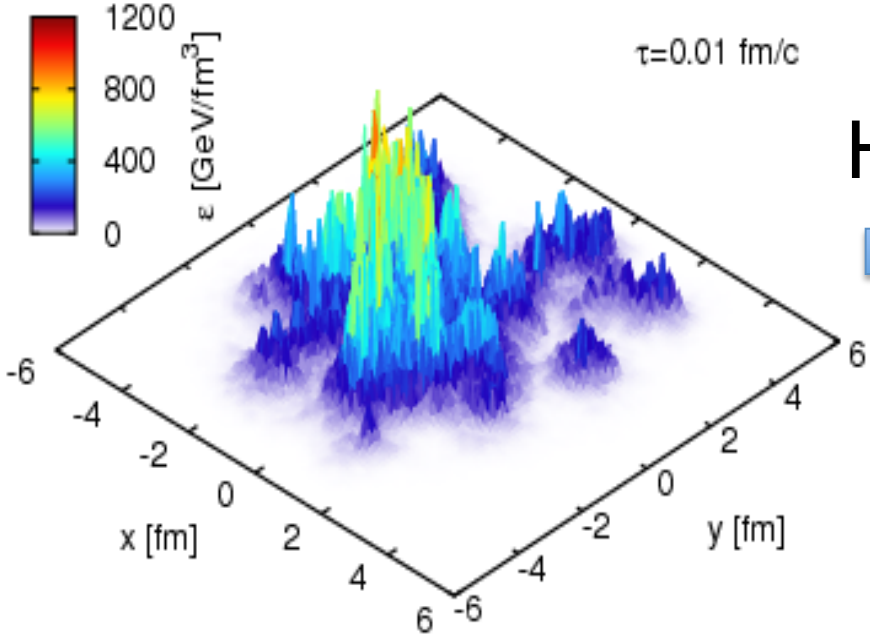
Particle correlations and collectivity in heavy-ion collisions at CMS

Wei Li (Rice University)

IWoC, September 14-20, 2014

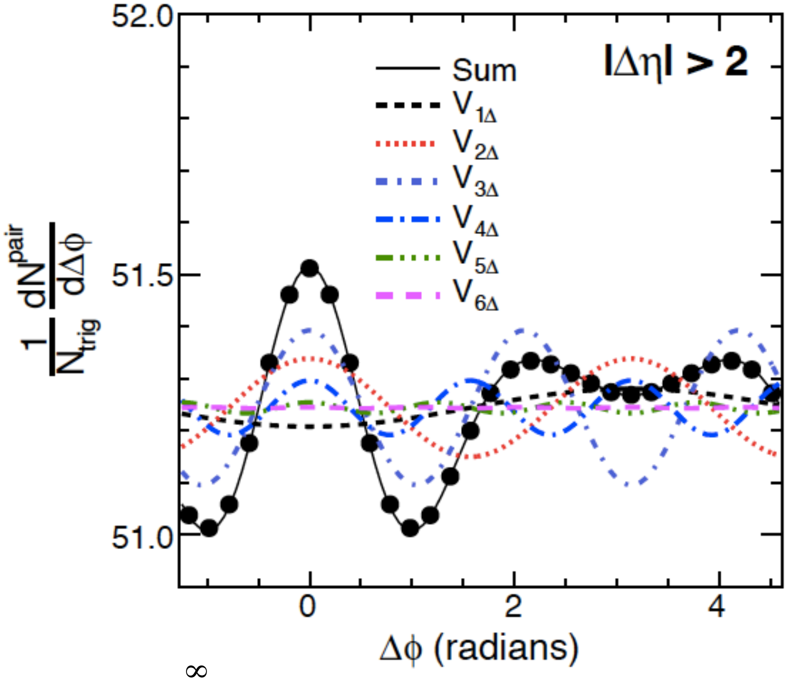
Paradigm of nearly perfect fluidity

Initial-state fluctuations



Hydro.

Final-state correlations



$$\sim 1+2\sum_{n=1}^{\infty} V_{n\Delta}(p_T^{trig}, p_T^{assoc})\cos(n\Delta\phi)$$

Paradigm of nearly perfect fluidity

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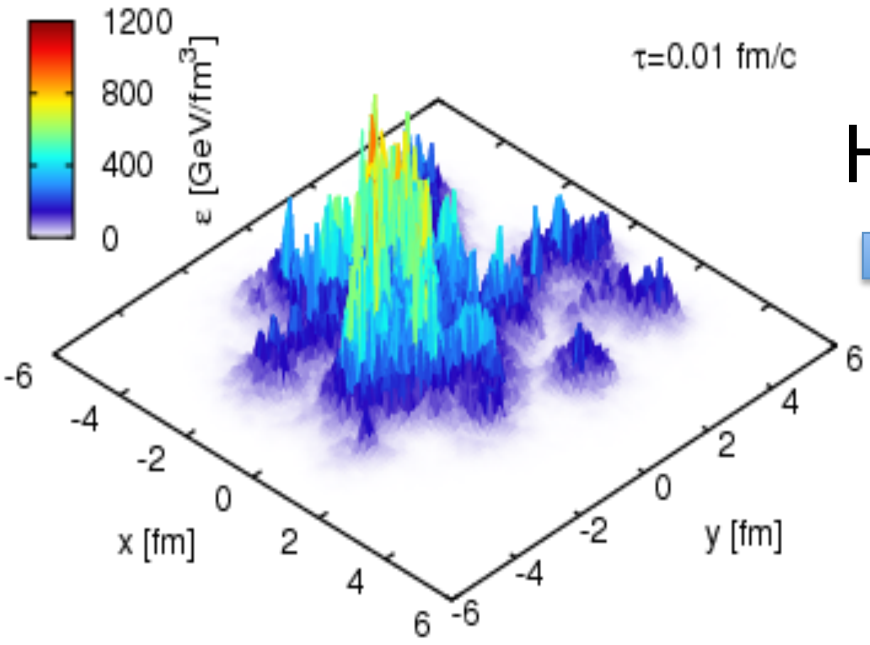

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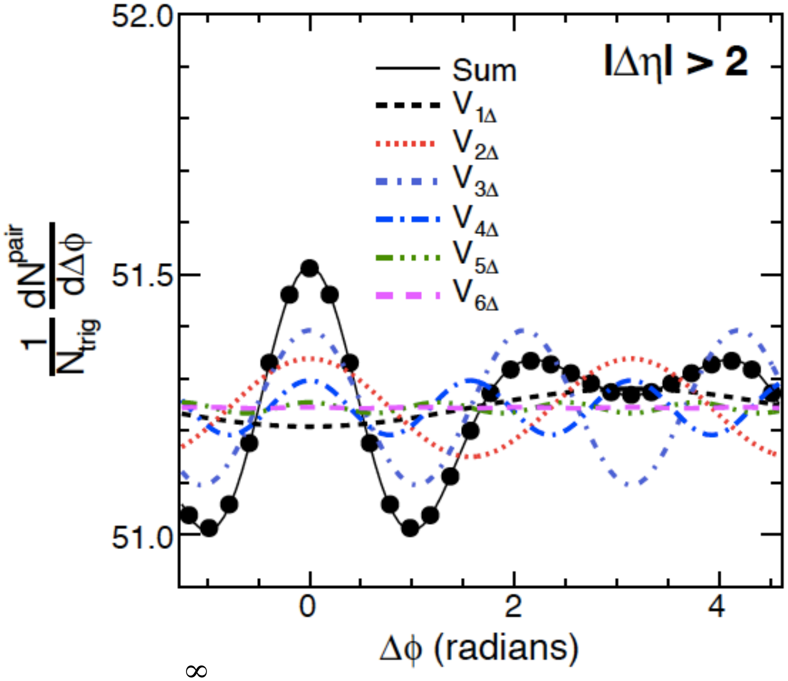
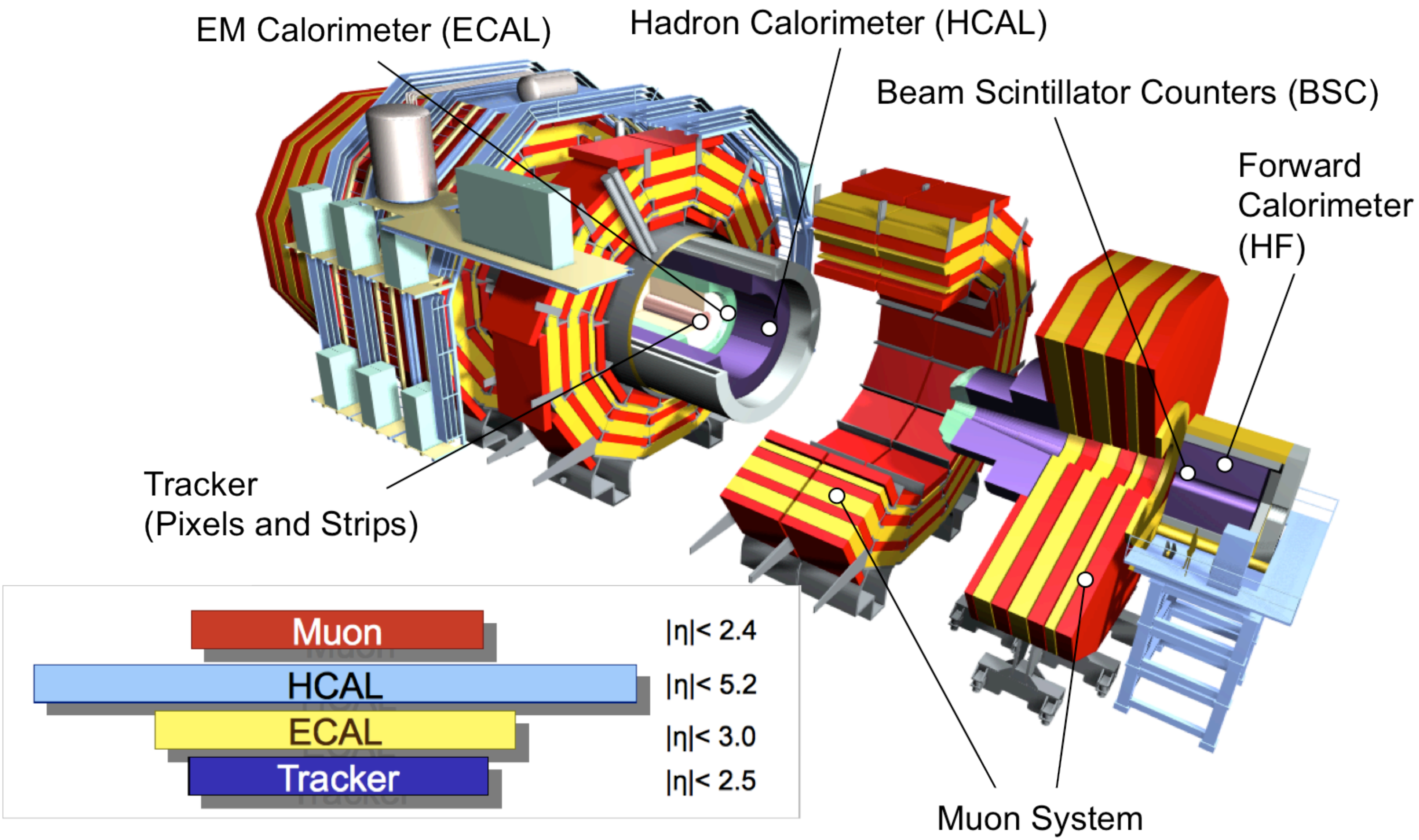


$$\sim 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}(p_T^{trig}, p_T^{assoc}) \cos(n\Delta\phi)$$

- ➢ Understand the initial state and its fluctuations
- ➢ Extract the QGP’s transport coefficients (η/s)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN, 10 papers on flow/correlations!

Compact Muon Solenoid (CMS) at the LHC

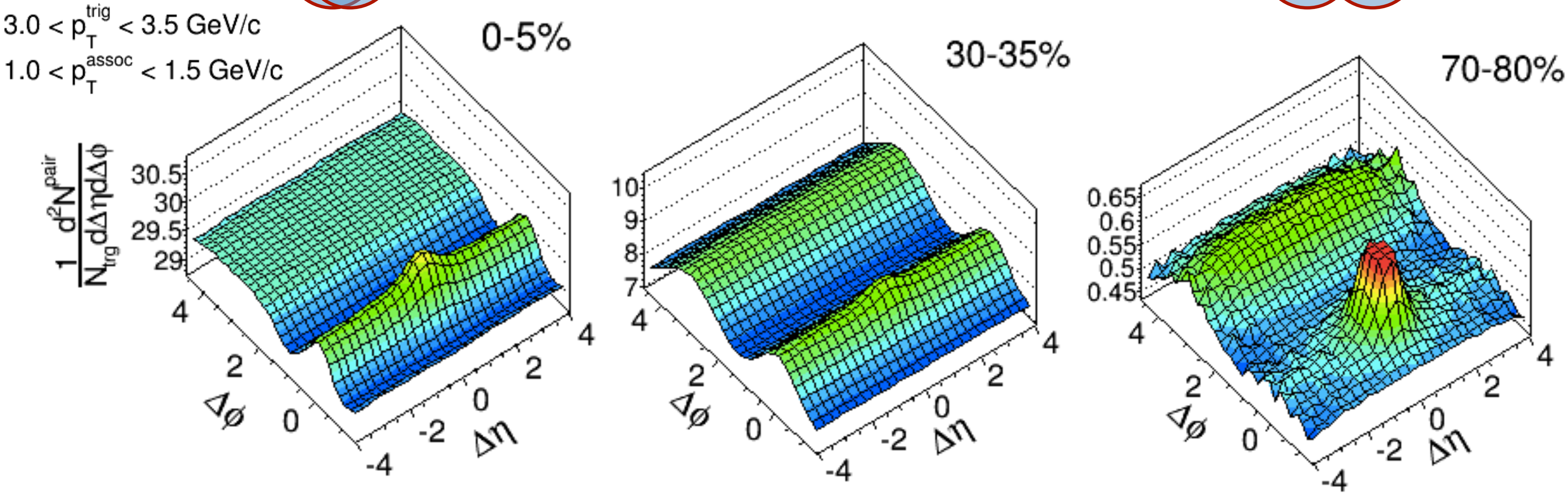


Large acceptance and wide kinematic coverage!

Long-range azimuthal correlations ("ridge")

centrality

PbPb



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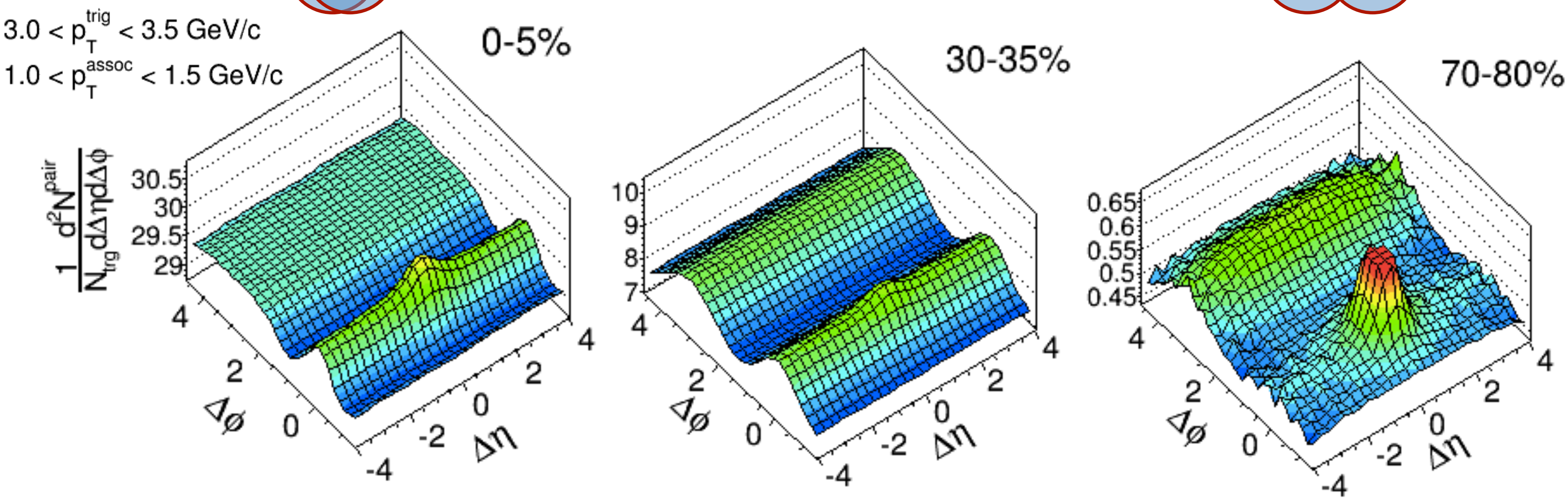

Collectivity diminishing as system size decreases

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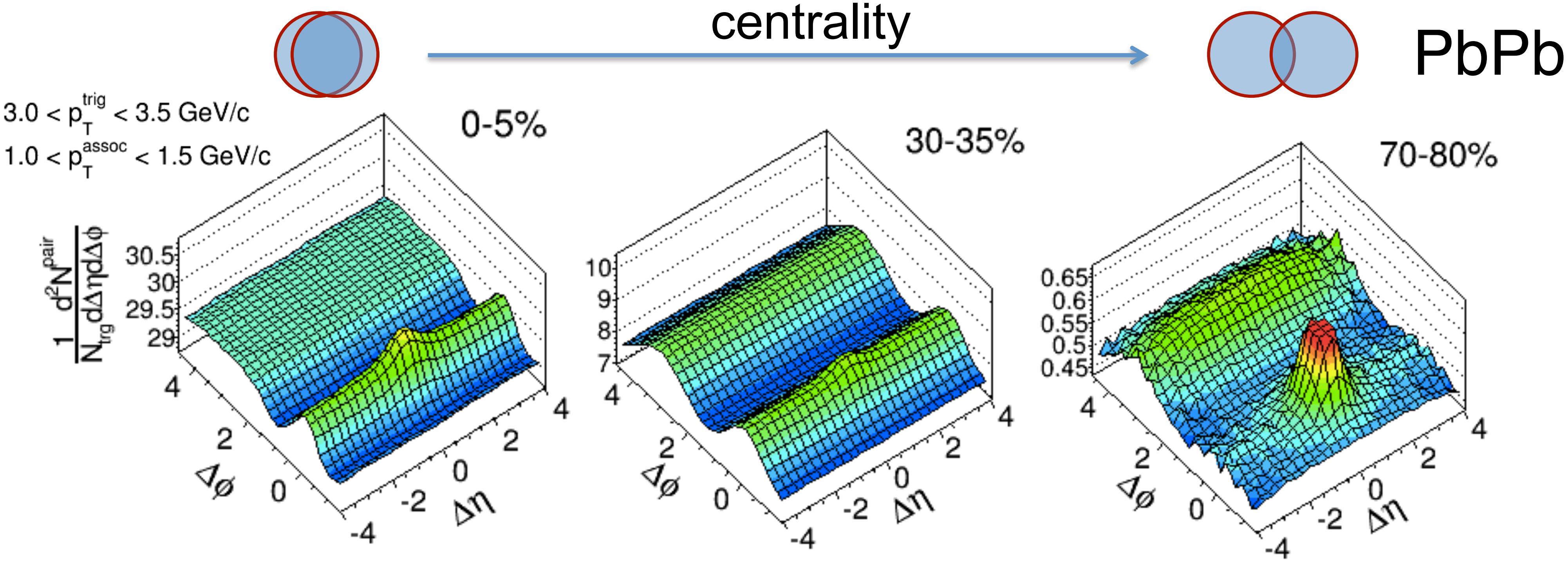
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No collectivity in pp and pPb expected

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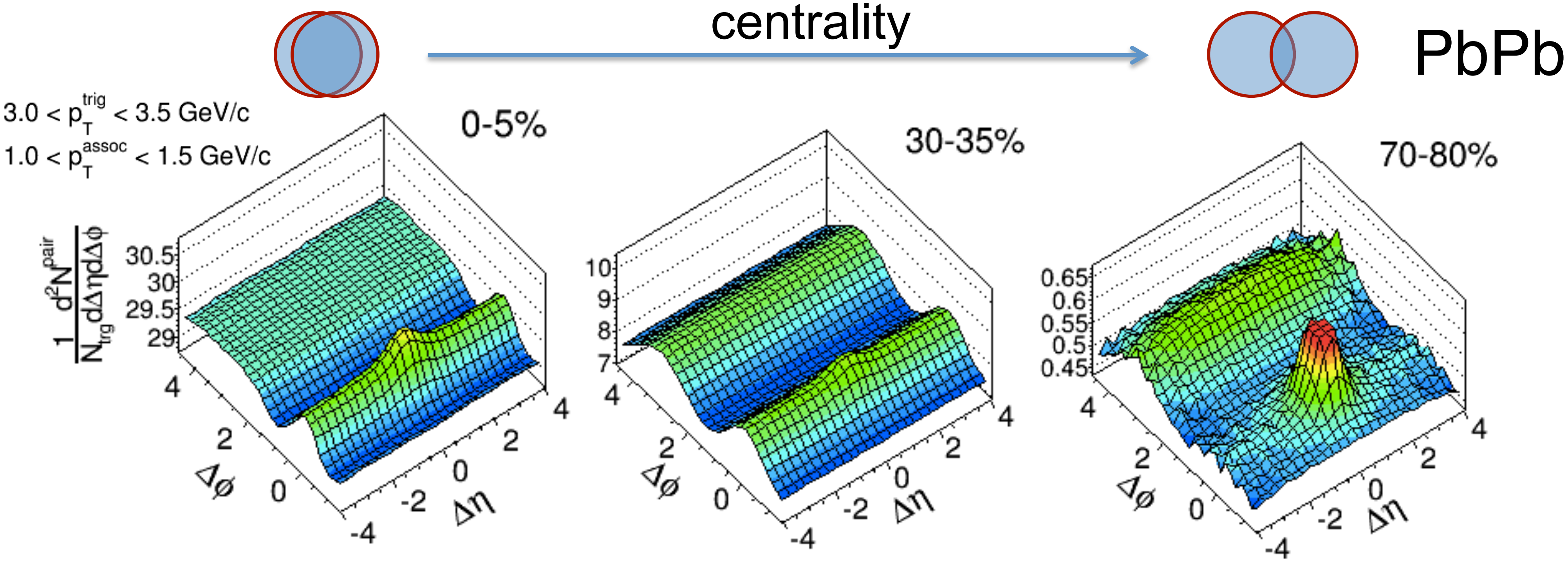

