A new look at the initial state

– the p_T and η dependent event planes

Wei Li (Rice University)
for the CMS collaboration

IS2014, December 3-7, 2014

Decode the initial-state inhomogeneity

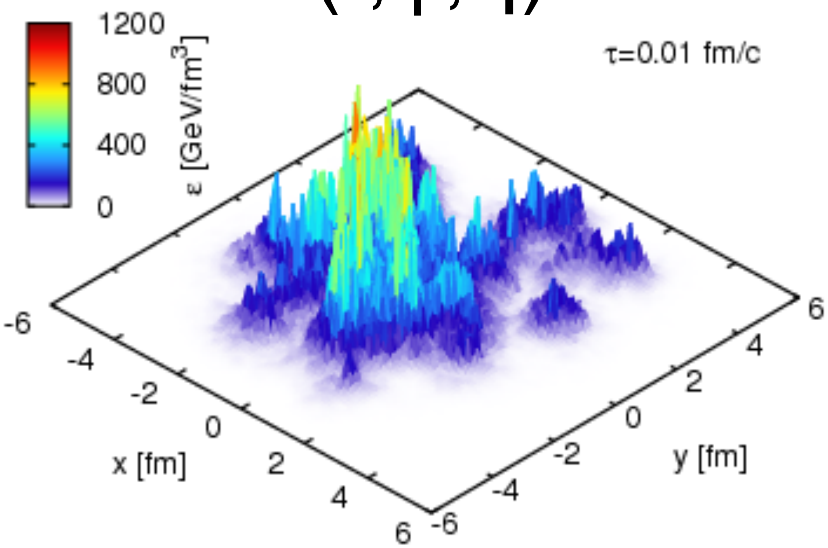
Initial state

$\varepsilon(r,\varphi,\eta)$

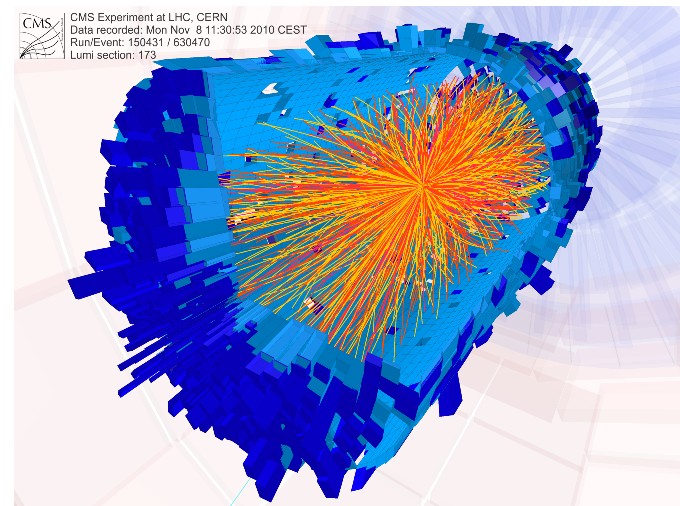
EbE hydro. $\longrightarrow$

Final state

$f(p_T,\varphi,\eta)$



overlap zone in x-y



Decode the initial-state inhomogeneity

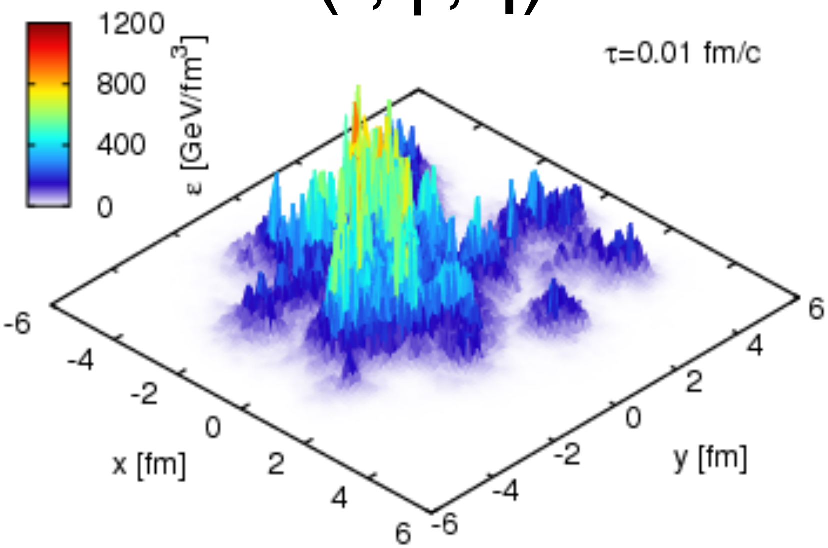
Initial state

$\varepsilon(r,\varphi,\eta)$

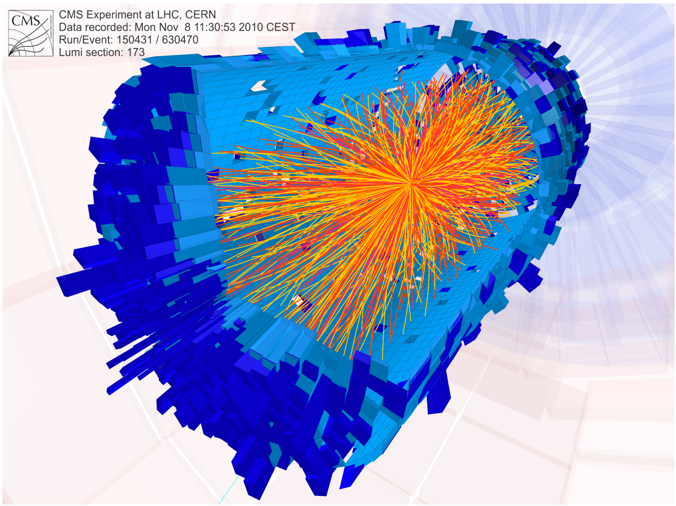
EbE hydro.

Final state

$f(p_T,\varphi,\eta)$



overlap zone in x-y



Ultimate goal: map out initial state and its fluctuations ($\delta\varepsilon(r,\varphi,\eta)$) in 3D event-by-event

Decode the initial-state inhomogeneity

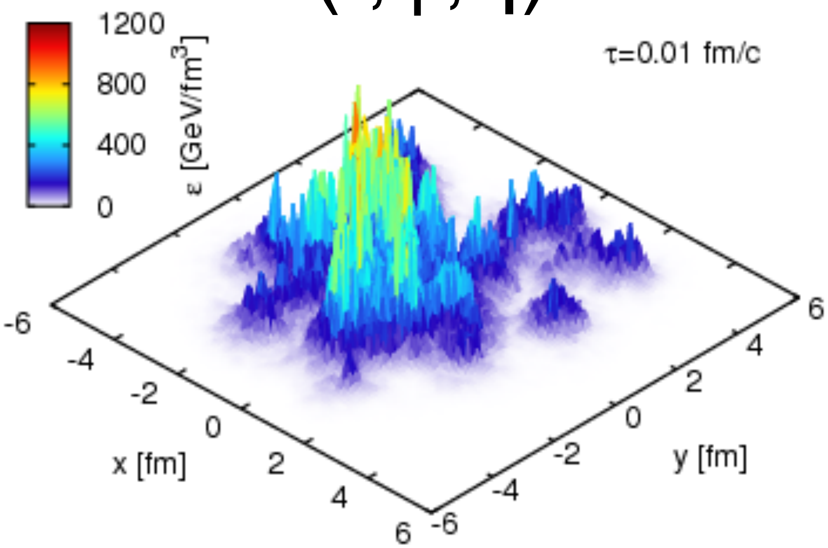
Initial state

$\varepsilon(r,\varphi,\eta)$

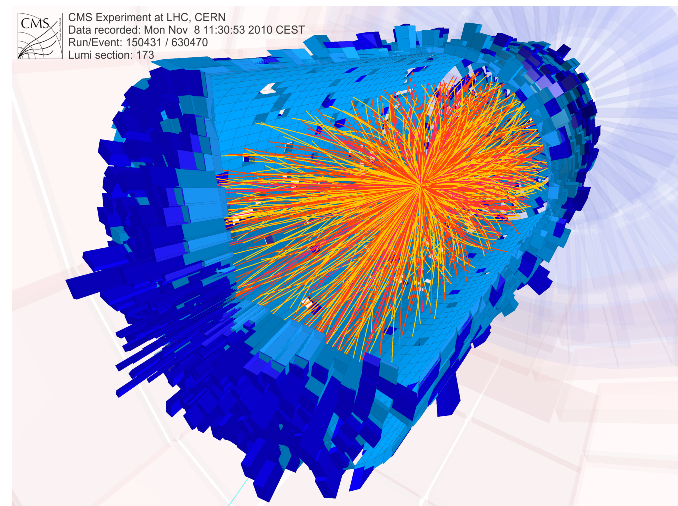
EbE hydro. $\longrightarrow$

Final state

$f(p_T,\varphi,\eta)$



overlap zone in x-y



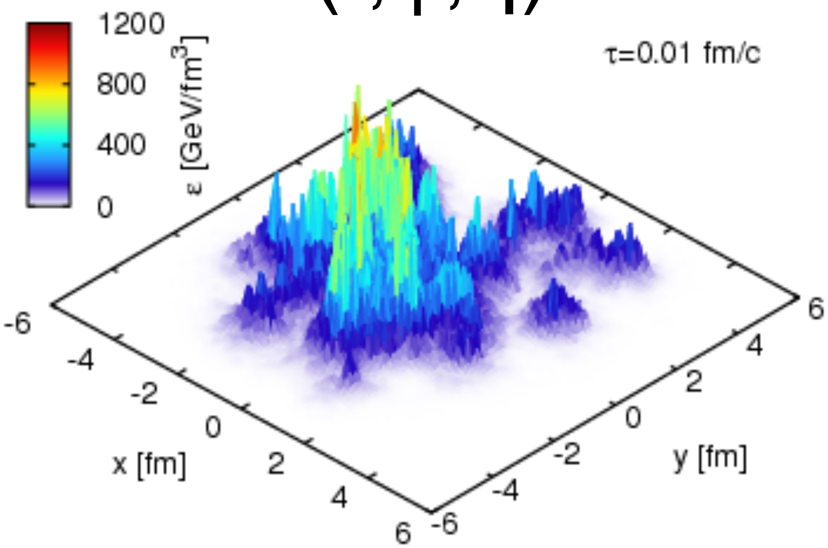
Ultimate goal: map out initial state and its fluctuations ($\delta\varepsilon(r,\varphi,\eta)$) in 3D event-by-event

$\delta\varepsilon(r,\varphi,\eta)$ uniquely probed by AA, while ep, pA or eA can mainly access $<\varepsilon>$

Decode the initial-state inhomogeneity

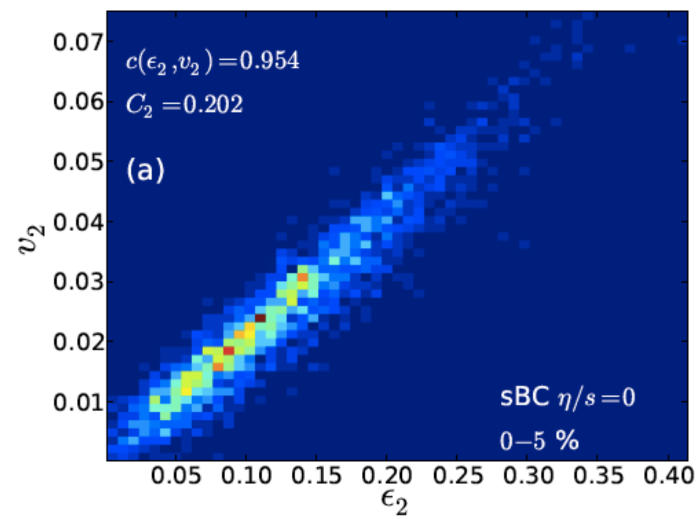
Initial state $\varepsilon(r,\varphi,\eta)$ $\xrightarrow{\text{EbE hydro.}}$ Final state $f(p_T,\varphi,\eta)$

