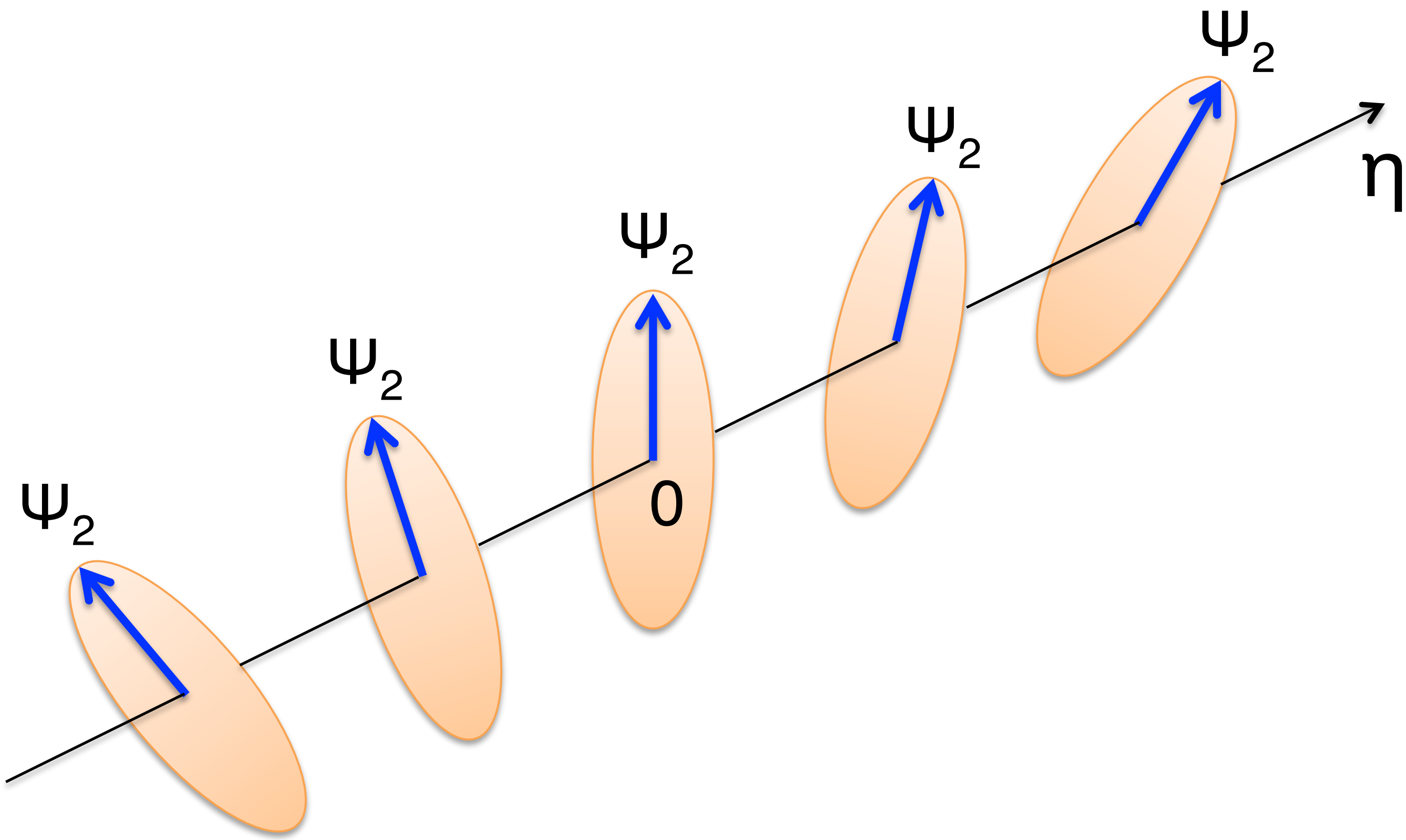
Longitudinal decorrelations of flow orientation angle (Ψ_n) in AA and pA

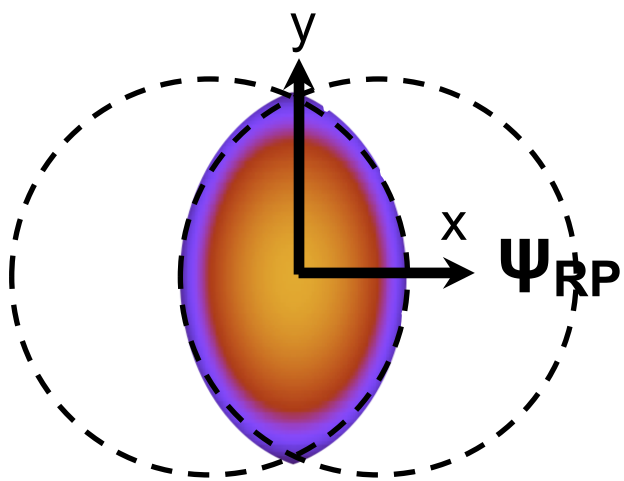


Wei Li, Rice University

INT program, Seattle, July 16

Initial-state anisotropy

1990s

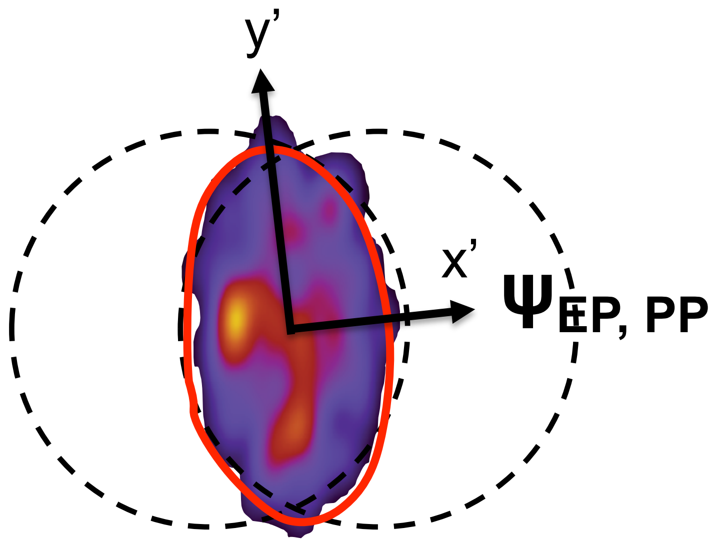


Final state:

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

Initial-state inhomogeneity

2003-2005



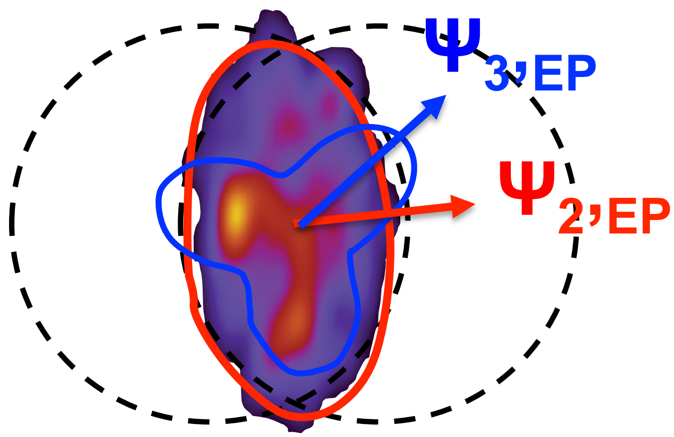
Ψ_{EP}: Direction of maximum particle density

Final state:

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

Initial-state inhomogeneity

2010



ψ_{EP}: Direction of maximum particle density

Final state:

$$f(p_T,\varphi,\eta) \sim 1 + 2v_2(p_T,\eta)\cos[2(\phi - \Psi_2)]$$ Elliptic flow

$$+2v_3(p_T,\eta)\cos[3(\phi - \Psi_3)]$$ Triangular flow

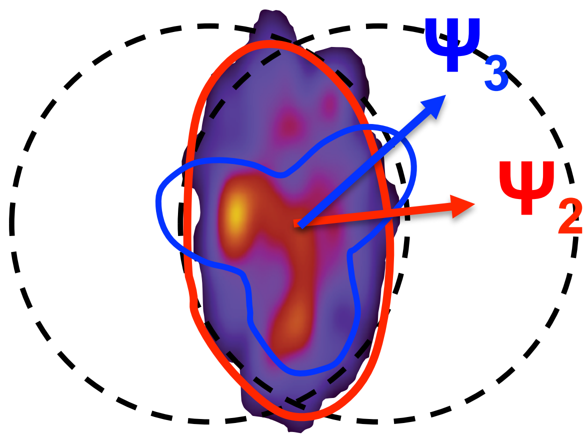
$$+2v_4(p_T,\eta)\cos[4(\phi - \Psi_4)]$$

$$+2v_5(p_T,\eta)\cos[5(\phi - \Psi_5)]$$

$$+\ldots$$

Initial-state inhomogeneity

2012-2013



ψ_{EP}: Direction of maximum particle density

(particle properties dependent)

Final state:

$$f(p_T,\varphi,\eta) \sim 1 + 2v_2(p_T,\eta)\cos\left[2\left(\phi - \underline{\Psi_2\left(p_T,\eta\right)}\right)\right]$$

$$+2v_3(p_T,\eta)\cos\left[3\left(\phi - \underline{\Psi_3\left(p_T,\eta\right)}\right)\right]$$

Naturally true for any Fourier decomposition

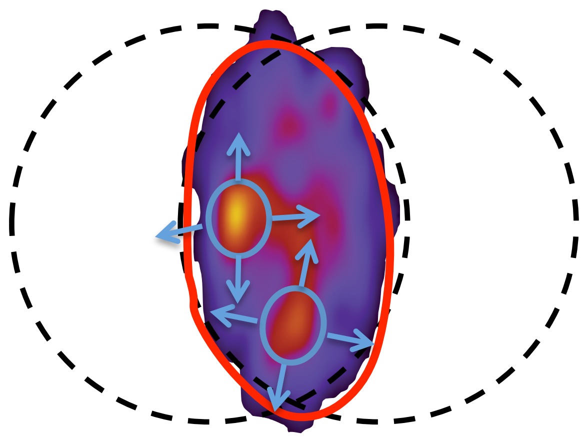
$$+2v_4(p_T,\eta)\cos\left[4\left(\phi - \underline{\Psi_4\left(p_T,\eta\right)}\right)\right]$$

$$+2v_5(p_T,\eta)\cos\left[5\left(\phi - \underline{\Psi_5\left(p_T,\eta\right)}\right)\right]$$

$+\ldots$

Decode the initial-state inhomogeneity

2012-2013



ψ_{EP}: Direction of maximum particle density

(particle properties dependent)

Final state:

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

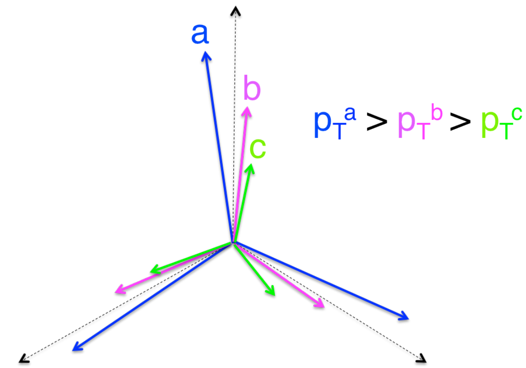
Local hot spots perturb the event plane of a smooth background, in a (p_T, η,…) dependent fashion.

$\Psi_n(p_T, \eta)$ contains details of the lumpy initial state: fluctuations in r, ϕ and η directions

Flow factorization breaking in p_T

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

(two-particle) (single-particle)

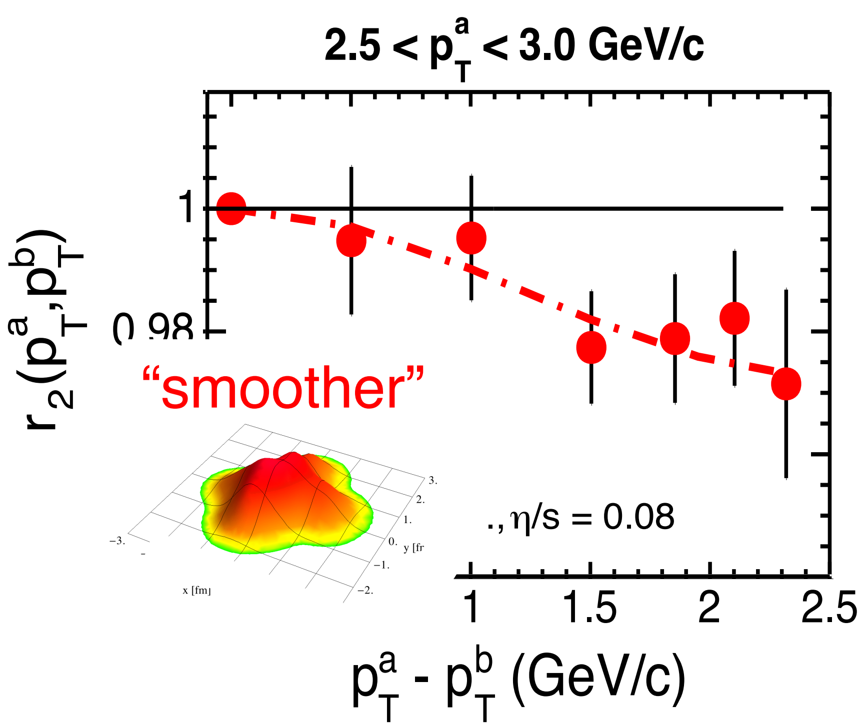


—— due to EP $\Psi_n(p_T)$, caused by **"lumpy"** initial state

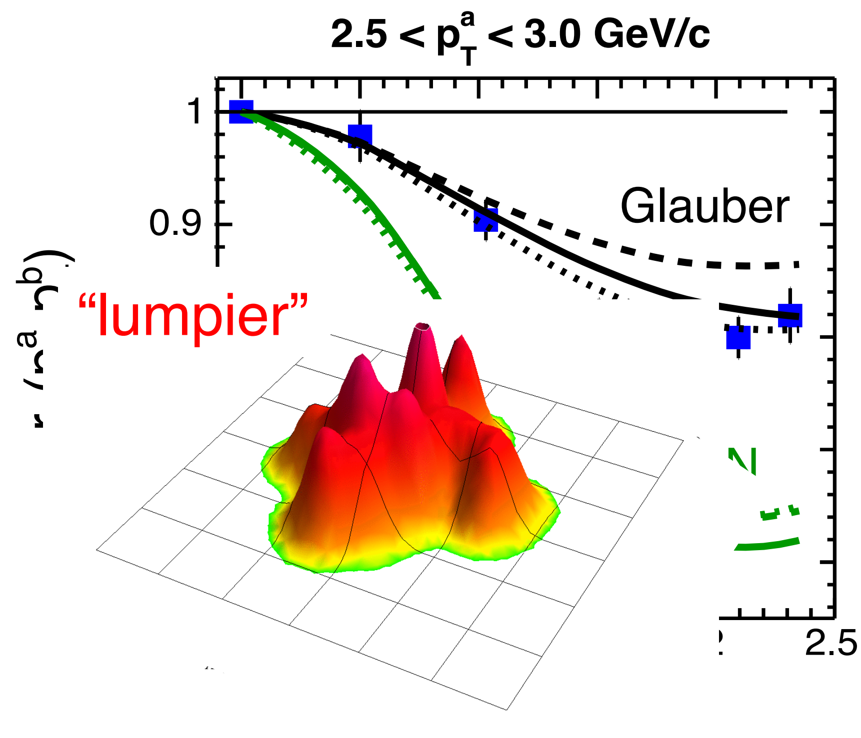
$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

arXiv:1503.01692

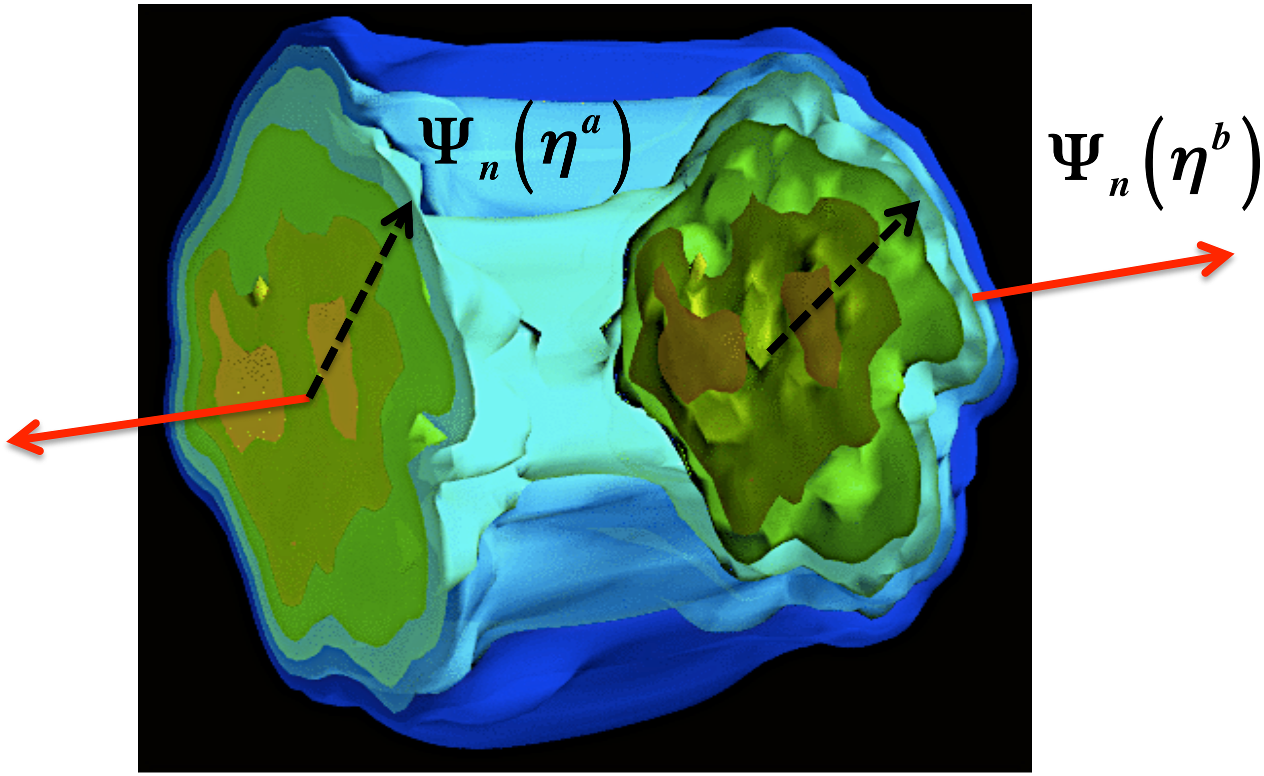
pPb, $220 < N_{trk} < 260$



0-0.2% ultra-central PbPb



Longitudinal dynamics: QGP expands in **3D**

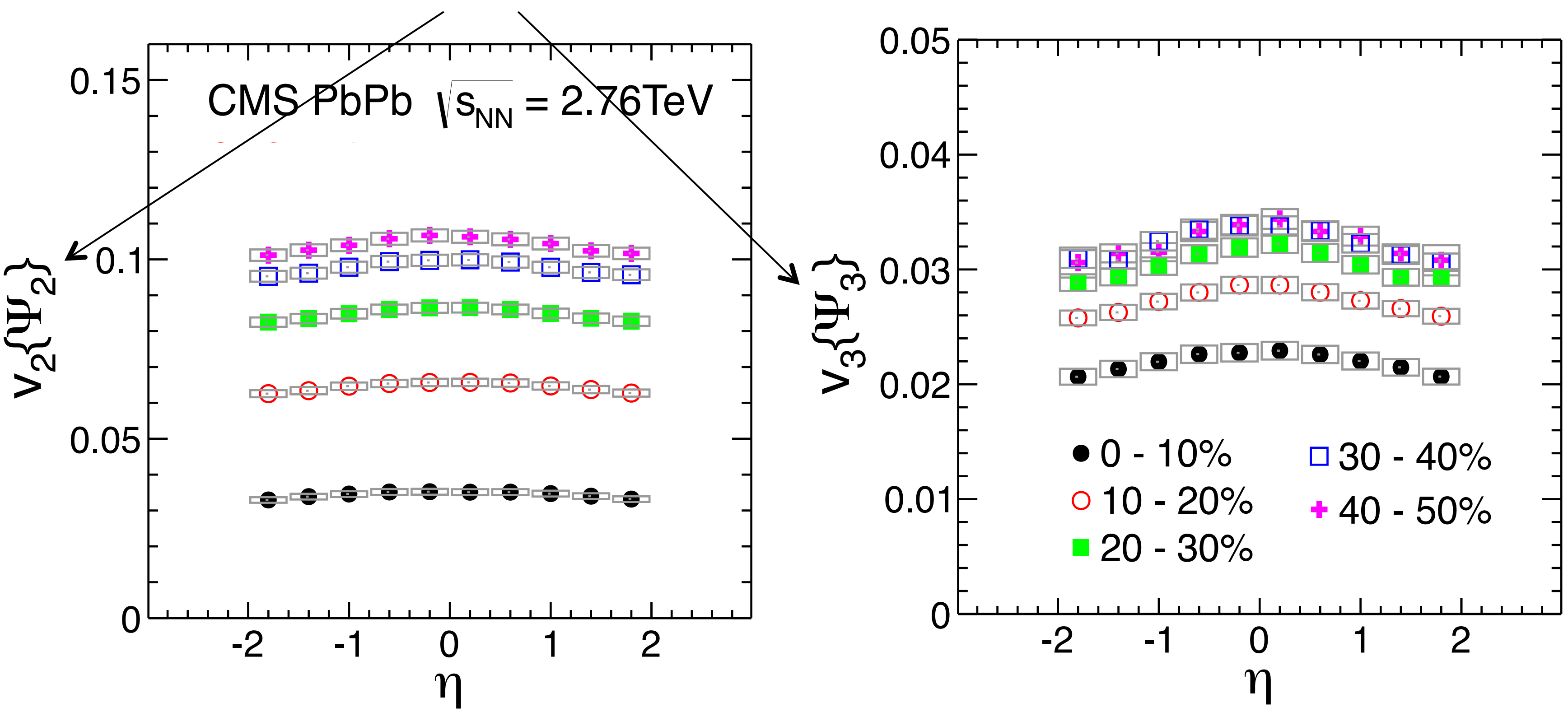


$$f(p_T,\phi,\eta) \sim 1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\left[n\left(\phi - \Psi_n\left(p_T,\eta\right)\right)\right]$$

