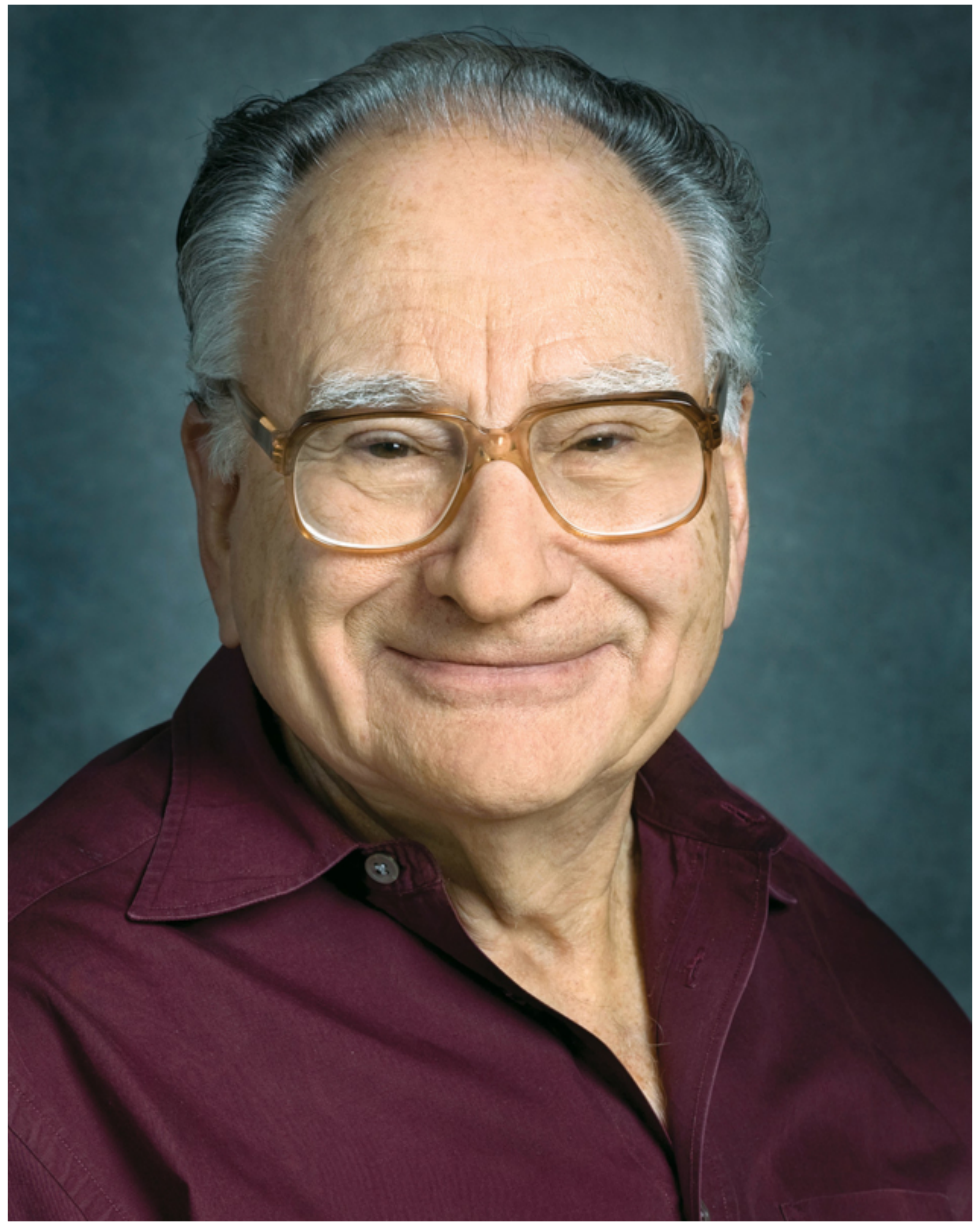
Flow from RHIC to the LHC

Symposium on collective flow in nuclear matter: a celebration of Art Poskanzer’s life and career



Color by Roberta Weir

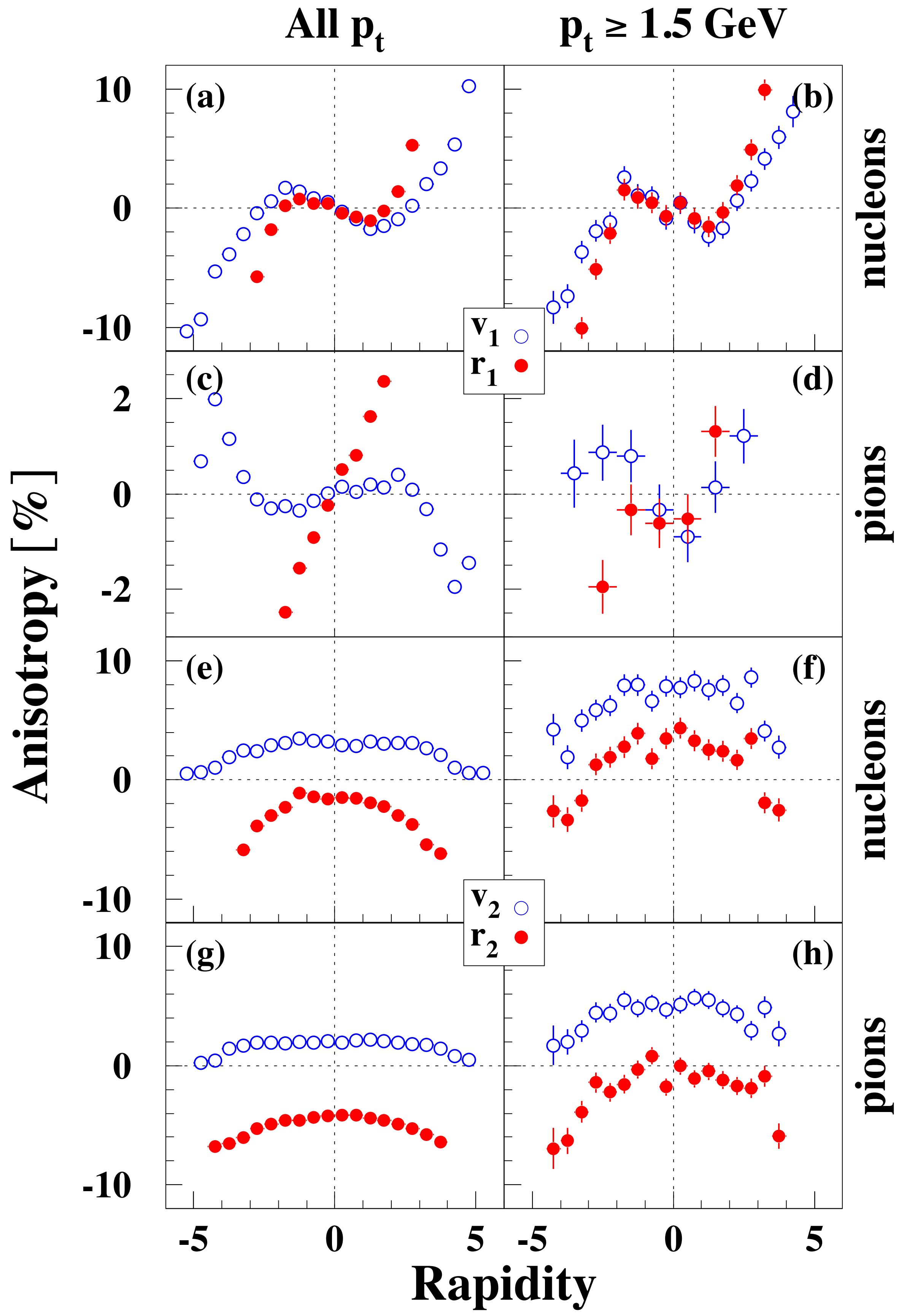
Exploring the secrets
of the universe

Art Poskanzer

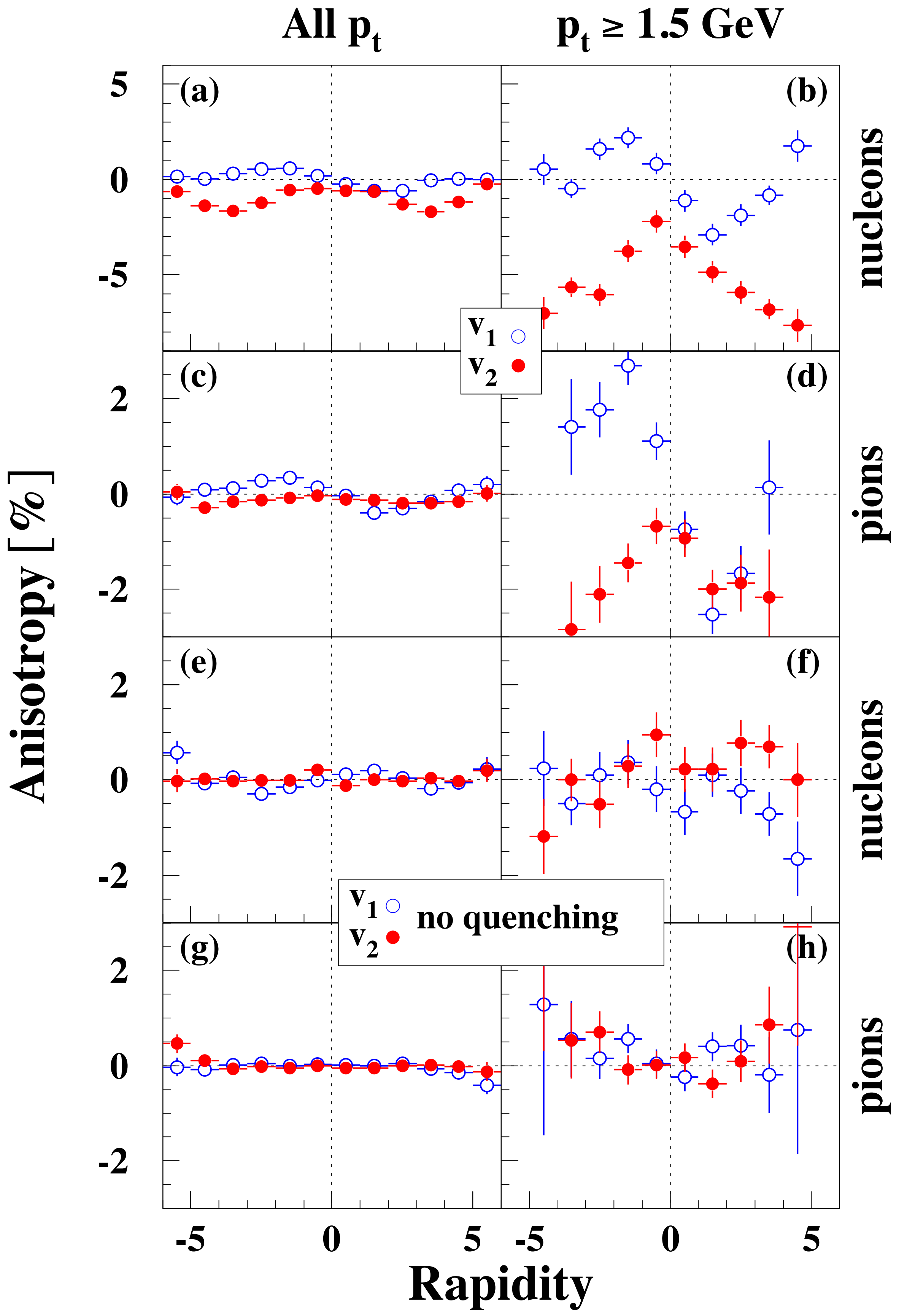
Anisotropic Flow (pre-RHIC)

Nikhef

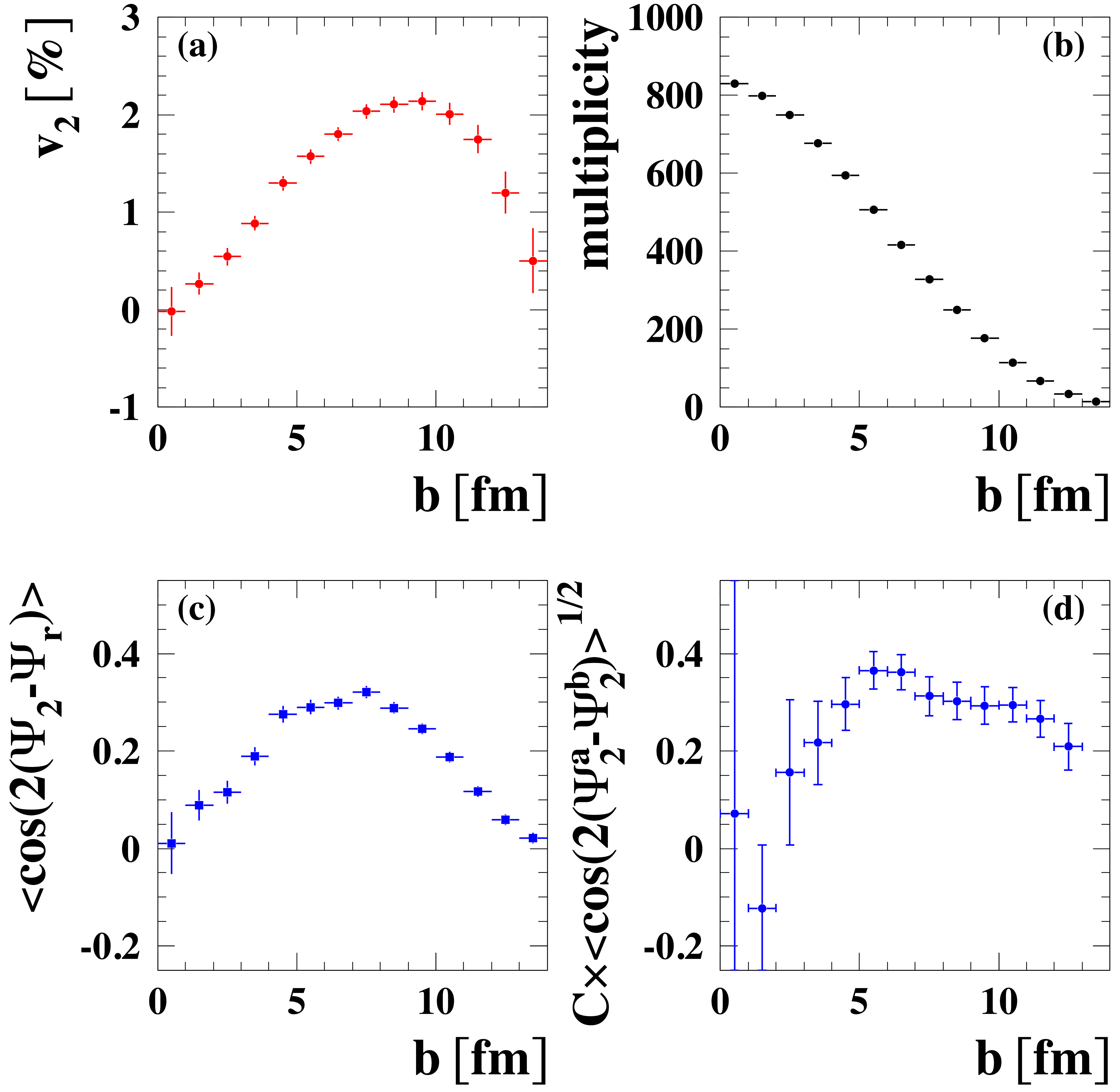
RQMD



HIJING



RQMD



we only need the momenta of the charged hadrons and thus anisotropic flow could be one of the first results from STAR. For future analyses it would be good to have particle identification.

Day-1 physics at RHIC

RHIC Winter Workshop at LBNL

Flow

- **Radial:**
  - Will (continue to) be a very large effect
  - Essential component to understanding spectra at RHIC.
- **Directed:**
  - Already small at SPS
  - Almost irrelevant at RHIC
- **Elliptic:**
  - Zero for truly central events (at any energy)
  - Is it
    - A necessary evil for understanding events with non-zero impact parameter?

    Or

    - An essential tool to our understanding of EoS+(time evolution) of (non-isotropic) initial conditions?
  - My *prejudice:*
    Effects of elliptic flow will be small at RHIC

09-Jan-98 W.A. Zajc

Time to Physics

Again, learn from the past:

First CDF publication:

Transverse-Momentum Distributions of Charged Particles Produced in p-pbar Interactions at 630 and 1800 GeV, F. Abe et al., Phys. Rev. Lett. 61, 1819 (1988).

- ~One year from data-taking.
- Much simpler final state!

➡ *We will be hard-pressed to reach this goal*

➡ *And much harder-pressed to maintain "CDF-like" rate*


VOLUME 61, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1988

Transverse-Momentum Distributions of Charged Particles Produced in $\bar{p}p$ Interactions at $\sqrt{s}$ = 630 and 1800 GeV

