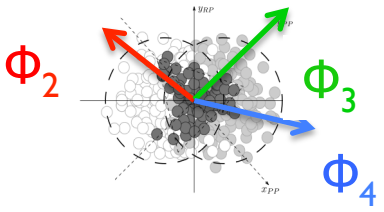
Anisotropic flow measurements at LHC energies

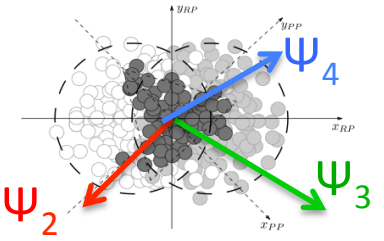
Michael Weber (CERN)

Anisotropic flow

Initial symmetry planes



Final symmetry planes ??



Anisotropic flow

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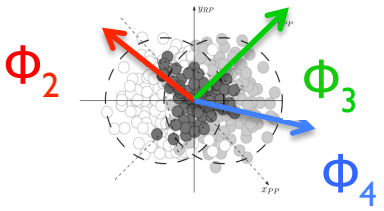

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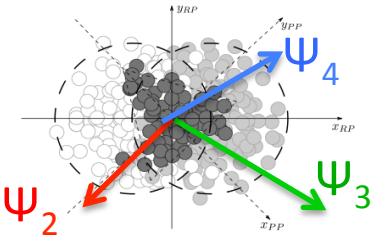
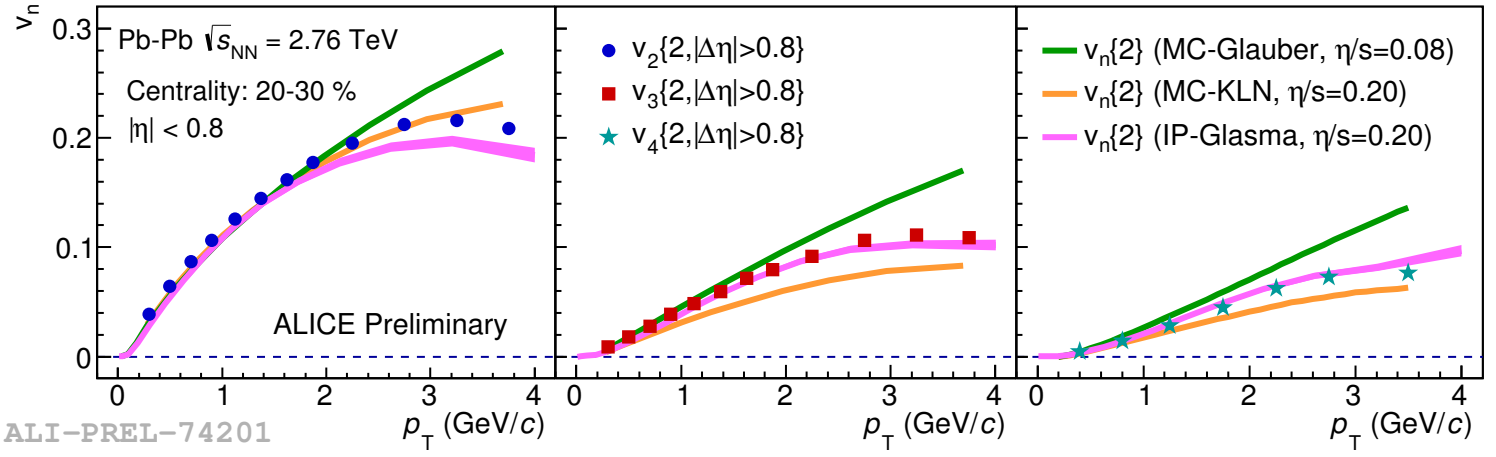


$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T\, dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\varphi-\Psi_n\right)\right)\right)$$

$$v_n=\left\langle\cos\left(n\left(\varphi-\Psi_n\right)\right)\right\rangle$$



Anisotropic flow

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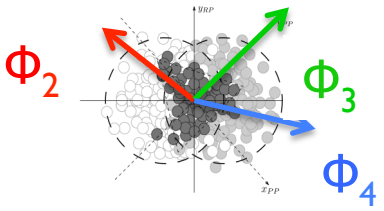

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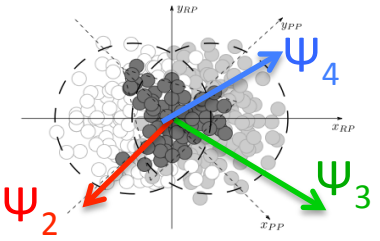

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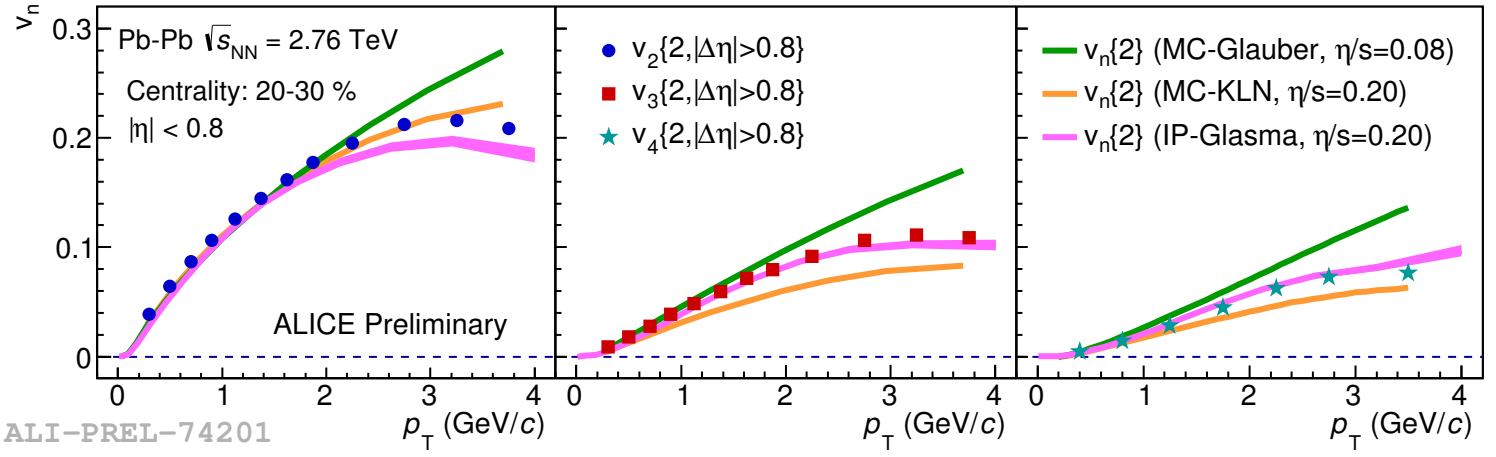
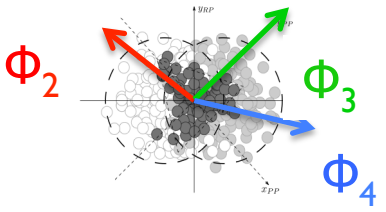


Constraints on initial state and η/s

How to measure

Initial symmetry planes



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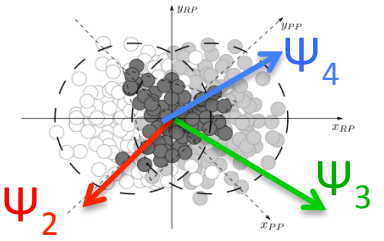
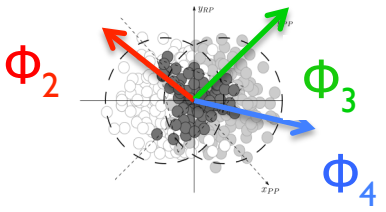


Two- and multi-particle azimuthal correlations subject to:

- **Non – flow**: $\langle \cos[n(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_n.$
- **Flow fluctuations**: $\sigma_{vn}^2 = \langle v_n^2 \rangle - \langle v_n \rangle^2 .$

How to measure

Initial symmetry planes



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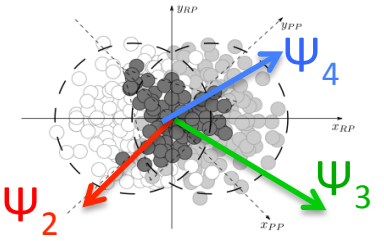

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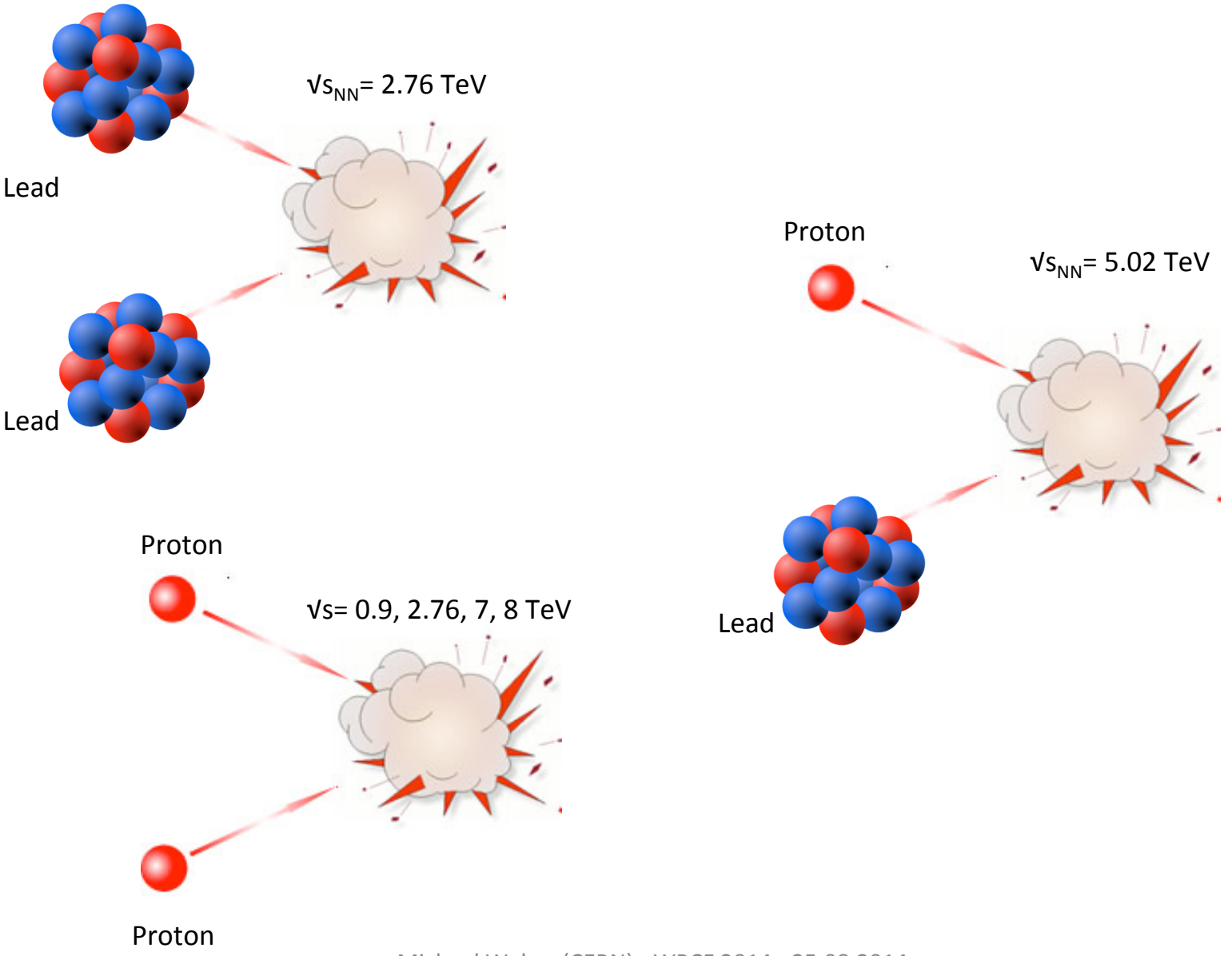
Different sensitivity of different methods:

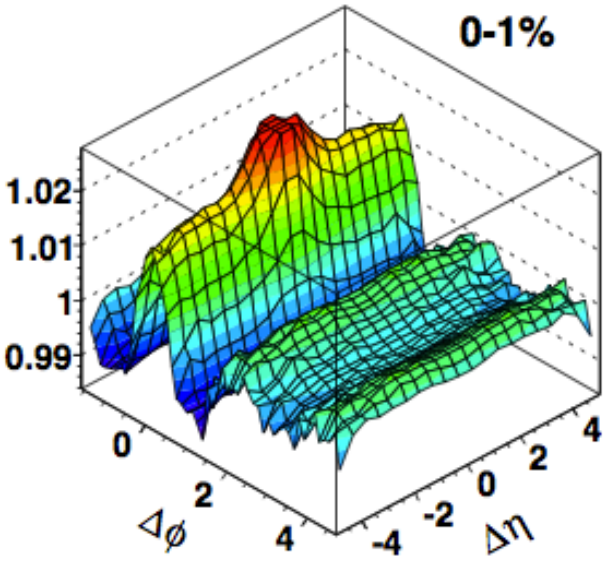
- Two-particle methods (v_2{2PC},v_2{2},v_2{SP})
  - Sensitive to non-flow and flow fluctuations (can be suppressed by rapidity gap)
- Event plane method (v_2{EP})
  - Non-trivial biases in presence of flow fluctuations
- Higher order cumulants (v_2{4,6,8}) and Lee-Yang-Zero (v_2{LYZ}) methods
  - Suppress non-flow and flow fluctuations

Three systems studied at LHC

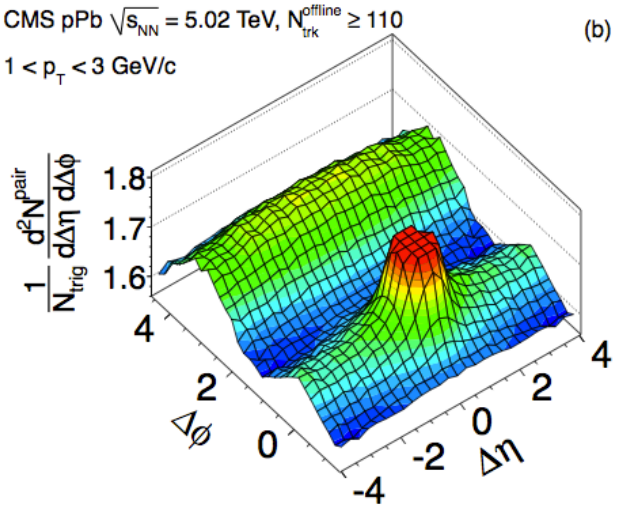


… and three “ridges” found

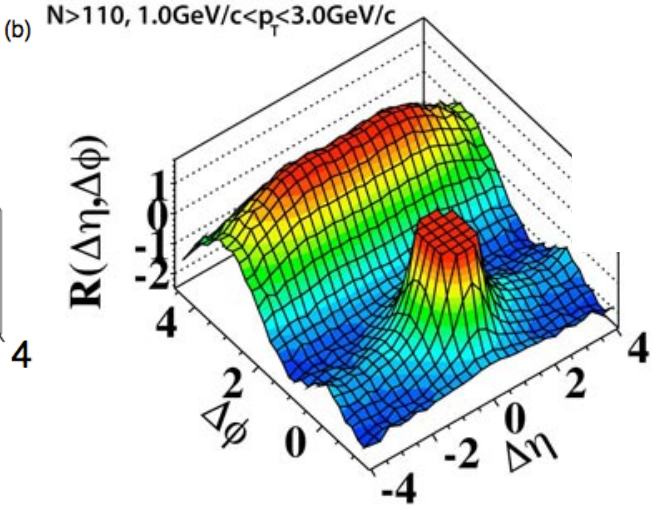
in high multiplicity events



Pb+Pb ridge



p+Pb ridge

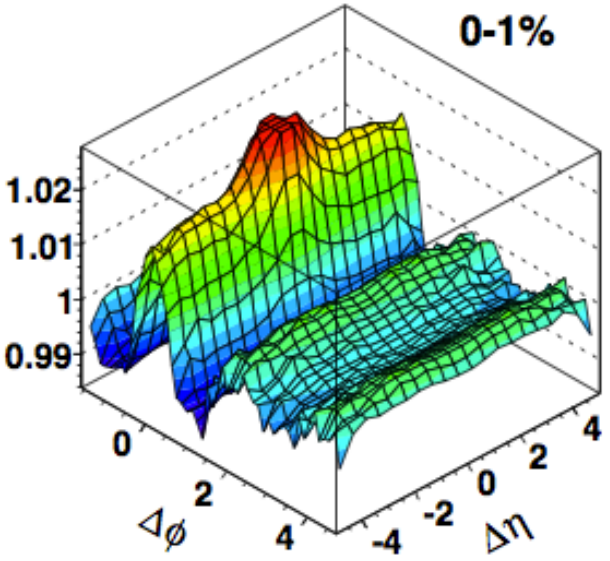


p+p ridge

$$\frac{1}{N_{trig}}\frac{dN_{assoc}(\Delta\varphi)}{d\Delta\varphi} = a_0 + \sum_{n=1}^{\infty} 2a_n \cos(n\Delta\varphi)$$

… and three “ridges” found

in high multiplicity events



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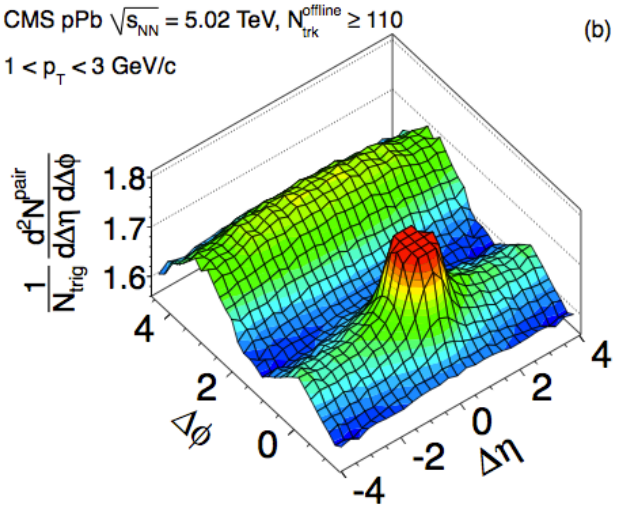

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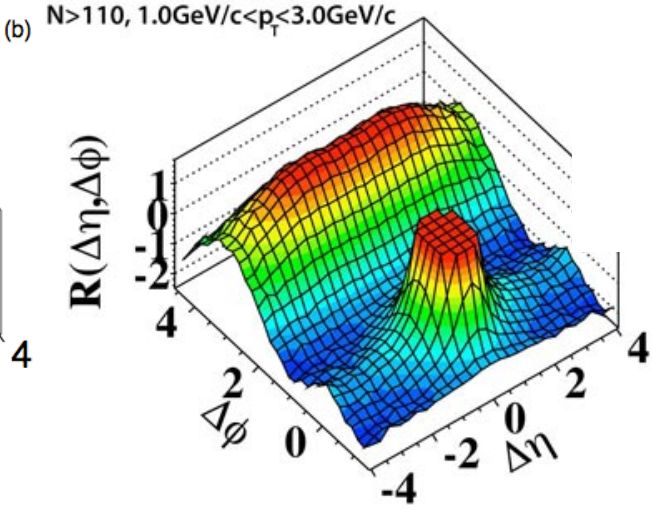

