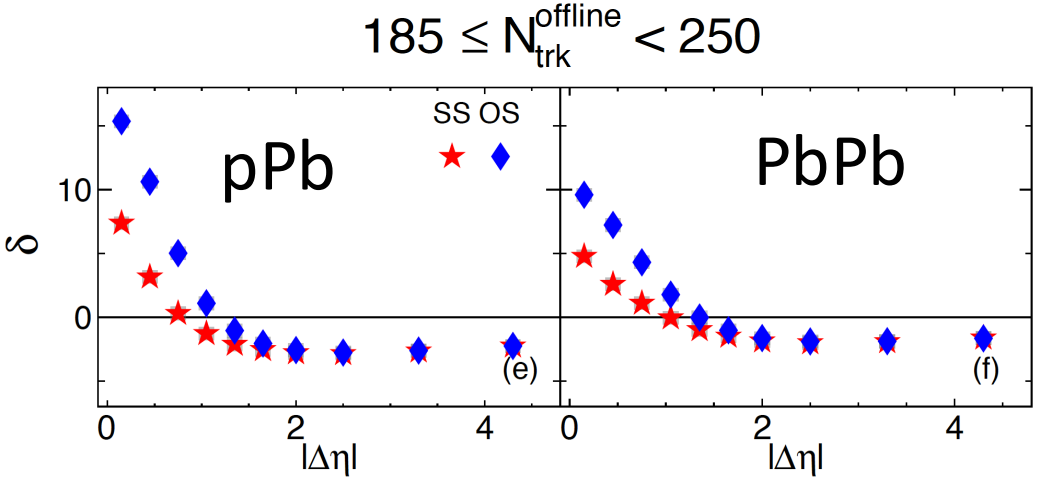
BKG scenario:

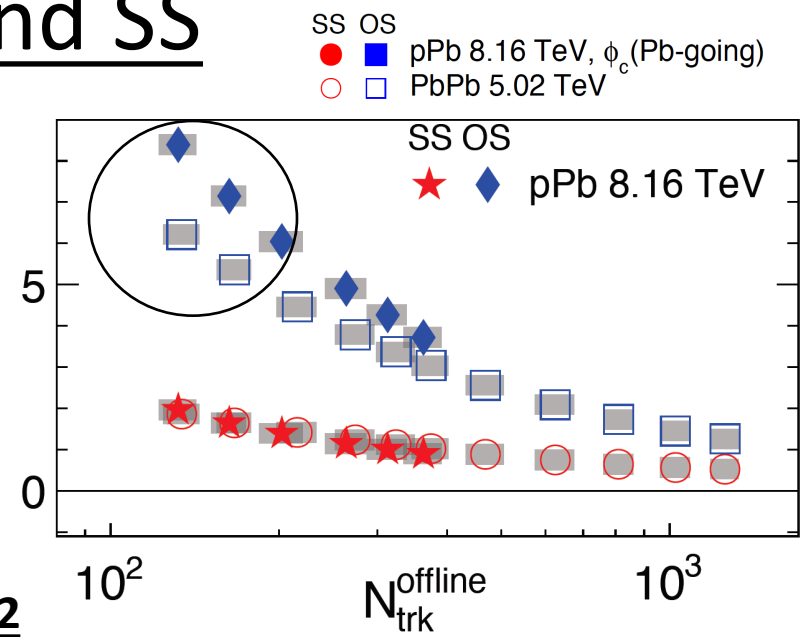
$$\gamma_{112} = \kappa \cdot v_2 \cdot \delta$$

How about δ btw pPb and PbPb?

