Collective flow and charged hadron correlations in 2.76 TeV PbPb collisions at CMS

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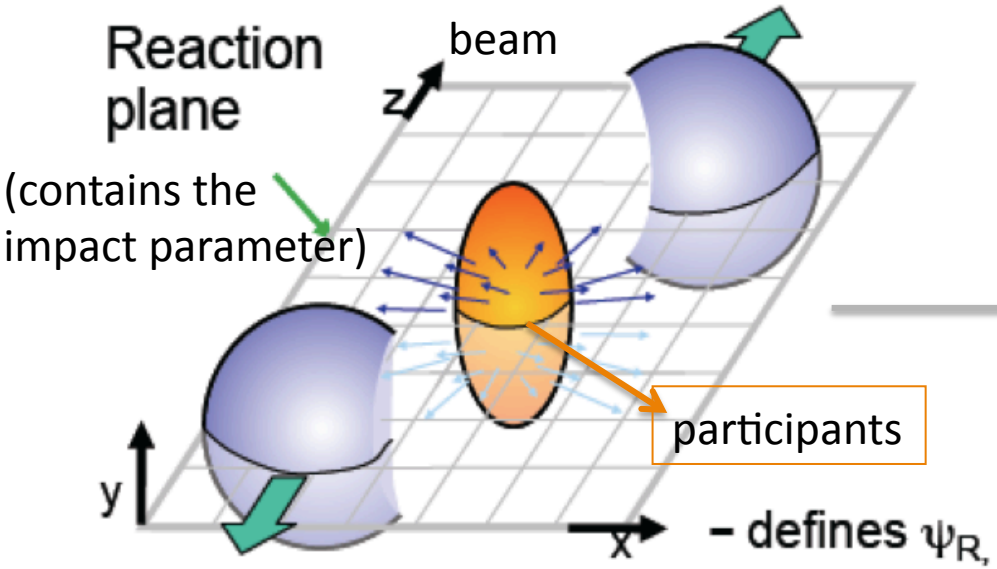
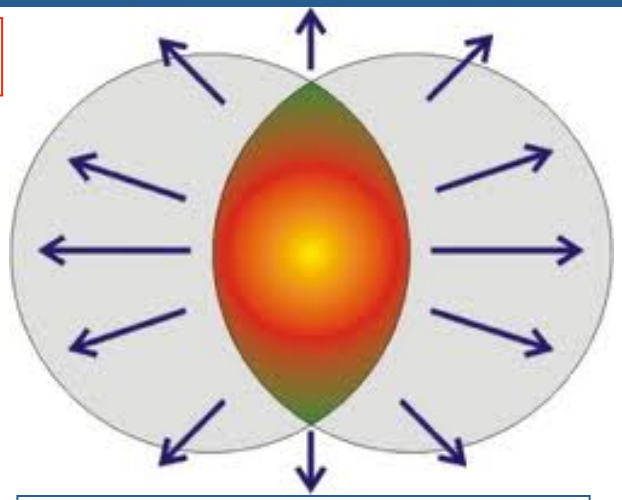
for the CMS collaboration

Origin of azimuthal correlations



Event Plane



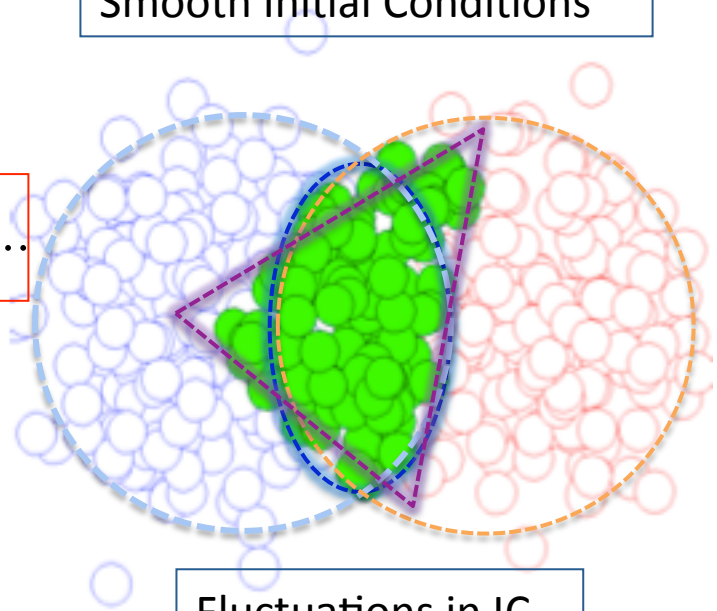
Smooth Initial Conditions

Elliptic flow Triangular flow

$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots$$

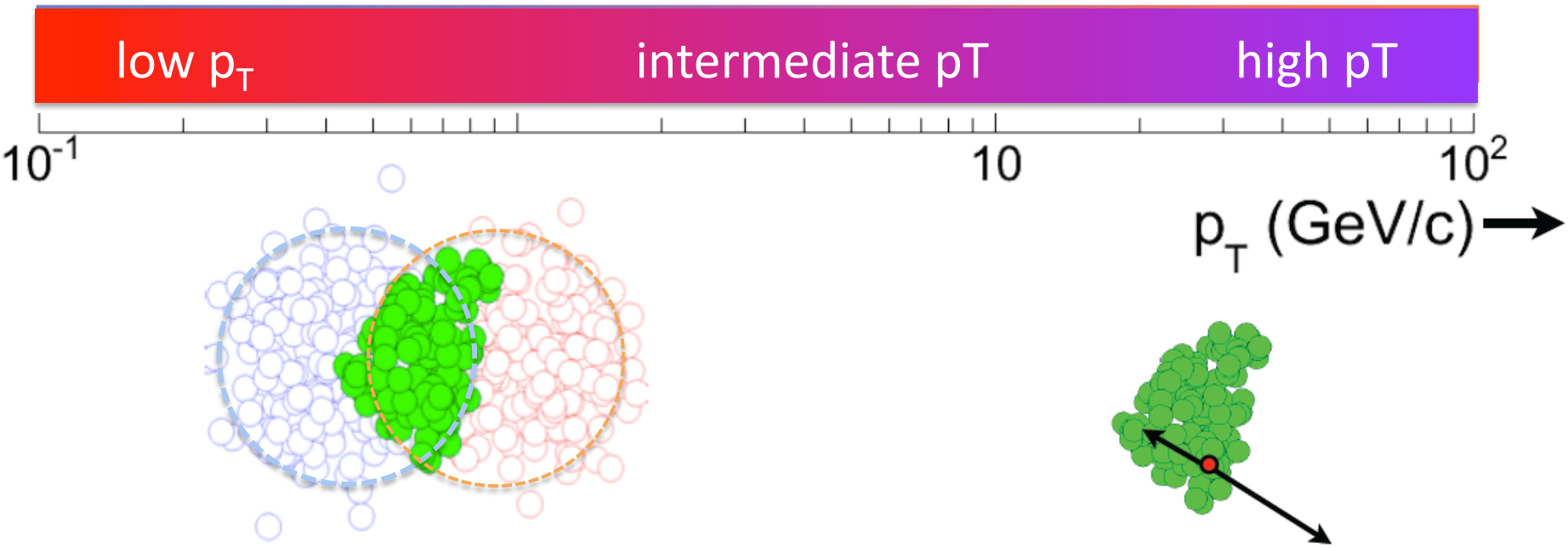
- Smooth IC
  - odd harmonics = 0 (by symmetry)
- Fluctuations in IC

  → give rise to odd harmonics ≠ 0



Fluctuations in IC

Azimuthal correlations investigated in CMS



Hydrodynamic flow driven by asymmetric pressure gradients & spatial anisotropies

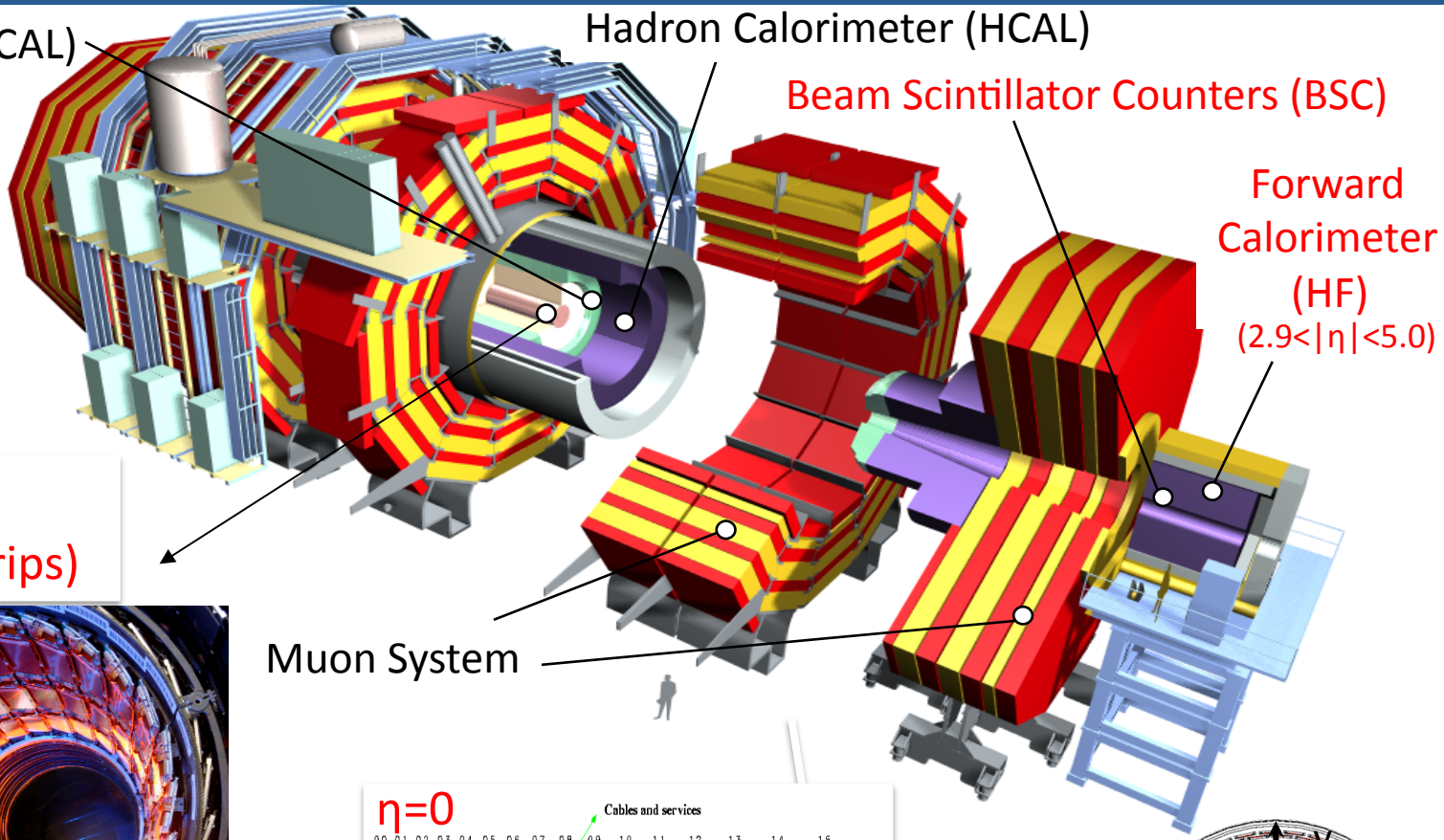
Soft-hard interplay (hadrons from thermal quarks + jet fragmentation)