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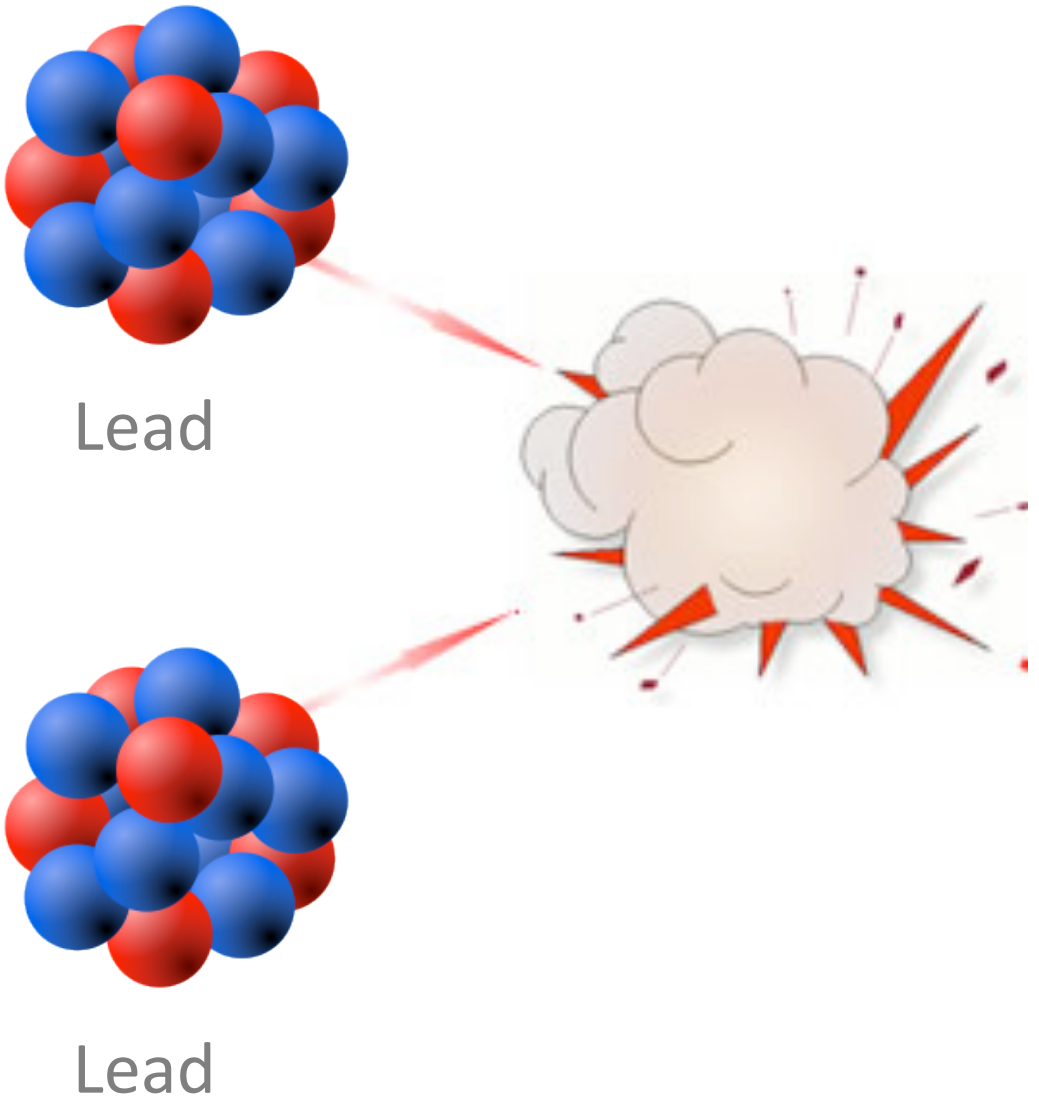
$$\frac{1}{N_{trig}}\frac{dN_{assoc}(\Delta\varphi)}{d\Delta\varphi} = a_0 + \sum_{n=1}^{\infty} 2a_n \cos(n\Delta\varphi)$$

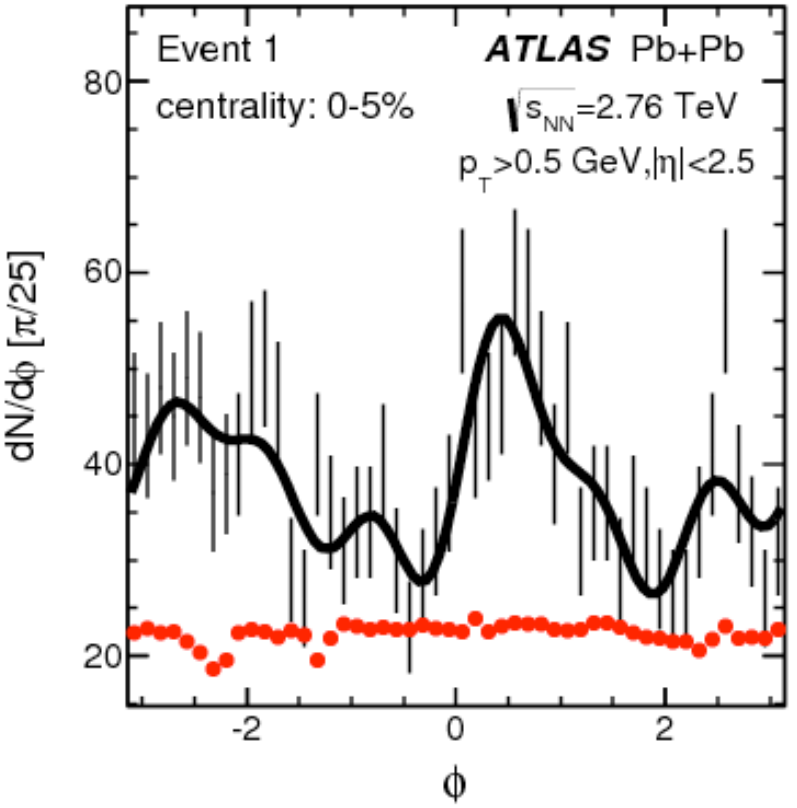
Sizeable 2nd order coefficient:

→ Collectivity from large to even in smallest systems?

→ Contribution of non-flow and fluctuations?


Lead
Lead

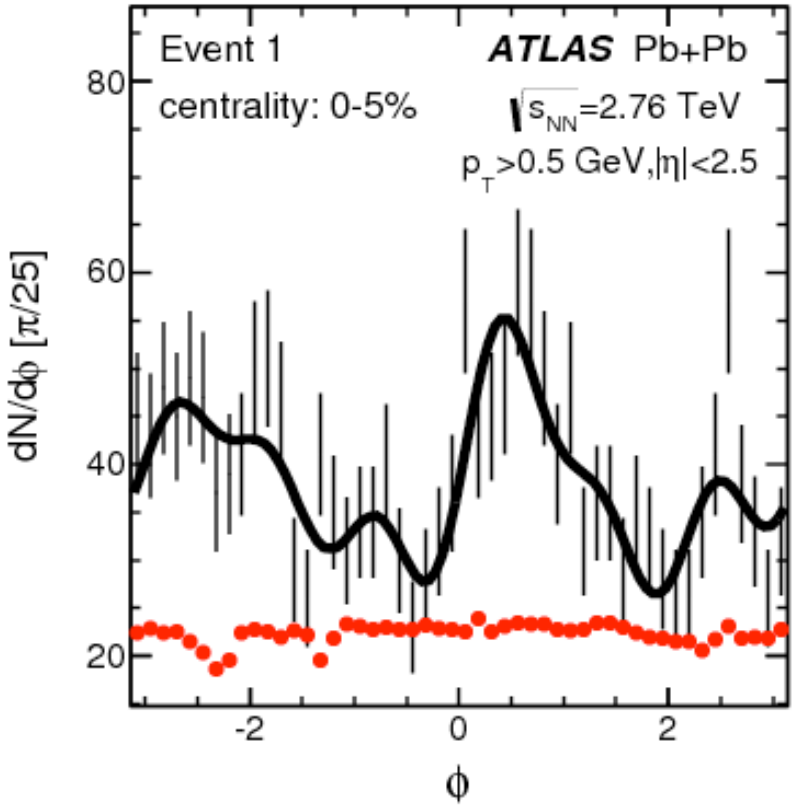
Flow event-by-event

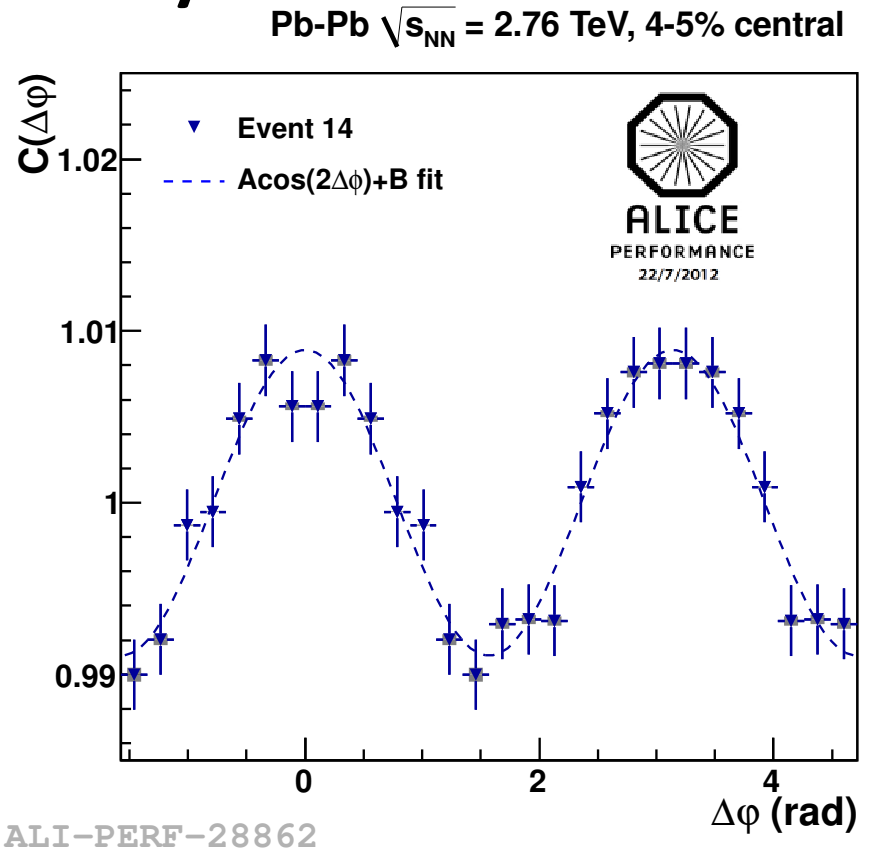


Measure event-by-event:

- Event planes
- Flow coefficients
- And their correlations

Flow event-by-event





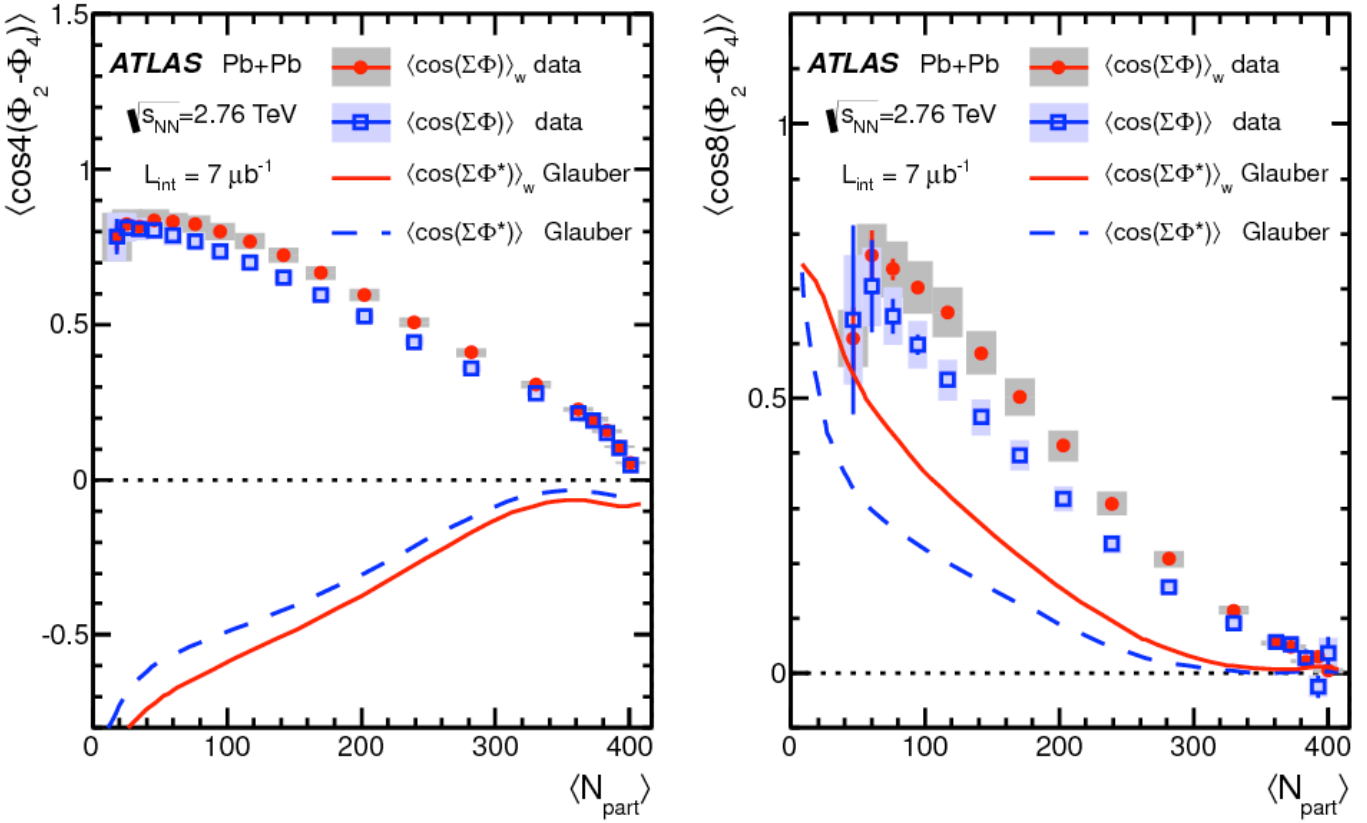
Measure event-by-event:

- Event planes
- Flow coefficients
- And their correlations

Event shape engineering:

- Select events with different elliptic flow

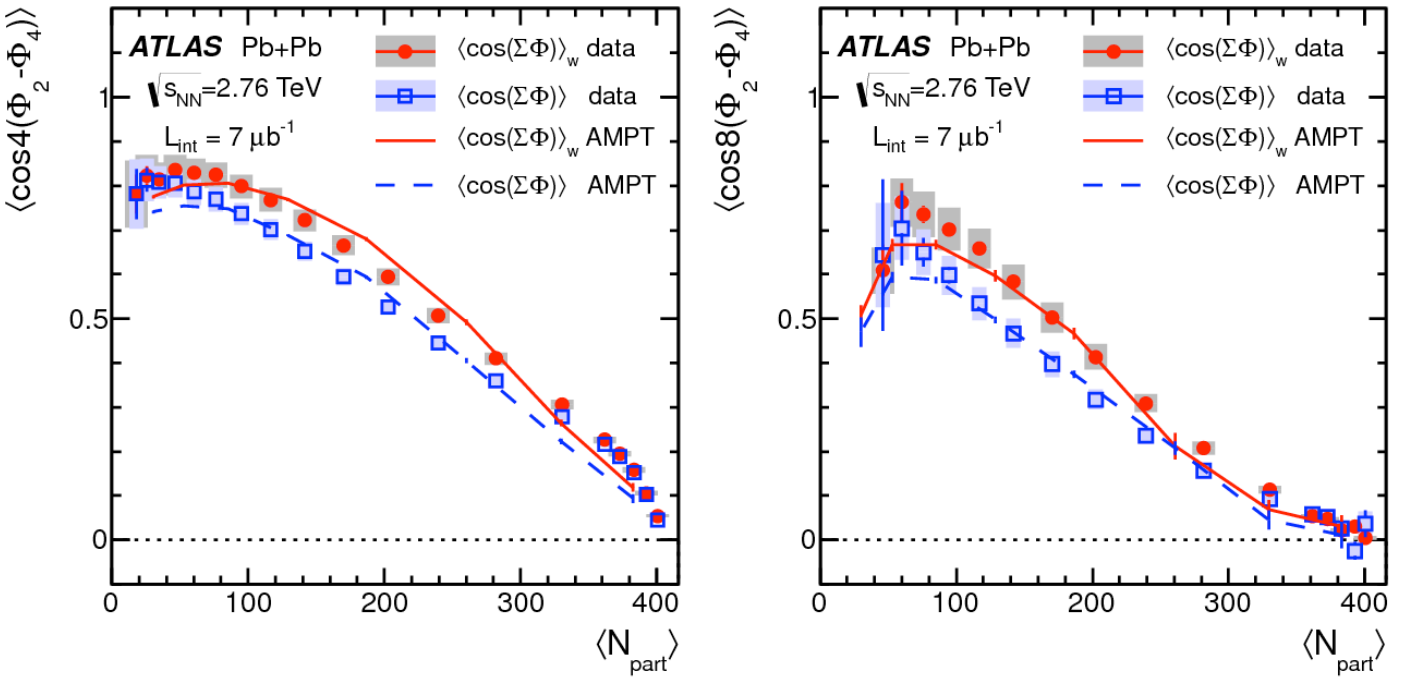
Event-plane correlations



- Measure event-by-event event plane angles (with the ATLAS Forward Calorimeter): $\langle\cos k(\Phi_n - \Phi_m)\rangle$
- Significant positive correlation
- Centrality dependence **different from Glauber model**

arXiv:1403.0489 [hep-ex]

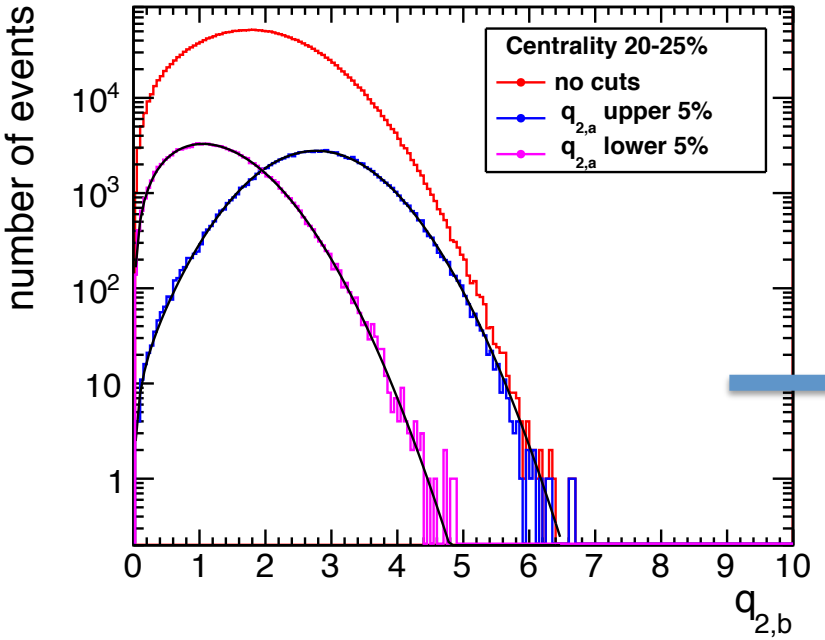
Event-plane correlations

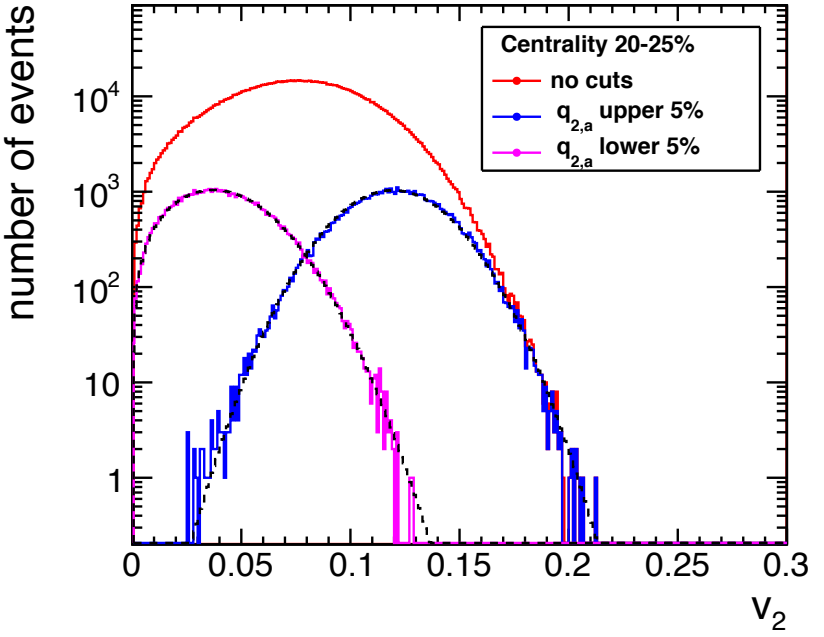


- Measure event-by-event event plane angles (with the ATLAS Forward Calorimeter): $\langle\cos k(\Phi_n - \Phi_m)\rangle$
- Significant positive correlation
- **Good agreement to AMPT** (includes the final-state collective dynamics)

arXiv:1403.0489 [hep-ex]

