Charged Hadron Azimuthal Anisotropy (v_2) in $\sqrt{s_{NN}}$ = 2.76 TeV PbPb collisions from CMS

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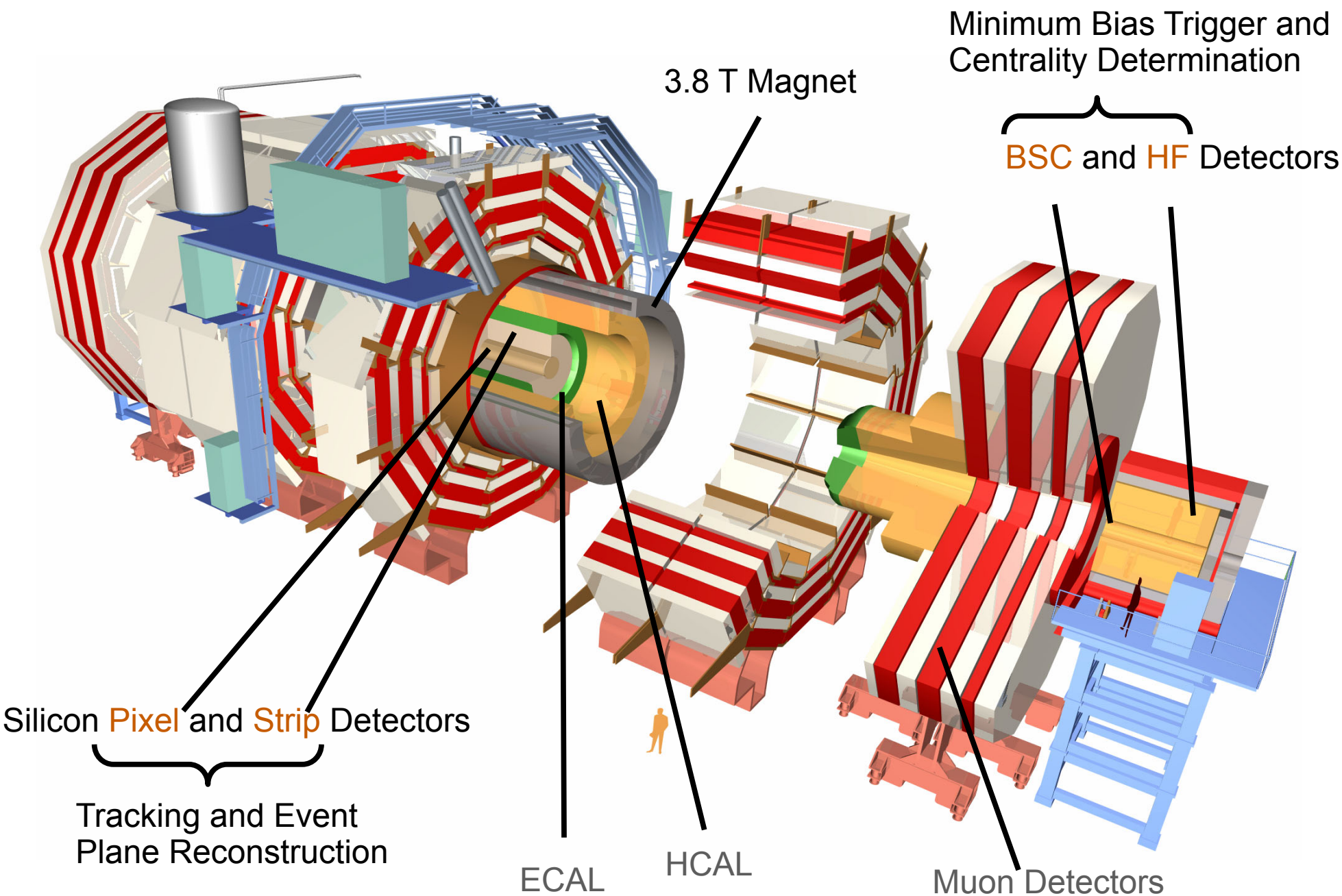
for the CMS Collaboration

Motivation

- Goal: To explore hydrodynamic flow at the LHC energy by measuring azimuthal anisotropy as a function of transverse momentum, pseudorapidity and centrality in a broad kinematic range:
  - $0.3 < p_T < 12.0$ GeV/c
  - $|\eta| < 2.4$
  - 12 centrality classes in the range 0-80%
- Four Methods:
  - Event Plane
  - Cumulant 2nd order
  - Cumulant 4th order
  - Lee-Yang Zeros

each has a different sensitivity to non-flow!

CMS Detector

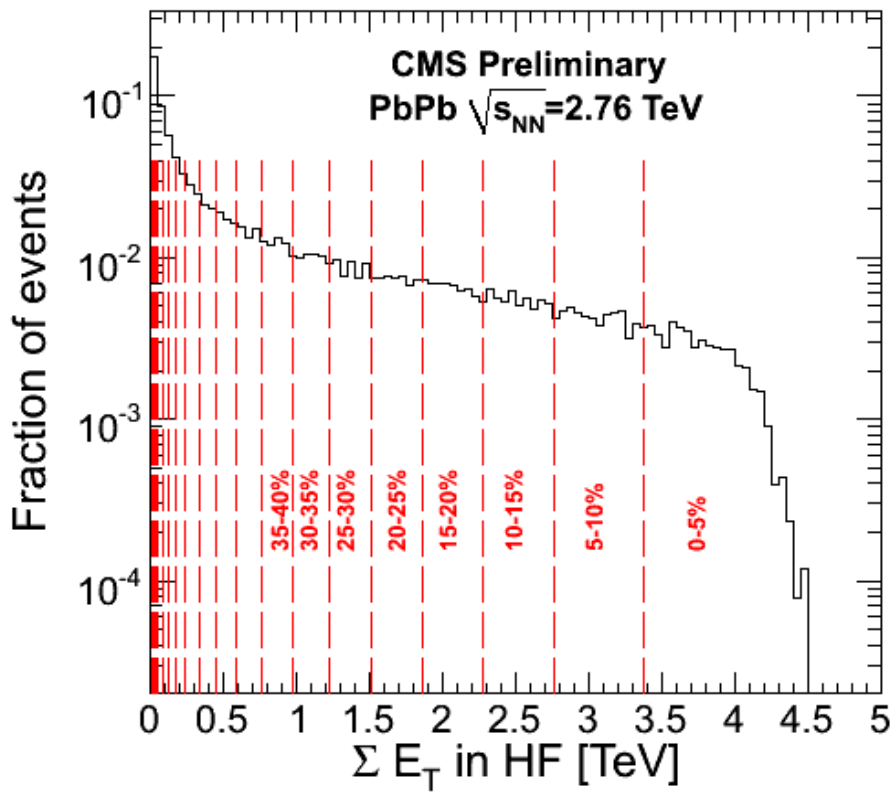


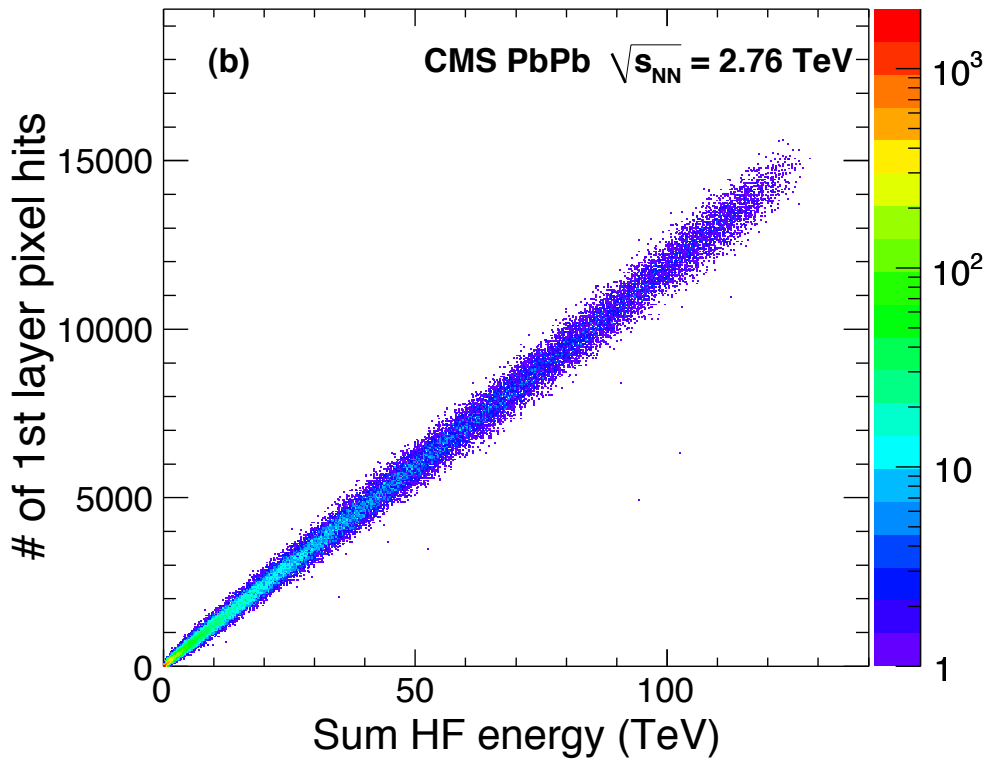
Event Selection

- Event selection:
  - Minimum bias event selection: double coincidence of either the Beam Scintillation Counters (BSC) or Forward Hadronic calorimeters (HF)
  - Additional off-line selection (removal of beam gas, beam scraping, etc.)
  - Vertex position: $|z| < 10$cm
- Total number of events after applying cuts ~ 2.3M