Path-length dependent energy loss

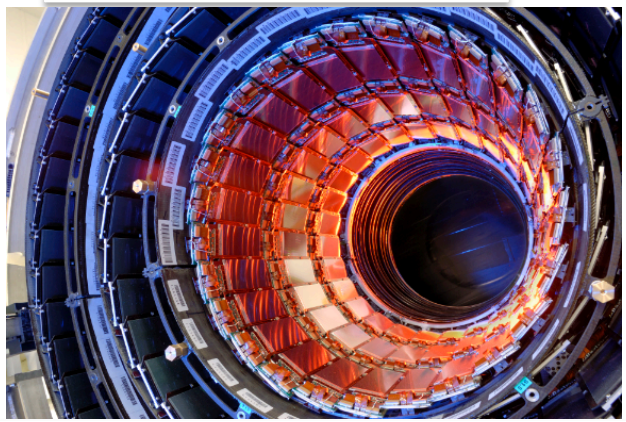
Highlights

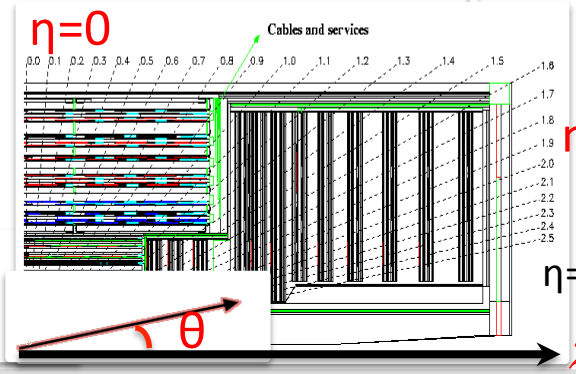
- Measuring azimuthal anisotropy of charged particles:
  - Physics motivation:
    - EoS, opacity, and viscosity of the medium
    - Initial conditions and the role of fluctuations
  - Elliptic anisotropy at lower p_T → different methods
    - Event Plane
    - Cumulants
      - Two-particle: $v_2\{2\}$
      - Four-particle: $v_2\{4\}$
    - Lee-Yang Zeros
  - Elliptic anisotropy at high p_T (Event Plane)
  - Dihadron correlations
    - Investigate anisotropies of higher order Fourier harmonics
- Summary

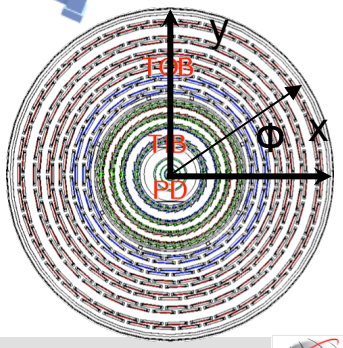
CMS Detector



TRACKER
(Pixels and Strips)







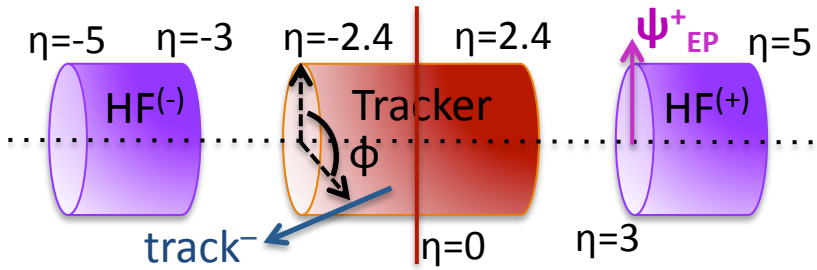
Very large coverage
($|\Delta\phi| \leq 2\pi$, $|\Delta\eta| < 5$)

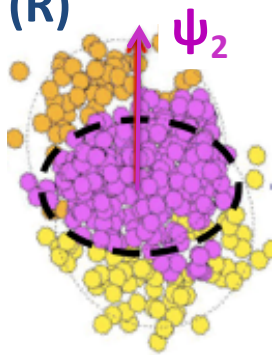
Four methods: EP, $v_2\{2\}$, $v_2\{4\}$, LYZ

Event Plane

$$v_2\{\mathrm{EP}\} = \langle \cos\left[2(\phi - \psi_{\mathrm{EP}})\right]\rangle / R$$

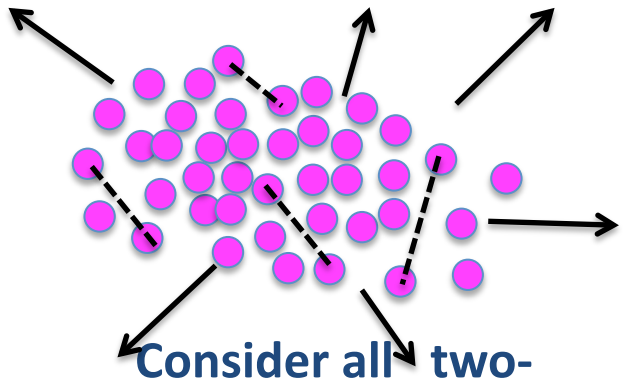
Need to correct for ψ_{EP} resolution (R)





Two-particle Cumulant

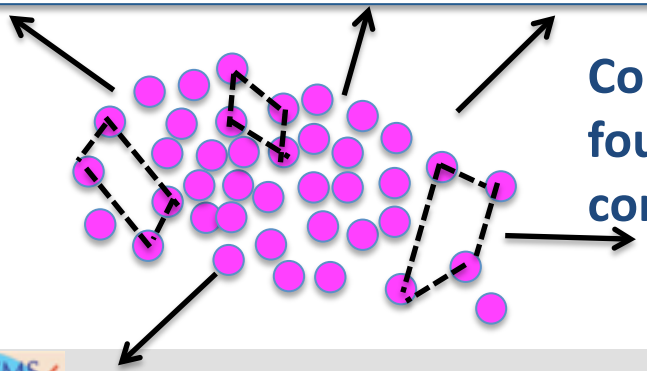
$$v_2\{2\} = \sqrt{\langle \cos\left[2(\phi_1 - \phi_2)\right]\rangle}$$



Consider all two-particle correlations

Four-particle Cumulant

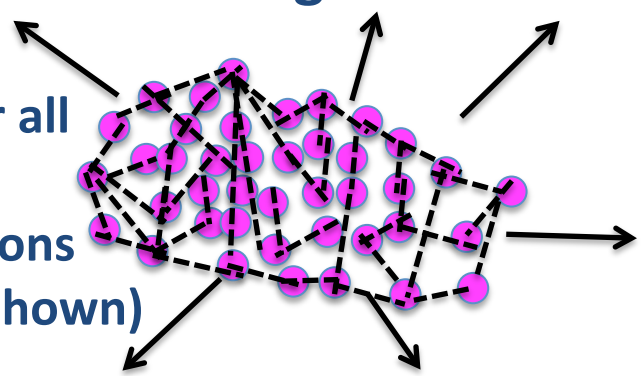
$$v_2\{4\} = \left(2\langle\cos[2(\phi_1 - \phi_2)]\rangle^2 - \langle\cos(\phi_1 + \phi_2 - \phi_3 - \phi_4)\rangle\right)^{1/4}$$



Consider all four-particle correlations

Lee-Yang Zeros

Consider all particle correlations (not all shown)



Di-hadron correlations (5th method)

Signal

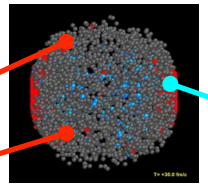
$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta\, d\Delta\phi}$$

Particle 1: trigger
Particle 2: associated

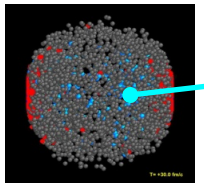
Background distribution:

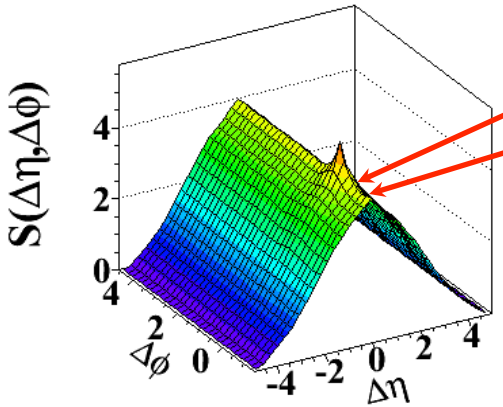
$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta\, d\Delta\phi}$$

Event 1

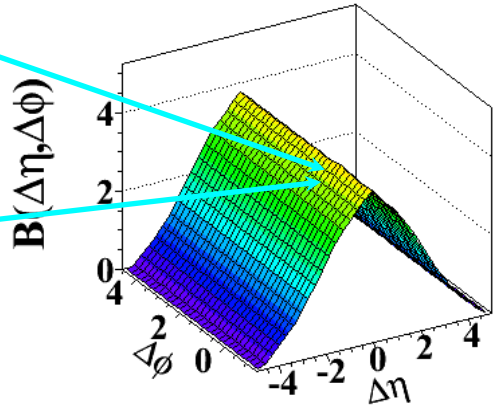


Event 2





same event pairs



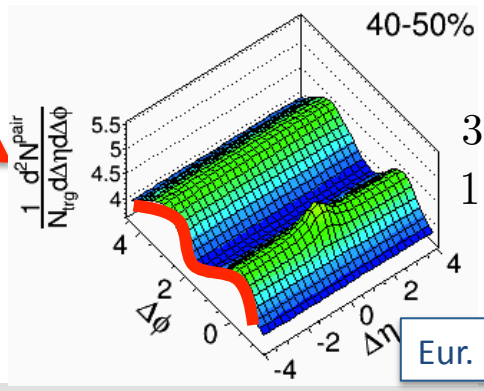
mixed event pairs

$$\Delta\eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$$
$$\Delta\phi = \phi^{\text{assoc}} - \phi^{\text{trig}}$$

Associated hadron yield per trigger:

$$\frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{pair}}}{d\Delta\eta\, d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

1st analysis: PbPb@ $\sqrt{s_{NN}}$ = 2.76 GeV:
0-5% most central coll. → JHEP**07**, 076 (2011)



$$3 < p_T^{\text{trig}} < 3.5\text{GeV/c}$$
$$1 < p_T^{\text{assoc}} < 1.5\text{GeV/c}$$

