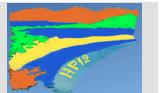


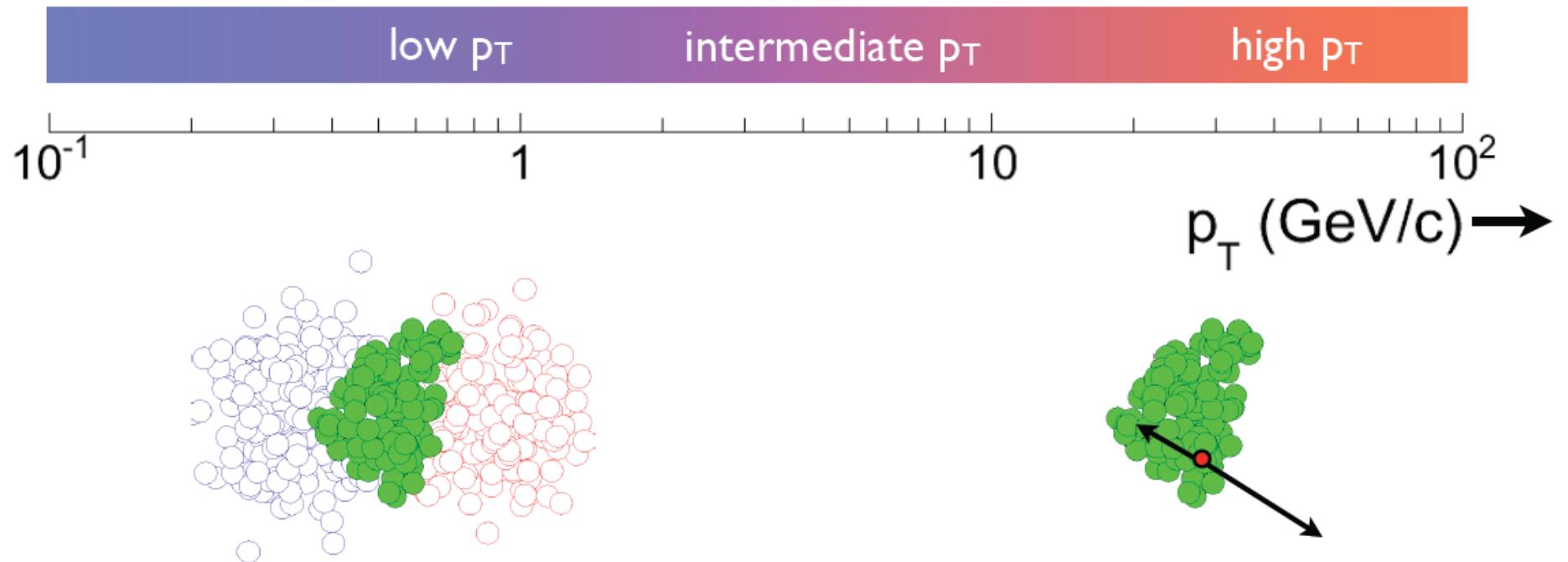
# Hadron Correlations in CMS

Charles F. Maguire  
Vanderbilt University

On behalf of the CMS Collaboration



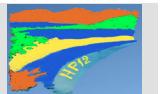
# Azimuthal Correlations in CMS



Hydrodynamic flow  
driven by asymmetric  
pressure gradients

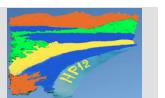
Soft-hard  
interplay  
recombination

Path-length  
dependent  
energy loss

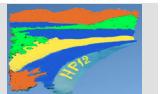
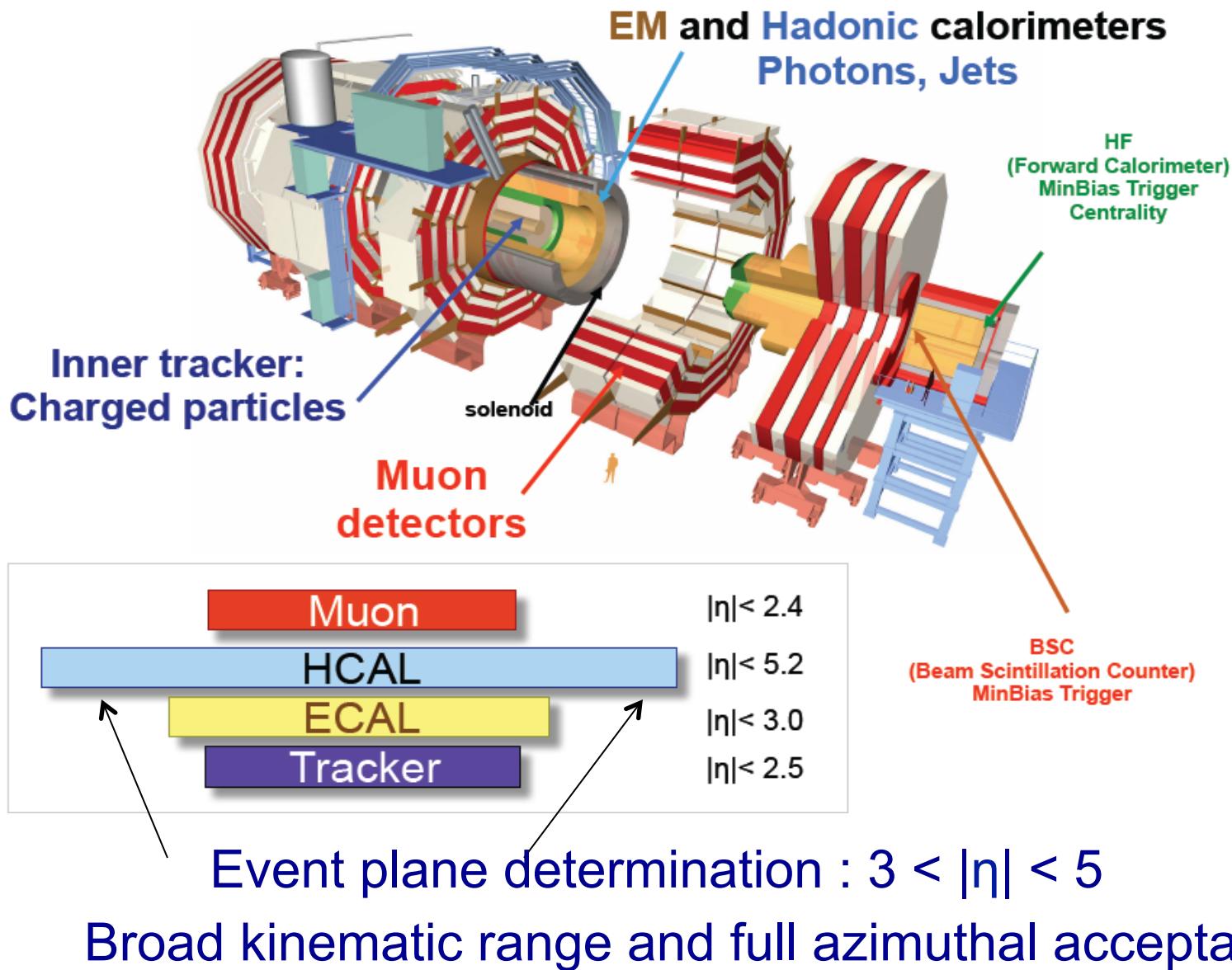


# Physics Motivation and Tools

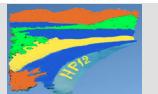
- **Measure the Anisotropic Asymmetry to Address**
  - EoS, Opacity, and Viscosity of the Medium
  - Role of Fluctuations and Initial State
  - Particle production mechanisms and degrees of freedom
  - More details in parallel talks given yesterday in session IC by Victoria Zhukova and Rylan Conway
- **Use Multiple Methods For Elliptic Flow Determination**
- **Study Single and Particle-Pair Correlations**
  - Anisotropies of higher order harmonics are investigated and compared
- **Look at the  $v_2$  of an Identified Hadron: the  $\pi^0$**



# The CMS Detector



# Correlations in the bulk system (low $p_T$ )

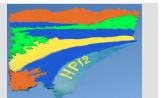
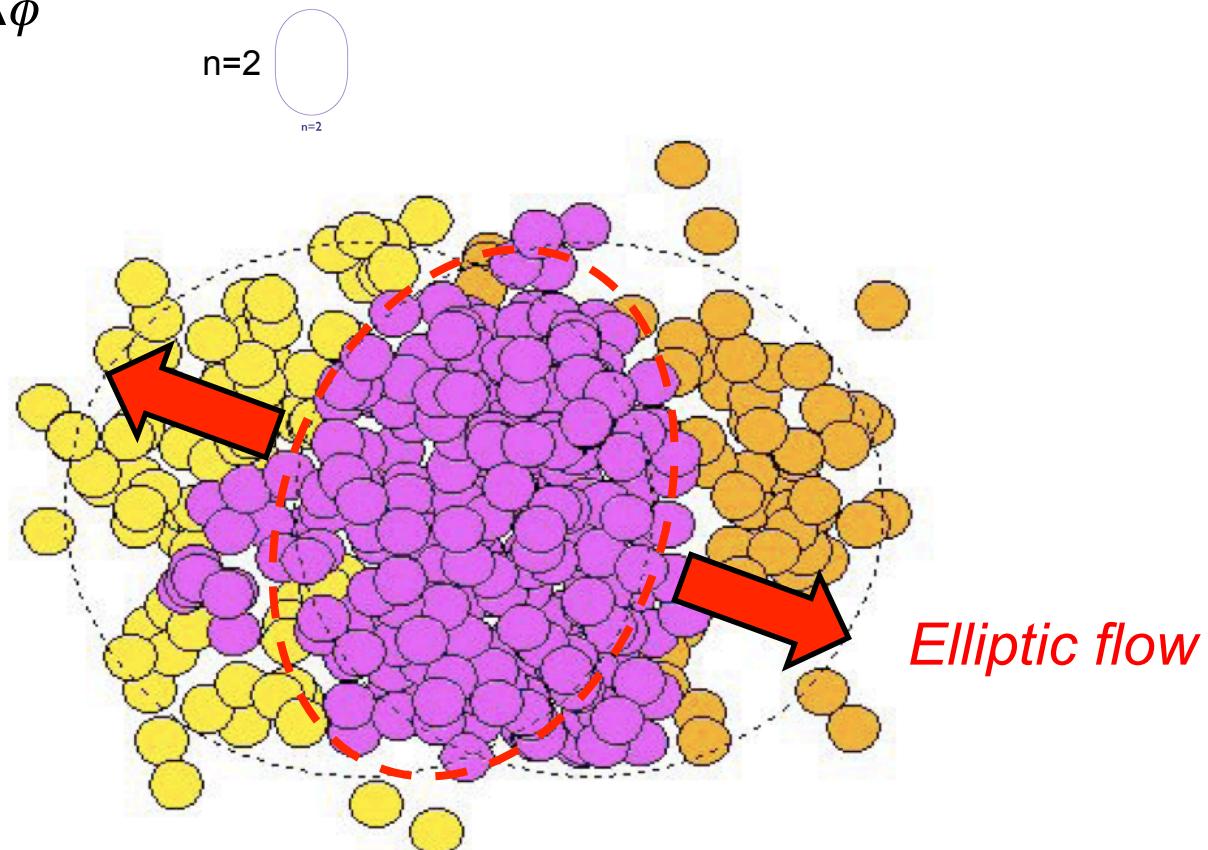


# Hydro flow with Fluctuating Initial Conditions

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

**Elliptic flow**

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

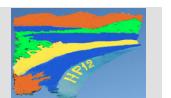
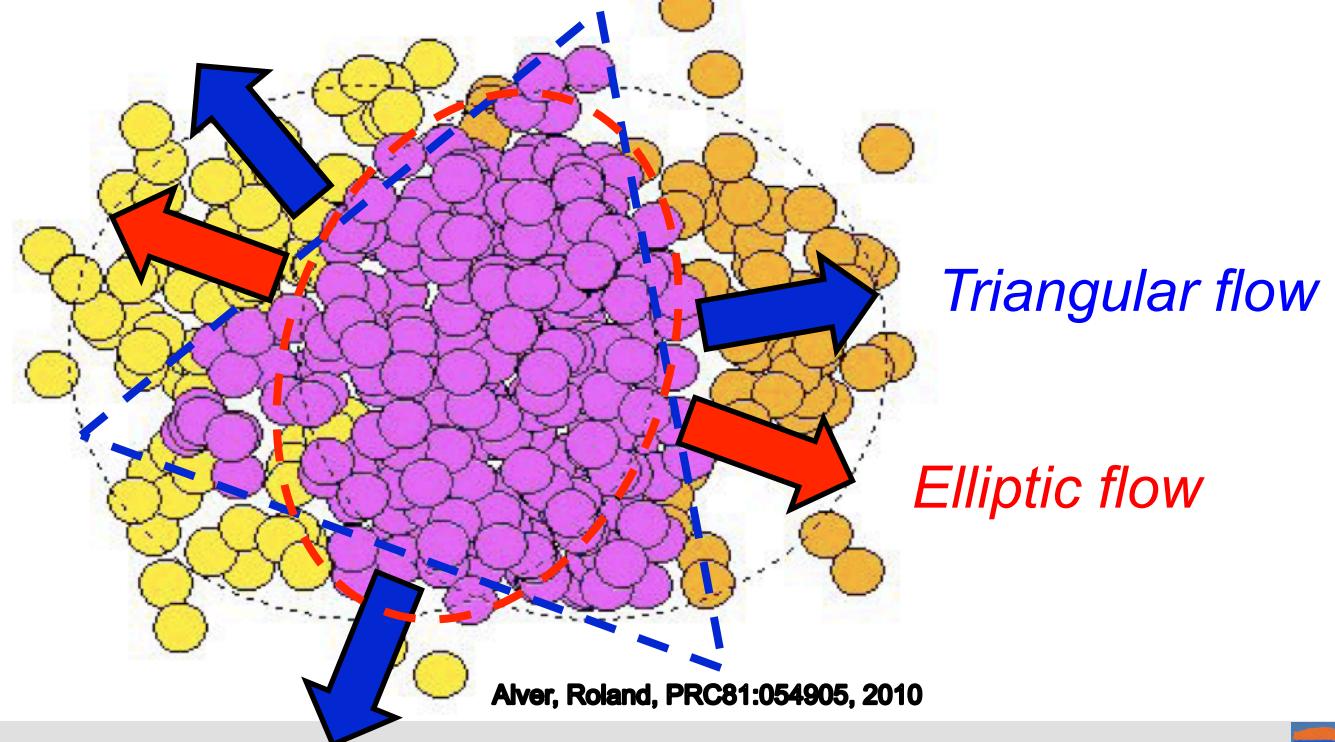
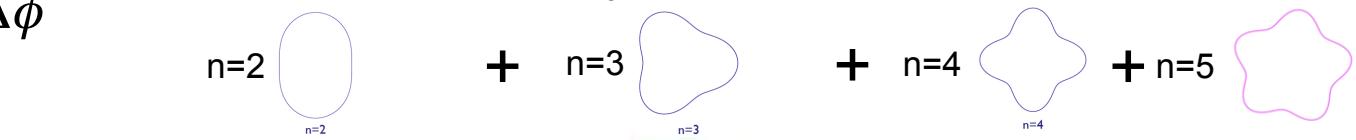


# Hydro flow with Fluctuating Initial Conditions

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

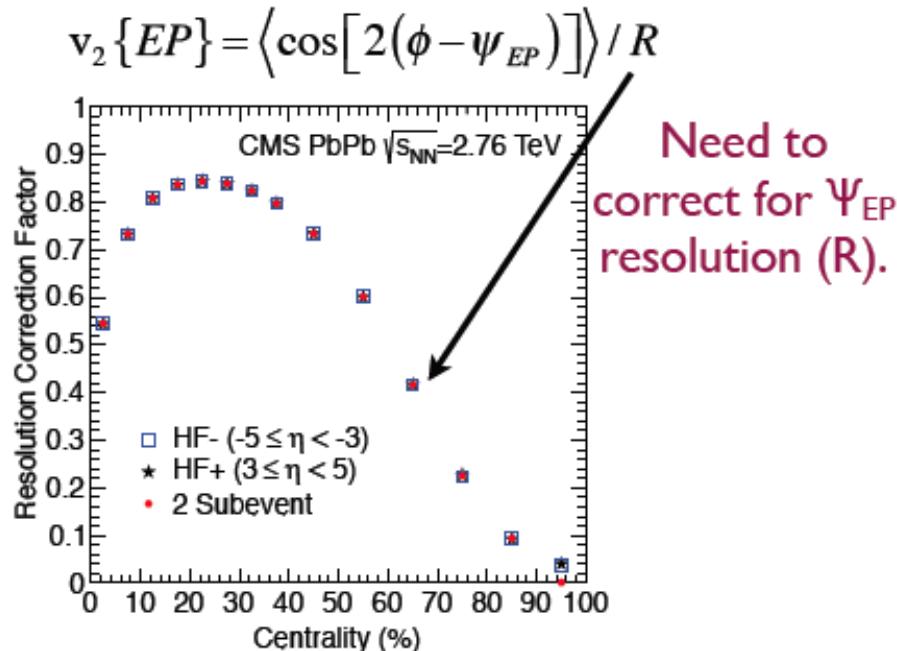
Elliptic flow              Triangular flow

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



# Charged Particle $v_2$ Extraction Methods

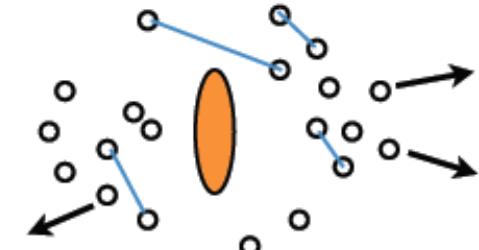
## Event Plane



## Two-particle Cumulant

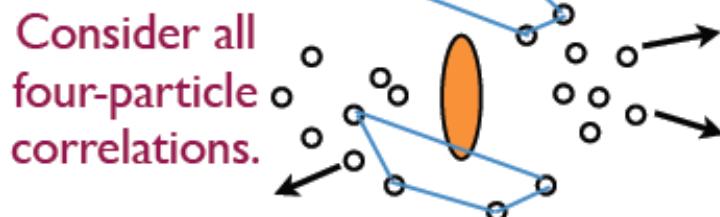
$$v_2\{2\} = \sqrt{\langle \cos[2(\phi_1 - \phi_2)] \rangle}$$

Consider all two-particle correlations.



