Flow Phenomena in CMS

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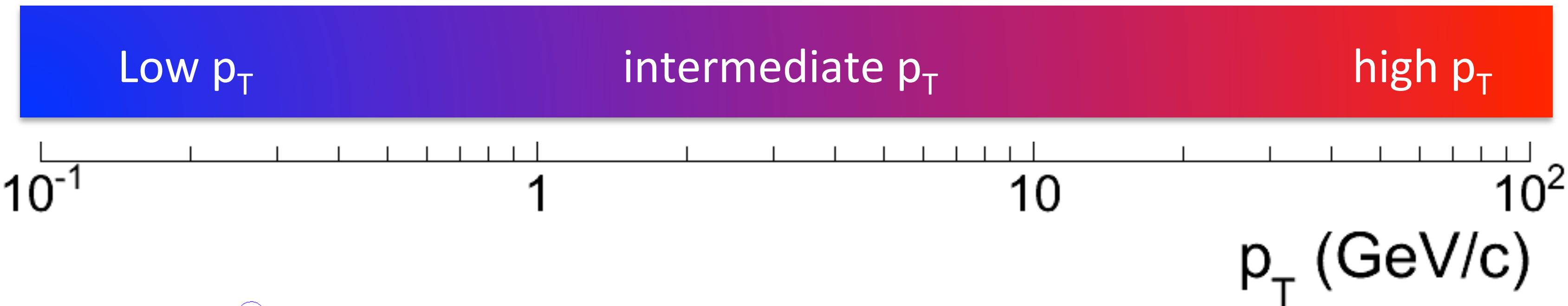
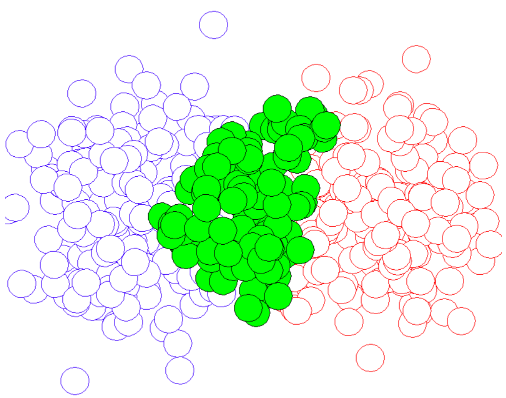
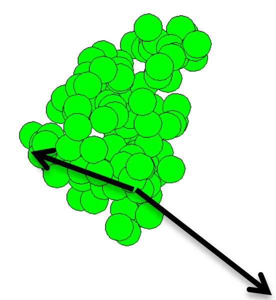
for the CMS Collaboration

Azimuthal Correlations in CMS





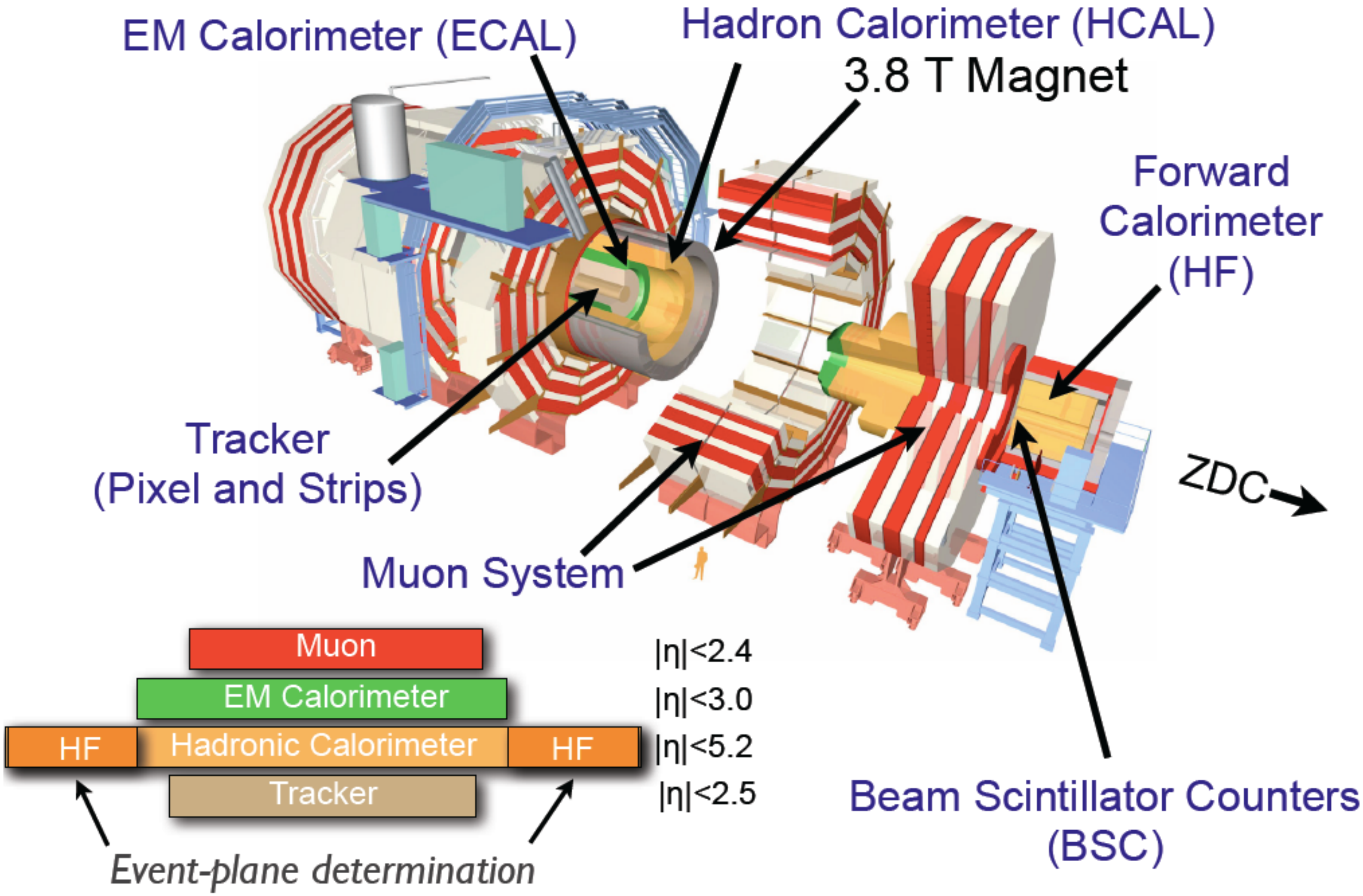


- Hydrodynamic flow driven by asymmetry pressure gradients
- Soft-Hard interplay recombination
- Path length dependent energy loss

