Collective flow measurements in Gold-Gold collisions at 1.23 AGeV with HADES

Behruz Kardan

for the
HADES Collaboration

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions
INT WORKSHOP INT-22-84W

6th December, 2022

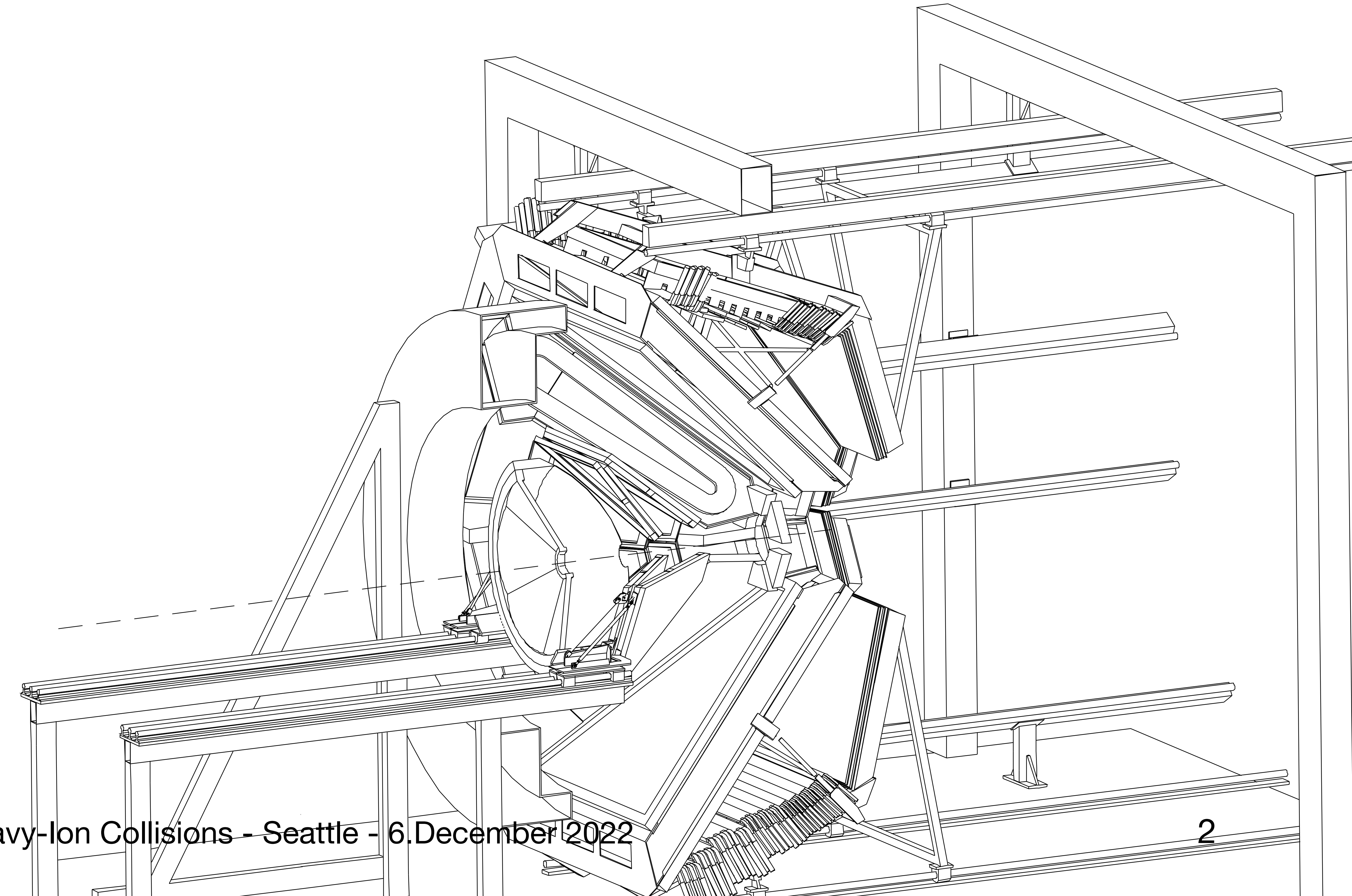
Outline

- Dense nuclear matter and collective phenomena
- HADES and Au+Au data at 1.23 AGeV
- Directed v_1, elliptic v_2, and higher flow harmonics (v_3, v_4, v_5, v_6) of protons, deuterons and tritons
- Scaling properties of flow harmonics
- Model comparisons

Talk based on following publication:

HADES, PRL 125 (2020) 262301 arXiv:2005.12217 [hepdata]

HADES, arXiv:2208.02740 submitted to EPJ A



Motivation

Nuclear and Neutron Star Matter

Neutron Star Merger

Observation via gravitational waves

GW170817: B.P. Abott et al. (LIGO + VIRGO)
PRL **119** (2017) 1611001

Sensitivity to equation-of-state

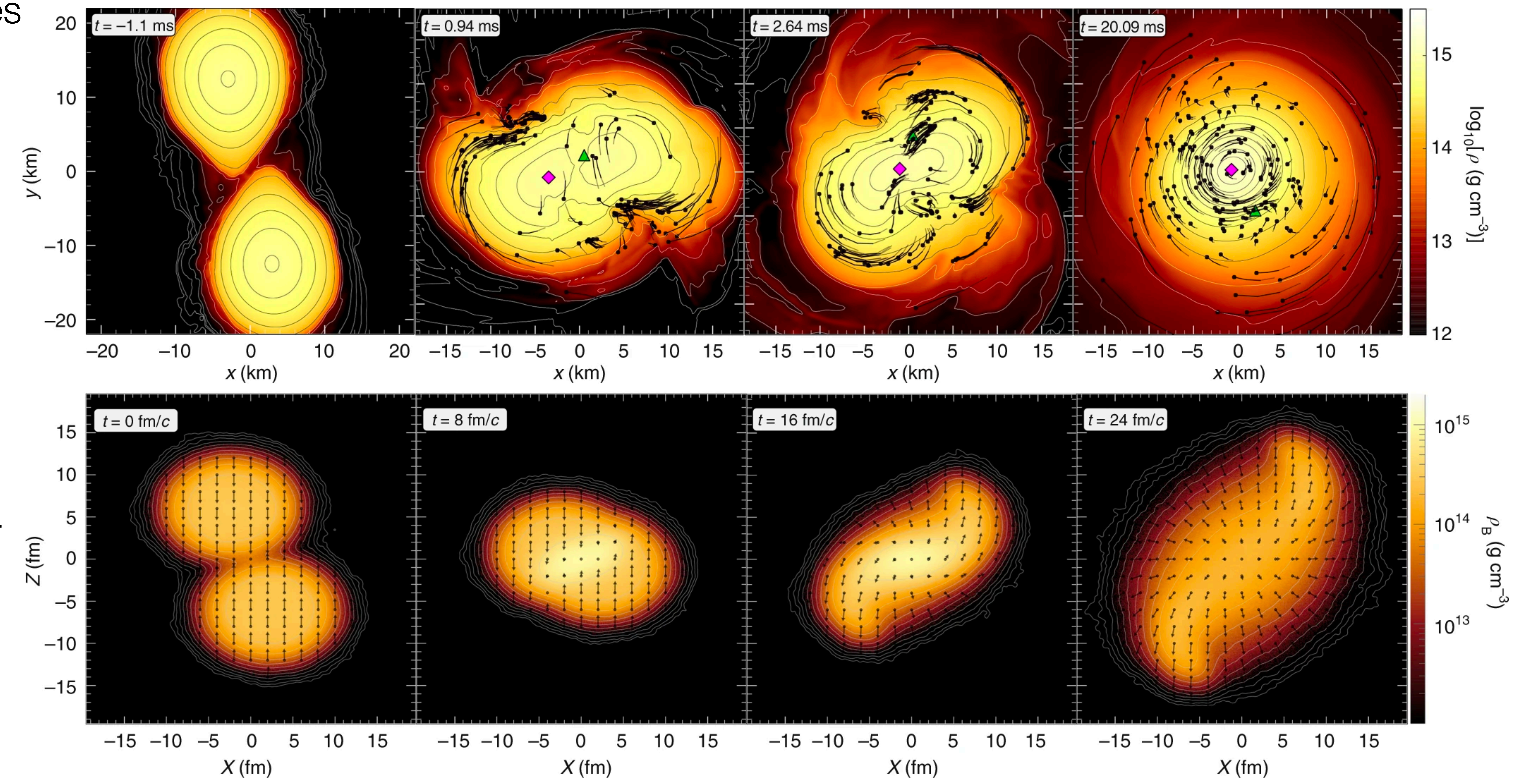
Matter at super nuclear density in the universe

Heavy-ion Collision

Equation-of-state of dense matter

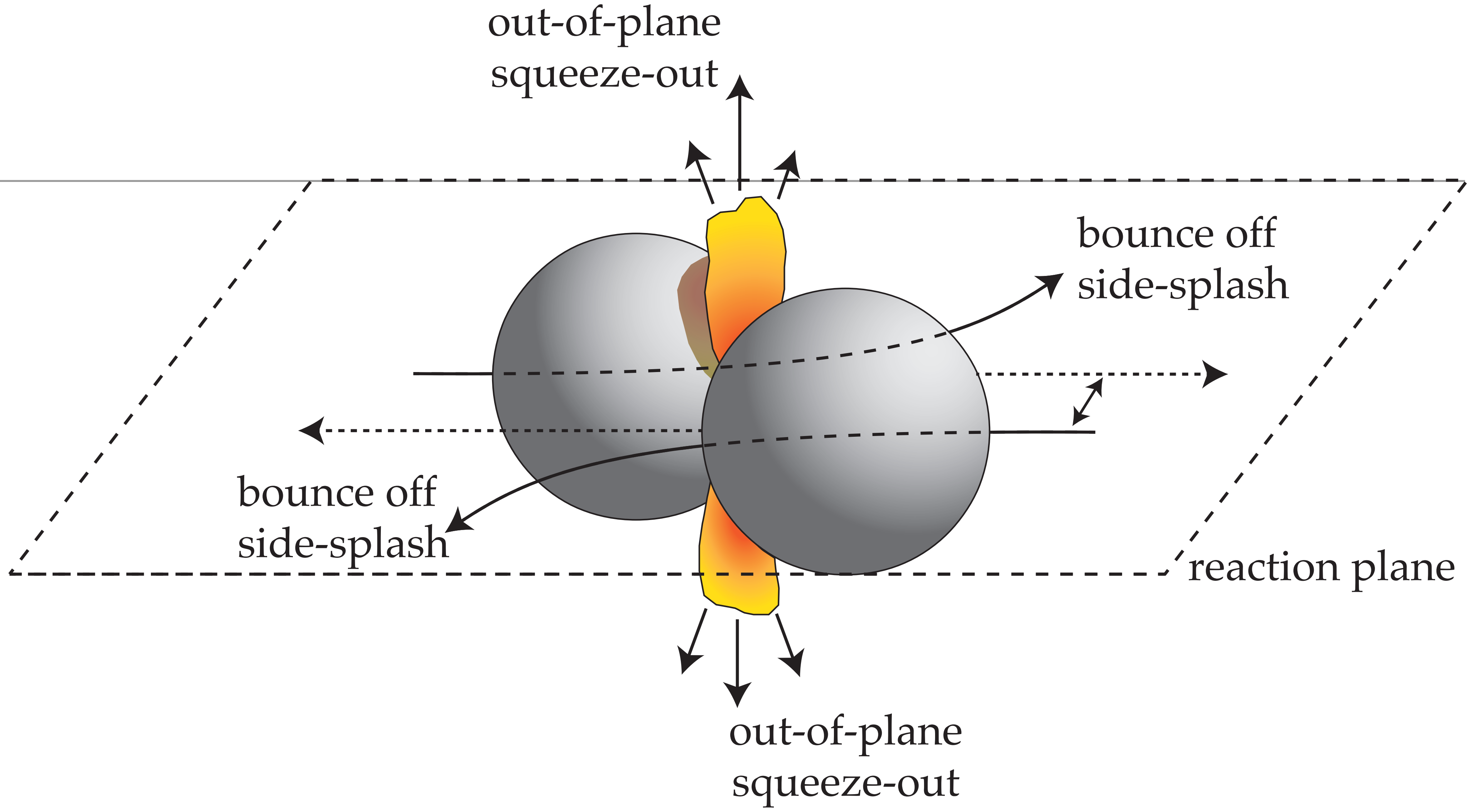
Matter at super nuclear density in the laboratory

HADES, Nature Phys. **15** (2019) 1040



Collective Effects

Flow Phenomenology



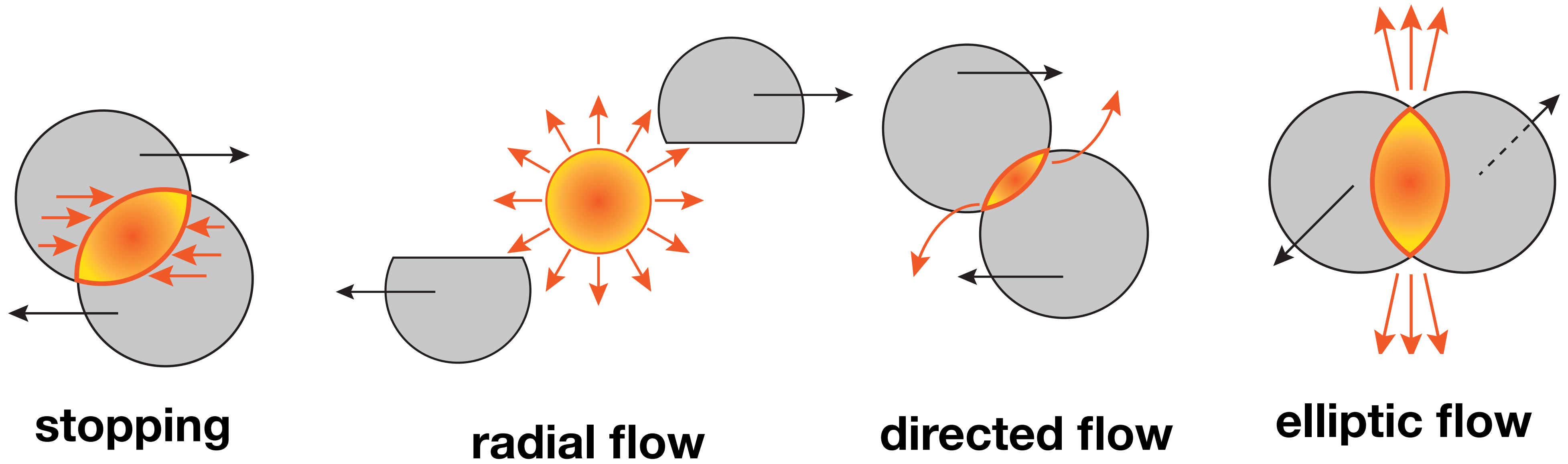
Emission relative to event plane

Interactions in medium, nuclear stopping

$\Longrightarrow$ buildup of non-uniform pressure gradients

provides accelerating forces in different directions

Access to medium properties, e.g. viscosity, equation-of-state



Fourier-decomposition

of the triple differential invariant cross section

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_t, y)\cos(n\phi)\right)$$

$$\phi = (\varphi - \Psi_{RP})$$

Extraction of azimuthal moments v_n

$$v_n(p_t, y) = \langle\cos(n\phi)\rangle$$

$$\begin{aligned}
v_1 &= \langle\cos\phi\rangle = \langle p_x/p_t\rangle,\\
v_2 &= \langle\cos(2\phi)\rangle = \langle(p_x^2 - p_y^2)/p_t^2\rangle,\\
v_3 &= \langle\cos(3\phi)\rangle = \langle(p_x^3 - 3p_xp_y^2)/p_t^3\rangle,\\
v_4 &= \langle\cos(4\phi)\rangle = \langle(p_x^4 - 6p_x^2p_y^2 + p_y^4)/p_t^4\rangle,\\
v_5 &= \langle\cos(5\phi)\rangle = \langle(p_x^5 - 10p_x^3p_y^2 + 5p_xp_y^4)/p_t^5\rangle,\\
v_6 &= \langle\cos(6\phi)\rangle = \langle(p_x^6 - 15p_x^4p_y^2 + 15p_x^2p_y^4 - p_y^6)/p_t^6\rangle.
\end{aligned}$$

Event Plane Reconstruction

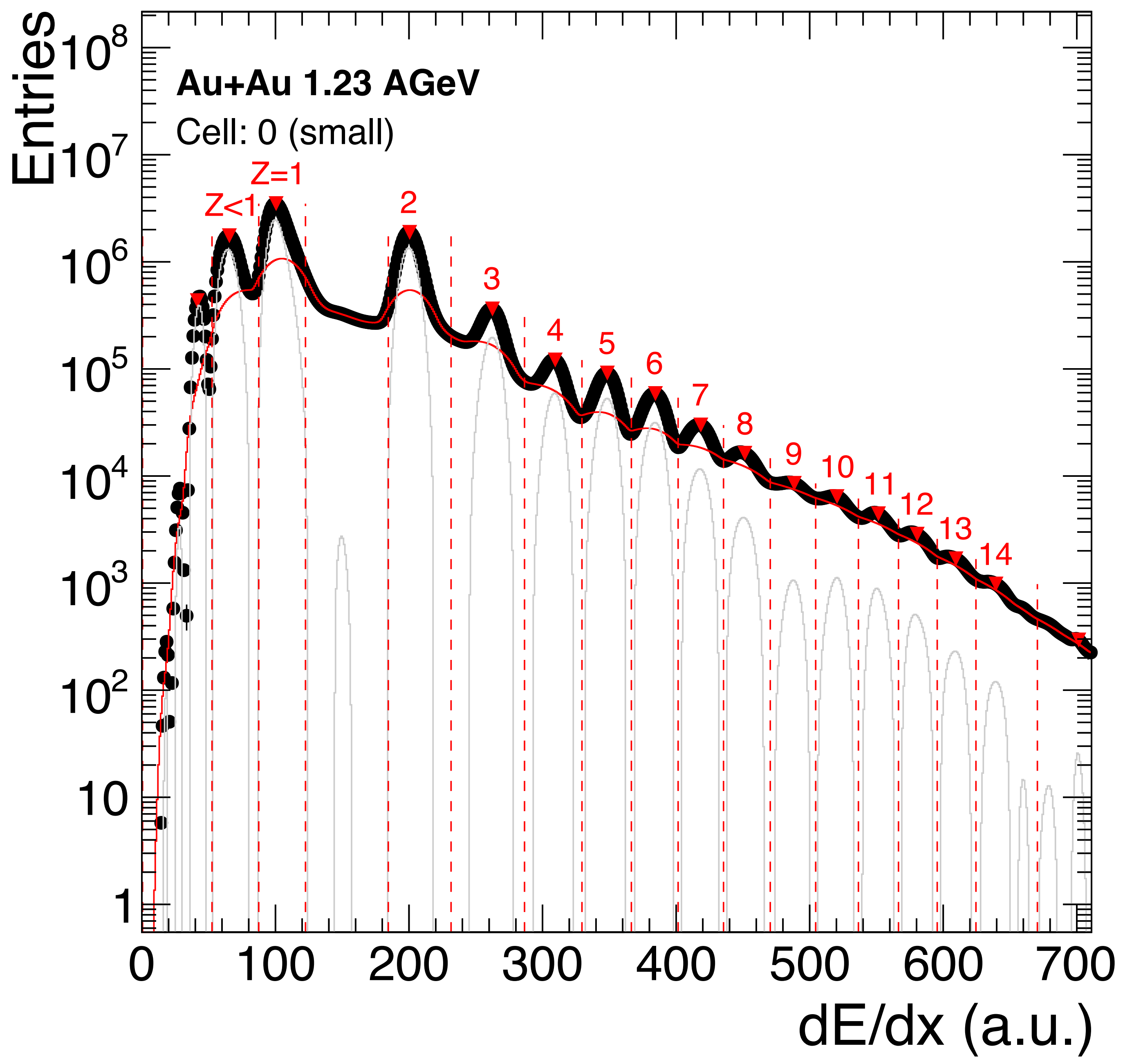
1st-Order event plane from Q-Vector
Projectile spectators in Forward Wall

