# Initial-state fluctuations and factorization breaking in Pb-Pb and p-Pb collisions at LHC energies

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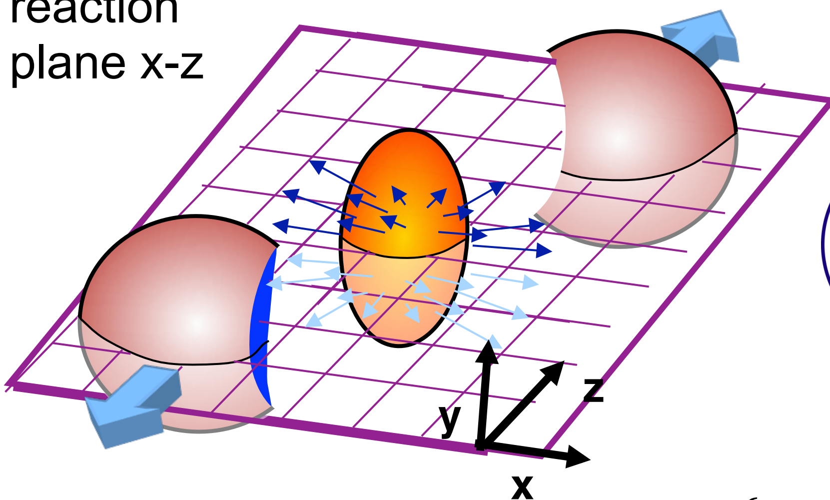
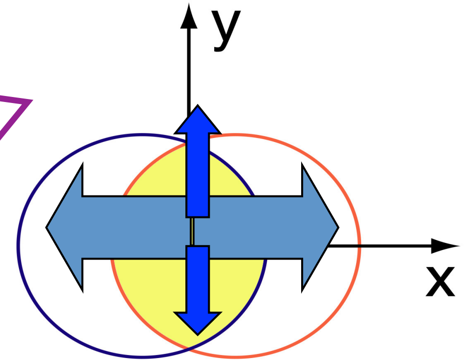
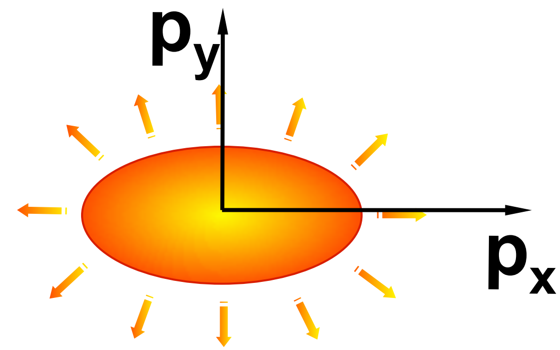
# Outline

- Motivation
- Azimuthal anisotropy and two-particle correlations
- Factorization breaking
- CMS experiment and used data
- Results on factorization breaking in PbPb and pPb collisions
- Comparison to the hydrodynamic predictions
- Conclusions

# Anisotropy harmonics $v_n$




$$\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{d^2N}{p_T dp_T d\eta}\frac{1}{2\pi}\left\{1+2\sum_n v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right\}, \quad v_n = \left\langle \cos n(\phi-\Psi_n)\right\rangle$$

- The most famous is the elliptic flow, $v_2$
- Spatial anisotropy $\longrightarrow \nabla p_x > \nabla p_y \longrightarrow$ momentum anisotropy
- Azimuthally anisotropic emission of particles w.r.t the event plane (EP)
- In each event, $\Psi_n$ of EP is constructed from emitted particles
- There are methods which do not require knowing of the EP

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\{1+2\sum_n V_{n\Delta}\cos(n\Delta\phi)\}$$

# $v_n$ from 2D two-particle correlations

correlation: $$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta\Delta\phi)},$$

$$\Delta\phi = \phi^{trigg} - \phi^{assoc}$$
$$\Delta\eta = \eta^{trigg} - \eta^{assoc}, \quad |\Delta\eta| > 2$$

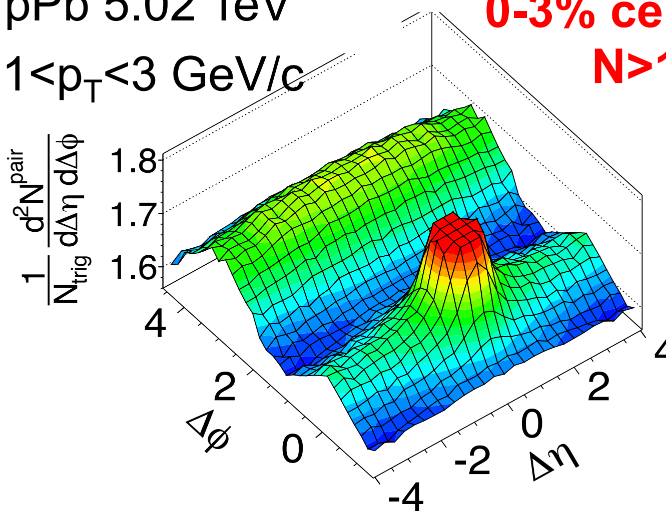
$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\phi} \qquad B(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\phi}$$

Fourier harmonics $V_{n\Delta}$ directly from: $\langle\langle\cos(n\Delta\phi)\rangle\rangle_S - \langle\langle\cos(n\Delta\phi)\rangle\rangle_B$

pPb 5.02 TeV

$1<p_T<3$ GeV/c

**0-3% centrality**
**N>110**




PLB 718 (2013) 795

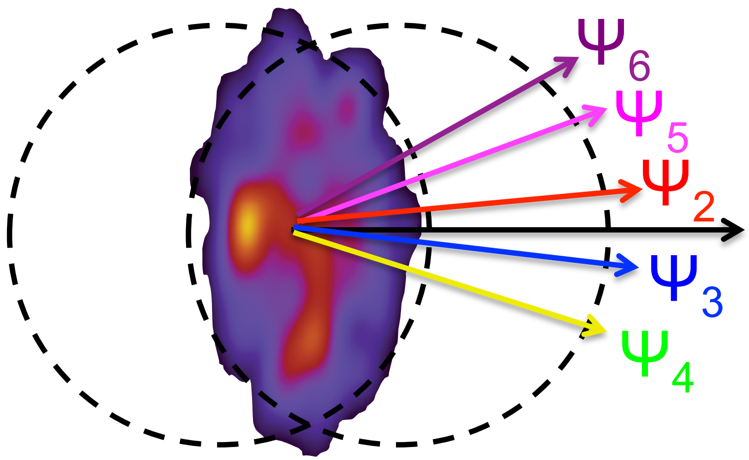
Anisotropy harmonics, $v_n$, are then extracted from $V_{n\Delta}$ as:

$$v_n\{2,|\Delta\eta|>2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

# Role of initial state fluctuations on anisotropy

Phys.Rev. C89 (2014) 044906 *(arXiv:1310.8651)*

**Anisotropy harmonics with order higher than 2**



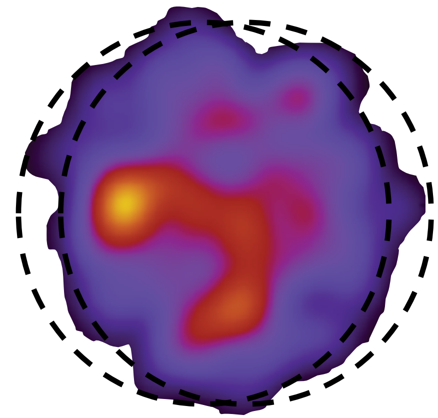

$v_2$, $v_3$, $v_4$, $v_5$ and $v_6$

Approaching UC collisions, $v_n$ are mainly driven by fluctuations:

**Ultra-central collisions ideally suited to test effects due to initial-state fluctuations**

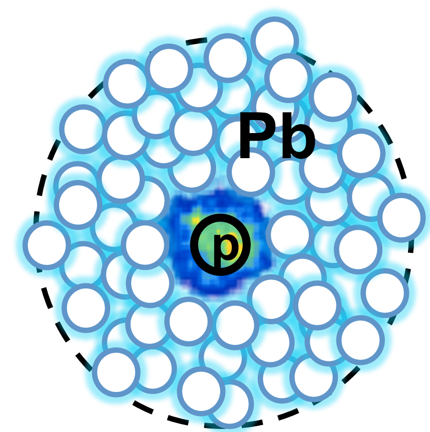
**What about pPb collisions?**

**Ultra-central collisions (UCC)**



JHEP 1402 (2014) 088 *(arXiv:1312.1845)*

**Asymmetric (pPb) high--multiplicity collisions**




Phys.Lett. B724 (2013) 213 *(arXiv:1305.0609)*

# Factorization breaking

❖ How to connect $v_n(p_T)$ and $V_{n\Delta}(p_T)$?

❖ Usual assumption that EP angle $\Psi_n$ does not depend on $p_T$ leads to factorization

$$V_{n\Delta}(p_{T1},p_{T2}) = \sqrt{V_{n\Delta}(p_{T1},p_{T1})} \times \sqrt{V_{n\Delta}(p_{T2},p_{T2})} = v_n(p_{T1}) \times v_n(p_{T2})$$

❖ Recently, *Gardim et al., PRC 87, 031901(R) (2013)* and *Heinz et al., PRC 87, 034913 (2013)* proposed that not only $v_n$ depends on $p_T$, but also $\Psi_n$ could depends on $p_T$ due to event-by-event (EbE) fluctuating initial state

❖ then:

$$V_{n\Delta}(p_{T1},p_{T2}) = \left\langle v_n(p_{T1}) v_n(p_{T2}) \cos\left[n(\Psi_n(p_{T1}) - \Psi_n(p_{T2}))\right]\right\rangle$$

$$\neq \sqrt{V_{n\Delta}(p_{T1},p_{T1})} \times \sqrt{V_{n\Delta}(p_{T2},p_{T2})}$$

even if hydro flow is the only source of the correlation

initial state fluctuations $\rightarrow$ $\Psi_n(p_T)$ $\rightarrow$ factorization breaking

# Factorization breaking

❖ new observable: $r_n = \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{trig}, p_T^{trig})}\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}} =$

$$\frac{\left\langle v_n(p_T^{trig}) v_n(p_T^{assoc}) \cos\left[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{assoc}))\right]\right\rangle}{\sqrt{v_n^2(p_T^{trig}) v_n^2(p_T^{assoc})}} = \begin{Bmatrix} 1 \\ <1 \\ >1 \end{Bmatrix} \begin{matrix} \text{fact. holds} \\ \text{fact. breaks} \\ \text{non-flow} \end{matrix}$$

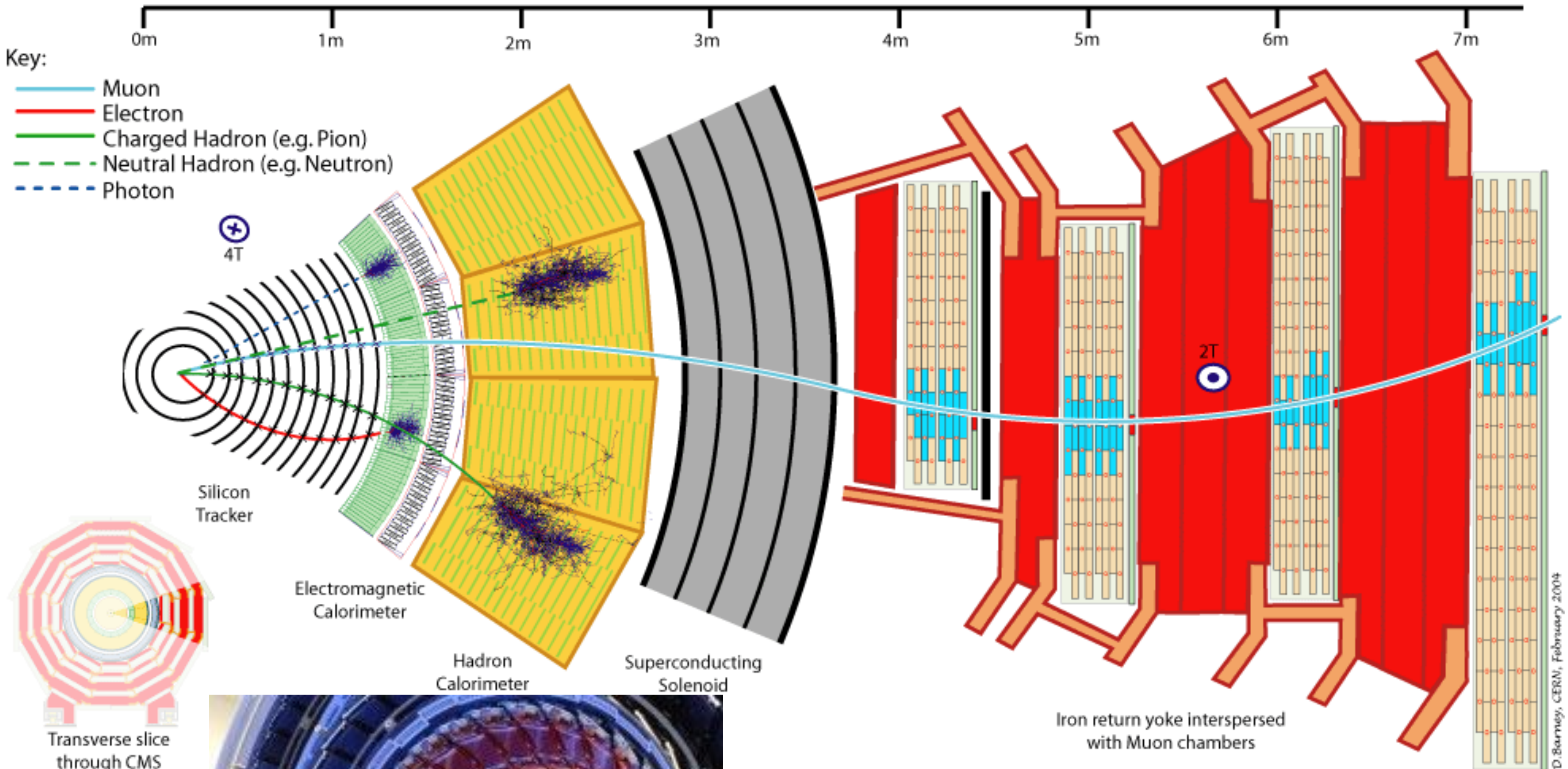
❖ Large effect is expected and confirmed in ultra central PbPb collisions
***CMS collaboration****: Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV , JHEP* ***1402*** *(2014)088*