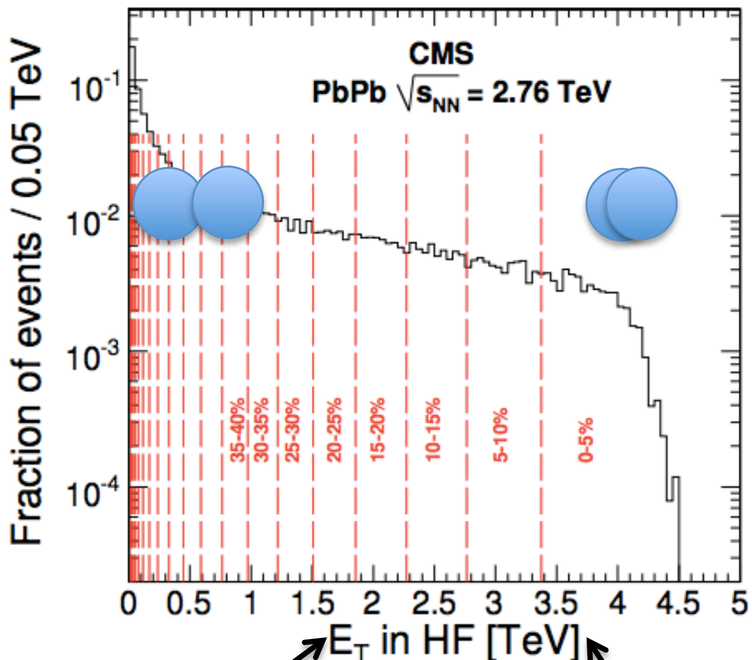
Outline

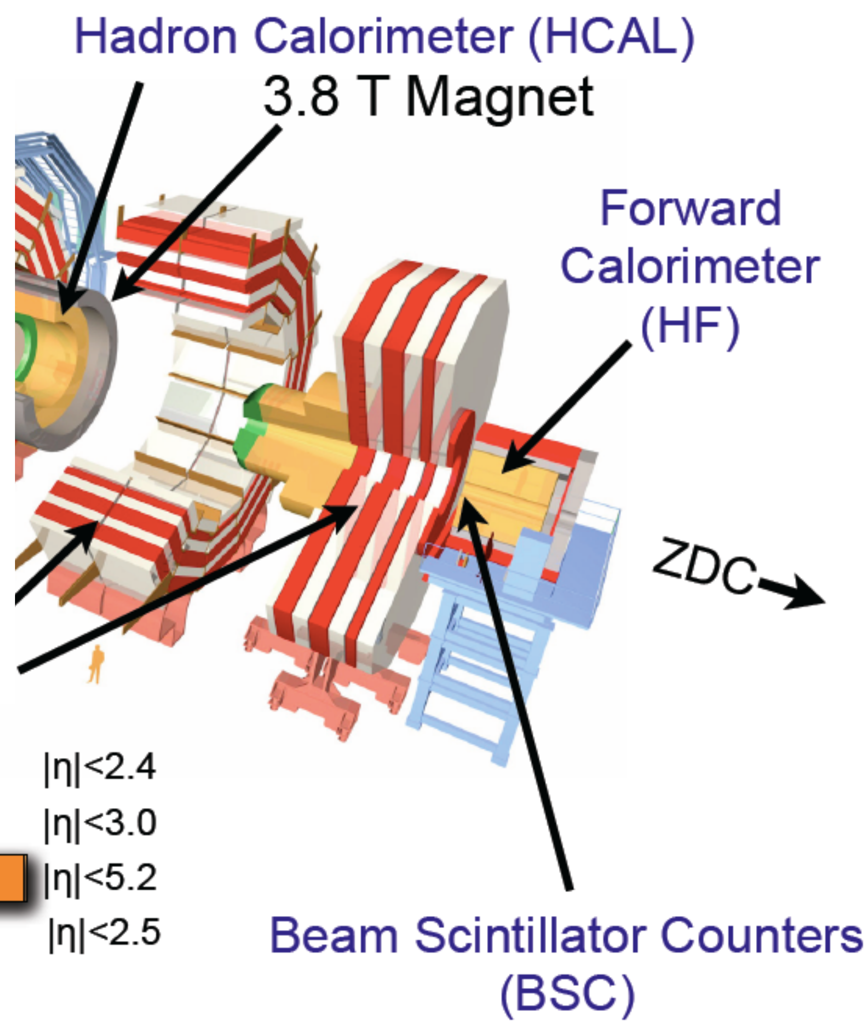
- Azimuthal anisotropy
- Multiple methods for flow determination
- Measurement of flow and higher order harmonics
- Neutral hadron π^0 v_2 at intermediate p_T
- Charged particle v_2 at high p_T
- Di-hadron correlation result in pPb

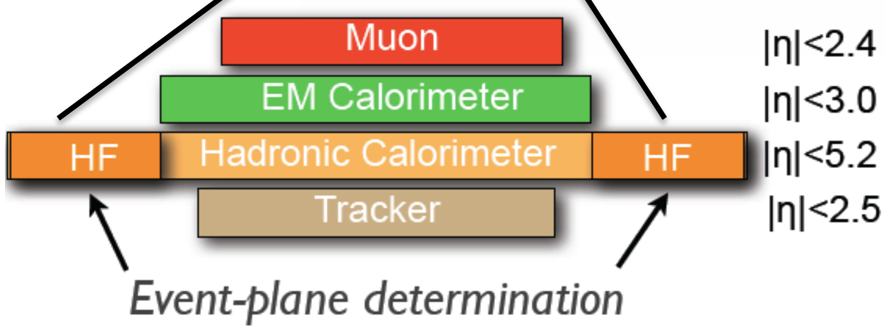
The CMS Detector



The CMS Detector





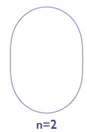


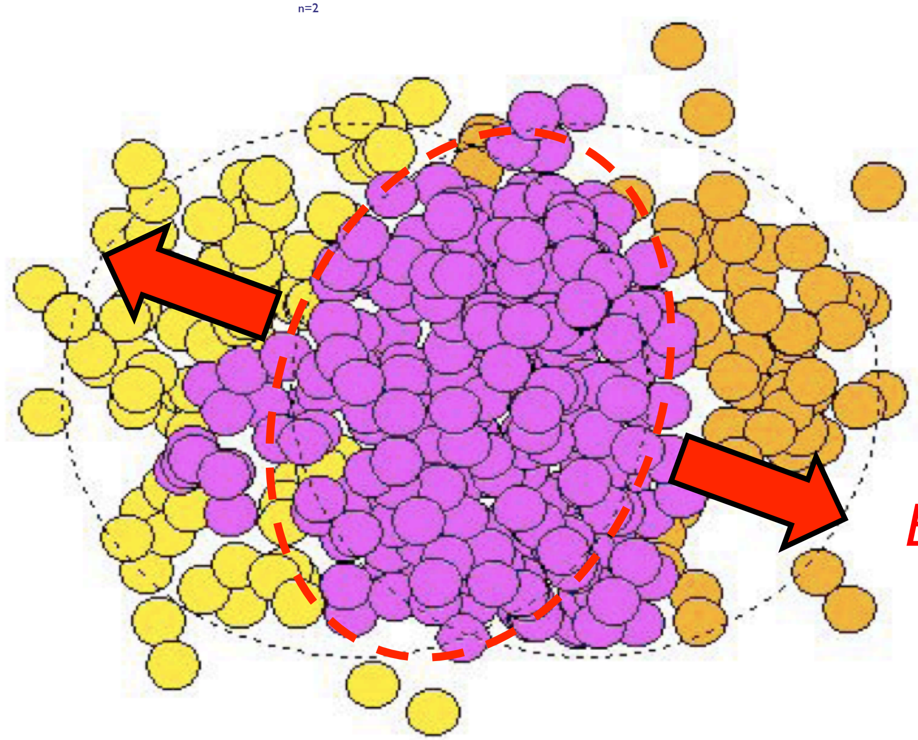
Hydro Flow with Initial State Fluctuation

