Parallel session: Collective Dynamics II

Studies on longitudinal fluctuations of anisotropic flow event planes in Pb-Pb and p-Pb collisions at CMS

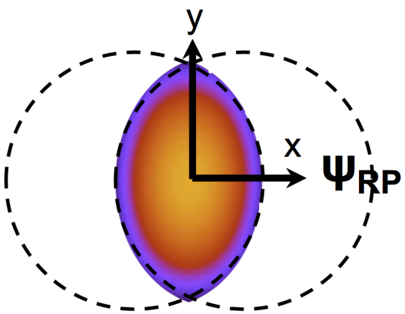
Maxime Guilbaud

Bonner Laboratory, RICE University, Houston TX

On behalf of CMS collaboration

QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions



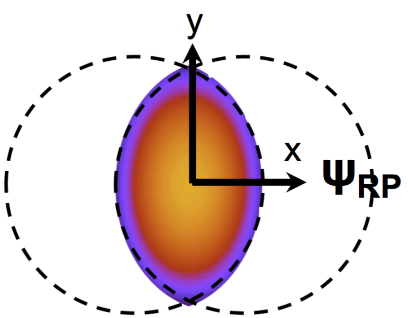
Initial-state anisotropy

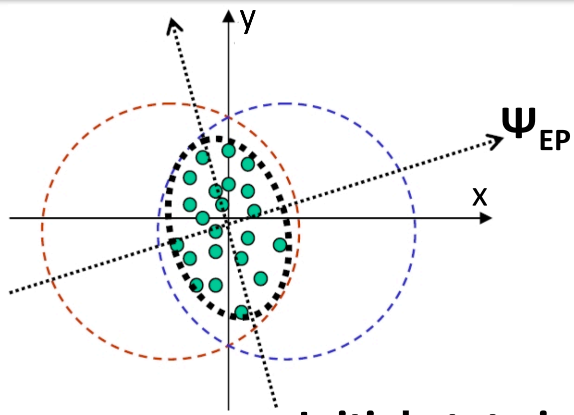
Final state:

$$f(p_T, \phi, \eta) \sim 1 \quad +2v_2(p_T, \eta)cos\left[2(\phi - \Psi_{RP})\right]$$

Elliptic flow

Initial-state: an evolving picture





Ψ_{EP}: Direction of maximum particle density

<u>Final state:</u>

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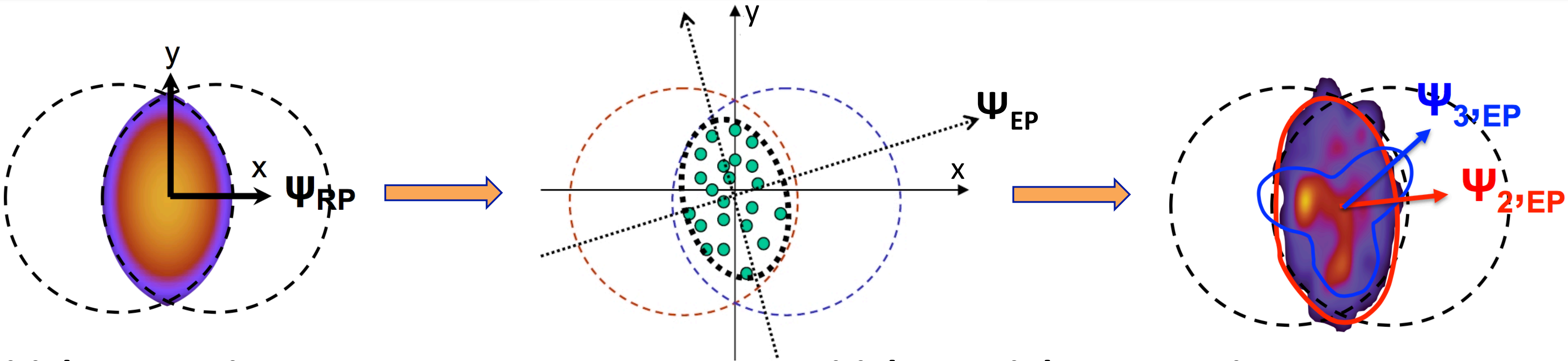


Initial-state anisotropy **Initial-state inhomogeneity**

Ψ_{EP}: Direction of maximum particle density

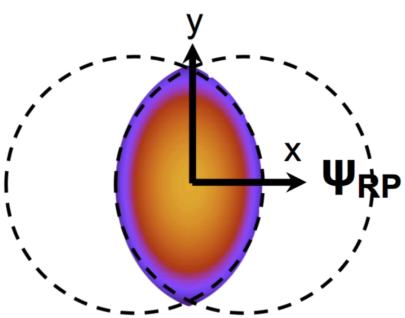
<u>Final state:</u>

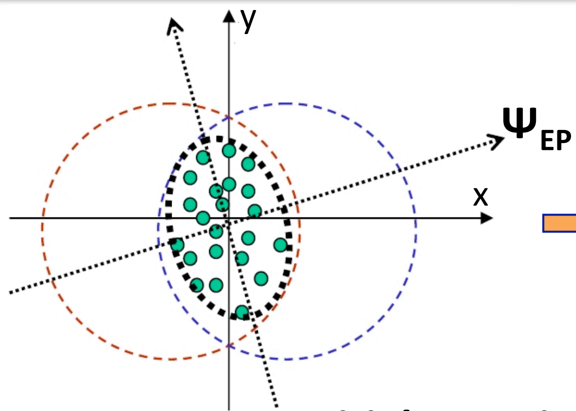
$$f(p_T,\phi,\eta) \sim 1 \quad +2v_2(p_T,\eta)cos\left[2(\phi-\Psi_2)\right]$$
$$+2v_3(p_T,\eta)cos\left[3(\phi-\Psi_3)\right]$$
$$+2v_4(p_T,\eta)cos\left[4(\phi-\Psi_4)\right]$$
$$+2v_5(p_T,\eta)cos\left[5(\phi-\Psi_5)\right]$$
$$+\ldots$$

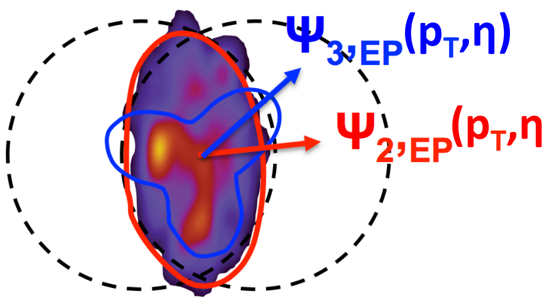
Elliptic flow

Triangular flow

Initial-state: an evolving picture







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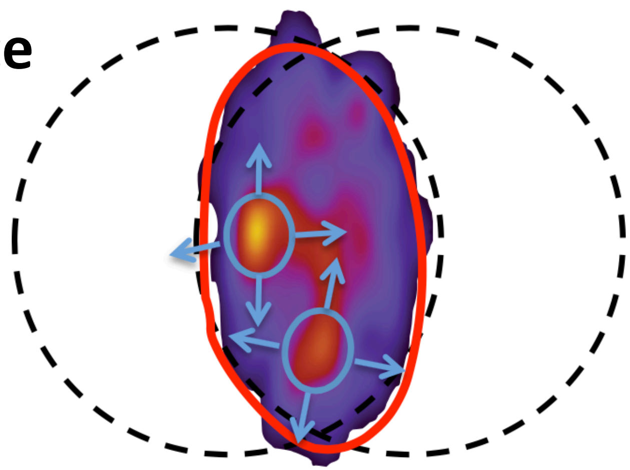
Elliptic flow

Triangular flow

Initial-state granularity

Closer look at initial-state and its fluctuations:



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<u>Final state:</u>

$$f(p_T, \phi, \eta) \sim 1 + 2\sum_n v_n(p_T, \eta) cos\left[2(\phi - \Psi_n(p_T, \eta))\right]$$

- Local hot spots: **decorrelation?**
- $\Psi_n(p_T, \eta)$: details about **3-D initial state fluctuations** (r, ϕ, η)

Flow factorization breaking in p_T

Most of flow measurement assume factorization:

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

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} = 1$$

Due to EP $\Psi_n(p_T)$ caused by lumpy initial state:

$$V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a) \times v_n(p_T^b)$$

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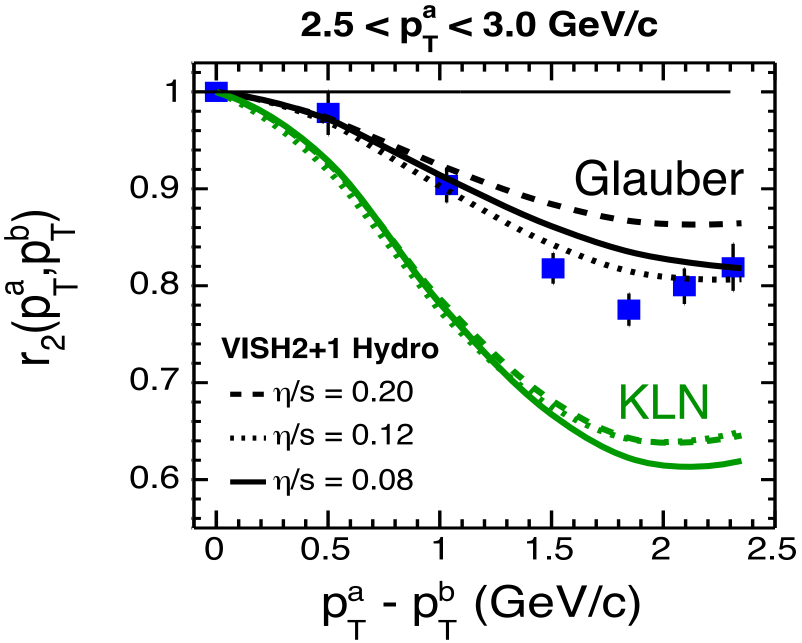
0-0.2% ultra-central PbPb



arXiv:1503.01692

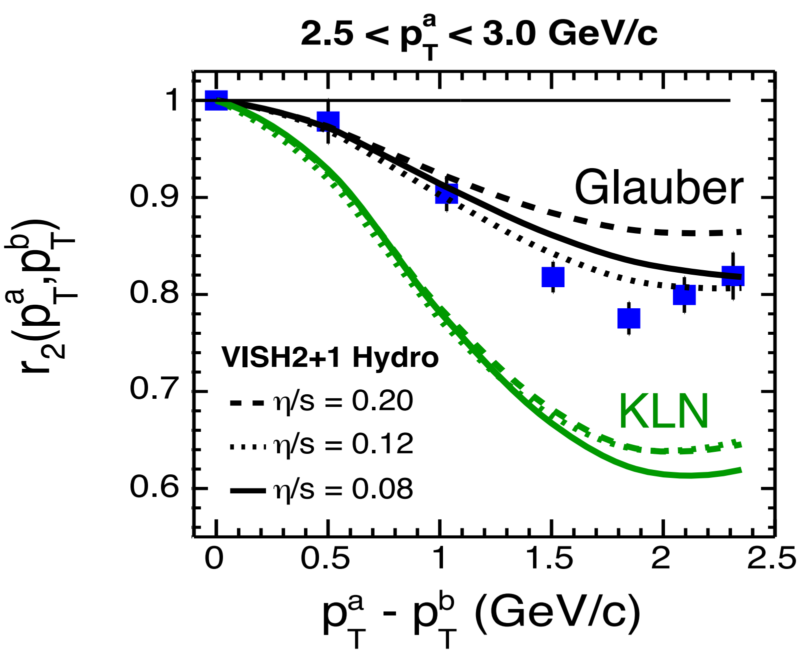
Flow factorization breaking in p_T

Due to EP $\Psi_n(p_T)$ caused by lumpy initial state:

Does not depend much on η/s

access to initial state effect only

0-0.2% ultra-central PbPb



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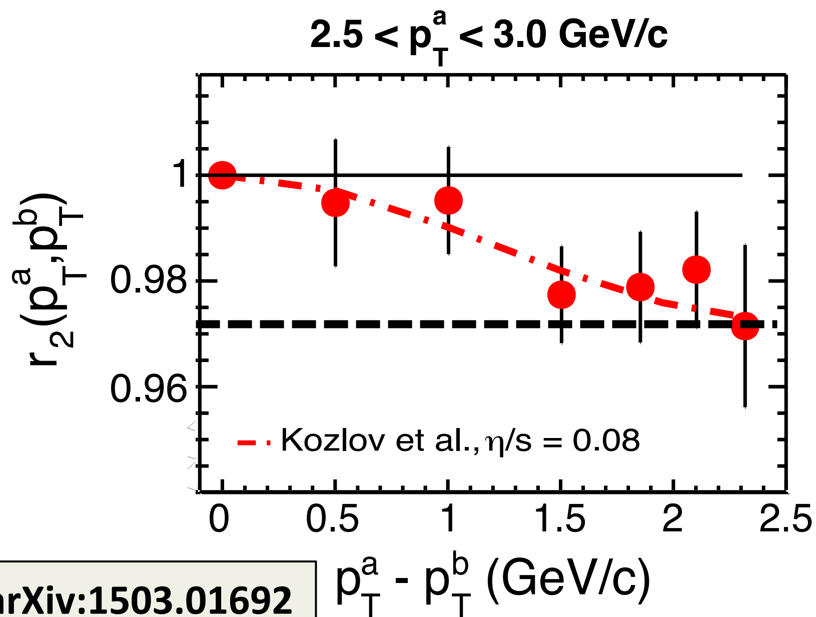
pPb, $220<N_{trk}<260$



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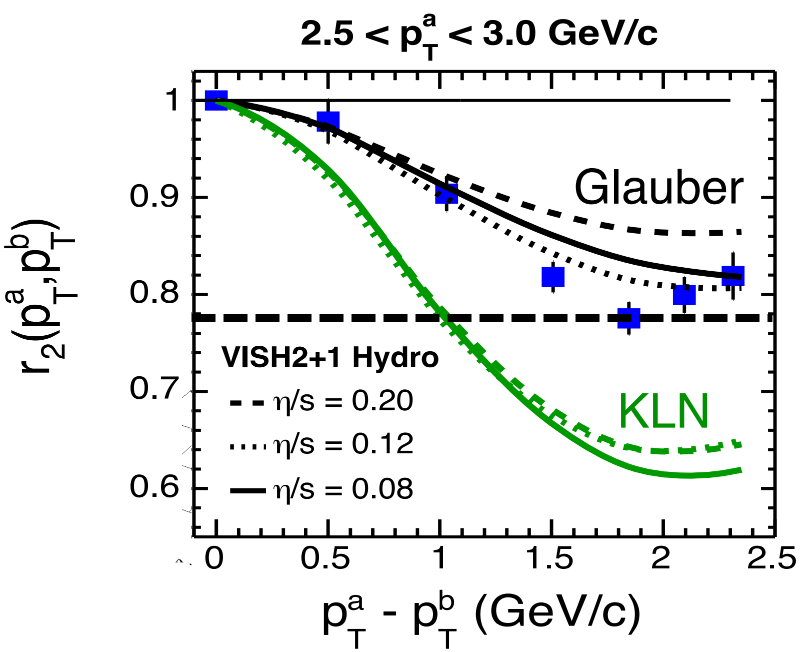

Flow factorization breaking in p_T

Due to EP $\Psi_n(p_T)$ caused by lumpy initial state:

Bigger effect in Pb-Pb (20% at maximum)
than in p-Pb (3% at maximum)

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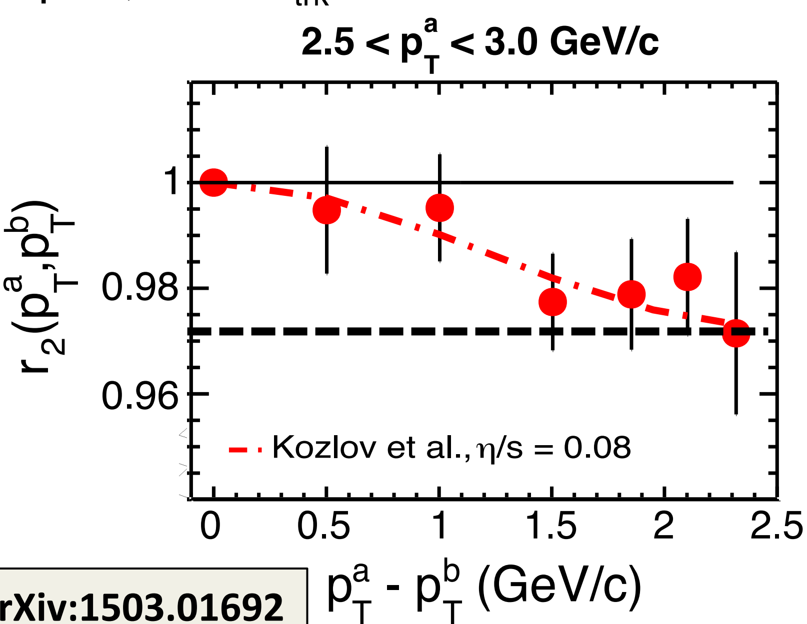

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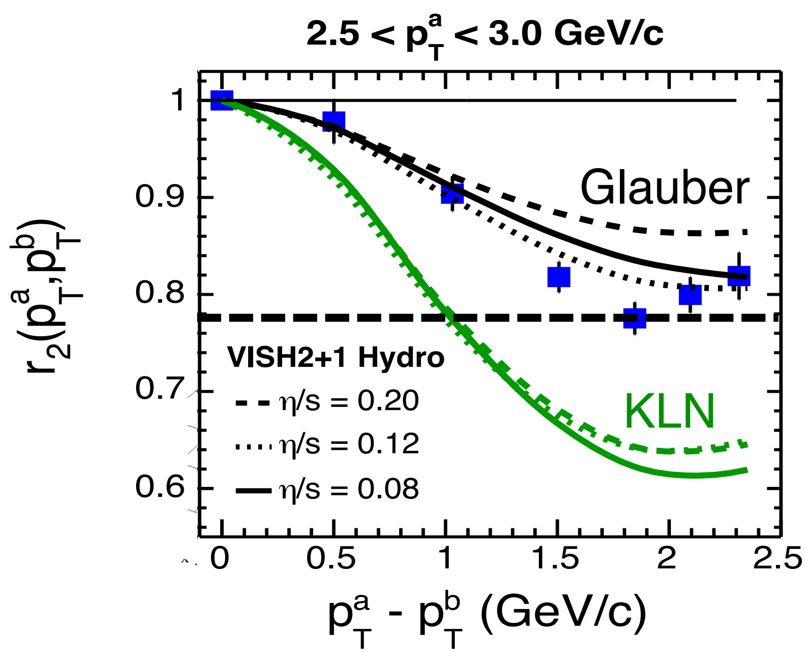

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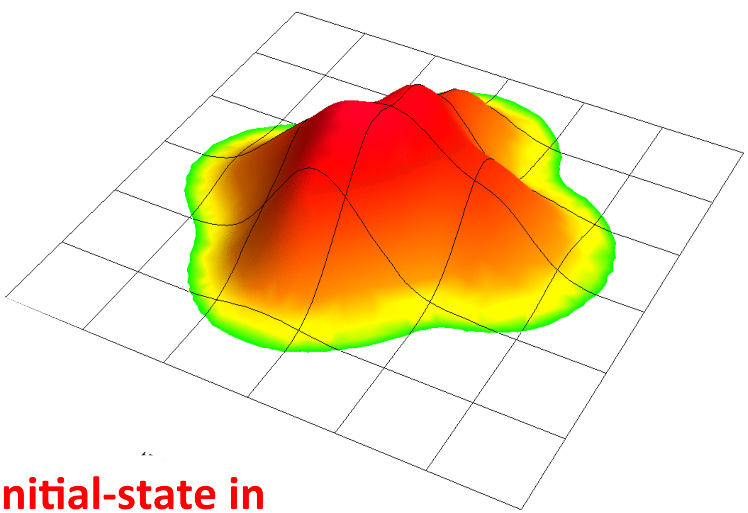
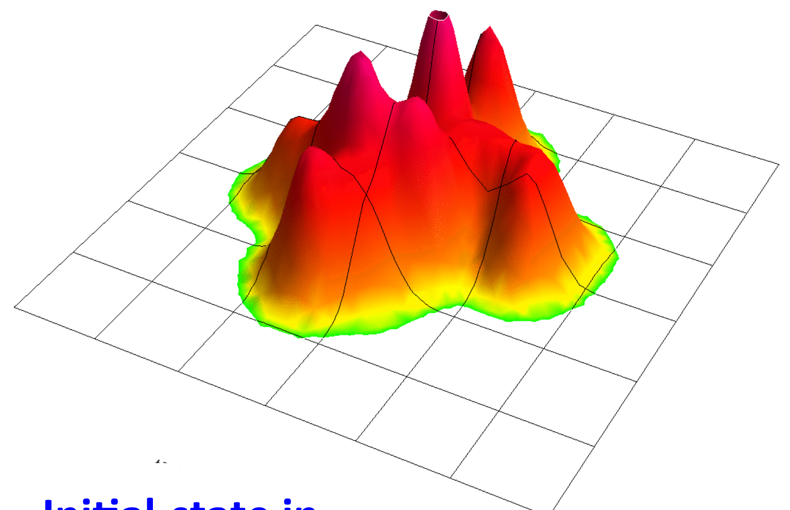


