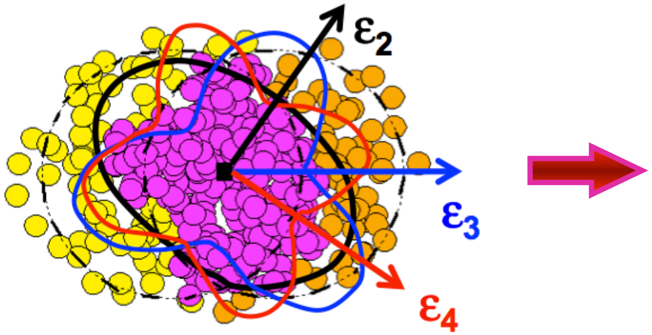
Initial Geometry & jet quenching



$$\epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi\rangle^2 + \langle r^n \sin n\phi\rangle^2}}{\langle r^n\rangle}$$

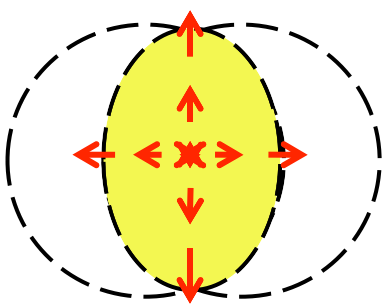
$$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n\left(\phi - \Phi_n\right)$$

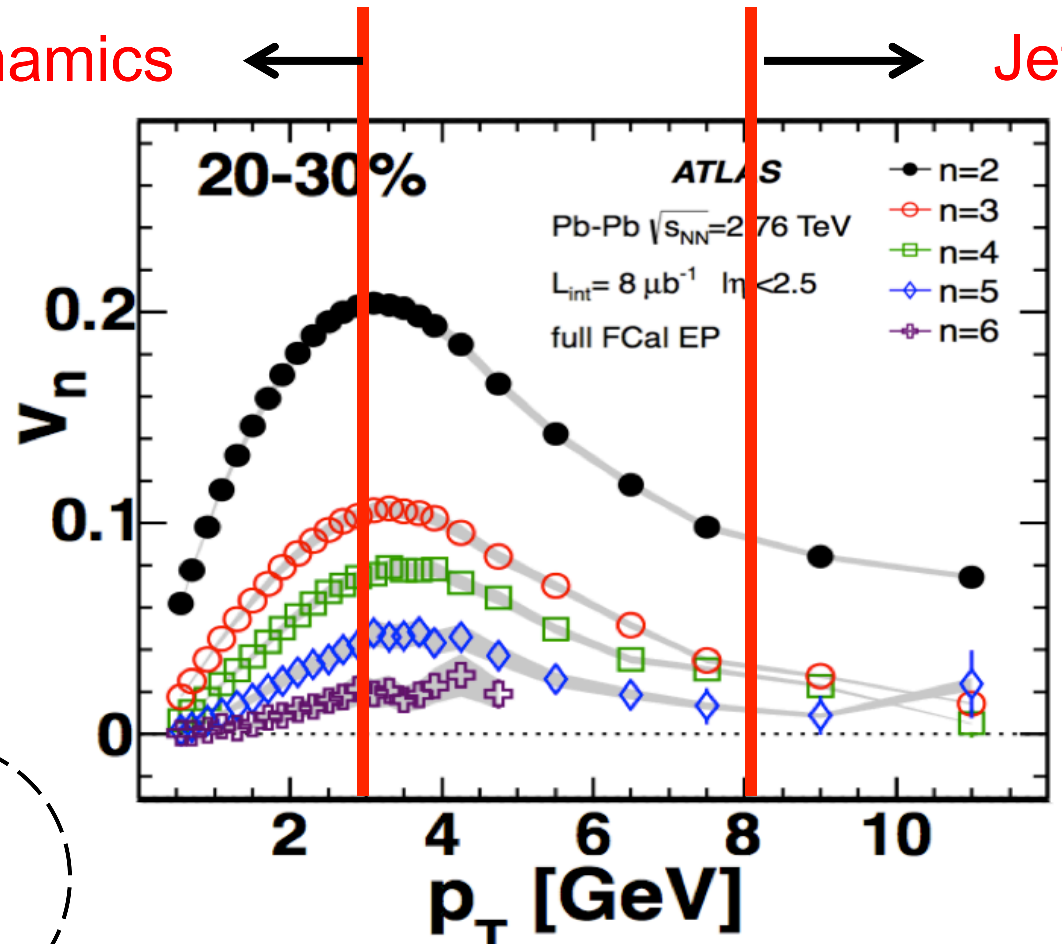
$$\frac{dN}{d\Delta\phi} = \left[\frac{dN}{d\phi_a} * \frac{dN}{d\phi_b}\right] \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n}^\mathrm{a}\mathrm{v}_\mathrm{n}^\mathrm{b} \cos\left(n\Delta\phi\right)$$

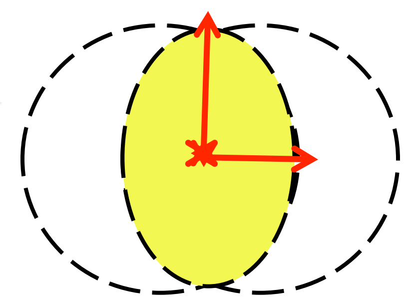
- Event averaged quantities: $\mathrm{v}_\mathrm{n}(\mathrm{p}_\mathrm{T},\eta,\mathrm{cent},\mathrm{n},\mathrm{PID})$
  - Geometry & high p_T v_n
  - Dipole asymmetry and v_1
- Event-by-event quantities
  - Correlations between Φ_n.
  - Distribution of v_n
  - Event shape engineering.

Origin of single particle $v_n(p_T,\eta,cent,n)$

Hydrodynamics ← → Jet quenching



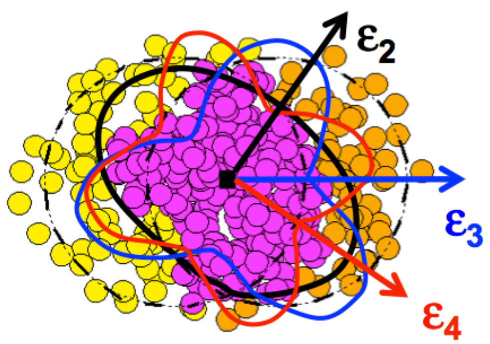




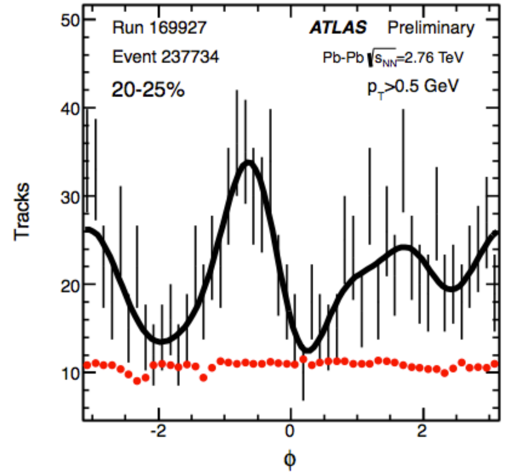
- Both effects are related to global geometry → ridge & factorization

Three different planes

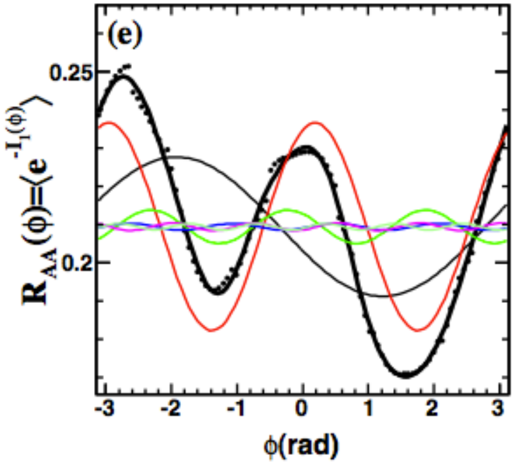
$$I_m \approx \int_0^{\infty} dl\, l^{m-1}\, \rho(\vec{\mathbf{r}} + l\hat{\mathbf{v}}),$$



Participant plane (PP)



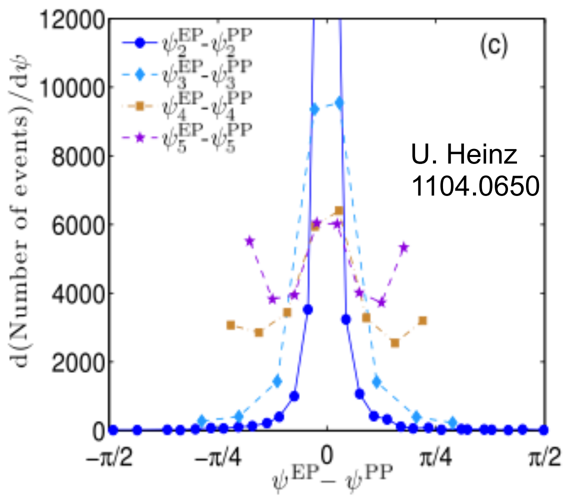
Event plane (EP)



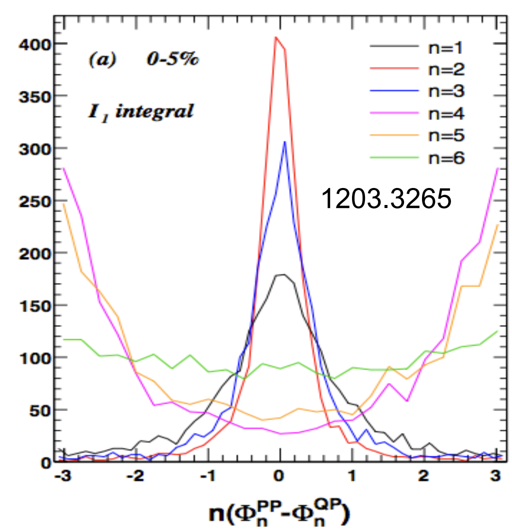
Quenching plane (QP)

- PP, EP and QP can be different from each other

EP vs PP

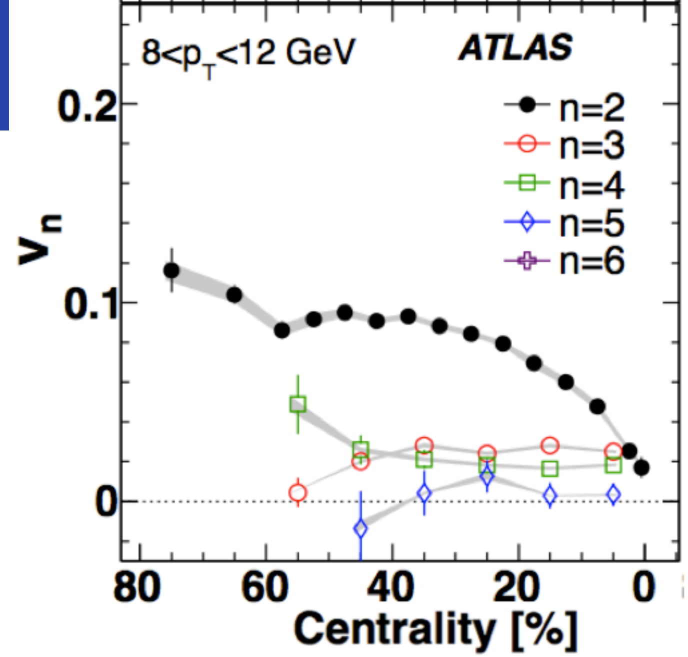


QP vs PP

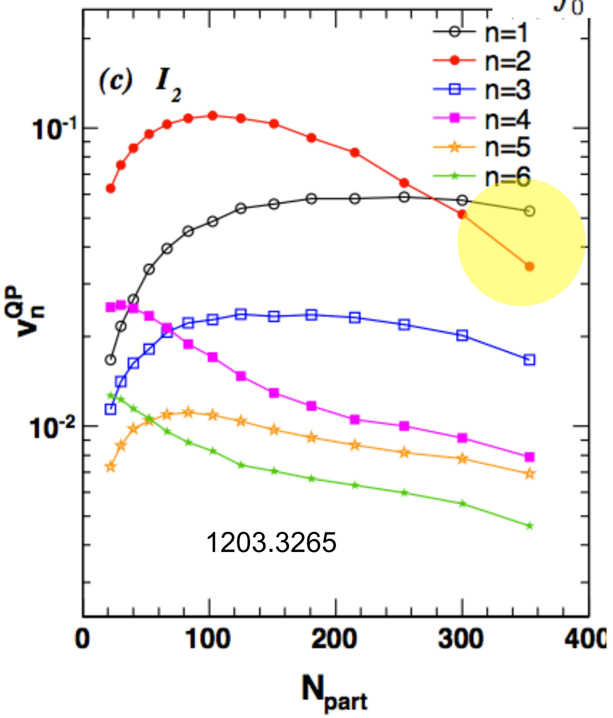


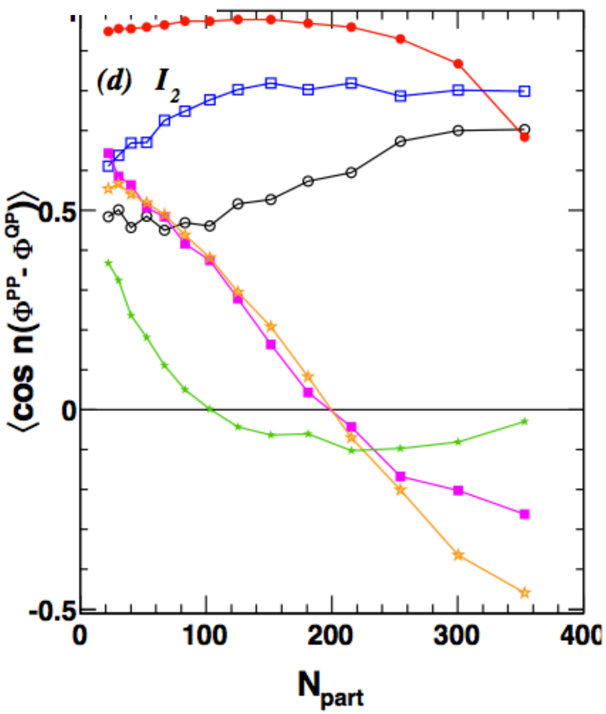
Consequence on high p_T v_n

- Intrinsic anisotropy due to jet quenching can be sizable
- But QP de-correlated with the PP, so possibly also with EP.
- Interpretation of v_n for n>3 can be complicated.