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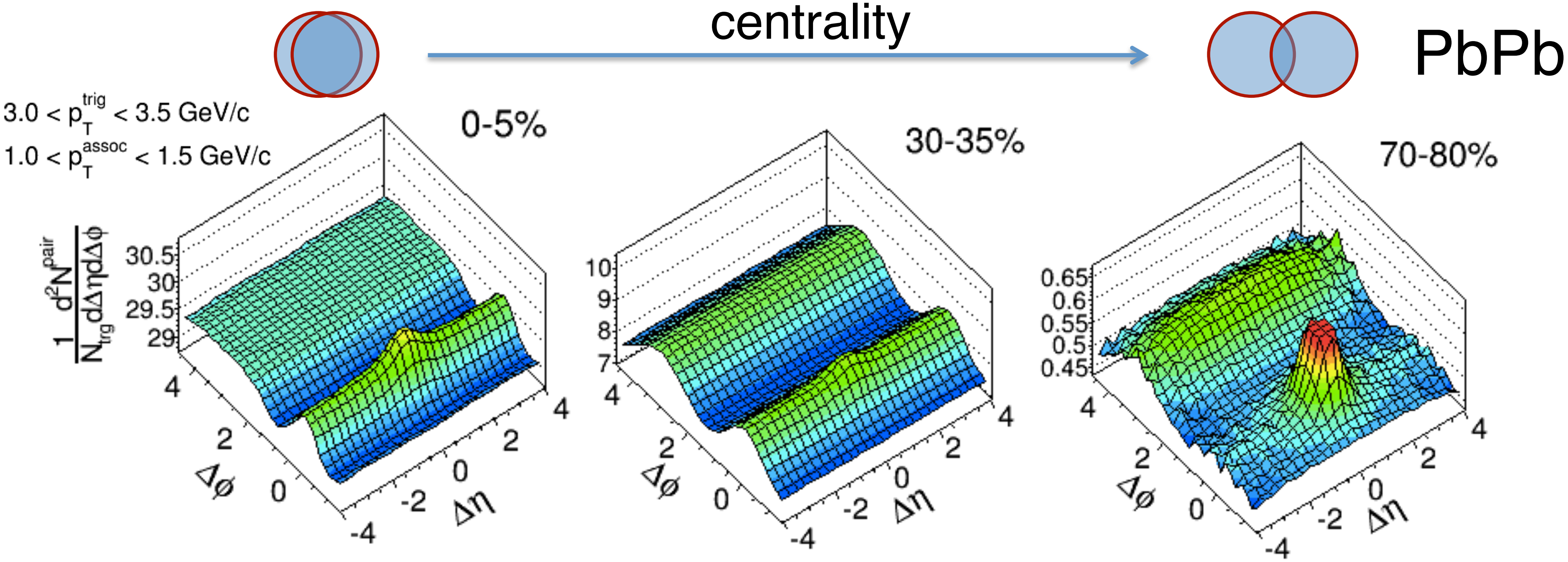

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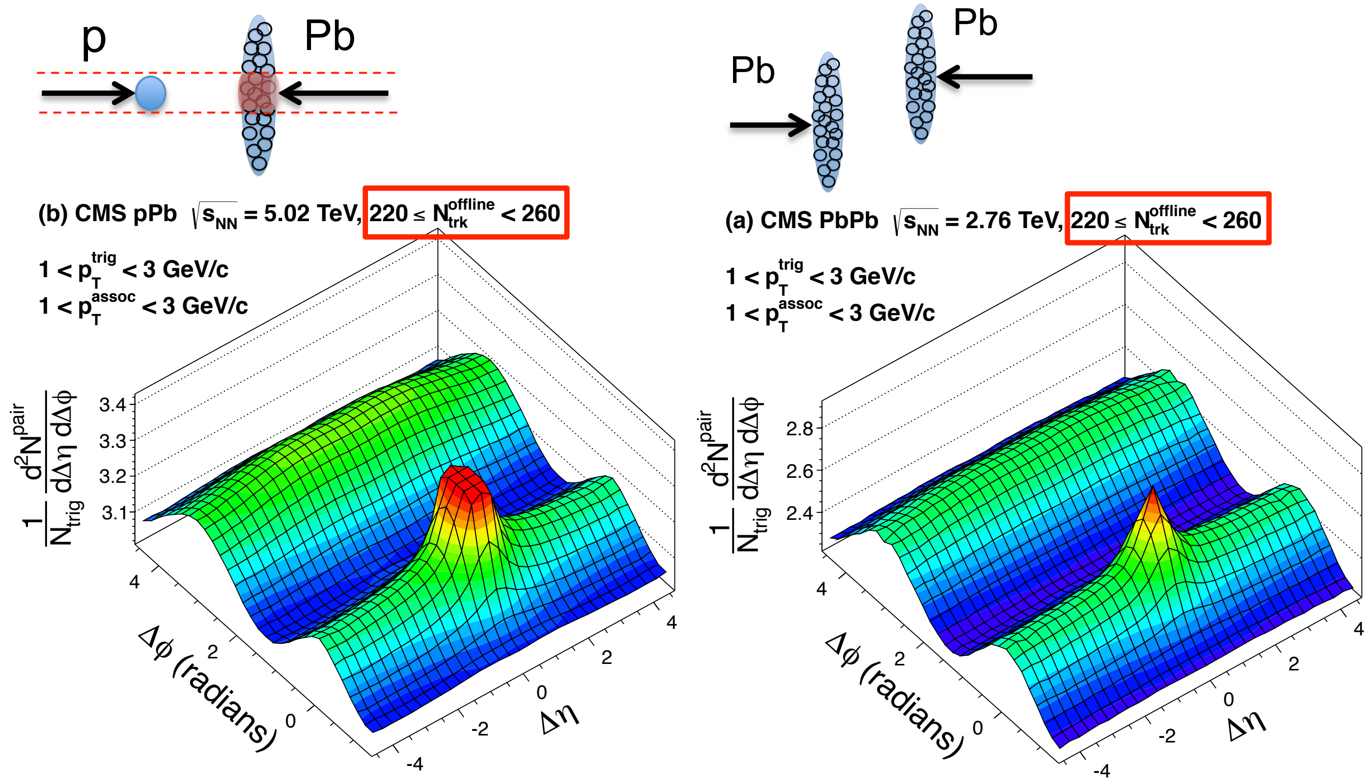
No collectivity in pp and pPb expected

But what if depositing much more energies

➔ a smaller but hotter QGP?!

The “ridge” tsunami at the LHC



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

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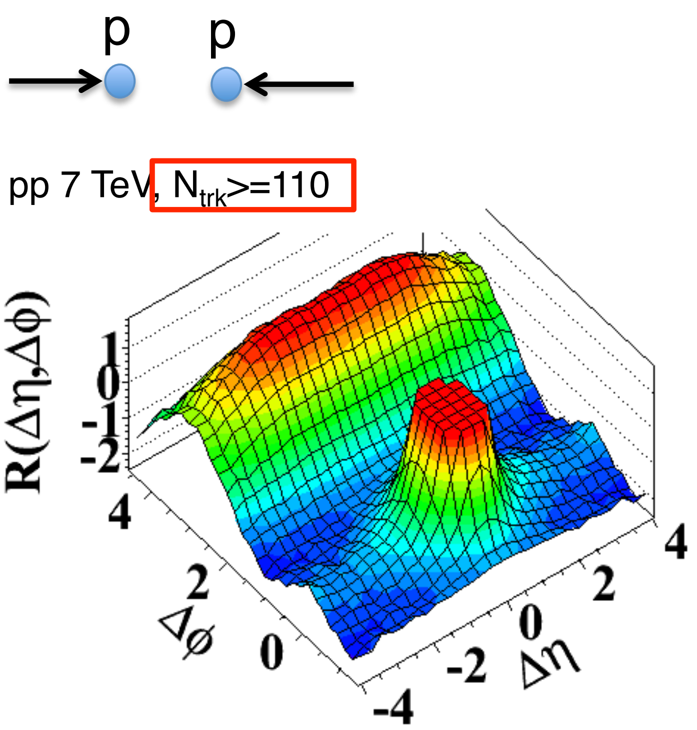

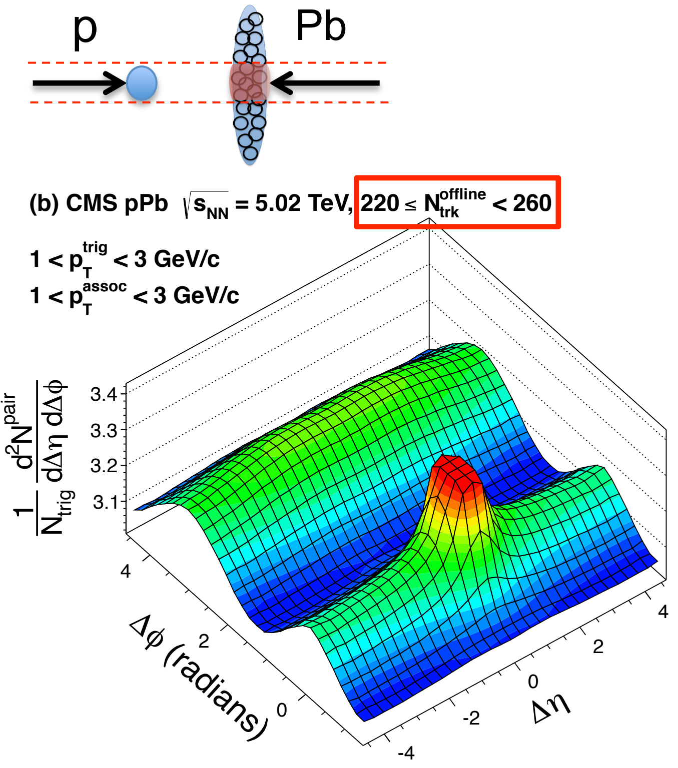

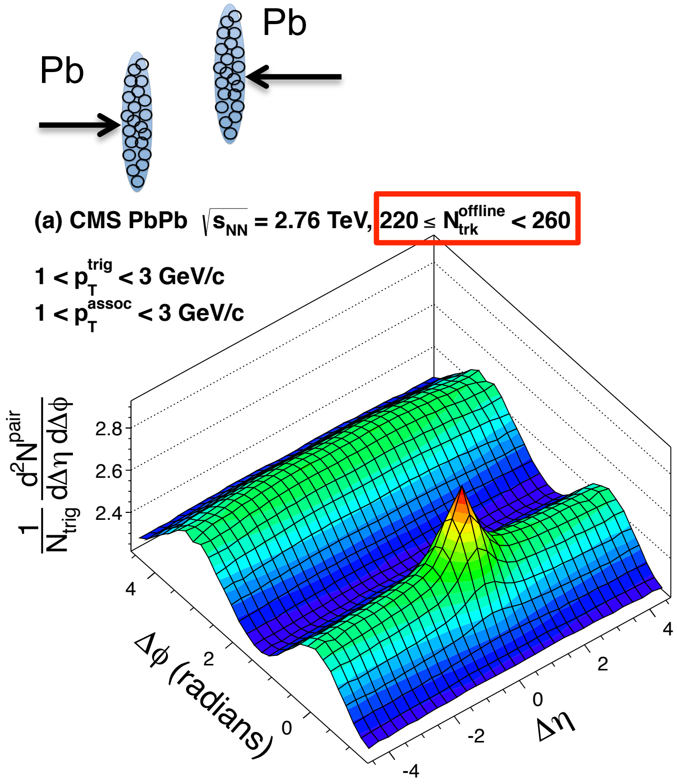

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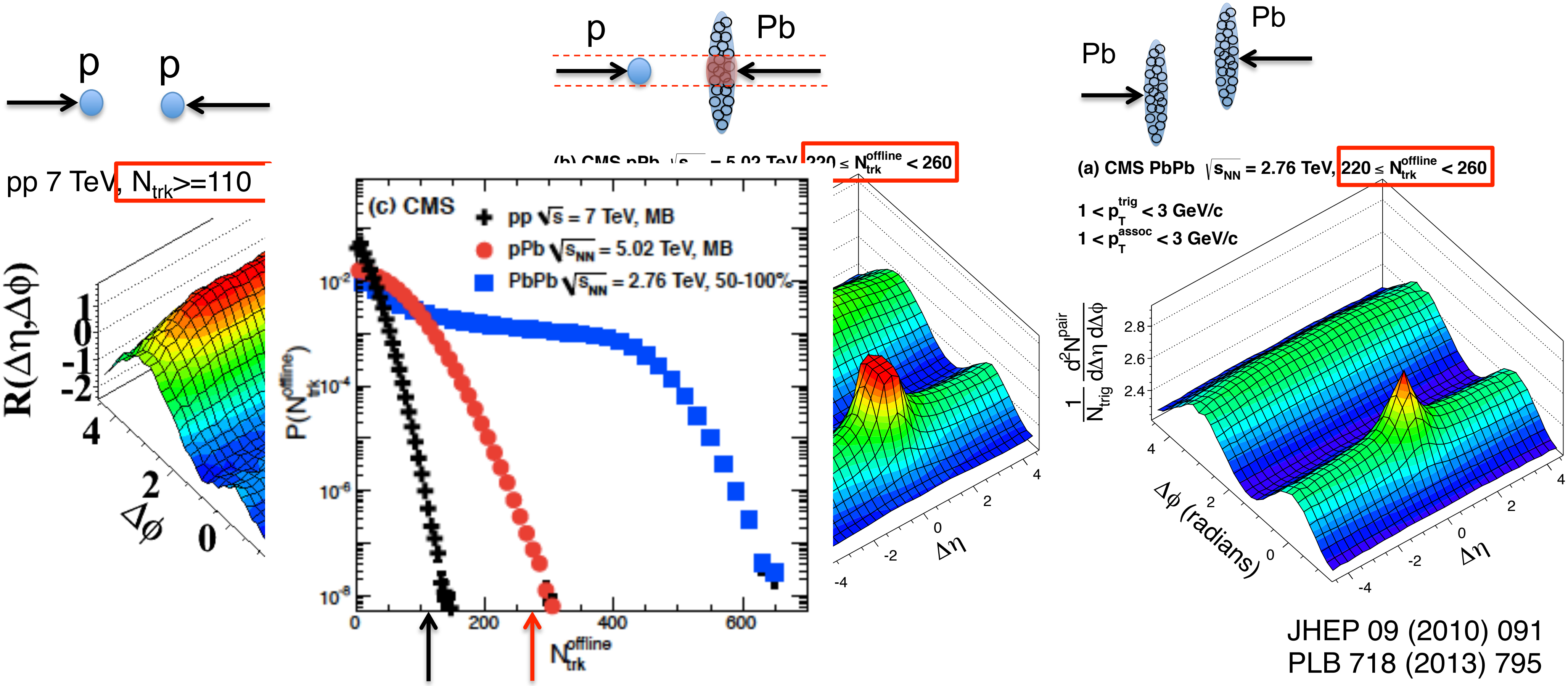
The “ridge” seen in all systems at the LHC!

➔ Everything flows?

The “ridge” tsunami at the LHC



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The “ridge” seen in all systems at the LHC!

➔ **Everything flows?**

“Flow” (v_n) in pPb

Factorization assumption:

$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}) = v_n(p_T^{trig}) \times v_n(p_T^{assoc})$$

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

— imposed in all flow methods!

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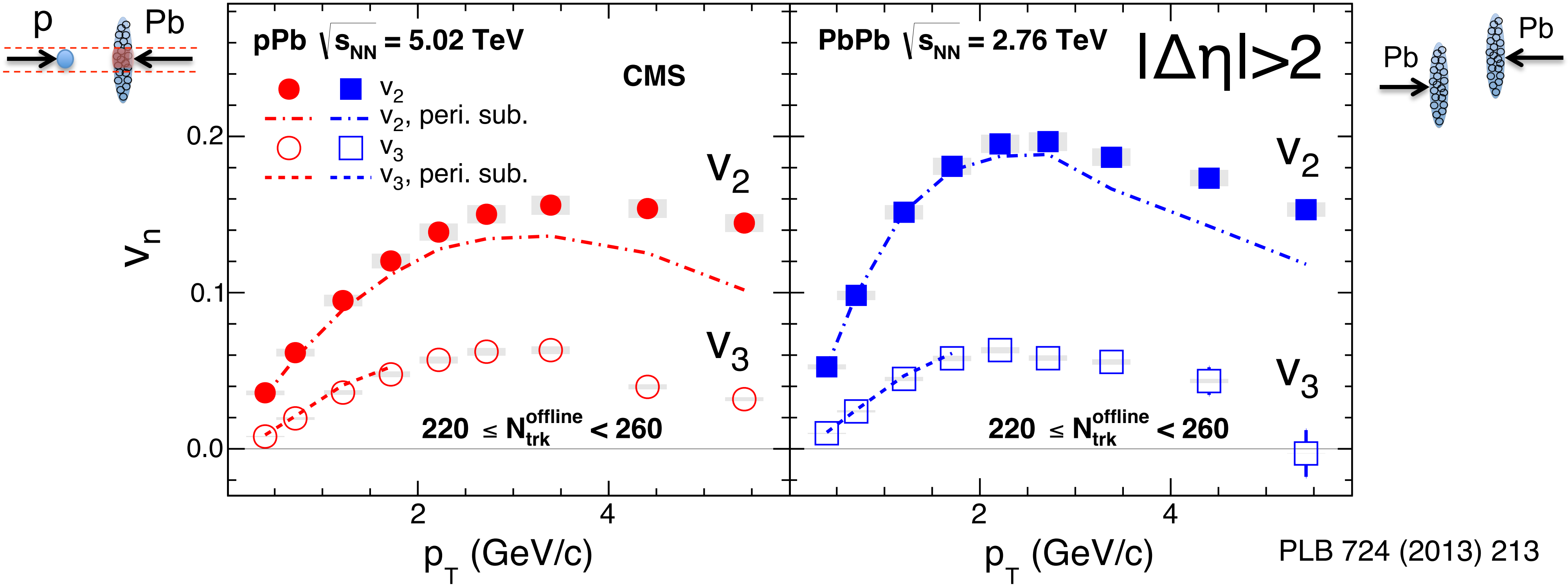

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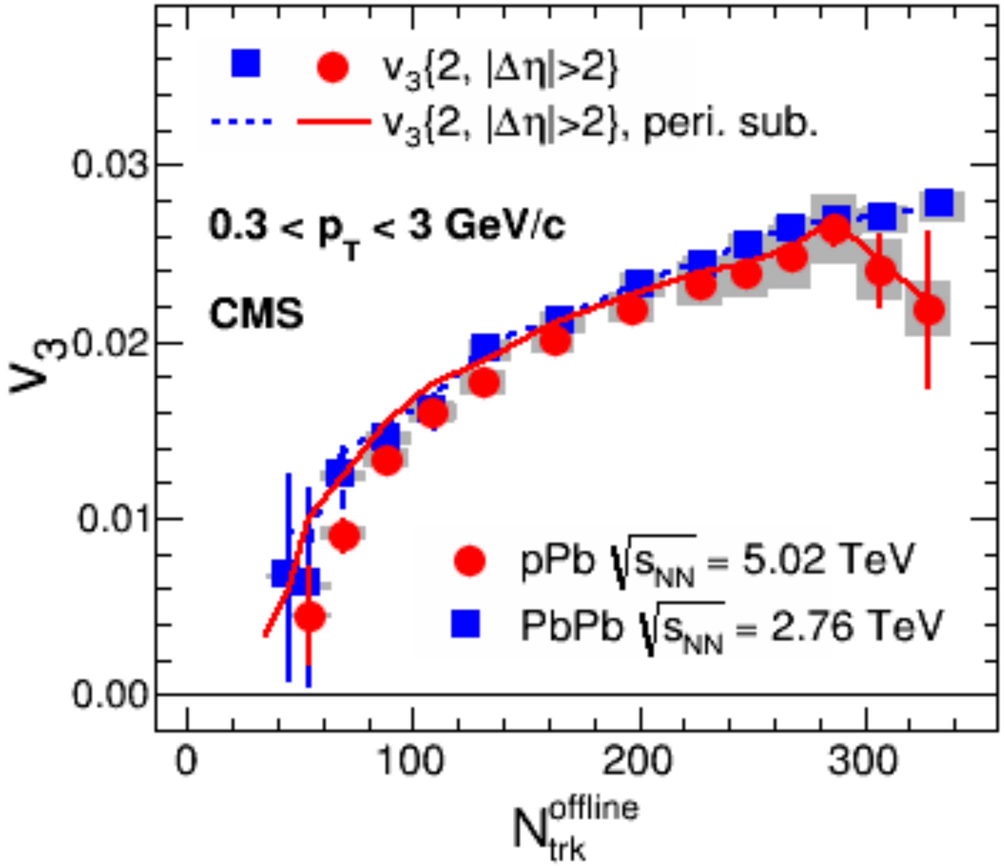

identical v_3 in pPb and PbPb!

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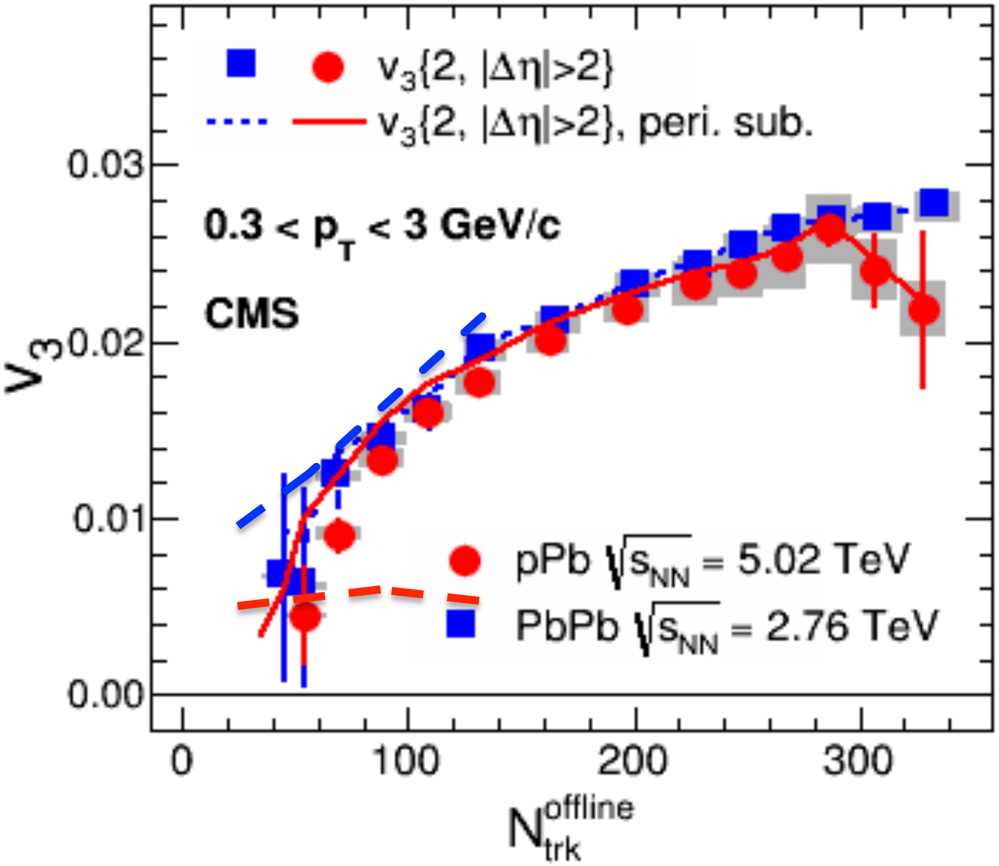
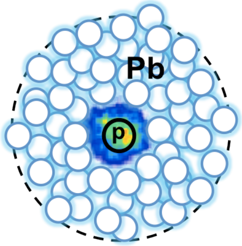