Charge-Weighting of the projectile hits, according their energy loss in scintillators

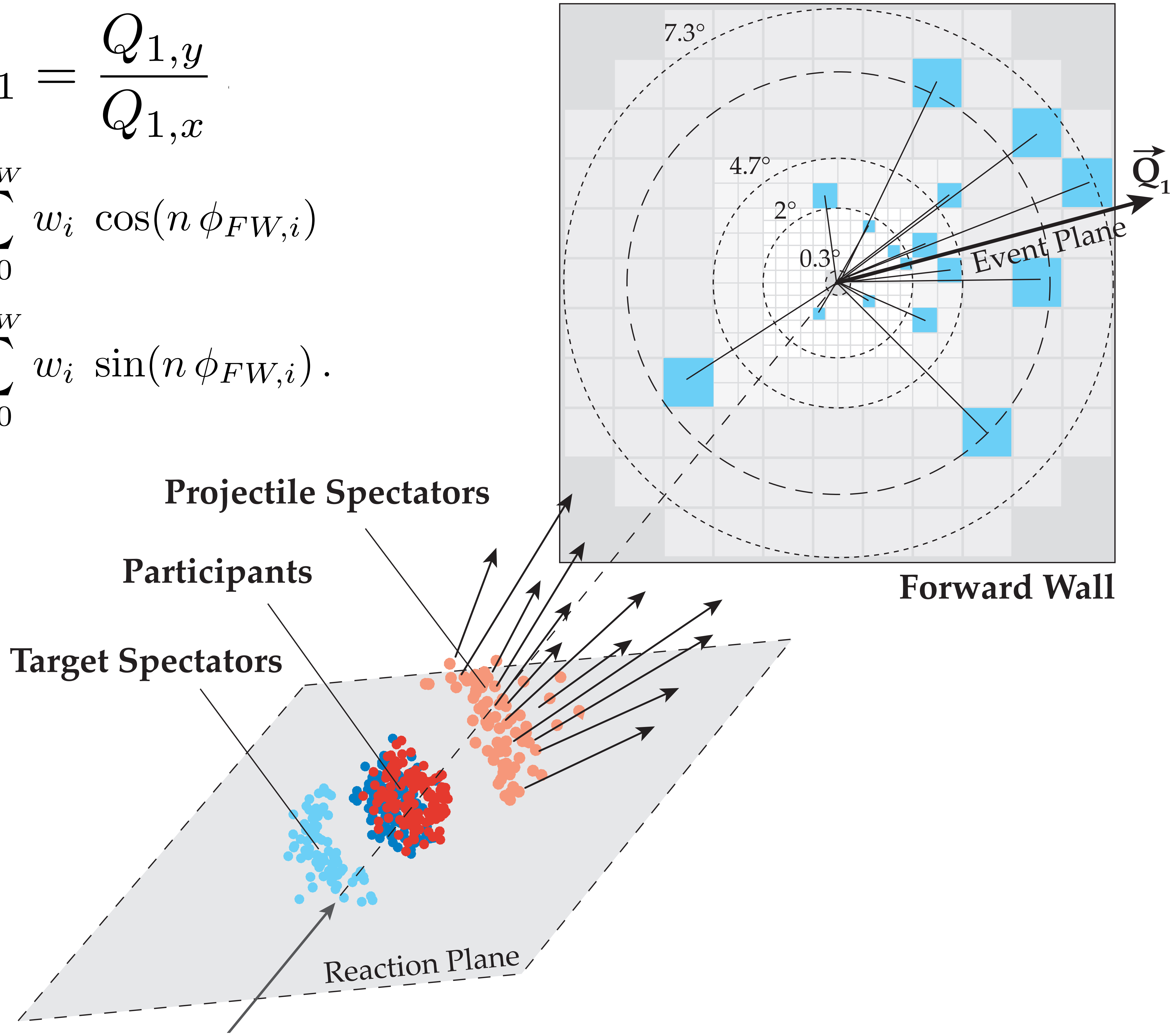
$$\tan \psi_{EP,1} = \frac{Q_{1,y}}{Q_{1,x}}$$

$$Q_{n,x} = \sum_{i=0}^{N_{FW}} w_i \cos(n\,\phi_{FW,i})$$

$$Q_{n,y} = \sum_{i=0}^{N_{FW}} w_i \sin(n\,\phi_{FW,i})\,.$$



Charge Weighting



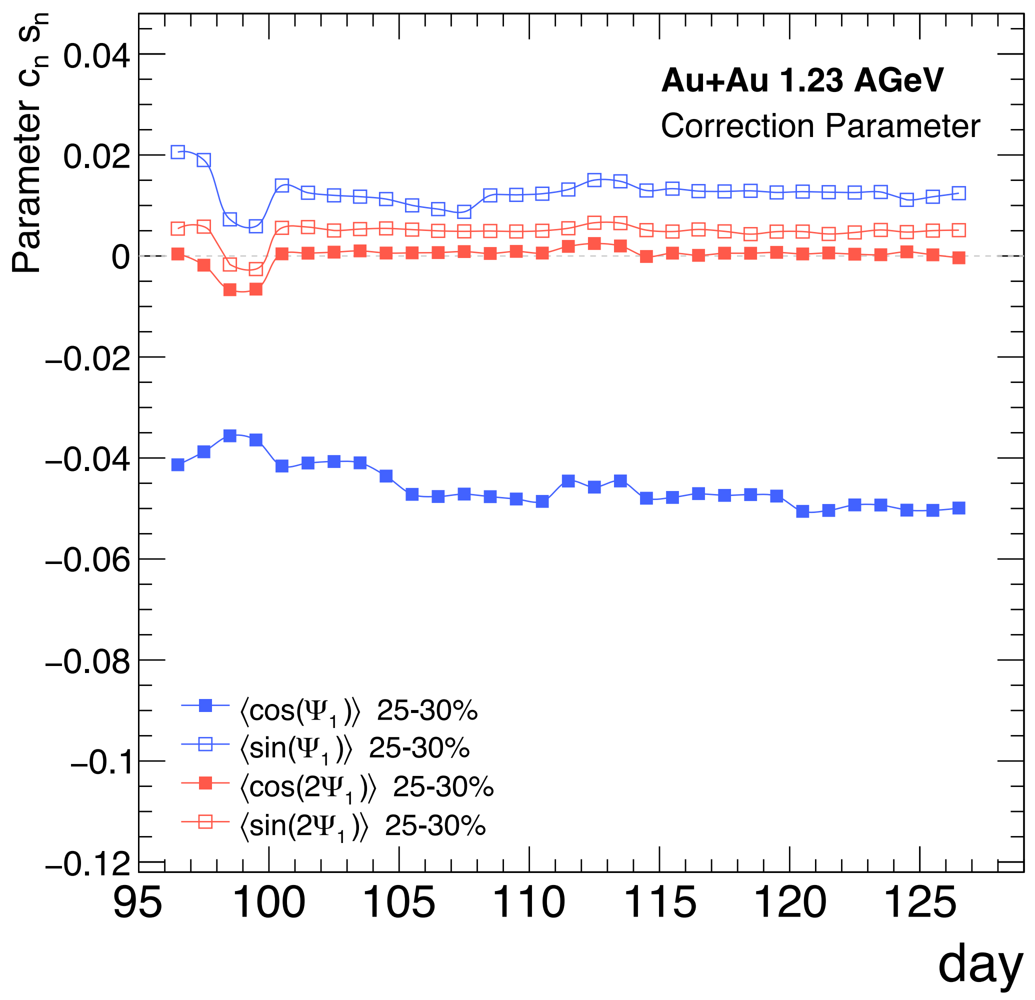
Event Plane Determination

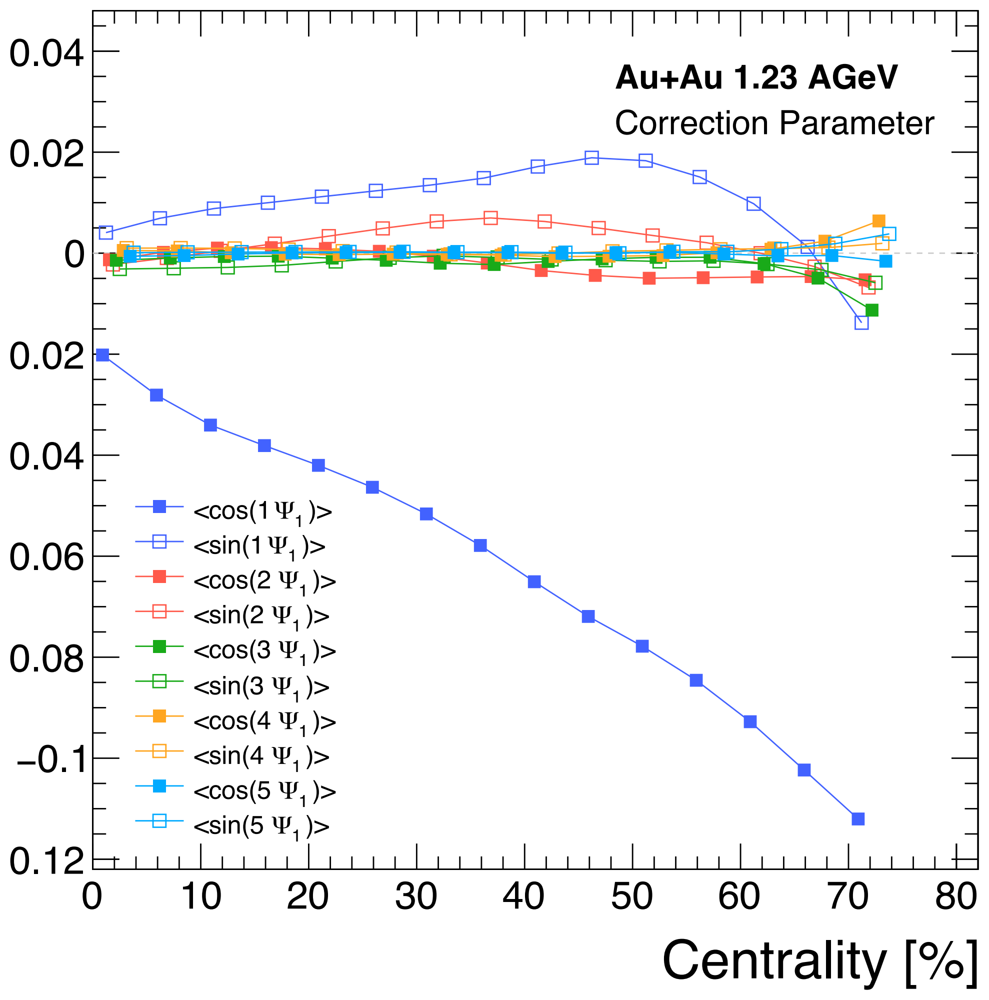
Correction of non-uniformities in the EP distribution (day-by-day and centrality)

