Flow harmonics in ATLAS

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for the ATLAS Collaboration

Outline

Introduction

- **The ATLAS apparatus**
- **Event samples**
- **Heavy Ion event environment**

Measurement of flow harmonics

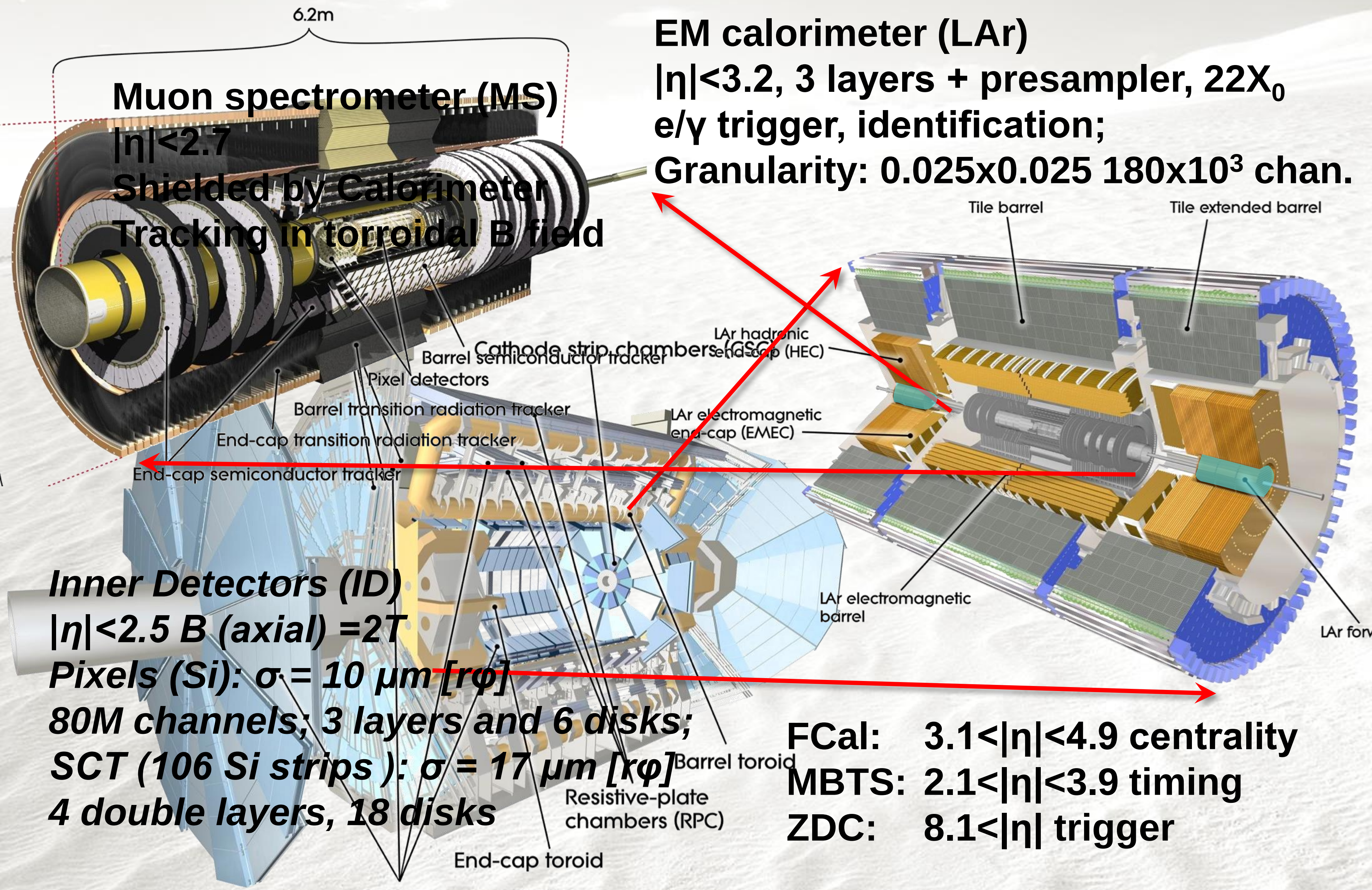
- **Event by event method**
- **Average flow method**
- **Event plane correlations**
- **Two particle correlation**
- **Cumulant method**
- **Integrated flow**

Summary

The ATLAS detector

EM calorimeter (LAr)
|η|<3.2, 3 layers + presampler, $22X_0$
e/γ trigger, identification;
Granularity: 0.025x0.025 180×10^3 chan.

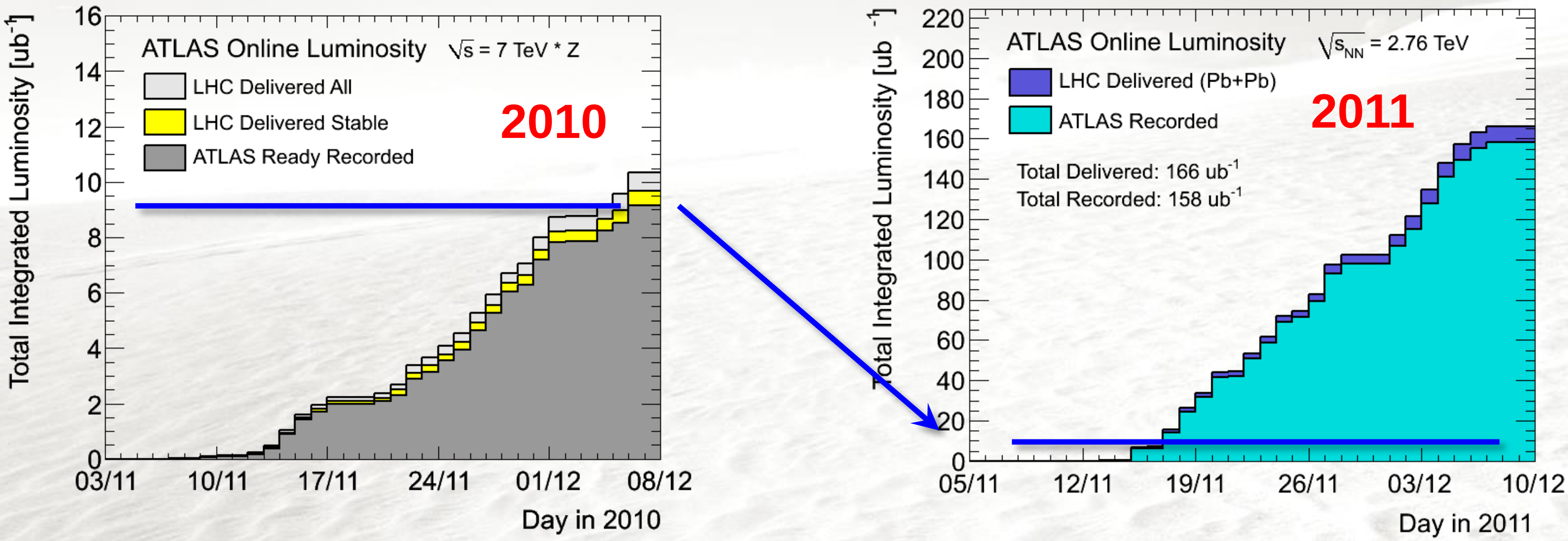
Muon spectrometer (MS)
|η|<2.7
Shielded by Calorimeter
Tracking in torroidal B field



Inner Detectors (ID)
|η|<2.5 B (axial) =2T
Pixels (Si): σ = 10 μm [rφ]
80M channels; 3 layers and 6 disks;
SCT (106 Si strips): σ = 17 μm [rφ]
4 double layers, 18 disks

FCal: 3.1<|η|<4.9 centrality
MBTS: 2.1<|η|<3.9 timing
ZDC: 8.1<|η| trigger

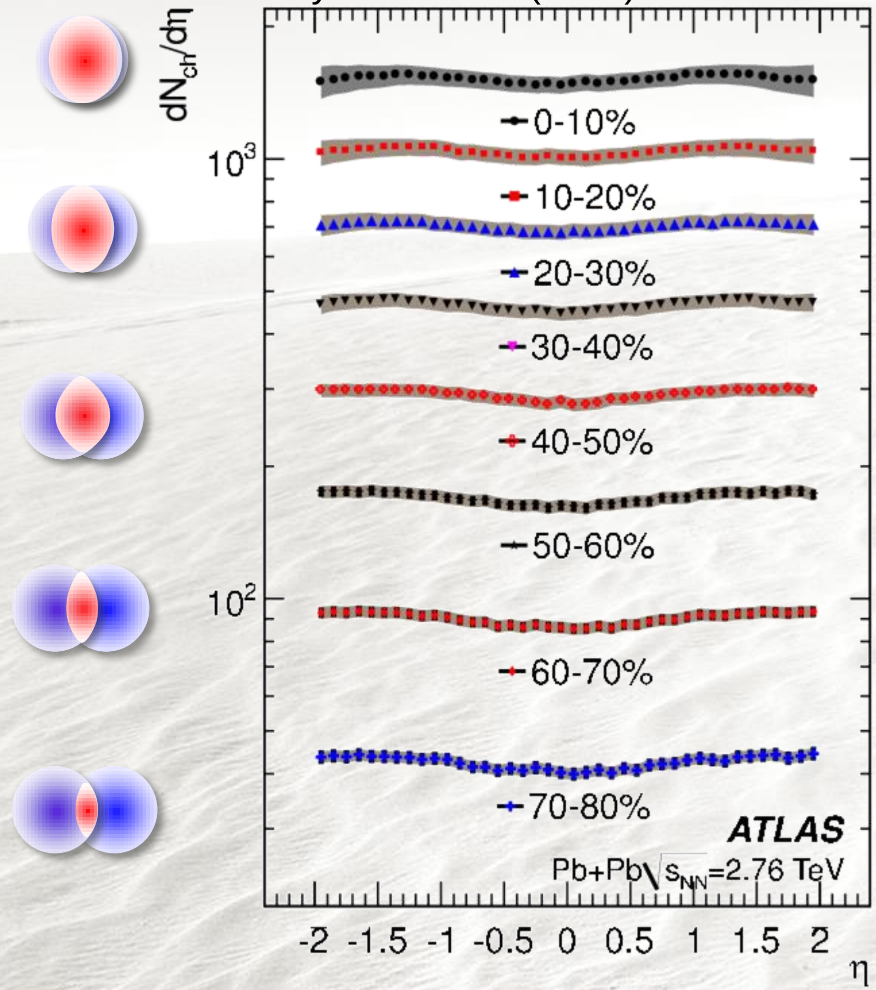
Data samples

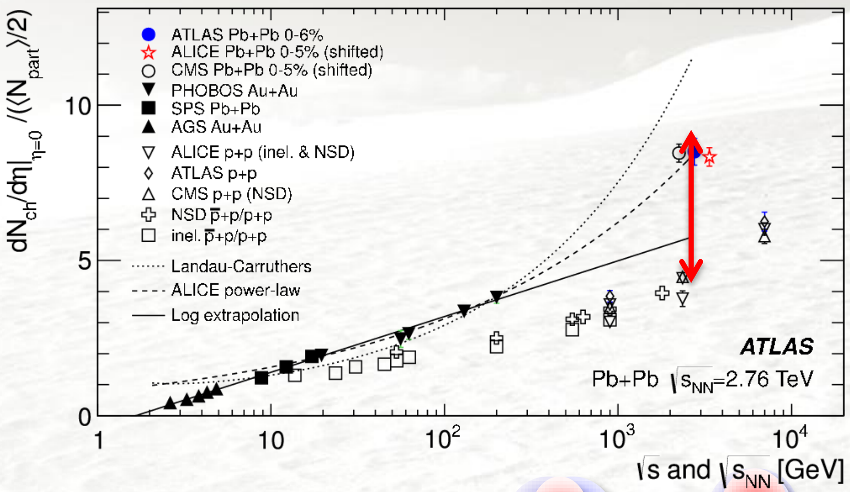


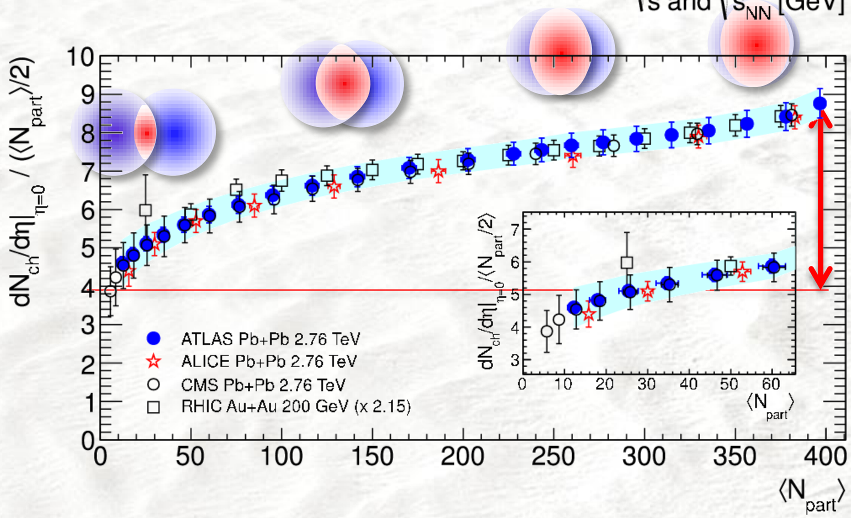
Run:	2010	2011
L_{int}	$8ub^{-1}$	$0.15nb^{-1}$
Triggers	Min Bias	γ, μ, jets, Min Bias, UPC
N_{events} (0-80)%	30-40M	750-800M

Multiplicity

Phys.Lett.B710 (2012) 363-382







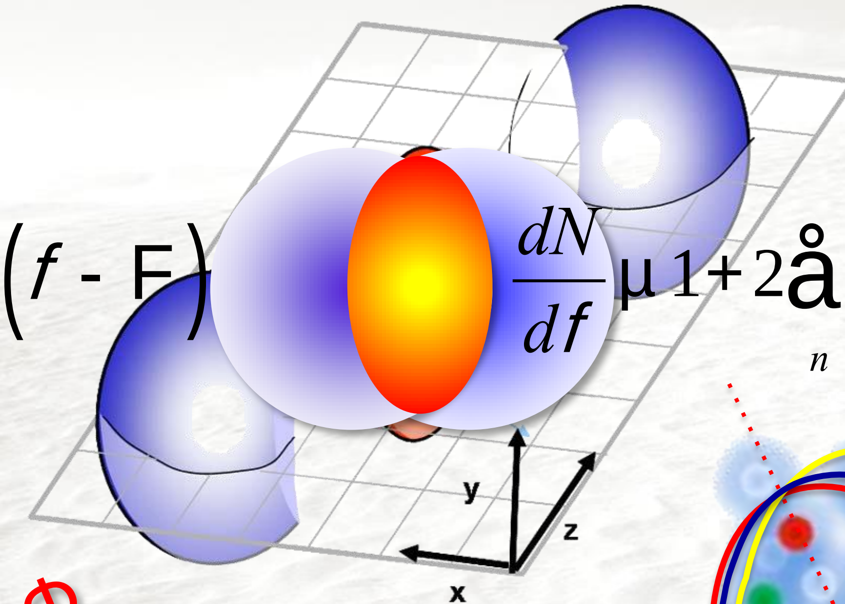
Up to 8,000 charged particles in ATLAS tracking @ $\sqrt{s_{NN}}$=2.76 TeV

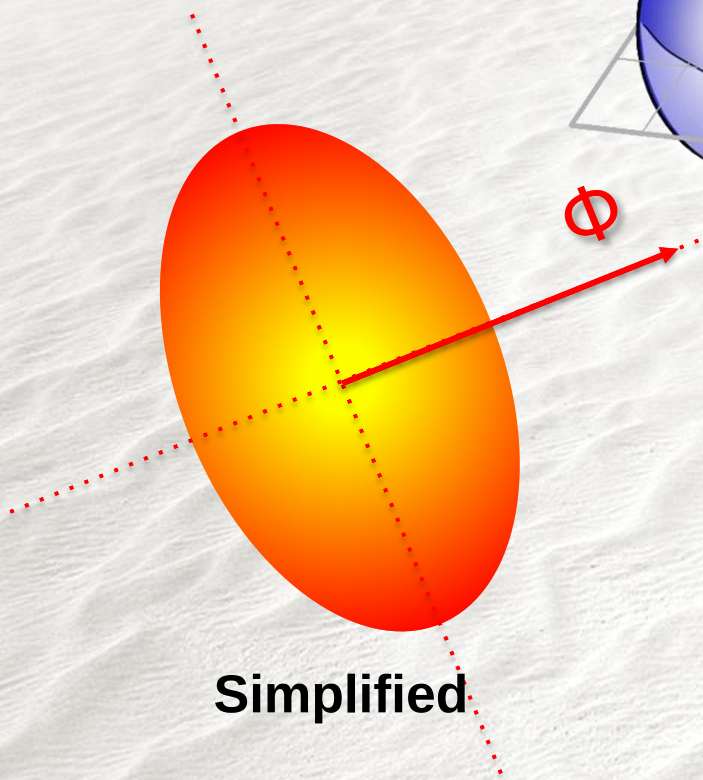
Flat in rapidity within |η|<2, similar to p+p