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

Elliptic flow

Two-particle correlation $\Longrightarrow$ $$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2v_2^2 \cos 2\Delta\phi$$

n=2 



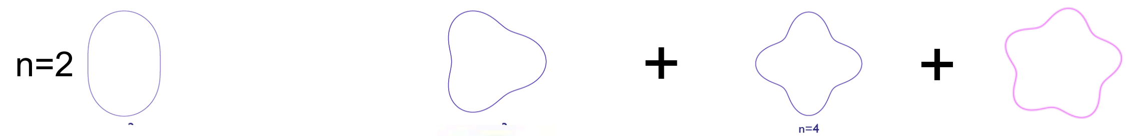
Elliptic flow

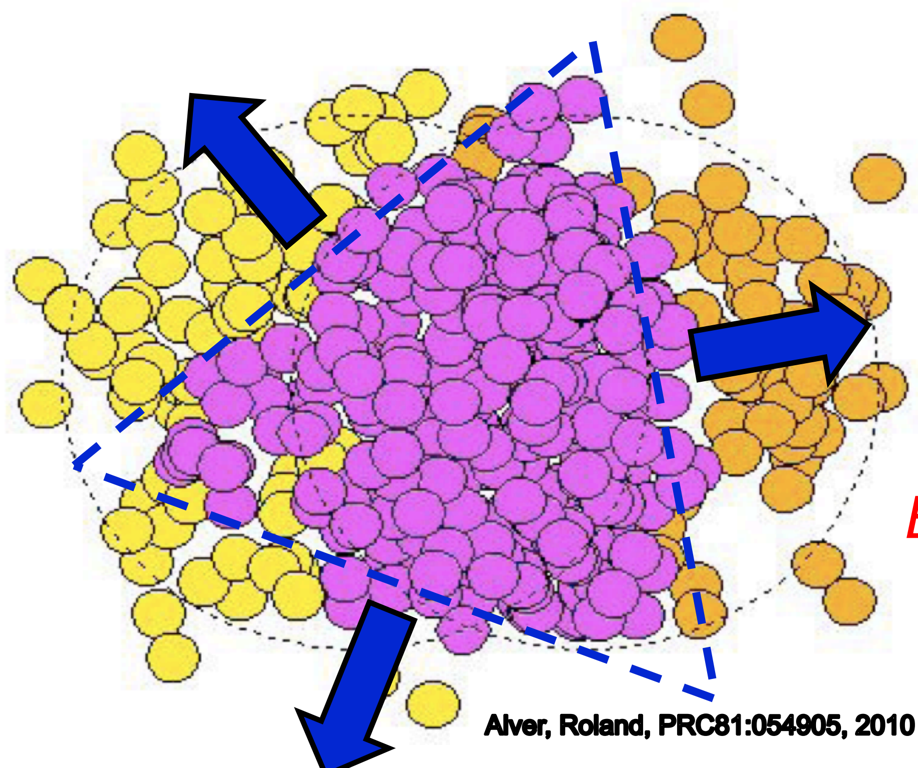
Hydro Flow with Initial State Fluctuation

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

Elliptic flow   Triangular flow

Two-particle correlation $\Longrightarrow$ $$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2v_2^2 \cos 2\Delta\phi + 2v_3^2 \cos 3\Delta\phi + \ldots$$





Triangular flow

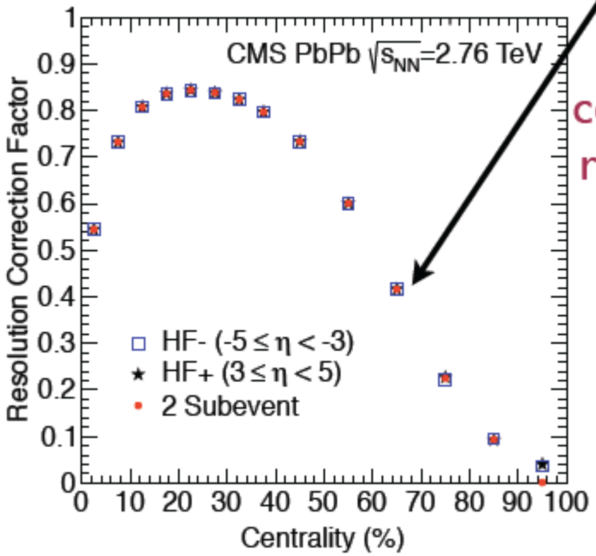
Elliptic flow

Alver, Roland, PRC81:054905, 2010

v_2 measurement methods

Event Plane

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

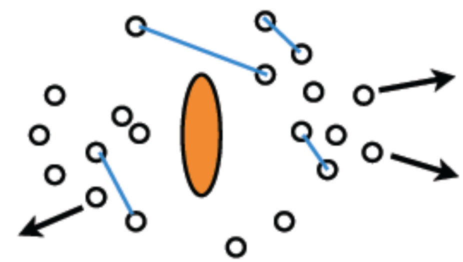


Need to correct for Ψ_{EP} resolution (R).

Two-particle Cumulant

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

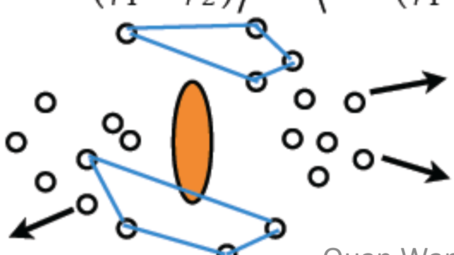
Consider all two-particle correlations.



Four-particle Cumulant

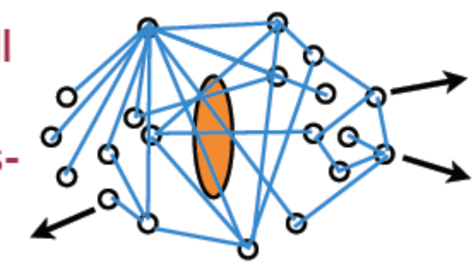
$$v_2\{4\} = \left(2\langle \cos 2(\phi_1 - \phi_2)\rangle^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4)\rangle\right)^{1/4}$$

Consider all four-particle correlations.



Lee-Yang Zeros

Consider all particle correlations- (Not all shown!).



v_2 measurement methods

Event Plane

Non-flow largely suppressed

Two-particle Cumulant

Very sensitive to non-flow

Non-flow:

- **Di-jet back-to-back correlation**
- **Resonance decay**
- **HBT (Hanbury Brown and Twiss)**
- **Momentum conservation, etc.**