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

Flow is not quite boost-invariant in rapidity

With respect to Ψ_n at a fixed η



Stronger η dependence for v_3

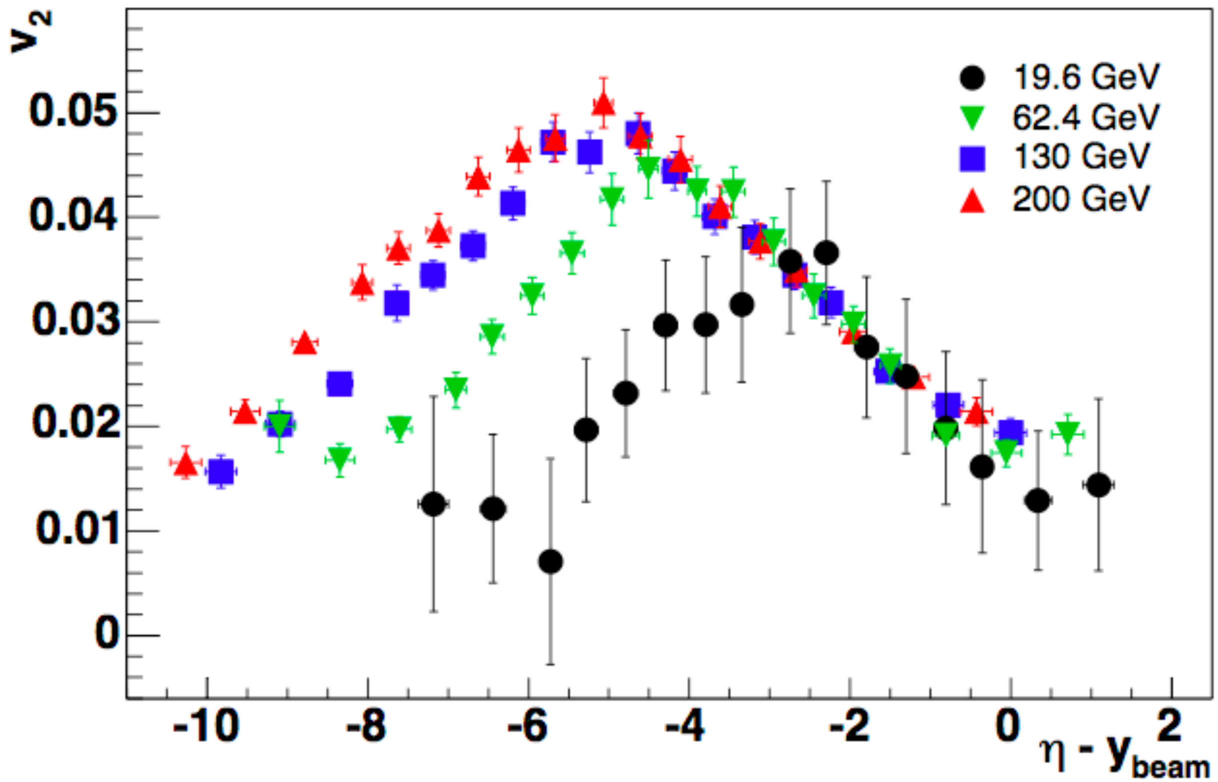
Rapidity dependence of

v_n magnitude or **Ψ_n orientation**?

(energy density, η/s) (geometry, initial state)

"Extended longitudinal scaling" of v_2

PHOBOS - PRL 94, 122303 (2005)



Still not understood

Rapidity dependence of

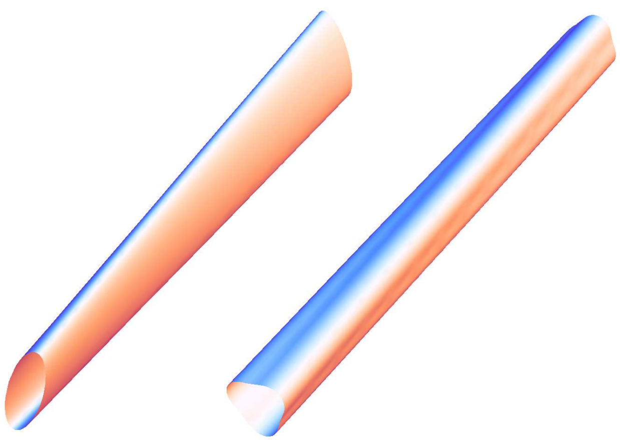
v_n magnitude or **Ψ_n orientation**?

(energy density, η/s) (geometry, initial state)

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

Wounded nucleon model

Torqued fireball

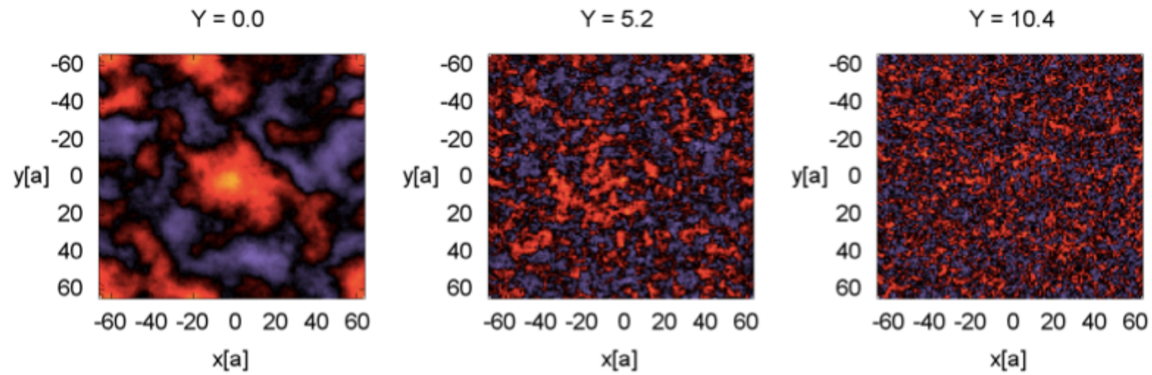


Bozek et.al., arXiv:1011.3354

Global twist

CGC-based model

Correlation length of gluon field JIMWLK



Dumitru et. al., arXiv:1108.4764

Rapidity dependent granularity of gluon field fluctuations

Next, quantify this effect experimentally and compare to theoretical calculations

How to probe $\Psi_n(\eta)$ fluctuations experimentally

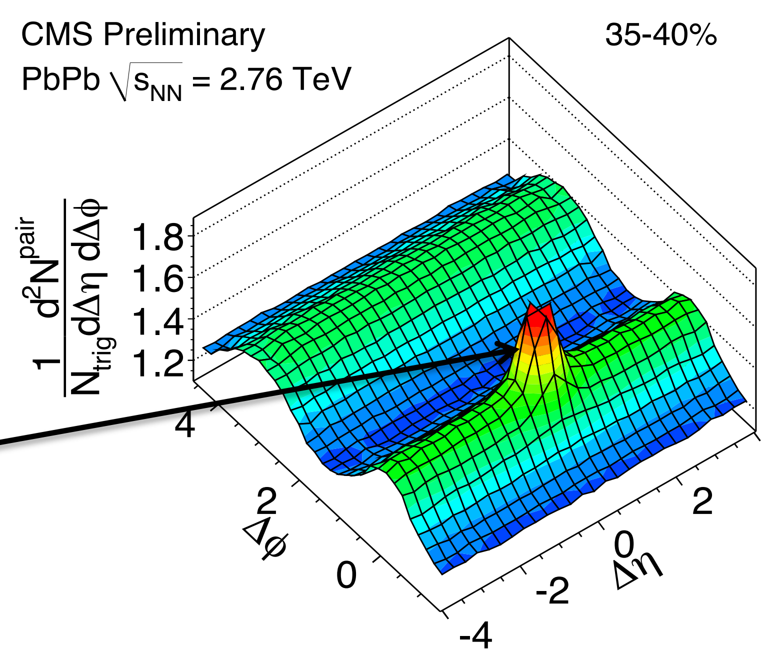
How about factorization ratio?

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

Problem:

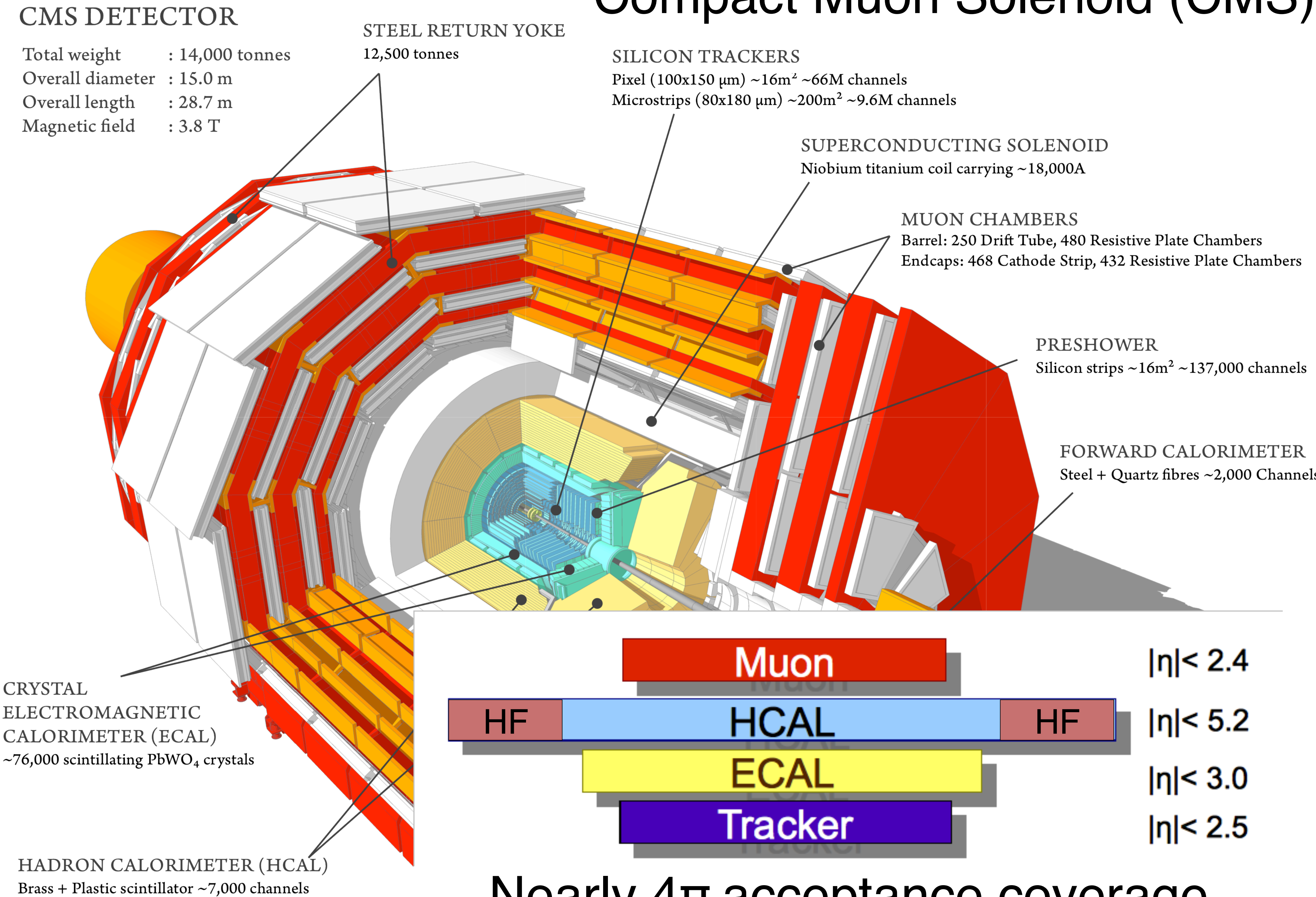
A narrow window of $\Delta\eta \sim 0$

➔ significant nonflow from near-side peak (jets, clusters, resonances etc.)



Need to find a way to always guarantee a large $\Delta\eta$!

Compact Muon Solenoid (CMS)



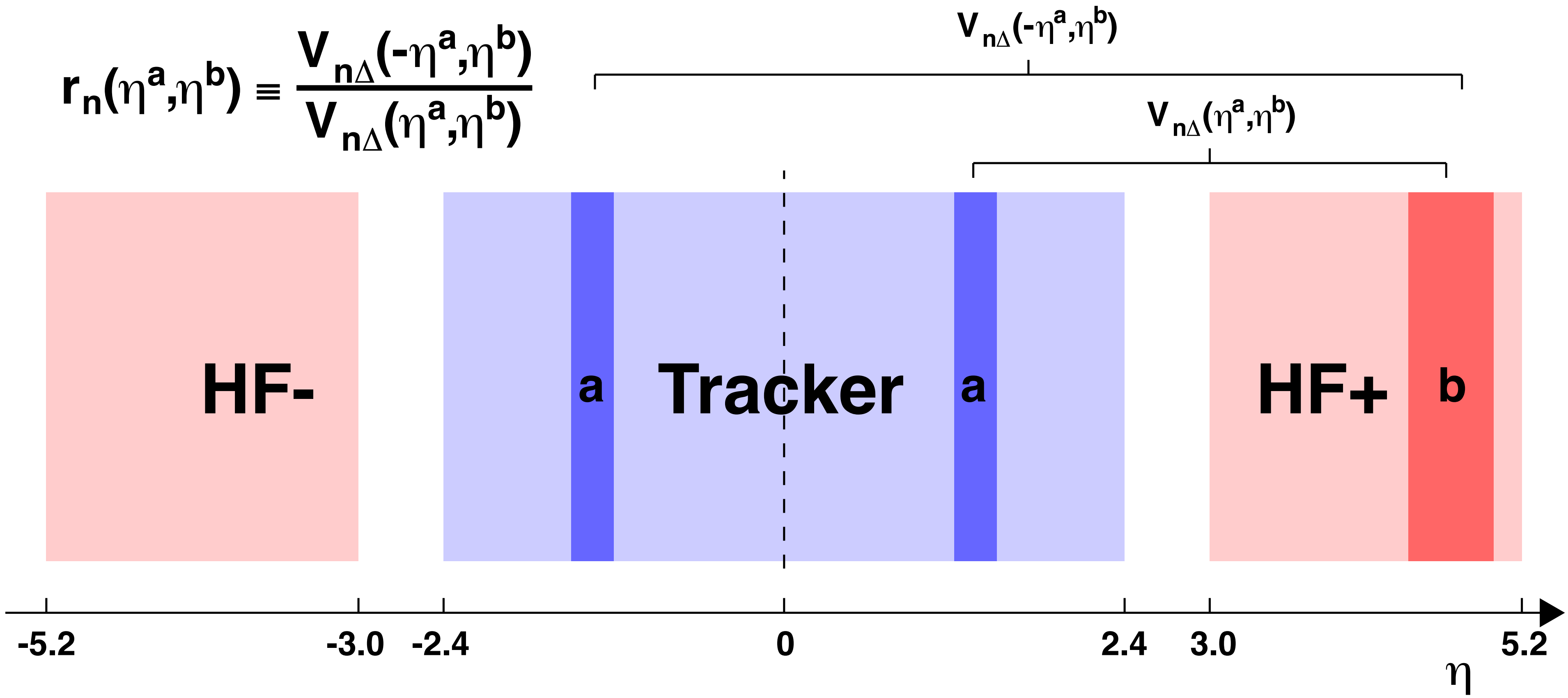
Nearly 4π acceptance coverage

How to extract $\Psi_n(\eta)$ fluctuations?

Redefine "factorization ratio":

$$V_{n\Delta}(\eta^a,\eta^b) = \langle\langle \cos[n(\phi^a - \phi^b)] \rangle\rangle$$

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



HF towers (tracks) weighted by E_T (p_T)

CMS, arXiv:1503.01692

Ensure all pairs used have η gap > 2 units!

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,

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

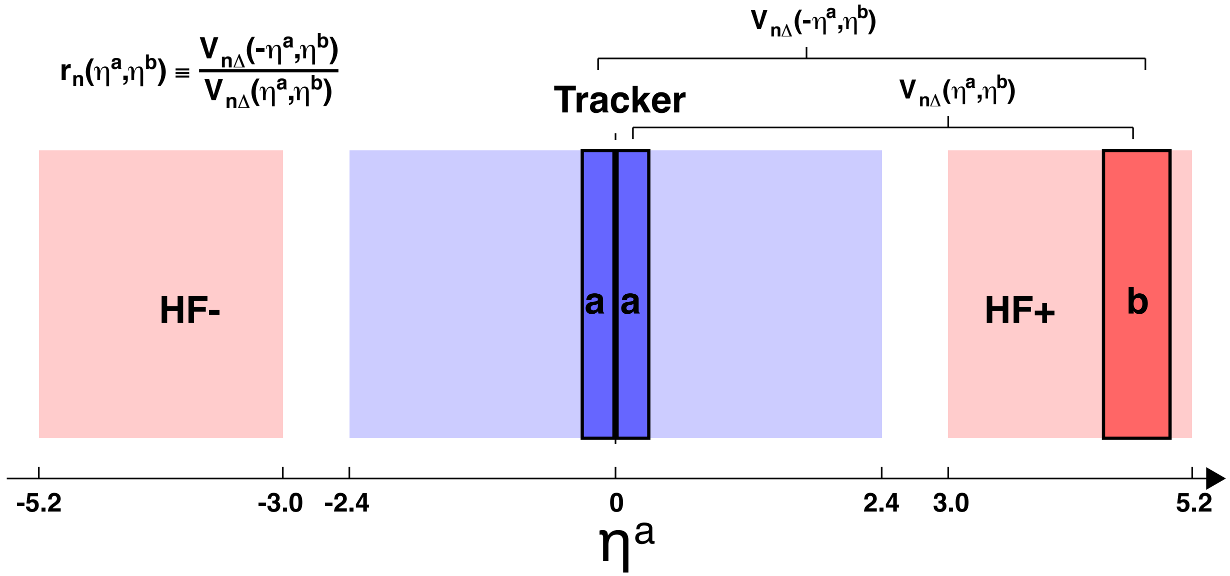
Otherwise,

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

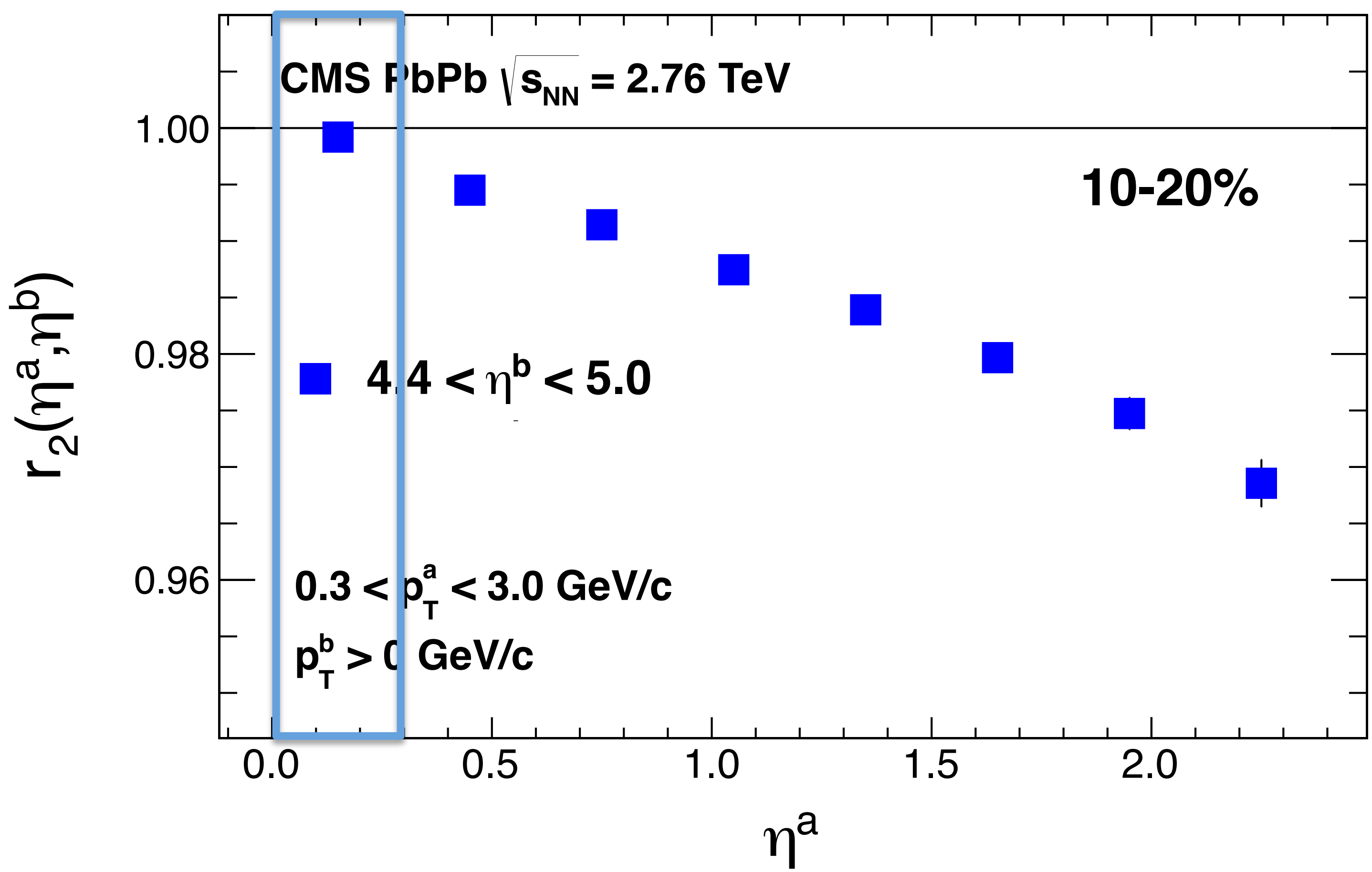
$$\sim \frac{\langle \cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\rangle}{\langle \cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\rangle}$$ (for symmetric system)