Hydro. failed



arXiv:1405.3605

proton is mostly spherical
in the IP-glasma model

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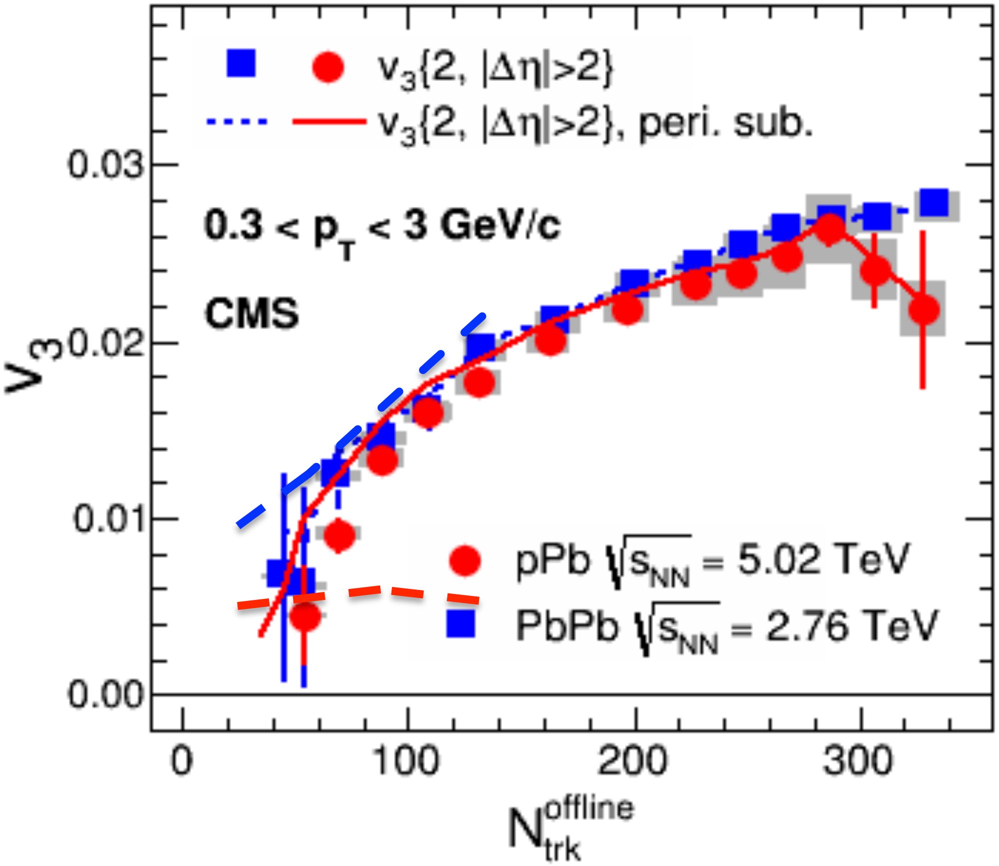
PLB 724 (2013) 213



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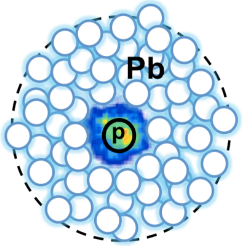

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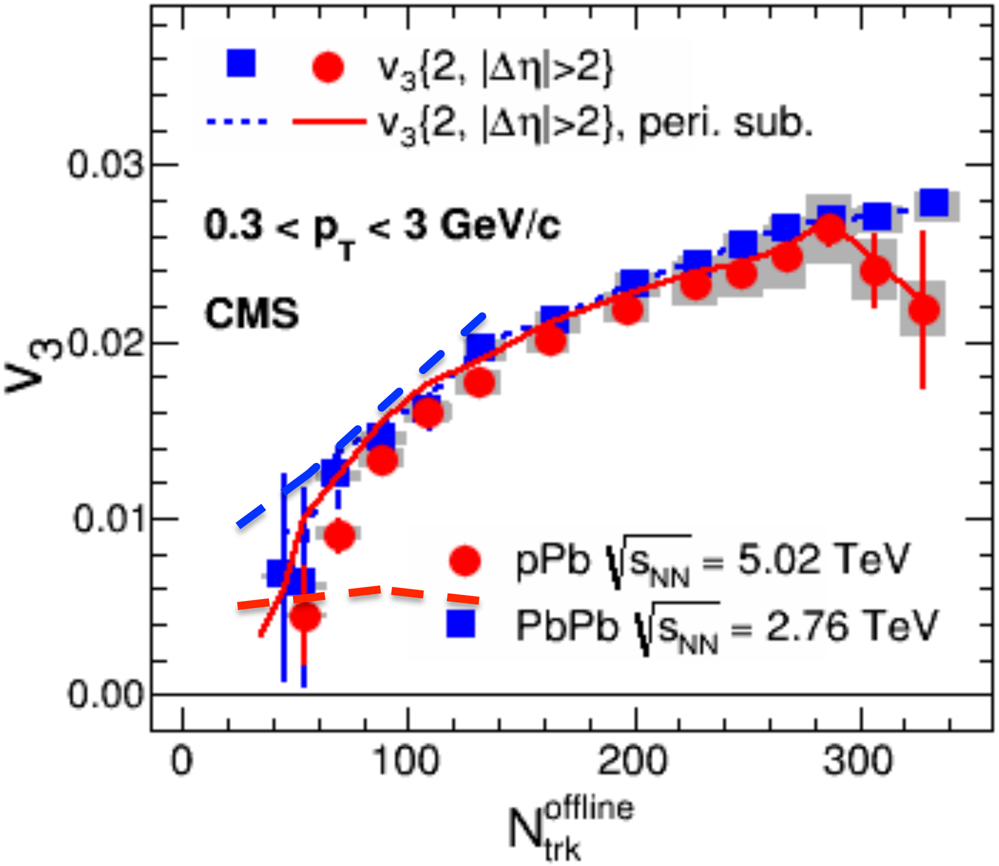
Stringy proton caught by nucleus?

PRD 89, 025019 (2014)

“Flow” (v_n) in pPb

PLB 724 (2013) 213



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Initial state not understood,
esp. subnucleonic structure

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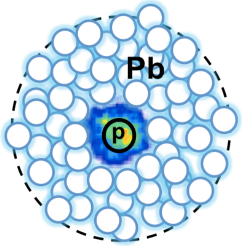

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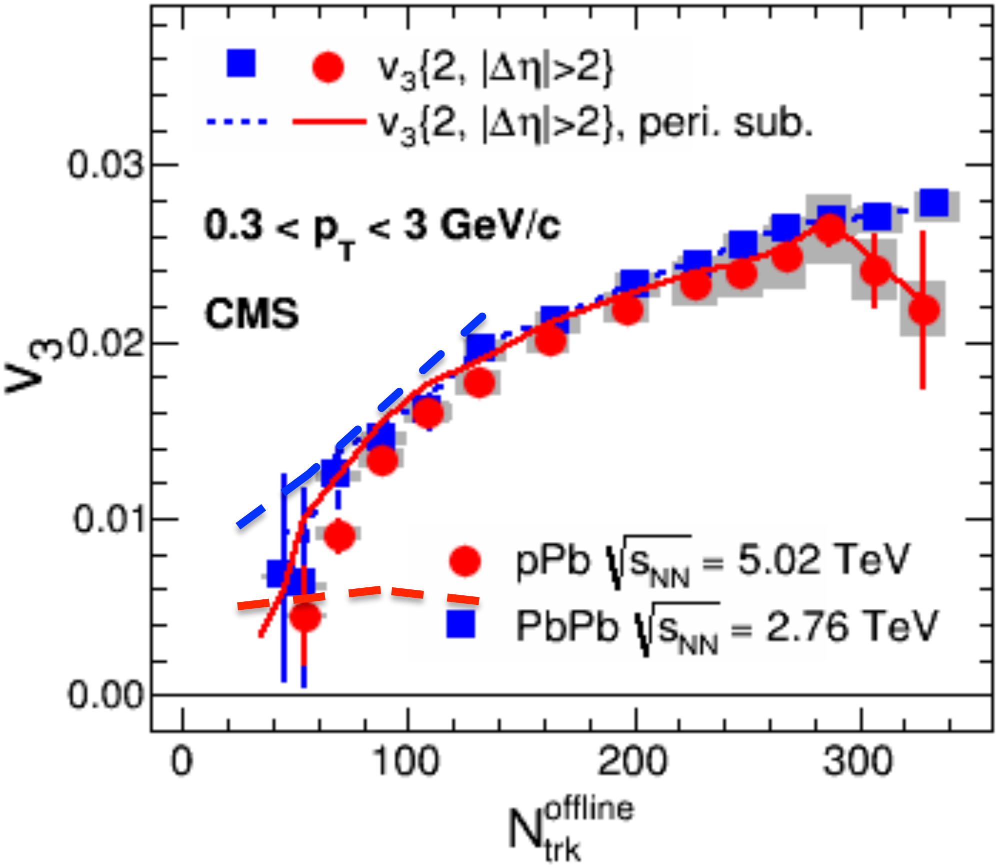

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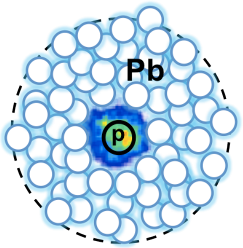

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proton is mostly spherical
in the IP-glasma model

Stringy proton
caught by nucleus?

PRD 89, 025019 (2014)

Initial state not understood,
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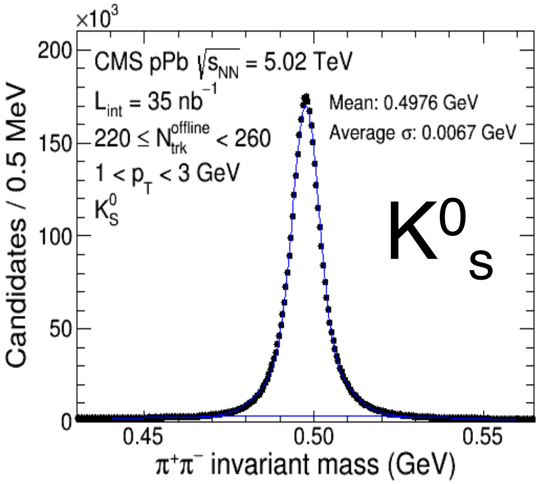
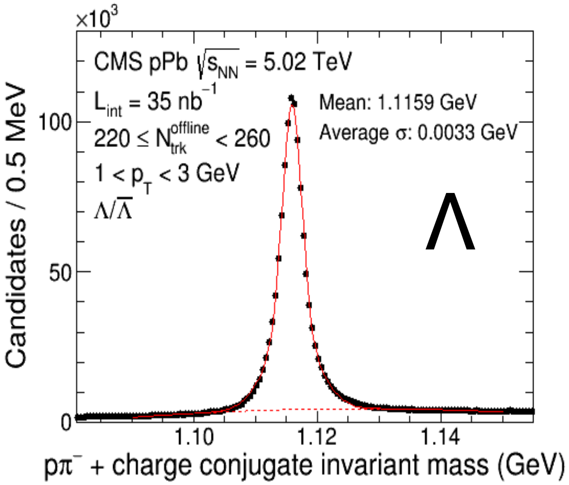
or

Non-hydro correlations

(PRD 87 (2013) 094034, arXiv:1405.7825)

Identified particle correlations at CMS





Clean V^0 hadron reconstruction!

arXiv:1409.3392

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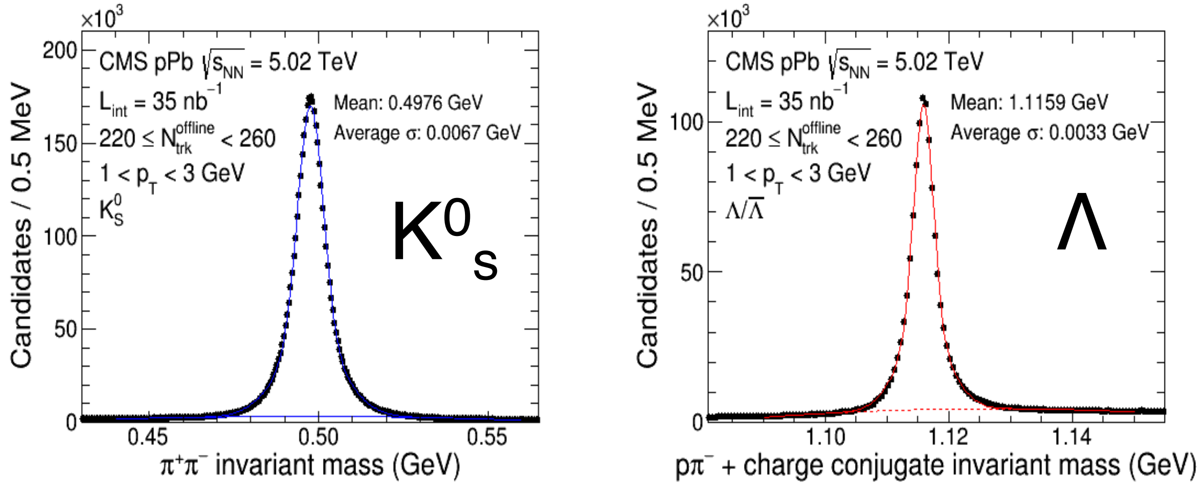

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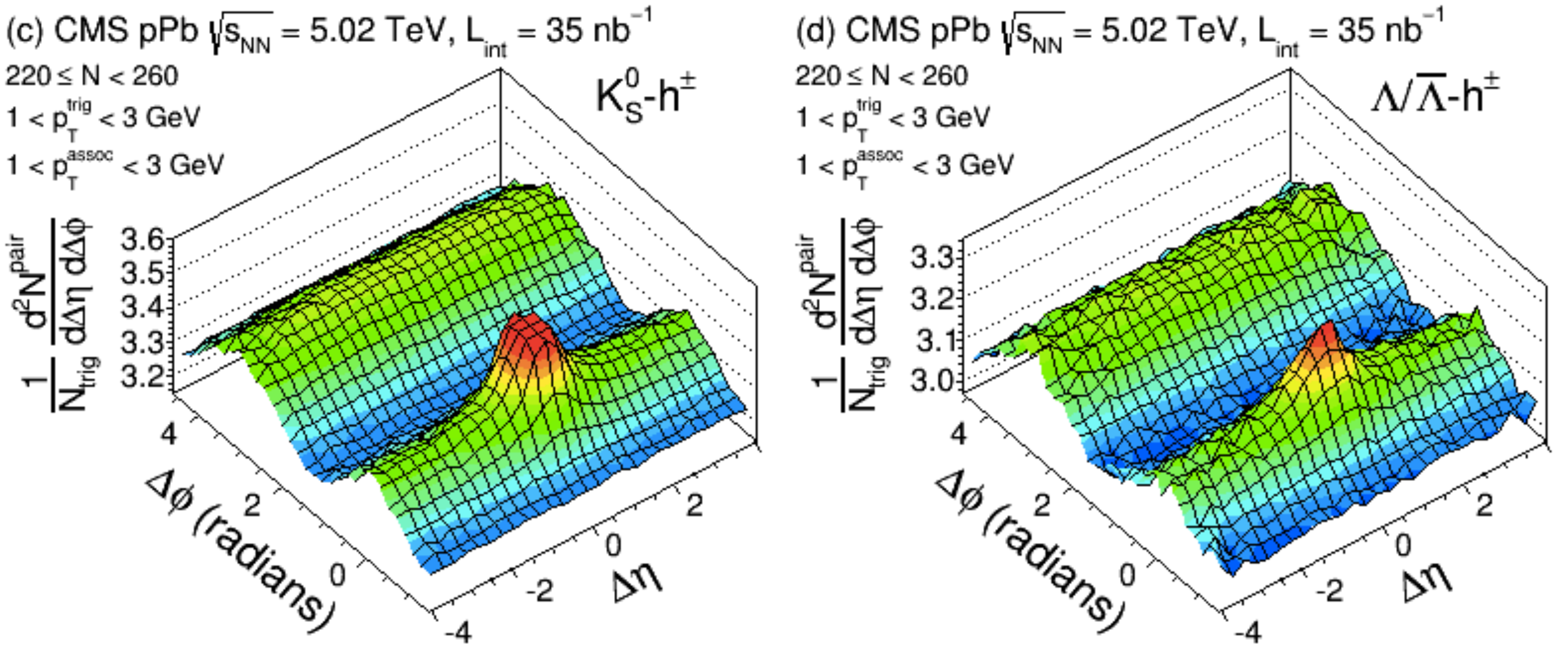
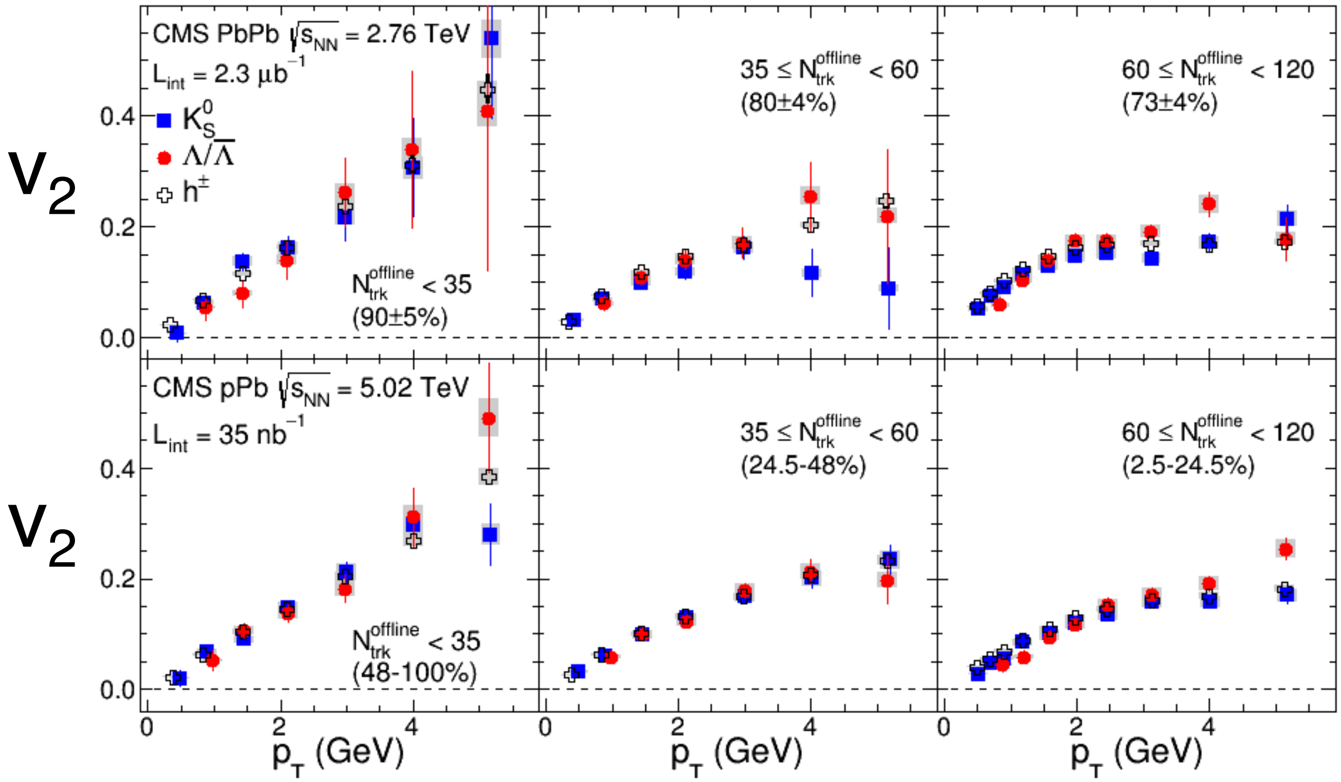
"ridge" with K^0_s and Λ

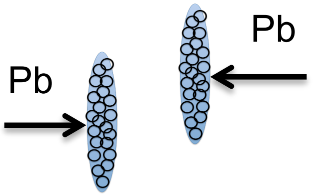


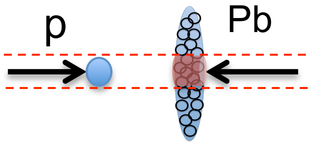
Identified particle v_n in pPb

Low multiplicity

Increasing N_{trk}



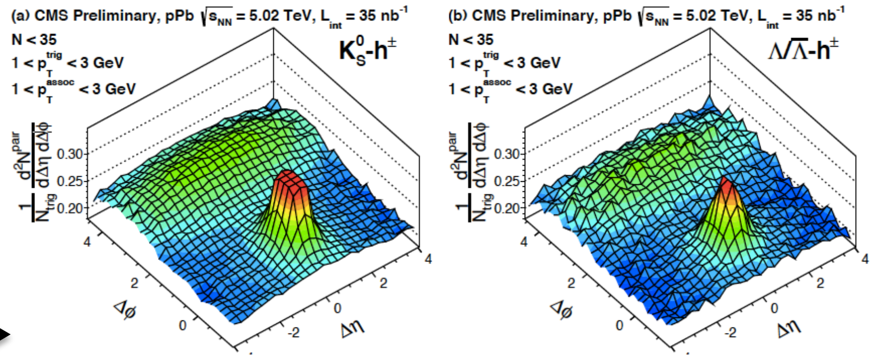




No PID dependent at low N_{trk} from jet correlations

Identified particle v_n in pPb

Low multiplicity



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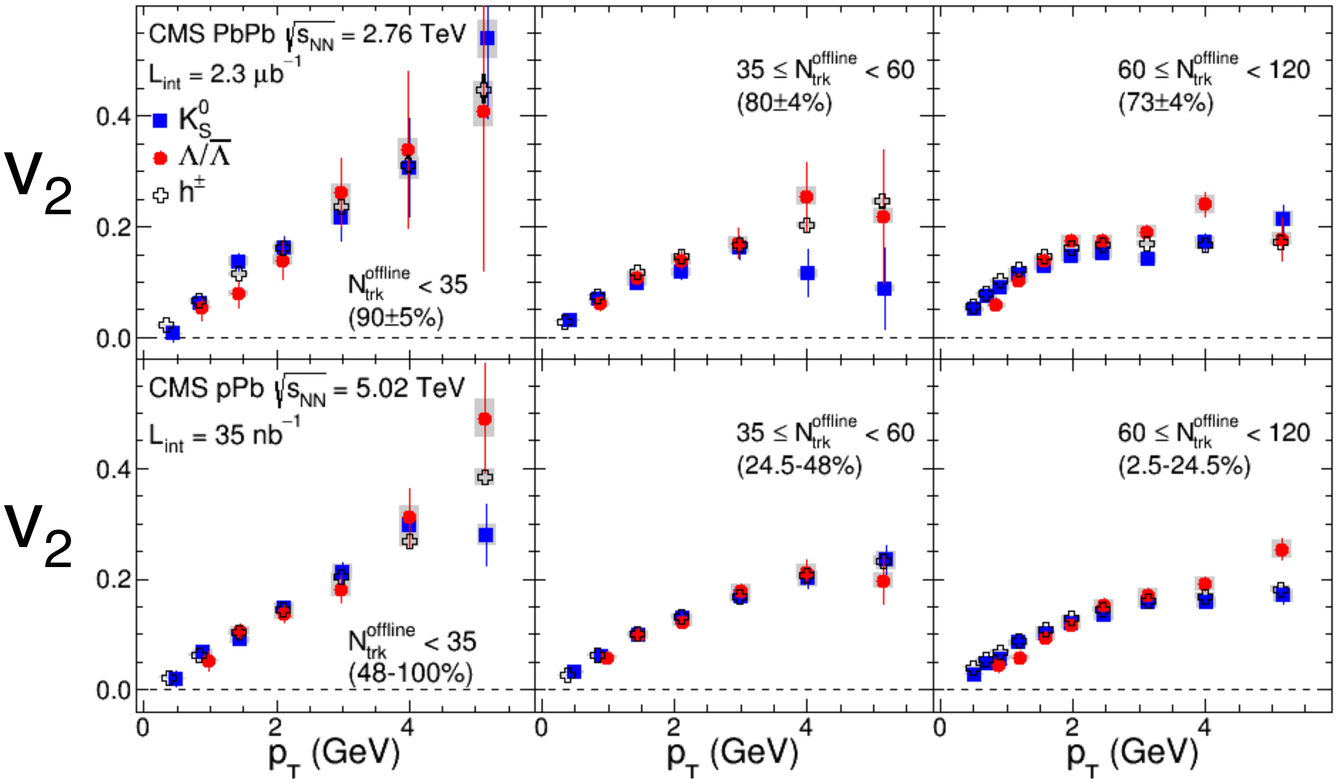

