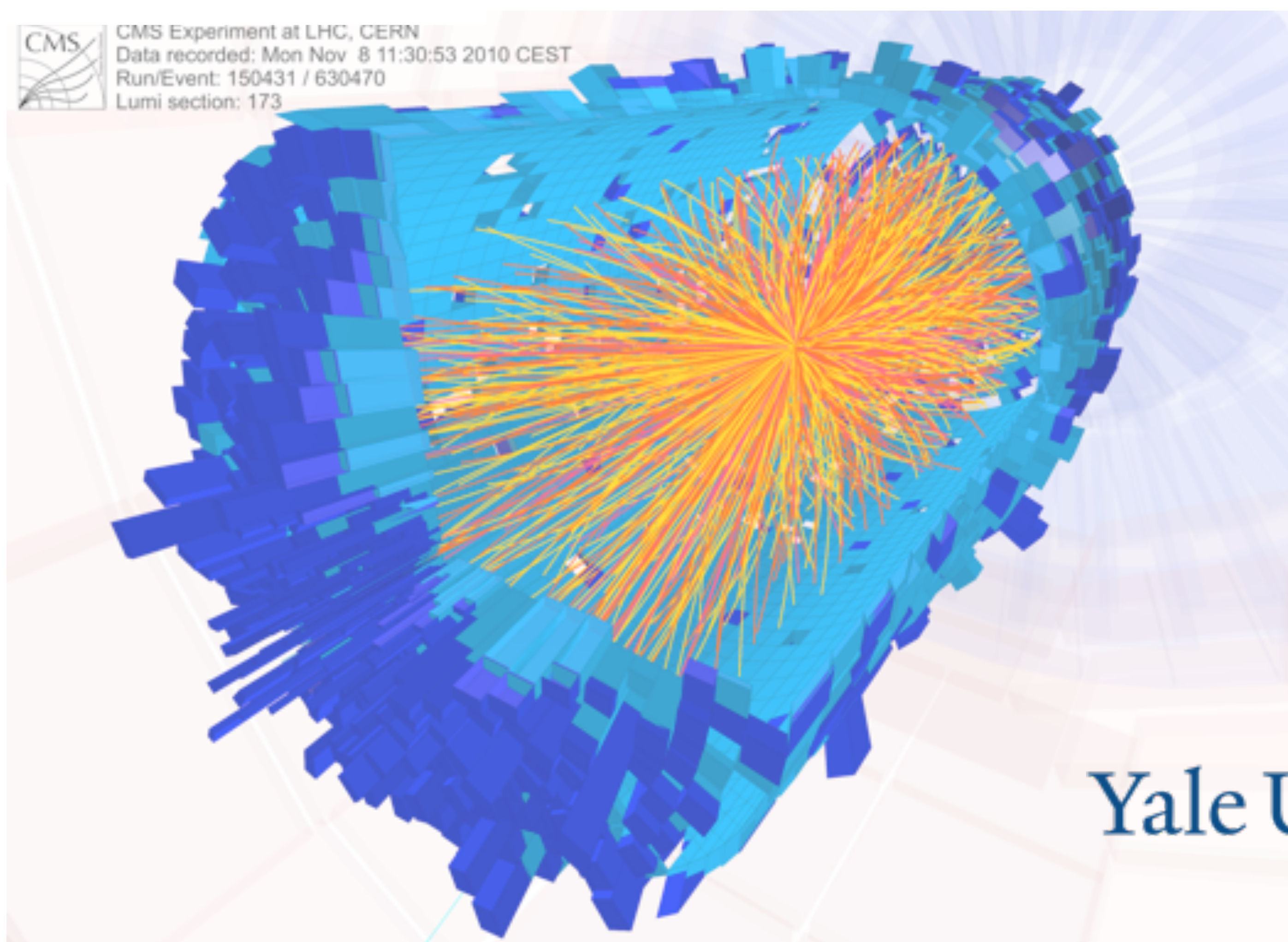
Hydrodynamic flow results from the Large Hadron Collider:

The latest and greatest

Andrew M. Adare
Yale University

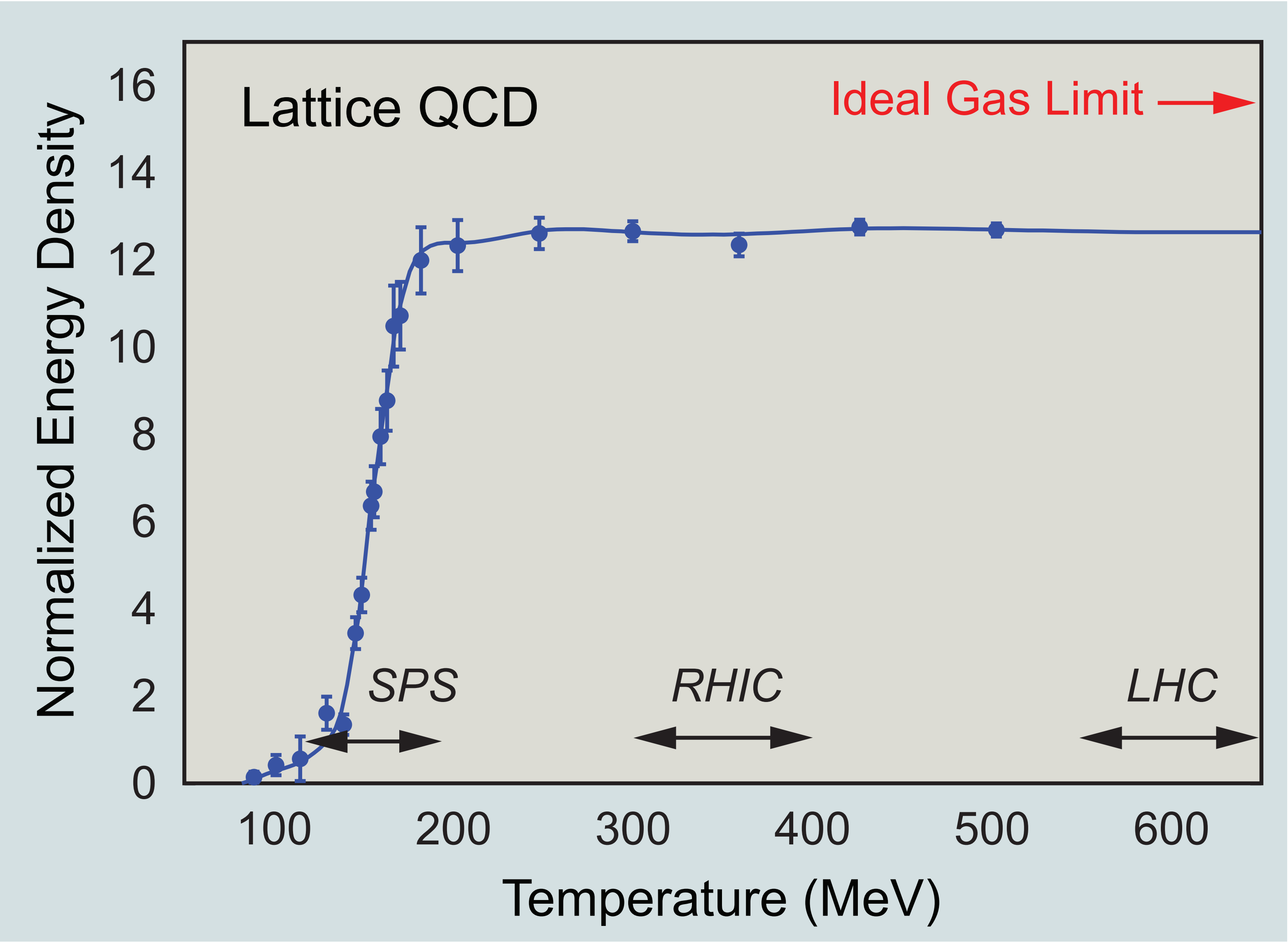
APS April Meeting
Atlanta, GA
April 2, 2012



Quark-gluon plasma

THE QGP: a partonic superfluid

QCD deconfinement: hadronic → partonic phase as T > 150-170 MeV



"The Frontiers of Science: A Long Range Plan"
http://science.energy.gov/np/nsac/

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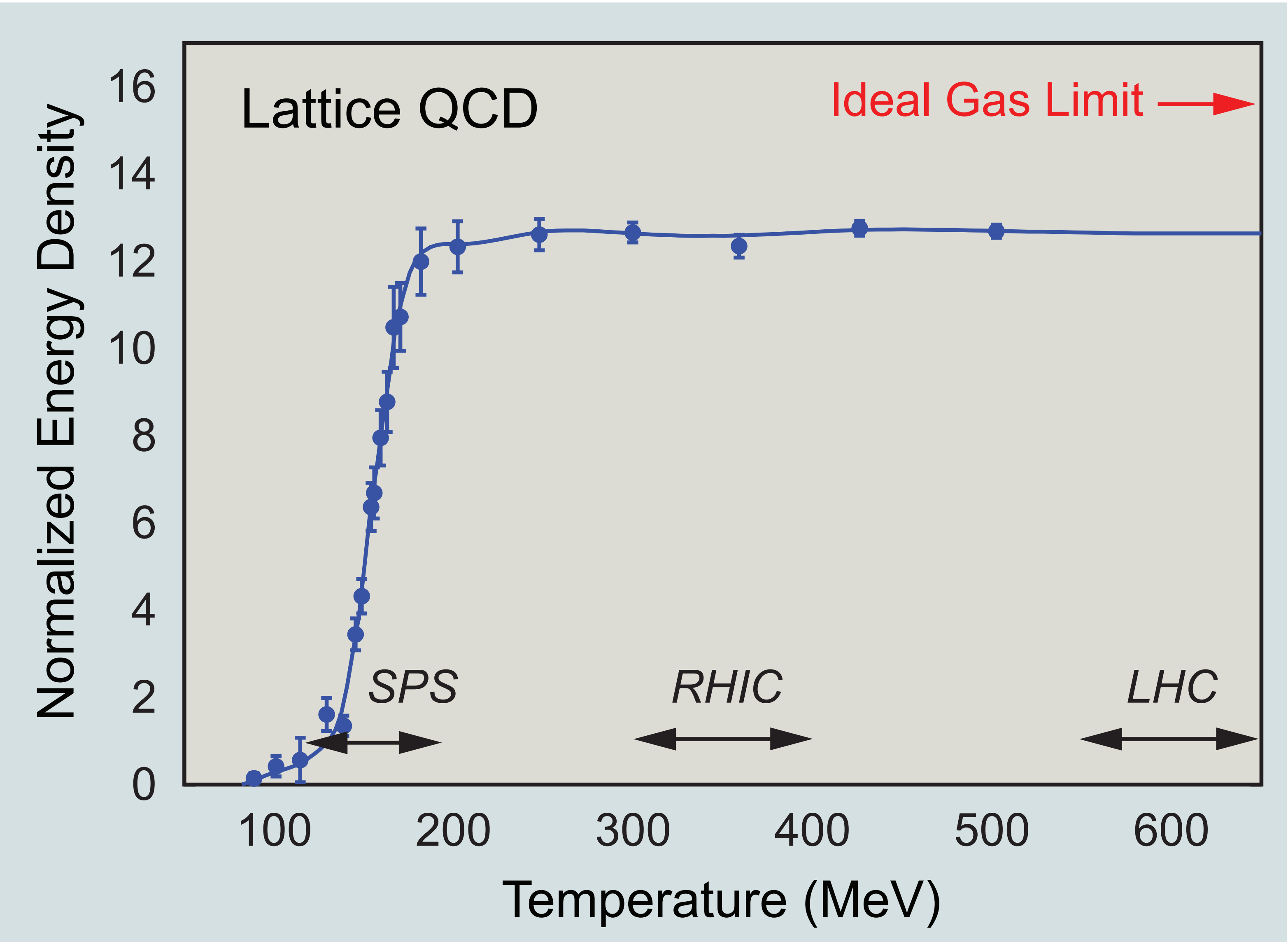

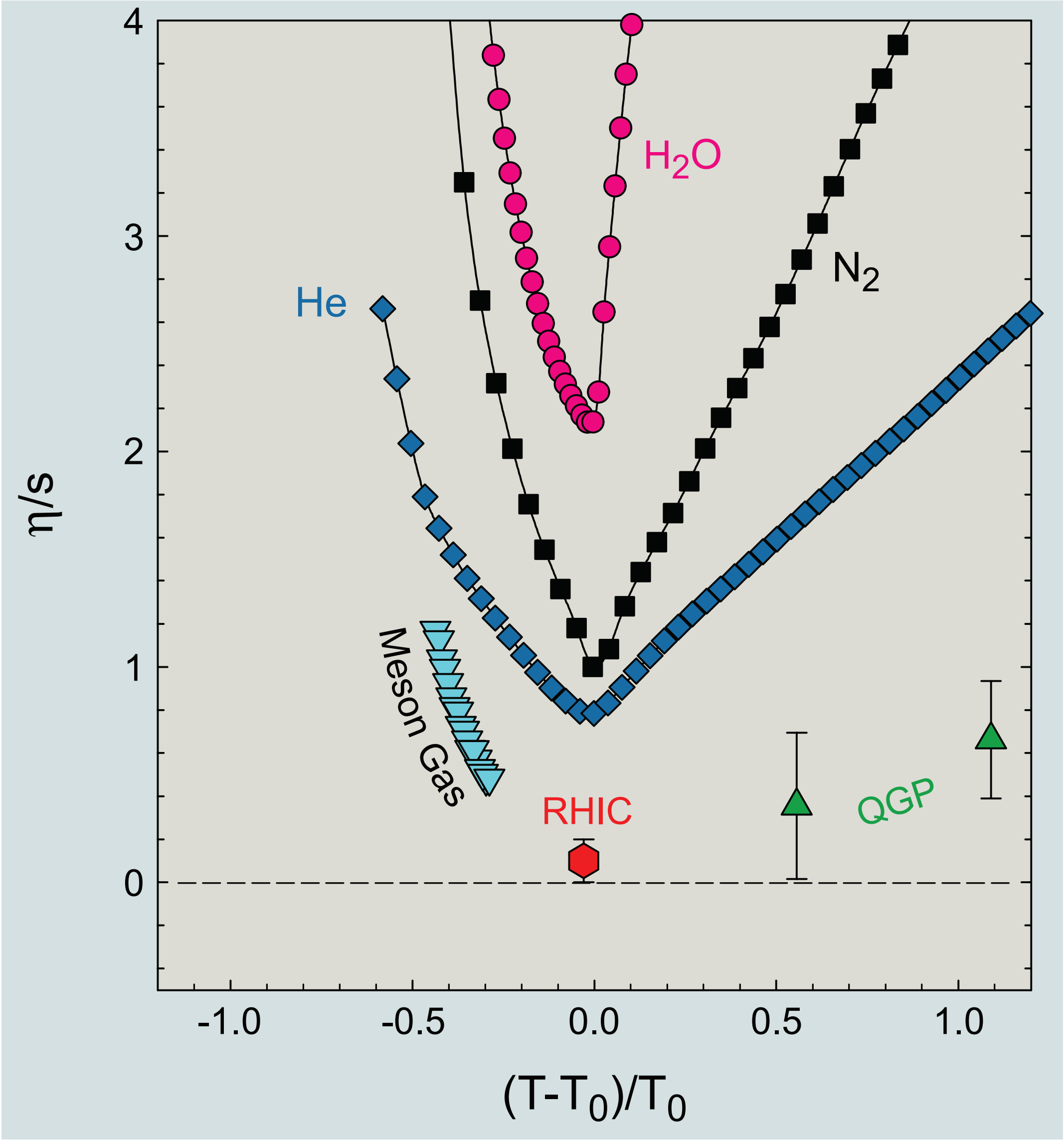

10+ years of heavy ions at RHIC

Support lattice predictions

Suggest fluidlike behavior

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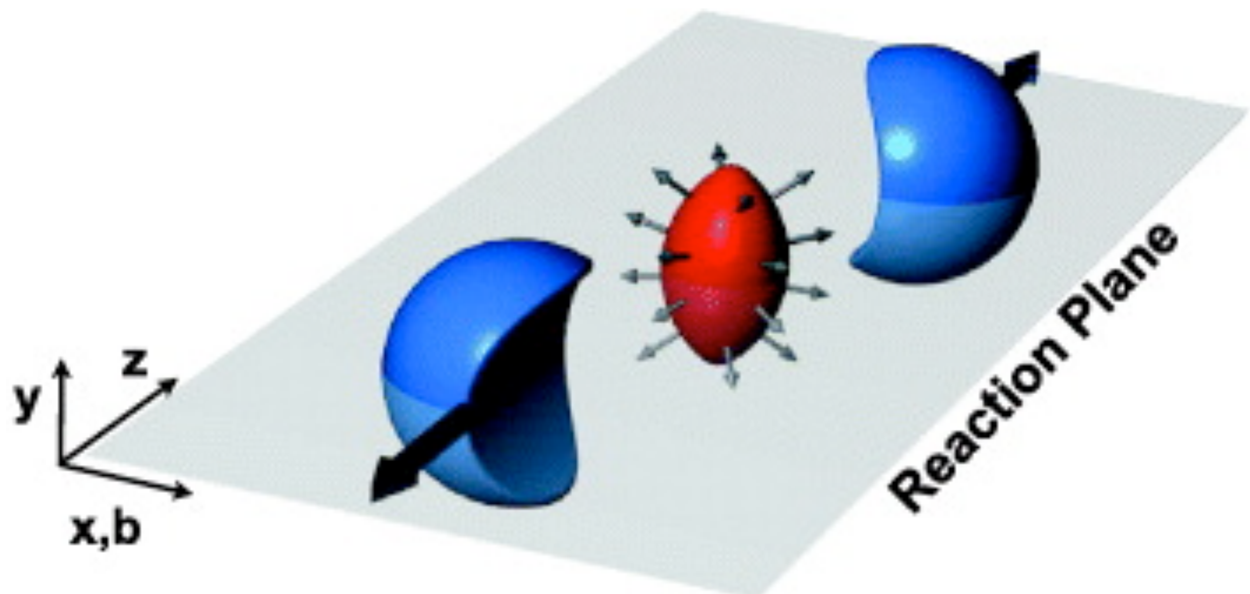
"The Frontiers of Science: A Long Range Plan"

http://science.energy.gov/np/nsac/

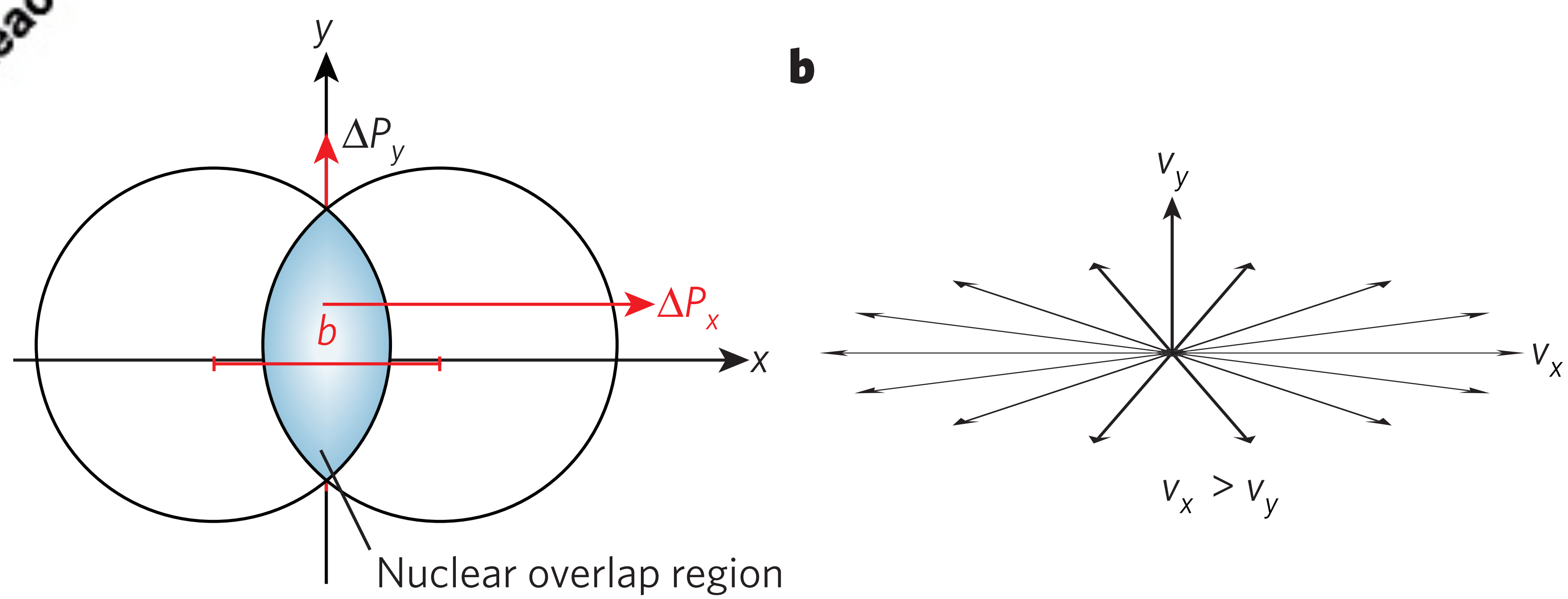
Hydrodynamics in nuclear collisions

Anisotropic flow of exploding fireball

Initial spatial eccentricity ⇒ final momentum eccentricity



New J. Phys. **13** (2011) 055008



Anisotropic pressure gradients drive particles in-plane

Similar "flow" also observed in other systems

Science **298** (2002) 2179

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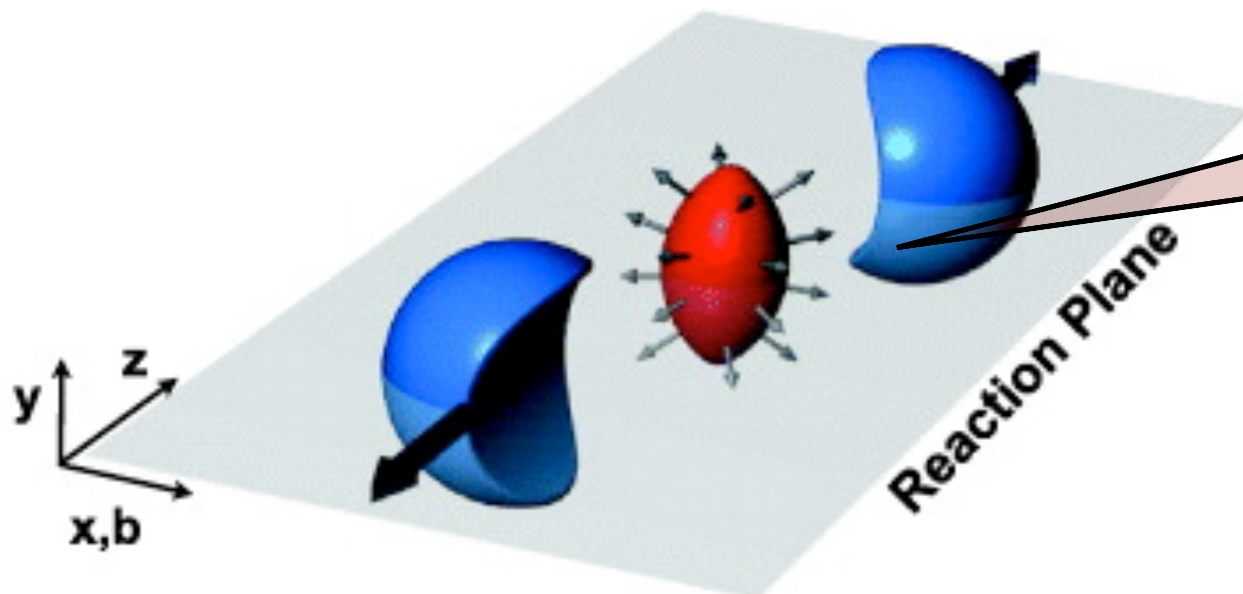

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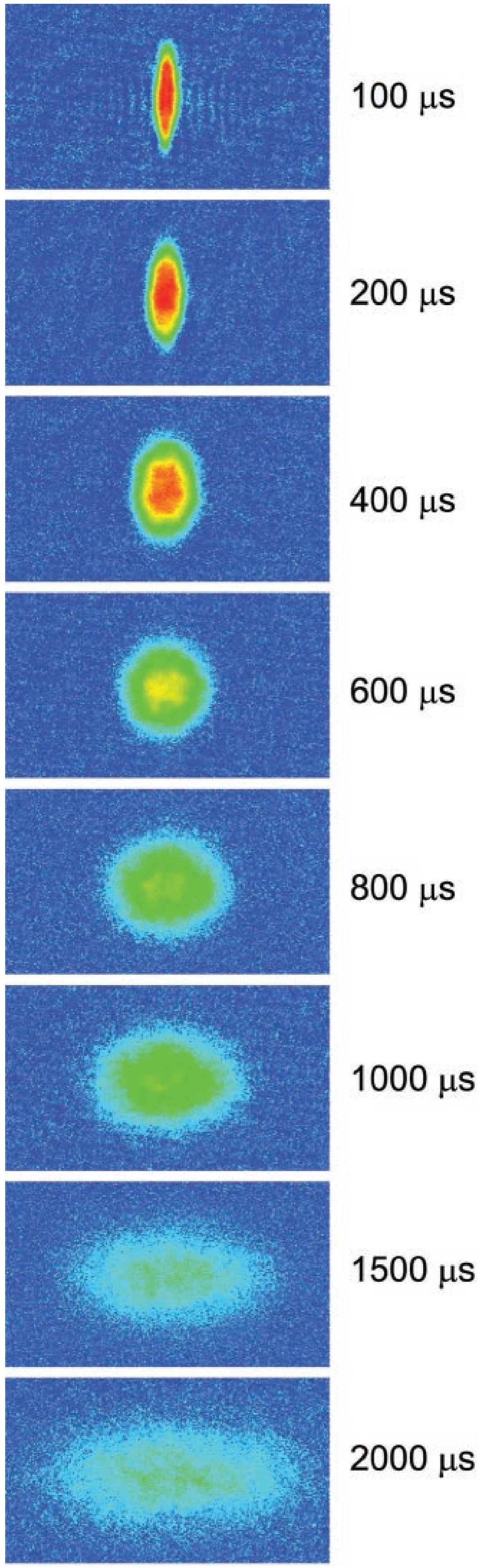
QGP (1 TK)

^{6}Li gas (1 nK)

strong coupling
+
low specific viscosity:
→ hydrodynamic flow



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PbPb at the LHC

The November revolution

November 2009

First p-p collisions, 900 GeV

November 2010

First Pb-Pb collisions, 2.76 TeV

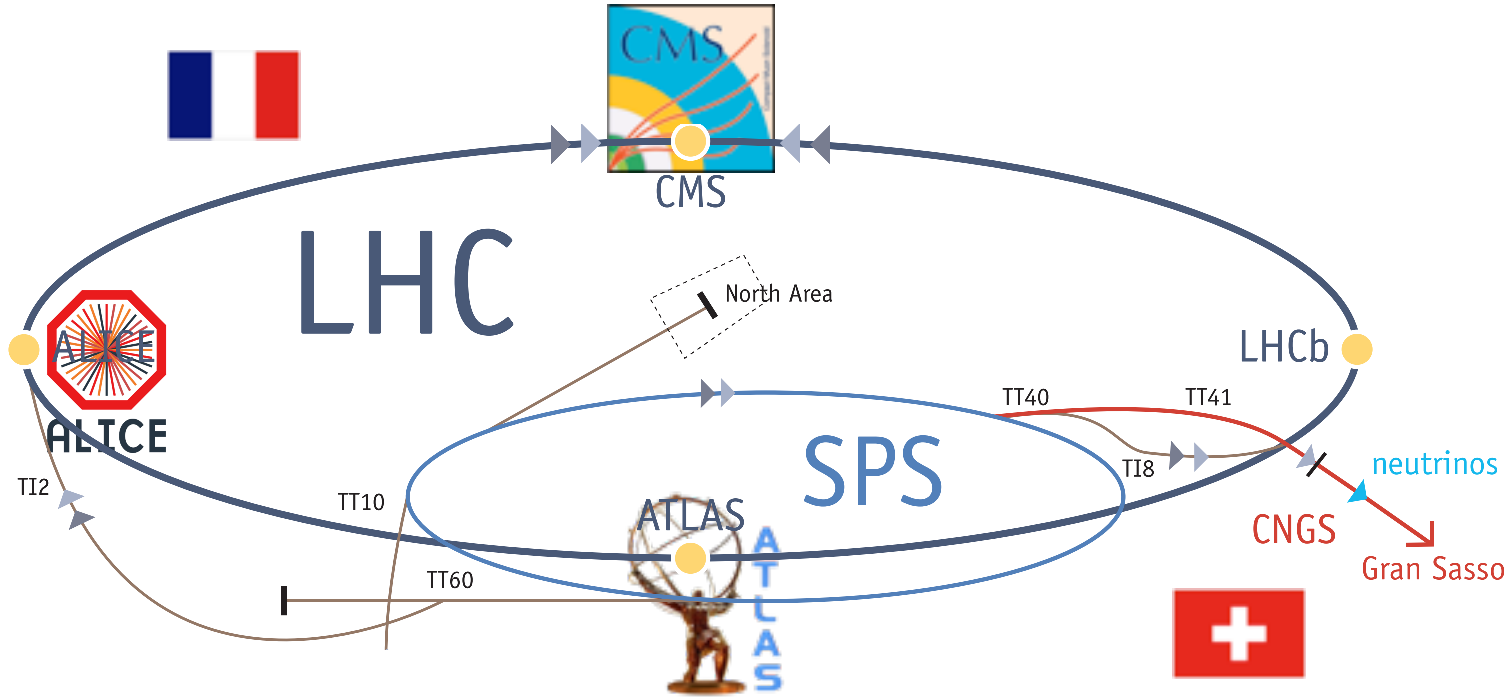
L_{PbPb} reached 2 x 10^{25} cm^{-2} s^{-1}

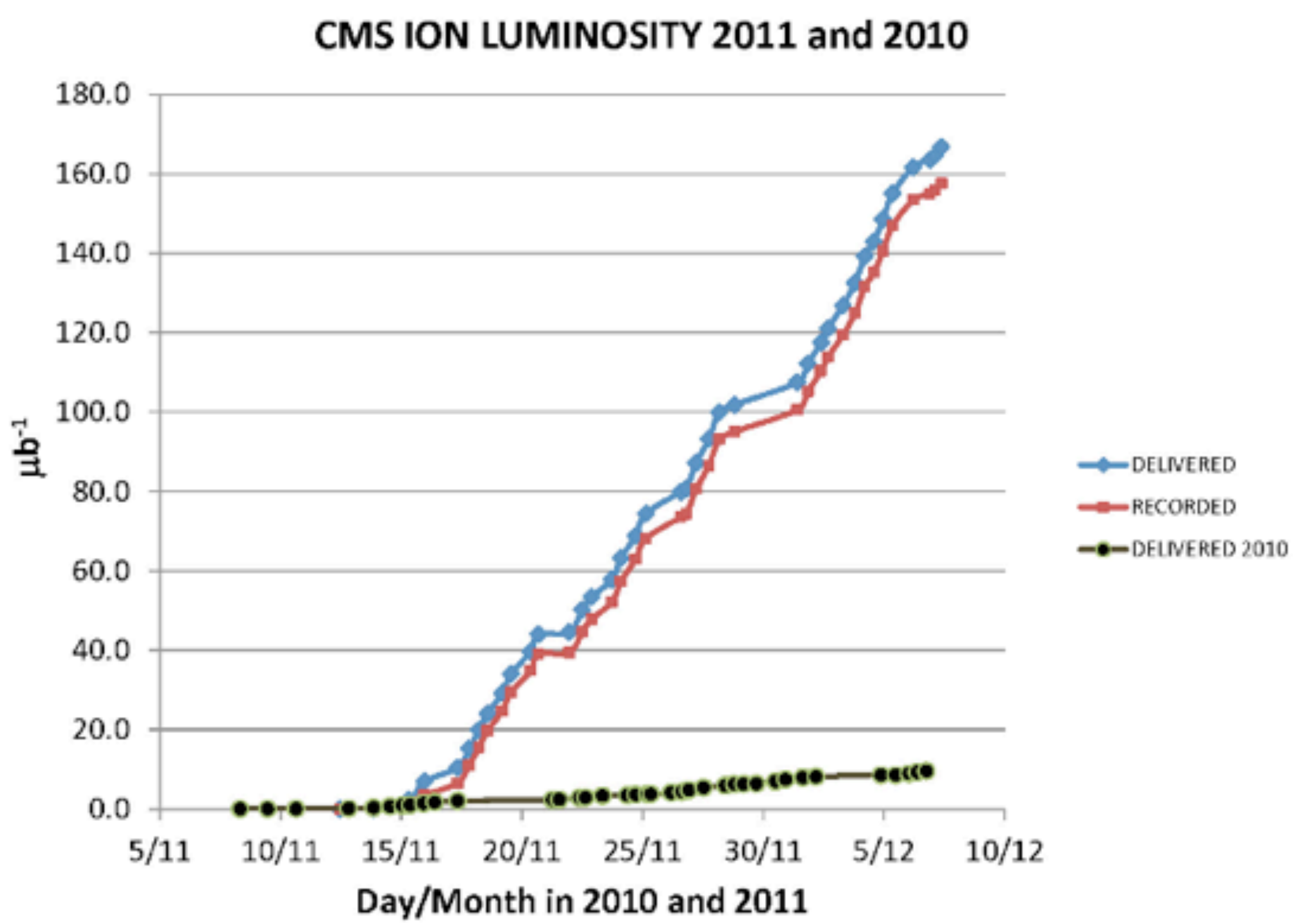
(Pb-Pb Design luminosity = 10^{27})

November 2011

20x increase over 2010 ∫Ldt

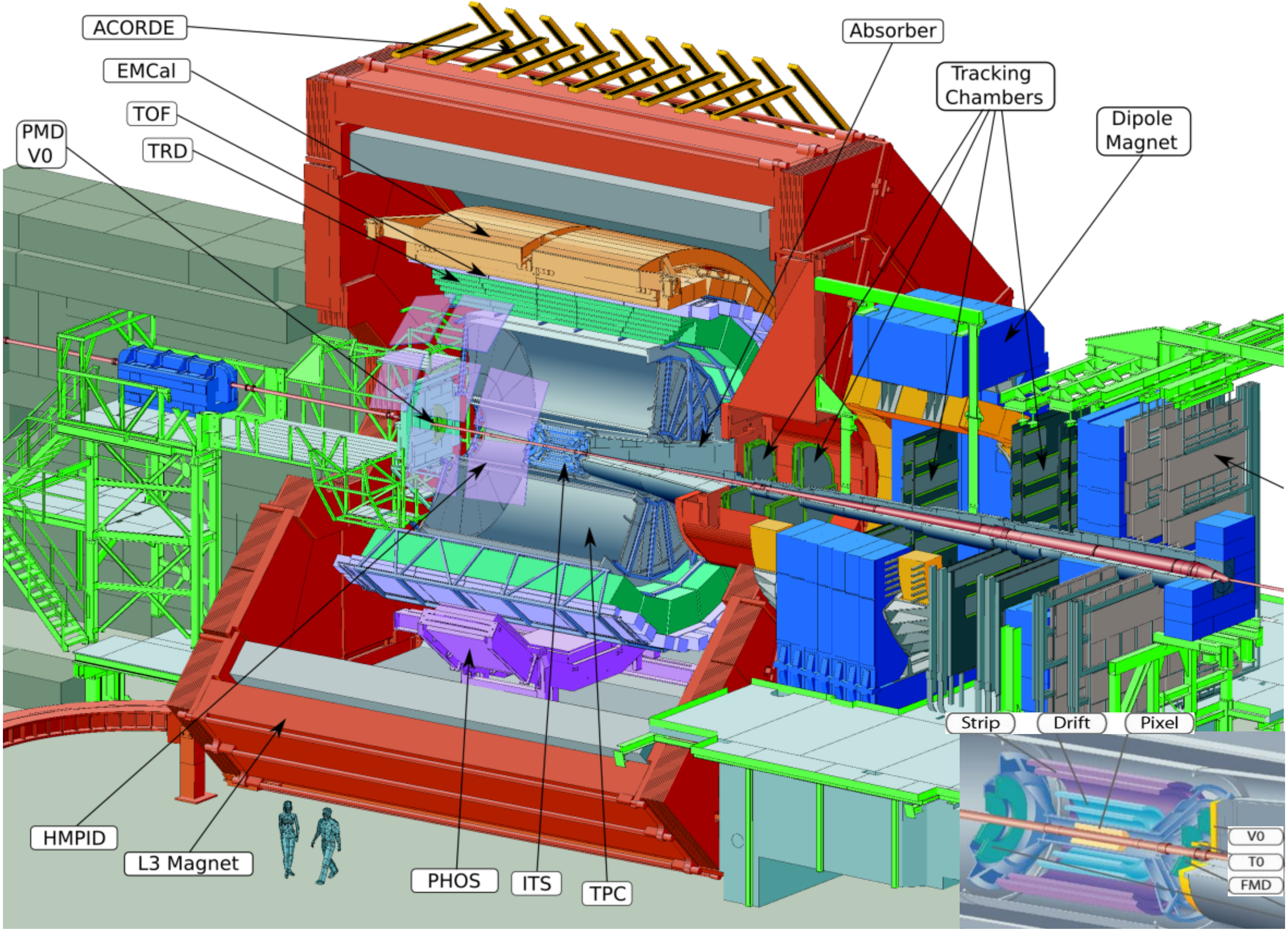
CMS matched their 2010 data volume in 1 day!





The LHC experiments

ALICE
ATLAS
CMS



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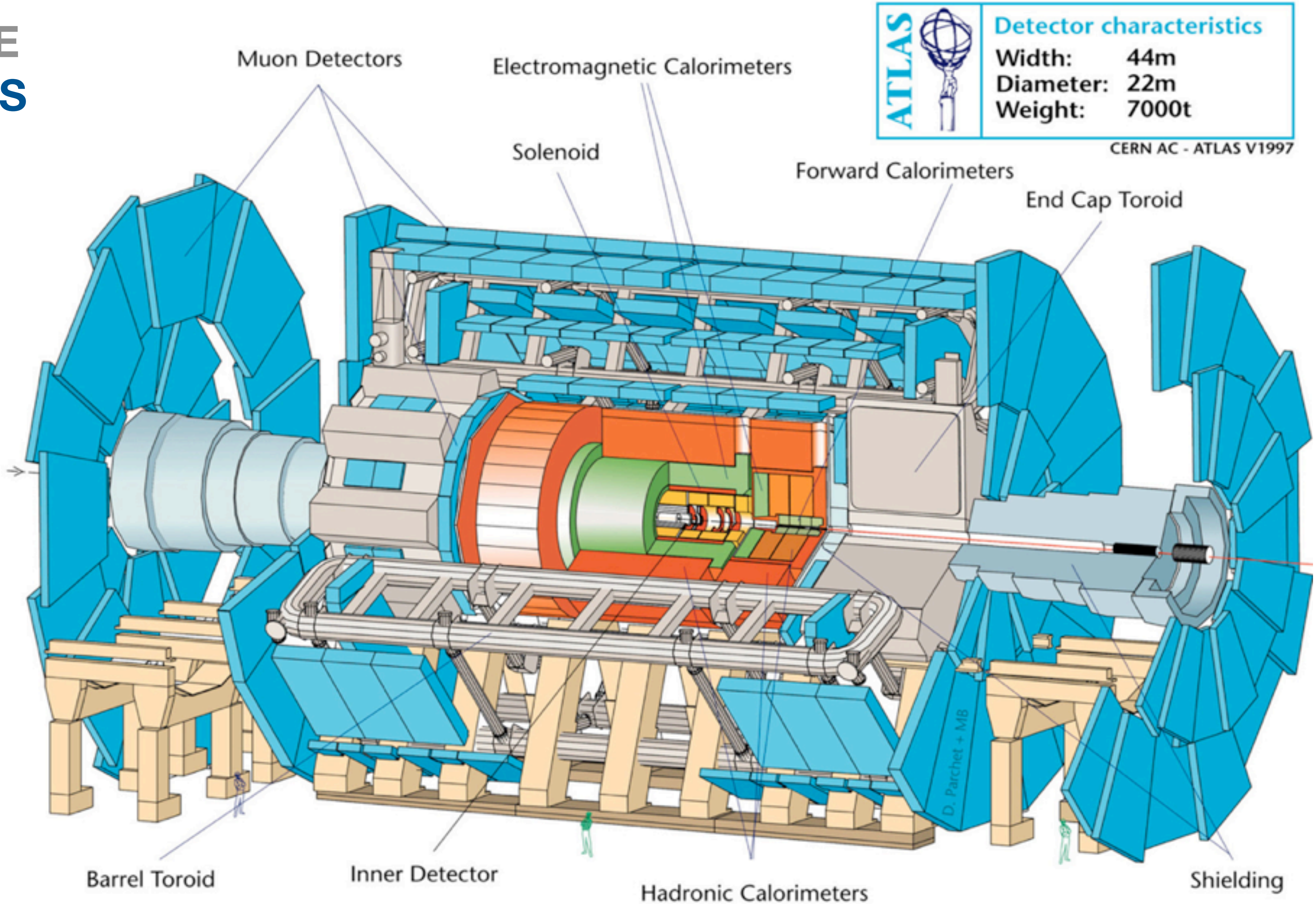

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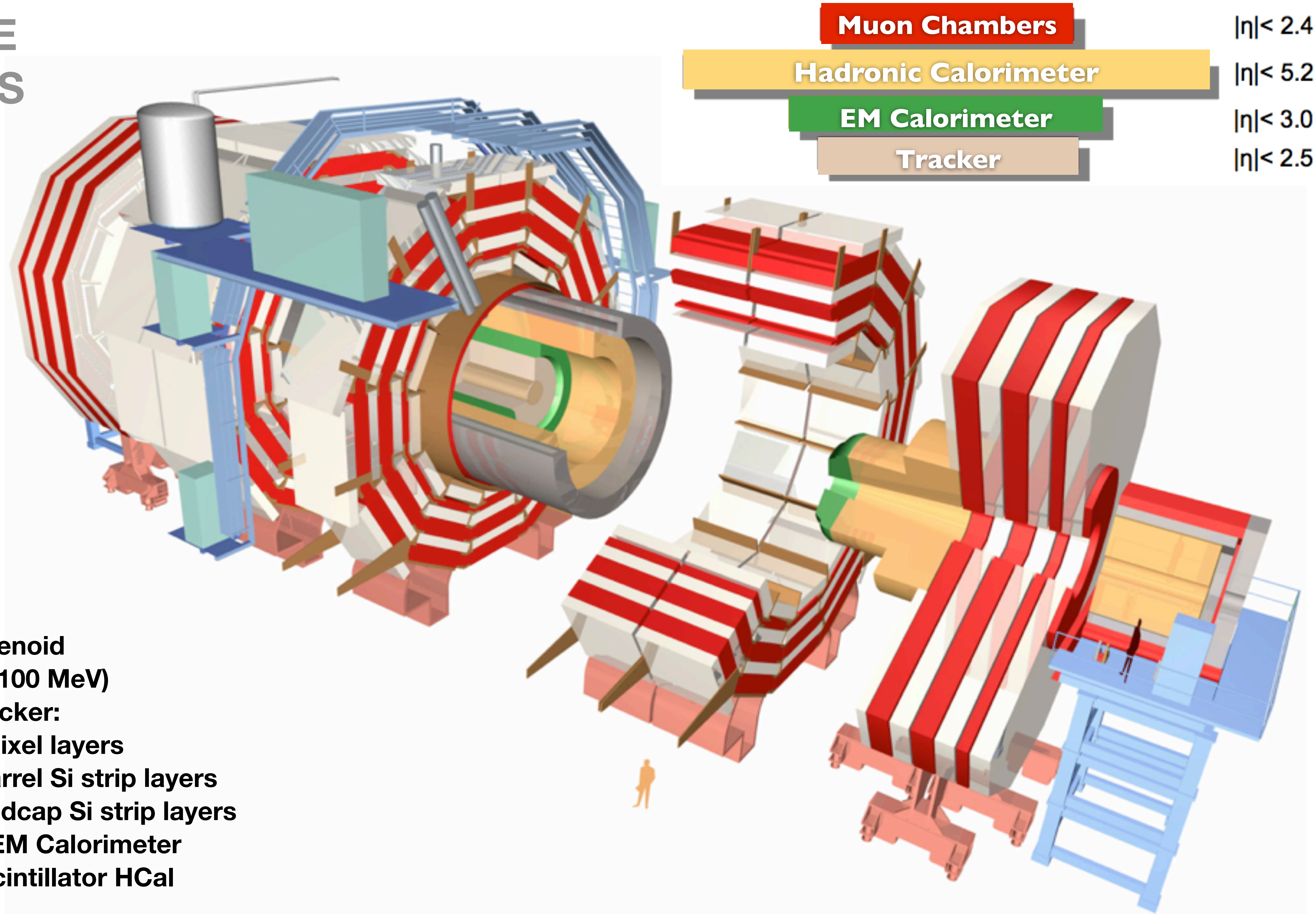

3.8 T solenoid
(p_T > 100 MeV)
Inner tracker:
- **3 Si pixel layers**
- **10 Barrel Si strip layers**
- **11 Endcap Si strip layers**

Crystal EM Calorimeter
Brass/Scintillator HCal

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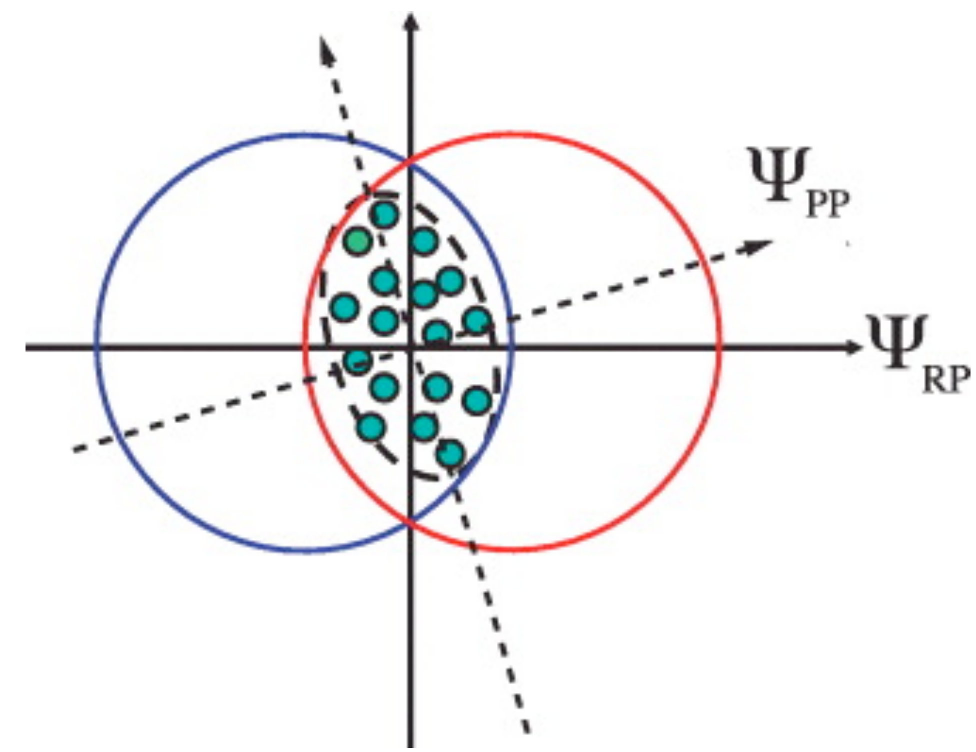
Measuring anisotropic flow (I)

Parametrize azimuthal particle density



New J. Phys. **13** (2011) 055008

Quantify using n[th] Fourier coefficient v_n

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n^{RP})\right]$$

$$v_n^{\text{ideal}} = \langle \cos n(\phi - \Psi_n^{RP}) \rangle$$

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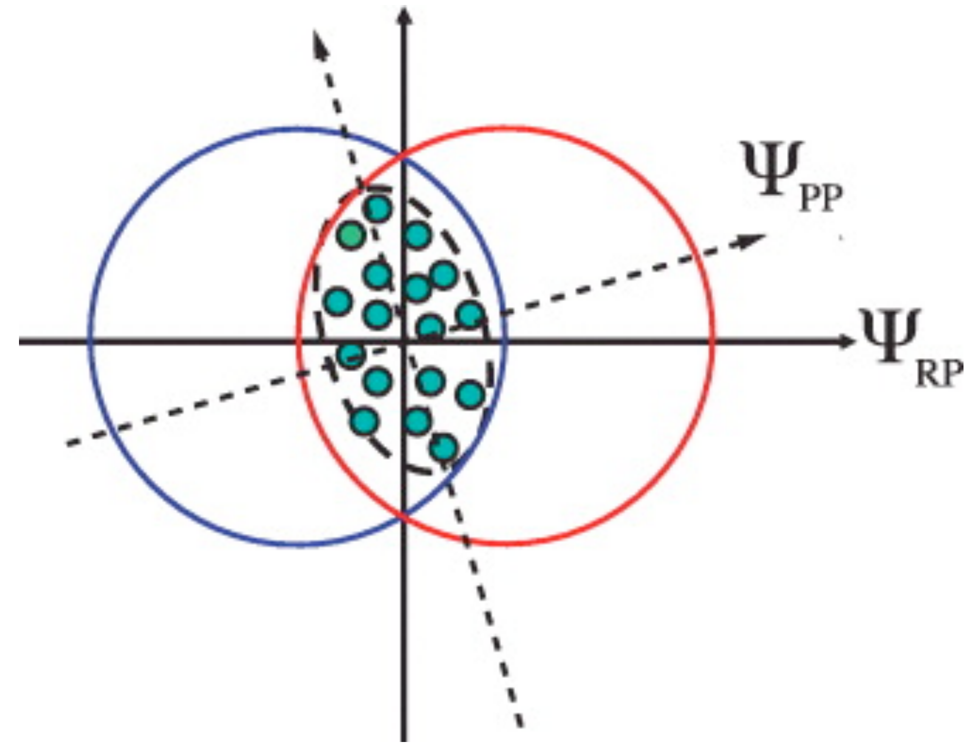

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$$v_n^{\text{ideal}} = \langle \cos n(\phi - \Psi_n^{RP})\rangle$$

Ψ^{RP} is the <u>ideal</u> reaction plane.
Fluctuations: symmetry axes rotated from collision coordinates.

The n[th]-order event plane (of participants) is measured:

$$\Psi_n^{EP} = \frac{1}{n}\tan^{-1}\frac{\sum_i w_i \sin n\phi_i}{\sum_i w_i \cos n\phi_i}$$

$$v_n\{EP\} = \frac{v_n^{obs}\{EP\}}{\text{resolution}} = \frac{\langle \cos n(\phi - \Psi_n^{EP})\rangle}{C \times \sqrt{\langle \cos n(\Psi_n^a - \Psi_n^b)\rangle}}$$

Event plane method

Measuring anisotropic flow (II)

Multi-particle cumulants

No event plane measurement required!

2-particle and 4-particle cumulants:

$$c_n\{2\} \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$$

$$c_n\{4\} \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

Borghini, Dihn and Ollitrault, PRC 64, 054901 (2001)
Bilandzic, Snellings and Voloshin, PRC 83, 044913 (2011)

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Different sensitivities to fluctuations and nonflow:

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2 + \delta$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

useful!

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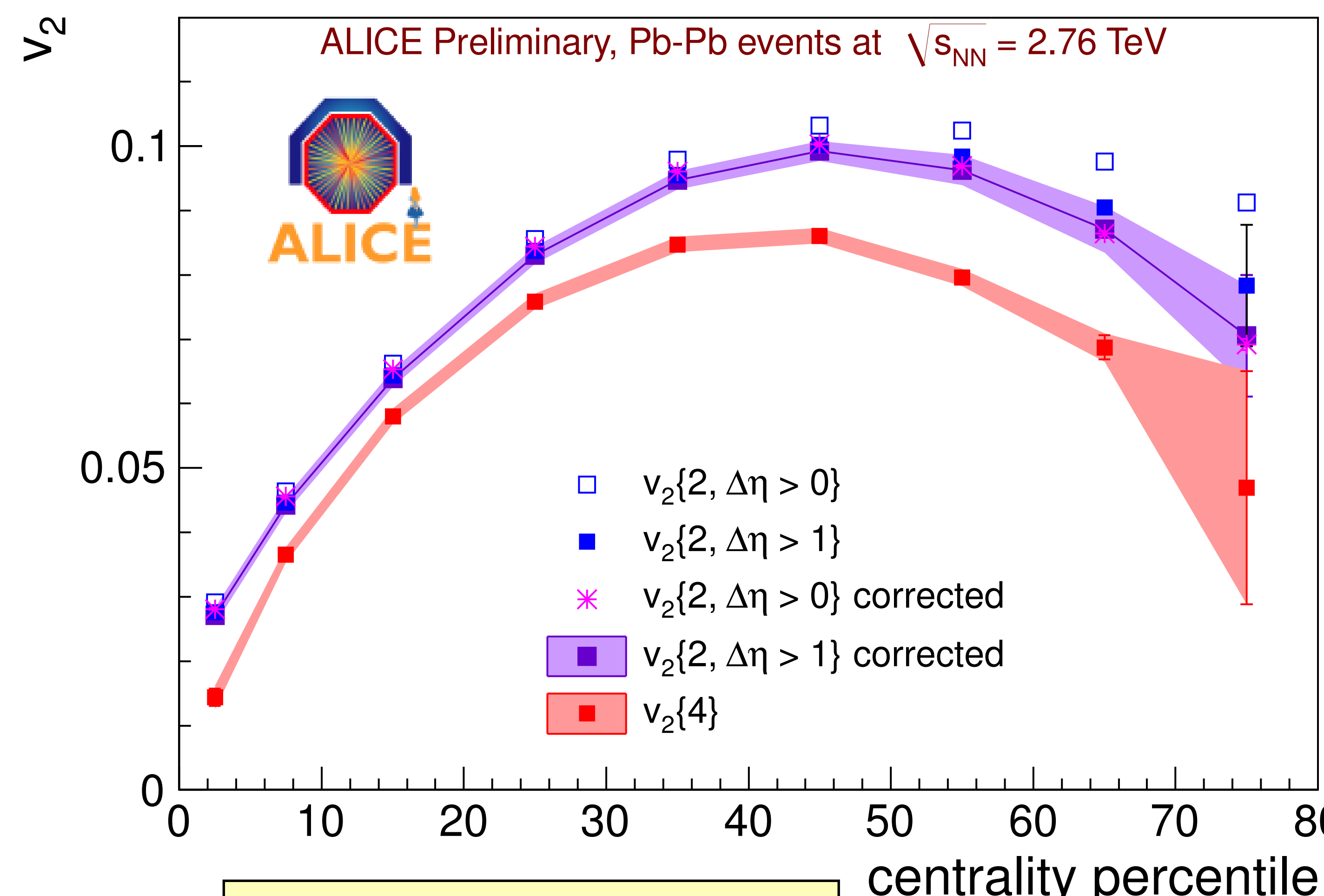
Flow is a collective effect. Correlating 4 particles vs. 2 suppresses "nonflow"



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useful!

Cumulant method

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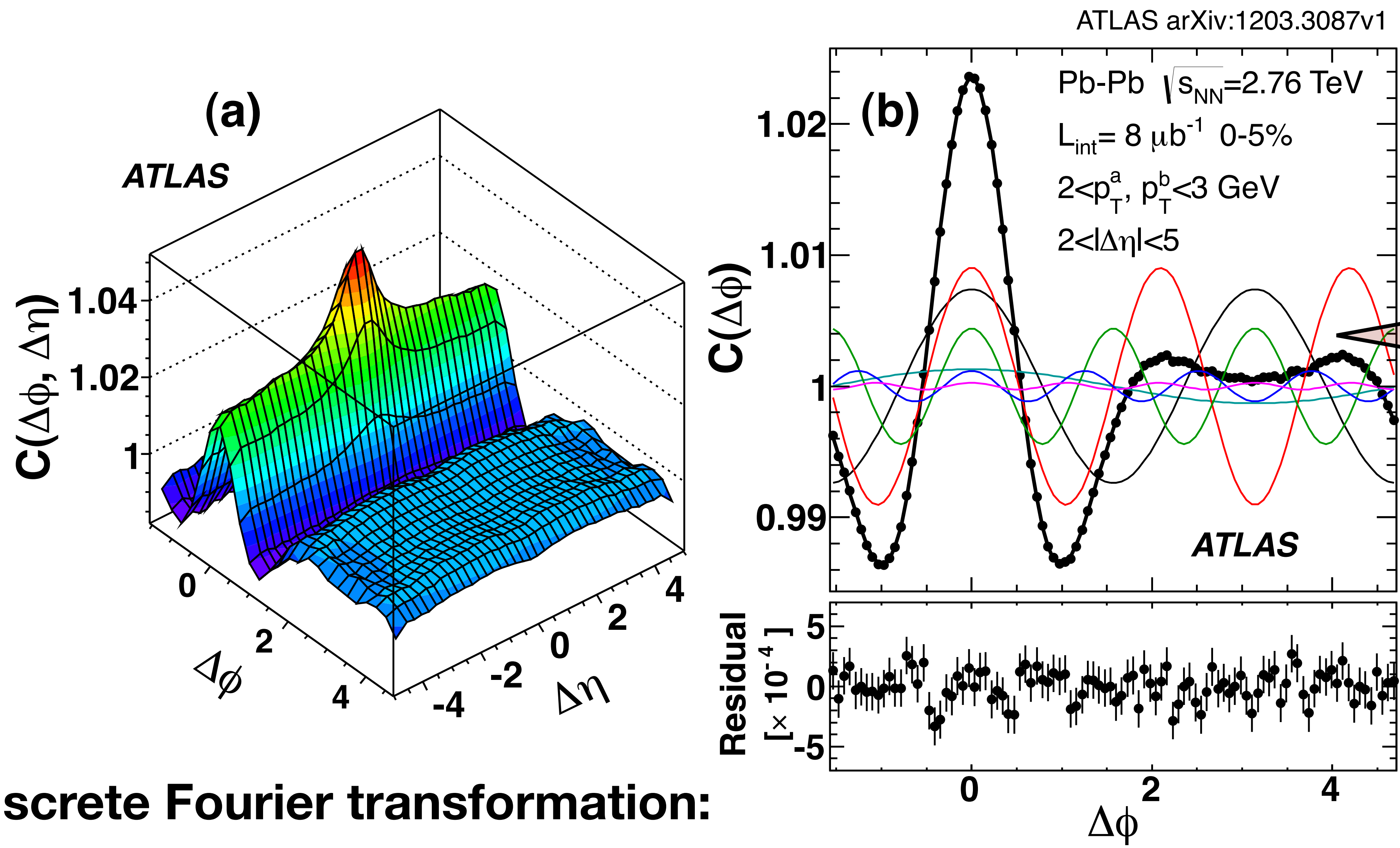
Measuring anisotropic flow (III)

Extract harmonics from 2-particle correlation functions

Δη gap excludes (0, 0) peak → suppresses nonflow

Harmonic amplitude ≡ $V_{n\Delta}$ (ALICE, CMS) a.k.a. $v_{n,n}$ (ATLAS)



Harmonics (from DFT or fit) related to v_n:

amplitude = $v_n^a \times v_n^b$

Discrete Fourier transformation:

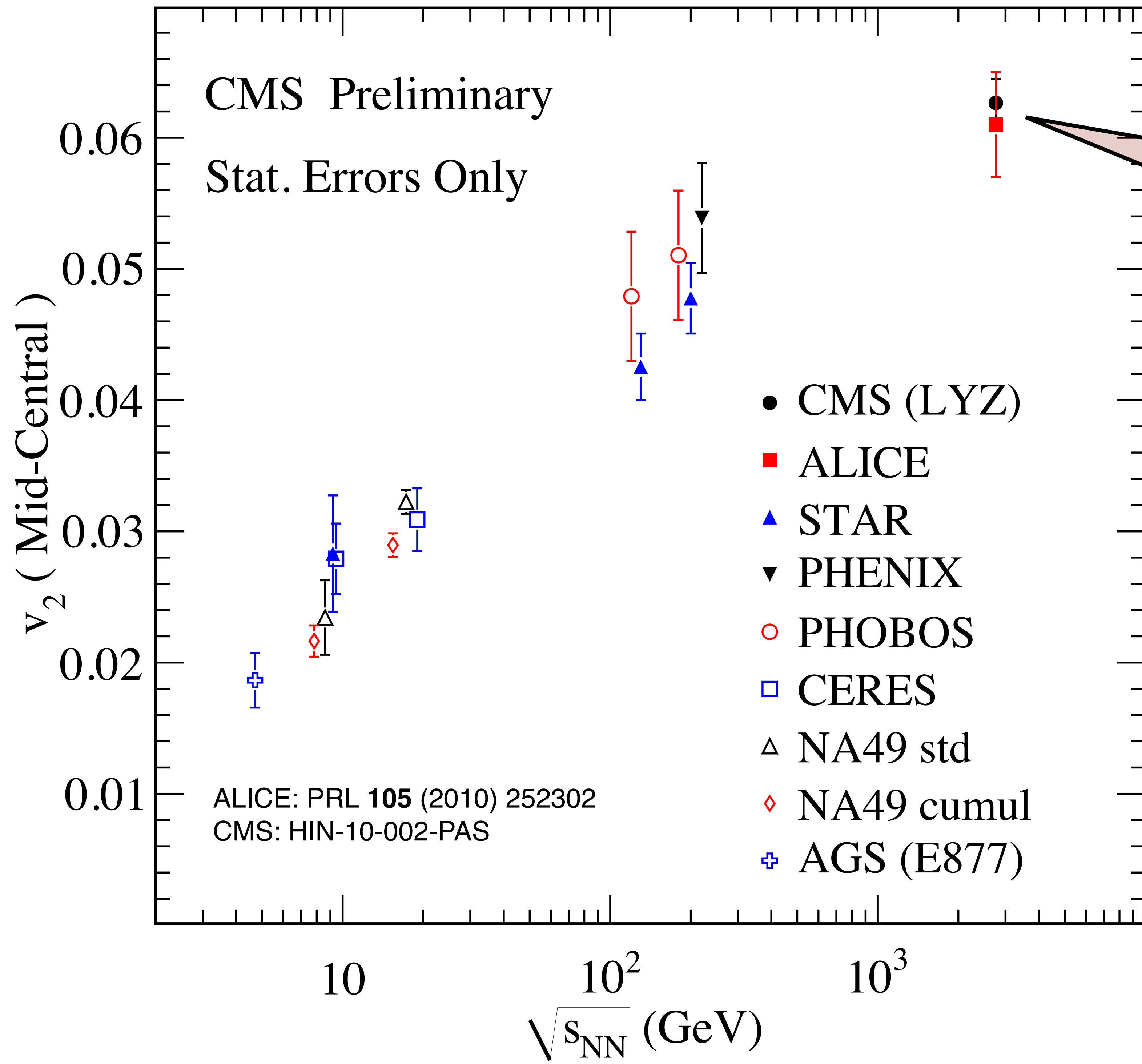
$$\langle \cos n\Delta\phi \rangle = \frac{\sum_{m=1}^{N} \cos(n\Delta\phi_m) C(\Delta\phi_m)}{\sum_{m=1}^{N} C(\Delta\phi_m)}$$

Fourier decomposition method

v_2 @ LHC and predecessors

v_2 vs. collision energy for 20-30% most central collisions

Hydro behavior follows extrapolated RHIC trend



Flow at LHC 30% higher than at RHIC

CMS and ALICE in close agreement

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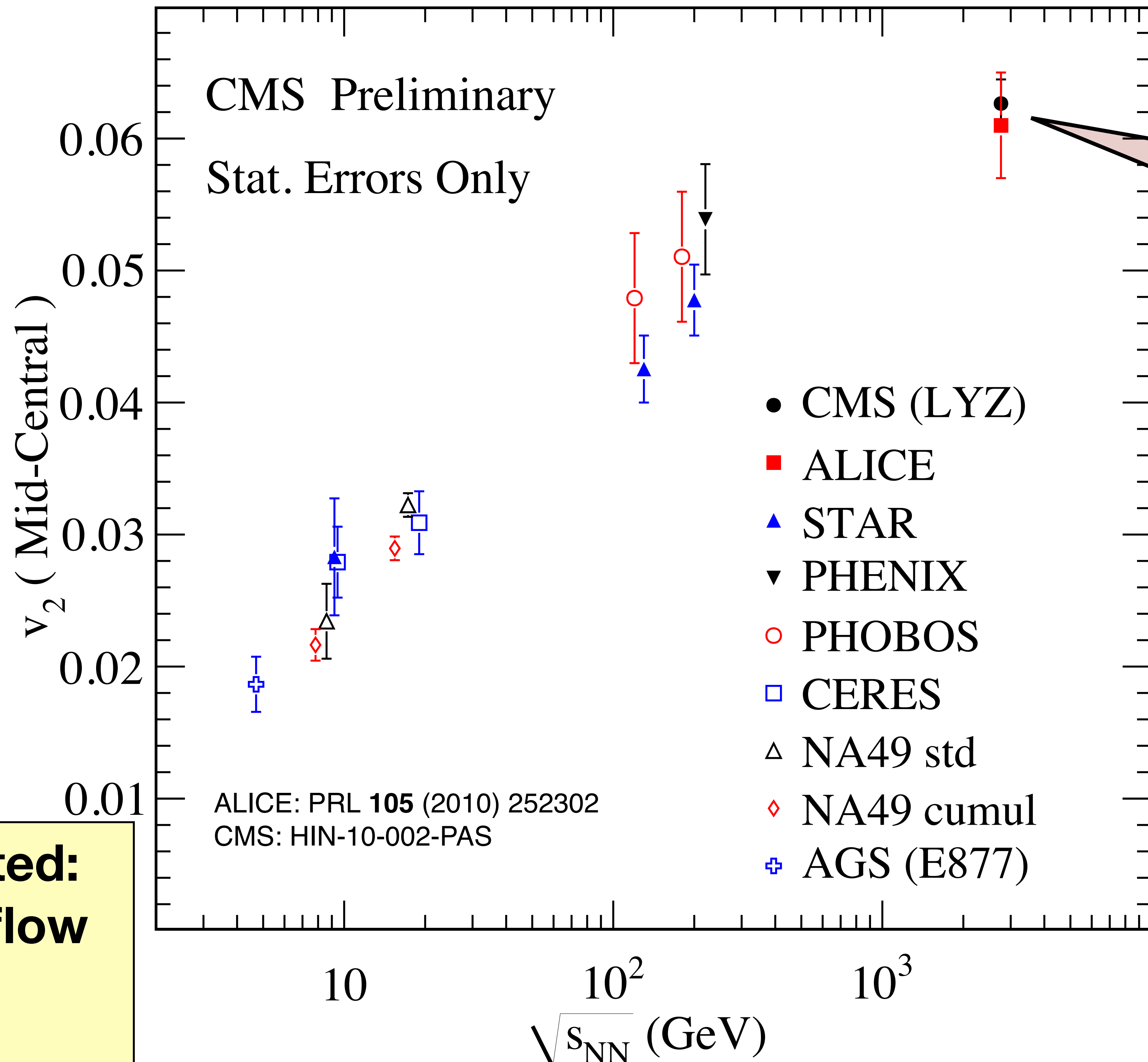


Flow at LHC 30% higher than at RHIC

CMS and ALICE in close agreement

Not unexpected: larger radial flow velocity, thus higher <p_T>

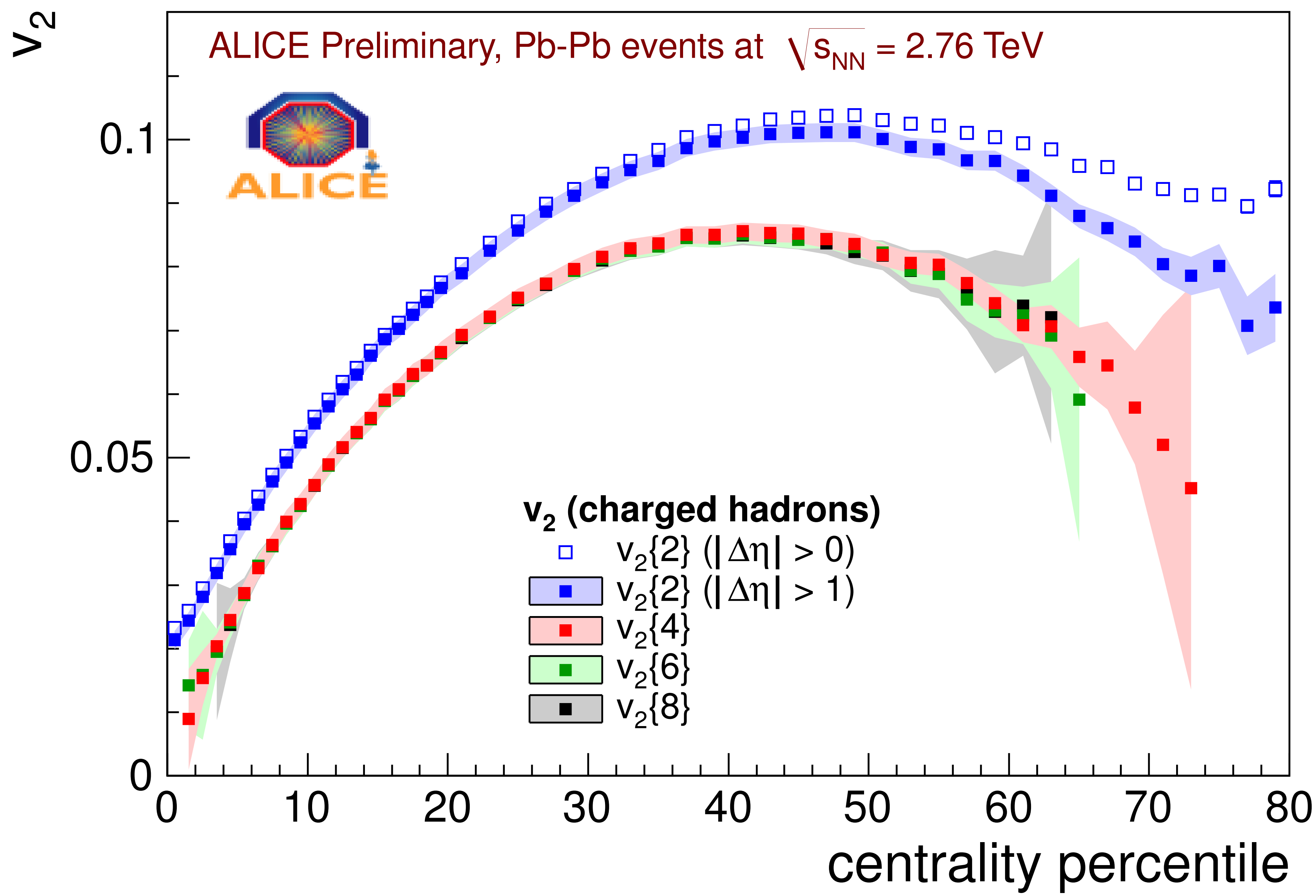
v_2 vs. centrality

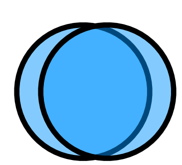
ALICE $v_2\{2\}$ and $v_2\{4\}$

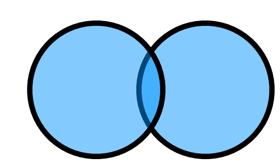
Sharp rise from central to mid-central collisions
reflects increasing eccentricity

Declines in most peripheral events
weaker pressure from smaller system

Large difference between 2- and 4-particle cumulants
Quantifies fluctuations!
What can be learned from this?







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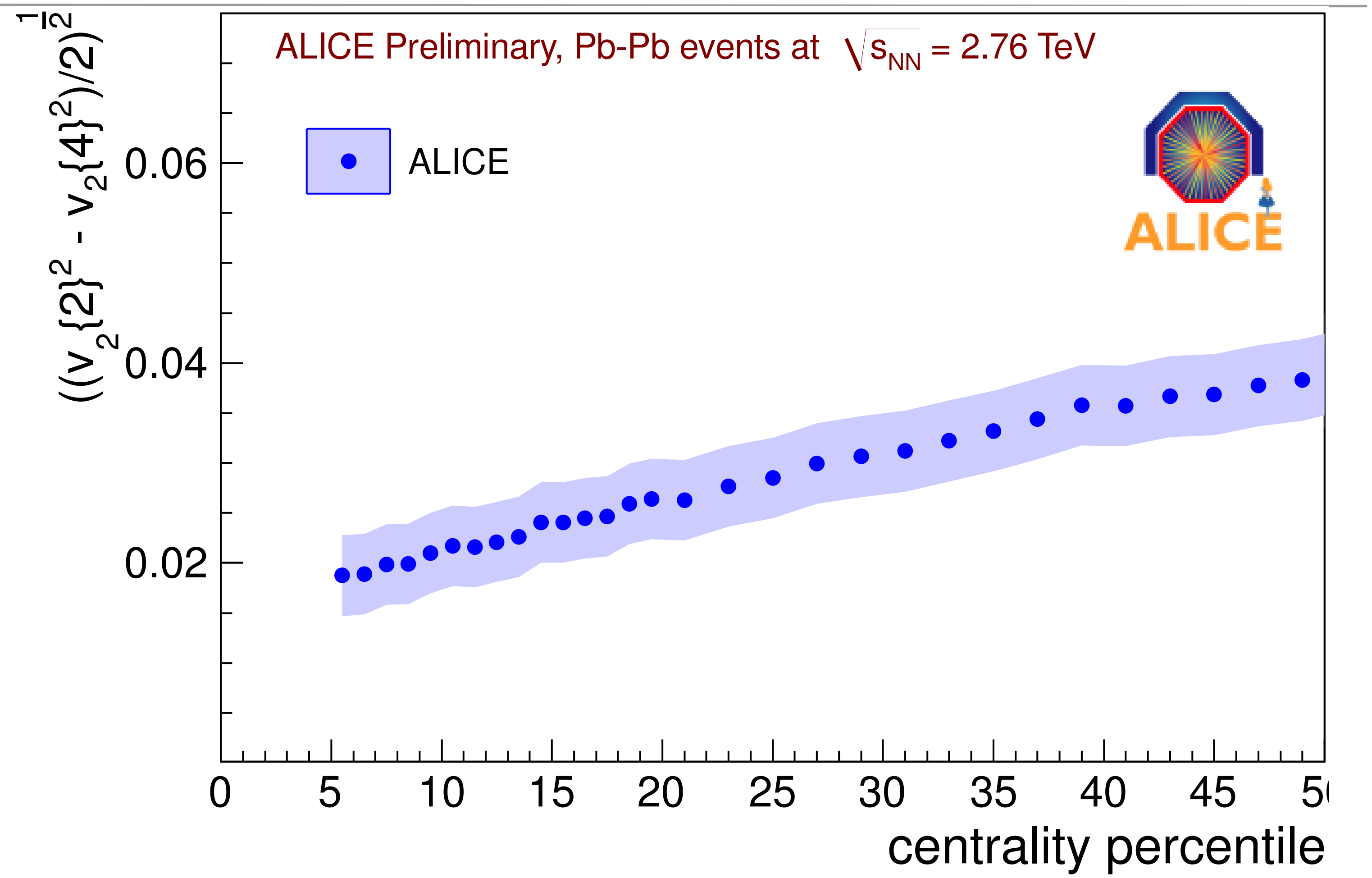
Fluctuations and initial-state models

Flow fluctuations:

$$\sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}} \simeq \sigma_{v_n}^2$$



Fluctuations and initial-state models

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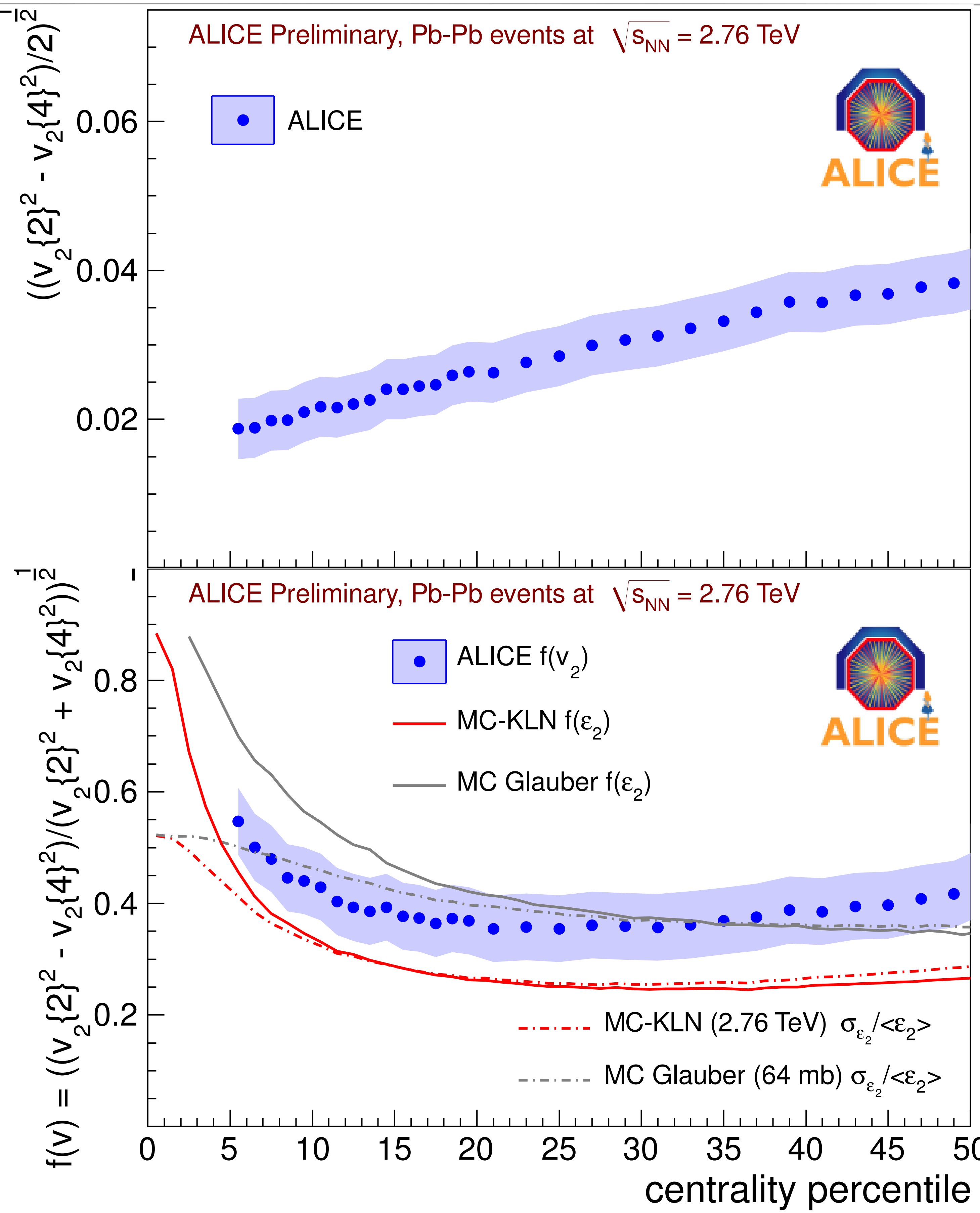
$$\sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}} \simeq \sigma_{v_n}^2$$

Normalized by v_2 or ε_2:

$$\sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}} \simeq \frac{\sigma_{v_n}^2}{\bar{v}_n} \text{ or } \frac{\sigma_{\epsilon_n}^2}{\bar{\epsilon}_n}$$

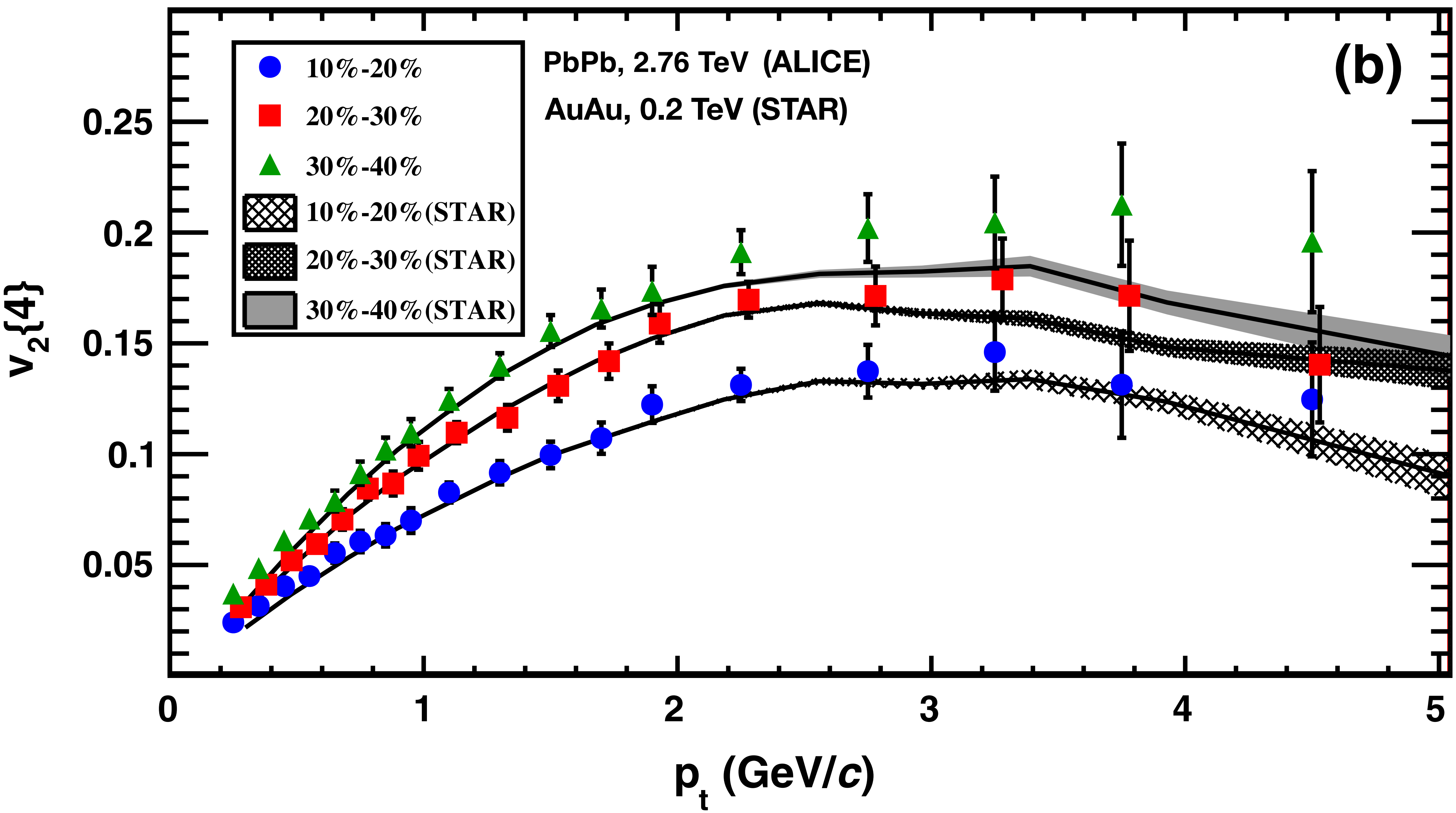
Much ongoing theory work on initial state
See talk by H. Petersen today



v_2 at RHIC and LHC: ALICE and STAR

ALICE data (colored) matches RHIC within 5%

PRL **105** (2010) 252302



Agreement also consistent with hydro predictions

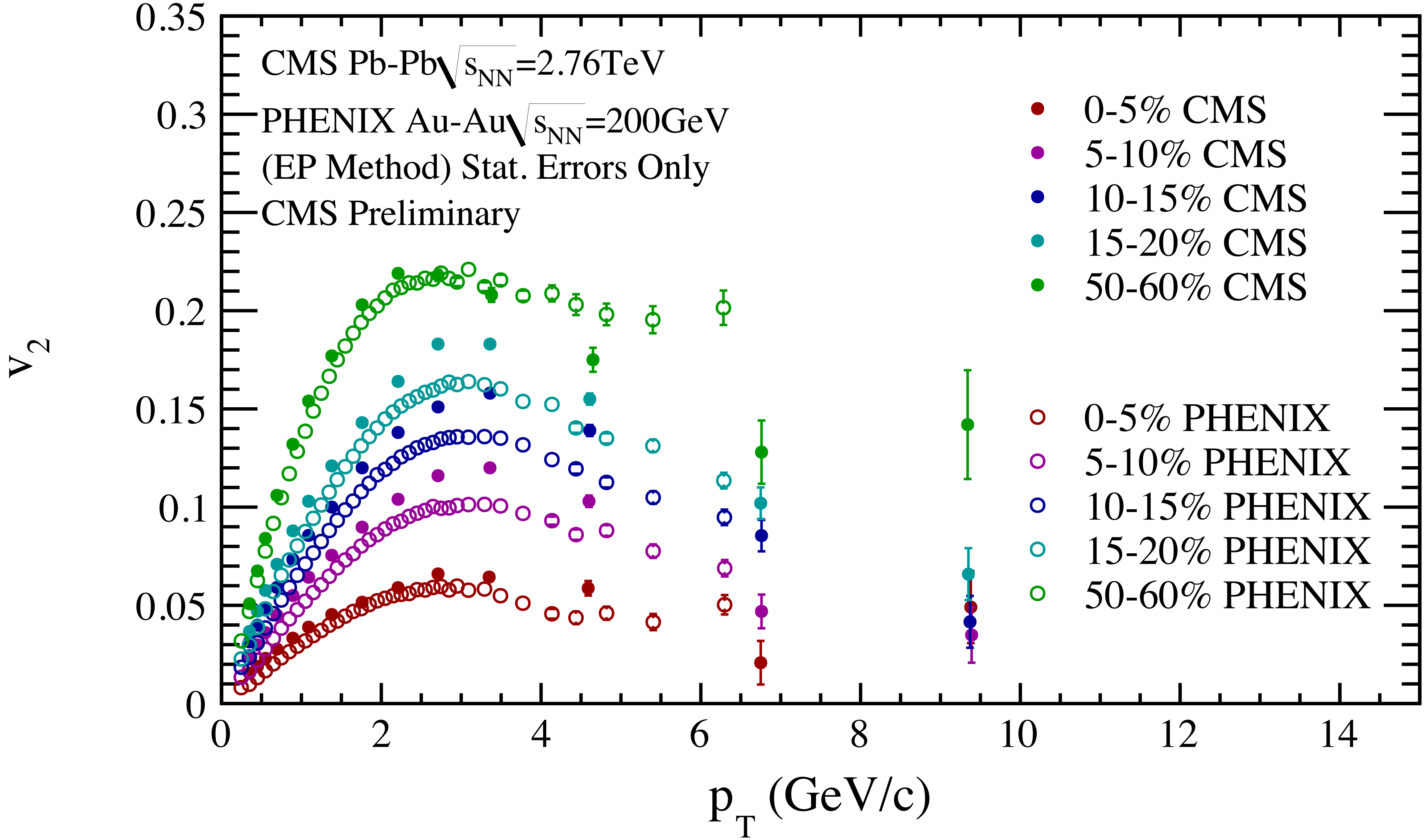
e.g. PRC 84 (2011) 044903

v_2 at RHIC and LHC: CMS and PHENIX

CMS v_2 slightly higher than PHENIX in midcentral collisions

But consistent within 15%

CMS: HIN-10-002-PAS
PHENIX: PRL **105** (2010) 062301



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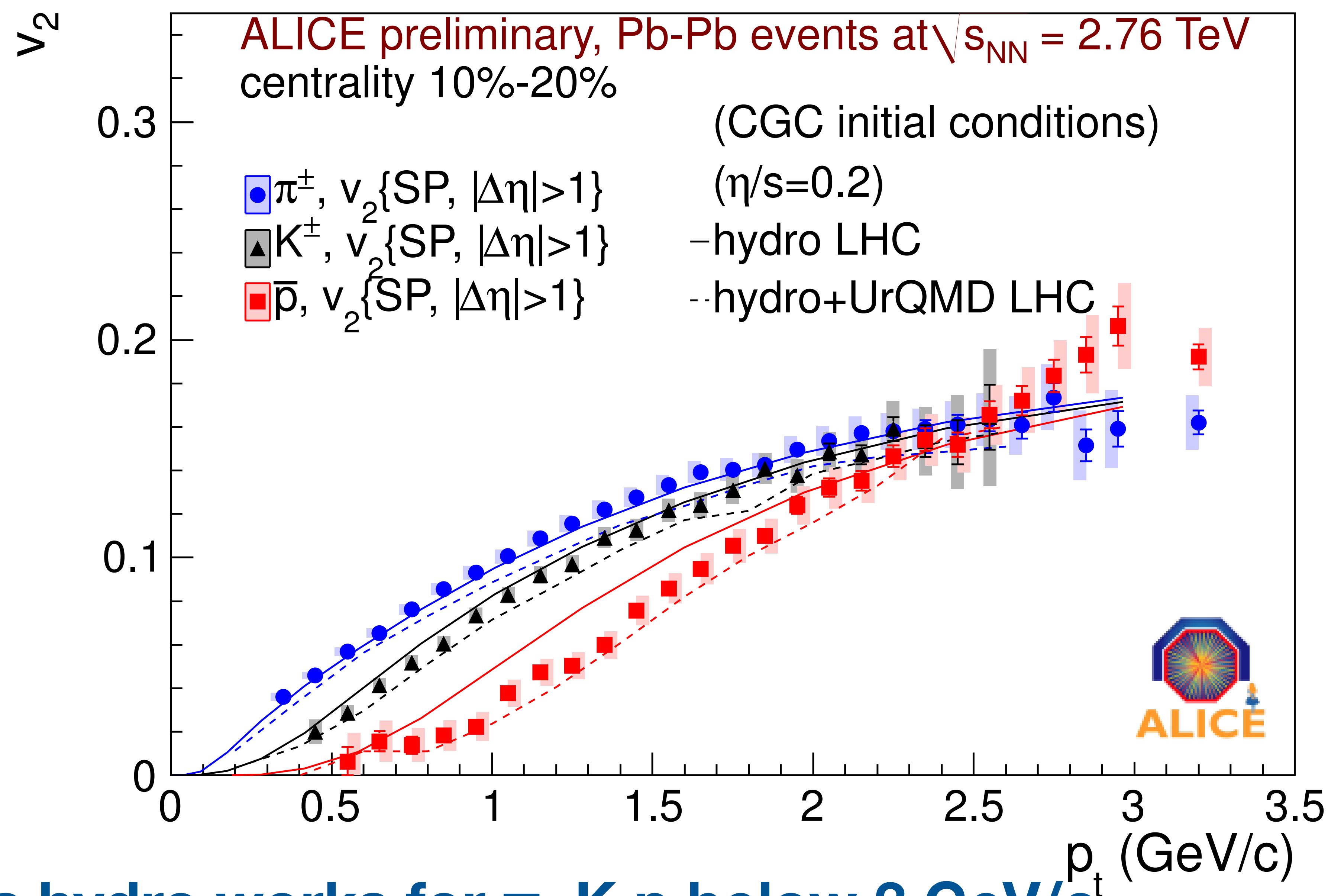
Differential v_2: pions, kaons, protons

Significant mass dependence

Expected: radial flow gives all species similar β, thus different p_T



Viscous hydro works for π, K p below 3 GeV/c

Need hadronic rescattering to match antiprotons in central data

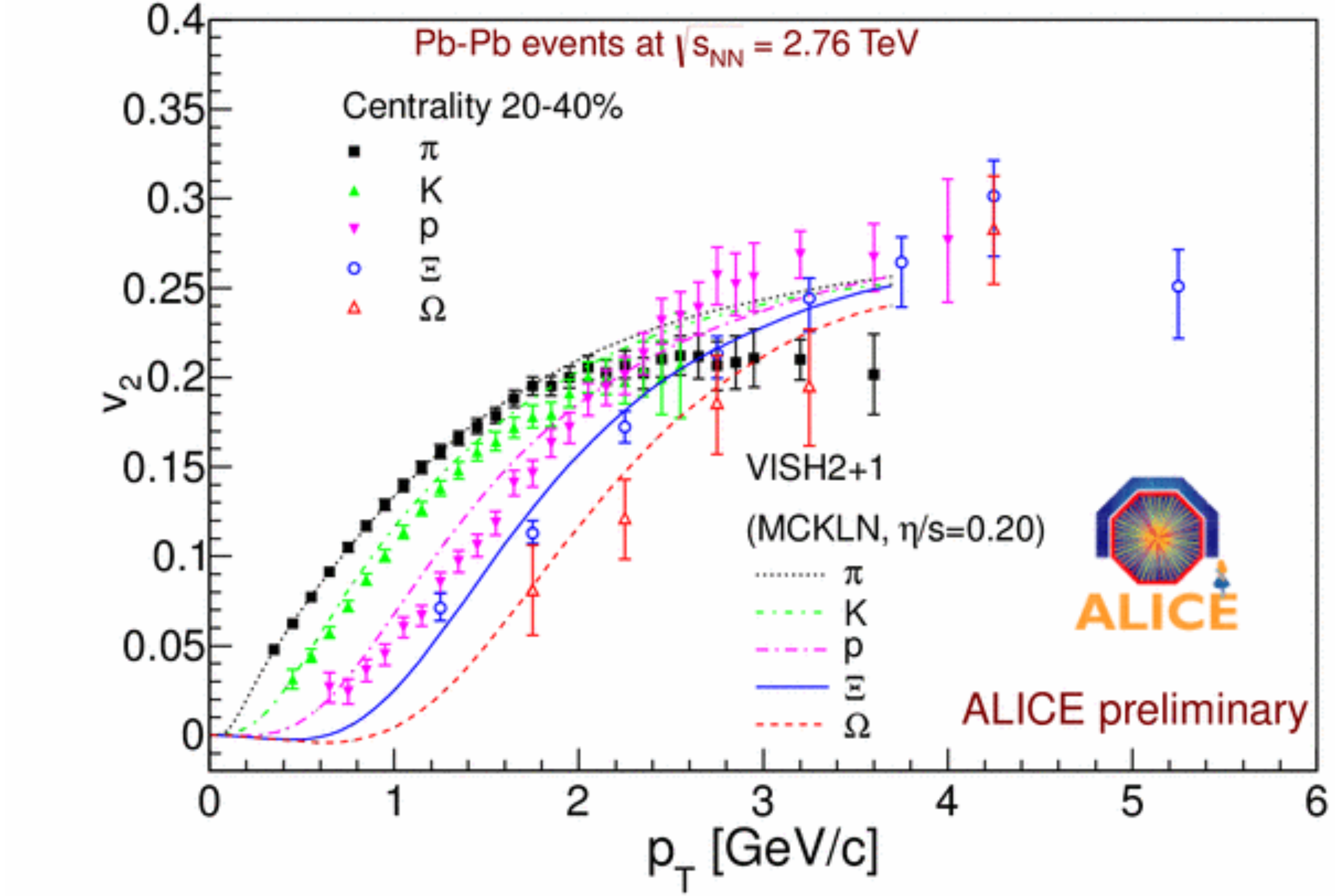
(UrQMD/VISHNU, arXiv:1108.5323v1)

Getting even heavier: multistrange v_2

Mass separation continues

viscous hydro still gives approximate description

arXiv:1202.0365



Moving up in momentum

Hydro not expected to match data above 3-4 GeV.

What is v_2 at high p_T?

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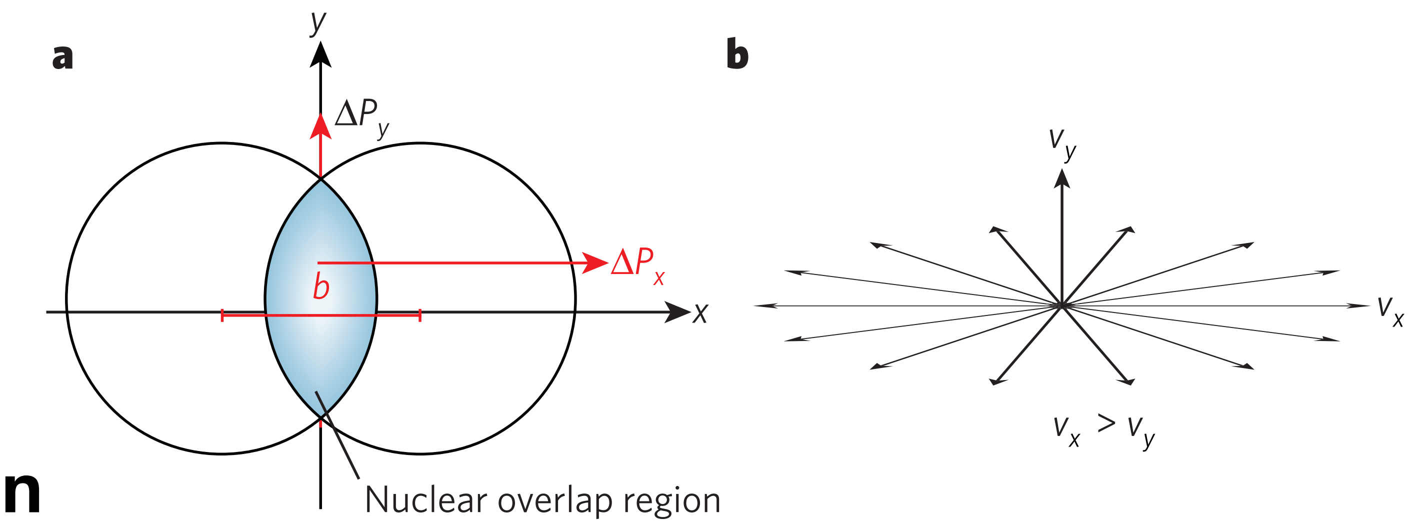
What is v_2 at high p_T?

At low p_T

Pressure-driven anisotropic expansion

→ more particles emitted in direction of largest pressure gradients



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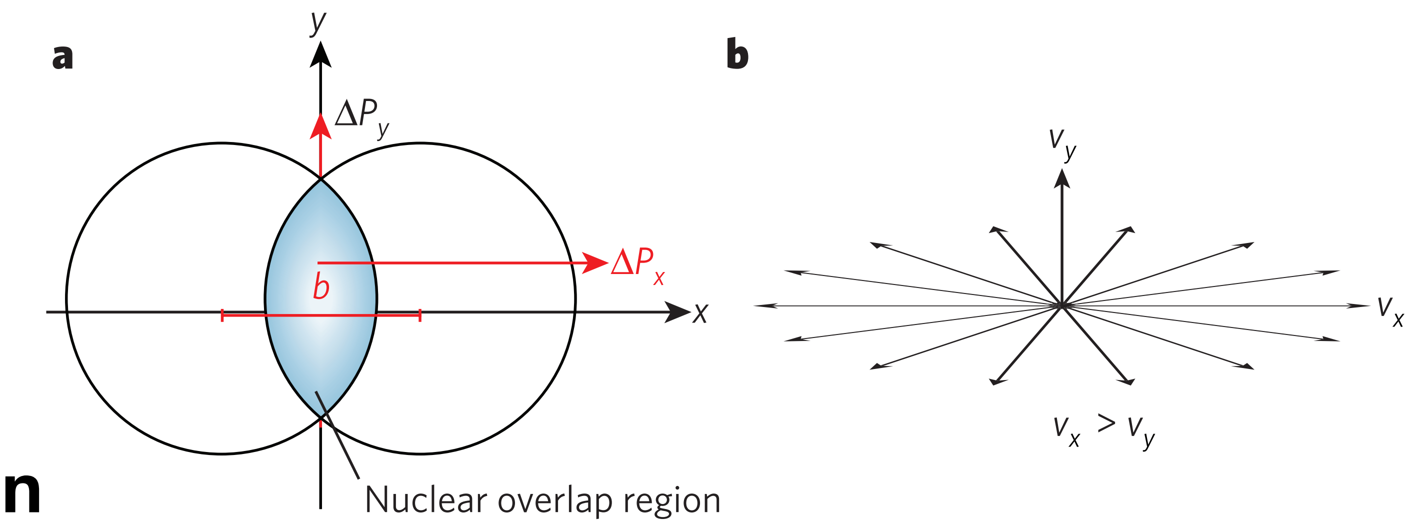

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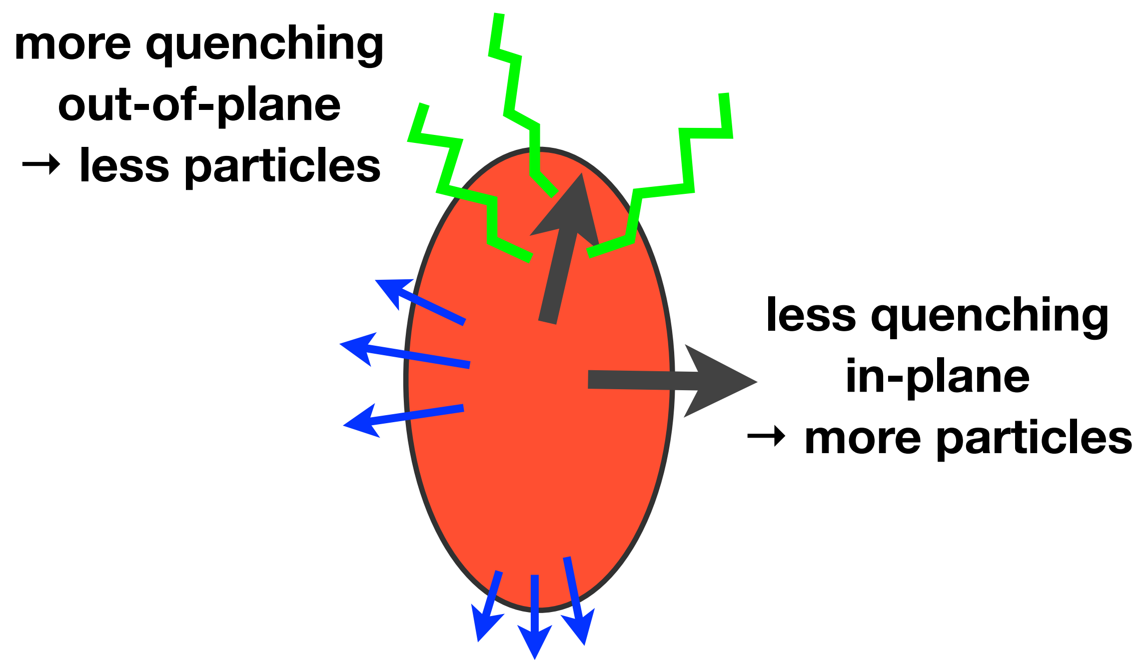
Pathlength-dependent energy loss

→ more particles emitted in direction of shortest path

Betz, Gyulassy, Torrieri: PRC **84** (2011) 024913



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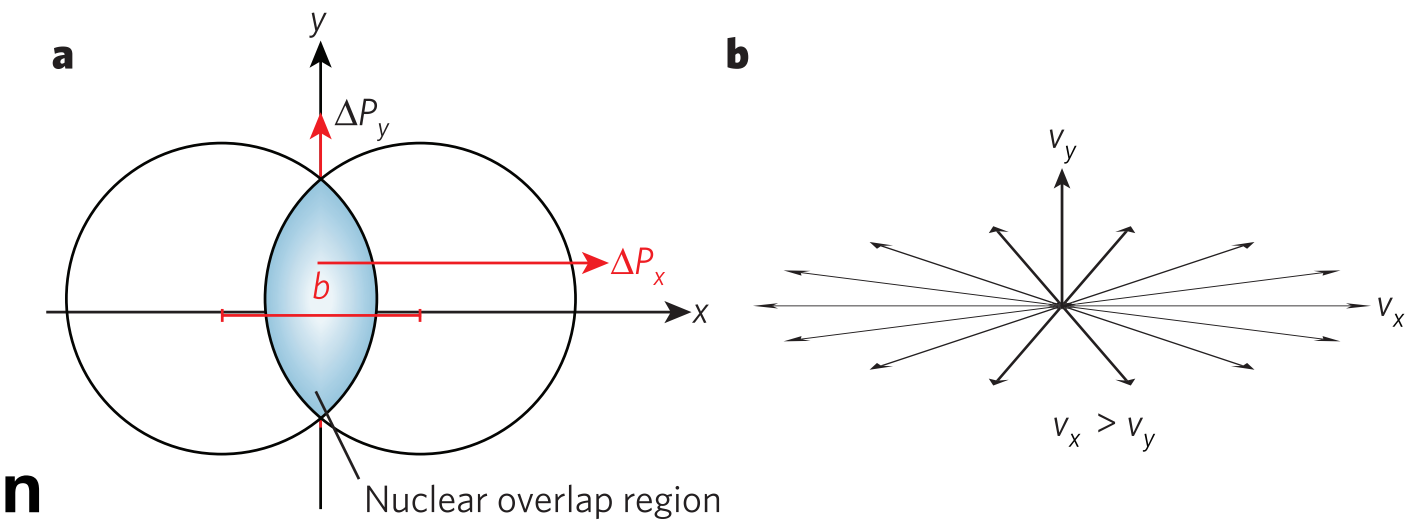

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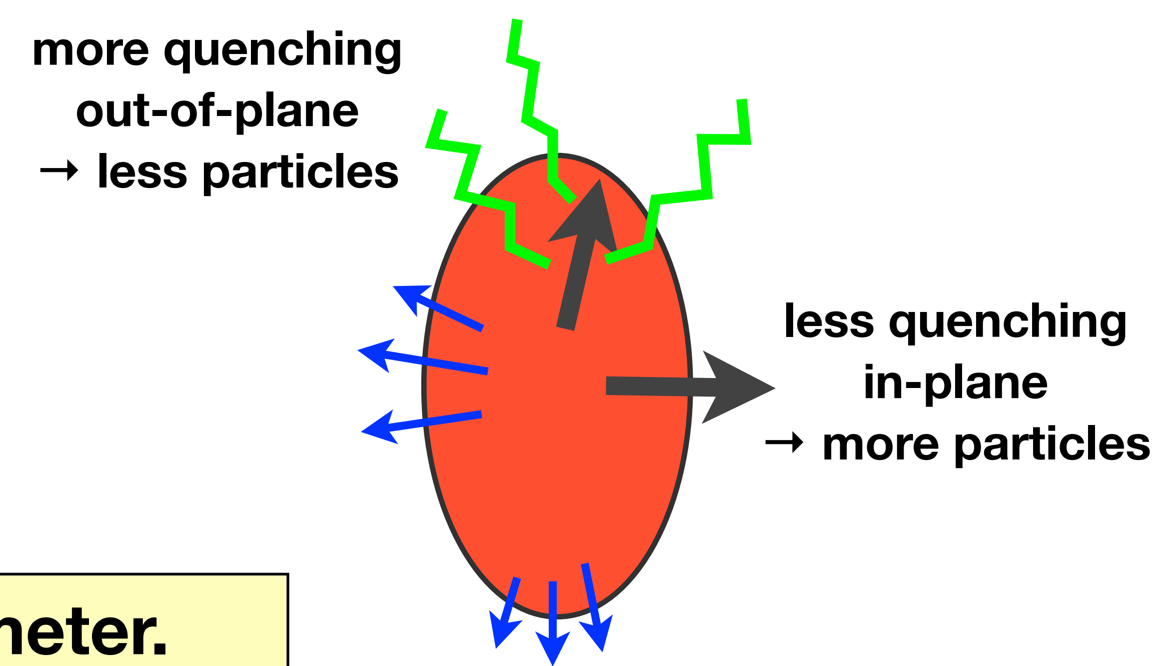

Connected phenomena: similar geometry dependence

v_2 ≠ elliptic flow! It is an anisotropy parameter.

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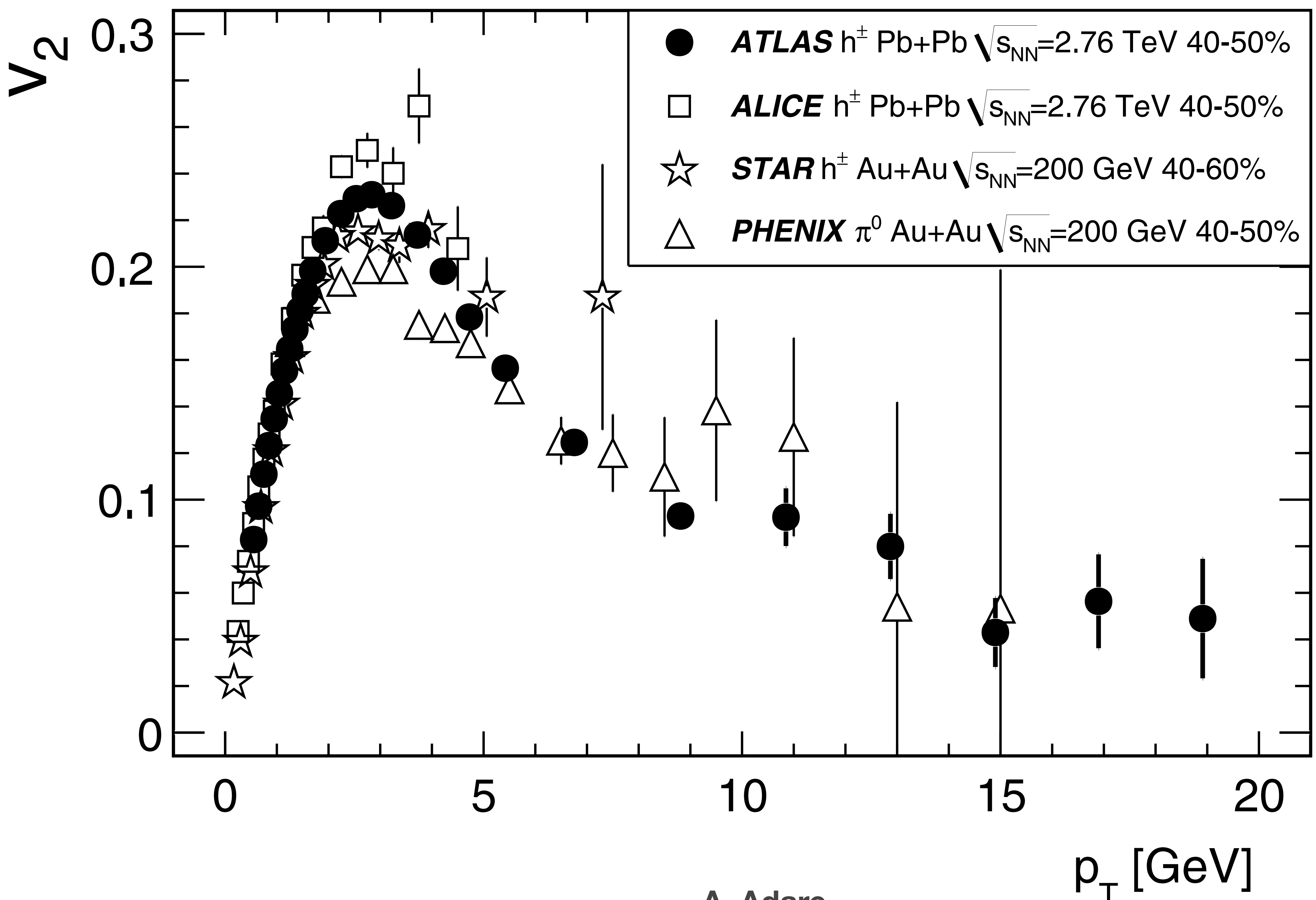
v_2 at high p_T

v_2 falls steeply from 4 to 10 GeV/c

Flow anisotropy at low p_T → anisotropic quenching at high p_T

RHIC and LHC agree

ATLAS: Phys Lett B **707** (2012) 330

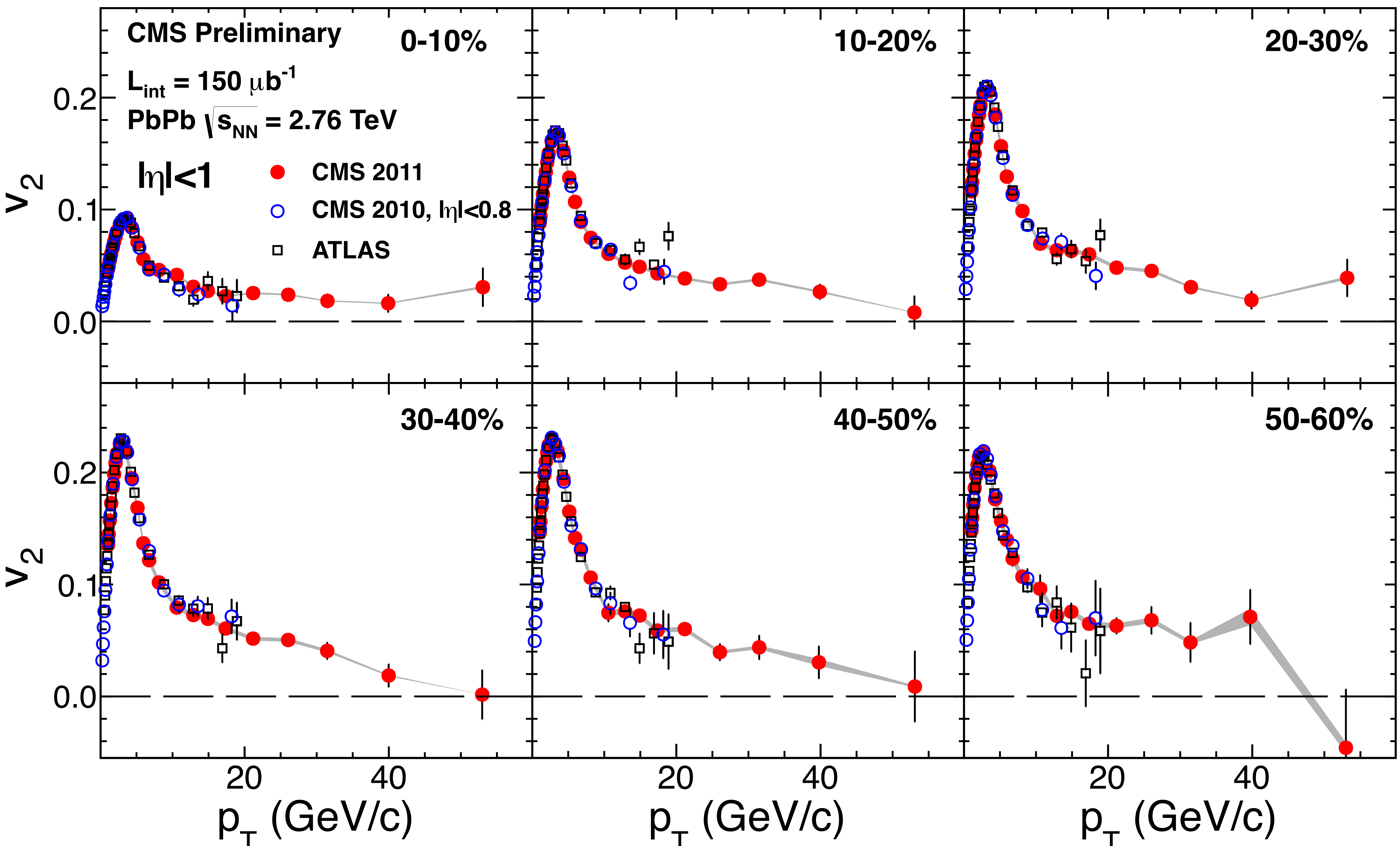


v_2 at really high p_T (!)

Steep drop from 4-10 GeV; gradually vanishes as $p_T \to 60$ GeV/c

Energy loss becomes isotropic? Surface or "punch-through" bias?

CMS: HIN-10-002-PAS



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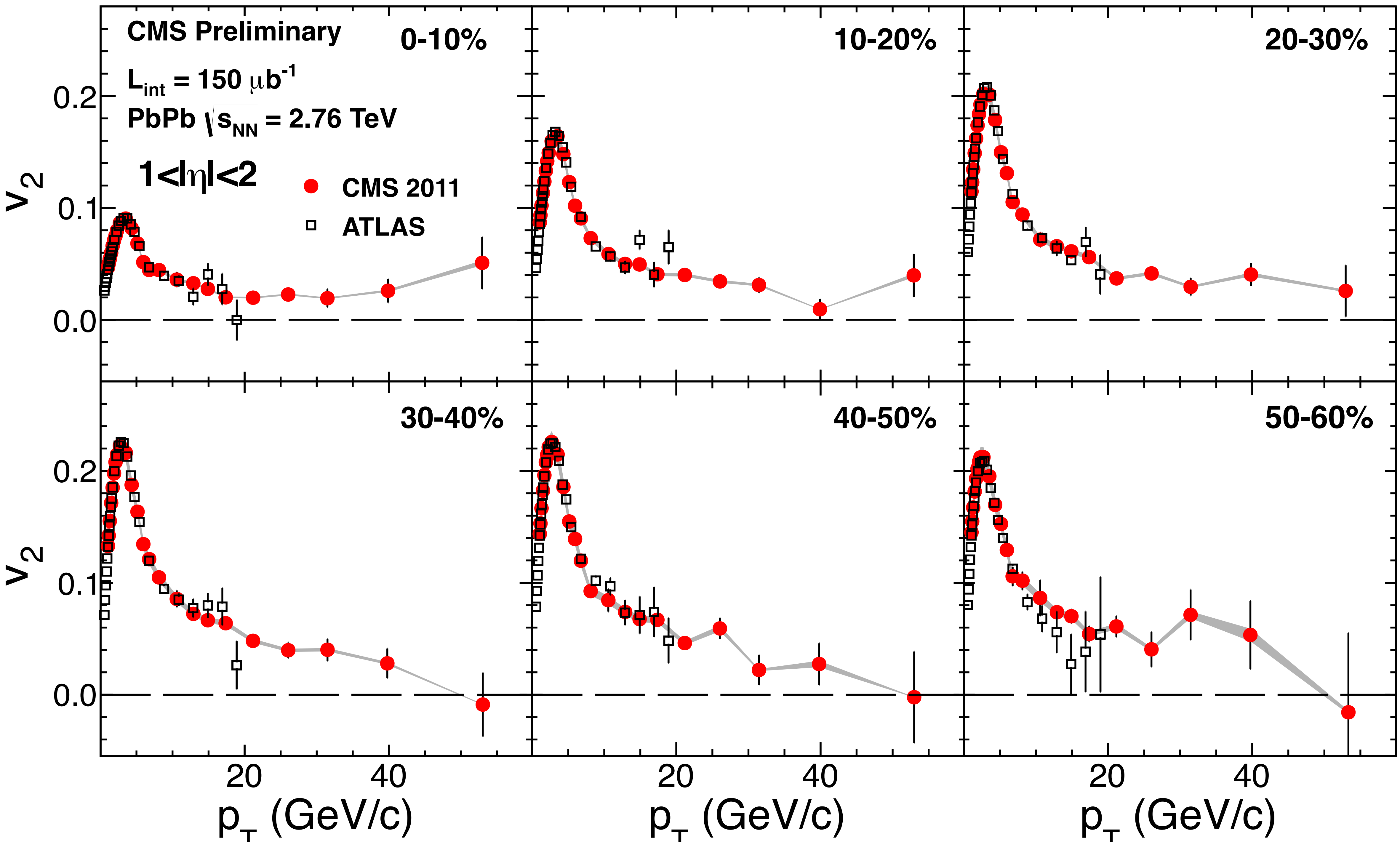

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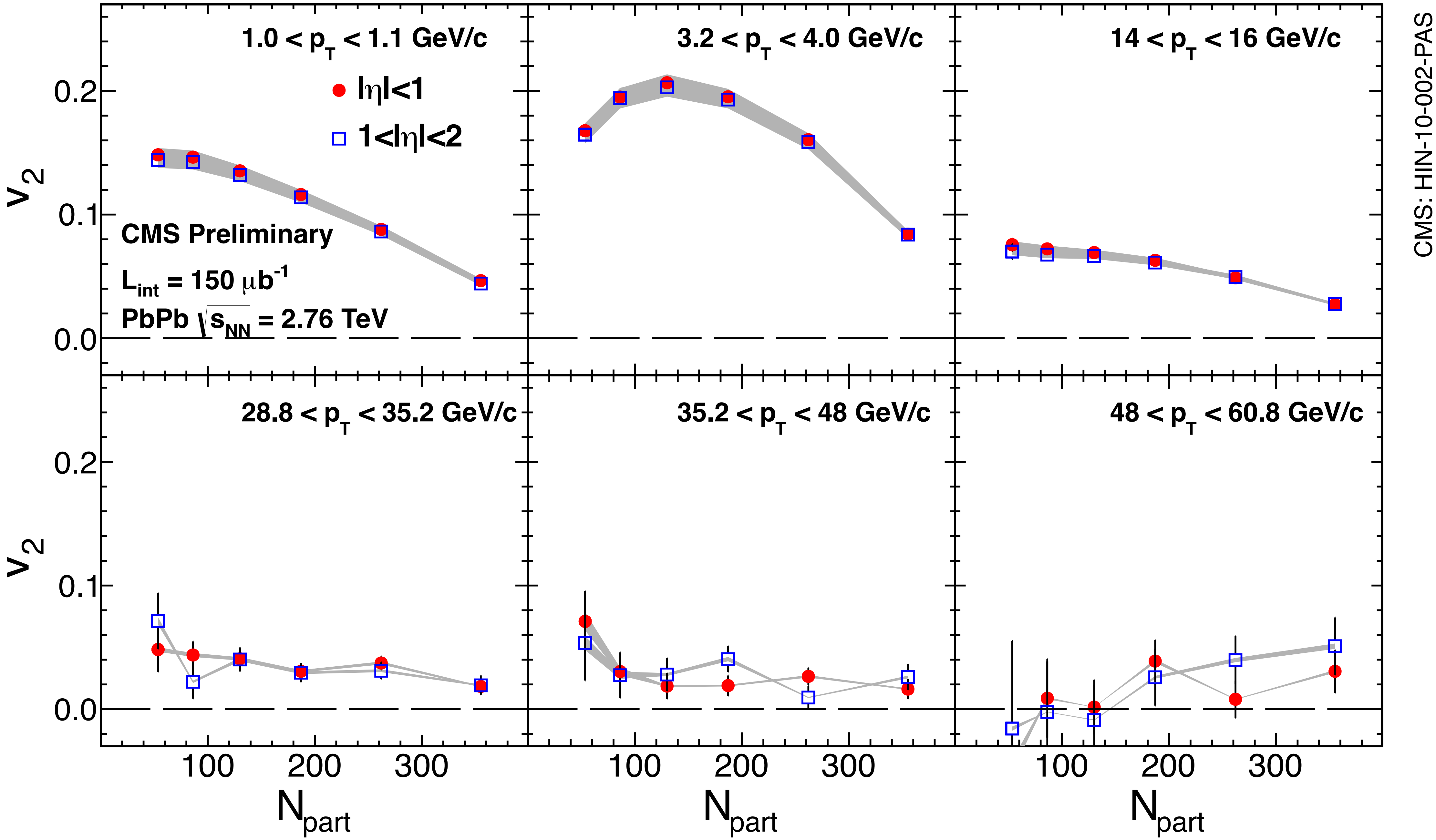
v_2 vs. system size at different p_T



Low to intermediate p_T (< 4 GeV/c) from CMS

v_2 reflects collision geometry & system size

Higher p_T:

N_{part} dependence weakens

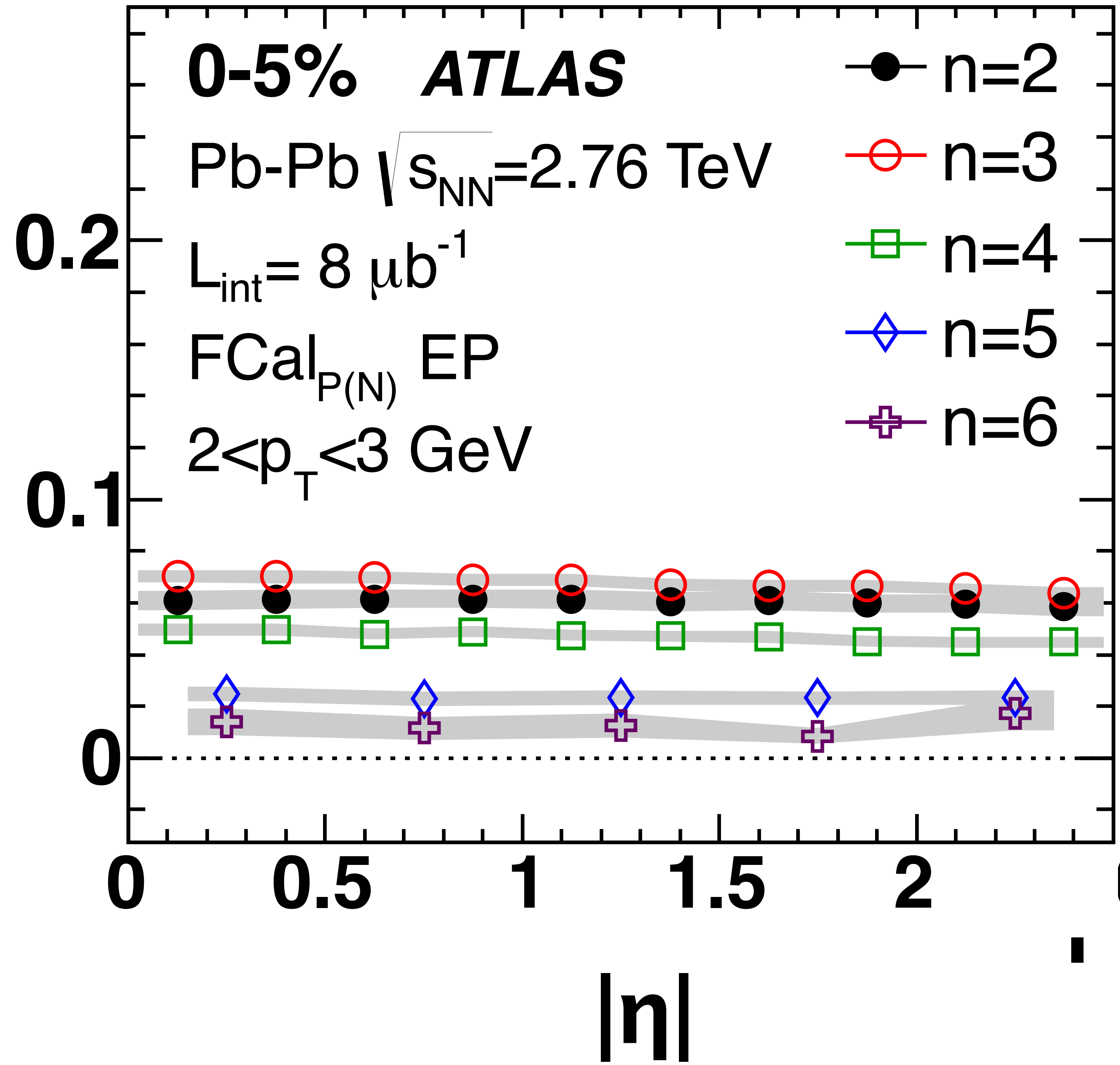
Pseudorapidity dependence of v_n

There is (almost) none!

Precise ATLAS v_n\{EP\} measurements up to n=6

For all harmonics (n=1 excepted), flow anisotropy is almost uniform for |η| < 2.5

Slight decline with |η| appears in most peripheral collisions



Hydrodynamic flow is a long-range effect

ATLAS arXiv:1203.3087v1

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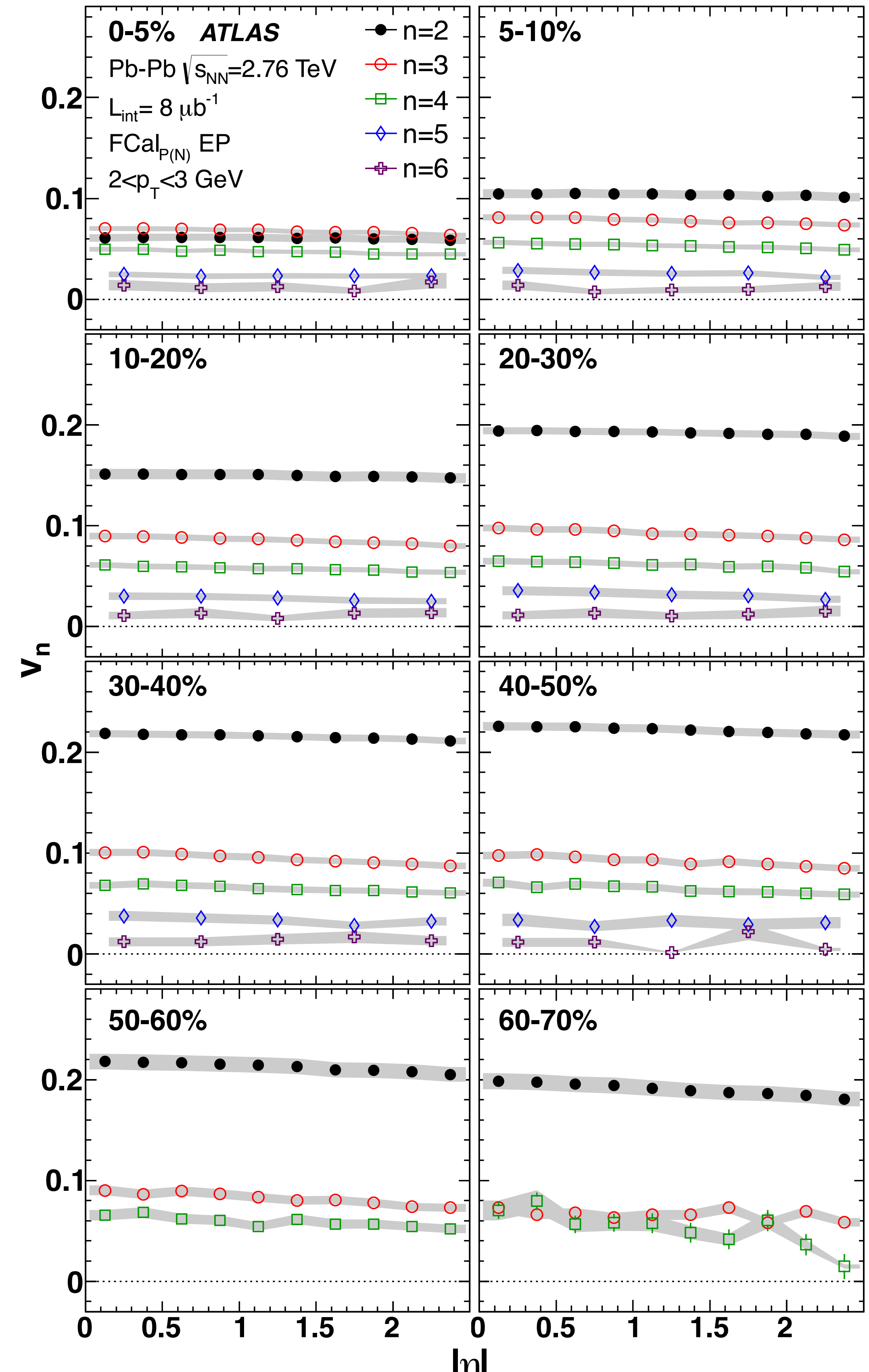

ATLAS arXiv:1203.3087v1

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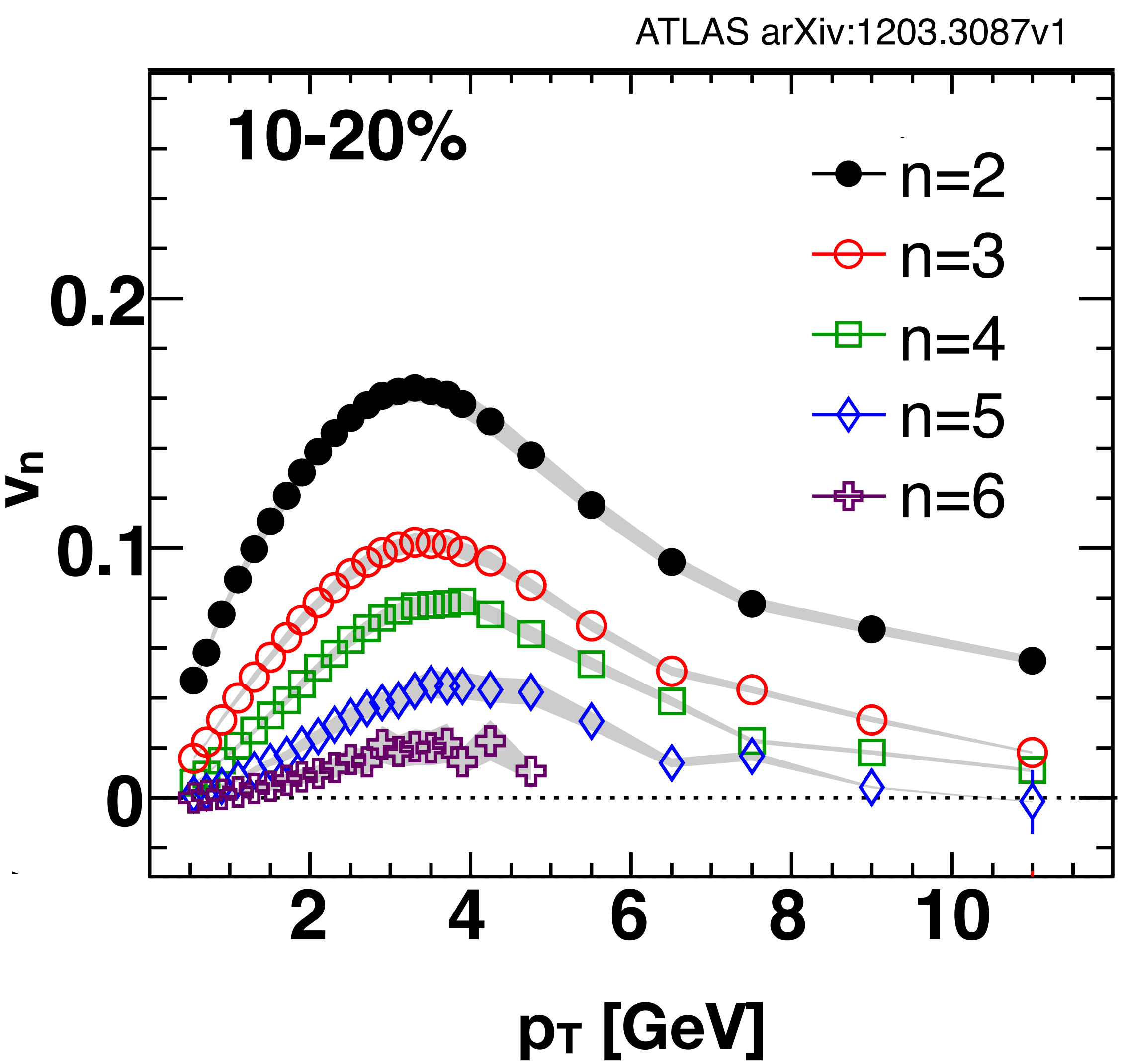
p_T dependence of v_2 - v_6



v_2-v_6 have similar trends with p_T

Flow + initial fluctuations < 3-4 GeV

High p_T anisotropic quenching

n=2 strongly centrality-dependent

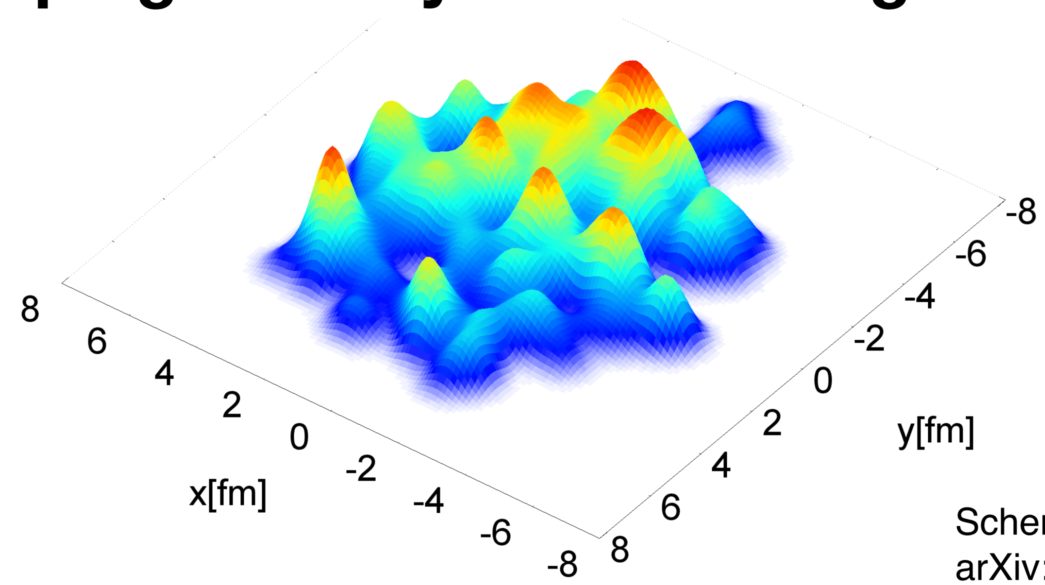
Reflects collision geometry

n=3..6 weakly centrality-dependent

"lumpy" initial state

v_n gets smaller as n increases

Damping: the key to measuring viscosity?



Schenke et al
arXiv:1202.6646
PRC **85** (2012) 024901

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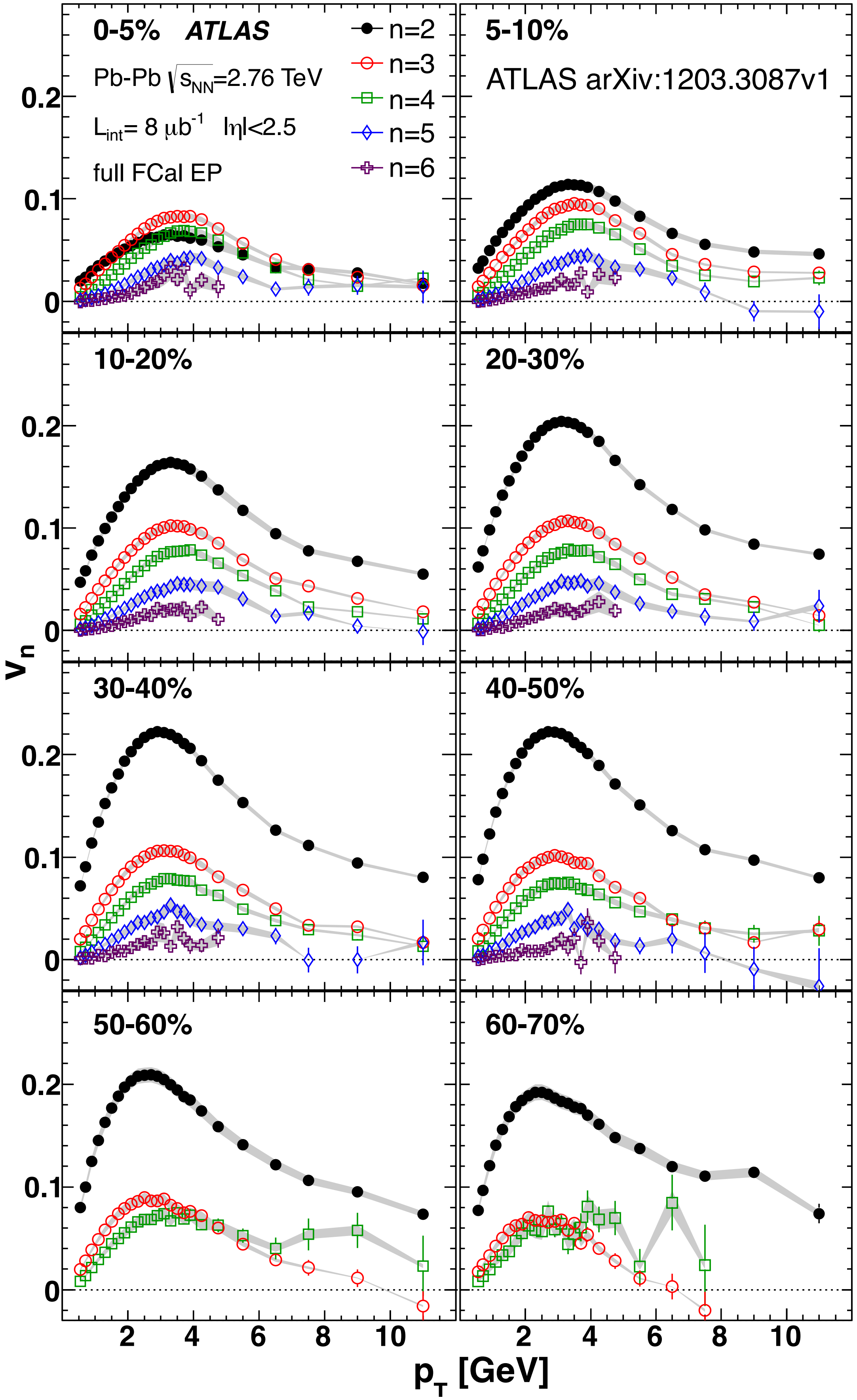
p_T dependence of v_2 - v_6



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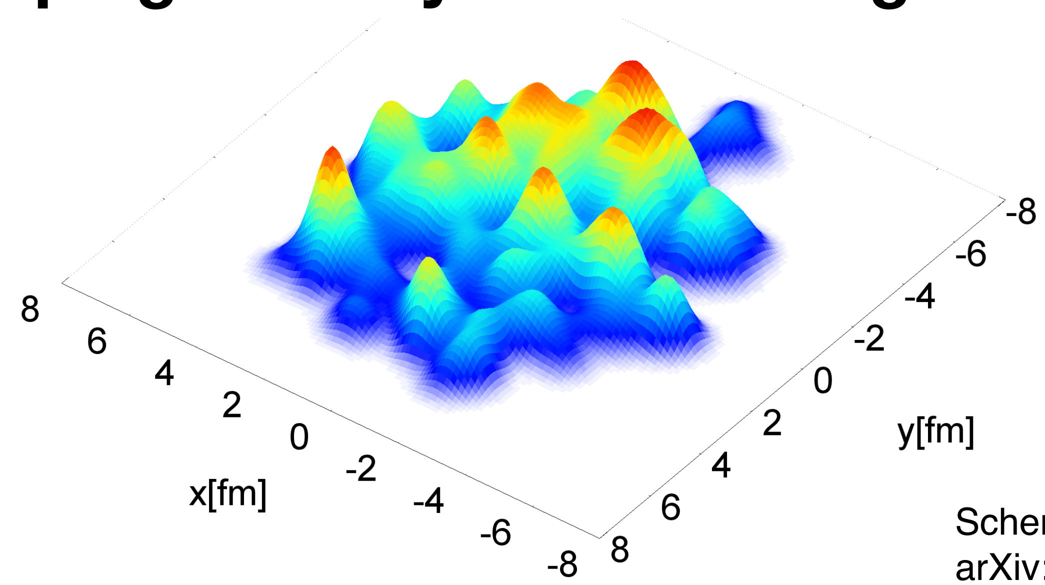
Reflects collision geometry

n=3..6 weakly centrality-dependent

“lumpy” initial state

v_n gets smaller as n increases

Damping: the key to measuring viscosity?



Schenke et al
arXiv:1202.6646
PRC **85** (2012) 024901

A. Adare

ATLAS v_n vs centrality

ATLAS arXiv:1203.3087v1

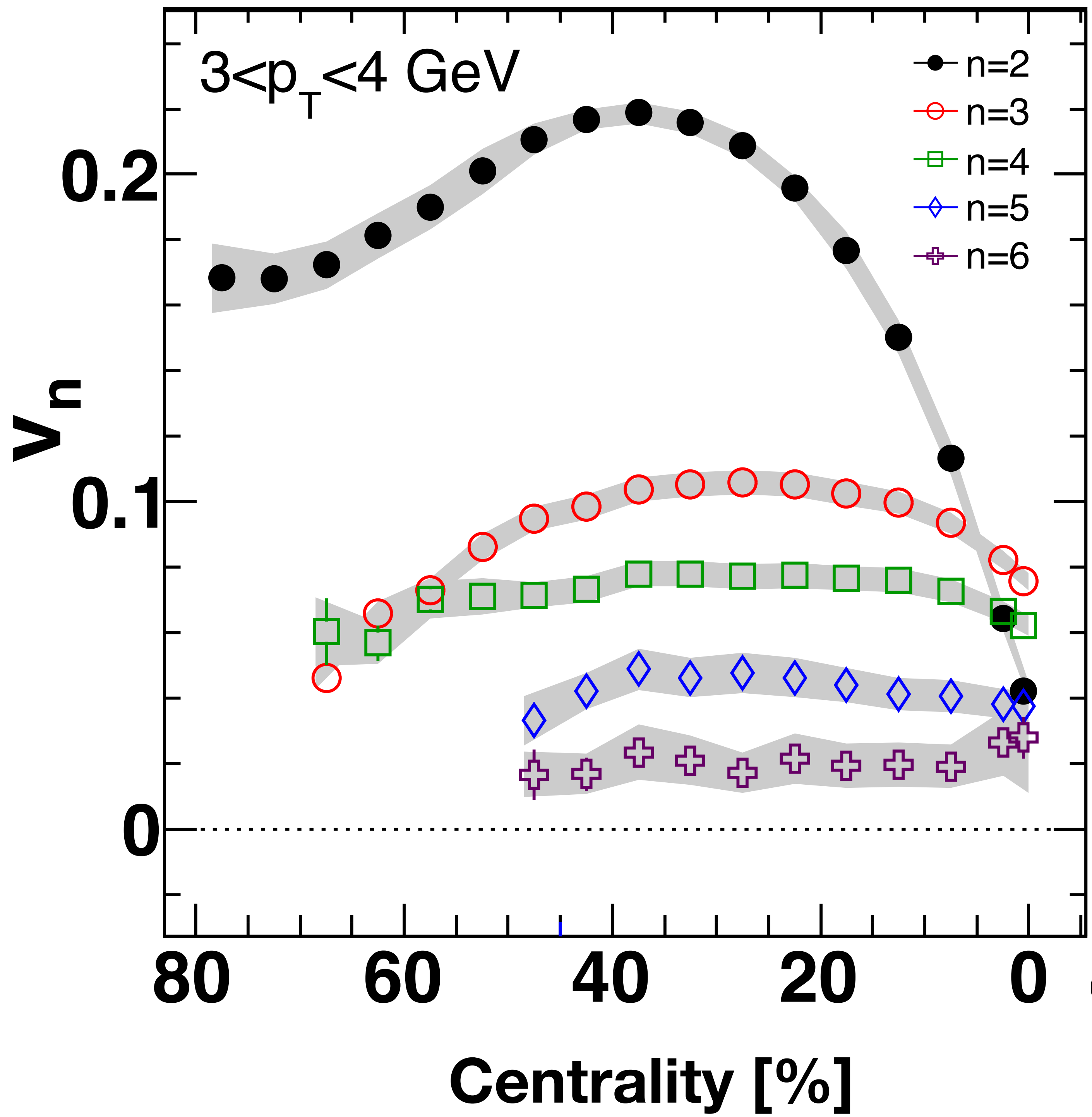
Similar trends as for $v_n(p_T)$:

- strong size/geometry dependence for v_2, much weaker for v_3 - v_6

- anisotropy peaks near 3-4 GeV

- higher harmonics are weaker

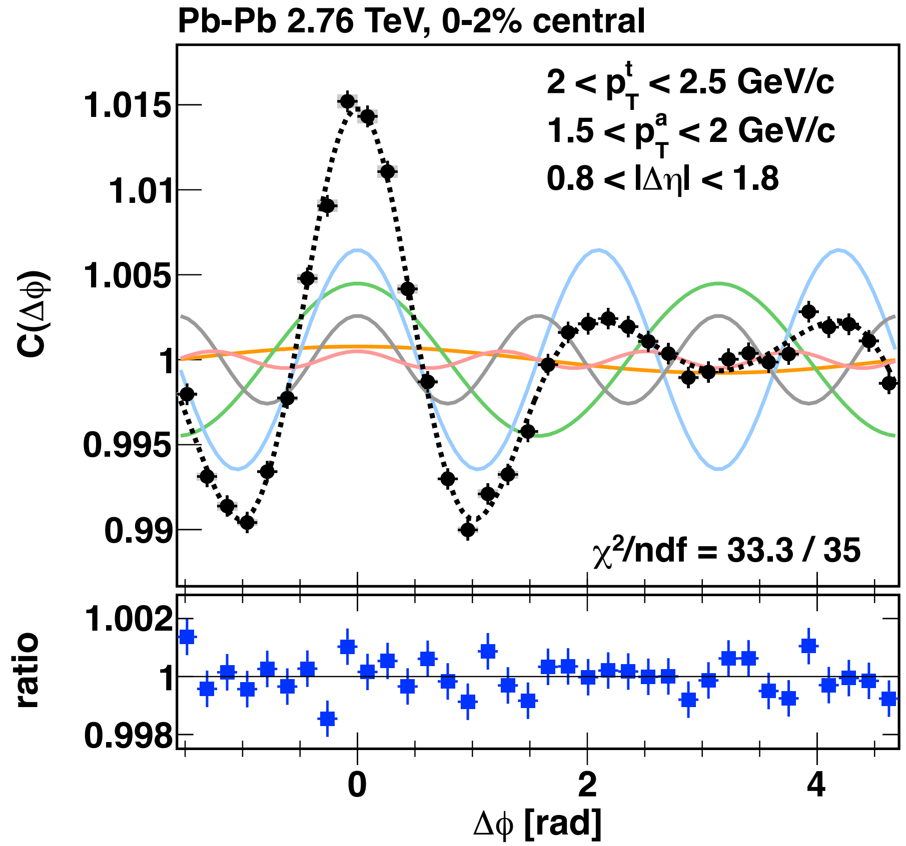
In 1-2% most central events, v_2 becomes smaller than v_3 or v_4



"Power spectra" from correlations

2-particle harmonics

$V_{n\Delta}$ = <cos n$\Delta\varphi$>



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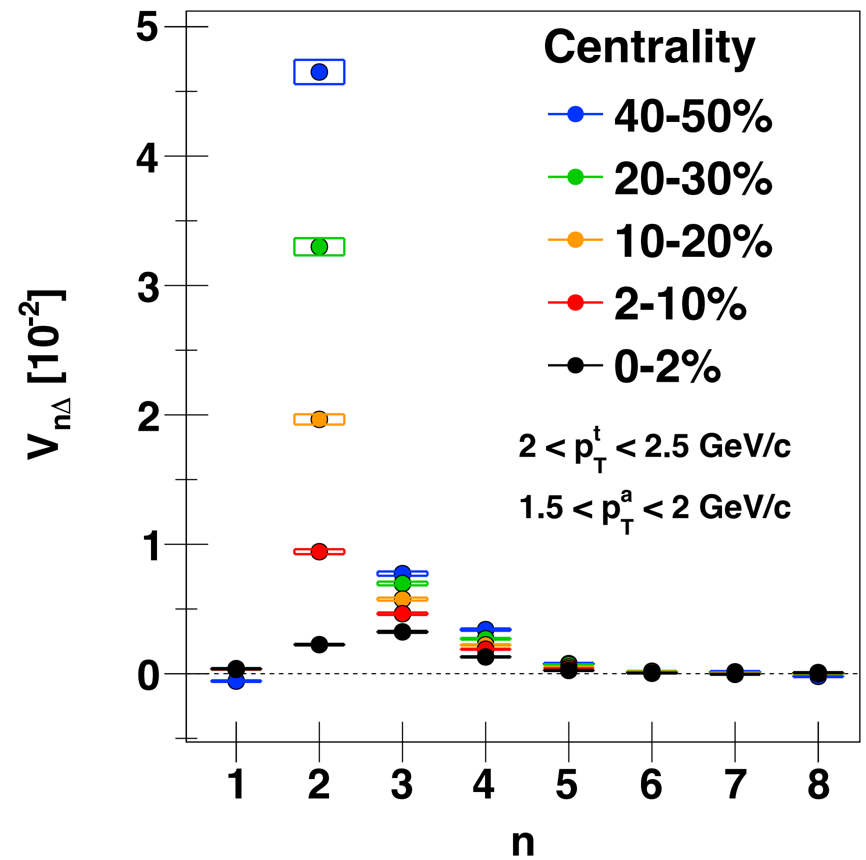

At lower pt

follow "flow-like" trends

At higher pt

Completely different pattern: harmonics reflect the recoil jet

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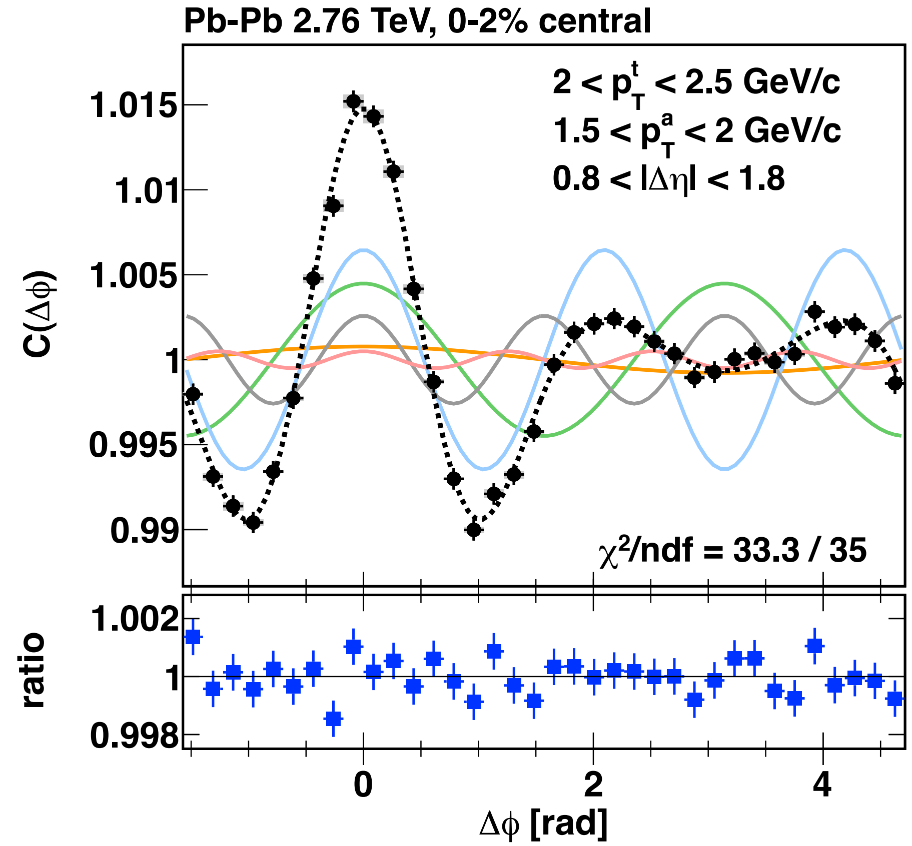

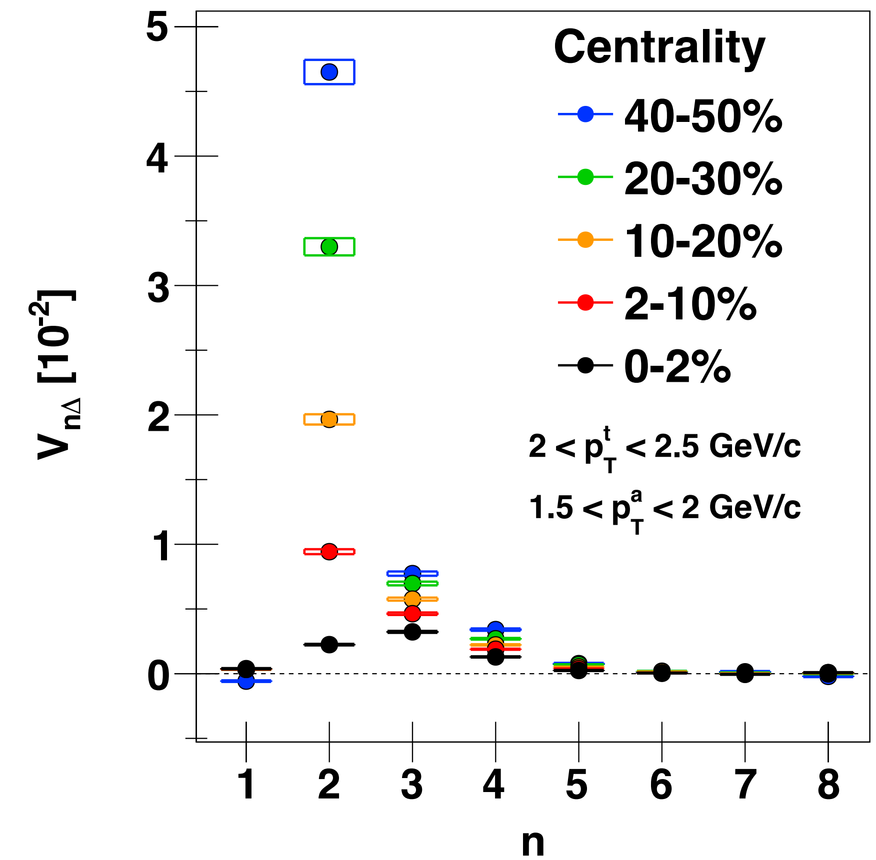

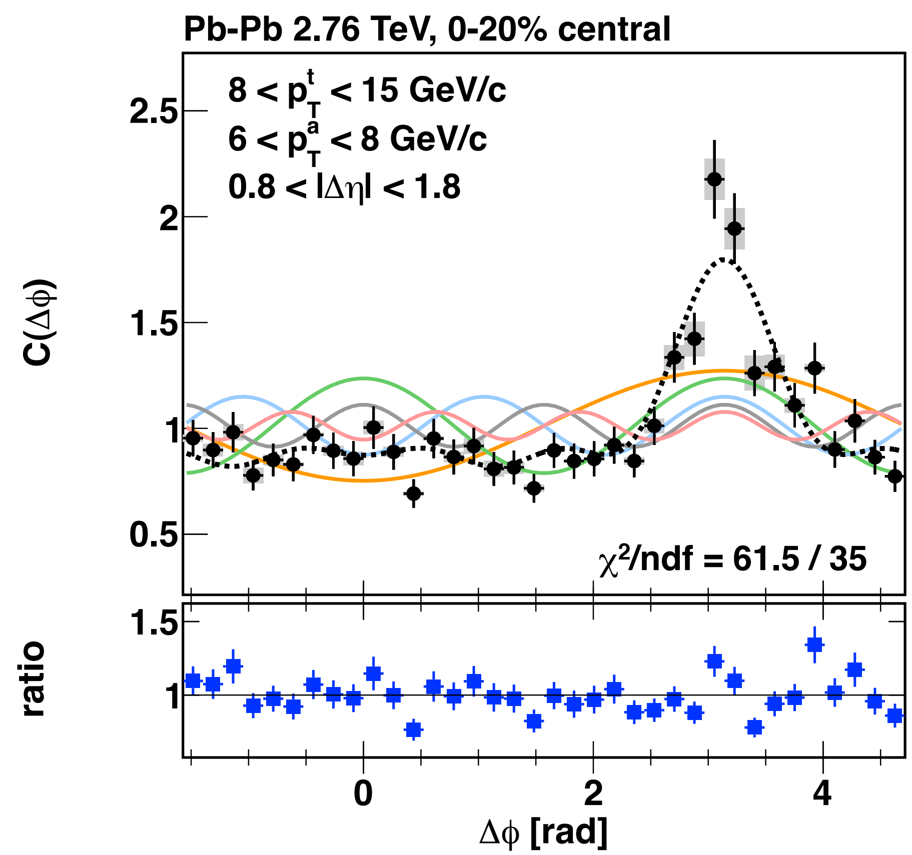

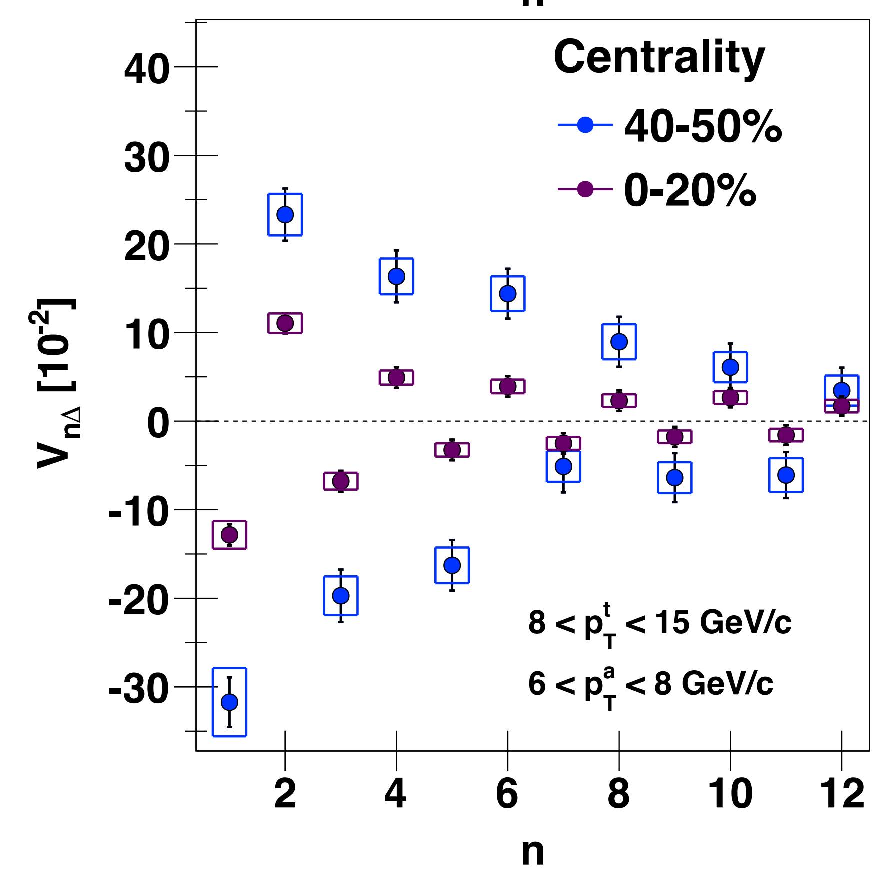

Factorization of 2-particle anisotropy

1-particle and 2-particle anisotropy:

For any single p_T^{trig}, p_T^{assoc} combination,

$$\frac{dN^{\mathrm{pairs}}}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n(p_T^t) v_n(p_T^a) \cos(n\Delta\phi).$$

$$V_{n\Delta}(p_{\mathrm{T}}^{\mathrm{trig}}, p_{\mathrm{T}}^{\mathrm{assoc}}) = v_n(p_{\mathrm{T}}^{\mathrm{trig}}) \times v_n(p_{\mathrm{T}}^{\mathrm{assoc}})$$

e.g. for fixed-p_T correlations ($p_T^{trig} = p_T^{assoc}$),

$$v_n = \sqrt{V_{n\Delta}}$$

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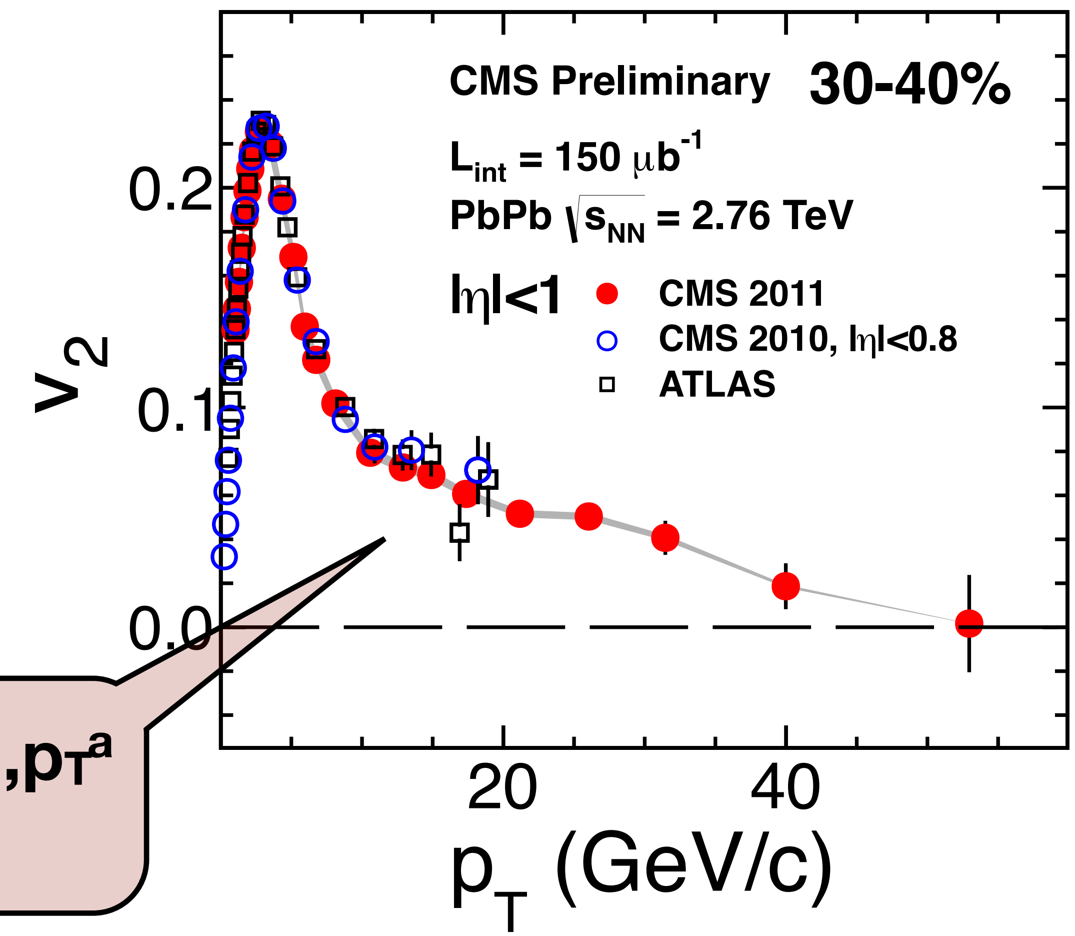
e.g. for fixed-p_T correlations ($p_T^{trig} = p_T^{assoc}$),

$$v_n = \sqrt{V_{n\Delta}}$$

Go further:

check for simultaneous description of all ($p_T^{trig} >= p_T^{assoc}$) combinations

Can $V_{n\Delta}$ be generated from one $v_n(p_T)$ curve?



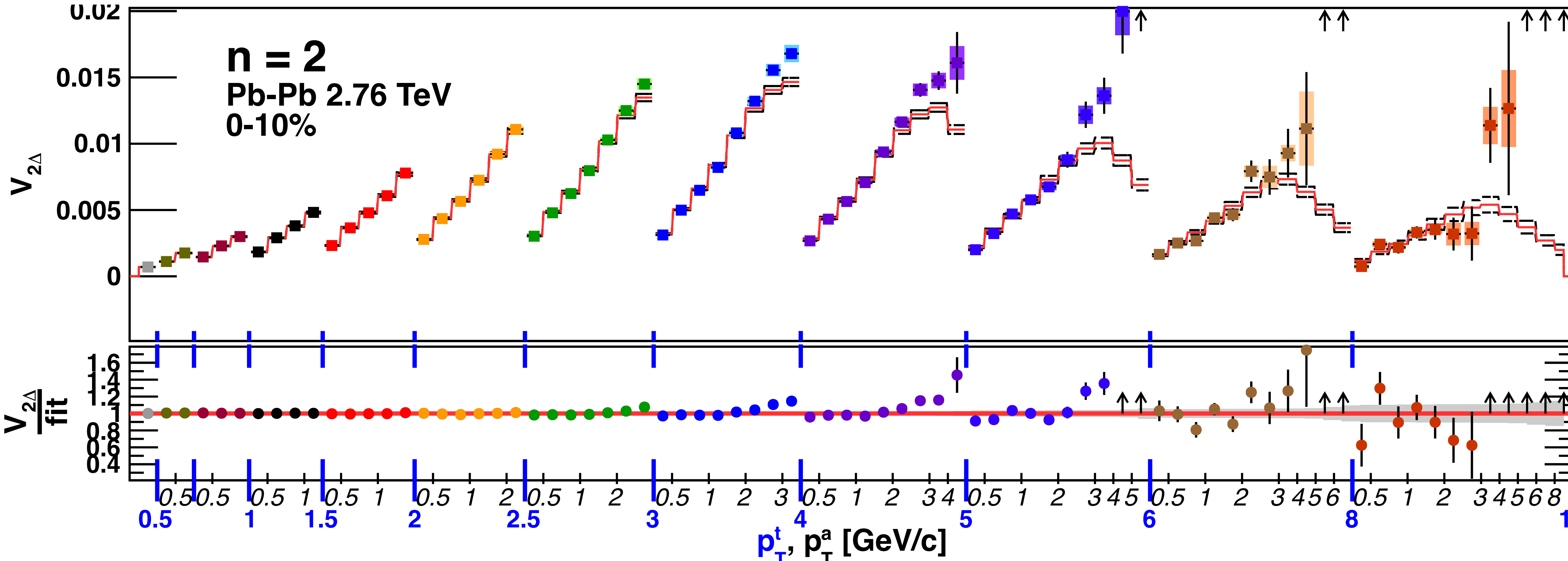
Would this curve reproduce $V_{2\Delta}$ for p_T^t, p_T^a combinations up to 60 GeV/c?

Test factorization with a global fit

Improving on $V_{n\Delta} = v_n(p_T)^2$ with triggered correlations...

12 p_T^t bins, 12 p_T^a bins; $p_T^t \geq p_T^a$ ⇒ 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T^t)$ x $v_n(p_T^a)$ product.



ALICE Phys Lett B **708** (2012) 249

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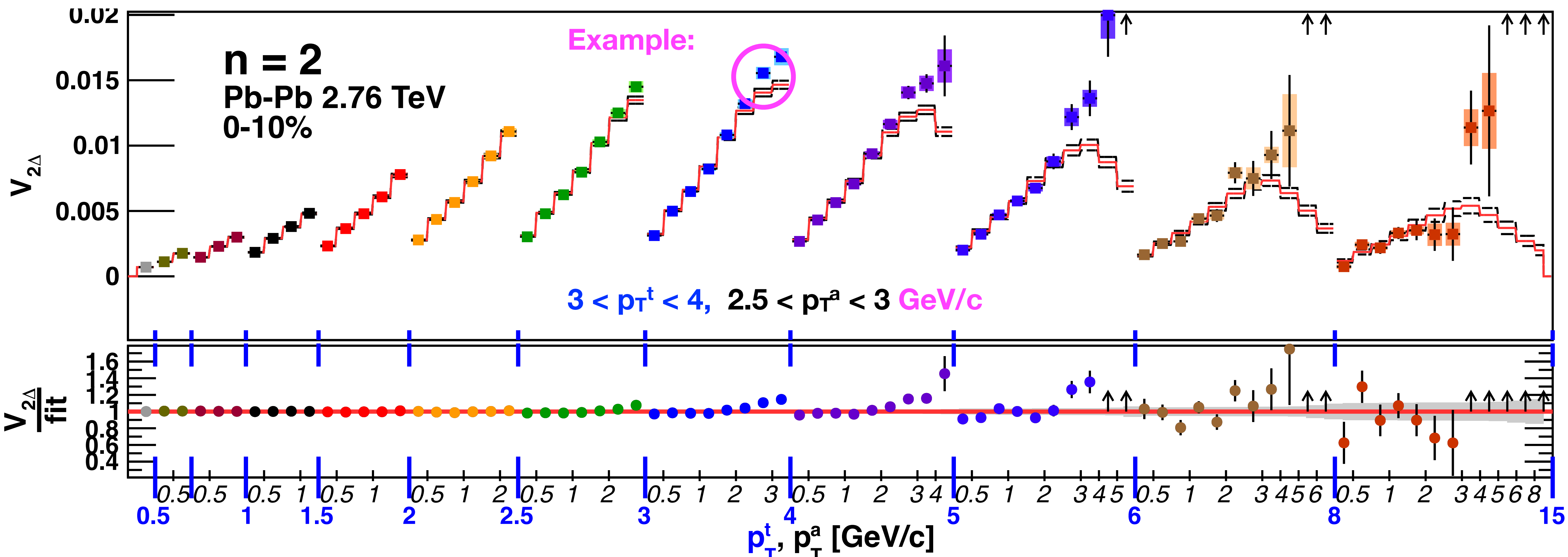

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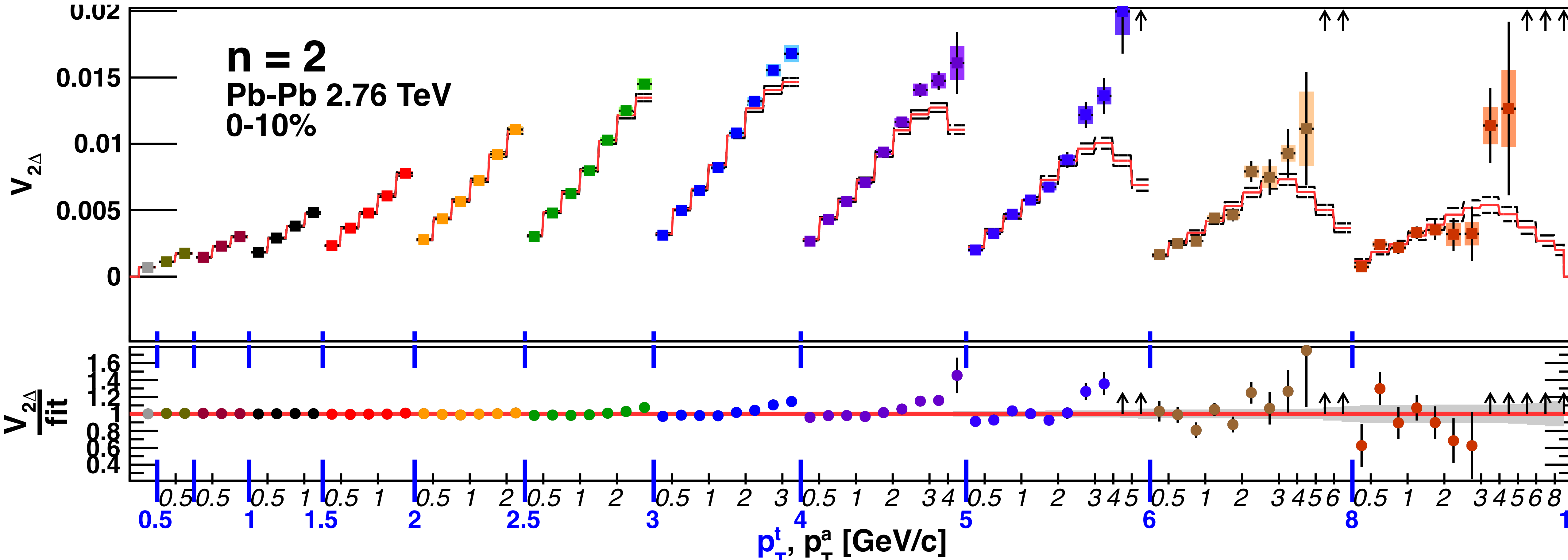

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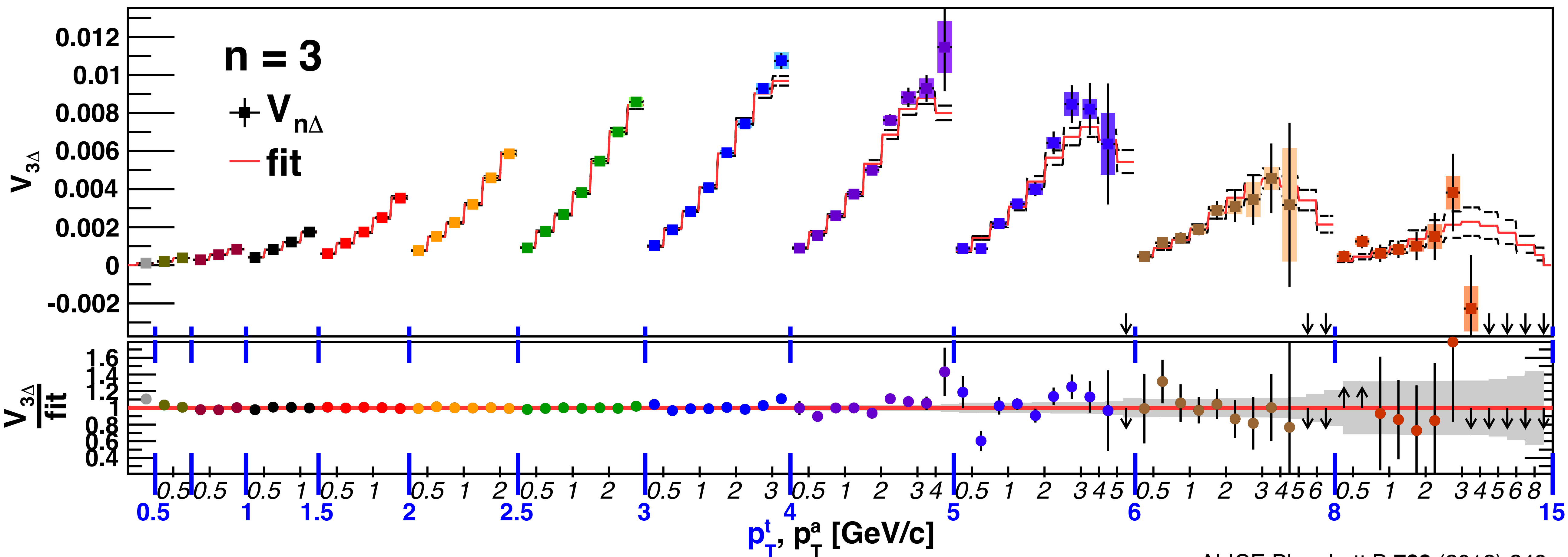

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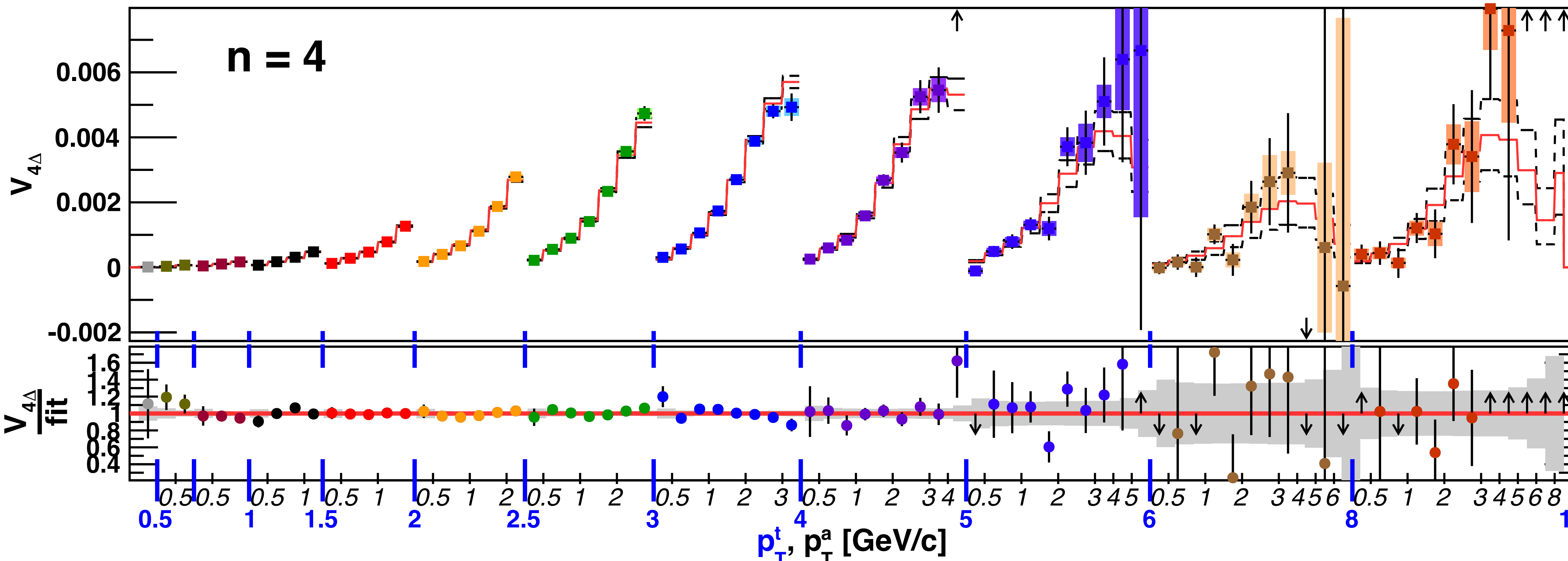

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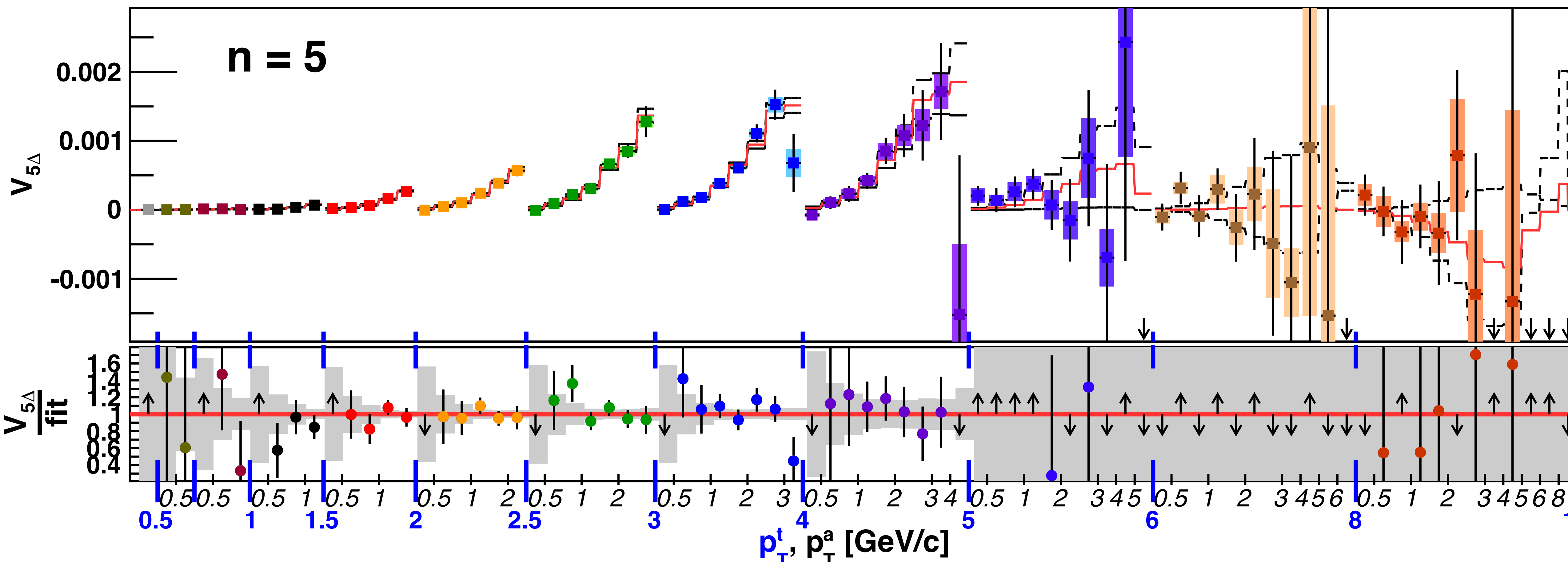

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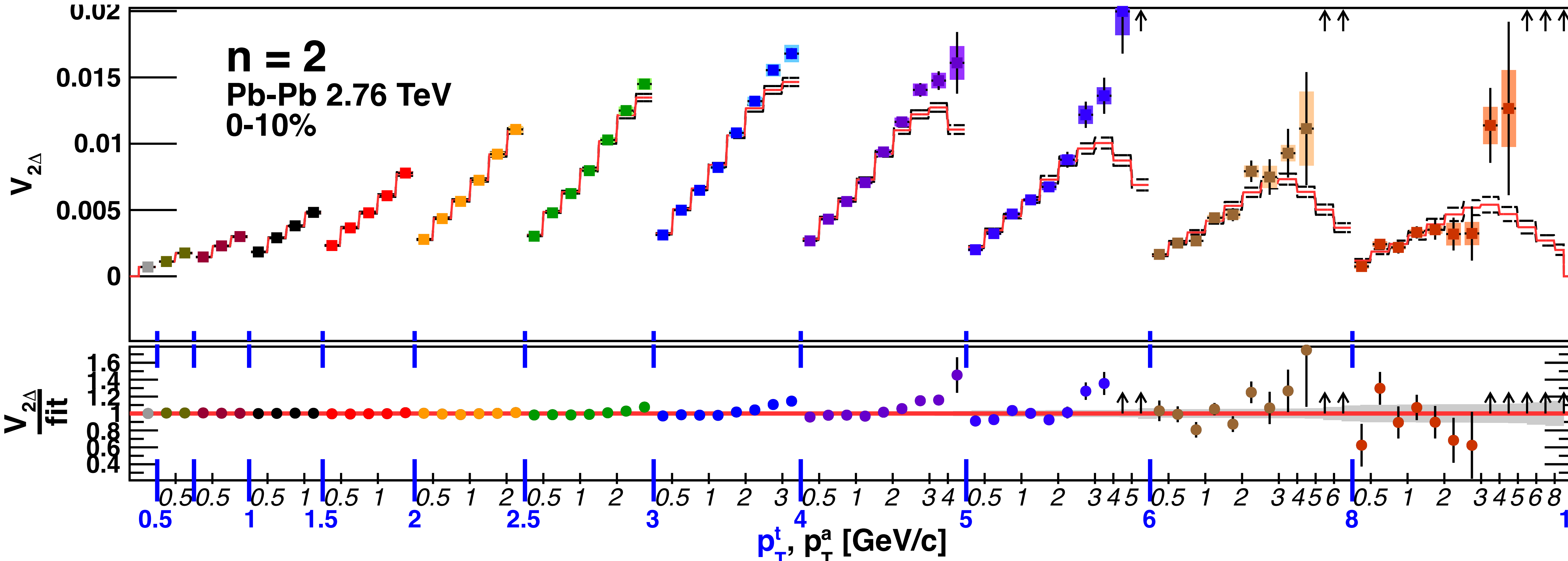

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v_n from global fits

Global fit parameters are $v_n(p_T)$

Agree well with $v_n\{2\}$ measurements

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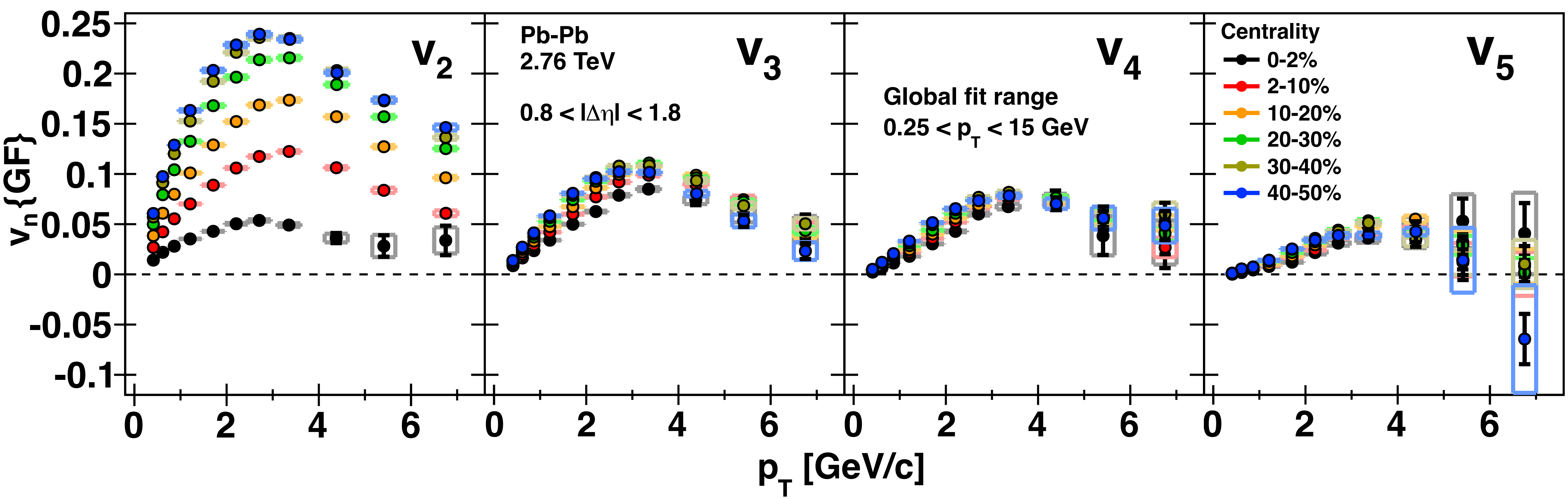


Steeply falling particle p_T distribution → fits dominated by low-p_T particles

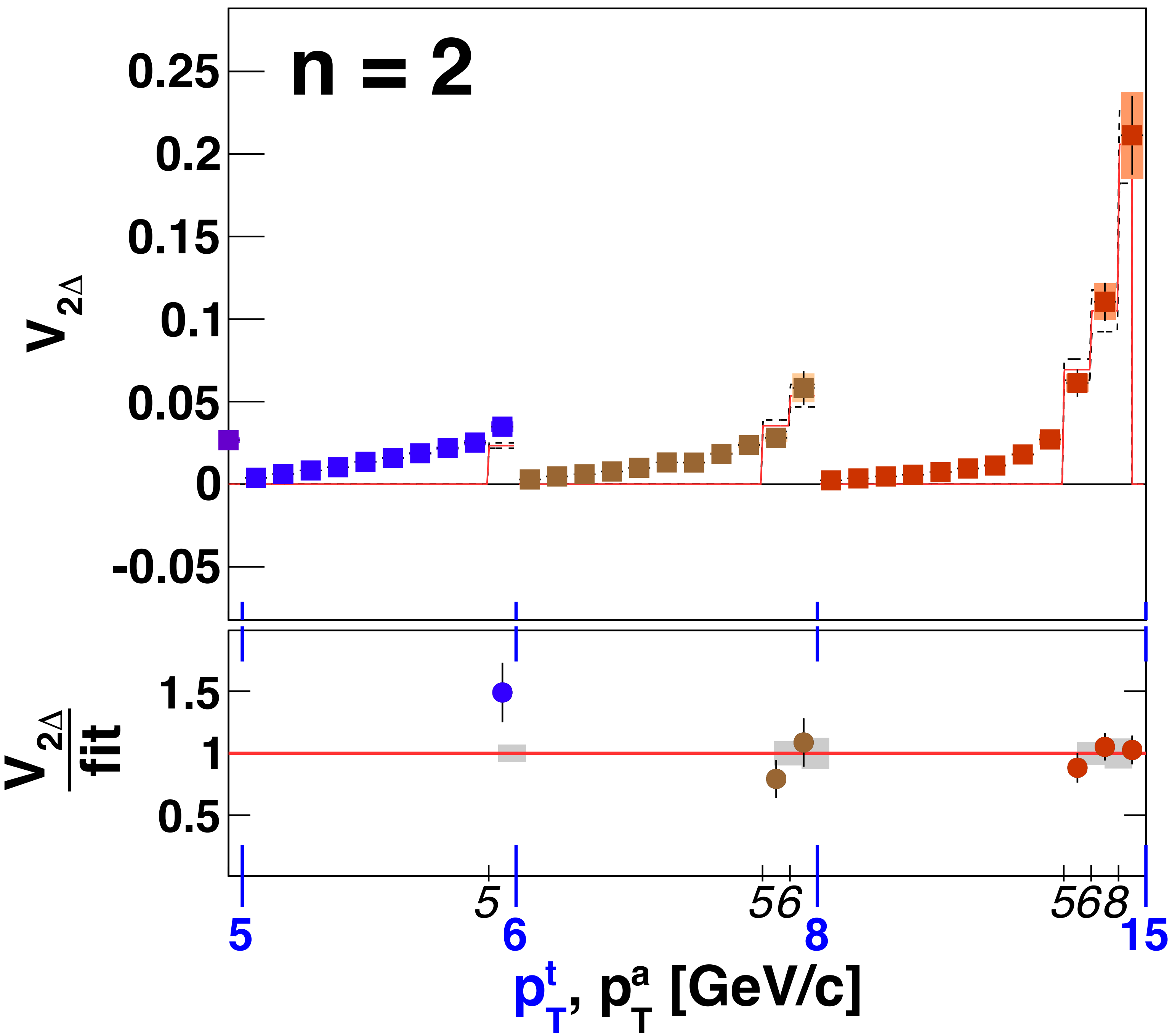
What if global fits were applied where nonflow (jets) dominate?

High-p_T factorization

ALICE Phys Lett B **708** (2012) 249

"Global" fit <u>only</u> where both particles have p_T > 5 GeV

An approximate factorization is obtained, but of a very different nature...



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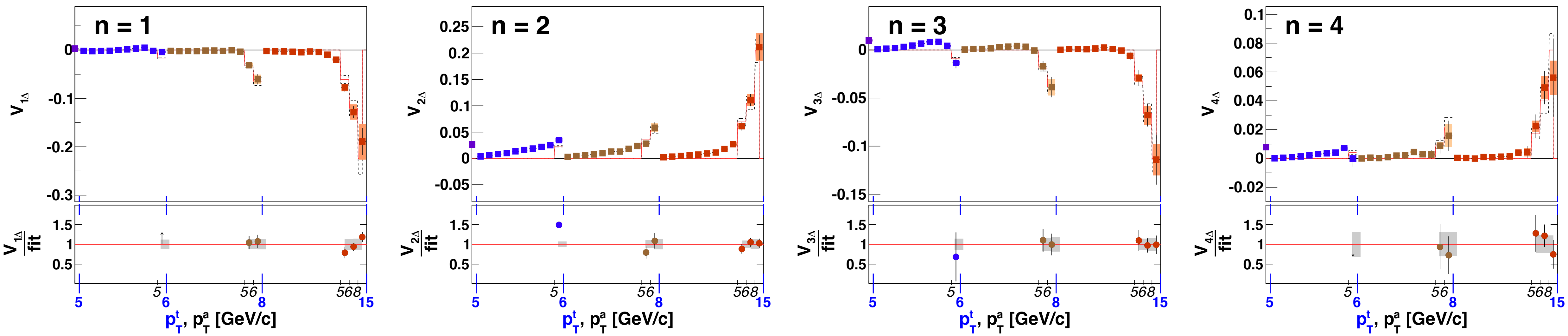

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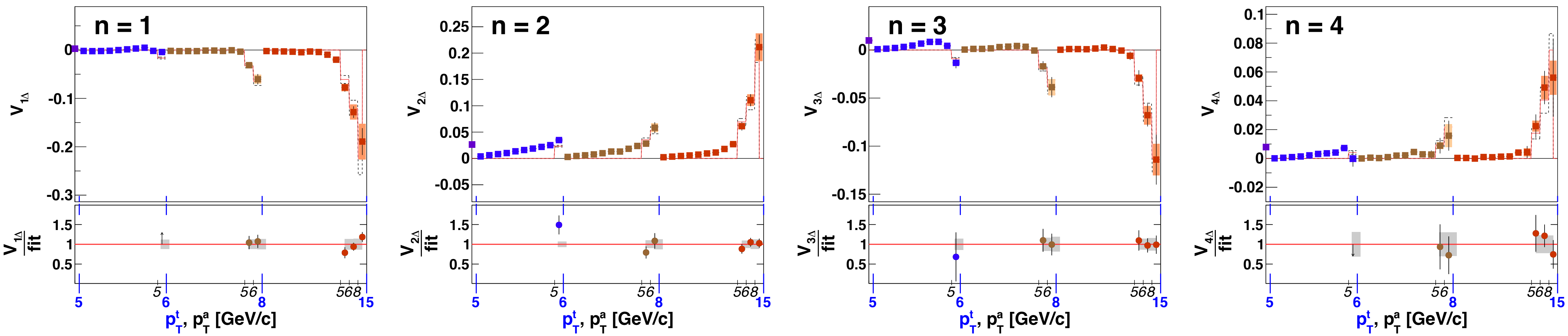

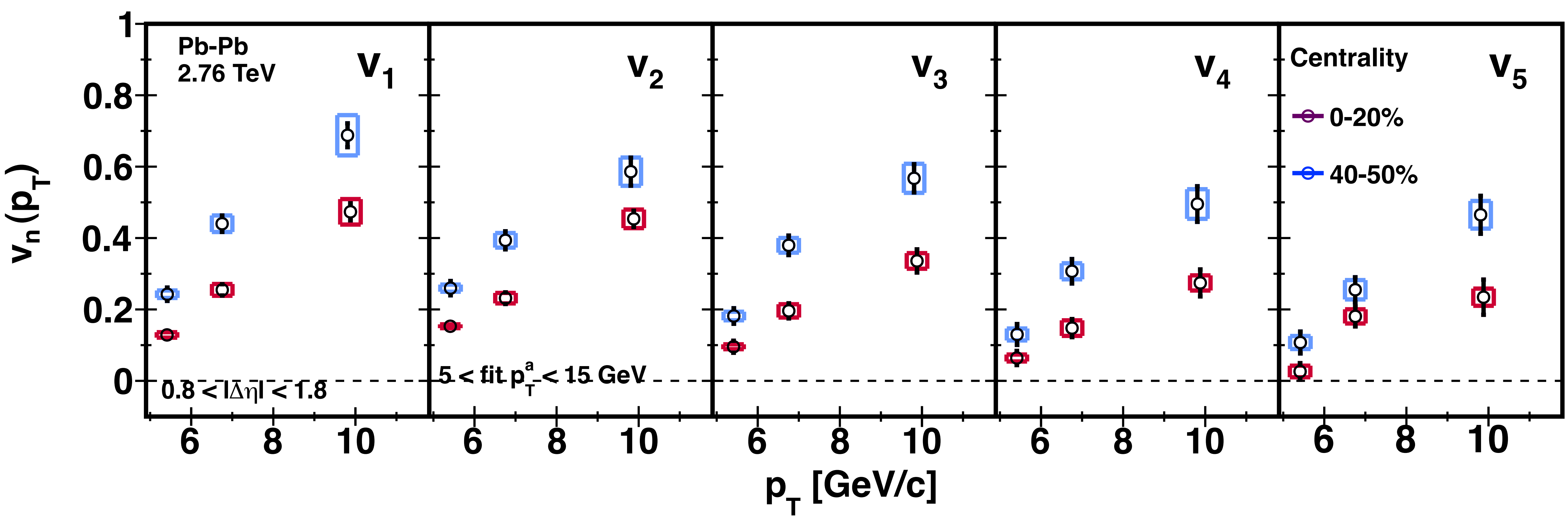

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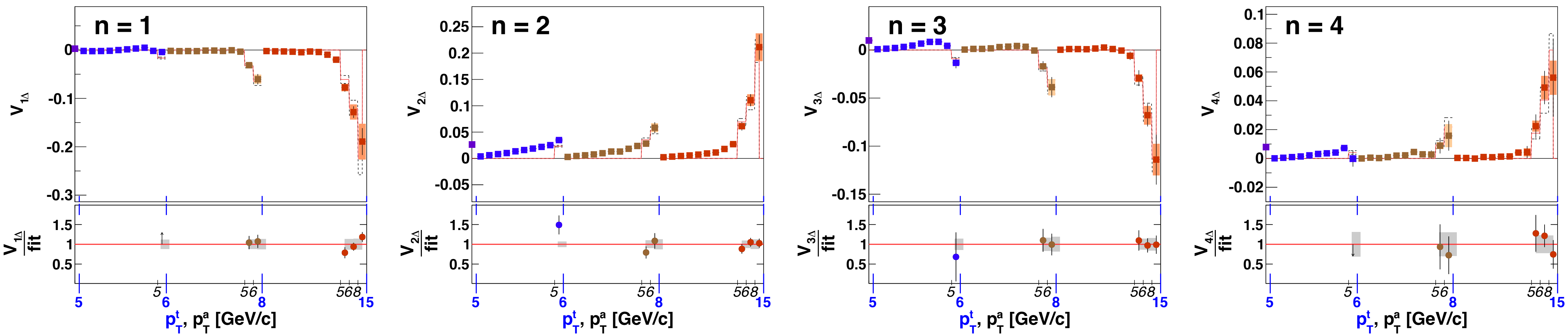

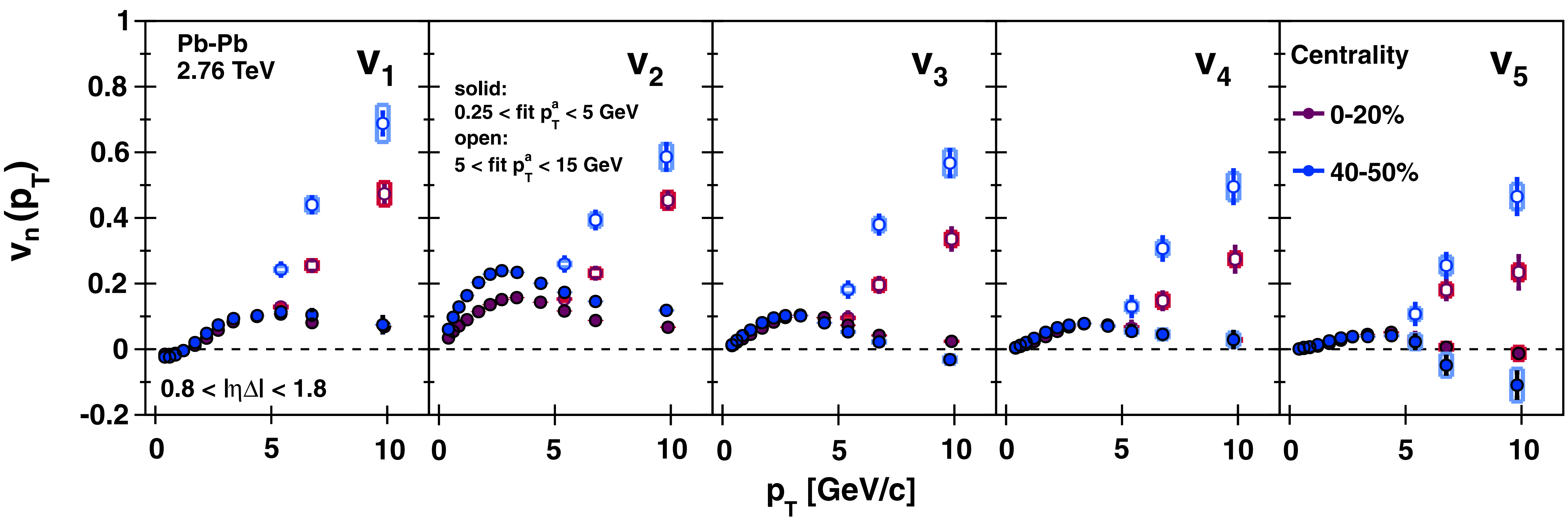

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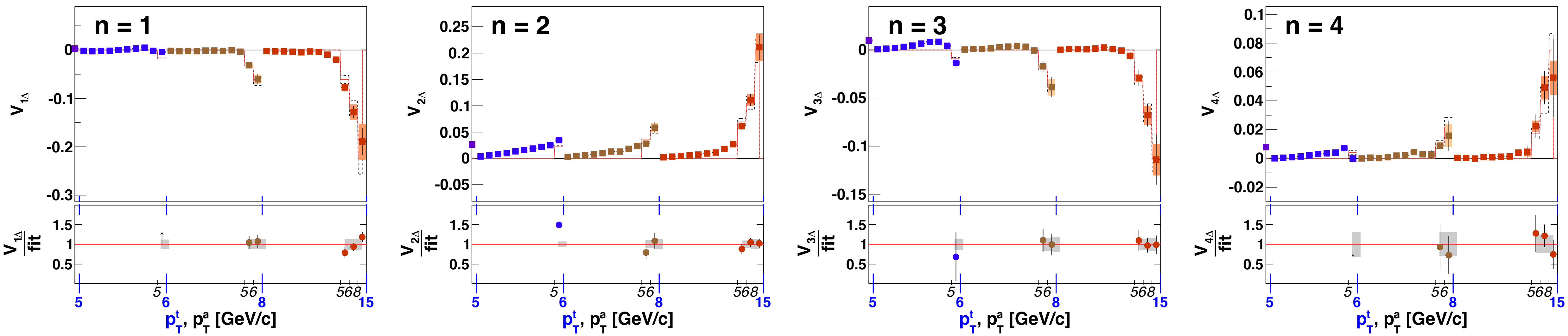

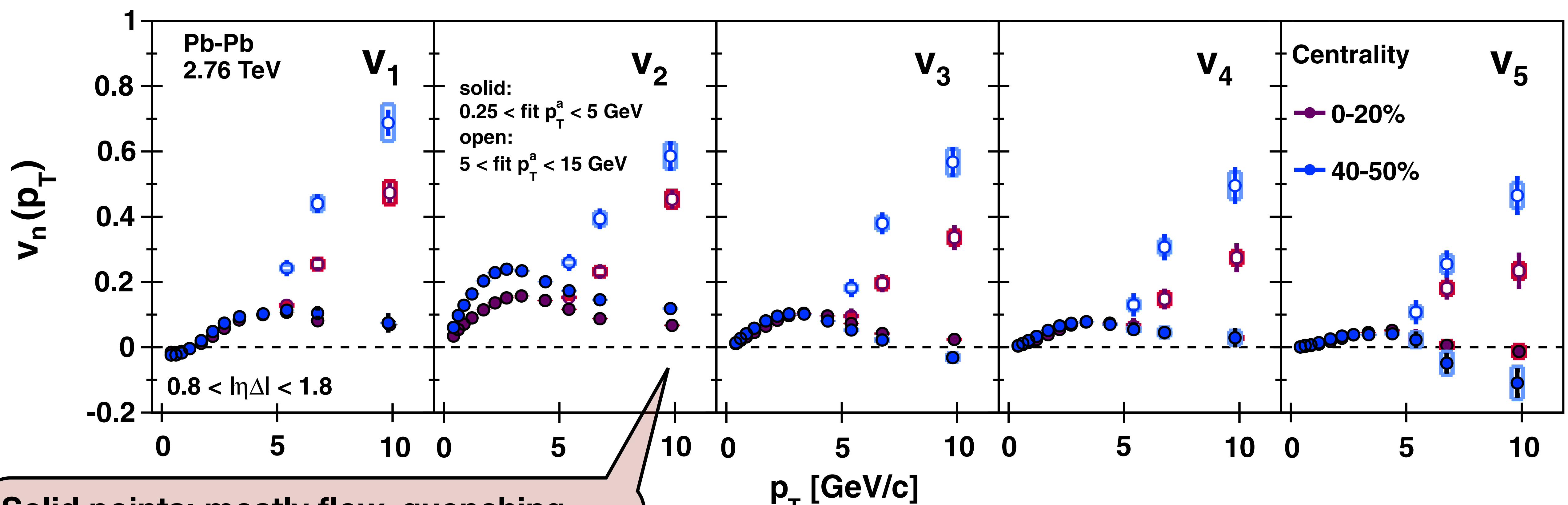

Solid points: mostly flow, quenching
Open points: mostly from recoil jet peak

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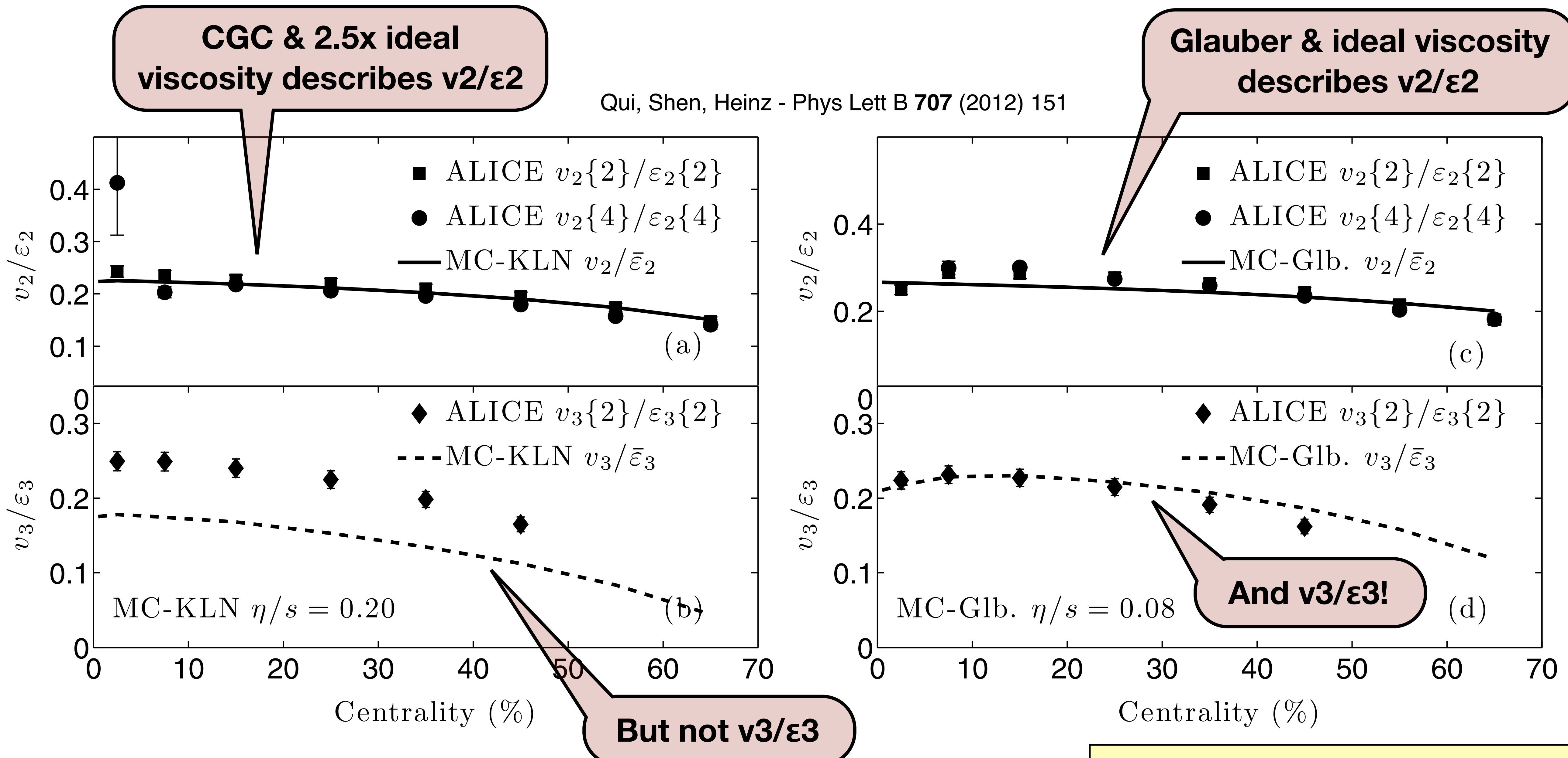
Testing hydro & initial state pictures

LHC v_2, v_3 data adds strong constraints to I.C. + η/s combination

Qui, Shen, Heinz - Phys Lett B **707** (2012) 151



Data favors very low specific shear viscosity

Caveat: models don't get $v_n(p_T)$ quite right.

Future work: event-by-event hydro, hadronization/chemistry improvements

Future directions

Can we probe hydrodynamic flow at the partonic level?
What is the nature of the initial state?
What are the state properties of the QGP (sound speed, η/s, ...)
How does hadronization occur?

Experimental:

- Joint-harmonic observables (e.g. PRC 84, 034910 (2011))
- PID at high p_T <--constituent quark scaling violation?
- Prompt photons (both thermal and hard QCD γs)
- Heavy flavor
- v_n of fully reconstructed jets

Theoretical: enormous recent progress.
Given the recent bounty of data, much catching up to do!

- v_n for higher harmonics (n > 3)
- models predicting suppression (R_{AA}) and v_n simultaneously (especially for heavy quarks)
- Full evolution: initial state, hydro, freezeout/hadronization matching data

Summary

Integrated elliptic flow is larger than at RHIC

expected from larger radial flow

Differential v_2 is roughly the same

Do we understand this?

Fluctuations are significant

Higher harmonics in models constrain initial state and viscosity

Viscous hydro continues to describe v_n data

- Data seem to favor low viscosity and Glauber I.C.s
- Need event-by-event modeling to capture fluctuation effects

v_n at high p_T

Transition from flow to jet quenching

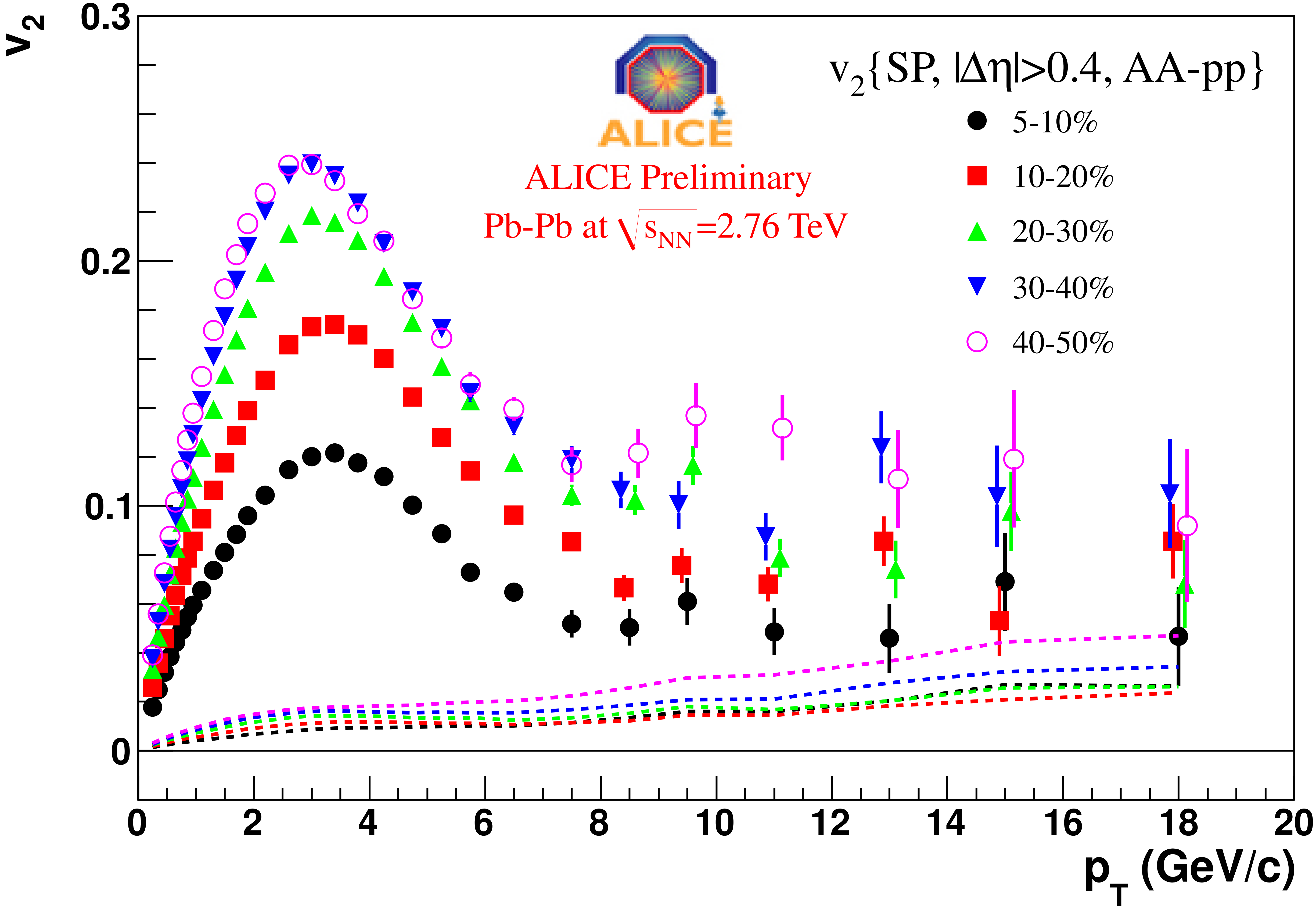
Harmonic factorization → understanding jet vs. flow in correlations

Many 2011 dataset analyses underway! Much action still to come.

Thanks!!

Extras

ALICE v2 at high pt



ALICE v2, v3 with hydro

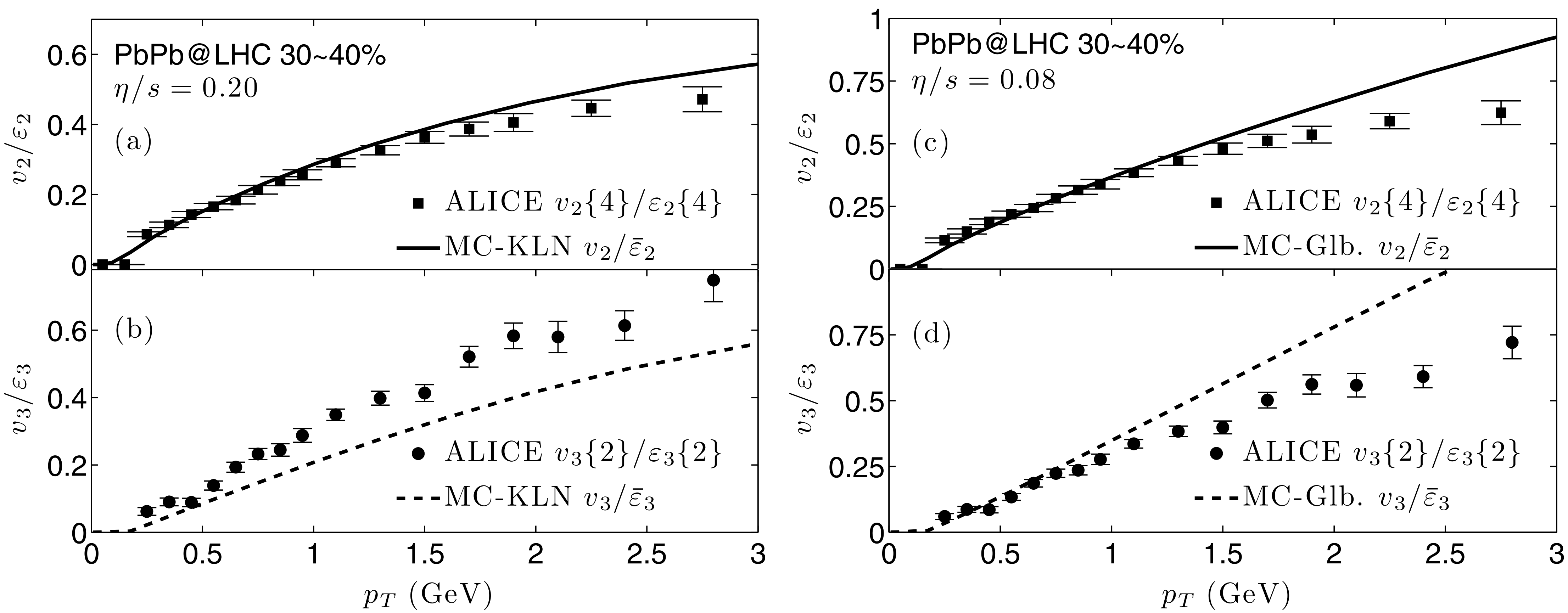


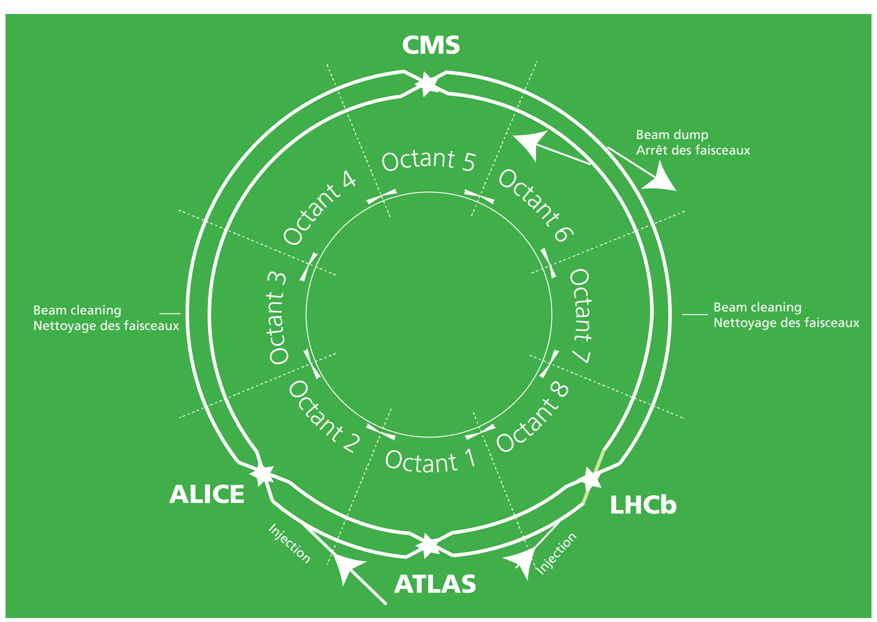
Fig. 4. Eccentricity-scaled, p_T-differential elliptic and triangular flow for 2.76*A* TeV Pb–Pb collisions from viscous hydrodynamics with MC-KLN (a, b) and MC-Glauber (c, d) initial conditions. The ALICE data [25] are scaled according to their corresponding eccentricities, see text.

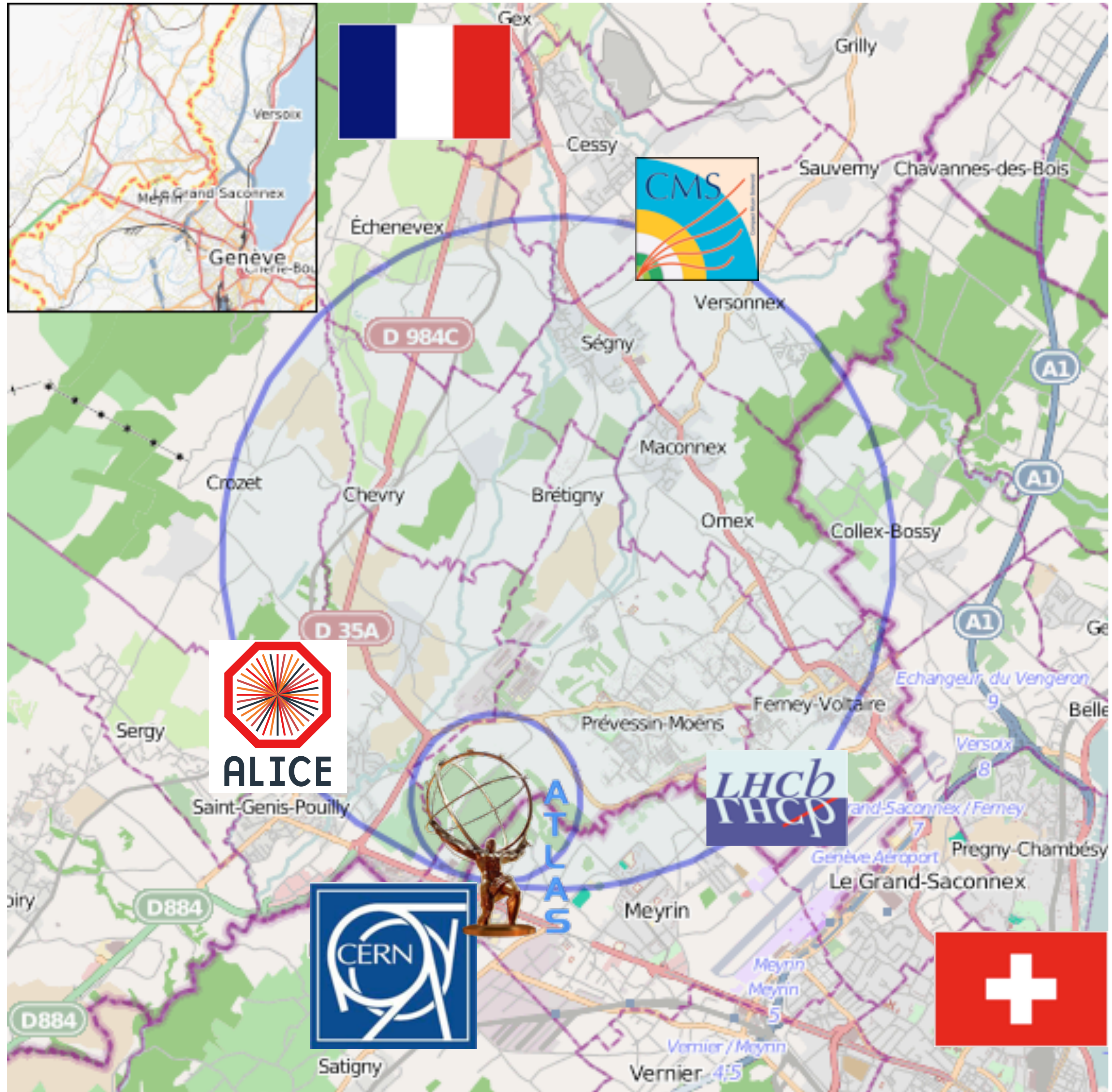
A. Adare

The Large Hadron Collider

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon





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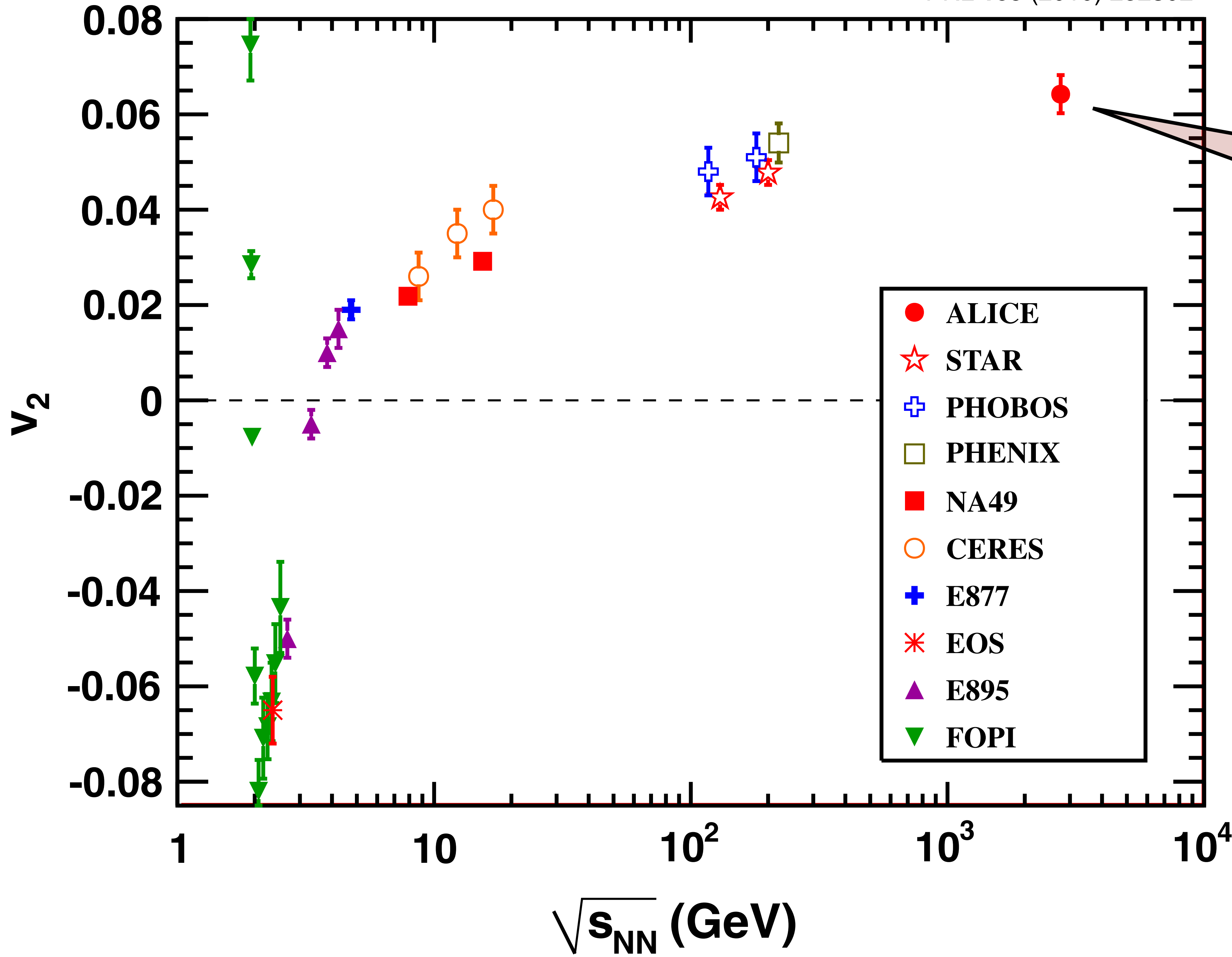
v_2 @ LHC and predecessors

v_2 vs. collision energy for 20-30% most central collisions

Hydro behavior follows extrapolated RHIC trend

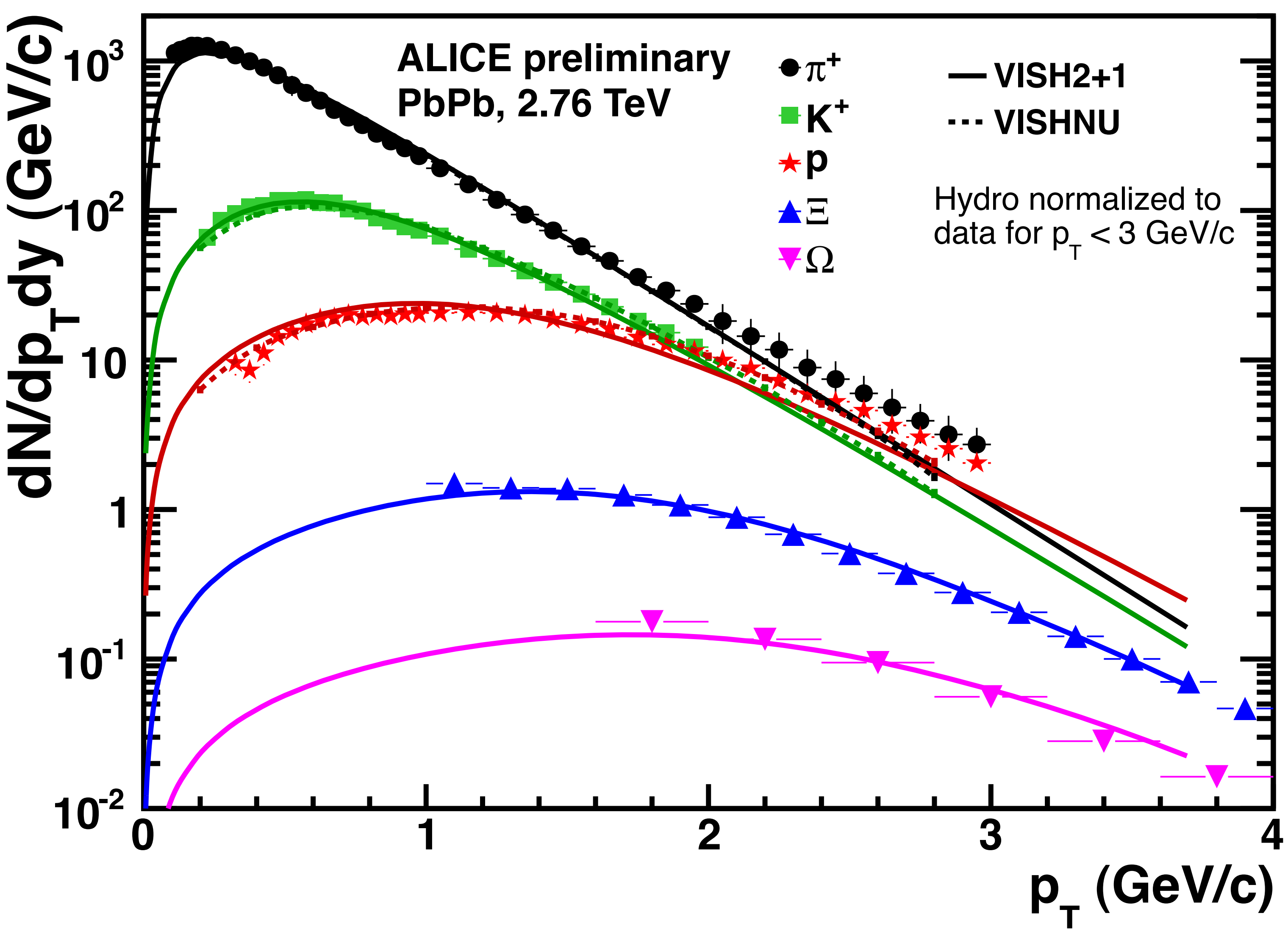
PRL **105** (2010) 252302



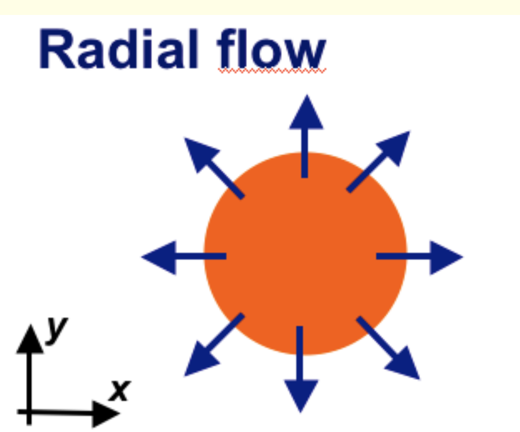
Flow at LHC 30% higher than at RHIC

Not unexpected: larger radial flow velocity, thus higher <p_T>

Radial flow slide from Klaus Reygers

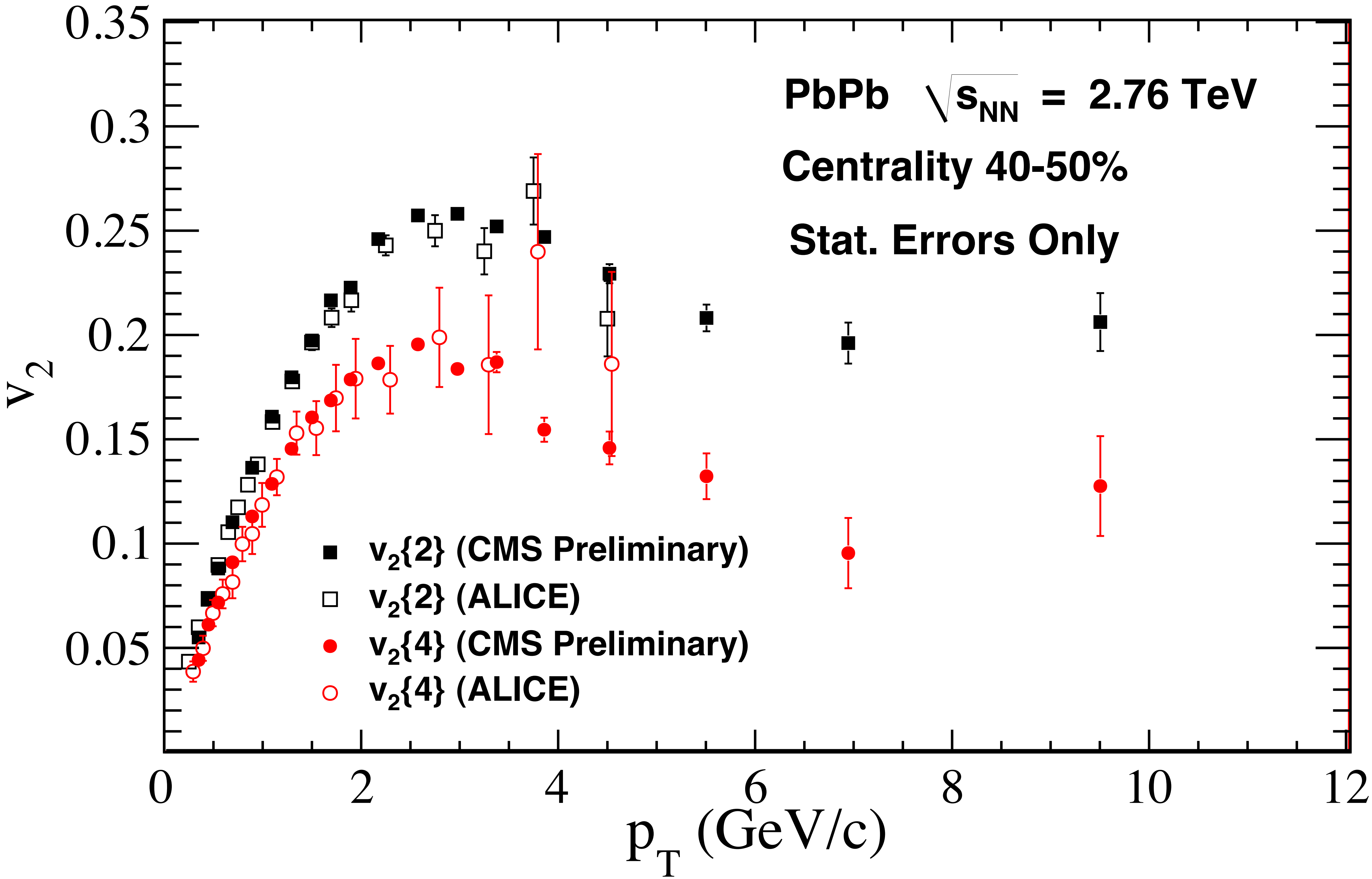


- Shapes of p_T spectra for particles with different masses indicate radial flow
- Hydro models describe data
- Hydro inspired blast wave fits for central Pb+Pb at LHC:
  - $\langle \beta_{T,\mathrm{flow}} \rangle \approx 0.65\, c$
  - $\langle \beta_{T,\mathrm{flow}} \rangle_{\mathrm{LHC}} \approx 1.1 \times \langle \beta_{T,\mathrm{flow}} \rangle_{\mathrm{RHIC}}$
  - kinetic freeze-out: $T_{\mathrm{fo}} \approx$ 80 - 100 MeV



$$p_T^{\mathrm{w/\ flow}} = p_T^{\mathrm{w/o\ flow}} + \beta_{T,\mathrm{flow}} \gamma_{T,\mathrm{flow}}\, m$$

CMS and ALICE v2



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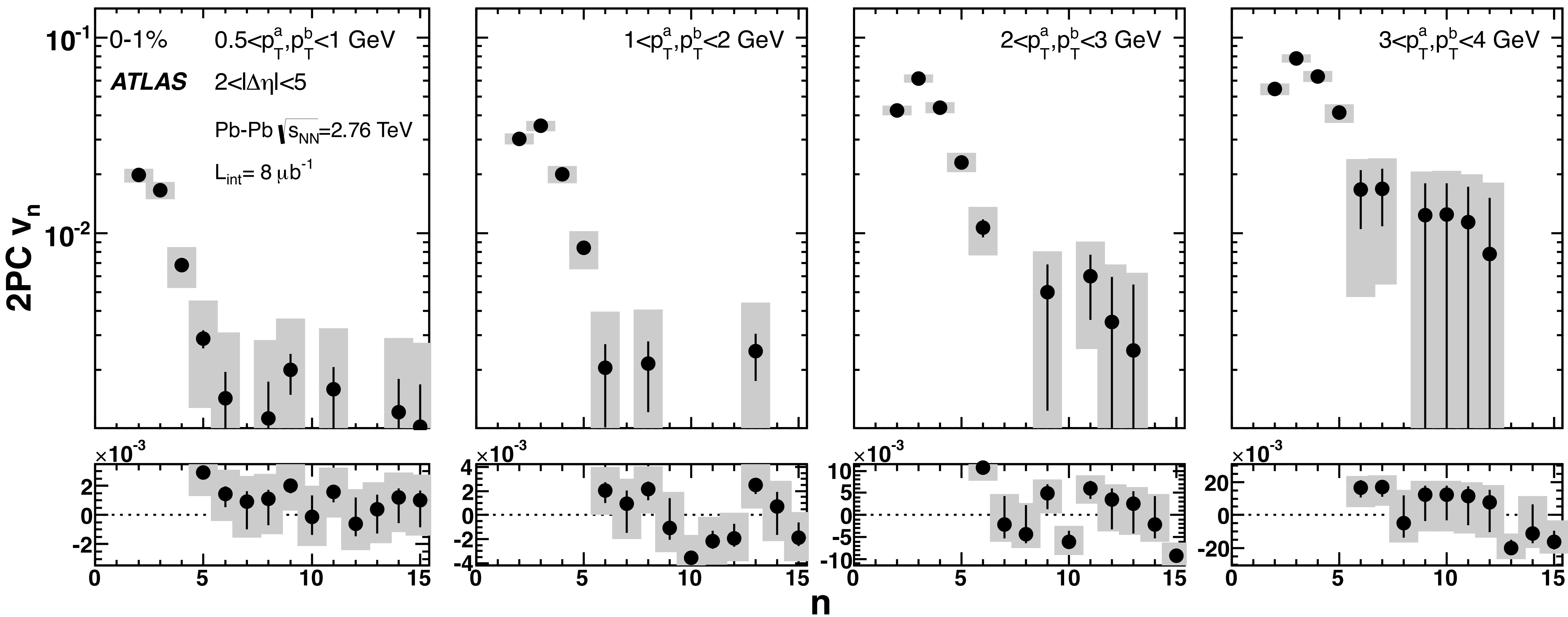
Harmonics up to n = 15

2-particle power spectra at a various momenta

Above n = 6, harmonics are vanishingly small

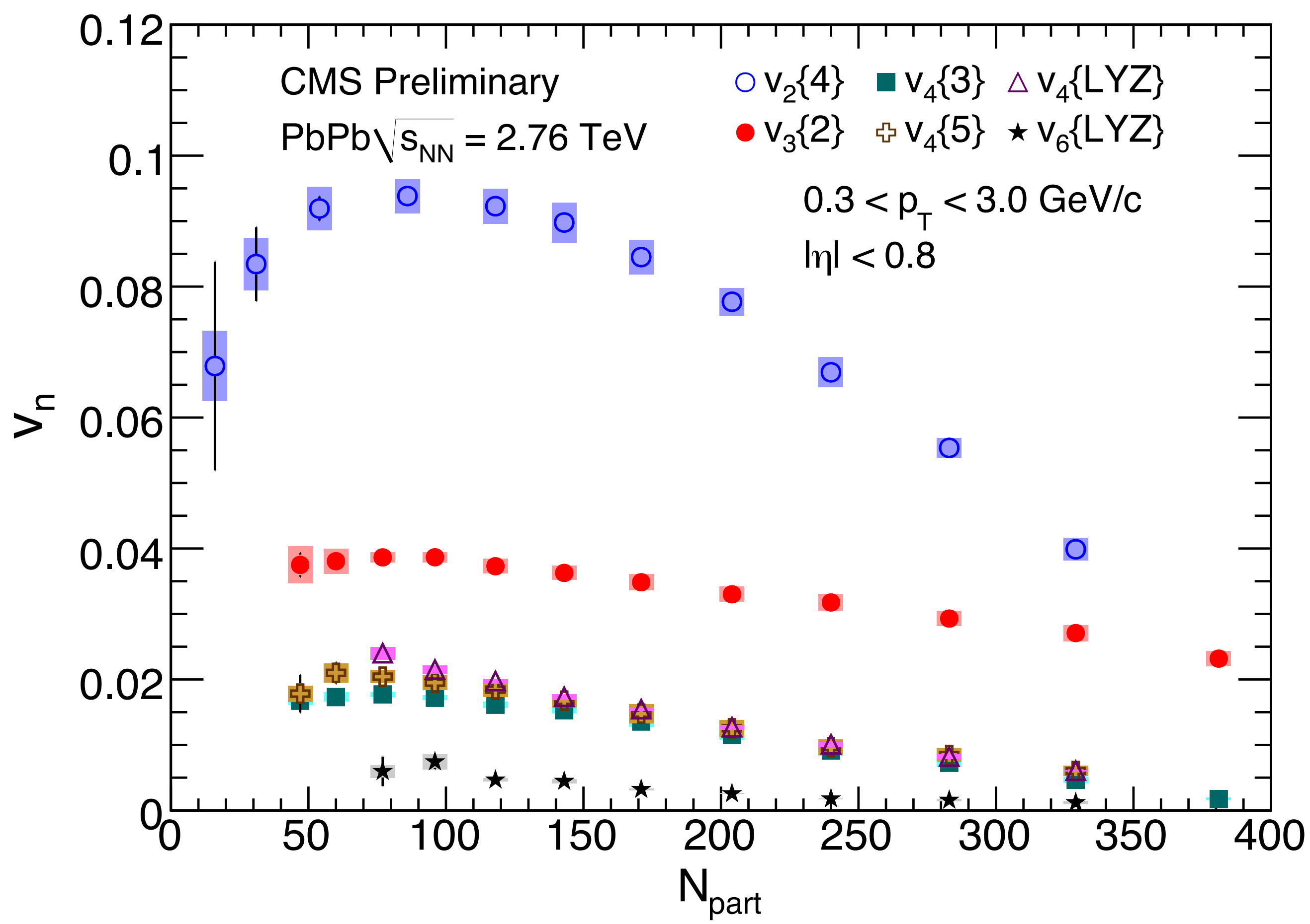
ATLAS arXiv:1203.3087v1

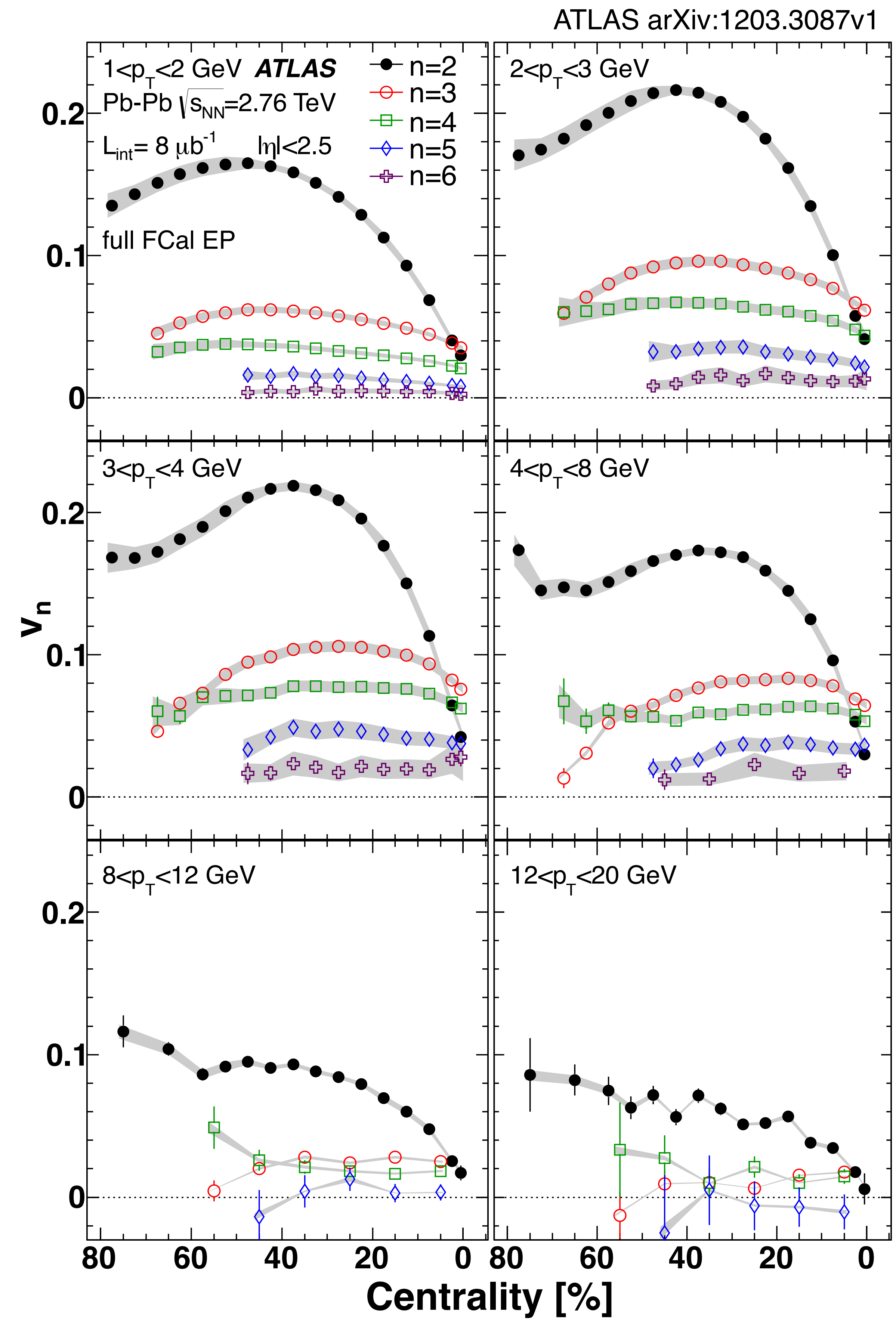


ATLAS and CMS v_n vs centrality

v_n at various different p_T ranges
Same features as before:

- strong size/geometry dependence for v_2, much weaker for v_3 - v_6
- anisotropy peaks near 3-4 GeV/c
- higher harmonics are weaker





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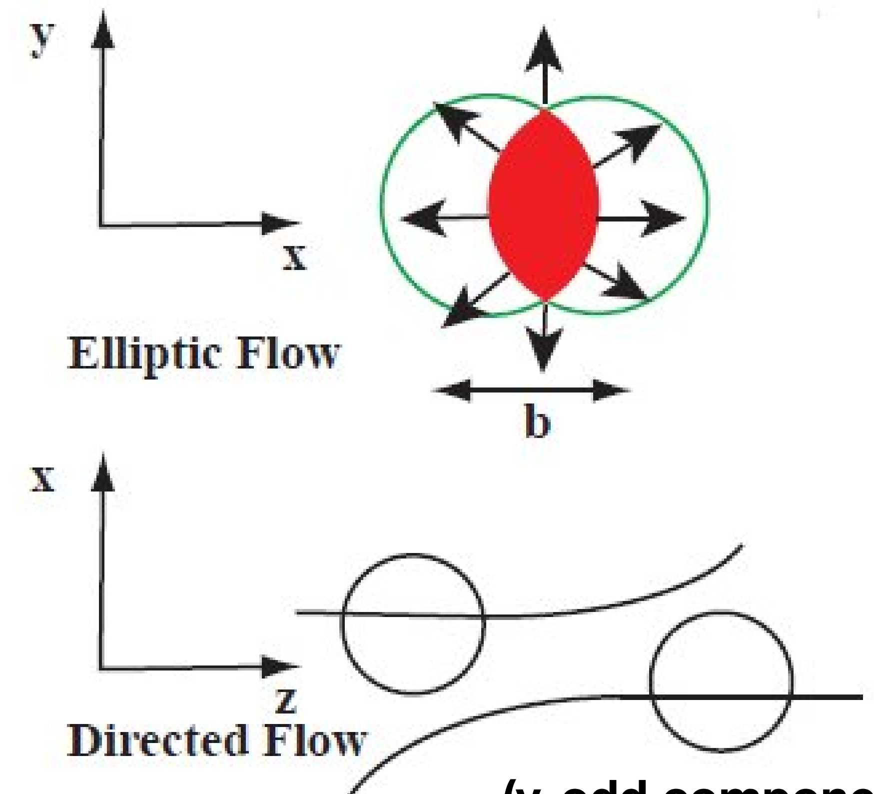
The first harmonic

v1 has a rapidity-odd component

- From recoil of collision spectators
- Vanishes over symmetric η interval



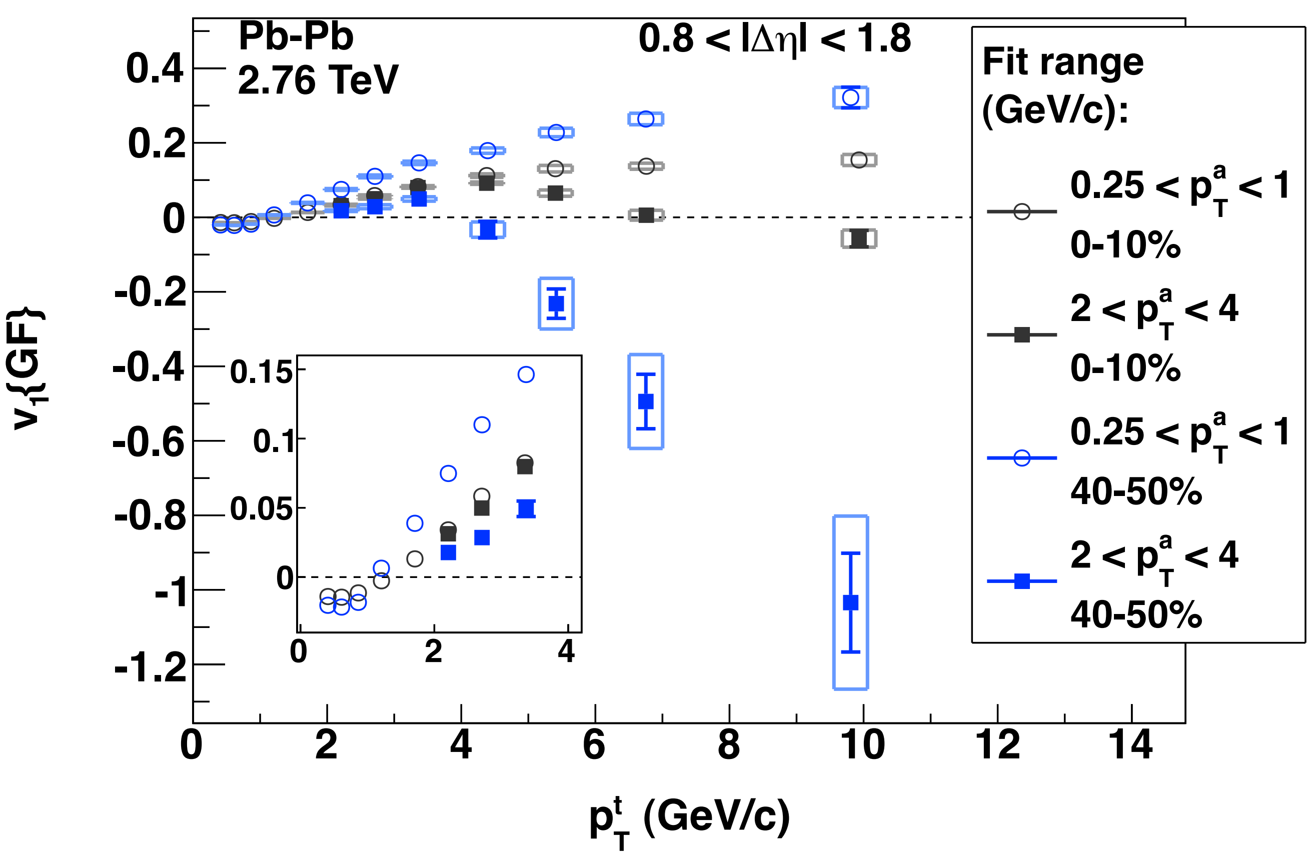
(y-odd component)

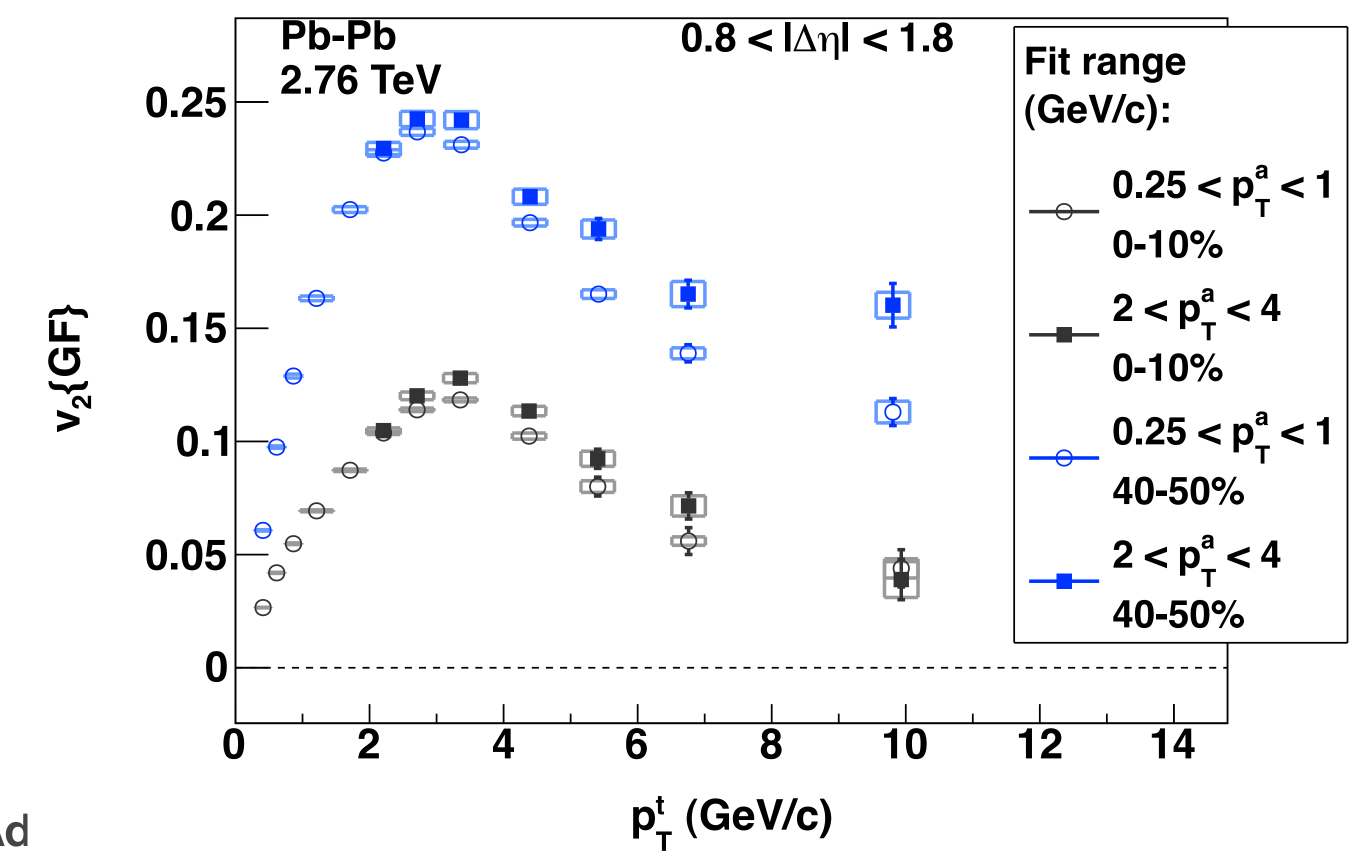
and a rapidity-even component

from

- fluctuation-induced directed flow,
- global p_T conservation (arXiv:0809.2949v2),
- jet fragmentation

This pT-dependent admixture complicates factorization





Ad

Fluctuations

Fluctuations arise from

- event-by-event initial-state nonuniformities
- at fixed b, mult (F.S. density anisotropies)
- b variations w/in cent bin

Bjoern schenke

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