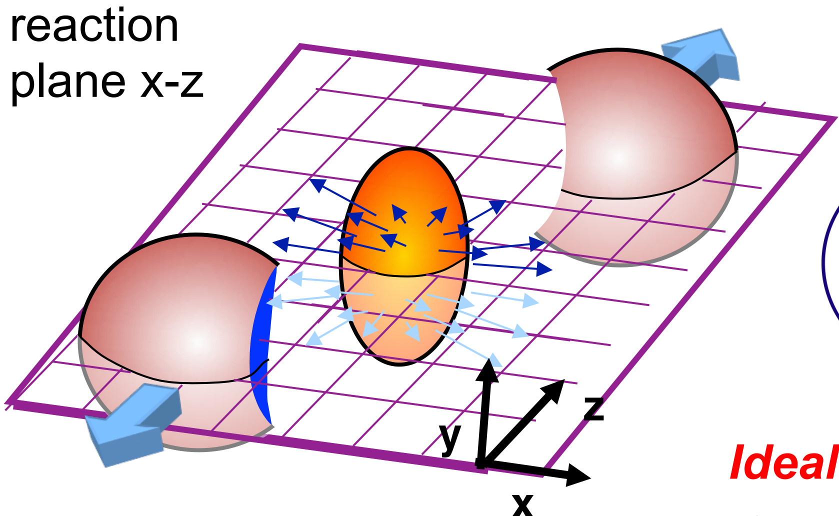
Evidence for transverse momentum and pseudorapidity dependent event plane fluctuations in PbPb and pPb collisions

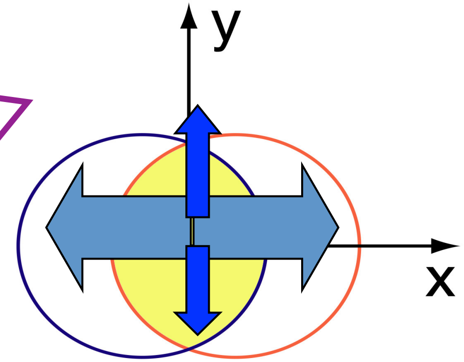
J. Milošević
University of Belgrade and
Vinča Institute of Nuclear Sciences,
Belgrade, Serbia
on behalf of the CMS Collaboration

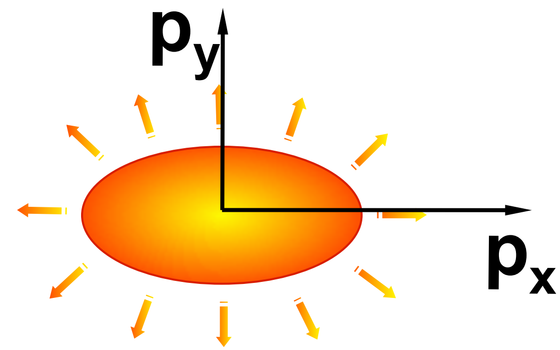
Outline

- Azimuthal anisotropy
- Anisotropy in ultra-central PbPb collisions
- Factorization breaking mechanism and its consequences to the anisotropy measurements w.r.t. the global event plane
- p_T-dependent event plane fluctuations in PbPb and pPb collisions
- Comparison to the hydrodynamic predictions
- η-dependent event plane fluctuations in PbPb and pPb collisions
- Conclusions

Anisotropy harmonics v_n







Ideal circle-like geometry – v_2

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

- The most famous, and the most pronounced 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, Ψ_n of EP is constructed from emitted particles
- There are methods which do not require knowledge 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: $$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta\Delta\phi)},$$ $$\Delta\phi = \phi^{trigg} - \phi^{assoc}$$ $$\Delta\eta = \eta^{trigg} - \eta^{assoc},$$

To remove jets: $|\Delta\eta| > 2$

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

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

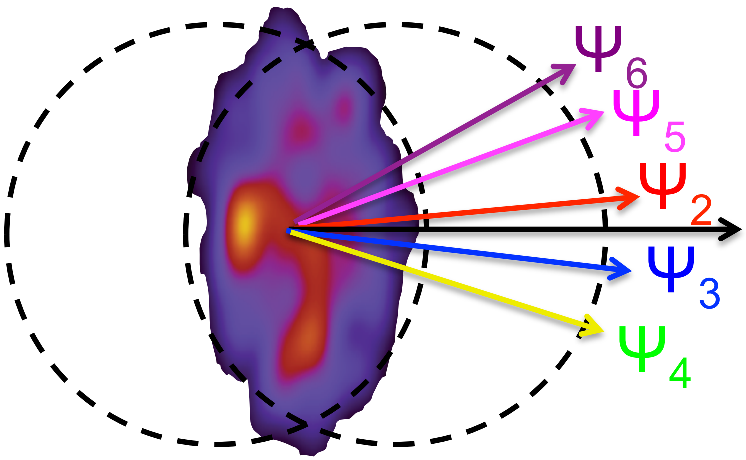
Anisotropy harmonics, v_n, are then extracted from $V_{n\Delta}$ as:

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

Role of initial state fluctuations on anisotropy

Anisotropy harmonics with order higher than 2

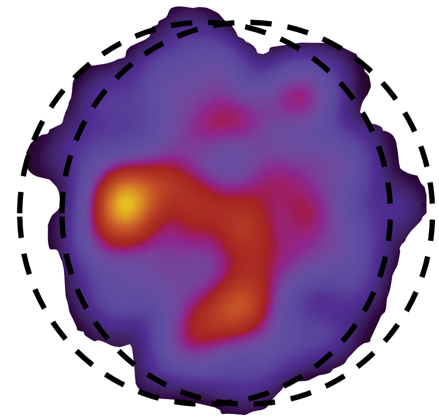
Phys.Rev. C89 (2014) 044906 *(arXiv:1310.8651)*



v_2, v_3, v_4, v_5 and v_6 using multiple methods

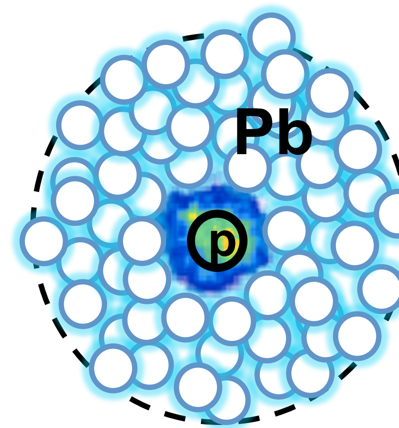
Simple, circle-like geometry does not describe the formed system precisely enough

Ultra-central collisions



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

Asymmetric (pPb) high--multiplicity collisions

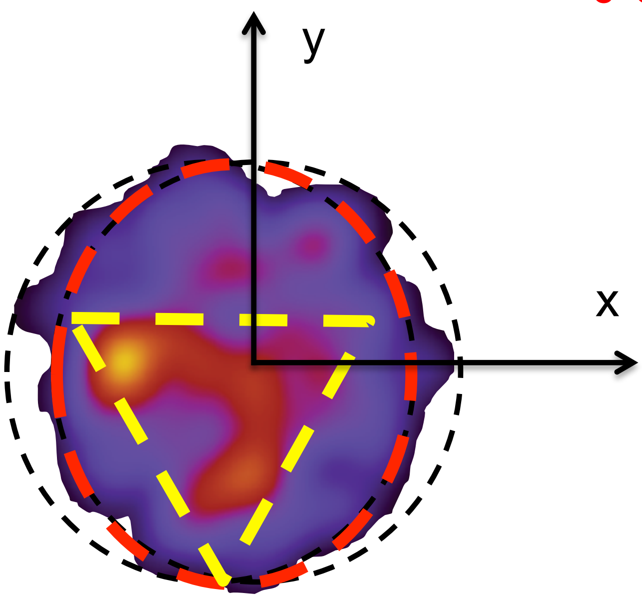


Phys.Lett. B724 (2013) 213 *(arXiv:1305.0609)*

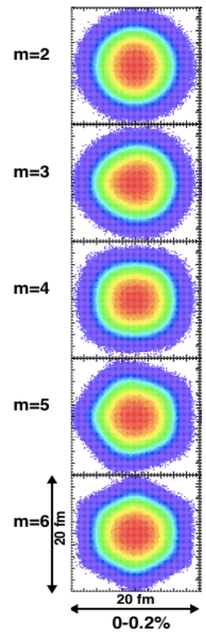
Ultra-central PbPb collisions

Ultra-central PbPb collisions

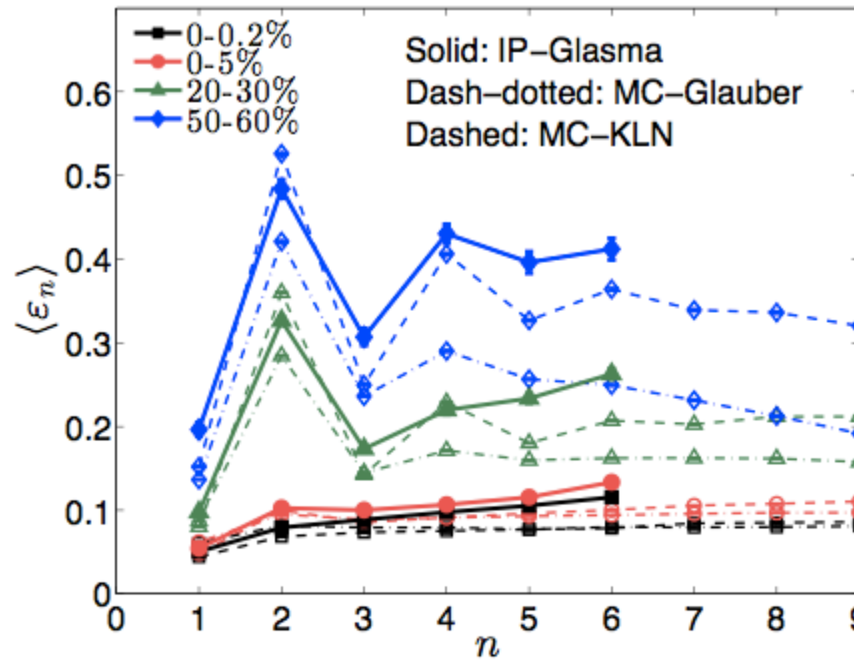
Approaching UC collisions, v_n are mianly driven by fluctuations:



0-0.2% centrality



various order of ε_n converge as collision becomes central



JHEP 1402 (2014) 088
(arXiv:1312.1845)

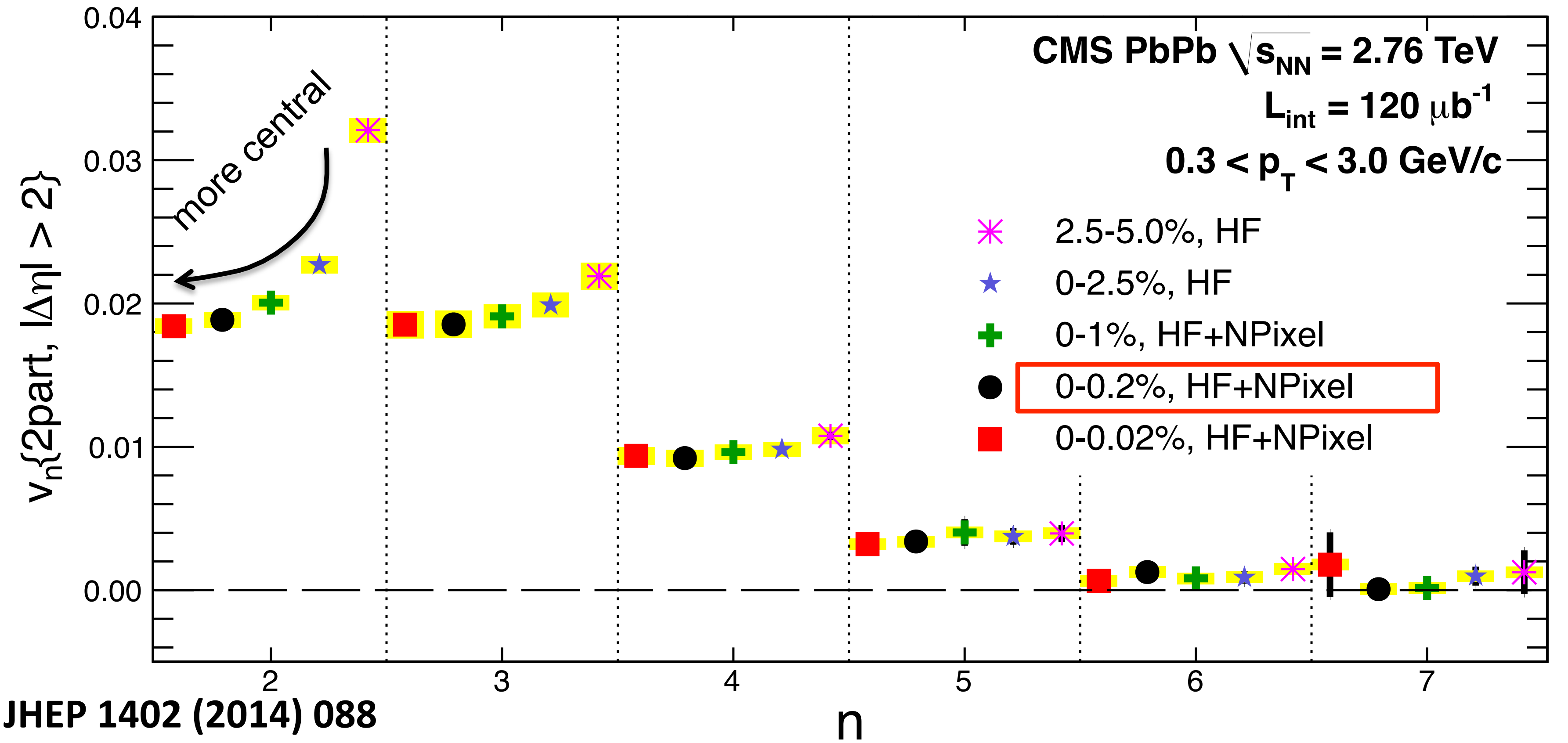
Participant distribution relative to the n^{th} order participant plane

Annu. Rev. Nucl. Part. Sci. 63 (2013) 123

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

Flow in ultra-central PbPb collisions

v_n from two-particle correlations for different harmonic order

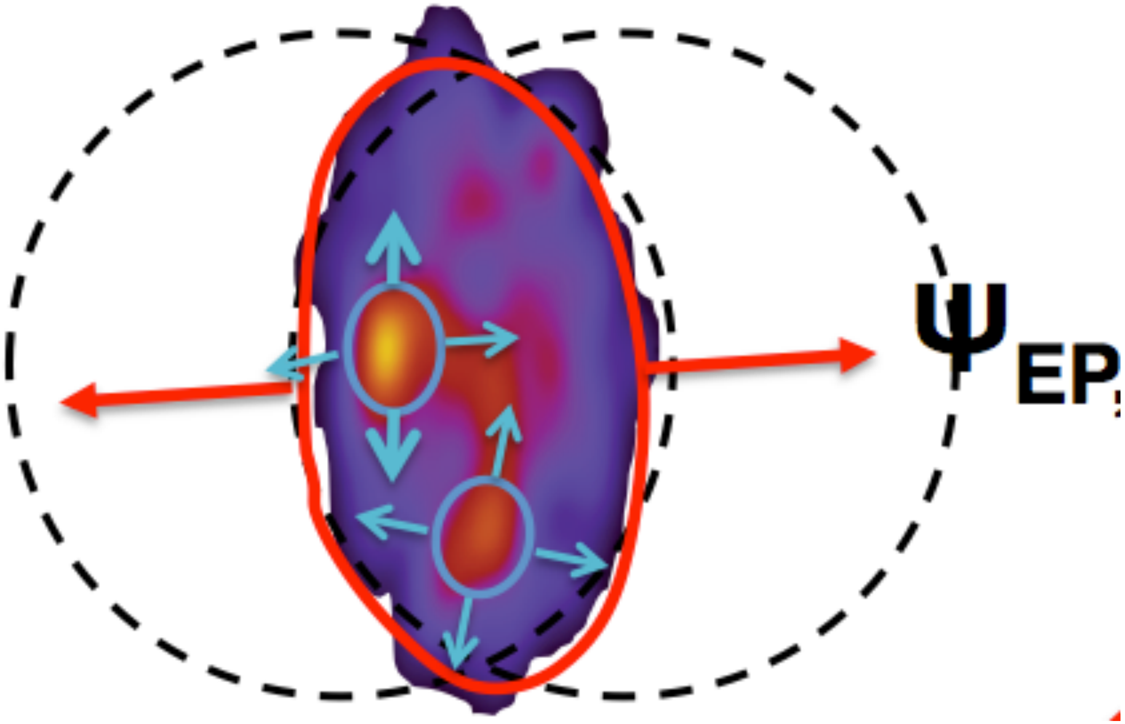


JHEP 1402 (2014) 088
(arXiv:1312.1845)

All orders of v_n tend to saturate approaching 0.0-0.2% centrality

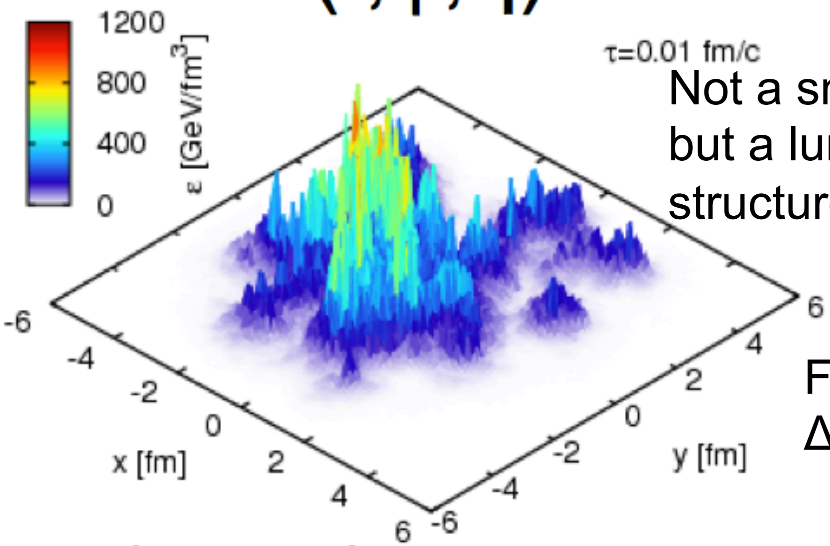
➔ Effect dominantly induced by initial state fluctuations