Event-shape engineering





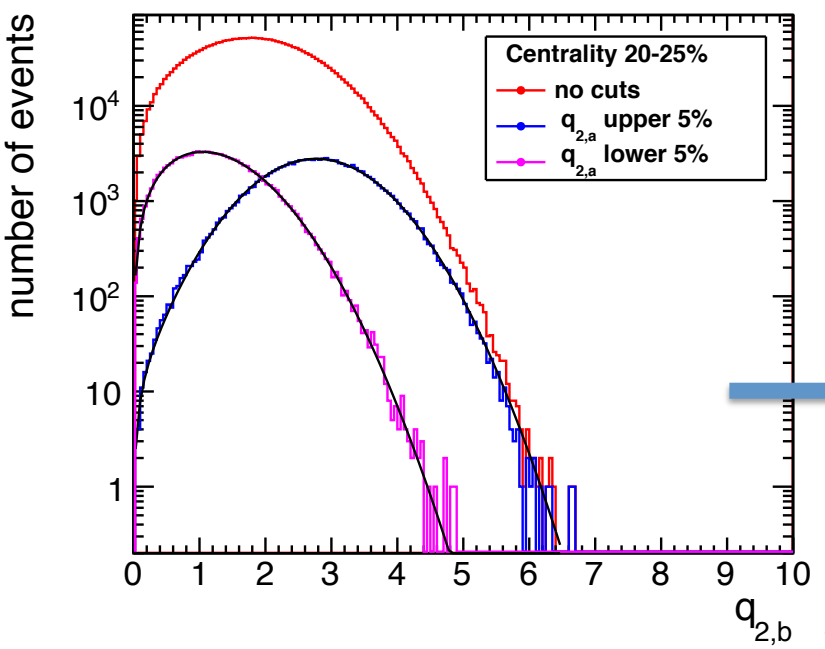
Select events according to their q value

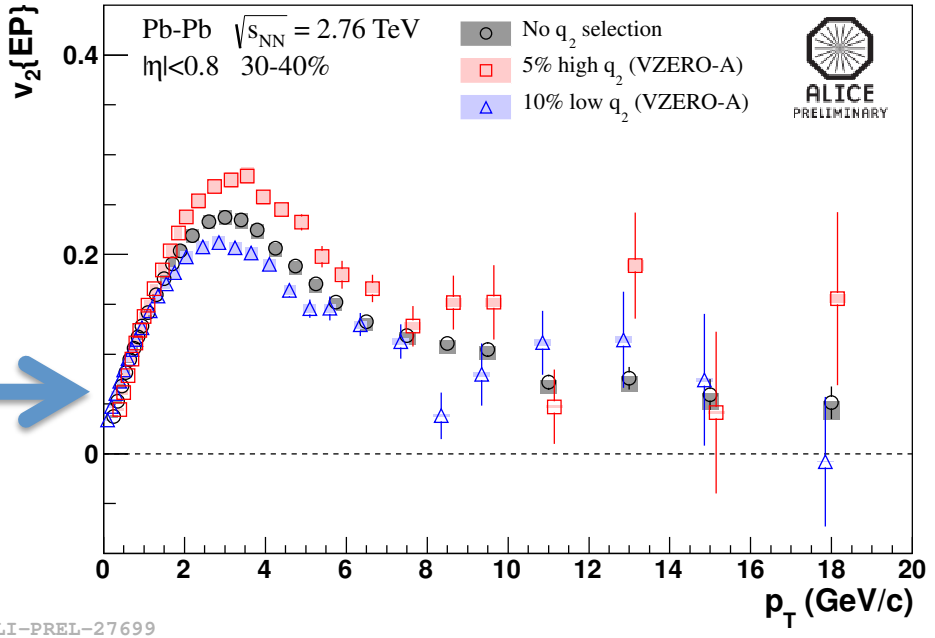
$$Q_n = \sum_{i=1}^{M} e^{in\varphi_i}$$

Study correlations between flow coefficients

Phys. Lett. B719, (2013) 394

Event-shape engineering





ALI-PREL-27699

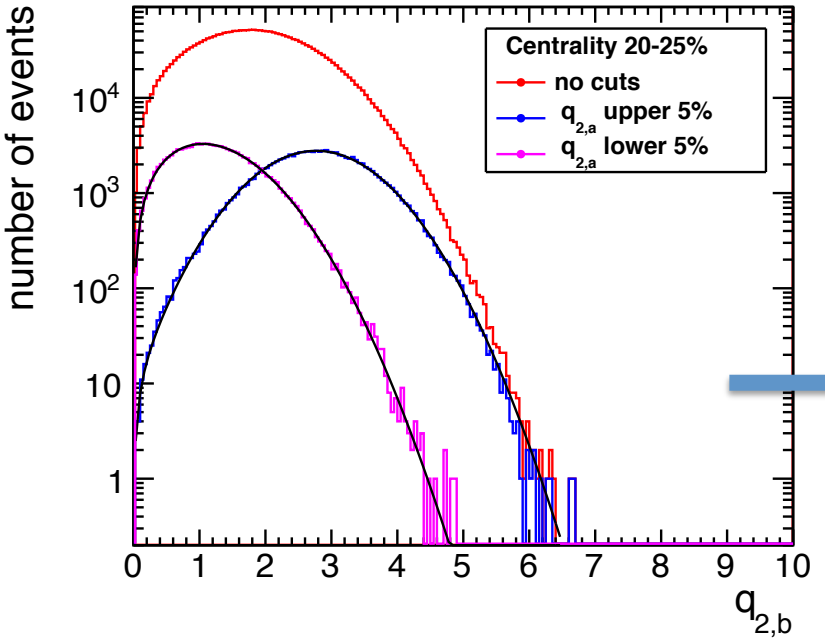
Select events according to their q value

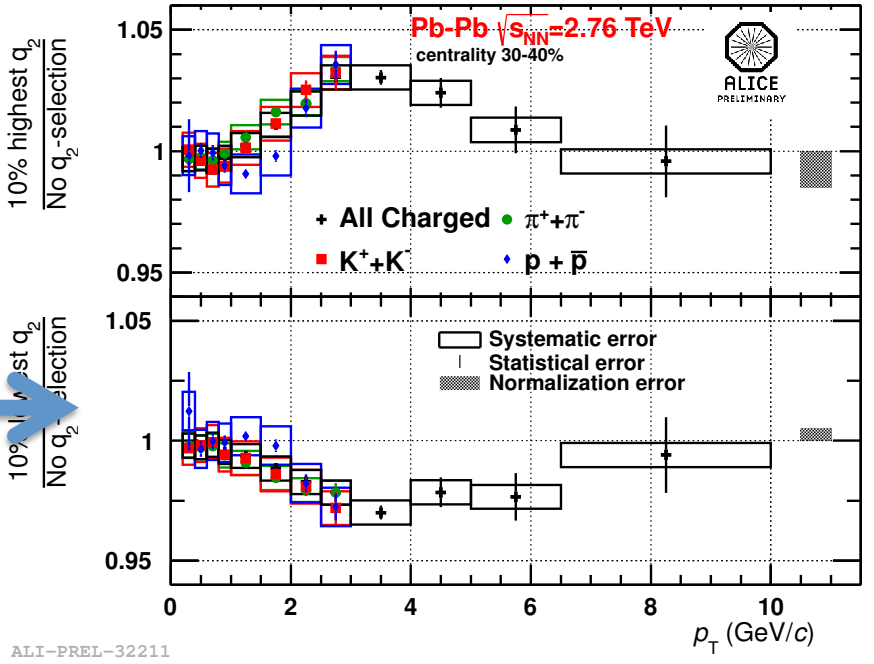
$$Q_n = \sum_{i=1}^{M} e^{in\varphi_i}$$

Study correlations between flow coefficients **experimentally**

Phys. Lett. B719, (2013) 394

Event-shape engineering





Select events according to their q value

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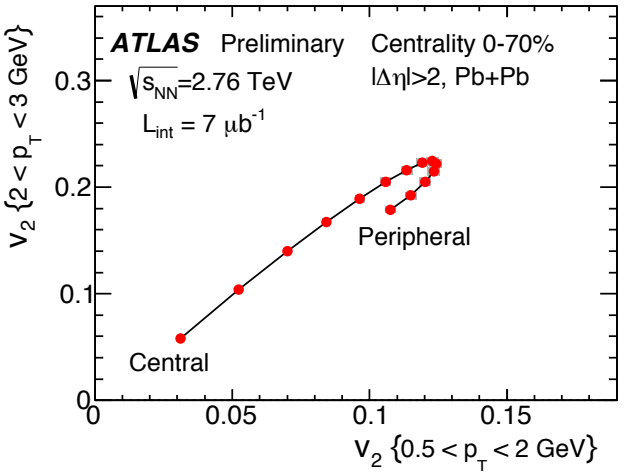
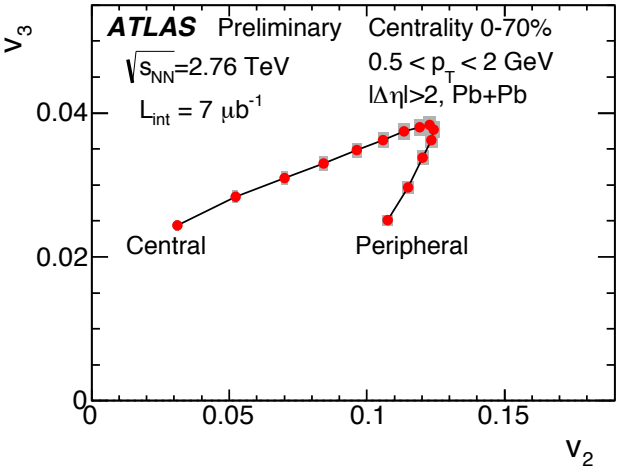
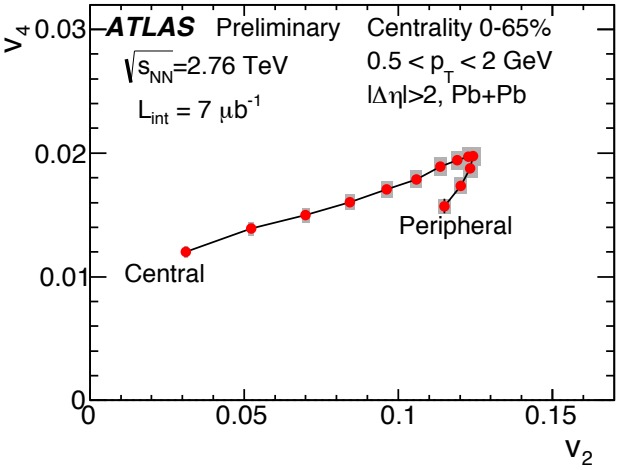
Study correlations between **radial and elliptic flow**

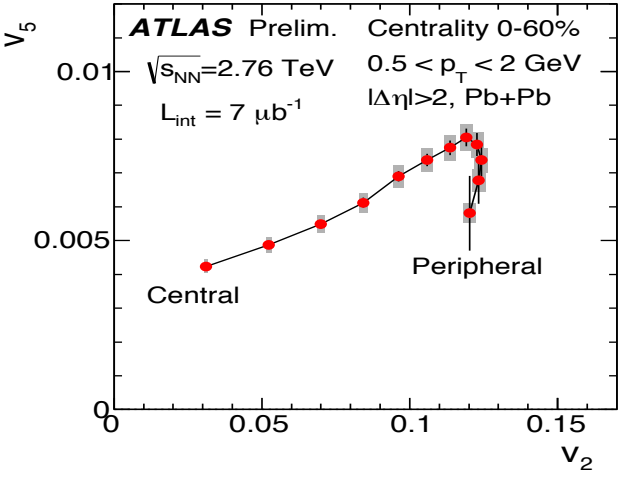
Phys. Lett. B719, (2013) 394

Event-shape engineering









Correlation between flow coefficients:

- Non monotonic variation

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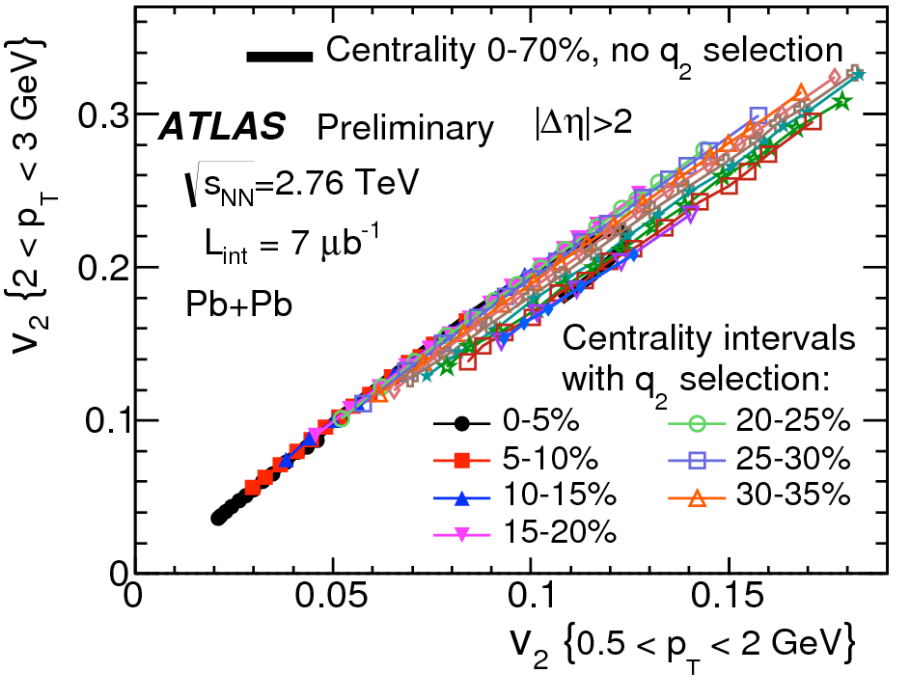
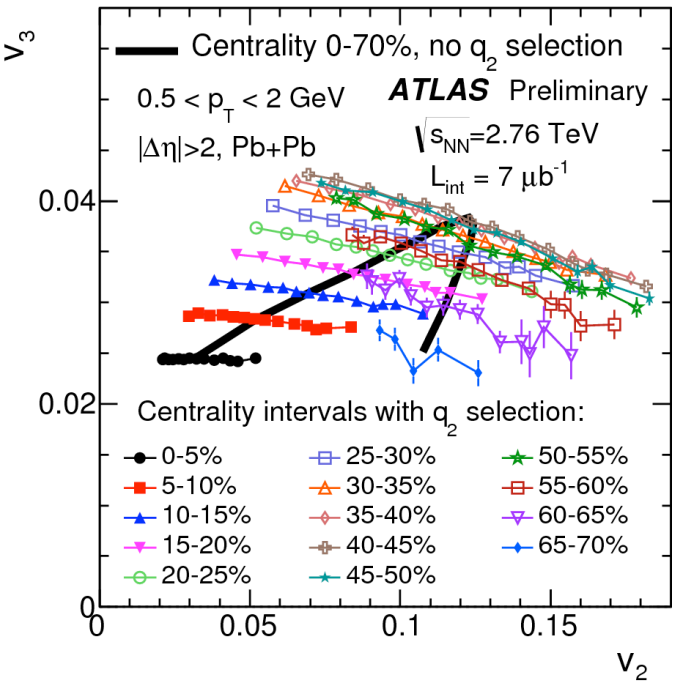
Event-shape engineering

Select q_2 in forward direction (FCAL)





Linear correlation between v_2 for low and high p_T

Anti correlation between v3 and v2 (for non-central collisions)

ATLAS-CONF-2014-022

Event-shape engineering

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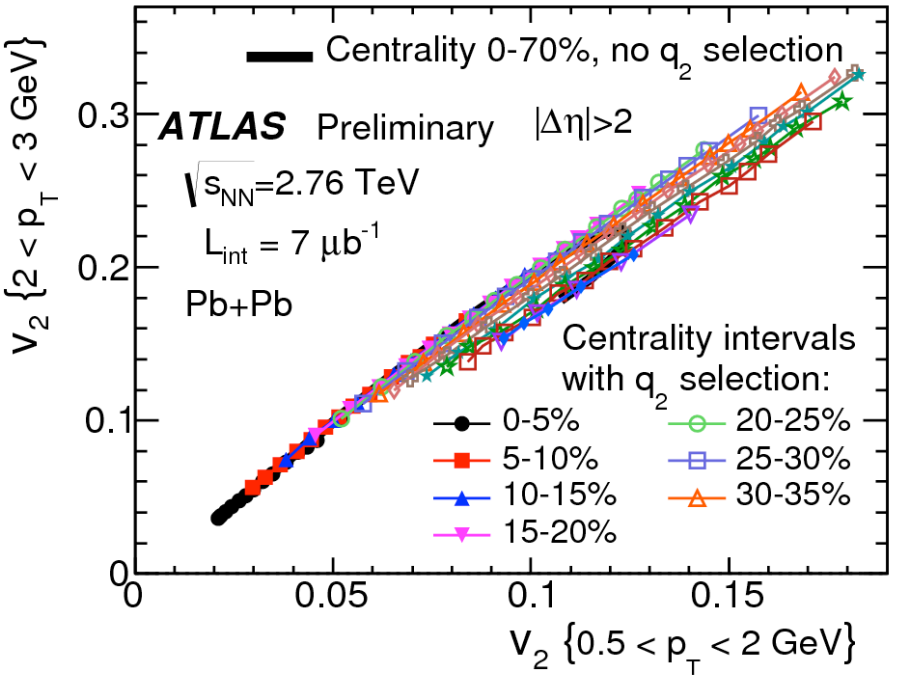
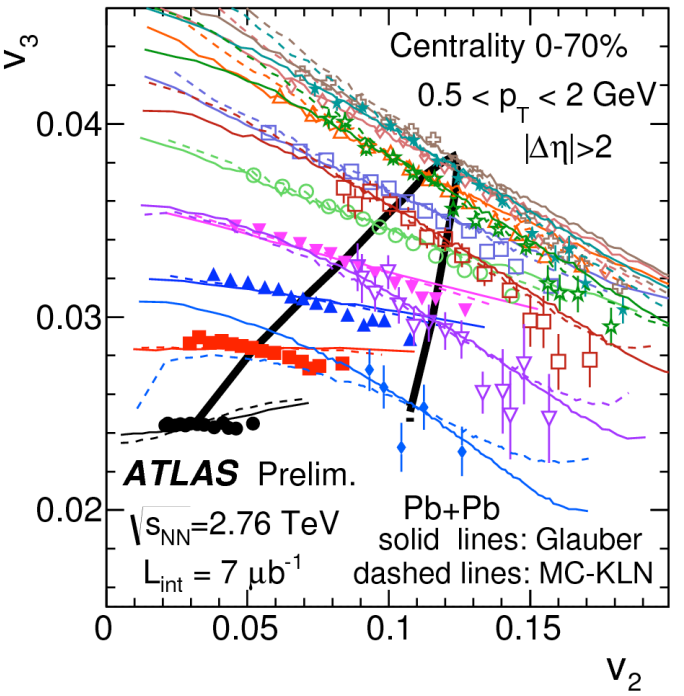




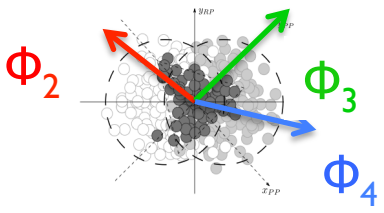
Linear correlation between v_2 for low and high p_T

Anti correlation between v3 and v2 (for non-central collisions) → **mostly initial geometry effect**

ATLAS-CONF-2014-022

Flow fluctuations

Initial symmetry planes



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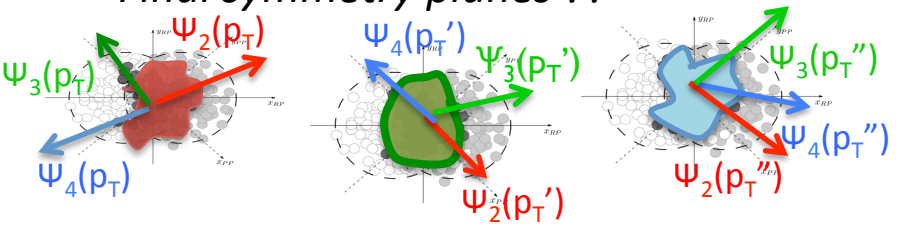
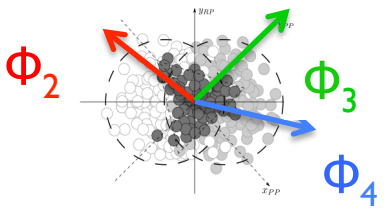


p_T dependent flow angle and magnitude fluctuations?