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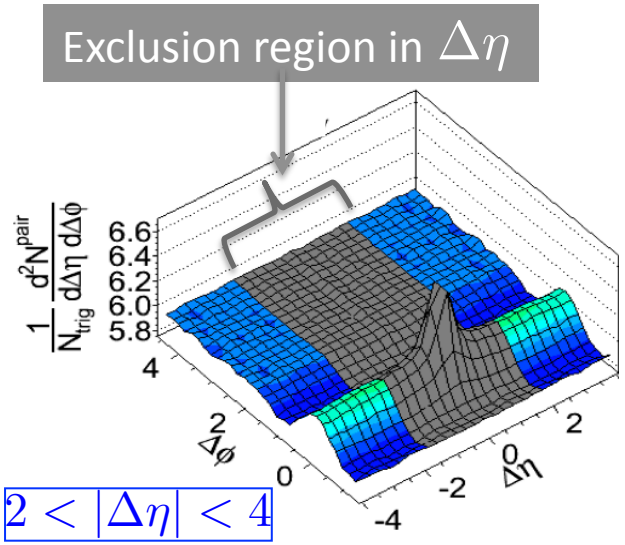
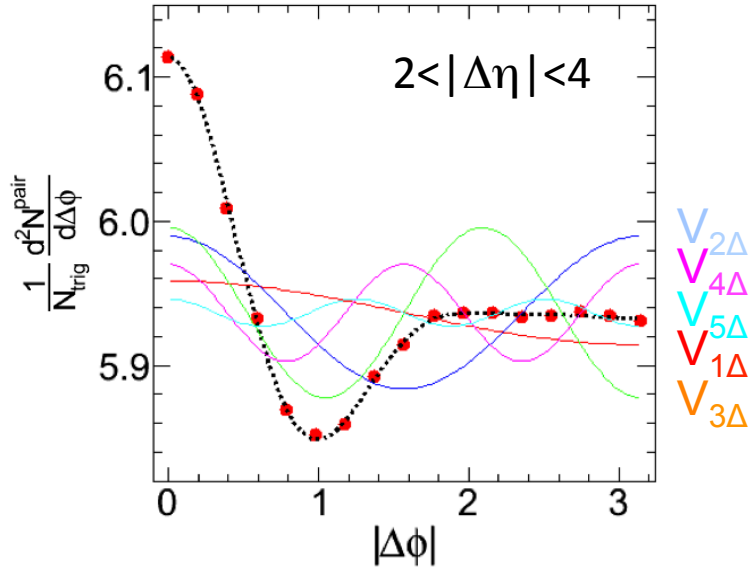
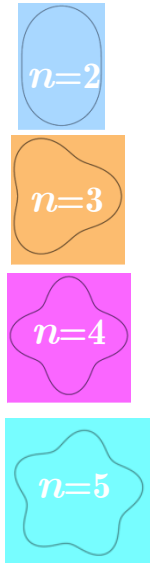
Fourier analysis of Δϕ correlations







Fourier decomposition: fitting the 1D $\Delta\phi$-projected distribution for 1 < $|\Delta\eta|$ < 4 as

$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N_{\rm assoc}}{2\pi}\left\{1+\sum_{n=1}^{N_{\rm max}} 2V_{n\Delta}\cos(n\Delta\phi)\right\} \quad (N_{\rm max}=5)$$

Flow driven correlations:

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

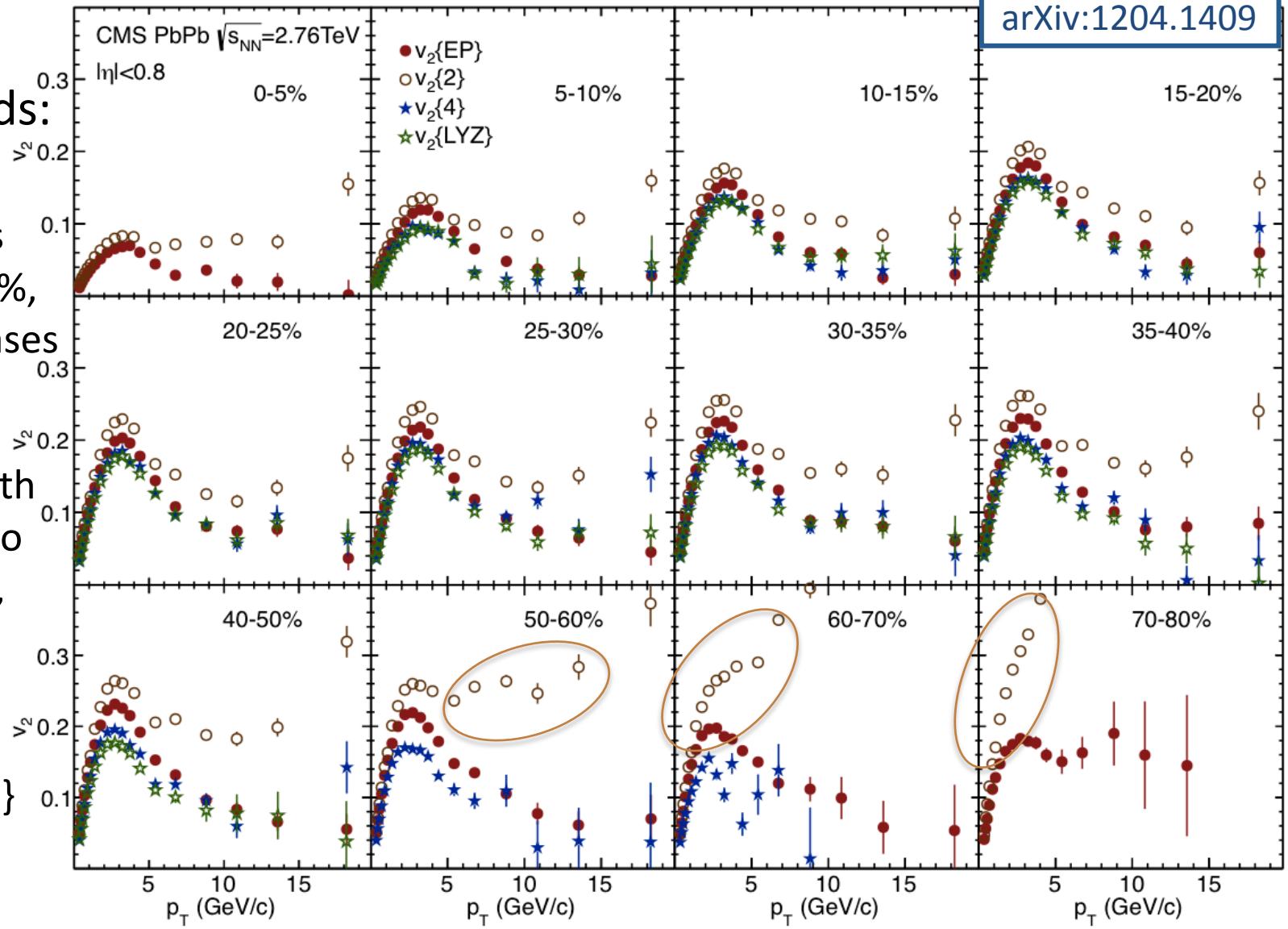
Complementary to standard flow methods (i.e., EP, cumulants, LYZ)

$v_2(p_T)$: results for the 4 first methods

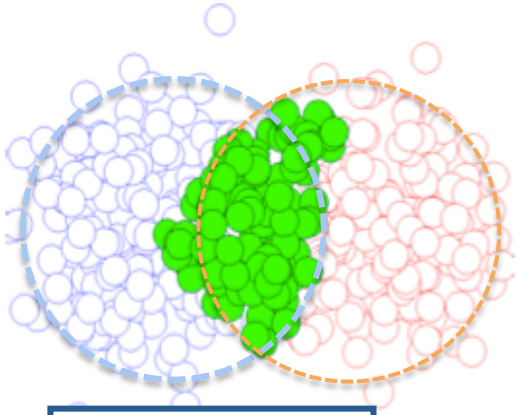
arXiv:1204.1409

All methods:

- $v_2(p_T)$ grows up to 40-50%, then decreases
- Behavior with p_T: rise up to p_T ~ 3GeV/c, then gradually decreases (except $v_2\{2\}$ above 50%)



Integrated v_2 scaled by eccentricity



Participant Eccentricity

$$\epsilon_{\rm part} \equiv \frac{\sqrt{\left(\sigma_{y'}^2 - \sigma_{x'}^2\right)^2 + 4\sigma_{x'y'}^2}}{\sigma_{y'}^2 + \sigma_{x'}^2}$$

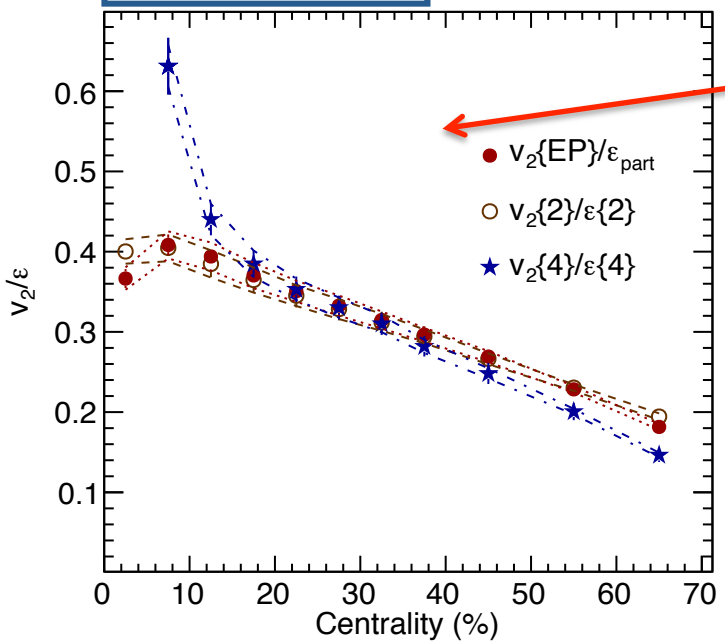
Cumulant Moments

$$\epsilon\{2\}^2 \equiv \langle \epsilon_{\rm part}^2 \rangle,$$

$$\epsilon\{4\}^4 \equiv 2\langle \epsilon_{\rm part}^2 \rangle^2 - \langle \epsilon_{\rm part}^4 \rangle$$

$$\frac{v_2\{2\}}{\epsilon\{2\}} = \frac{v_2\{4\}}{\epsilon\{4\}} \sim \frac{v_2\{\rm EP\}}{\epsilon_{\rm part}}$$