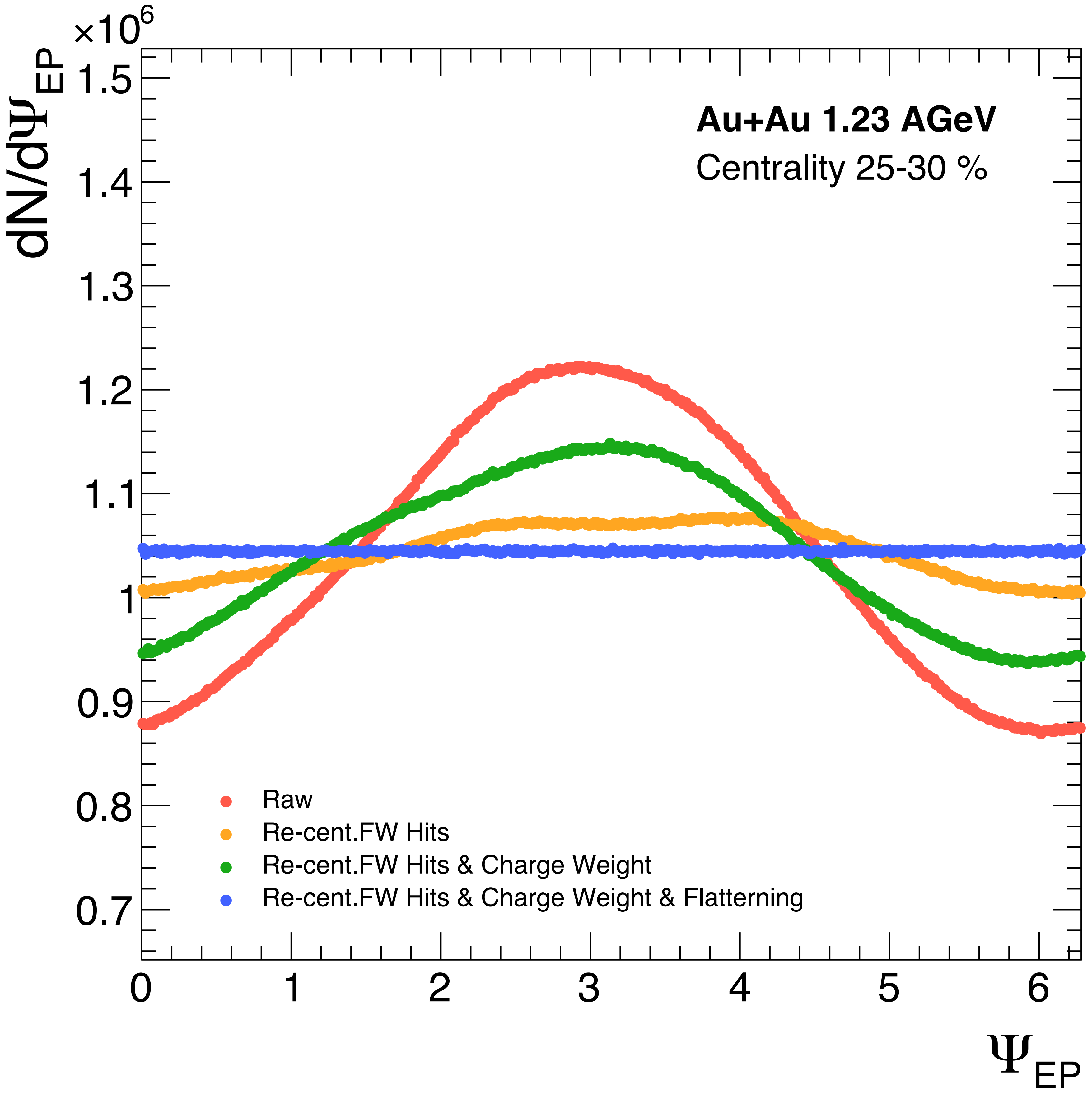
Re-centering of X and Y of all FW hits

Flattening of residual Fourier components with 8 cos- and 8 sin-terms

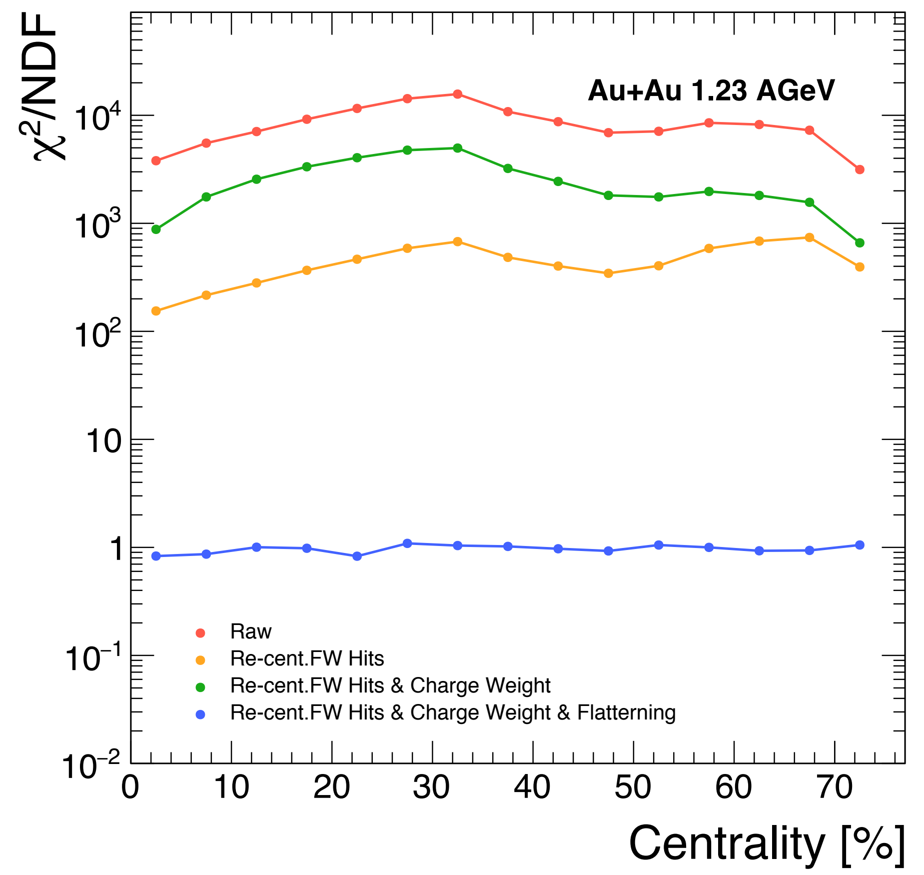
Flattening Parameter

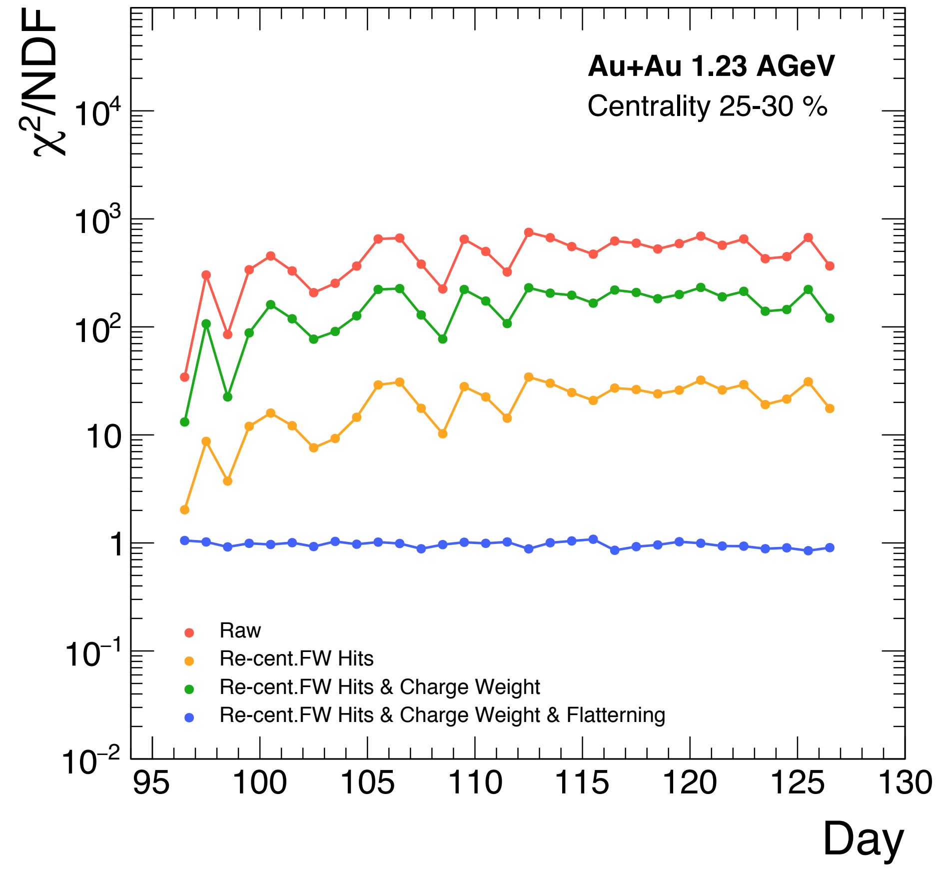






Quality of Flatness



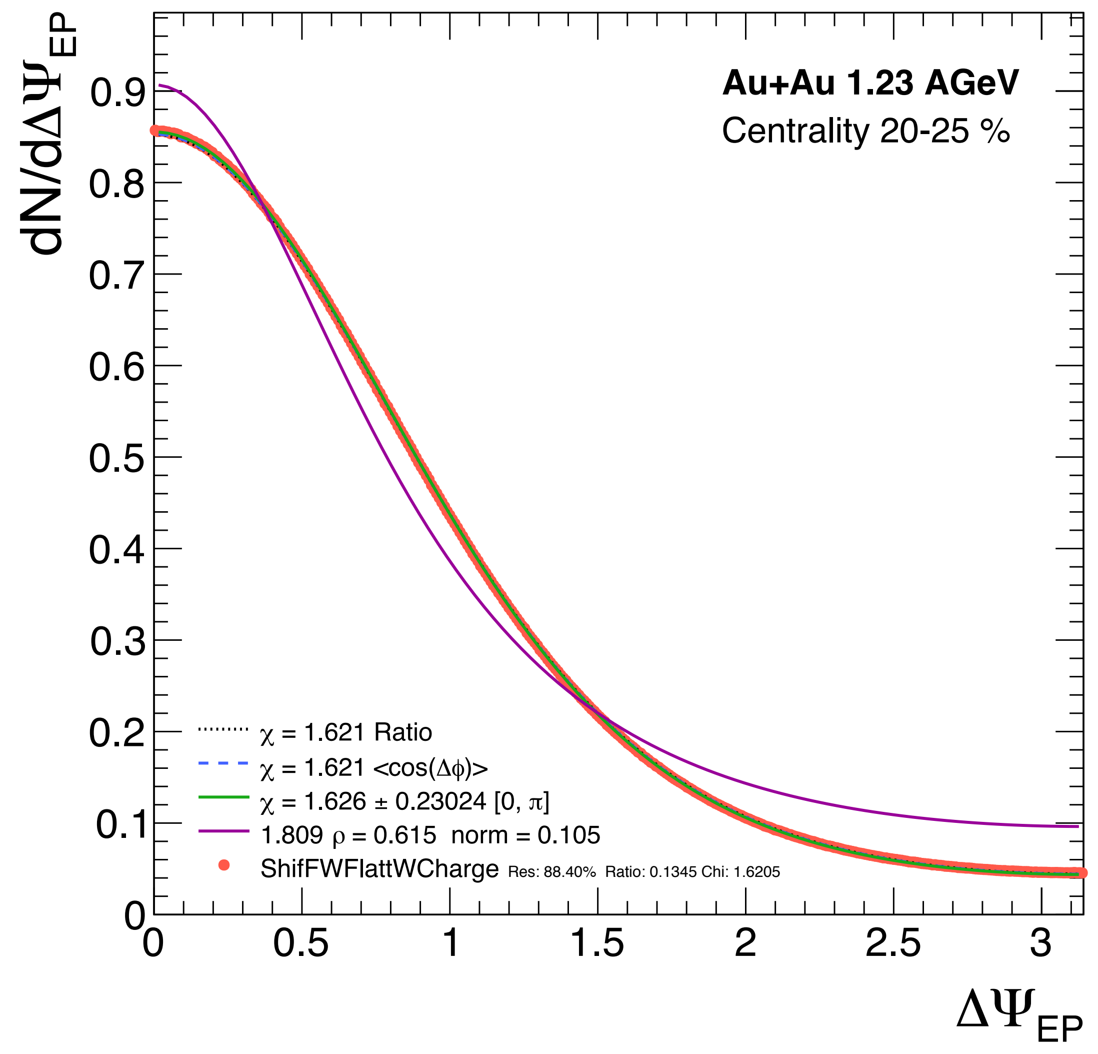


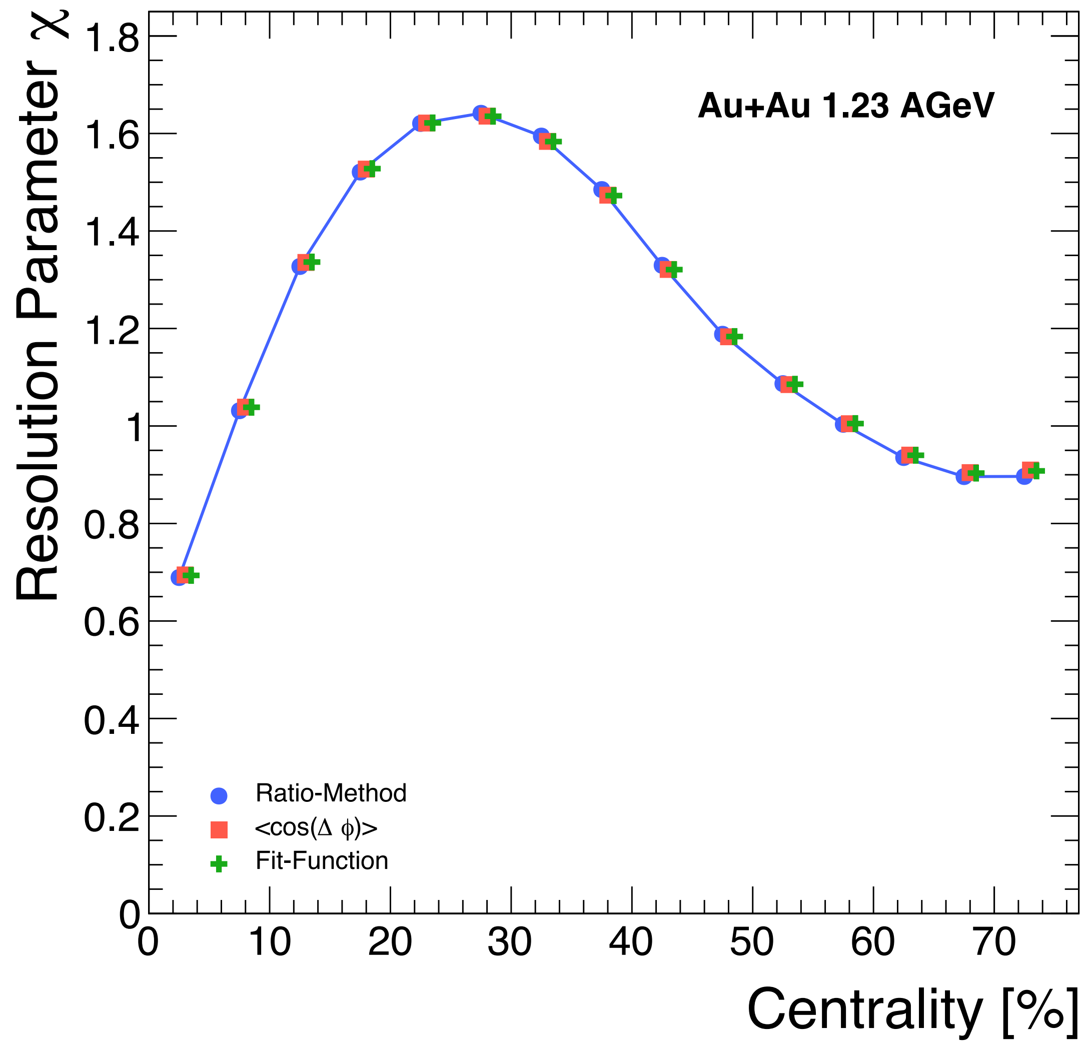
Event Plane Resolution

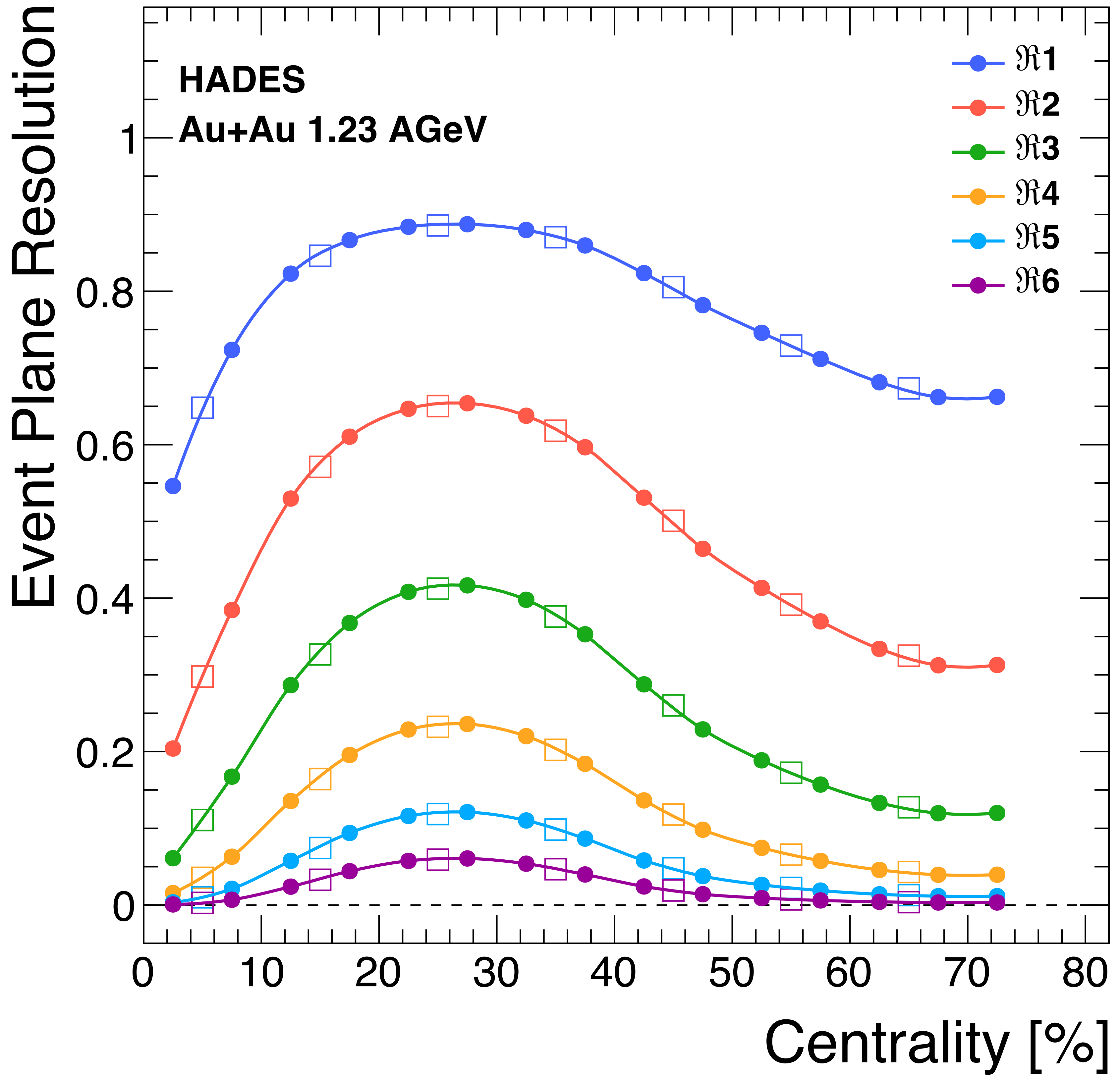
EP-resolution via sub-event method with three implementations

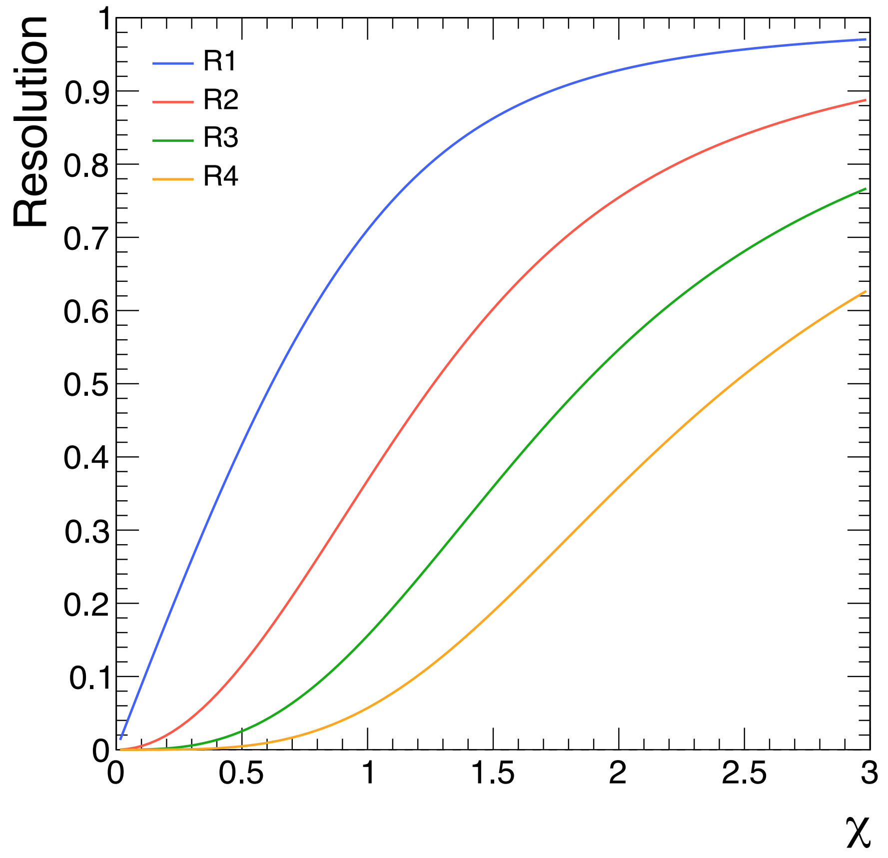
Determination of resolution parameter χ
- directly via <cos (ΔΦ)>
- Approximation via Fraction of Events with ΔΦ > π/2
- Fit-Method

Calculation of EP-Resolution of different order









$$v_n = v_n^{obs} \,/\, \mathfrak{R}_n$$

$$\mathfrak{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

Systematic Uncertainties

Validation and Consistency Checks

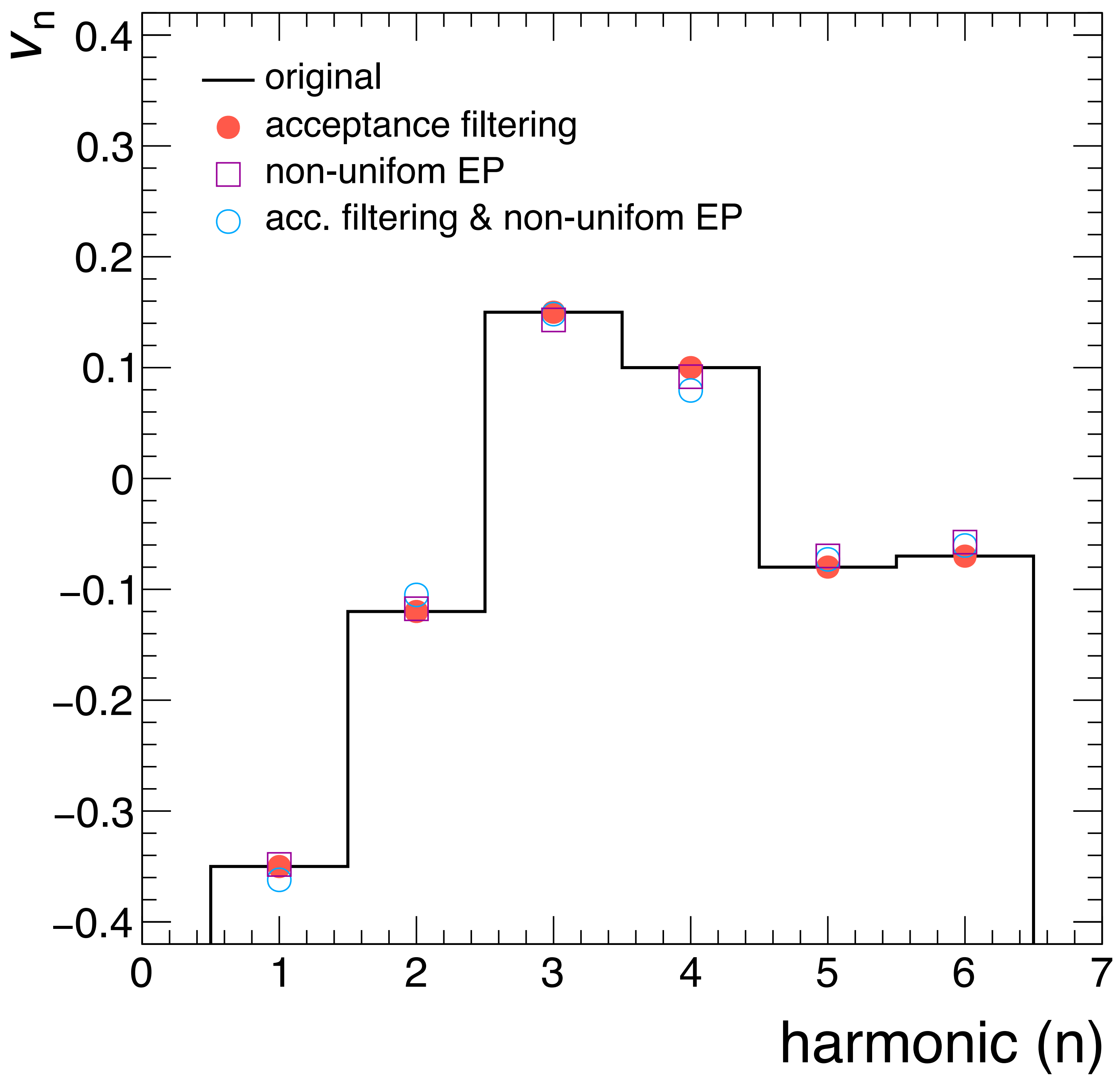
Sources of uncertainties
- Track selection and PID
- Occupancy correction
- Non-uniform acceptance