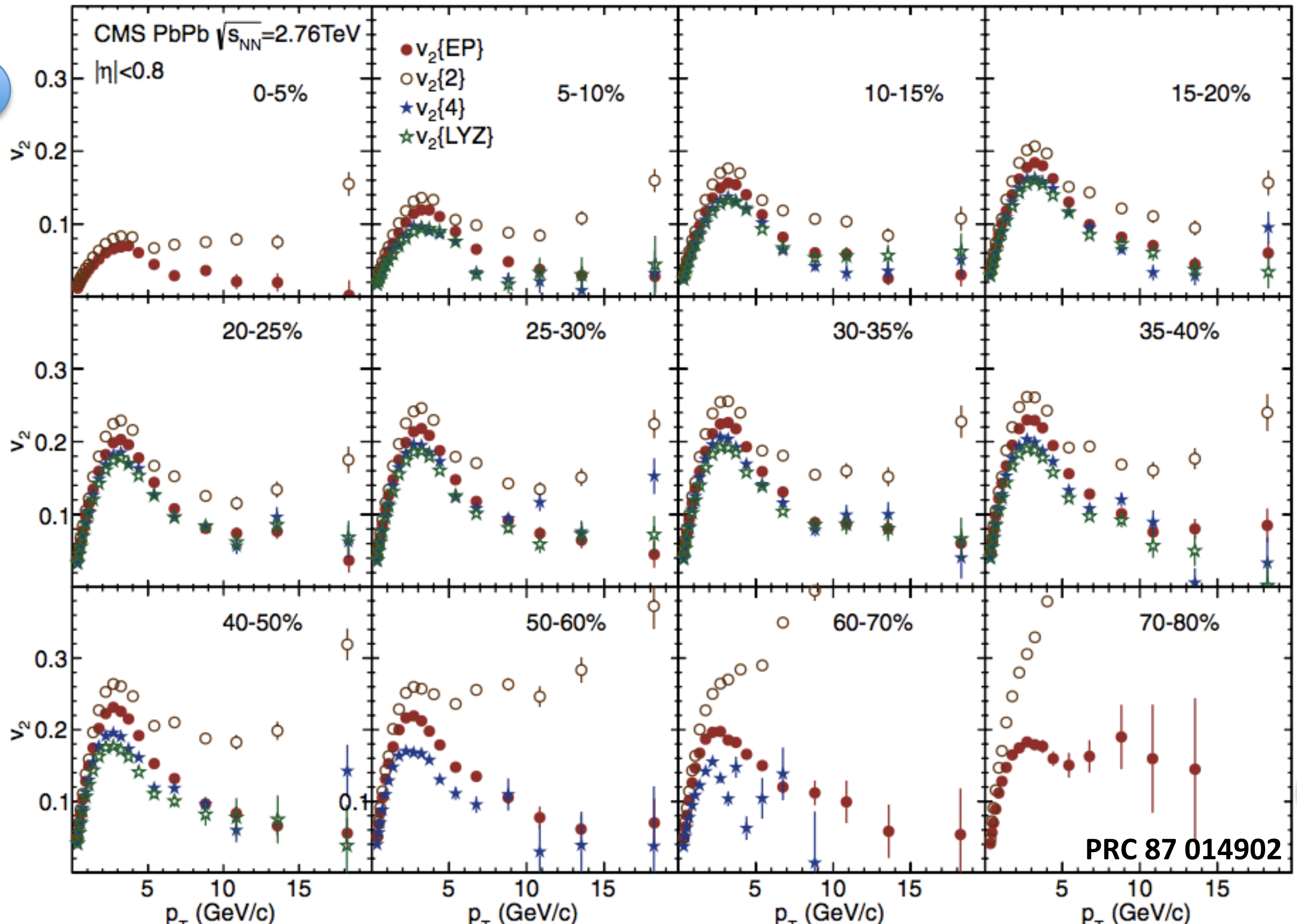
Four-particle Cumulant

Less sensitive to non-flow

Lee-Yang Zeros

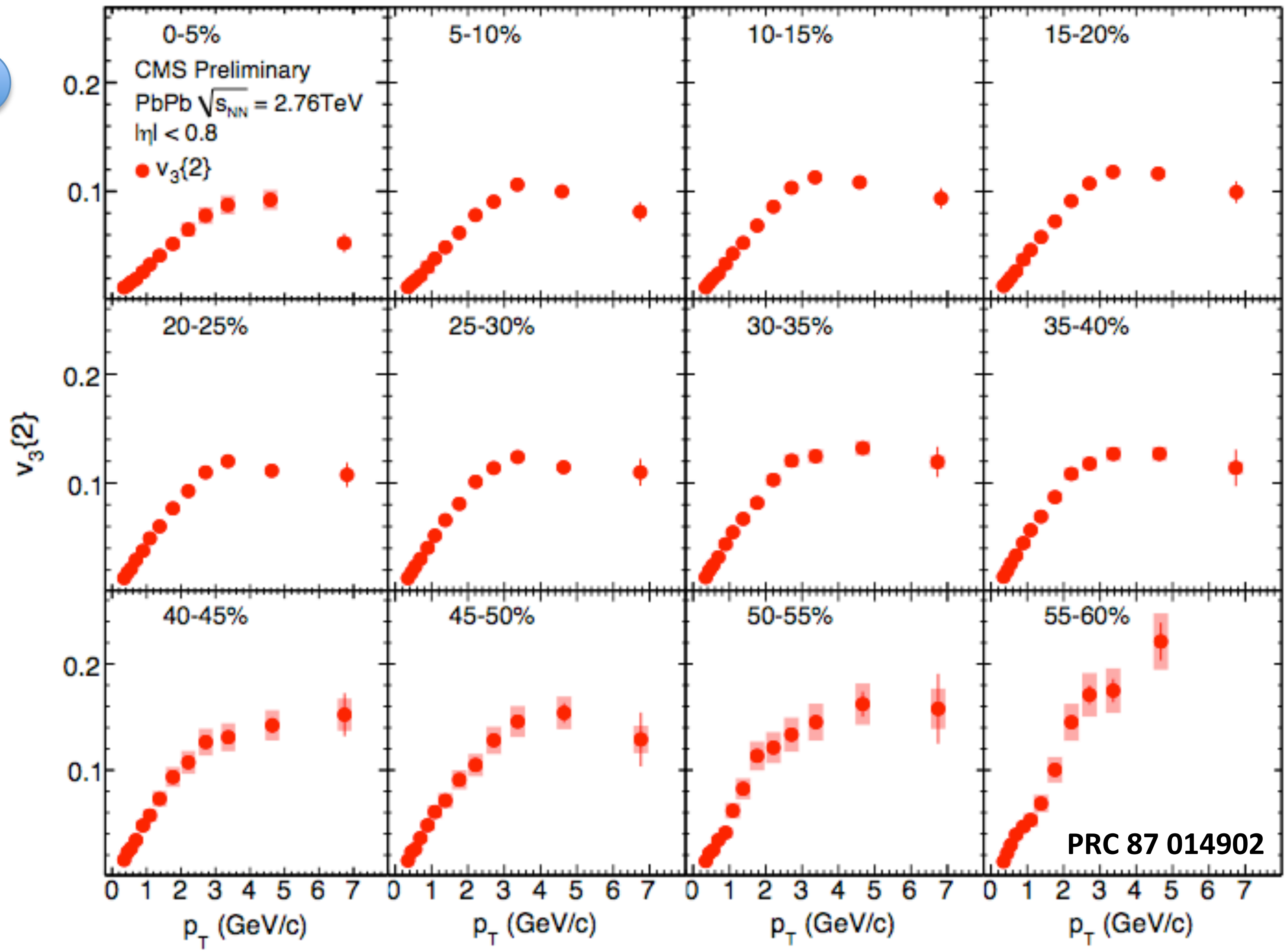
Insensitive to non-flow

PbPb Charged Particle v_2 Results



- ➢ **Differences between methods understood in terms of eccentricity fluctuation and non-flow correlation.**

PbPb Charged Particle v_3 Results



- Cumulant $v_3\{2\}$ result suggesting significant role of fluctuations.