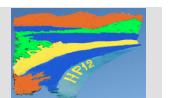
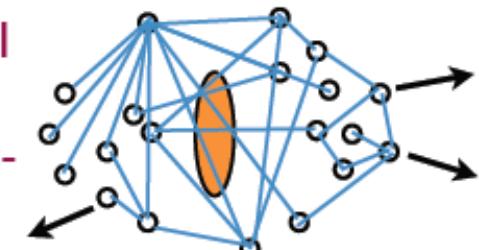
## Four-particle Cumulant

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



## Lee-Yang Zeros

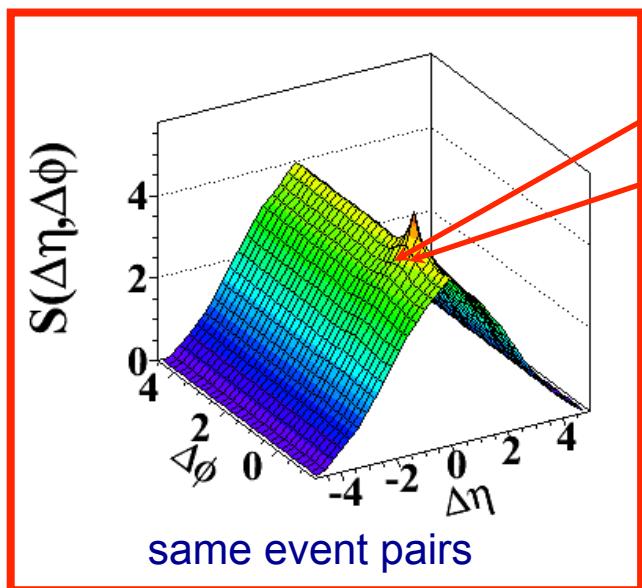
Consider all particle correlations- (Not all shown!).



# Di-hadron Correlations in CMS

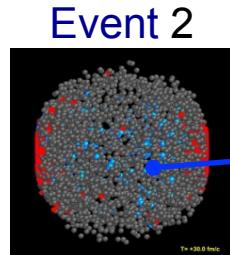
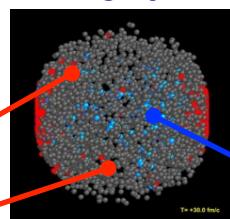
Signal distribution:

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



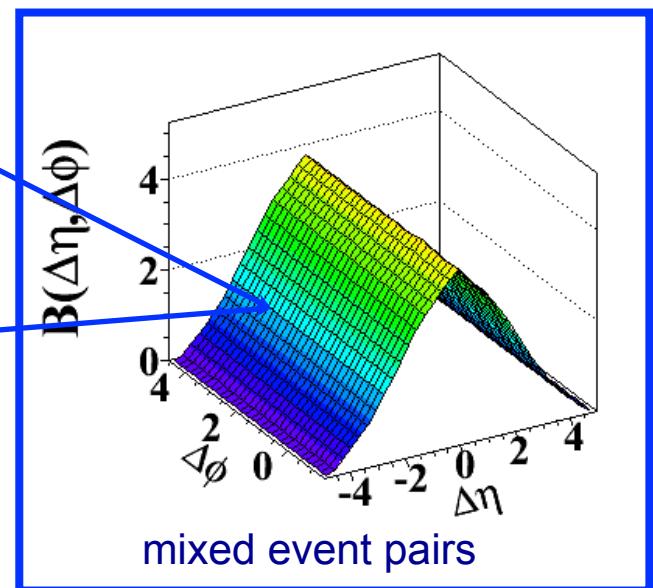
Particle 1: trigger

Particle 2: associated  
Event 1



Background distribution:

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

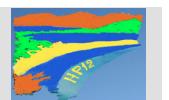


$$\Delta\eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$$

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

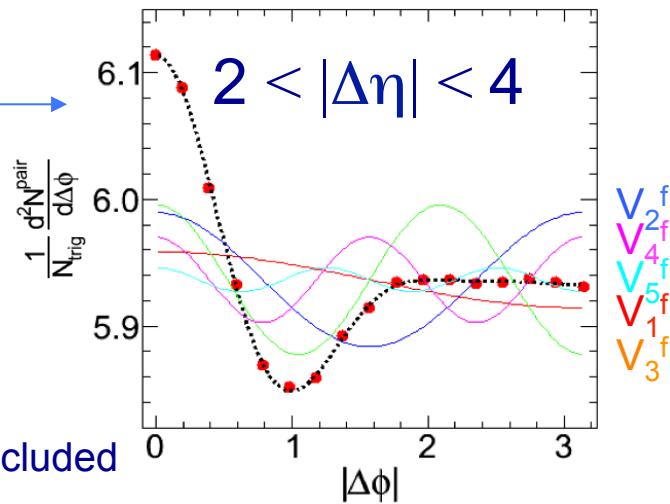
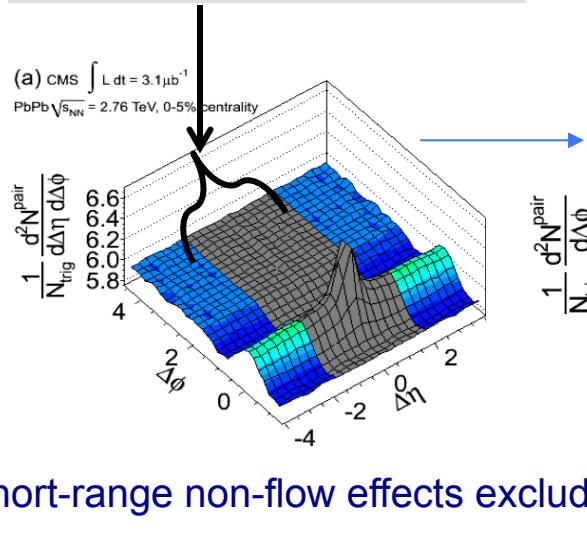
Associated hadron yield per trigger:

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



# Fourier Analysis of $\Delta\phi$ Correlations

Exclusion region in  $\Delta\eta$



Short-range non-flow effects excluded

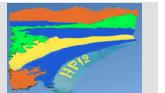
Flow driven correlations:

$$V_n^f = V_n^f(p_T^{\text{trig}}) \times v_n^f(p_T^{\text{assoc}})$$

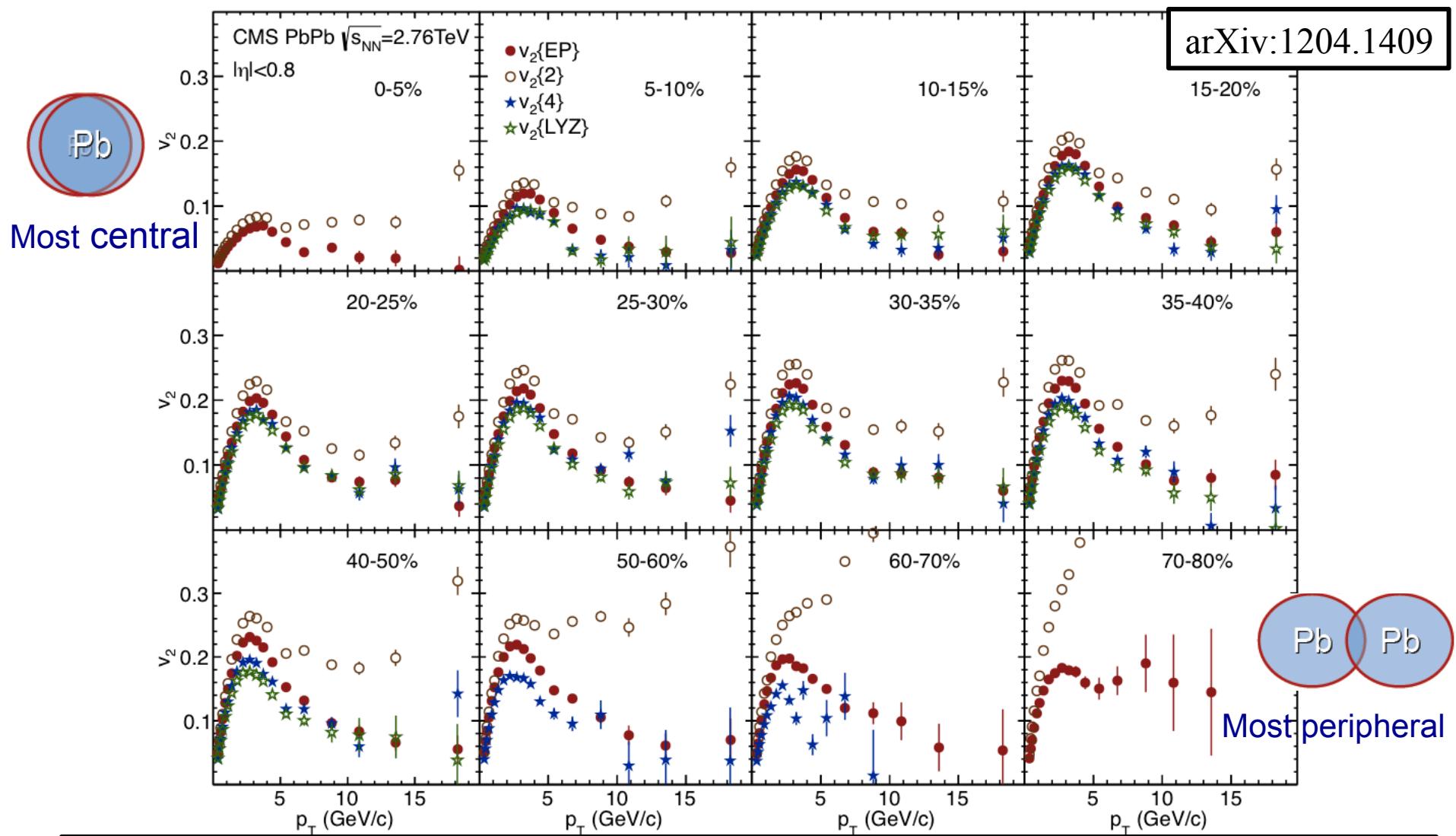
f: Fourier analysis of long range dihadron correlations

Fourier decomposition: 
$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} (1 + 2 \sum_{n=1} V_n^f \cos(n\Delta\phi))$$

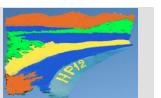
Complementary to standard flow methods (EP, cumulants, LYZ)



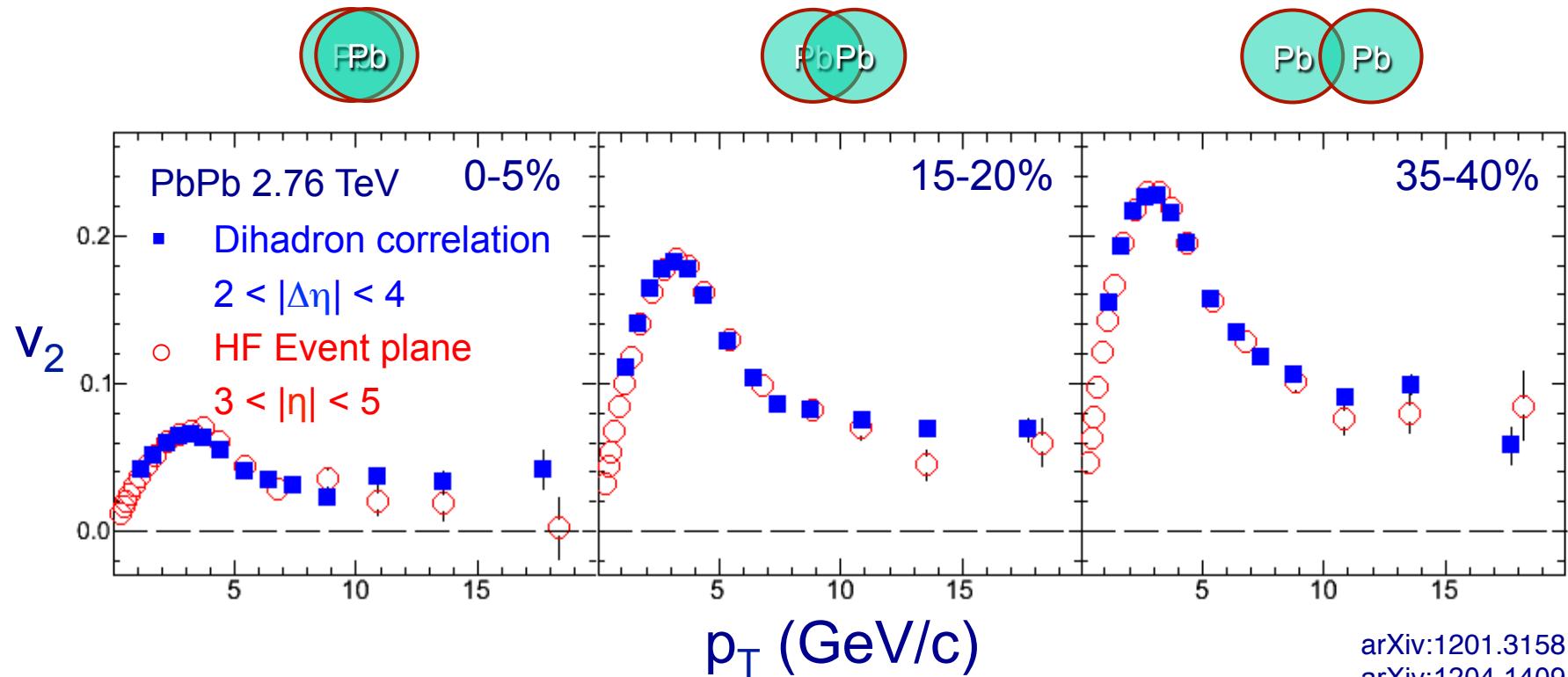
# $v_2(p_T)$ Results Using Different Methods



These  $v_2(p_T)$  CMS results are only slightly larger than the PHENIX results

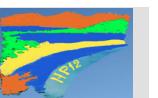


# $v_2$ from Di-hadron Correlations

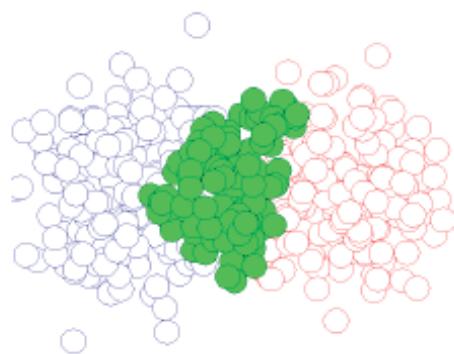


$v_2(p_T)$  from correlation method derived using fixed  $p_T^{\text{assoc}}$  of 1-1.5 GeV/c agrees well with EP method

