Flow measurements at CMS

Dávid Englert
Wigner RCP, Eötvös University

for the CMS Collaboration

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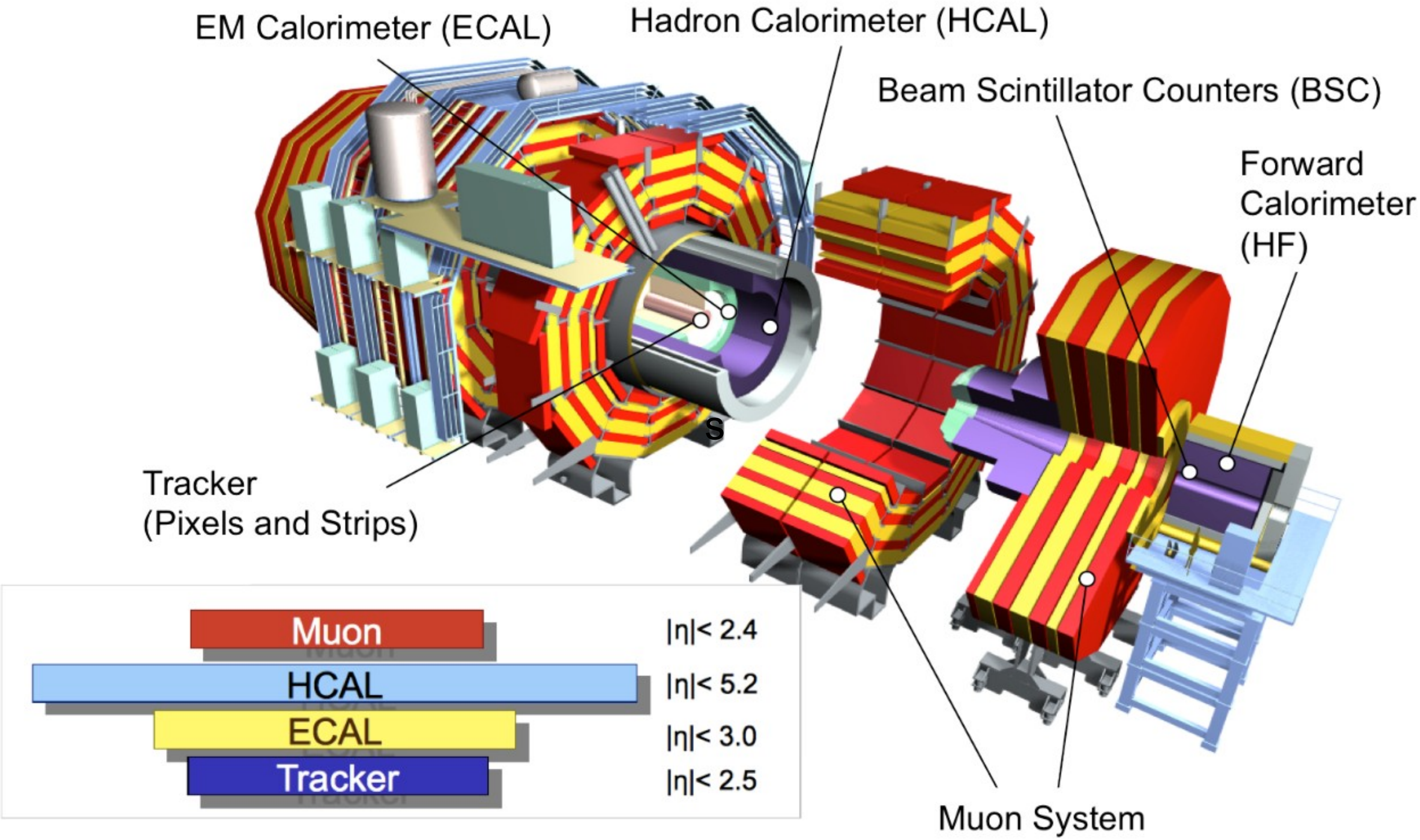
CMS detector

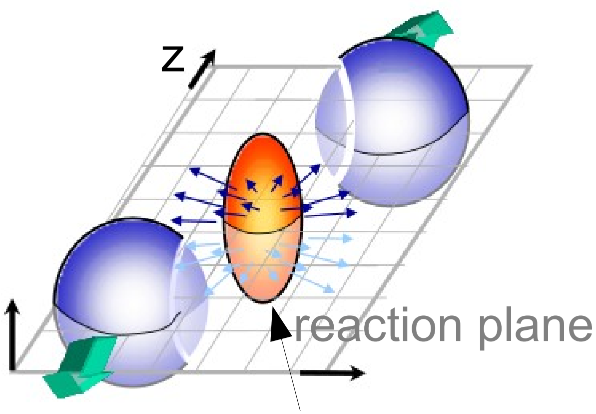


Subdetectors used for flow studies

- Tracker |Δη| up to 5 (charged hadrons)
- HF (Event plane and centrality determination)

Full acceptance in Φ and large acceptance in η
→ provides wide domain for correlation analysis

Flow in heavy ion collisions



almond shaped fireball

Anisotropic azimuthal distribution of particles in coordinate space

↓

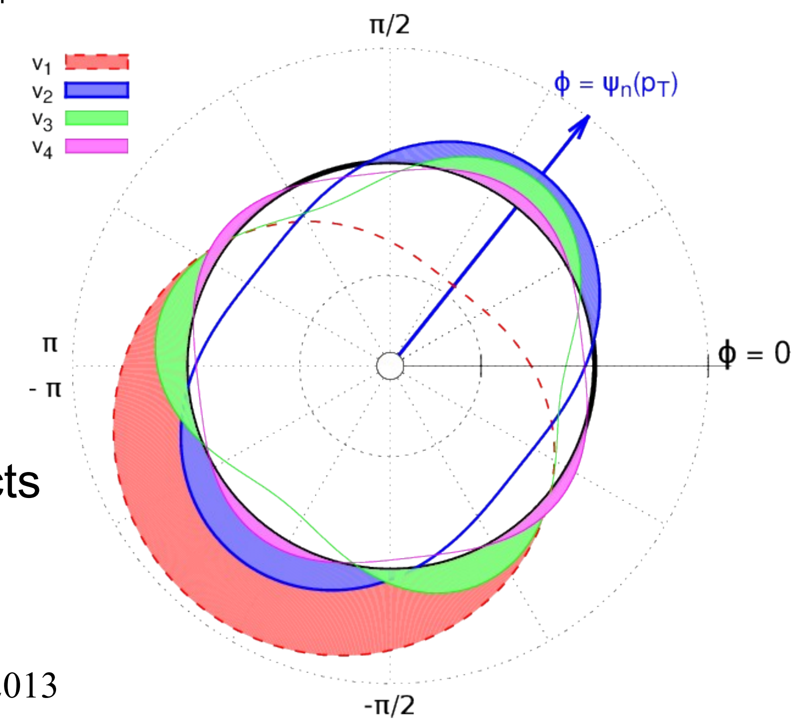
Anisotropic azimuthal distribution of particles in momentum space

Distribution decomposed into Fourier series:

$$\frac{dN}{d\Phi} \sim a_0\left[1+2\sum_{n=1}^{k} v_n \cos\left(n\left(\Phi-\Psi_n\right)\right)\right]$$

v_n - anisotropic harmonic flow coefficient

Overlap of nuclei define the reaction plane which is estimated by the experimental observable -> event plane



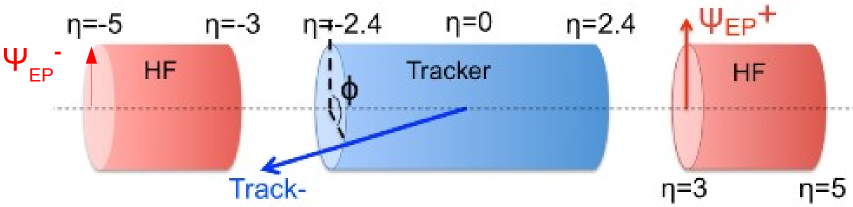
Sources that can contribute to the measured flow value:

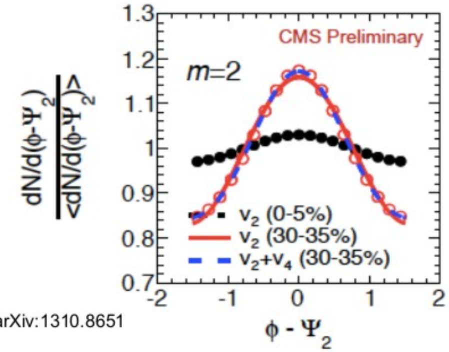
- geometry driven (almond shape) } Flow
- initial state fluctuations
- jet and dijet events
- resonances
- other type of correlations