Centrality Determination

- Based on the total sum of the transverse energy in HF





- 12 centrality classes: 0-80%

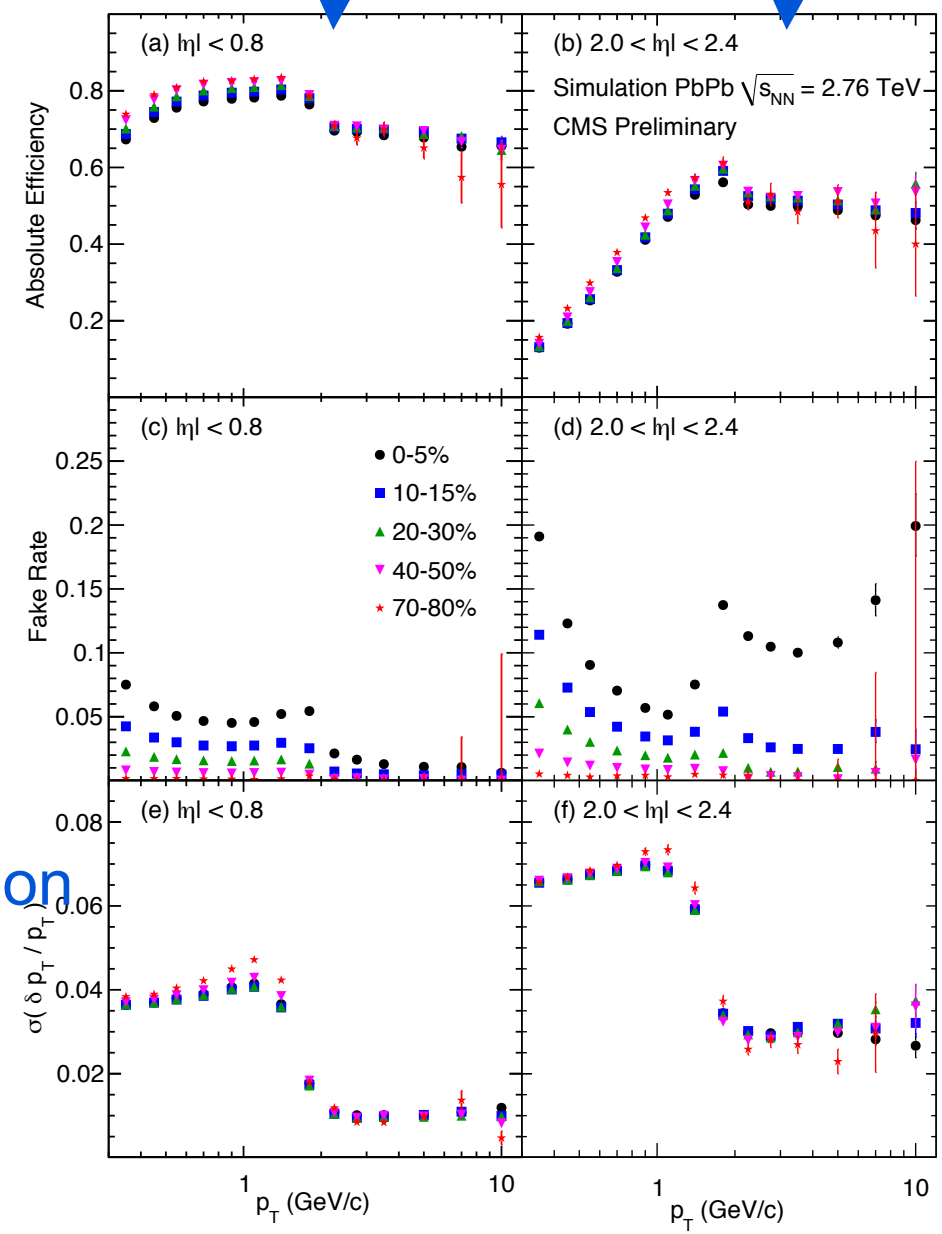
Track Reconstruction

|η|<0.8 2.0<|η|<2.4

absolute efficiency

fake rate

p_T resolution



-high p_T tracks(>0.9 GeV/c) were reconstructed using both the silicon strip and pixel detectors

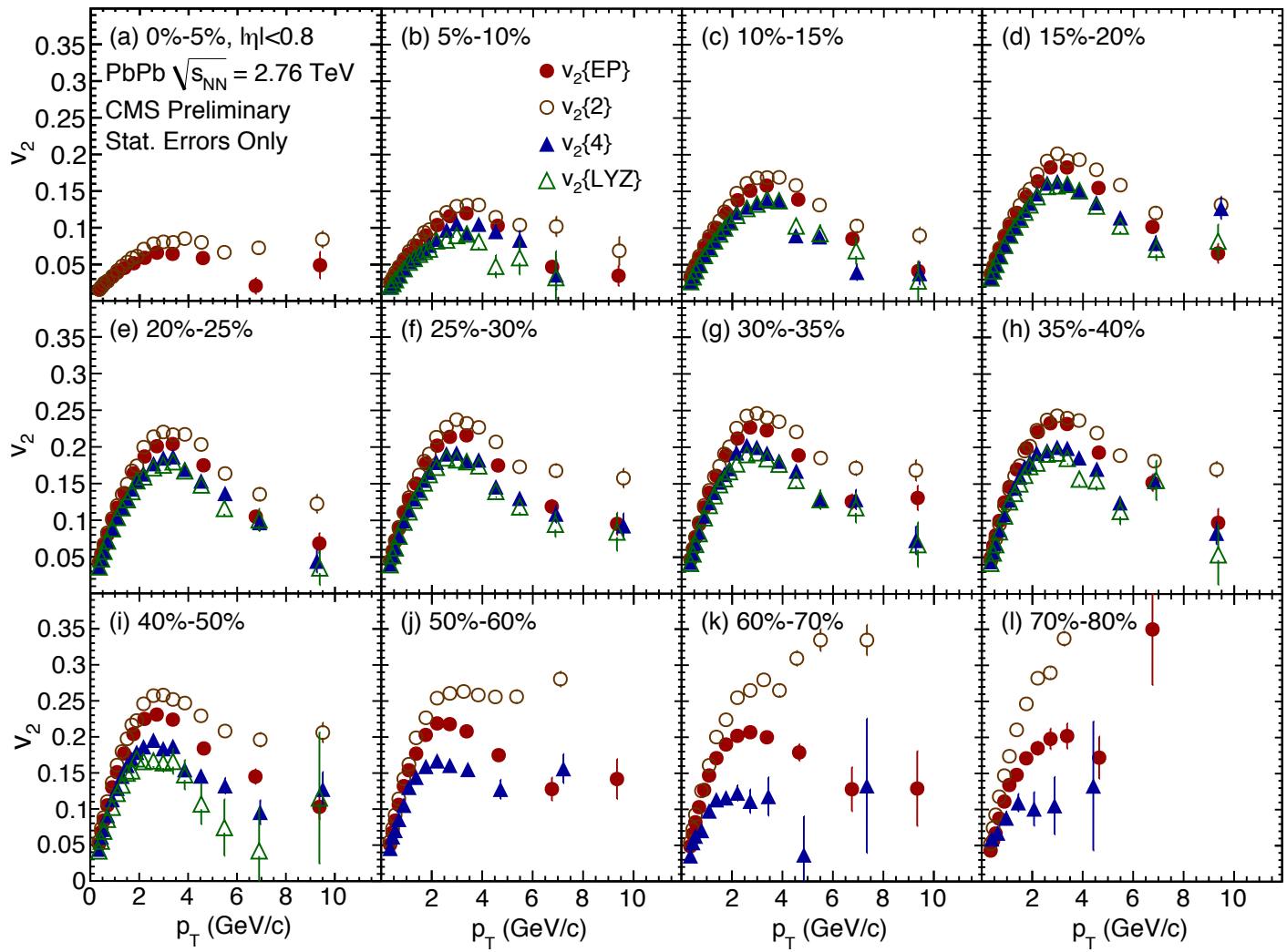
-a second tracking iteration used only the pixel detector to produce “pixel-only” tracks with p_T down to 0.2 GeV/c

-the two iterations were merged, using only “full” tracks with a p_T above 1.5 GeV/c, and using “pixel-only” tracks below 1.8 GeV/c

