Flow phenomena at high nuclear densities with HADES

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for the
HADES Collaboration

Seminarium Fizyki Jądra Atomowego

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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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HADES

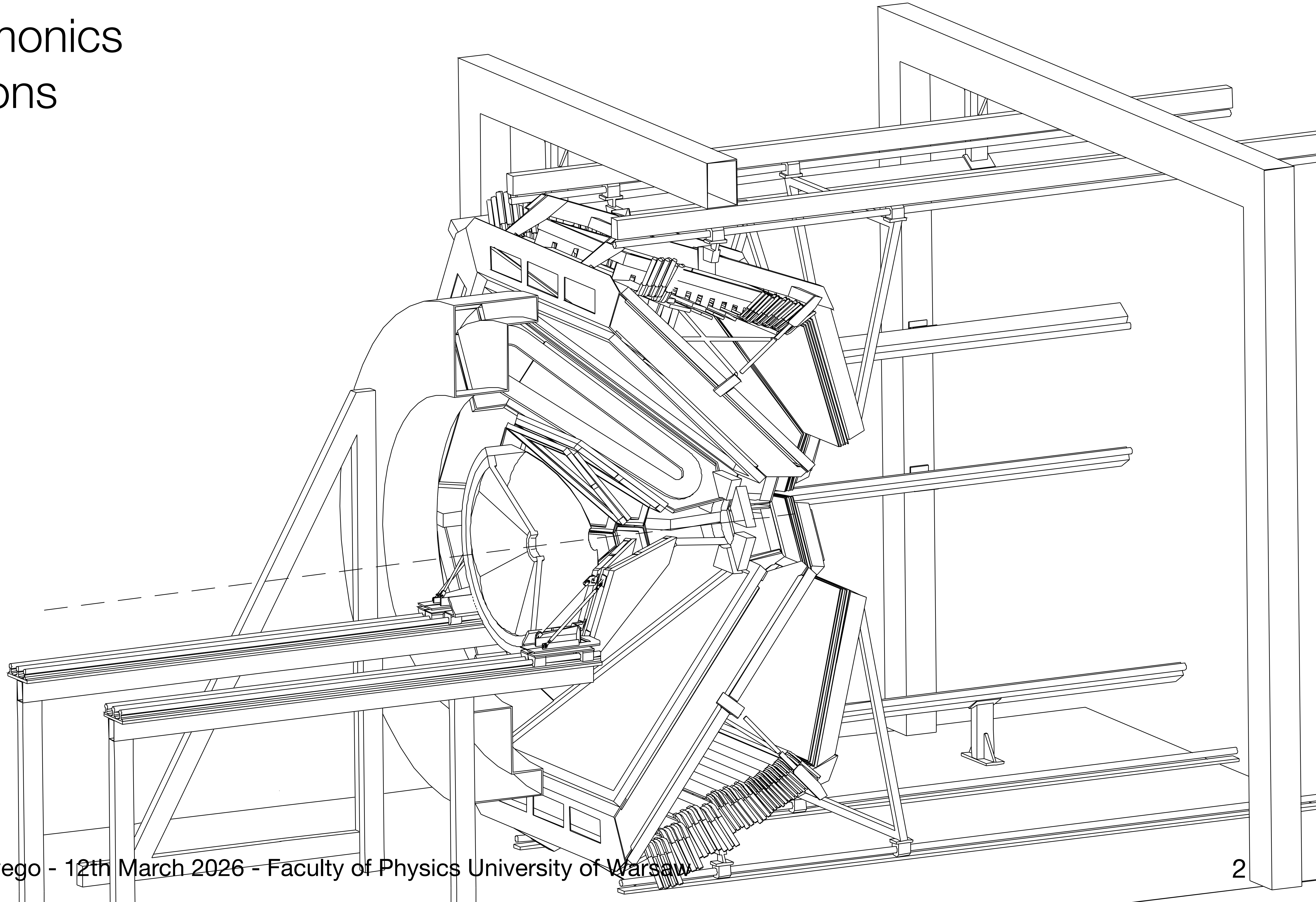
Outline

- 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 publications:

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

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

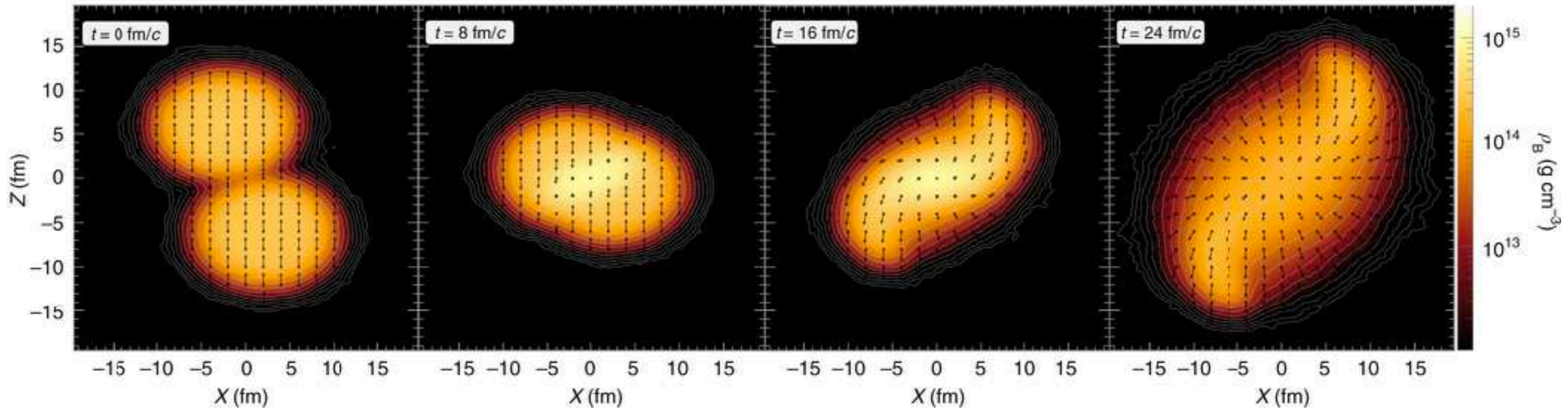


Dense nuclear matter and astrophysics

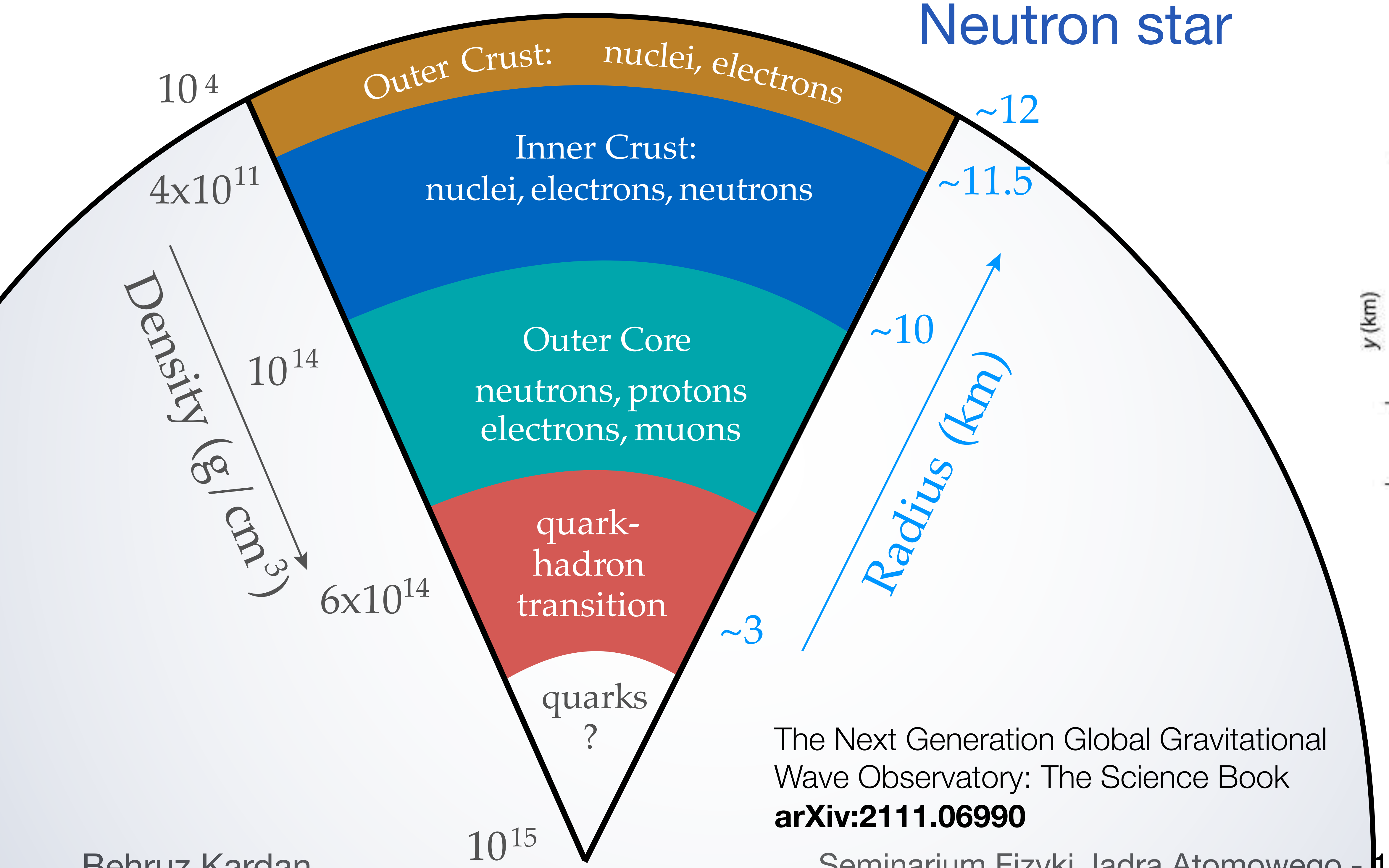
- Properties of neutron star matter and its Equation-of-State (EoS)
- Similar conditions in heavy-ion collisions at SIS18 energies than in merging neutron stars

Heavy-ion collision

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



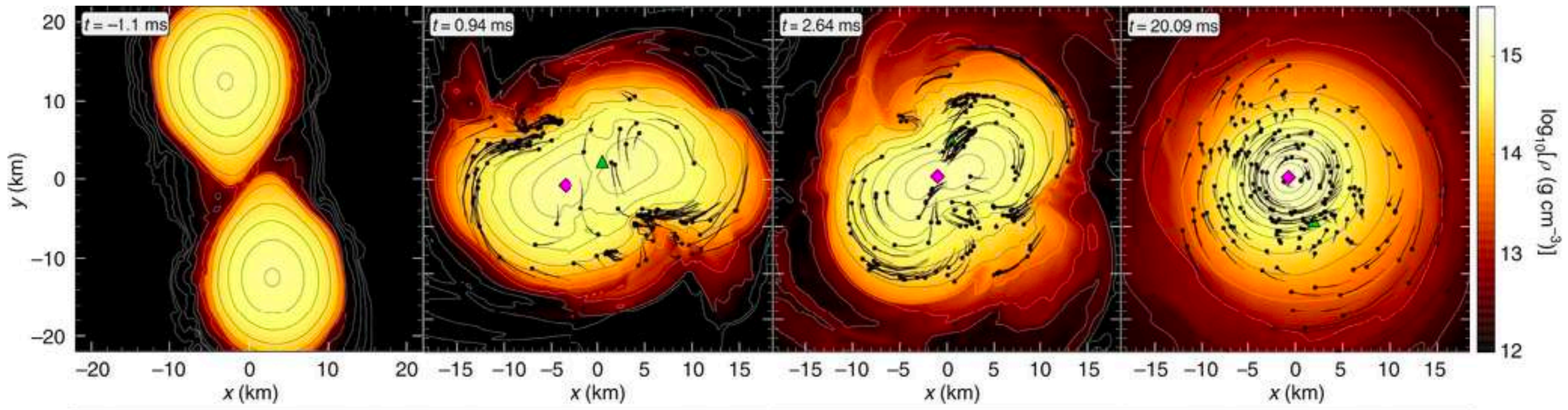
Neutron star



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

Neutron star merger

Observation via gravitational waves
GW170817: B.P. Abott et al. (LIGO + VIRGO)
PRL 119 (2017) 1611001