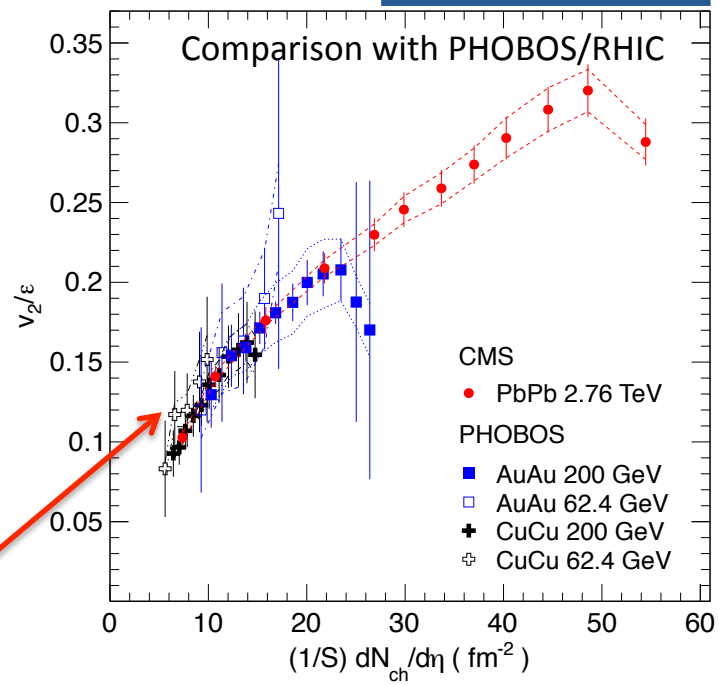
arXiv:1204.1409



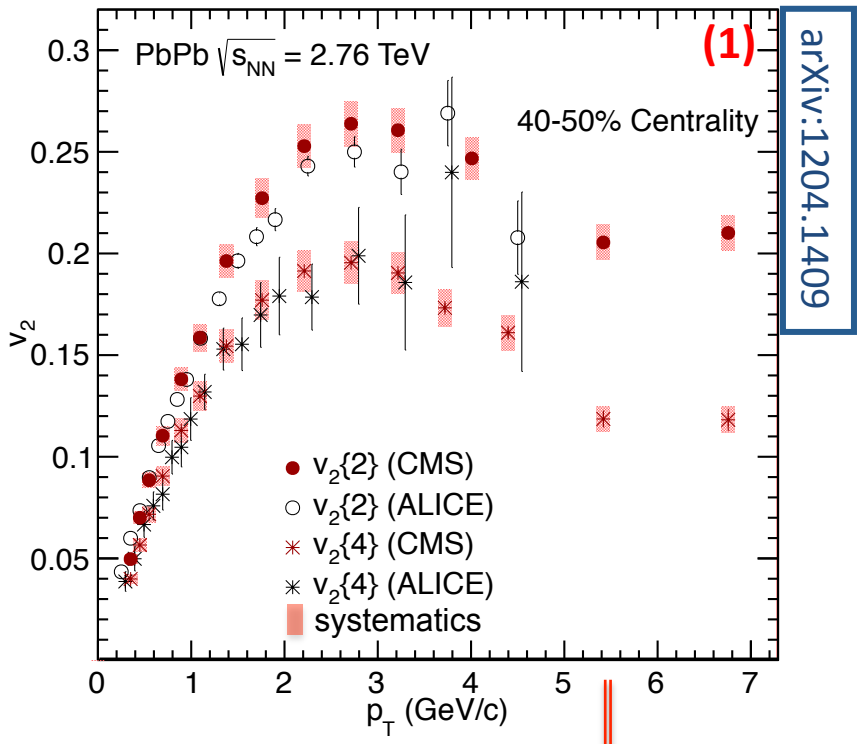
Differences between the methods → well described by Glauber model eccentricities for 15-40% centrality

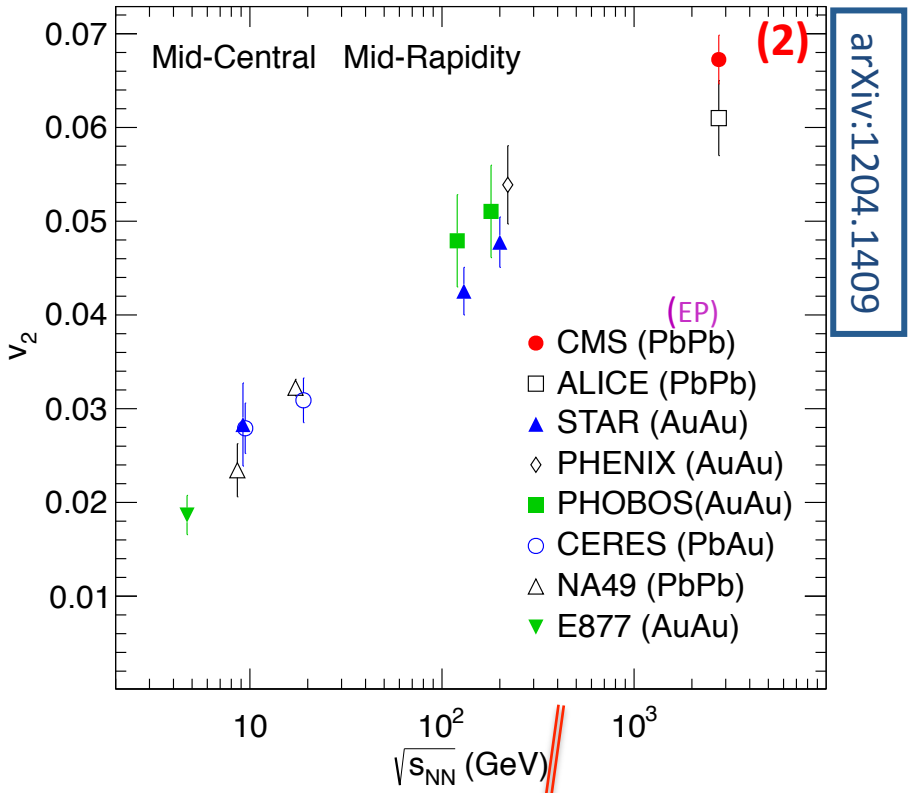
v_2/ε scales with the charged-particle rapidity density & is in good agreement with PHOBOS

arXiv:1204.1409



$v_2(p_T)$: comparison with ALICE & low energies

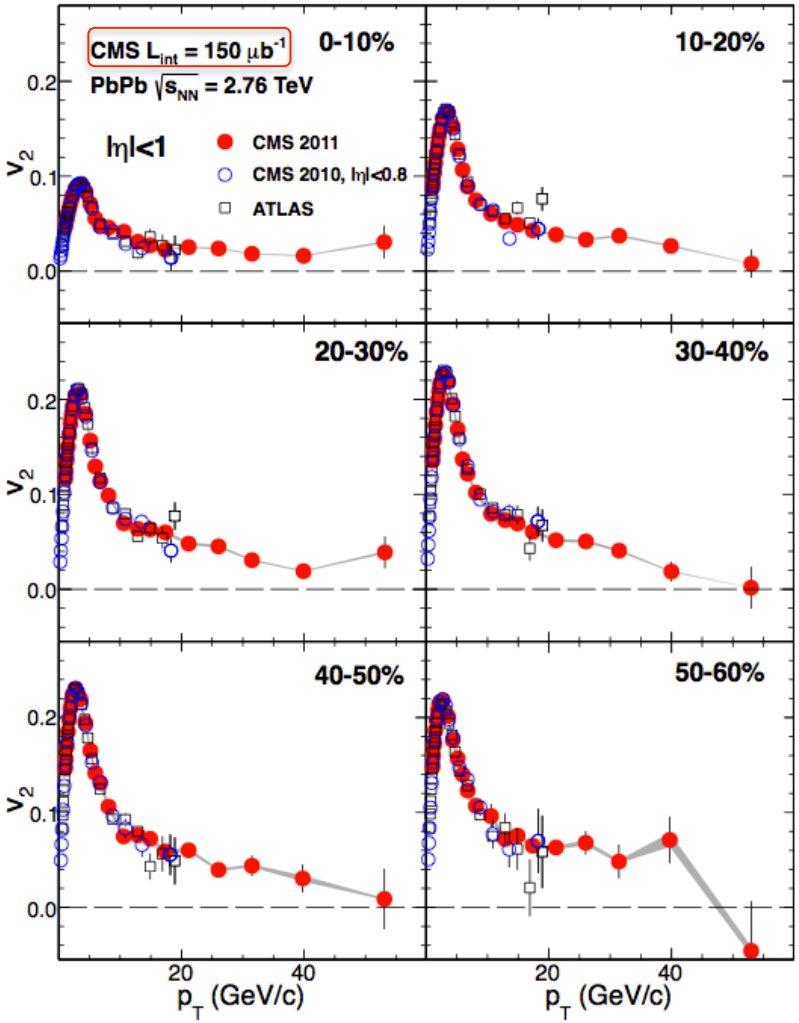


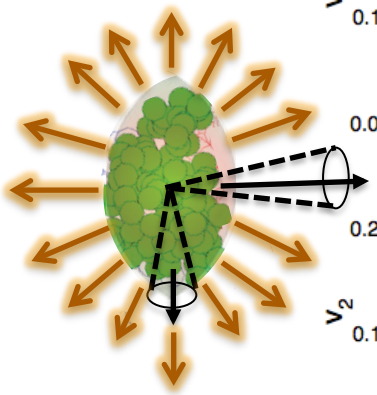


- (1) CMS & ALICE for $v_2\{2\}$ and $v_2\{4\}$ → good agreement within uncertainties
- (2) Qualitative $\sqrt{s_{NN}}$ dependence of integrated v_2 [4.7 GeV (AGS) -2.76 TeV (LHC)]: 20-30% log increase with $\sqrt{s_{NN}}$ from RHIC@200GeV to LHC@2.76 GeV

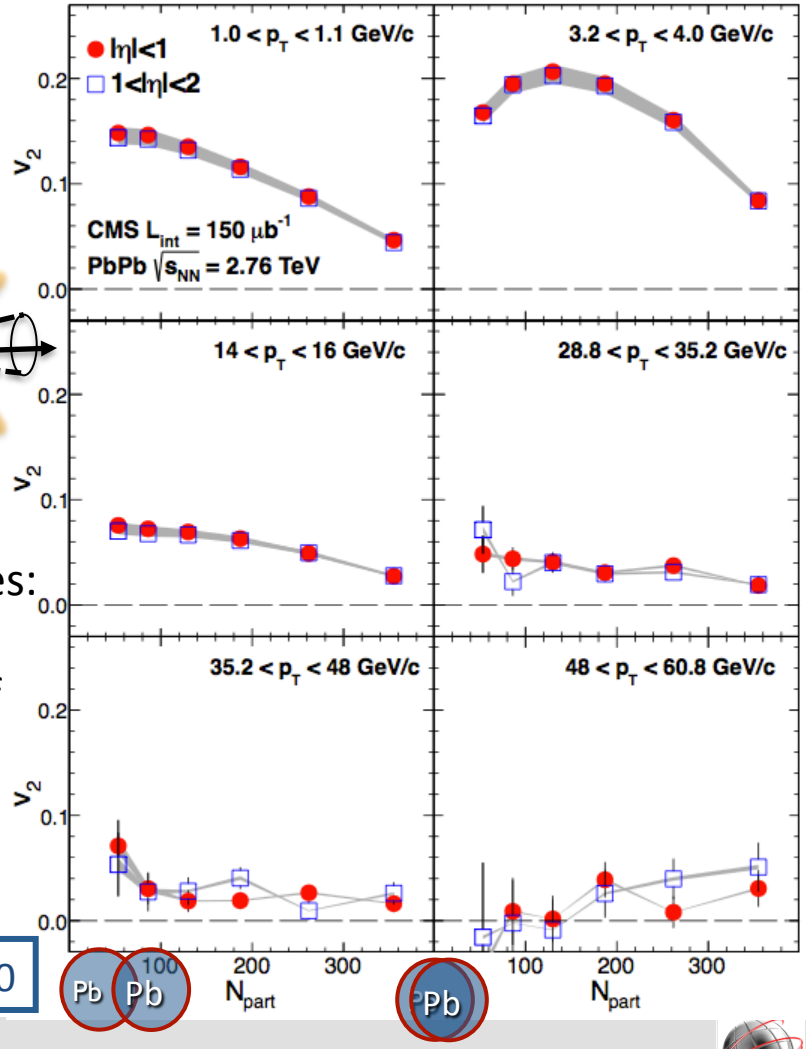
$v_2(p_T)$ extended to high p_T & versus N_{part} (EP)