See parallel talk by Rylan Conway: Monday May 28, Session IC



# Integrated $v_2$ Scaled by Eccentricity



Participant Eccentricity

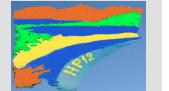
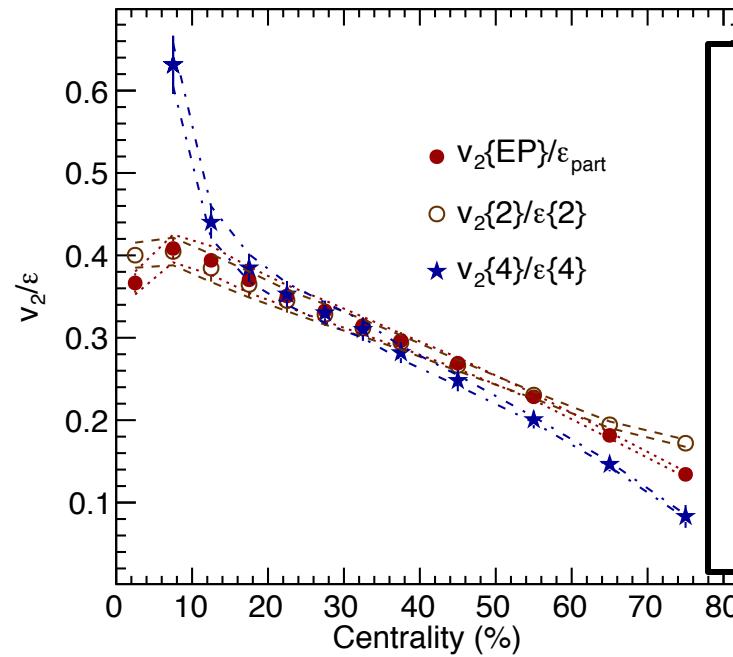
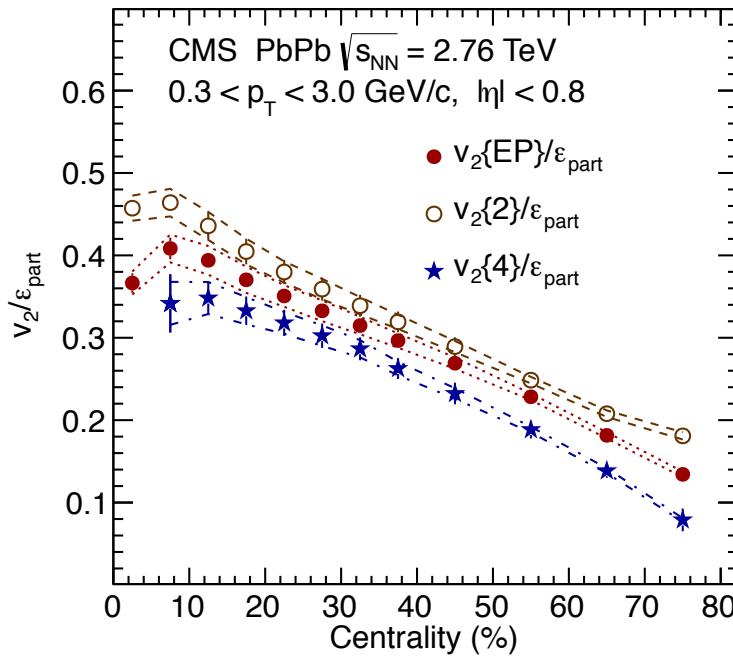
$$\epsilon_{\text{part}} \equiv \sqrt{\frac{(\sigma_{y'}^2 - \sigma_{x'}^2)^2 + 4\sigma_{x'y'}^2}{\sigma_{y'}^2 + \sigma_{x'}^2}}$$

Cumulant Moments

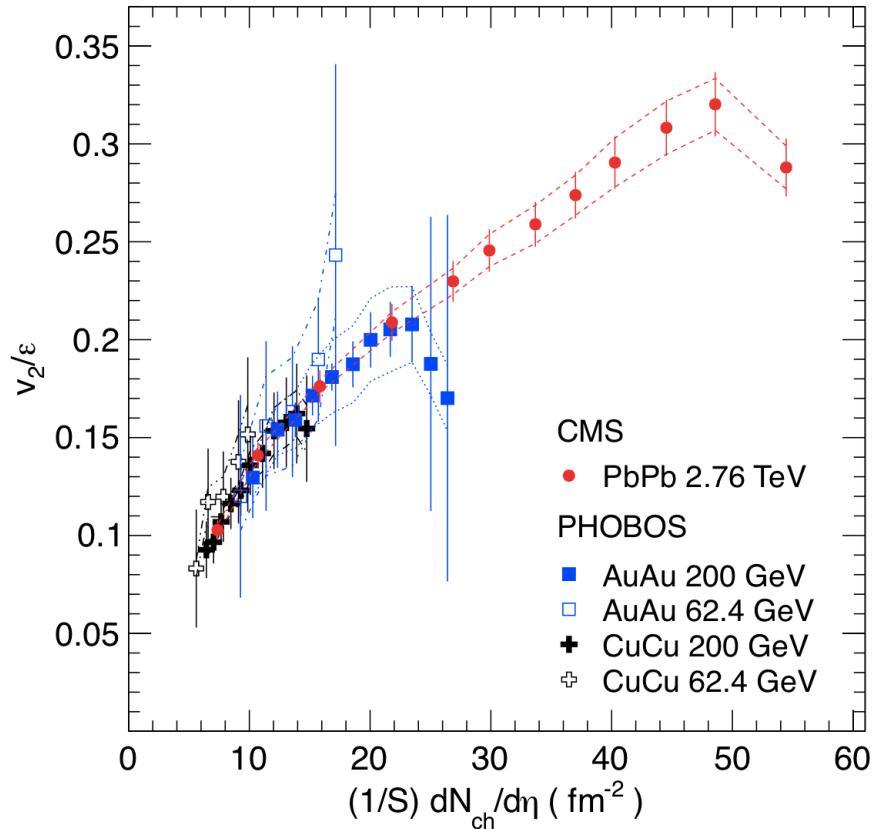
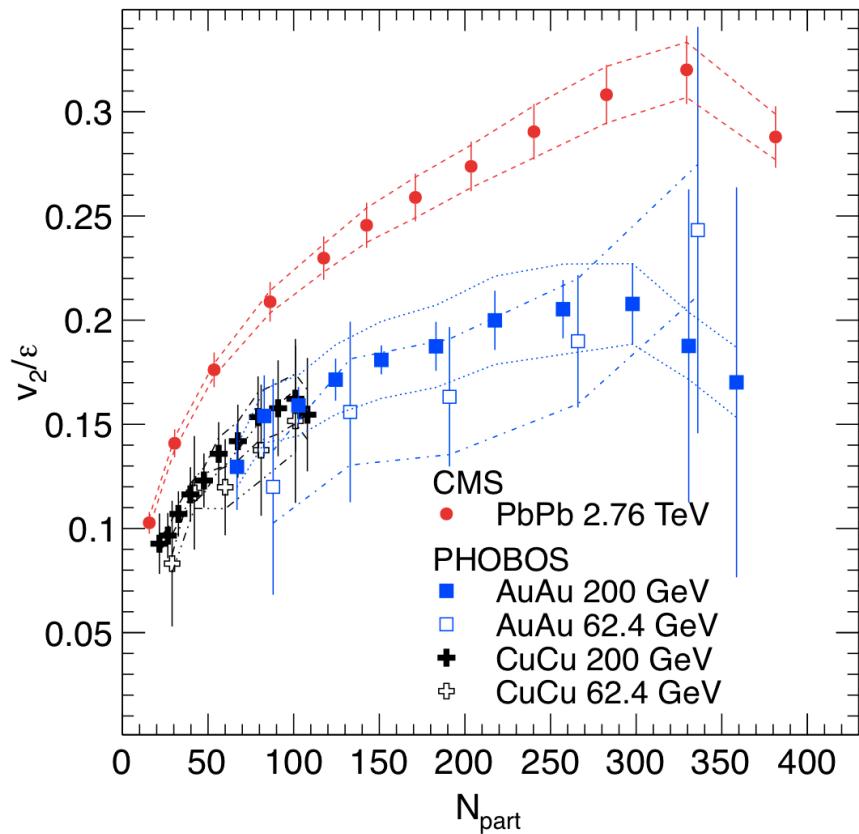
$$\epsilon\{2\}^2 \equiv \langle \epsilon_{\text{part}}^2 \rangle,$$

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

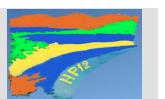
$$\frac{v_2\{2\}}{\epsilon\{2\}} = \frac{v_2\{4\}}{\epsilon\{4\}} \sim \frac{v_2\{\text{EP}\}}{\epsilon_{\text{part}}}$$



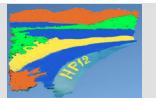
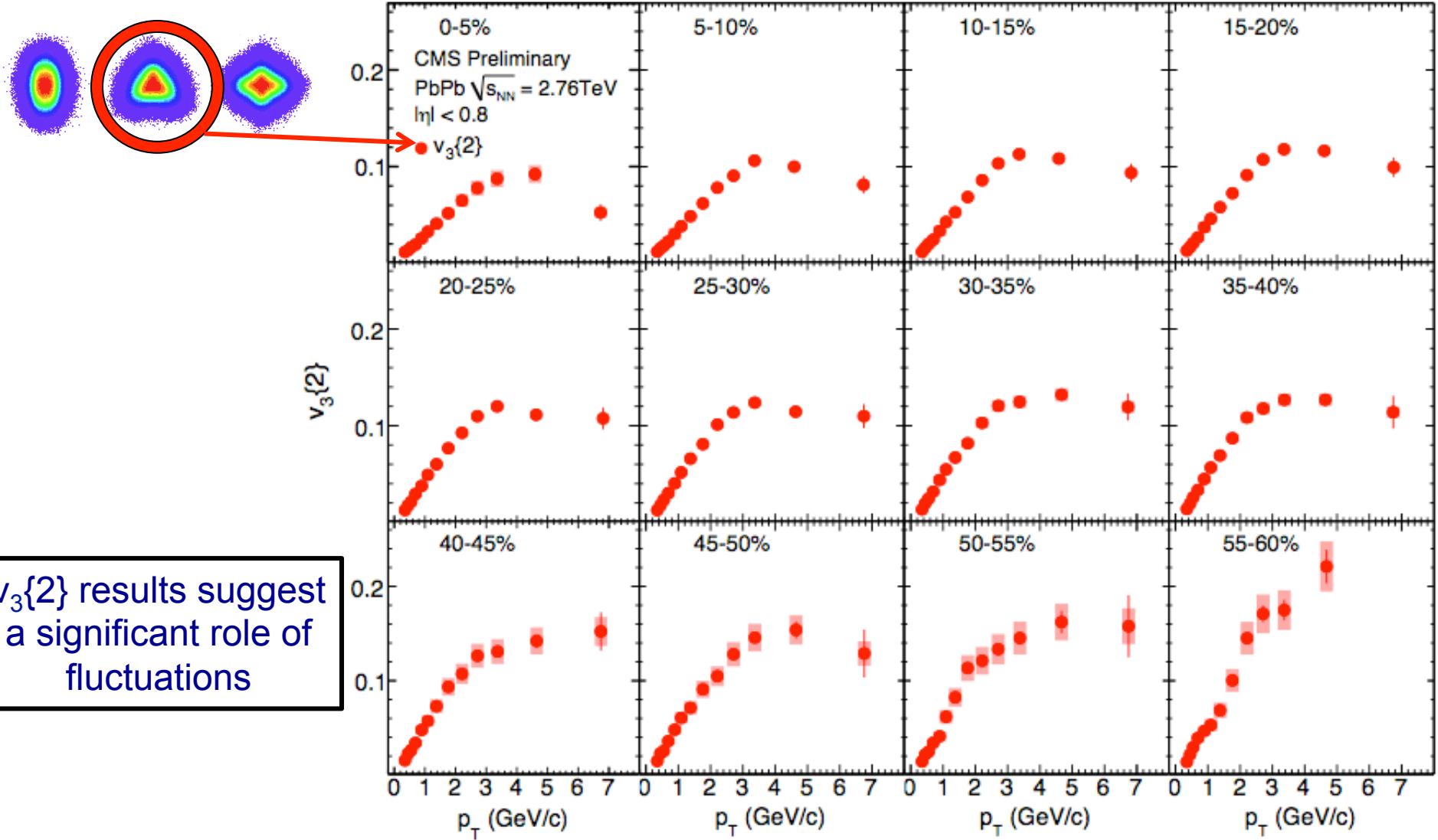
# $\varepsilon$ -scaled Integrated $v_2$ ( $N_{\text{part}}$ and Density Dependence)