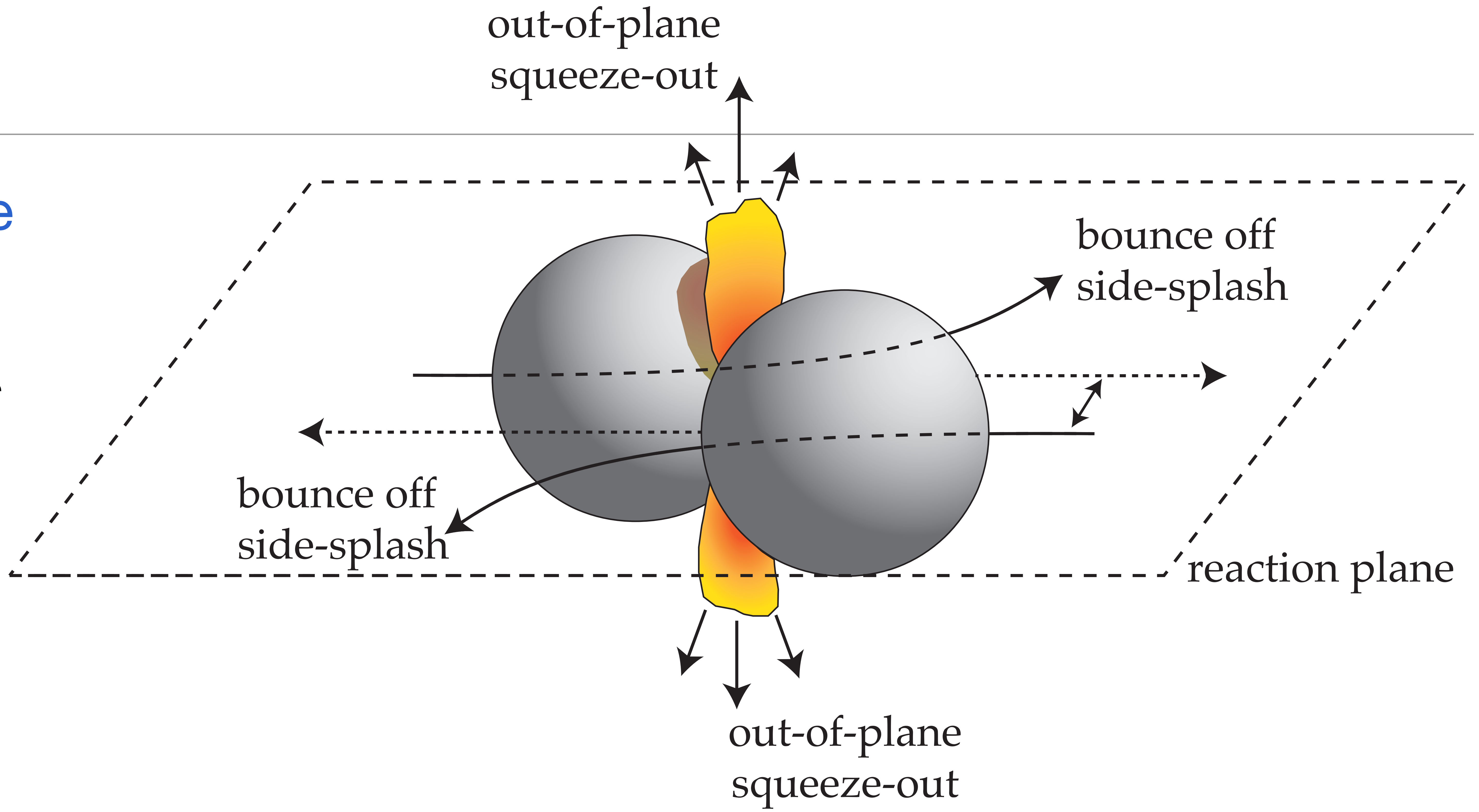


⇒ Heavy-ion collisions can provide access to equation-of-state of neutron star matter