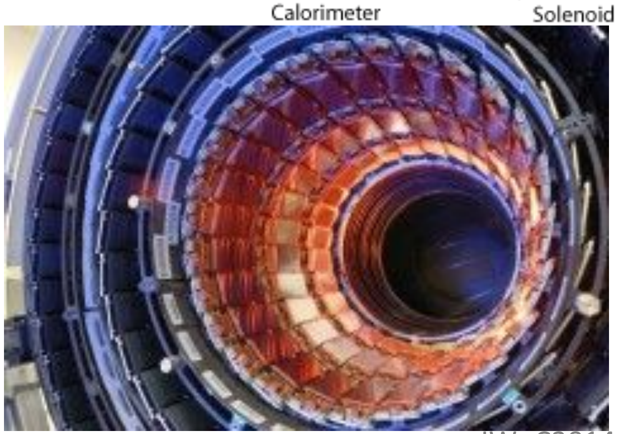
❖ As in pPb collisions initial-state fluctuations play a dominant role could we expect a similar (in size) effect?

❖ Two hydro models with different initial conditions and *η/s* were developed:
- ✧ *Heinz-Shen VISH2+1: PRC* ***87****, 034913 (2013)*
- ✧ *Kozlov et. al.: arXiv:1405.3976*

❖ Constraining of initial conditions and *η/s* by comparing to the exp. data

# Schematic view of the CMS detector in transverse plane



Used data from Silicon Tracker:

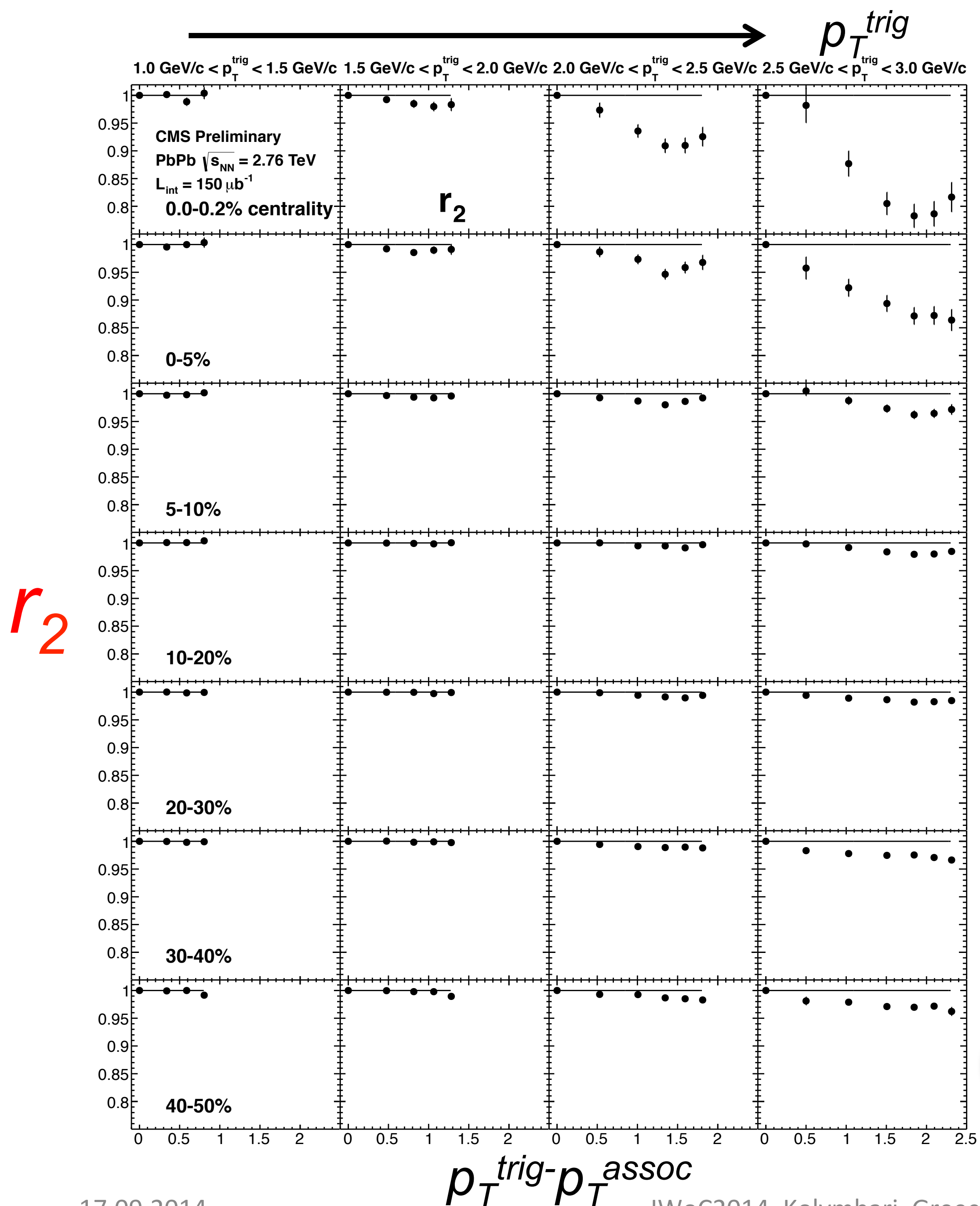
charged particles with:

$$|\eta| \le 2.4 \qquad p_T \ge 0.3 GeV/c$$

Huge acceptance + precise $p_T$ meas.