Flow fluctuations

Initial symmetry planes



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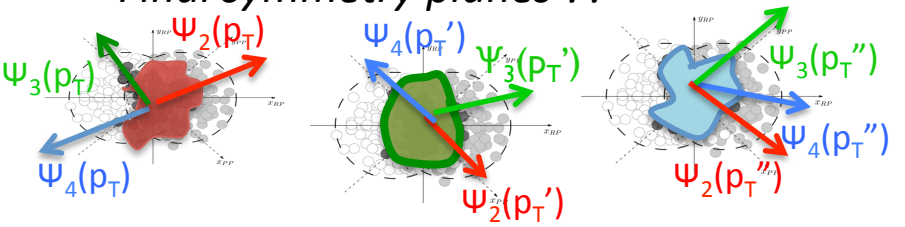

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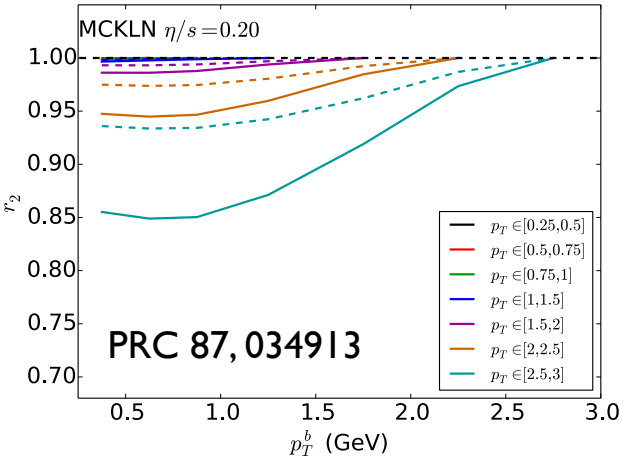
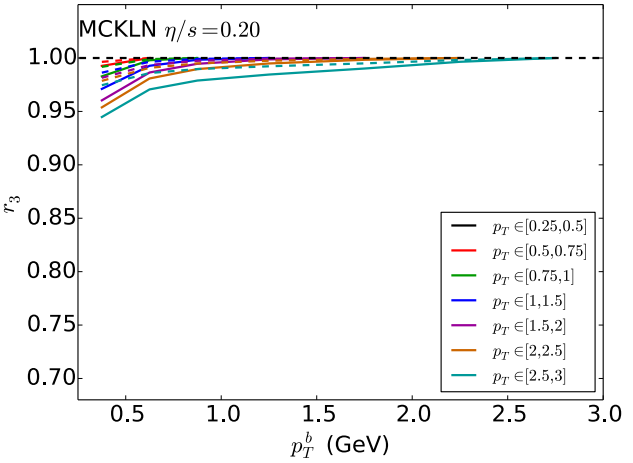
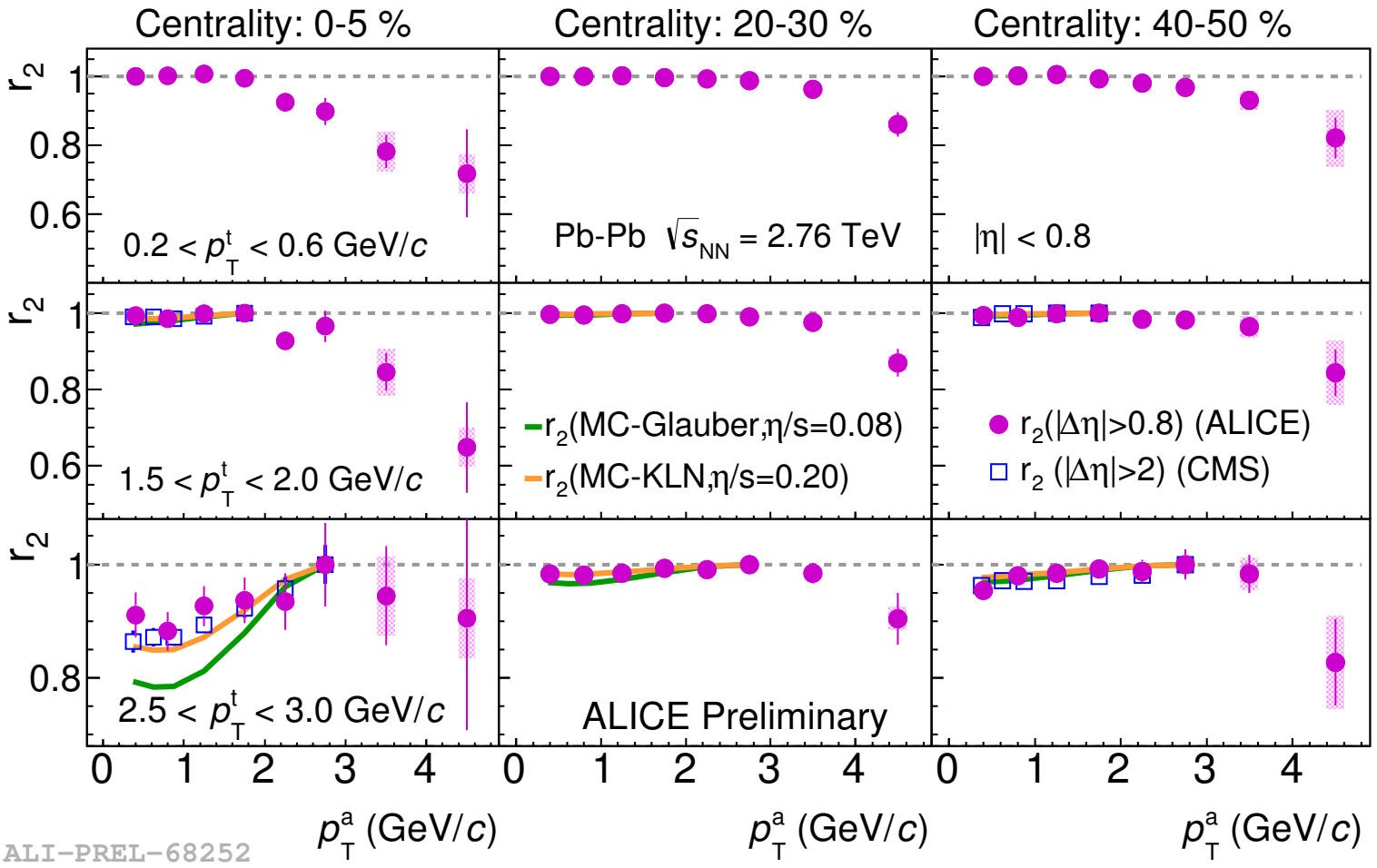




Test via factorization: $r_n = \dfrac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) \cdot V_{n\Delta}(p_T^b, p_T^b)}}$

r_n < 1 observed in hydro calculations →indication for flow fluctuations

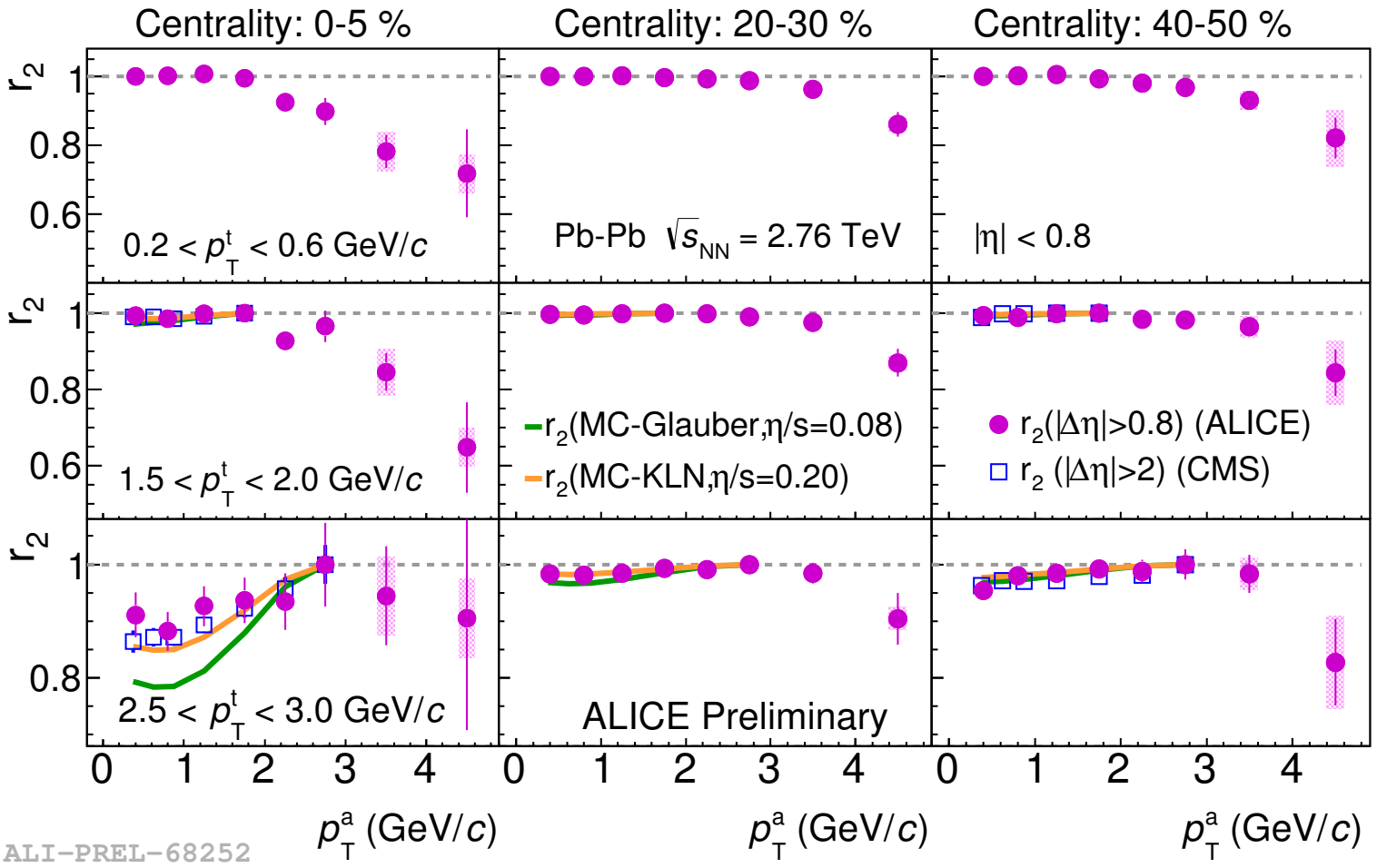
Flow fluctuations



- Large breaking in central collisions
- Qualitatively reproduced by hydro calculations
- CMS and ALICE data in agreement

CMS-HIN-14-012

Flow fluctuations



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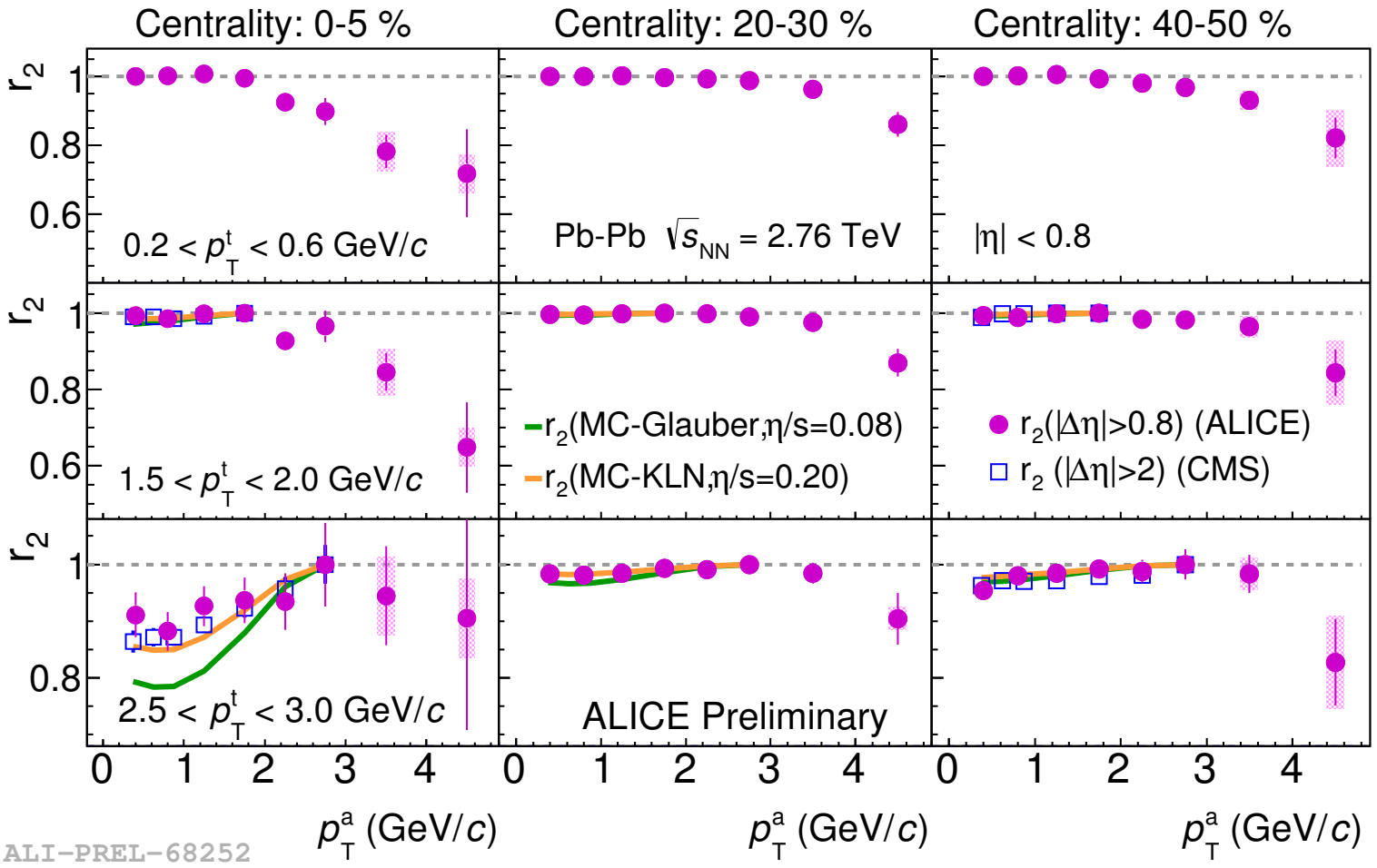
- **What is the contribution from non-flow?**

CMS-HIN-14-012

Flow fluctuations



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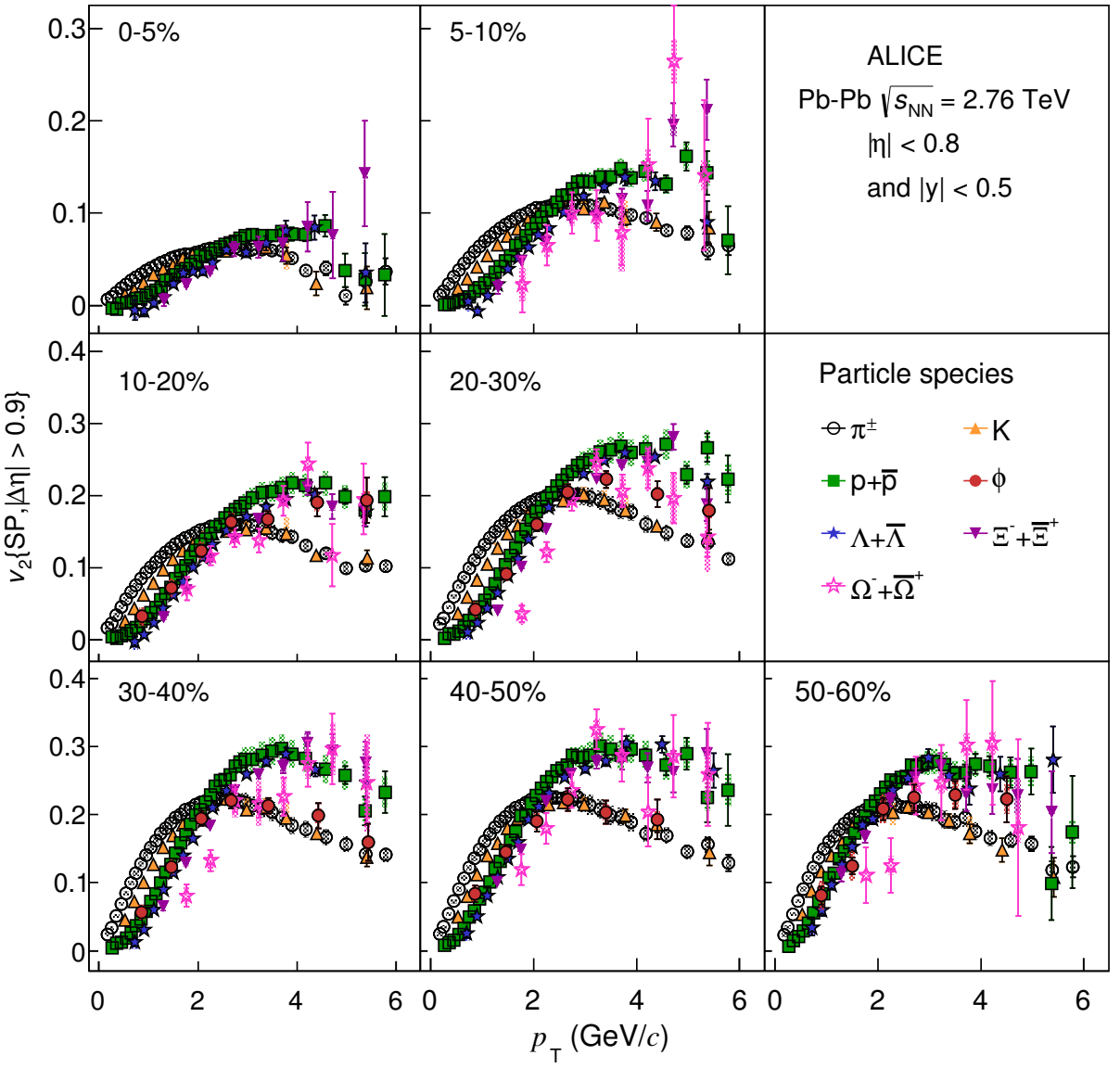
- **What is the contribution from non-flow?**

