Hydrodynamic flow in Pb+Pb collisions observed via azimuthal angle correlations of charged hadrons

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CMS Collaboration

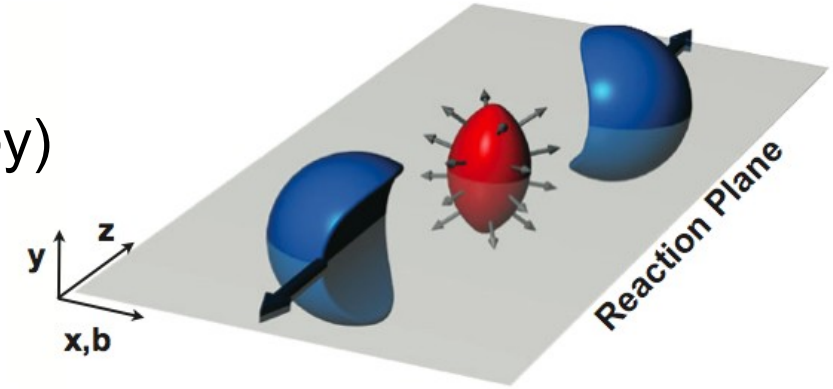
Particles and Nuclei International

Conference 2011

Physics Motivation

Measure the Anisotropic Asymmetry to Address:

- EoS and Viscosity of the Medium
- Opacity of the Medium (via high-p_T anisotropy)
- Role of Fluctuations and Initial State



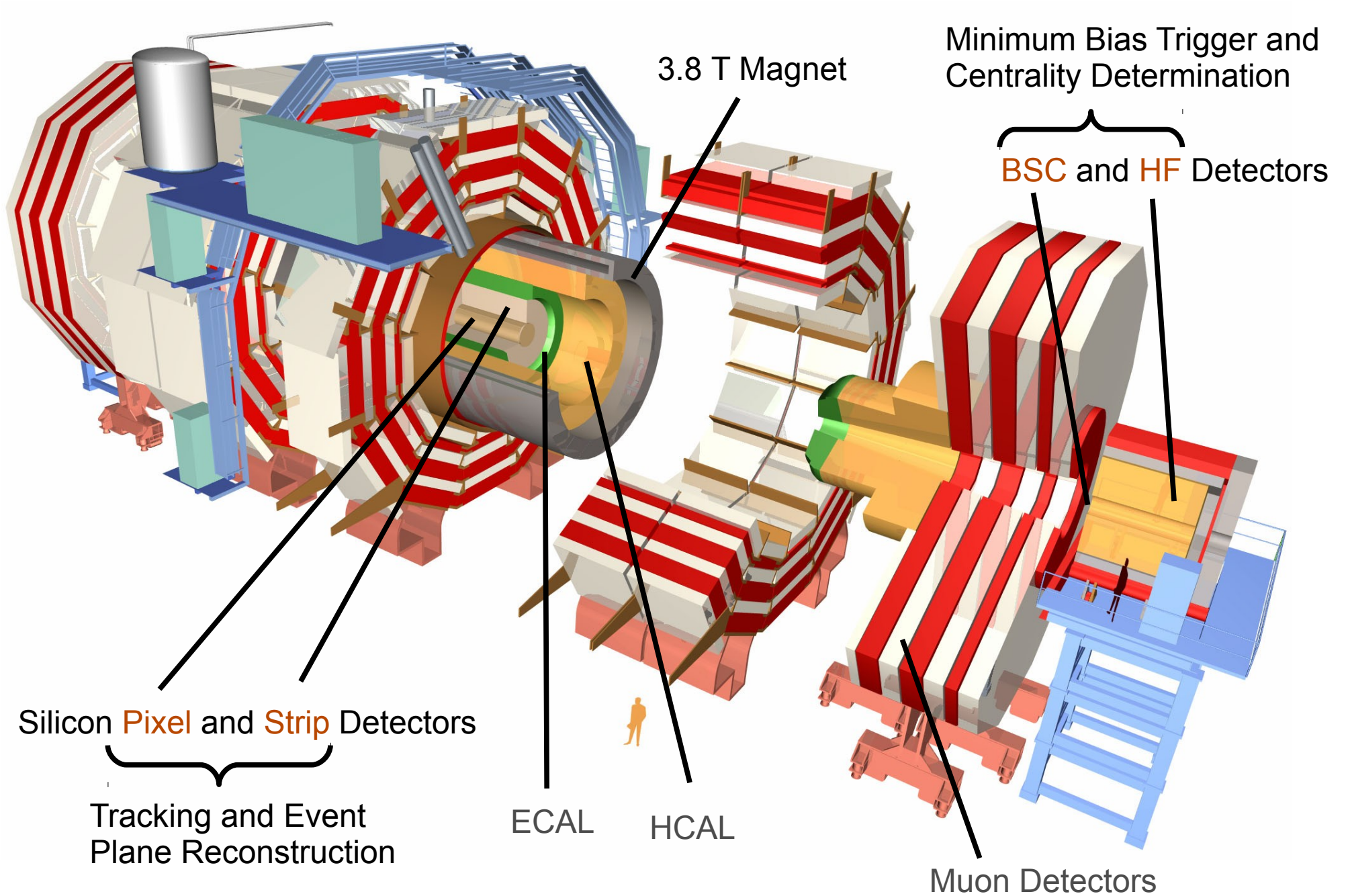
Difficulties from Complications:

- Non-Flow Correlations: Jets, Resonance Decays, ...
- Initial State Fluctuations

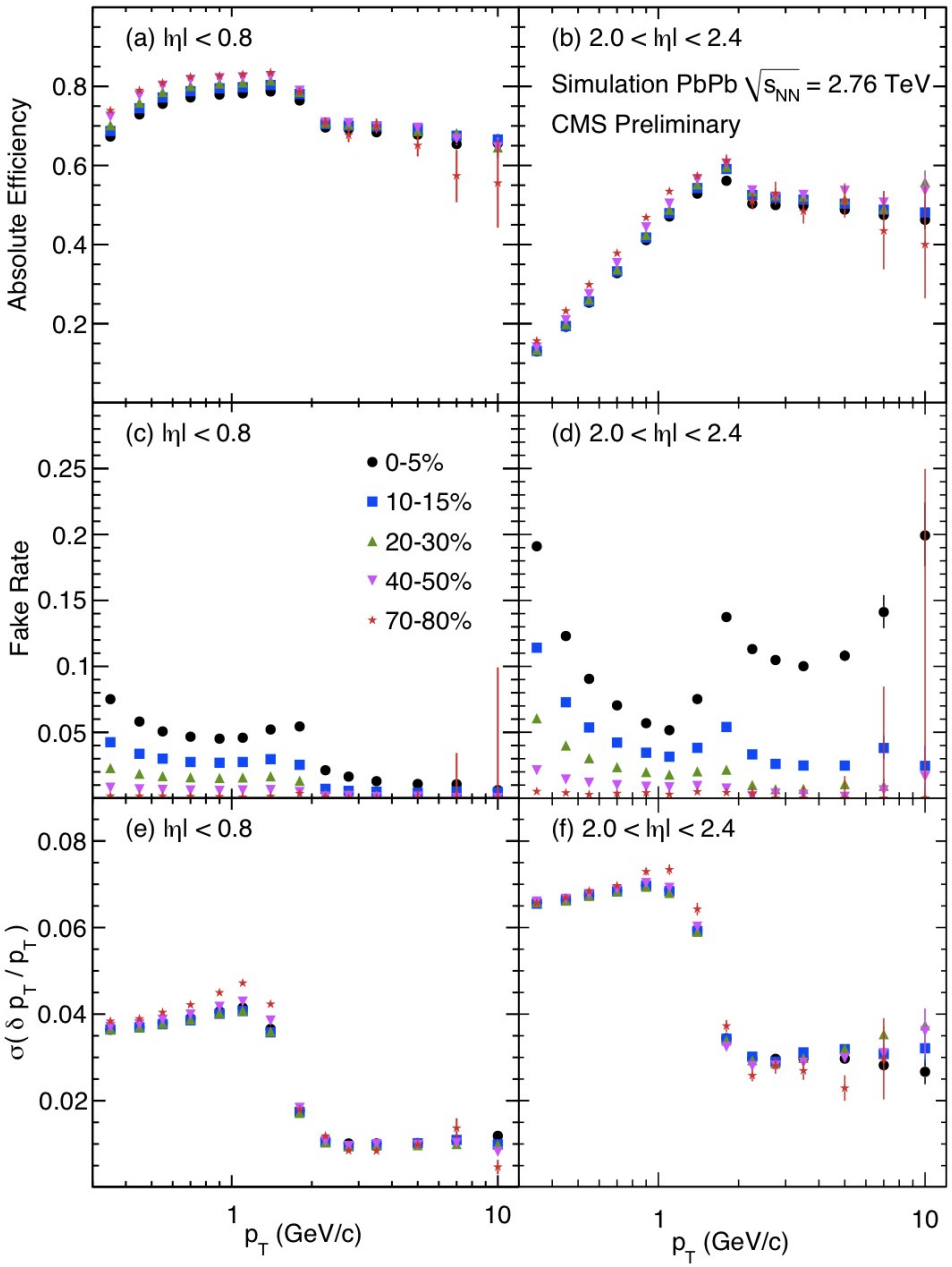
Addressed by Multiple Methods and Higher-Order Harmonics:

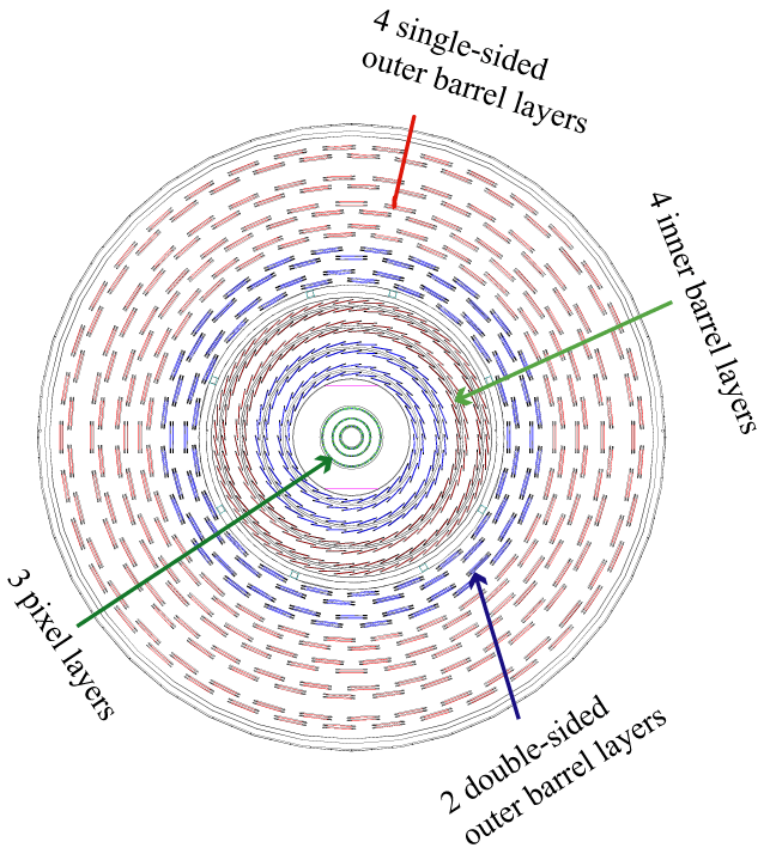
- use different methods with different sensitivities to non-flow
- v_3, v_5 dominated by fluctuations
- v_2, v_4, v_6 from hydrodynamic flow and fluctuations
- higher harmonics probe different length scales