Methods

- Event Plane Method:
  - 3-subevent method is used to calculate resolution corrections based on pseudorapidity ($-2 \leq \eta < -1$) , ($-0.75 < \eta \leq 0.75$) , ($1 \leq \eta < 2$)
  - $\Delta\eta > 1$ pseudorapidity separation between event plane and v_2 tracks
  - flattening of the event planes (Fourier expansion)
  - high p_T limit of 3.0 GeV/c on the tracks to determine event planes
- Cumulant 2nd and 4th Order Method:
  - auto-correlations are avoided by removing the particles that are used for determining differential flow from the integral flow
  - fixed multiplicity in each centrality class
- Lee-Yang Zeros Method:
  - sum and product generating functions were used

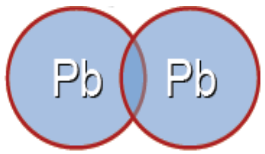
$v_2(p_T)$ as a function of centrality



0-20%

20-40%

40-80%

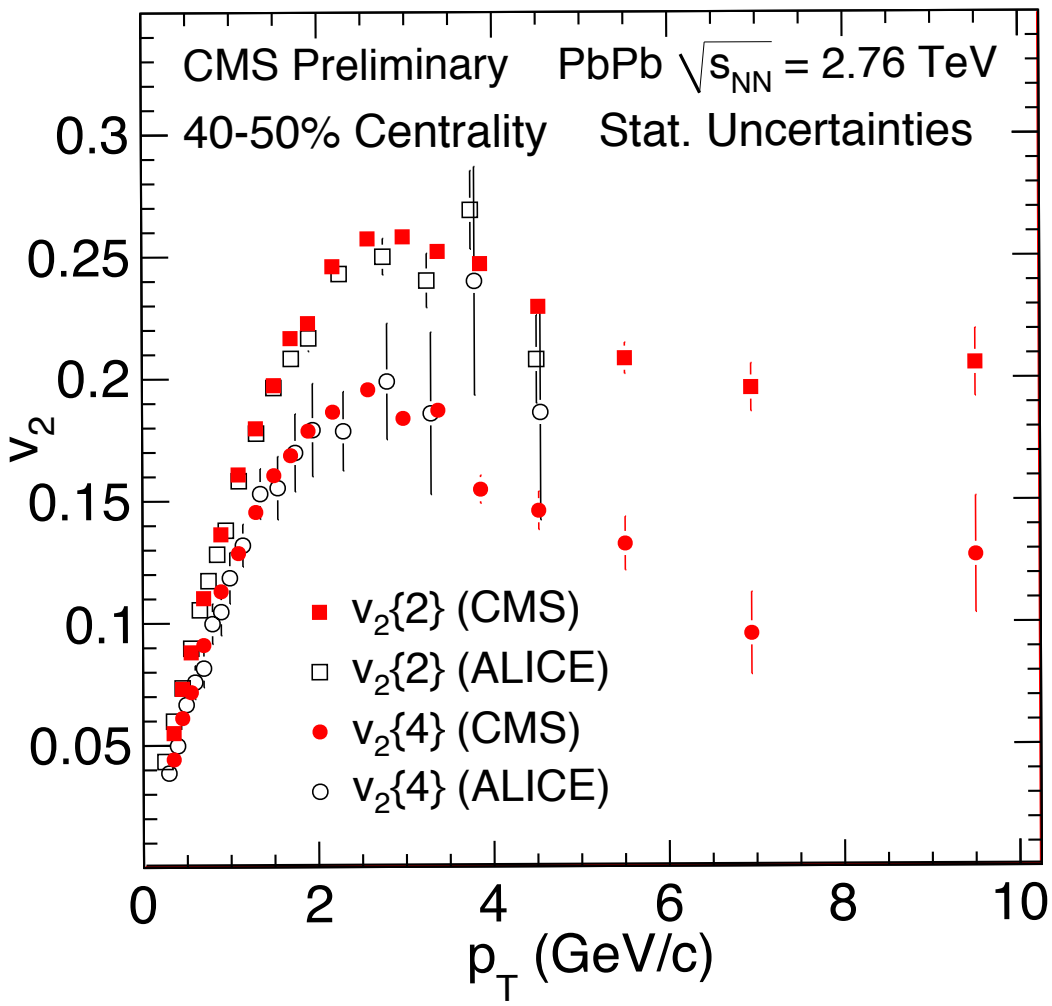


Several trends can be observed:

- v_2 increases from central to peripheral collisions up to 50% centrality.
- v_2 peaks at around 3 GeV/c.
- The different methods show differences consistent with the expected sensitivity to non-flow effects.

$v_2(p_T)$ Comparison with ALICE

Good agreement between CMS and ALICE, with the CMS $v_2(p_T)$ measurement extended from $p_T \sim 5$ GeV/c to $p_T \sim 10$ GeV/c.

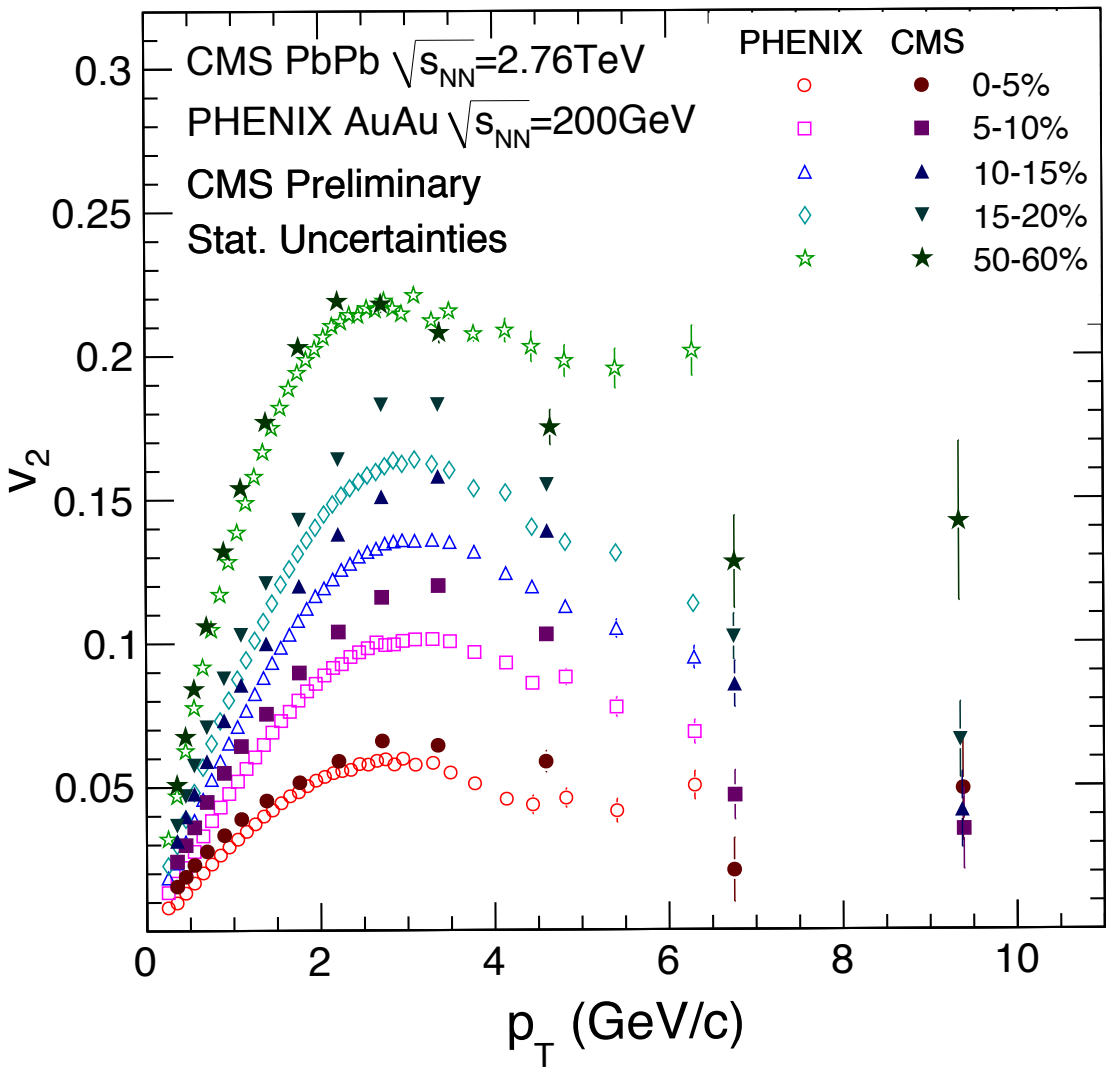


ALICE Collaboration, *Phys. Rev. Lett.*, **105**, 252302 (2011)