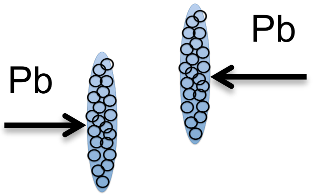

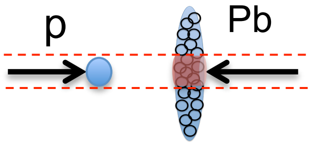

No PID dependent at low N_{trk} from jet correlations

Identified particle v_n in pPb

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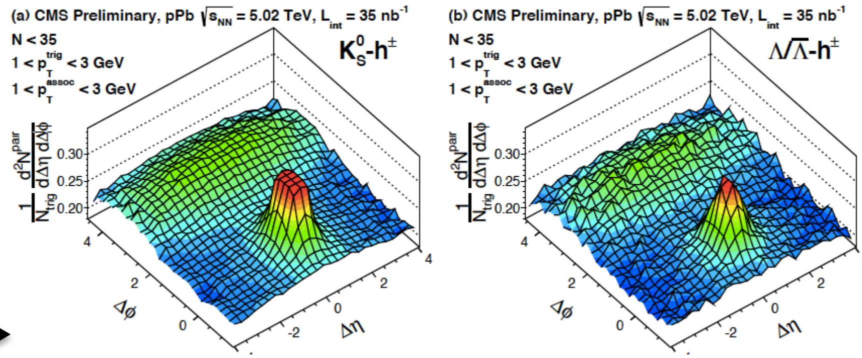

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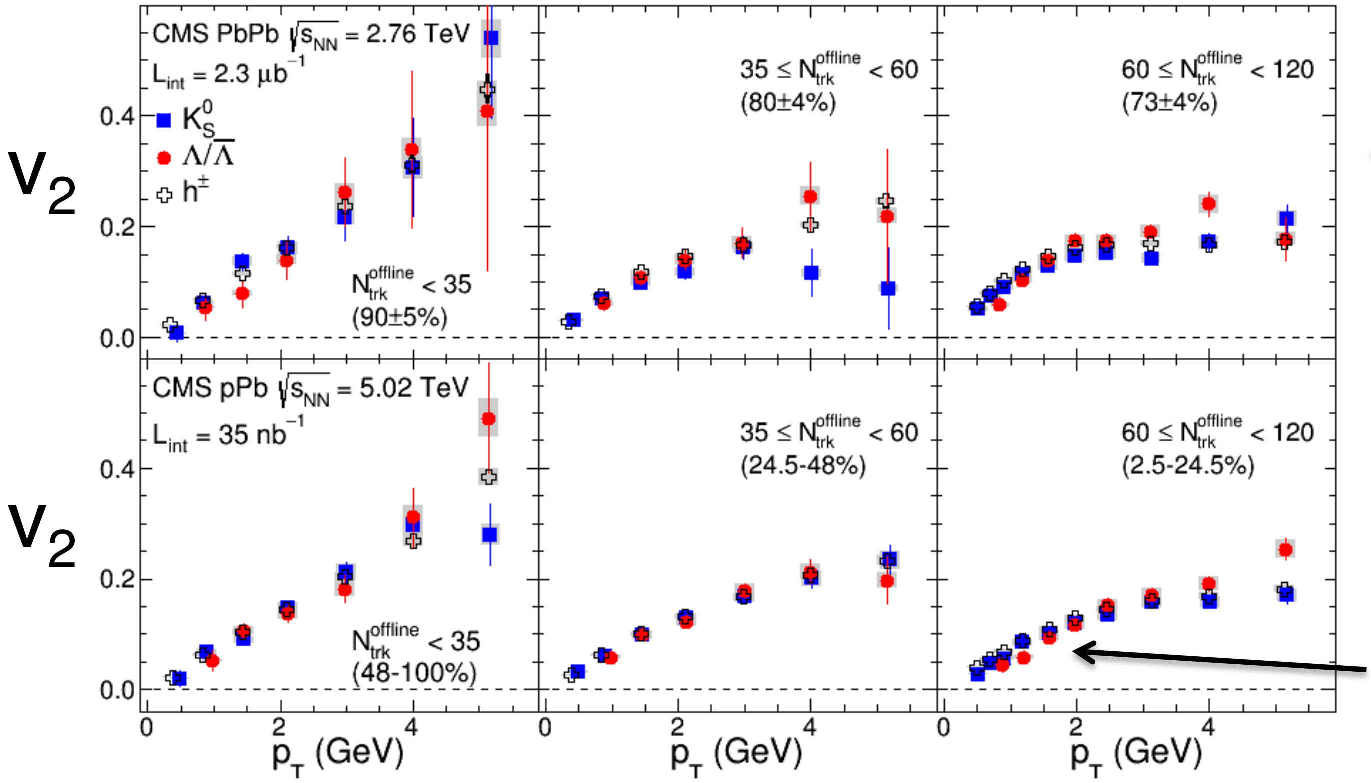
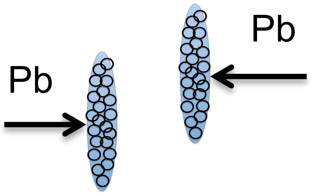
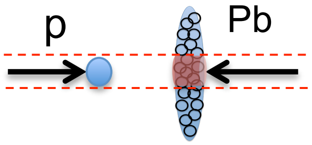




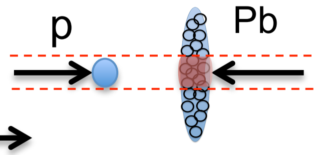


Splitting emerges

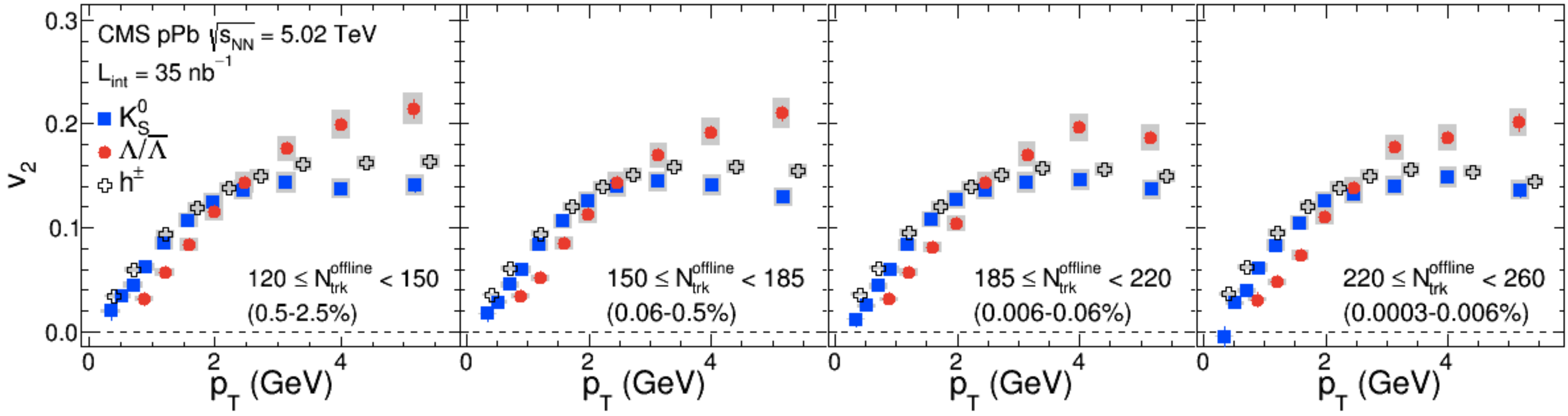
No PID dependent at low N_{trk} from jet correlations

Identified particle v_n in pPb

High multiplicity



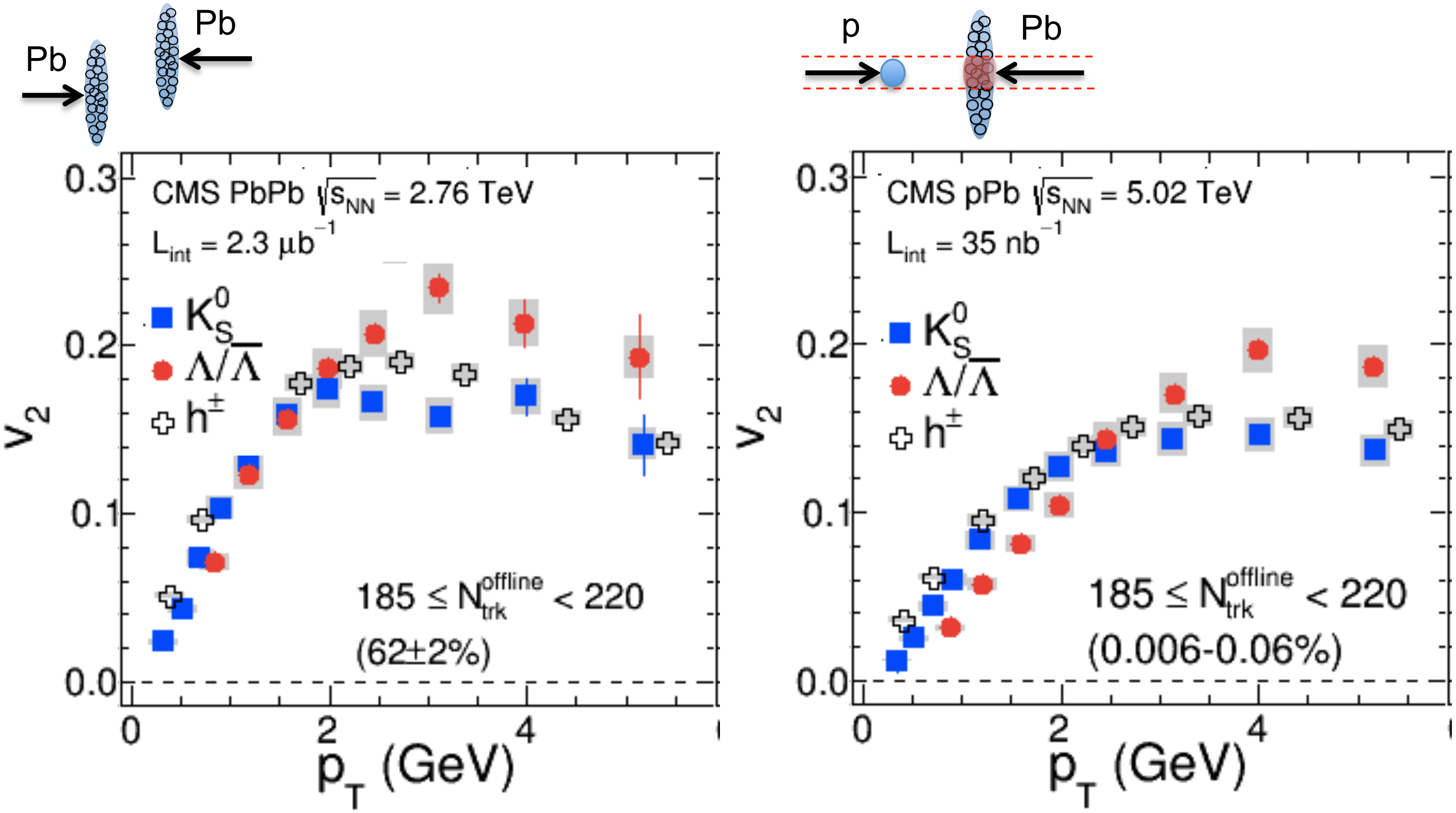
Increasing N_{trk} →



At fixed p_T:

- low p_T: $v_2(h^{+/-}) > v_2(K^0_s) > v_2(\Lambda)$ —— Radial flow!?
- higher p_T: $v_2(\text{baryon}) > v_2(\text{meson})$

PID v_n in pPb vs PbPb



Larger mass splitting in pPb at similar multiplicity

➔Stronger radial flow for smaller/denser system?

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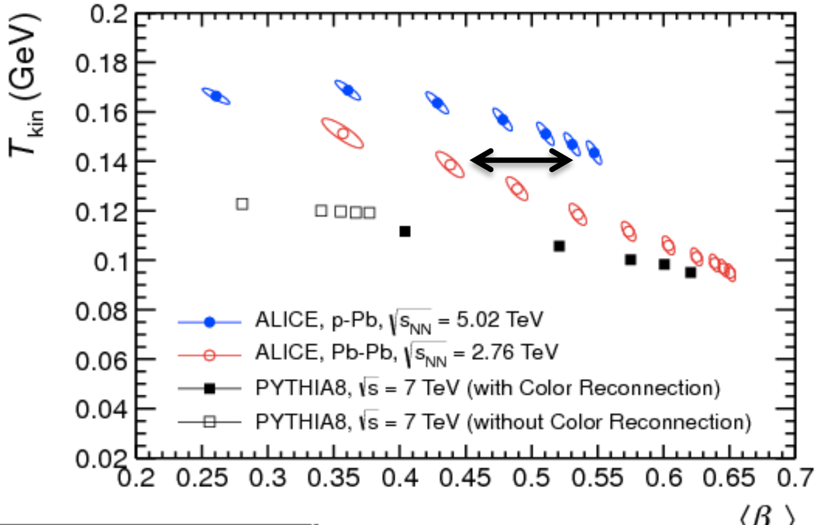

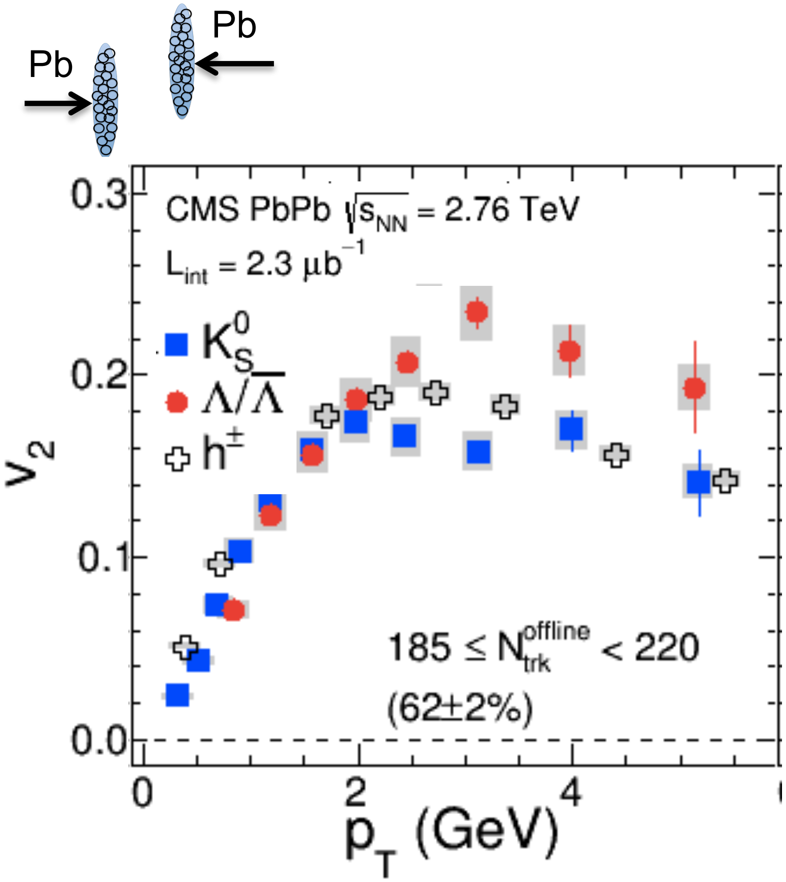

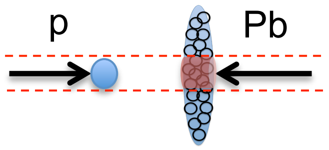

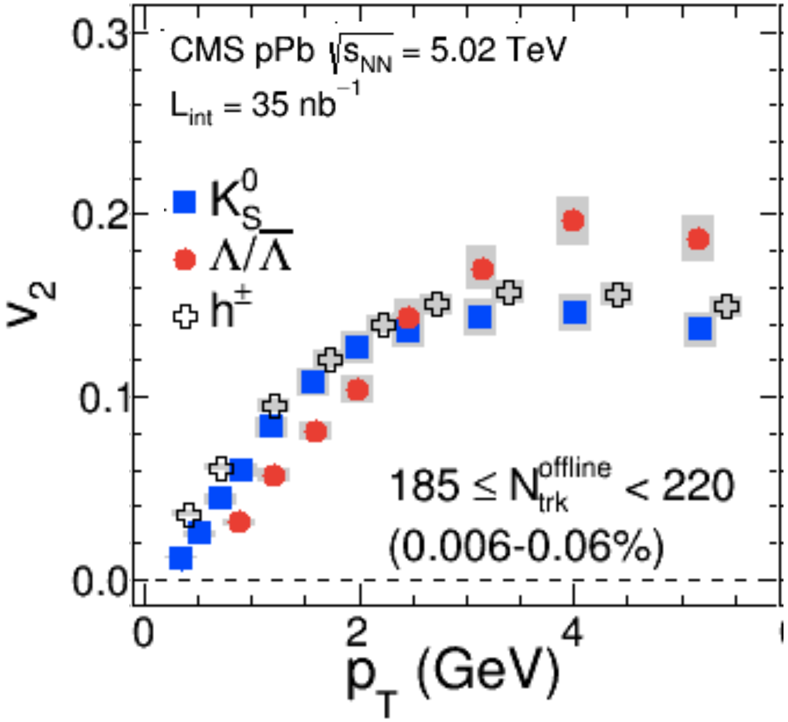

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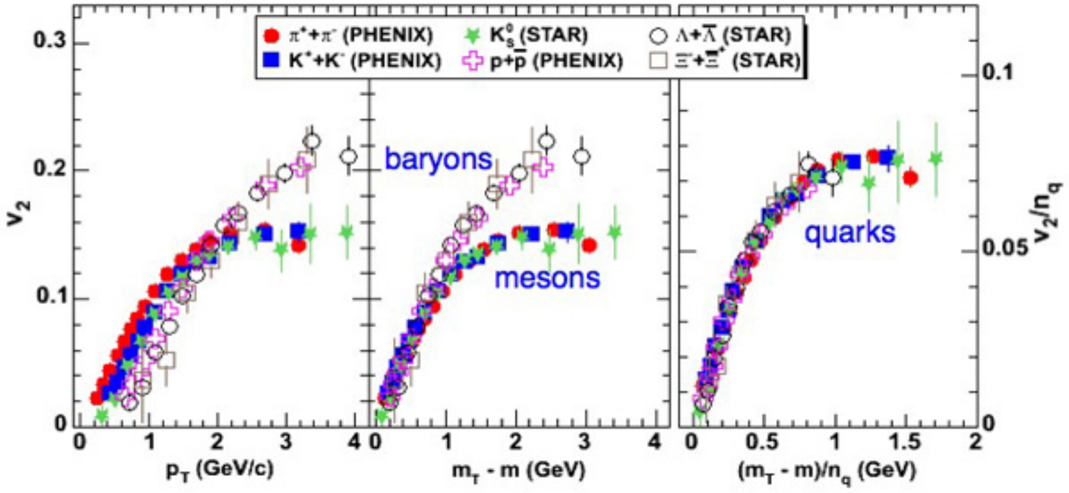
Partonic degree of freedom?

Number of Constituent Quark (NCQ) scaling in AuAu at RHIC



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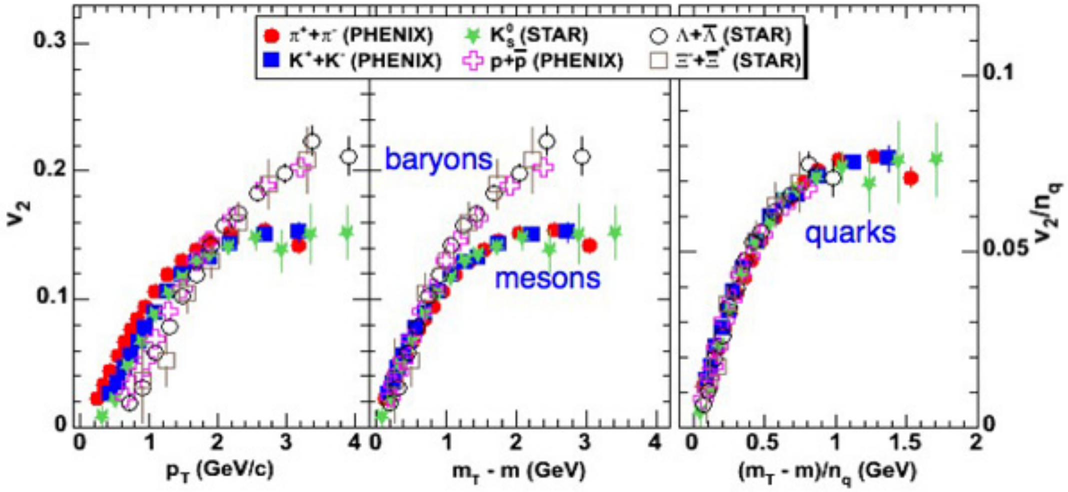
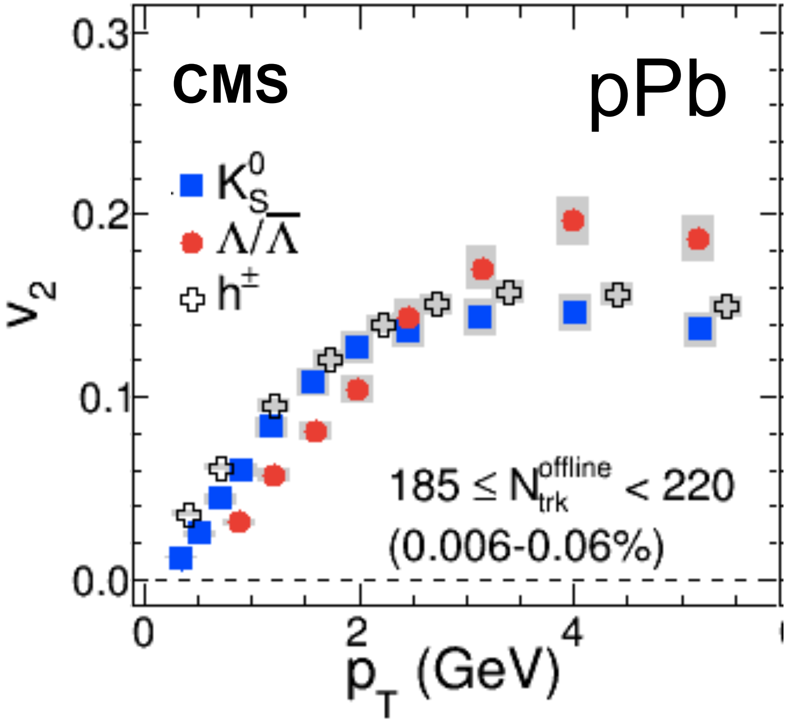
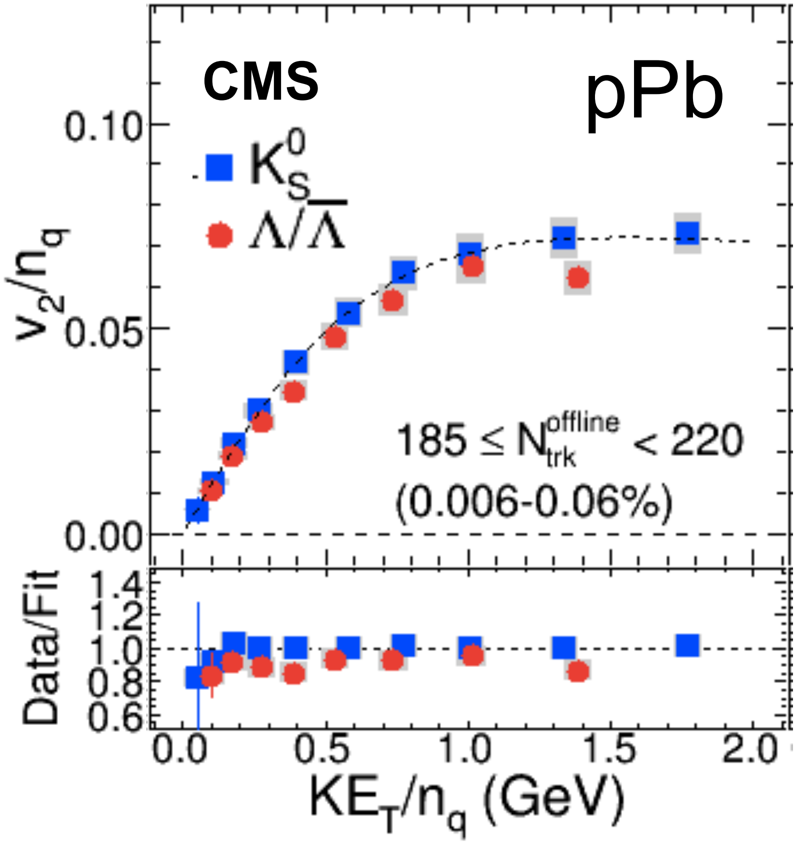