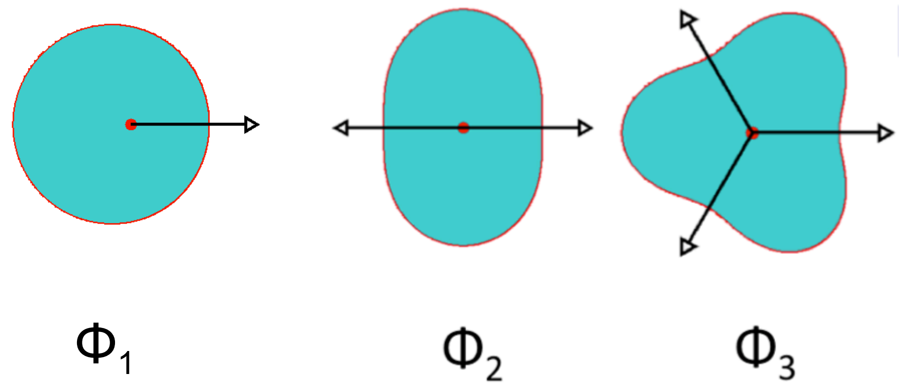
$$I_m \approx \int_0^\infty dl\, l^{m-1}\, \rho(\vec{\mathbf{r}} + l\hat{\mathbf{v}}),$$

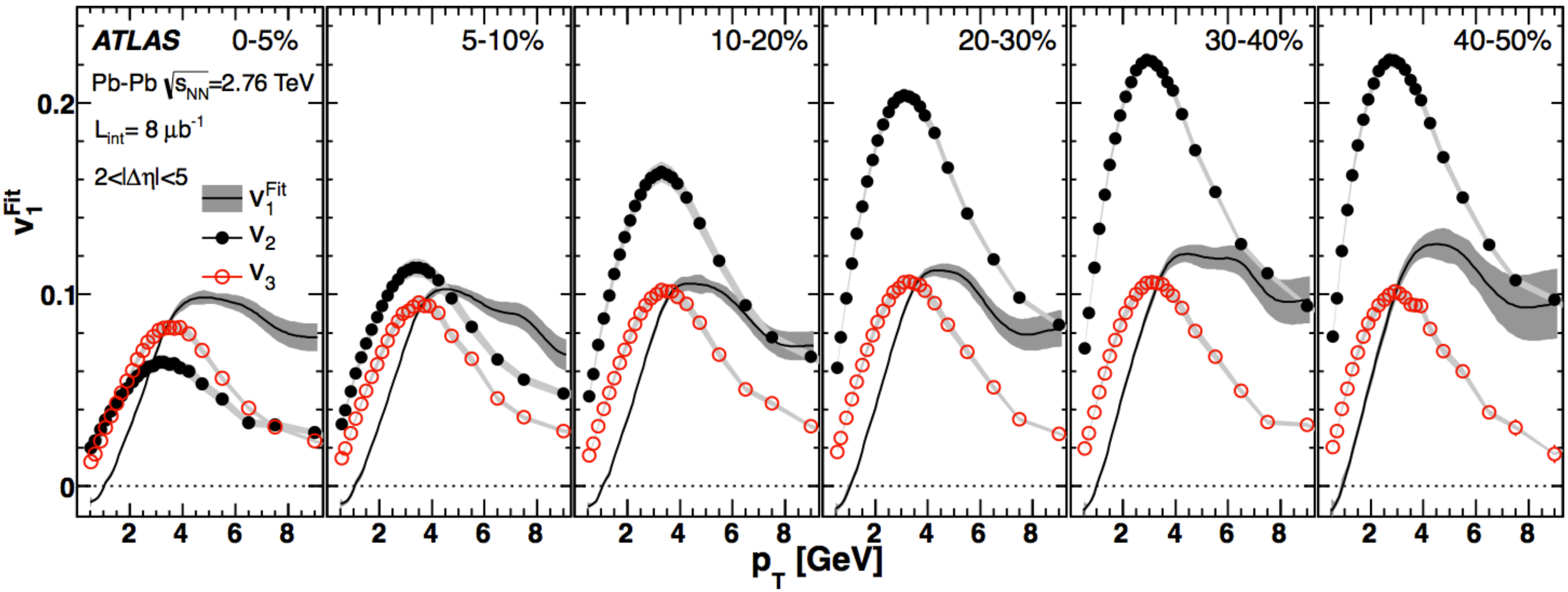




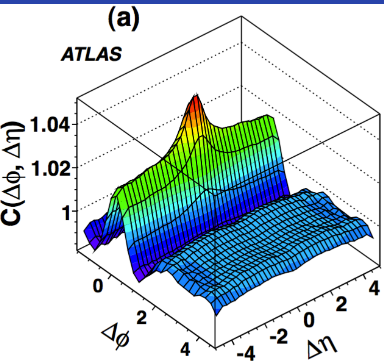
"Surprisingly" large rapidity-even (dipolar) v_1

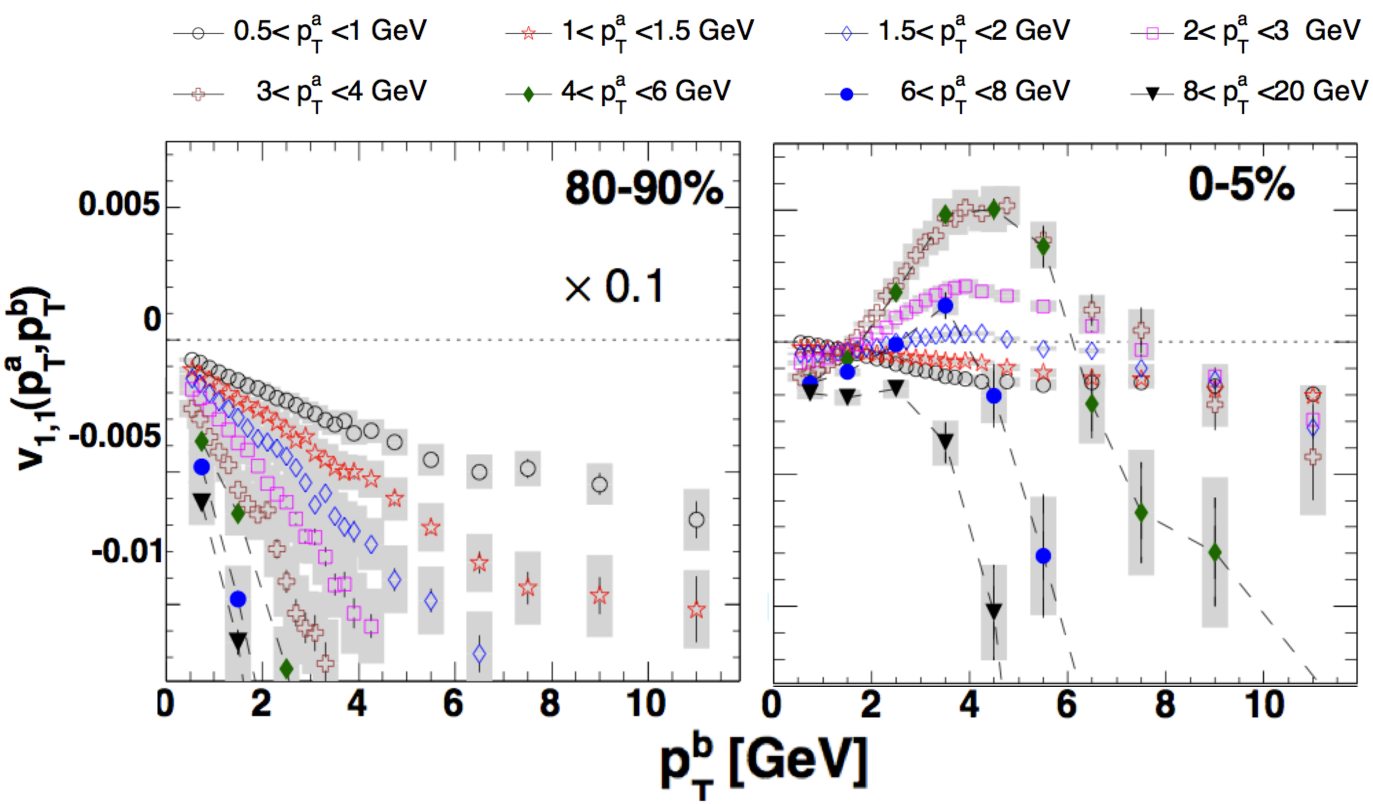
- Sizable dipole asymmetry in initial geometry





First coefficient $v_{1,1}=\langle\cos\Delta\phi\rangle$ from 2PC



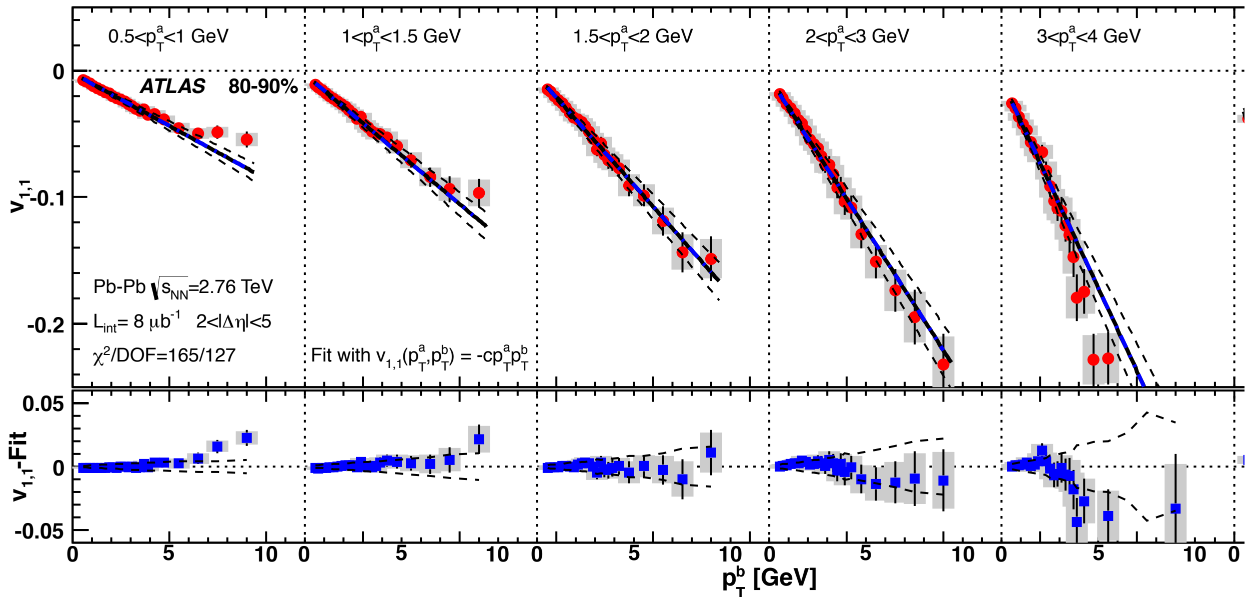


- Peripheral collisions (GMC dominated): $v_{1,1}$ negative, linear in p_T^a,p_T^b.
- Central collisions (flow dominated): $v_{1,1}$ becomes positive at 1.5-6 GeV range, but on top of a negative momentum conservation component
- Cross each other at low p_T→ where flow driven $v_{1,1}$ ~ zero.