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



overlap zone in x-y

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



Niemi et al, arXiv:1212.1008

Decode the initial-state inhomogeneity

Initial state

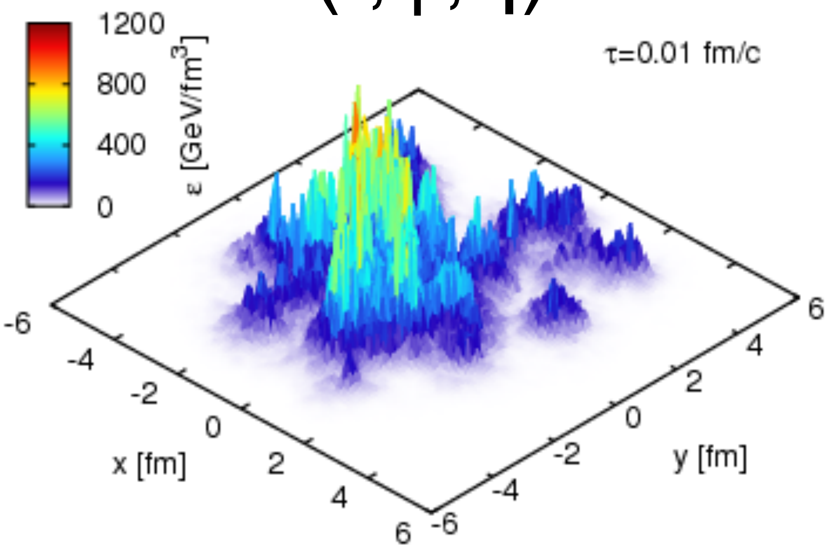
$\varepsilon(r,\varphi,\eta)$

EbE hydro. $\longrightarrow$

Final state

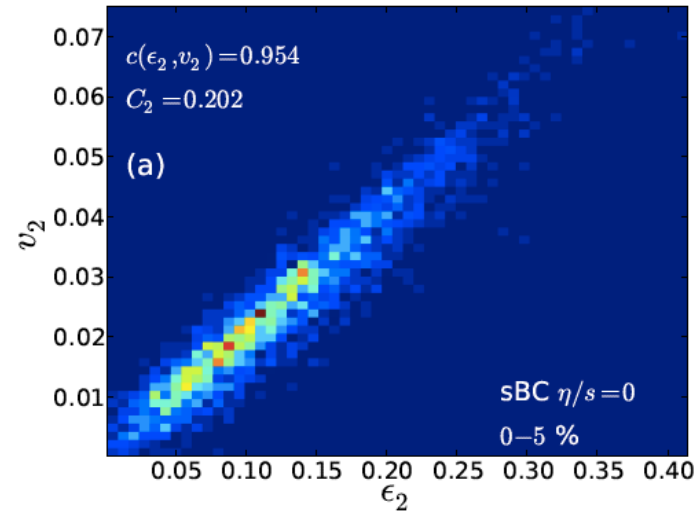
$f(p_T,\varphi,\eta)$

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



overlap zone in x-y

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



Niemi et al, arXiv:1212.1008

$v_n = k_n \times \varepsilon_n$ not perfect

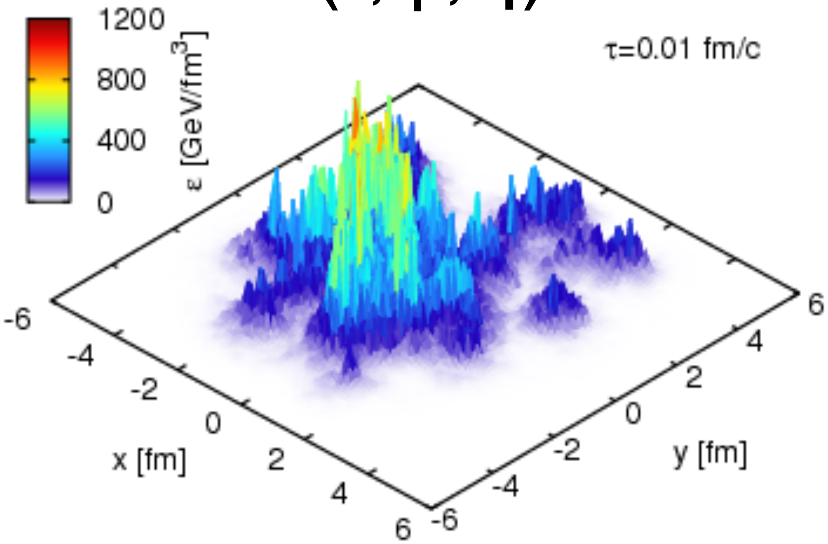
Decode the initial-state inhomogeneity

Initial state

$\varepsilon(r,\varphi,\eta)$ $\xrightarrow{\text{EbE hydro.}}$ $f(p_T,\varphi,\eta)$

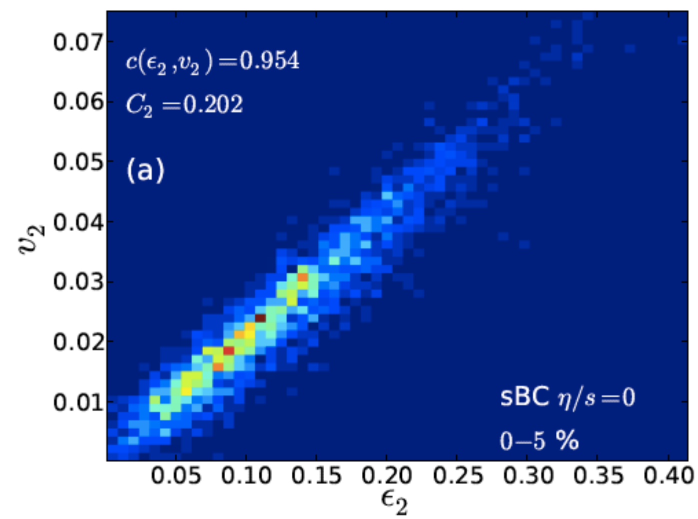
Final state

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



overlap zone in x-y

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



Niemi et al, arXiv:1212.1008

$v_n = k_n \times \varepsilon_n$ not perfect

➢ Radial (r) fluctuation is averaged out in ε_n

Decode the initial-state inhomogeneity

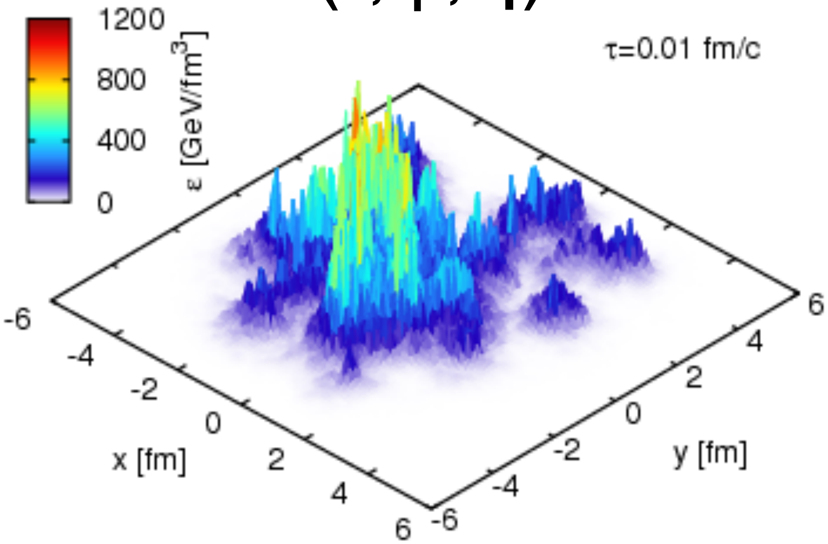
Initial state

$\varepsilon(r,\varphi,\eta)$ $\xrightarrow{\text{EbE hydro.}}$

Final state

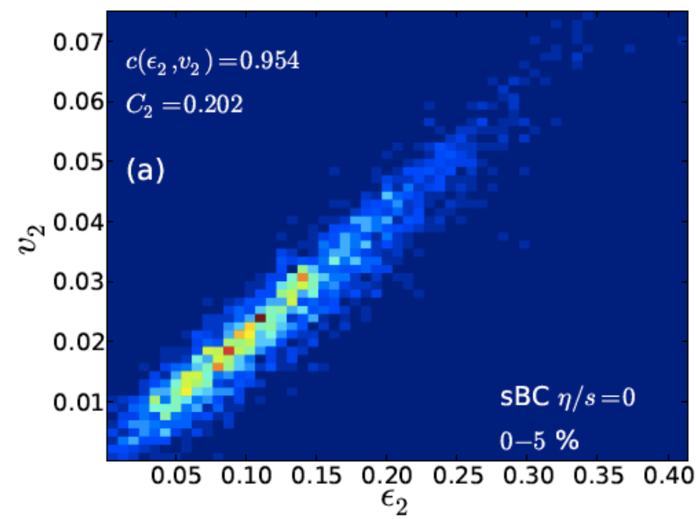
$f(p_T,\varphi,\eta)$

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



overlap zone in x-y

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



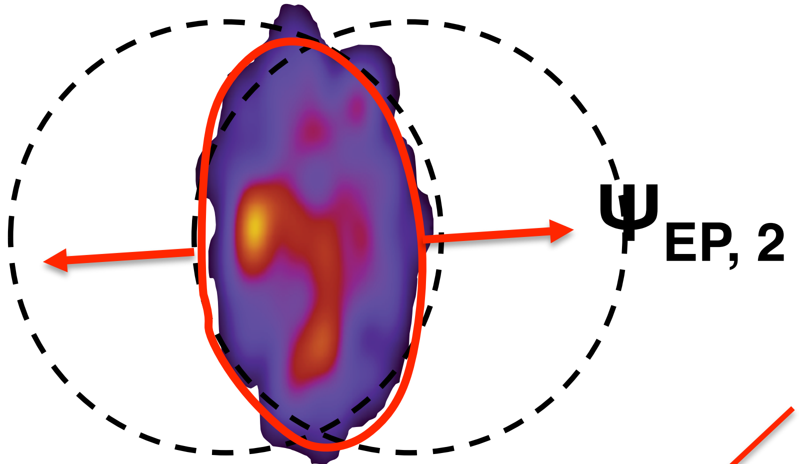
Niemi et al, arXiv:1212.1008

$v_n = k_n \times \varepsilon_n$ not perfect

- ➢ Radial (r) fluctuation is averaged out in ε_n
- ➢ Longitudinal (η) dynamics not probed

A new look at the initial state

Transverse plane



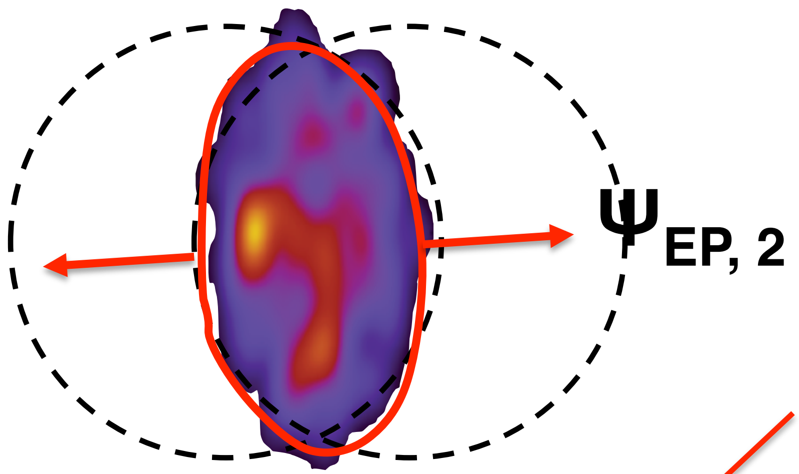
Phase should also be p_T dependent

For one event:

$$f(p_T,\varphi) \sim 1 + 2v_2(p_T)\cos\left[2\left(\phi - \boxed{\Psi_{EP,2}(p_T)}\right)\right] + \ldots$$

A new look at the initial state

Transverse plane



Phase should also be p_T dependent

For one event:

$$f(p_T,\varphi) \sim 1 + 2v_2(p_T)\cos\left[2\left(\phi - \boxed{\Psi_{EP,\,2}\left(p_T\right)}\right)\right] + \ldots$$

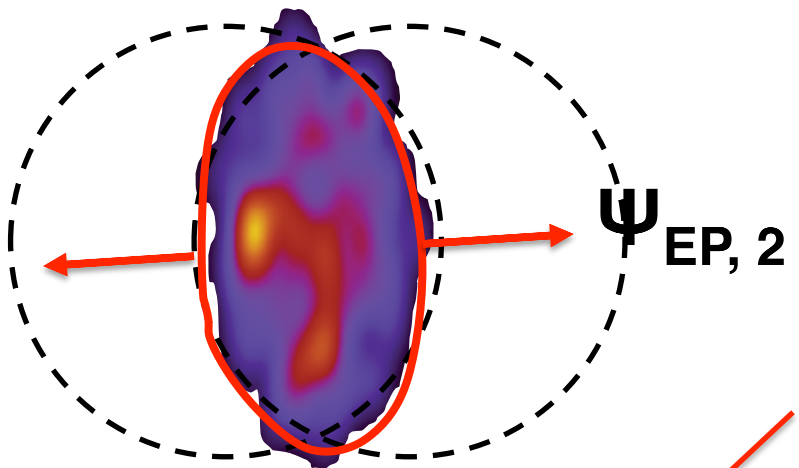
In general,

True for Fourier decomposition without **sin** terms;

Function must be **even** around $\Psi_{EP,\,2}$ at any p_T

A new look at the initial state

Transverse plane



Phase should also be p_T dependent

For one event:

