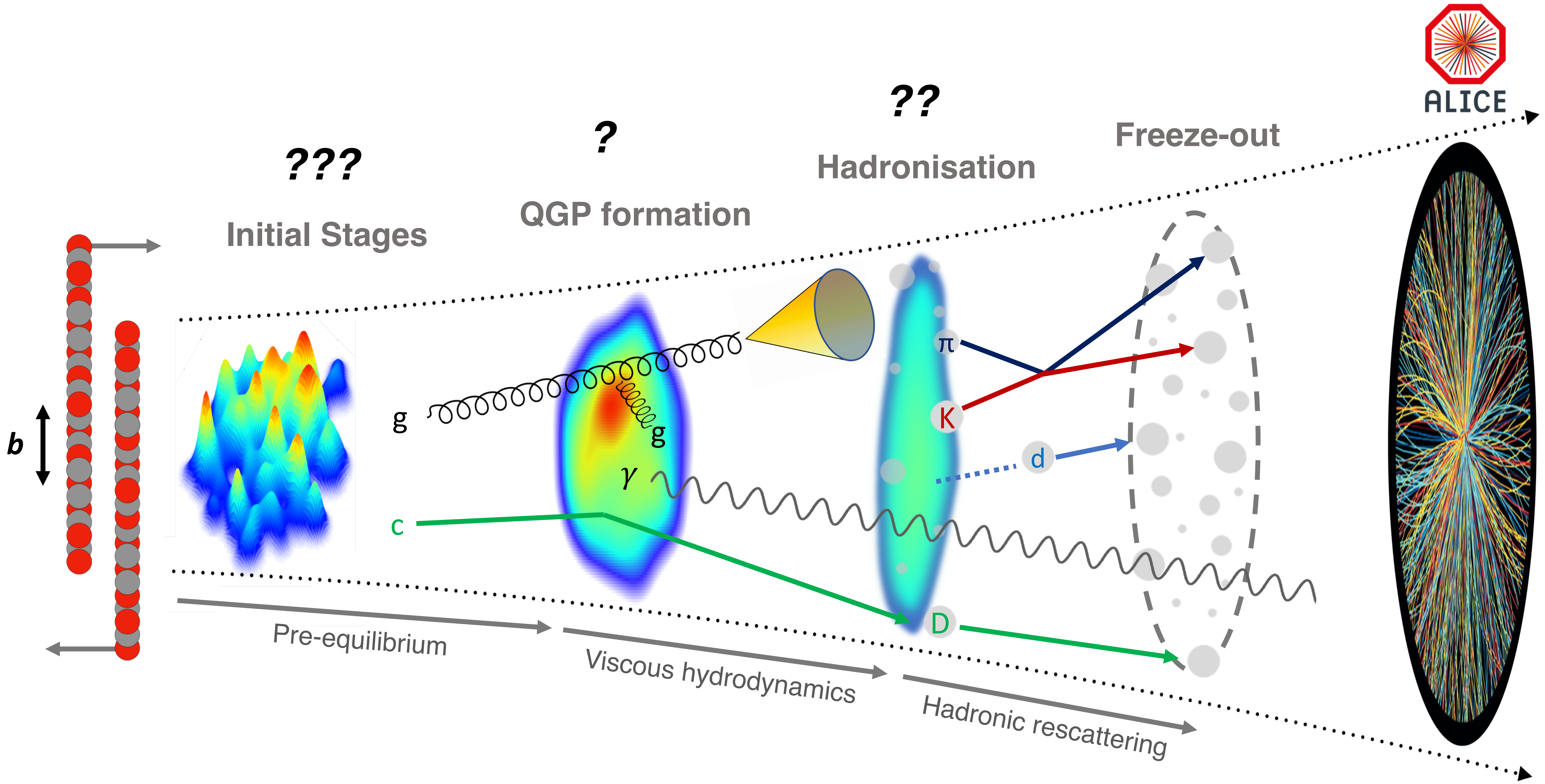
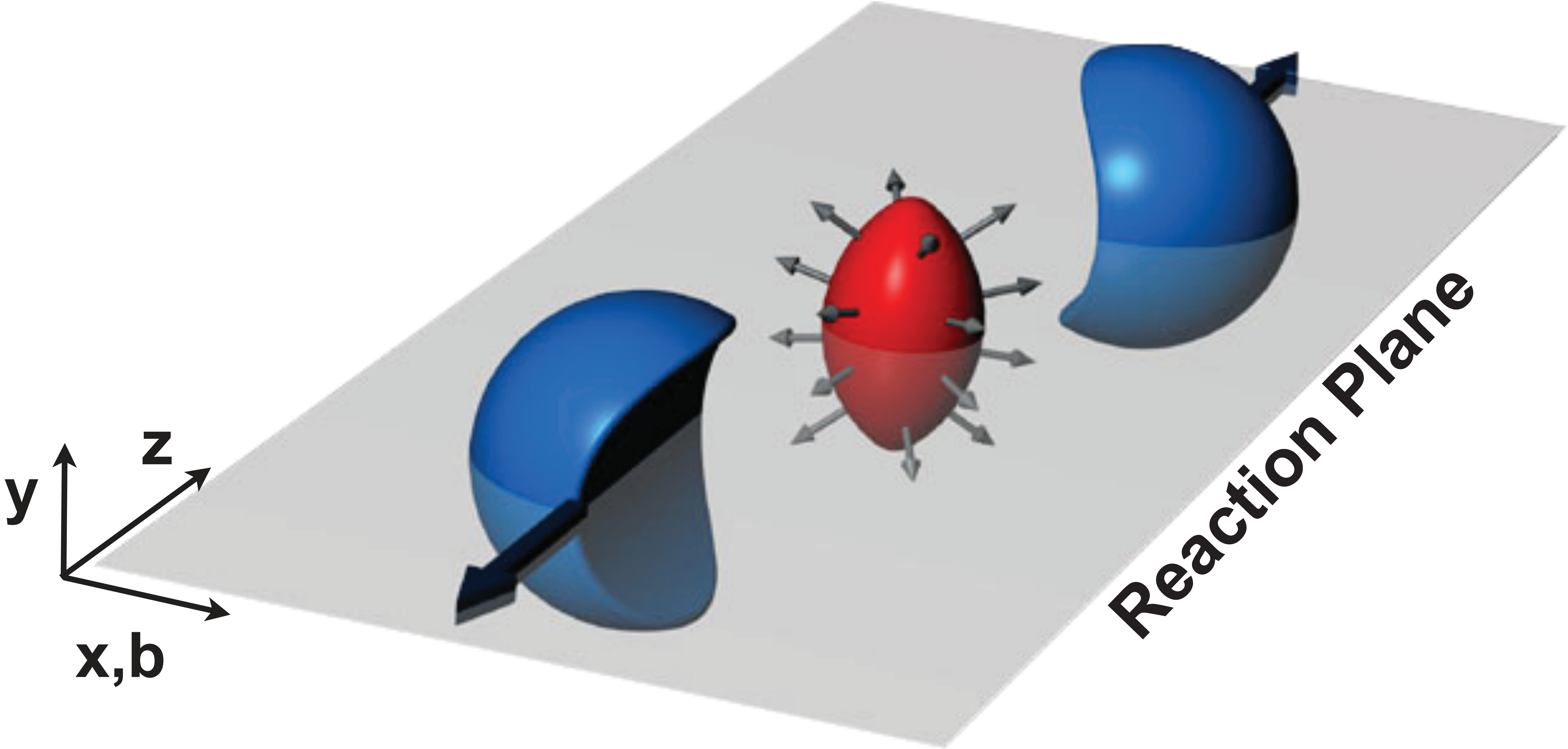
(Anisotropic) Flow; Quo Vadis

Raimond Snellings

Heavy Ion Collisions



Time: 0 fm/*c* < 1 fm/*c* ~10 fm/*c* ~10^{15} fm/*c*



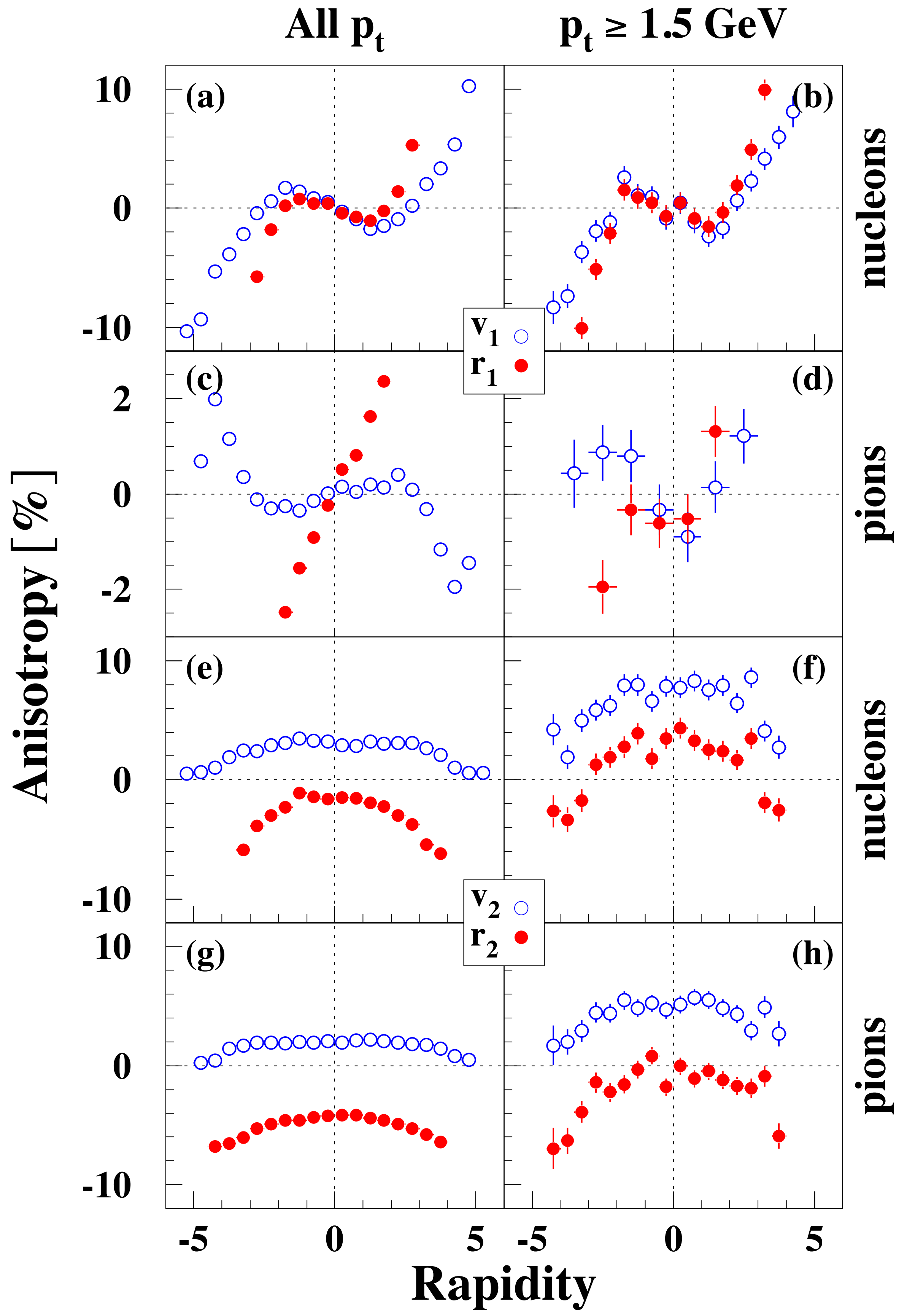
The traditional picture

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

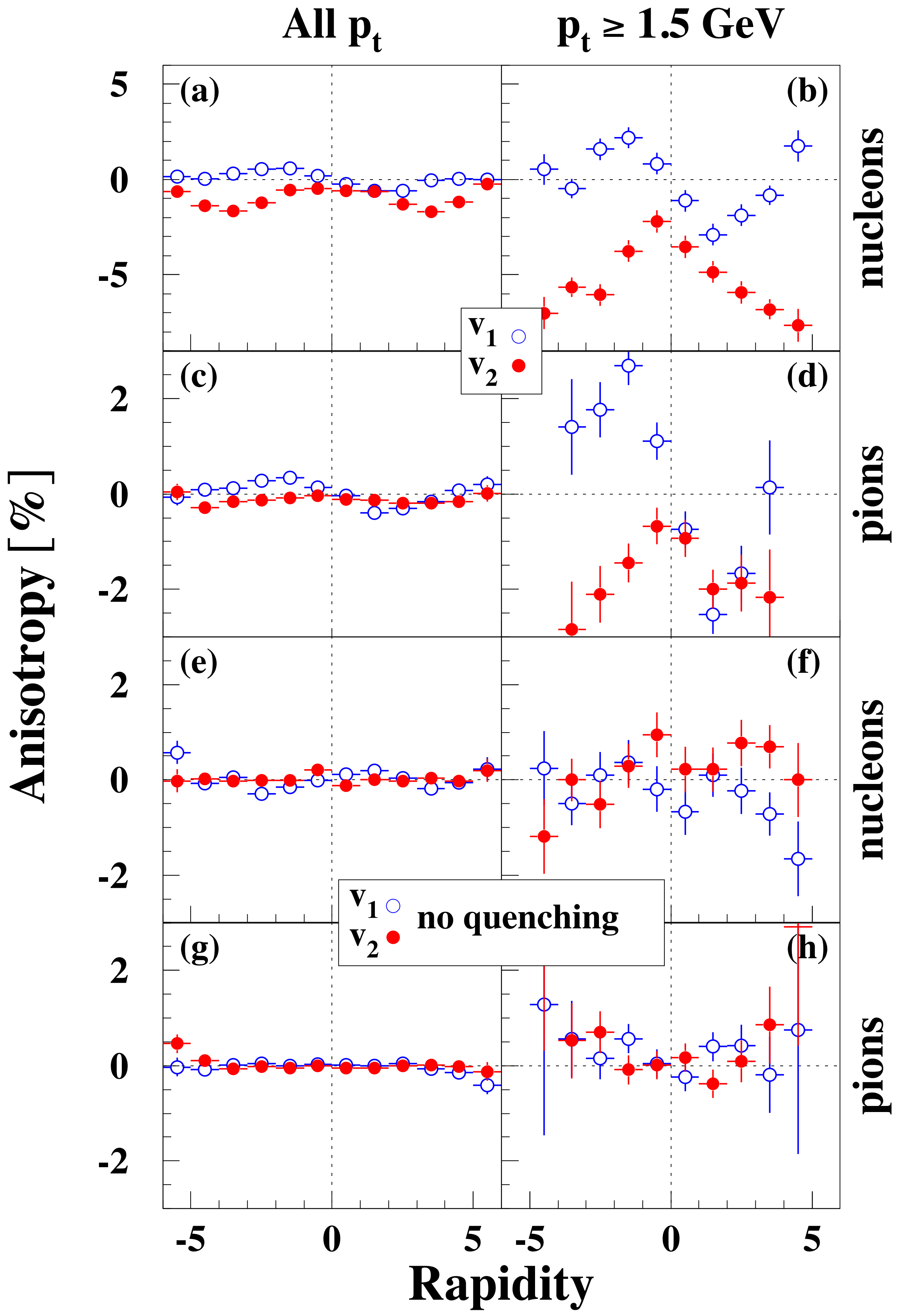
v_n depends on EoS, transport parameters, initial conditions

Anisotropic Flow (pre-RHIC)

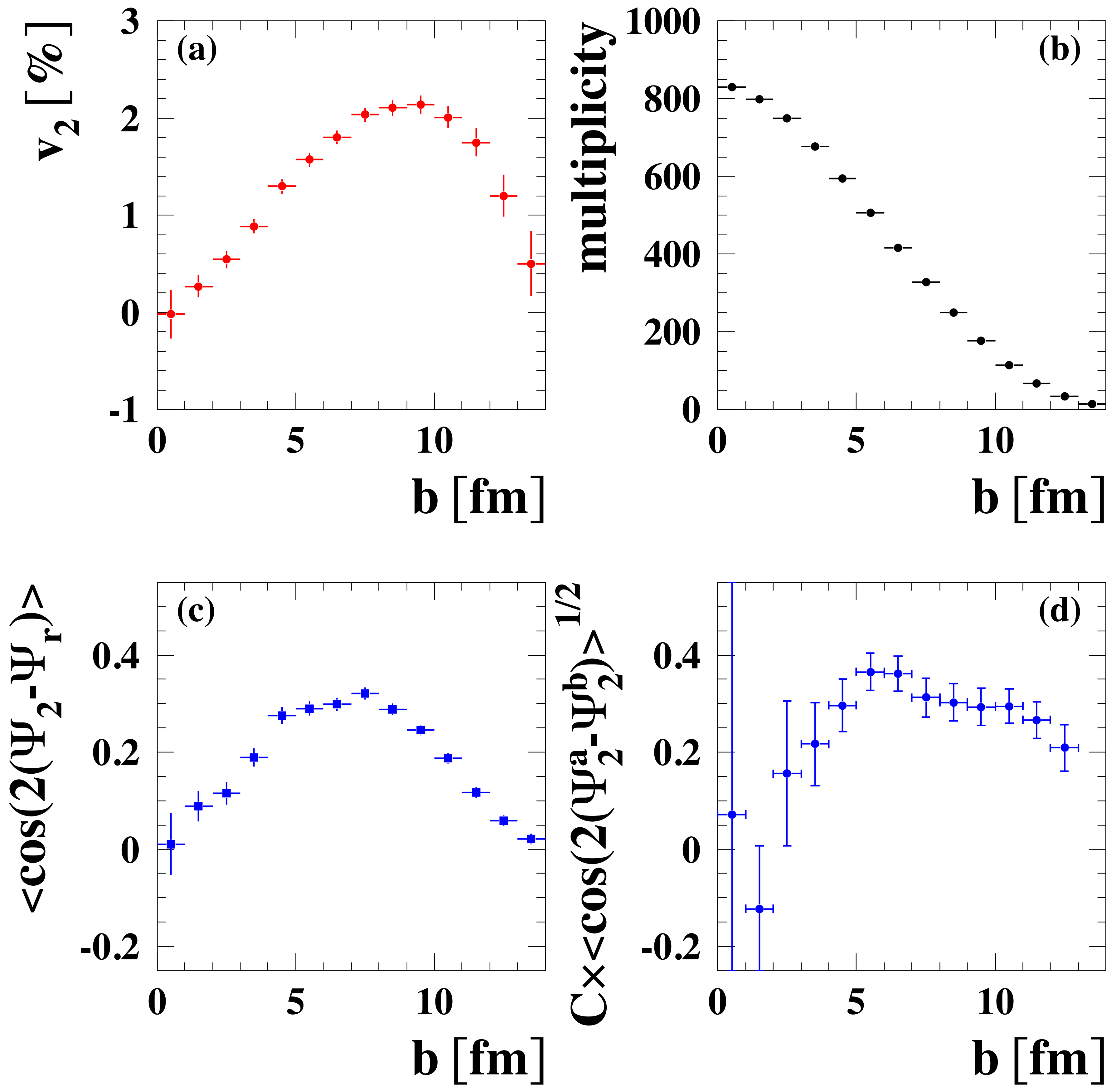
RQMD



HIJING



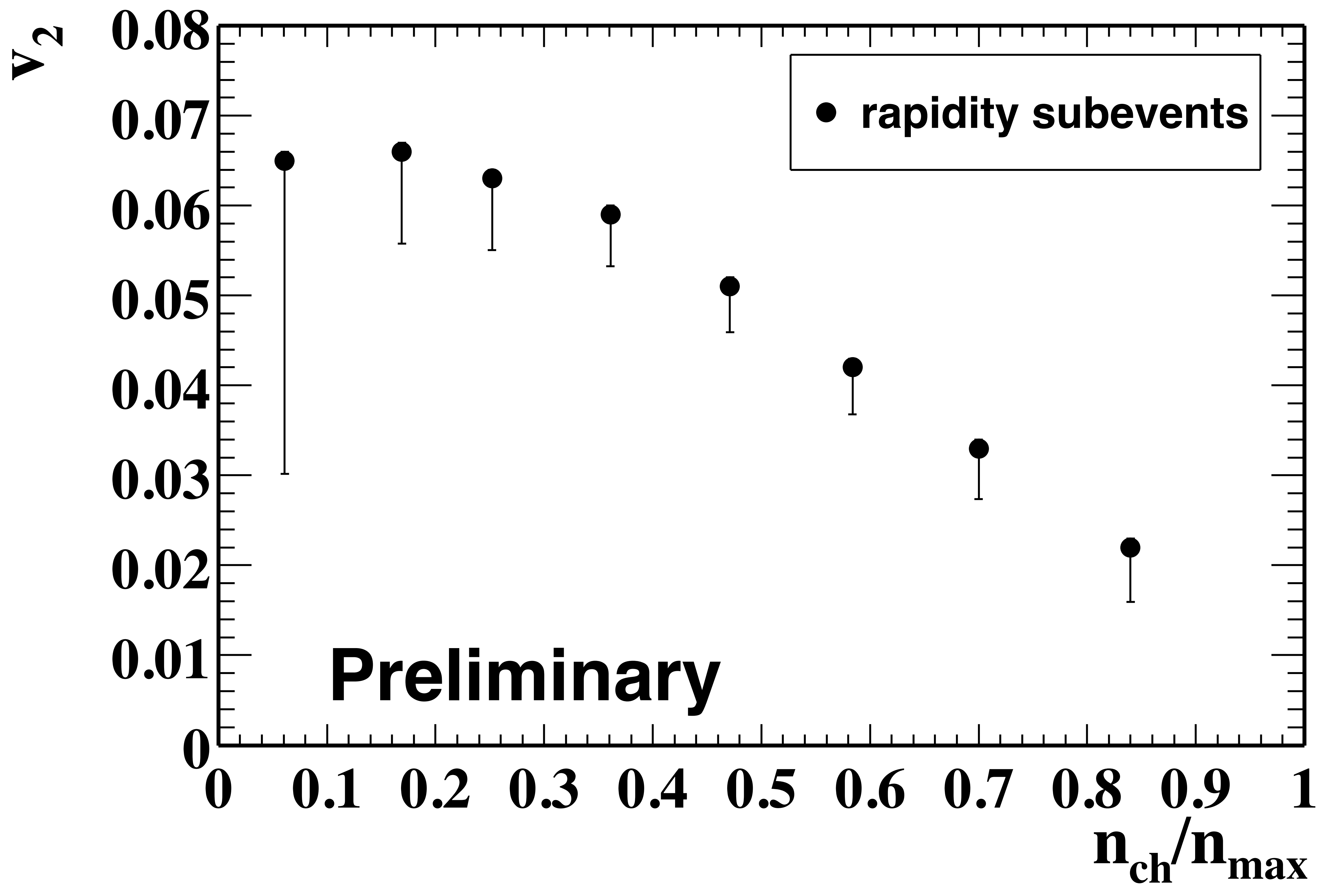
RQMD

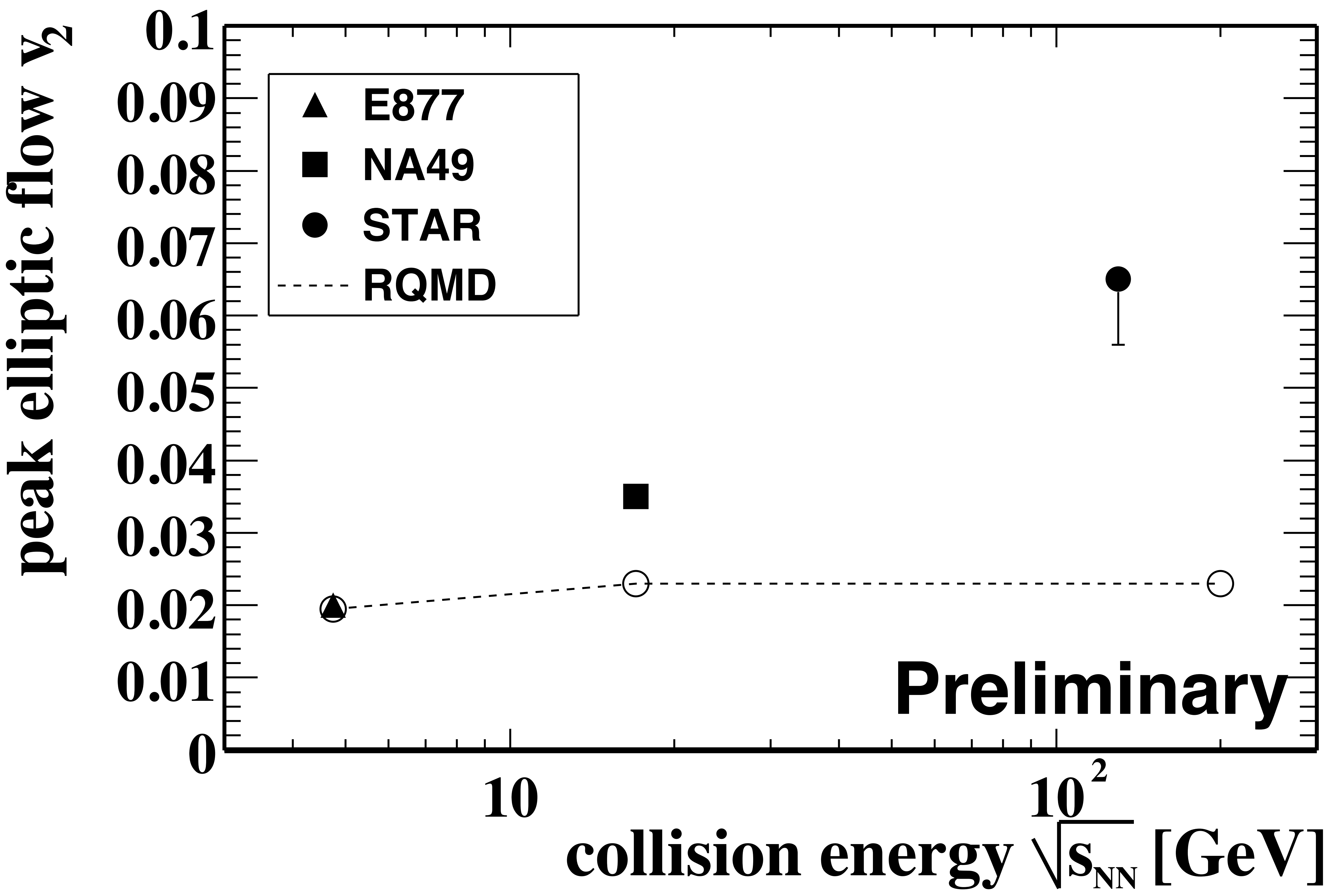


we only need the momenta of the charged hadrons and thus anisotropic flow could be one of the first results from STAR. For future analyses it would be good to have particle identification.

R.J.M.Snellings, A.M. Poskanzer and S.A. Voloshin (STAR Note SN388) nucl-ex/9904003

STAR (QM2001)

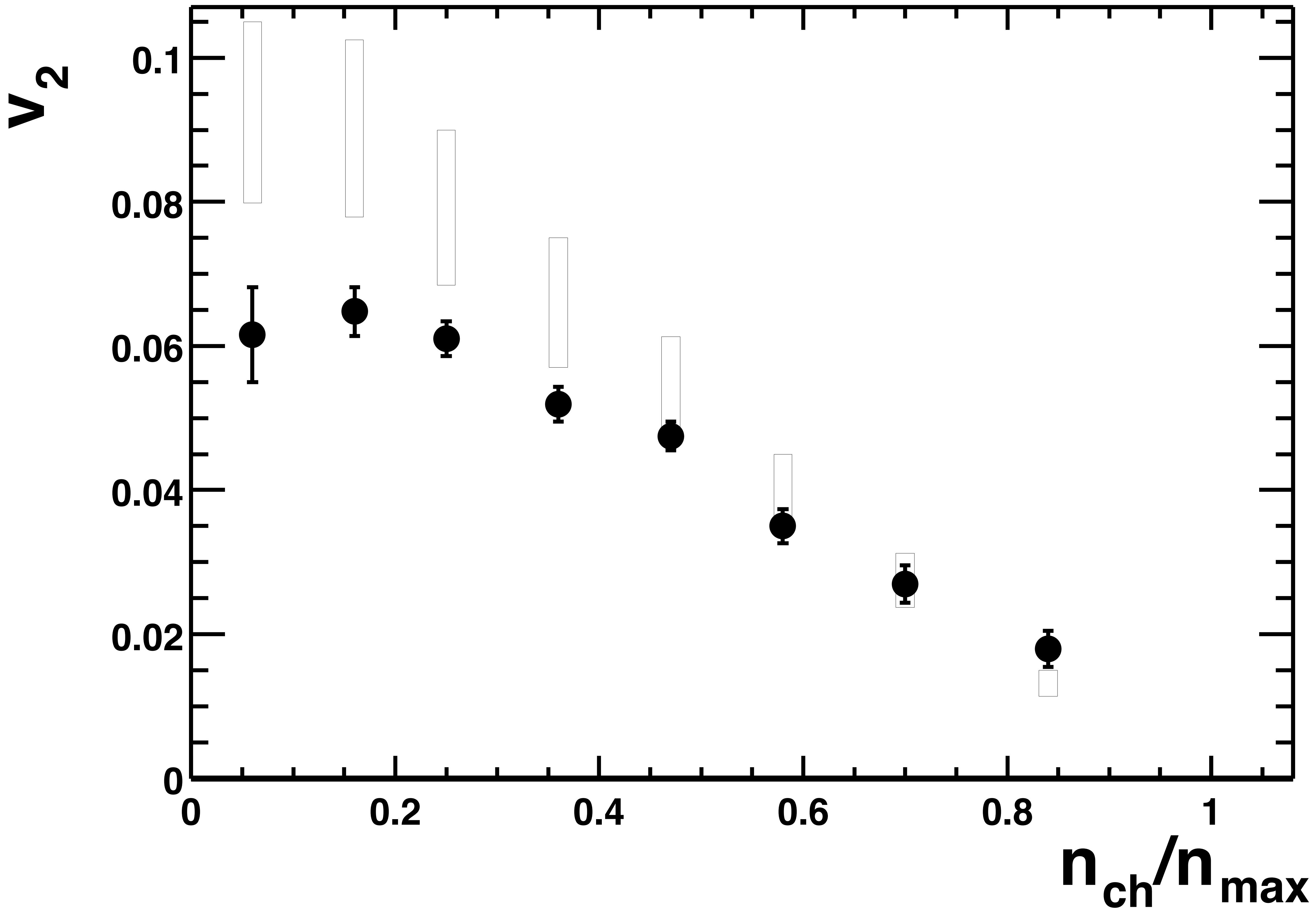




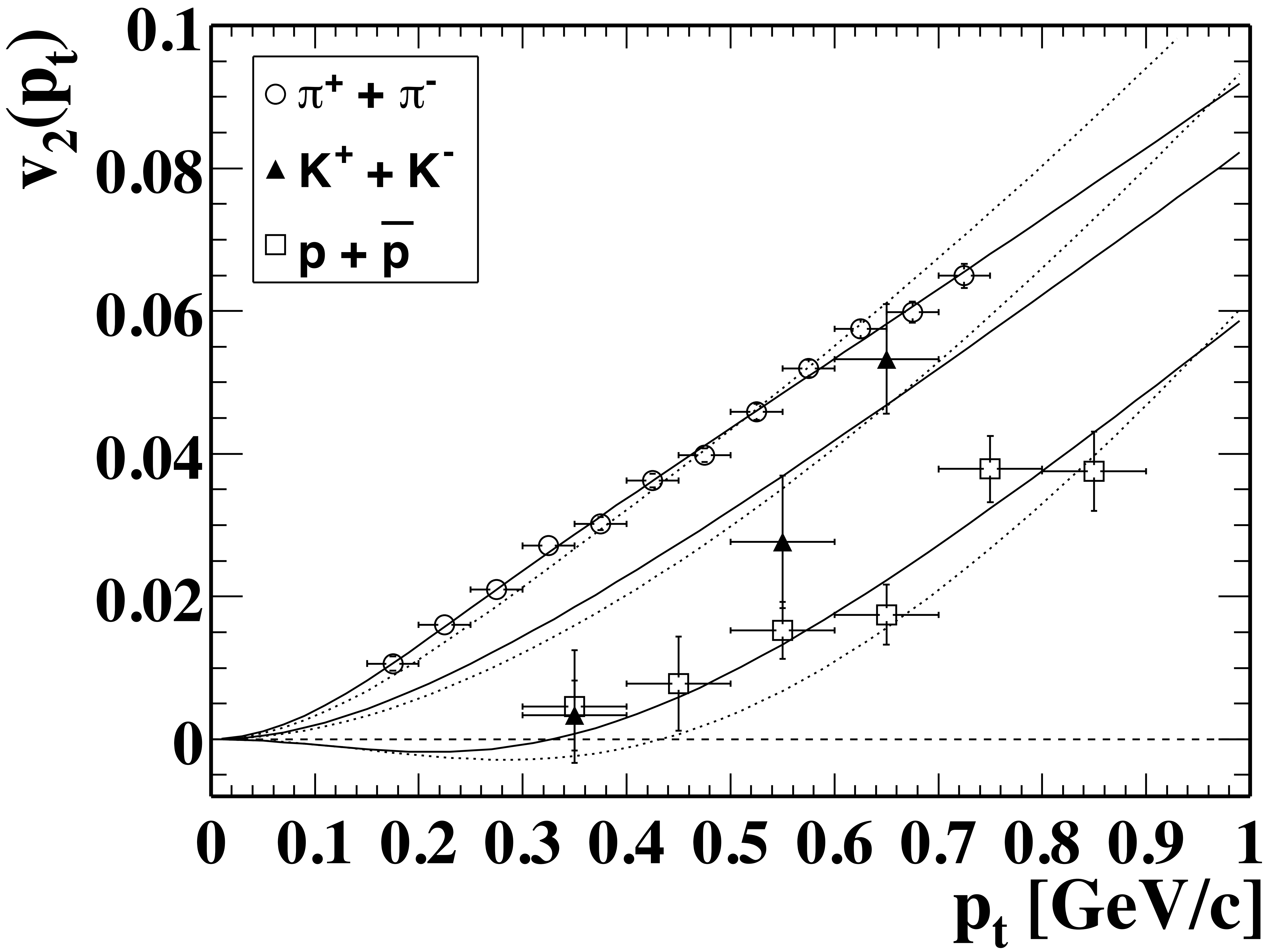
big increase measured compared to predictions hadron cascade model(s)

R.Snellings (STAR Collaboration) nucl-ex/0104006 (2001) QM2001

STAR (2001)



in good agreement for mid central collisions with “hydro”



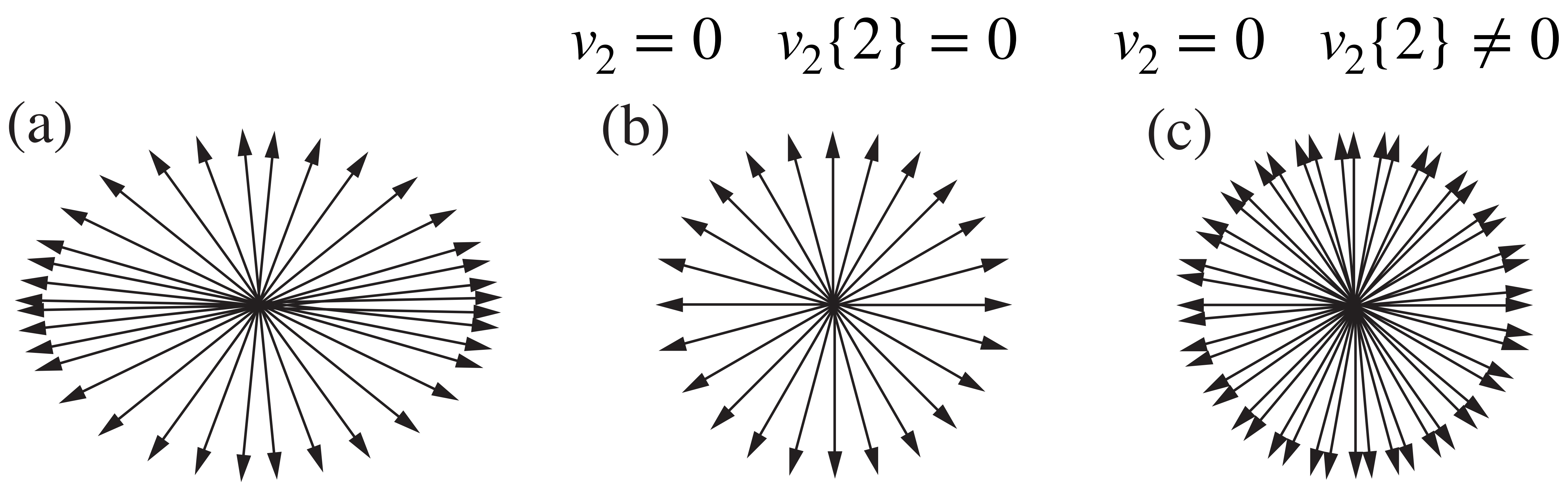
T_f (MeV)	ρ_0	ρ_a	s_2
135 ± 19	0.58 ± 0.03	0.09 ± 0.02	0
101 ± 24	0.61 ± 0.05	0.04 ± 0.01	0.04 ± 0.01

well described by improved blast-wave

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

Observables

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



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

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

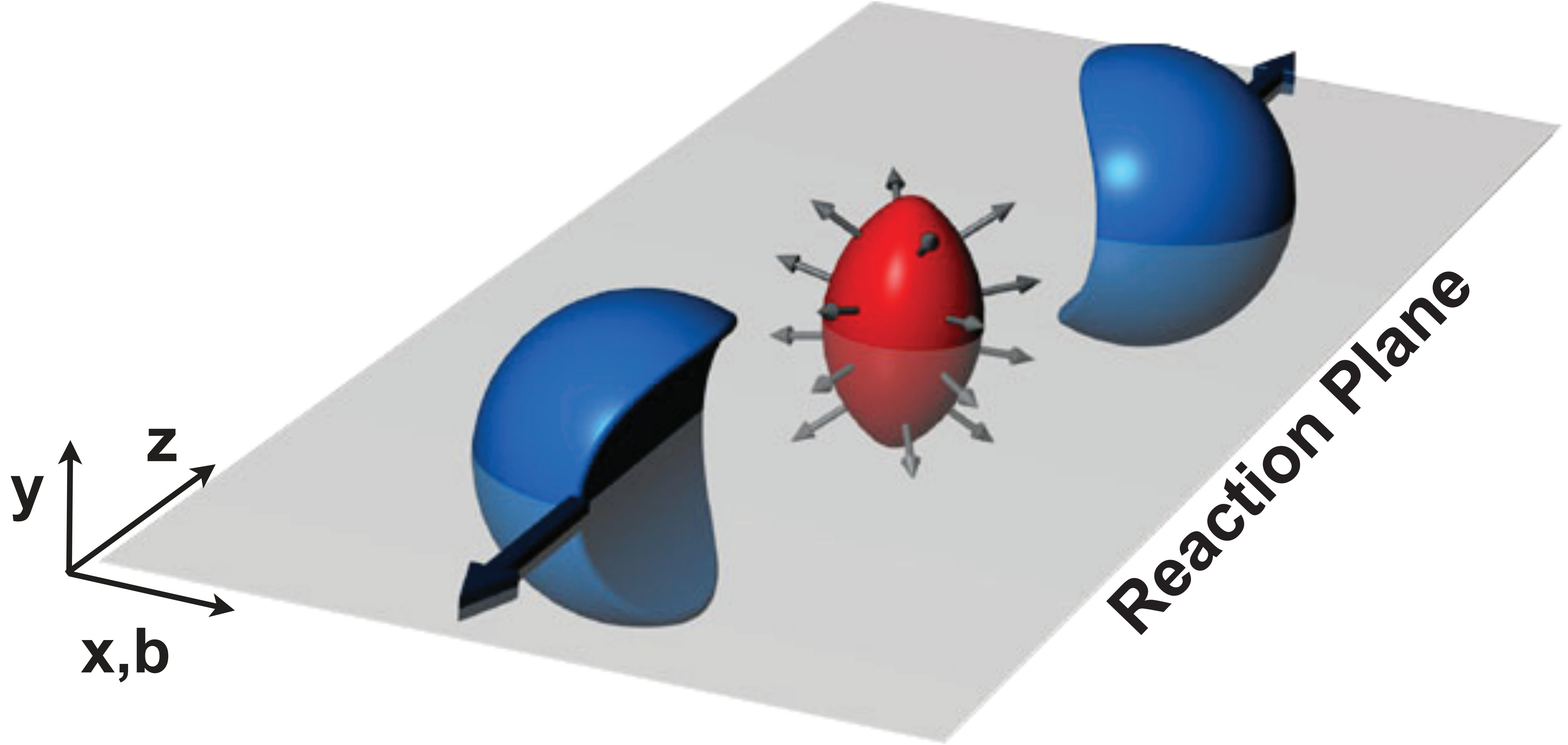
Non flow $\quad \delta_2 \propto 1/M_c \quad \delta_4 \propto 1/M_c^3$

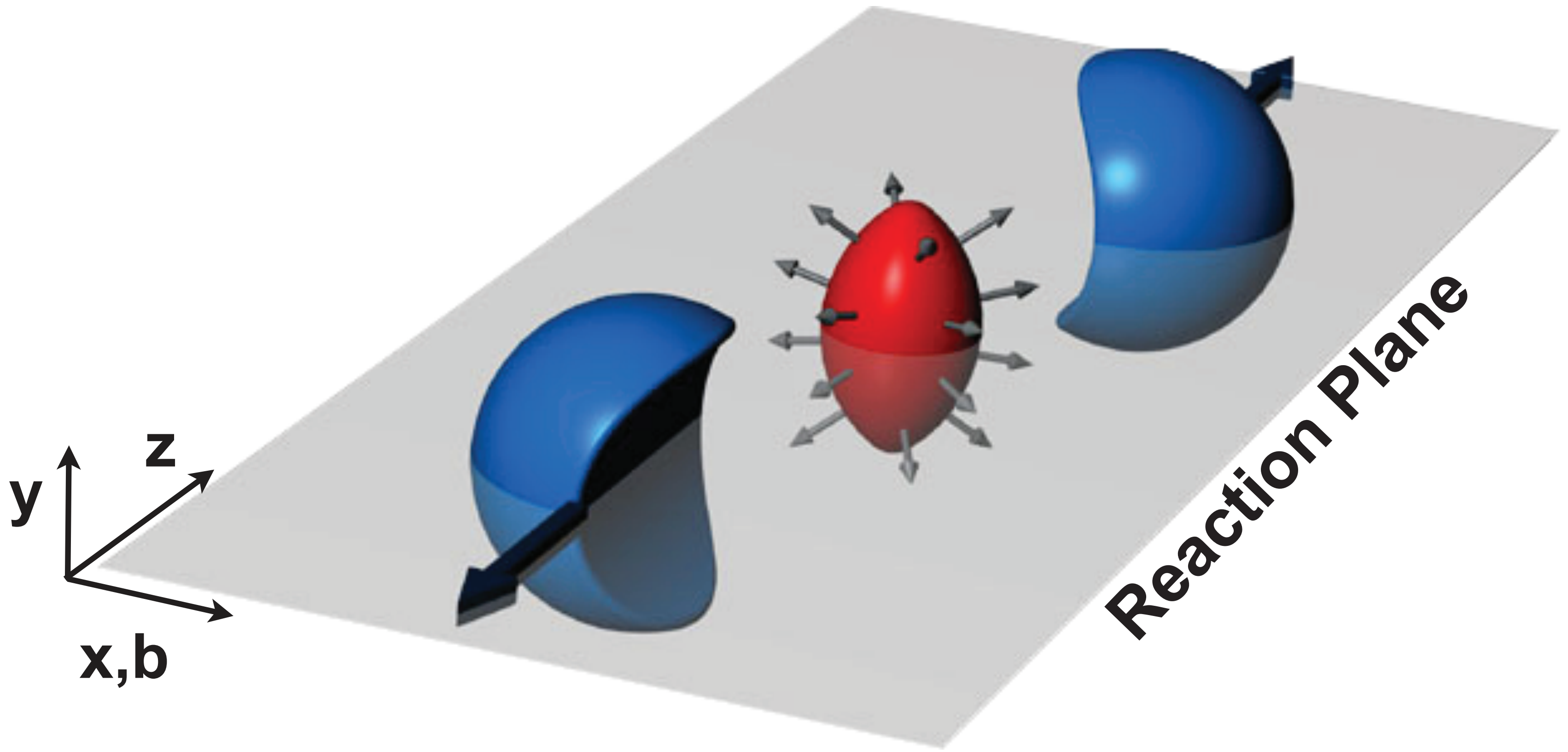
Fluctuations $\quad \langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma^2$

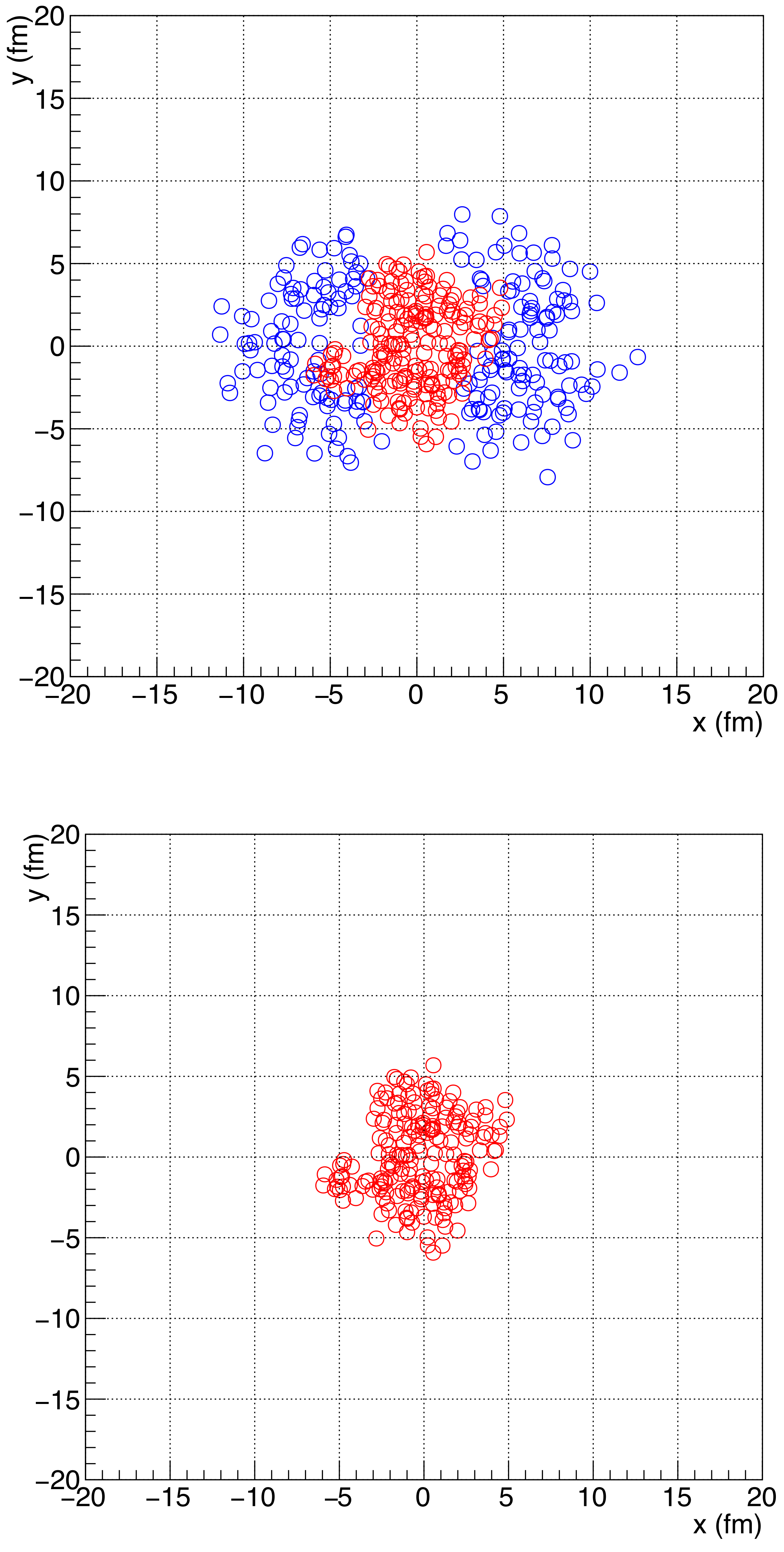
if $\sigma \ll \langle v \rangle$ then

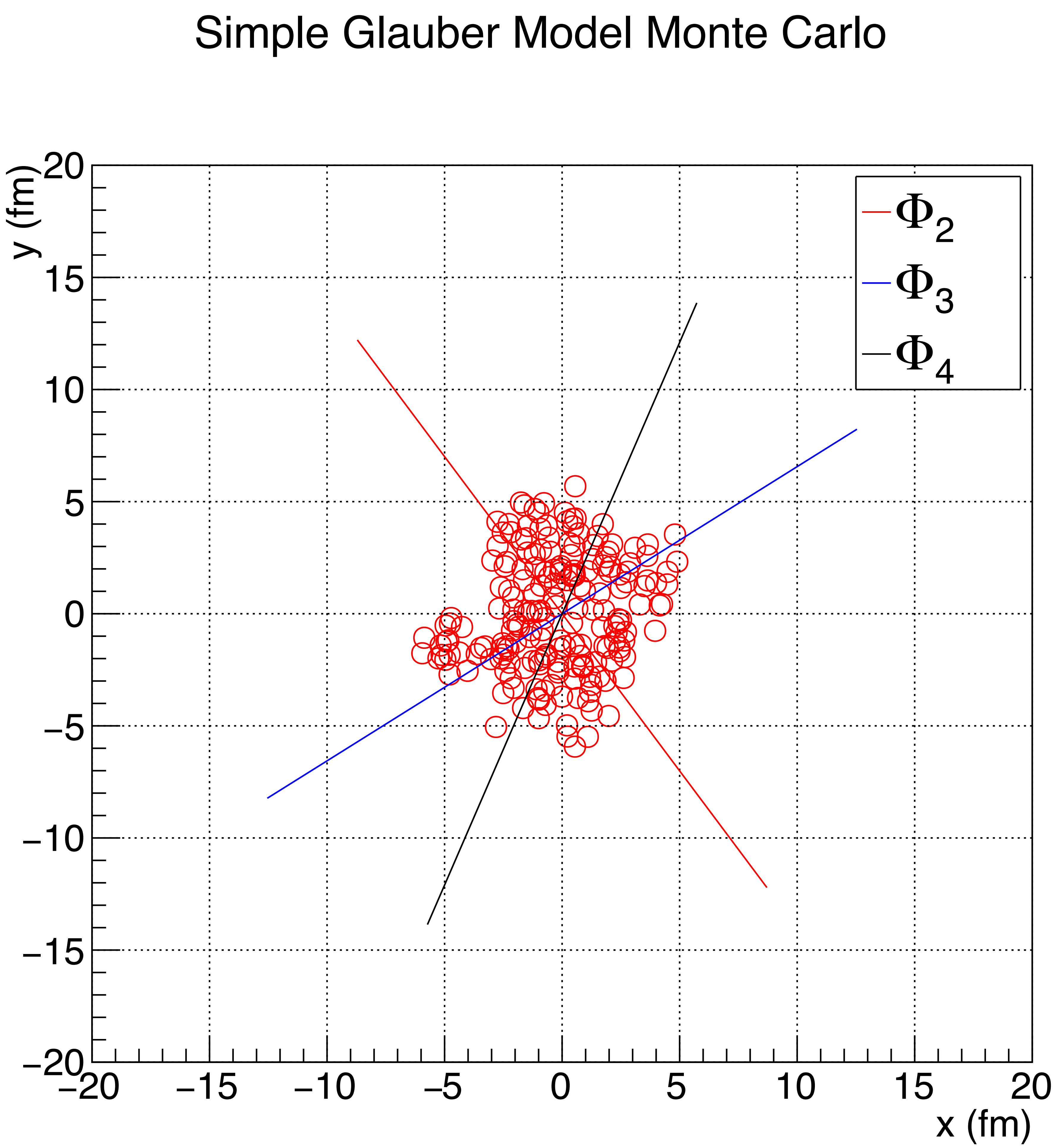
$$\begin{aligned}
v_2\{2\} &= \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}, \\
v_2\{4\} &= \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}, \\
v_2\{6\} &= \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}.
\end{aligned}$$

Planes

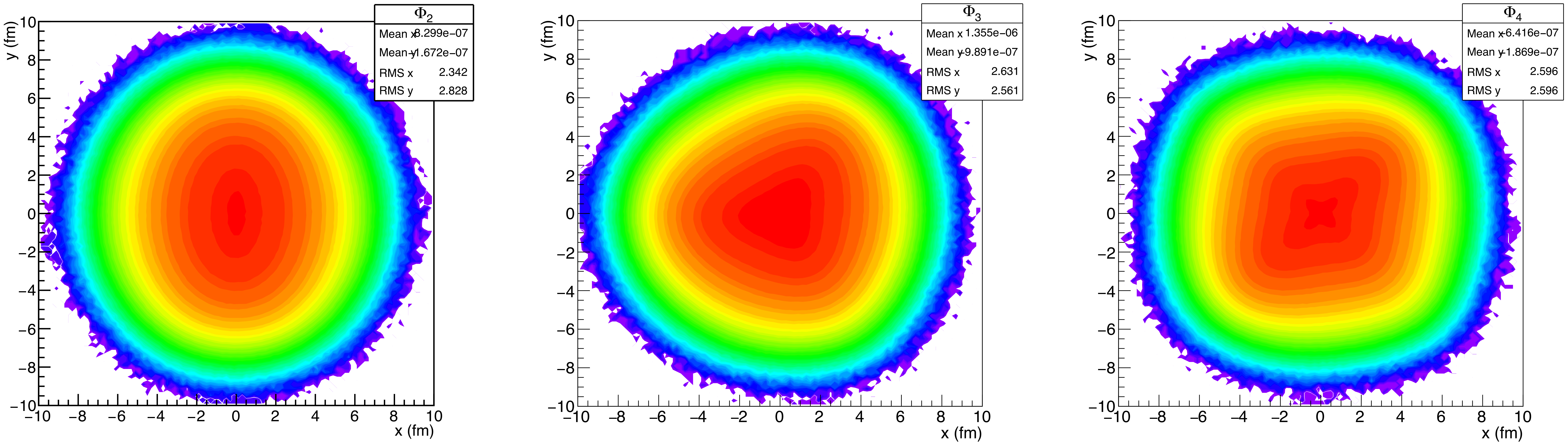



y
z
x,b
Reaction Plane


y (fm)
x (fm)


Simple Glauber Model Monte Carlo
y (fm)
x (fm)
Φ_2
Φ_3
Φ_4

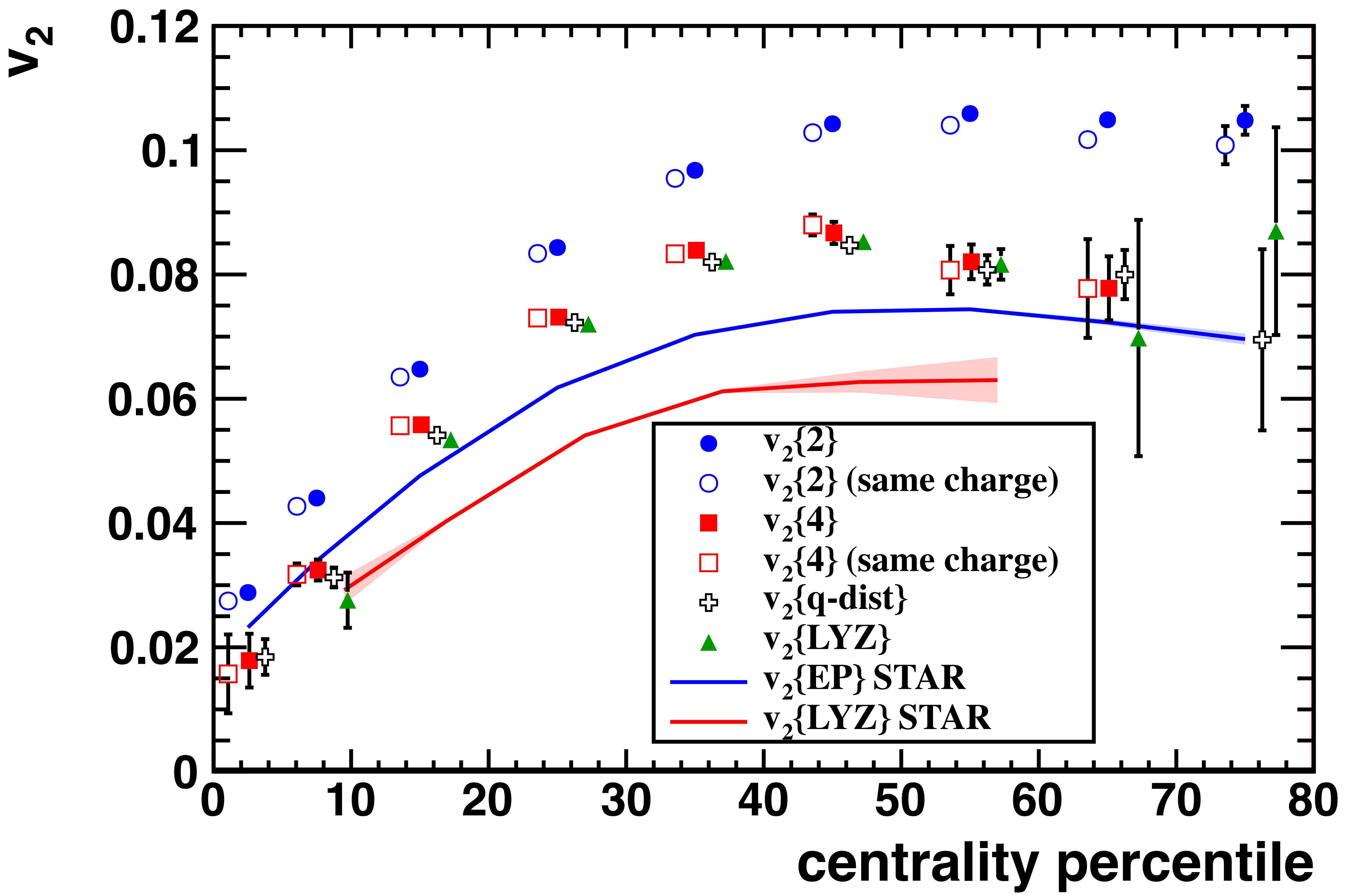
Simple Glauber Model Monte Carlo

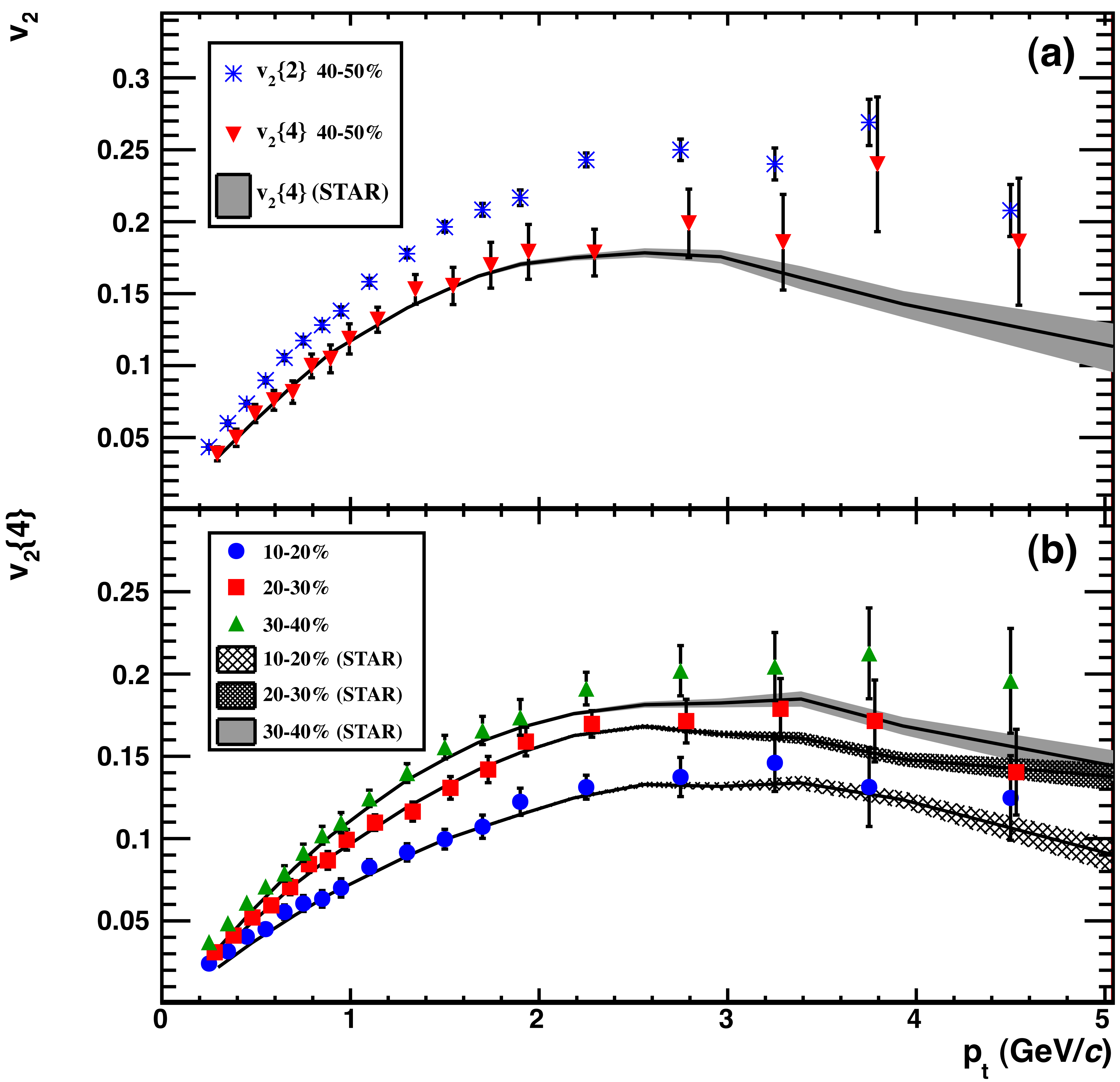


These geometries are thought to be responsible for the v_n's which we observe

$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

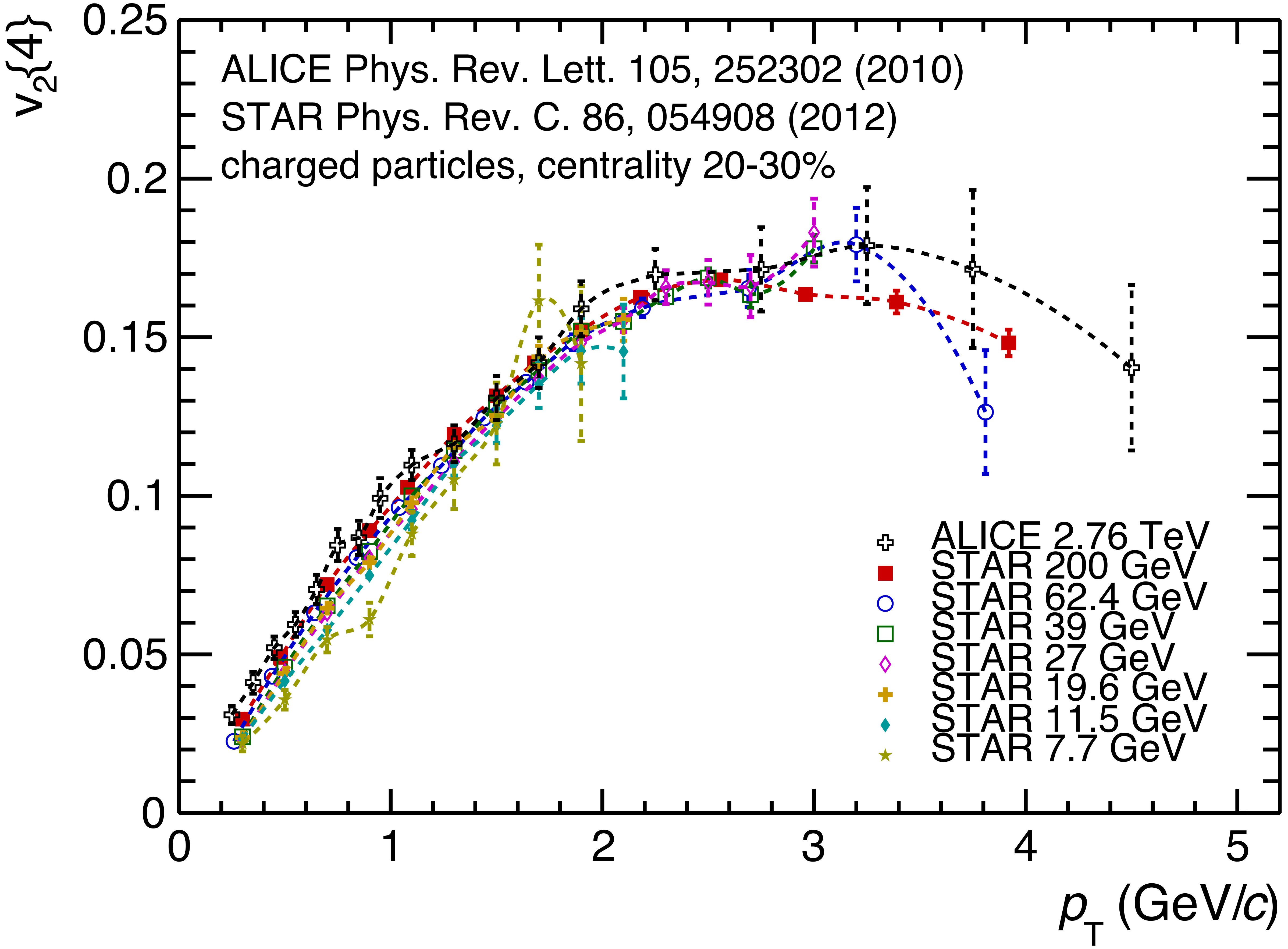
ALICE (2010)



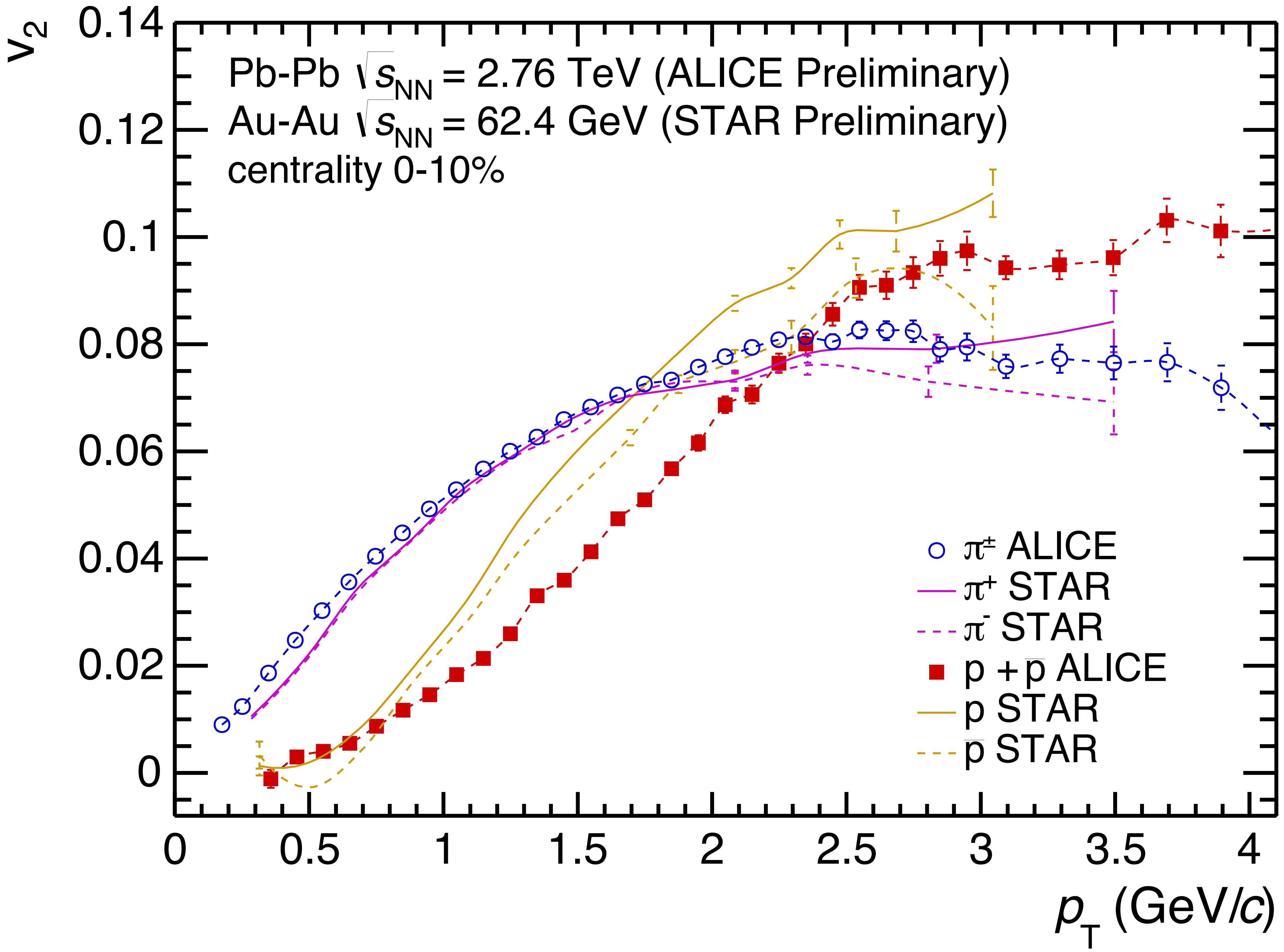


ALICE Collaboration: Phys. Rev. Lett. 105 (2010) 252302

Energy Dependence

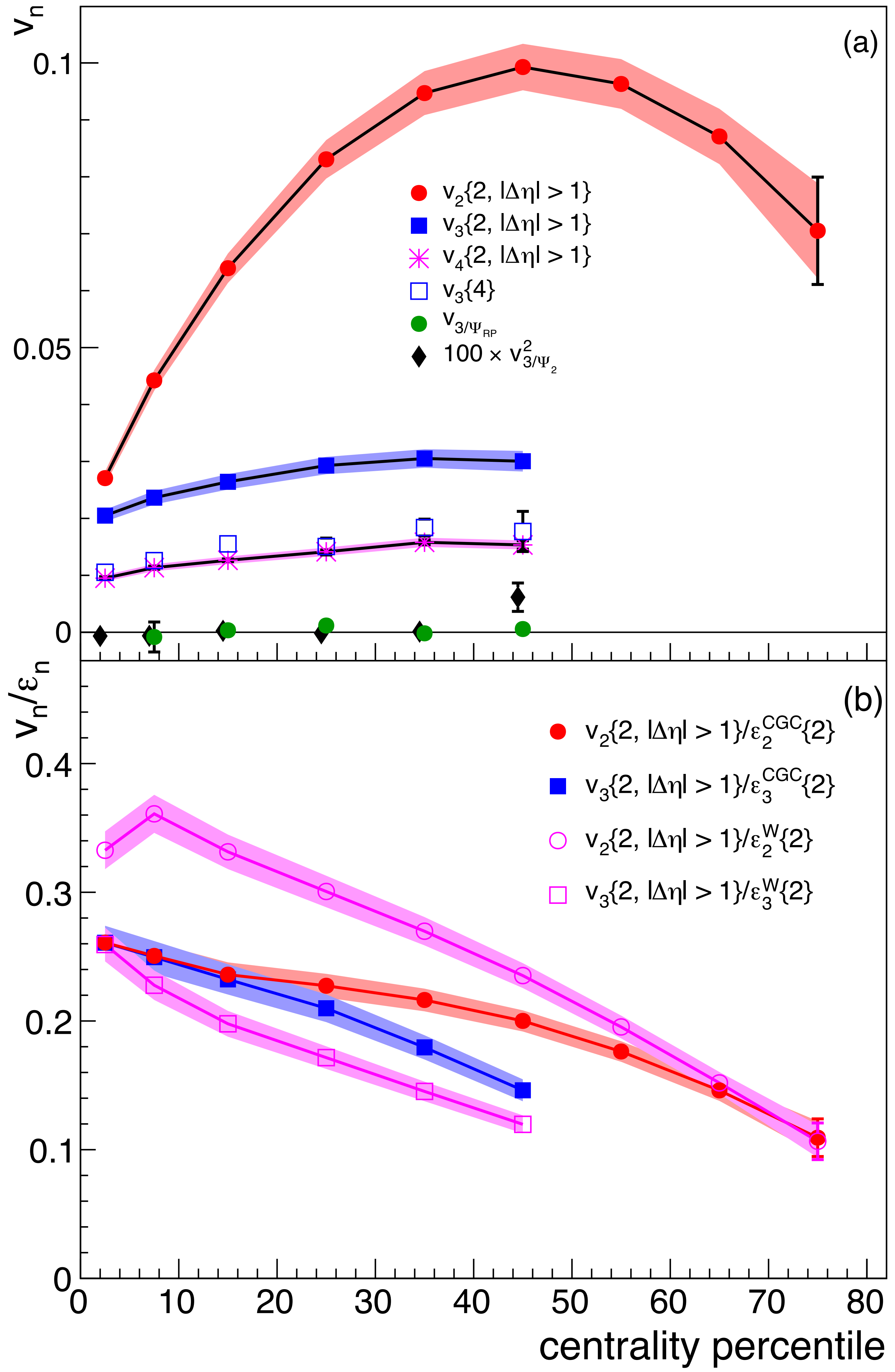


$v_2(p_t)$ is changing very little as function of collision energy

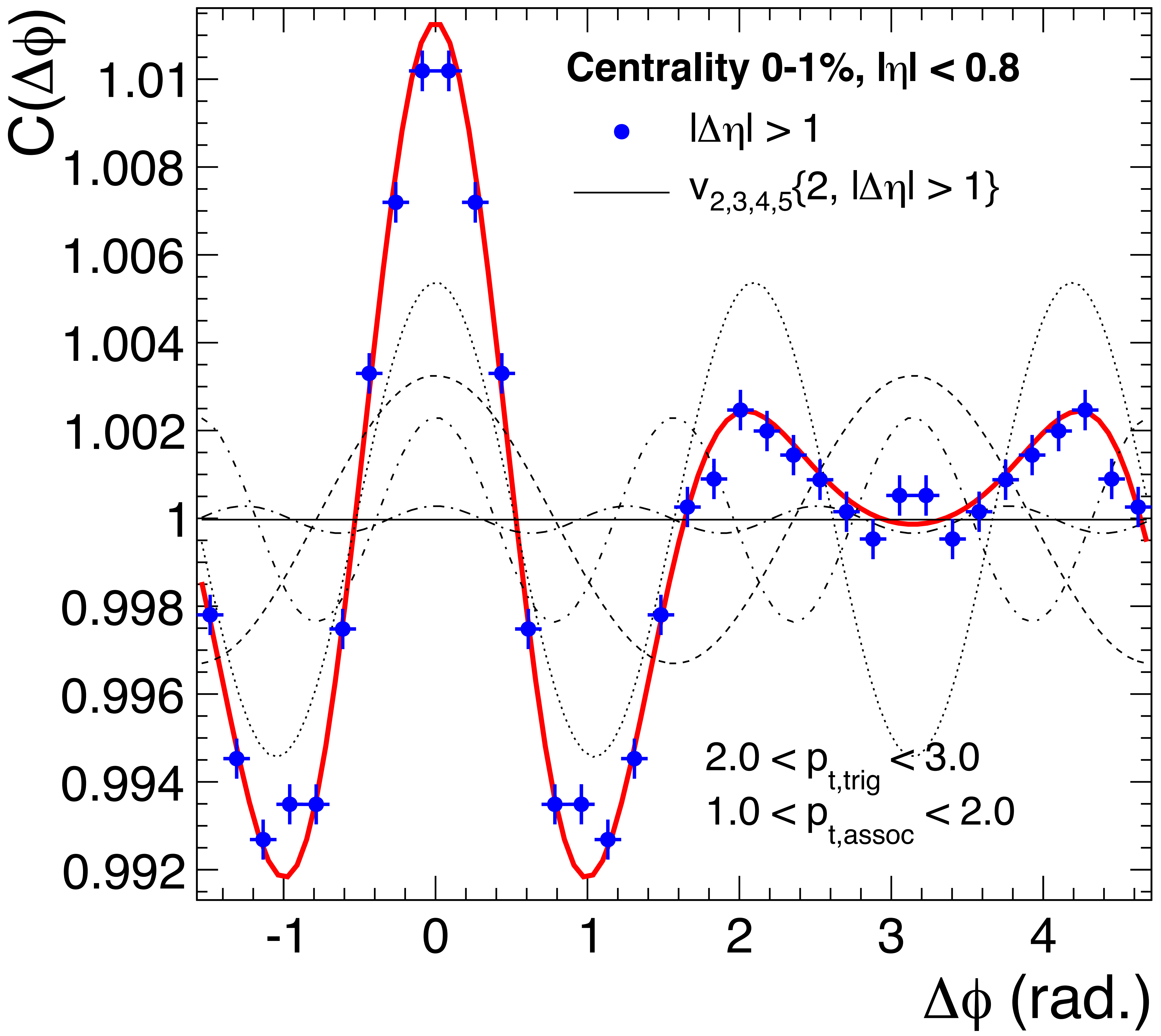


$v_2(p_t)$ for different particles is changing as expected for a boosted system

ALICE (2011)

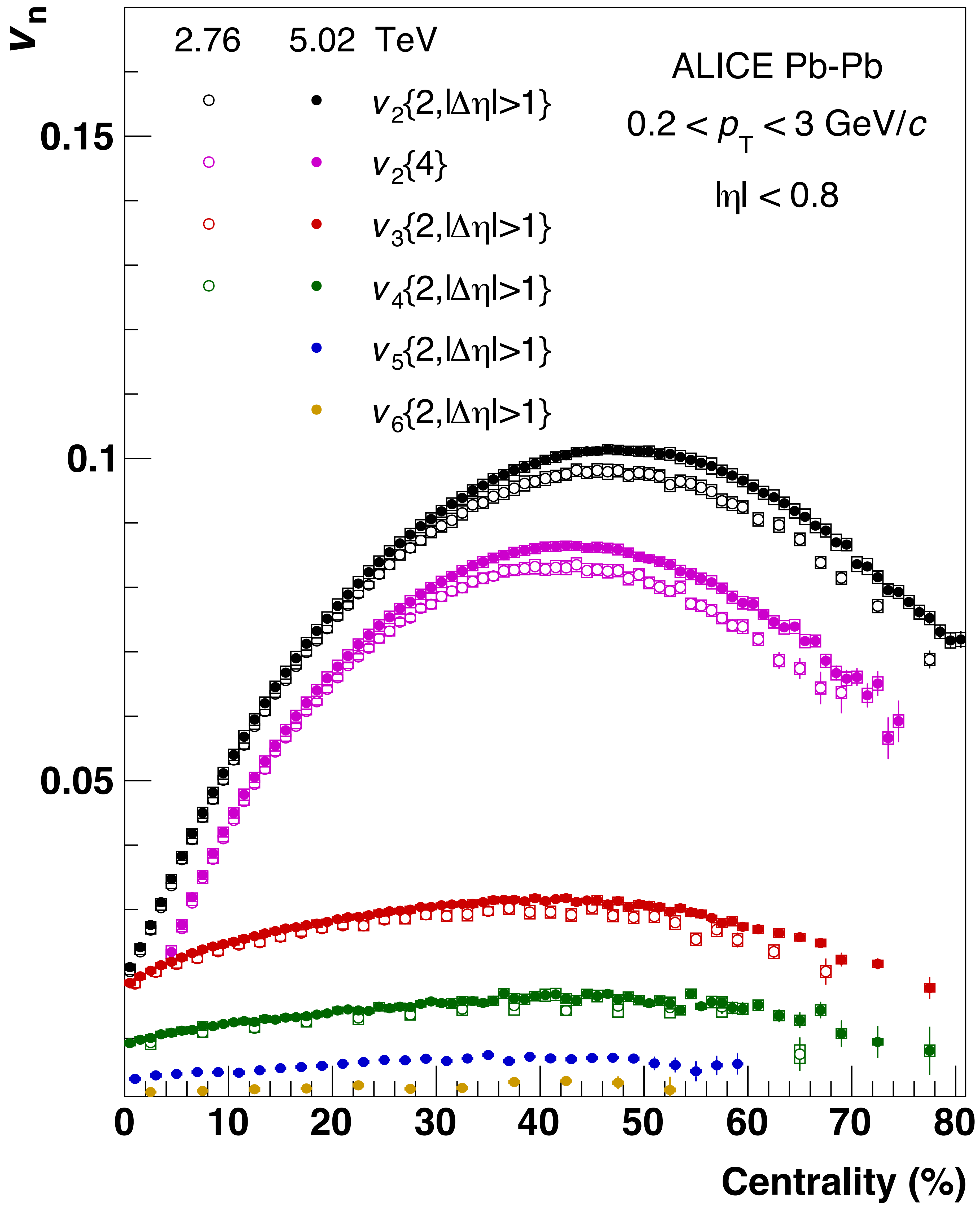


Convincing measurement of the higher harmonics
Indication of non-Glauber initial conditions



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

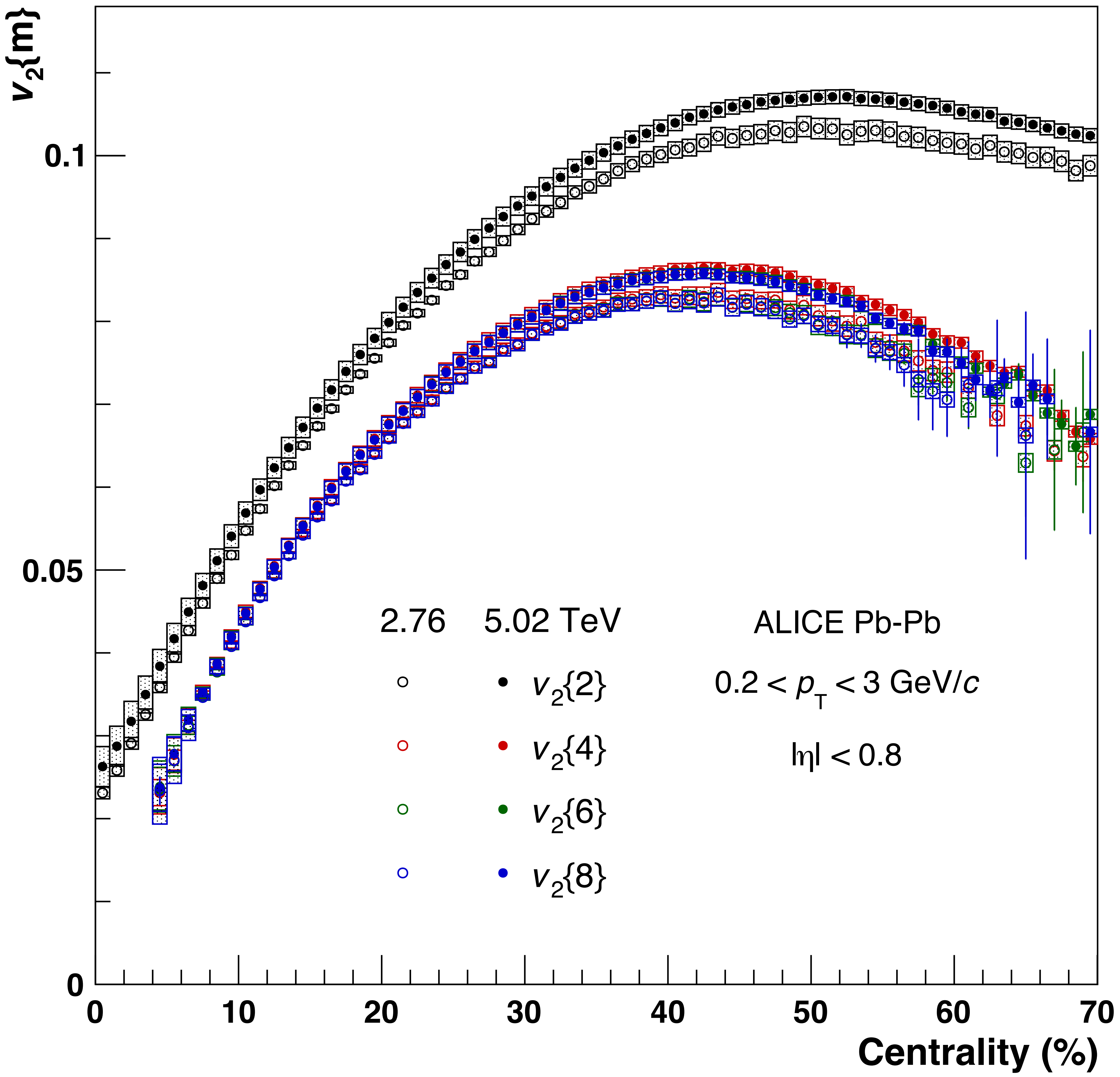
Fluctuations and initial conditions



- Experimentally we can use within one experiment detailed measurements of the energy dependence of the v_n to constrain the temperature dependence of the parameters on which they depend the most
- In addition we can use detailed cumulant measurements 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

Fluctuations and initial conditions



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.

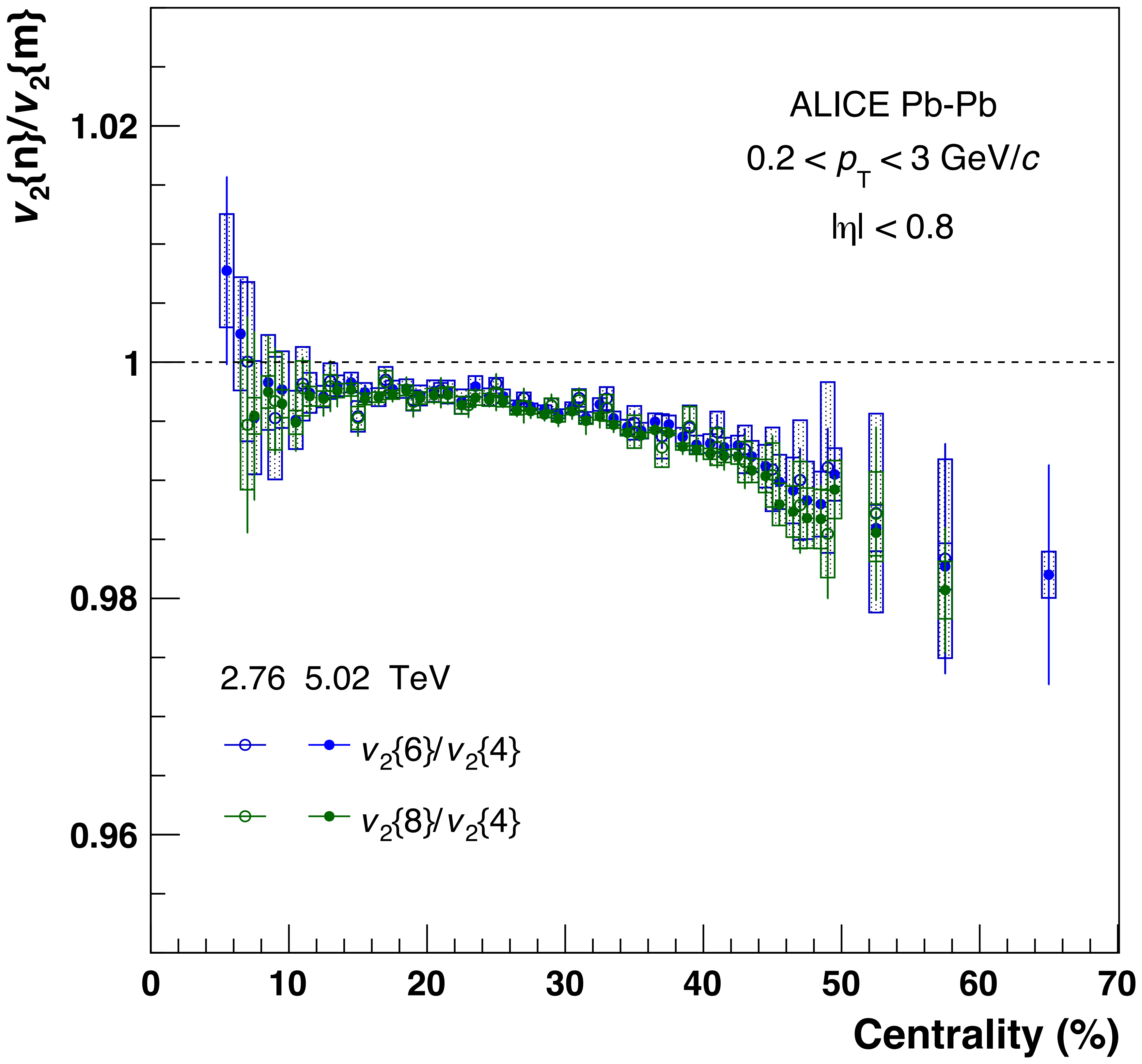
$$v_2\{2\} = \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

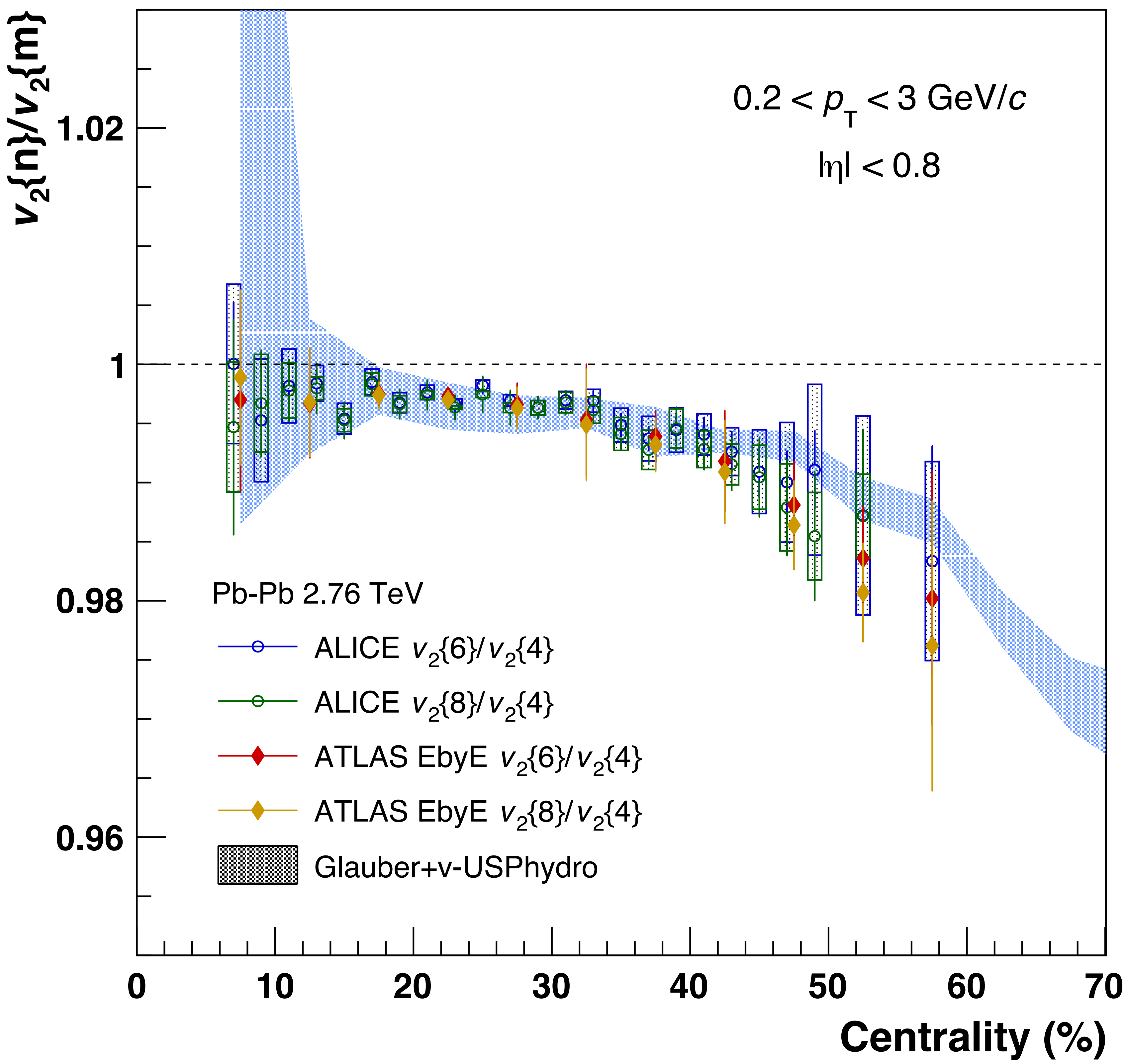
$$v_2\{4\} = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle},$$

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

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

Fluctuations and initial conditions





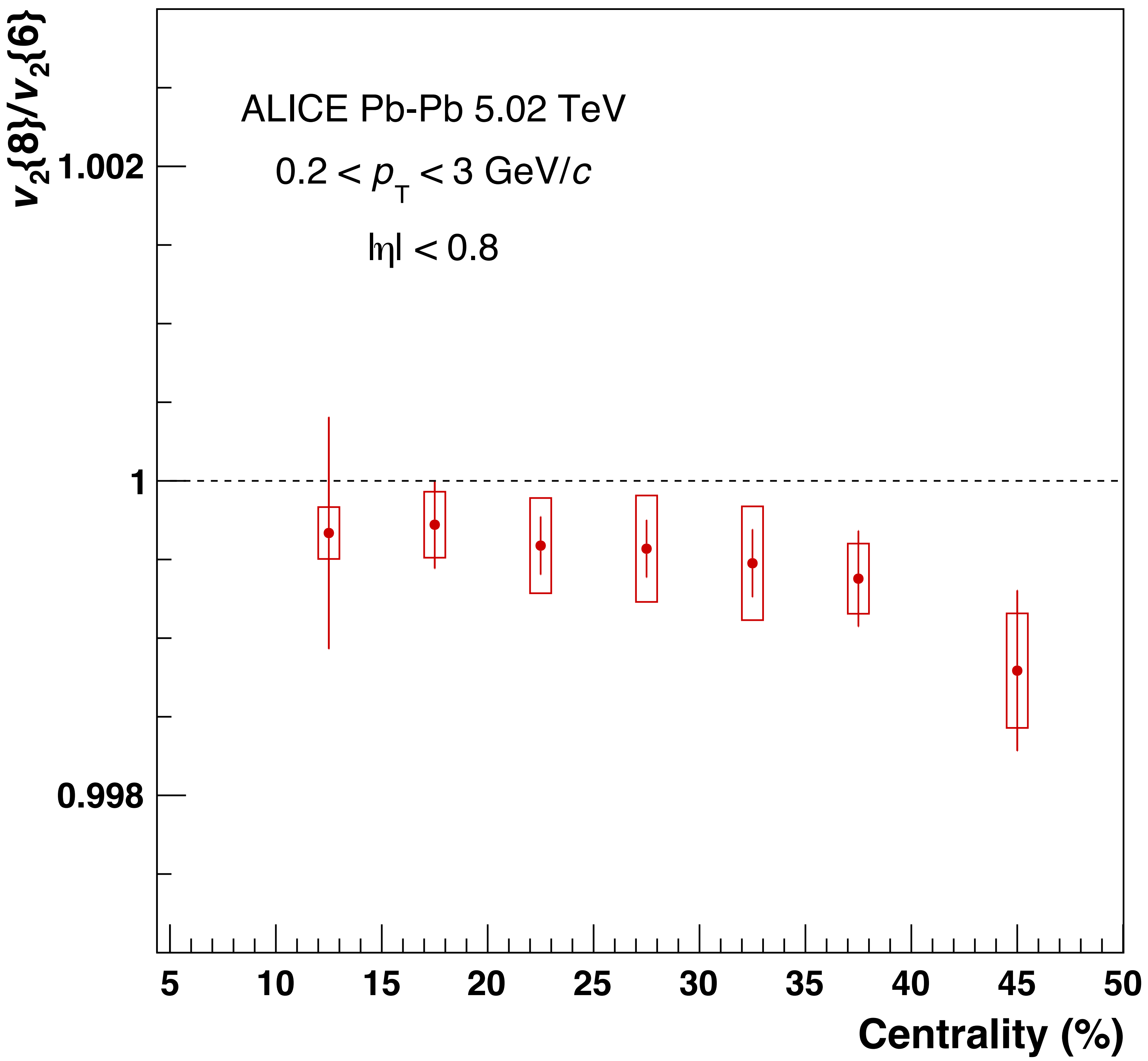
A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution

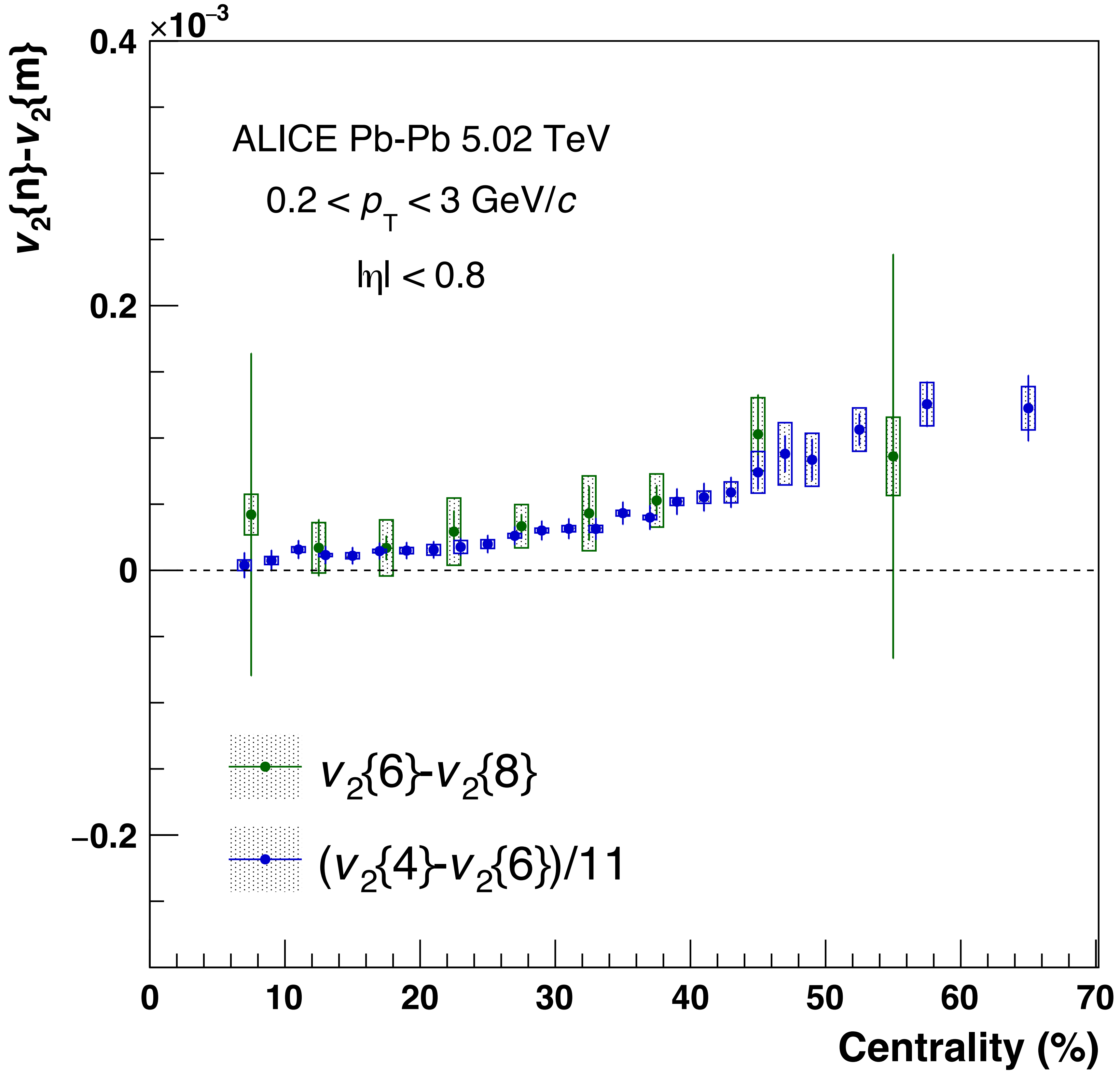
The splitting does not depend on the p_t range used and collision energy

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.

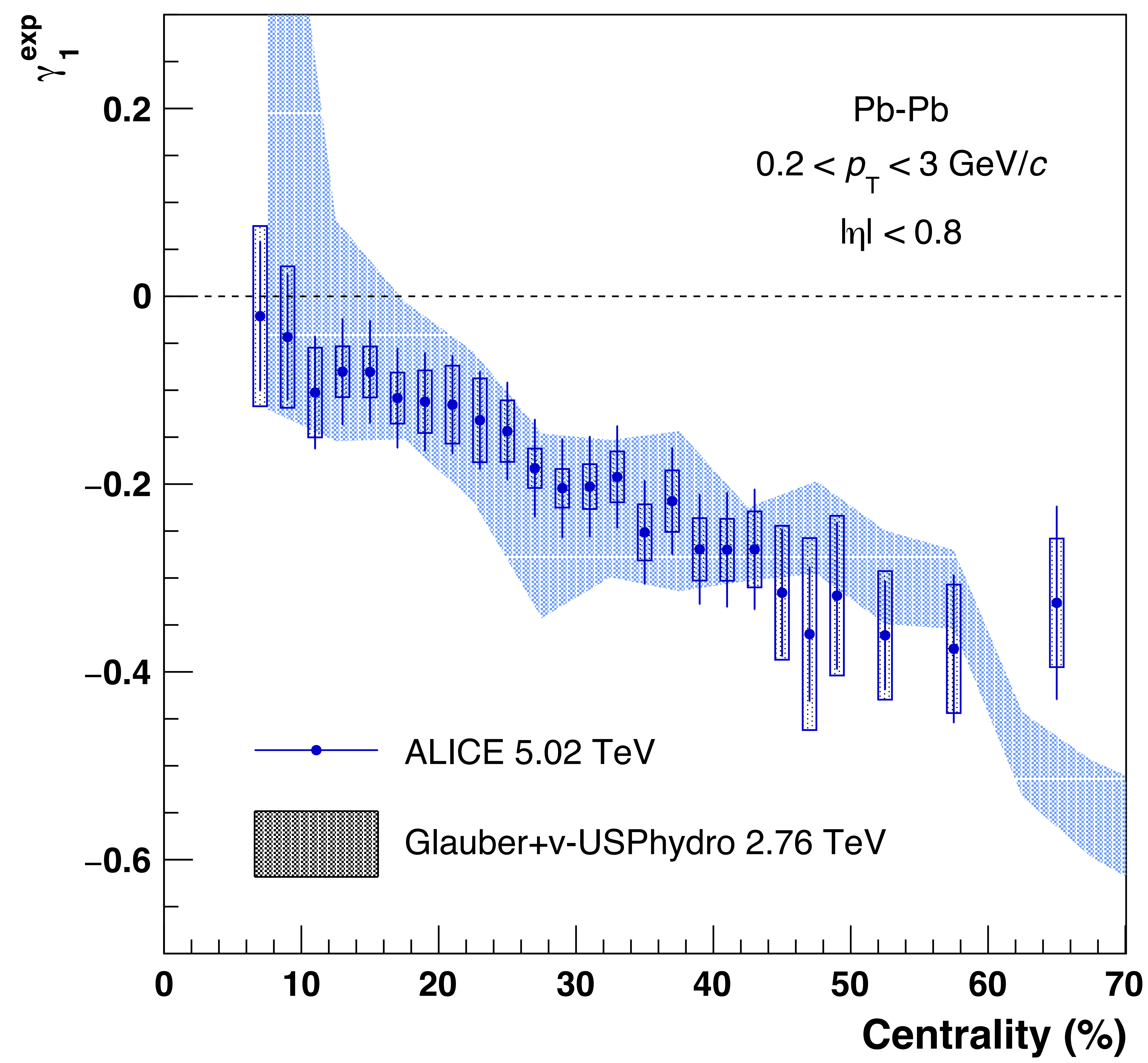
Higher order contributions are constrained in the equality

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

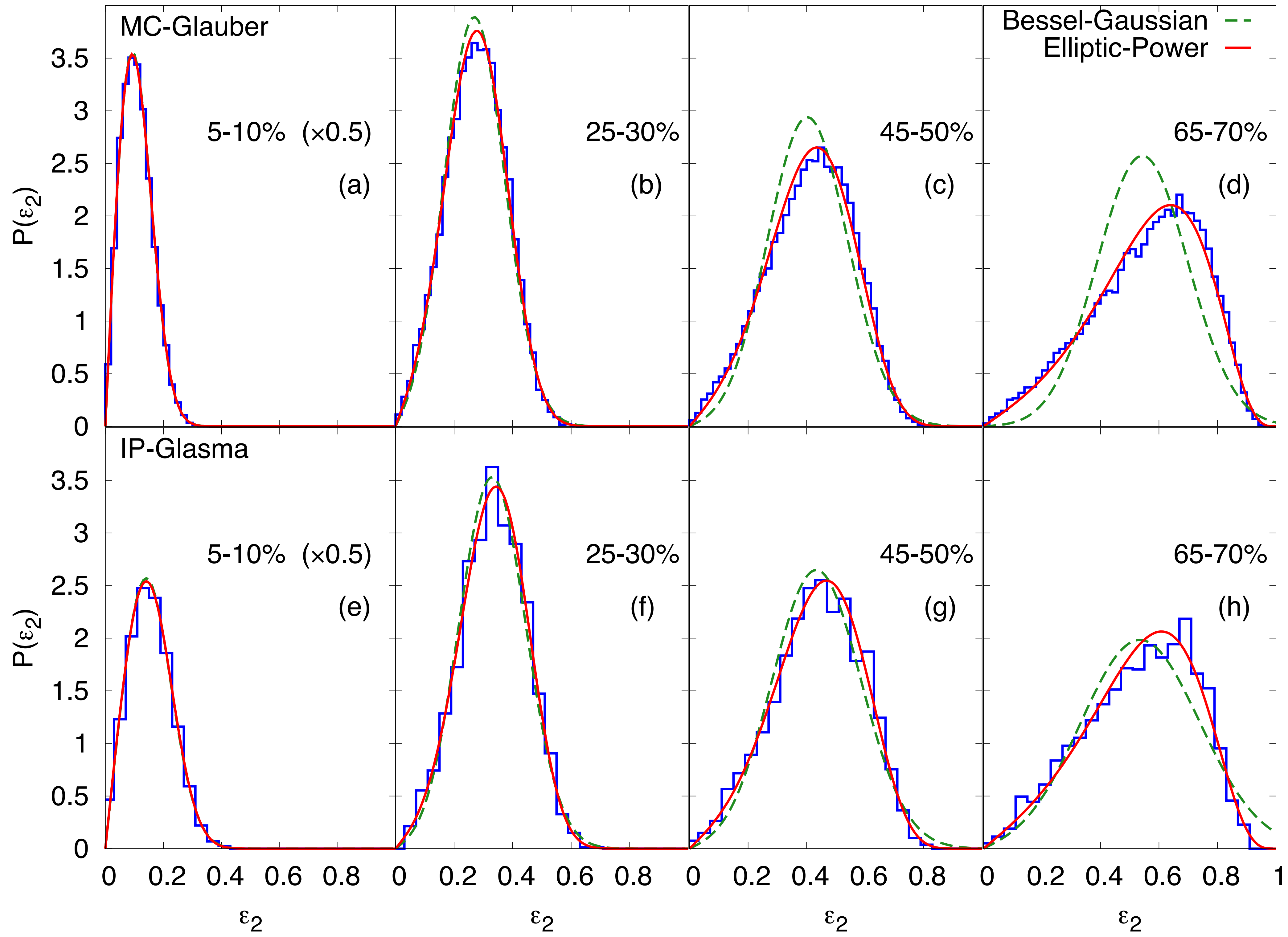
ALICE Collaboration: https://doi.org/10.1007/JHEP07 (2018) 103

Fluctuations and initial conditions

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



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



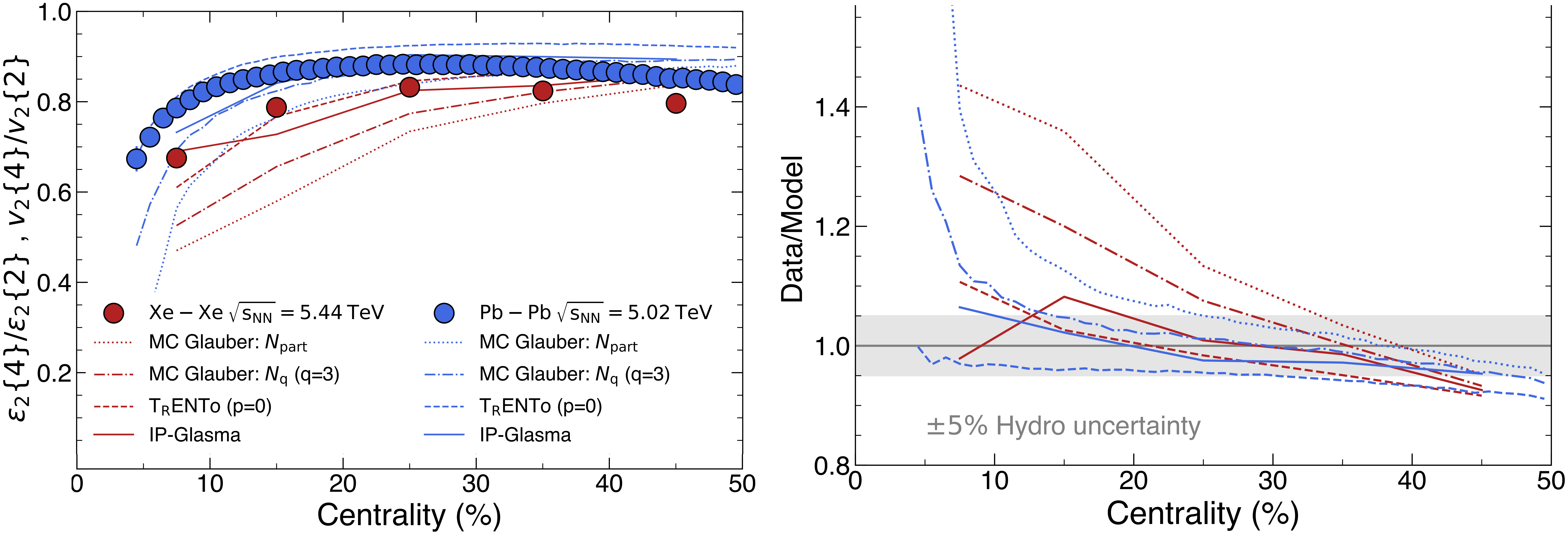
- A negative skewness is observed as expected due to the constrains on ε_2 between 0-1
- The skewness agrees well with model calculations and increases towards peripheral collisions due to the constraint of 1

$$v_2 \propto \varepsilon_2$$

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

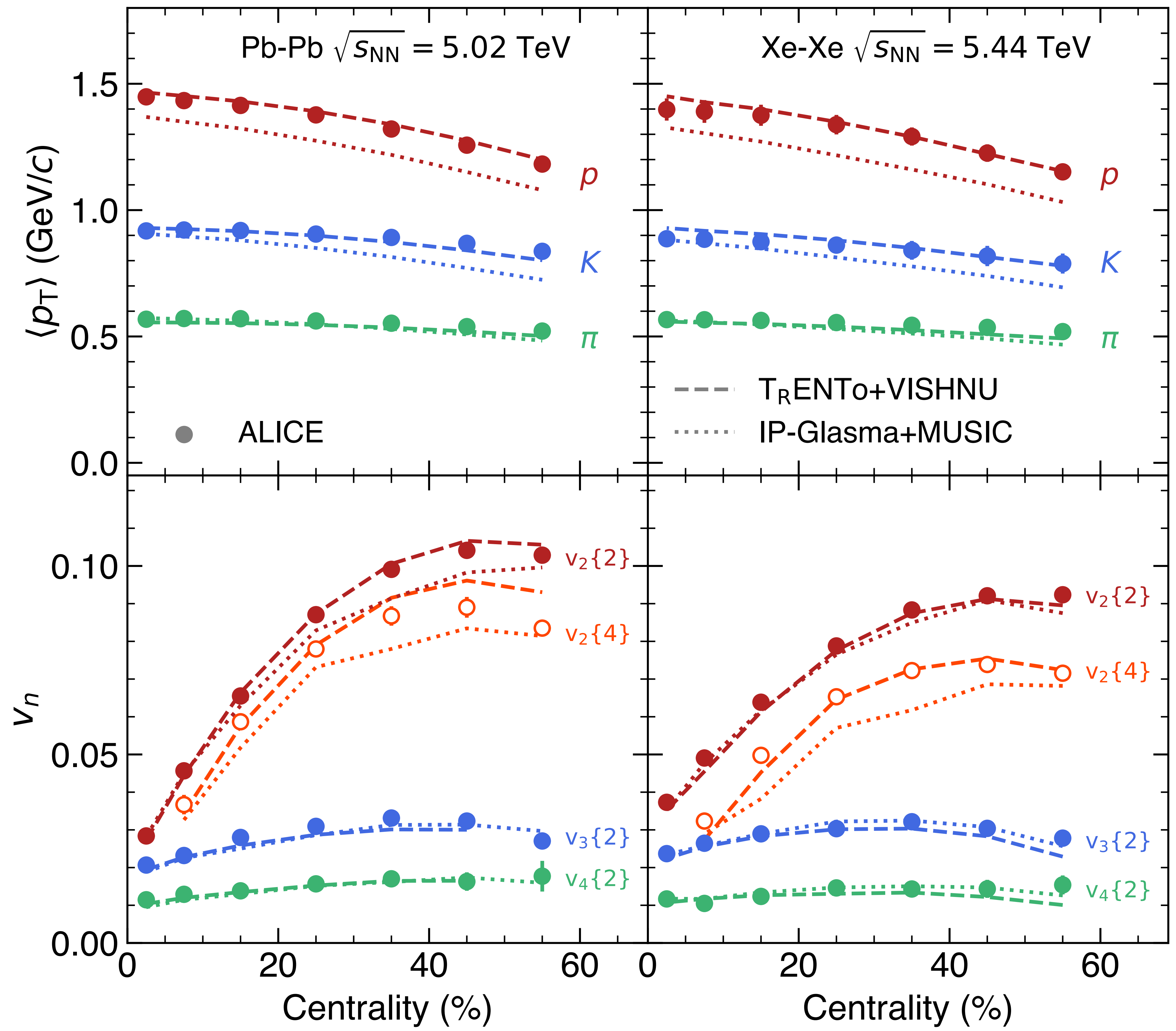
Fluctuations and initial conditions

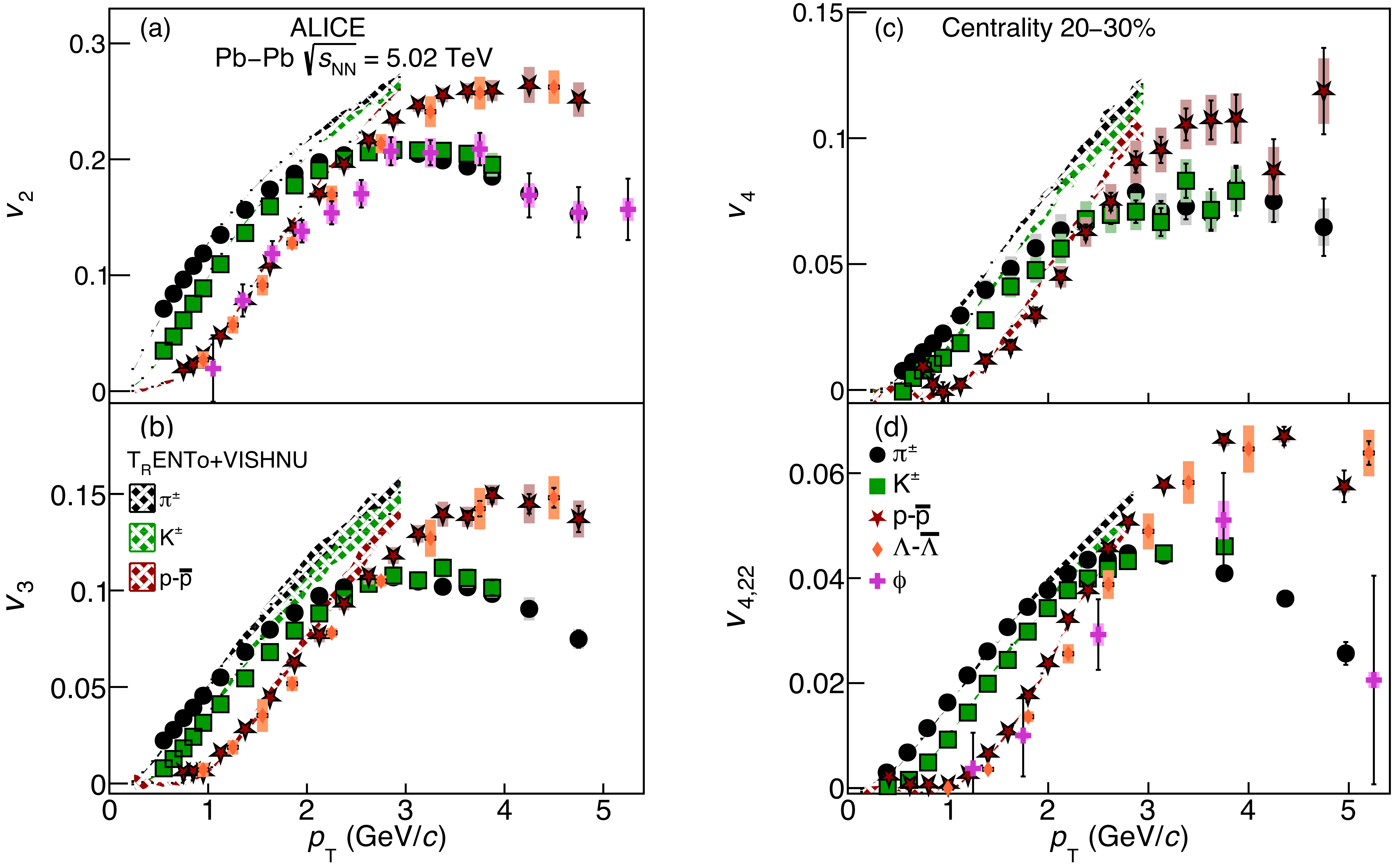
$$v_2\{2\} \propto \varepsilon\{2\} \qquad v_2\{4\} \propto \varepsilon\{4\}$$



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

v_n's and $<p_T>$

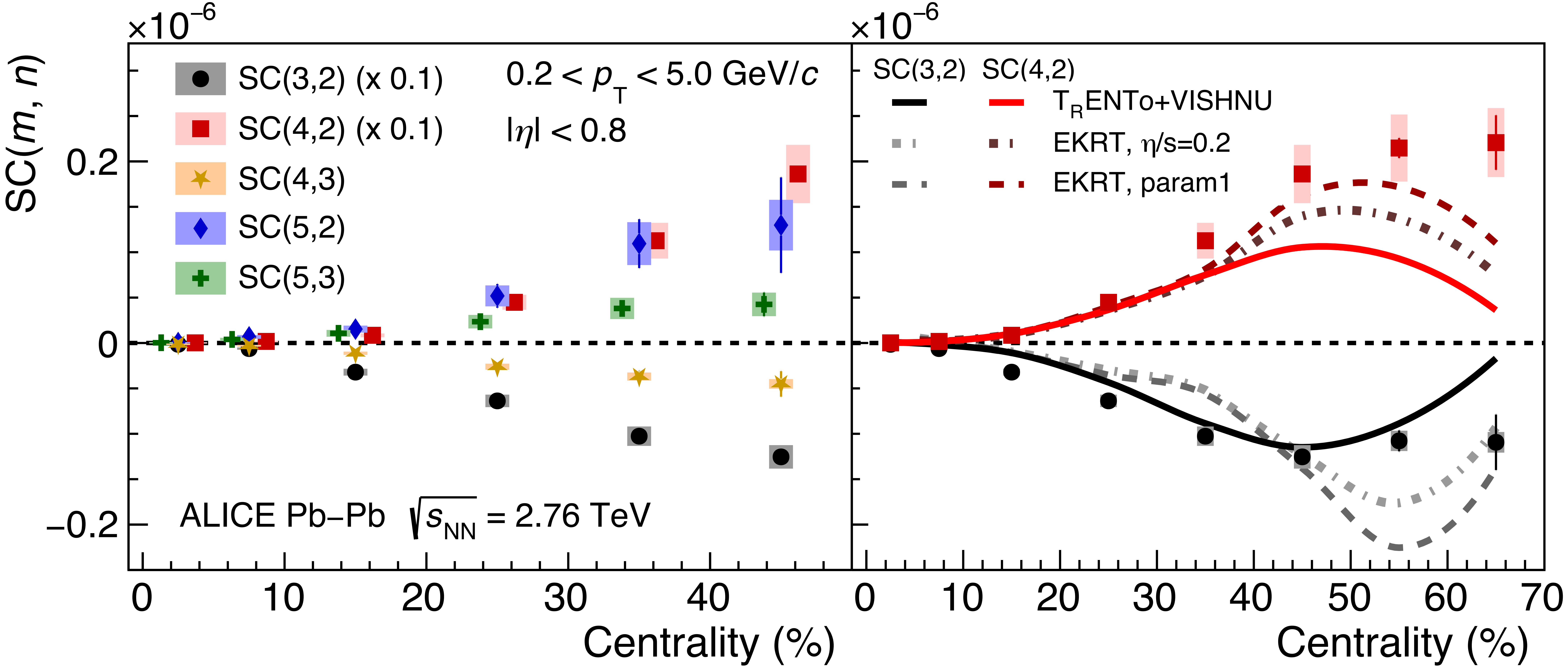




ALICE Collaboration:arXiv:2211.04384

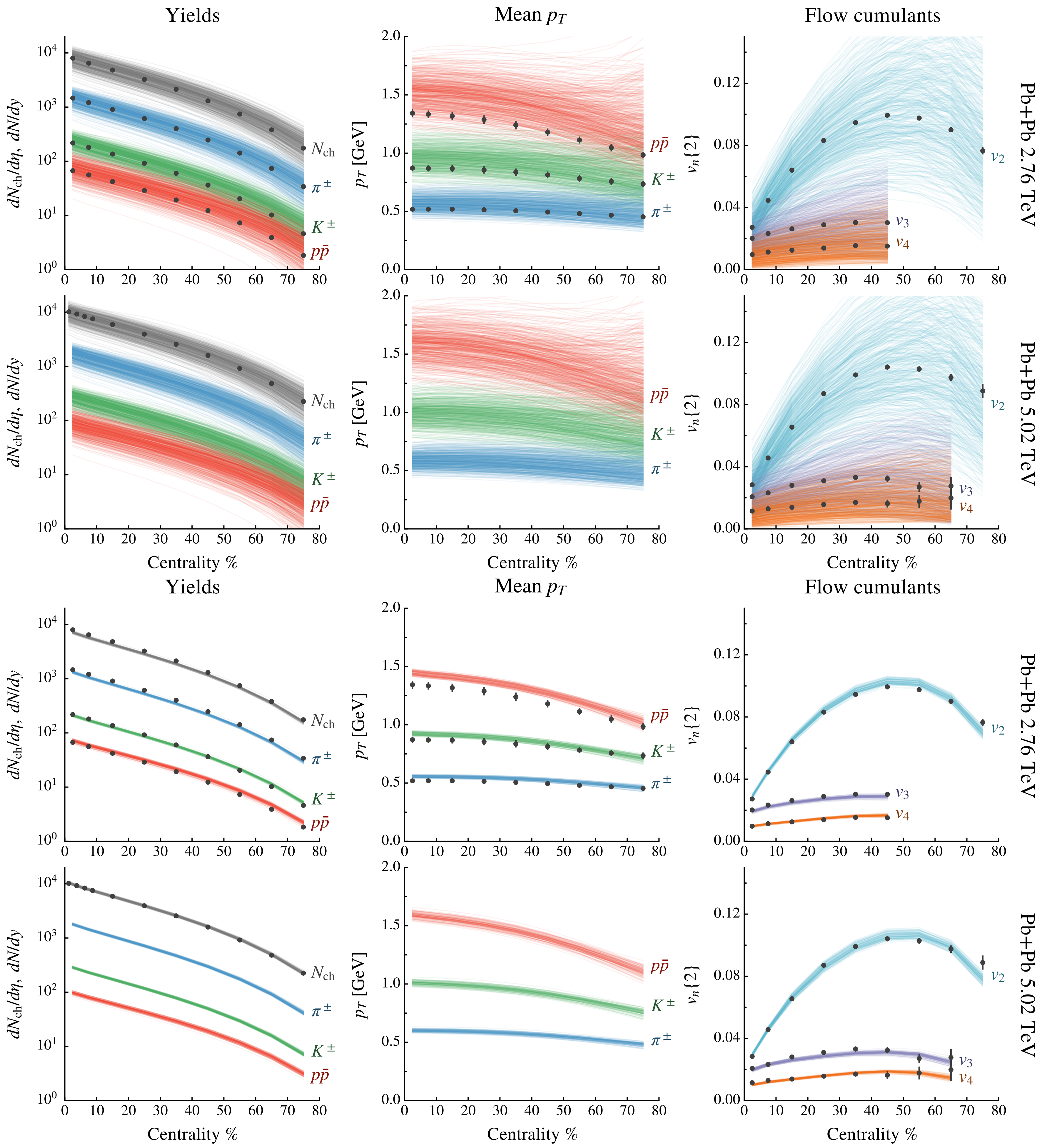
Symmetric Cumulants

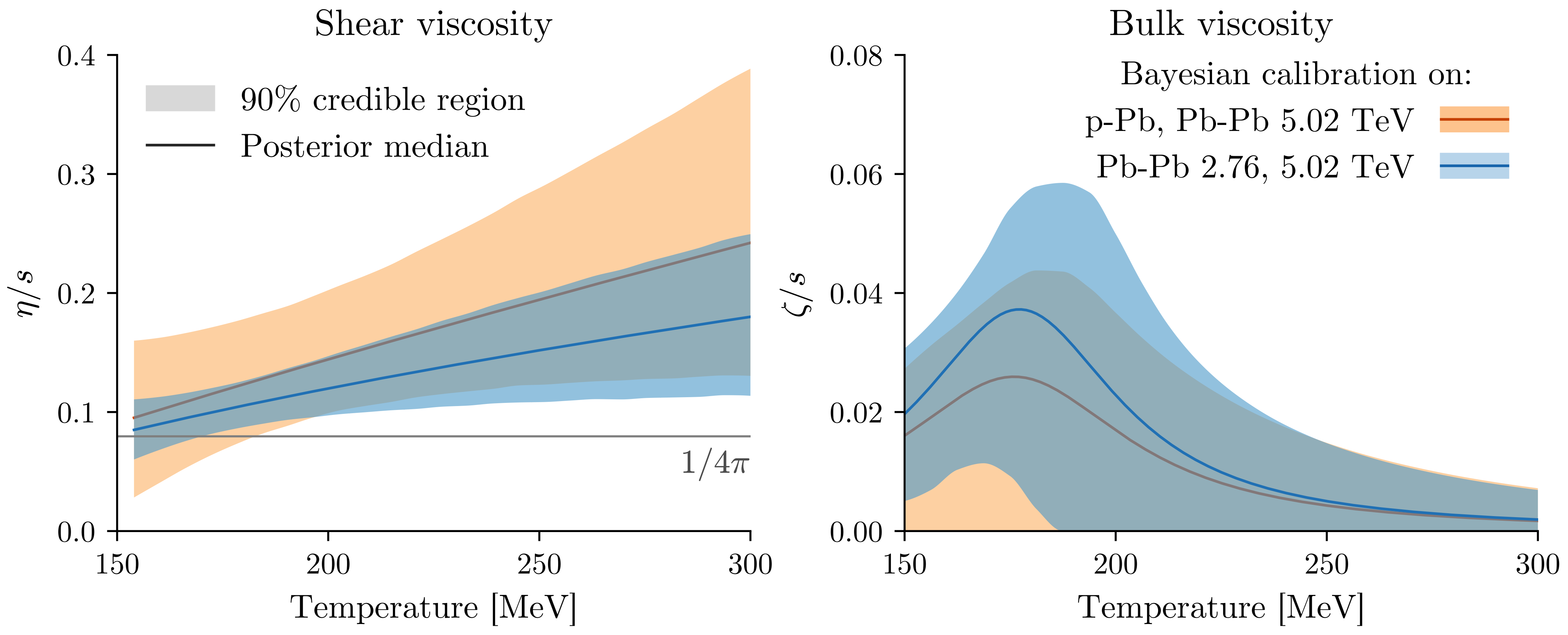
$$SC(k,l) = \langle v_k^2 v_l^2 \rangle - \langle v_k^2 \rangle \langle v_l^2 \rangle$$



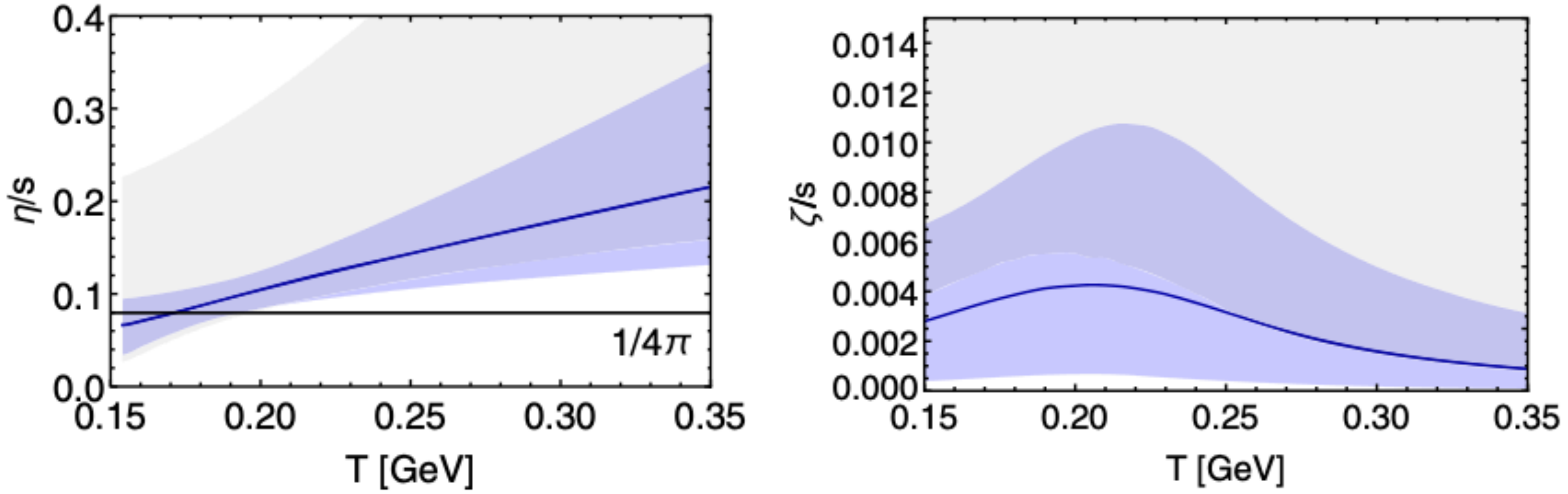
Global Bayesian Analysis

S. Bass, J. Bernhard, J. Scott Moreland, arXiv:1704.07671, arXiv:1808.02106

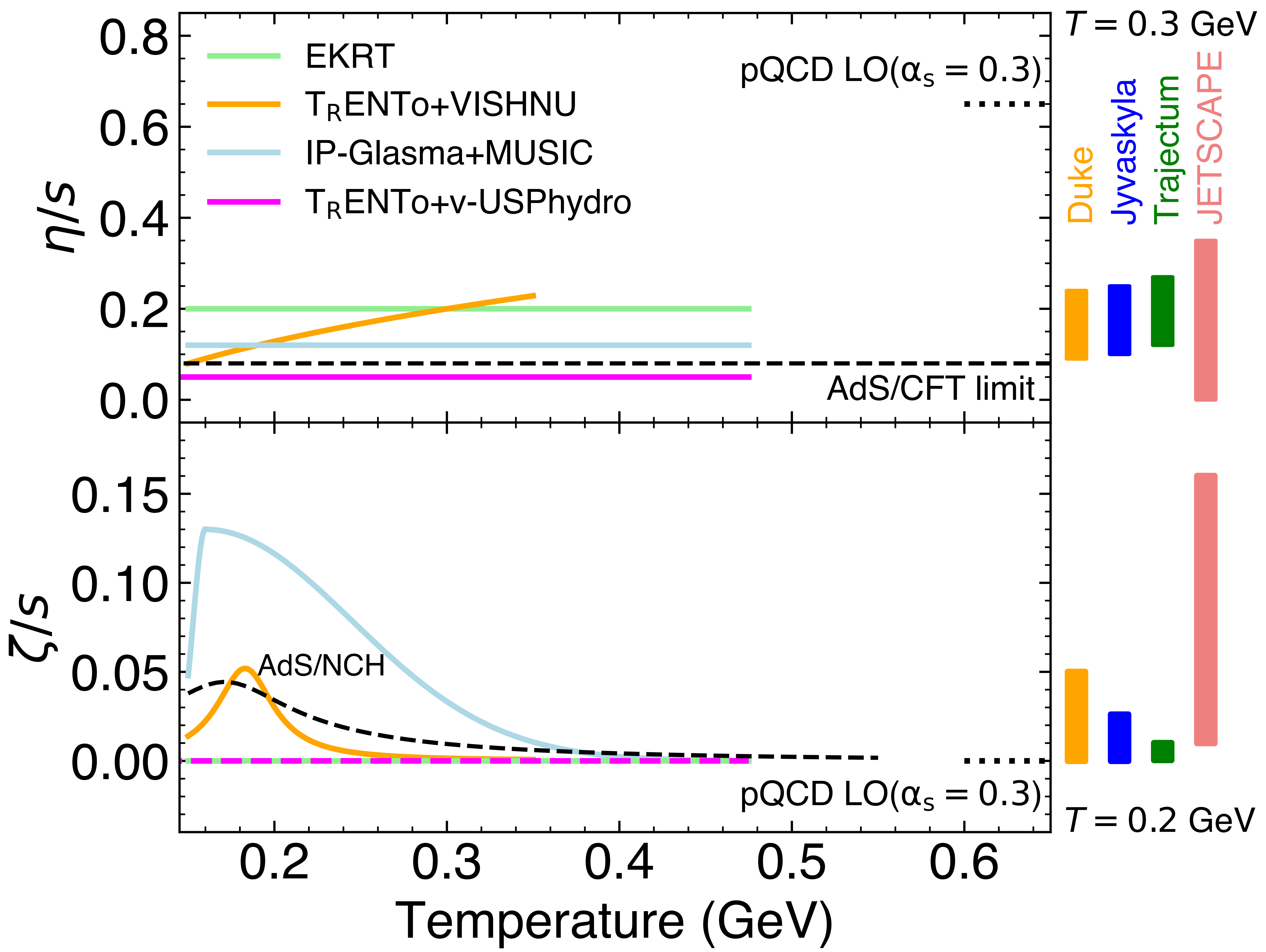




G. Nijs, W. van der Schee, U. Gursoy, RS, DOI: 10.1103/PhysRevLett.126.202301

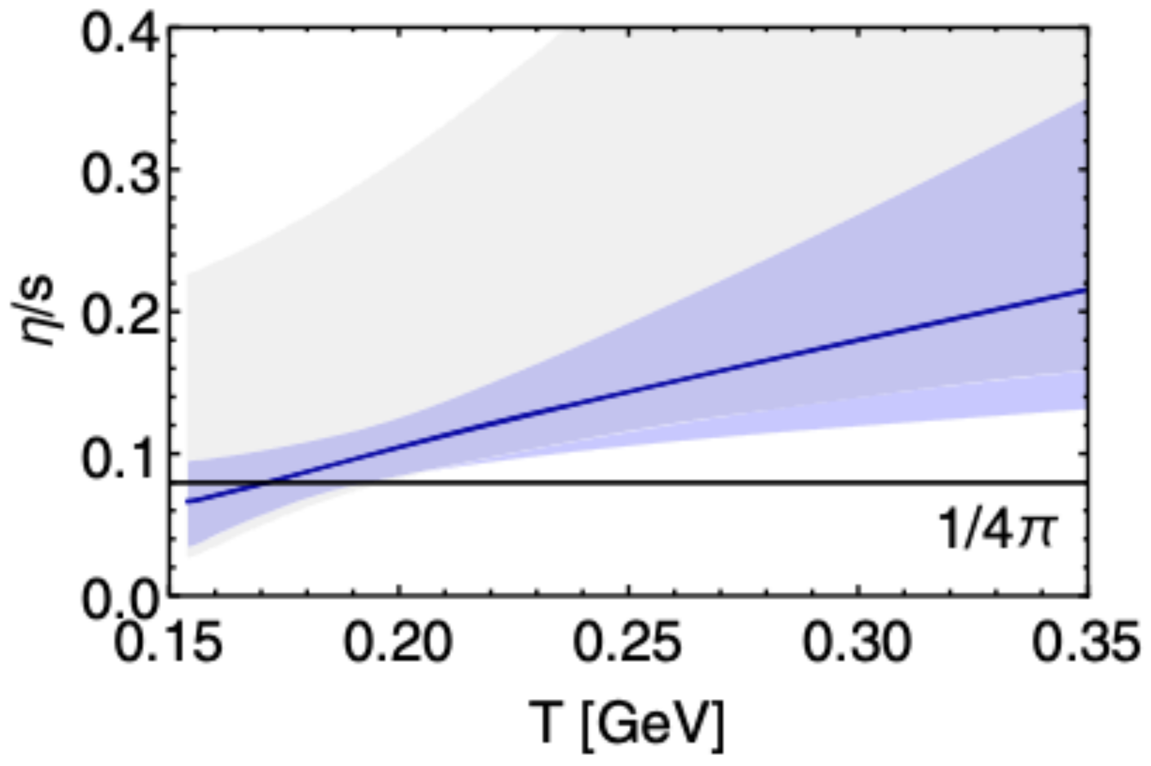


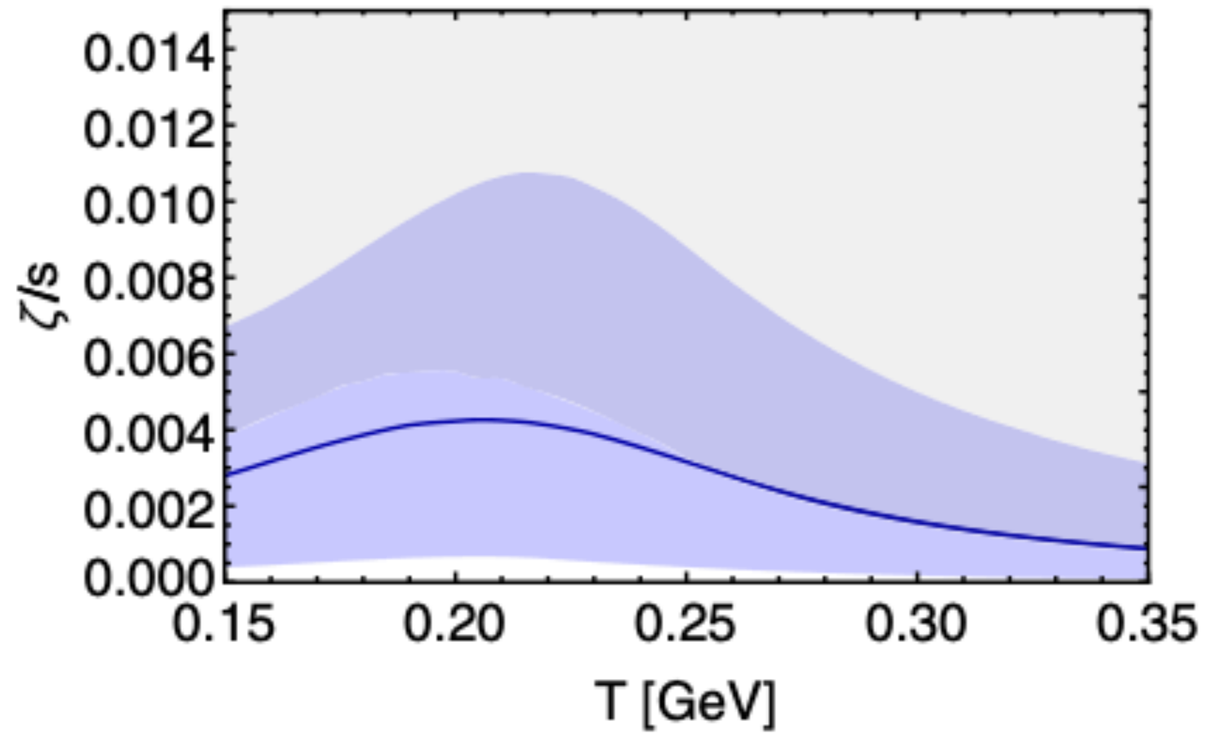
Transport parameters

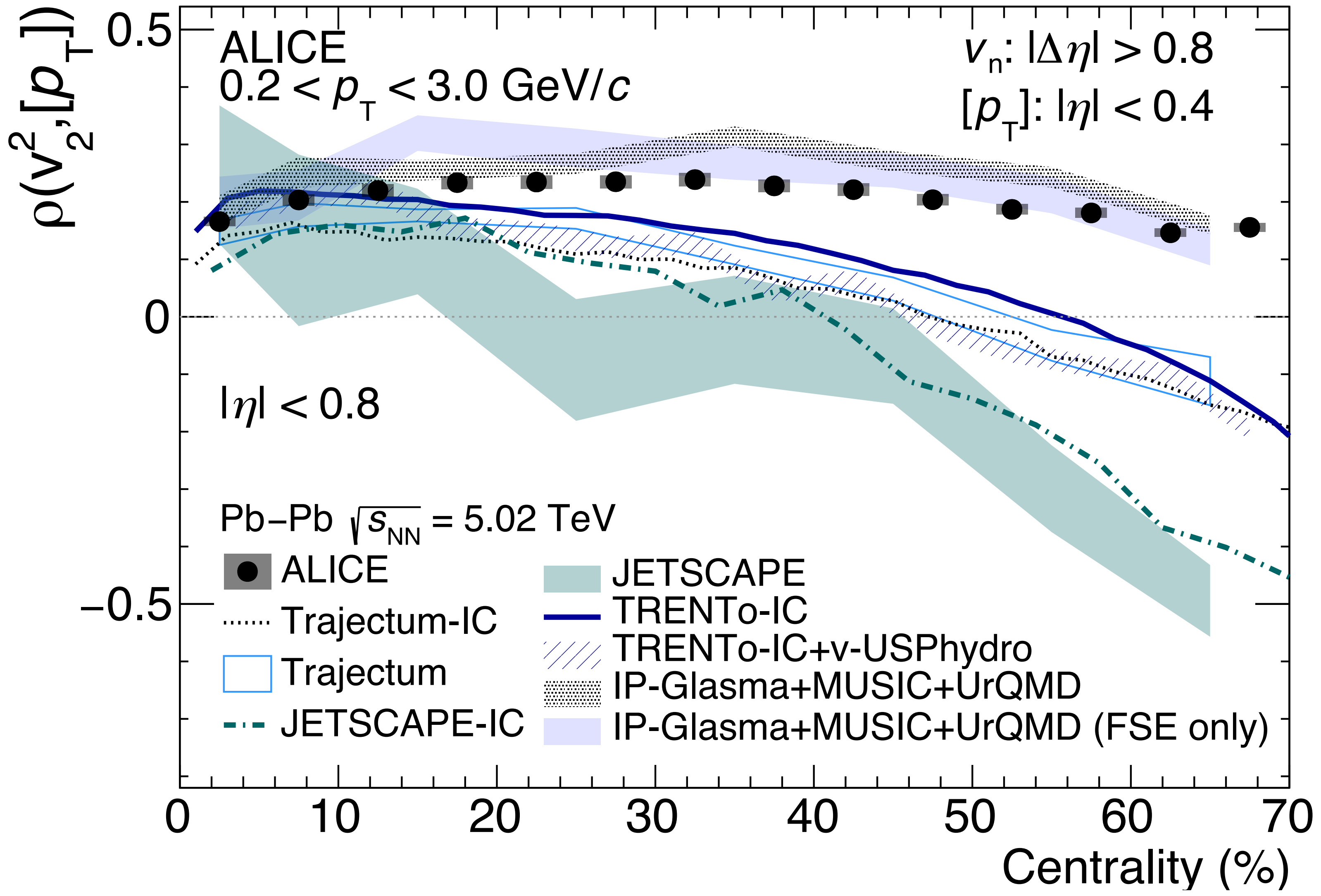


ALICE Collaboration:arXiv:2211.04384

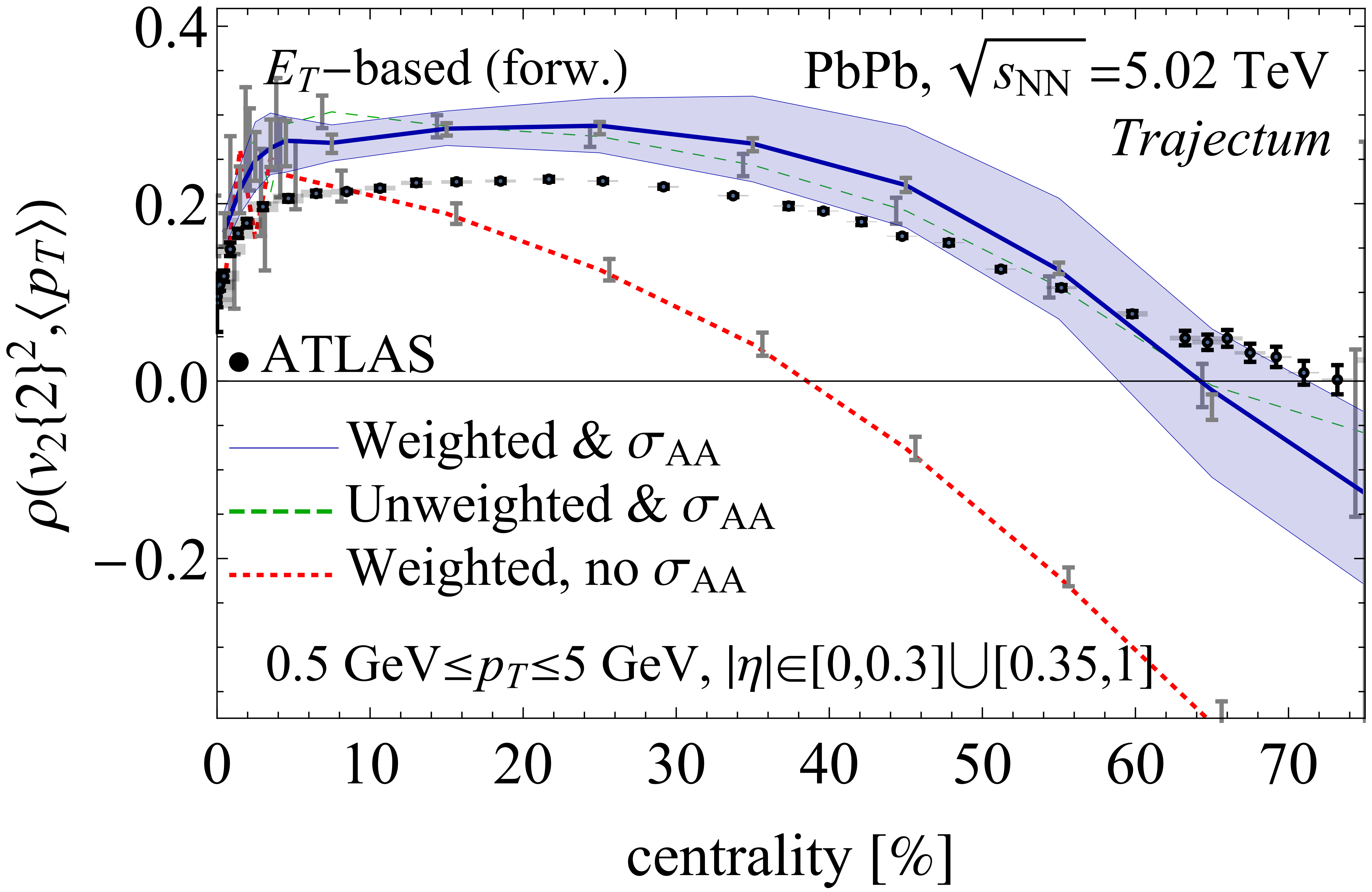
G. Nijs, W. van der Schee, U. Gursoy, RS, DOI: 10.1103/PhysRevLett.126.202301



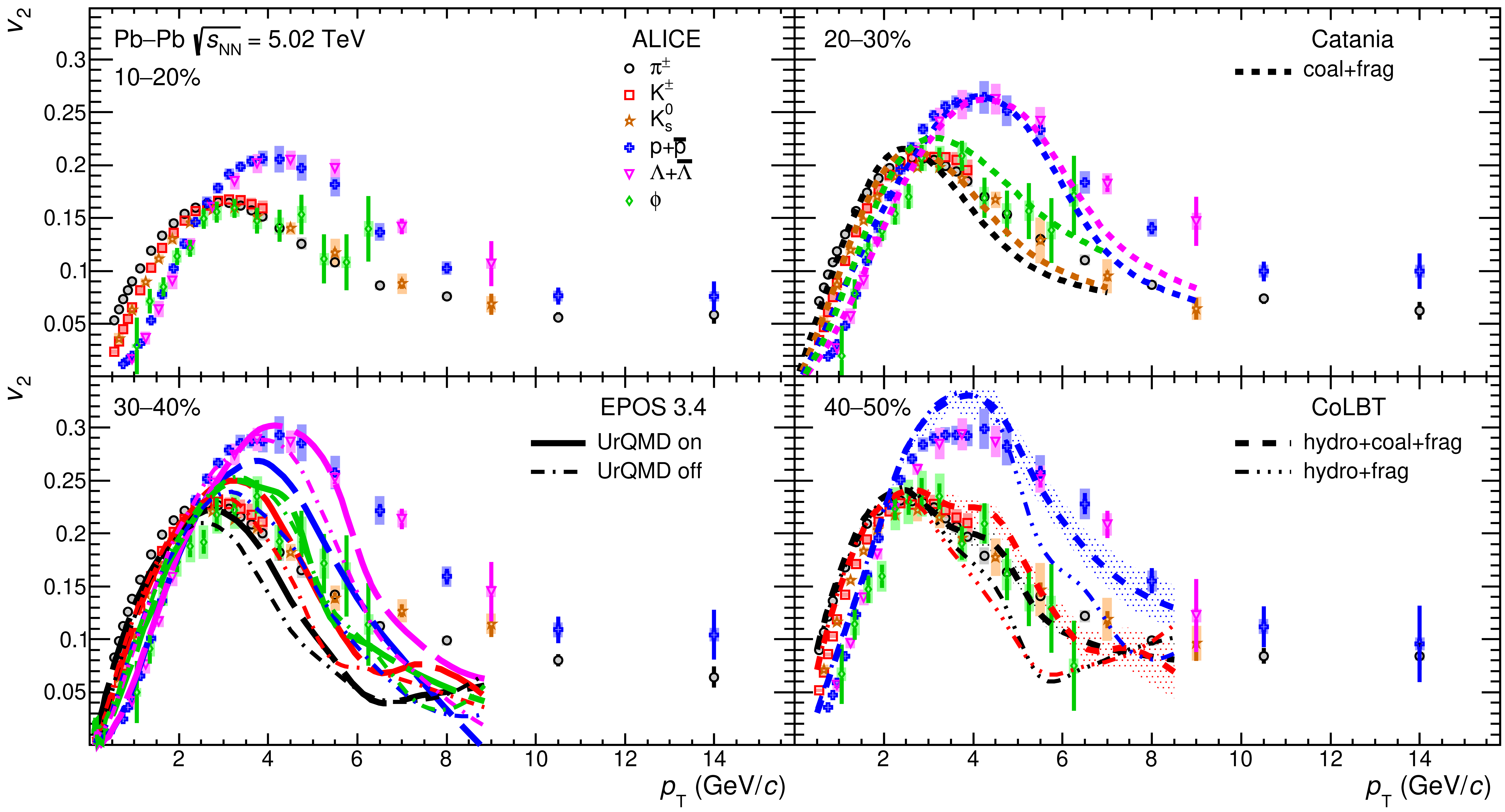




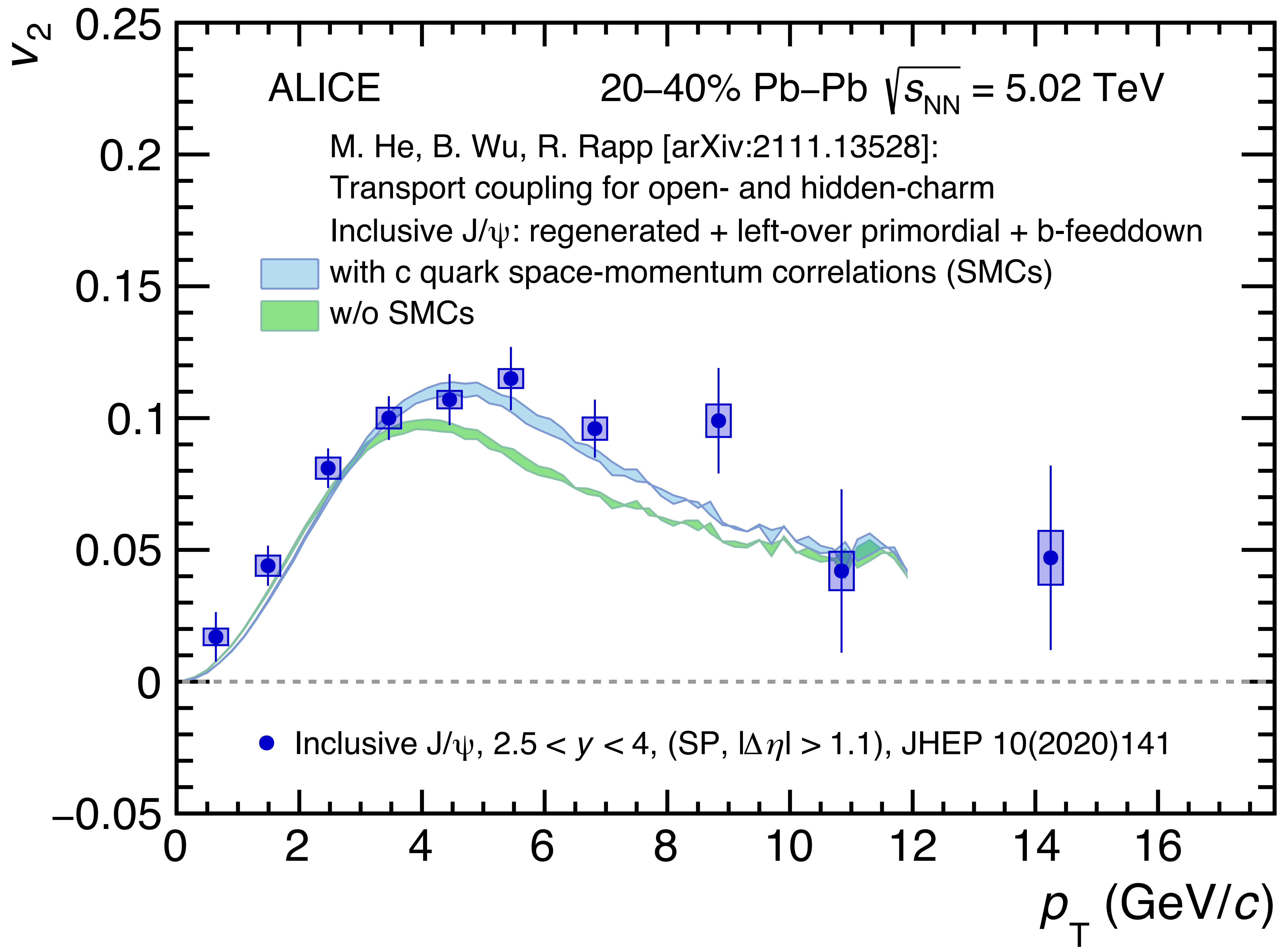
See updates in Govert Nijs and Wilke van der Schee arXiv:2206.13522



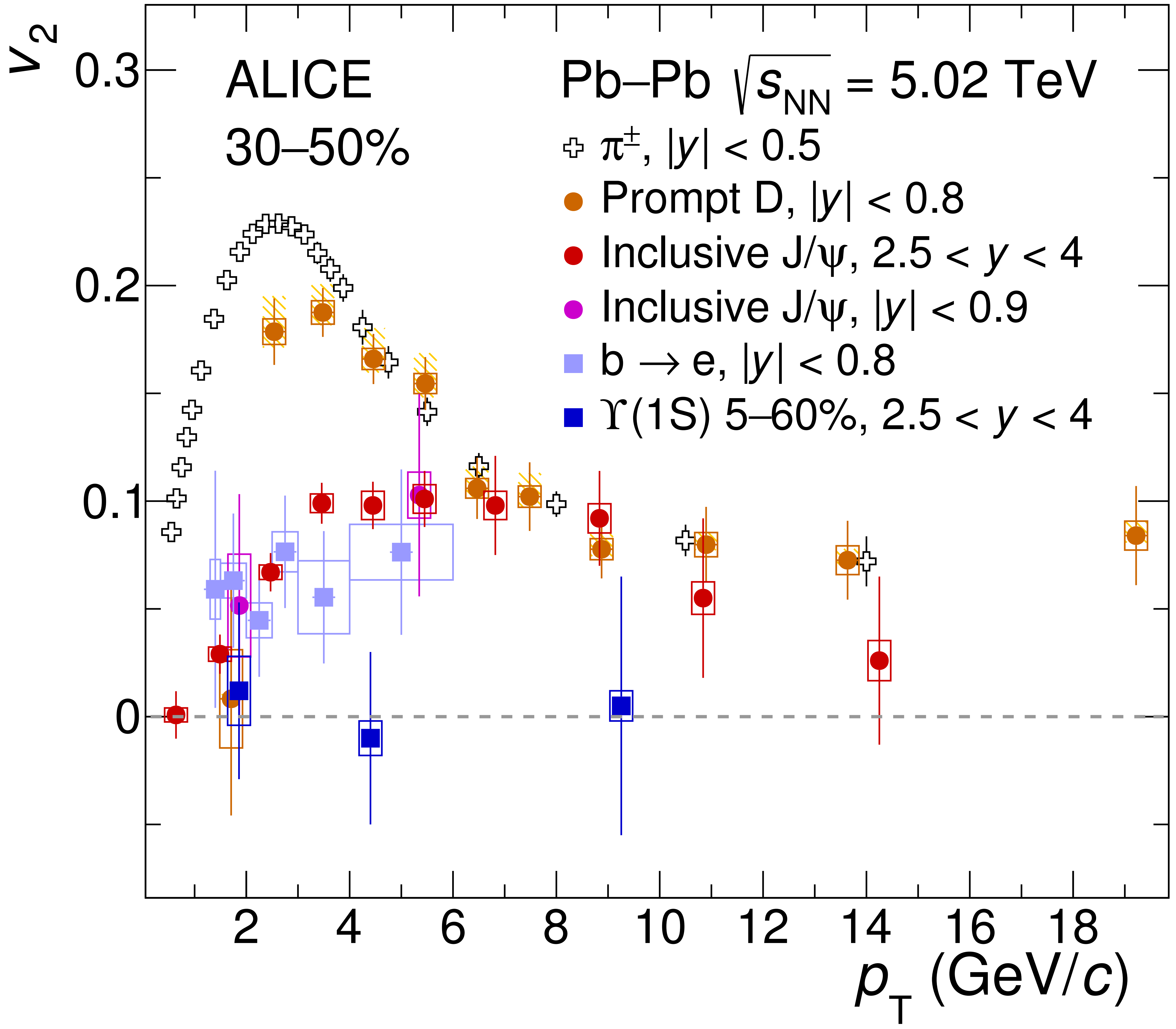
Coalescence/Recombination

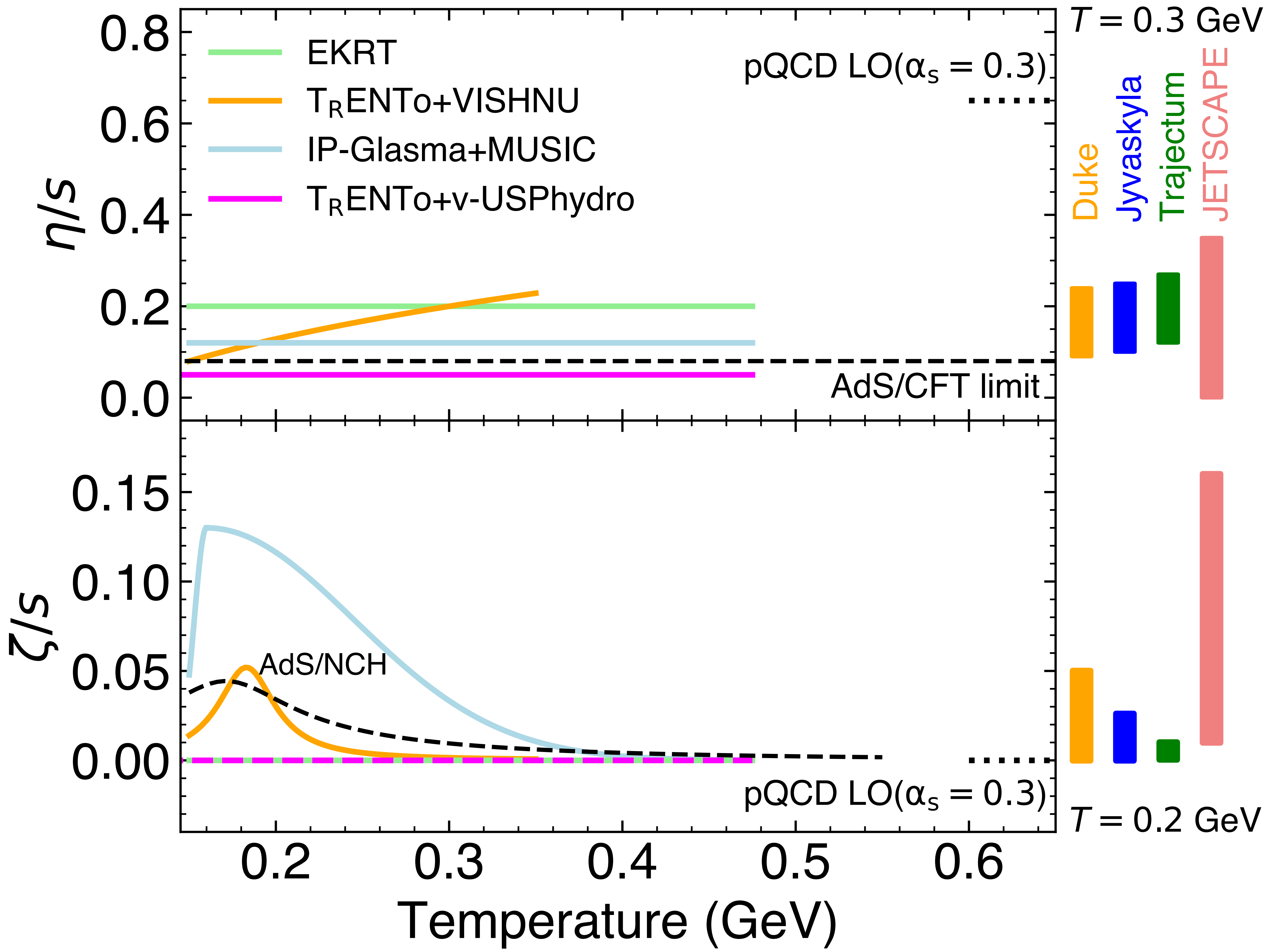


Coalescence/Recombination

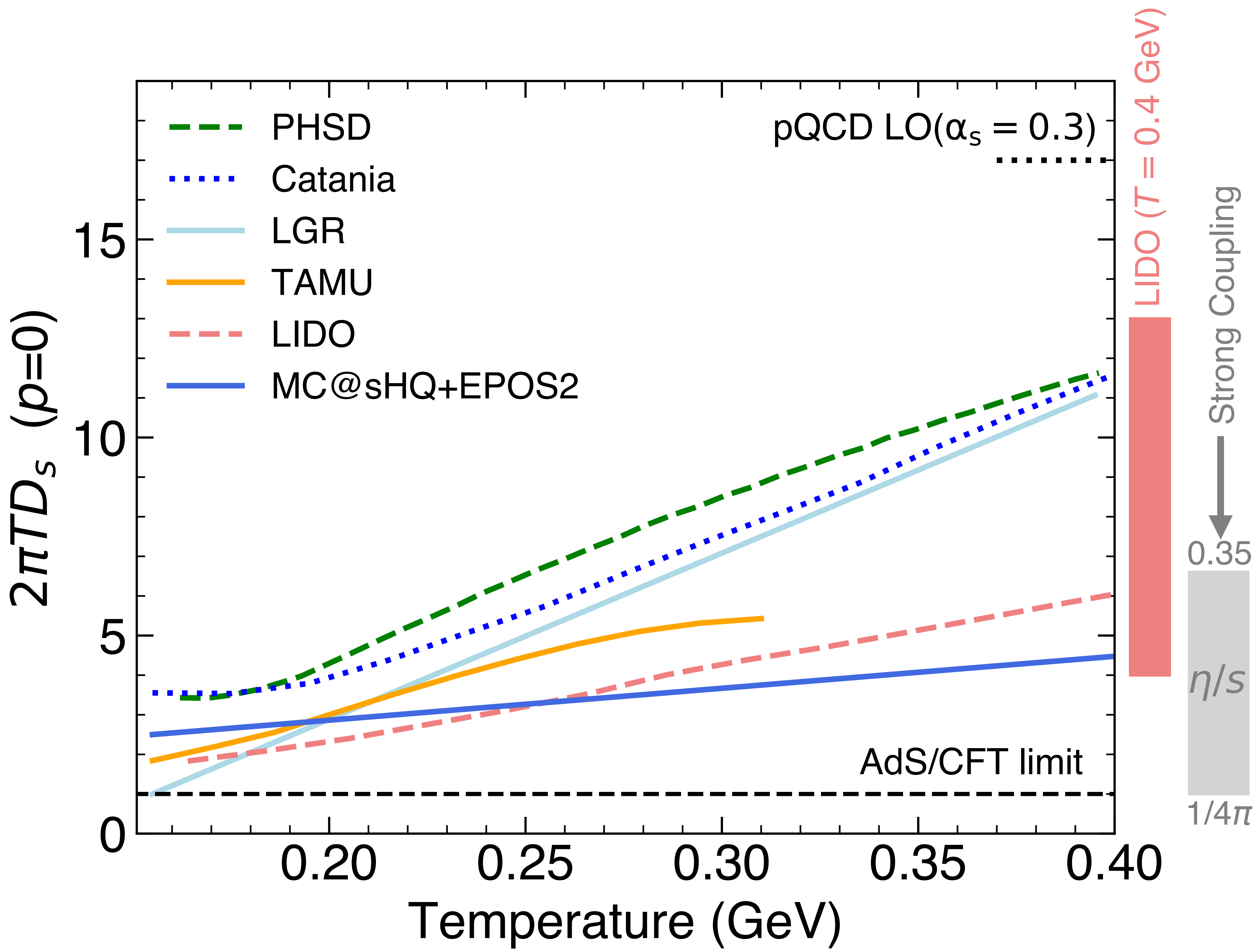


Heavy Flavor v_2

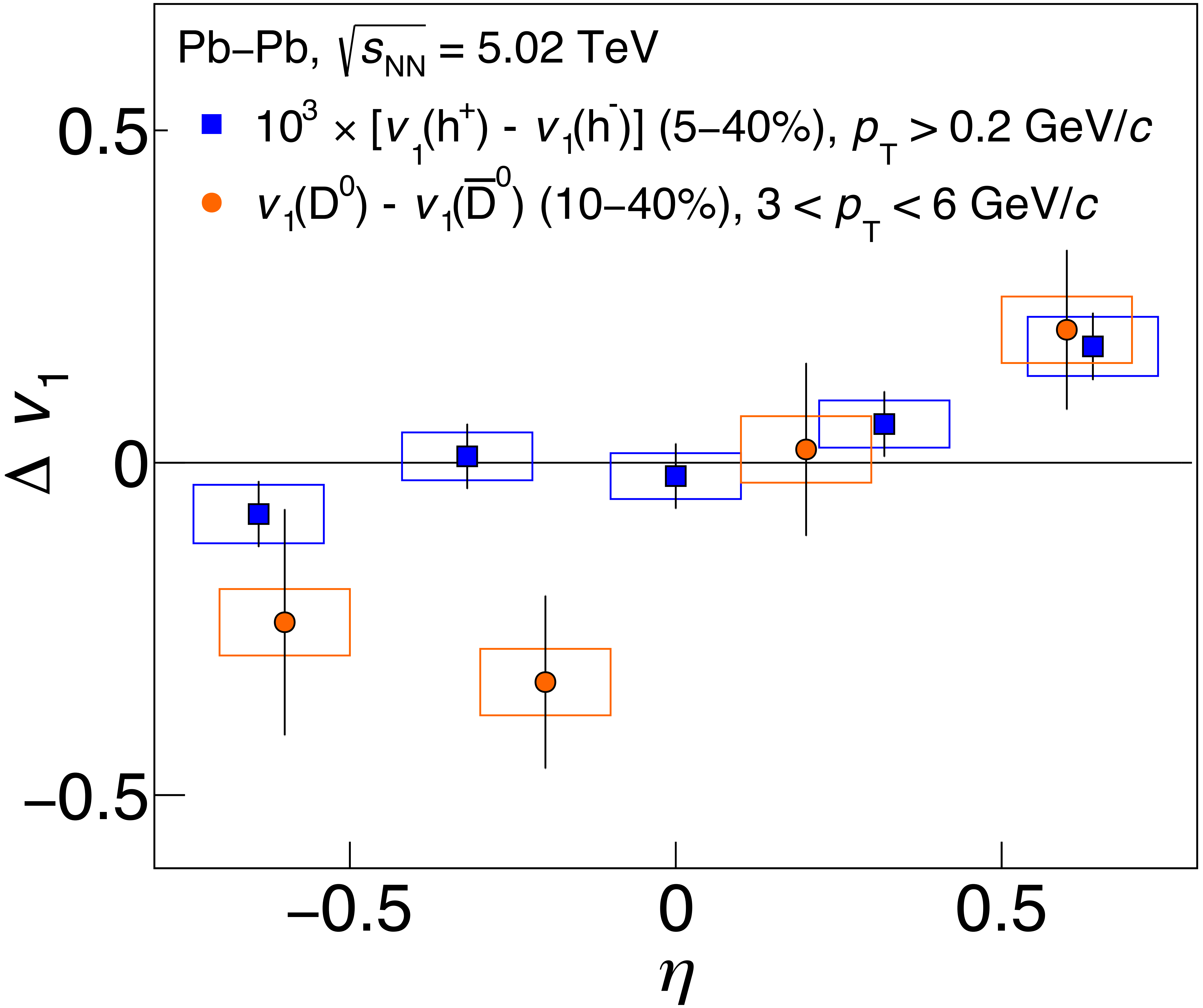




η/s
ζ/s
EKRT
TRENTo+VISHNU
IP-Glasma+MUSIC
TRENTo+v-USPhydro
pQCD LO(αs = 0.3)
AdS/CFT limit
AdS/NCH
T = 0.3 GeV
T = 0.2 GeV
Duke
Jyvaskyla
Trajectum
JETSCAPE
Temperature (GeV)

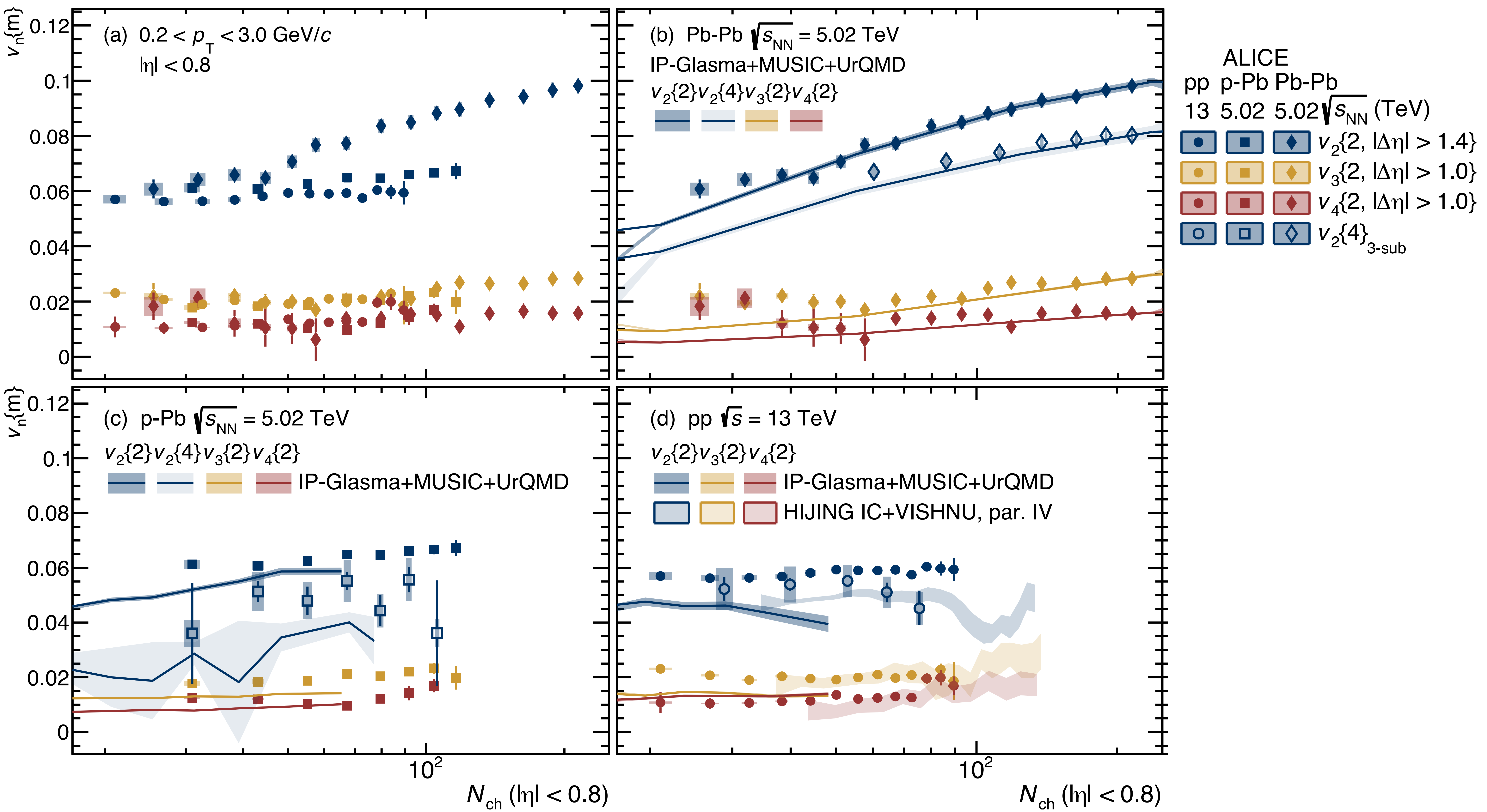


2πTDs (p=0)
PHSD
Catania
LGR
TAMU
LIDO
MC@sHQ+EPOS2
pQCD LO(αs = 0.3)
AdS/CFT limit
LIDO (T = 0.4 GeV)
Strong Coupling
0.35
η/s
1/4π
Temperature (GeV)



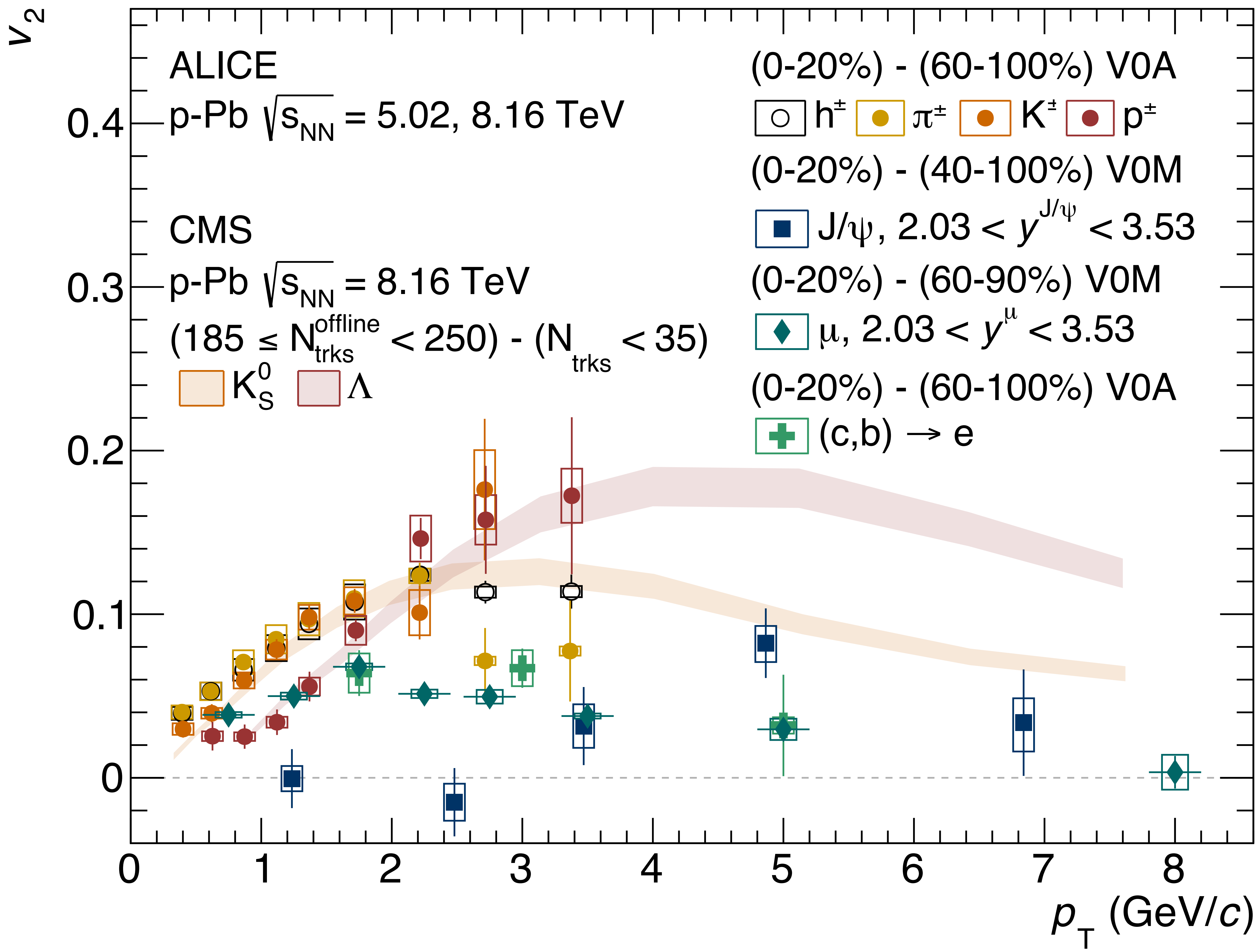
Indication of non-zero magnetic field contributions?
Needs to be looked at again with much better statistics and checked if this can also be generated without magnetic fields

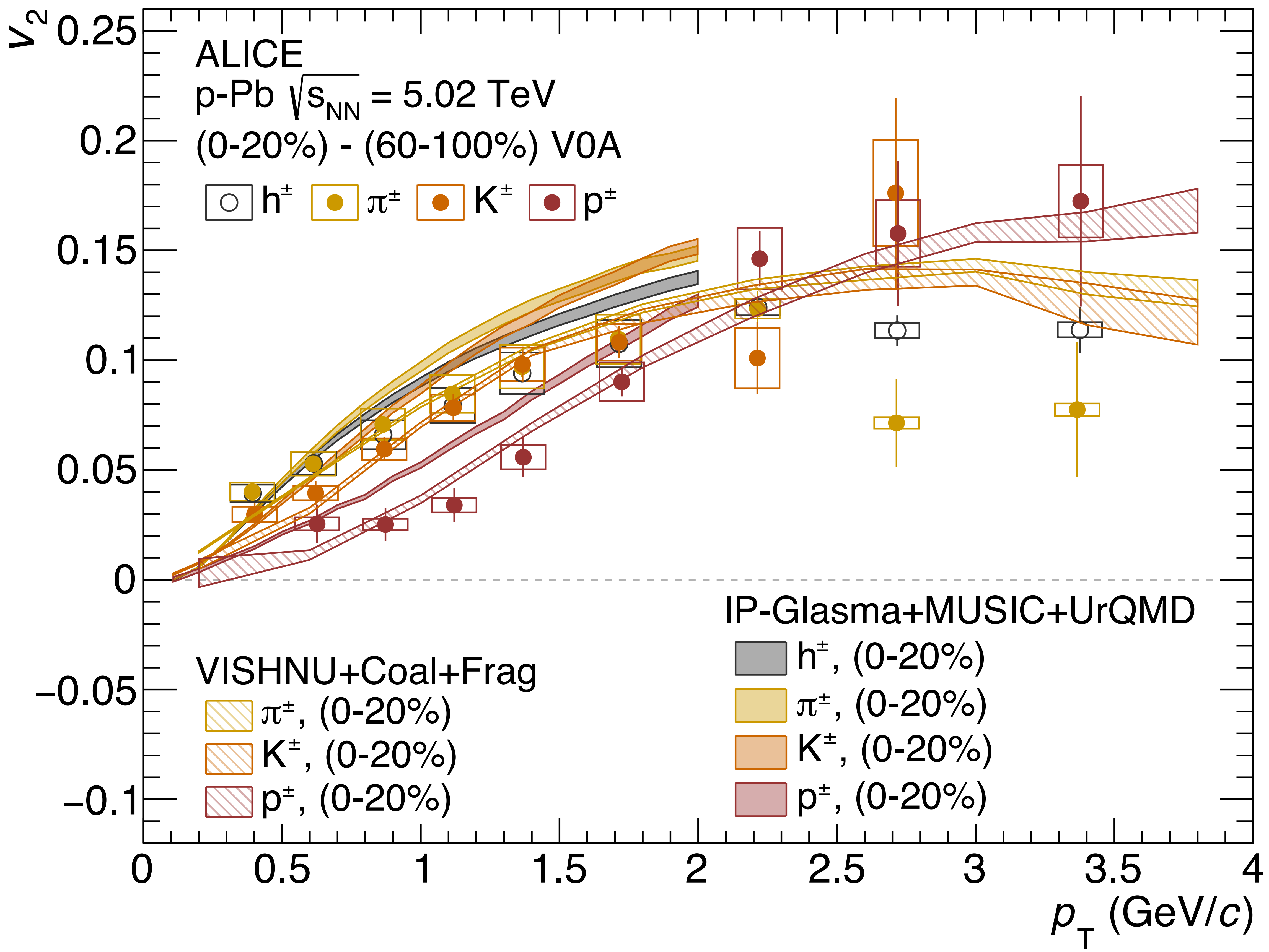
From pp to AA



(a) 0.2 < p_T < 3.0 GeV/c
|η| < 0.8
(b) Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
IP-Glasma+MUSIC+UrQMD
$v_2\{2\} v_2\{4\} v_3\{2\} v_4\{2\}$
(c) p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$v_2\{2\} v_2\{4\} v_3\{2\} v_4\{2\}$
IP-Glasma+MUSIC+UrQMD
(d) pp $\sqrt{s}$ = 13 TeV
$v_2\{2\} v_3\{2\} v_4\{2\}$
IP-Glasma+MUSIC+UrQMD
HIJING IC+VISHNU, par. IV
$v_n\{m\}$
N_{ch} (|η| < 0.8)
ALICE
pp 13
p-Pb 5.02
Pb-Pb 5.02
$\sqrt{s_{NN}}$ (TeV)
$v_2\{2, |\Delta\eta| > 1.4\}$
$v_3\{2, |\Delta\eta| > 1.0\}$
$v_4\{2, |\Delta\eta| > 1.0\}$
$v_2\{4\}_{3\text{-sub}}$

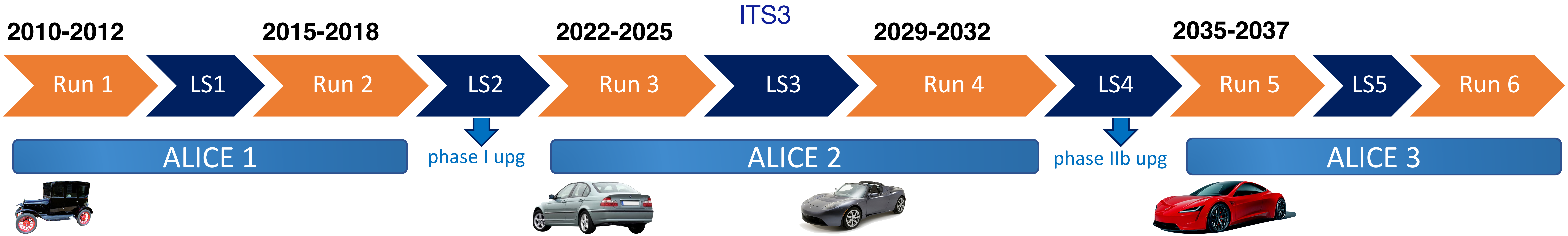
p-Pb





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)

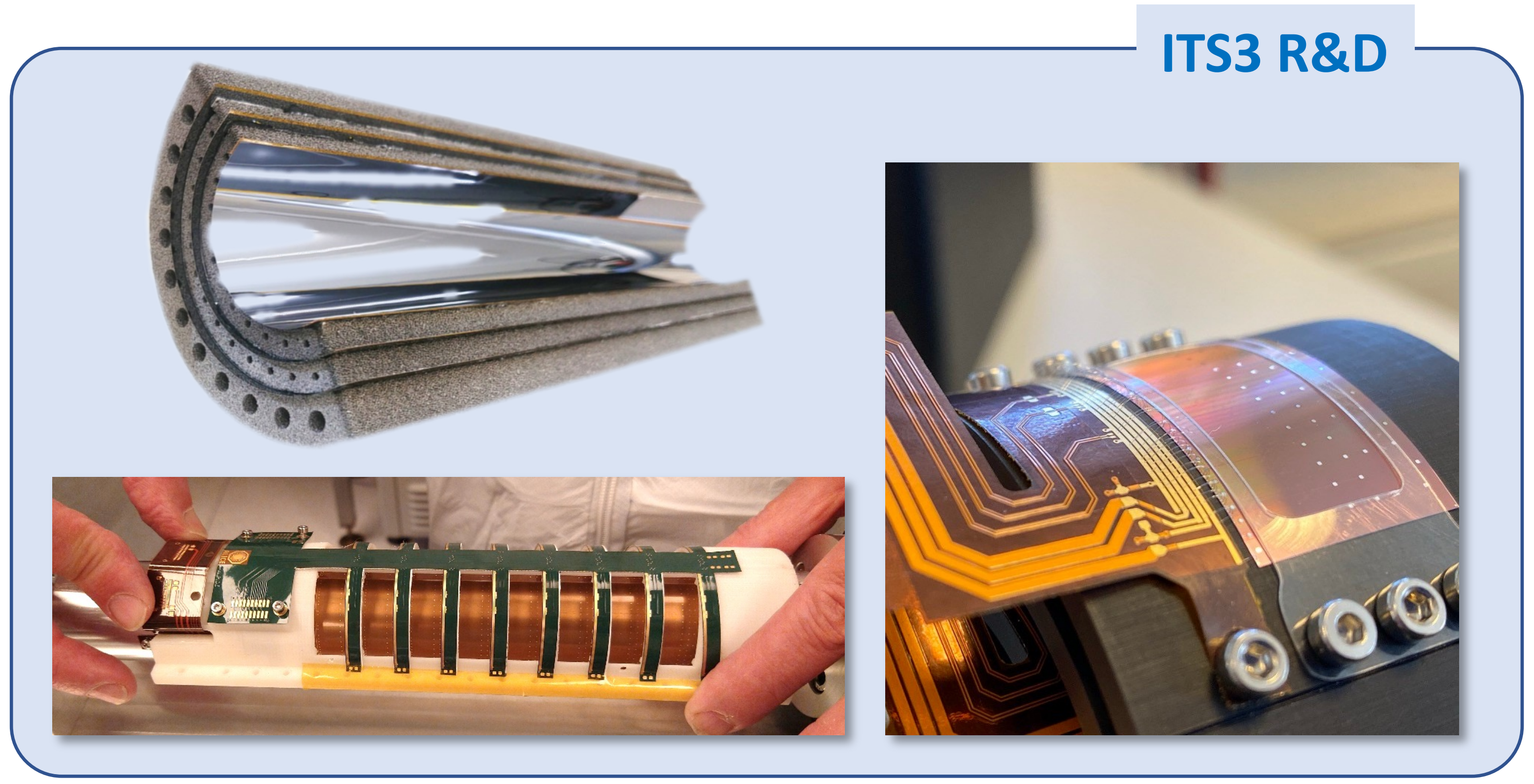
2026 – 2027: large-scale engineered prototypes (~75% of R&D funds) ➪ Technical Design Reports

2028 – 2030: construction and testing

2031 – 2032: contingency

2033 – 2034: installation and commissioning

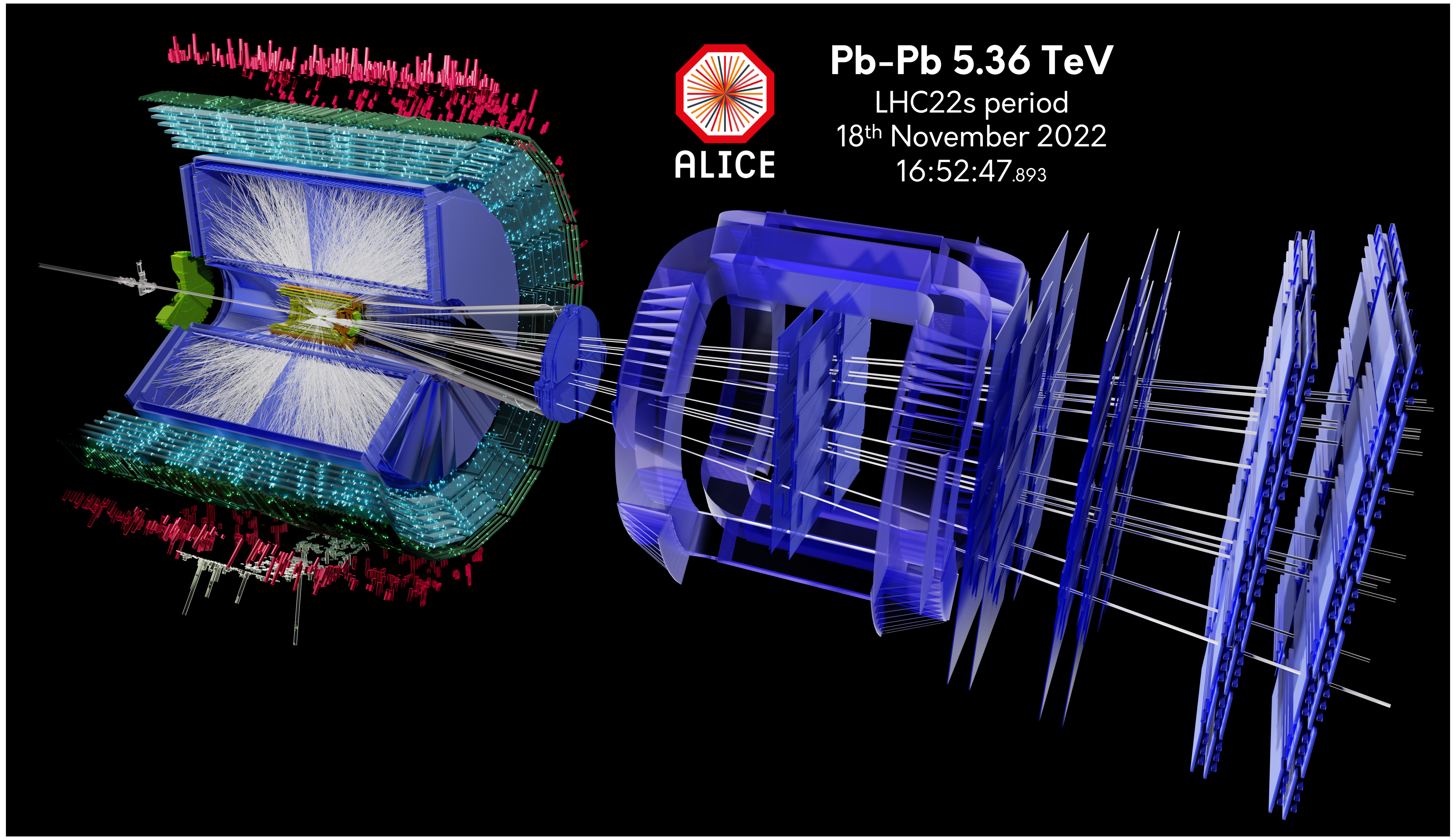
2035 – 2042: physics campaign

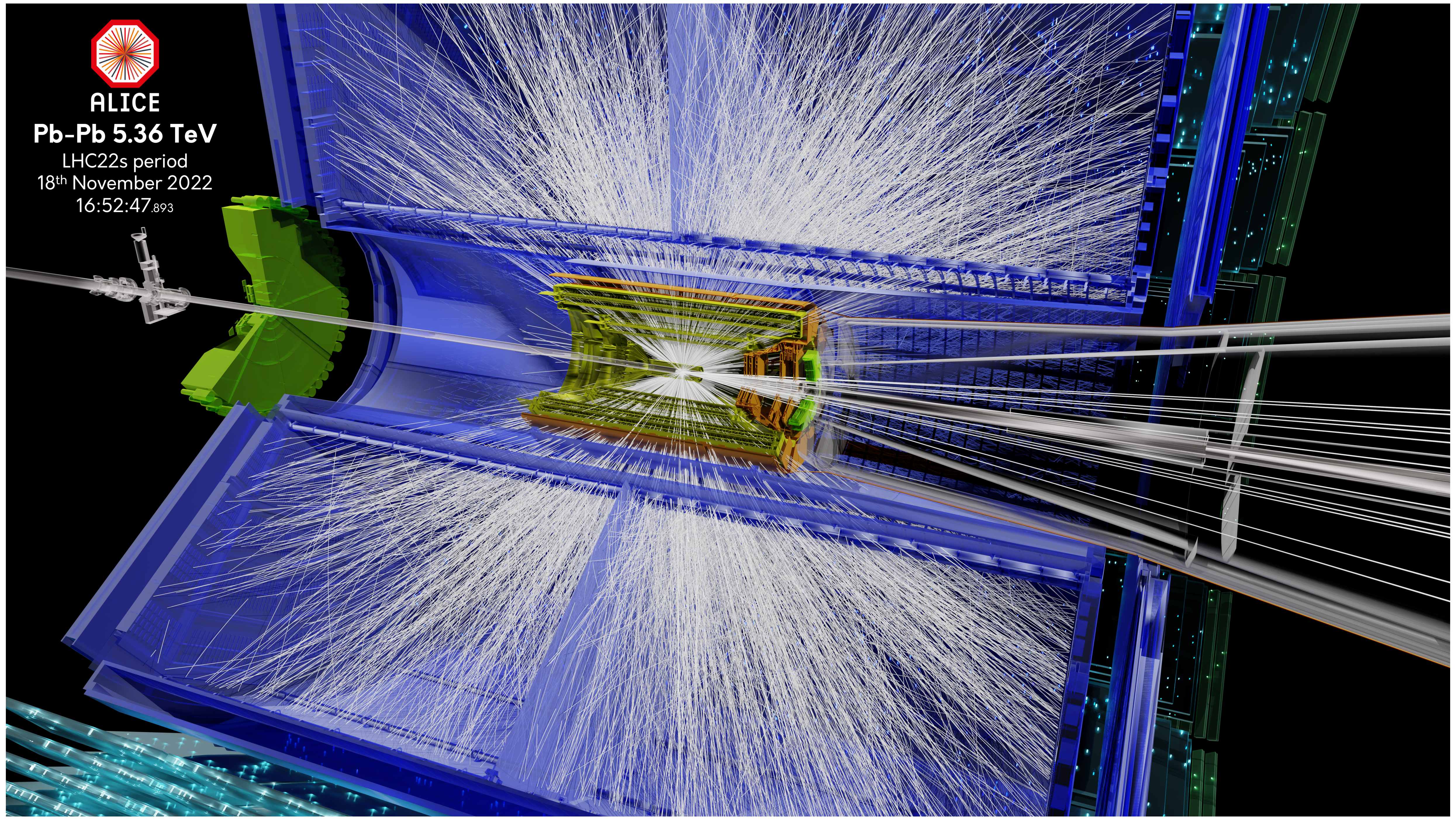


ITS3 LoI:

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)

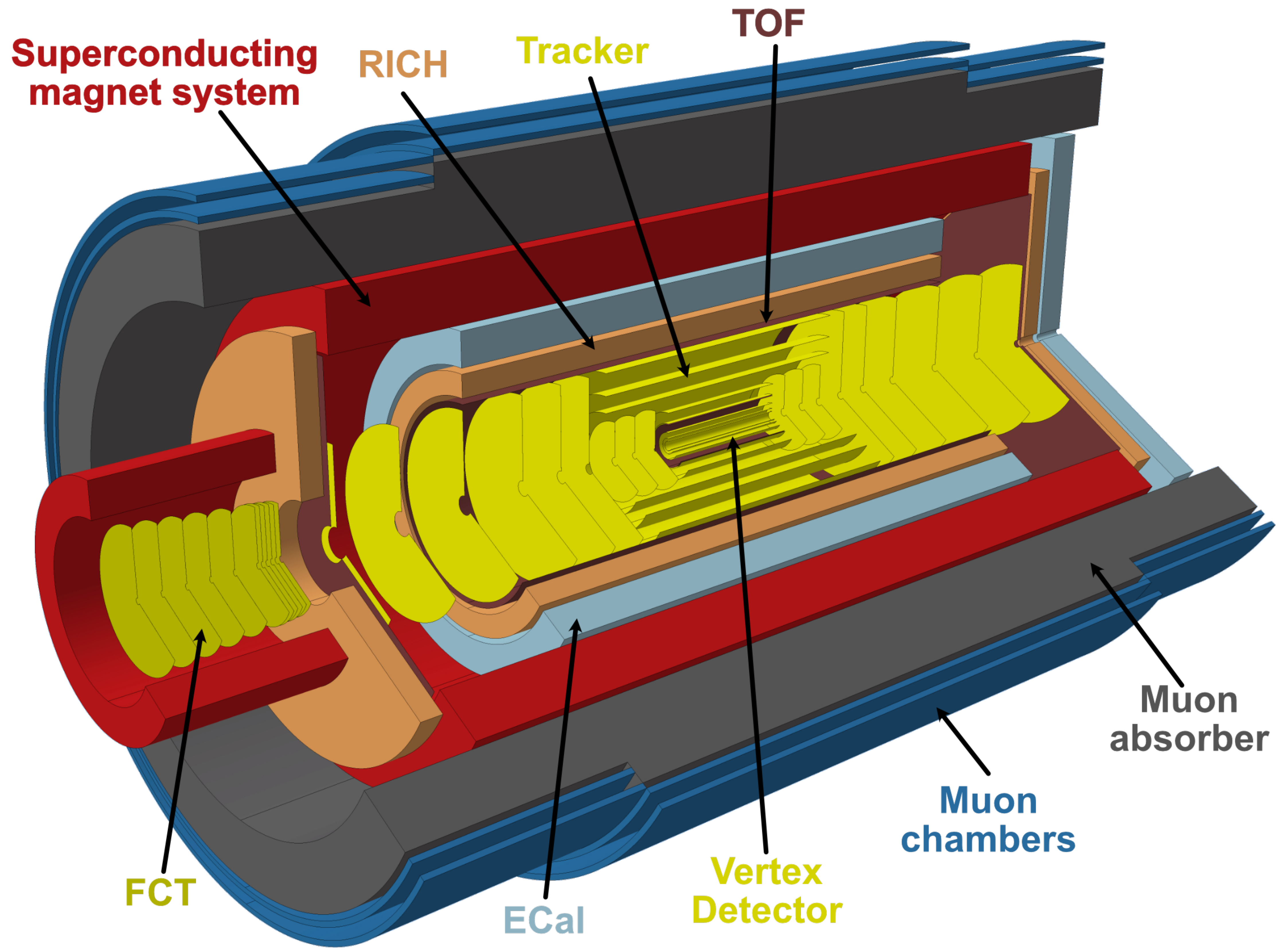
- Muon ID down to $p_T \approx 1.5\ \mathrm{GeV}/c$

ECAL

- Photons/jets over large η

Superconductor magnet system (2T)

Continuous read-out and online processing



Unique Detector Concept and Features at the LHC

Transport parameters