$v_2\{\text{EP}\}/\varepsilon_{\text{part}}$  scales with  
particle density

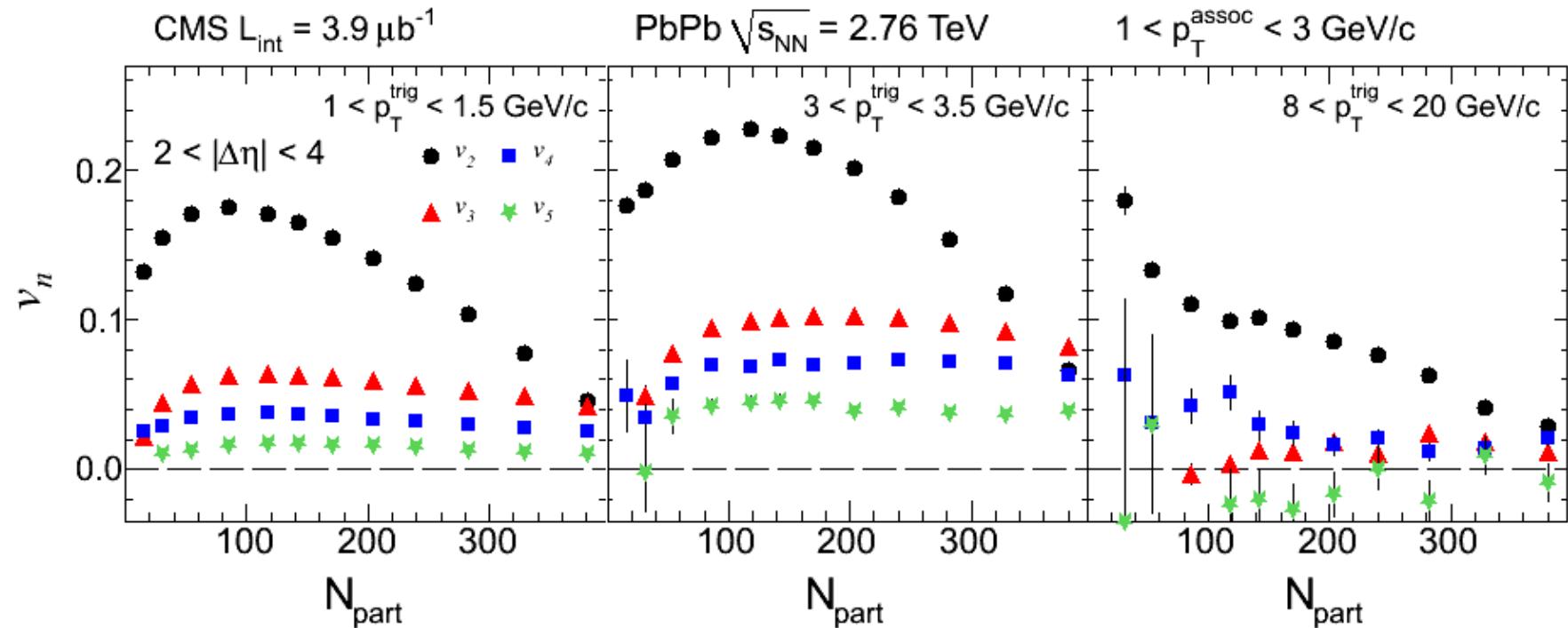


# $v_3$ Flow From Cumulant Analysis

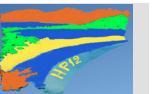


# Higher Harmonics from Di-Hadron Analysis

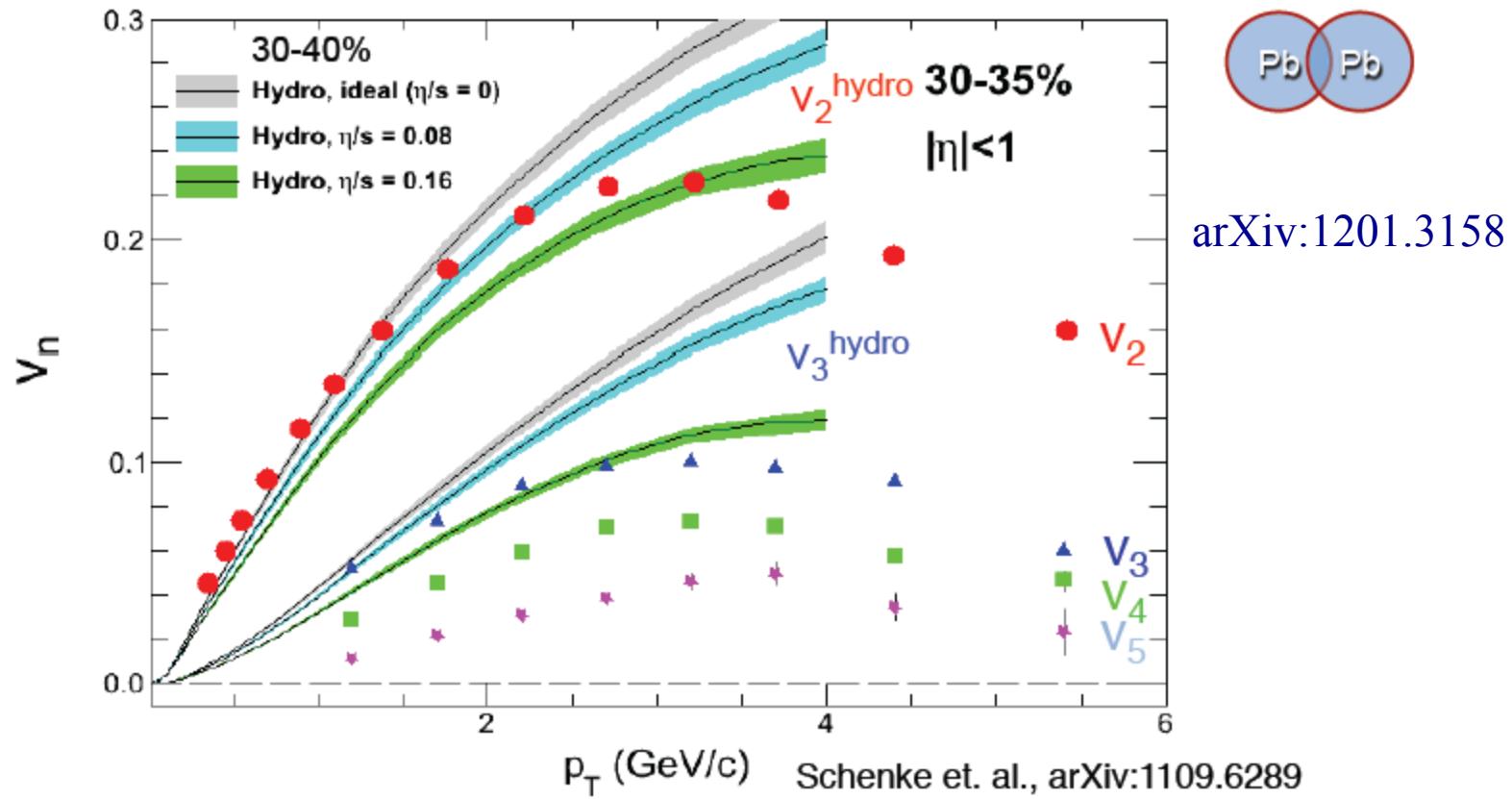
arXiv:1201.3158  
arXiv:1204.1409



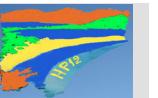
Higher-order coefficients,  $n > 2$ , do not show a significant centrality dependence, which is consistent with fluctuations in the initial collision geometry being the driving force



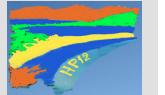
# Extract the Full Harmonic Spectrum ( $v_2, v_3, \dots$ )



- Measure multiple  $v_n$  to over-constrain the hydro calculations
  - $\eta/s$
  - Initial conditions (Glauber vs CGC)

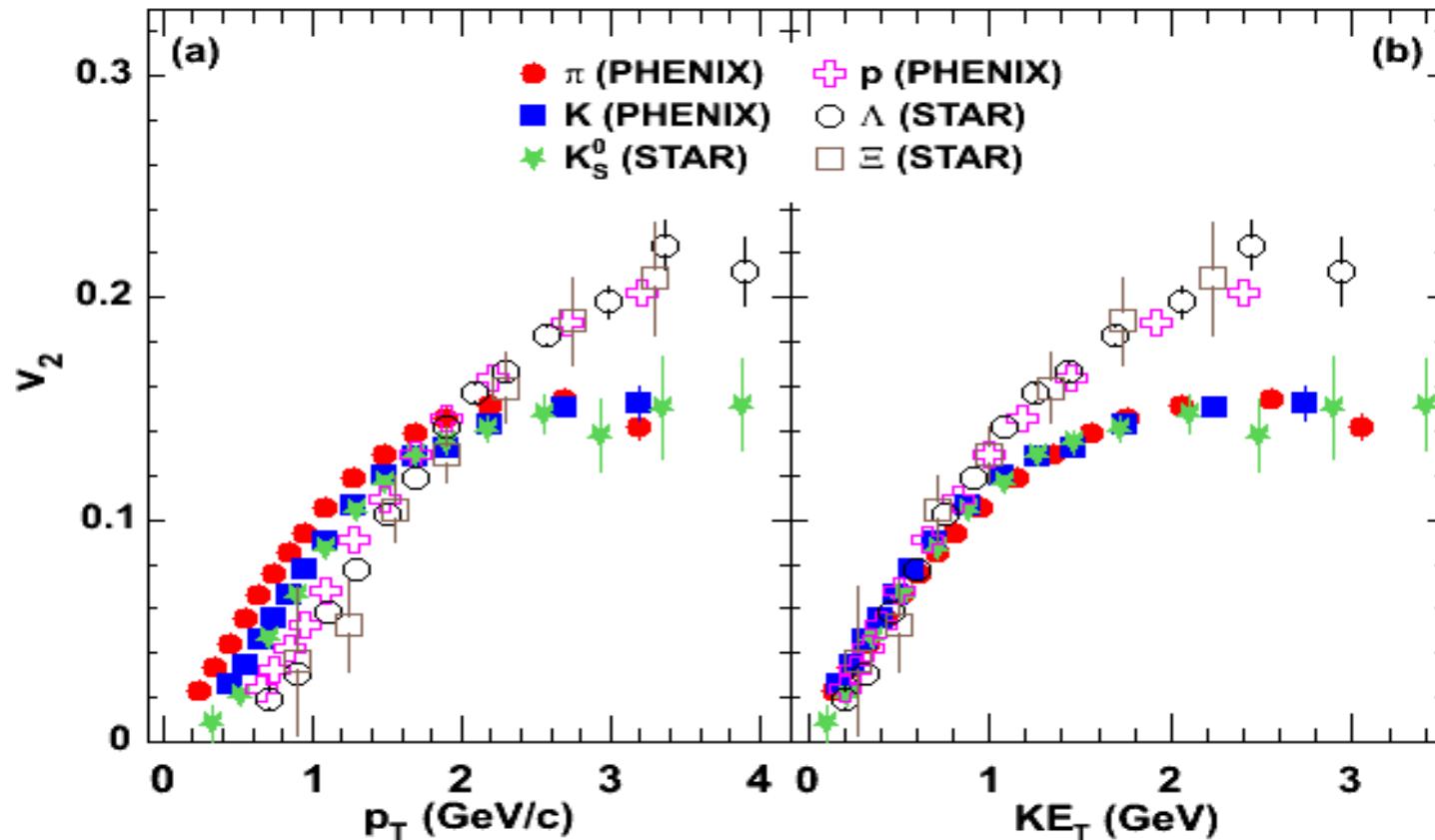


# Identified Hadrons at Intermediate $p_T$



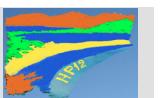
# Baryon vs meson $v_2$ (Result from RHIC)

PHENIX Collaboration: Phys. Rev. Lett. 98, 162301 (2007)

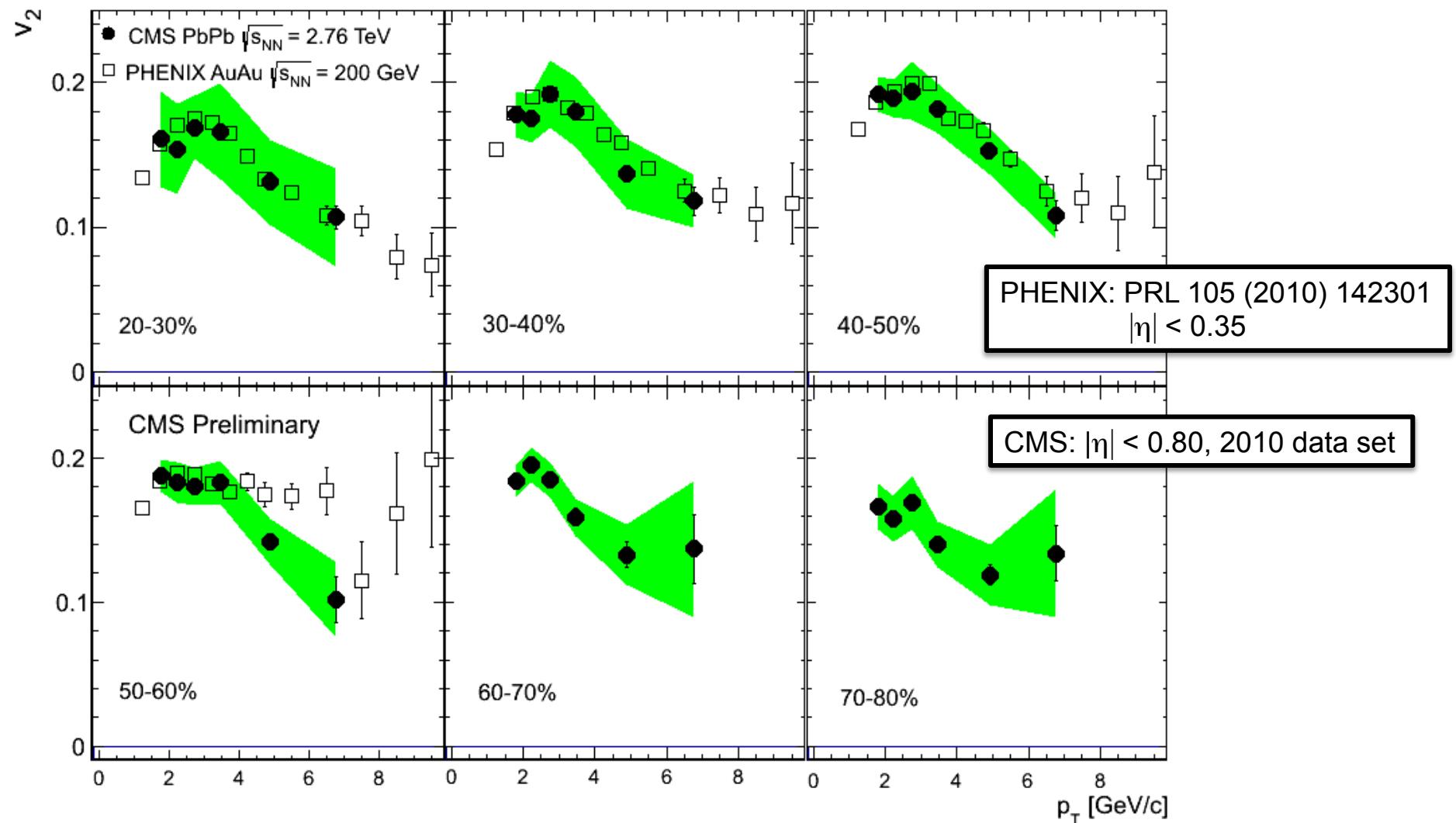


At RHIC baryons have a larger  $v_2$  than mesons at intermediate  $p_T$

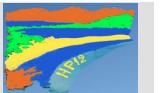
In CMS we can study  $\pi^0$   $v_2$  in comparison to unidentified charged hadrons



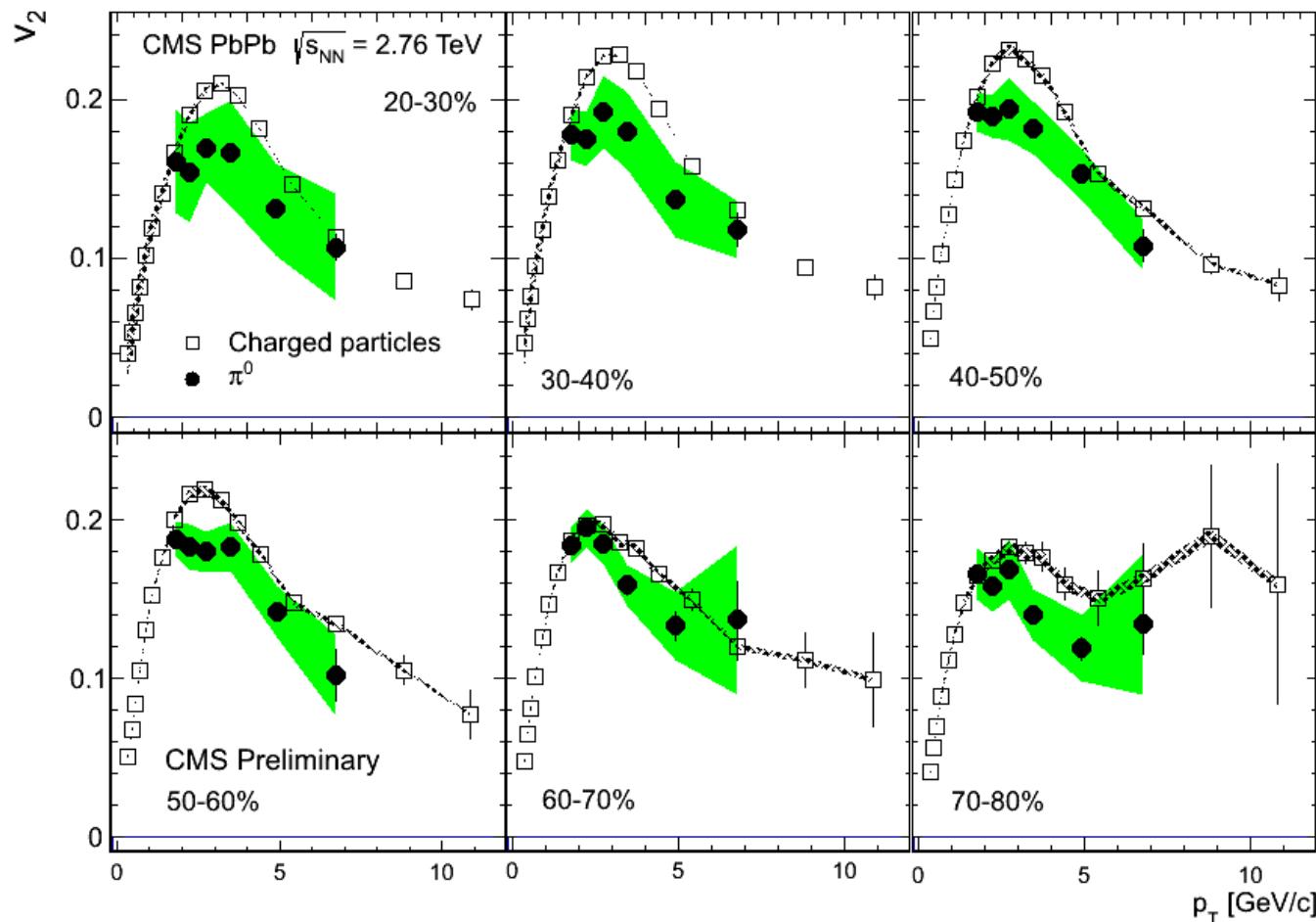
# CMS $\pi^0 v_2$ Results Compared to PHENIX $\pi^0 v_2$



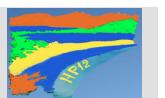
No change in  $v_2$  despite a factor of 14 increase in  $\sqrt{s_{NN}}$



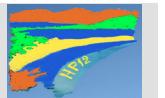
# $\pi^0 v_2$ Compared to Inclusive Charged Particles $v_2$



Differences in  $v_2$  of  $\pi^0$  and charged particles  
may be attributed to baryon contribution