Dipolar v_1 from 2PC via two-component fit

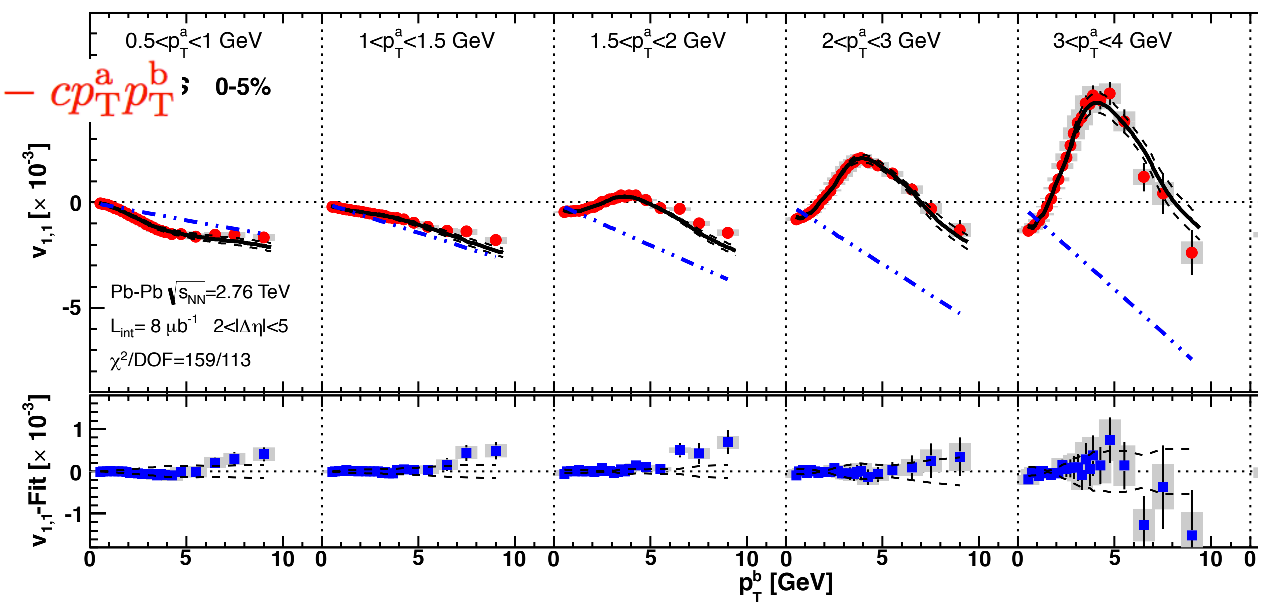
$$v_{1,1}(p_T^a, p_T^b) = -c p_T^a p_T^b$$

Momentum conservation describe the cosΔϕ even at 10 GeV!

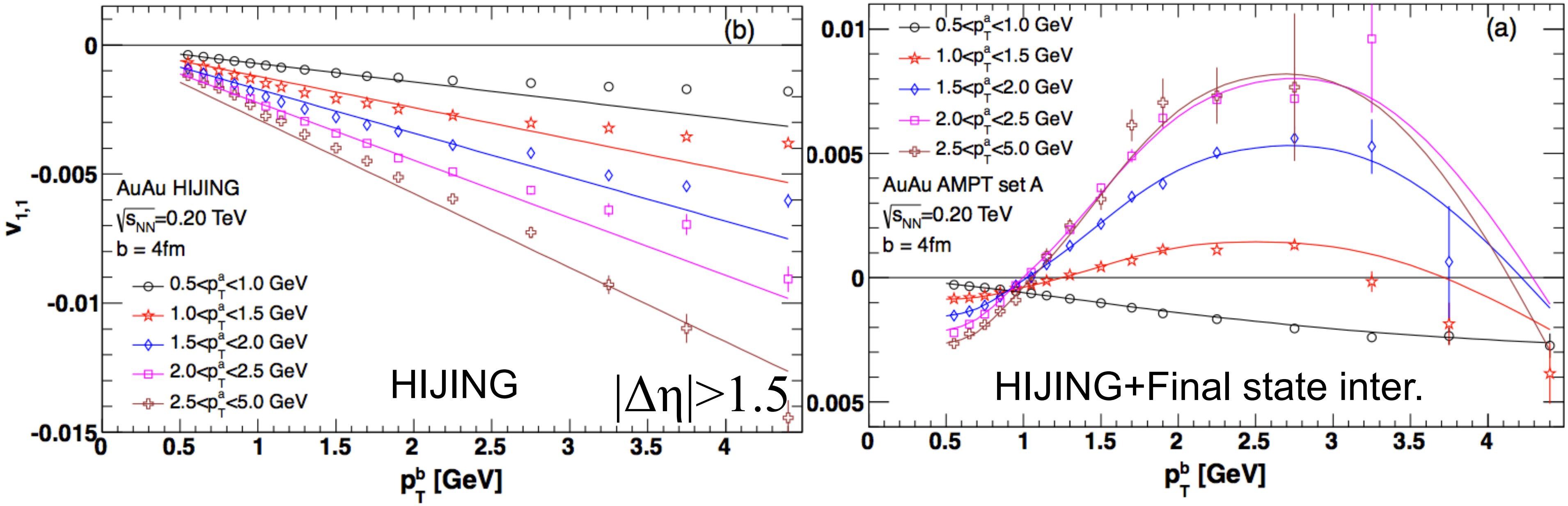


$$v_{1,1}(p_T^a, p_T^b) = v_1^{Fit}(p_T^a) v_1^{Fit}(p_T^b) - c p_T^a p_T^b$$

Dipolar flow is dominates over GMC over 2-6 GeV



Comparison with AMPT model: arxiv:1203.3410



$$v_{1,1}(p_T^a, p_T^b) = -c p_T^a p_T^b$$

$$v_{1,1}(p_T^a, p_T^b) = v_1^{Fit}(p_T^a) v_1^{Fit}(p_T^b) - c p_T^a p_T^b$$

- HIJING only need momentum conservation, while AMPT need both

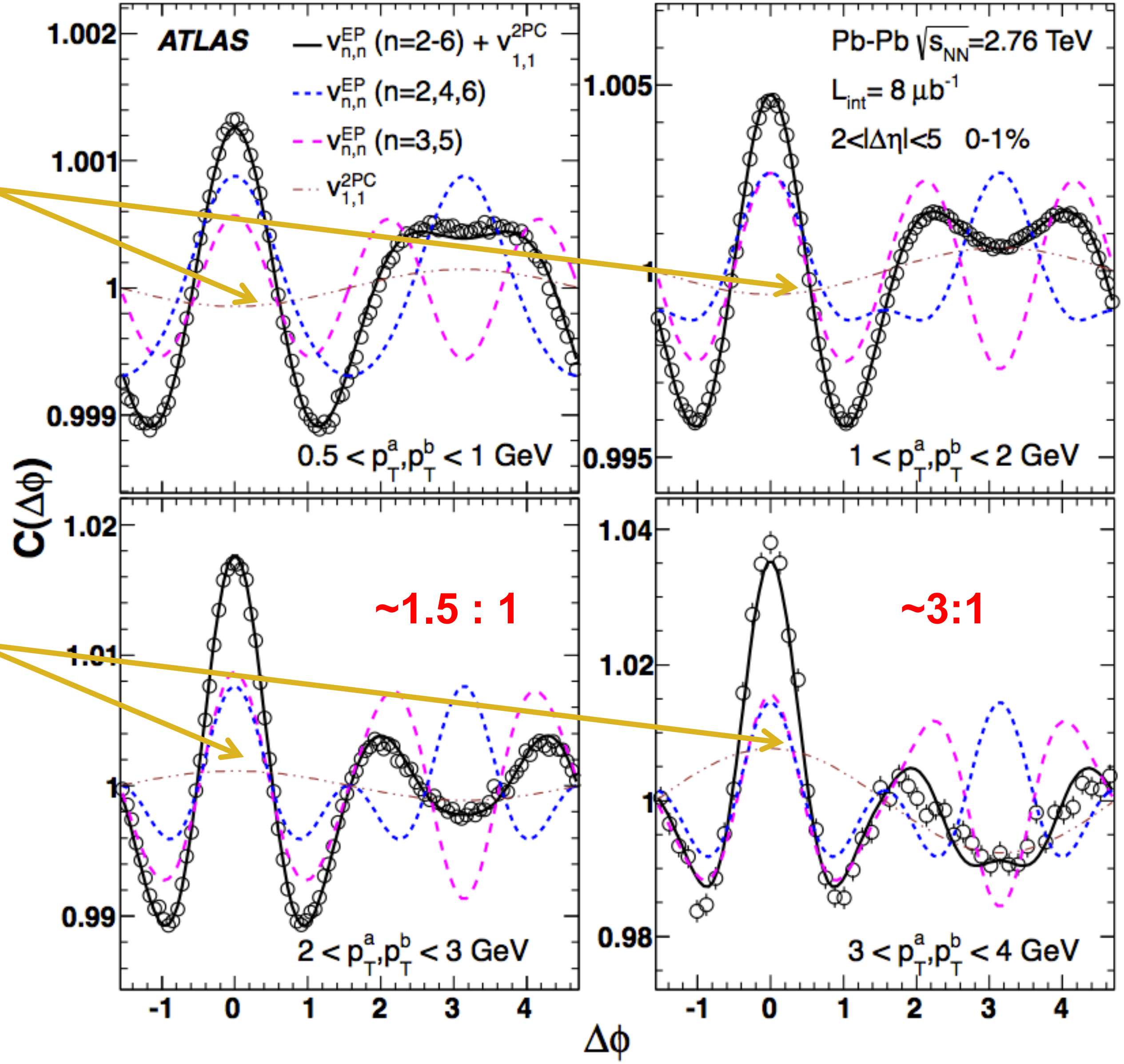
The complex p_T dependence of $v_{1,1}$ naturally generated from final state interactions

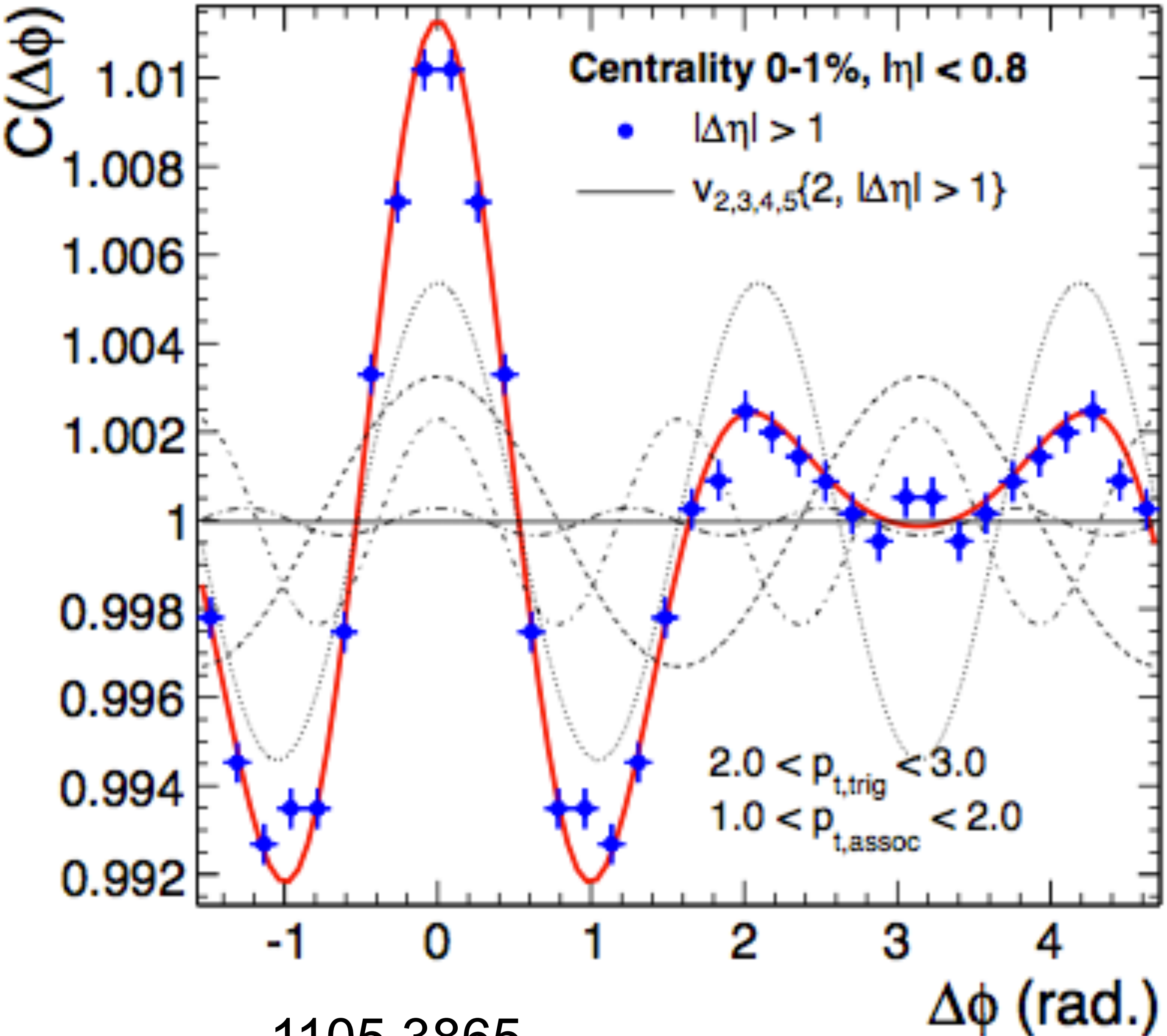
$v_{1,1}$=<cosΔϕ> in 2PC (0-5%)