The CMS Detector



Tracking Reconstruction in Heavy Ions



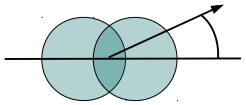


- High p_T tracks(>1.5 GeV/c) reconstructed from silicon strip and pixel detectors.
- Low p_T tracks (0.3-1.8 GeV/c) reconstructed from only the pixel detector.
- Collections merged and cleaned for duplicates

CMS-PAS-HIN-10-002

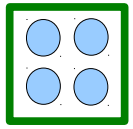
Four Methods Used for Extracting v_2 Signal

Event Plane



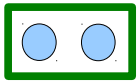
- based on particle correlations with the event plane
- gives an estimate of the reaction plane
- requires corrections for the detector acceptance

4th Order Cumulant



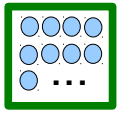
- based on 4-particle correlations
- removes lower order non-flow effects

2nd Order Cumulant



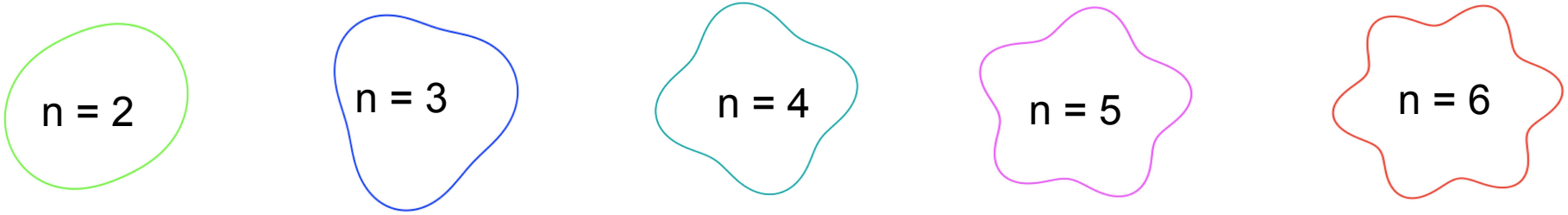
- based on 2-particle correlations

Lee-Yang Zeros

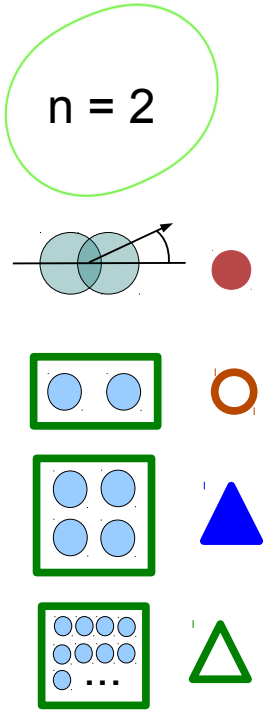


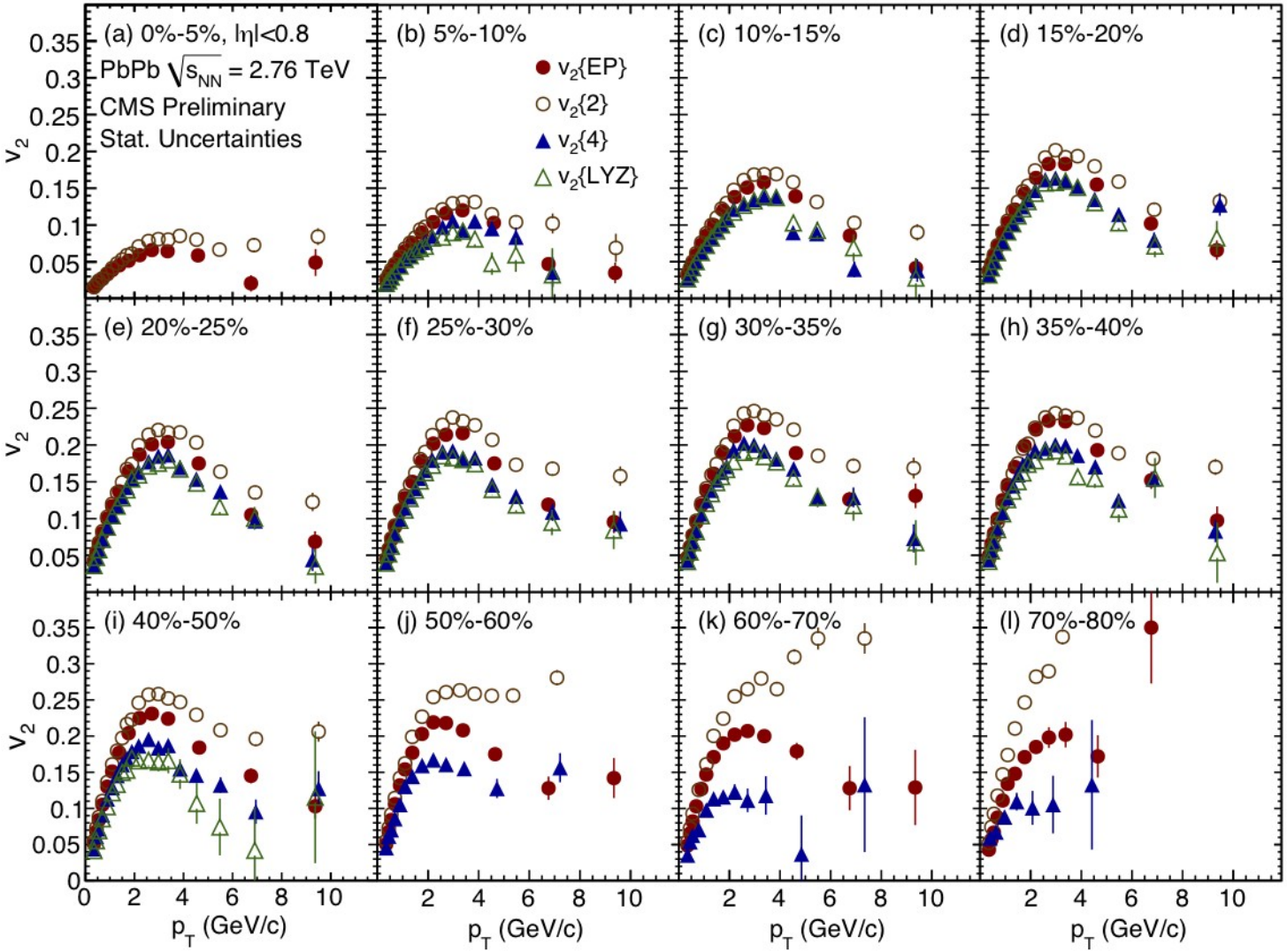
- based on all particle correlations in each event
- removes non-flow effects

Higher order harmonics up to v_6 were measured using select methods:



$v_2(p_T)$ as a Function of Centrality





0-20%

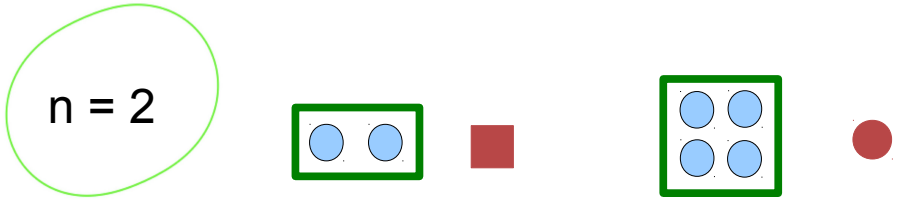
20-40%

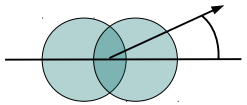
40-80%

CMS-PAS HIN-10-002

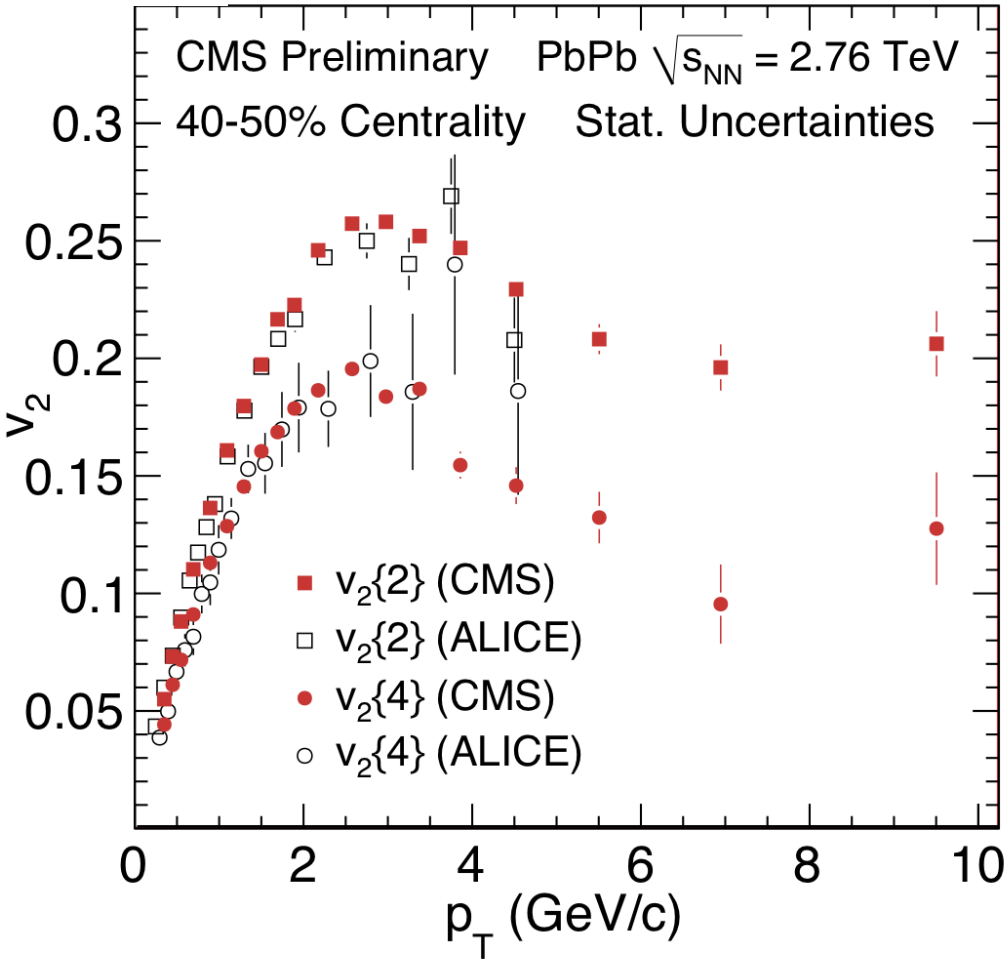
- v_2 increases from central to peripheral up to 50% centrality.
- v_2 peaks at around 3 GeV/c.
- method differences consistent with expected sensitivity to non-flow