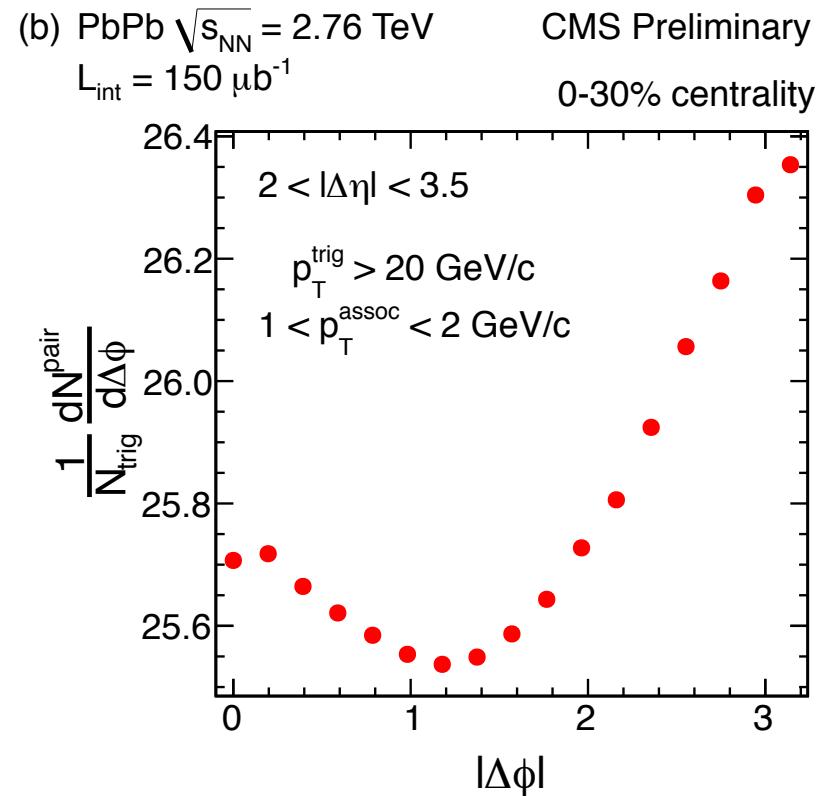
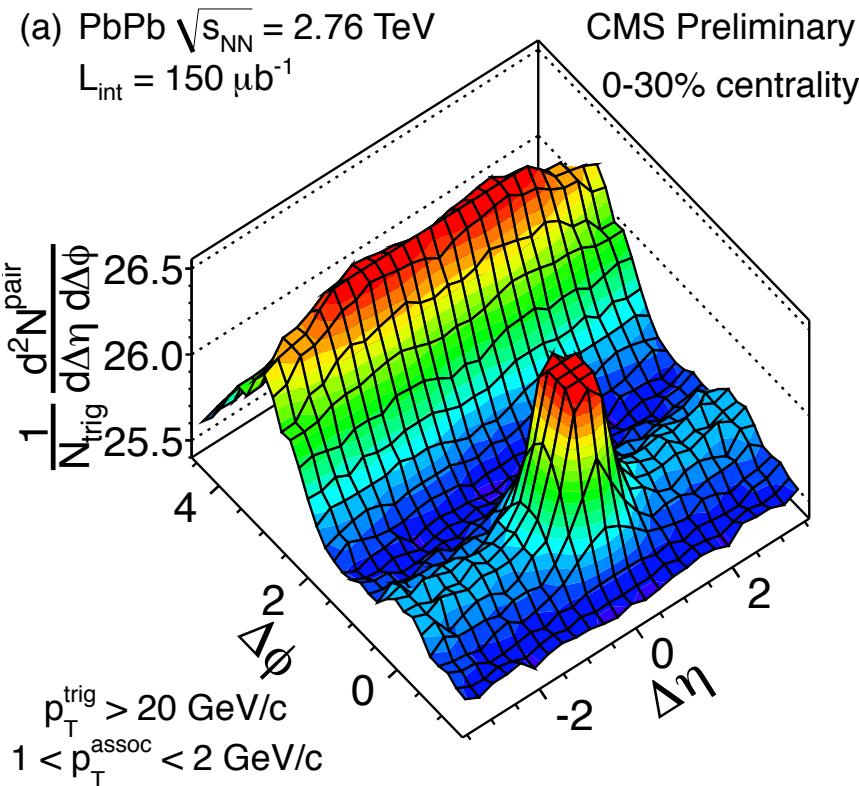


# Correlations at High $P_T$



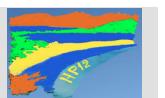
# Azimuthal Pair Correlations at High $p_T$

Di-hadron analysis shows that there are strong pair correlations at high  $p_T$

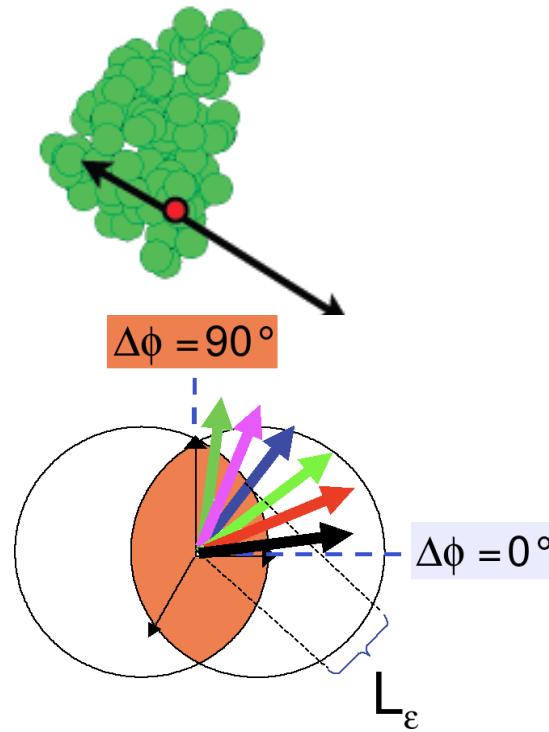


- 1) (Truncated) peak at  $\Delta\eta = \Delta\phi = 0$  from jets/decays
- 2) Away side ridge from jets or flow
- 3) Near side ridge from flow and ...

Azimuthal pair correlation in central events after excluding the  $|\Delta\eta| < 2$  region



# Azimuthal Dependence of High- $p_T$ Particles

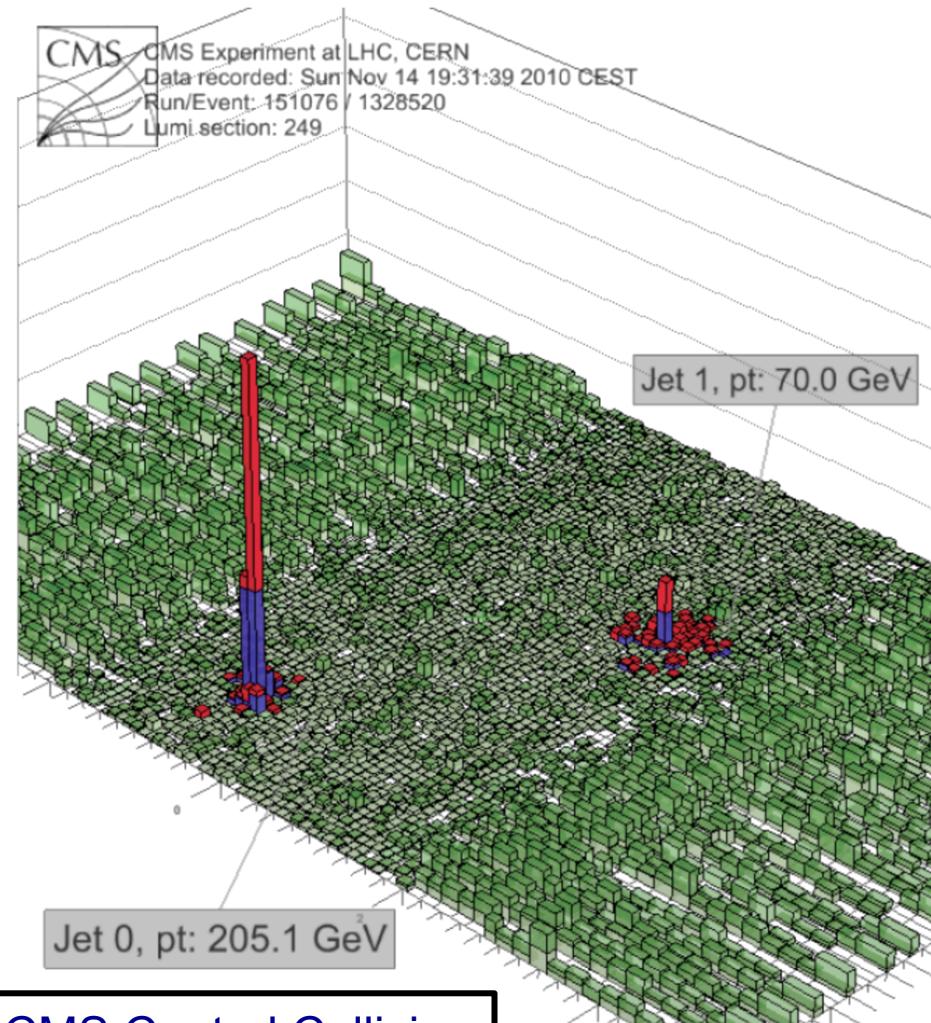


$$\Delta E \sim L^\alpha:$$

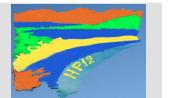
$\alpha = 1$  for QCD, collisional

$\alpha = 2$  for QCD, radiative

$\alpha = 3$  for AdS/CFT

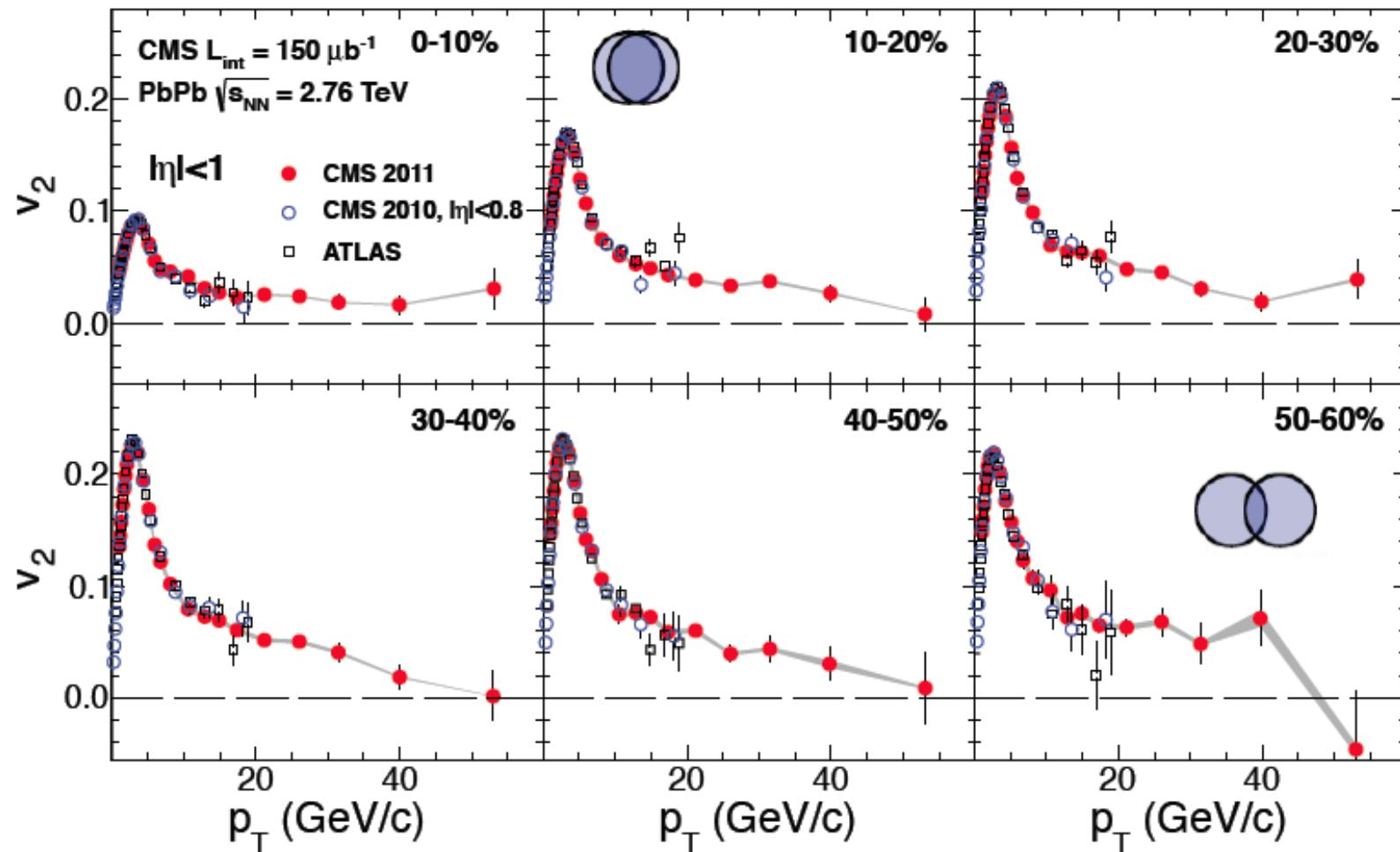


CMS Central Collision  
Dijet Example

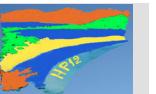


# Azimuthal Dependence of High- $p_T$ Particles

arXiv:1204.1850

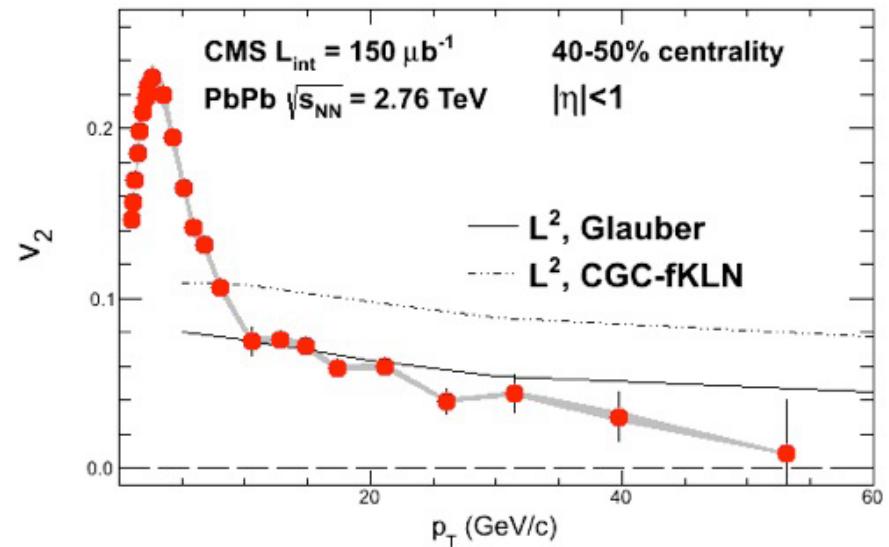
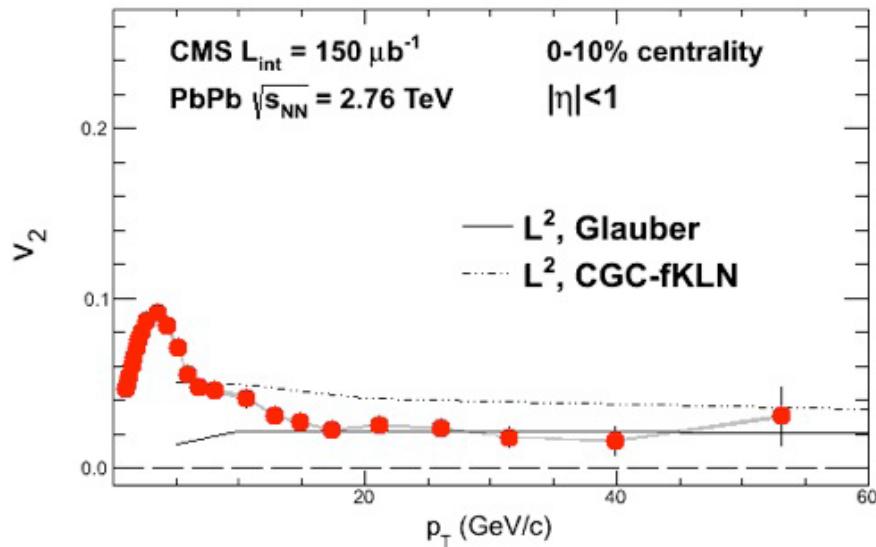


First  $v_2$  measurements for  $p_T > 20 \text{ GeV}/c$   
Gradual decrease of  $v_2$  above  $10 \text{ GeV}/c$



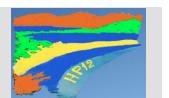
# Theory Comparison

Theory: B. Betz, M. Gyulassy, arXiv:1201.0281



Data can constrain different theoretical scenarios  
However, a lot of complications in modeling still need to  
be addressed (e.g., expansion of the system)

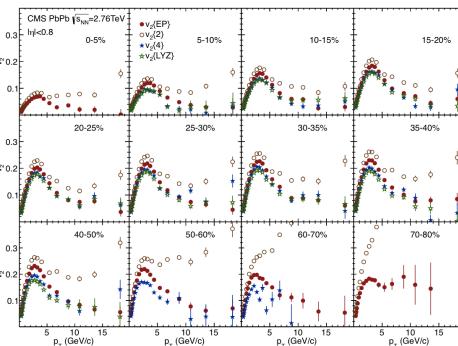
See parallel talk by Victoria Zhukova: Monday May 28, Session IC