# Factorization breaking
# PbPb results

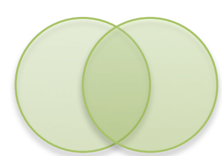
# PbPb case




0-0.2%

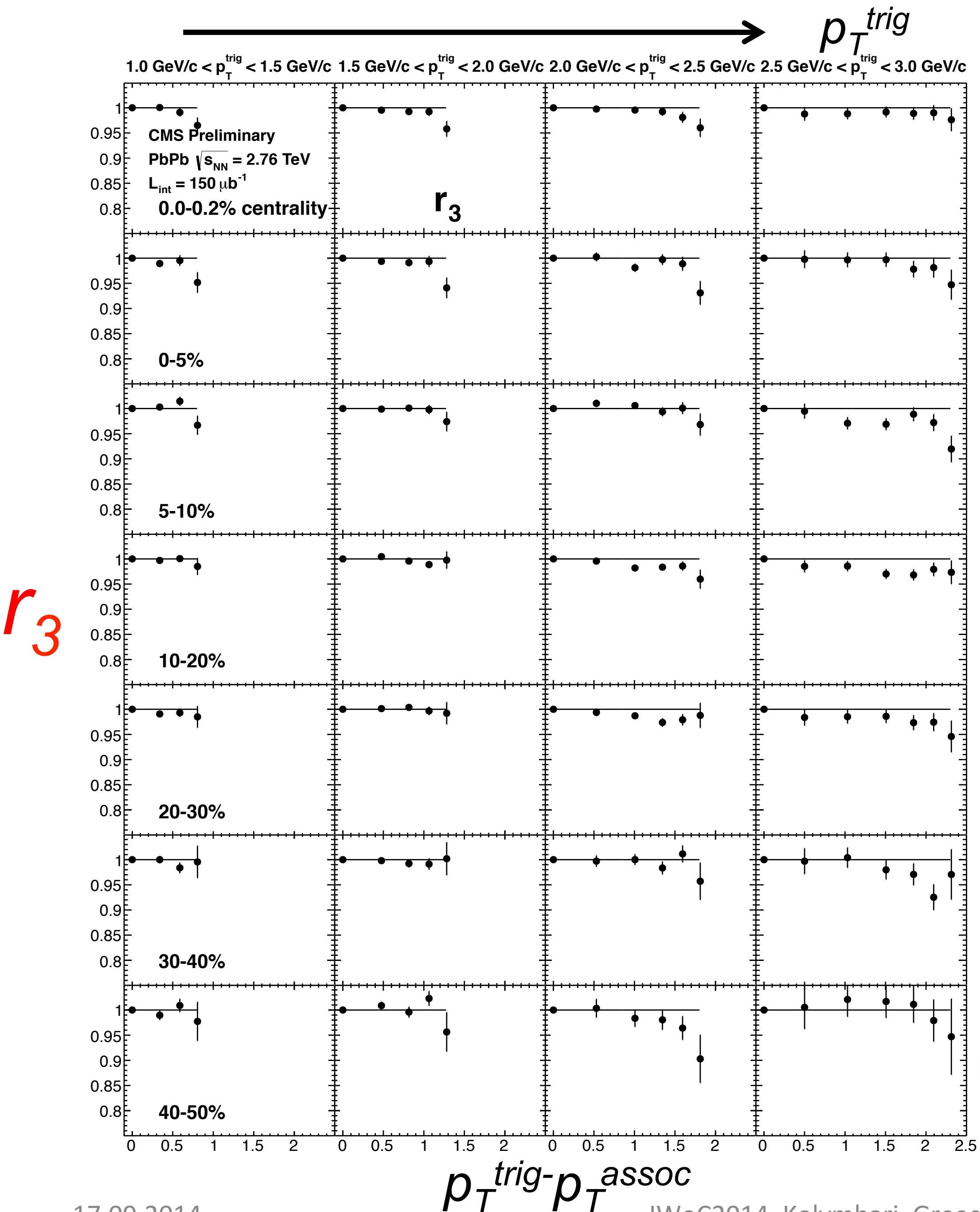
- ❖ The effect increases with rise of $p_T^{trig}$ and $p_T^{trig}$-$p_T^{assoc}$
- ❖ Approaching the central collisions, the effect dramatically increases achieving value over 20%
- ❖ For semi-central collisions, the effect achieves only a size of 2−3%

40-50%



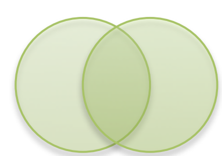
**CMS PAS HIN-14-012**

# PbPb case




0-0.2%

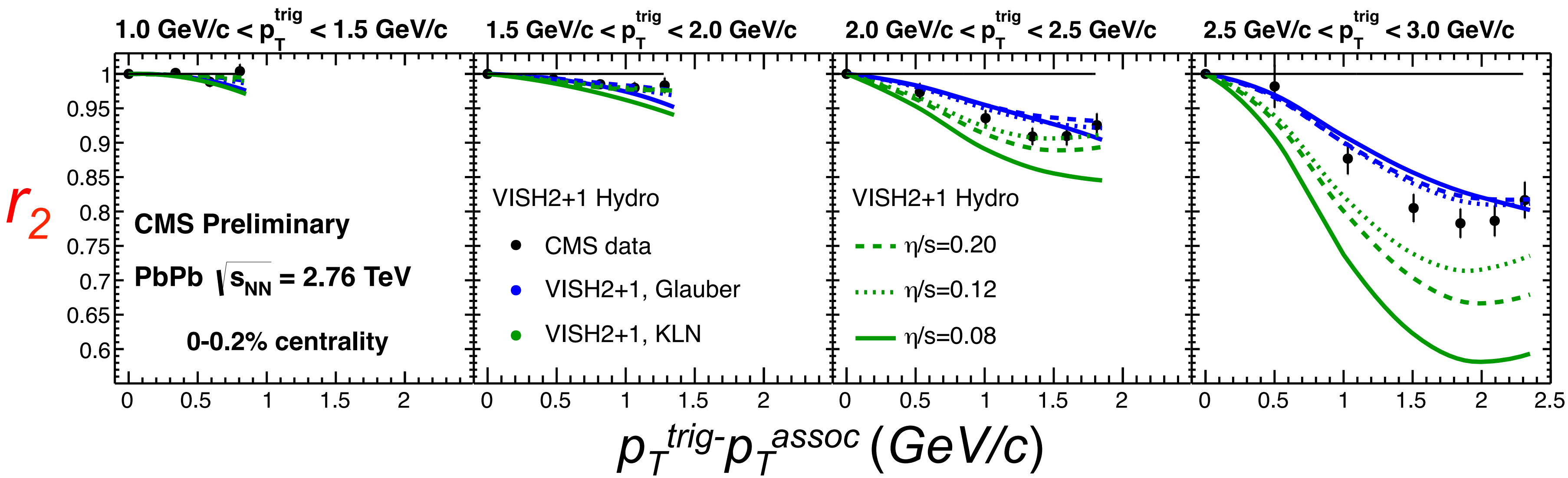
40-50%



- Factorization holds better for $V_3$
- Breaking visible only for the highest $p_T^{trig}$-$p_T^{assoc}$
- Very weakly depends on centrality