Collectivity

Emission pattern relative to reaction plane

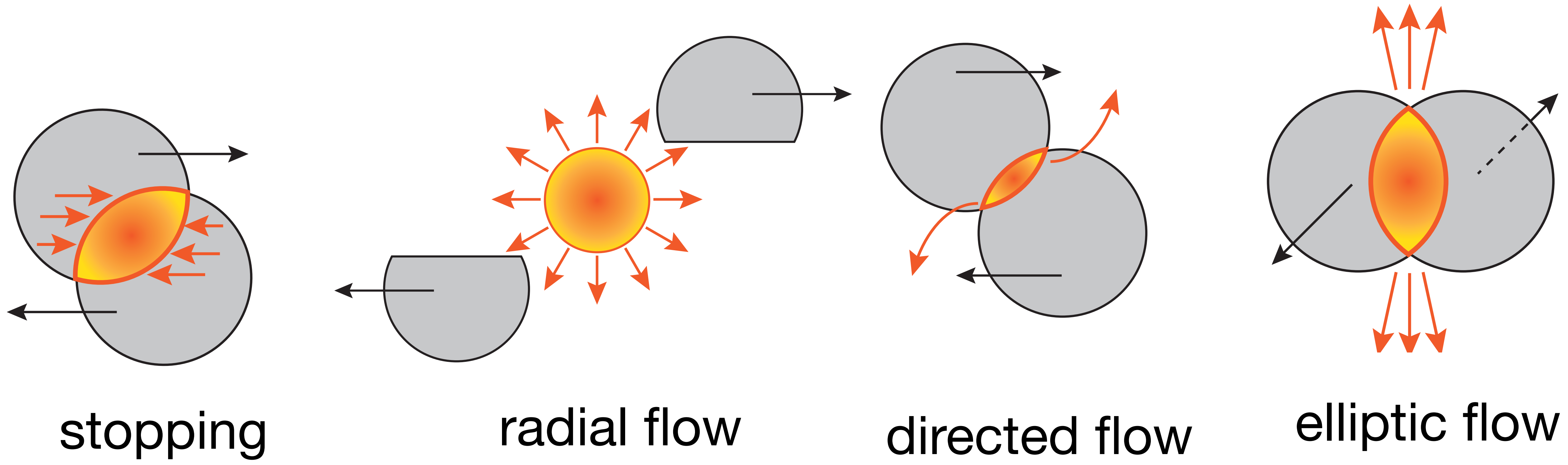
- Particle emission in different directions follow the *non-uniform pressure gradients* build-up in the dense compression phase
- Access to medium properties, e.g. *viscosity*, *Equation-of-state (EoS)*



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 and Warsaw

Volume 157B, number 2,3 PHYSICS LETTERS 11 July 1985

TRANSVERSE MOMENTUM ANALYSIS OF COLLECTIVE MOTION IN RELATIVISTIC NUCLEAR COLLISIONS ☆

P. DANIELEWICZ [1] and G. ODYNIEC

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Received 15 March 1985

VOLUME 53, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 1984

Stopping Power and Collective Flow of Nuclear Matter in the Reaction Ar + Pb at 0.8 GeV/u

R. E. Renfordt and D. Schall

R. Bock, R. Brockmann, J. W. Harris, A. Sandoval, R. Stock, and H. Ströbele

D. Bangert and W. Rauch

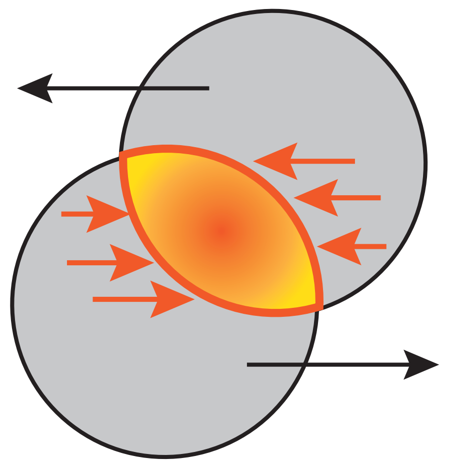
G. Odyniec, H. G. Pugh, and L. S. Schroeder