- Correlation function well described by v_2-v_6 and $v_{1,1}$

Most of $v_{1,1}$ is due to momentum conservation

Most of $v_{1,1}$ is due to dipolar flow

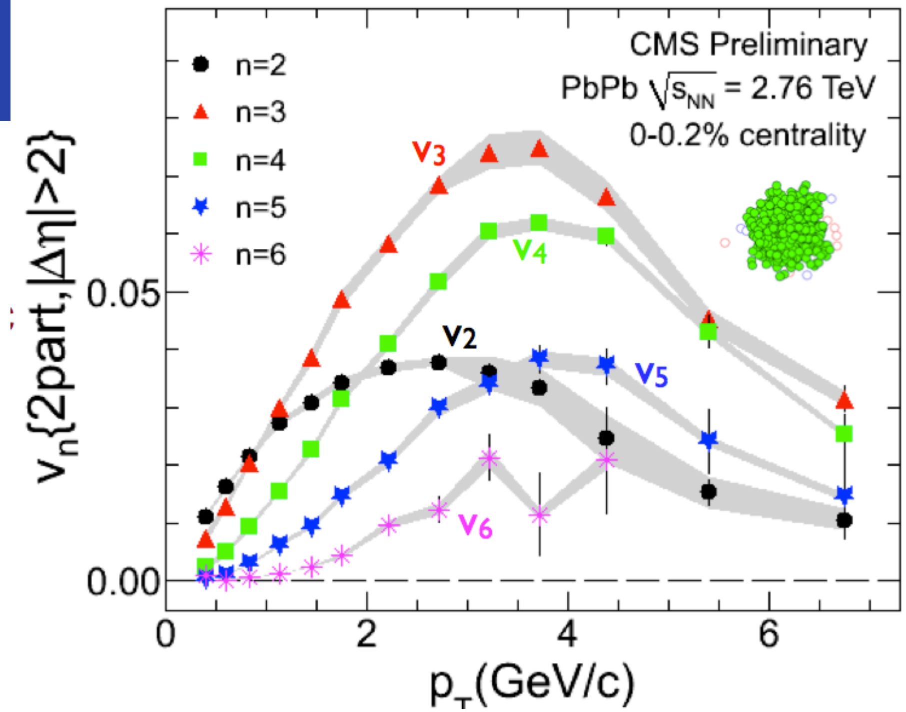


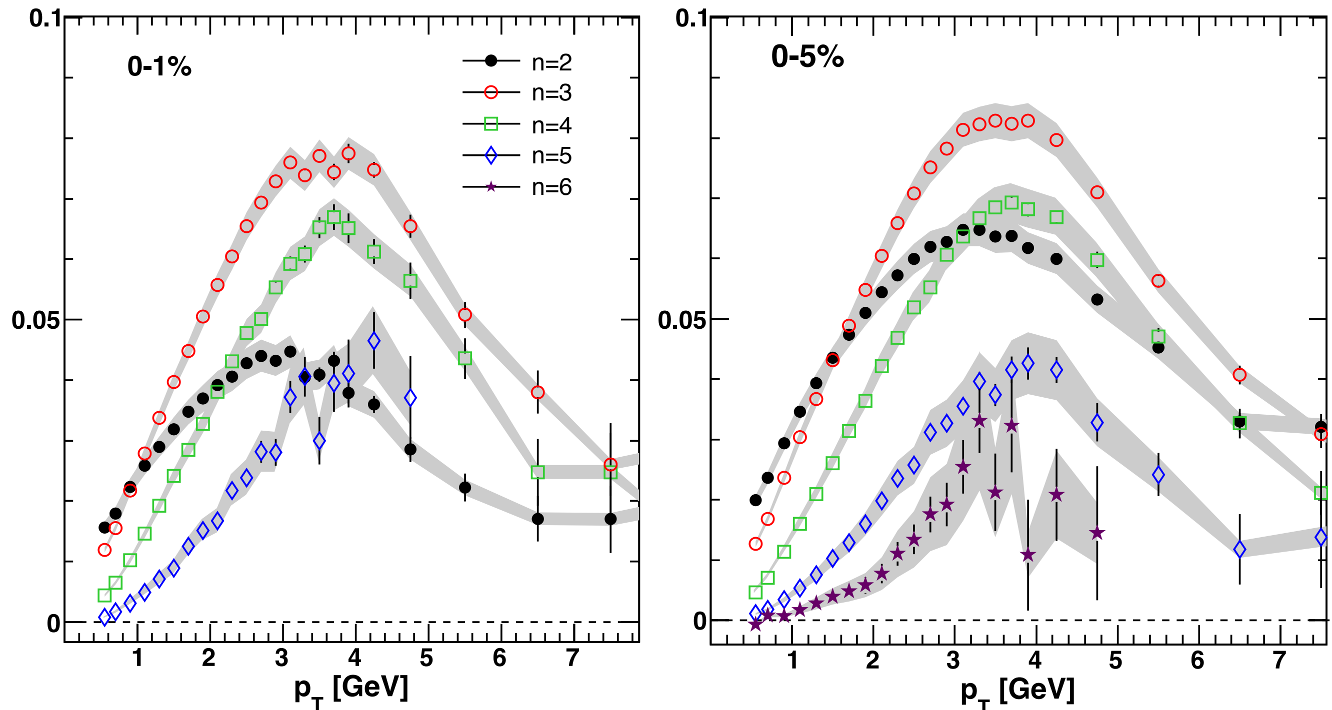

C(Δφ)
1.01
1.008
1.006
1.004
1.002
1
0.998
0.996
0.994
0.992
Centrality 0-1%, |η| < 0.8
|Δη| > 1
$v_{2,3,4,5}\{2, |\Delta\eta| > 1\}$
$2.0 < p_{t,trig} < 3.0$
$1.0 < p_{t,assoc} < 2.0$
-1
0
1
2
3
4
Δφ (rad.)

1105.3865

Ultra Central Collisions

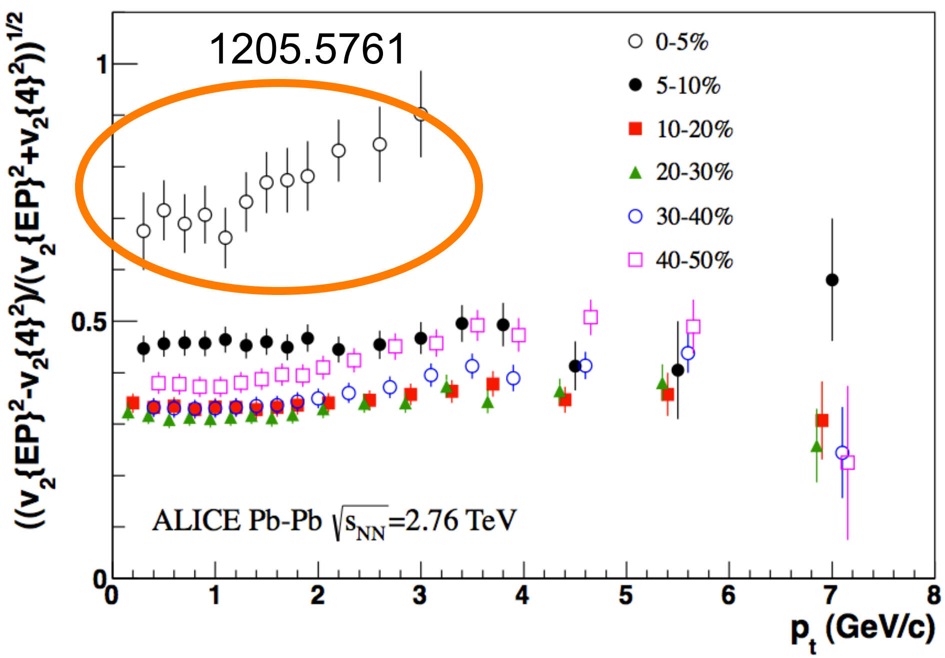
- The shape of v_n is very different from v_2.
- p_T of the peak increase with n.