Factorization breaking – p_T dependence



Initial state inhomogeneity

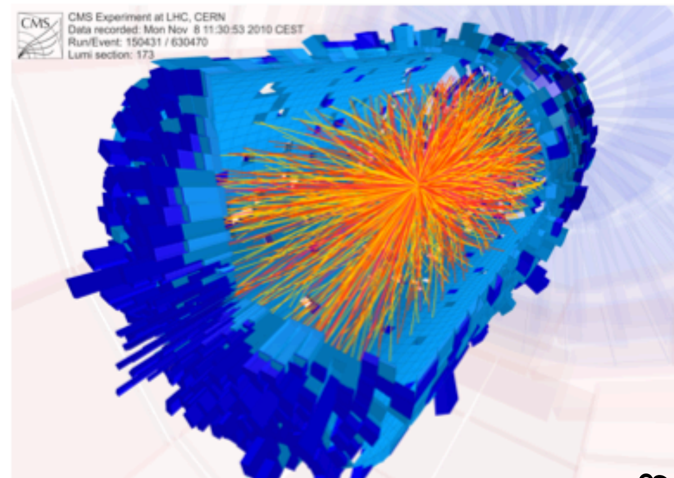
Initial state $\varepsilon(r,\varphi,\eta)$ —EbE hydro.→ Final state $f(p_T,\varphi,\eta)$



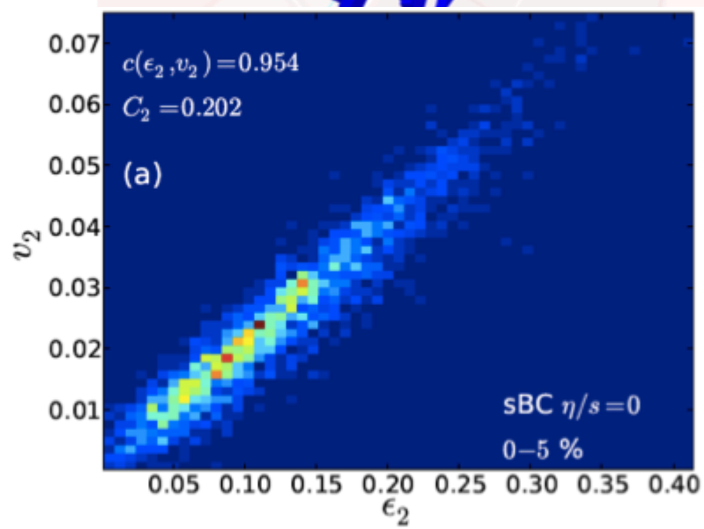
Not a smooth but a lumpy structure

Fluctuations $\Delta\varepsilon(r,\phi,\eta)$

overlap zone in x-y



- ✧ The goal is to map initial state and its fluctuations in 3D
- ✧ $v_n \sim \varepsilon_n$ is not perfectly correct
- ✧ Longitudinal (η) dynamics is not probed
- ✧ Local hotspots perturb the EP of a smooth medium, so $\Psi_n(p_T)$ contains detailed information about initial-state fluctuations



Niemi et al. arXiv:1212.1008

Factorization breaking – new insights on initial states

- How to connect $v_n(p_T)$ *and* $V_{n\Delta}(p_T)$?
- Usual assumption that EP angle Ψ_n does not depend on p_T leads to factorization

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

- *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 Ψ_n could depends on p_T due to event-by-event (EbE) fluctuating initial state. The overlapping region is not homogeneous but has a lumpy structure

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

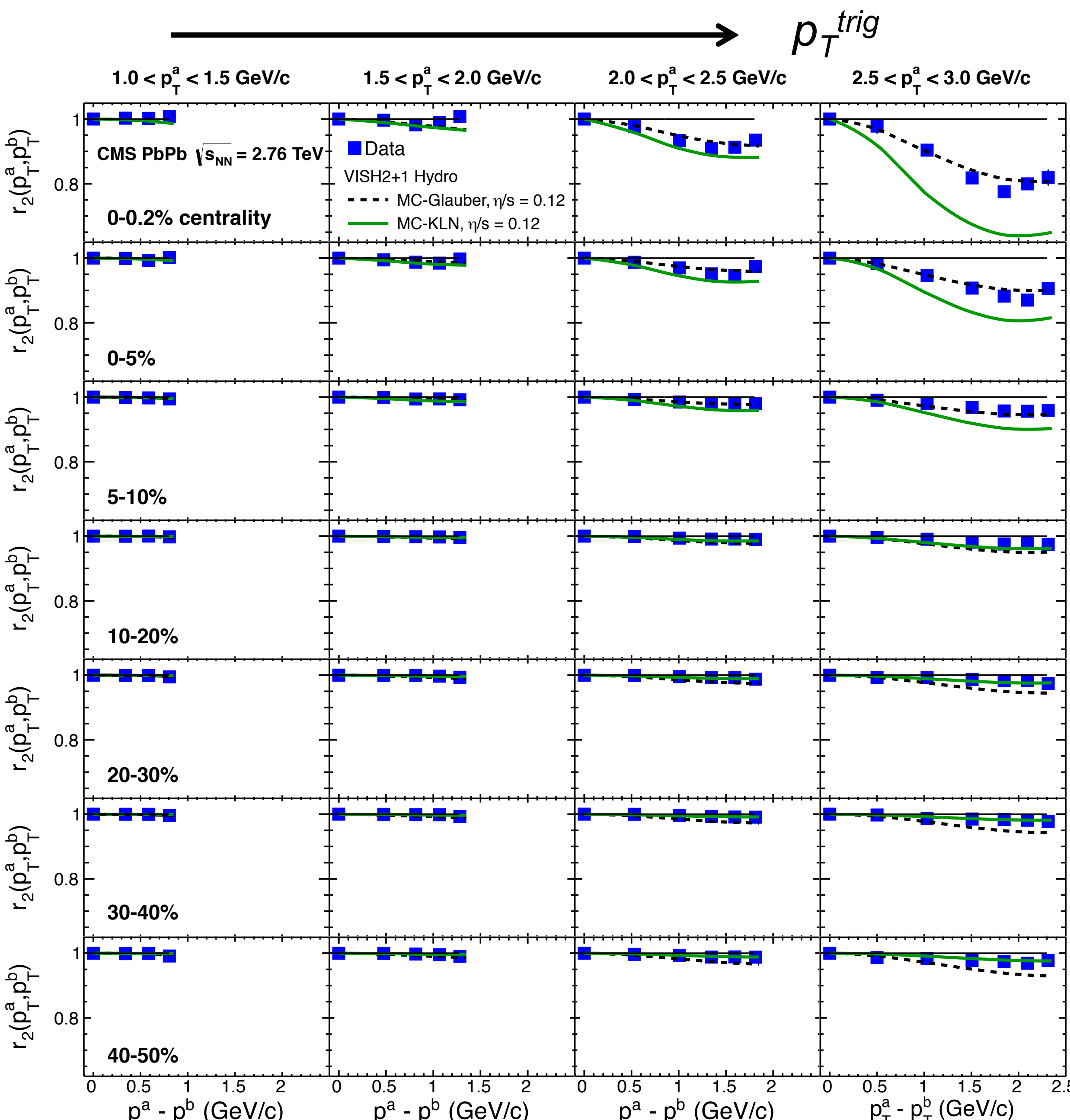
$$\frac{\left\langle v_n(p_T^{trig}) v_n(p_T^{assoc}) \cos\left[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{assoc}))\right]\right\rangle}{\sqrt{v_n^2(p_T^{trig}) v_n^2(p_T^{assoc})}} = \left\{ \begin{array}{ll} 1 & \text{fact. holds} \\ <1 & \text{fact. breaks} \\ >1 & \text{non-flow} \end{array} \right.$$

❖ 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?

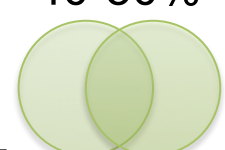


0-0.2%

PbPb case

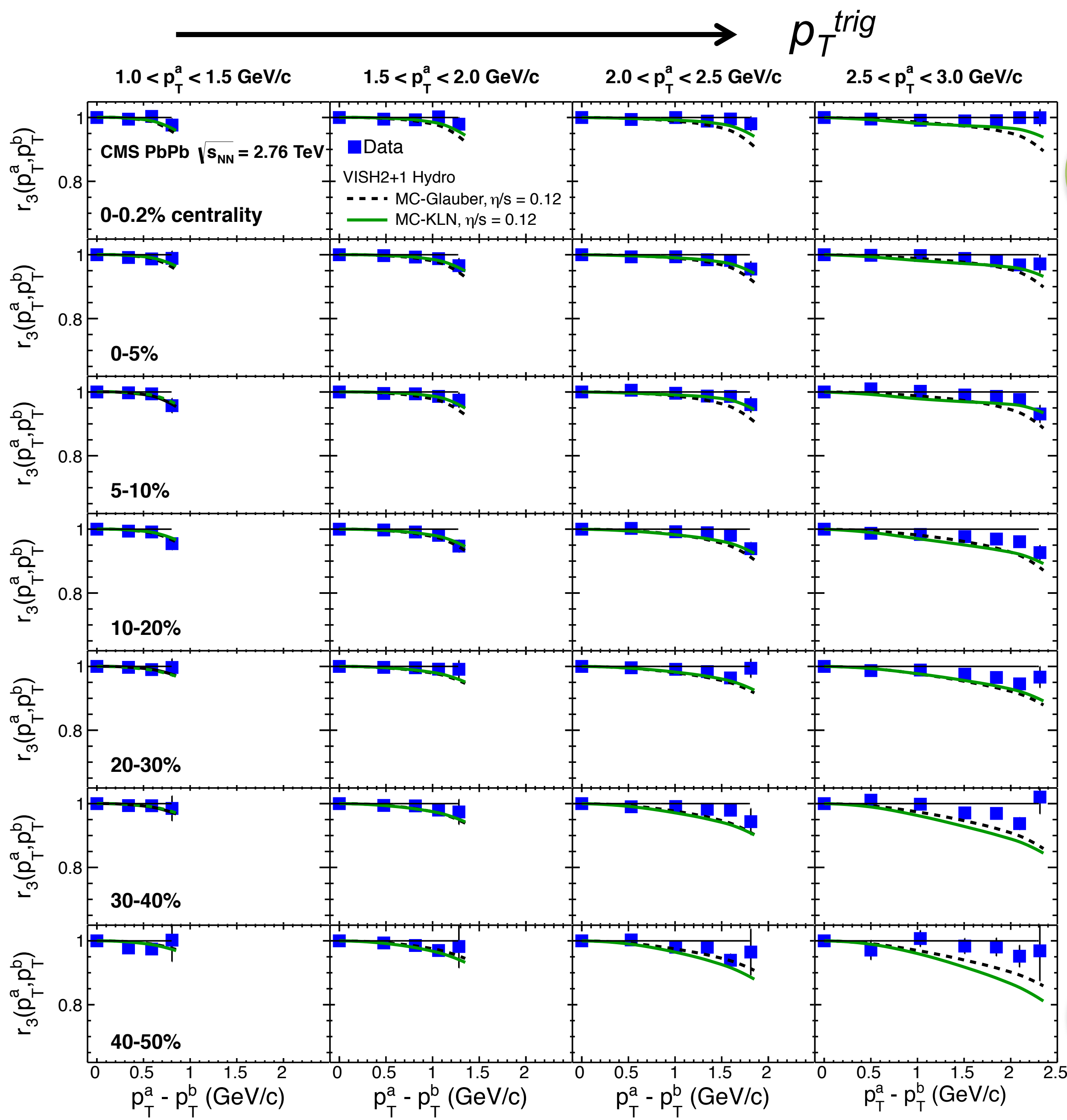
- ❖ The effect increases with rise of p_T^{trig} and p_T^{trig}-p_T^{assoc}
- ❖ Approaching the central collisions, the effect dramatically increases achieving value over 20%
- ❖ For semi-central collisions, the effect achieves only a size of 2−3%

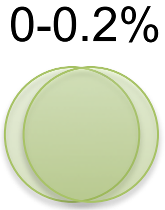
40-50%



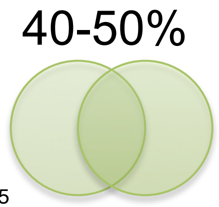
arXiv: 1503.01692 submitted to **PRC**

PbPb case



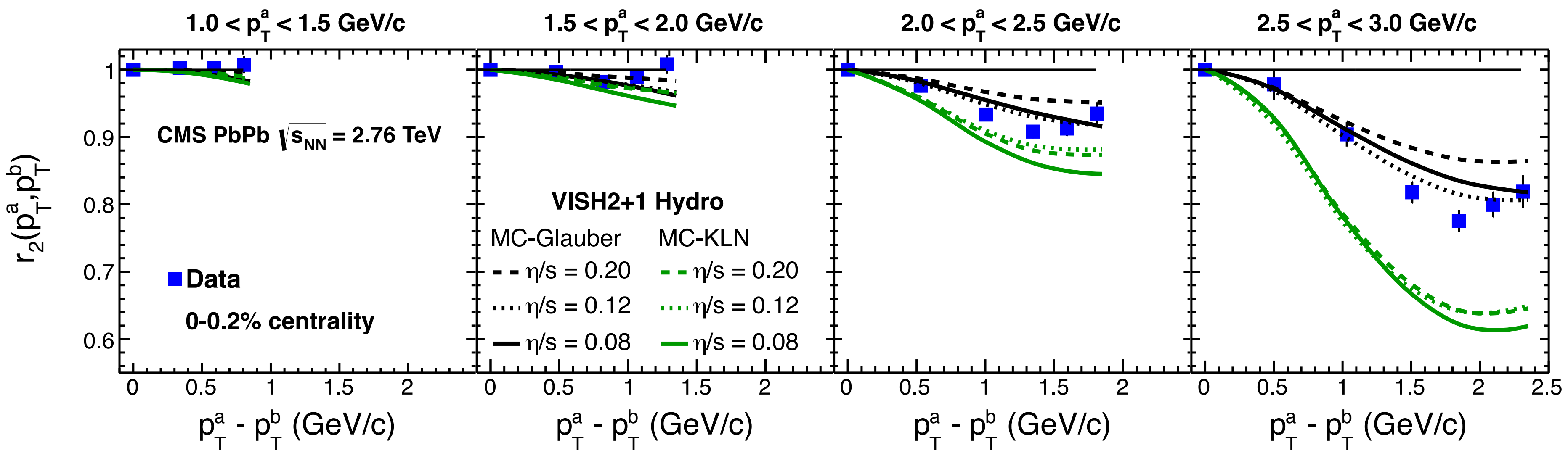


- Factorization holds better for V_3
- Breaking visible only for the highest p_T^{trig}-p_T^{assoc}
- Very weakly depends on centrality



arXiv: 1503.01692
submitted to **PRC**

r_2 in ultra-central PbPb collisions and VISH2+1

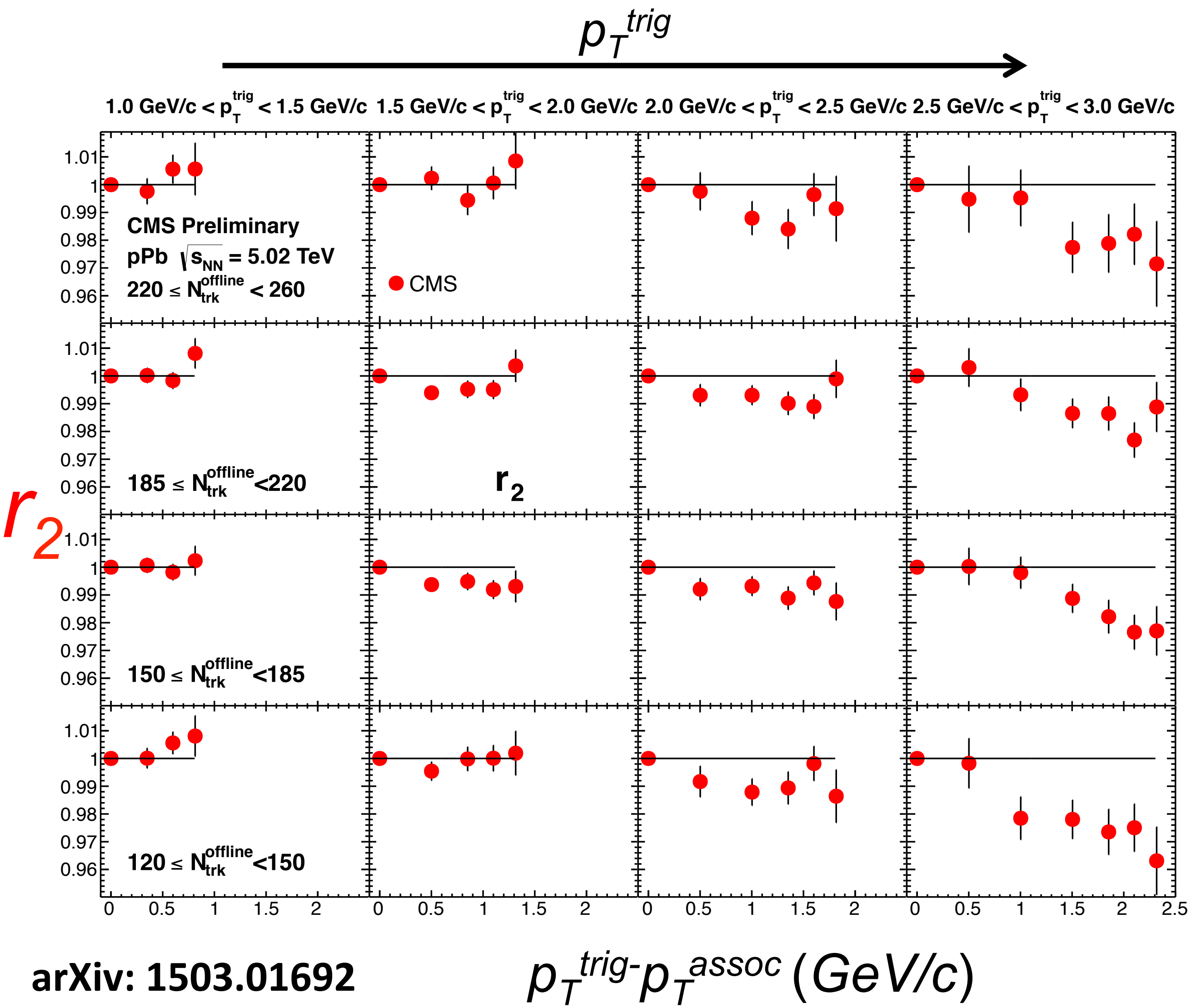


arXiv: 1503.01692 submitted to **PRC**

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 MC-Glauber and MC-KLN initial conditions
- Large insensitivity to η/s ➔ an independent constraint to the initial-state

