Flow phenomena at high nuclear densities with HADES

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for the
HADES Collaboration

EMMI Workshop
Probing dense baryonic matter with hadrons II: FAIR Phase-0

20th Februar 2024

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

HFHF

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HADES

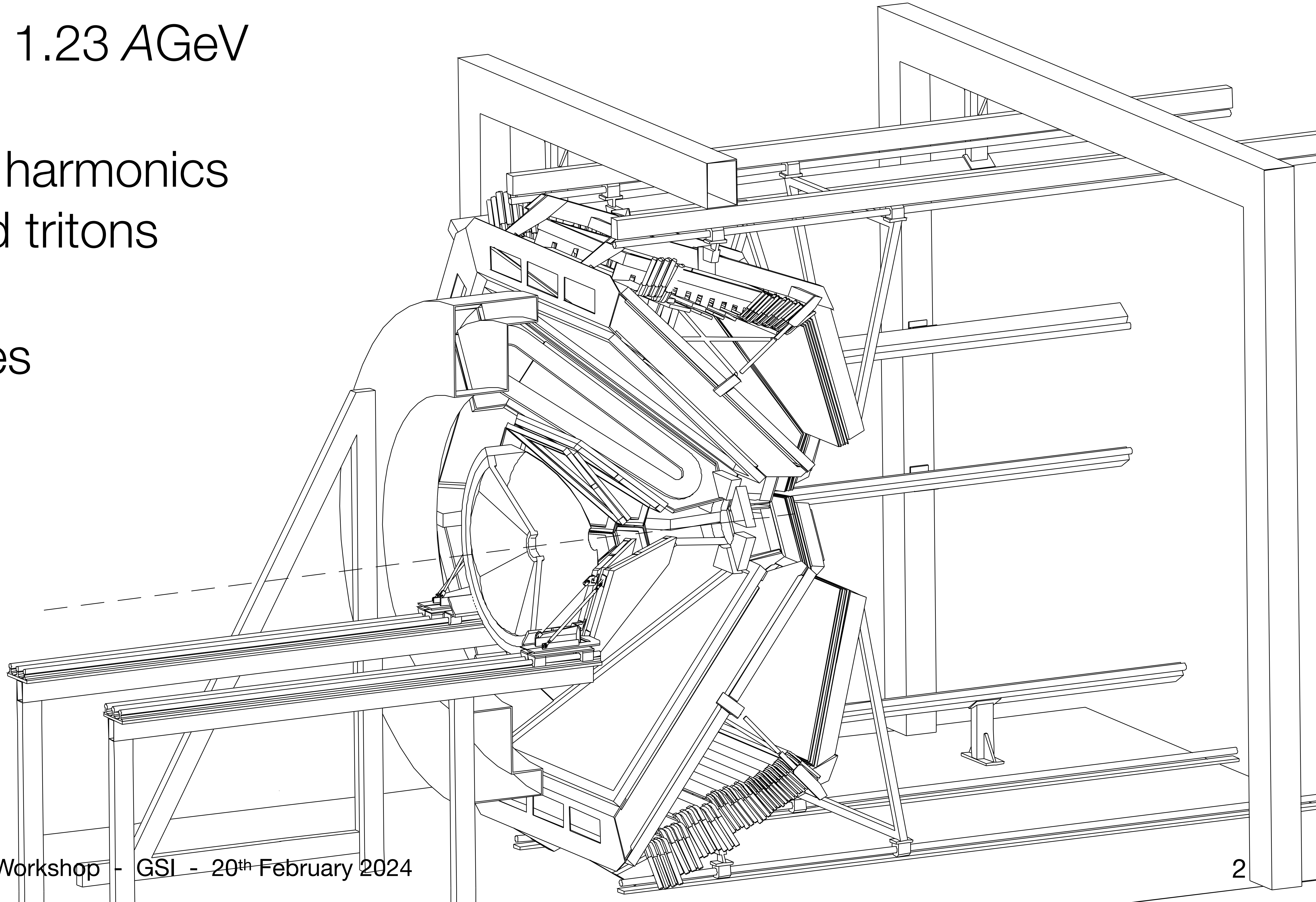
Outline

- 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
- Parameterization 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



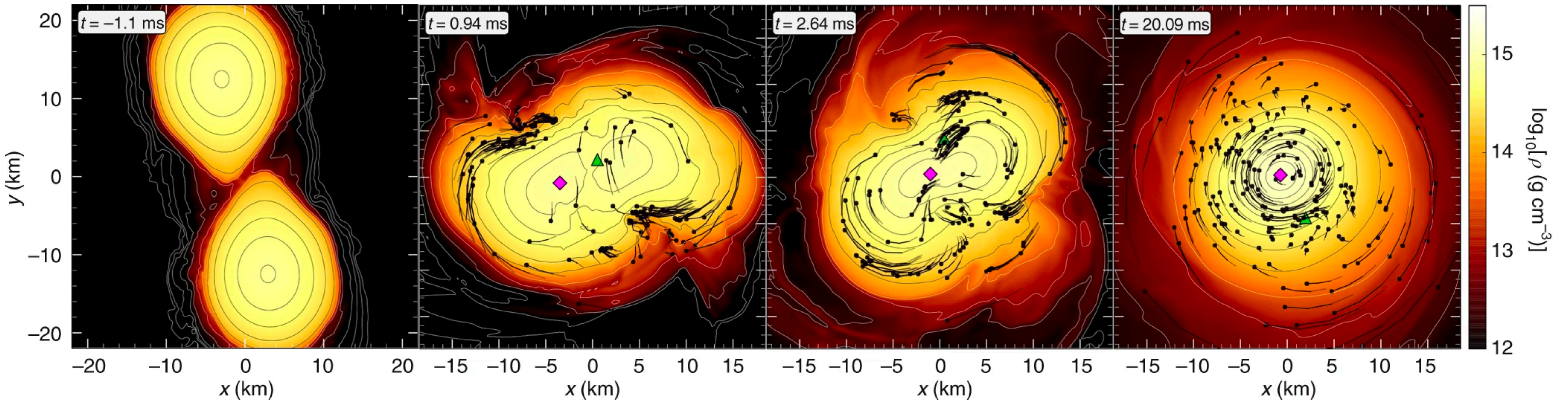
Nuclear matter under Extreme Conditions

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*

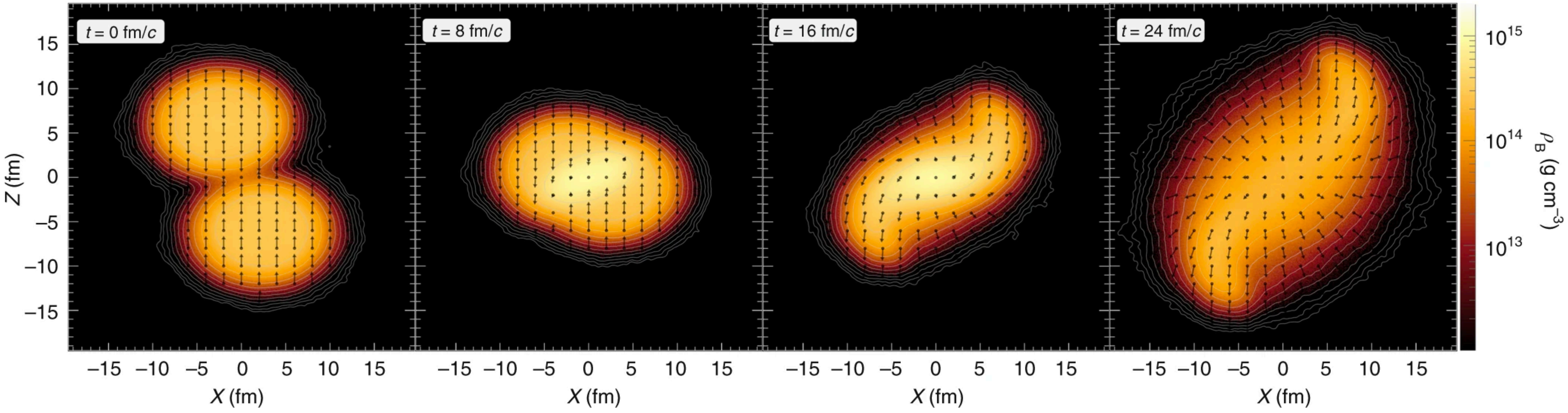
HADES, Nature Phys. **15** (2019) 1040



Neutron Star Merger

Observation via gravitational waves

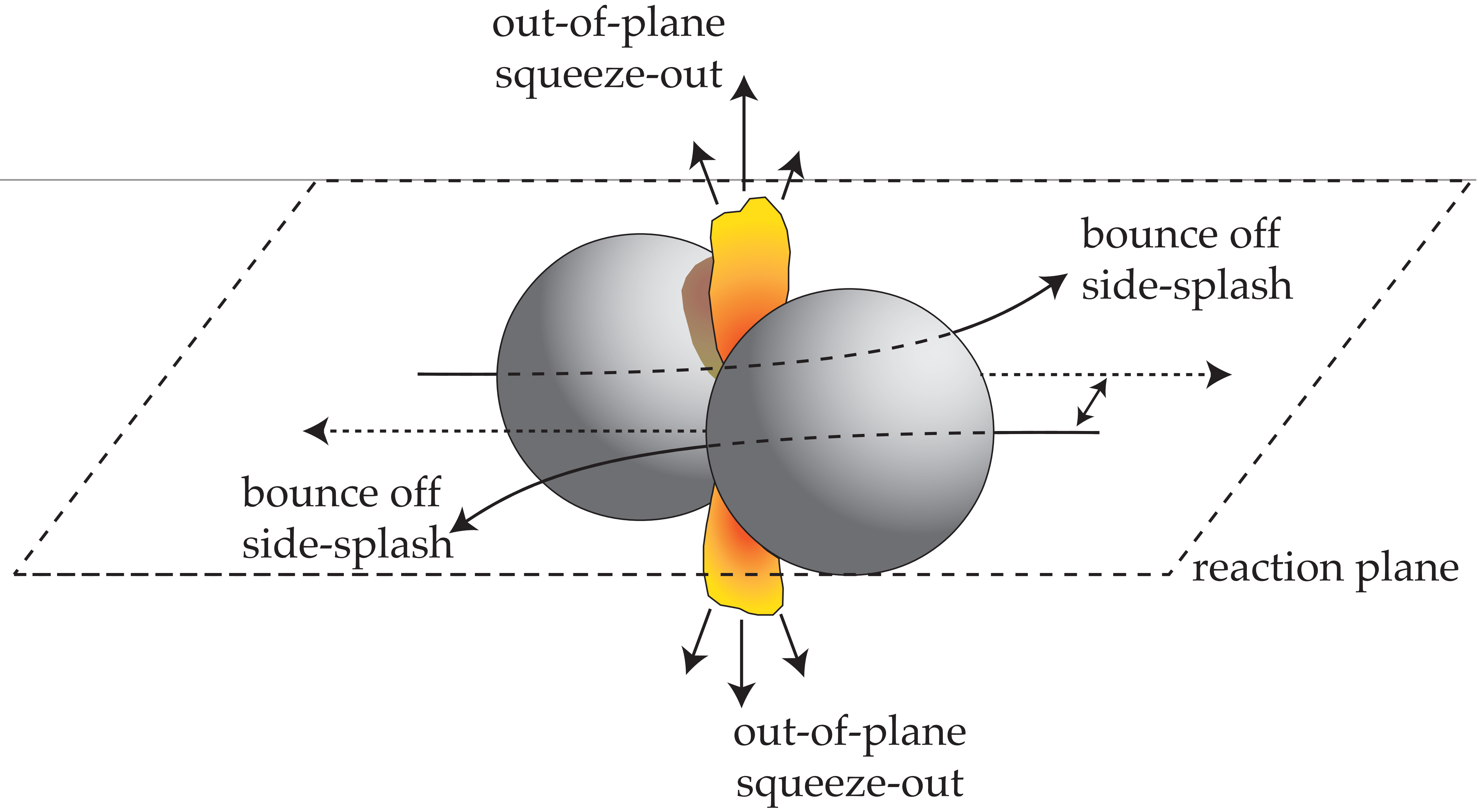
GW170817: B.P. Abott et al. (LIGO + VIRGO)
PRL **119** (2017) 1611001



Heavy-ion Collision

Collective Effects

Flow Phenomenology



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

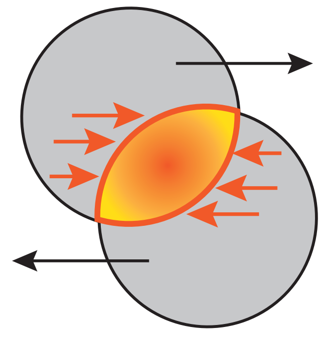
of the triple differential invariant cross section

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

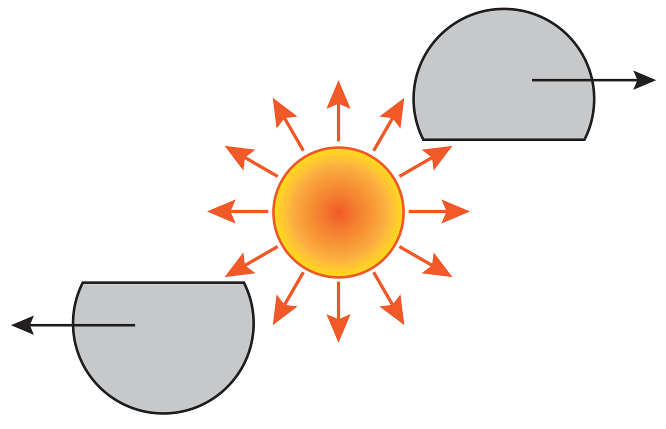
$$\phi = (\varphi - \Psi_{RP})$$

Extraction of azimuthal moments v_n

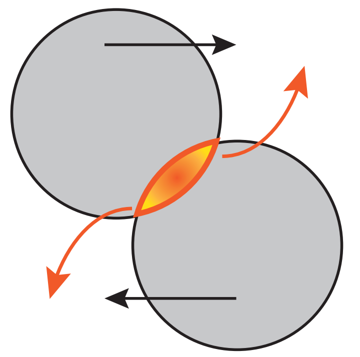
$$v_n(p_t, y) = \langle\cos(n\phi)\rangle$$



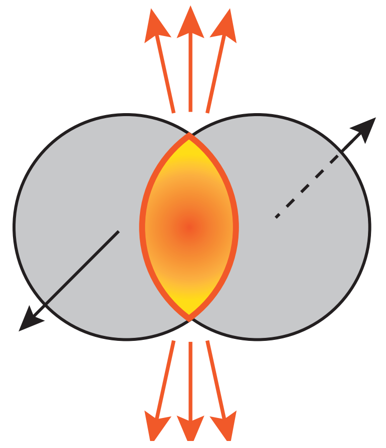
stopping



radial flow



directed flow

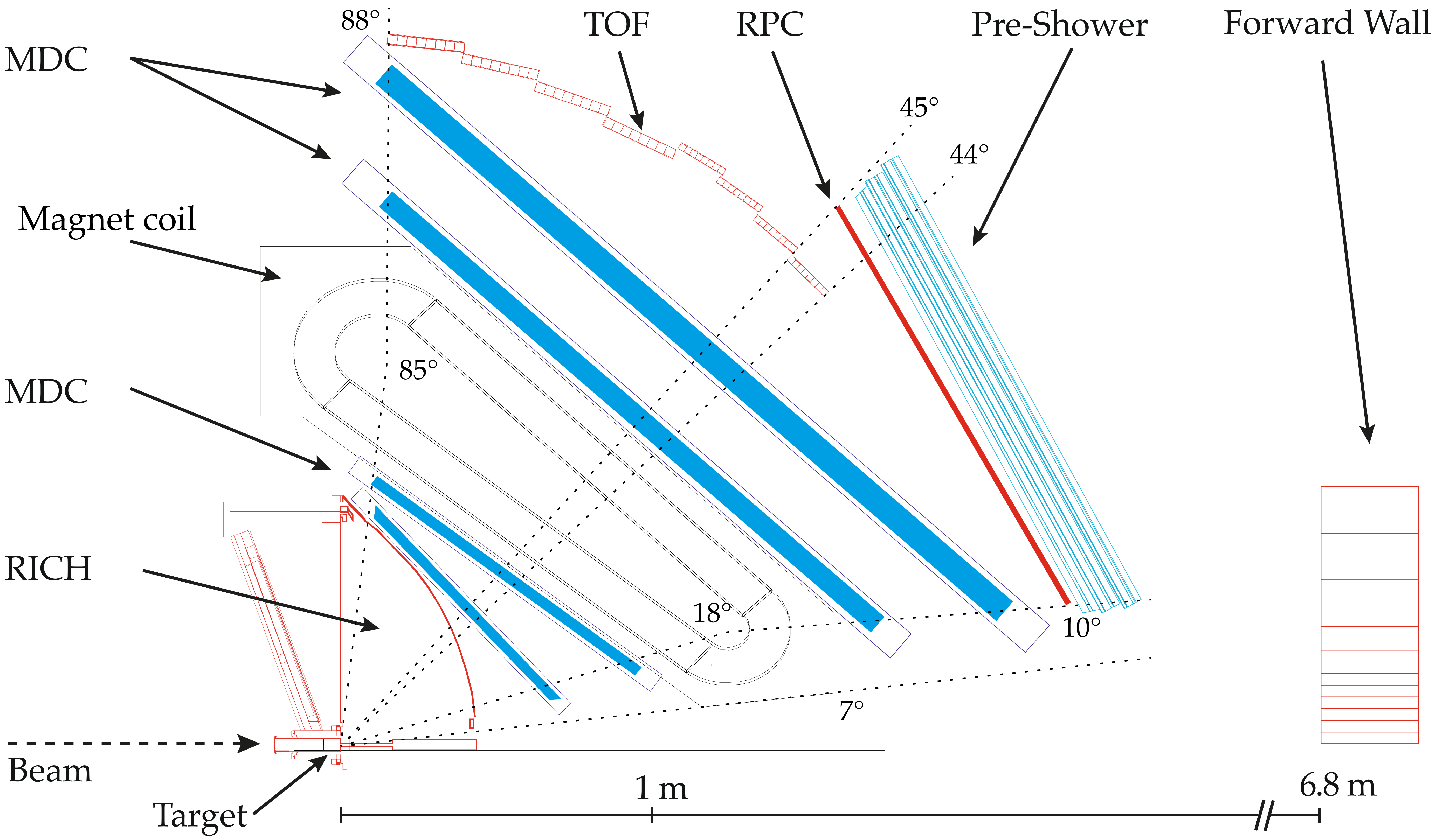


elliptic flow

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

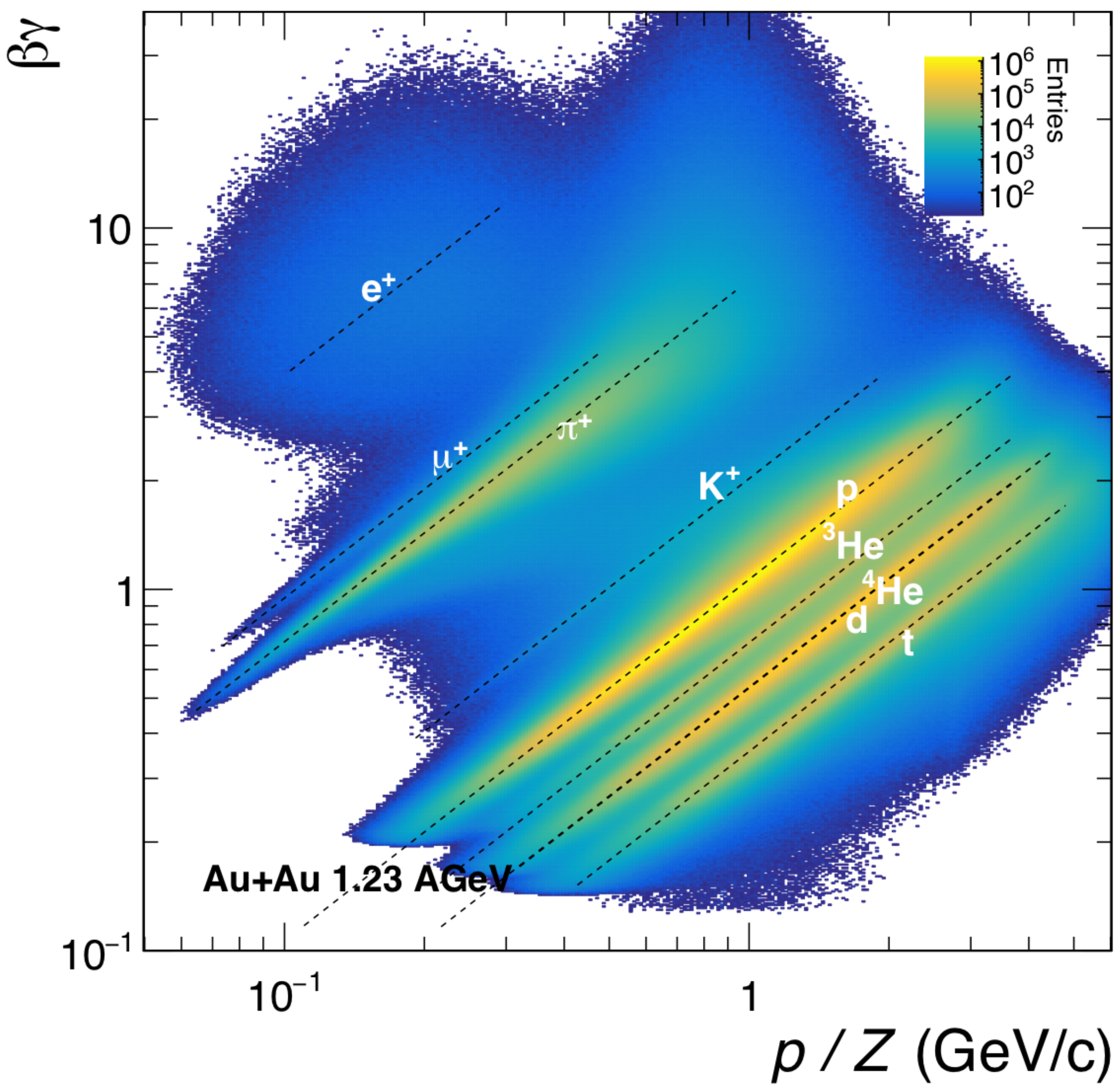
High Acceptance Di-Electron Spectrometer

- 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



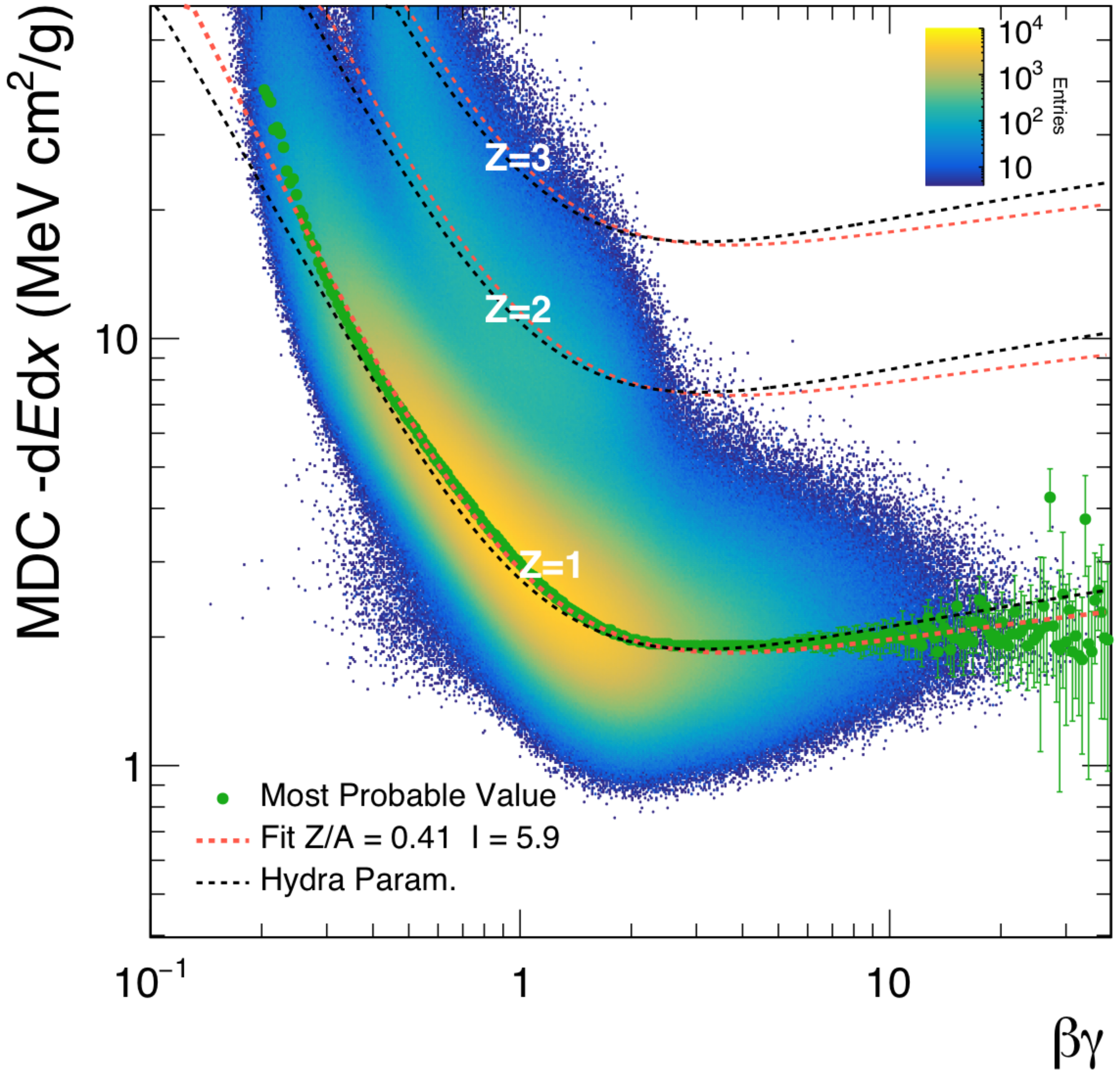
Particle Identification

Time-of-Flight (TOF and RPC)



$$\beta\gamma\ m/Z = p/Z$$

Energy loss in the MDC

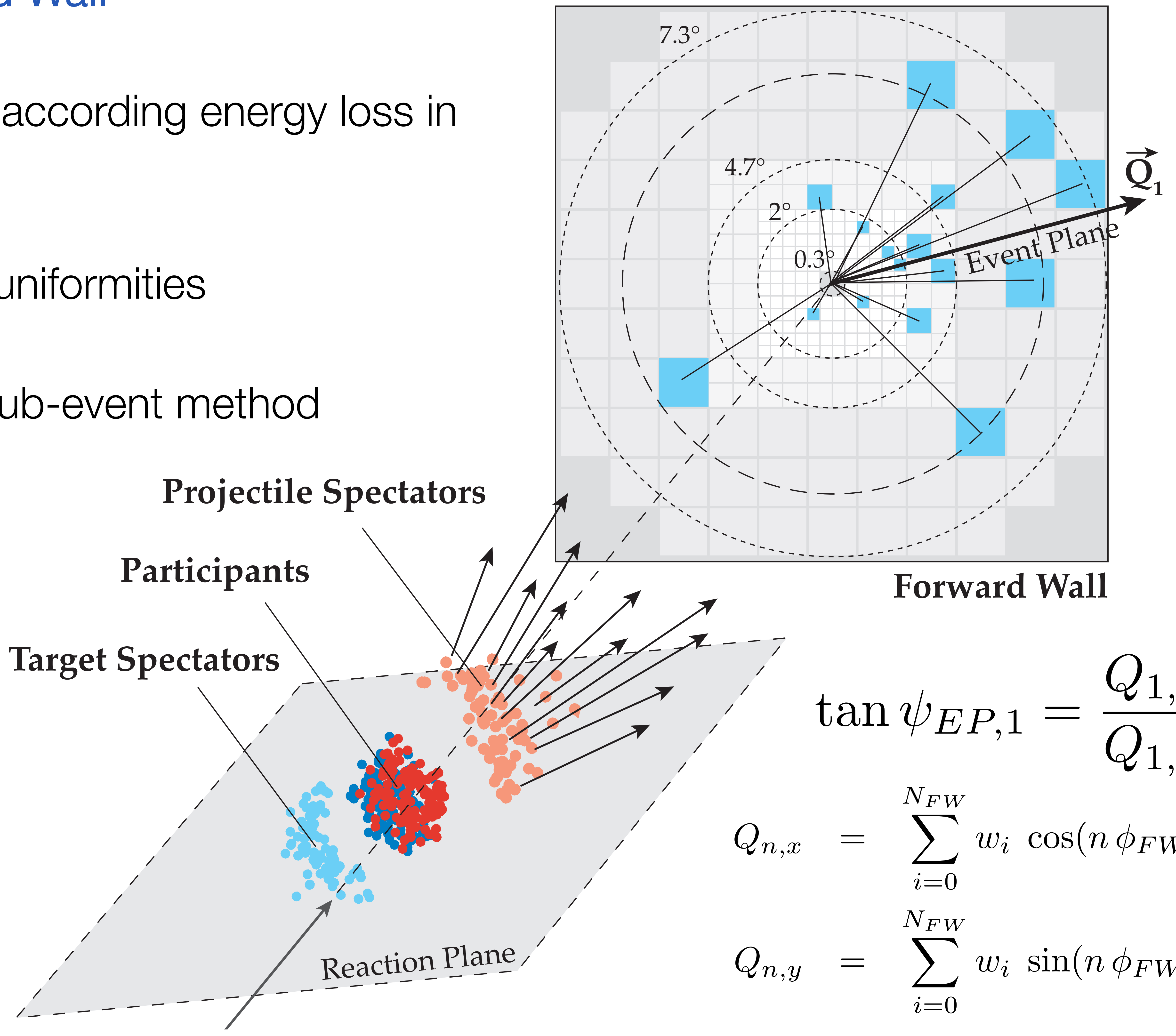


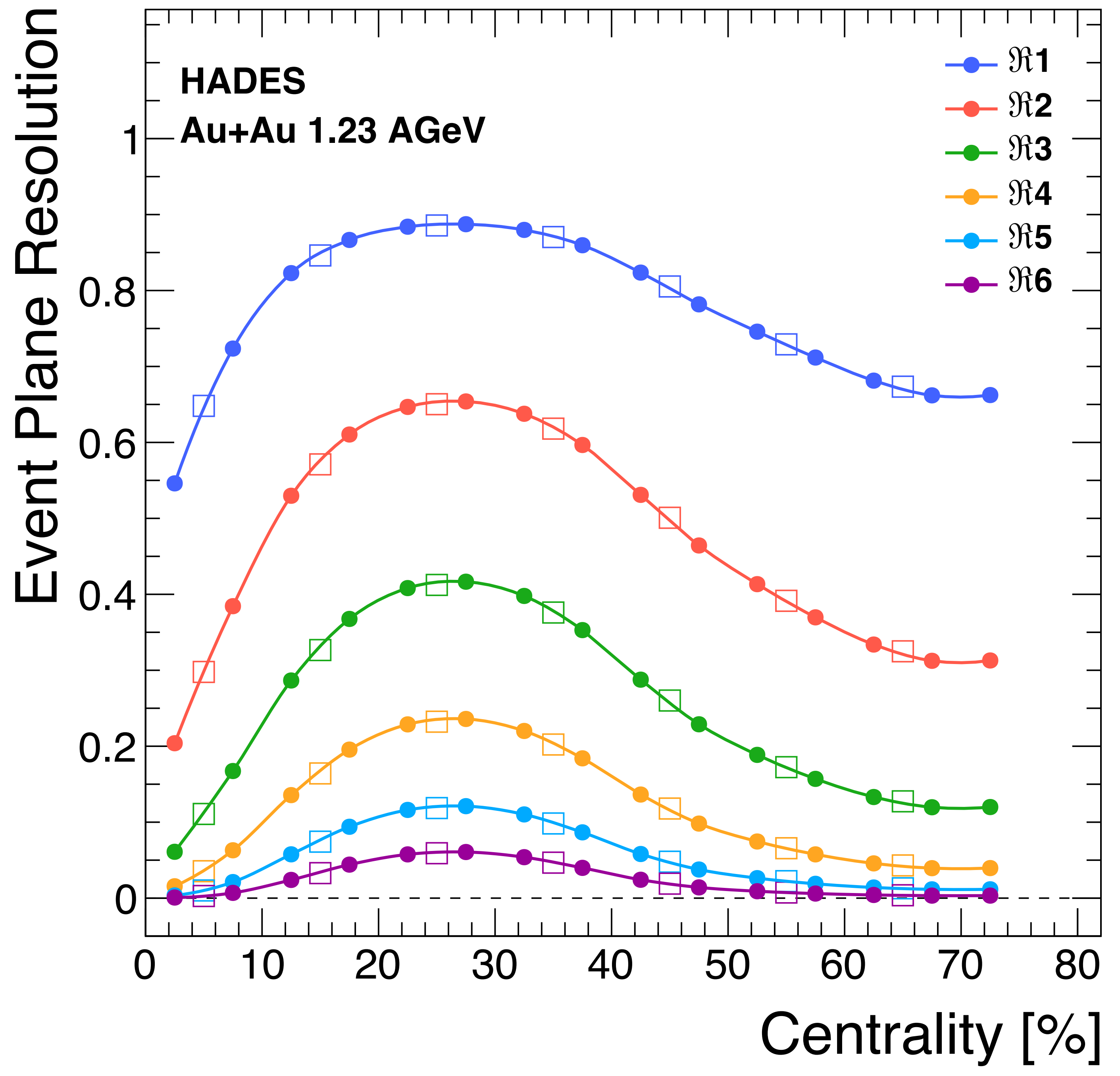
$$-\left\langle\frac{\mathrm{d}E}{\mathrm{d}x}\right\rangle \propto f(Z,\beta)$$

Event Plane Reconstruction

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





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

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

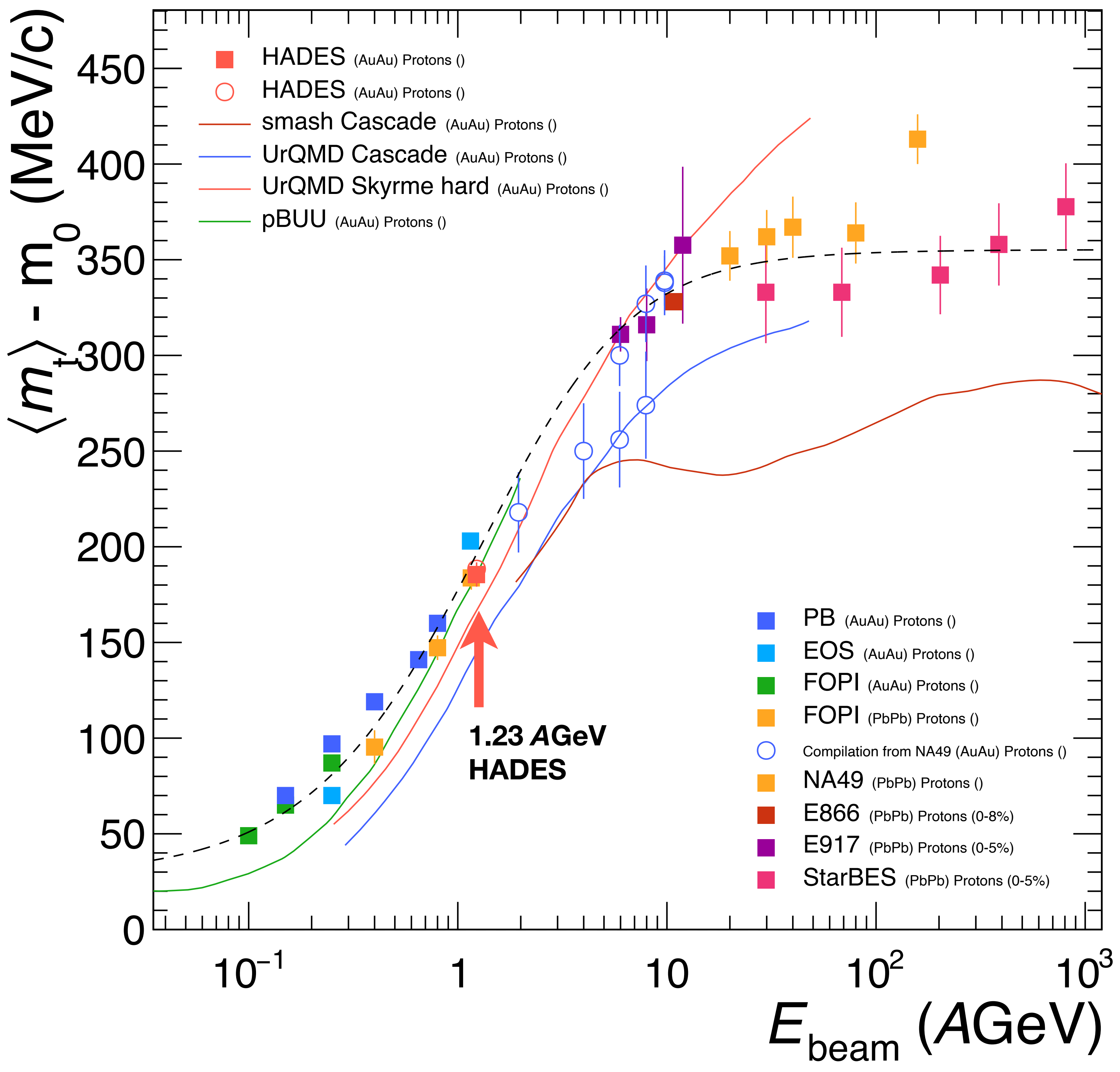
$$Q_{n,y} = \sum_{i=0}^{N_{FW}} w_i \, \sin(n\,\phi_{FW,i})\,.$$