$v_2(p_T)$ Comparison to Other Experiments

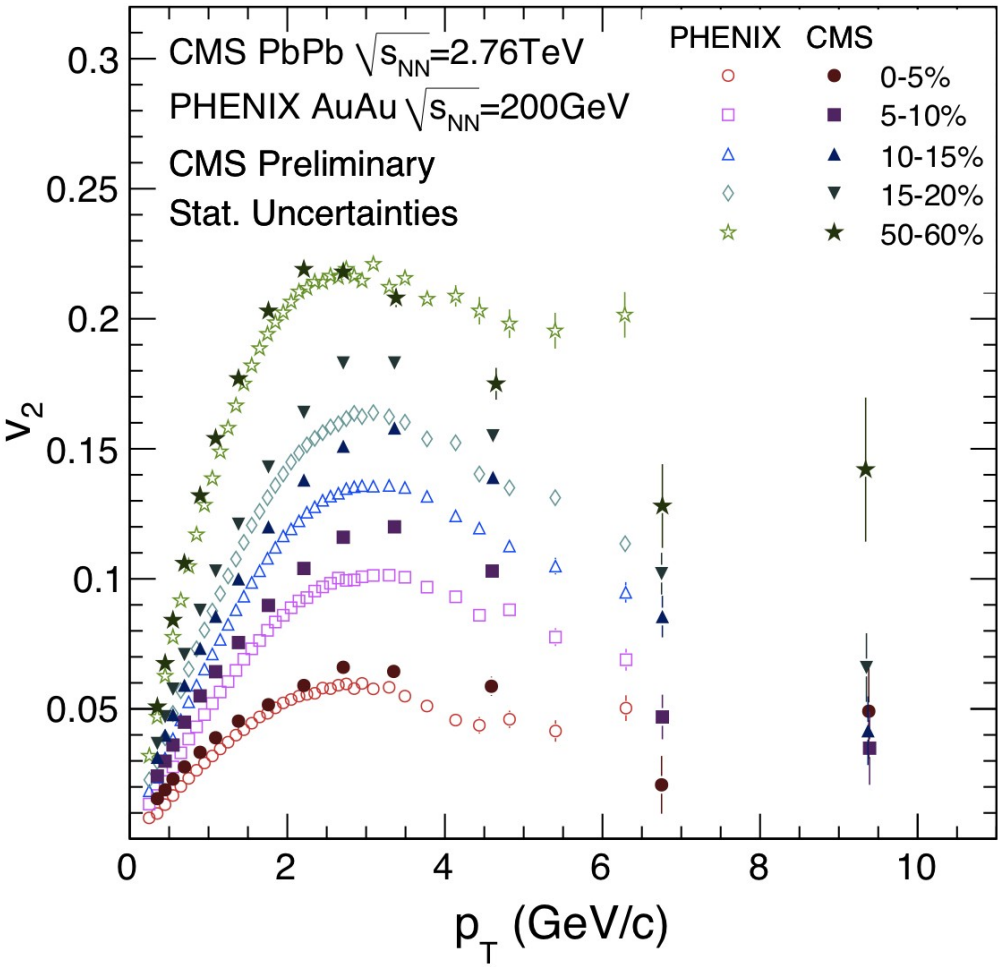




CMS-PAS HIN-10-002

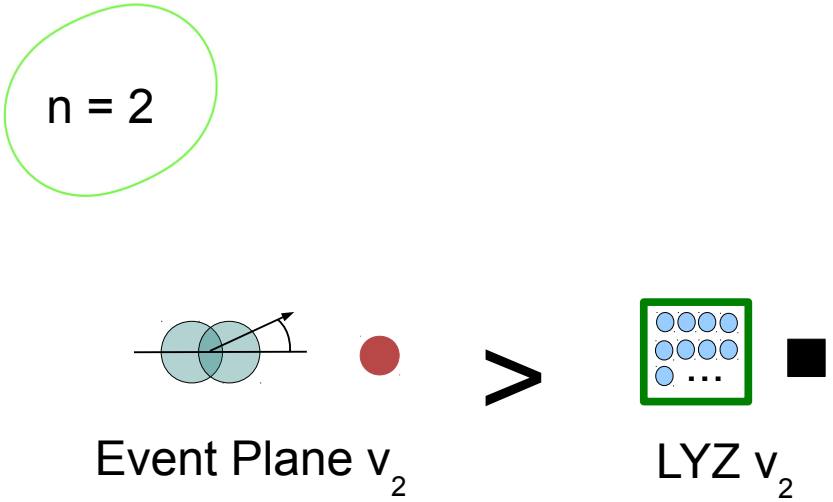


ALICE Collaboration,
Phys. Rev. Lett., 105, 252302 (2011)



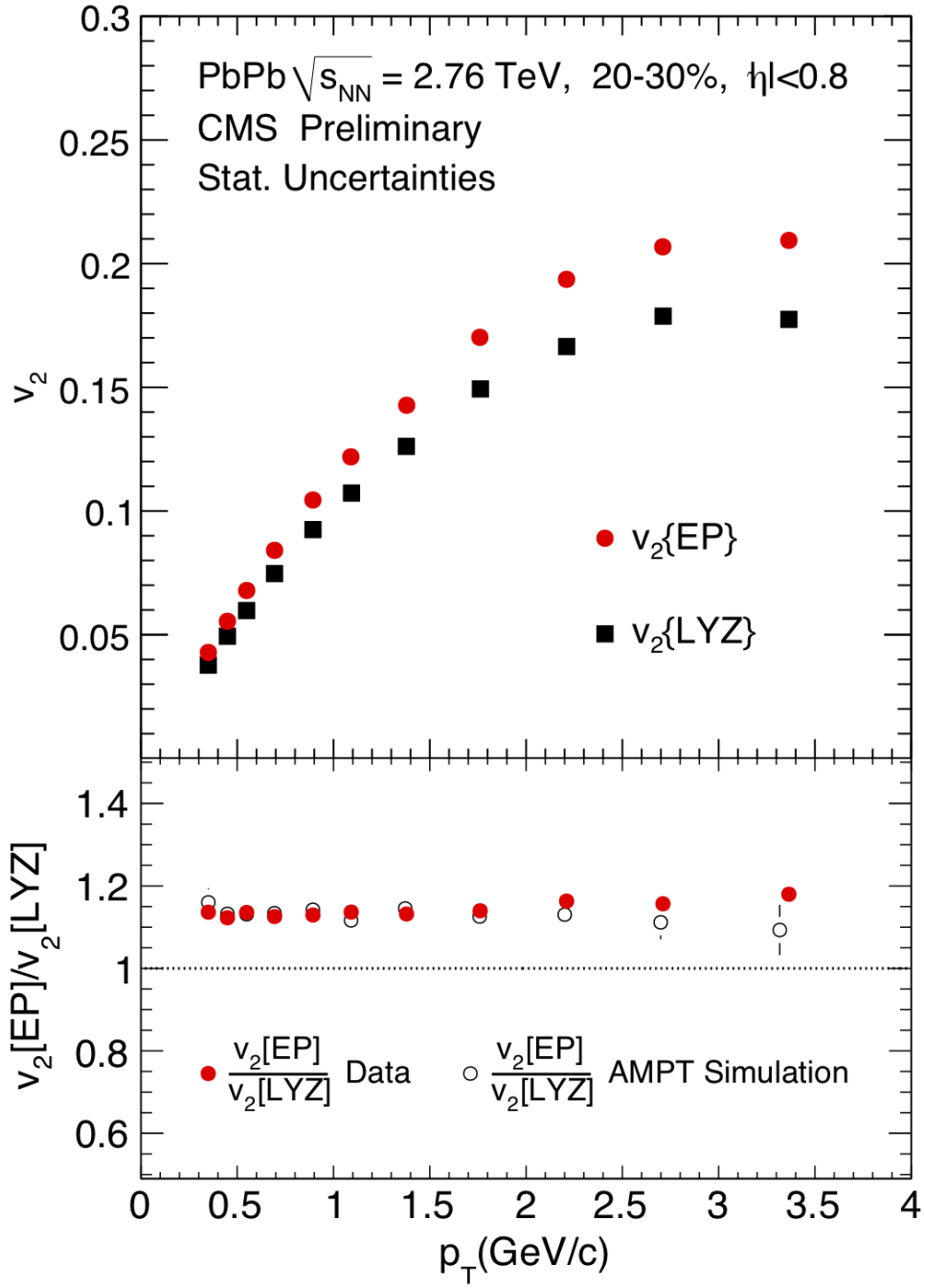
PHENIX Collaboration,
Phys. Rev. Lett., 105, 062301 (2010)

$v_2(p_T)$ Data and AMPT Comparison

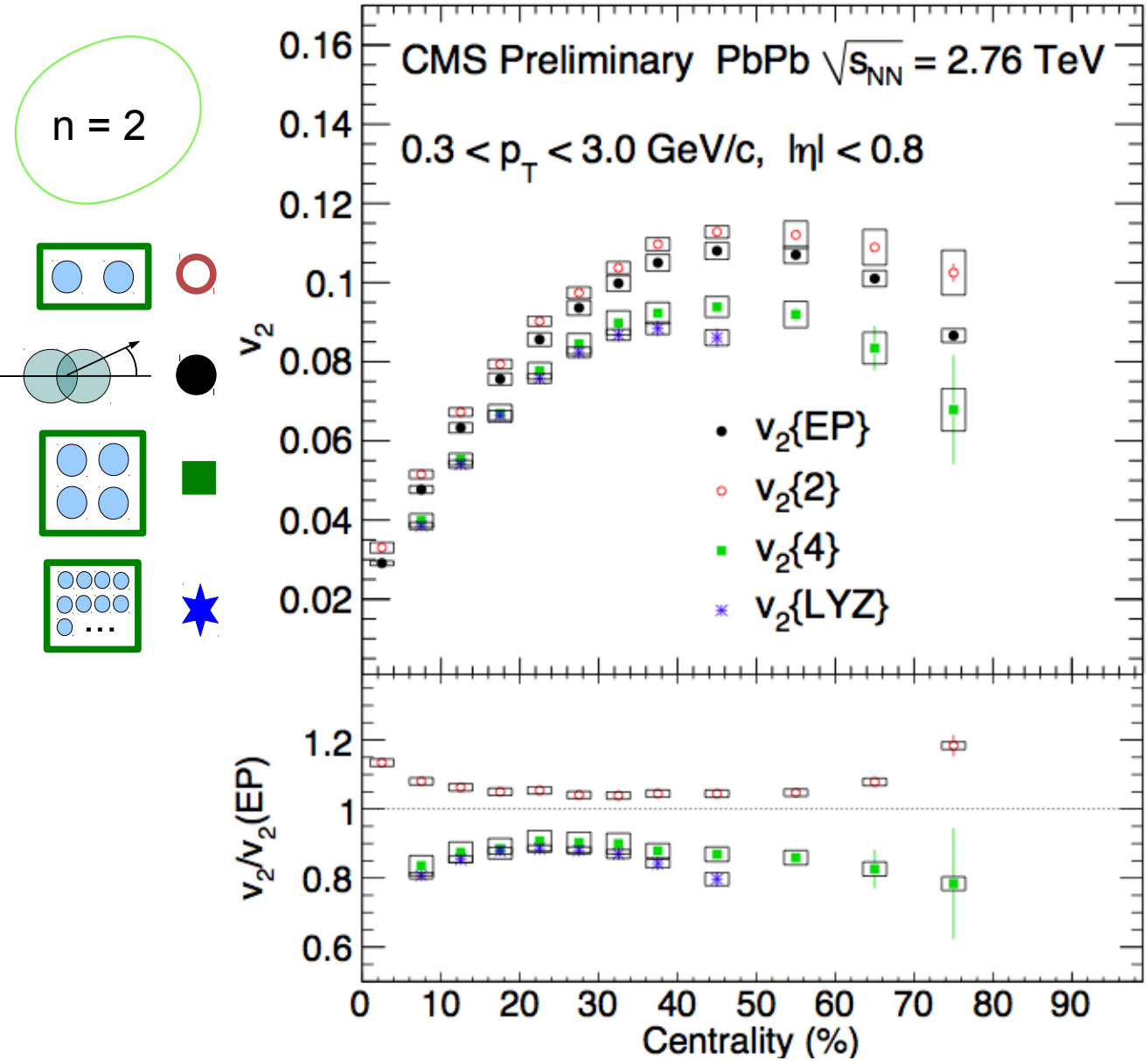


The relationship between methods is well described by AMPT.

Fluctuations are important!