r_2 from high-multiplicity pPb collisions



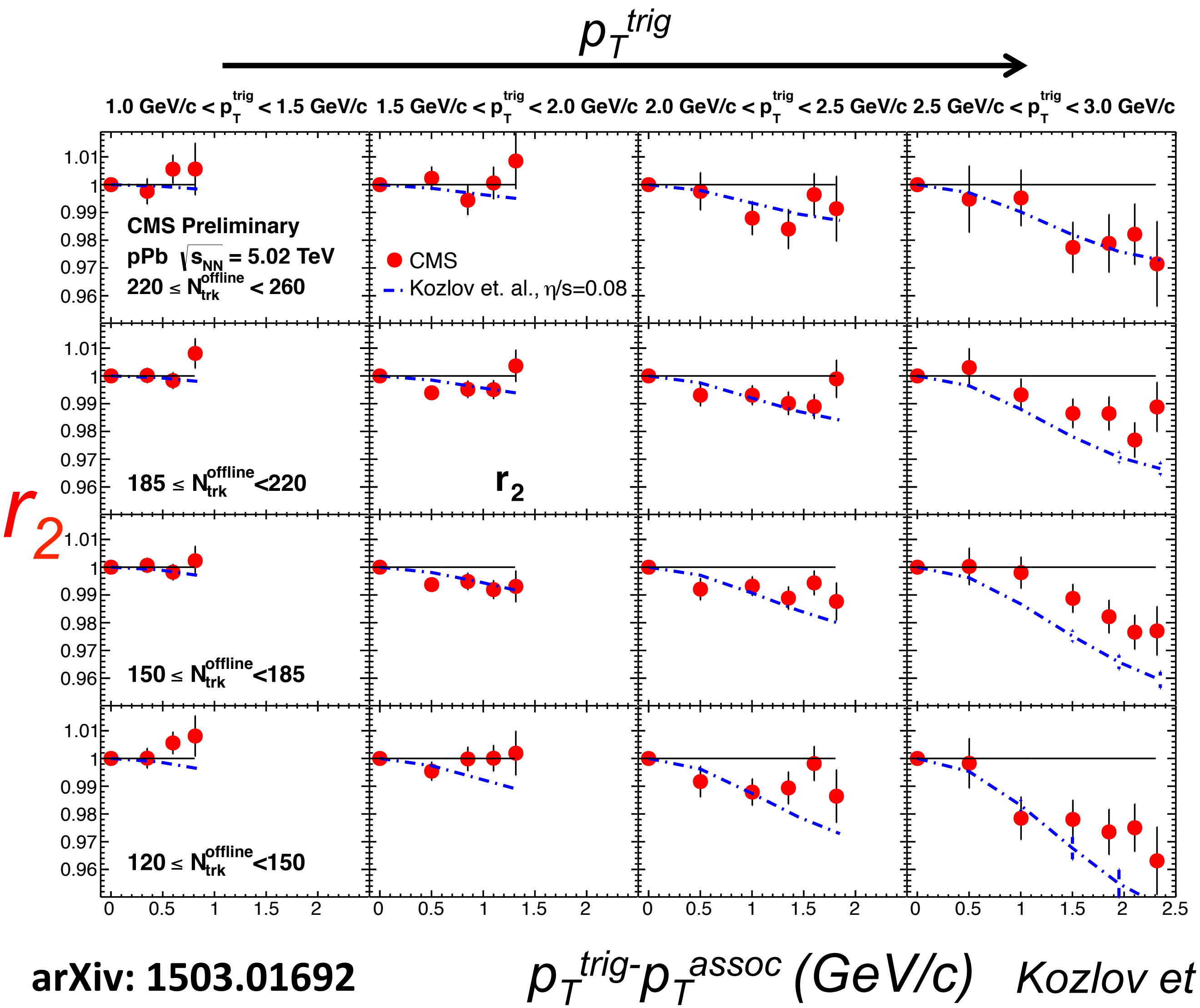
$220<N_{trk}^{offline}<260$

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

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

arXiv: 1503.01692
submitted to **PRC**

pPb r_2: comparison to Kozlov et. al hydro model

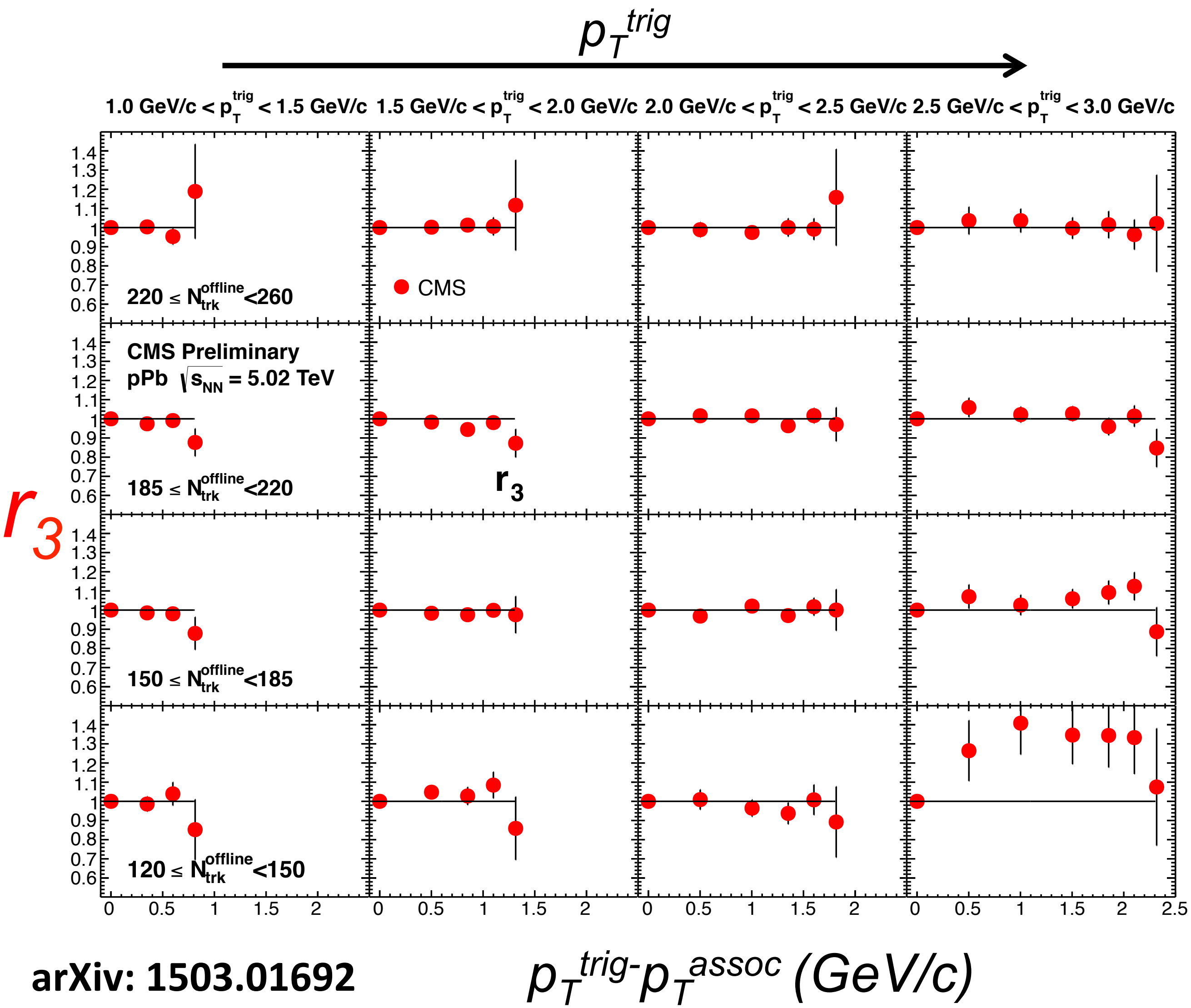


Kozlov et al. hydro model qualitatively describes data

arXiv: 1503.01692
submitted to **PRC**

Kozlov et al.: arXiv:1405.3976

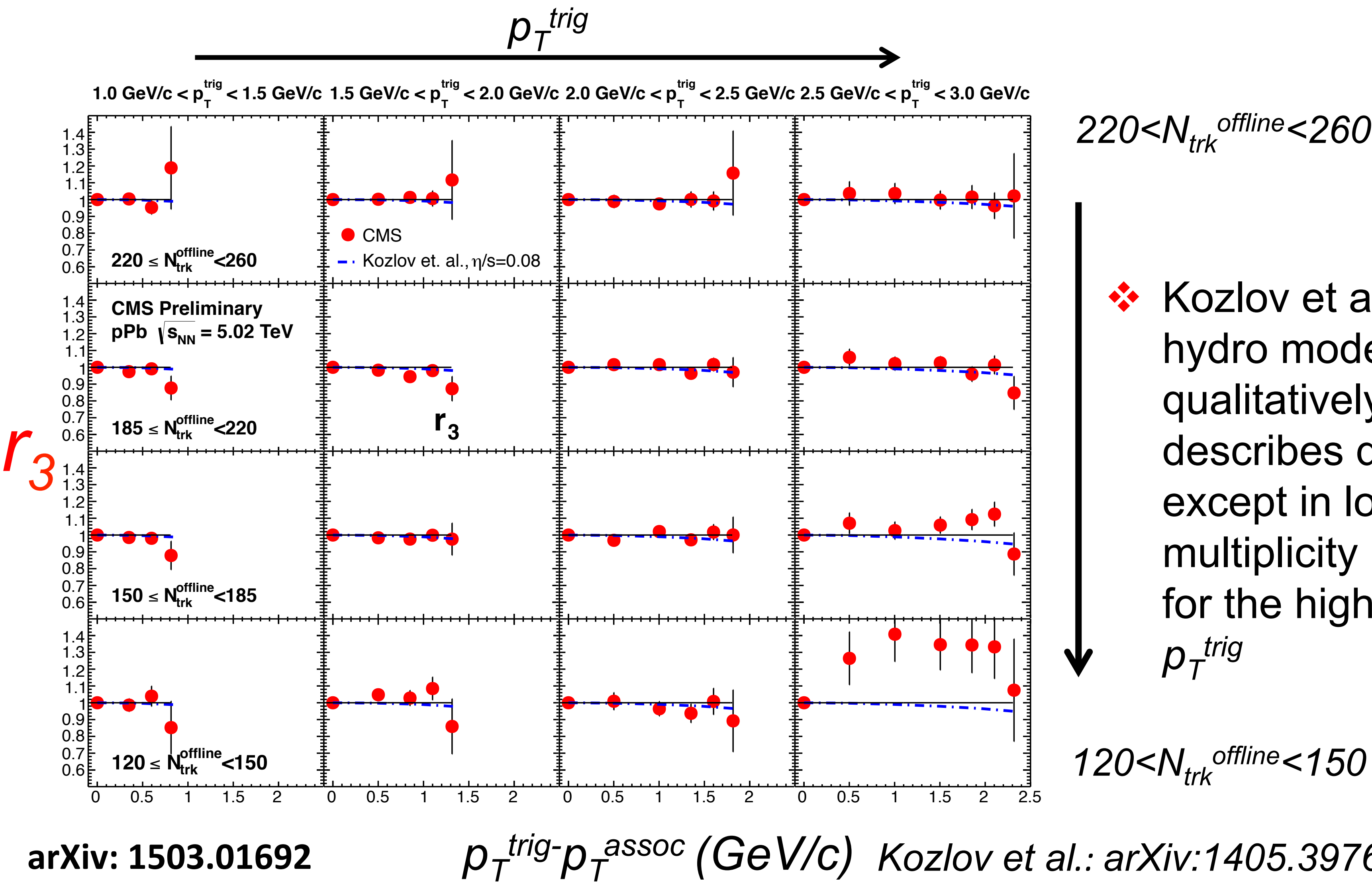
r_3 from high-multiplicity pPb collisions



- 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

arXiv: 1503.01692
submitted to **PRC**

pPb r_3: comparison to Kozlov et. al hydro model

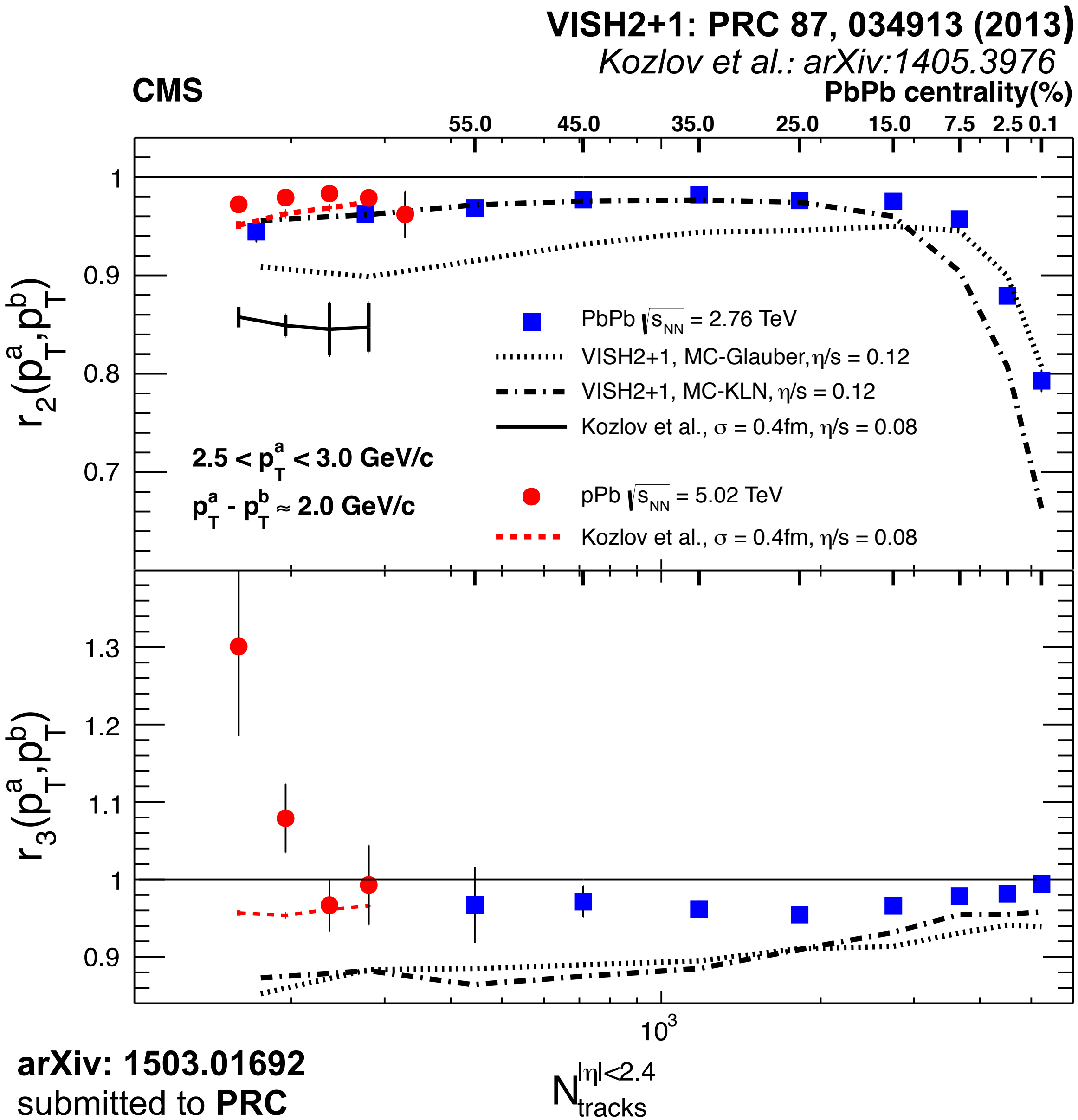


- Kozlov et al. hydro model qualitatively describes data except in lower multiplicity bins for the highest p_T^{trig}

arXiv: 1503.01692
submitted to **PRC**

Kozlov et al.: arXiv:1405.3976

r_n multiplicity dependence at the highest Δp_T

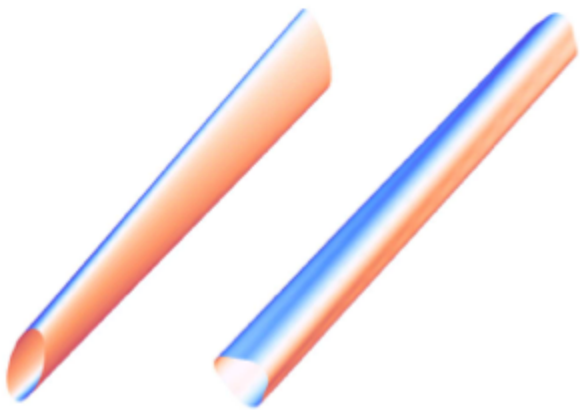


arXiv: 1503.01692
submitted to **PRC**

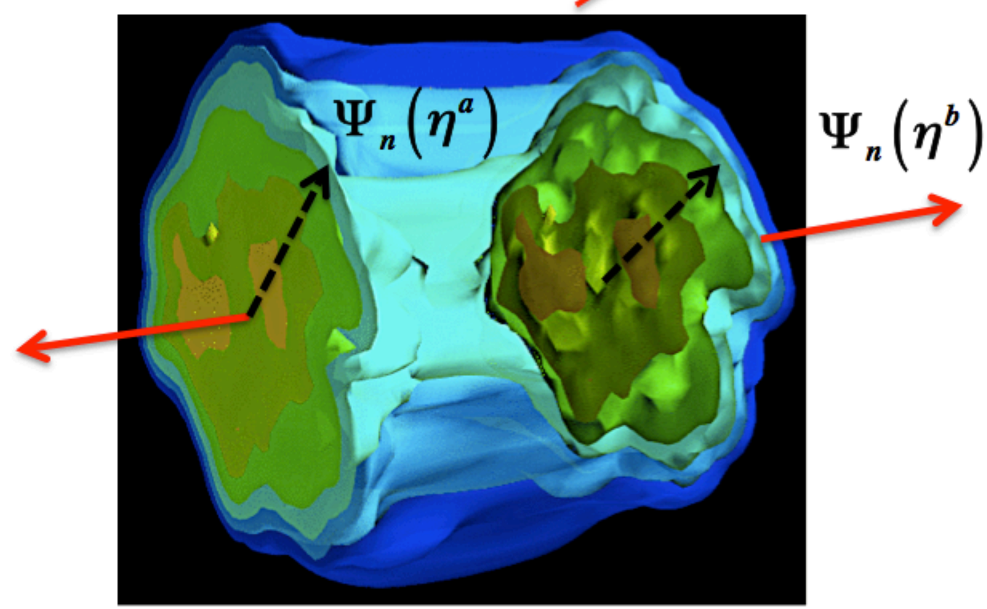
- Dramatic increase at ultra-central PbPb. For small centralities (>5%) ≈ few %
- The r_2 in pPb is a bit smaller than in PbPb
- Strong r_3 multiplicity dependence in pPb, but very weak in PbPb
- A non-flow effect in pPb for the highest p_T^{trig} in lower multiplicities
- VISH2+1 qualitatively describes CMS data
- Kozlov et al. hydro model describes pPb. Gives stronger effect for PbPb and fails for r_3 at low multiplicity