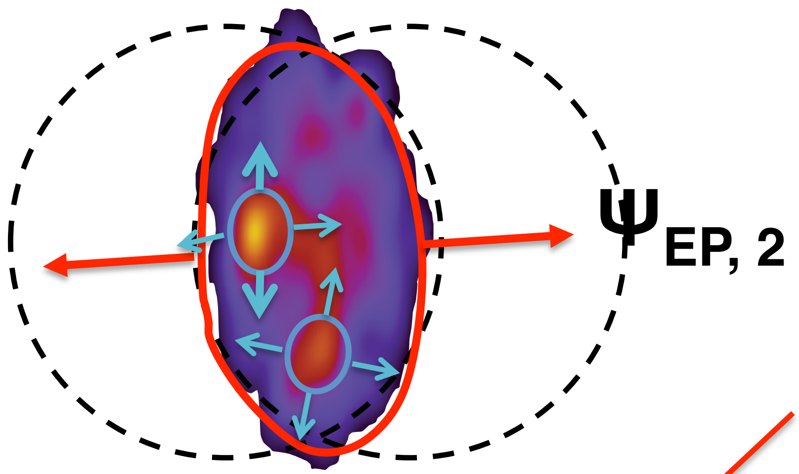
$$f(p_T,\varphi) \sim 1 + 2v_2(p_T)\cos\left[2\left(\phi - \boxed{\Psi_{EP,2}\left(p_T\right)}\right)\right] + \ldots$$

Experimentally,

$\psi_{EP,2}$ is the direction of maximum **particle** density (particle properties dependent)

A new look at the initial state

Transverse plane



Phase should also be p_T dependent

For one event:

$$f(p_T,\varphi) \sim 1 + 2v_2(p_T)\cos\left[2\left(\phi - \boxed{\Psi_{EP,2}\left(p_T\right)}\right)\right] + \ldots$$

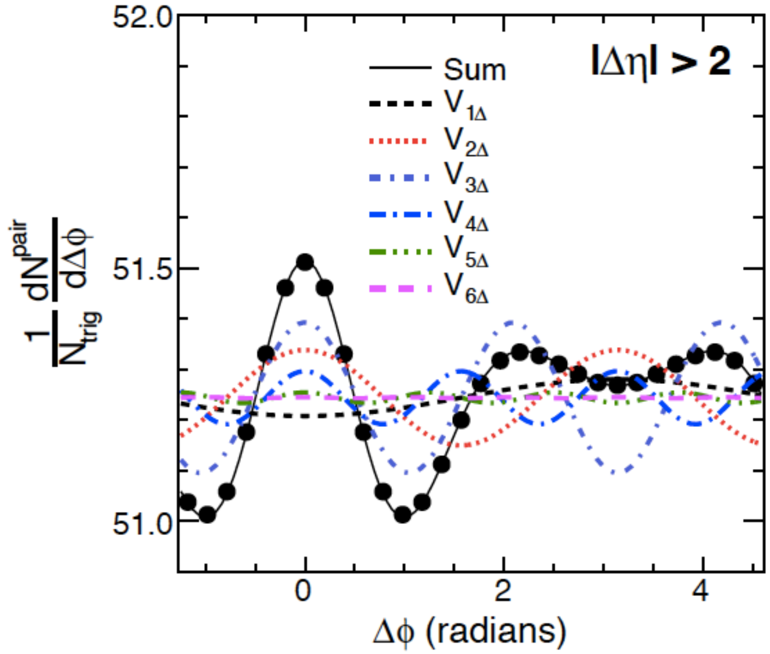
Physics picture,

Local hotspots perturb the EP of a smooth medium, in a p_T dependent fashion

Details of initial-state fluctuations (radial) in $\Psi_n(p_T)$

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Full final-state information imprinted in



Long-range correlations (|Δη|>2)

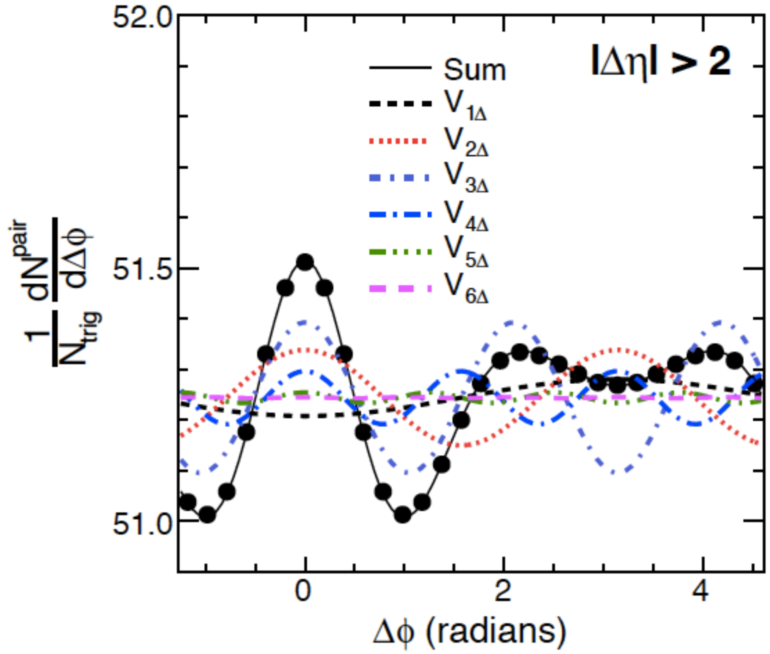
$$\boxed{\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_n V_{n\Delta}(p_T^a, p_T^b)\cos(n\Delta\phi)}$$

If all particles share a common Ψ_n

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$$ – "factorization"

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Full final-state information imprinted in



Long-range correlations (|Δη|>2)

$$\boxed{\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_n V_{n\Delta}(p_T^a, p_T^b)\cos(n\Delta\phi)}$$

If all particles share a common Ψ_n

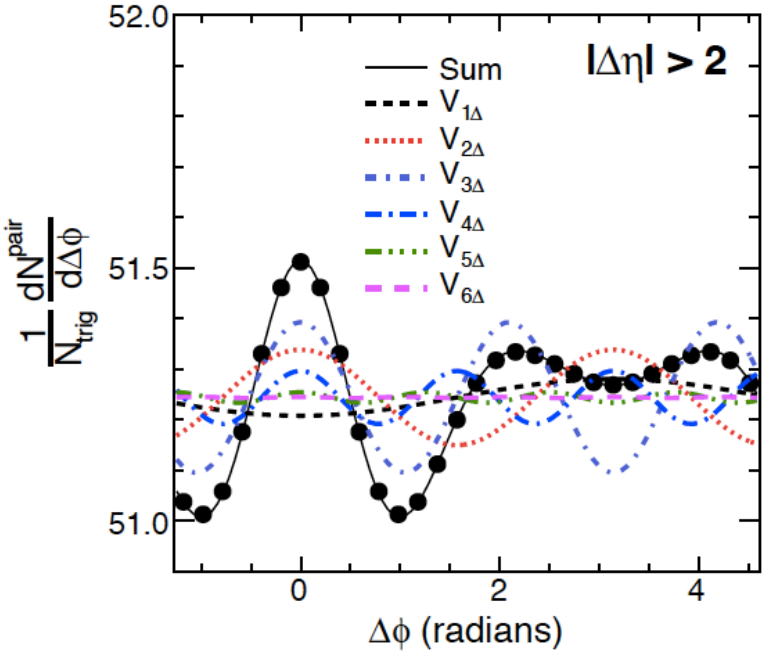
$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$$ – "factorization"

Otherwise

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)\cos\left[n\left(\Psi_n(p_T^a) - \Psi_n(p_T^b)\right)\right]$$

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Full final-state information imprinted in



Long-range correlations ($|\Delta\eta|>2$)

$$\boxed{\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_n V_{n\Delta}(p_T^a, p_T^b)\cos(n\Delta\phi)}$$

If all particles share a common Ψ_n

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)$$ – "factorization"

Otherwise

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)\boxed{\cos\left[n\left(\Psi_n(p_T^a) - \Psi_n(p_T^b)\right)\right]}$$

Factorization breakdown

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Factorization ratio:

Gardim et al, arXiv:1211.0989
Heinz et al, arXiv:1302.3535

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

event-averaged observable

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Factorization ratio:

Gardim et al, arXiv:1211.0989
Heinz et al, arXiv:1302.3535

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

event-averaged observable

(r_n = 1 if Ψ_n is independent of p_T; Otherwise, r_n<1)

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Factorization ratio:

Gardim et al, arXiv:1211.0989
Heinz et al, arXiv:1302.3535

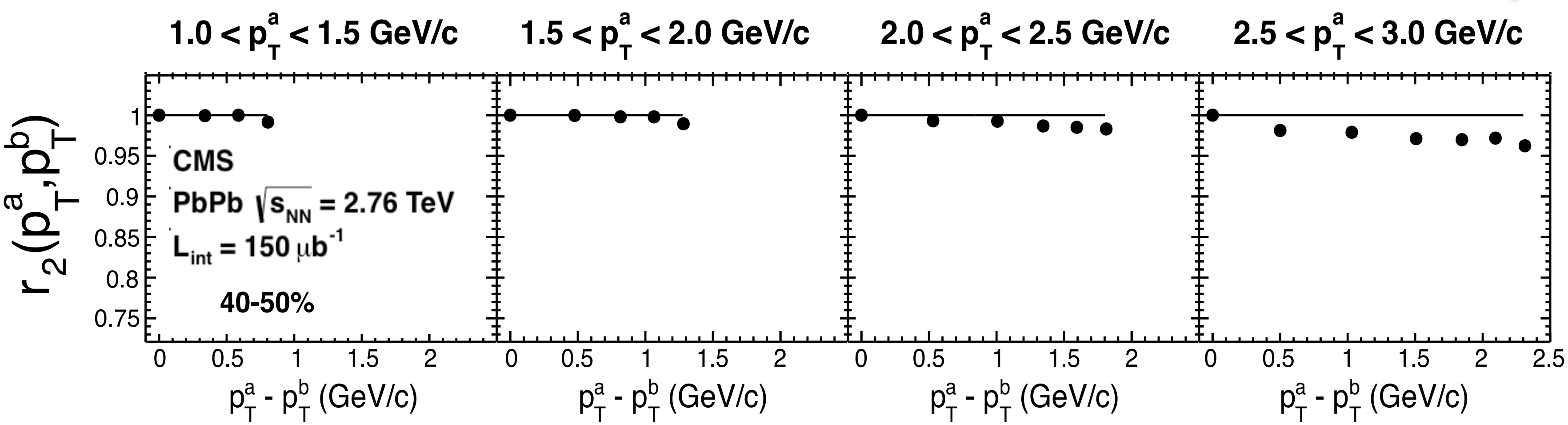
$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

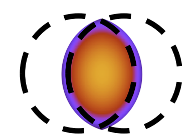
event-averaged observable

($r_n = 1$ if Ψ_n is independent of p_T; Otherwise, $r_n<1$)