Initial-state in p-Pb is smoother

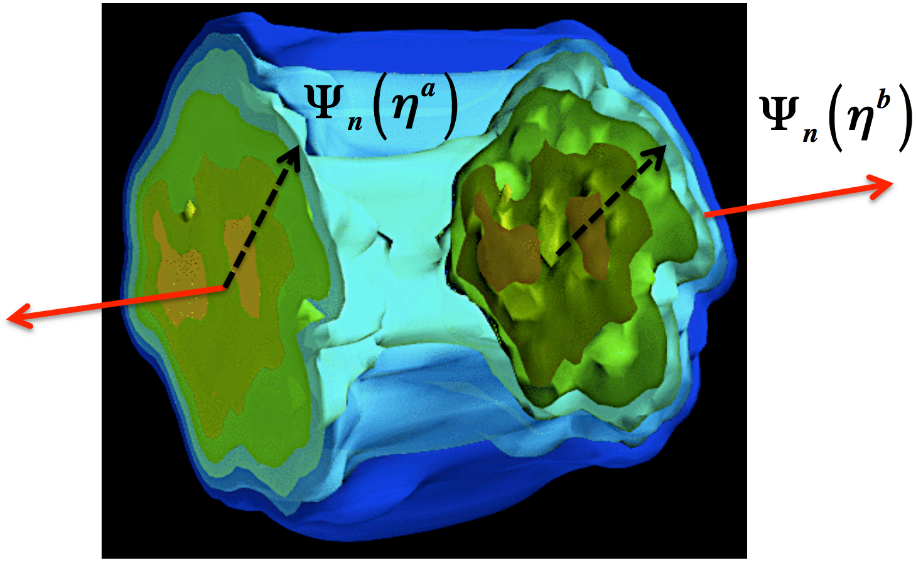
0-0.2% ultra-central PbPb



Initial-state in Pb-Pb is lumpier

Longitudinal expansion

Why looking at longitudinal dynamics?



$$f(p_T, \phi, \eta) \sim 1 + 2\sum_n v_n(p_T, \eta) cos\left[2(\phi - \Psi_n(p_T, \eta))\right]$$

- Access the **full granularity of initial-state fluctuations** and dynamics of the system: **3D picture**

Longitudinal expansion

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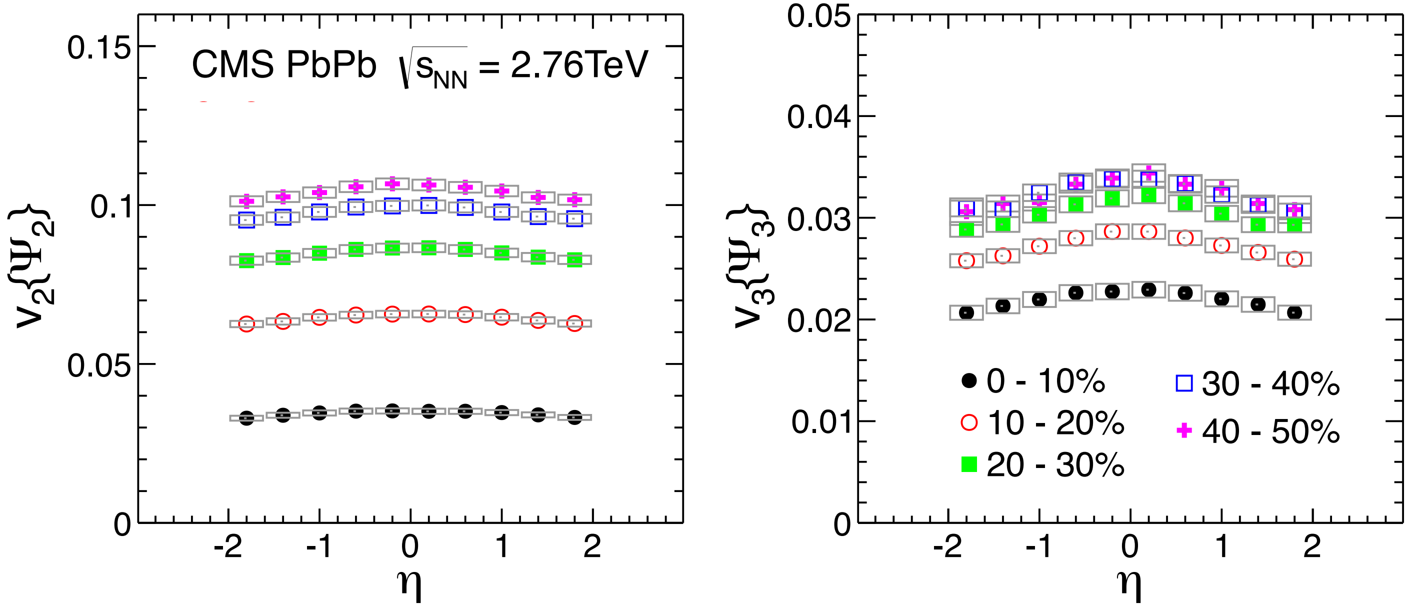

- v_n with respect to Ψ_n depends on η

Longitudinal expansion

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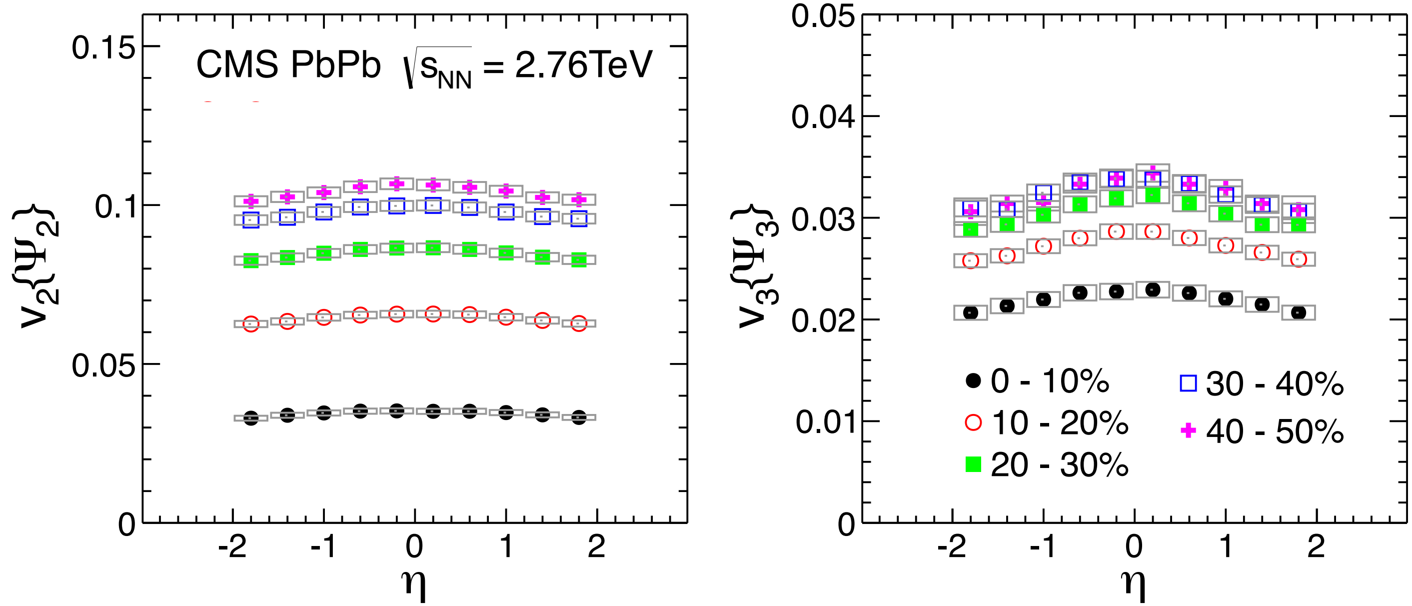

- v_n with respect to Ψ_n depends on η

In mid-peripheral events: **≈5%** effect on v_2 and **≈10%** on v_3

Longitudinal expansion

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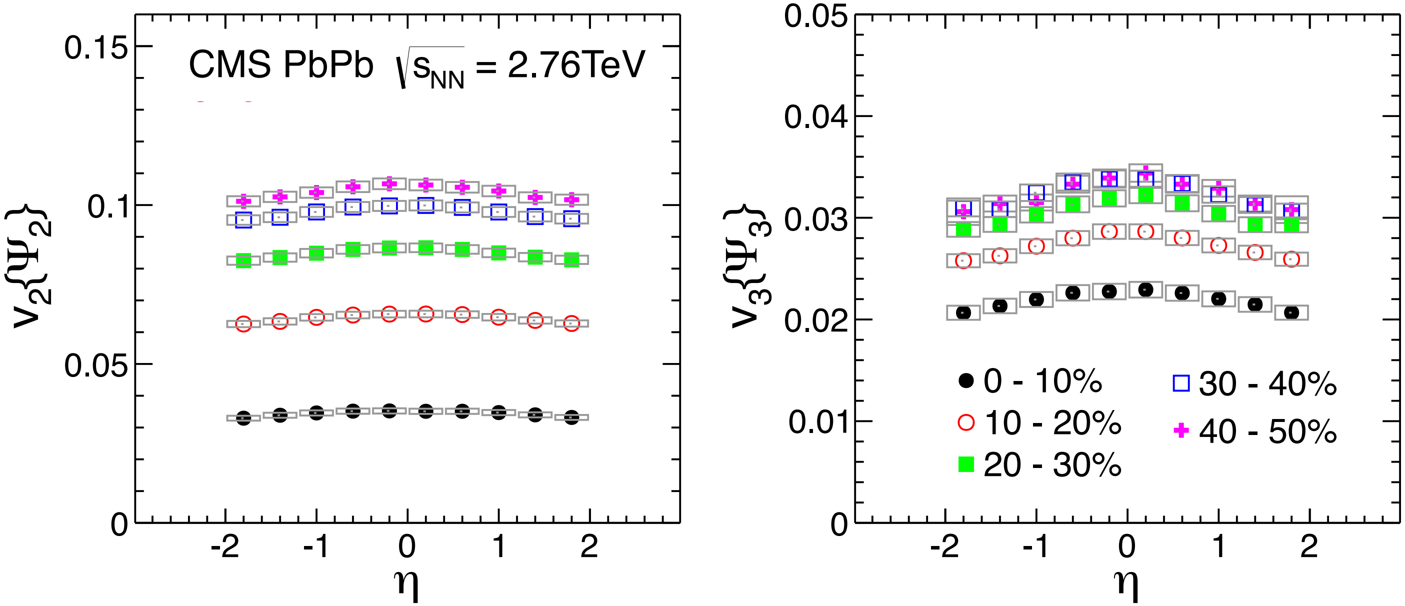
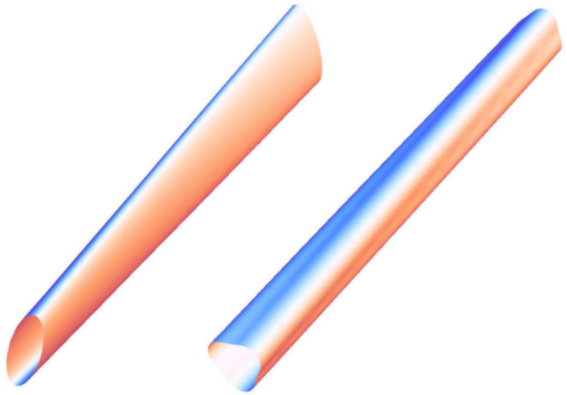


- v_n with respect to Ψ_n depends on η
- Where the η dependence come from?
  - **v_n magnitude**: energy density, η/s, …
  - **Ψ_n orientation**: geometry, initial state, …

Longitudinal expansion

How does $\Psi_n(\eta)$ fluctuate?

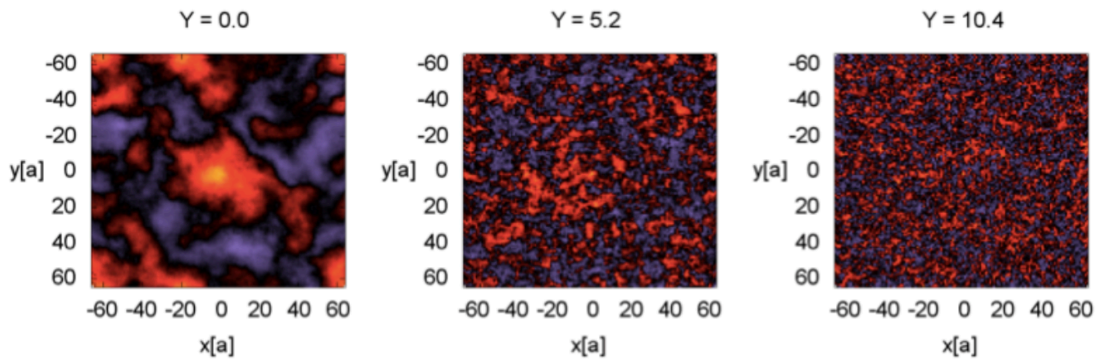
Torqued fireball



Bozek et.al., arXiv:1011.3354

Correlation length of gluon field

JIMWLK



Dumitru et. al., arXiv:1108.4764

- Global twist
- Rapidity dependent granularity of gluon field fluctuations

Longitudinal expansion

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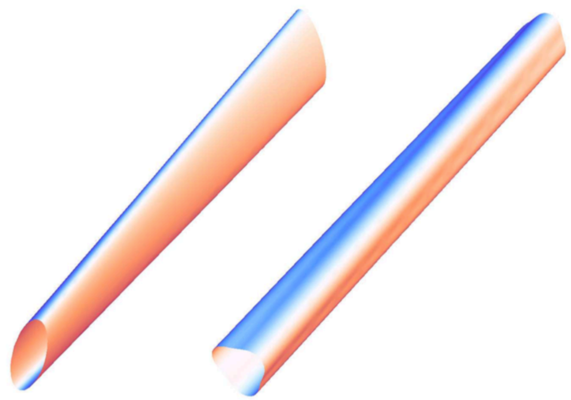

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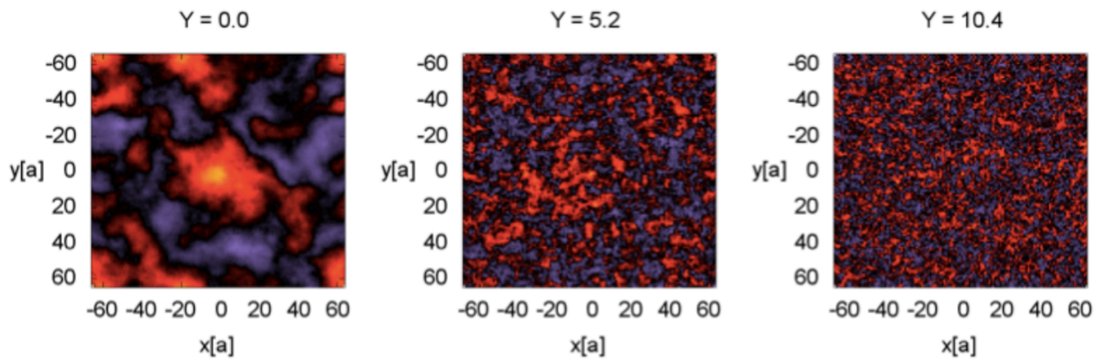

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- Global twist
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How to probe $\Psi_n(\eta)$ fluctuations experimentally?

Flow factorization breaking in η

Is it possible to use the same method as for the p_T study?

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

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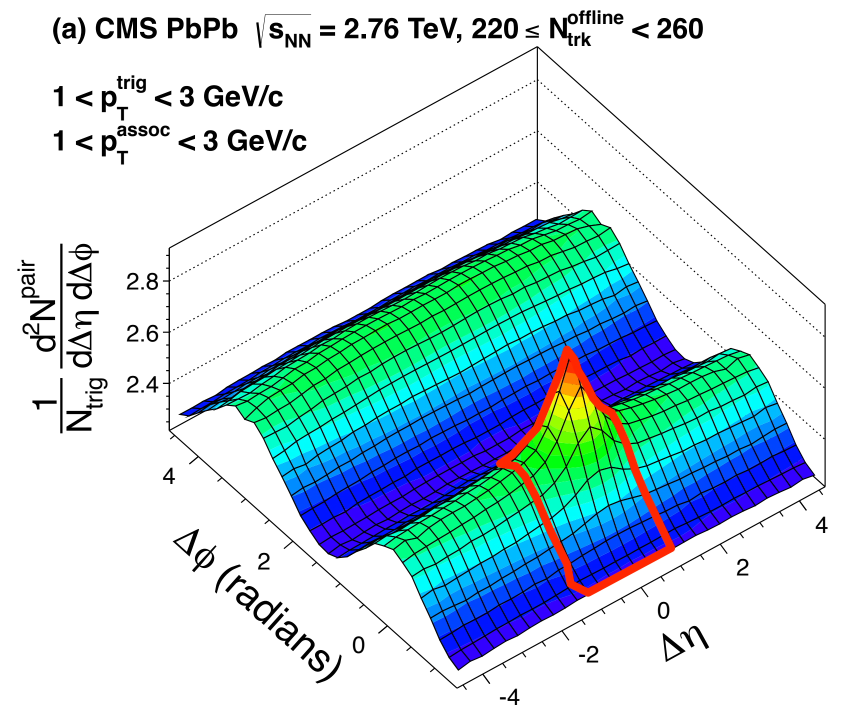
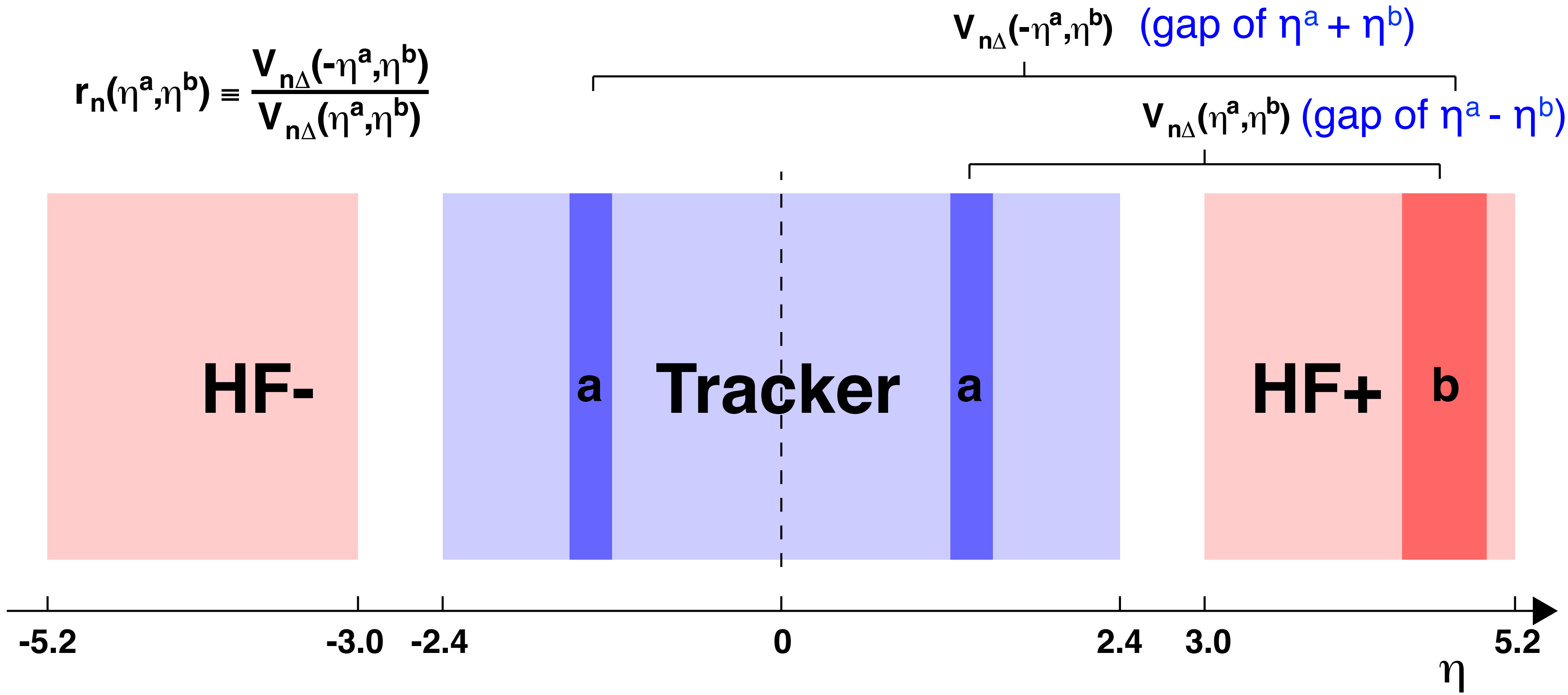
- At small Δη (Δη ≈ 0) significant non-flow from **jet contribution**
- **Need to include a large η gap for all pairs**