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

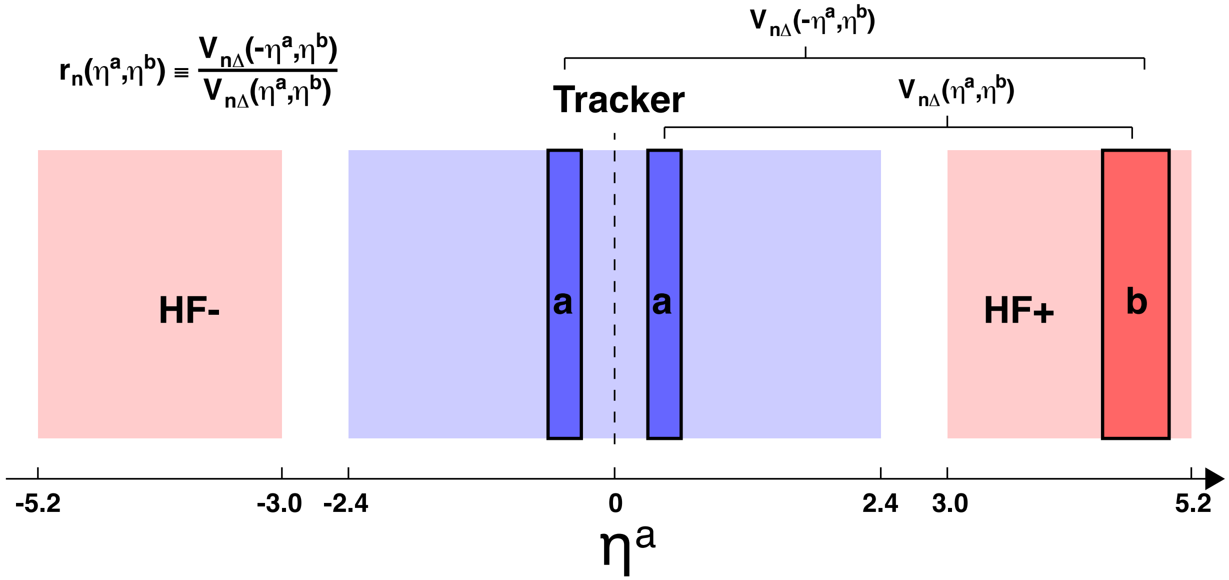
(two EPs separated a gap of $2\eta^a$)



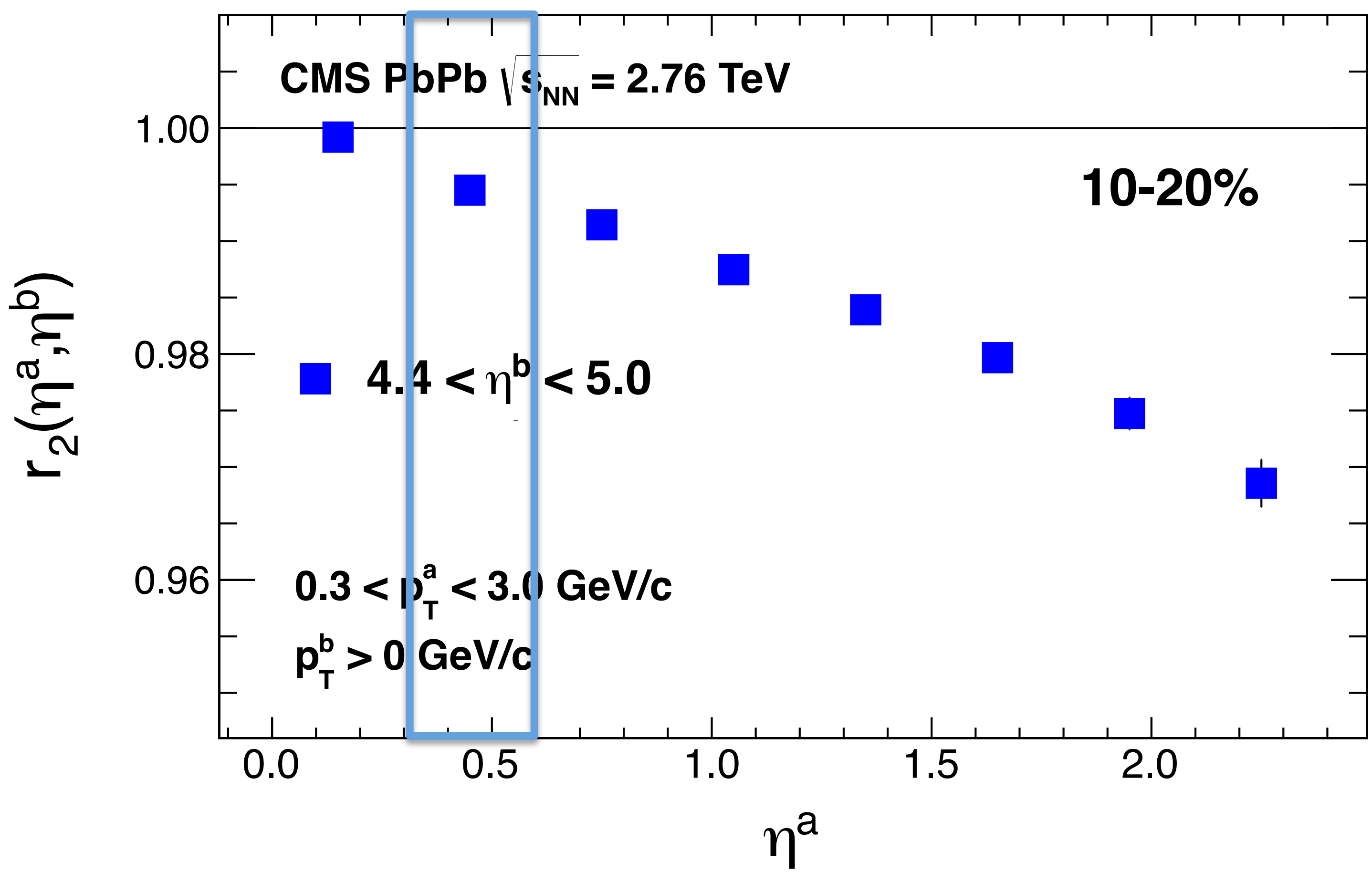
$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle, \ \Delta\eta = 2\eta^a$$



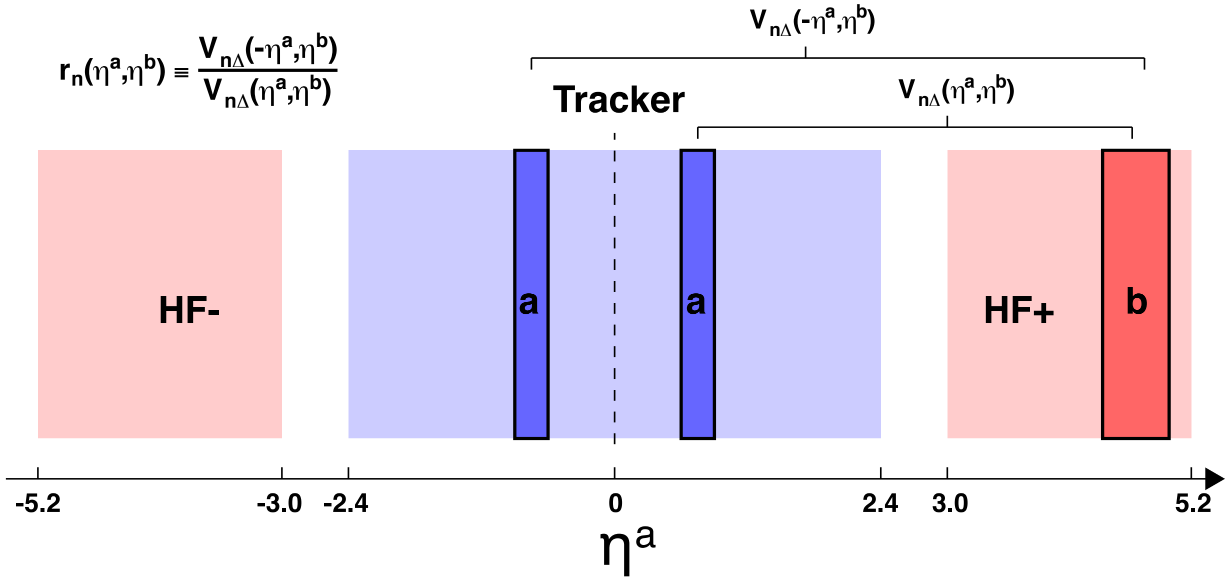
Decorrelation of Ψ_2 as $\Delta\eta$ increases



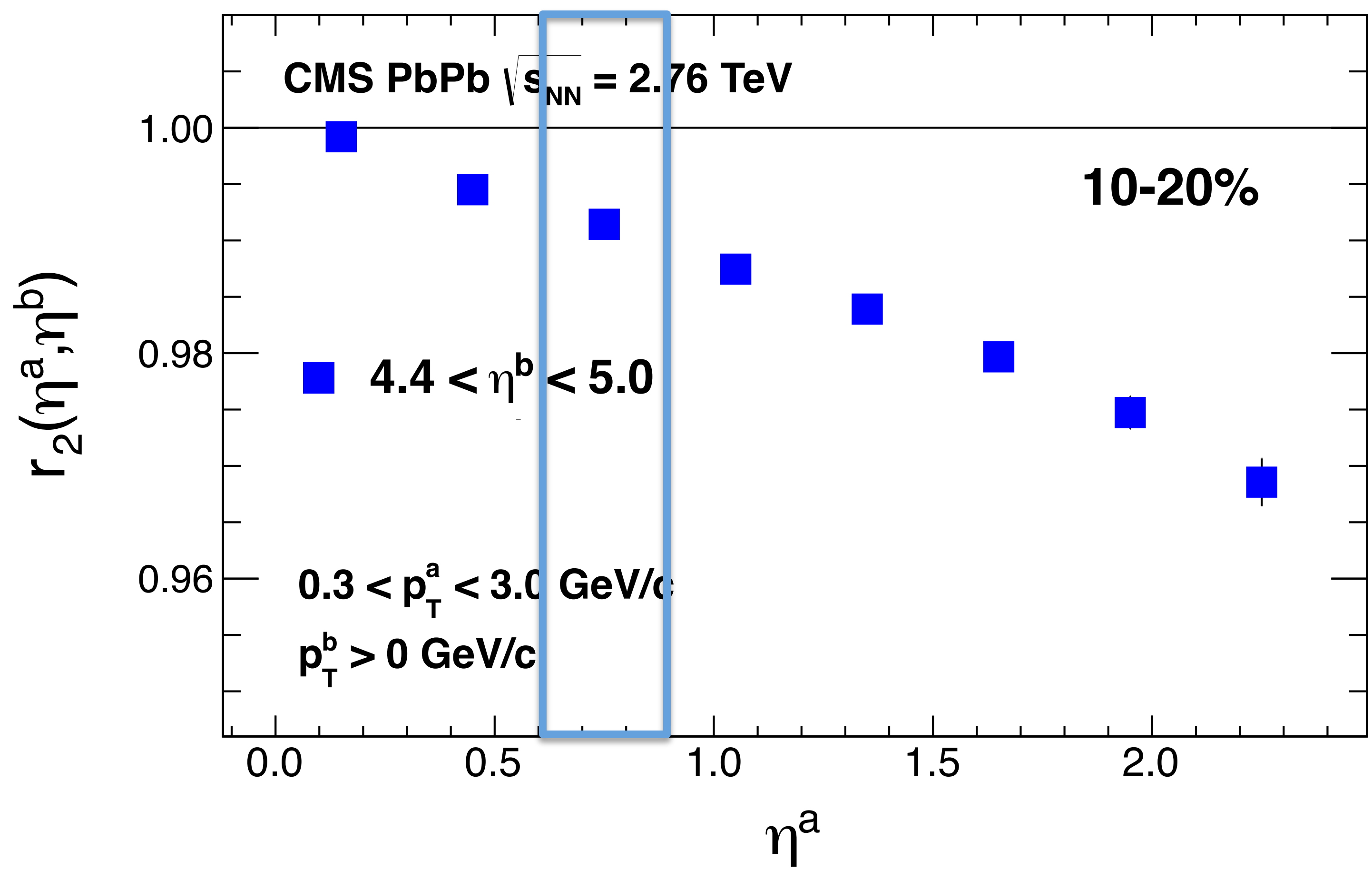
$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle,\ \Delta\eta = 2\eta^a$$



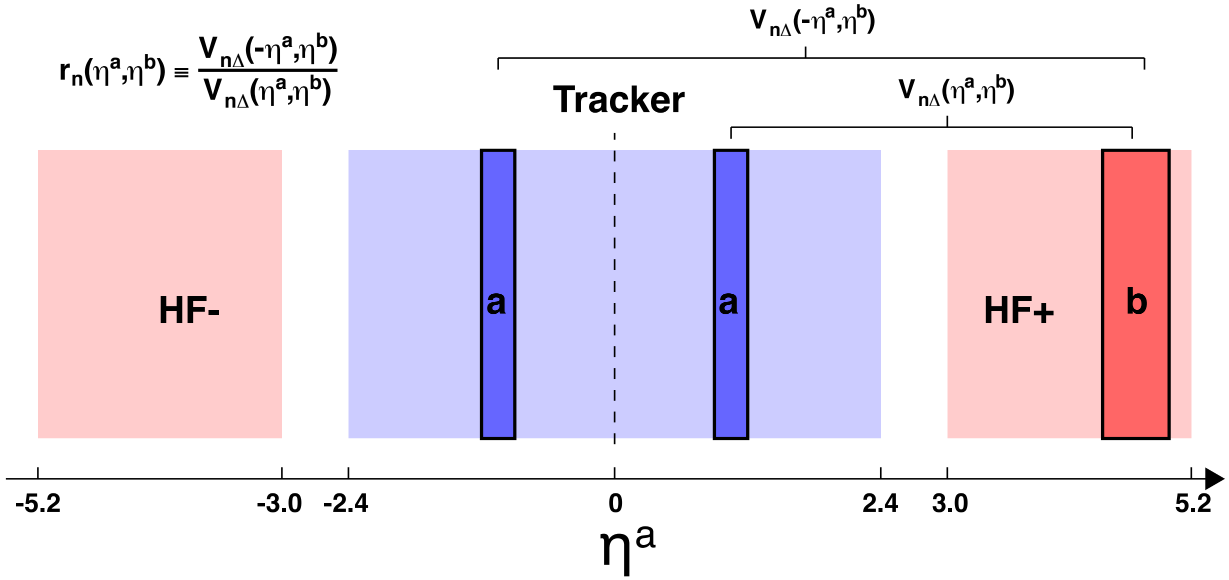
Decorrelation of Ψ_2 as $\Delta\eta$ increases



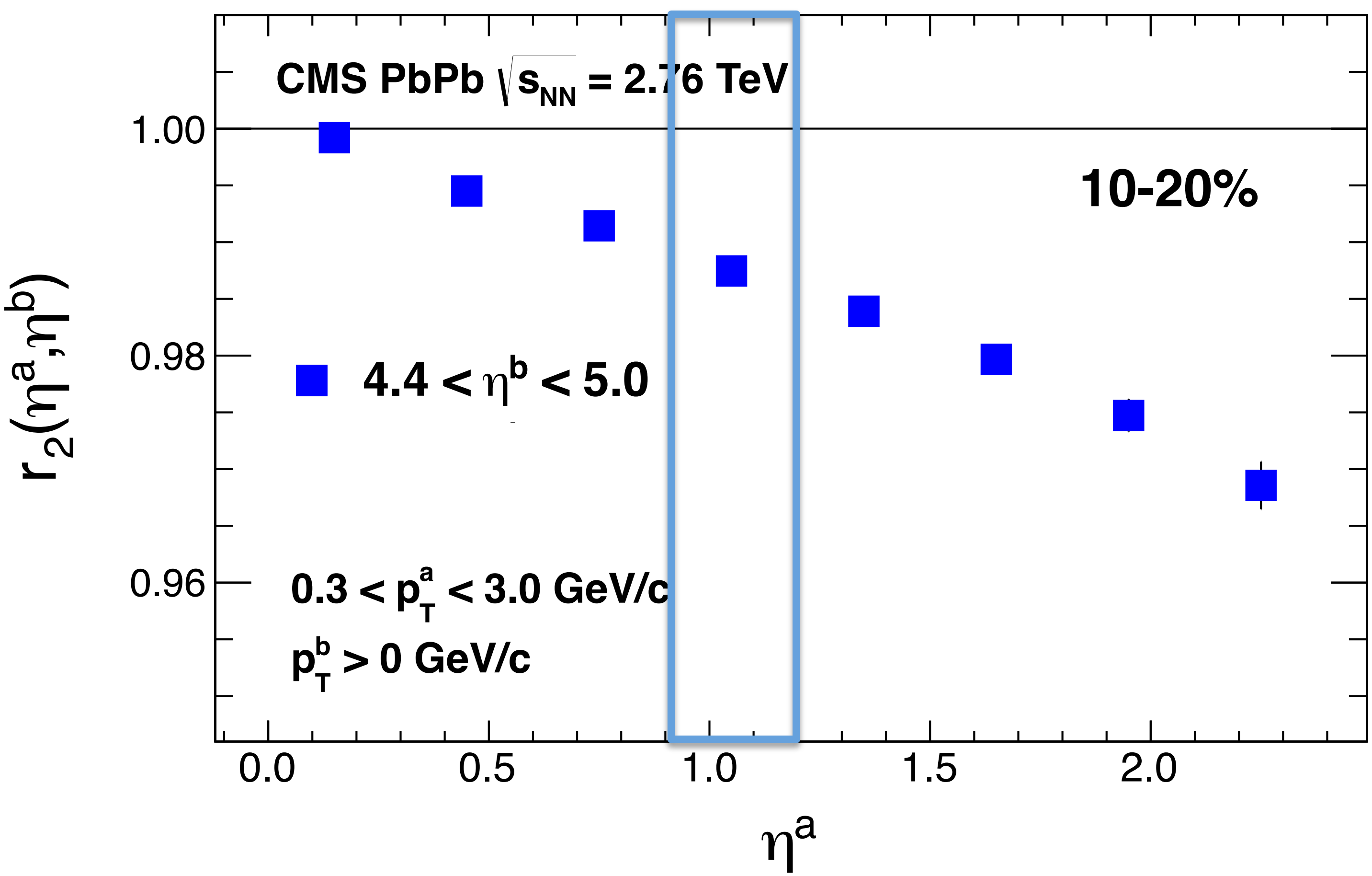
$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle,\ \Delta\eta = 2\eta^a$$



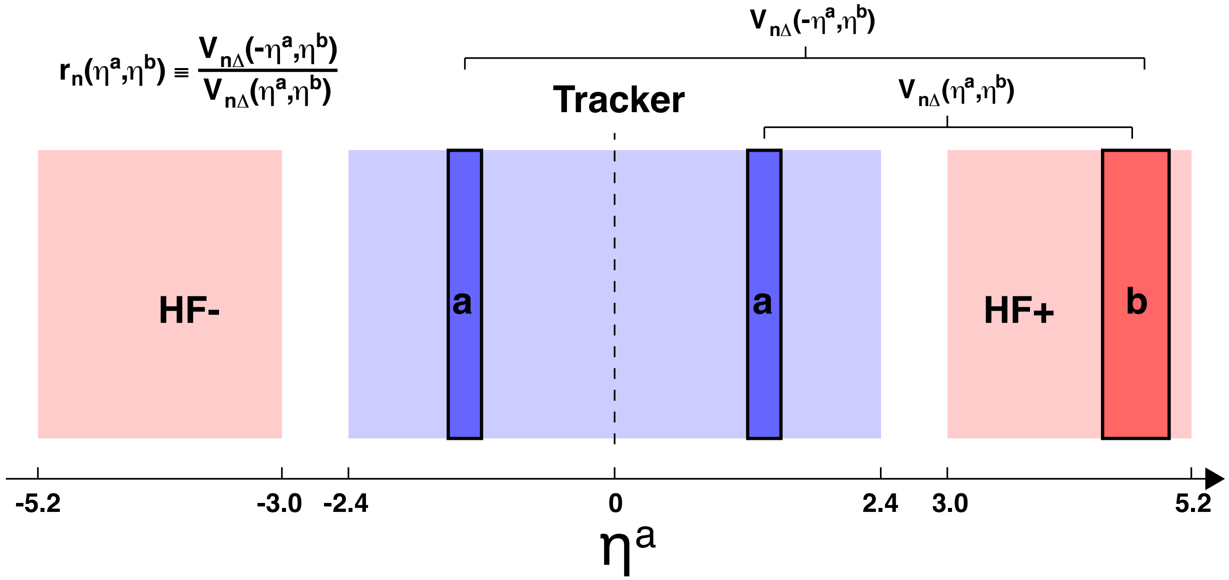
Decorrelation of Ψ_2 as $\Delta\eta$ increases