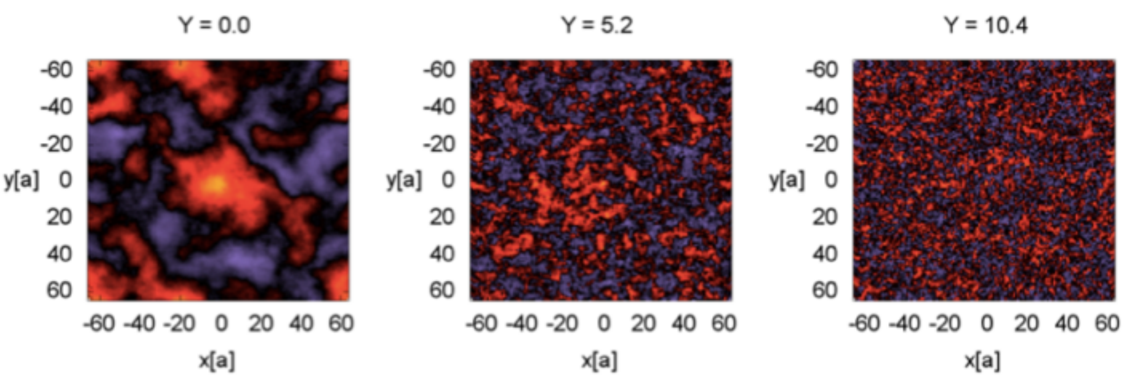
Factorization breaking – η dependence

$$f(p_T,\phi,\eta) \sim 1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\left[n\left(\phi - \Psi_n\left(p_T,\eta\right)\right)\right]$$



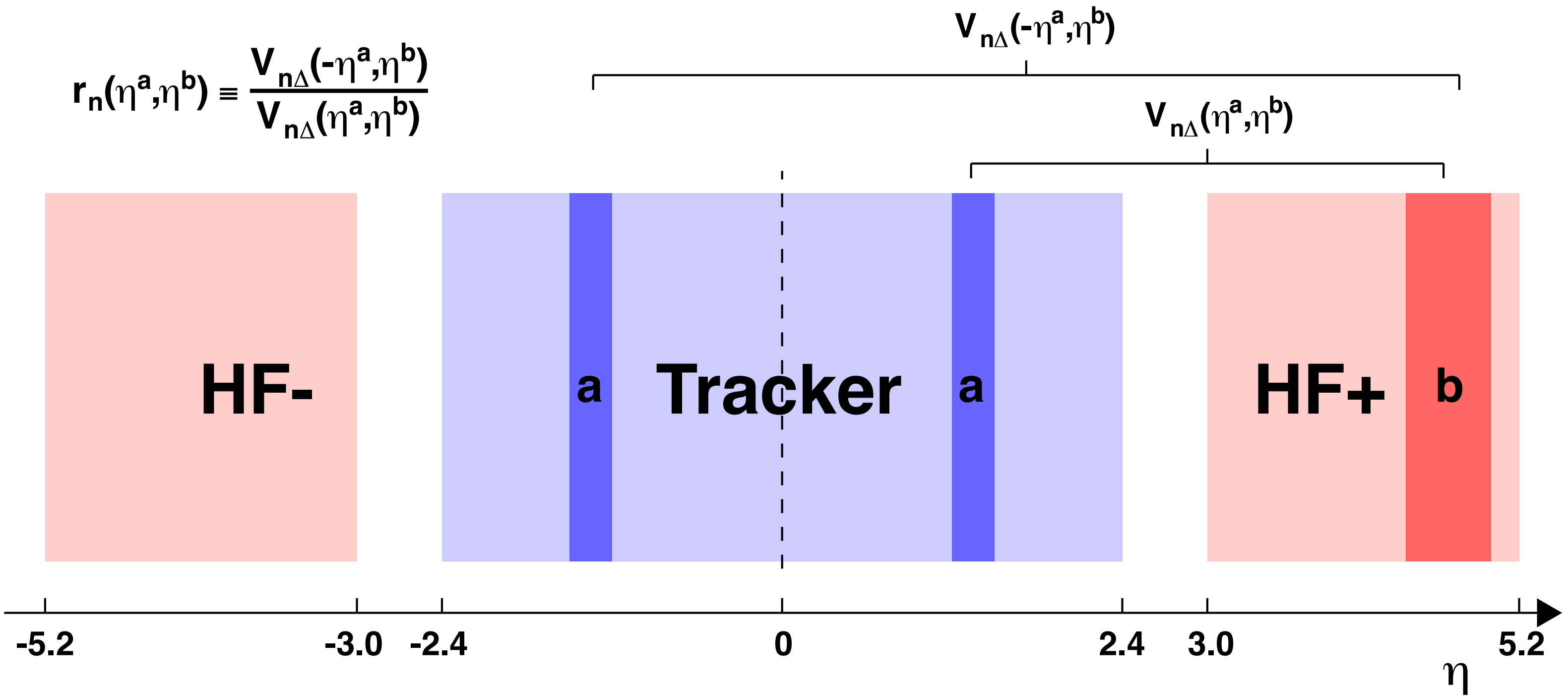
Bozek et al., arXiv: 1011.3354
Global twist





Dumitru et al., arXiv: 1108.4764

η-dependent r_n using Hadronic Forward (HF)



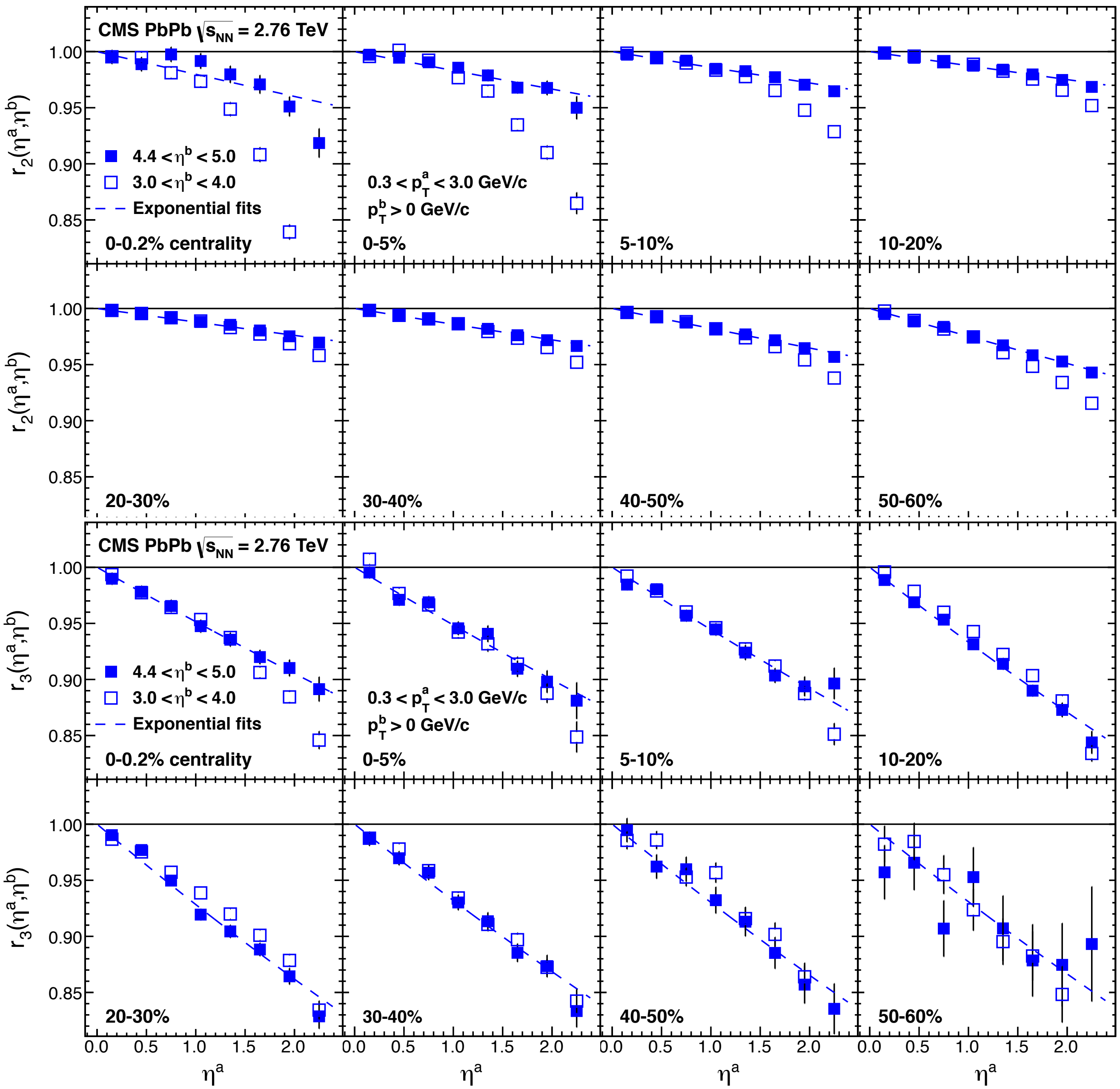
For symmetric collision:

$$r_n(\eta^a,\eta^b) \approx \frac{\left\langle \cos\left[n\left(\Psi_n(-\eta^a)-\Psi_n(\eta^b)\right)\right]\right\rangle}{\left\langle \cos\left[n\left(\Psi_n(\eta^a)-\Psi_n(\eta^b)\right)\right]\right\rangle}$$

For asymmetric collision:

$$\sqrt{r_n(\eta^a,\eta^b)\times r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\left\langle \cos\left[n\left(\Psi_n(-\eta^a)-\Psi_n(\eta^b)\right)\right]\right\rangle}{\left\langle \cos\left[n\left(\Psi_n(\eta^a)-\Psi_n(\eta^b)\right)\right]\right\rangle}\frac{\left\langle \cos\left[n\left(\Psi_n(\eta^a)-\Psi_n(-\eta^b)\right)\right]\right\rangle}{\left\langle \cos\left[n\left(\Psi_n(-\eta^a)-\Psi_n(-\eta^b)\right)\right]\right\rangle}}$$

η-dependent r_n in PbPb



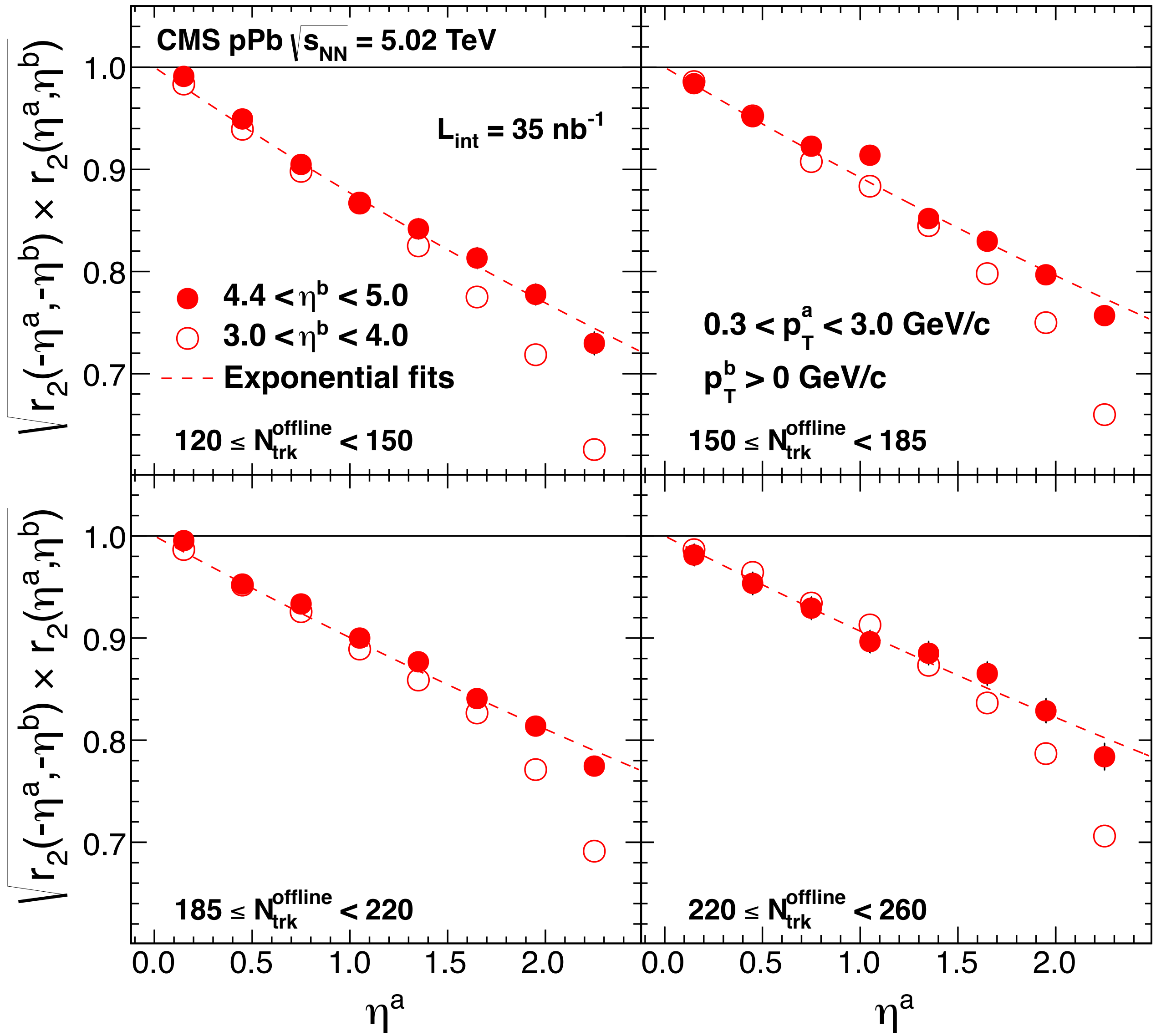
- ❖ The r_2 factorization
- breaking effect increases with increase of η^a
- ❖ Except for the most central collisions, the increase is approximately linear

arXiv: 1503.01692
submitted to **PRC**

- ❖ The effect of factorization breaking is much stronger for higher-order harmonic r_3 – opposite to the p_T dependence
- ❖ Almost linear increase of the effect size
- ❖ Parameterization:

$$r_n\left(\eta^a,\eta^b\right)\approx e^{-2F_n^{\eta}\eta^a}$$

η-dependent r_n in pPb



- A significant factorization breakdown in η found in pPb collisions with increase of η^a
- The effect increases approximately linearly with η^a
- Parameterization with F_n^η is purely empirical introduced just to quantify behavior of the data