scaled by n_q



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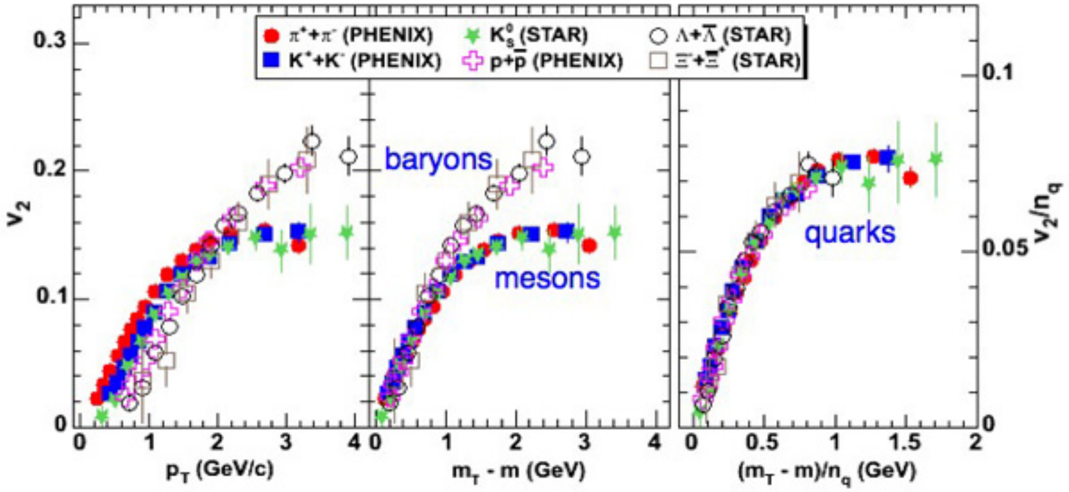
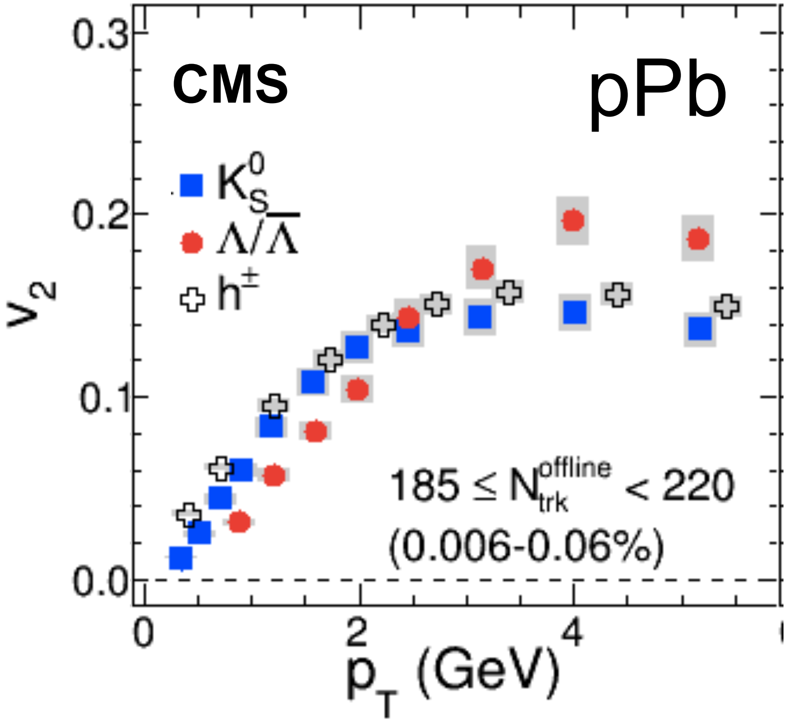


What does NCQ scaling really tell us?



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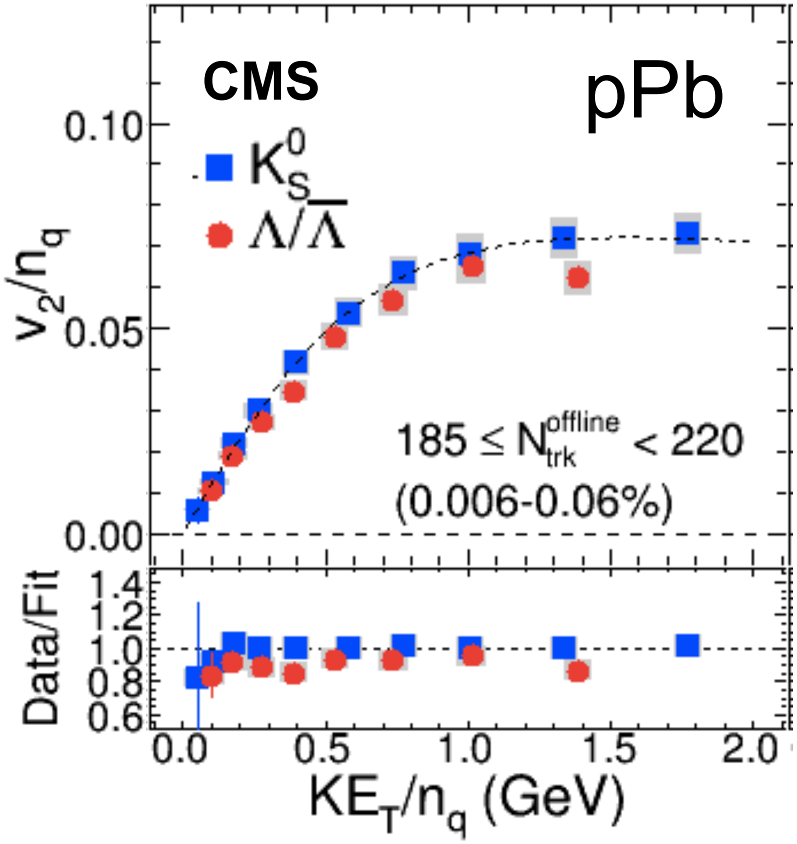

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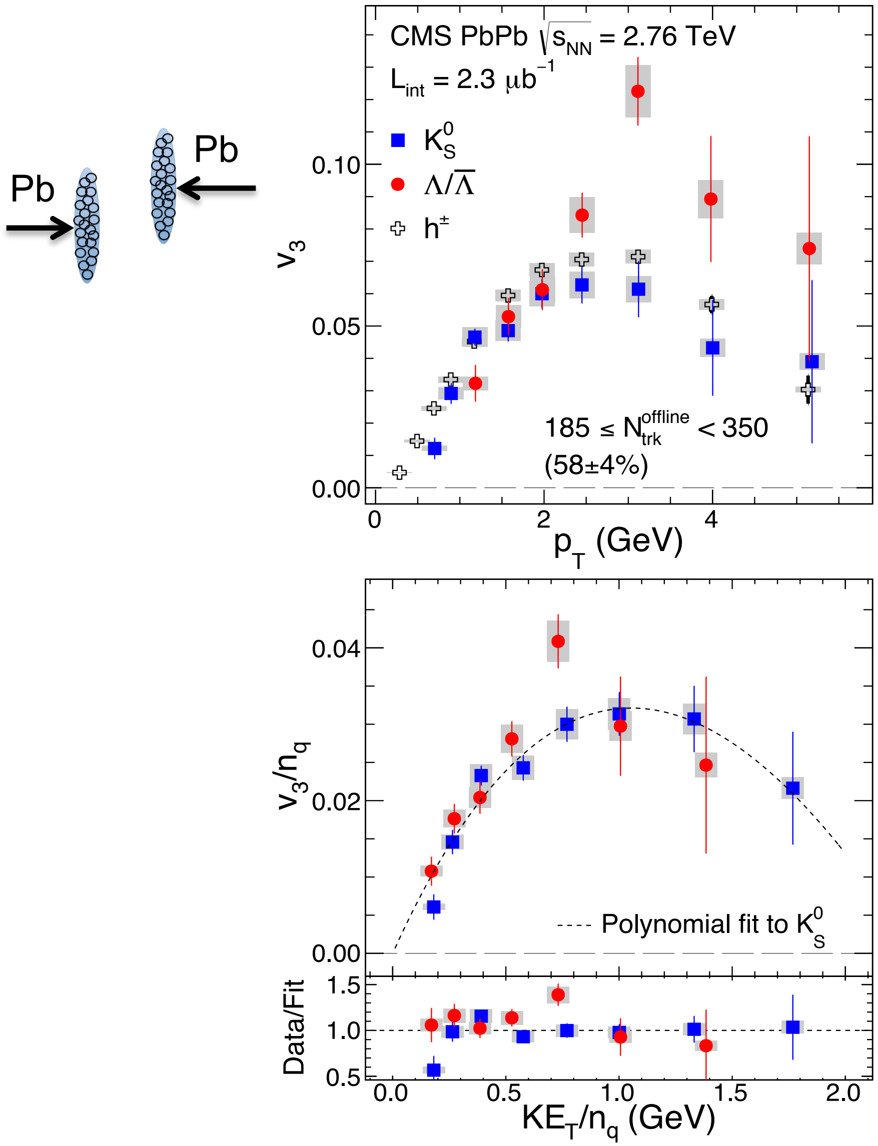
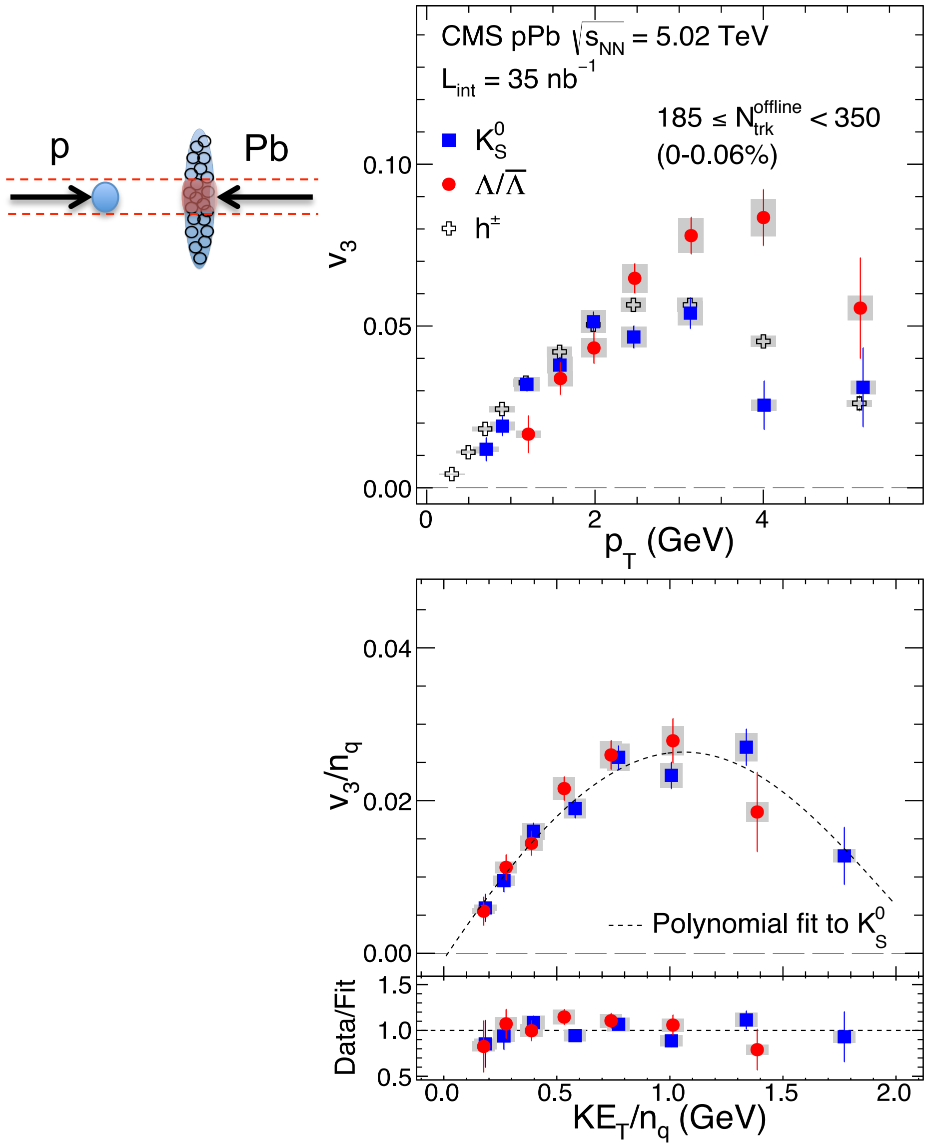
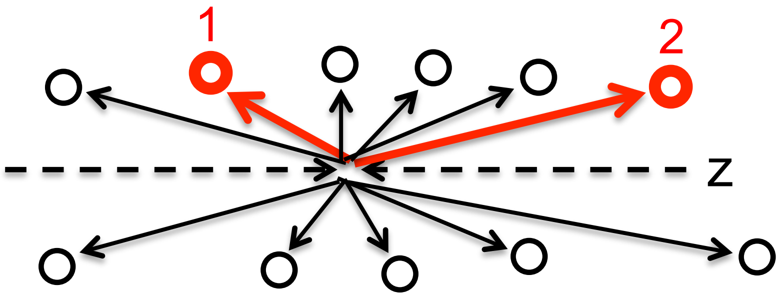




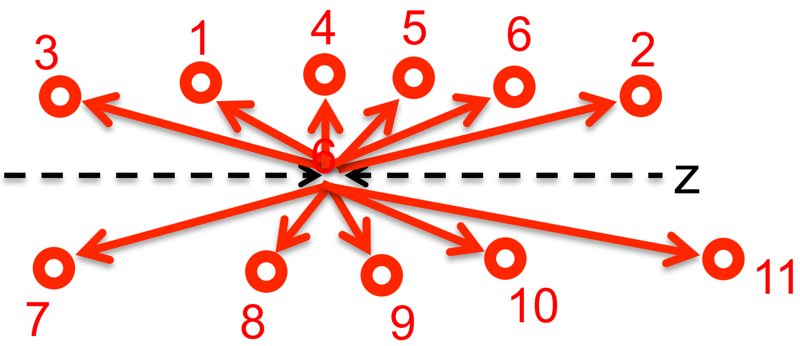
Similar behavior for PID v_3!

True collectivity in pPb?

Two- or more particle correlations?



OR



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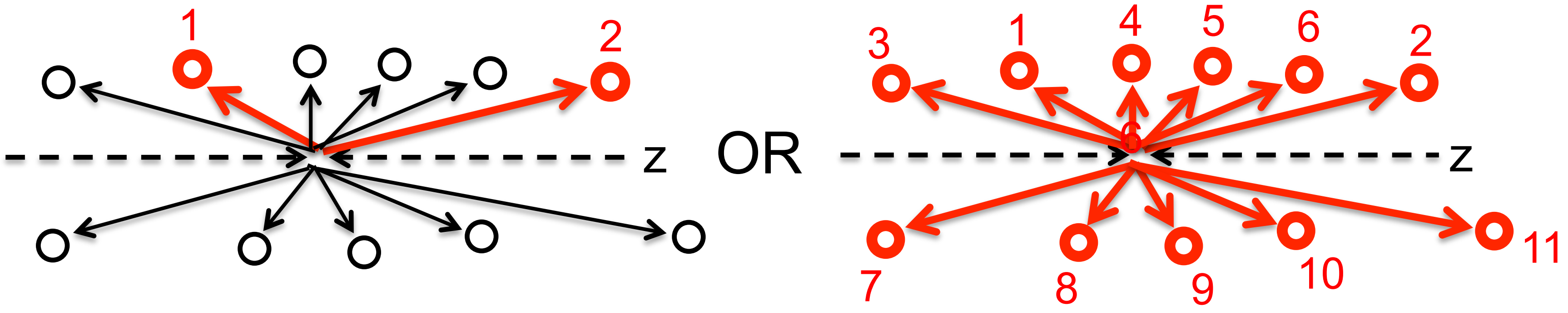


Multi-particle (>2) cumulants:

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

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

$\Rightarrow$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

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

$$v_n\{8\} = \sqrt[4]{-\frac{1}{33}c_n\{8\}}$$

Q-cumulant, PRC 83 (2011) 044913

In hydrodynamics:

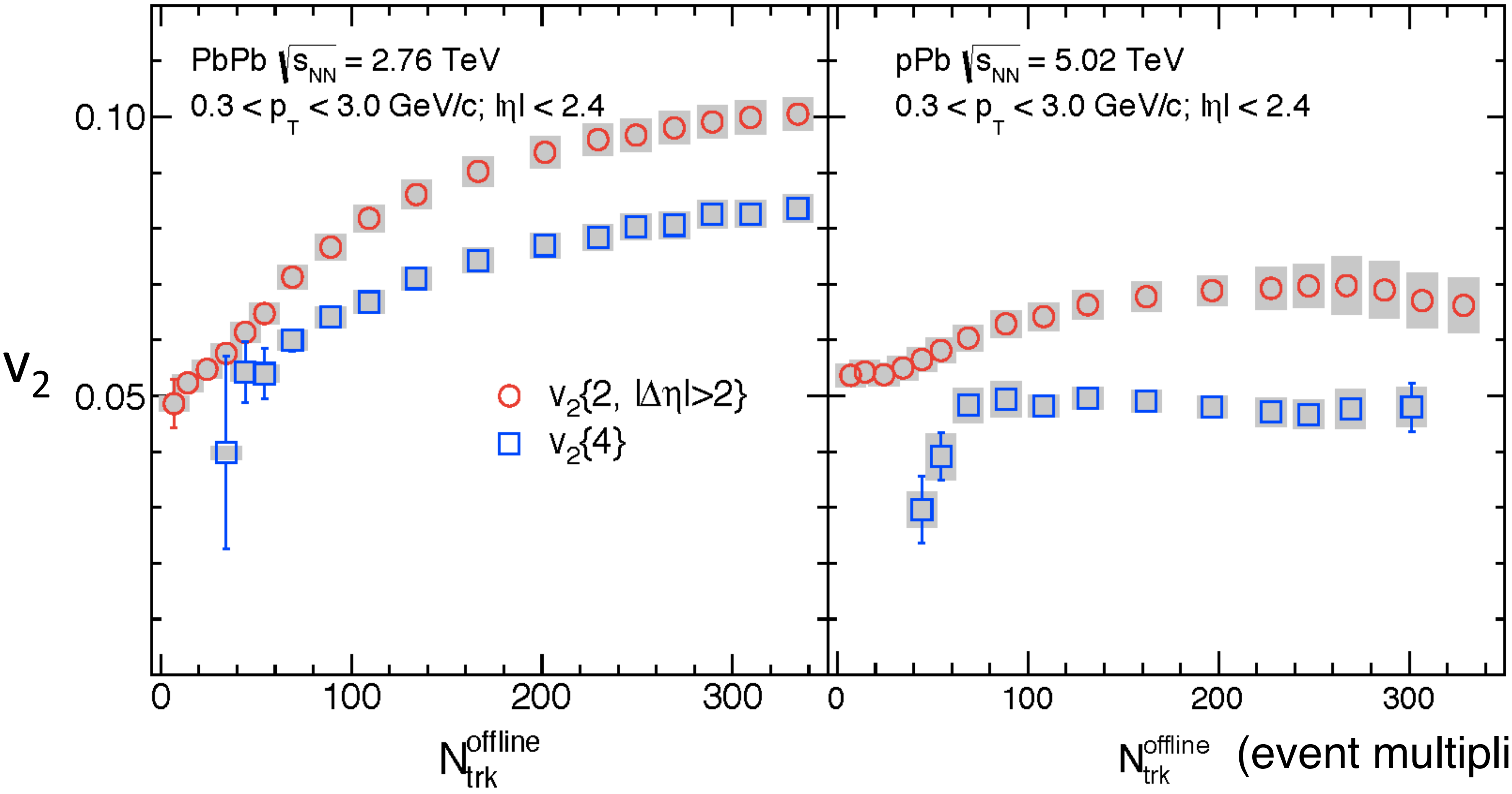
$$\mathbf{v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}}$$

True collectivity in pPb?

$v_2\{2\} > v_2\{4\}$

(v_2 fluctuations)

PLB724 (2013) 213



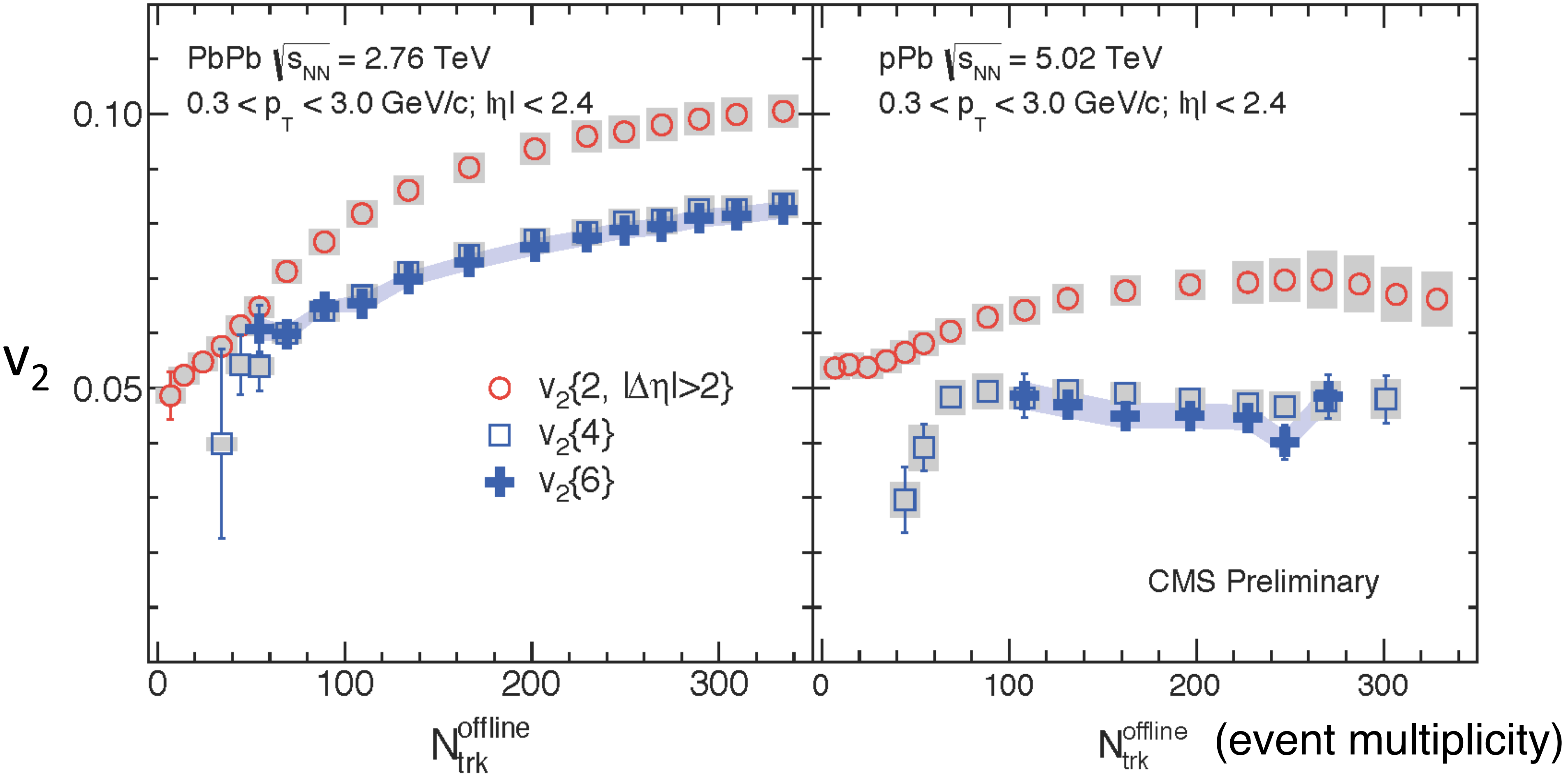
(event multiplicity)

True collectivity in pPb?