} Non-flow effects

Studies of flow phenomena in CMS

- **Event plane method**



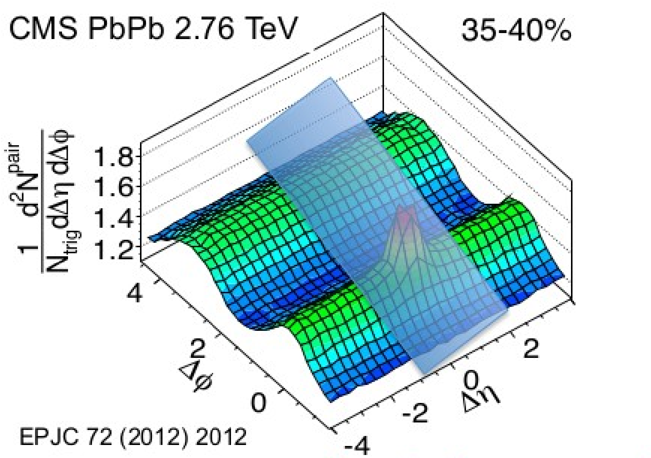


$$\frac{1}{N}\frac{dN}{d\Phi} \sim 1+2\sum_{n=1}^{inf} v_n \cos[n(\Phi-\Psi)]$$

Event plane angle

Event plane determined via transverse energy in HF detectors

- **Two particle Δη-ΔΦ correlation analysis method** (discussed in detail)



flow is long-range!

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\Phi} \sim 1+2\sum_{n=1}^{inf} V_{n\Delta}\cos(n\Delta\Phi)$$

$v_2(p_T^{trig})$ extracted using factorization assumption:

$$V_{n\Delta}(p_T^{trig},p_T^{assoc}) = v_2(p_T^{trig})v_2(p_T^{assoc})$$

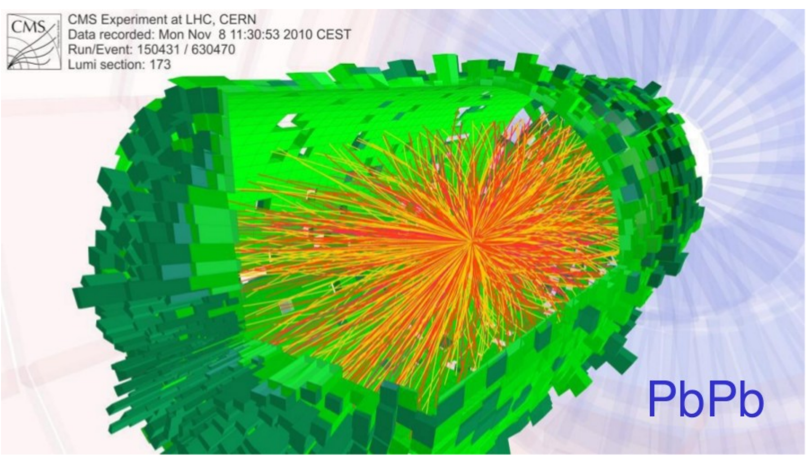
- **Multiparticle correlations**: Multi-particle cumulants and LYZ

Flow harmonics can be obtained from the cumulant terms of the cumulant expansion

Two particle correlation analysis

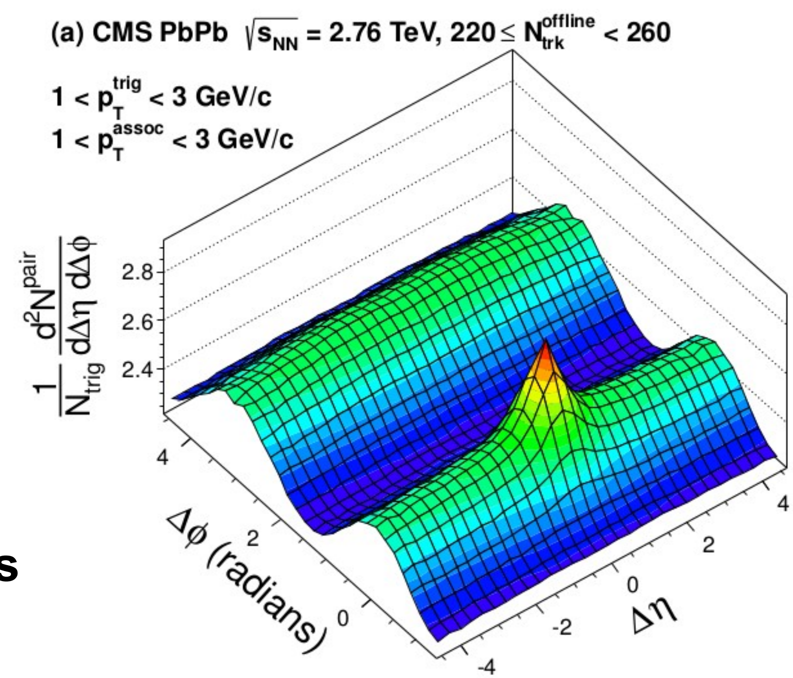
Perfect tool for examining:
• geometry of the particle production process
• the initial-state of the medium that is created in the collision.

One of the techniques to extract single particle v_n



PbPb event in CMS

Two particle correlation analysis



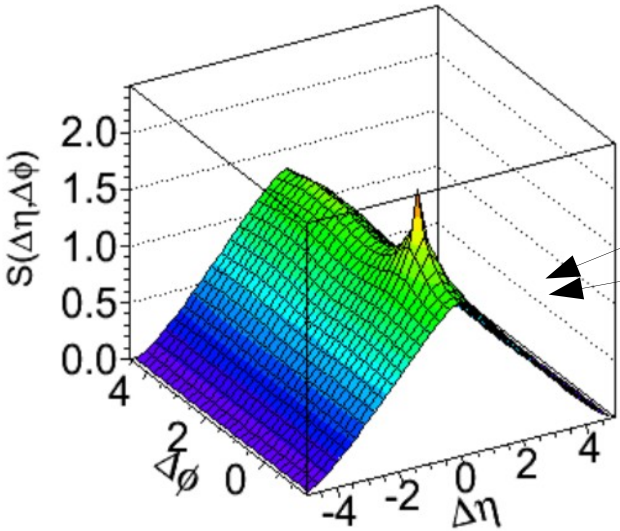
2D Correlation function

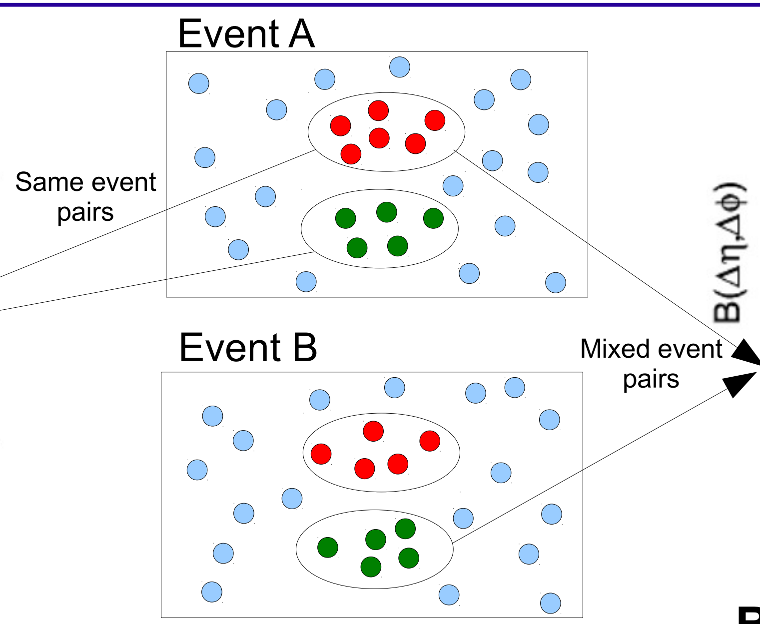
which depends on Δη and ΔΦ

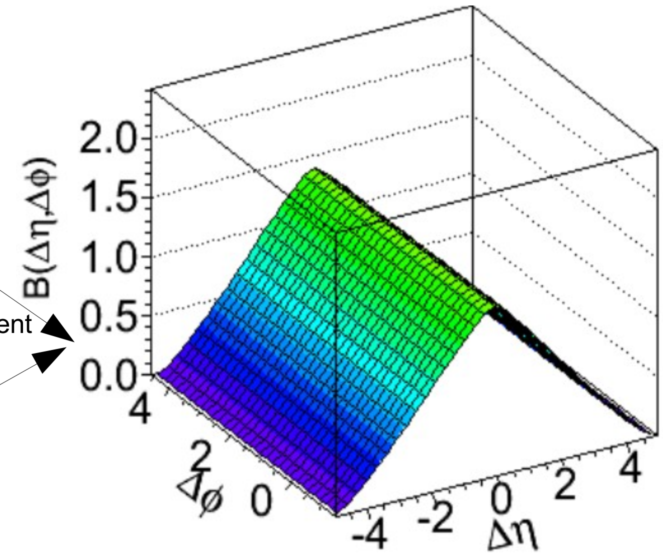
Pseudorapidity
$\eta = -\ln[\tan(\theta/2)]$