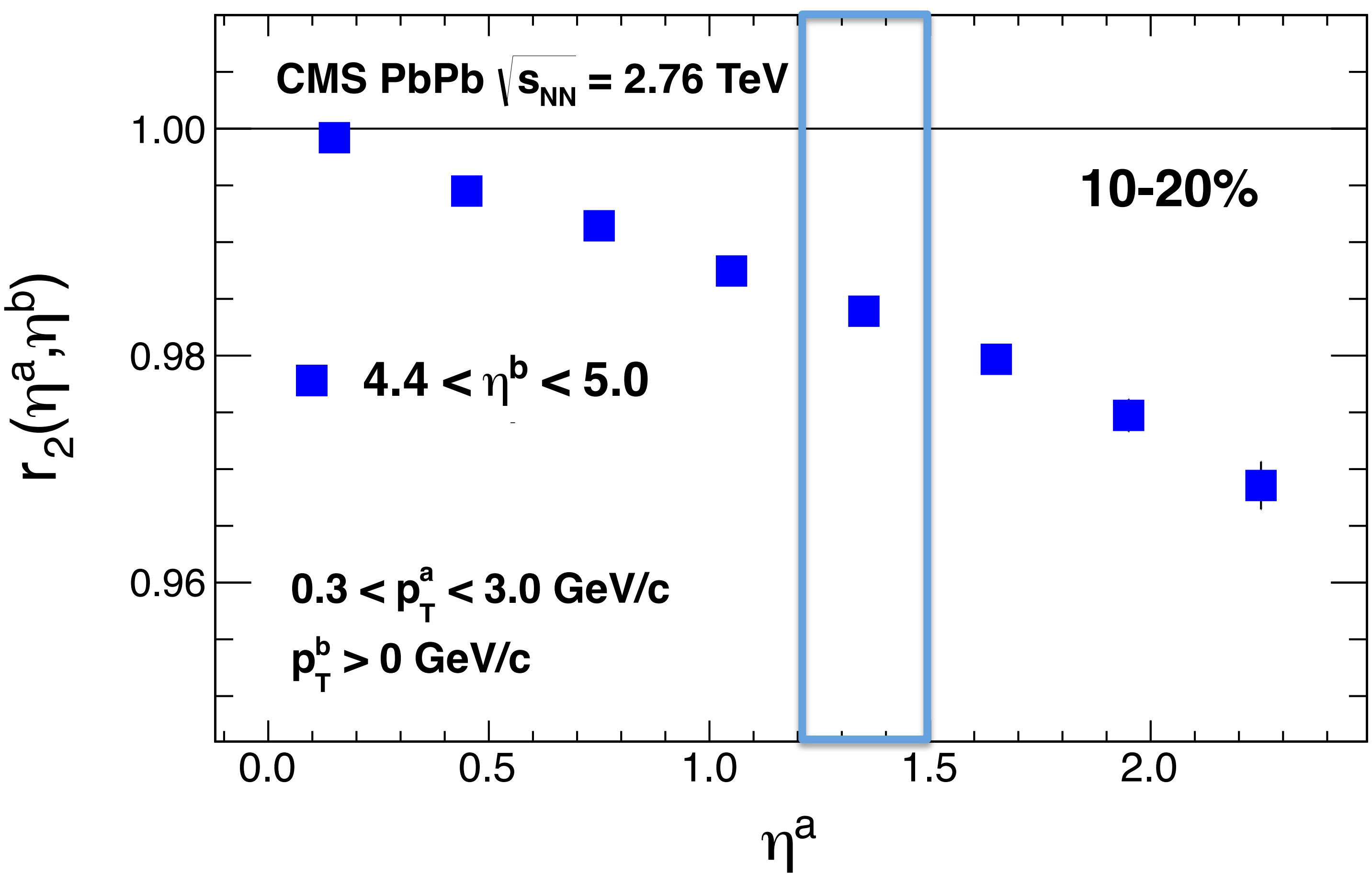
$$r_2(\eta^a,\eta^b) \approx \langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \rangle, \ \Delta\eta = 2\eta^a$$



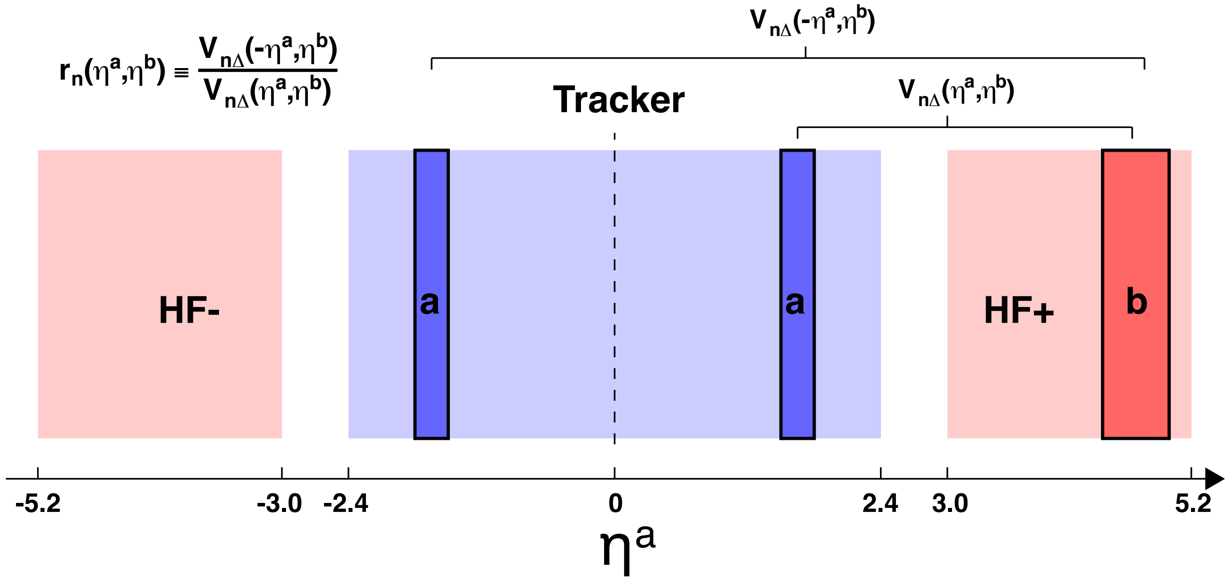
Decorrelation of Ψ_2 as $\Delta\eta$ increases



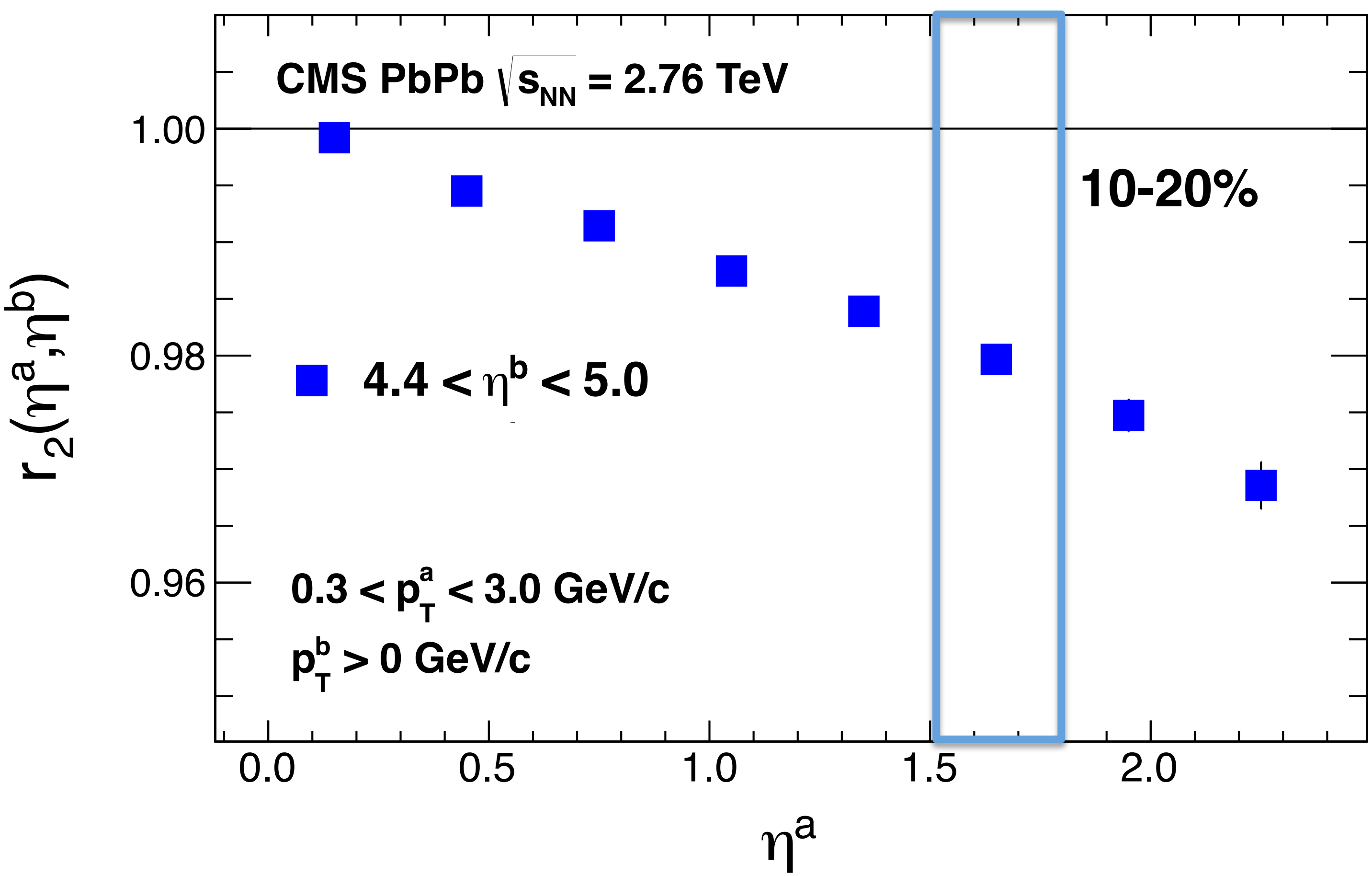
$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle, \ \Delta\eta = 2\eta^a$$



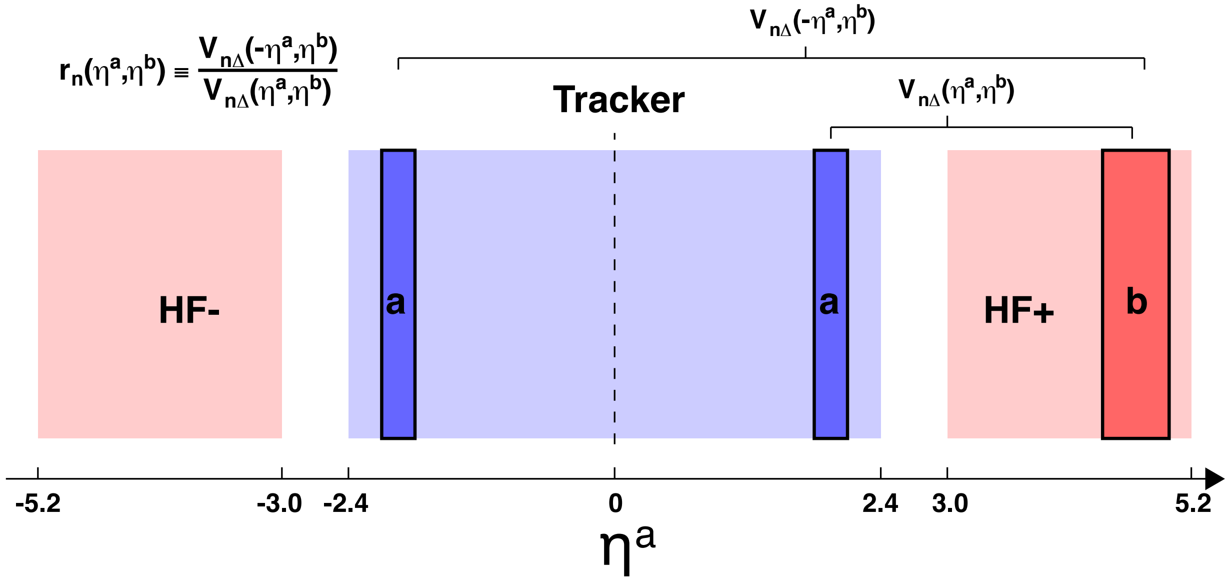
Decorrelation of Ψ_2 as $\Delta\eta$ increases



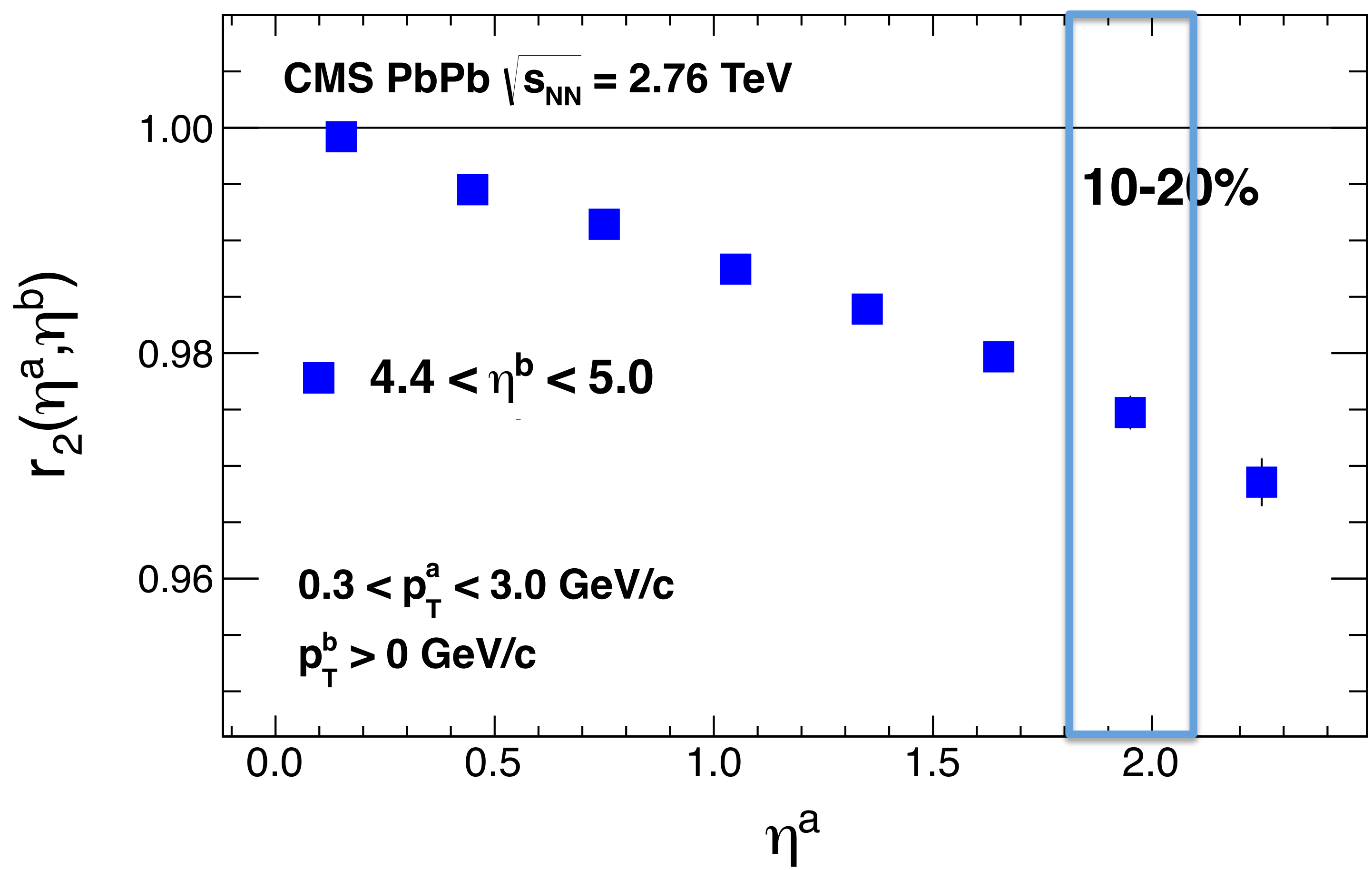
$$r_2(\eta^a,\eta^b) \approx \left\langle \cos[2(\Psi_2(\eta^a) - \Psi_2(-\eta^a))] \right\rangle,\ \Delta\eta = 2\eta^a$$

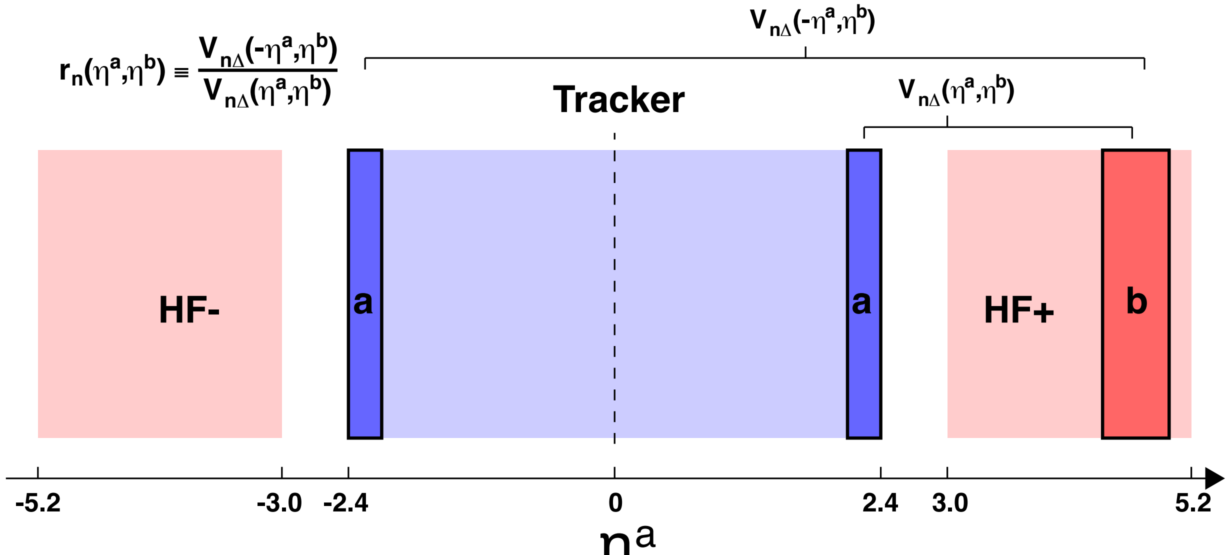


Decorrelation of Ψ_2 as $\Delta\eta$ increases



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

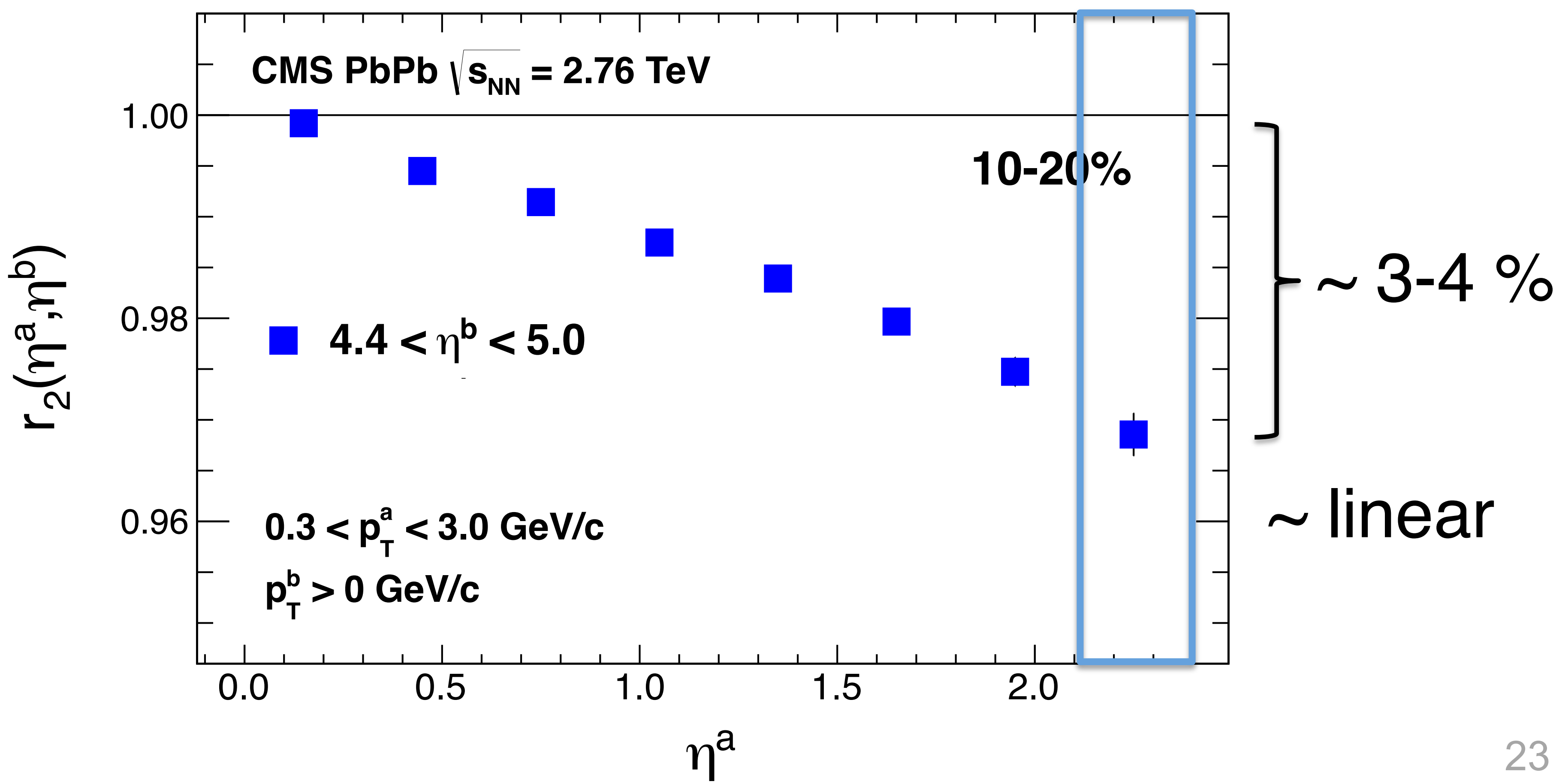




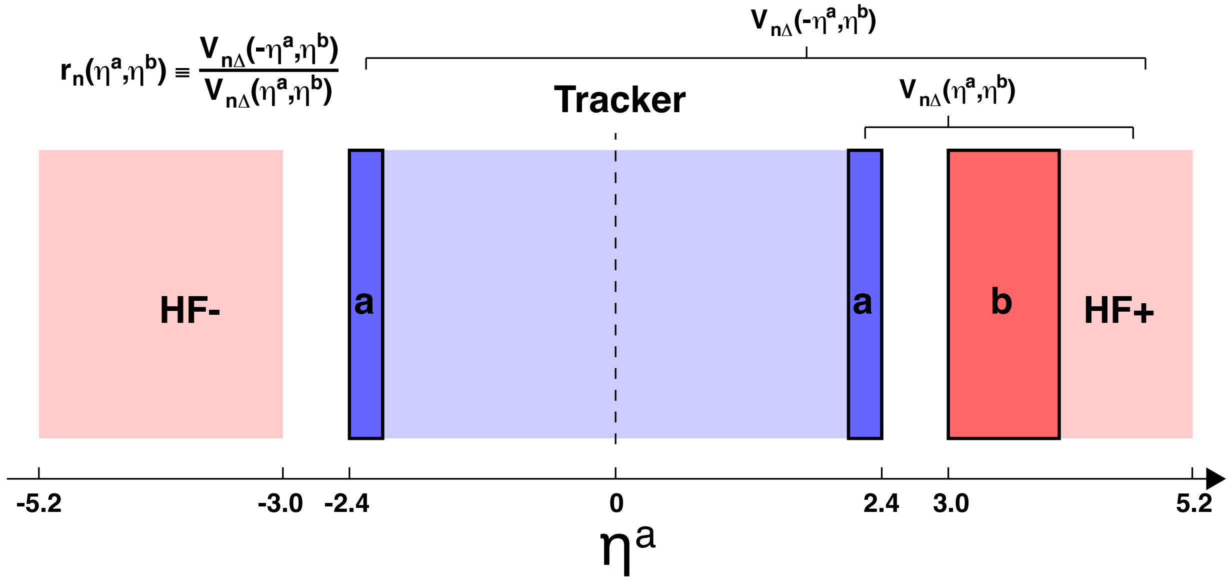
Decorrelation of Ψ_2 as $\Delta\eta$ increases