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

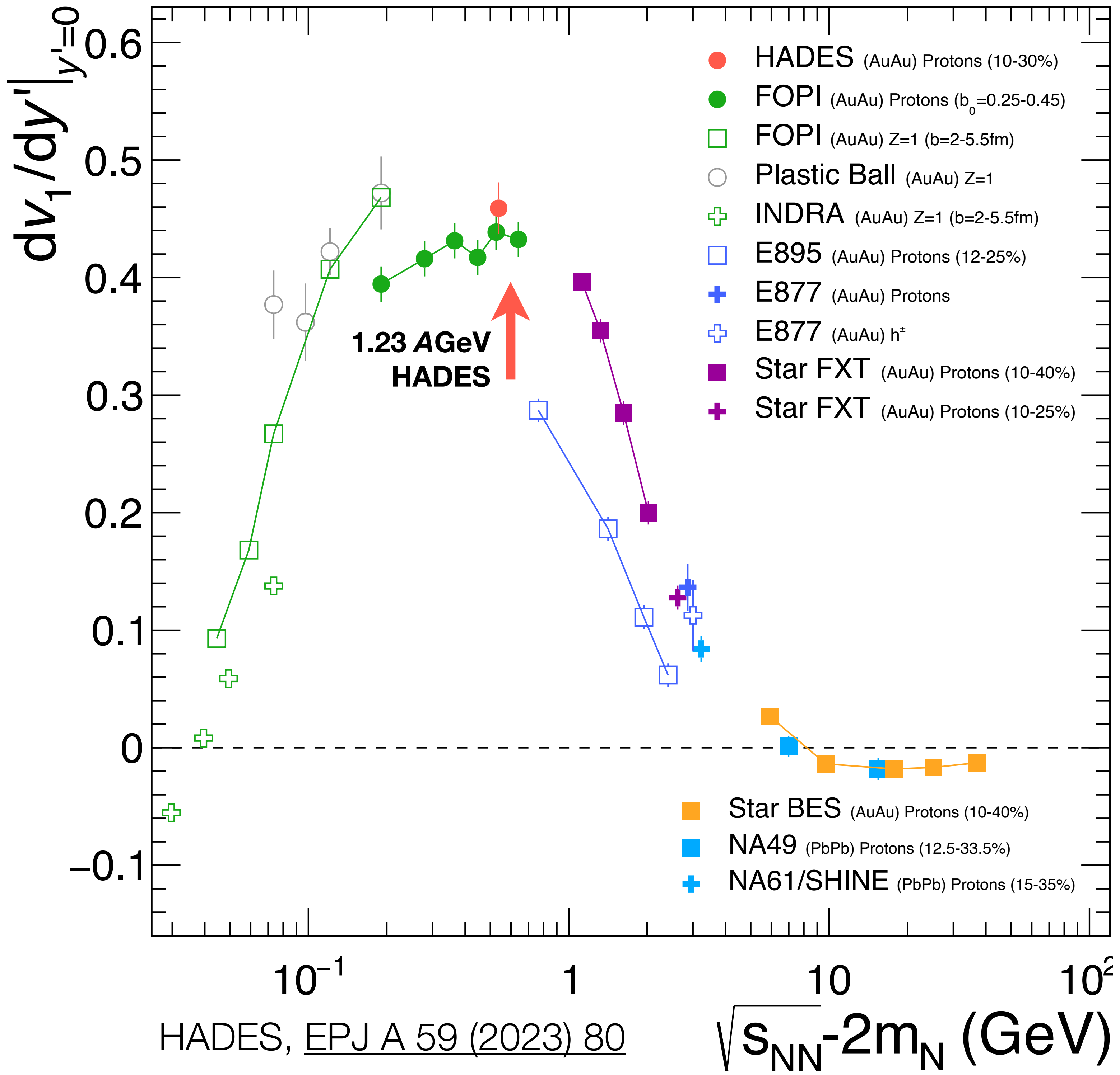
$$\boldsymbol{\mathfrak{R}_n} = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

Compilation of World Data

Energy-Dependence

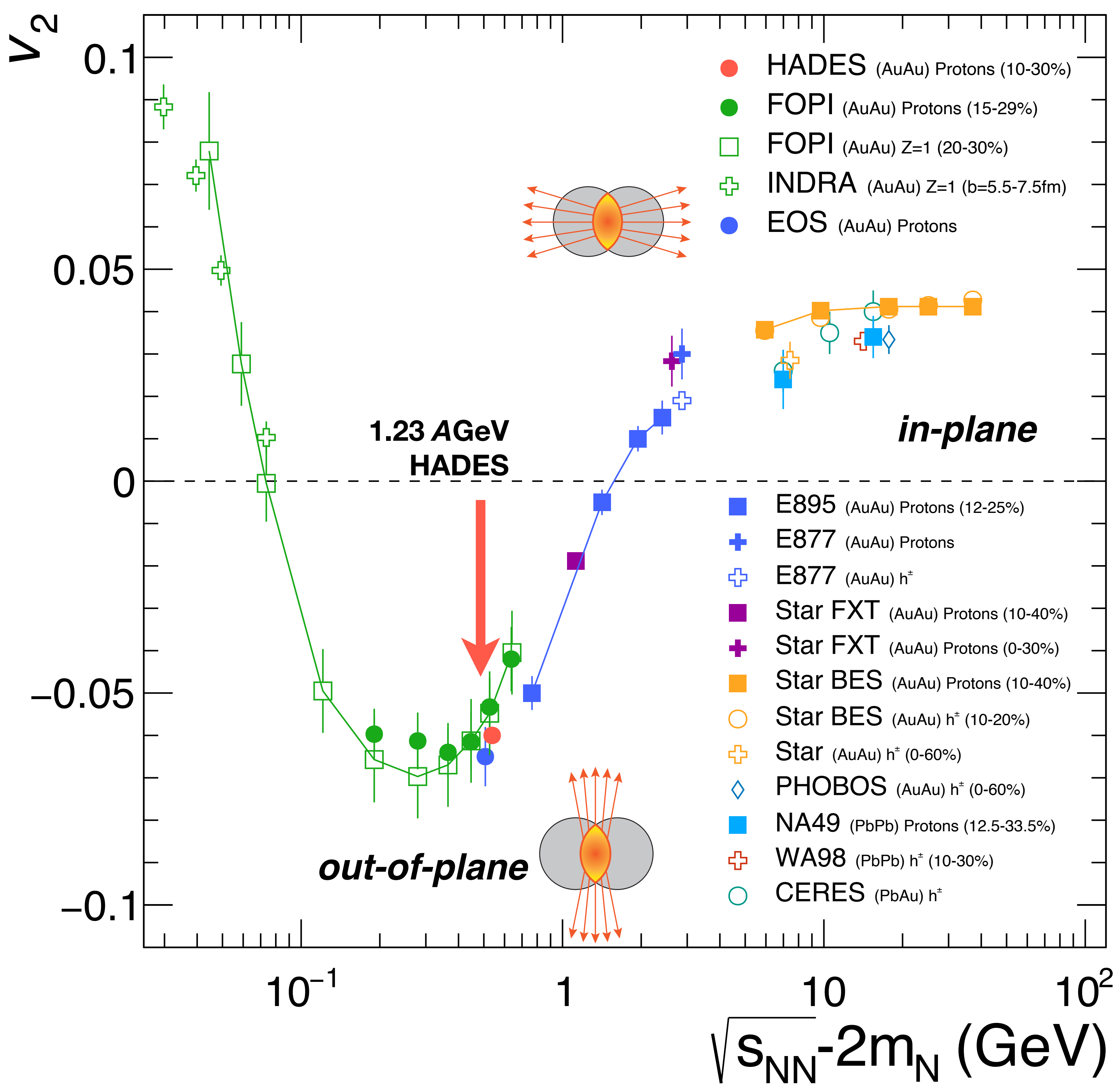


smash Analysis Results 2.2
UrQMD J. Steinheimer et al, EPJC 82 (2022) 911
pBUU P. Danielewicz, PRC 51 (1995) 716



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

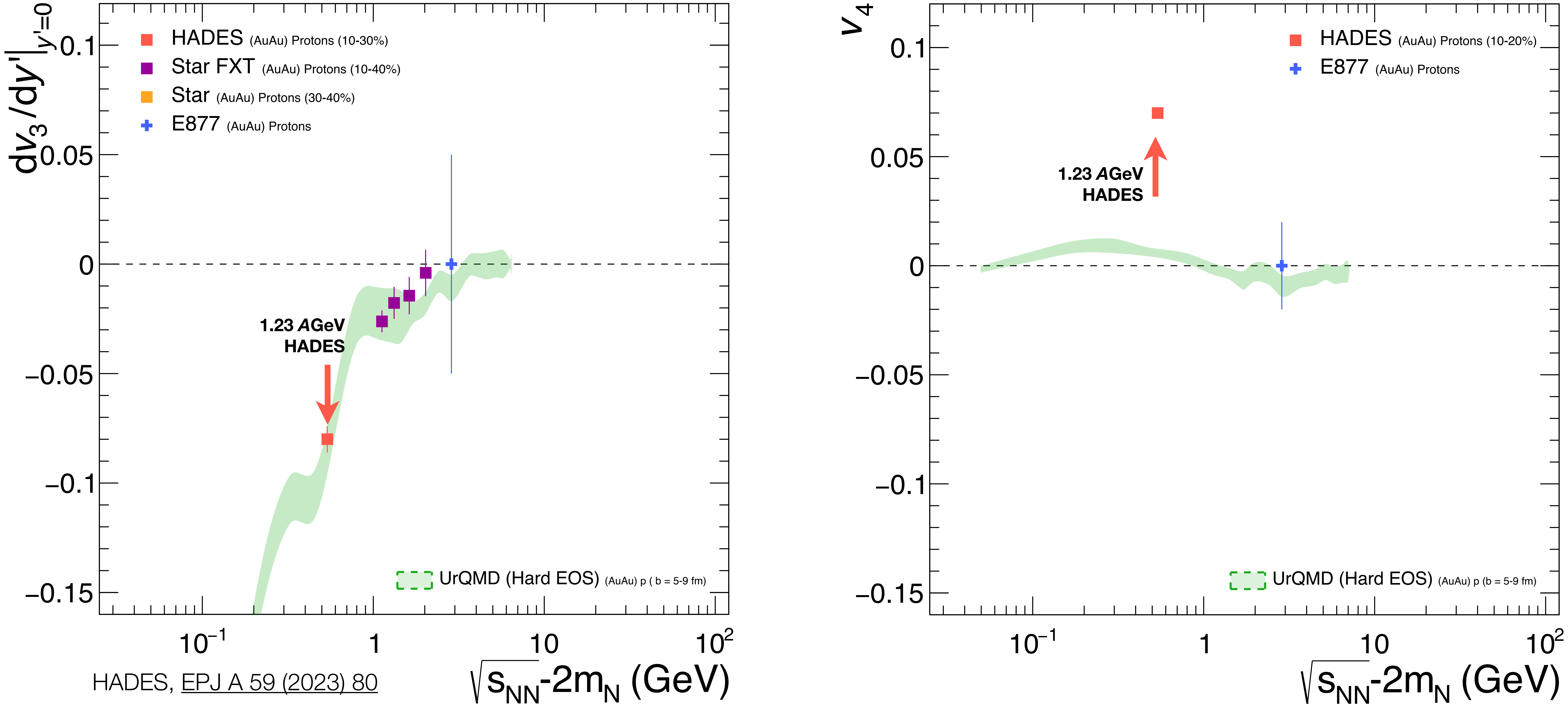
Out-of-Plane v_2

Long spectator passing time at
HADES energy

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

Compilation of World Data

Energy-Dependence



HADES, EPJ A 59 (2023) 80

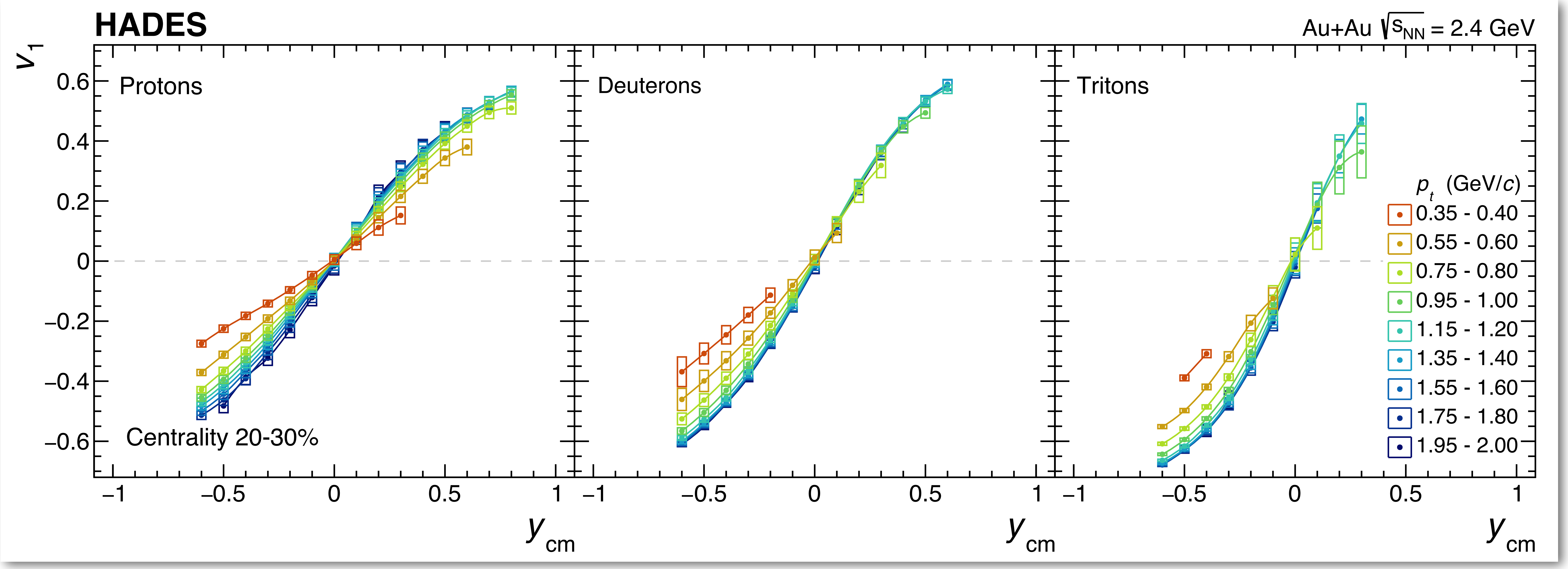
Update Star FXT QM2023

Compilation of world data

New Star FXT v3 data and E877 upper limit

Collective Effects

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



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

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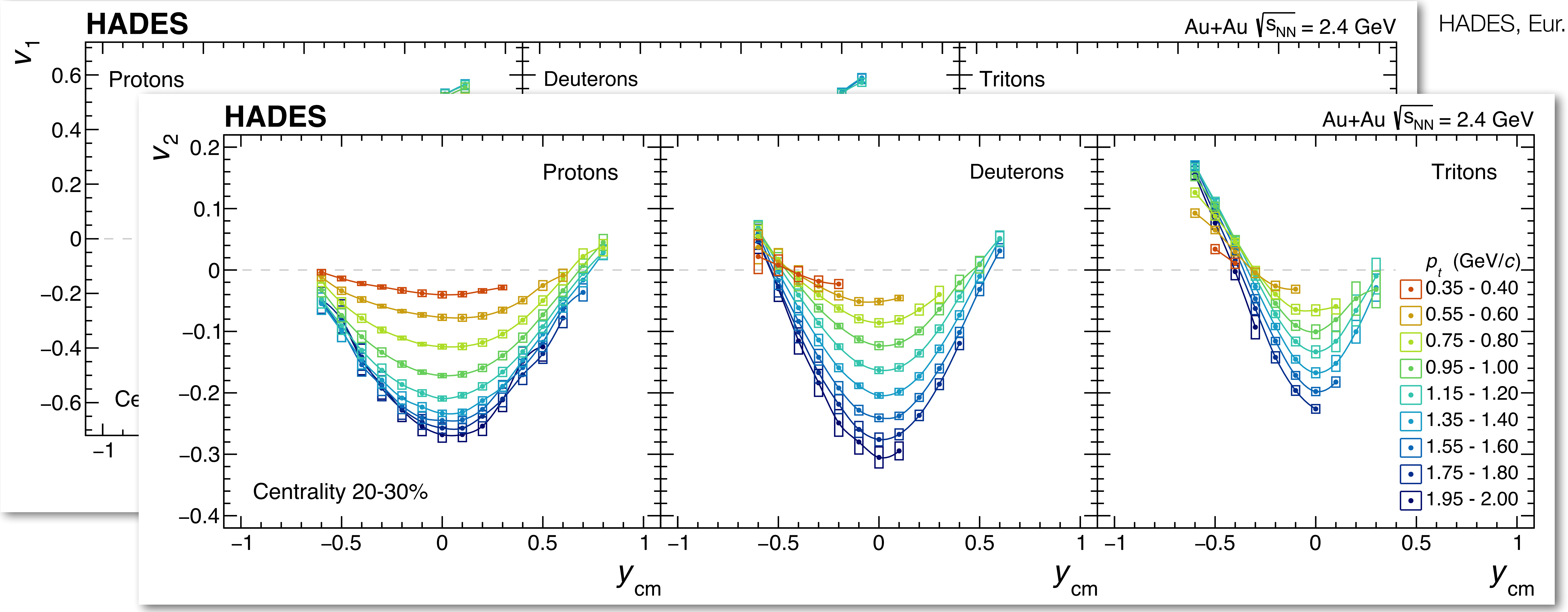

HADES, Eur.Phys.J.A 59 (2023) 4, 80

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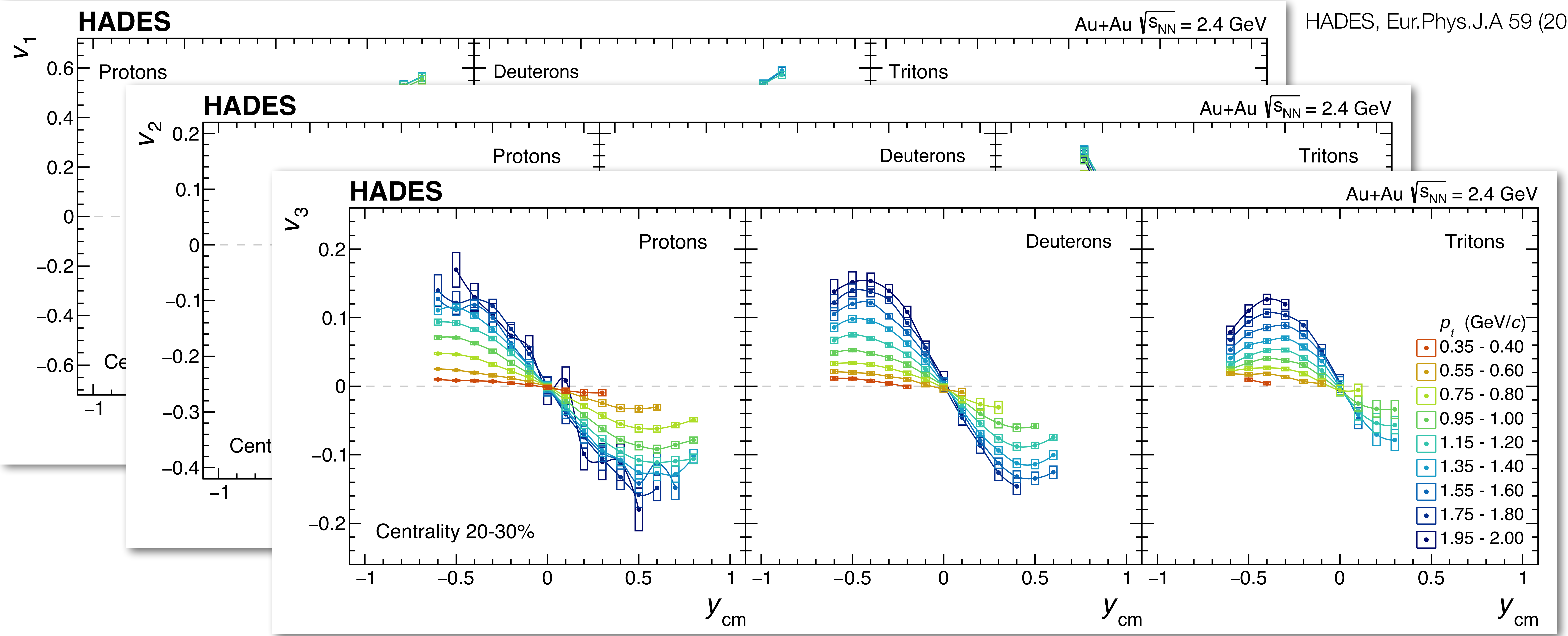

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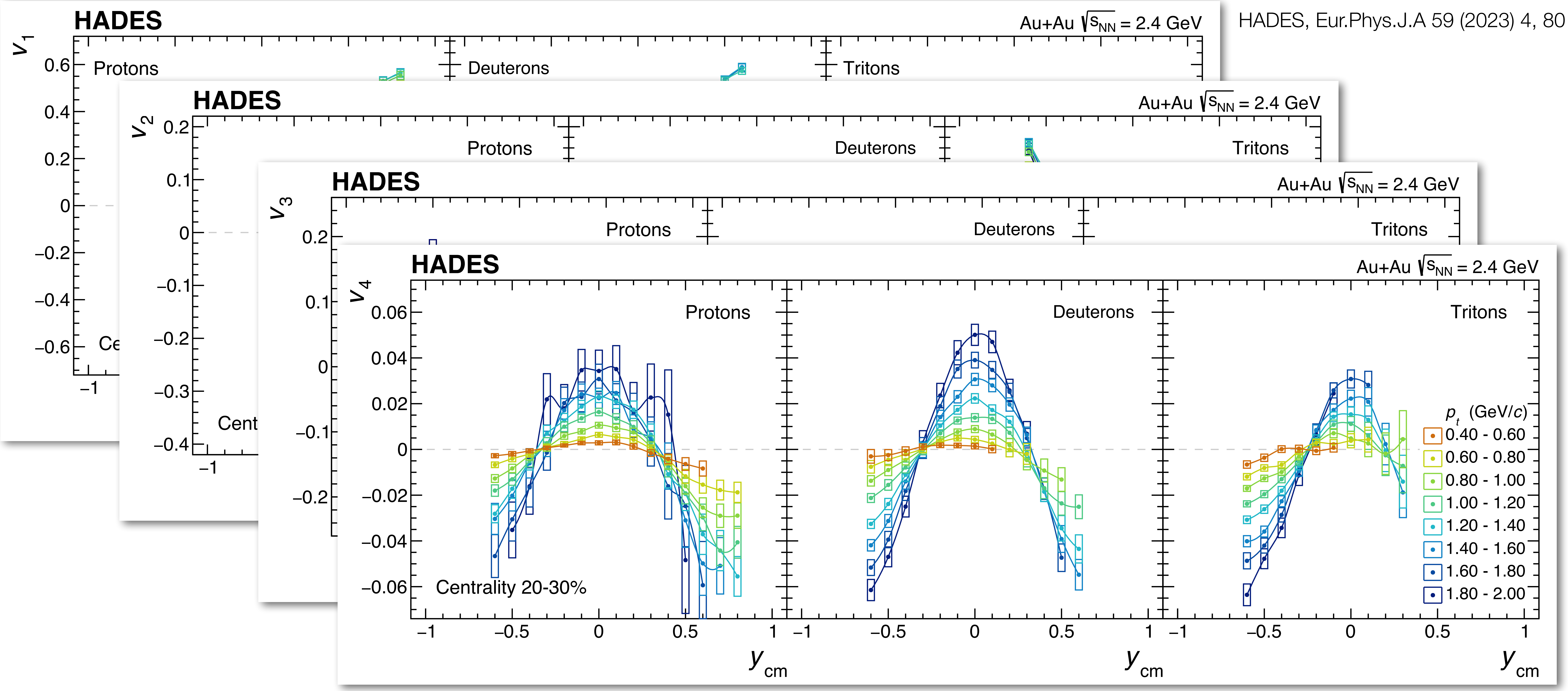

HADES, Eur.Phys.J.A 59 (2023) 4, 80

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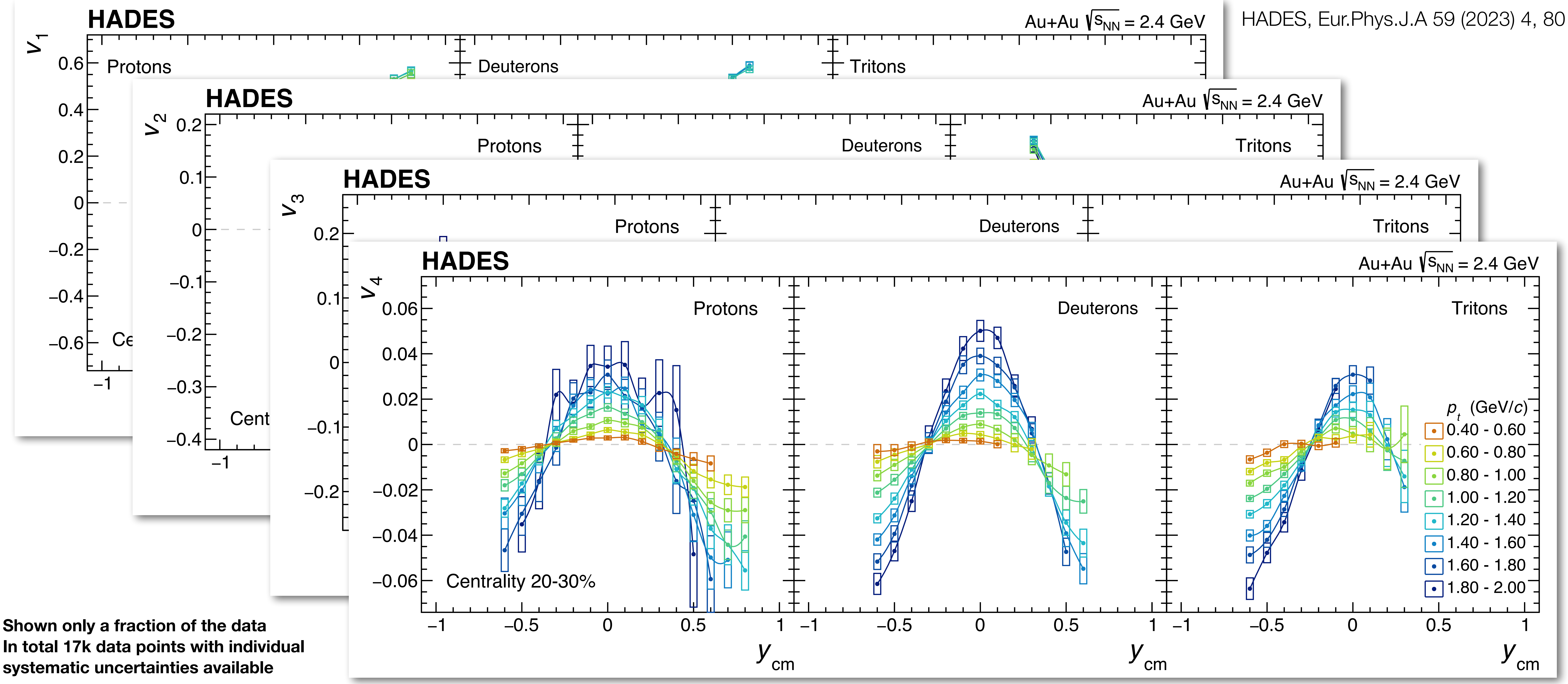
Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

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

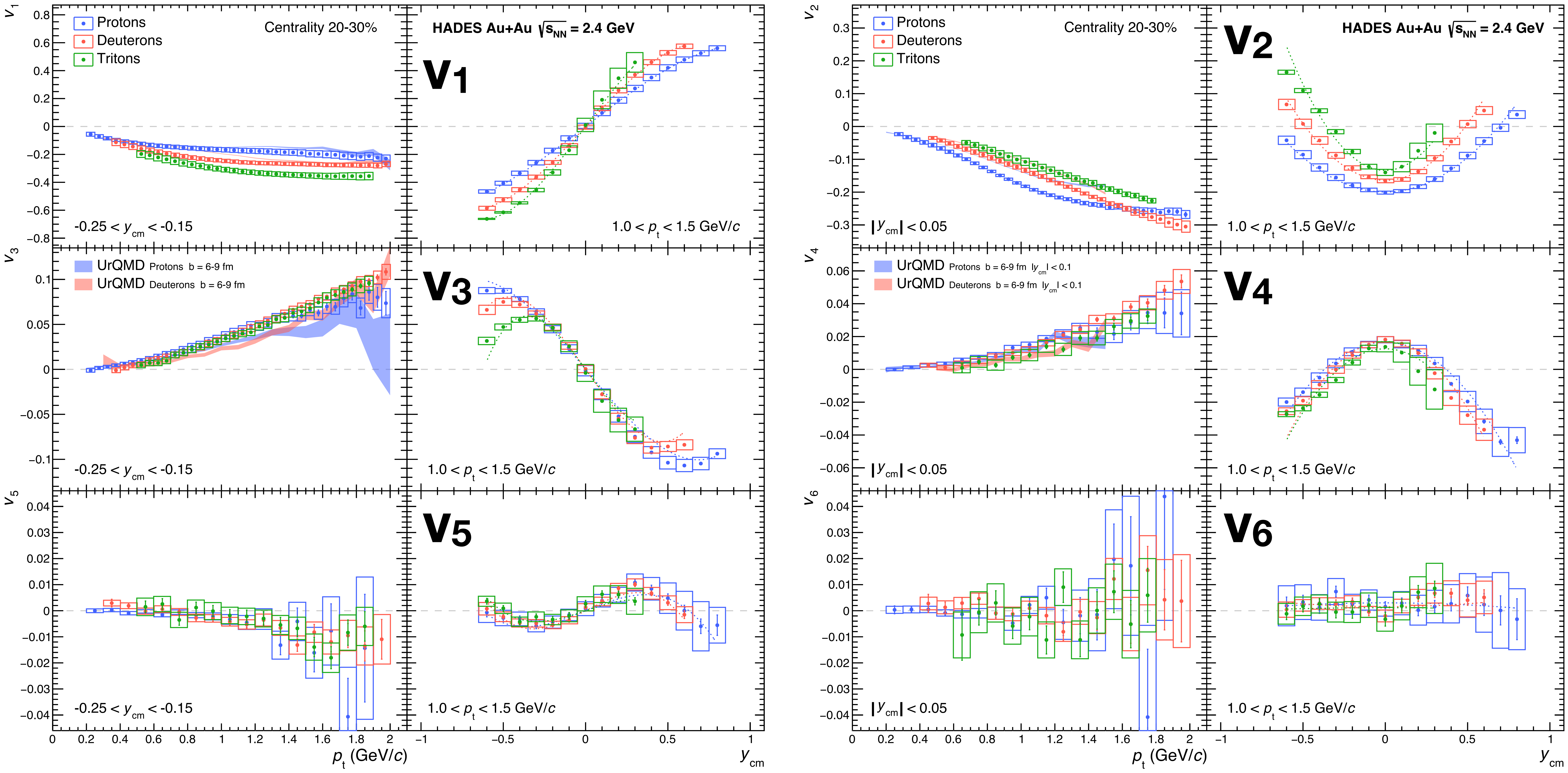


Shown only a fraction of the data
In total 17k data points with individual systematic uncertainties available

Collective Effects

Results on v_1 — v_6 for Protons, Deuterons and Tritons

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



“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

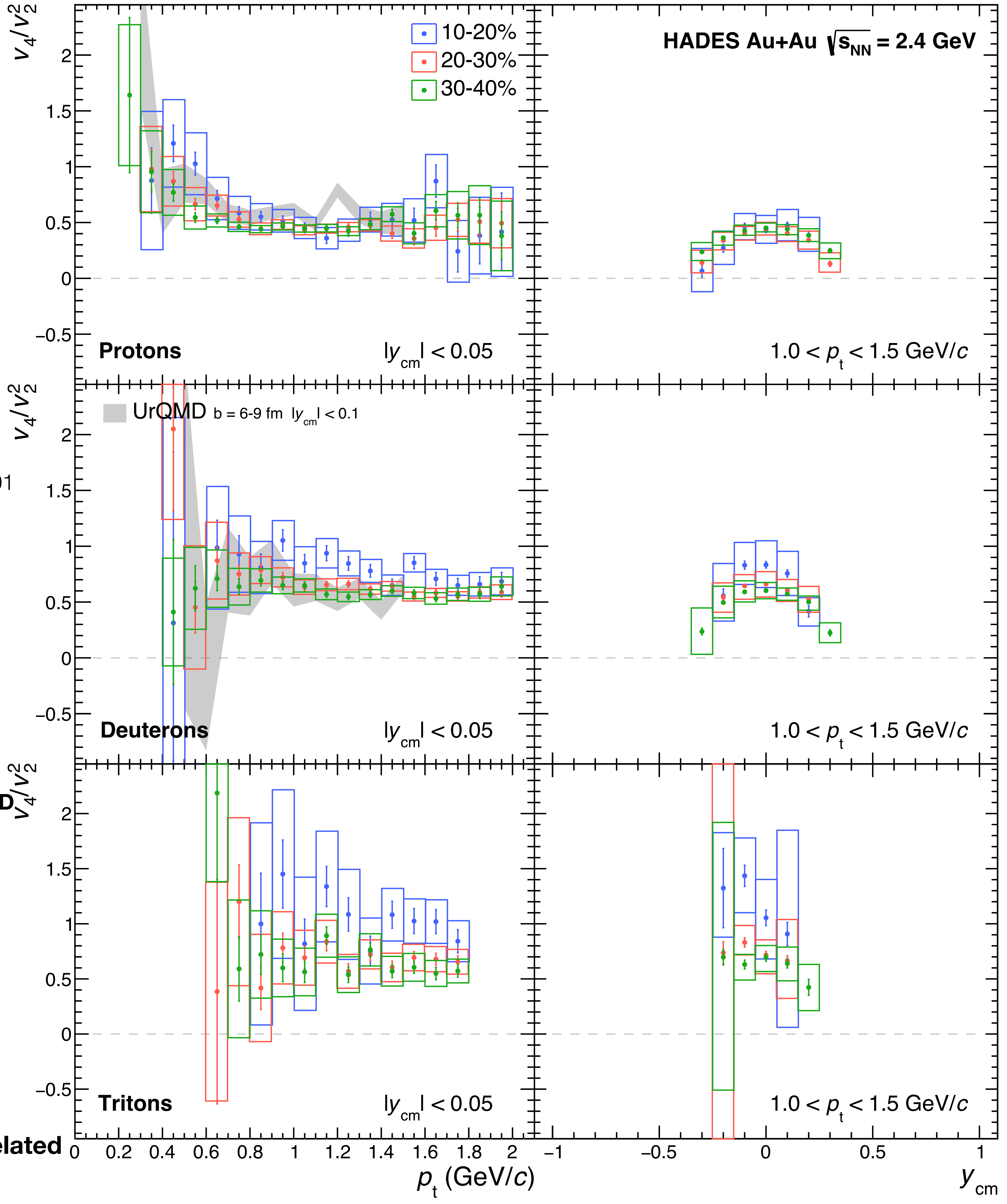
Independent of p_t and centrality
Close to predicted value of ~ 0.6

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?