Pawel Danielewicz

Streamer Chamber (1983): Grazyna Odyniec, Reinhard Stock …

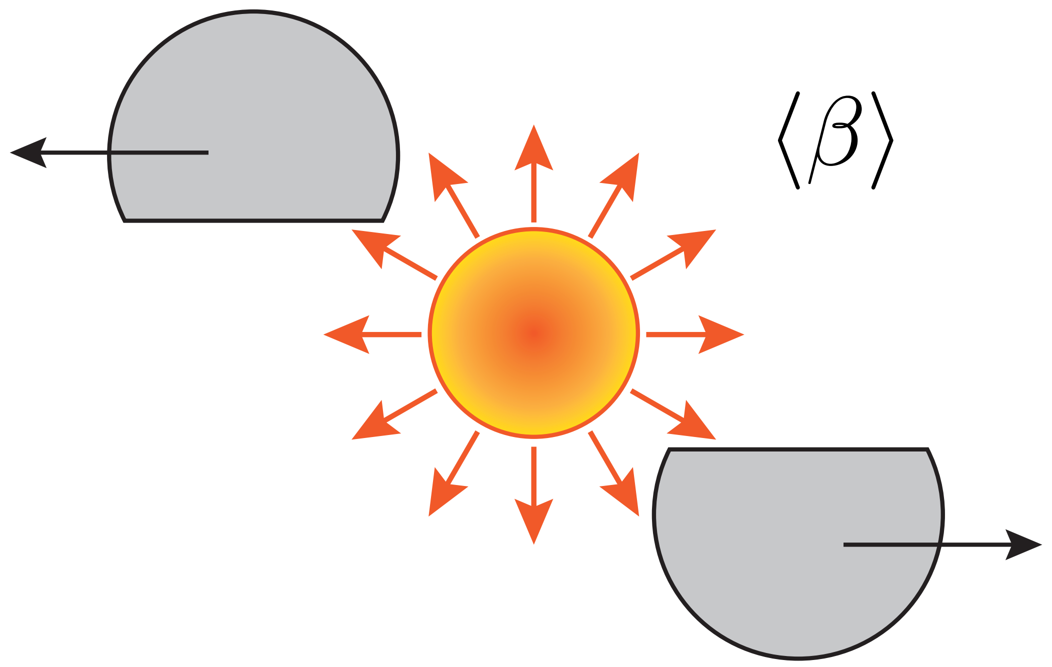
Motivation

Flow and Event Shapes

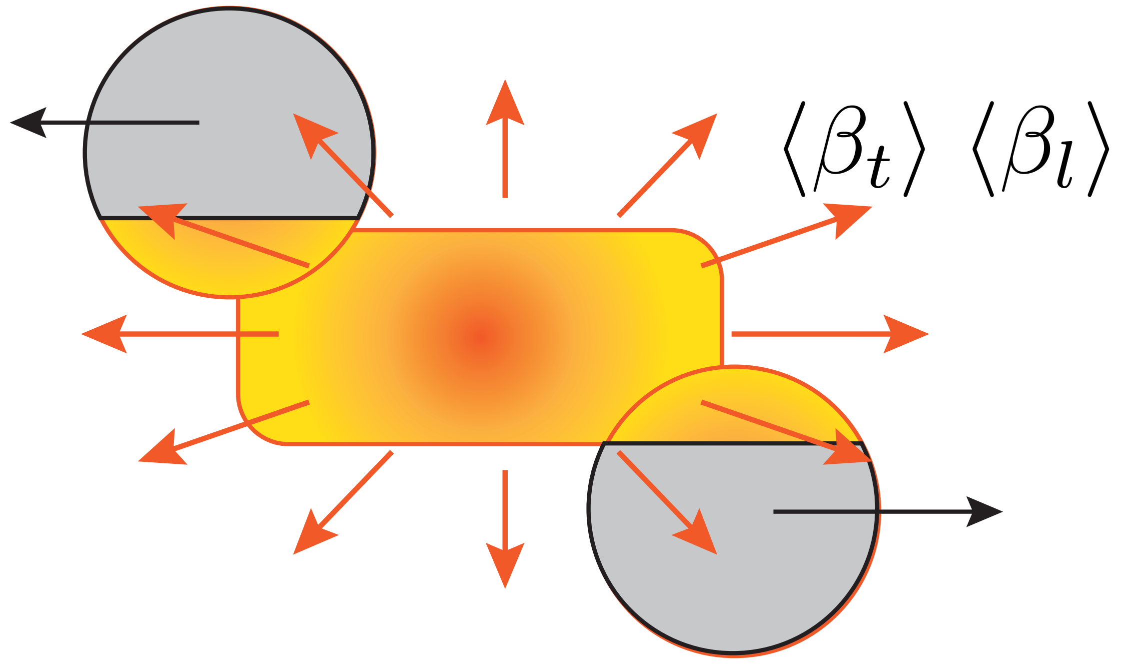


top view

radial flow

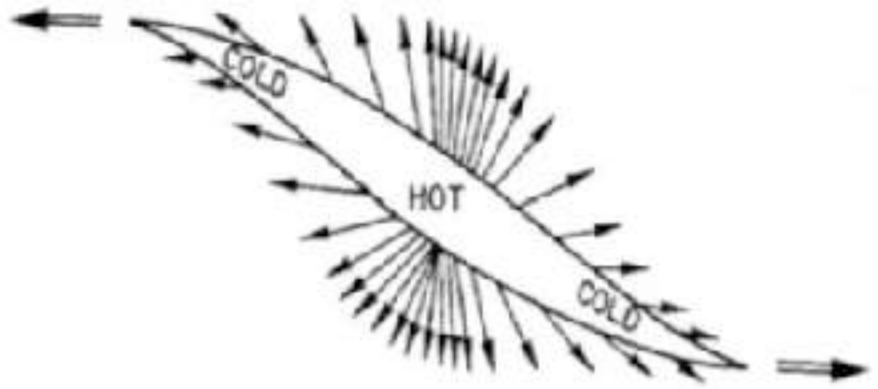


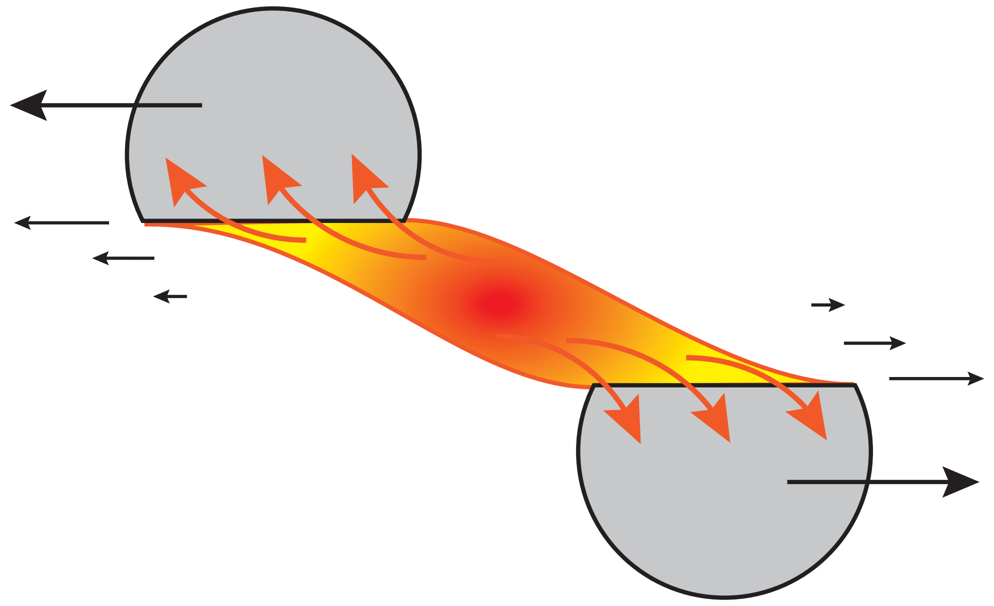
Landau scenario
total stopping