θ – polar angle
Φ – azimuthal angle

Two particle correlation analysis





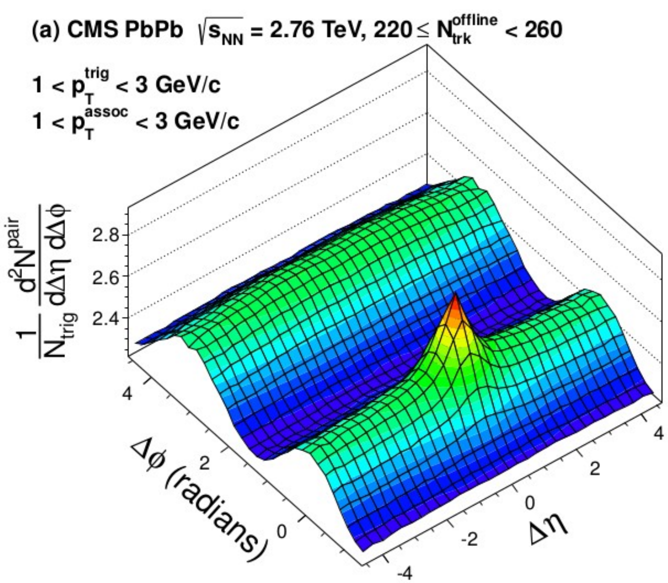


S(Δη, ΔΦ) - signal function from event by event particles

- Trigger particle
- Associated particle

B(Δη, ΔΦ) - background function from event mixing

Selection on the trigger and associated particle based on p_T



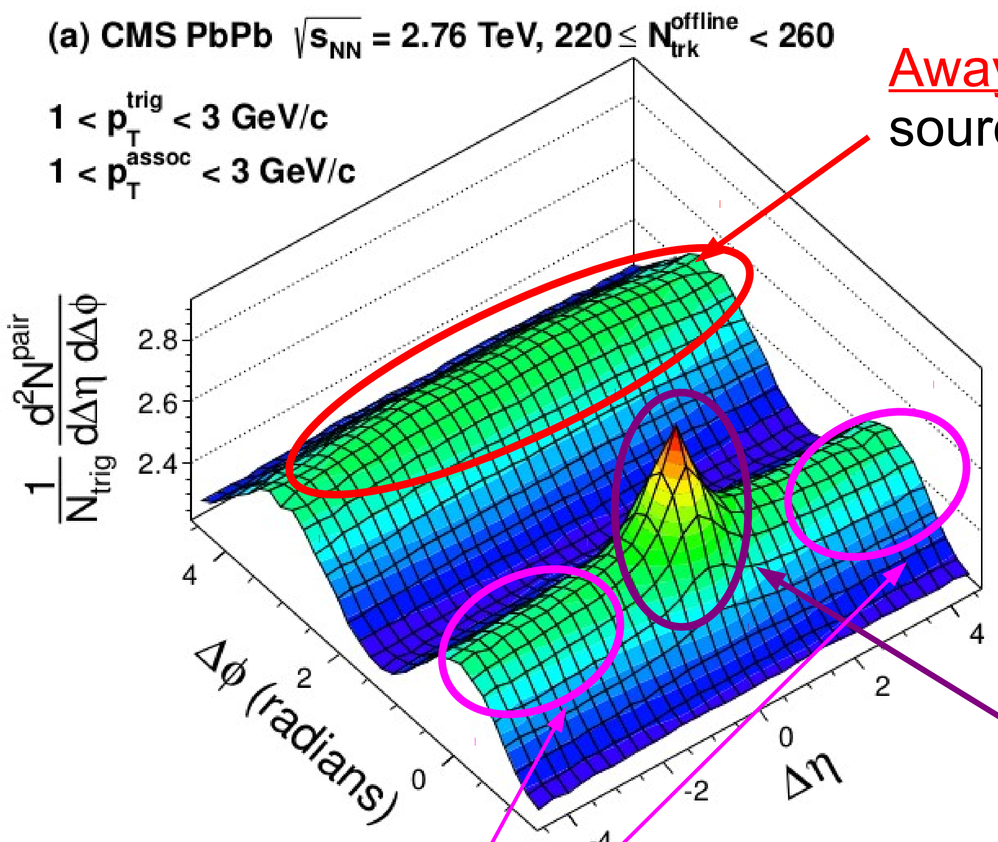
<u>2D Correlation function</u>:
(per-trigger particle associated yield)

$$\frac{B(0,0)}{B(\Delta\eta,\Delta\Phi)} \cdot S(\Delta\eta,\Delta\Phi)$$

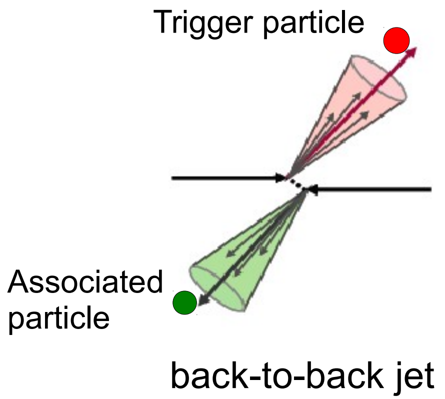
$$\frac{B(0,0)}{B(\Delta\eta,\Delta\Phi)}$$ factor

accounts for the random combinatorial background and pair acceptance effects

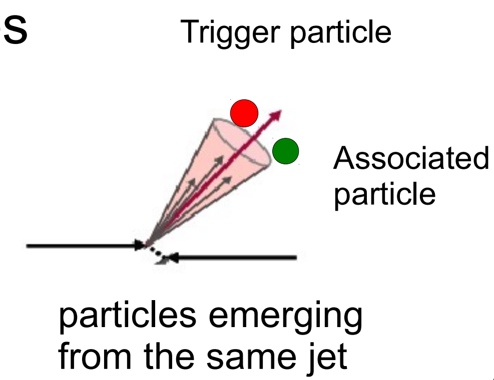
Understanding two particle correlation analysis – specific regions and their causes