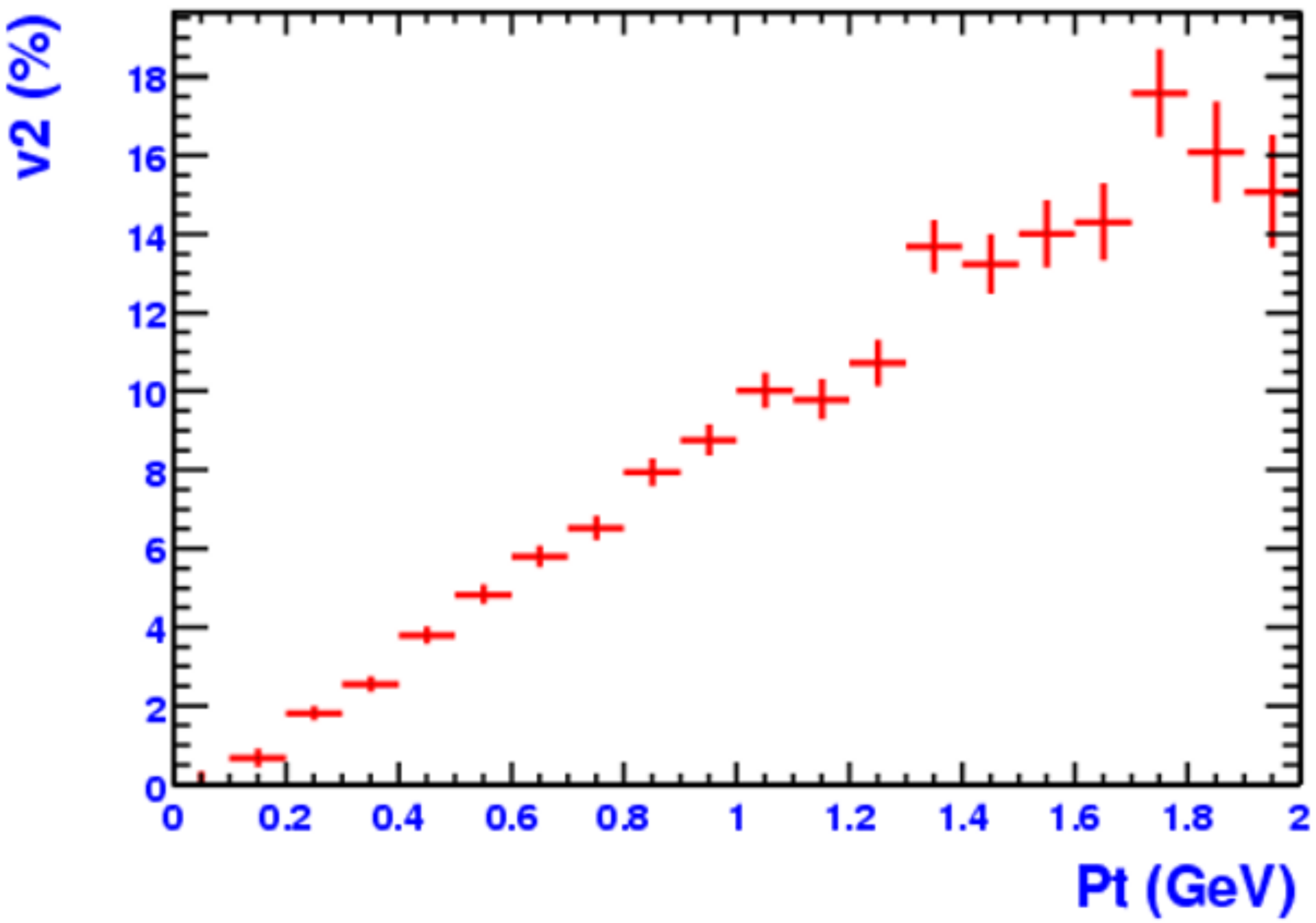
1819

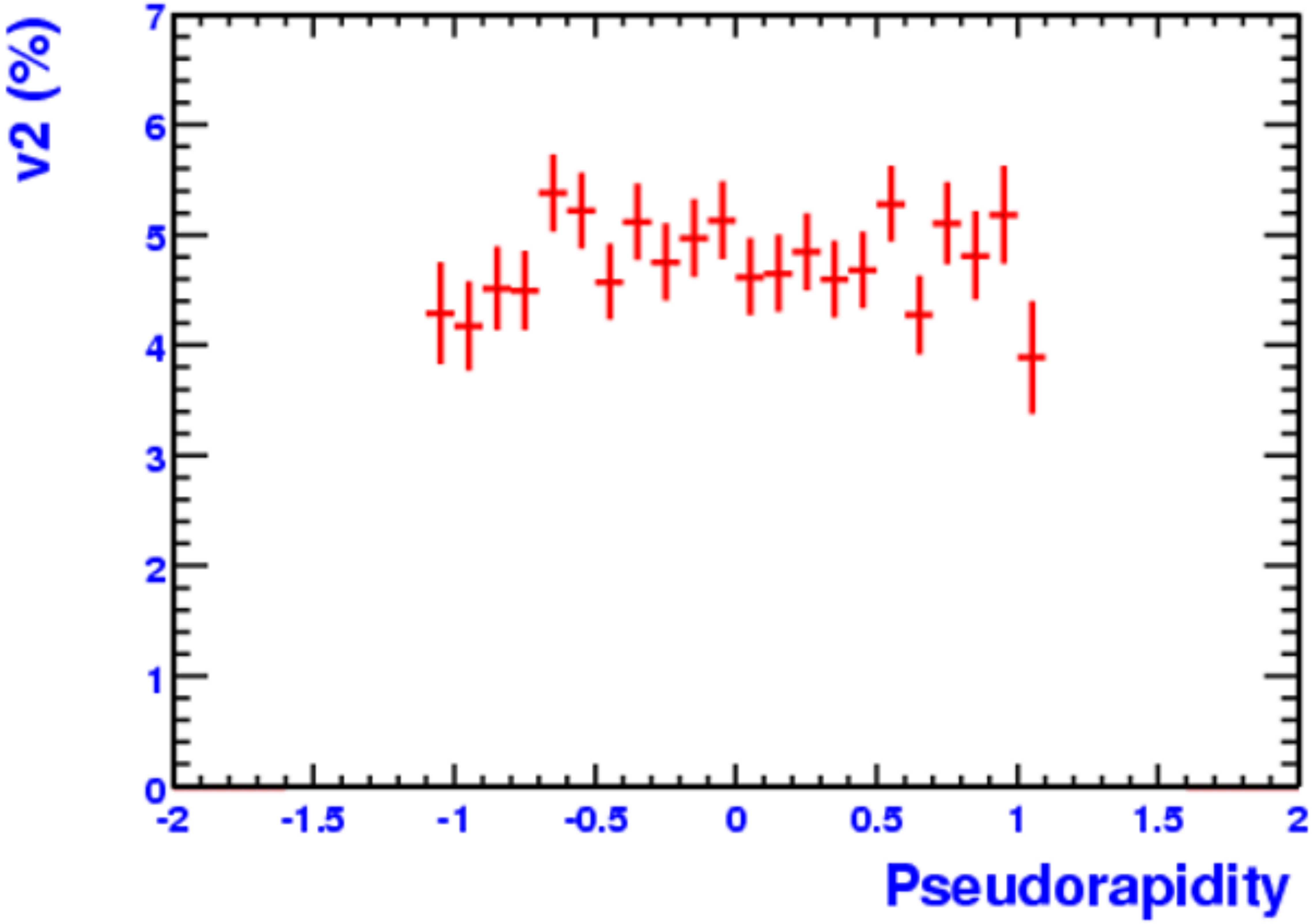
09-Jan-98 W.A. Zajc

Relativistic Heavy Ion Collider (RHIC) Begins Smashing Atoms

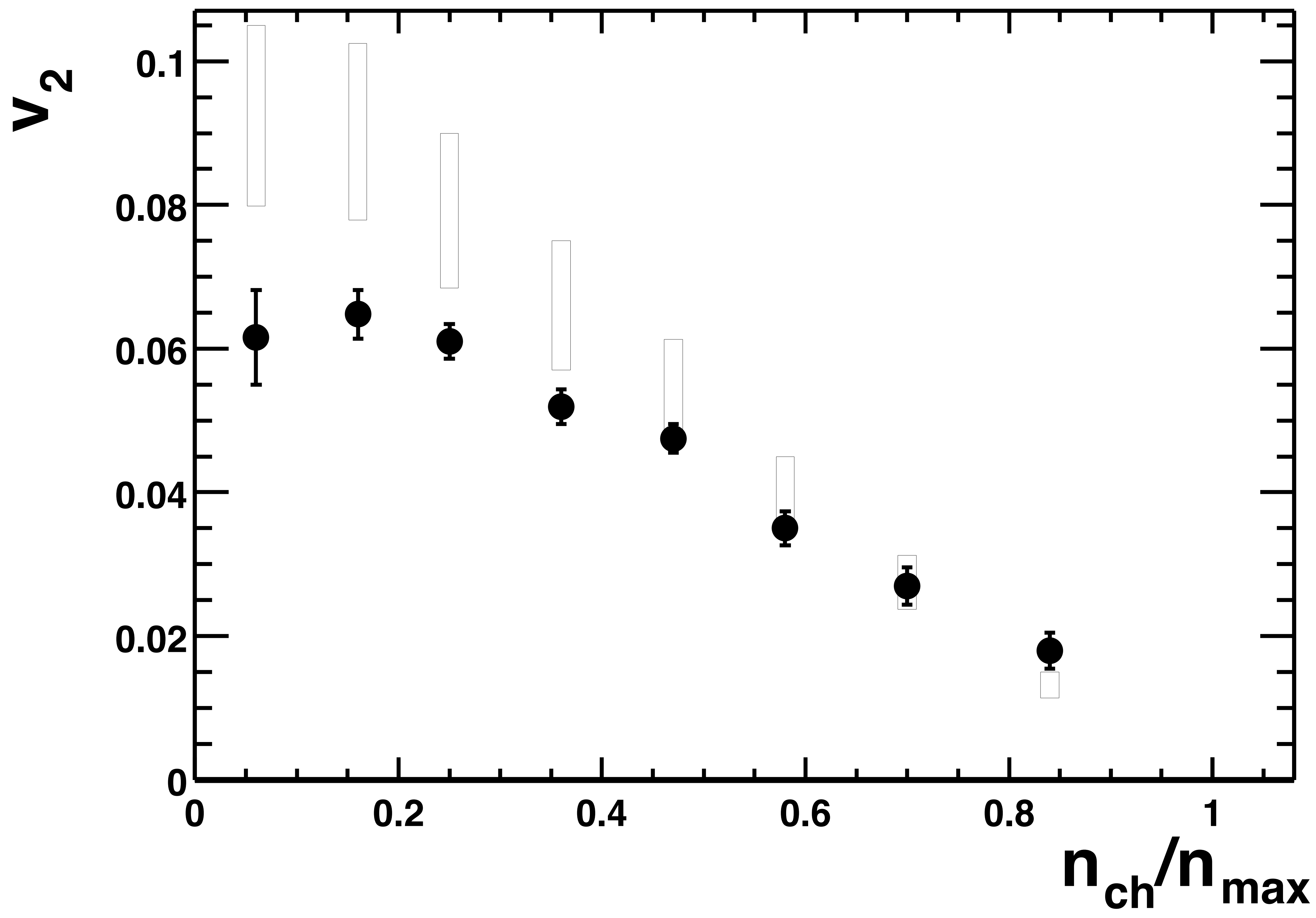
Experiments will yield insights into the structure of matter and how the universe evolved

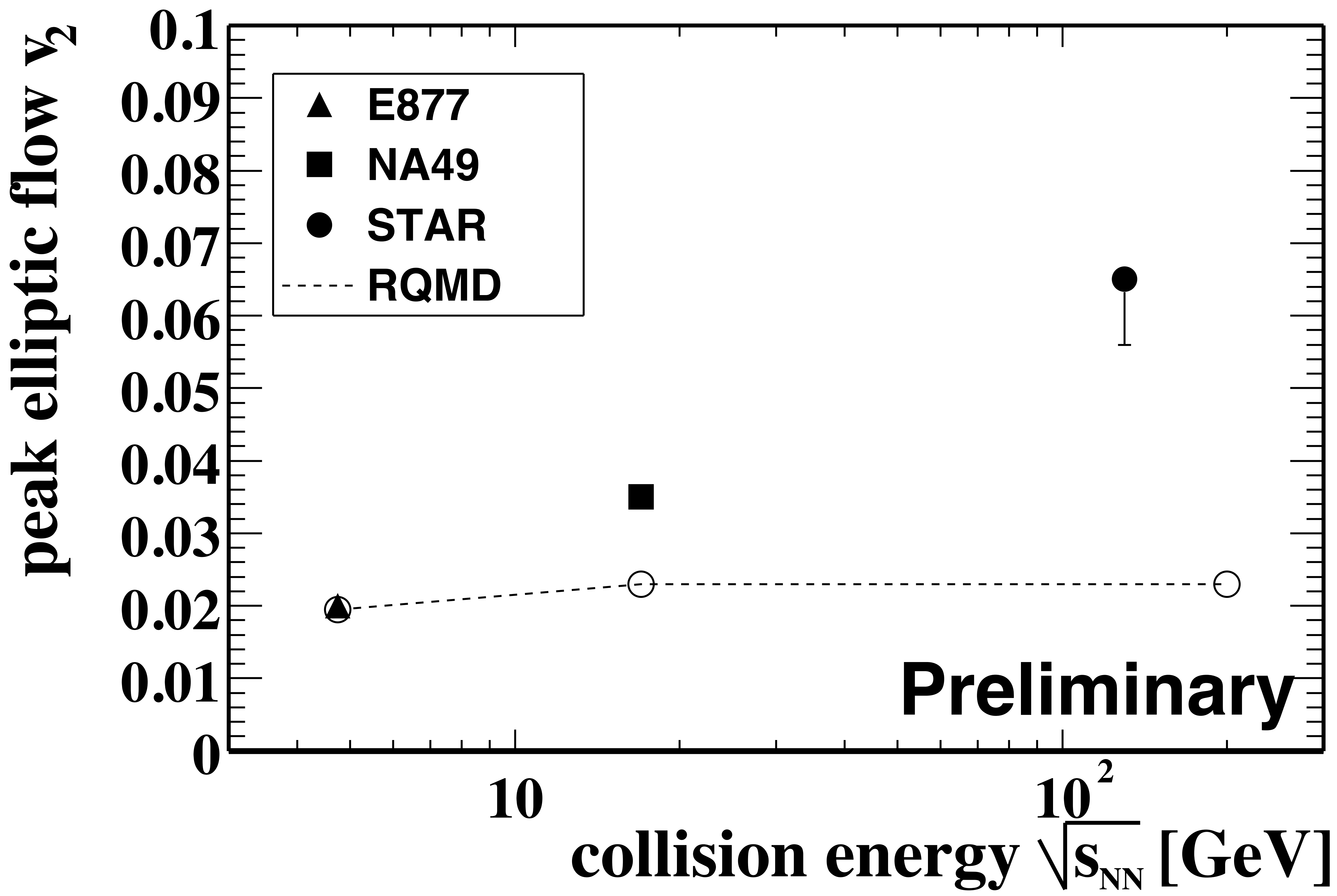
June 13, 2000





I am sure people here have pictures of these plots from the door of Art's office

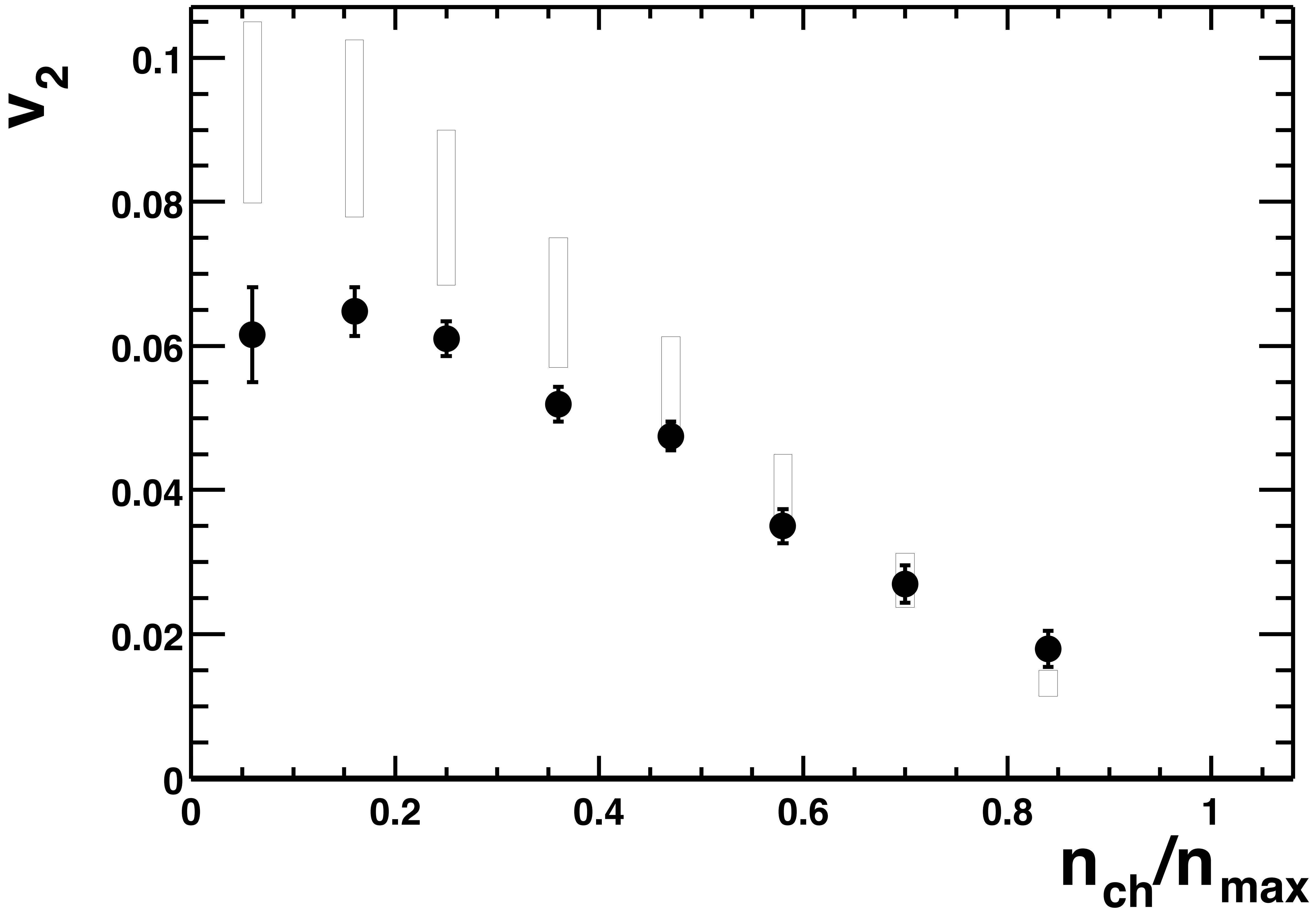


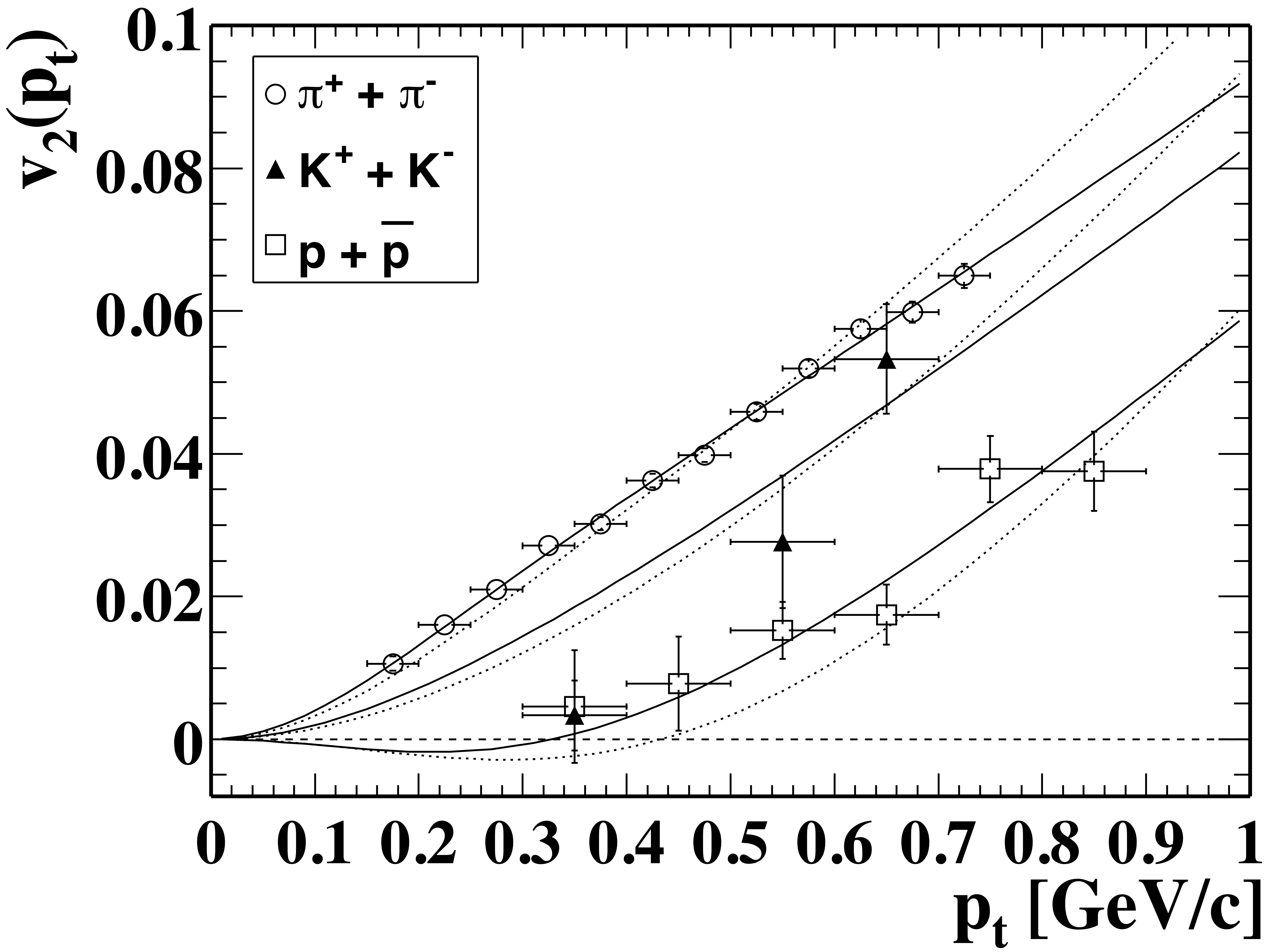


in good agreement for mid-central collisions with "hydro"

big increase measured compared to predictions hadron cascade model(s)

STAR Collaboration: Phys.Rev.Lett. 86 (2001) 402-407



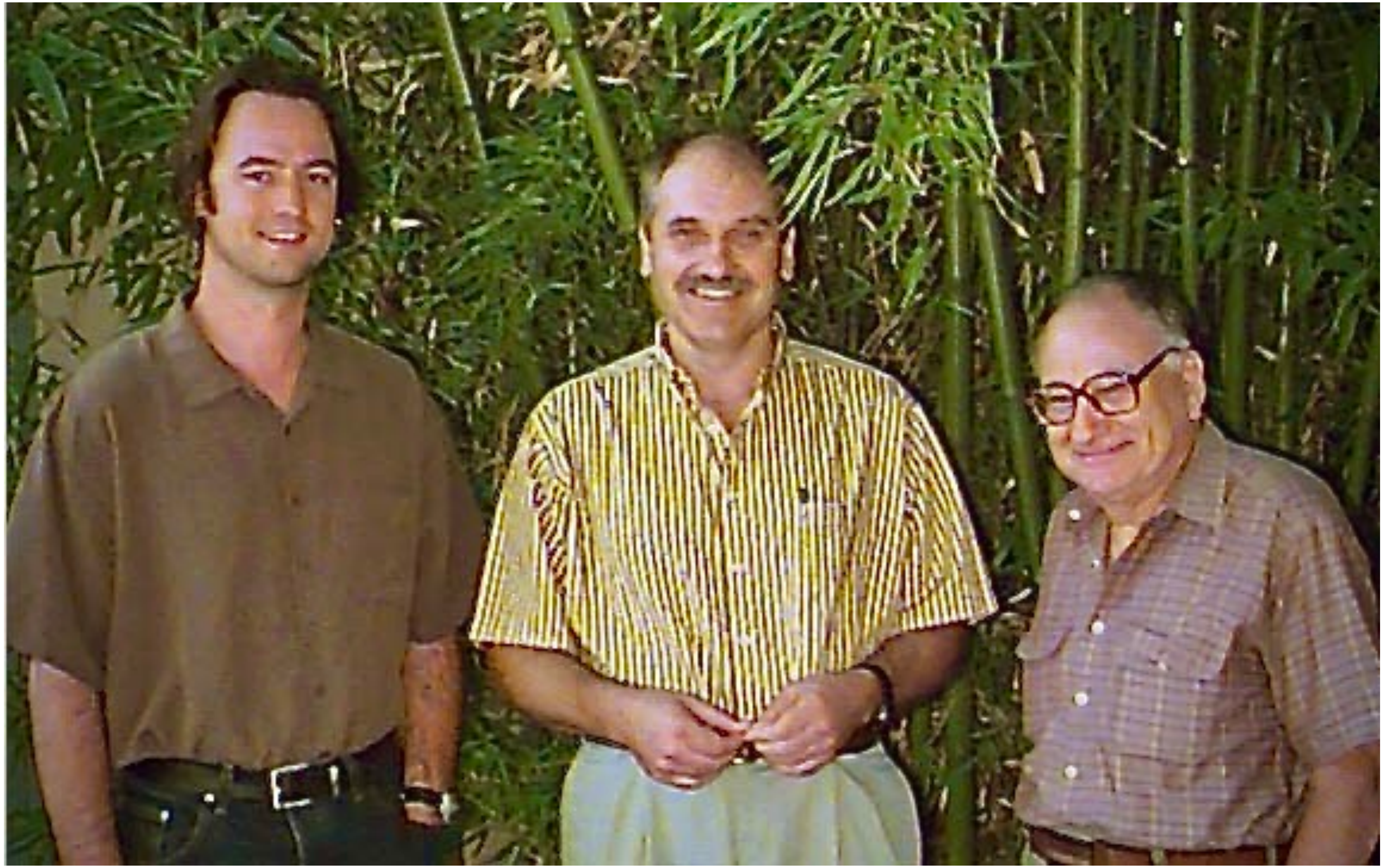


in good agreement for mid-central collisions with “hydro”

Behaves like a system with common temperature and flow boost

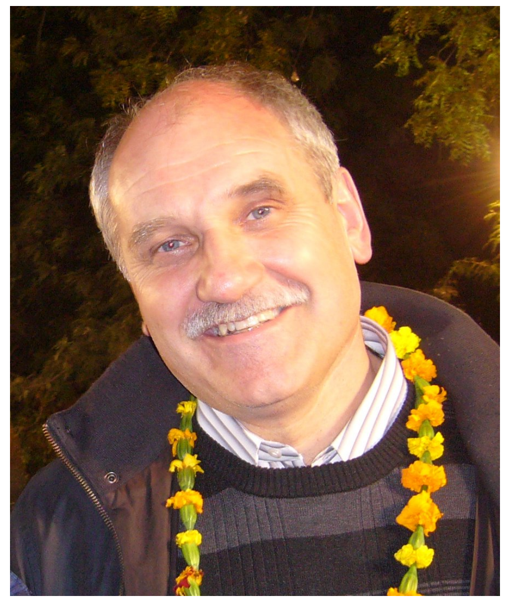
STAR Collaboration: Phys.Rev.Lett. 86 (2001) 402-407, Phys.Rev.Lett. 87 (2001) 182301

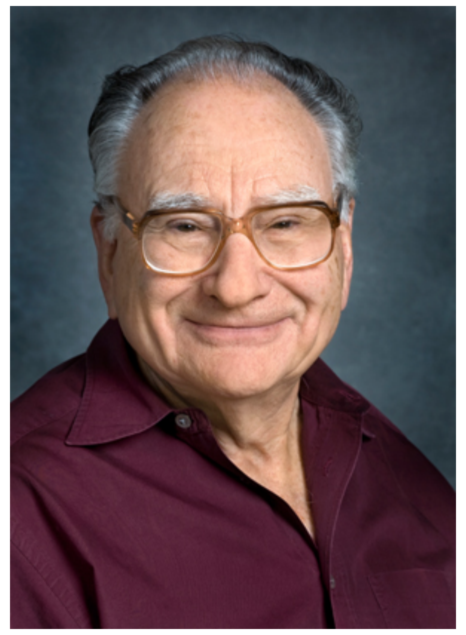
STAR (2001)



Collective phenomena in non-central nuclear collisions

Sergei A. Voloshin, Arthur M. Poskanzer, and Raimond Snellings





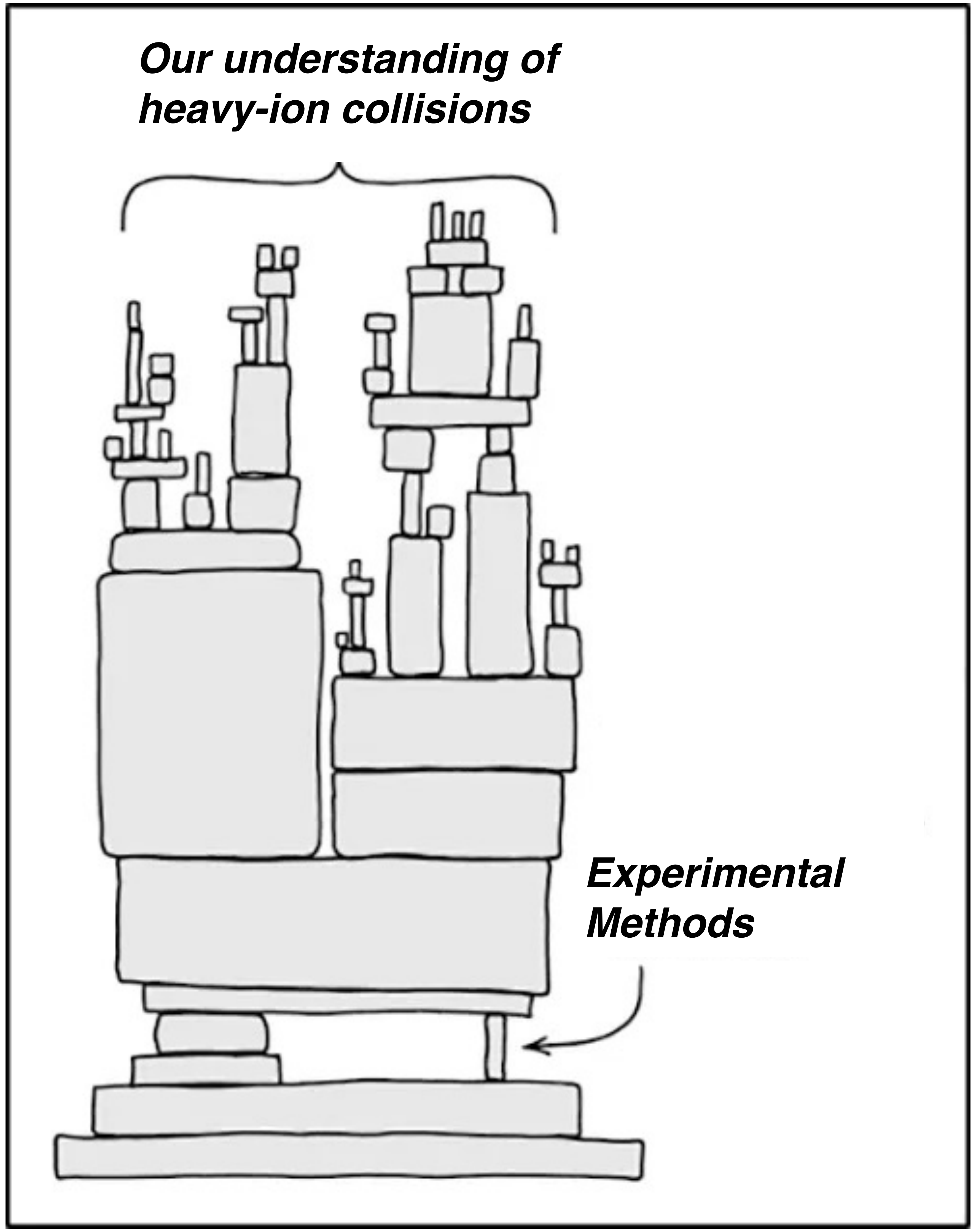
Contents

 S. Voloshin, A. Poskanzer, R. Snellings: *Landolt-Bornstein* 23 (2010) 293-333 e-Print: 0809.2949

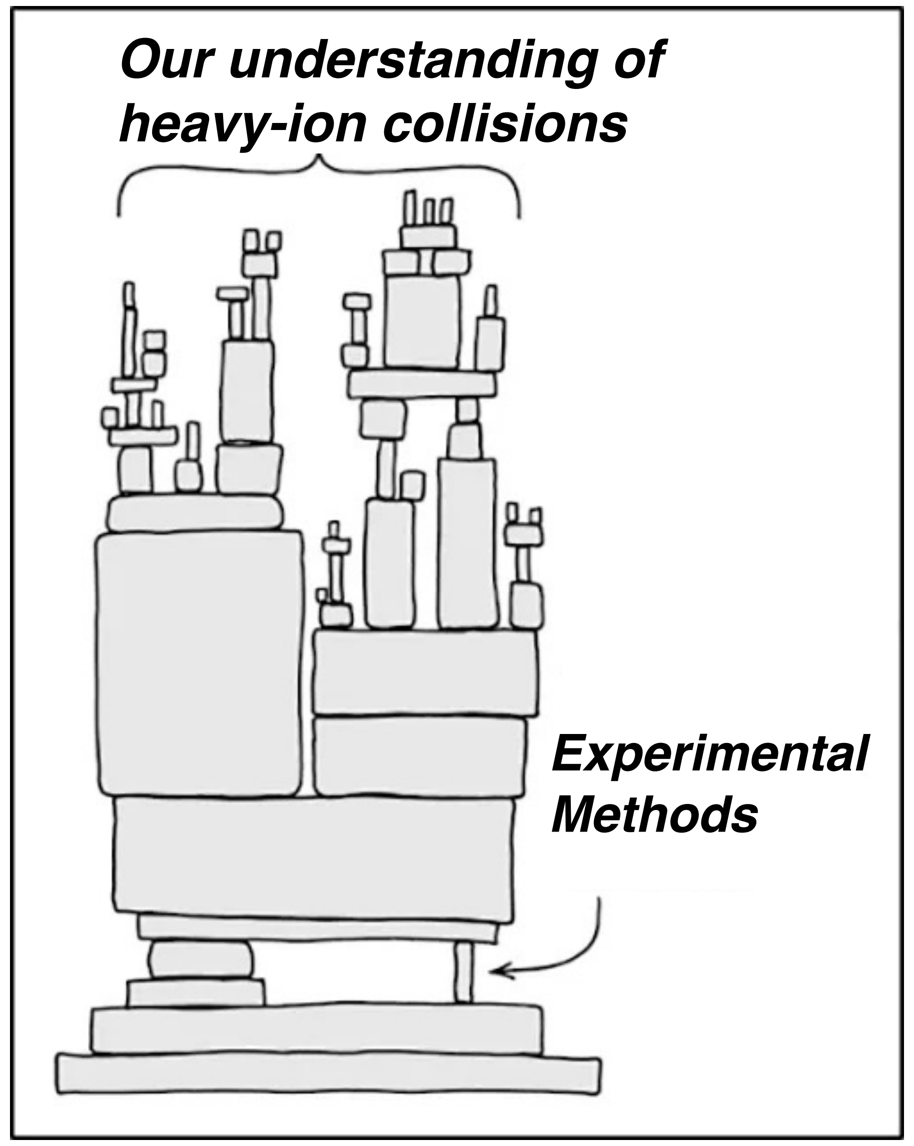
Color by Roberta Weir

Exploring the secrets
of the universe

Art Poskanzer



Experimental Methods



Quality Control

Art Poskanzer

Moral

- Every new analysis needs to be done by two independent people
- Everybody makes mistakes
  - Double check everything
  - Persevere to find the mistakes
  - Be open about correcting them

Generating function cumulants N. Borghini, P.M. Dinh, and J.-Y. Ollitrault, PRC 64, 054901 (2001)

Direct 4-Particle Cumulant

- Direct means not using a generating function
- Four nested loops take too much computer time
- Sergei devised a shortcut
- Paul programmed it, Navneet calculated
- Dhevan Gangadharan programmed $v_2\{4\}(p_t)$
- I convinced Dhevan to also do the integrated cumulant
- Done by Ante Bilandzic of ALICE
- Navneet used Year4, Dhevan Year7
- I convinced Dhevan to also do Year4

Flow analysis with cumulants: direct calculations

Ante Bilandzic,[1,2] Raimond Snellings,[2] and Sergei Voloshin[3]

[1] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[2] *Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*
[3] *Wayne State University, 666 W. Hancock Street, Detroit, MI 48201, USA*
(Dated: October 18, 2011)

$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

$$\langle\langle e^{i2(\varphi_1 - \varphi_2)}\rangle\rangle = \langle\langle e^{i2(\varphi_1 - \Psi_{RP} - (\varphi_2 - \Psi_{RP}))}\rangle\rangle$$

$$= \langle\langle e^{i2(\varphi_1 - \Psi_{RP})}\rangle\langle e^{-i2(\varphi_2 - \Psi_{RP})}\rangle + \delta_2\rangle,$$

$$= \langle v_2^2 + \delta_2\rangle,$$

$$c_2\{2\} \equiv \left\langle\left\langle e^{i2(\varphi_1 - \varphi_2)}\right\rangle\right\rangle = \left\langle v_2^2 + \delta_2\right\rangle .$$

$$c_2\{4\} \equiv \left\langle\left\langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{i2(\varphi_1 - \varphi_2)}\right\rangle\right\rangle^2,$$

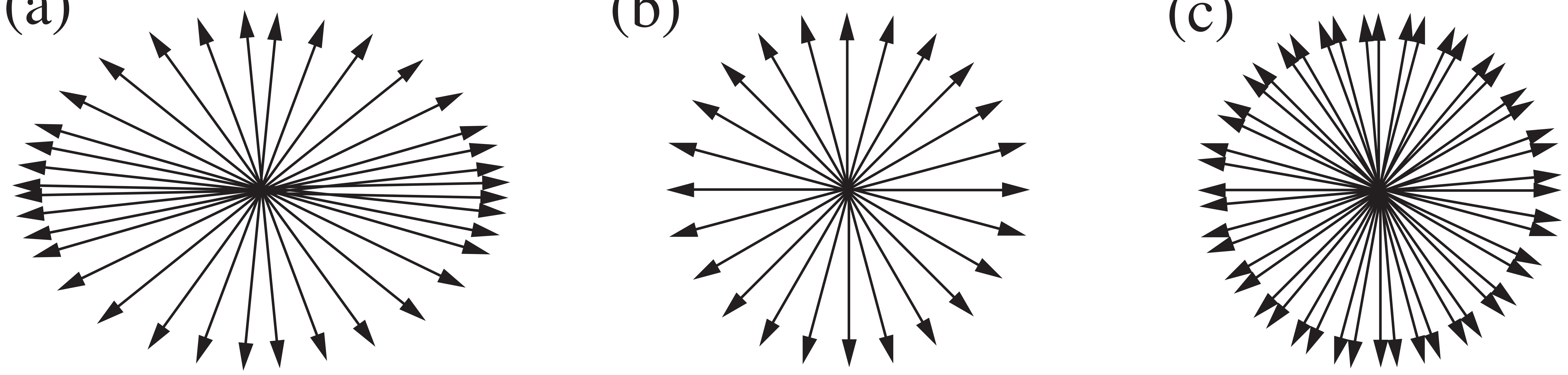
$$= \left\langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2\right\rangle - 2\left\langle v_2^2 + \delta_2\right\rangle^2,$$

$$= \left\langle -v_2^4 + \delta_4\right\rangle .$$

Non flow $\delta_2 \propto 1/M_c \quad \delta_4 \propto 1/M_c^3$

$v_2 = 0 \quad v_2\{2\} = 0 \qquad v_2 = 0 \quad v_2\{2\} \neq 0$

(a) (b) (c)



Fluctuations

$$\langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma^2$$

if $\sigma \ll \langle v \rangle$ then

$$v_2\{2\} = \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

$$v_2\{4\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

$$v_2\{6\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}.$$

Art
QM 2008
Jaipur

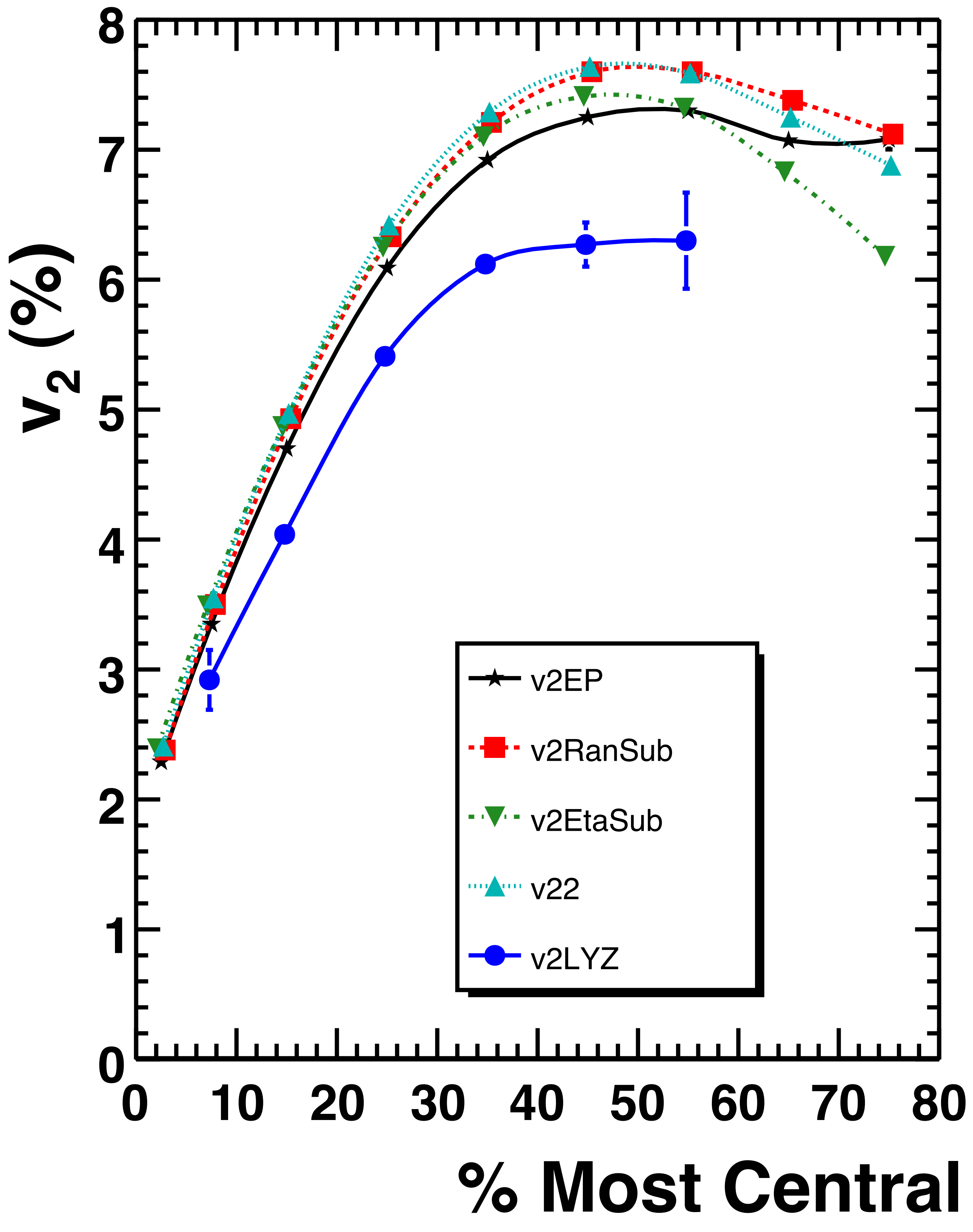


Figure 1: (Color online) The values of v_2 from various analysis methods vs centrality. Both the upper lines [3] and the lower line [12] are STAR data.

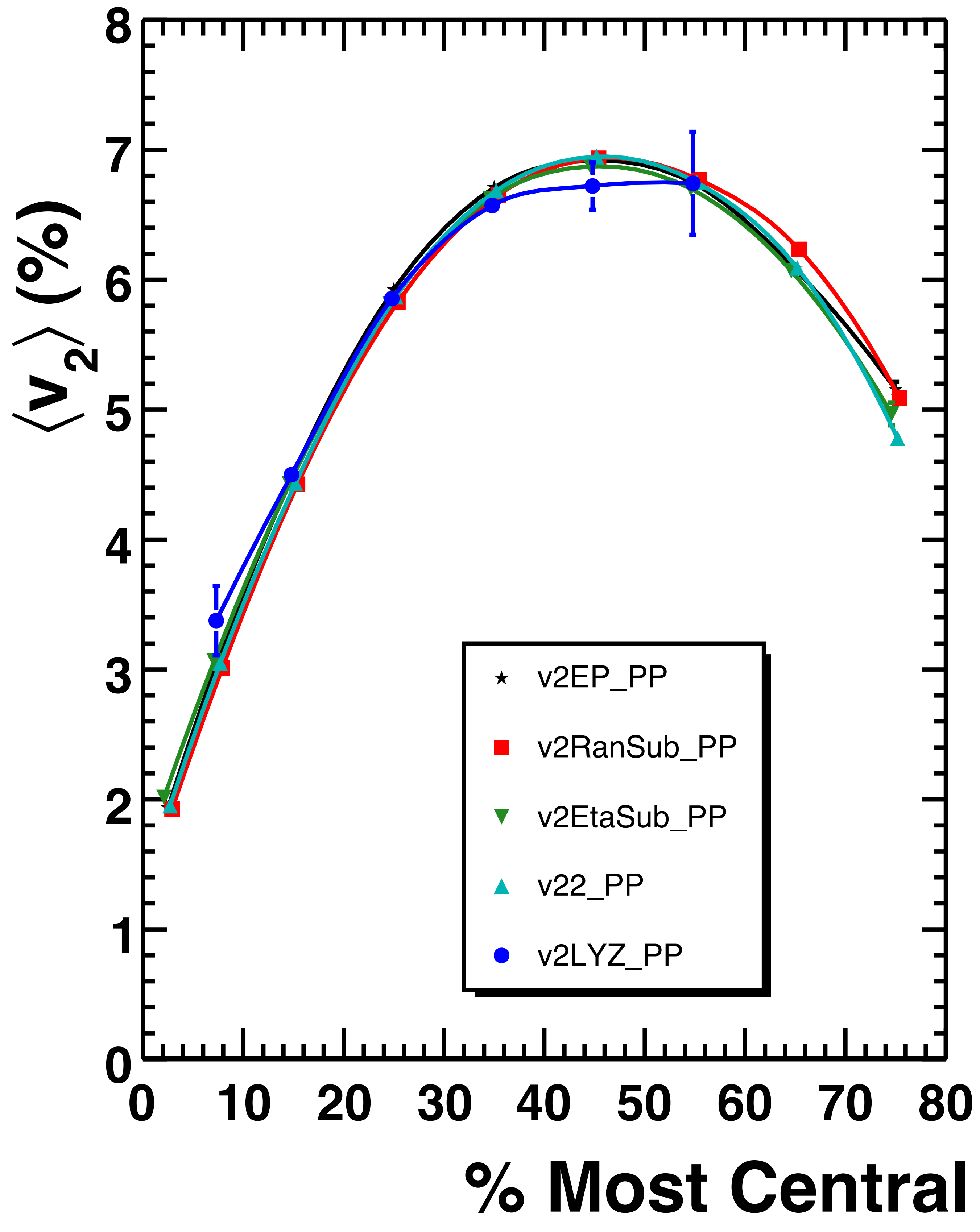


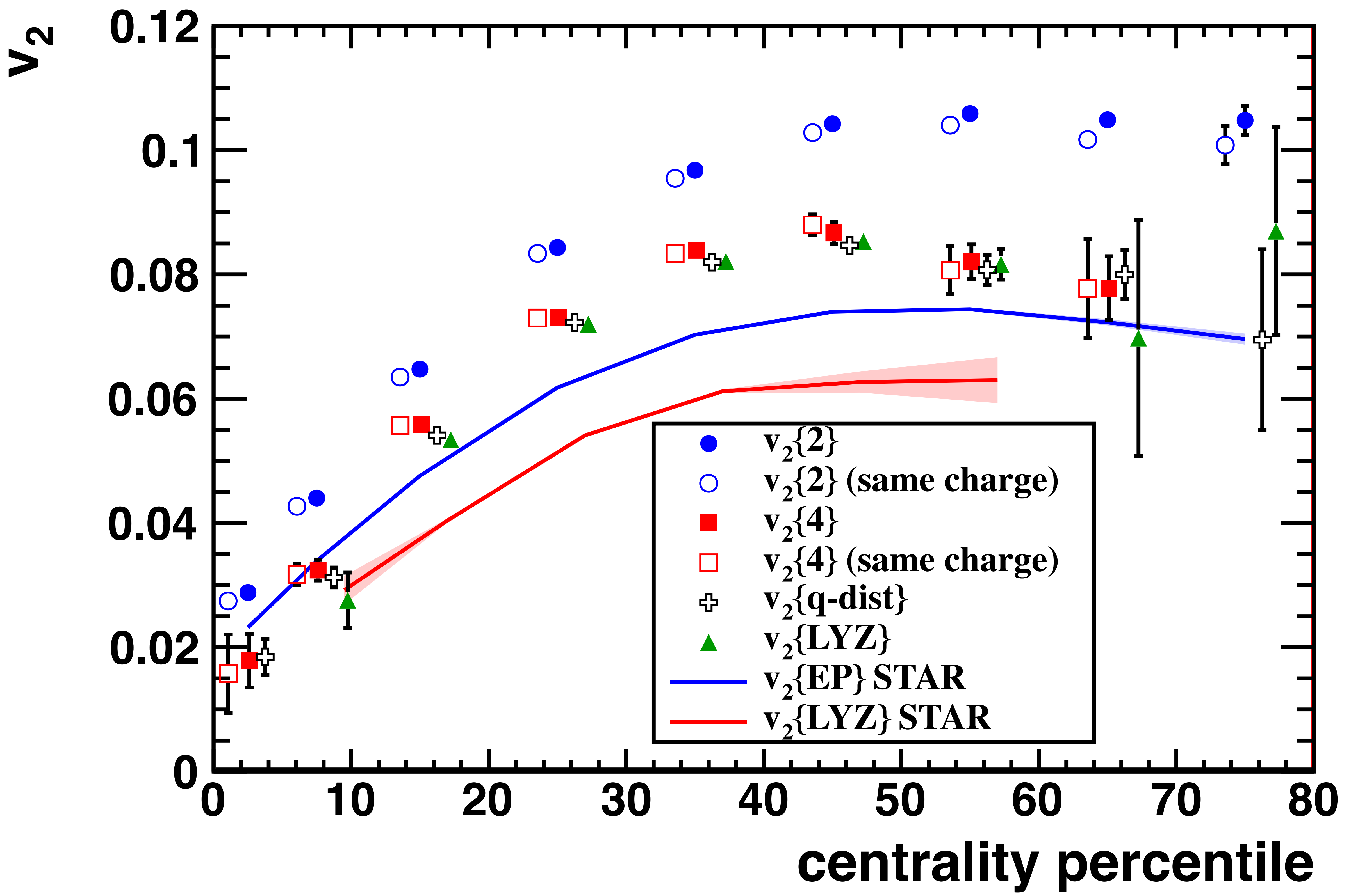
Figure 2: (Color online) The data from Fig. 1 corrected to $\langle v_2 \rangle$ in the participant plane.

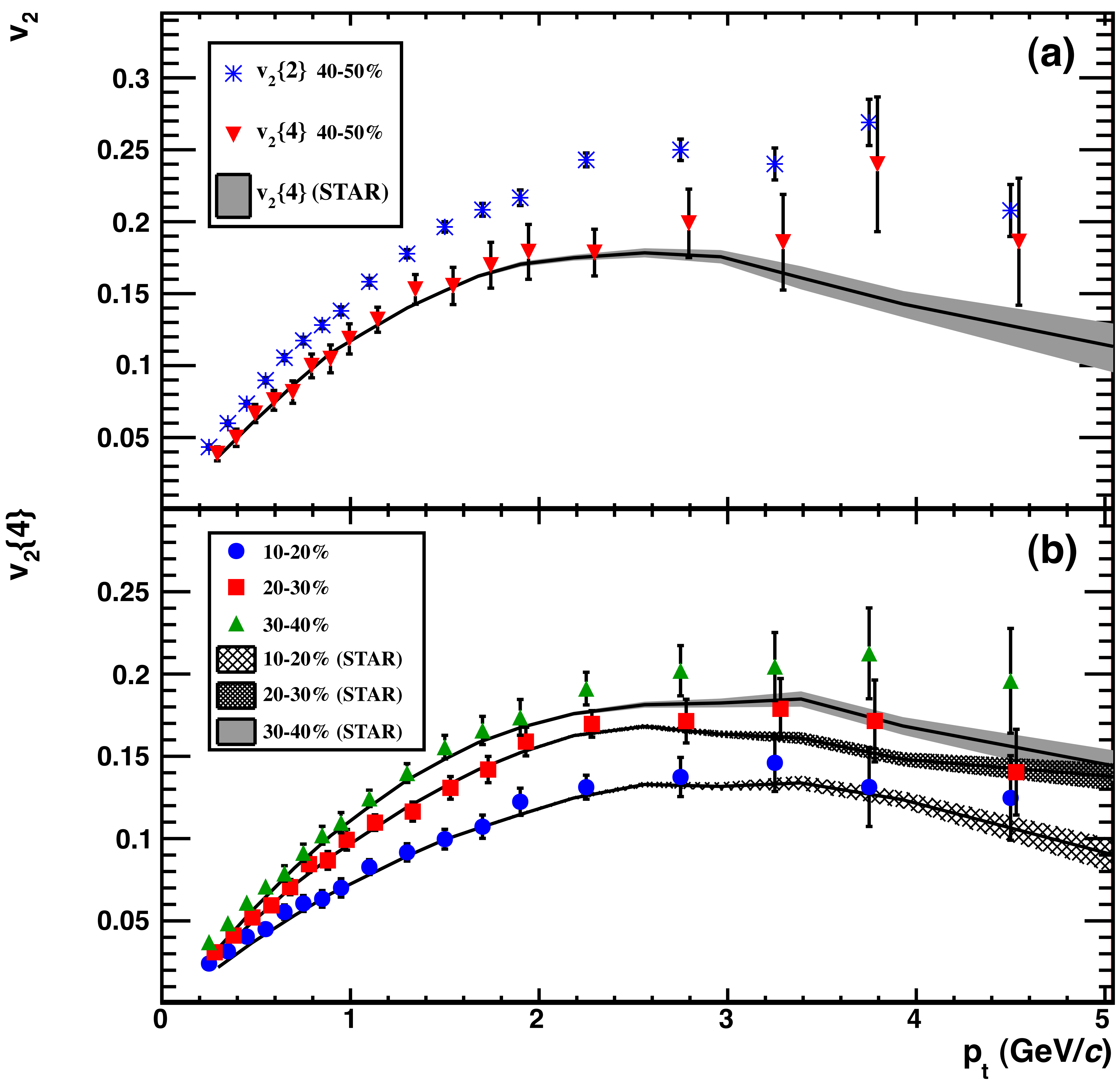
Elliptic flow of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

de M. Michel Nostradamus

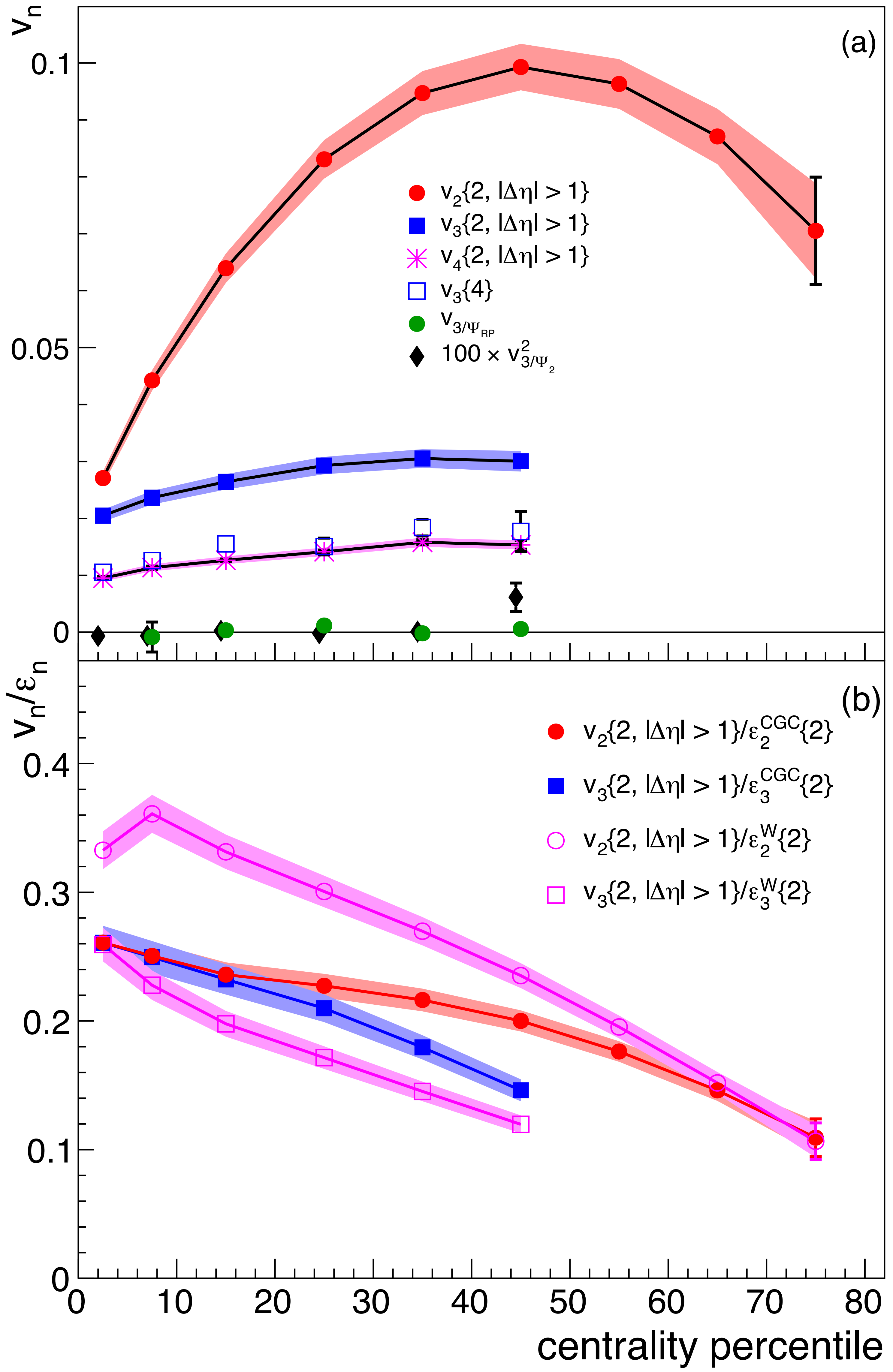
We report the first measurement of charged particle elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}}=$ 2.76 TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.25 < p_t < 5$ GeV/c. The elliptic flow signal, v_2, averaged over transverse momentum and pseudorapidity, reaches values of 0.085 for relatively peripheral collisions (40–50% most central). The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.25 around $p_t = 3$ GeV/c. Compared to RHIC Au+Au collisions at $\sqrt{s_{NN}}=$ 200 GeV, the elliptic flow increases by about 15% in agreement with expectations based on the observed trend at lower energies.

PACS numbers: 25.75.Ld, 25.75.Gz, 05.70.Fh

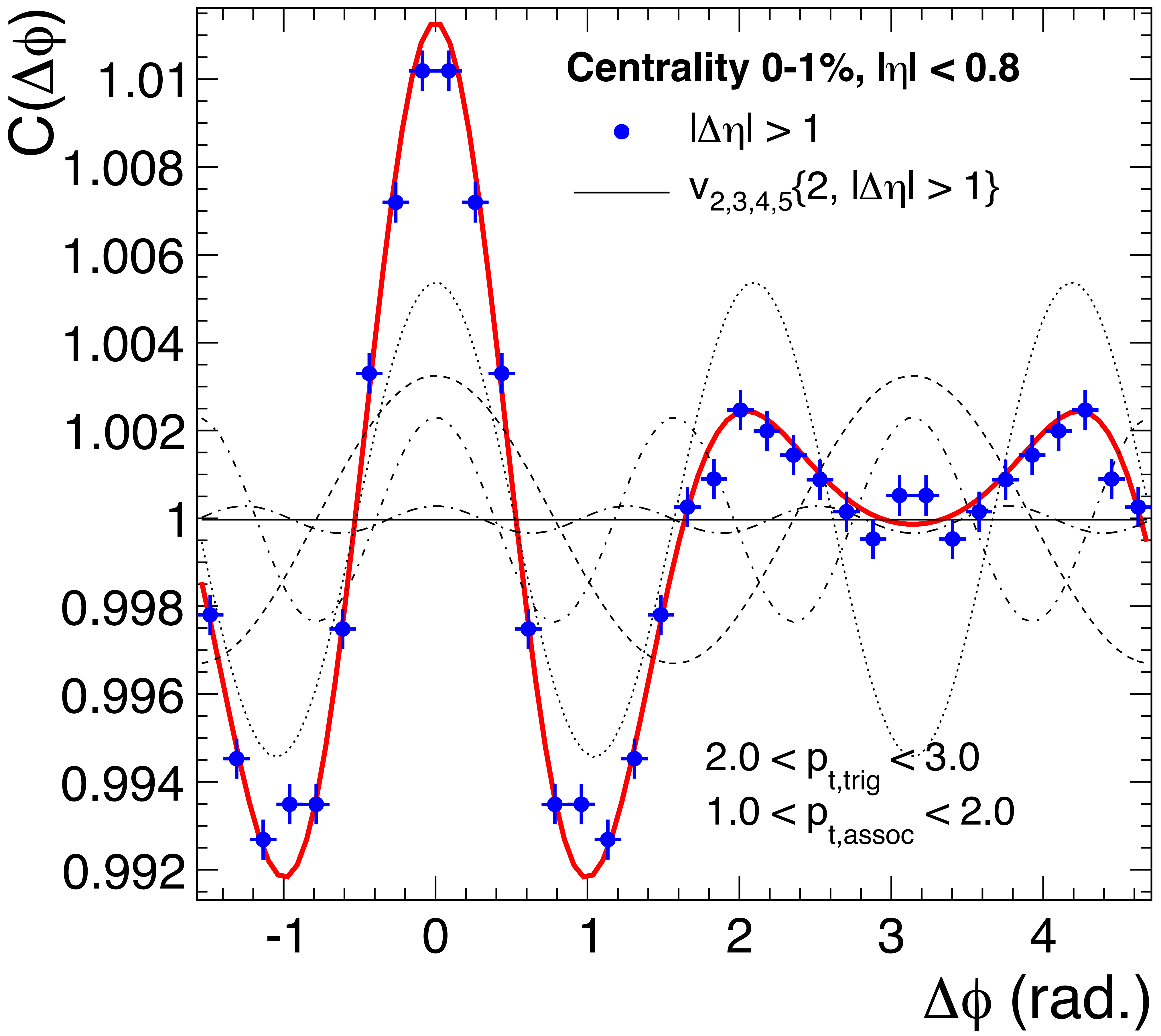

v2
0.12
0.1
0.08
0.06
0.04
0.02
0
0
10
20
30
40
50
60
70
80
centrality percentile
v2{2}
v2{2} (same charge)
v2{4}
v2{4} (same charge)
v2{q-dist}
v2{LYZ}
v2{EP} STAR
v2{LYZ} STAR


v2
(a)
v2{2} 40-50%
v2{4} 40-50%
v2{4} (STAR)
0.3
0.25
0.2
0.15
0.1
0.05
v2{4}
(b)
10-20%
20-30%
30-40%
10-20% (STAR)
20-30% (STAR)
30-40% (STAR)
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
pt (GeV/c)

ALICE (2011)

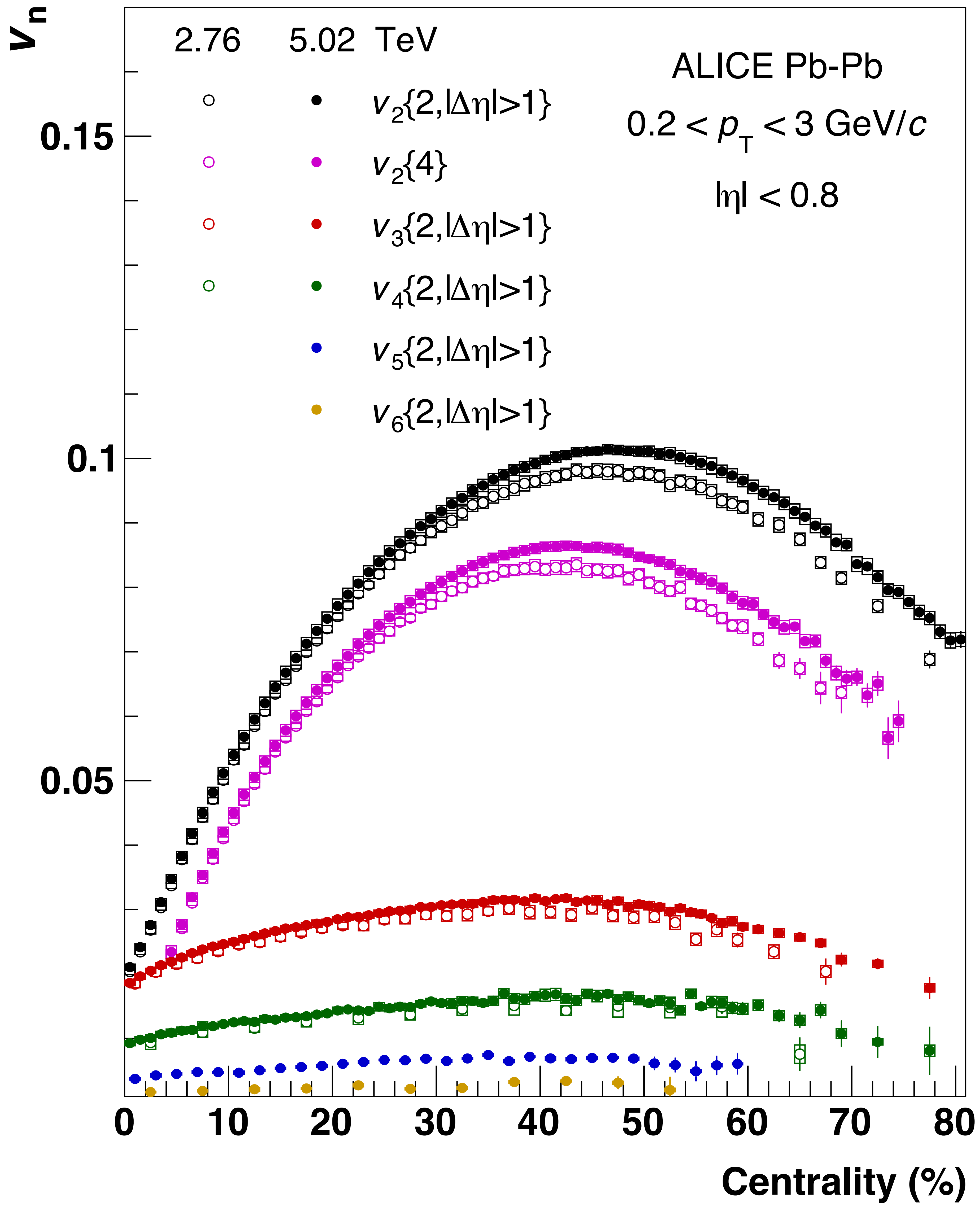


No shock waves - convincing measurement of the higher harmonics non-Glauber initial conditions



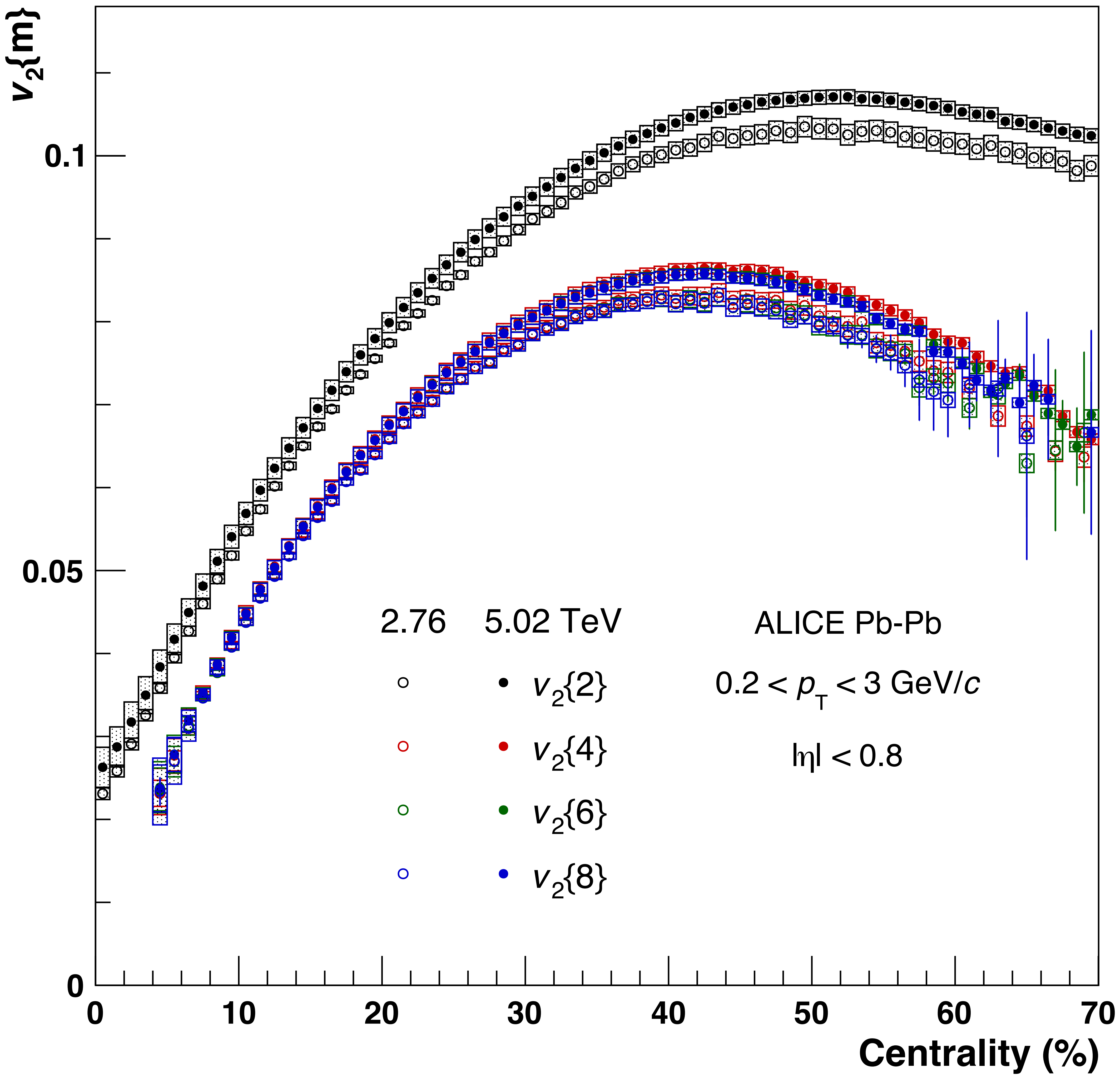
ALICE Collaboration: Phys. Rev. Lett. 107 (2011) 032301

Fluctuations and initial conditions



- Experimentally we can use within one experiment detailed measurements of the cumulants to constrain the p.d.f. of the v_n and with that help constrain the initial spatial distributions

ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103



The different estimates of v_2 are sensitive to the moments of the v_2 distribution, if $v_2\{4\}=v_2\{6\}=v_2\{8\}$ the distribution is a Bessel-Gaussian p.d.f.

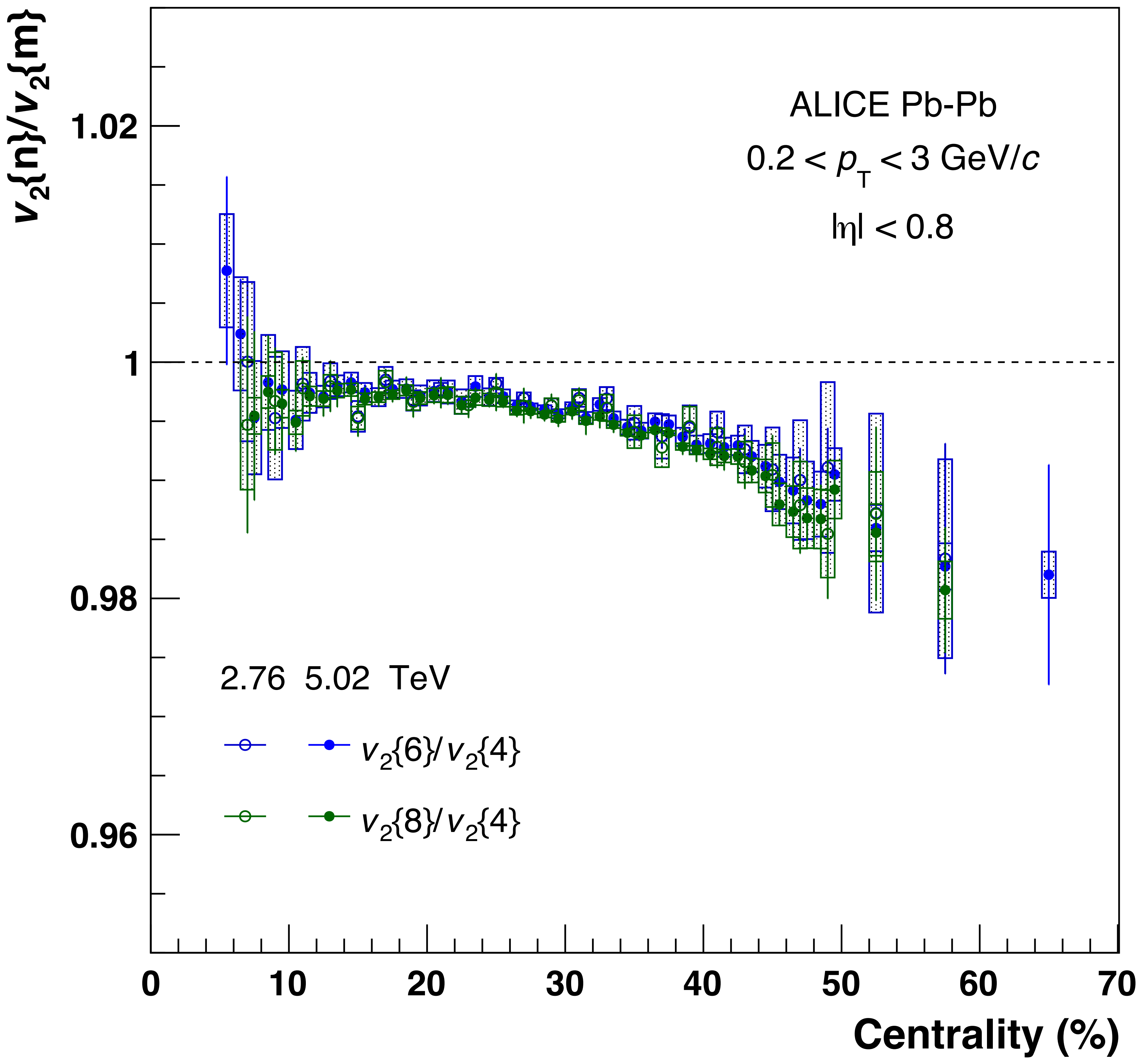
$$v_2\{2\} = \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

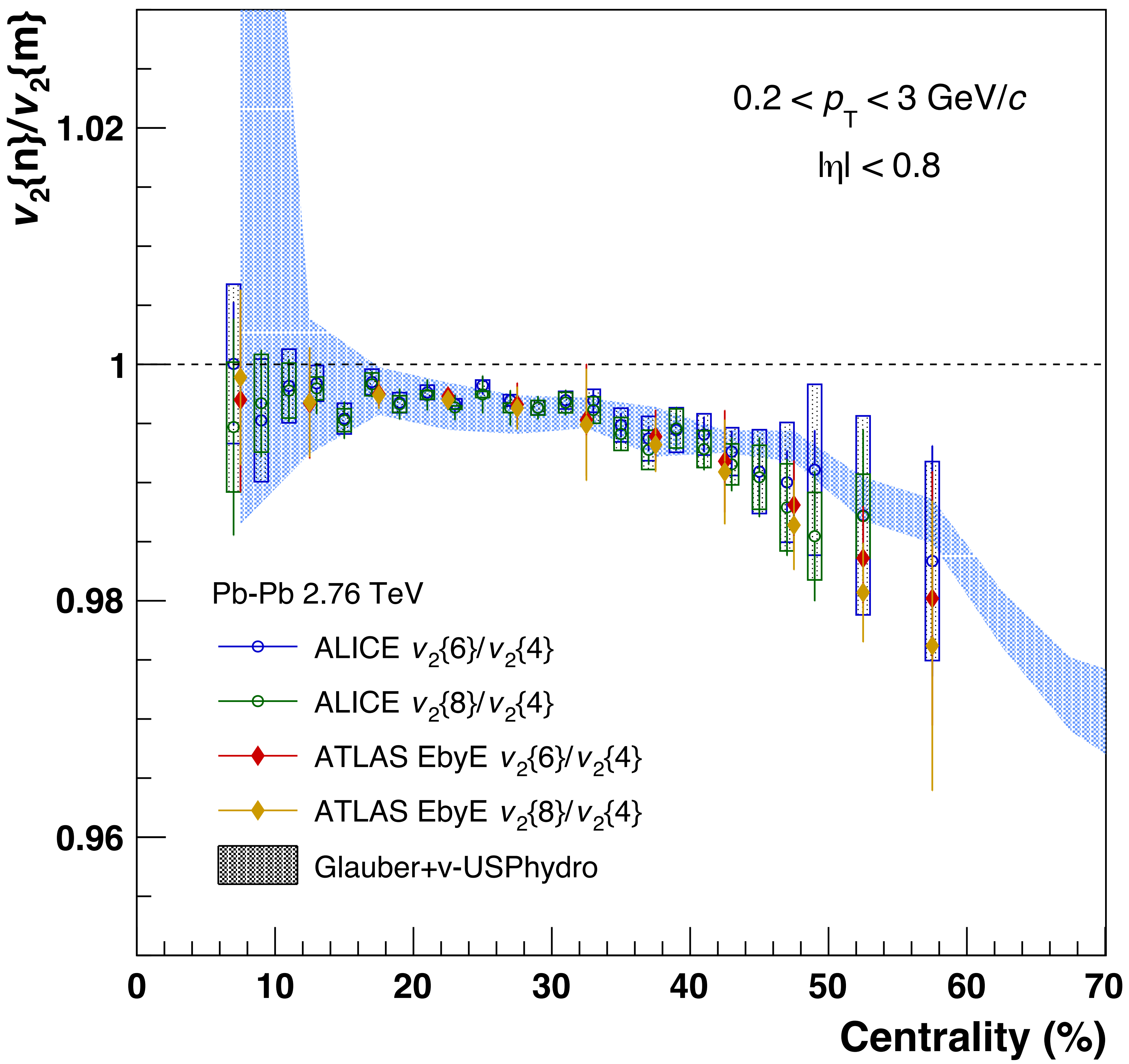
$$v_2\{4\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

$$v_2\{6\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}.$$

ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103

Fluctuations and initial conditions





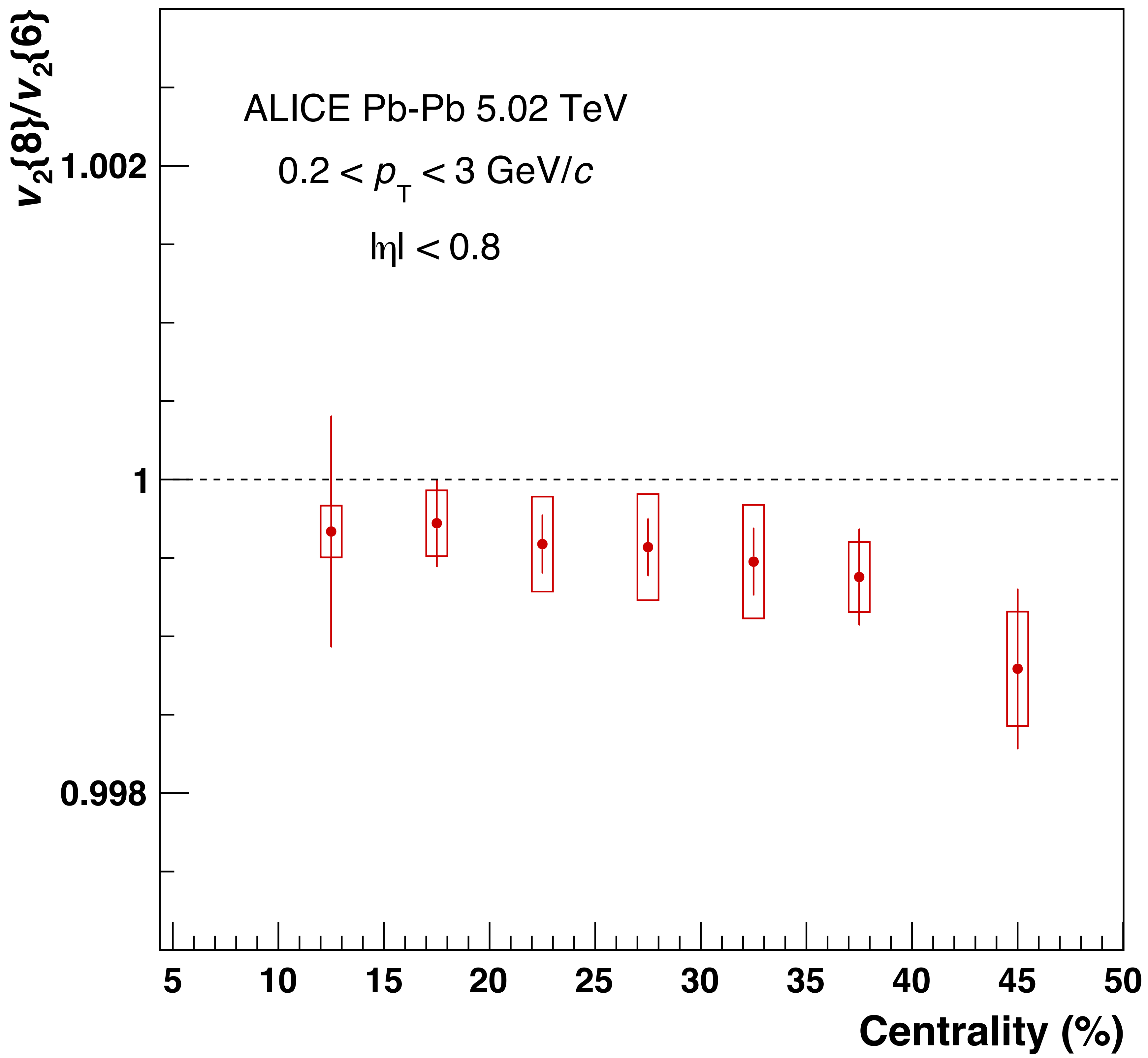
A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution

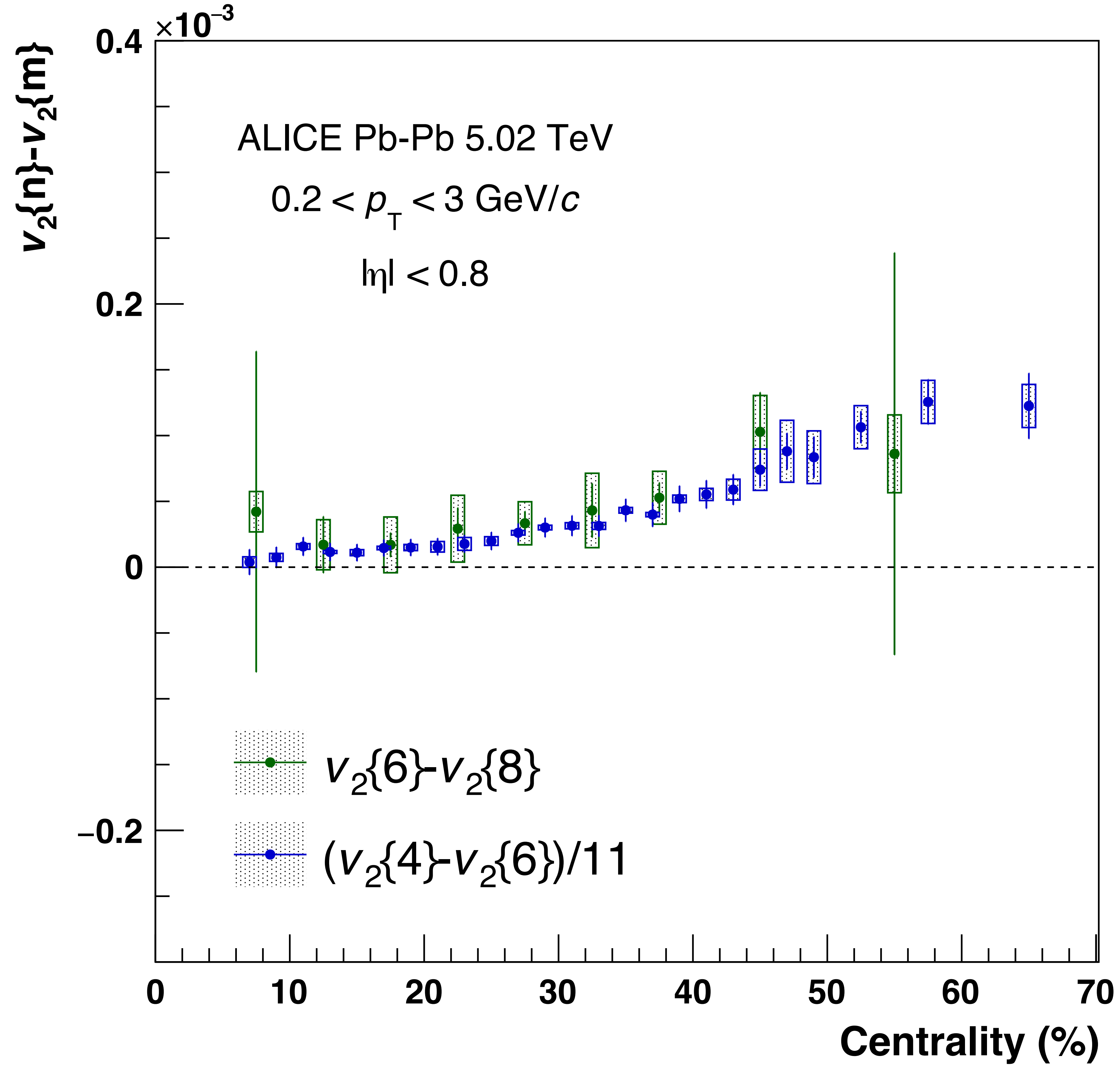
The splitting does not depend on the p_t range used and collision energy

The results agree well with model calculations as well as with ATLAS results based on a different technique

ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103

Fluctuations and initial conditions





A fine splitting is observed between $v_2\{8\}$ and $v_2\{6\}$

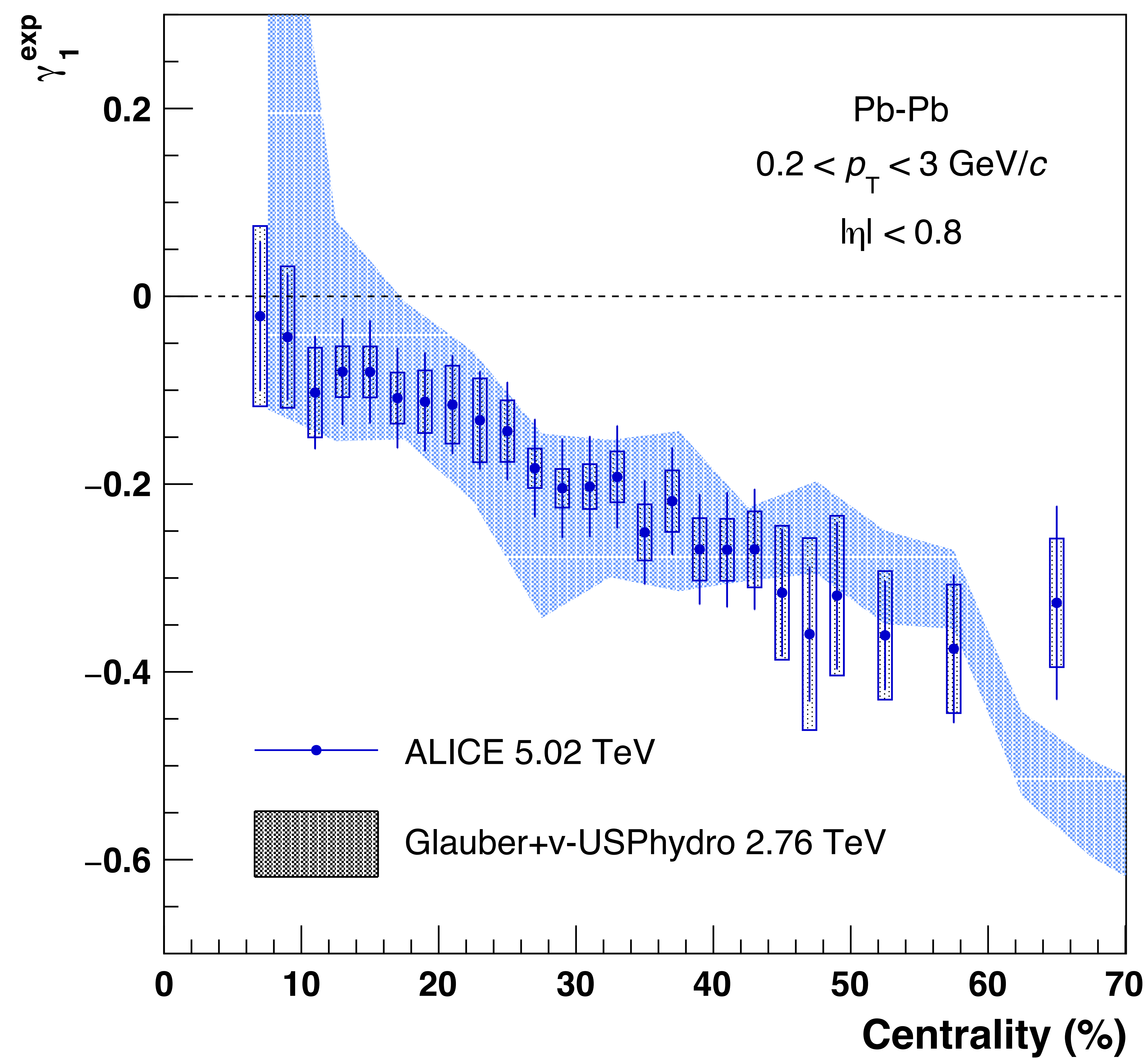
Can be contributed to the skewness of the p.d.f.

Higher order contributions are constrained in the equality

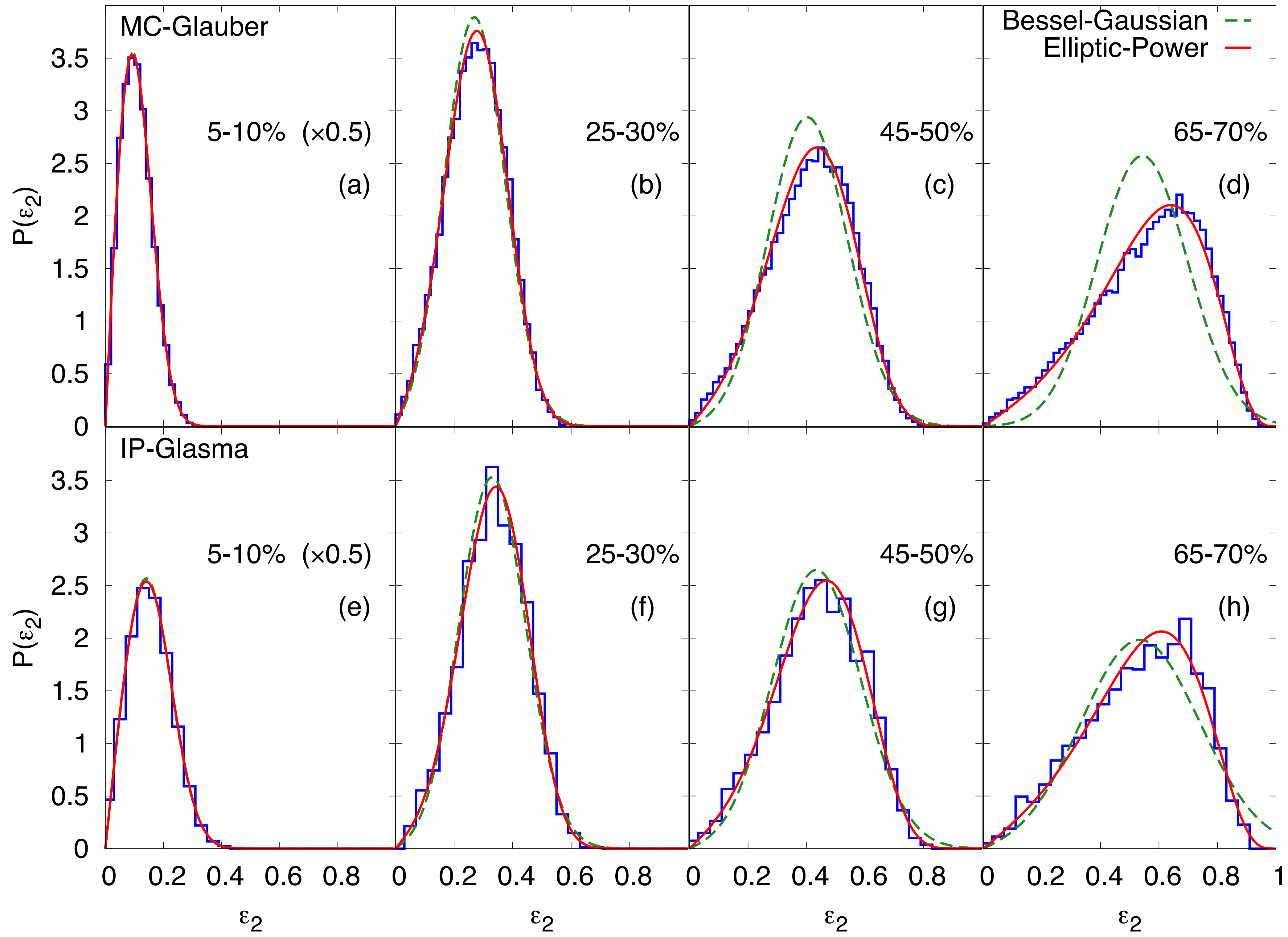
$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\}).$$

ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103

$$\gamma_1^{\mathrm{exp}} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}.$$



Li Yan, J-Y Ollitrault, A. M. Poskanzer, Phys. Rev. C 90, 024903 (2014)



- A negative skewness is observed as expected due to the constrains on ε_2 between 0-1
- The skewness agrees well with model calculations and increases towards peripheral collisions due to the constraint of 1

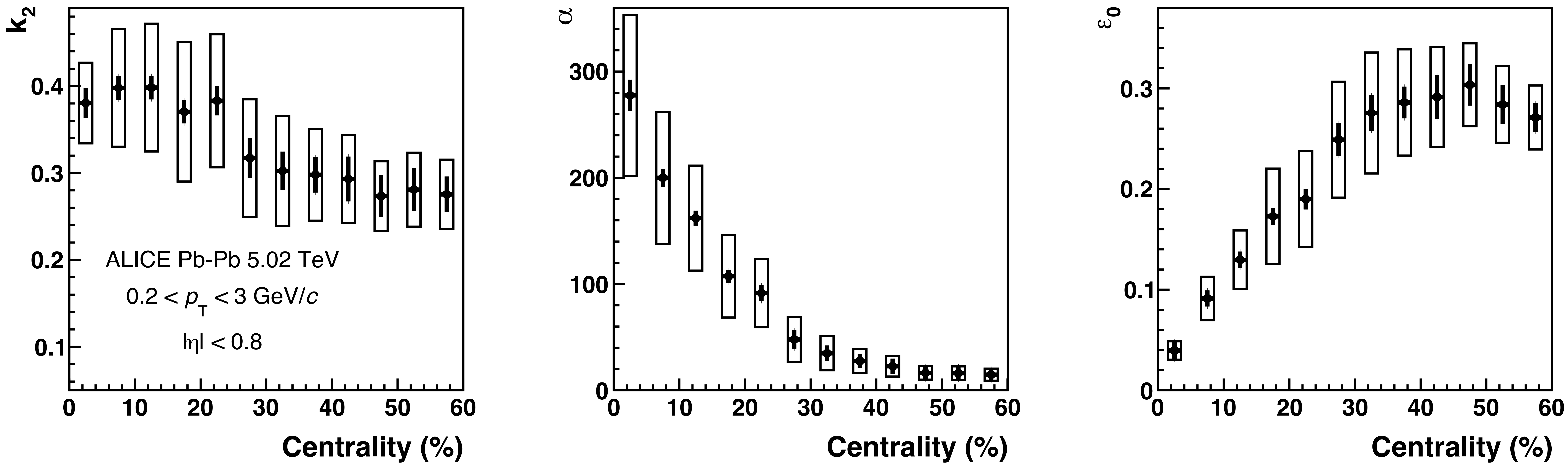
$$v_2 \propto \varepsilon_2$$

Fluctuations and initial conditions

$$v_2 \propto \varepsilon_2$$

Li Yan, J-Y Ollitrault, A. M. Poskanzer, Phys. Rev. C 90, 024903 (2014)

$$P(\varepsilon_2) = \frac{1}{k_2} 2\alpha\, \varepsilon_2 (1-\varepsilon_2^2)^{\alpha-1} (1-\varepsilon_0^2)^{\alpha+1/2} \frac{1}{\pi} \int_0^{\pi} (1-\varepsilon_2 \varepsilon_0 \cos\varphi)^{-2\alpha-1} d\varphi,$$



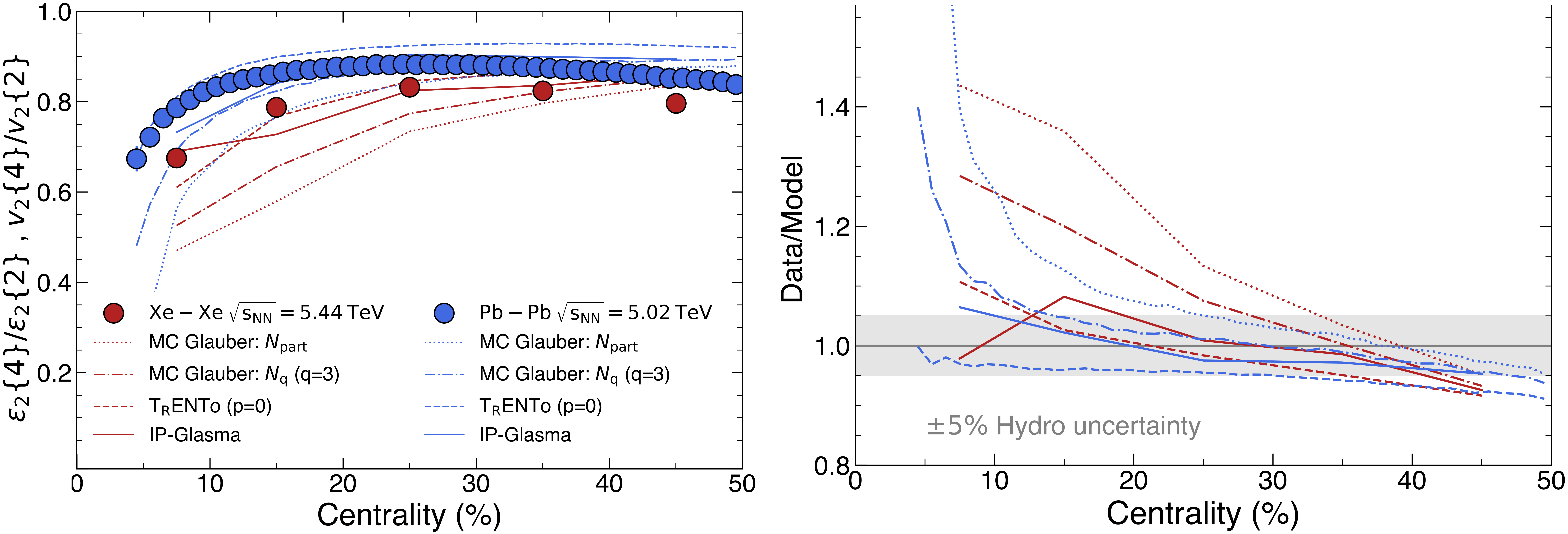
The elliptic power distribution can be used to describe the underlying p.d.f. of ε_2

The parameter α qualifies the magnitude of the flow fluctuations, ε_0 the mean eccentricity in the reaction plane and k_2 the proportionality between ε_2 and v_2; $v_2 = k_2\, \varepsilon_2$

ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103

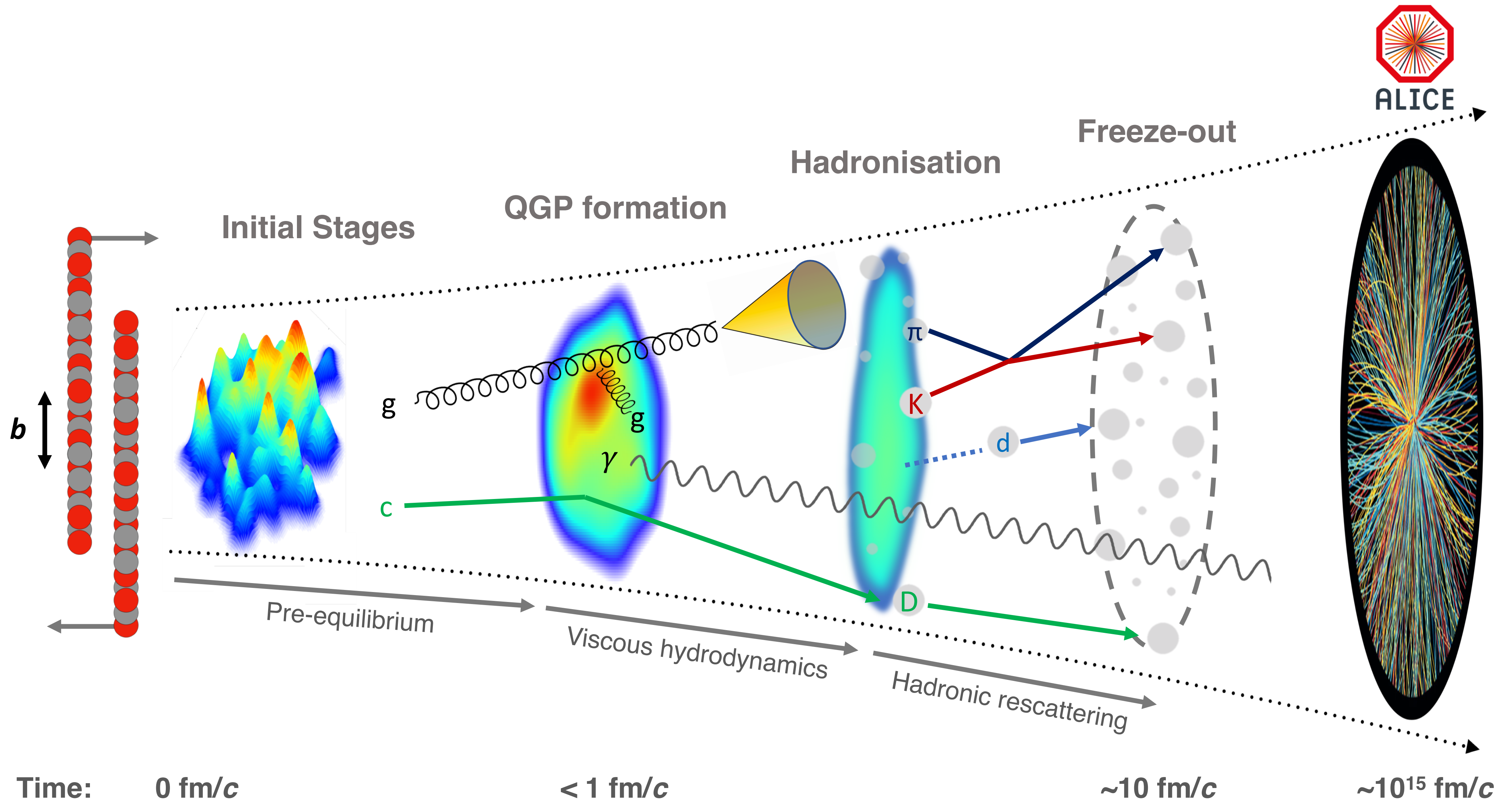
Fluctuations and initial conditions

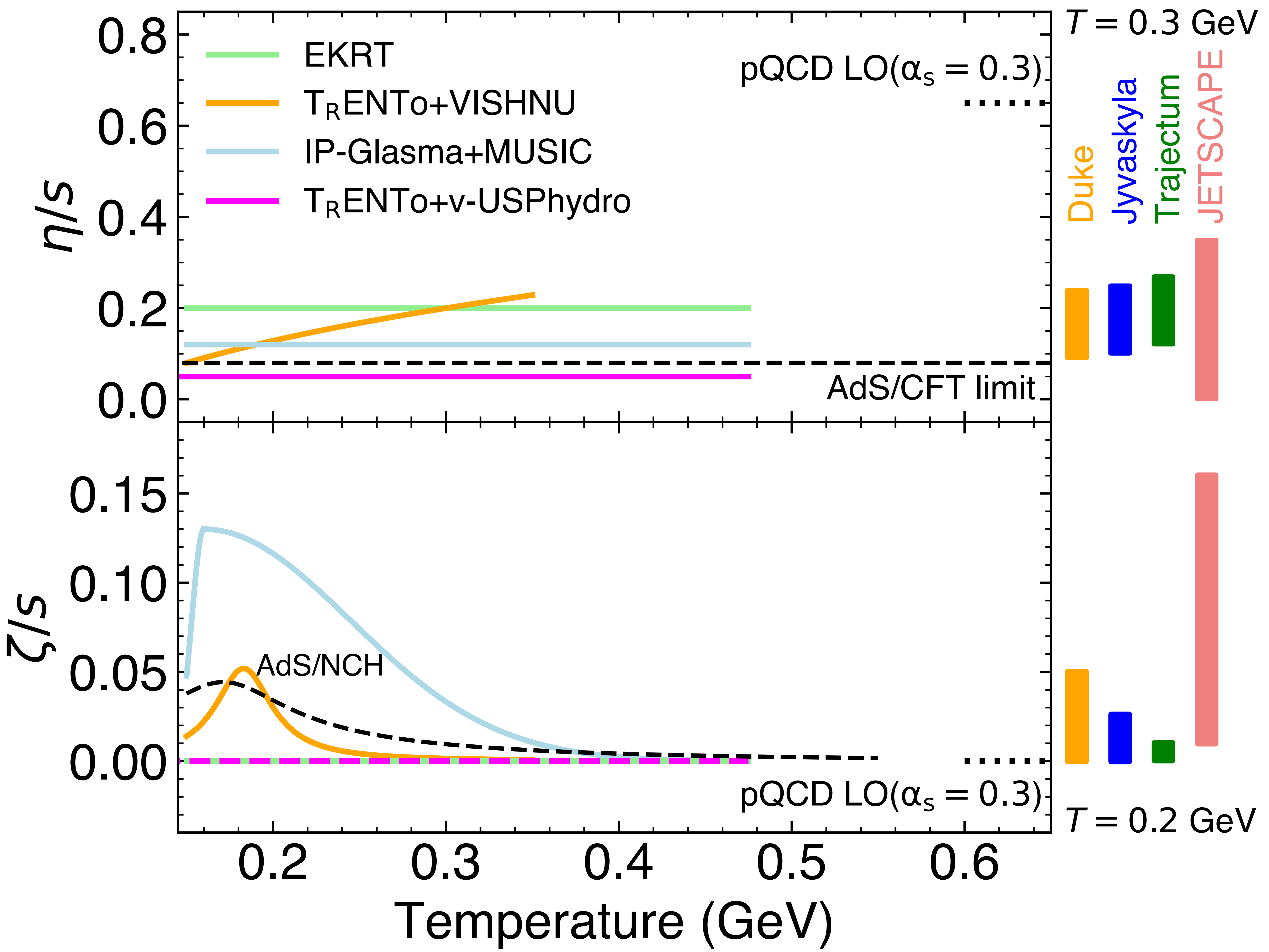
$v_2\{2\} \propto \varepsilon\{2\}$ $v_2\{4\} \propto \varepsilon\{4\}$



TRENTO (p=0) and IP-Glasma initial conditions describe measurements best

Transport parameters

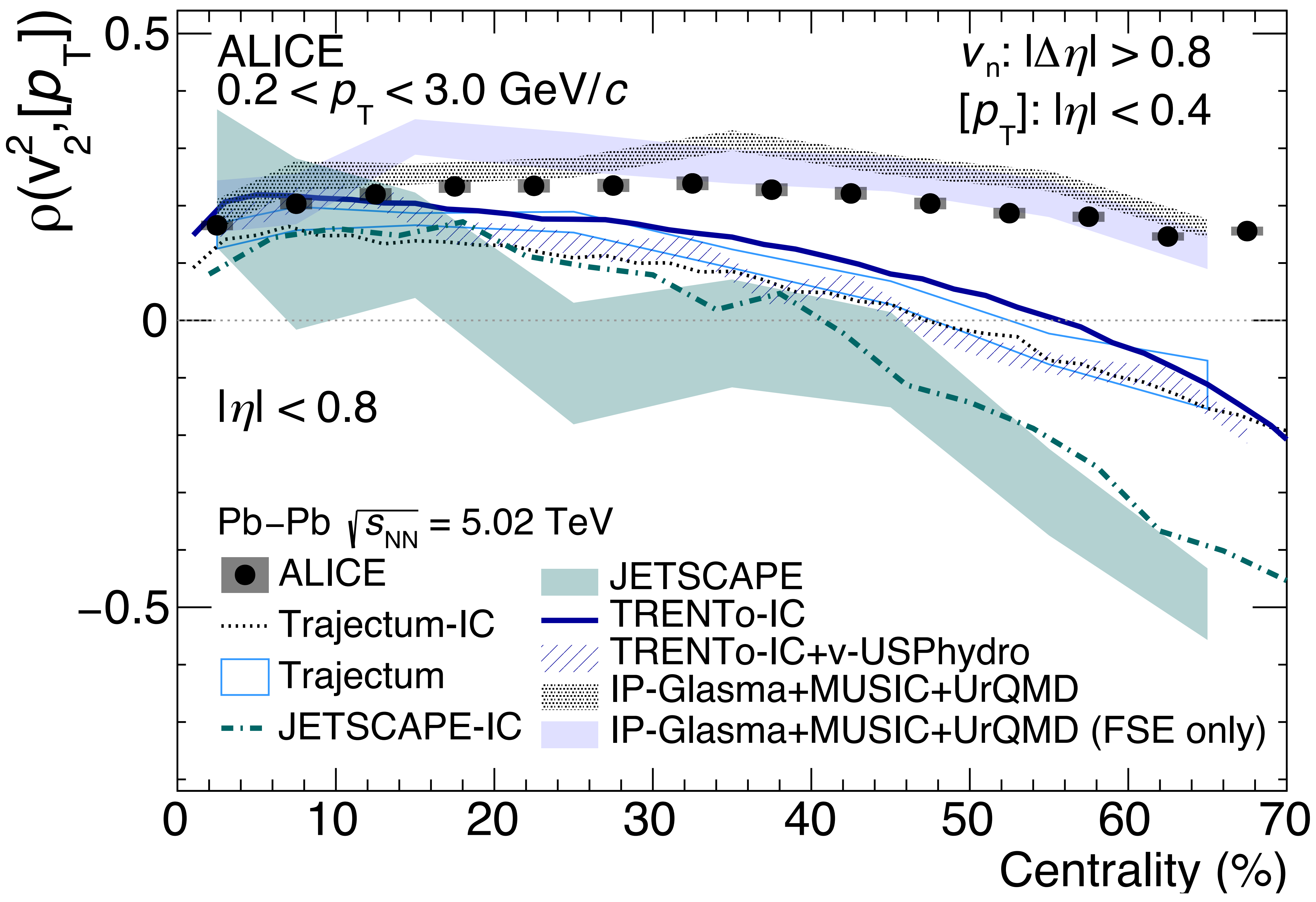


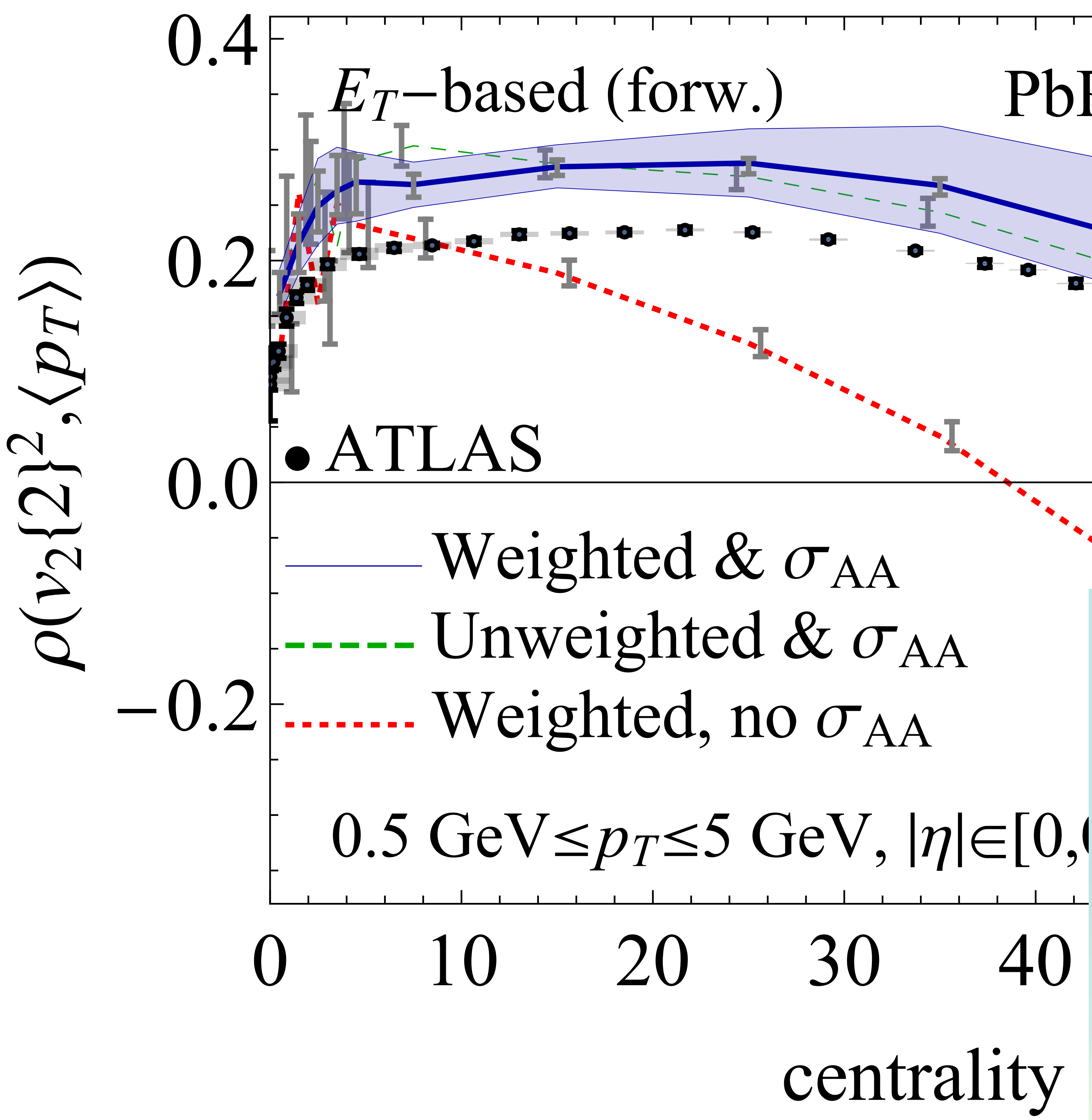


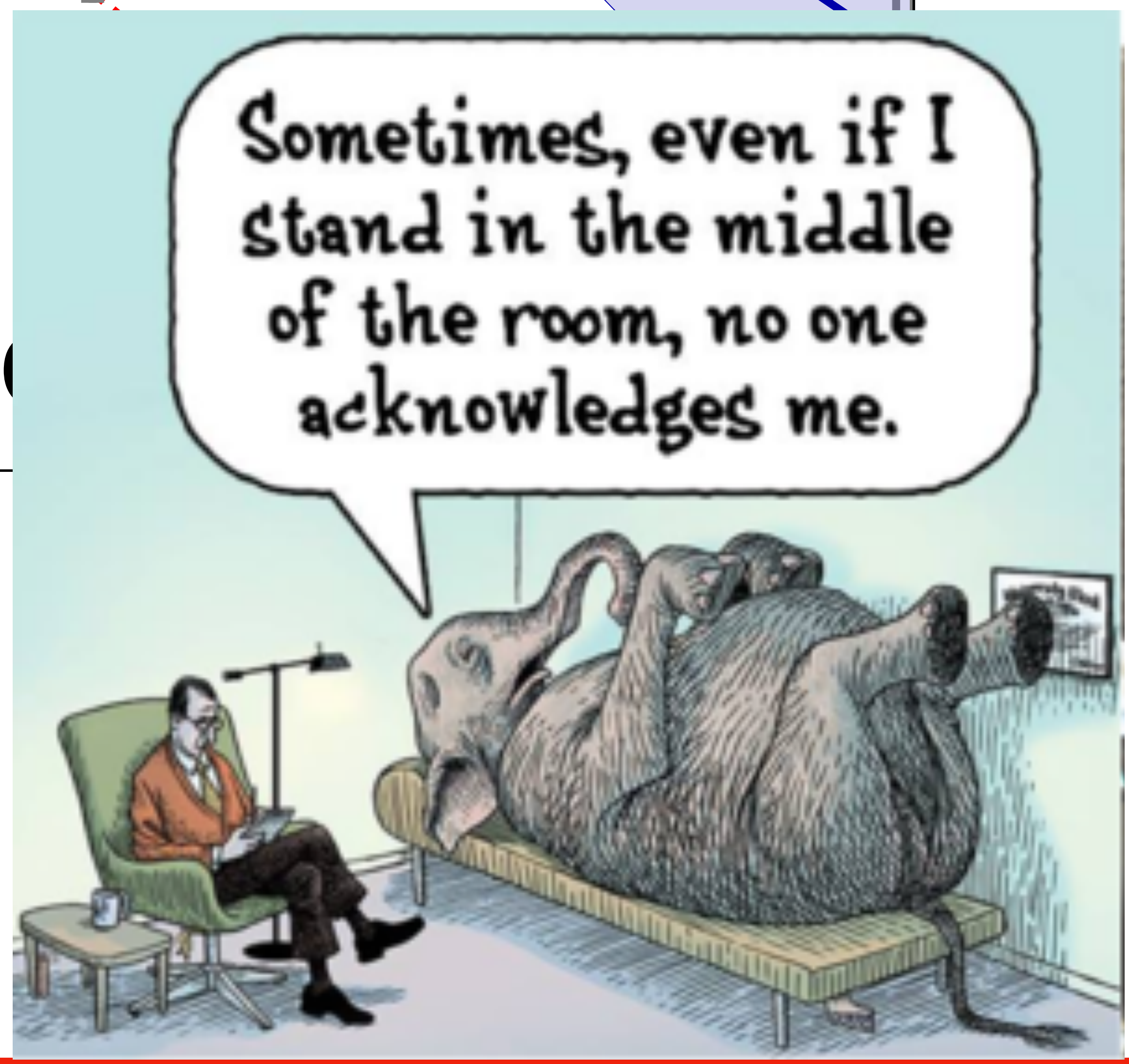
- Hybrid model description of heavy-ion collisions can be constrained and tested
- Currently only limited number of observables used
- Inclusion more observables will likely also effects extraction of transport parameters

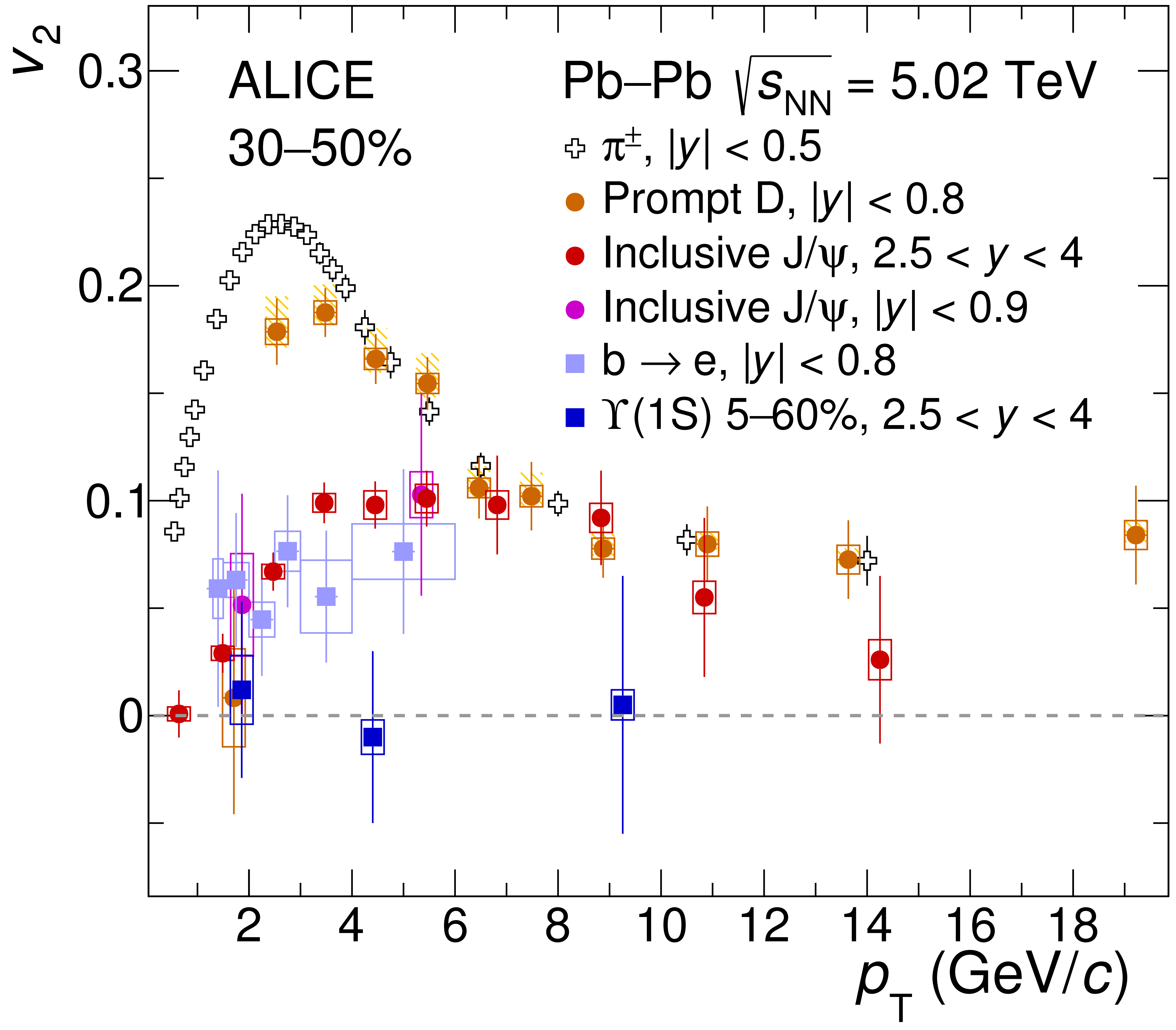
Global Bayesian Analysis

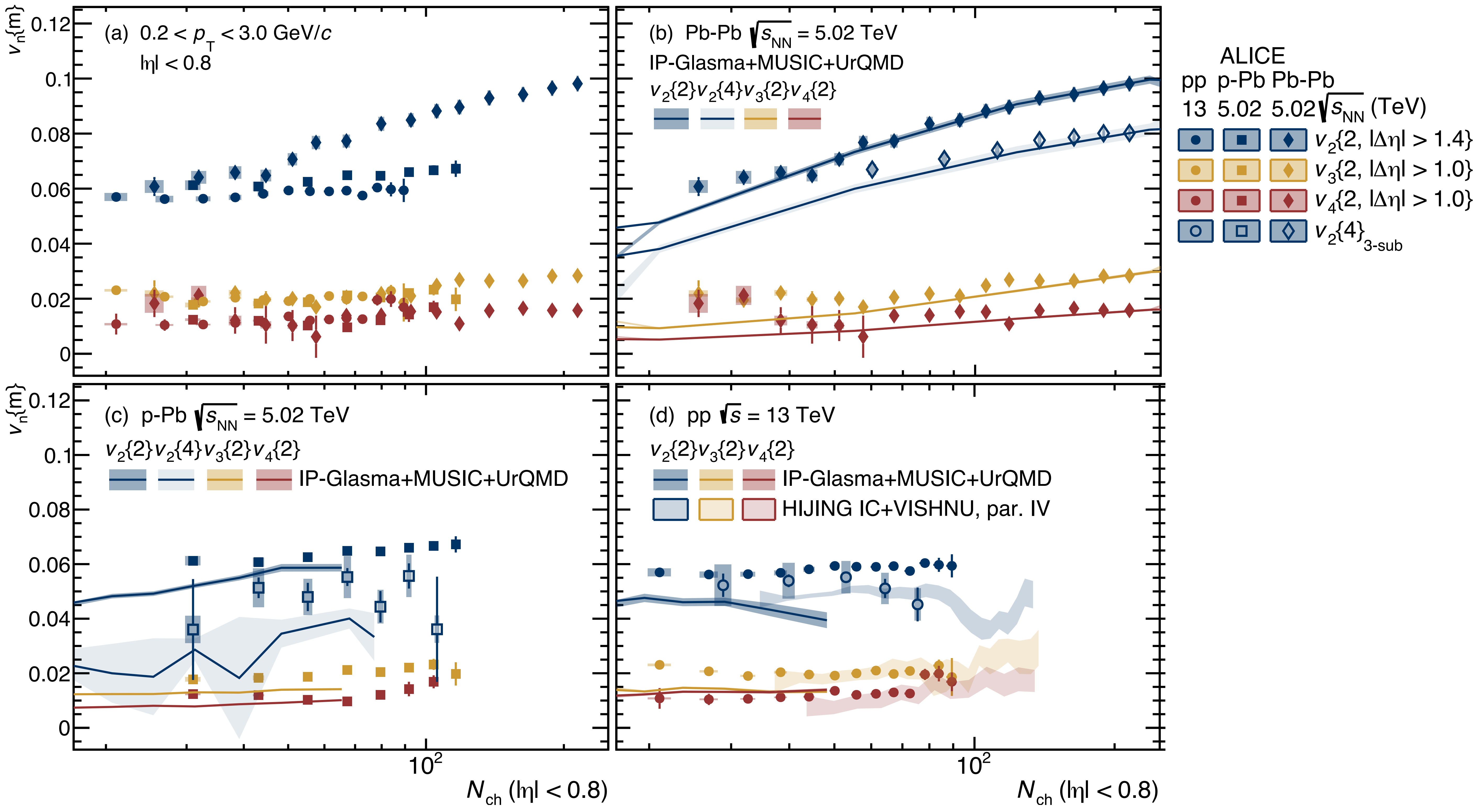
See updates in Govert Nijs and Wilke van der Schee
arXiv:2206.13522





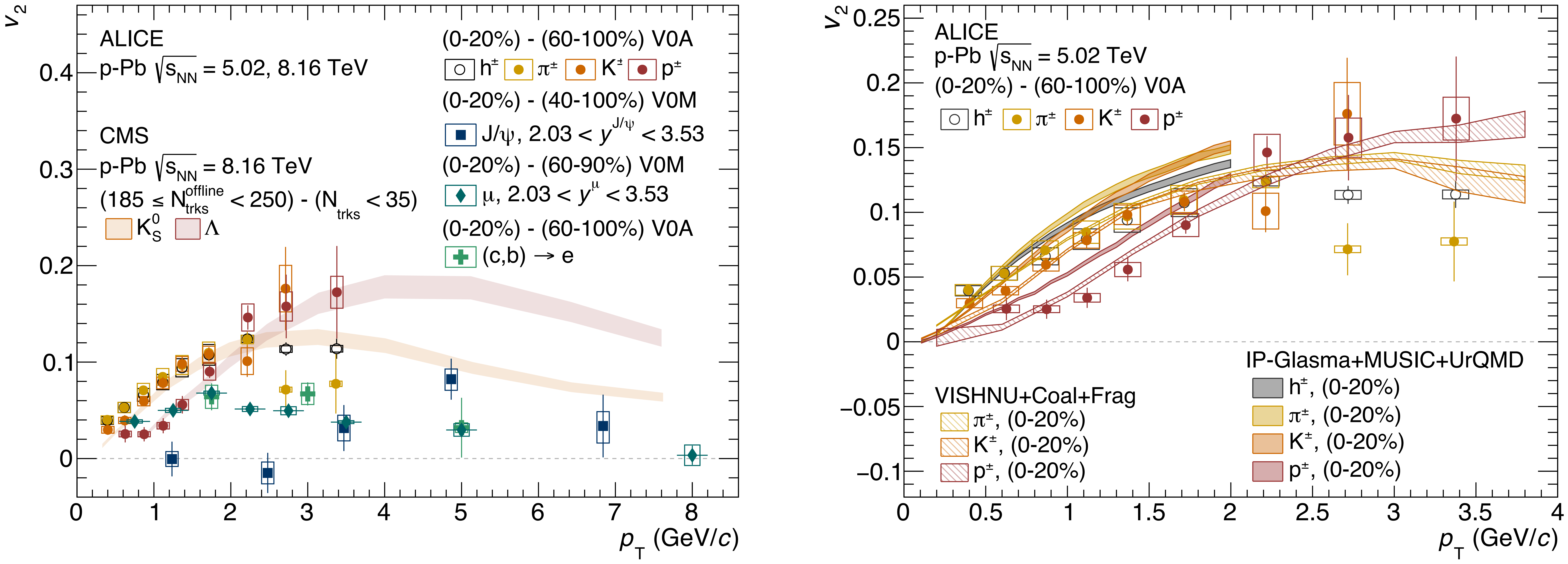






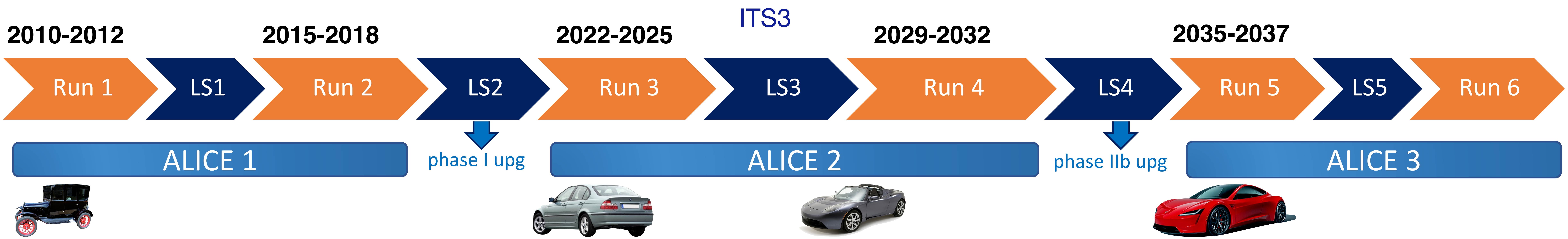
Still many open questions

The next decade(s)



Similar quality as early RHIC data, looking forward to the next decade(s) :-)

Timeline



2023 – 2025: selection of technologies, small-scale proof of concept prototypes (~25% of R&D funds)

2026 – 2027: large-scale engineered prototypes (~75% of R&D funds) ➪ Technical Design Reports

2028 – 2030: construction and testing

2031 – 2032: contingency

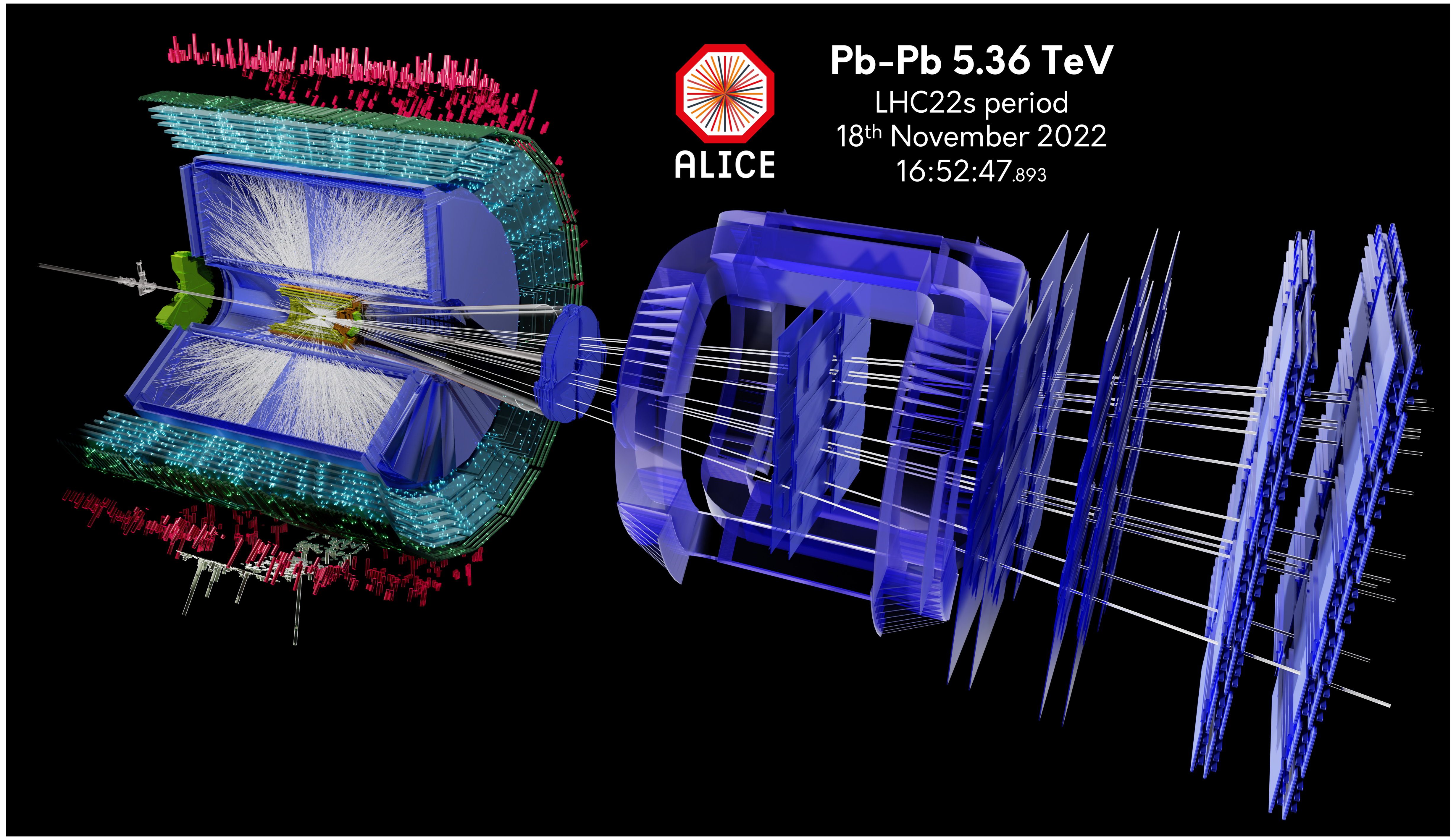
2033 – 2034: installation and commissioning

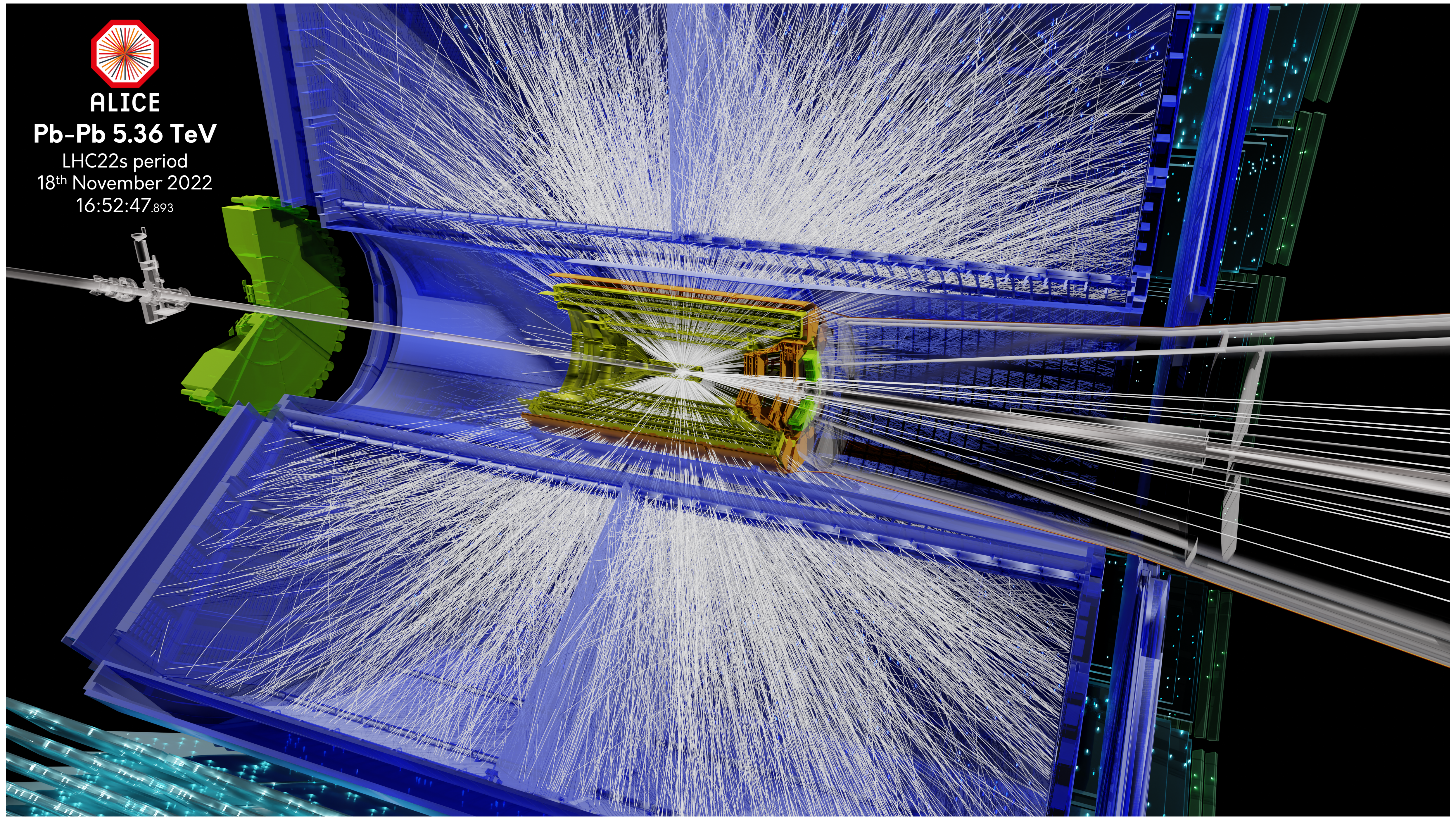
2035 – 2042: physics campaign

ITS3 LoI:

ALICE 3 LoI:

Heavy Ion Run 2022





ALICE 3 Detector

Compact ultra-light all-silicon tracker

- $\sigma_{p_T}/p_T \approx 1-2\,\%$

Large acceptance

- better statistics, correlations, rapidity dependence

Vertex detector with unprecedented pointing resolution

- $\sigma_{\mathrm{DCA}} \approx 10\mu\mathrm{m}\ (p_T = 200\ \mathrm{MeV}/c)$

Excellent electron and hadron identification (TOF + RICH)

- $\pi/K/p$ separation up to a few GeV/c
- Electron ID up to about 3 GeV/c with 10^3 pion rejection

Muon identification (Muon absorber + Muon chambers)

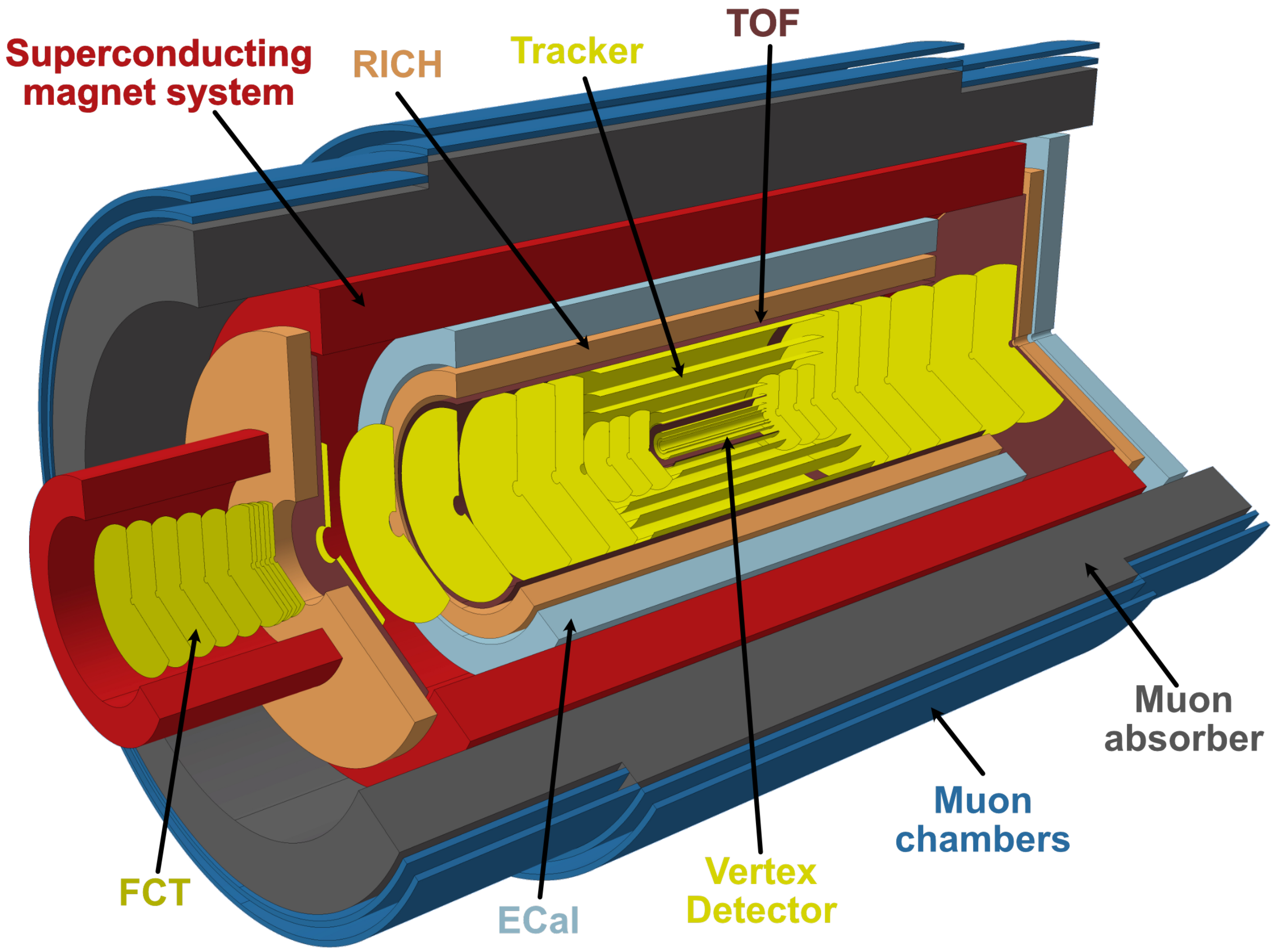
- Muon ID down to $p_T \approx 1.5\ \mathrm{GeV}/c$

ECAL

- Photons/jets over large η

Superconductor magnet system (2T)

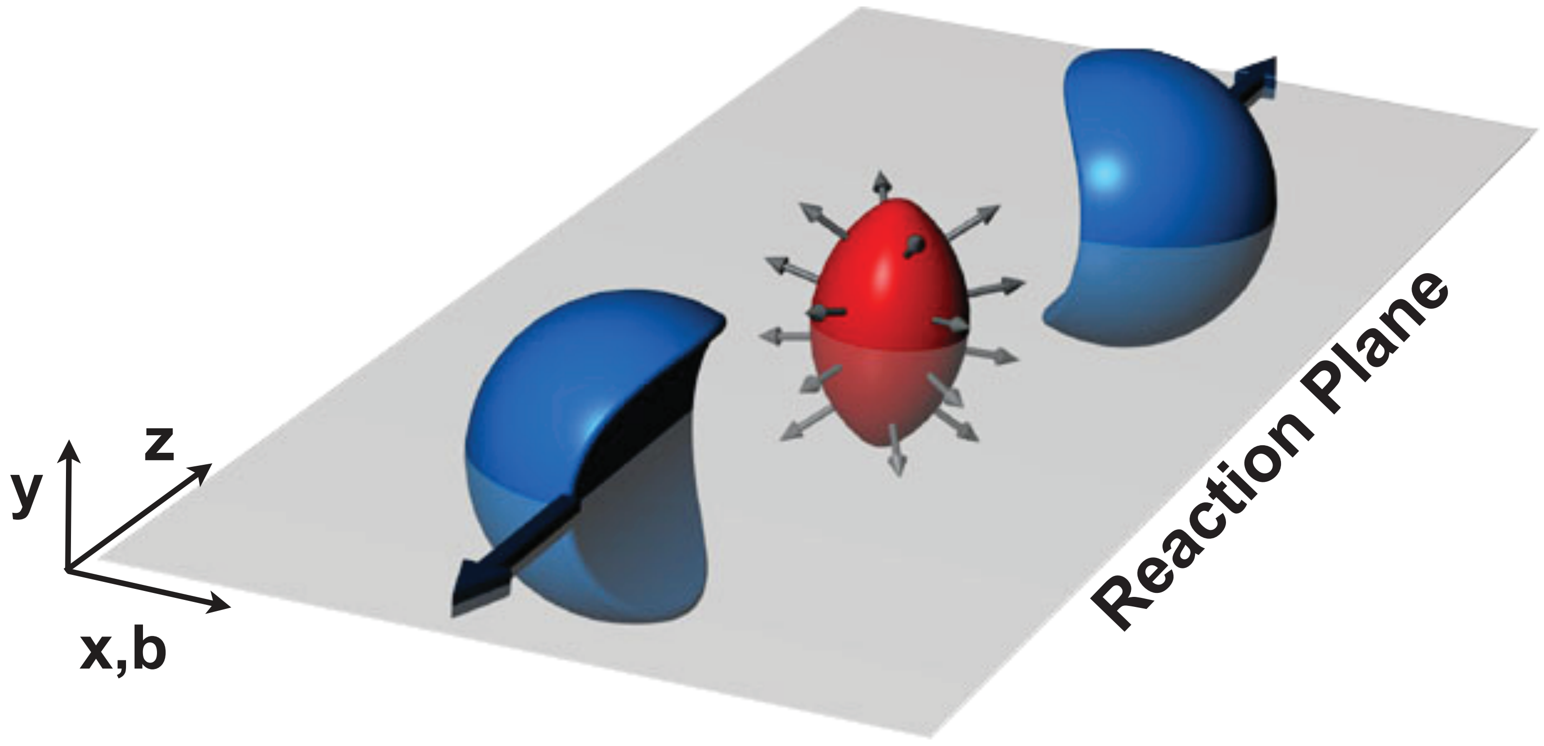
Continuous read-out and online processing



Unique Detector Concept and Features at the LHC

Thank you Art!

$$v_n(p_{\rm t}, y) = \langle \cos[n(\varphi - \Psi_{\rm RP})] \rangle$$



Contents