Damir DEVETAK
Thu, 11:45h

CMS-HIN-14-012

Collectivity in Pb-Pb



v2 of large particle zoo measured…

Low p_T:

- **Mass ordering**

Intermediate p_T:

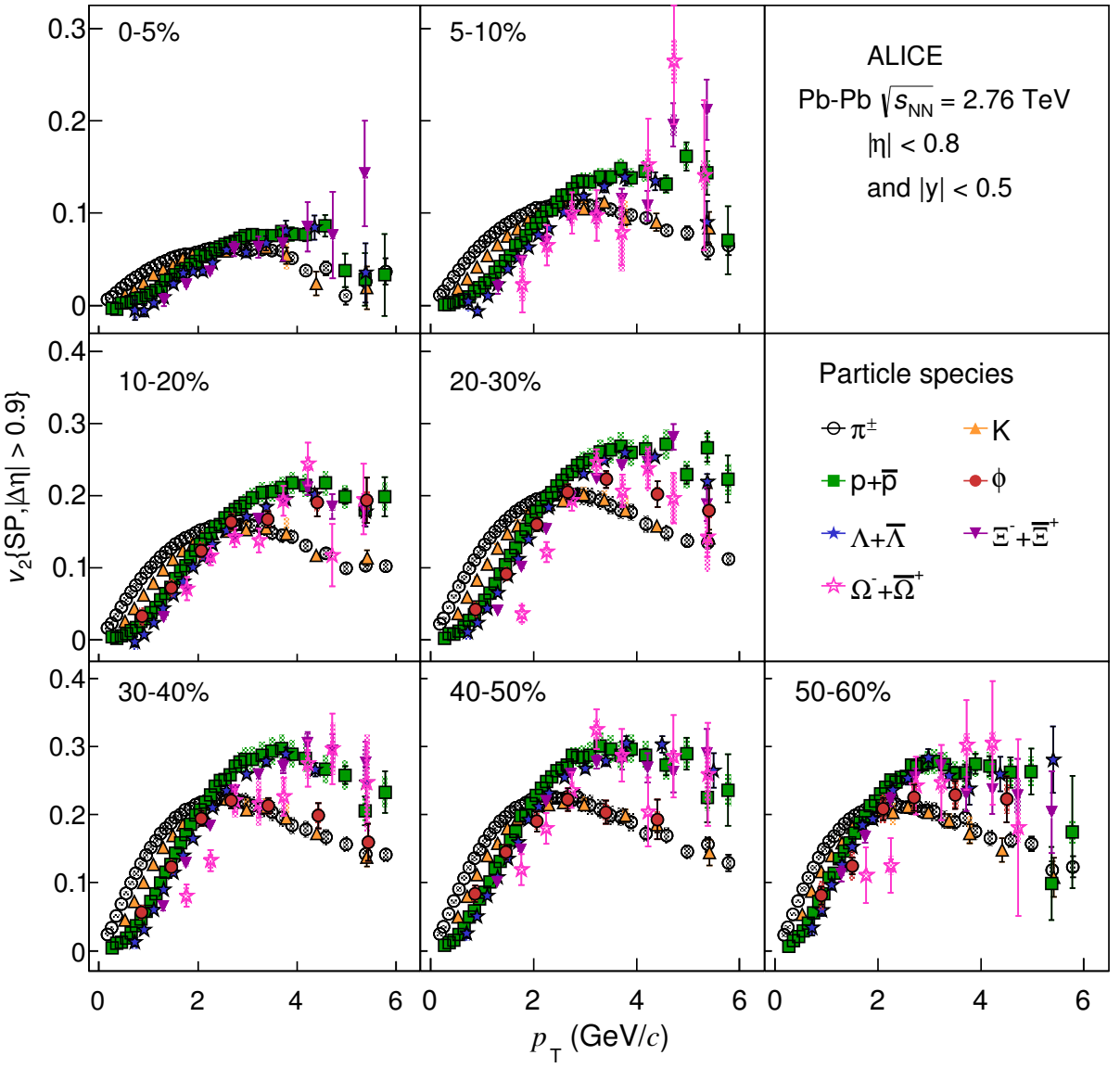
- apparent grouping into **mesons and baryons**

→ **Good explanation by collectivity in hydrodynamic models**

ALI-PUB-82892

arXiv:1405.4632 [nucl-ex]

Collectivity in Pb-Pb



v2 of large particle zoo measured…

Low p_T:

- **Mass ordering**

Intermediate p_T:

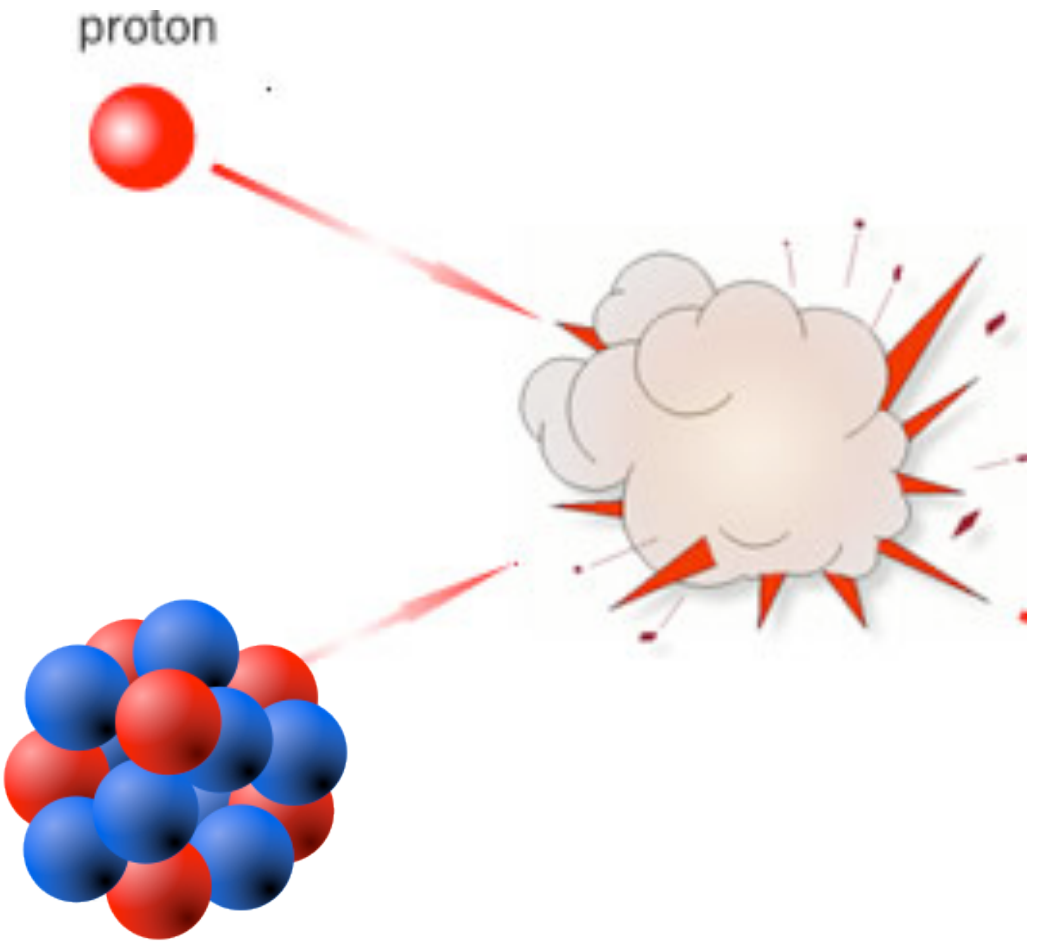
- apparent grouping into **mesons and baryons**

→ **Good explanation by collectivity in hydrodynamic models**

Panos CHRISTAKOGLOU
Thu, 14:00h

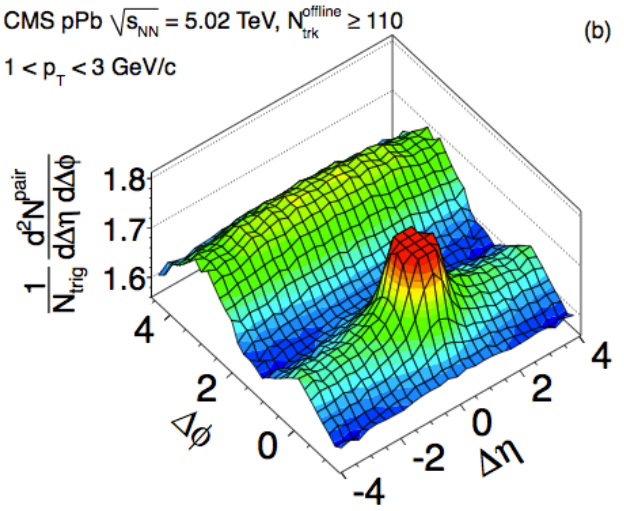
ALI-PUB-82892

arXiv:1405.4632 [nucl-ex]


proton
Lead

Collectivity in smaller systems?

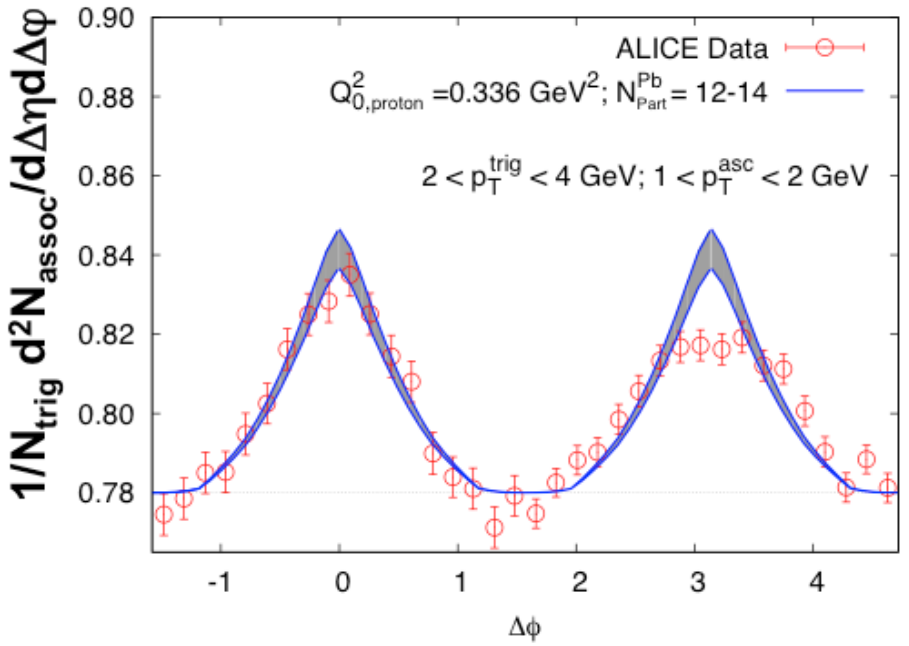
"Ridge" in p-Pb collisions



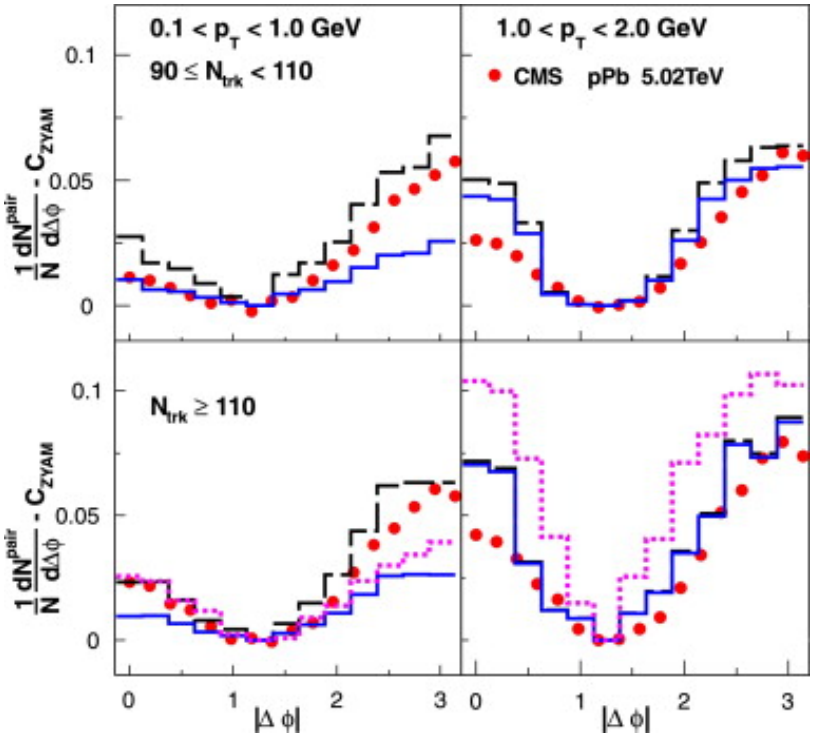
p+Pb ridge

Collectivity in smaller systems?

"Ridge" in p-Pb collisions



Initial state
(Color glass condensate)?

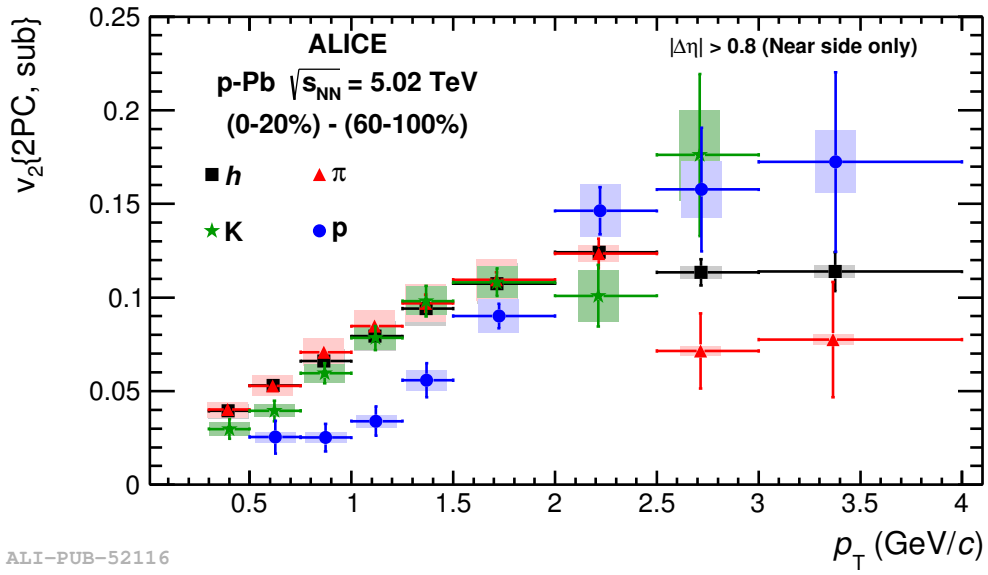


Final state
(Hydrodynamic models)?

Phys. Rev. D 87, (2013) 094034
Phys. Lett. B 718, (2013) 1557

Collectivity in smaller systems?

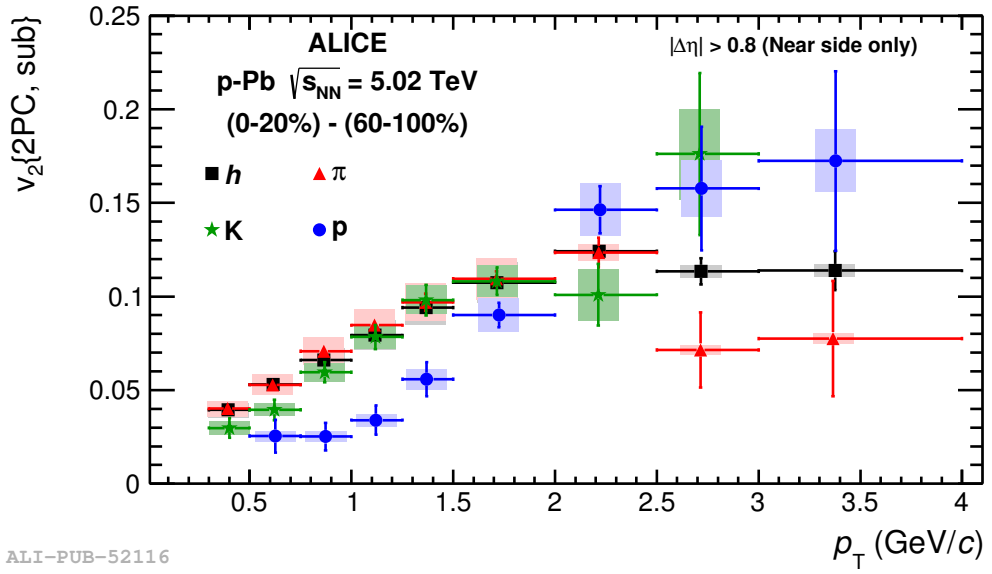
"Ridge" in p-Pb collisions

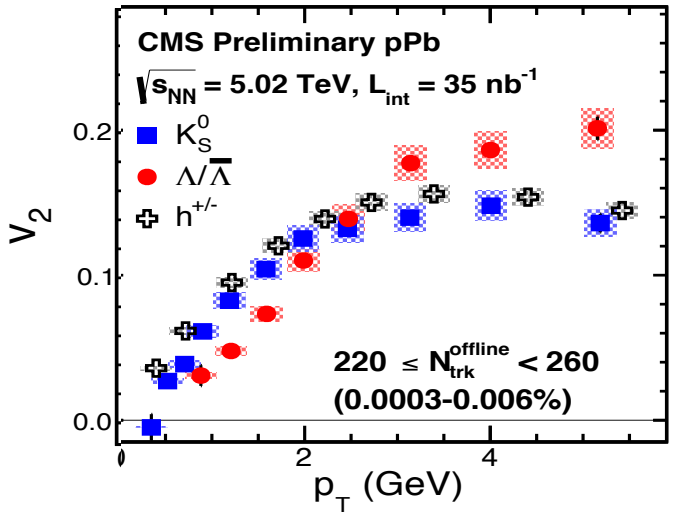


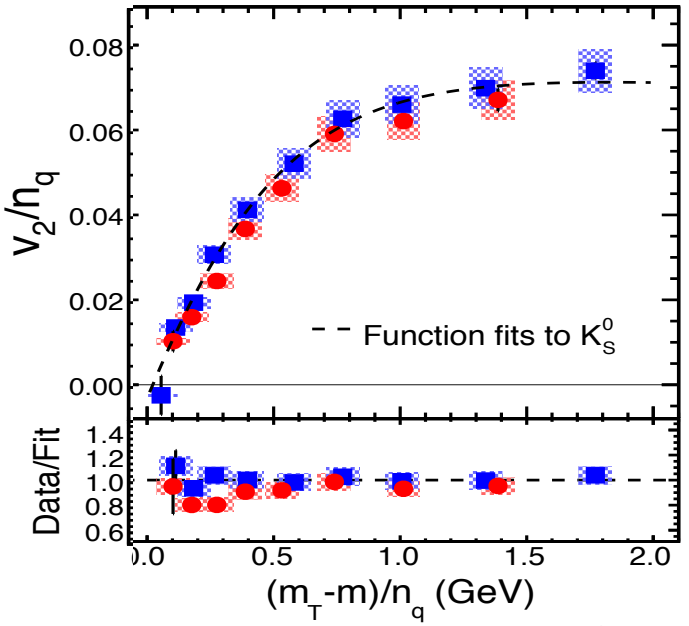
Phys. Lett. B 726 (2013), 164

Collectivity in smaller systems?