η gap ≥ 2 units between a and b

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

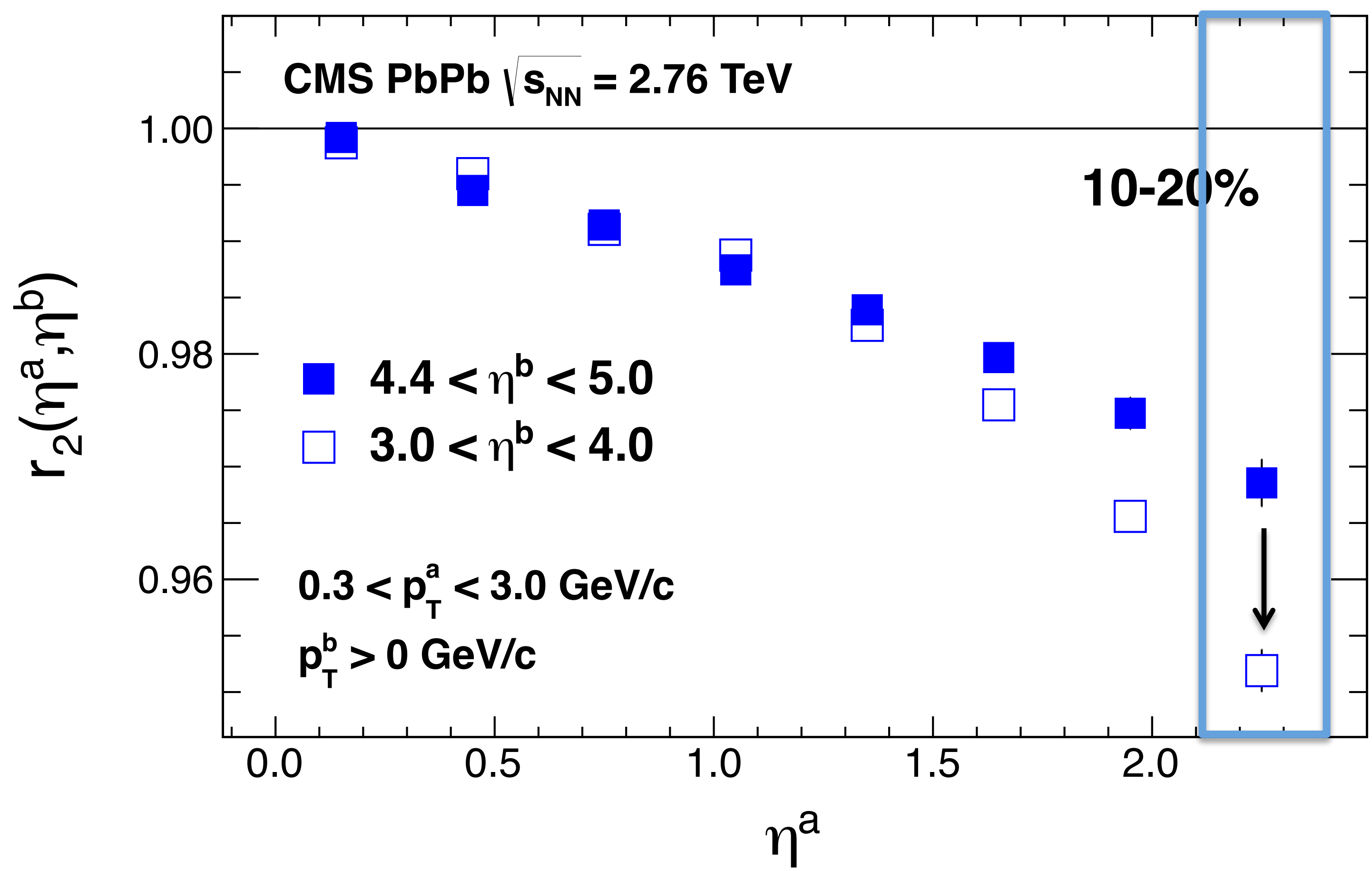


Let's vary η_b as well

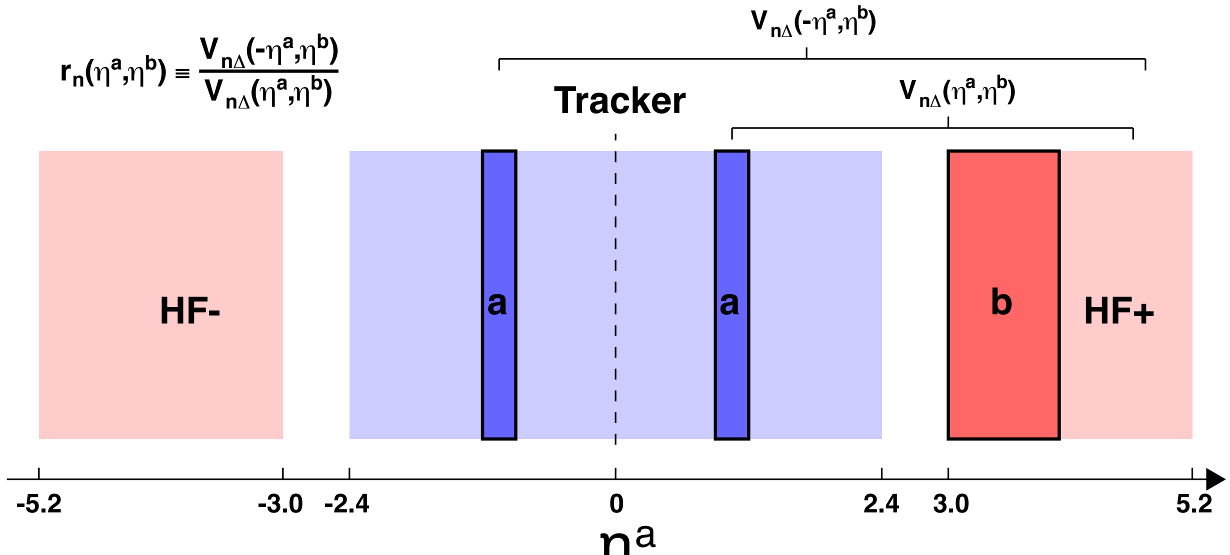


When $\Delta\eta$ is small for denominator, short-range correlations pull r_2 down

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



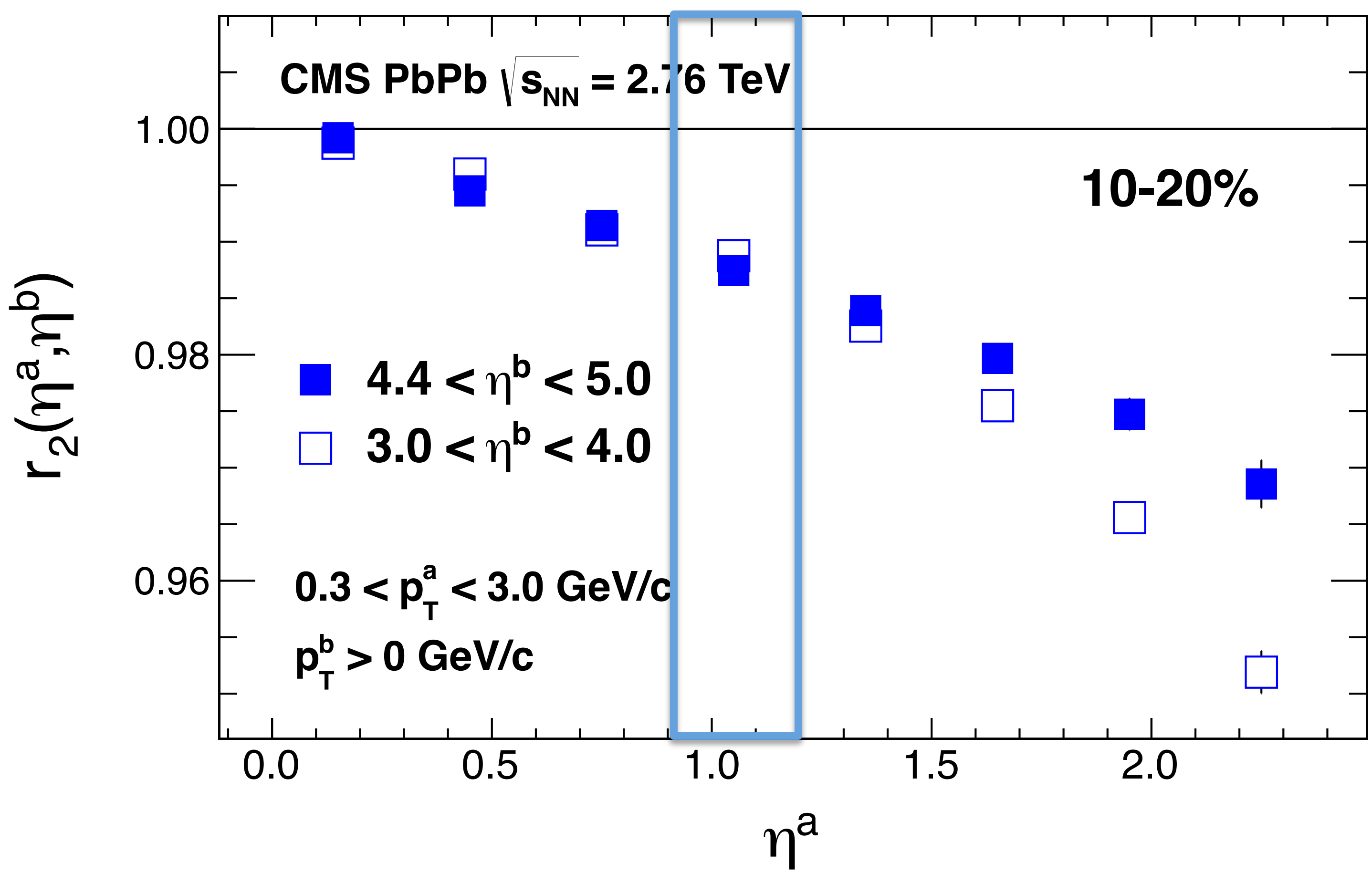
Let's vary η_b as well



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

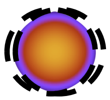
r_2 consistent for both η^b ranges if $\Delta\eta$ is large

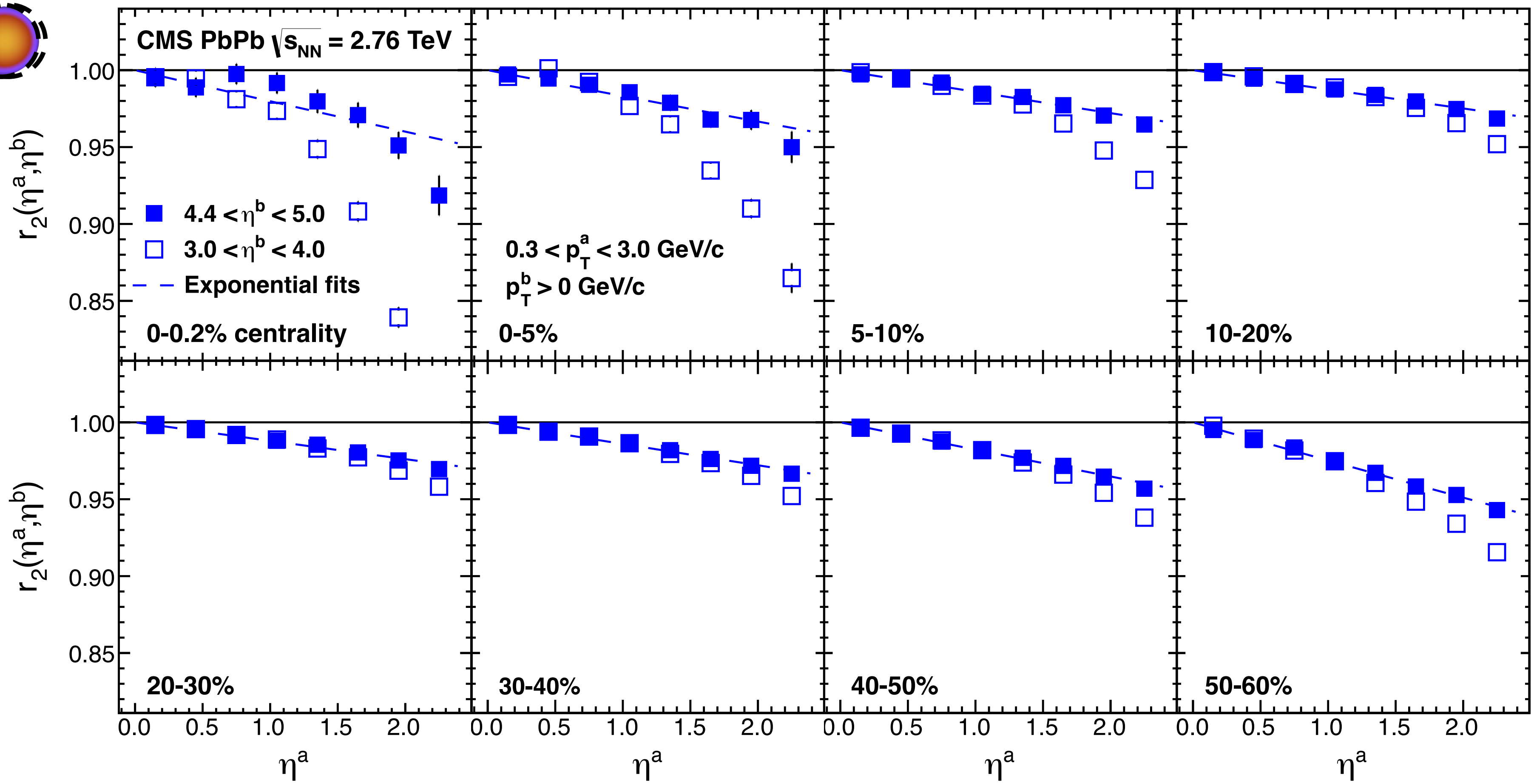
For long-range correlations, r_2 is largely η^b independent

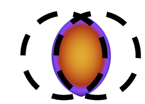


Centrality dependence of $r_2(\eta^a,\eta^b)$ in PbPb

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

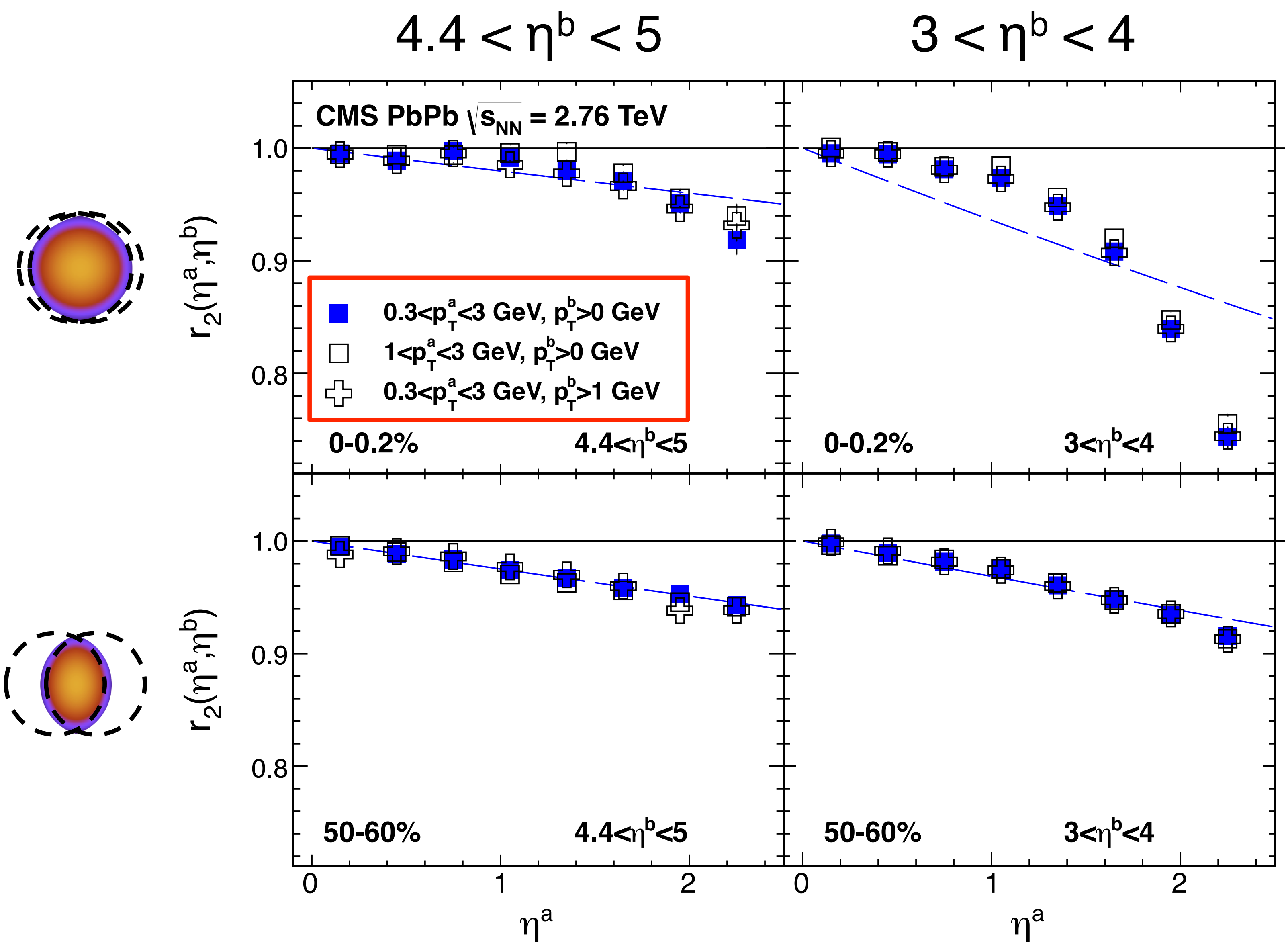






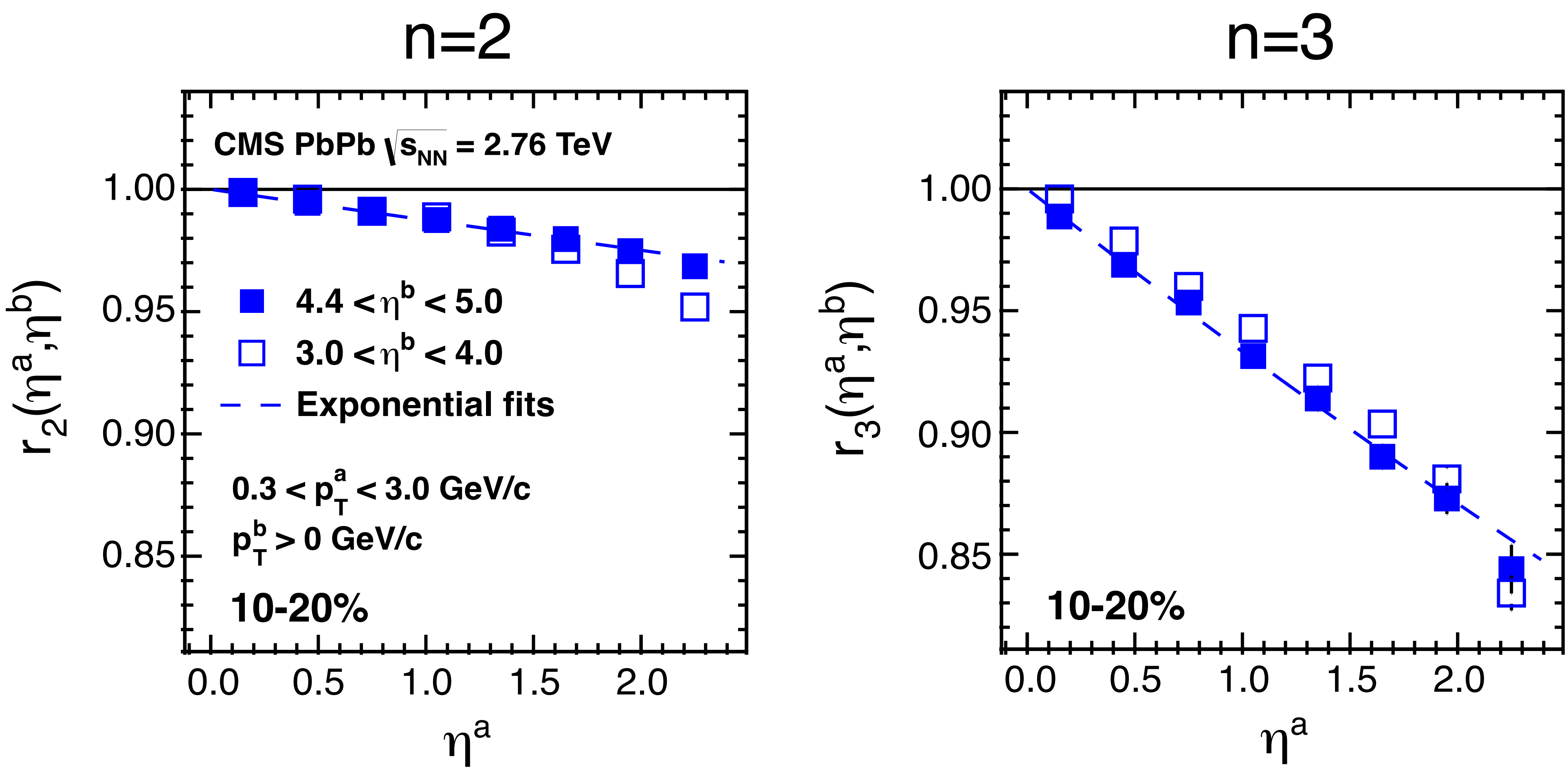
Roughly linear increase with η gap, except for 0-0.2% centrality

Nearly no p_T dependence …



Indication of an initial-state effect !?