# Summary Highlights

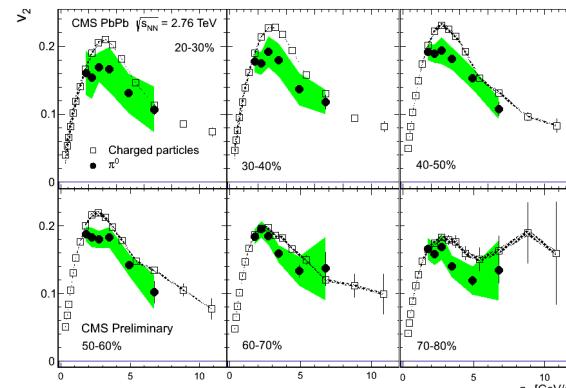
low  $p_T$

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



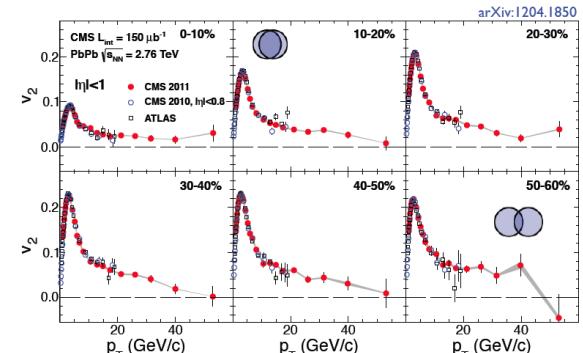
intermediate  $p_T$

$\pi^0 v_2(p_T)$  has same values as at RHIC, and  $v_2$  is also particle species dependent

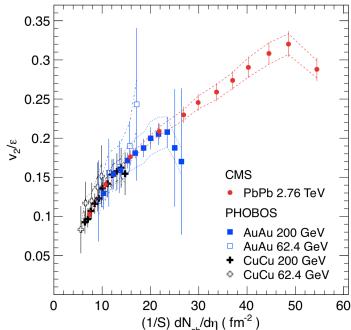


high  $p_T$

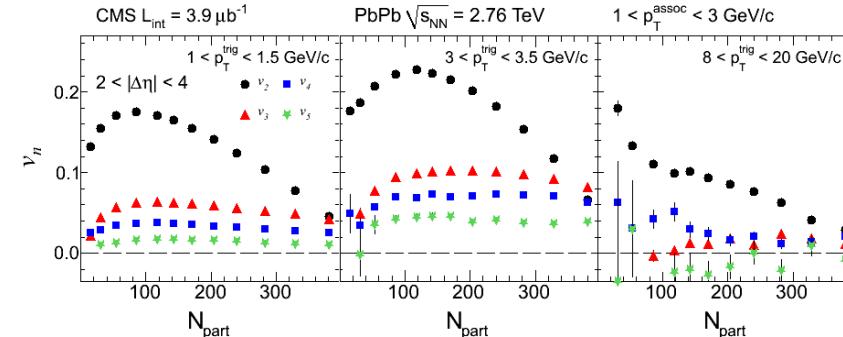
First  $v_2$  measurements at  $p_T > 20$  GeV/c



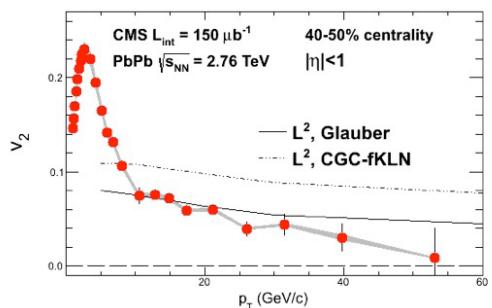
$v_2\{\text{EP}\} / \varepsilon_{\text{part}}$  scales with particle density over very large beam energy range.



Dihadron higher order  $v_n$  give new insights into sQGP



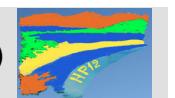
High  $p_T v_2$  results may constrain jet quenching models



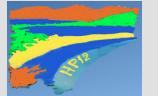
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## Back-up Slides

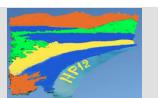
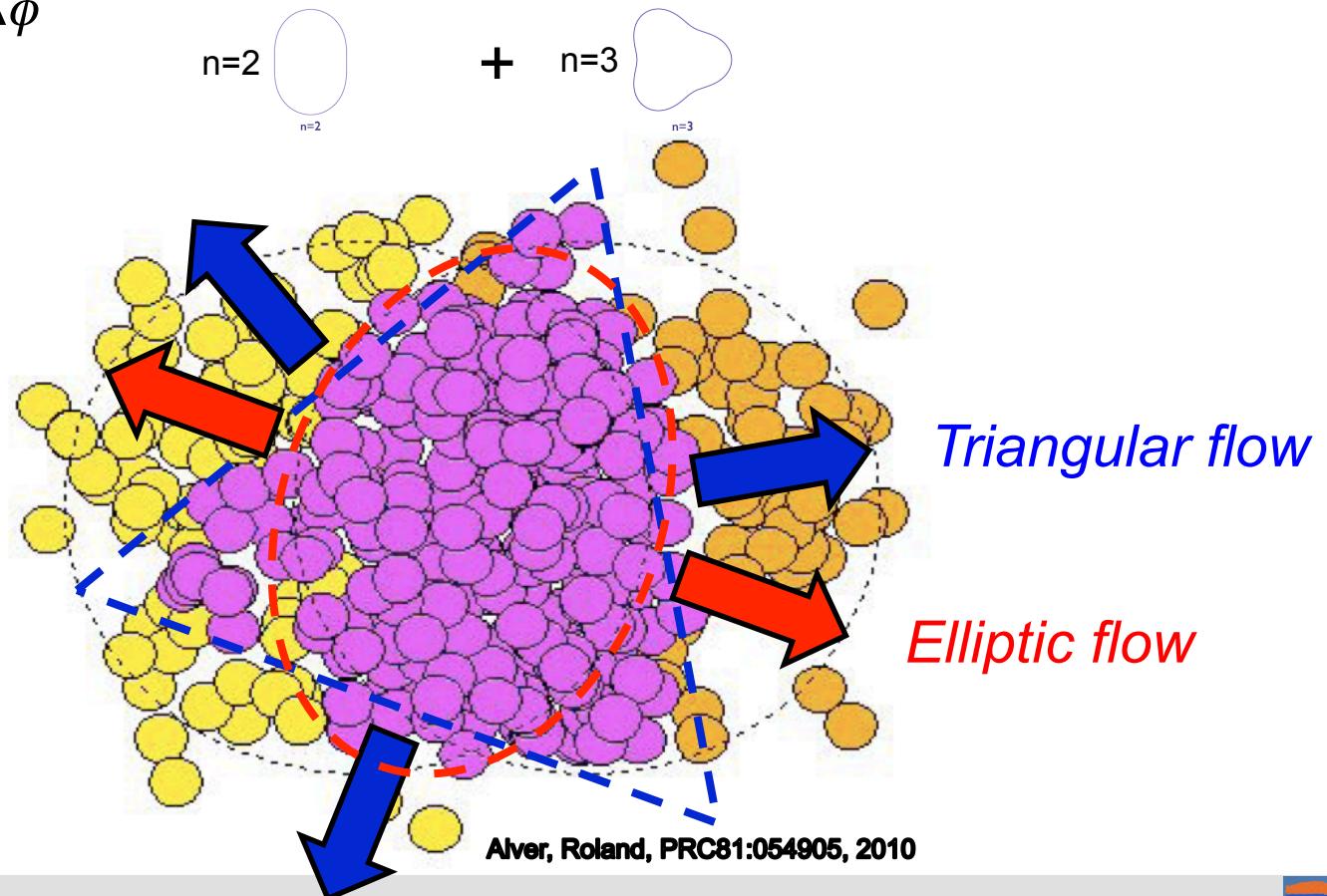


# Hydro flow with fluctuating initial conditions

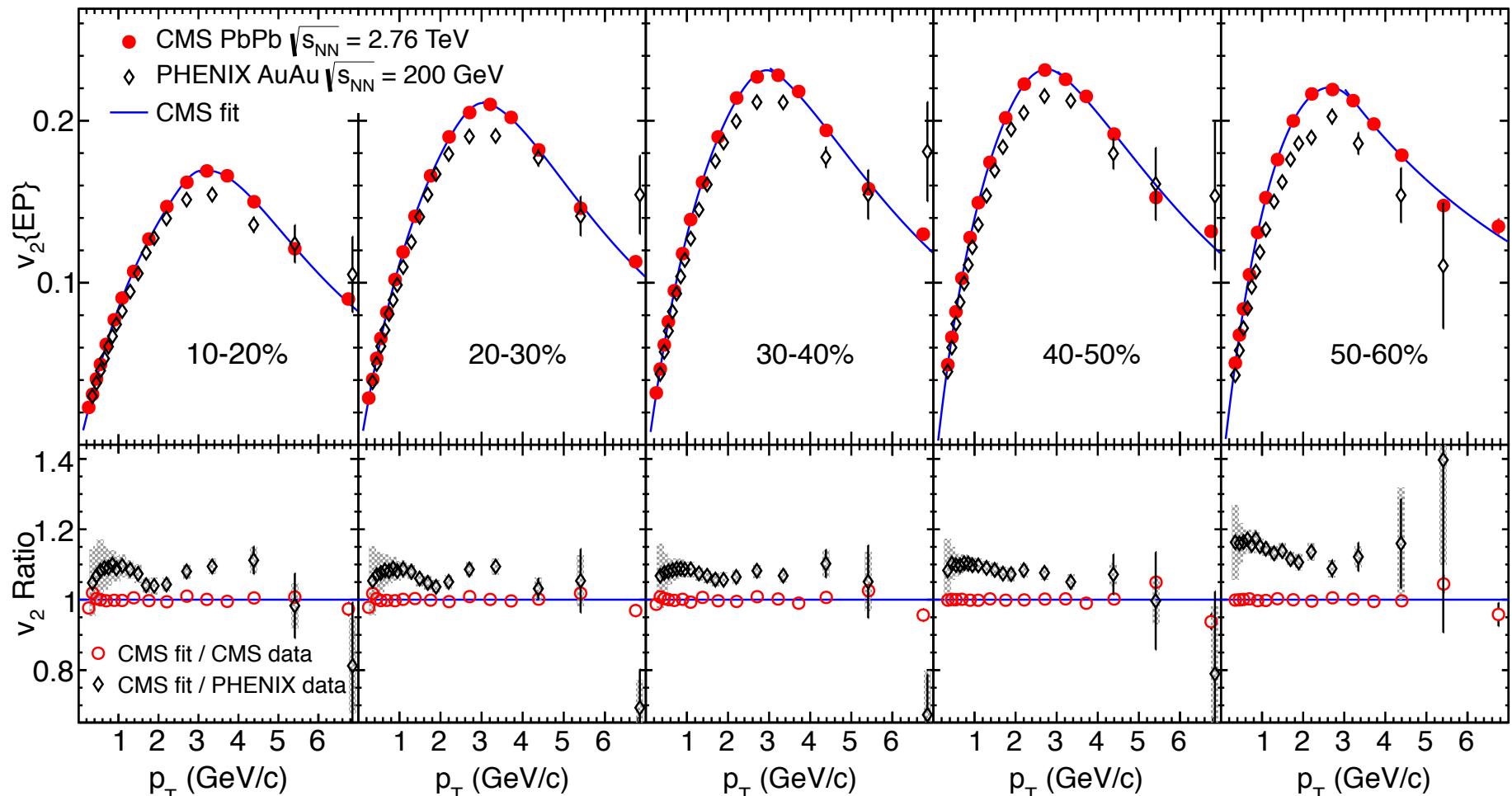
$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3)$$

Elliptic flow              Triangular flow

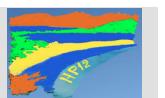
Two-particle correlation  $\Rightarrow \frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2v_2^2 \cos 2\Delta\phi + 2v_3^2 \cos 3\Delta\phi$



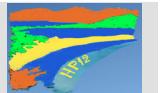
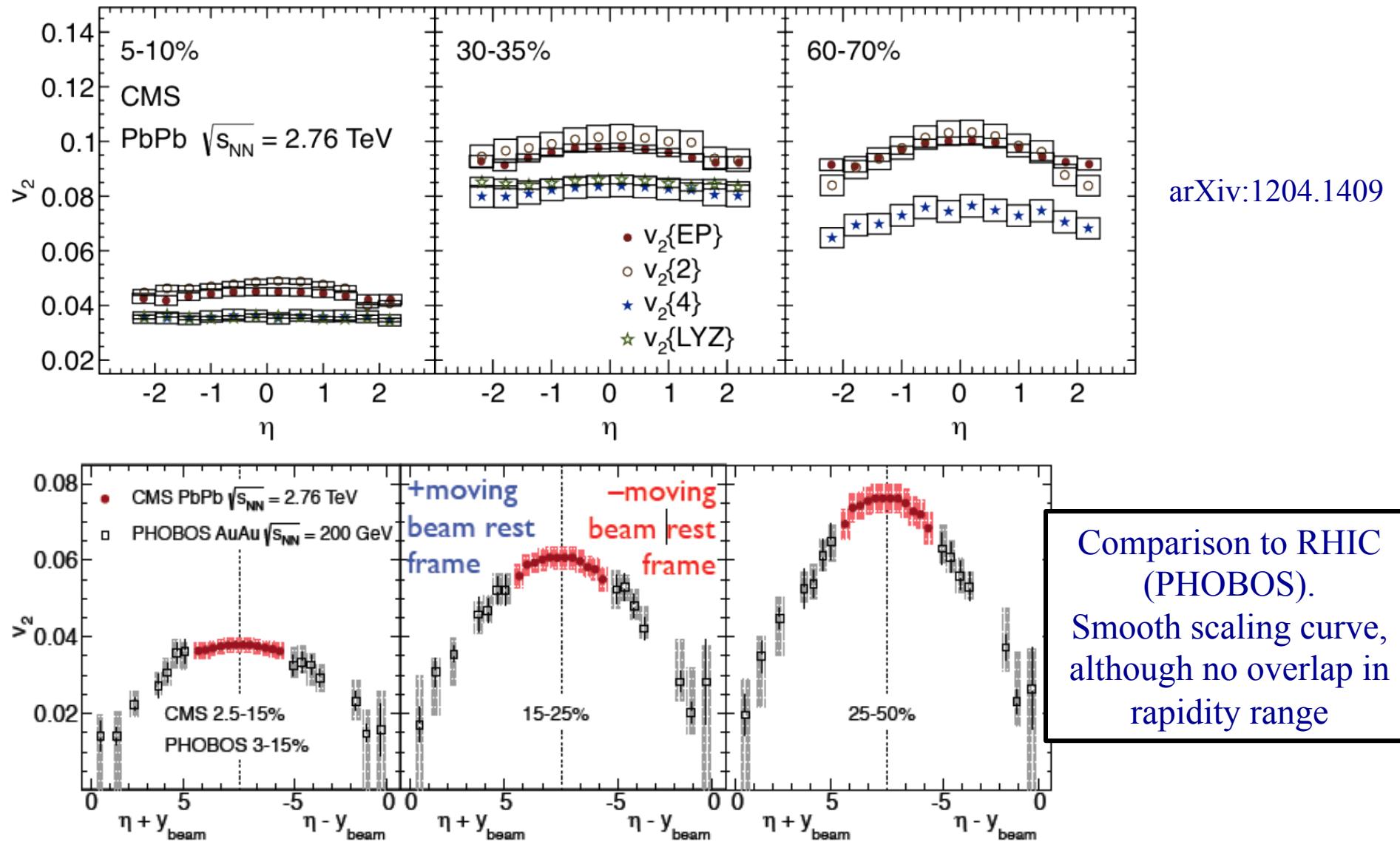
# CMS Results Compared with PHENIX Results



Large increase in  $\sqrt{s_{\text{NN}}}$  ( $\times 14$ ) leads to only small increase in  $v_2(p_T)$ .