"Ridge" in p-Pb collisions



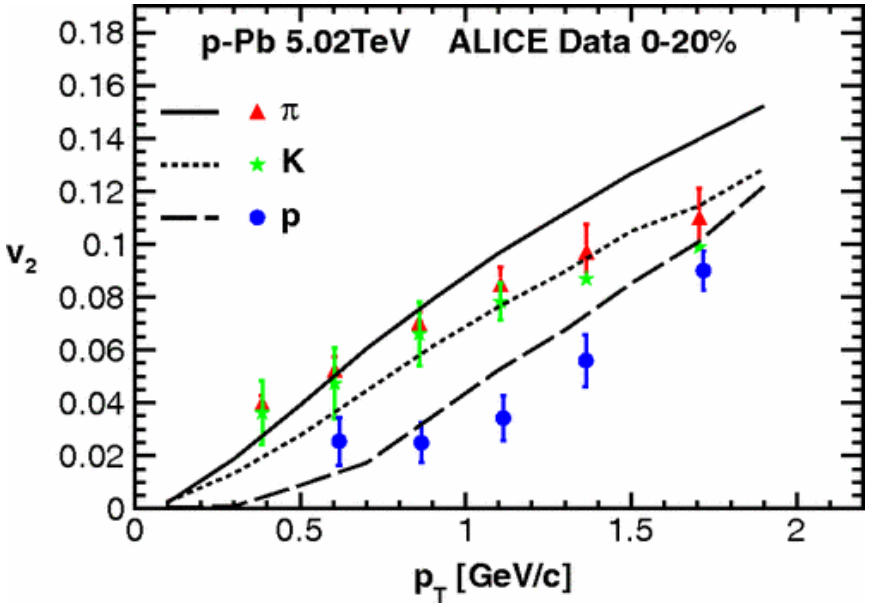


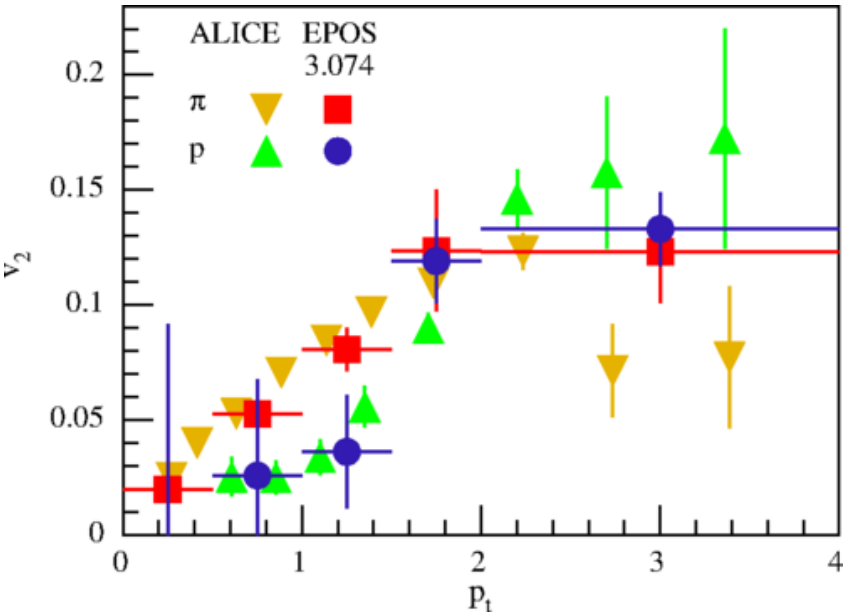


v_2 for many particle species measured
→ at low p_T **mass ordering** observed

Phys. Lett. B 726 (2013), 164
CMS-HIN-14-002

Collectivity in smaller systems?



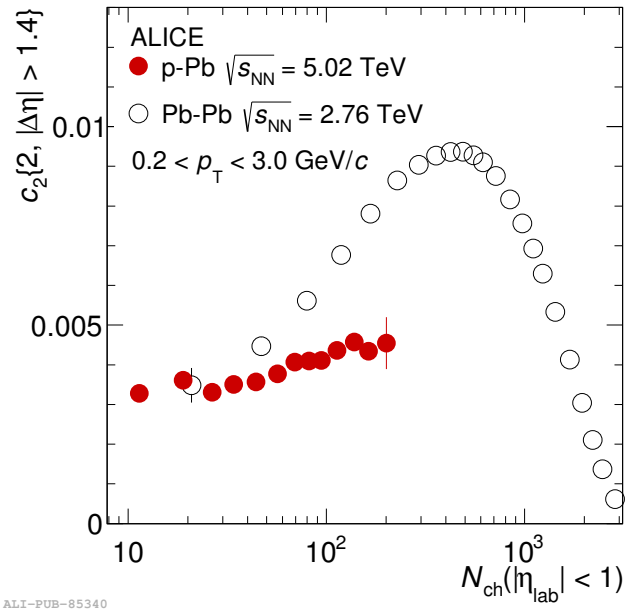


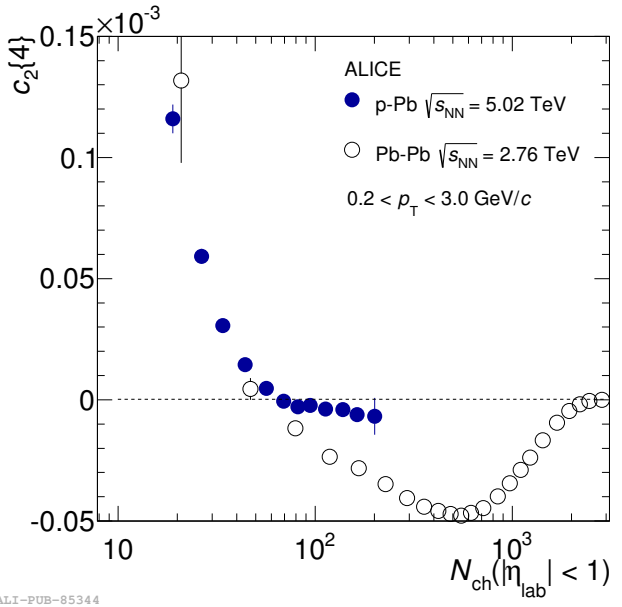
Described by Hydrodynamic models

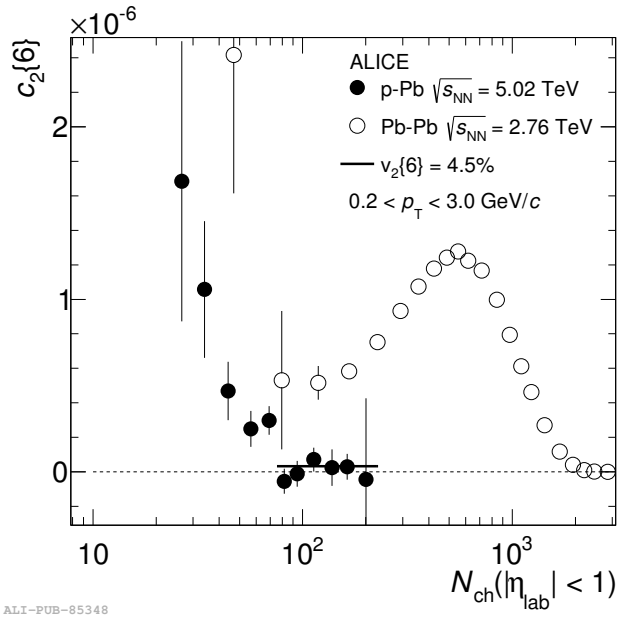
→Collectivity in small systems?

PRL 111, (2013) 172303
PRL 112, (2014) 232301

Collectivity in smaller systems?



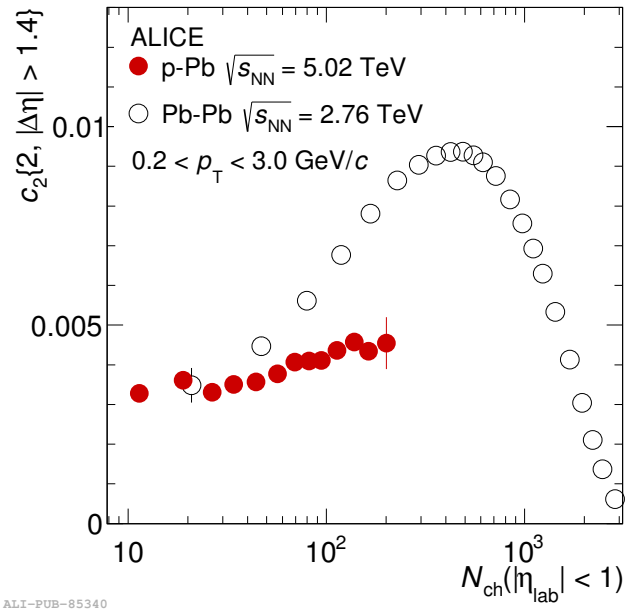


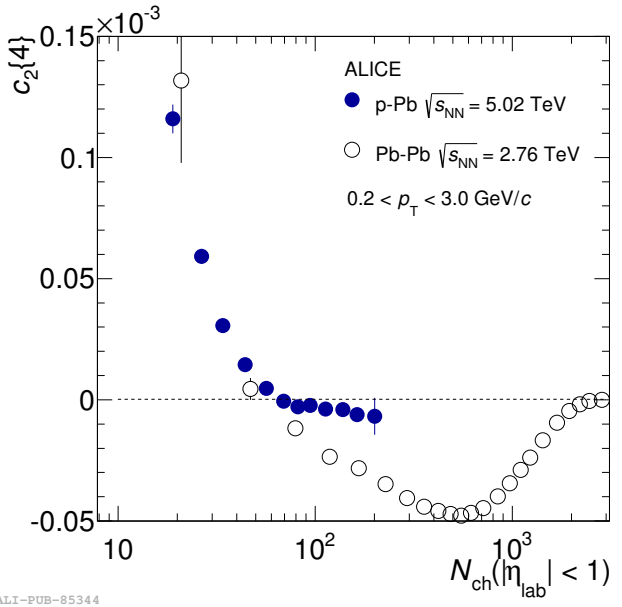


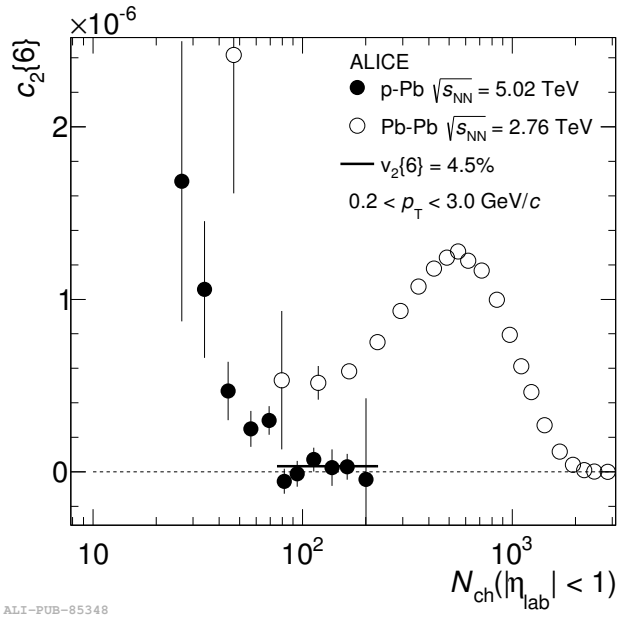
- Measured correlations in p-Pb between few (e.g. 2) or more particles ⇒ collectivity in p-Pb?
- Quantitative comparison between p-Pb and Pb-Pb at the same multiplicity
- Origin of odd harmonics in p-Pb similar as in Pb-Pb?

arXiv:1406.2474 [nucl-ex]

Collectivity in smaller systems?







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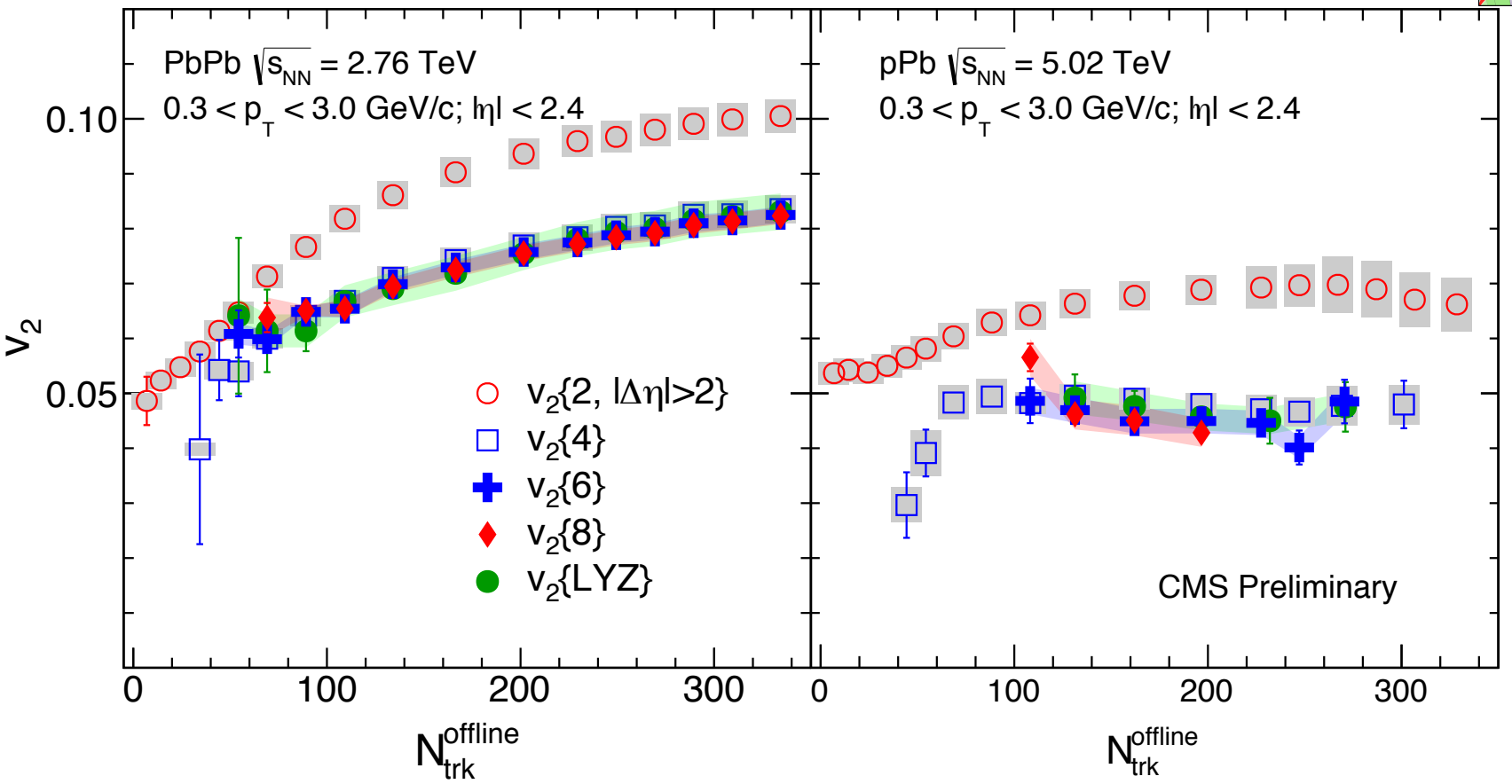
- Quantitative comparison between p-Pb and Pb-Pb at the same multiplicity
- Origin of odd harmonics in p-Pb similar as in Pb-Pb?

Qualitative similar picture in p-Pb and Pb-Pb but magnitude significantly different

arXiv:1406.2474 [nucl-ex]

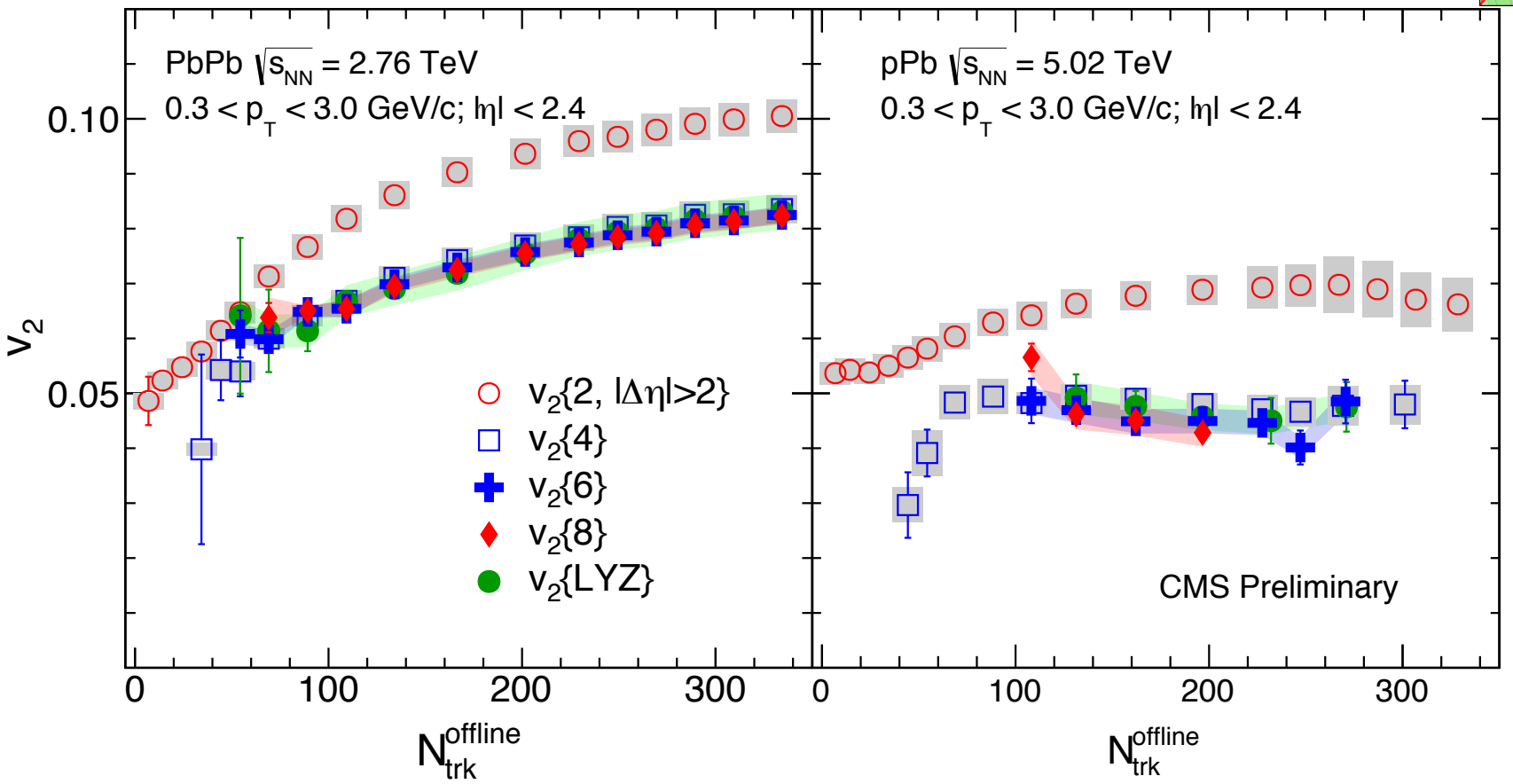
Collectivity in smaller systems?



- Correlations in p-Pb **more than a 2-particle effect**
- But **difference in strength** of v_2 between p-Pb and Pb-Pb

CMS-HIN-14-006

Collectivity in smaller systems?