$v_2\{2\} > v_2\{4\} \approx v_2\{6\}$

(v_2 fluctuations)

CMS PAS HIN-14-006



True collectivity in pPb?

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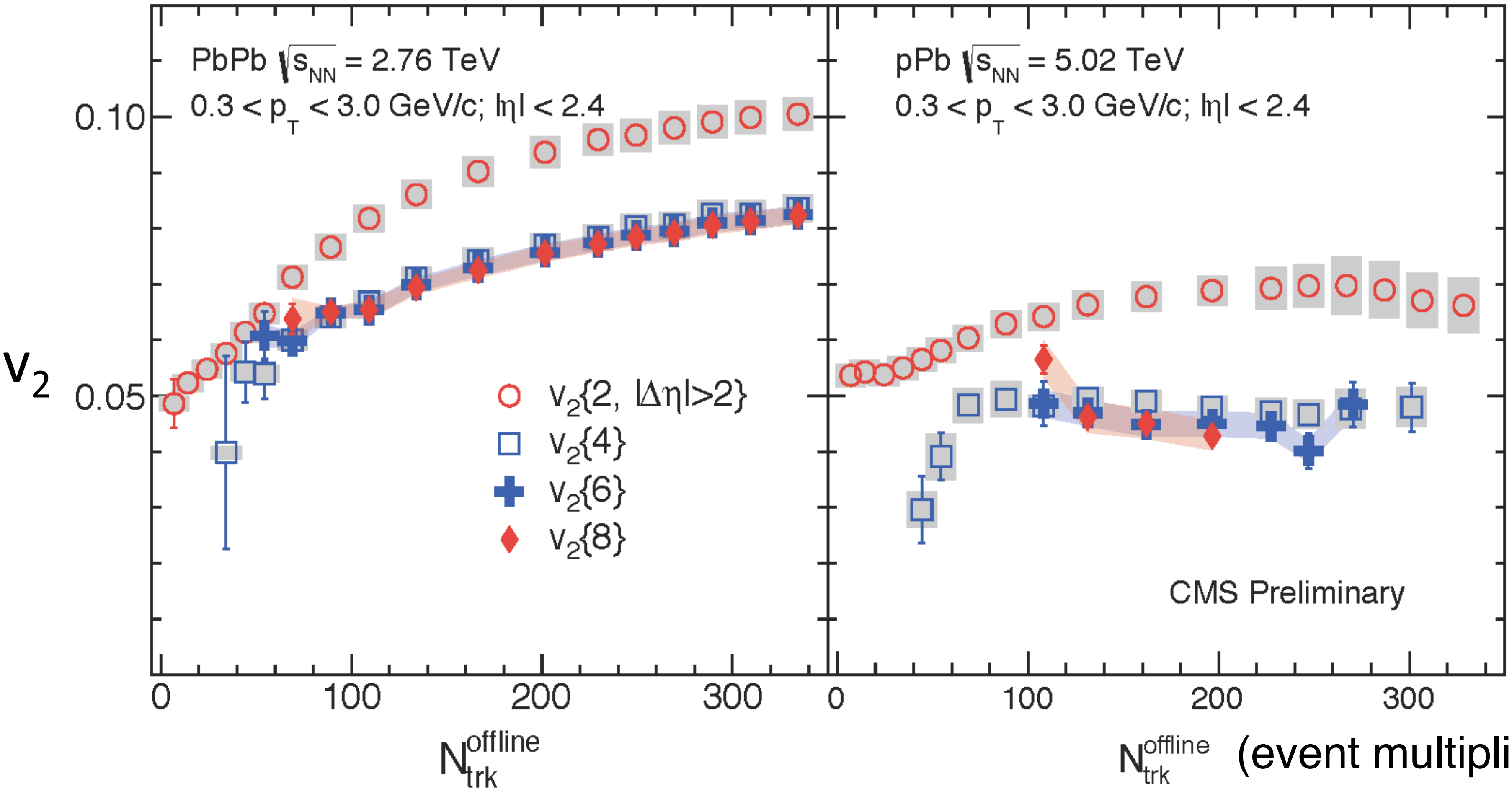
CMS PAS HIN-14-006



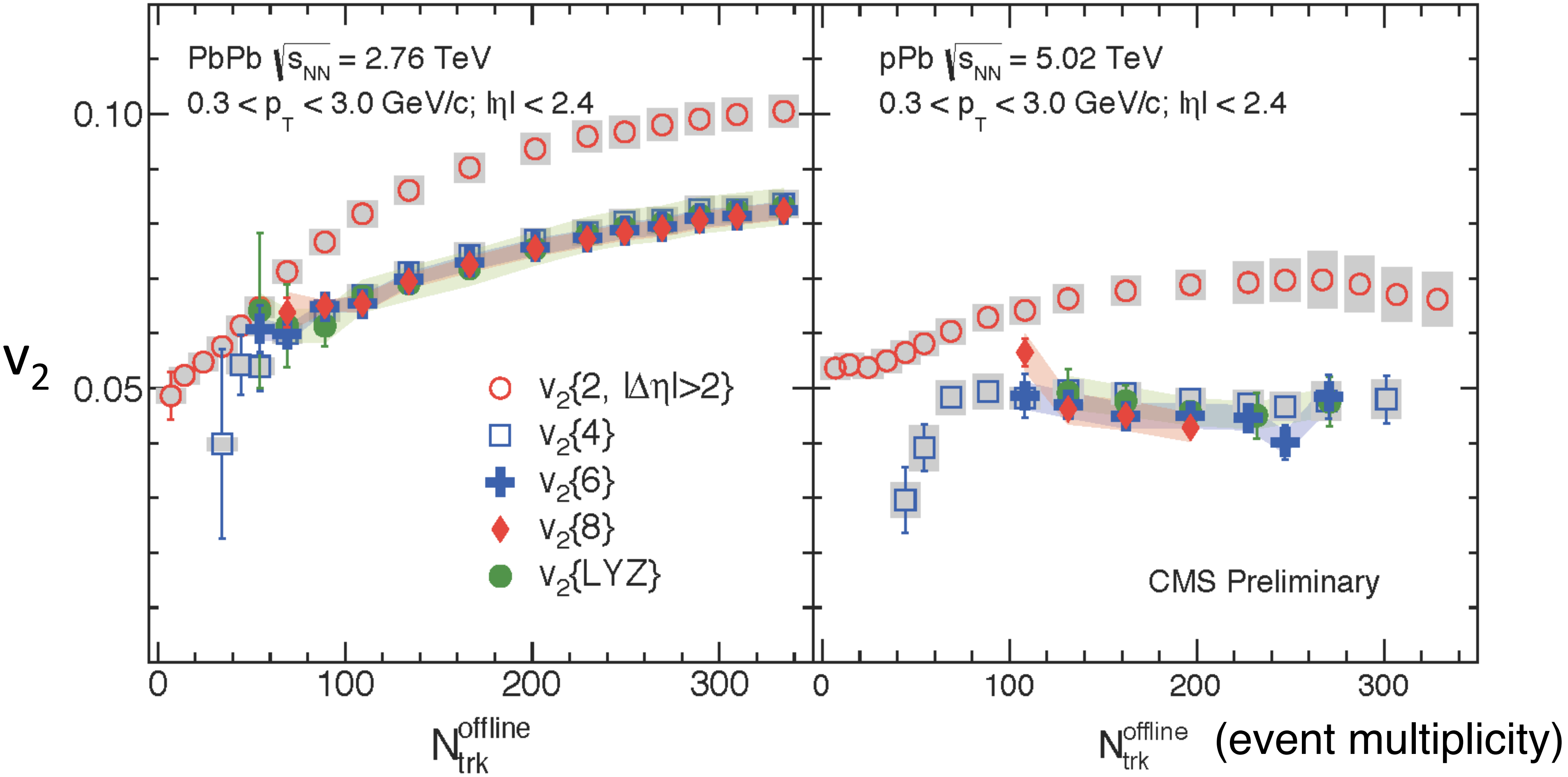
(event multiplicity)

True collectivity in pPb?

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

(v_2 fluctuations)

CMS PAS HIN-14-006



Direct evidence of collectivity in pPb!

True collectivity in pPb?

If Gaussian fluctuations,

$v_2\{4\} = v_2\{6\} = \ldots = v_2\{RP\}$

Why not all zeros in pPb?

True collectivity in pPb?

If Gaussian fluctuations,

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Why not all zeros in pPb?

Non-Gaussianity for small systems due to unitary bound of $\varepsilon_n<1$

$$p(\varepsilon_n) = 2\alpha\varepsilon_n(1-\varepsilon_n^2)^{\alpha-1}$$

Instead of Bessel-Gaussian

PRL 112, 082301 (2014)

True collectivity in pPb?

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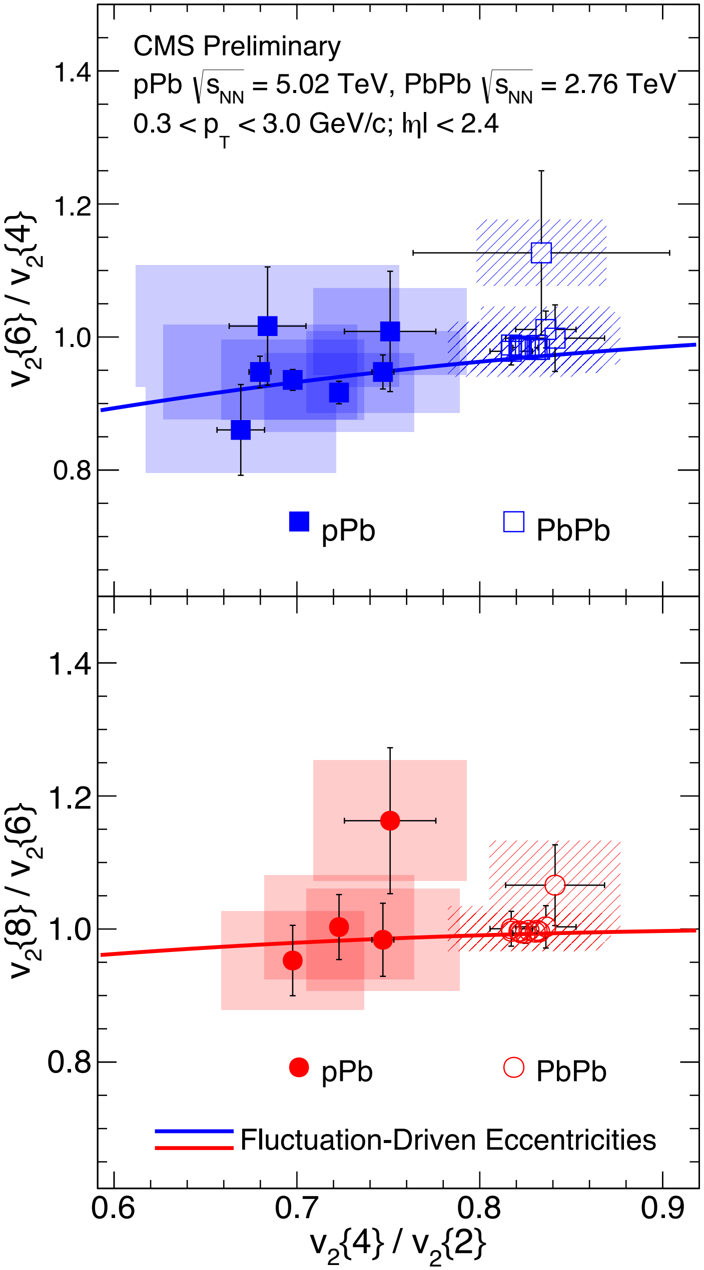
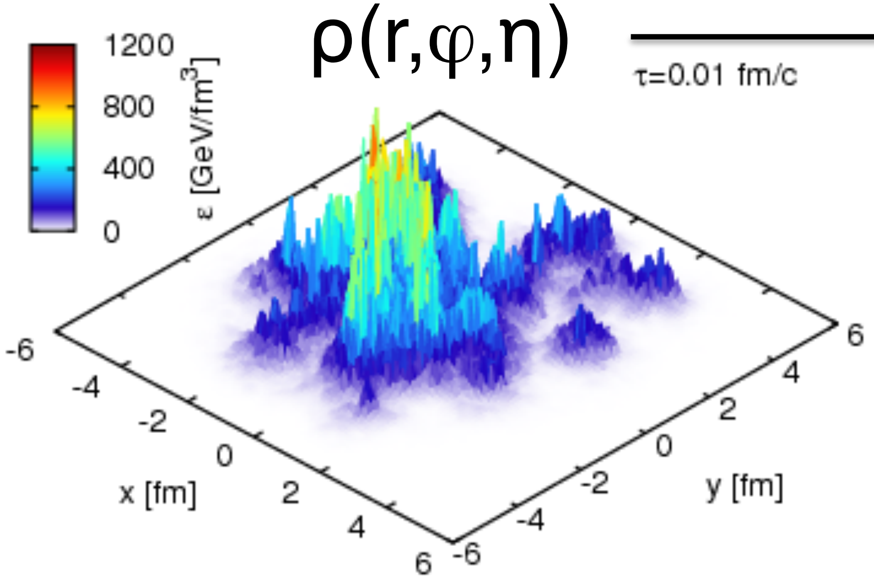


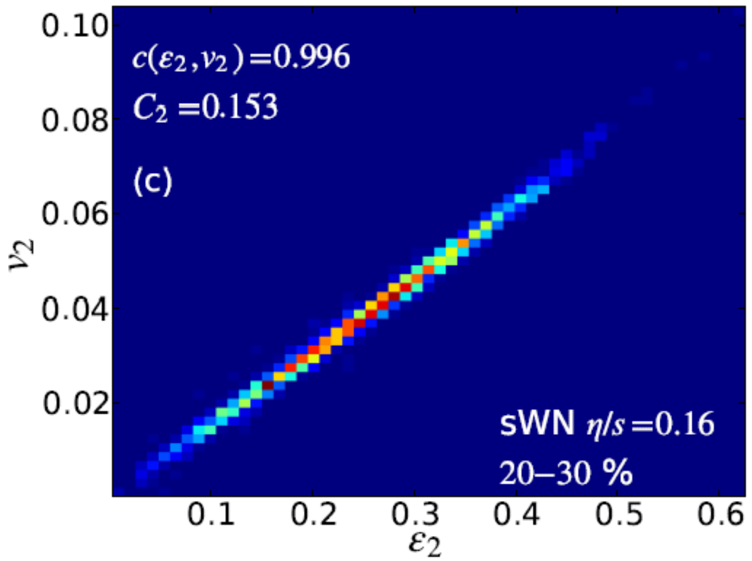
Back to AA

$\rho(r,\varphi,\eta) \longrightarrow f(p_T,\varphi,\eta)$



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

$$\varepsilon_n \equiv \frac{\left|\int r^n e^{in\phi}\epsilon(r,\phi)\, r\mathrm{d}r\mathrm{d}\phi\right|}{\int r^n \epsilon(r,\phi)\, r\mathrm{d}r\mathrm{d}\phi}$$

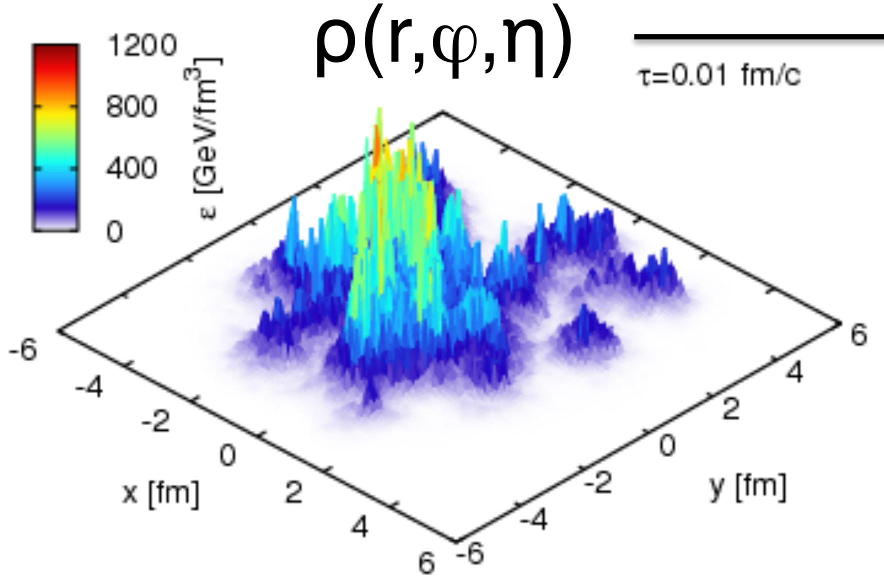


$v_n = k_n \times \varepsilon_n$, not perfect

Back to AA

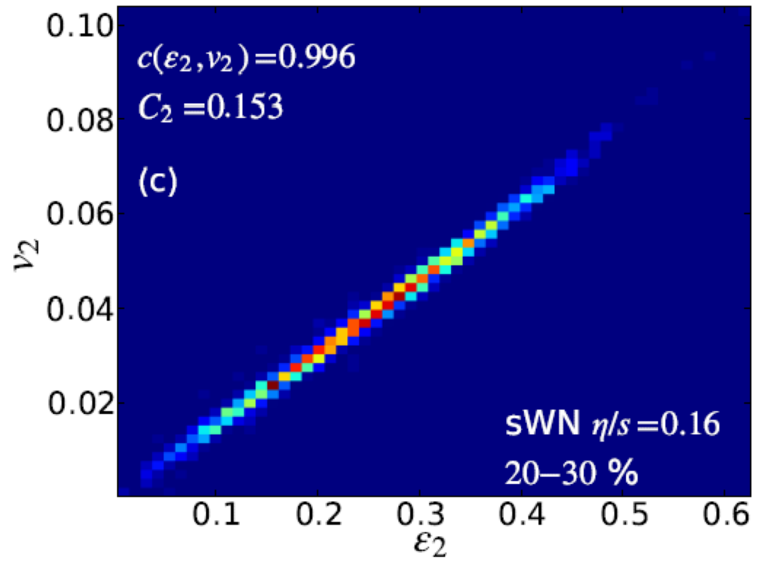
$$\rho(r,\varphi,\eta) \xrightarrow[\tau=0.01 \text{ fm/c}]{} f(p_T,\varphi,\eta)$$

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



$$\varepsilon_n \equiv \frac{\left|\int r^n e^{in\phi}\epsilon(r,\phi) r dr d\phi\right|}{\int r^n \epsilon(r,\phi) r dr d\phi}$$

Radial fluctuations averaged out



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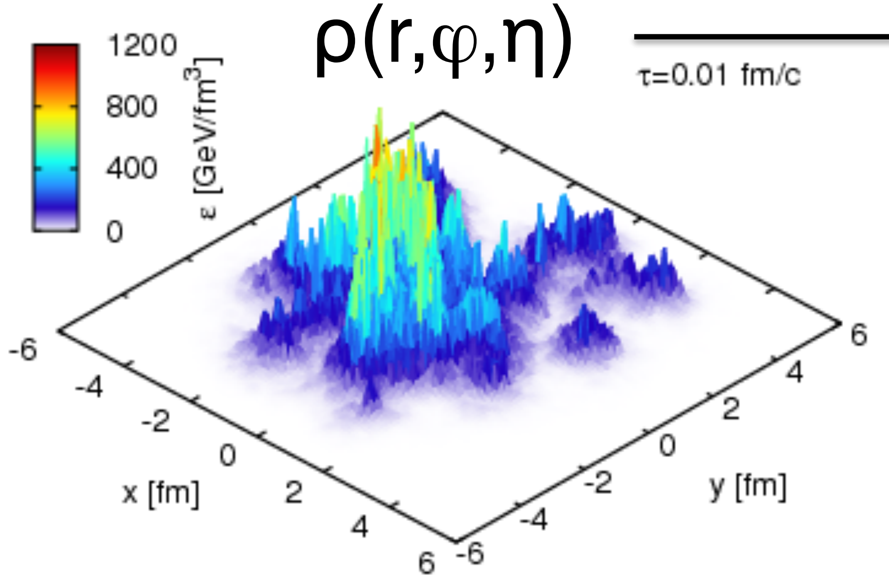
Back to AA

$$\rho(r,\varphi,\eta) \longrightarrow f(p_T,\varphi,\eta)$$



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

Orientation (event plane) angle depends on particle properties,

$$\Psi_n(p_T,\eta)$$

$$\varepsilon_n \equiv \frac{\left|\int r^n e^{in\phi}\epsilon(r,\phi)r\mathrm{d}r\mathrm{d}\phi\right|}{\int r^n\epsilon(r,\phi)r\mathrm{d}r\mathrm{d}\phi}$$

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$$\rho(r,\varphi,\eta) \xrightarrow[\tau=0.01\ \text{fm/c}]{} f(p_T,\varphi,\eta)$$

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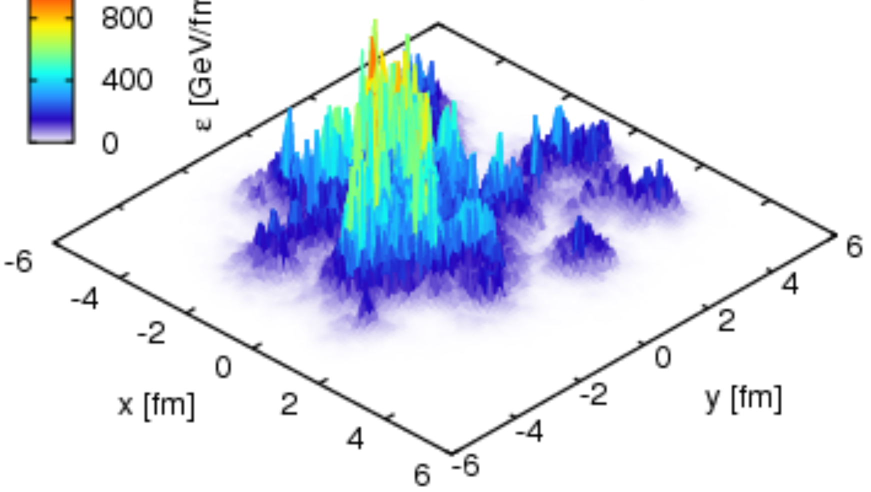

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Radial fluctuations averaged out

Orientation (event plane) angle depends on particle properties,

$$\Psi_n(p_T,\ \eta)$$

Details of initial state imprinted in

$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}, \eta^{trig}, \eta^{assoc})$$

Factorization: new insights on initial states

Factorization ratio:

$$r_n \equiv \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{trig}, p_T^{trig})}\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}} \sim \left\langle \cos[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{assoc}))] \right\rangle$$

J. Milosevic's talk
for details

Factorization: new insights on initial states

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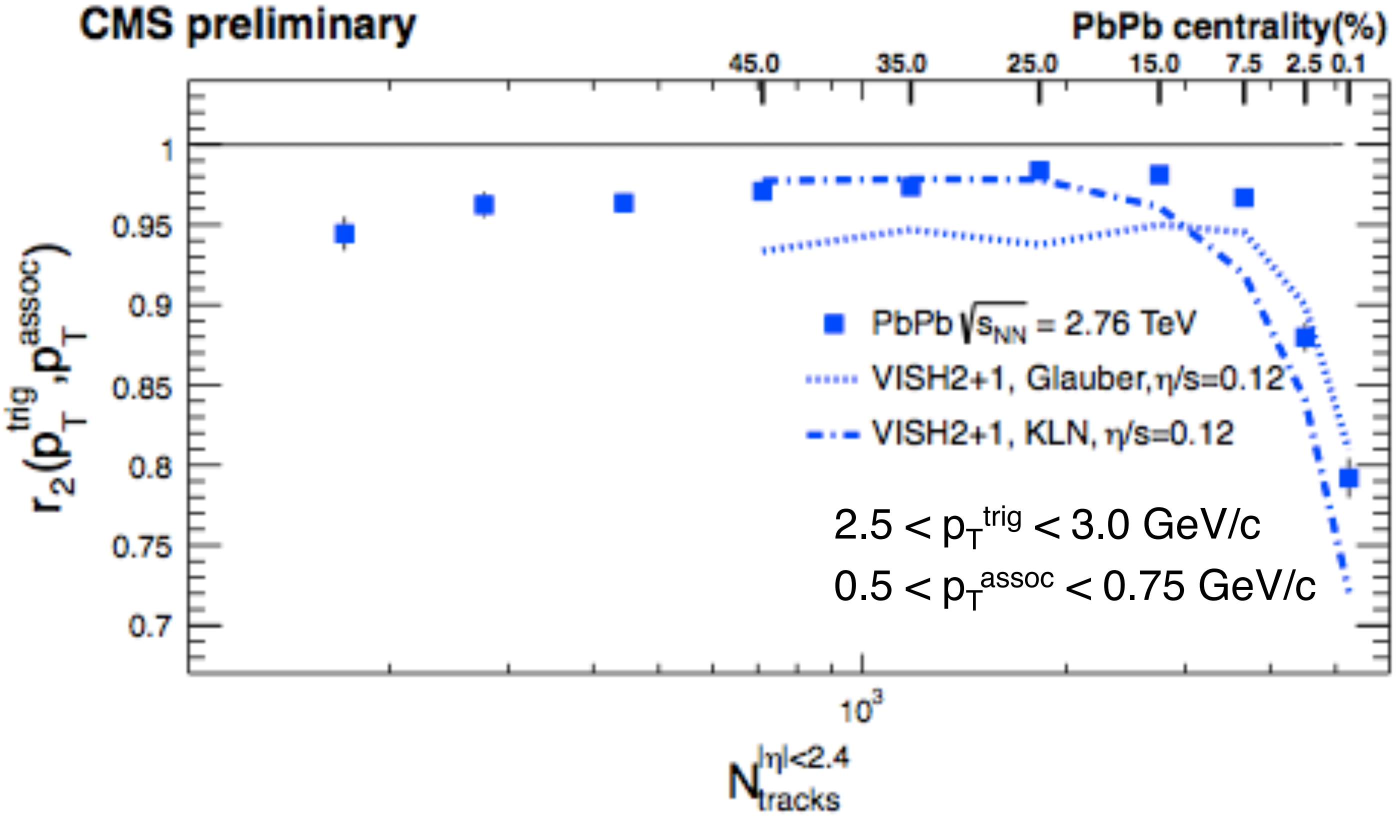
centrality



$2.5 < p_T^{trig} < 3.0$ GeV/c

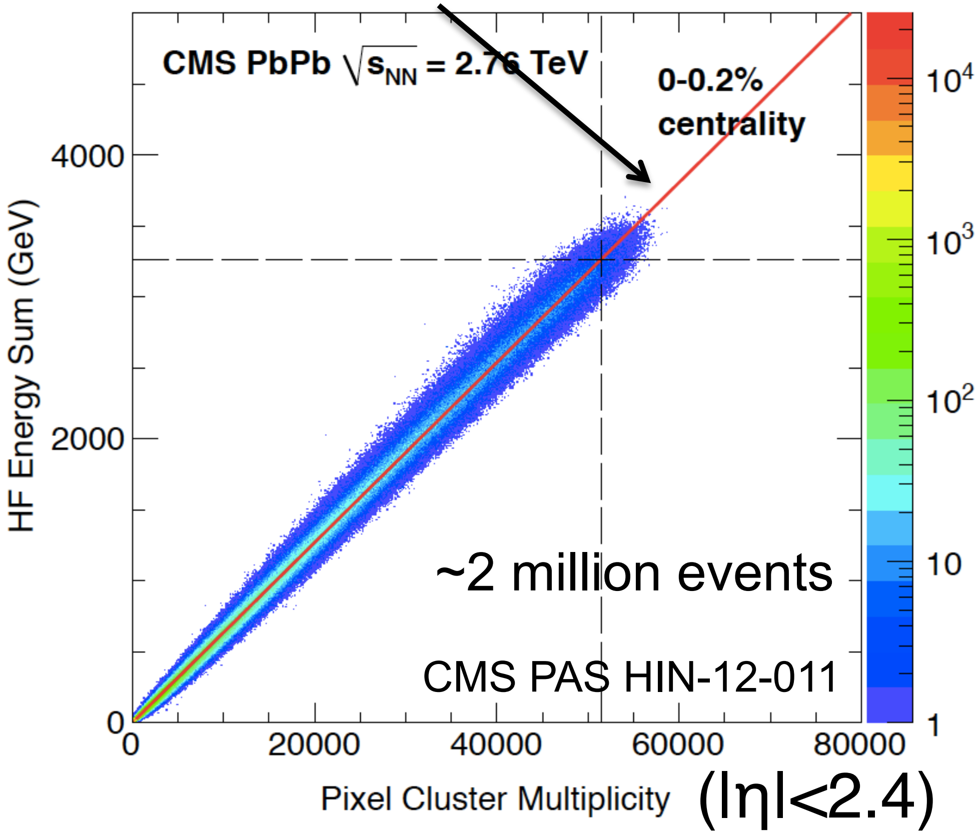
$0.5 < p_T^{assoc} < 0.75$ GeV/c

J. Milosevic's talk
for details

Strong effect in central PbPb ➔ More lumpiness?

Flow in ultra-central PbPb

Ultra-central events (~10^{-3})

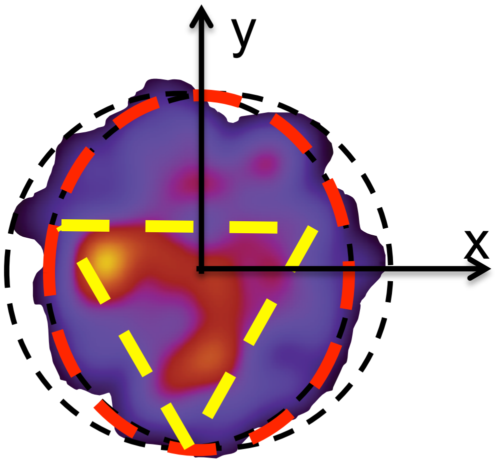


(3<|η|<5)

(|η|<2.4)

~2 million events

CMS PAS HIN-12-011



All v_n dominated by fluctuations

Flow in ultra-central PbPb

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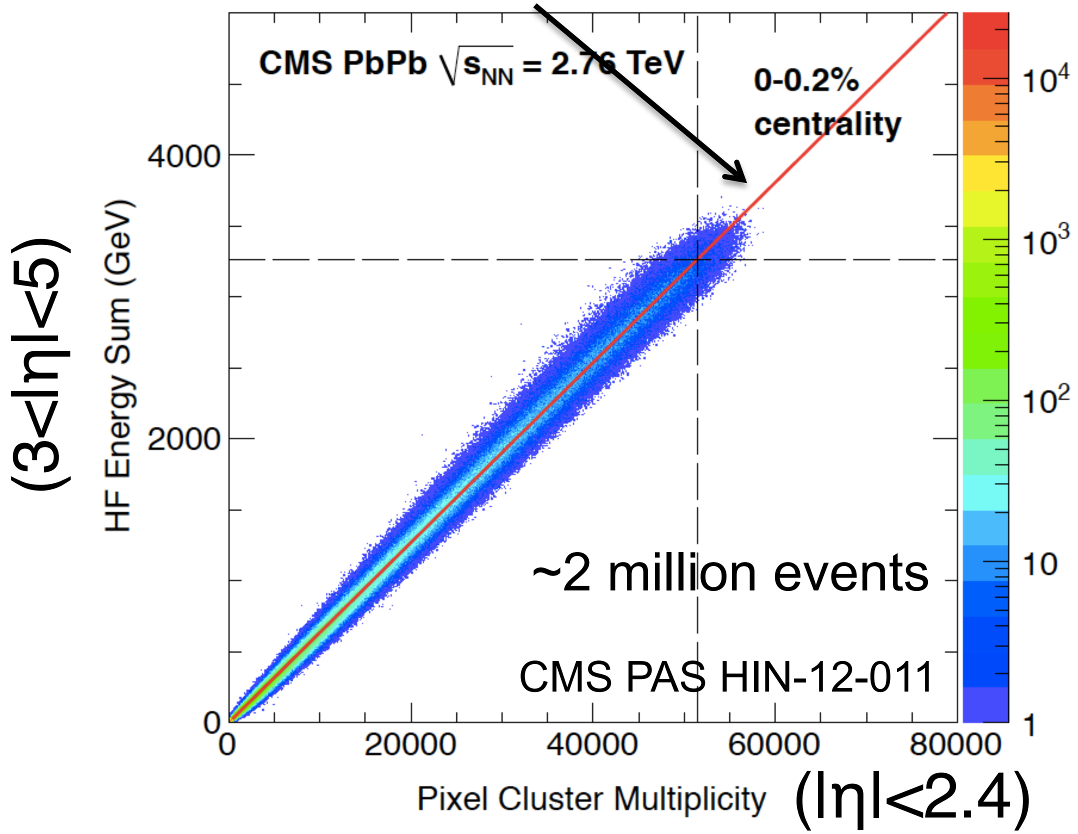

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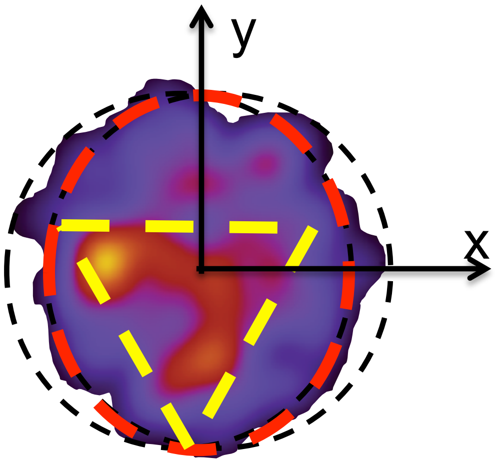
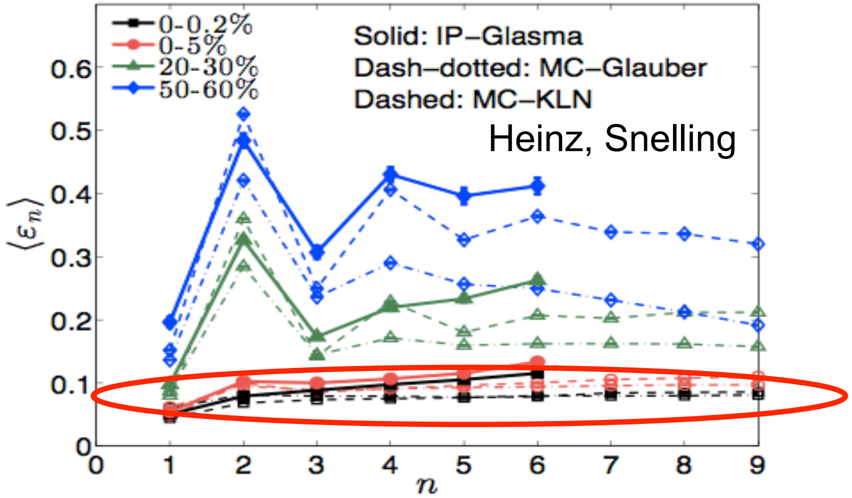


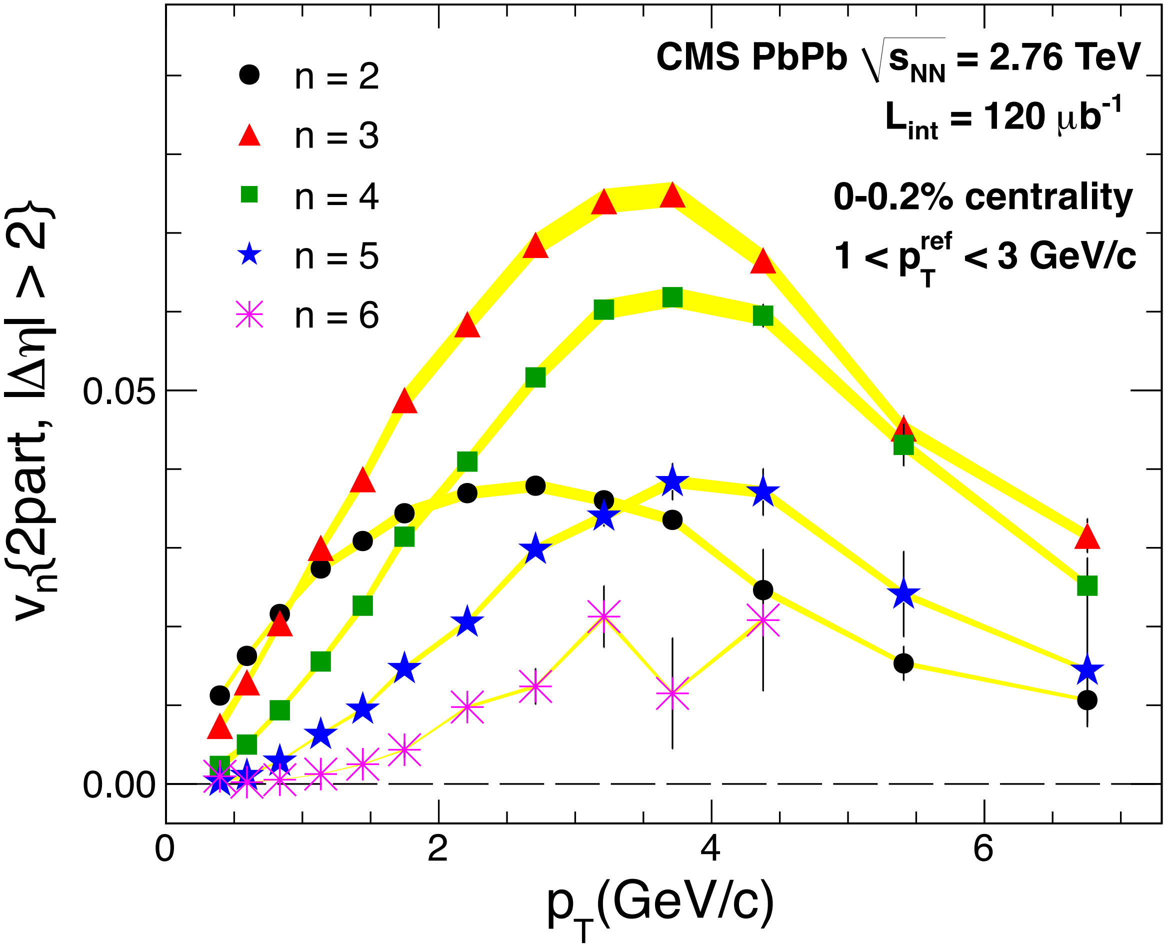
all ε_n converge in UCC



Ideal testing grounds for effects due to initial-state fluctuations!

Flow in ultra-central PbPb

0-0.2% centrality

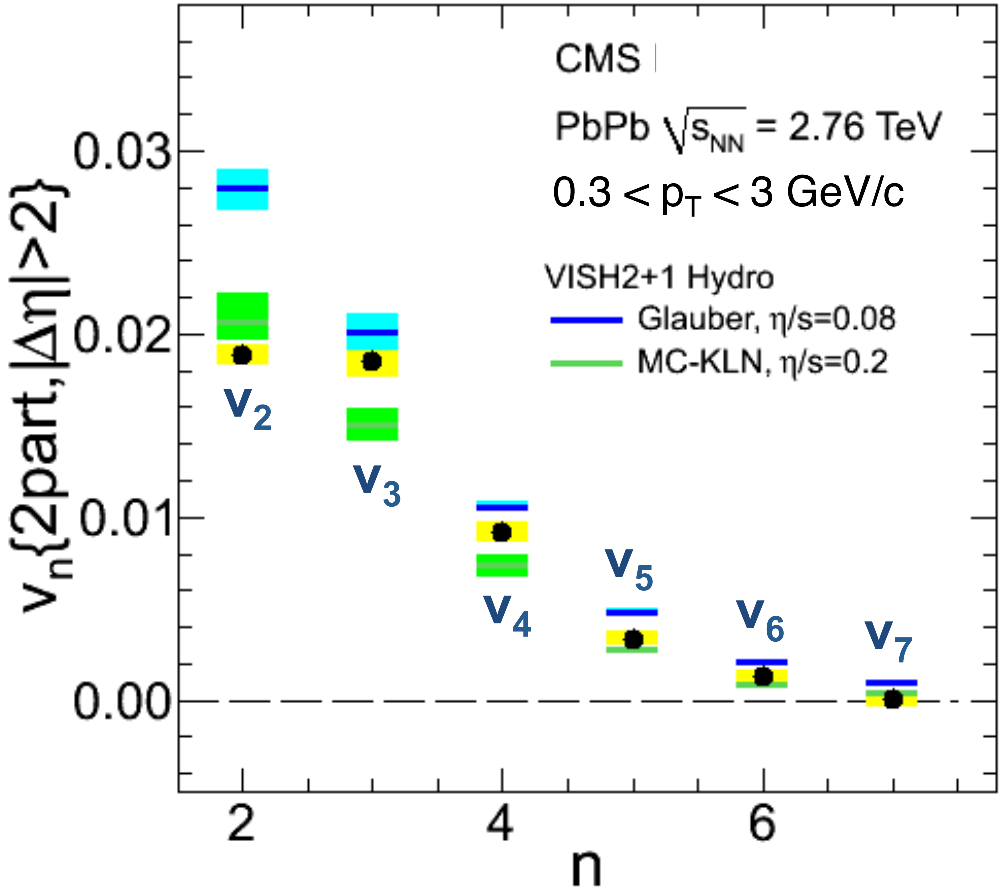


Intriguing p_T dependence, consistent with hydro.