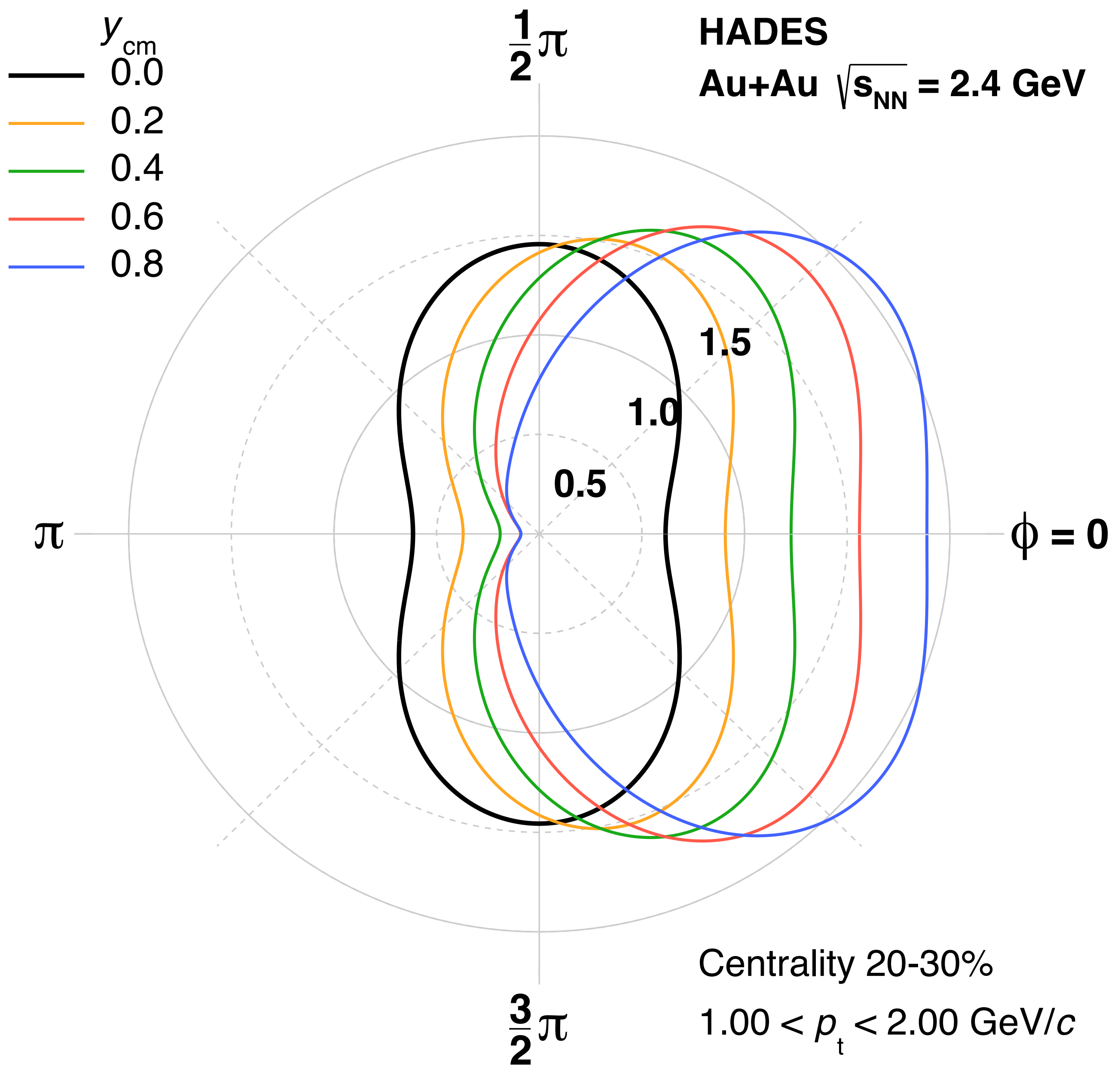
HADES, Phys. Rev. Lett. **125** (2020) 262301

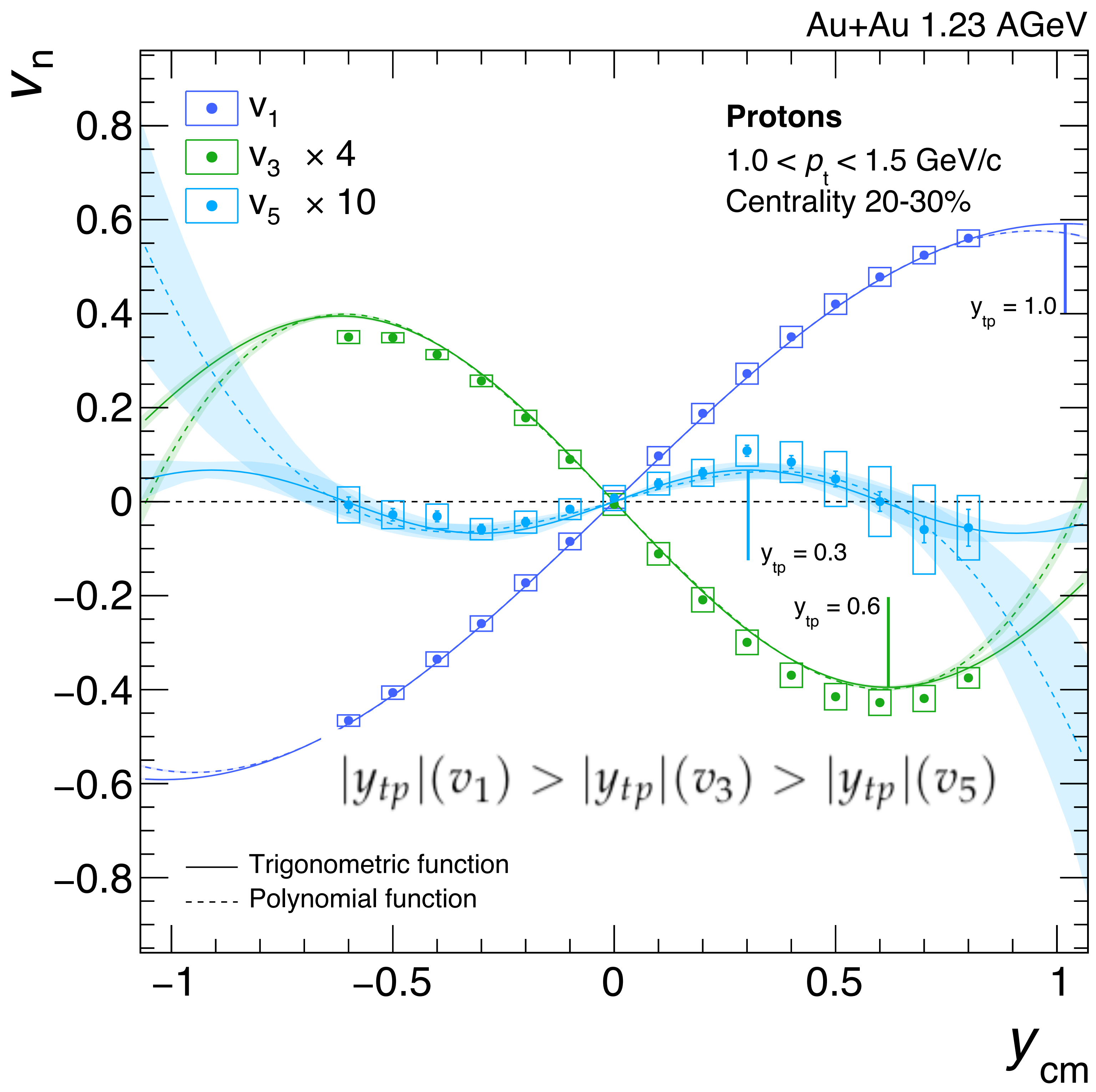


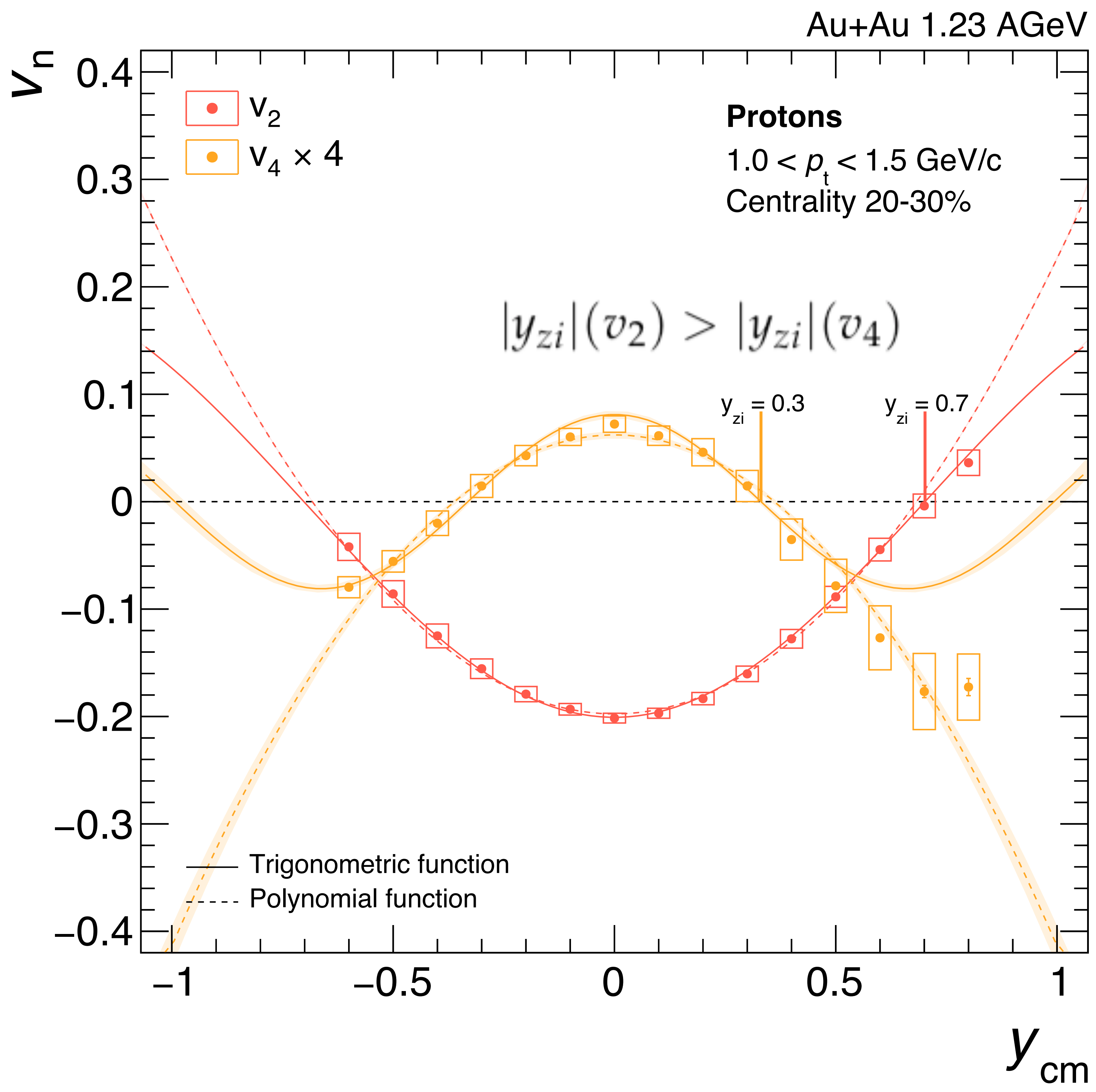
Systematic Error of v2 and v4 are treated as correlated

Parameterization

Rapidity-Dependence







HADES Data:
PRL 125 (2020) 262301

Polynomial function:

$$v_{n,\,odd}(y_{\rm cm}) = v_{n1}\, y_{\rm cm} + v_{n3}\, y_{\rm cm}^3$$
$$v_{n,\,even}(y_{\rm cm}) = v_{n0} + v_{n2}\, y_{\rm cm}^2$$

Trigonometric functions:

$$v_n^{odd}(y_{\rm cm}) = v_n^{\rm sat} \cdot \sin(y_{\rm cm}/y_{tp} \cdot \pi/2)$$
$$v_n^{even}(y_{\rm cm}) = v_n^{\rm sat} \cdot \cos(y_{\rm cm}/y_{zi} \cdot \pi/2)$$

Emission Pattern

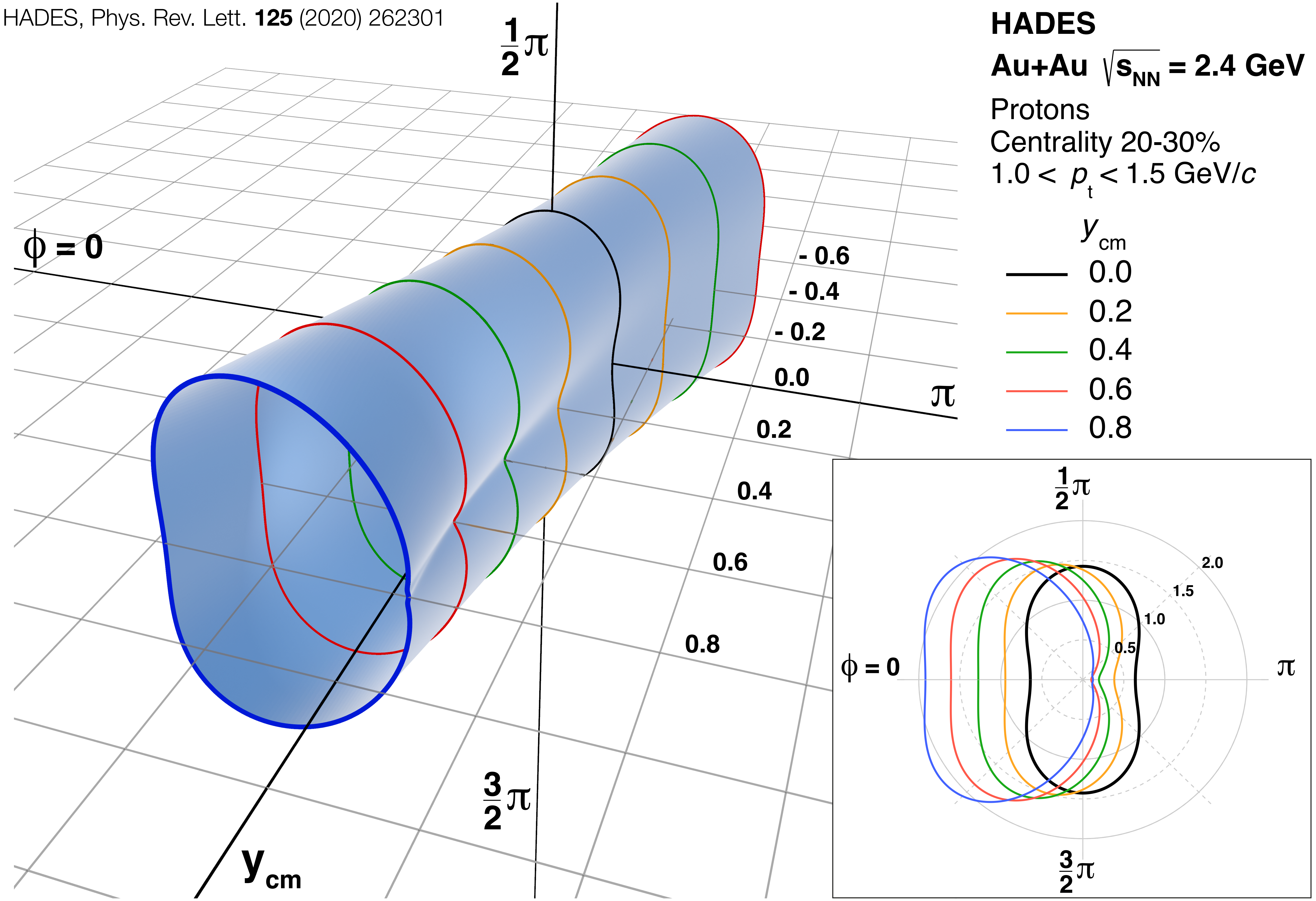
Protons

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 $v_1 - v_6$

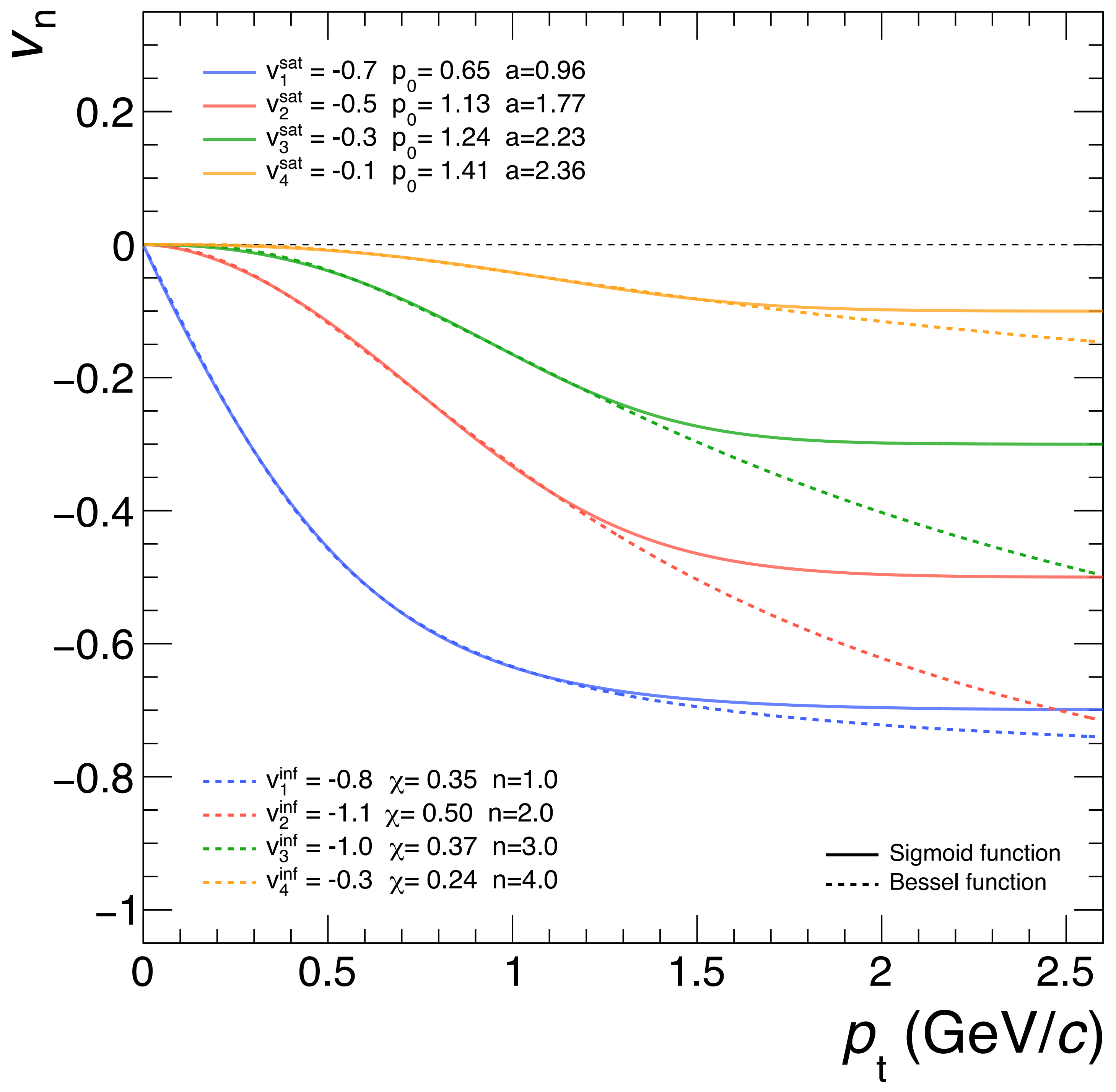
$$1 + 2\sum_{n=1}^{\infty} v_n(y_{cm}) \cos n(\phi - \psi_{RP})$$

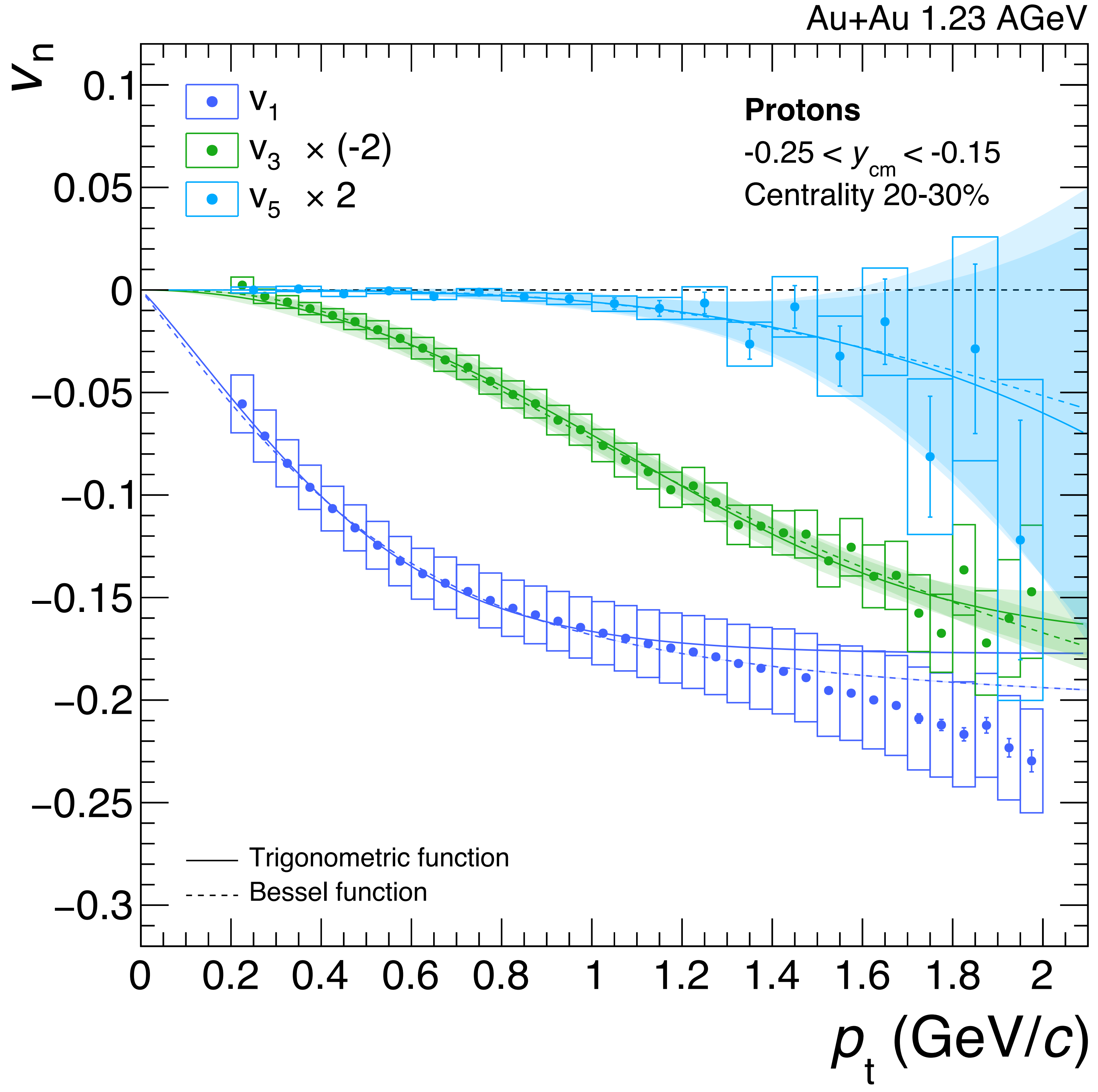
First Proposed in S. Voloshin and Y. Zhang
Z.Phys. C70 (1996) 665-672

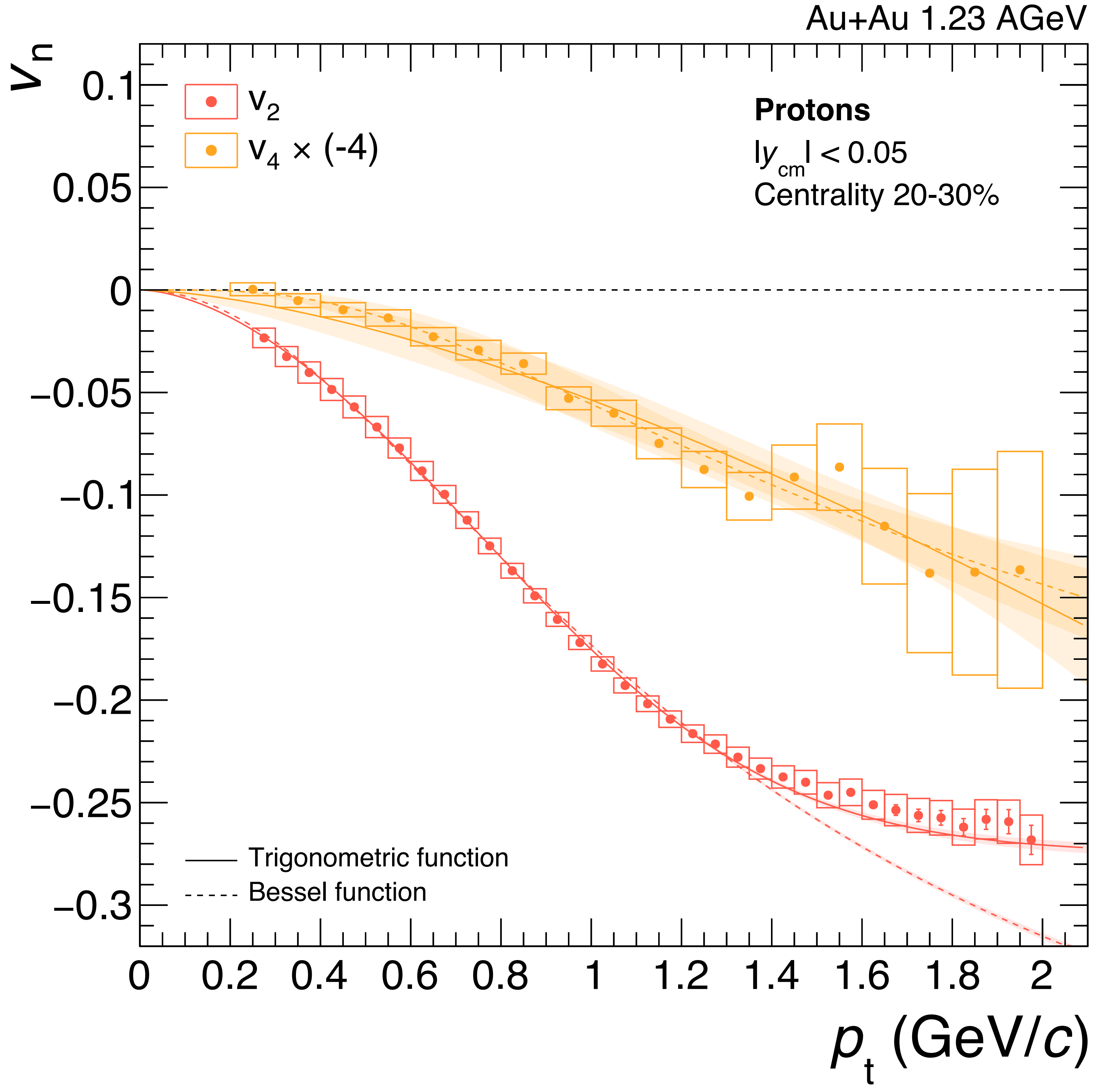

HADES, Phys. Rev. Lett. **125** (2020) 262301

Parameterization

p_t-Dependence







HADES Data:
PRL 125 (2020) 262301

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:

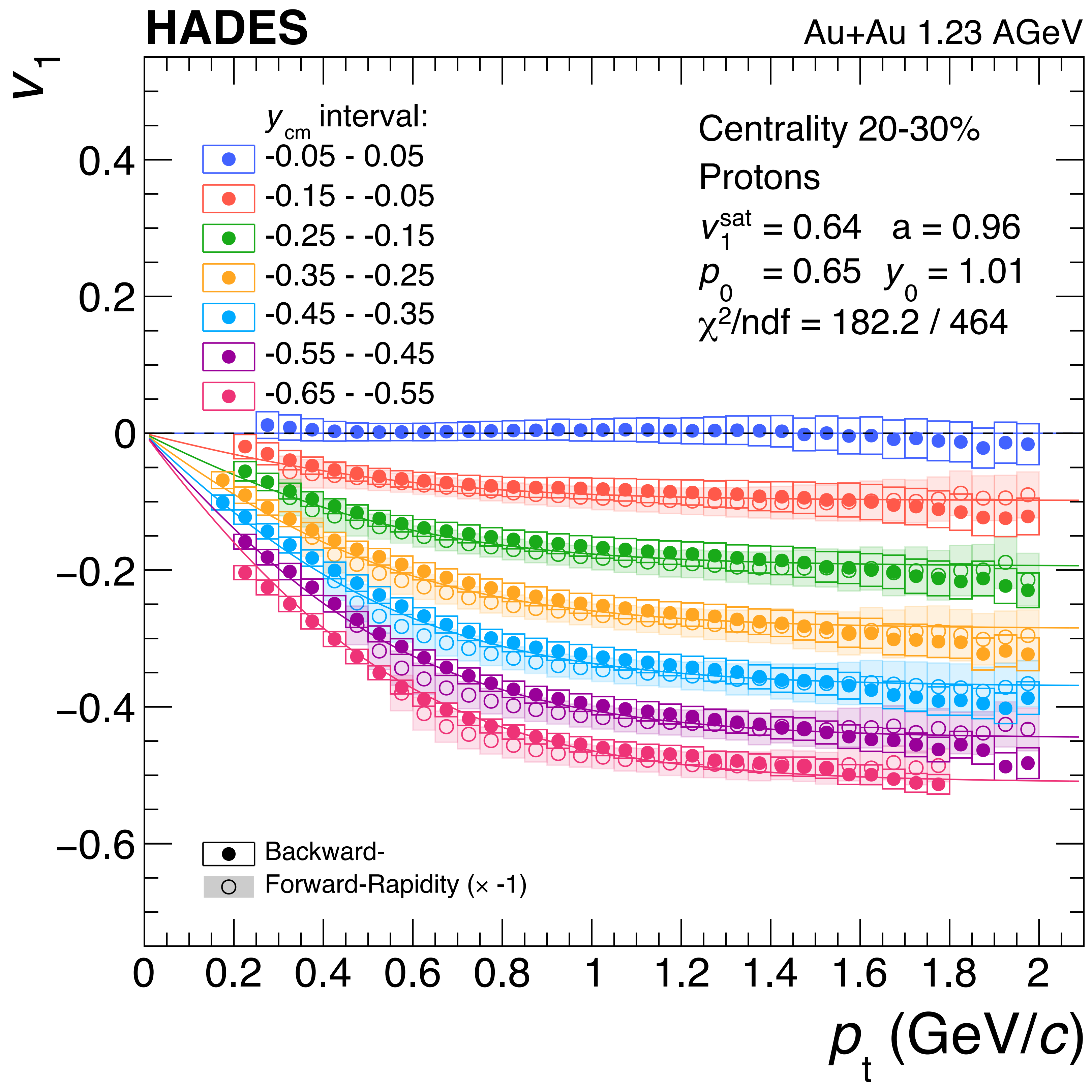
$$v_n(p_t) = v_n^{\text{inf}}\ I_n(p_t/\chi)/I_0(p_t/\chi)$$

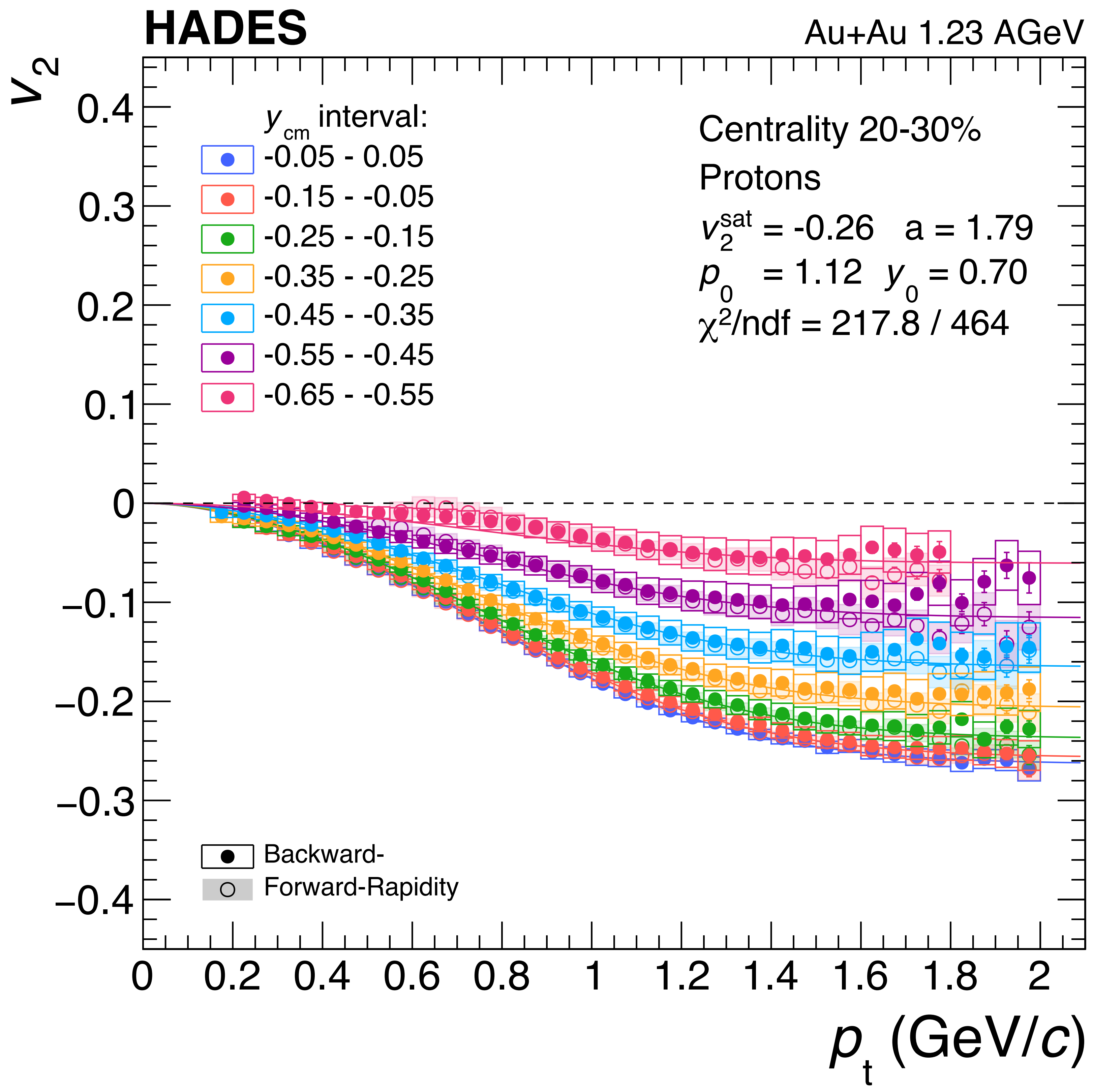
Trigonometric functions:

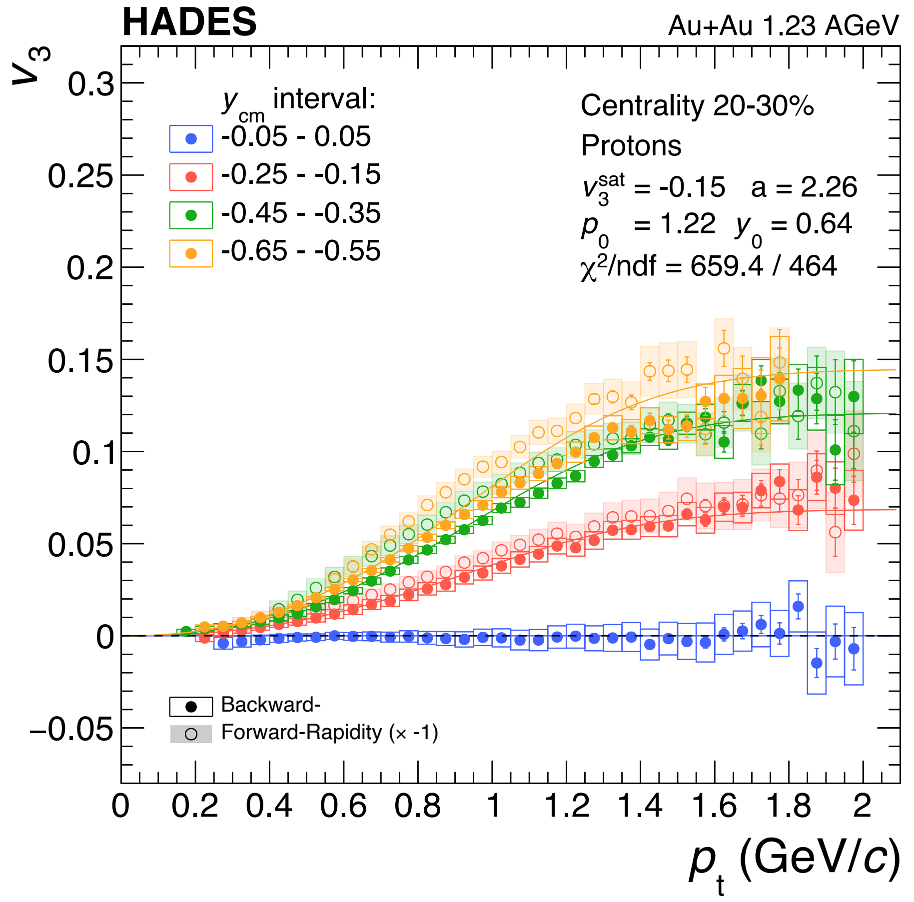
$$v_n(p_t) = v_n^{\text{sat}} \cdot \tanh(p_t/p_0)^a$$

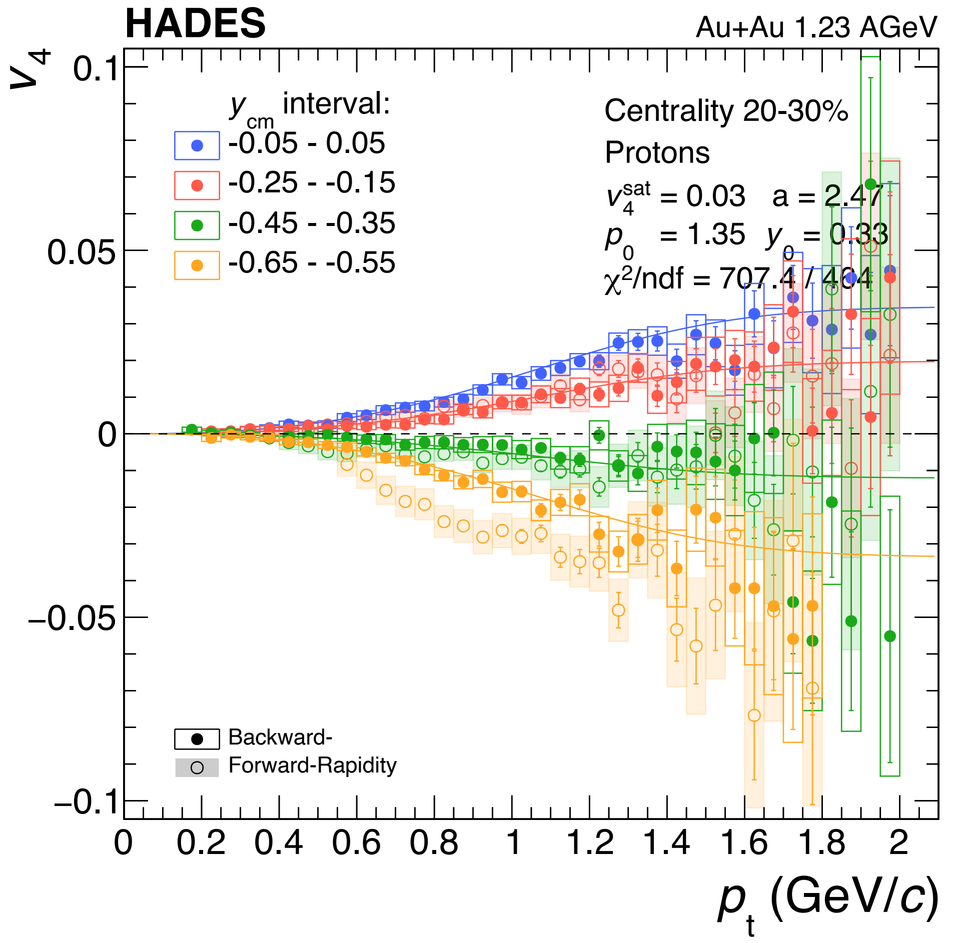
Global Parameterization

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 Parameter for each Centrality class, Particle Type and Flow Harmonic