JHEP 02 (2014) 088, CMS PAS HIN-14-012

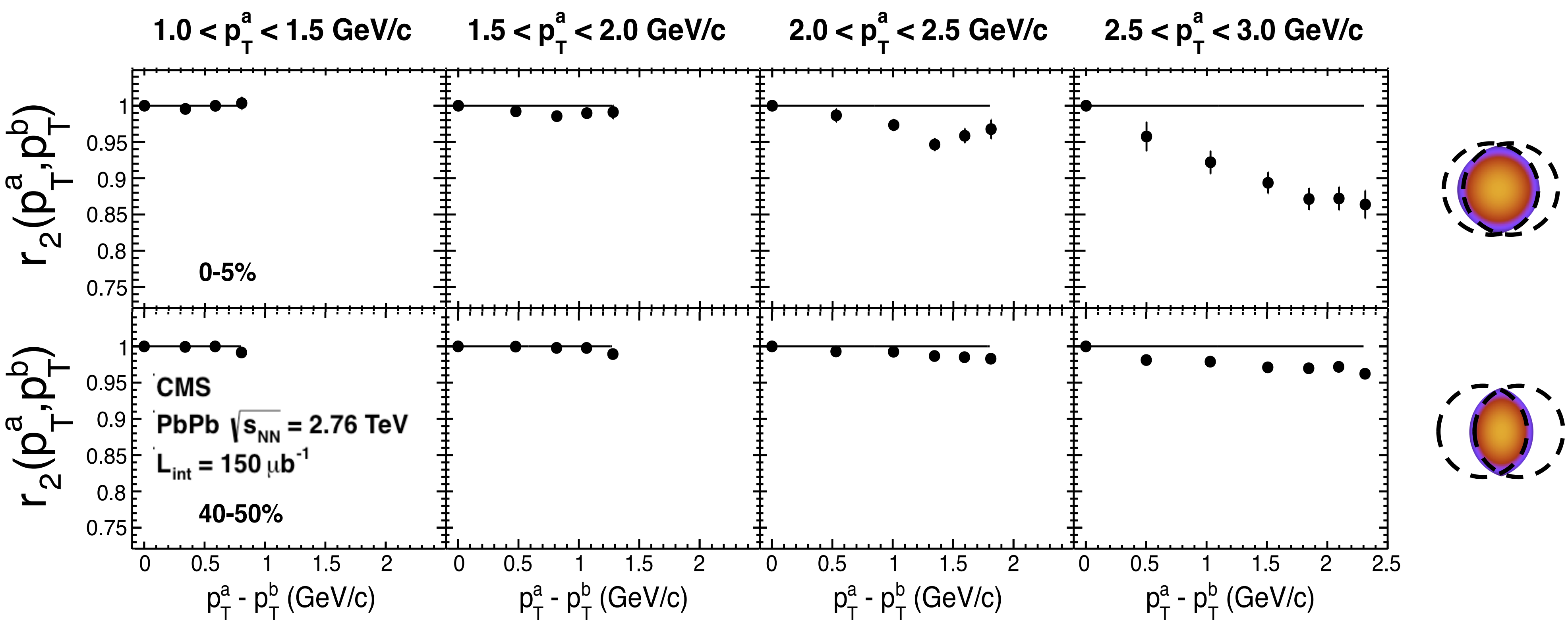
Increasing p_T^a



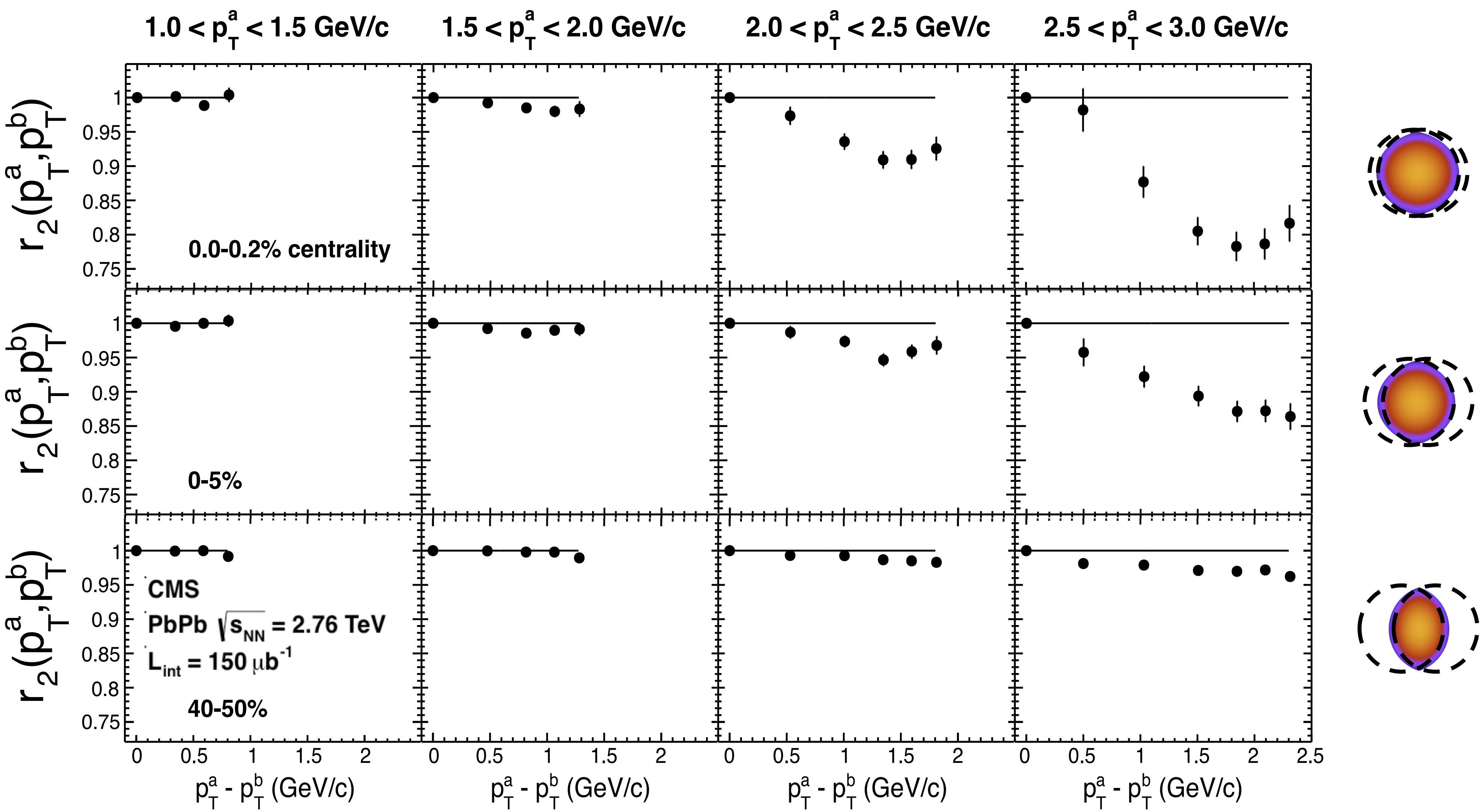


Small effect in periph. PbPb: global geometry driven

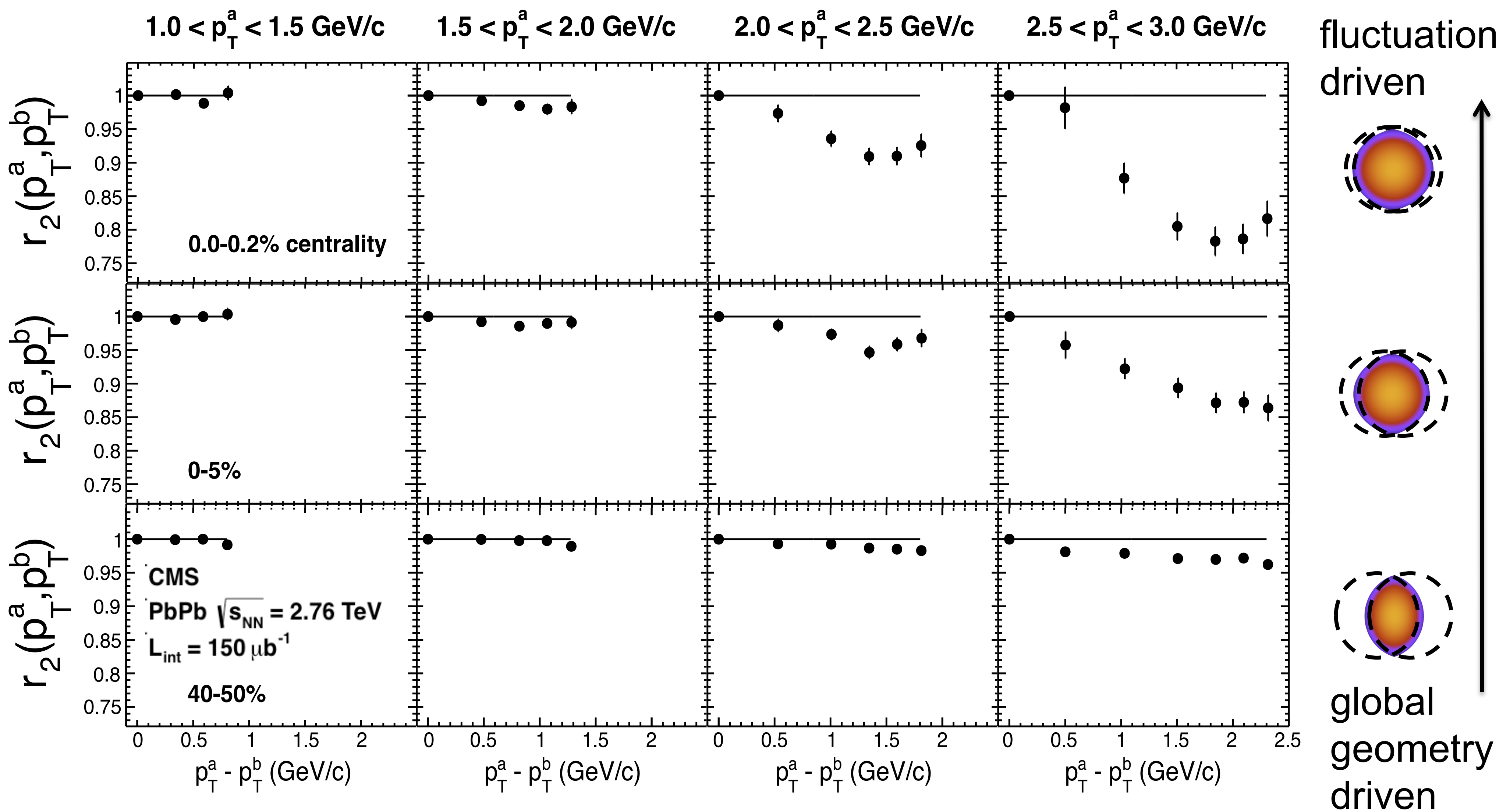
EP angle fluctuations in p_T: $\Psi_n(p_T)$