Ensure an η gap of at least 2 units

$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$



Analysis method

Ensure an η gap of at least 2 units

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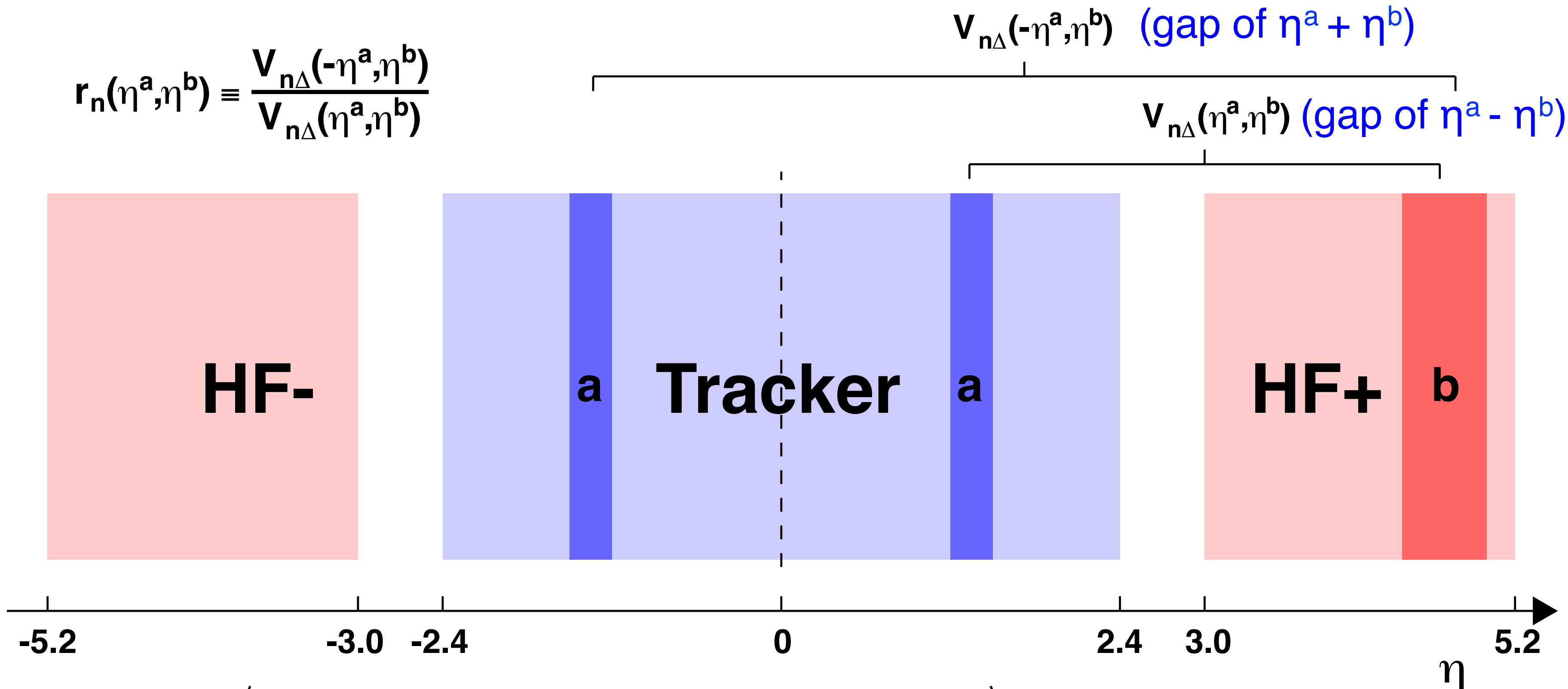

$$r_n(\eta^a,\eta^b) = \frac{\left\langle v_n(-\eta^a)v_n(\eta^b)\cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\right\rangle}{\left\langle v_n(\eta^a)v_n(\eta^b)\cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\right\rangle} \sim \left\langle \cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\right\rangle$$

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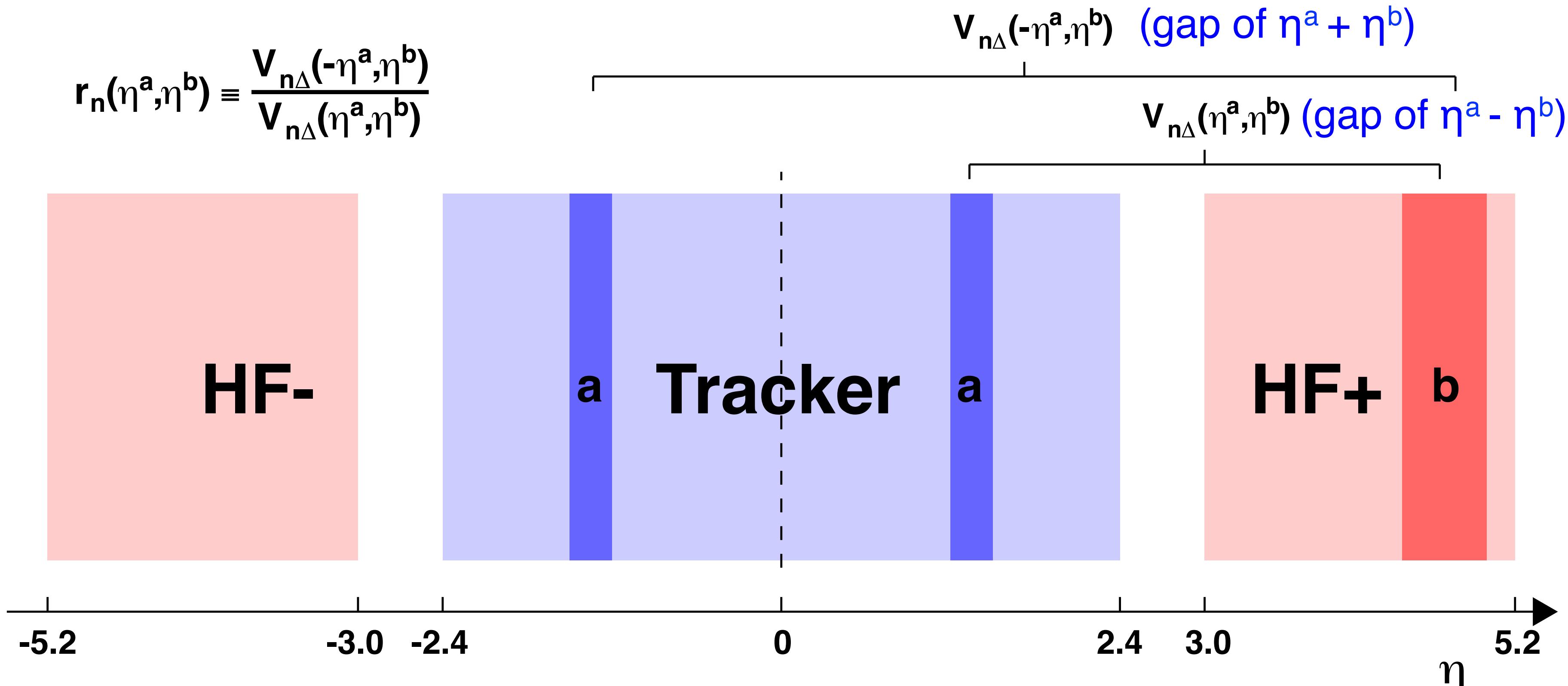

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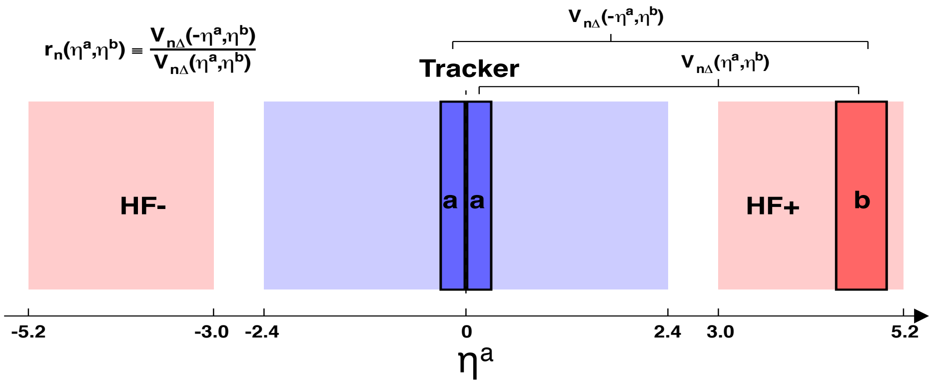
Pb-Pb results

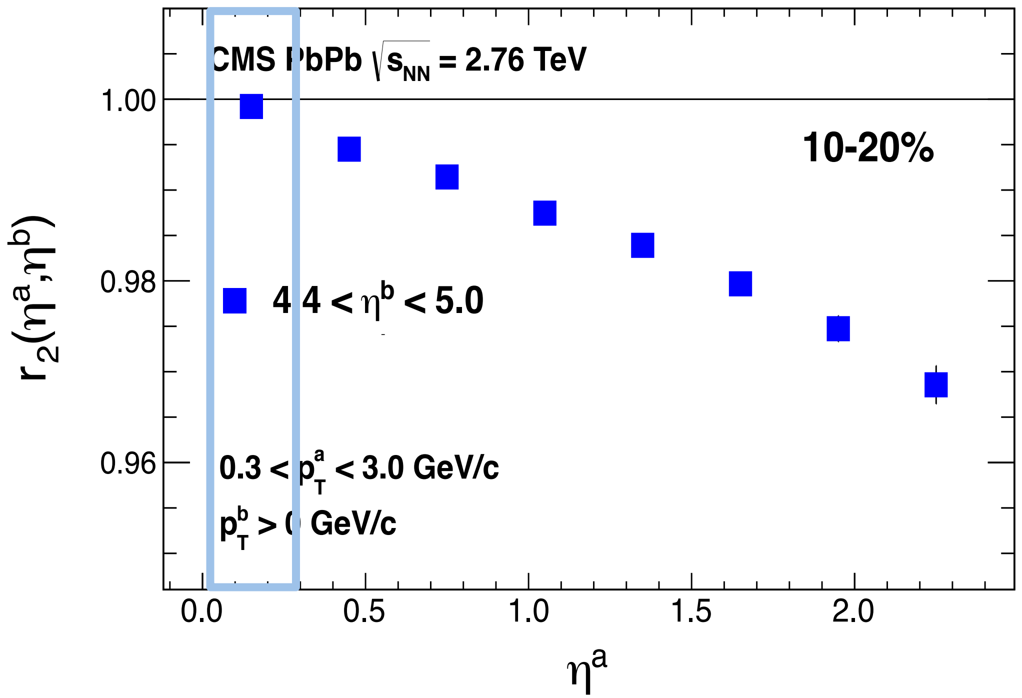


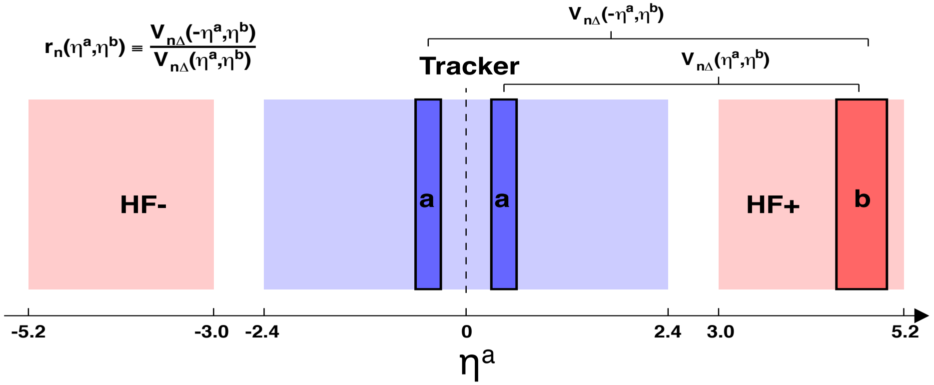
$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle$$

$\Delta\eta = 2\eta^a$

<u>η gap ≥ 2 units:</u>

- De-correlation of Ψ_2 increases as Δη increases





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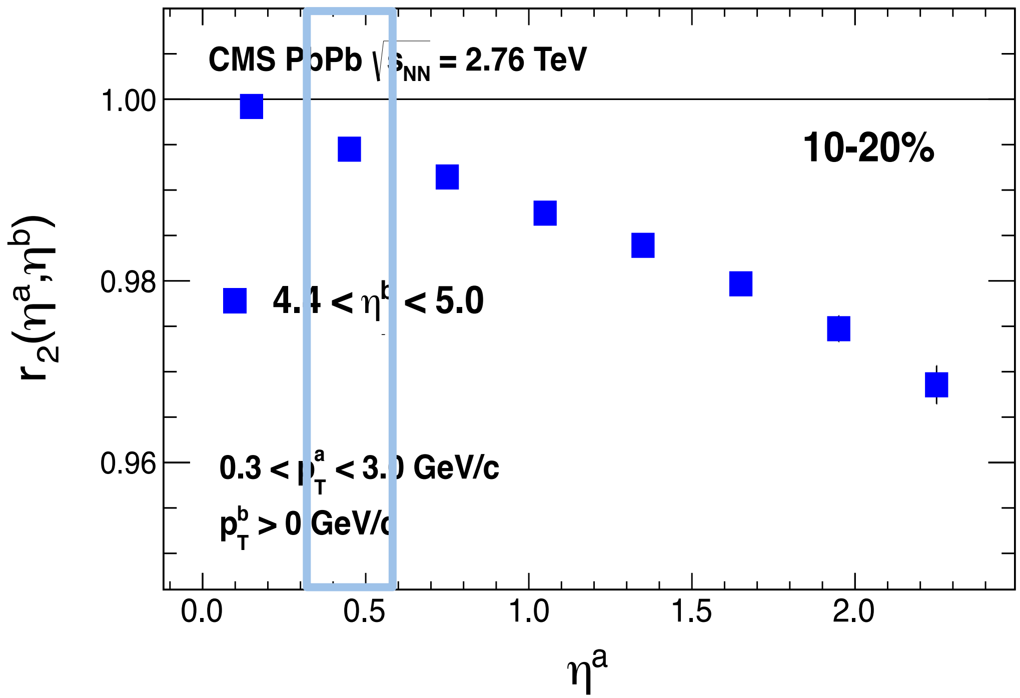

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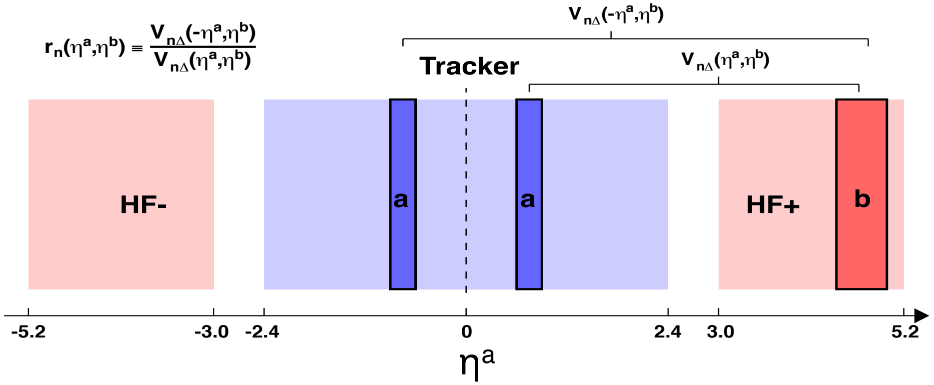

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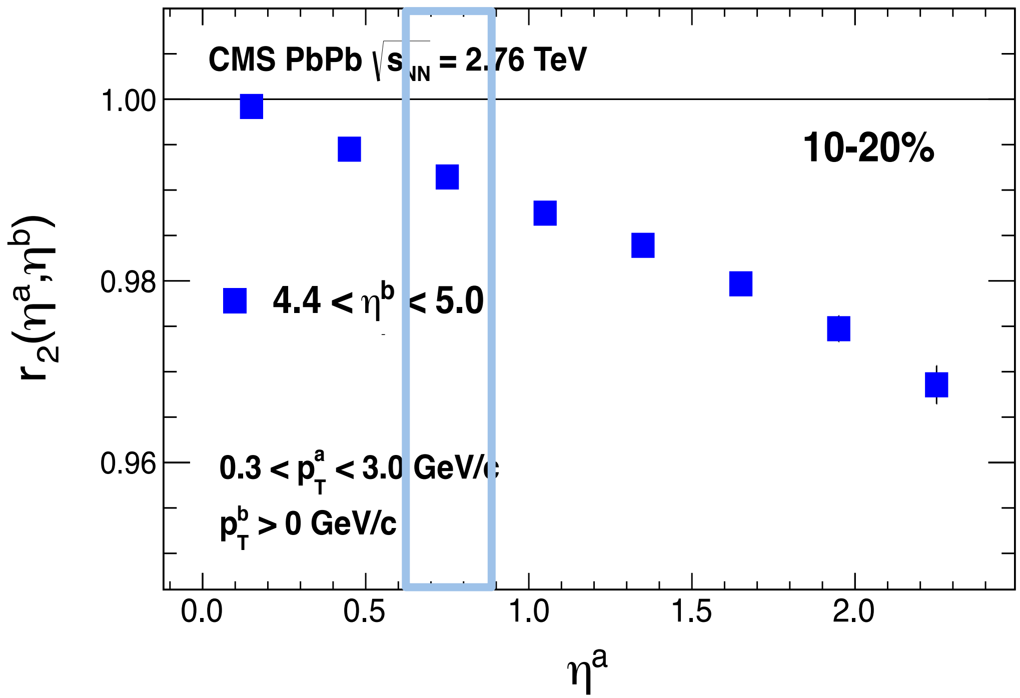

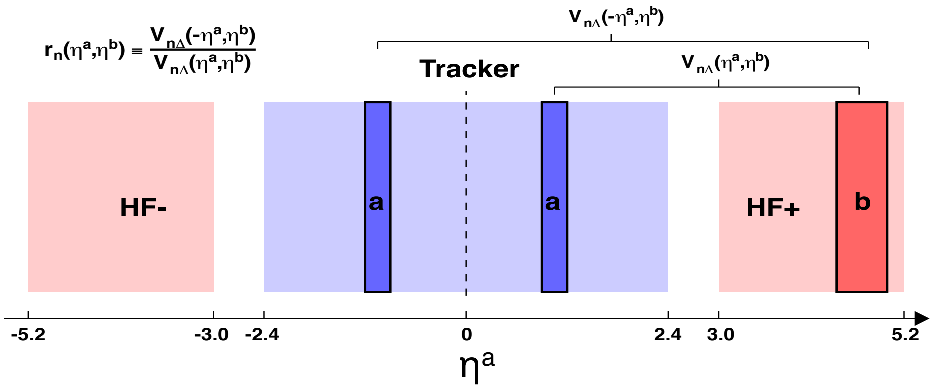

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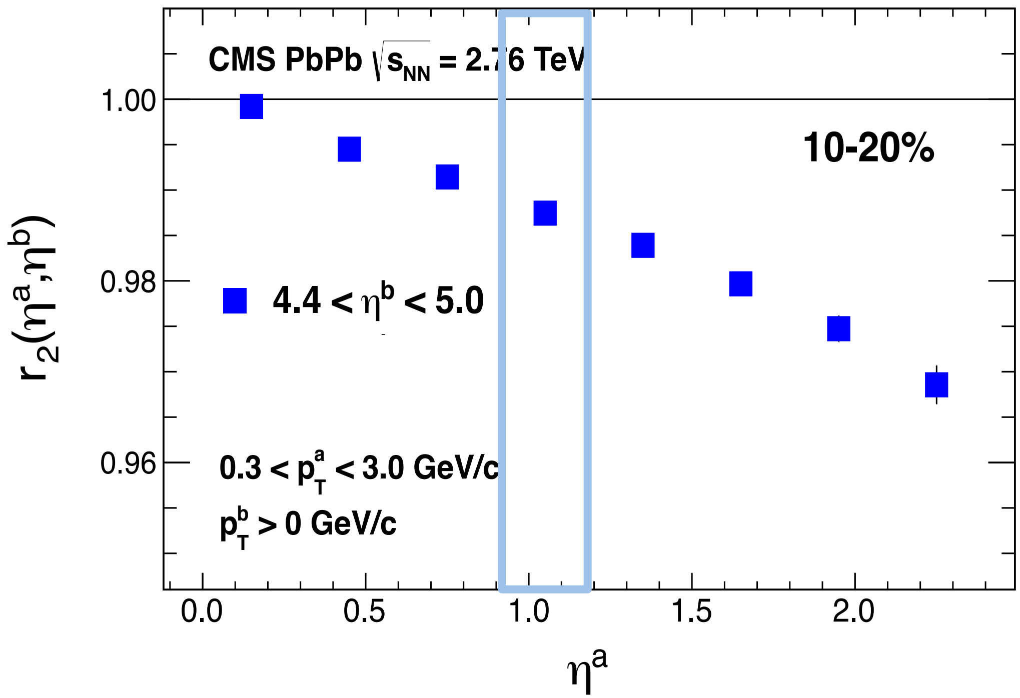