Away side structure (wide Δη, ΔΦ ~ π)
sources: - dijet (back-to-back)
- flow

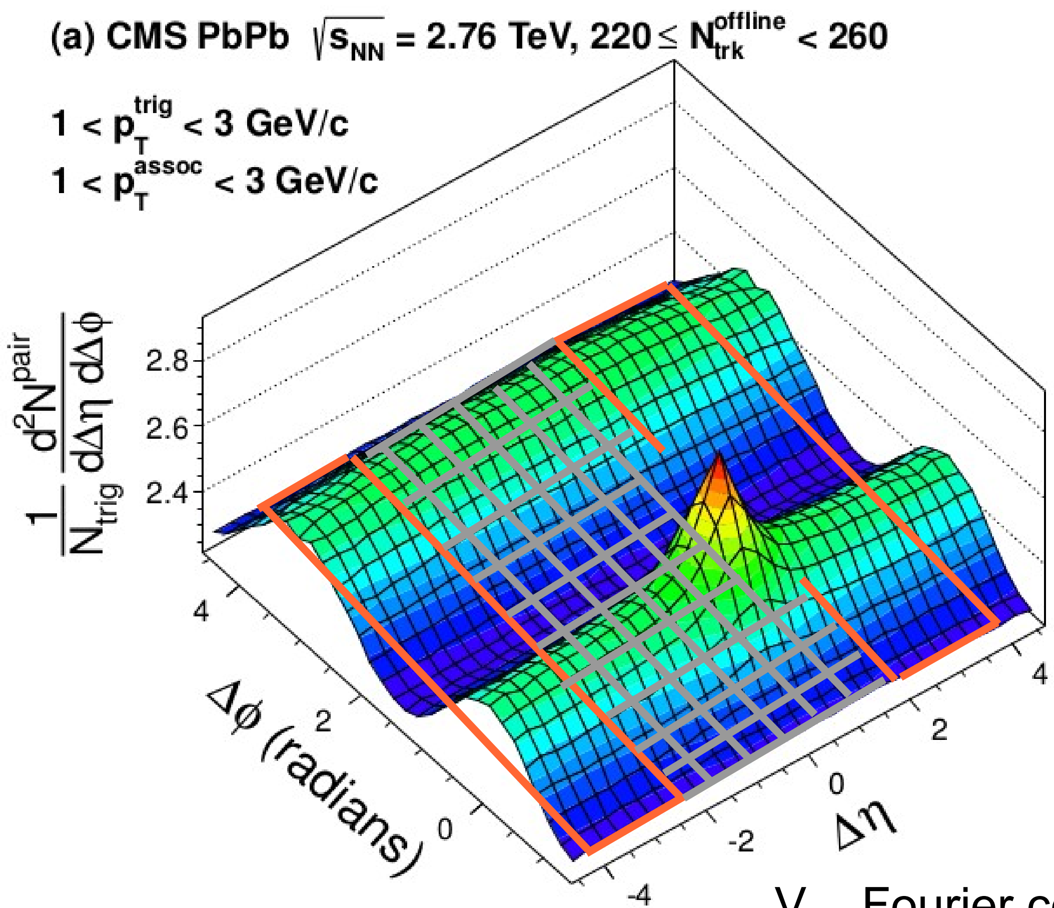


Near side peak (Δη ~ 0, ΔΦ ~ 0)
sources: - jets (part. pairs coming from same jet)
- resonances



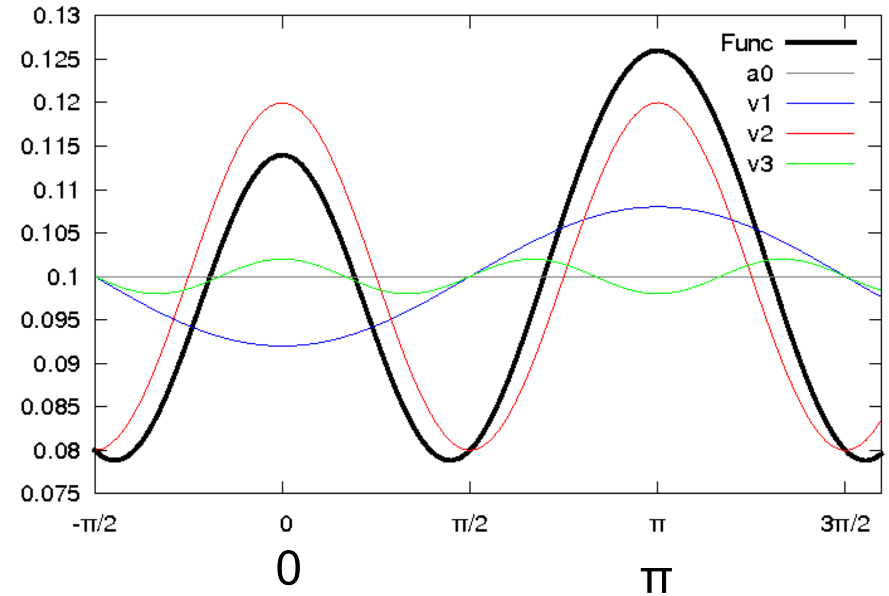
Near side ridge (wide Δη, ΔΦ ~ 0)
sources: - flow
- multiparticle interactions

Two particle correlation analysis - azimuthal correlation



Projection along Δη, in the domain of 2 < |Δη| < 4 to cut out the jet contribution

Azimuthal correlation function



$V_{n,\Delta}$ Fourier coefficients → v_n Single particle flow coefficients

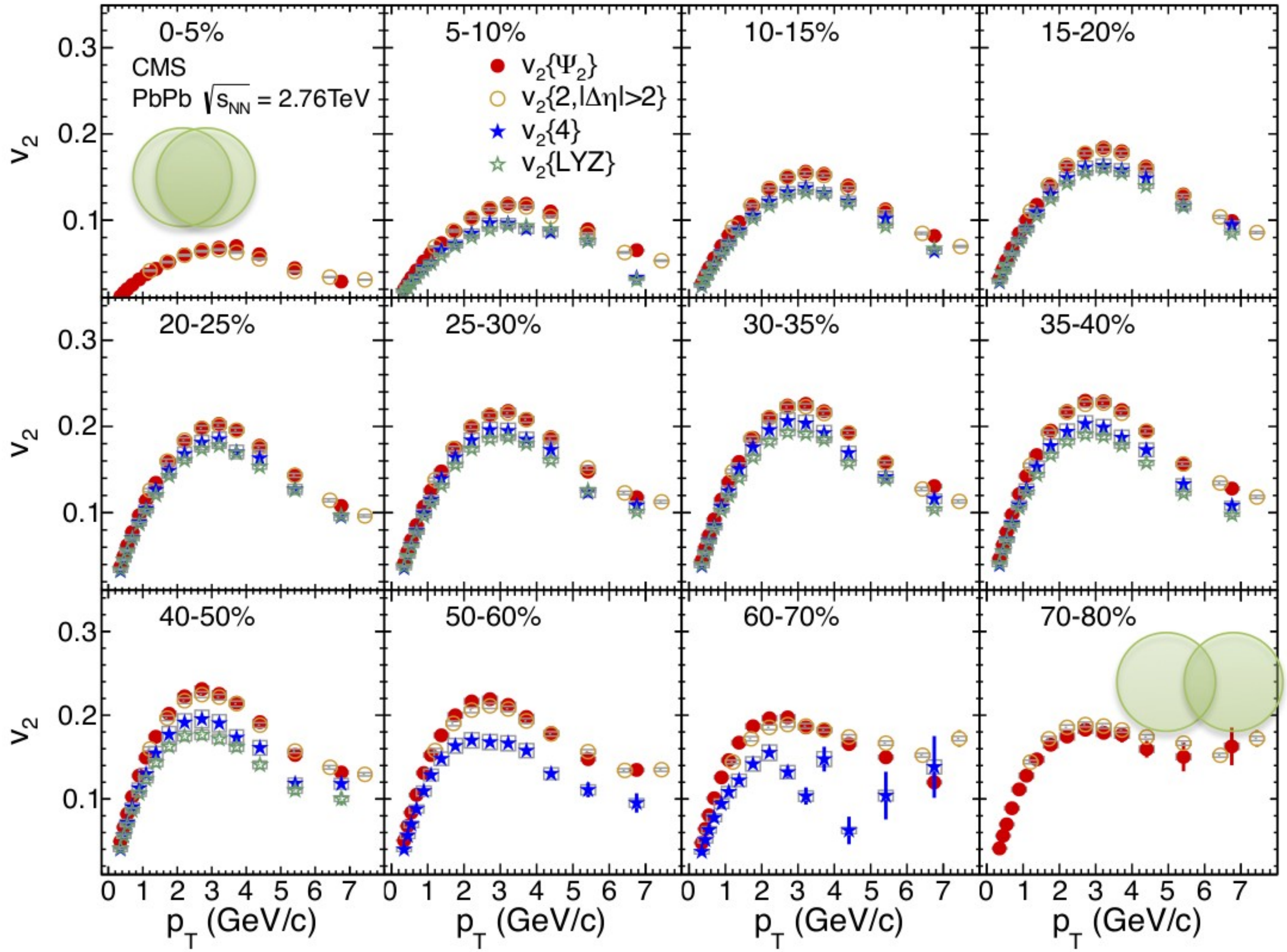
Fourier fit

$$a_0\left[1+2\sum_{n=1}^{k} V_{n\Delta}\cos(n\,\Delta\Phi)\right]$$

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

$$v_n(p_T) = \sqrt{V_{n\Delta}(p_T, p_T)}$$

Elliptic flow (v_2) in PbPb at CMS



PRC 87(2013) 014902
EPJC 72 (2012) 2012

four methods with different sensitivities to flow and non-flow fluctuations:

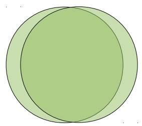
- $v_2(\psi_2)$ – EP method
- $v_2\{2,|\Delta\eta| > 2\}$ 2 particle corr.
- $v_2\{4\}$ 4-particle cum.
- $v_2\{LYZ\}$ - Lee Yang zero

$v_2\{LYZ\}$ and $v_2\{4\}$ are less sensitive to non-flow correlations

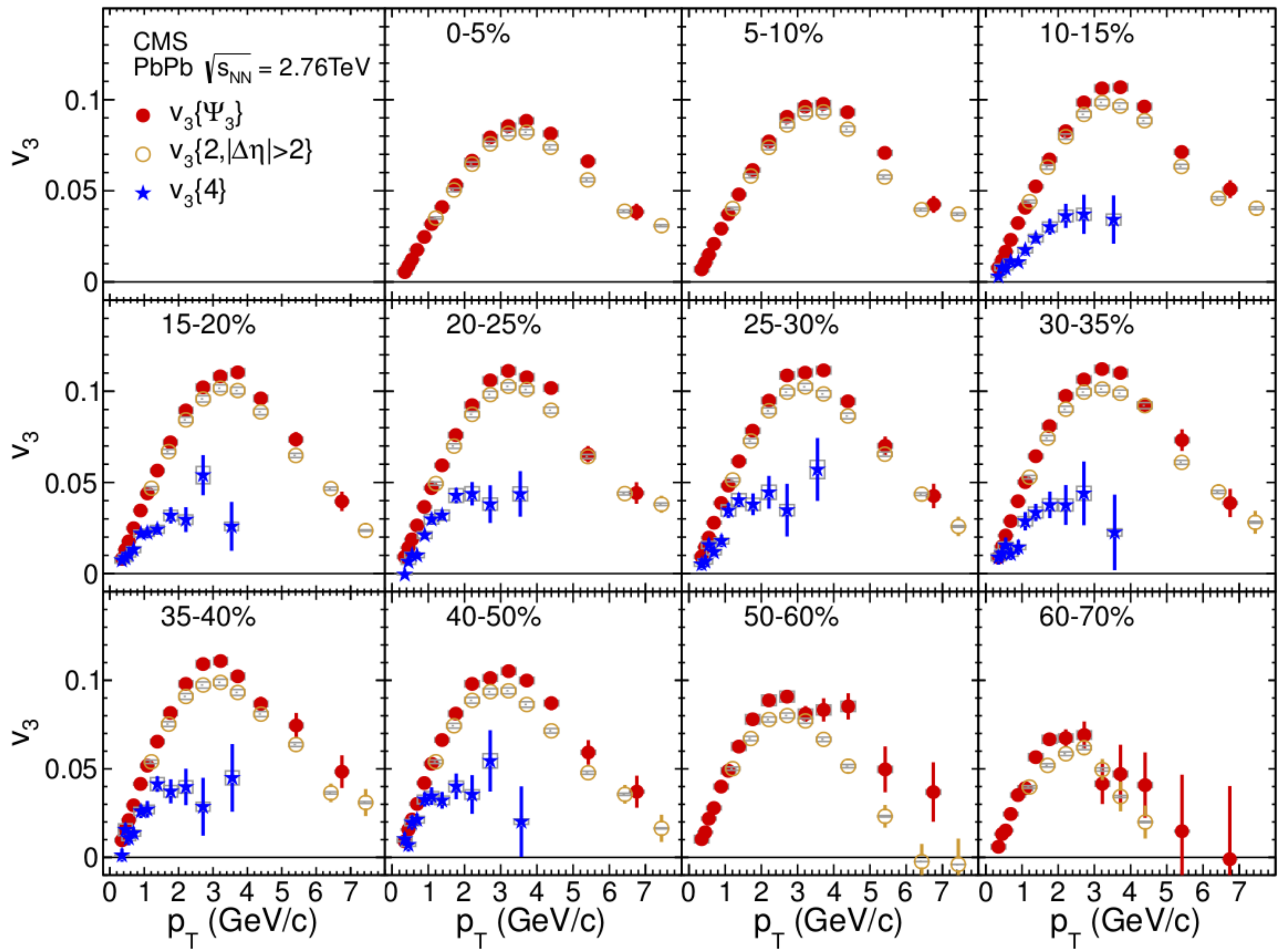
$$v_2\{LYZ\} \approx v_2\{4\} \quad < \quad v_2(\psi_2) \approx v_2\{2,|\Delta\eta| > 2\}$$

Triangular flow (v_3) in PbPb

0-5%

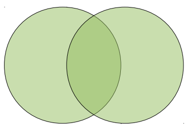


Central



CMS-HIN-11-005

Peripheral
60-70%



$v_3\{4\} \ll v_3(\psi_3) \approx v_3\{2,|\Delta\eta| > 2\}$

Strong effect of fluctuations compared to v_2

Factorization

Assuming factorization:

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

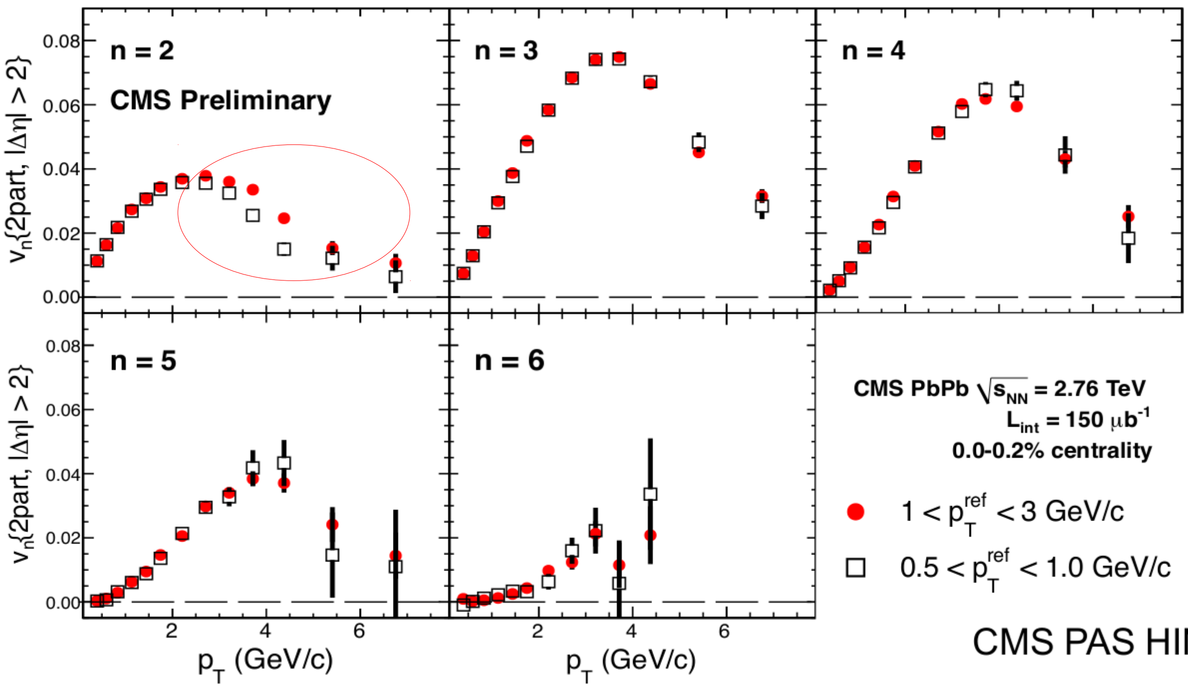
two particle harmonic

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

single particle harmonic

Factorization test:

$v_n(p_T^{trig})$ derived from two particle correlation analysis for different p_T^{ref} in ultra central collisions



CMS PAS HIN-12-011

Different v_2 values for different p_T^{assoc} range

Factorization breakdown for v_2 at high p_T

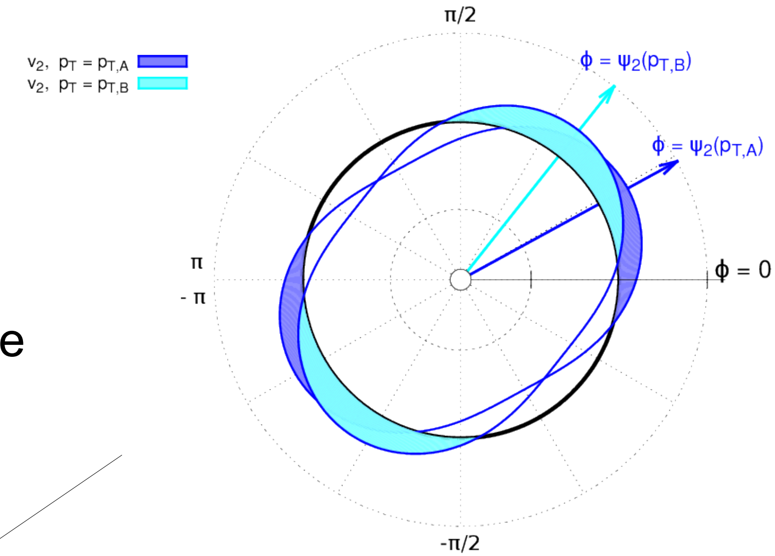
Is it really the sign of non-flow effects, and the breakdown of the hydrodynamic description too?