Di-hadron Correlation Method

Signal pair distribution:

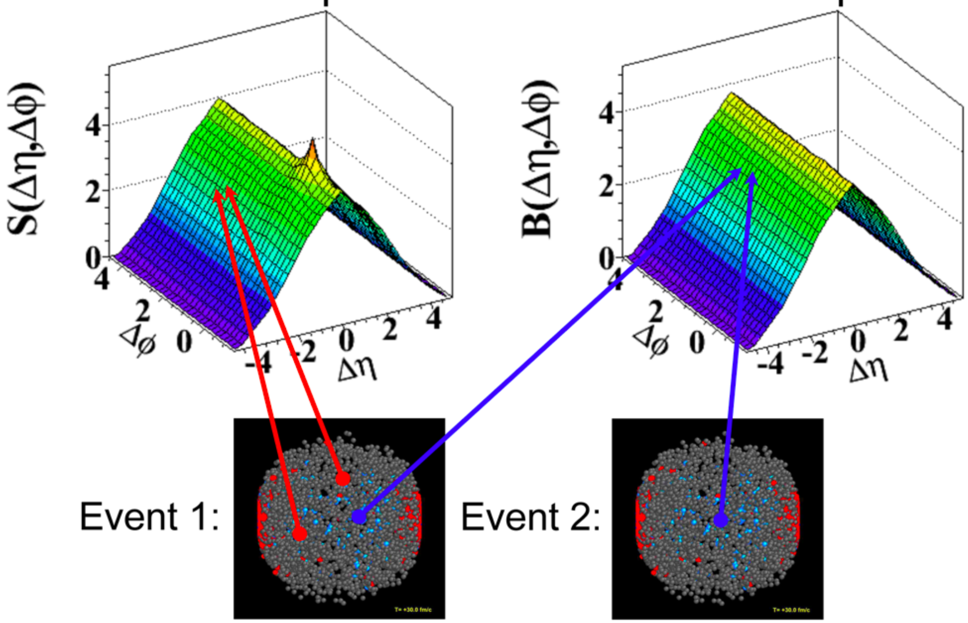
$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background pair distribution:

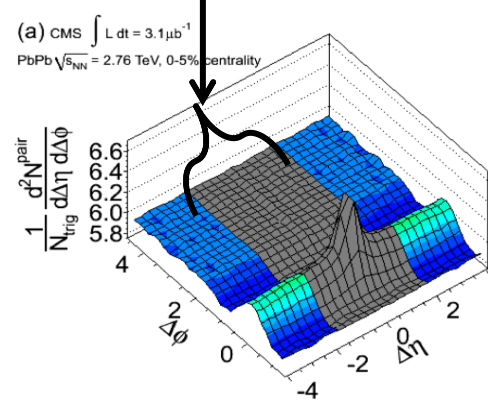
$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

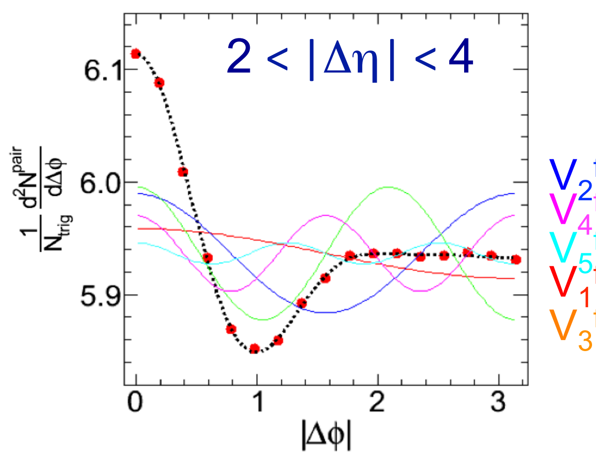
same event pairs

mixed event pairs



Exclusion region in Δη

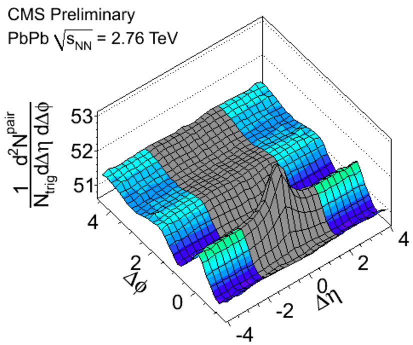


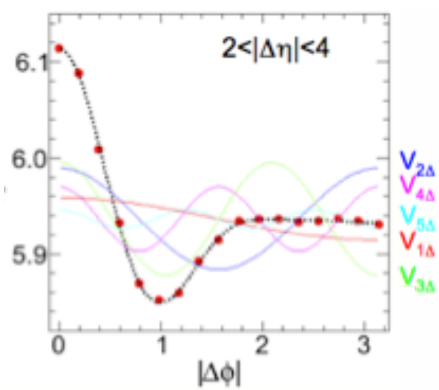


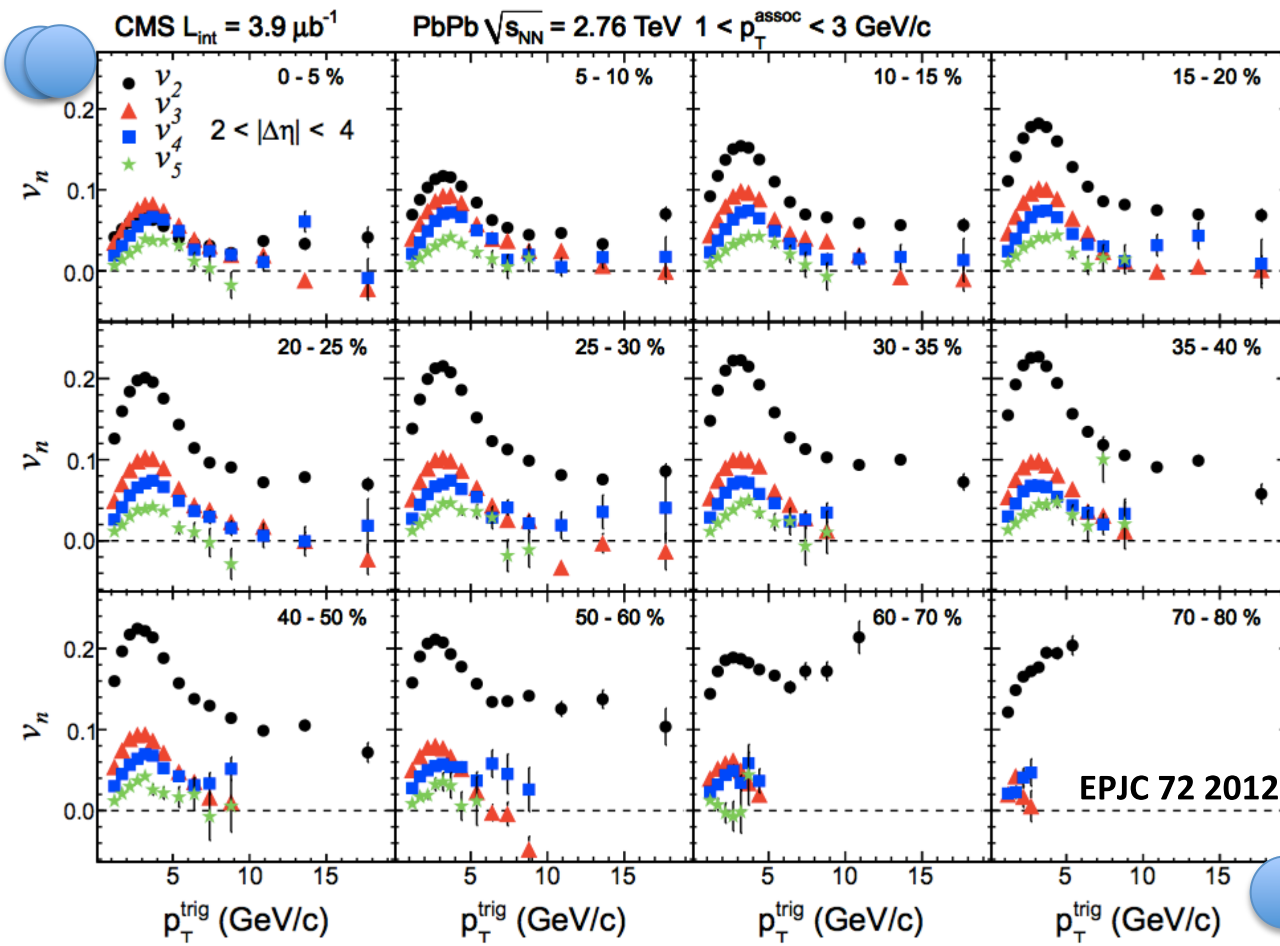
$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$
$$\Delta\phi = \phi^{assoc} - \phi^{trig}$$