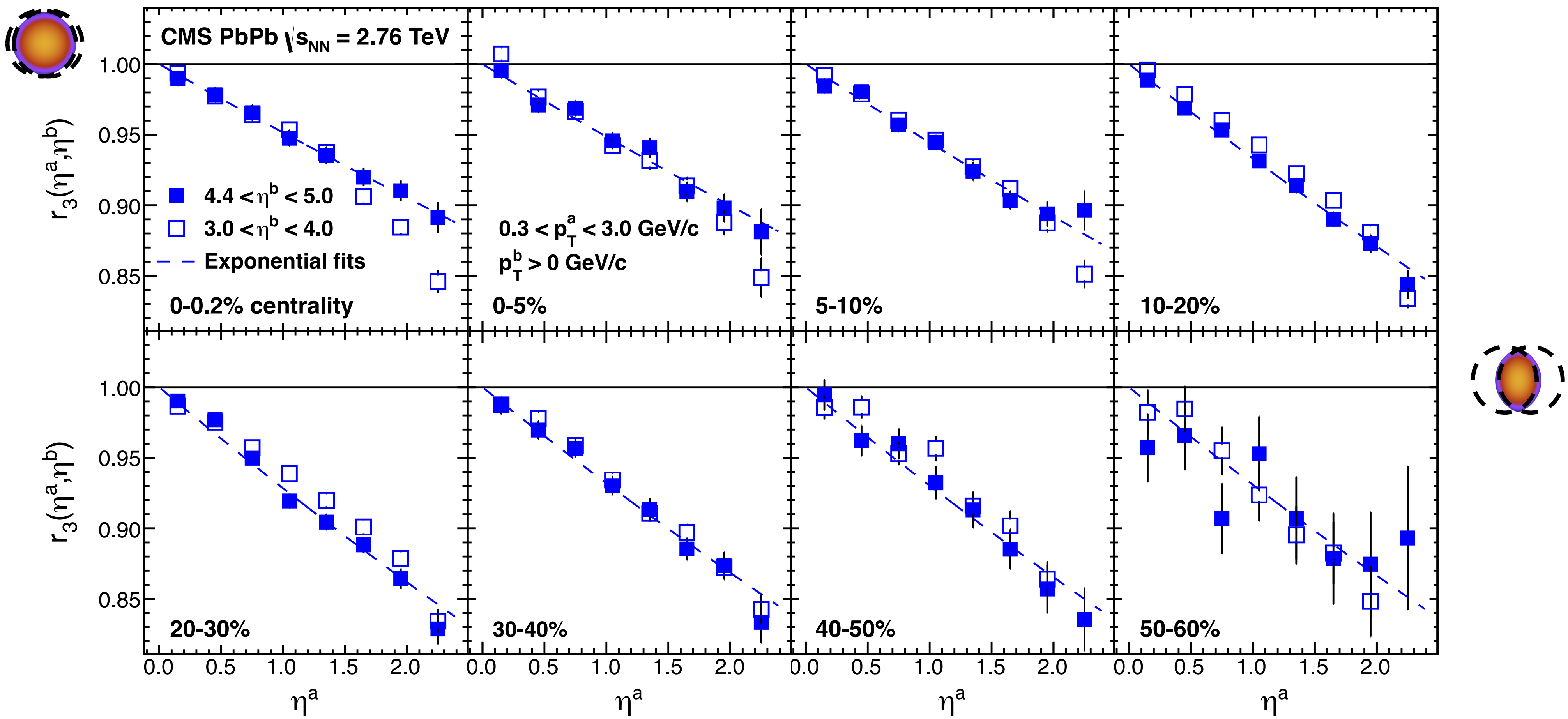
Higher-order $r_n(\eta^a,\eta^b)$ in PbPb



Much stronger effect up to 15% for n=3,
as it is entirely driven by fluctuations

Centrality dependence of $r_3(\eta^a,\eta^b)$ in PbPb

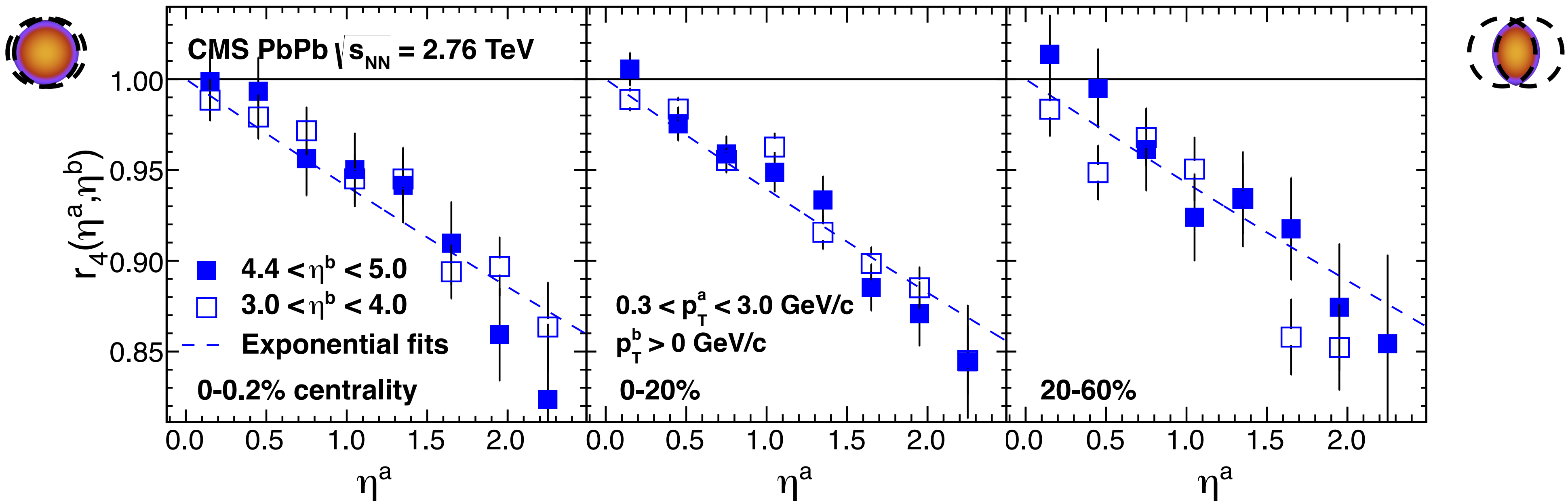
$$r_3(\eta^a,\eta^b) \approx \left\langle \cos[3(\Psi_3(\eta^a) - \Psi_3(-\eta^a))] \right\rangle$$



Little centrality dependent, consistent with expectation?

Centrality dependence of $r_4(\eta^a,\eta^b)$ in PbPb

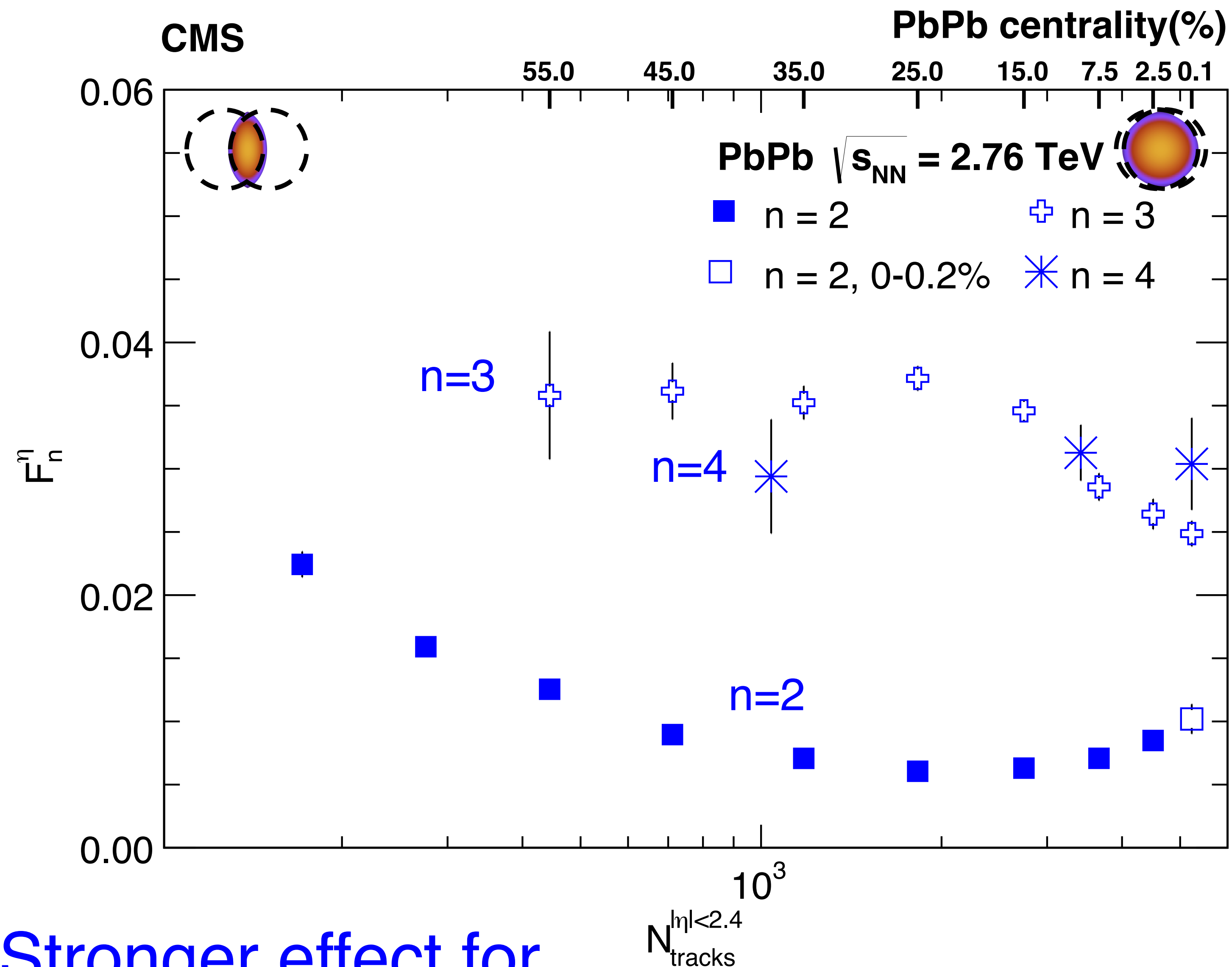
$$r_4(\eta^a,\eta^b) \approx \left\langle \cos[4(\Psi_4(\eta^a) - \Psi_4(-\eta^a))] \right\rangle$$



Also roughly linear increase with η gap

r_4 is related to r_2, esp. for peripheral events (linear vs non-linear contributions)

Empirical parameterization: $r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \approx 1 - 2F_n^\eta \eta^a$