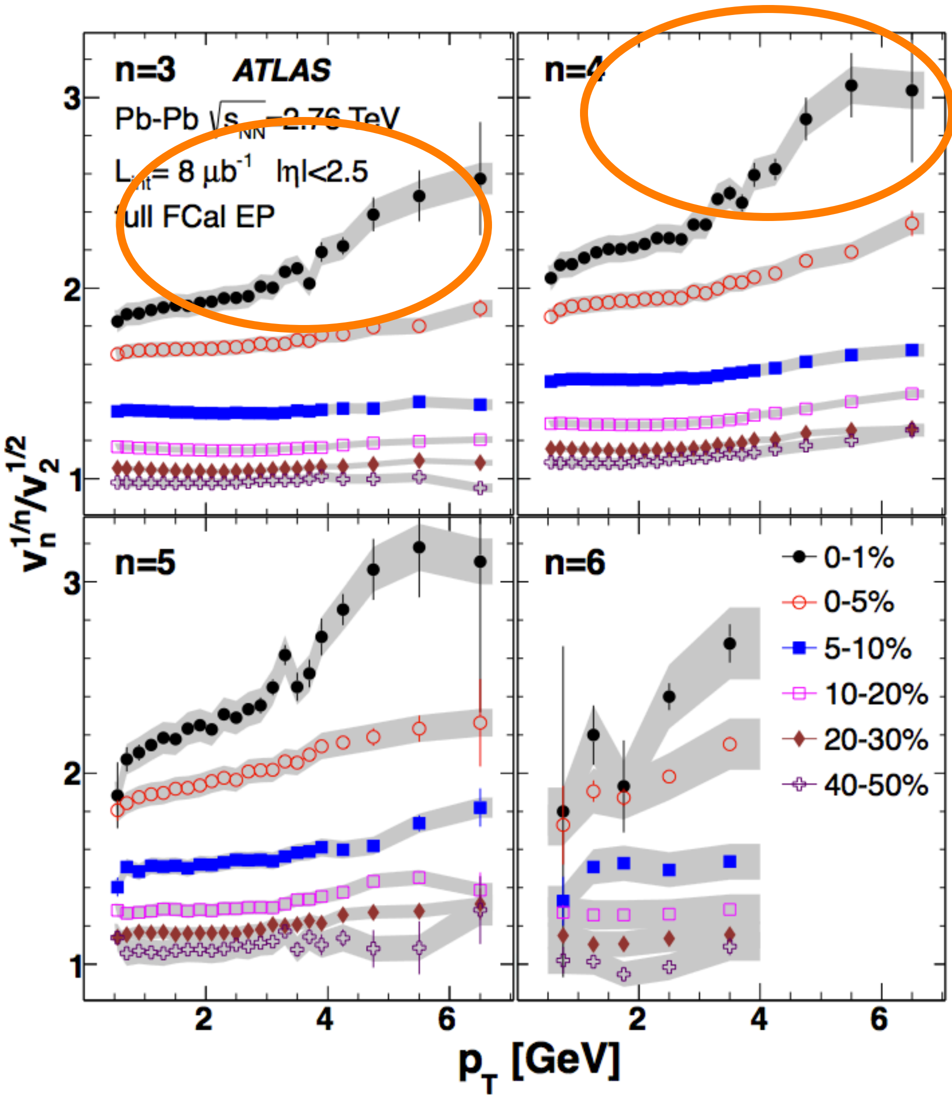




ATLAS 2010

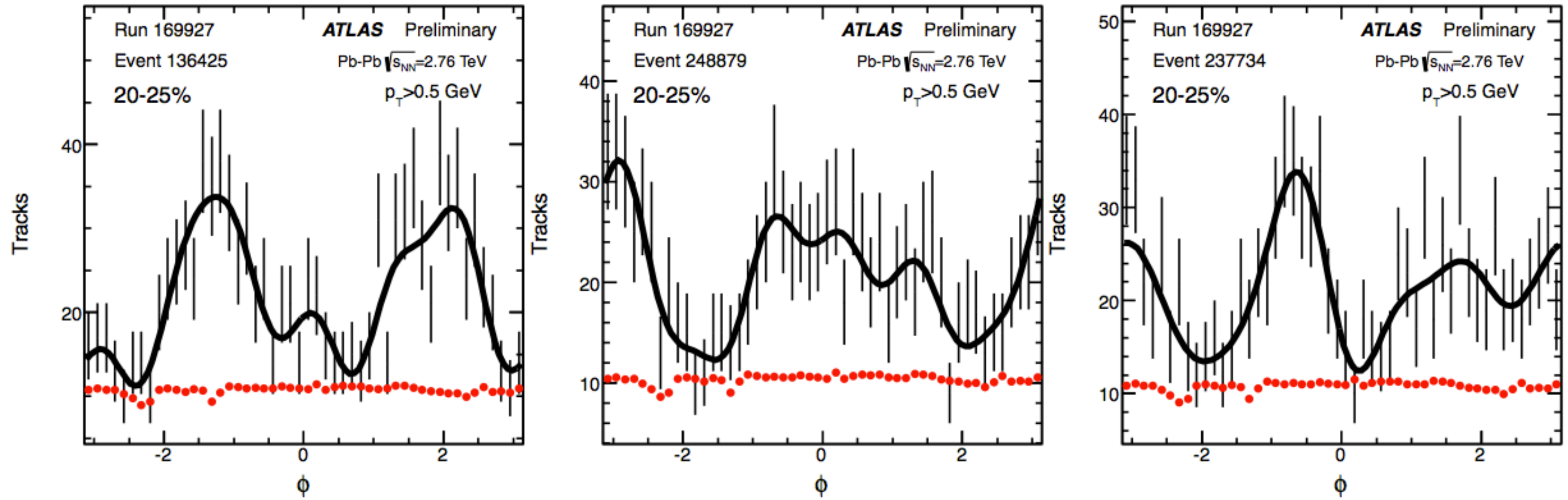
Seen in the v_n scaling and fluctuation

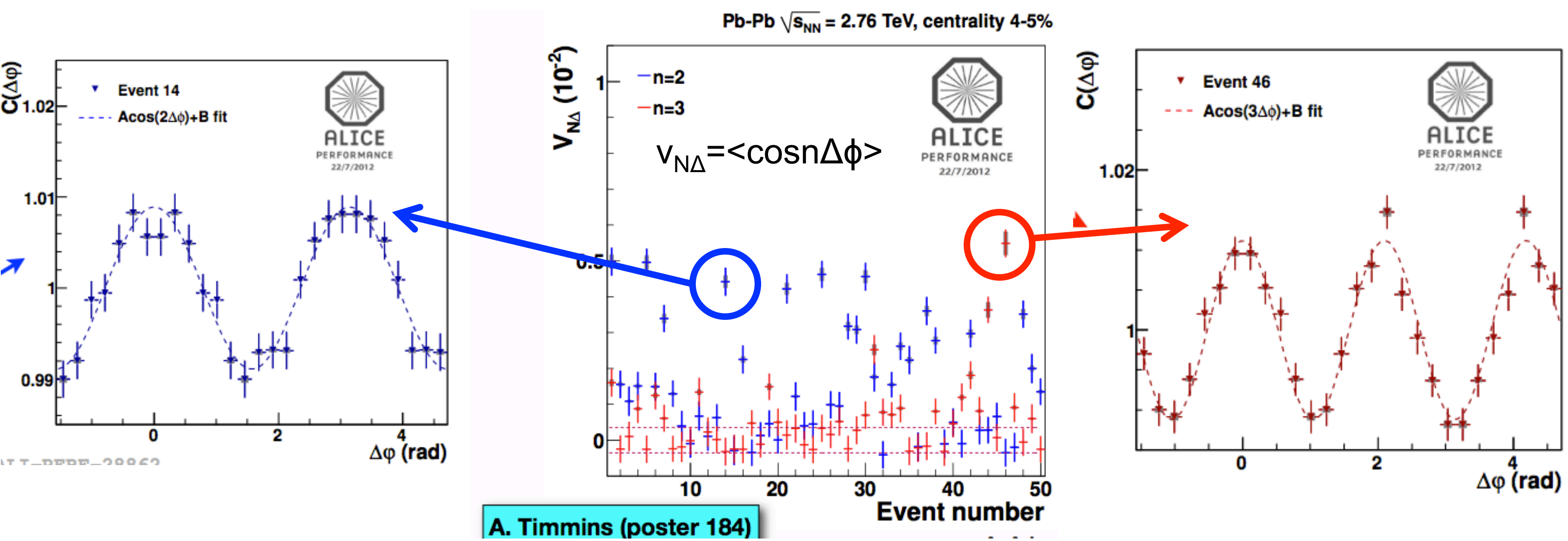




Event-by-event quantities

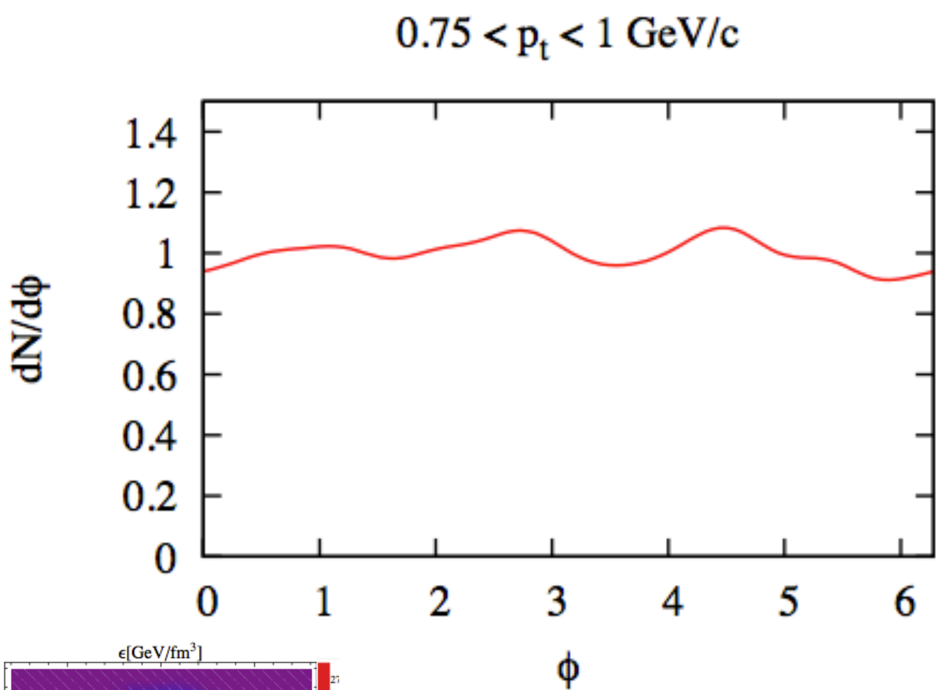
EbE v_n fluctuations

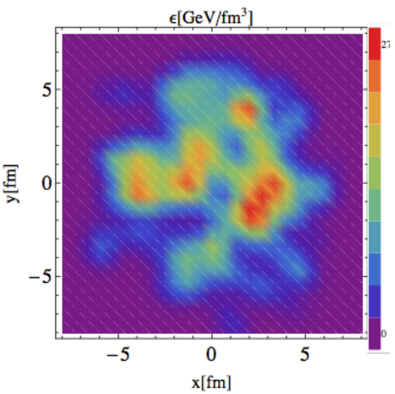




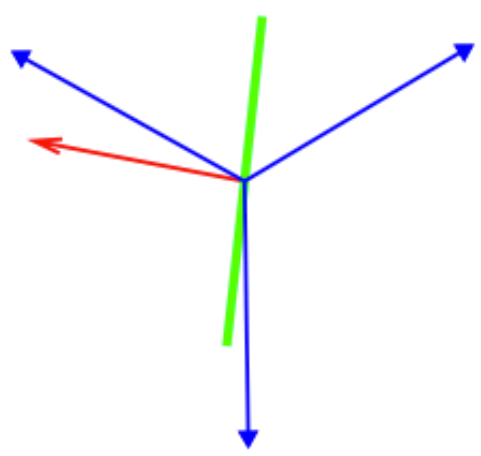
A close look at a hydro event

Jean-Yves QM2012, central event, NeXus+Ideal hydro





As p_t increases, anisotropic flow increases. ψ_2 and ψ_3 change mildly , ψ_1 rotates more strongly



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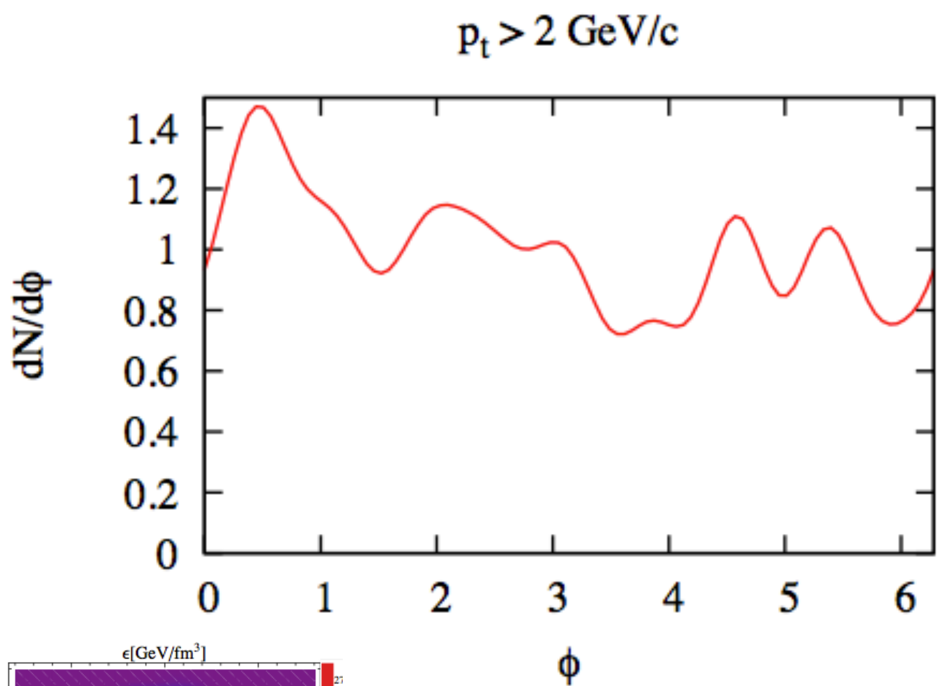
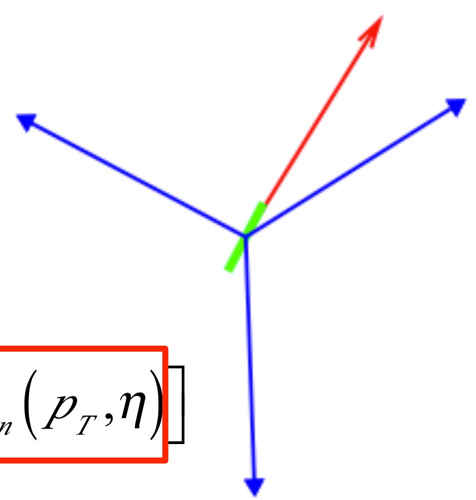
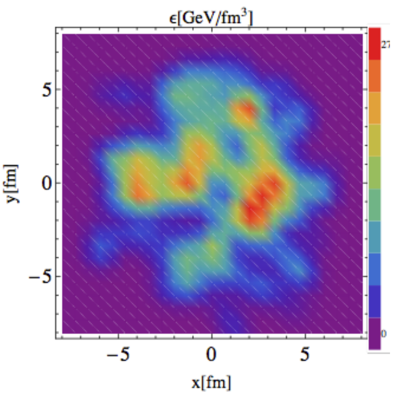


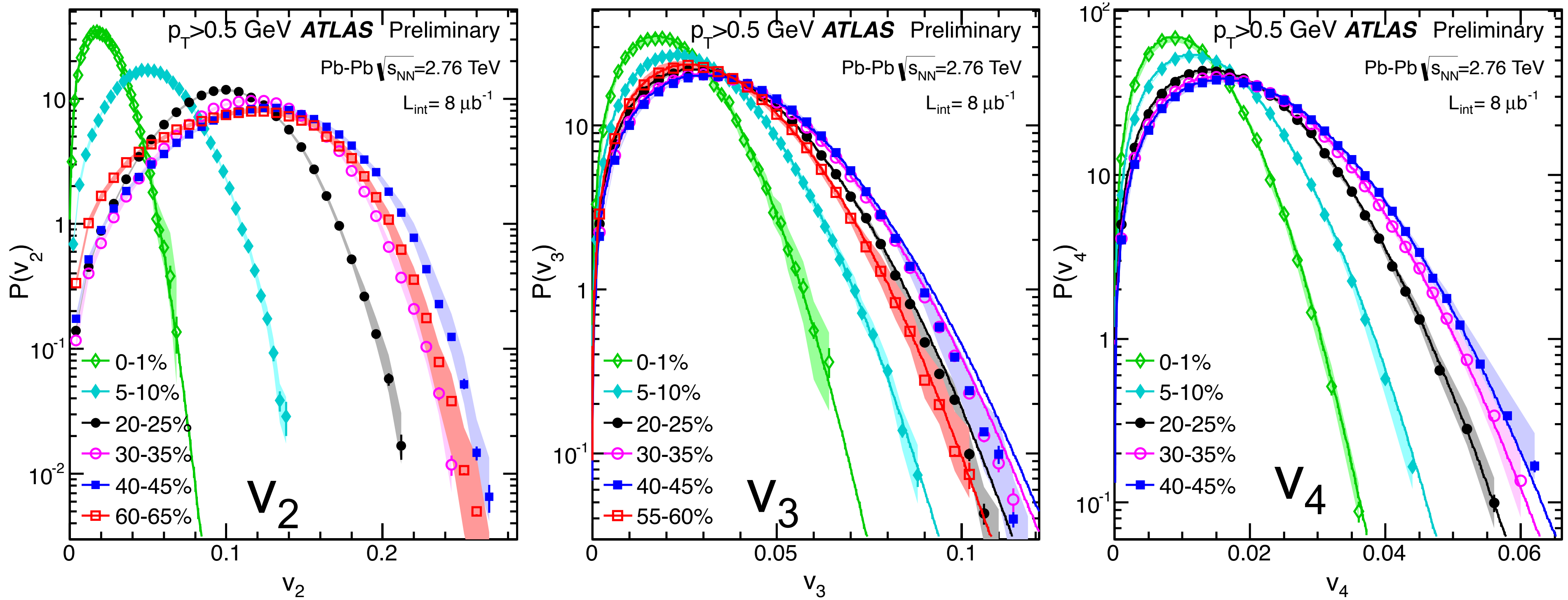
Ψ_1 rotates by π between low p_t and high p_t, because the total transverse momentum $\int p_t v_1 e^{i\Psi_1} \sim 0$.