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

PbPb Di-Hadron Correlation Results



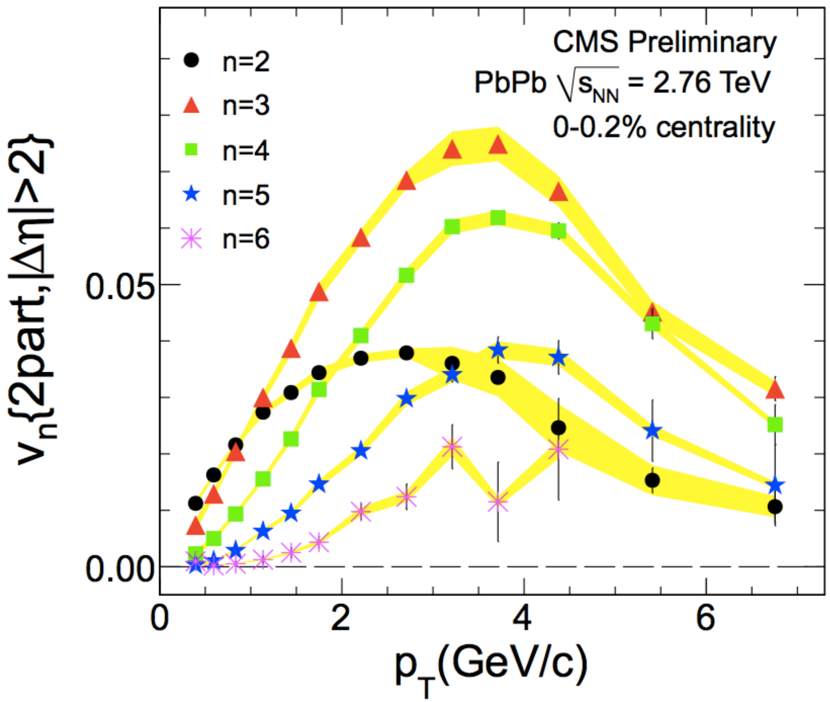




EPJC 72 2012

- ➢ Require $|\Delta\eta|>2$
- ➢ Extract v_n from di-hadron correlation

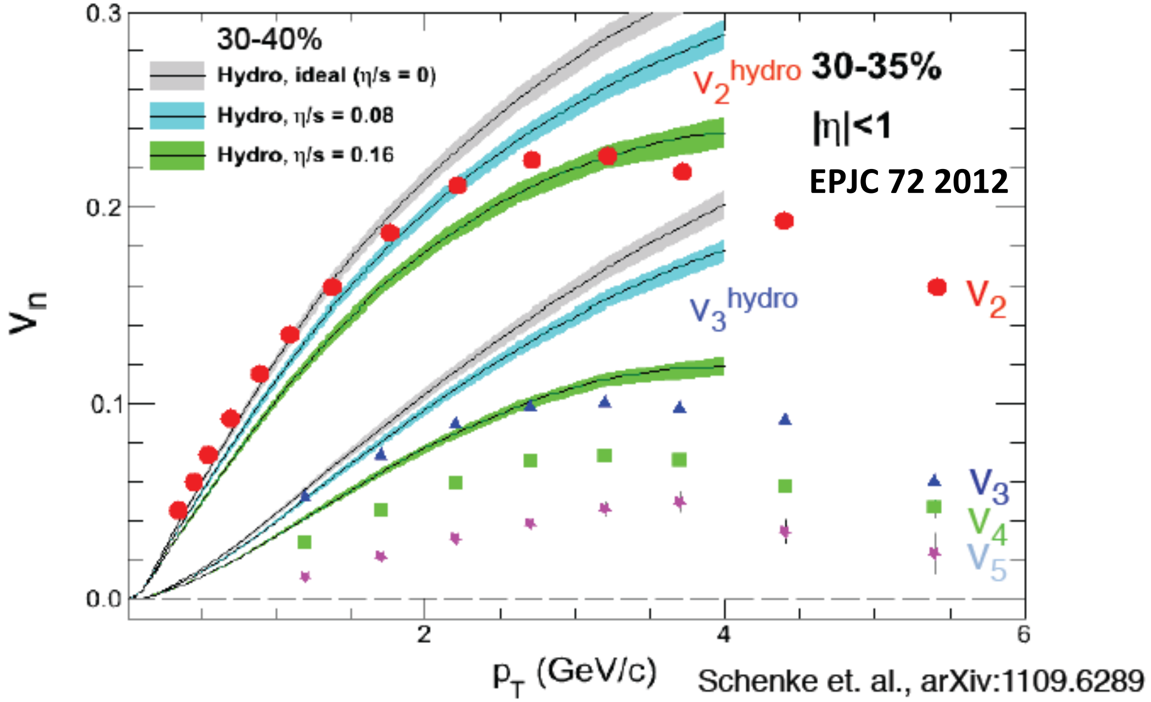
PbPb Ultra-Central Collisions



CMS-PAS-HIN-12-011

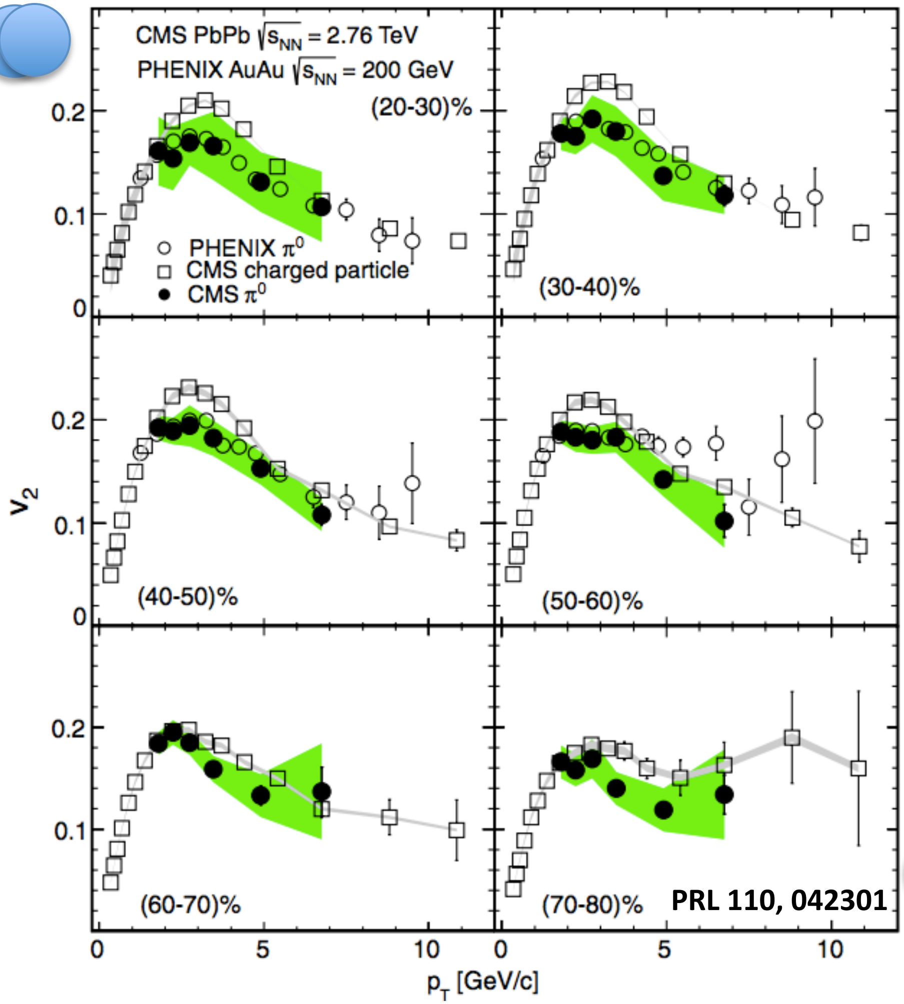
- Top 0.2% PbPb 2.76 TeV
- Purely driven by fluctuations
- Higher order harmonics are strongly excited
- v_3, v_4, v_5 rise above v_2