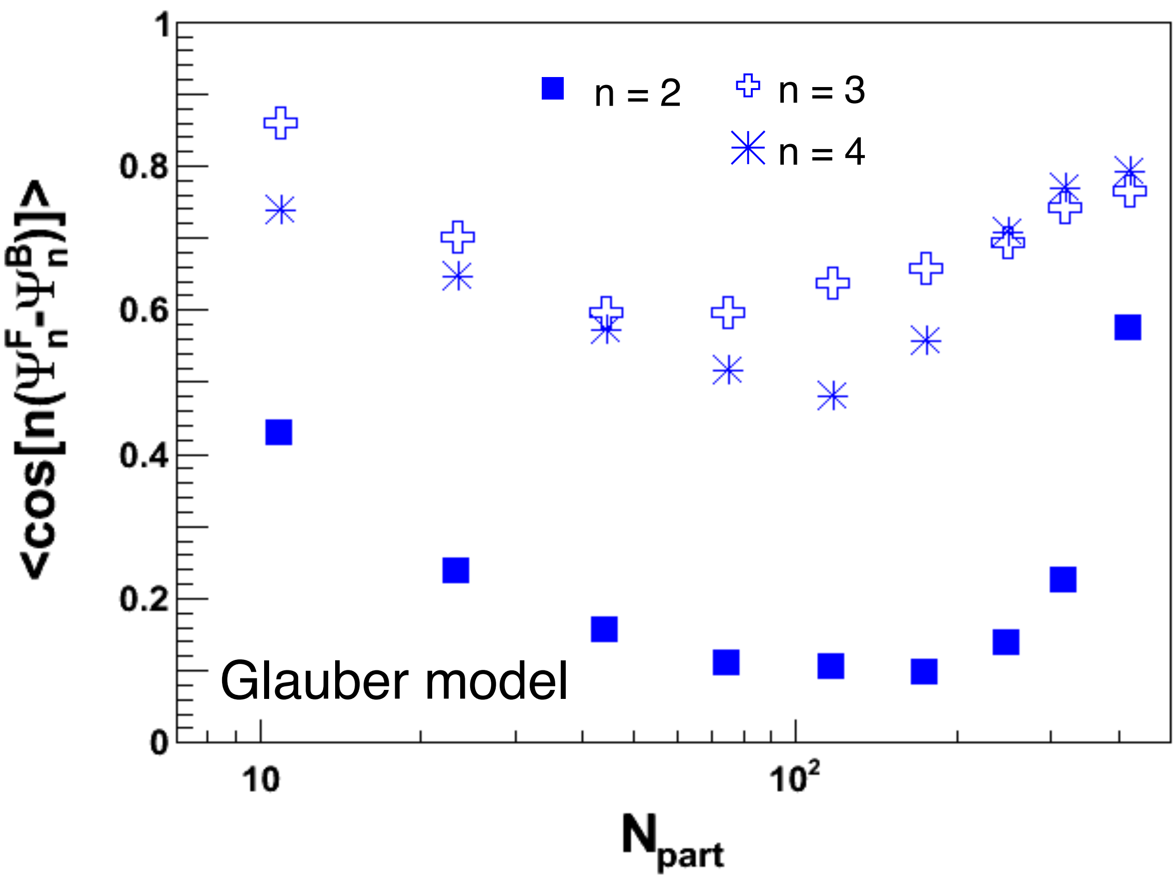


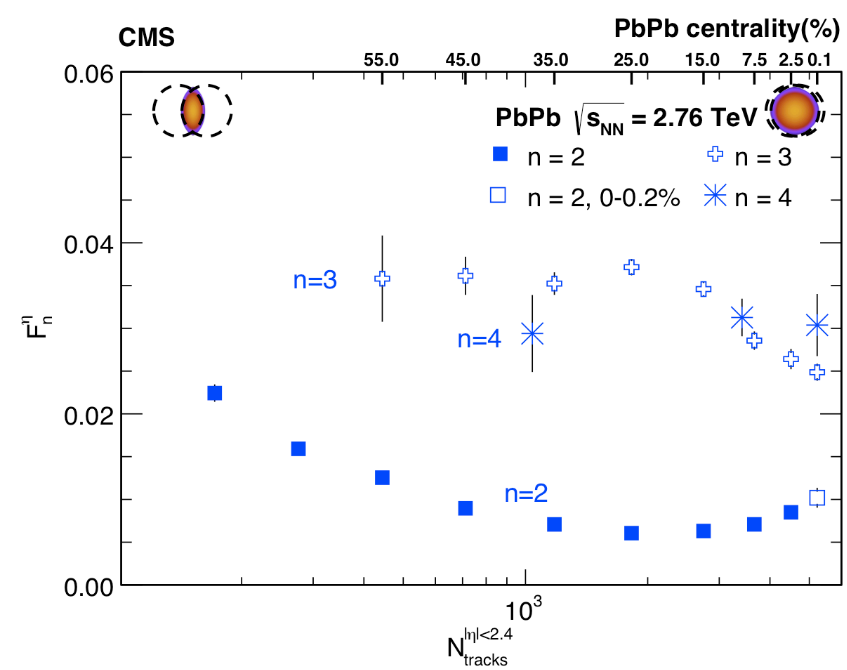
Stronger effect for

- Peripheral events
- higher-order n

Trend qualitatively consistent with participant fluctuations in Glauber model

F-B participant plane fluctuations



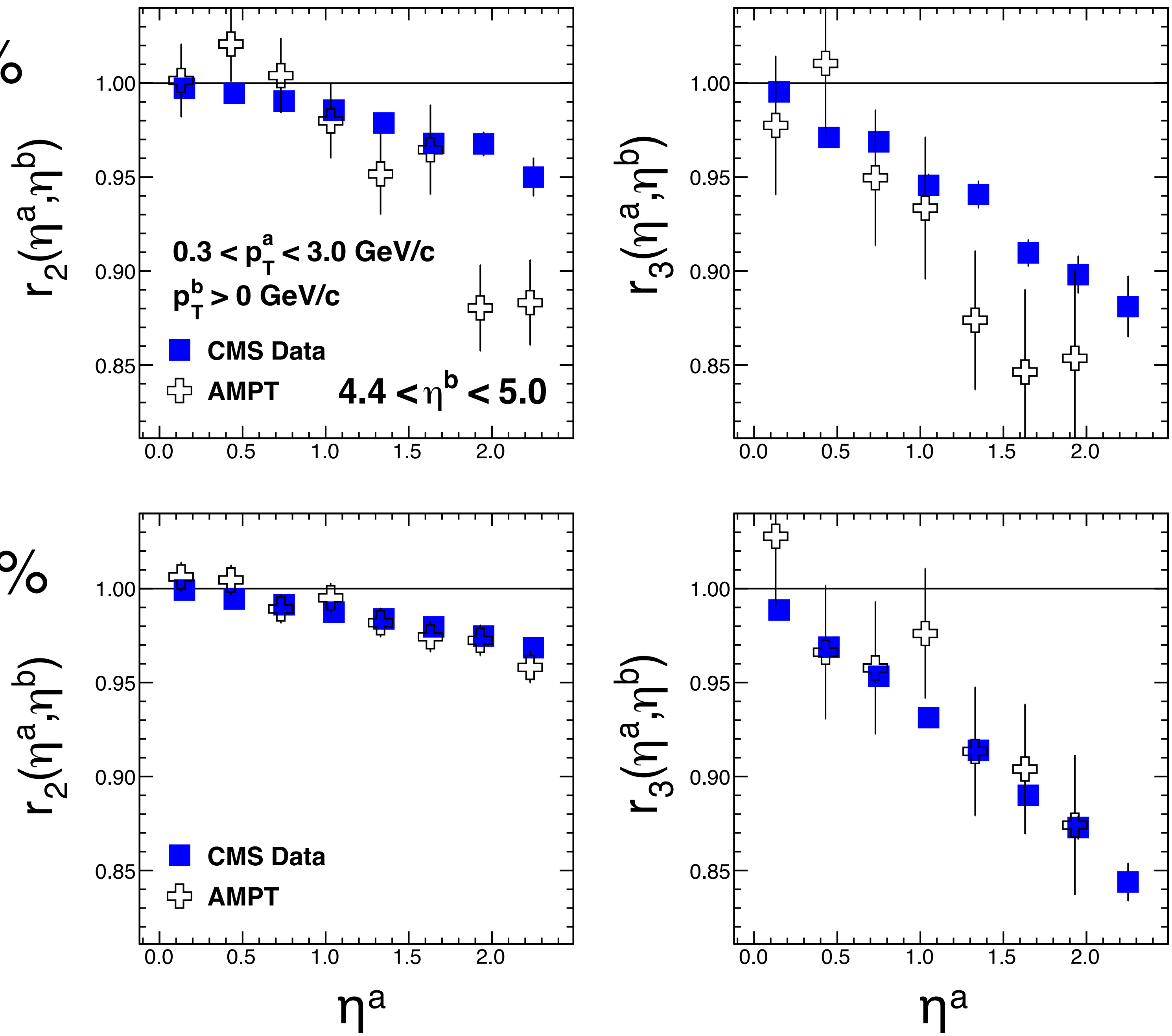


But details depend on dynamics

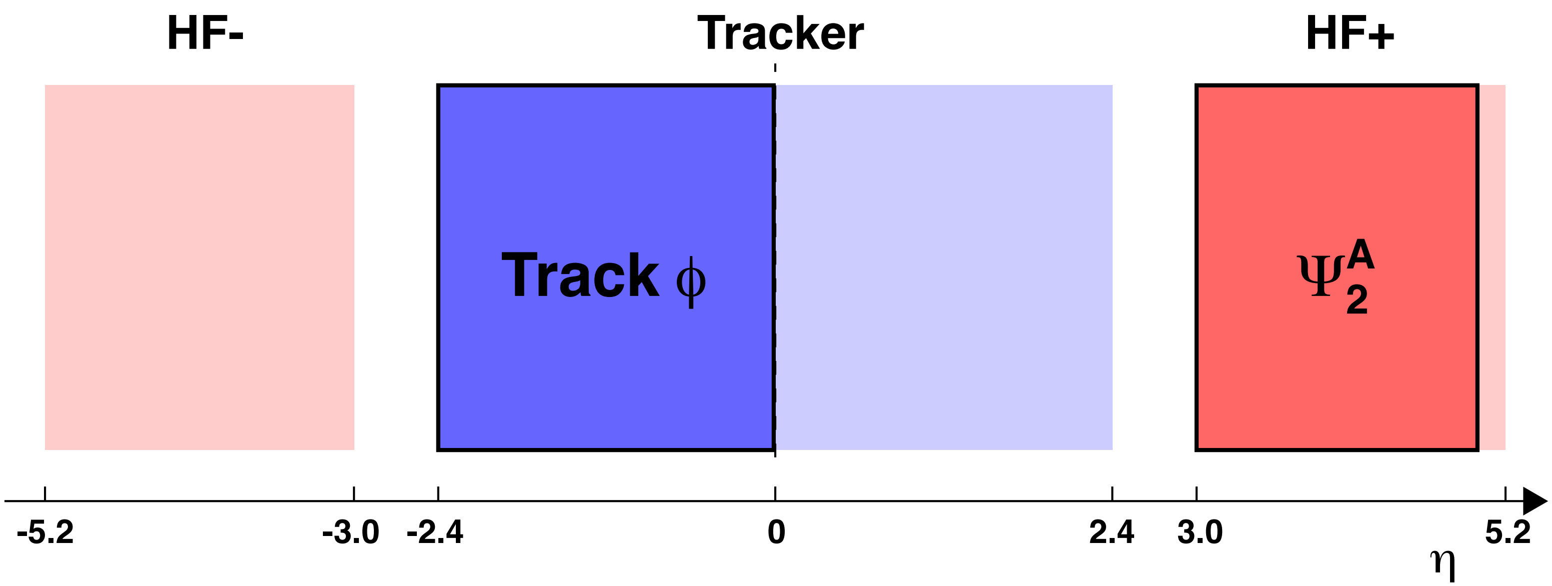
Comparison with AMPT model

0-5%

10-20%

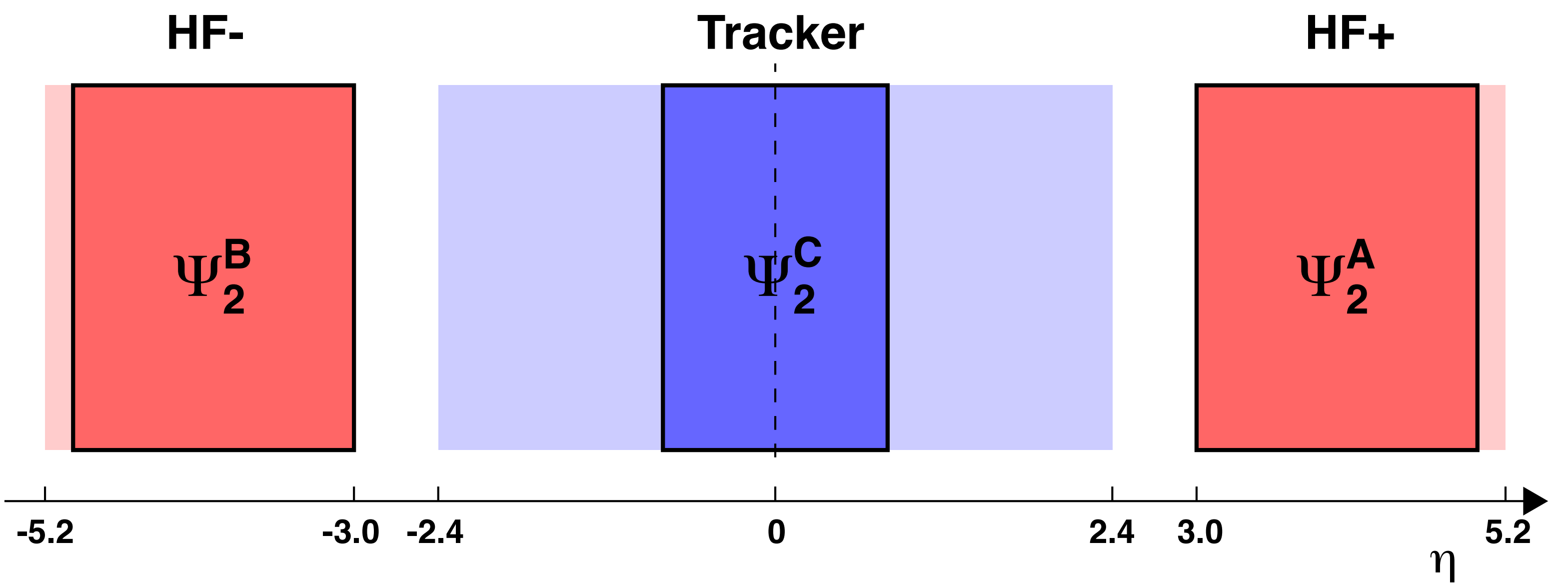


How is $v_2\{EP\}$ affected by EP decorrelations?



$$v_2 = \frac{v_2^{obs}}{R_A} = \frac{\left\langle \cos 2(\phi - \Psi_2^A) \right\rangle}{R_A} \quad \Delta\eta \geq 3$$

How is $v_2\{EP\}$ affected by EP decorrelations?

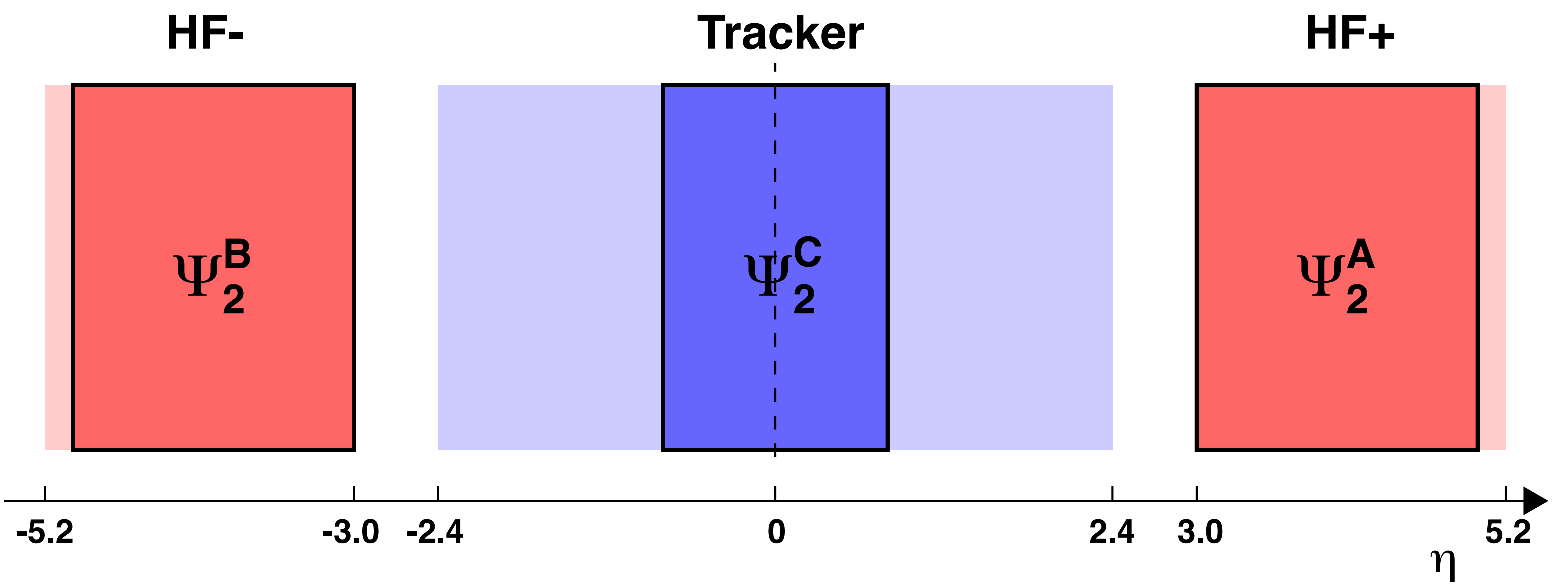


$$v_2 = \frac{v_2^{obs}}{R_A} = \frac{\left\langle \cos 2(\phi - \Psi_2^A) \right\rangle}{R_A} \quad \Delta\eta \geq 3$$

Resolution correction:

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

How is v_2\{EP\} affected by EP decorrelations?



If Ψ_2 depends on η

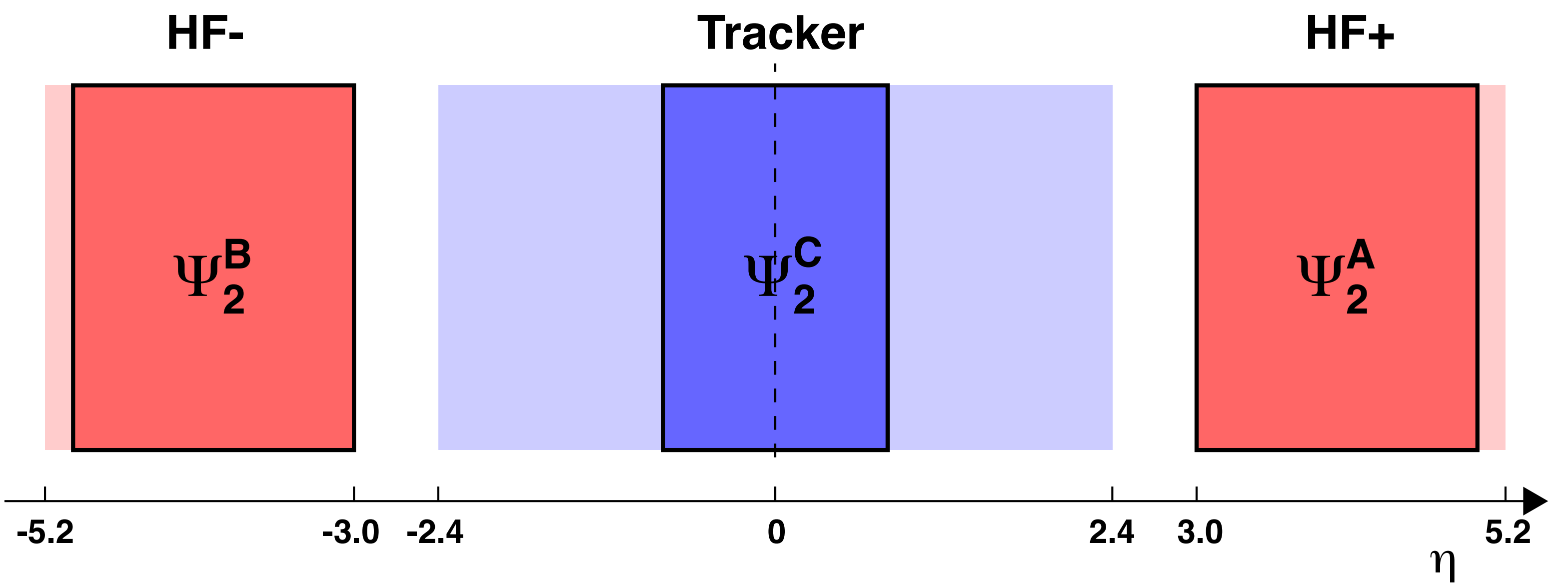
$$R_A = R_A^{res}\sqrt{\frac{\langle\cos(2(\Psi_2^+ - \Psi_2^-))\rangle\langle\cos(2(\Psi_2^+ - \Psi_2^0))\rangle}{\langle\cos(2(\Psi_2^- - \Psi_2^0))\rangle}}$$

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

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

$\Psi_2^+,\ \Psi_2^-,\ \Psi_2^0$: real EPs

How is $v_2\{EP\}$ affected by EP decorrelations?



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

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

$$\approx \frac{\langle \cos 2(\phi - \Psi_2^+) \rangle}{\langle \cos(2(\Psi_2^+ - \Psi_2^0)) \rangle} \approx \langle \cos 2(\phi - \Psi_2^0) \rangle$$

EP method measures v_2 w.r.t midrapidity EP

Some thoughts and remarks

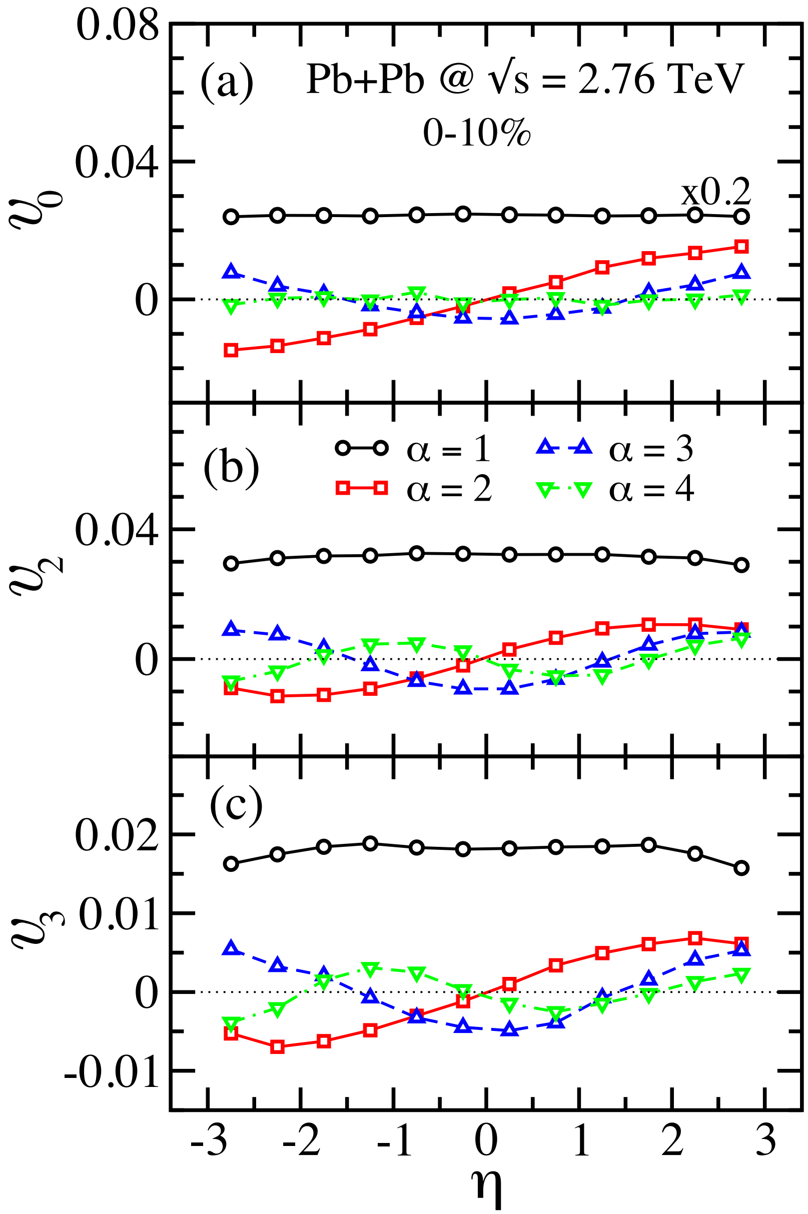
Will these studies invalidate all previous v_n results (assuming factorization)? **No, just need to be reinterpreted as v_n w.r.t. plane at a give (p_T, η)**

What particular constraints to 3D hydrodynamics from these data?

Could "extended longitudinal scaling" of v_2 somehow related to the plane decorrelations?

Principle Component Analysis (PCA) in η space

Bhalerao, PRL 114 (2015) 152301



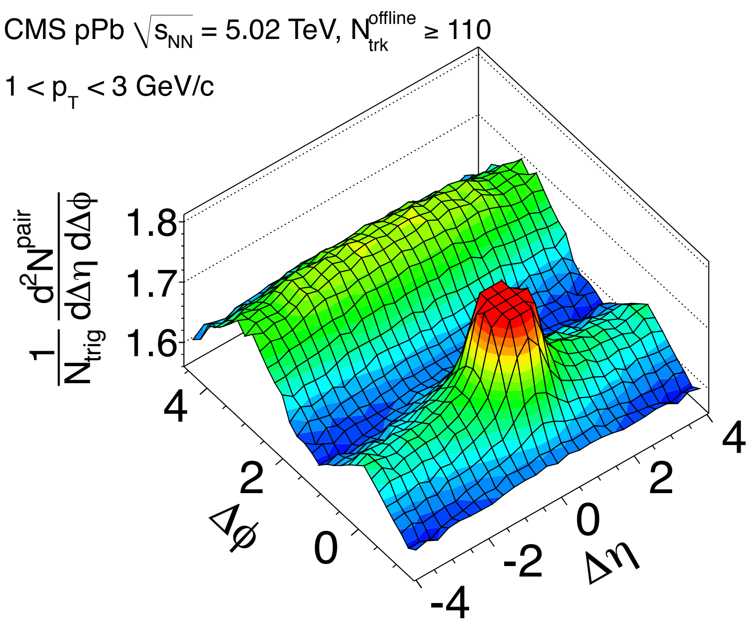
$$V_{n\Delta}(\eta^a,\eta^b) = \sum_{\alpha=1}^{k} V_n^{(\alpha)}(\eta^a) V_n^{(\alpha)*}(\eta^b)$$

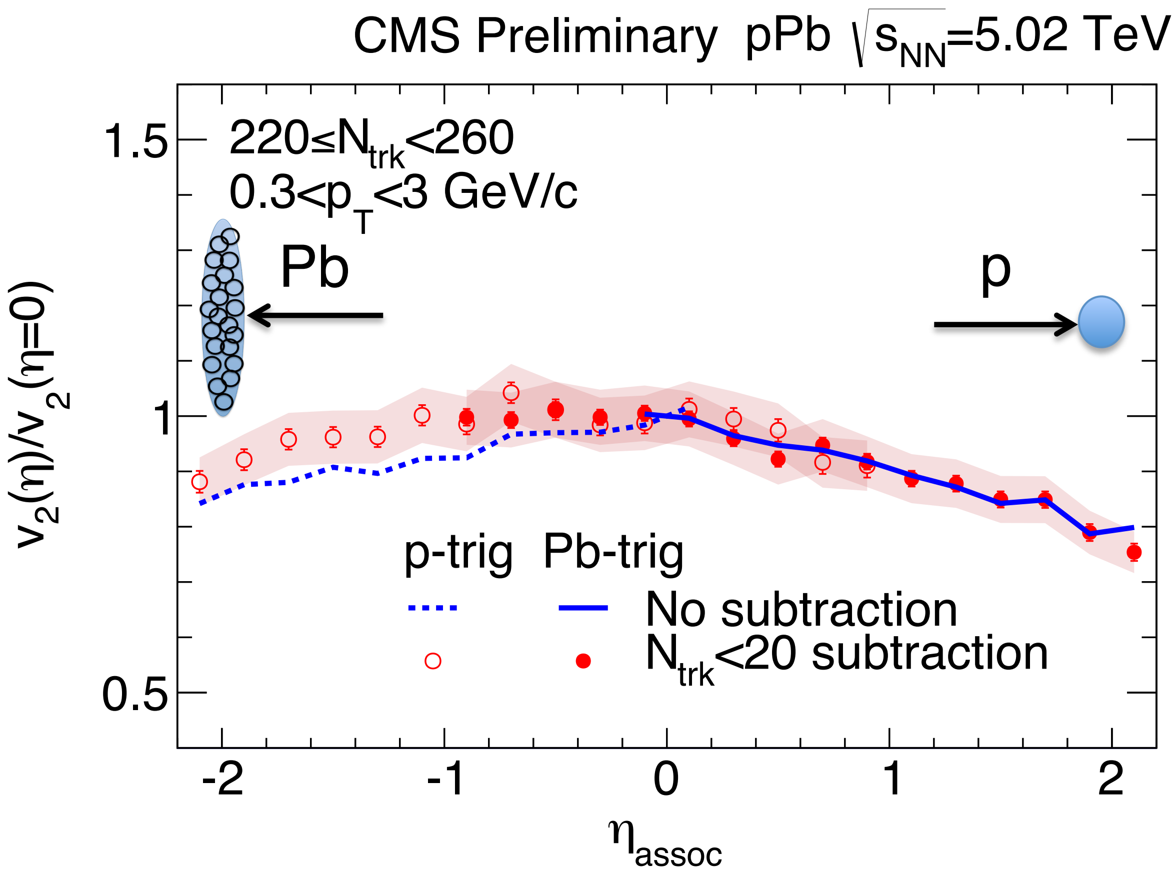
Due to short-range correlations, is it applicable experimentally?

Should be possible to ***fit*** the modes w/o diagonal $V_{n\Delta}$ terms

QGP in small systems (?)

Asymmetric (torqued?) QGP fireball
on p- and Pb-going side?





Again, is it η-dependence of v_n or Ψ_n?