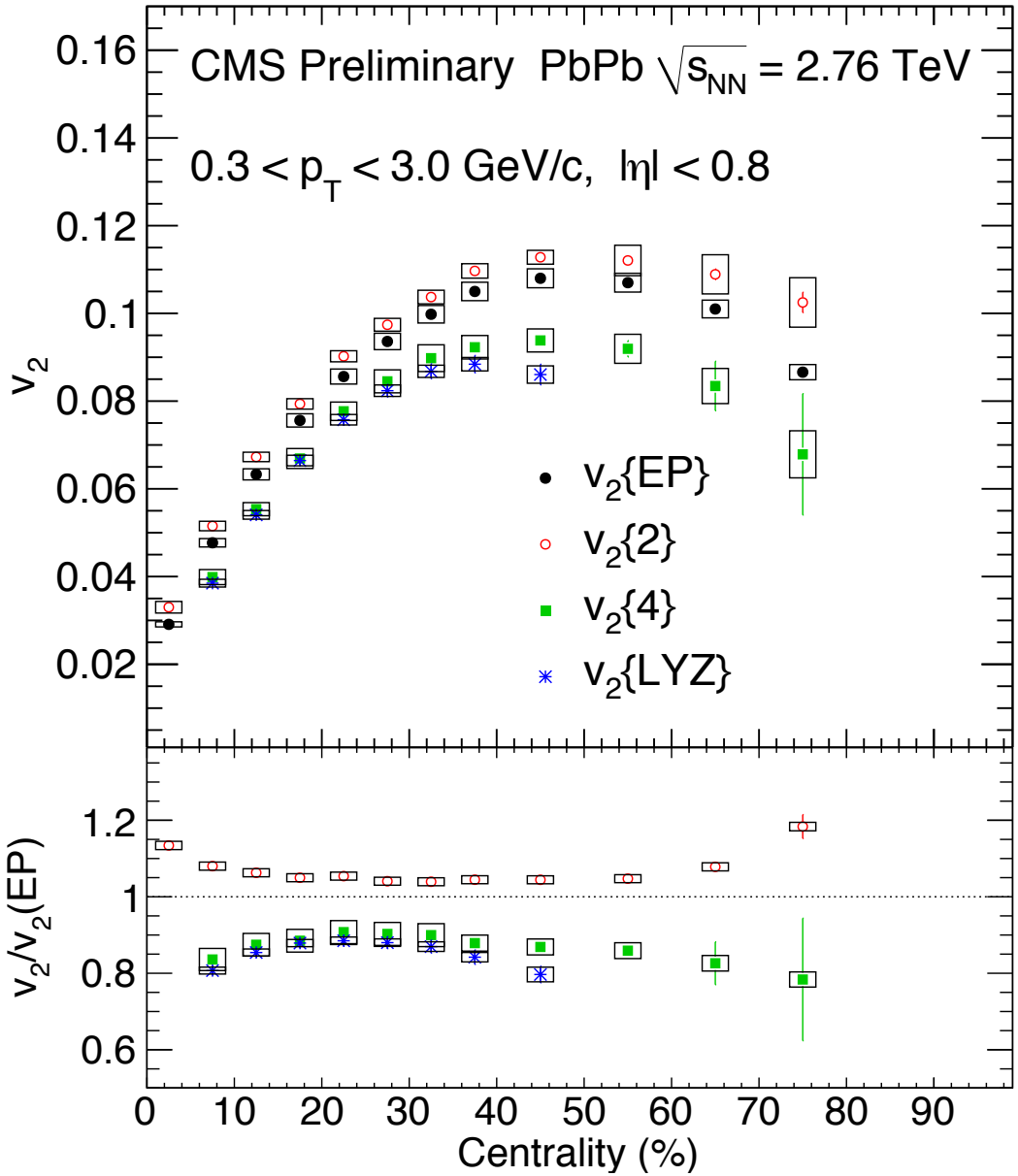
$v_2(p_T)$ Comparison with PHENIX

At low p_T (< 2GeV/c) measurements at the LHC energy are found to be only slightly larger than those obtained at RHIC. This increase is within the systematic uncertainties.

PHENIX Collaboration,
Phys. Rev. Lett., **105**, 062301 (2010)



Integrated v_2 vs centrality

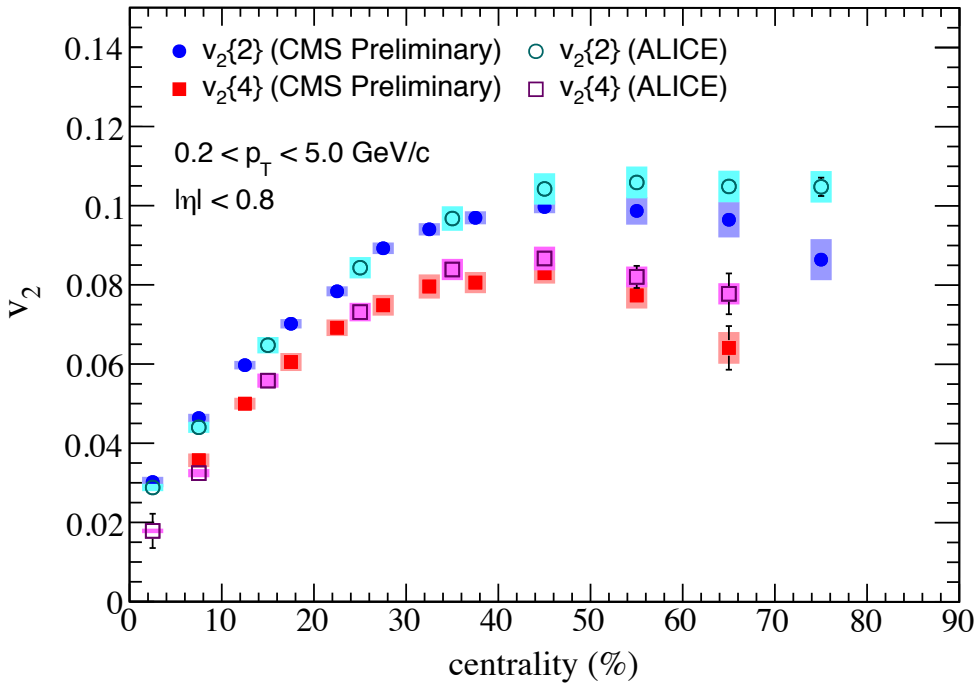


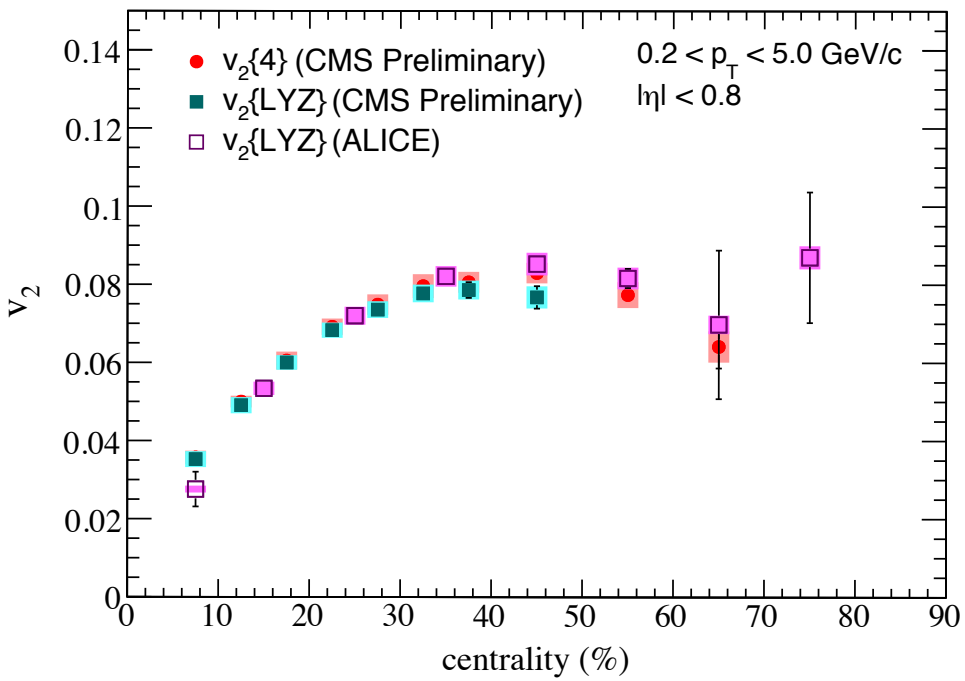
Flow is maximum around 40-50% centrality, consistent with RHIC results.

Integrated v_2 vs centrality

Good agreement between CMS and ALICE other than the most peripheral collisions.