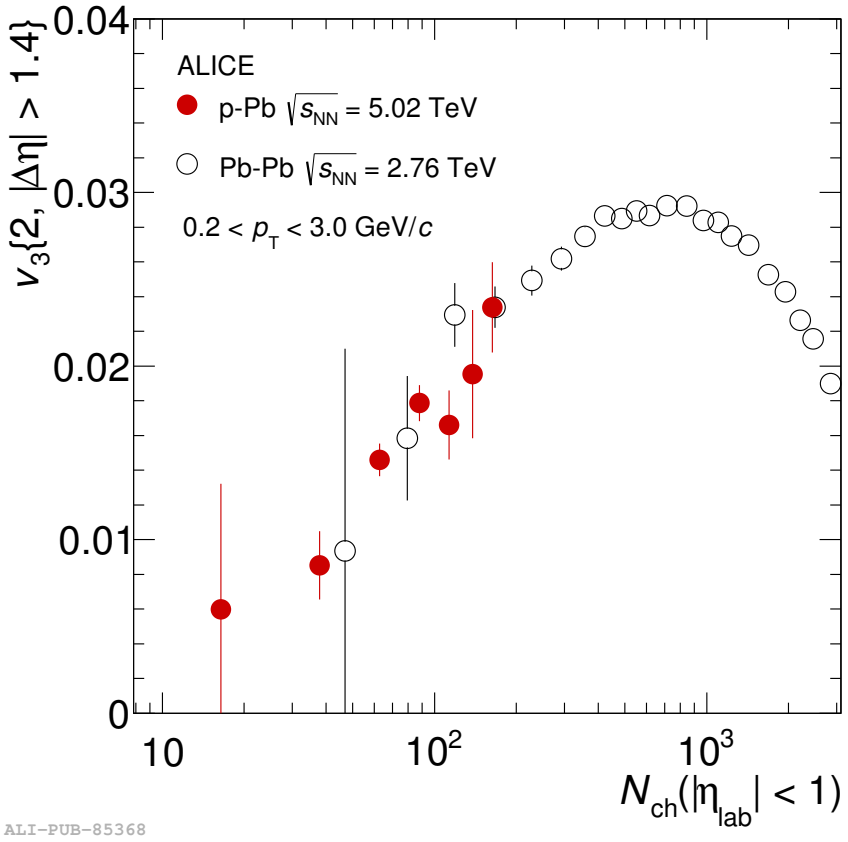


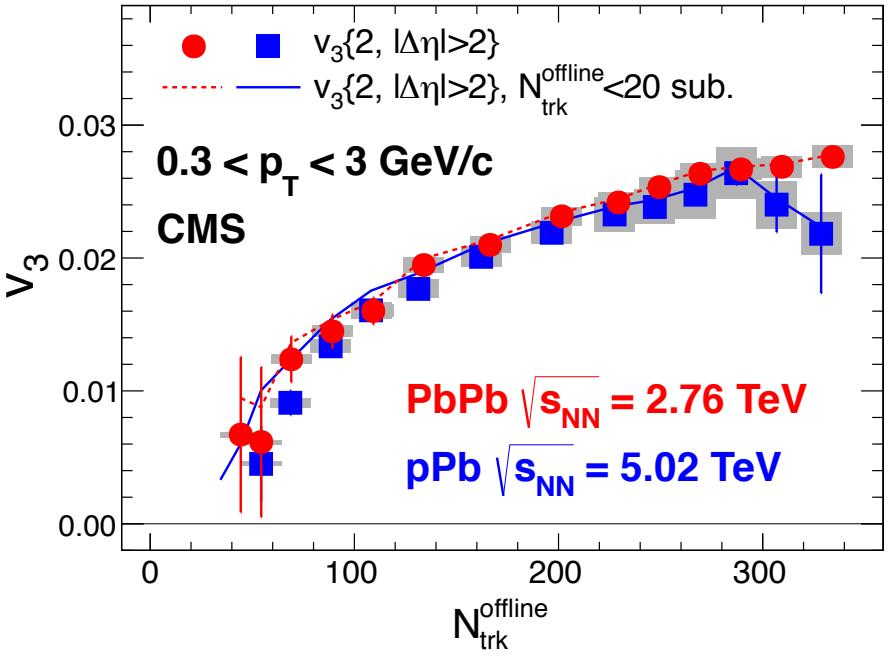
- Correlations in p-Pb **more than a 2-particle effect**
- But **difference in strength** of v_2 between p-Pb and Pb-Pb

Shengquan TUO
Fri, 14:35h

CMS-HIN-14-006

Higher orders

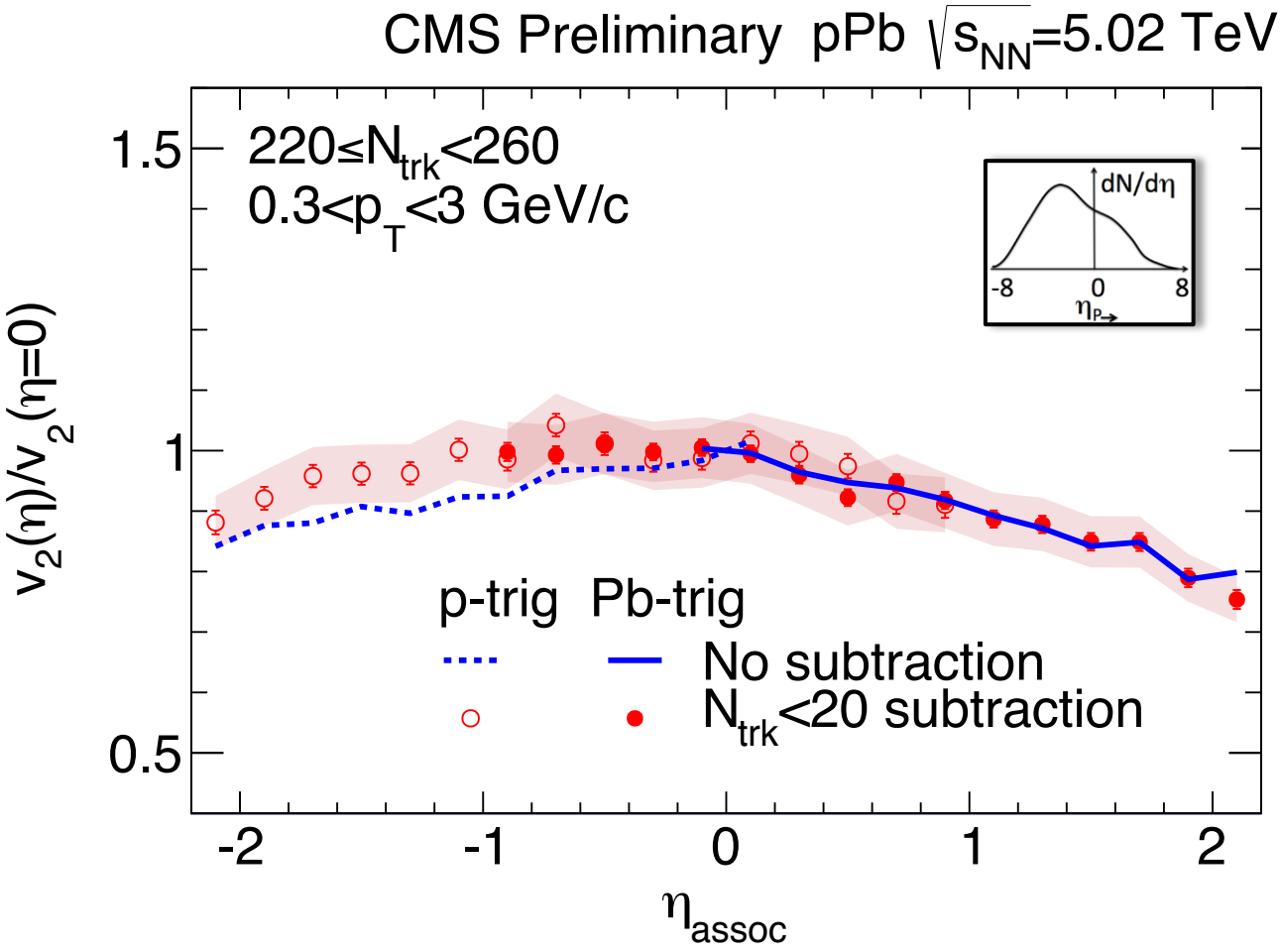




- **v_3 is similar** for both systems at same multiplicity
- Driven by fluctuations?

Phys. Lett. B 724, (2013) 213
arXiv:1406.2474 [nucl-ex]

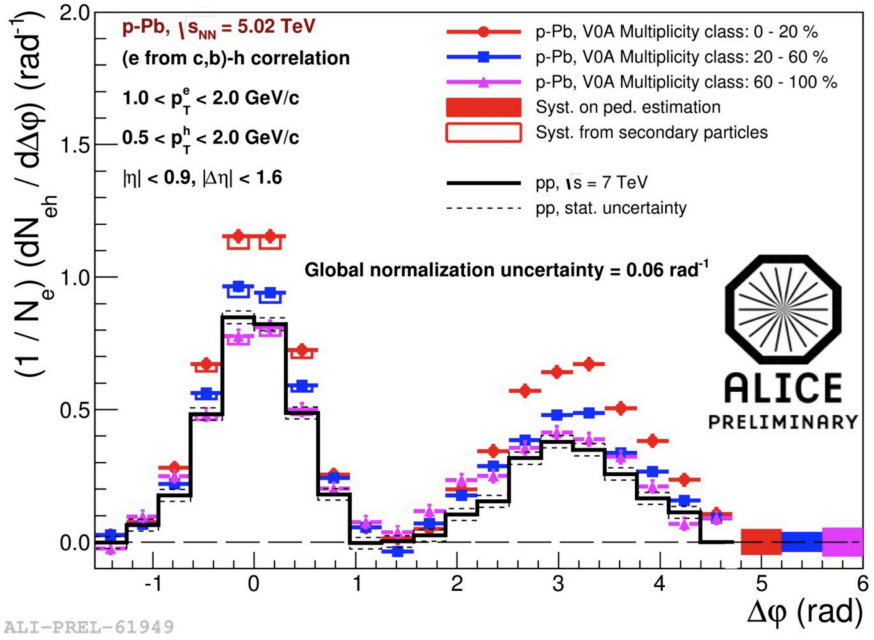
η dependence of ridge in p-Pb



- v_2 depends on eta (particle density dependence)
- Can this distinguish between CGC and Hydro?

CMS-HIN-14-008

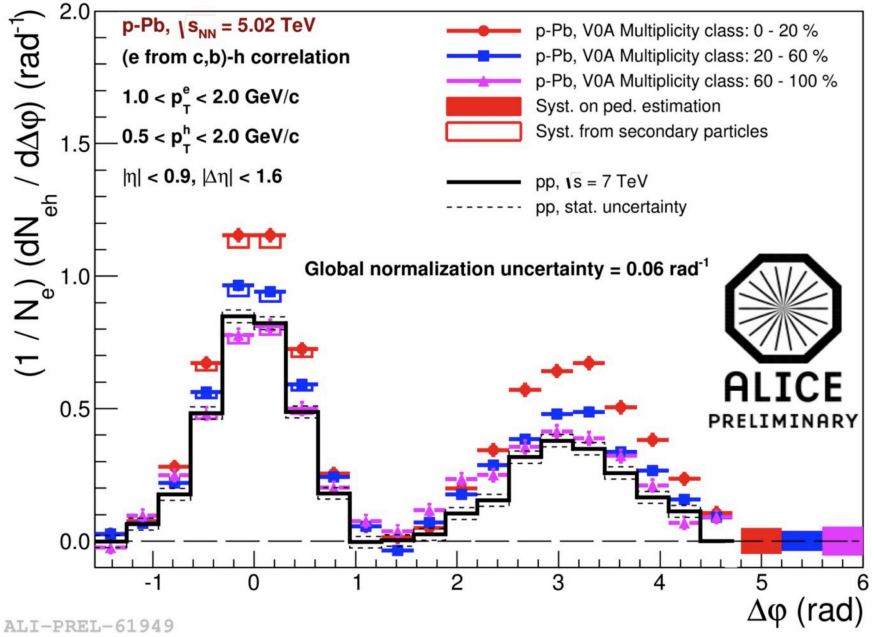
What about heavy flavours?

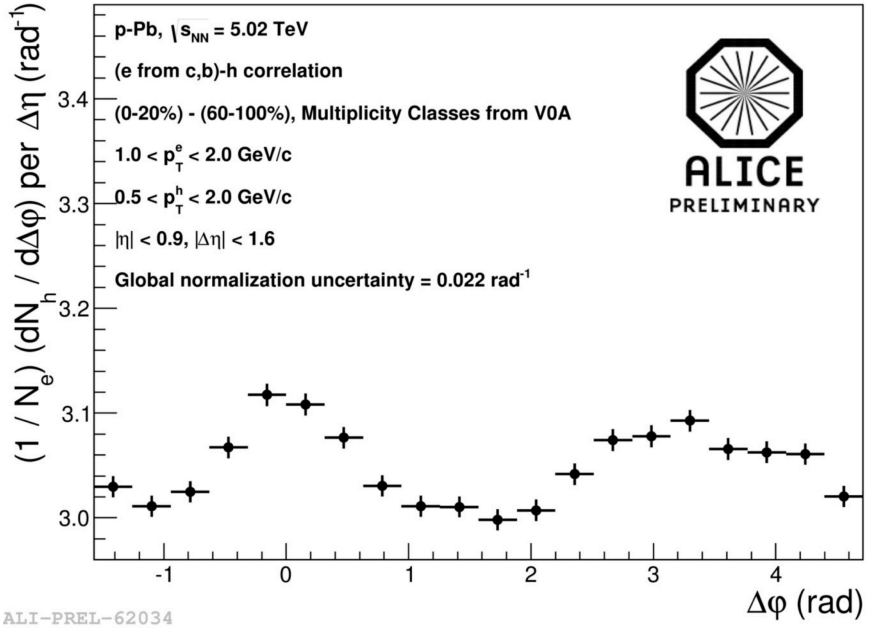


Correlations with heavy flavour particles:

- Trigger particles: heavy flavour (c,b) decay electron, 1.0-2.0 GeV/c
- Associated particle: charged hadrons, 0.5-2.0 GeV/c

What about heavy flavours?





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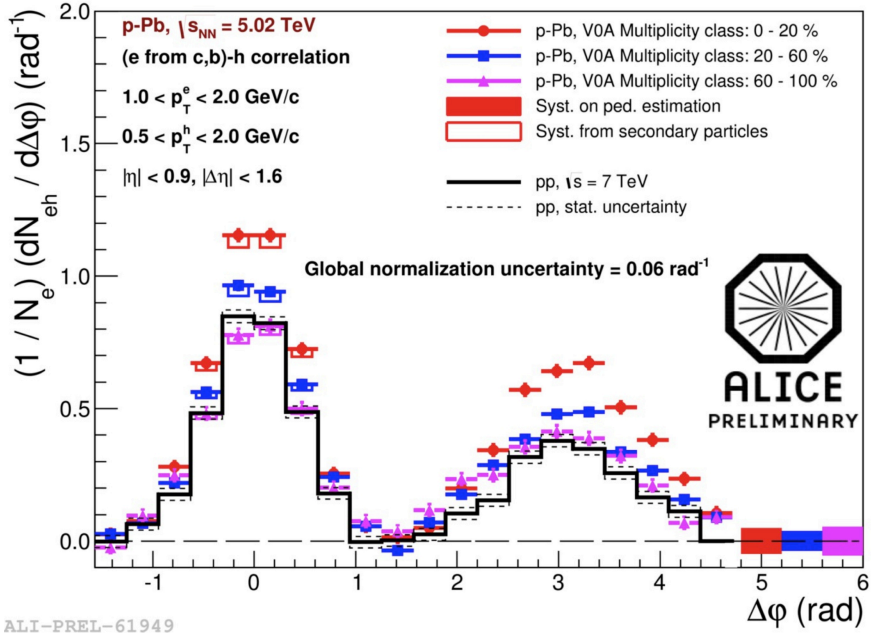
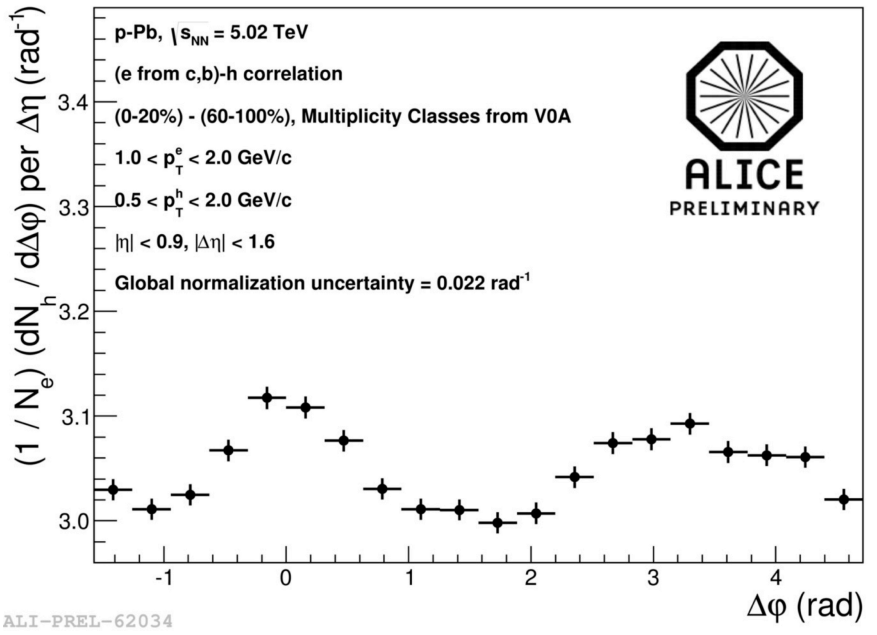
Subtraction:

- Double-ridge also in HF correlations
- Mechanism affects also HF particles

What about heavy flavours?