Ultra central collisions 0 – 0.2 %

Factorization breakdown in hydrodynamics

Is factorization breakdown really inconsistent with hydro?

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



Introducing the factorization ratio r_n to quantitatively measure the breakdown:

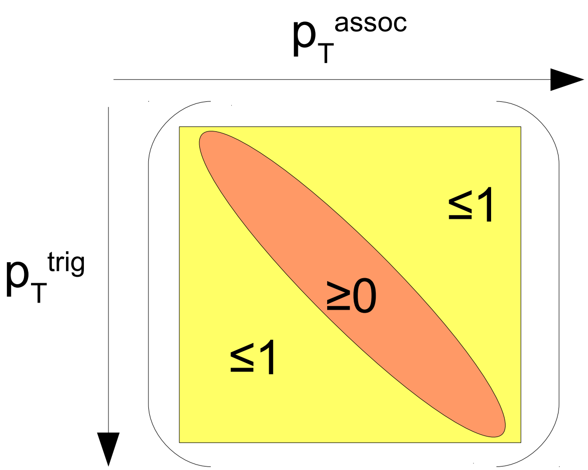
$$r_n = \frac{V_{n,\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n,\Delta}(p_T^{trig}, p_T^{trig})}\sqrt{V_{n,\Delta}(p_T^{assoc}, p_T^{assoc})}}$$

Fluctuating flow angles (ψ_n)

Event plane angle Ψ_n (determined by final-state particles) is a function of p_T due to event-by-event fluctuating initial-state geometry

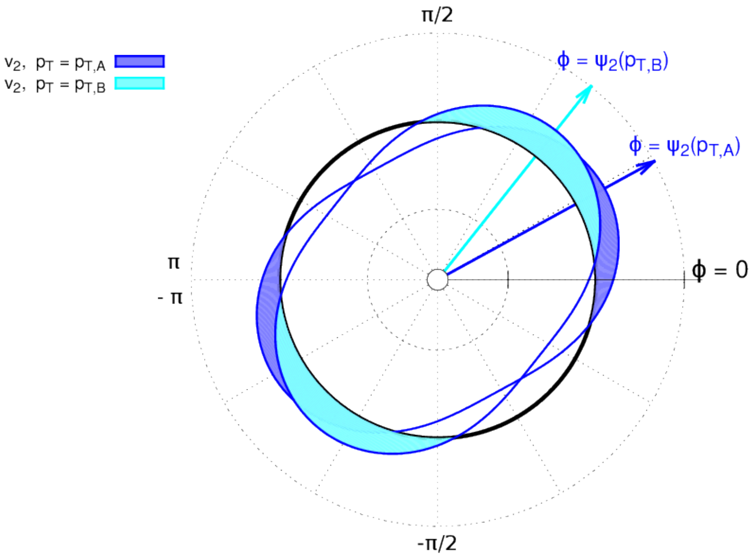
$$r_n = \frac{\langle v_n(p_T^{trig})\, v_n(p_T^{assoc}) \cos[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{assoc}))]\rangle}{\sqrt{v_n^2(p_T^{trig})\, v_{n,}^2(p_T^{assoc})}}$$

Factorization breakdown in hydrodynamics



$r_n(p_T^{trig}, p_T^{assoc})$
correlation matrix

Gardim et al., PRC 87, 031901(R) (2013)
Heinz et al., PRC 87, 034913 (2013)



Fluctuating flow angles (ψ_n)

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

In general, $r_n \leq 1$, if the event-by-event Ψ_n depends on p_T

- Violation of constraints (e.g. $V_{n\Delta}(p_T^A, p_T^A) < 0$) indicates non-flow correlations
- Simulations (Heinz et al. PRC 87, 034913 (2013)) indicate that viscous effects (η/s) reduce the amount by which event-by-event fluctuations break factorization!

Factorization breakdown in hydrodynamics, r_2

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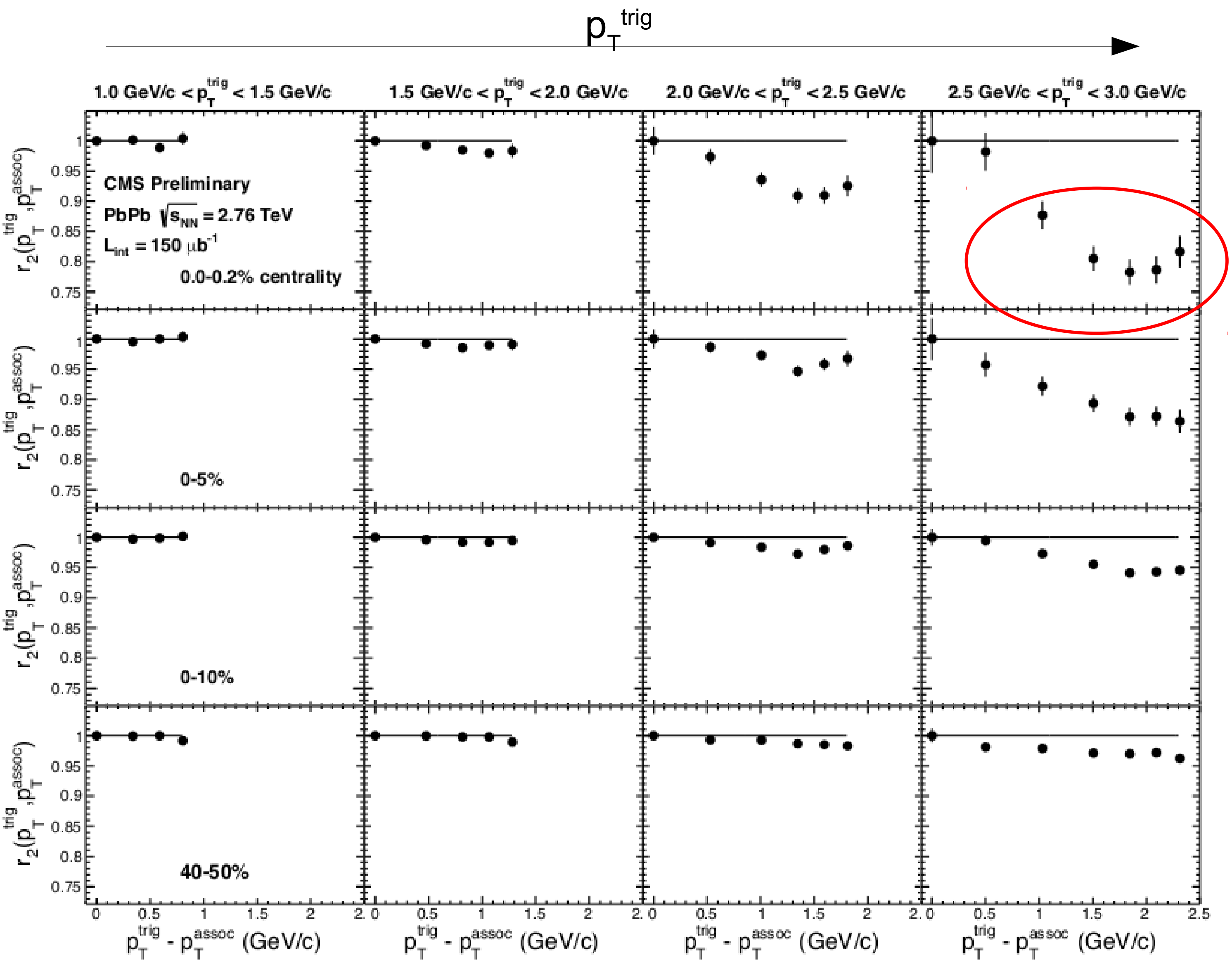