$\gamma_{112} = \kappa \cdot v_2 \cdot \delta$

Results: OS and SS



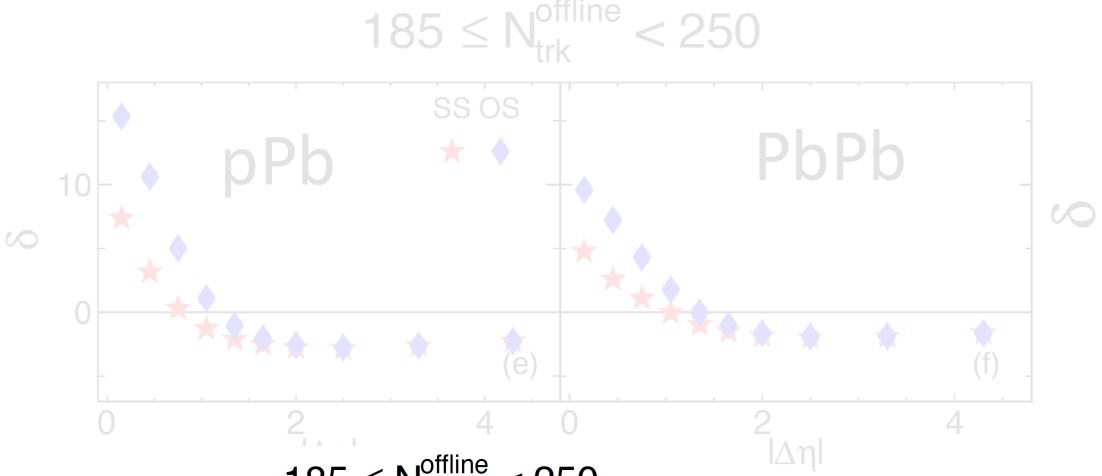


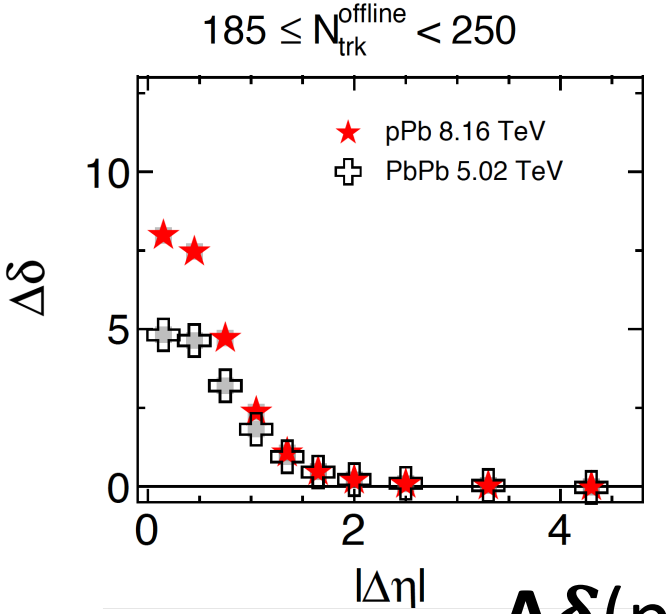
arXiv:1708.01602

$\gamma_{112} = \kappa \cdot v_2 \cdot \delta$

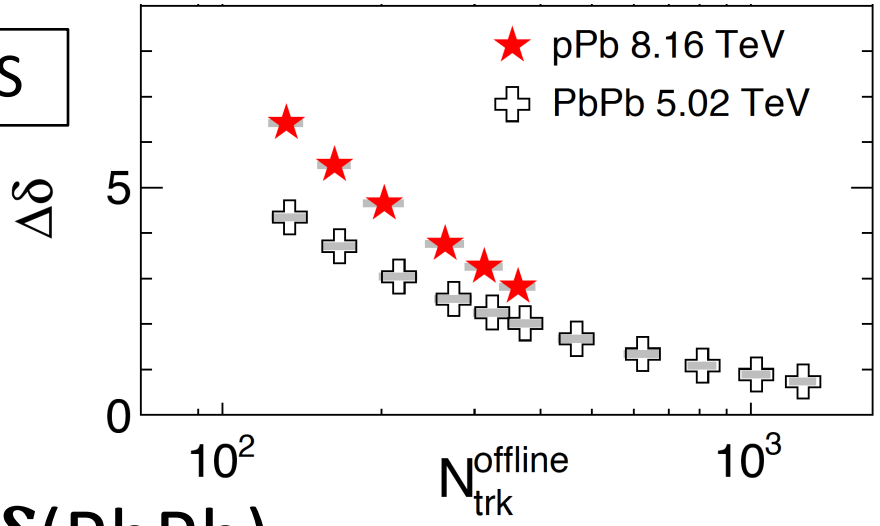
Results: (OS-SS)

arXiv:1708.01602





Δ = OS-SS



Δδ(pPb) > Δδ(PbPb)