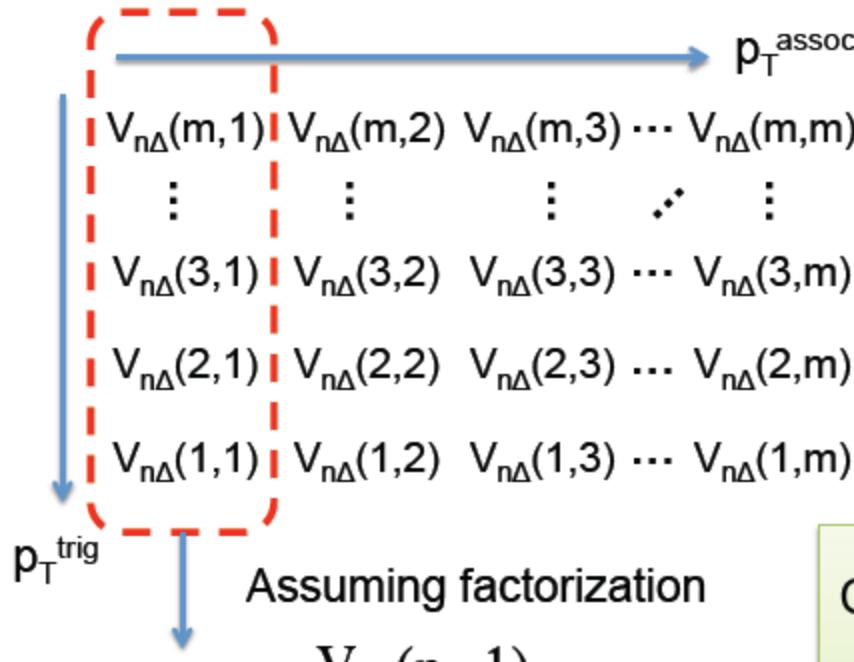


# $\eta$ -Dependence of the Integrated $v_2$



# Direct test of $V_{n\Delta}$ factorization

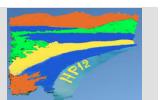
Test of factorization:  $V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \xleftrightarrow{?} v_n(p_T^{\text{trig}}) \times v_n(p_T^{\text{assoc}})$



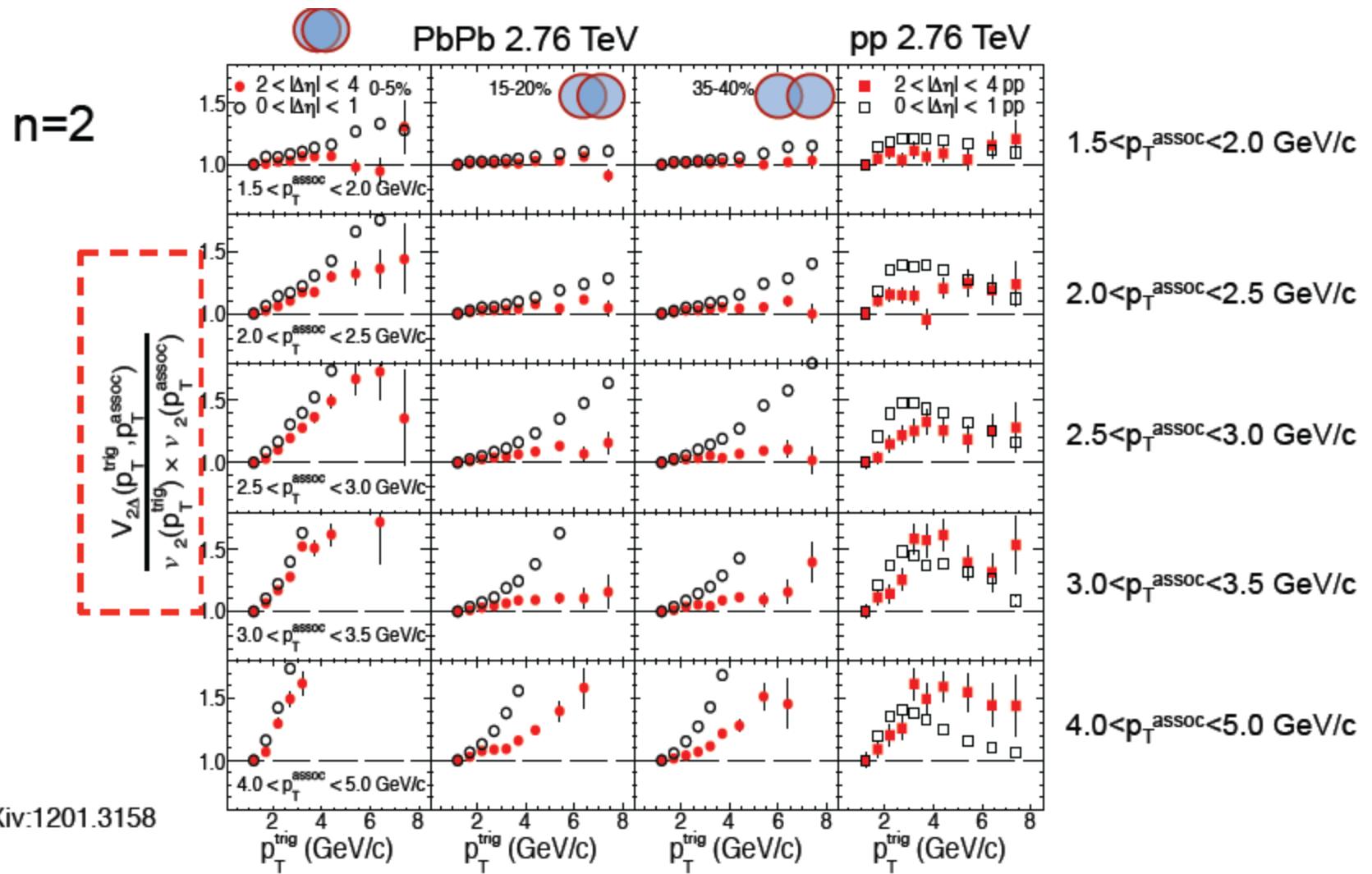
Take low reference  $p_T$  bin (1-1.5 GeV/c)

Check if  $v_n(p_T)$  can derive rest of matrix:

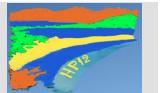
$$\frac{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}})}{v_n(p_T^{\text{trig}}) \times v_n(p_T^{\text{assoc}})} = ?_1$$



# Direct test of $V_{n\Delta}$ factorization: n=2

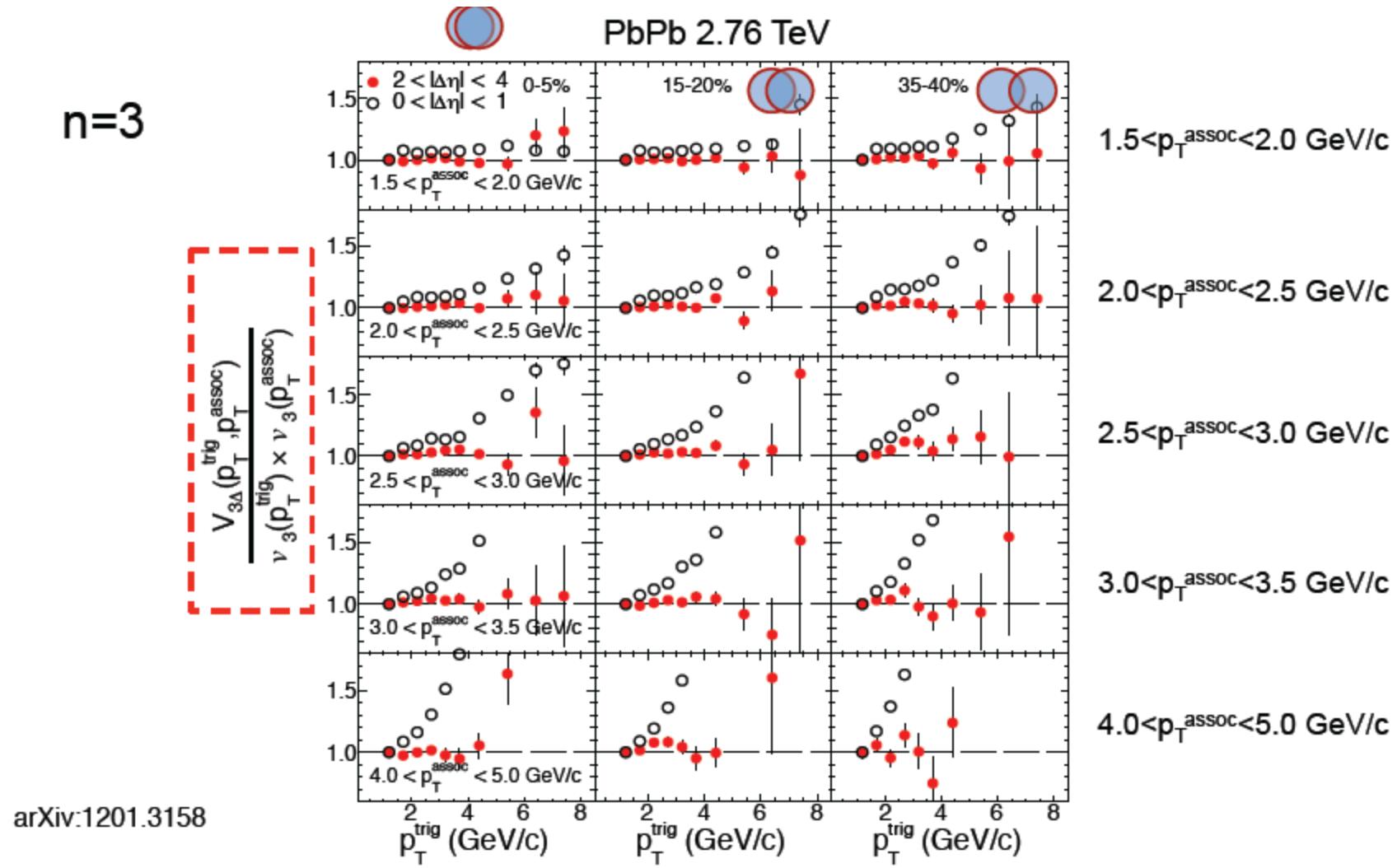


- $V_{2\Delta}$  from long-range corr factorizes for not very central PbPb

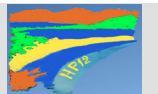


# Direct test of $V_{n\Delta}$ factorization: n=3

n=3

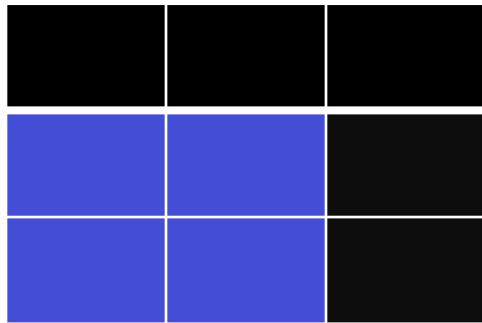


- $V_{3\Delta}$  from long-range shows good factorization



# Detection of the $\pi^0$ Decay Photons

## Selection of the $\gamma$ -Clusters



### CMS ECAL Barrel Specifics

75,848 PbWO<sub>4</sub> Crystals

$$-1.49 < \eta < +1.49$$

Crystal Area is 2.2 x 2.2 cm

Moliere radius = 2.19 cm

The two  $\gamma$  from the  $\pi^0$  decay are identified in clusters of 3x3 crystals

Standard CMS  $\gamma$  identification (e.g.  $H \rightarrow \gamma+\gamma$ ) uses a 5x5 cluster

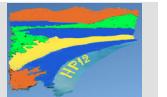
And super-clusters are extended in the azimuthal direction

A 5x5 cluster size would limit the  $\pi^0$   $p_T$  range to  $< 4.0$  GeV/c

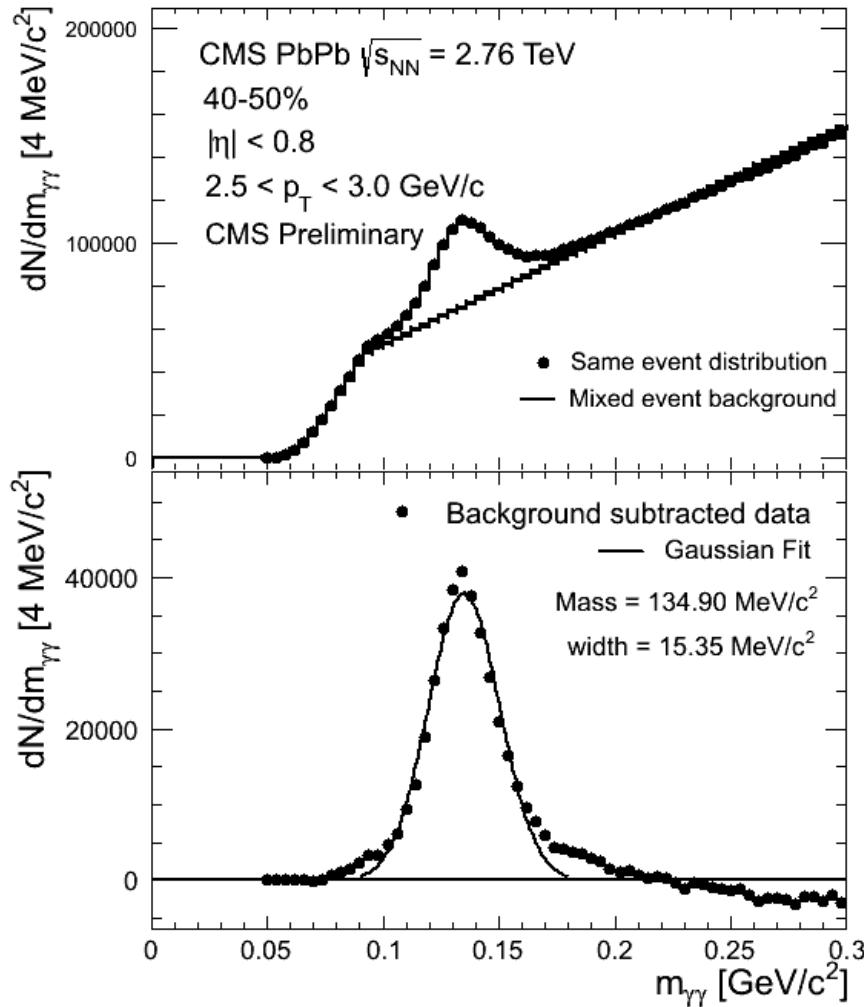
With a 3x3 cluster size, we can go to  $p_T = 8.0$  GeV/c

Primary shape cut is S4/S9 ratio: largest 2x2 energy/energy in 3x3

S4/S9 set at 0.87, with systematic checks at 0.83 and 0.91



# $\pi^0$ Invariant Mass Distribution

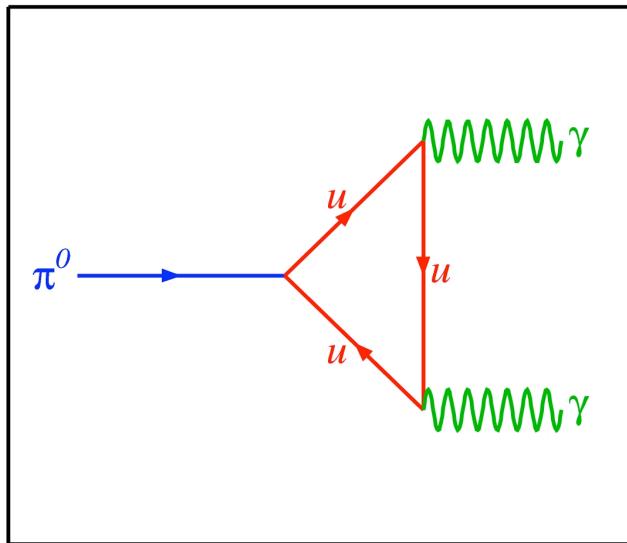


- Combinatoric background estimated from mixed events and subtracted
- Yield extracted in 6 bins of  $\varphi$ - $\Psi_{EP}$
- EP determined in HF – separated by 3 units of  $\eta$

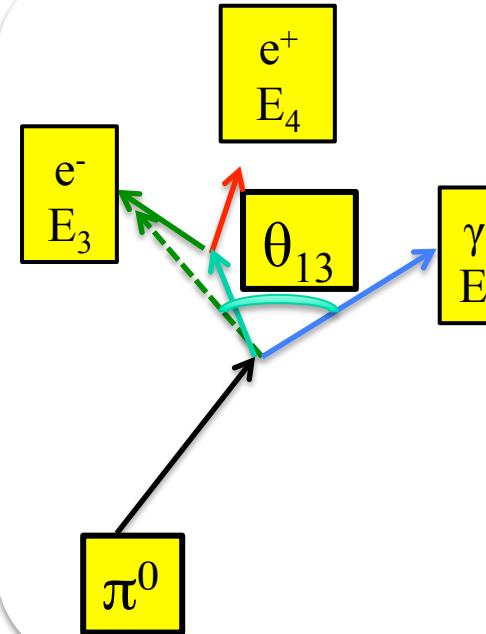
# Reason for negative yield: conversion correlations

## Ideal case: no conversion

$\pi^0$  Decay



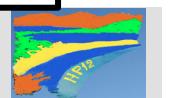
## Conversion case I: only one photon decays