Bjorken scenario
partial stopping
initial longitudinal flow

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

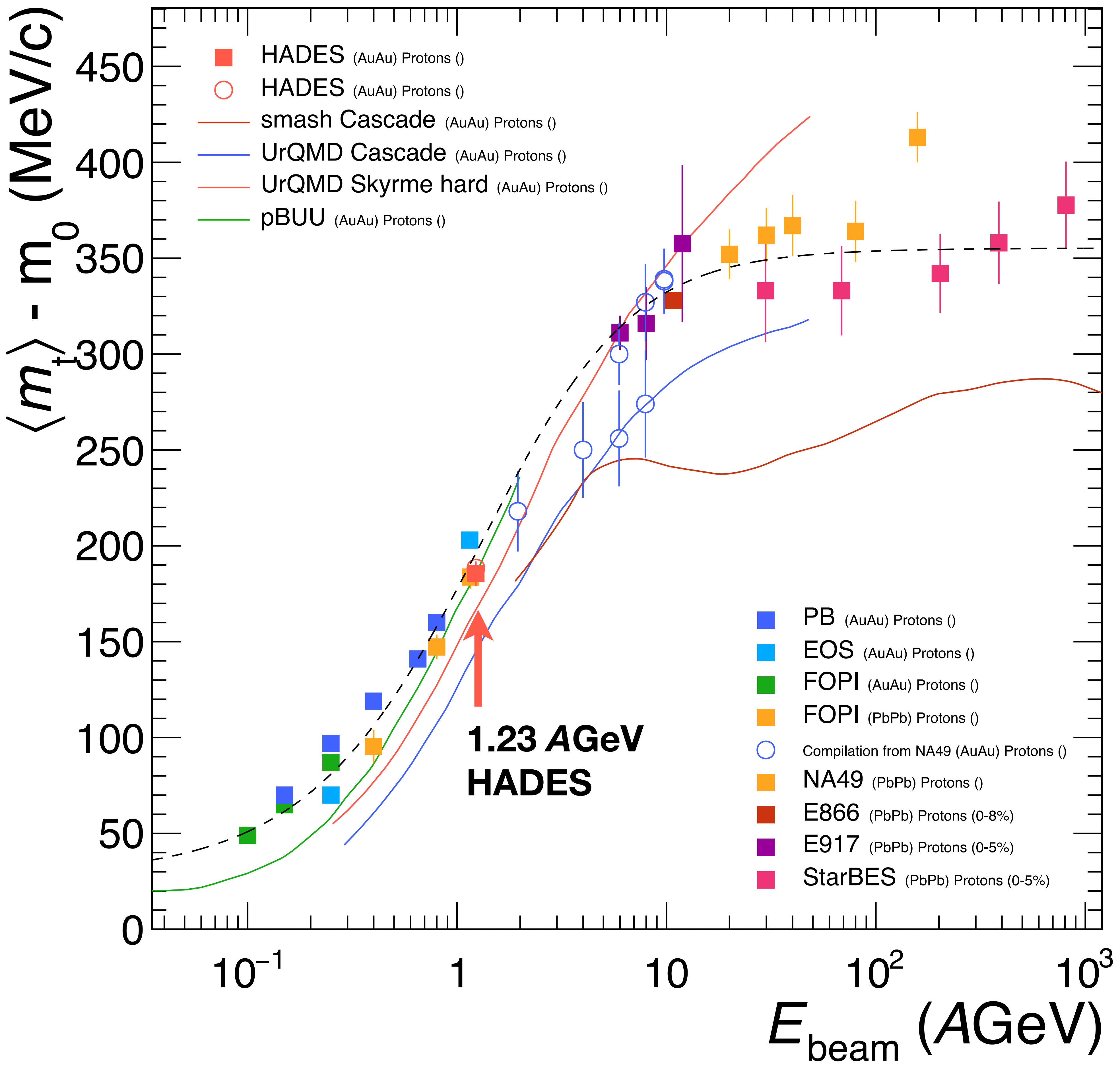


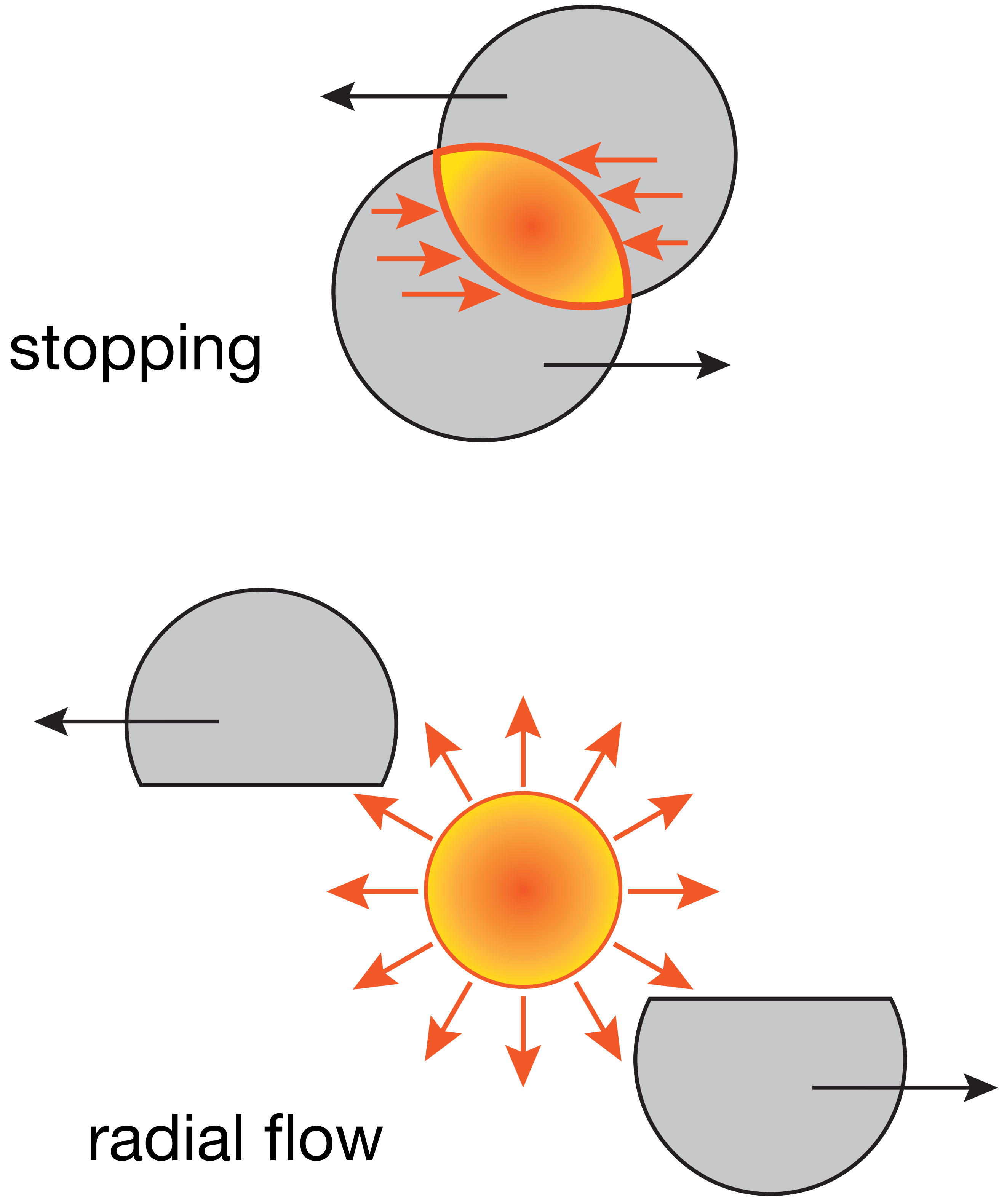


Hagedon-Myers scenario
(similar to "firestreak" model)
stopping dependent on nuclear density
partial stoped matter moves with
different rapidities