$$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n(p_T, \eta) \cos n\left[\phi - \Phi_n(p_T, \eta)\right]$$

EbE distribution of v_n

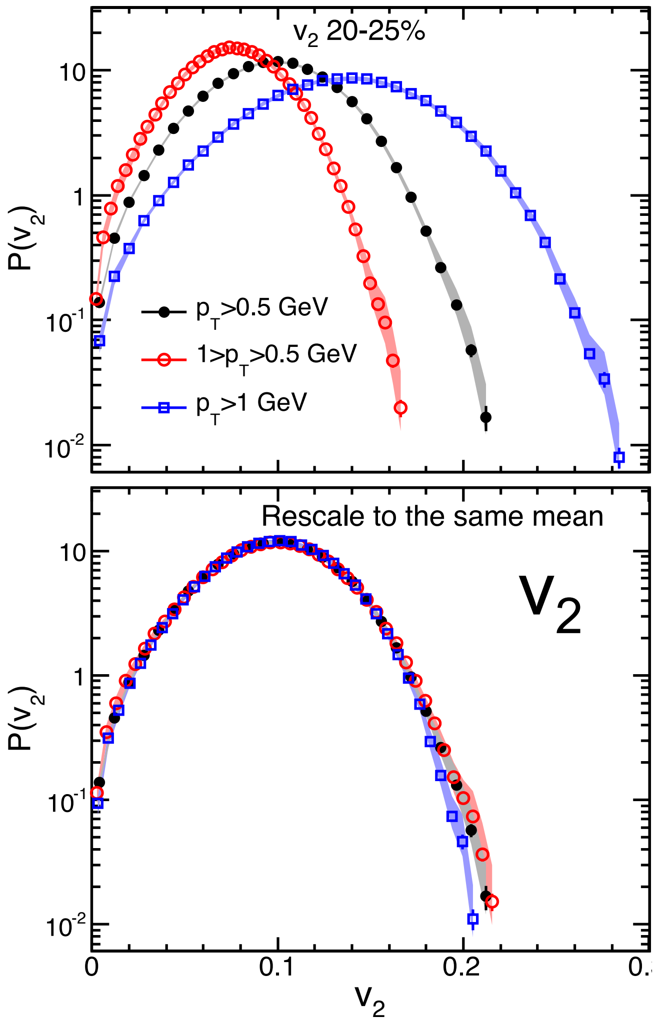


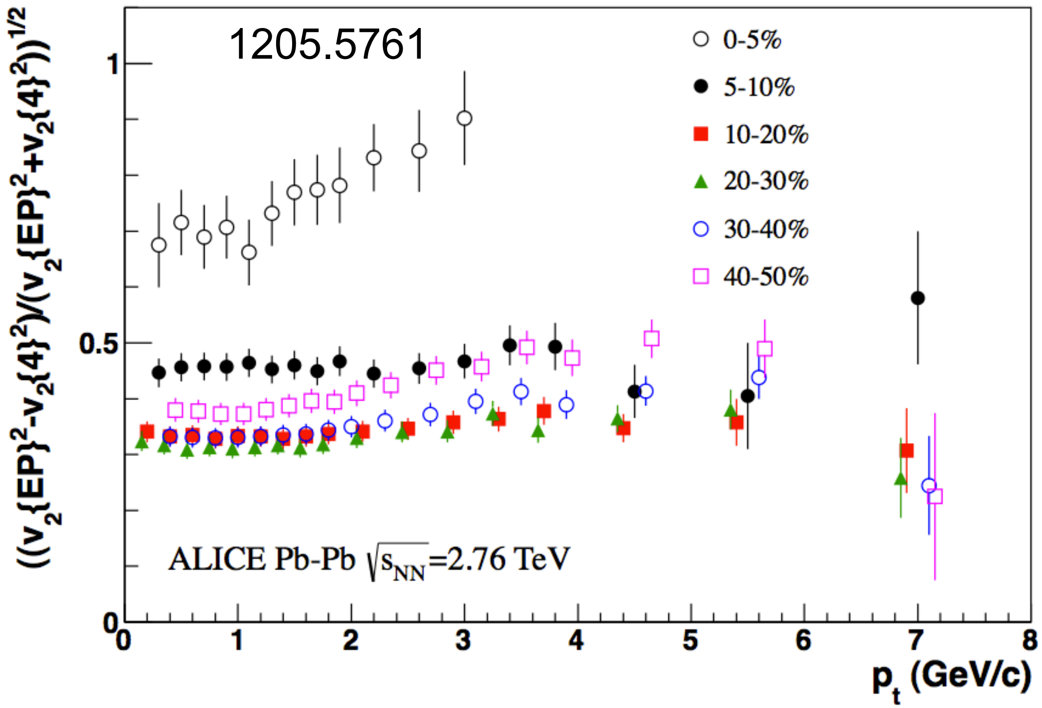
- $p(v_n)$ distributions with shape uncertainty only
- Overlaid with Gaussian function adjust to the same mean (curves)

Gaussian PDF $$P(v_n) = \frac{v_n}{\sigma^2} e^{-\frac{v_n^2}{2\sigma^2}}, \sigma = \sqrt{\frac{2}{\pi}} \langle v_n \rangle$$

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} = \sqrt{\frac{4}{\pi} - 1} = 0.523 \qquad \sqrt{\langle v_n^2 \rangle} = \frac{2}{\sqrt{\pi}} \langle v_n \rangle = 1.13 \langle v_n \rangle$$

p_T dependence of v_n shape





- Distributions for higher p_T bin is broader, but they all have ~same reduced shape. Also works at higher p_T.

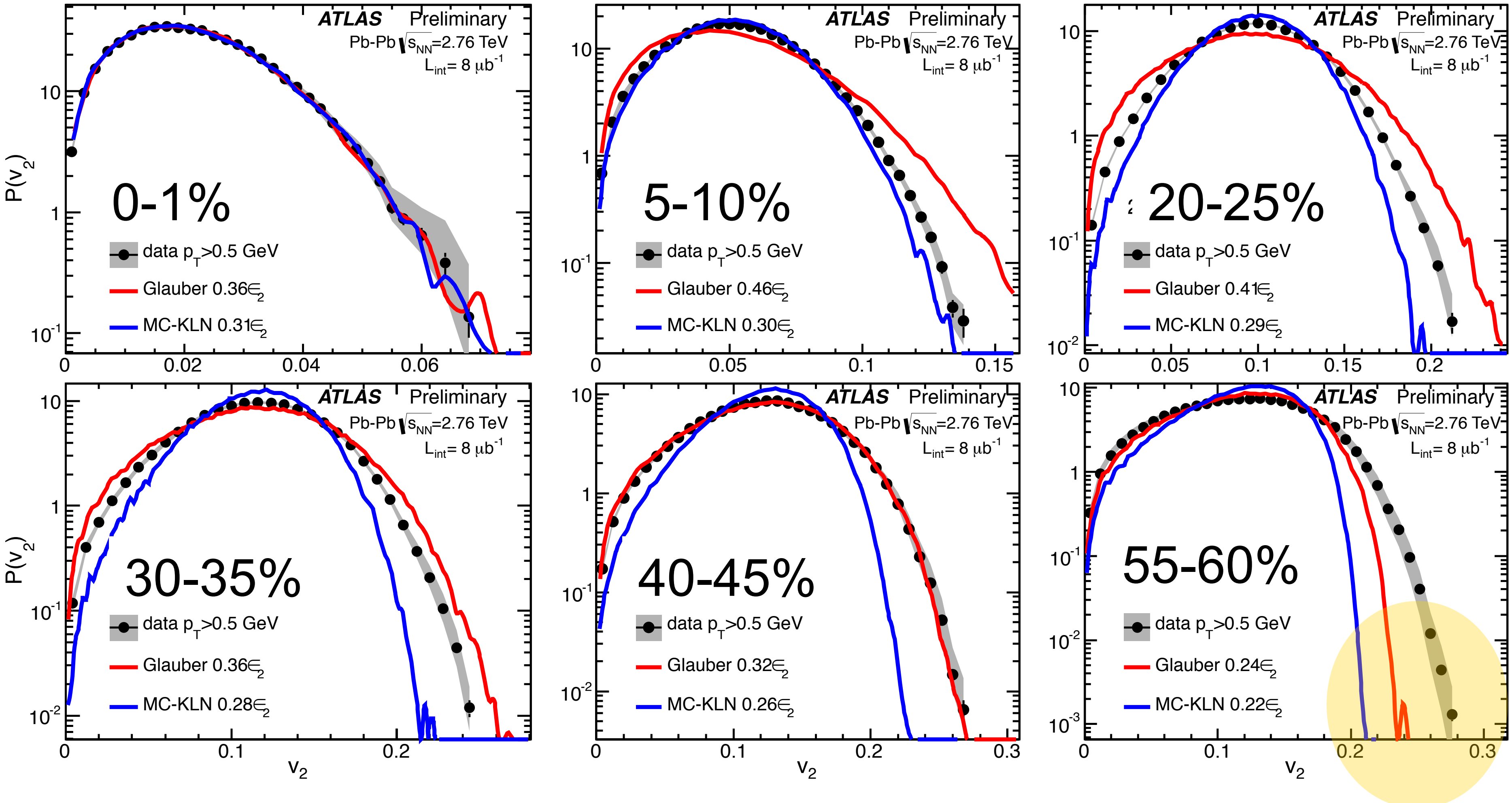
  Hydrodynamic/jet-quenching response ~ geometry.

Measuring the hydrodynamic response: v_2

- Check: $$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

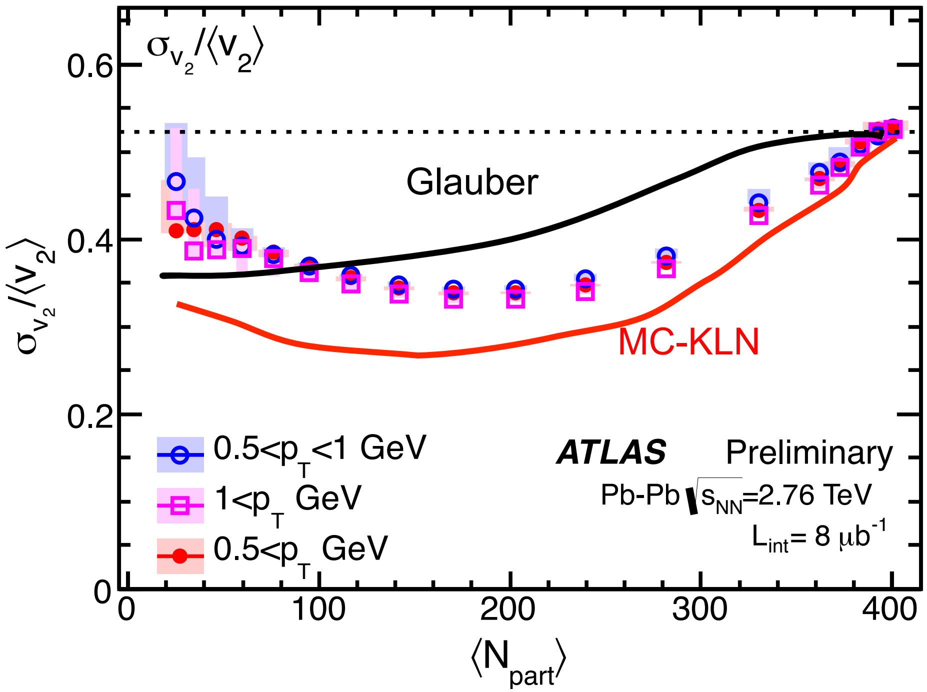
For Glauber and CGC mckln 3.46

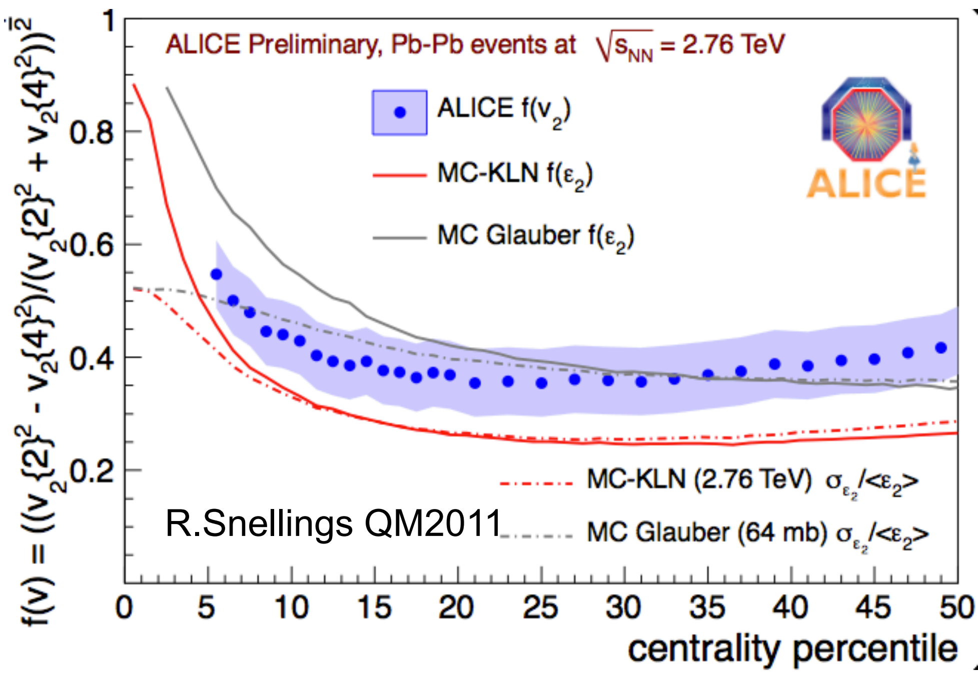
Rescale ε_n distribution to the mean of data



Both models fail describing $p(v_2)$ across the full centrality range

Glauber or MC-KLN?