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'

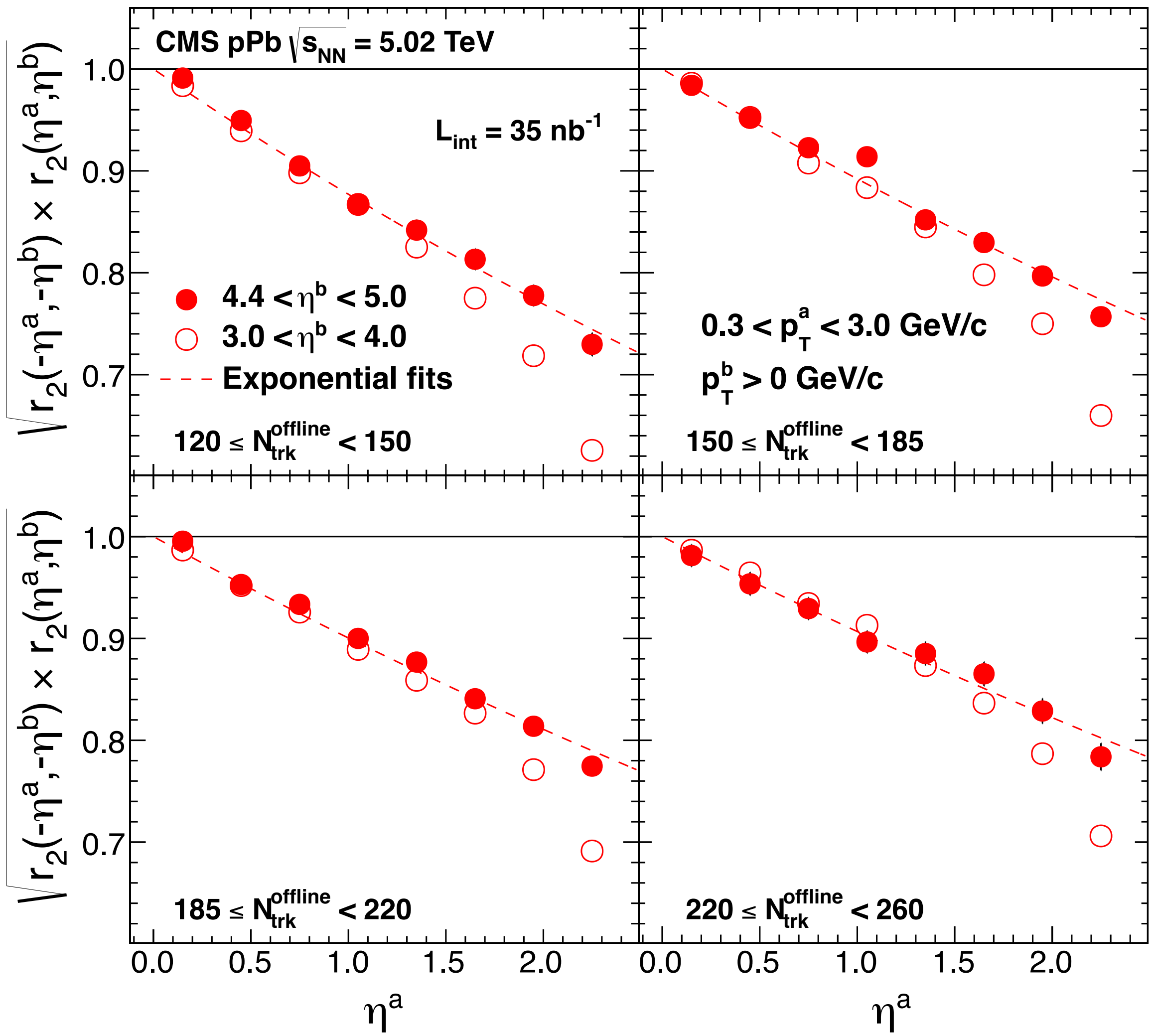
$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} = \sqrt{\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)} \frac{V_{n\Delta}(\eta^a,-\eta^b)}{V_{n\Delta}(-\eta^a,-\eta^b)}}$$

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

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

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

Multiplicity dependence of $r_2(\eta^a,\eta^b)$ in PbPb



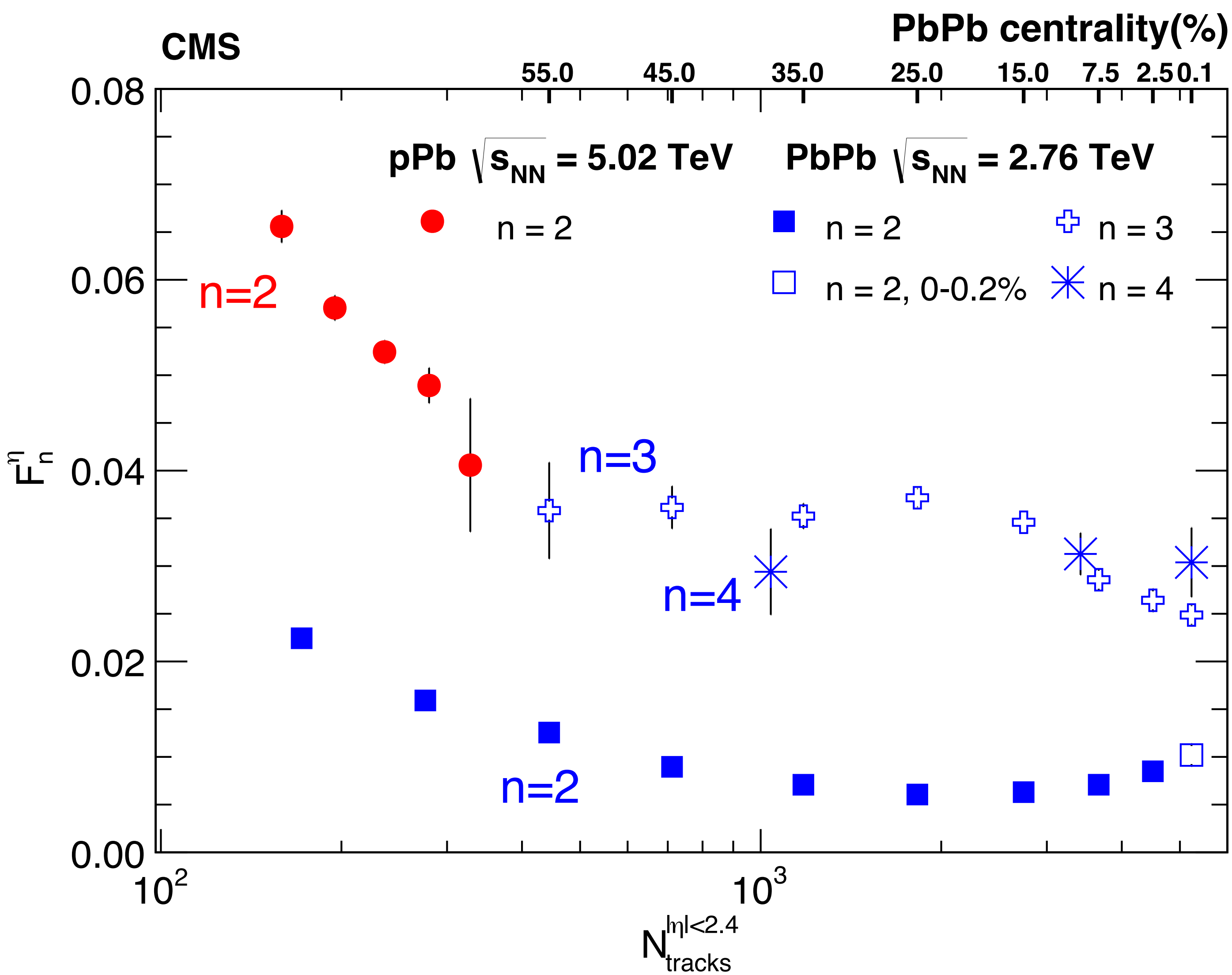
Huge effect in pPb!

up to 20%

- Intuitively, fluctuations should be larger in pPb
- New constraints on the origin of ridge in pPb

Direct comparison of pPb and PbPb data

Empirical parameterization: $r_n(\eta^a,\eta^b) = e^{-2F_n^\eta \eta^a} \approx 1 - 2F_n^\eta \eta^a$



What's next

Experimentally,

- Quantitatively disentangle η dep. of v_n and Ψ_n
- Disentangle *global twist* vs *random* Ψ_n fluctuations?
- p- vs Pb-side in high-multiplicity pPb

Summary

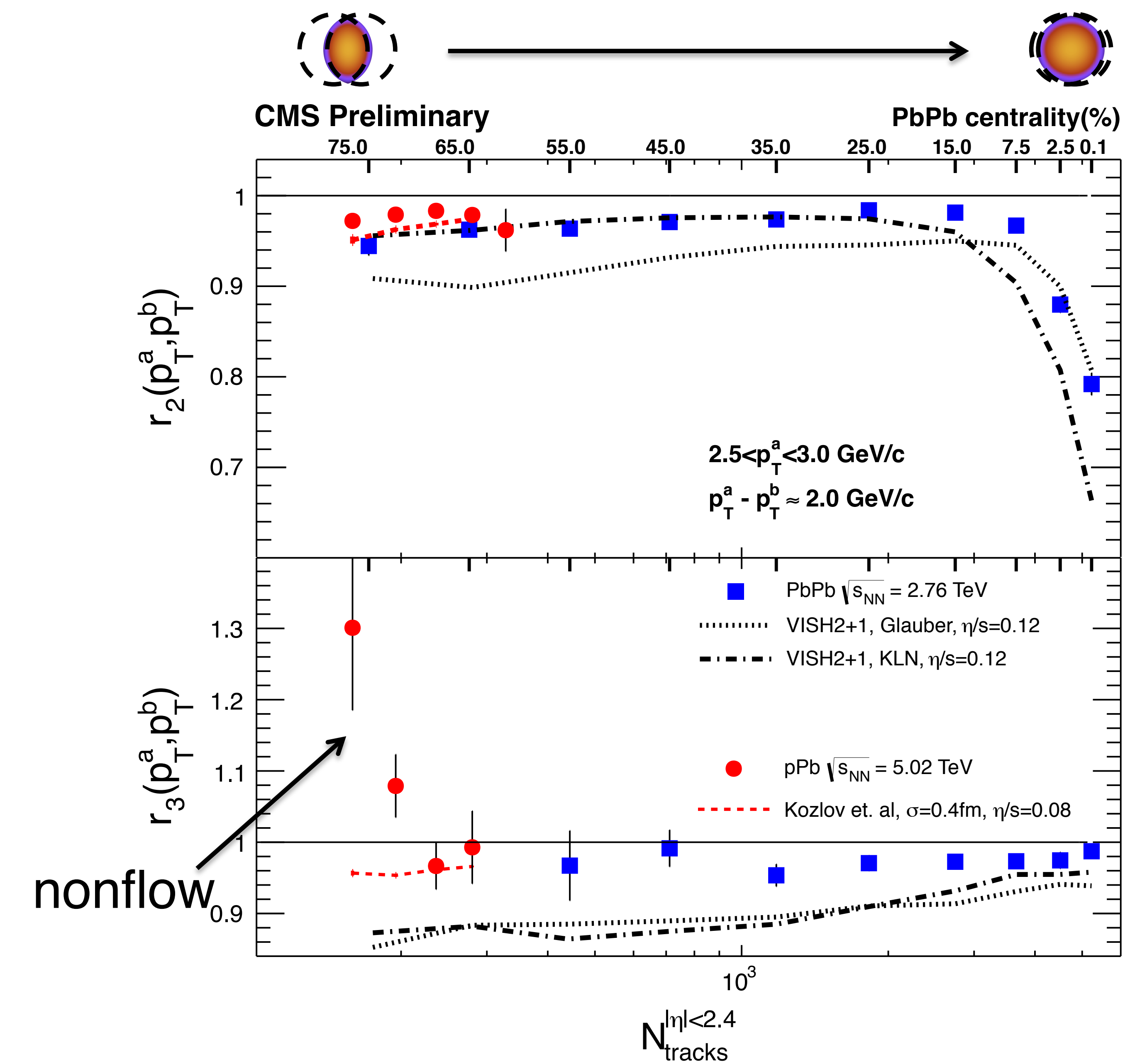
- New handles on the initial state and transport from detailed two-particle correlation structure

- New results of longitudinal factorization breaking
  - Evidence for EP fluctuations in η
  - New constraints on longitudinal dynamics
  - Promising for completing the picture of QGP evolution in 3D

- Stronger effect observed in high-multiplicity pPb

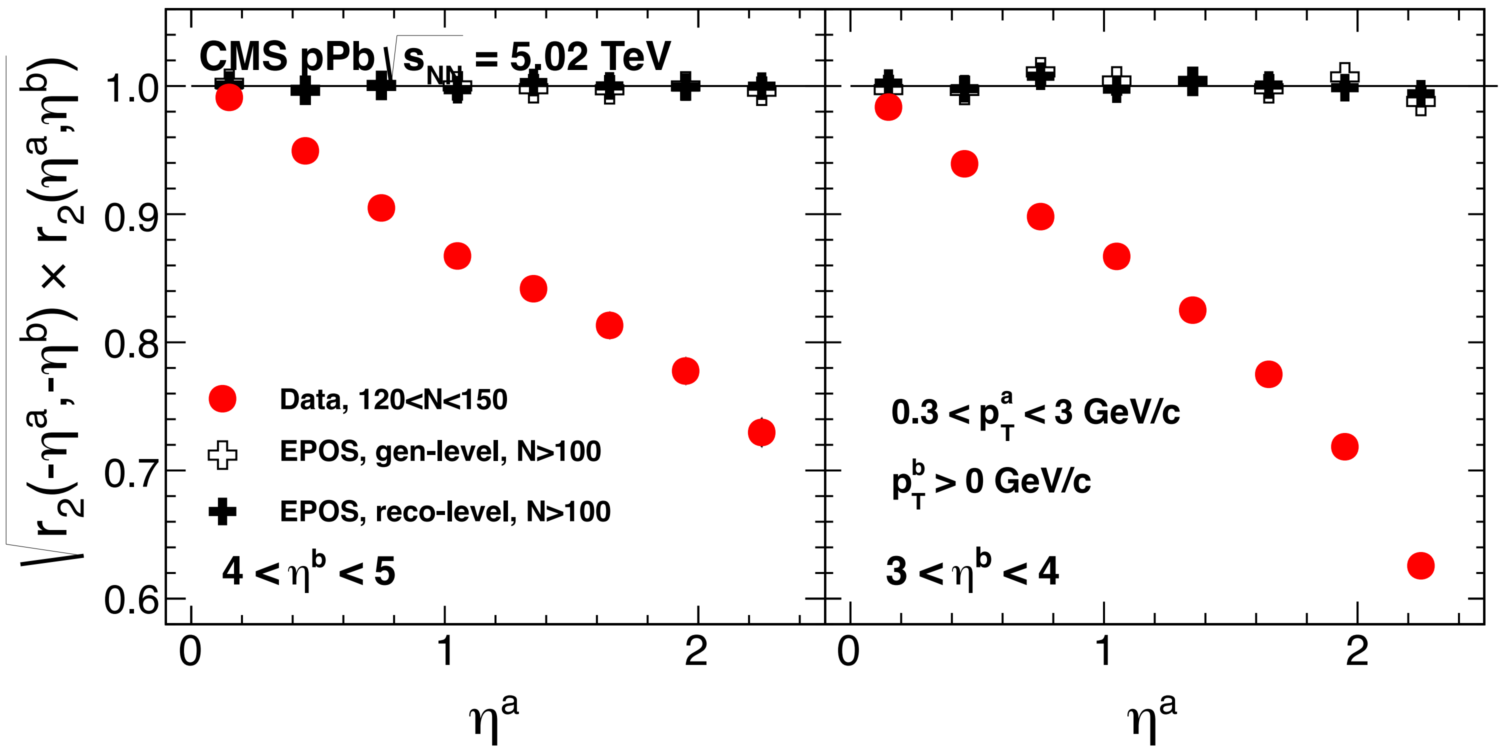
Backups

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

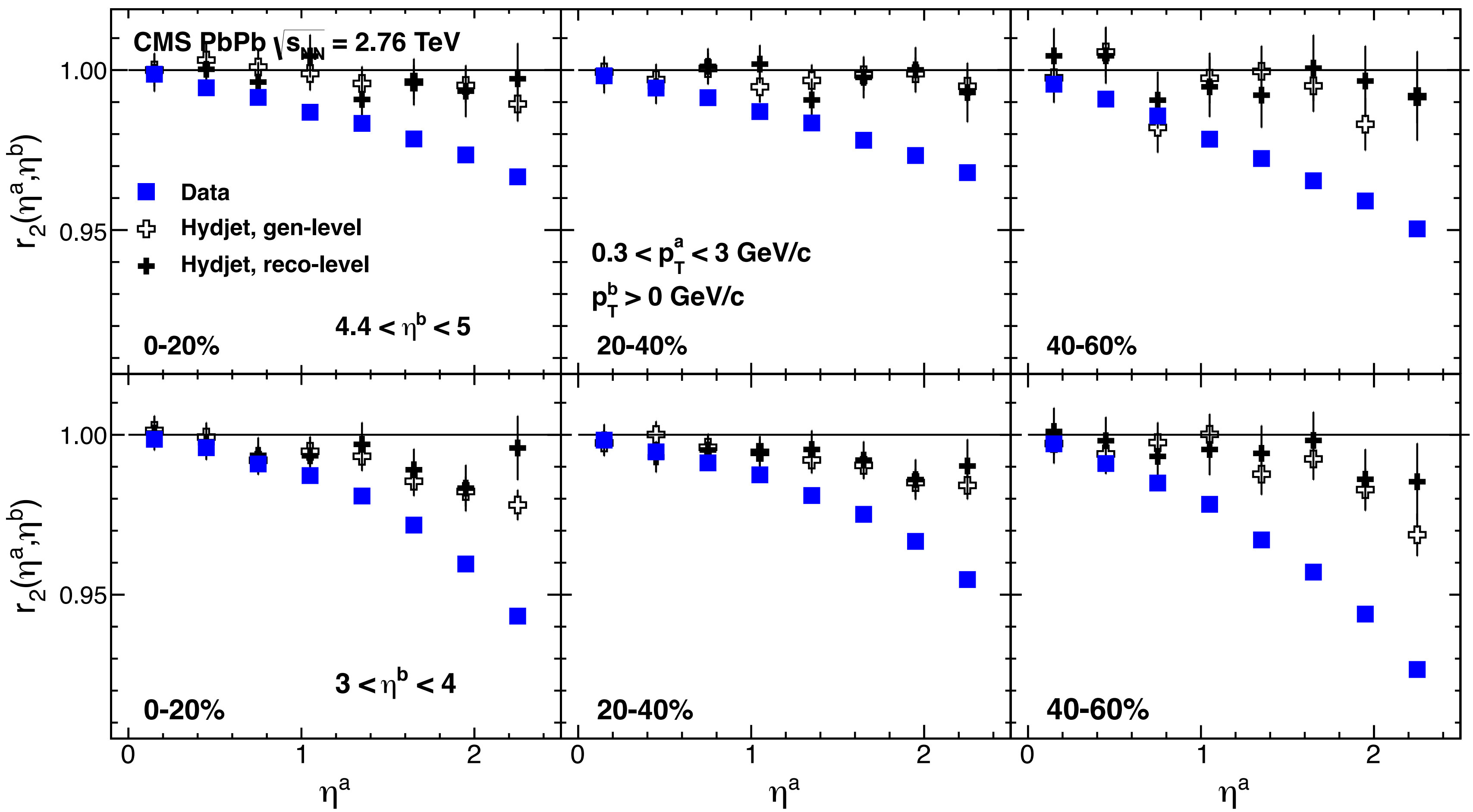


Significant effect toward central PbPb

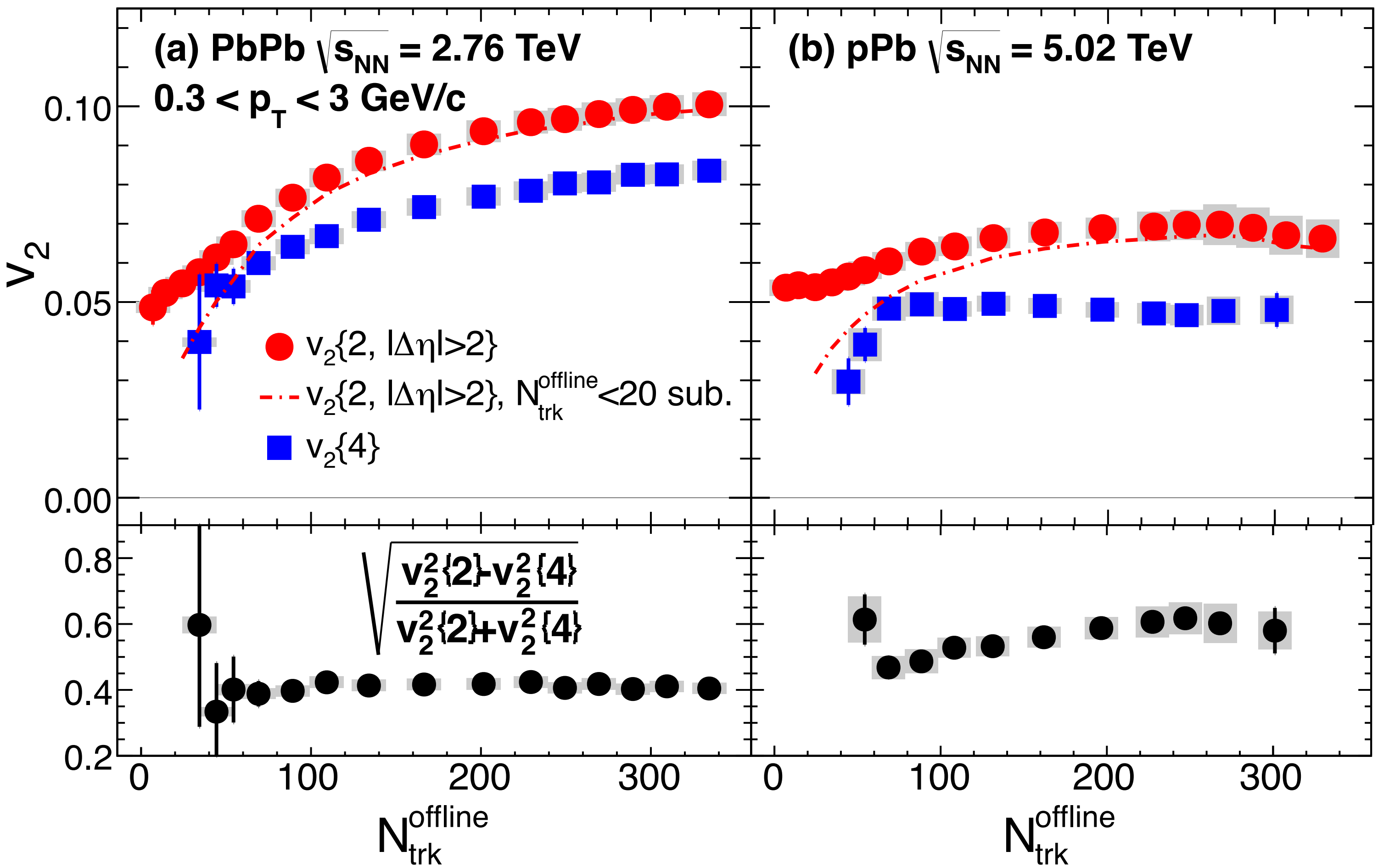
EPOS


CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{r_2(-\eta^a,-\eta^b) \times r_2(\eta^a,\eta^b)}$
Data, 120<N<150
EPOS, gen-level, N>100
EPOS, reco-level, N>100
$4 < \eta^b < 5$
$0.3 < p_T^a < 3$ GeV/c
$p_T^b > 0$ GeV/c
$3 < \eta^b < 4$
η^a
η^a

HYDJET



CMS PbPb √sNN = 2.76 TeV
Data
Hydjet, gen-level
Hydjet, reco-level
0.3 < pTa < 3 GeV/c
pTb > 0 GeV/c
4.4 < ηb < 5
3 < ηb < 4
0-20%
20-40%
40-60%
0-20%
20-40%
40-60%
r2(ηa,ηb)
ηa
1.00
0.95
0
1
2


(a) PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0.3 < p_T < 3 GeV/c
(b) pPb $\sqrt{s_{NN}}$ = 5.02 TeV
v_2
$v_2\{2, |\Delta\eta|>2\}$
$v_2\{2, |\Delta\eta|>2\}$, $N_{trk}^{offline}$<20 sub.
$v_2\{4\}$
$\sqrt{\frac{v_2^2\{2\}-v_2^2\{4\}}{v_2^2\{2\}+v_2^2\{4\}}}$
$N_{trk}^{offline}$
0.10
0.05
0.00
0.8
0.6
0.4
0.2
0
100
200
300