$$r_n\left(\eta^a,\eta^b\right) \approx e^{-2F_n^\eta \eta^a}$$

arXiv: 1503.01692
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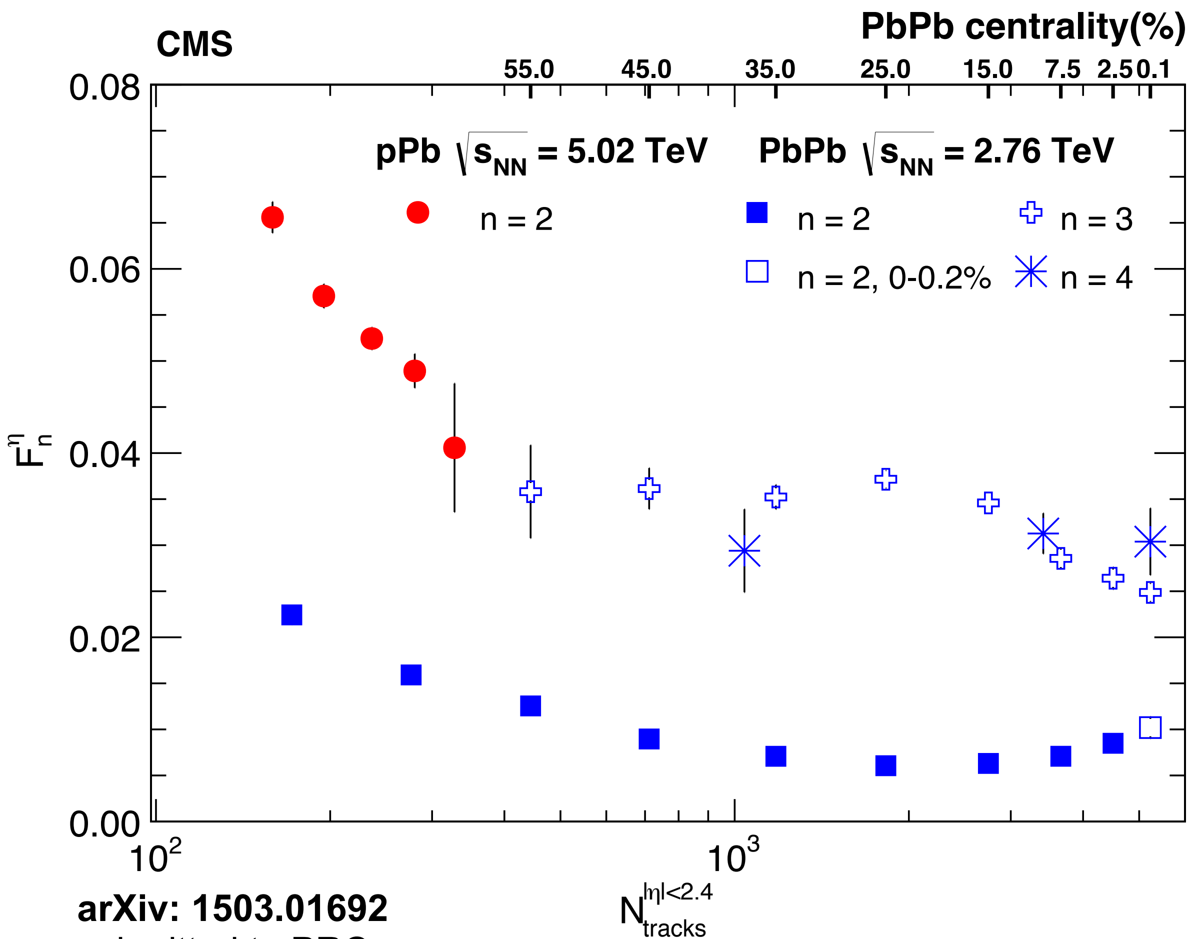
η-dependent r_n *vs* multiplicity



arXiv: 1503.01692
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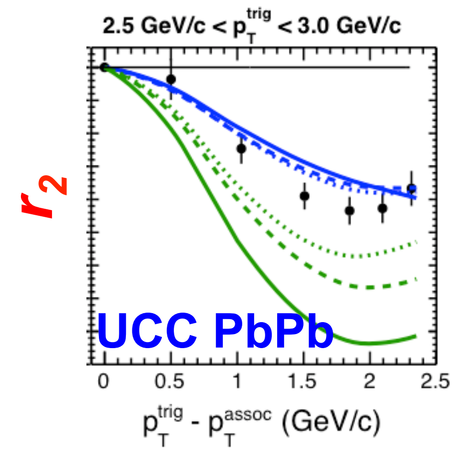
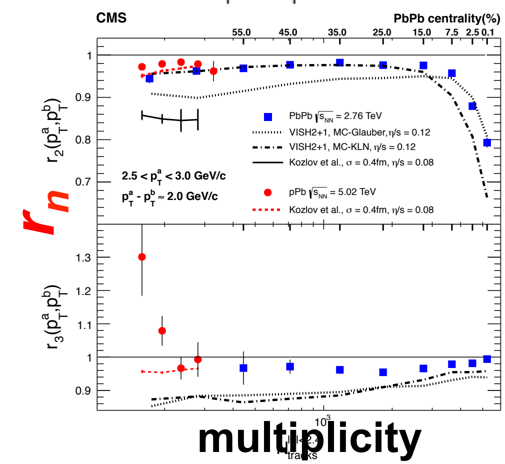
- The F_2^η has a minimum around midcentral PbPb and increases for peripheral and most central collisions
- At similar multiplicity, F_2^η in pPb larger than the one in PbPb
- Except for the most central PbPb, there is a very weak centrality dependence of F_3^η

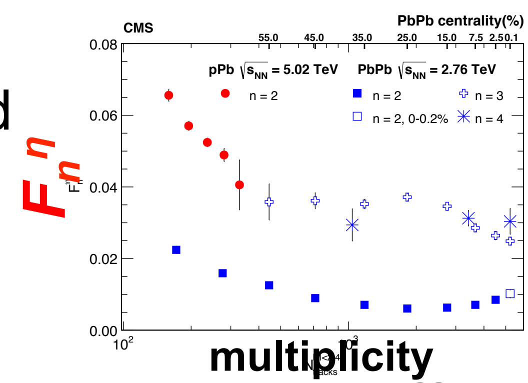
- In PbPb, higher-orders F_3^η and F_4^η, show much stronger factorization breaking than for the second order

Conclusions

- Azimuthal anisotropy in ultra-central PbPb collisions dominantly induced by initial state fluctuations
- CMS measured factorization breaking of two-particle correlations in PbPb and pPb
- Strong p_T-dep. effect in ultra-central PbPb
- 2-3% in pPb, comparable to PbPb at similar mult.
- Qualitatively consistent with hydro models with p_T dependent EP angle induced by initial-state fluct.
- The factorization breaking effect in η is smallest for mid-central PbPb; increases going to peripheral and most central collisions
- Significantly larger effect in pPb than in PbPb
- 3-rd and 4-th order effect are stronger than the 2-nd

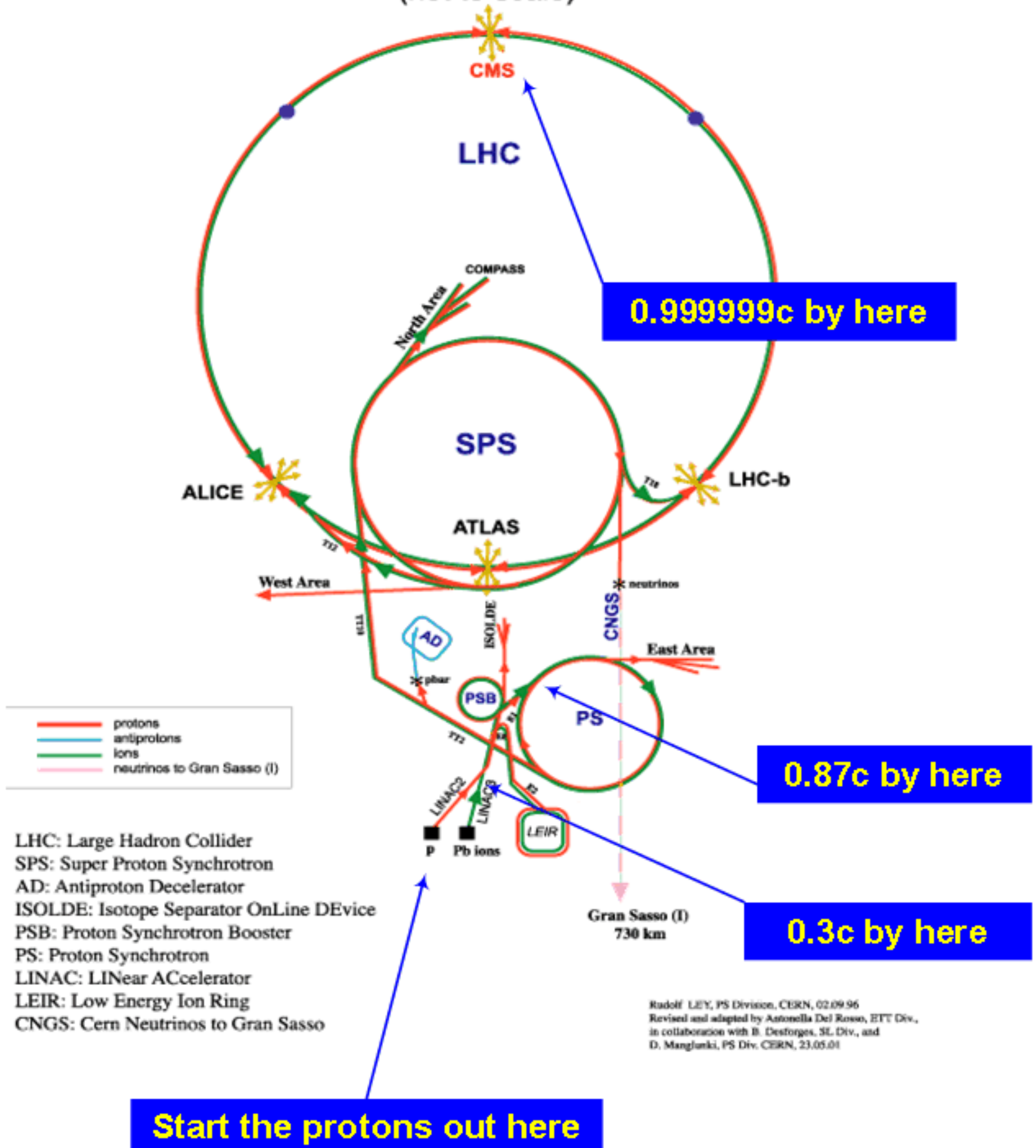






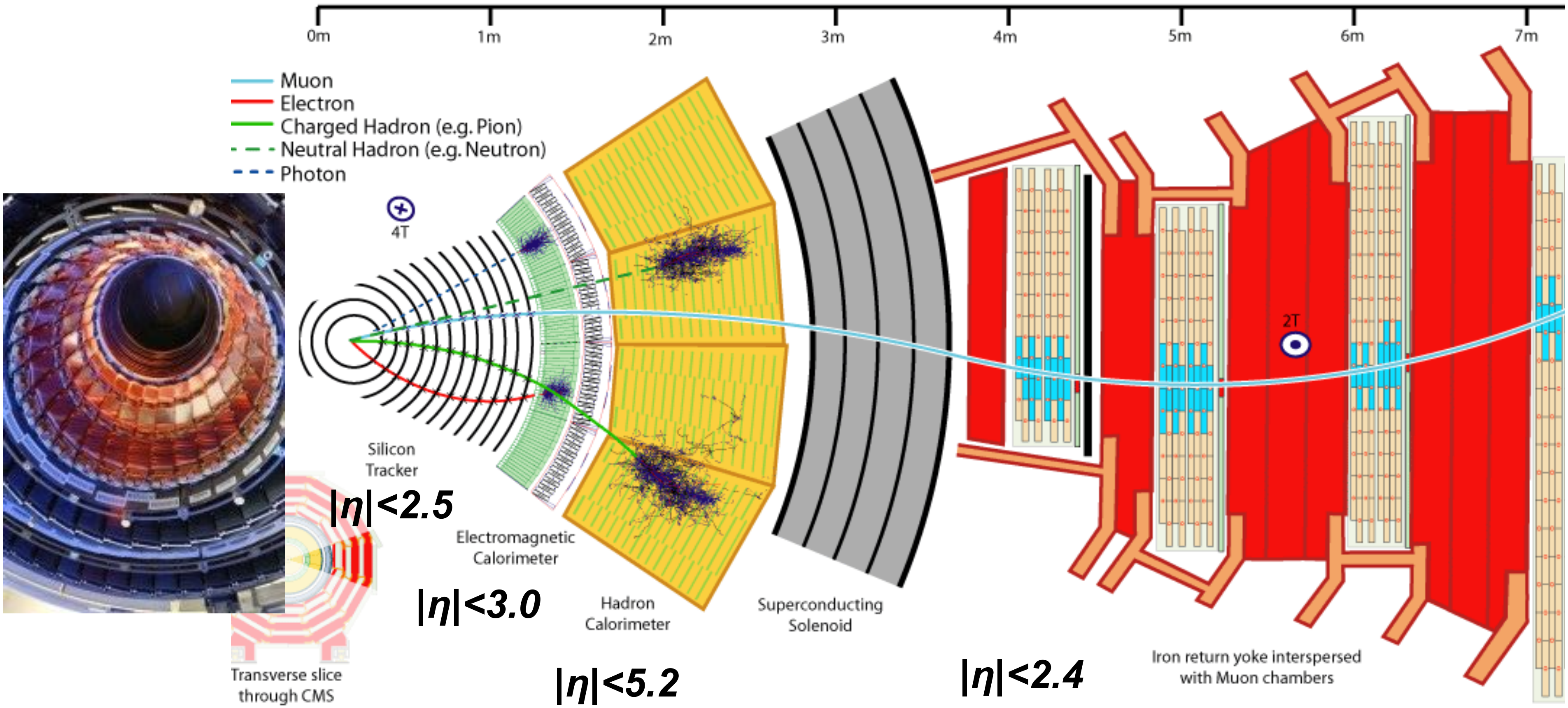
Backup

CERN Accelerators
(not to scale)



Compact Muon Solenoid (CMS) - schematic view

A slice through CMS detector in a plane perpendicular to the beam axis



Used data from Silicon Tracker:

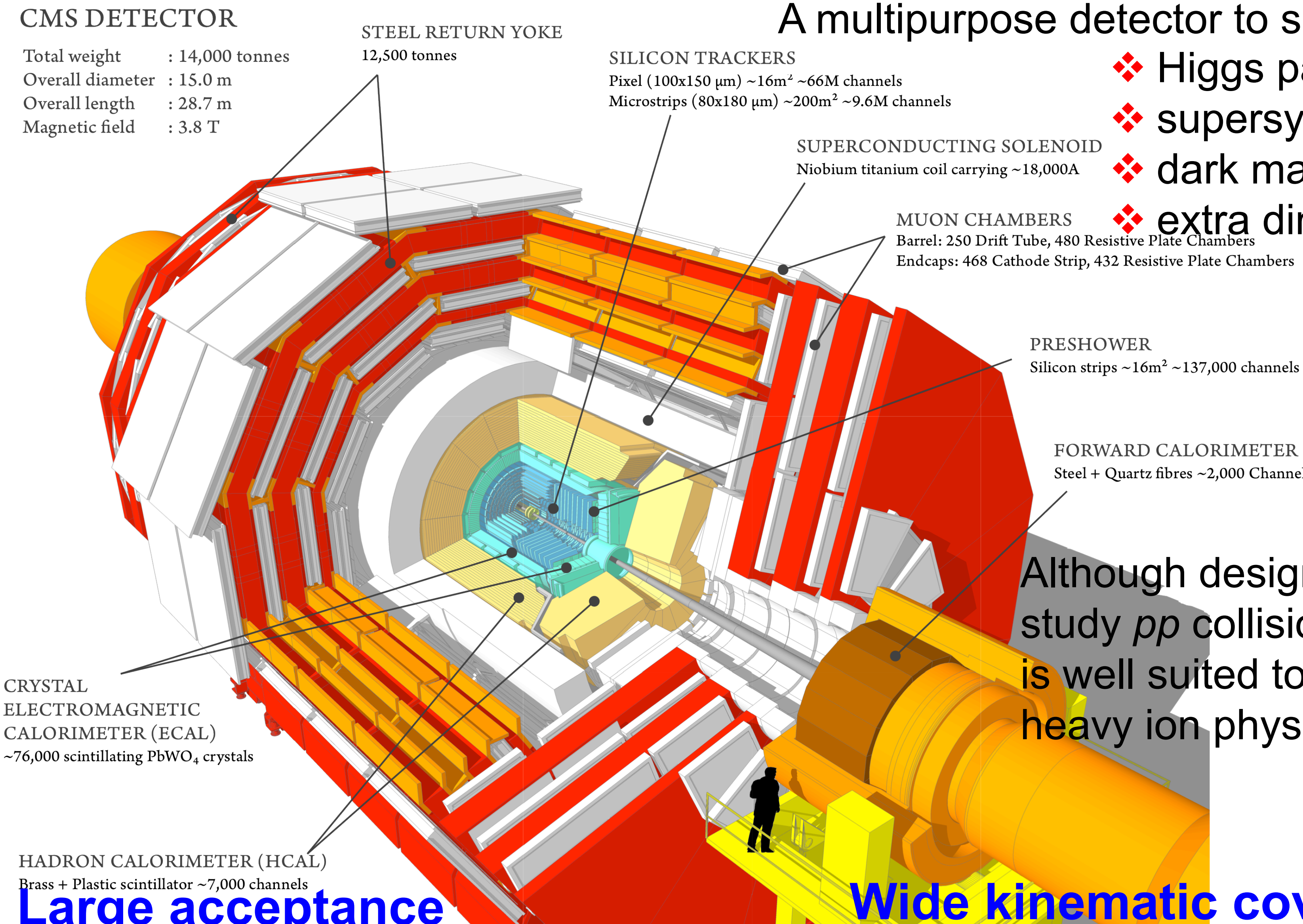
charged particles with: $|\eta| \leq 2.4 \quad p_T \geq 0.3 GeV/c$

Large acceptance

Wide kinematic coverage

Compact Muon Solenoid (CMS) - schematic view

A multipurpose detector to search for:
- Higgs particle
- supersymmetry
- dark matter
- extra dimensions

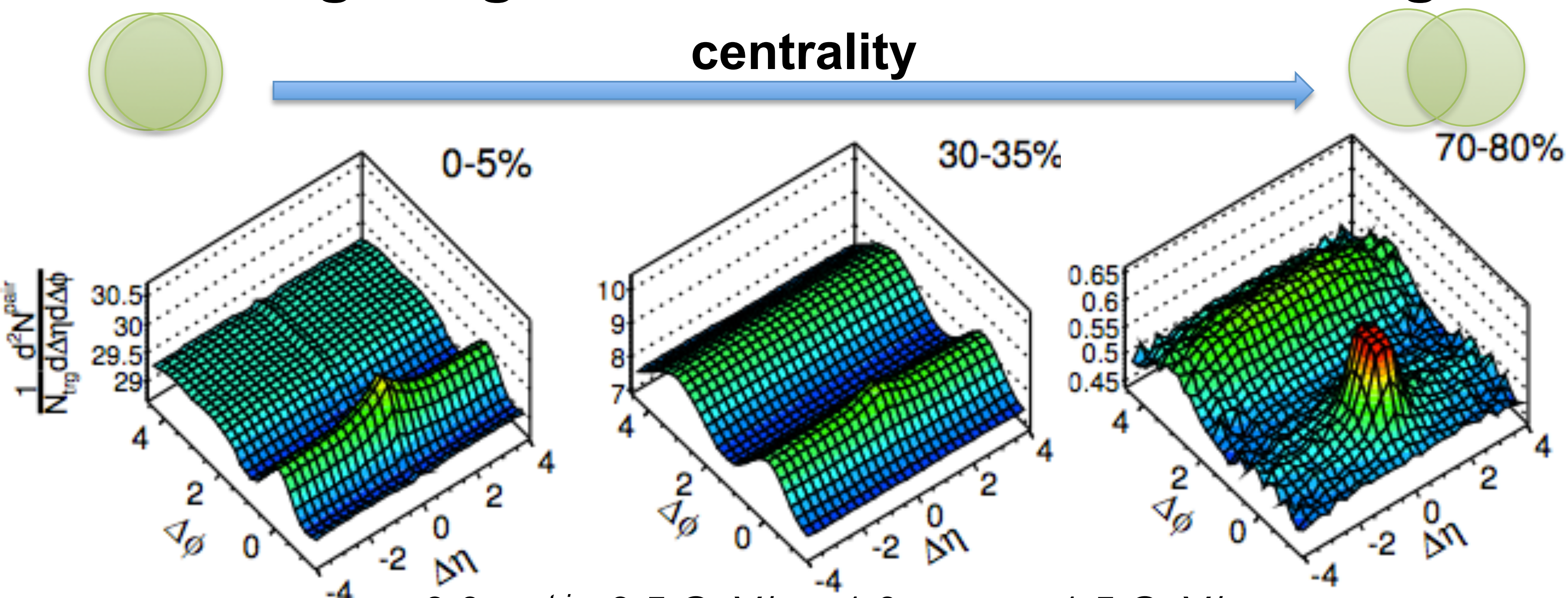


Although designed to study *pp* collisions, CMS is well suited to study heavy ion physics too