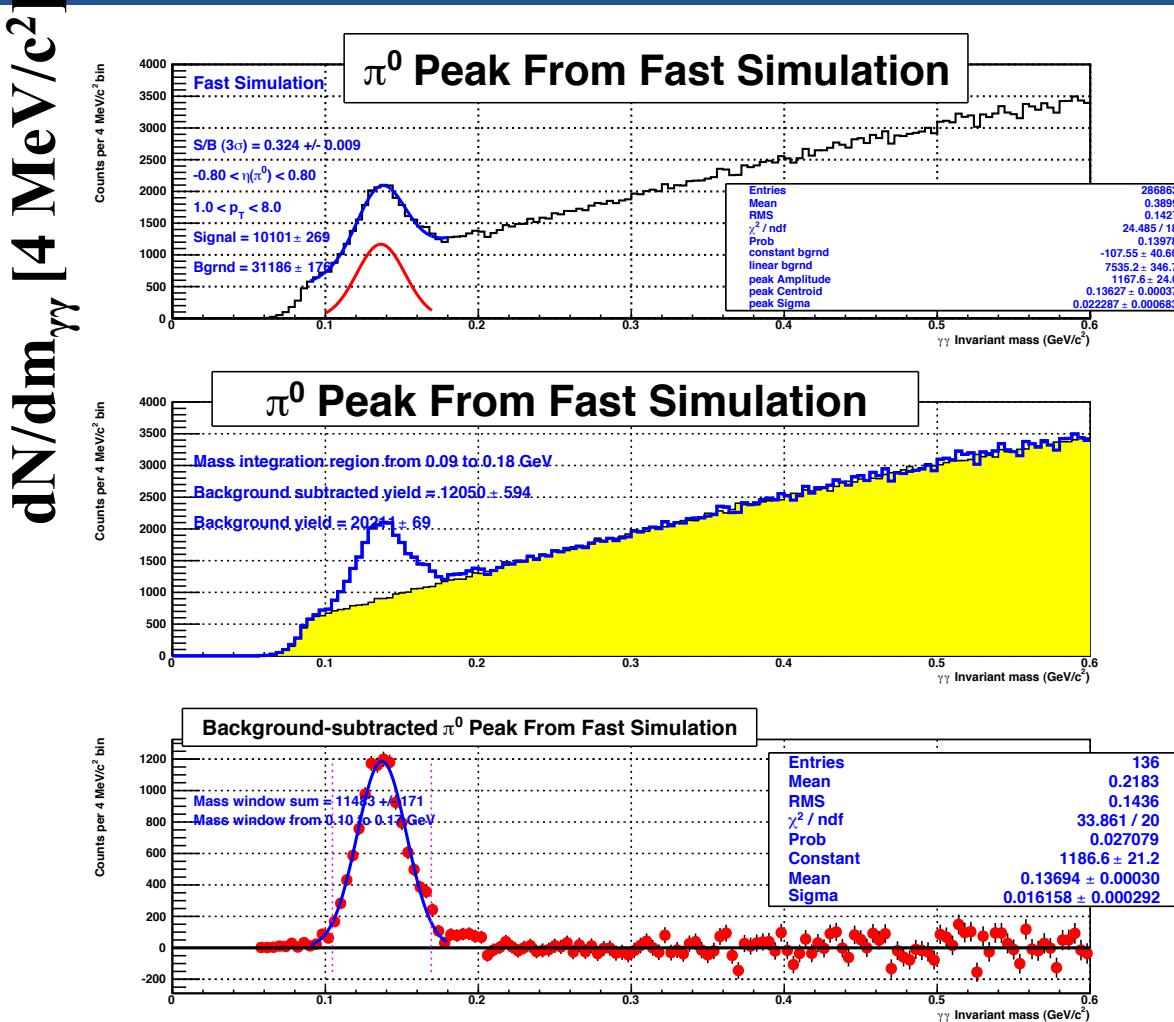
**But life is not always so simple.....**

- The apparent opening angle  $\theta_{13}$  can become large due to the magnetic deflection of the electron, and out-of-plane effects
- So even though  $E_3 < E_2$ , the  $m_{YY}^{PC} > m(\pi^0)$

The pair survival probability for the CMS ECAL is  $(1 - 0.25)^2 = 0.56$



# Understanding conversions using fast simulations (result with conversions suppressed)

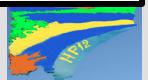


Slide taken from Monika's draft CIPANP talk

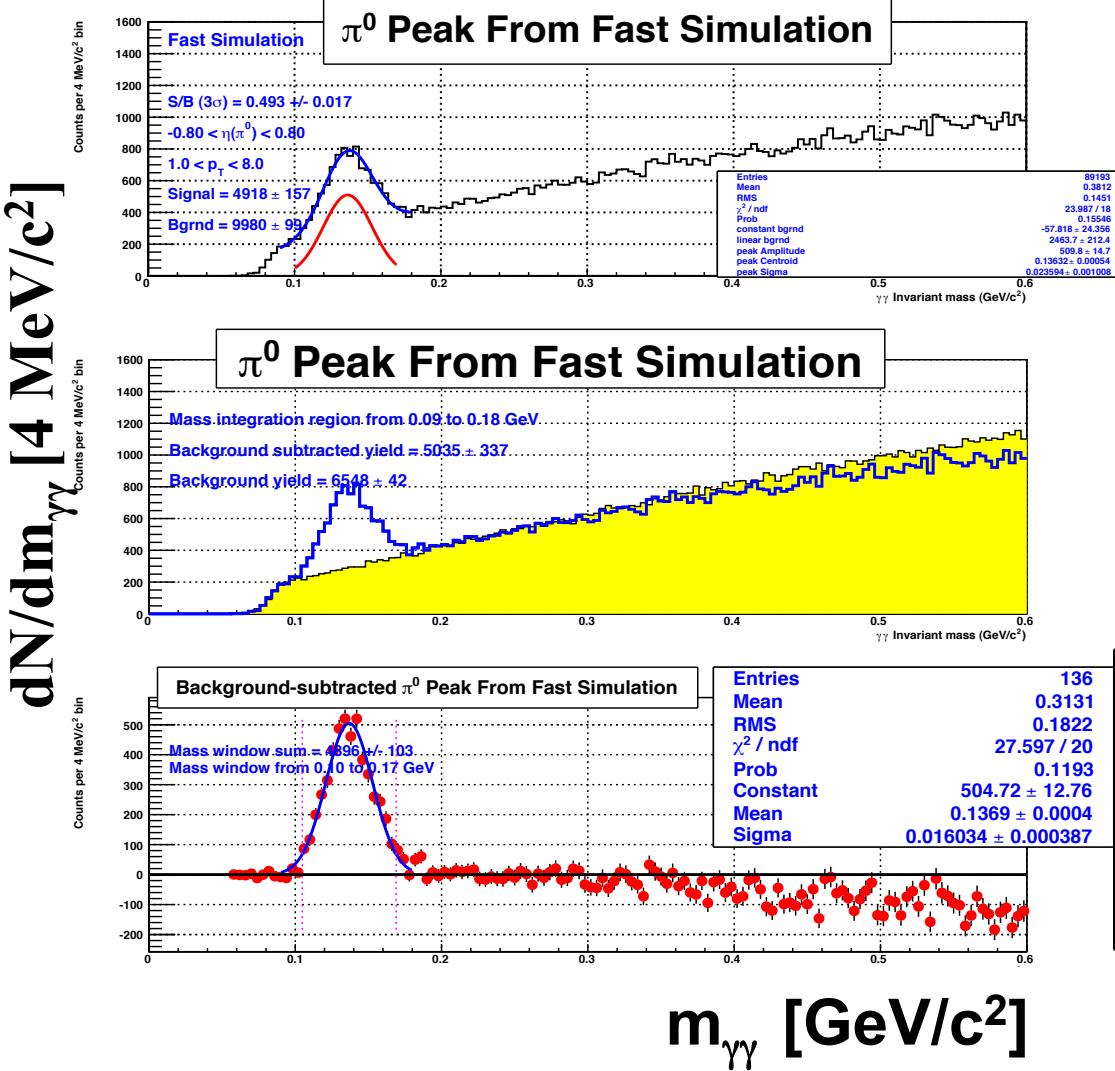
$m_{\gamma\gamma}$  [GeV/c<sup>2</sup>]

## Fast Simulation

- 1) Events have pairs of  $\pi^0$ , with a realistic  $p_T$  spectrum
- 2) Events are given a random event plane angle
- 3) Each  $\pi^0$  in the pair is given an azimuthal angle in the event plane according to a  $v_2$  distribution
- 4) The  $\pi^0$  decay correctly
- 5) The decay photon values ( $E$ ,  $\eta$ , and  $\phi$ ) are distorted according to the resolution parameters of the ECAL, with optional conversion effects possible
- 6) The  $\pi^0$  mass is reconstructed using the distorted photon values, giving a realistic mass.



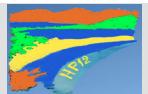
# Understanding conversions using fast simulations (result with conversions enabled)



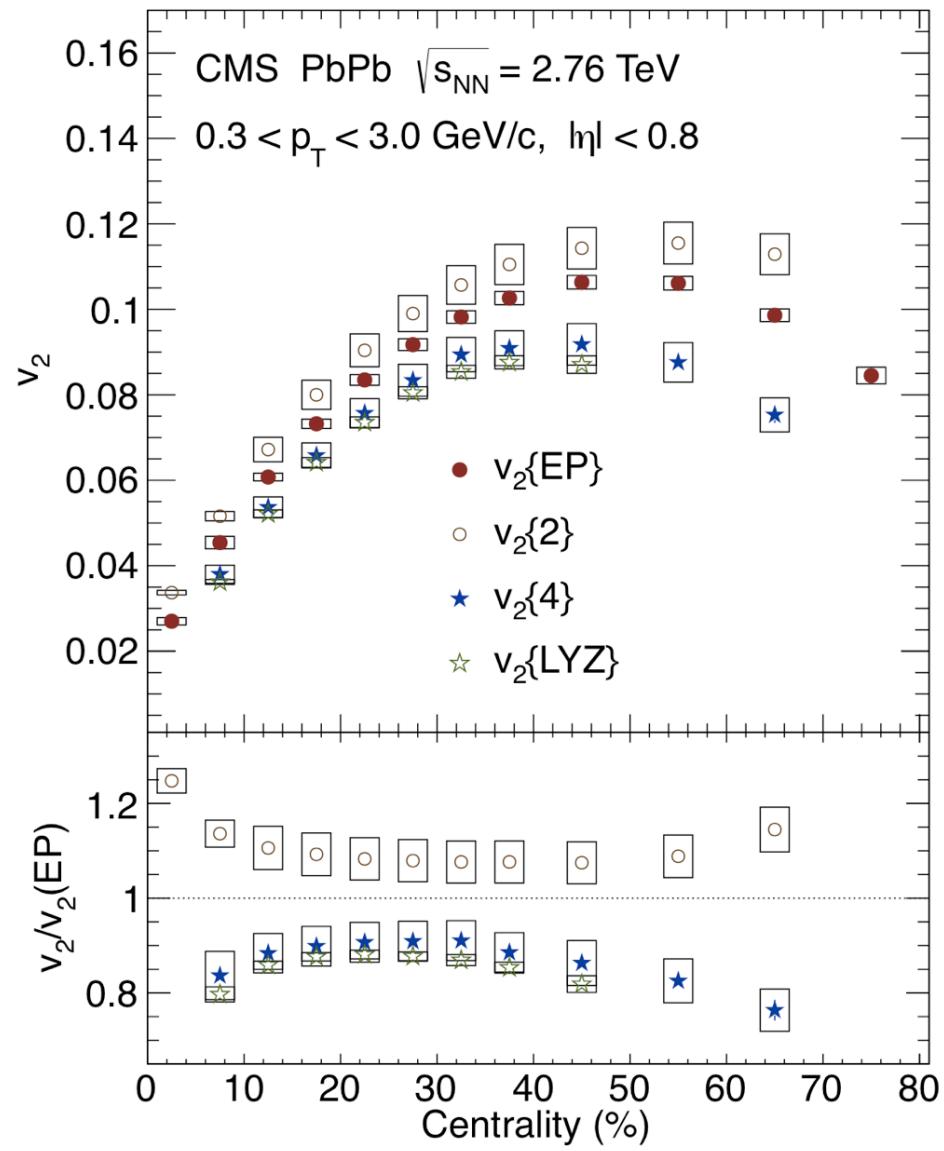
## Fast Simulation

Negative yield observed for higher mass regions when photons are allowed to convert

Similar results for the appearance of the over-subtraction are obtained using the full HYDJET generator events.  
Fast simulation has much higher statistics



# Integrated $v_2$ at Mid-Rapidity for Different Methods



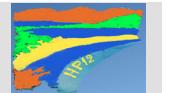
arXiv:1204.1409



Charles Maguire (Vanderbilt)

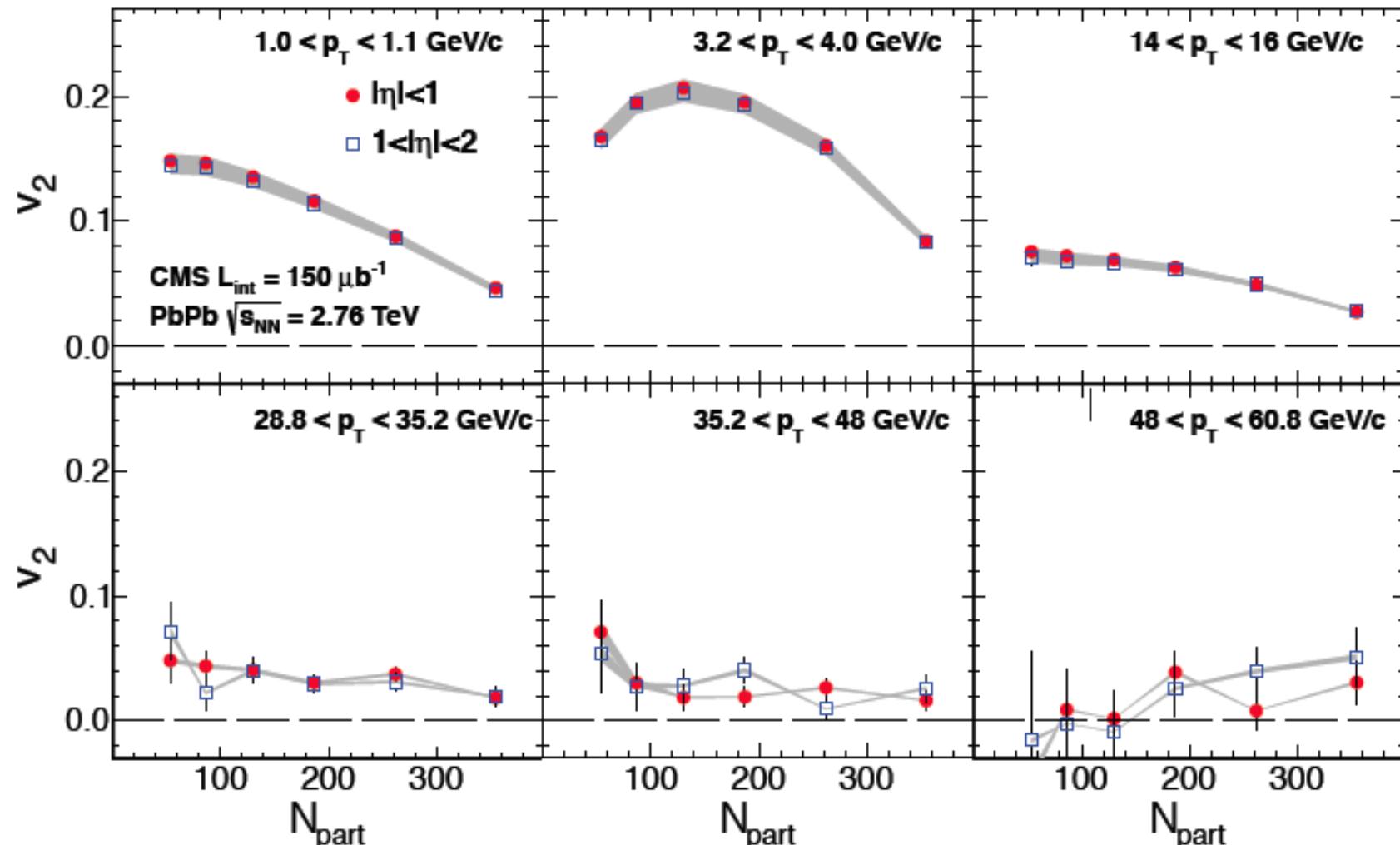
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# Azimuthal Dependence of High- $p_T$ Particles

arXiv:1204.1850



No  $\eta$  dependence over a wide range of  $p_T$