**CMS PAS HIN-14-012**

# $r_2$ in ultra-central PbPb collisions and VISH2+1

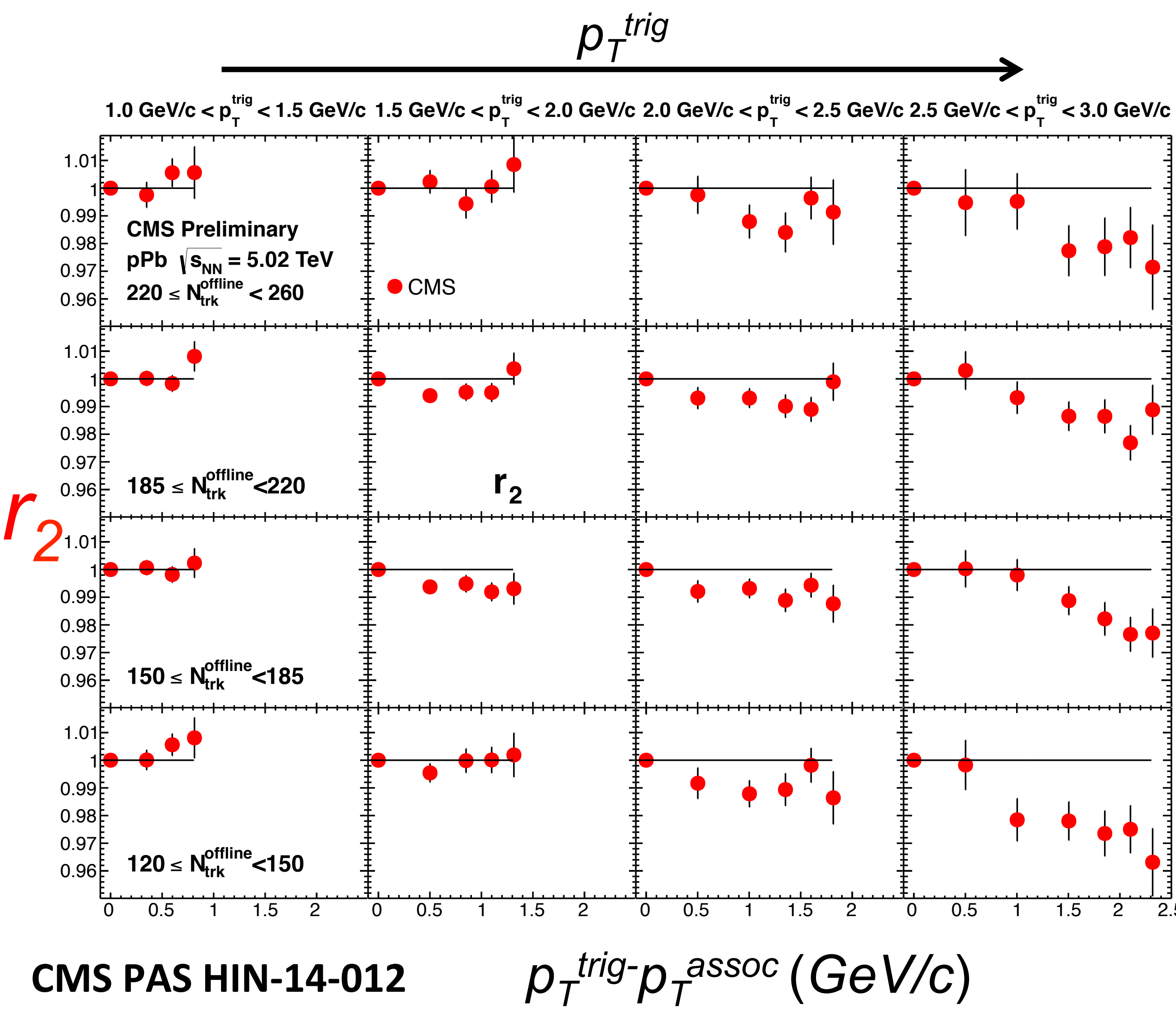



**CMS PAS HIN-14-012** **VISH2+1: PRC 87, 034913 (2013)**

- The effect increases with rise of $p_T^{trig}$ and $p_T^{trig}$-$p_T^{assoc}$
- The biggest effect seen in ultra-central collisions while for semi-central collisions, the effect achieves only a size of 2−3%
- The VISH2+1 model qualitatively gives a good description of CMS data for both Glb and KLN initial conditions
- Very roughly, both initial conditions are closest to the experimental data for η/s=0.12