ALICE Collaboration, *Phys. Rev. Lett.*, **105**, 252302 (2011)

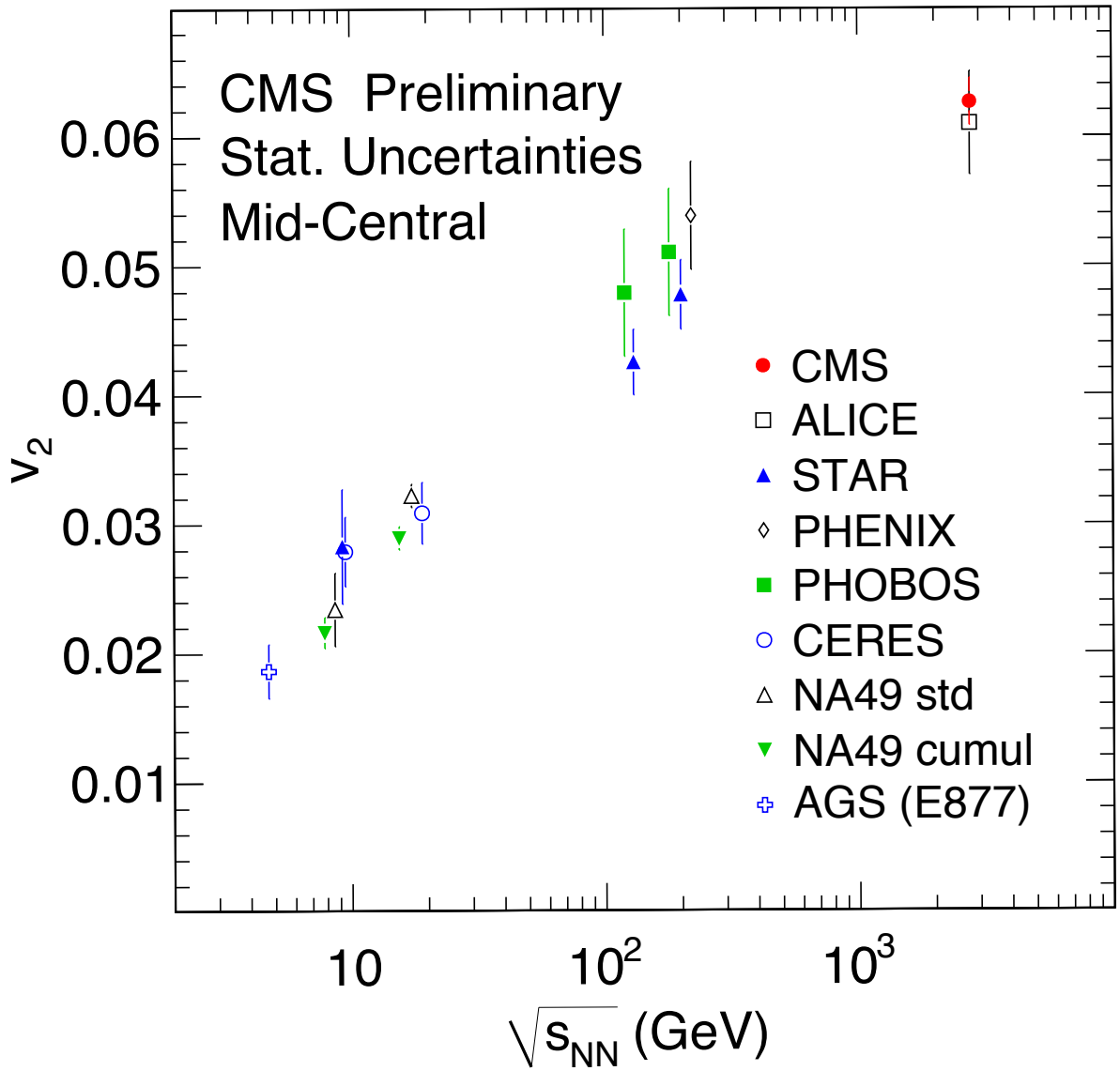




Error bars are statistical errors. Shaded boxes represent systematic errors.

Collision Energy Dependence

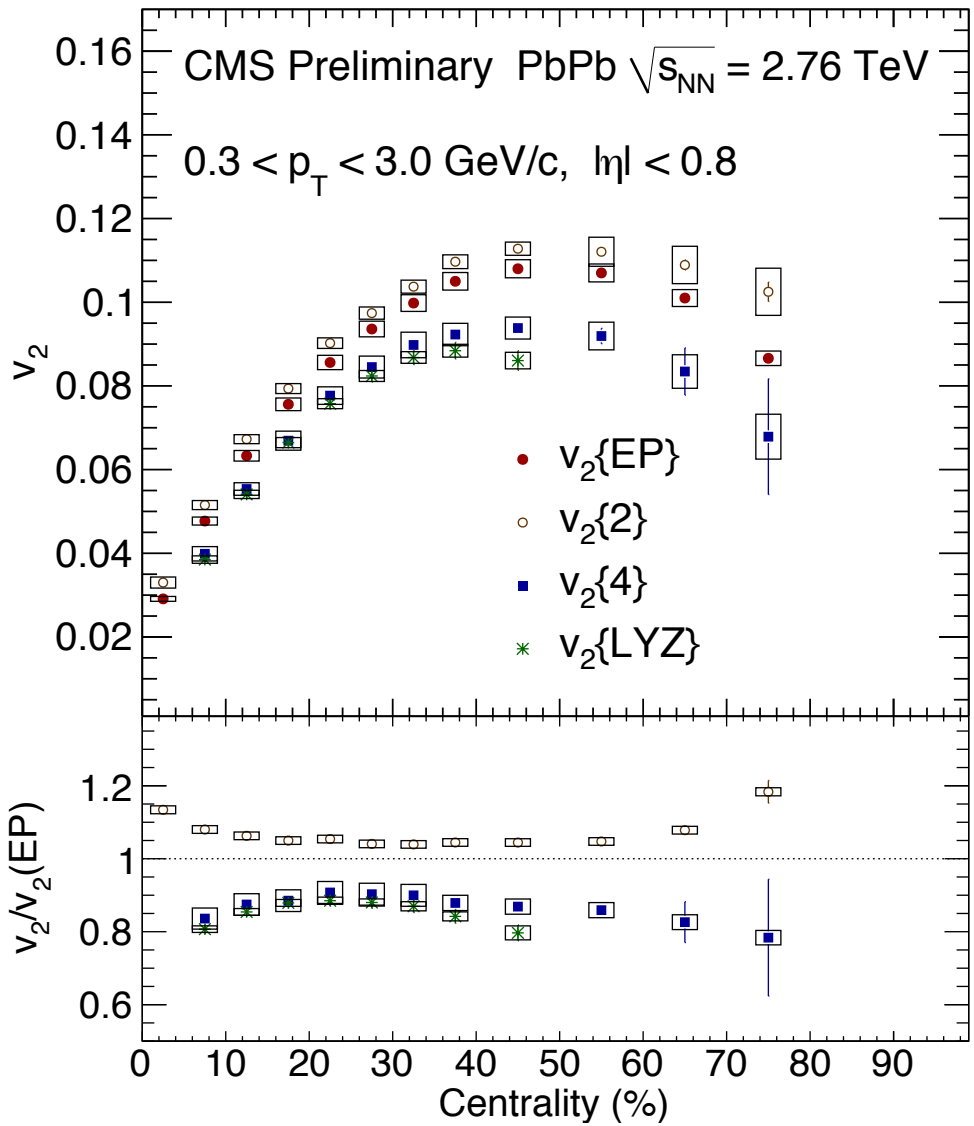
The logarithmic scaling of v_2 with $\sqrt{s_{NN}}$ persists to LHC energies.



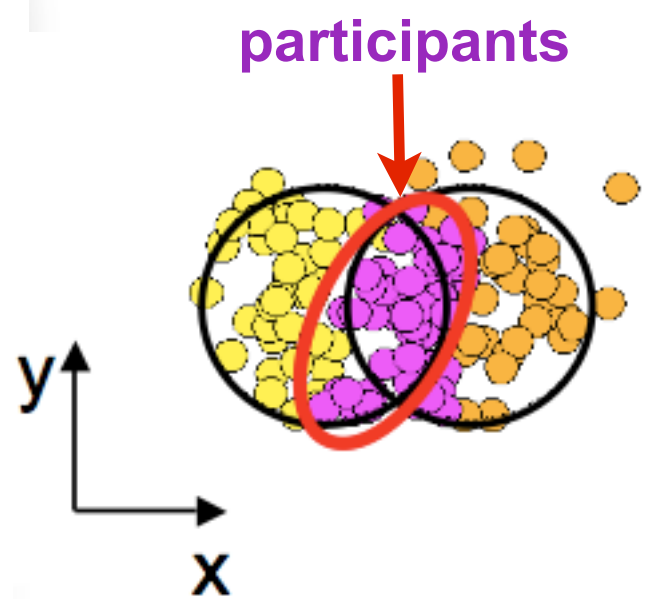
CMS: 20-30%, $v_2\{LYZ\}$, extrapolated to $p_t=0$

Participant Eccentricity Dependence

Collective flow is driven by the initial asymmetry in the participant overlap zone and subsequent hydrodynamic expansion of the reaction system.