Twice more particles per participant pair compared to p+p

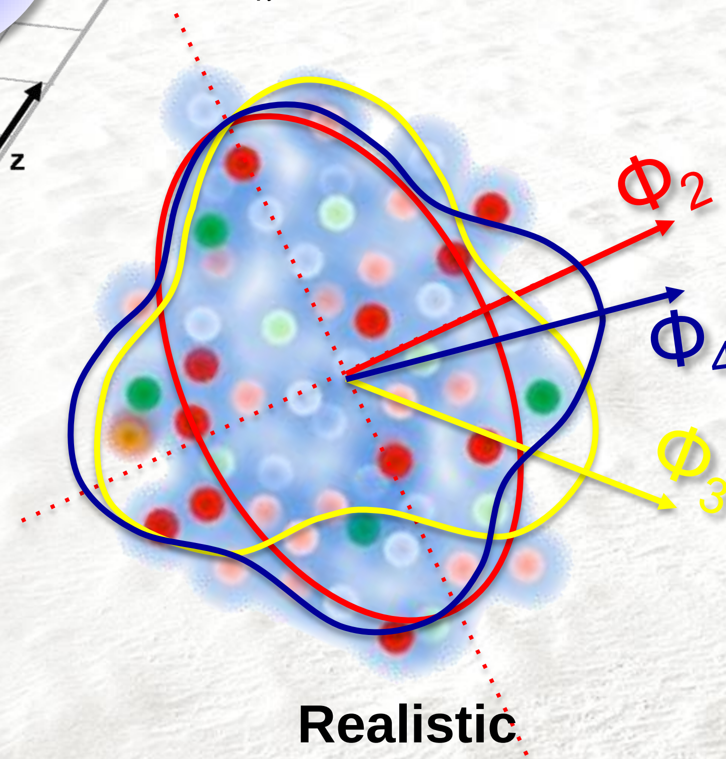
Initial geometry

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2(\phi - \Phi) \qquad \frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$





Simplified



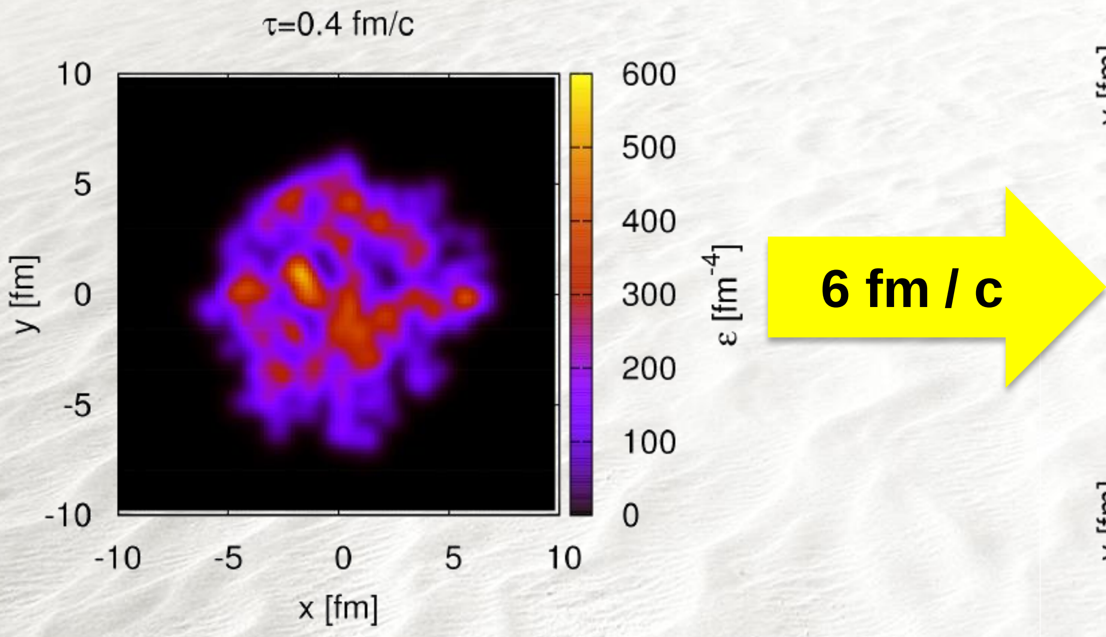
Realistic

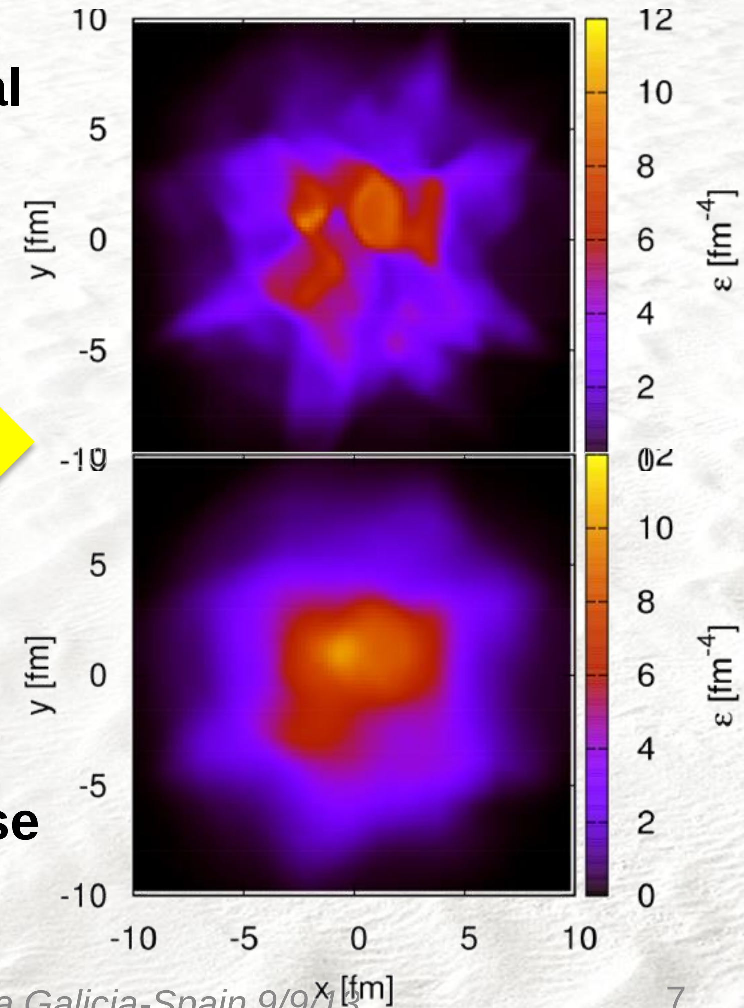
Initial → Final

Hydrodynamic evolution of the system

Natural parameter: viscosity scaled with the particle density (entropy density, s)

low η/s means strong coupling



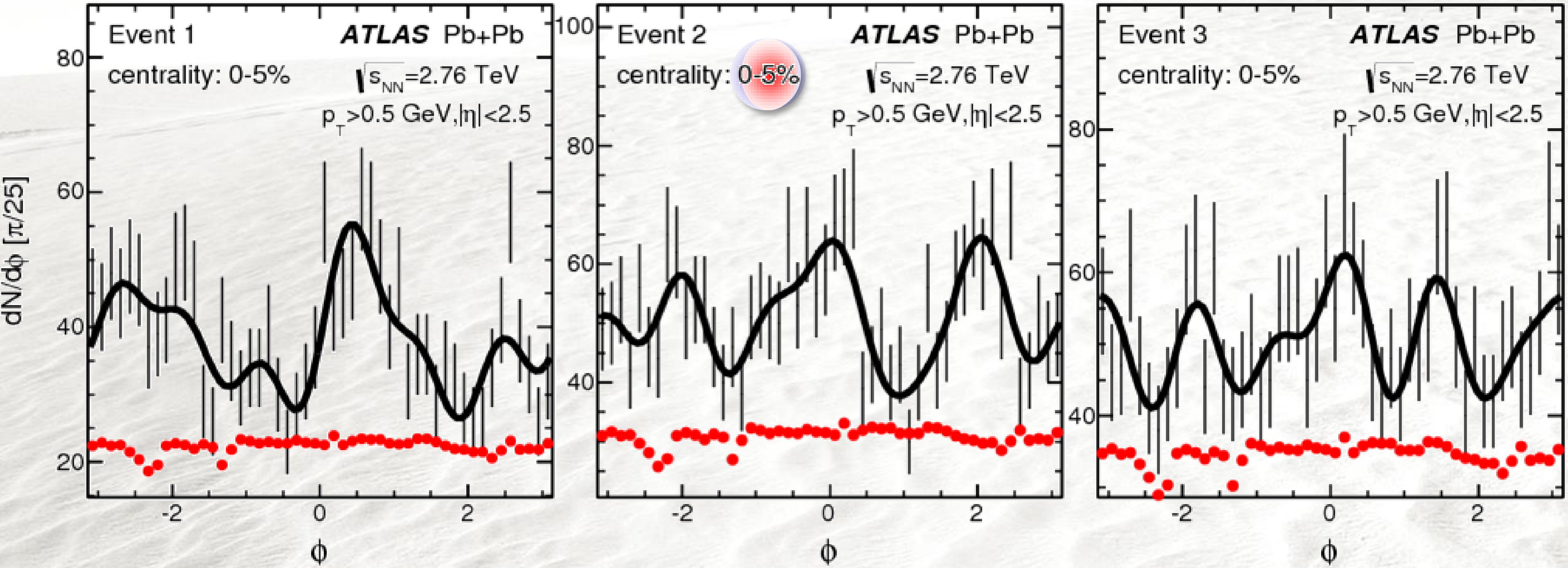


Phys.Rev.Lett.106, 042301 (2011)

Fluctuations event-by-event

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

arXiv:1305.2942



Significant fluctuations, factor of ~2
Cannot be explained by detector effects
Shall be corrected for:

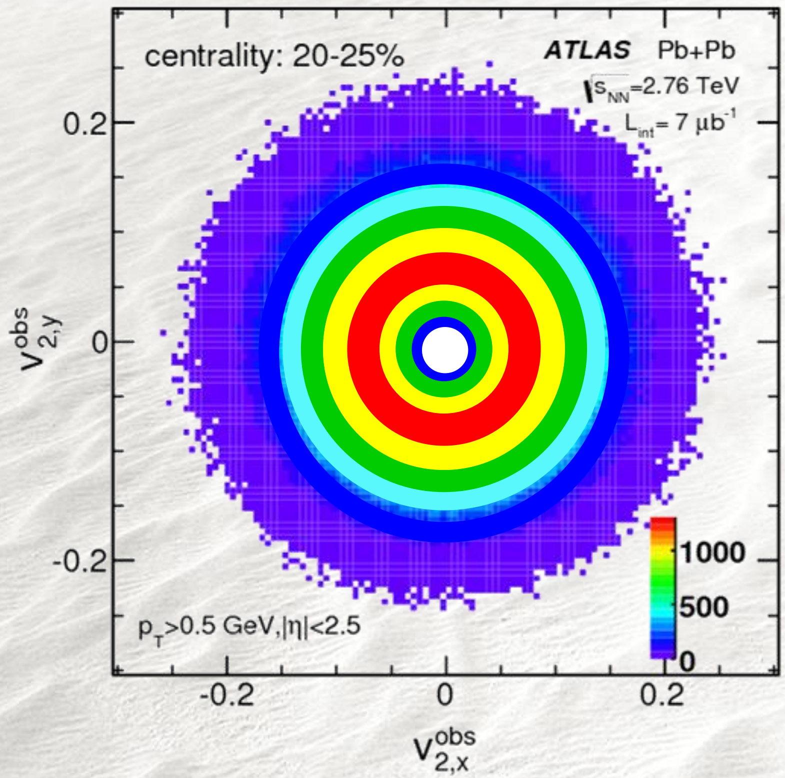
- **efficiency**
- **acceptance**
- **limited statistics**

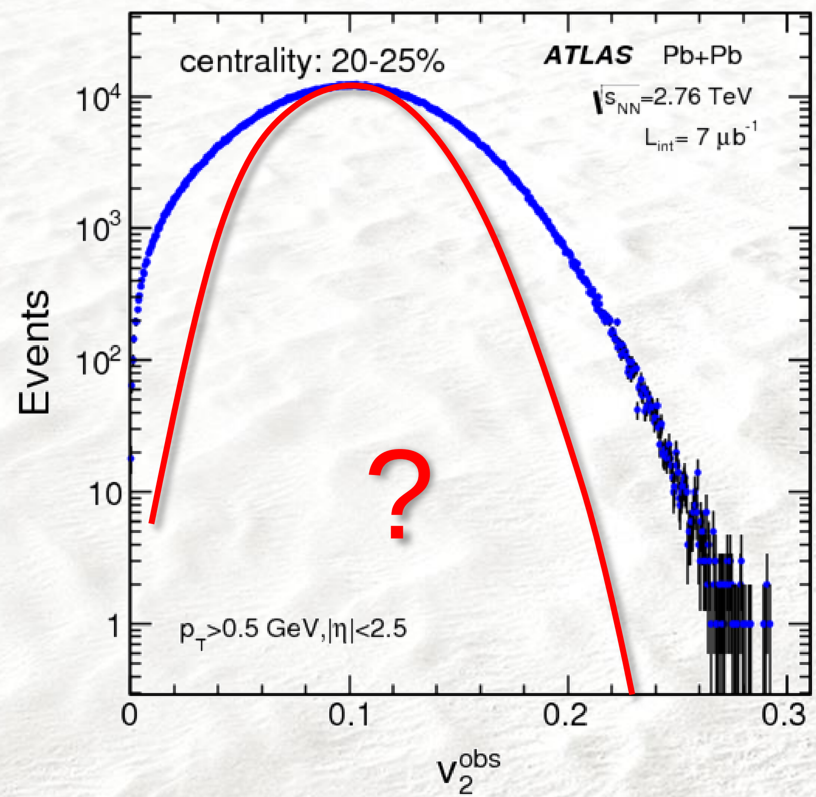
Flow vector and smearing

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \left(v_{n,x}^{obs}\cos(n\phi) + v_{n,y}^{obs}\sin(n\phi) \right)$$

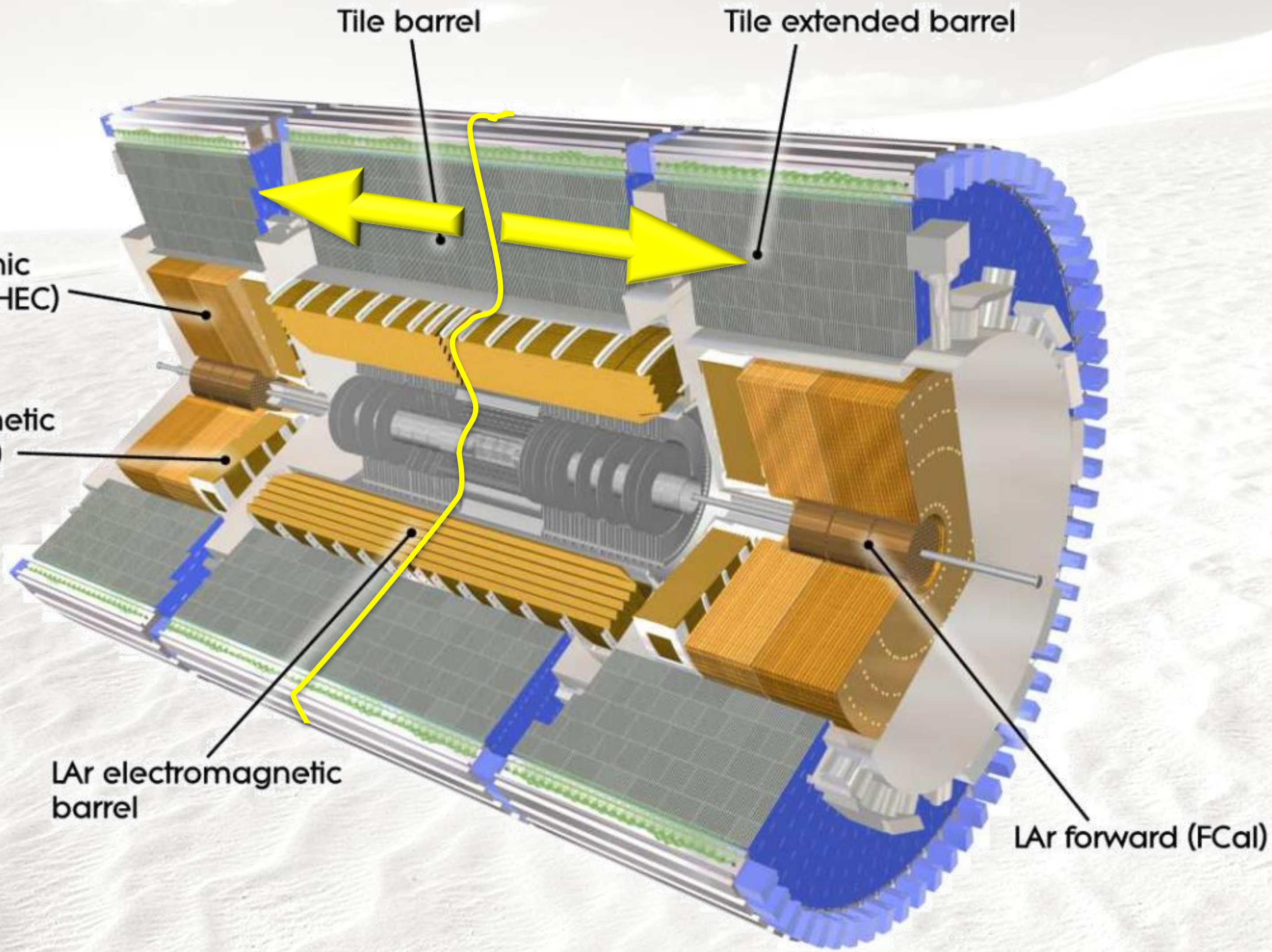
$$\vec{v}_n^{\,obs} = (v_{n,x}^{obs}, v_{n,y}^{obs}) = \vec{v}_n^{\,true} + \vec{p}_n^{\,smear}$$

arXiv:1305.2942



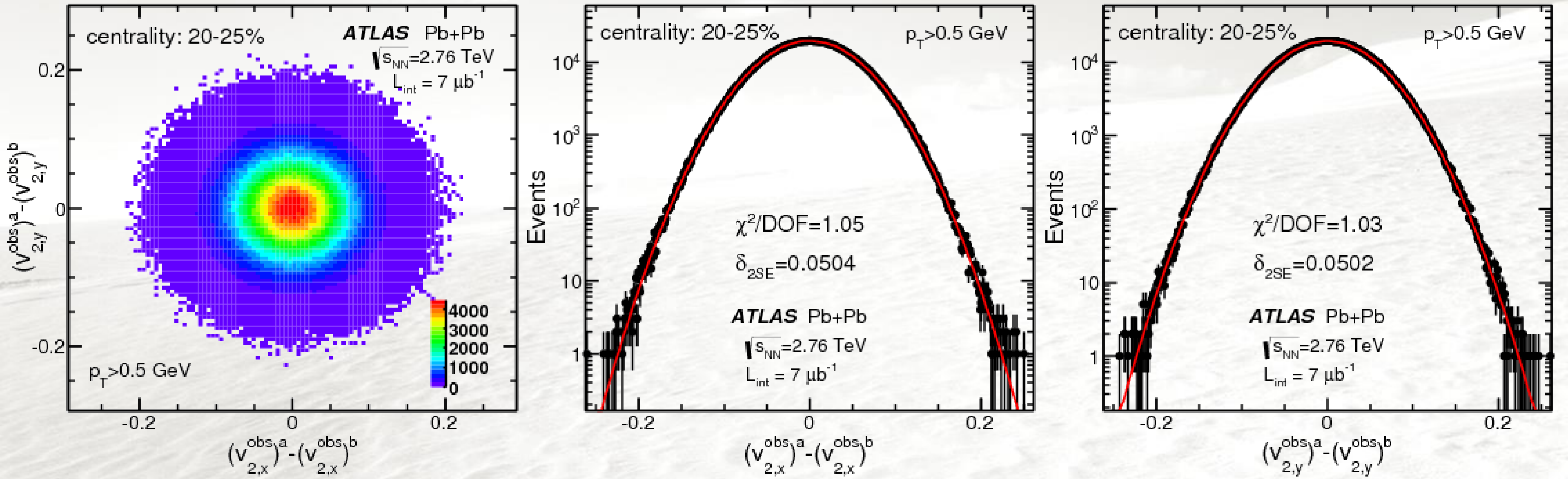


Split event into two



Sub-event "A" – Sub-event "C" =
- **Signal: subtracted**
- **Fluctuations: √2 larger**