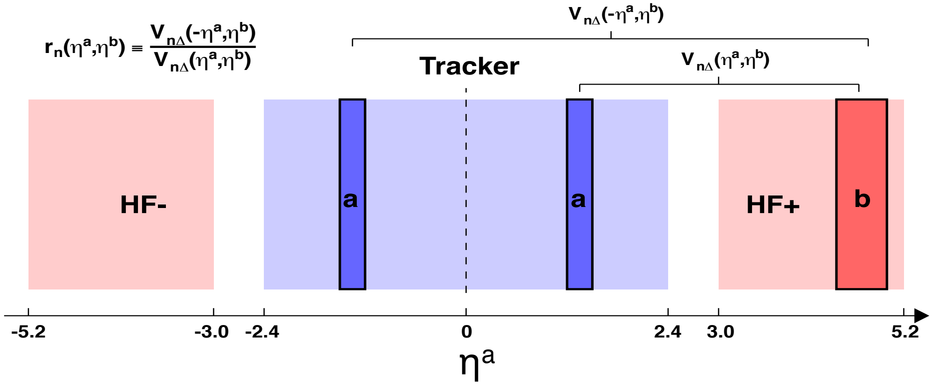

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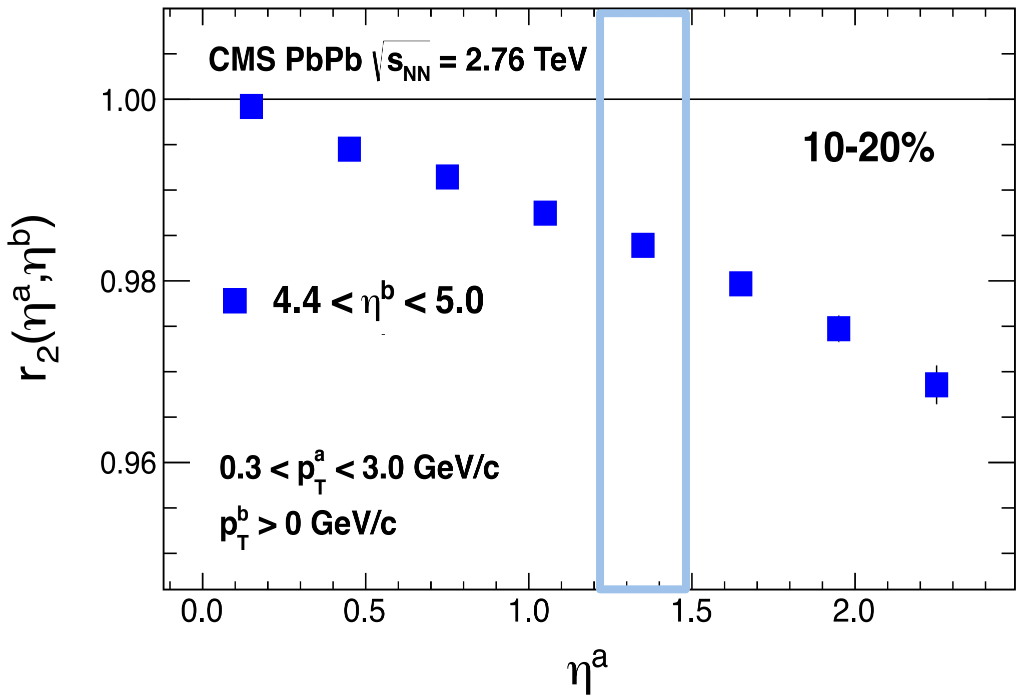

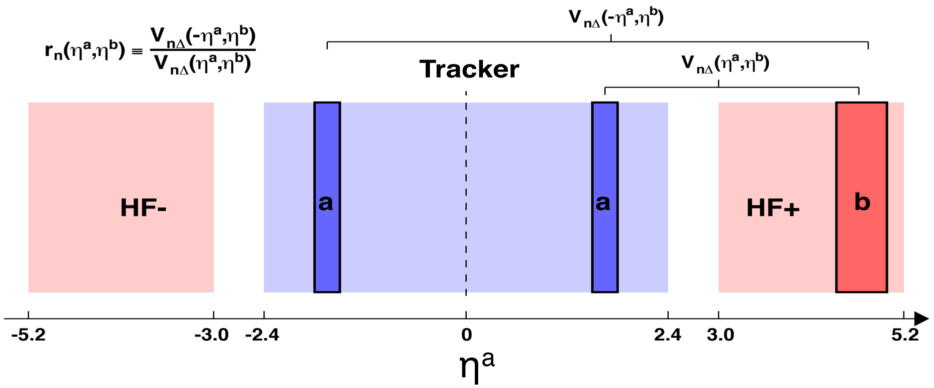

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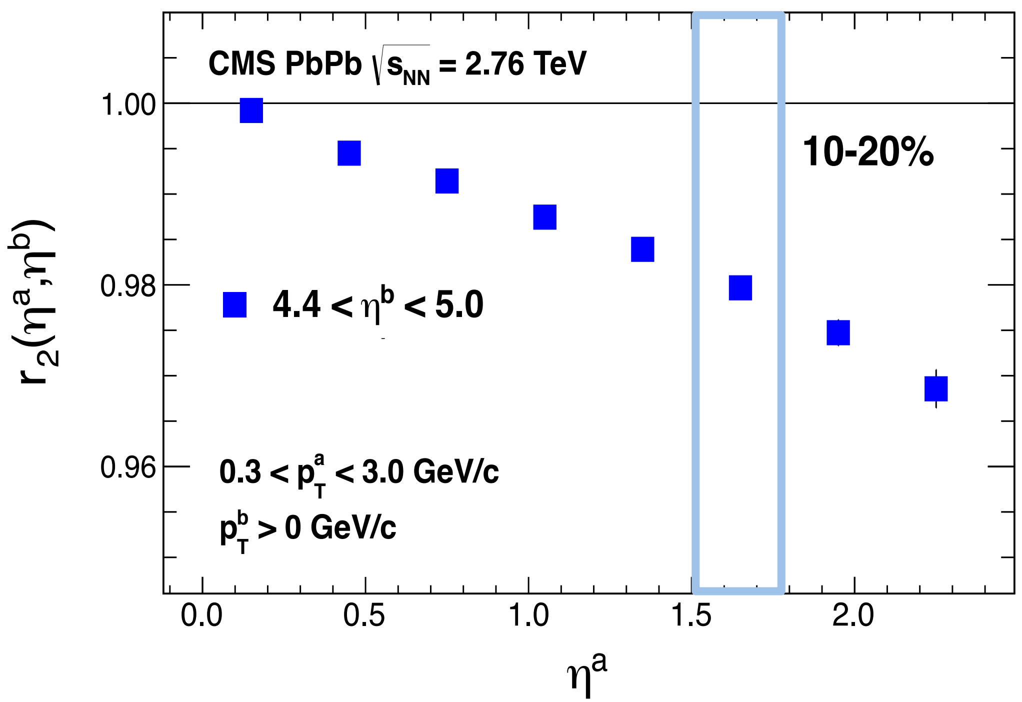

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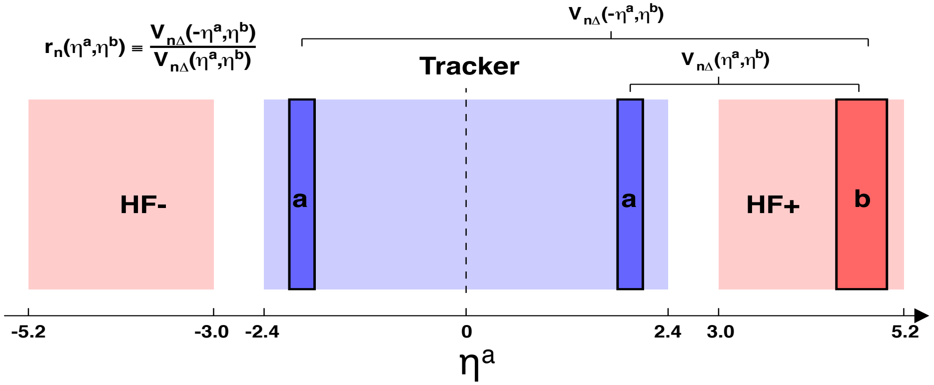

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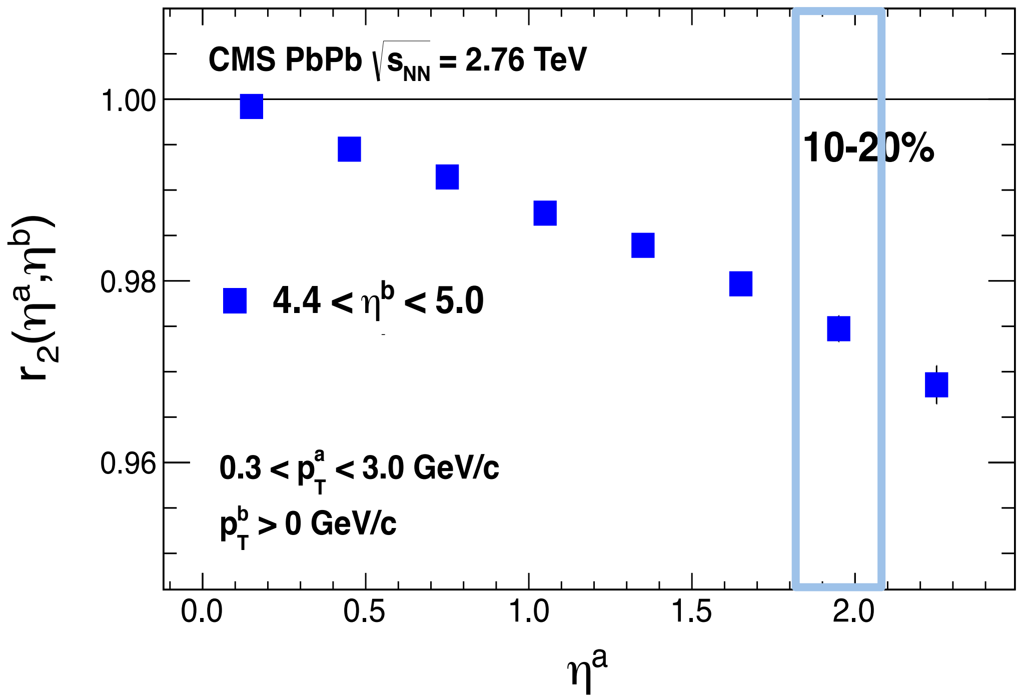

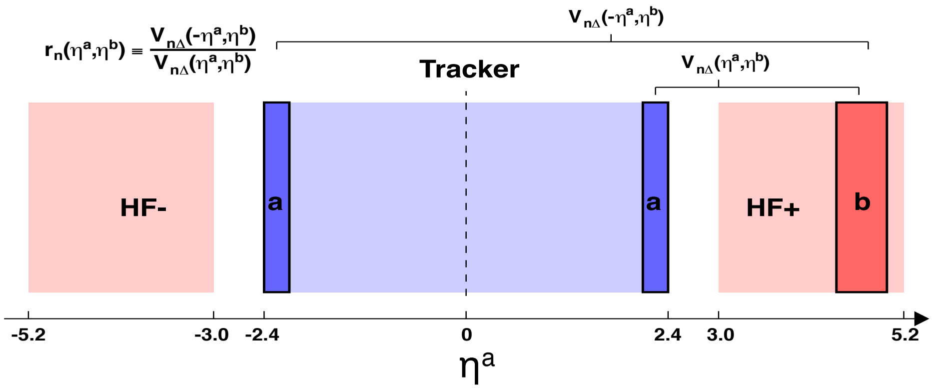

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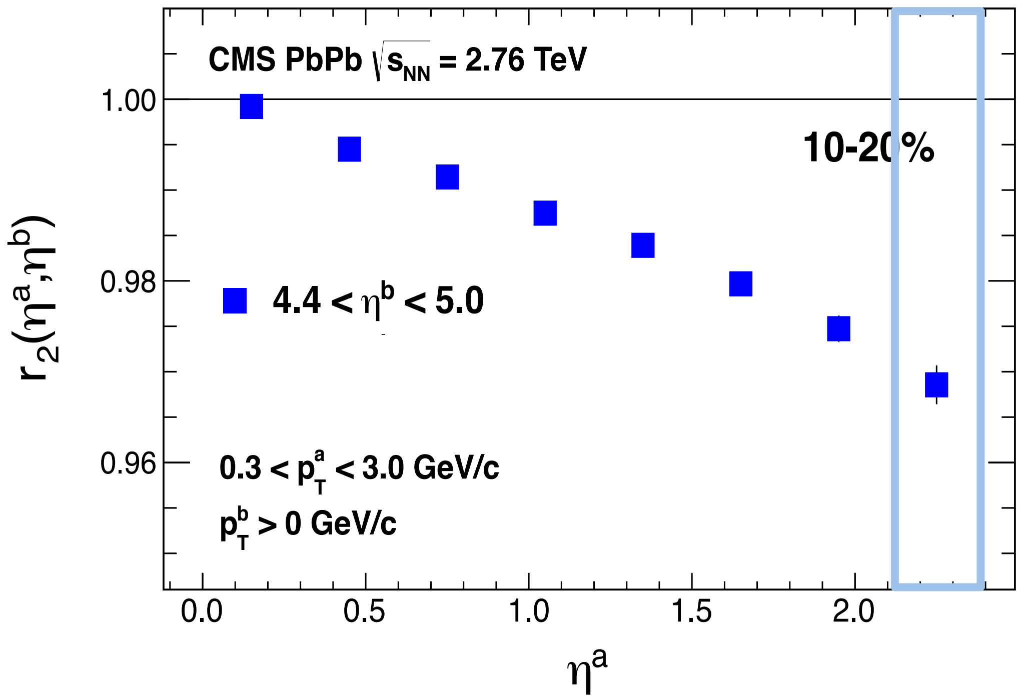
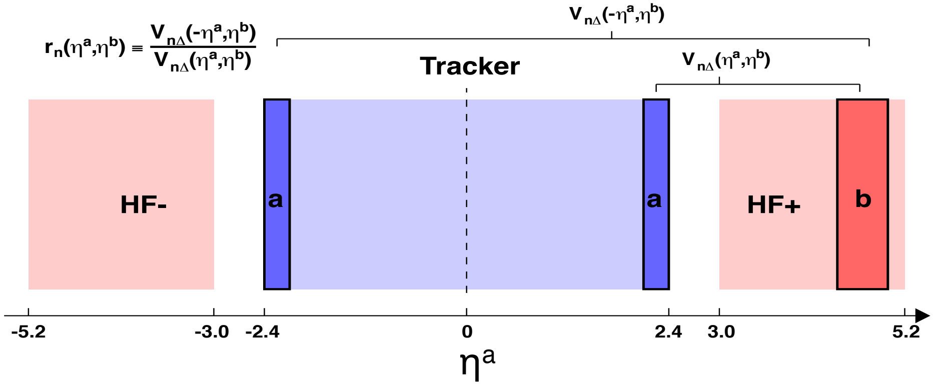


Pb-Pb results

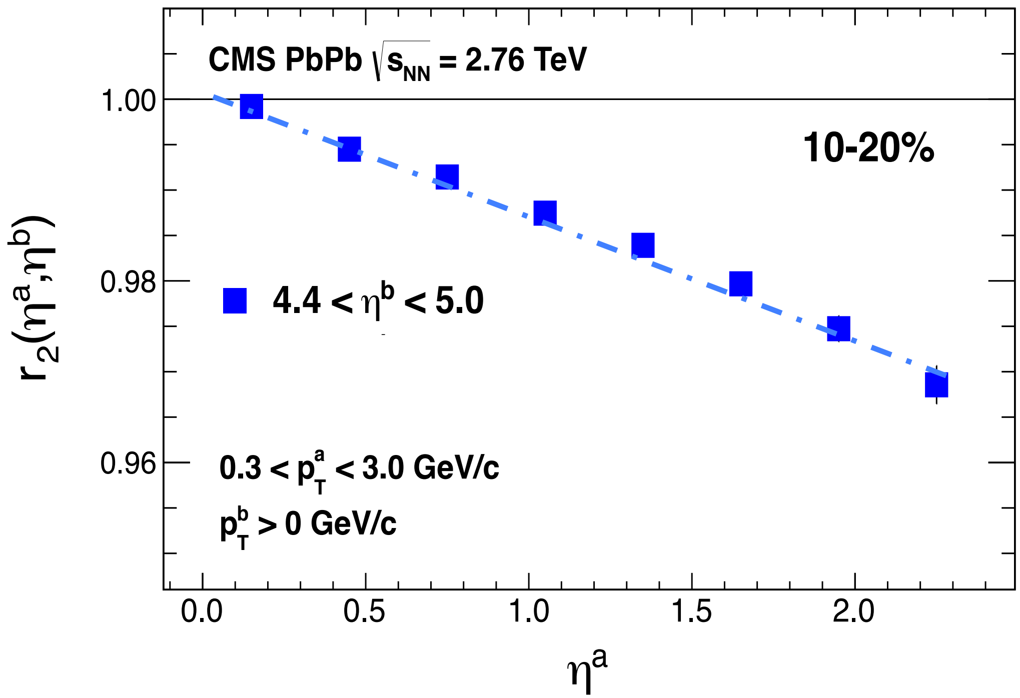


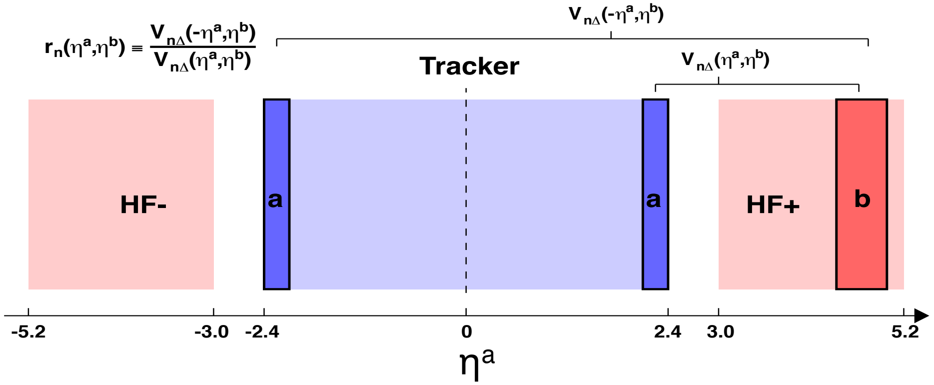
$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle$$