- First precise measurements of $v_2(p_T)$ up to p_T ~ 60 GeV/c (comparison with ATLAS)
- v_2 gradually decreases above p_T=10 GeV/c; remains ≠ 0 up to very high p_T





high-p_T particles: v_2 reflects path dependence of jet energy loss



arXiv: 1204.1850

2nd-5th order single-particle azimuthal harmonics

- Assuming factorization, i.e.,

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

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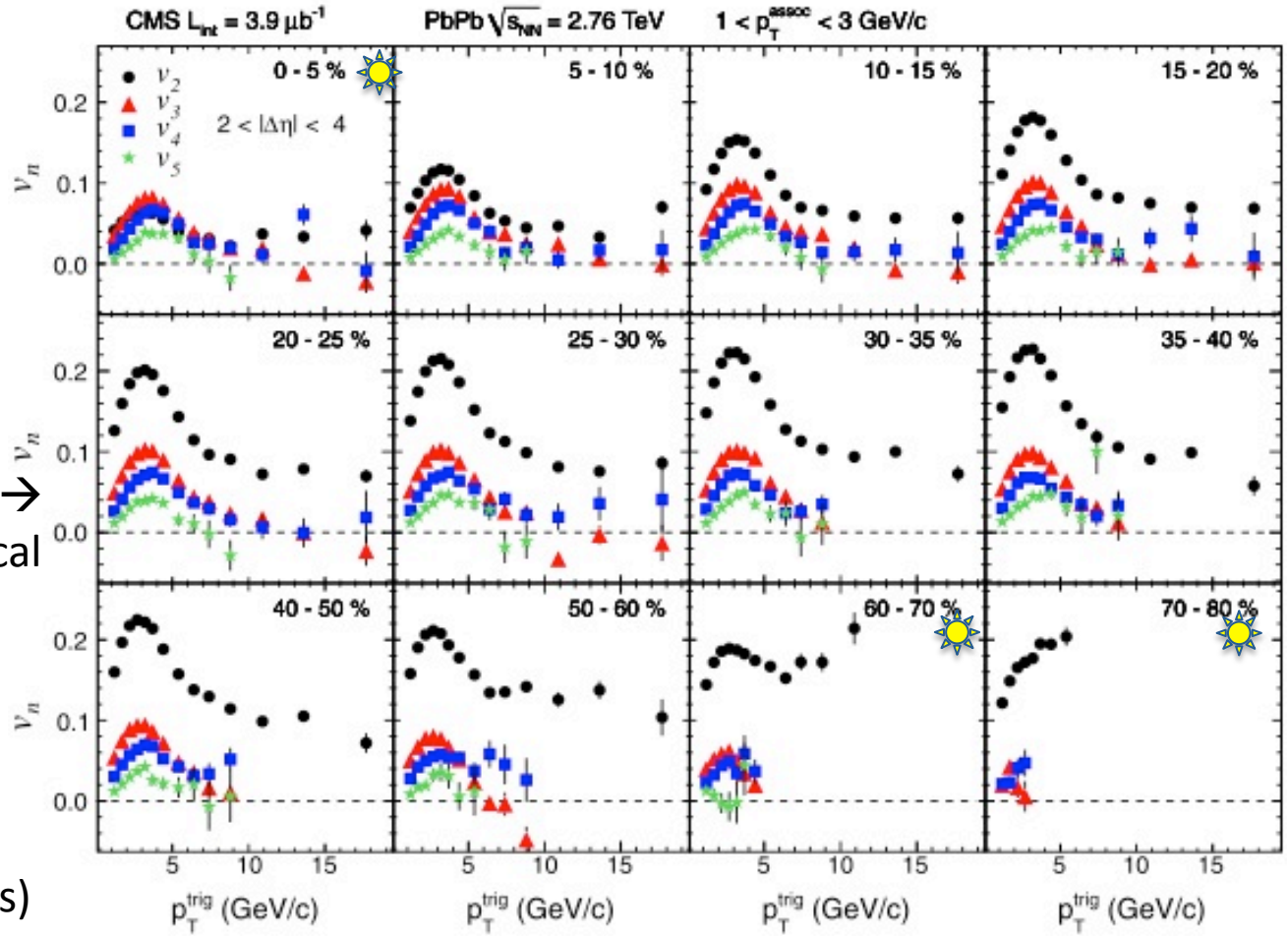


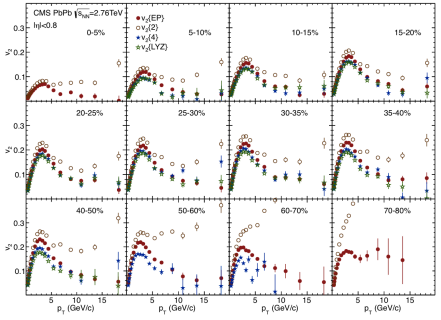
- Non-zero v_3 and v_5 → reflect fluctuations in IC
- For most peripheral (> 30%) → v_3-v_5 truncated due to statistical limitations

(☀ included for completeness)

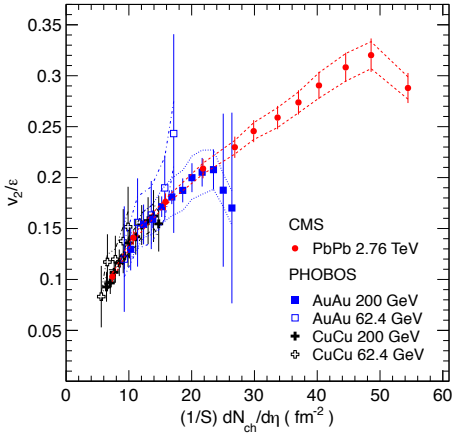
Summary & highlights

low p_T | high pT

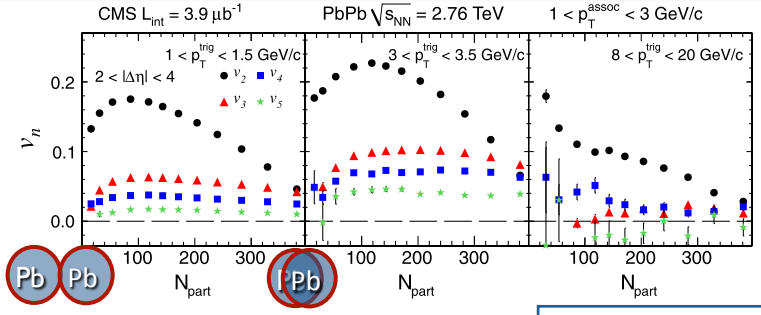
$v_2(p_T)$ at LHC with 4+1 complementary methods



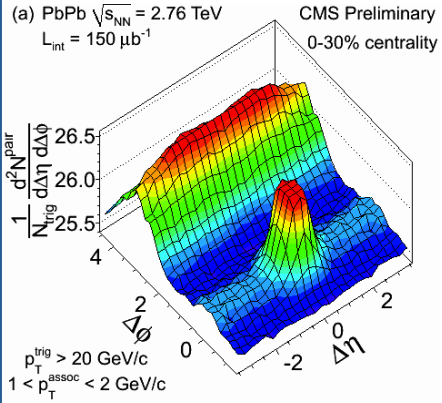
$v_2(p_T)$ at LHC behaves similarly as at RHIC

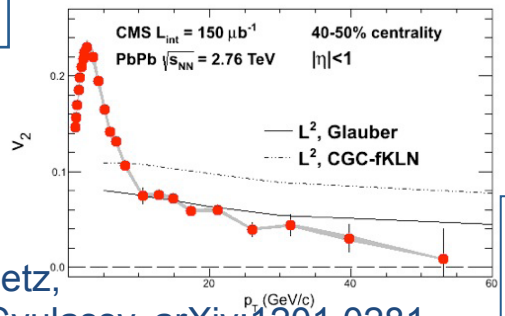


First measurements at high p_T



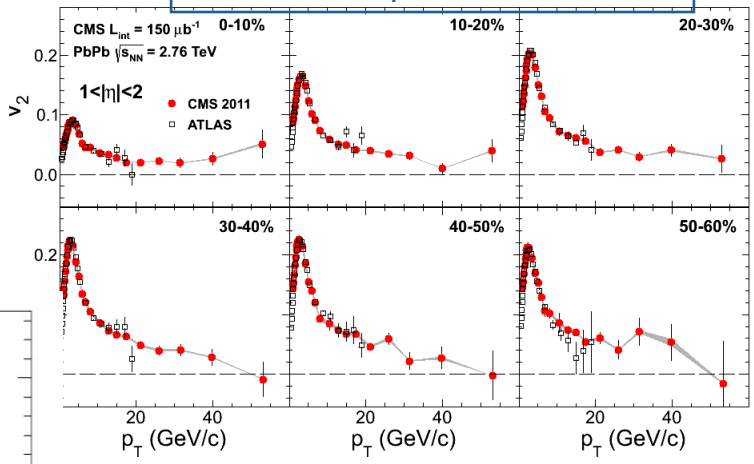
Dihadron higher order v_n → new insight in IC, etc.