Large acceptance

Wide kinematic coverage

Long-range azimuthal correlations - ridge

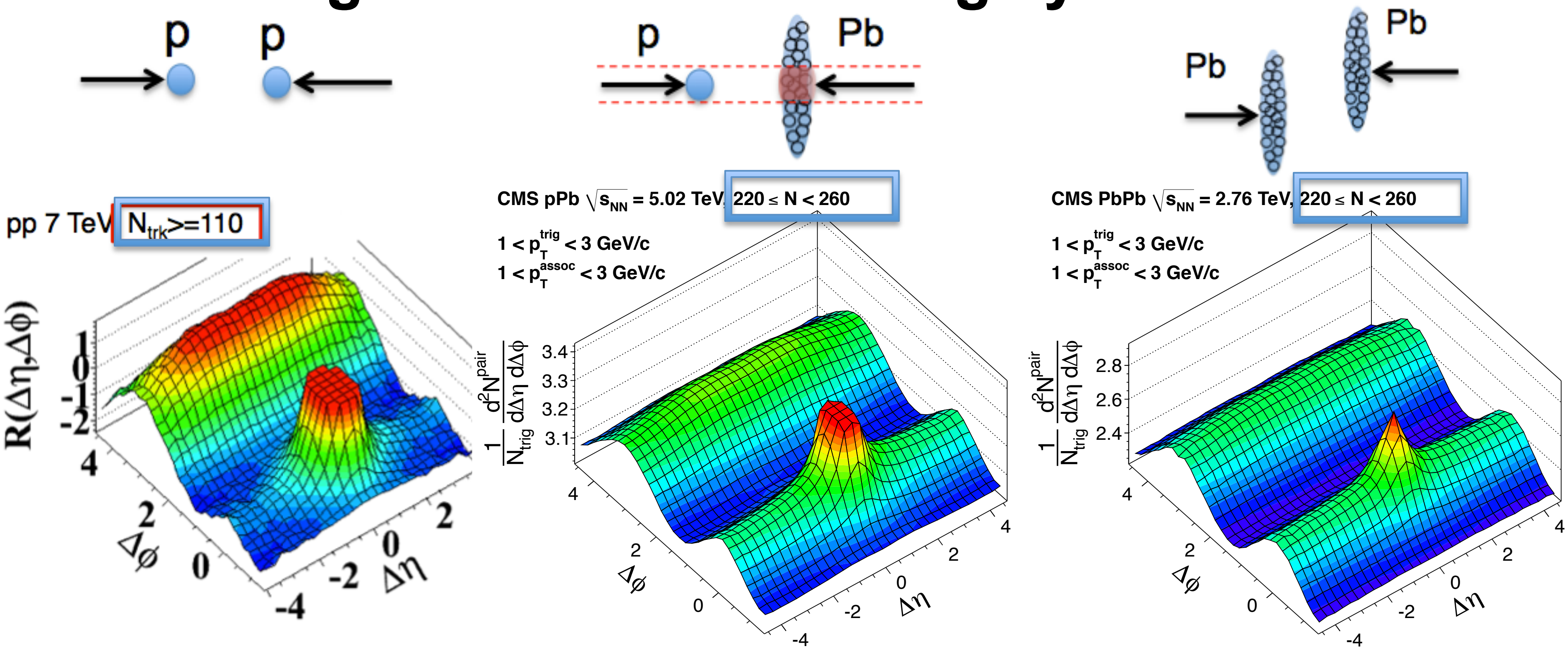


3.0<p_T^{trig}<3.5 GeV/c 1.0<p_T^{assoc}<1.5 GeV/c

Eur. Phys. J. C. 72(2012)

- ❖ Collectivity diminishing as system size decreases
- ❖ Thus, in pp and pPb collisions no collectivity is expected
- ❖ But with increasing the incident energy in pp or pPb collisions a small and hot QGP could be created and collectivity could appear

The ridge seen in all colliding systems at LHC

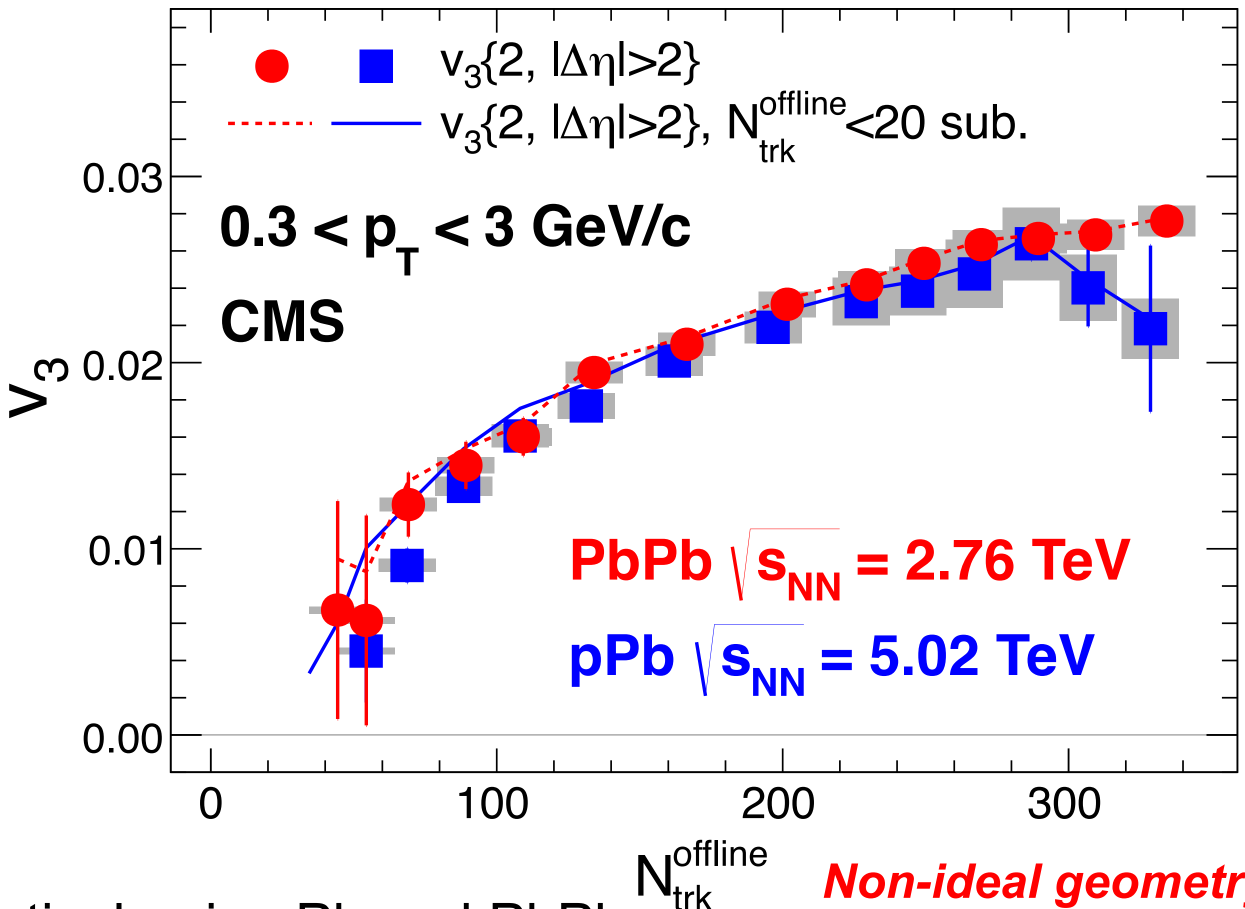


JHEP 09 (2010) 091 — **PLB 718 (2013) 795** — **PLB 724 (2013) 213**

- Does the ridge in *pp* and *pPb* collisions originate from hydrodynamics flow like in PbPb collisions or it is connected with color-glass condensate (CGC)

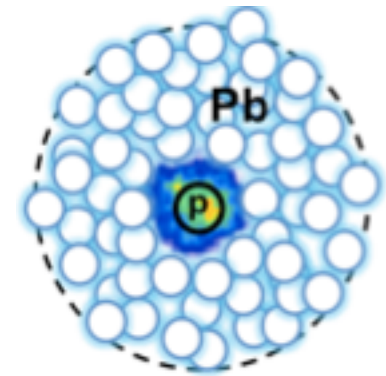
Triangular flow (v_3) in PbPb and pPb

Phys.Rev.Lett. 724 (2013) 213



Non-ideal geometry

Hydro failed



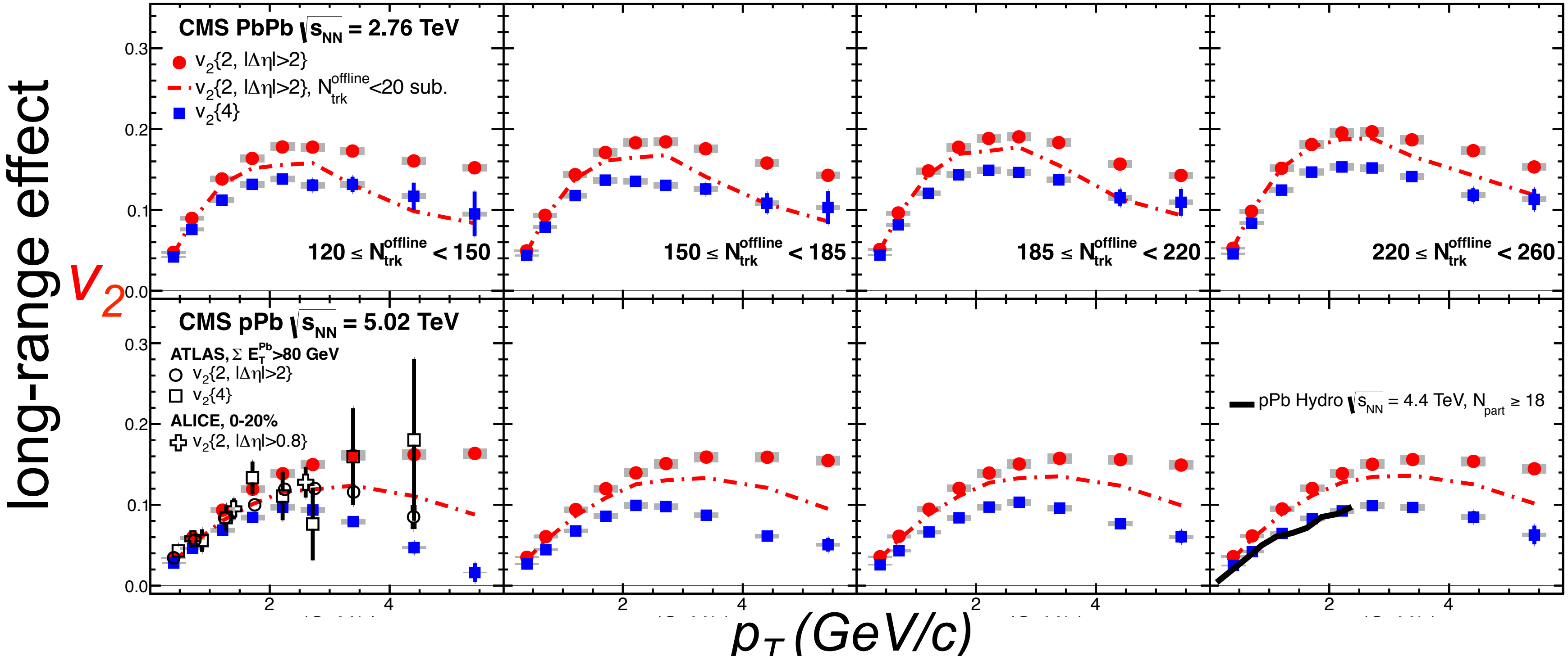
Proton is mainly spherical in IP glasma (1405.3605)

Stringy proton caught by nucleus?
(PRD **89** (2014) 025019)

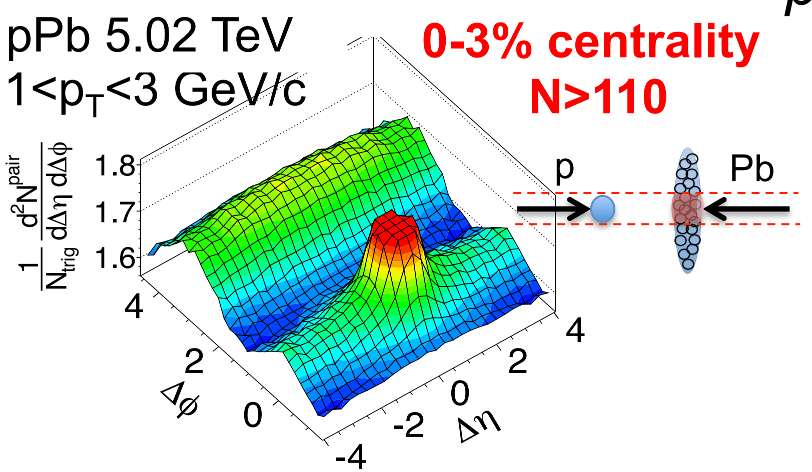
Identical v_3 in pPb and PbPb

Initial state not understood,
especially subnucleonic structure or
non-hydro correlations? PRD **87** (2013) 094034

v_2 in peripheral PbPb and high-multiplicity pPb collisions



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

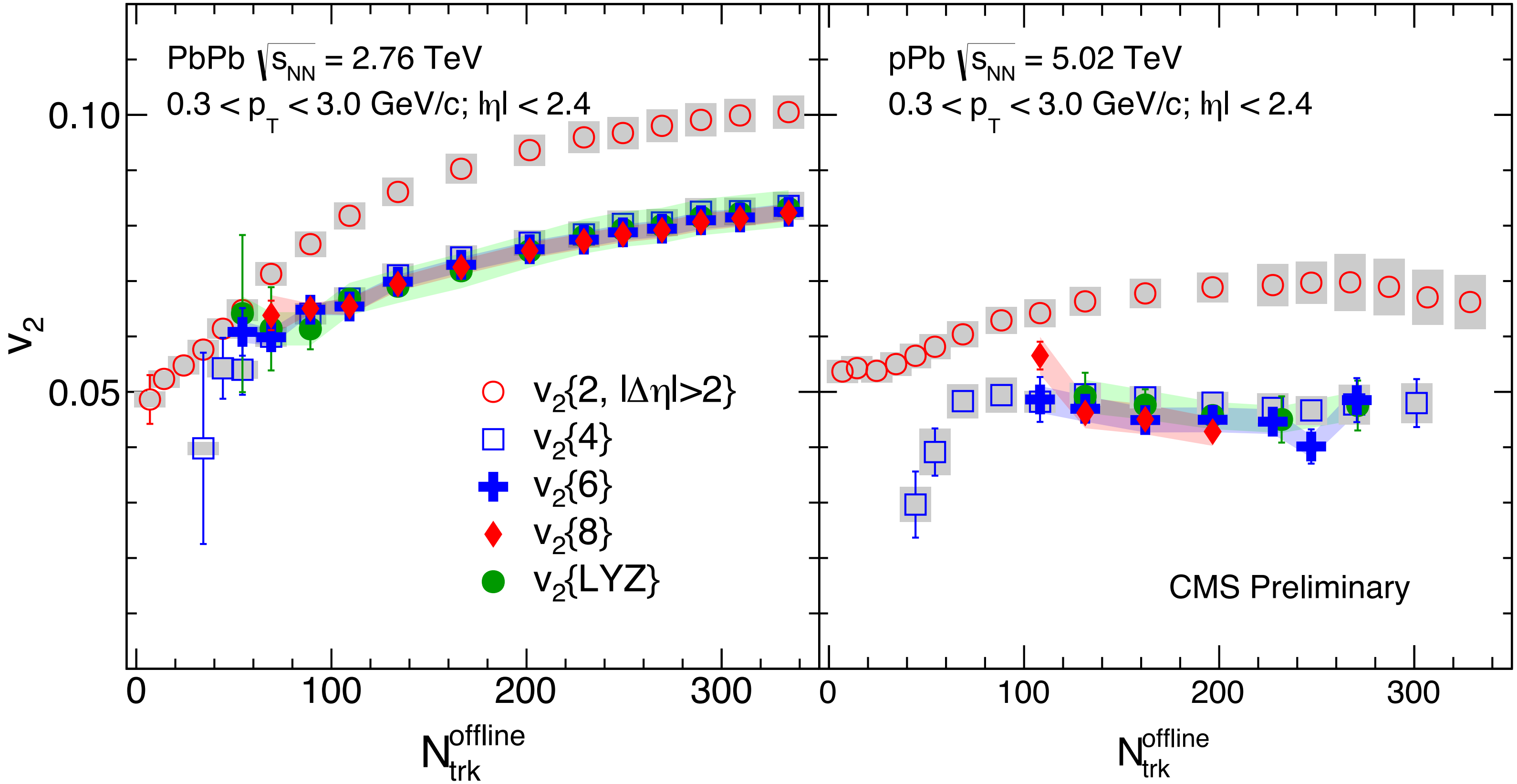


PLB 718 (2013) 795

- ❖ v_2 is a bit larger in PbPb than in pPb
- ❖ $v_2\{2,|\Delta\eta|>2\}>v_2\{4\}$ could be due EbE initial state fluctuations
- ❖ Hydro describes $v_2\{4\}$, although it does not includes EbE fluctuations
- ❖ Do we see hydro flow in pPb or quantum interference of gluons (CGC)?