$\Delta\eta = 2\eta^a$

<u>**η gap ≥ 2 units:**</u>

- De-correlation of Ψ_2 increases as $\Delta\eta$ increases
- Mostly **linear**



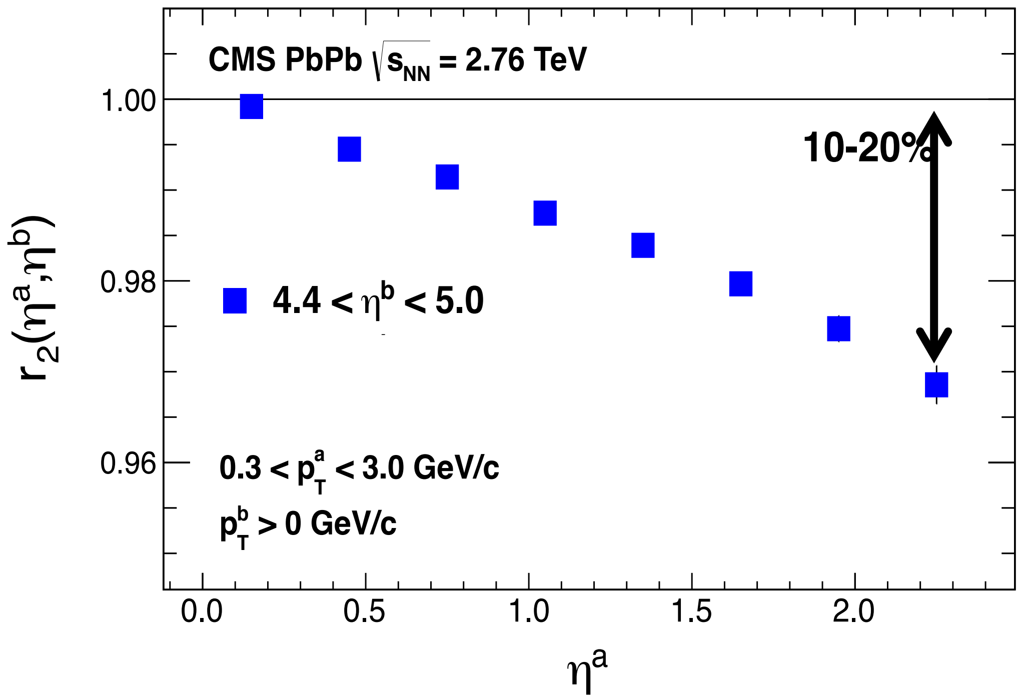


$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle$$

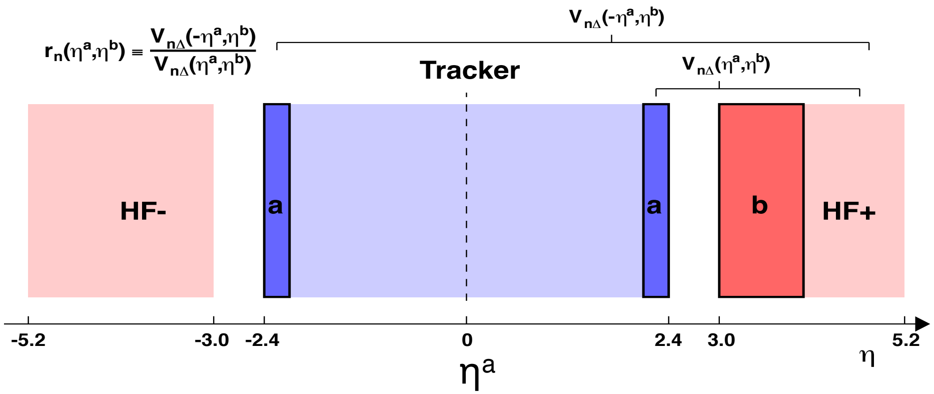
$$\Delta\eta = 2\eta^a$$

η gap ≥ 2 units:

- De-correlation of Ψ_2 increases as $\Delta\eta$ increases
- Mostly **linear**
- **3-4% effect**



Pb-Pb results

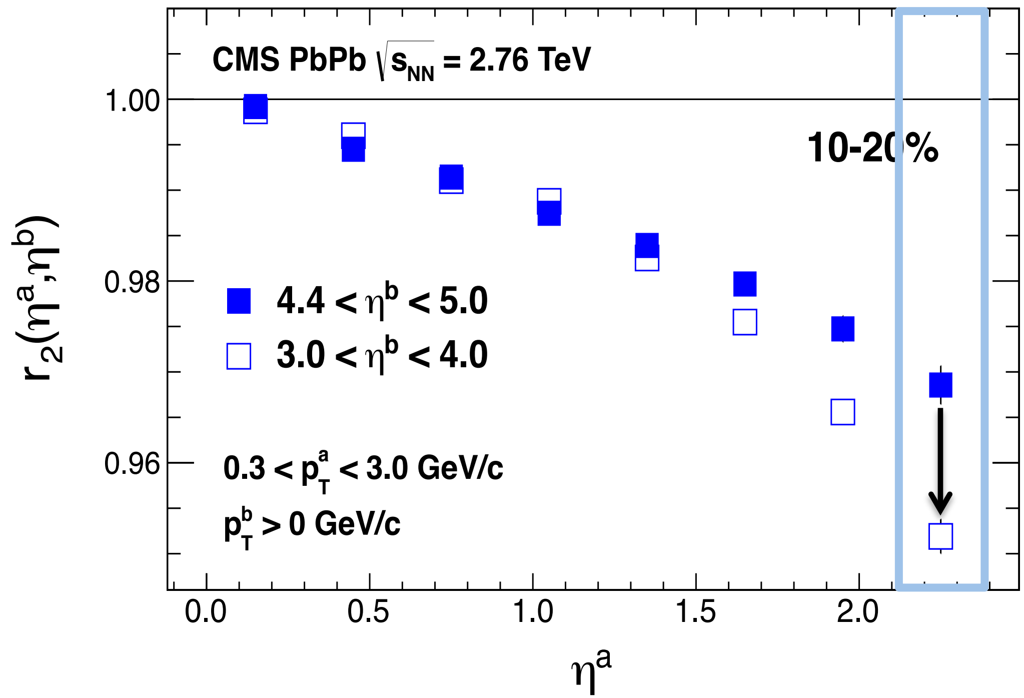


$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle$$

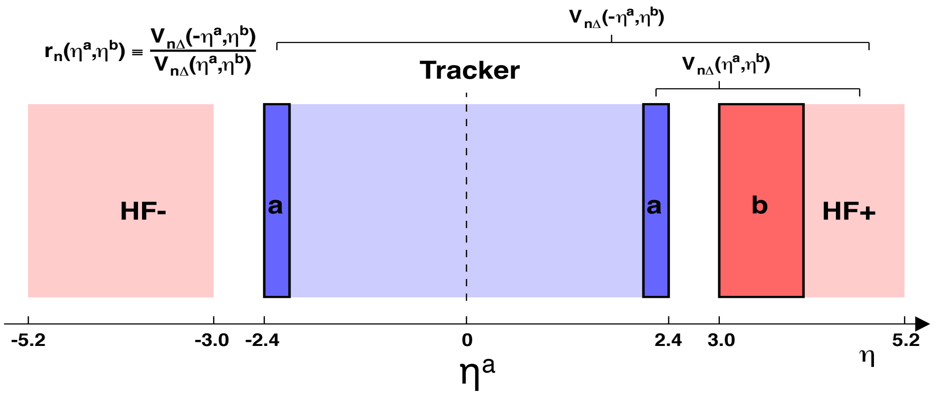
$$\Delta\eta = 2\eta^a$$

η gap < 2 units:

- r_2 decreases **faster for short-range**



Pb-Pb results



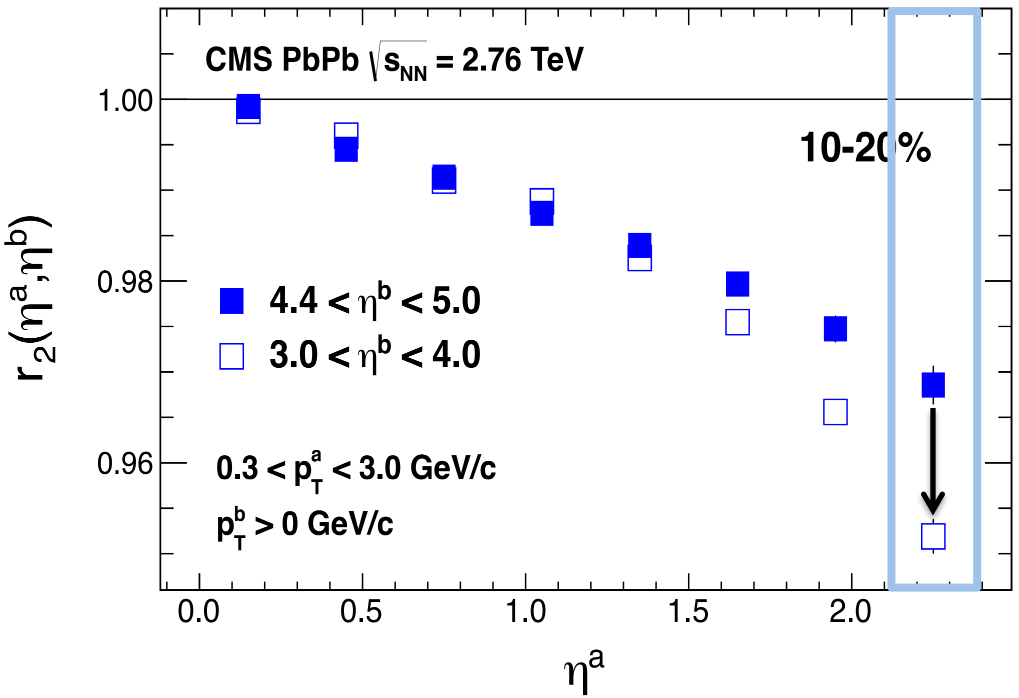
$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle$$

$$\Delta\eta = 2\eta^a$$

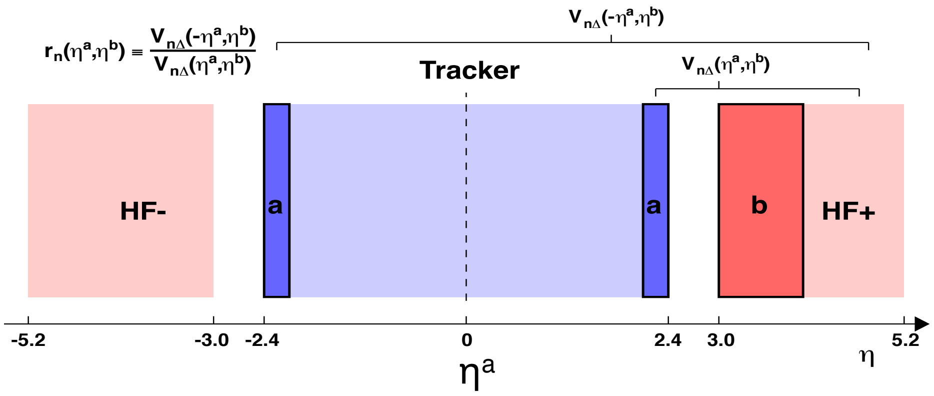
η gap < 2 units:

- r_2 decreases **faster for short-range**

$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$



Pb-Pb results



$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle$$

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η gap < 2 units:

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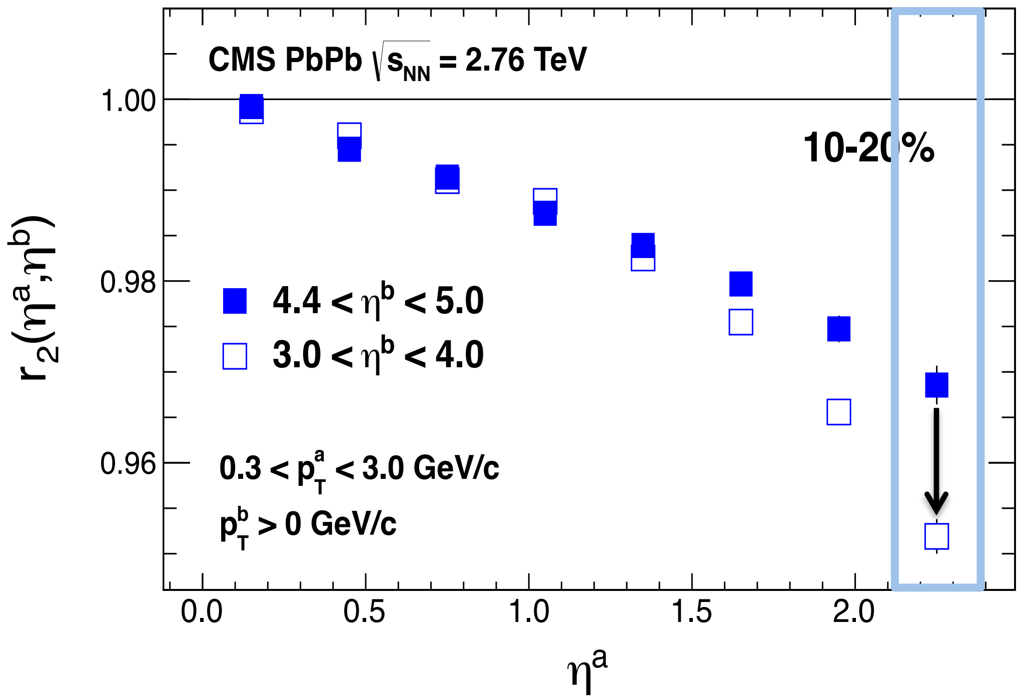
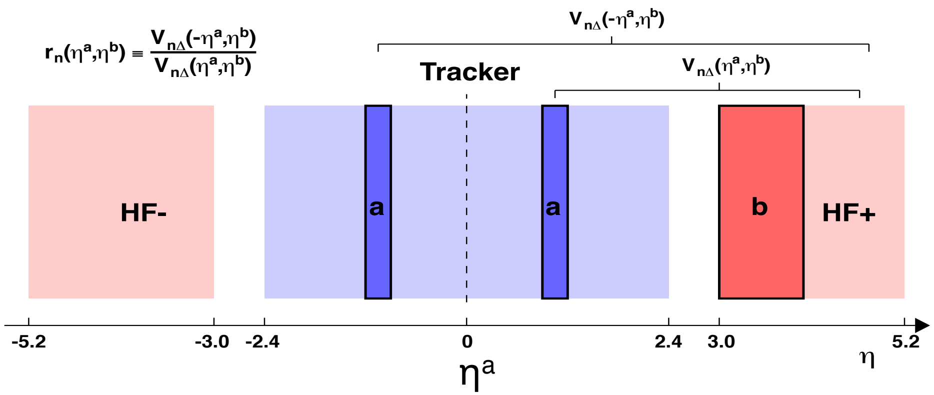


Pb-Pb results

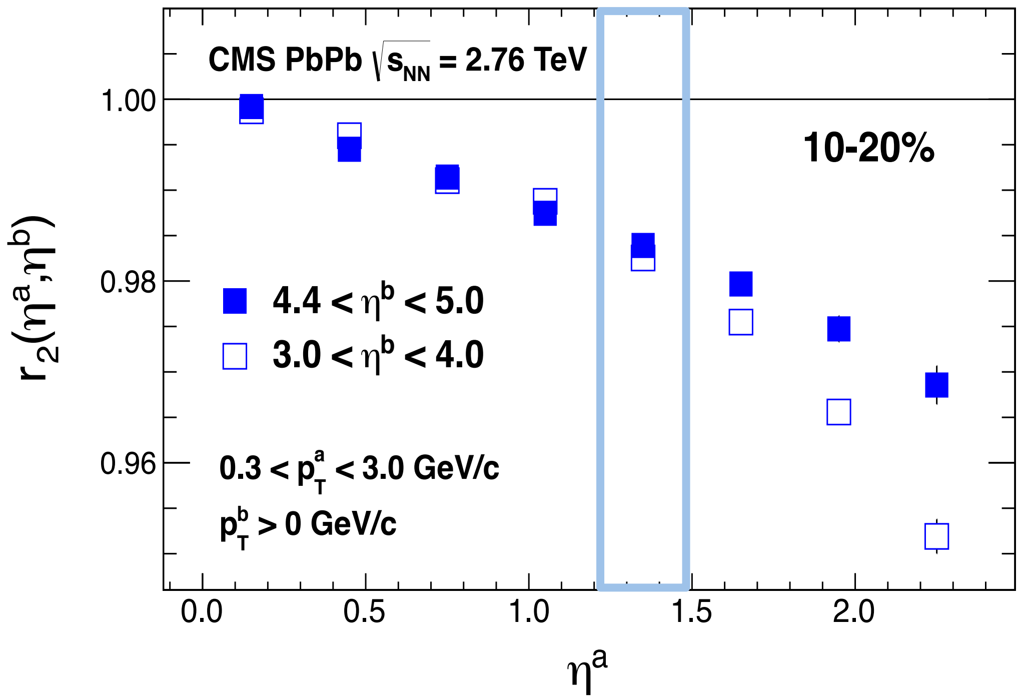


$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle$$

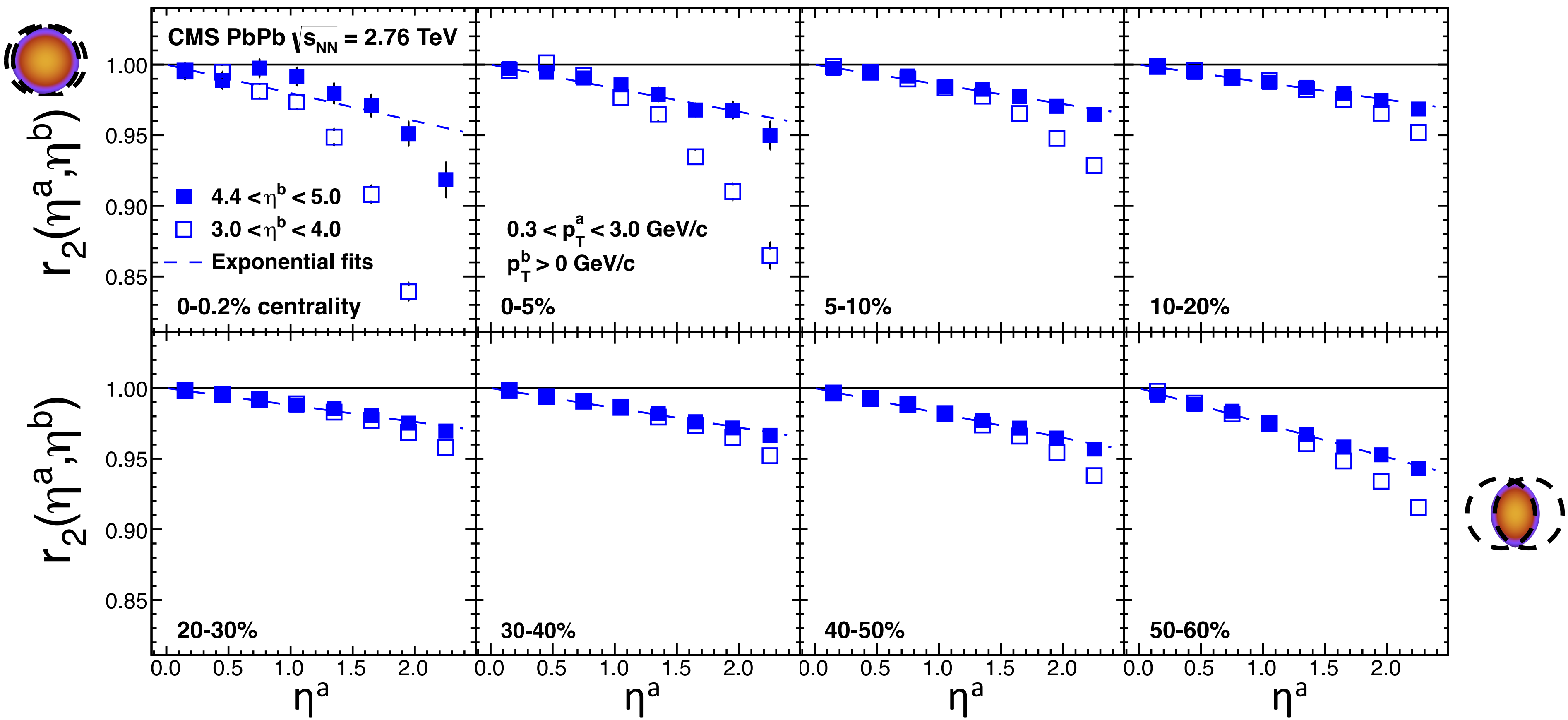
$\Delta\eta = 2\eta^a$

η gap < 2 units:

- r_2 decreases **faster for short-range**
- r_2 mostly **insensitive for long-range**