B. Betz, M. Gyulassy, arXiv:1201.0281

First v_2 measurements at $20 < p_T \leq 60$ GeV/c

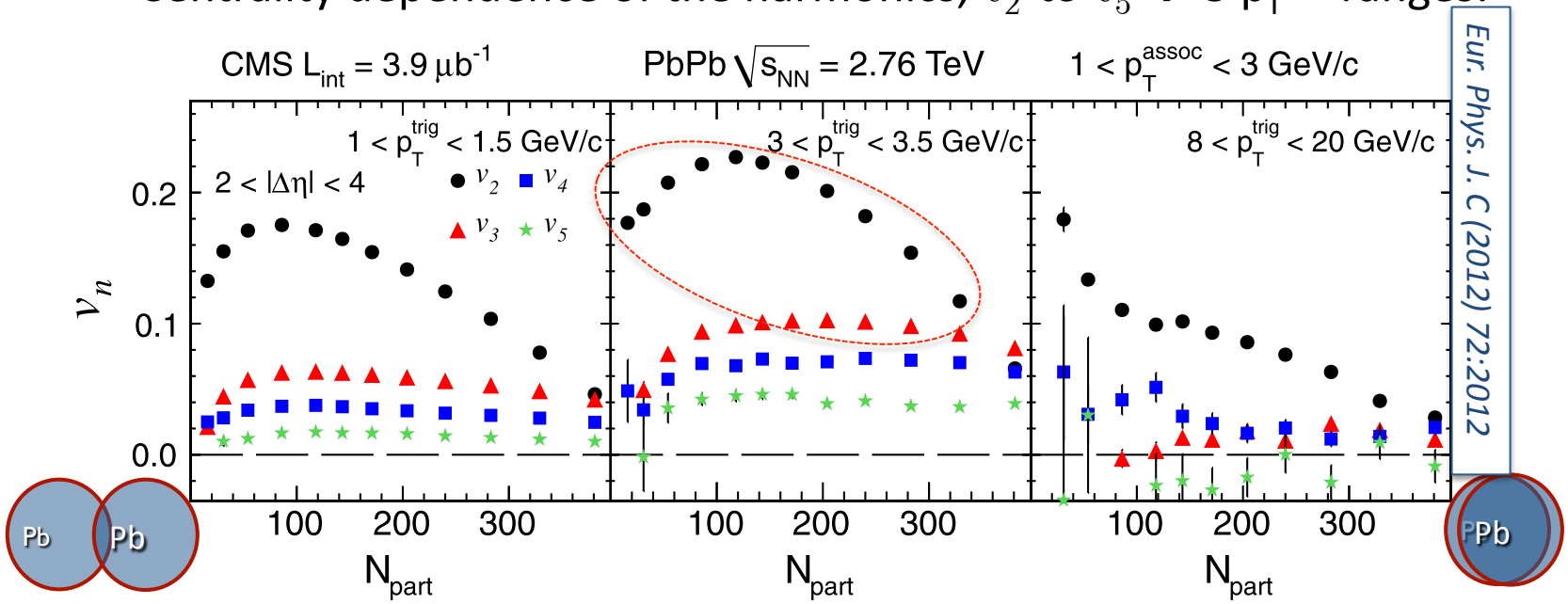


High-p_T v_2 results → constraints on energy loss models

BACK UP

Extracted single-particle azimuthal anisotropy harmonics

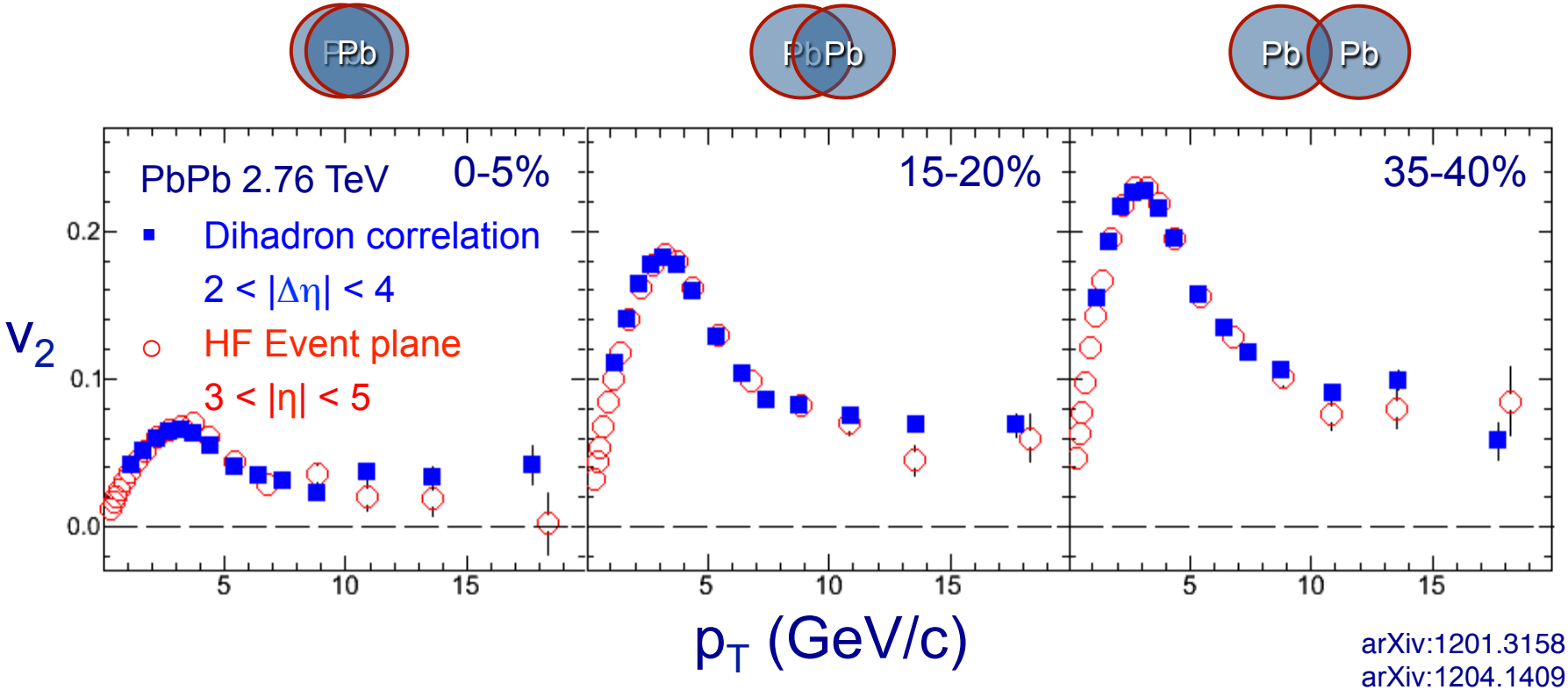
» Centrality dependence of the harmonics, v_2 to v_5 → 3 p_T^{trig} ranges:



» Strong v_2 x N_{part} dependence on centrality (not significant for v_3-v_5)

- Expected from both hydrodynamic flow phenomena (lower-p_T) & path-length dependence of the parton energy-loss (higher p_T)
- v_2 → sensitive to the lenticular shape (larger for peripheral coll.) of initial collision region; v_3-v_5 mostly driven by fluctuations in IC

v_2 from Di-hadron Correlations



arXiv:1201.3158
arXiv:1204.1409

$v_2(p_T)$ from dihadron correlation method (derived using fixed $1 < p_T^{assoc} < 1.5$ GeV/c) agrees well with EP method

Ridge in PbPb - centrality dependence

(30M events) CMS $L_{int} = 3.9\ \mu b^{-1}$ PbPb $\sqrt{s_{NN}} = 2.76$ TeV $3.0 < p_T^{trig} < 3.5$ GeV/c $1.0 < p_T^{assoc} < 1.5$ GeV/c

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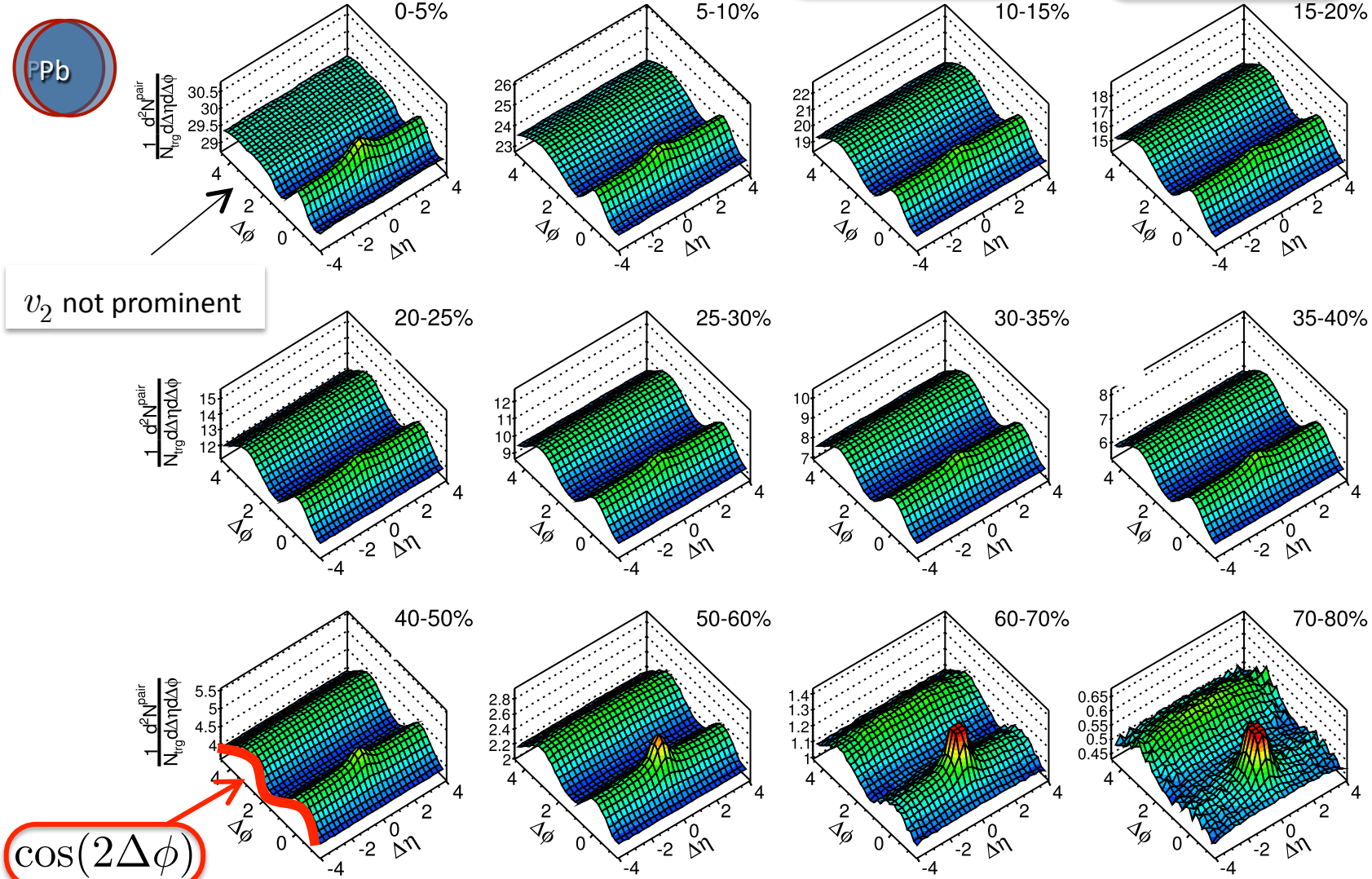
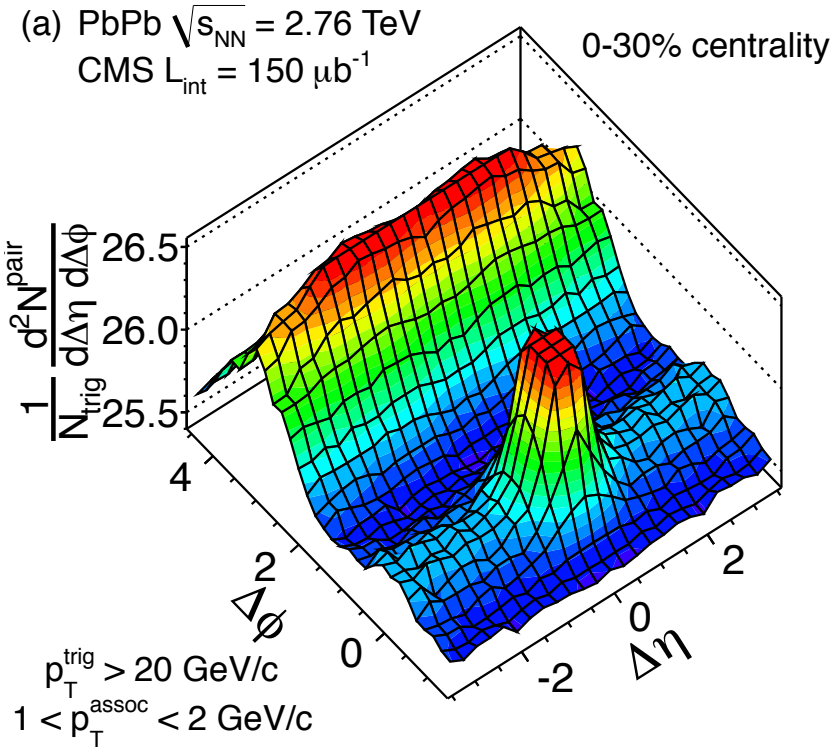