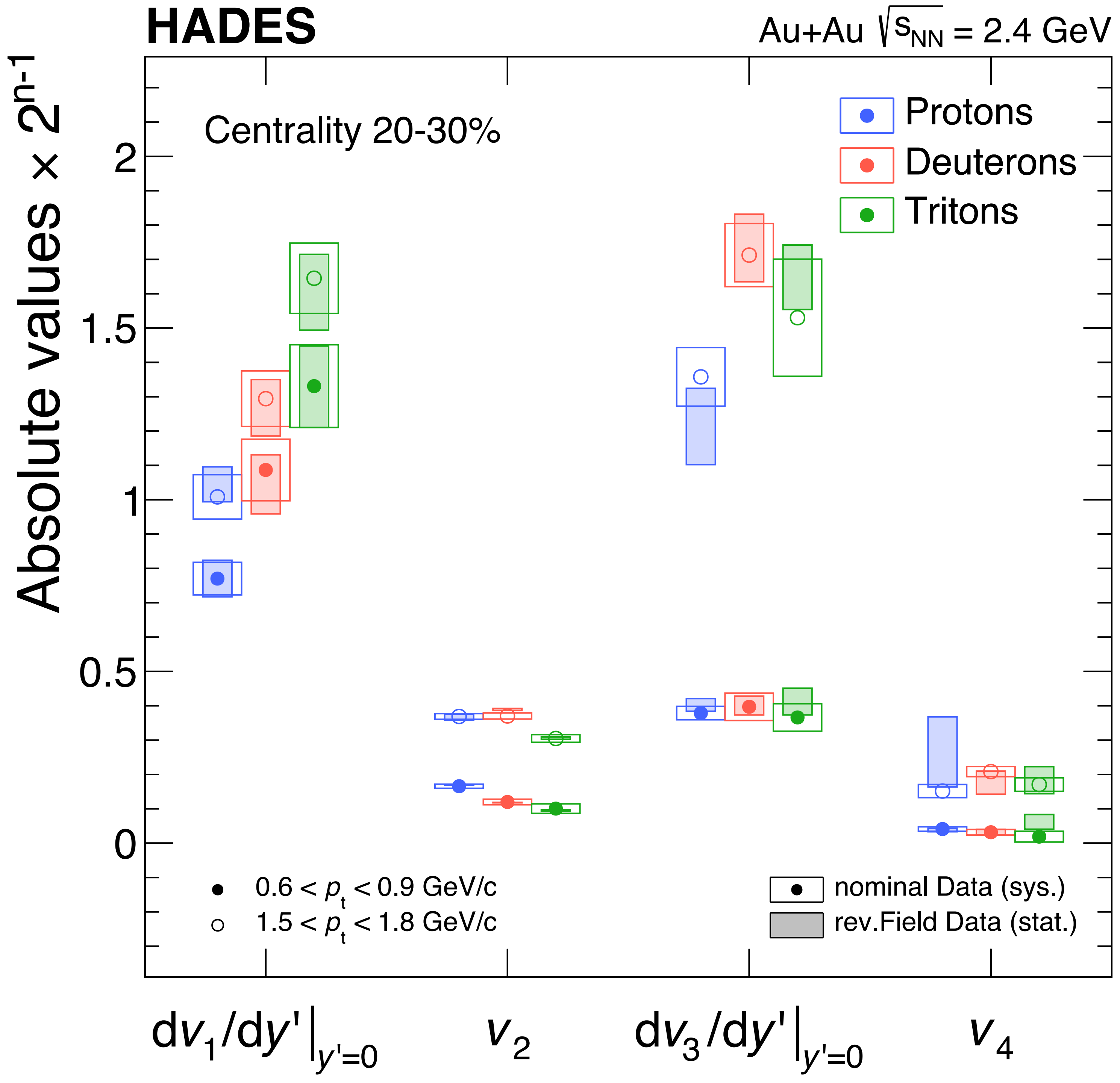
Toy MC study
Influence of the incomplete acceptance and a non-uniform event-plane distribution

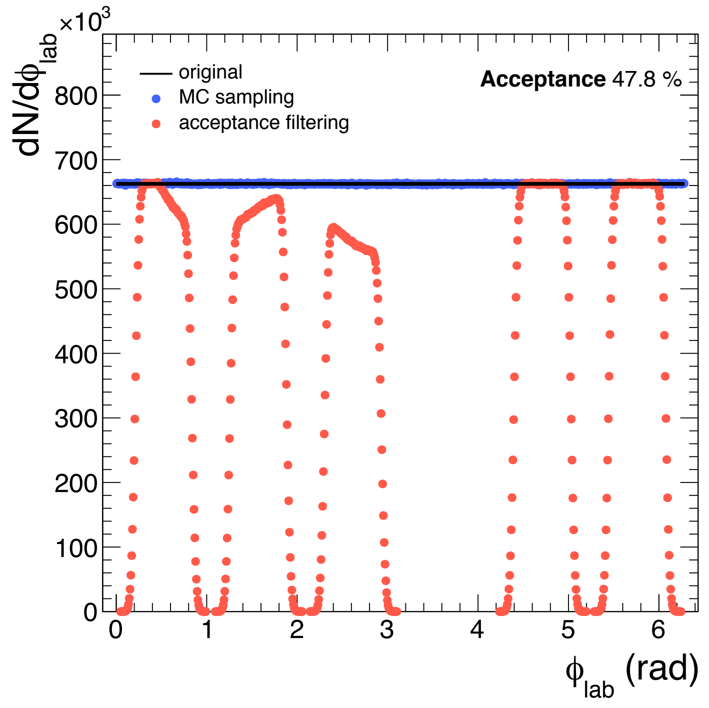
Consistency checks:
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at y_{cm}=0
- Vanishing residual sine-terms
- Time-dependent systematic effects

Reversed field polarity
Comparison with flow coefficients from the full data set

HADES, arXiv:2208.02740

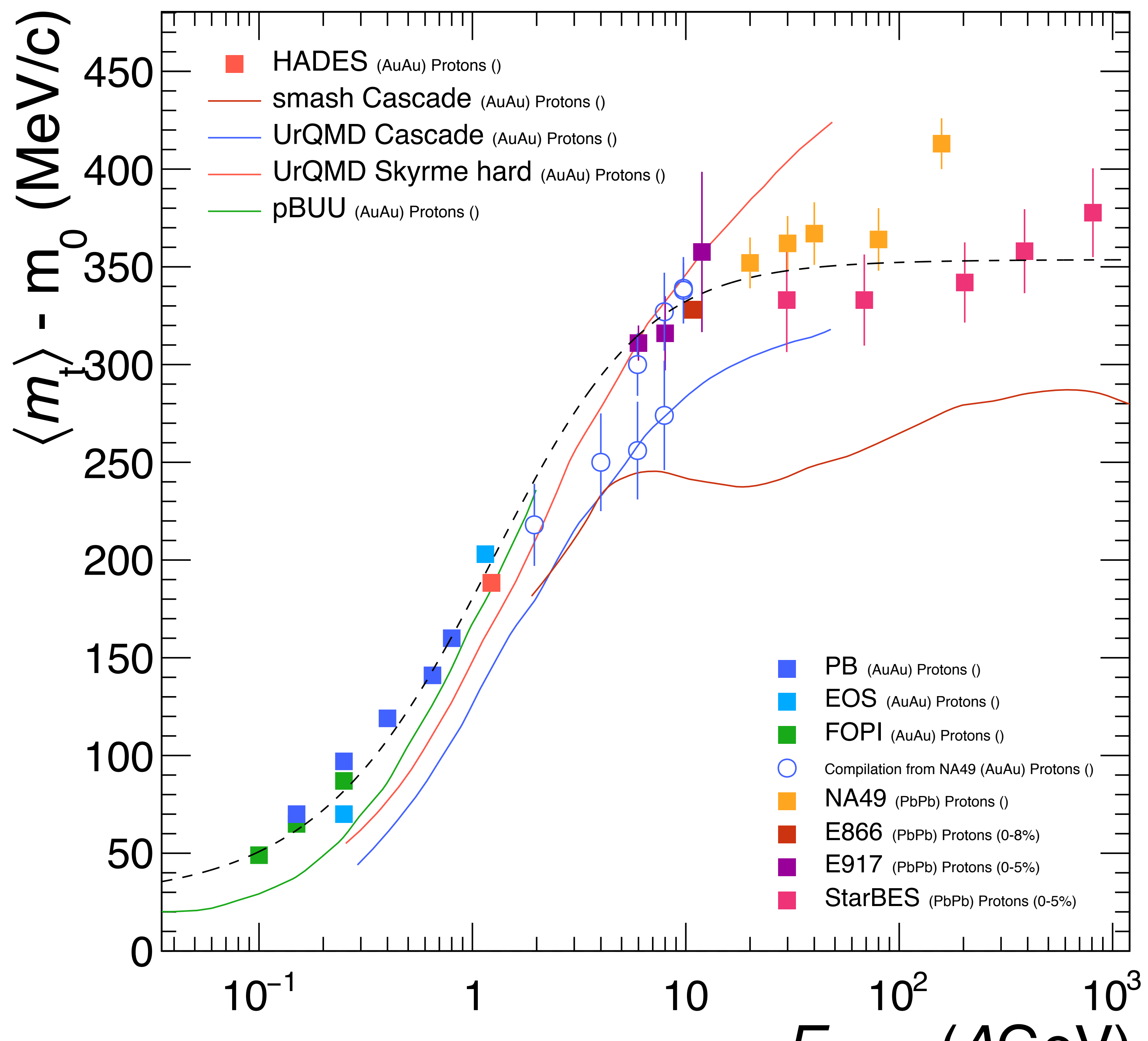




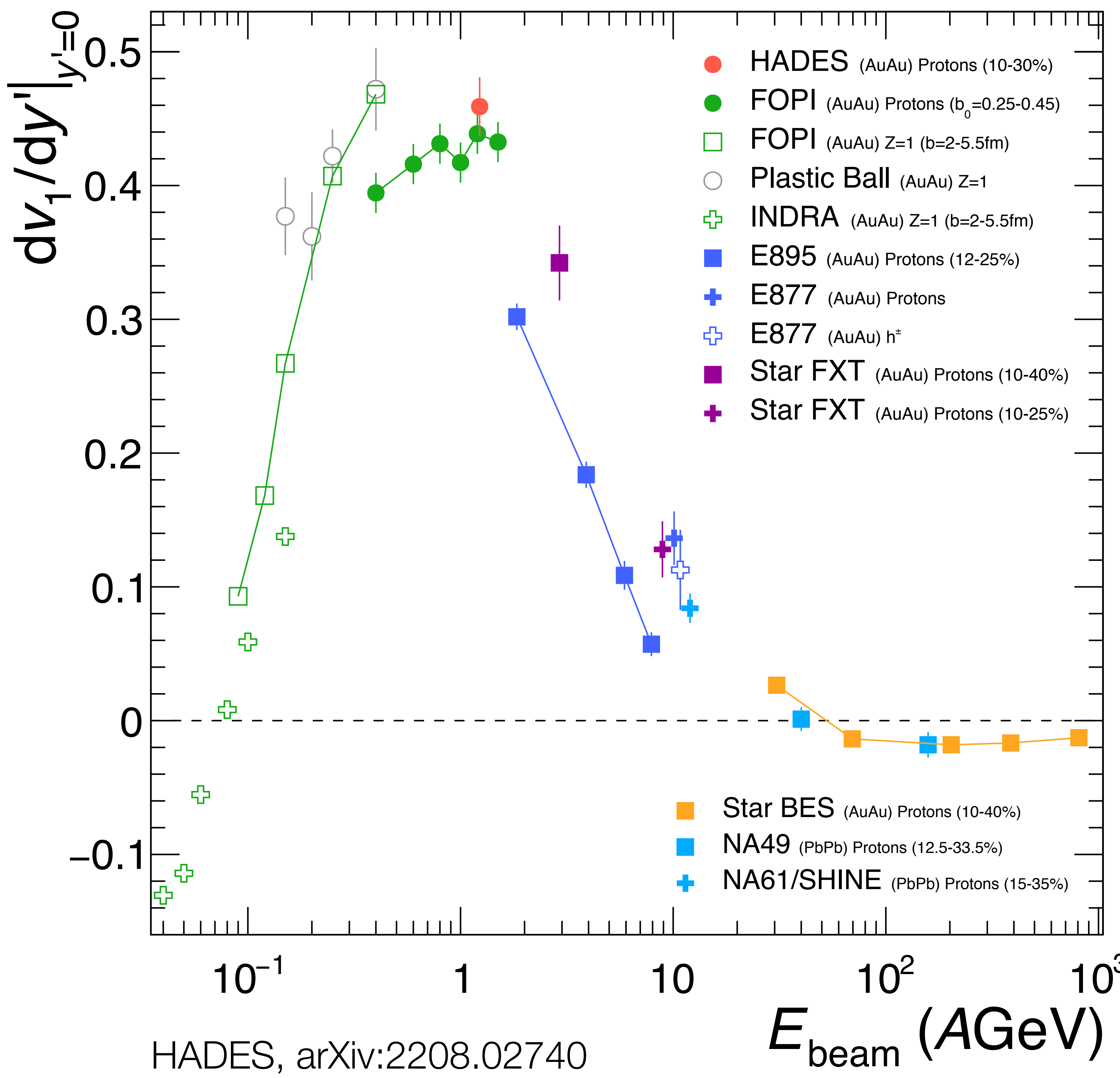


Collective Effects

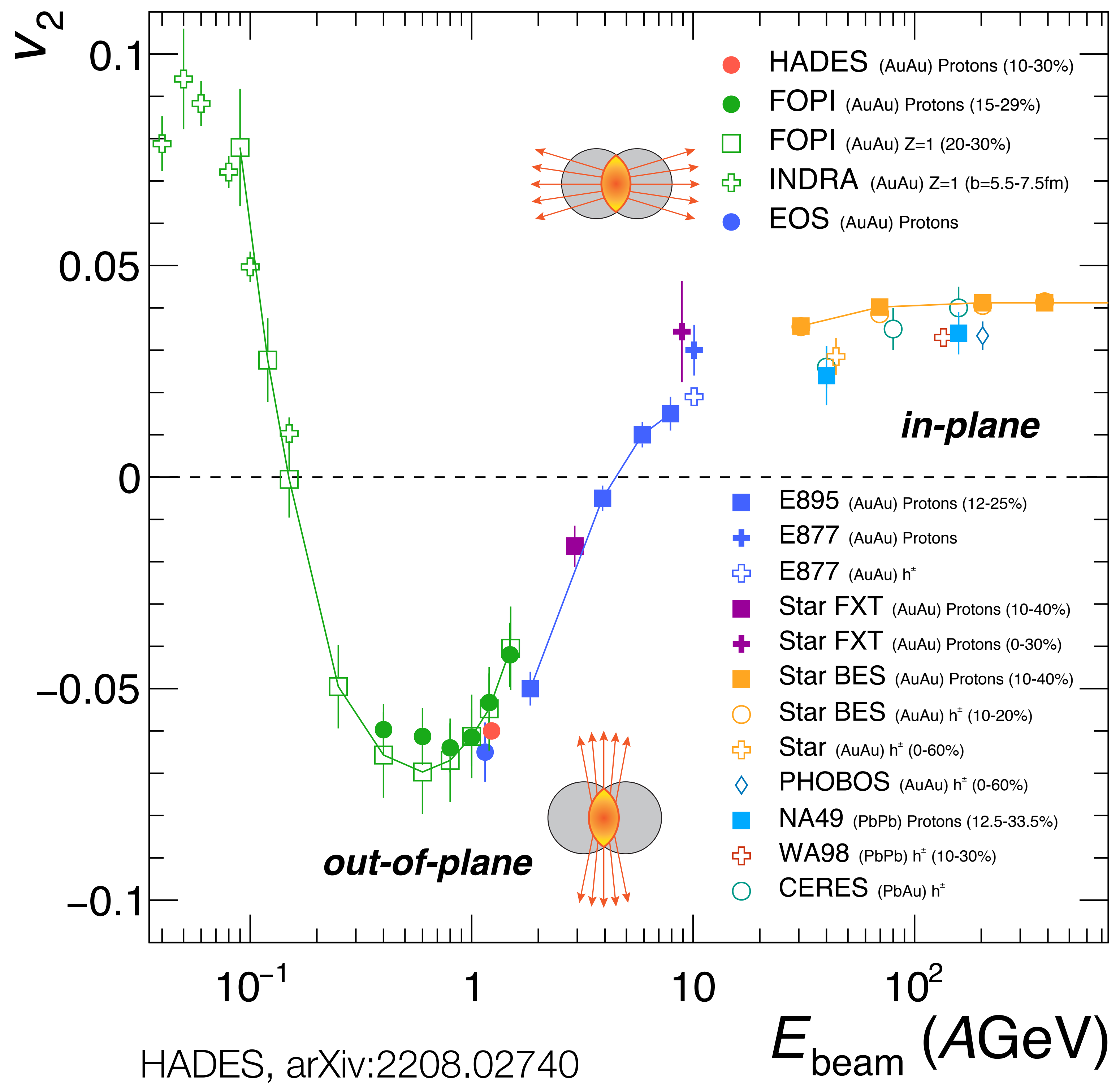
Energy-Dependence



smash Analysis Results 2.2
UrQMD J. Steinheimer et al, EPJC 82 (2022) 911
pBUU P. Danielewicz, PRC 51 (1995) 716



HADES, arXiv:2208.02740



HADES, arXiv:2208.02740

Compilation of world data

Good agreement of
mean transverse mass $<m_t>-m_0$,
integrated directed flow dv_1/dy
and elliptic flow v_2

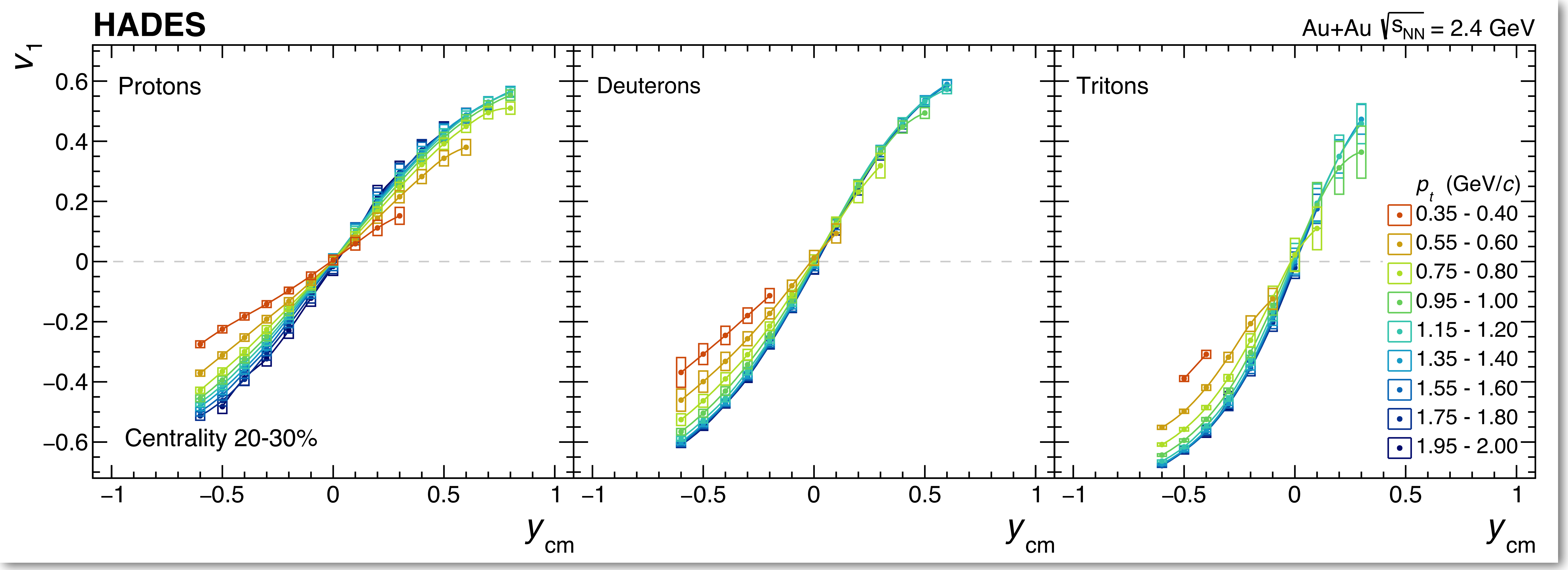
Out-of-Plane v_2

Long spectator passing time at HADES energy

$\tau_{passing} \approx \tau_{expansion} \Longrightarrow$ “squeeze-out”