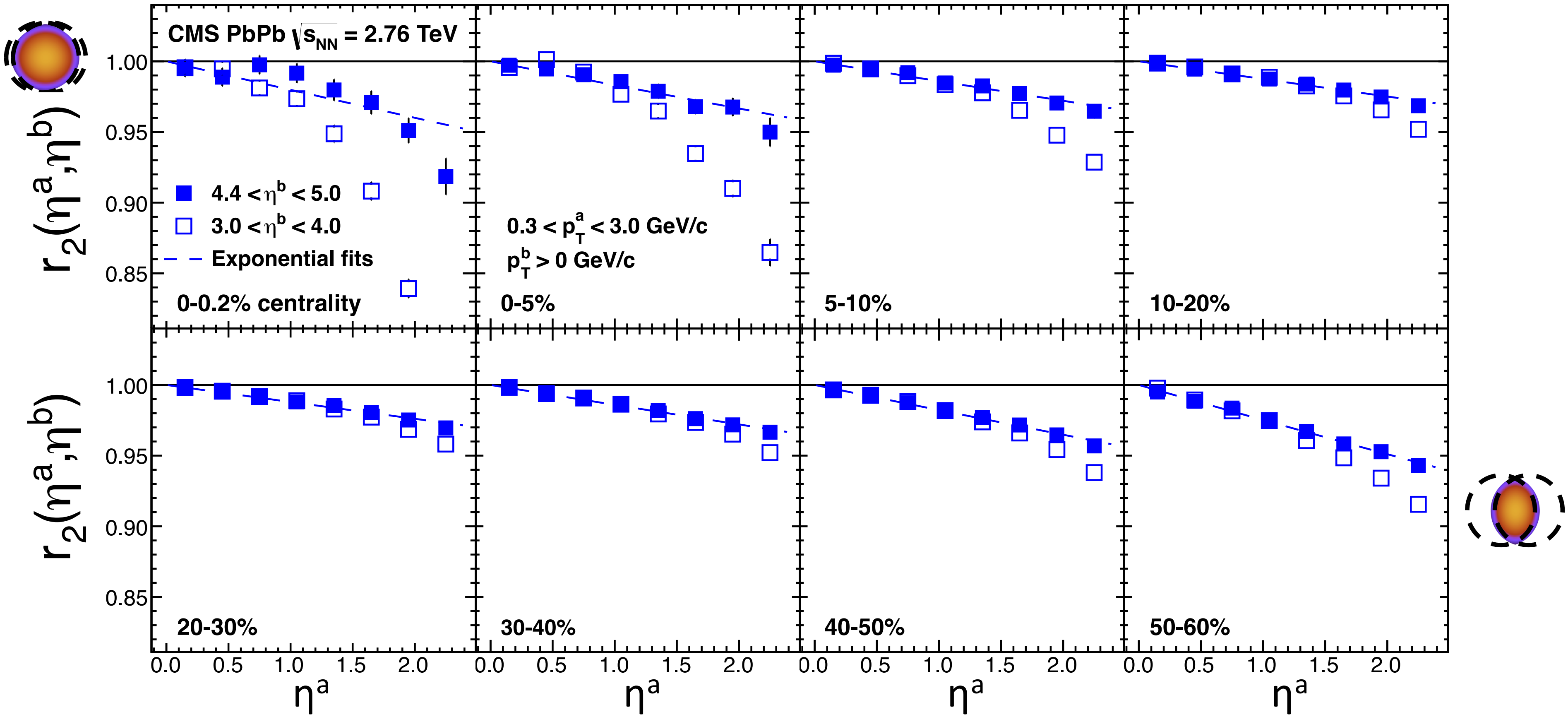
Pb-Pb results



As a function of centrality:

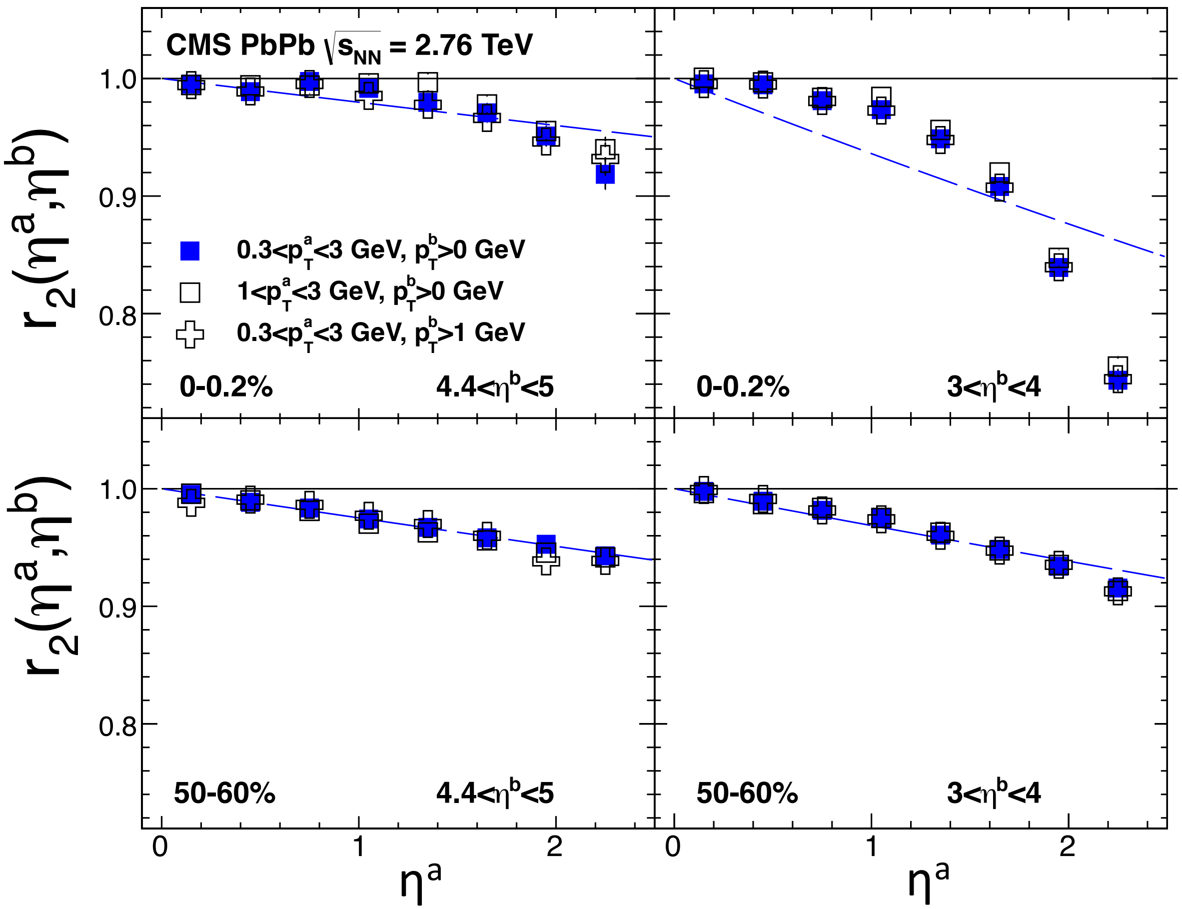
- **Same trend in all centrality bins** except for ultra-central bin (0-0.2%)

Pb-Pb results



≈ **5%** effect ➔ play a **non-negligible role in v_2 η-dependence**

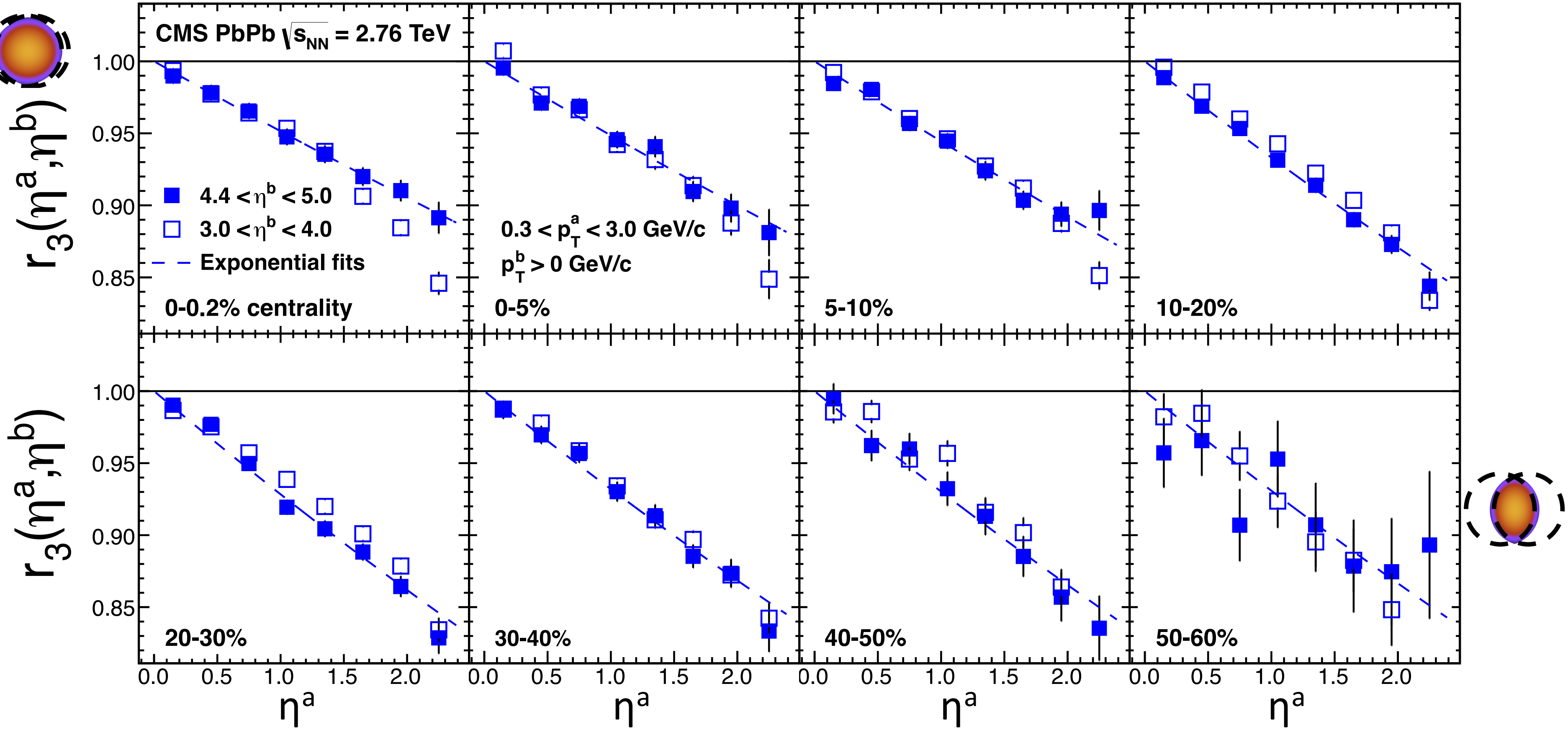
Pb-Pb results



p_T-dependance:

- **No significant p_T dependence** observed: **Initial-state effect?**

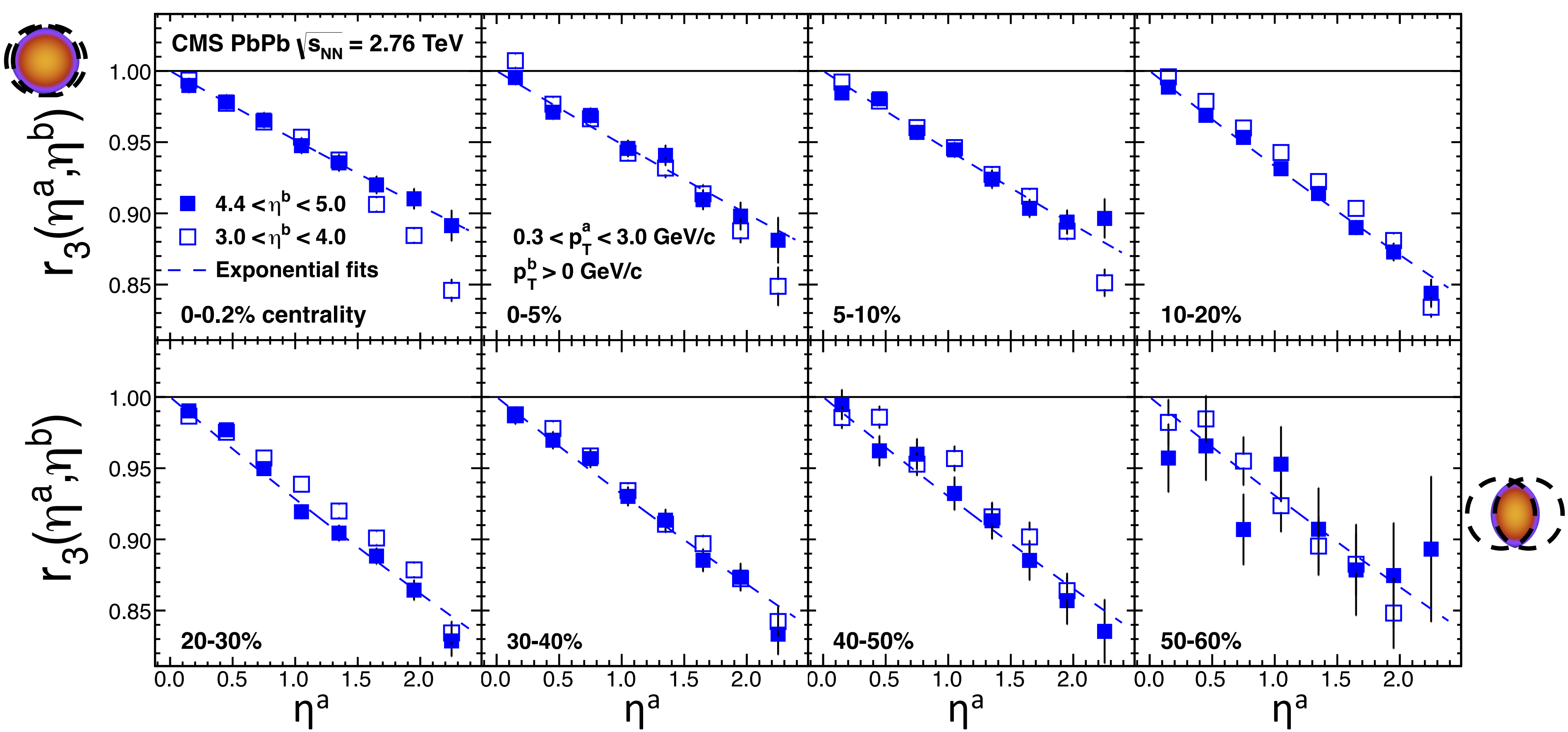
Pb-Pb results



Higher order

- **Stronger (15%) and slightly centrality dependent**

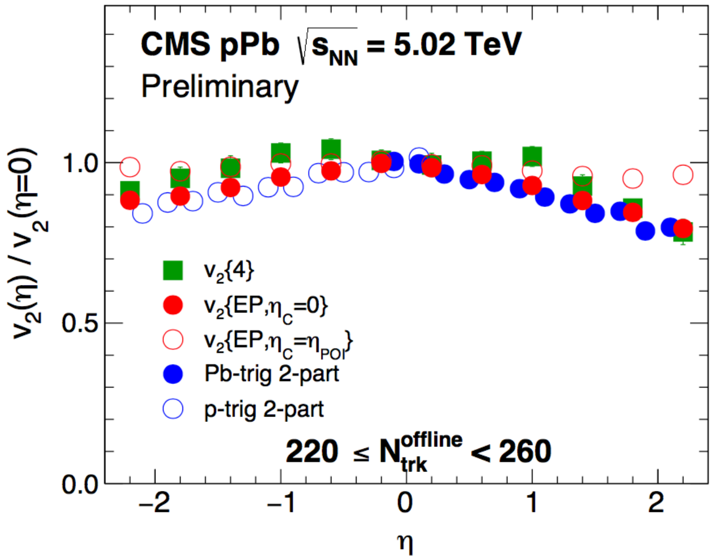
Pb-Pb results



Stronger ➔ **Fluctuation driven effect**

Magnitude ➔ **Compatible with v_3 η-dependence**

How does it look like in p-Pb?



- Asymmetric η-dependence is observed
  - **See Quan's talk on Monday for more details (QGP in small system I, 18:00)**
- **Does it come from v_n magnitude or Ψ_n de-correlation?**

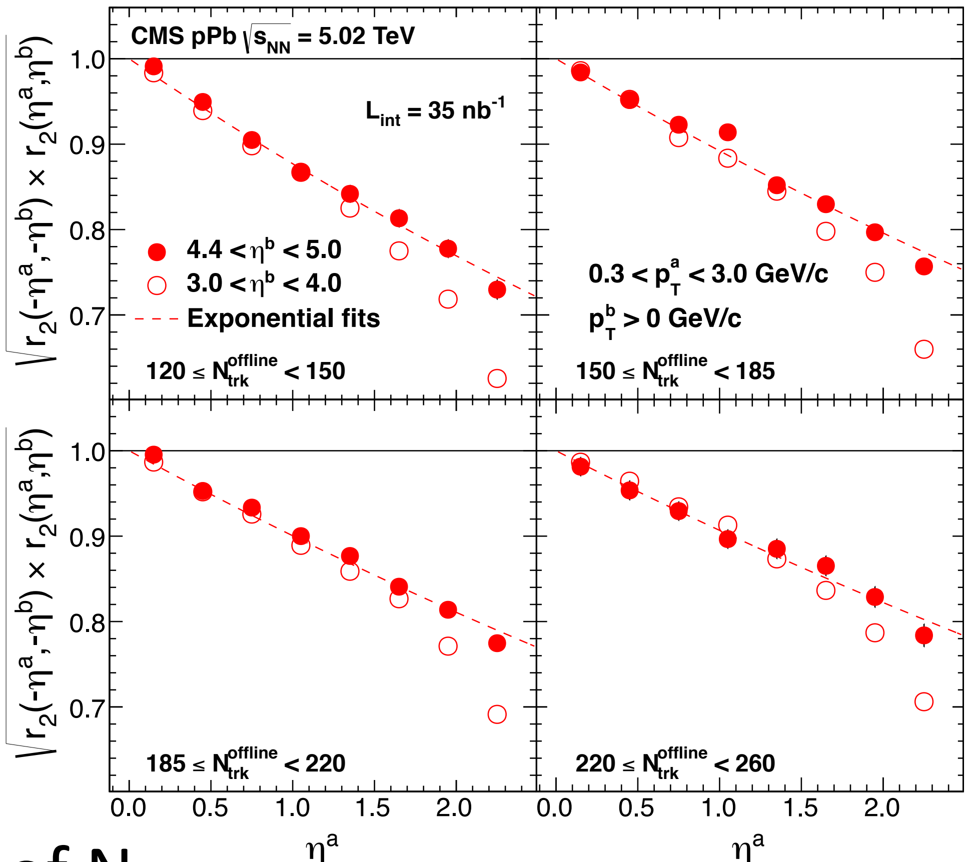
Analysis method:

- **Geometric mean** (account for the asymmetry as a function of η):

$$\sqrt{r_n(\eta^a, \eta^b) \times r_n(-\eta^a, -\eta^b)}$$

- **p- and Pb-side are averaged and not differentiable** with this method

p-Pb results



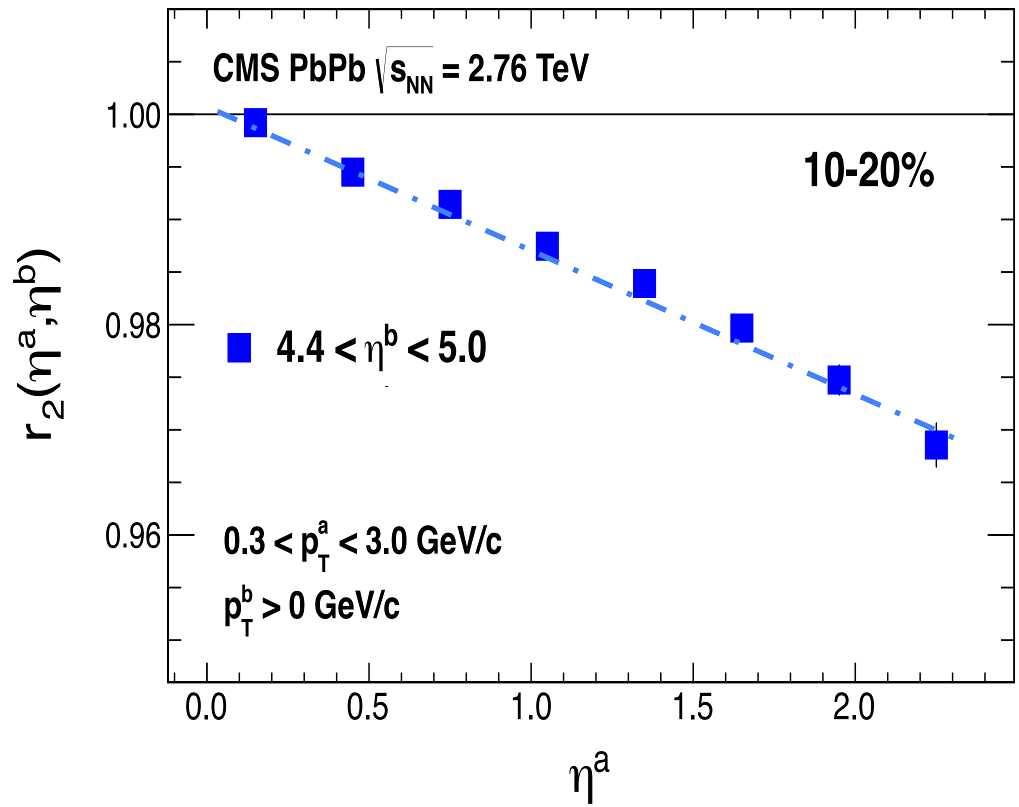
As a function of N_{trk}

- **Same trend (linear) in all N_{trk} bins**
- Bigger effect (20%): **larger fluctuation in p-Pb** than in Pb-Pb

p-Pb and Pb-Pb comparison

Empirical parameterization:

- $r_n(\eta^a, \eta^b) = e^{-2F_n^{\eta}\eta^a} \sim 1 - 2F_n^{\eta}\eta^a$



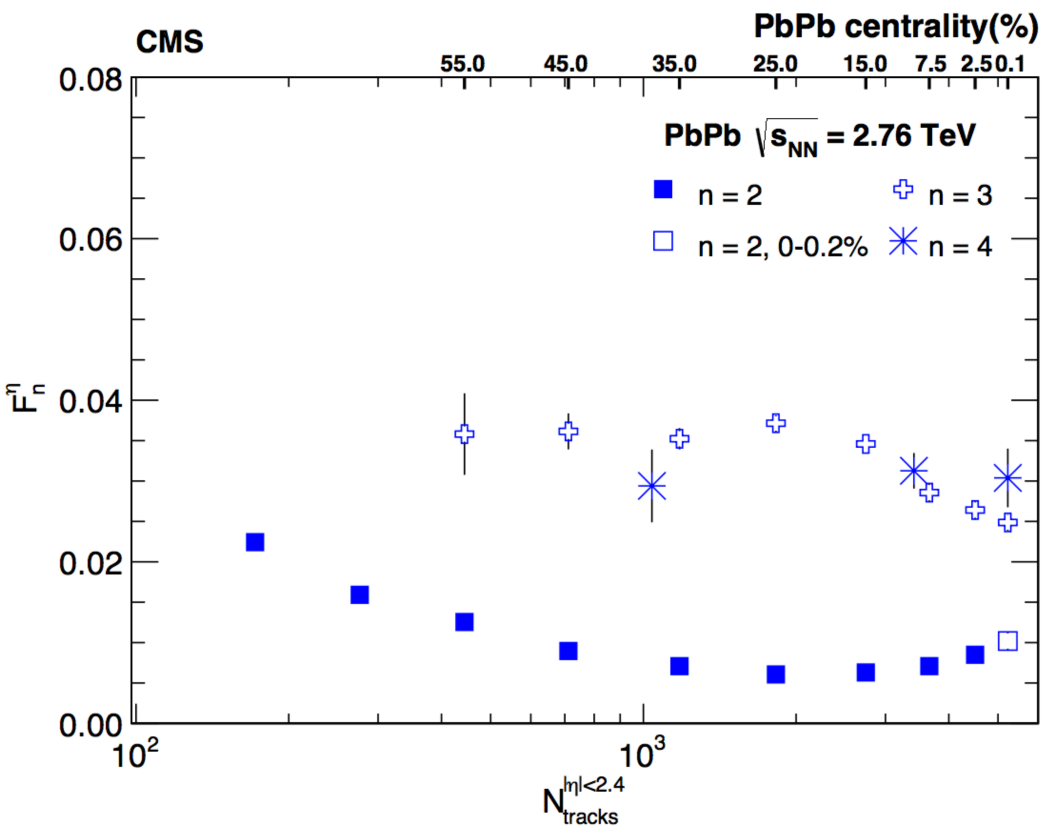
p-Pb and Pb-Pb comparison

Empirical parameterization:

- $r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \sim 1 - 2F_n^\eta \eta^a$

Pb-Pb:

- For n = 2, F^η increases toward more peripheral events
- Higher factorization breakdown for n = 3,4 than n = 2
- No centrality dependence on N_{trk} for n = 4



p-Pb and Pb-Pb comparison

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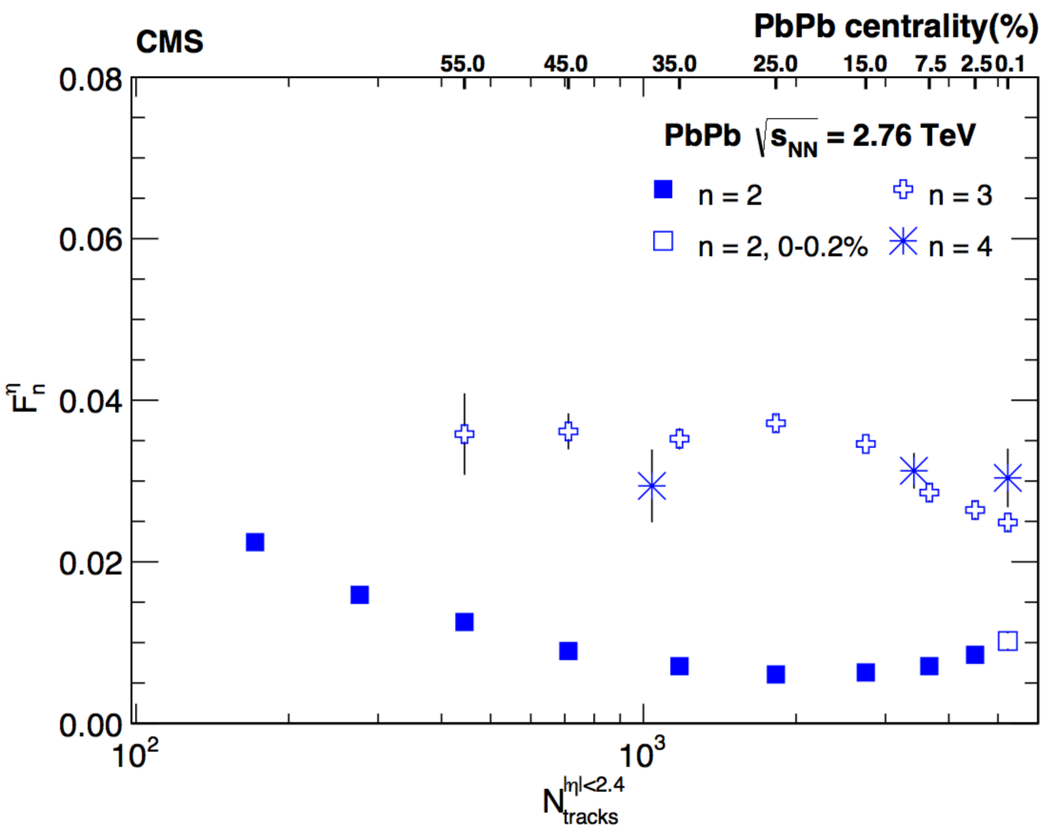
- Higher factorization breakdown for n = 3,4 than n = 2
- No centrality dependence on N_{trk} for n = 4
- If $\Psi_4 \approx \Psi_2$ ➔ $F_4^\eta \approx 4.F_2^\eta$



p-Pb and Pb-Pb comparison

Empirical parameterization:

- $r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \sim 1 - 2F_n^\eta \eta^a$

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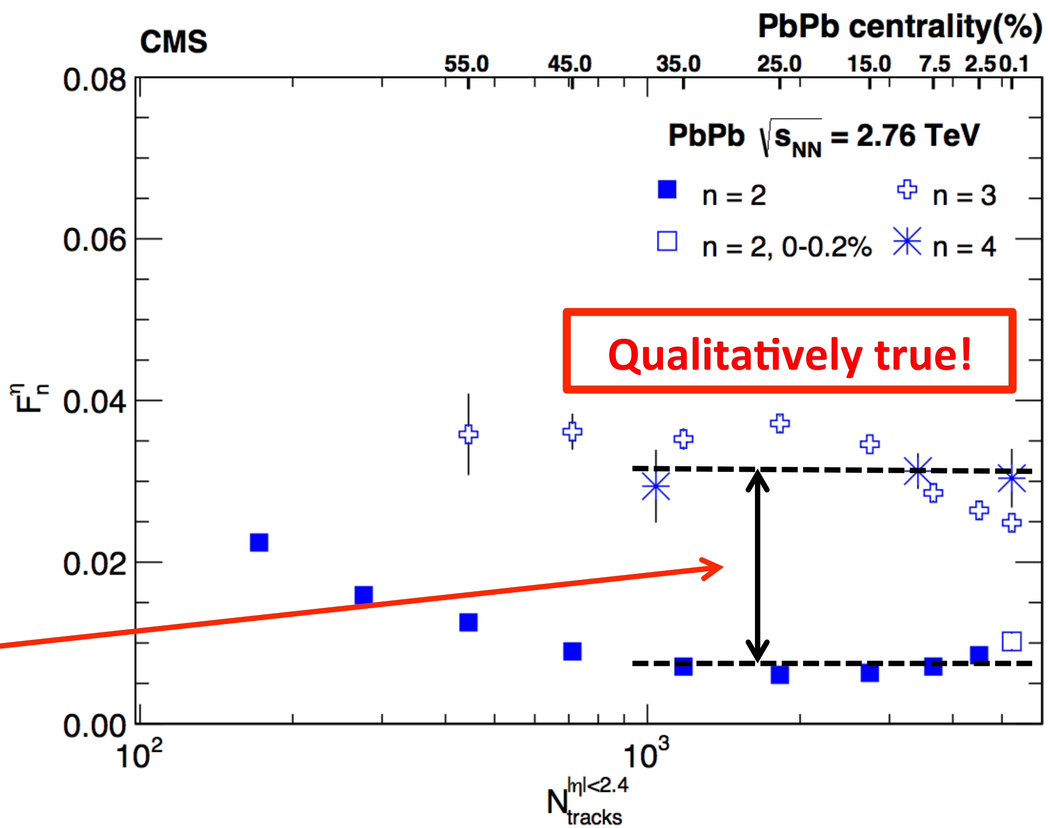

p-Pb and Pb-Pb comparison

Empirical parameterization:

- $r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \sim 1 - 2F_n^\eta \eta^a$

Pb-Pb:

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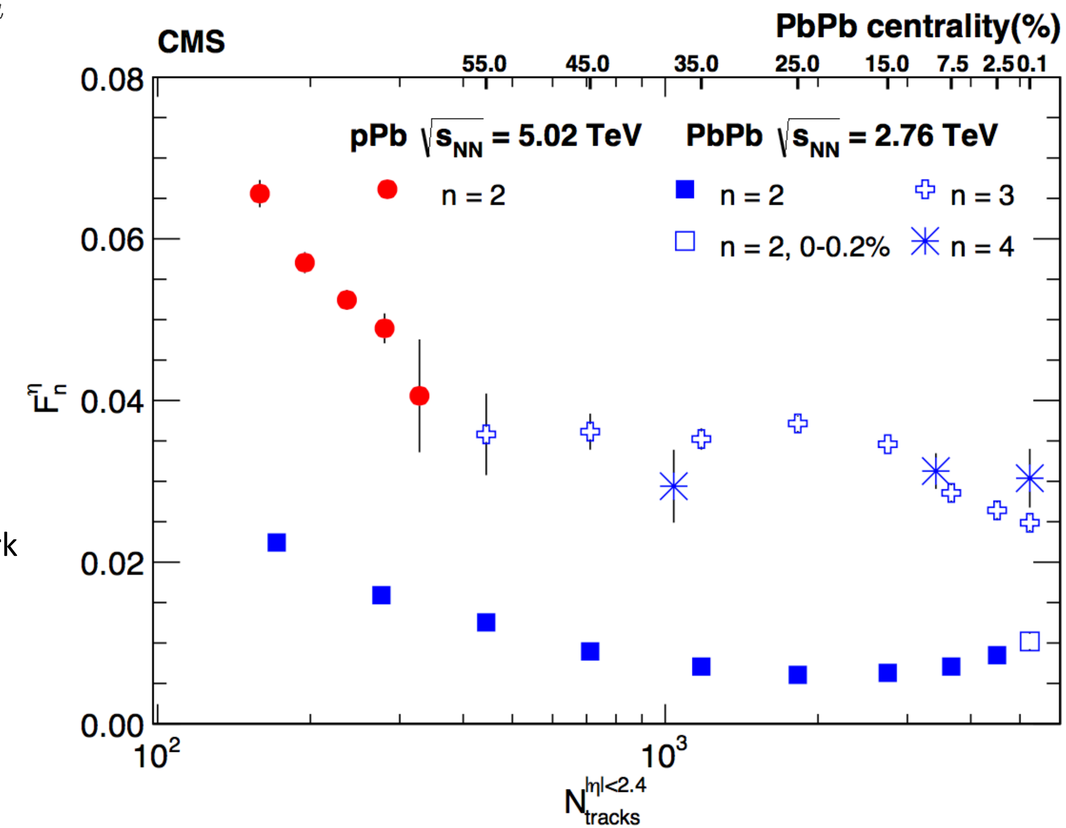


p-Pb:

- Much higher value for n = 2
- Decrease faster toward high multiplicity events

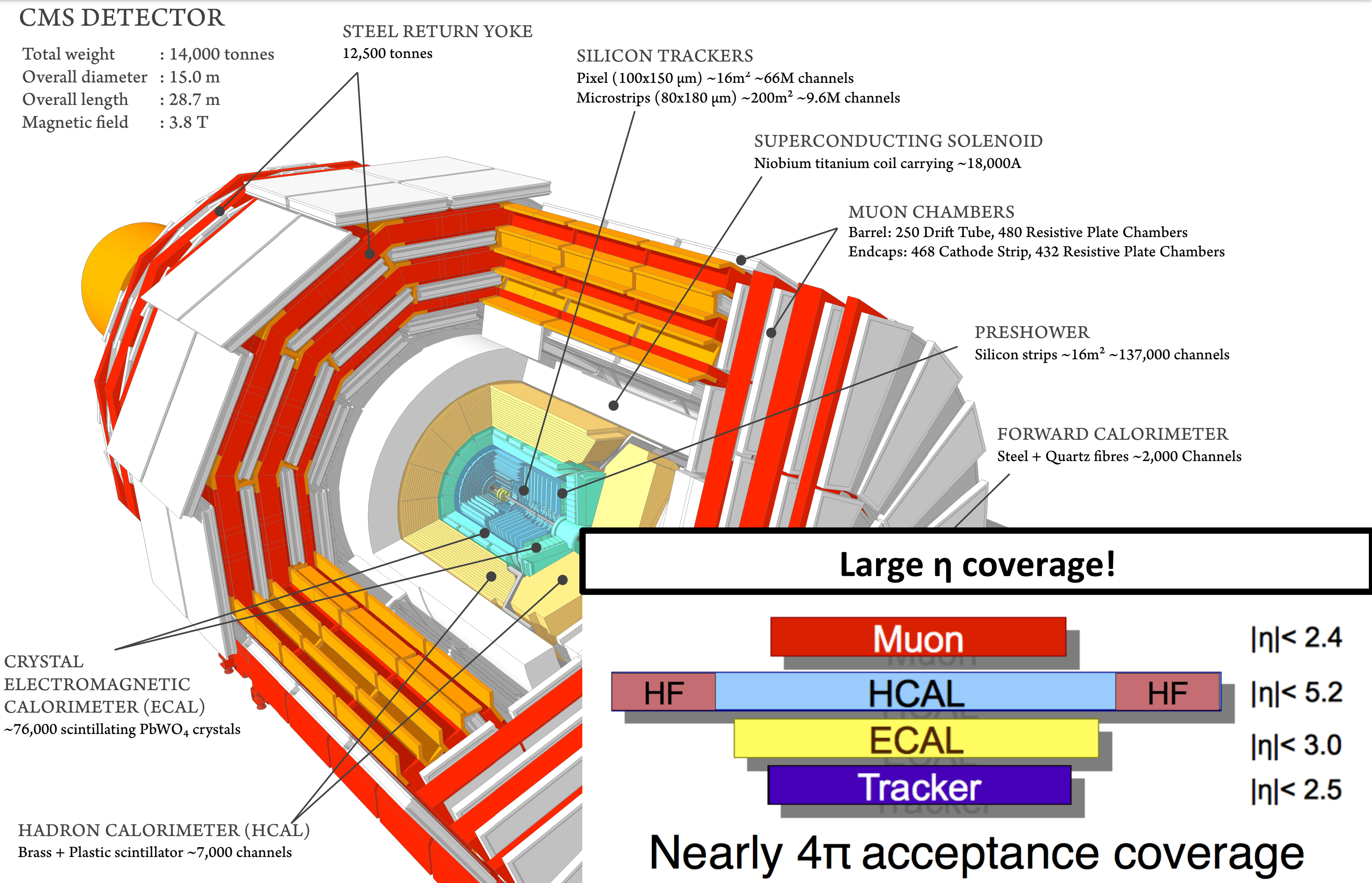
Summary

- Fluctuations and Ψ_n de-correlation along the longitudinal direction were observed in Pb-Pb and p-Pb
- Access to the full granularity (3D) of the initial state
  - **More constraints on longitudinal dynamics**
- No p_T-dependence observed in Pb-Pb
  - Could point to an **initial state effect**
- The effect is larger in p-Pb than in Pb-Pb
  - **Larger fluctuation along longitudinal direction** in the initial-state in p-Pb
- EP de-correlation have **non-negligible effect on v_n η-dependence**

BACKUP

QM2015

CMS detector



Pb-Pb analysis method

How $r_n(\eta^a,\eta^b)$ is related to factorization and $\Psi_n(\eta)$ fluctuations?

If $V_{n\Delta}$ factorizes or $\Psi_n(\eta)$ indep. of η,

$$r_n(\eta^a,\eta^b) = \frac{\langle v_n(-\eta^a)v_n(\eta^b)\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\rangle} = 1$$ (for symmetric system)

Otherwise,

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

$$\sim \frac{\langle \cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\rangle}{\langle \cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\rangle}$$ (for symmetric system)

$$\sim \langle \cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\rangle$$

(two EPs separated a gap of $2\eta^a$)

p-Pb analysis method

A subtlety in pPb as $v_n(-\eta^a) \neq v_n(\eta^a)$

$$r_n(\eta^a,\eta^b) = \frac{\langle v_n(-\eta^a) \times v_n(\eta^b) \times \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) \times v_n(\eta^b) \times \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle}$$

Do not cancel!

Let's take a 'geometric mean'

$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} = \sqrt{\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)} \frac{V_{n\Delta}(\eta^a,-\eta^b)}{V_{n\Delta}(-\eta^a,-\eta^b)}}$$

$$= \sqrt{\frac{\langle v_n(-\eta^a) v_n(\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle} \frac{\langle v_n(\eta^a) v_n(-\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^b))] \rangle}{\langle v_n(-\eta^a) v_n(-\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(-\eta^b))] \rangle}}$$

$$\sim \sqrt{\frac{\langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle} \frac{\langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^b))] \rangle}{\langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(-\eta^b))] \rangle}} \sim \langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^a))] \rangle$$

Drawback: p- and Pb-side averaged ,not differentiable

p-Pb analysis method

A subtlety in pPb as $v_n(-\eta^a) \neq v_n(\eta^a)$

$$r_n(\eta^a,\eta^b) = \frac{\langle v_n(-\eta^a) \times v_n(\eta^b) \times \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) \times v_n(\eta^b) \times \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle}$$

Do not cancel!