EP angle fluctuations in p_T: $\Psi_n(p_T)$

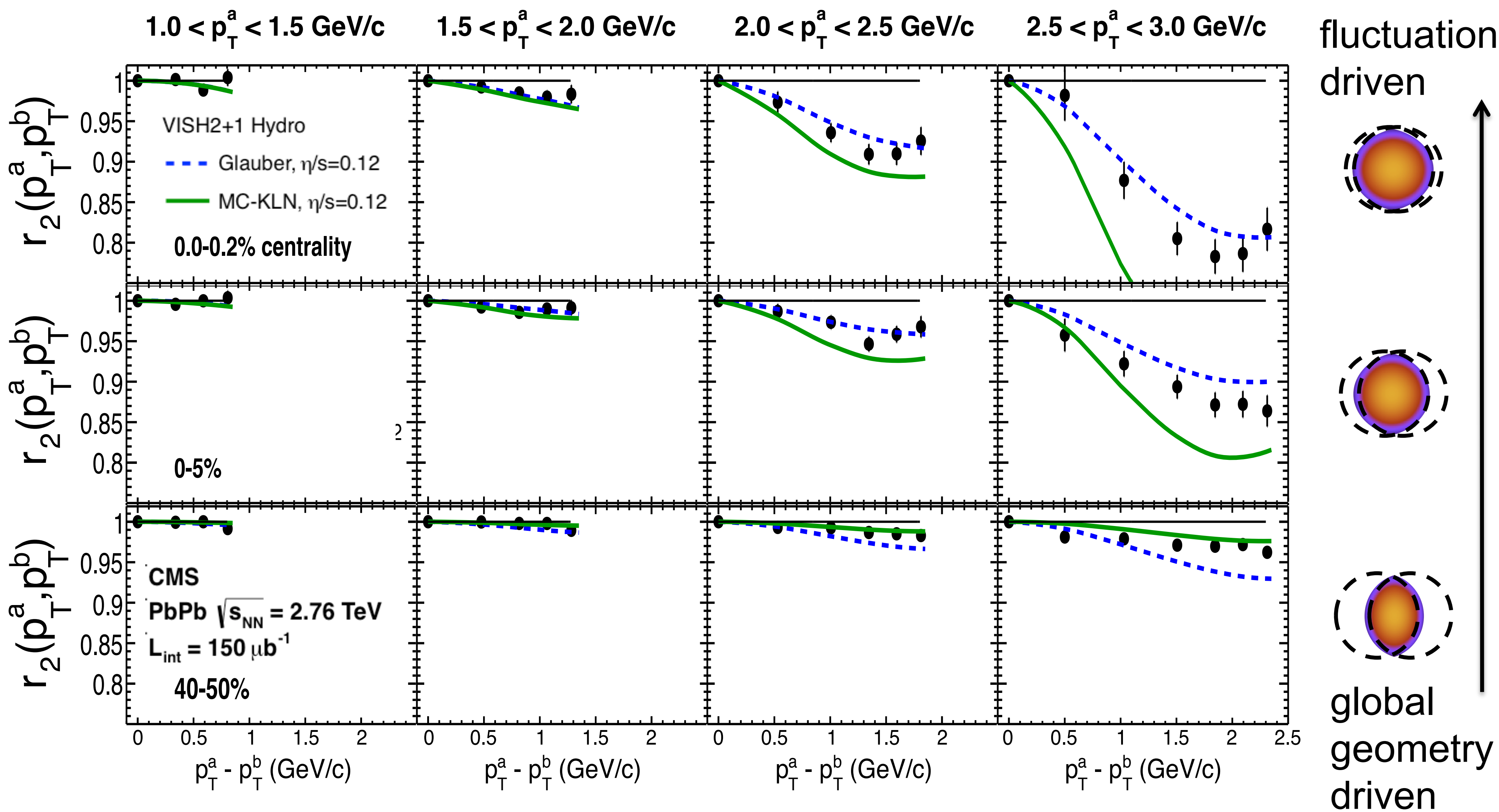


EP angle fluctuations in p_T: $\Psi_n(p_T)$



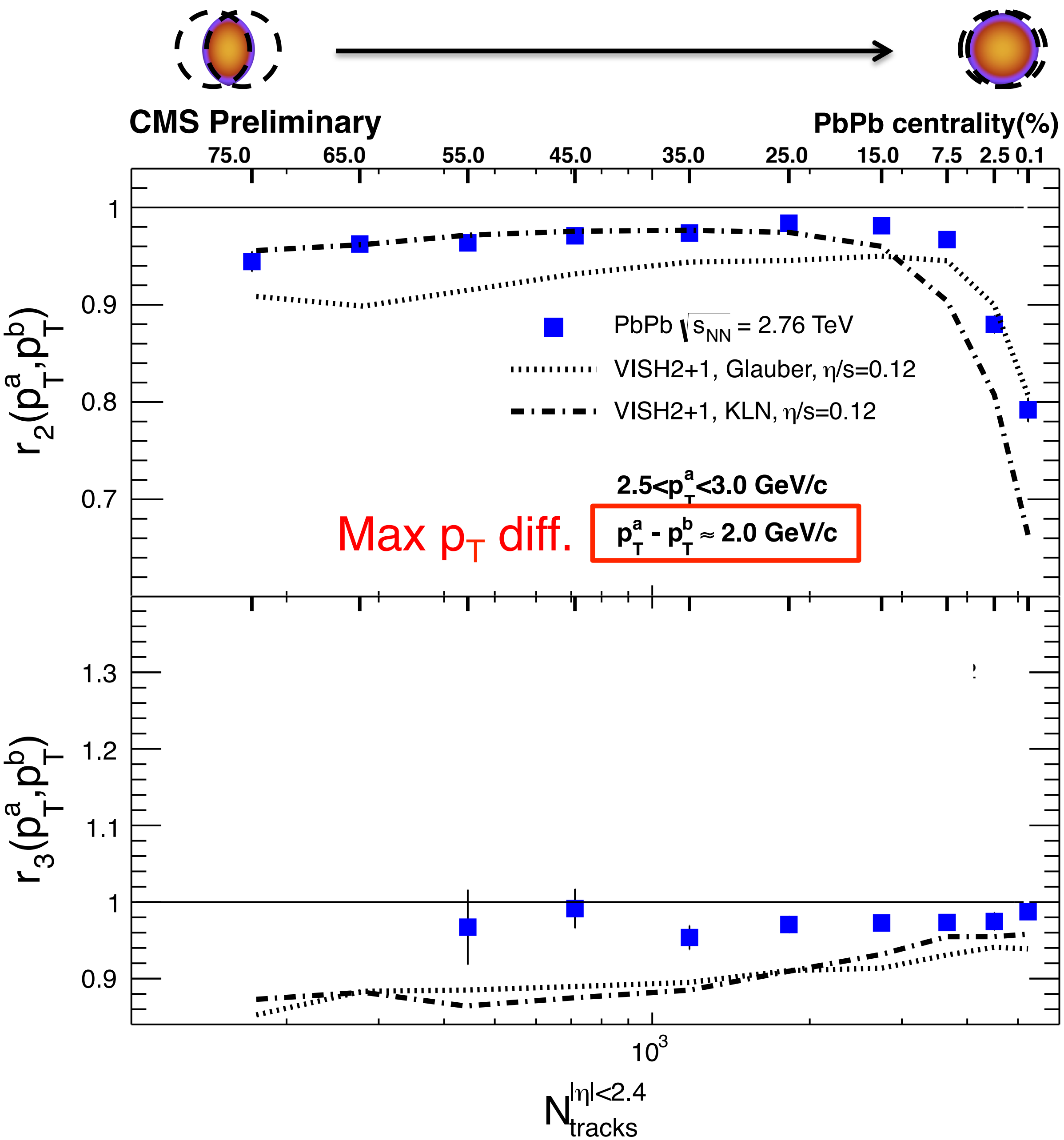
Much larger $\Psi_n(p_T)$ fluctuations in central PbPb

EP angle fluctuations in p_T: $\Psi_n(p_T)$



Semi-quantitatively predicted by hydrodynamics

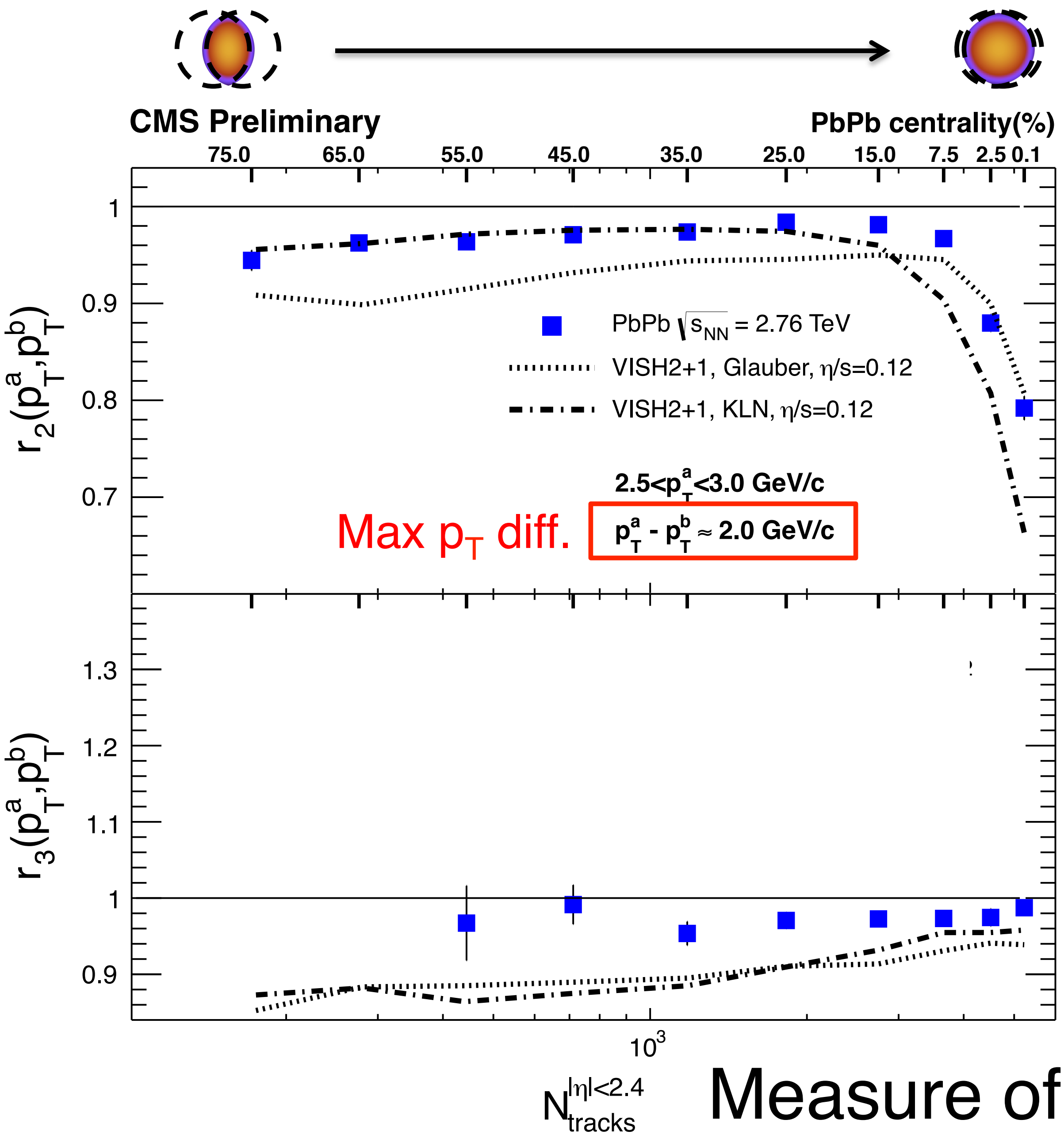
EP angle fluctuations in p_T: $\Psi_n(p_T)$



Strong effect for v_2 in central PbPb

Little effect for v_3

EP angle fluctuations in p_T: $\Psi_n(p_T)$



Strong effect for v_2 in central PbPb

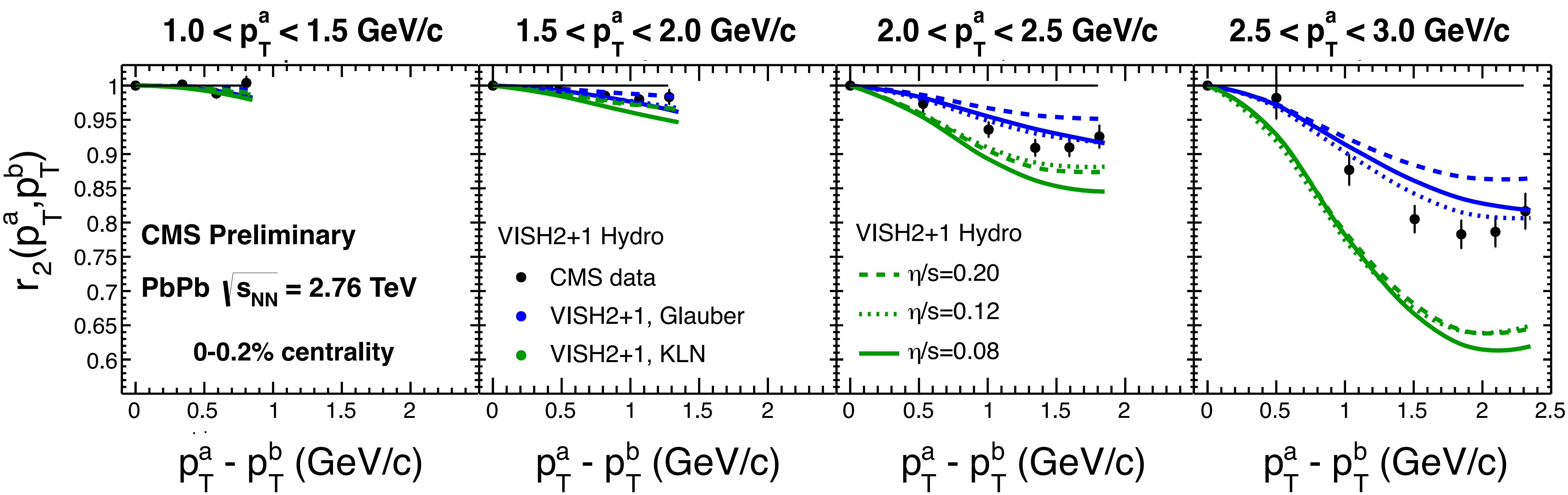
Little effect for v_3

Measure of fluctuation granularity

EP angle fluctuations in p_T: $\Psi_n(p_T)$

$$r_n(p_T^a, p_T^b) \sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

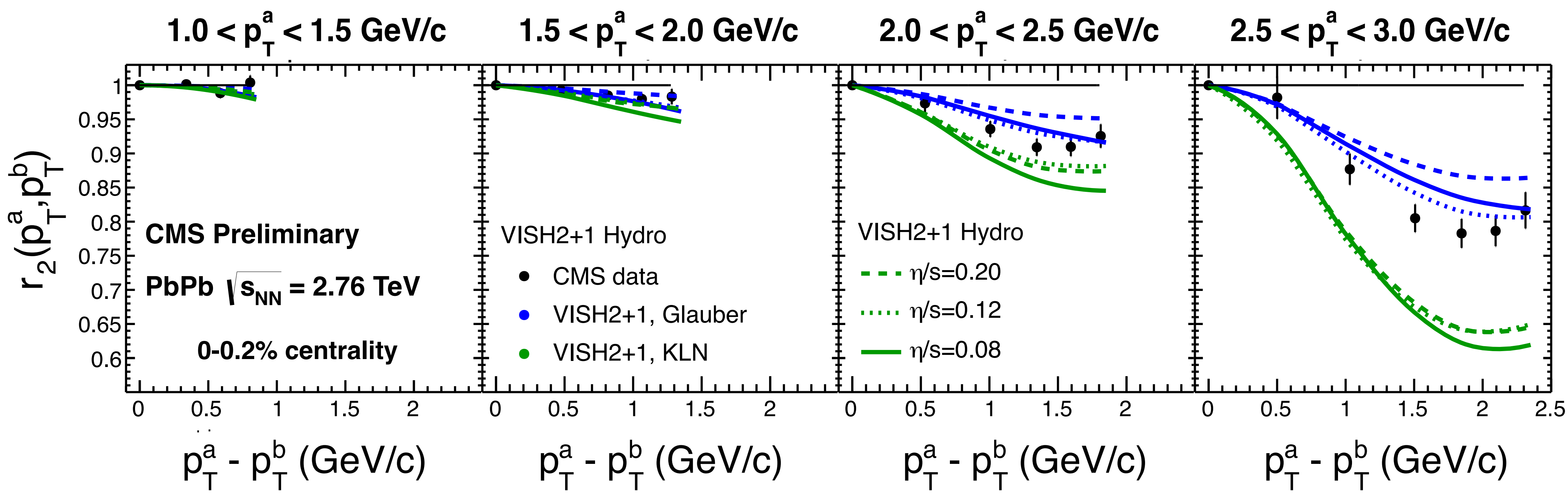
Top 0.2% central events



EP angle fluctuations in p_T: $\Psi_n(p_T)$

$$r_n(p_T^a, p_T^b) \sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

Top 0.2% central events

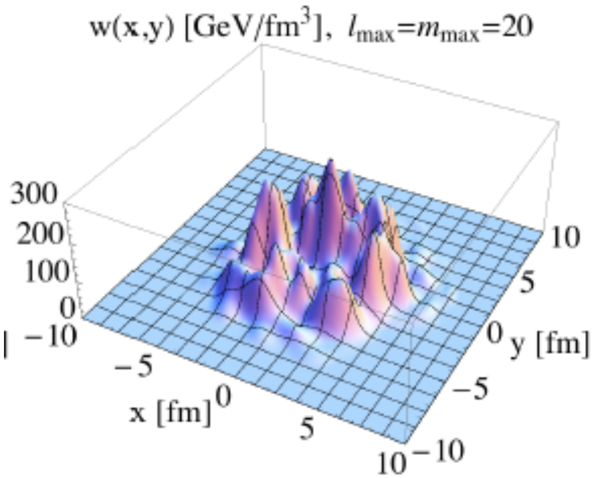


$r_2(p_T^a, p_T^b)$ largely insensitive to η/s

➔ an independent constraint on the initial state

EP angle fluctuations in p_T: $\Psi_n(p_T)$

Mode-by-mode hydrodynamics



S. Florchinger, U. Wiedemann
arXiv:1307.3453

Bessel-Fourier basis:

$$w(r,\phi) = w_{BG}(r) + w_{BG}(r) \sum_{m,l} w_l^{(m)} e^{im\phi} J_m\left(z_l^{(m)} \rho(r)\right)$$