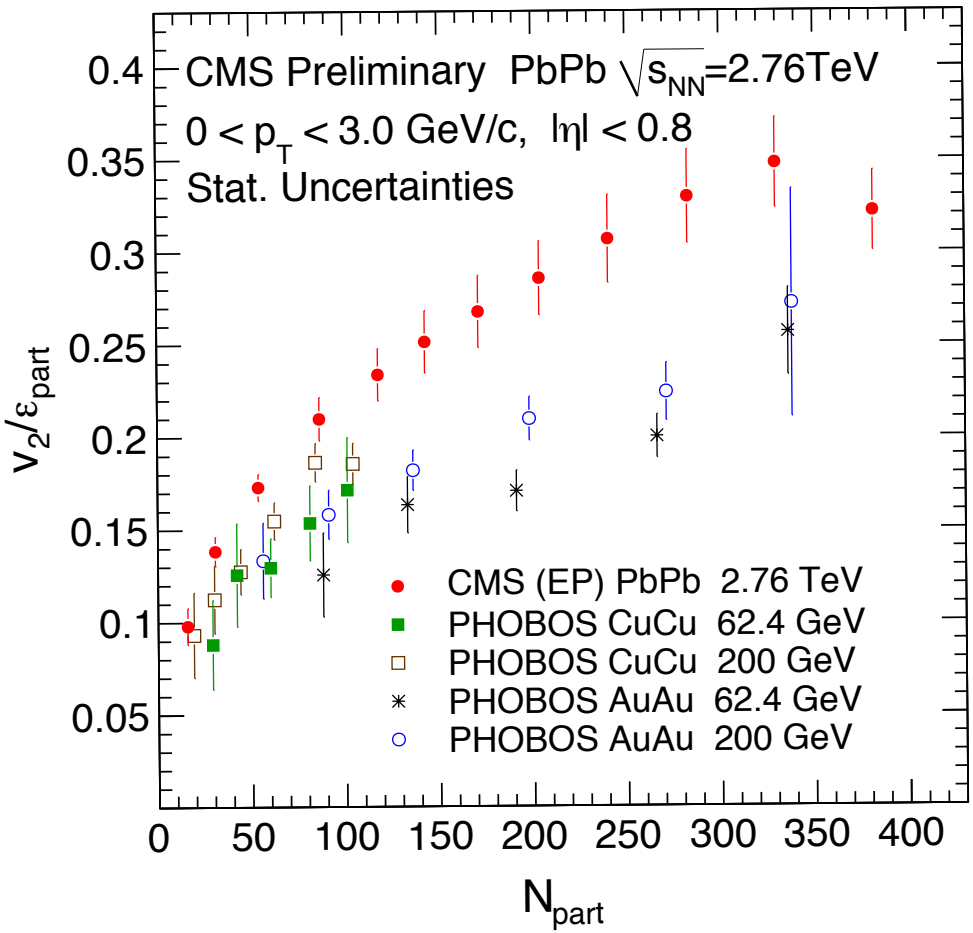


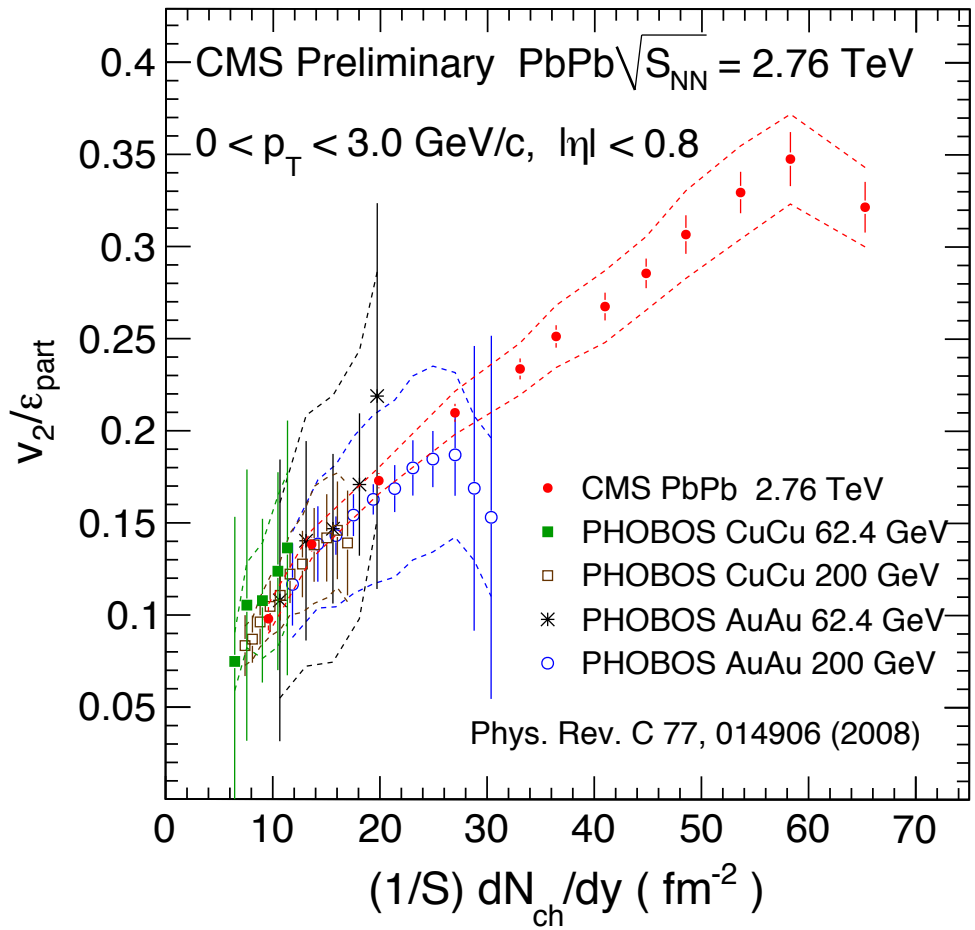
$$\varepsilon_{part} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



v_2 rises up to ε_{part} ~ 0.4. The subsequent decrease may indicate lack of equilibration.

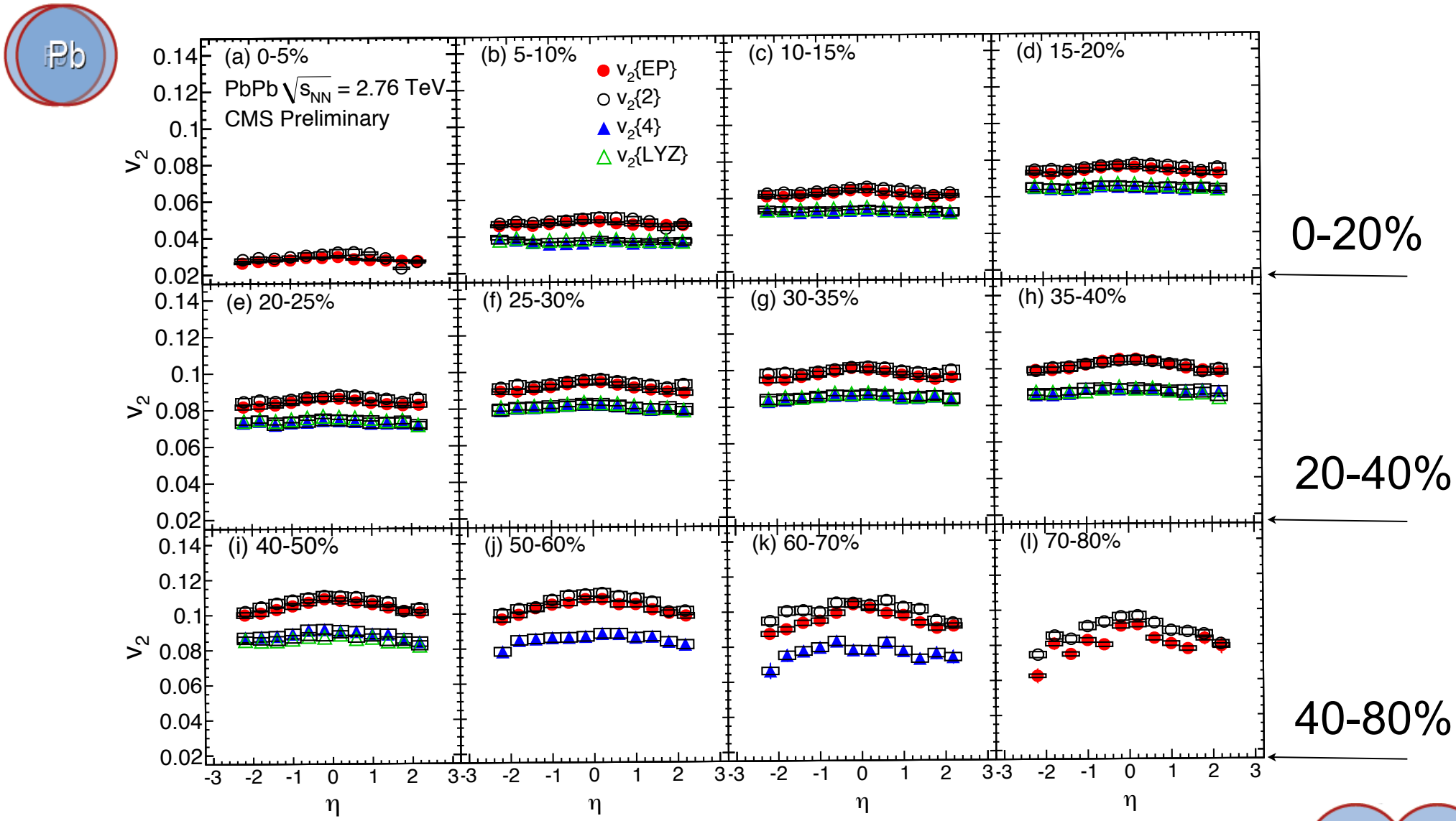
Participant eccentricity & transverse particle density scaling