# Factorization breaking
# pPb results

# $r_2$ from high-multiplicity pPb collisions




*220<$N_{trk}^{offline}$<260*

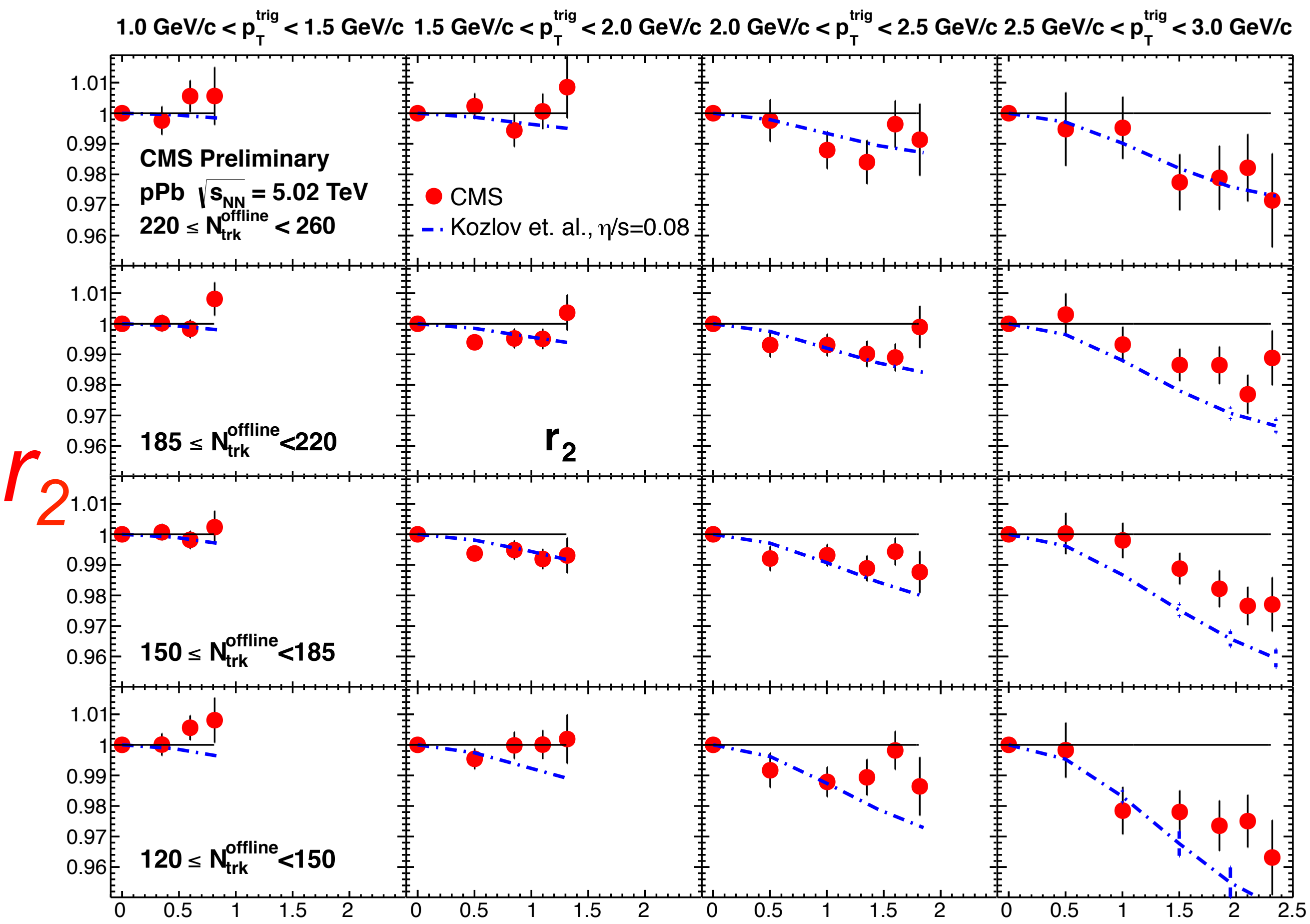
- The effect increases with $p_T^{trig}$ and $p_T^{trig}$-$p_T^{assoc}$
- Maximum around 2-3%
- Nearly no dependence on multiplicity