Azimuthal mode

Radial mode

See also Coleman-Smith et al, arXiv:1204.5774

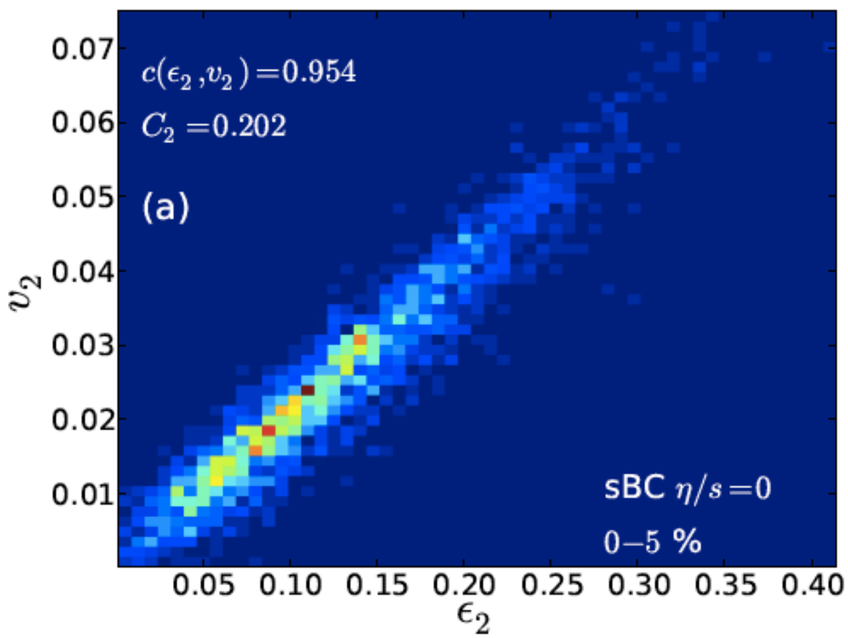
Mix of radial modes breaks v_n factorization in p_T!

$$V_{m\Delta}(p_T^a, p_T^b) = \sum_{l_1,l_2=1}^{l_{max}} \theta_{l_1}^{(m)}(p_T^a)\theta_{l_2}^{(m)}(p_T^b)\langle \tilde{w}_{l_1}^{(m)} \tilde{w}_{l_2}^{(m)*}\rangle$$

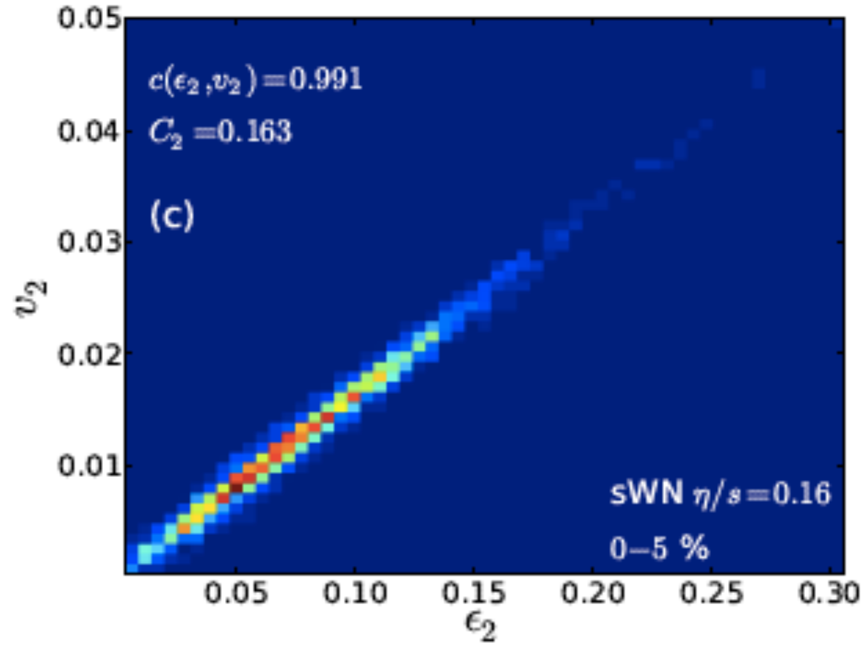
EP angle fluctuations in p_T: $\Psi_n(p_T)$