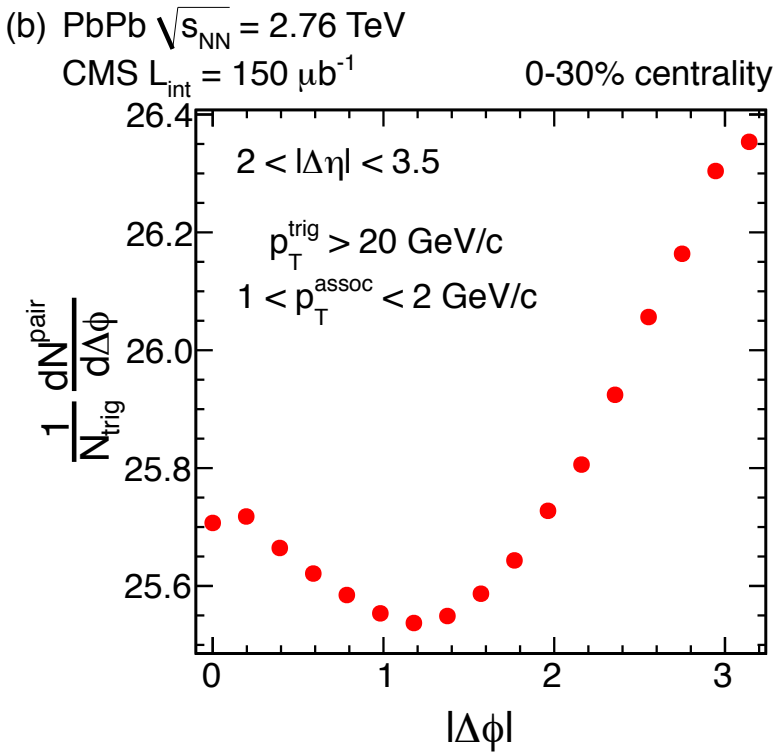
v_2 not prominent

$\cos(2\Delta\phi)$

Dihadron correlations @ high p_T

- First obsevation of long range near-side ($\Delta\phi \sim 0$) structure for $p_T^{trig} > 20$ GeV/c

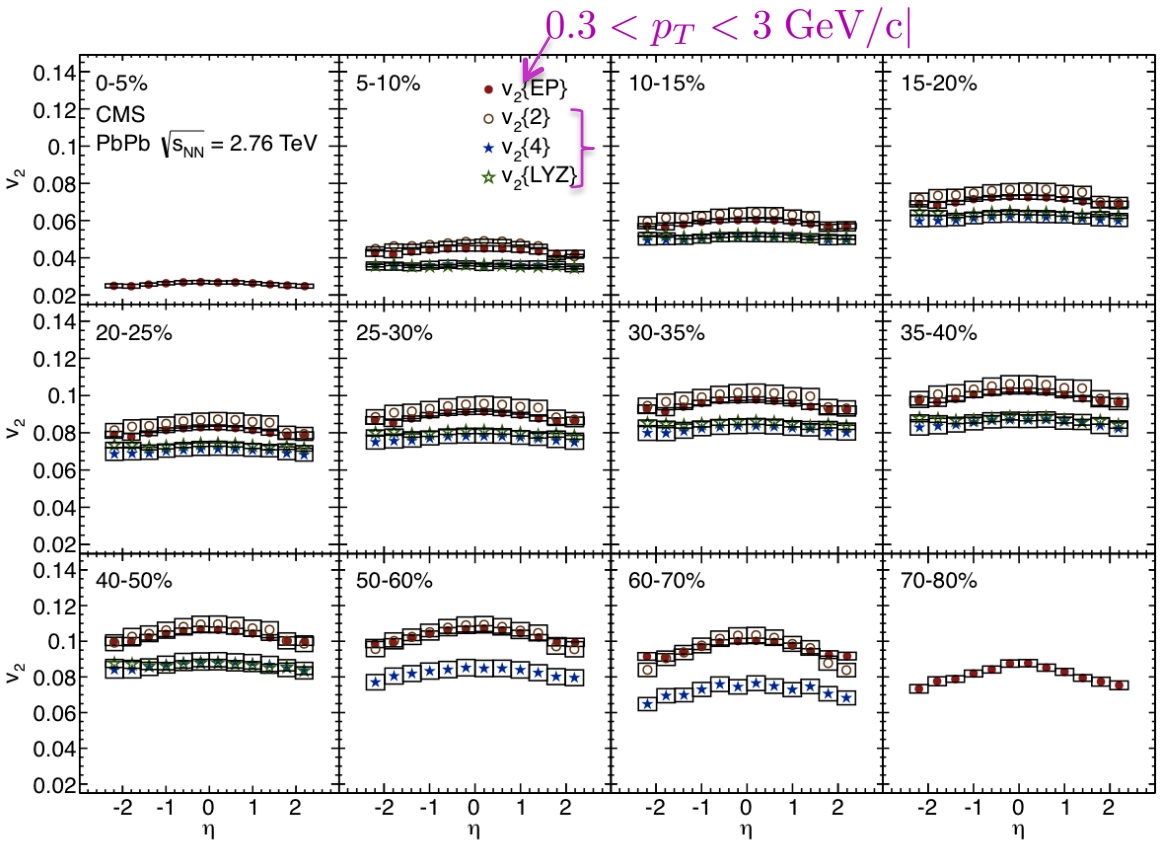


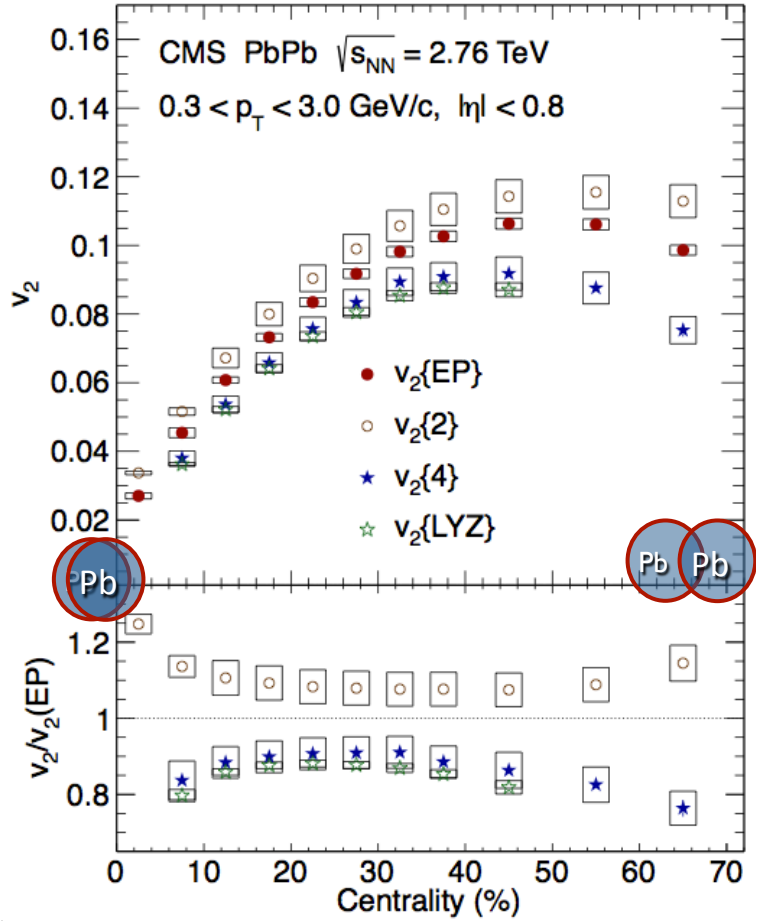


$v_2(\eta)$ and centrality of integrated v_2

- $v_2(\eta)$ is larger at mid-rapidity
- constant or decreases very slowly at larger values of $|\eta|$