Δ = OS-SS

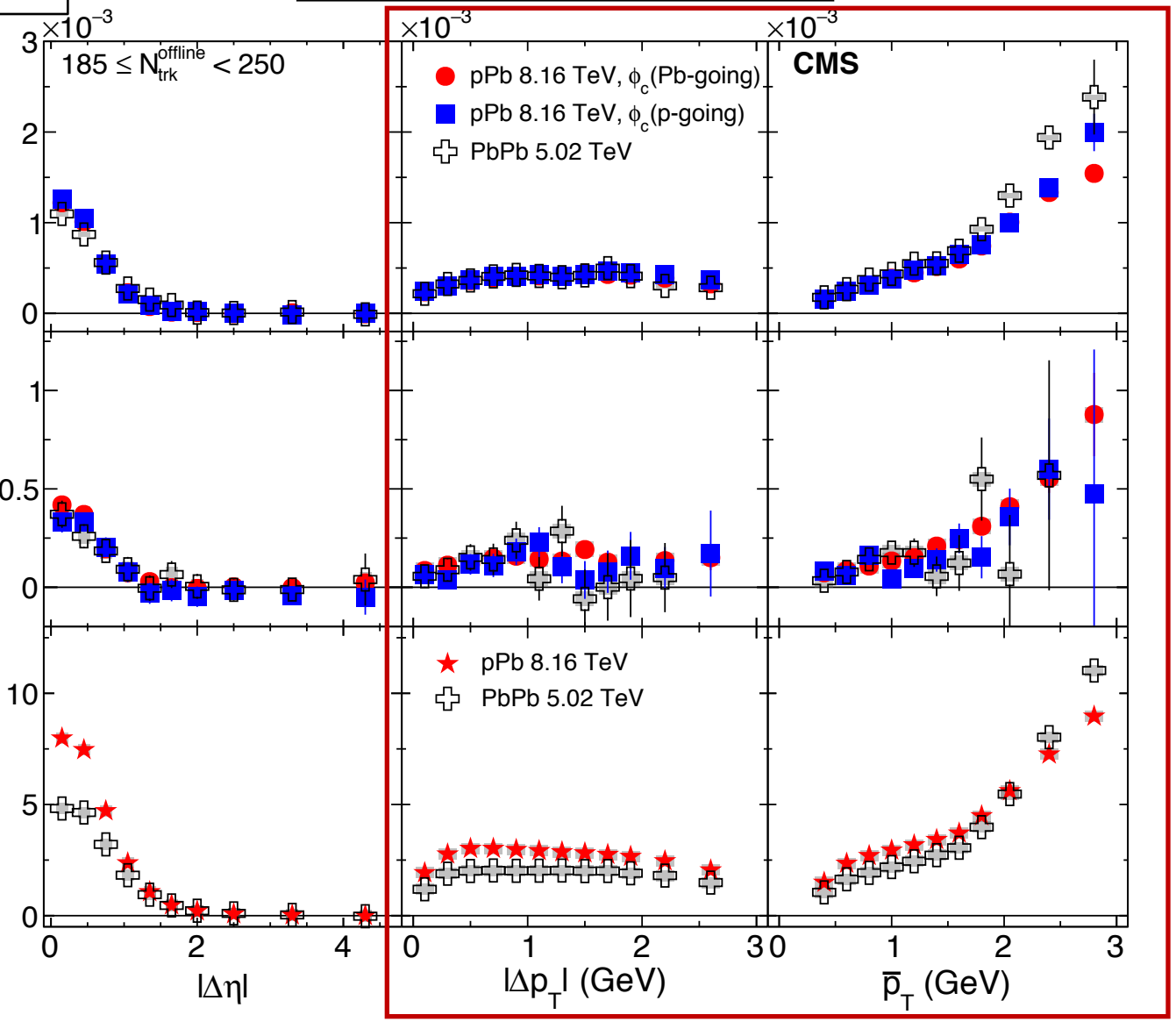
Results: (OS-SS)