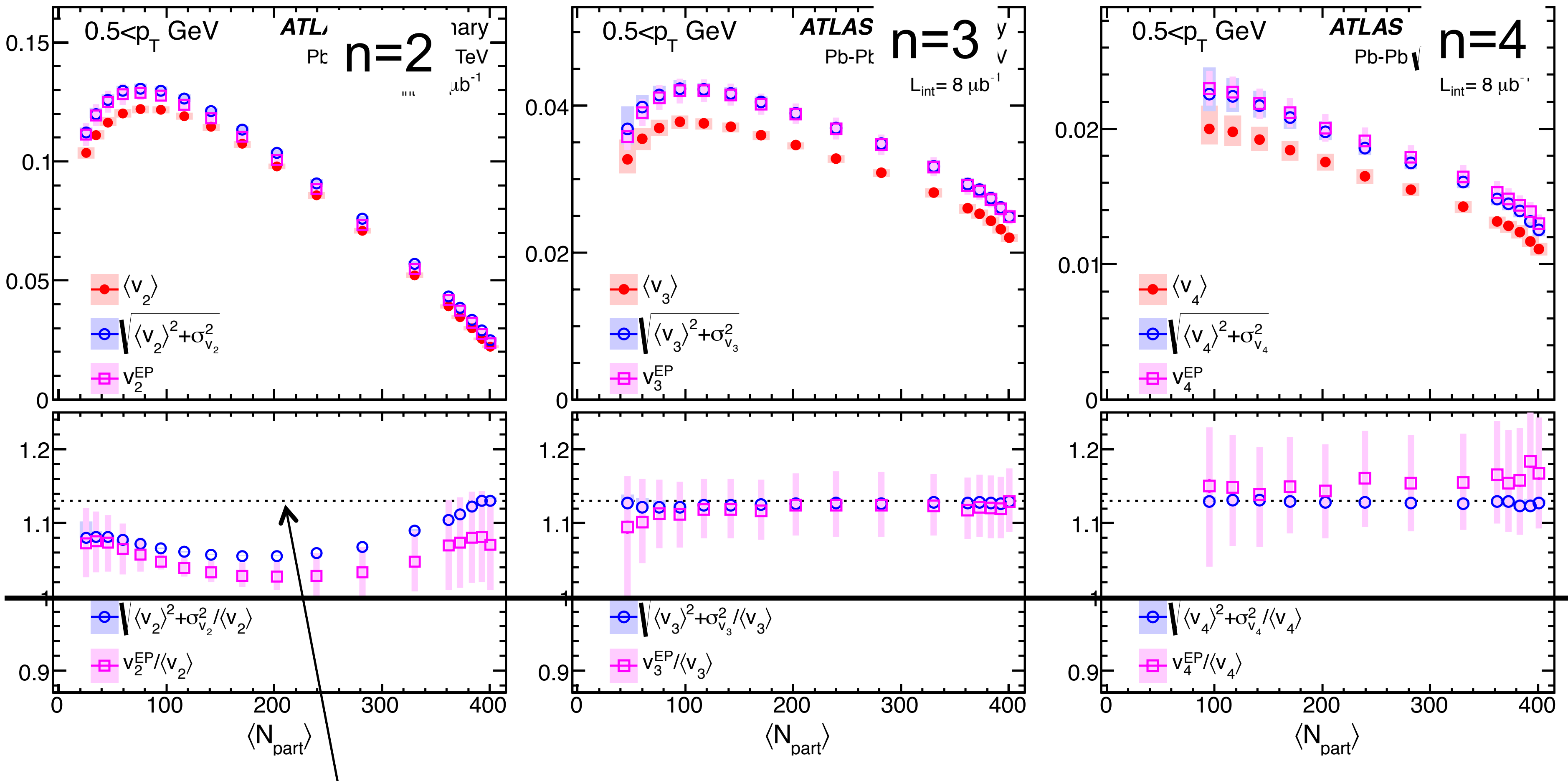




- MC-KLN works better in more central collisions
- Glauber better in more peripheral collisions

Compare to v_n^{EP} results

- Expectations: $\langle v_n\rangle \le v_n^{EP} \le \sqrt{\langle v_n^2\rangle} = \sqrt{\langle v_n\rangle^2 + \sigma_{v_n}^2}$ **Verified!!**

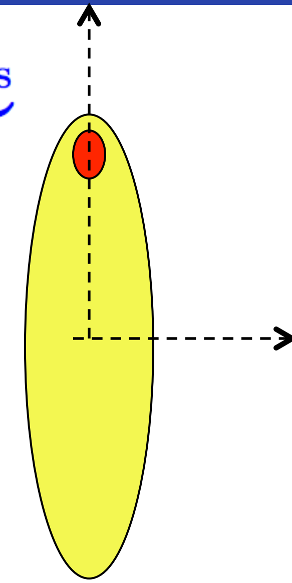


$$\sqrt{\langle v_n^2\rangle} = \frac{2}{\sqrt{\pi}}\langle v_n\rangle = 1.13\langle v_n\rangle$$

Correlations between Φ_n, Φ_m etc

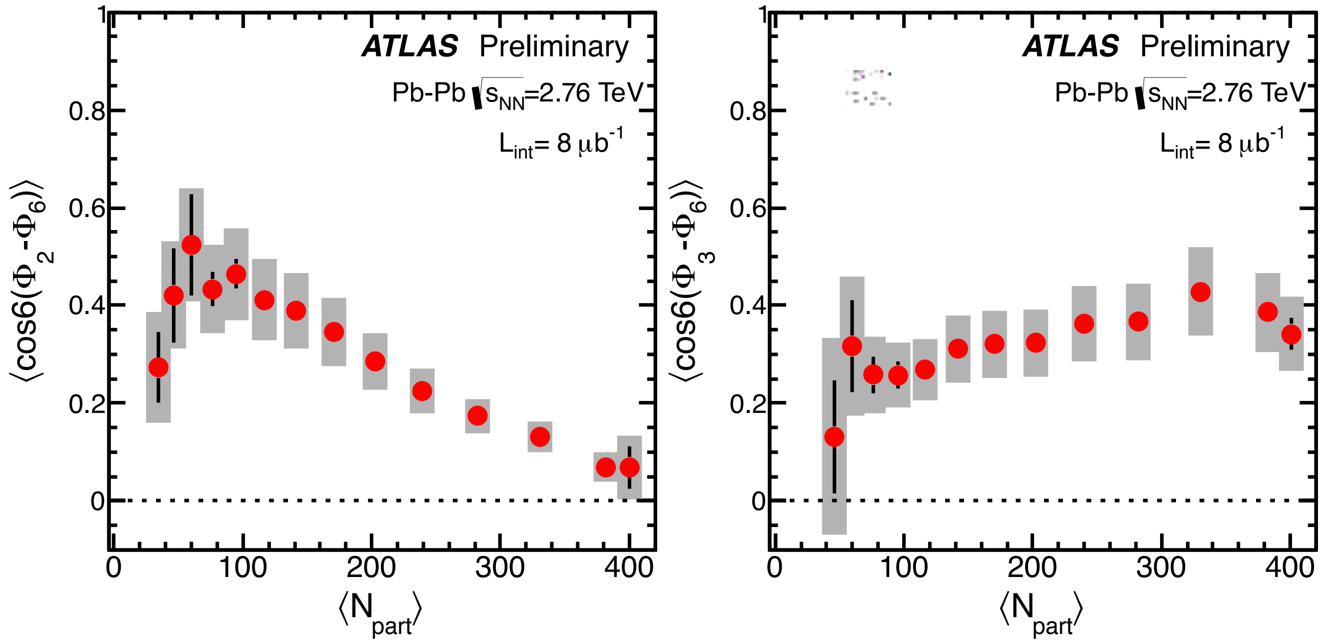
Initial correlations + Flow response = Reaction place correlations

Initial state(cumulants) | Linear & Non-linear | Final state



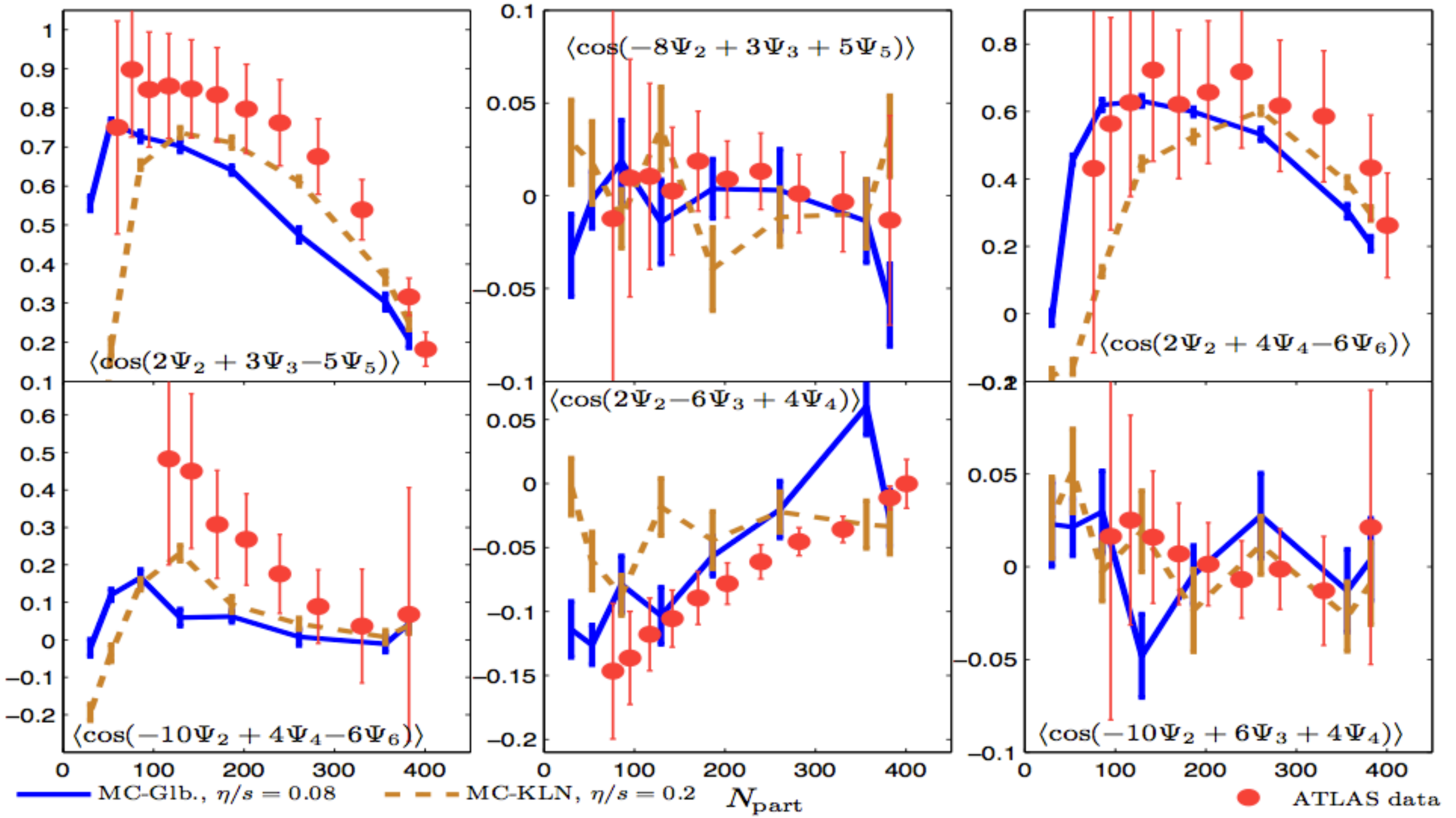
$$\frac{dN_{\text{evts}}}{d\,(k(\Phi_n-\Phi_m))} \propto 1+2\sum_{j=1}^{\infty} V^j_{n,m}\cos jk(\Phi_n-\Phi_m)$$

$$V^j_{n,m} = \langle \cos jk(\Phi_n-\Phi_m)\rangle$$



$$v_6 e^{-i6\Psi_6} = \text{geometry} + v_2 v_2 v_2 e^{-i6\Psi_2} + v_3 v_3 e^{-i6\Psi_3} + v_2 v_4 e^{-i2\Psi_2 - i4\Psi_4} + \ldots$$