Nucleon Coalescence

Scaling Properties of v_2 at Mid-Rapidity

Scaling of v_2 and p_t with nuclear mass number A

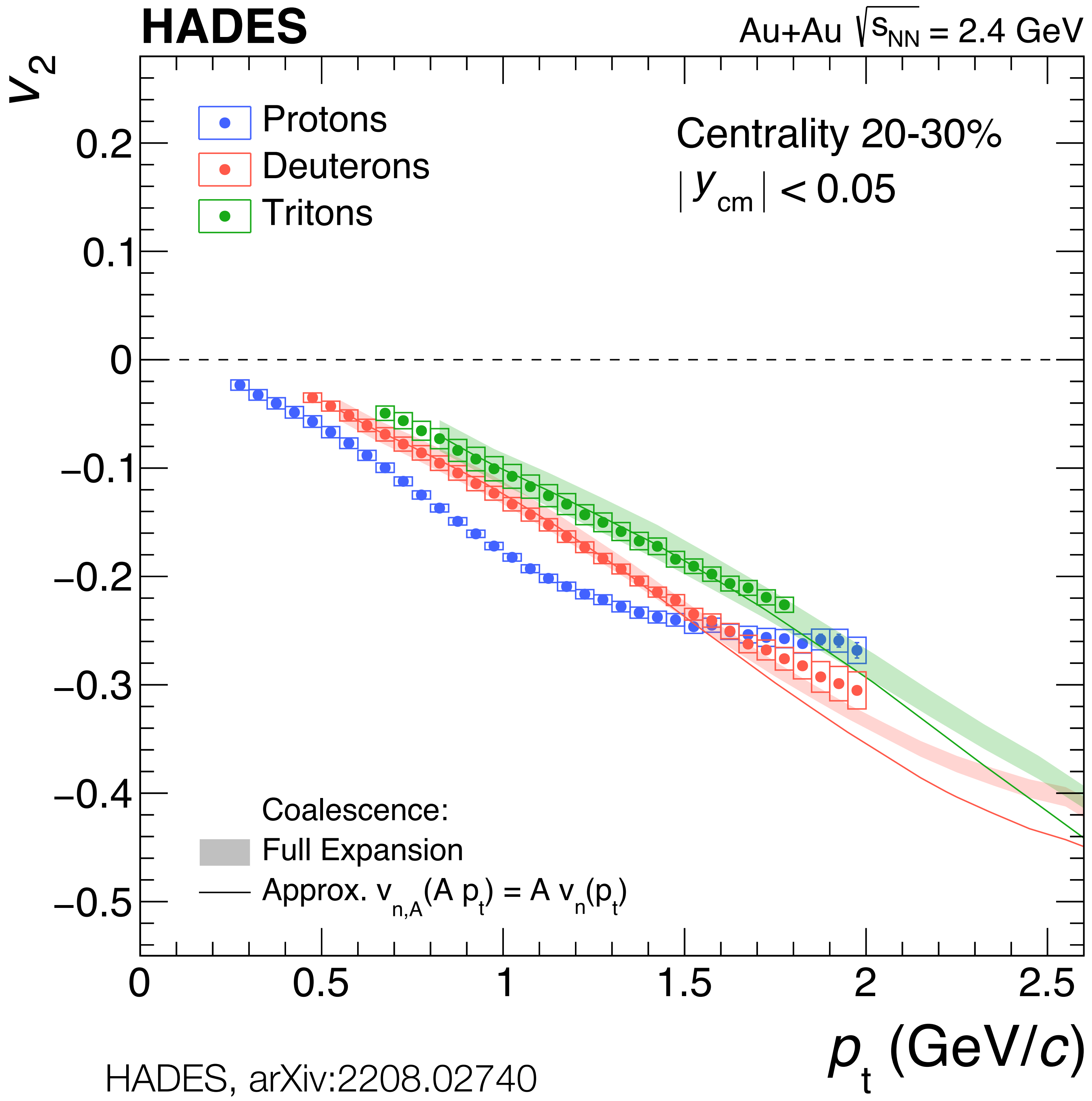
Inclusion of higher order terms

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

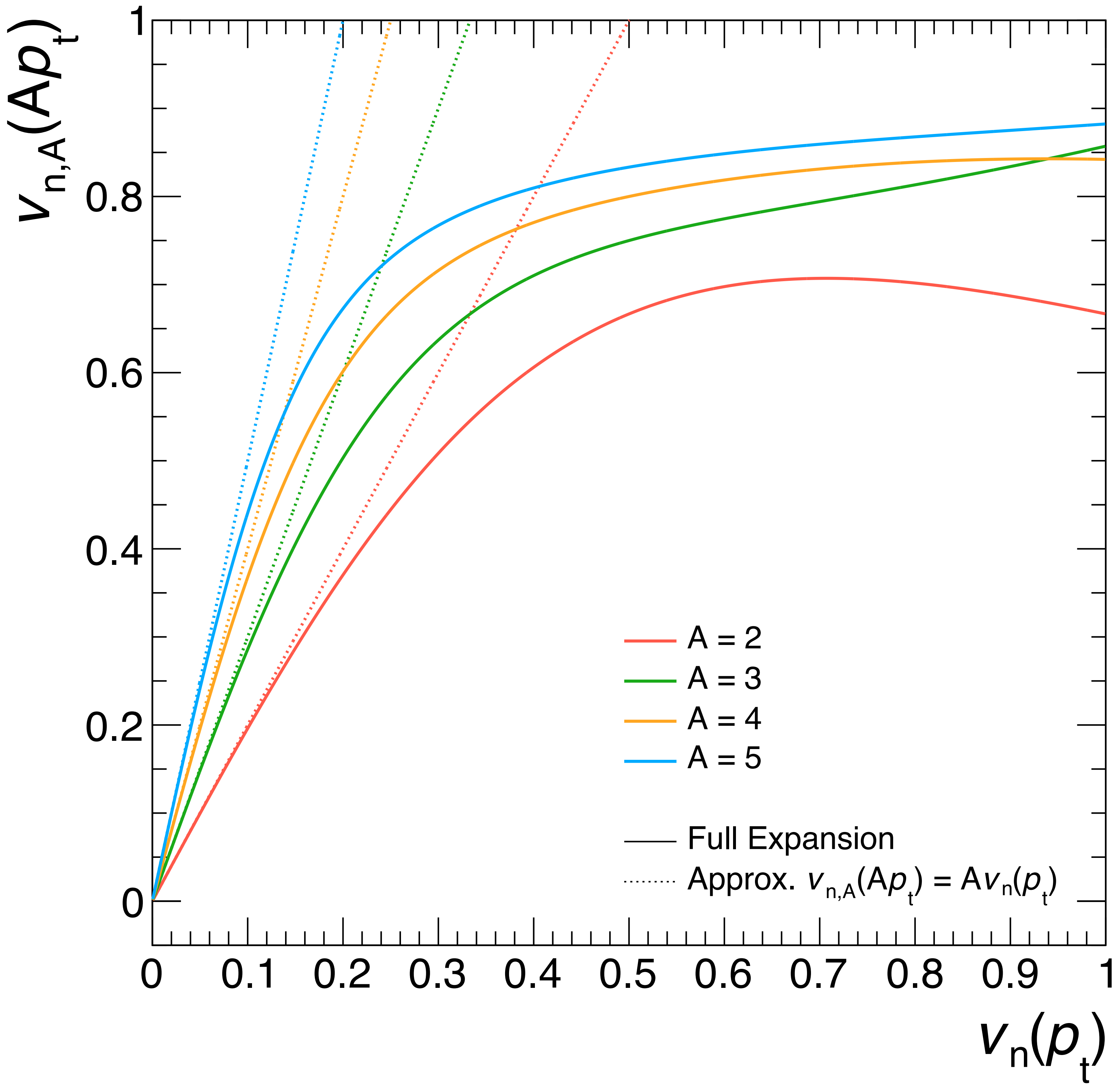
Odd flow coefficients vanish at mid-rapidity and v_4 contribution is negligible

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

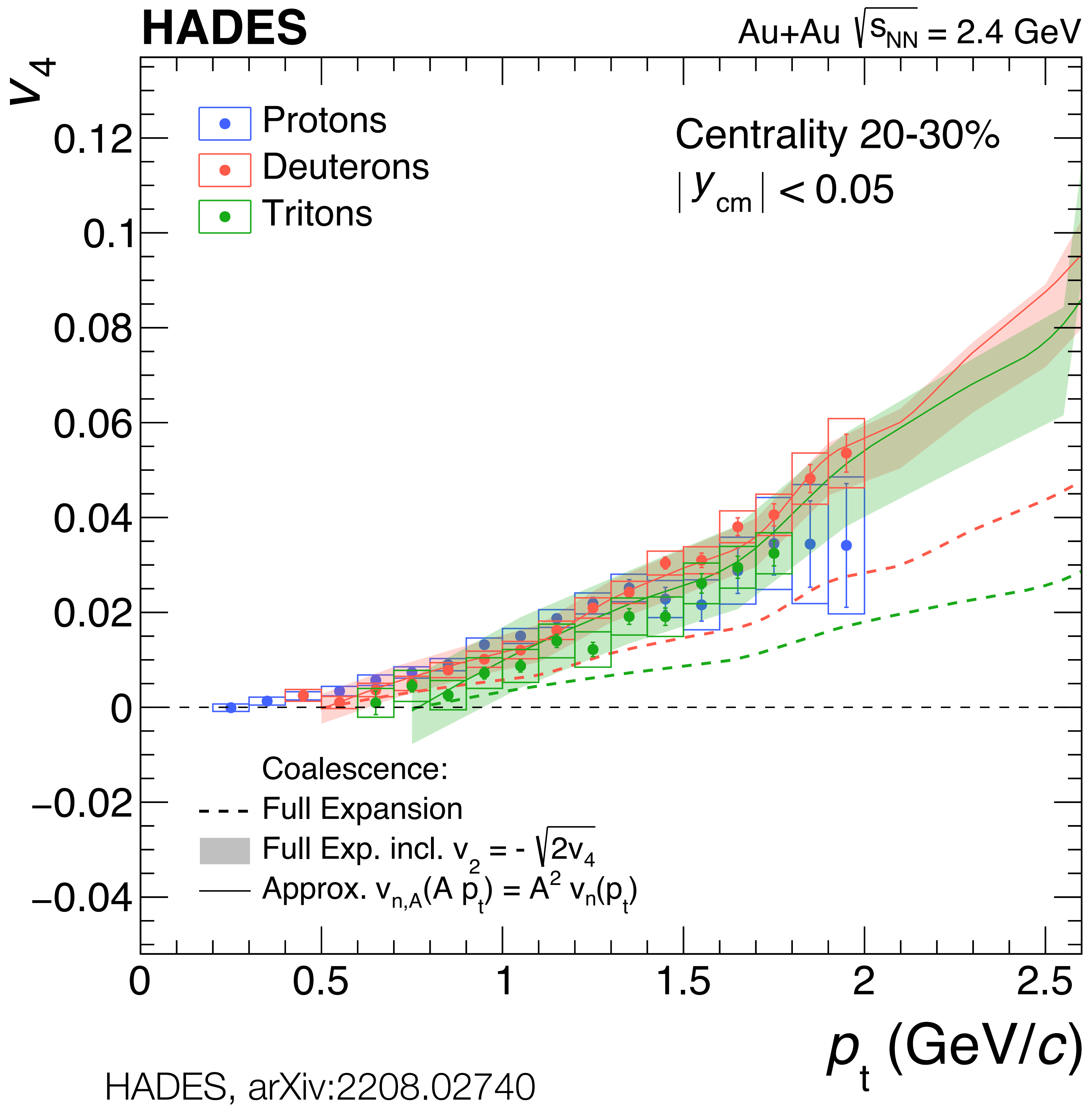
Scaling of v_4 and p_t with nuclear mass number A

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:

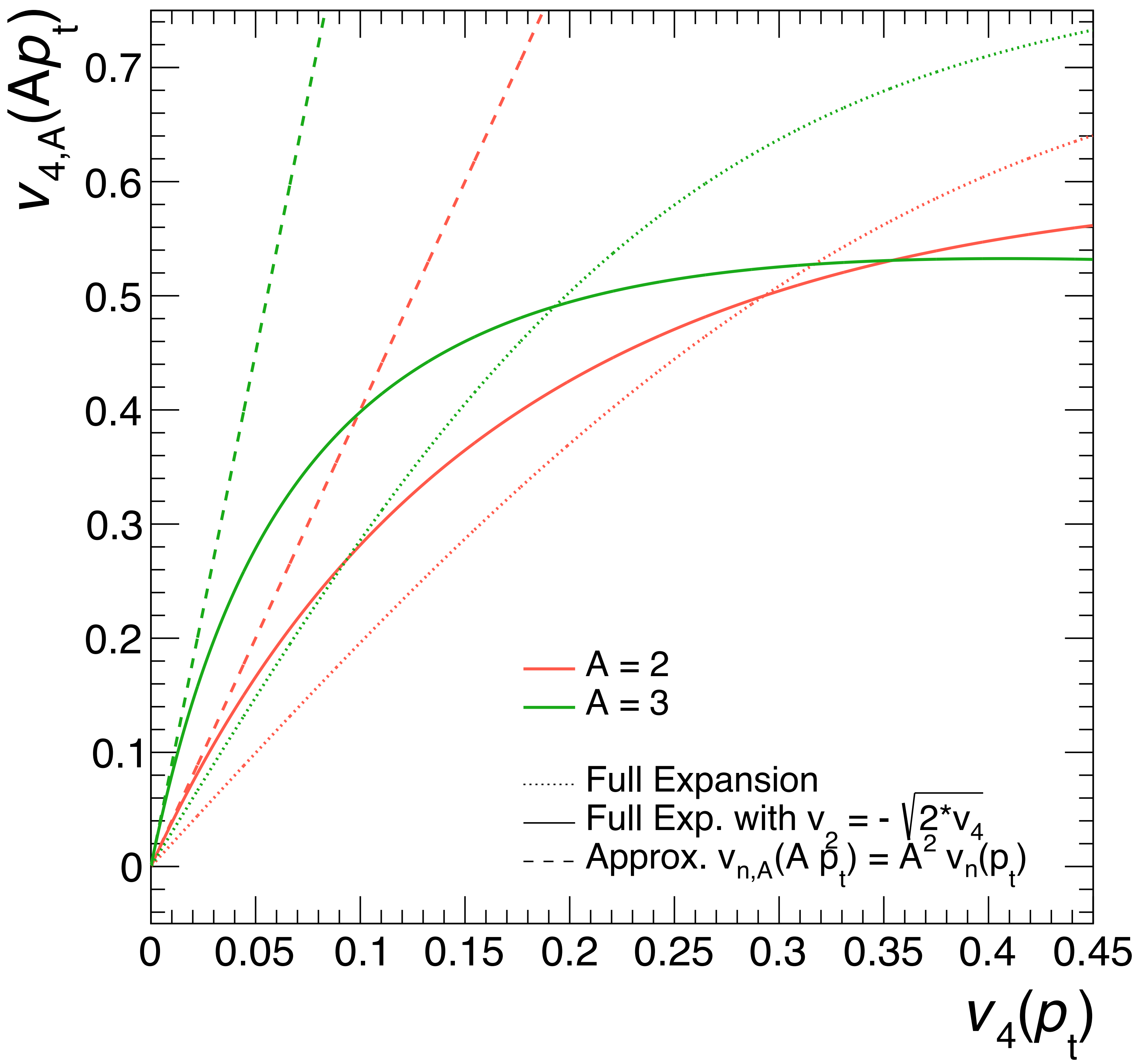
$$v_{n,A}(A\,p_t) = A^2\,v_n(p_t)$$



HADES, arXiv:2208.02740

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

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

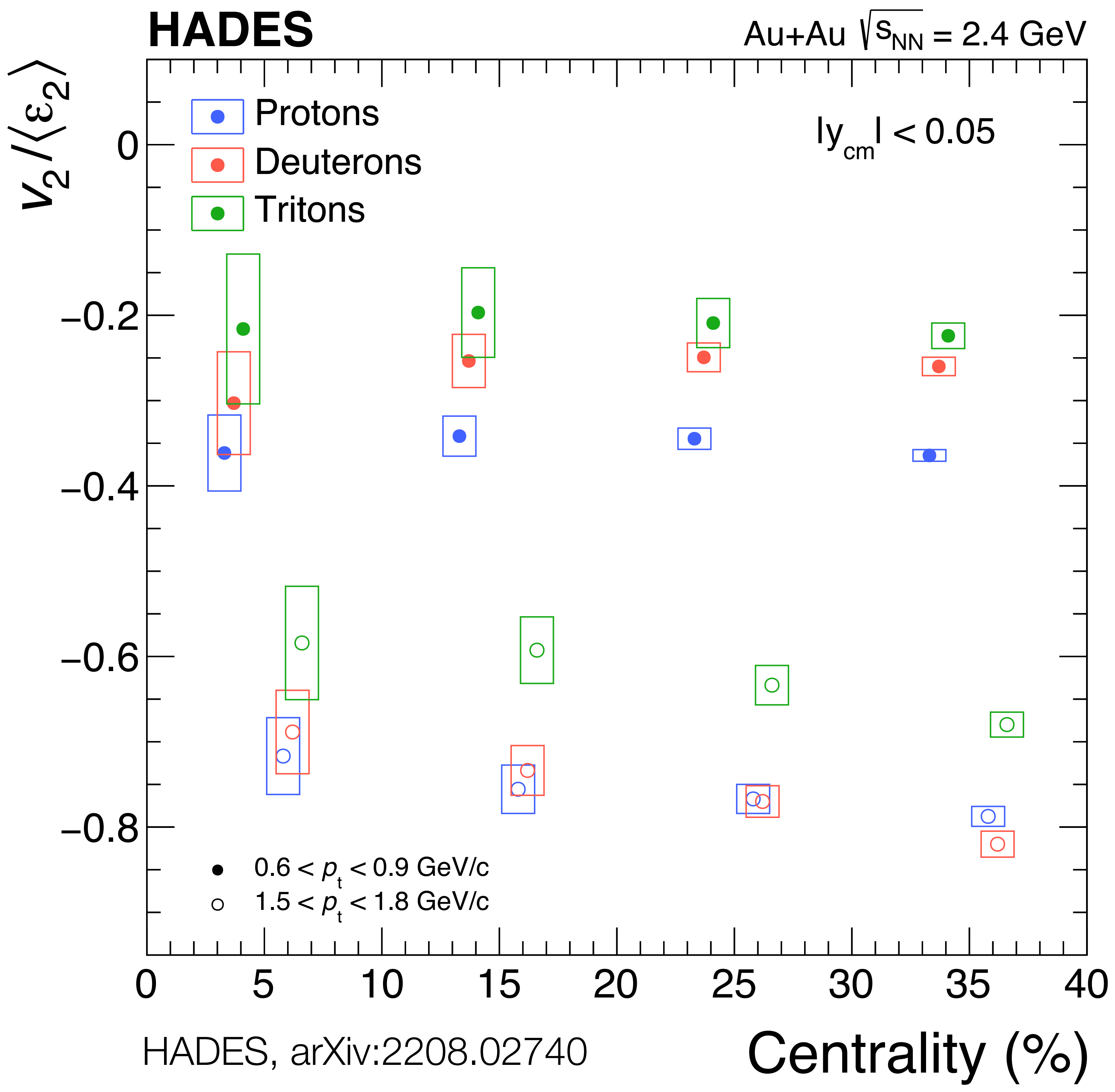


assuming: $v_4(p_t)/v_2^2(p_t) = 1/2$

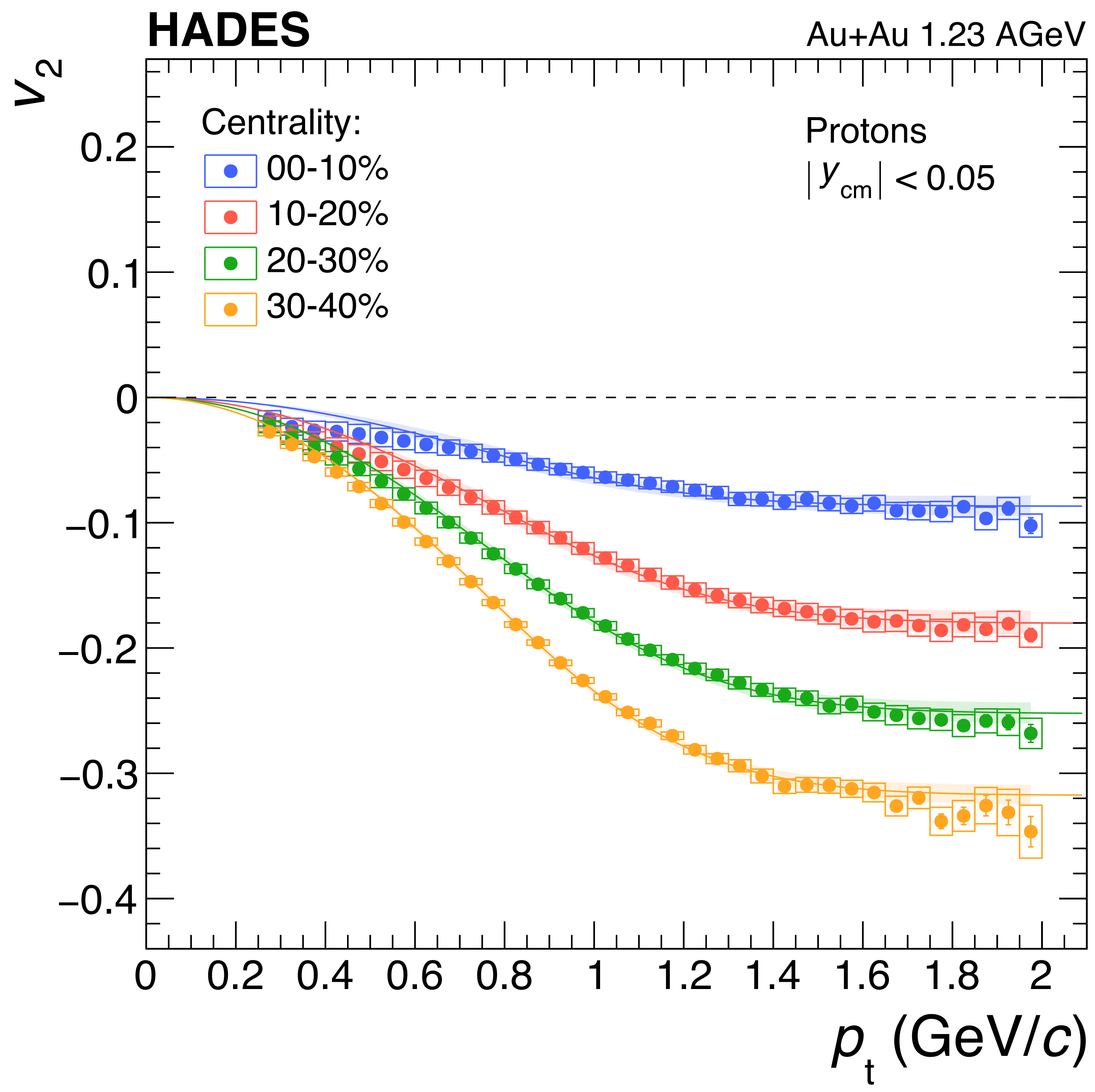
D. Molnar and S.A. Voloshin PRL **91** (2003) 092301
P.F. Kolb et al., PRC **69** (2004) 051901

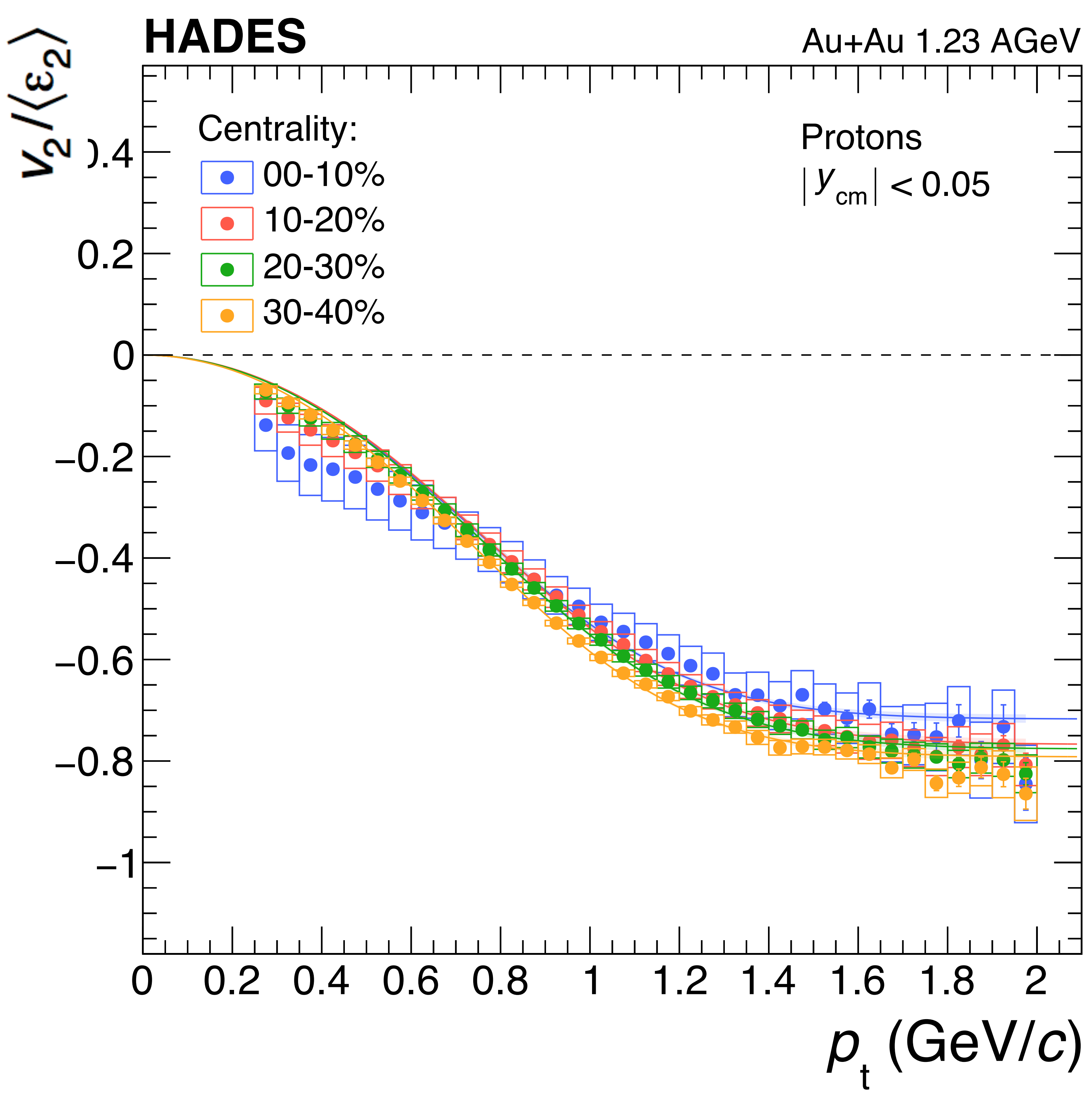
Geometry Scaling

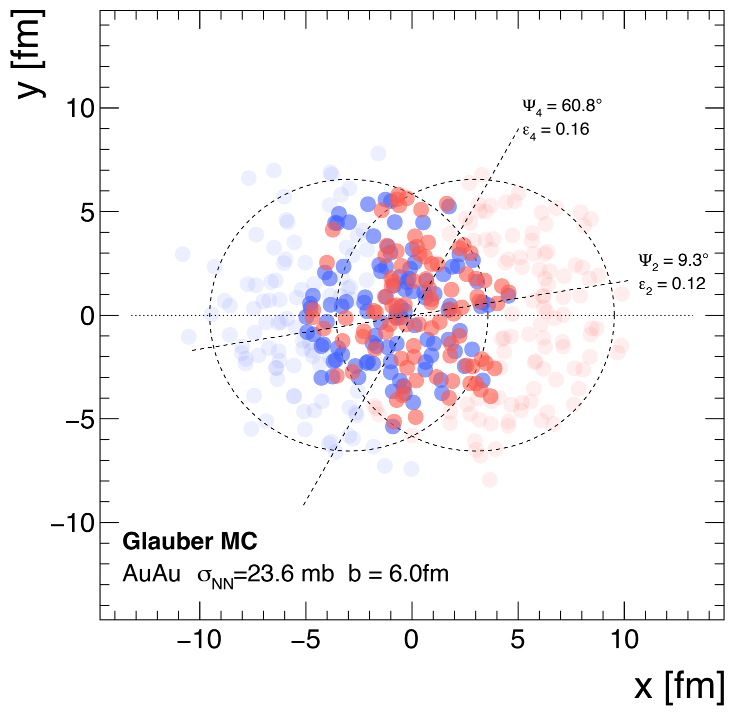
Elliptic Flow v2



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

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

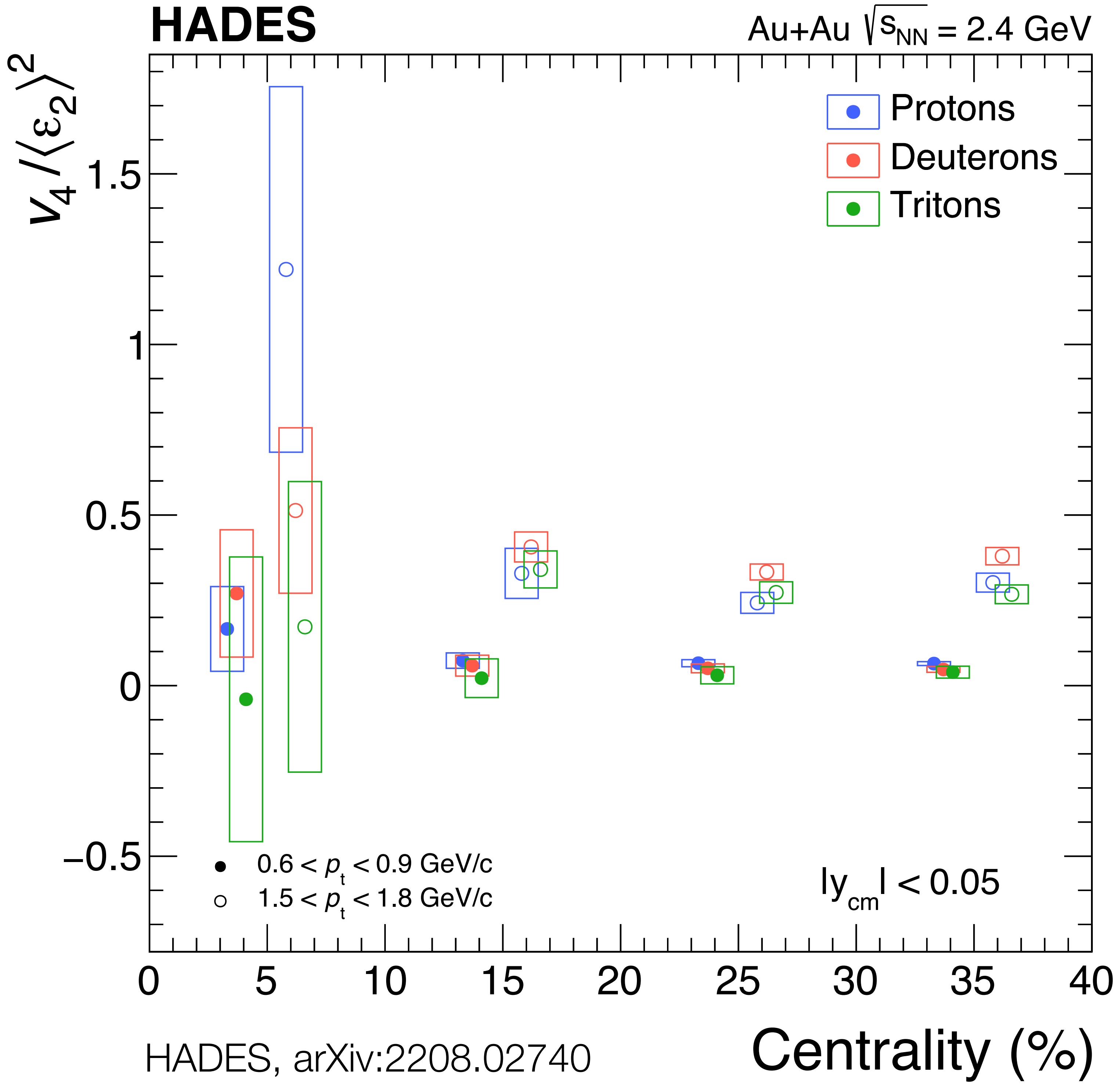
Orientation of symmetry-planes

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

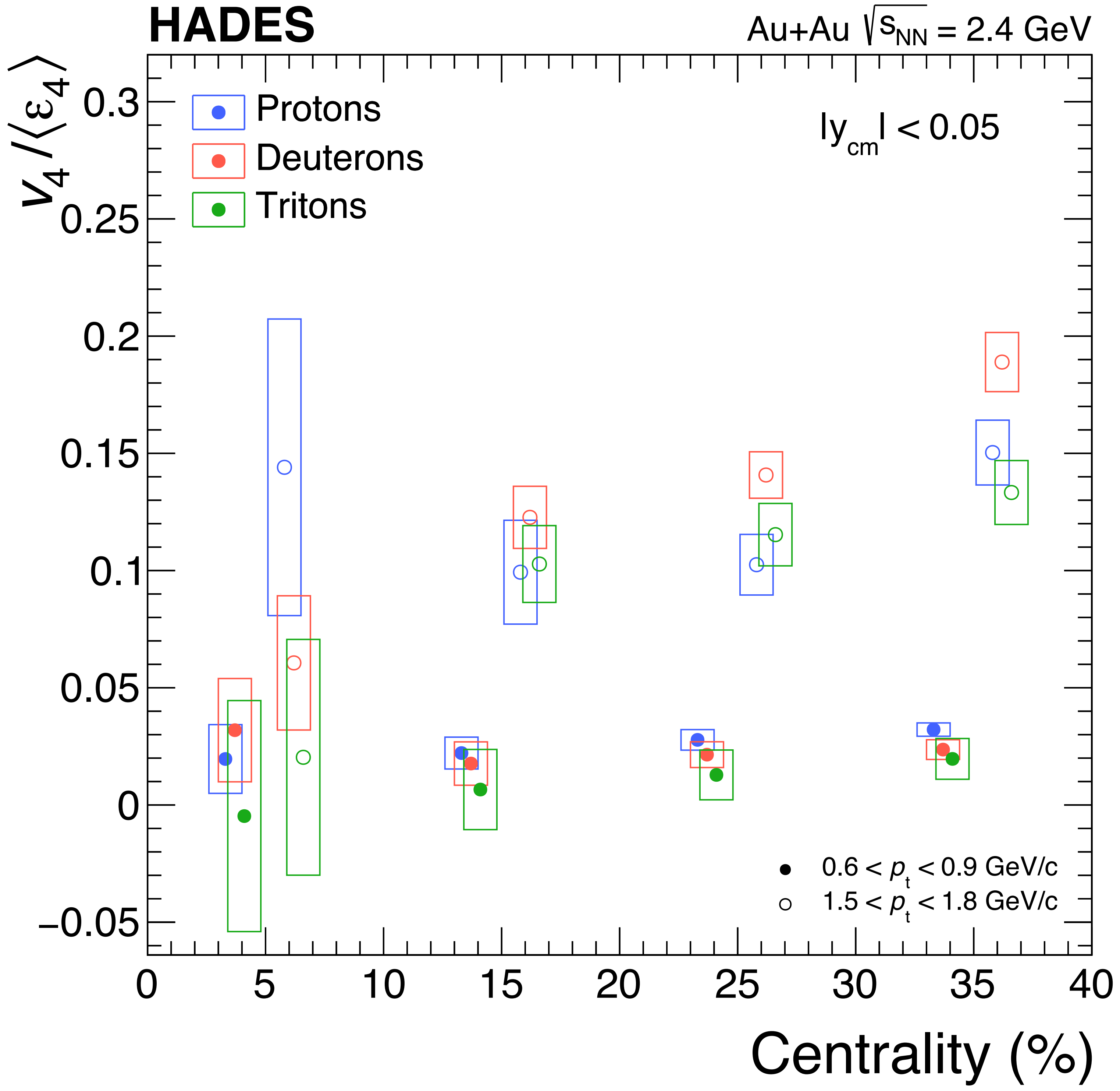
Similar scaling for v4 with $\langle\varepsilon 2\rangle^2$