Collectivity

Energy dependence of radial flow



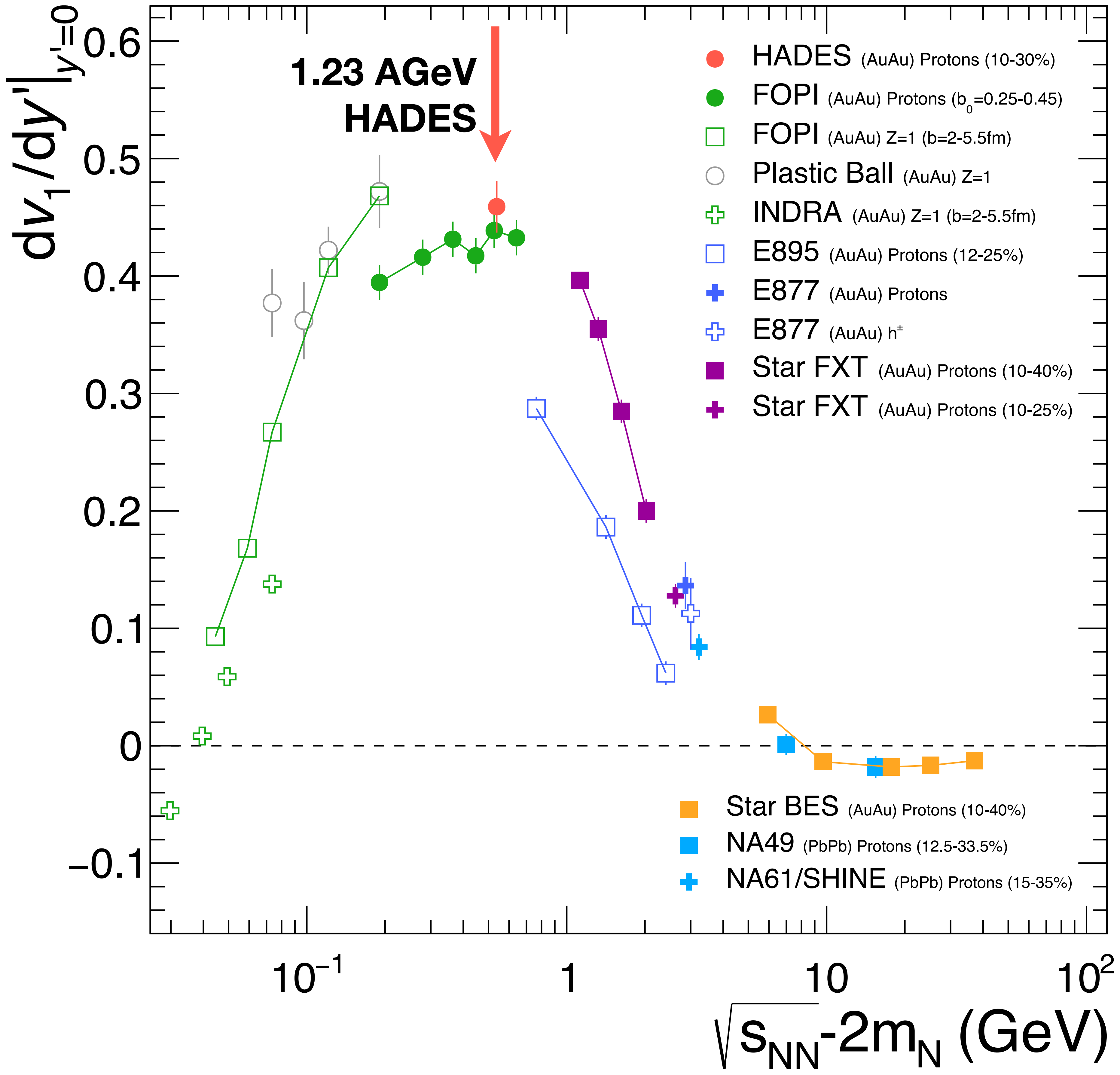


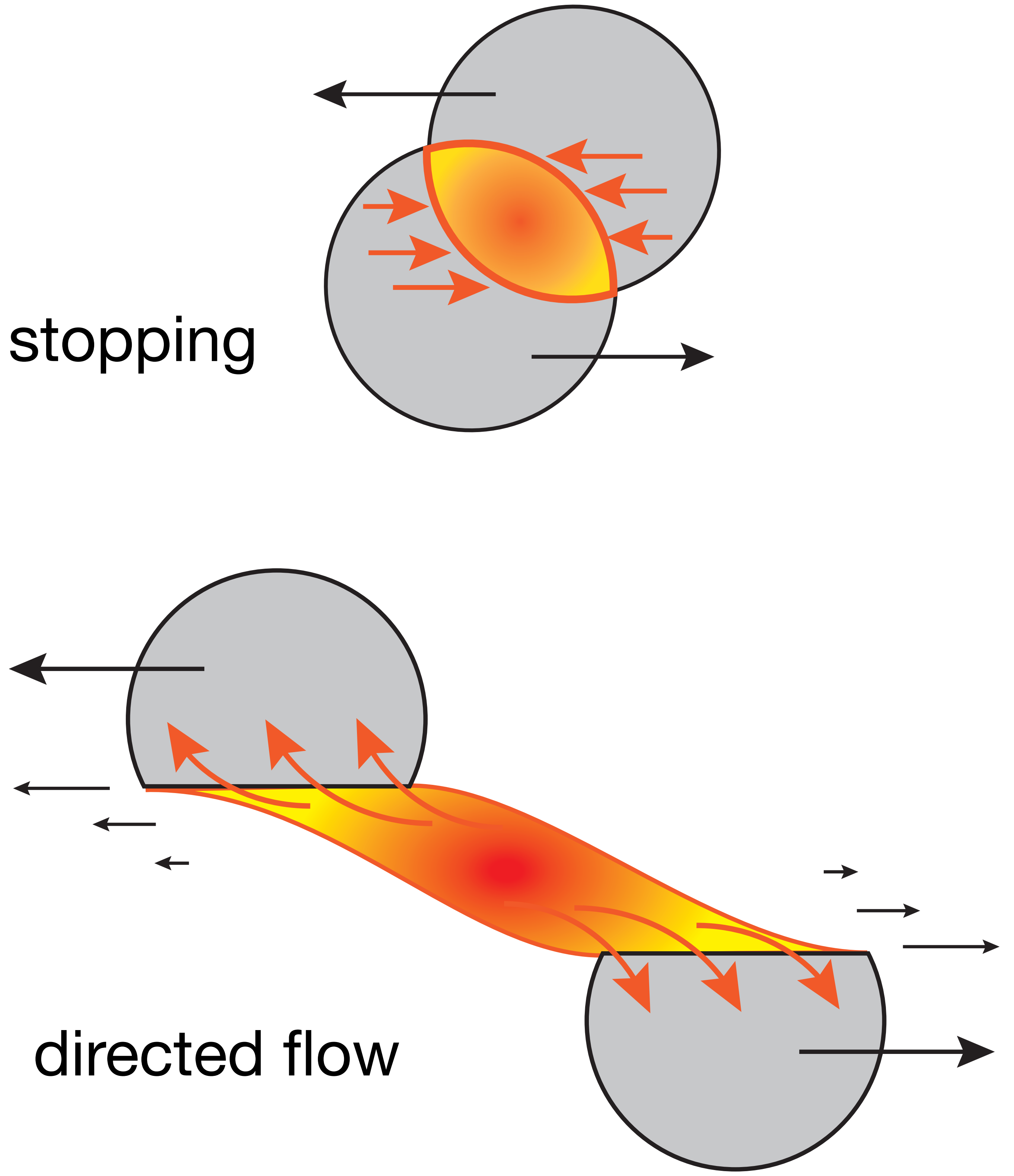
- Good agreement of the ***proton mean transverse mass*** $\langle m_t \rangle - m_0$ between experiments