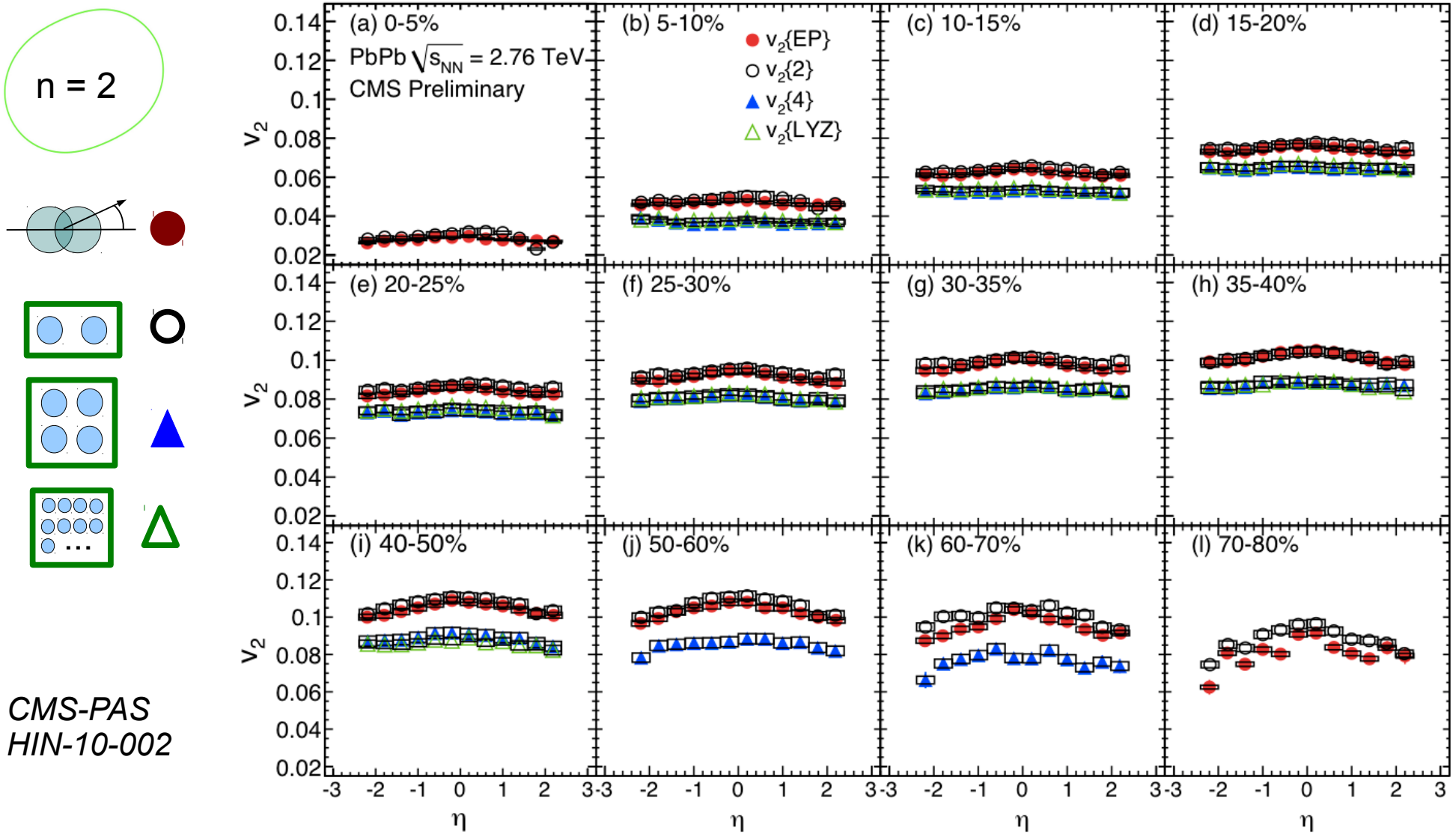
Integrated v_2 versus Centrality



CMS-PAS-HIN-10-002

- Maximal flow at 40-50% centrality
- Method Differences: as expected due to non-flow and fluctuations

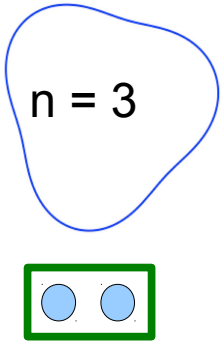
Integrated v_2 as a Function of Pseudorapidity

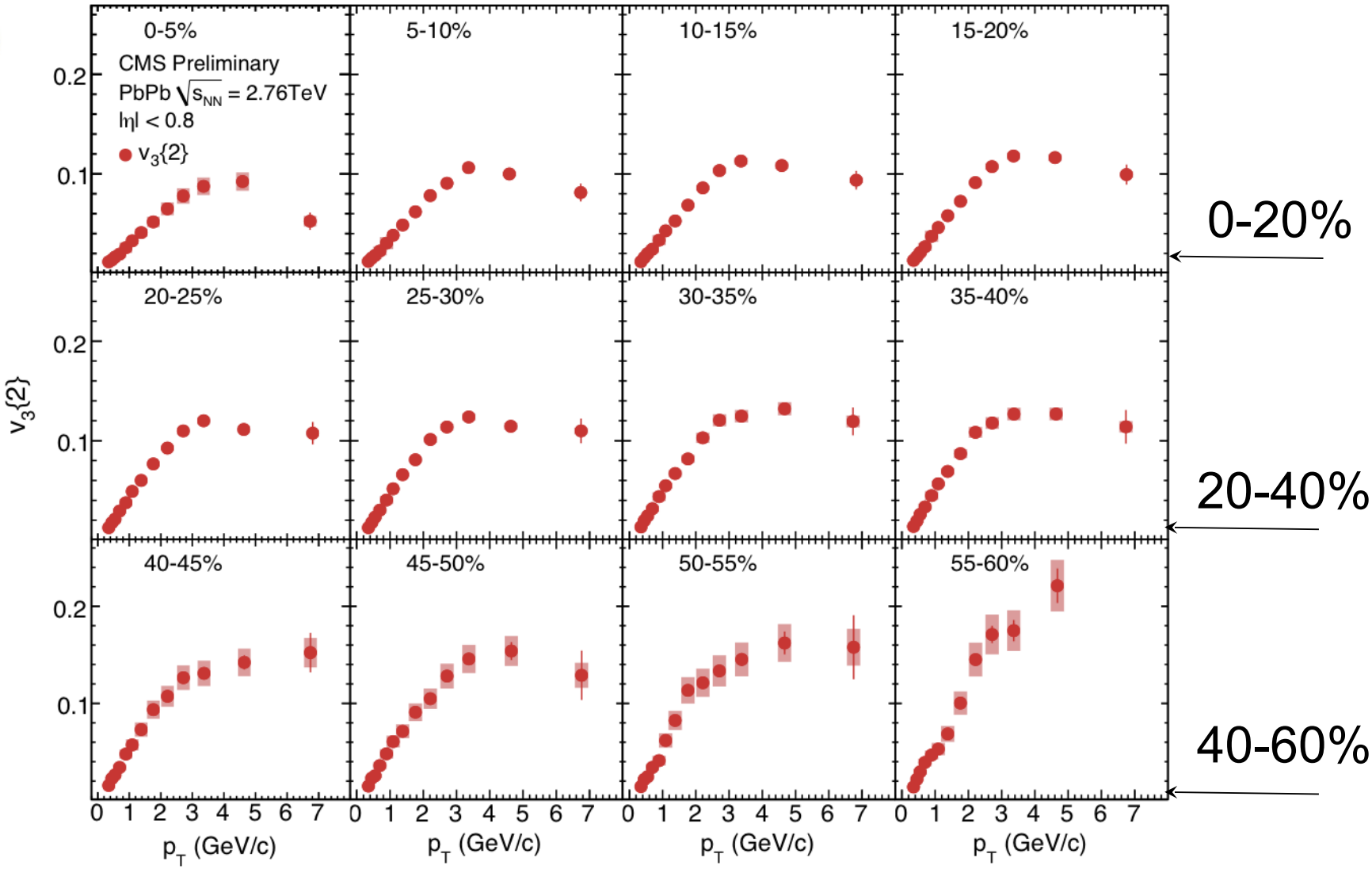


CMS-PAS HIN-10-002

- Weak η-dependence, stronger for most peripheral collisions(EP and v_2{2})
- May constrain descriptions of the longitudinal dynamics

$v_3(p_T)$ as a Function of Centrality

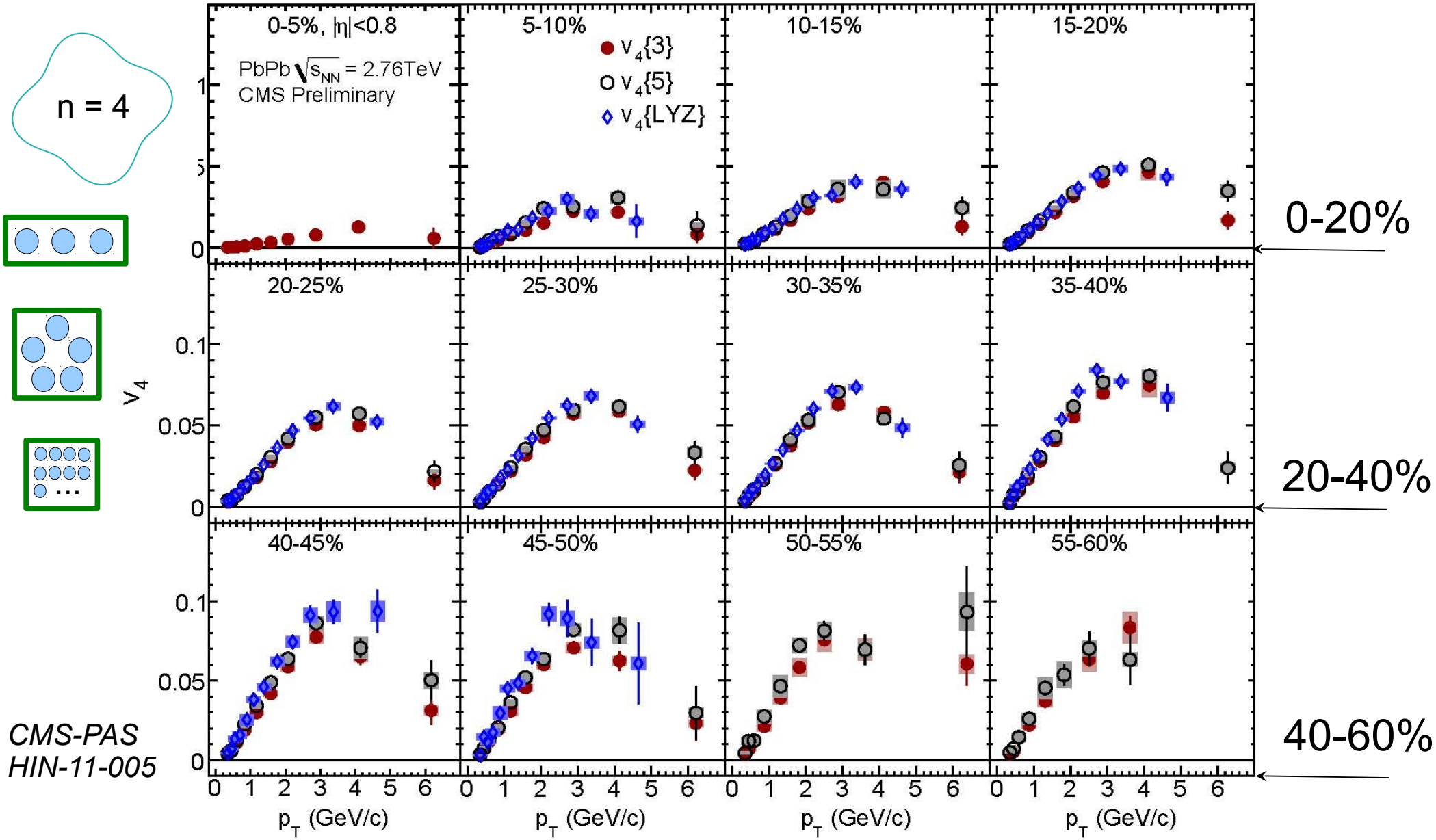




CMS-PAS HIN-11-005

- Sizable signal; weak centrality dependence for integrated v_2
- v_3 at mid-rapidity driven by fluctuations