v_2 in PbPb and pPb collisions *vs* multiplicity

long-range effect

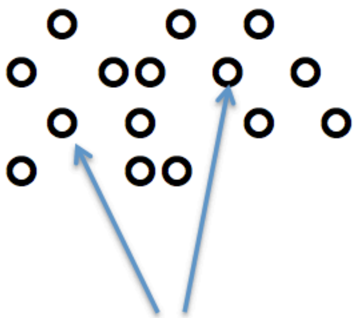


arXiv:1502.05382 submitted to **PRL**

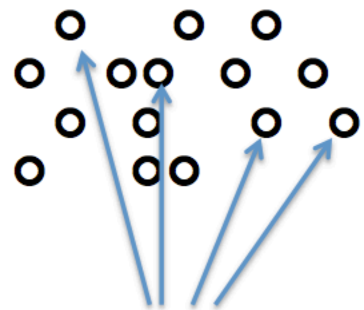
Shown at **Quark Matter 2014**

- *v_2{4}, v_2{6}, v_2{8}* and *v_2{LYZ}* are in a mutual agreement within 10% for both PbPb and pPb collisions
- As v_2 in pPb does not depend on number of particles used in its reconstruction, it is a strong evidence to support interpretation of the long-range correlation as a collective phenomenon

v_n from multi-particle correlations – cumulants



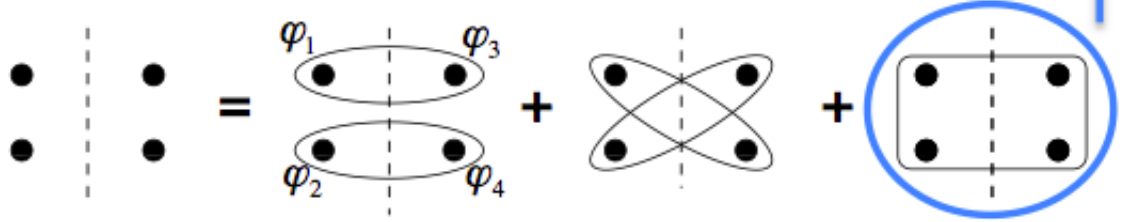
$$\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle$$



$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle$$

Adventage wrt 2-part.corr.: four-particle correlations remove two- and three-particle non-flow correlation etc.

$$\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle - \left\langle e^{in(\phi_1-\phi_3)}\right\rangle\left\langle e^{in(\phi_2-\phi_4)}\right\rangle - \left\langle e^{in(\phi_1-\phi_4)}\right\rangle\left\langle e^{in(\phi_2-\phi_3)}\right\rangle$$



$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$

Reference flow: $v_2^{ref}\{4\} = \sqrt[4]{-c_2\{4\}}$ Differential flow: $v_2\{4\}(p_T) = \dfrac{-d_2\{4\}(p_T)}{(v_2^{ref}\{4\})^3}$

where in $d_2\{4\}(p_T)$ one of four reference particles is replaced with a particle from a particular p_T region.

v_n from even higher order cumulants

$$\langle\langle 6\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\right\rangle$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

→

$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

8-th order even more complicated c_n formulae $v_n\{8\} = \sqrt[4]{-\frac{1}{33}c_n\{8\}}$

and corresponding differential flow coefficients

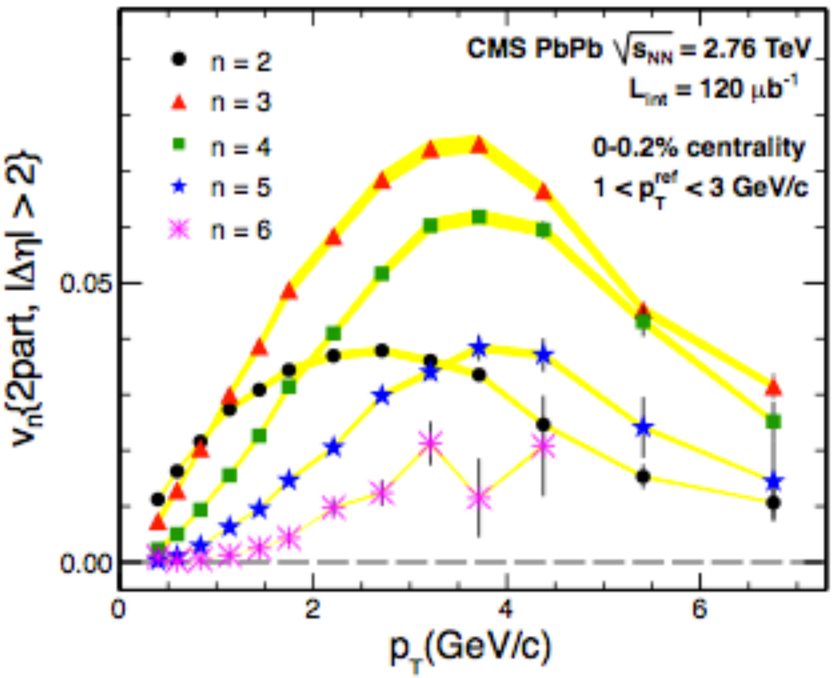
Within hydrodynamics is:

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \ldots \approx v_2\{\infty\}$$

Lee-Yang Zero (LYZ) method correlates all particles of interest seen in an event and in principle should exclude any non-flow effect

Flow in ultra-central PbPb collisions

v_n from two-particle correlations for different harmonic order



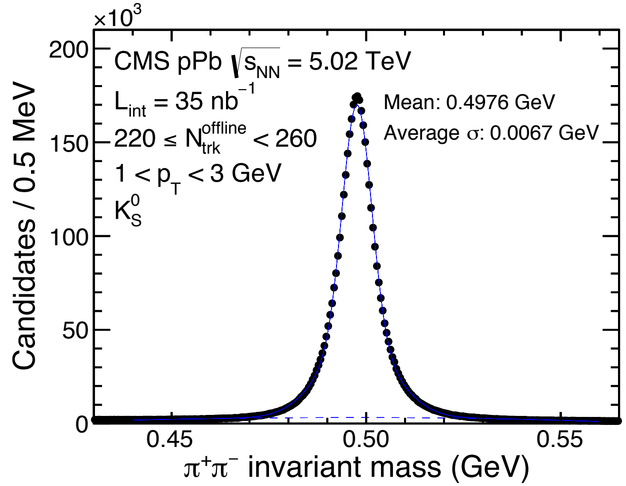
JHEP 1402 (2014) 088
(arXiv:1312.1845)

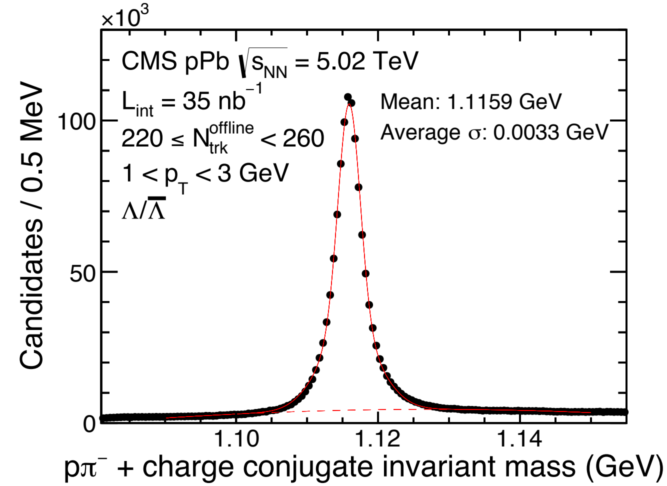
All orders of v_n tend to saturate approaching 0.0-0.2% centrality

➔ Effect dominantly induced by initial state fluctuations

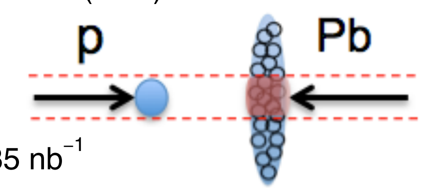
Long-range correlations of strange particles at CMS

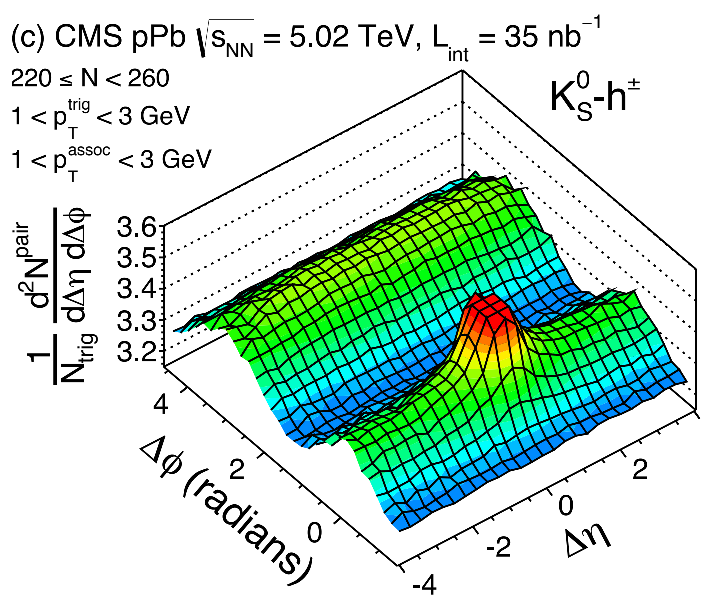
PLB **742** (2015) 200

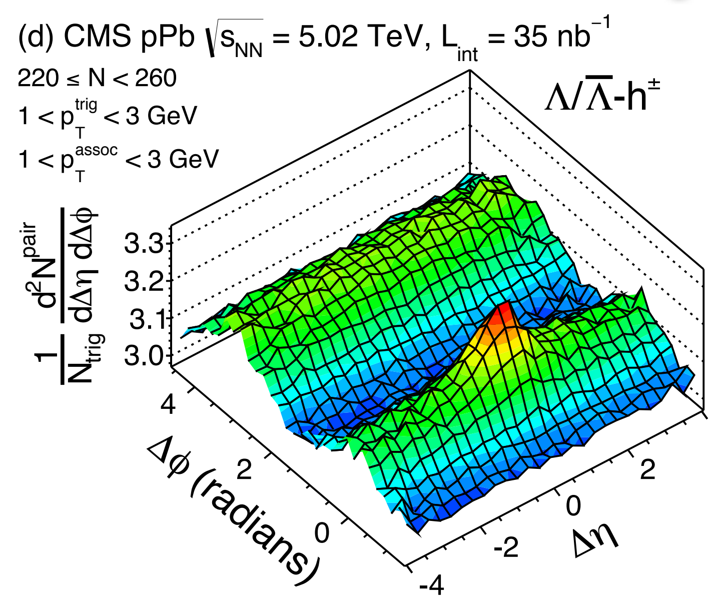




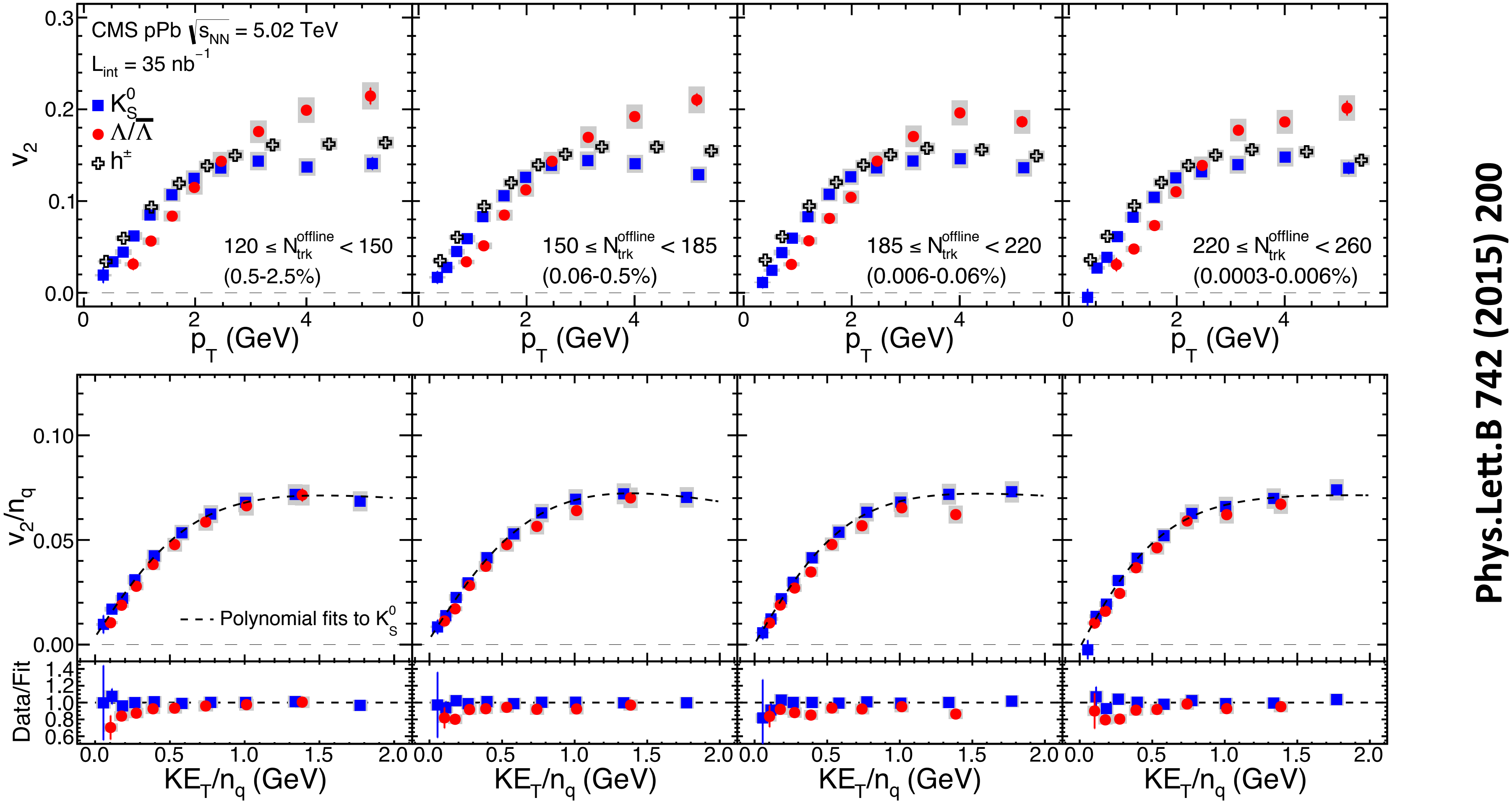
Ridge seen with K^0_S and Λ also



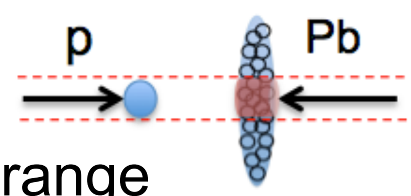




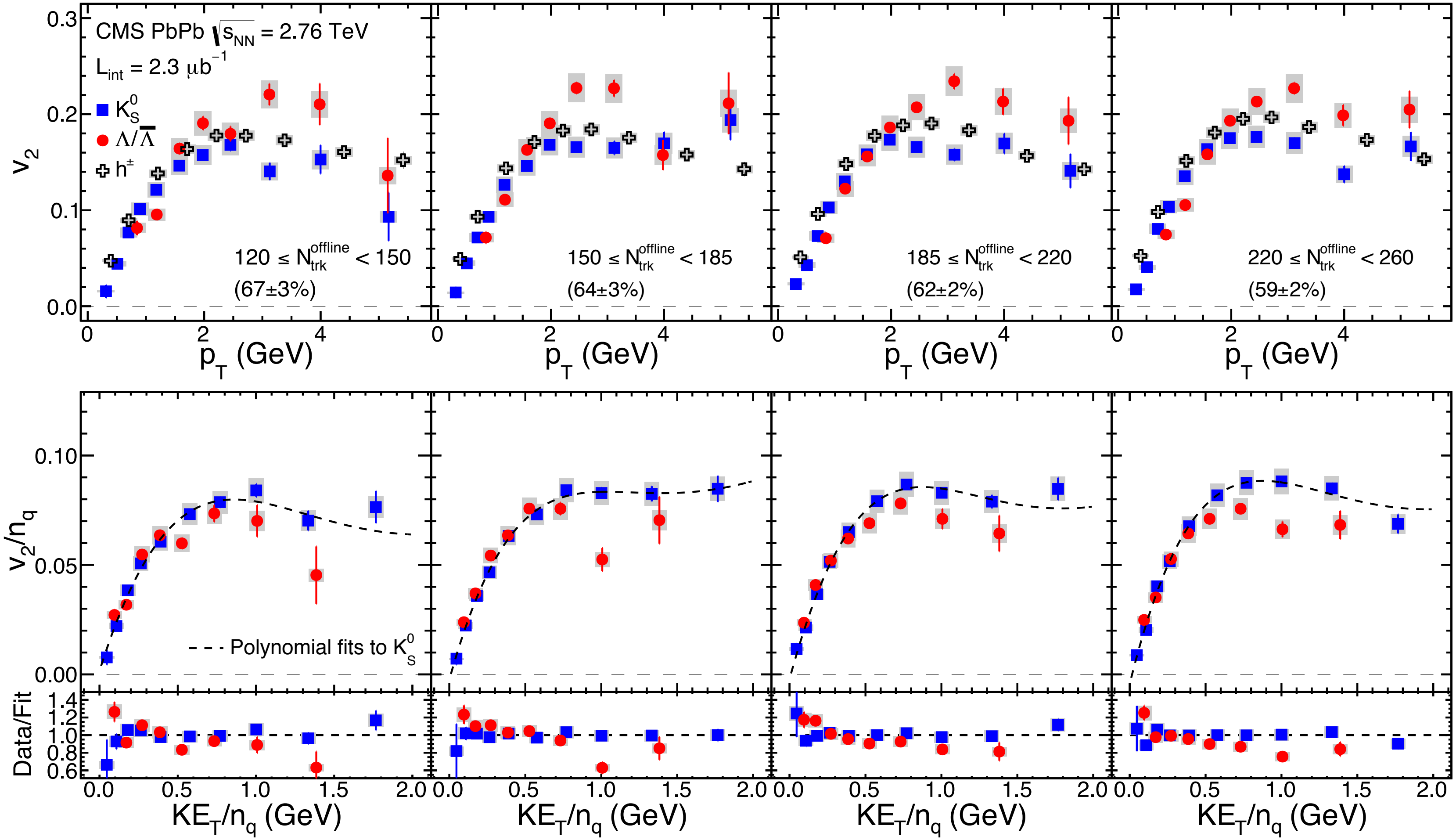
Partonic degree of freedom in pPb collisions



