Decoding the EOS of neutron star-like matter via flow patterns of nuclear cluster emitted in HI collisions

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for the
HADES Collaboration

MU Days 2023

15th September 2023

GEFÖRDERT VOM
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HFHF

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HADES

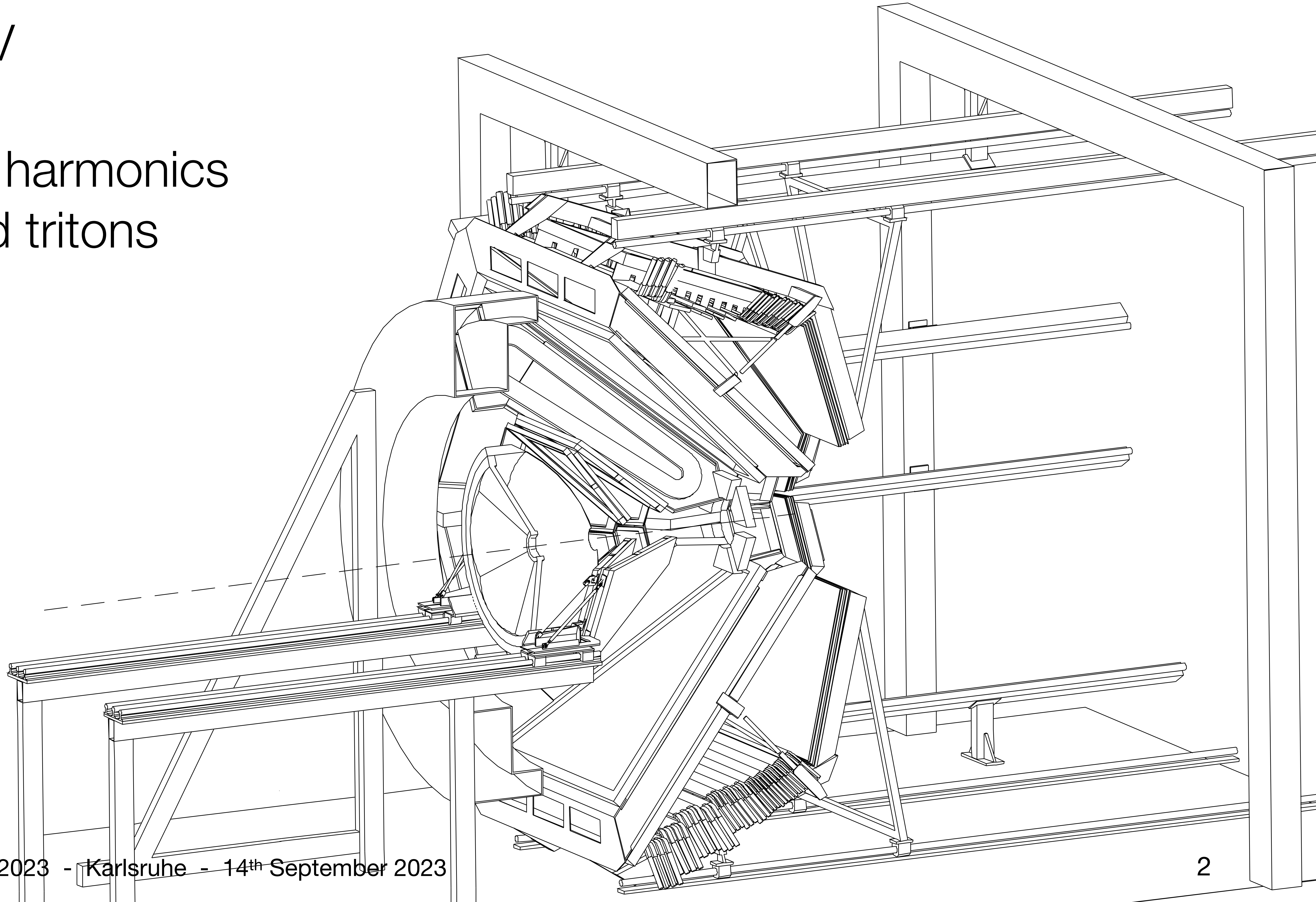
Outline

Talk based on following publication:

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

HADES, EPJ A 59 (2023) 80 arXiv:2208.02740 [hepdata soon]

- 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
- Model comparisons
- Event-wise flow correlations



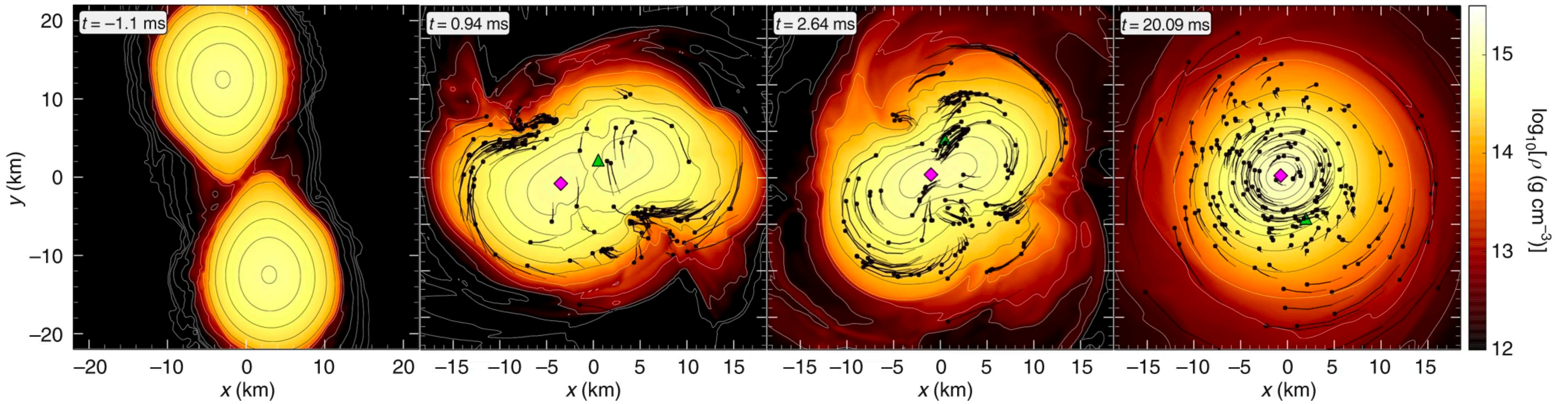
Nuclear Matter under Extreme Conditions

What is the nature of matter?

And what are the properties of nuclear matter under the most extreme conditions?

Equation-of-state of dense matter in the *universe* and in the *laboratory*

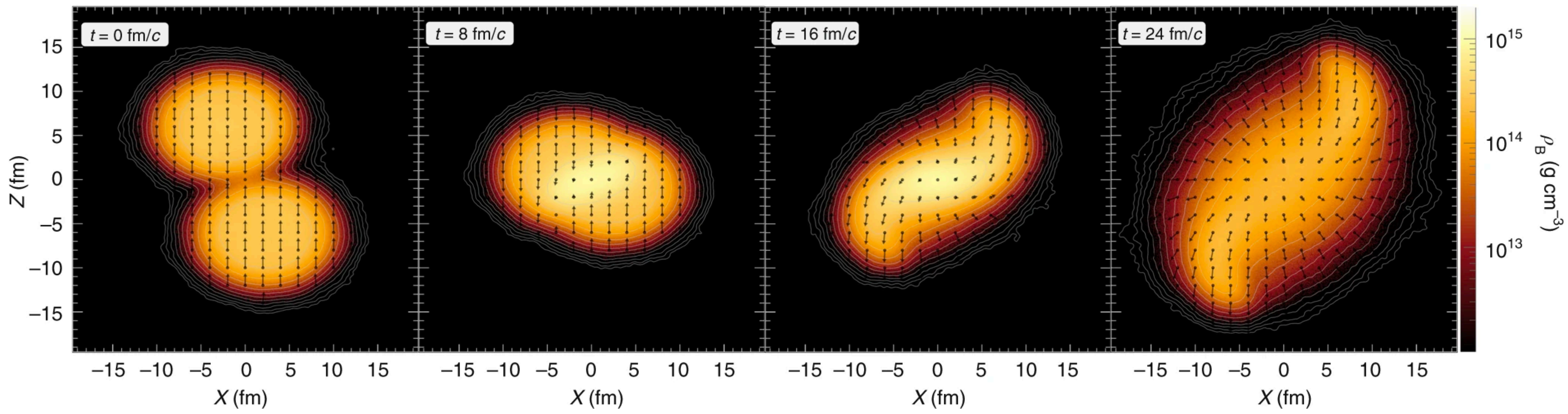
HADES, Nature Phys. **15** (2019) 1040



Neutron Star Merger

Observation via gravitational waves

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



Heavy-ion Collision

Equation-of-state of dense matter

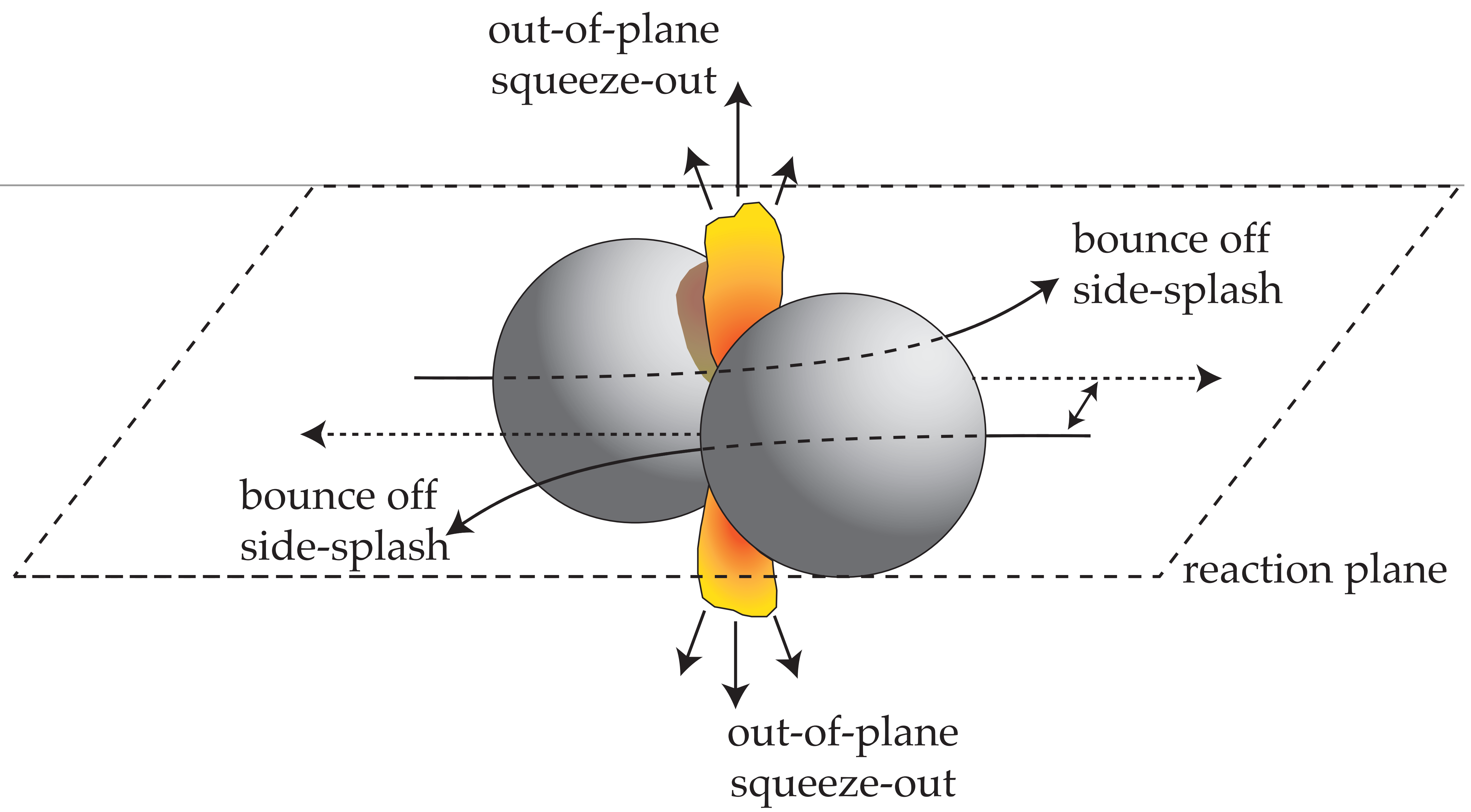
Collective Effects

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



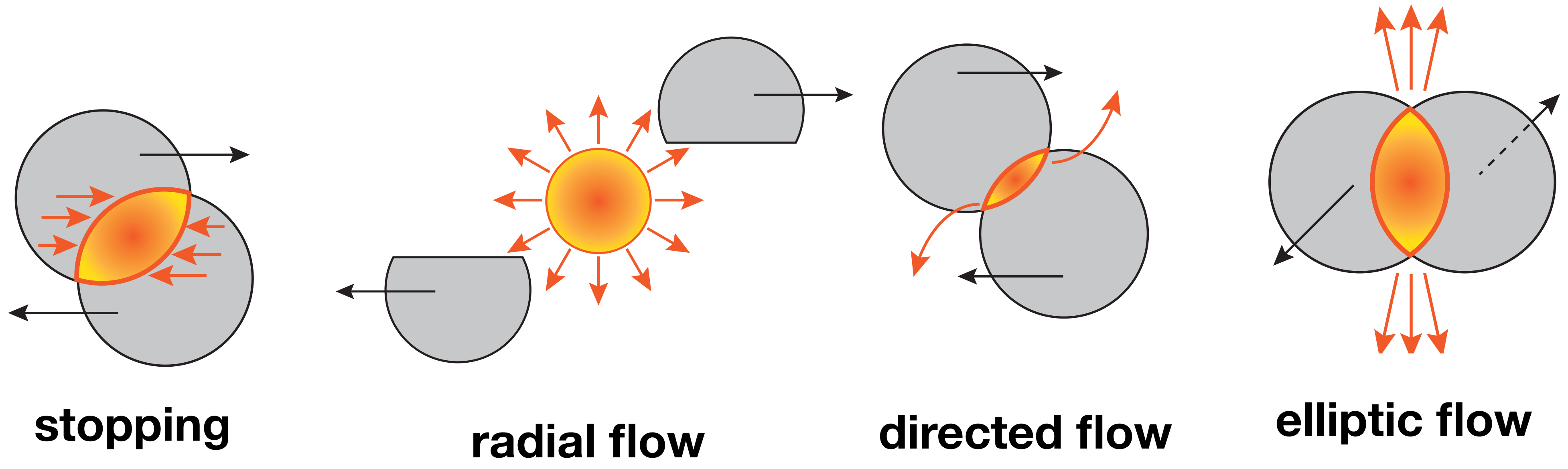
Fourier-decomposition

of the triple differential invariant cross section

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

Extraction of azimuthal moments v_n $\phi = (\varphi - \Psi_{RP})$

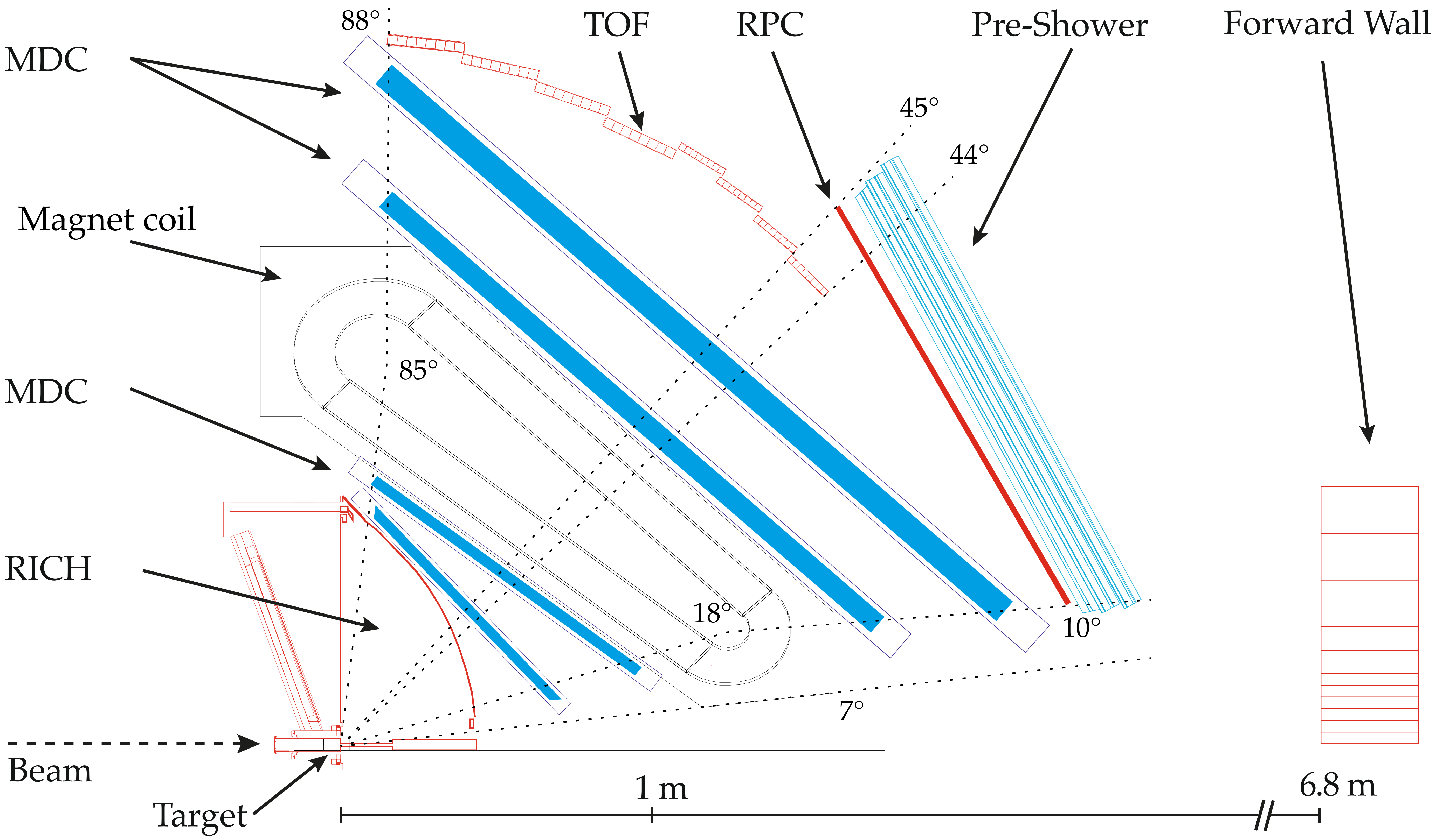
$$v_n(p_t, y) = \langle\cos(n\phi)\rangle$$



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

High Acceptance Di-Electron Spectrometer

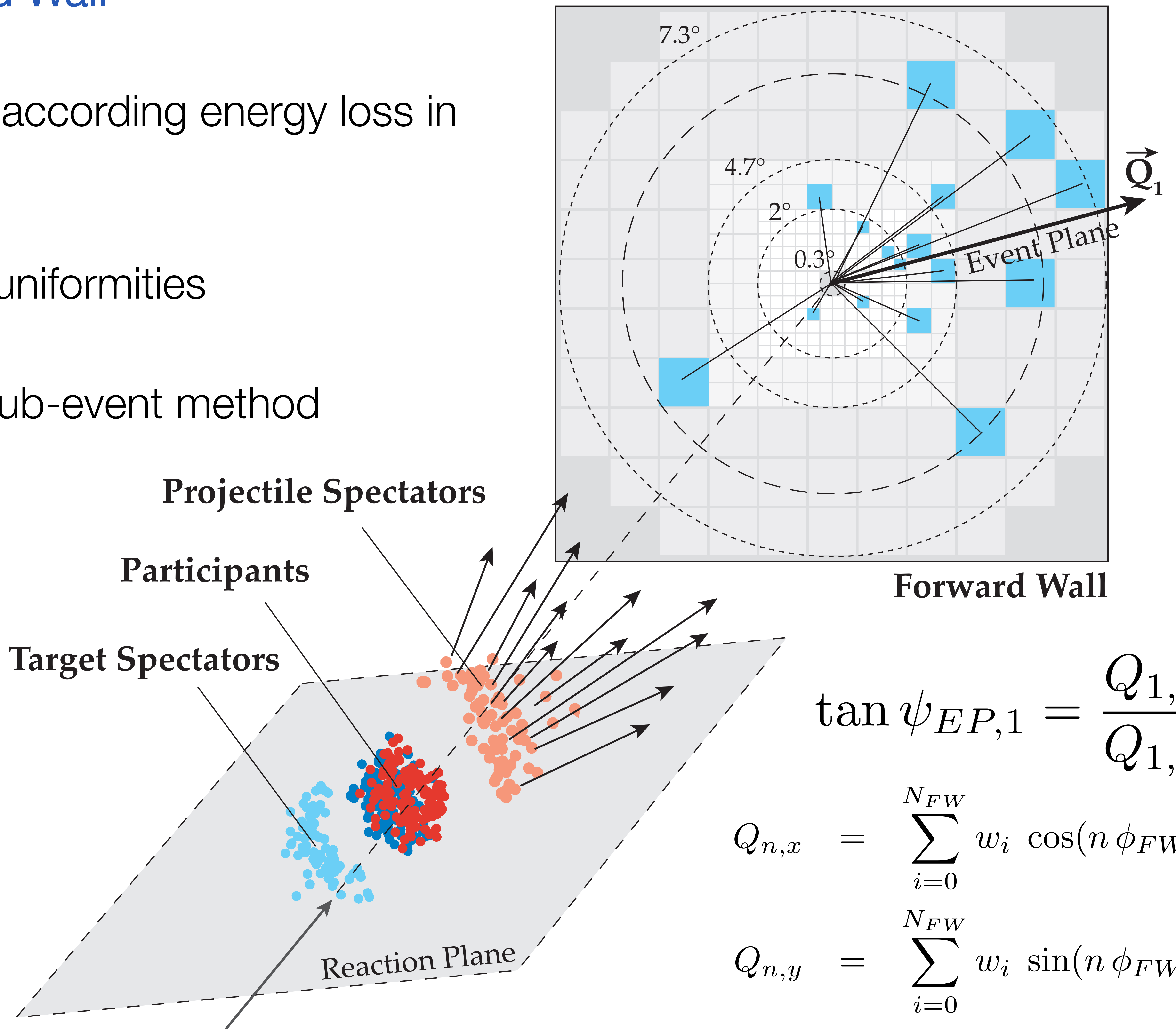
- High interaction rates and statistics
  - 5 weeks (558.3 hours) of Au+Au data taking with 7×10^9 recorded events
  - Beam intensities 1.2 - 2.2 x 10^6
- Large acceptance in 6 identical sectors
  - Symmetric azimuthal coverage
  - 18°-85° in polar angle
- Low-mass tracking system
  - 4 Planes of multi-wire chambers with Mini-Drift Cells (MDC)
  - 6 Coils of superconducting toroidal magnets
- Particle Identification
  - Time-of-Flight (TOF and RPC)
  - Energy loss in the MDC
- Forward Wall
  - Reaction plane reconstruction