Full Harmonic Spectra



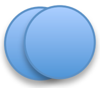
- Measure multiple v_n to over-constrain the hydro calculations
  - η/s (sheer viscosity/entropy)
  - Initial conditions - fluctuations (Glauber vs CGC)

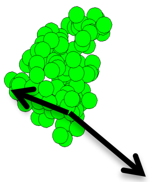
π^0 Elliptic Anisotropy at Intermediate p_T

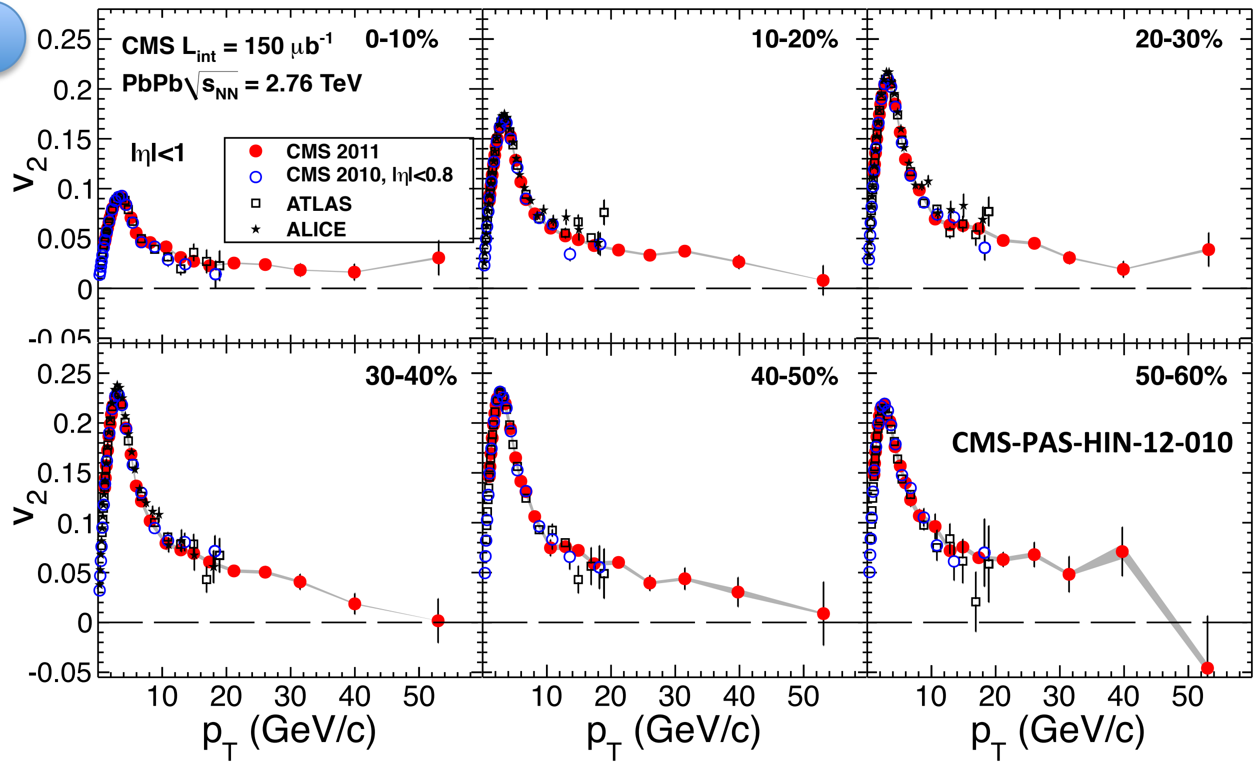


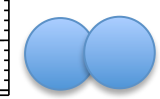
- π^0 reconstructed from $\gamma\gamma$
- Correlated to HF Event-Plane
- 14X increase in energy, no significant change from RHIC
- Charged hadron v_2 higher in central collisions
  - Consistent with higher v_2 for baryons
- No difference in peripheral collisions
  - Consistent with the centrality dependence in the proton/pion ratio with a baryon enhancement both in spectra and v_2