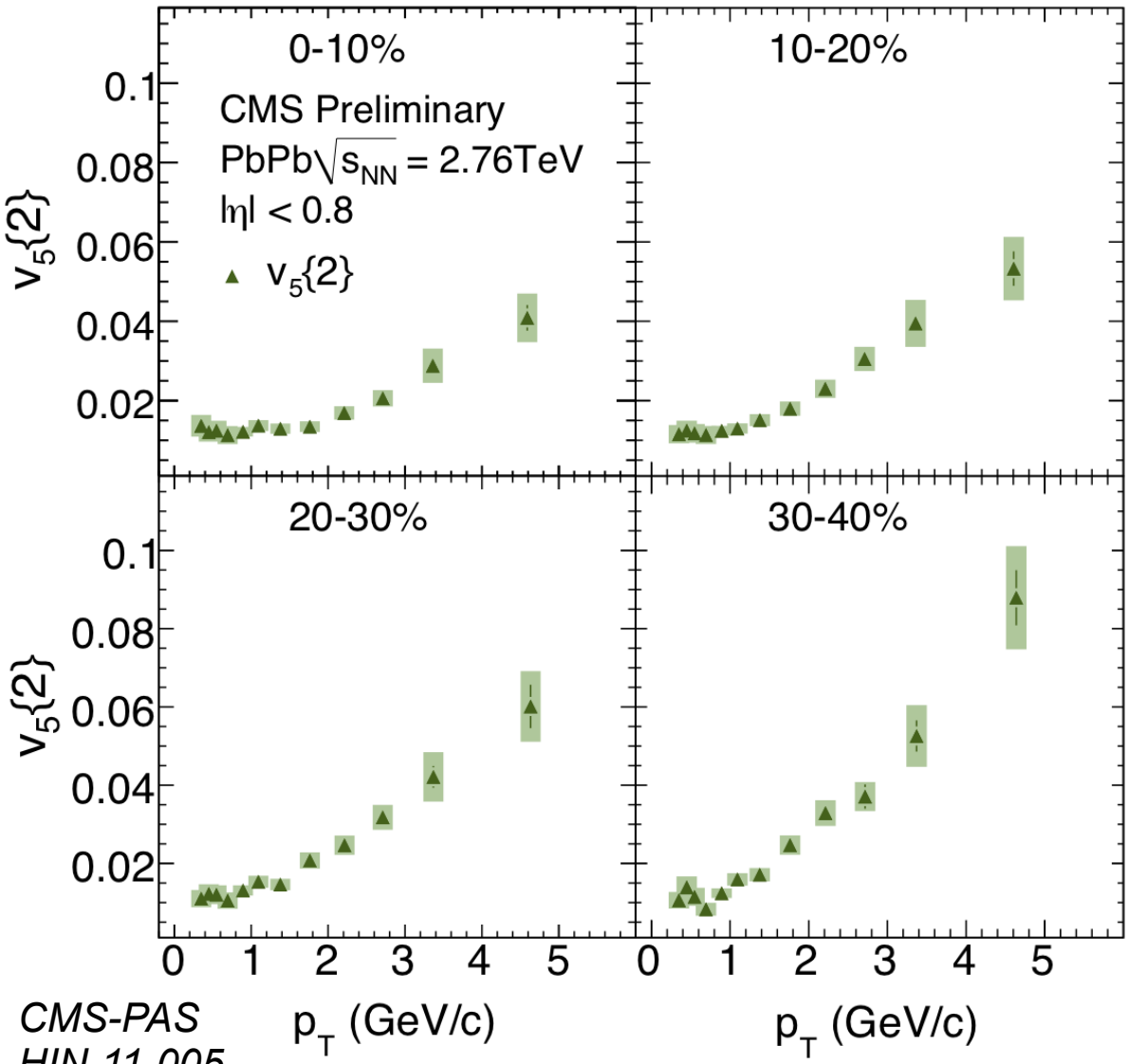
$v_4(p_T)$ as a Function of Centrality



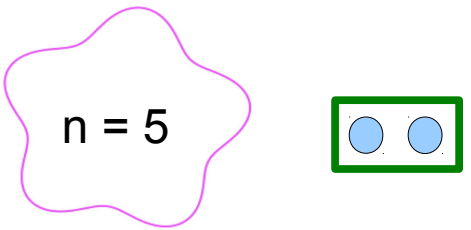
CMS-PAS HIN-11-005

- LYZ , $v_4\{3\}$ and $v_4\{5\}$ – consistent results

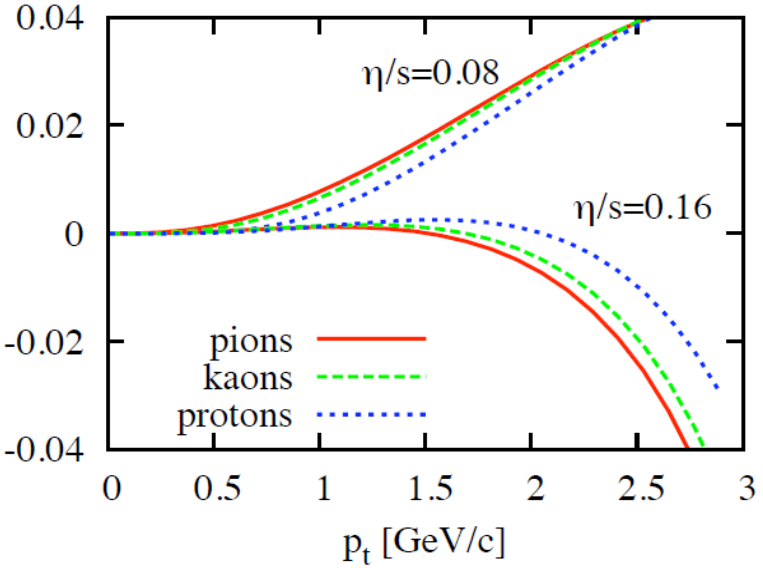
$v_5(p_T)$ as a Function of Centrality



CMS-PAS HIN-11-005

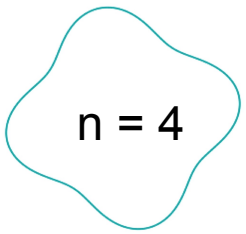


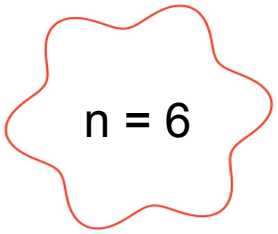
Alver et al Phys. Rev. C82 (2010) 034913
Prediction for RHIC, 0-5% centrality

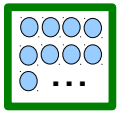


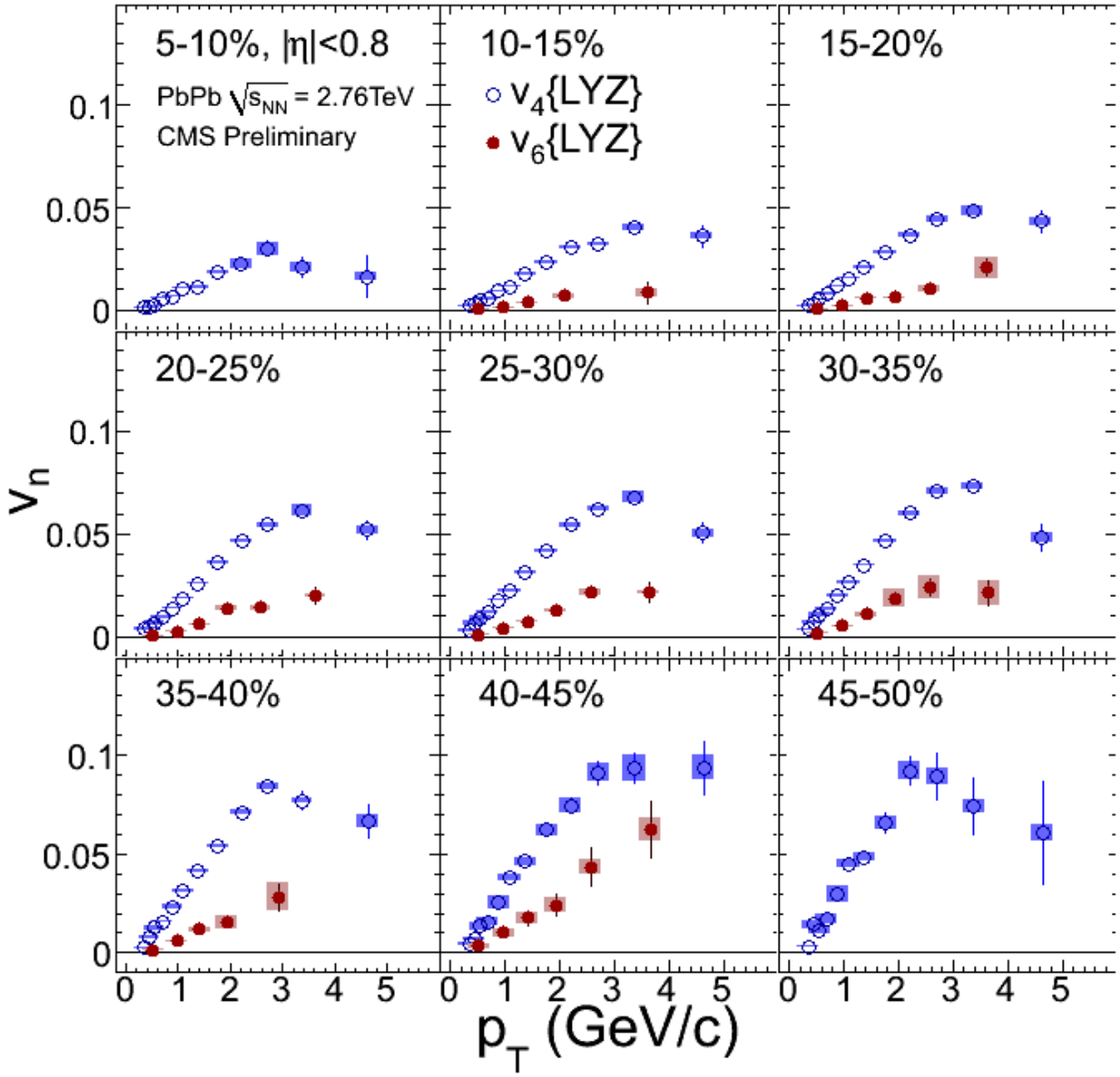
- v_5 rises quadratically with p_T in contrast with other flow harmonics