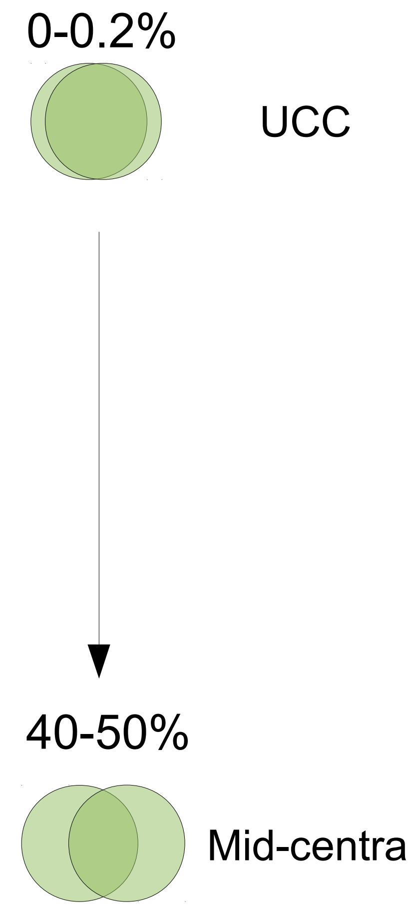

Sizeable effect for v_2 in ultra-central events

Factorization breakdown in hydrodynamics, r_2

p_T^{trig} →

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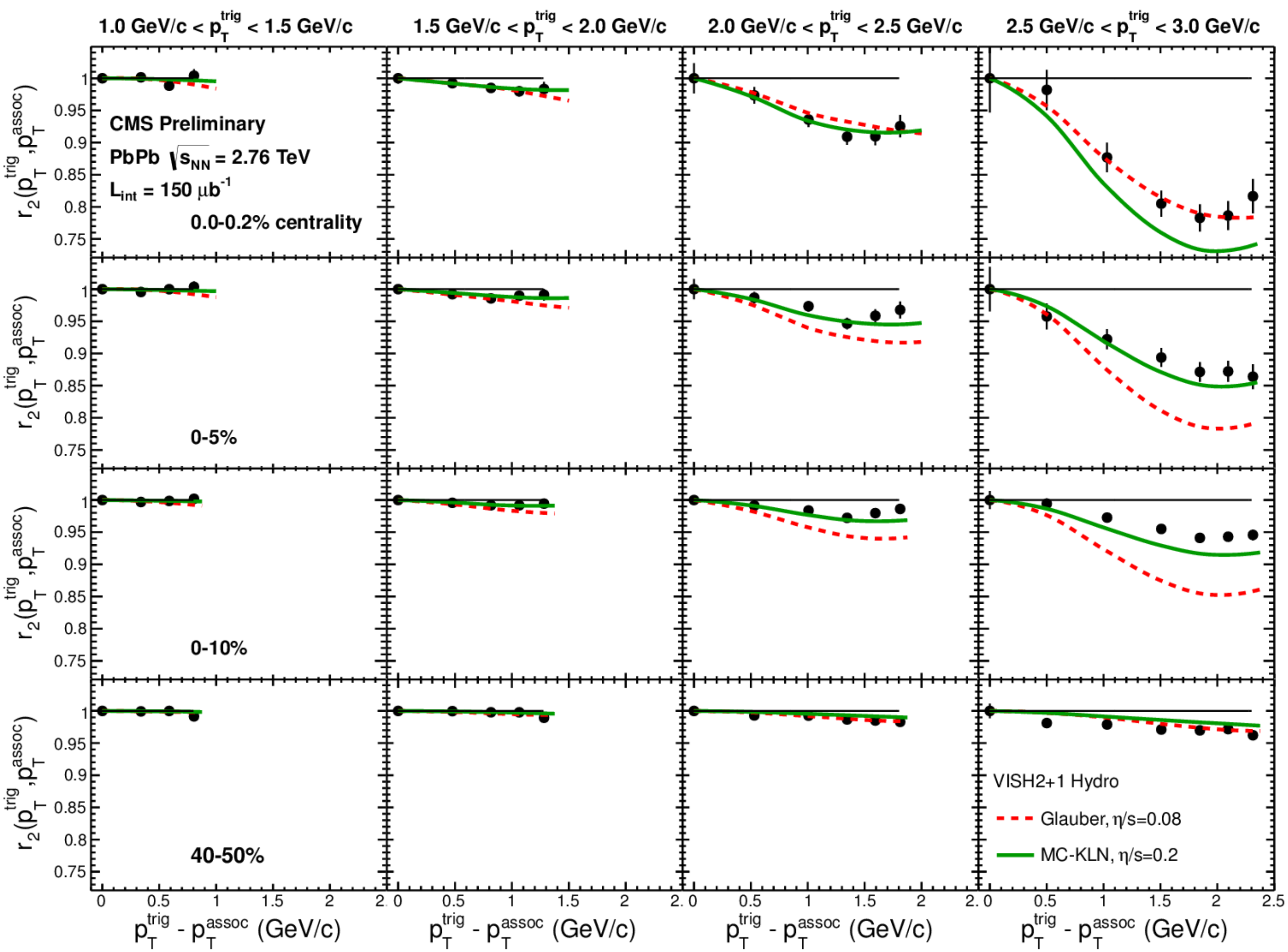
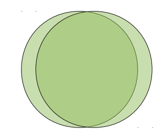
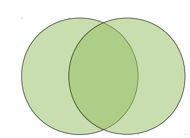


0-0.2%



UCC

40-50%



Mid-central

Hydro from Heinz and Shen
PRC 87, 034913 (2013)