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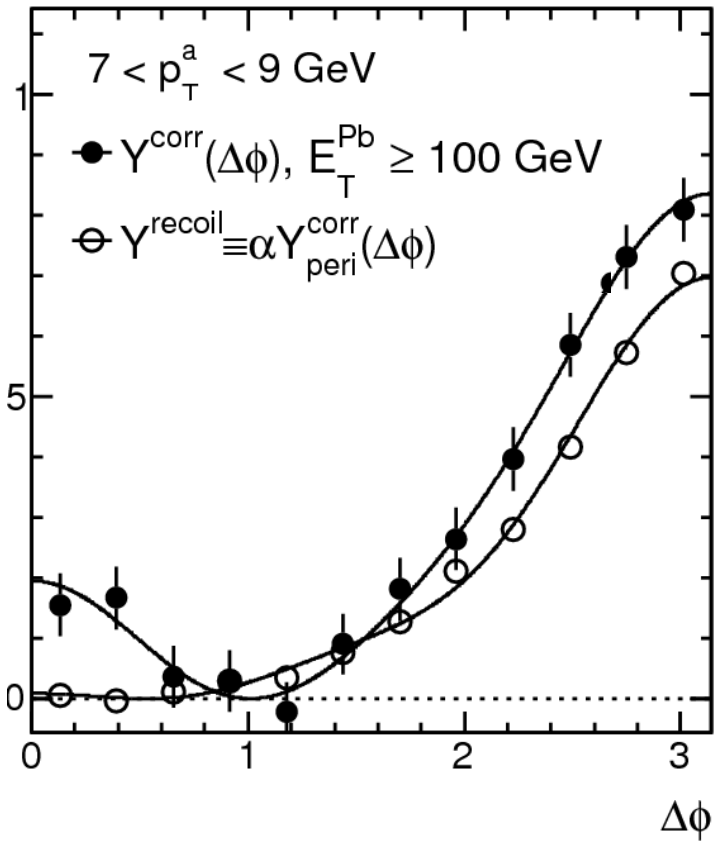
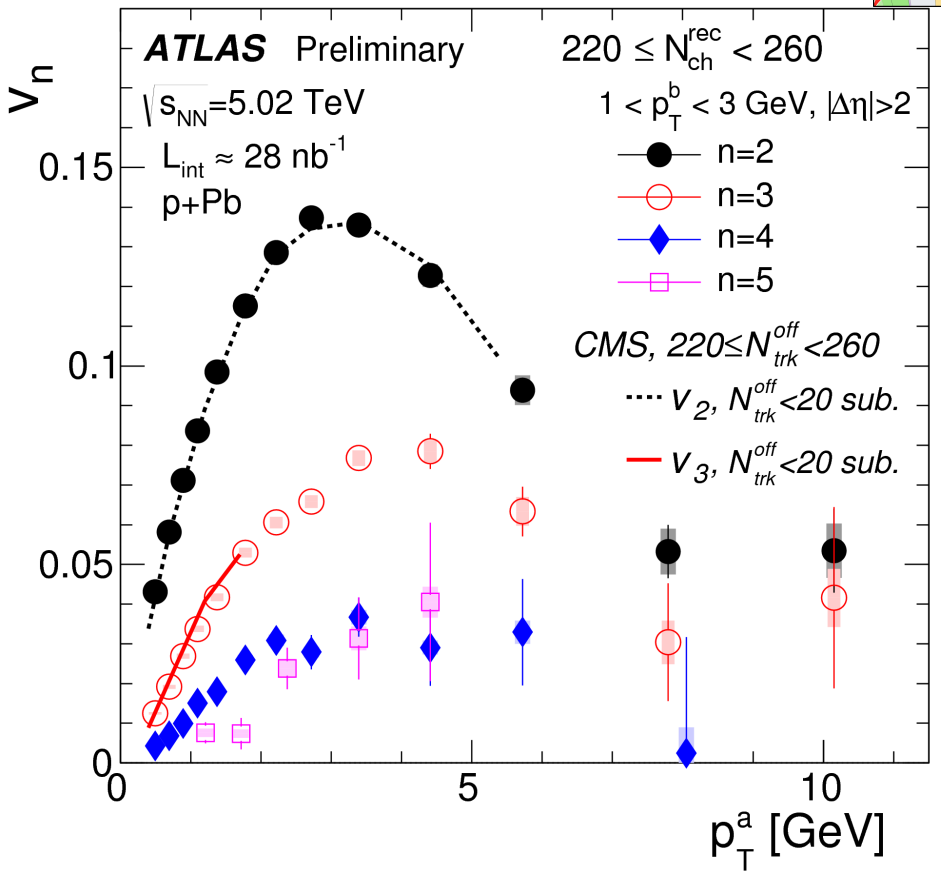
Subtraction:

- Double-ridge also in HF correlations
- Mechanism affects also HF particles

Denise GODOY
Thu, 15:05h

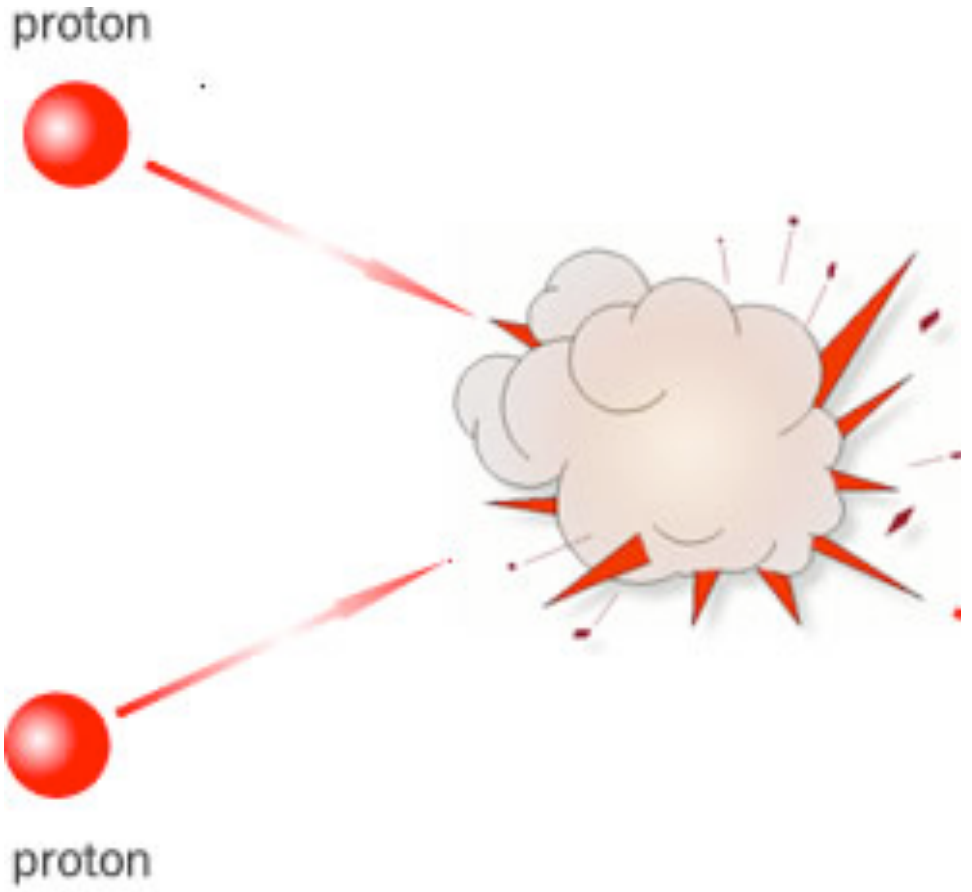
Ridge at high p_T



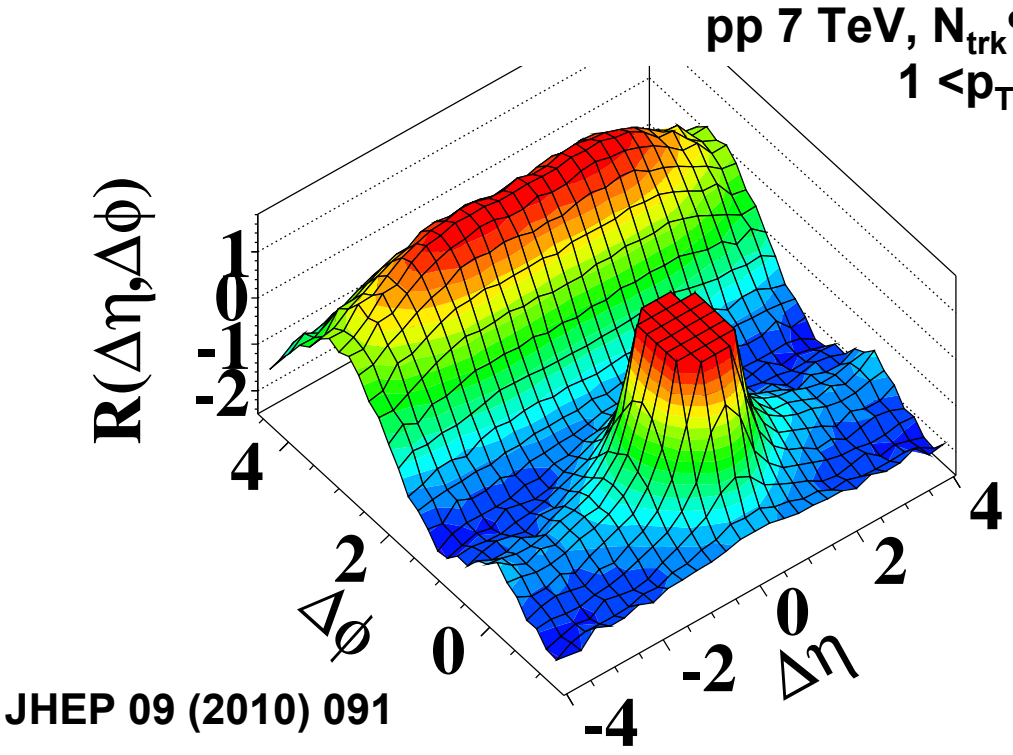


- At high multiplicity, even at high p_T: $v_2 > 0$
- In Pb-Pb this addressed to jet medium interactions (R_{pPb} for charged hadrons in this p_T range found to be one)

ATLAS-CONF-2014-021

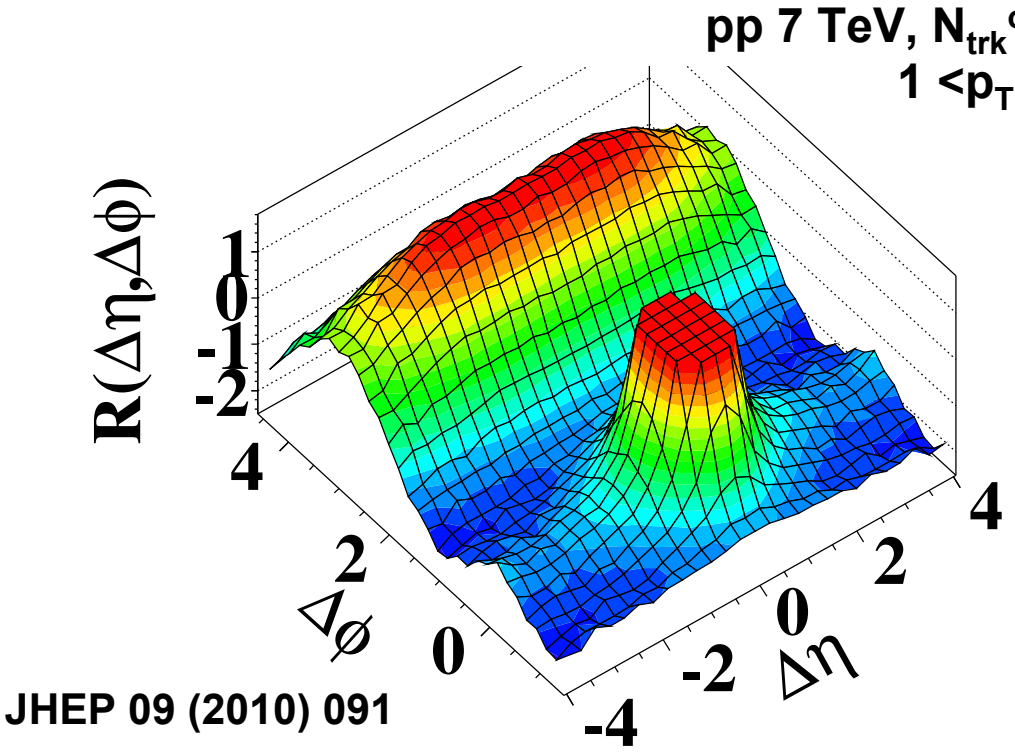

proton
proton

High multiplicity pp collisions



Long range correlations also in pp collisions at high multiplicities observed

High multiplicity pp collisions



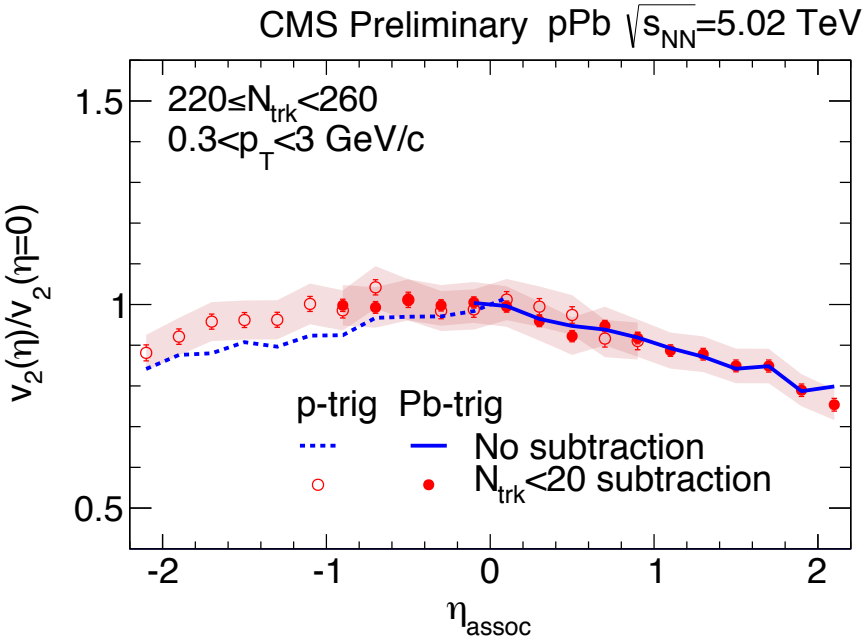
JHEP 09 (2010) 091

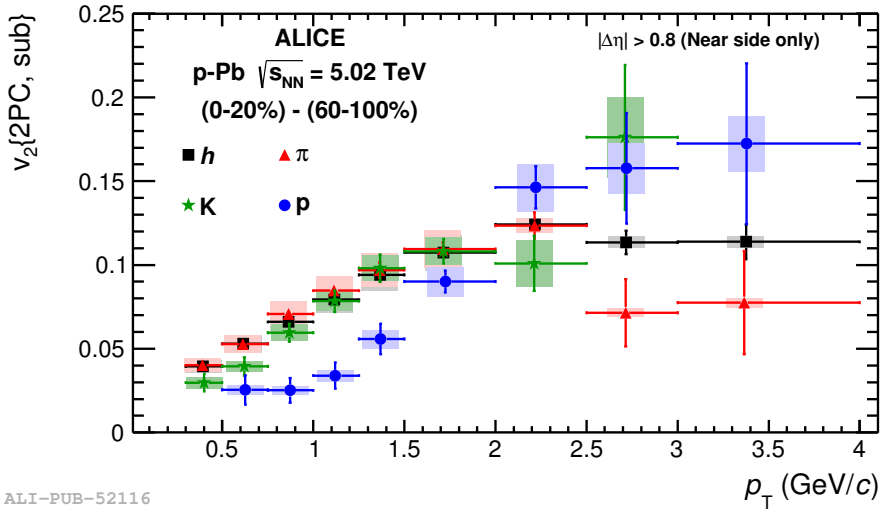
Long range correlations also in pp collisions at high multiplicities observed

Origin unclear

Still ....

High multiplicity pp collisions





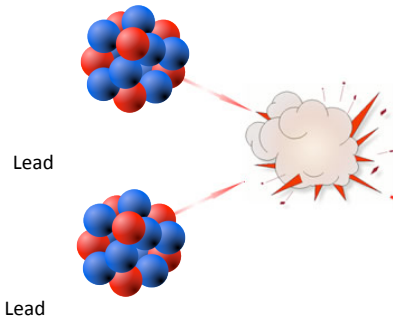
η dependence ?

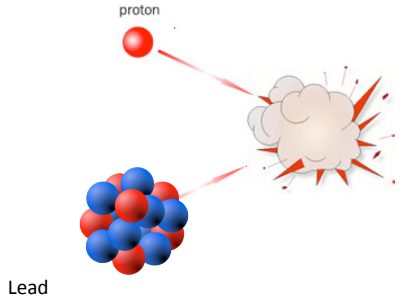
PID dependence?

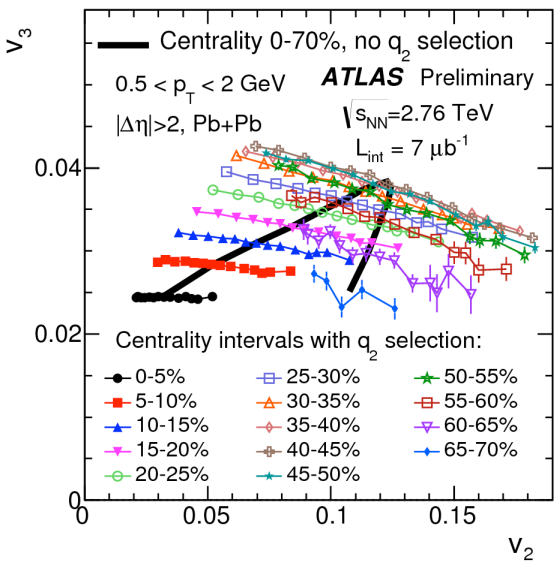
Origin unclear

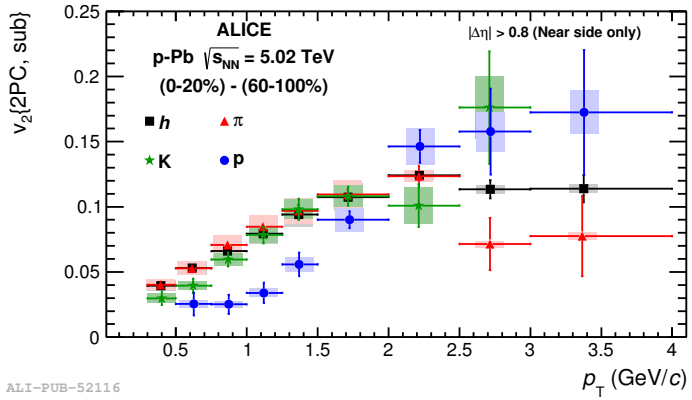
(lacking detailed, systematic study of "ridge properties", e.g. similar to what was done in p-Pb).

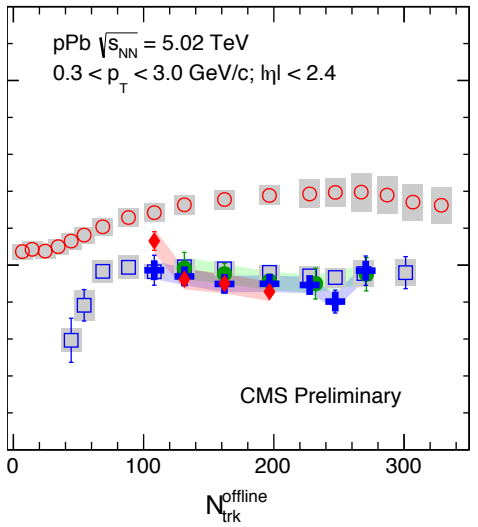
Summary







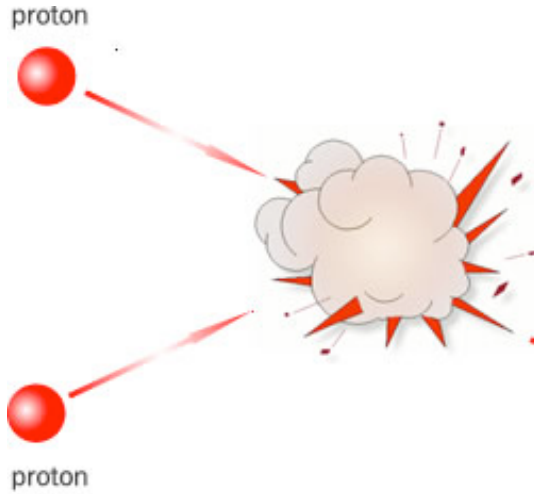




Event-by-event fluctuations and correlations

Collectivity in small systems

Outlook



More surprises to come?

Backup

Flow methods

- Event plane method:

$$v_n = \langle \cos\left(n\left(\varphi - \Psi_{EP,n}\right)\right)\rangle$$

- Q vector:

$$Q_n = \sum_{i=1}^{M} e^{in\varphi_i} \xrightarrow{\text{e.g.}} \langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

- Cumulant method:

$$\begin{aligned} c_n\{2\} &= \langle\langle 2\rangle\rangle \\ c_n\{4\} &= \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2 \\ c_n\{6\} &= \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3 \end{aligned} \longrightarrow \begin{aligned} v_n\{2\} &= \sqrt{c_n\{2\}} \\ v_n\{4\} &= \sqrt[4]{-c_n\{4\}} \\ v_n\{6\} &= \sqrt[6]{\frac{1}{4}c_n\{6\}} \end{aligned}$$

- 2-particle correlations:

$$\frac{1}{N_{trig}}\frac{dN_{assoc}(\Delta\varphi)}{d\Delta\varphi} = a_0 + \sum_{n=1}^{\infty} 2a_n \cos(n\Delta\varphi)$$