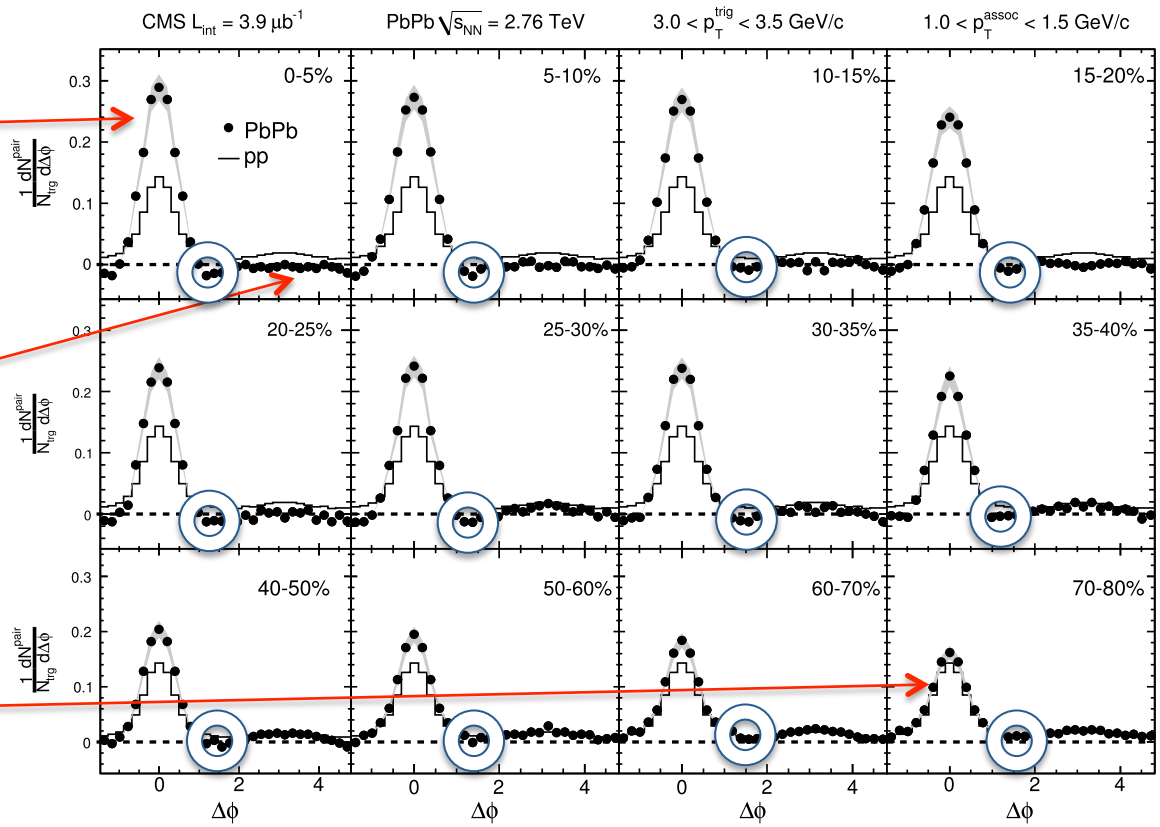
- integrated v_2 vs. centrality for $|\eta| < 0.8$: increase from central to peripheral collisions (max. ~ 40–50%)



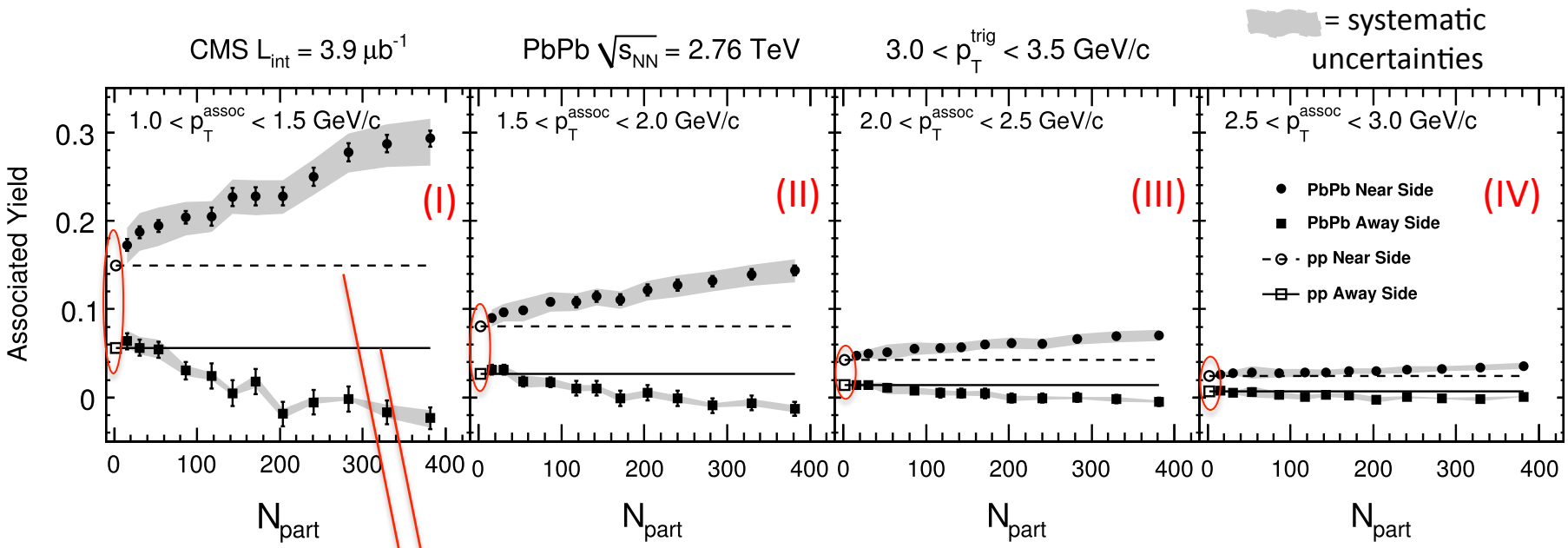


Subtracting flat background in $\Delta\eta$

- Near-side peak ($\Delta\phi \approx 0$): mostly jet fragmentation
- Away-side region ($\Delta\phi \approx \pi$): nearly flat (weakly dependent in $\Delta\eta$)
- pp data at 2.76 GeV: similar structure to 70-80% peripheral PbPb
- Strength of 2 regions → quantified by integrating over 2 ranges wrt $\Delta\phi_{\min} \approx 1.18$



Integrated associated yields



(expected for trivial extrapolations from pp results)

- Near-side peak: increases by 1.7 from 70=80% to 0-5% [in (I)]; but only 1.3 in (IV) (at RHIC almost no centrality dependence)
- Away-side: yield decrease with centrality (negative for most central)
- On both near and away sides → yield in PbPb matches that in pp for the most peripheral events.

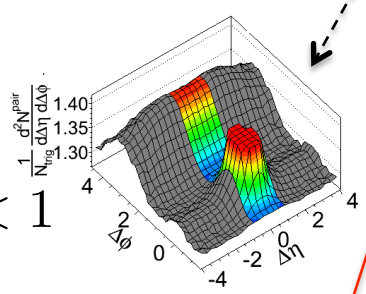
Centralities of the 1D $\Delta\phi$ distribution

- Averaging the 2D $(\Delta\eta, \Delta\phi)$ in limited region in $\Delta\eta$

$$\frac{1}{N_{\text{trig}}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{1}{(\Delta\eta_{\max} - \Delta\eta_{\min})} \times \int_{\Delta\eta_{\min}}^{\Delta\eta_{\max}} \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{pair}}}{d\Delta\eta\Delta\phi} d\Delta\eta$$

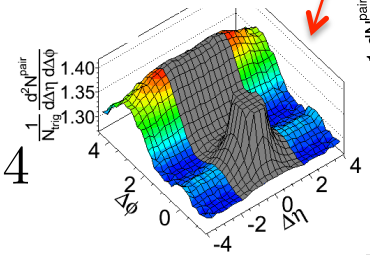
Short-range

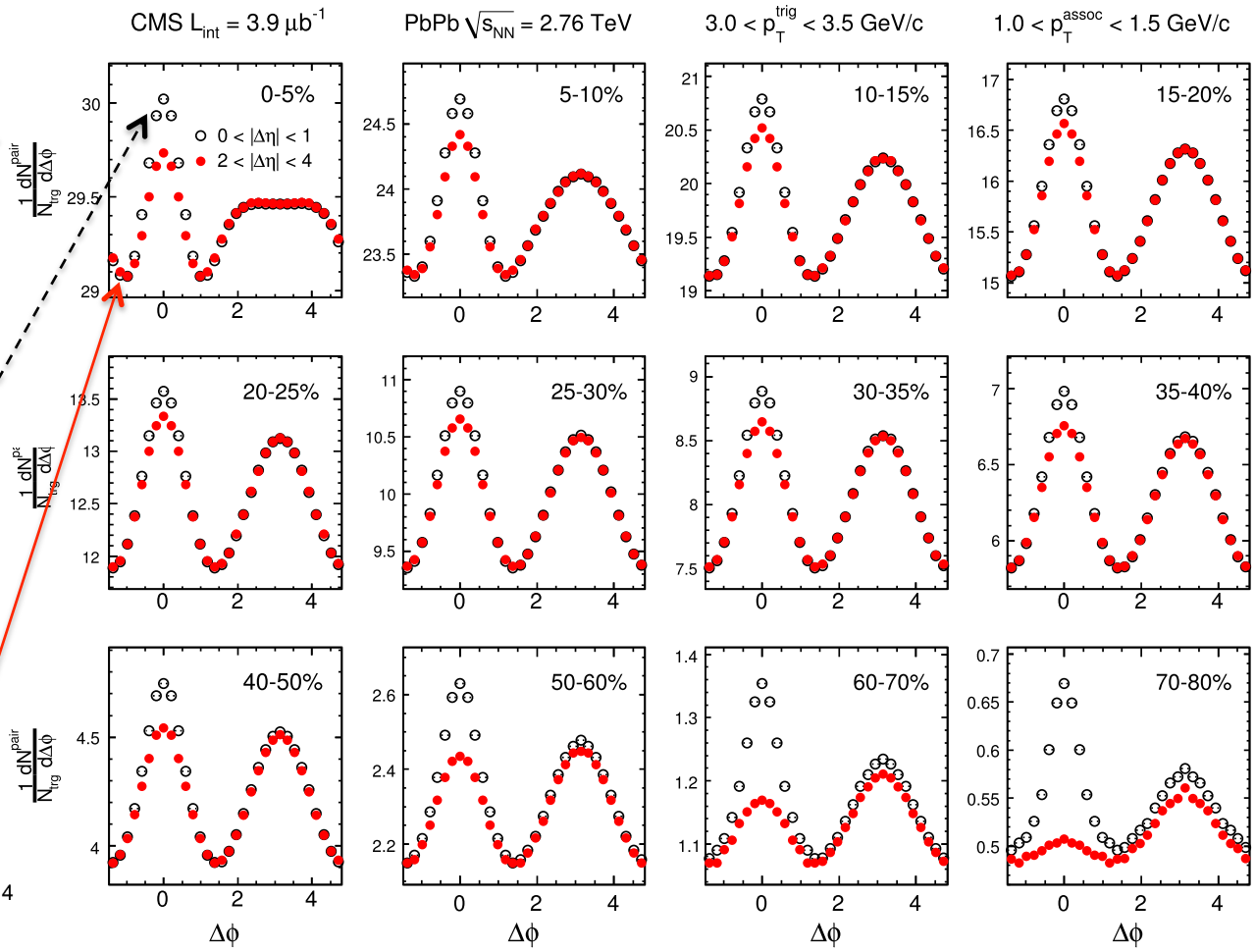
$$0 < |\Delta\eta| < 1$$



Long-range:

$$2 < |\Delta\eta| < 4$$





Dihadron correlations and single-particle anisotropies

- Factorization: valid up to p_T^{assoc} ~ 3.5 GeV/c & p_T^{assoc} ~ 8 GeV/c

- For 0-5% events→ complex situation: factorization does not apply and other mechanisms must be at action, perhaps a complicated interplay of different particle production mechanisms between low-pT (hydrodynamic flow) and high-pT (dijet production) particles.