$v_4(p_T)$ and $v_6(p_T)$ as a Function of Centrality





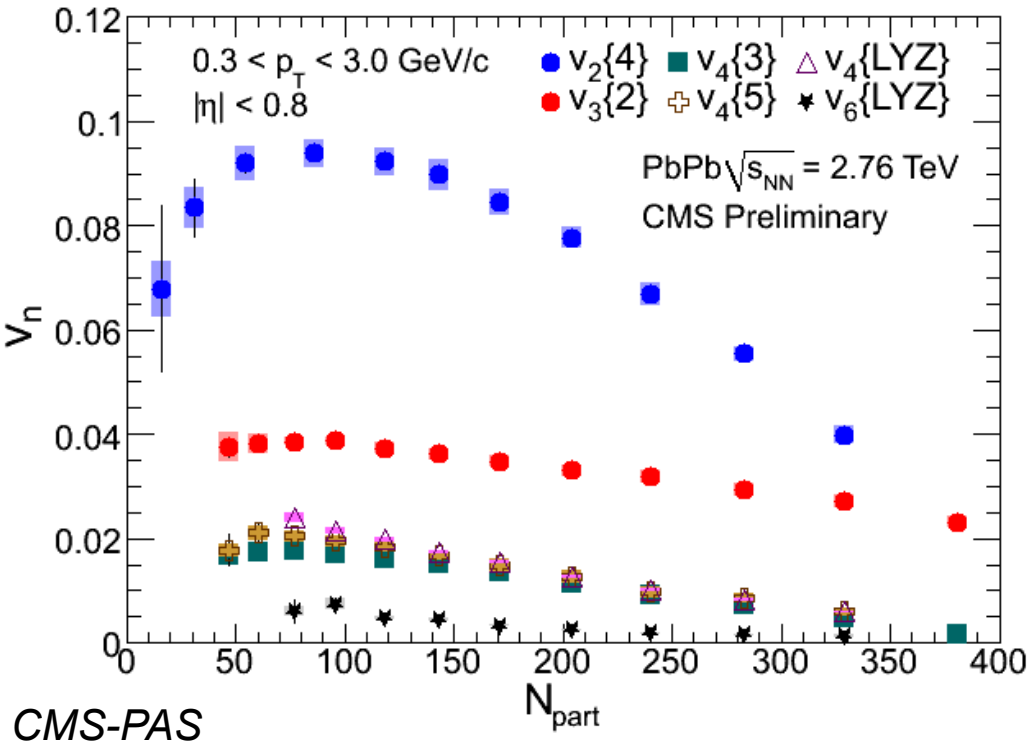


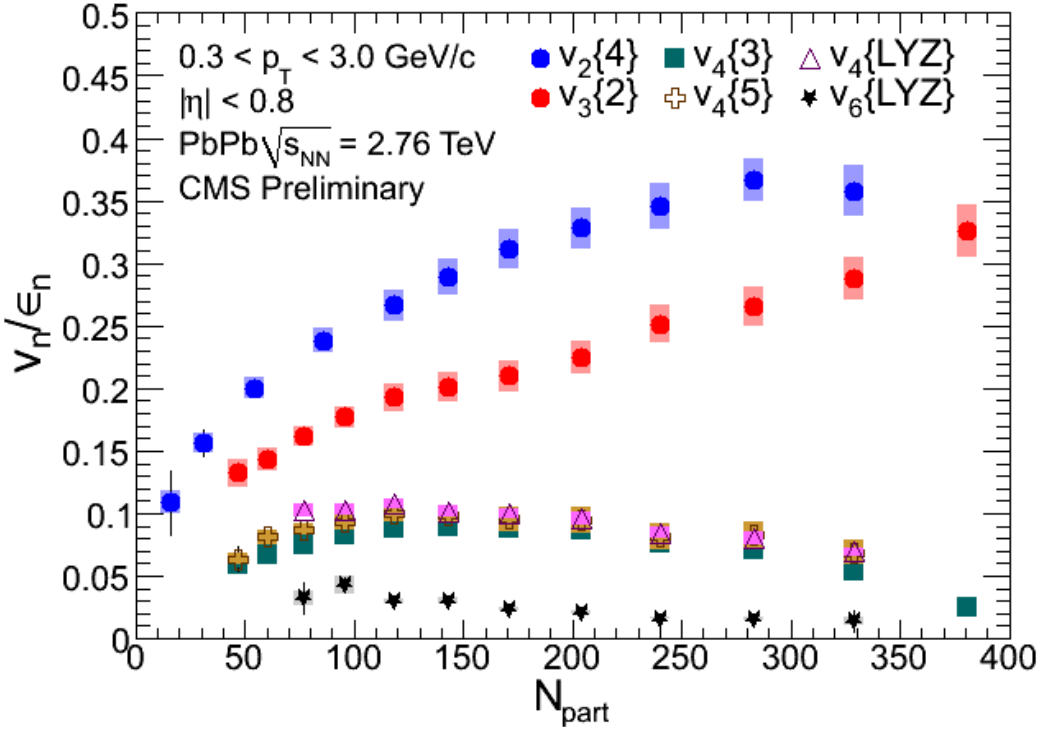


CMS-PAS HIN-11-005

- v_6(LYZ) is small but finite : reaches 2% in mid-central collisions

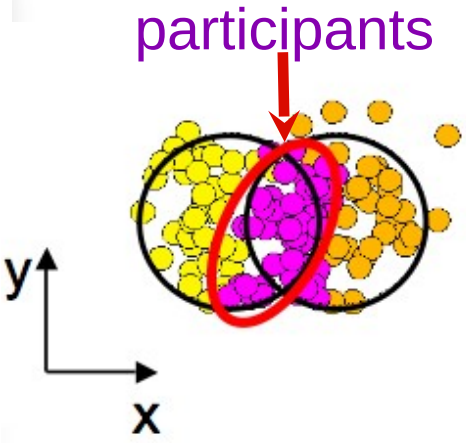
The Full Harmonic Spectrum





CMS-PAS HIN-11-005

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



- v_n vs N_{part} shows different trends:
  - even harmonics have similar centrality dependence:
    - decreasing → 0 with increasing N_{part}
  - v_3 has weak centrality dependence, finite for central collisions

Conclusions

- Detailed Measurements of v_n in PbPb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - Good statistics and pseudorapidity Coverage

- v_2(pt) : maximum at 3 GeV/c then decreases
  - still finite at 10 GeV/c

- Integral v_2 is strongest at midrapidity; slowly decreases at forward rapidity

- v_2 comparable to RHIC measurements at $\sqrt{s_{NN}}$ = 200 GeV
  - similar p_T dependence
  - small increase in integral v_2

- v_3 is sizable and almost independent of centrality
  - expected by fluctuations

- v_5 and v_6 are finite

Physics Analysis Summaries

These preliminary results are published and available publicly on the CERN Document Server.

Elliptic Flow Results:

CMS Collaboration, *CMS-PAS-HIN-10-002*, http://cdsweb.cern.ch/record/1347788 (2011)

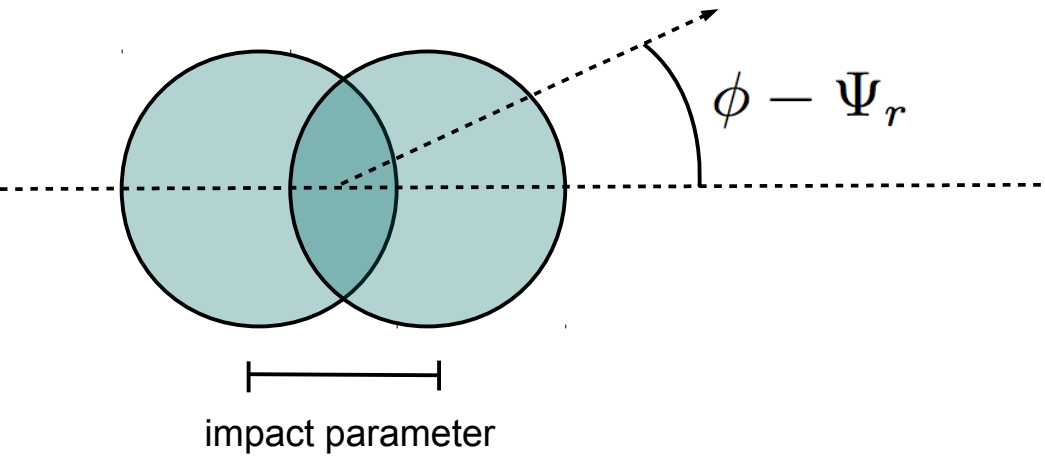
Higher-Order Flow Results:

CMS Collaboration, *CMS-PAS-HIN-11-005*, http://cdsweb.cern.ch/record/1361385 (2011)

Backup

Anisotropic Flow

Schematic of a heavy ion collision:



Fourier decompose the azimuthal angle of the particle emission spectrum with respect to the reaction plane:

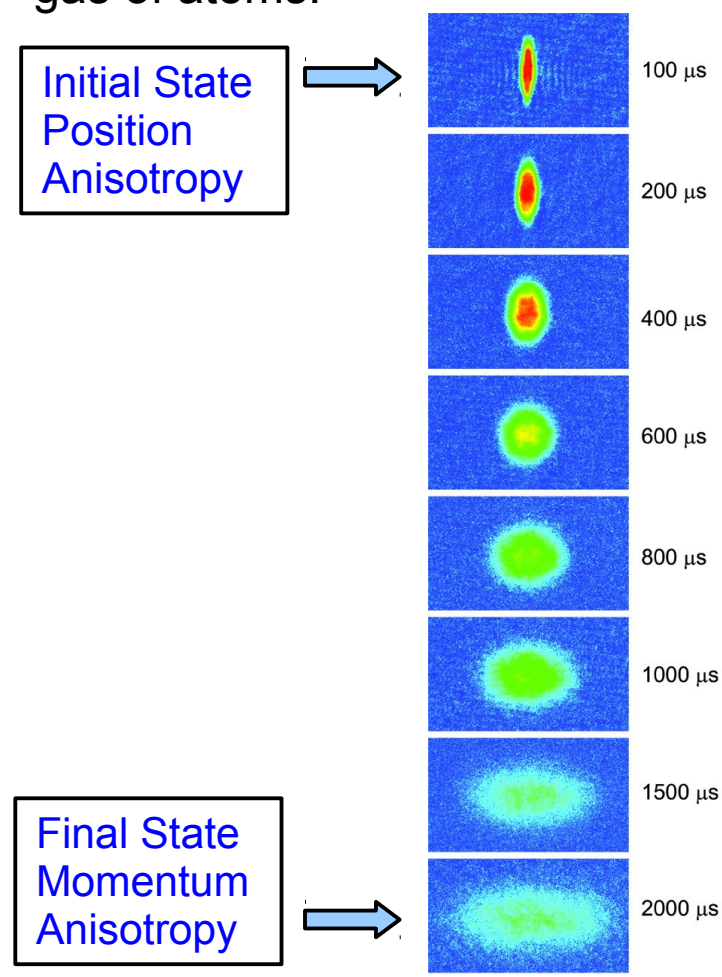
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r)))$$

$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$

Second Fourier coefficient n=2 quantifies the particle emission "in-plane" versus "out-of plane"