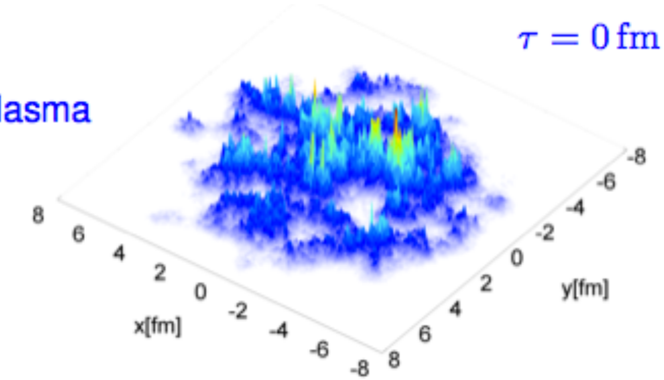
Correlations between three EP

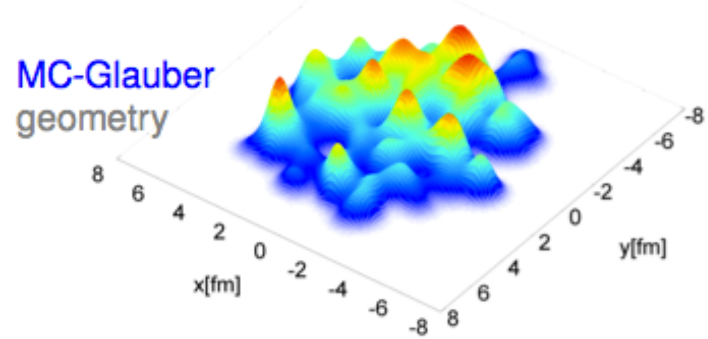


- Dynamic mixing in hydrodynamics Not only v_n, but also $v_{n,m}$, $v_{n,m,k}$ etc

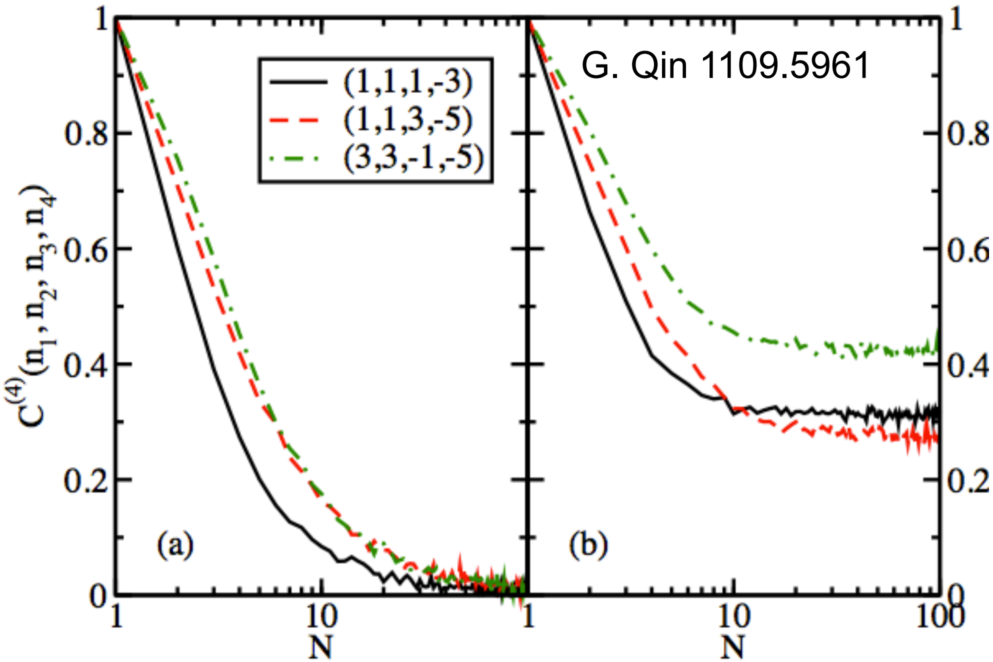
$$v_5 e^{-i5\Psi_5} = \text{geometry} + v_2 v_3 e^{-i2\Psi_2 - i3\Psi_3} + \ldots$$

How to measure number/size of the hot spots?





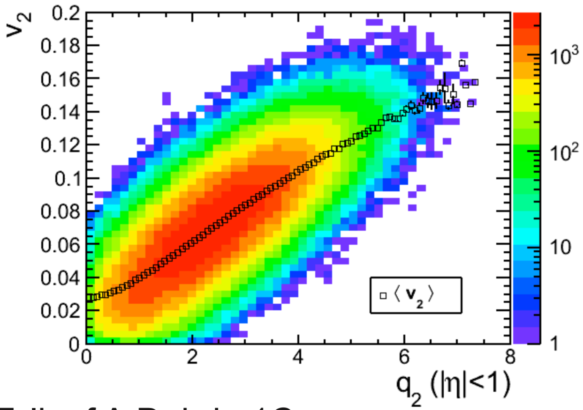
Not so easy due to non-linear effects



EVENT SHAPE ENGINEERING

Talk of S.Voloshin: Plenary IC

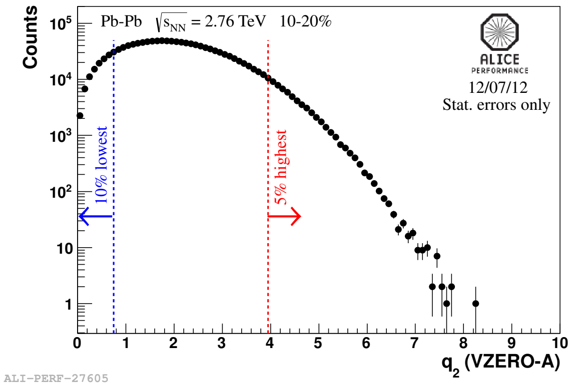
- Selection of azimuthally anisotropic events: length of flow vector, q_2



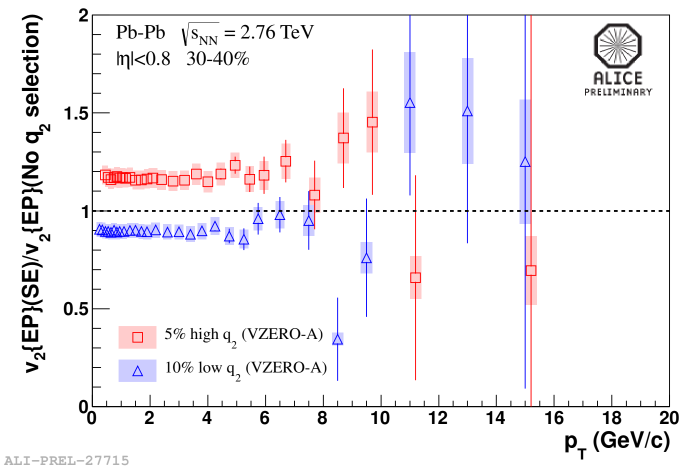
$$Q_{n,X} = \sum_{i=1}^{M} \cos(n\phi_i)$$

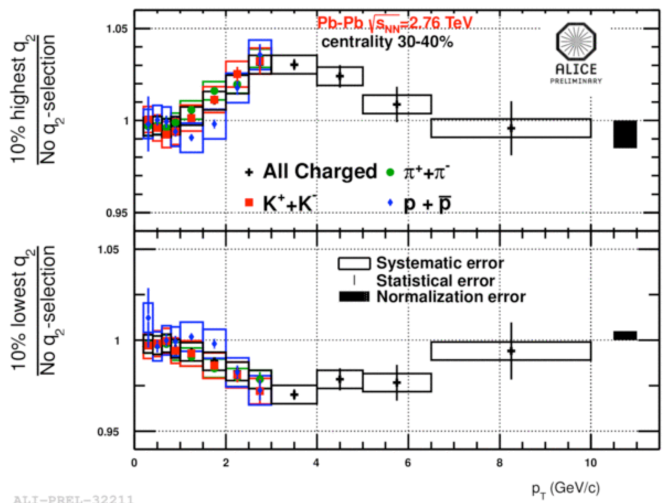
$$Q_{n,Y} = \sum_{i=1}^{M} \sin(n\phi_i)$$

$$q_n = Q_n/\sqrt{M}$$



Talk of A.Dobrin:1C





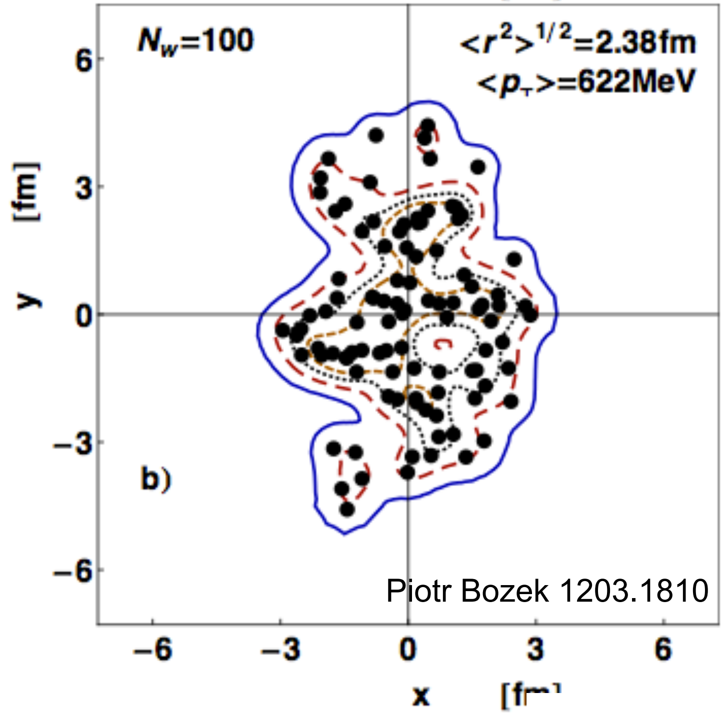
Talk of L.Milano: 5A

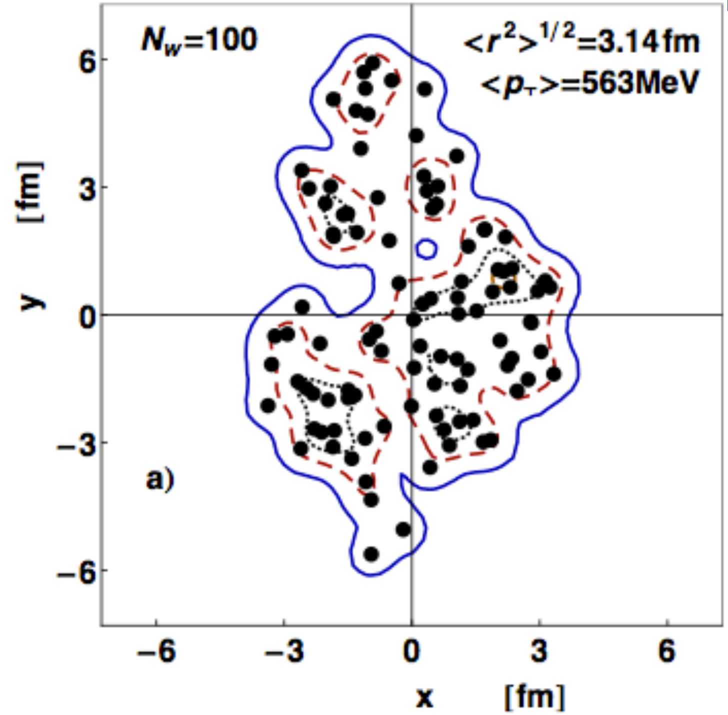
expected effect on v_2 and consequence on PID'ed transverse momentum spectra

Largely expected since $v_2 \sim \varepsilon_2$.

More useful as a tool for jet tomography?

Transverse size fluctuation





$$\frac{\sigma(\langle p_T \rangle)}{\langle\langle p_T \rangle\rangle} \simeq 0.3 \frac{\sigma(\langle r \rangle)}{\langle\langle r \rangle\rangle}$$