*120<$N_{trk}^{offline}$<150*

**CMS PAS HIN-14-012**

# pPb $r_2$: comparison to Kozlov et. al hydro model

$p_T^{trig}$ →



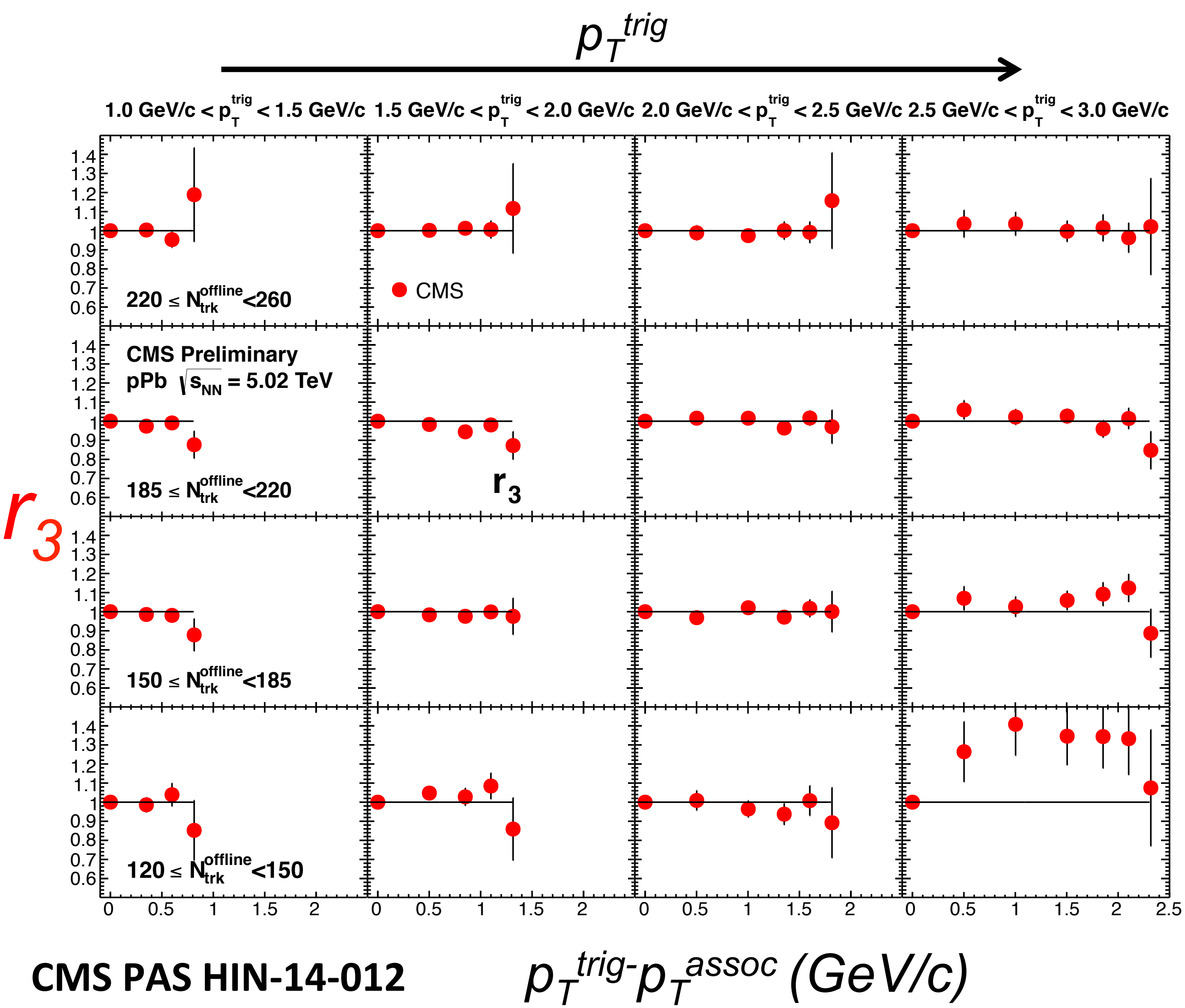

*220<$N_{trk}^{offline}$<260*

Kozlov et. al. hydro model qualitatively describes data

*120<$N_{trk}^{offline}$<150*

**CMS PAS HIN-14-012** $p_T^{trig}$-$p_T^{assoc}$ *(GeV/c)* *Kozlov et. al.: arXiv:1405.3976*

# $r_3$ from high-multiplicity pPb collisions



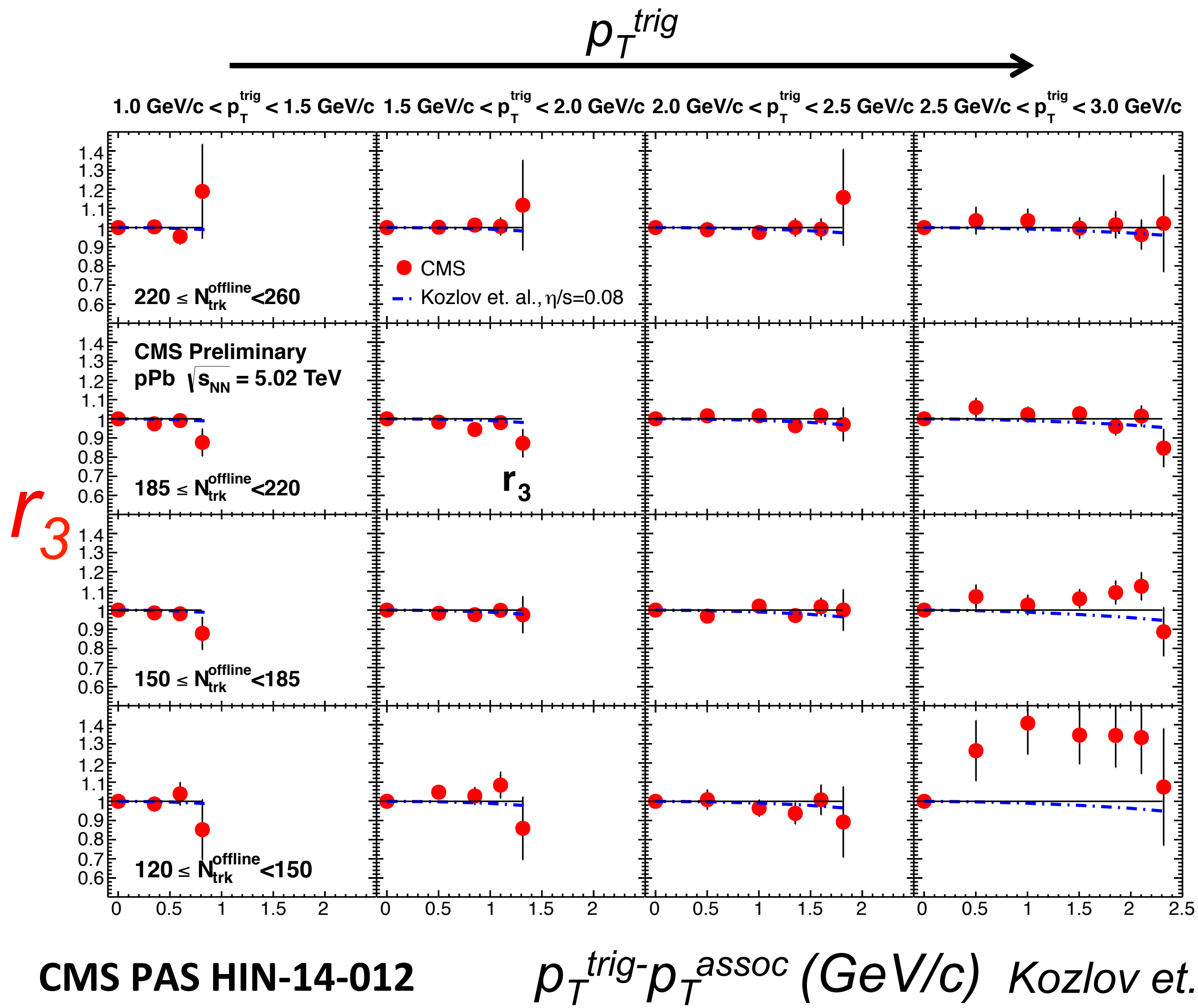

$220<N_{trk}^{offline}<260$

- $V_3$ factorize better than $V_2$
- A direct indication of non-flow effect seen in $r_3$ for the highest $p_T^{trig}$ in lower multiplicity bins

$120<N_{trk}^{offline}<150$

**CMS PAS HIN-14-012**

# pPb $r_3$: comparison to Kozlov et. al hydro model




- Kozlov et. al. hydro model qualitatively describes data except in lower multiplicity bins for the highest $p_T^{trig}$

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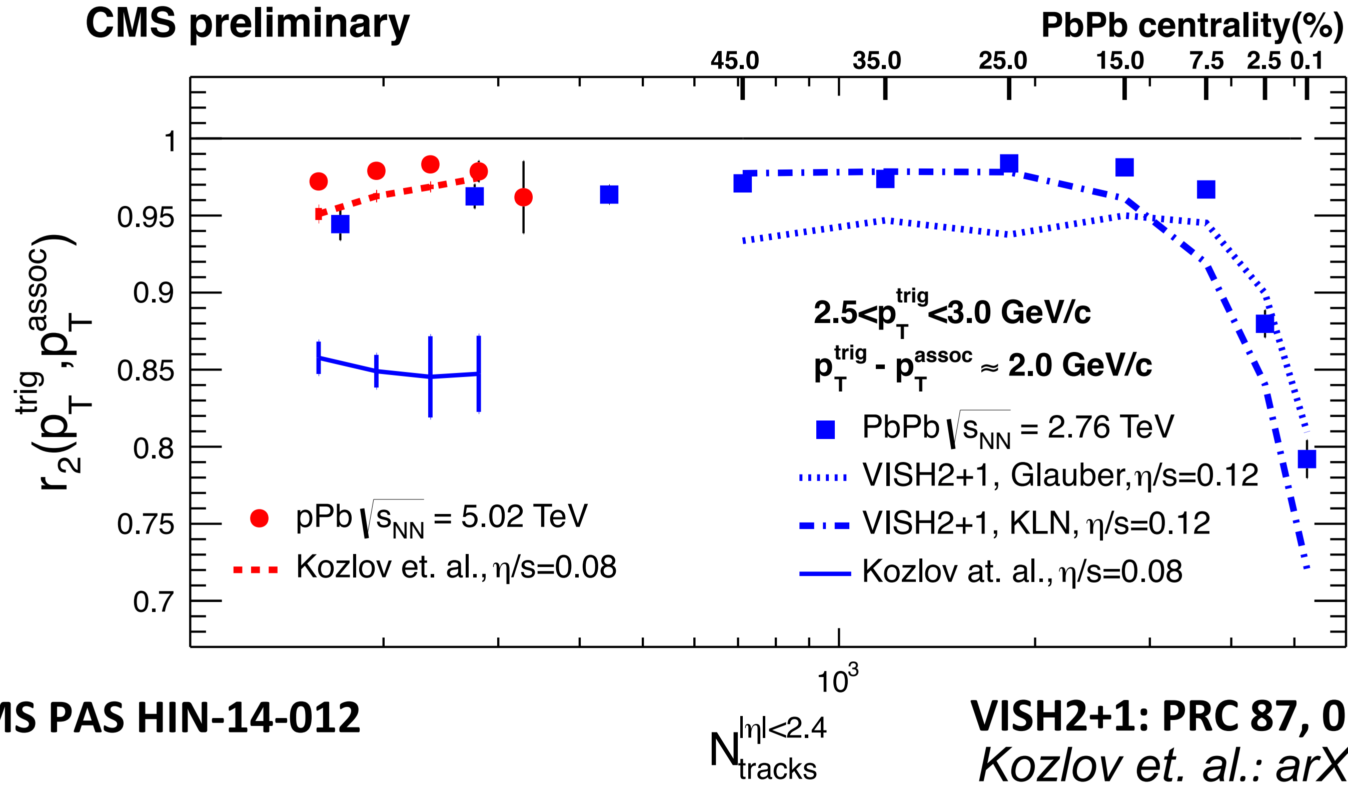
*Kozlov et. al.: arXiv:1405.3976*