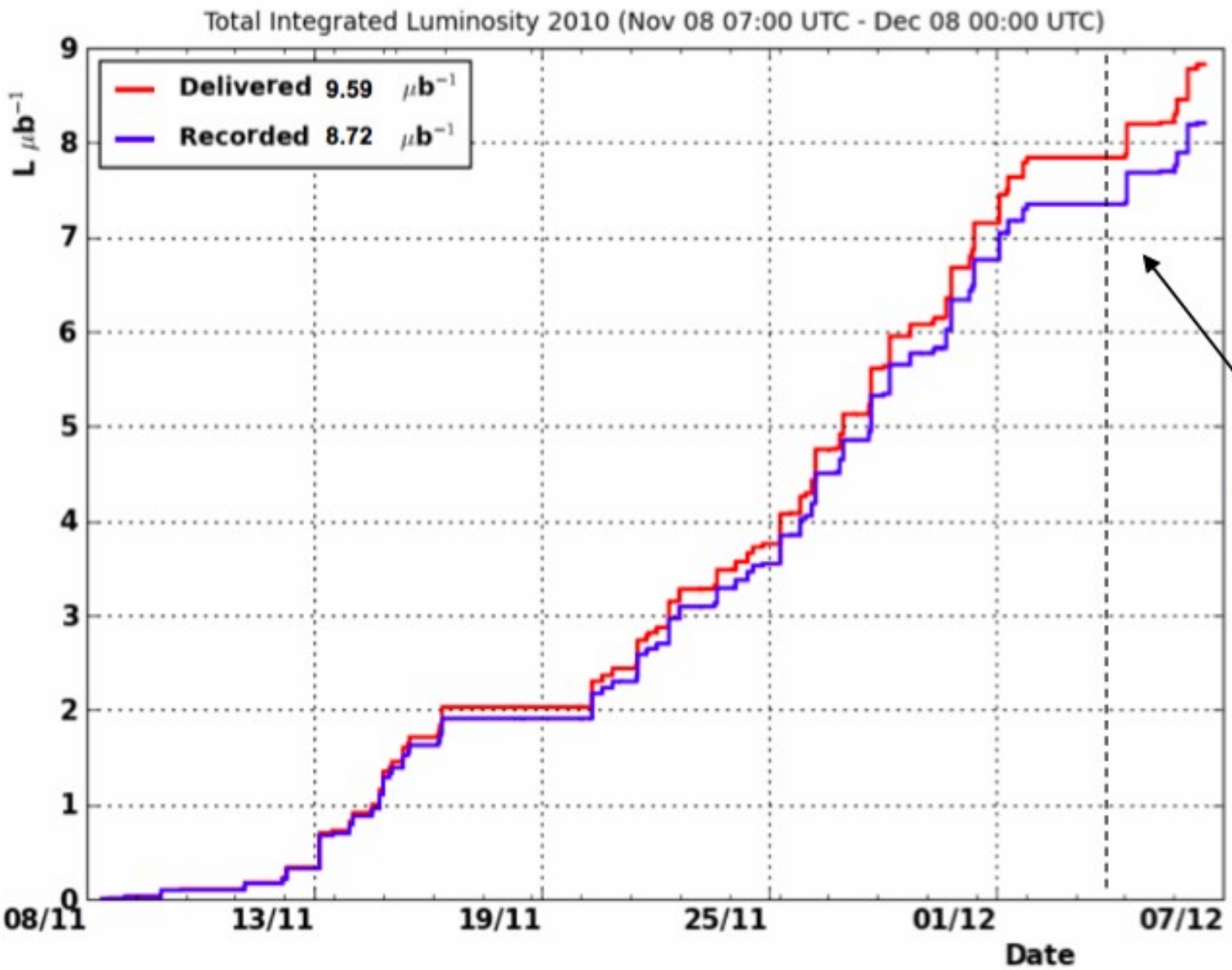
Measuring the v_2 coefficient can constrain hydrodynamic and transport properties of the hot and dense medium produced in the collision.

Analogous system: A strongly-interacting degenerate fermi gas of atoms.



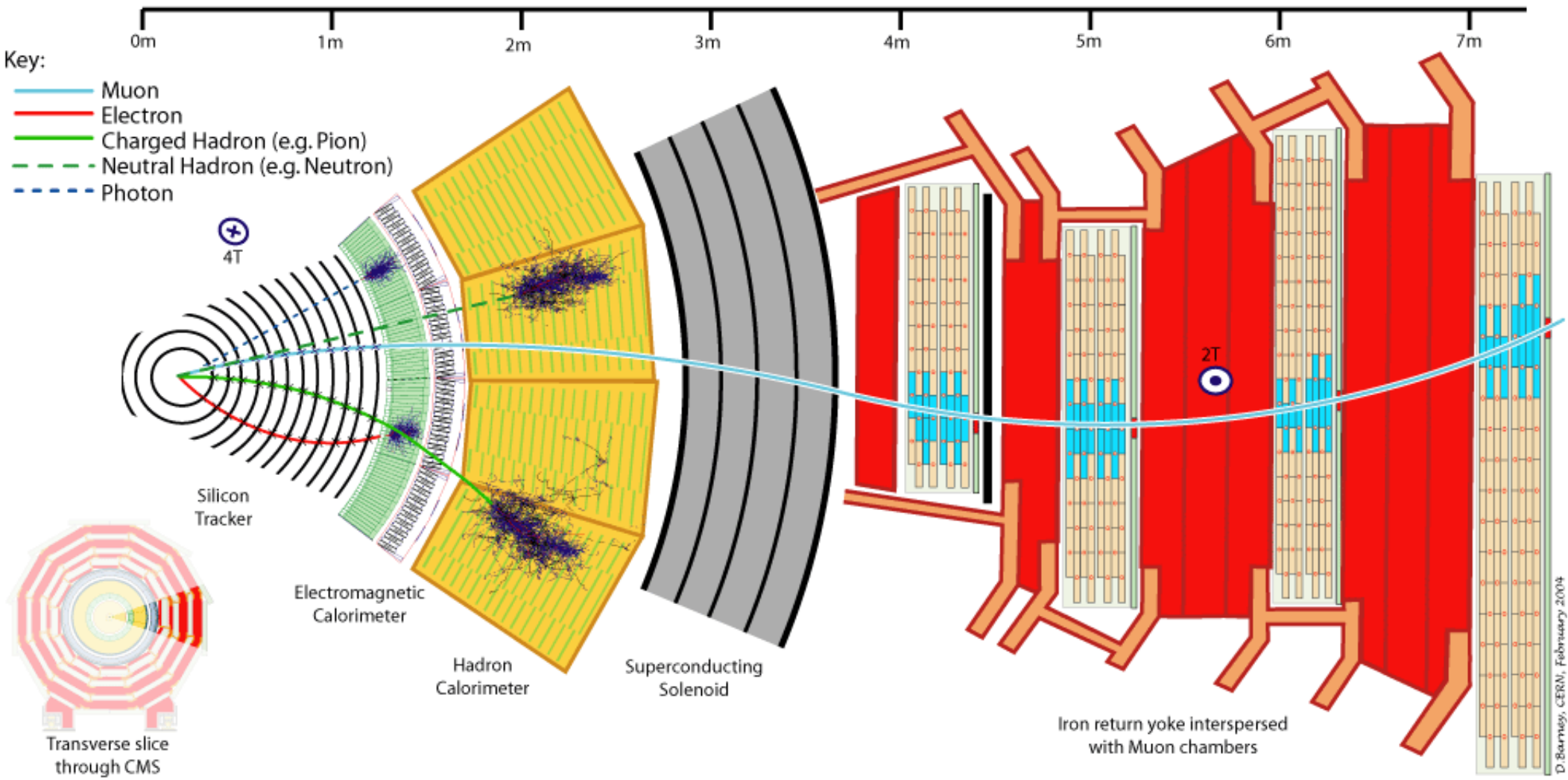
K. M. O'Hara et.al, *Science*, **298**, 2179 (2002)

LHC: 2010 Heavy Ion Run

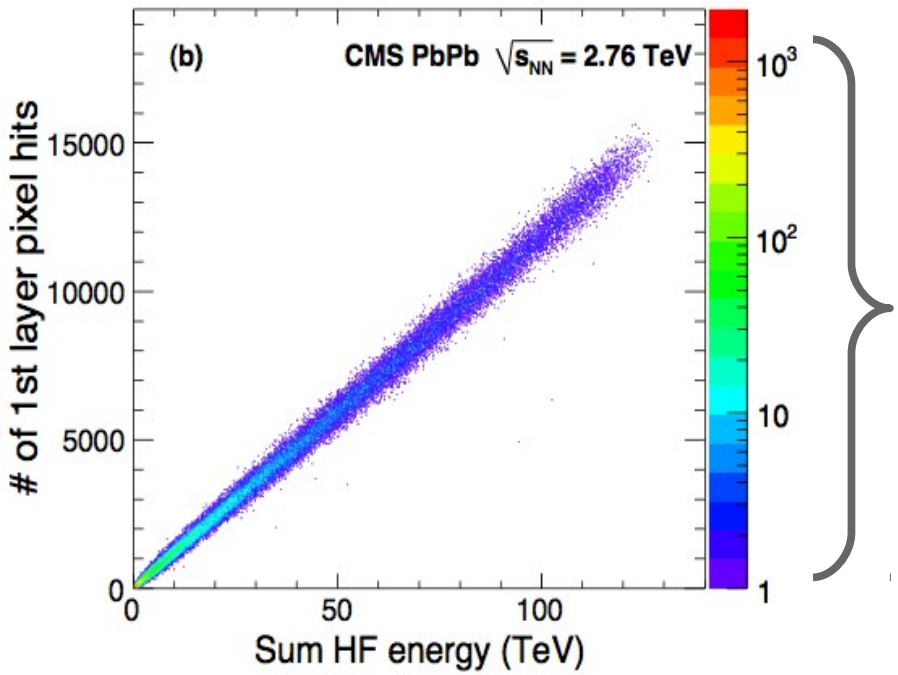


Data taking without magnetic field

CMS Detector Profile

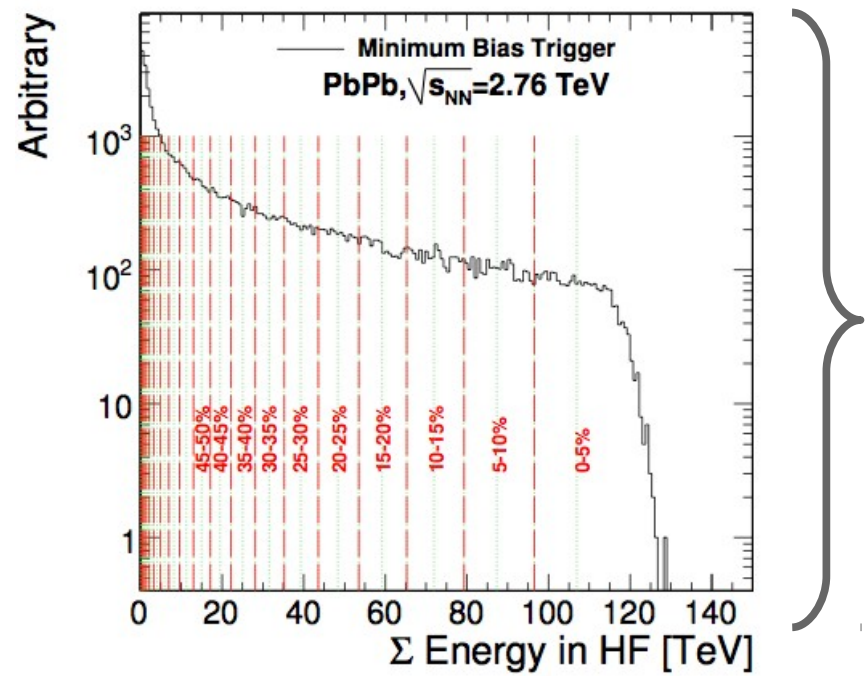


Event Selection and Centrality Determination



Minimum Bias trigger based on double-coincidence of either the beam scintillation counters (BSC) or forward hadronic calorimeters (HF).

Additional offline event selection used to remove electromagnetic ultra-peripheral collisions, beam gas, beam scraping, and other non-collision events.