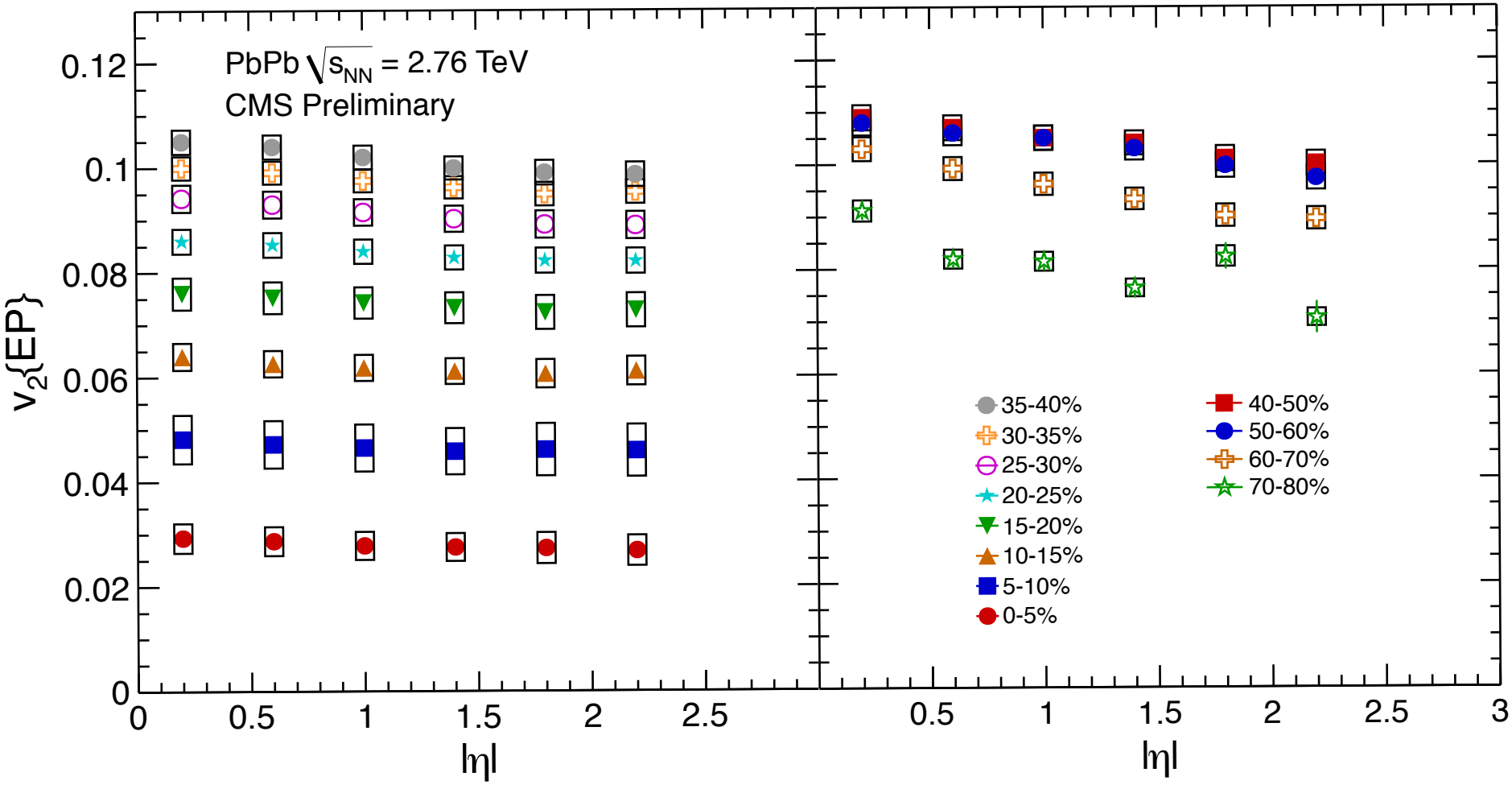
-15 to 40% increase is seen from RHIC to LHC
-the increase is most pronounced for central events
-v_2/ε_{part} scales with the transverse particle density

Integrated v_2 (all methods) as a function of pseudorapidity



Clearly shows the separation of methods.

Integrated v_2(EP) as a function of pseudorapidity



Stronger pseudorapidity dependence is observed for the most peripheral collisions.

Conclusions

We have presented detailed measurements of v_2 for $\sqrt{s_{NN}}$ = 2.76 TeV PbPb collisions with good statistics and large pseudorapidity coverage.

$v_2(p_T)$ at mid-rapidity for $p_T < 2$ GeV/c is similar to that measured at the highest RHIC energy.

The integral v_2 value is strongest at midrapidity. A stronger rapidity dependence is observed for the most peripheral collisions.

The evolution of v_2 with centrality and eccentricity indicates that in more peripheral collisions (>40-50%) the system may not be completely equilibrated.

These data provide the basis for future detailed comparisons to models

Higher Harmonics?

Julia Velkovska
Plenary
“Flow Measurements from CMS”
Tuesday 24 May 2011

Michael Issah
Poster Session I
Tuesday 24 May 2011 17:20
Board # 31

BACKUP

Systematic Studies

- **Systematic studies common to all methods include:**
  - Particle composition
  - Centrality determination and trigger efficiency
  - Track kinematic cuts
  - Fake track contribution to integral v_2
  - Uncertainty in efficiency corrections
- **EP specific systematic checks:**
  - Different track p_T cuts when calculating Event Plane angles
  - Acceptance
  - Flattening check
  - Subevent pseudorapidity gap
  - Flattening parameters as a function of vertex
- **Cumulant specific systematic checks:**
  - Numeric stability with respect to r_0 parameter
- **LYZ specific systematic checks:**
  - Multiplicity fluctuations

Systematic Uncertainties

Table 2: Systematic uncertainties in the measurement of $v_2(p_T)$ for $|\eta| < 0.8$ with the event plane method.

	Centrality	00-10%	10-20%	20-30%	30-40%	40-80%
Source	$p_T(GeV/c)$					
Particle composition	All	0.5%	0.5%	0.5%	0.5%	0.5%
Centrality determination	All	1%	1%	1%	1%	1%
Track p_T cuts in EP	All	1.0%	1.0%	1.0%	1.0%	1.0%
Acceptance	All	< 2%	< 1%	< 0.8%	< 0.5%	< 0.5%
Track kinematic cuts	[0.3; 1.0]	7.0%	3.0%	2.0%	< 1.0%	< 1.0%
	[1.0; 2.0]	4.0%	2.0%	< 1.0%	< 1.0%	< 1.0%
	[2.0; 12.0]	2.0%	< 1.0%	< 1.0%	< 1.0%	< 1.0%
Total	[0.3; 1.0]	7.4%	3.5%	2.6%	1.9%	1.9%
	[1.0; 2.0]	4.7%	2.7%	2.0	1.9%	1.9%
	[2.0; 12.0]	3.2%	2.1%	2.0%	1.9%	1.9%

Systematic Uncertainties

Table 3: Systematic uncertainties in the measurement of $v_2(\eta)$ for $0.3 < p_T < 3.0 GeV/c$ with the event plane method.

	Centrality	00-10%	10-20%	20-30%	30-40%	40-80%
Source	$\lvert\eta\rvert$					
Particle composition	All	0.5%	0.5%	0.5%	0.5%	0.5%
Centrality determination	All	1%	1%	1%	1%	1%
Acceptance	All	< 2%	< 1%	< 0.8%	< 0.5%	< 0.5%
Efficiency corrections	[0.0; 0.8]	< 1.0%	< 1.0%	< 1.0%	< 1.0%	< 1.0%
	[0.8; 1.6]	1.0%	< 1.0%	< 1.0%	< 1.0%	< 1.0%
	[1.6; 2.4]	5.0%	2.0%	1.0%	1.0%	1.0%
Fake track v_2	All	0.8%	0.6%	0.4%	0.4%	0.1%
Track p_T cuts in EP	All	1.0%	1.0%	1.0%	1.0%	1.0%
Track kinematic cuts	All	< 3.0%	< 2.5%	< 1.6%	< 1.0%	< 1.0%
Total	[0.0; 0.8]	4.2%	3.4%	2.8%	2.4%	2.3%
	[0.8; 1.6]	4.2%	3.4%	2.8%	2.4%	2.3%
	[1.6; 2.4]	8.1%	4.2%	2.8%	2.4%	2.3%