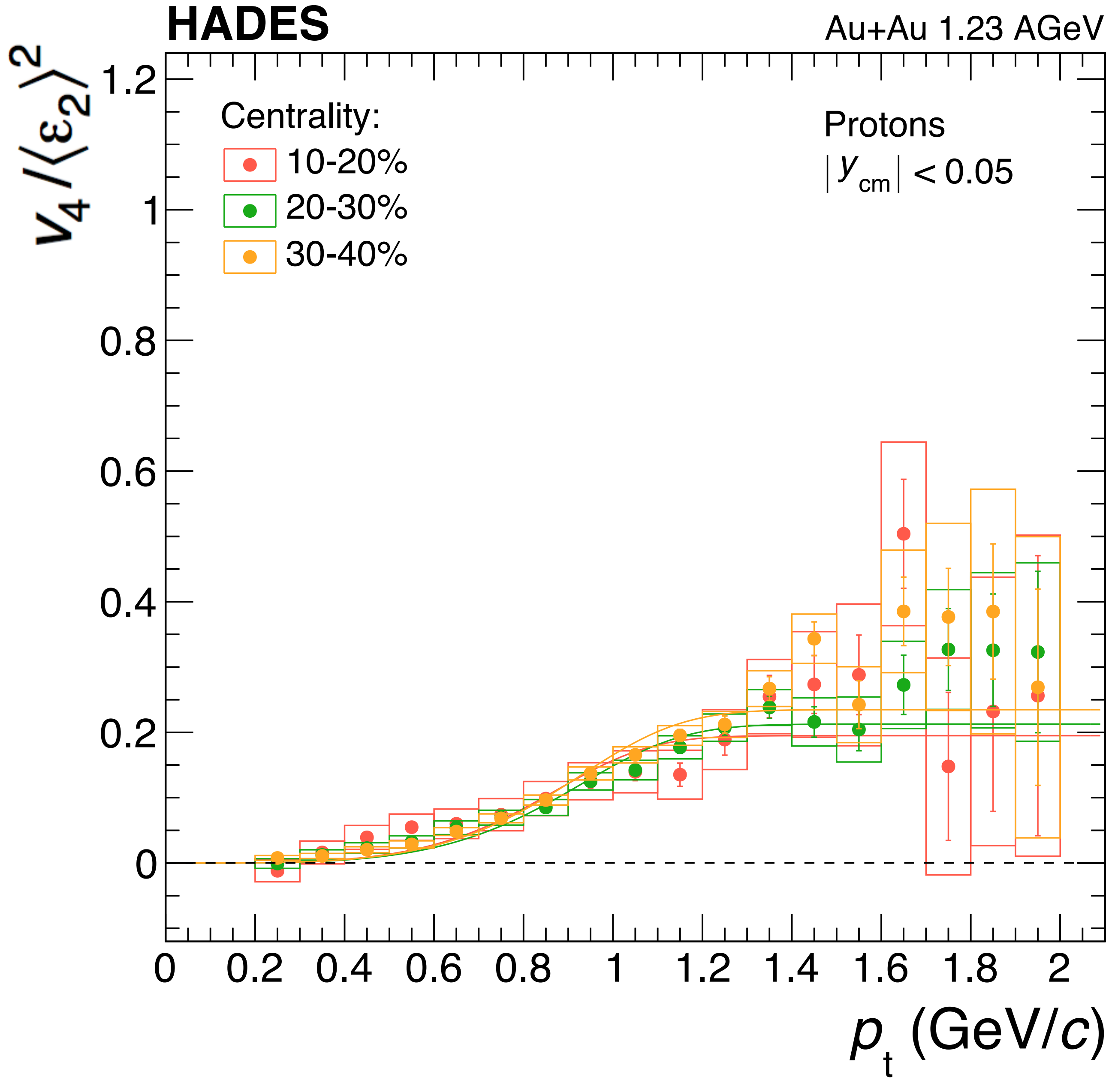
Geometry Scaling

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)

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

Model Comparisons to Proton Data

HADES, arXiv:2208.02740

Determination of EOS

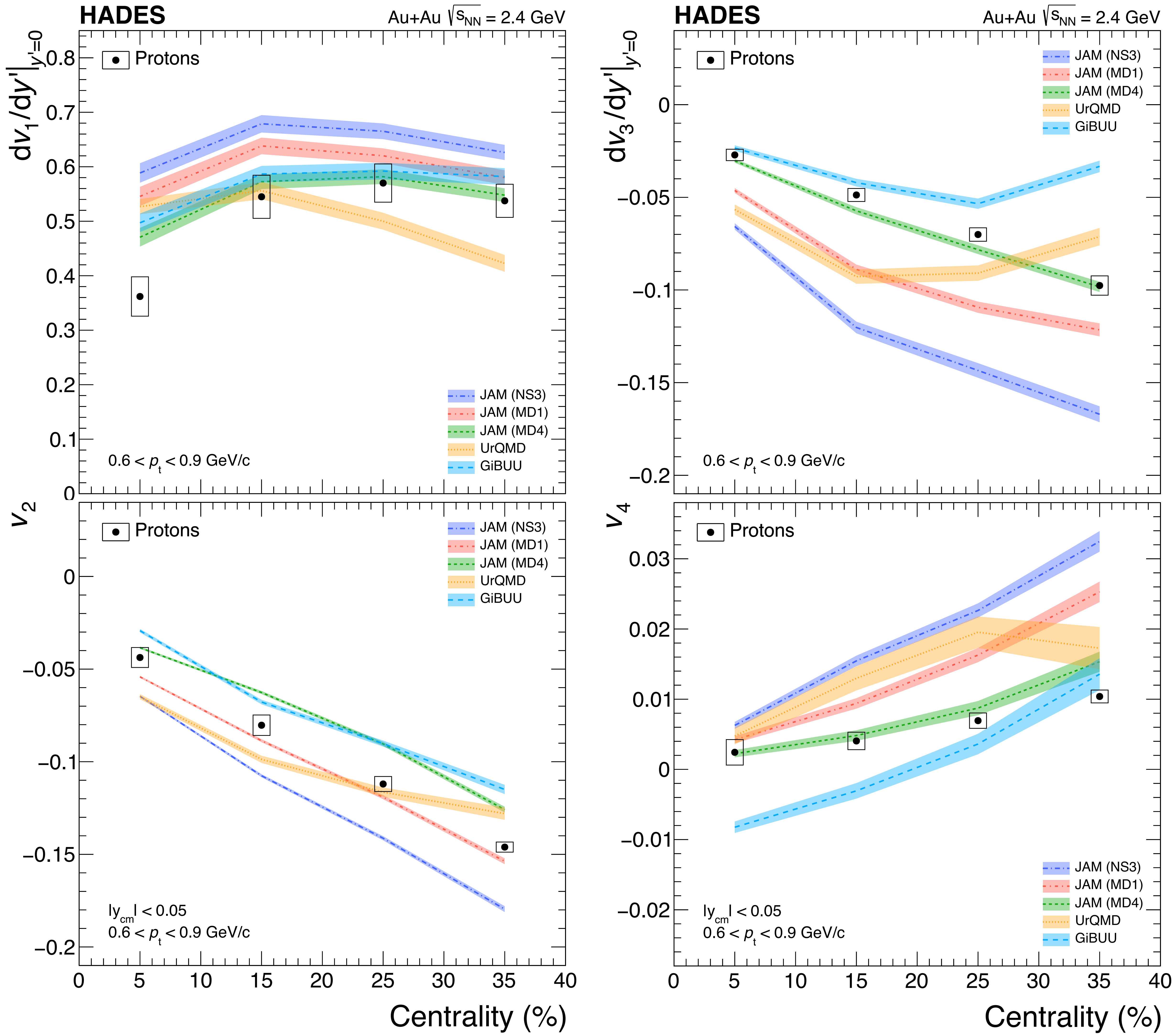
New level of precision - multi differential

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



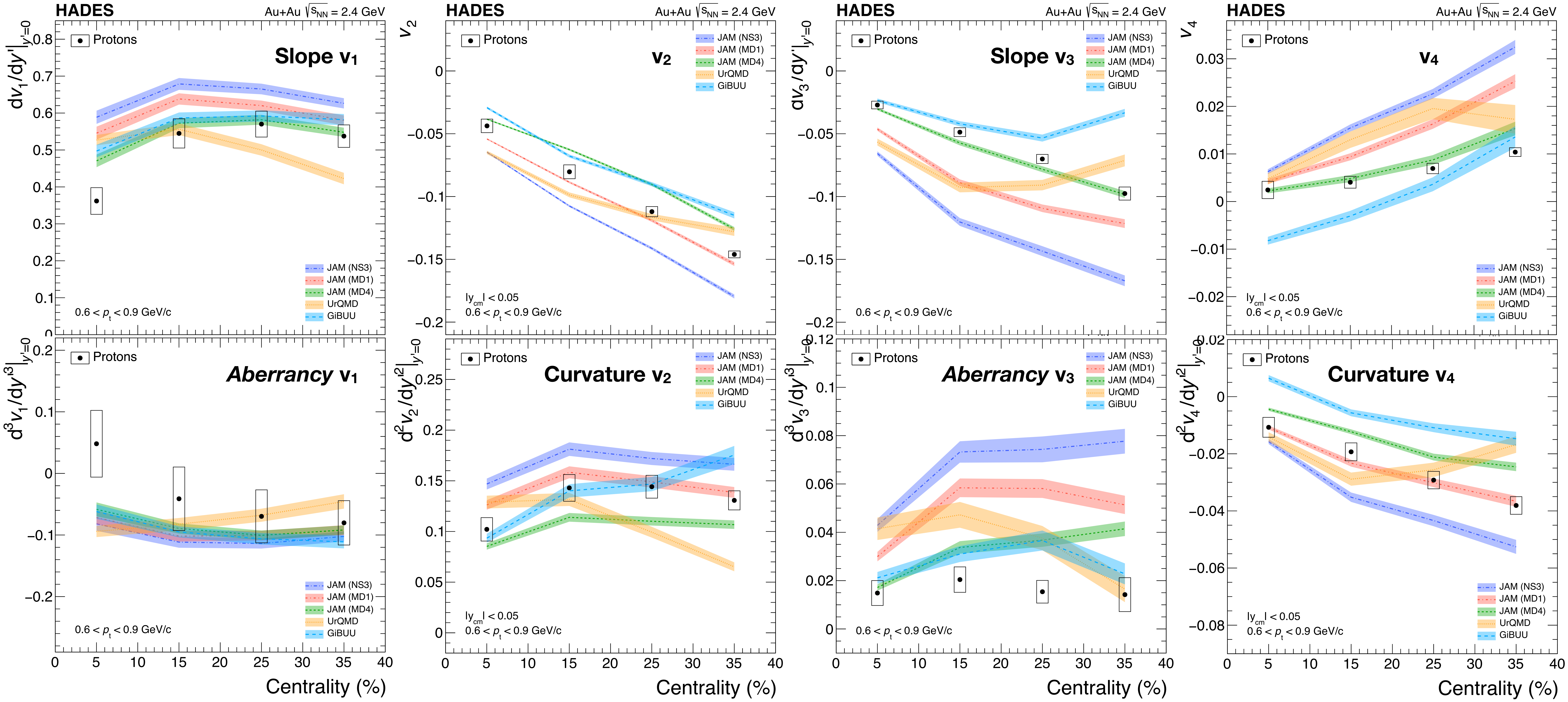
Conclusions

Overall trend reasonably described, but no model works everywhere

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

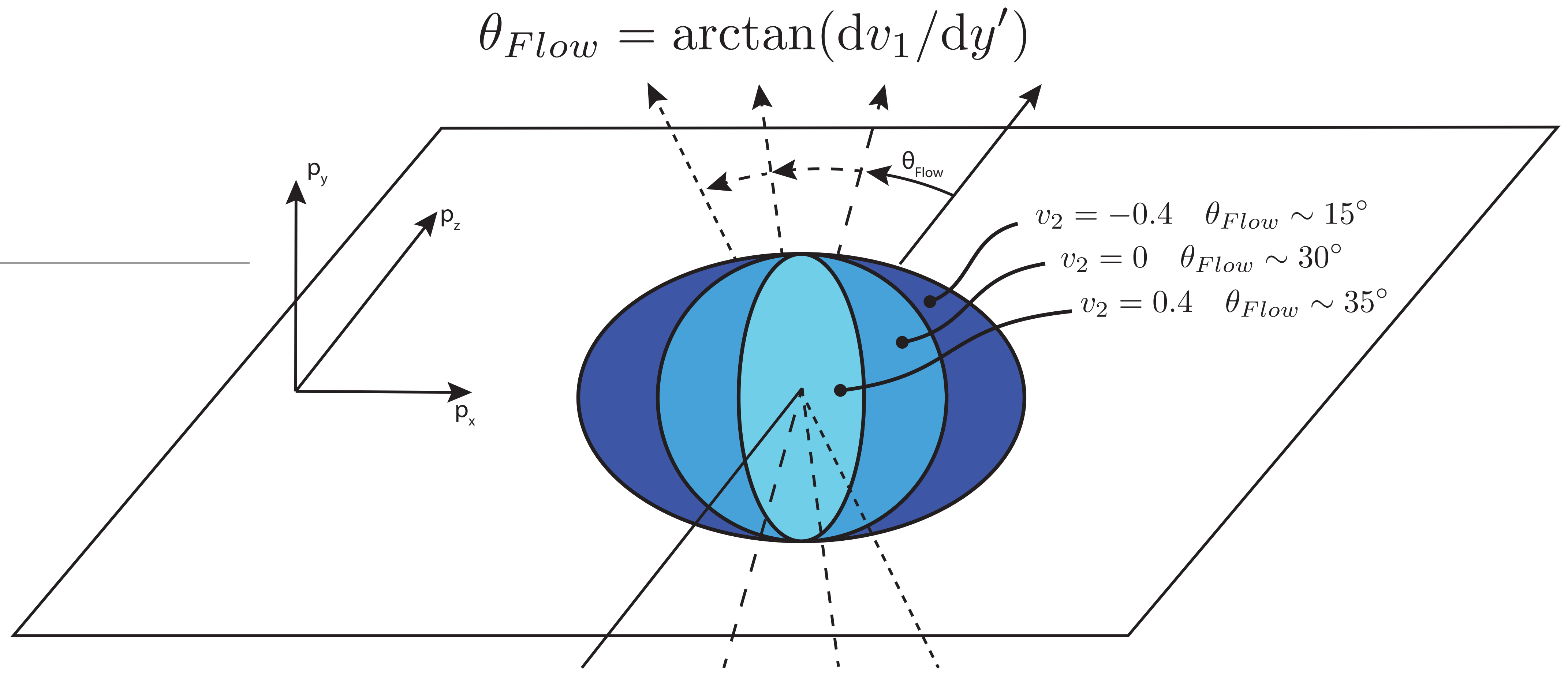
For unified description a consistent modelling of light nuclei formation is essential

Model Comparisons to Proton Data



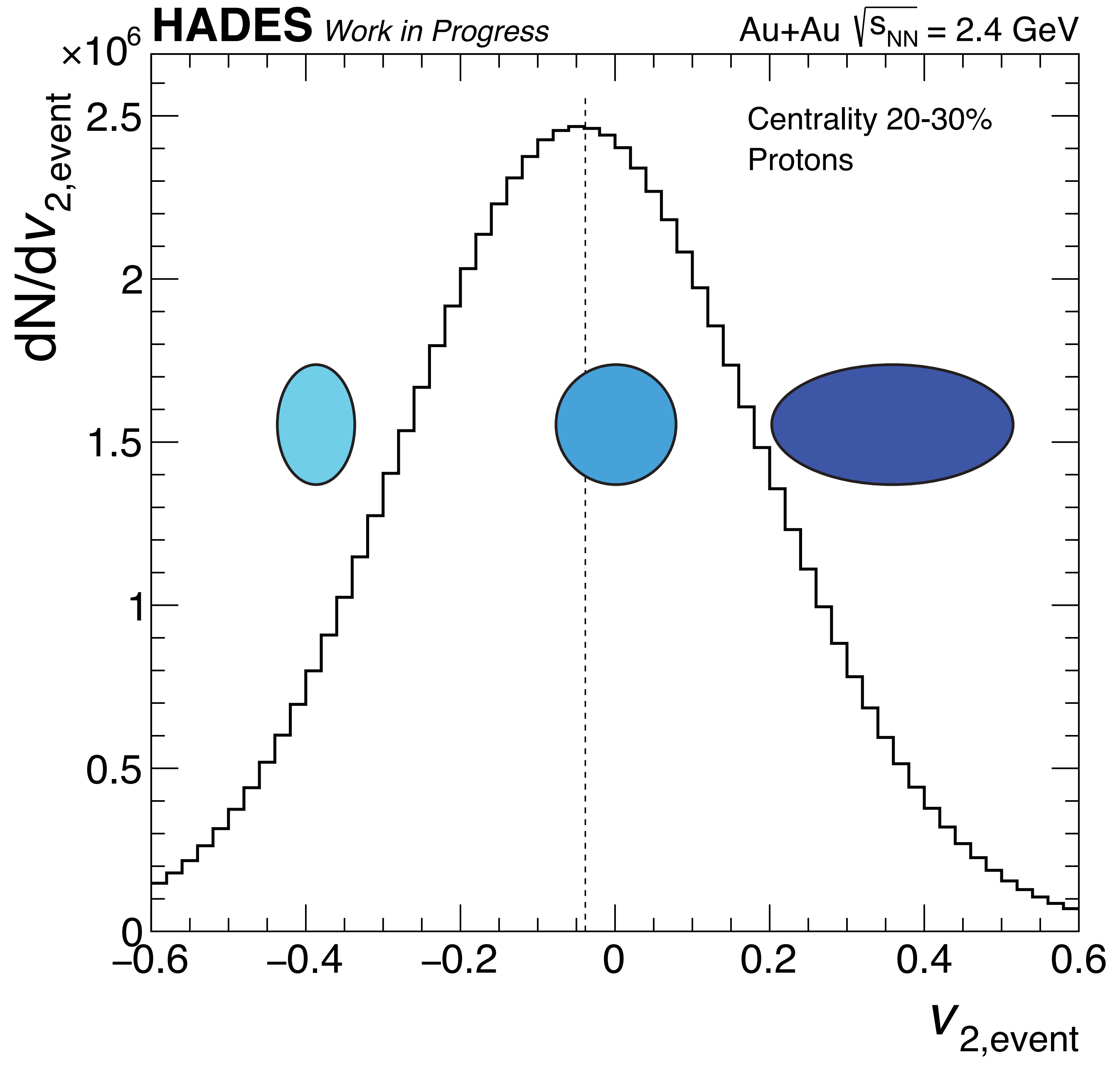
* ***Aberrancy***: **the third derivative of a curve**

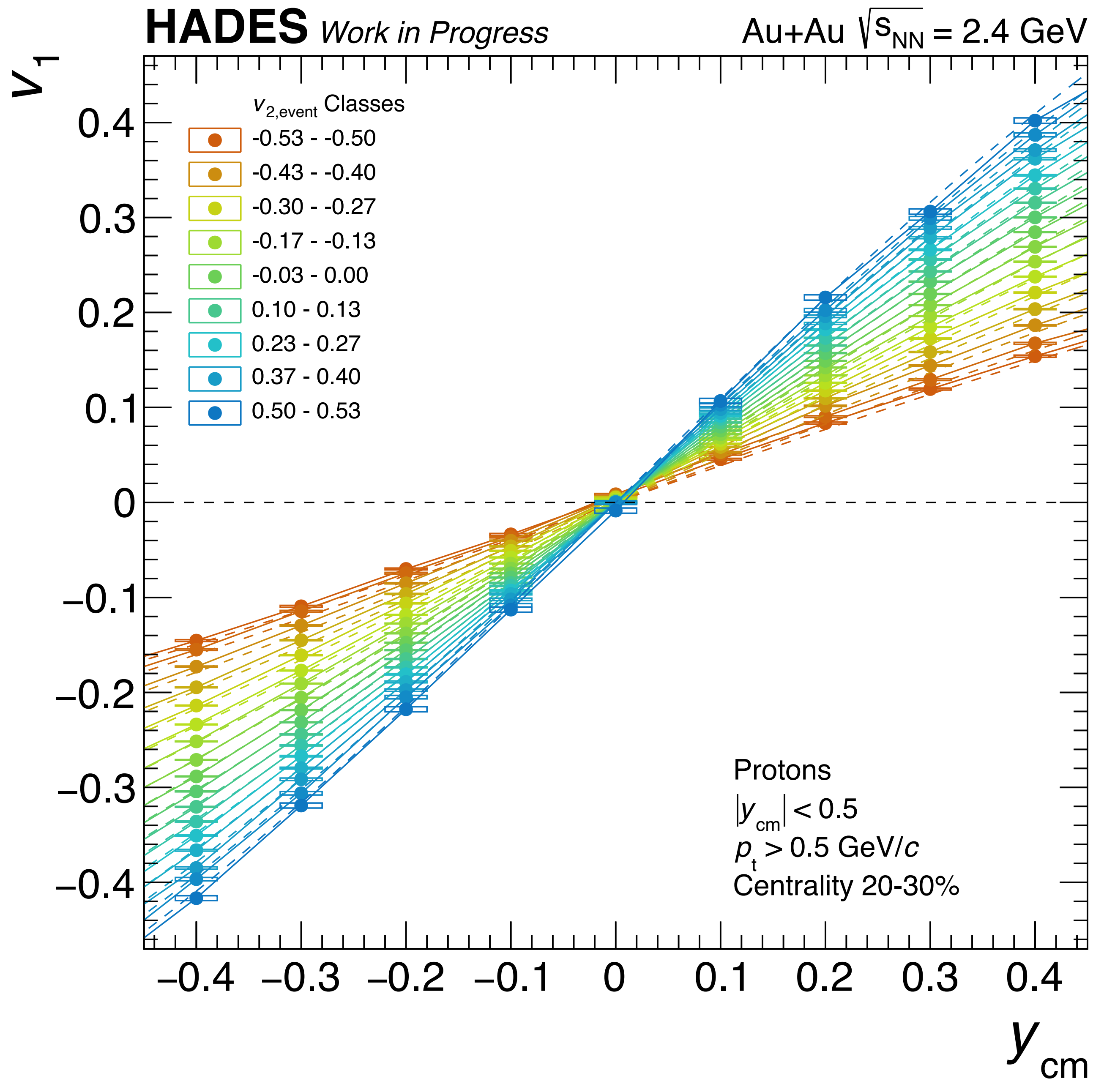
Event-wise Flow Correlations



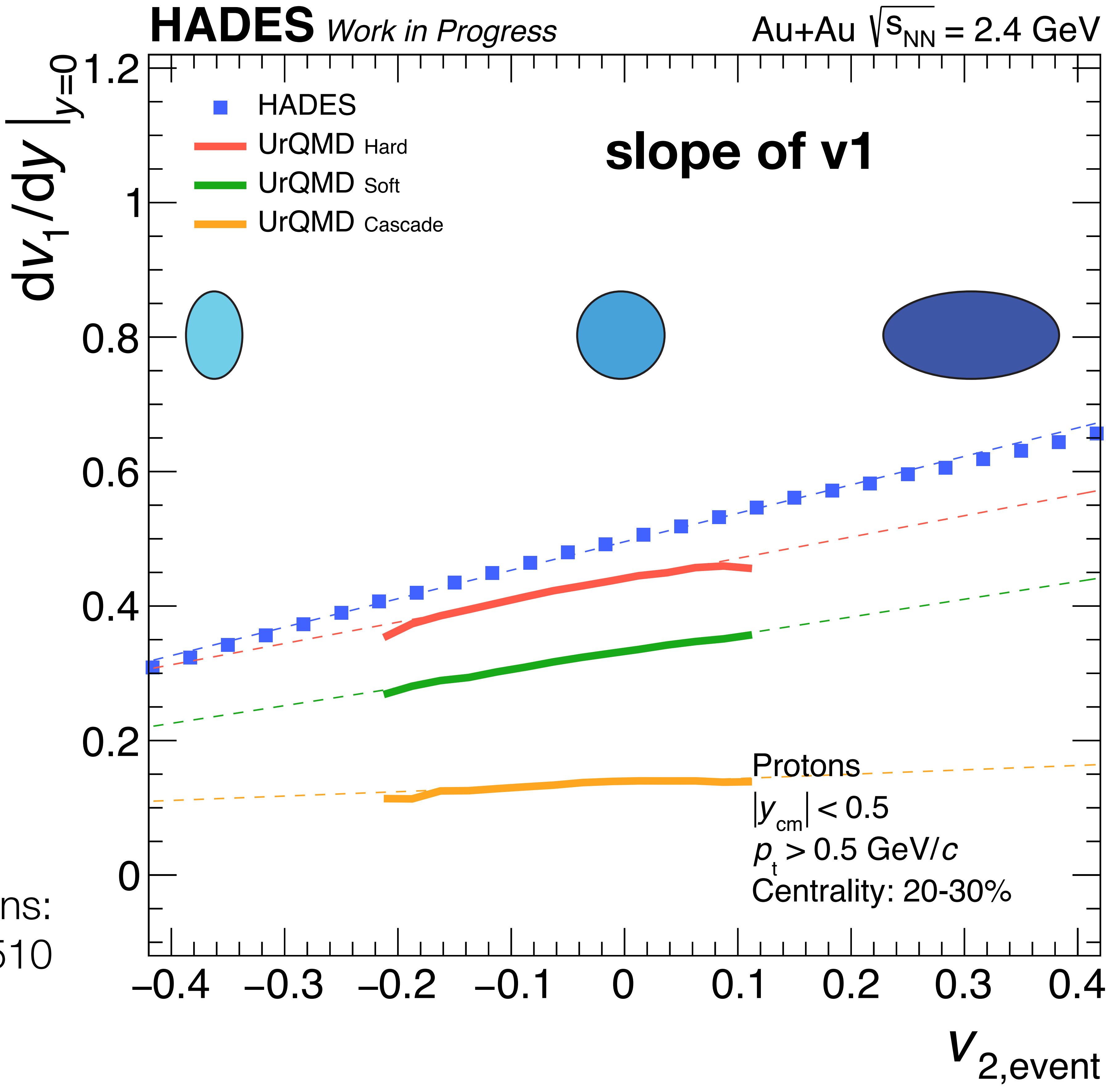
Events can characterised according the event-wise magnitude of the elliptic flow $v_{2,event}$

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

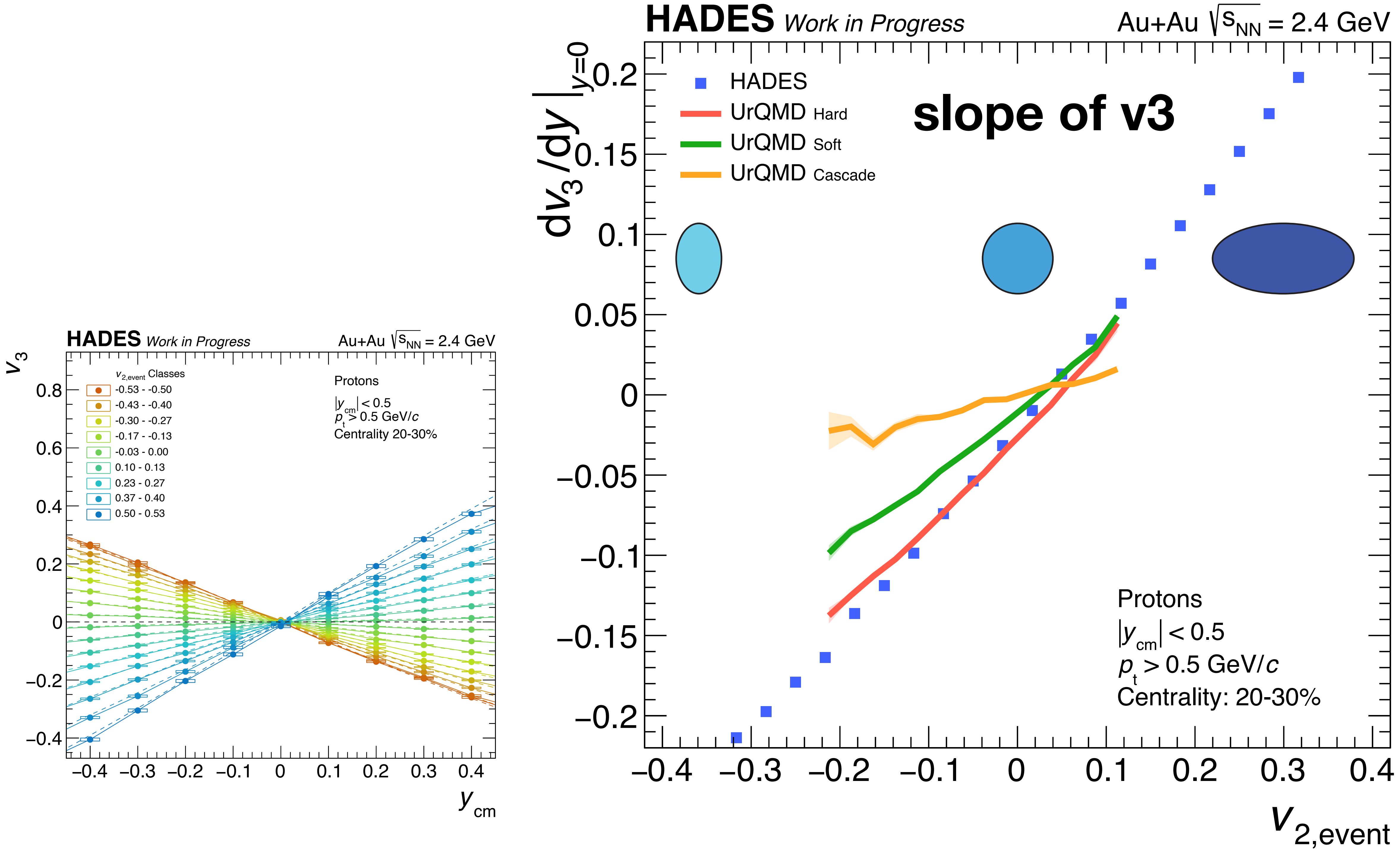




UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

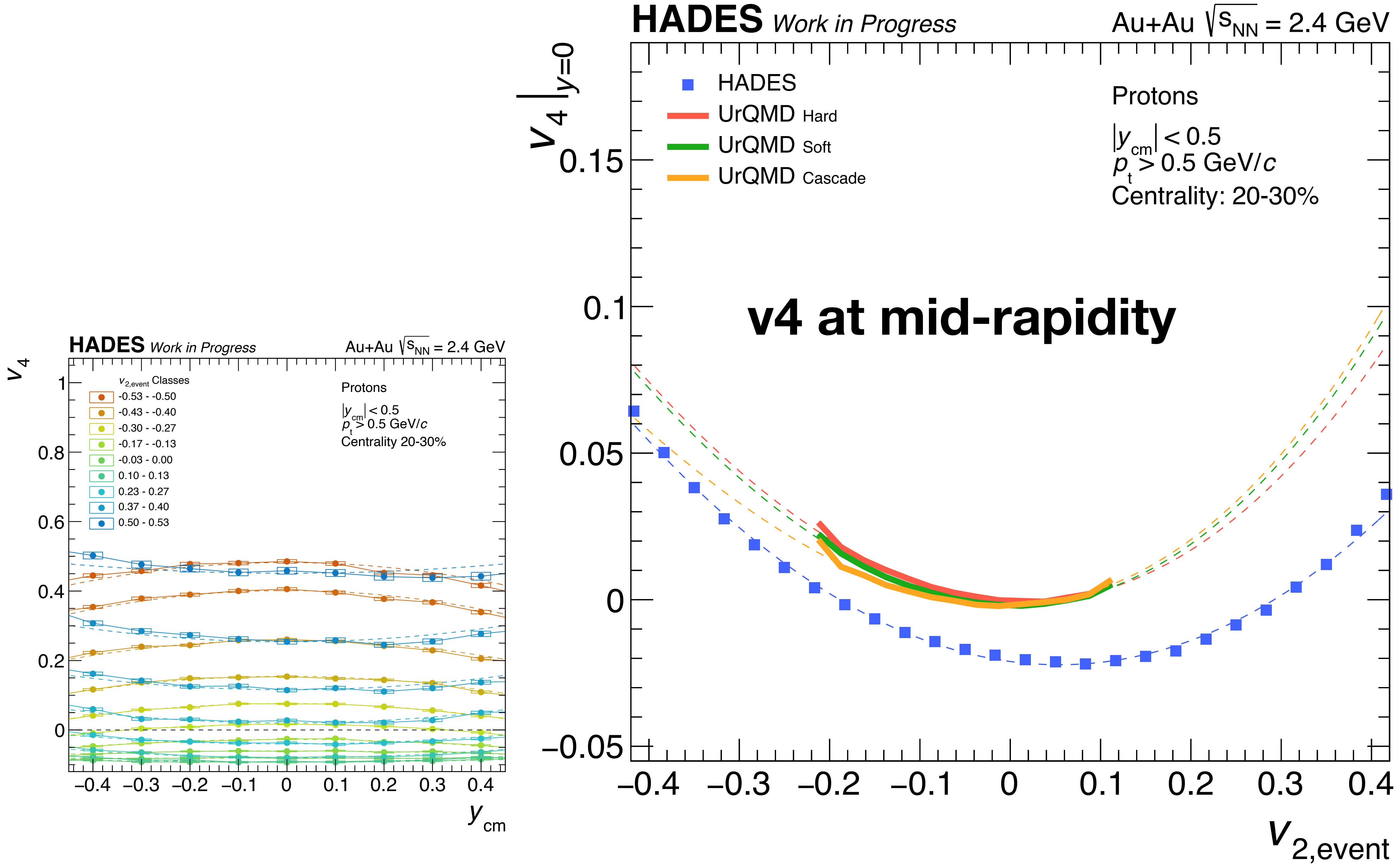


Event-wise Flow Correlations



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

General Parameterisation

- Phenomenological approach based on hydrodynamic inspired Blast Wave model

Scaling Properties

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

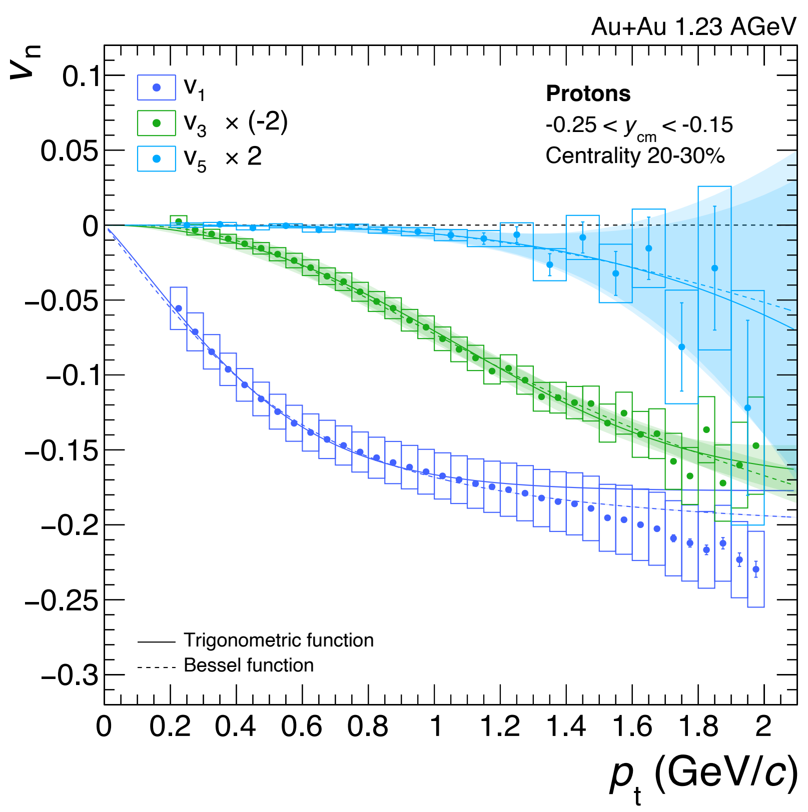
Nucleon Coalescence

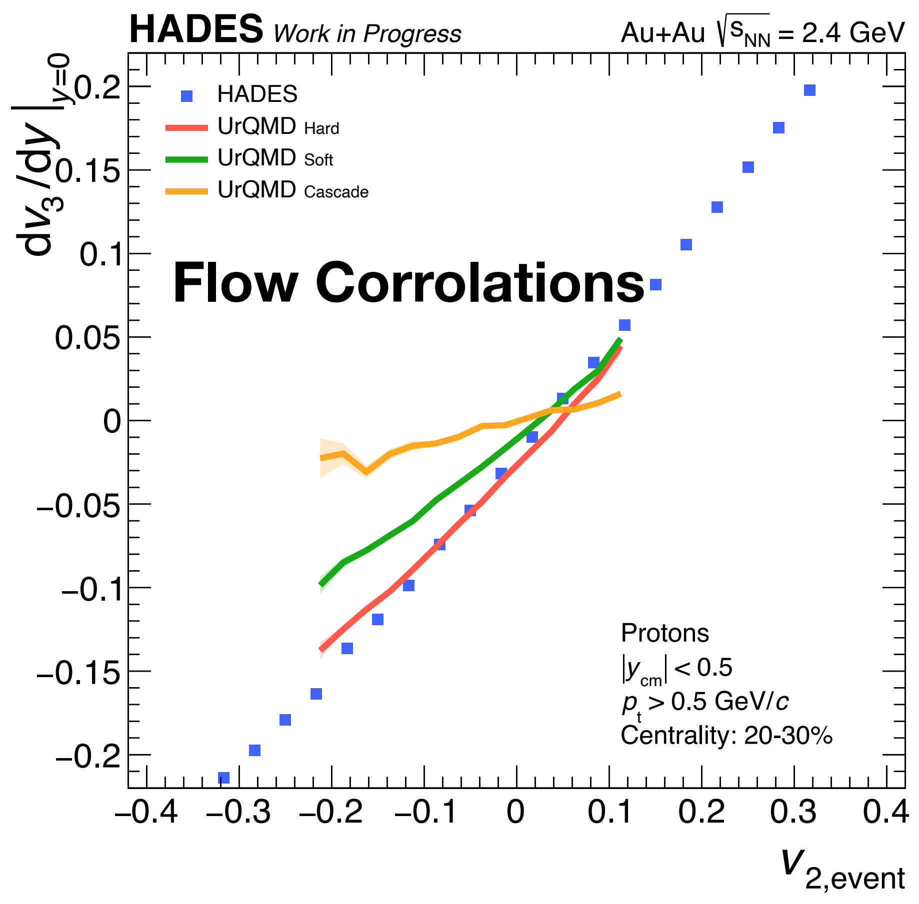
- Scaling of v2 and v4 according simple “nucleon coalescence” via momentum addition