Let's take a 'geometric mean'

$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} = \sqrt{\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)} \frac{V_{n\Delta}(\eta^a,-\eta^b)}{V_{n\Delta}(-\eta^a,-\eta^b)}}$$

$$= \sqrt{\frac{\langle v_n(-\eta^a) v_n(\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle} \frac{\langle v_n(\eta^a) v_n(-\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^b))] \rangle}{\langle v_n(-\eta^a) v_n(-\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(-\eta^b))] \rangle}}$$

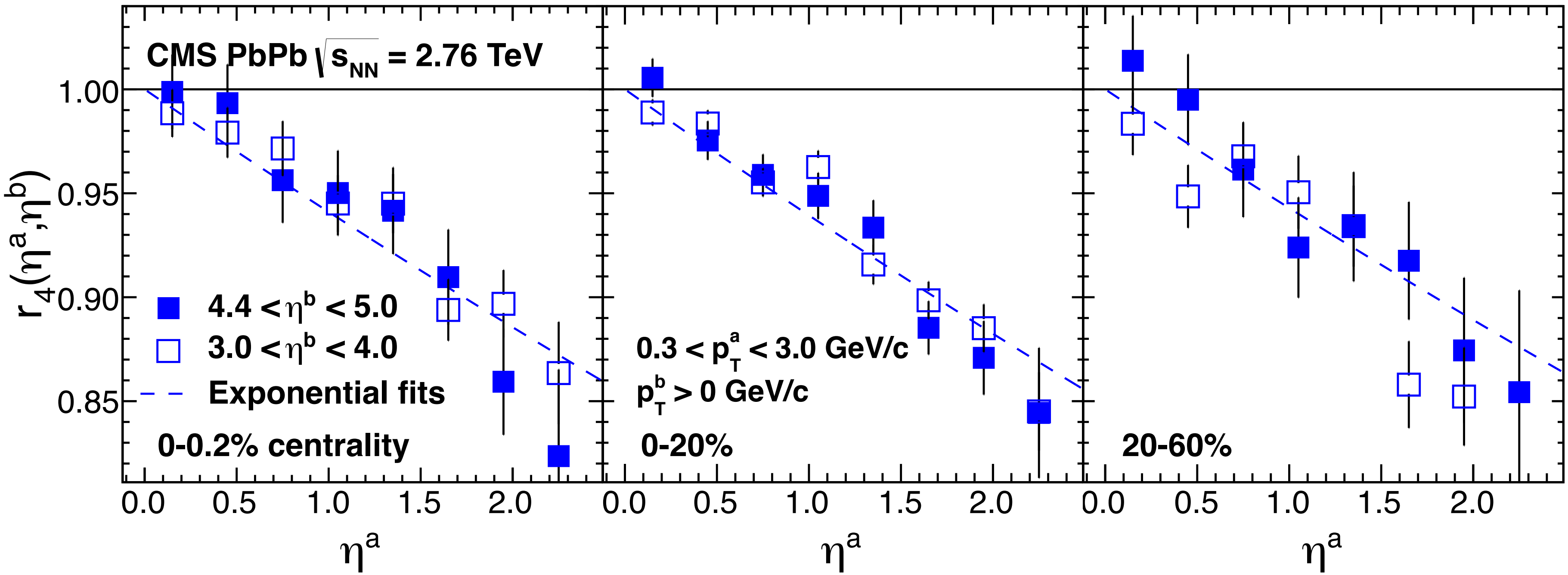
$$\sim \sqrt{\frac{\langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle} \frac{\langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^b))] \rangle}{\langle \cos[n(\Psi_n(-\eta^a) - \Psi_n(-\eta^b))] \rangle}} \sim \langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^a))] \rangle$$

Drawback: p- and Pb-side averaged ,not differentiable

41

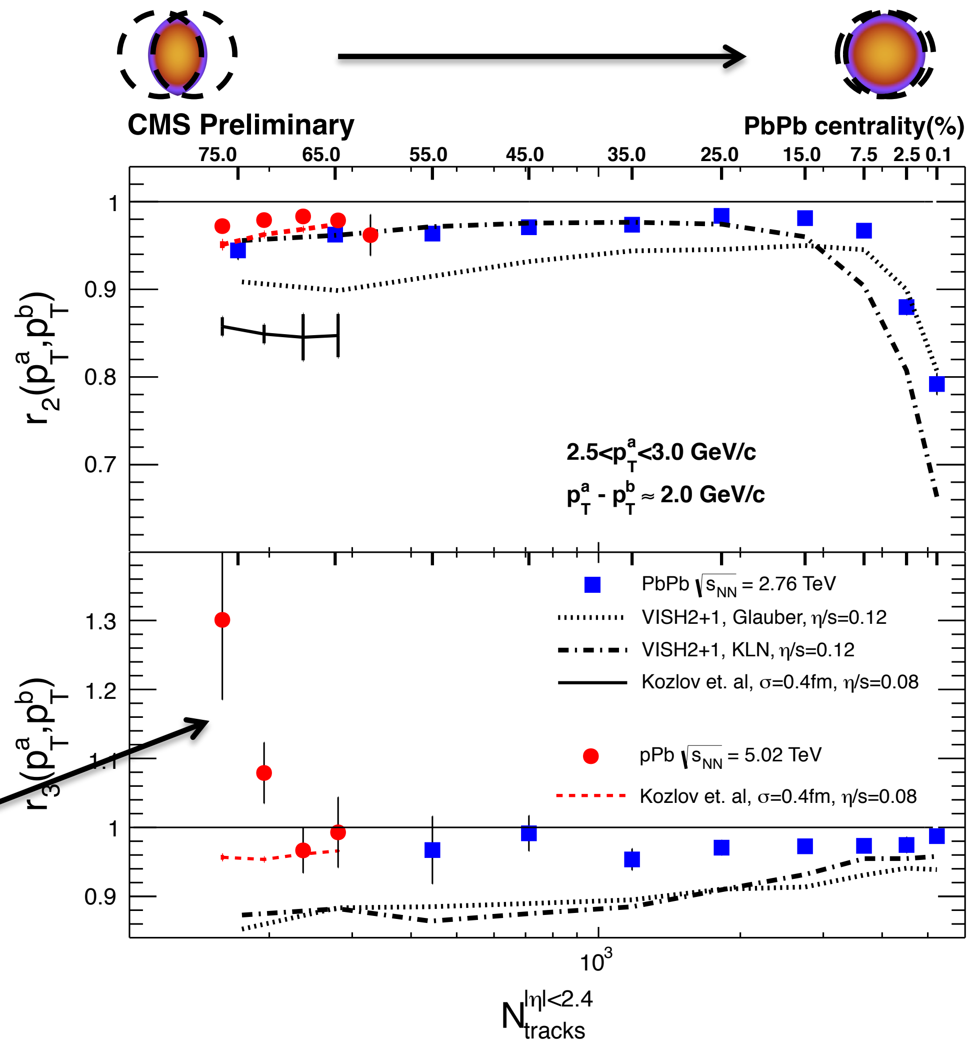
Centrality dependence of r_4

$$r_4(\eta^a,\eta^b) \approx \left\langle \cos[4(\Psi_4(\eta^a) - \Psi_4(-\eta^a))] \right\rangle$$



- Also roughly linear increase with η gap
- r_4 is related to r_2, esp. for peripheral events (linear vs non-linear contributions)

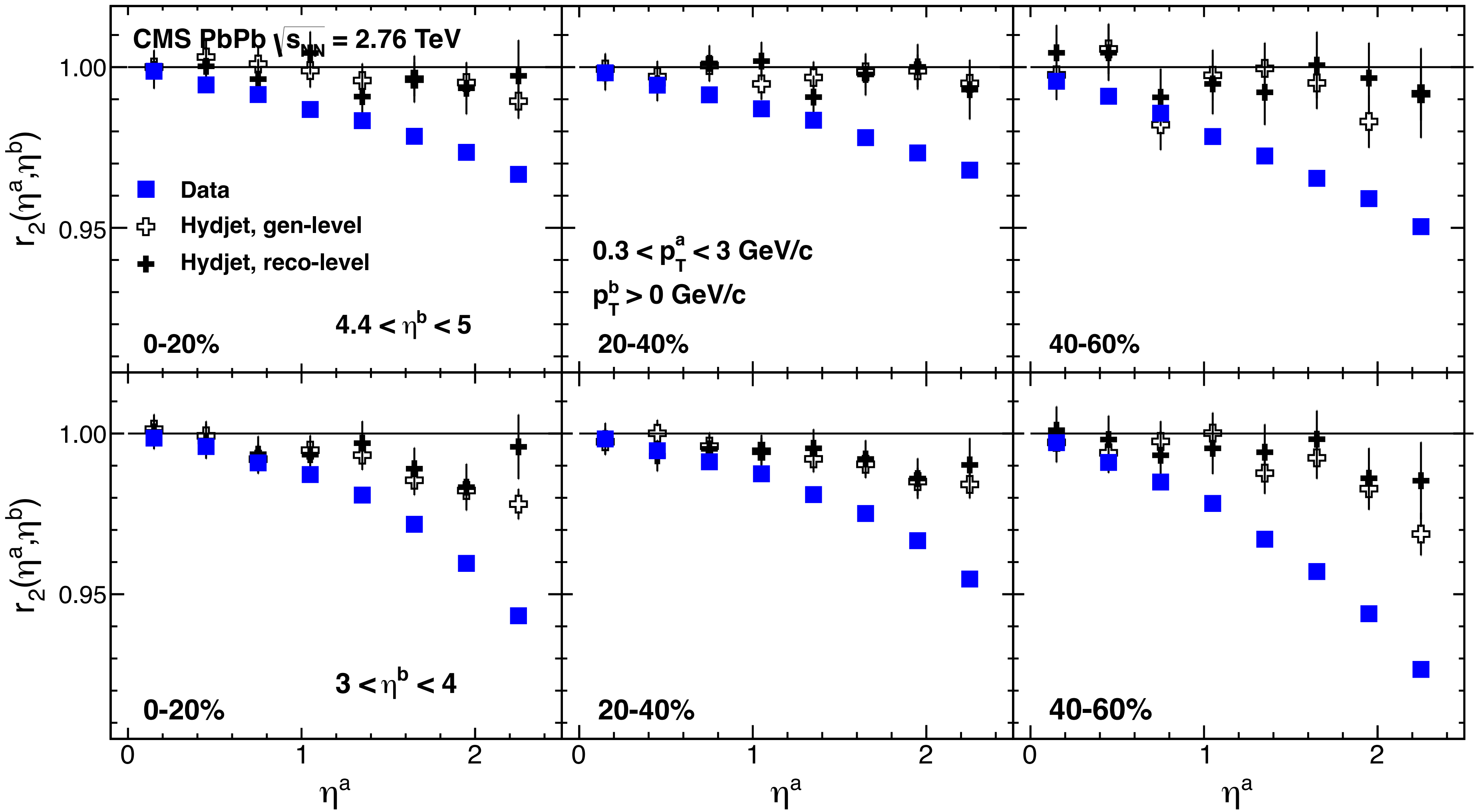
$\Psi_n(p_T)$ fluctuations in p-Pb and Pb-Pb



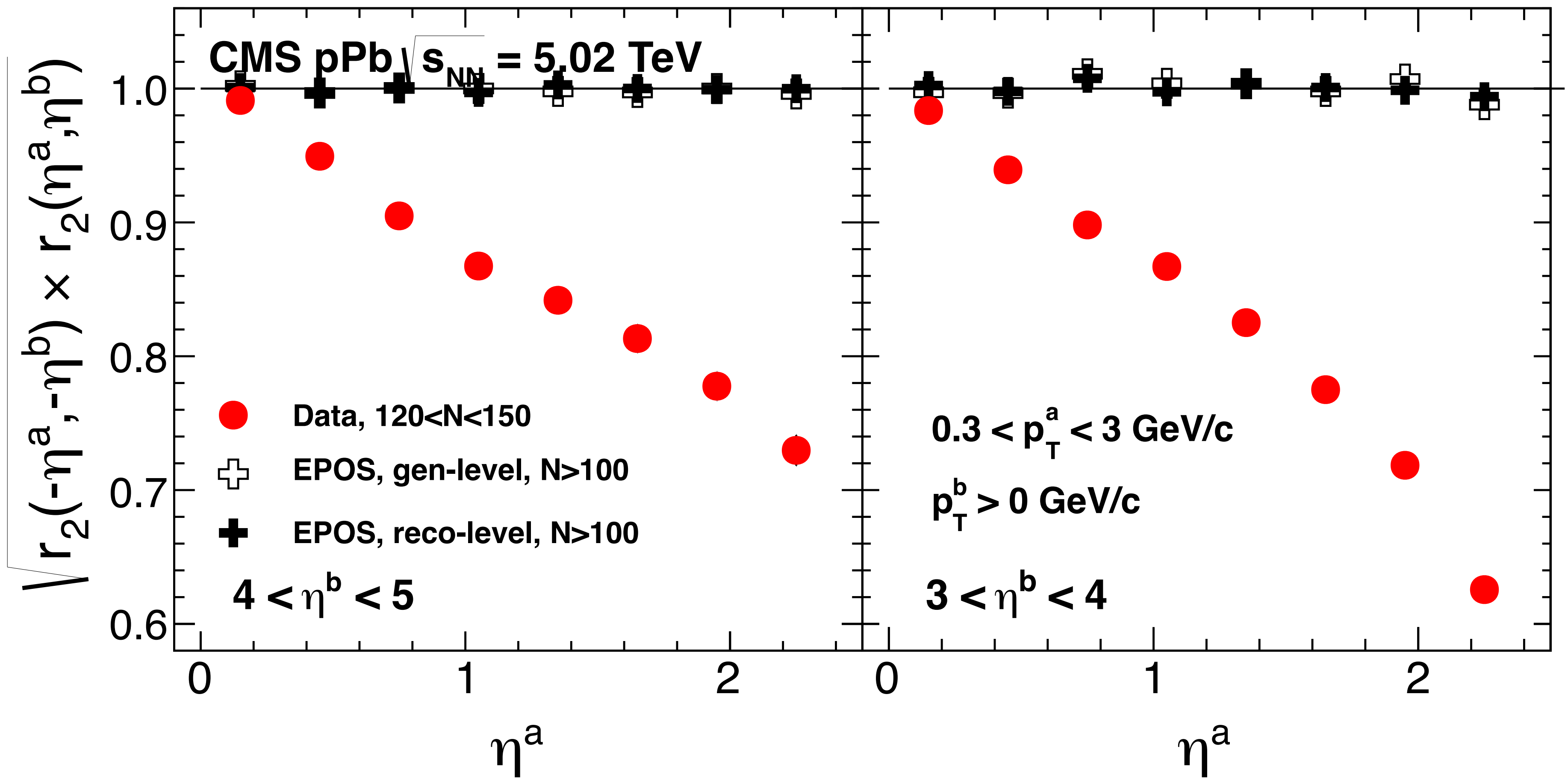
Significant effect toward central PbPb

nonflow

Comparison with HYDJET



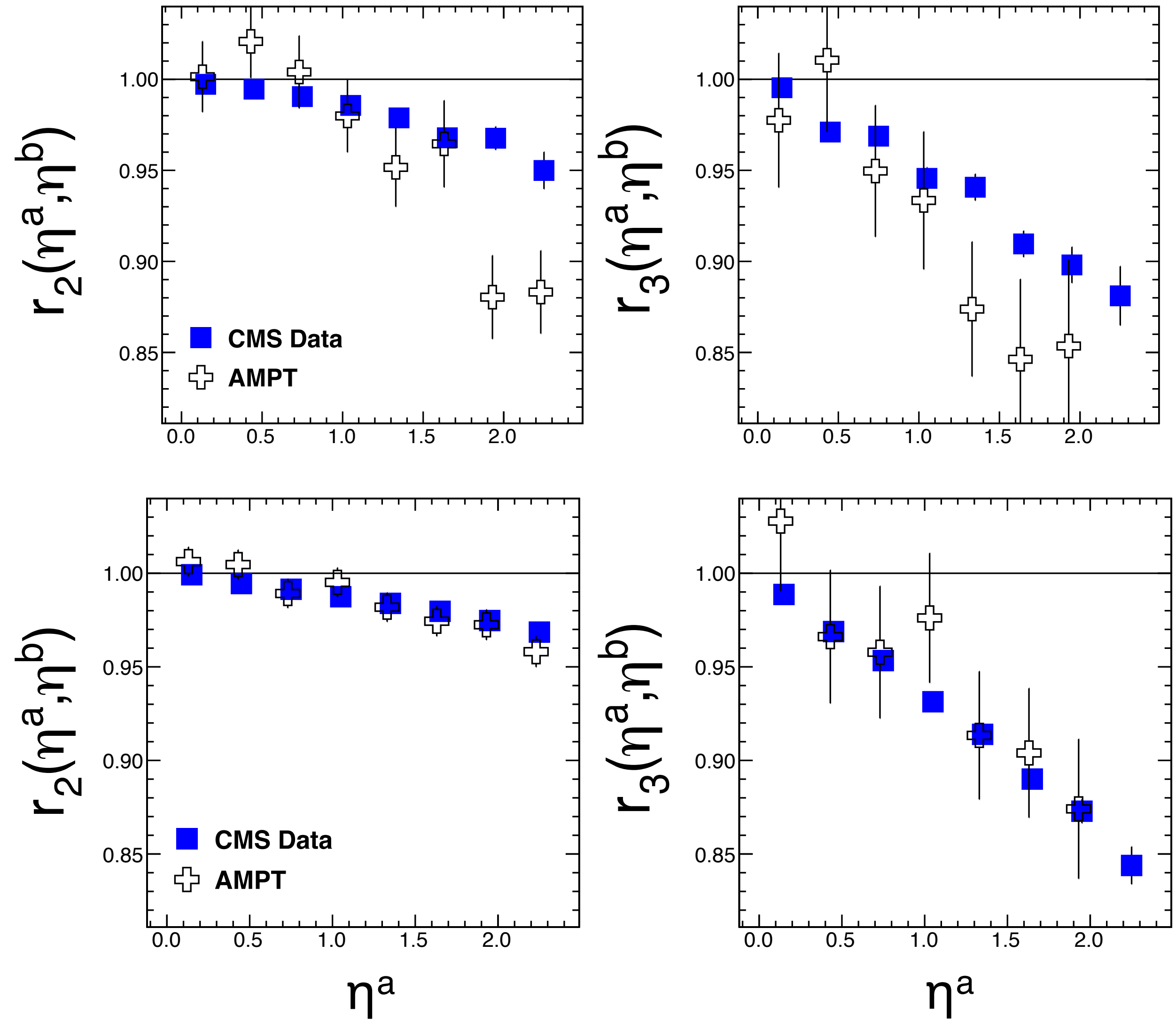
Comparison with EPOS



Comparison with AMPT

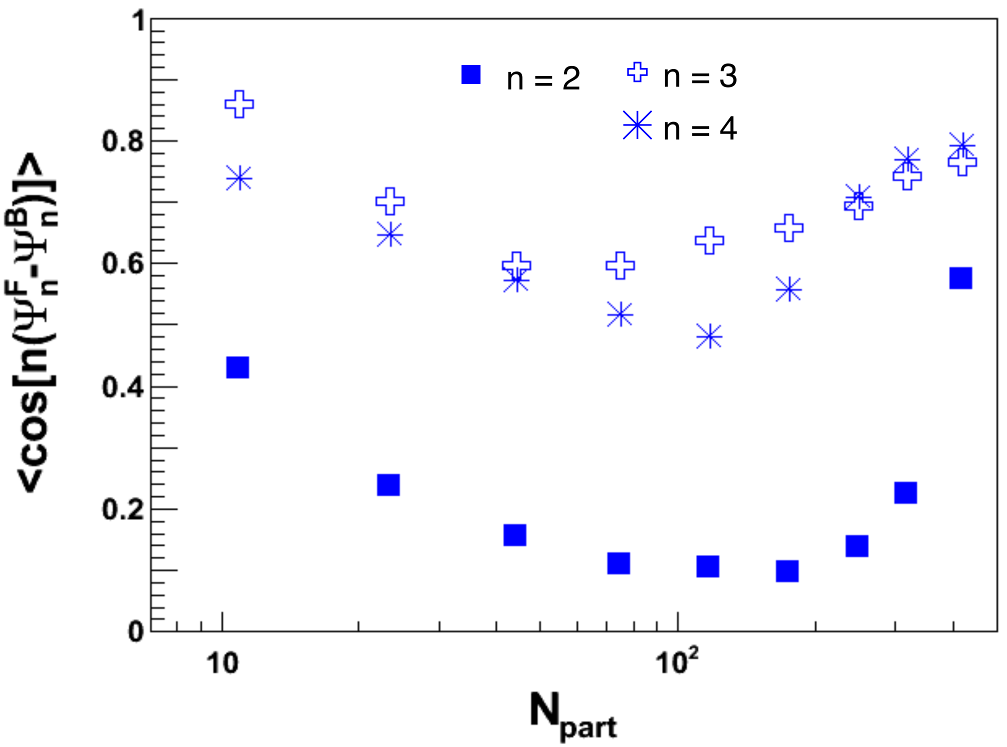
0-5%

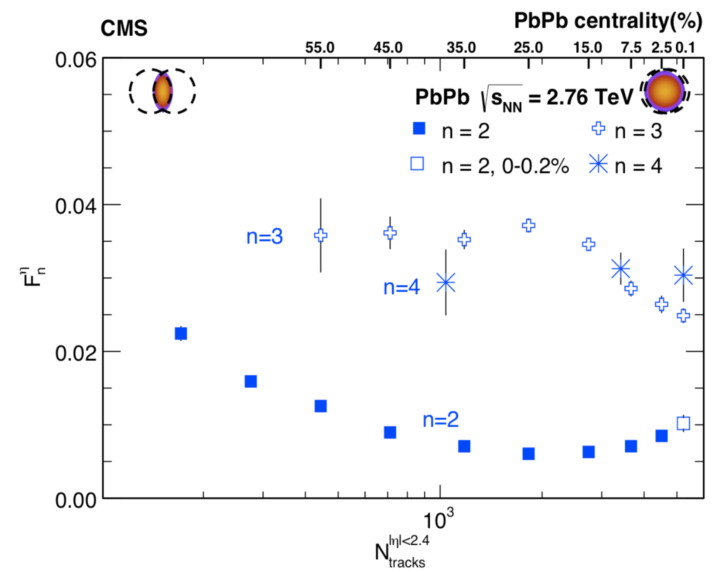
10-20%



Glauber model

- Trend **qualitatively consistent** with participant fluctuations in Glauber model
- Details **depend on dynamics**





v_n η-dependence scaled