Collective Effects

Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

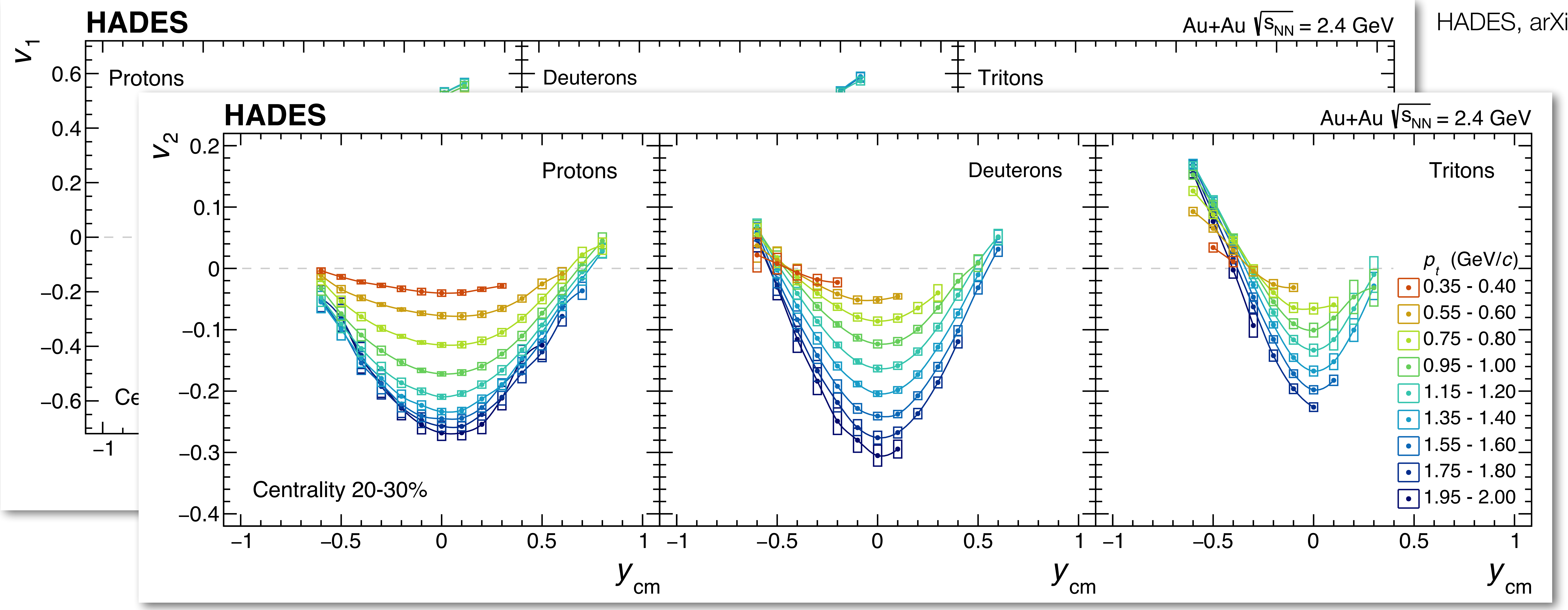


HADES, arXiv:2208.02740

Collective Effects

Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

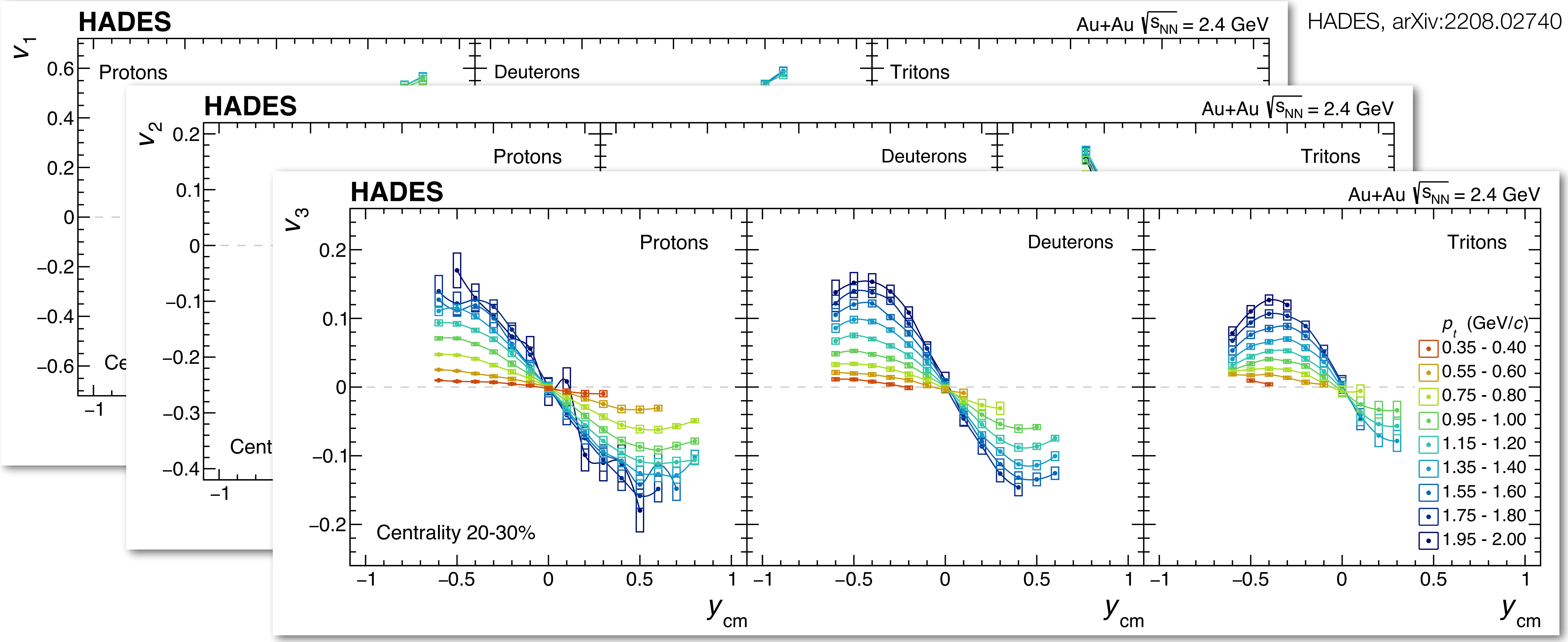
HADES, arXiv:2208.02740



Collective Effects

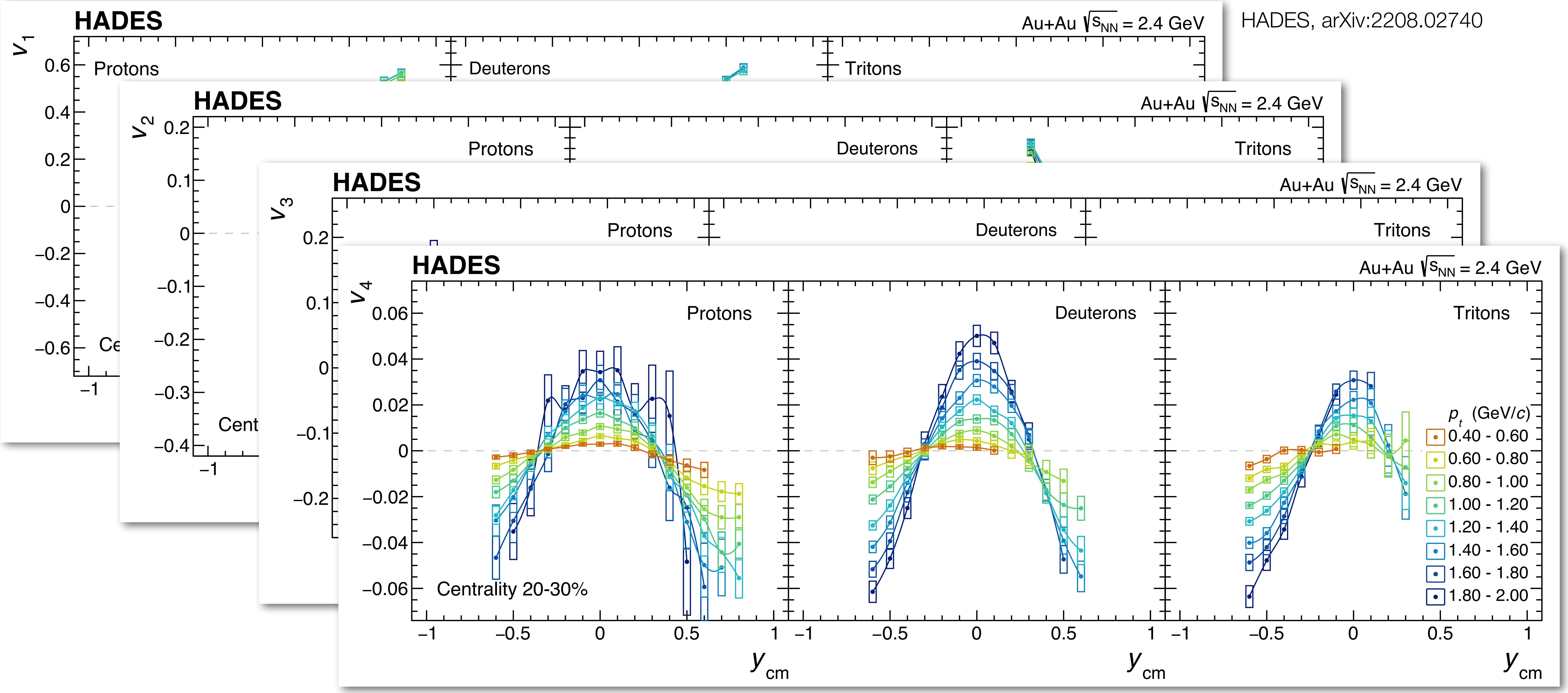
Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

HADES, arXiv:2208.02740



Collective Effects

Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

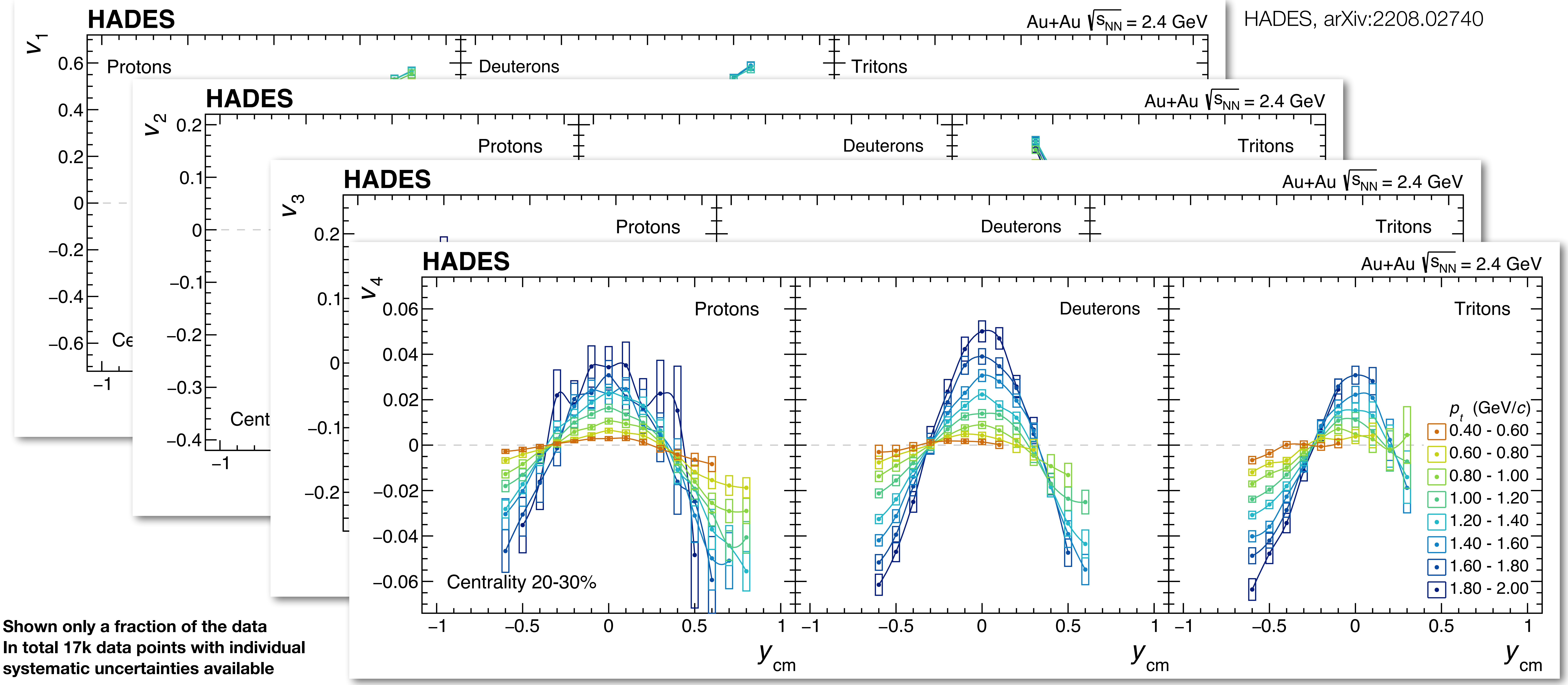


HADES, arXiv:2208.02740

Collective Effects

Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

HADES, arXiv:2208.02740

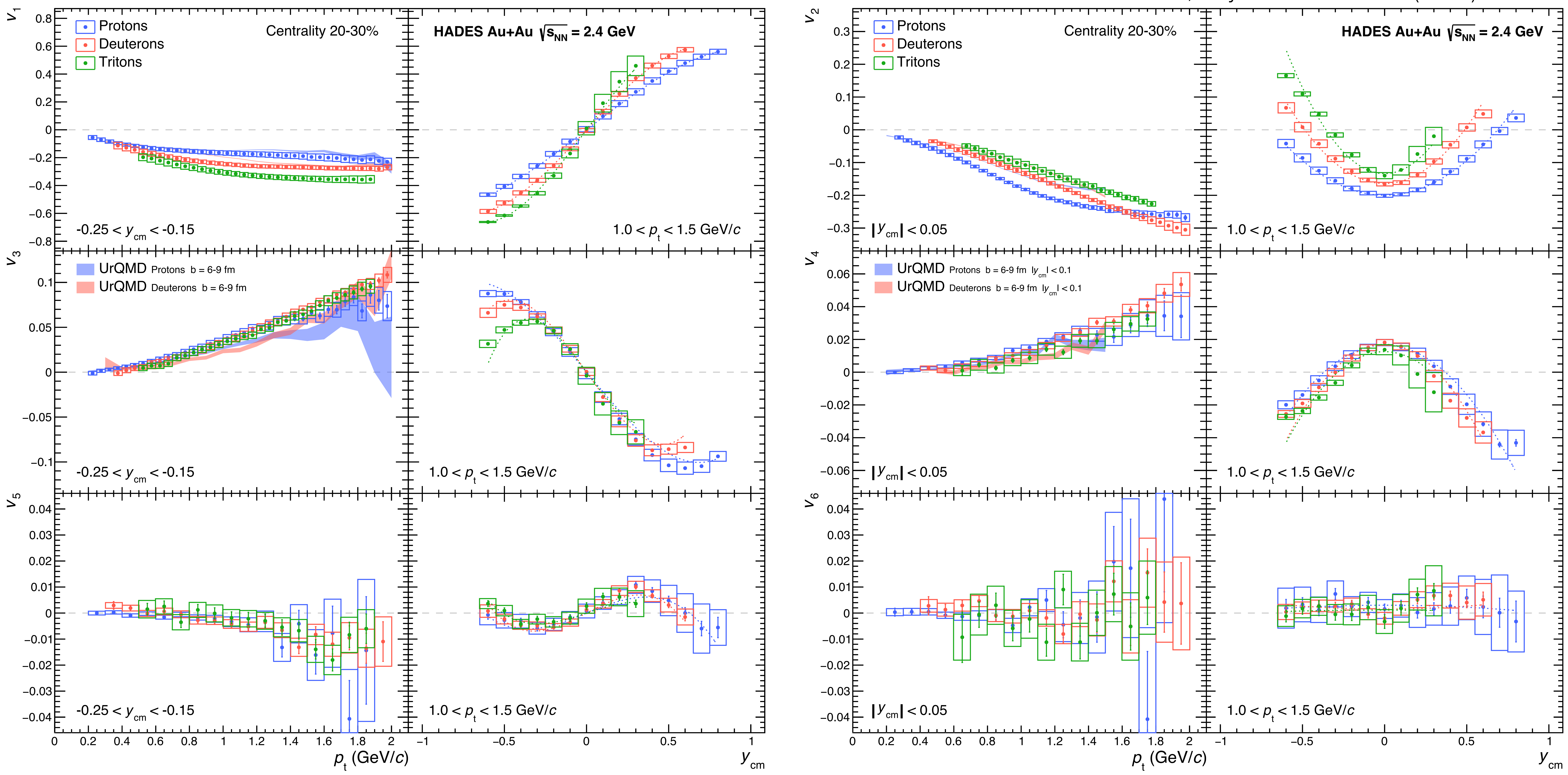


Shown only a fraction of the data
In total 17k data points with individual systematic uncertainties available

Collective Effects

Results on $v_1 - v_6$ for Protons, Deuterons and Tritons

HADES, Phys. Rev. Lett. **125** (2020) 262301



Emission Pattern

Protons

Allows to reconstruct a full 3D-picture of the emission pattern in momentum space

Shape determined by flow coefficients v_1 — v_6

Complex evolution of shape as function of rapidity

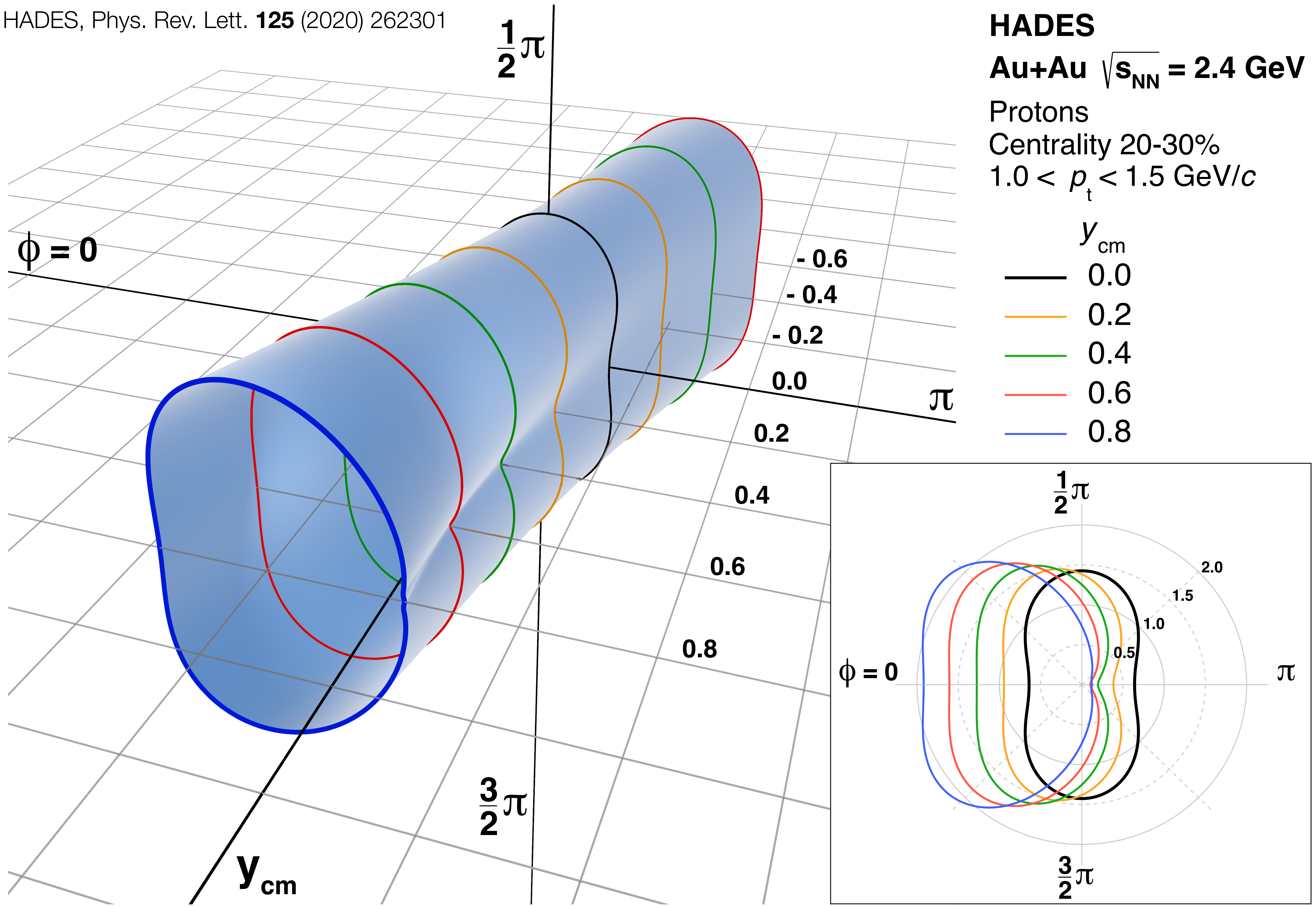
$$1 + 2\sum_{n=1}^{\infty} v_n(y_{cm})\cos n(\phi - \psi_{RP})$$

$$v_{1,3,5}(y_{cm}) = a\,y_{cm} + b\,y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d\,y_{cm}^2$$

First Proposed in S. Voloshin and Y. Zhang
Z.Phys. C70 (1996) 665-672

HADES, Phys. Rev. Lett. **125** (2020) 262301



“Ideal fluid scaling”

Relation between v_2 and v_4

Scaling properties

Prediction for ideal fluid:

$$v_4(p_t)/v_2^2(p_t) = 1/2$$

Slightly higher values (~ 0.6) expected in more realistic scenario

P.F. Kolb, PRC **67** (2003) 031902
N. Borghini and J.-Y. Oliitrault, PLB **642** (2006) 227
C. Gombeaud and J.-Y. Ollitrault, PRC **81** (2010) 014901

Observed ratios for p, d and t

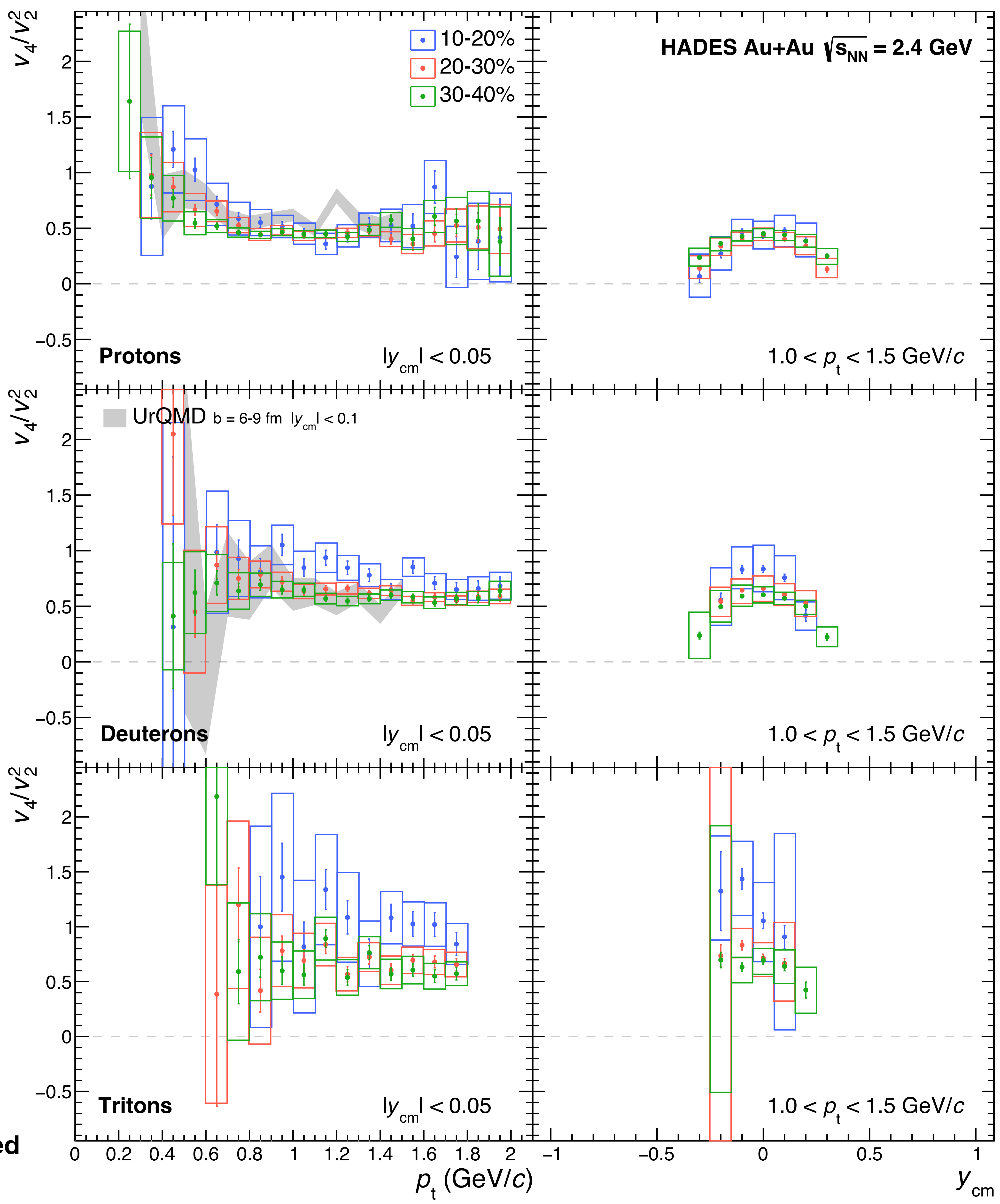
Independent of p_t and centrality
Close to predicted value of ~ 0.6

Confirmed by transport models

J. Wang et al., PRC **90** (2014) 054601 **IQMD**
P. Hillmann et al., J.Phys. G **47** (2020) 5, 055101 **UrQMD**
Justin Mohs et al., PRC **105** (2022) 034906 **SMASH**

Hydro-like matter at SIS energies?

HADES, Phys. Rev. Lett. **125** (2020) 262301



Systematic Error of v2 and v4 are treated as correlated

Nucleon Coalescence

Scaling Properties of v_2 at Mid-Rapidity

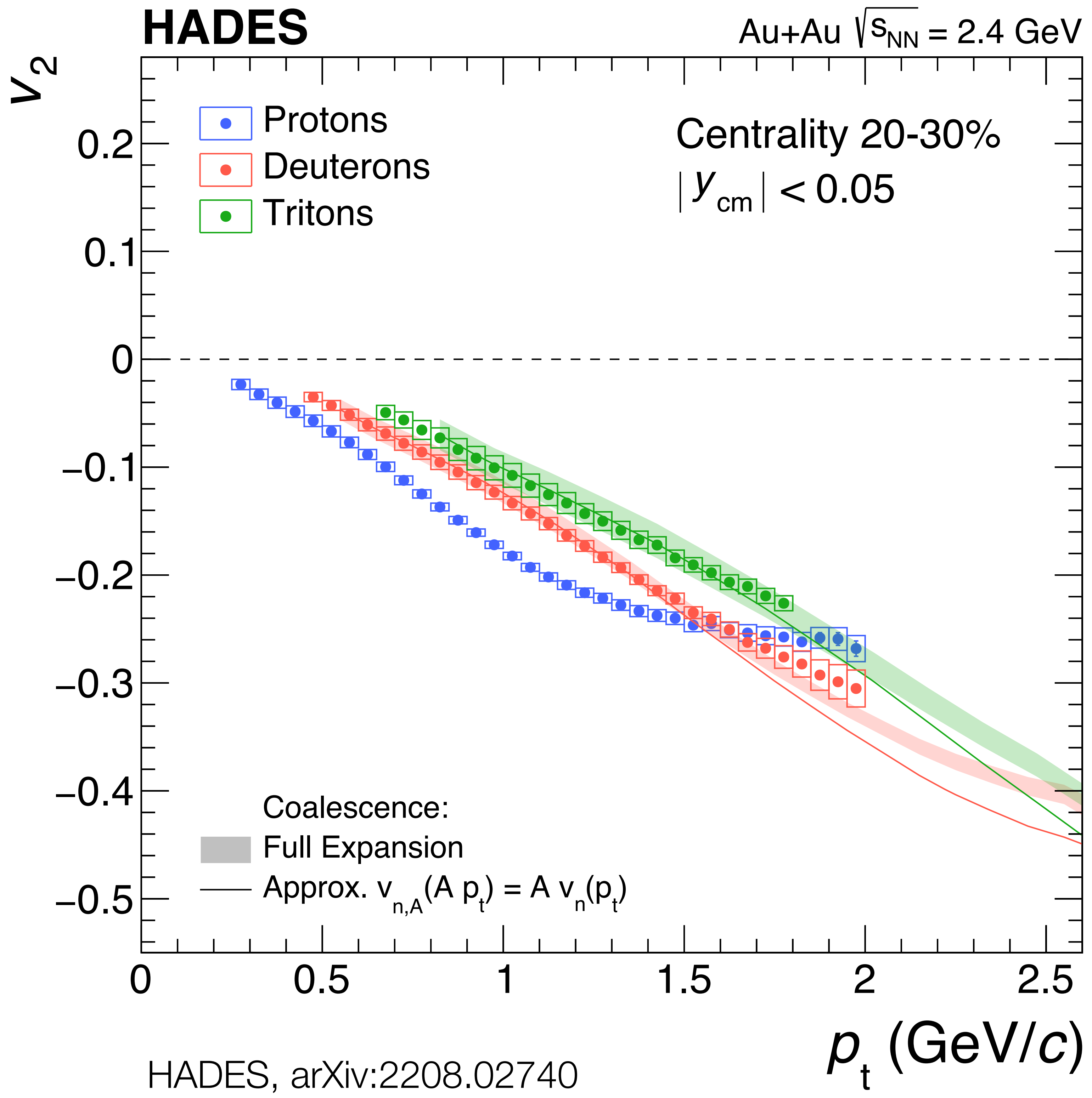
Scaling of v_2 and p_t with nuclear mass number A (including higher terms)

Works as expected in simple coalescence picture for the dominant flow coefficient

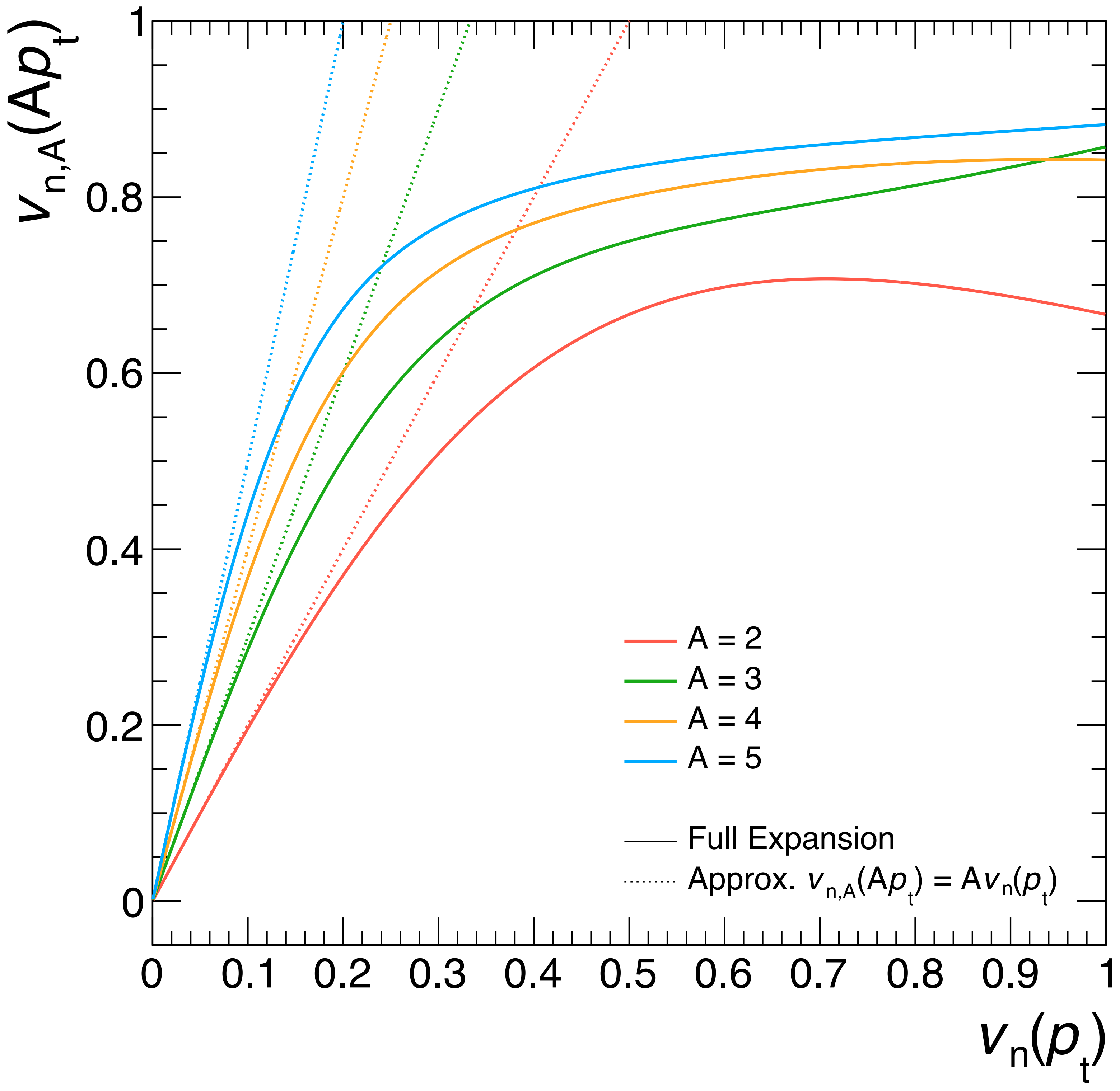
Only at mid-rapidity:
odd flow coefficients vanish and v_4 contribution is negligible

Approximation for small v_n

$$v_{n,A}(A\,p_t) = A\,v_n(p_t)$$



HADES, arXiv:2208.02740



$$v_{n,A=2}(A\,p_t) = 2\,v_n(p_t)\,\frac{1}{1+2\,v_n^2(p_t)}$$

$$v_{n,A=3}(A\,p_t) = 3\,v_n(p_t)\,\frac{1+v_n^2(p_t)}{1+6\,v_n^2(p_t)}$$

D. Molnar and S.A. Voloshin PRL **91** (2003) 092301
P.F. Kolb et al., PRC **69** (2004) 051901

Nucleon Coalescence

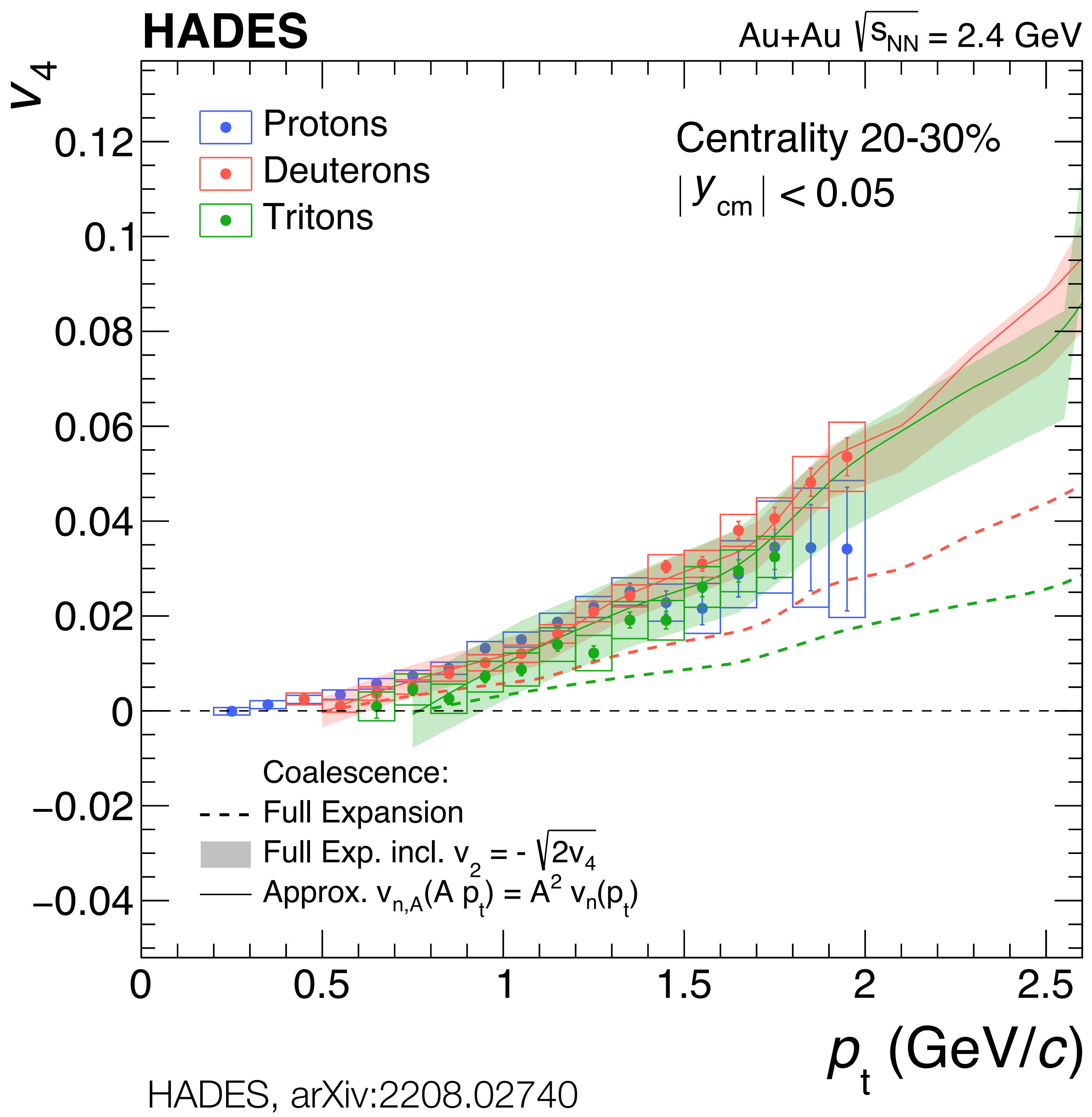
Scaling Properties of v_4 at Mid-Rapidity

Scaling of v_4 and p_t with nuclear mass number A (including higher terms)

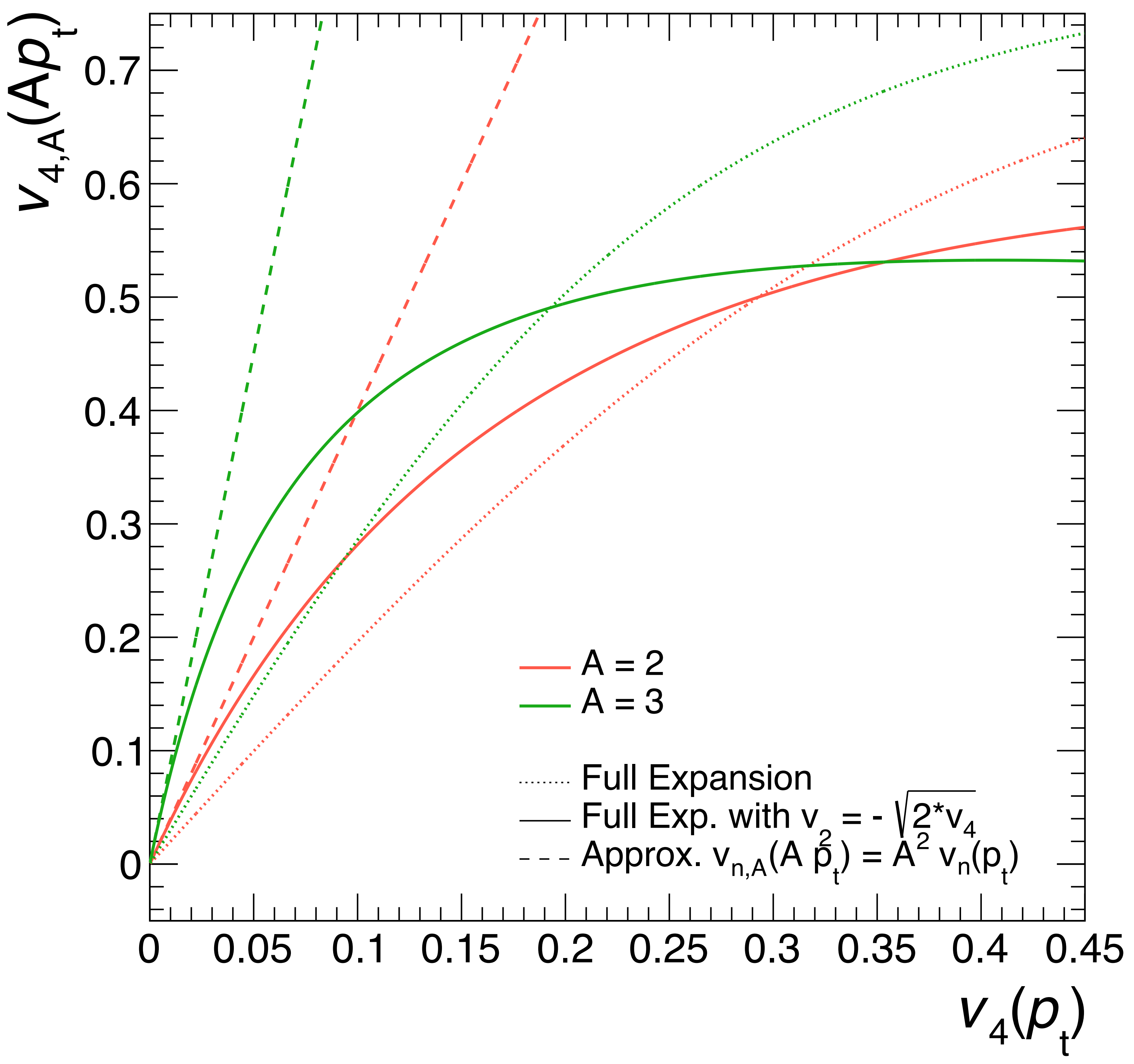
Works as expected in simple coalescence picture if contribution of dominant flow coefficient is included

Approximation for small v_4 with v_2 contribution:

$$v_{n,A}(A\,p_t) = A^2\,v_n(p_t)$$



HADES, arXiv:2208.02740



$$v_{4,A=2}(A\,p_t) = 4\,v_4(p_t)\,\frac{1}{1 + 4\,v_4(p_t) + 2\,v_4^2(p_t)}$$

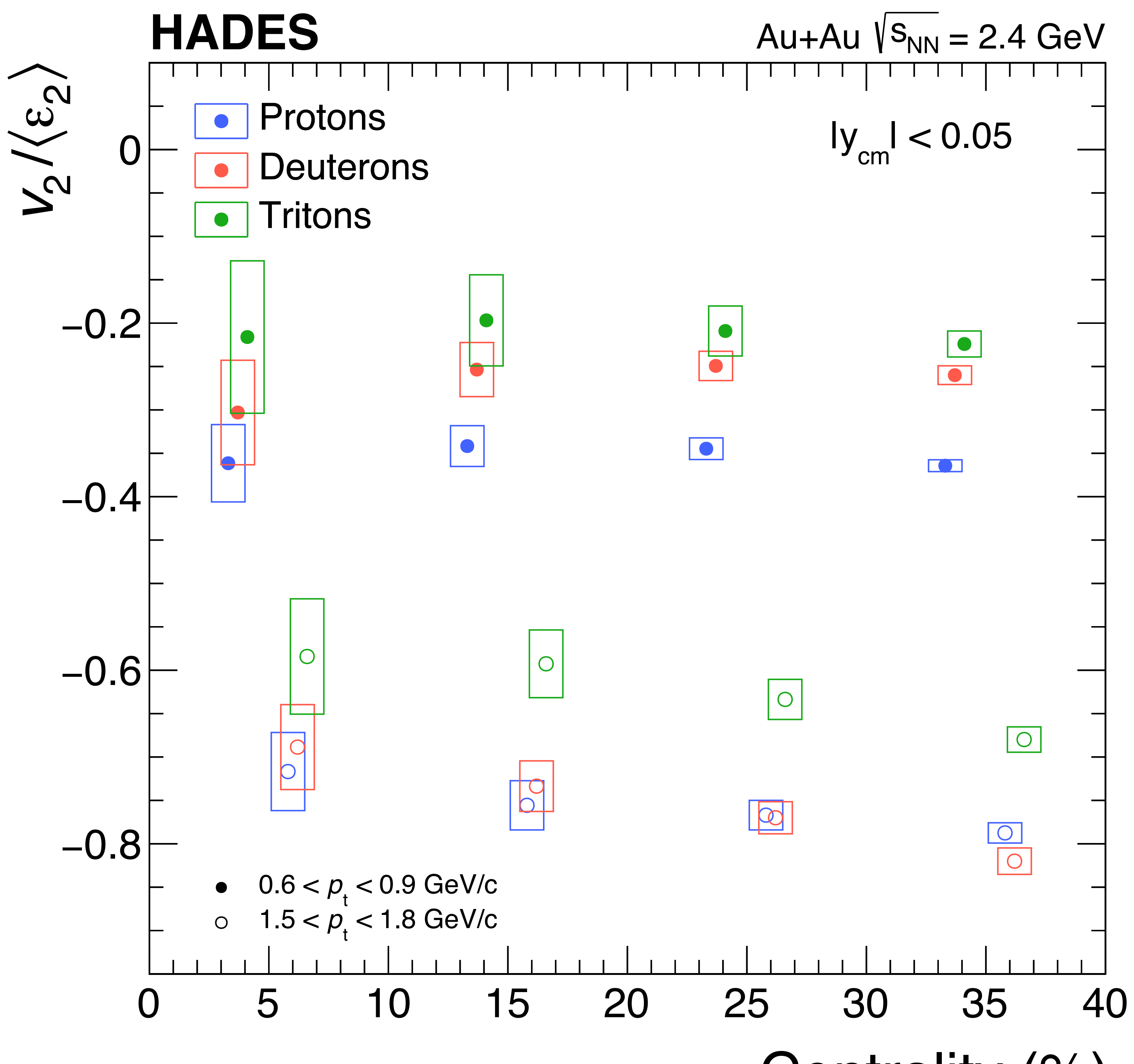
$$v_{4,A=3}(A\,p_t) = 9\,v_4(p_t)\,\frac{1}{1 + 12\,v_4(p_t) + 6\,v_4^2(p_t)}$$

assuming: $v_4(p_t)/v_2^2(p_t) = 1/2$

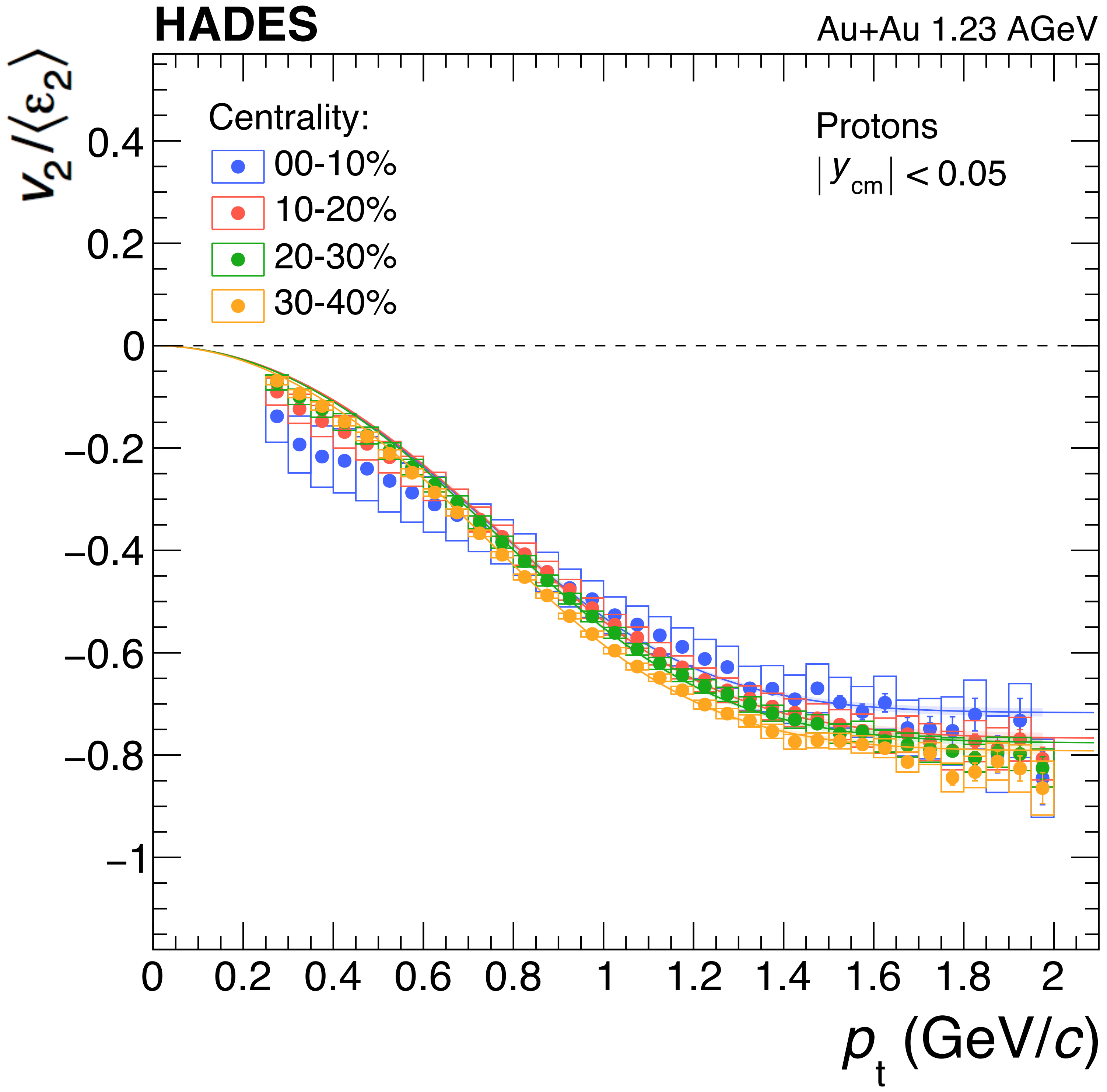
D. Molnar and S.A. Voloshin PRL **91** (2003) 092301
P.F. Kolb et al., PRC **69** (2004) 051901

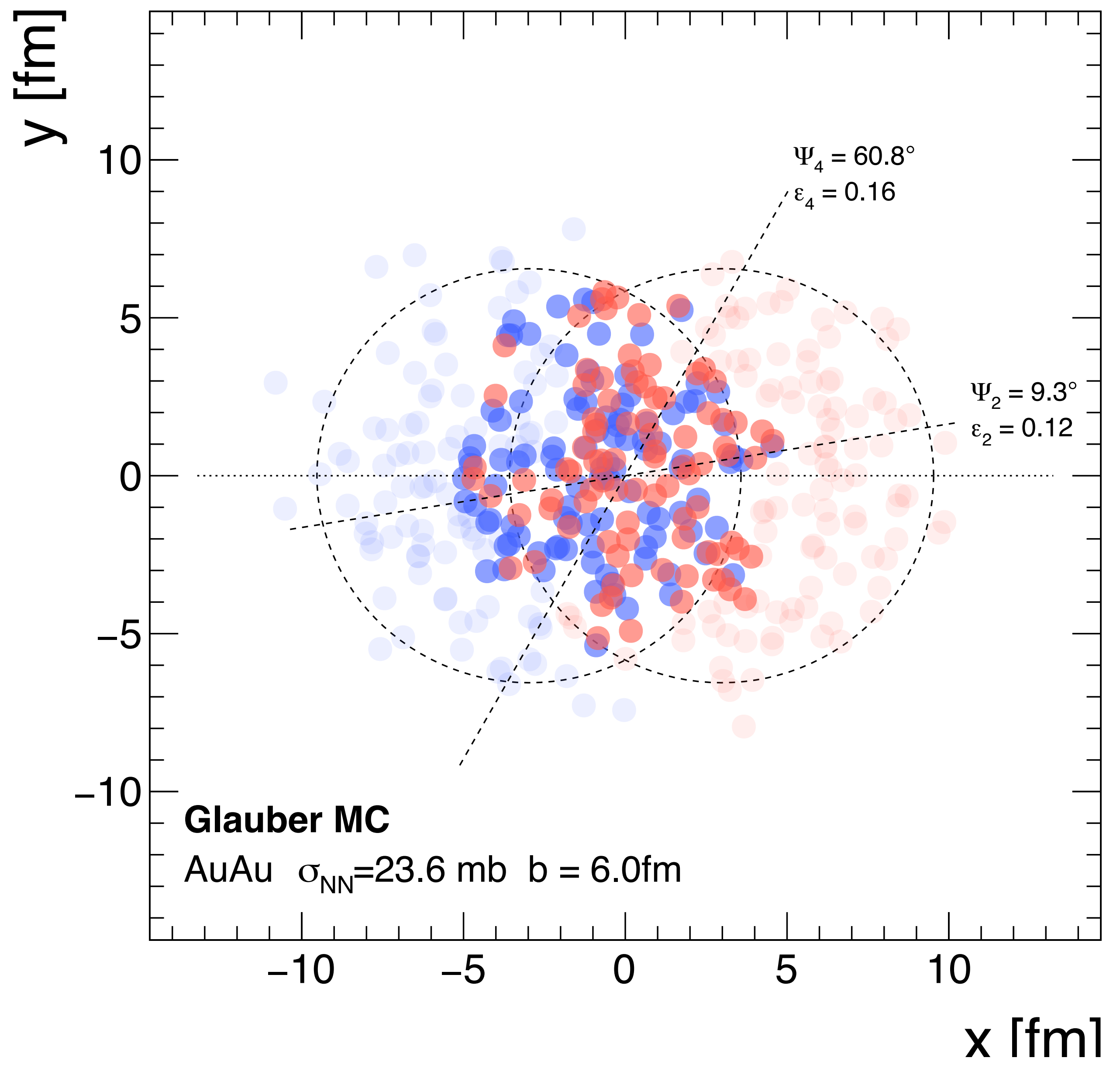
Geometry Scaling

Elliptic Flow v_2



HADES, arXiv:2208.02740





$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Scaling with initial eccentricities

Calculated for overlap zone with Glauber MC

$v_2/\langle\varepsilon_2\rangle$ almost independent of centrality and p_t

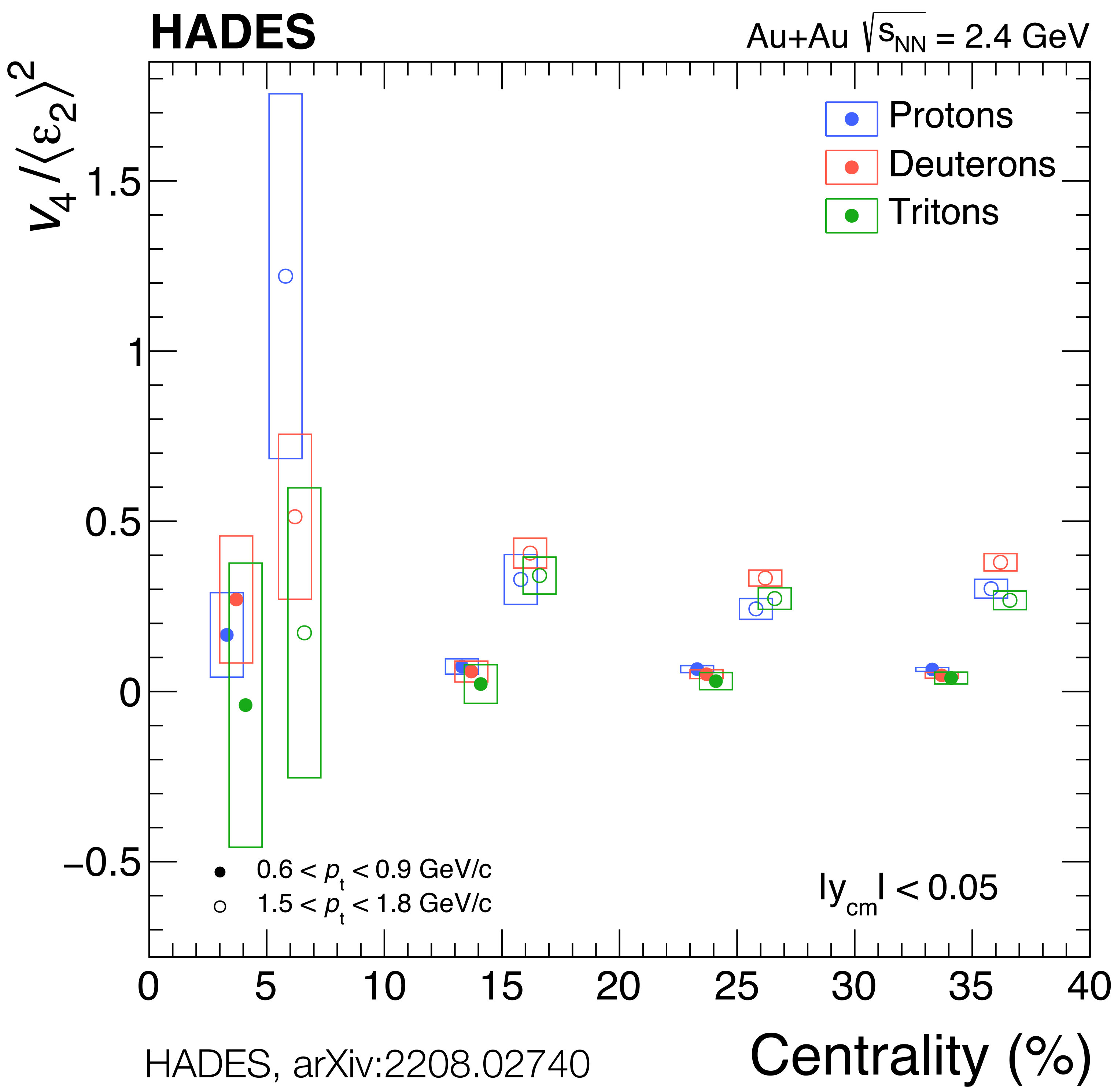
Orientation of symmetry-planes

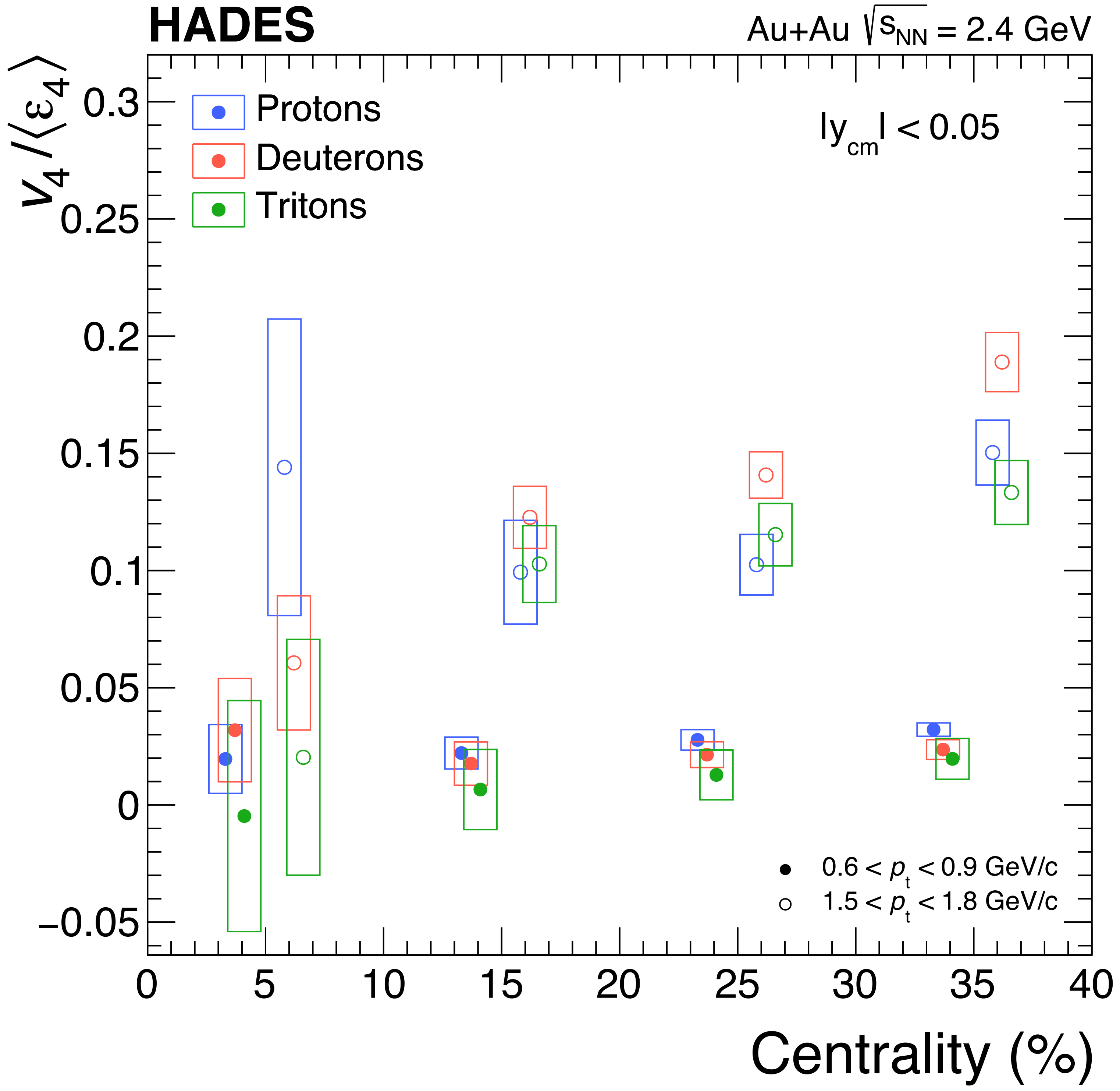
Negative $v_2/\langle\varepsilon_2\rangle$ values

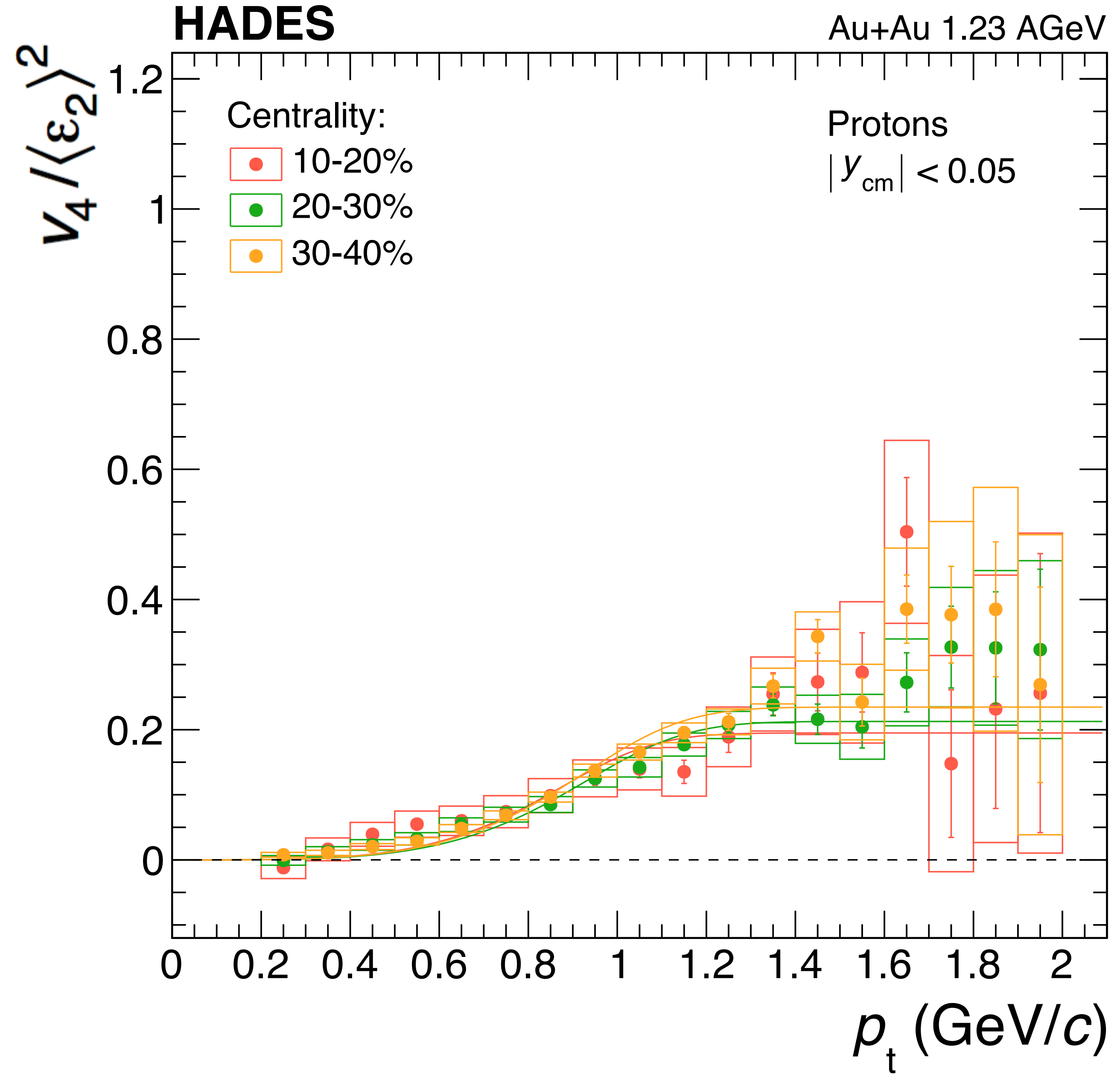
$\Longrightarrow$ v_2 Flow- and ε_2 eccentricity-plane are perpendicular

Geometry Scaling

Quadrangular Flow v_4







Scaling with initial eccentricities

Calculated for overlap zone with Glauber MC

$v_4/\langle\varepsilon_2\rangle^2$ almost independent of centrality and p_t ($v_4/\langle\varepsilon_4\rangle$ is not)

$\Longrightarrow$ Fixed relation between v_2 and v_4 (different to high energies)

Model Comparisons to Proton Data

HADES, arXiv:2208.02740

Determination of EOS

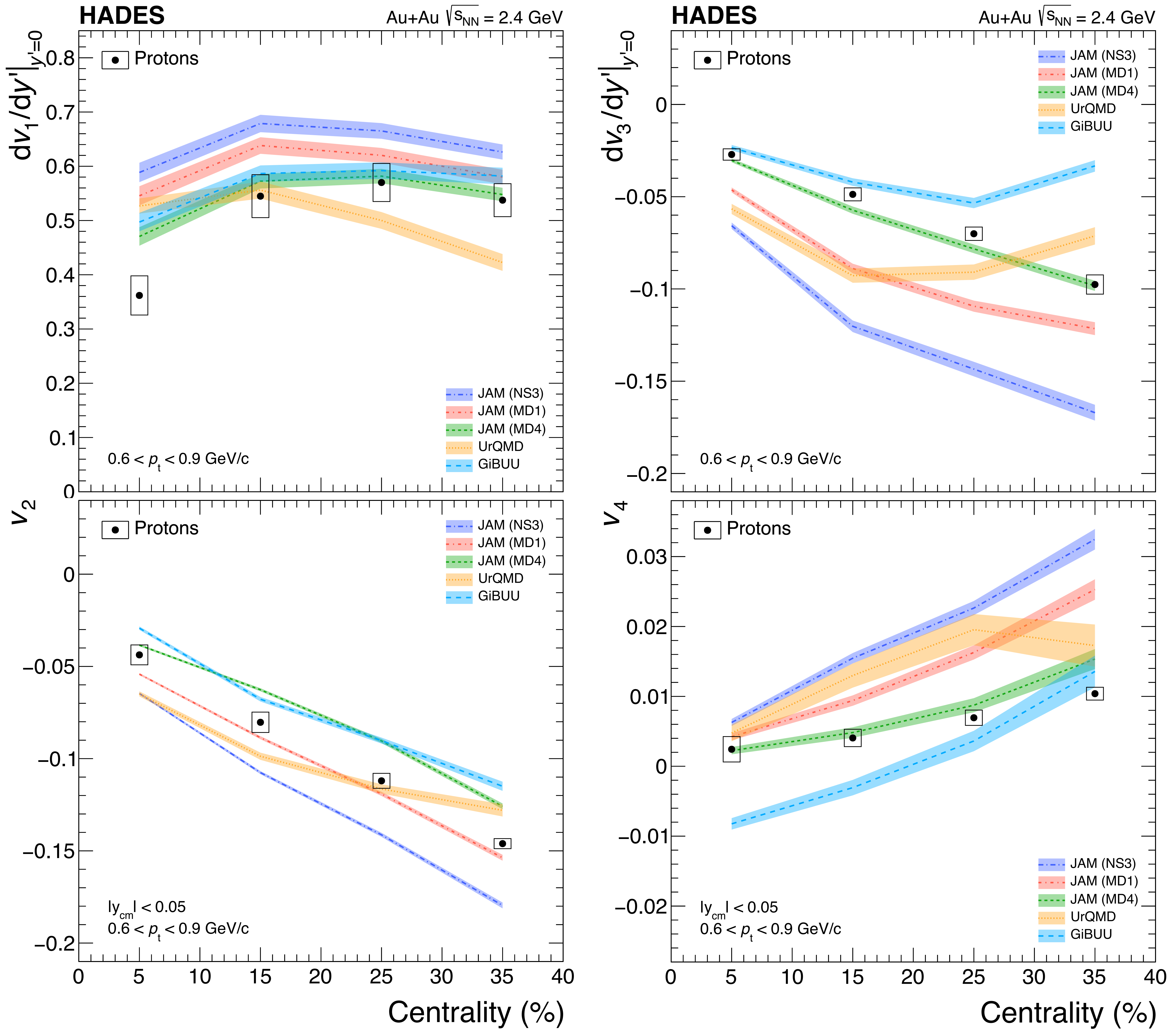
New level of precision

Additional information from higher orders

Models:

JAM 1.9 NS3 (hard EOS, mom.-indep.)
JAM 1.9 MD1 (hard EOS, mom.-dep.)
JAM 1.9 MD4 (soft EOS, mom.dep.)
UrQMD 3.4 (hard EOS, mom.-indep.)
GiBUU Skyrme 12 (soft EOS)

Model	EOS	K (MeV)	m^*/m	mom-dep.
JAM 1.90591	NS1	380	0.83	no
	MD1	380	0.65	yes
	MD4	210	0.83	yes
UrQMD 3.4	Hard	380		no
GiBUU 2019 (patch7)	Skyrme 12	240	0.75	no



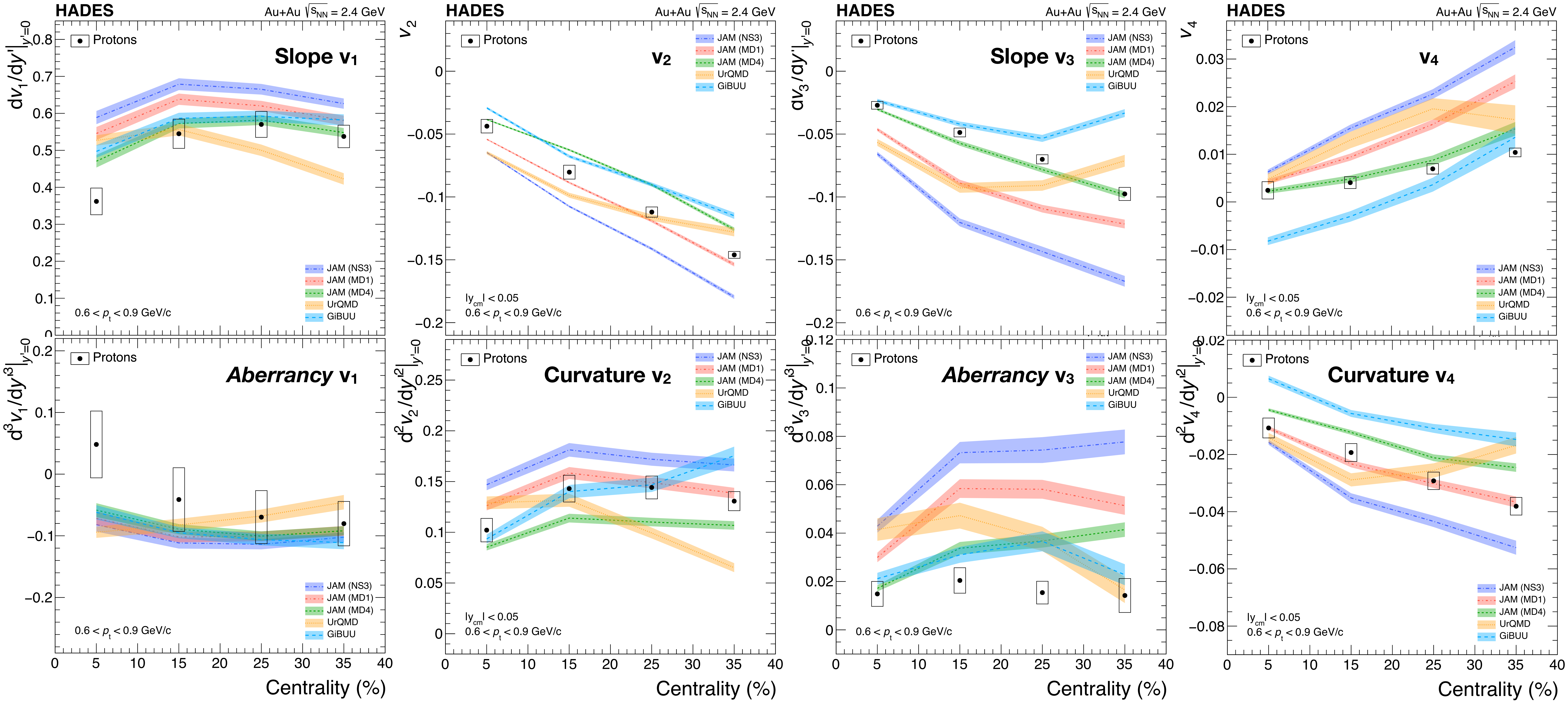
Conclusions

Overall trend reasonably described,
but no model works everywhere

Several systematic deviations

Unified description of cluster production missing

Model Comparisons to Proton Data



* ***Aberrancy*: the third derivative of a curve**

Conclusions and Outlook

Scaling properties of Flow Coefficients

Relation between v_2 and v_4
Hydro-like matter at SIS energies?

Scaling of v_2 and v_4 according simple “nucleon coalescence” via momentum addition

Scaling with Initial Eccentricities reveals fixed relation between v_2 and v_4

Model Comparison

New level of precision - multi-differential
Additional information from higher orders

Consistent modelling of cluster formation is essential

Next Steps towards EOS

Detailed comparisons and sensitivity to model parameter space $\Longrightarrow$ Bayesian analysis

System-Size and Energy-dependence

Ag+Ag Beam data
at 1.23 and 1.58 *A*GeV (2019)

SIS Beam Energy Scan
Au+Au 0.2, 0.4, 0.6 and 0.8 *A*GeV is planned

HADES Collaboration

Thank you for your attention!