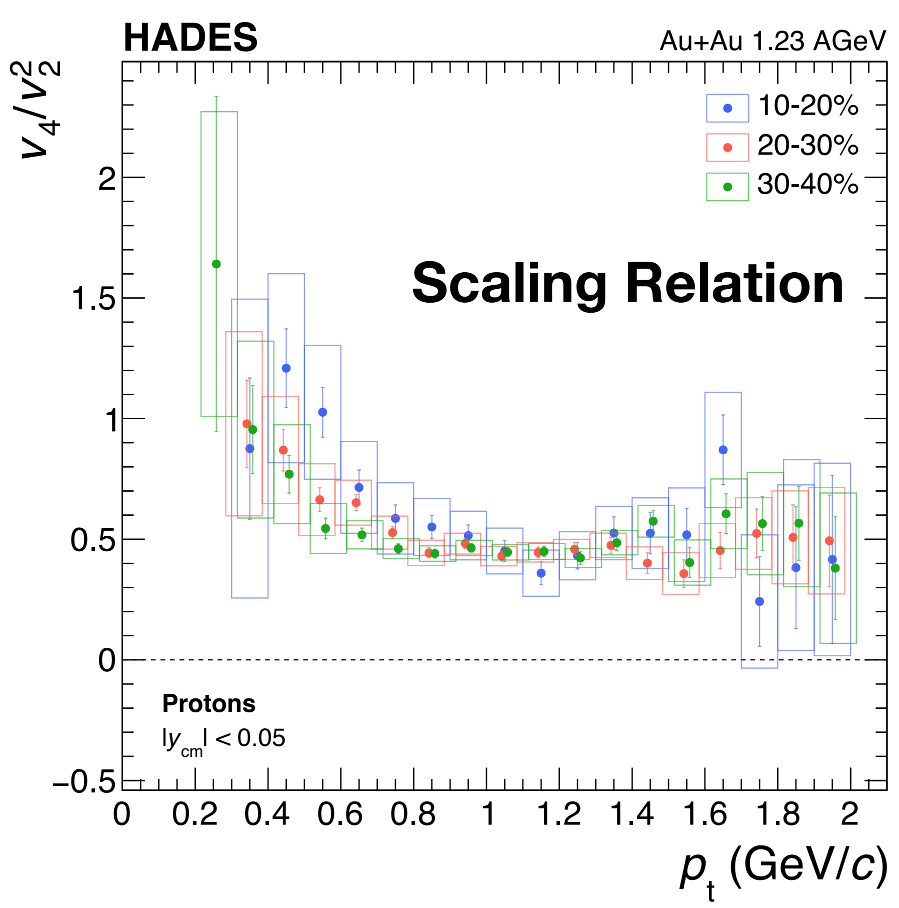
Model Comparison

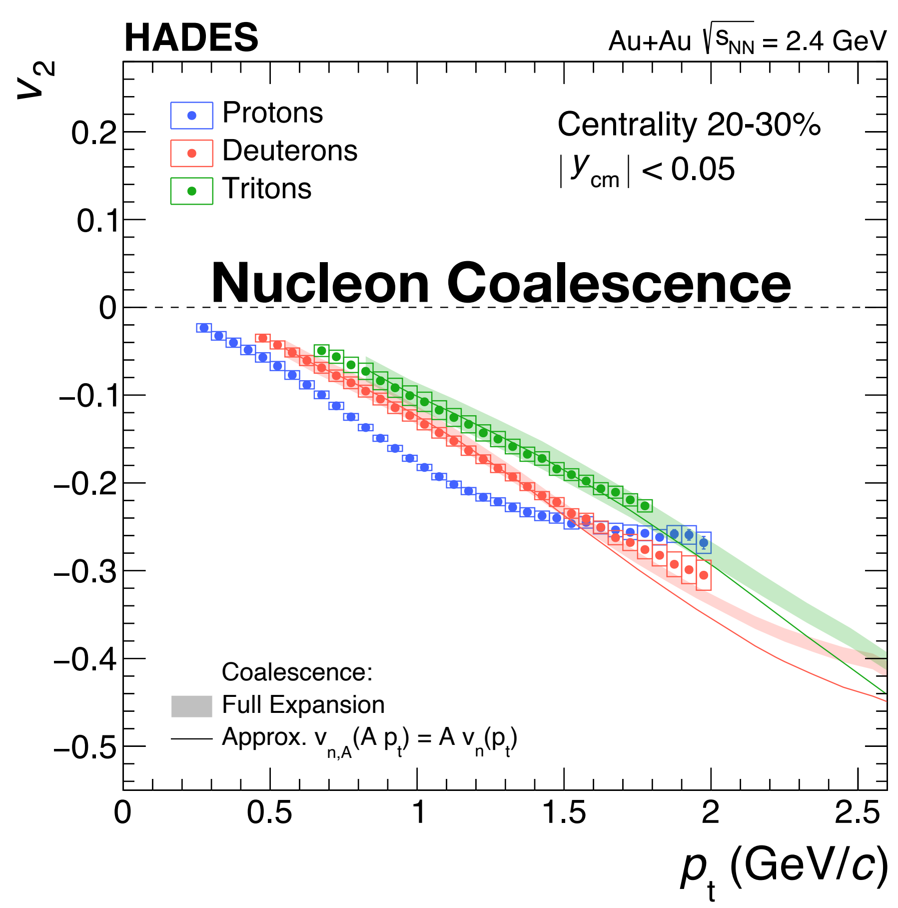
- Multi-differential analysis including higher orders
  New level of precision
- Consistent modelling of light nuclei formation

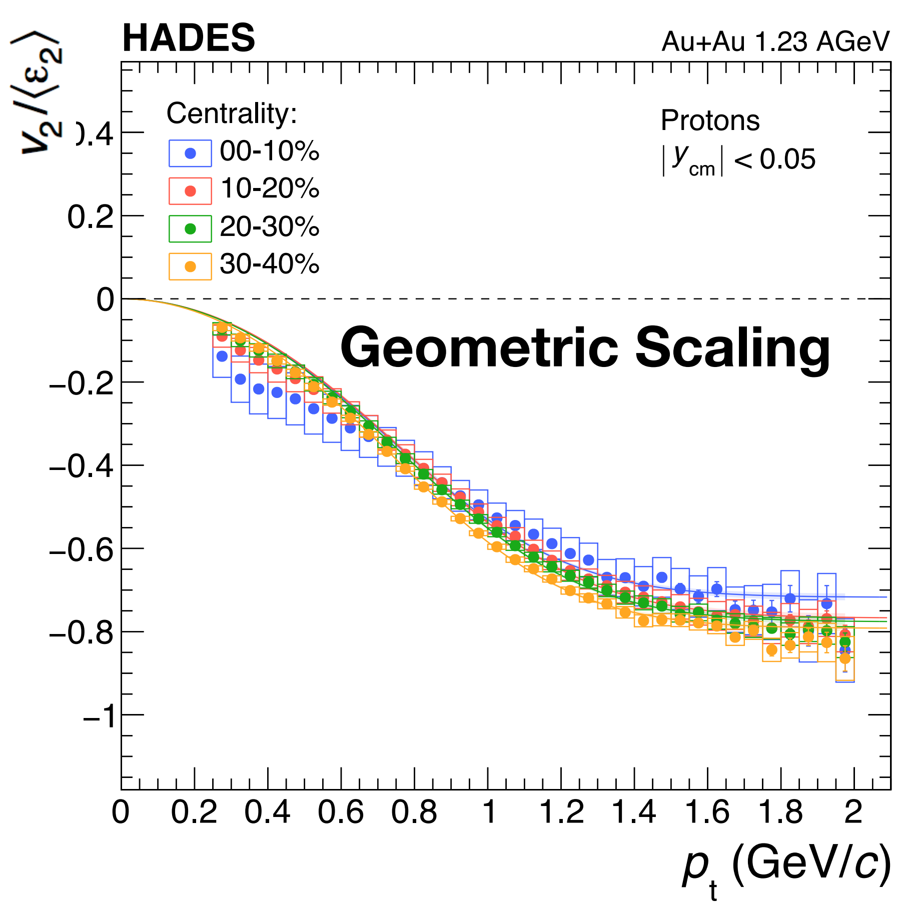
General Parameterisation

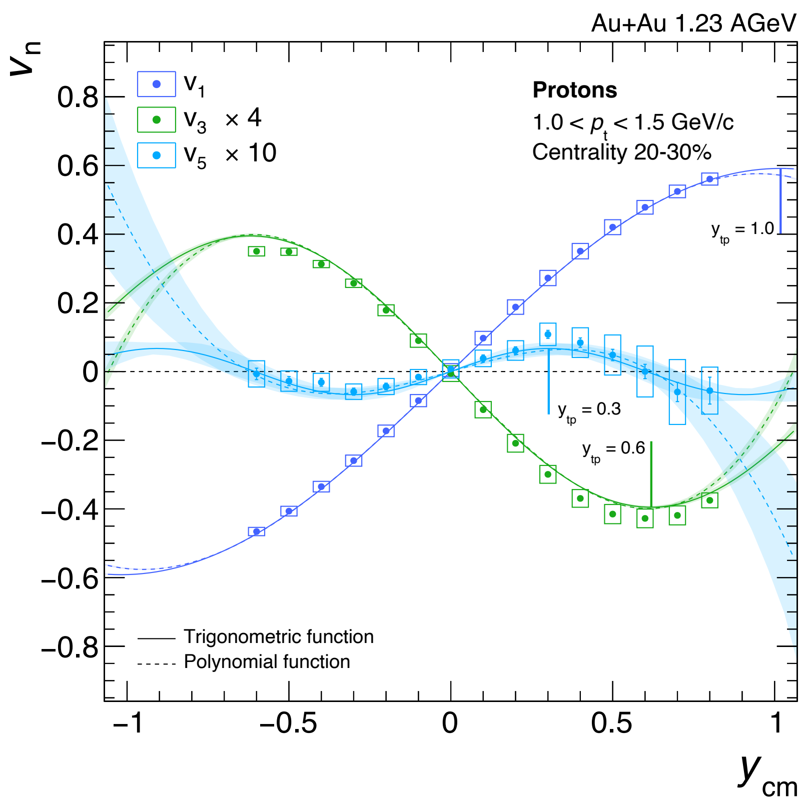












Outlook

Event-wise Flow Fluctuations

Correlation and Relation between Flow Harmonics

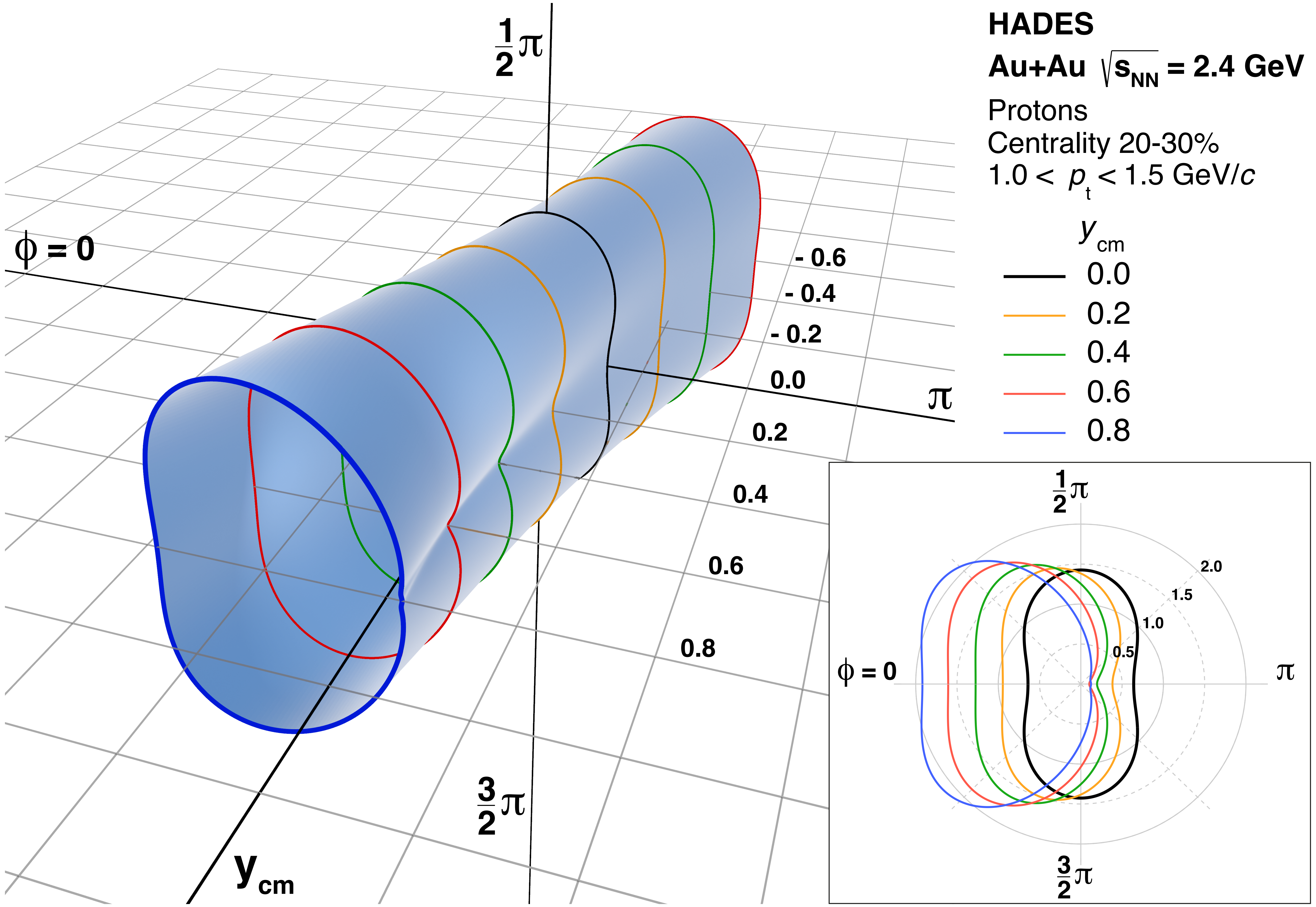
Next Steps towards EOS

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 - 0.8 *A*GeV (March 2024)




GSI March 2023

HADES Collaboration

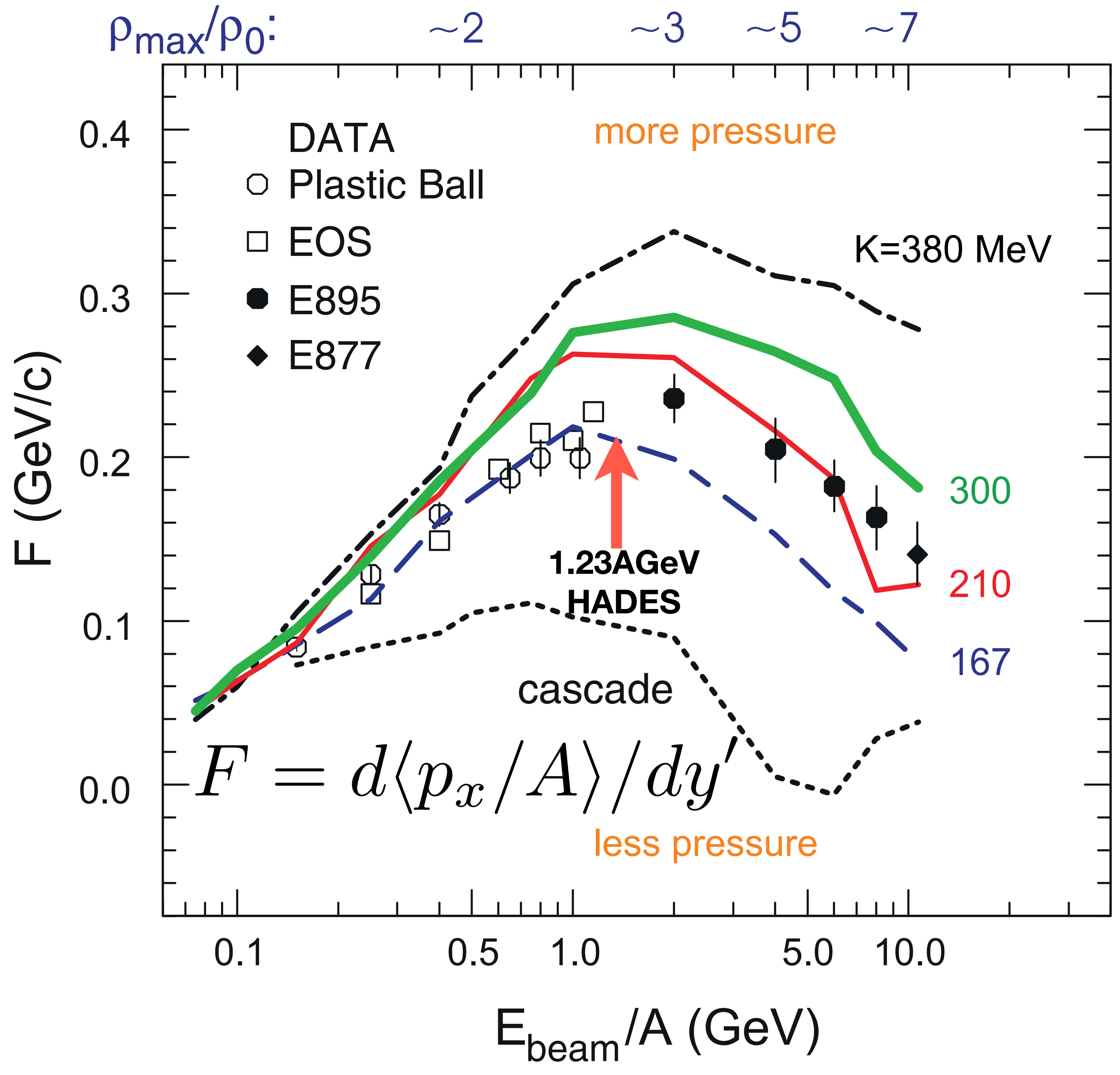
Thank you for your attention!

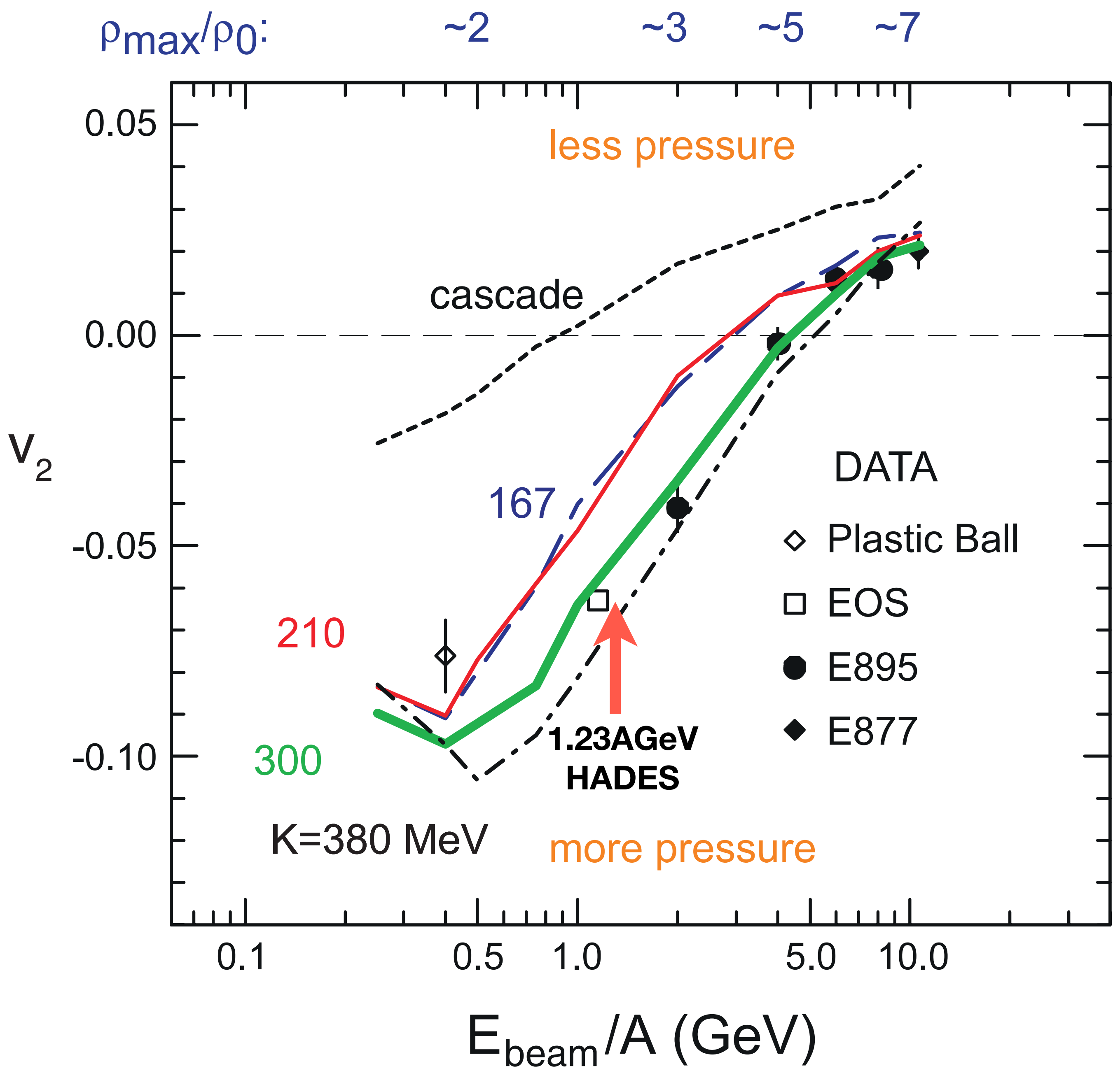
Equation of State of Dense Matter

- EoS is the *equilibrium* property of Hydrodynamical simulations

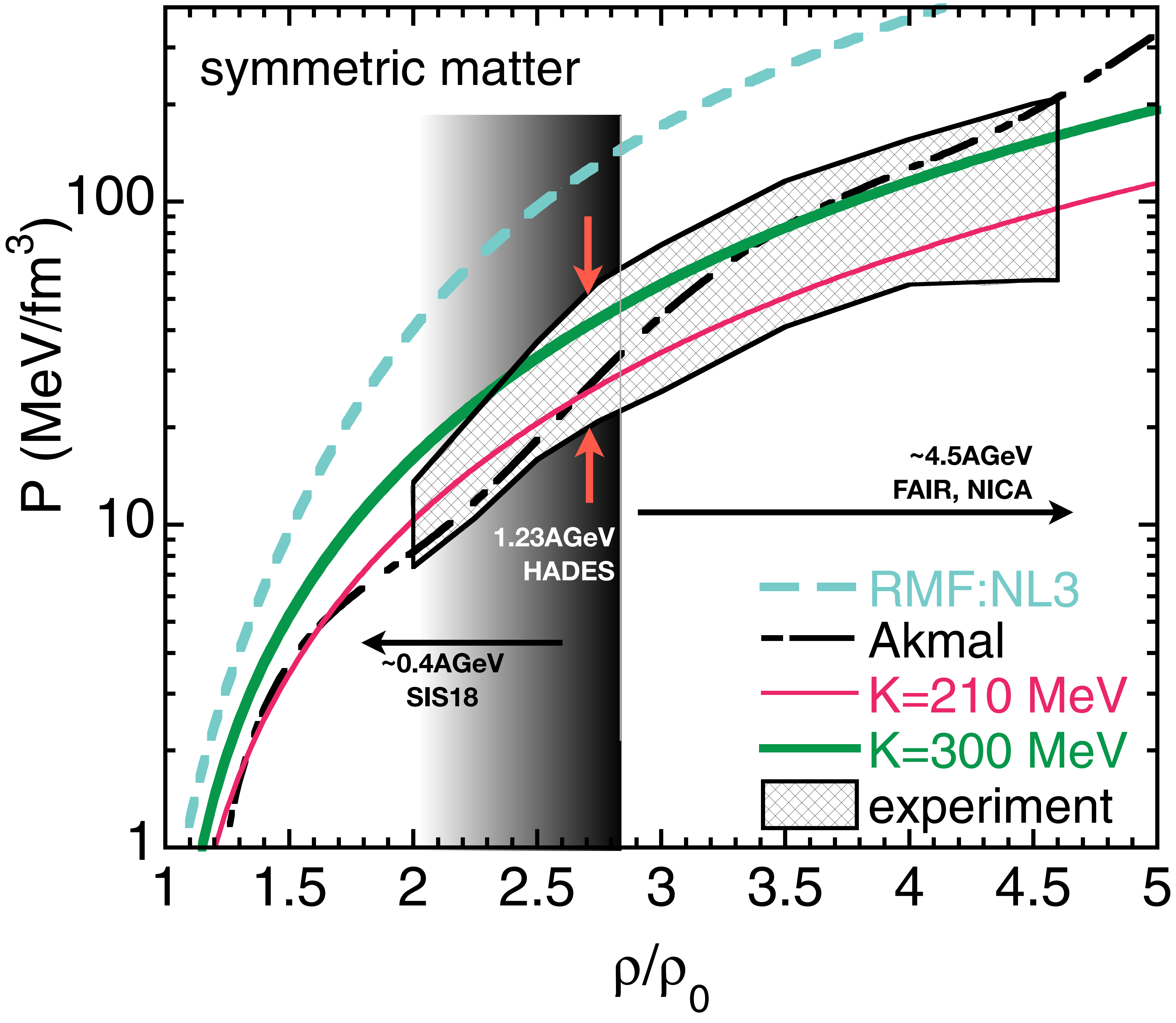
  Non-equilibrium dissipative effects are described by transport coefficients (shear viscosity ***η***)

- 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

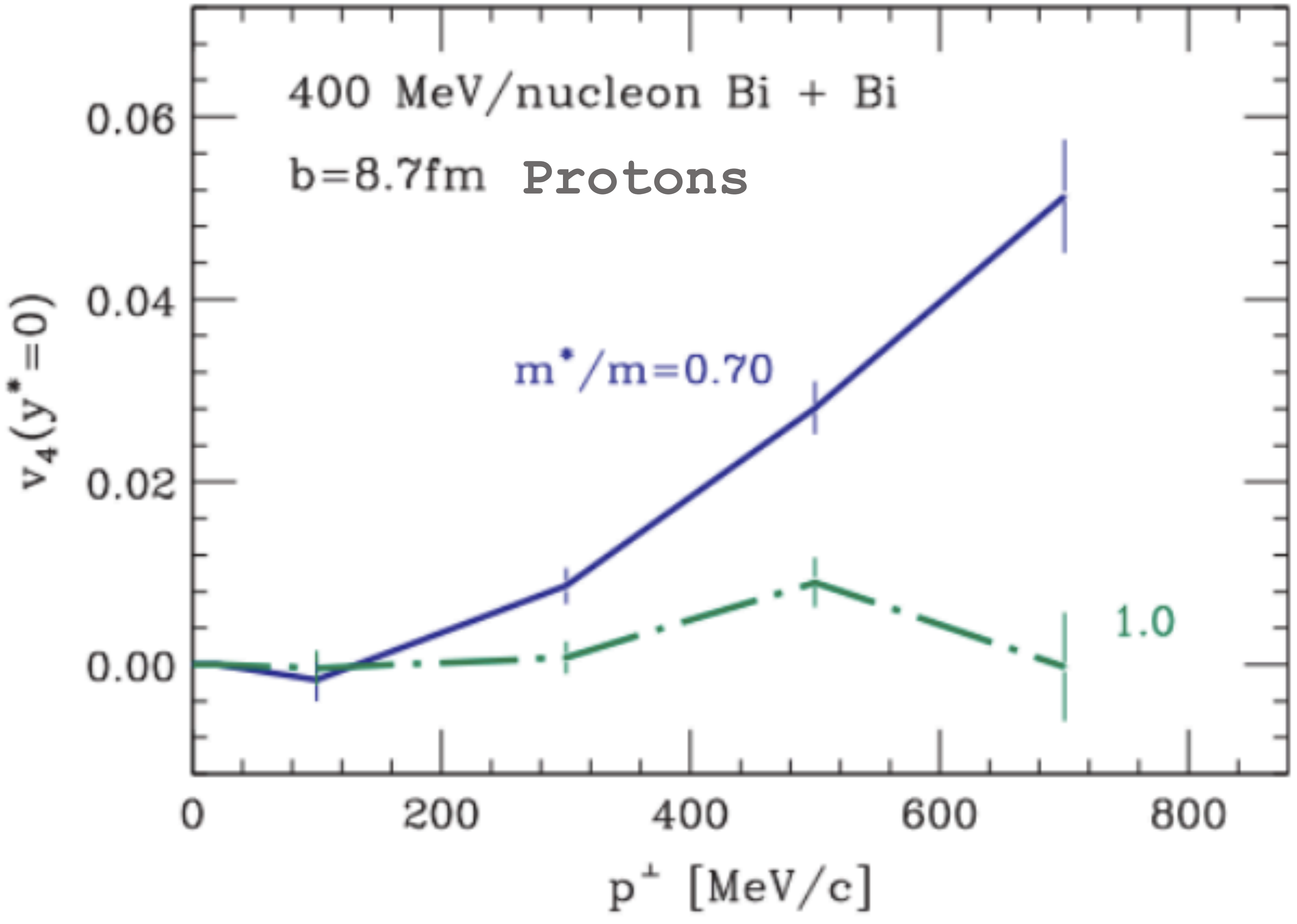


Equation of State of Dense Matter

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

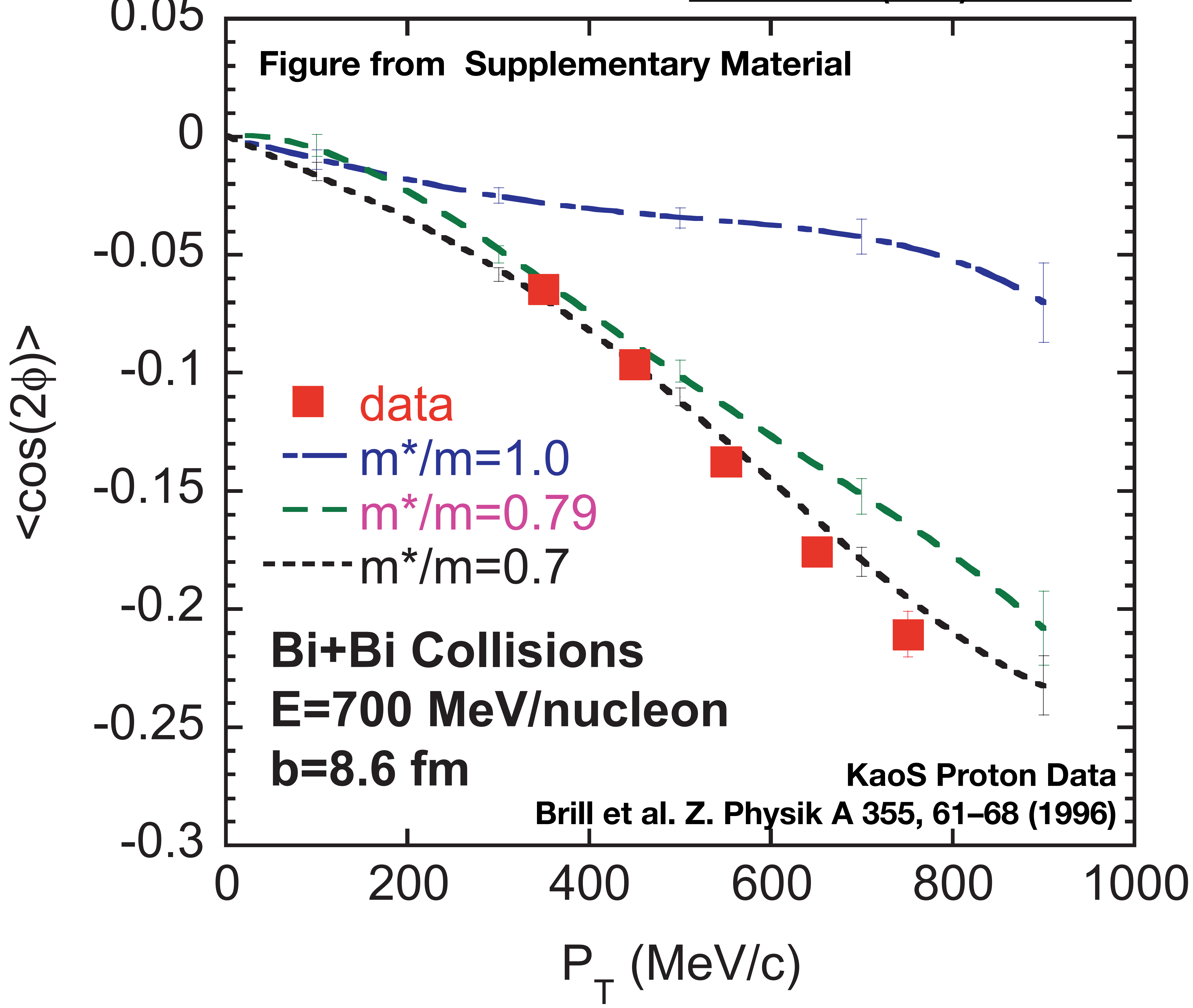


Figure from Supplementary Material

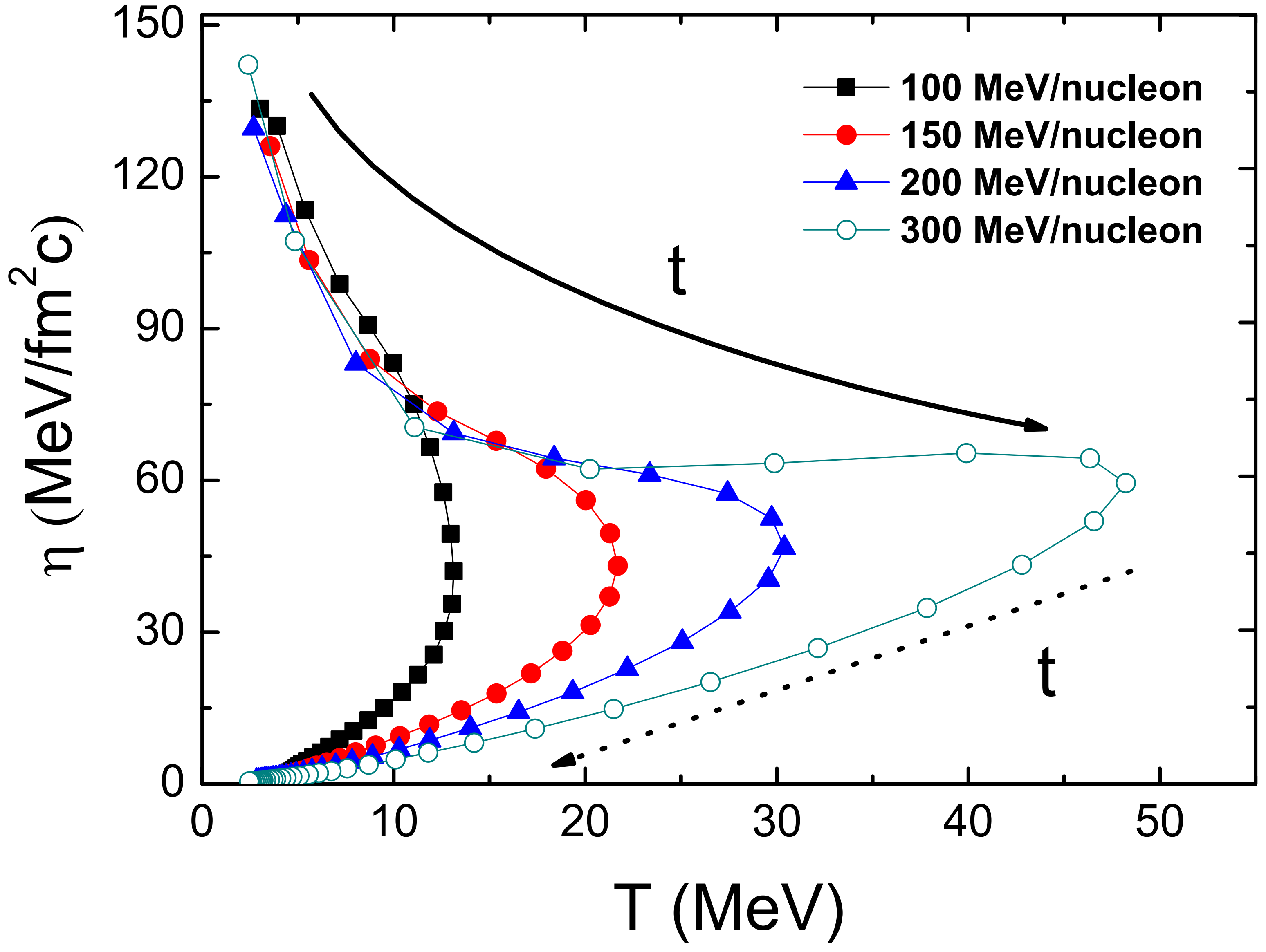
KaoS Proton Data
Brill et al. Z. Physik A 355, 61–68 (1996)