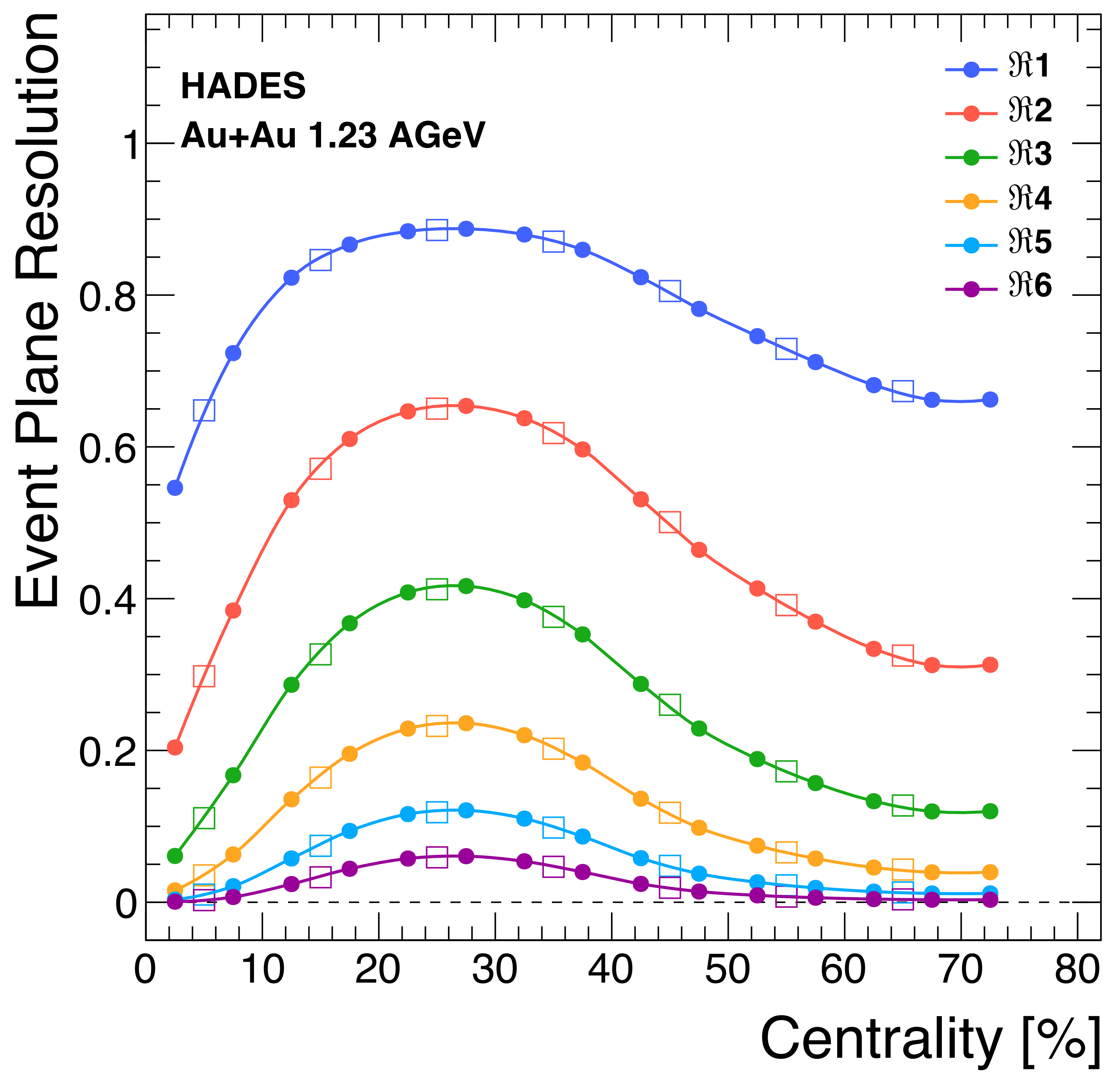


Event Plane Reconstruction

Event plane of 1st-Order from Projectile spectators in Forward Wall

- Charge-Weighting according energy loss in scintillators
- Correction of non-uniformities
- EP-resolution via sub-event method





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

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

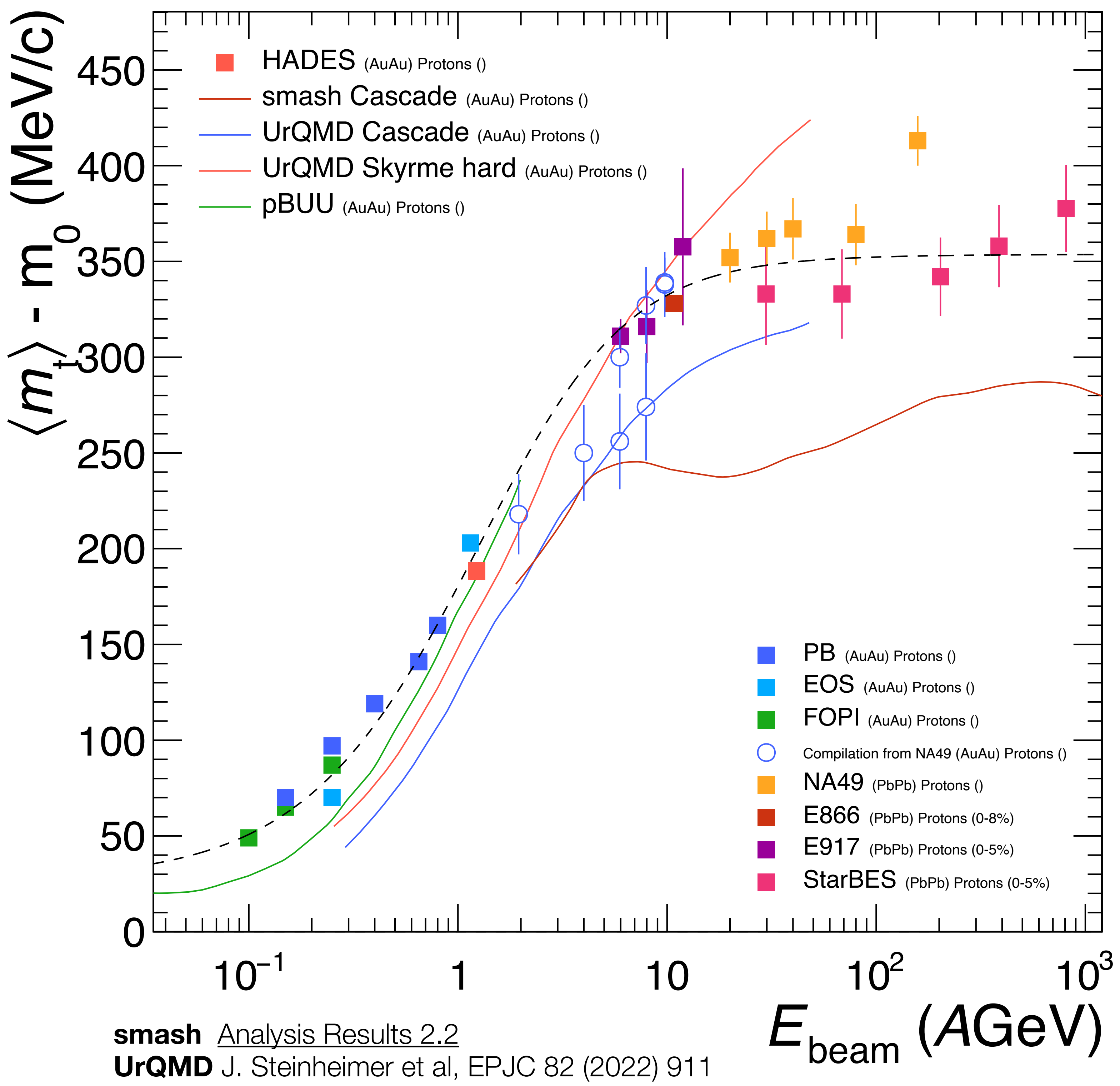
$$Q_{n,y} = \sum_{i=0}^{N_{FW}} w_i \sin(n\,\phi_{FW,i}) .$$

$$v_n = v_n^{obs} \,/\, \boldsymbol{\Re_n}$$

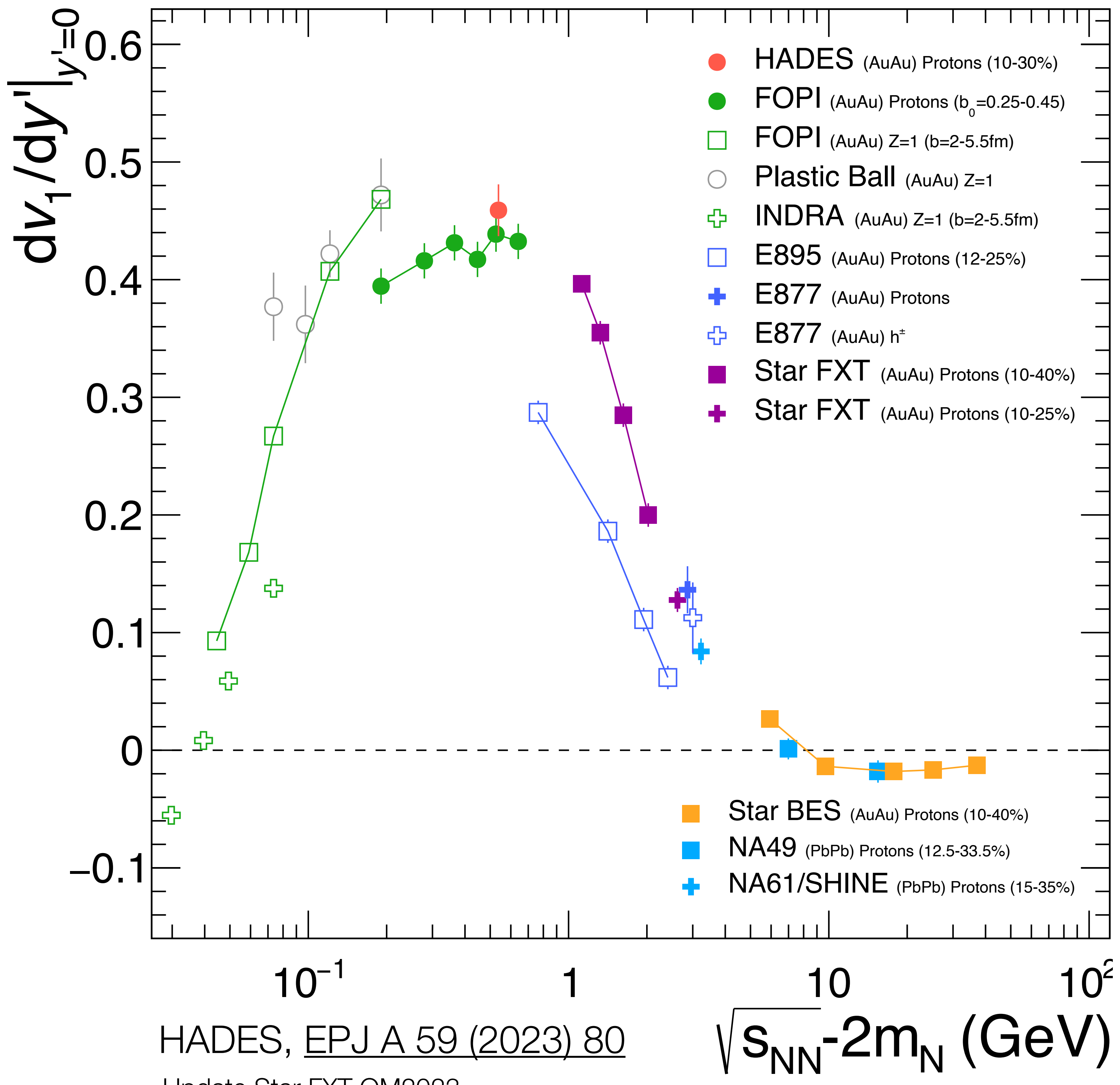
$$\boldsymbol{\Re_n} = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

Collective Effects

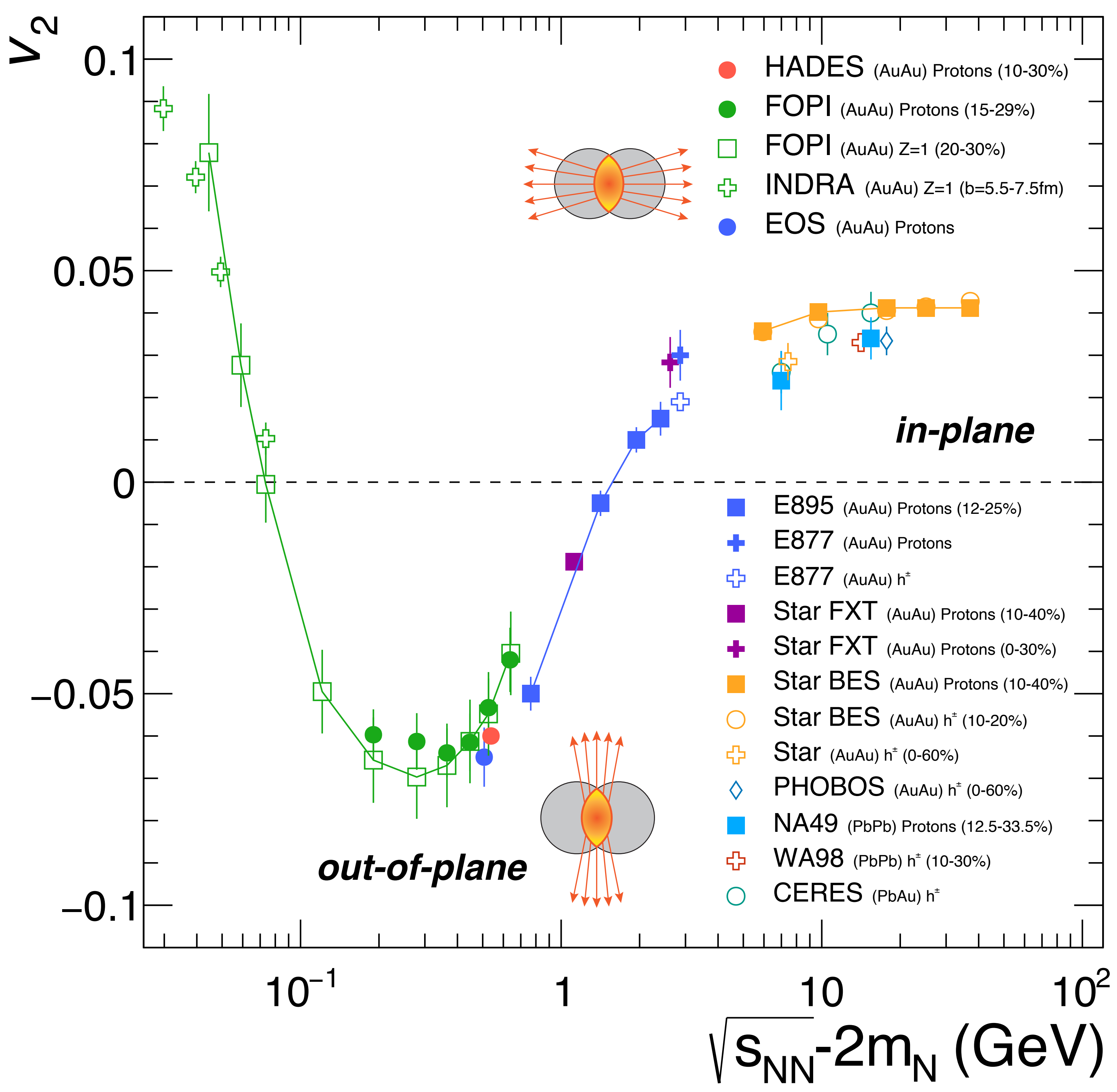
Energy-Dependence



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



HADES, EPJ A 59 (2023) 80
Update Star FXT QM2023



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

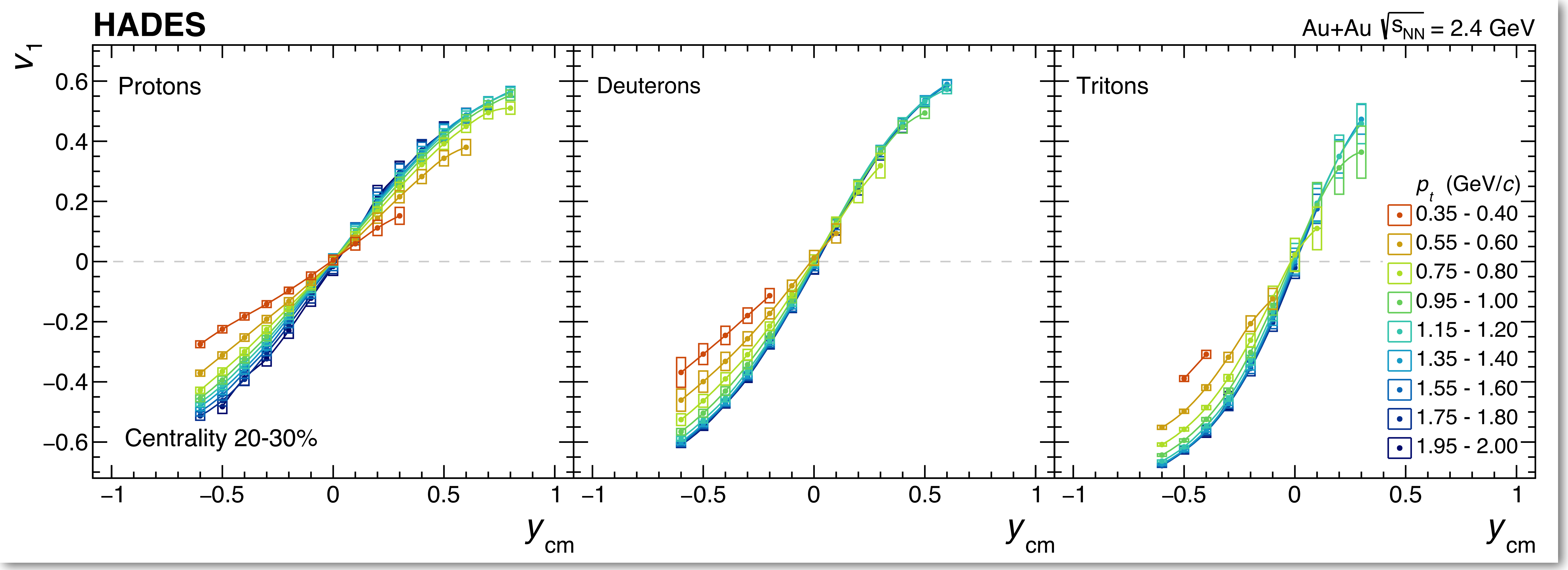
Out-of-Plane v_2

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, EPJ A 59 (2023) 80

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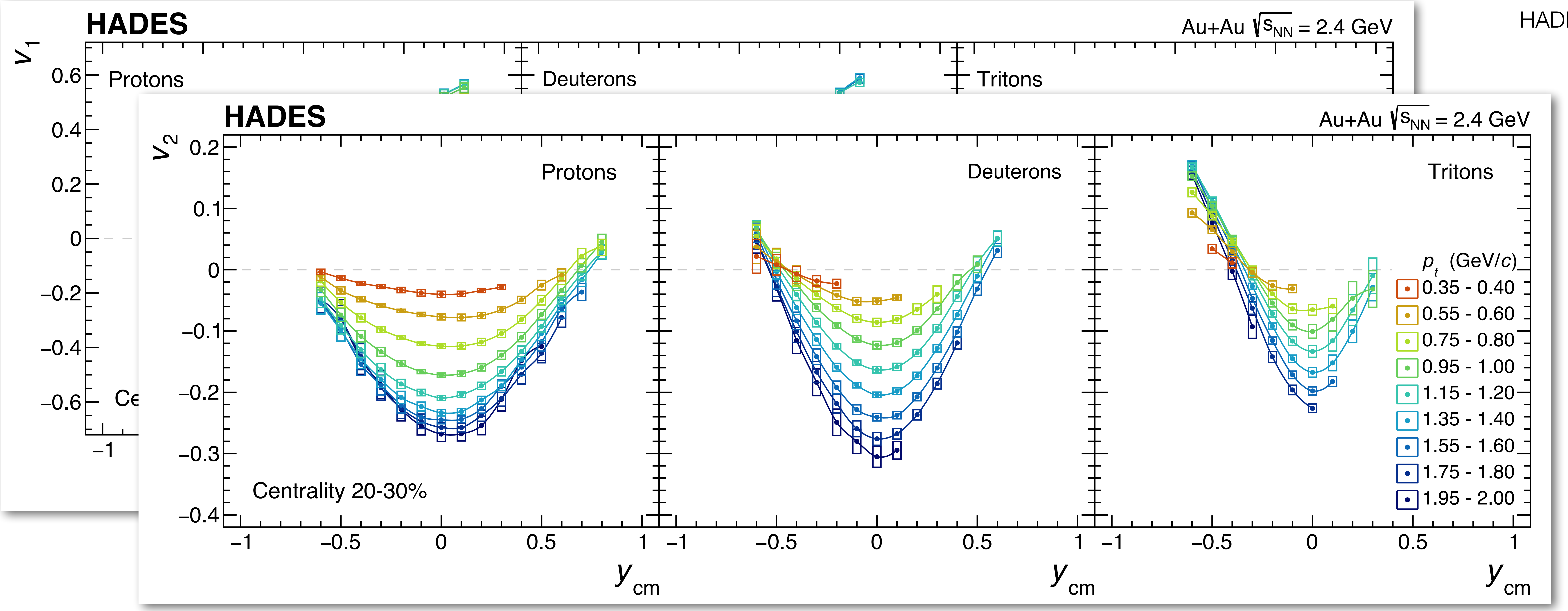

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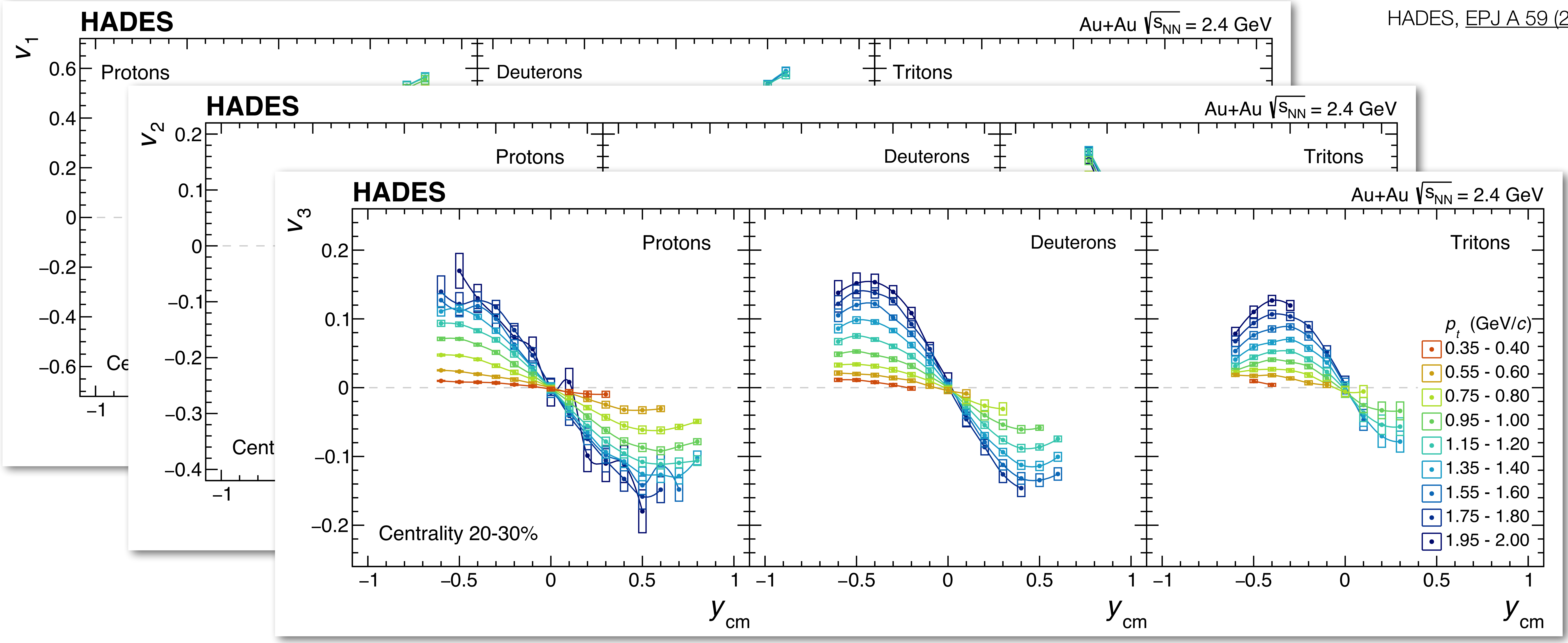
HADES, EPJ A 59 (2023) 80



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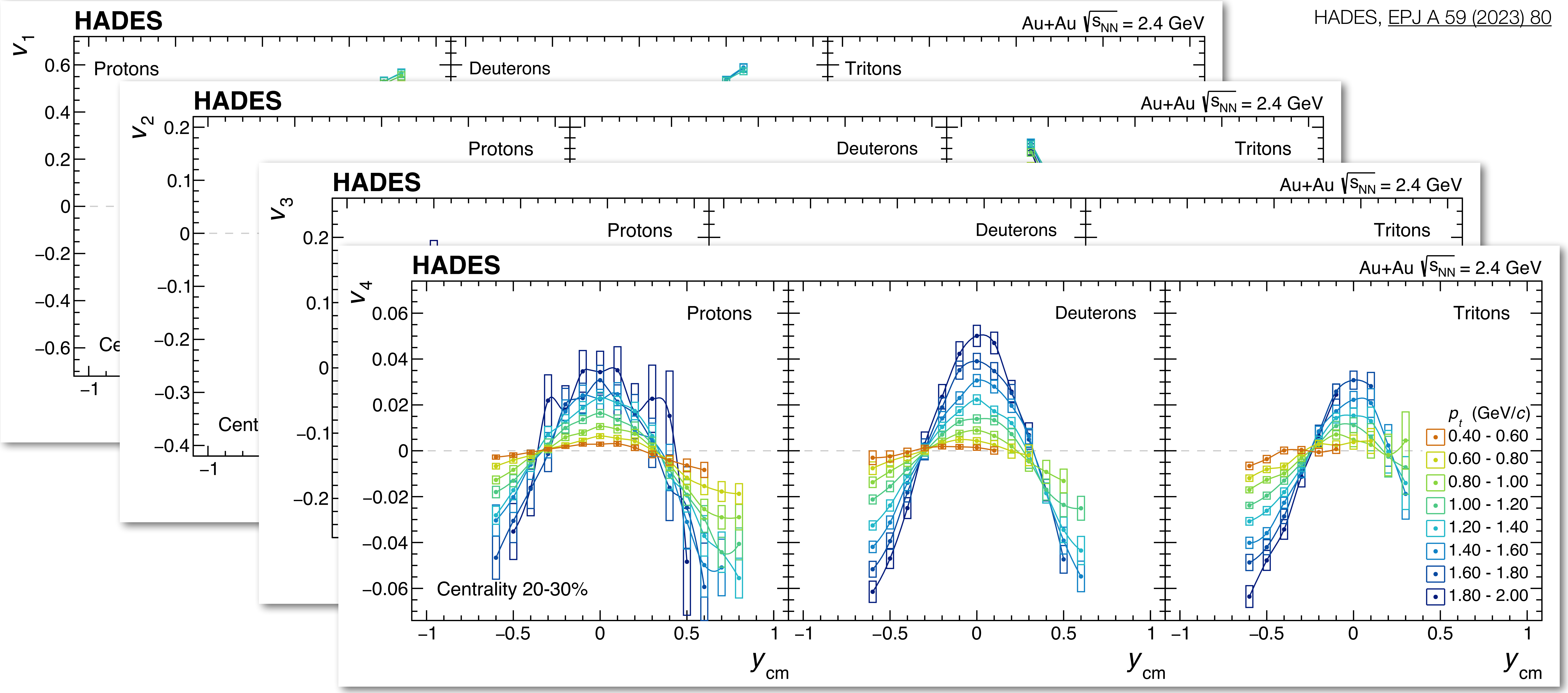
HADES, EPJ A 59 (2023) 80



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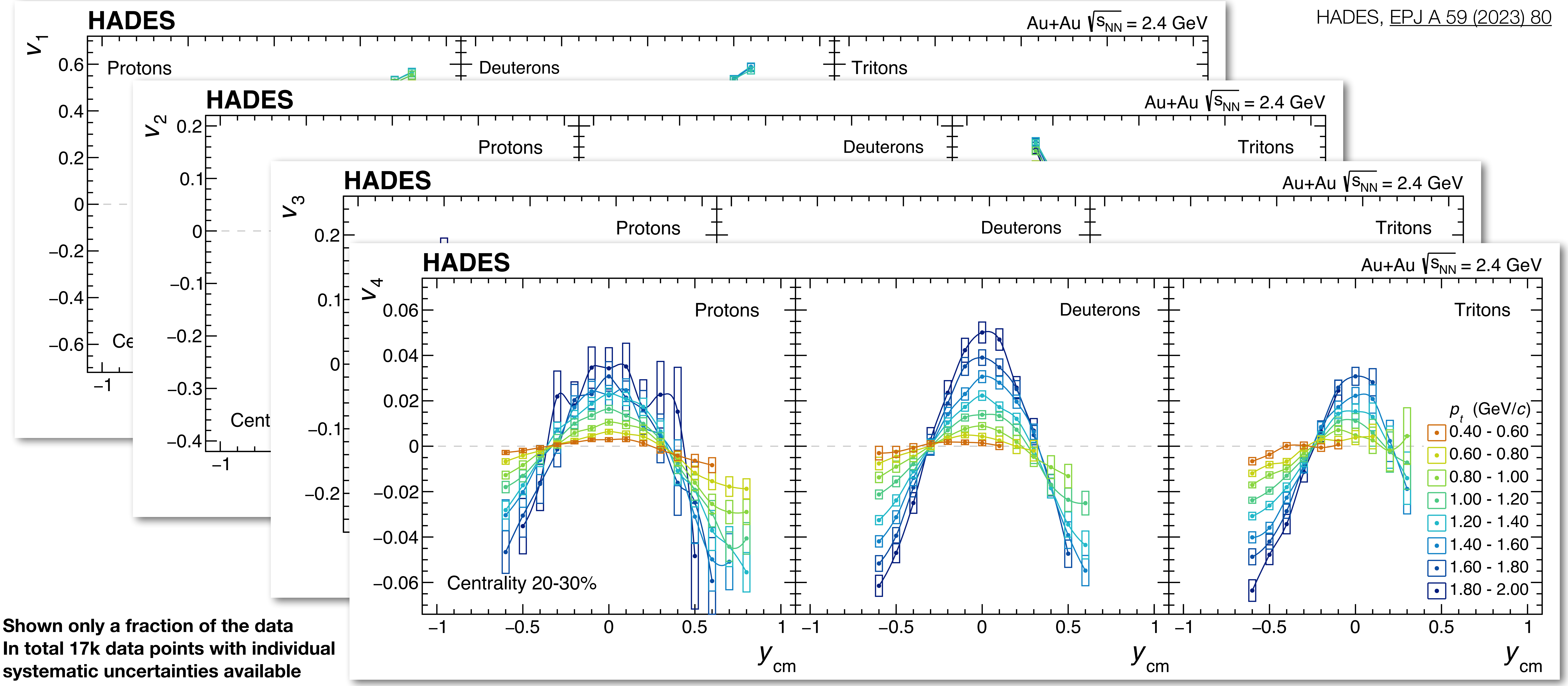
HADES, EPJ A 59 (2023) 80



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

Model Comparisons to Proton Data

HADES, EPJ A 59 (2023) 80

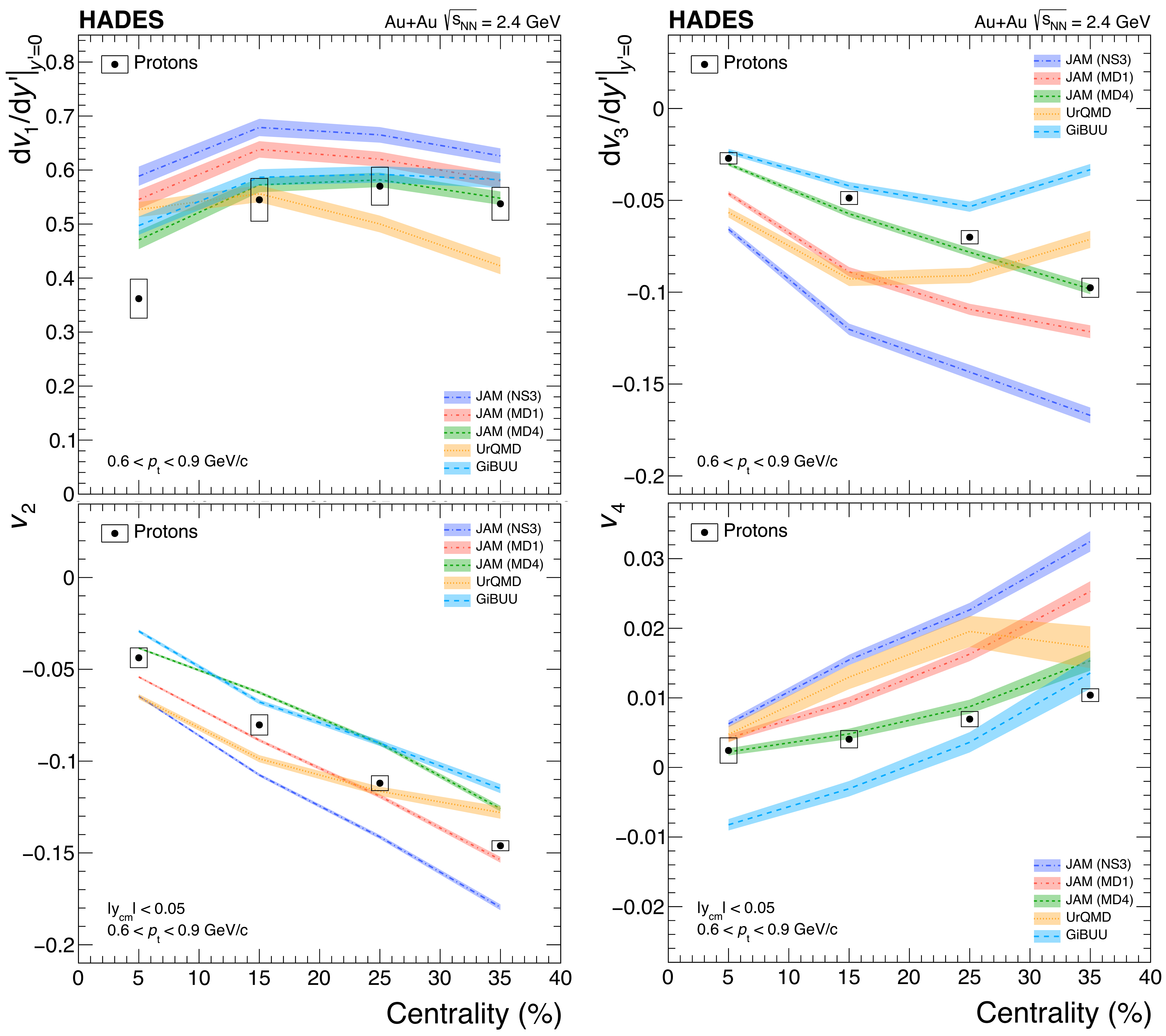
Determination of EOS

New level of precision - multi differential
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 light nuclei production missing

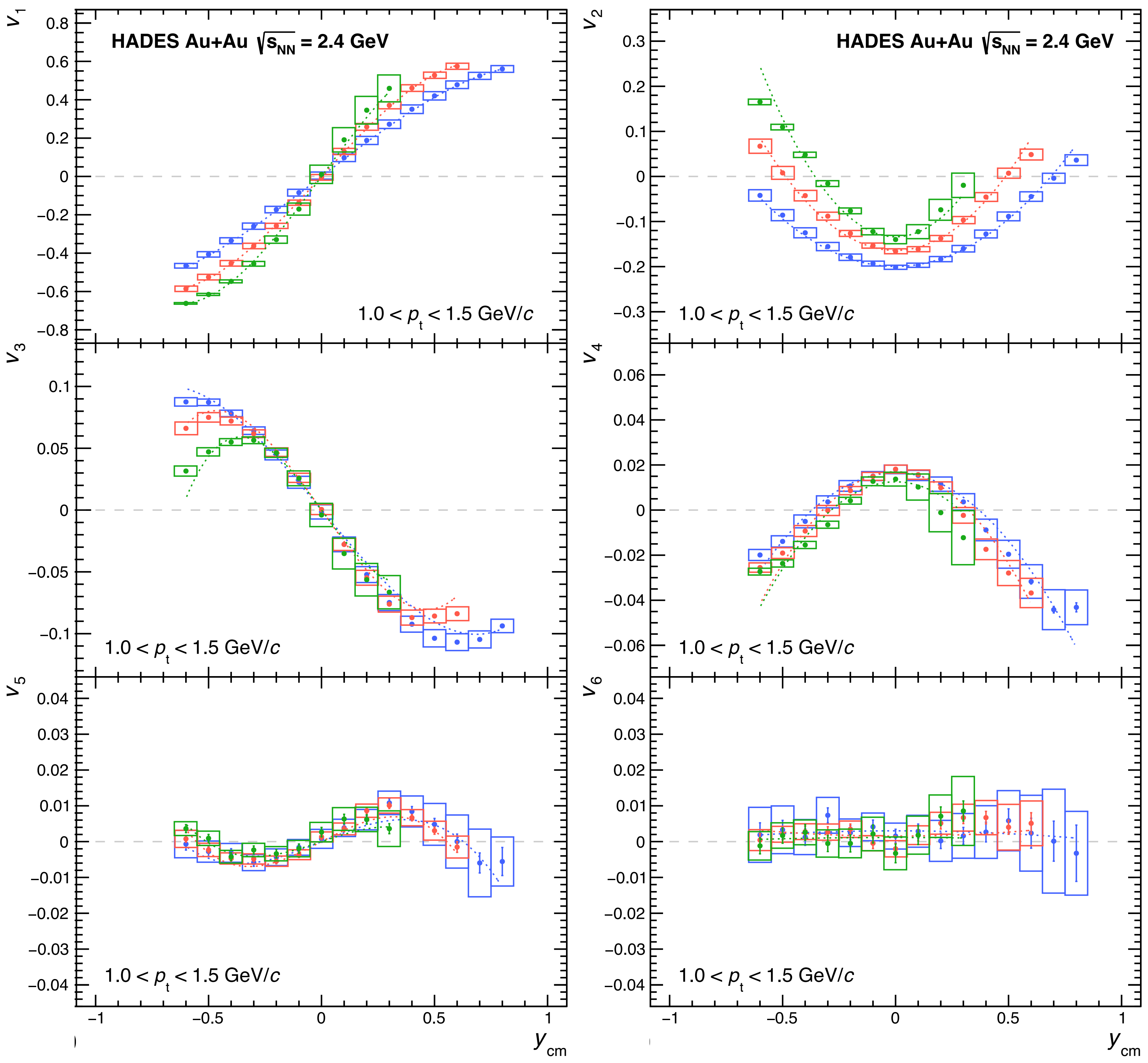
Emission Pattern

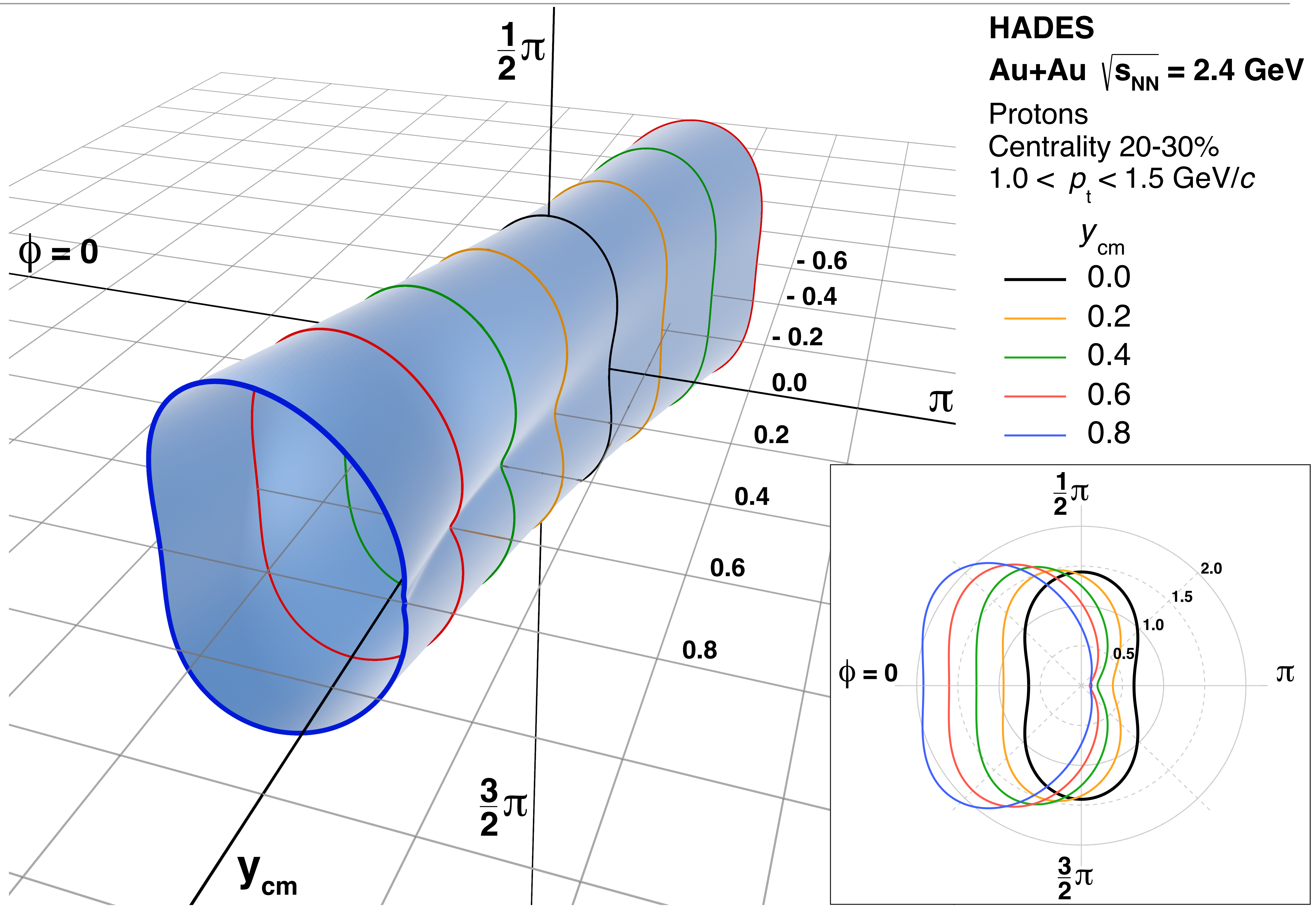
Protons

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

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

Complex evolution of shape as function of rapidity determined by flow coefficients v_1 — v_6





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

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

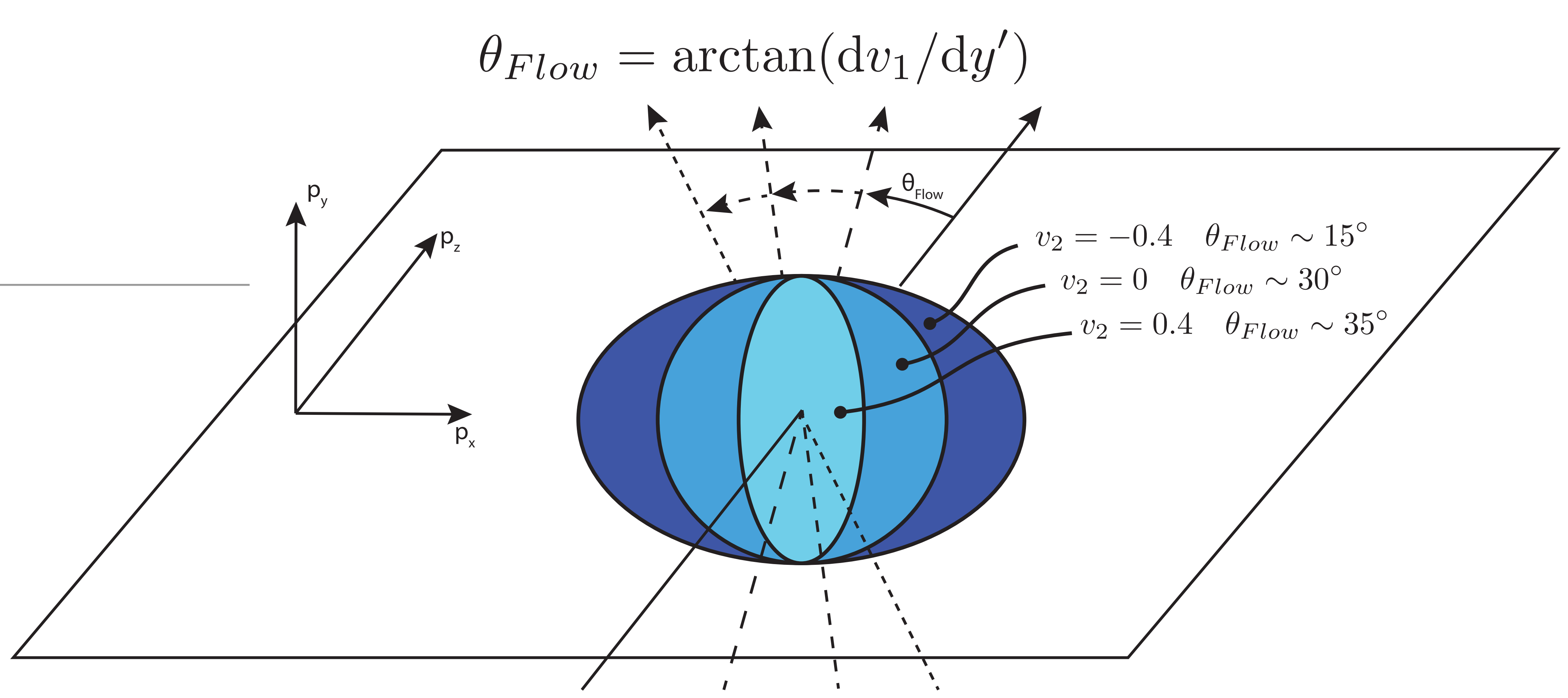
$$v_{2,4,6}(y_{cm}) = c + d\, y_{cm}^2$$

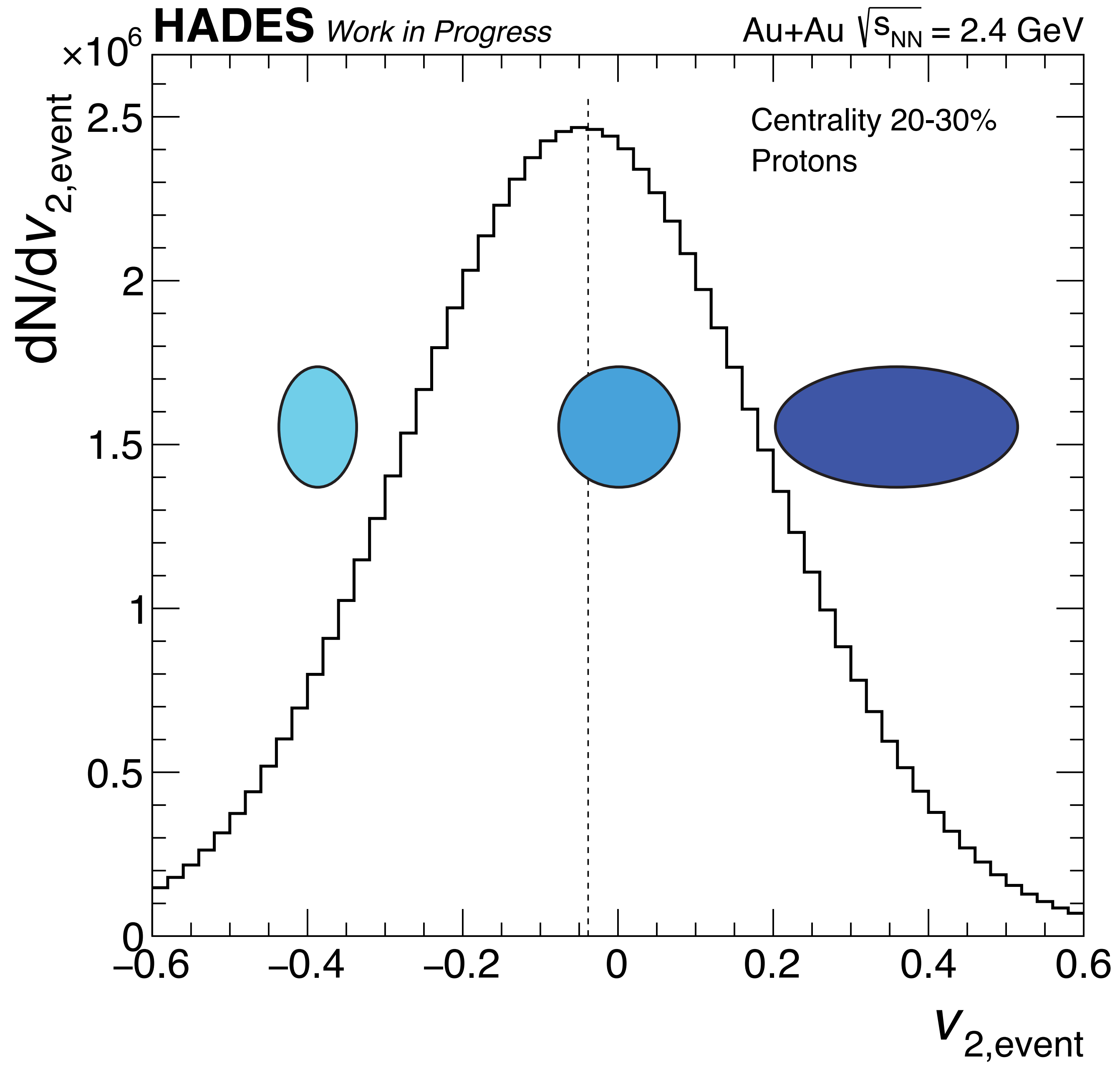
First Proposed in S. Voloshin and Y. Zhang Z.Phys. C70 (1996) 665-672

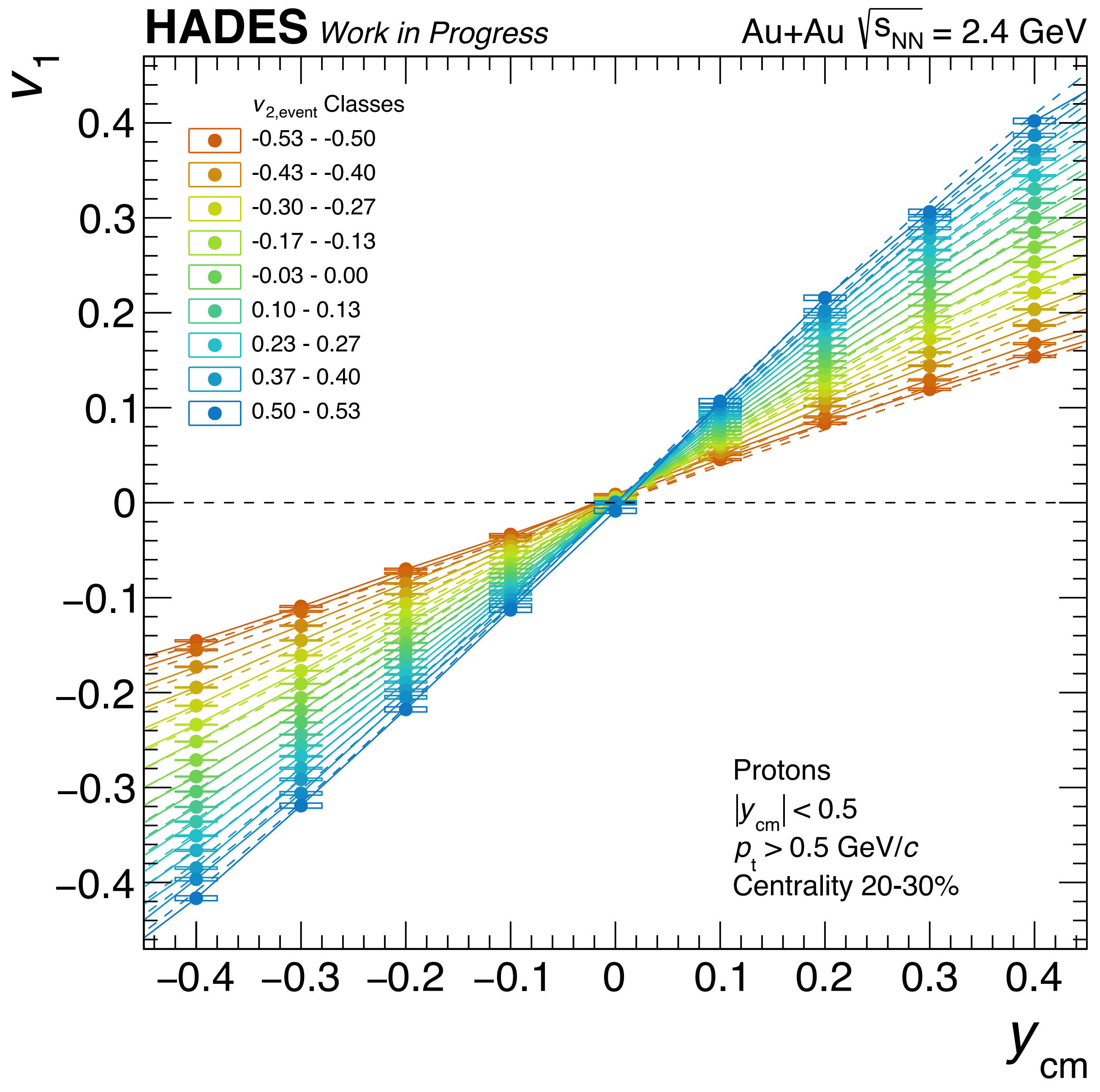
Event-wise Flow Correlations

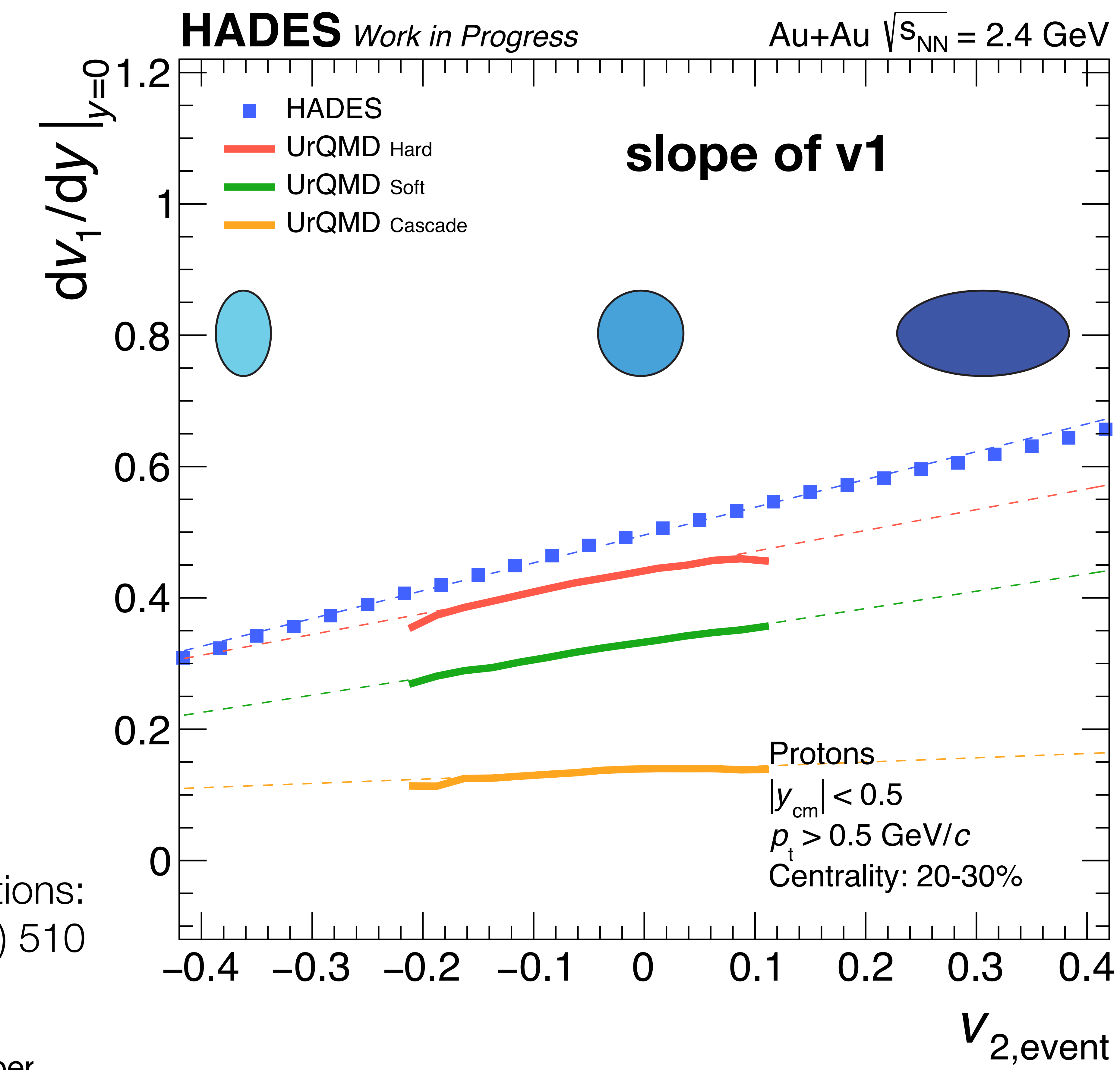
Events can characterised according the event-wise magnitude of the elliptic flow $v_{2,event}$

Slope of directed flow $dv_1/dy|_{y=0}$ resp. flow angle θ_{Flow}



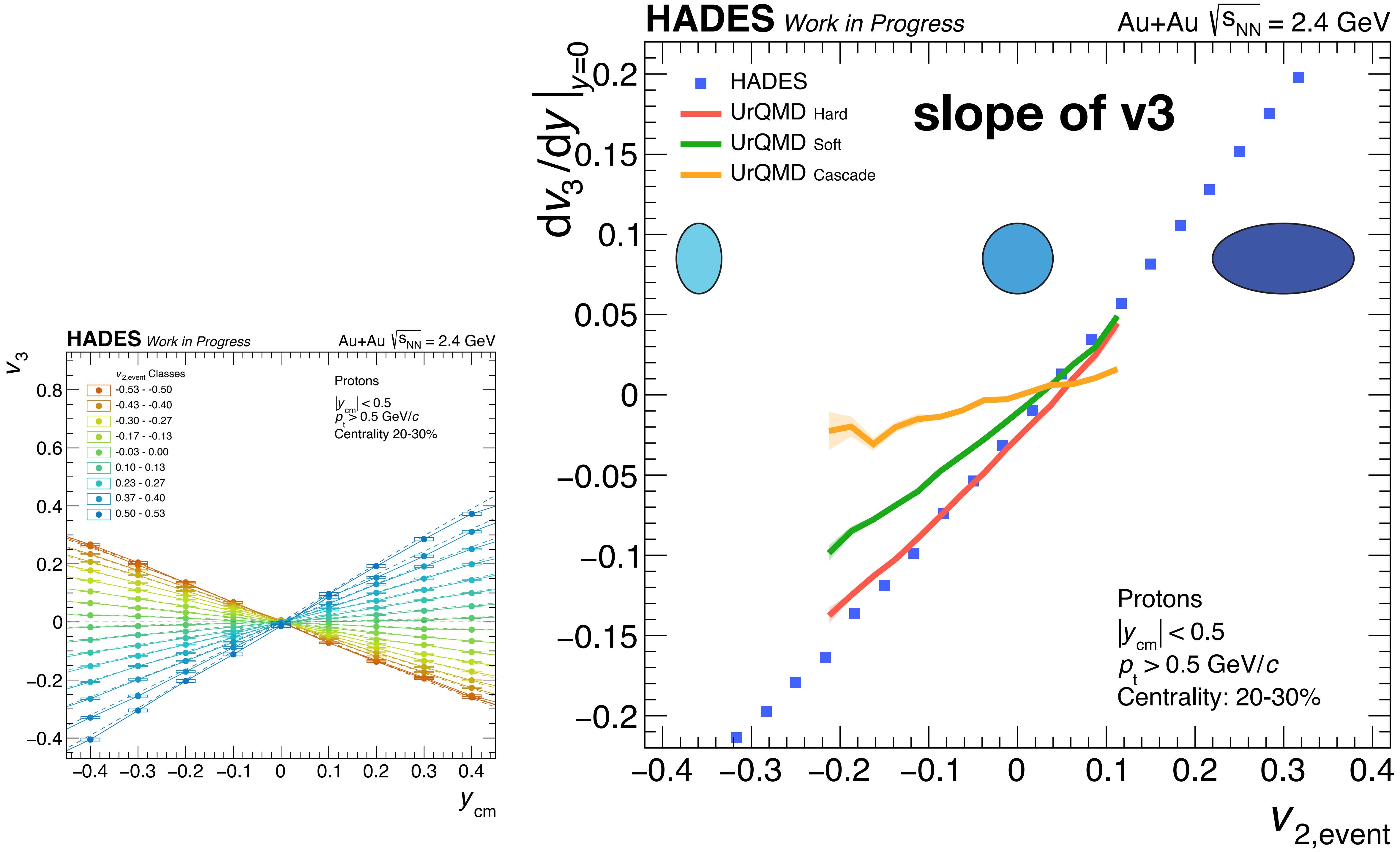


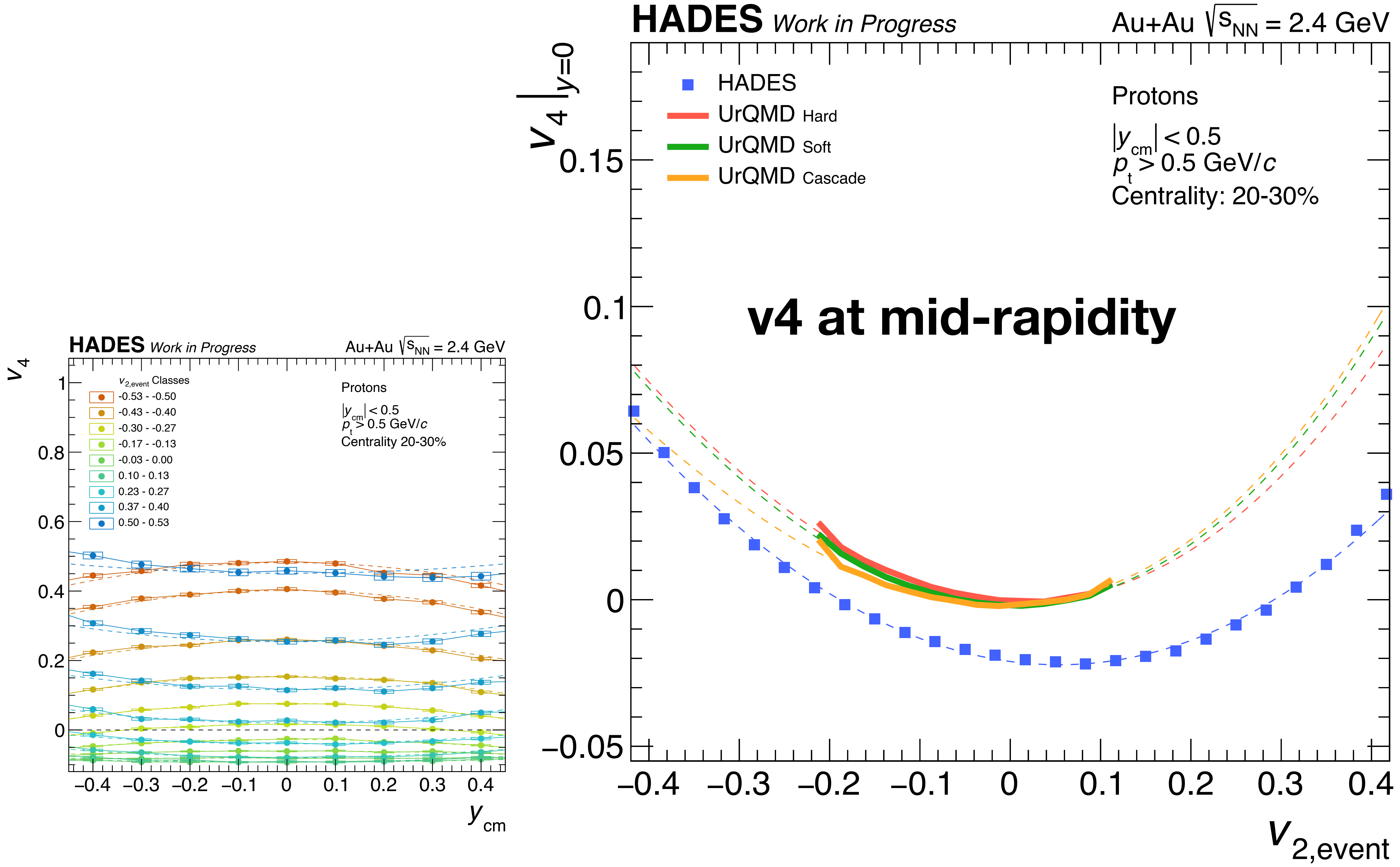




UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

Event-wise Flow Correlations





Slope of the Triangular Flow v3

A strong sensitivity to the EoS is seen

Quadrangular Flow v_4

The magnitude of v4 seems to follow an almost quadratic dependence

UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

Not corrected the underlying Multiplicity Fluctuations

Conclusions and Outlook

Flow Coefficients

Full 3D-picture of the emission pattern with complex shape determined by flow coefficients v_1 — v_6

Model Comparison

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

Consistent modelling of light nuclei formation is essential

Event-wise Flow Fluctuations

Correlation and Relation between Flow Coefficients

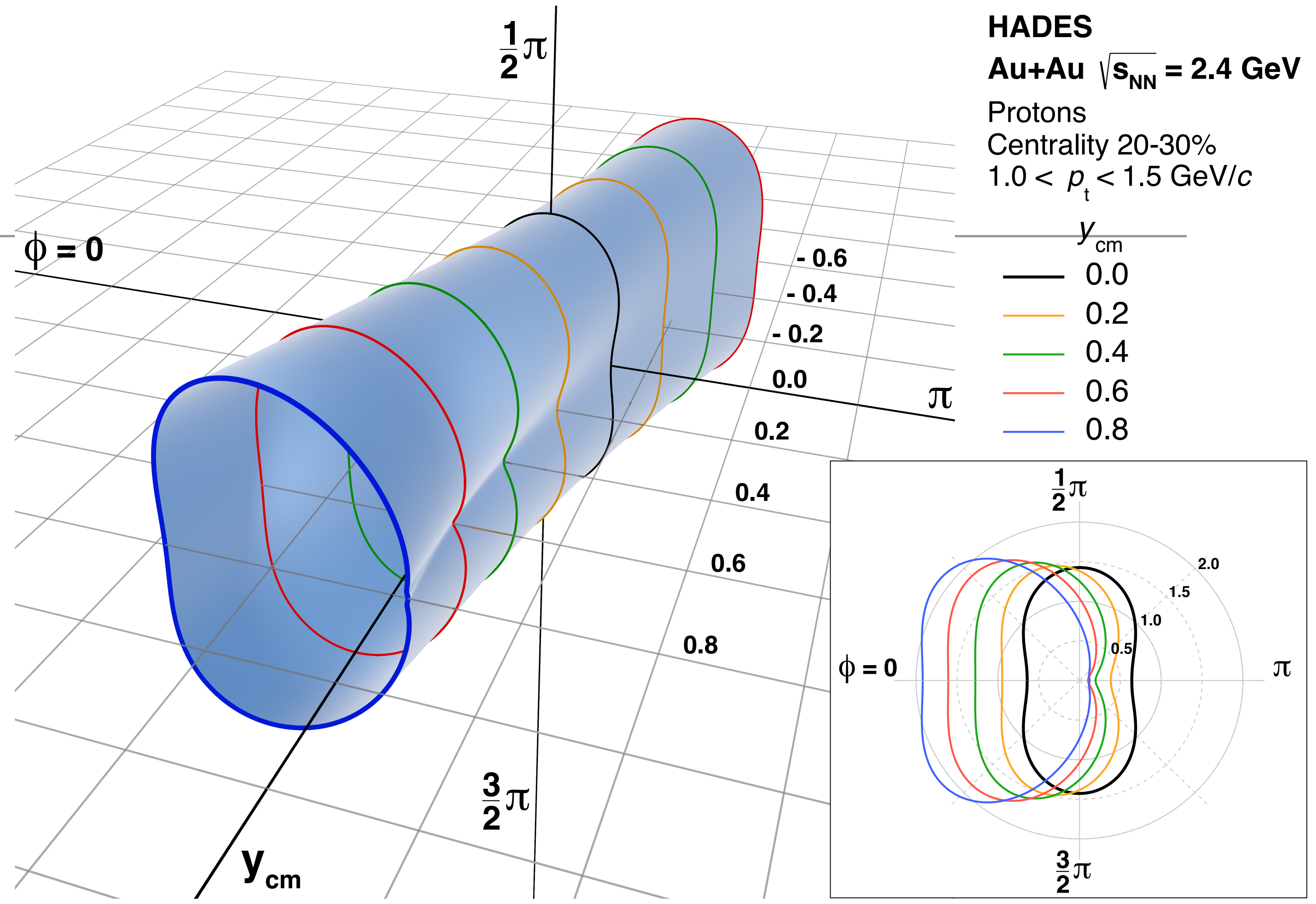
Next Steps towards EOS

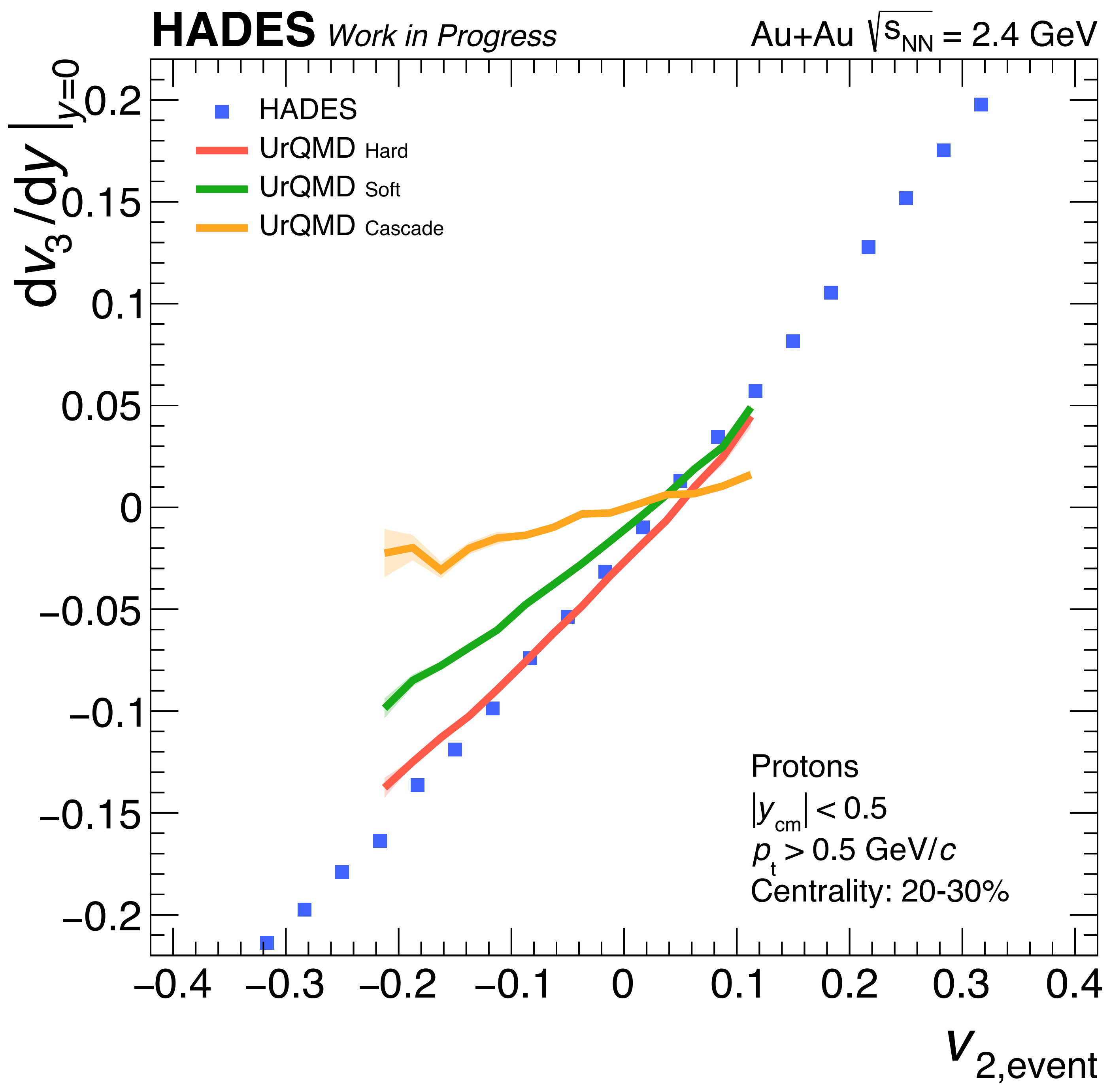
Detailed comparisons and sensitivity to model parameter space
⟹ Bayesian analysis

System-Size and Energy-dependence

Au+Au at 1.23 *A*GeV (2012)
Ag+Ag at 1.23 and 1.58 *A*GeV (2019)

SIS Beam Energy Scan
Au+Au 0.2, 0.4, 0.6 and 0.8 AGeV planned (2024)





HADES Collaboration

Thank you for your attention!

Event Plane Reconstruction

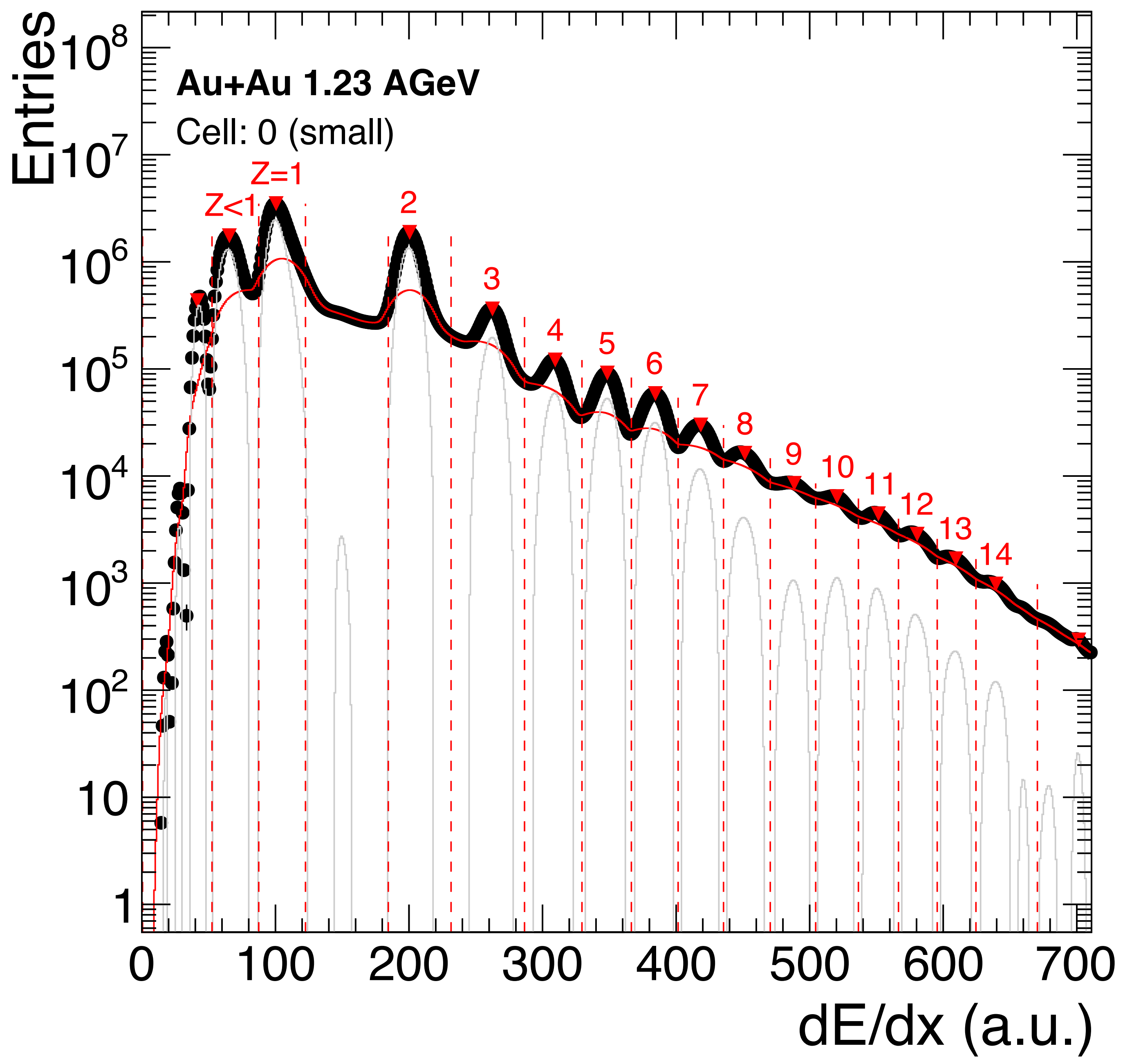
1st-Order event plane from Q-Vector
Projectile spectators in Forward Wall

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

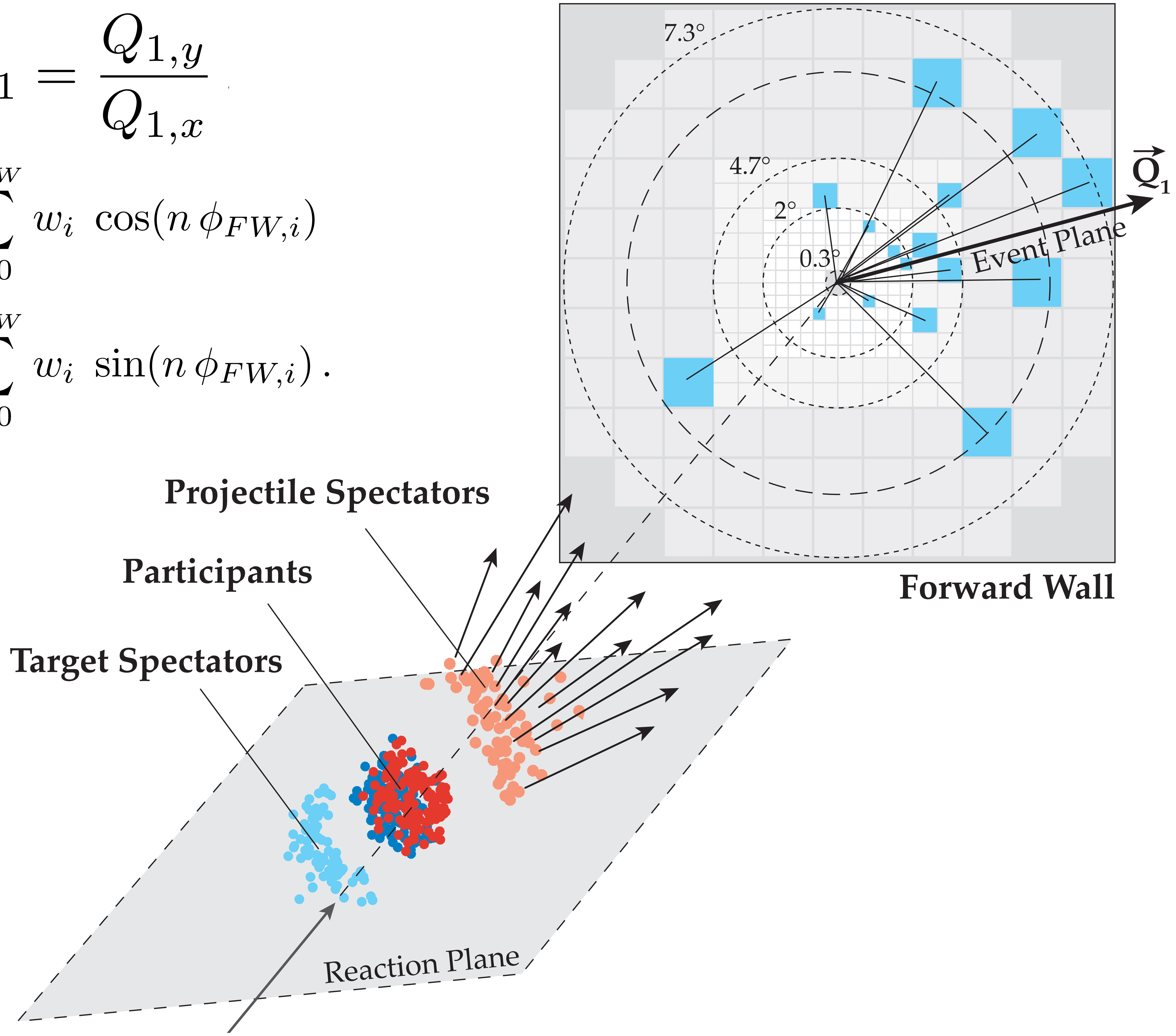
$$\tan\psi_{EP,1} = \frac{Q_{1,y}}{Q_{1,x}}$$

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

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



Charge Weighting



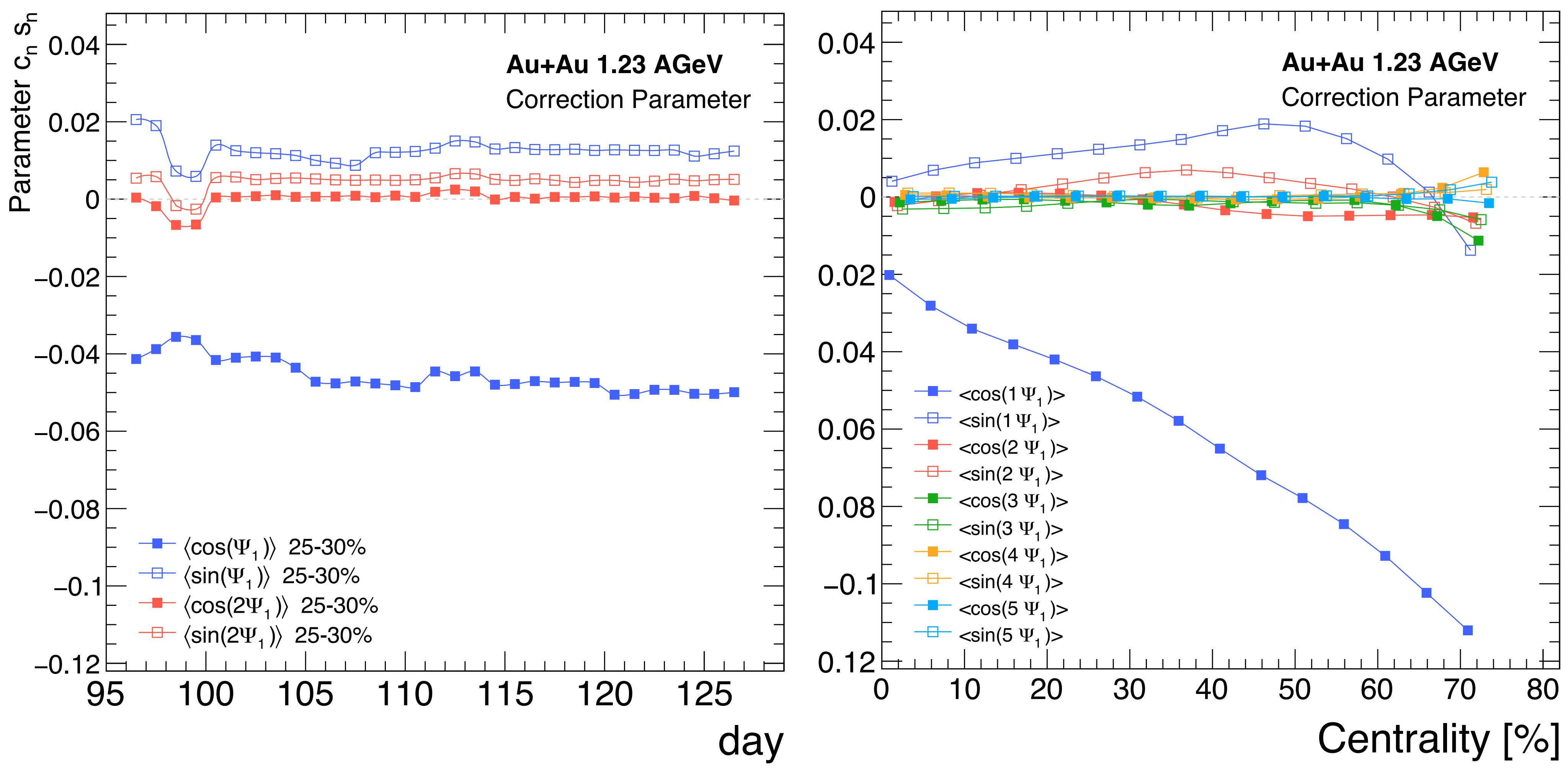
Event Plane Determination

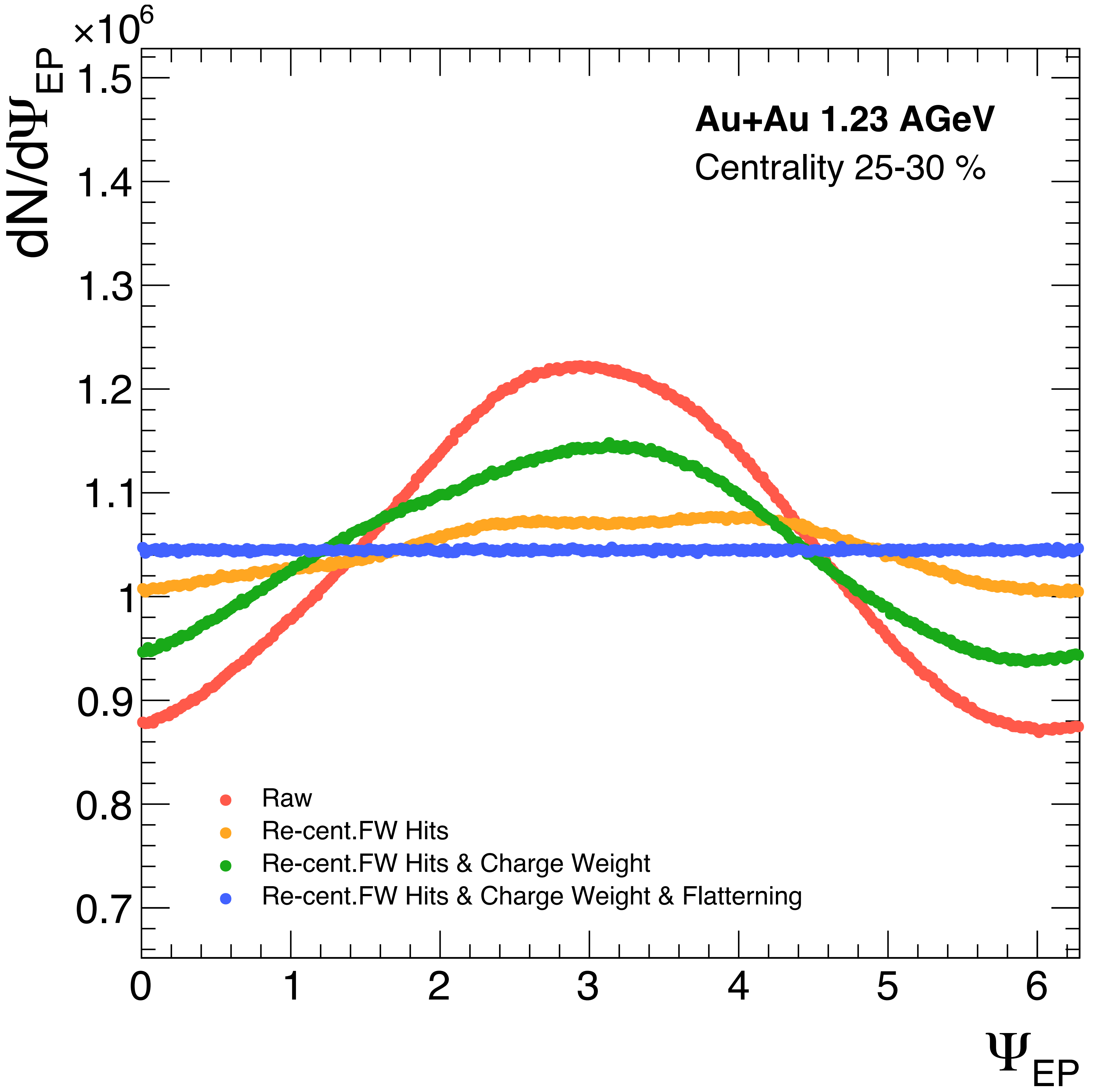
Correction of non-uniformities in the EP distribution (day-by-day and centrality)

Re-centering of X and Y of all FW hits

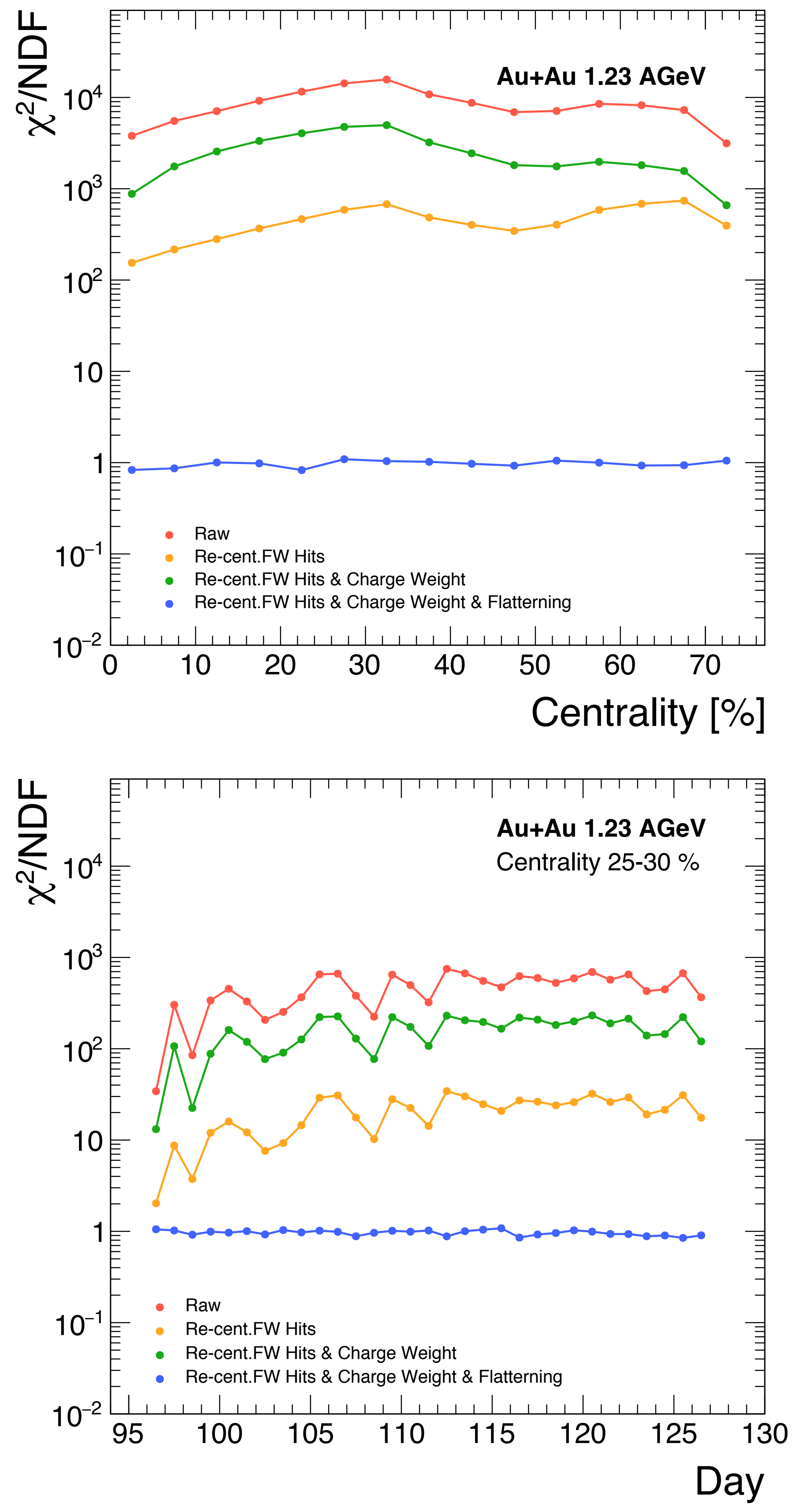
Flattening of residual Fourier components with 8 cos- and 8 sin-terms

Flattening Parameter





Quality of Flatness

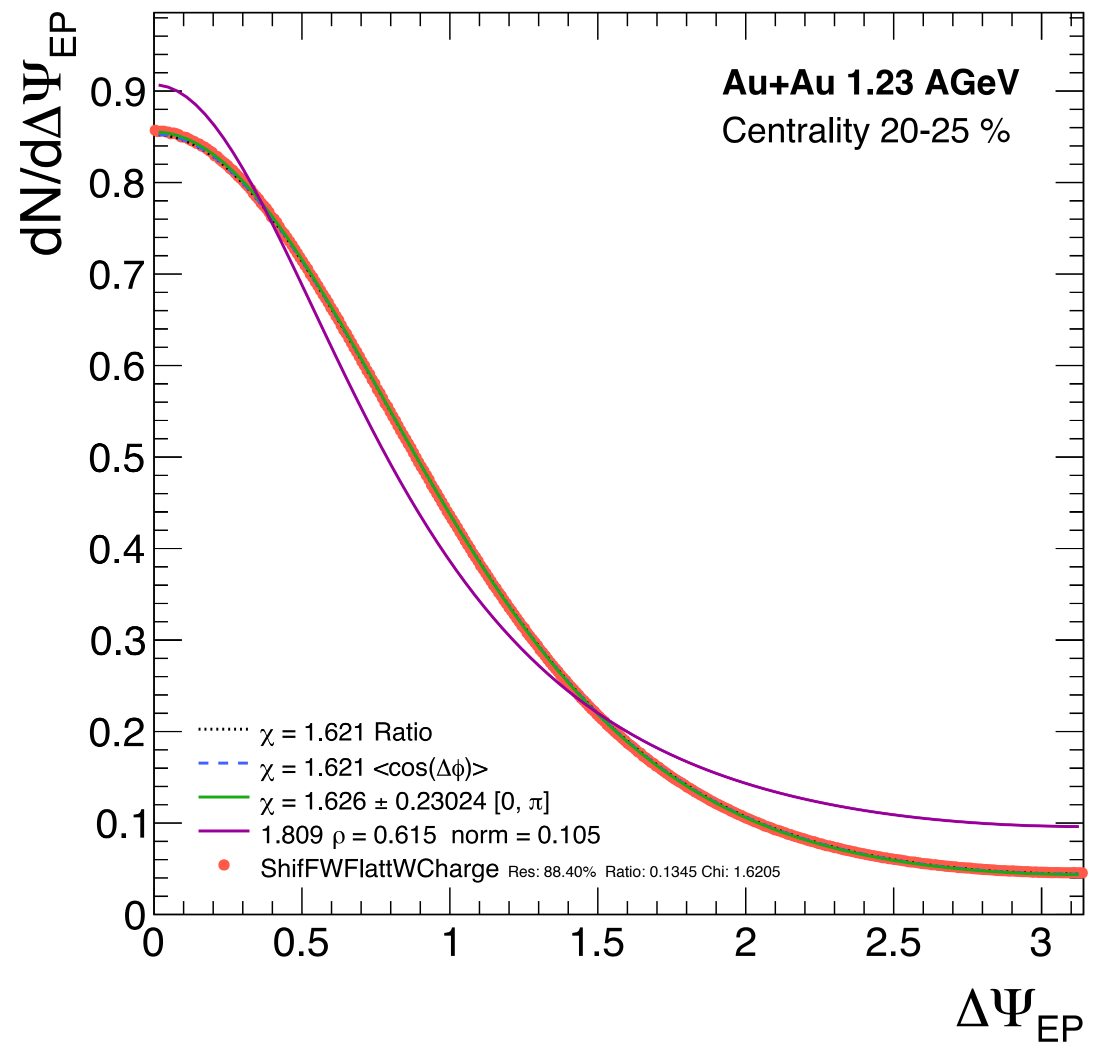


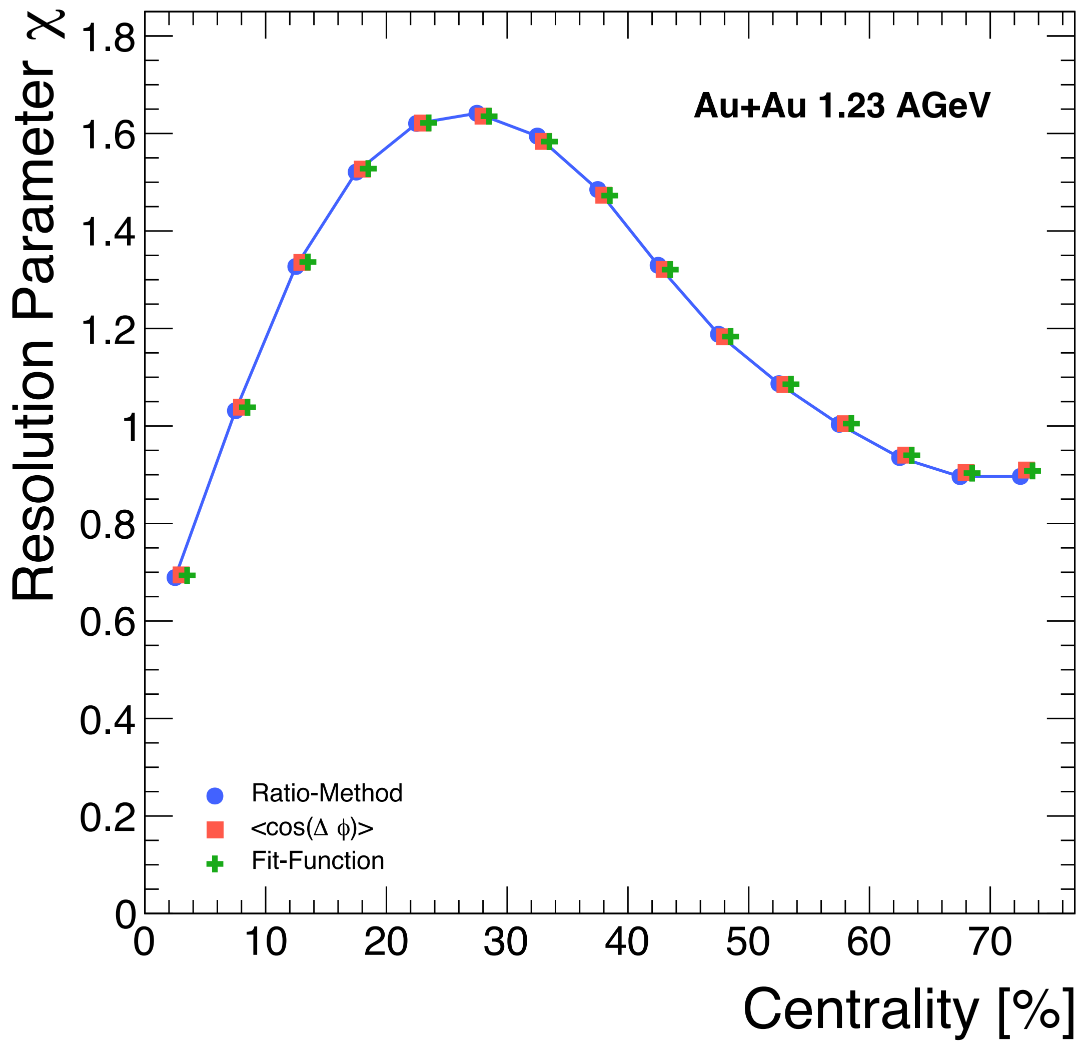
Event Plane Resolution

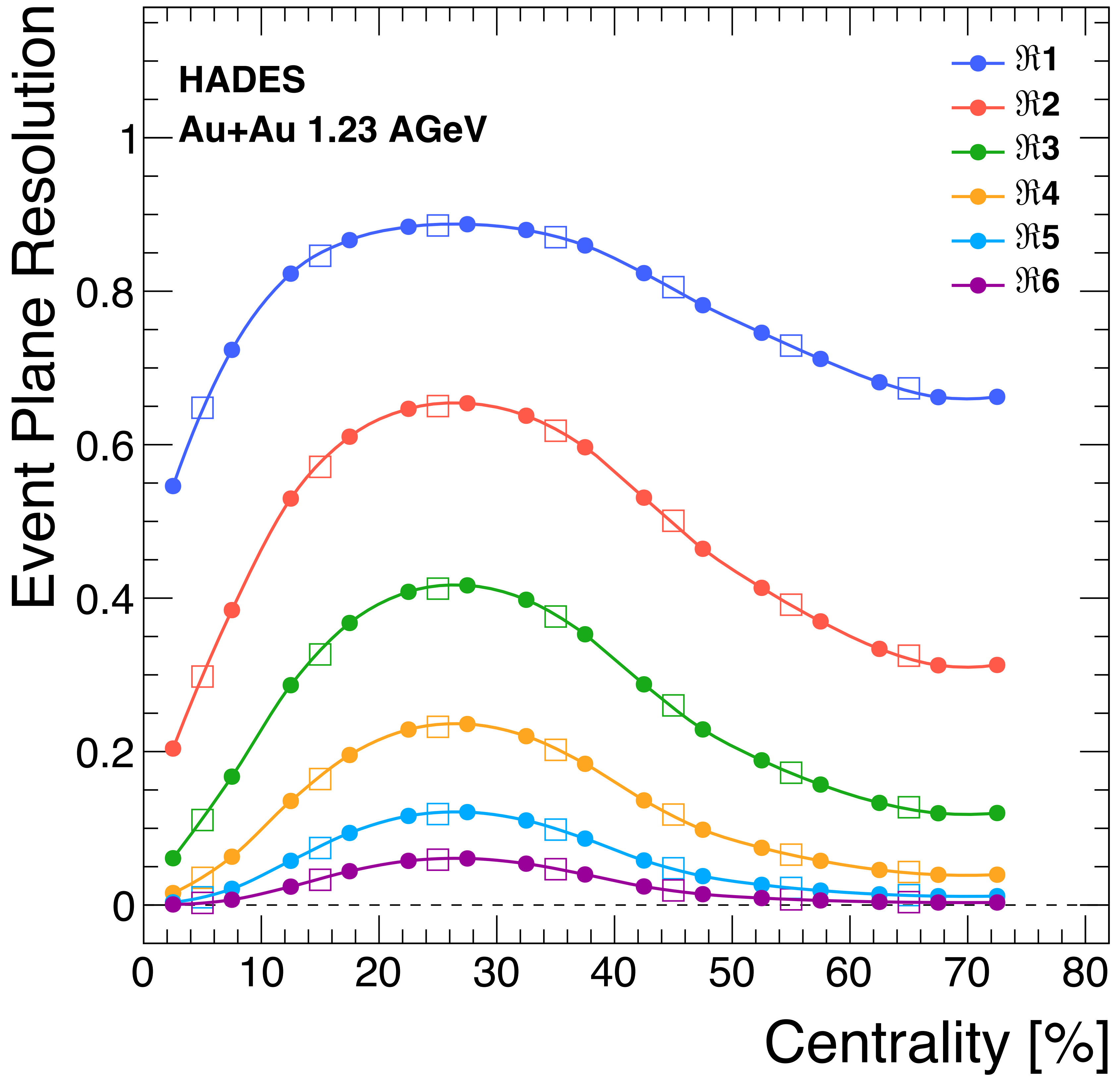
EP-resolution via sub-event method with three implementations

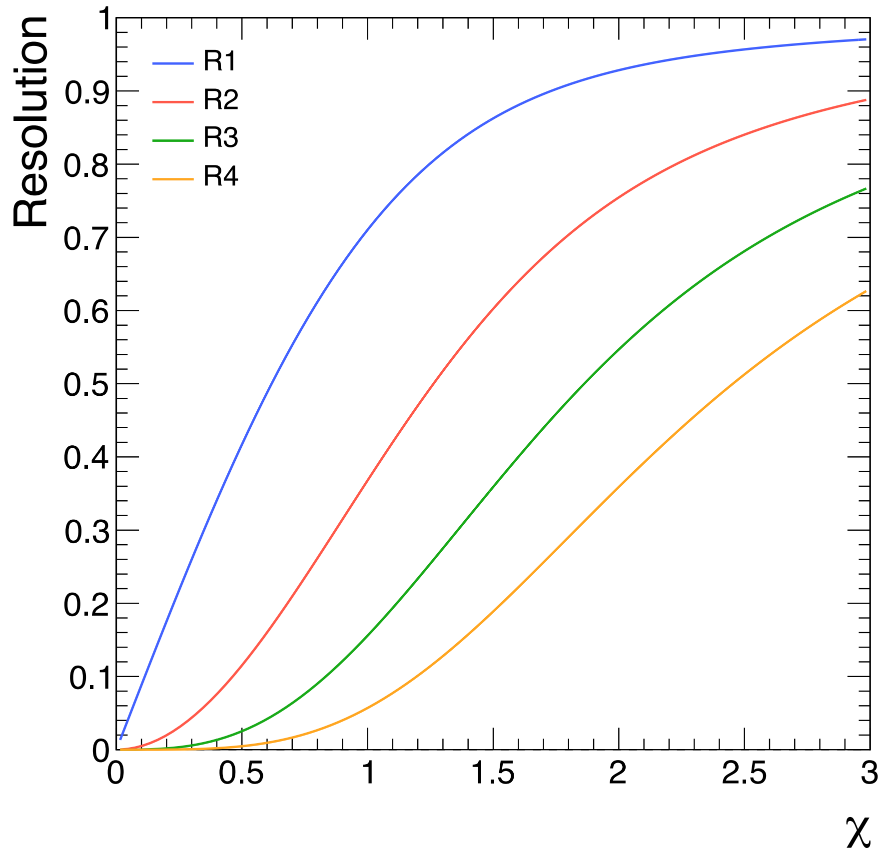
Determination of resolution parameter χ
- directly via <cos (ΔΦ)>
- Approximation via Fraction of Events with ΔΦ > π/2
- Fit-Method

Calculation of EP-Resolution of different order









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

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

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

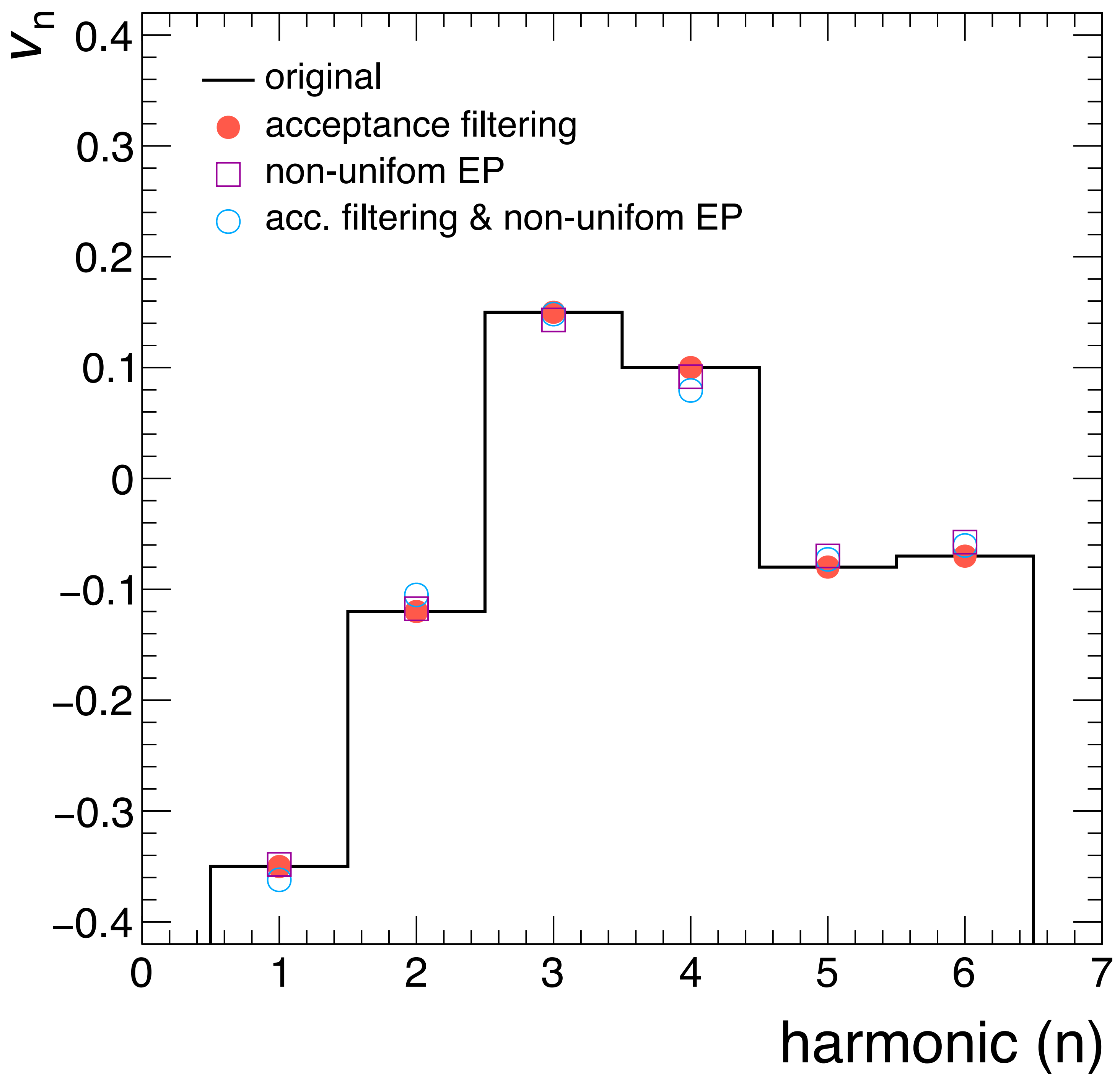
Consistency checks:

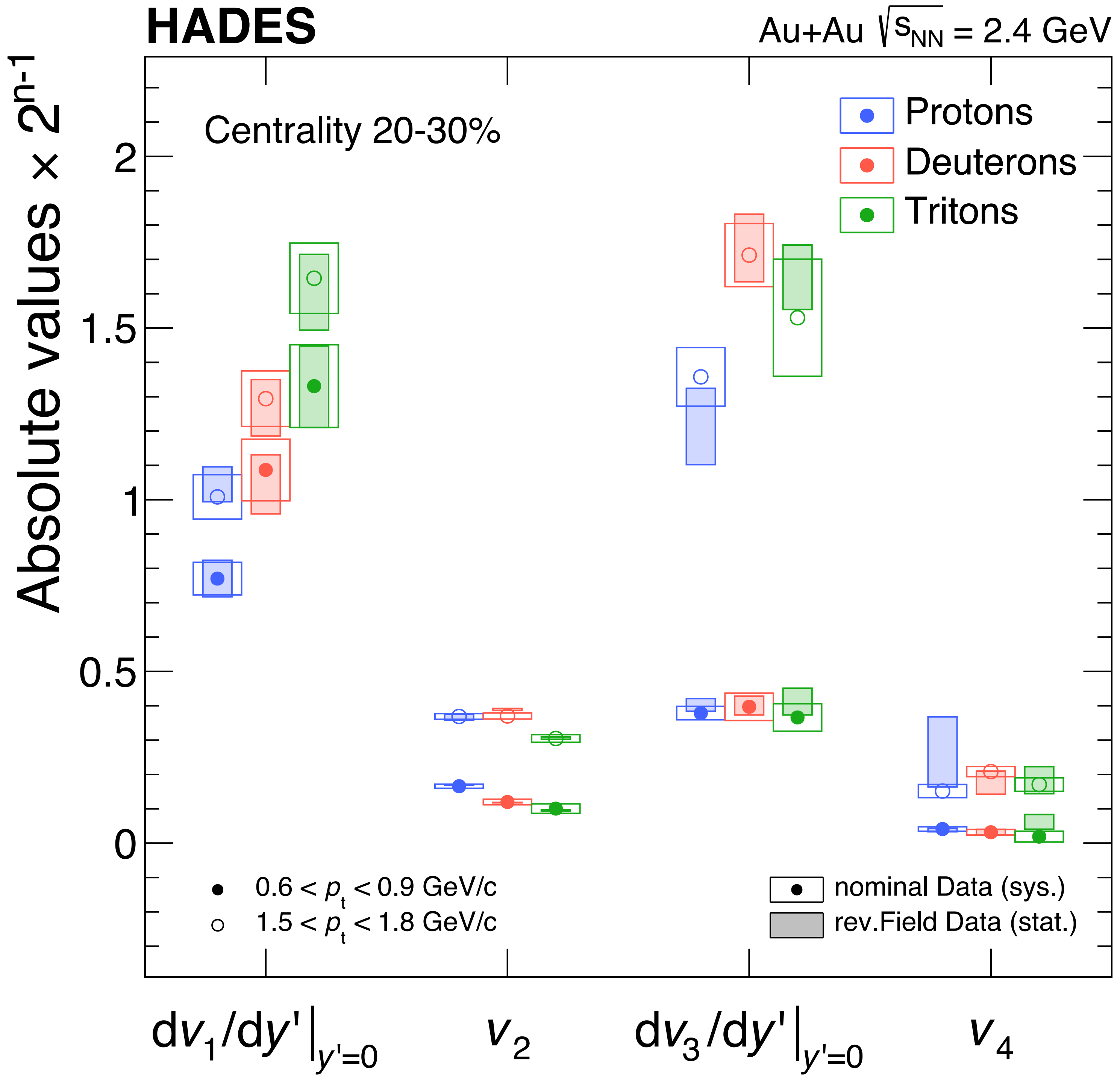
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at y_{cm}=0
- Vanishing residual sine-terms
- Time-dependent systematic effects

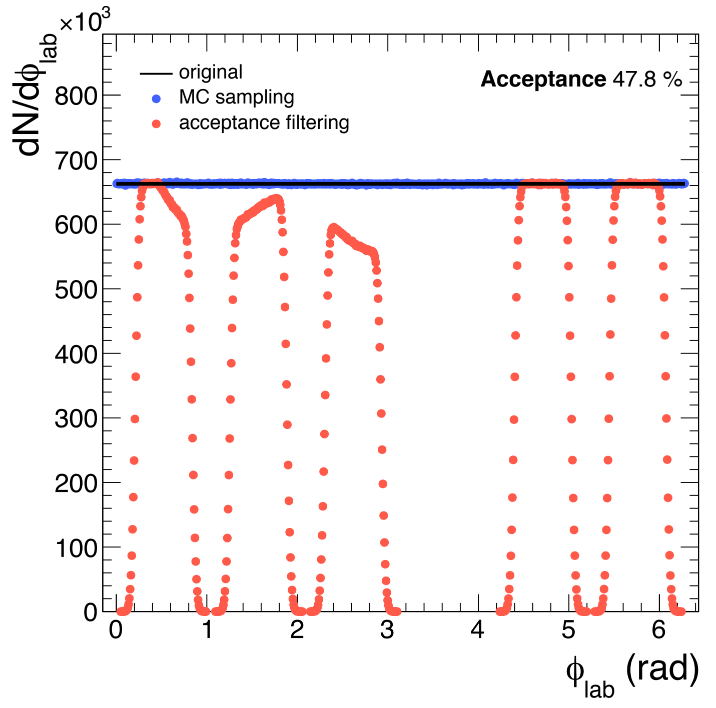
Reversed field polarity

Comparison with flow coefficients from the full data set

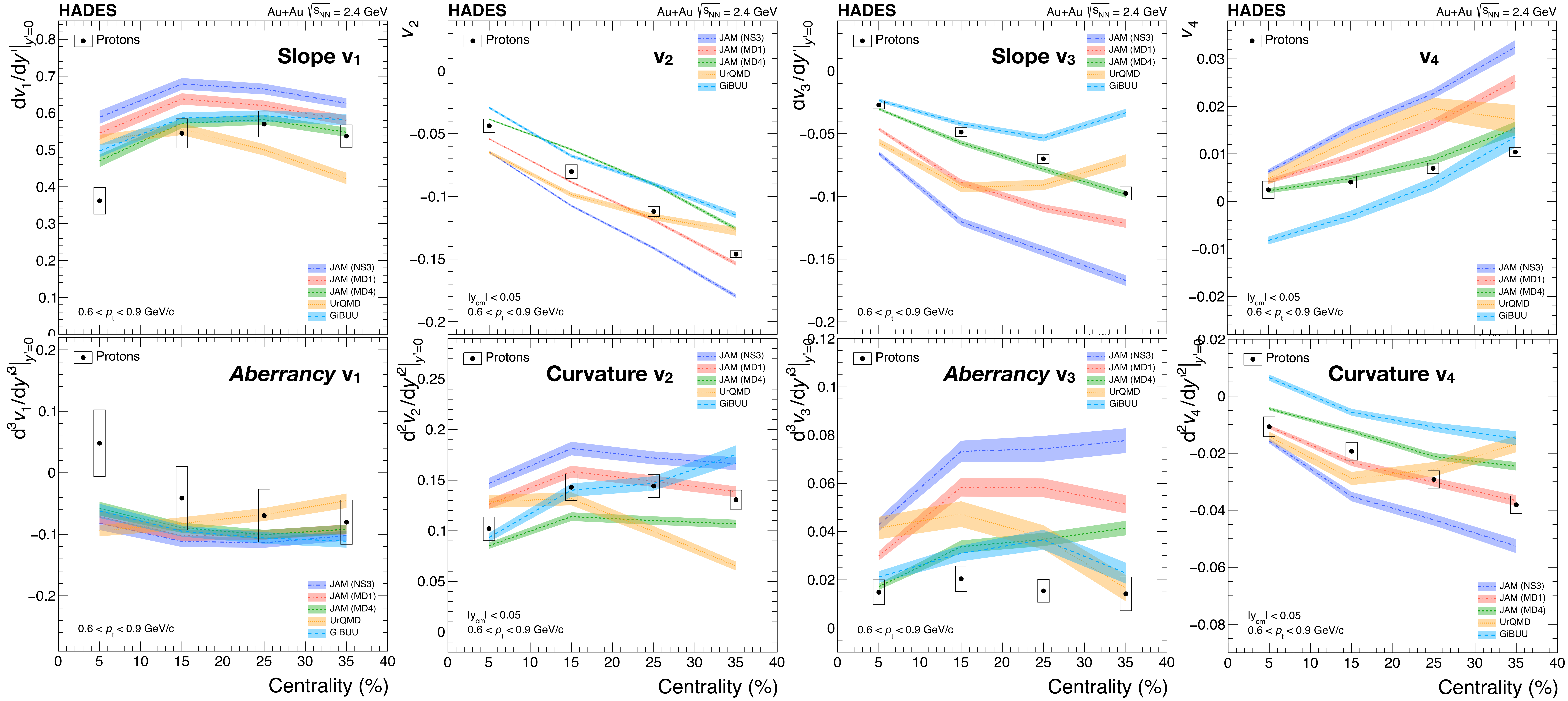
HADES, arXiv:2208.02740







Model Comparisons to Proton Data



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

“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

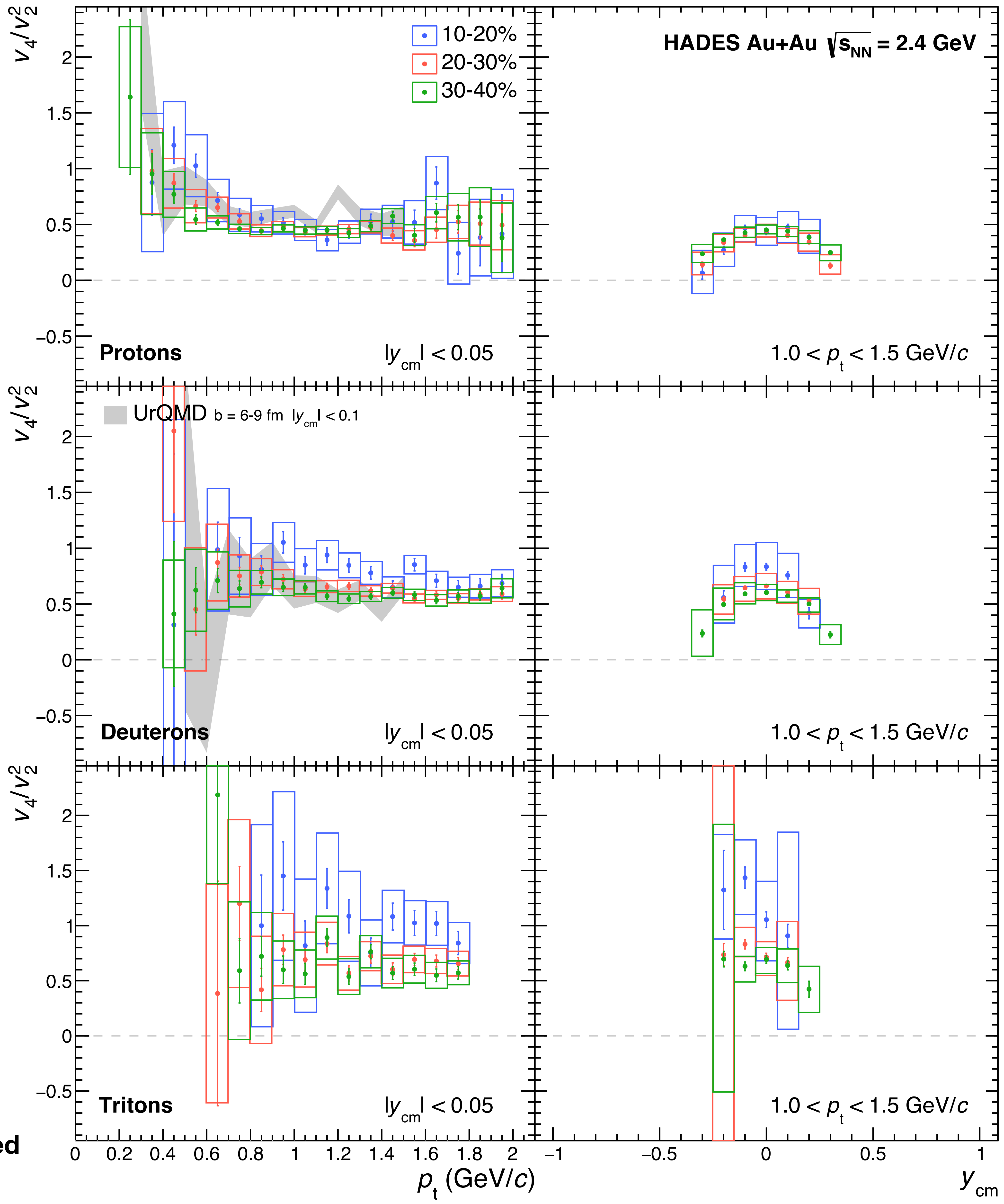
Independent of p_t and centrality
Close to predicted value of ~ 0.6

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)

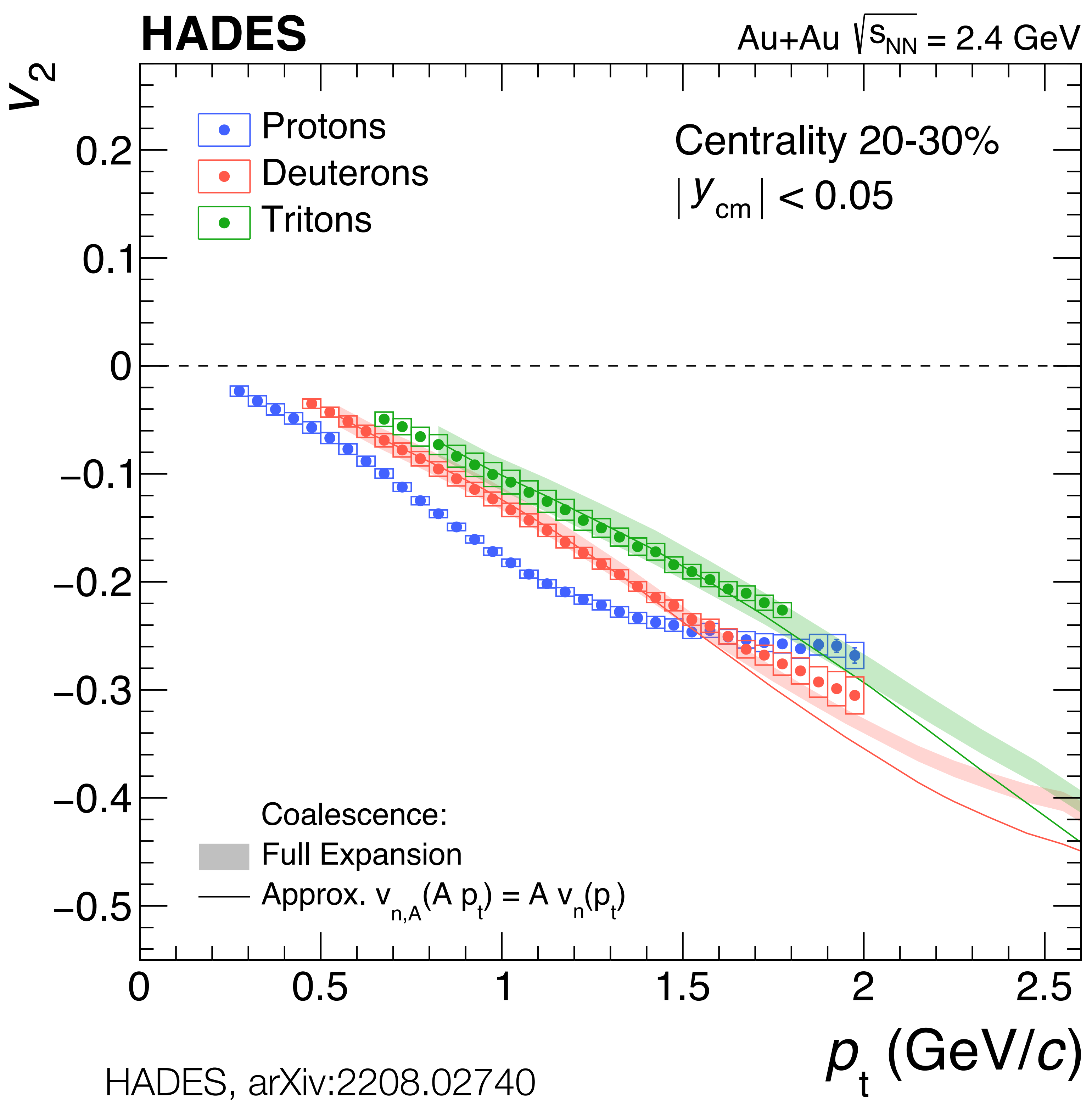
Works as expected in simple coalescence picture for the dominant flow coefficient

Odd flow coefficients vanish at mid-rapidity and v_4 contribution is negligible

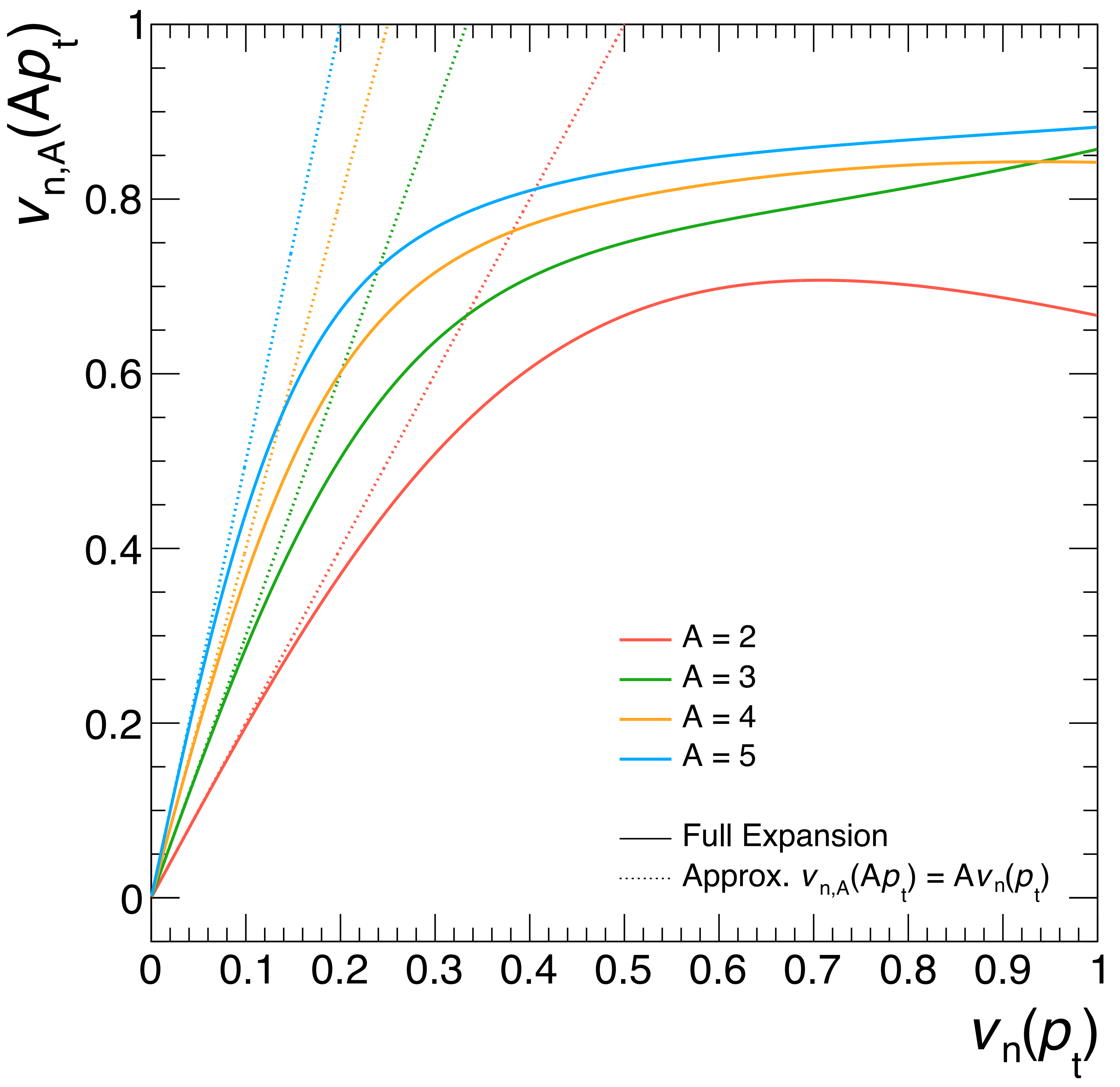
Approximation for small v_n

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

Scaling also for v4 observed



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

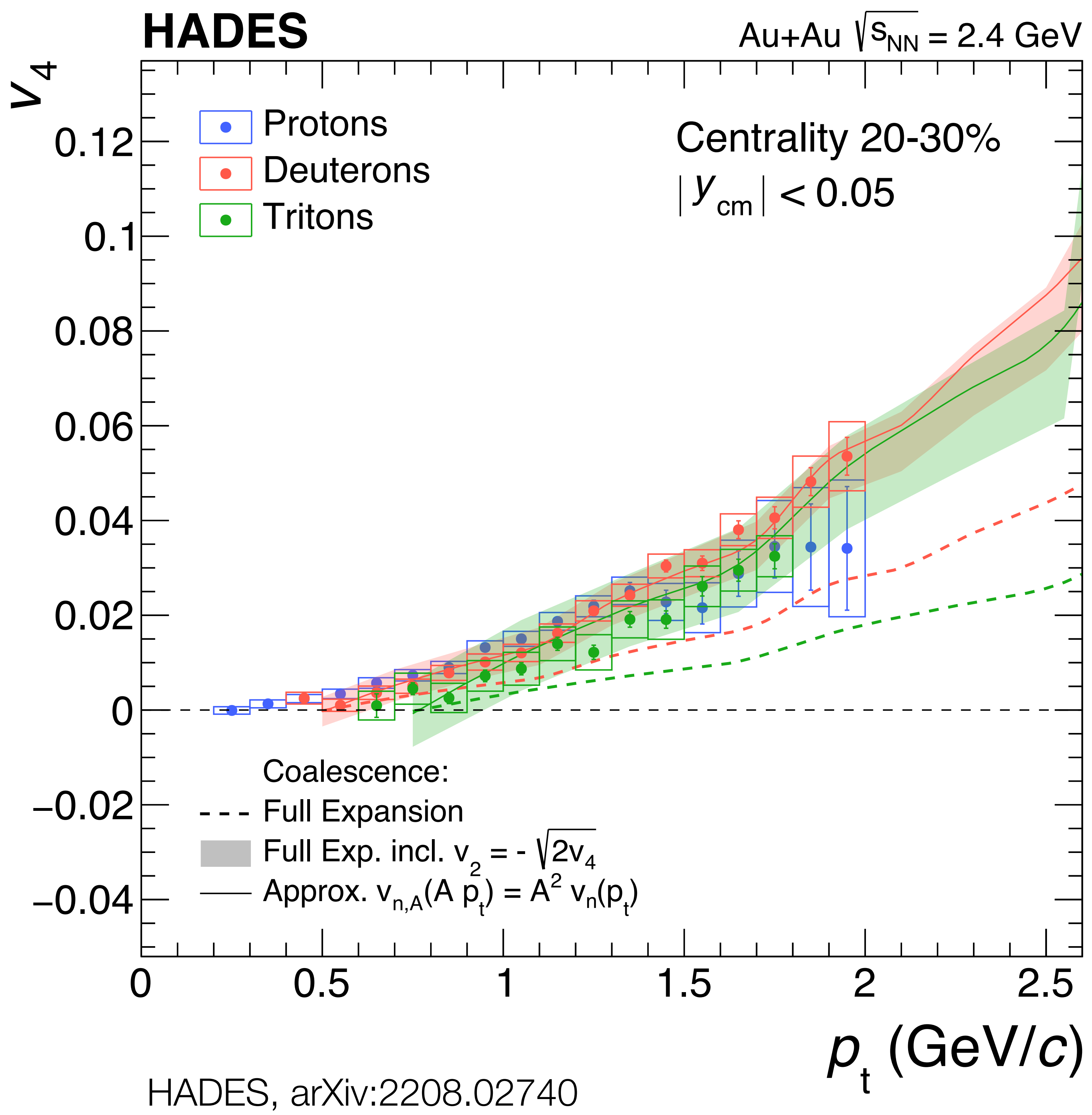
Scaling Properties of v_4 at Mid-Rapidity

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

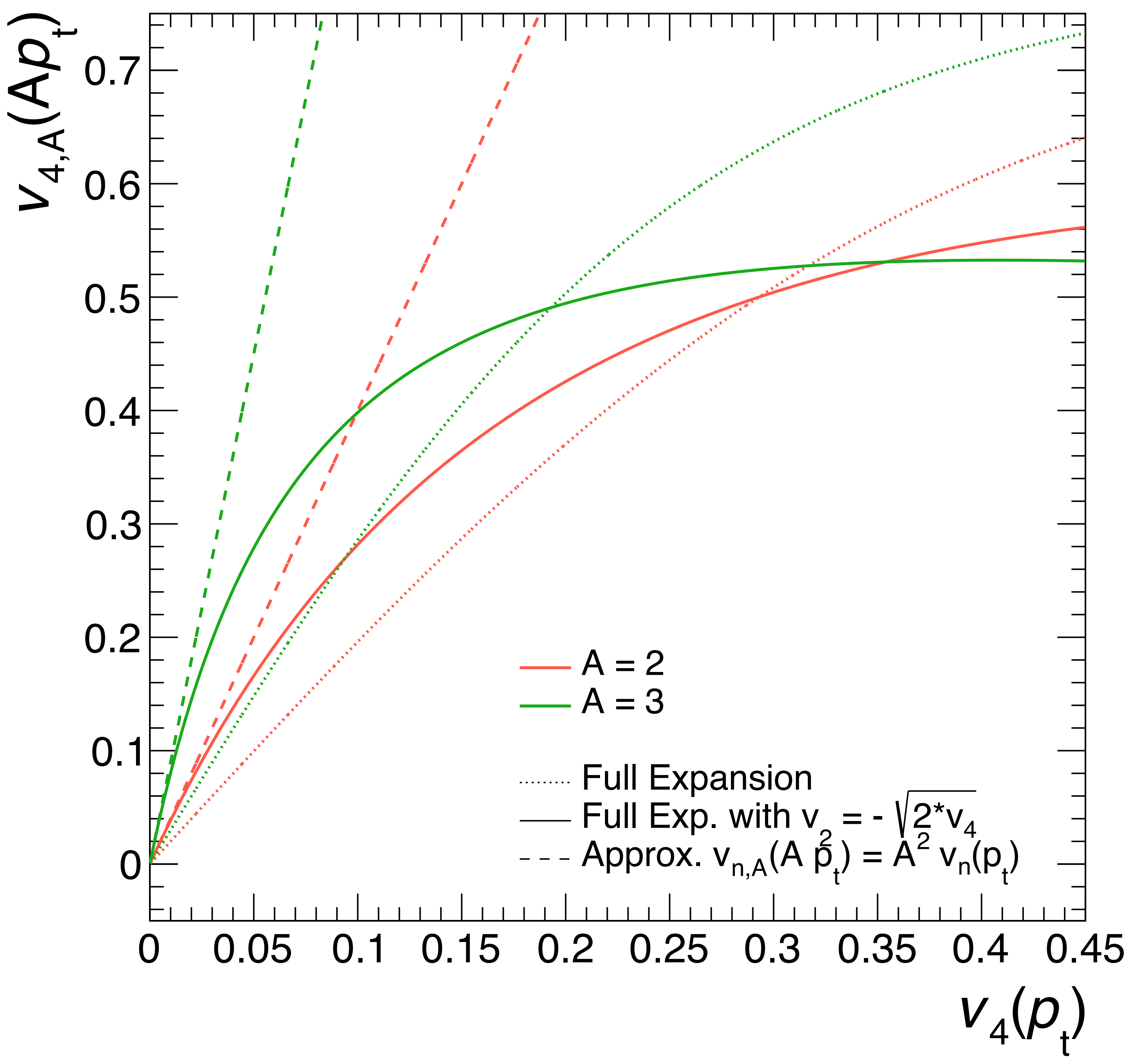
Works as expected in simple coalescence picture if contribution of dominant flow coefficient is included

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



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

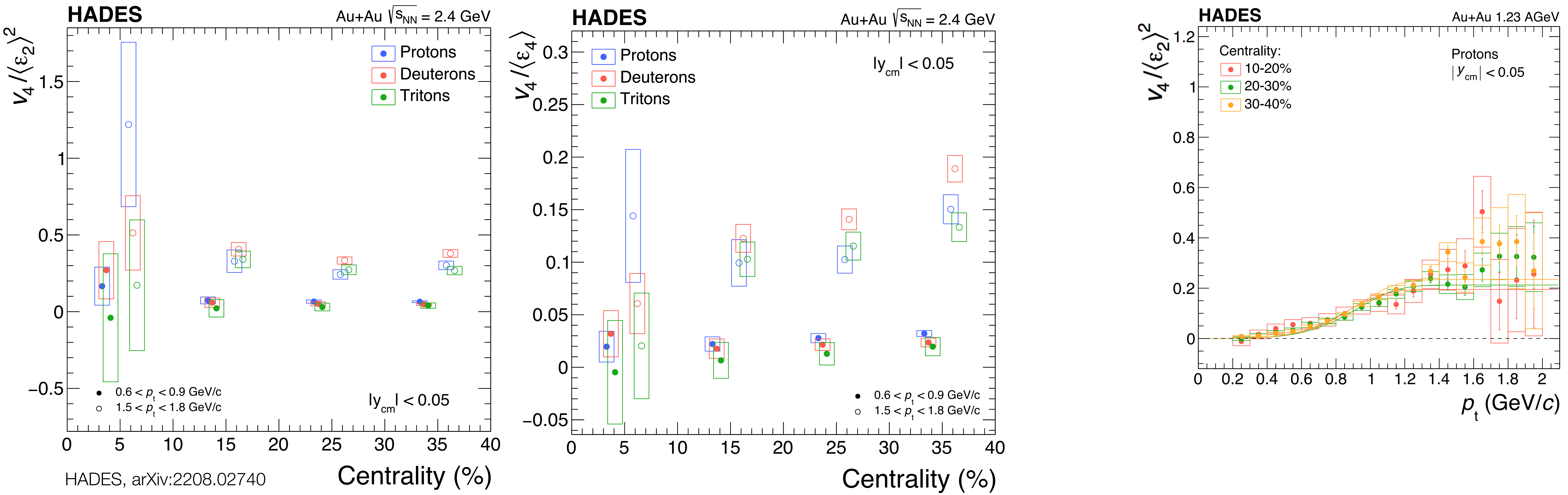
$$v_{4,A=3}(A\,p_t) = 9\,v_4(p_t)\,\frac{1}{1+12\,v_4(p_t)+6\,v_4^2(p_t)}$$

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

Quadrangular Flow v_4



Scaling with initial eccentricities

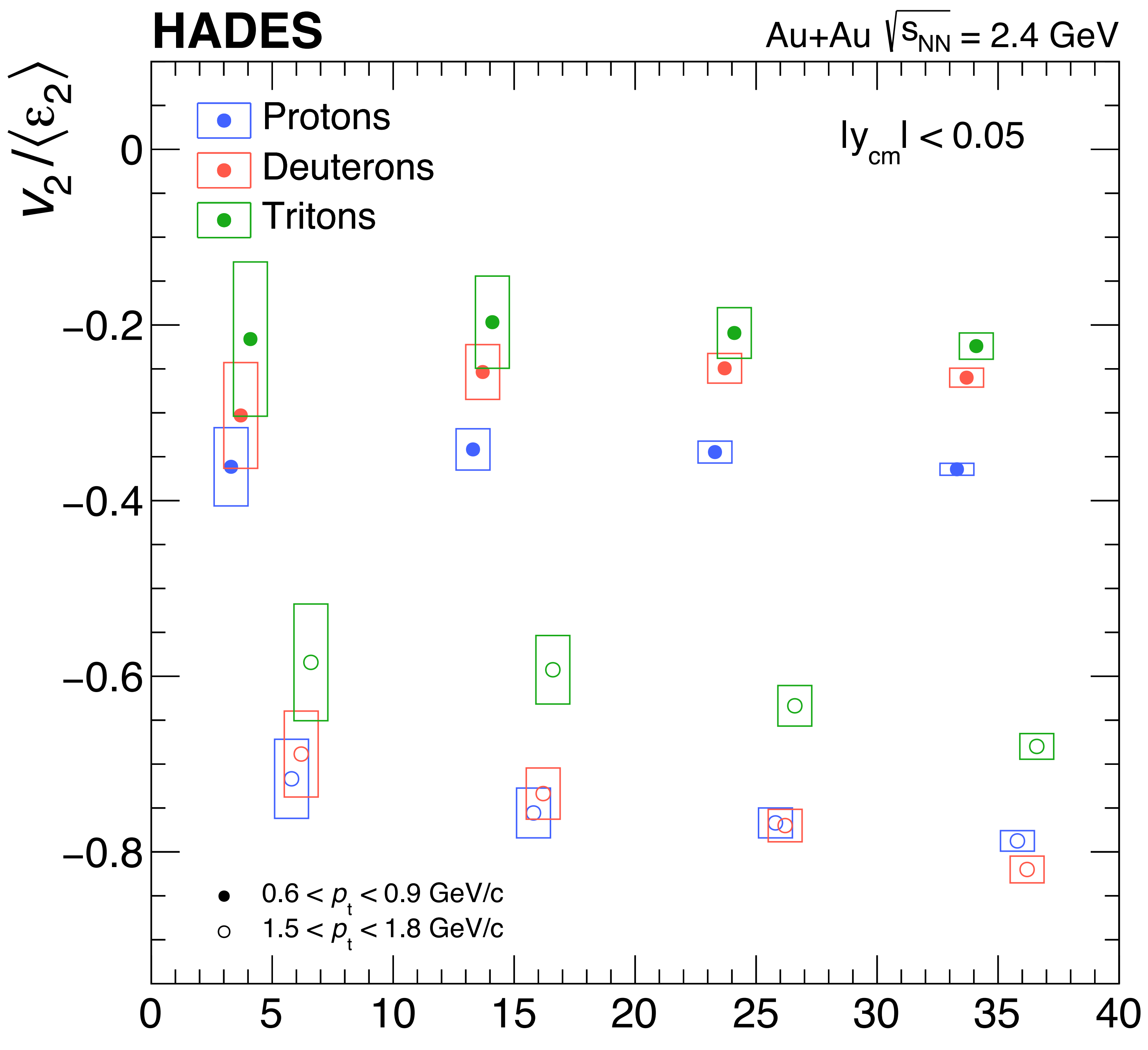
Calculated for overlap zone with Glauber MC

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

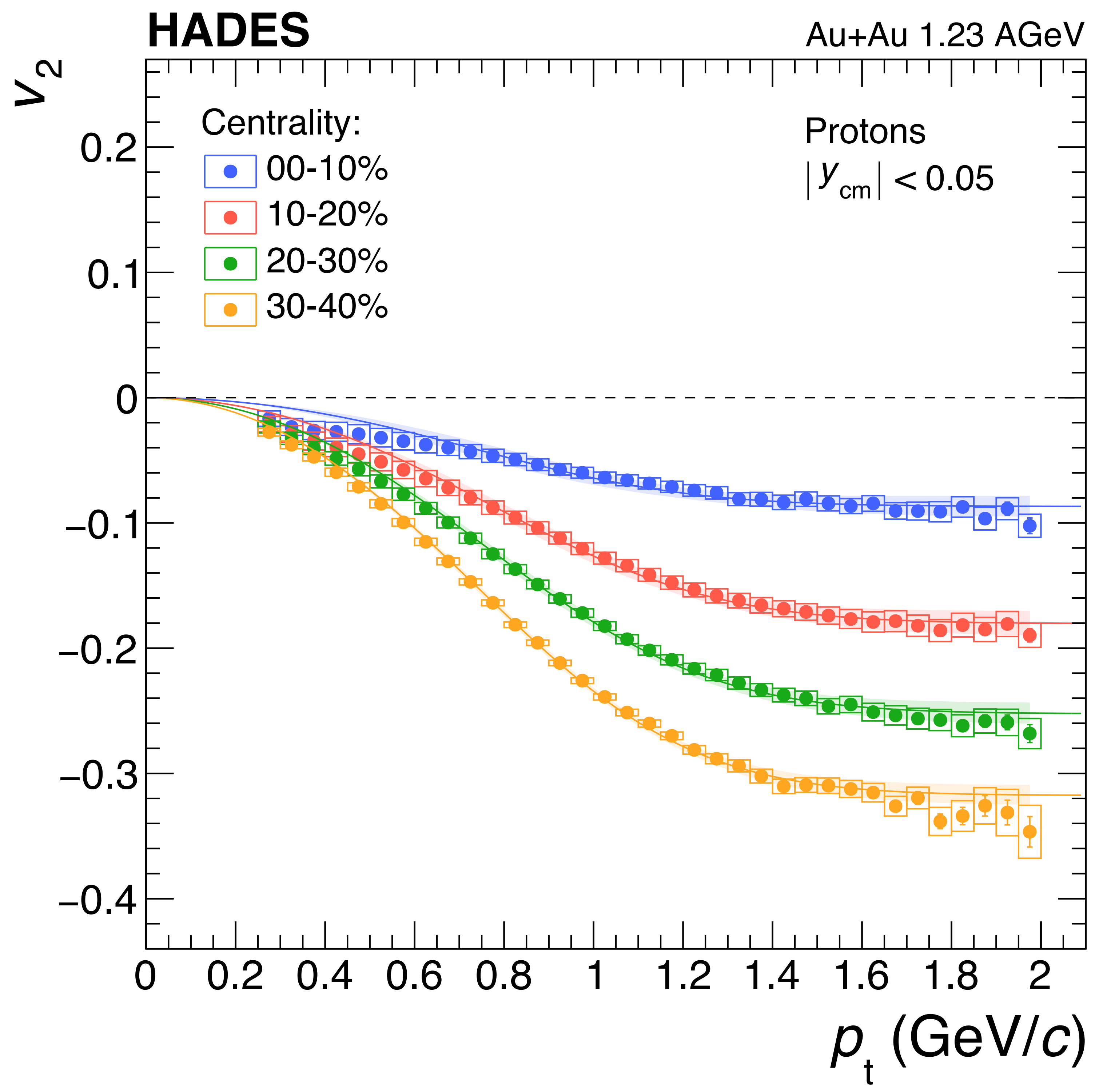
$\Longrightarrow$ Fixed relation between v_2 and v_4 (different to high energies)

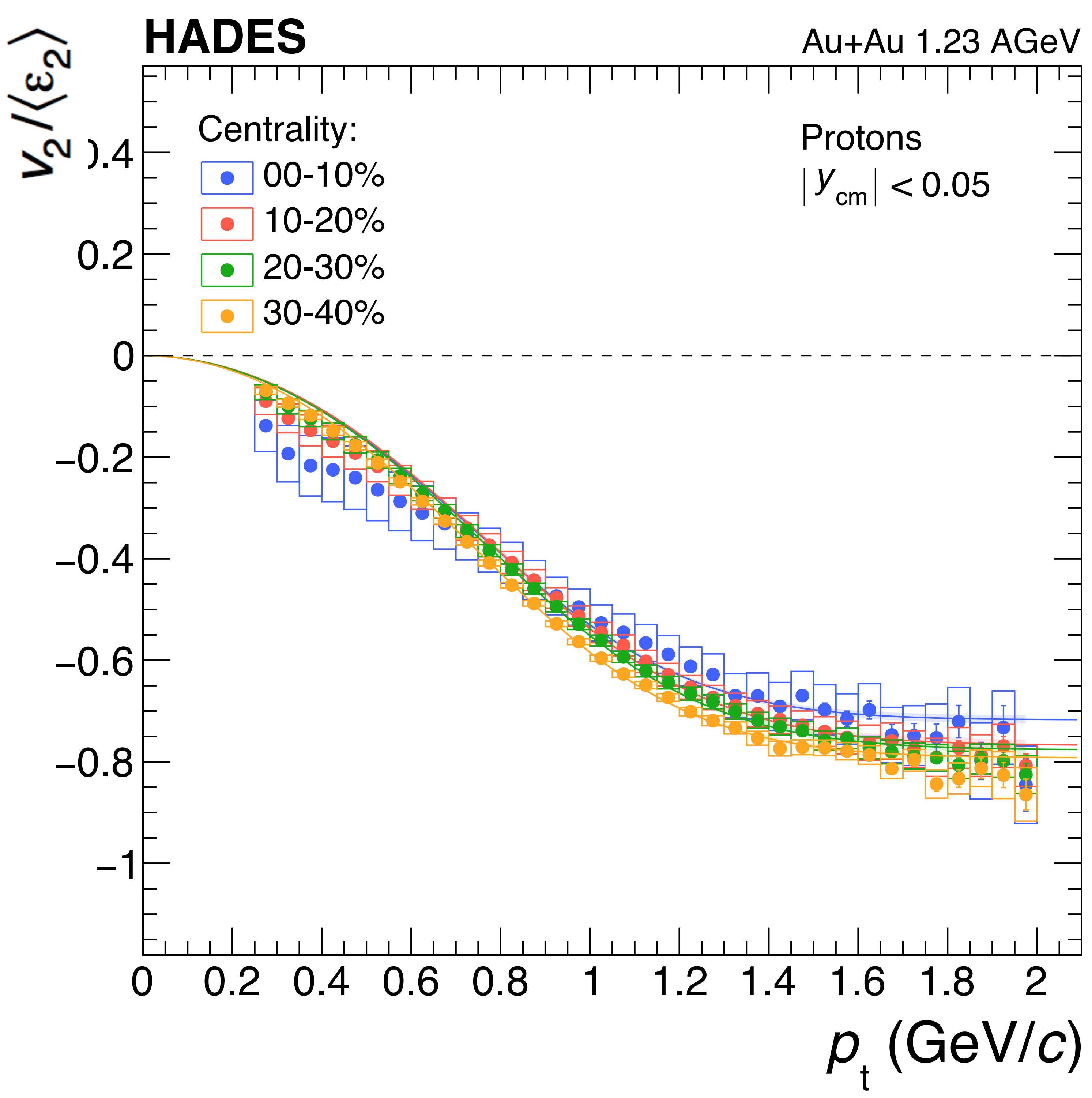
Geometry Scaling

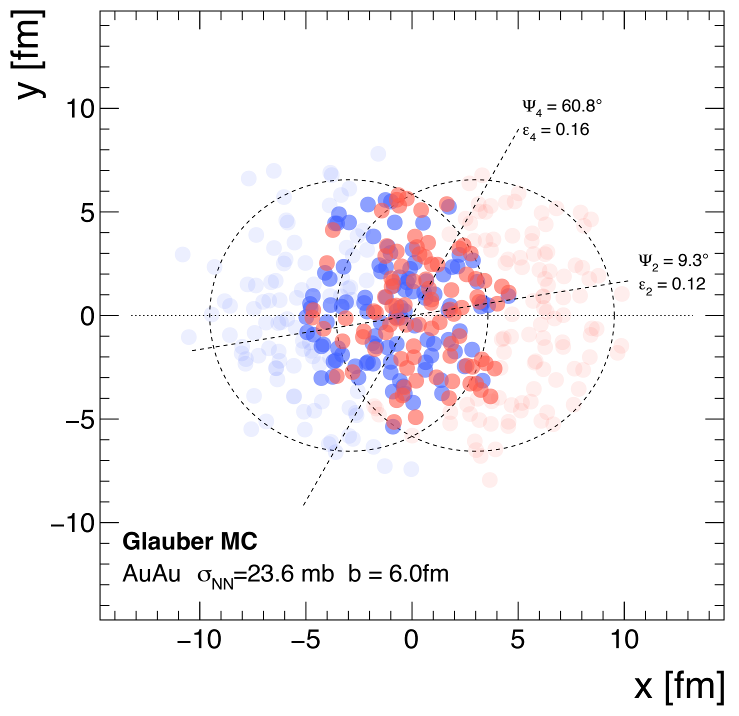
Elliptic Flow v_2



HADES, arXiv:2208.02740







Scaling with initial eccentricities

Calculated for overlap zone with Glauber MC

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

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

Orientation of symmetry-planes

Negative $v_2/\langle\varepsilon_2\rangle$ values $\Longrightarrow$ v_2 Event- and ε_2 Eccentricity-plane are perpendicular

Similar scaling for v4 with $\langle\varepsilon 2\rangle^2$