arXiv:1708.01602

$\Delta\gamma_{112}$

$\Delta\gamma_{123}$

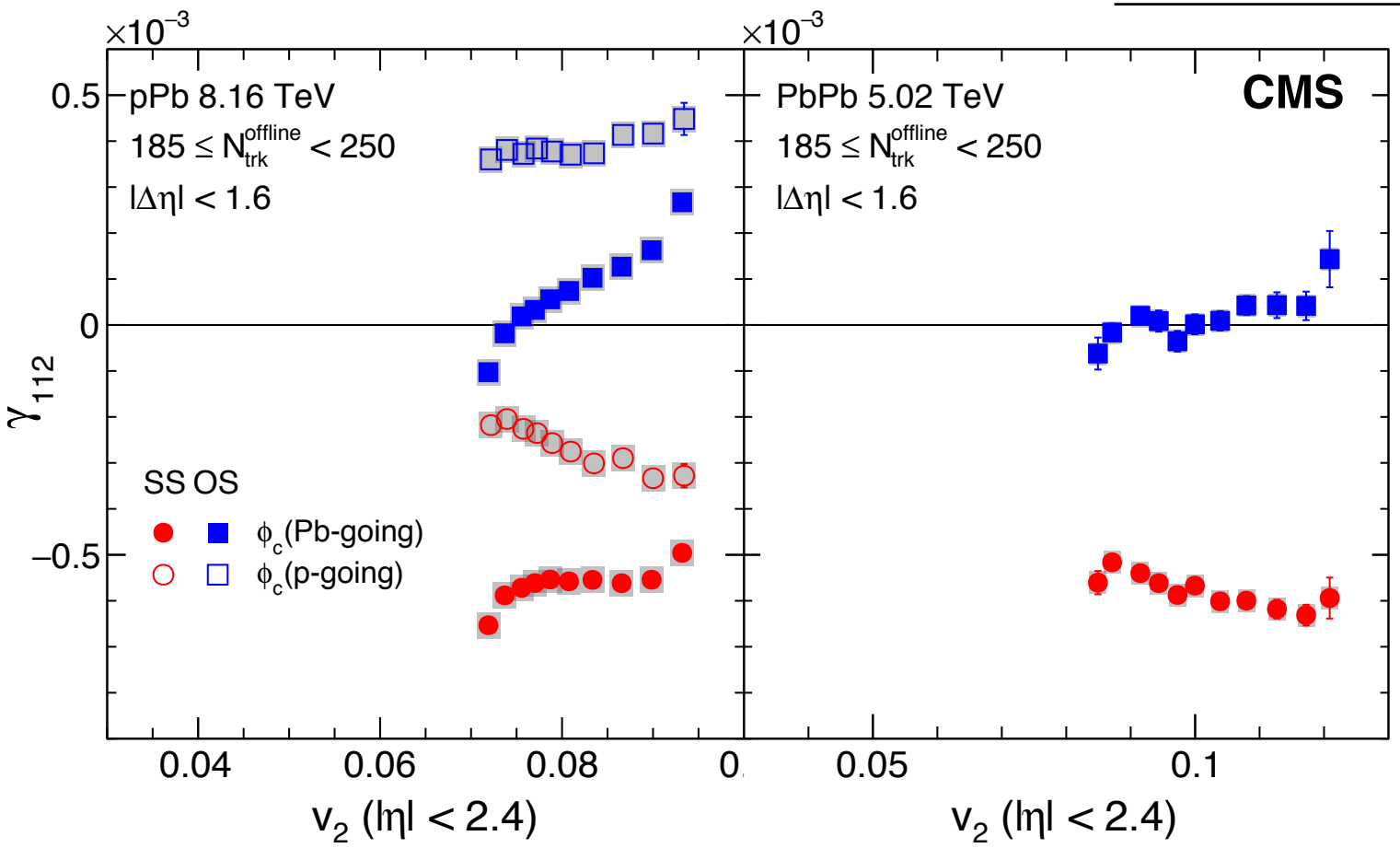
$\Delta\delta$



❖ **Suspected BKG should also describe other differential variables**

Results: ESE

arXiv:1708.01602



- Nontrivial to interpret the data, due to mixture of charge-(in)dependent correlations.

- How about the difference OS-SS?