Properties of Dense Nuclear Matter

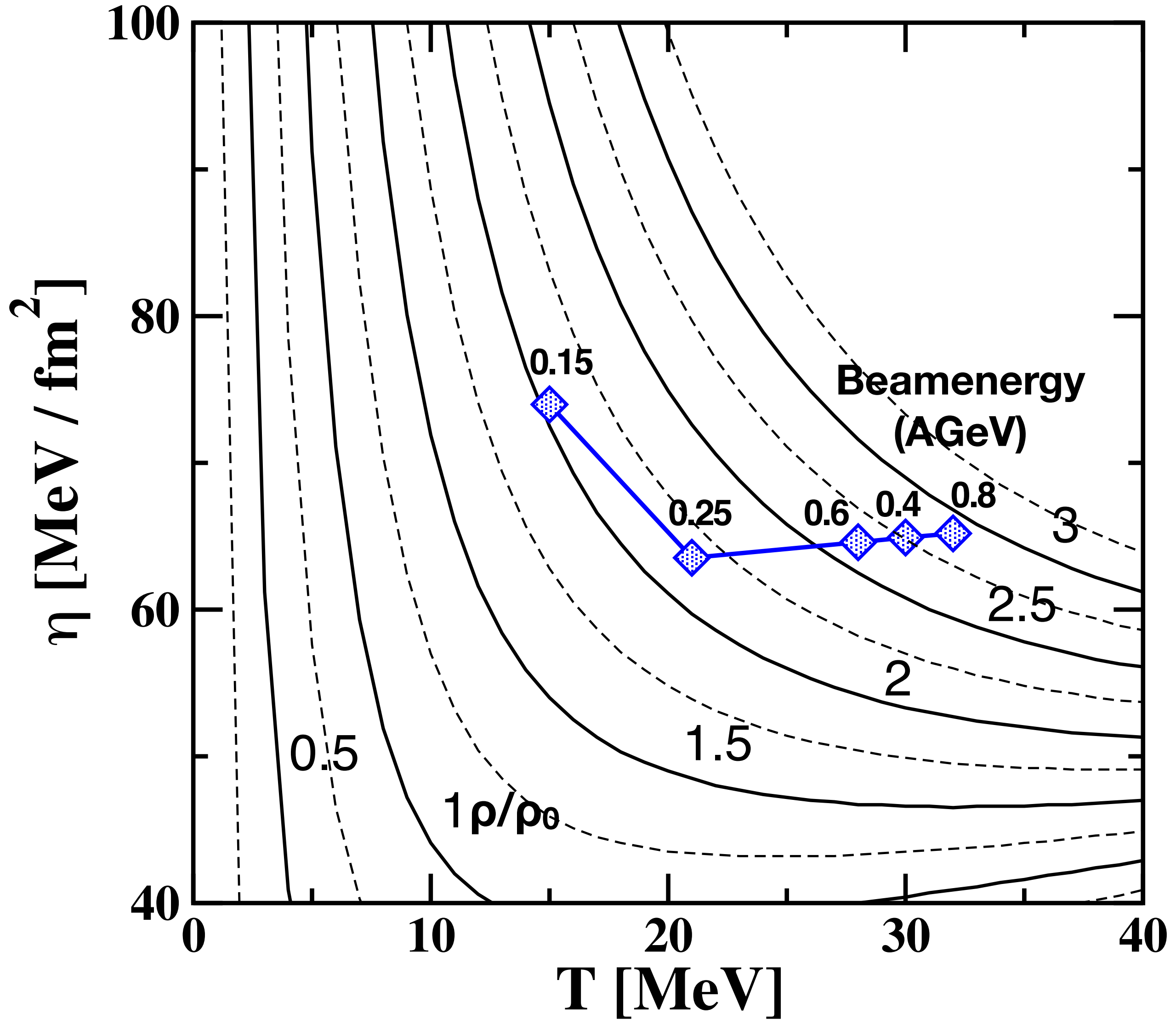
Shear viscosity

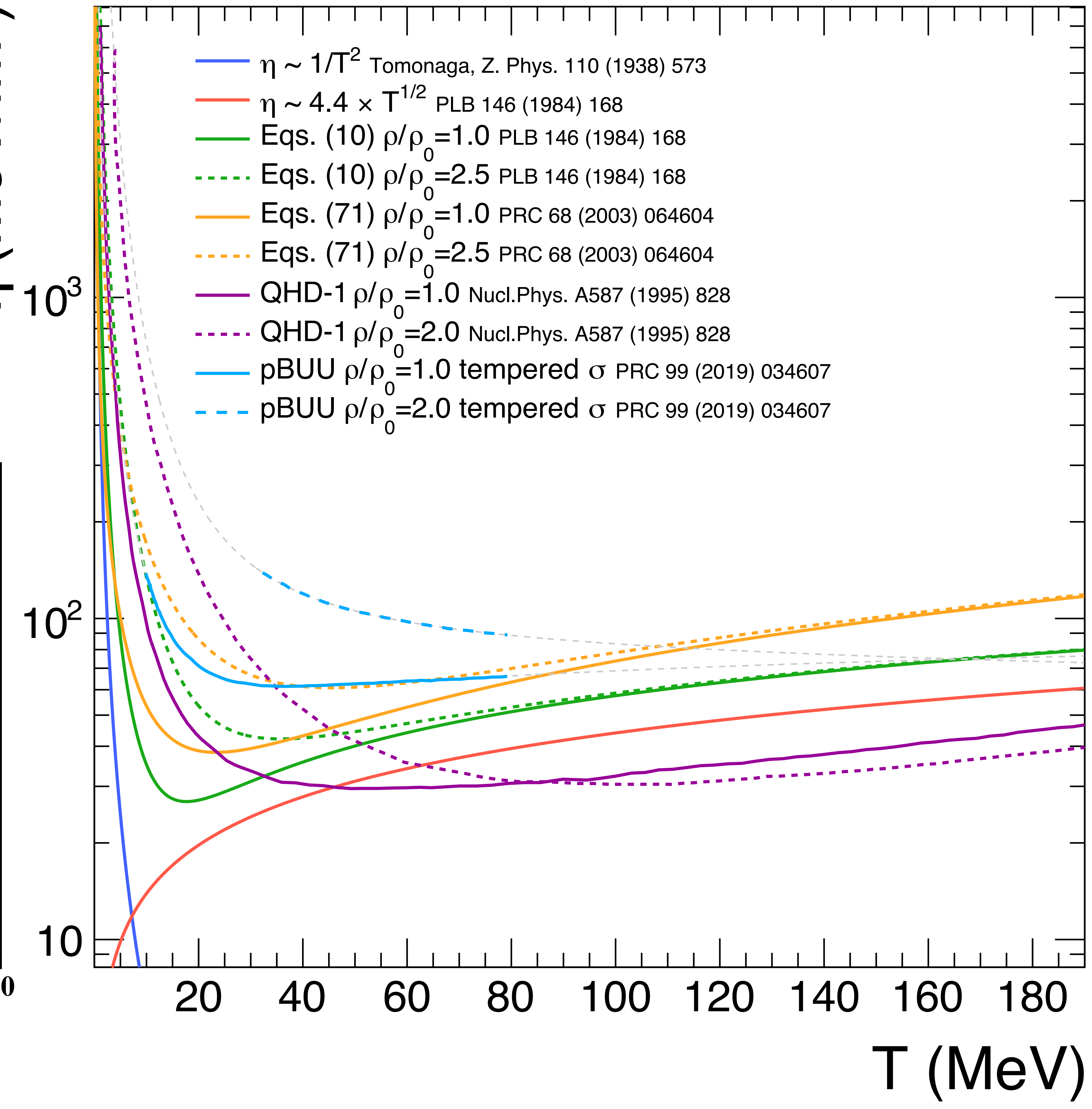
- Nuclear shear viscosity extracted from transport models
- Mean-field potentials and in-medium cross section are constrained by stopping and flow observables

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



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

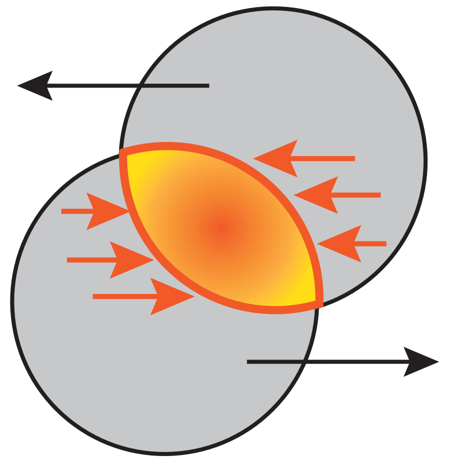




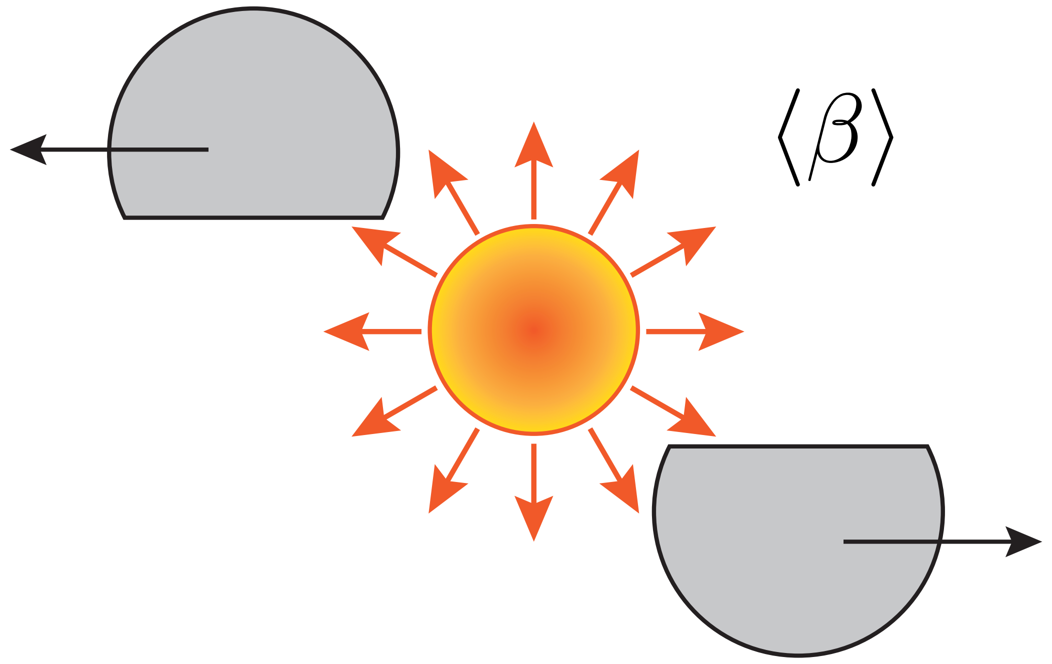
Motivation

Flow and Event Shapes

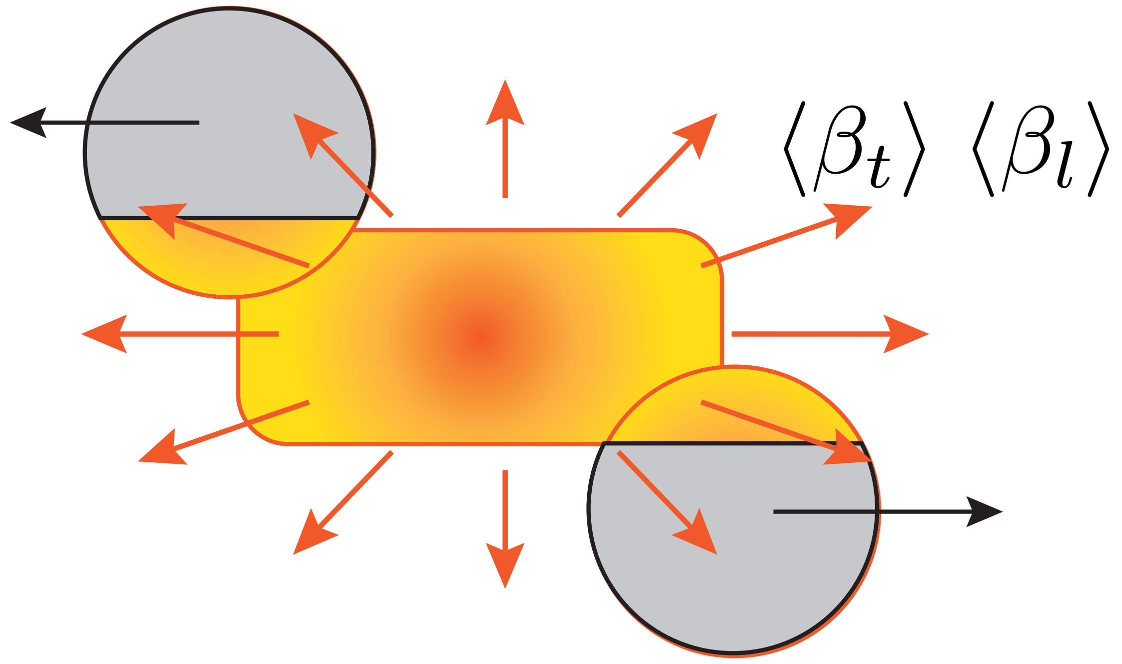
radial flow



top view

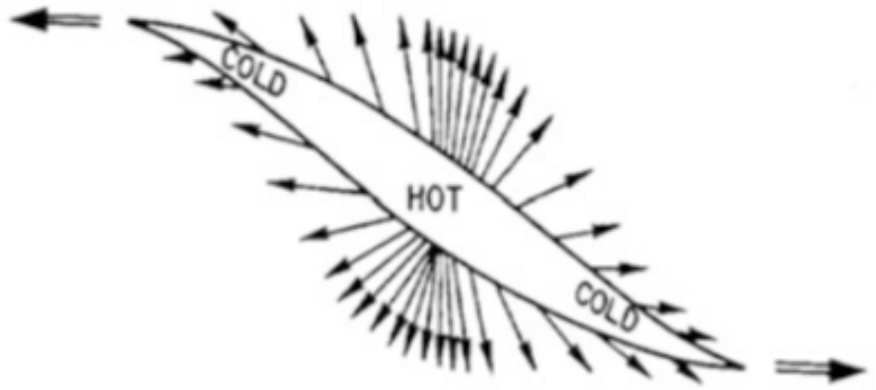


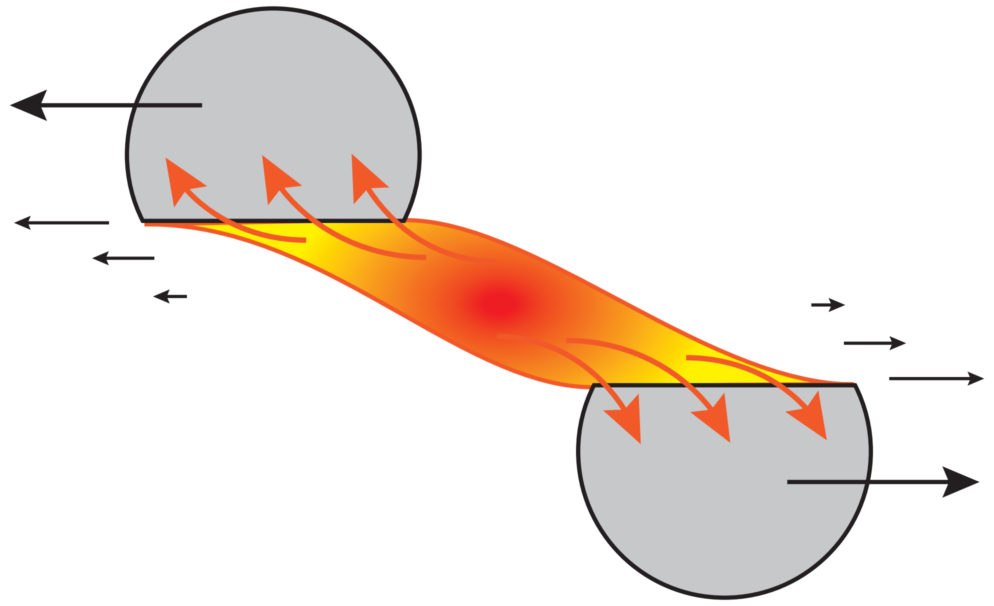
Landau scenario
total stopping



Bjorken scenario
partial stopping
initial longitudinal flow

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





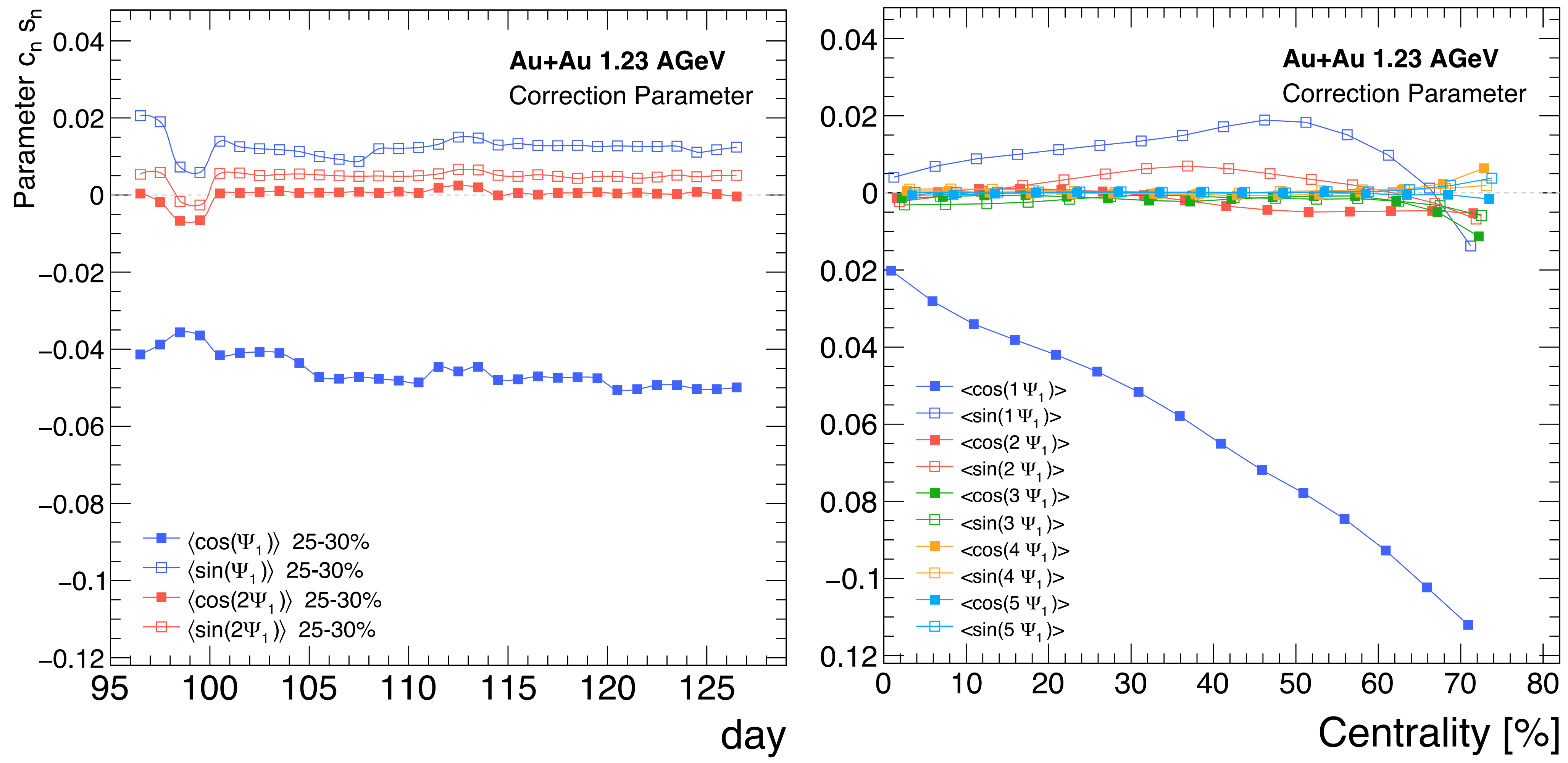
Hagedon-Myers scenario
(similar to “firestreak” model)
stopping dependent on nuclear density
partial stoped matter moves with
different rapidities

Event Plane Determination

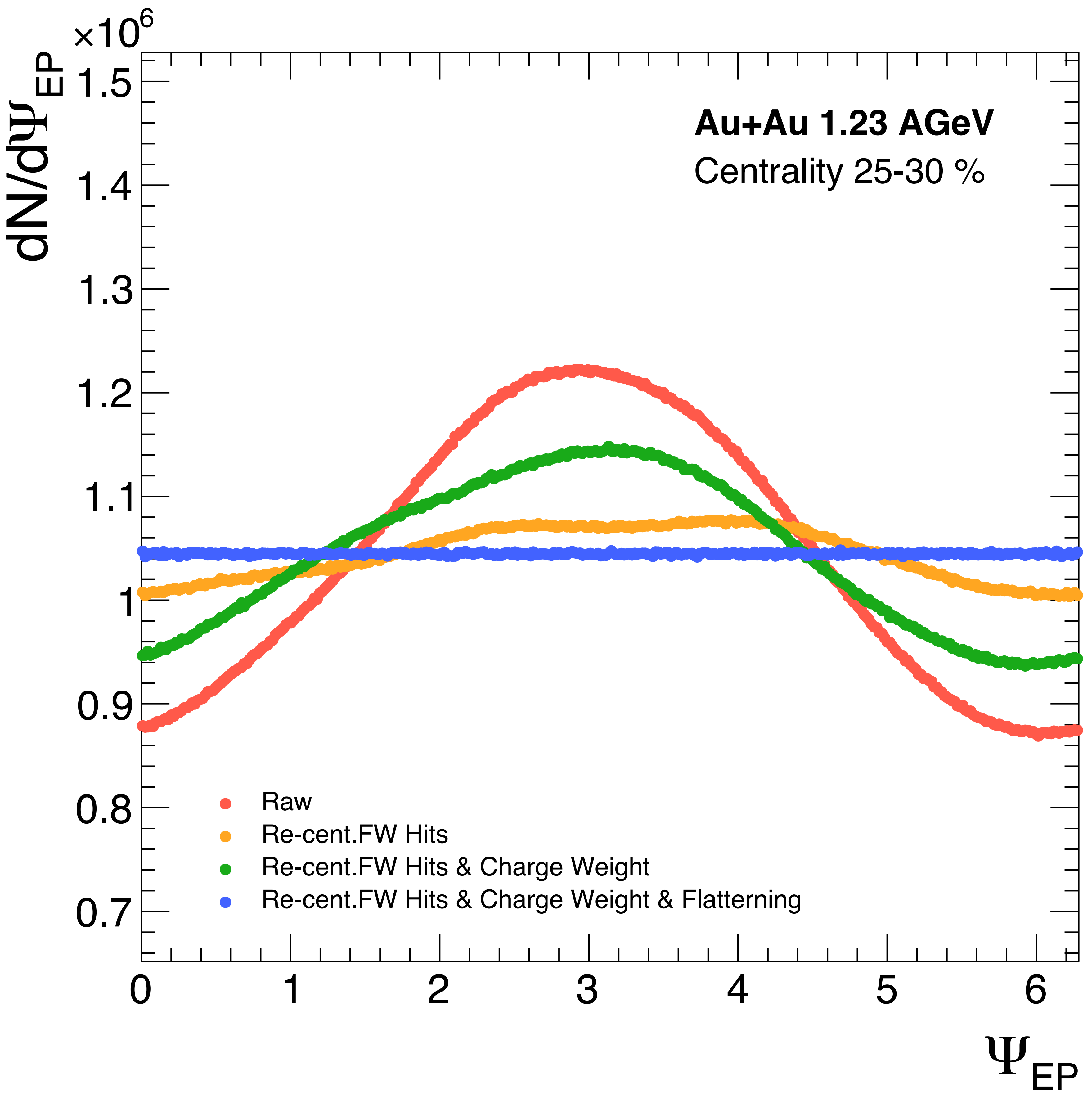
Correction of non-uniformities in the EP distribution (day-by-day and centrality)

Re-Centering of X and Y of all FW hits

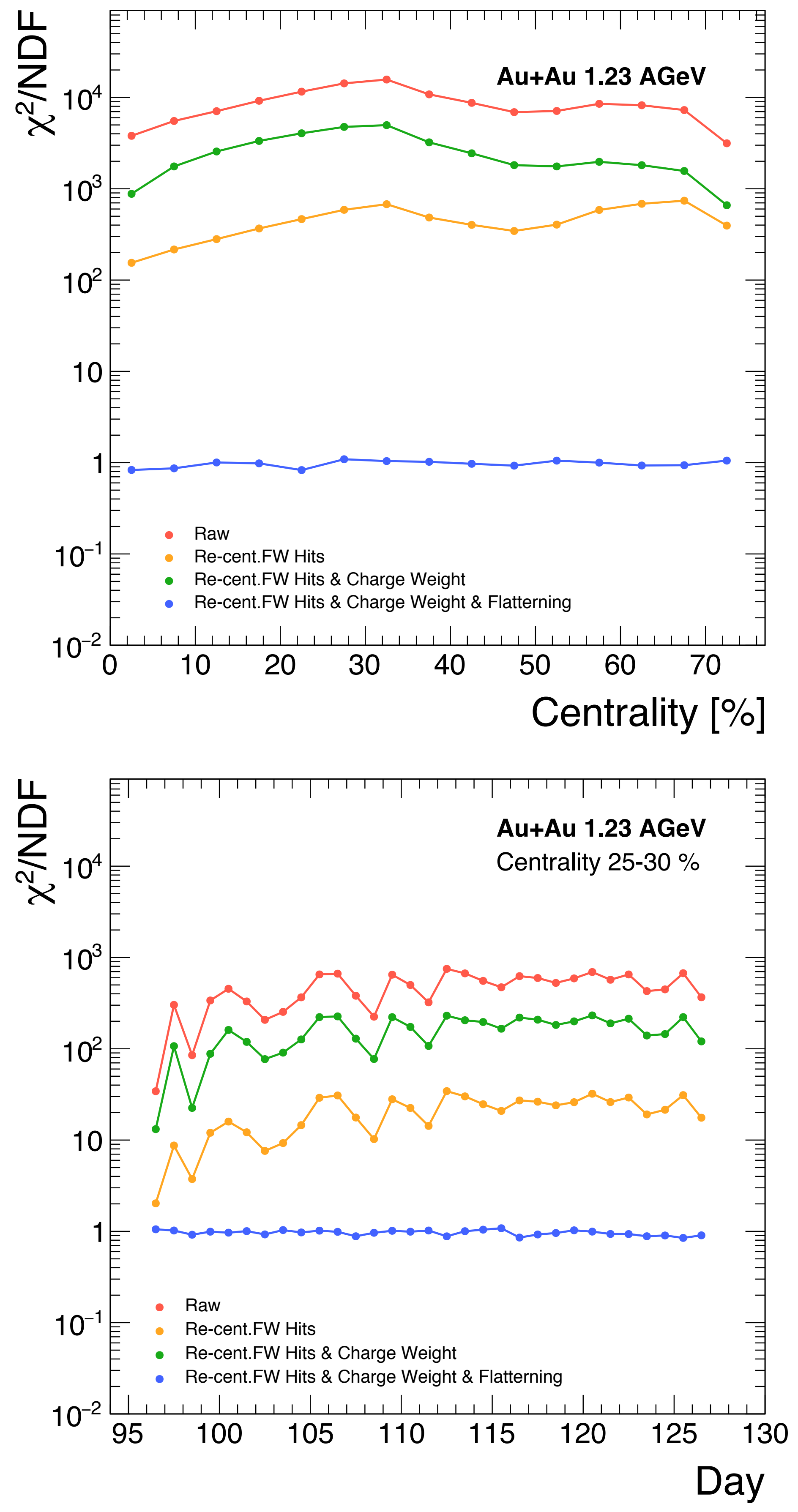
Flattening of residual Fourier components
with 8 cos- and 8 sin-terms



Flattening Parameter



Quality of Flatness

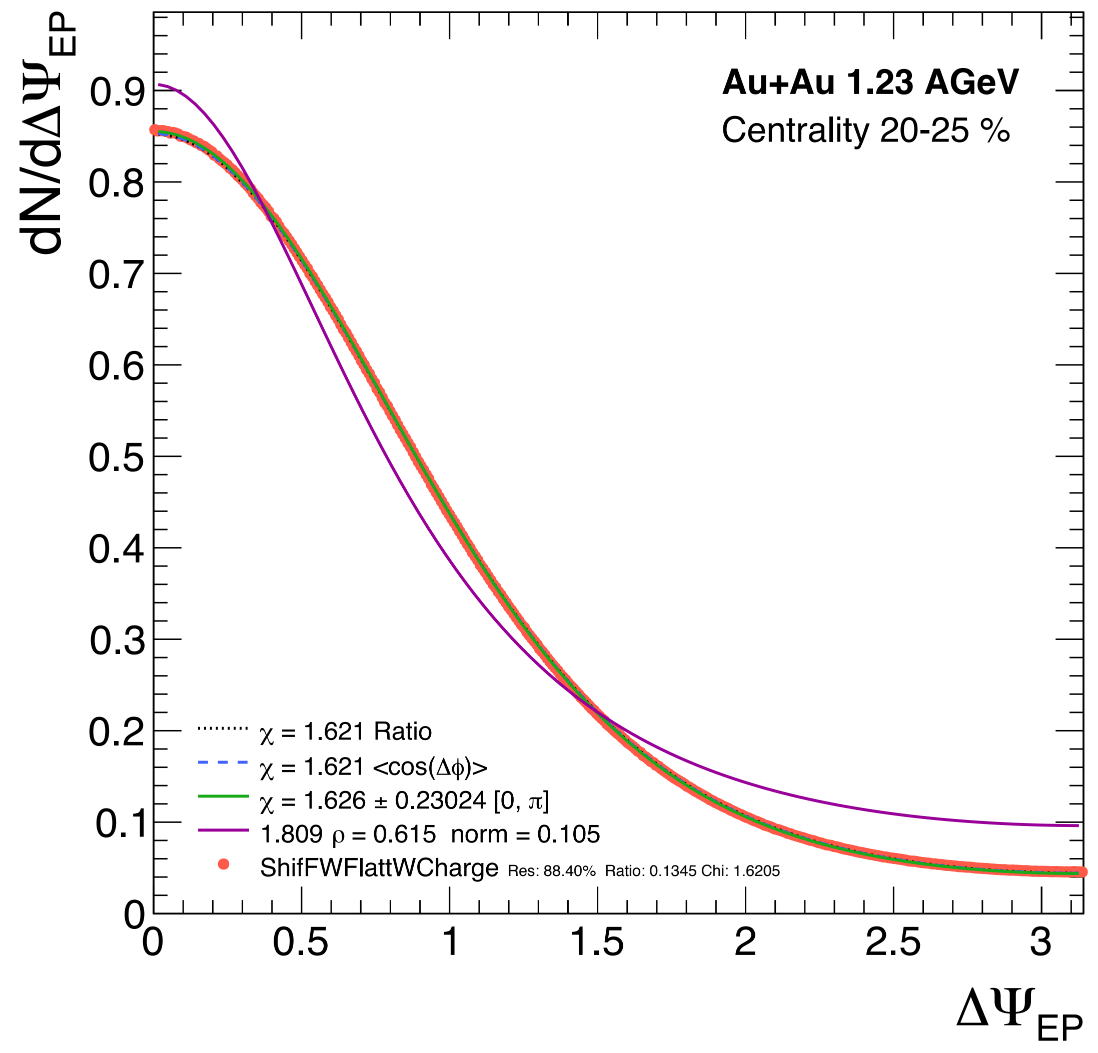


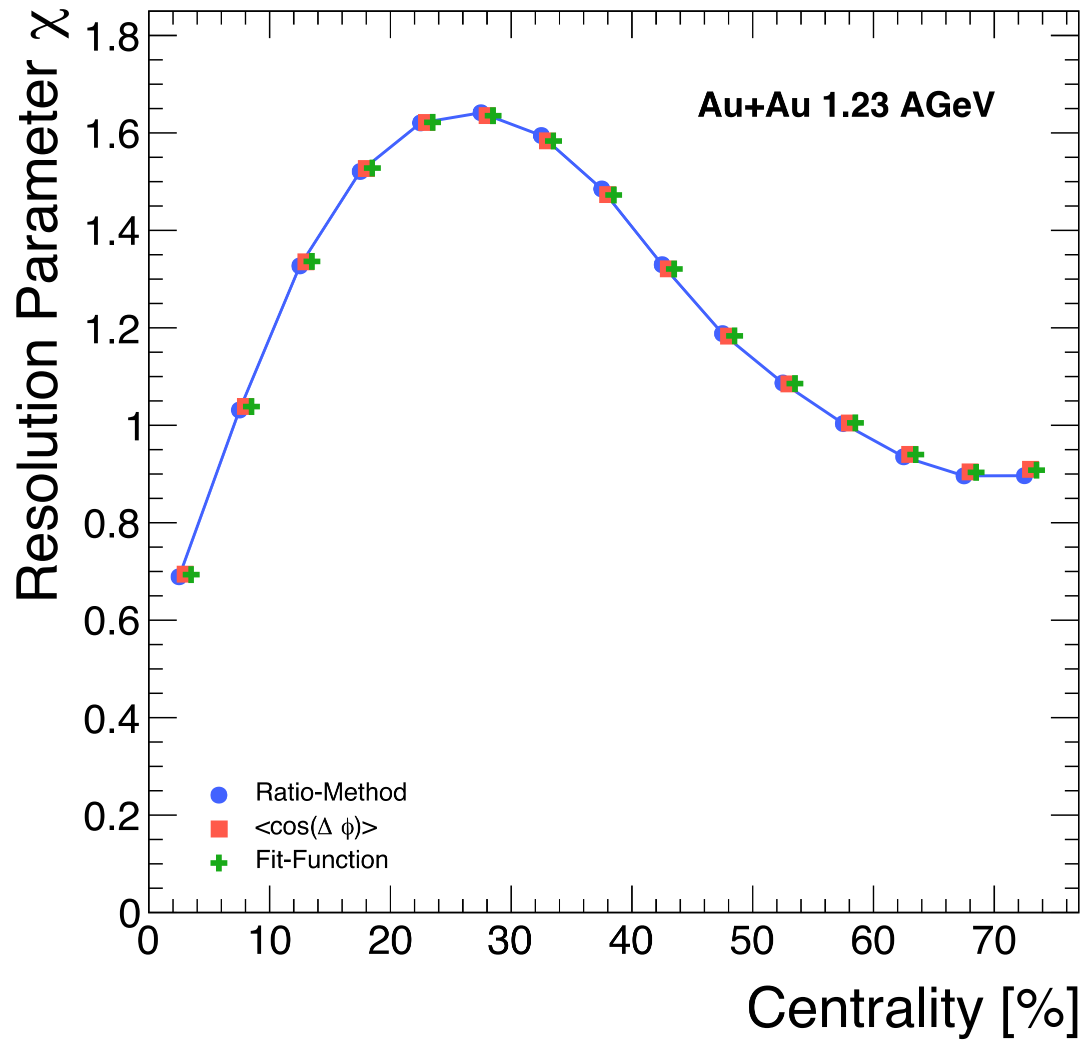
Event Plane Resolution

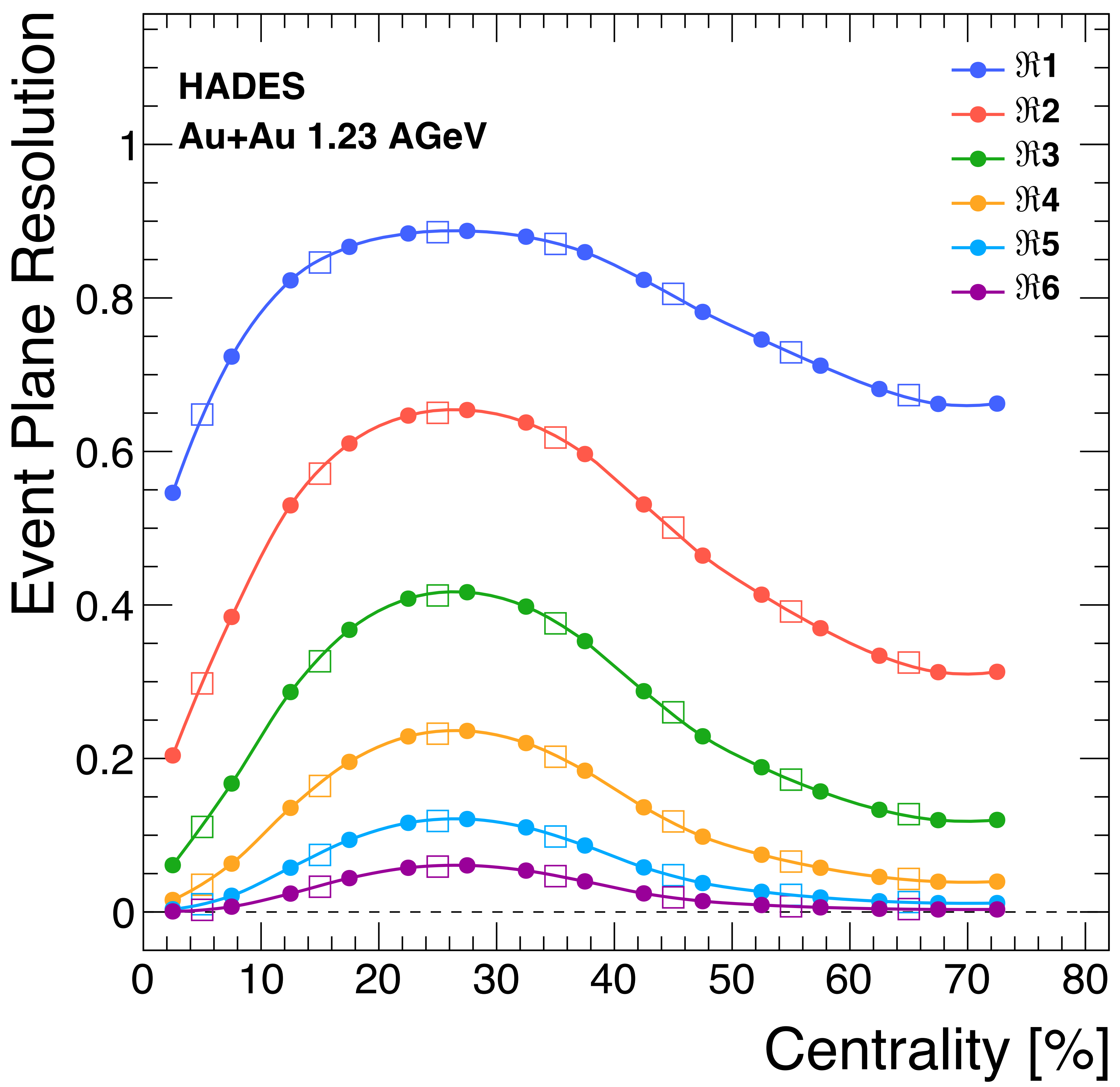
EP-resolution via sub-event method
with three implementations

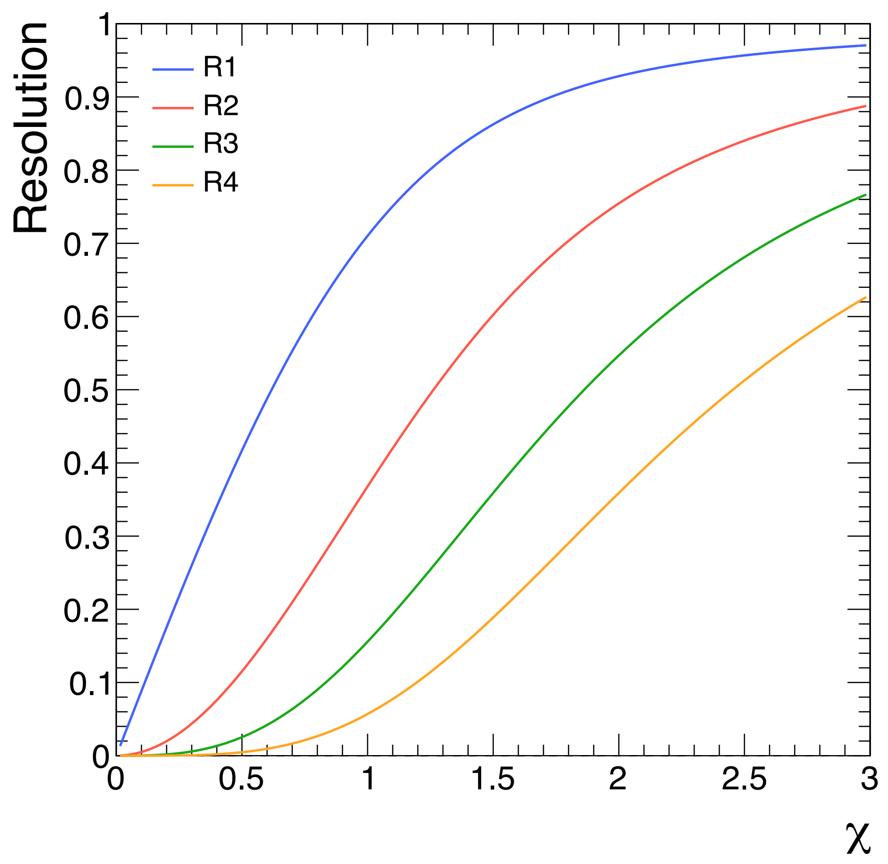
Determination of resolution parameter χ
- directly via <cos (ΔΦ)>
- Approximation via Fraction of Events with ΔΦ > π/2
- Fit-Method

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

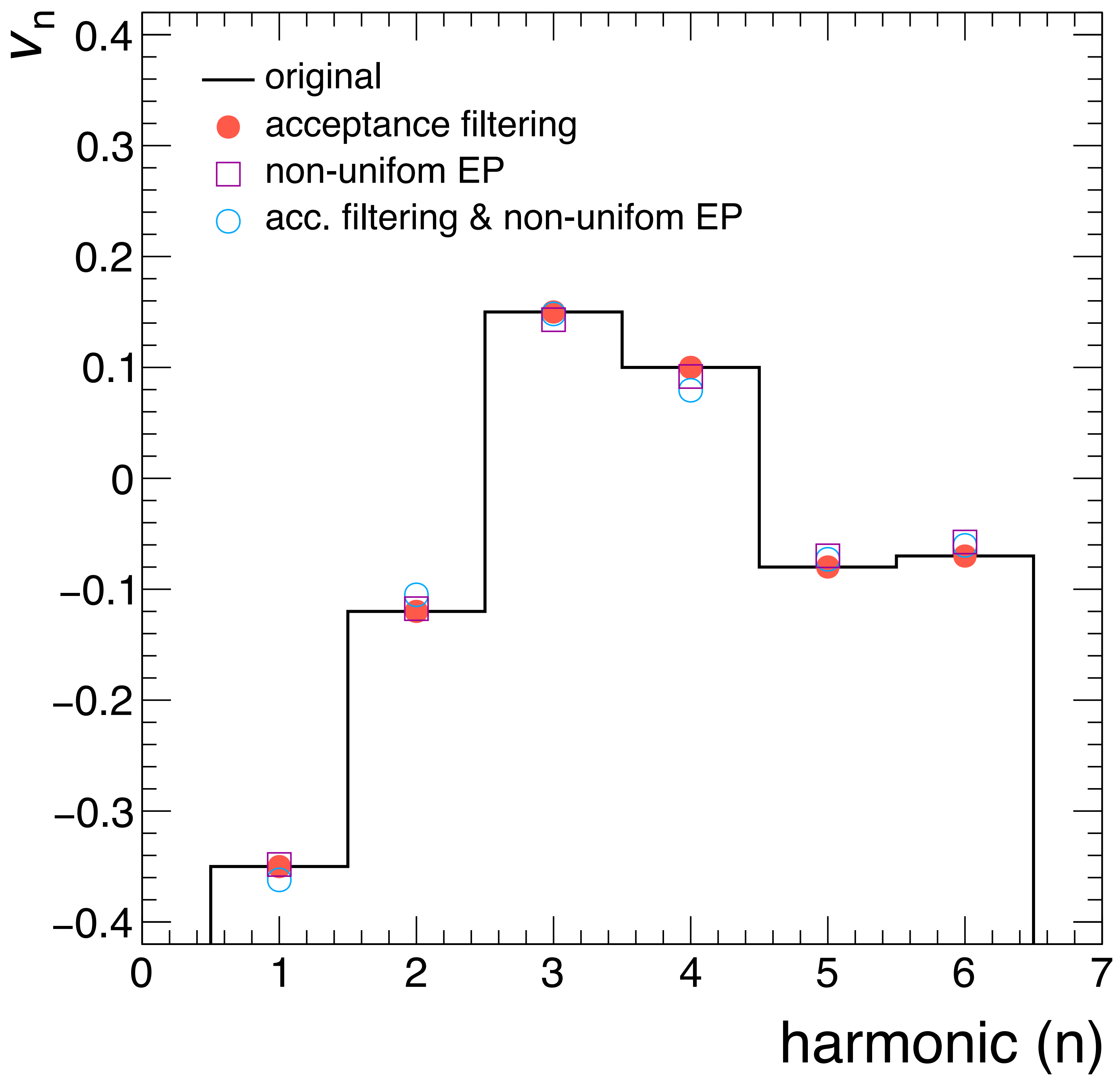
Consistency checks:

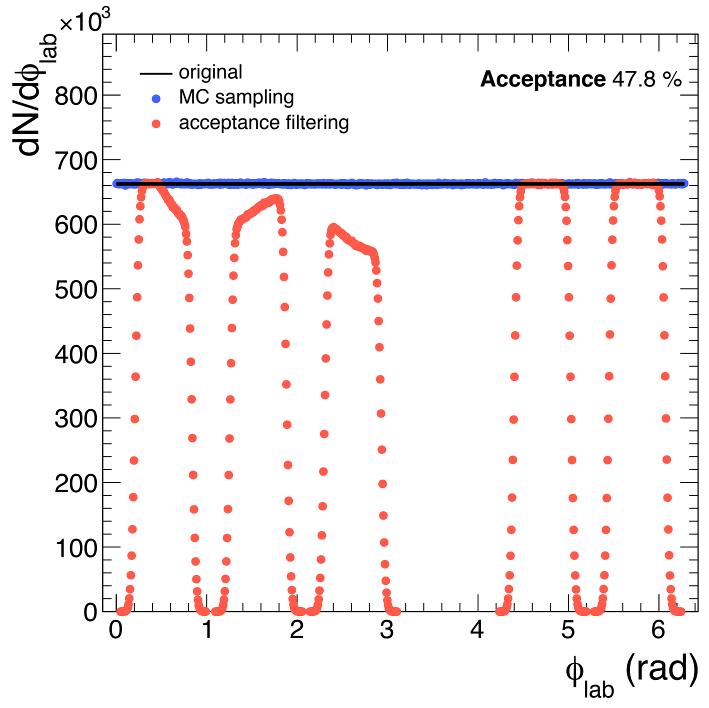
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at $y_{cm}=0$
- Vanishing residual sine-terms
- Time-dependent systematic effects

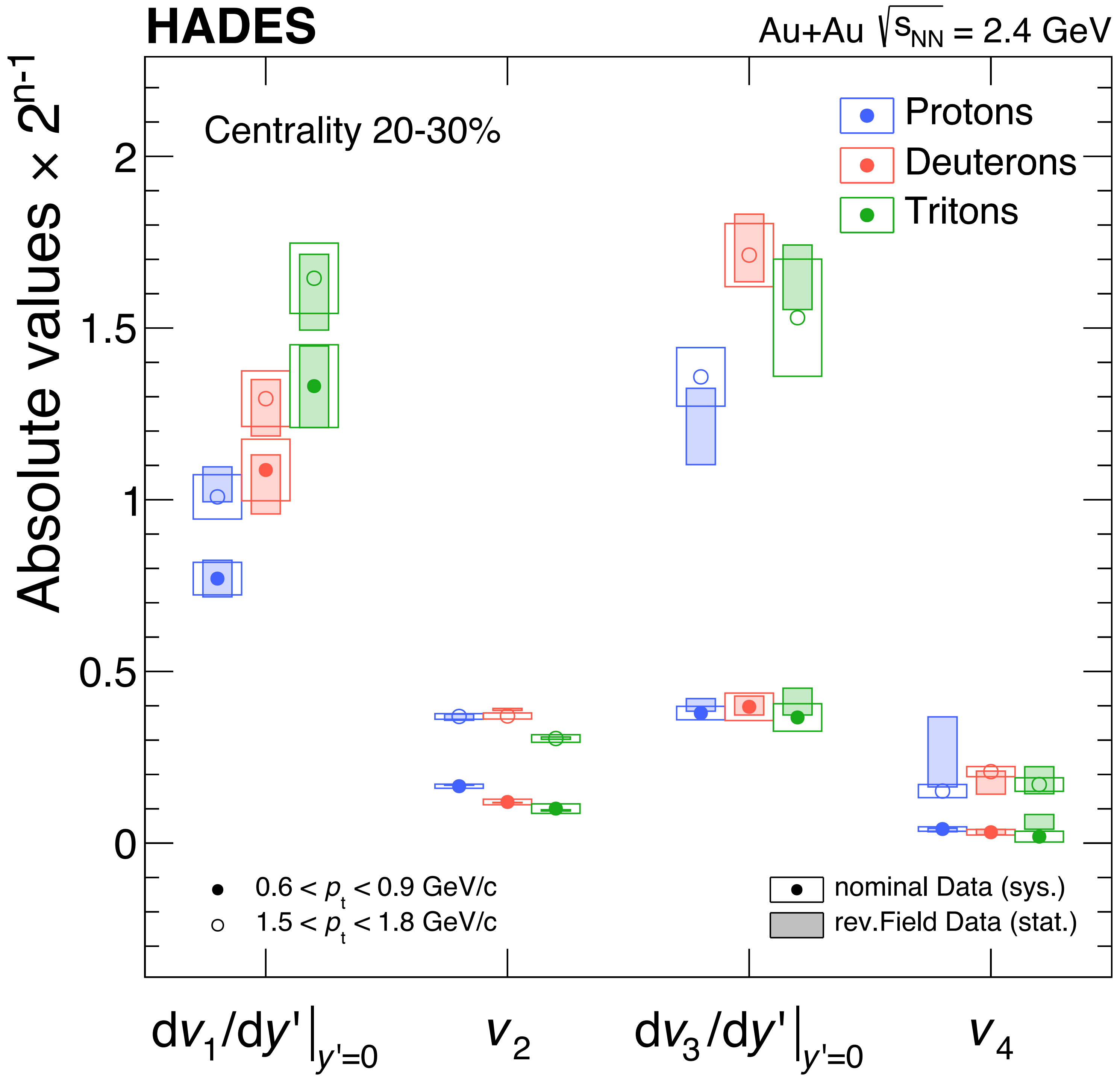
Reversed field polarity

Comparison with flow coefficients from the full data set

HADES, arXiv:2208.02740

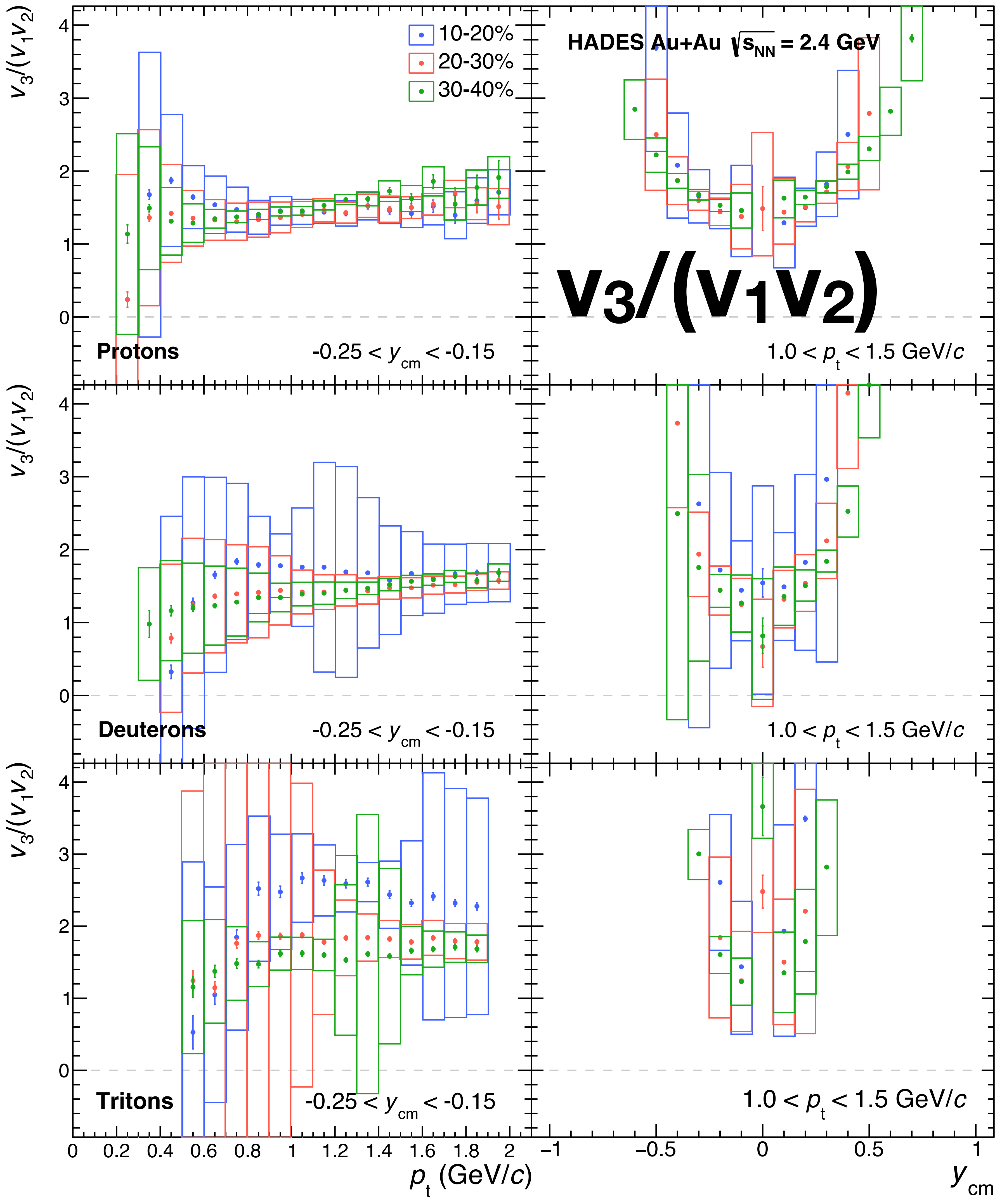


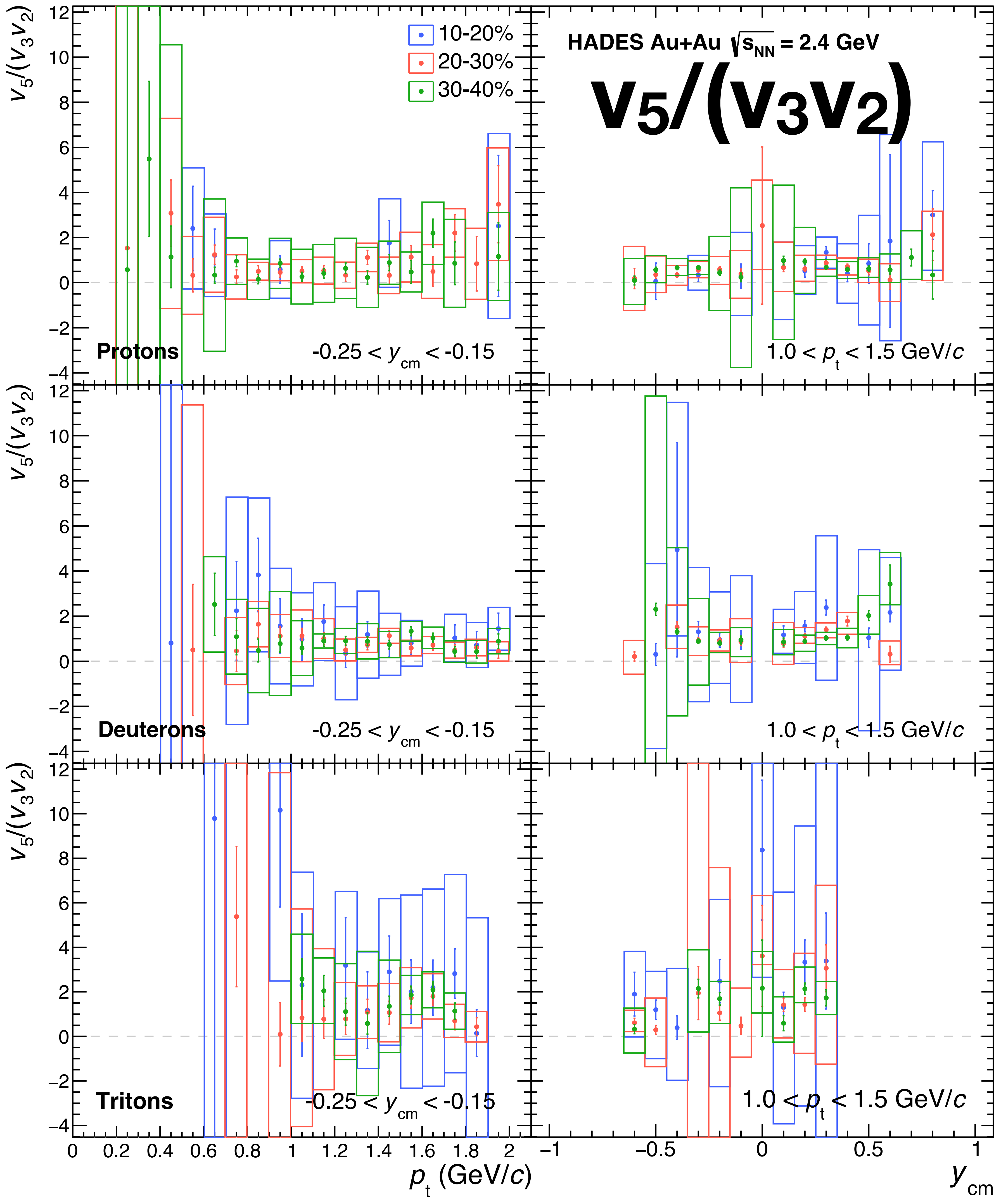




Other Ratio-Scalings?

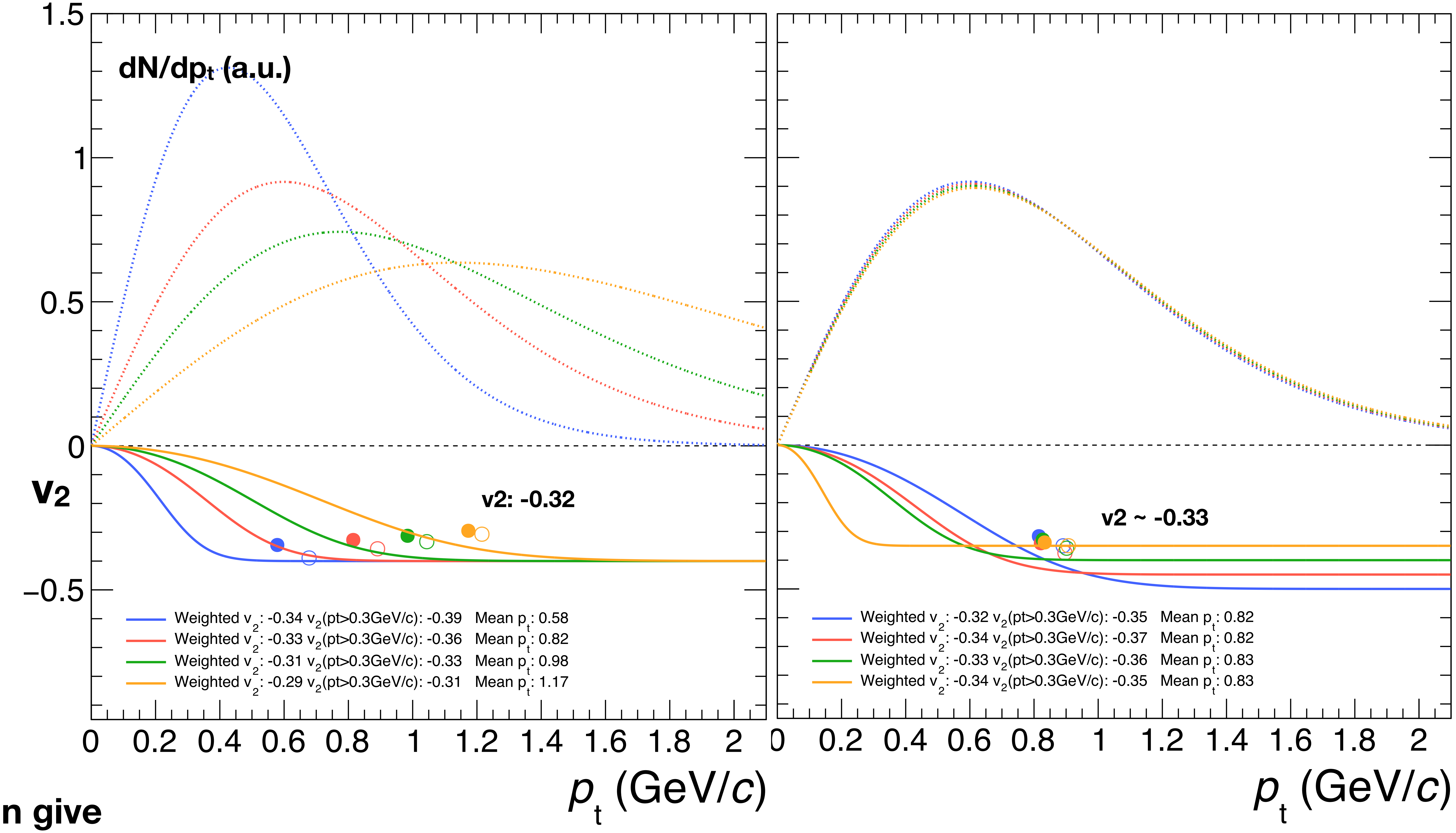
Protons and light nuclei





Elliptic Flow v_2

Integrated and p_t-Dependence

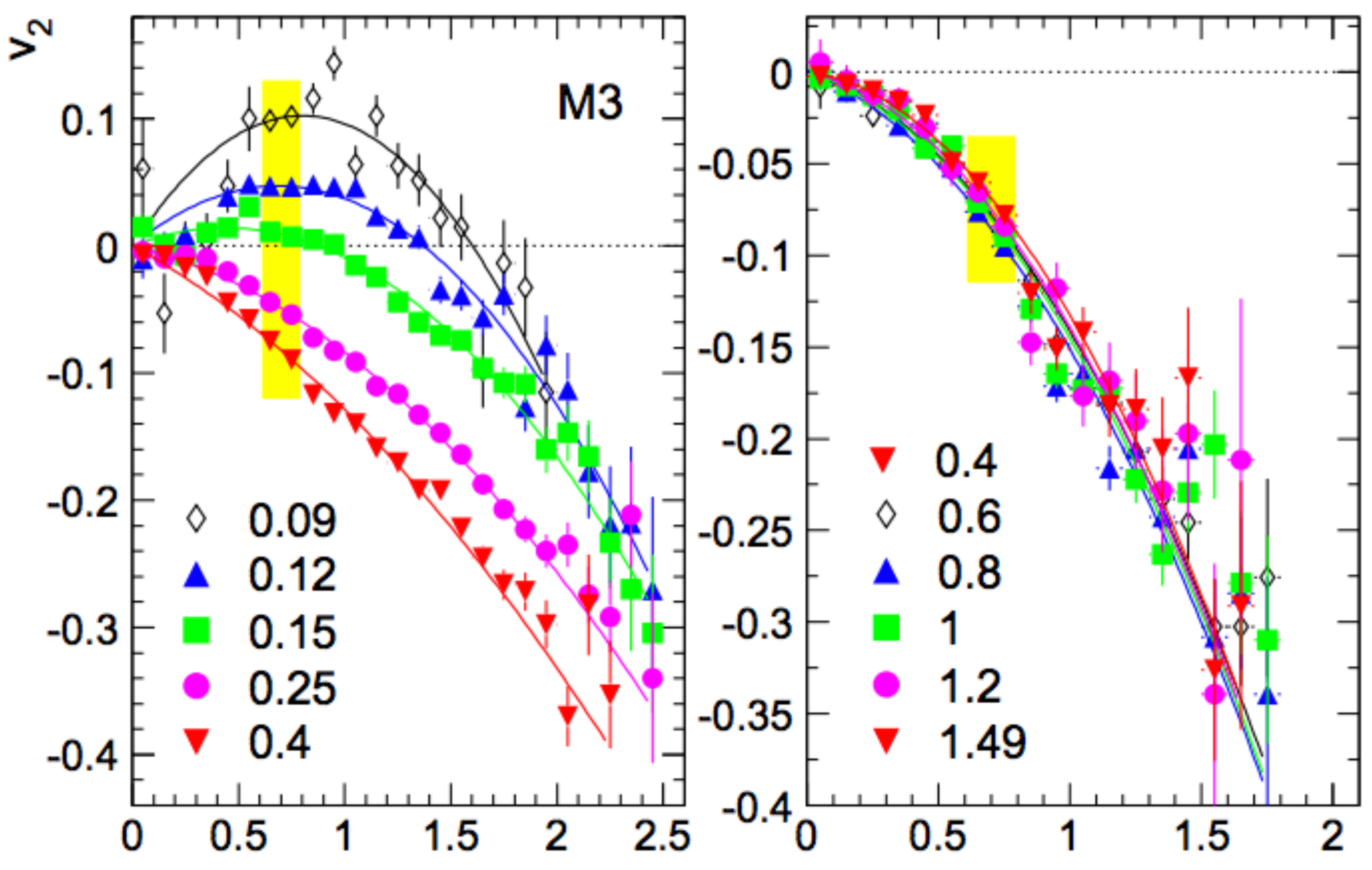


Integrated v2 (pt-weighted) can give similar values even underling yield- and v2-spectra are different

Elliptic Flow v_2

Energy- and p_t-Dependence

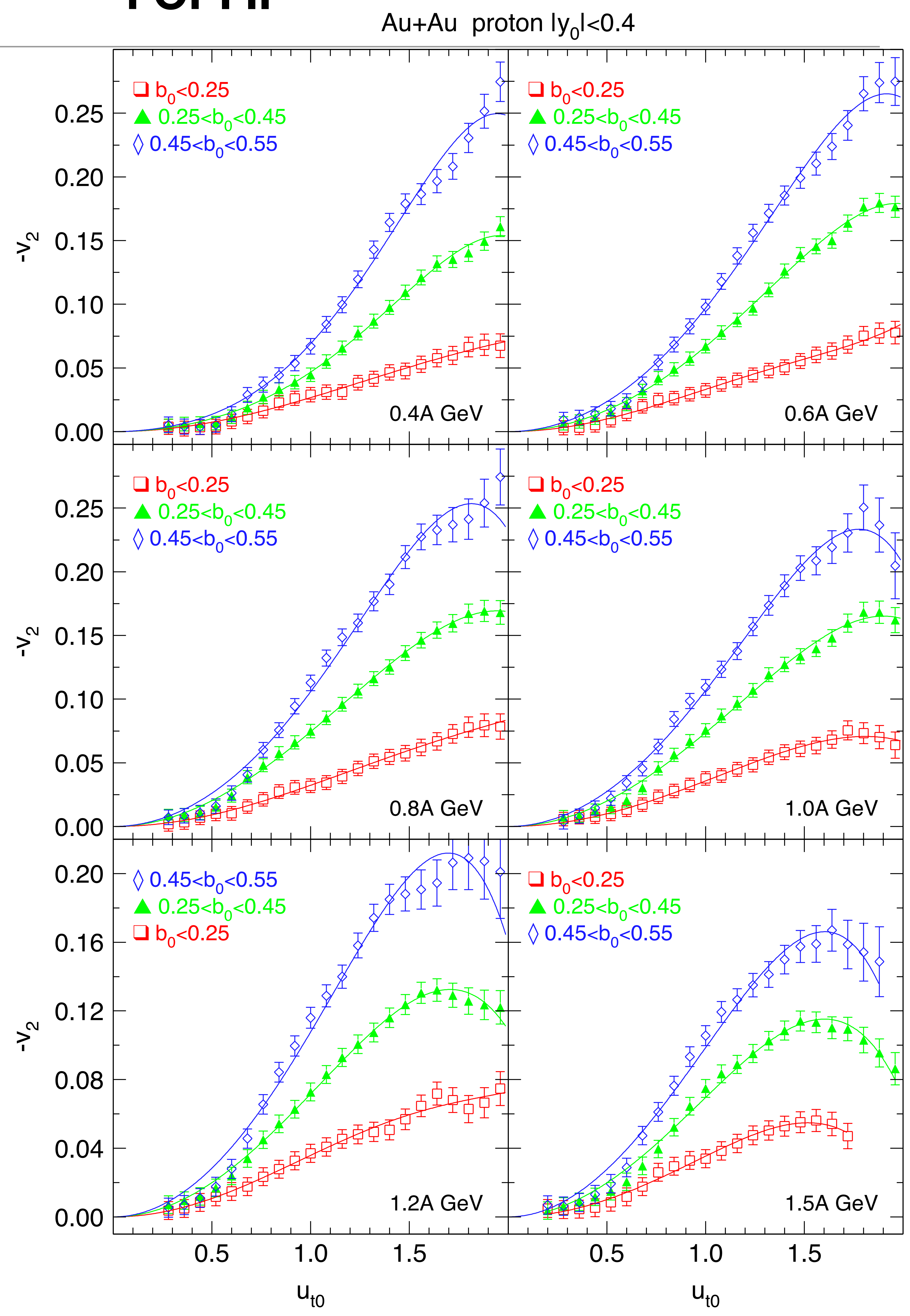
FOPI I



$$p_t^{(0)} = (p_t/A)/(p_P^{\mathrm{c.m.}}/A_P)$$

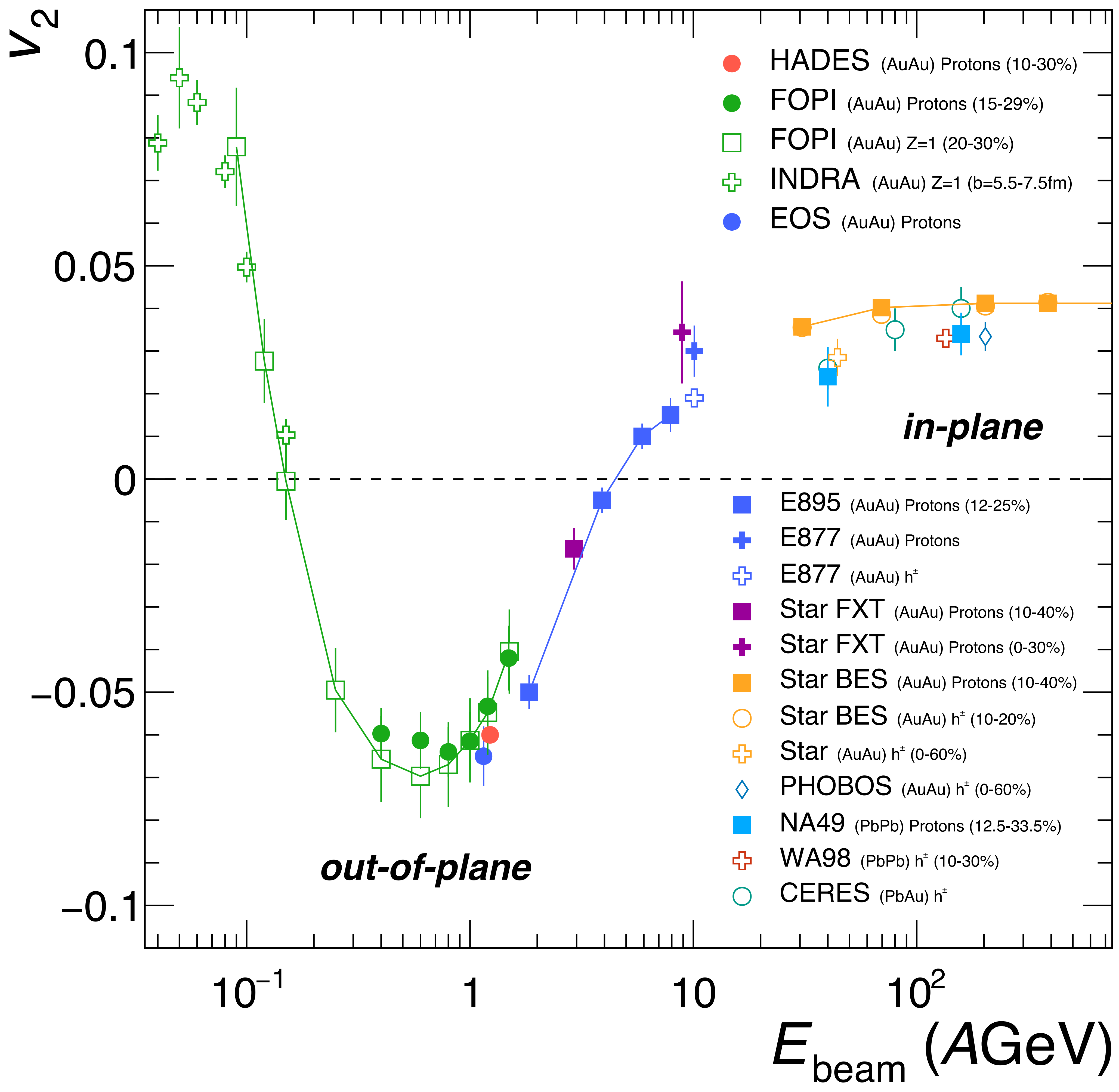
Parameterization with Polynomial

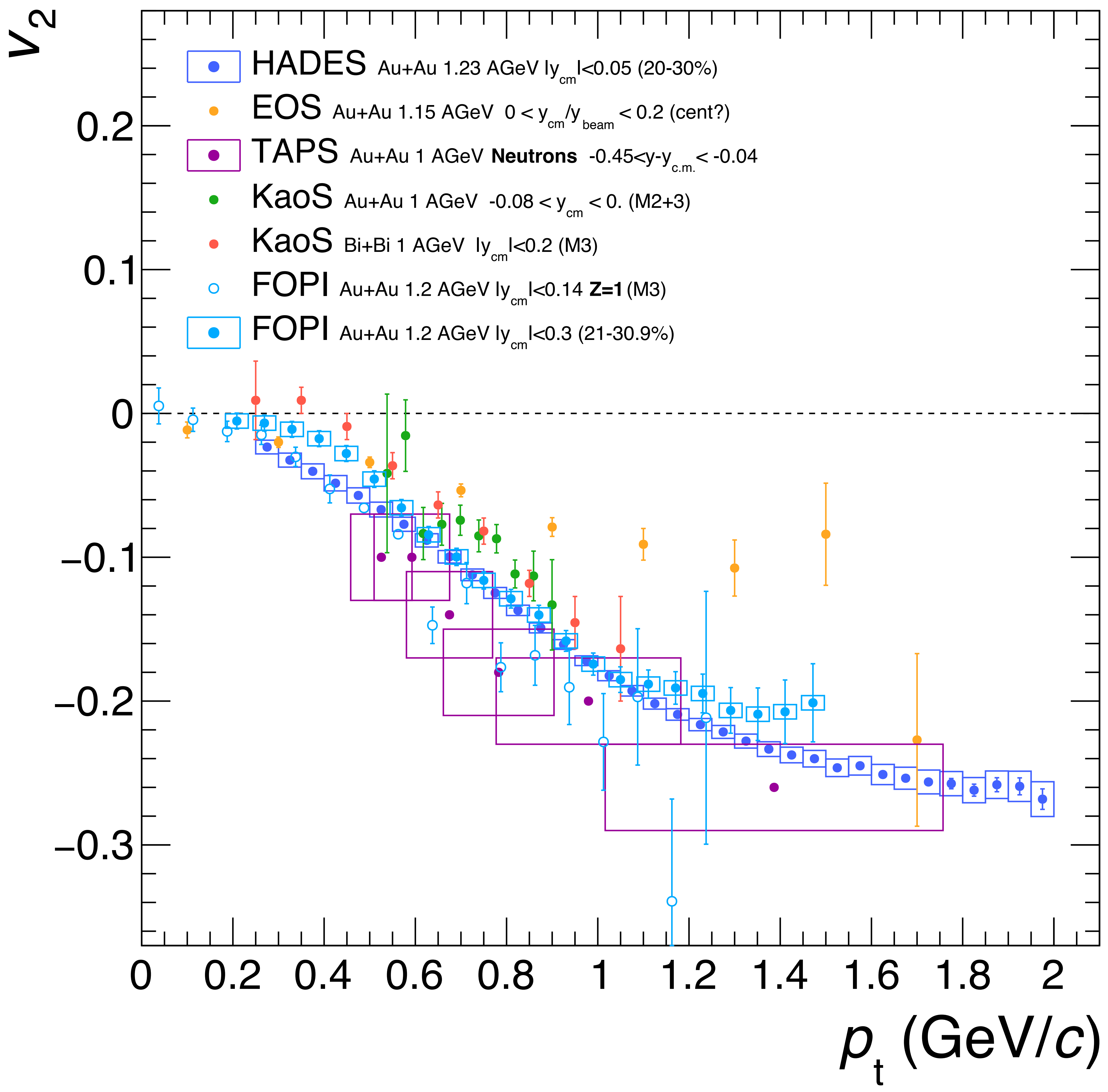
FOPI II



Elliptic Flow v_2

Energy- and p_t-Dependence





EOS:
J. Kintner, Squeeze-Out and Flow of Pions from 1.5 GeV/Nucleon Au+Au. Dissertation, University of California Davis (1993)
KaoS AuAu:
D. Brill, Azimutal anisotrope Teilchenemission in relativistischen Schwerionenstössen. Dissertation, Goethe-University, 1993
KaoS BiBi:
D. Brill, et al., Z. Phys. A355, 61 (1996).
FOPI:
Nucl.Phys. A876 (2012) 1-60