Better correlation between v_2 and ε_2 with larger η/s

$\eta/s = 0$



$\eta/s = 0.16$

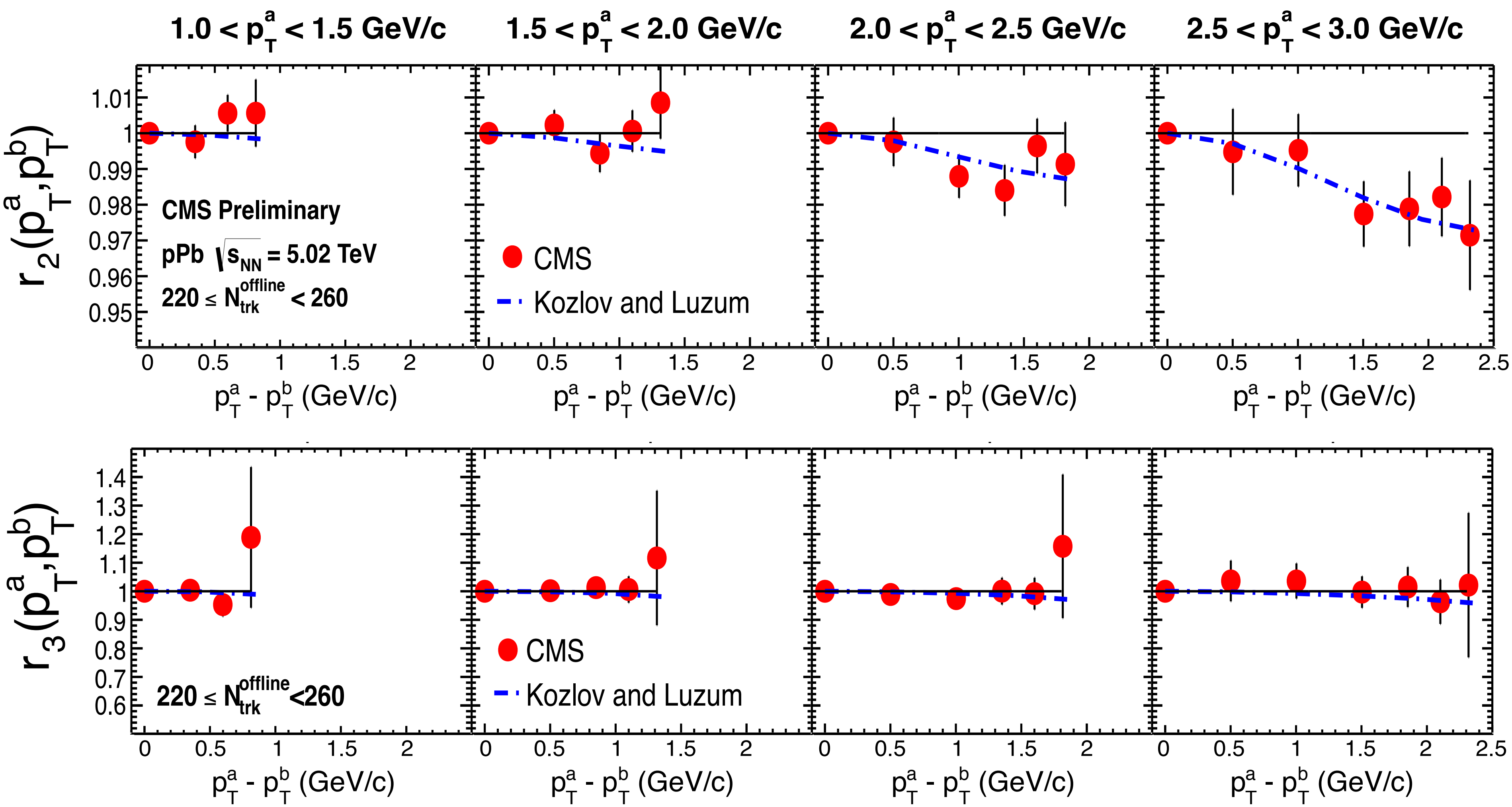


Higher order radial modes removed by large η/s

$\Psi_n(p_T)$ fluctuations in pPb

$220 < N_{trk} < 260$

Increasing p_T^a

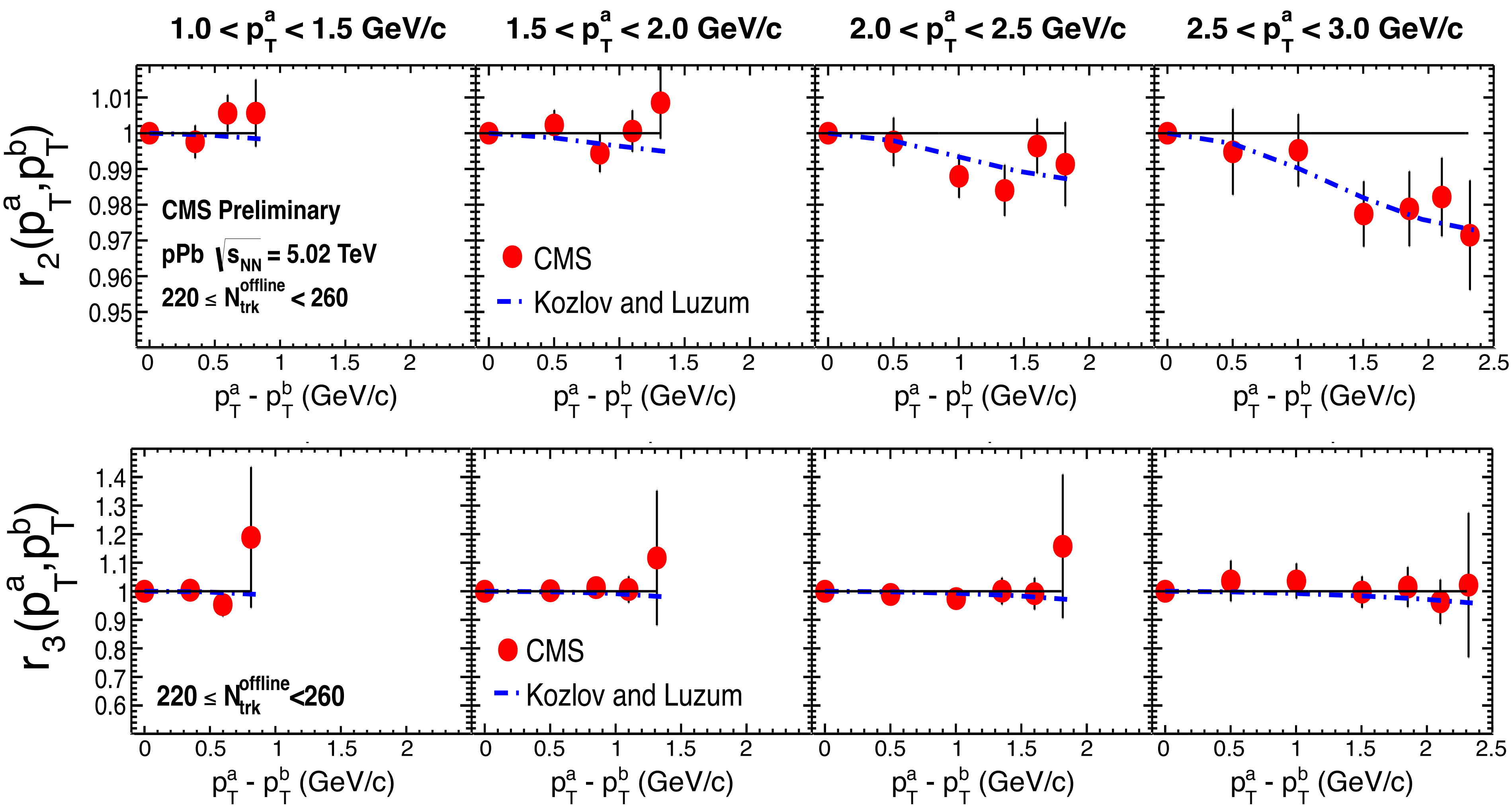


More "flow" in pPb from Zhenyu Chen's talk tomorrow

$\Psi_n(p_T)$ fluctuations in pPb

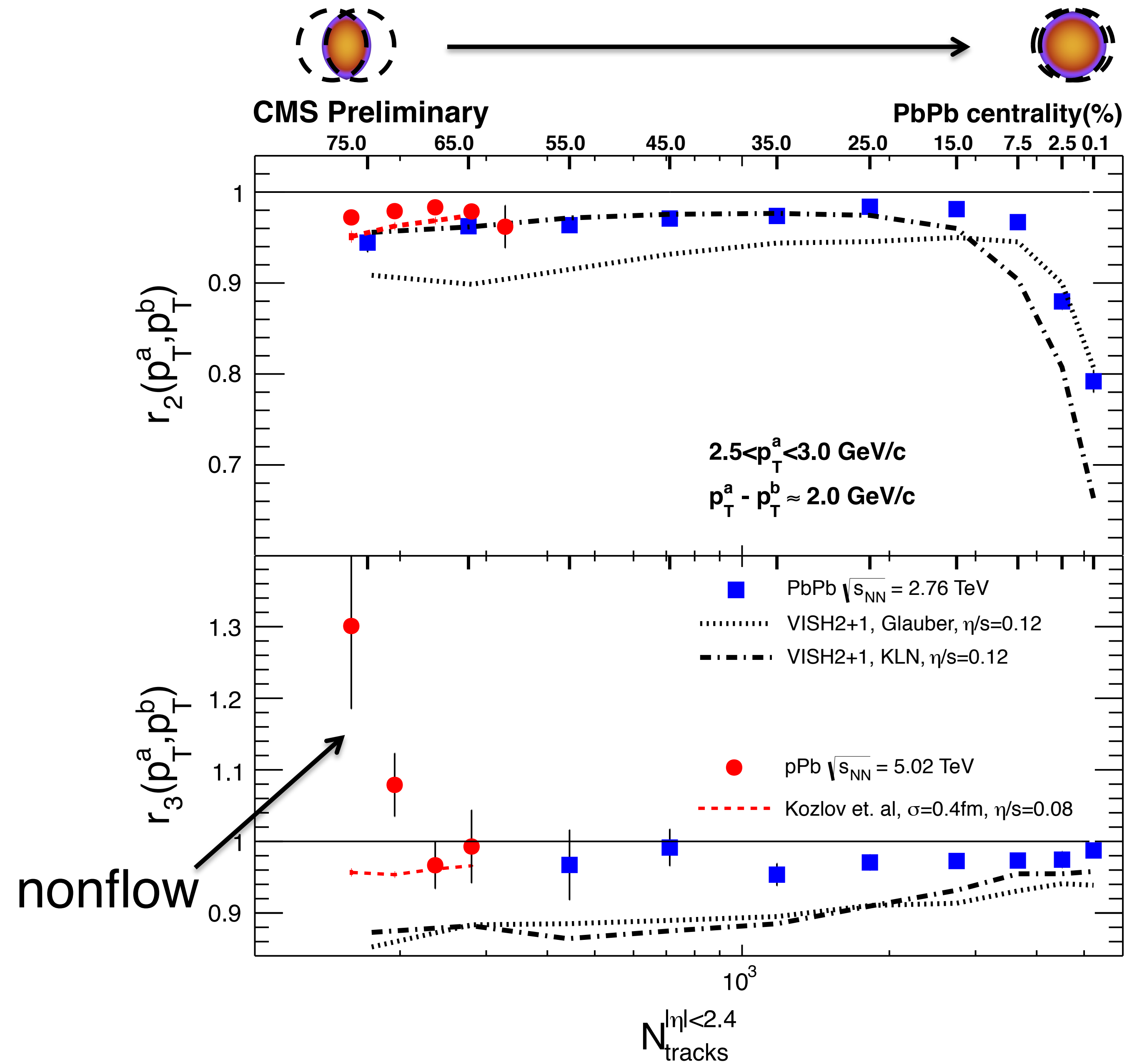
$220<N_{trk}<260$

Increasing p_T^a



Up to a few % effect ⇨ pPb is relatively smooth

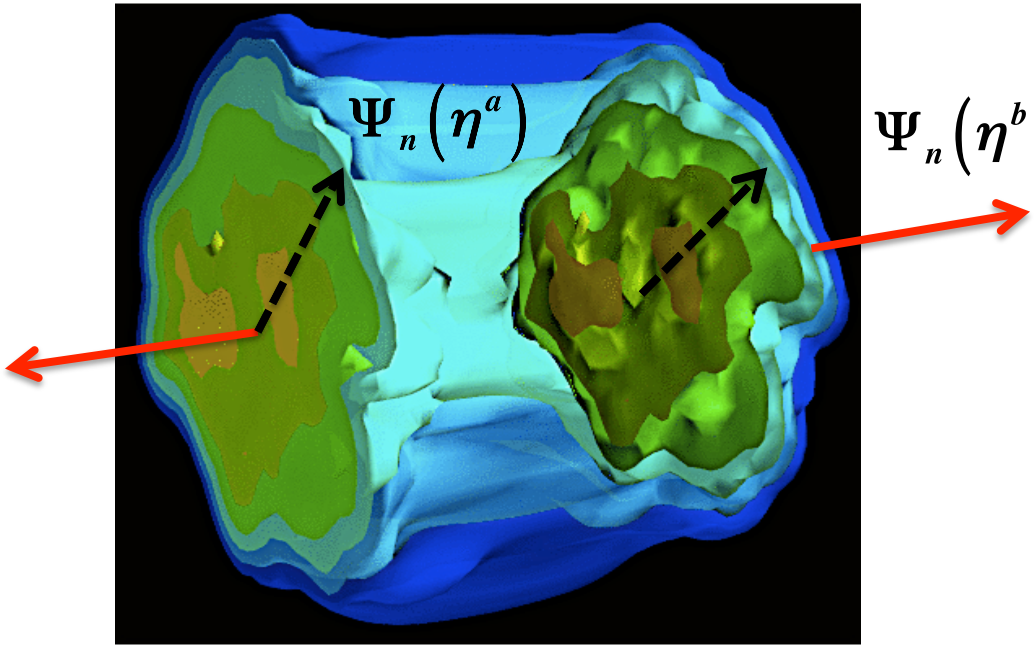
$\Psi_n(p_T)$ fluctuations in pPb and PbPb



Effect in pPb is comparable to peripheral PbPb

Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

3D expansion



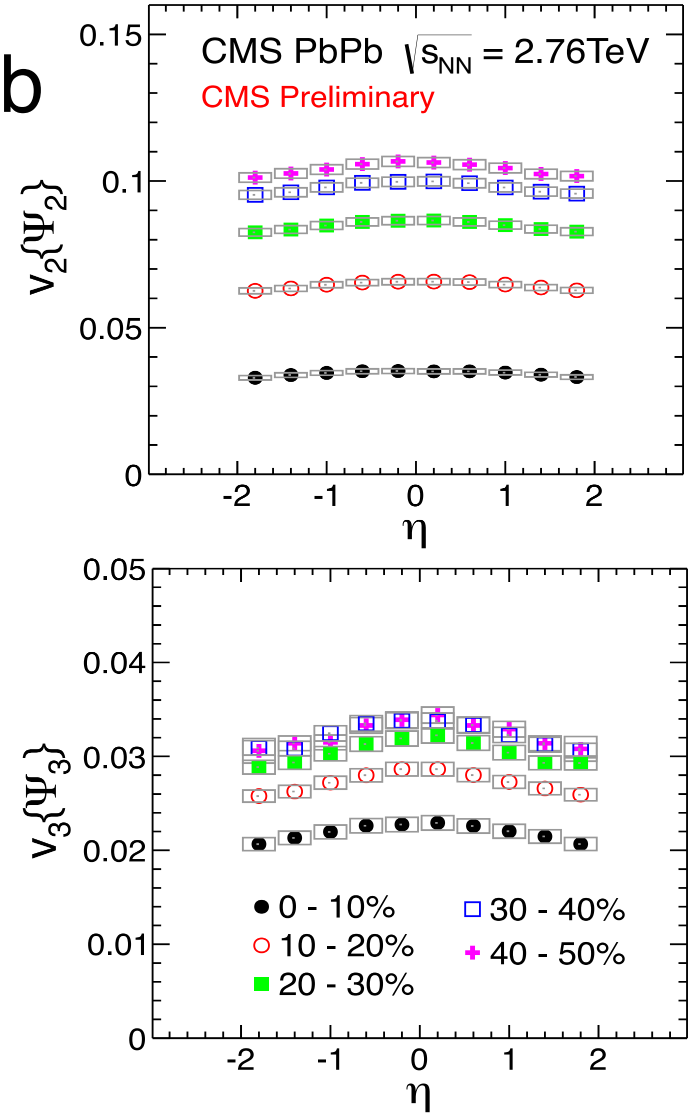
$$f(p_T,\phi,\eta) \sim 1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\left[n\left(\phi - \Psi_n\left(p_T,\boxed{\eta}\right)\right)\right]$$

Gateway to a full 3D description of initial-state fluctuations and dynamics of system evolution

Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

Flow is not boost-invariant

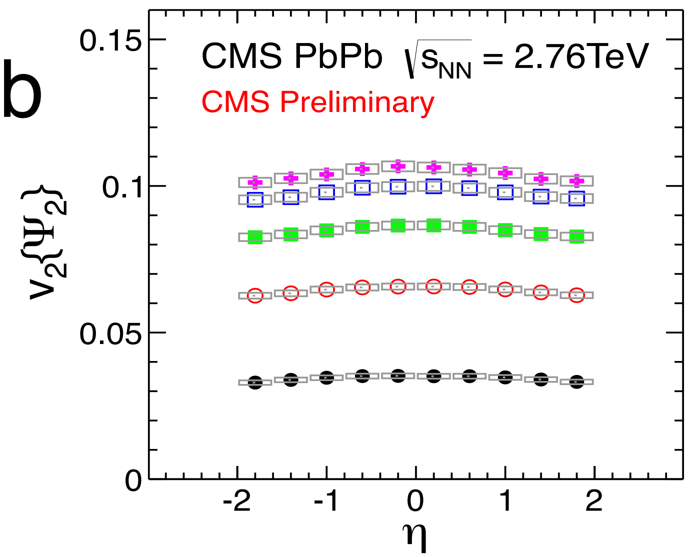
PbPb

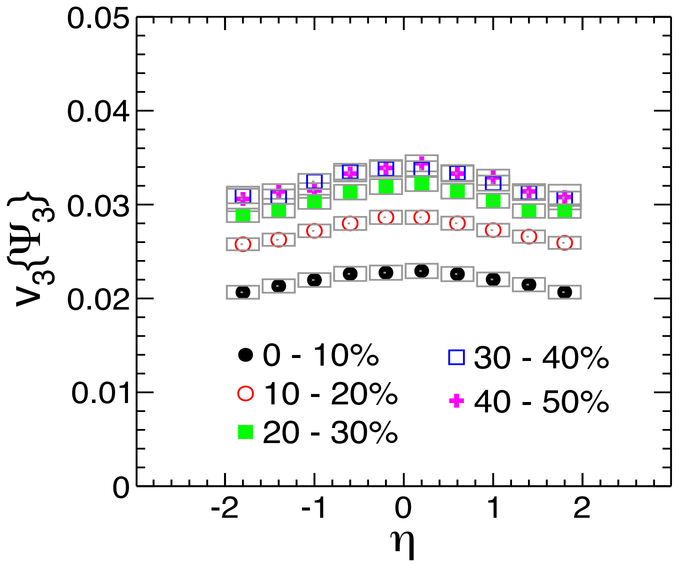


Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

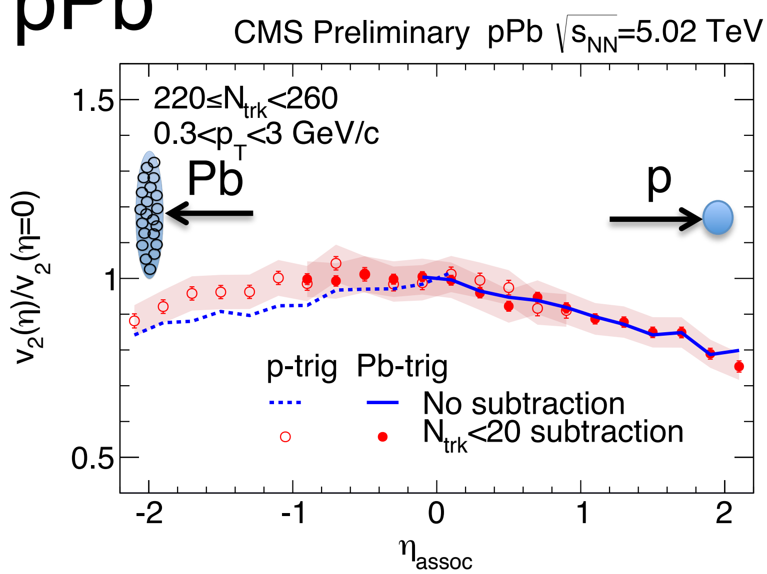
Flow is not boost-invariant

PbPb





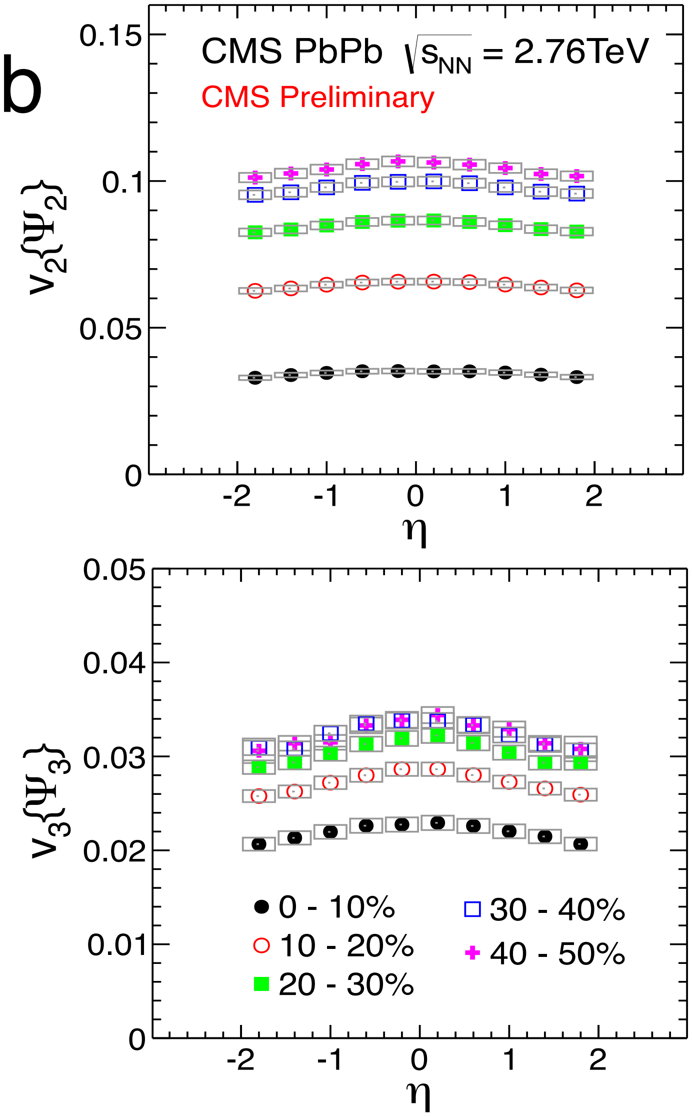
pPb



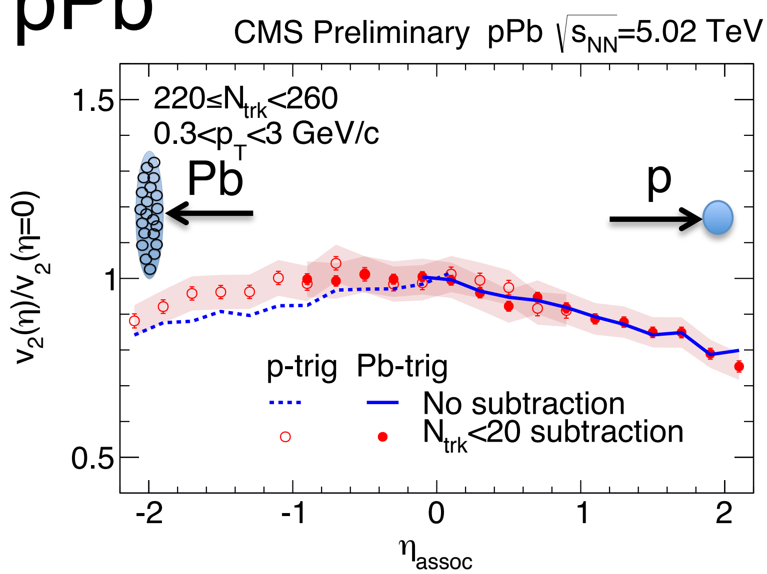
Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

Flow is not boost-invariant

PbPb



pPb

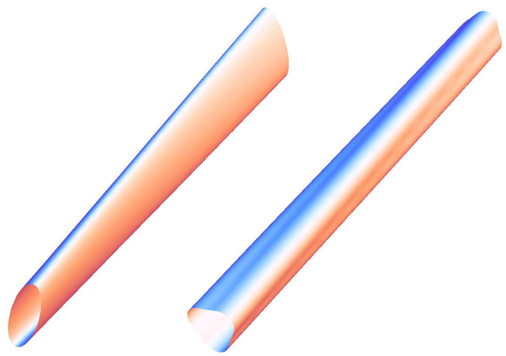


Measured w.r.t. Ψ_n at a fixed η
(at $\eta \approx 0$ due to resolution correction)

η dependence of v_n or Ψ_n?

Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

Torqued fireball

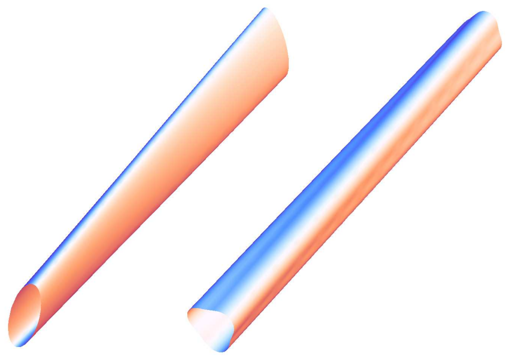


Bozek et.al., arXiv:1011.3354

Global twist

Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

Torqued fireball

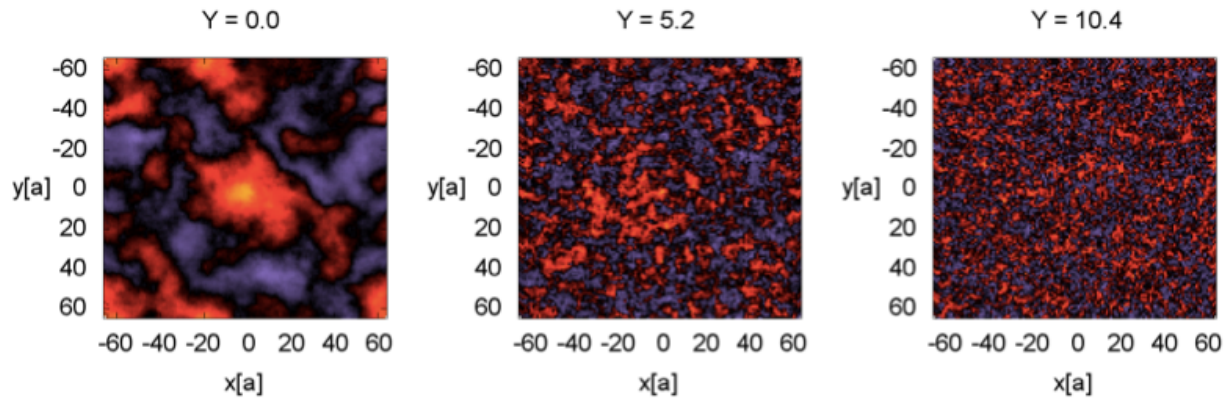


Bozek et.al., arXiv:1011.3354

Global twist

Correlation length of gluon field

JIMWLK

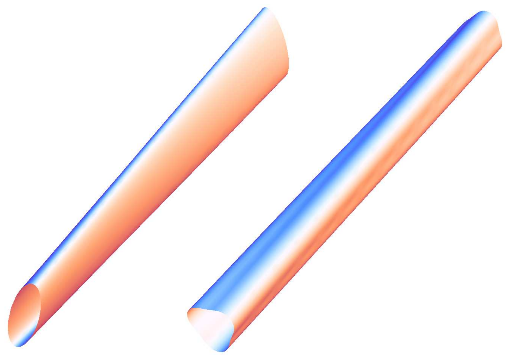


Dumitru et. al., arXiv:1108.4764

Random fluctuations?

Longitudinal dynamics: $\Psi_n(\eta)$ fluctuations

Torqued fireball

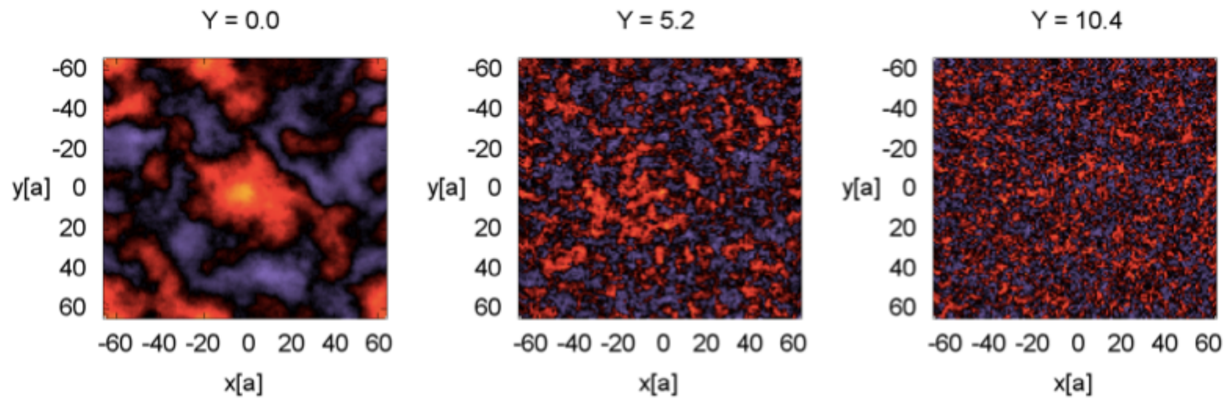


Bozek et.al., arXiv:1011.3354

Global twist

Correlation length of gluon field

JIMWLK



Dumitru et. al., arXiv:1108.4764

Random fluctuations?

Can be probed via two-particle correlations

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

Summary and Outlook

Initial-state fluctuations of nuclei can be uniquely probed in heavy-ion collisions

Evidence of p_T dependent event plane fluctuations

- provide details of initial-state fluctuations in 2D (transverse granularity)
- insensitive to η/s

Longitudinal dynamics to be probed via η dependent event plane fluctuations

Back-ups

How is EP plane method affected by η-dependent EP angle

$$v_2 = \frac{\left\langle \cos 2(\phi - \Psi_2^A) \right\rangle}{R_A}$$

Resolution correction

$$R_A = \sqrt{\frac{\langle \cos(2(\Psi_2^A - \Psi_2^B)) \rangle \langle \cos(2(\Psi_2^A - \Psi_2^C)) \rangle}{\langle \cos(2(\Psi_2^B - \Psi_2^C)) \rangle}}$$

If there is η-dependent EP angle:

$$R_A = R_A^{res} \sqrt{\frac{\left\langle \cos(2(\Psi_2^+ - \Psi_2^-)) \right\rangle \left\langle \cos(2(\Psi_2^+ - \Psi_2^0)) \right\rangle}{\left\langle \cos(2(\Psi_2^- - \Psi_2^0)) \right\rangle}}$$

$$= R_A^{res} \sqrt{\left\langle \cos(2(\Psi_2^+ - \Psi_2^-)) \right\rangle}$$

$$\approx R_A^{res} \left\langle \cos(2(\Psi_2^+ - \Psi_2^0)) \right\rangle$$

How is EP plane method affected by η-dependent EP angle

$$v_2 = \frac{\left\langle \cos 2(\phi - \Psi_2^A) \right\rangle}{R_A}$$

$$\approx \frac{\left\langle \cos 2(\phi - \Psi_2^A) \right\rangle}{R_A^{res}} \frac{1}{\left\langle \cos(2(\Psi_2^+ - \Psi_2^0)) \right\rangle}$$

$$= \left\langle \cos 2(\phi - \Psi_2^+) \right\rangle \frac{1}{\left\langle \cos(2(\Psi_2^+ - \Psi_2^0)) \right\rangle}$$

$$= \left\langle \cos 2(\phi - \Psi_2^0) \right\rangle$$