Getting the response function



2D response function is a 2D Gaussian

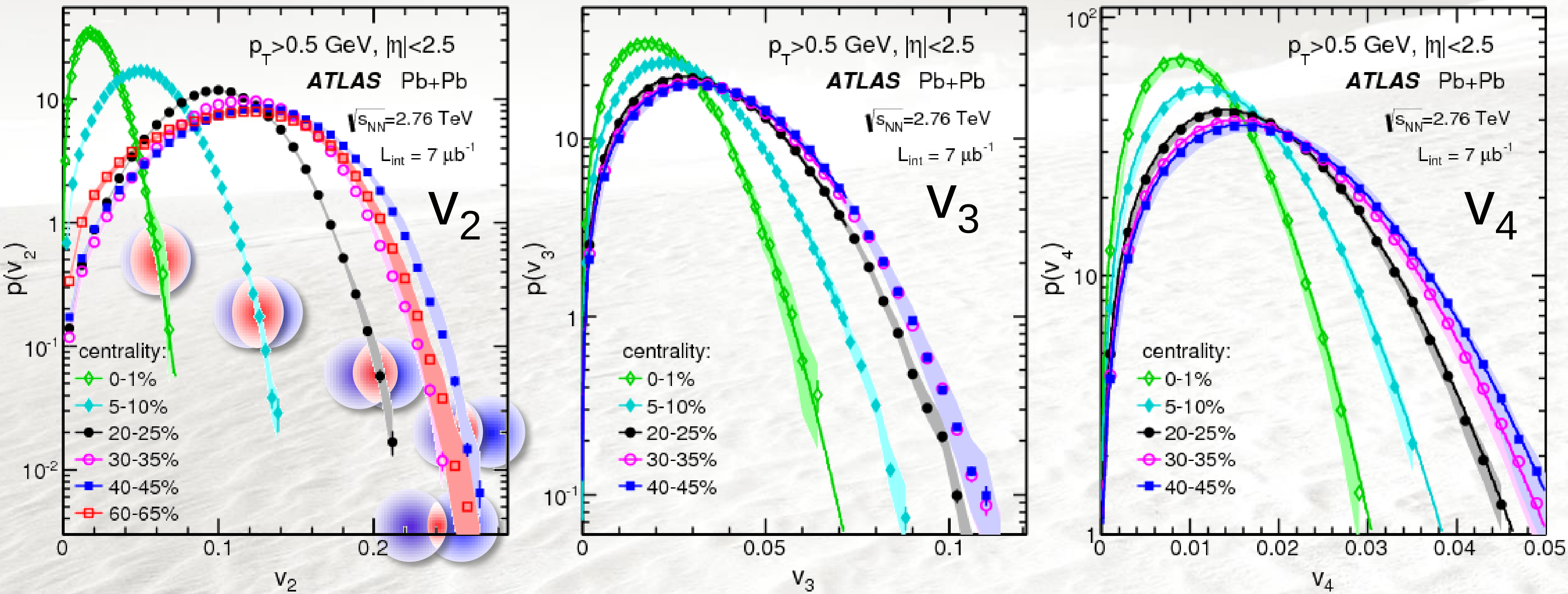
arXiv:1305.2942

$$p(\vec{v}_n^{\,obs}|\vec{v}_n) \propto e^{-\frac{|\vec{v}_n^{\,obs}-\vec{v}_n|^2}{2\delta^2}} \qquad \delta = \begin{cases} \delta_{2SE}/\sqrt{2} & \text{for half ID} \\ \delta_{2SE}/2 & \text{for full ID} \end{cases}$$

Done by iterations, convergence after N_{iter}=8, some require longer.