Centrality was determined using the total energy in both HF calorimeters, dividing events into 40 categories. These were divided into 12 larger bins for this analysis:

0-5%	20-25%	40-50%
5-10%	25-30%	50-60%
10-15%	30-35%	60-70%
15-20%	35-40%	70-80%

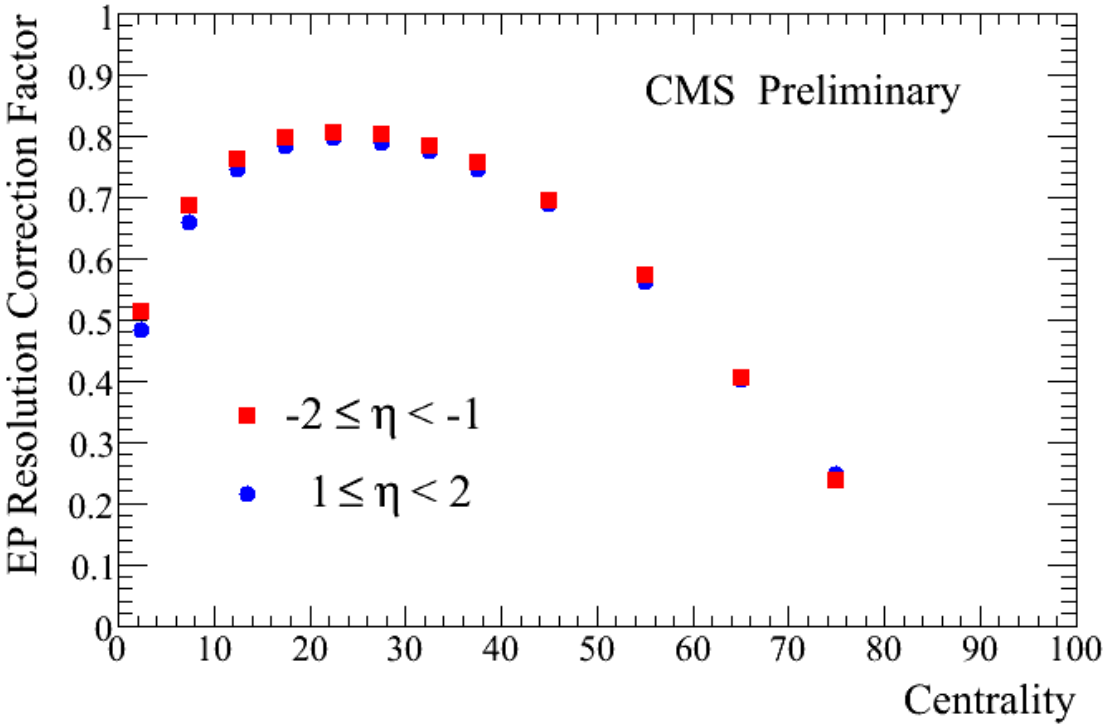
Details of the Event Plane Method

- **Uses 3-subevent event plane resolution correction.**

A. M. Poskanzer and S. A. Voloshin, *Phys. Rev.* **C58** (1998) 1671

- **Standard f lattening procedure to remove azimuthal detector asymmetries (21st order Fourier decomposition)**

E877 Collaboration, *Phys. Rev.* **C56** (1997) 3254



1. Event Plane is Determined from the Azimuthal Correlations themselves:

$$\Psi_n = \left(\tan^{-1}\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)/n$$

2. Resolution correction factor is determined by splitting particles into three sub-events based on pseudorapidity:

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

3. Extracted v_2 signal is corrected for the resolution:

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

Details of the 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

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

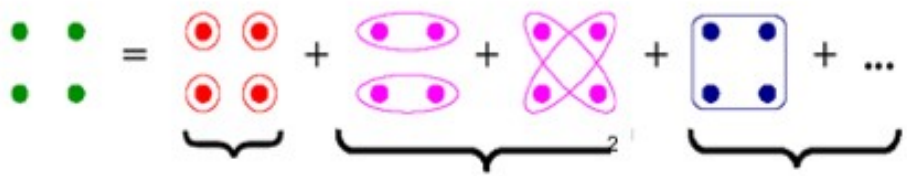
differential flow

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

- the few particle correlations (resonance decays, jets, etc.)

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

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



$$v_n^4 \qquad 2 < e^{in(\phi_1-\phi 2)} >_c^2 \qquad O(\frac{1}{N^3})$$

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

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

Details of the Lee-Yang Zeros Method

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

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

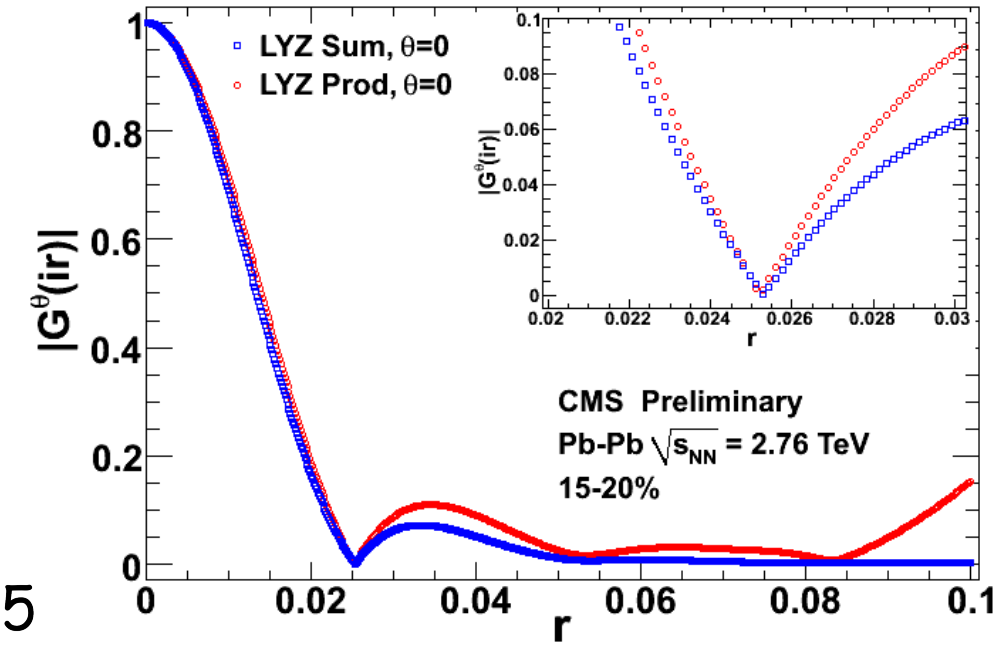
with

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

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 :

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

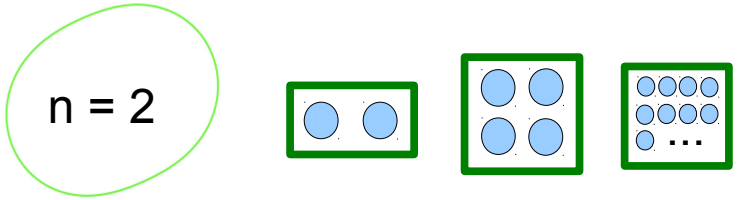
J_m is Bessel function of the first kind
m=1 for v_2

The method:

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

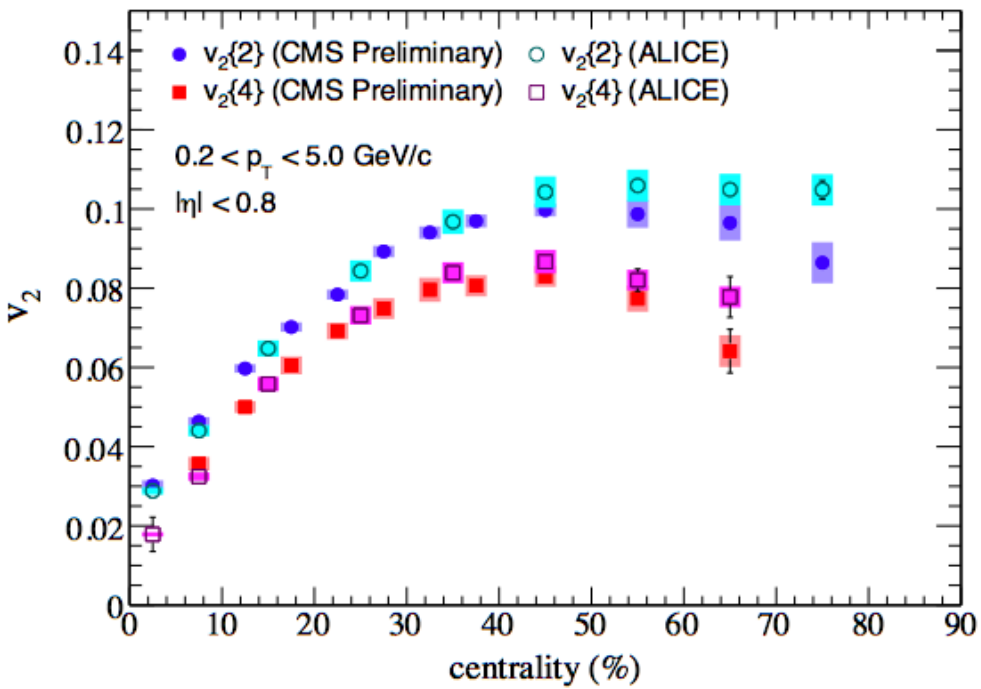
Another generating function(Product) can be used in LYZ. It gives the same results for v_2

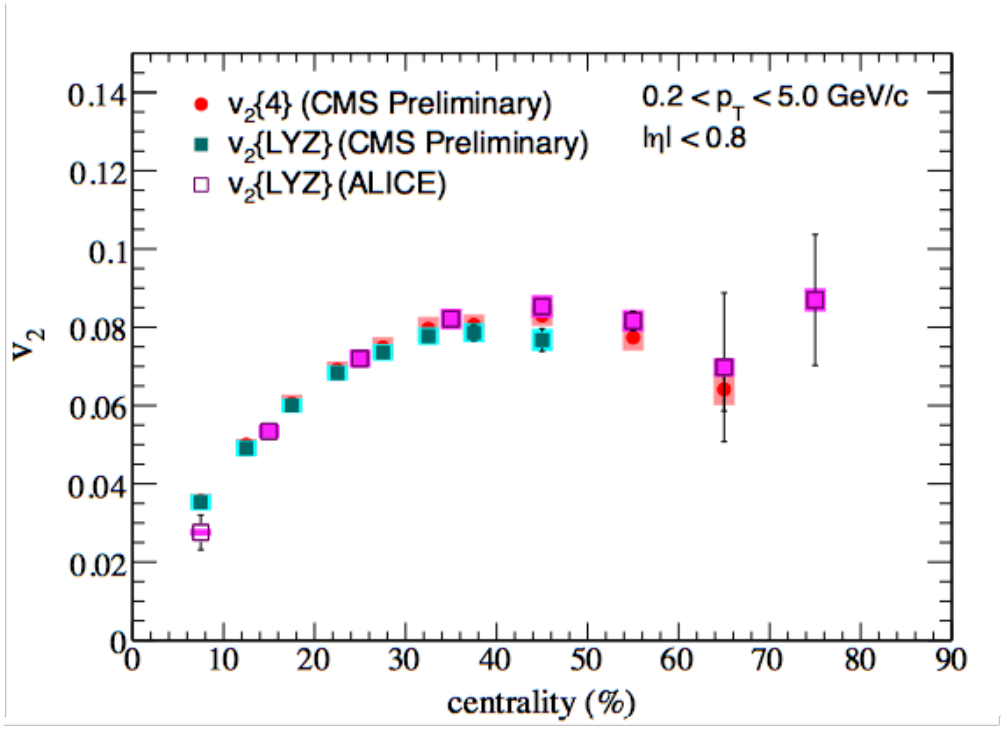
Integrated v_2 Comparison to ALICE



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.

Systematic Studies

Systematic Studies Common to all Methods Include:

- Particle composition (pion/kaon/proton ratio)
- Centrality determination and trigger efficiency
- Tracking kinematic cuts
- Fake track contribution to elliptic flow
- Uncertainty in efficiency corrections

Systematic Studies for the Event Plane Method Include:

- Tracking transverse momentum cut for calculating the event plane angle
- Detector acceptance
- Flattening check
- Subevent pseudorapidity gap
- Flattening parameters as a function of the vertex position

Event Selection Summary

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

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%