Event Selection

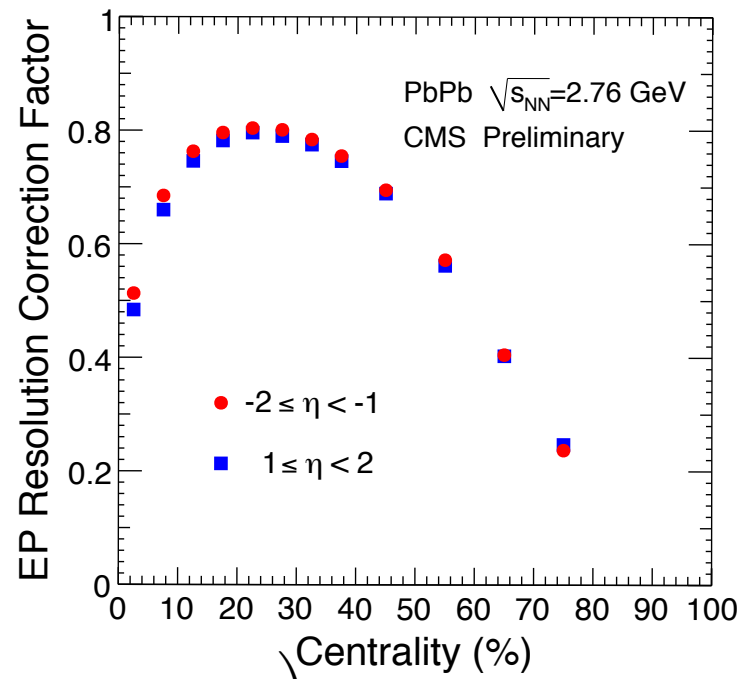
Table 1: The effects of various cuts on the data sample. % values are always with respect to to the line above (the cuts are applied in sequence).

Cut	events remaining	% of events remaining
Core Physics events	4604505	100.00
HLT_HIMinBiasHfOrBSC_Core trigger	2889239	62.75
no BSC halo	2857150	98.89
HF offline coincidence	2762005	96.67
reconstructed vertex	2686247	97.26
Beam-gas removal	2682361	99.86
ECAL cleaning	2673123	99.66
HCAL cleaning	2672977	99.99
vertex position	2316724	86.67

Event Plane Method

- Event plane angles are defined in three pseudorapidity regions (-2 ≤ η < -1, |η| ≤ 0.75, 1 ≤ η < 2)

$$\Psi'_n = \frac{1}{n}\tan^{-1}\frac{\sum_i w_i \sin(n\varphi_i)}{\sum_i w_i \cos(n\varphi_i)}$$



-Event plane flattening (21st order)

$$\Psi_2 = \Psi'_2\left(1+\sum_j^{j_{max}}\frac{1}{j}\left(-\langle\sin(2j\Psi'_2)\rangle\cos(2j\Psi_2)+\langle\cos(2j\Psi'_2)\rangle\sin(2j\Psi_2)\right)\right)$$

- 3-subevent method is used to calculate resolution corrections:

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

-Extracted v_2 signal is corrected for resolution:

$$v_n\{EP\} = \frac{v_n^{obs}\{EP\}}{R} = \frac{\langle\cos n(\varphi-\Psi_n)\rangle}{\langle\cos n(\Psi_n-\Psi_R)\rangle}$$

Cumulant Method

- Since all particles are correlated to the reaction plane, they are also indirectly correlated with each other.

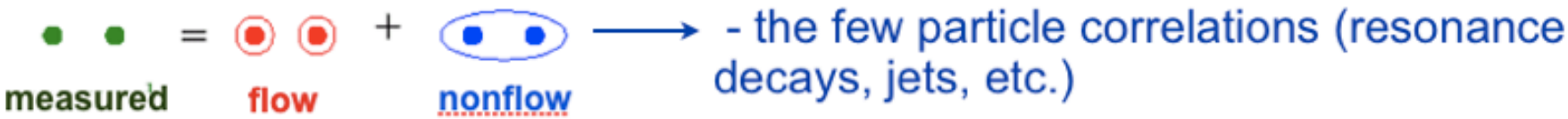
$$< v_n >^2 = < cos[n(\phi_i - \phi_j)] >$$

integrated flow

$$v_n(p_T) = \frac{< cos[n(\phi_i - \phi_j)] >}{< v_n >}$$

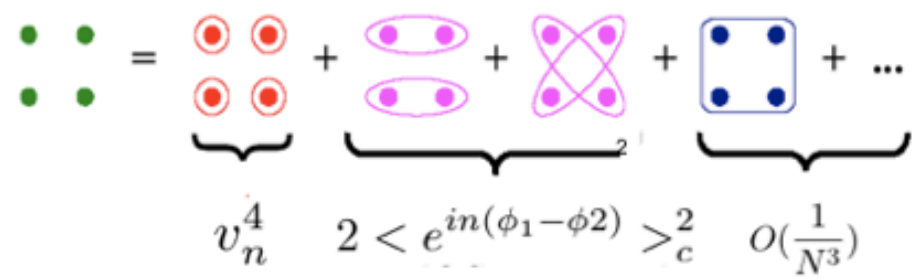
differential flow

- **2-particle correlations** can be expressed in terms of flow and non-flow components:



$$\left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle_m = V_n^2 + \left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle_c$$

- **4-particle correlation** can be decomposed in the similar way:



- Integral and differential flow signals are obtained by using generating functions:

$$G_n = \prod_{i=1}^{M}\left(1 + \frac{2\,x\,\cos(n\varphi_i) + 2\,y\,\sin(n\varphi_i)}{M}\right) \qquad D_{p/n} = \frac{\langle e^{ip\psi} G_n(z)\rangle}{\langle G_n(z)\rangle}$$

Lee-Yang Zeros Method

For each centrality, define the complex-valued generating function :

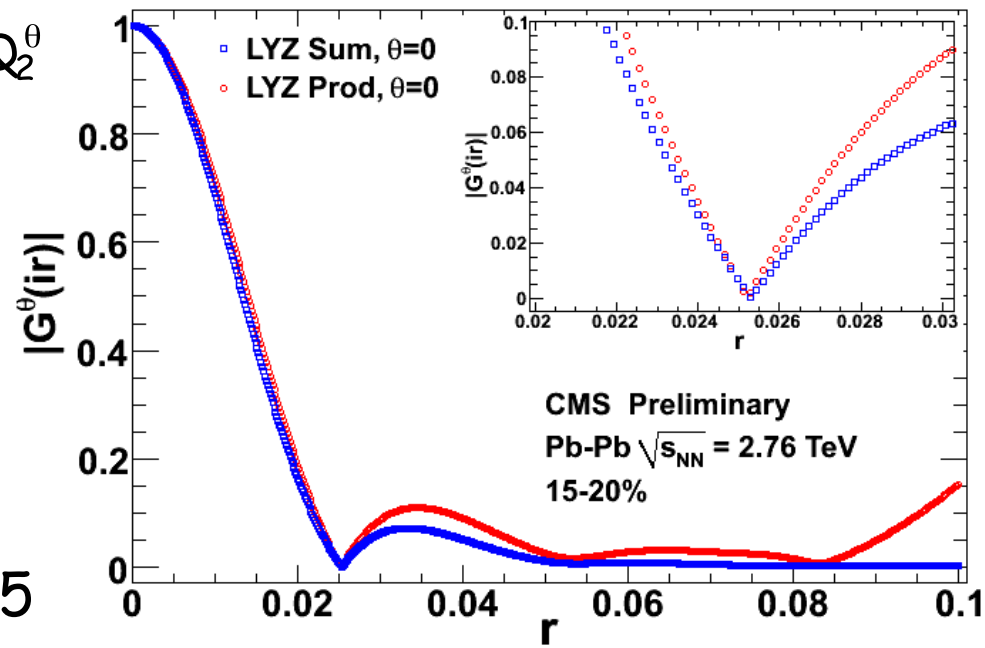
$$G_2^{\theta}(ir) \equiv \left\langle e^{irQ_2^{\theta}} \right\rangle = \frac{1}{N_{evt}} \sum_{events} e^{irQ_2^{\theta}}$$

with $Q_2^{\theta} = \sum_{j=1}^{M} w_j \cos(2(\phi_j - \theta))$

weight : w_j , θ : fixed angle

Then Integrated flow is : $V_2^{\theta} = j_{01} / r_0^{\theta}$

r_0^{θ} is first minimum of $|G_2^{\theta}(ir)|$, j_{01} ; 2.405



First minimum

Then Differential flow is :

$$v_{2m}^{\theta}(\eta, p_T) = V_2^{\theta} \frac{J_1(j_{01})}{J_m(j_{01})} \mathrm{Re}\left(\frac{\left\langle \cos[2m(\phi_j - \theta)] e^{ir_0^{\theta} Q_2^{\theta}} \right\rangle}{i^{m-1} \left\langle Q_2^{\theta} e^{ir_0^{\theta} Q_2^{\theta}} \right\rangle} \right)$$

J_m is Bessel function of the first kind

m=1 for v_2

Another generating function(Product) can be used in LYZ. It gives the same results for v_2

The method:

- less biased by non-flow correlations than other methods.
- less biased by autocorrelations.
- less biased by detector asymmetry.