PbPb $v_2(p_T)$ Results at High-p_T



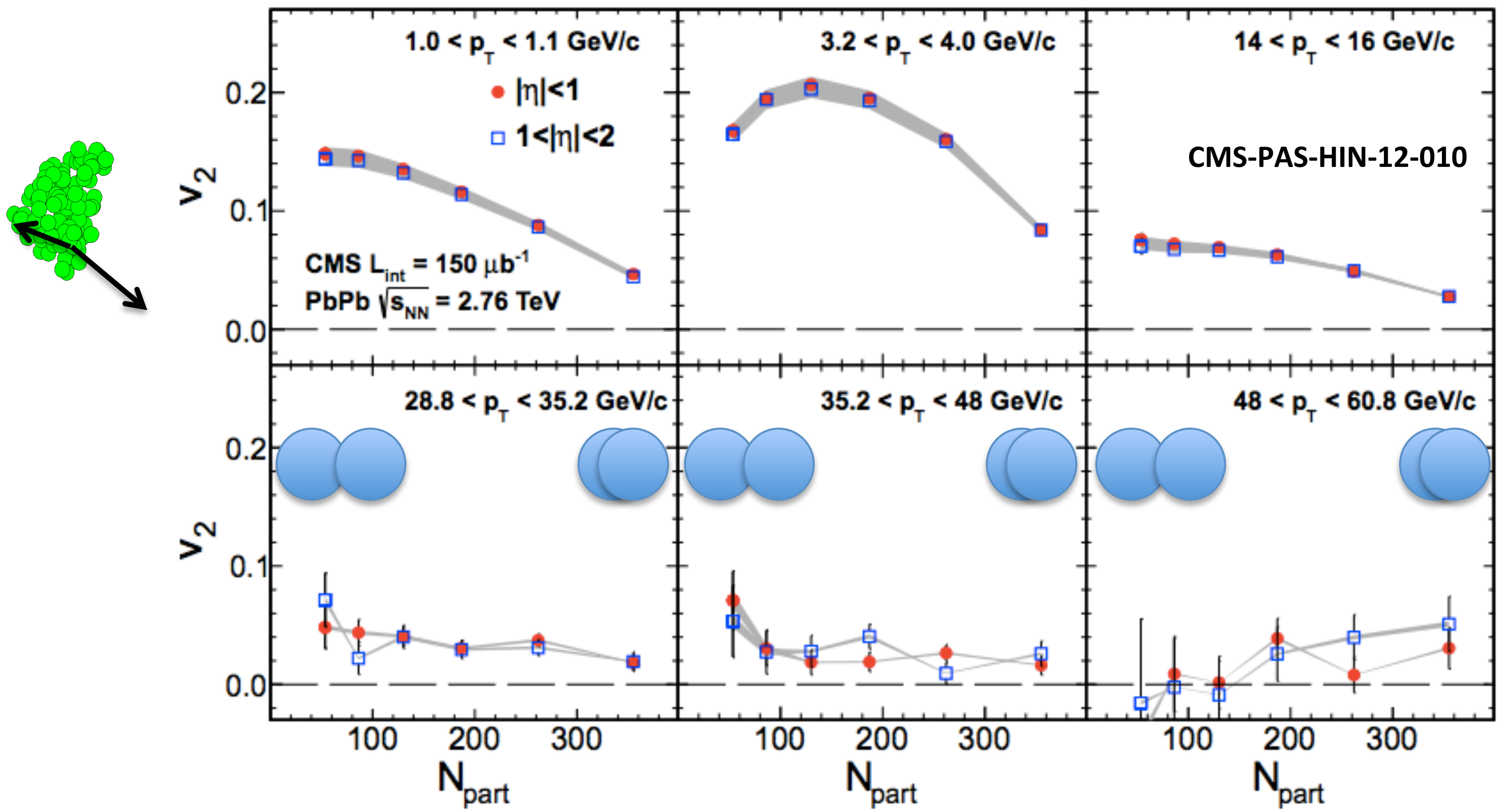






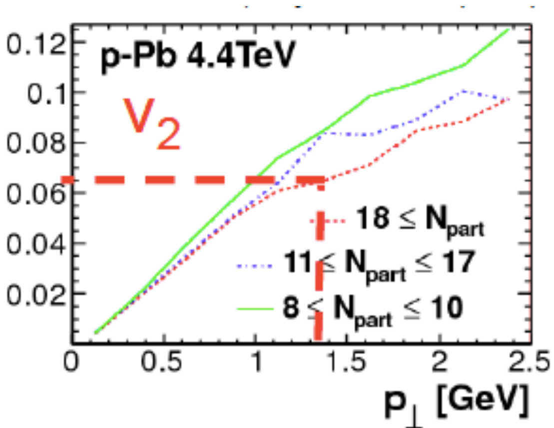
- v_2 azimuthal anisotropy up to p_T~60 GeV/c
- v_2 gradually decreases above p_T>10 GeV/c
- Data can constrain different theoretical scenarios

PbPb $v_2(N_{part})$ Results at High-p_T

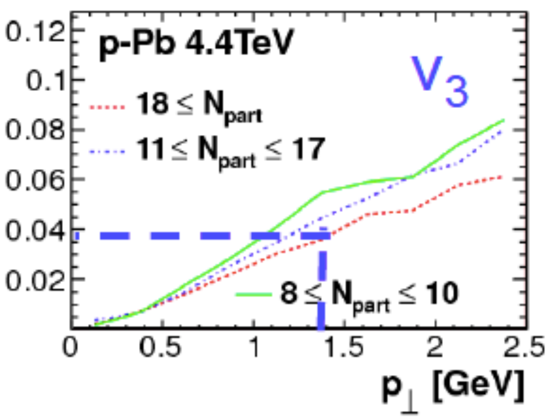


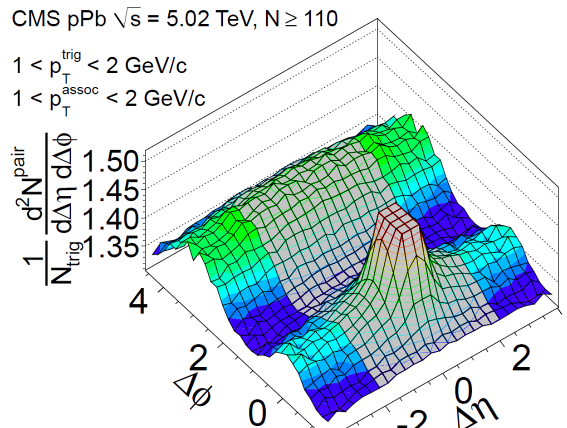
- v_2 at high-p_T depends on geometry
- v_2 at high-pT remains finite up to 40 GeV/c

pPb Di-Hadron Correlation Results



P.Bozek, PRC 85 014911





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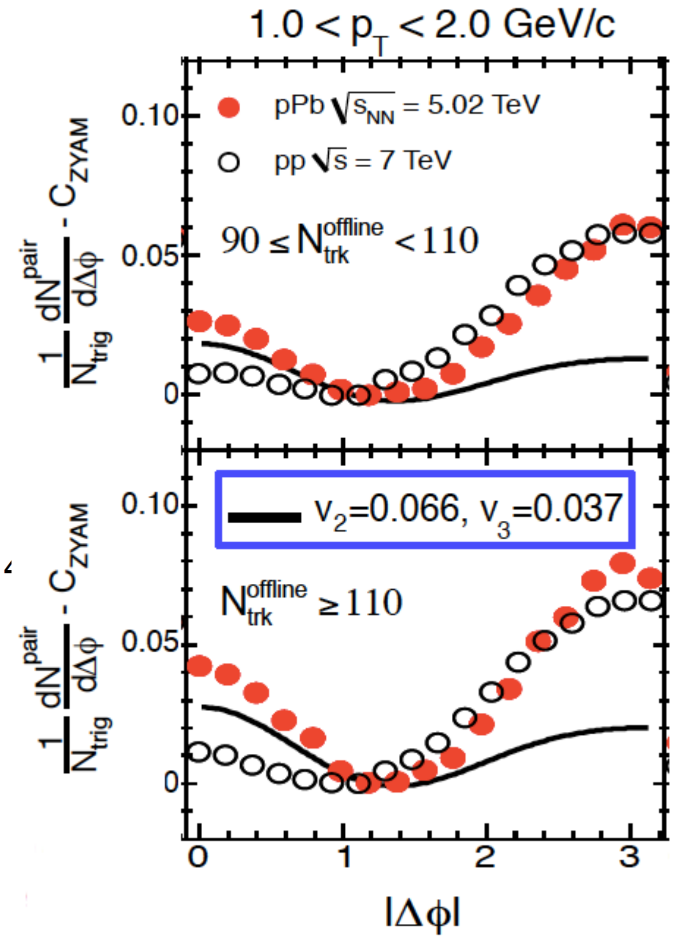

Viscous hydrodynamics calculation in pPb

Open question: Is hydro still valid in such small system and life time?

Summary

- at low-p_T $v_n(p_T)$ are sensitive to the initial state fluctuations and the property of the medium (η/s)
- π^0 $v_2(p_T)$ is the same as RHIC, and is also particle species dependent
- First high-p_T (>20 GeV/c) v_2 measurement, sensitive to path length dependent of parton energy loss
- First hydro-like correlation in pPb collisions at 5.02 TeV