Data driven method, no additional assumptions are required

Flow probability distributions



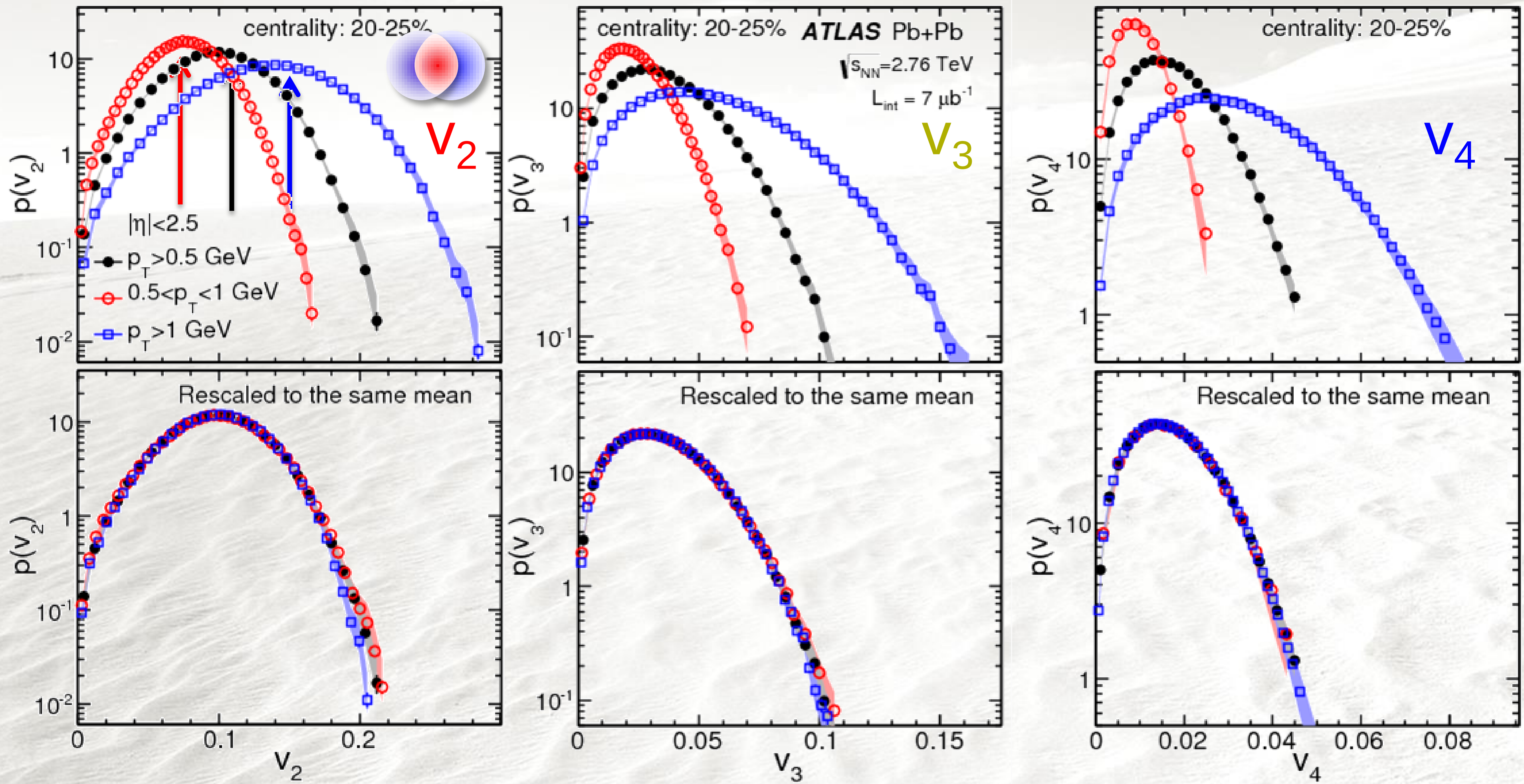
arXiv:1305.2942

v_n distributions in p_T and centrality

Fully corrected for detector effects an unfolded for limited statistics

arXiv:1305.2942

p_T scaling

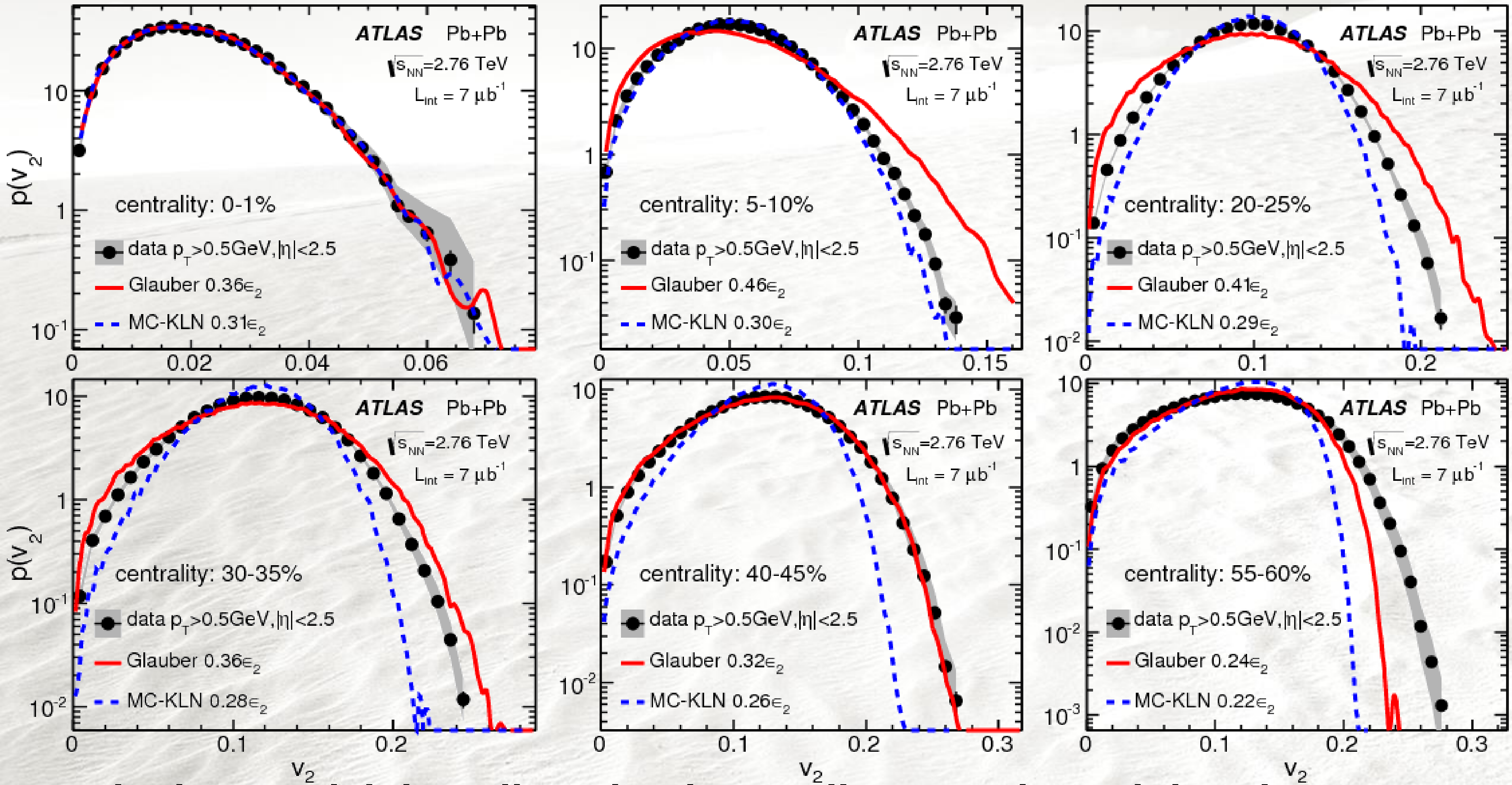


All p_T bins have similar shape

Holds for all measured n

Comparison to models

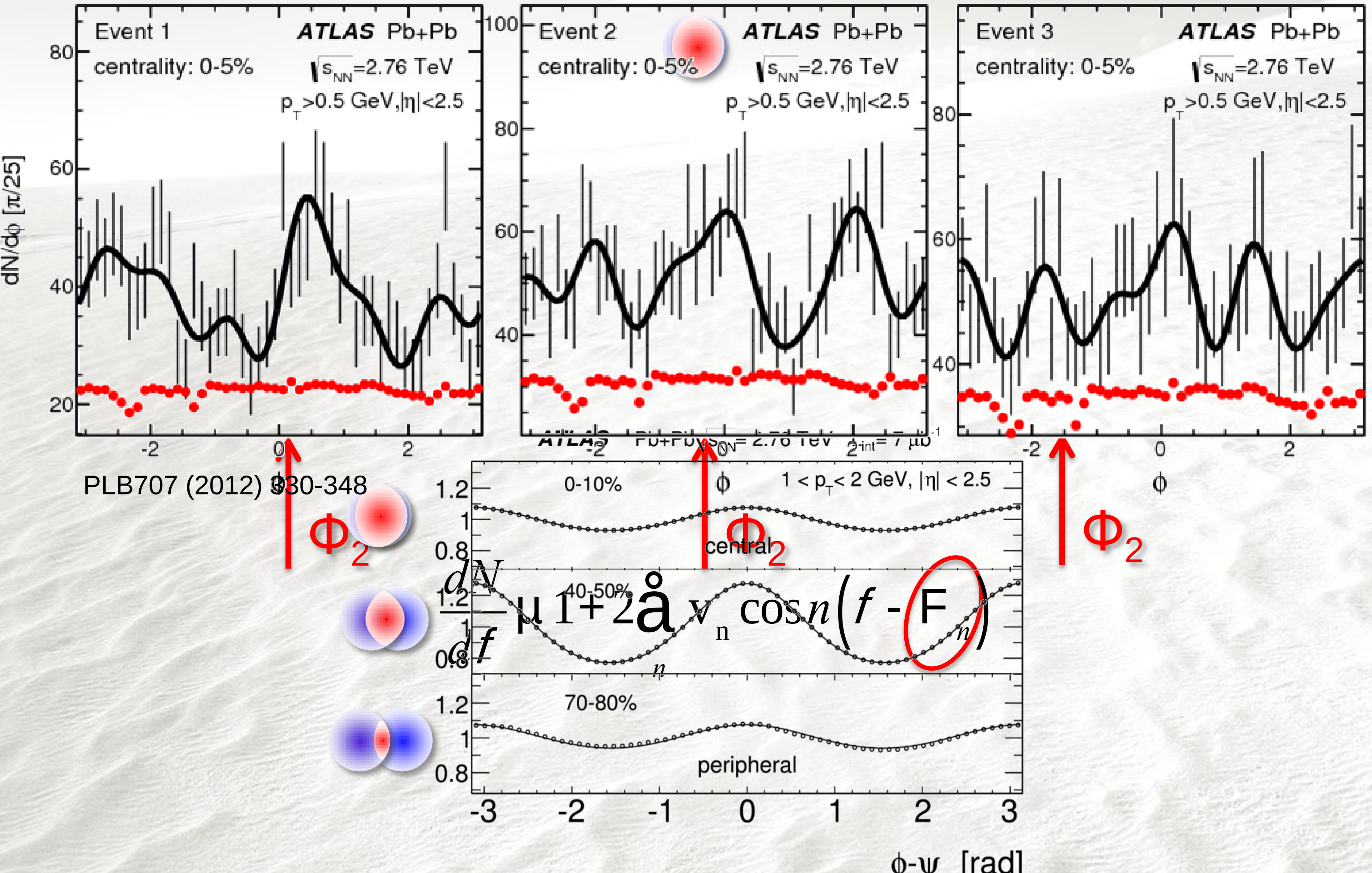
arXiv:1305.2942



Glauber model describes the data well, except in peripheral events

MC-KLN is less accurate even in mid-central collisions

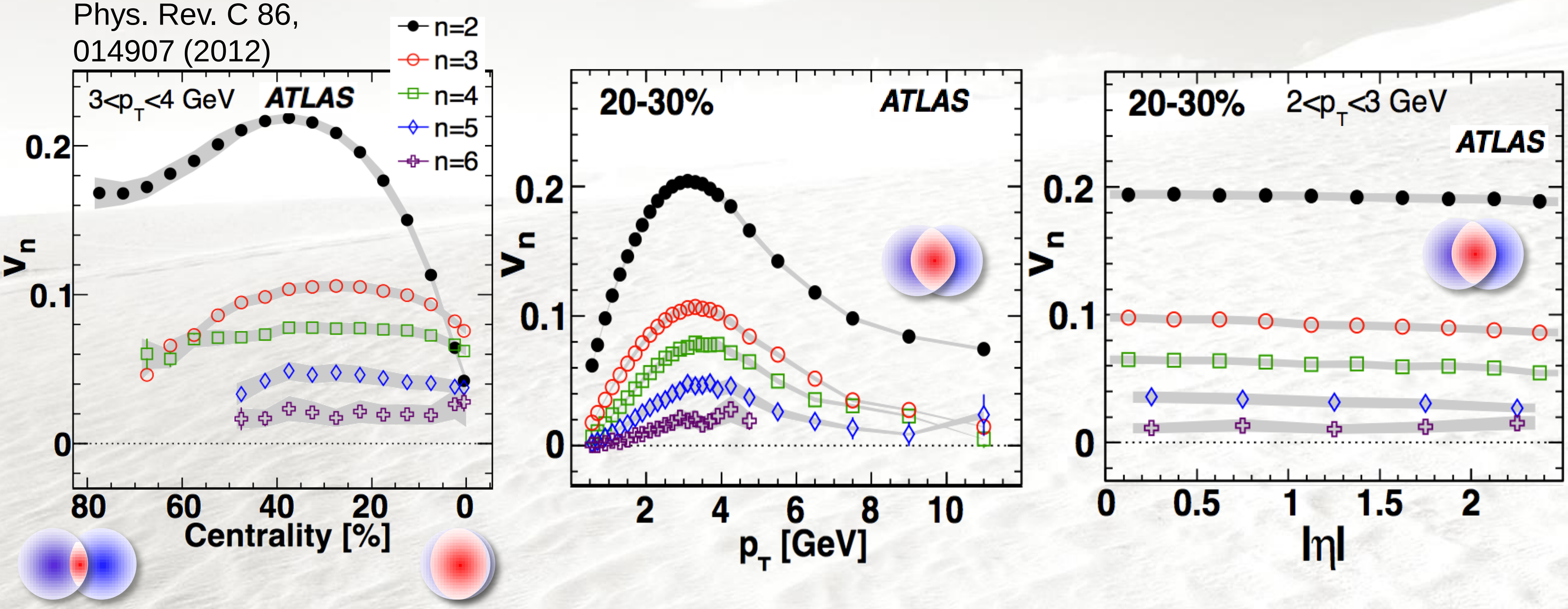
Fluctuations event-by-event



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

Averaged flow

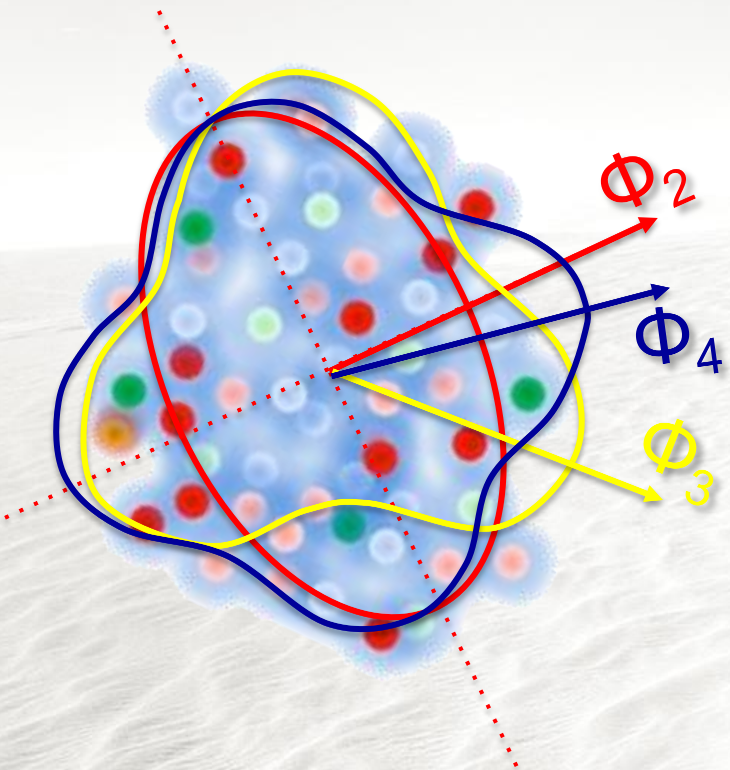
Phys. Rev. C 86, 014907 (2012)

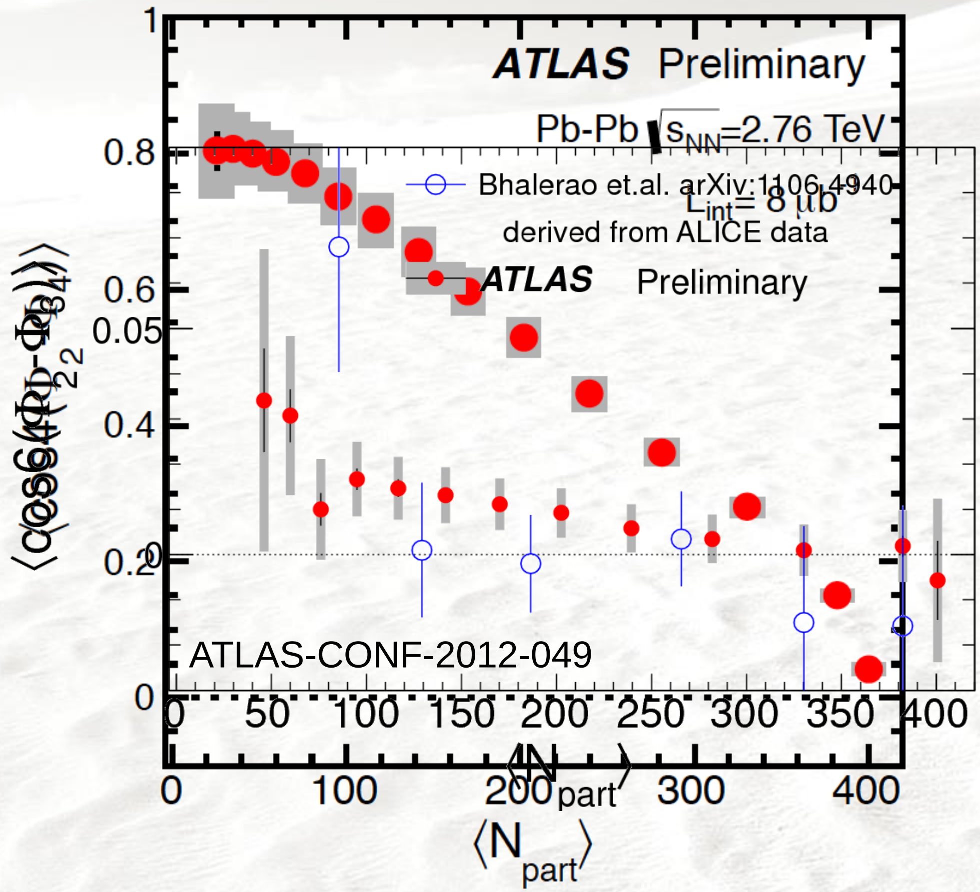


- **Features of Fourier coefficients**
  - **v_n coefficients rise and fall with centrality.**
  - **v_n coefficients rise and fall with p_T.**
  - **v_n coefficients are ~boost invariant.**

Caveat: Event planes are correlated

Event plane correlations

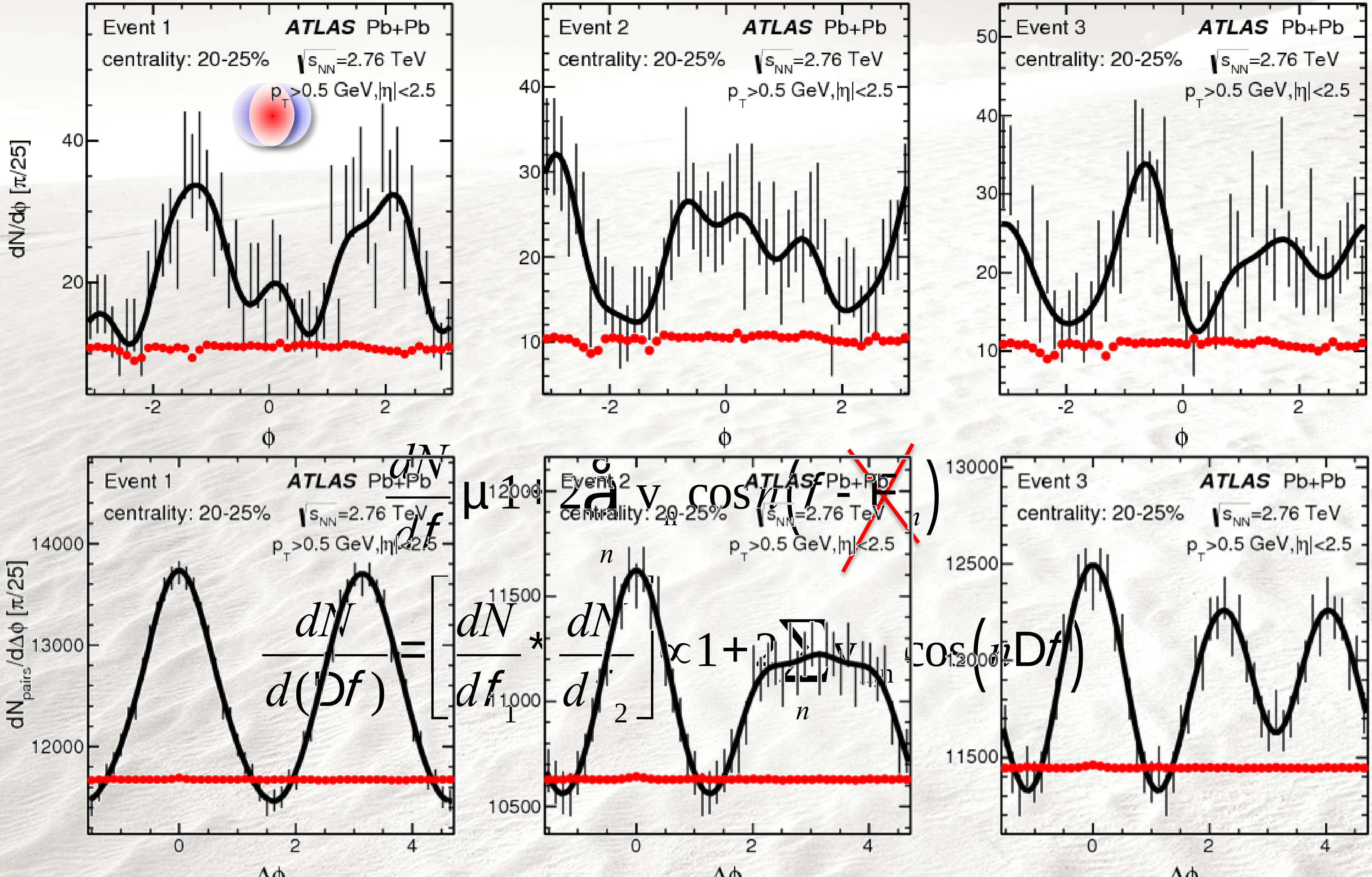




Model predicts even planes to be correlated.
Data shows strong correlation of Φ_2 and Φ_4, stronger than expected
Correlations between even and odd planes is not expected
Data shows significant correlations between Φ_2 and Φ_3

Shape, event-by-event

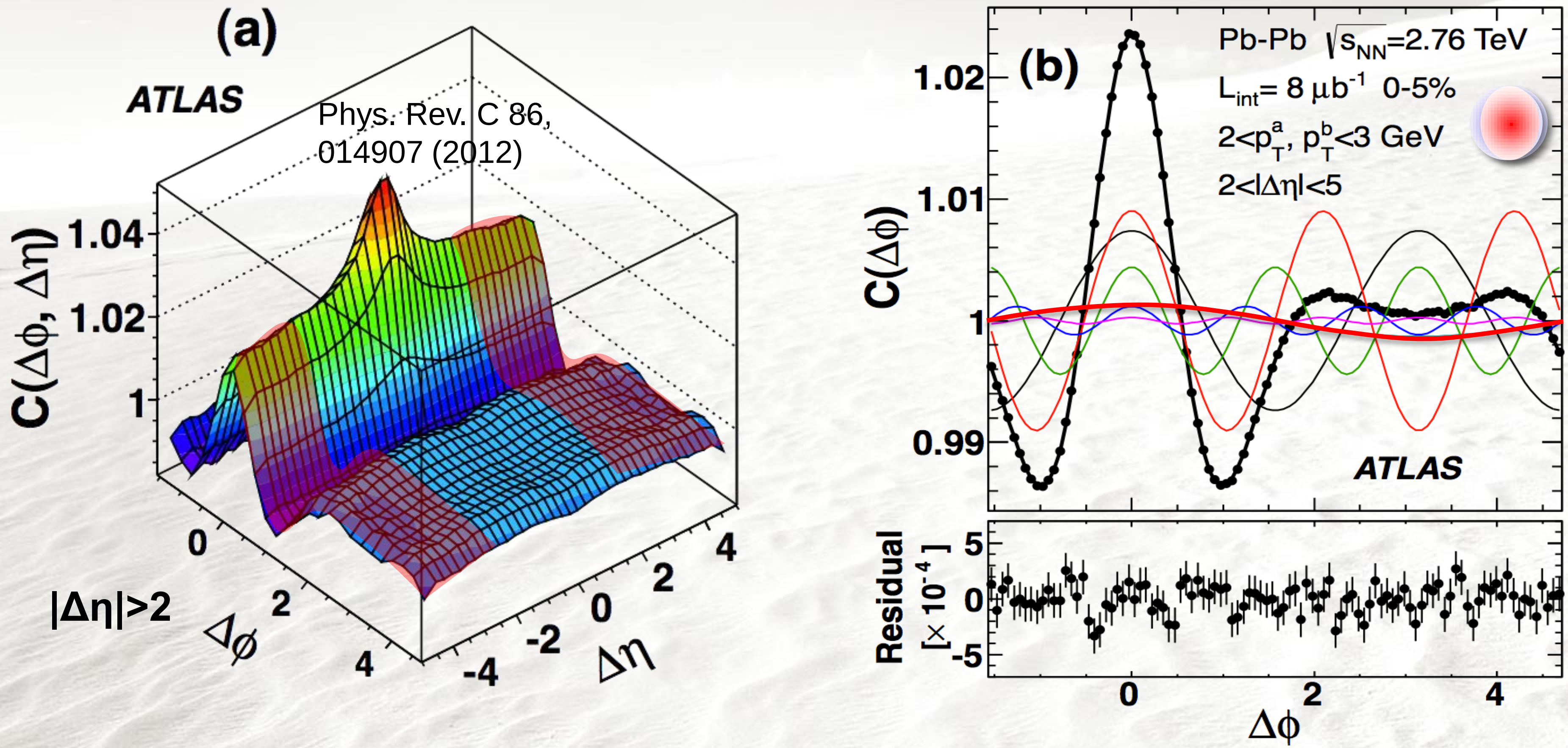
arXiv:1305.2942



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

$$\frac{dN}{d(\Delta\phi)} = \left[\frac{dN}{d\phi_1} * \frac{dN}{d\phi_2}\right] \propto 1 + 2\sum_n v_{n,n} \cos(n\Delta\phi)$$

Shape via two particle correlations



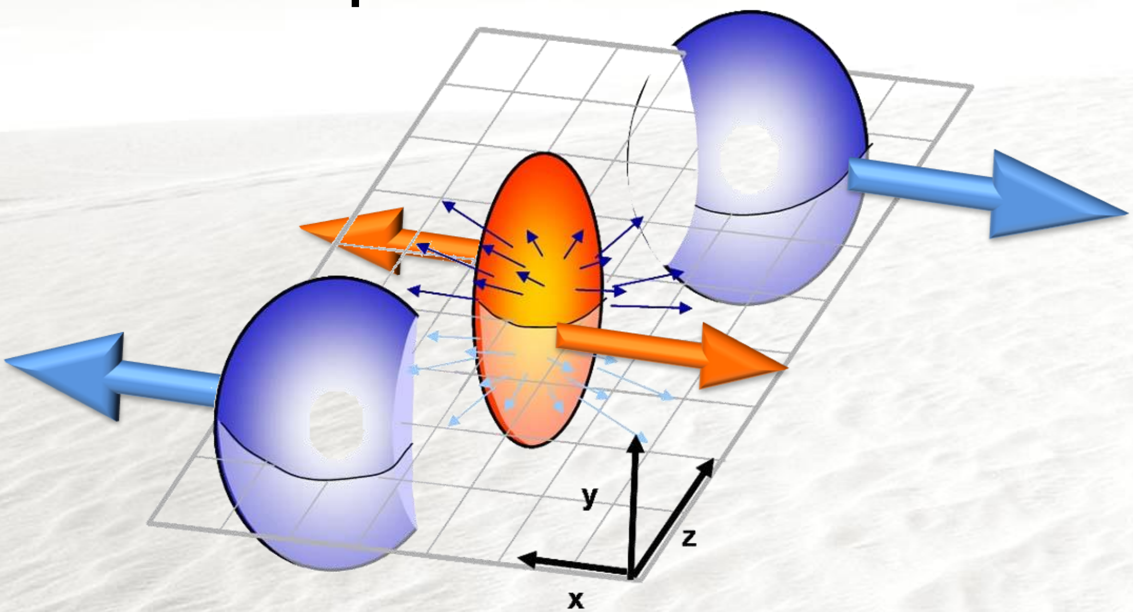
Long range structures ("ridges") described by harmonics $v_{1,1}$-$v_{6,6}$

$$v_{n,n}\left(p_T^a, p_T^a\right) = v_n\left(p_T^a\right) v_n\left(p_T^b\right) + non - \ flow$$

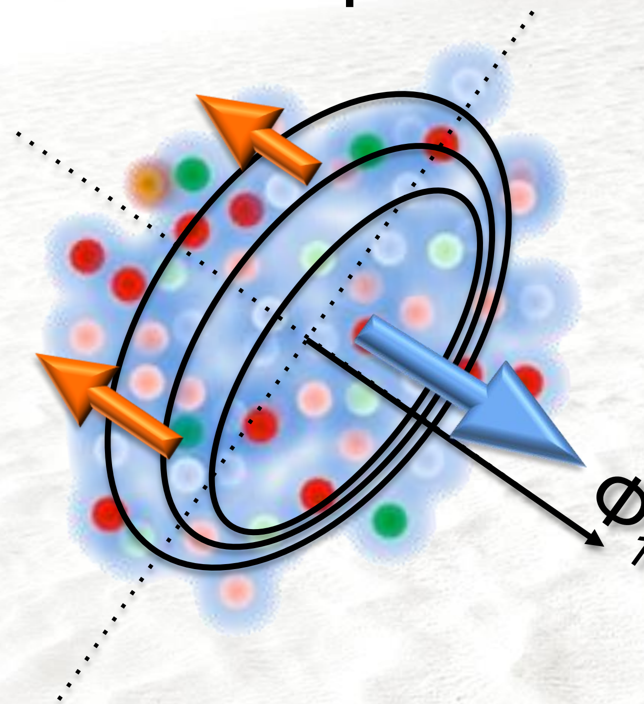
However, one assumption is needed, for n=1

Dipolar flow

Directed (odd component) flow vanishes at η=0



Dipolar (even component) flow ~boost invariant in η

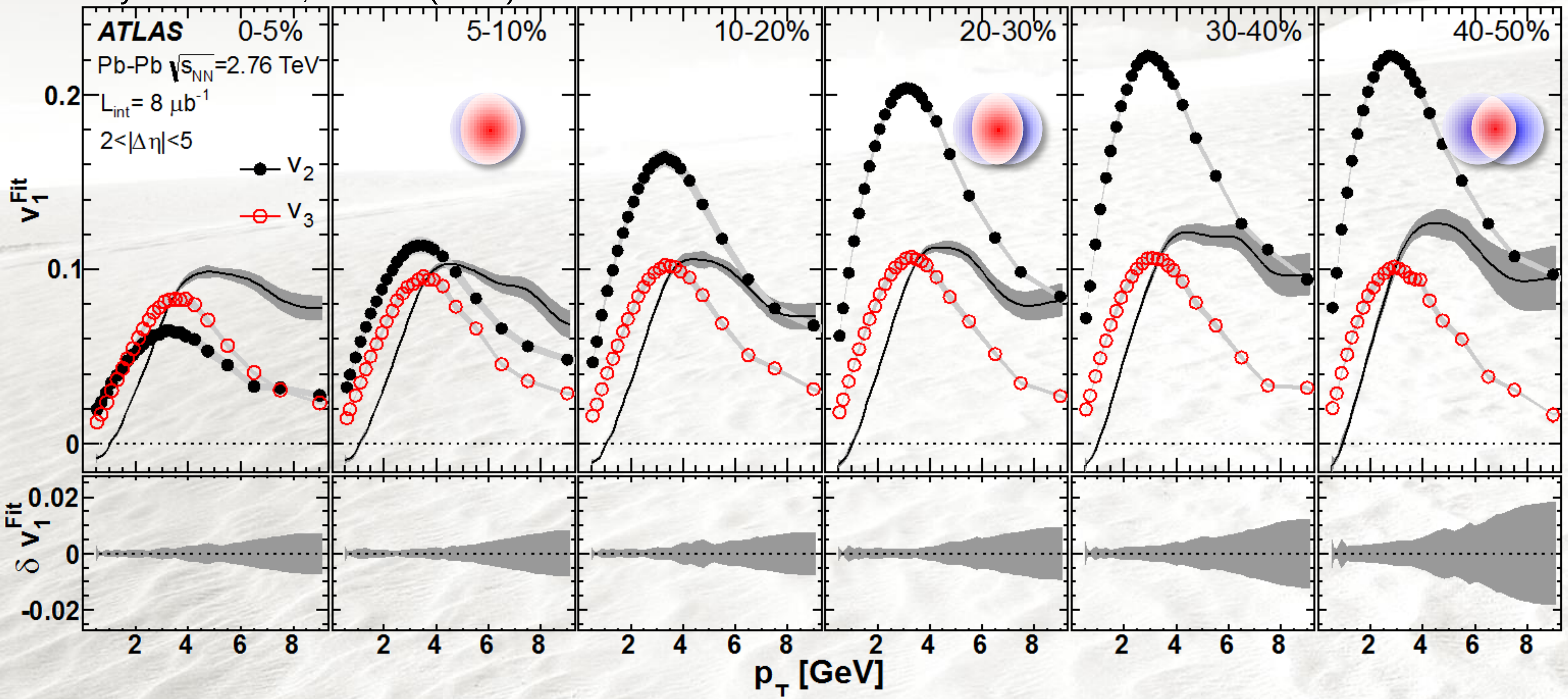


$$v_{n,n}\left(p_T^a, p_T^a\right) = v_n\left(p_T^a\right) v_n\left(p_T^b\right) + non\text{-}\ flow$$

Dipolar flow must be affected by global momentum conservation

Dipolar flow

Phys. Rev. C 86, 014907 (2012)

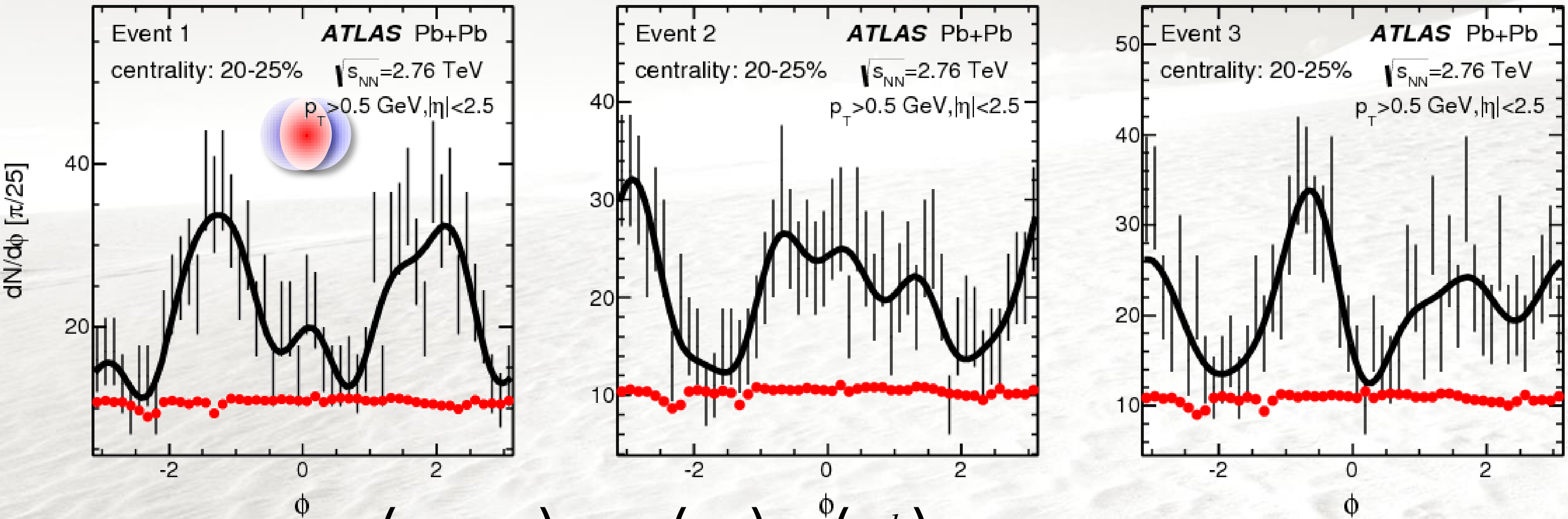


Similar magnitude as triangular flow

Negative at low p_T

Cumulant method

arXiv:1305.2942

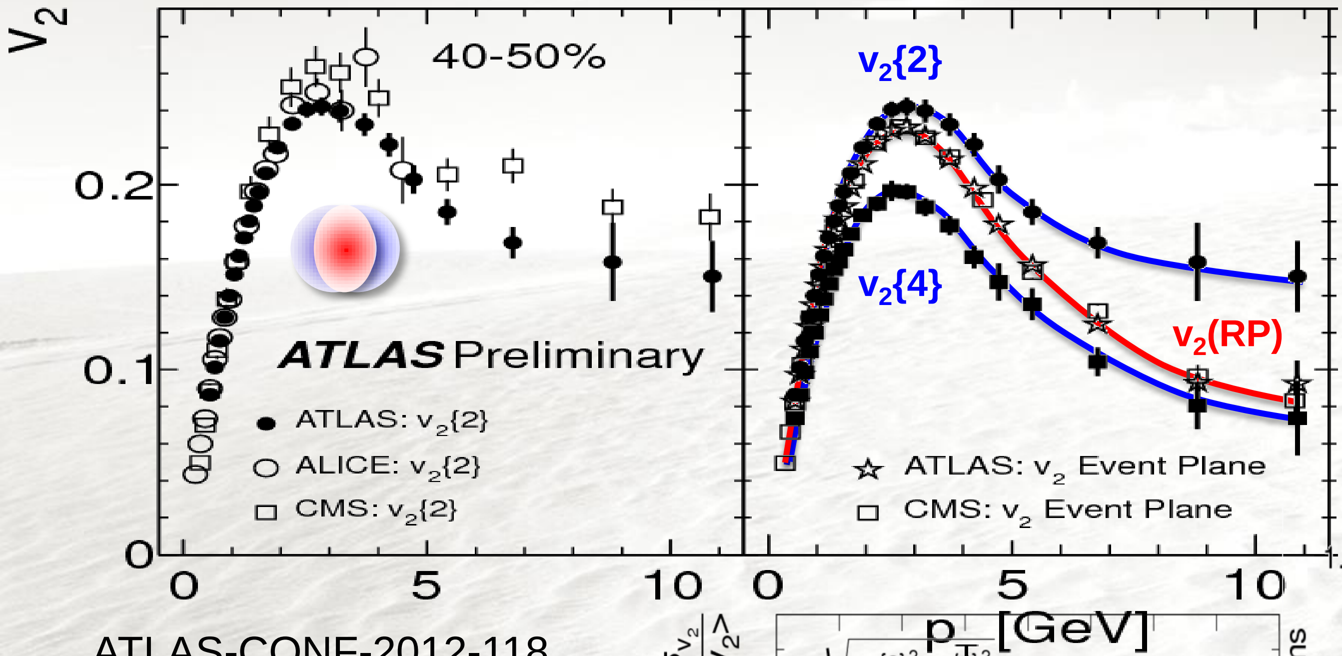


$$v_{n,n}\left(p_T^a, p_T^a\right) = v_n\left(p_T^a\right) v_n\left(p_T^b\right) + non\text{-}\ flow$$

$$\left\langle corr_n\{2\}\right\rangle = \left\langle v_{n,n}\left(p_T^a, p_T^a\right)\right\rangle = \left\langle v_n\left(p_T^a\right) v_n\left(p_T^b\right) + non\text{-}\ flow\right\rangle = \left\langle v_n\{2\}^2\right\rangle$$

2PC → 2k particle correlation, cumulant method

Relative fluctuations



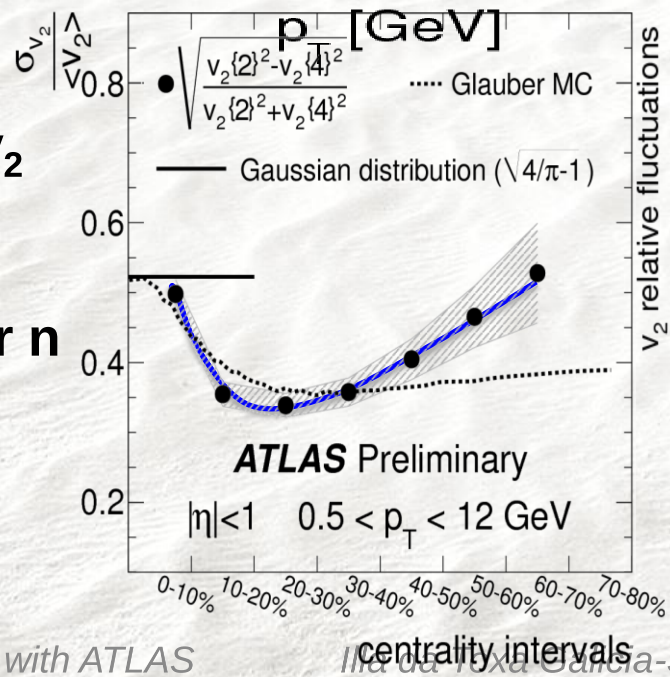
$v_2\{4\} < v_2(EP) < v_2\{2\}$

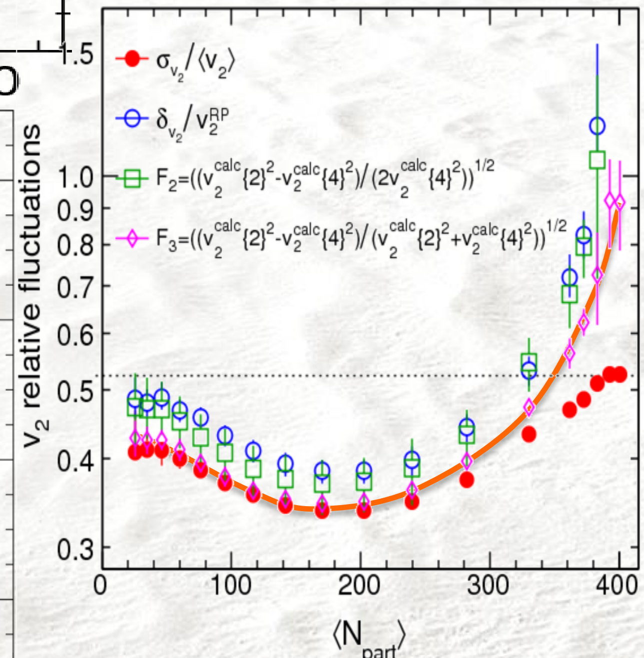
Behavior expected from non-flow contributions

ATLAS-CONF-2012-118

Relative fluctuation of v_2 are Gaussian-like in central & everywhere for higher n

Event-by-event method and cumulants agree.



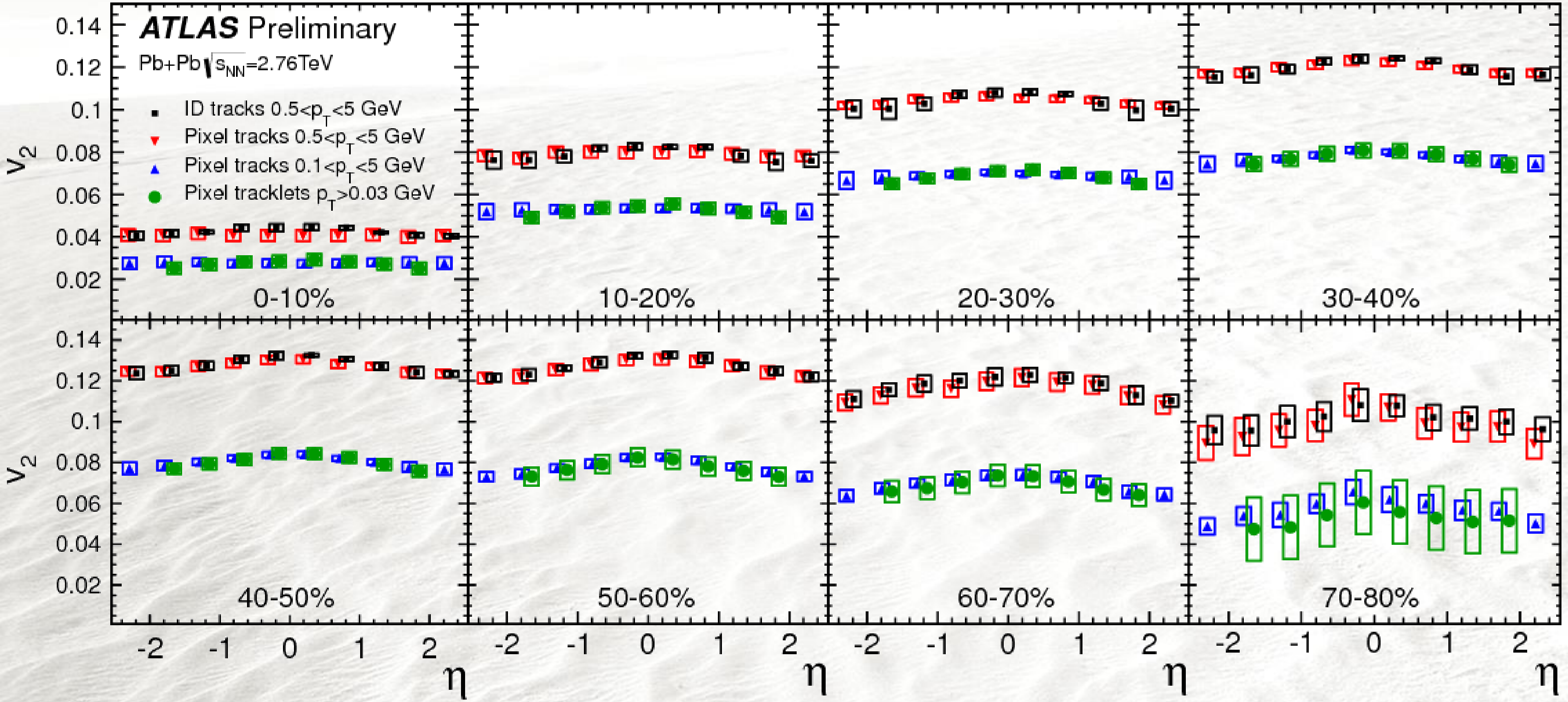


arXiv:1305.2942

Integrated (averaged) v_2

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

ATLAS-CONF-2012-117



Significant elliptic flow, reaching 0.12.
Weak pseudo-rapidity dependence

Summary

ATLAS provides a widest spectra of correlation and fluctuation analysis measuring event-by-event, averaged, cumulant, integrated two-particle correction harmonic analysis.

Complete study of v_n in p_T, rapidity and centrality for v_2-v_6 and beyond, first measurement of v_1

2 particle correlations decomposition into Fourier coefficients of harmonic flow.

$v_2\{2\}$ and $v_2\{4\}$ cumulant analysis, understanding of fluctuations in comparison to other methods.

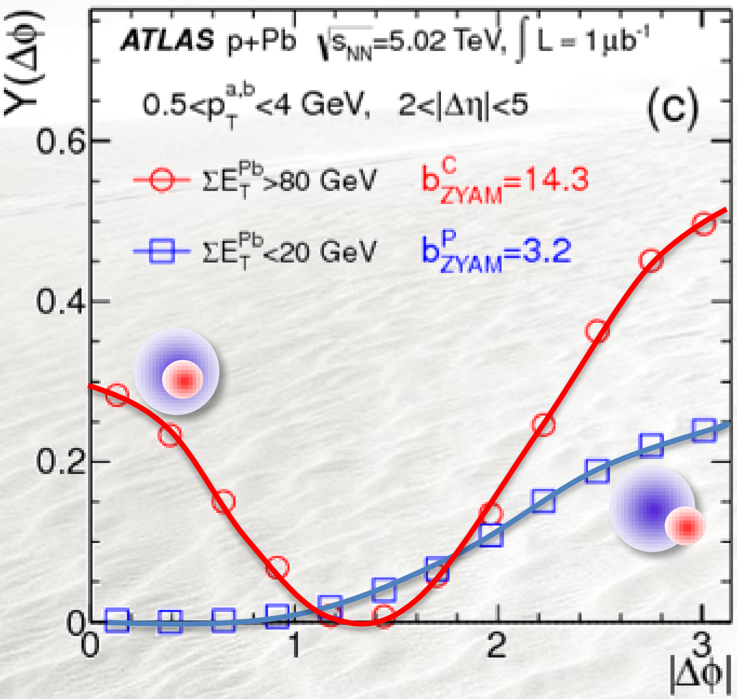
First measurement of event plane correlations

High multiplicity and wide pseudo-rapidity coverage allows measuring event-by-event fluctuations using ATLAS detector

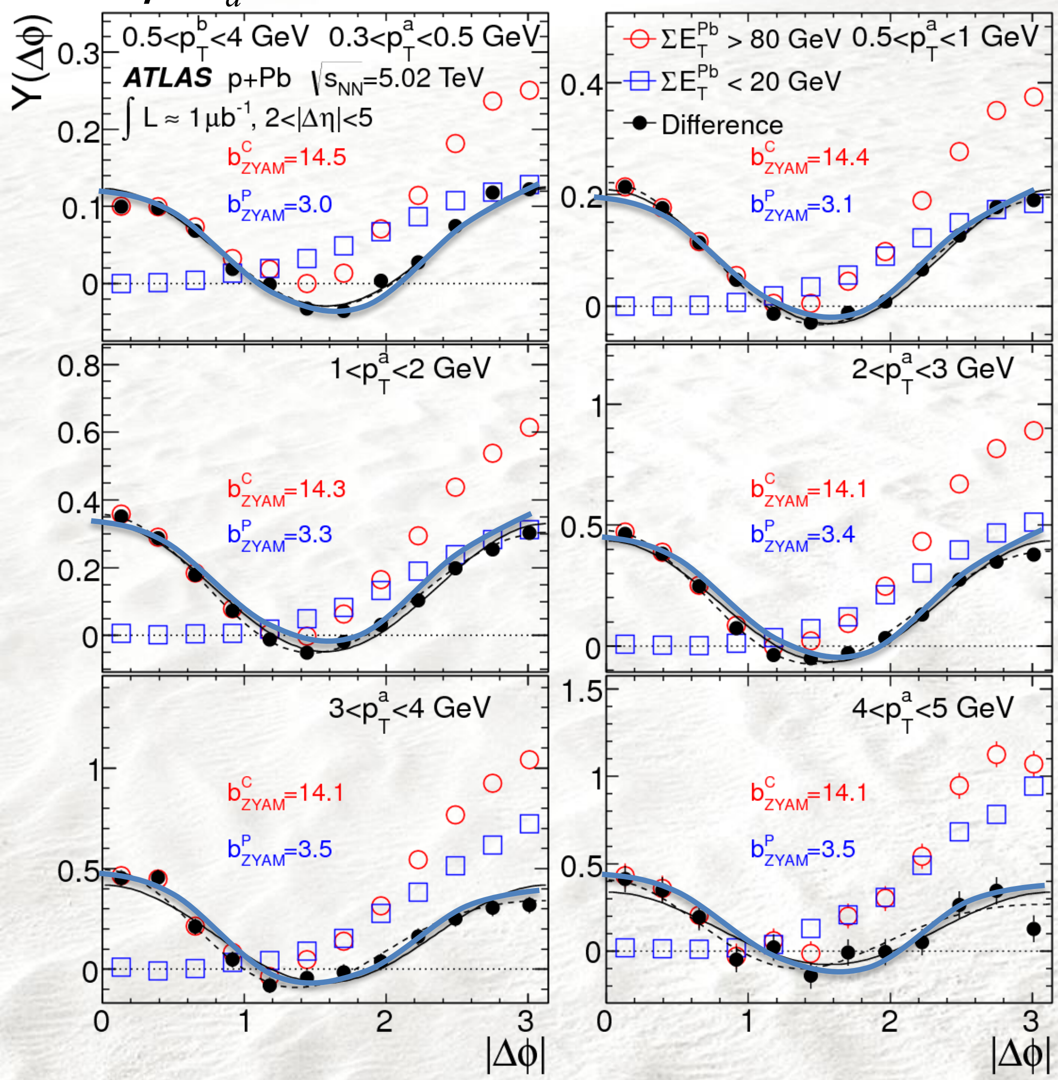
Two particle correlations in p+Pb

$$Y(\Delta\phi) = \frac{\int B(\Delta\phi)\,d\Delta\phi}{\pi N_a} C(\Delta\phi) - b_{ZYAM}$$

PRL 110, 182302 (2013)



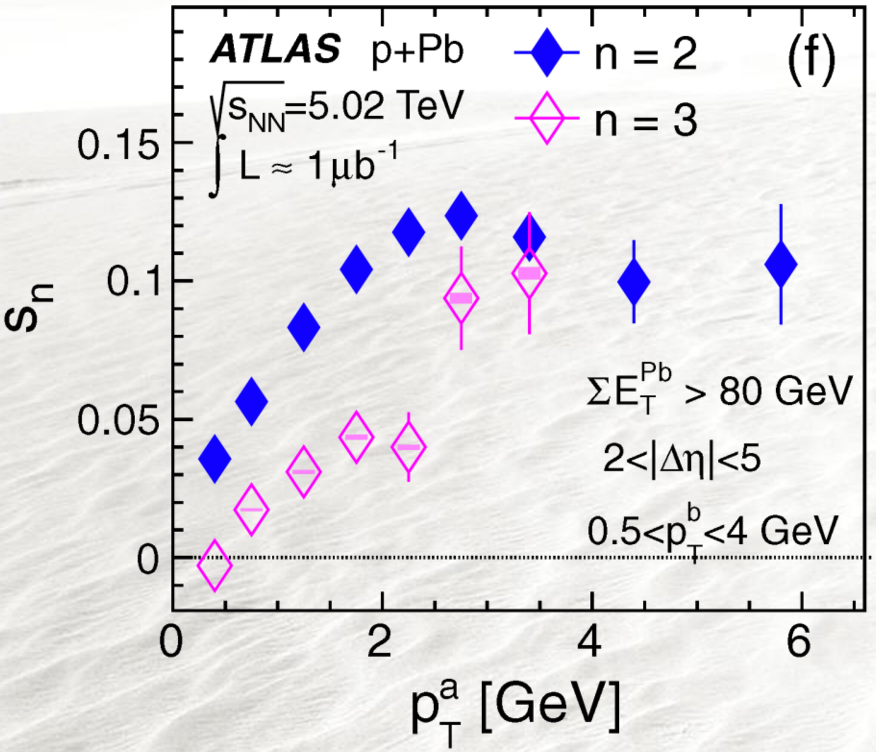
Near side **Away side**



Long range component:
Recoil + Δφ-Symmetric

Two particle correlations in p+Pb

PRL 110, 182302 (2013)



Convert to a single particle level assuming factorization:

$c_n(p_T^a,p_T^b) = s_n(p_T^a)s_n(p_T^b)$

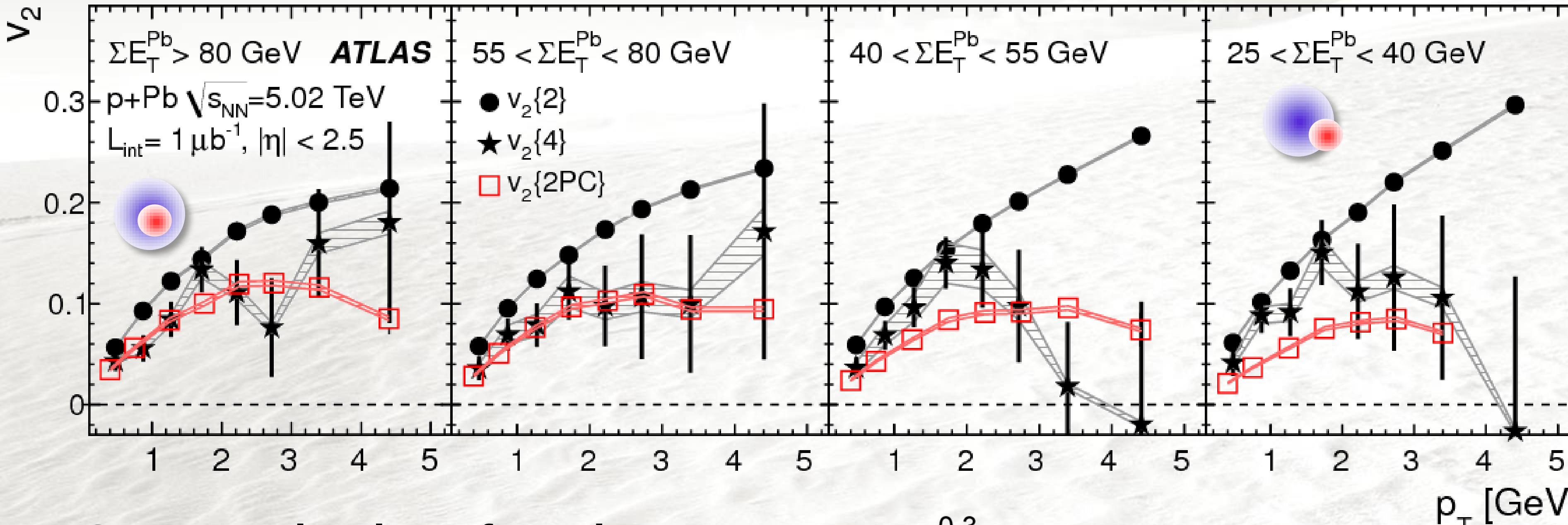
$s_n(p_T^a) = c_n(p_T^a,p_T^b) / \sqrt{c_n(p_T^b,p_T^b)}$

$s_n(p_T^a) \Leftrightarrow v_n\{2PC\}$

s_2 increases with p_T up to 3 GeV and than drops
s_3<s_2 over the measured p_T region

p_T dependence of cumulants in p+Pb

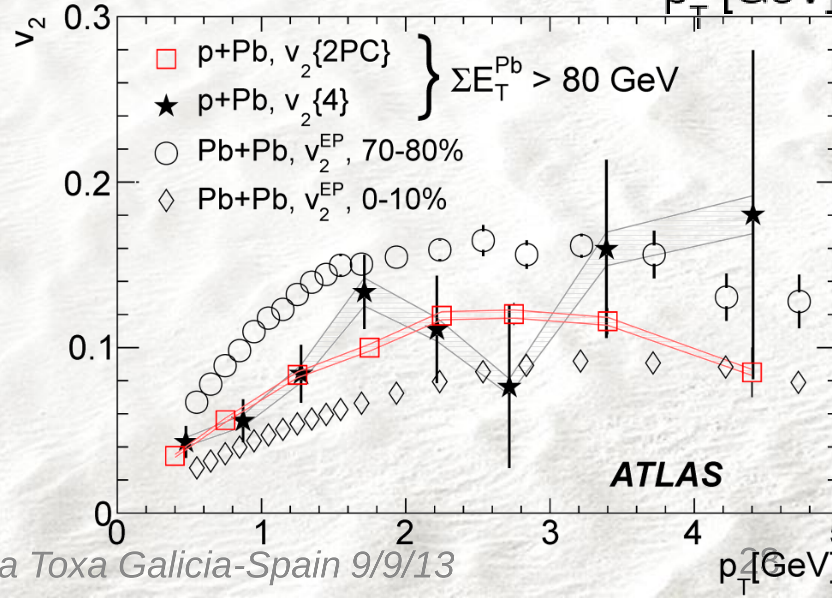
PLB 725, 182302 (2013) 60



Strong reduction of v_2 when using 4-particle cumulants

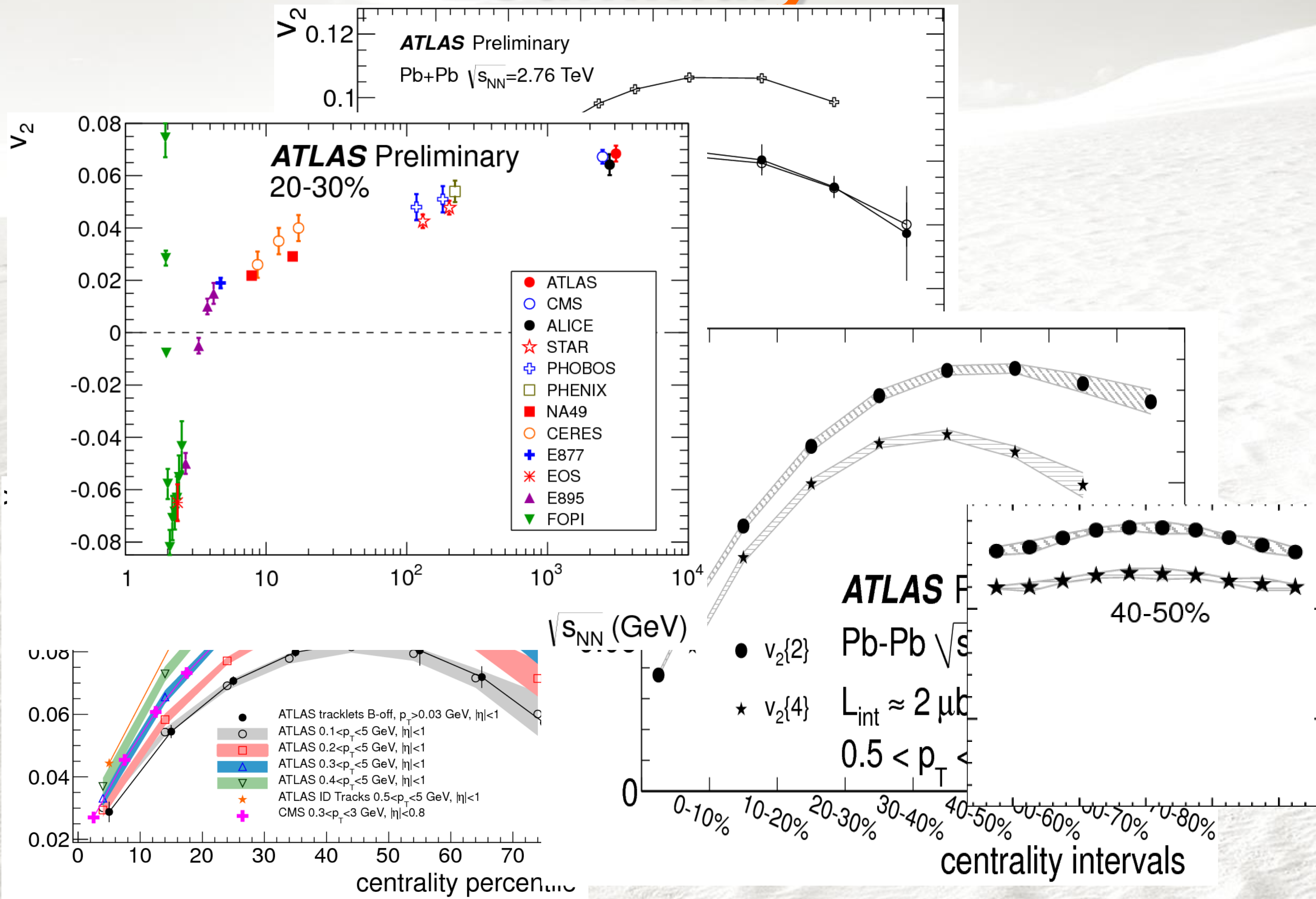
Good agreement with $v_2\{2PC\}$ for 0-20% central

Large difference in more peripheral events

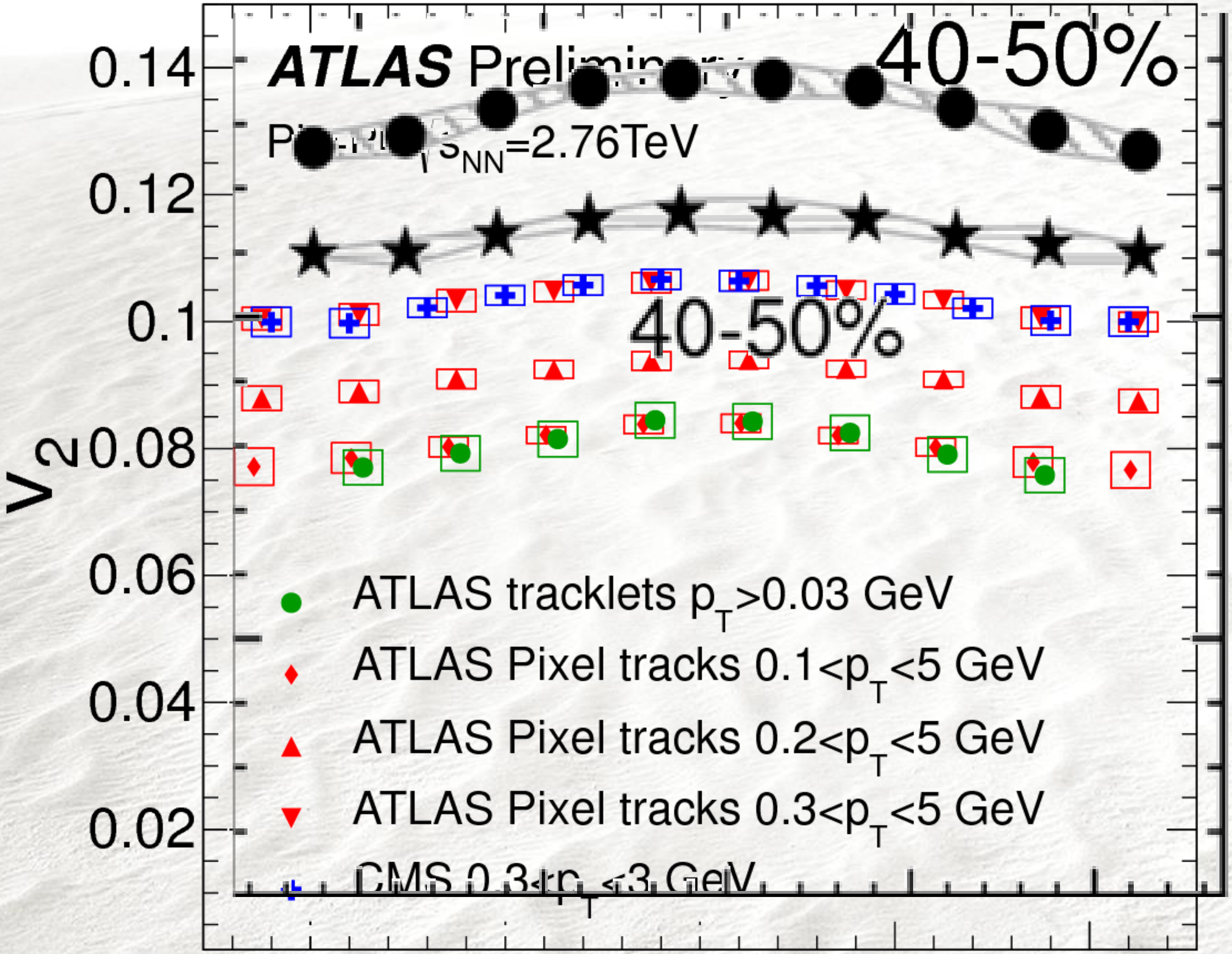


Backups

Summary

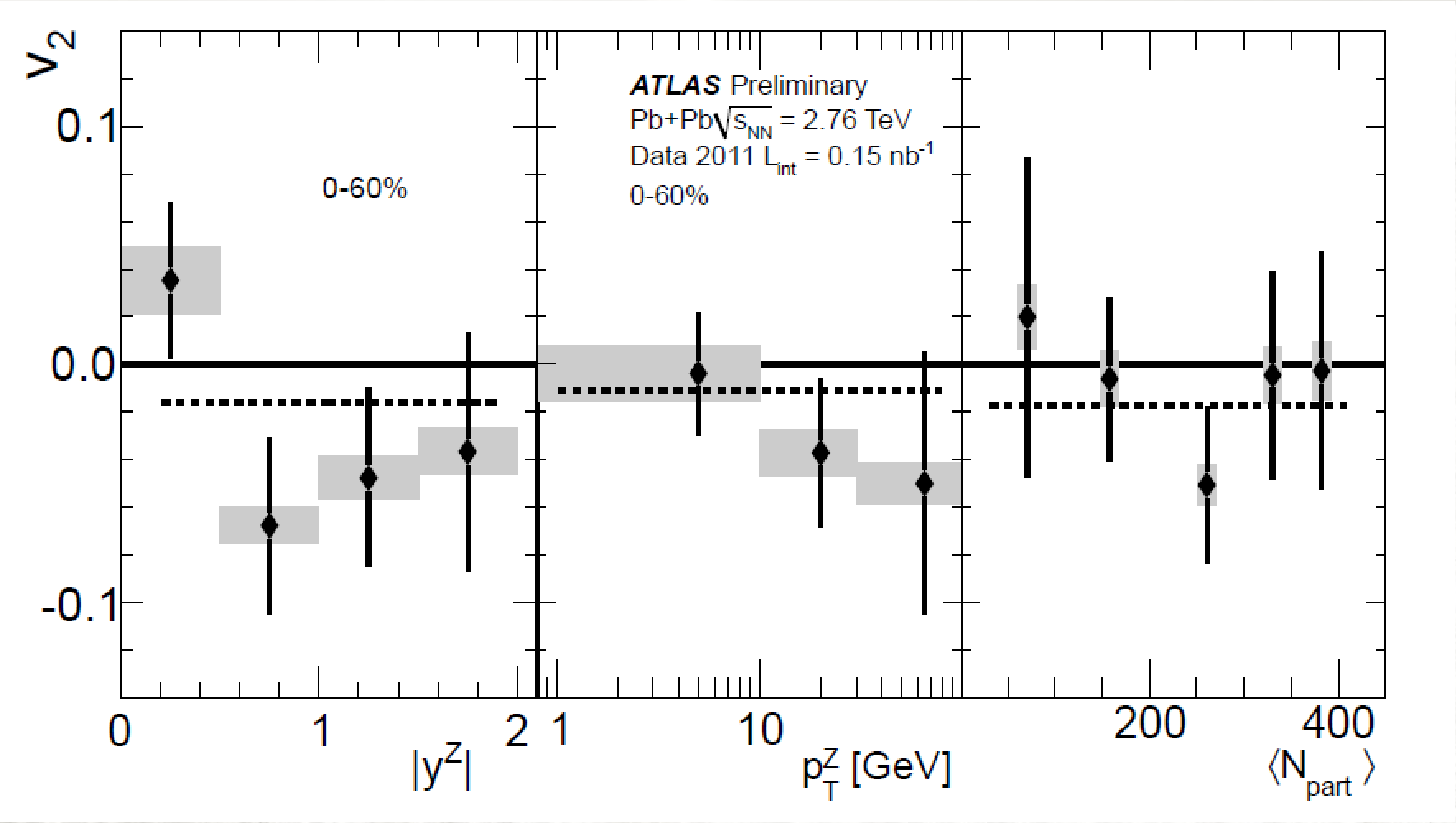

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
v_2
0.12
0.1
ATLAS Preliminary
20-30%
ATLAS
CMS
ALICE
STAR
PHOBOS
PHENIX
NA49
CERES
E877
EOS
E895
FOPI
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
1
10
10^2
10^3
10^4
$\sqrt{s_{NN}}$ (GeV)
0.06
0.04
0.02
0
10
20
30
40
50
60
70
ATLAS tracklets B-off, p_T>0.03 GeV, |η|<1
ATLAS 0.1<p_T<5 GeV, |η|<1
ATLAS 0.2<p_T<5 GeV, |η|<1
ATLAS 0.3<p_T<5 GeV, |η|<1
ATLAS 0.4<p_T<5 GeV, |η|<1
ATLAS ID Tracks 0.5<p_T<5 GeV, |η|<1
CMS 0.3<p_T<3 GeV, |η|<0.8
$v_2\{2\}$
$v_2\{4\}$
0
0-10%
10-20%
20-30%
30-40%
40-50%
centrality intervals
40-50%

Summary



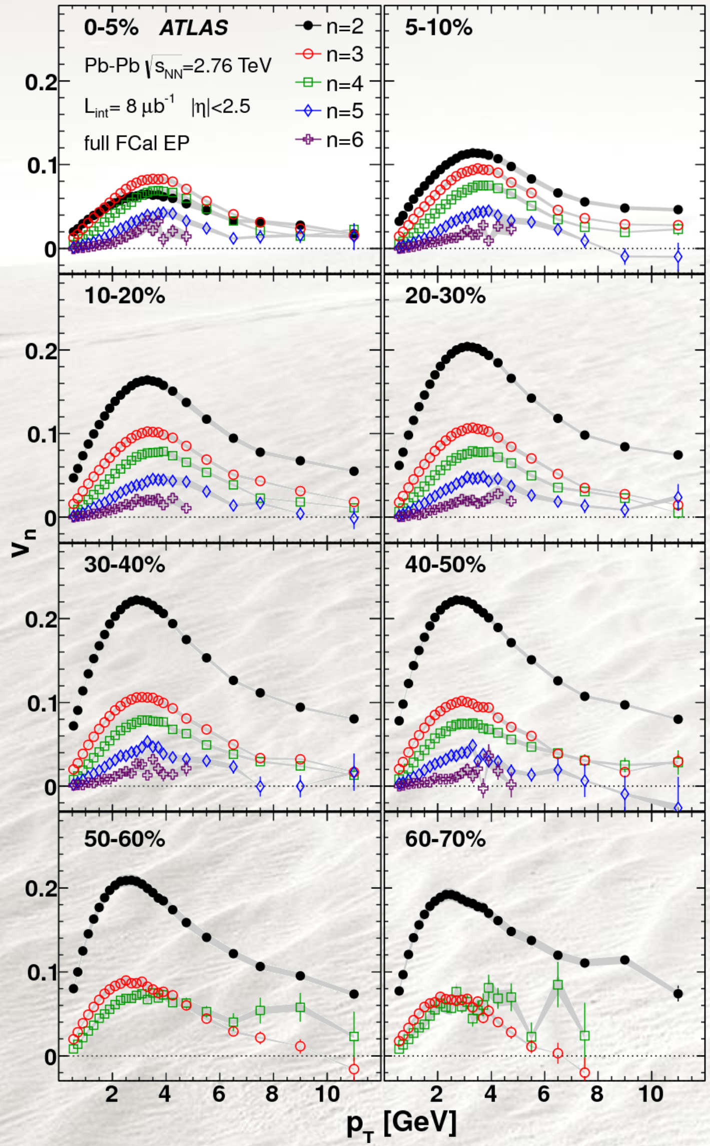
ATLAS Preliminary
40-50%
$\sqrt{s_{NN}}$=2.76TeV
40-50%
v_2
0.14
0.12
0.1
0.08
0.06
0.04
0.02
ATLAS tracklets p_T>0.03 GeV
ATLAS Pixel tracks 0.1<p_T<5 GeV
ATLAS Pixel tracks 0.2<p_T<5 GeV
ATLAS Pixel tracks 0.3<p_T<5 GeV
CMS 0.3<p_T<3 GeV
-2
-1
0
1
2

Z azimuthal anisotropy



$v_2 = -0.015 \pm 0.018(\text{stat.}) \pm 0.014(\text{sys.})$

Higher order flow.



Phys. Rev. C 86, 014907 (2012)

ATLAS measures higher order flow.

Harmonics up to 6th show significant amplitudes.

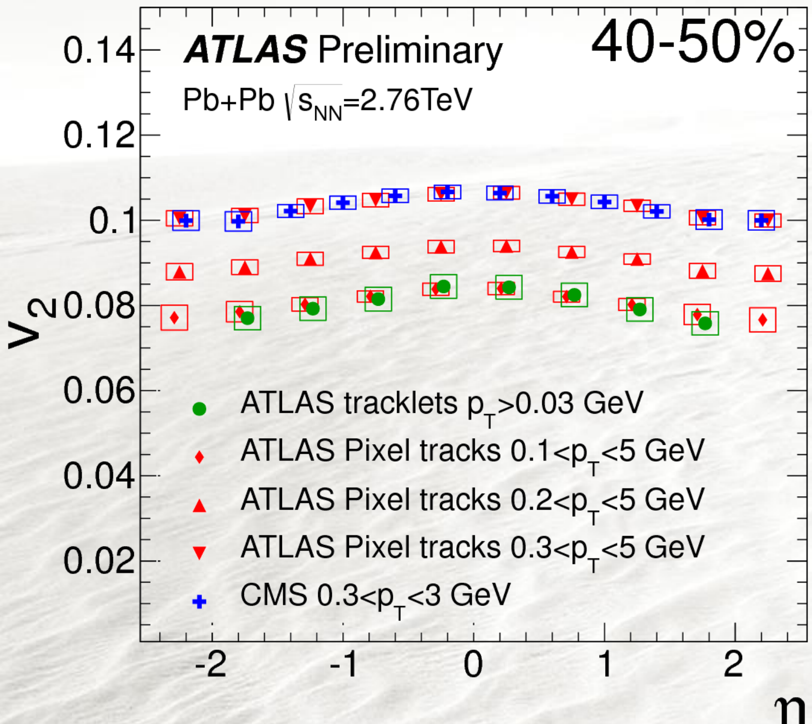
In the most central the 3rd harmonic is stronger than the elliptic (2nd) harmonic.

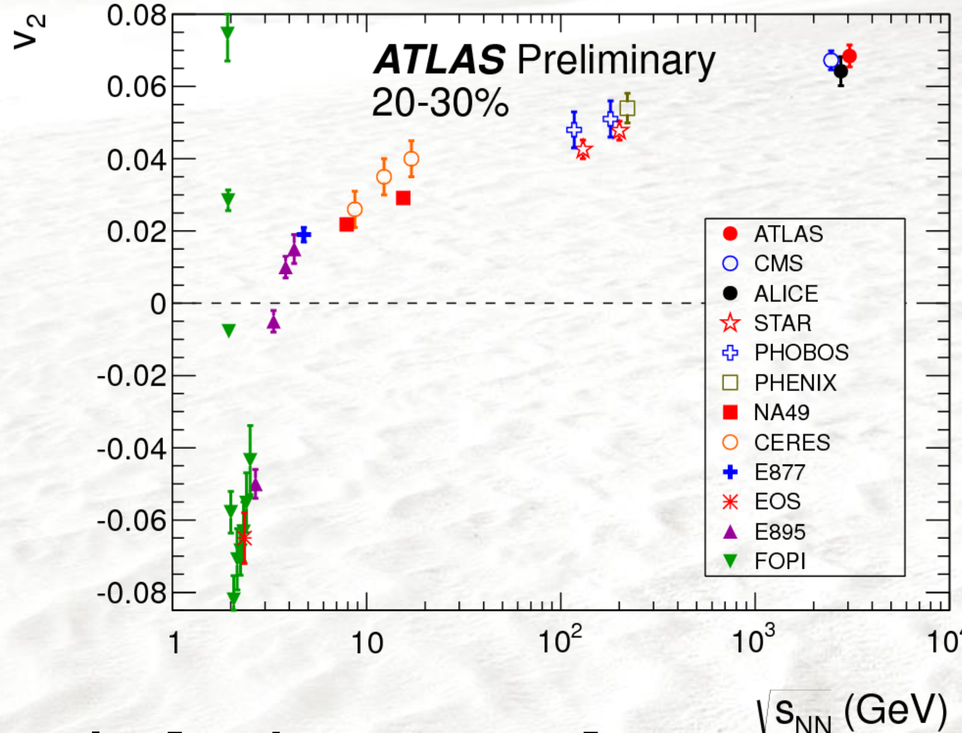
v_2 varies with centrality much stronger compared to v_n (n>2)

Consistent with elliptic flow being driven by geometric shape whereas higher order harmonics coming from fluctuations.

Particle flow (integrated)

ATLAS-CONF-2012-117



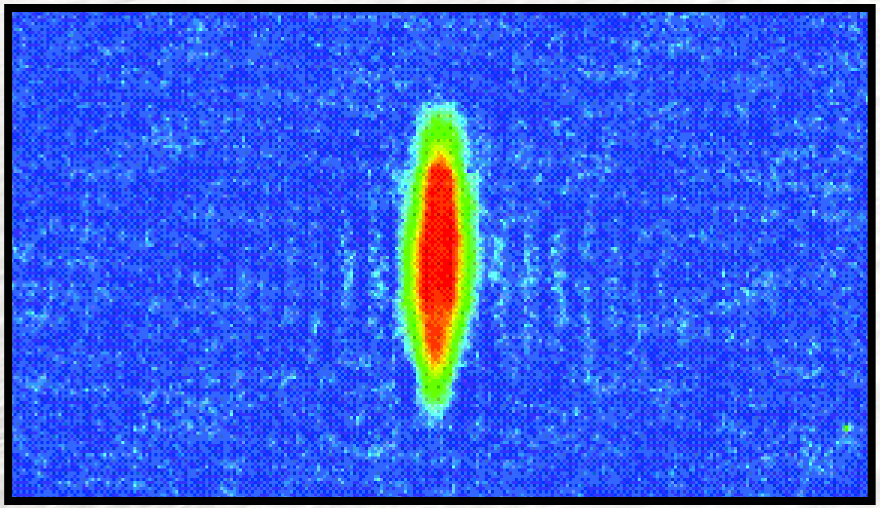


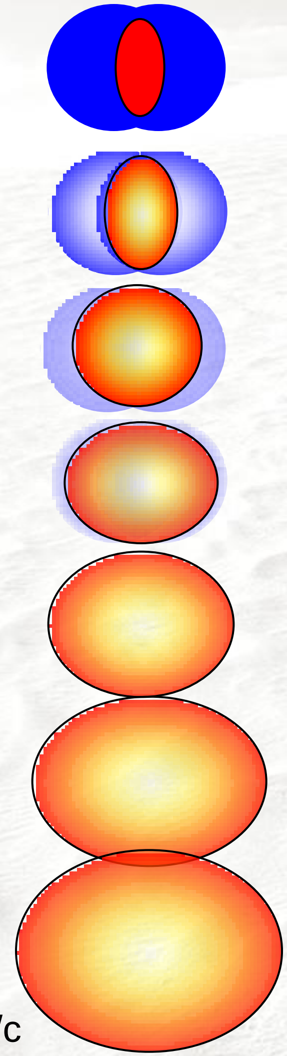
Good agreement with the CMS results [arXiv:1204.1409]
All LHC experiments agree for data η=0 [ALICE: Phys. Rev. Lett. 105 (2010) 252302]

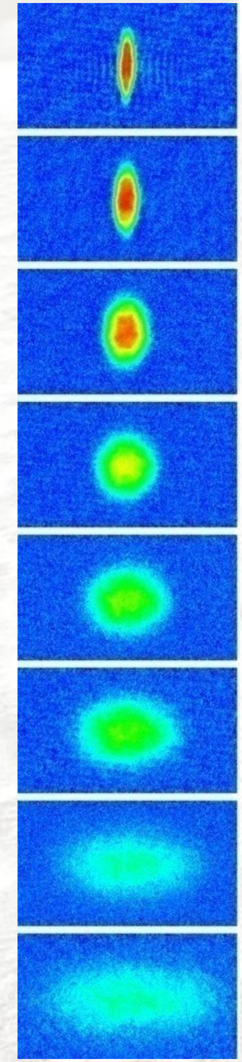
Integrated flow grows with incident energy.
More particle or more flow?

Analogy in Atomic System

Same phenomena observed in gases of strongly interacting atoms







The RHIC fluid behaves like this,

that is, a strongly coupled fluid.

Distribution of a single event.

- Ideal detector:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\mathrm{obs}} \cos n(\phi - \Psi_n^{\mathrm{obs}}) = 1 + 2\sum_{n=1}^{\infty} \left(v_{n,\mathrm{x}}^{\mathrm{obs}} \cos n\phi + v_{n,\mathrm{y}}^{\mathrm{obs}} \sin n\phi\right)$$

$$\vec{v}_n^{\,\mathrm{obs}} = (v_{n,\mathrm{x}}^{\mathrm{obs}}, v_{n,\mathrm{y}}^{\mathrm{obs}})$$

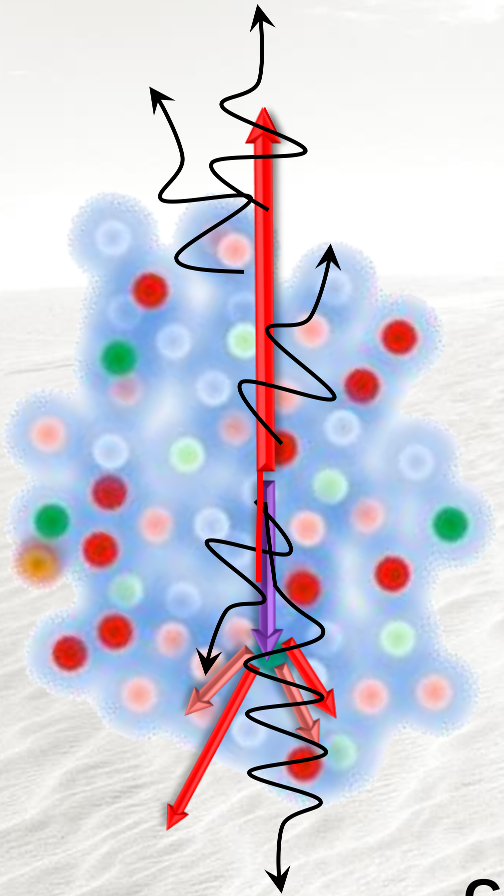
- Correct for acceptance & efficiency:

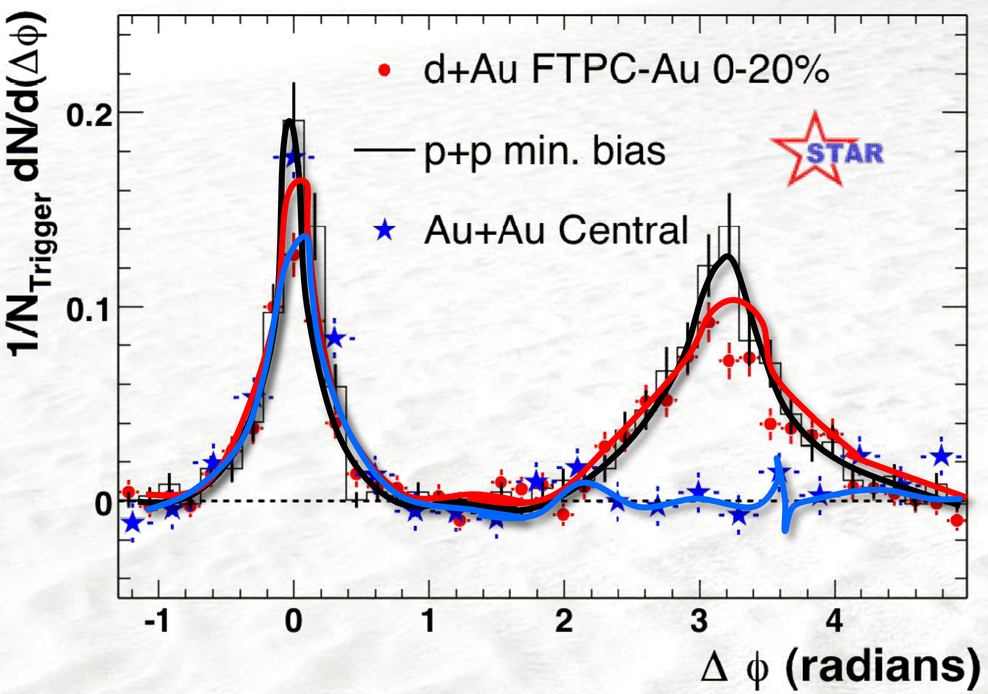
$$\frac{dN}{d\phi} \propto C(\phi) = \frac{S(\phi)}{B(\phi)} = \frac{1 + 2\sum_{n=1}^{\infty}\left(v_{n,\mathrm{x}}^{\mathrm{raw}} \cos n\phi + v_{n,\mathrm{y}}^{\mathrm{raw}} \sin n\phi\right)}{1 + 2\sum_{n=1}^{\infty}\left(v_{n,\mathrm{x}}^{\mathrm{det}} \cos n\phi + v_{n,\mathrm{y}}^{\mathrm{det}} \sin n\phi\right)}$$

Efficiency weight $\frac{1}{e(h, \mathrm{p_T})}$ applied track by track as function of p_T and η

$$v_{n,\mathrm{x}}^{\mathrm{obs}} \approx v_{n,\mathrm{x}}^{\mathrm{raw}} - v_{n,\mathrm{x}}^{\mathrm{det}}, v_{n,\mathrm{y}}^{\mathrm{obs}} \approx v_{n,\mathrm{y}}^{\mathrm{raw}} - v_{n,\mathrm{y}}^{\mathrm{det}}$$

The probes





Center at a high-p_T particle
2PC in p+p show both sides of a jet
The same in d+Au
Near-side jet in Au+Au
And no back-to-back partner

Shape, event-by-event

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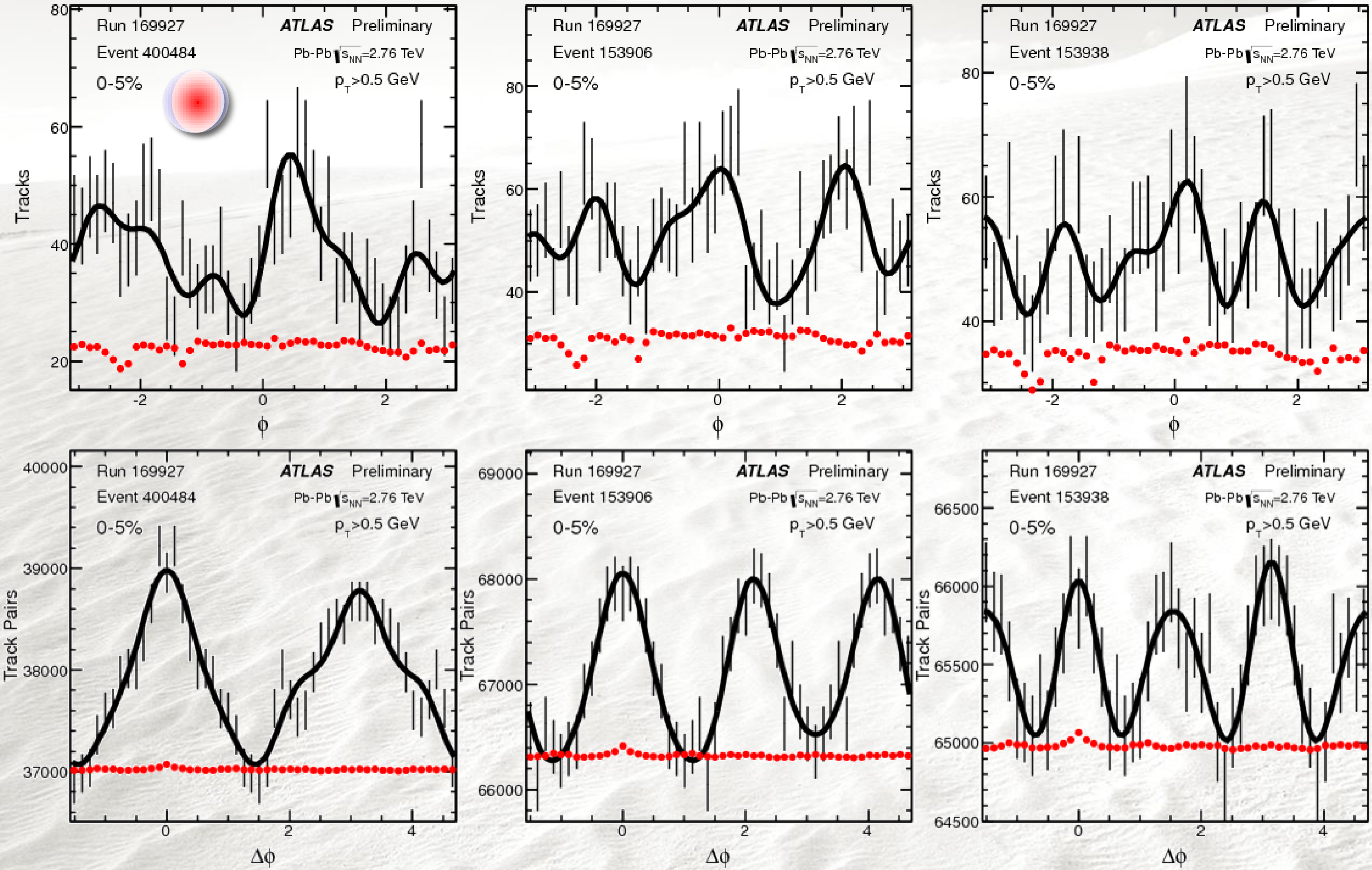

Centrality

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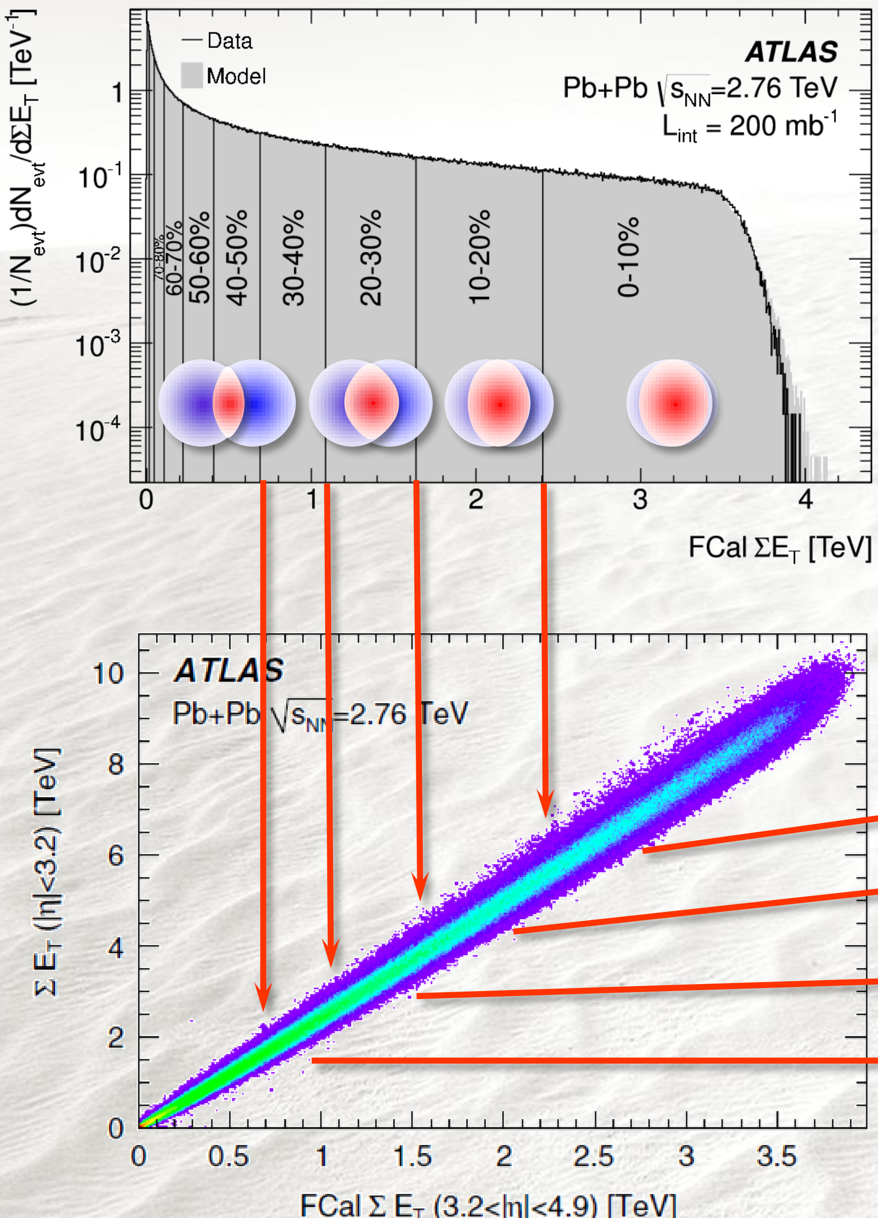

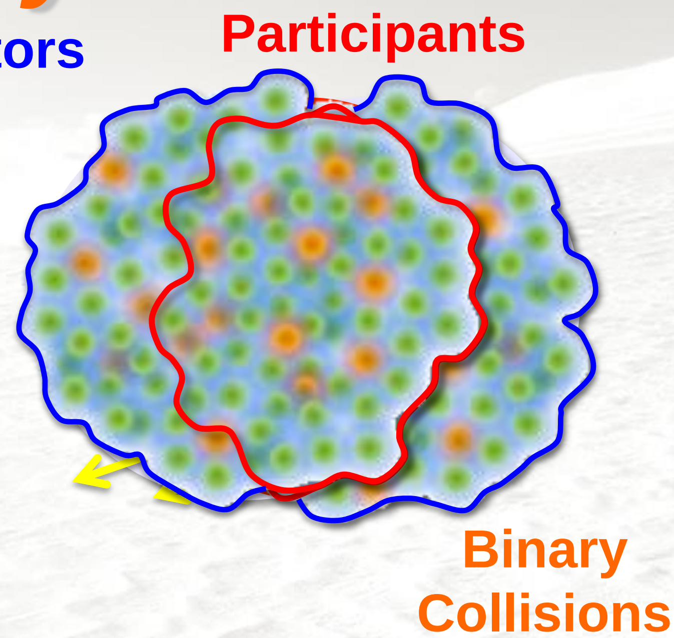

	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
0-5%	382 ± 1%	1683 ± 8%
5-10%	330 ± 1%	1318 ± 8%
10-20%	261 ± 2%	923 ± 7%
20-40%	158 ± 3%	441 ± 7%
40-80%	46 ± 6%	78 ± 9%