Glauber
MC-KLN
} Initial density profiles

Sizeable effect for v_2 in ultra-central events

Factorization breakdown in hydrodynamics, r_3

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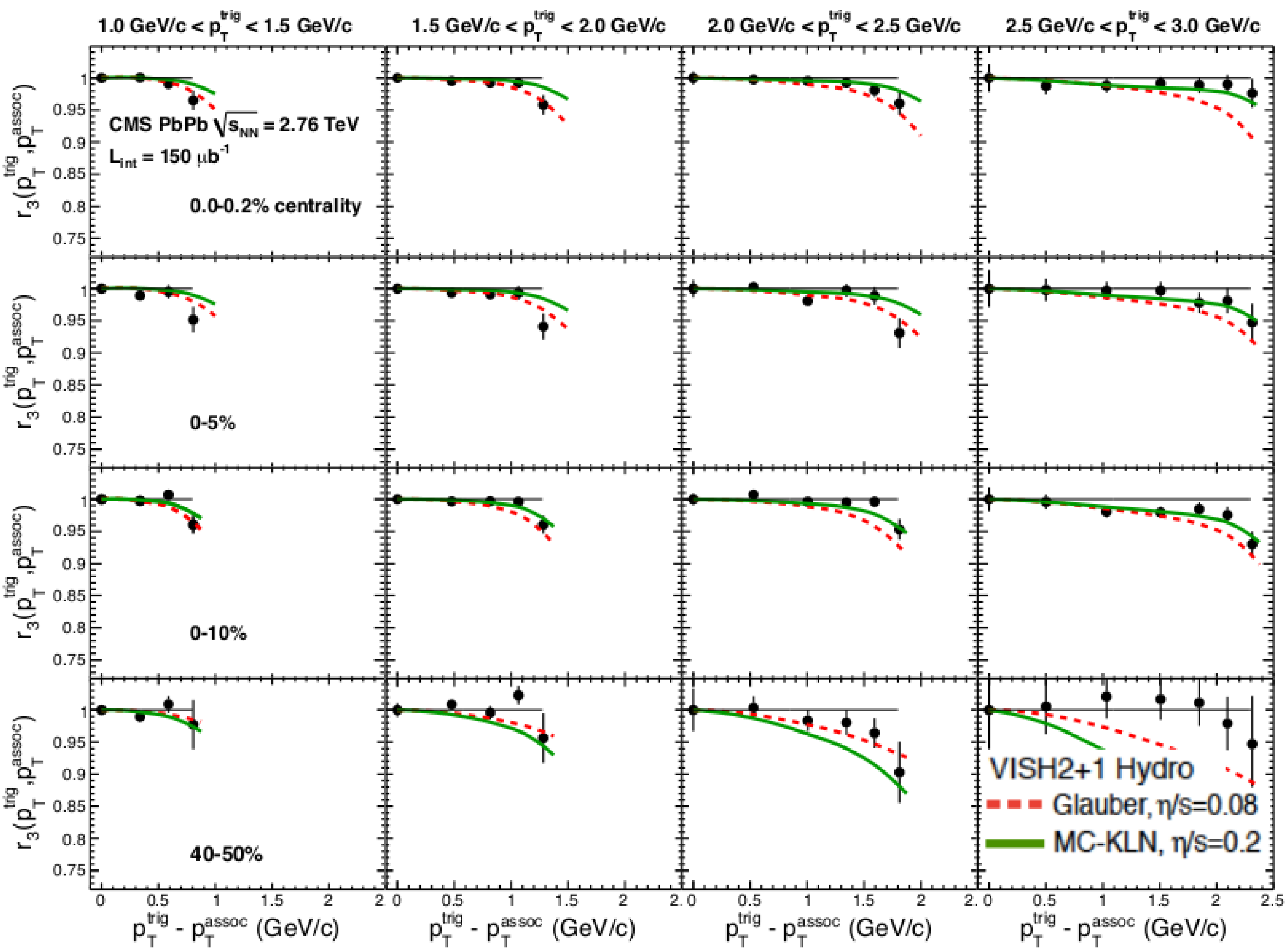
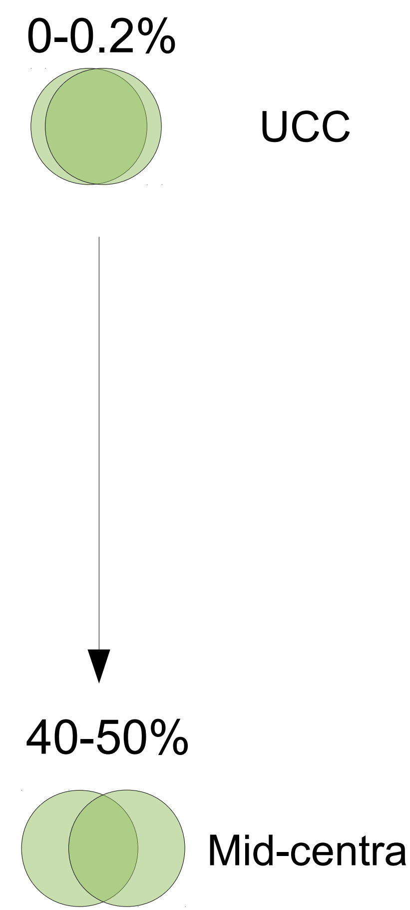
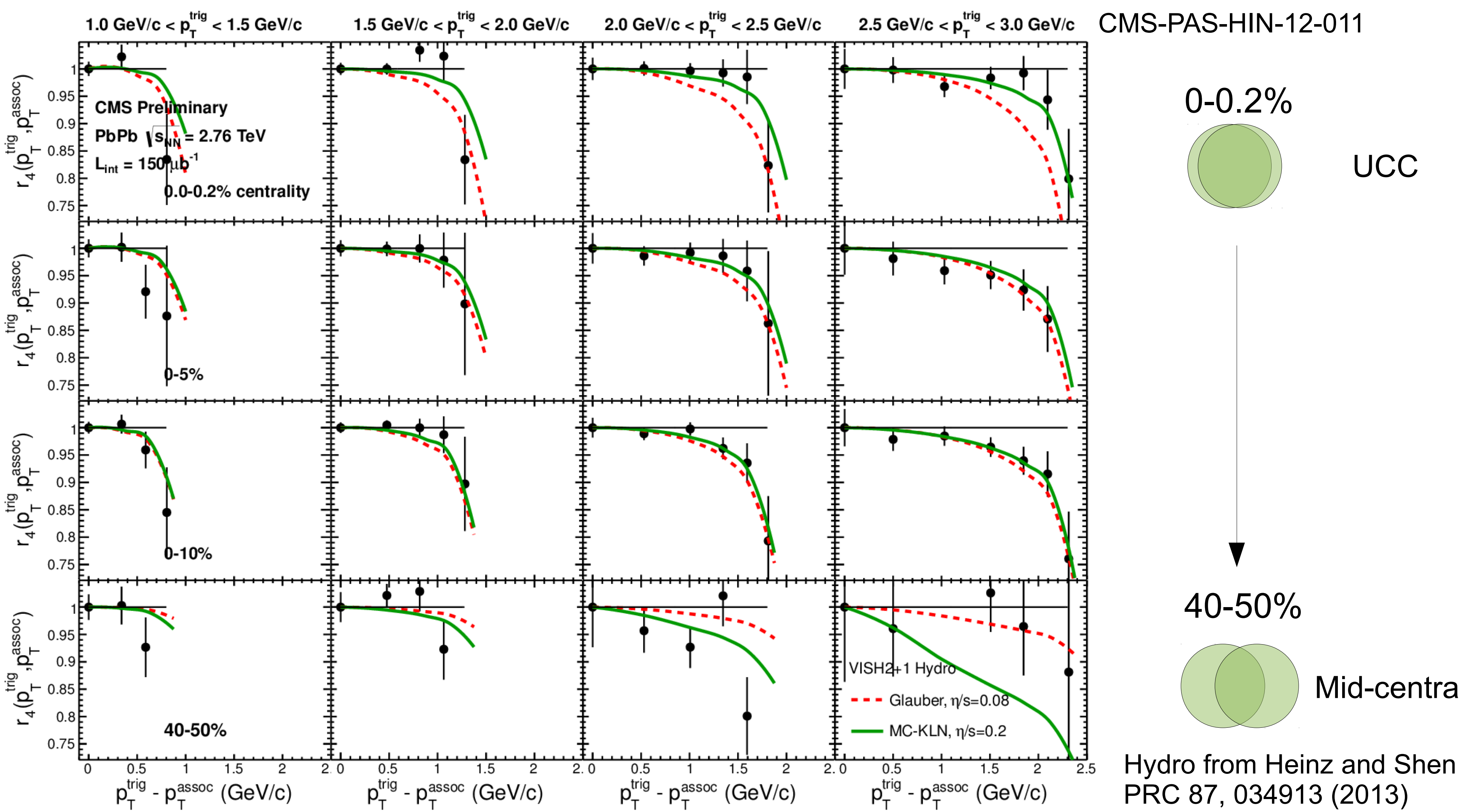




Hydro from Heinz and Shen
PRC 87, 034913 (2013)

Smaller effect for v_3 → is it more sensitive to η/s, and therefore reduces factorization?

Factorization breakdown in hydrodynamics, r_4



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Hydro from Heinz and Shen
PRC 87, 034913 (2013)

Smaller effect for v_4 → is it more sensitive to η/s, and therefore reduces factorization?

Summary

Different measurement techniques (EP, two-particle, multi-particle) with varying sensitivity to flow and non-flow effects were used to extract v_n

Factorization breakdown

• consistent with hydrodynamics, as besides harmonics coefficients v_n, associated anisotropic flow angles Ψ_n are also dependent on p_T

• considerable deviation from factorization if the difference between p_T^{trig} and p_T^{assoc} is large

• ultra-central collisions - where the anisotropic flow is dominated by initial density fluctuations rather than overlap geometry - yield the largest deviation from perfect factorization

Thank you for your attention!

CMS flow and correlations results

	Analysis	Type	Report	Publication
HIN-10-002	Elliptic flow and low-pt spectra	PbPb	arXiv:1204.1409	PRC 87(2013) 014902
HIN-11-001	Dihadron correlations	PbPb	arXiv:1105.2438	JHEP 07 (2011) 076
HIN-11-006	Dihadron correlations centrality dependence	PbPb	arXiv:1201.3158	EPJC 72 (2012) 2012
HIN-11-009	Neutral pion v_2 in PbPb collisions	PbPb	arXiv:1208.2470	PRL 110 (2013) 042301
HIN-11-012	Azimuthal anisotropy at high p_T	PbPb	arXiv:1204.1850	PRL 109 (2012) 022301
HIN-12-015	Ridge (2-particle correlations) in pPb	pPb	arXiv:1210.5482	PLB 718 (2013) 795
HIN-13-002	2- and 4-particle correlations in pPb	pPb	arXiv:1305.0609	PLB 724 (2013) 213
HIN-11-005	Higher order harmonics flow	PbPb	arXiv:1310.8651	submitted to PRC
HIN-12-010	Very high p_T triggered correlations	PbPb	PAS	-
HIN-12-011	v_n in ultra-central collisions	PbPb	PAS	-

CMS Heavy-Ion Public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN