Flow phenomena at high nuclear densities with HADES

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for the
HADES Collaboration

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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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HADES

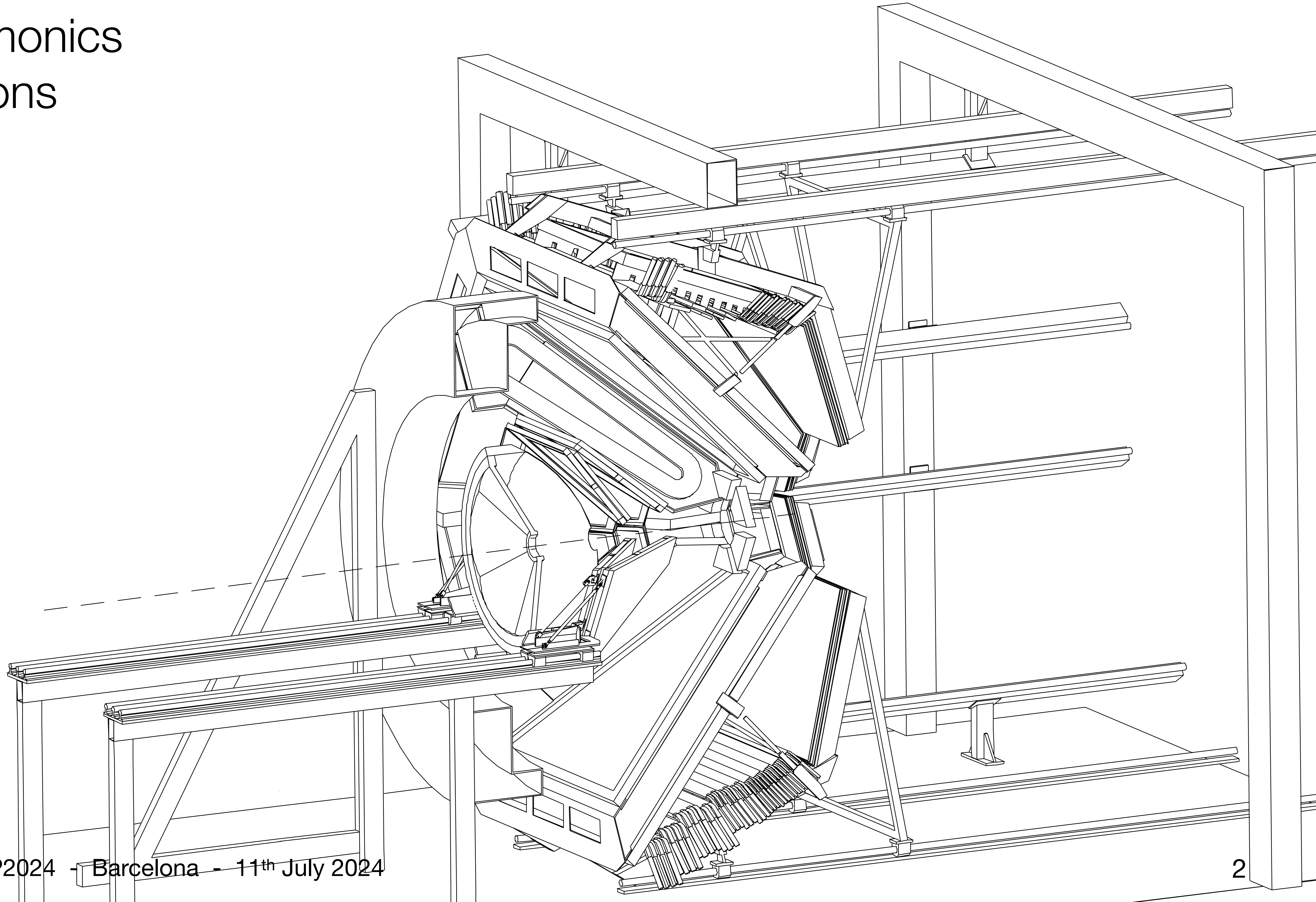
Outline

- Dense nuclear matter and collective phenomena
- HADES and experimental data Au+Au 1.23 *A*GeV
- Directed v_1, elliptic v_2, and higher flow harmonics (v_3, v_4, v_5, v_6) of protons, deuterons and tritons
- Parameterisation and scaling properties
- Model comparisons

Talk based on following publication:

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

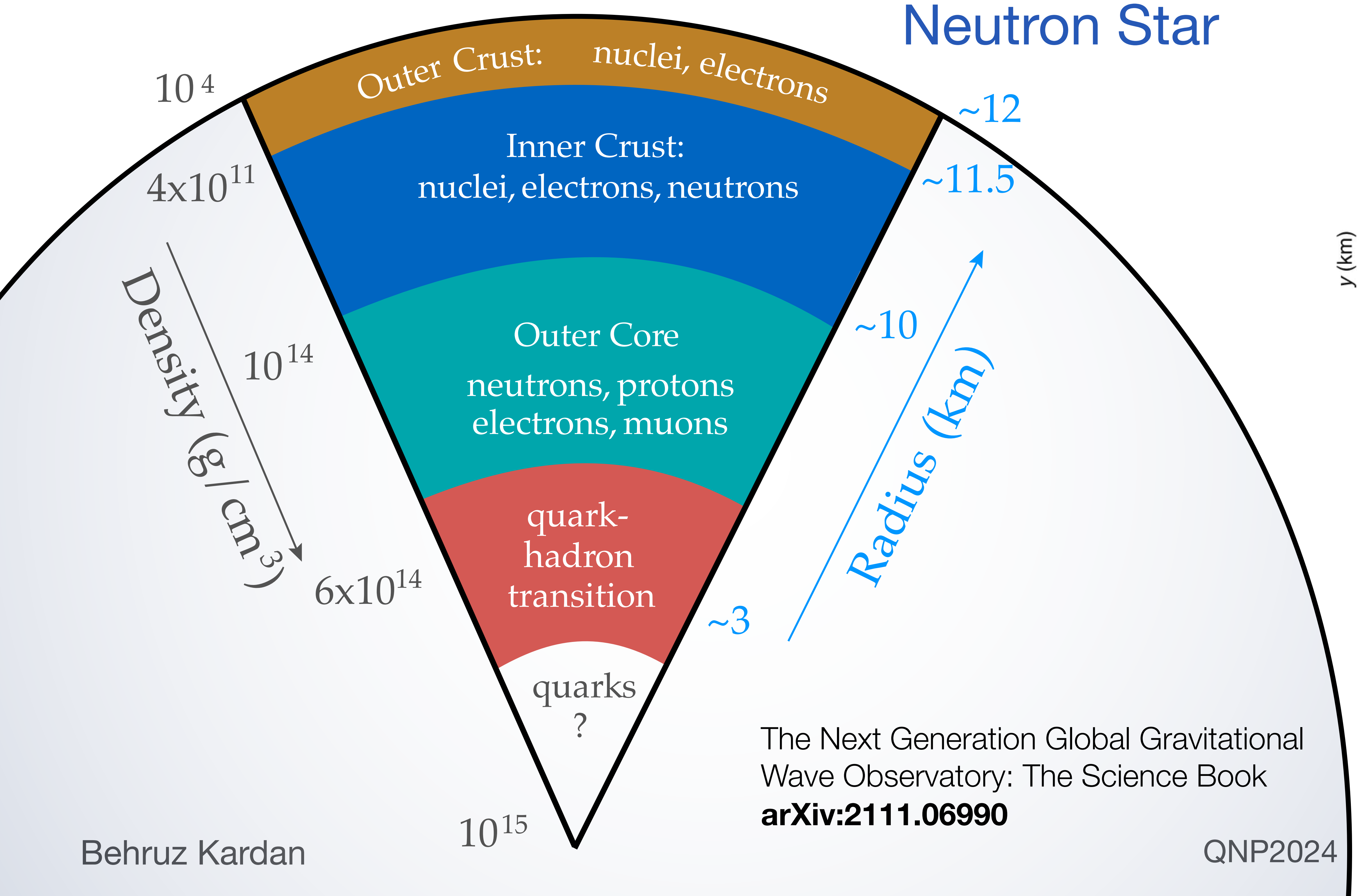
HADES, EPJA 59 (2023) 80 arXiv:2208.02740 [hepdata]



Dense nuclear matter and astrophysics

- Properties of neutron star and its Equation-Of-State (EOS)
- Similar conditions in heavy-ion collisions at SIS18 energies than in merging neutron stars

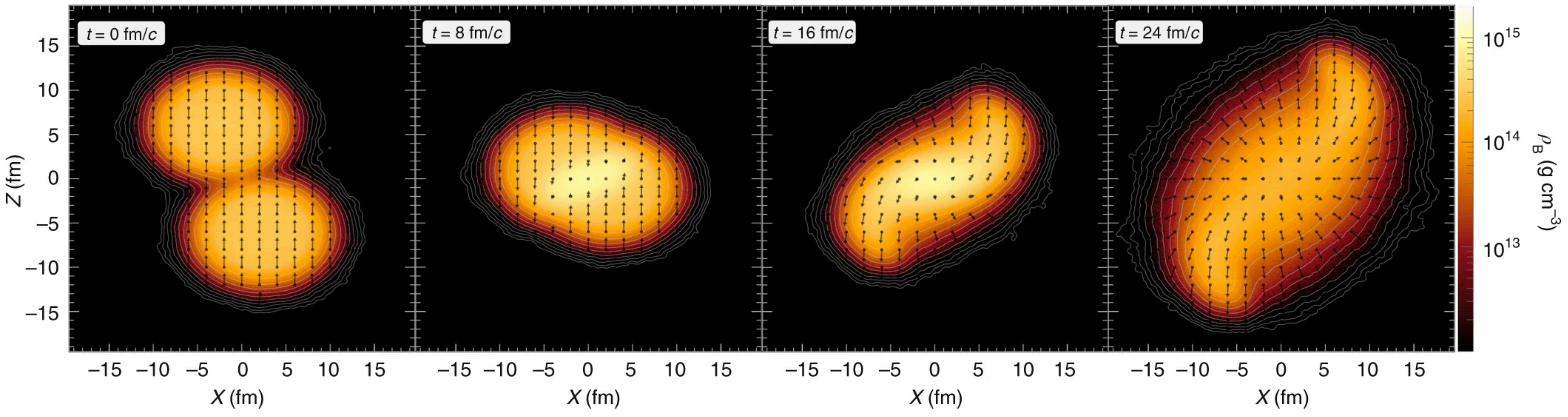
Neutron Star



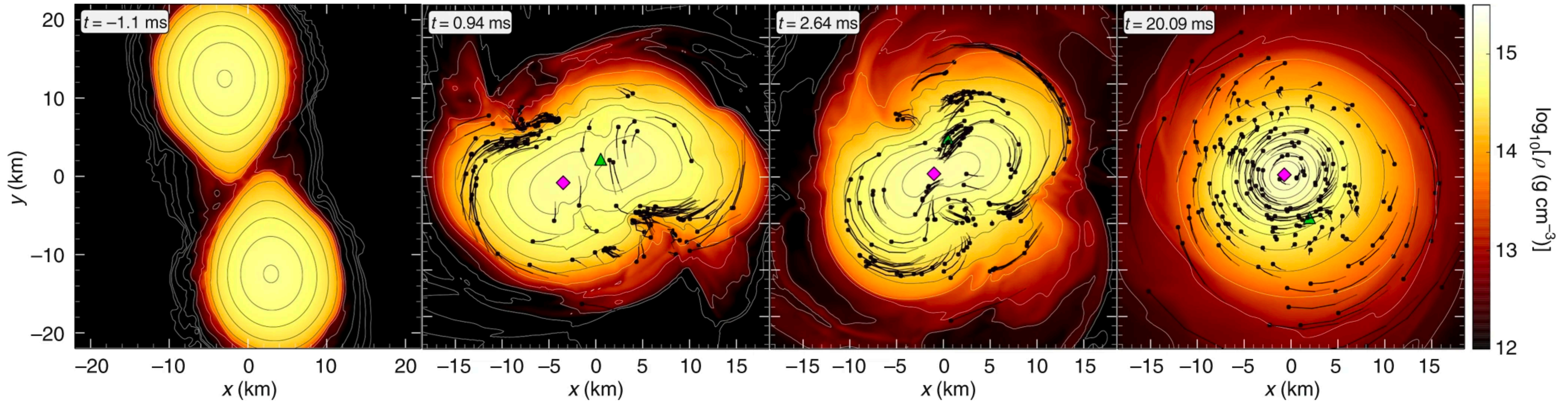
The Next Generation Global Gravitational Wave Observatory: The Science Book **arXiv:2111.06990**

Heavy-ion Collision

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



Neutron Star Merger



⇒ Heavy-ion collisions can provide access to equation-of-state of neutron star matter

The HADES experiment

Fixed-target experiment at SIS18(GSI, Germany)

Large acceptance in 6 identical sectors

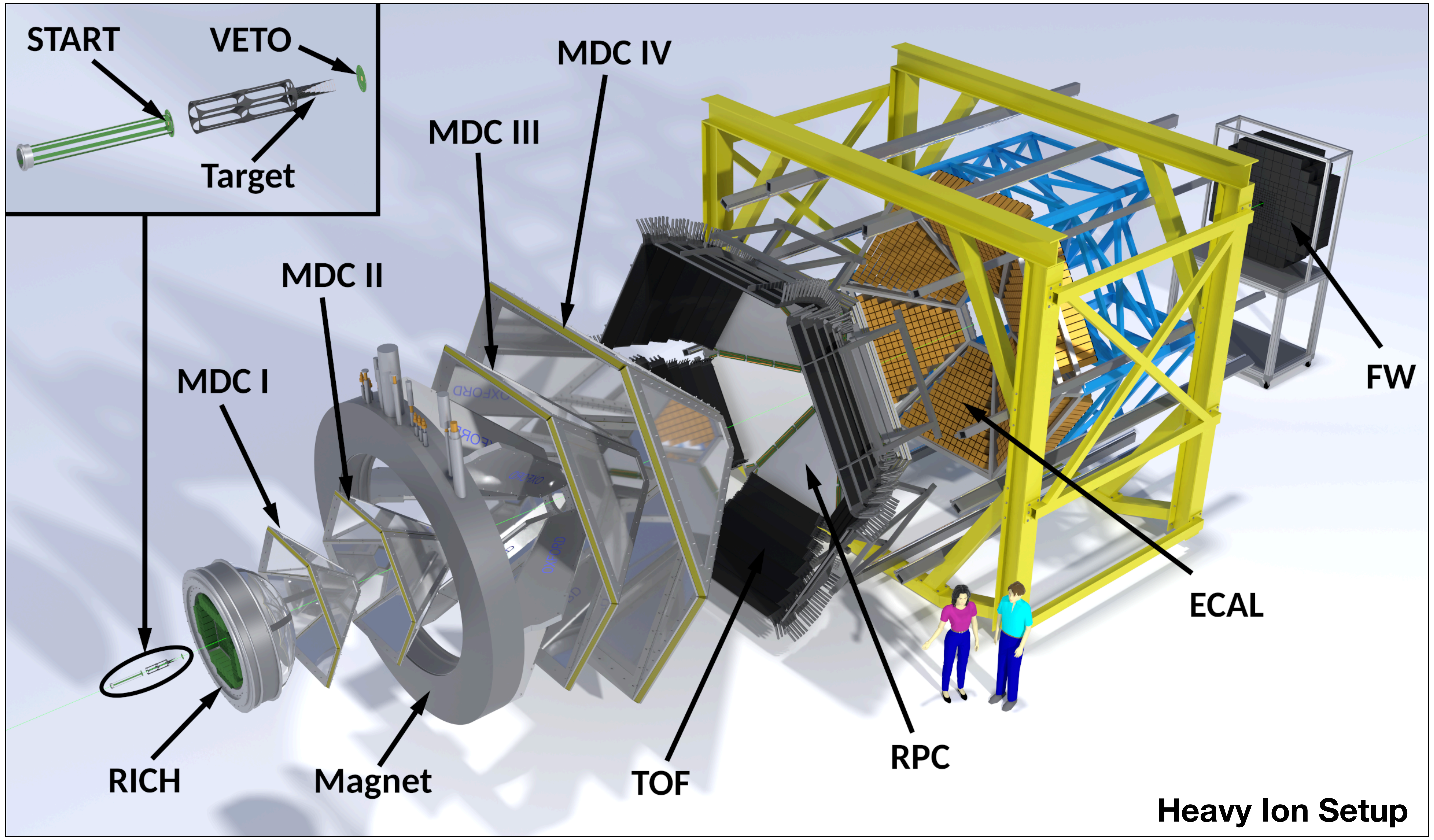
- Symmetric azimuthal coverage
- Superconducting toroidal magnets
- Low-mass Drift Chambers (MDC)

Particle identification

- Time-of-Flight walls (TOF and RPC)
- Energy loss (MDC and TOF)
- e^+/e^- and photon identification (RICH and ECAL)

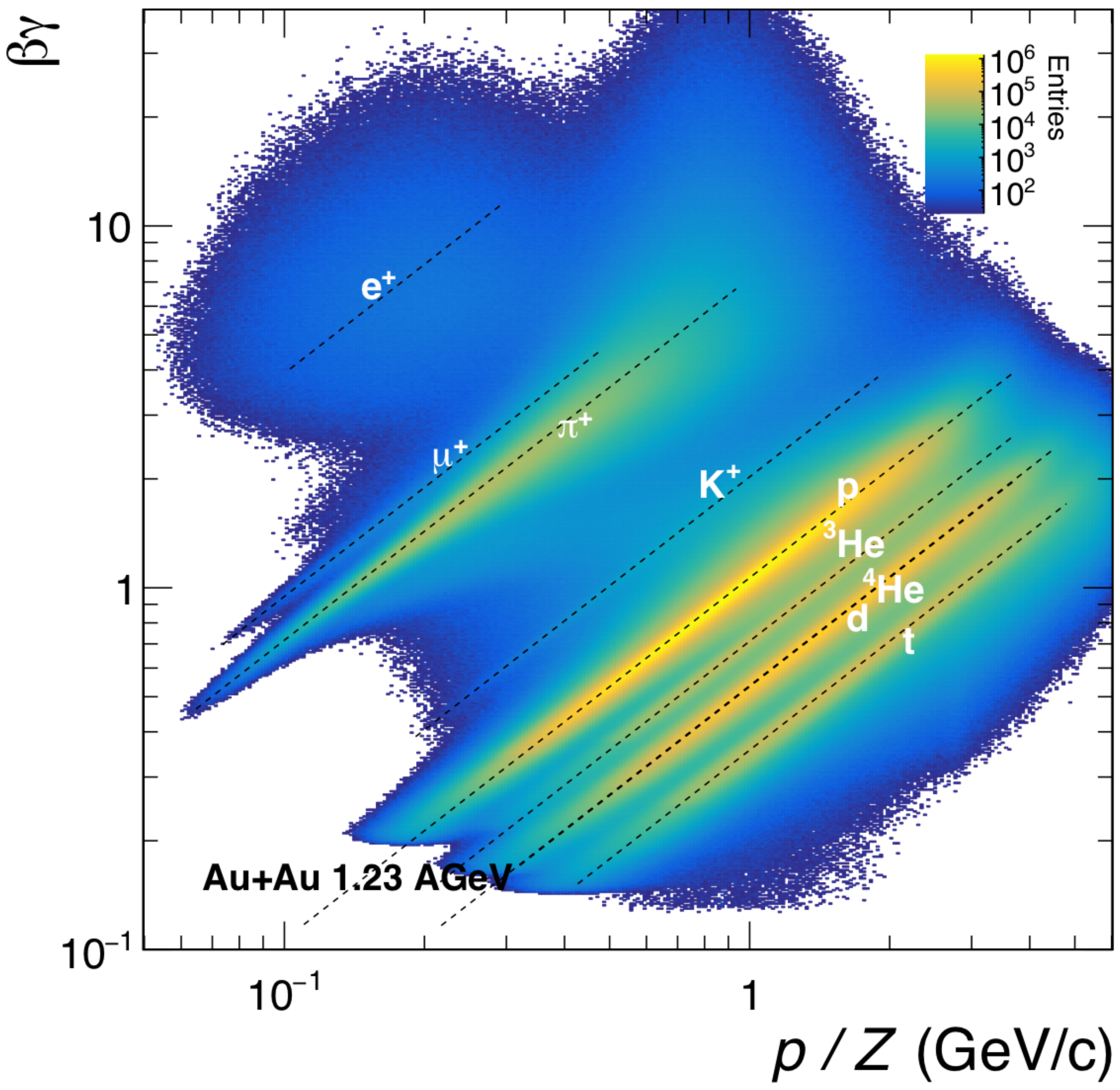
Forward Wall

- Reaction plane reconstruction

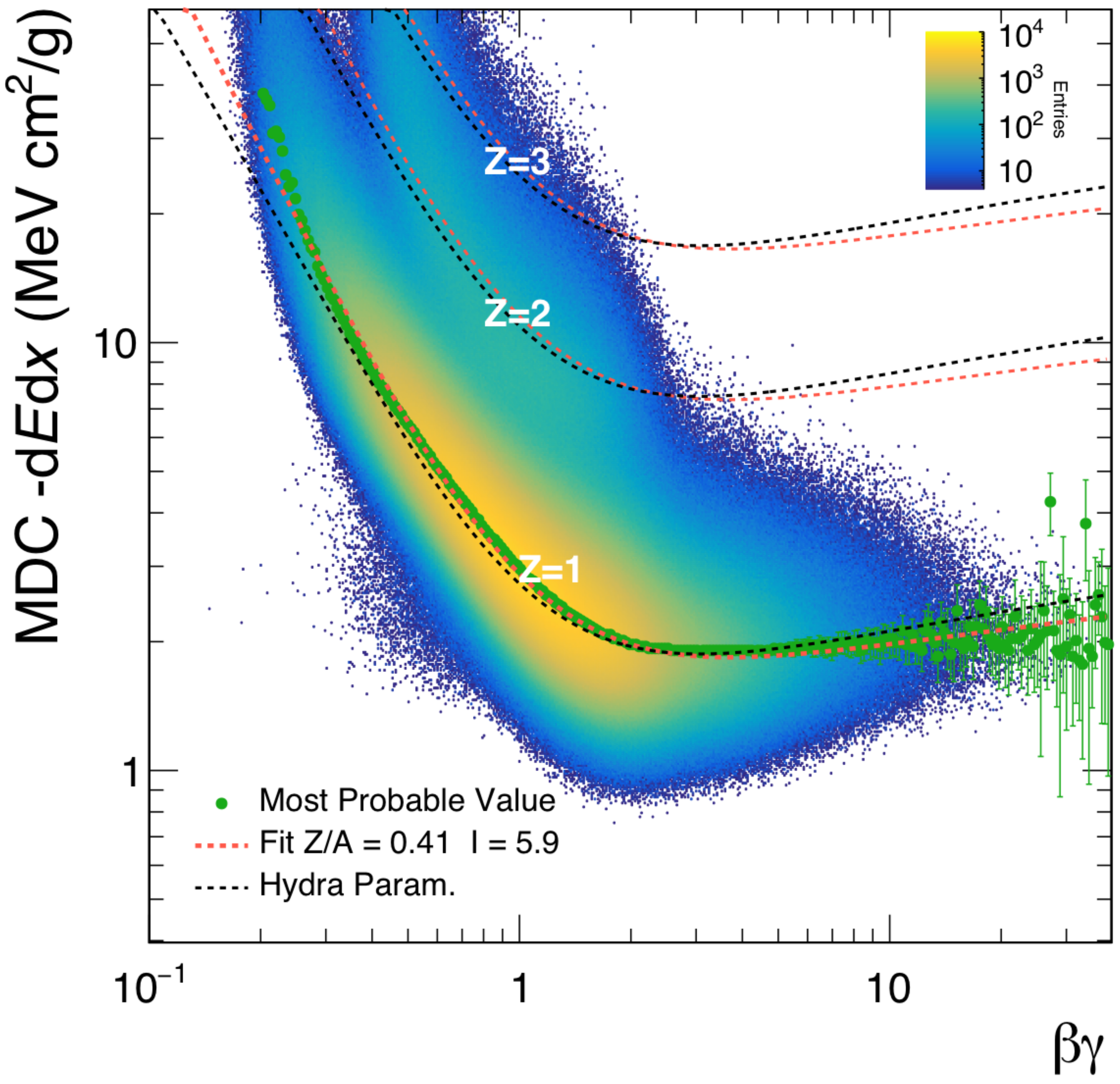


Particle Identification

Time-of-Flight (TOF and RPC) $\beta\gamma\, m/Z = p/Z$



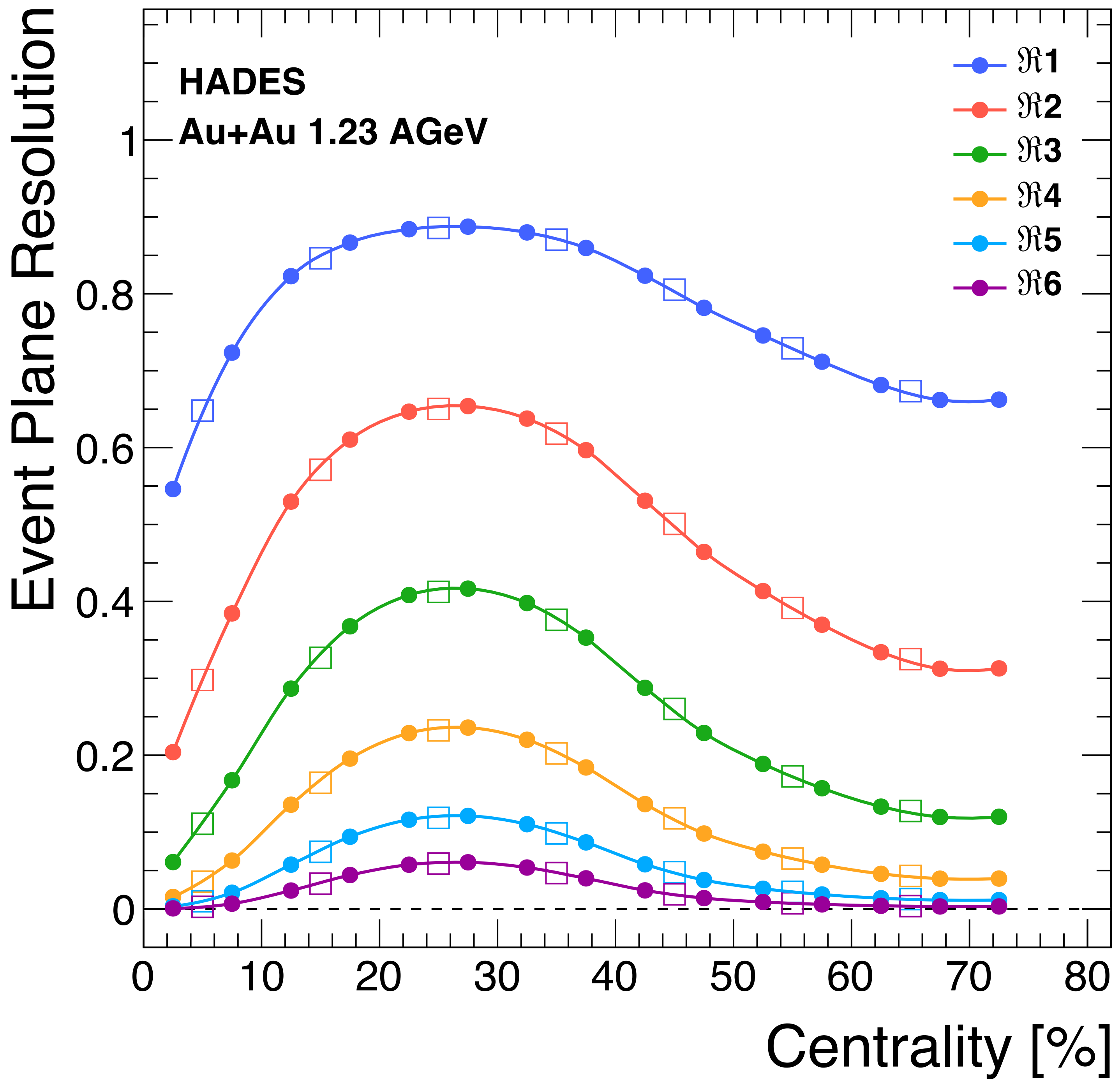
Energy loss in the MDC $-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \propto f(Z,\beta)$

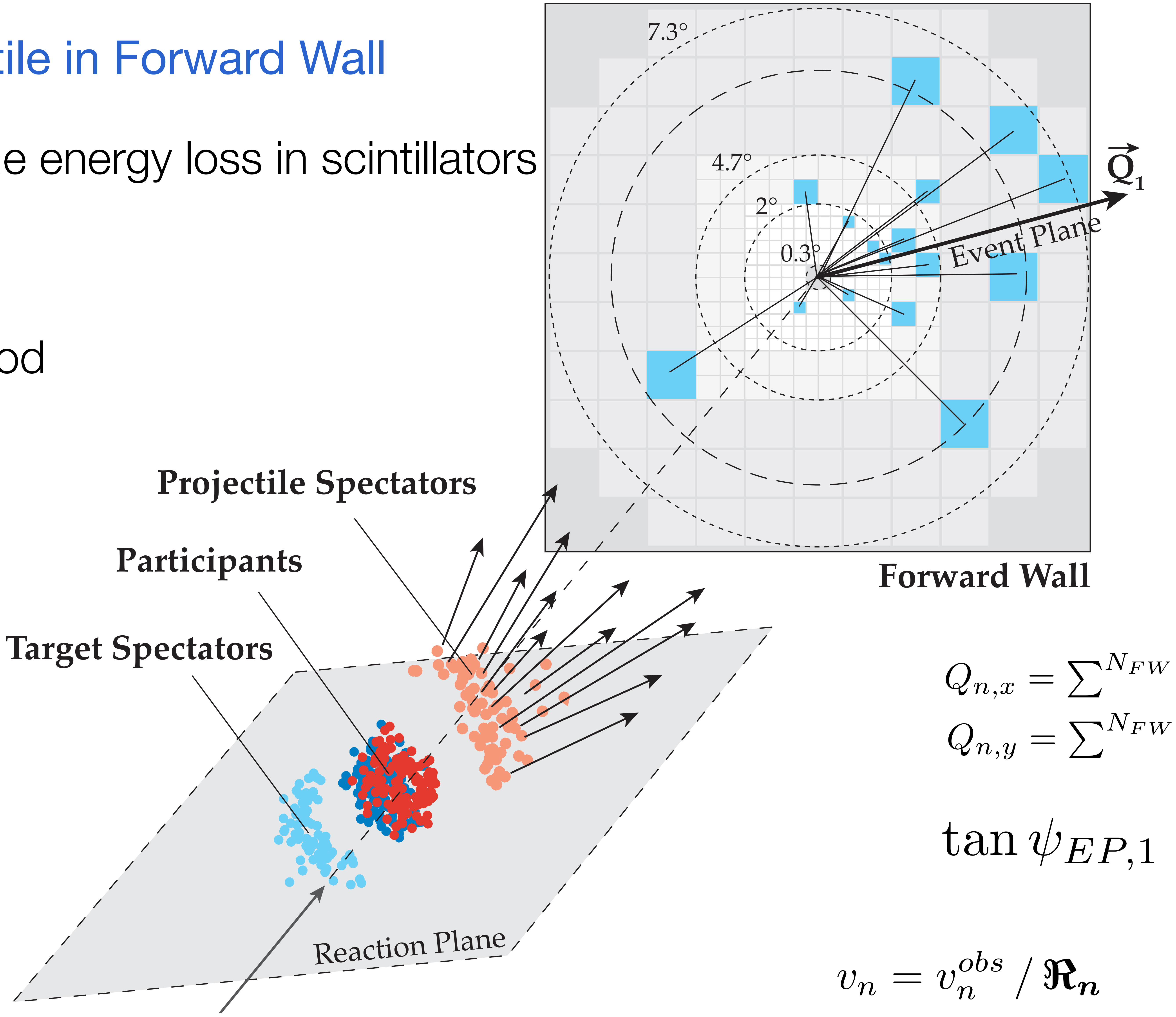


Event Plane Reconstruction

1st-order event plane from projectile in Forward Wall

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





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

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

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

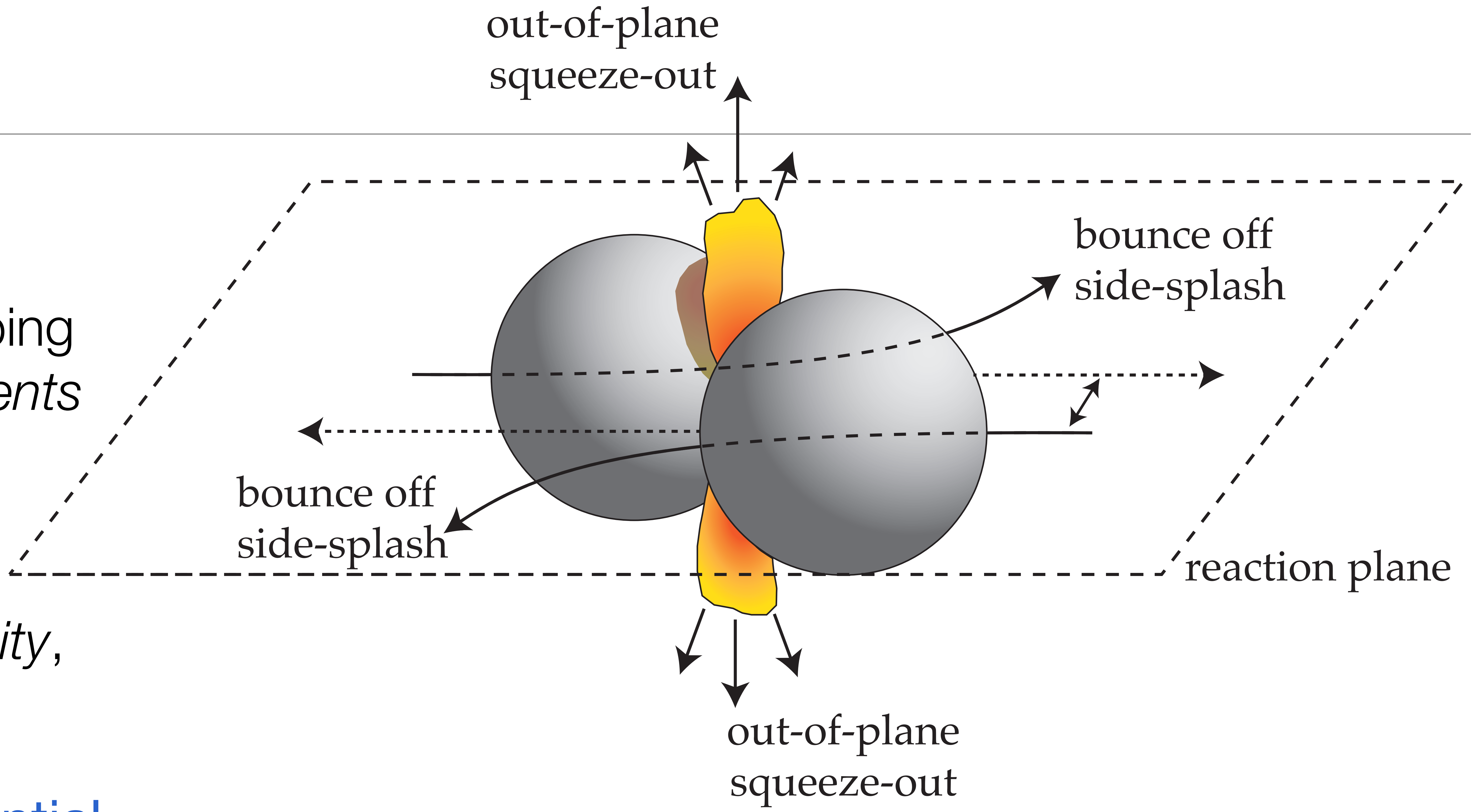
$$v_n = v_n^{obs} \,/\, \boldsymbol{\mathfrak{R}_n}$$

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

Collectivity

Emission relative to event plane

- In-medium interactions and 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*



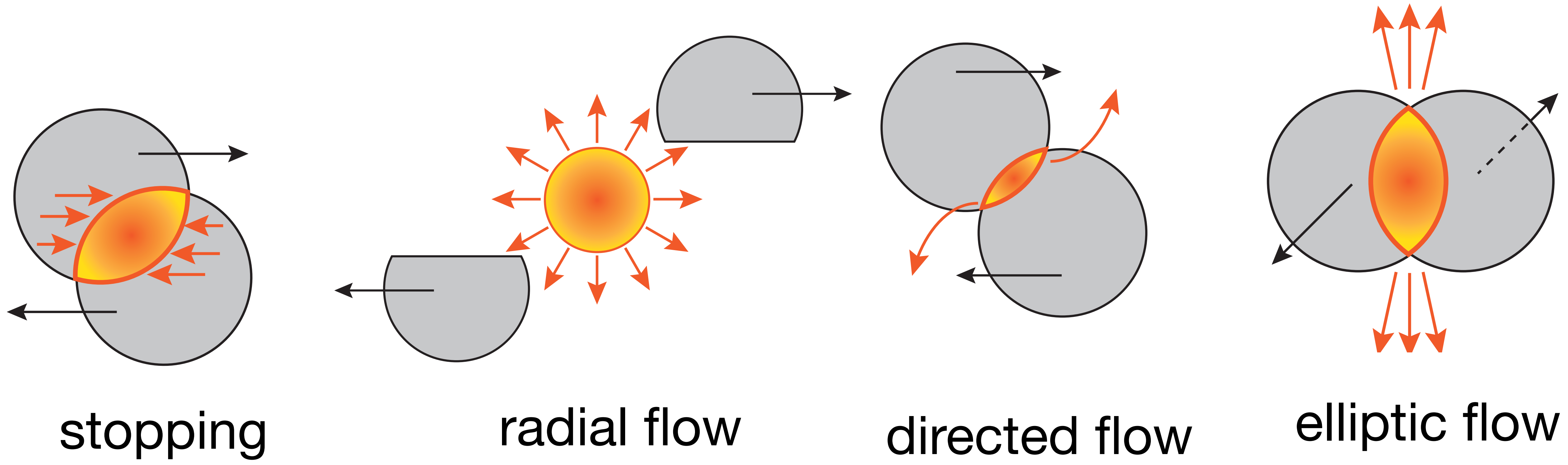
Fourier-decomposition of the triple differential invariant cross section

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

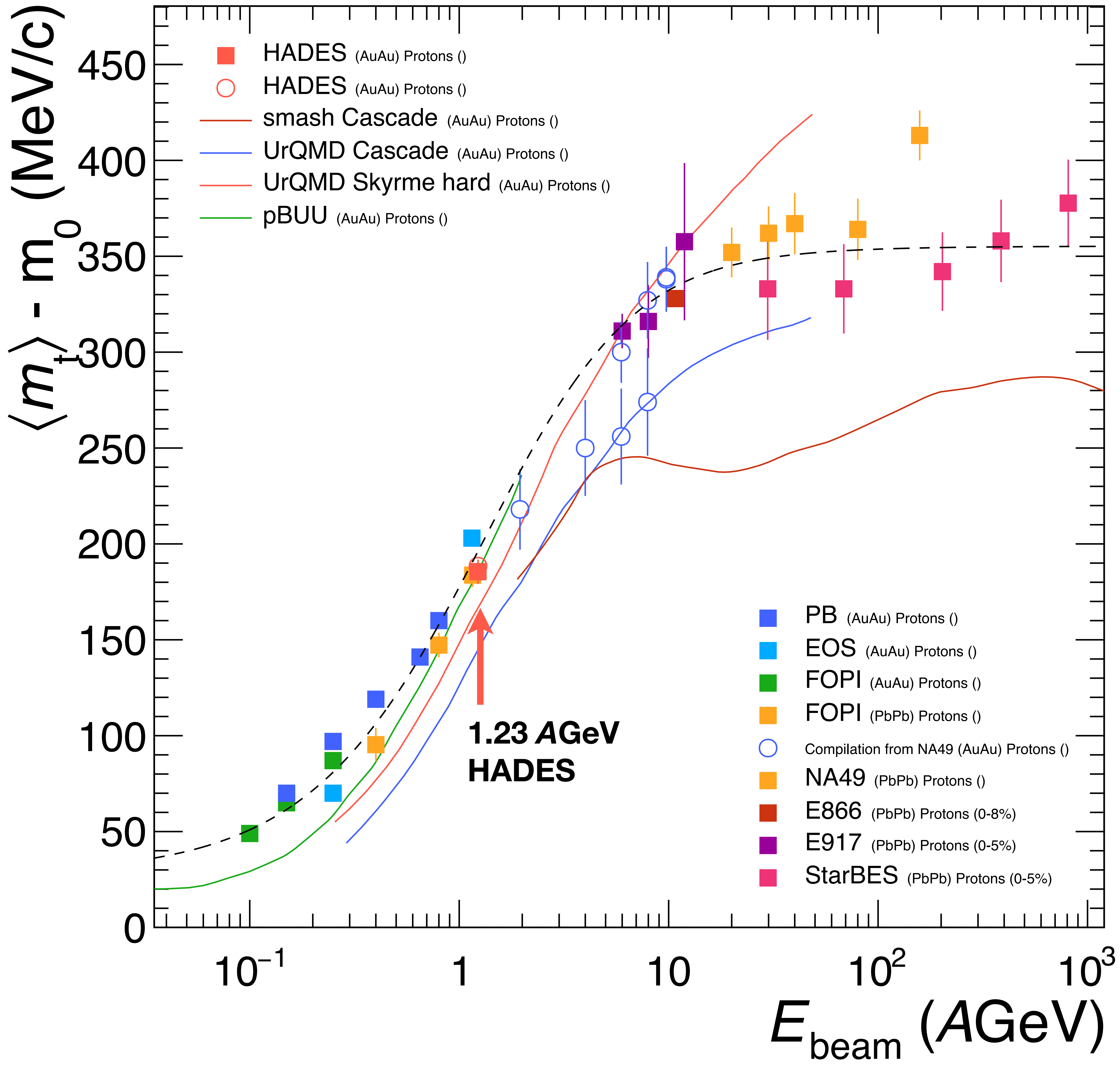
$$\phi = (\varphi - \Psi_{RP})$$

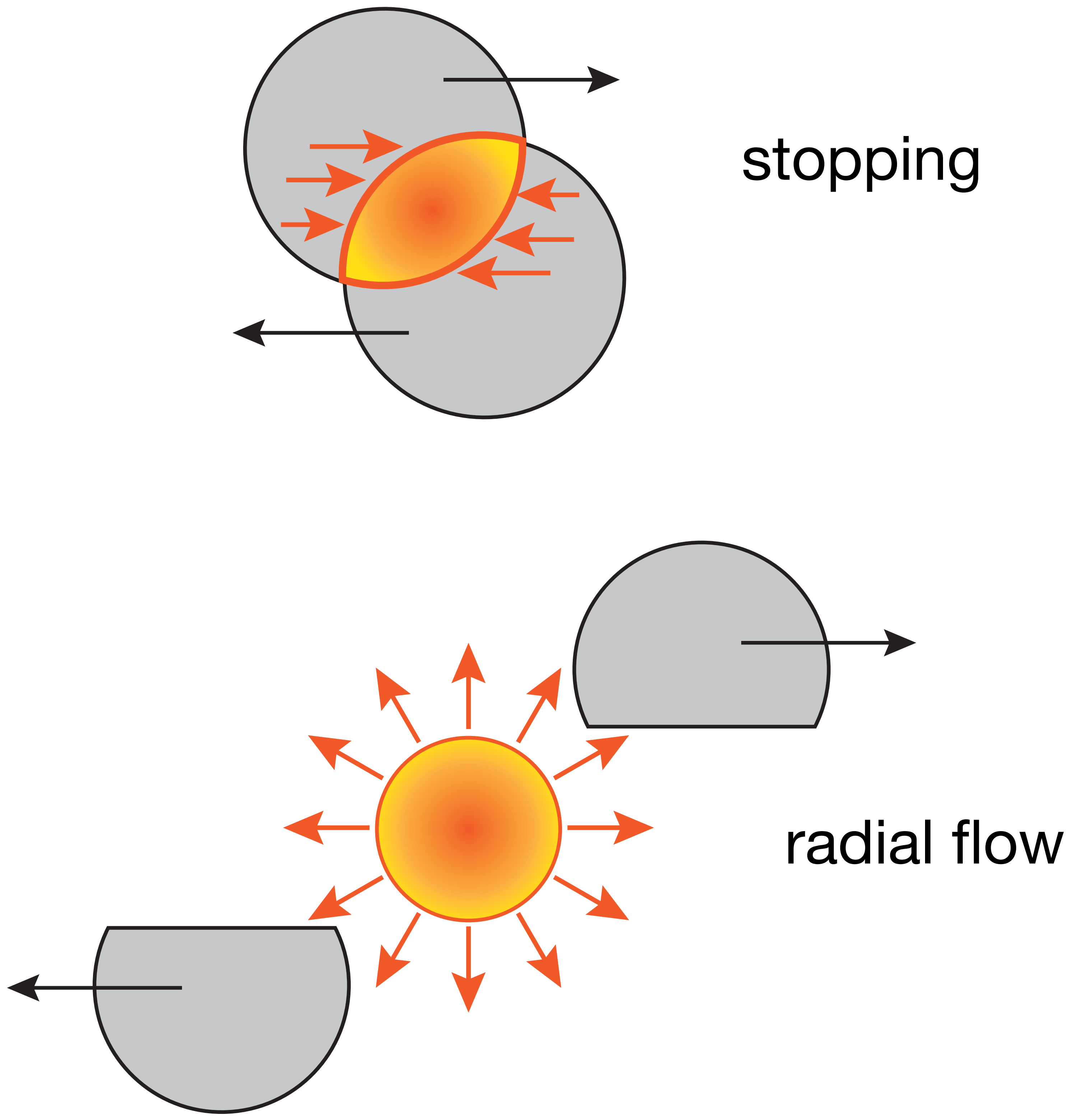
Extraction of azimuthal moments v_n

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



Collectivity

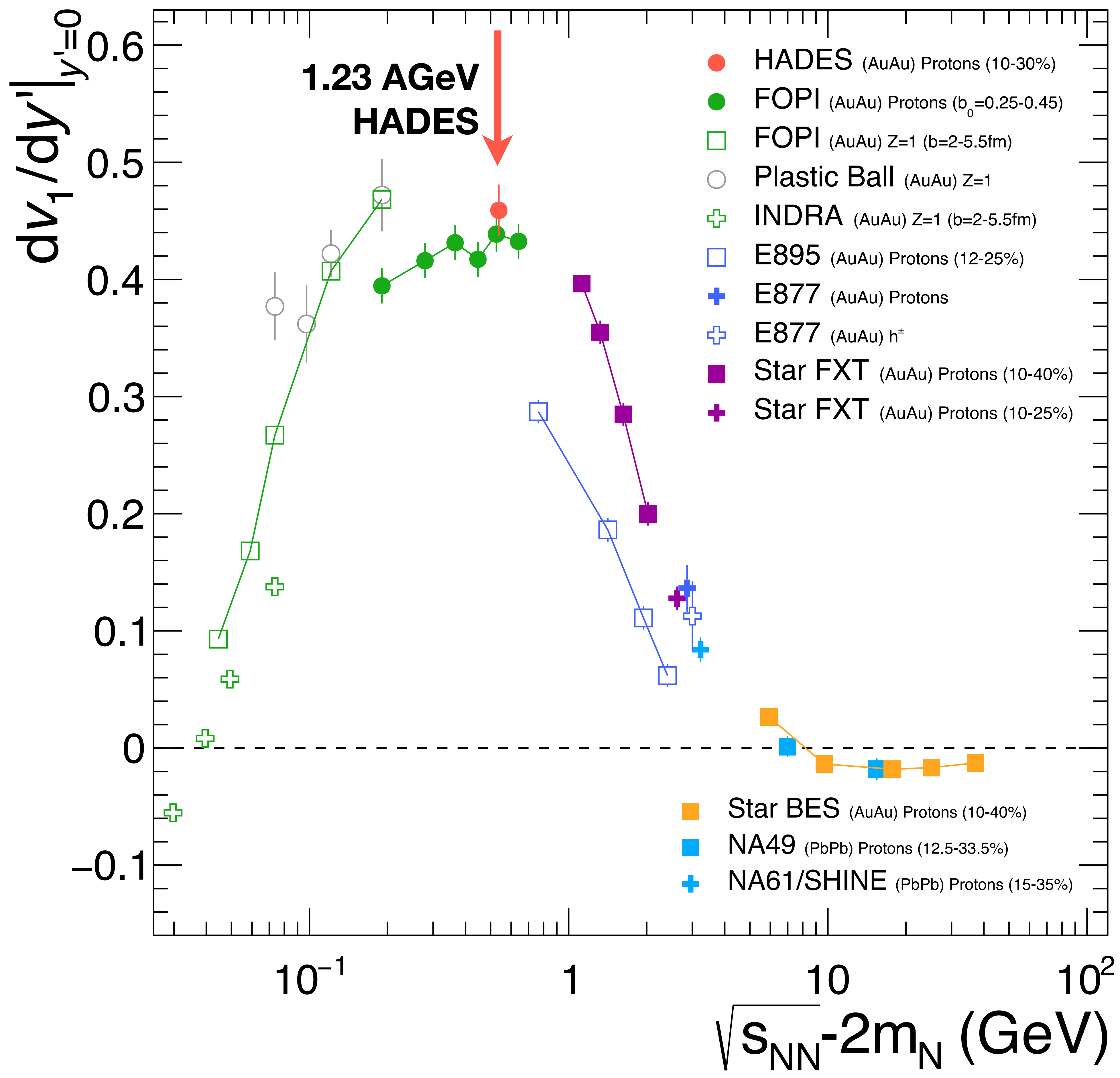



stopping

radial flow

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

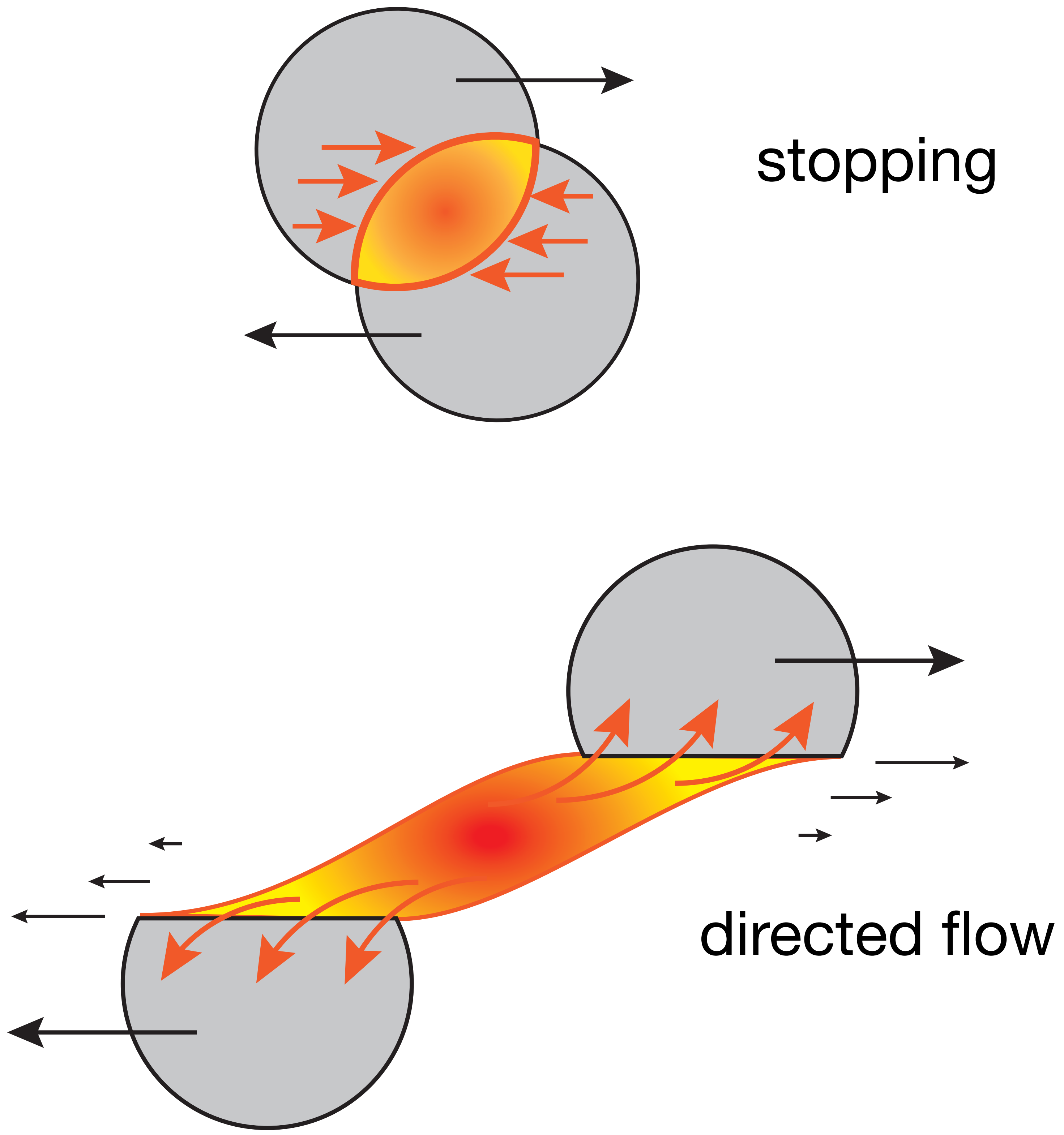
Collectivity



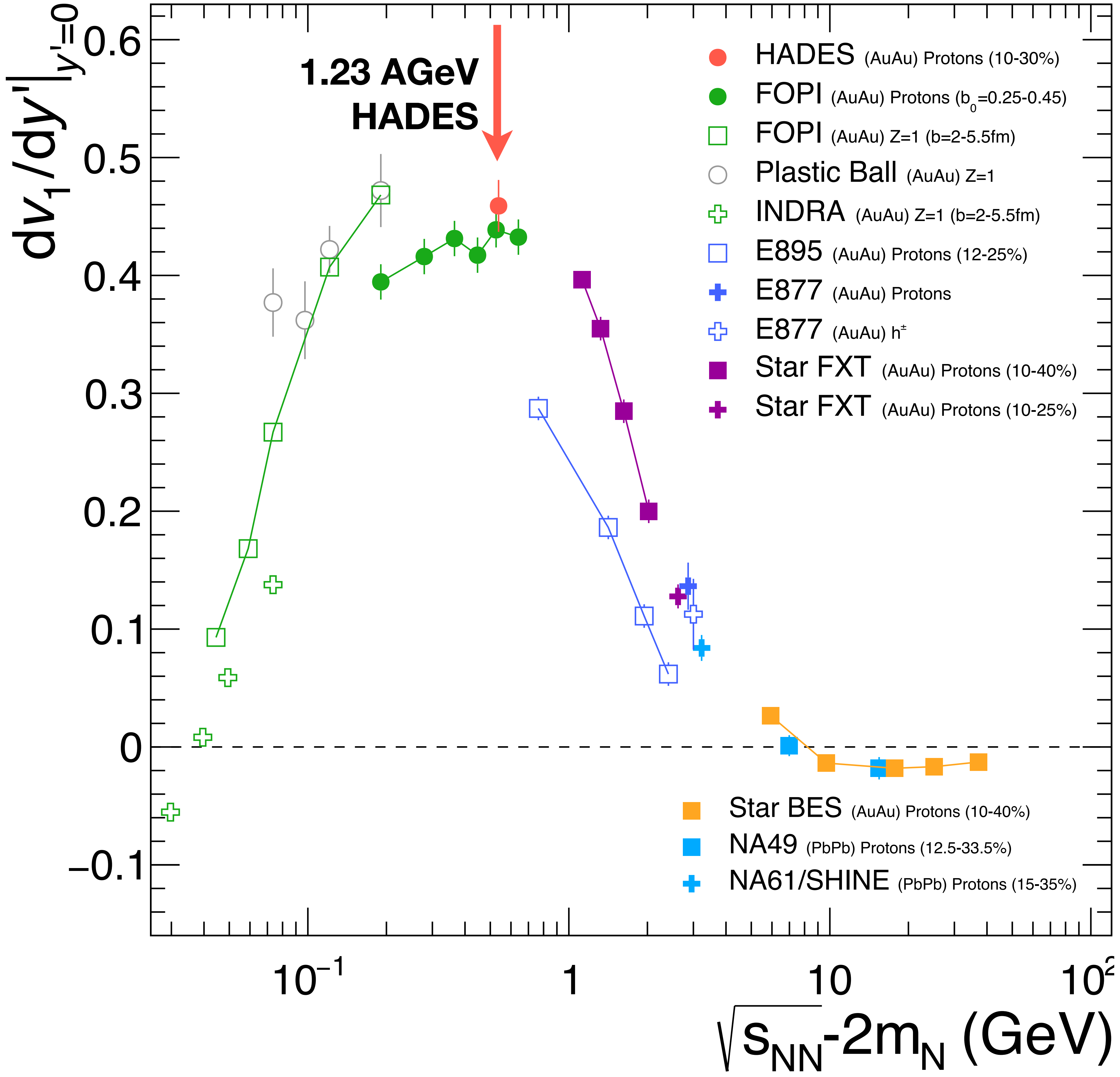
HADES, EPJ A 59 (2023) 80

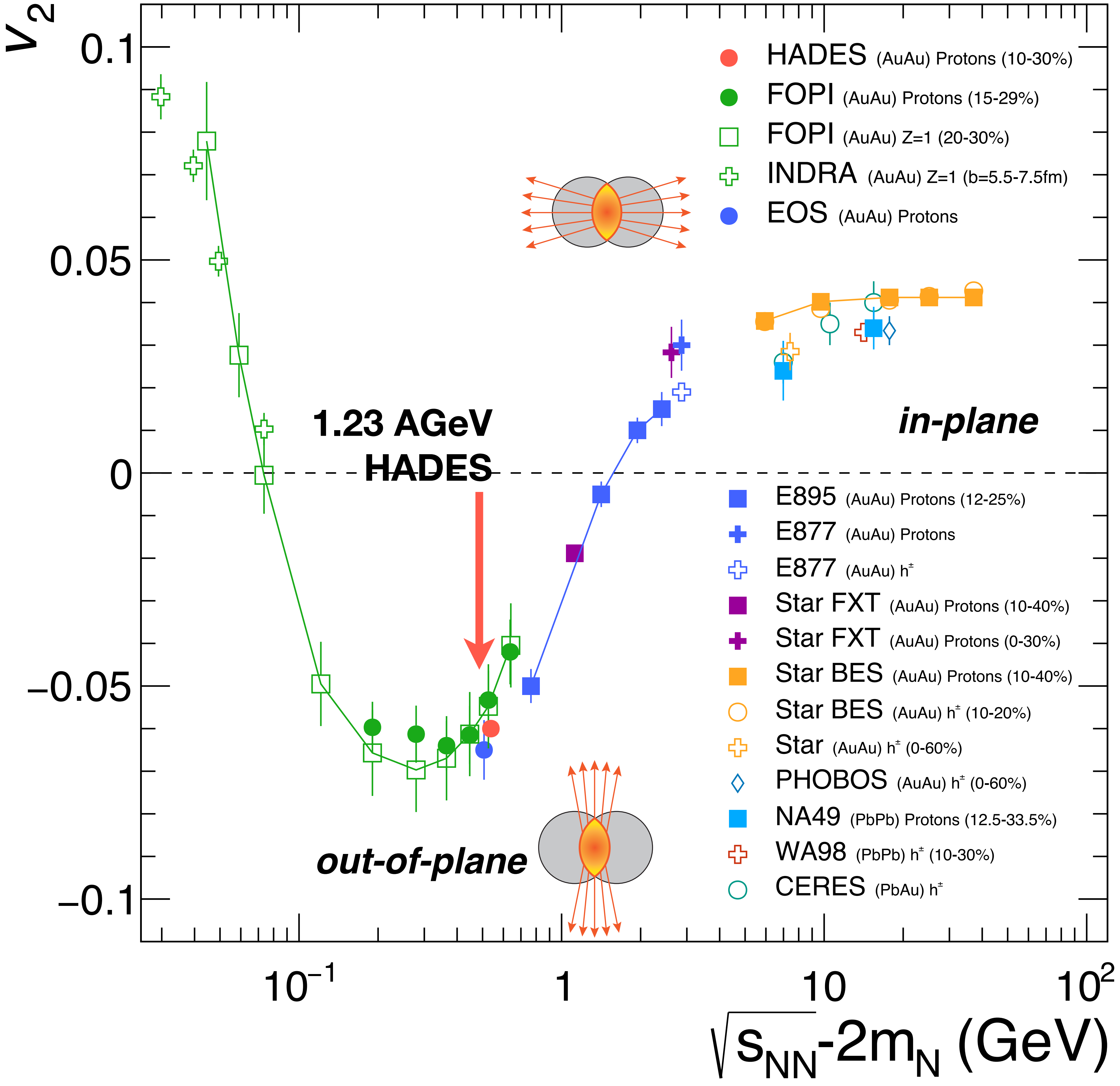
STAR FXT (QM2023), Universe 10 (2024) 3, 118

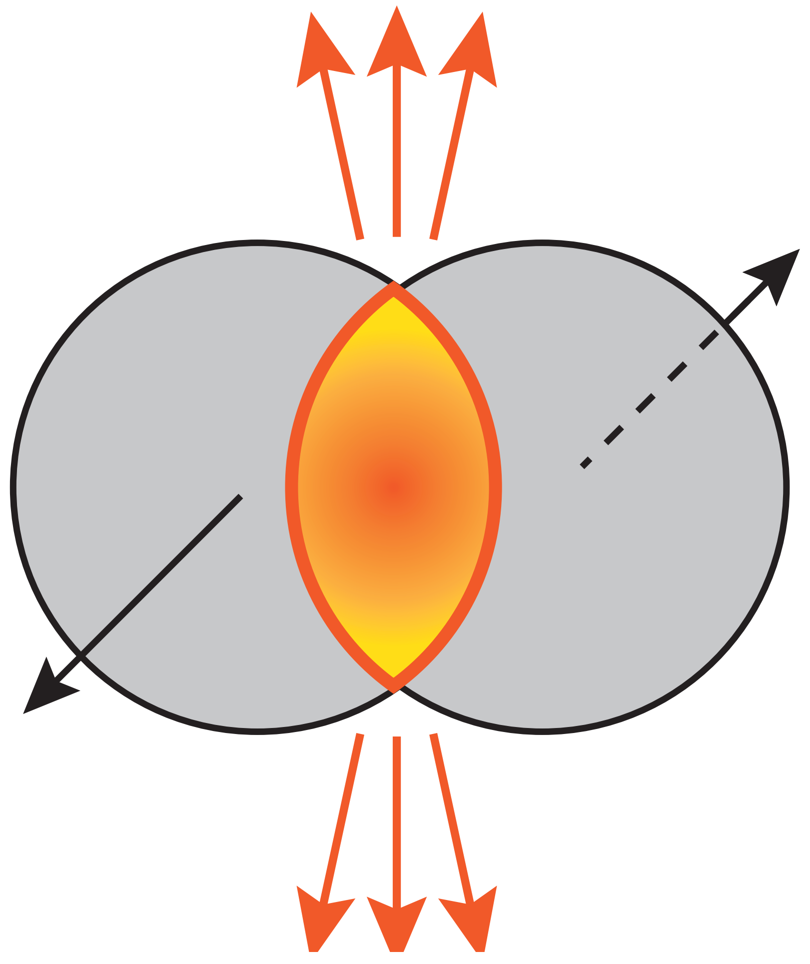
Good agreement with world data



Collectivity







elliptic flow

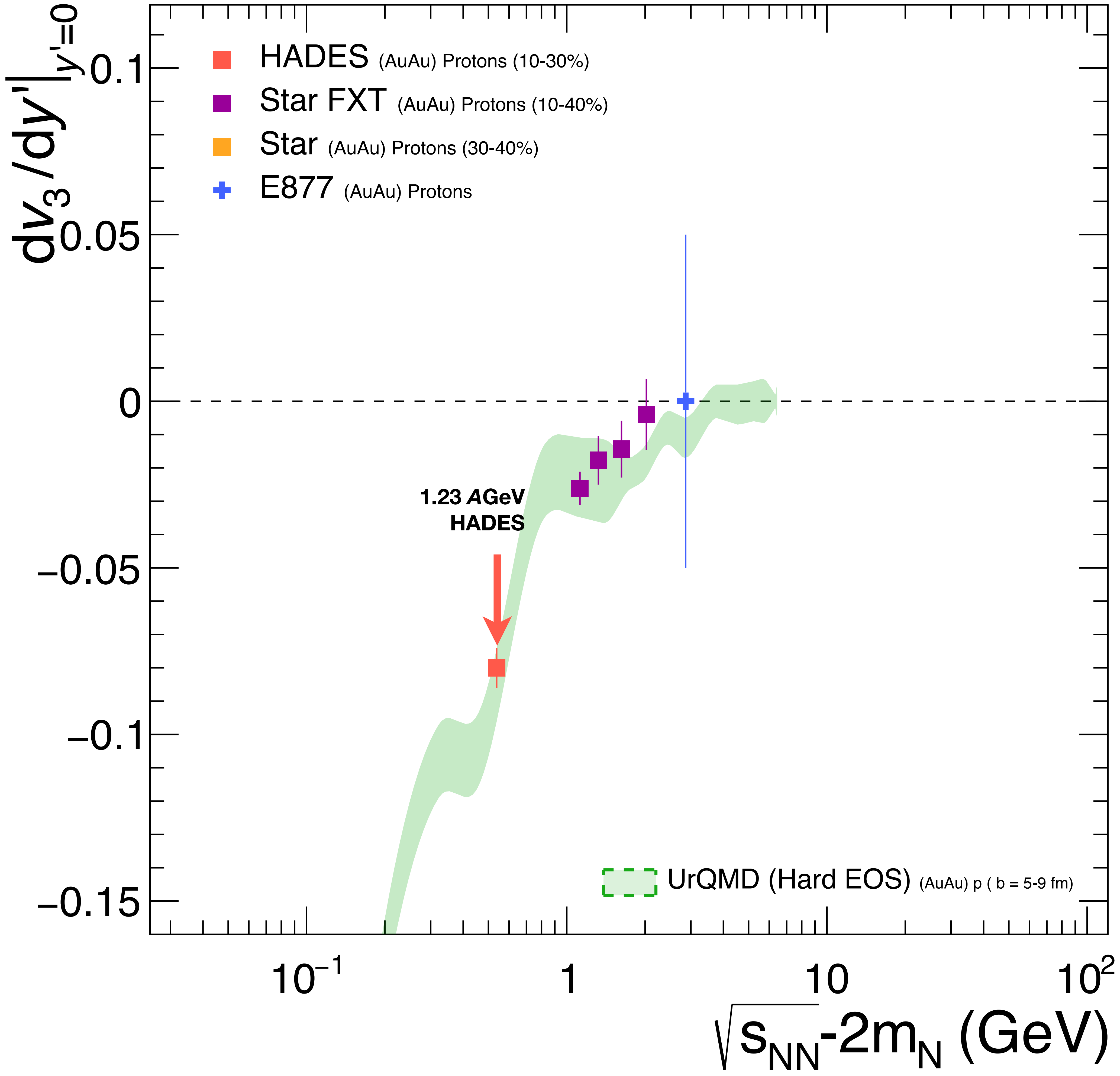
HADES, EPJ A 59 (2023) 80
STAR FXT (QM2023), Universe 10 (2024) 3, 118

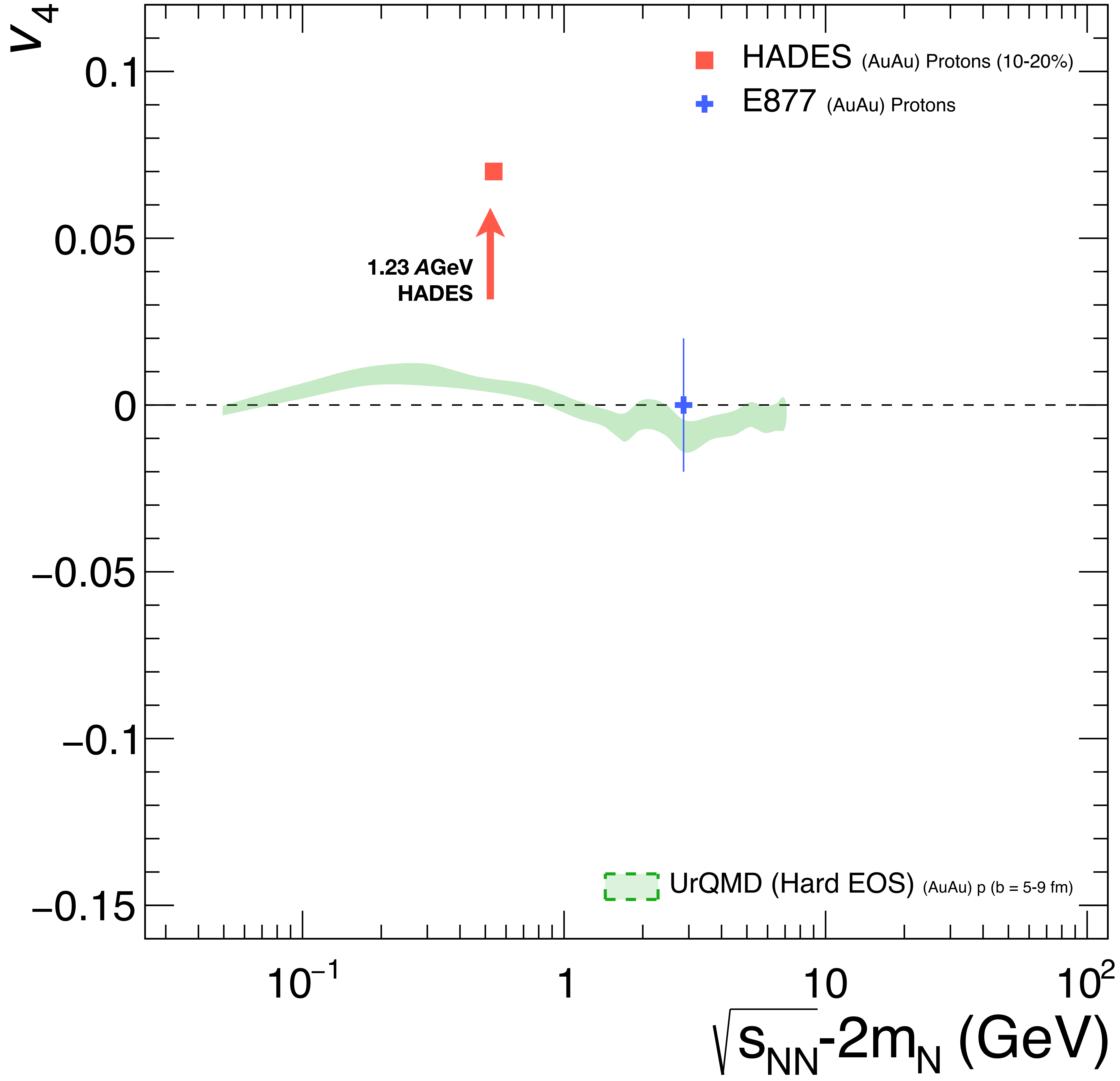
Good agreement with world data

Update Star FXT QM2023

Compilation of World Data

Energy-Dependence





Compilation of world data

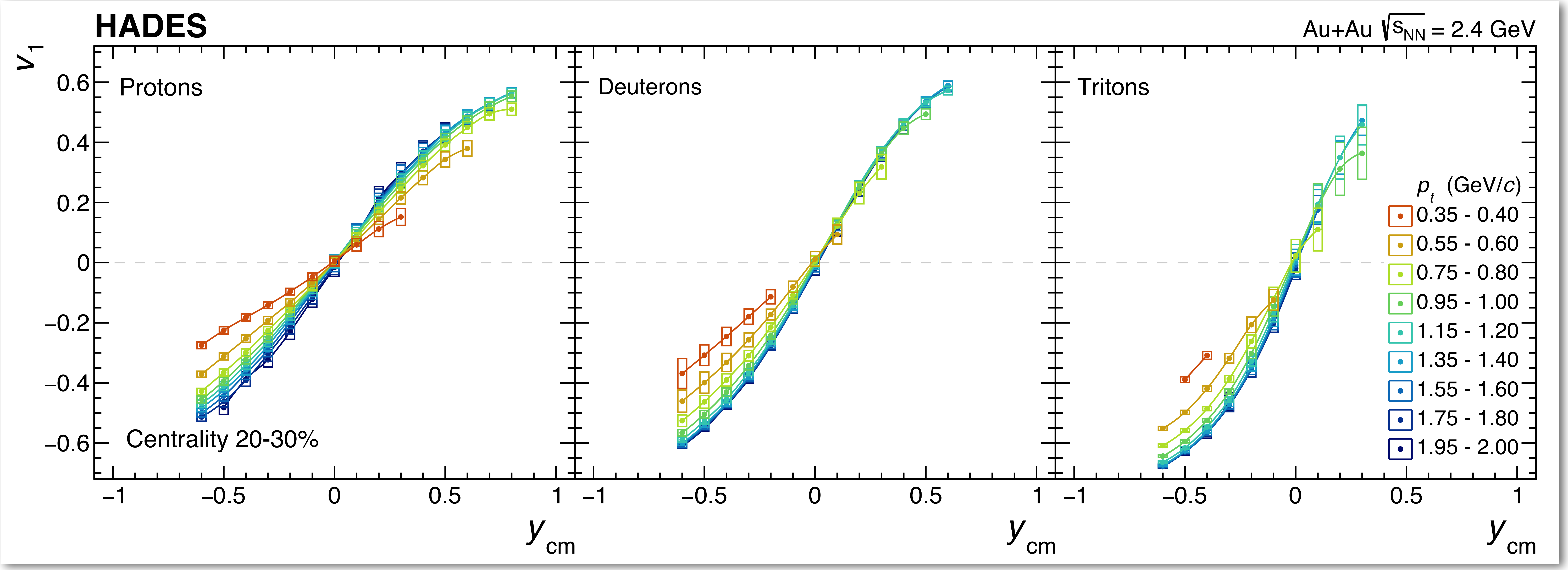
New STAR FXT v_3 data and E877 upper limit for v_3 and v4

HADES, EPJ A 59 (2023) 80
E877 (AGS), PRL 73 (1994) 2532, PRC 56 (1997) 3254
STAR FXT (QM2023), Universe 10 (2024) 3, 118

Collective Effects

Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons

HADES, Eur.Phys.J.A 59 (2023) 4, 80



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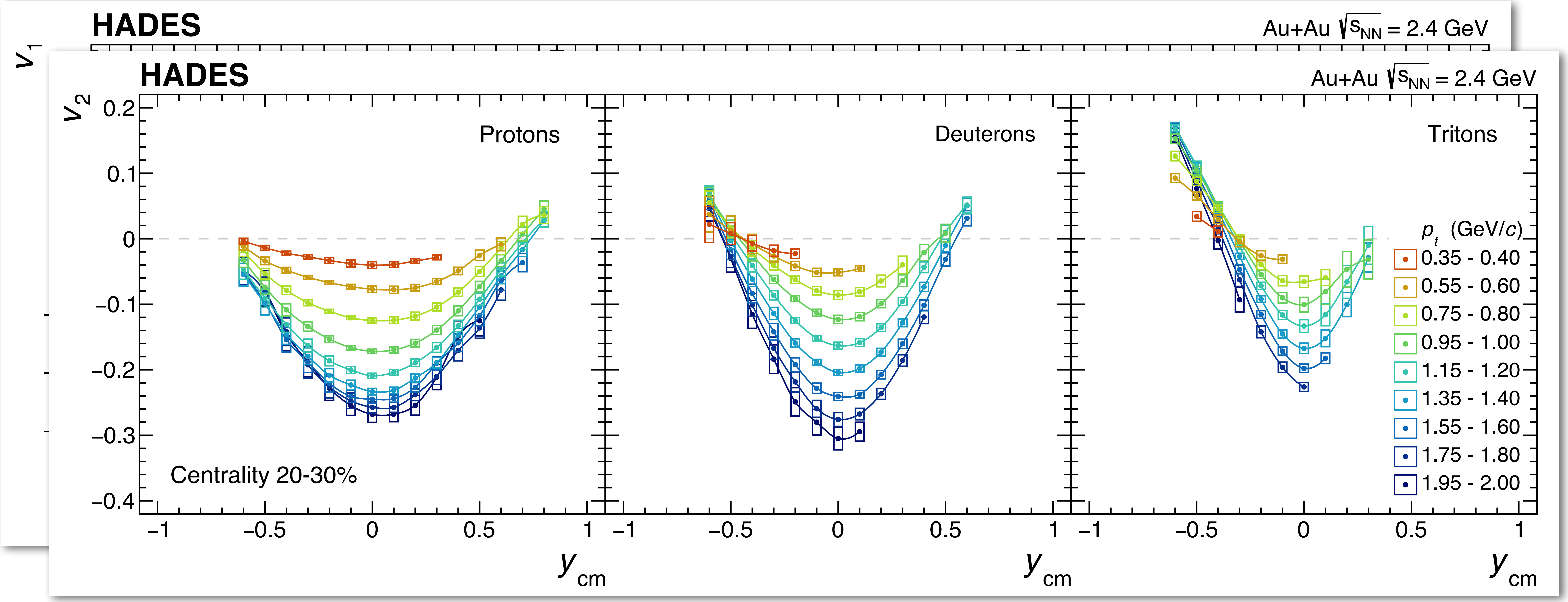

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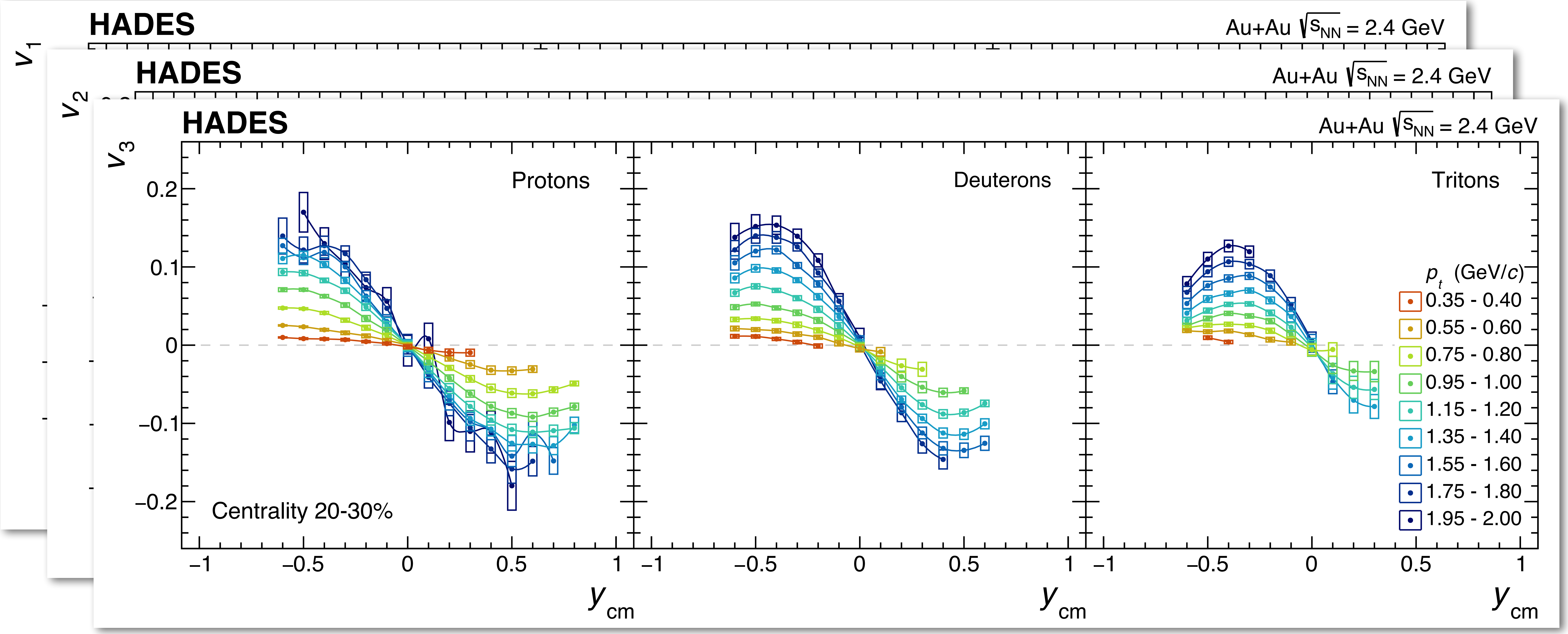

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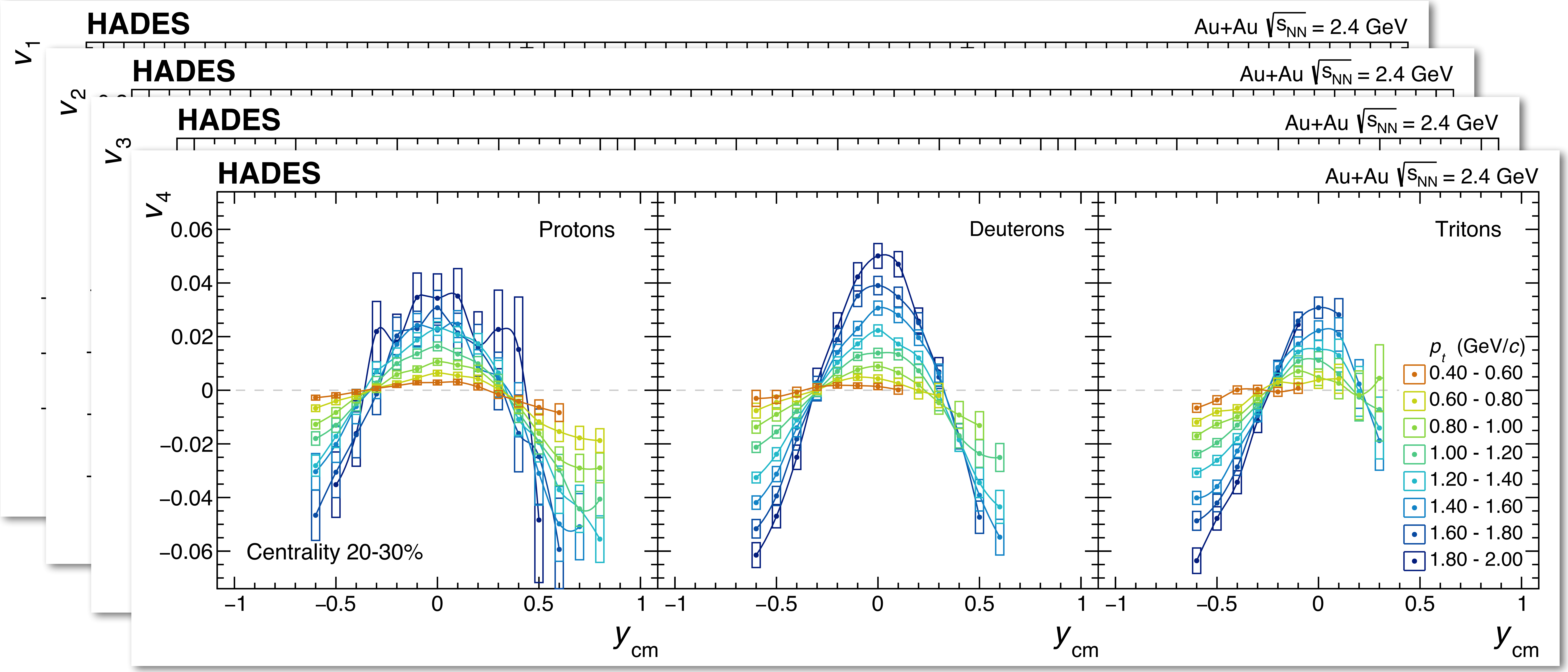
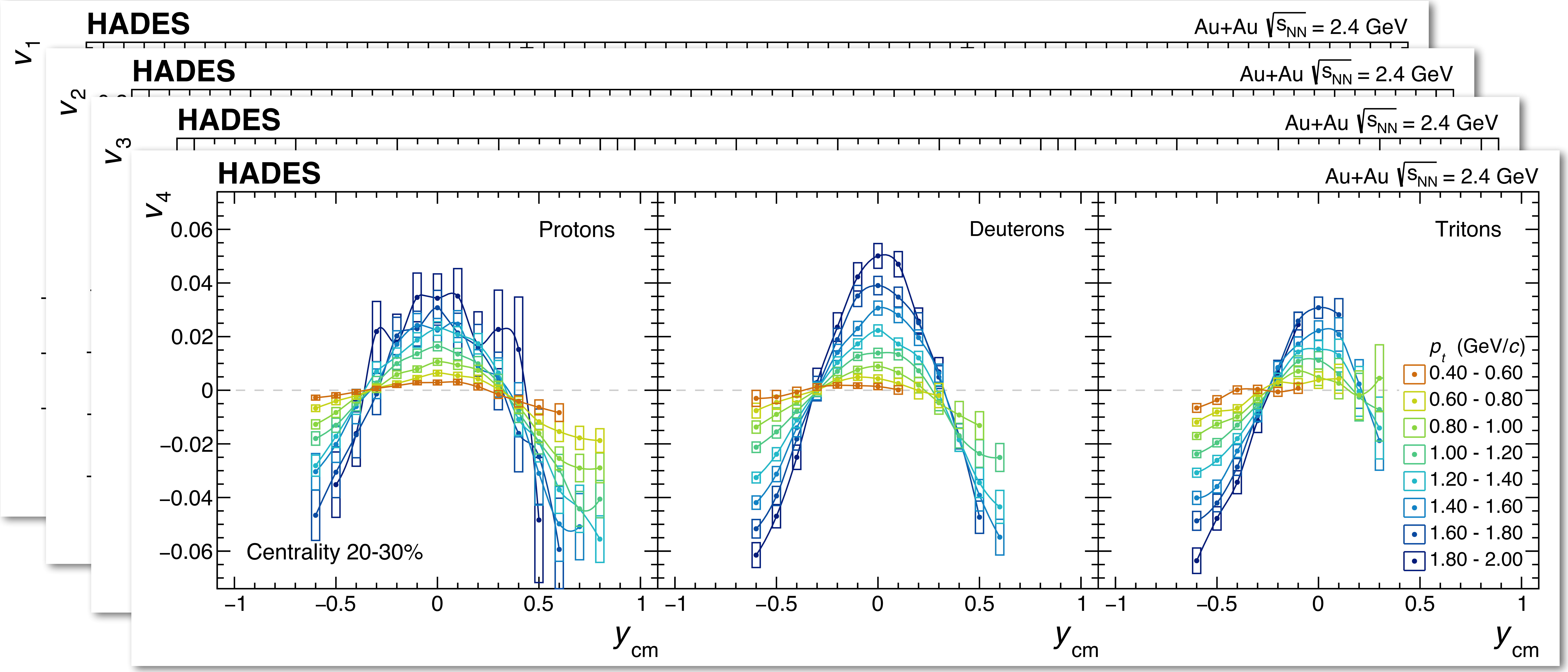


Collective Effects

Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons

HADES, Eur.Phys.J.A 59 (2023) 4, 80



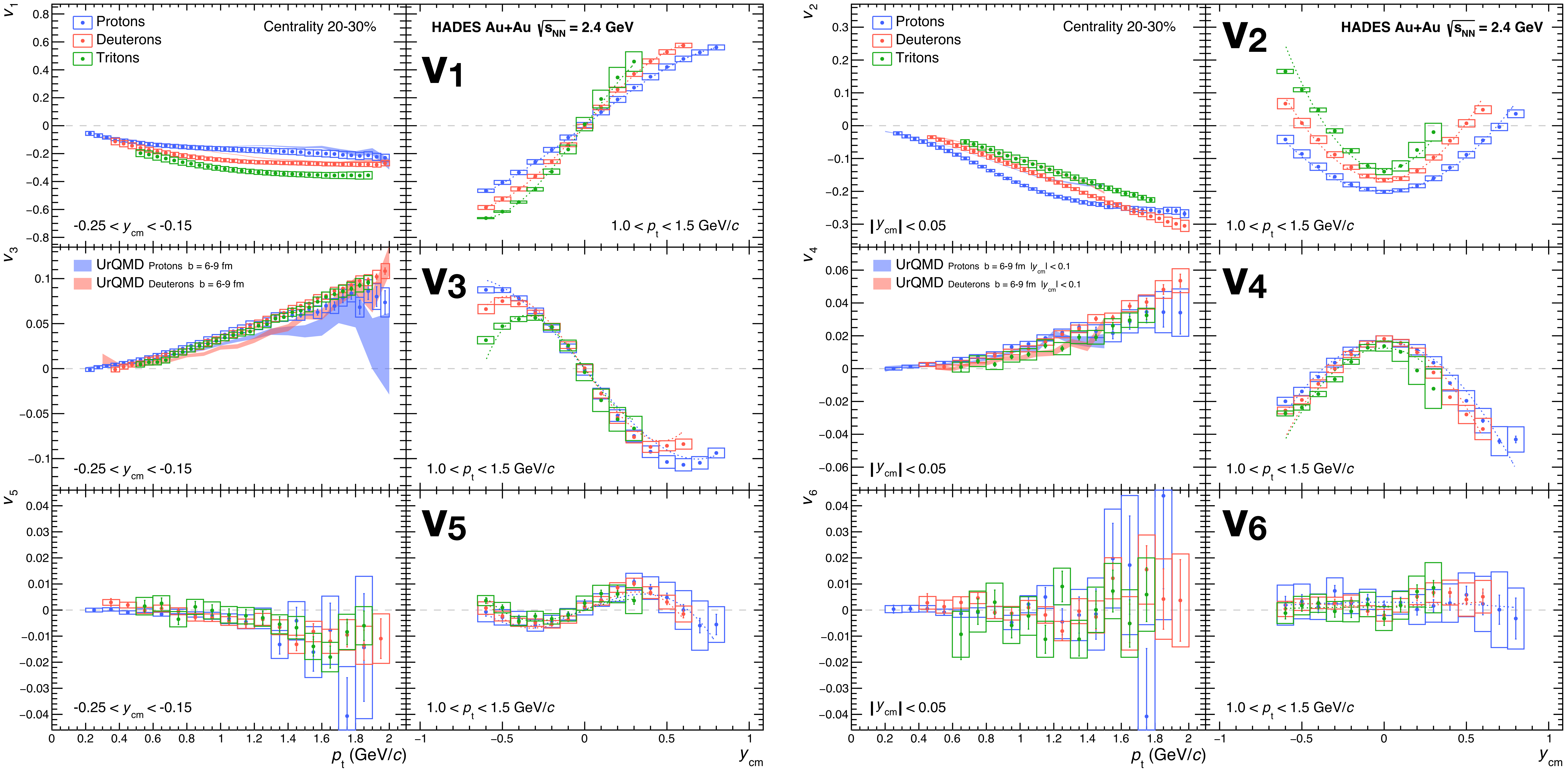
Only a fraction of the data is shown

In total 17k data points with individual systematic uncertainties available: [hepdata]

Collective Effects

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

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

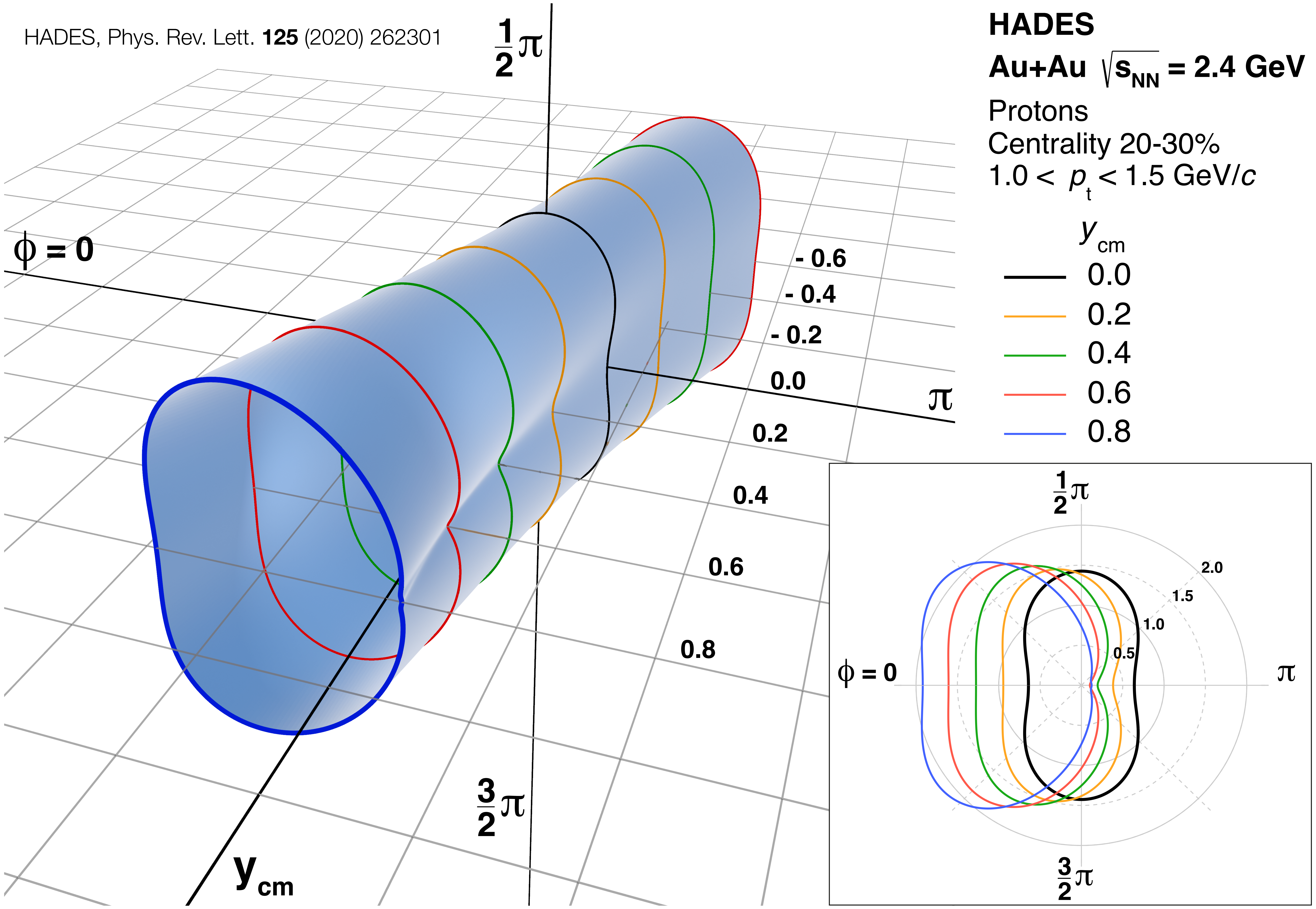


Emission Pattern

Protons

- Allows to reconstruct a full 3D-picture of the emission pattern in momentum space
- Complex evolution of shape as function of rapidity determined by flow coefficients v_1 — v_6

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

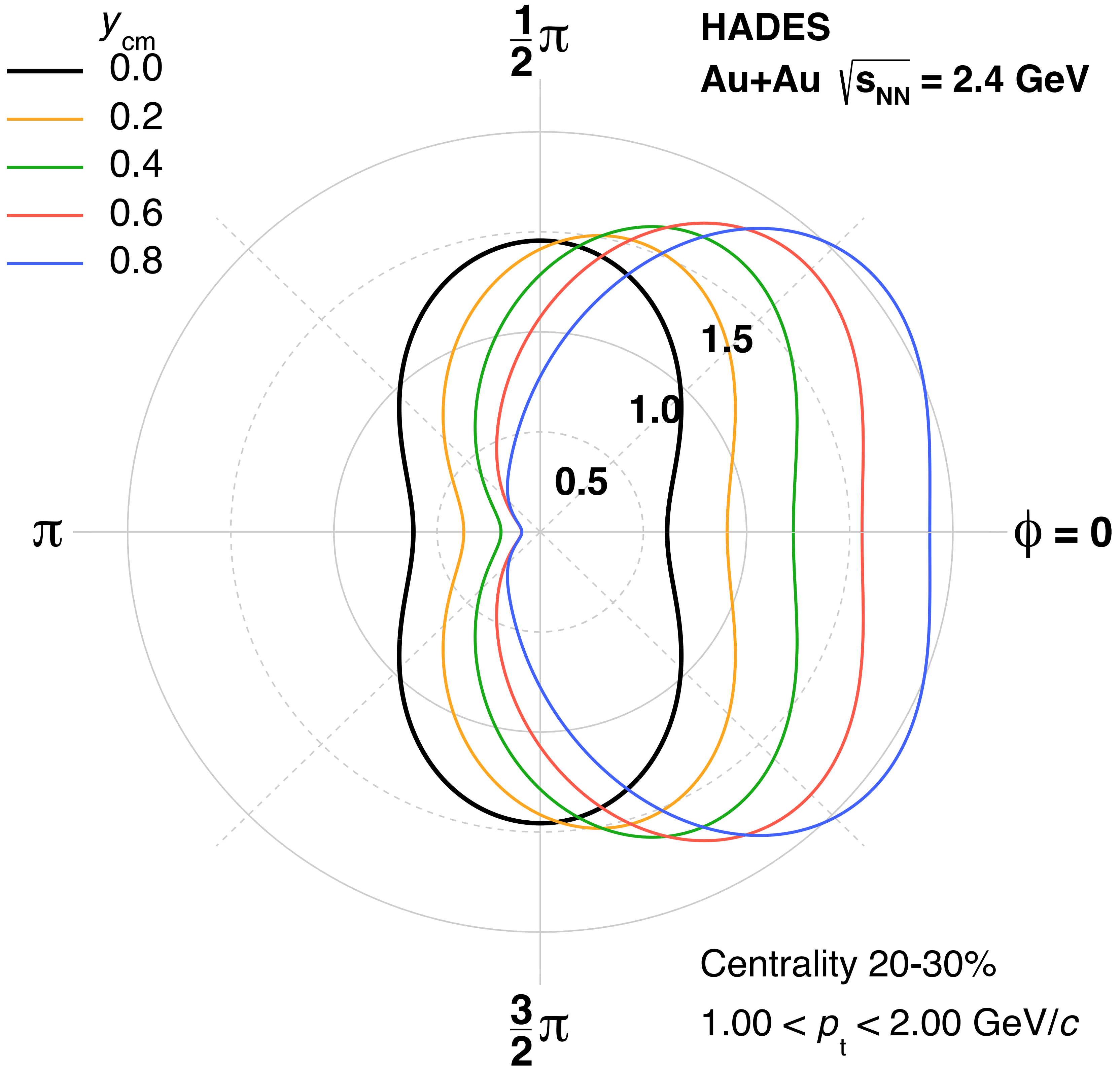


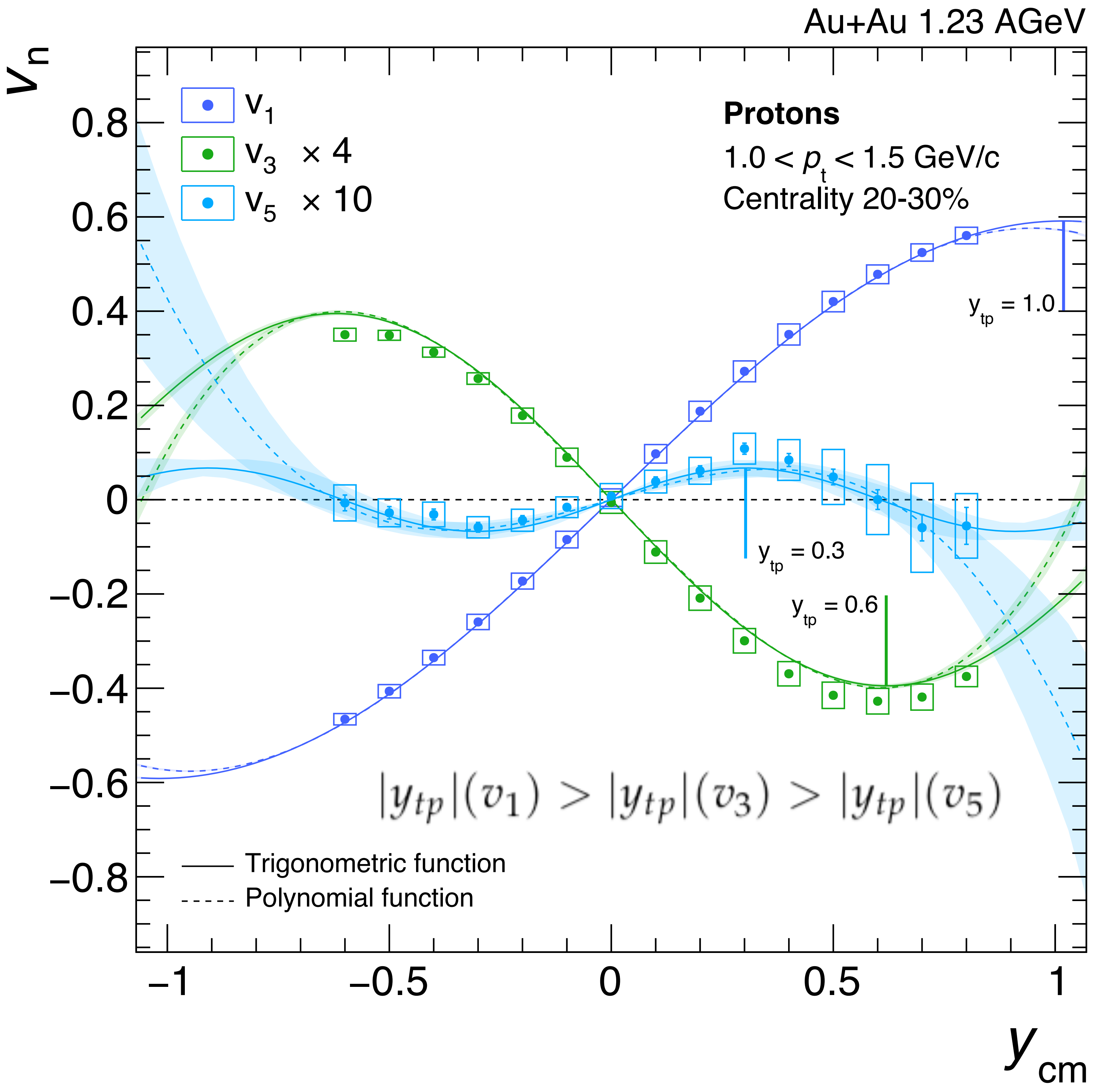
HADES, Phys. Rev. Lett. **125** (2020) 262301

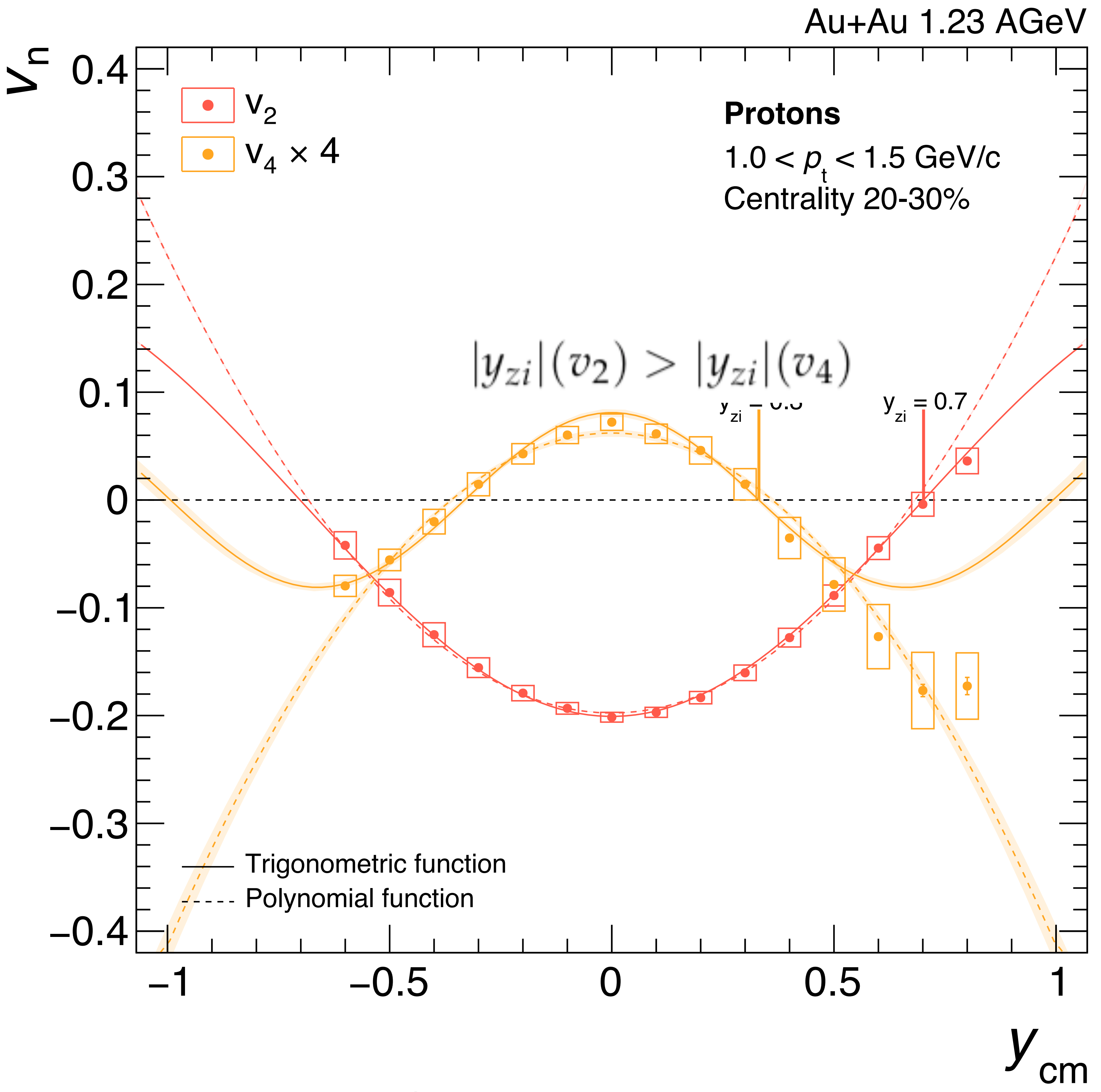
First Proposed in S. Voloshin and Y. Zhang
Z.Phys. C70 (1996) 665-672

Parameterisation

Rapidity-Dependence







HADES data:
PRL 125 (2020) 262301 [hepdata]

Polynomial function:

$$v_{n,\,odd}(y_{\text{cm}}) = v_{n1}\,y_{\text{cm}} + v_{n3}\,y_{\text{cm}}^3$$

$$v_{n,\,even}(y_{\text{cm}}) = v_{n0} + v_{n2}\,y_{\text{cm}}^2$$

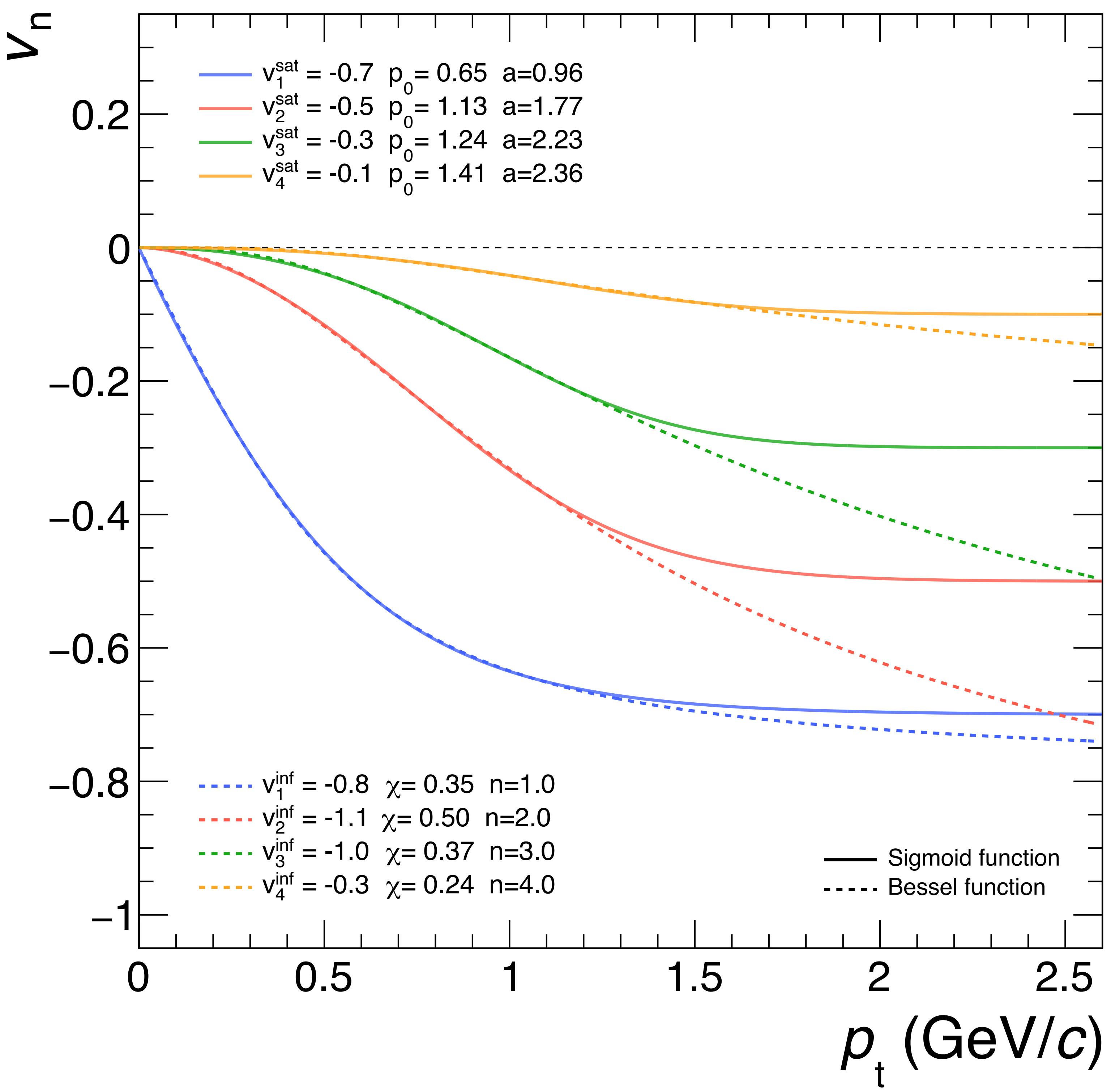
Trigonometric functions:

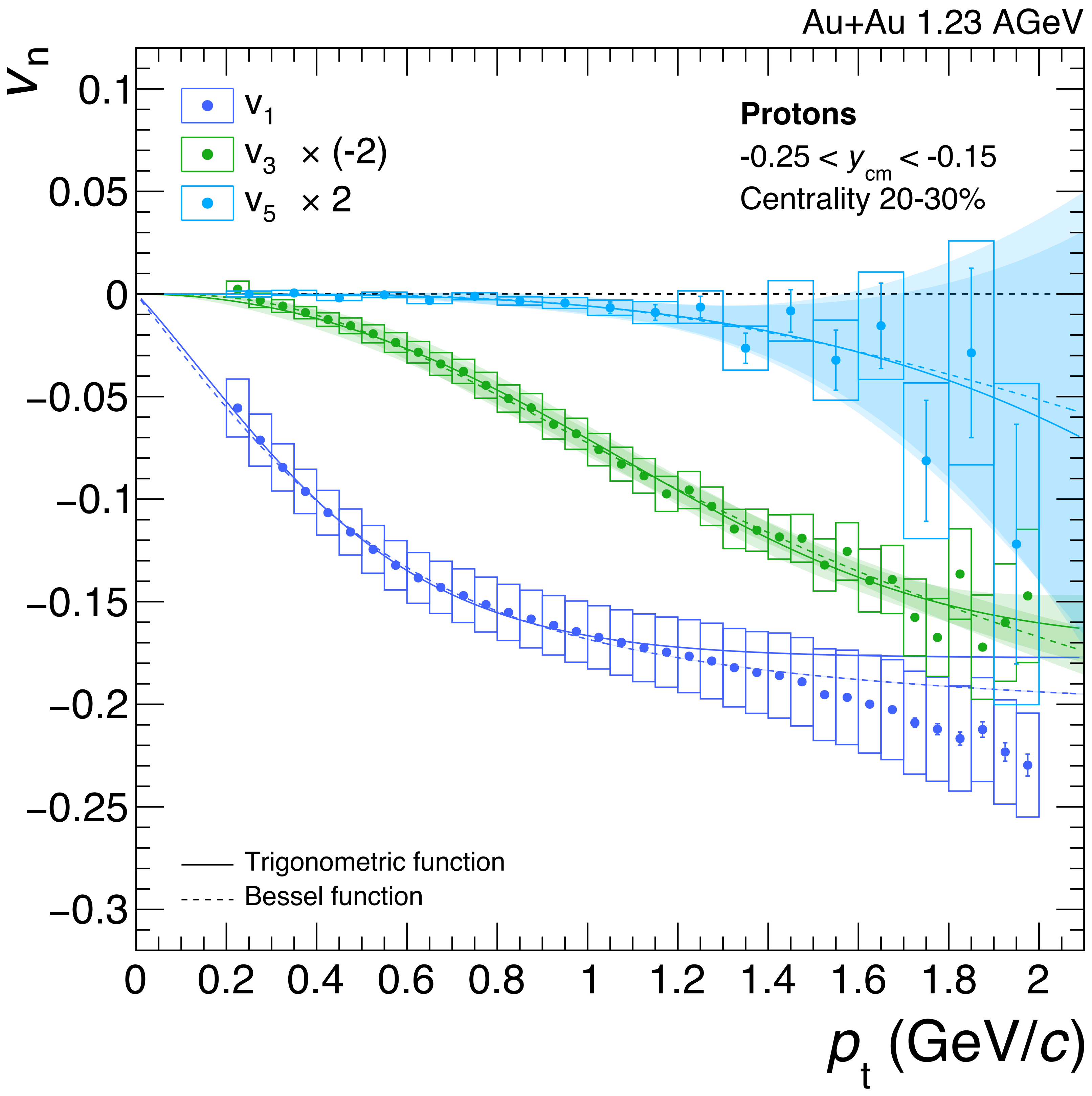
$$v_n^{odd}(y_{\text{cm}}) = v_n^{\text{sat}} \cdot \sin(y_{\text{cm}}/y_{tp} \cdot \pi/2)$$

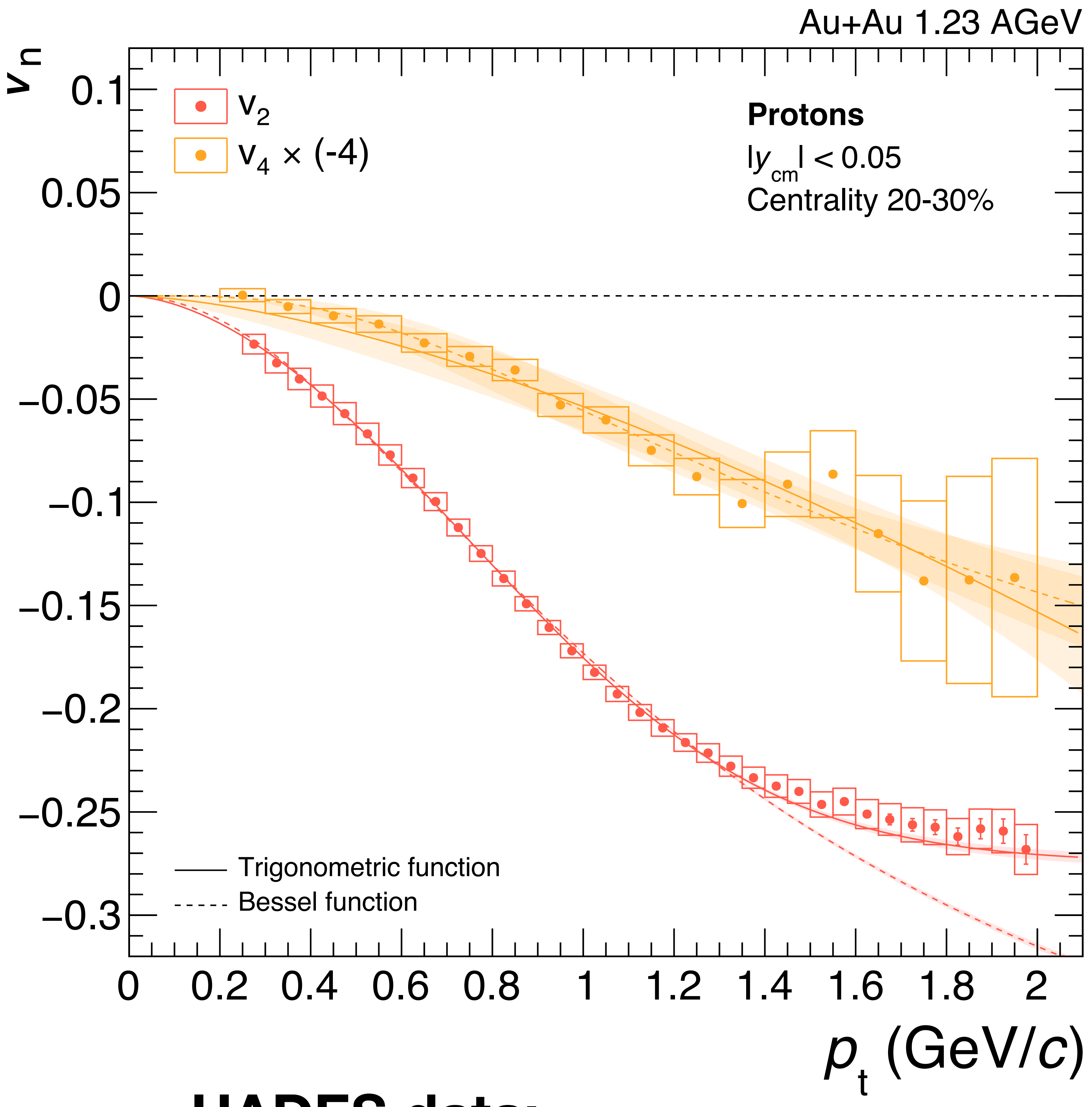
$$v_n^{even}(y_{\text{cm}}) = v_n^{\text{sat}} \cdot \cos(y_{\text{cm}}/y_{zi} \cdot \pi/2)$$

Parameterisation based on Blast-Wave Model

p_t-Dependence







Based on Blast-Wave Model (with azimuthal modulation):

$$v_n(p_t) = \frac{\int_0^{2\pi} \cos(n\phi_s)\ I_n(\alpha_t(\phi_s))\, K_1(\beta_t(\phi_s))\, d\phi_s}{\int_0^{2\pi} I_0(\alpha_t(\phi_s))\, K_1(\beta_t(\phi_s))\, d\phi_s} \qquad \rho(\phi_s) = \rho_0(1 + 2\rho_n\ \cos(n\phi_s))$$

Bessel functions:

$$v_n(p_t) = v_n^{\text{inf}}\ I_n(p_t/\chi)/I_0(p_t/\chi)$$

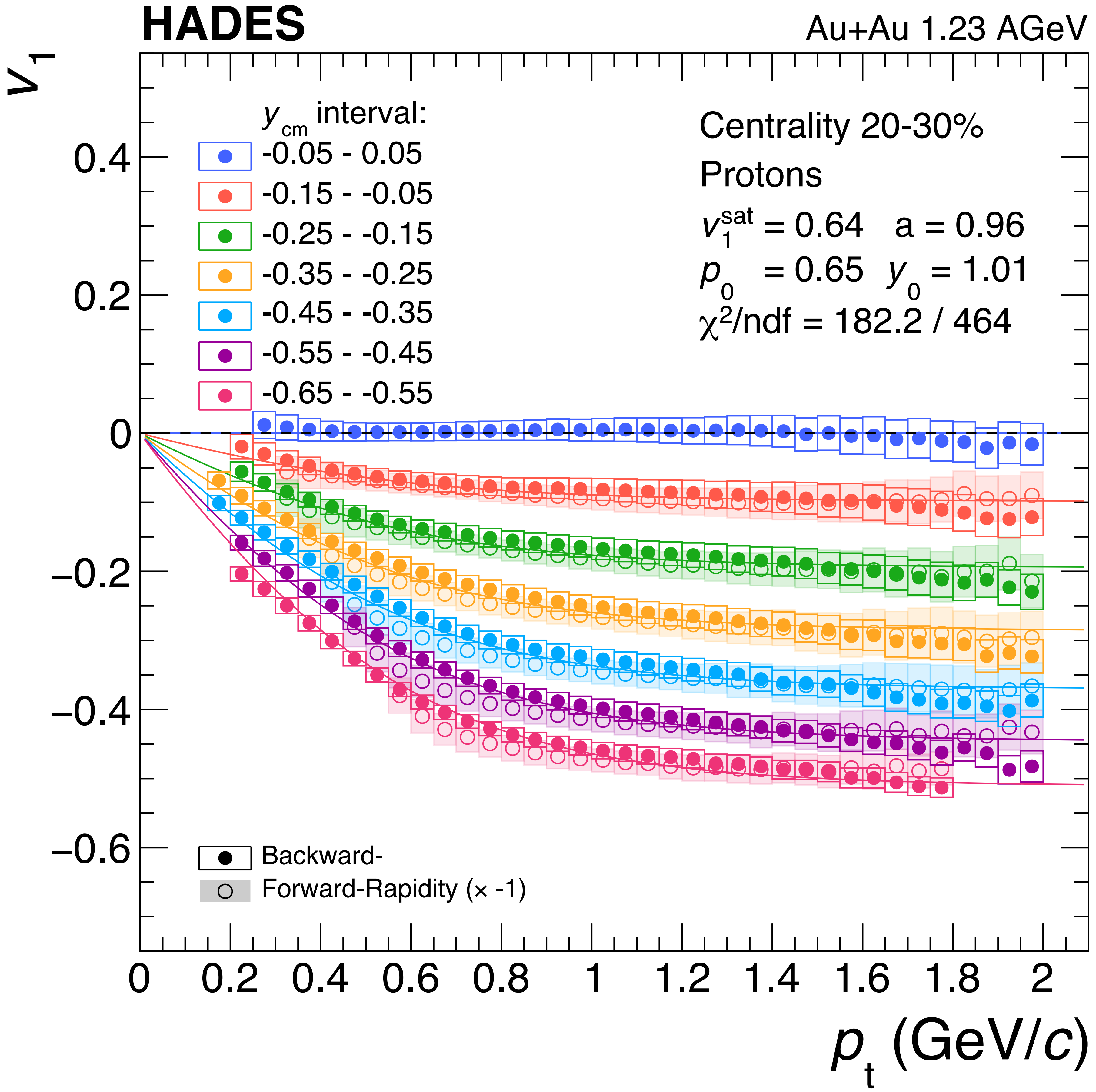
HADES data:
PRL 125 (2020) 262301 [hepdata]

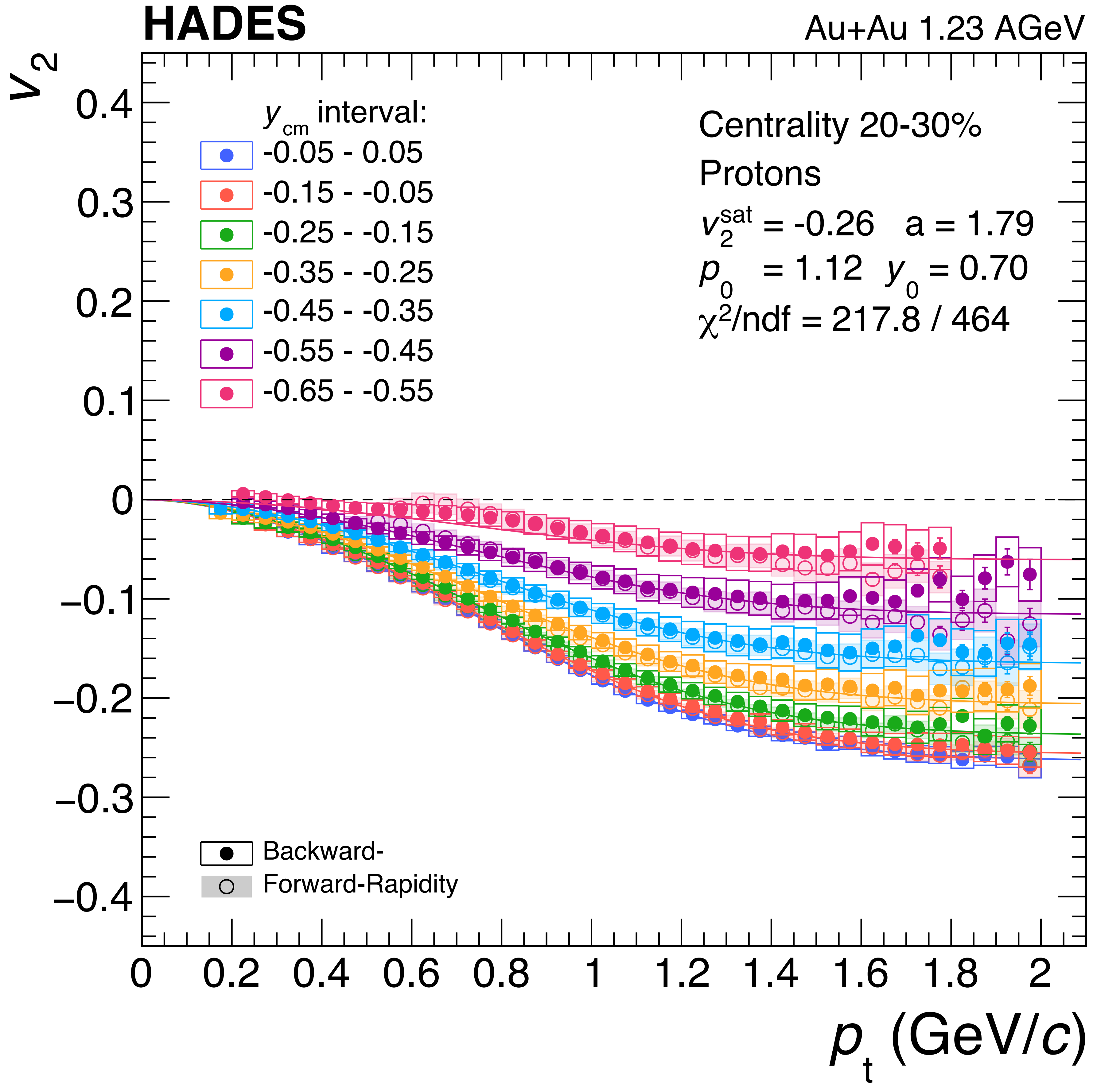
Trigonometric functions:

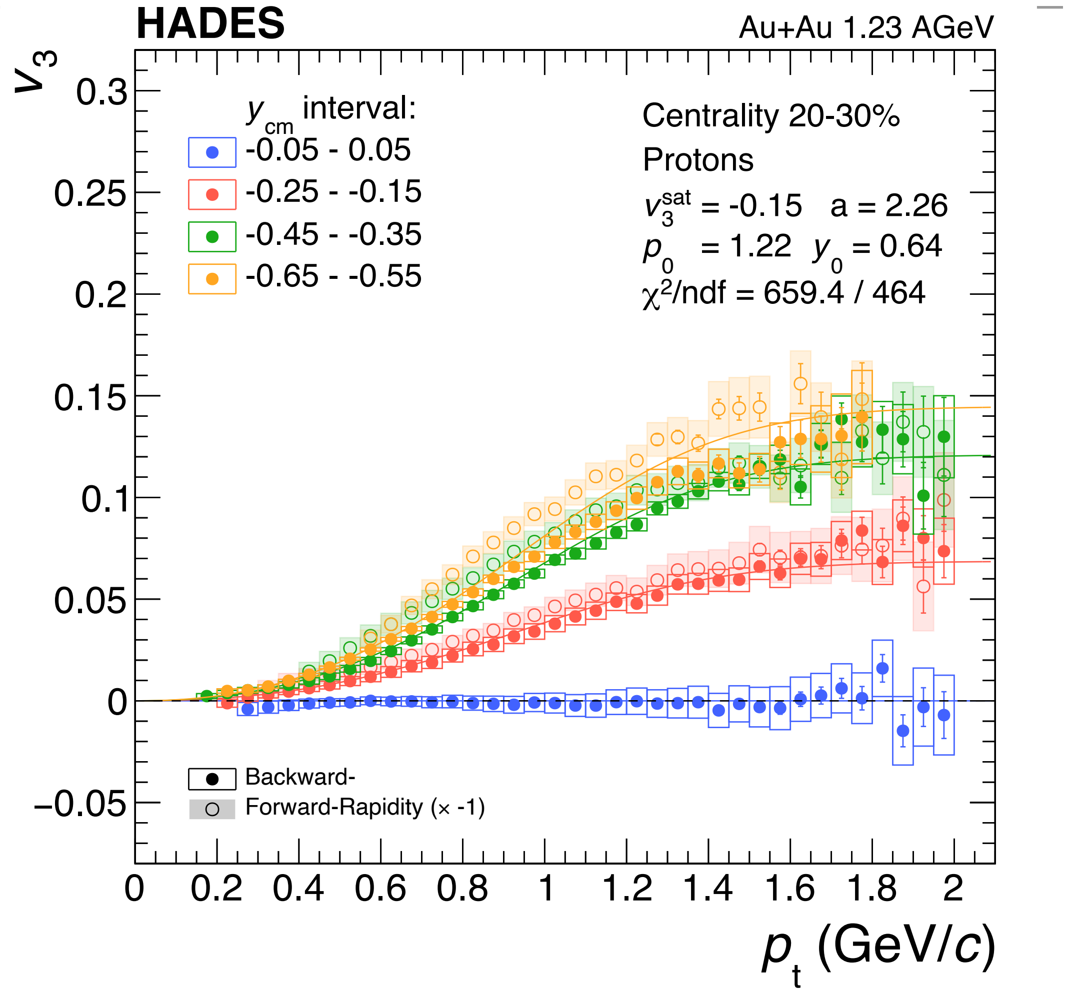
$$v_n(p_t) = v_n^{\text{sat}} \cdot \tanh(p_t/p_0)^a$$

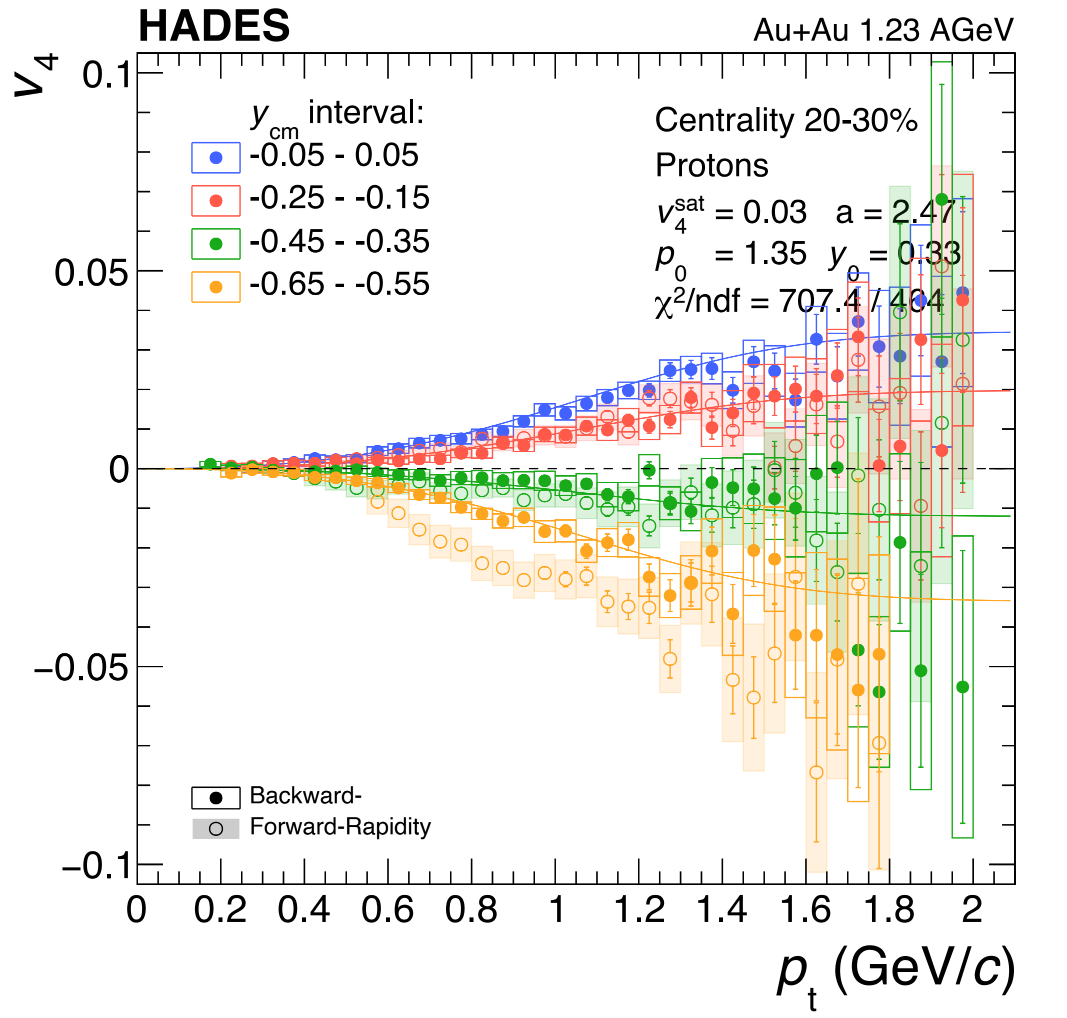
Global Parameterisation

Rapidity- and p_t-Dependence









Combined Trigonometric functions (y, pt):

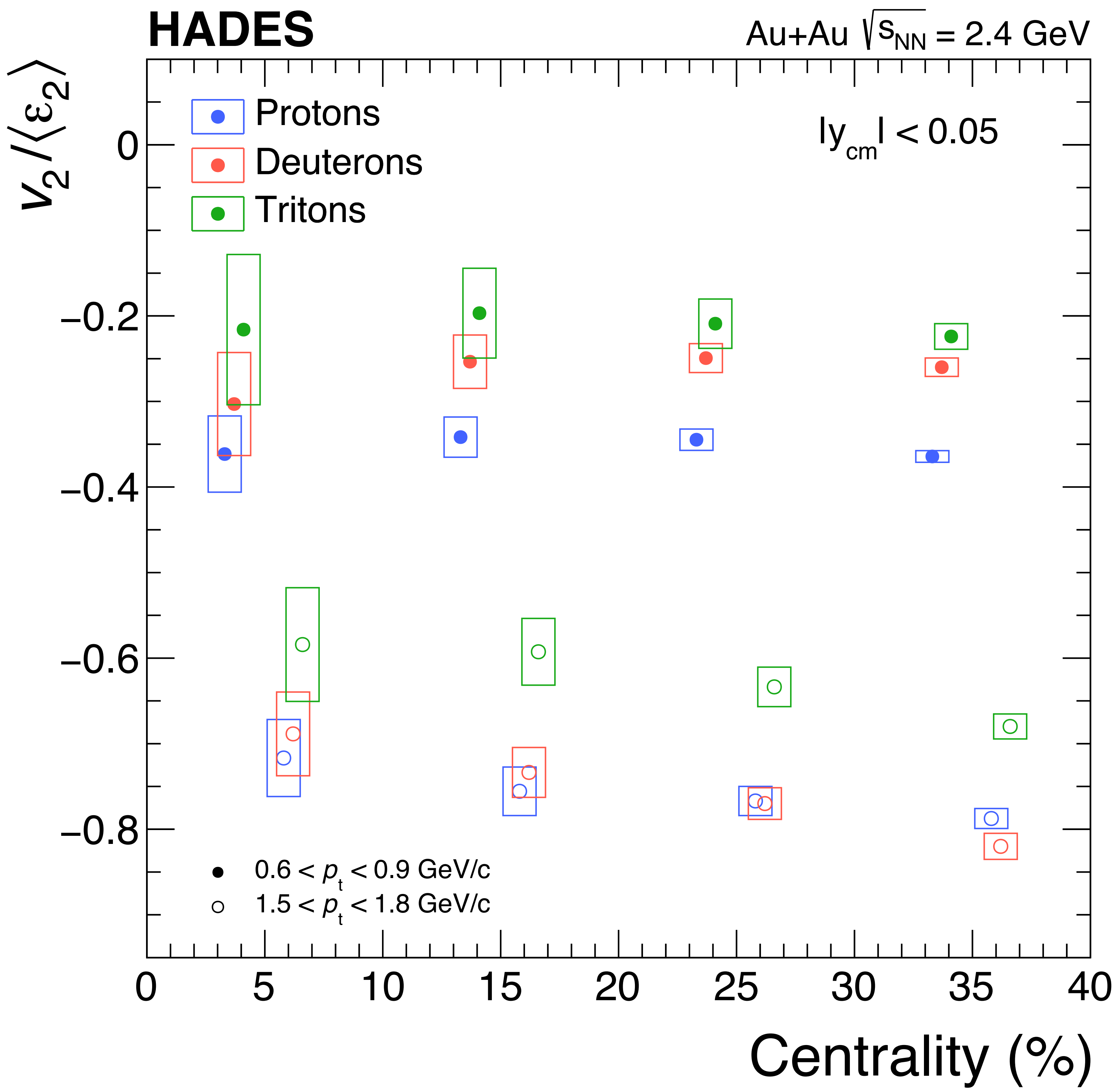
$$v_n^{odd}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \sin(y_{cm}/y_{tp} \cdot \pi/2)$$

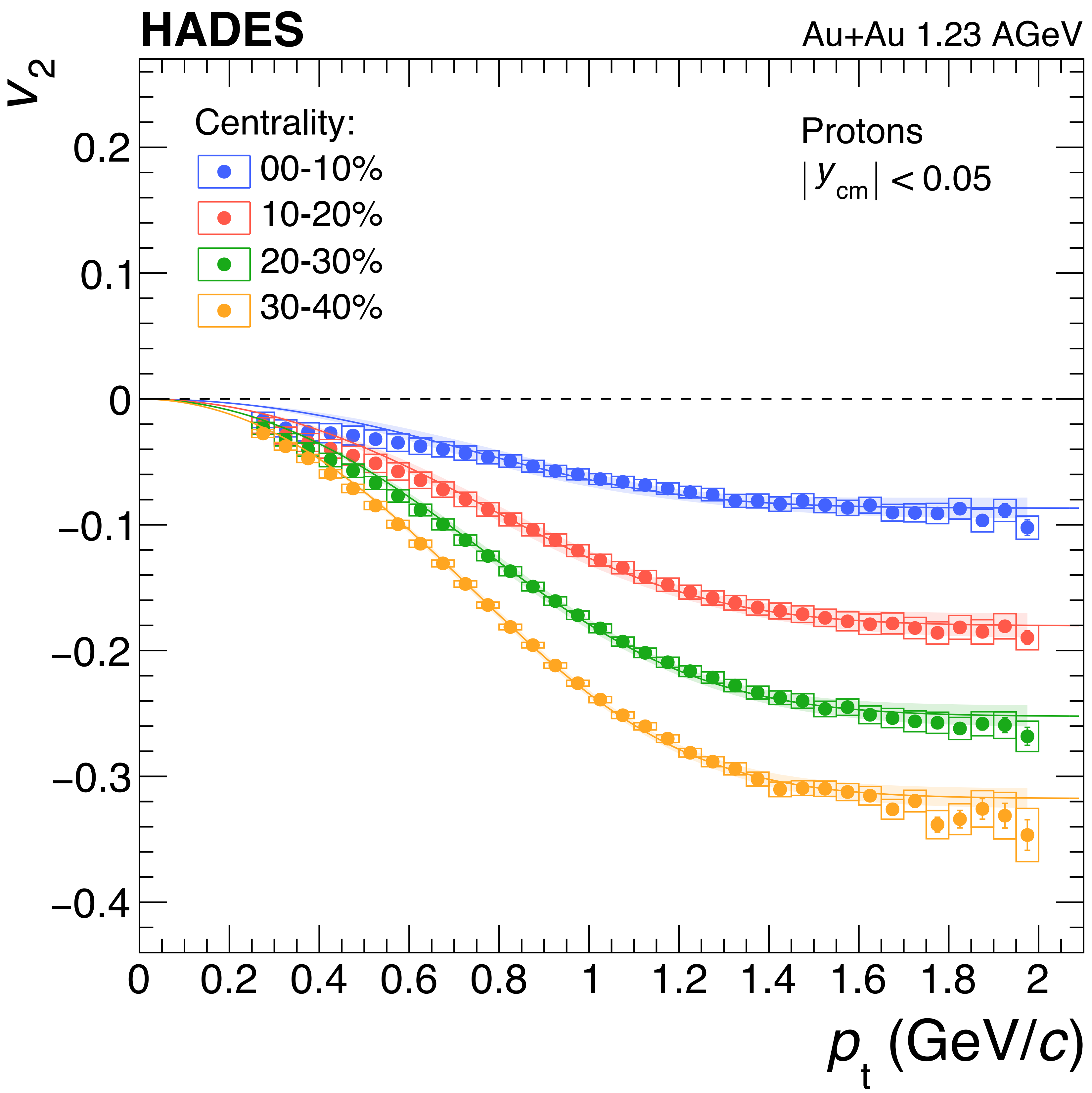
$$v_n^{even}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \cos(y_{cm}/y_{zi} \cdot \pi/2)$$

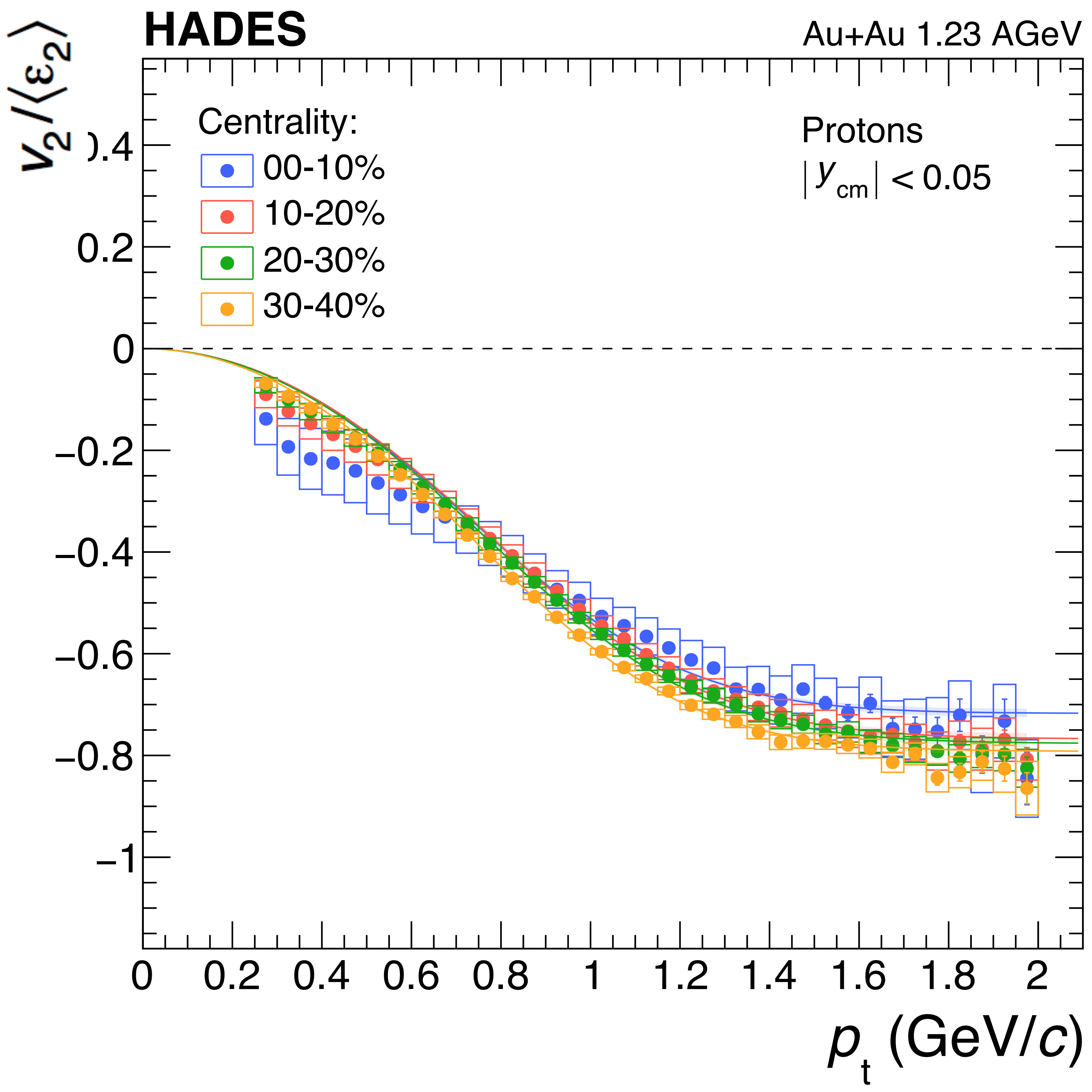
Simultaneous description of the rapidity and transverse momentum dependence with only 4 parameters for each centrality class, particle type and flow harmonic

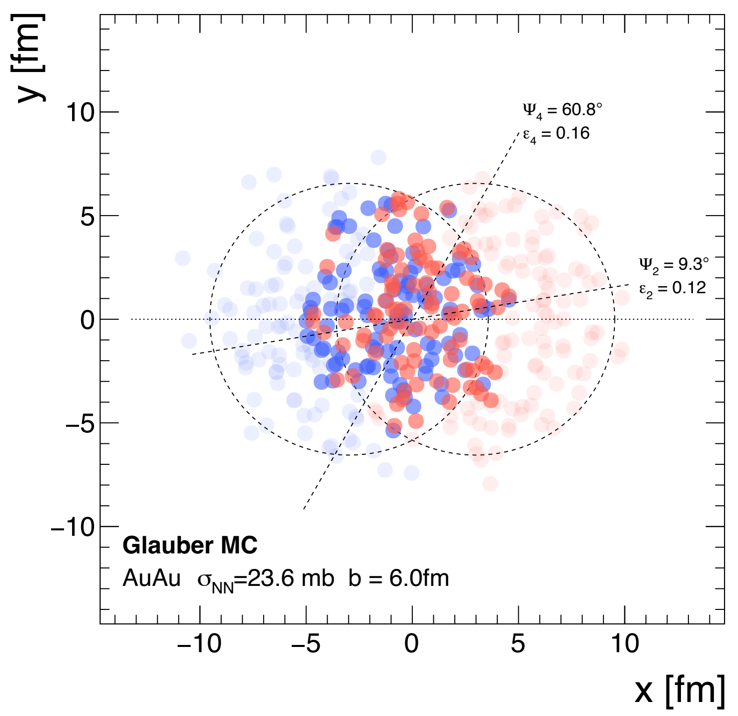
Geometry Scaling

Elliptic Flow v_2









Scaling with initial eccentricities

Calculated for overlap zone with Glauber MC

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

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

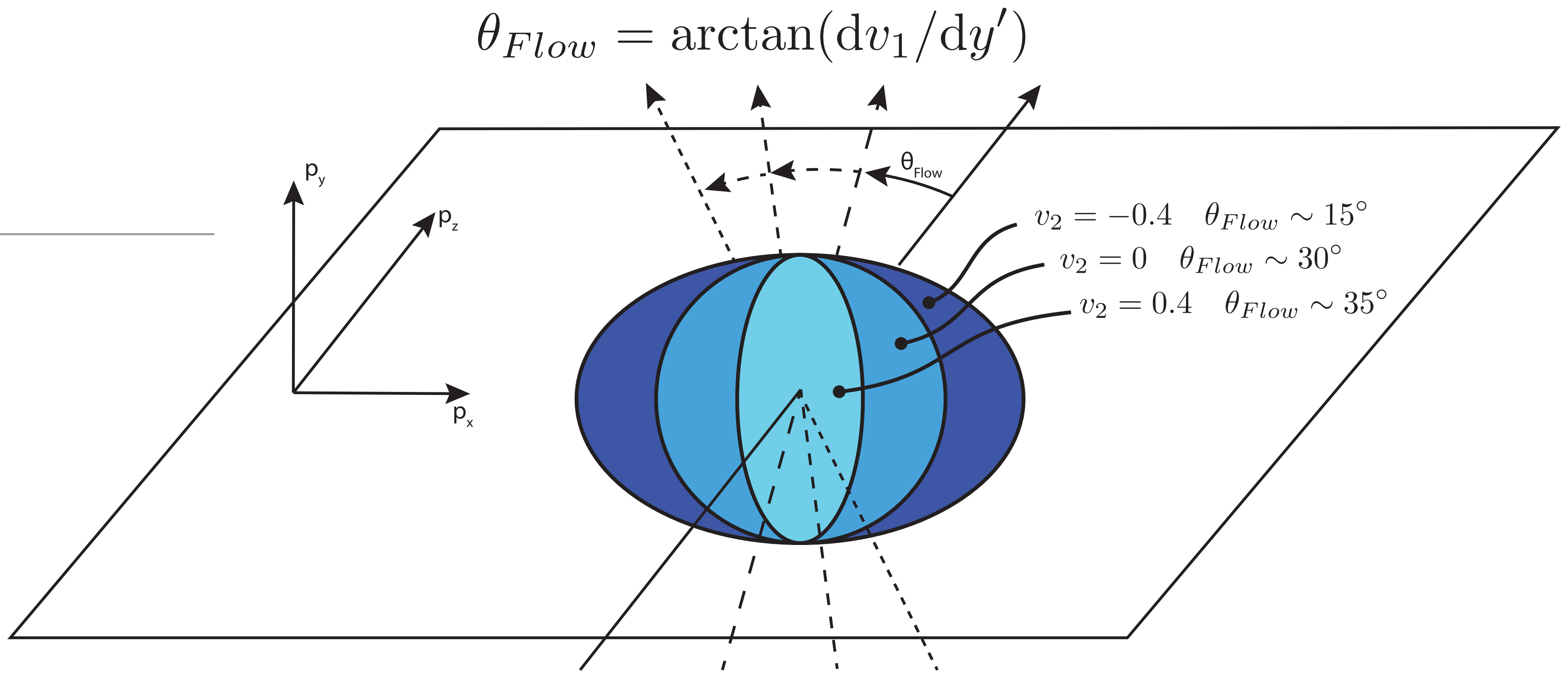
Orientation of symmetry-planes

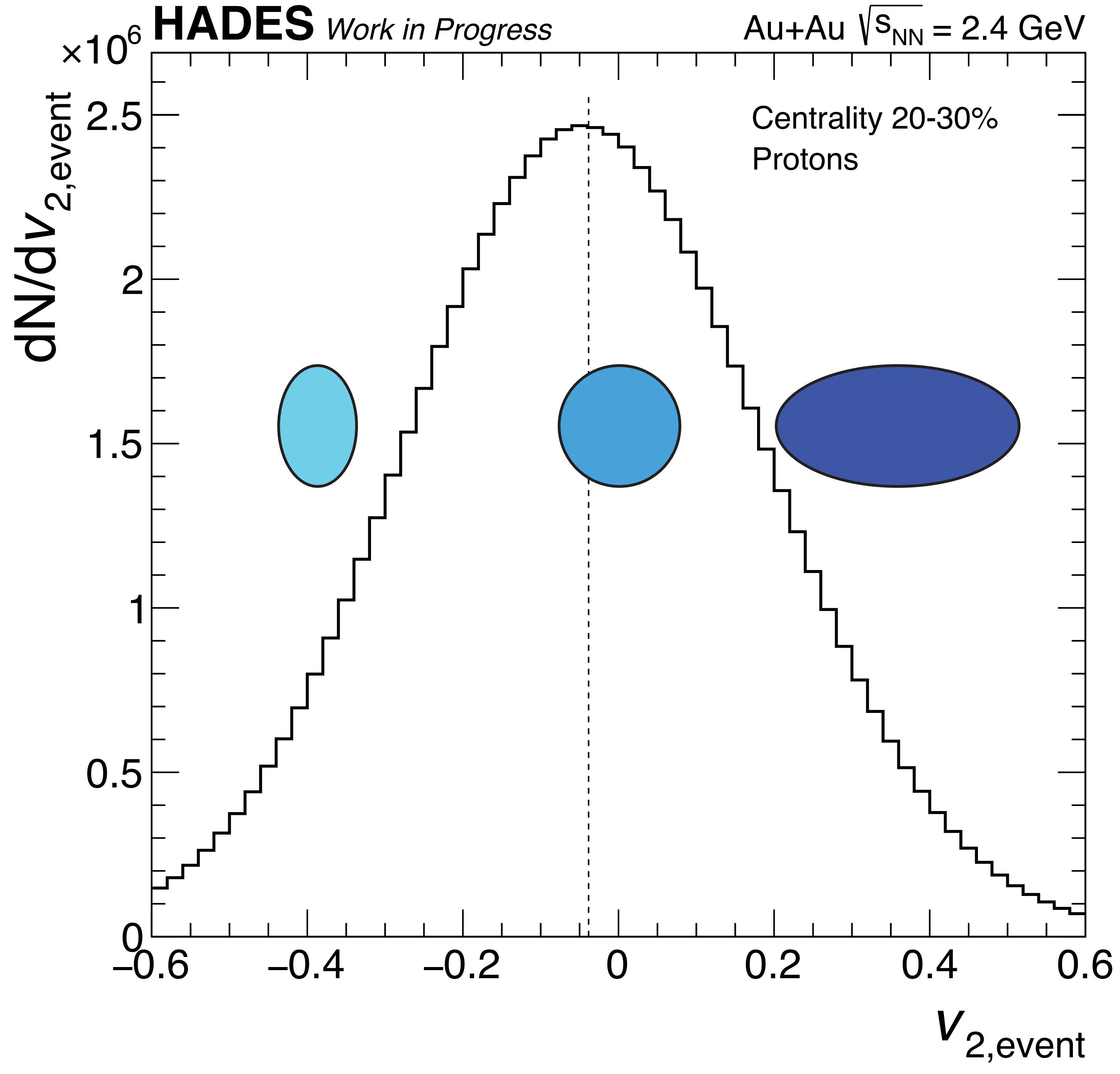
Negative $v_2/\langle\varepsilon_2\rangle$ values $\Longrightarrow$ v_2 Event- and ε_2 eccentricity-plane are orthogonal

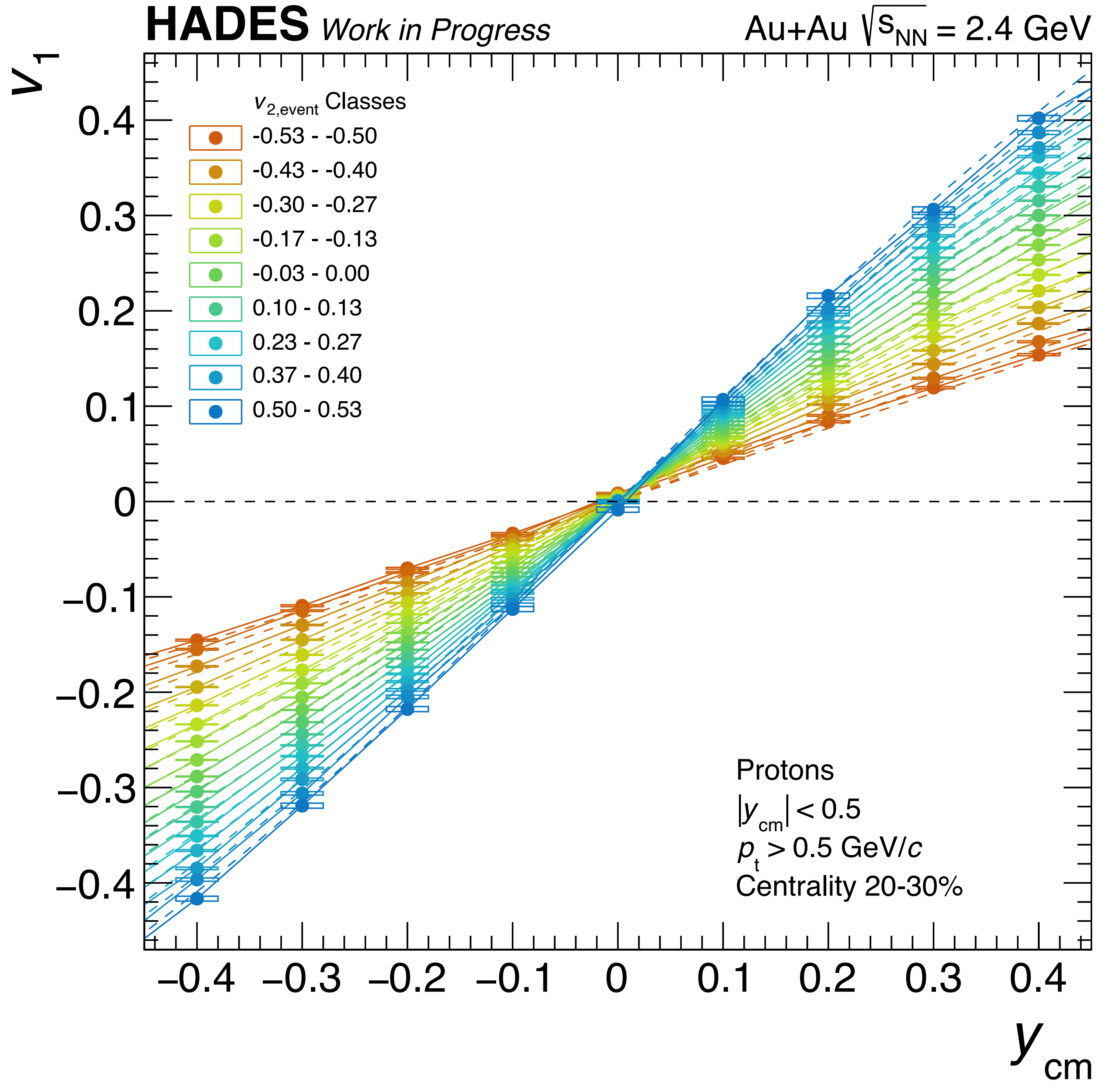
Similar scaling for v_4 with $\langle\varepsilon_2\rangle^2$

Event-wise Flow Correlations

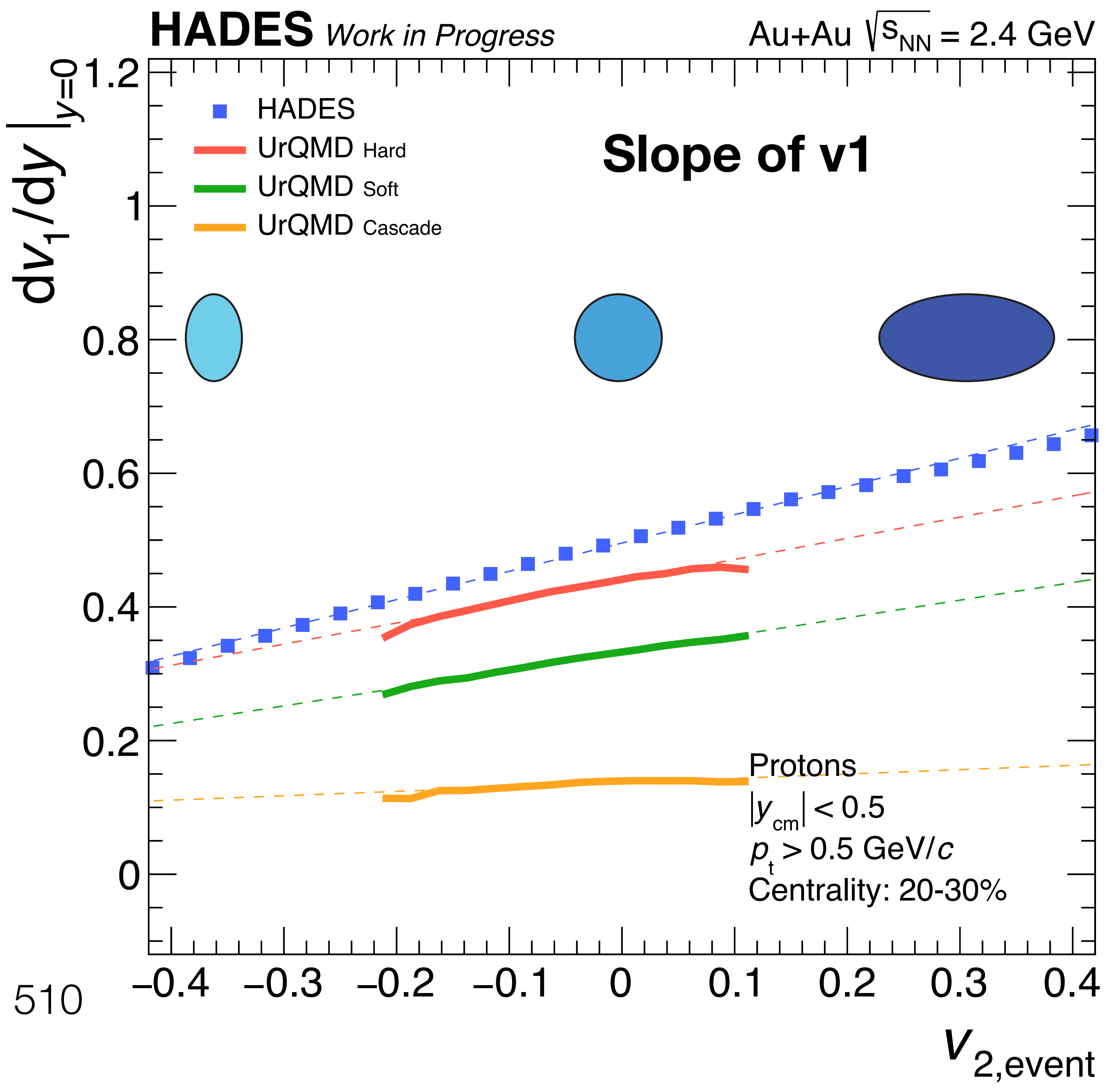
- Events can be characterised according the event-wise magnitude of the elliptic flow $v_{2,\mathrm{event}}$
- Slope of directed flow $dv_1/dy|_{y=0}$ resp. flow angle θ_{Flow}



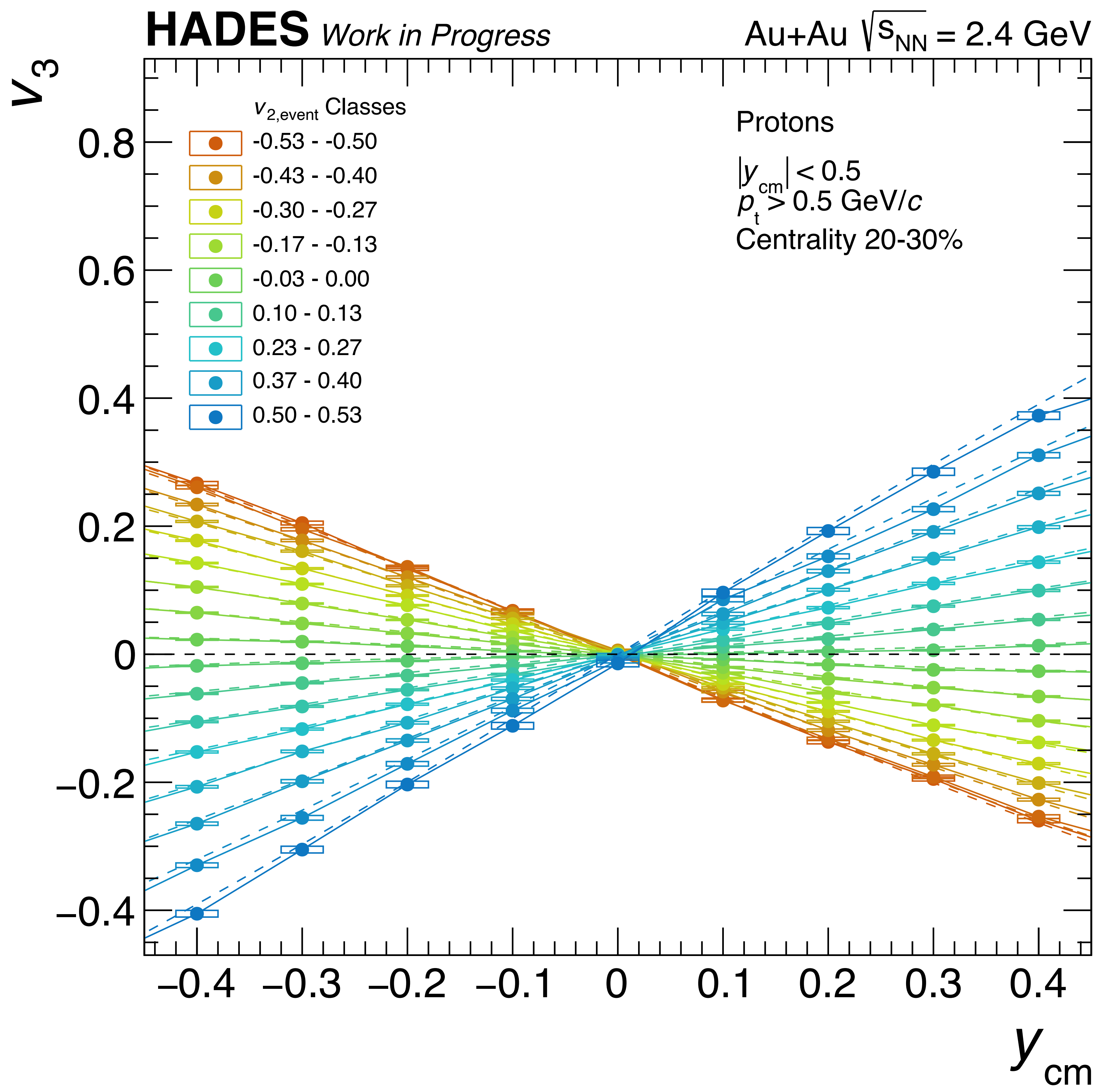


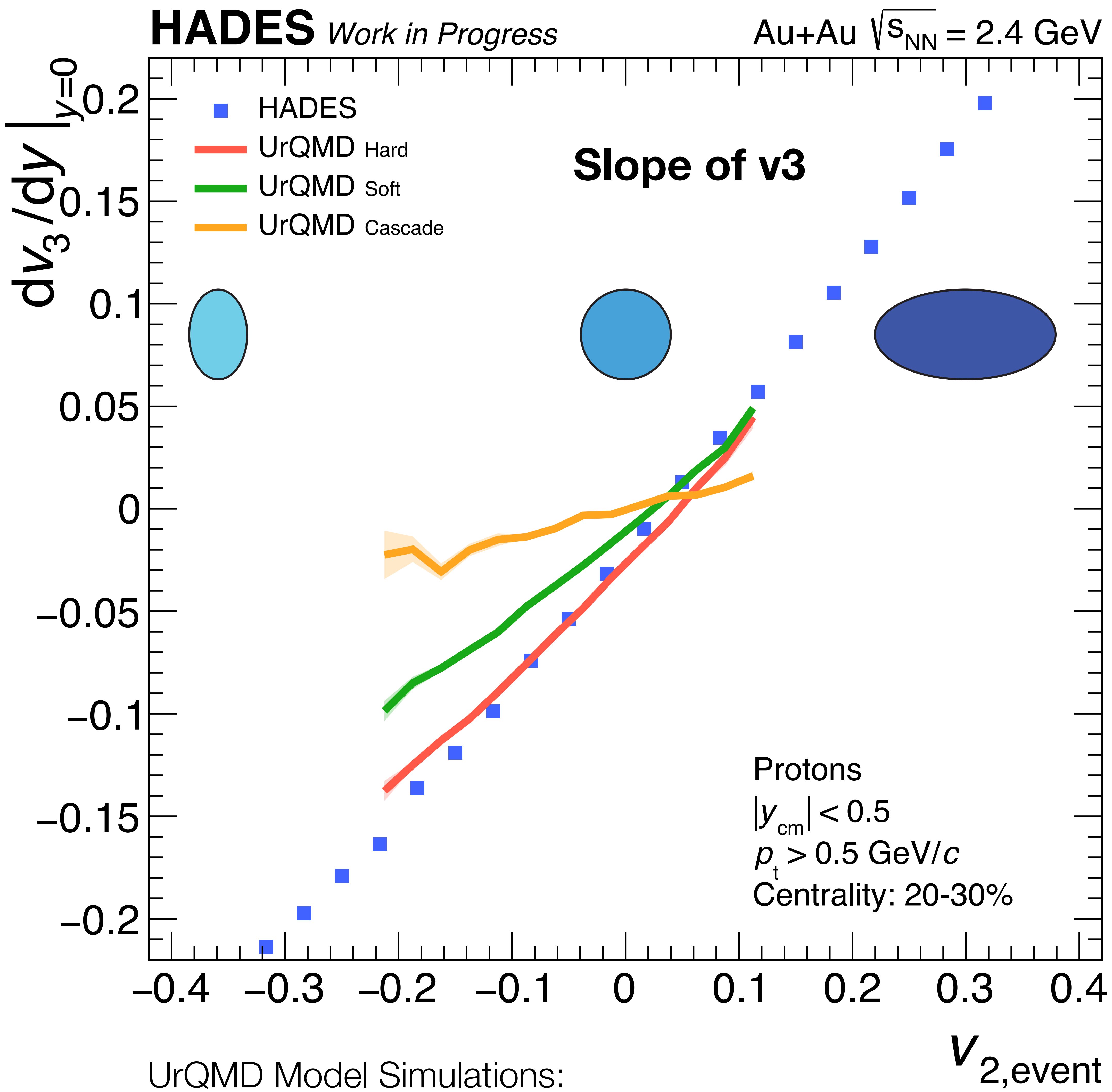


UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510



Event-wise Flow Correlations





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

Slope of the Triangular Flow v_3

A strong sensitivity to the EoS is seen

Not corrected the underlying multiplicity fluctuations

Model Comparisons to Proton Data

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

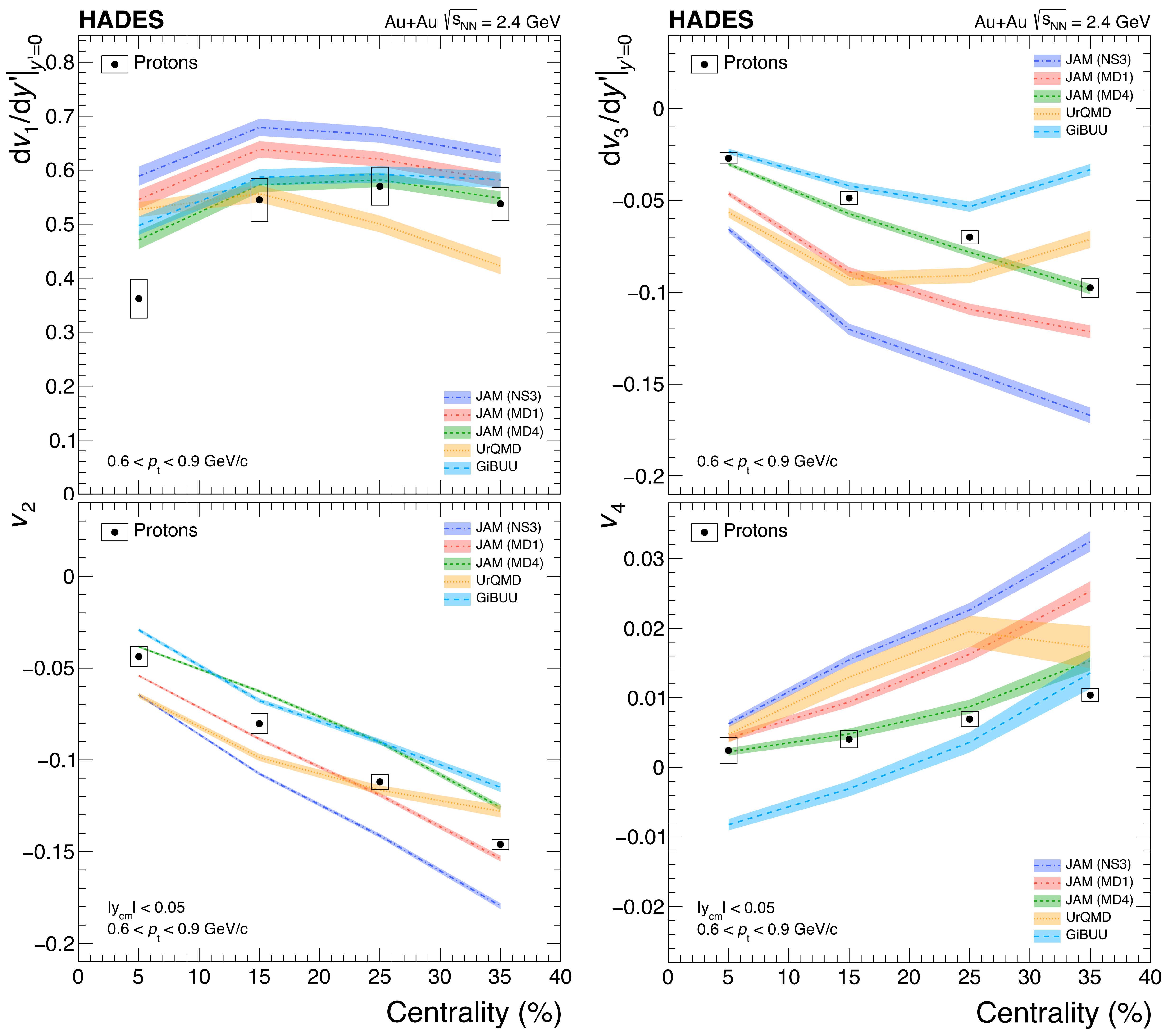
Conclusions

Overall trend reasonably described, but no model works everywhere

Several systematic deviations can be linked to different implementation in transport codes

Mechanism of light nuclei production is essential for the description of the data

HADES, arXiv:2208.02740



Conclusions

General Parameterisation

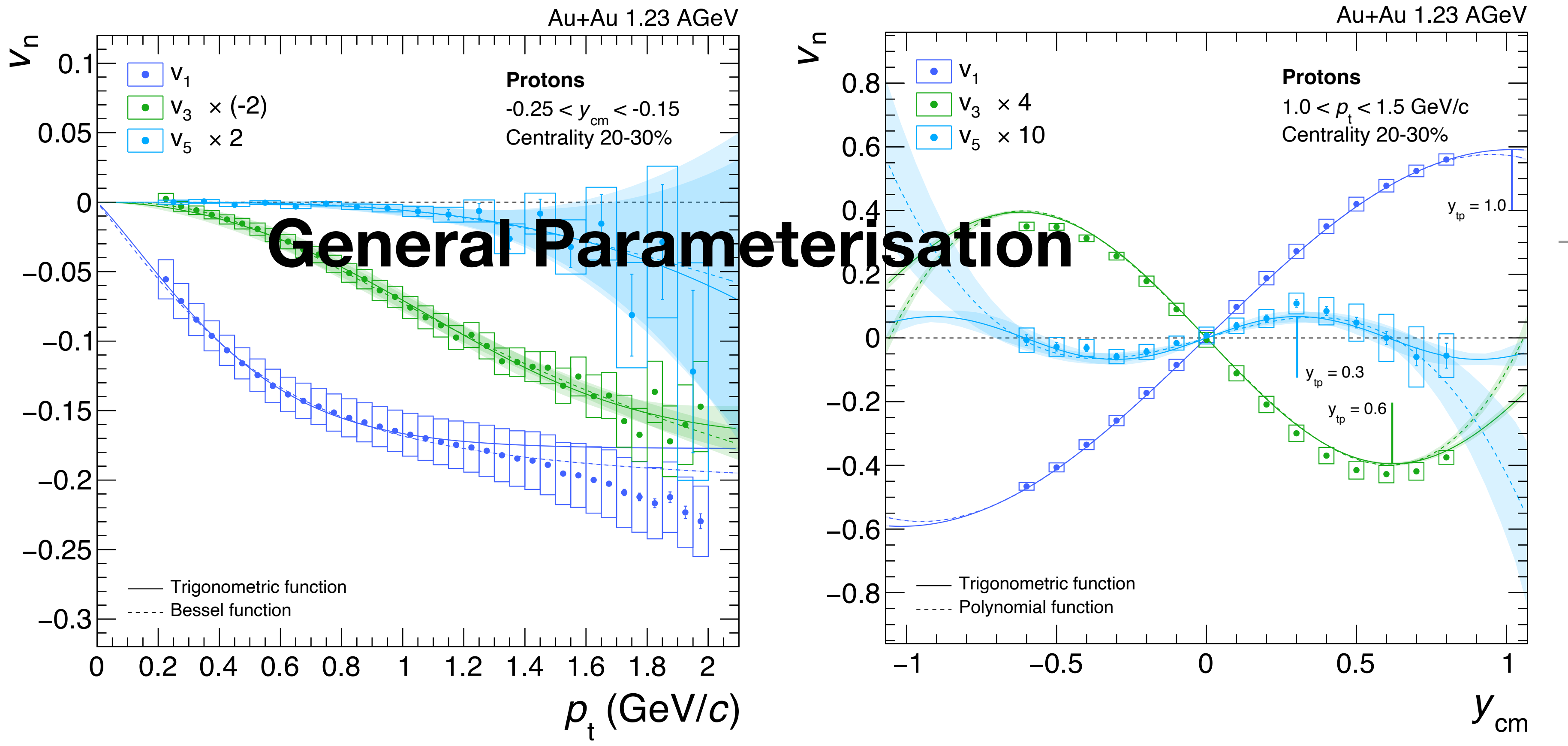
- Phenomenological approach based on hydrodynamic inspired Blast Wave model

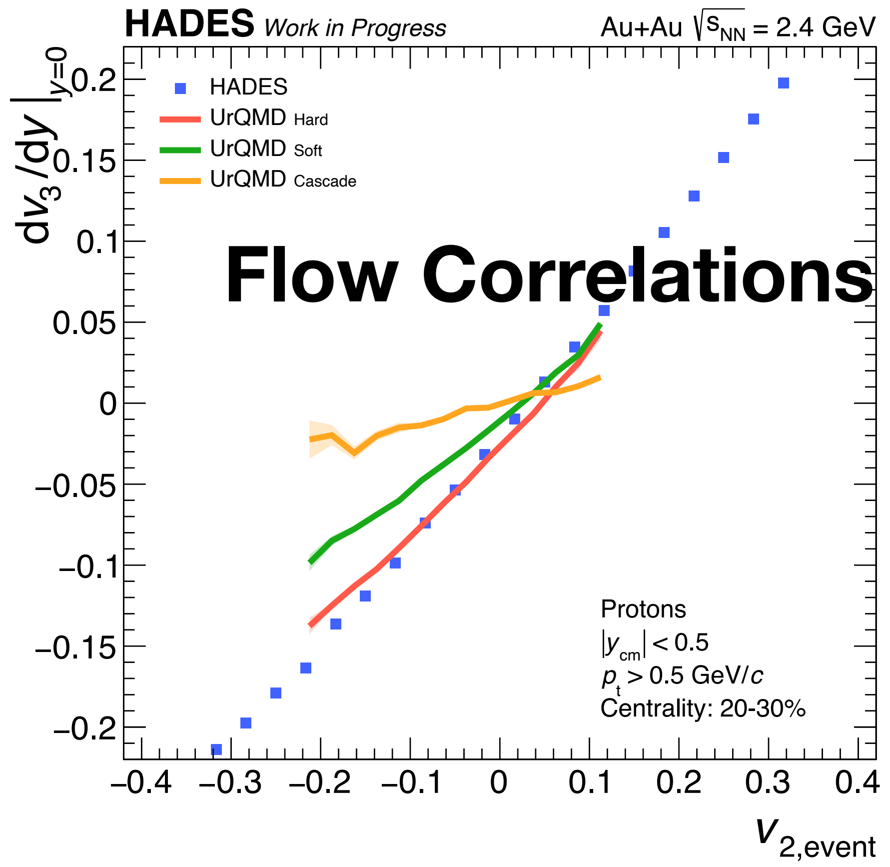
Scaling Properties

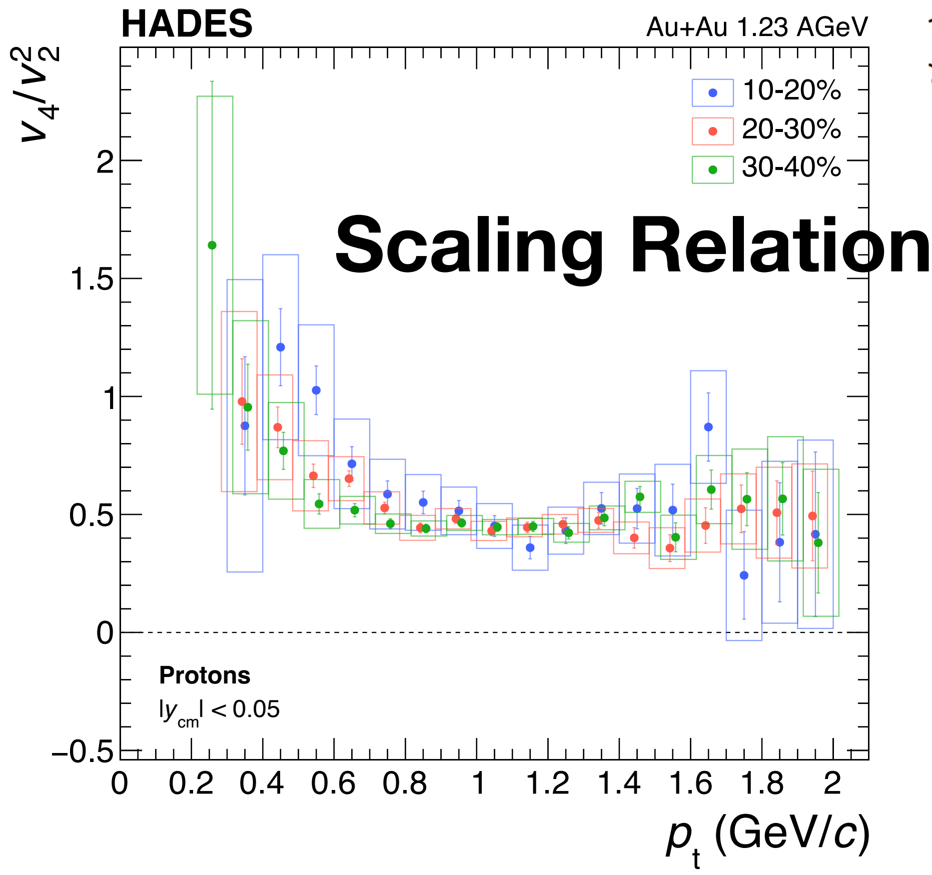
- Scaling relation between flow coefficients
  Hydro-like matter at SIS energies?
- Correlation between Flow coefficients event-wise
- Geometrical Scaling to initial overlap eccentricities

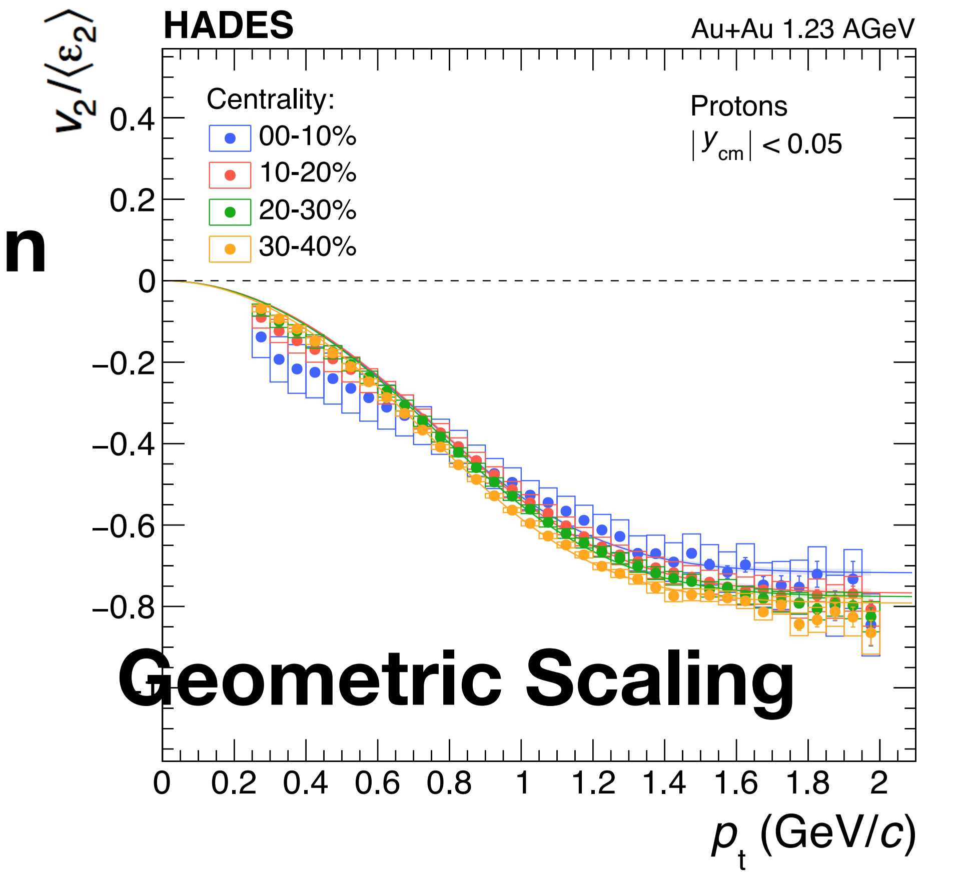
Model Comparison

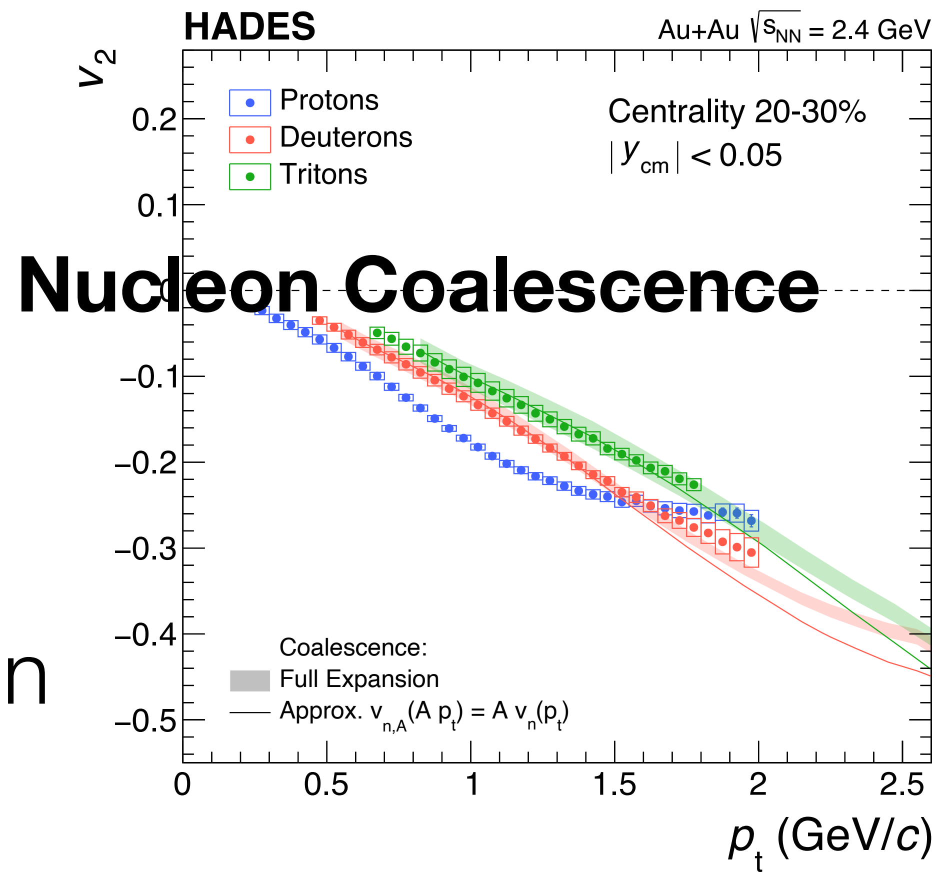
- Multi-differential analysis including higher orders
  New level of precision
- Importance of the mechanism of light nuclei production

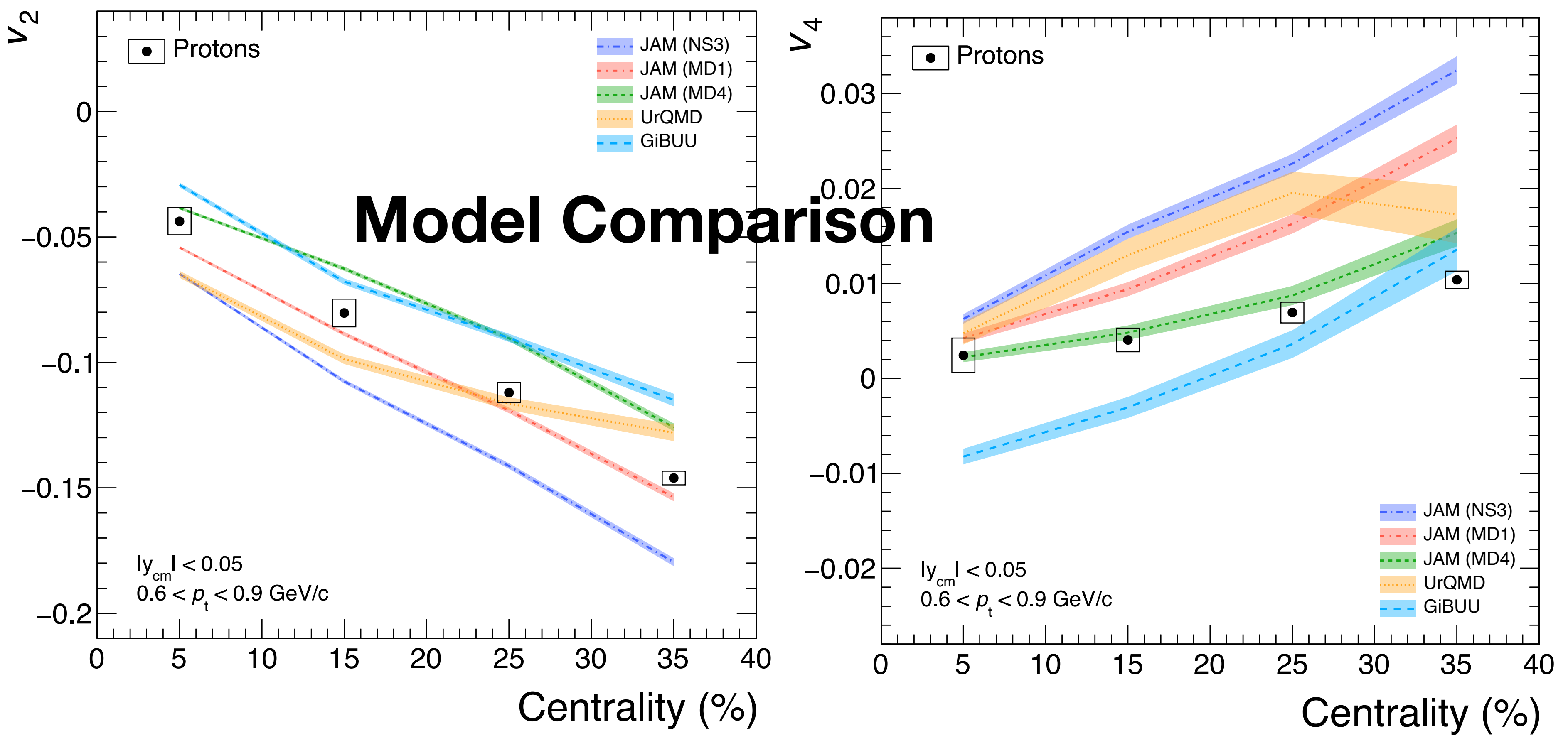

General Parameterisation


Flow Correlations


Scaling Relation


Geometric Scaling


Nucleon Coalescence


Model Comparison

Outlook

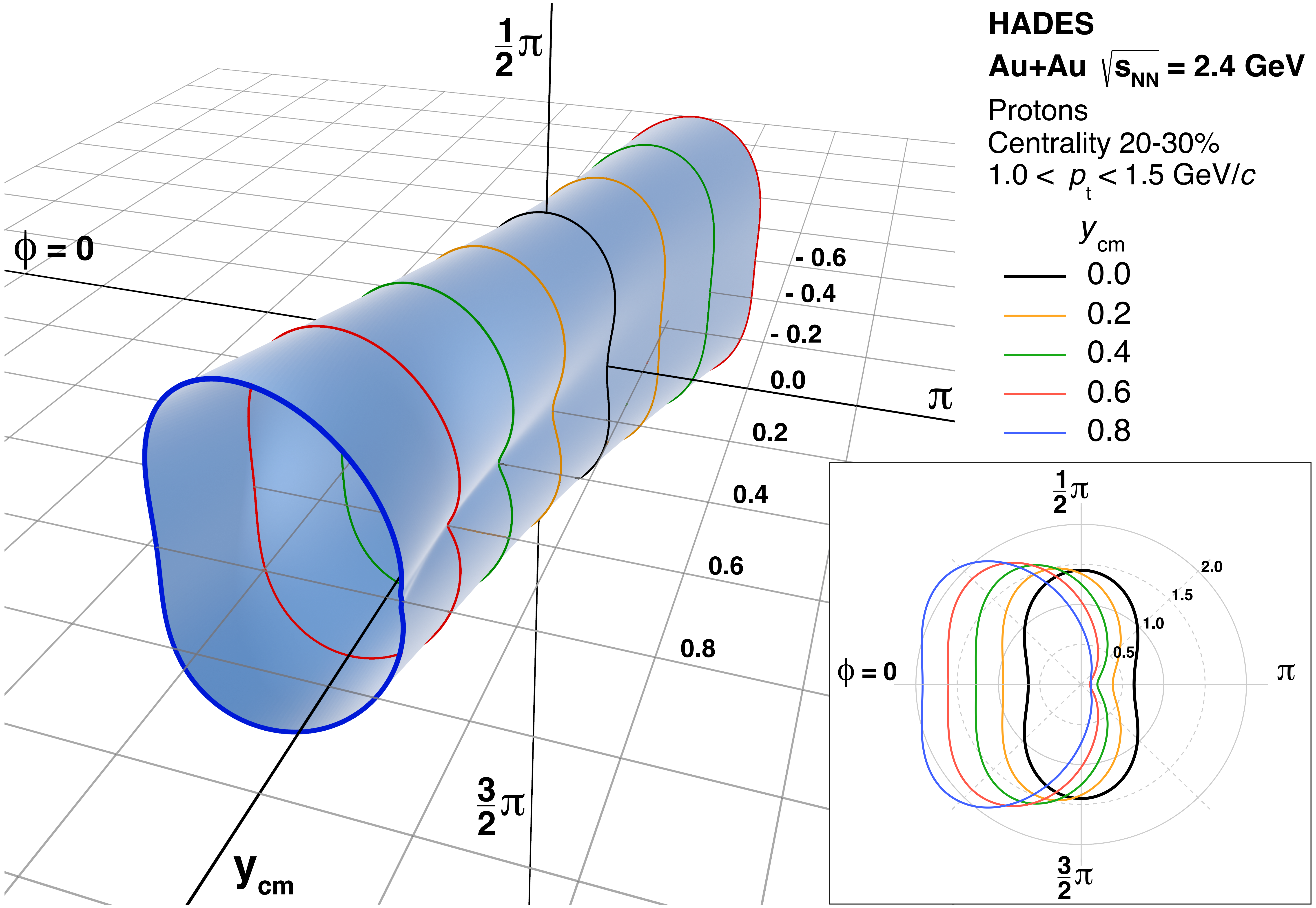
Next Steps towards EOS

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
C+C at 0.8 AGeV (Feb. 2024)
Au+Au at 0.2 and 0.8 *A*GeV (March 2024)




GSI April 2024

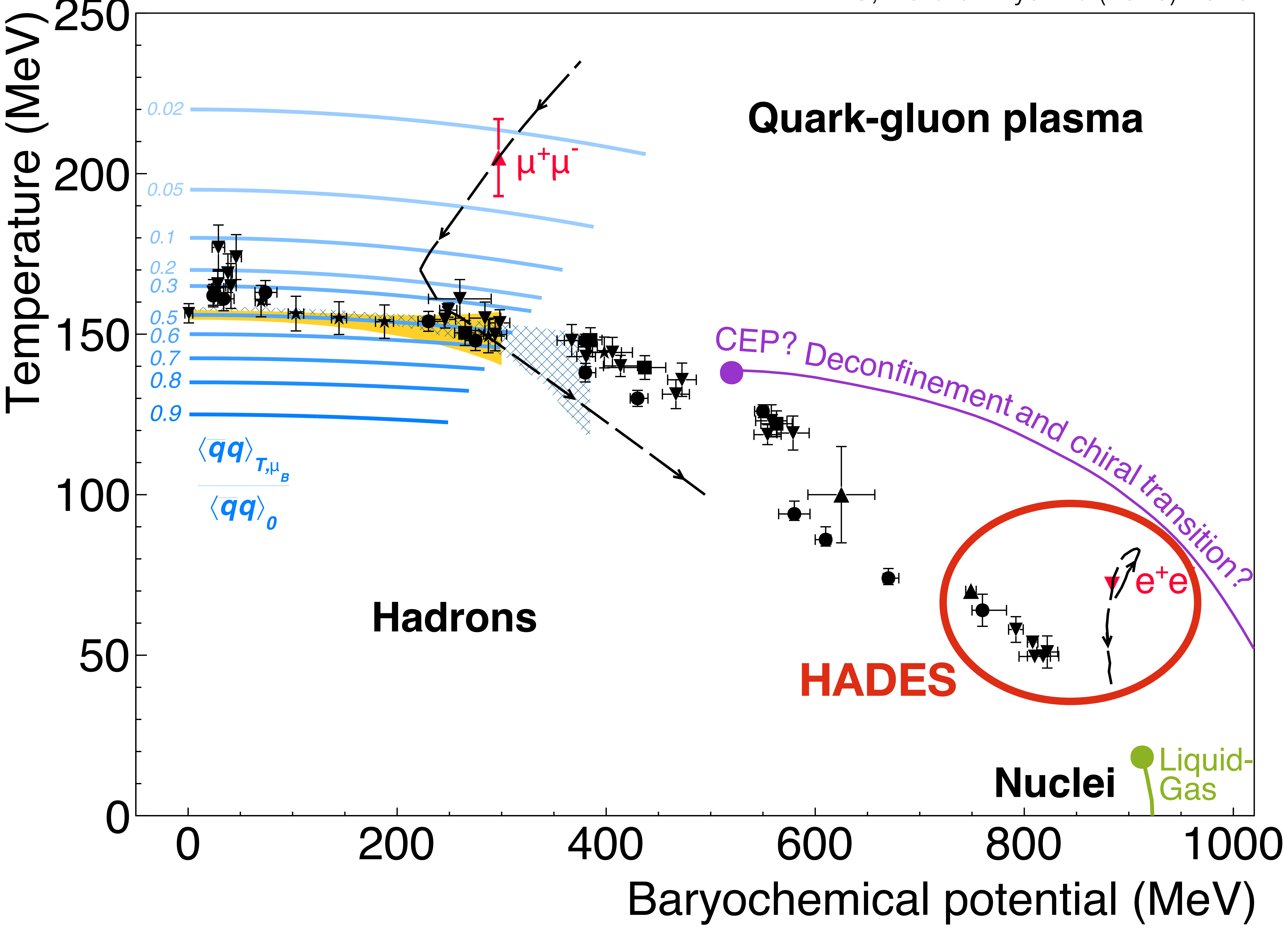
HADES Collaboration

Thank you for your attention!

Dense nuclear matter and astrophysics

Phase diagram of QCD Matter

- Deconfinement phase transition
  - Indications for crossover transition at high energies corresponding to vanishing μ_B (e.g. LHC)
  - Conjecture of 1. order phase transition at low energies corresponding to high μ_B (e.g. SIS100/FAIR, SIS18/GSI)
  - Critical End Point (CEP)
- HADES at SIS18
  - Nucleons essentially stopped in collision zone
  - Baryon dominated fireball ⇒ μ_B ~ 800 MeV



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

Nucleon Coalescence

Scaling Properties of v_2 at Mid-Rapidity

Scaling of v_2 and p_t with nuclear mass number A

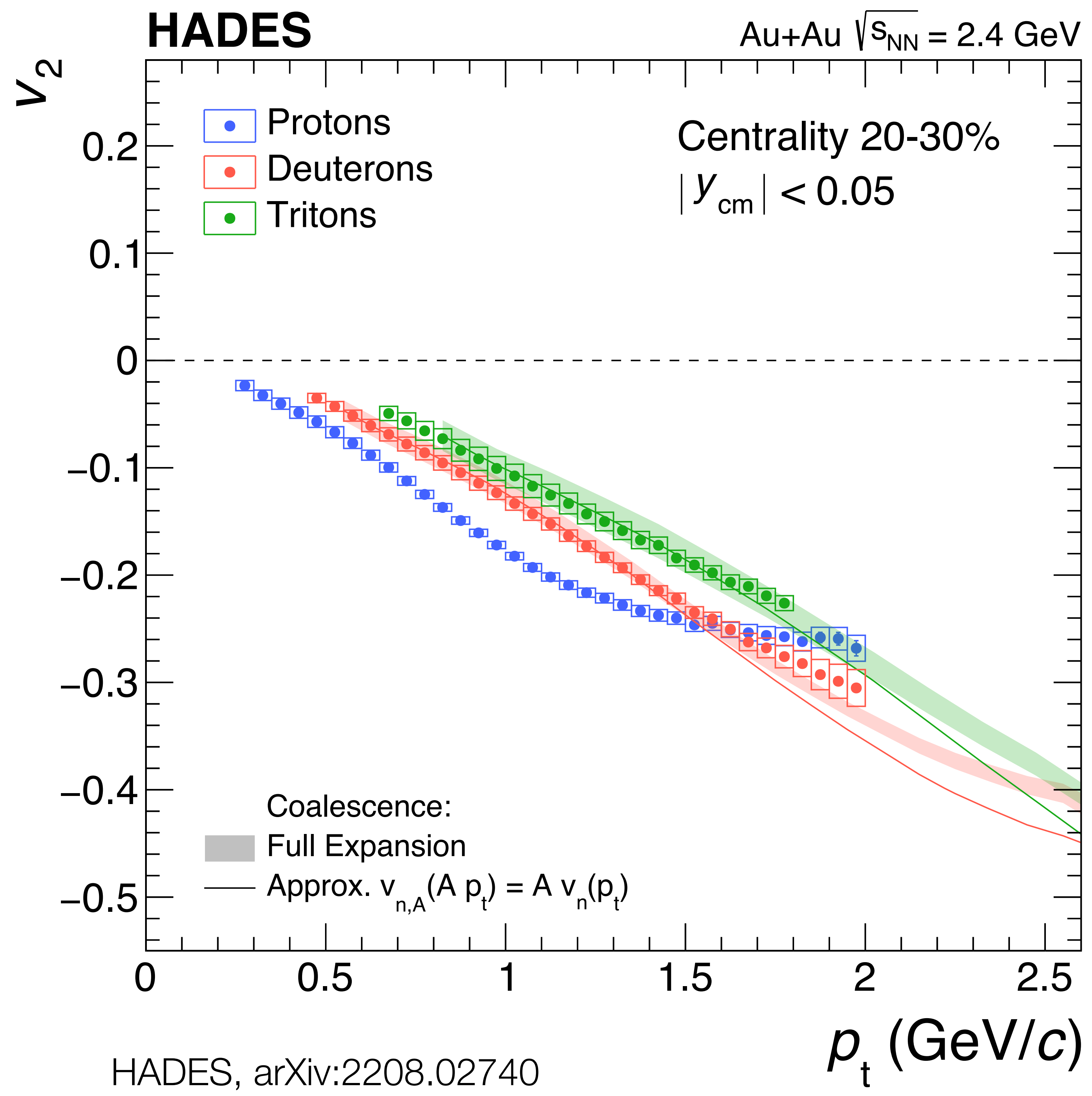
Inclusion of higher order terms

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

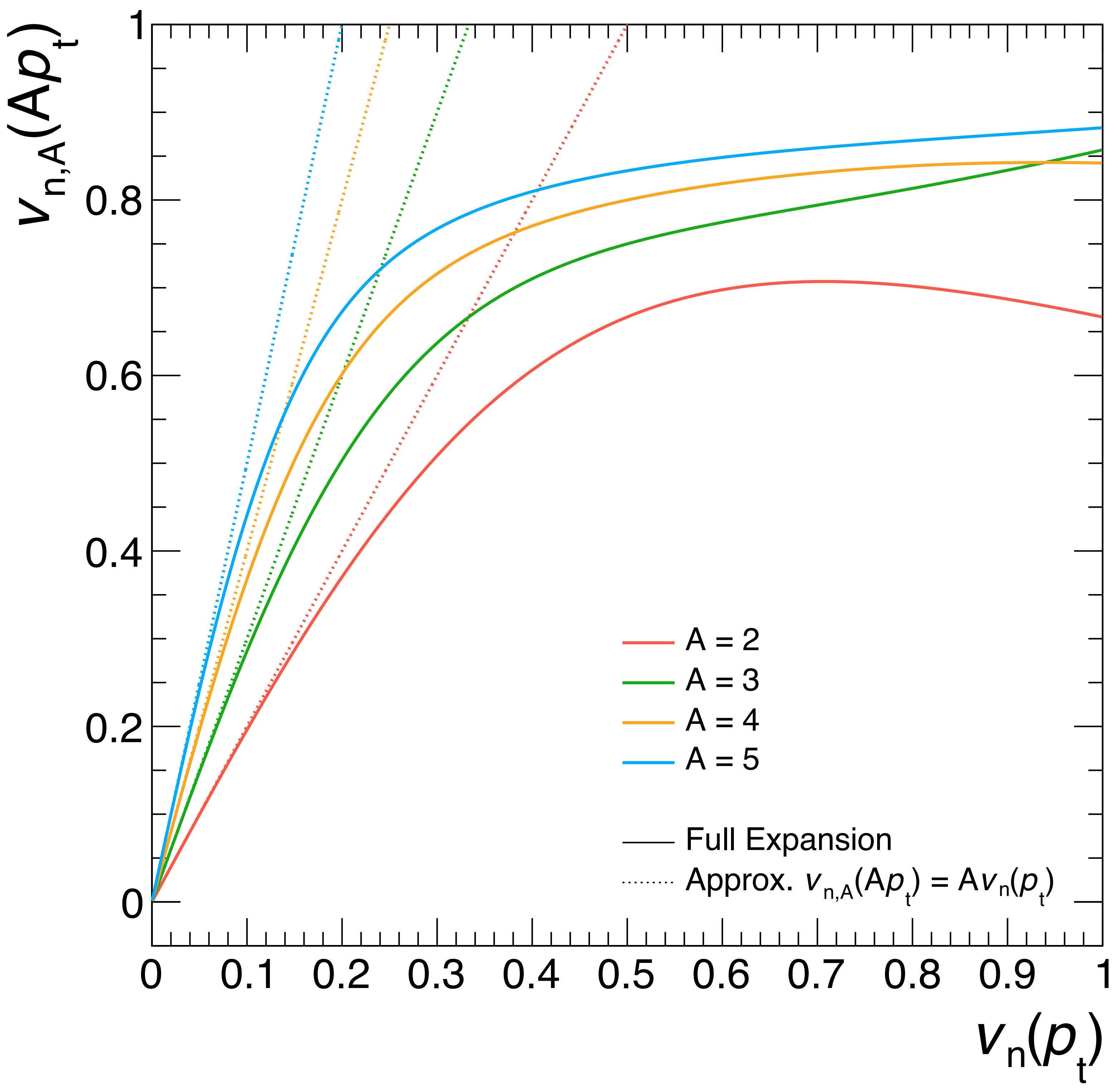
Odd flow coefficients vanish at mid-rapidity and v_4 contribution is negligible

Approximation for small v_n

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



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

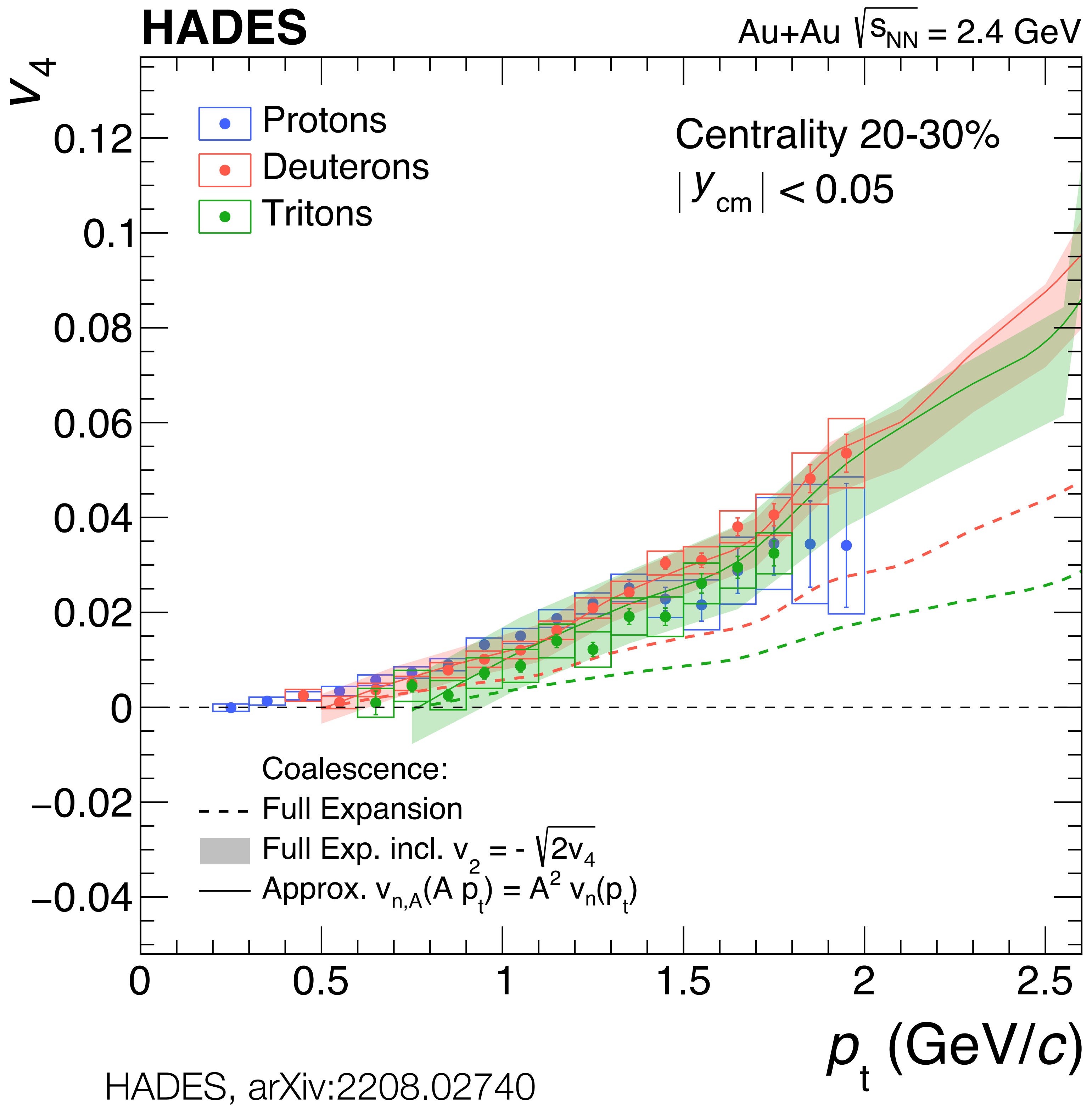
Scaling of v_4 and p_t with nuclear mass number A

Inclusion of higher order terms and contribution of v_2

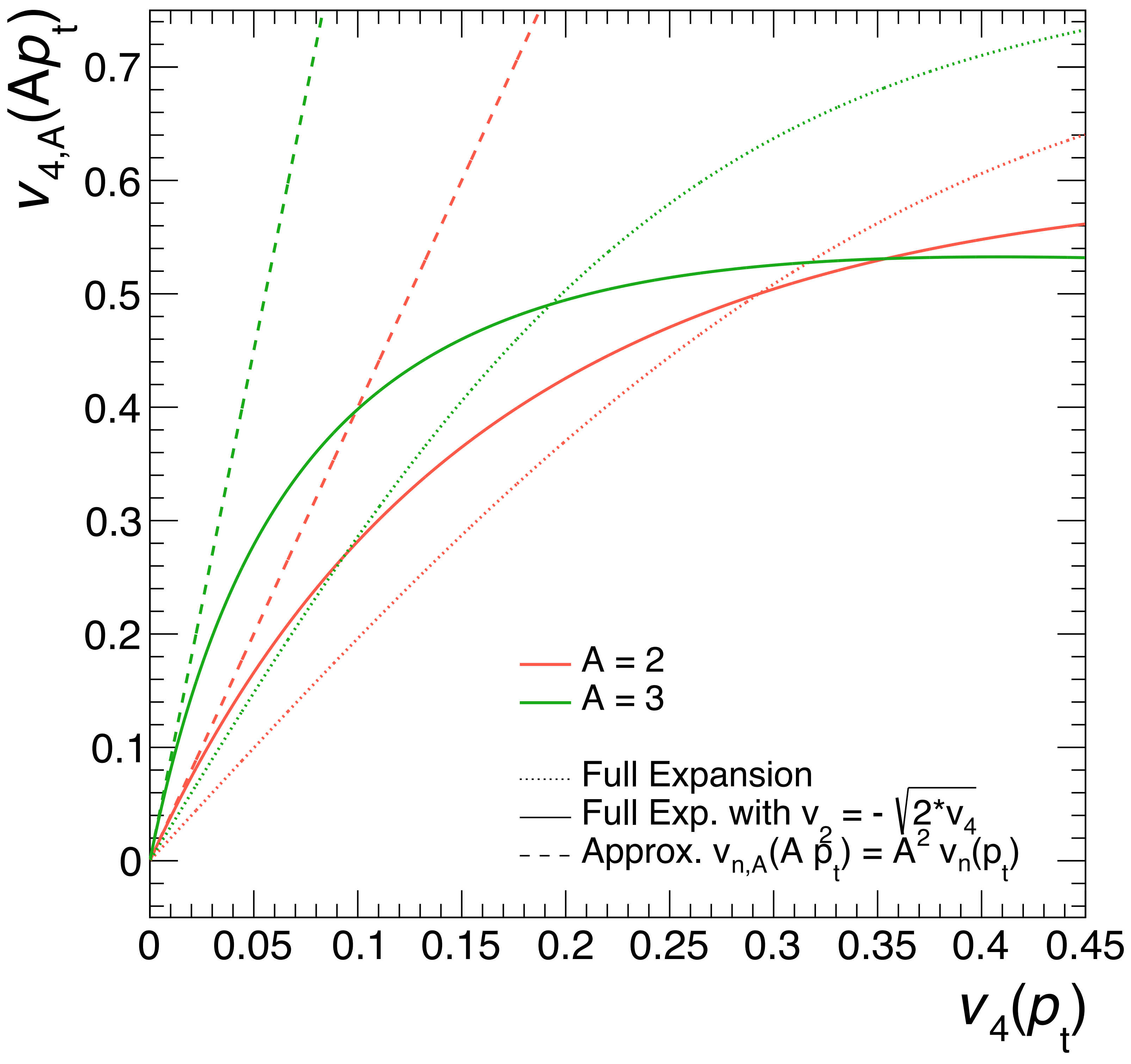
Works as expected in simple coalescence picture if contribution of dominant flow coefficient is included

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

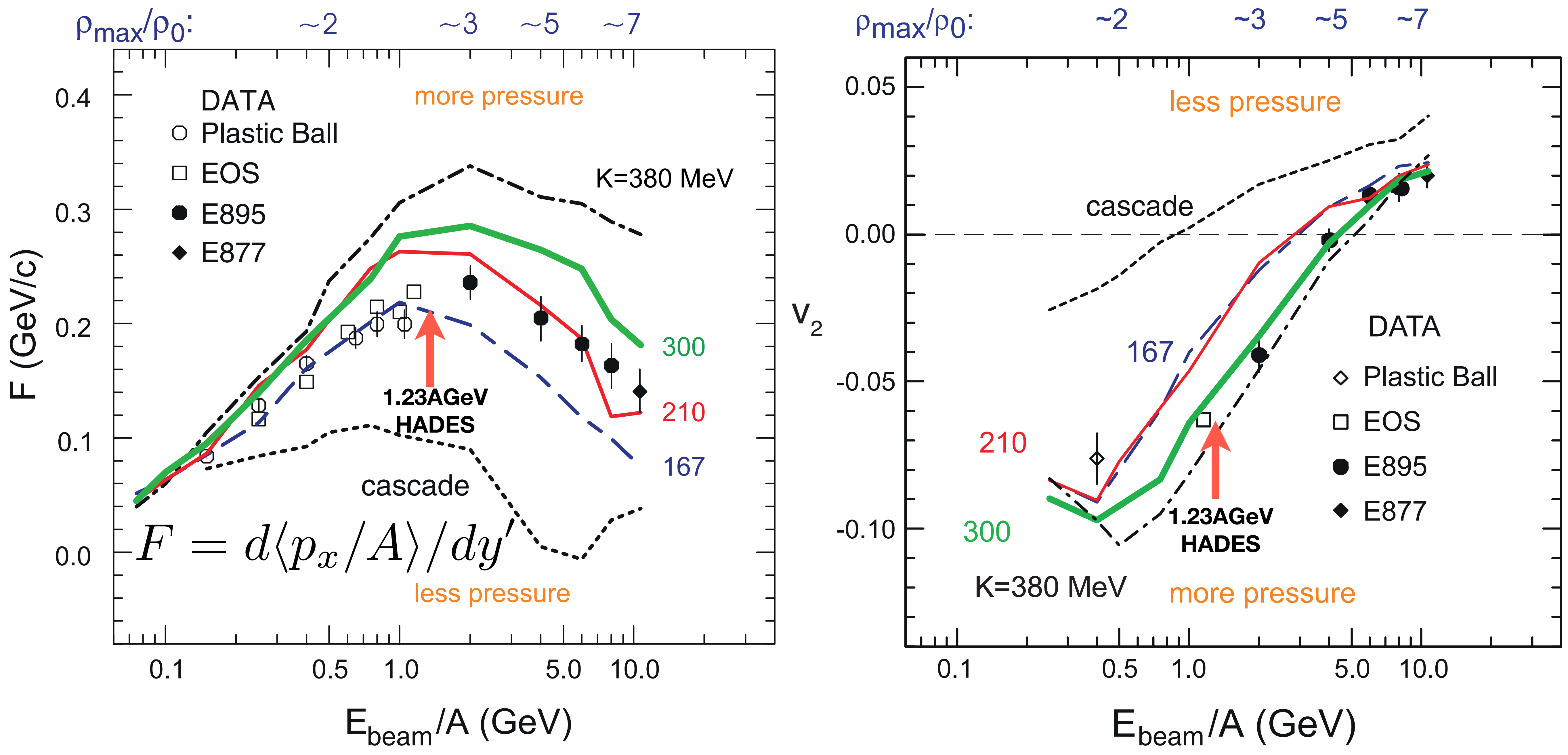
D. Molnar and S.A. Voloshin PRL **91** (2003) 092301
P.F. Kolb et al., PRC **69** (2004) 051901

Equation of State of Dense Matter

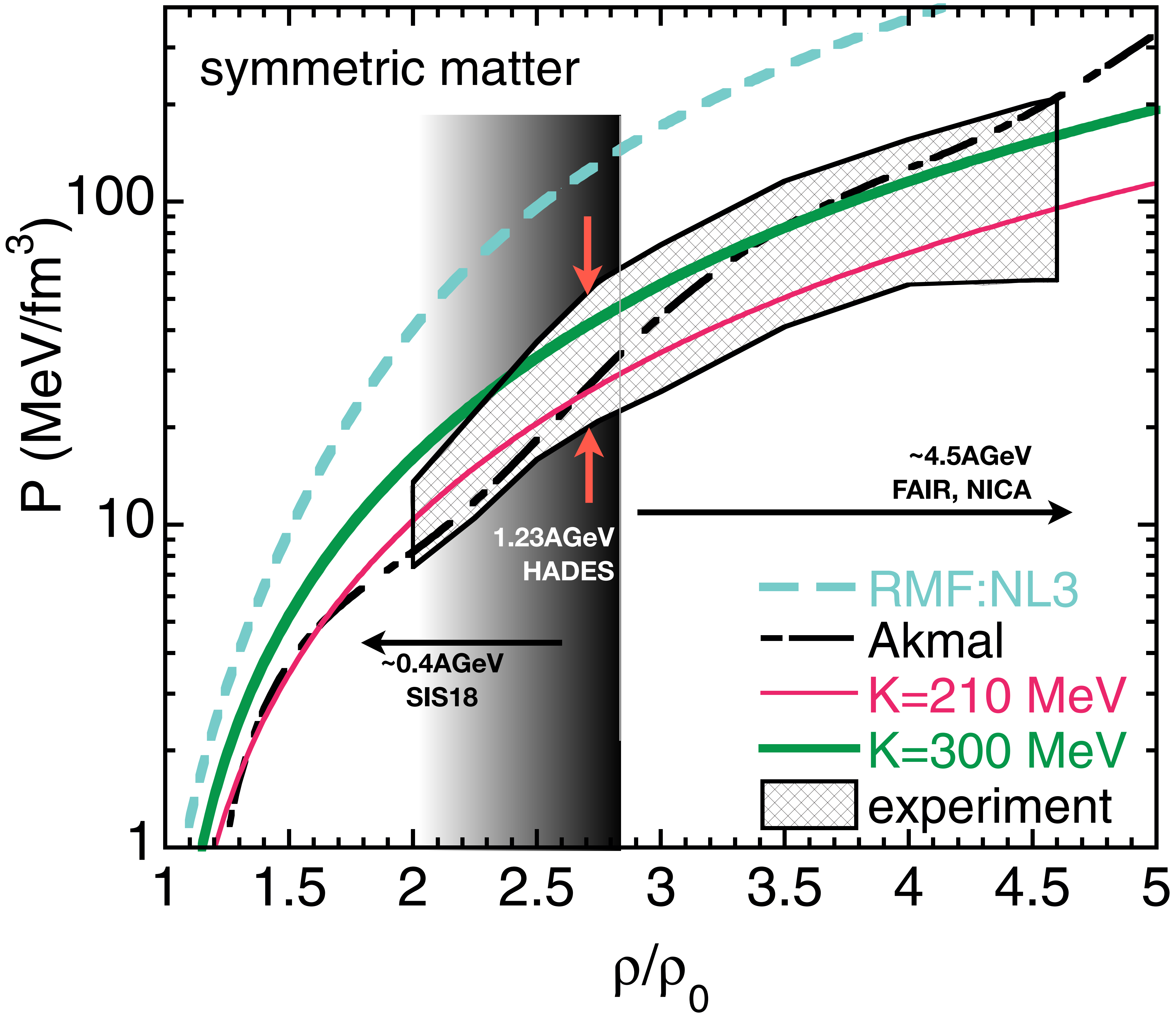
- EoS is the *equilibrium* property of Hydrodynamical simulations

  Non-equilibrium dissipative effects are described by transport coefficients (shear viscosity $\boldsymbol{\eta}$)

- In microscopic transport models implemented via *averaged mean-field potentials* (Skyrme-like or RMF)



P. Danielewicz, R. Lacey, W.G. Lynch
Science 298 (2002) 1592-1596

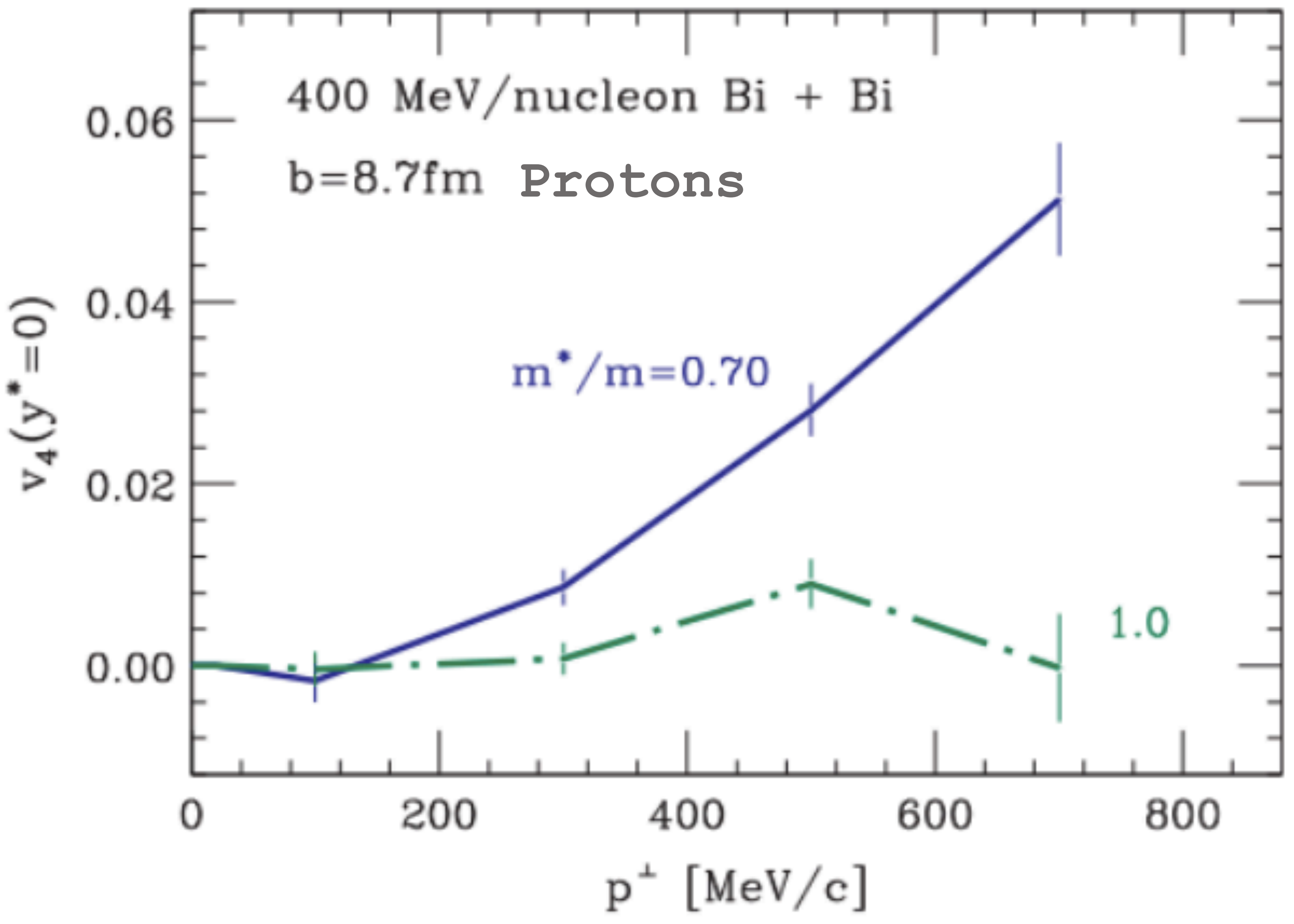


Equation of State of Dense Matter

Momentum Dependence of the mean fields

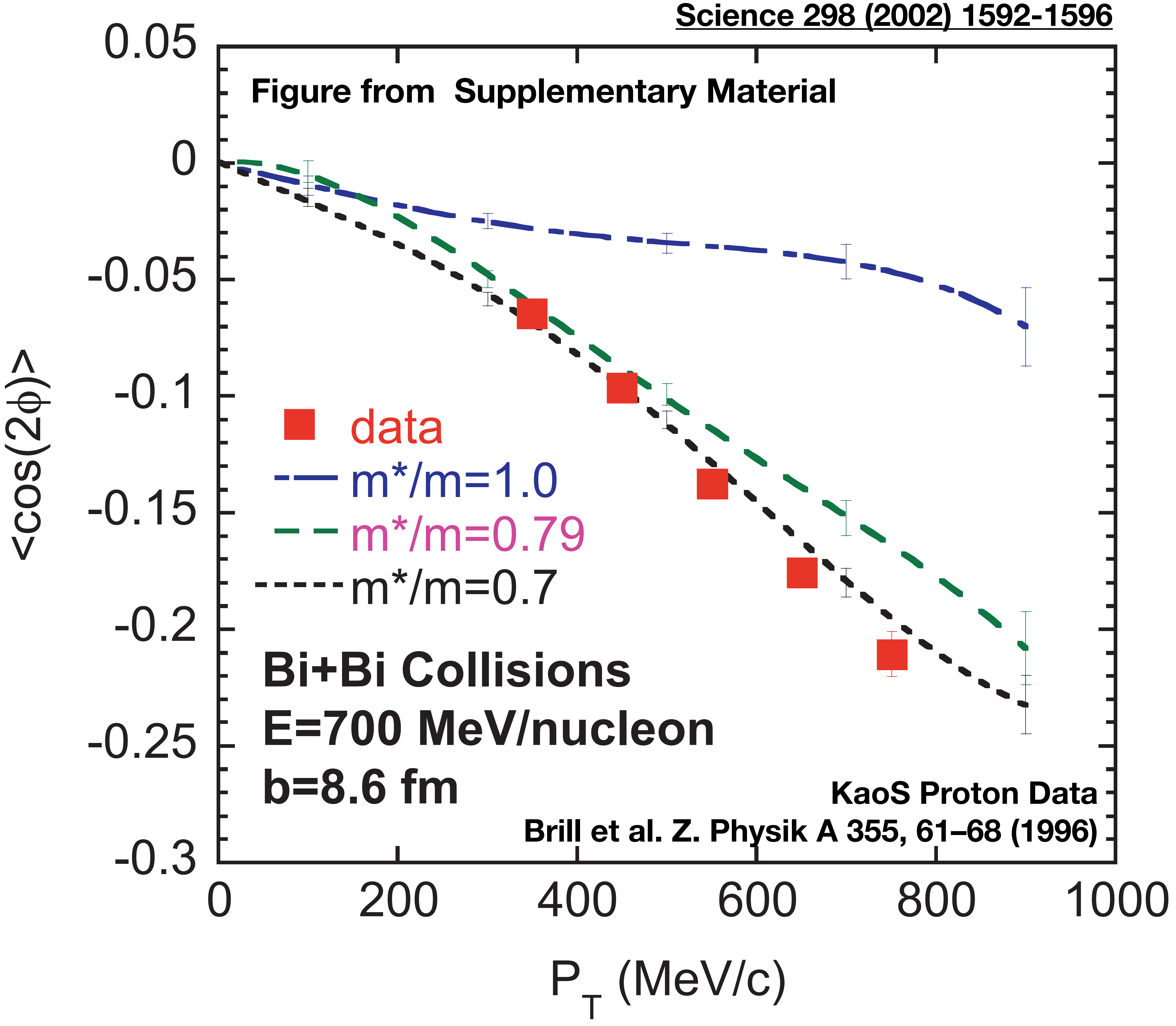
Momentum dependence characterized by **$m^*=0.7m_N$**

P. Danielewicz
Nucl.Phys.A 673 (2000) 375-410



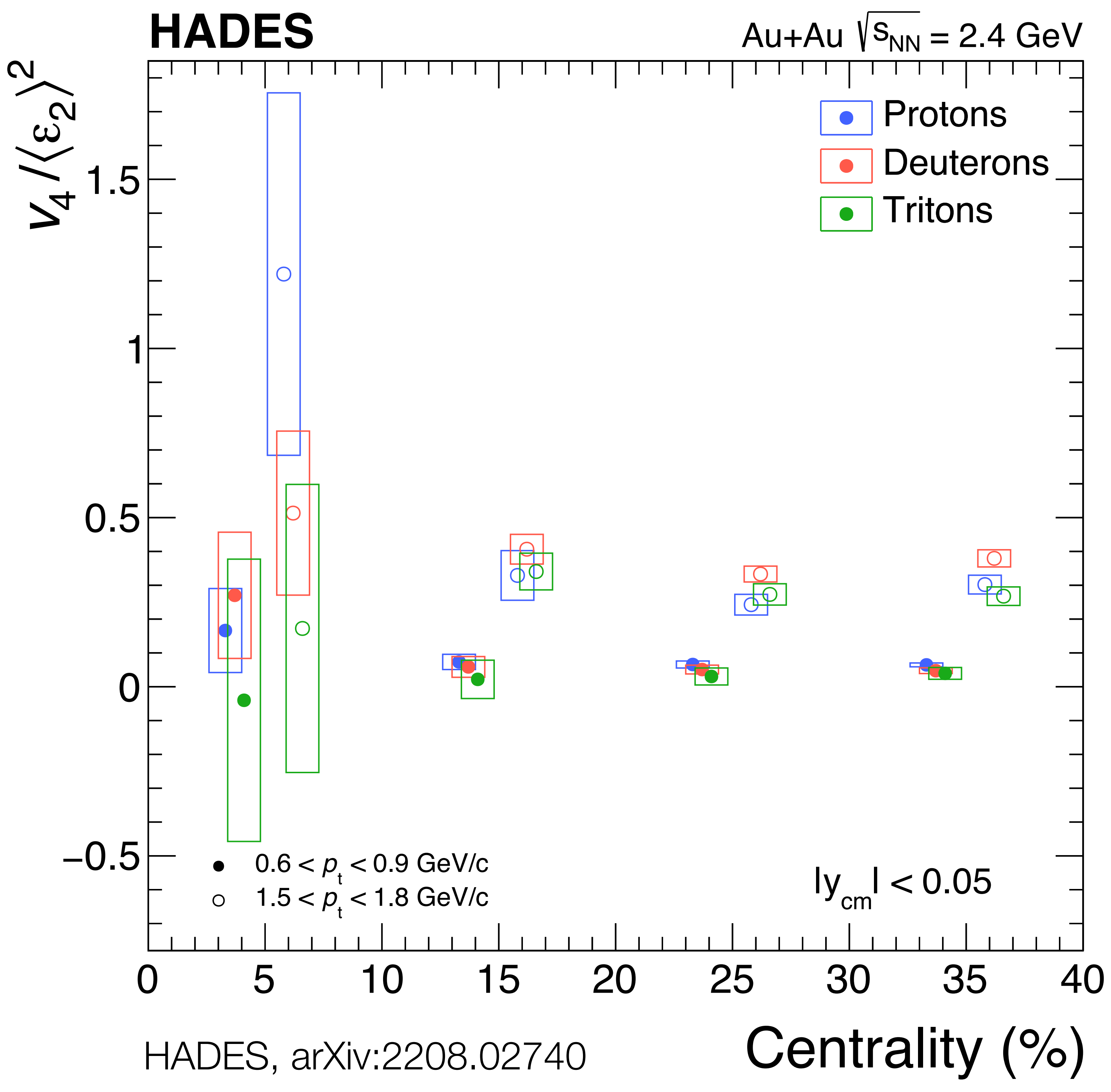
First prediction of v_4{RP} in 2000!

P. Danielewicz, R. Lacey, W.G. Lynch
Science 298 (2002) 1592-1596

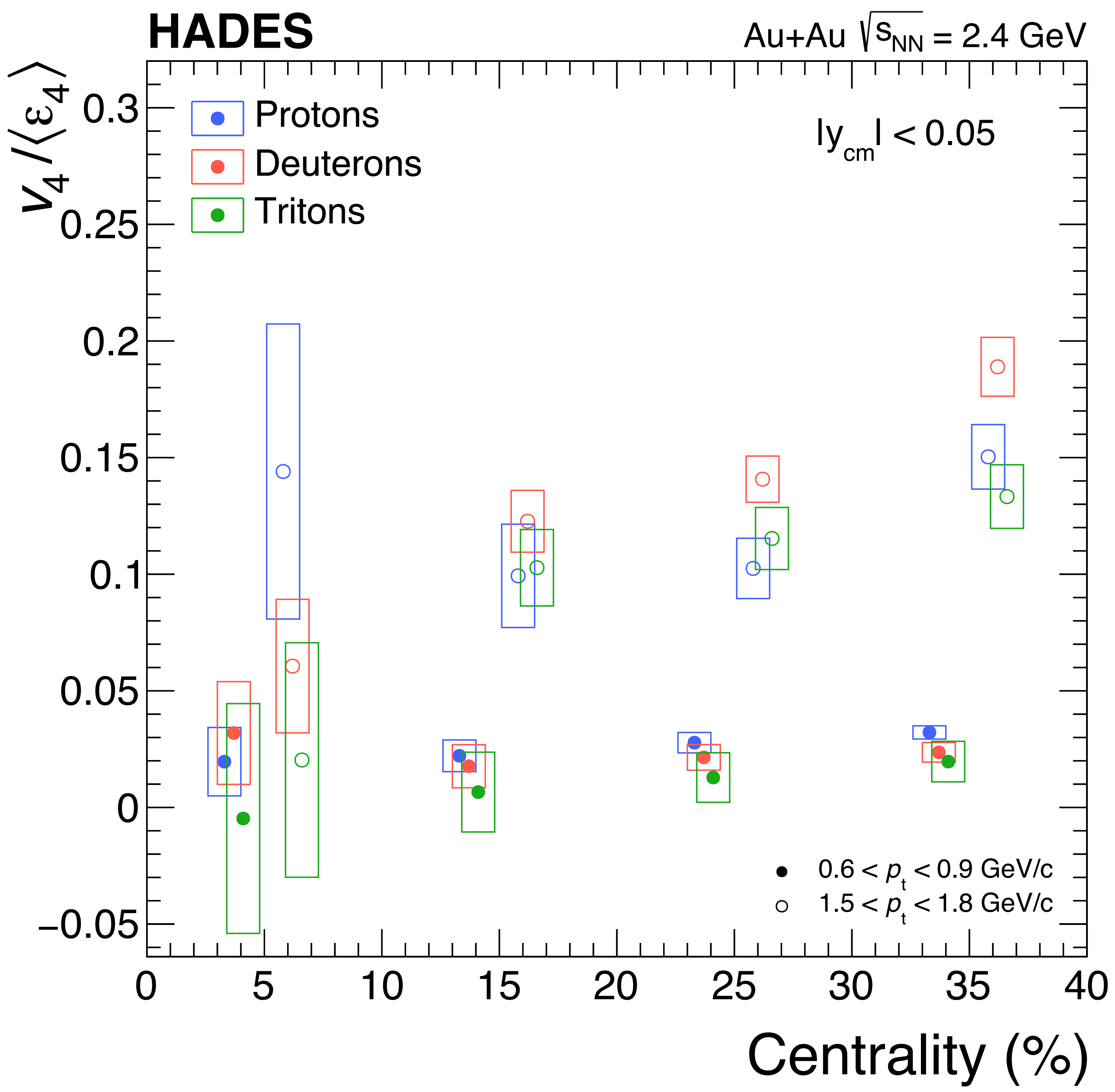


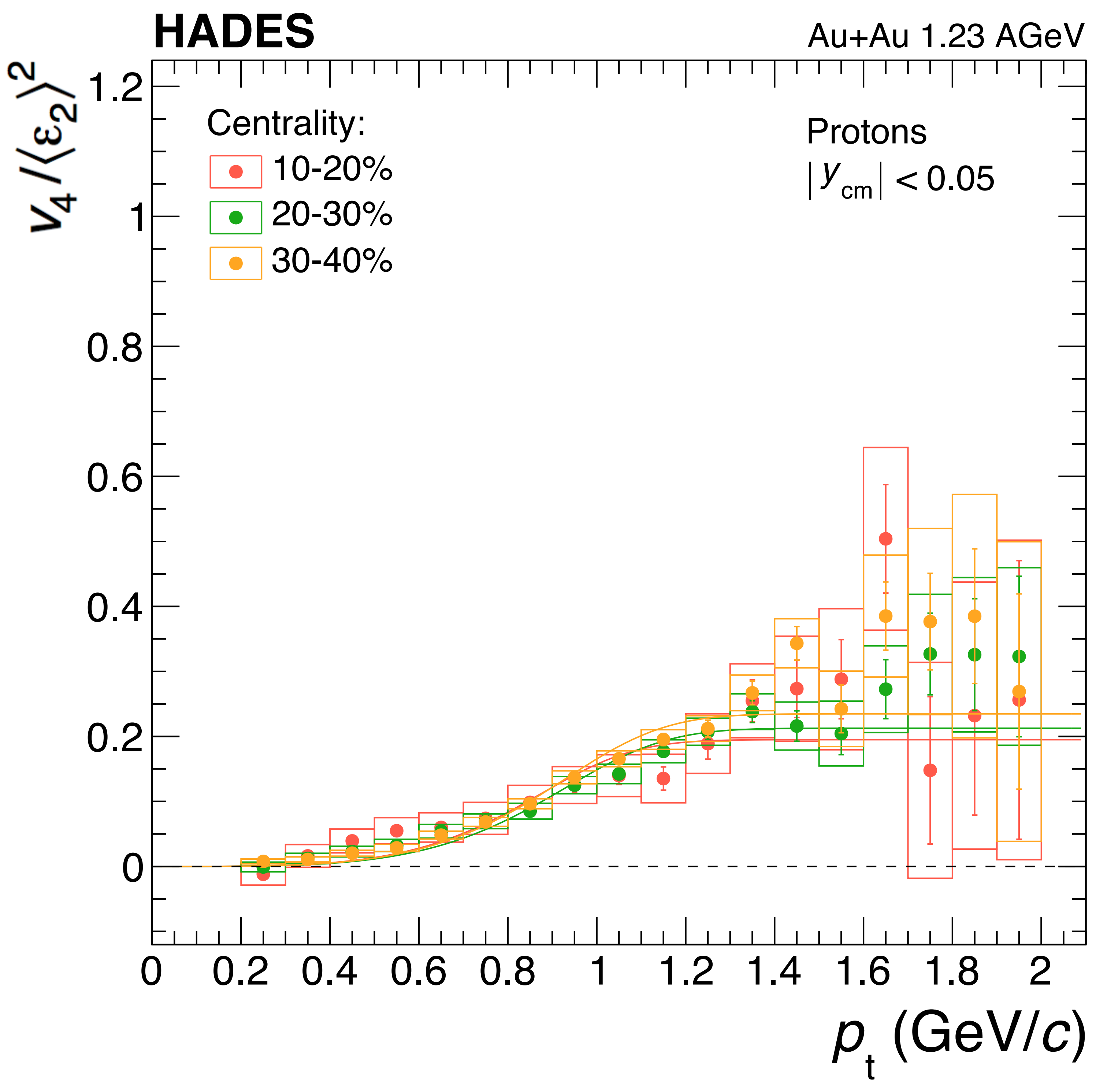
Geometry Scaling

Quadrangular Flow v_4



HADES, arXiv:2208.02740





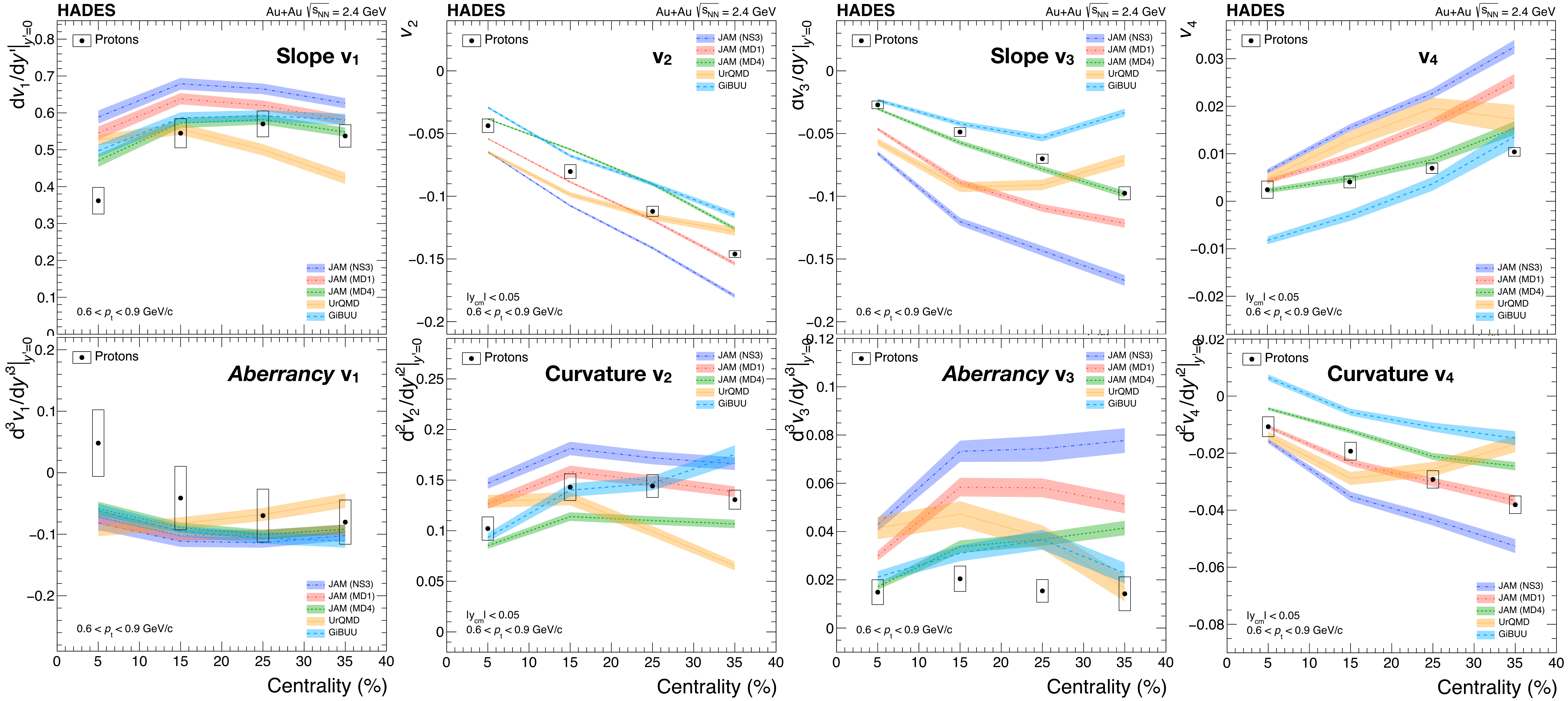
Scaling with initial eccentricities

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)

⟹ Fixed relation between v_2 and v_4 (different to high energies)

Model Comparisons to Proton Data



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

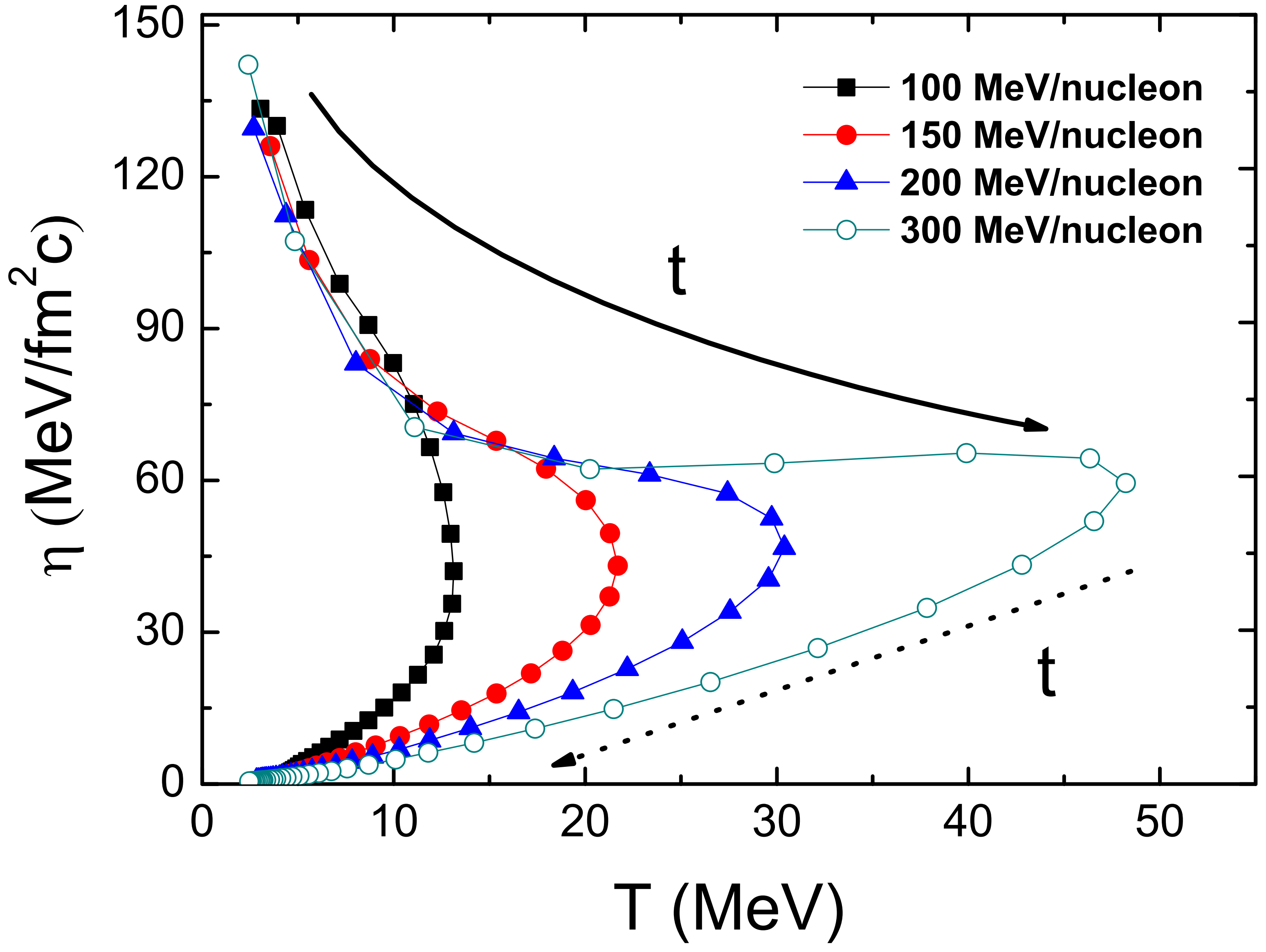
Properties of Dense Nuclear Matter

Shear viscosity

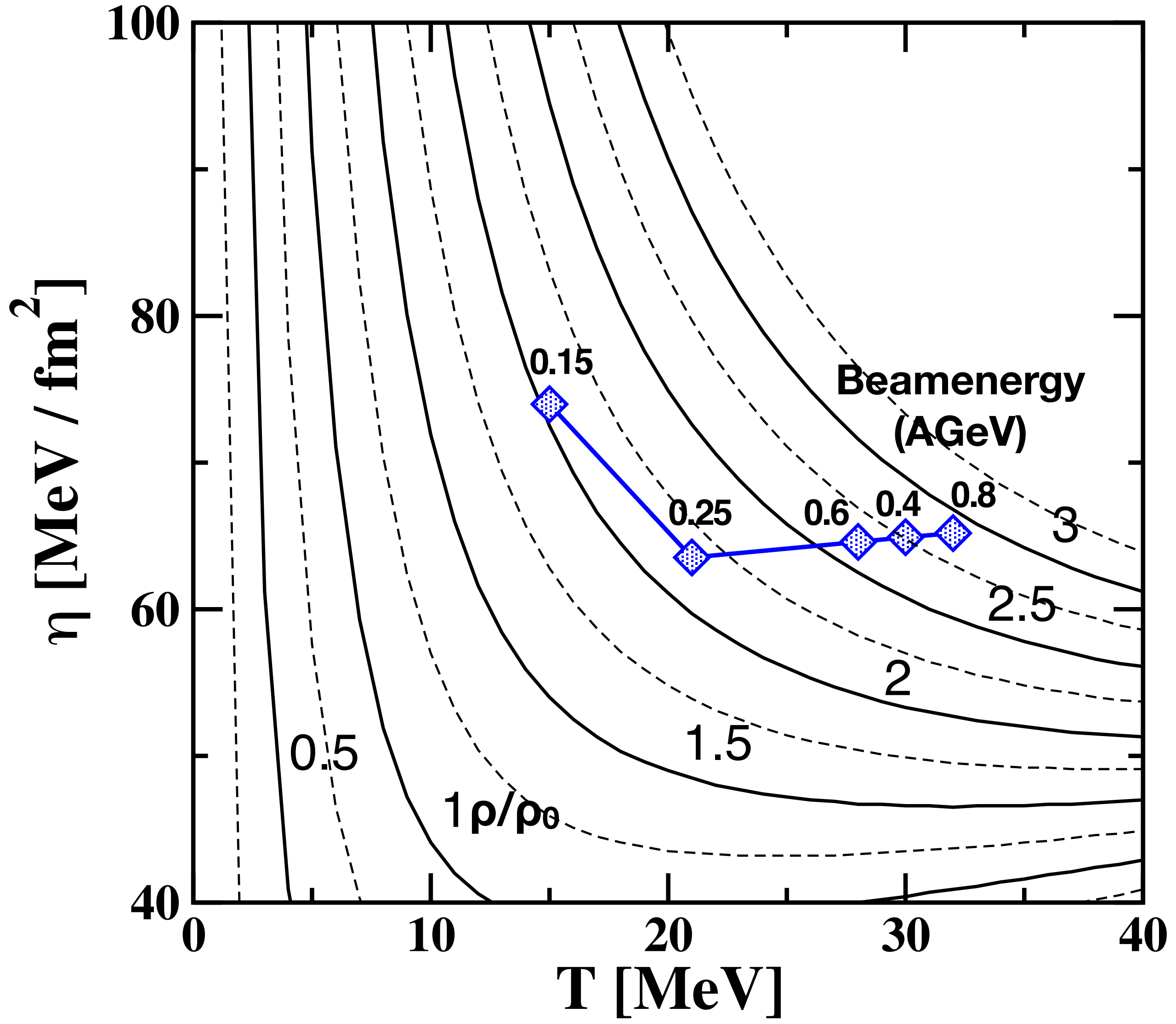
Nuclear shear viscosity extracted from transport models

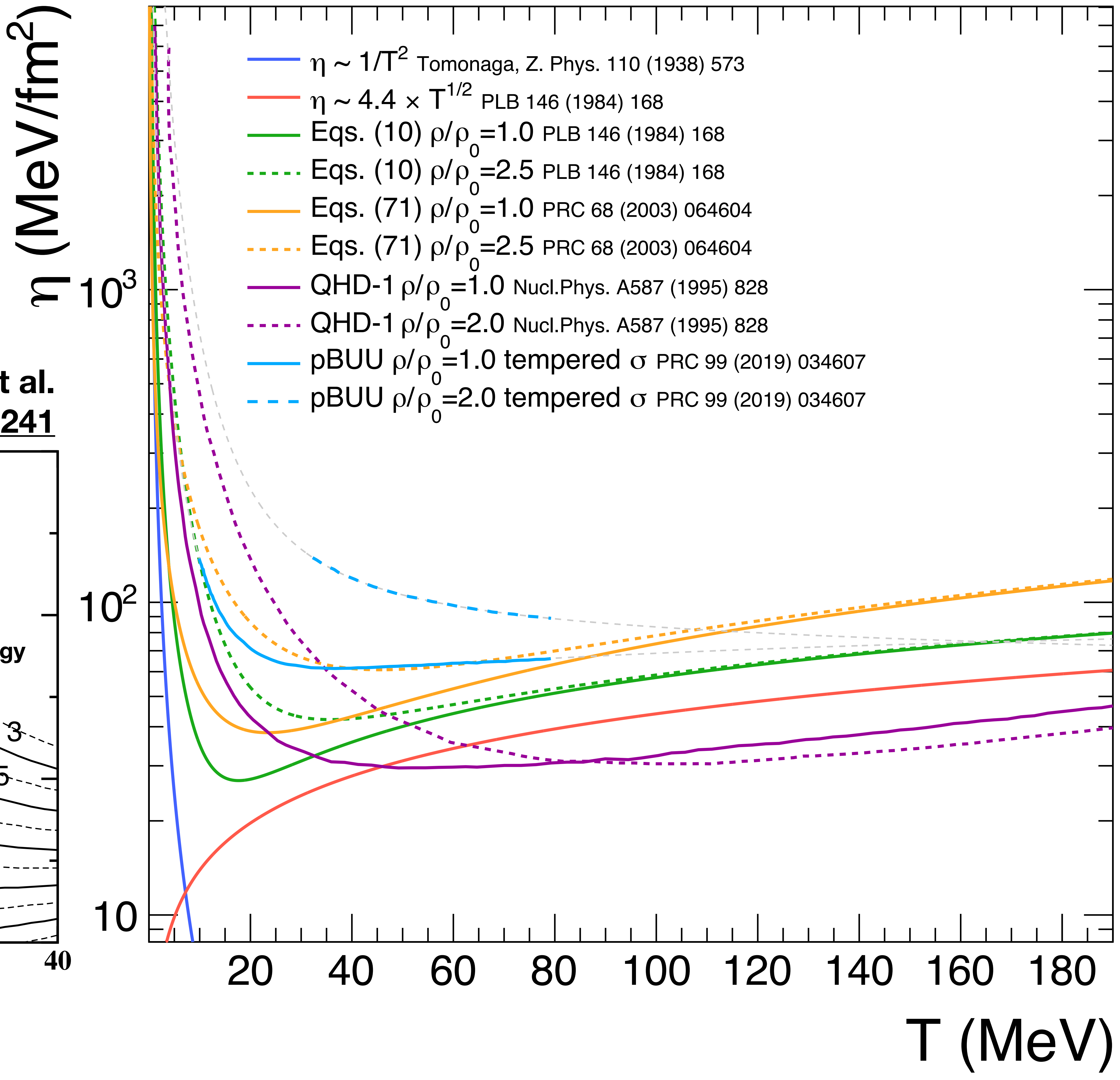
Mean-field potentials and in-medium cross section are constrained by stopping and flow observables

X.G. Deng et al.
Phys.Rev.C 94 (2016) 044622



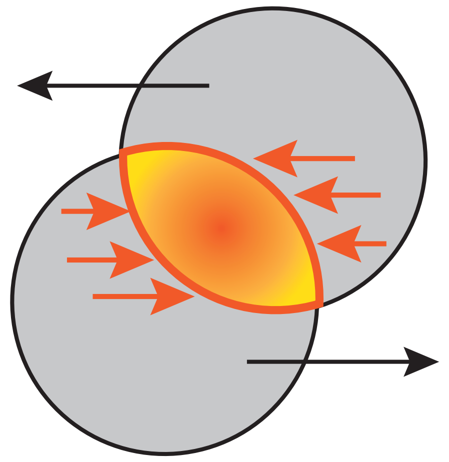
T. Gaitanos et al.
Phys.Lett.B 609 (2005) 241





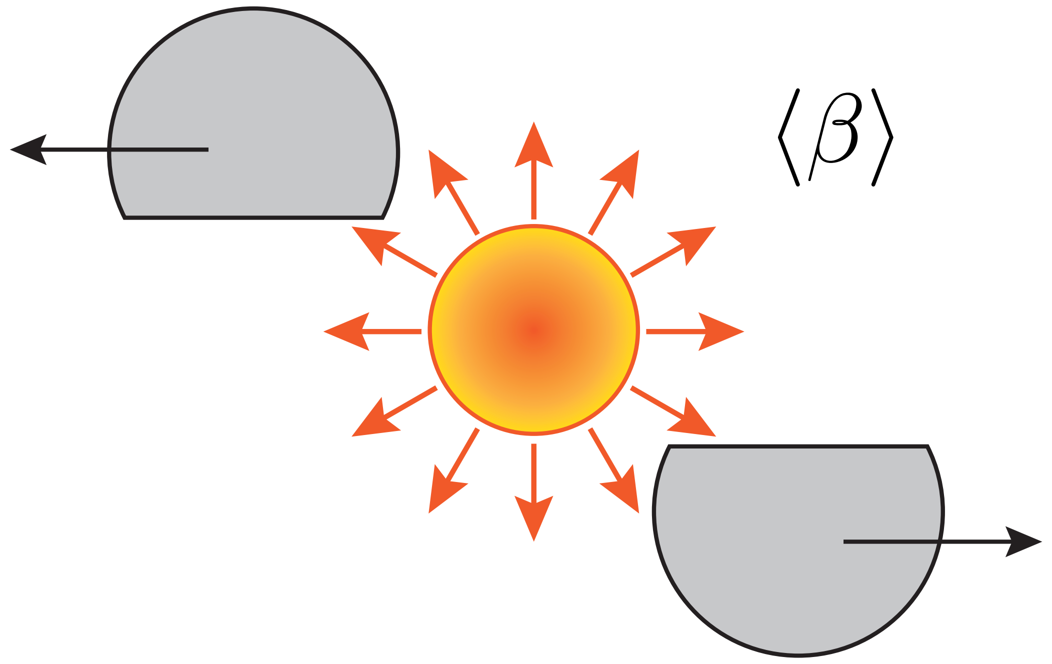
Motivation

Flow and Event Shapes

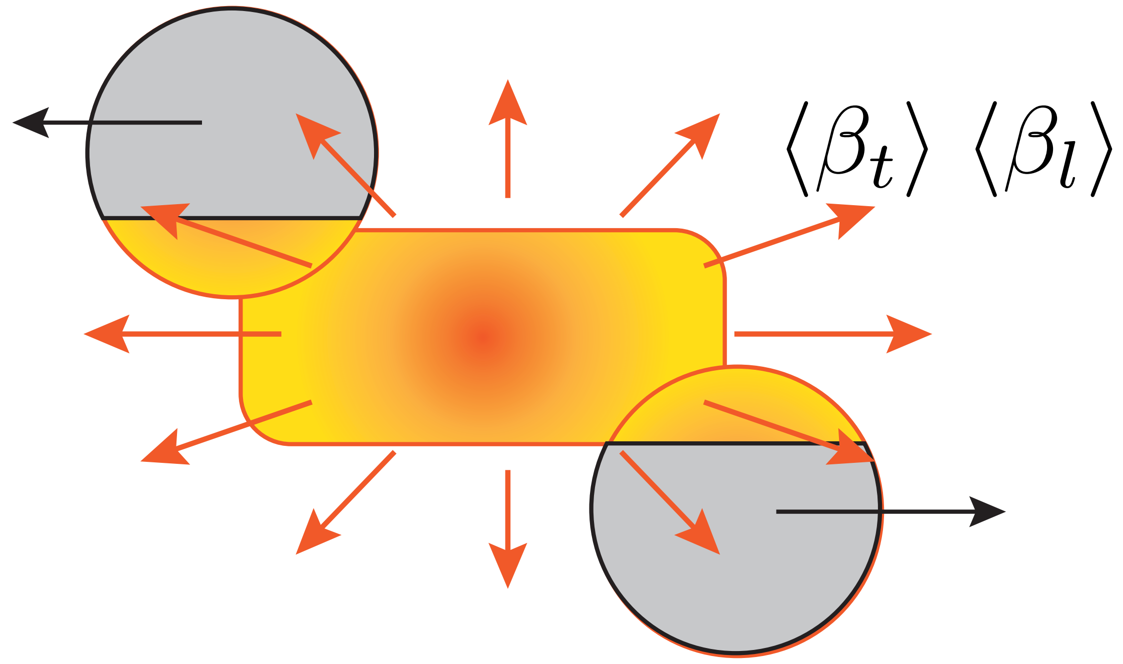


top view

radial flow

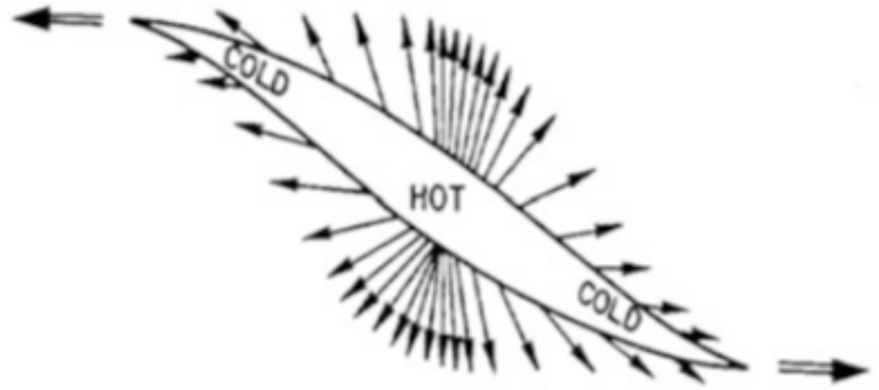


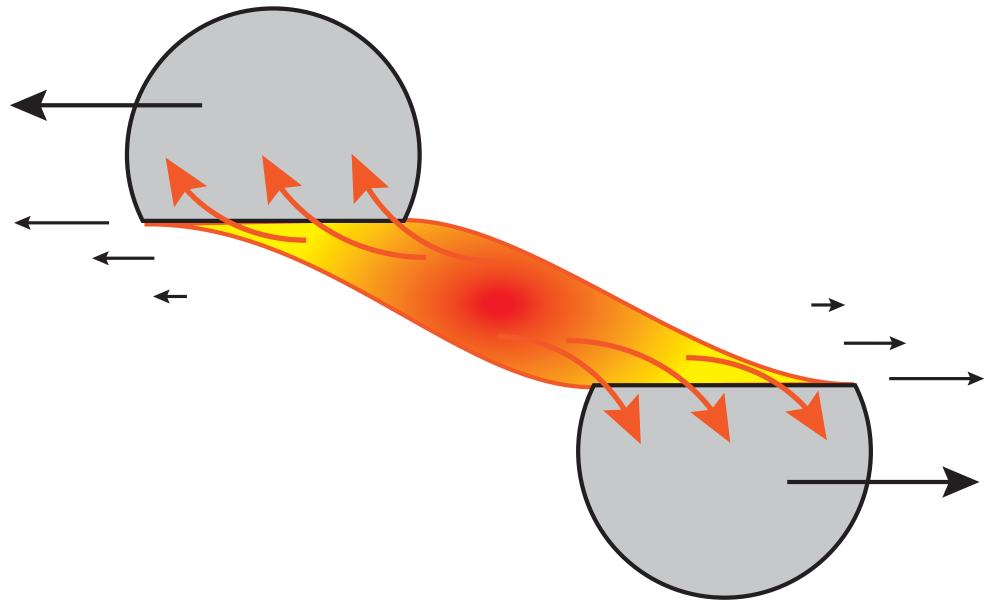
Landau scenario
total stopping



Bjorken scenario
partial stopping
initial longitudinal flow

How to Deal with Relativistic Heavy Ion Collisions
R. Hagedorn (1981)





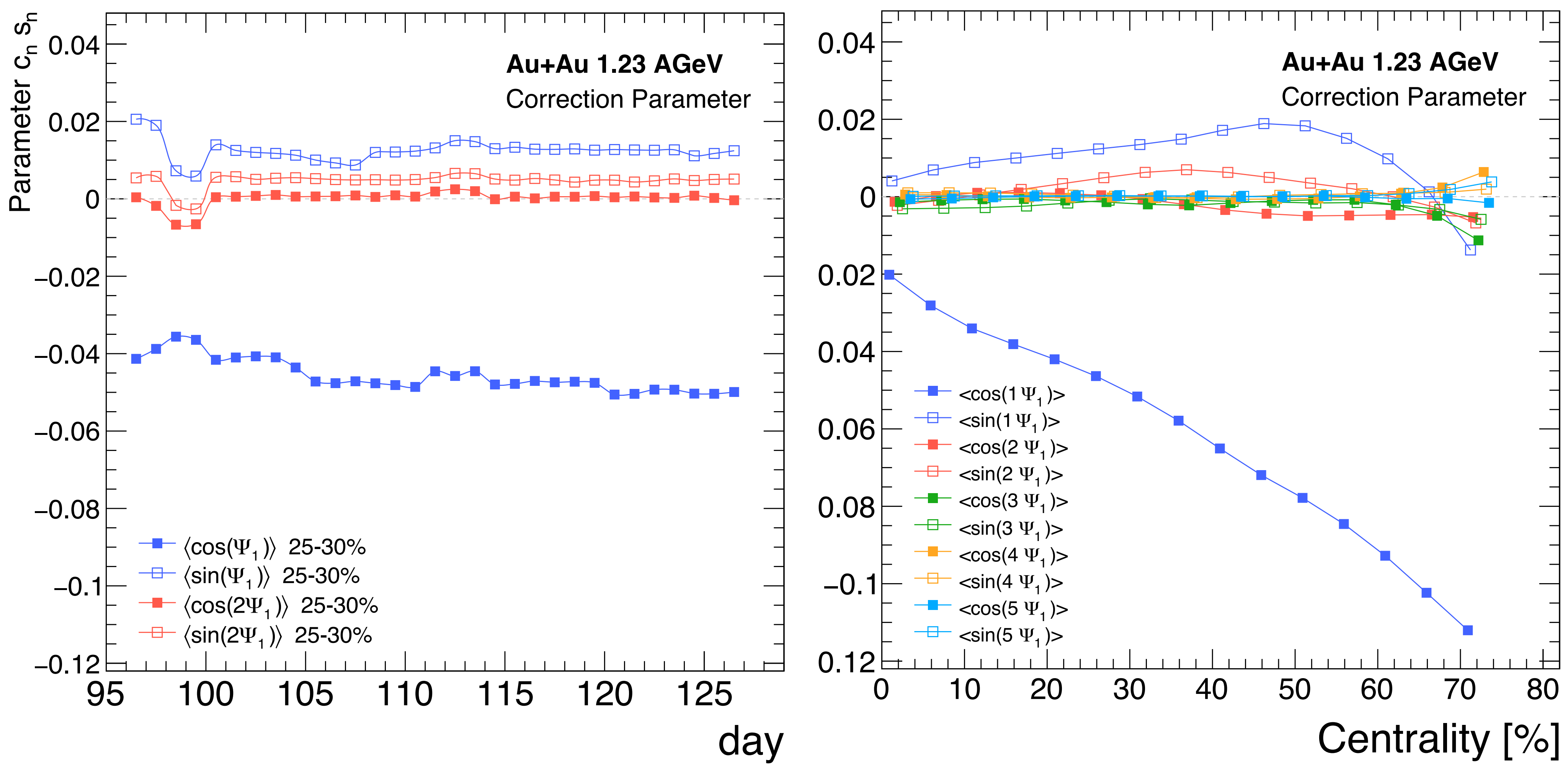
Hagedon-Myers scenario
(similar to “firestreak” model)
stopping dependent on nuclear density
partial stoped matter moves with
different rapidities

Event Plane Determination

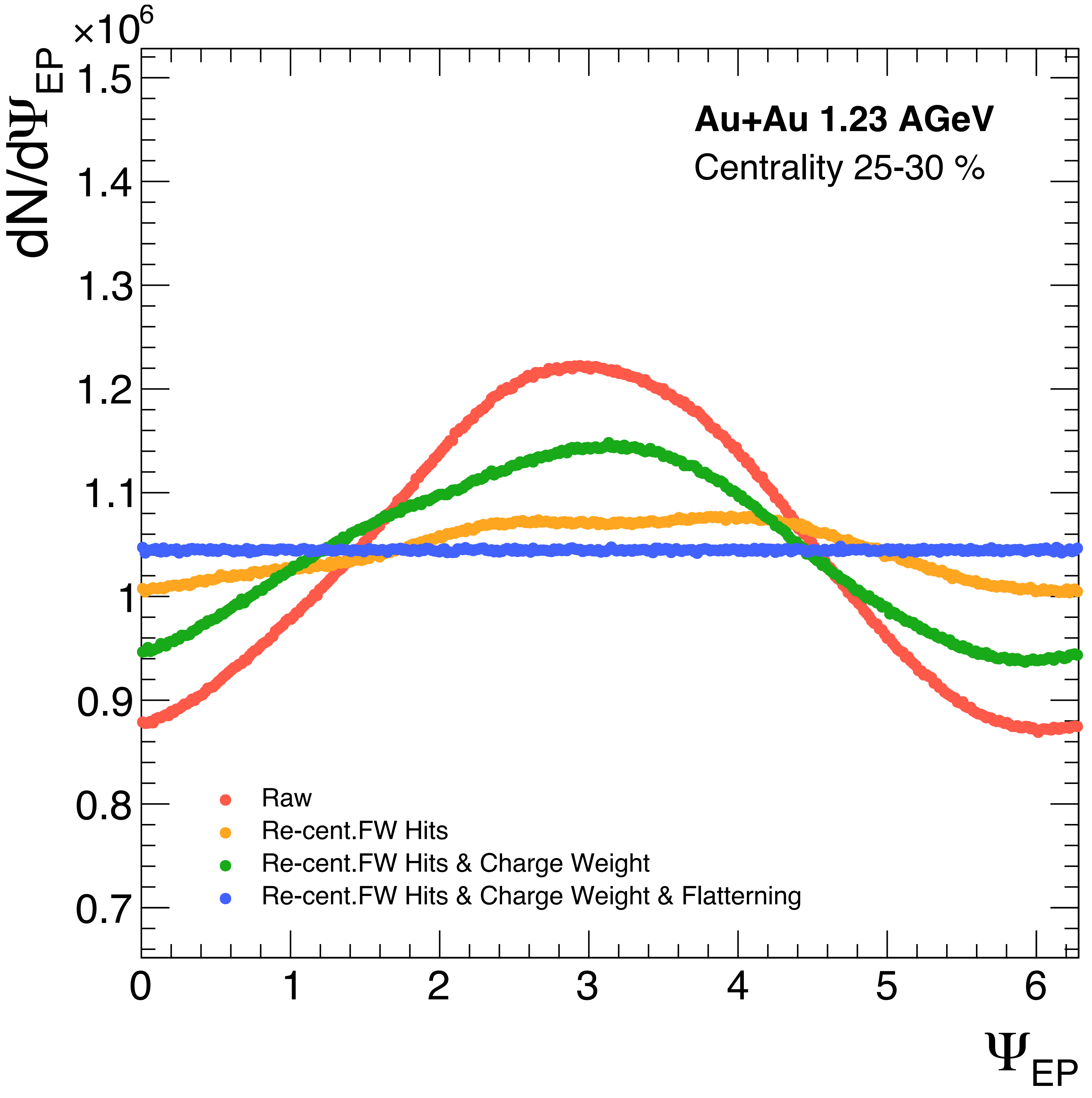
Correction of non-uniformities in the EP distribution (day-by-day and centrality)

Re-Centering of X and Y of all FW hits

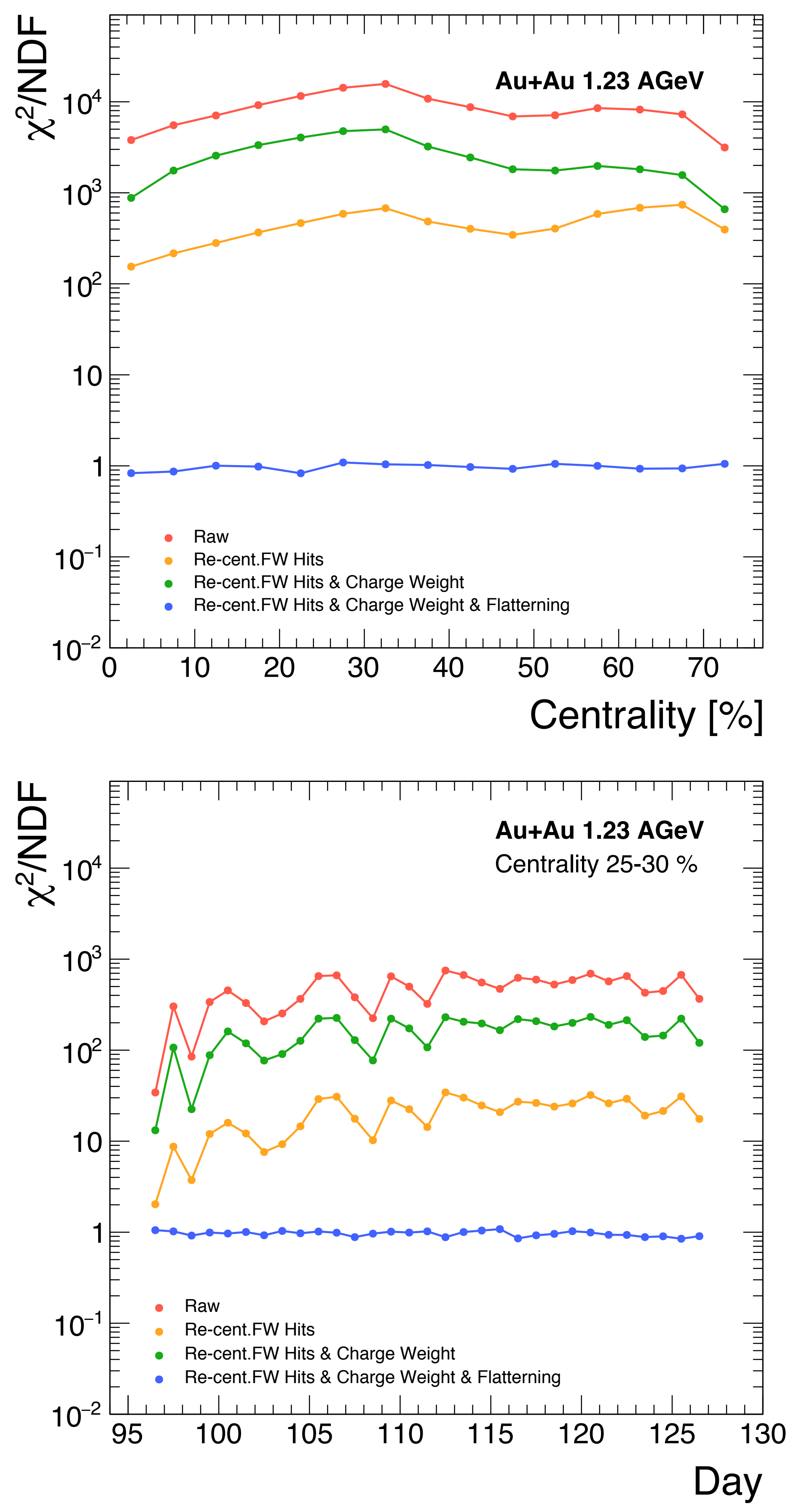
Flattening of residual Fourier components with 8 cos- and 8 sin-terms



Flattening Parameter



Quality of Flatness

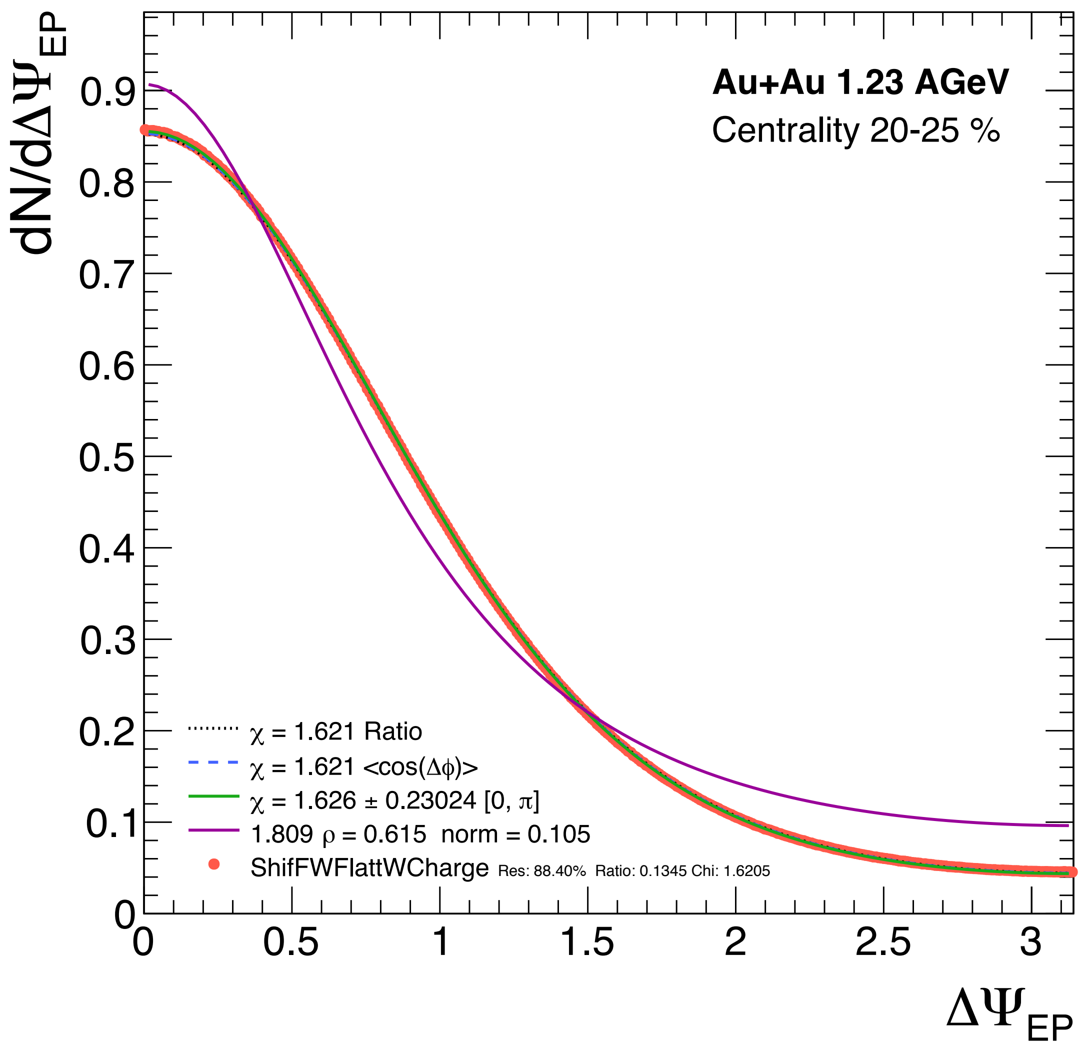


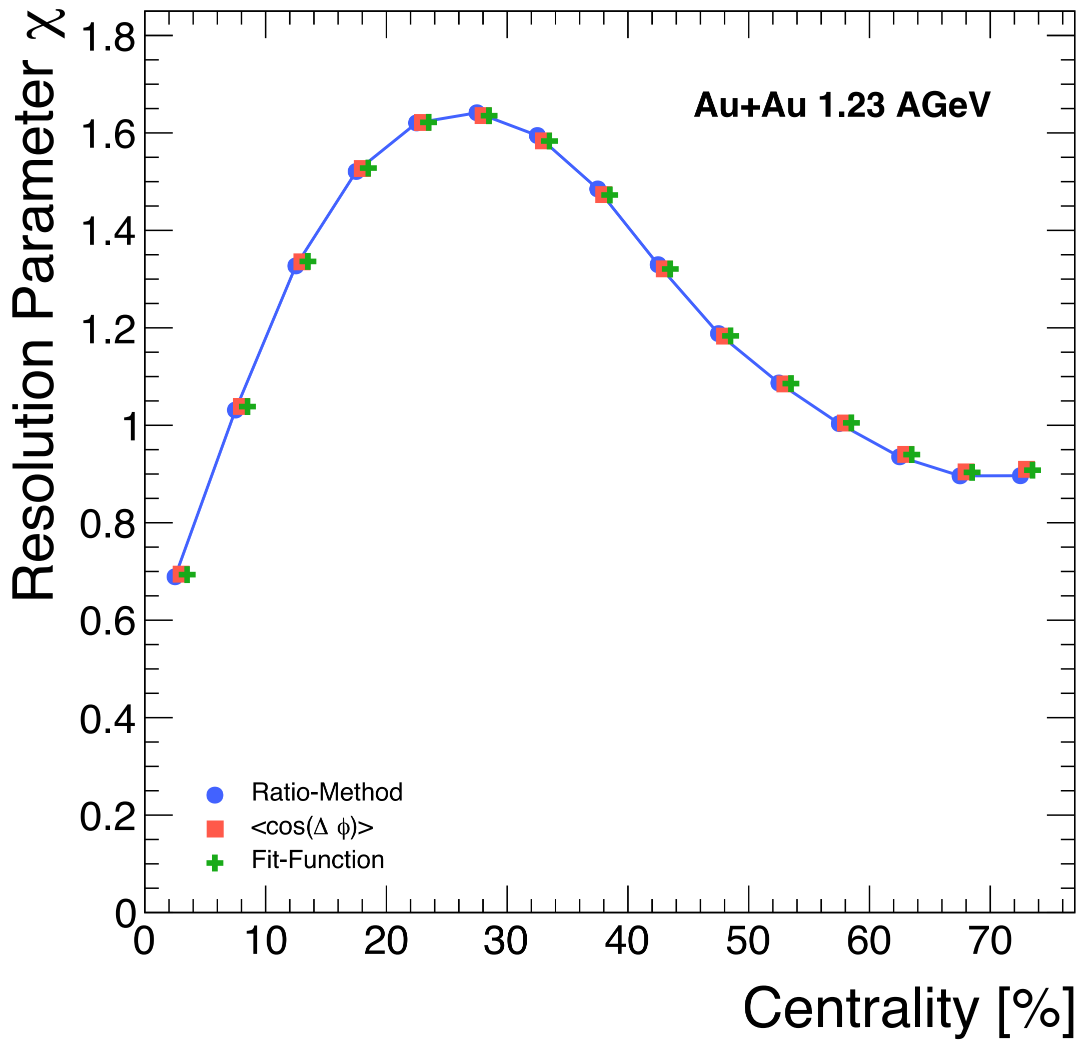
Event Plane Resolution

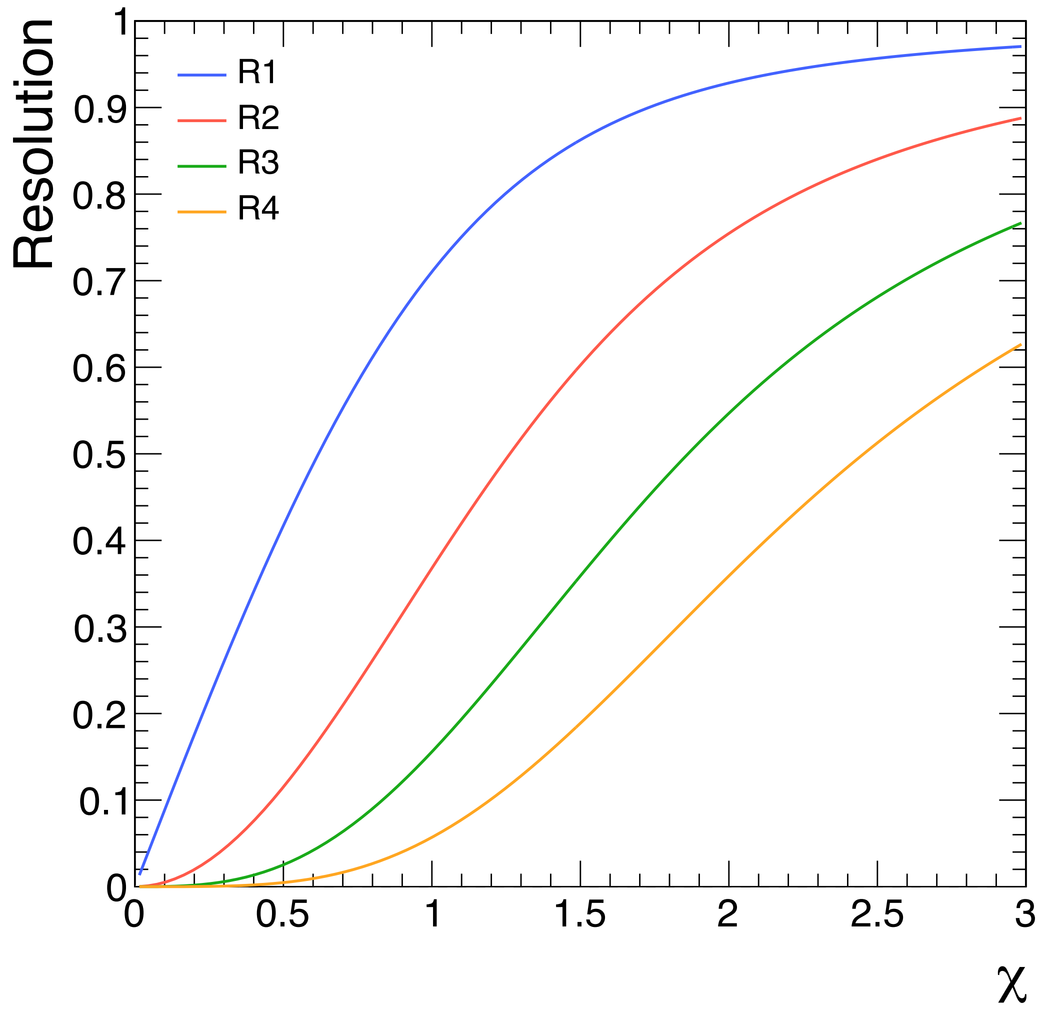
EP-resolution via sub-event method with three implementations

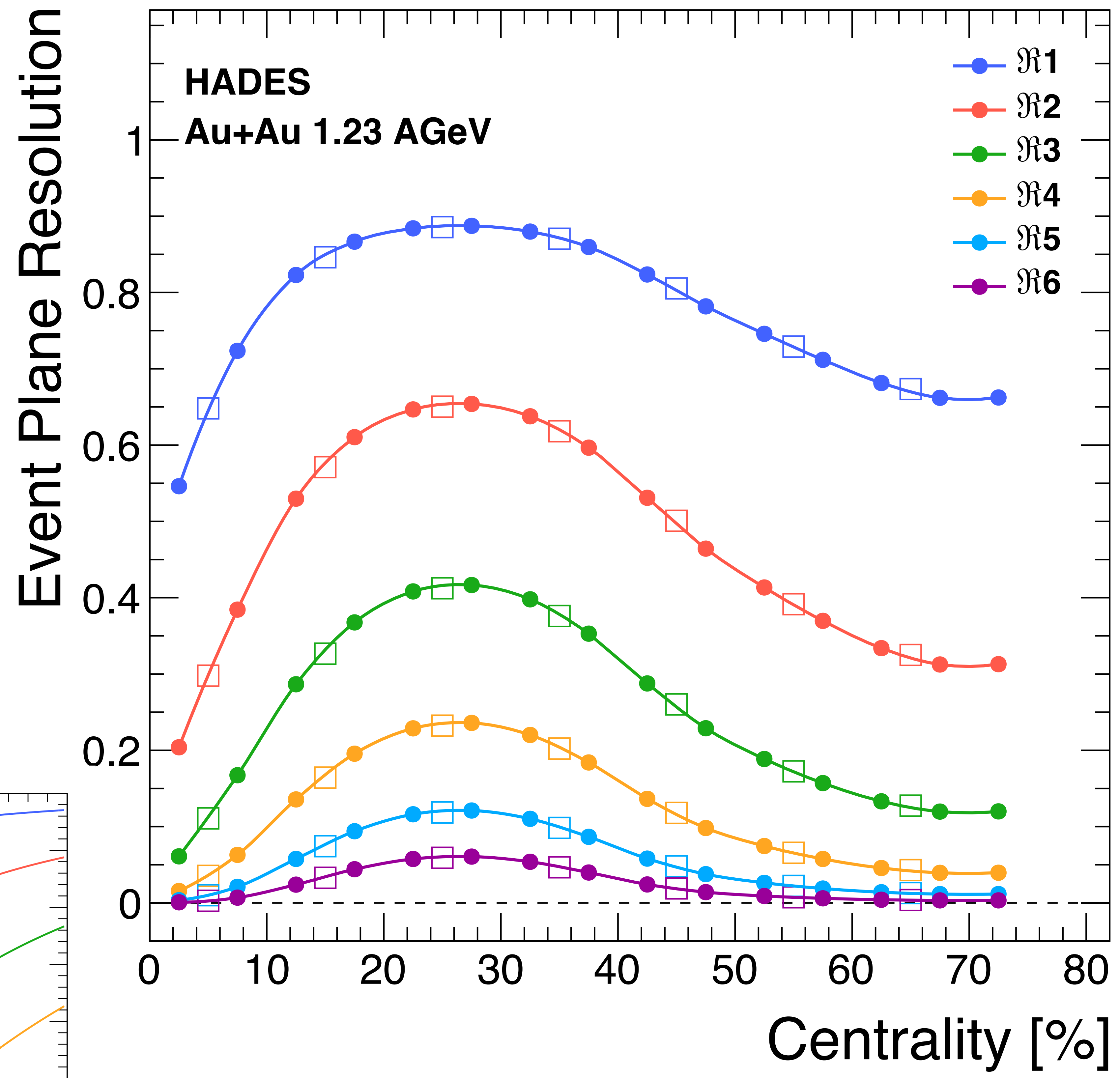
- Determination of resolution parameter χ
    - directly via <cos (ΔΦ)>
    - Approximation via Fraction of Events with ΔΦ > π/2
    - Fit-Method

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

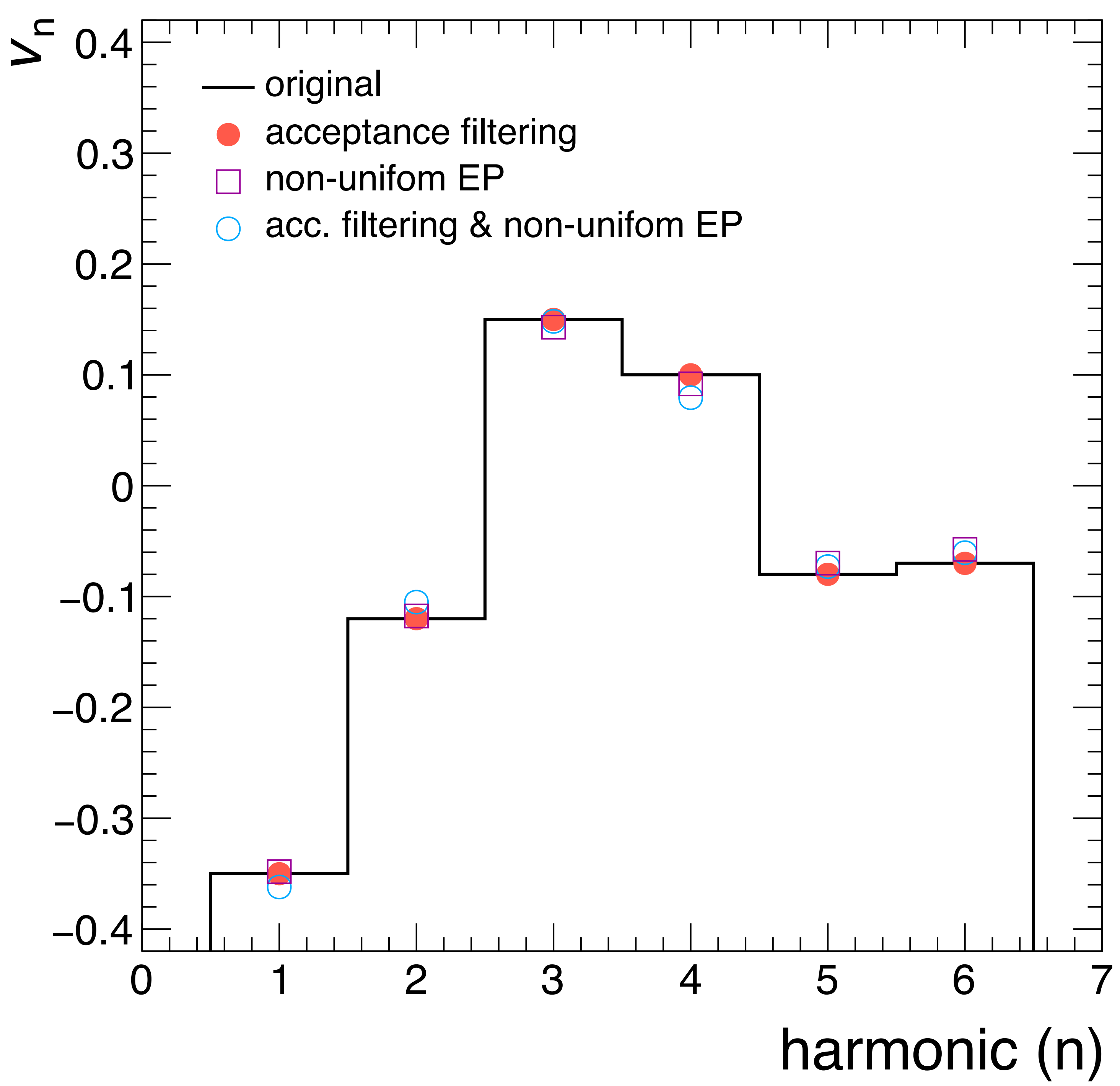
Consistency checks:

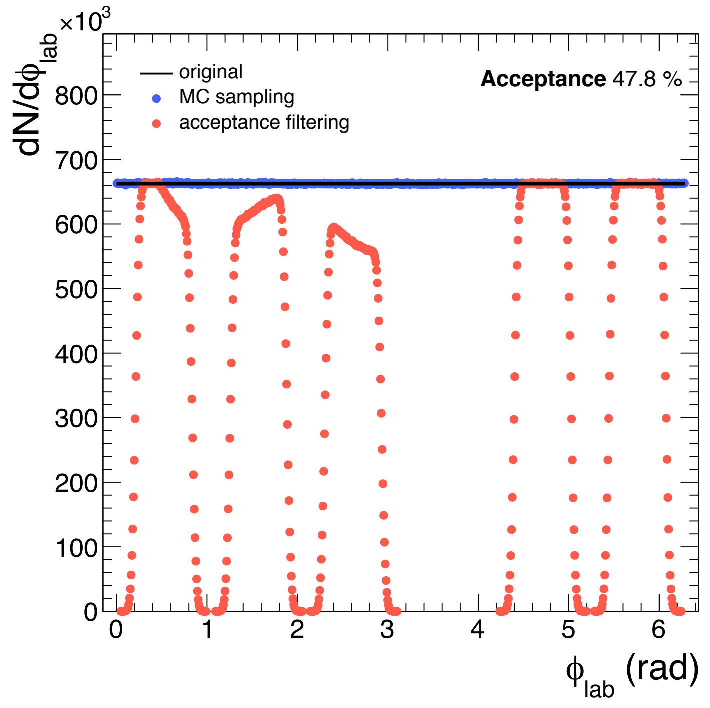
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at $y_{cm}=0$
- Vanishing residual sine-terms
- Time-dependent systematic effects

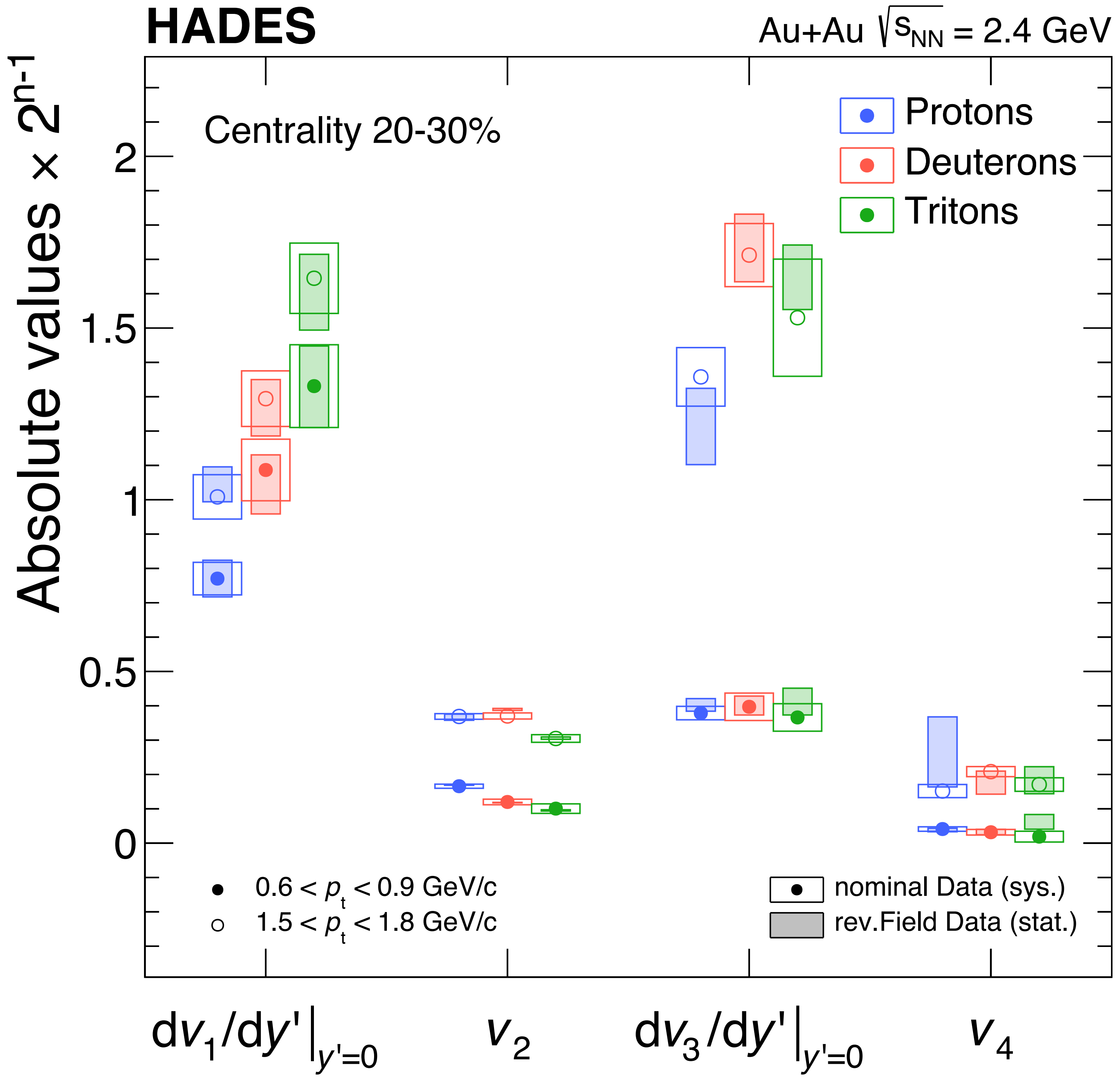
Reversed field polarity

Comparison with flow coefficients from the full data set

HADES, arXiv:2208.02740







“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

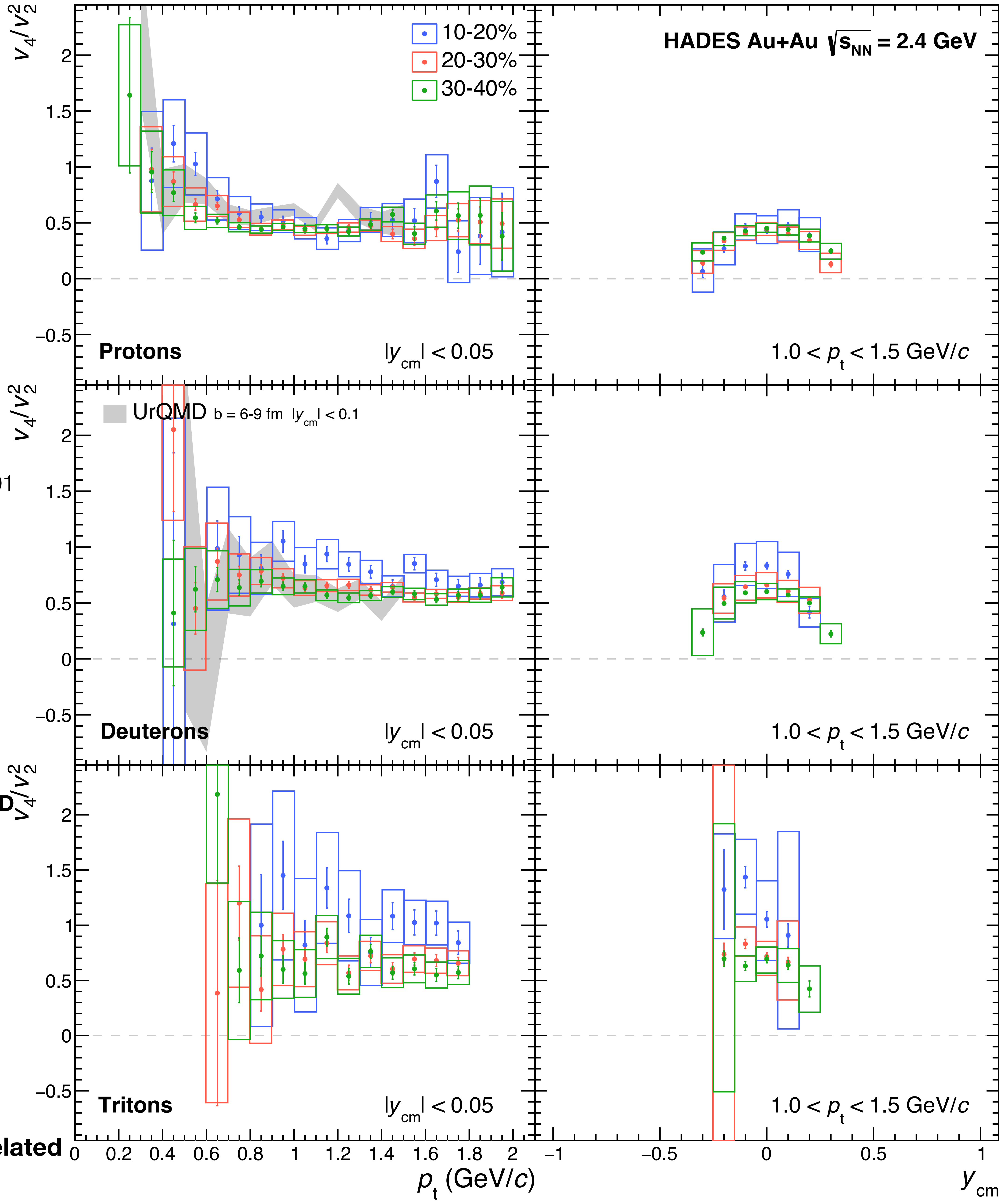
Independent of p_t and centrality
Close to predicted value of ~ 0.6

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

Other Ratio-Scalings?

Protons and light nuclei