# $r_2$ multiplicity dependence in pPb and PbPb collisions



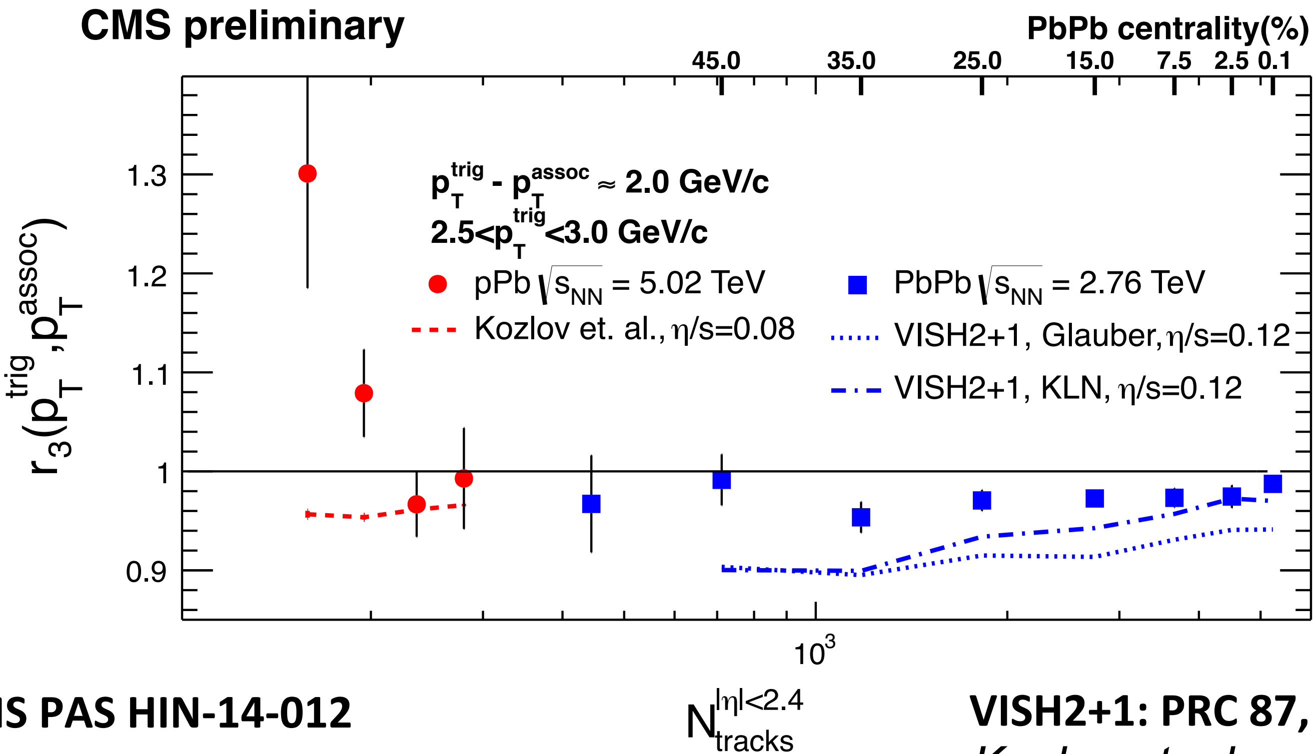

**CMS PAS HIN-14-012**

**VISH2+1: PRC 87, 034913 (2013)**

*Kozlov et. al.: arXiv:1405.3976*

- The effect increases dramatically approaching ultra-central PbPb collisions
- For smaller centralities (>5%), the effect is on the level of few percent
- VISH2+1 for both initial conditions qualitatively describe CMS data
- The magnitude of $r_2$ in pPb is a bit smaller w.r.t. the one in PbPb collisions
- Kozlov et. al hydro model describes pPb data, but gives stronger effect in case of PbPb collisions

# $r_3$ multiplicity dependence in pPb and PbPb collisions

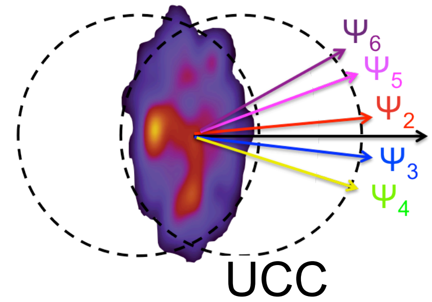



**CMS PAS HIN-14-012**

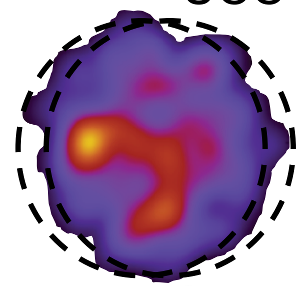
**VISH2+1: PRC 87, 034913 (2013)**
*Kozlov et. al.: arXiv:1405.3976*

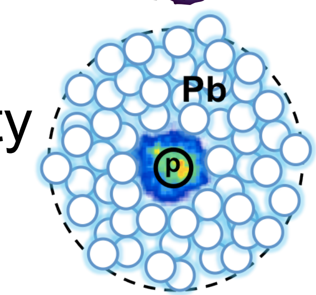
- Strong multiplicity dependence in pPb, but very weak in PbPb
- A non-flow effect seen in pPb for the highest $p_T^{trig}$ in lower multiplicities
- VISH2+1 qualitatively describes $r_3$ in PbPb
- Kozlov et. al. hydro qualitatively describes $r_3$ for the highest multiplicities in pPb, but fails for lower multiplicities

# Conclusions




- Ultra central PbPb collisions are well suited to test initial-state fluctuations and could provide stringent constraints to *η/s* of the QGP
- CMS measured factorization breaking of two-particle correlations in PbPb and pPb
- Strong effect in ultra-central PbPb
- 2-3% in pPb, comparable to PbPb at similar multiplicity
- Qualitatively or even semi-quantitatively consistent with hydro models with $p_T$ dependent EP angle induced by initial-state fluctuations






CMS HIN-14-012: http://cds.cern.ch/record/1703015

Public CMS HI results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN