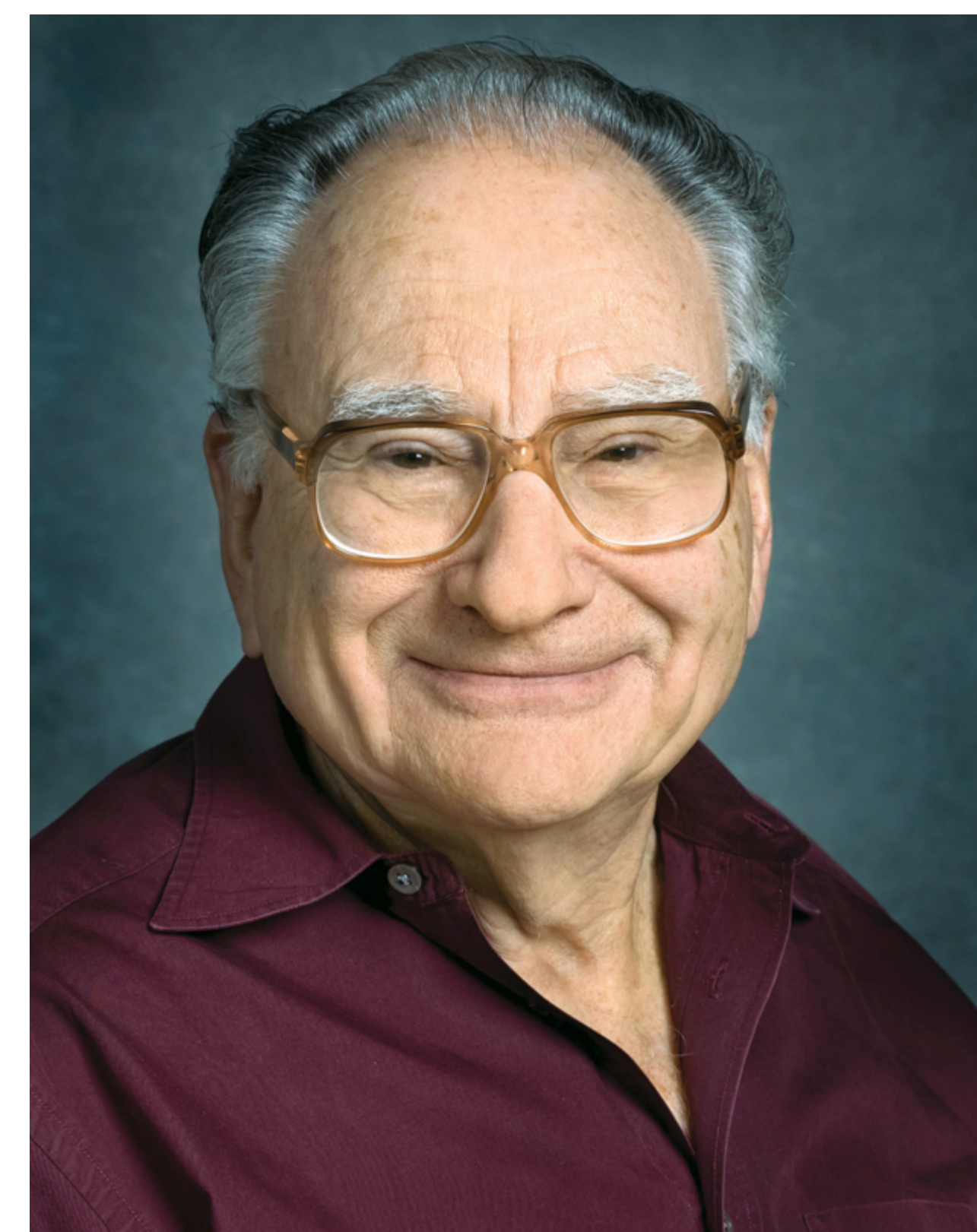




Symposium on collective flow in nuclear matter:
a celebration of Art Poskanzer's life and career





Flow from RHIC to the LHC



Color by Roberta Weir

Exploring the secrets
of the universe

Art Poskanzer

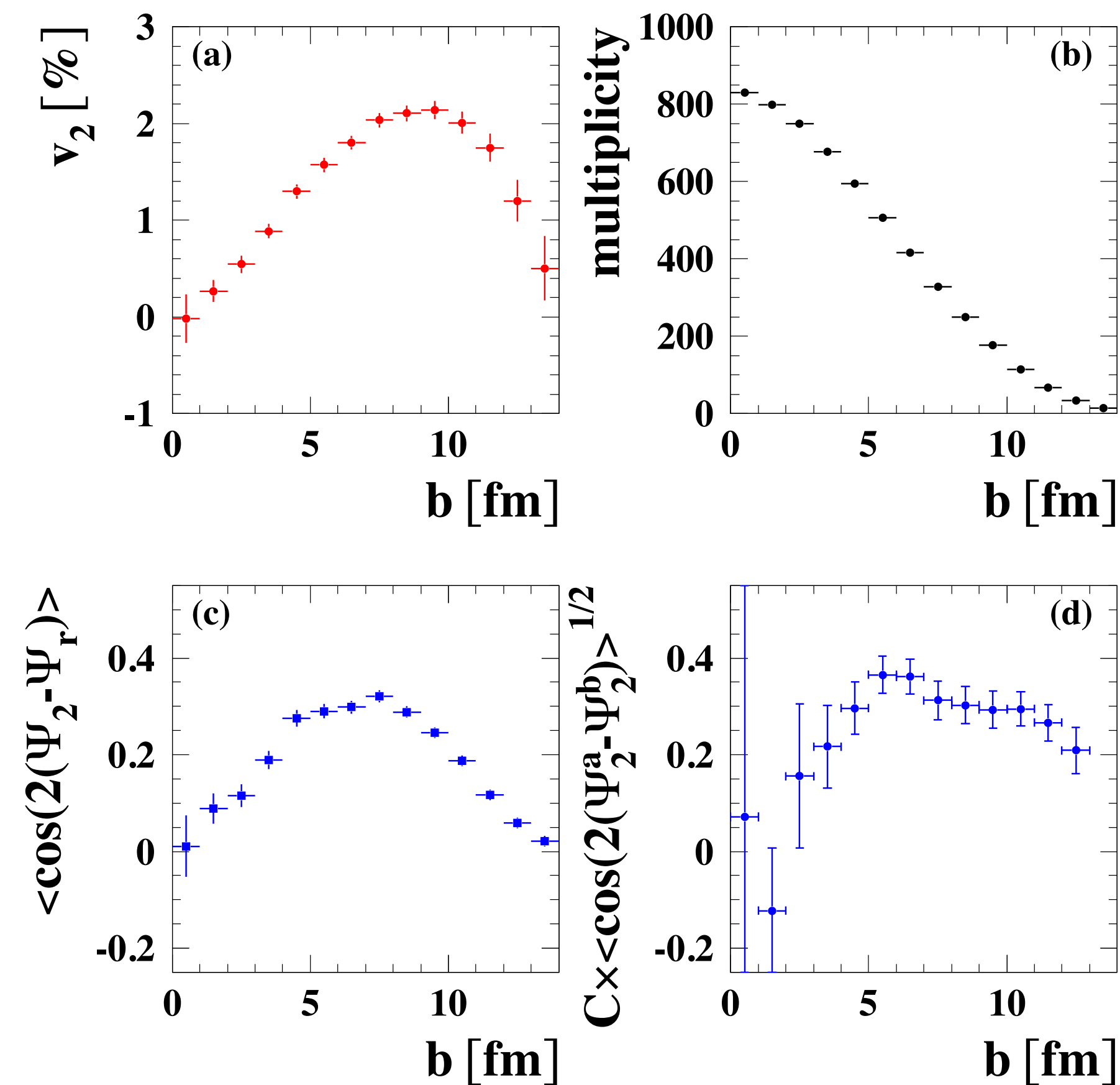
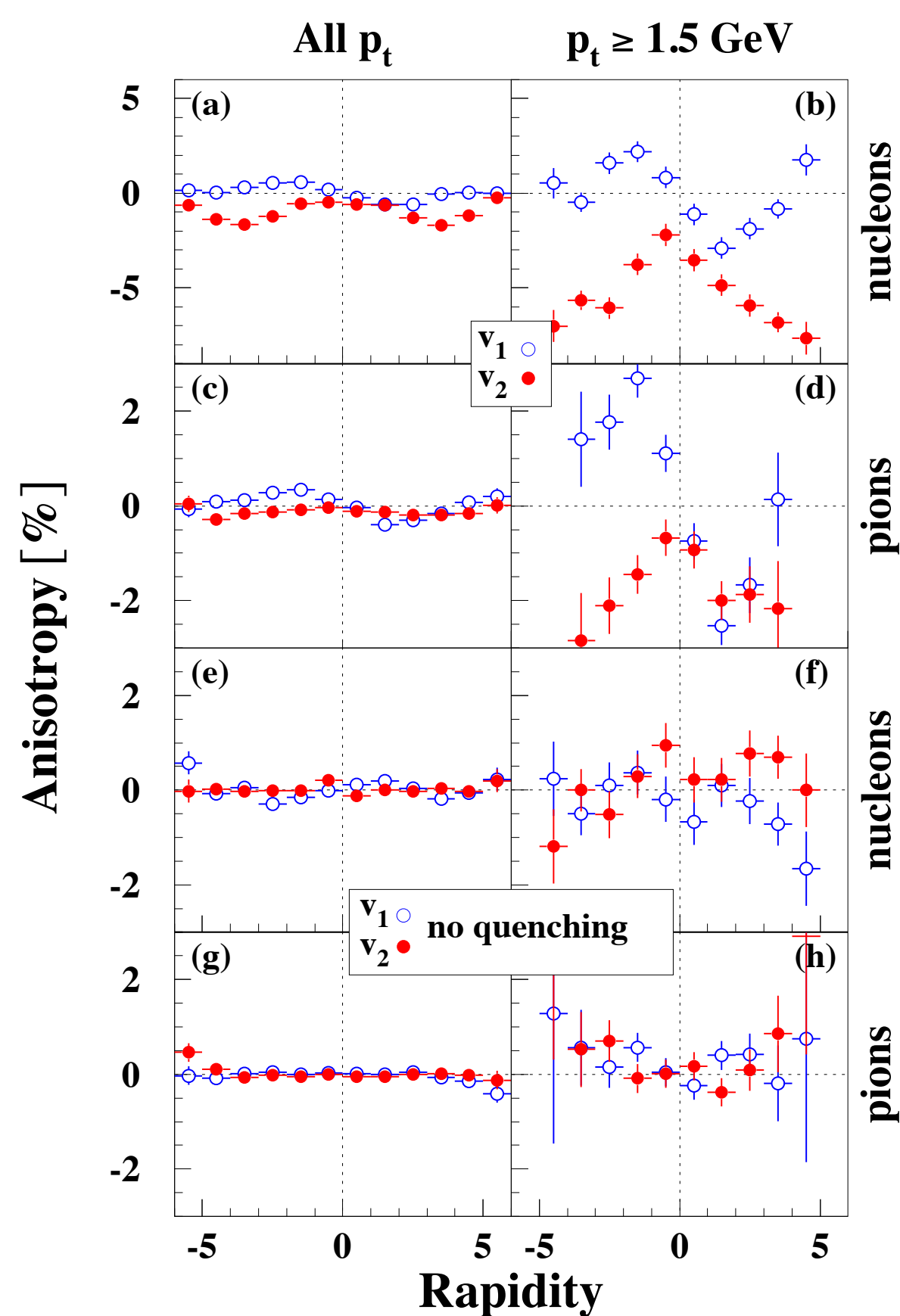
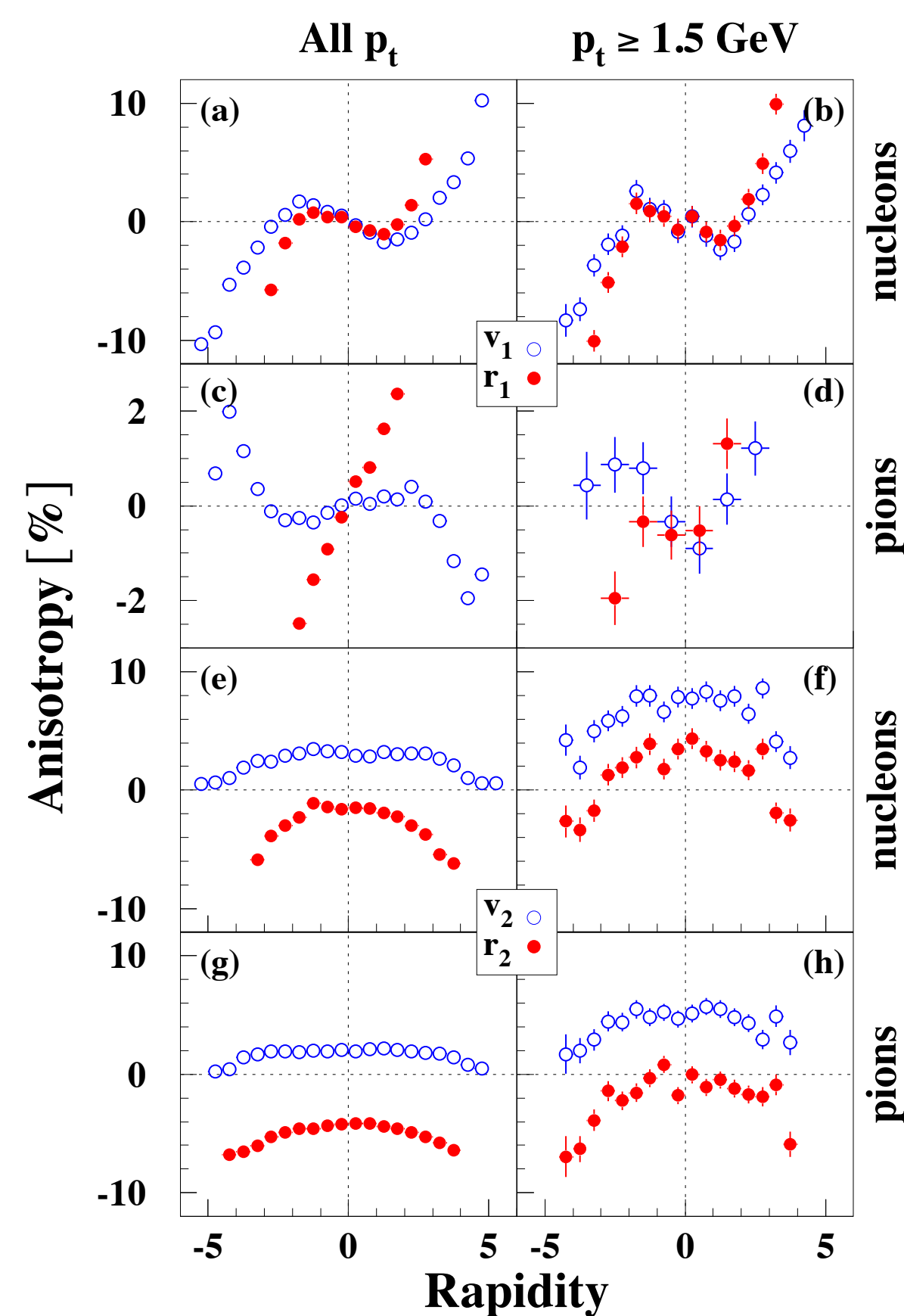


Anisotropic Flow (pre-RHIC)

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

09-Jan-98

W.A. Zajc

VOLUME 61, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1988

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

F. Abe,¹²³ D. Amidei,¹²³ G. Apollinari,¹²³ G. Ascoli,¹²³ M. Atar,¹²³ P. Auchincloss,¹²³ A. R. Baden,¹²³ A. Barbaro-Galleani,¹²³ V. E. Barnes,¹²³ F. Bedeschi,¹²³ S. Bellorini,¹²³ G. Bellotti,¹²³ J. Bellinger,¹²³ J. Benziger,¹²³ A. Bezruva,¹²³ P. Borge,¹²³ S. Bertolini,¹²³ S. Bhattarai,¹²³ M. Binkley,¹²³ R. Blair,¹²³ C. Blocker,¹²³ J. Boll,¹²³ A. W. Booth,¹²³ G. Brandenburg,¹²³ D. Brown,¹²³ A. Byon,¹²³ K. L. Byrum,¹²³ M. Campbell,¹²³ R. Carey,¹²³ W. Casburn,¹²³ D. Carlsmith,¹²³ J. T. Carroll,¹²³ R. Cashmore,¹²³ F. Cervelli,¹²³ K. Chadwick,¹²³ T. Chapin,¹²³ G. Chiarini,¹²³ W. Chiswick,¹²³ S. Chiswick,¹²³ D. Chin,¹²³ D. Connor,¹²³ M. Conteras,¹²³ J. Cooper,¹²³ M. Cordell,¹²³ M. Corradini,¹²³ C. Day,¹²³ R. Dell'Orso,¹²³ M. Dell'Orso,¹²³ L. DeMott,¹²³ T. Devita,¹²³ D. DiBartolo,¹²³ R. Diebold,¹²³ F. Dittus,¹²³ A. DiVirgilio,¹²³ J. E. Elias,¹²³ R. Ely,¹²³ S. Errede,¹²³ B. Esposito,¹²³ A. Feldman,¹²³ R. Flaugher,¹²³ E. Fogarty,¹²³ G. W. Foster,¹²³ M. Franklin,¹²³ J. Freeman,¹²³ H. Frisch,¹²³ Y. Fukui,¹²³ A. F. Gagliardi,¹²³ P. Giannini,¹²³ N. Giokaris,¹²³ P. Giromini,¹²³ L. Gladysz,¹²³ M. Gold,¹²³ K. Goulianos,¹²³ C. Gronow-Pfecher,¹²³ C. Haber,¹²³ S. R. Hahn,¹²³ R. Handler,¹²³ R. M. Harris,¹²³ J. Hauser,¹²³ T. Haxel,¹²³ R. Hellbock,¹²³ L. Holloway,¹²³ P. He,¹²³ B. Hubbard,¹²³ P. Hurst,¹²³ J. Huth,¹²³ H. Jansen,¹²³ R. P. Johnson,¹²³ U. Joshi,¹²³ R. W. Kadis,¹²³ T. Kanou,¹²³ S. Kanda,¹²³ D. A. Karolins,¹²³ I. Karliner,¹²³ E. Keane,¹²³ R. Kephart,¹²³ P. Kesten,¹²³ H. Kestelmeier,¹²³ S. Kim,¹²³ L. Kirsh,¹²³ K. Kondo,¹²³ U. Kruss,¹²³ S. E. Kuhlmann,¹²³ A. T. Laxson,¹²³ W. Li,¹²³ T. Lin,¹²³ N. Lockyer,¹²³ F. Marchetto,¹²³ R. Markeloff,¹²³ I. A. Markovits,¹²³ P. McIntyre,¹²³ A. Menzione,¹²³ T. Meyer,¹²³ S. Mikumo,¹²³ M. Miller,¹²³ T. Minami,¹²³ S. Minicci,¹²³ M. Mishina,¹²³ S. Miyashita,¹²³ N. Moadil,¹²³ S. Mori,¹²³ Y. Morita,¹²³ A. Mukherjee,¹²³ C. Newman-Holmes,¹²³ L. Nodulman,¹²³ R. Prodet,¹²³ A. Pura,¹²³ J. Patrick,¹²³ T. J. Phillips,¹²³ H. Pickett,¹²³ R. Piuschke,¹²³ L. Pondrom,¹²³ J. Prosser,¹²³ G. Puzi,¹²³ D. Quarrie,¹²³ K. Ragan,¹²³ G. Reffinger,¹²³ J. Rhoades,¹²³ F. Rimondi,¹²³ L. Ristori,¹²³ T. Rohaly,¹²³ A. Rodman,¹²³ A. Saxon,¹²³ R. Sere,¹²³ V. Scarpino,¹²³ P. Schlabach,¹²³ E. E. Schmidt,¹²³ P. Schwaner,¹²³ M. H. Schuch,¹²³ R. Schwitters,¹²³ A. Scribano,¹²³ S. Segler,¹²³ M. Seligson,¹²³ P. Sestini,¹²³ M. Shapiro,¹²³ M. Sheaff,¹²³ M. Shihata,¹²³ M. Shochet,¹²³ J. Singarier,¹²³ P. Sirois,¹²³ J. Skarba,¹²³ D. A. Smith,¹²³ F. D. Snider,¹²³ R. St. Denis,¹²³ A. Stefanini,¹²³ Y. Takaiwa,¹²³ K. Takikawa,¹²³ S. Taroni,¹²³ D. Thein,¹²³ A. Tollstrey,¹²³ G. Tonelli,¹²³ Y. Tuzy,¹²³ F. Uggare,¹²³ D. Underwood,¹²³ R. Vidal,¹²³ R. G. Wagner,¹²³ R. L. Wagner,¹²³ J. Walsh,¹²³ T. Watts,¹²³ R. Webb,¹²³ T. Werthmiller,¹²³ S. White,¹²³ A. Wicklund,¹²³ H. N. Williams,¹²³ T. Yamamoto,¹²³ A. Yamashita,¹²³ K. Yasuda,¹²³ G. P. Yeh,¹²³ J. Yeh,¹²³ and F. Zetti,¹²³

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¹²⁴Brunel University, Uxbridge, Massachusetts 02254
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¹²⁷Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Frascati, Italy
¹²⁸Harvard University, Cambridge, Massachusetts 02138
¹²⁹University of Illinois, Urbana, Illinois 61801
¹³⁰National Laboratory for High Energy Physics (KEK), Tsukuba-gun, Ibaraki-ken 305, Japan
¹³¹Lawrence Berkeley Laboratory, Berkeley, California 94720
¹³²University of Pennsylvania, Philadelphia, Pennsylvania 19104
¹³³Indiana University, West Lafayette, Indiana 47907
¹³⁴Rutgers University, New York, New York 10821
¹³⁵Rutgers University, Piscataway, New Jersey 08854
¹³⁶Texas A&M University, College Station, Texas 77843
¹³⁷University of Toronto, Toronto, Ontario M5S 1A5, Canada
¹³⁸University of Wisconsin, Madison, Wisconsin 53706
 (Received 5 June 1988; revised manuscript received 5 September 1988)

Measurements of inclusive transverse-momentum spectra for charged particles produced in proton-antiproton collisions at \sqrt{s} of 630 and 1800 GeV are presented and compared with data taken at lower energies.

PACS number: 13.55.Ni

1819

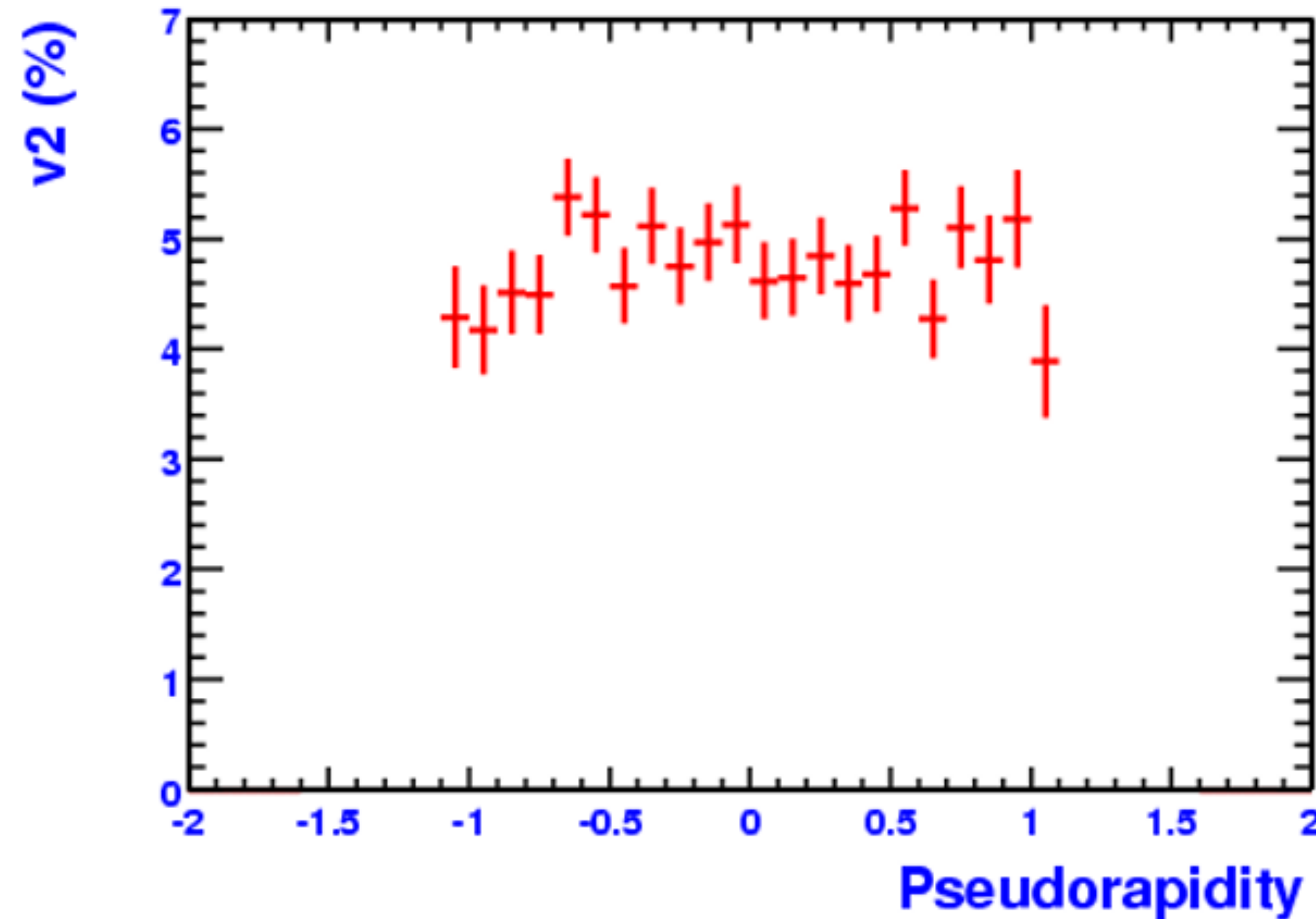
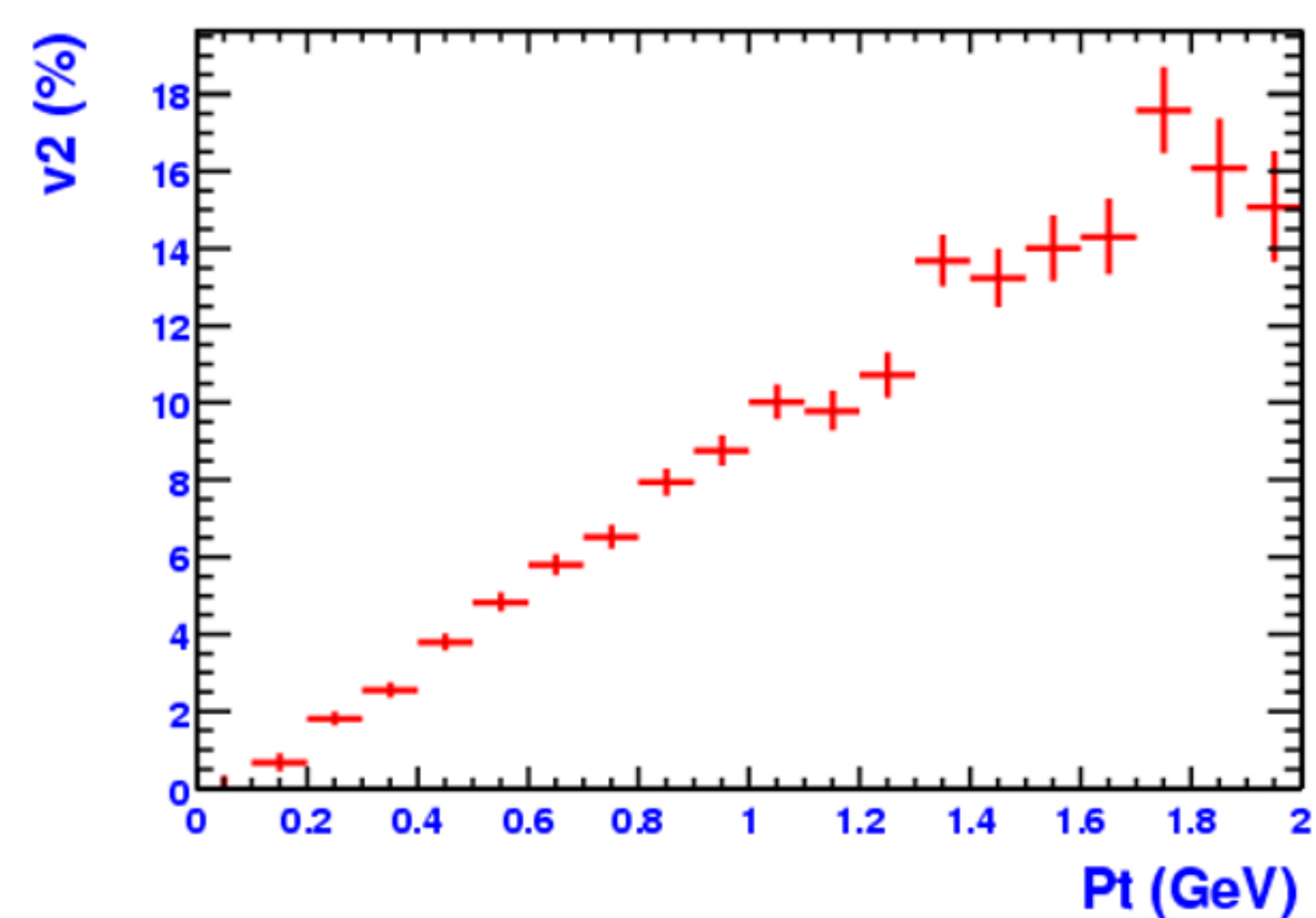


STAR (2000)

Relativistic Heavy Ion Collider (RHIC) Begins Smashing Atoms

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

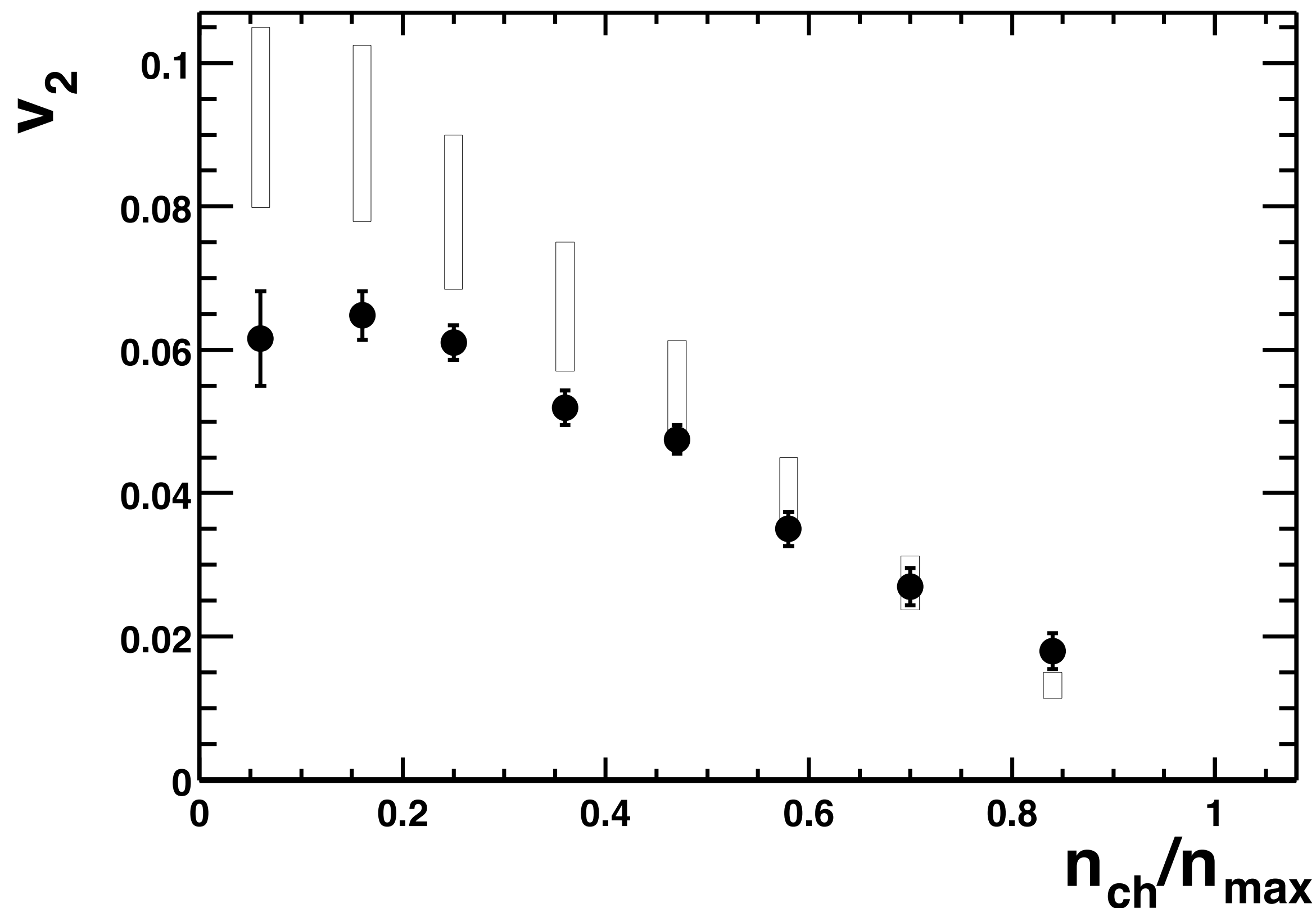
June 13, 2000



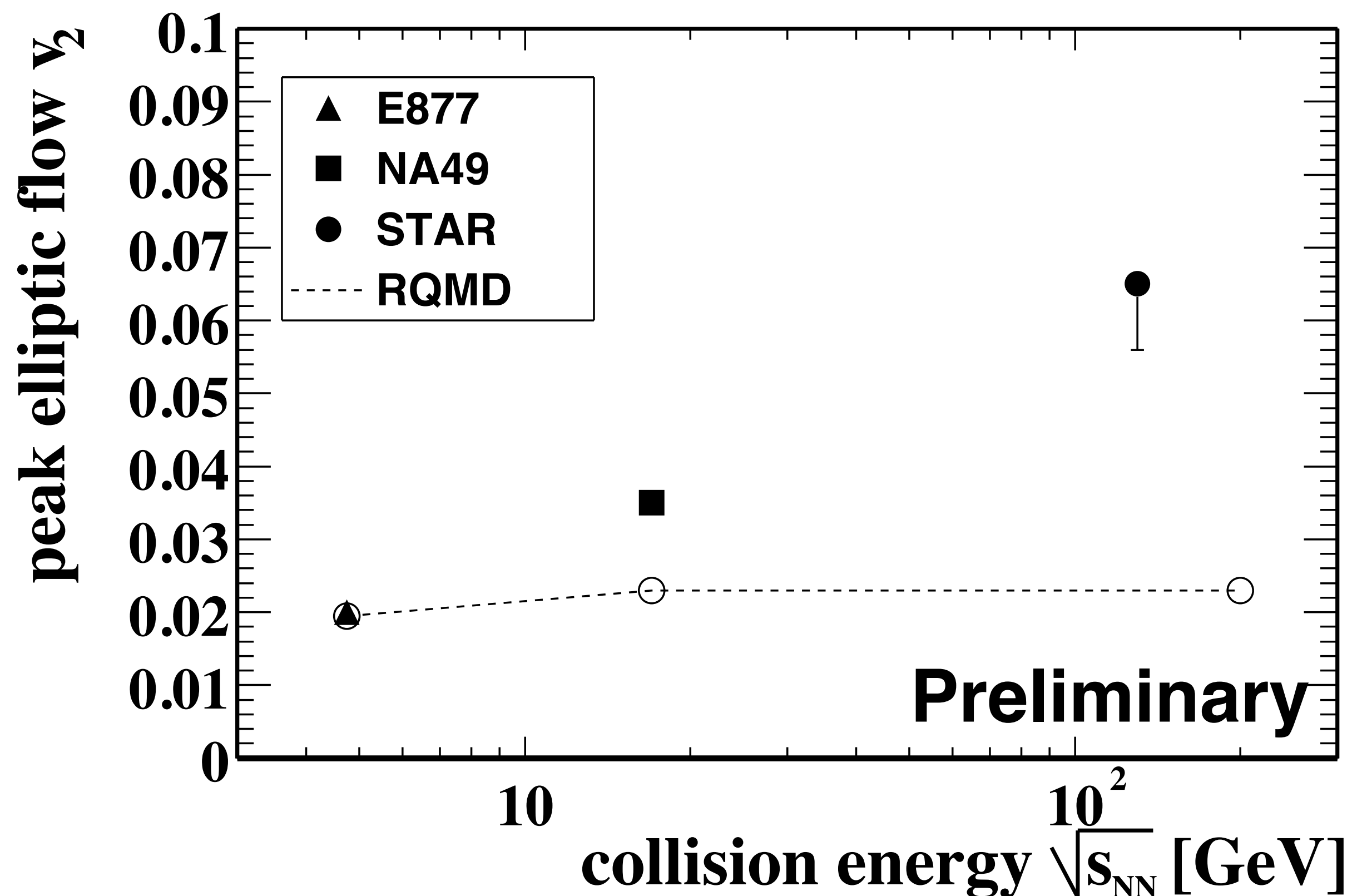
I am sure people here have pictures of these plots from the door of Art's office



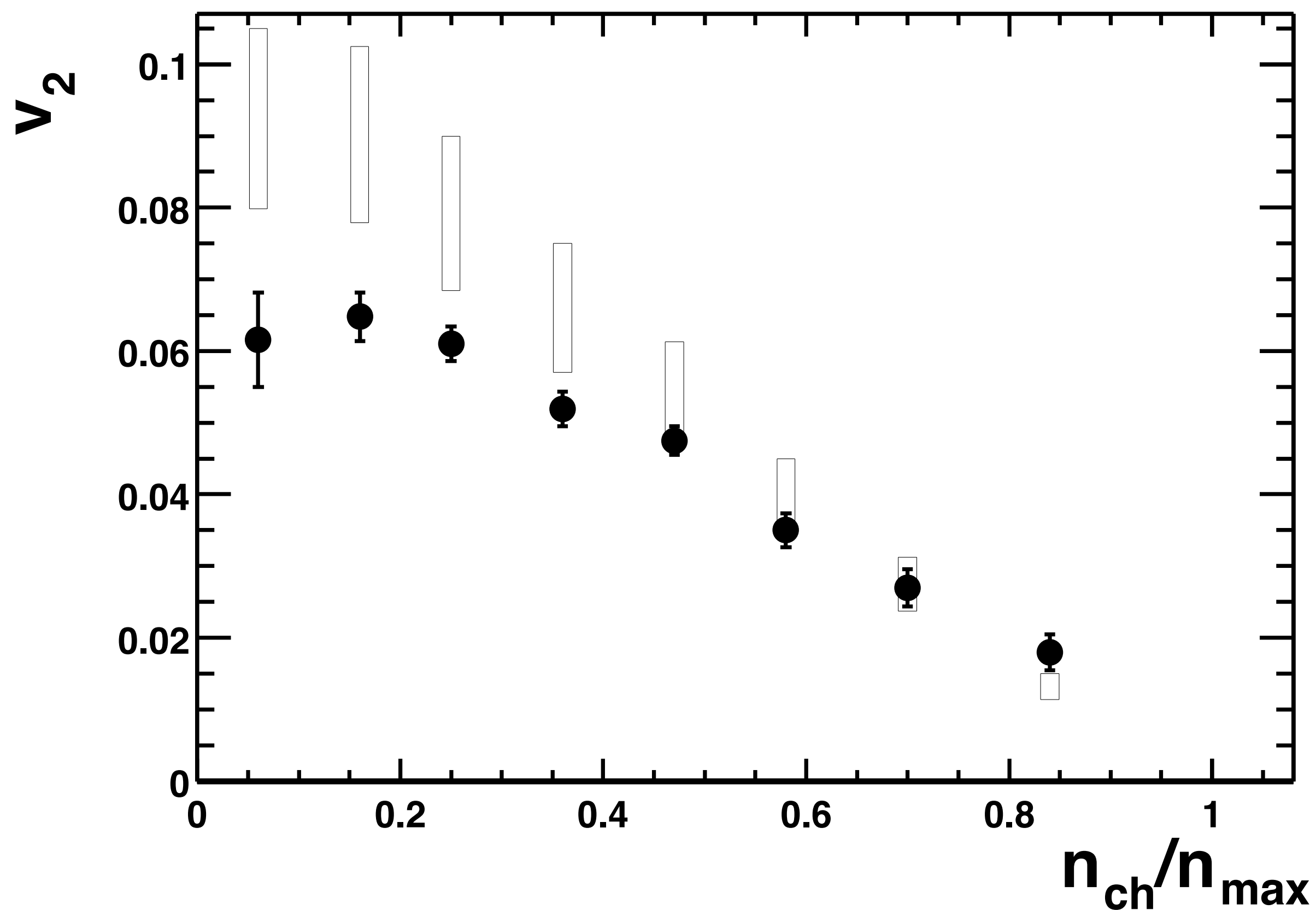
STAR (2001)



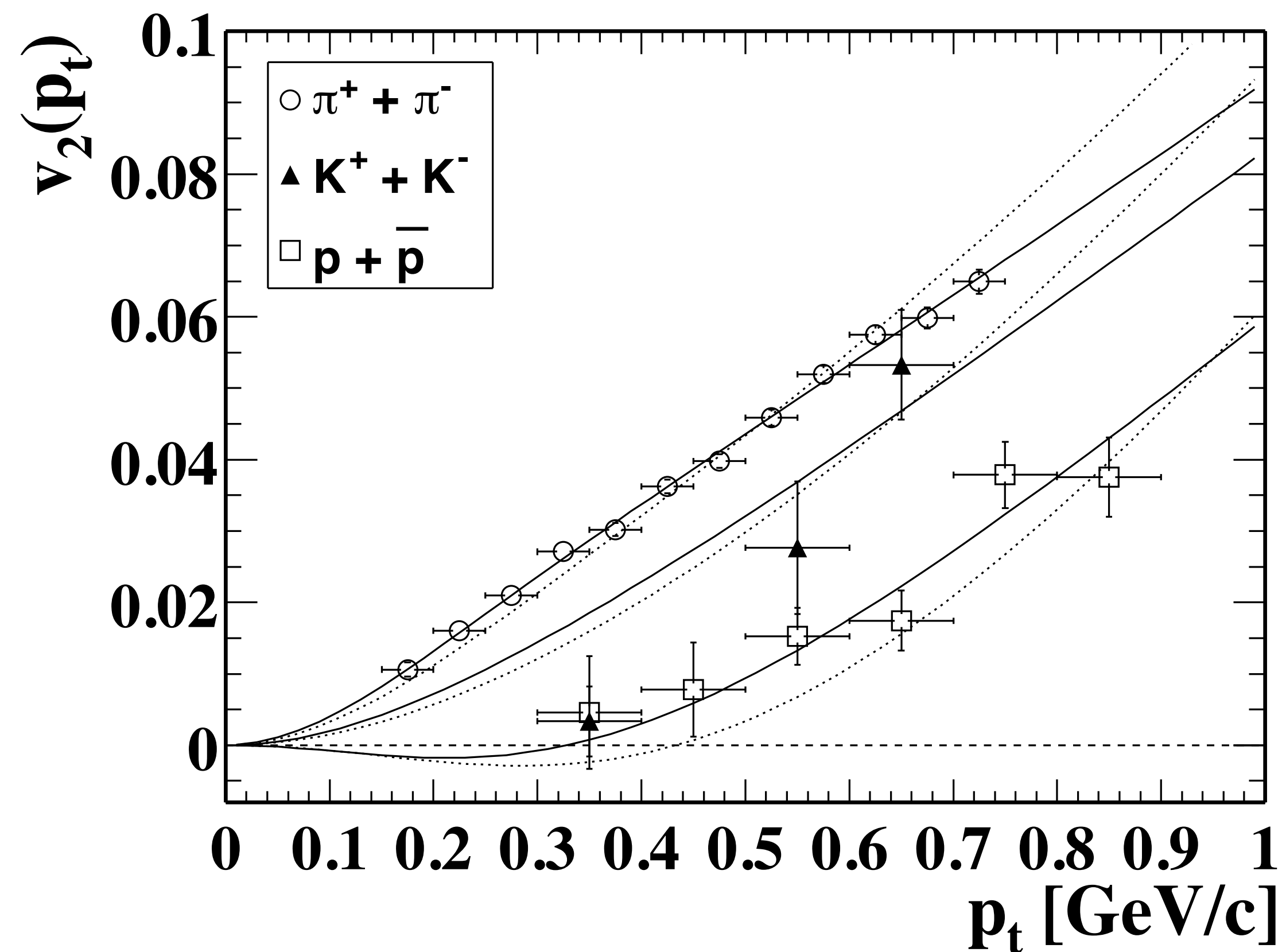
in good agreement for mid-central collisions with “hydro”



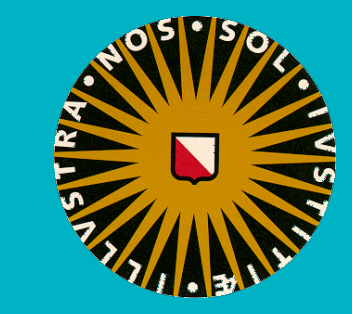
big increase measured compared to predictions hadron cascade model(s)



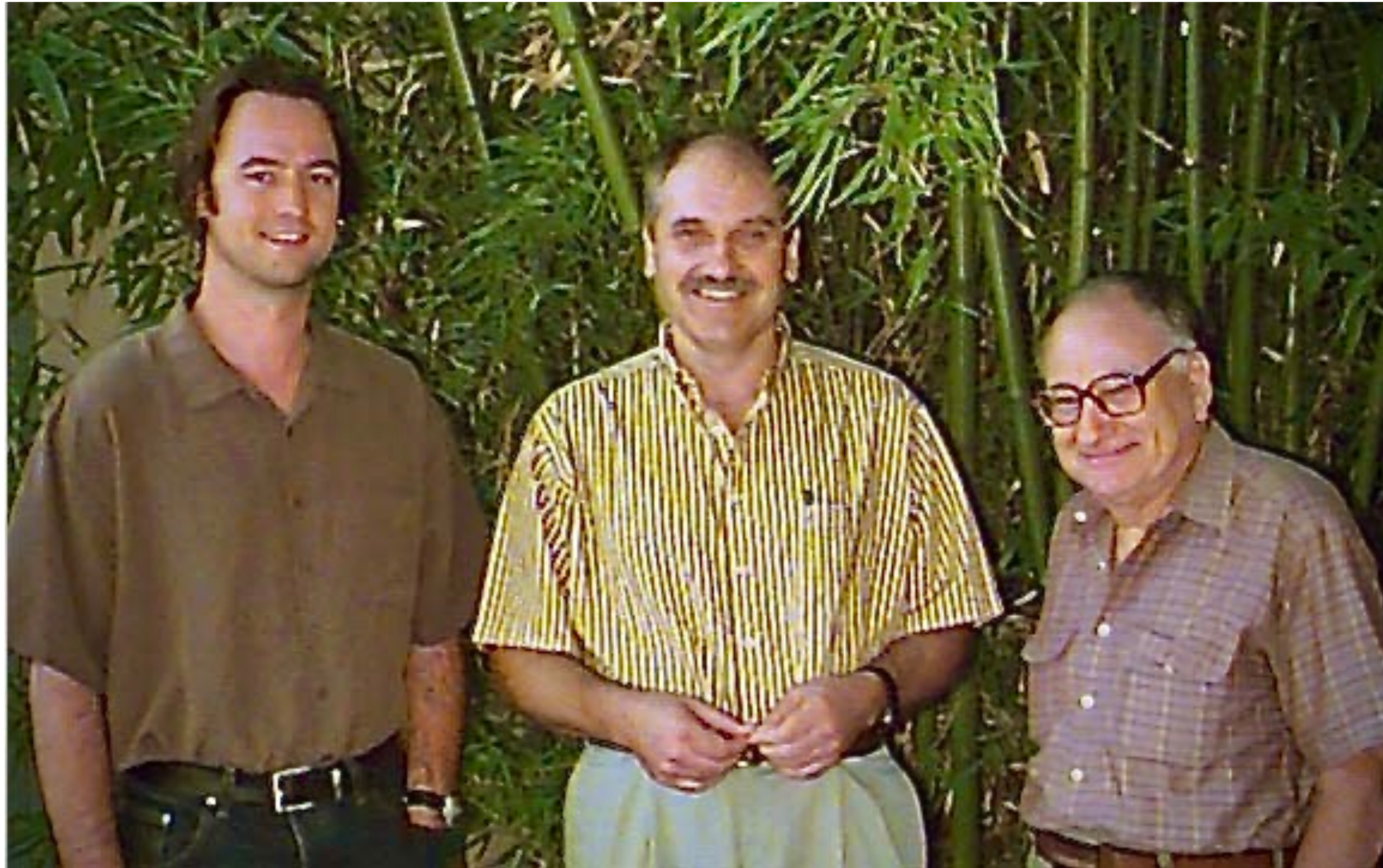
in good agreement for mid-central collisions with “hydro”



Behaves like a system with common temperature and flow boost



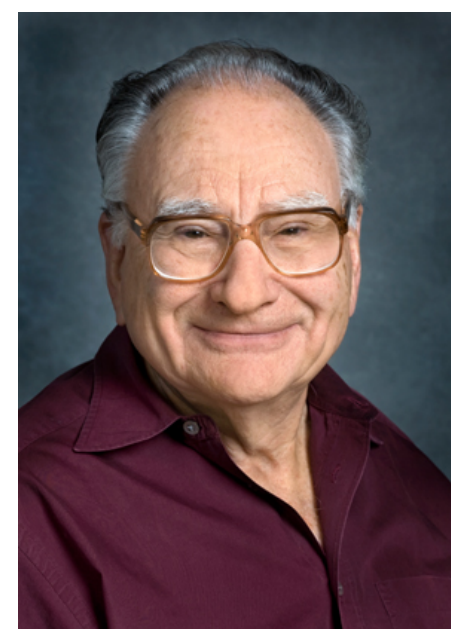
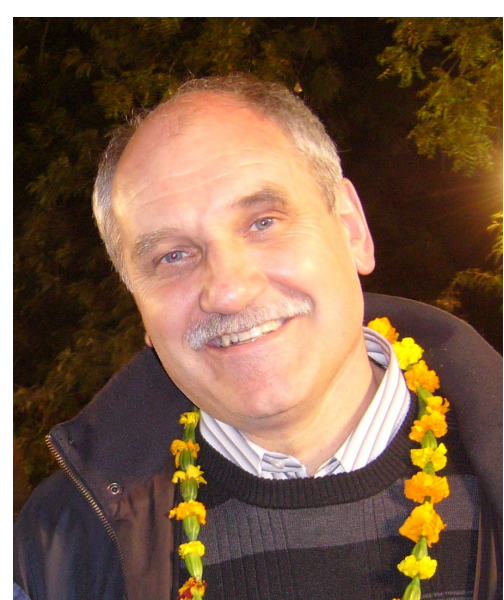
STAR (2001)





Collective phenomena in non-central nuclear collisions

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



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Collective phenomena in non-central nuclear collisions

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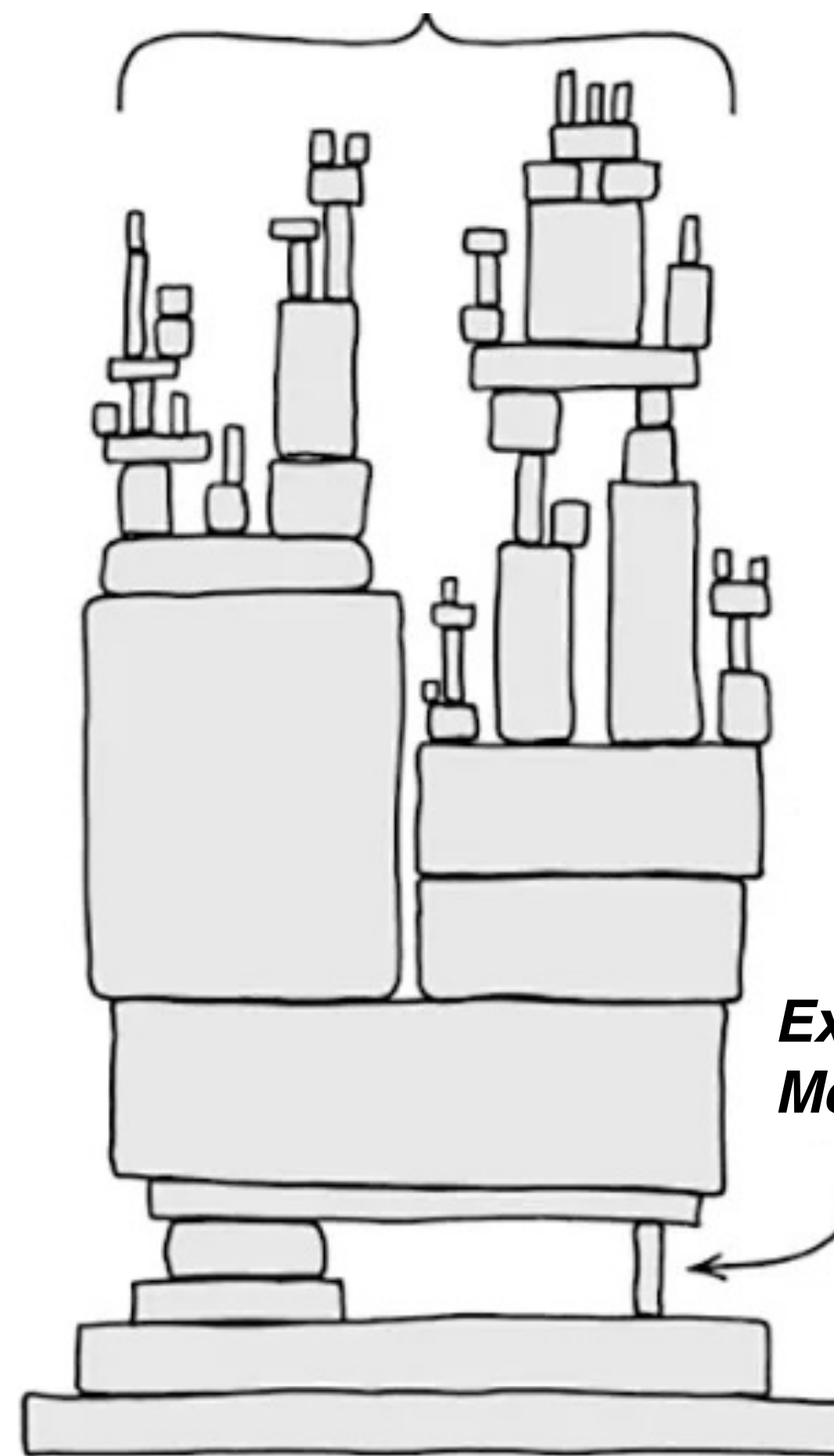


Color by Roberta Weir

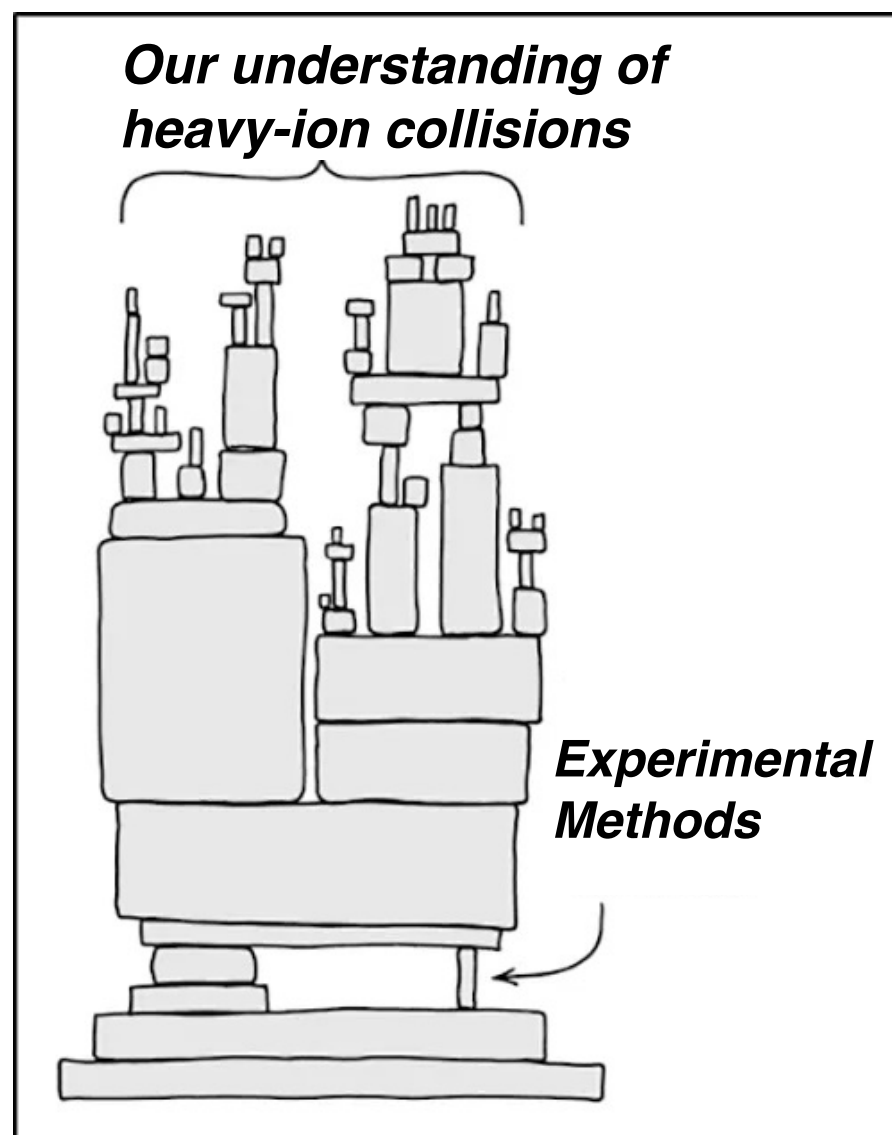
Exploring the secrets of the universe

Art Poskanzer

Our understanding of heavy-ion collisions



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 Voloshin³

¹Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

²Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

³Wayne State University, 666 W. Hancock Street, Detroit, MI 48201, USA

(Dated: October 18, 2011)

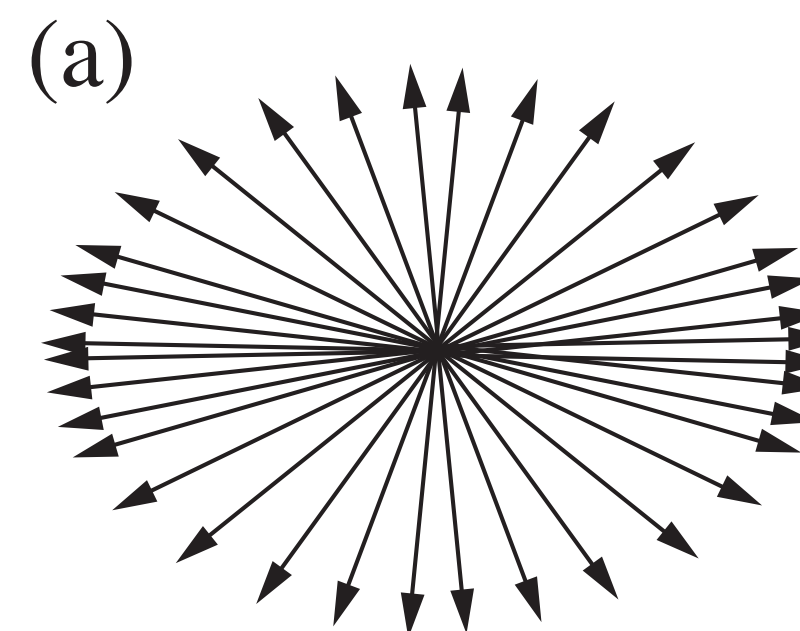
$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_{\text{RP}})] \rangle$$

$$\begin{aligned} \langle \langle e^{i2(\varphi_1 - \varphi_2)} \rangle \rangle &= \langle \langle e^{i2(\varphi_1 - \Psi_{\text{RP}} - (\varphi_2 - \Psi_{\text{RP}}))} \rangle \rangle \\ &= \langle \langle e^{i2(\varphi_1 - \Psi_{\text{RP}})} \rangle \langle e^{-i2(\varphi_2 - \Psi_{\text{RP}})} \rangle + \delta_2 \rangle, \\ &= \langle v_2^2 + \delta_2 \rangle, \end{aligned}$$

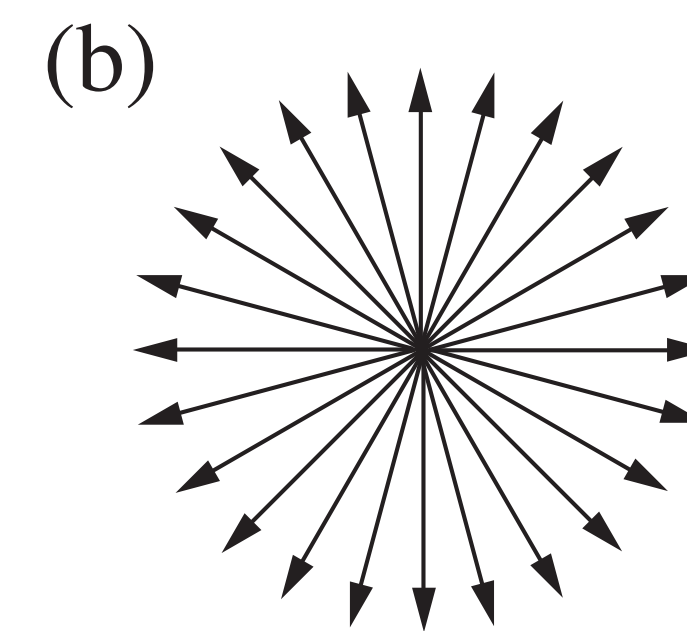
$$c_2\{2\} \equiv \langle \langle e^{i2(\varphi_1 - \varphi_2)} \rangle \rangle = \langle v_2^2 + \delta_2 \rangle.$$

$$\begin{aligned} c_2\{4\} &\equiv \langle \langle e^{i2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle \rangle - 2 \langle \langle e^{i2(\varphi_1 - \varphi_2)} \rangle \rangle^2, \\ &= \langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2 \rangle - 2 \langle v_2^2 + \delta_2 \rangle^2, \\ &= \langle -v_2^4 + \delta_4 \rangle. \end{aligned}$$

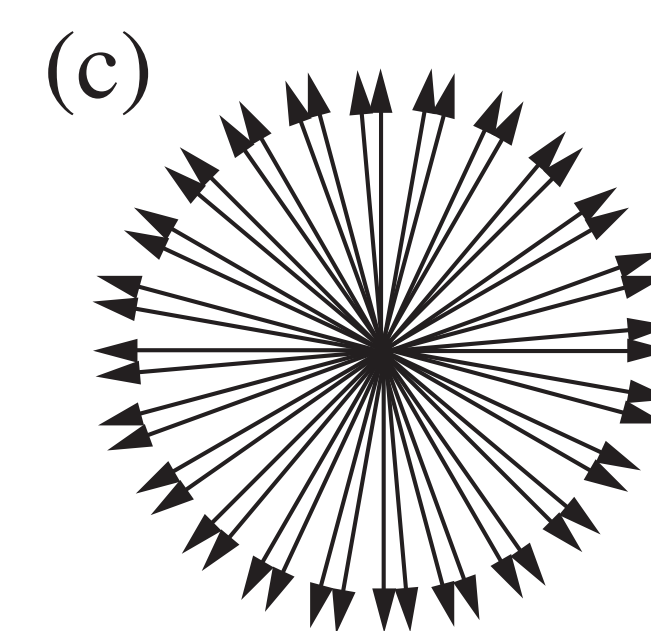
Non flow $\delta_2 \propto 1/M_c$ $\delta_4 \propto 1/M_c^3$



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



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



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

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

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

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

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

Fluctuations



**Art
QM 2008
Jaipur**

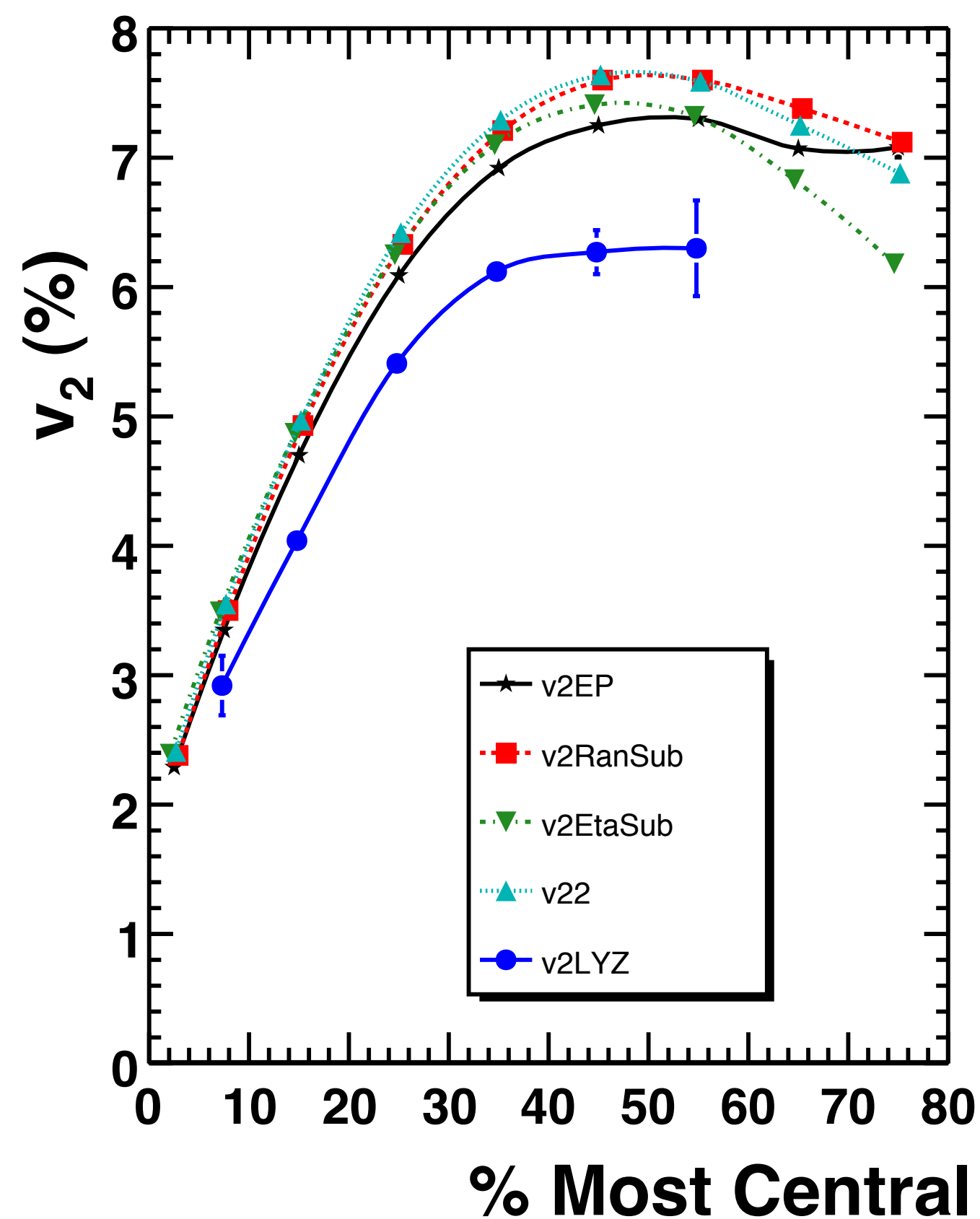


Figure 1: (Color online) The values of v_2 from various analysis methods vs centrality. Both the upper lines [3] and the lower line [12] are STAR data.

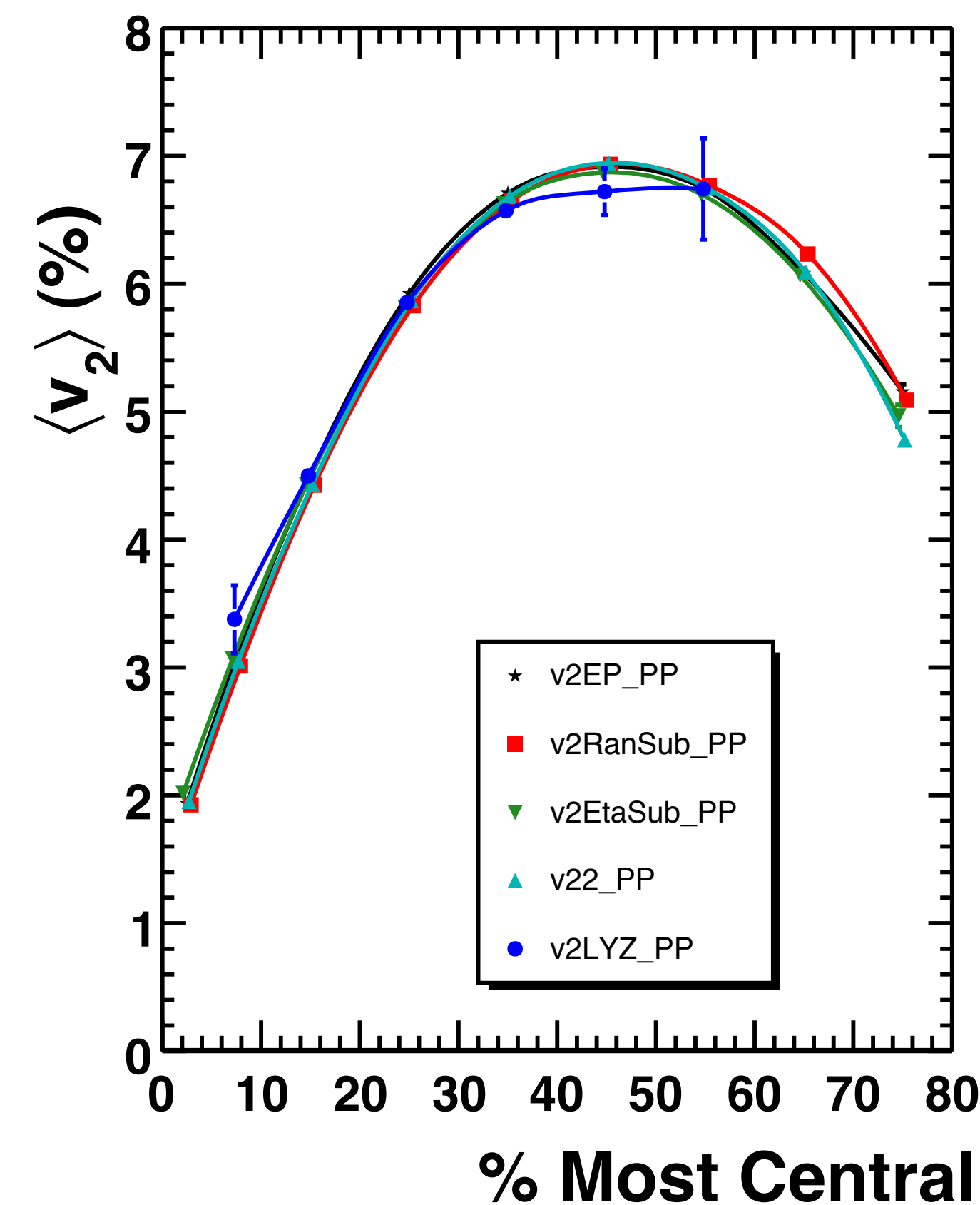


Figure 2: (Color online) The data from Fig. 1 corrected to $\langle v_2 \rangle$ in the participant plane.



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

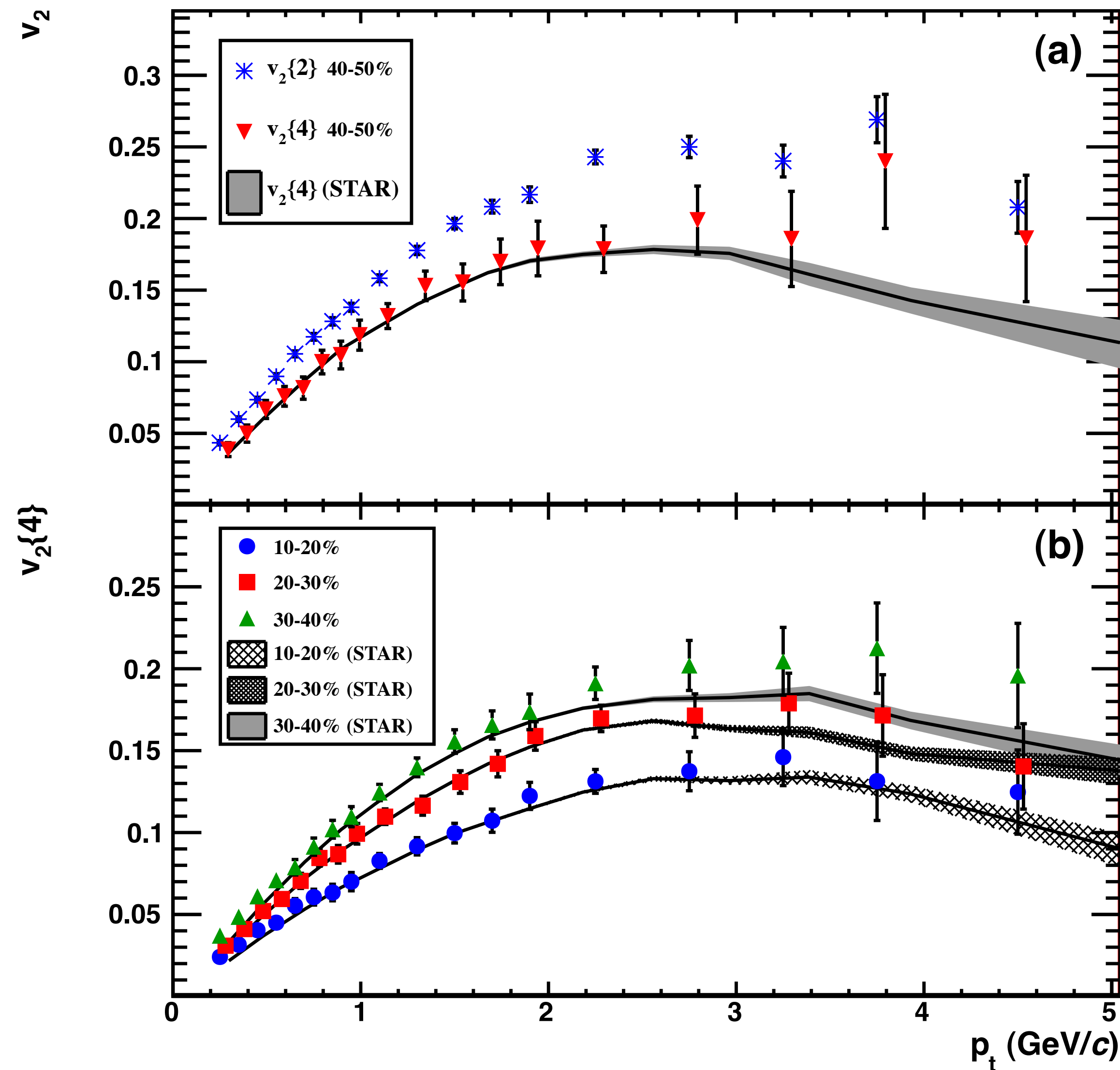
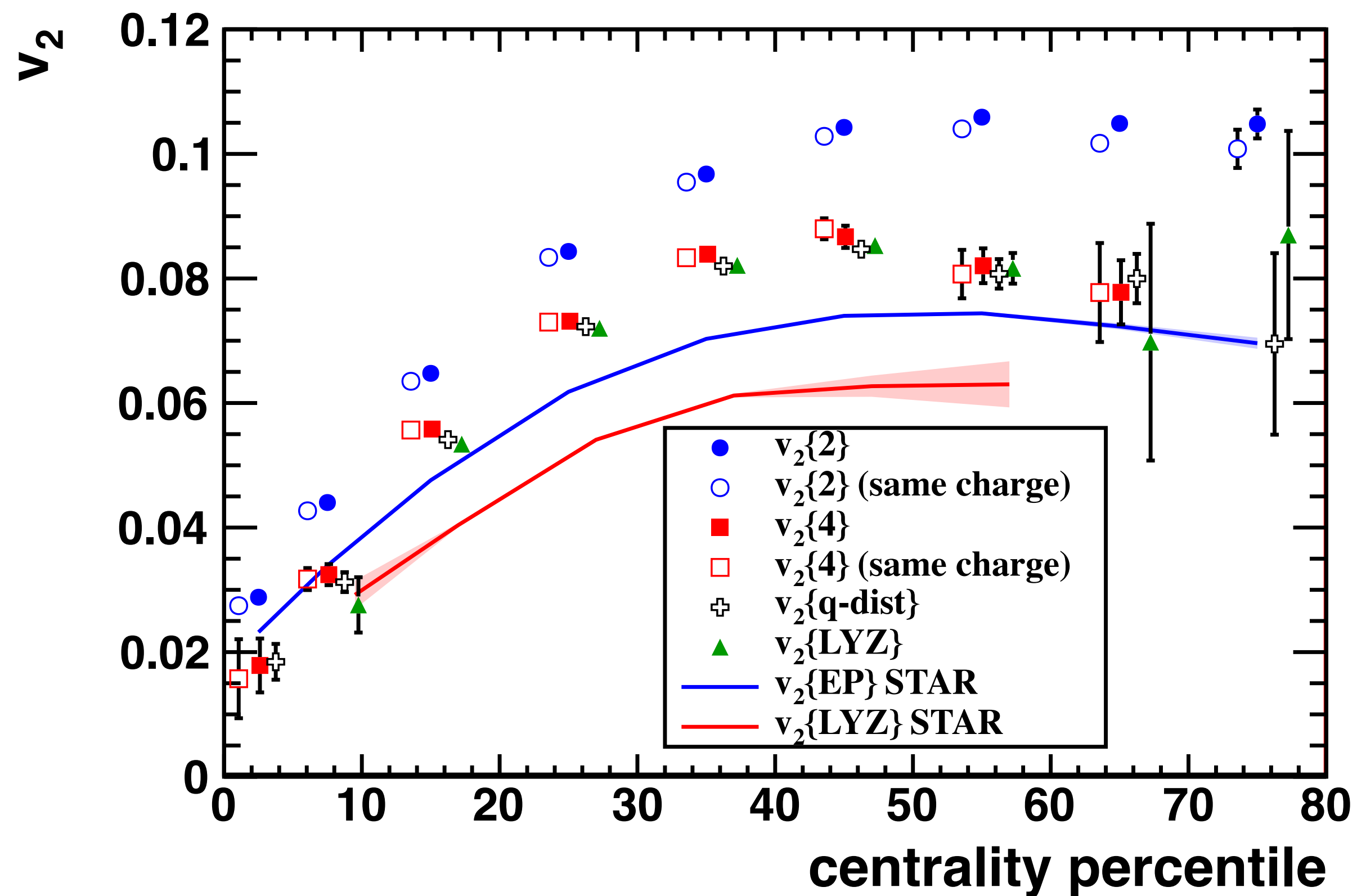
de M. Michel Nostradamus

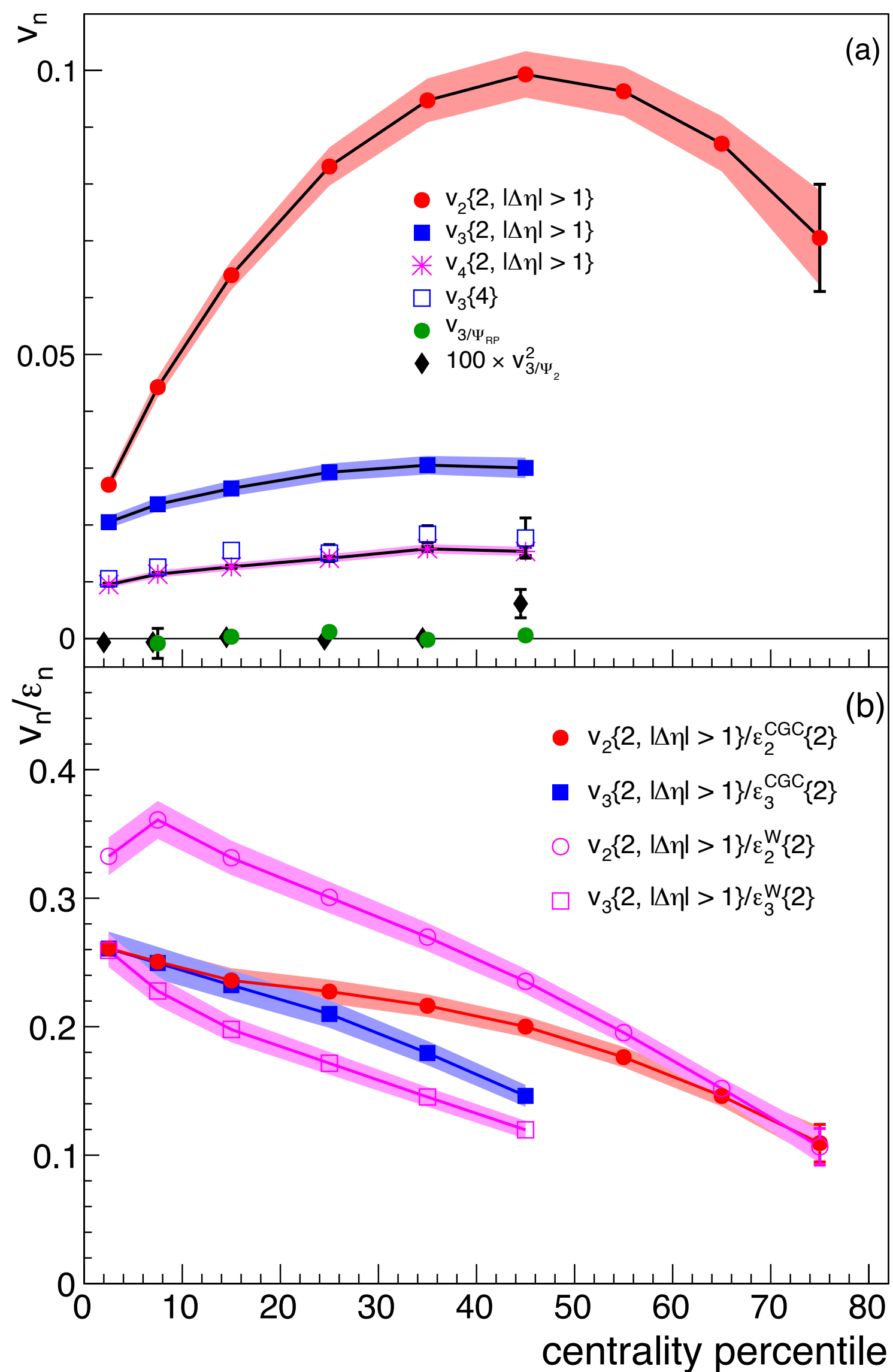
We report the first measurement of charged particle elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.25 < p_t < 5$ 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

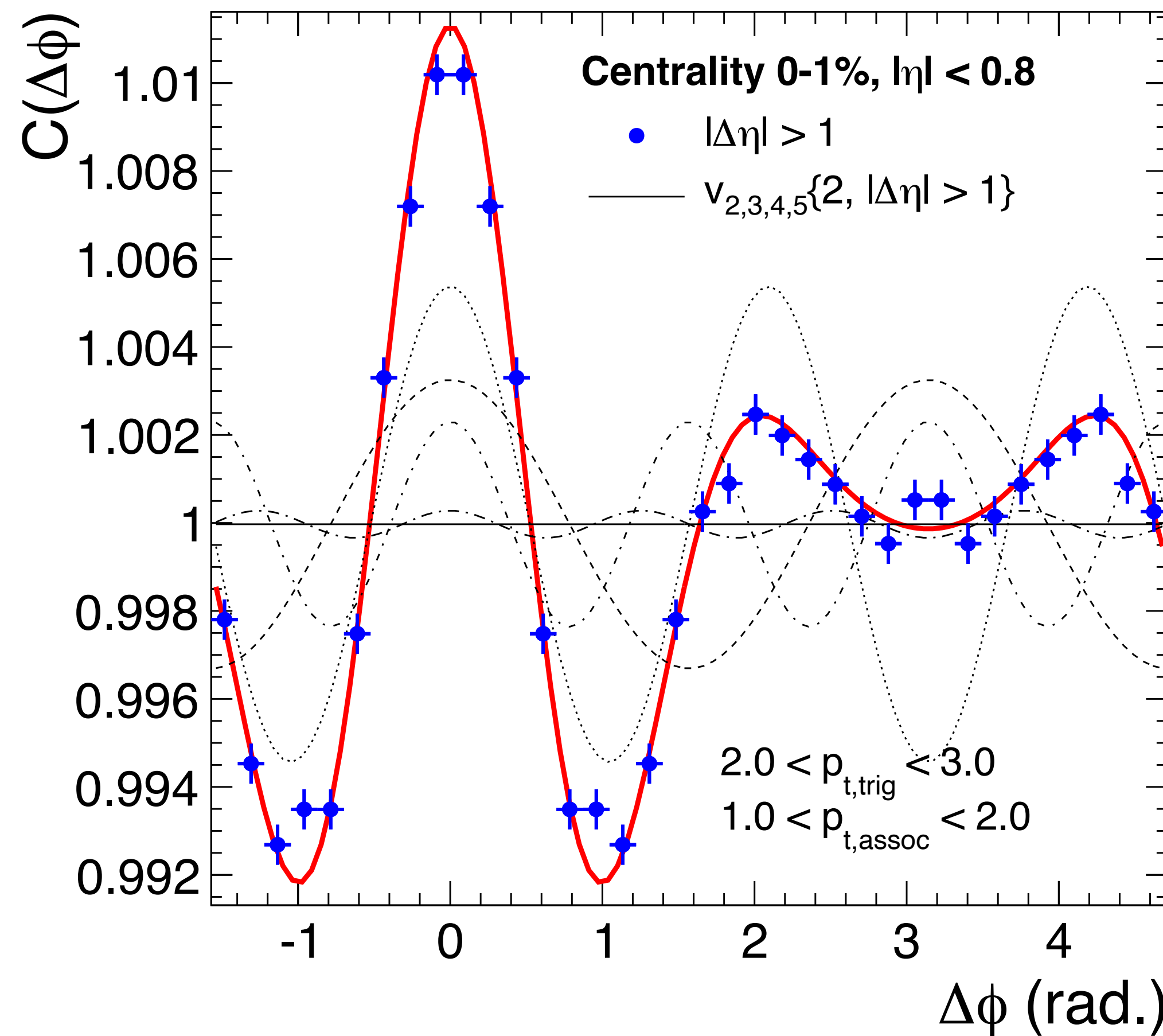


ALICE (2010)



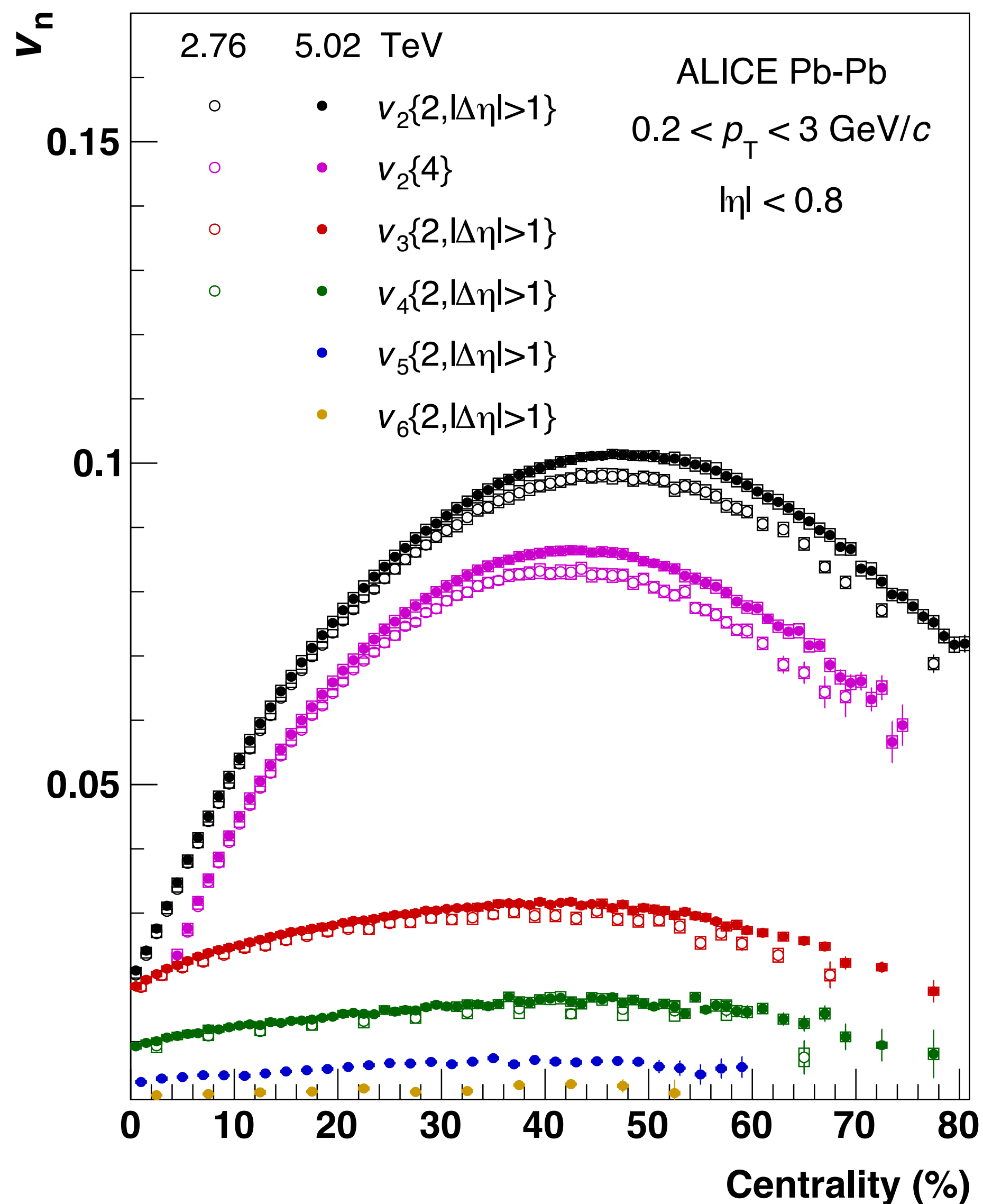


No shock waves - convincing measurement of the higher harmonics
non-Glauber initial conditions

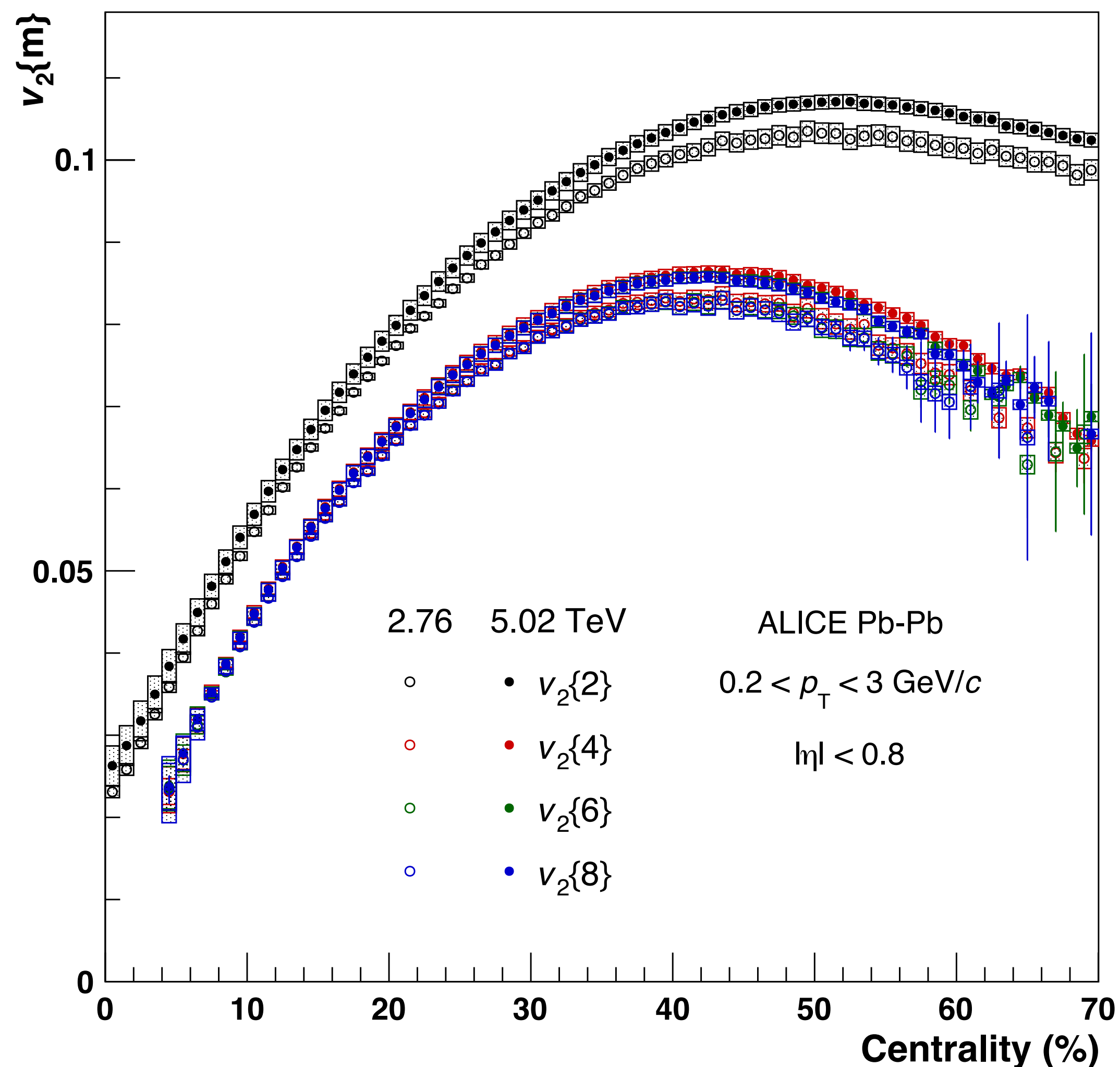




Fluctuations and initial conditions



- 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



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.

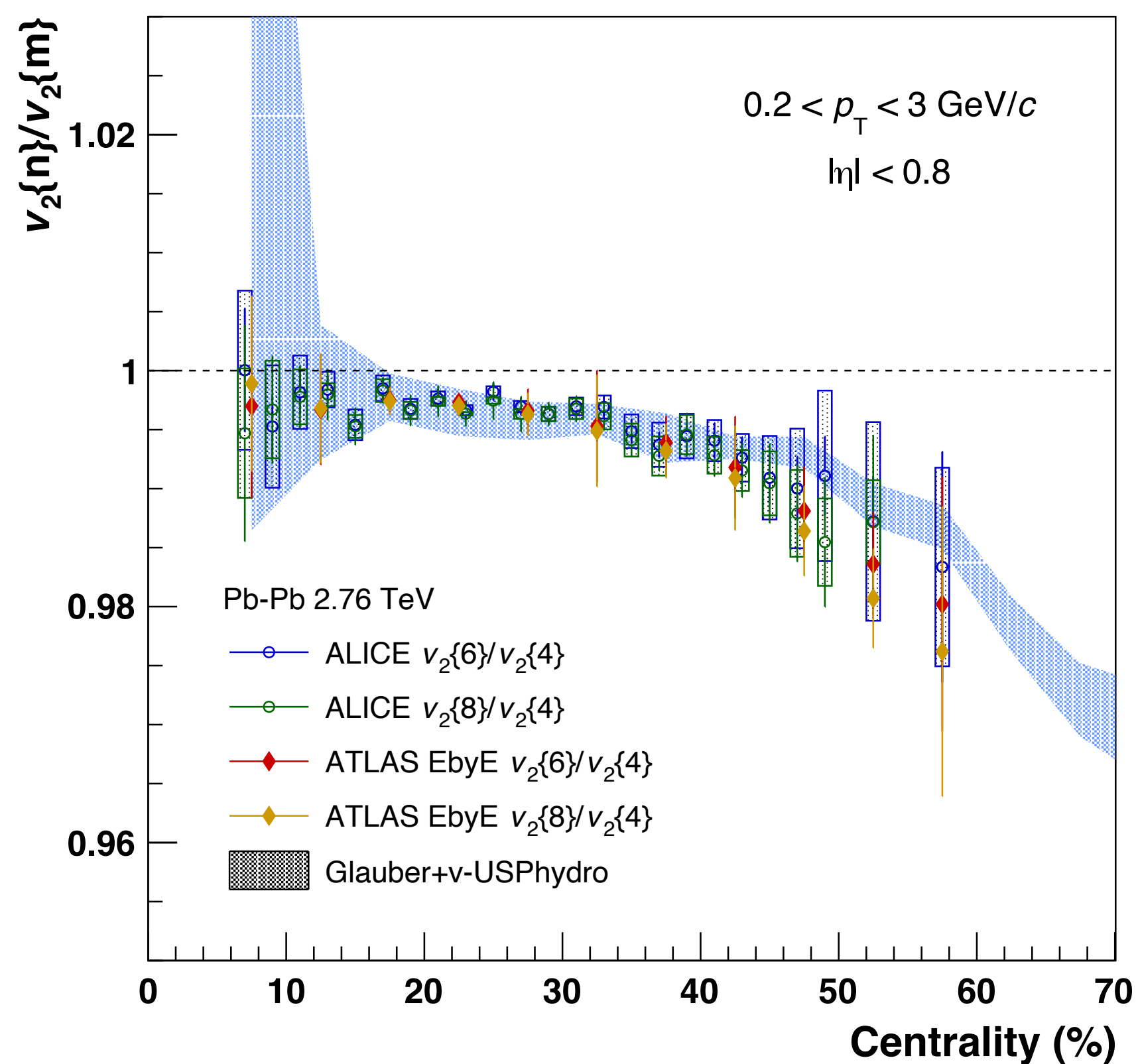
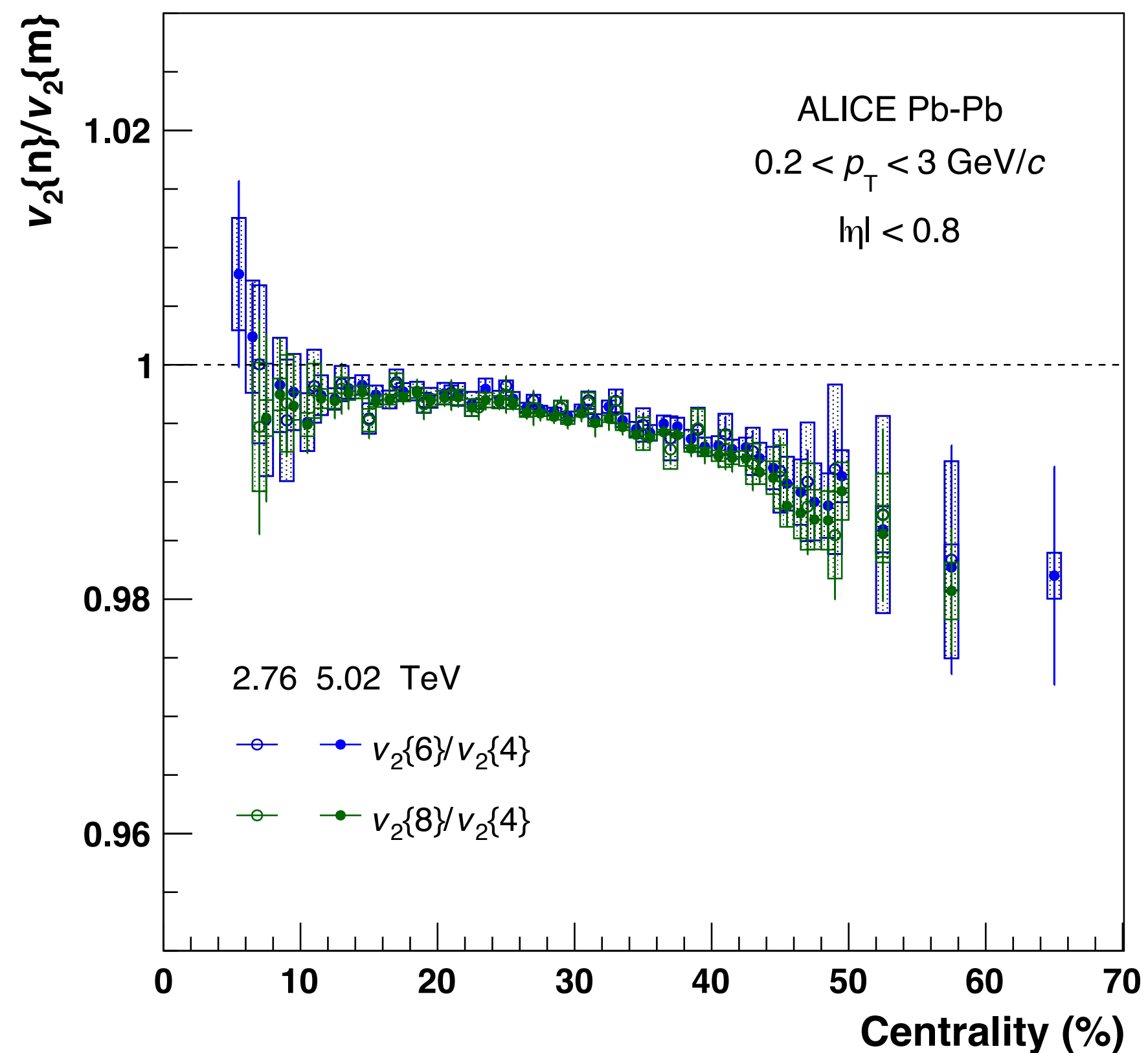
$$v_2\{2\} = \langle v_2 \rangle + \frac{1}{2} \frac{\sigma^2}{\langle v_2 \rangle},$$

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

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



Fluctuations and initial conditions



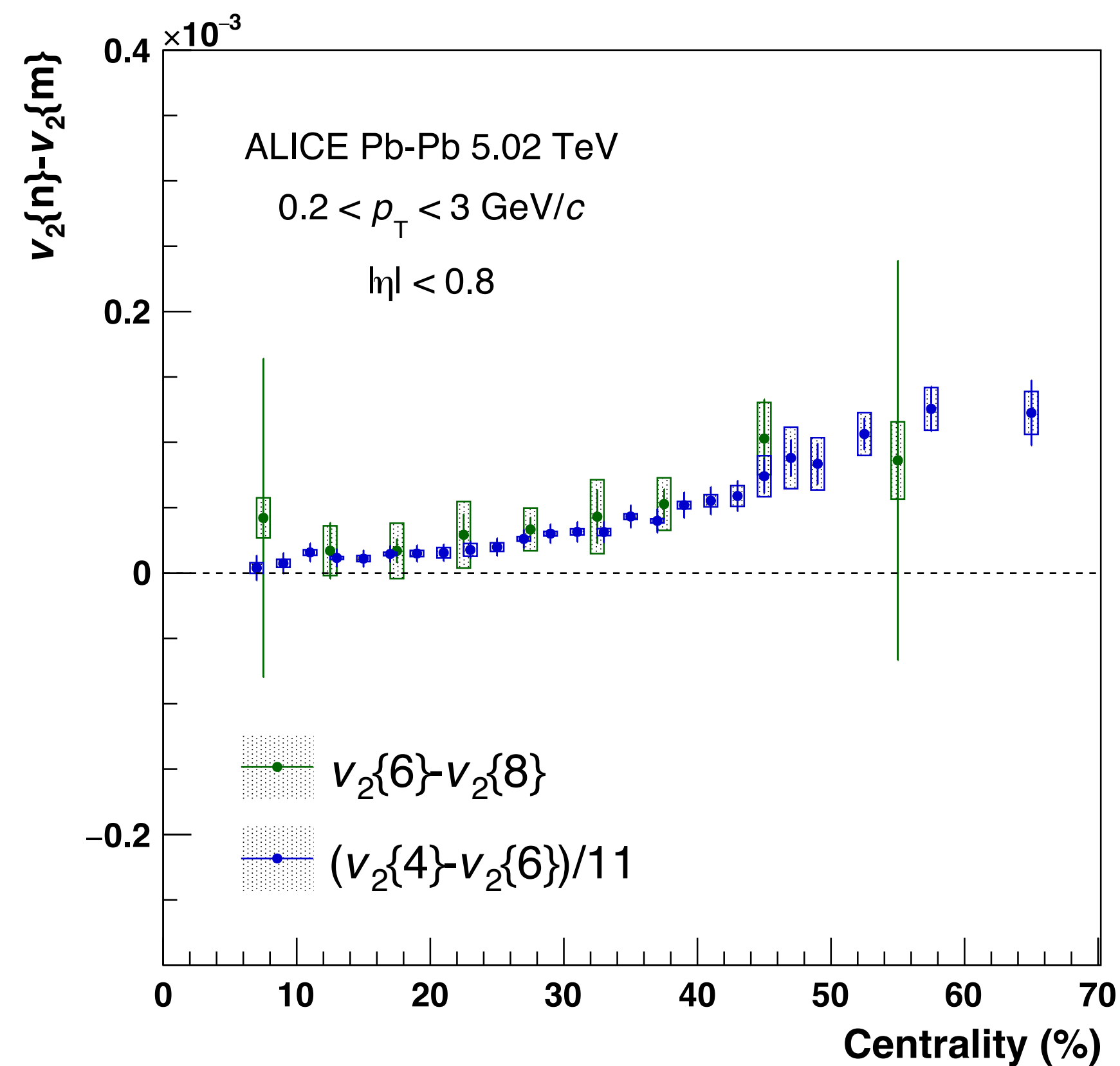
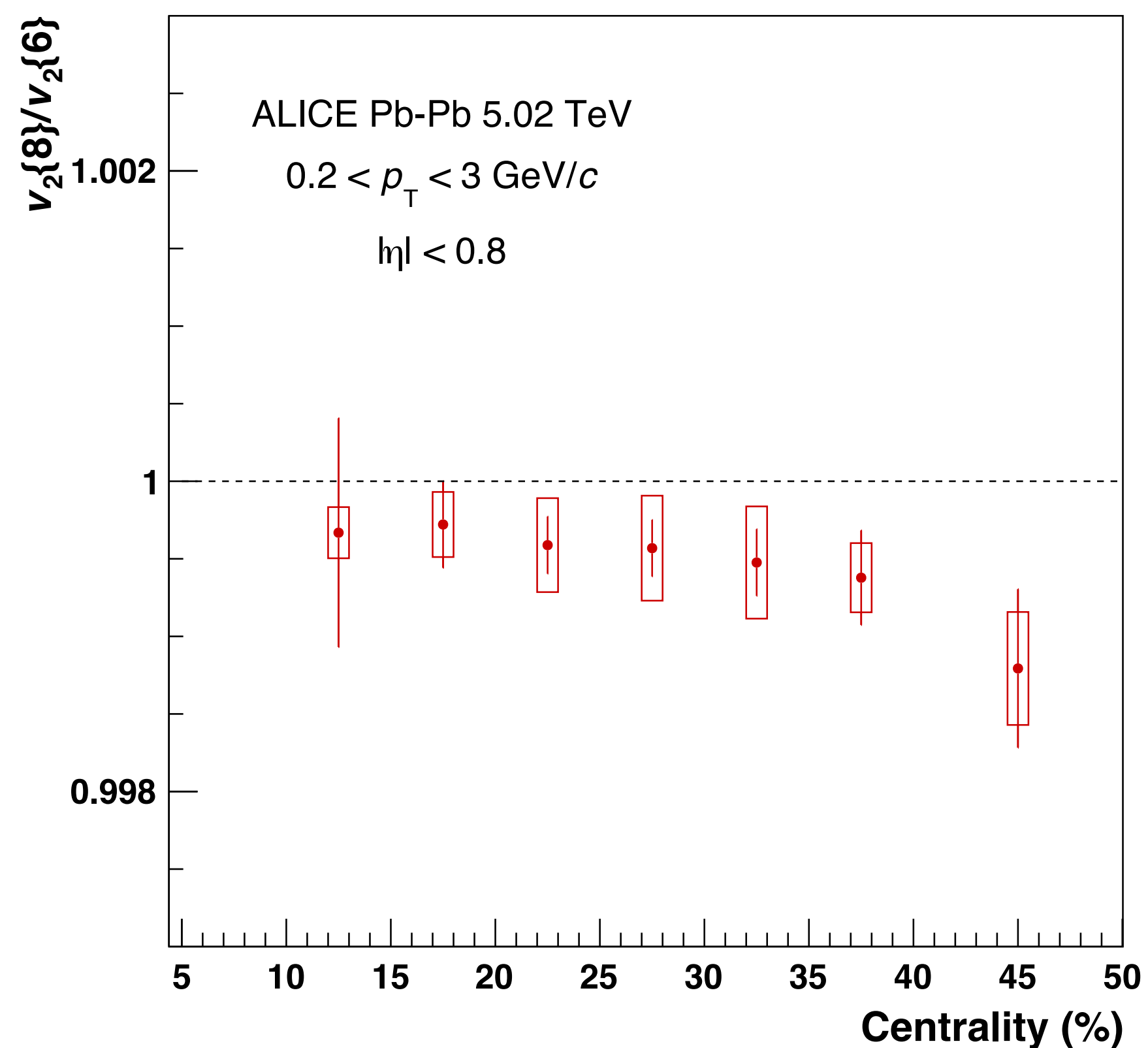
A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution

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



Fluctuations and initial conditions



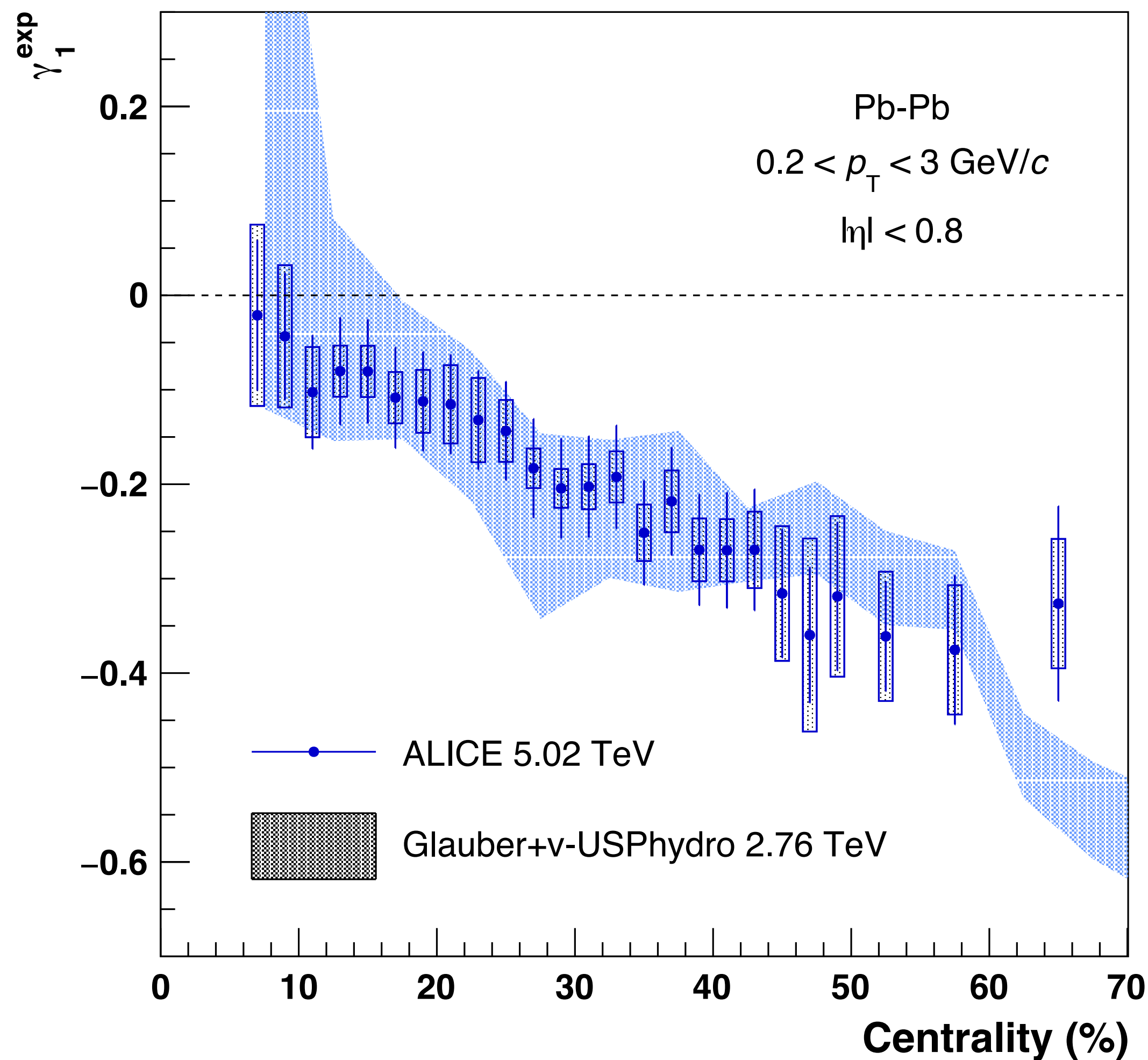
A fine splitting is observed between $v_2\{8\}$ and $v_2\{6\}$

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

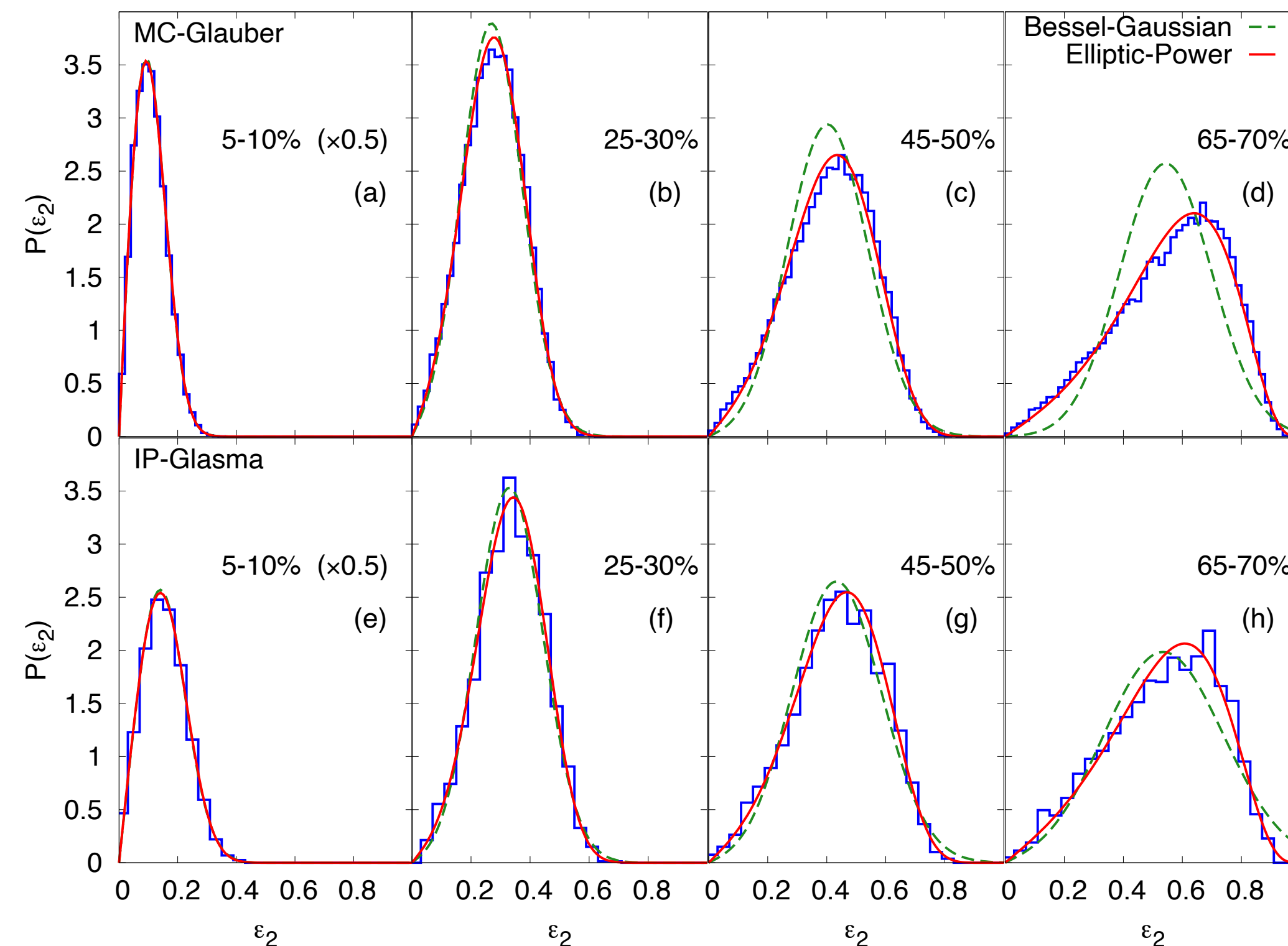
Higher order contributions are constrained in the equality

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

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



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

$$v_2 \propto \epsilon_2$$

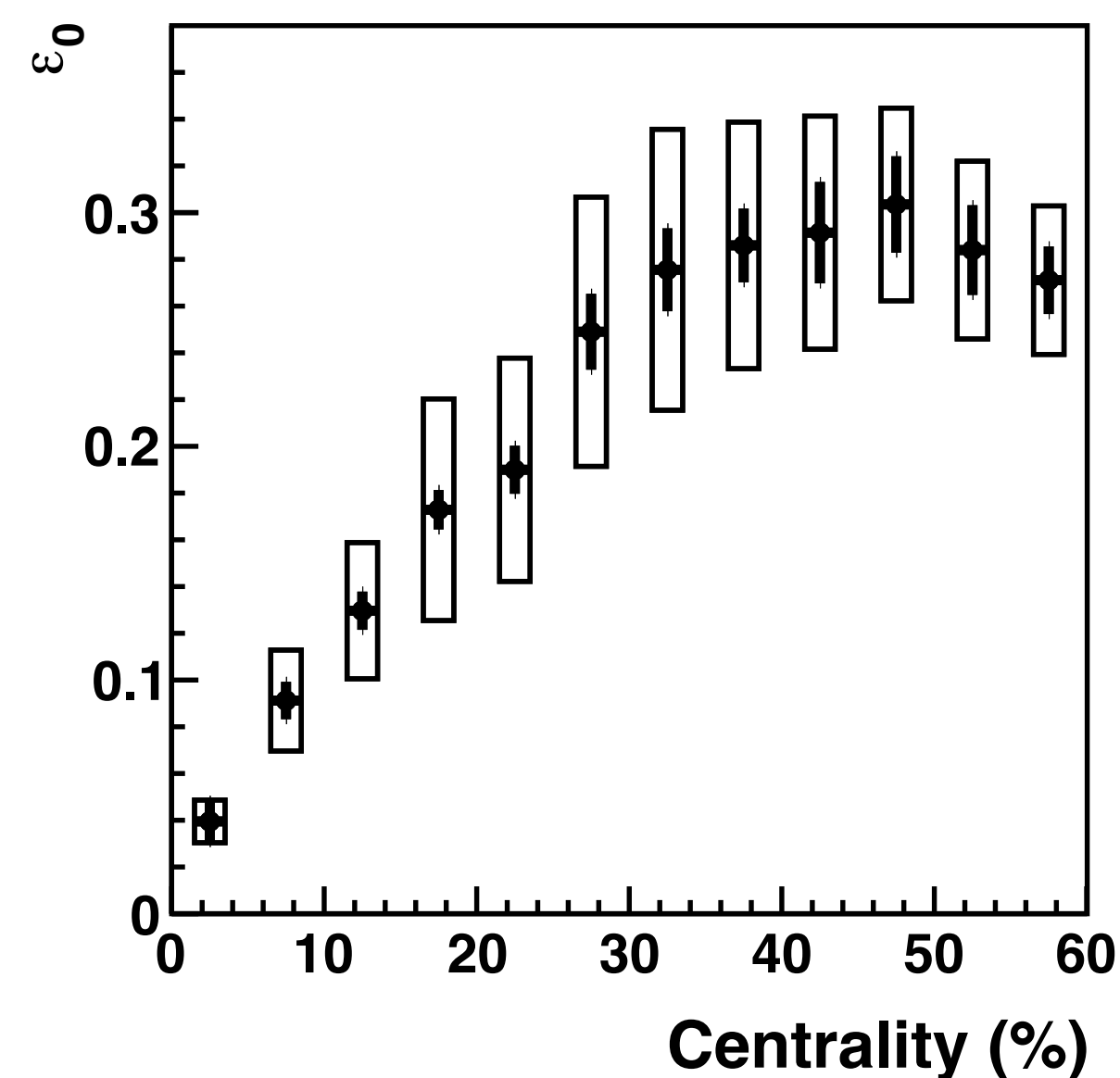
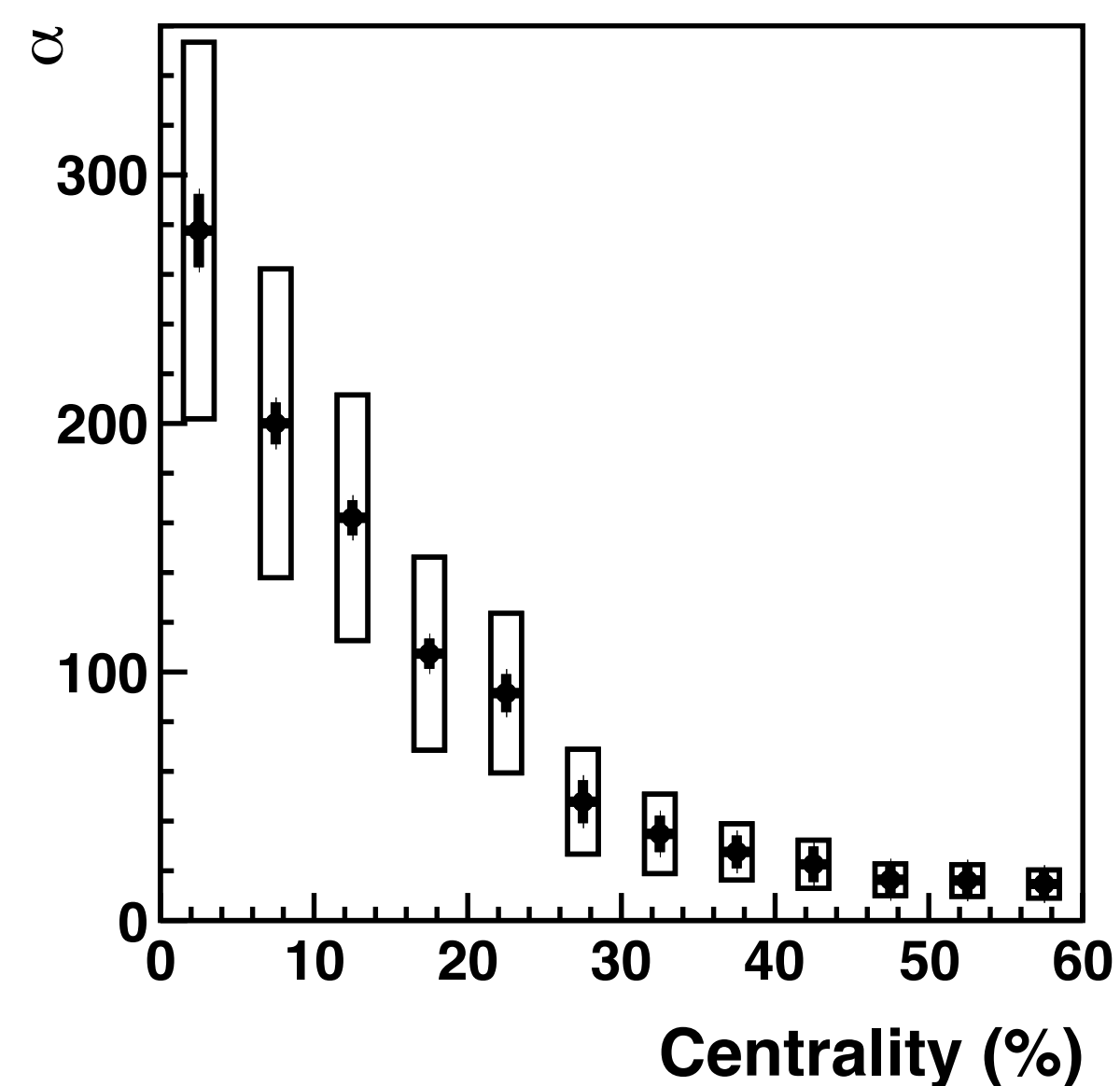
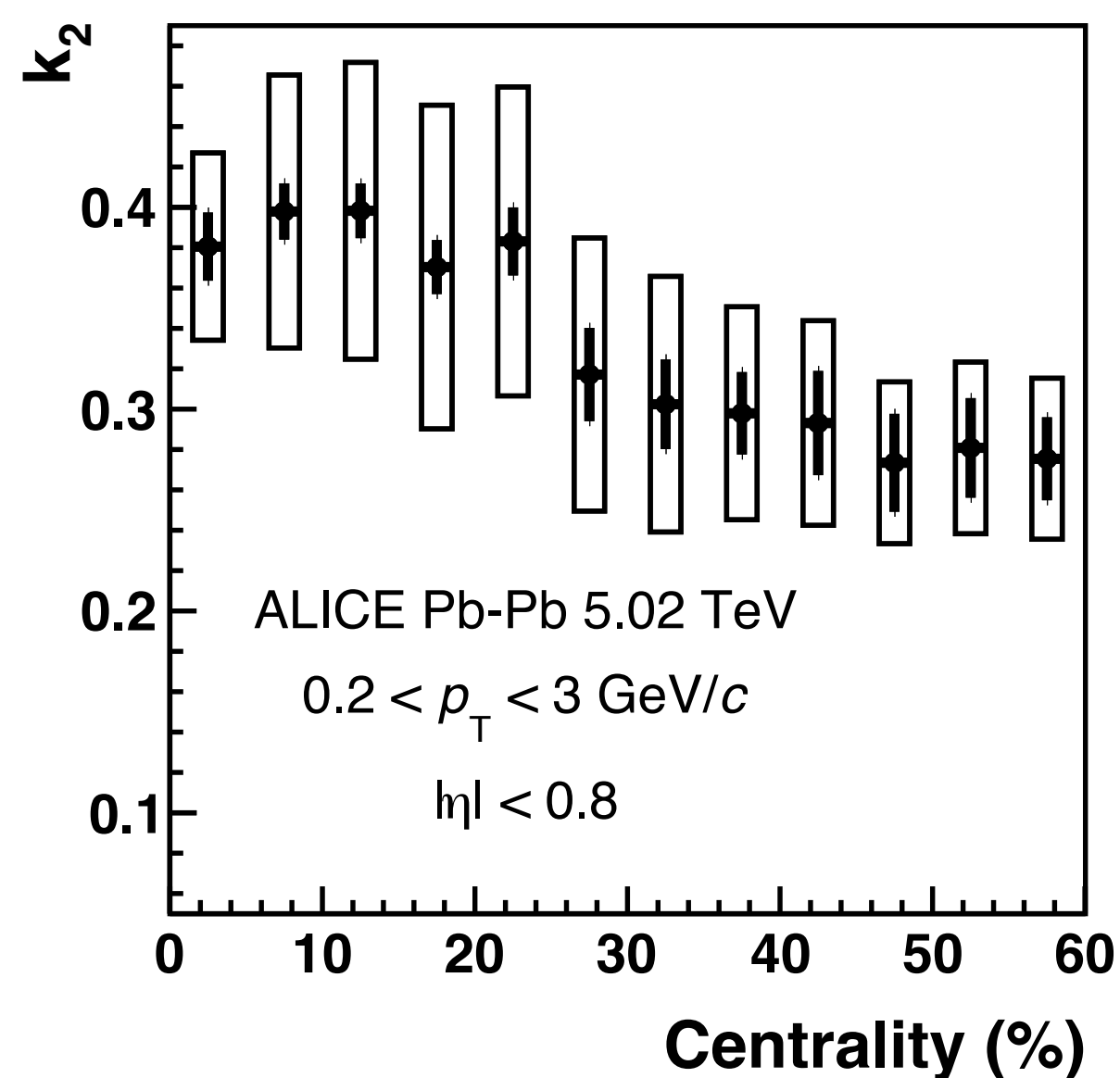
$$v_2 \propto \varepsilon_2$$

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 ; $v_2 = k_2 \varepsilon_2$

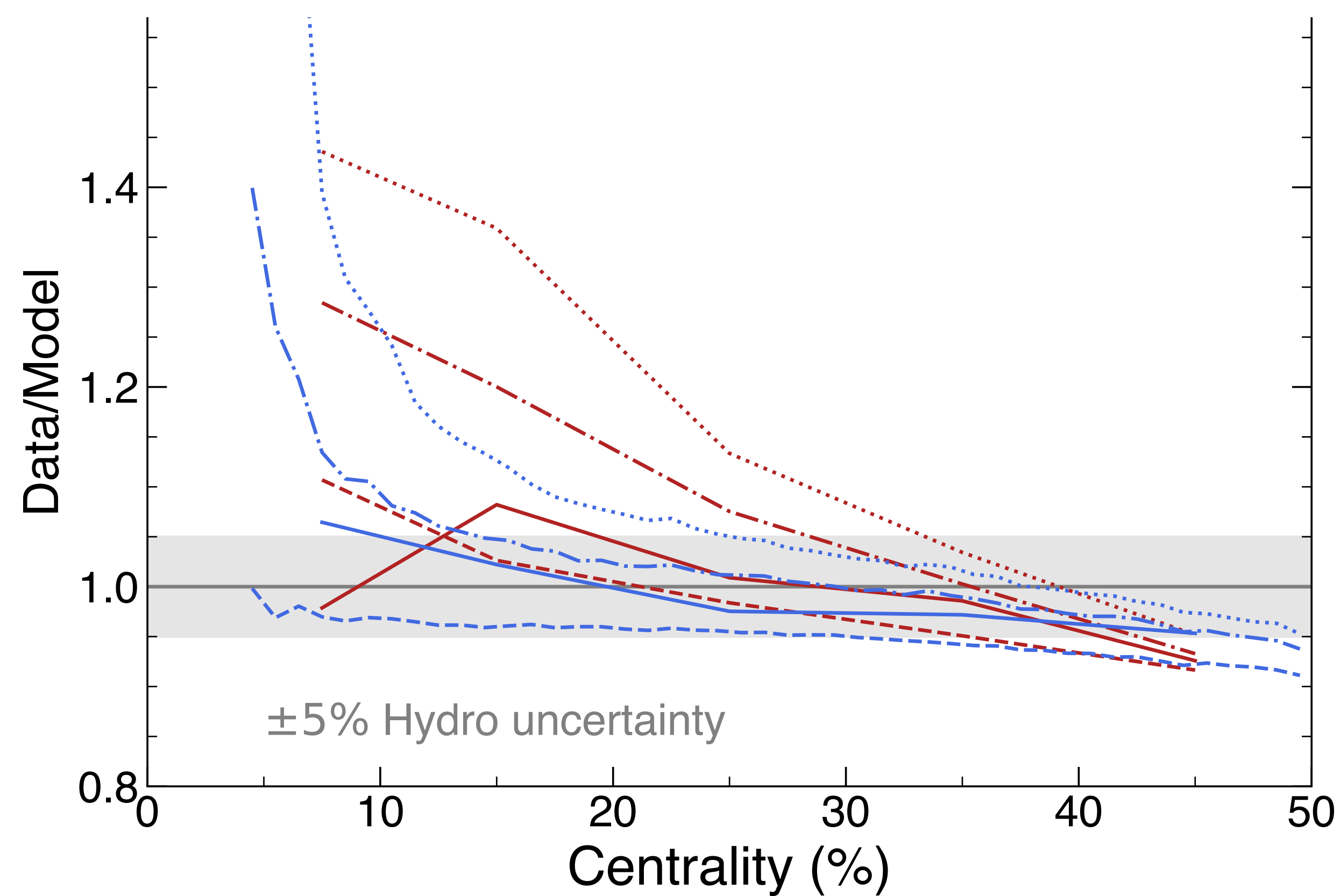
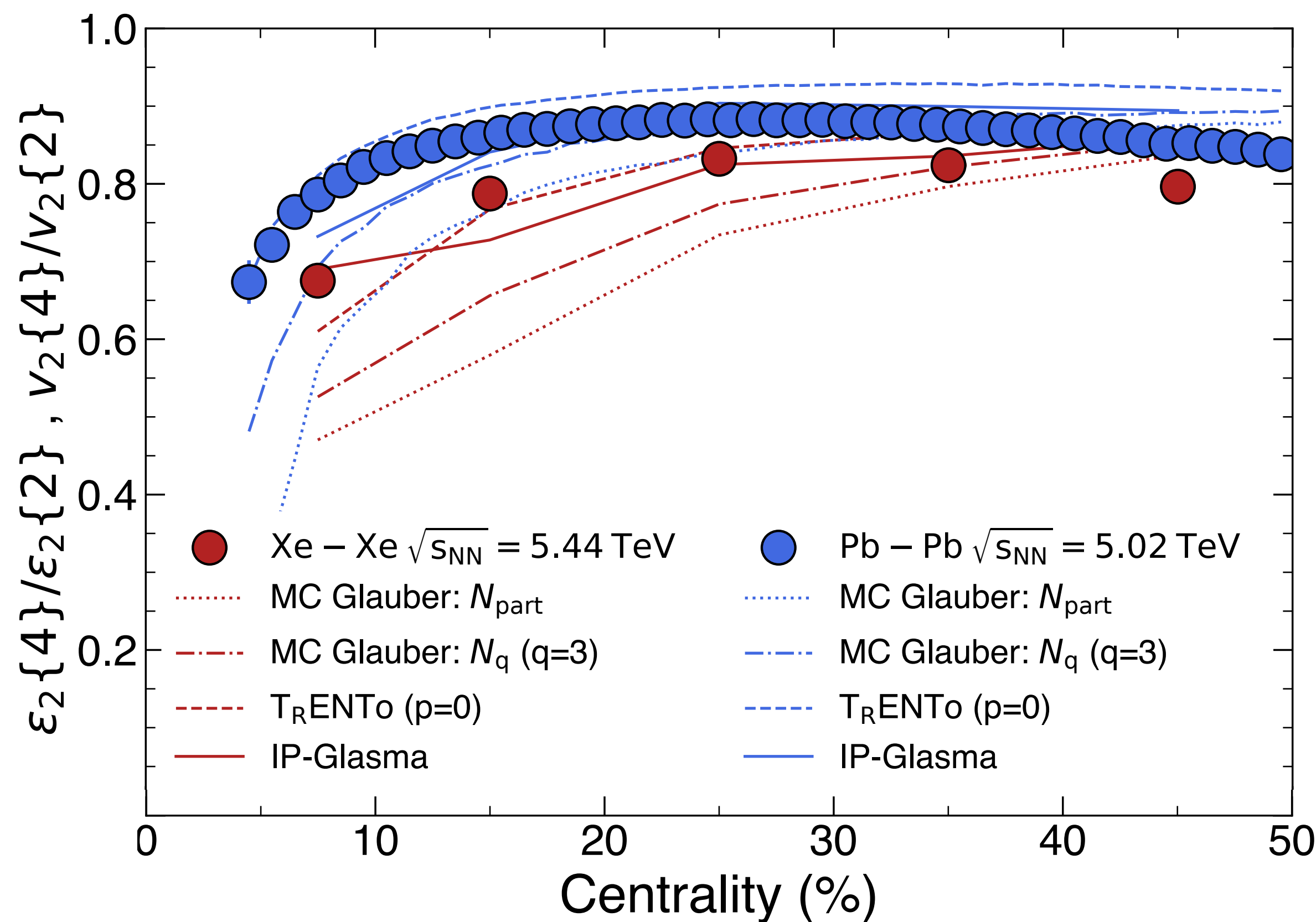




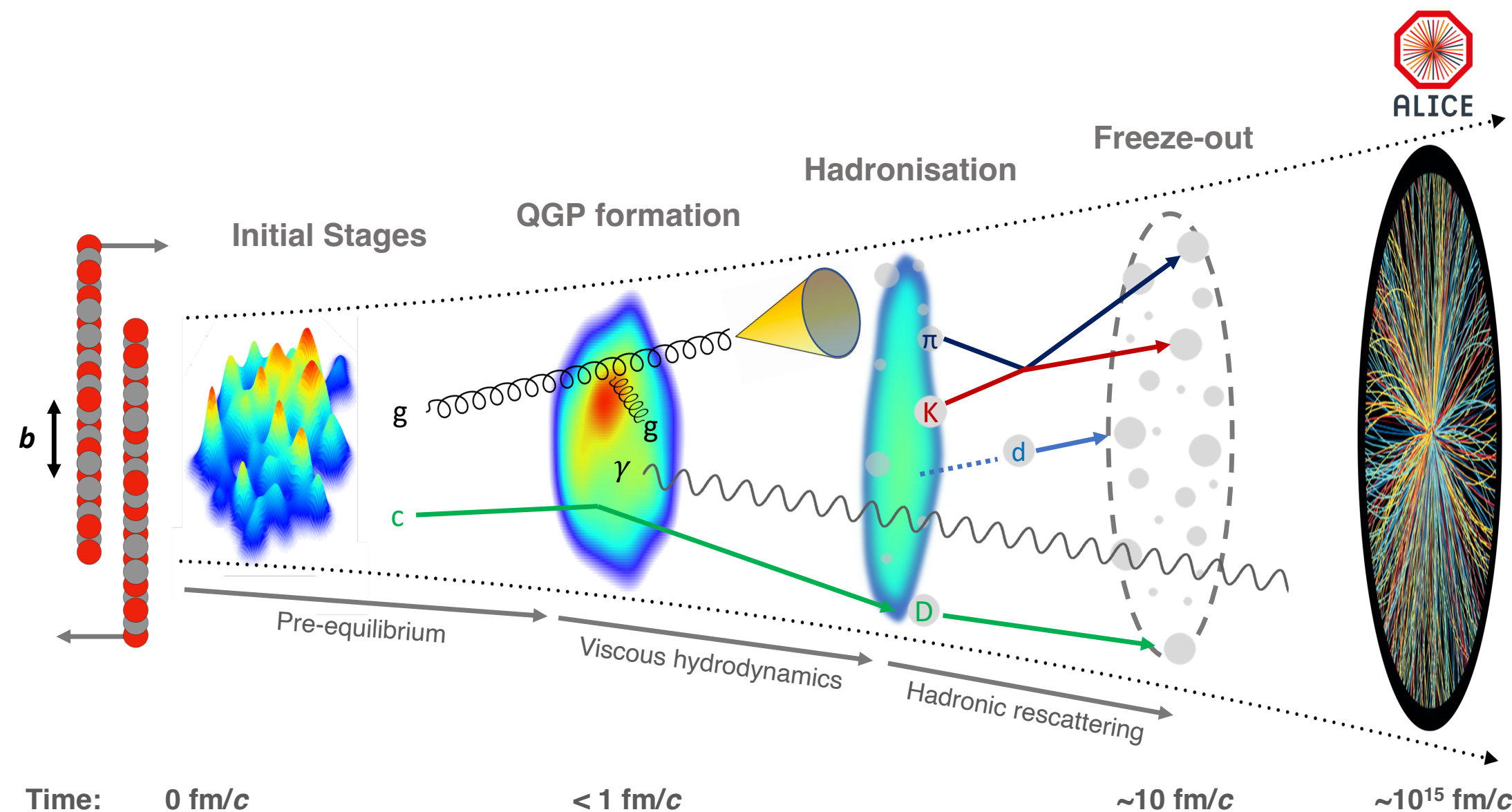
Fluctuations and initial conditions

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

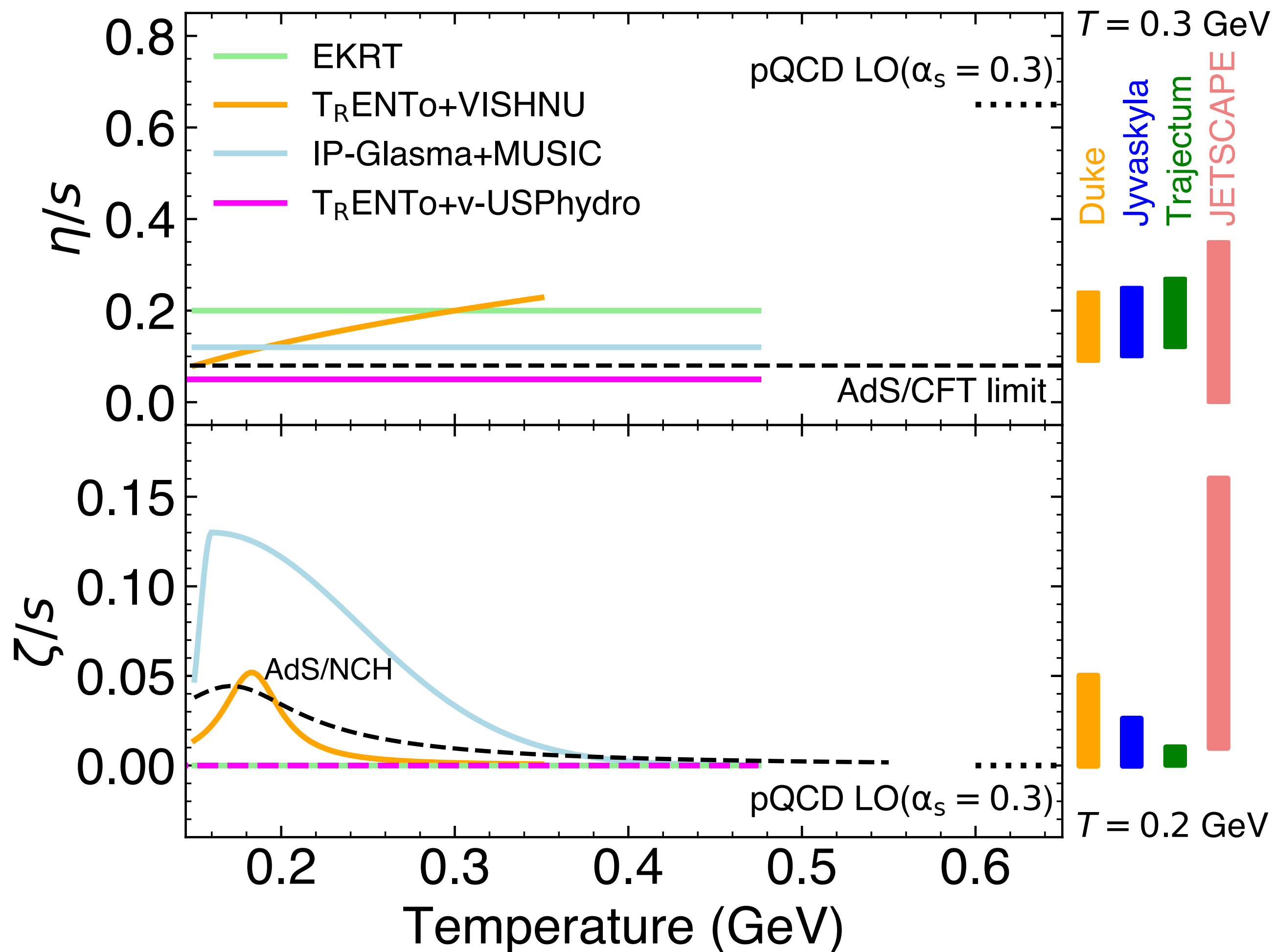
$$v_2\{4\} \propto \varepsilon\{4\}$$



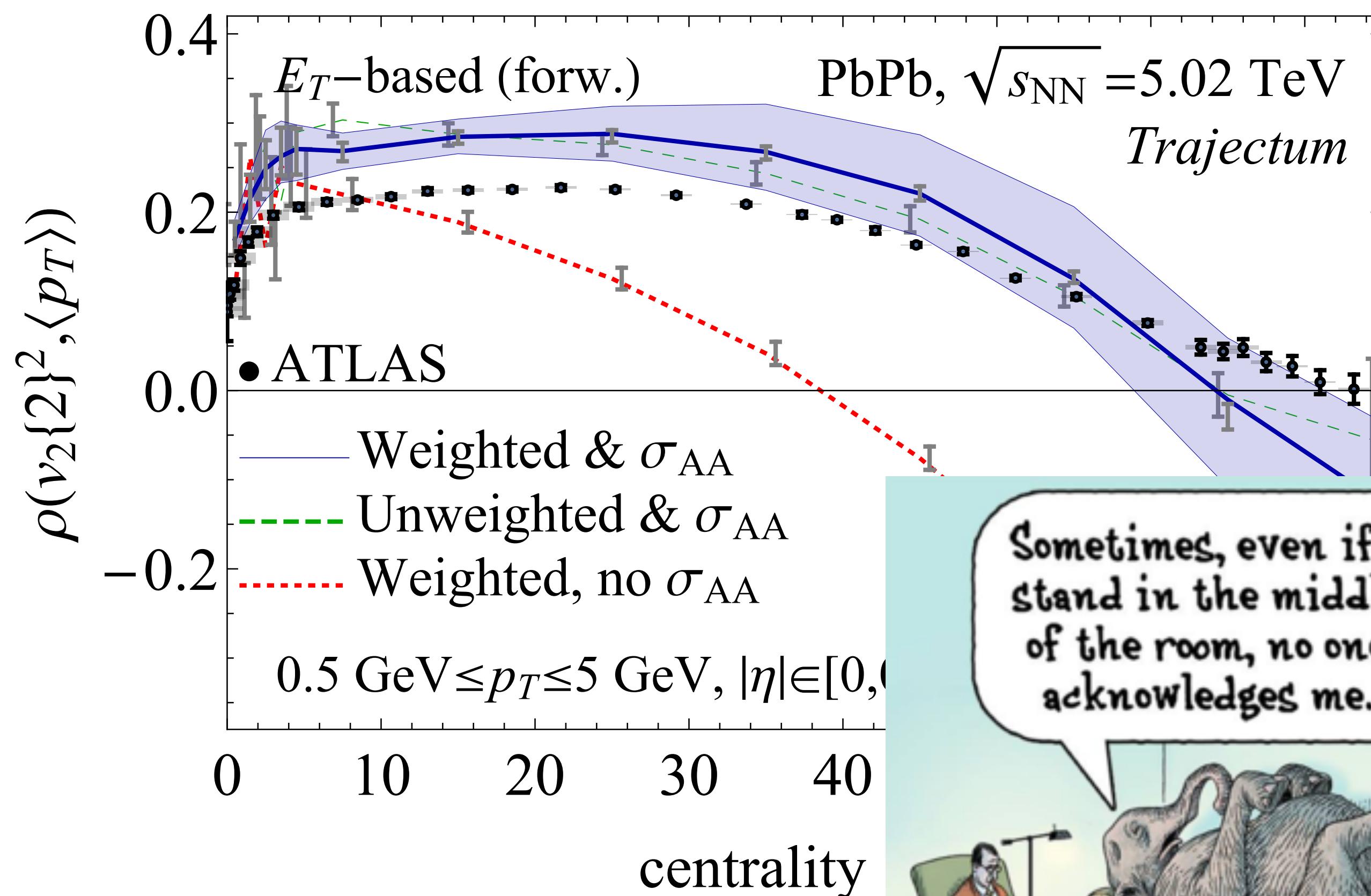
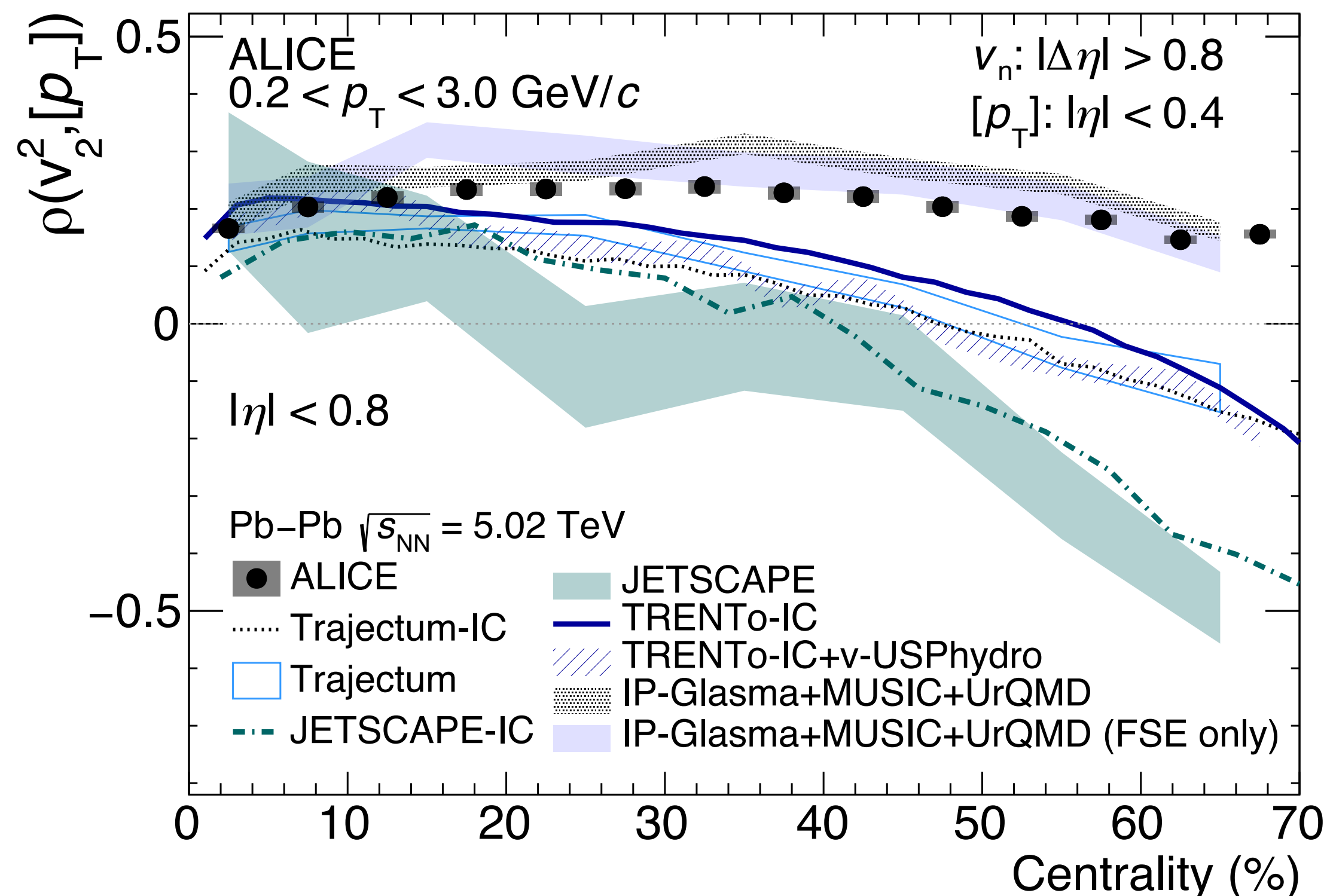
TR-ENTo ($p=0$) and IP-Glasma initial conditions describe measurements best

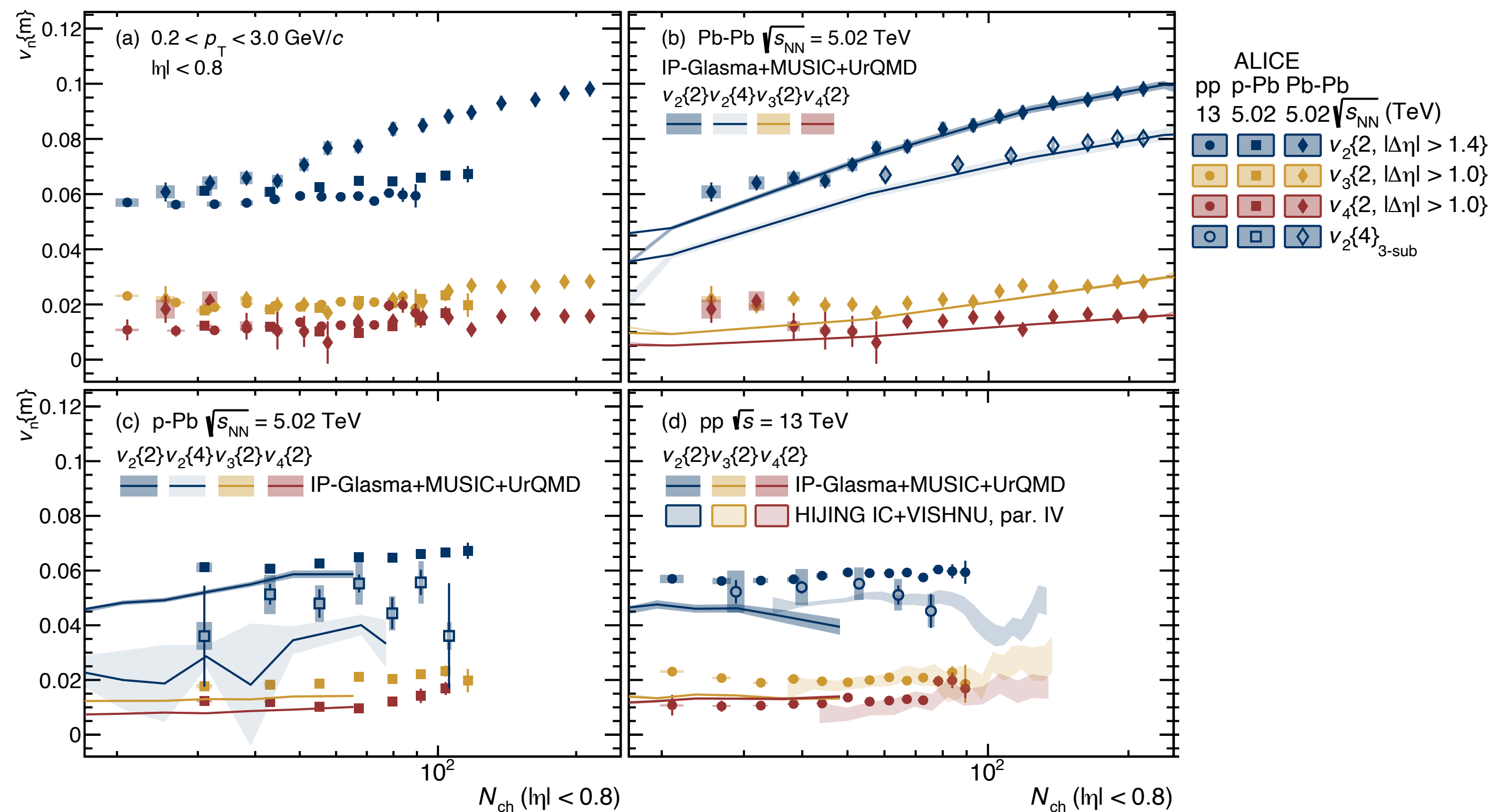
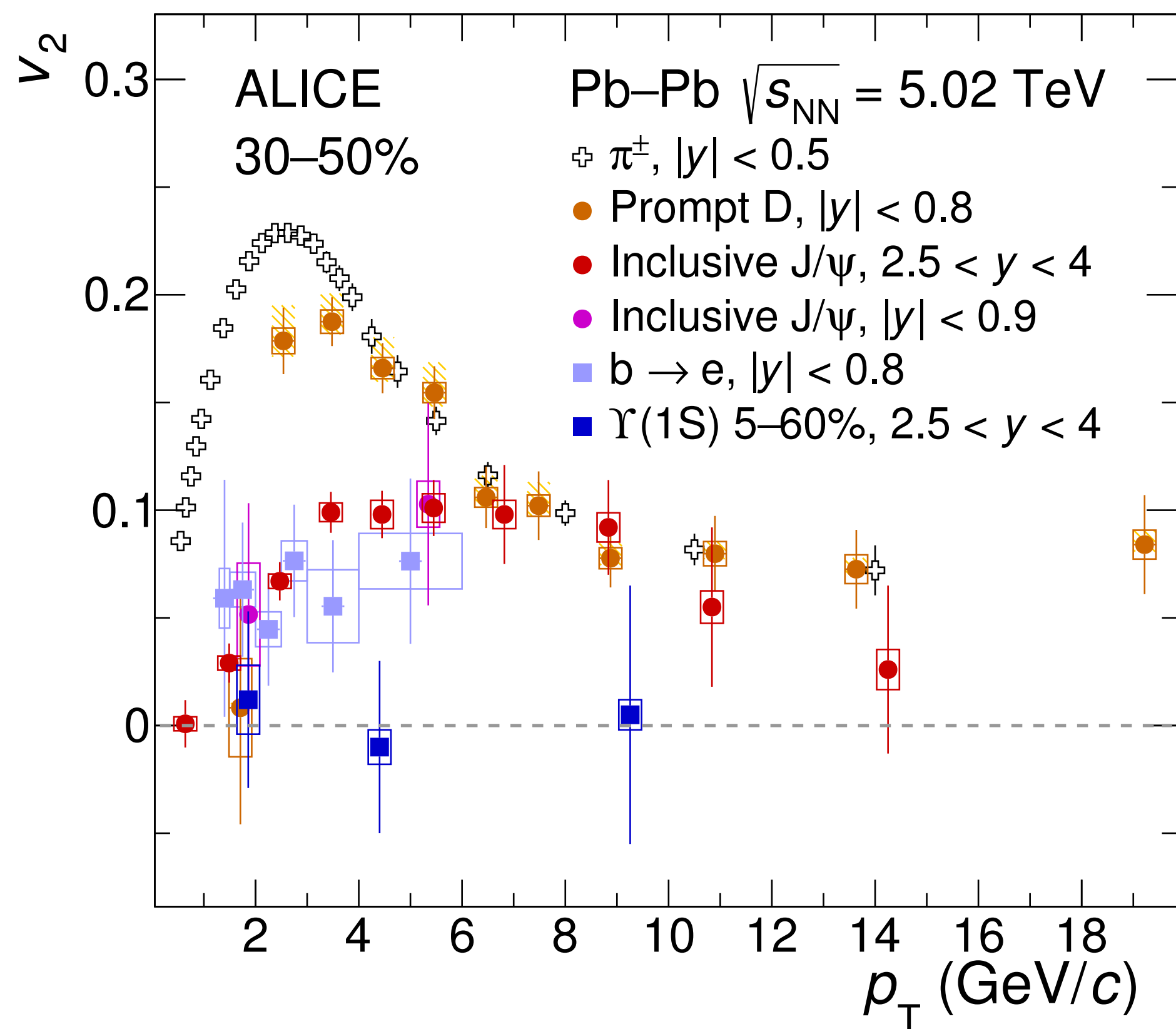


- Hybrid model description of heavy-ion collisions can be constrained and tested
- Currently only limited number of observables used
- Inclusion more observables will likely also effects extraction of transport parameters

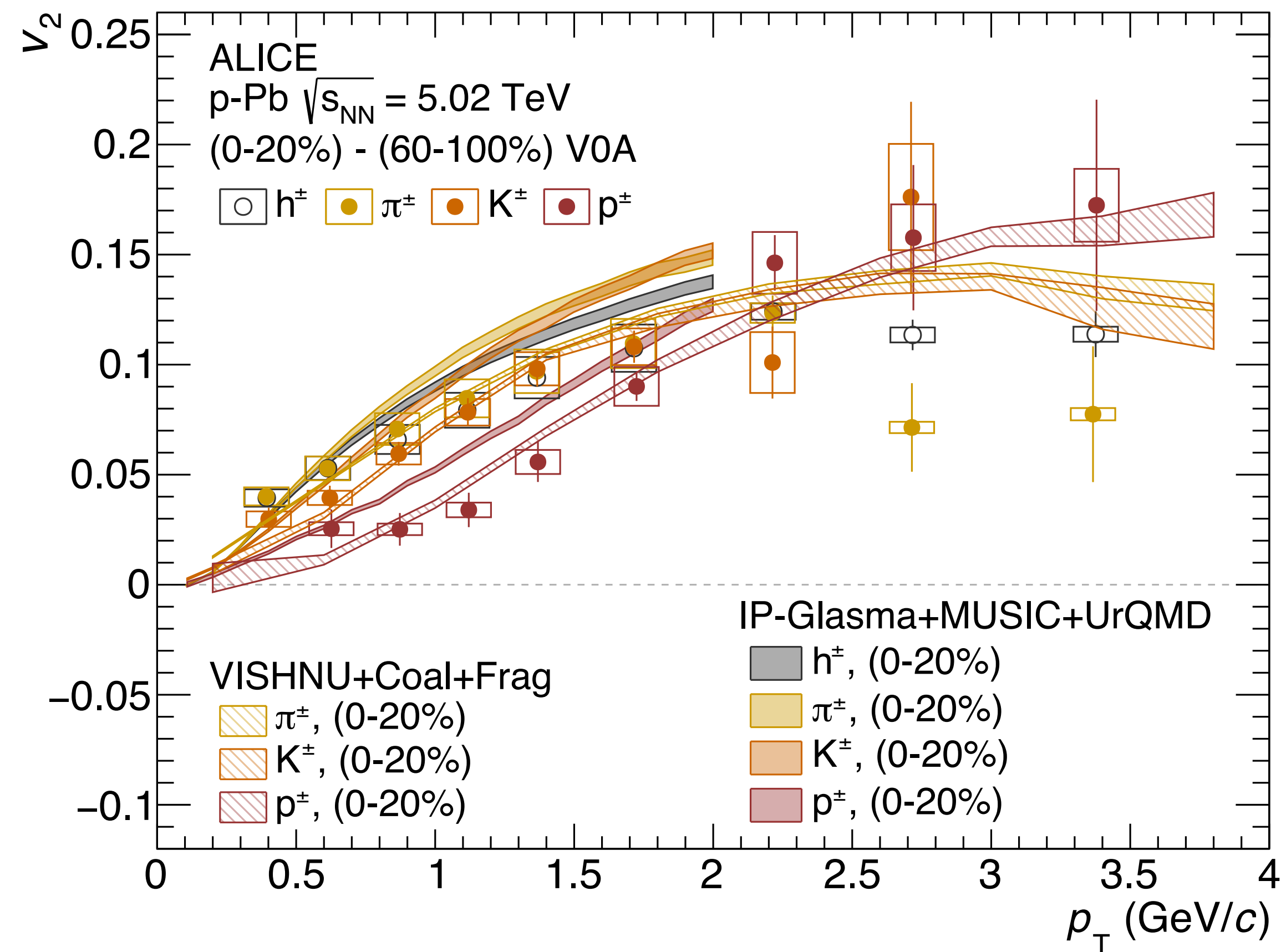
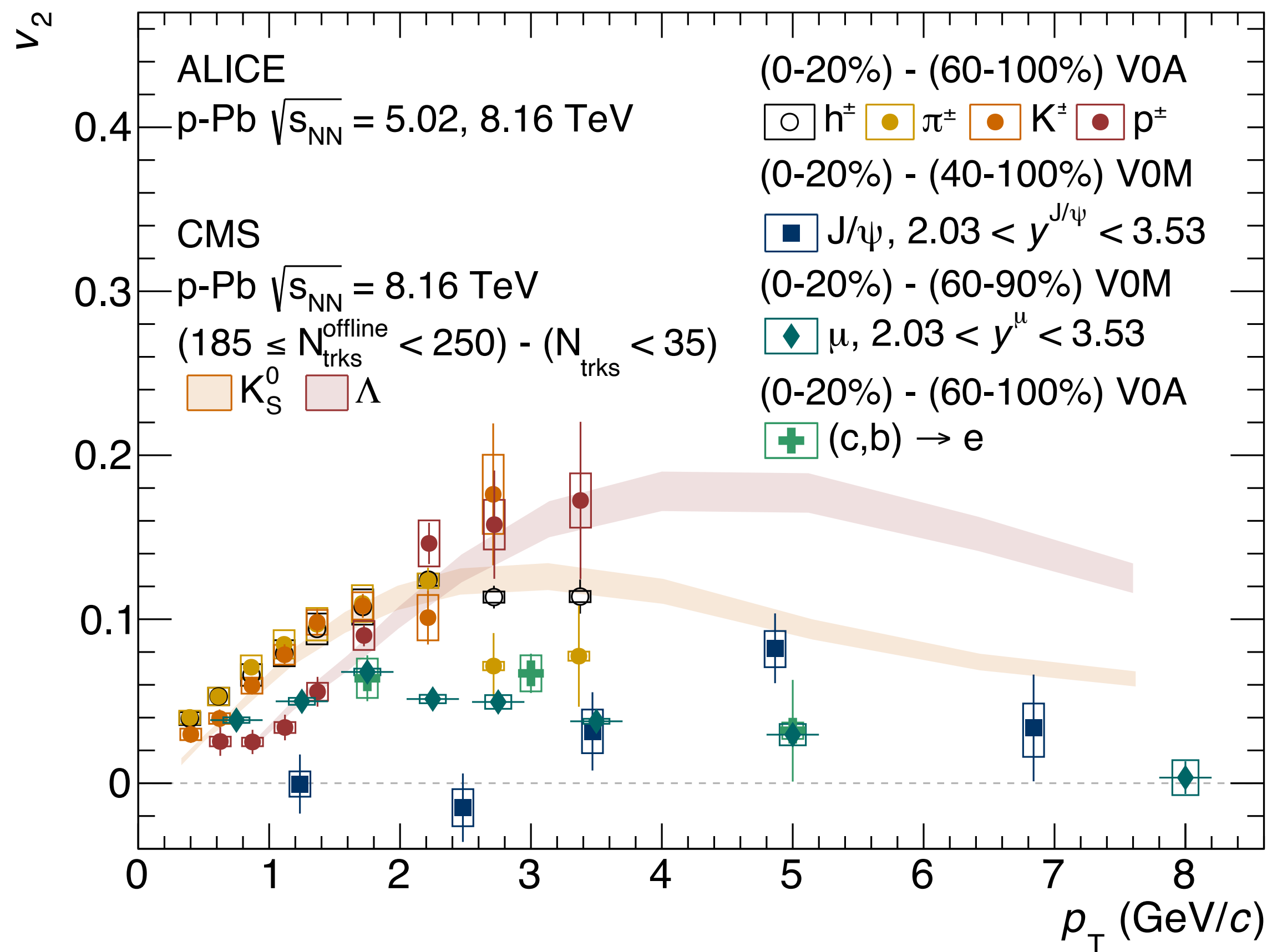


See updates in Govert Nijs and Wilke van der Schee
arXiv:2206.13522

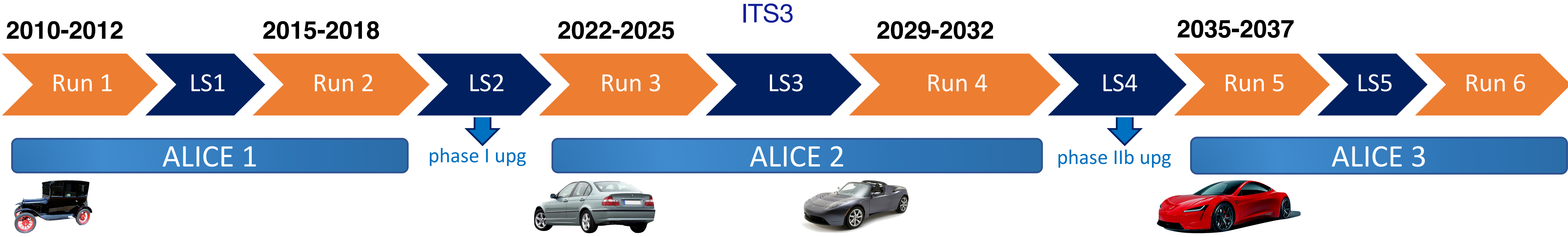




Still many open questions



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



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

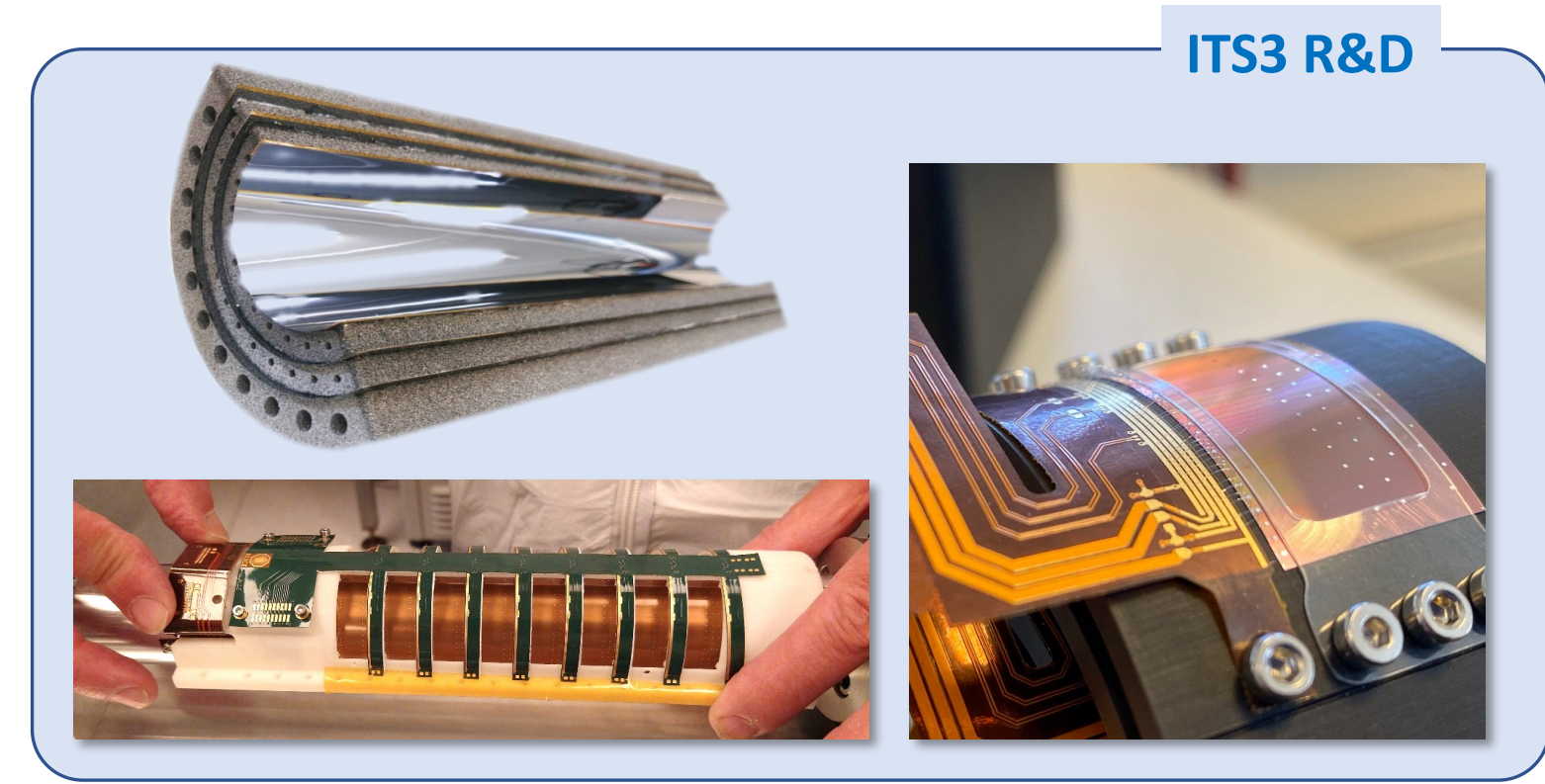
2026 – 2027: large-scale engineered prototypes (~75% of R&D funds) ⇒ Technical Design Reports

2028 – 2030: construction and testing

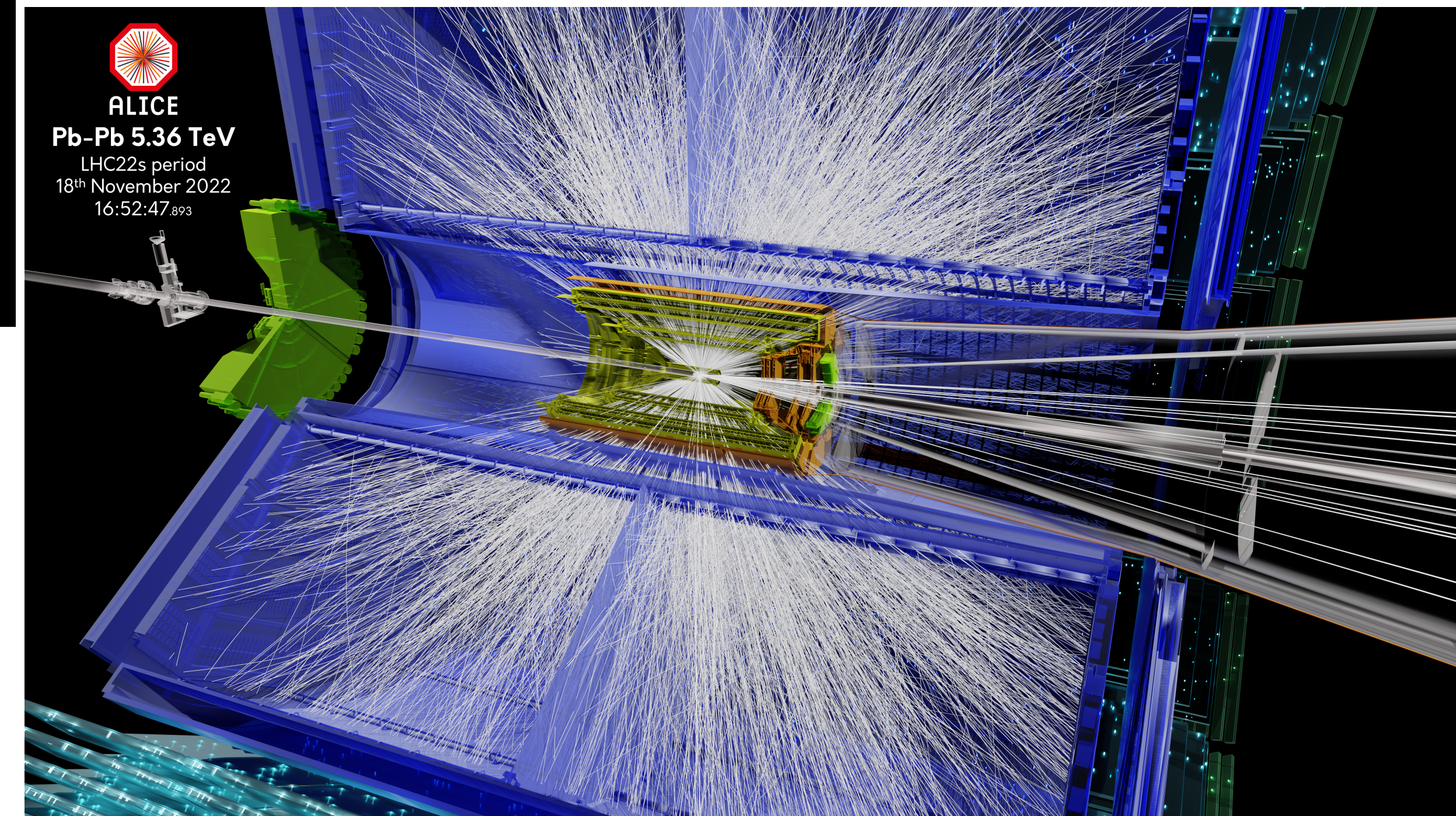
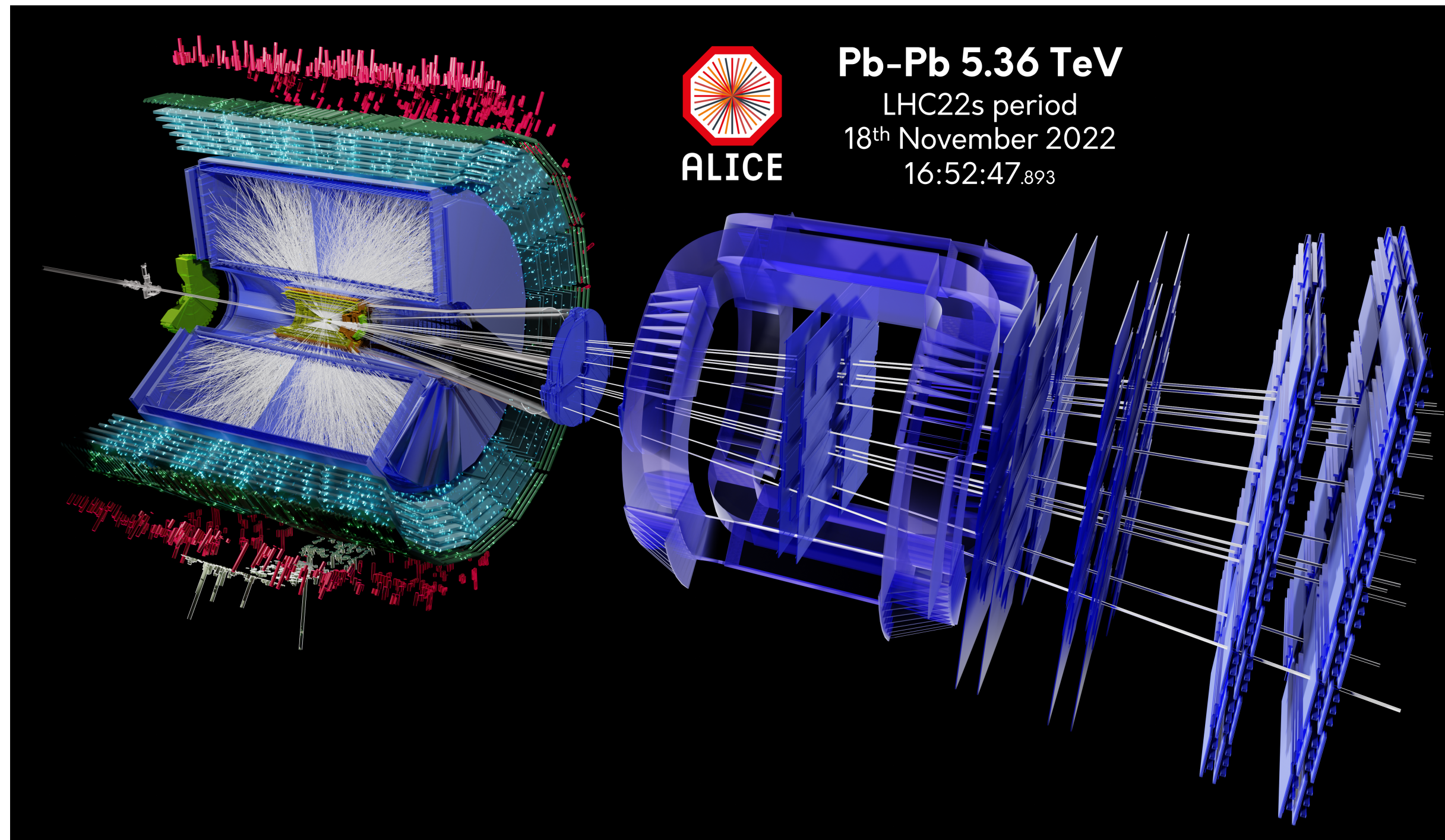
2031 – 2032: contingency

2033 – 2034: installation and commissioning

2035 – 2042: physics campaign



ITS3 Lol:
ALICE 3 Lol:



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

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

Excellent electron and hadron identification (TOF + RICH)

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

Muon identification (Muon absorber + Muon chambers)

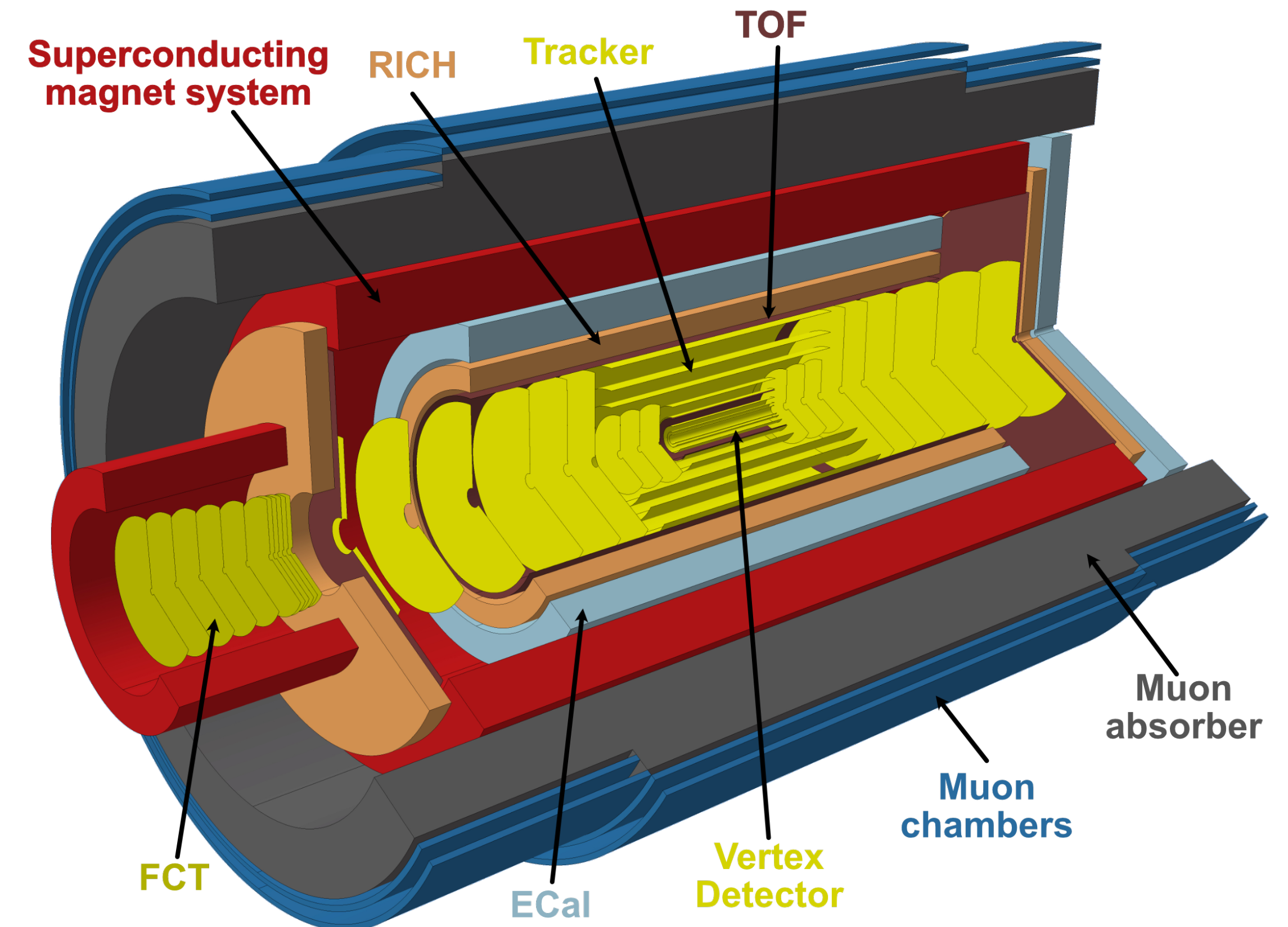
- Muon ID down to $p_T \approx 1.5 \text{ GeV}/c$

ECAL

- Photons/jets over large η

Superconductor magnet system (2T)

Continuous read-out and online processing

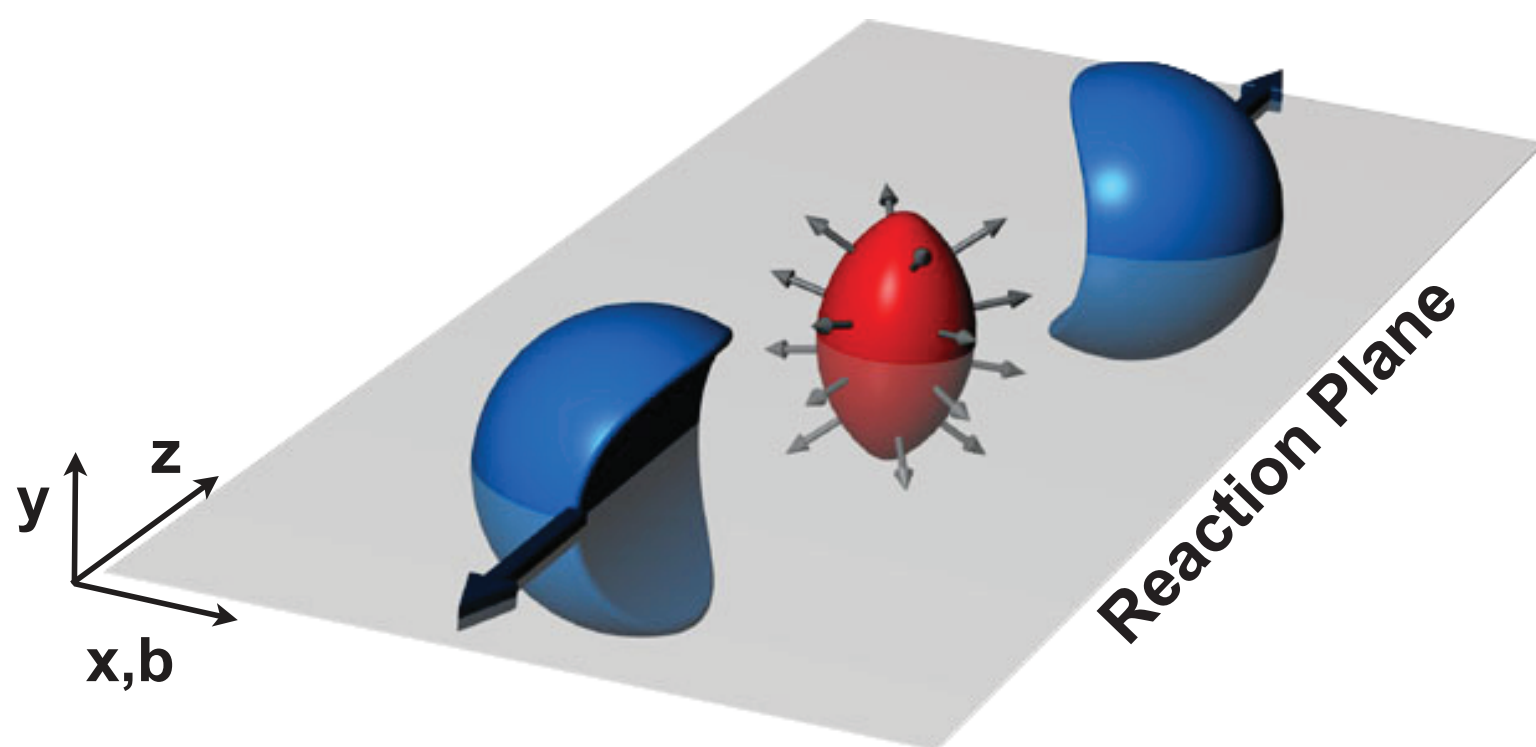


Unique Detector Concept and Features at the LHC



Thank you Art!

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



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