Flow in ultra-central PbPb

0-0.2% centrality

JHEP 02 (2014) 088

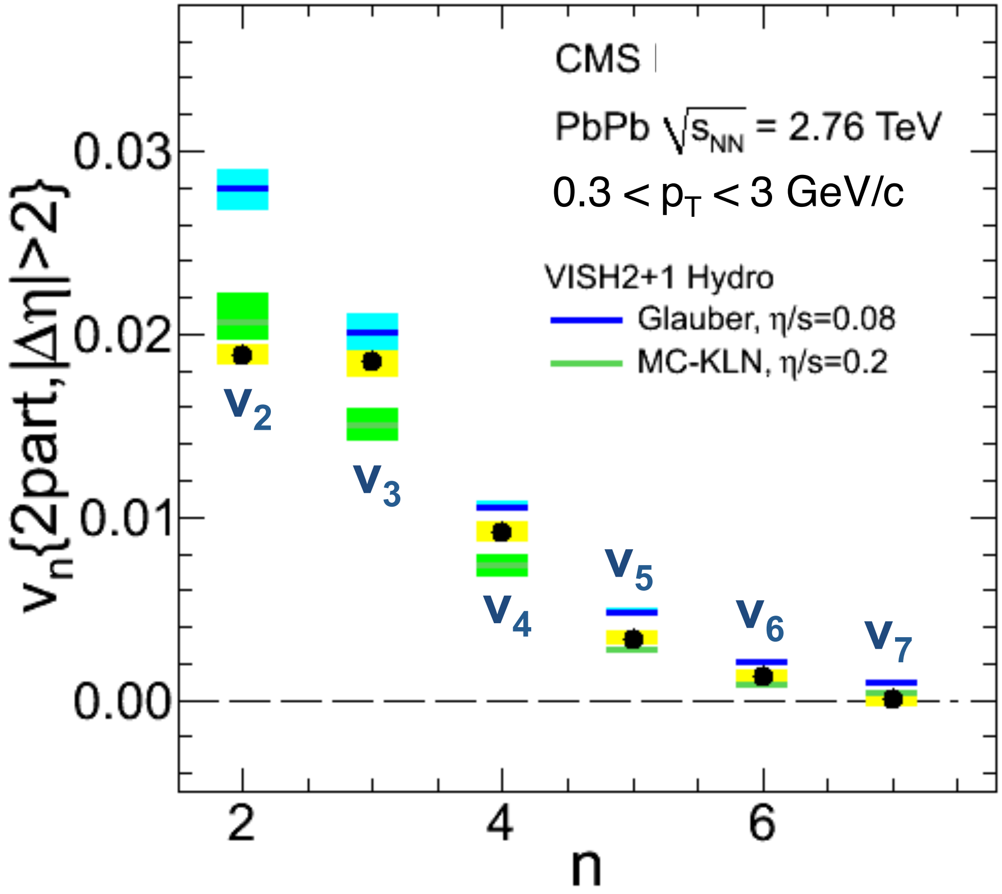


Initial state dominated
by density fluctuations

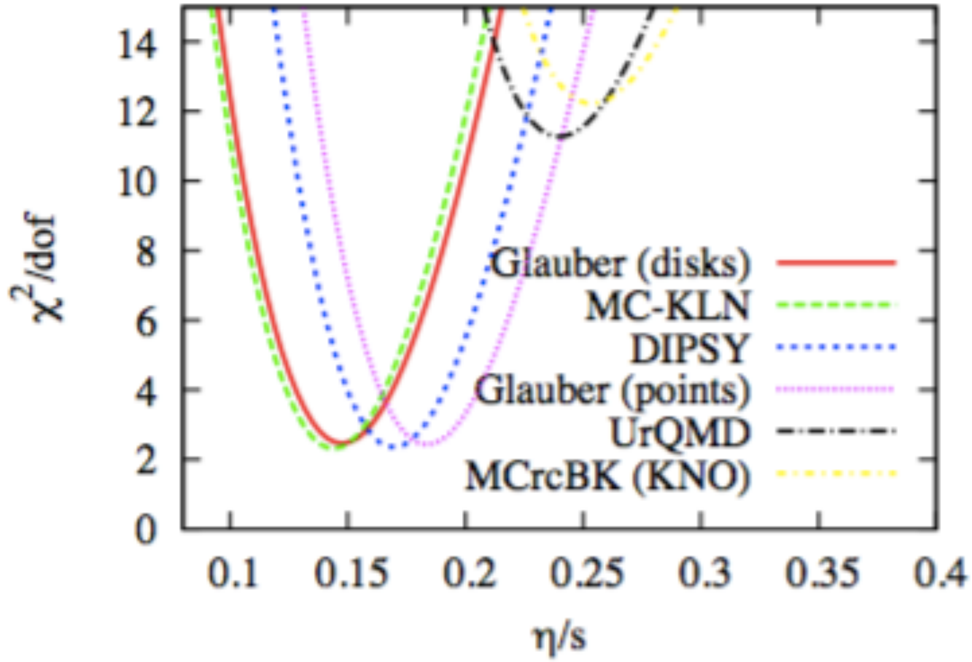
Flow in ultra-central PbPb

0-0.2% centrality

JHEP 02 (2014) 088



arXiv:1210.6010



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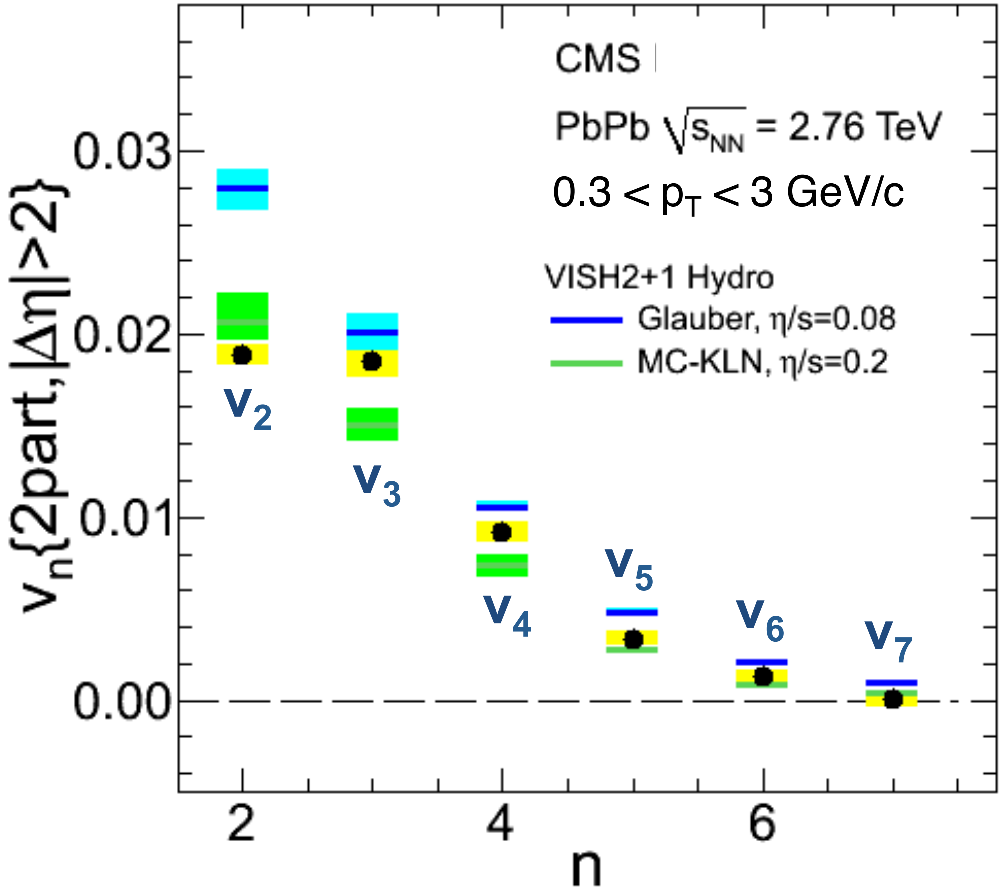
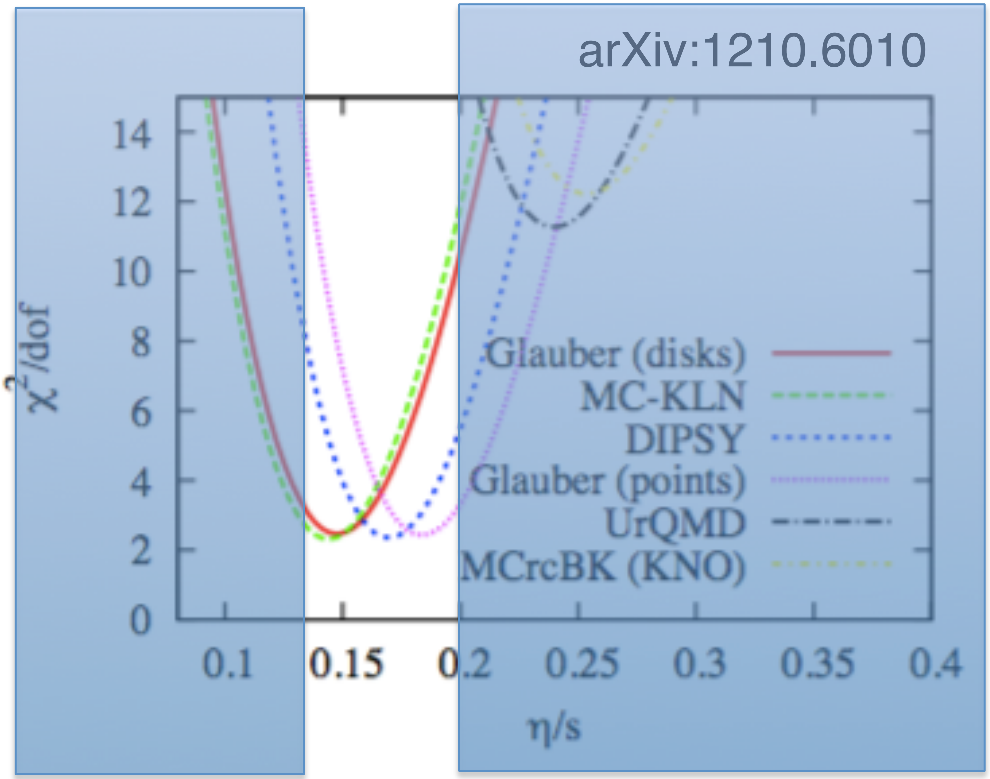
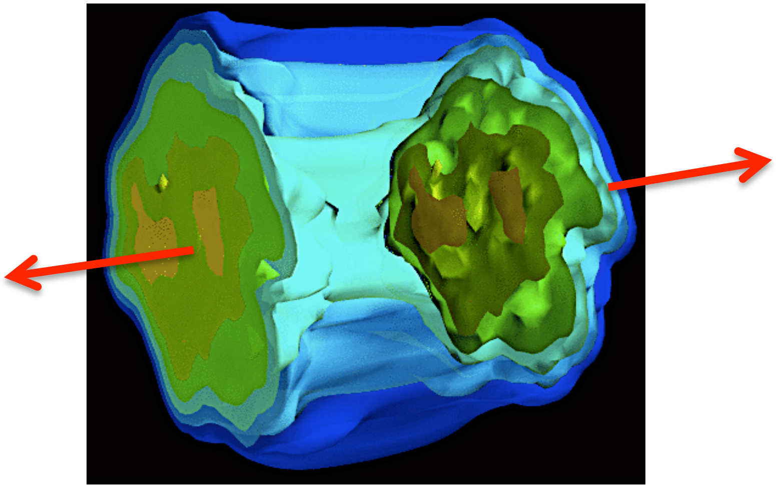

JHEP 02 (2014) 088

Initial state dominated by density fluctuations


arXiv:1210.6010

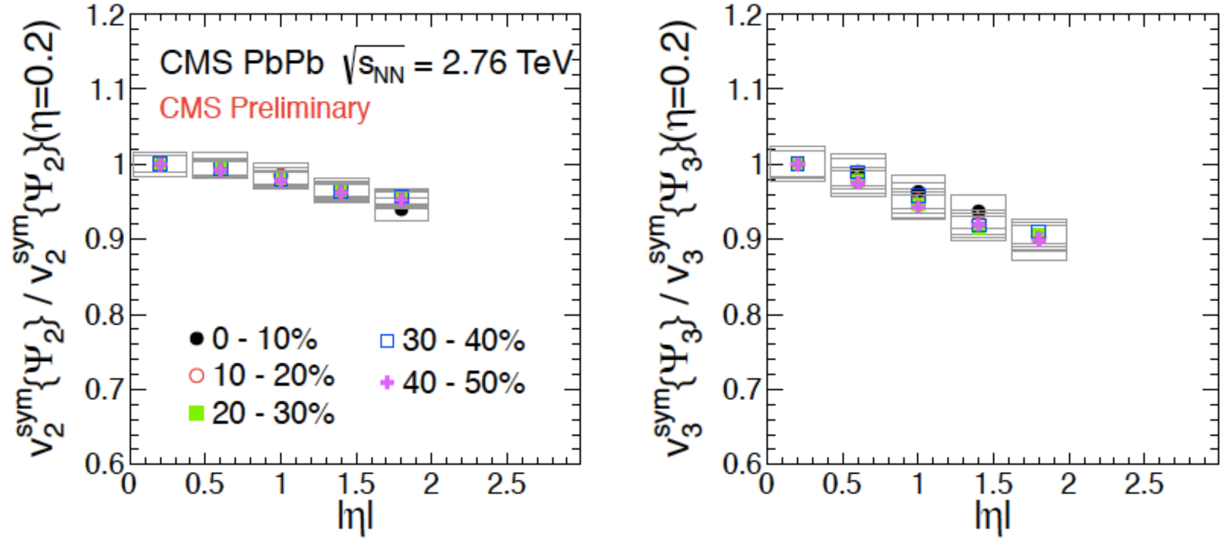
Stringent constraints on η/s

Longitudinal dynamics



Not boost-invariant

PbPb



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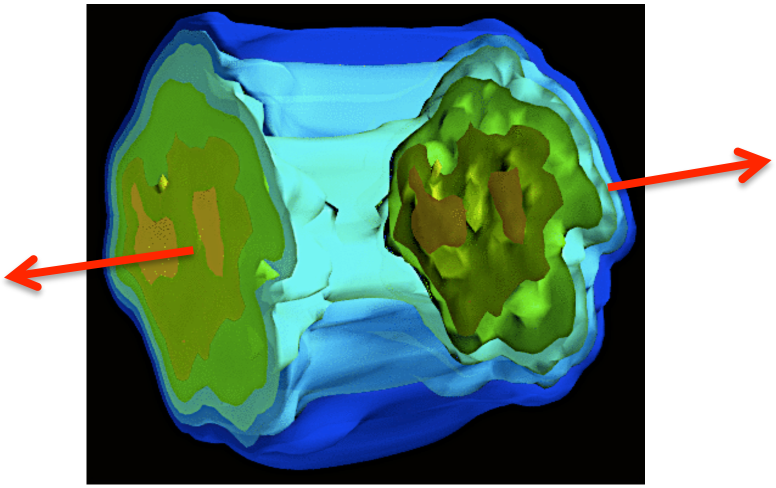

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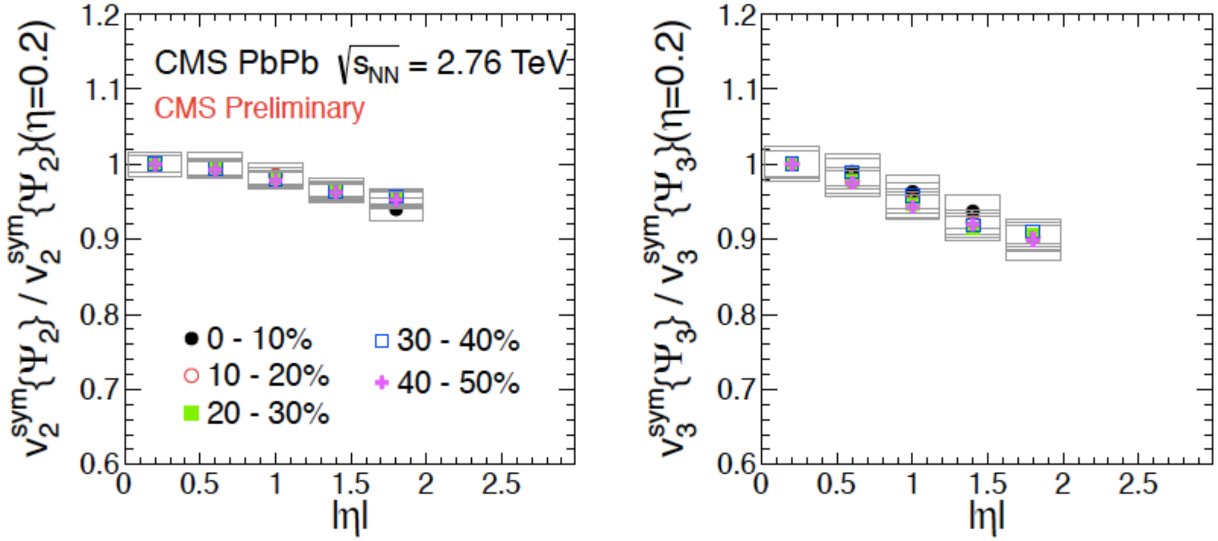
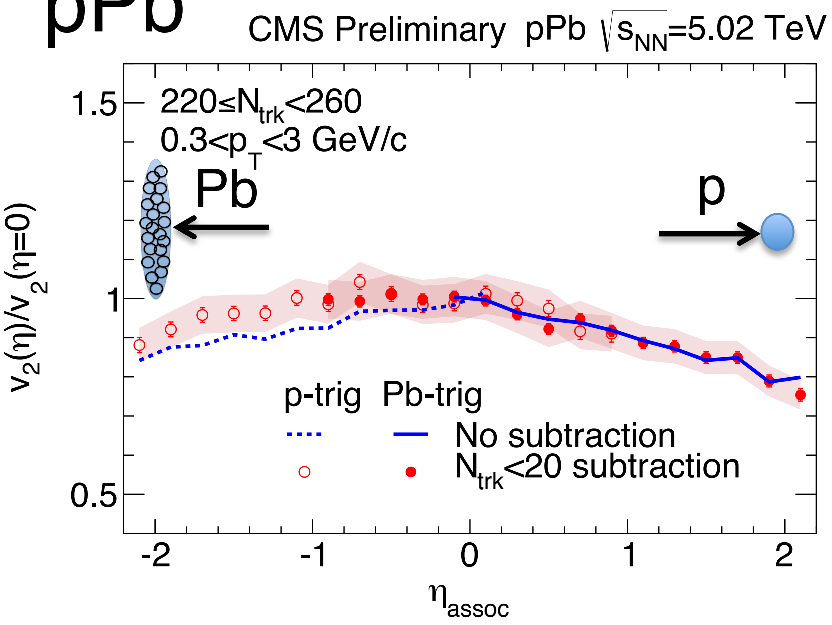


pPb

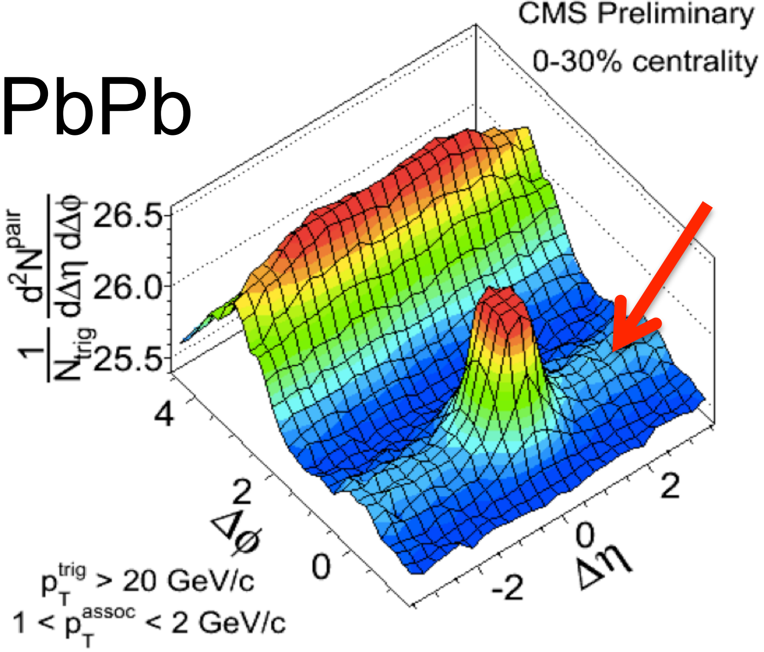


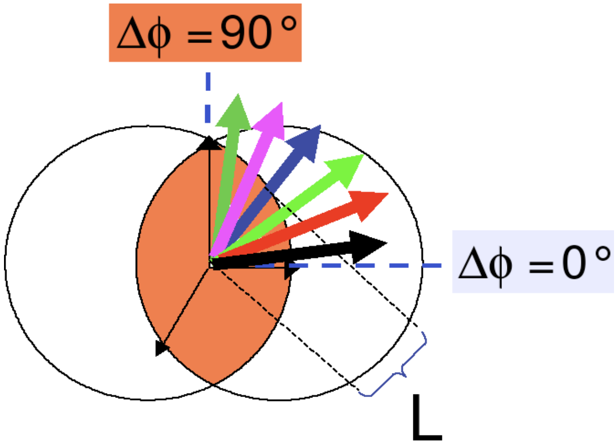
Factorization in η
to be examined

"Collectivity" at high p_T

p_T^{trig} > 20 GeV!

PbPb





$\Delta E \sim L^{\alpha}$:

α = 1 for pQCD, collisional

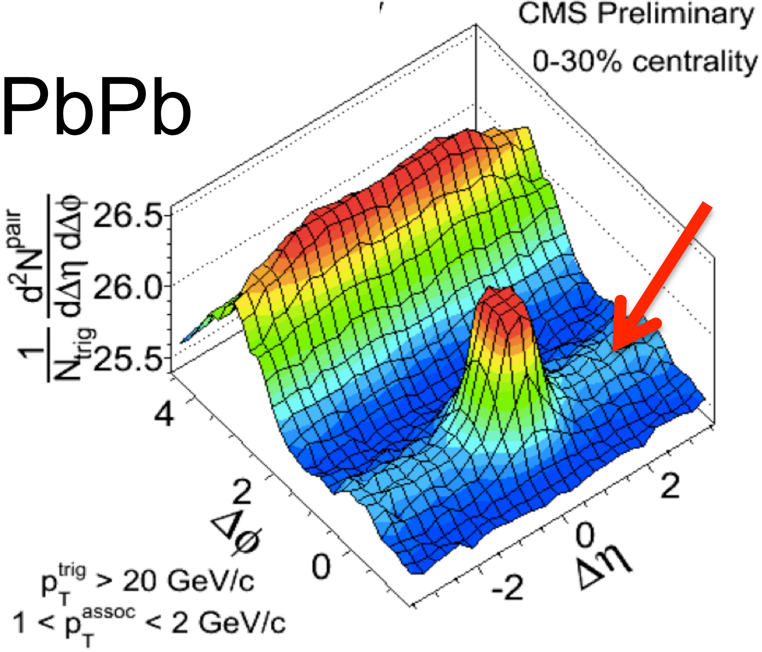
α = 2 for pQCD, radiative

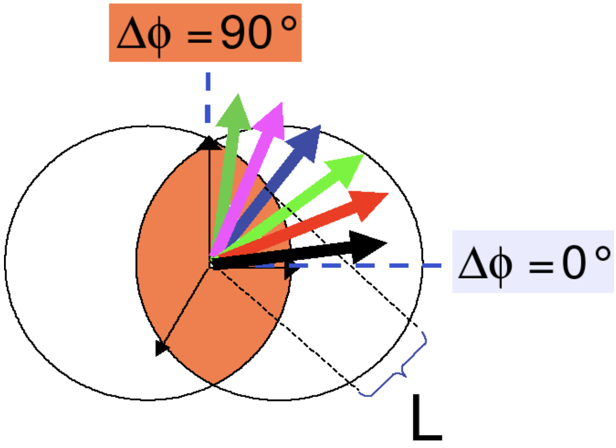
α = 3 for AdS/CFT

"Collectivity" at high p_T

$p_T^{trig} > 20$ GeV!

PbPb





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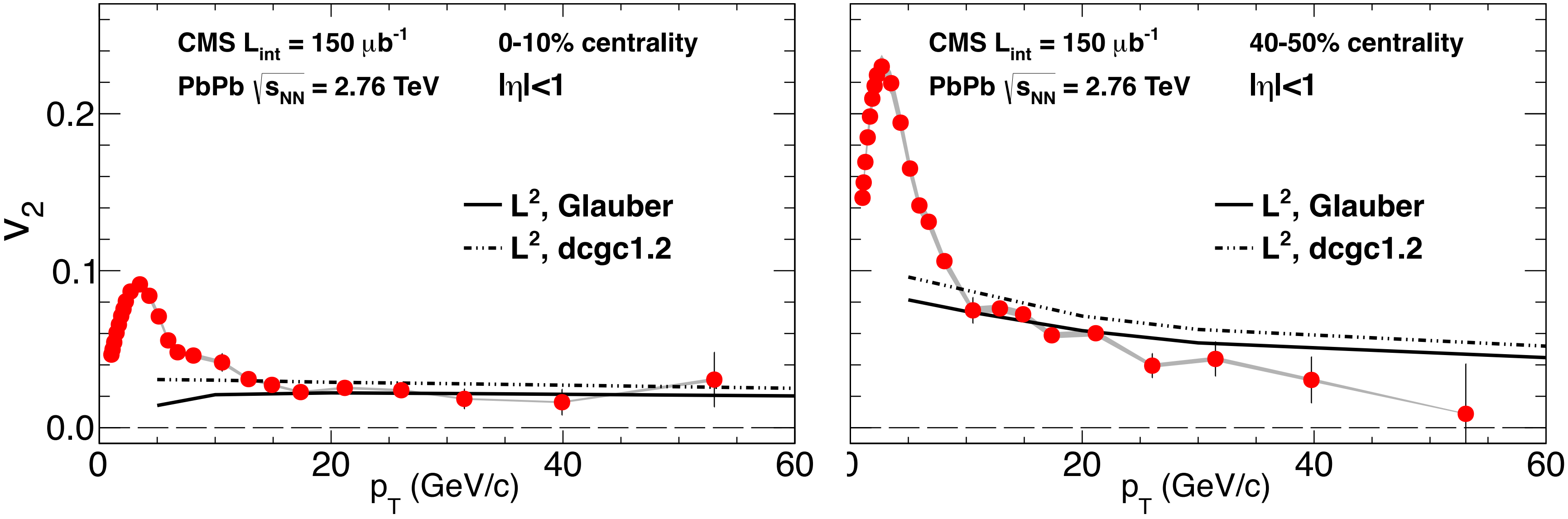
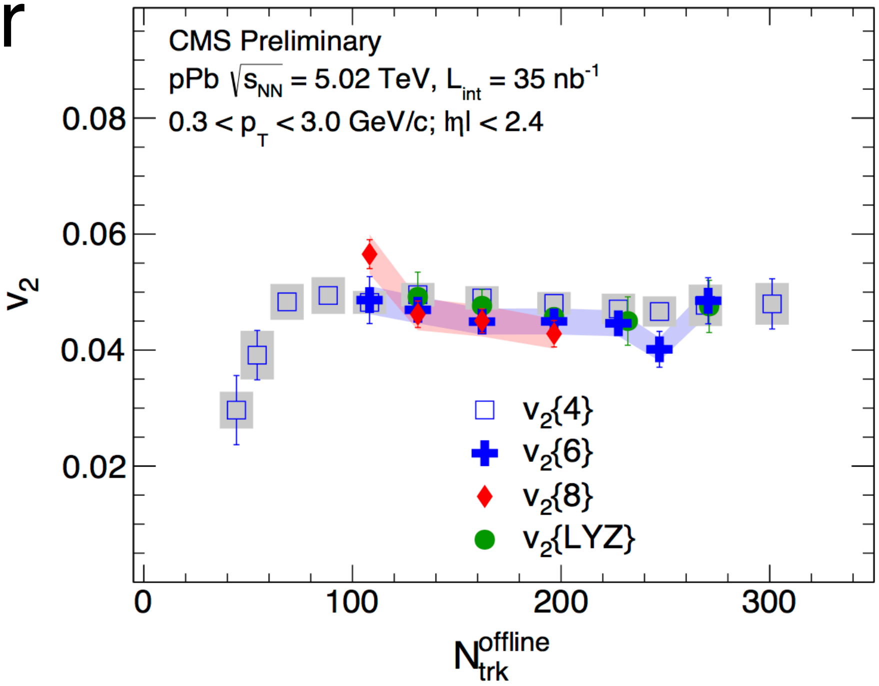


Summary and Outlook

Surprising collective behavior observed in pPb at the LHC:

- Smaller QGP droplet ($v_2\{N\geq4\}$, mass ordering, …)?
- Theoretical challenge in understanding the initial state
- What about pp?



Study of collectivity in AA remains an active field:

- Great promise of constraining η/s from ultra-central collisions
- Detailed 3D imaging of initial state from v_n factorization
- "Flow" at high p_T to probe ***L*** dependence of jet quenching