- At low p_T: $v_2\{h^{+/-}\}>v_2\{K^0_S\}>v_2\{\Lambda\}$
- At high p_T: $v2(baryon)>v_2(meson)$
- Scaling to the n_q better than 10% over whole KE_T/n_q range

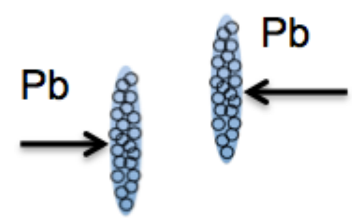


Partonic degree of freedom in PbPb collisions



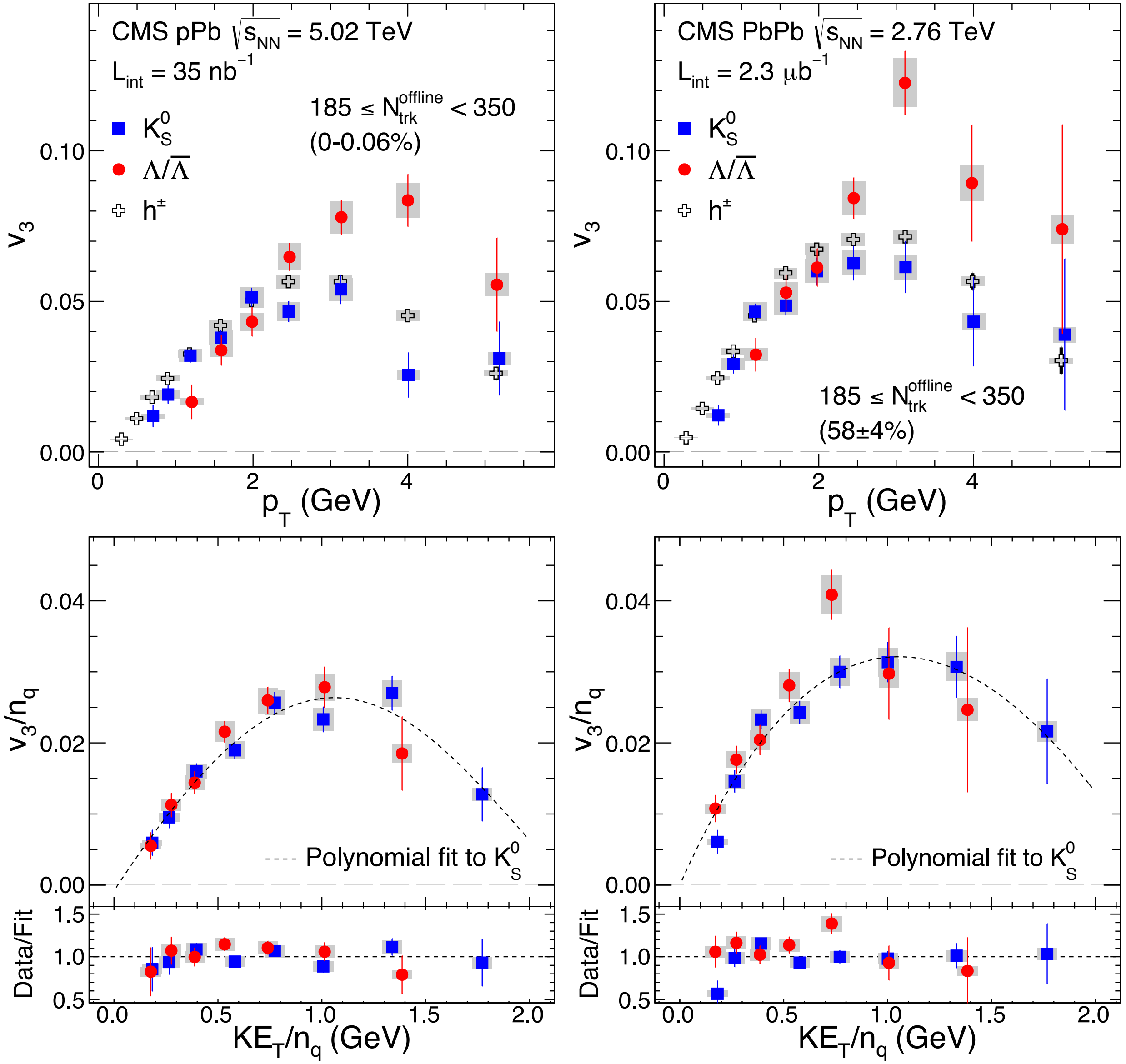
Phys.Lett.B 742 (2015) 200

- At low p_{T}: $v_2\{h^{+/-}\}>v_2\{K^0_S\}>v_2\{\Lambda\}$
- As high p_T: $v2(baryon)>v_2(meson)$
- Scaling to the n_q less evident than in the pPb data



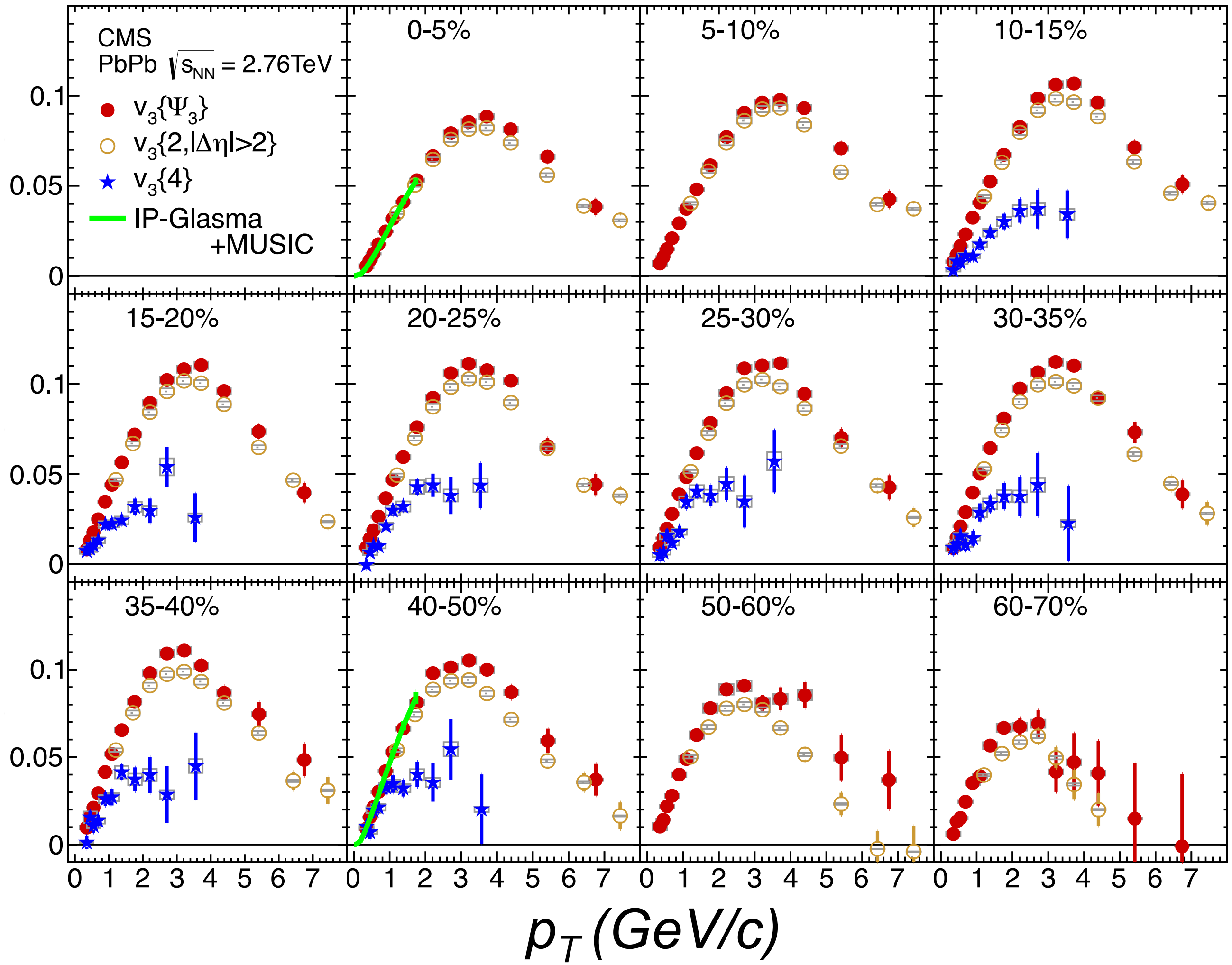
Partonic degree of freedom – triangular flow

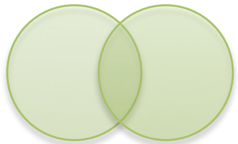
Phys.Lett.B 742 (2015) 200



- Strange particles, $K^0{}_S$ and Λ, show a similar behavior concerning the scaling to the n_q also for v_3
- No calculations on v_3 scaling to the n_q has been performed in recombination models

Triangular flow (v_3) in PbPb



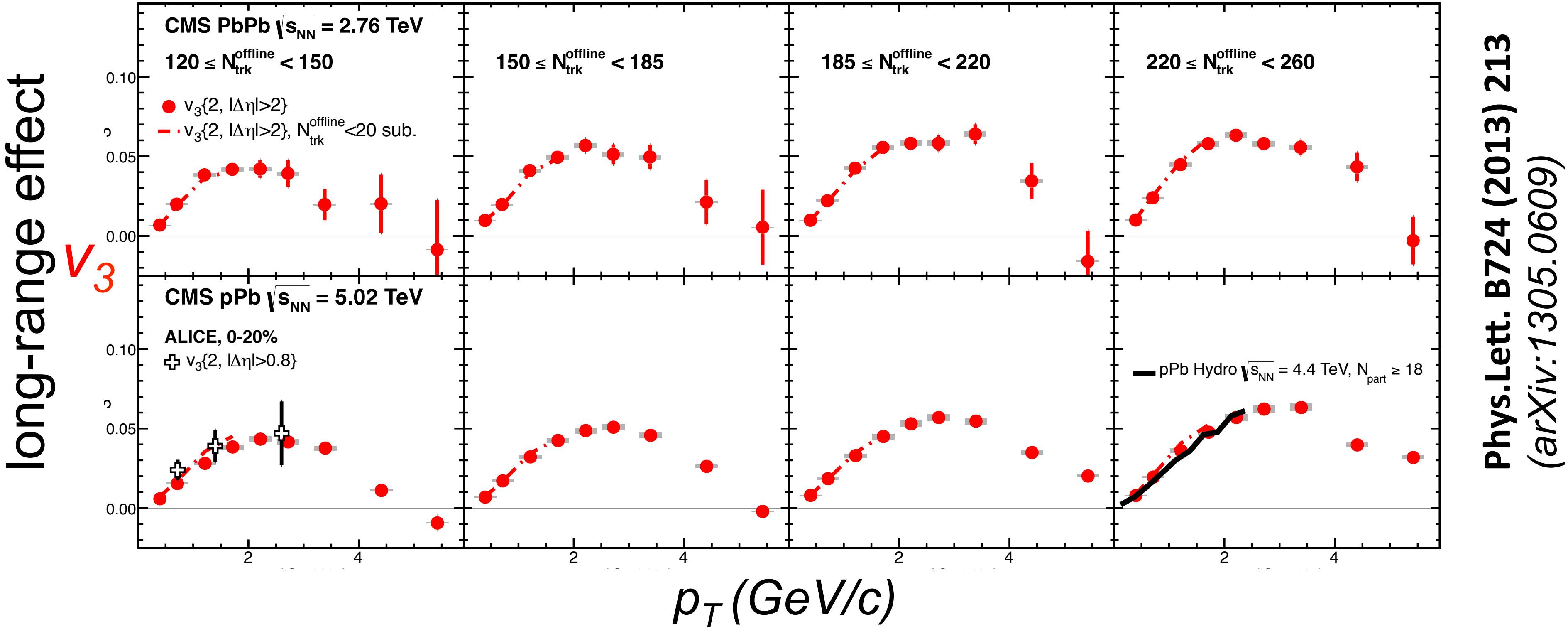


Phys.Rev. C89 (2014) 044906
(arXiv:1310.8651)

$$v_3(\Psi_3) \approx v_3\{2, |\Delta\eta| > 2\} >> v_3\{4\}$$ nearly independent on centrality

➔ Strong effect of initial state fluctuations

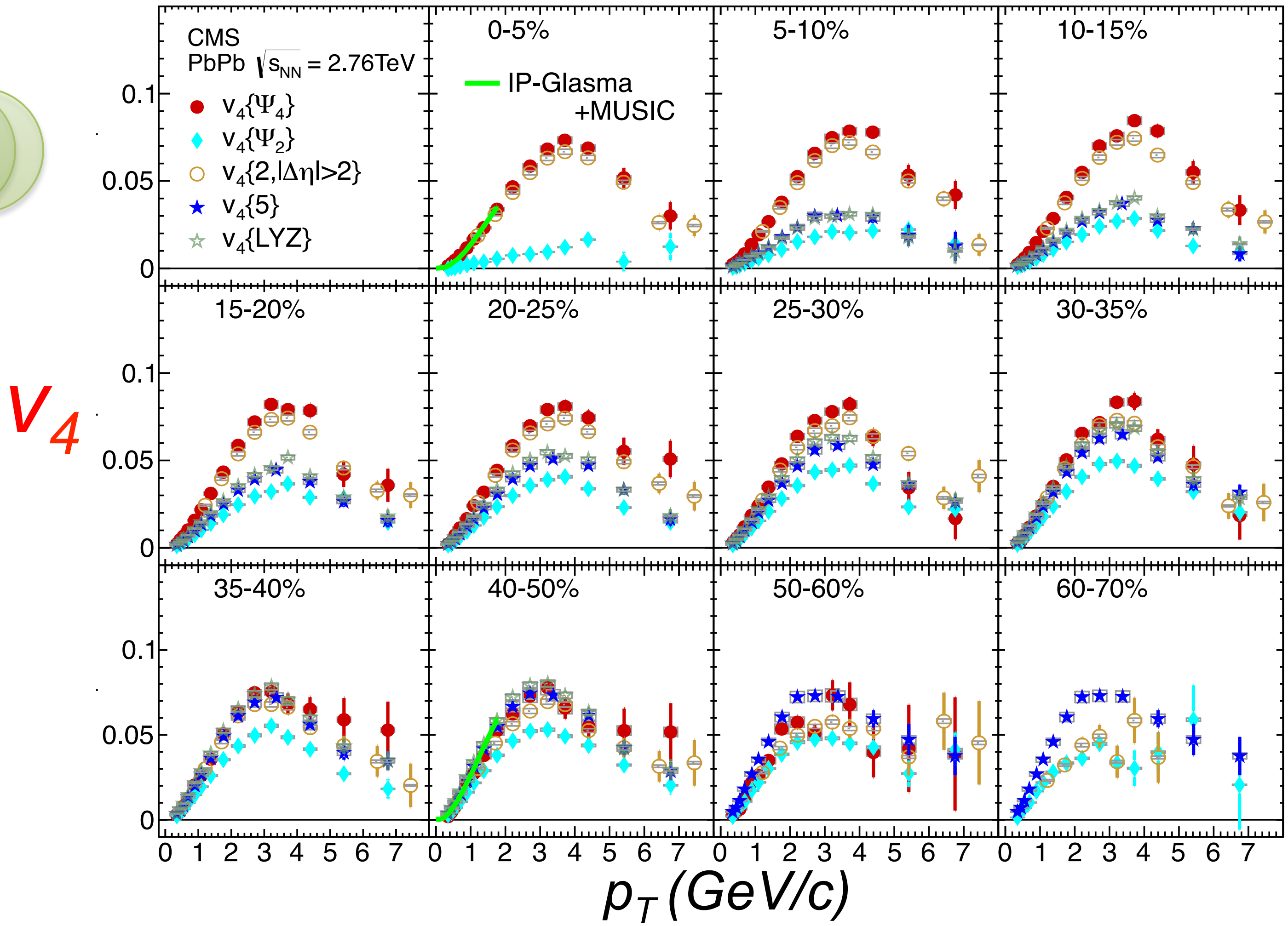
v_3 in peripheral PbPb and high-multiplicity pPb collisions

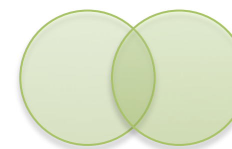


- Remarkable similarity of v_3 magnitude in both, PbPb and pPb
- If jet-induced correlations are independent of pPb multiplicity, they could be removed by subtracting low-multiplicity yields

- The low-multiplicity-subtracted $v_2\{2,|\Delta\eta|>2\}$ pPb results are between $v_2\{2\}$ and $v_2\{4\}$, while the triangular flow remains unchanged under such a subtraction

Quadrangular flow (v_4) in PbPb





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

$v_4(\Psi_4)$ and $v_4\{2, |\Delta\eta| > 2\}$: Ψ_4 ref.

- ➢ Weak centrality dependence
- ➢ **Fluctuation dominant**

$v_4(\Psi_2)$, $v_4\{5\}$ and $v_4\{LYZ\}$: Ψ_4 ref.

- ➢ Stroger centrality dependence
- ➢ **Elliptic geometry dominant**