- ***Stopping*** is necessary condition for the creation of dense and hot nuclear matter

Collectivity

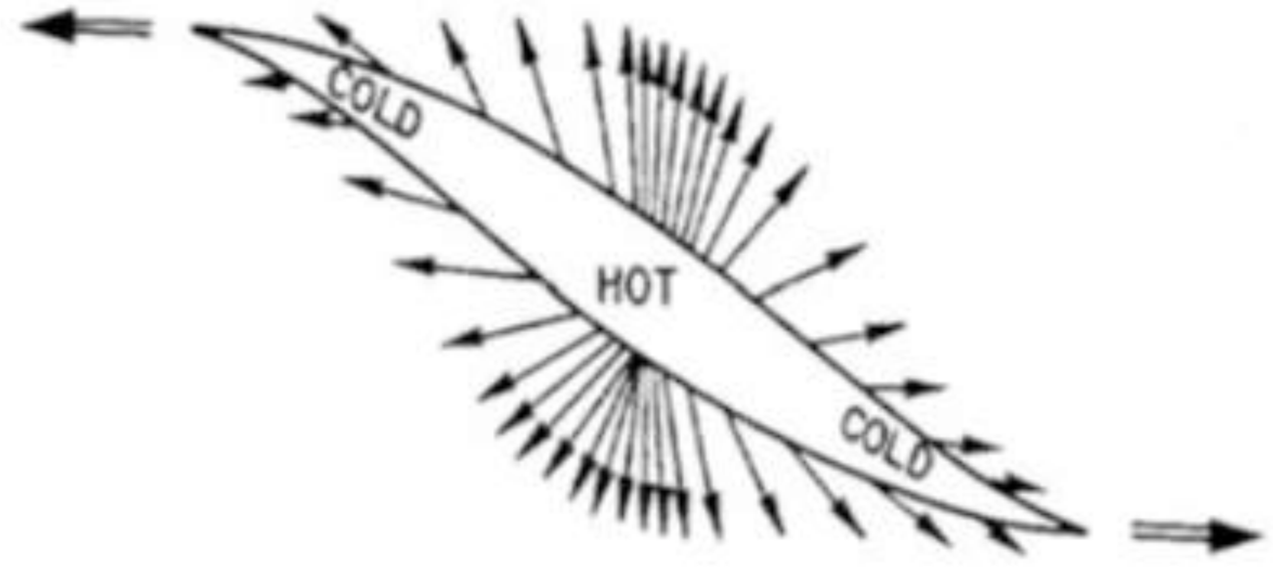
HADES, EPJ A 59 (2023) 80
STAR FXT (QM2023), Universe 10 (2024) 3, 118

Energy dependence of directed flow





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

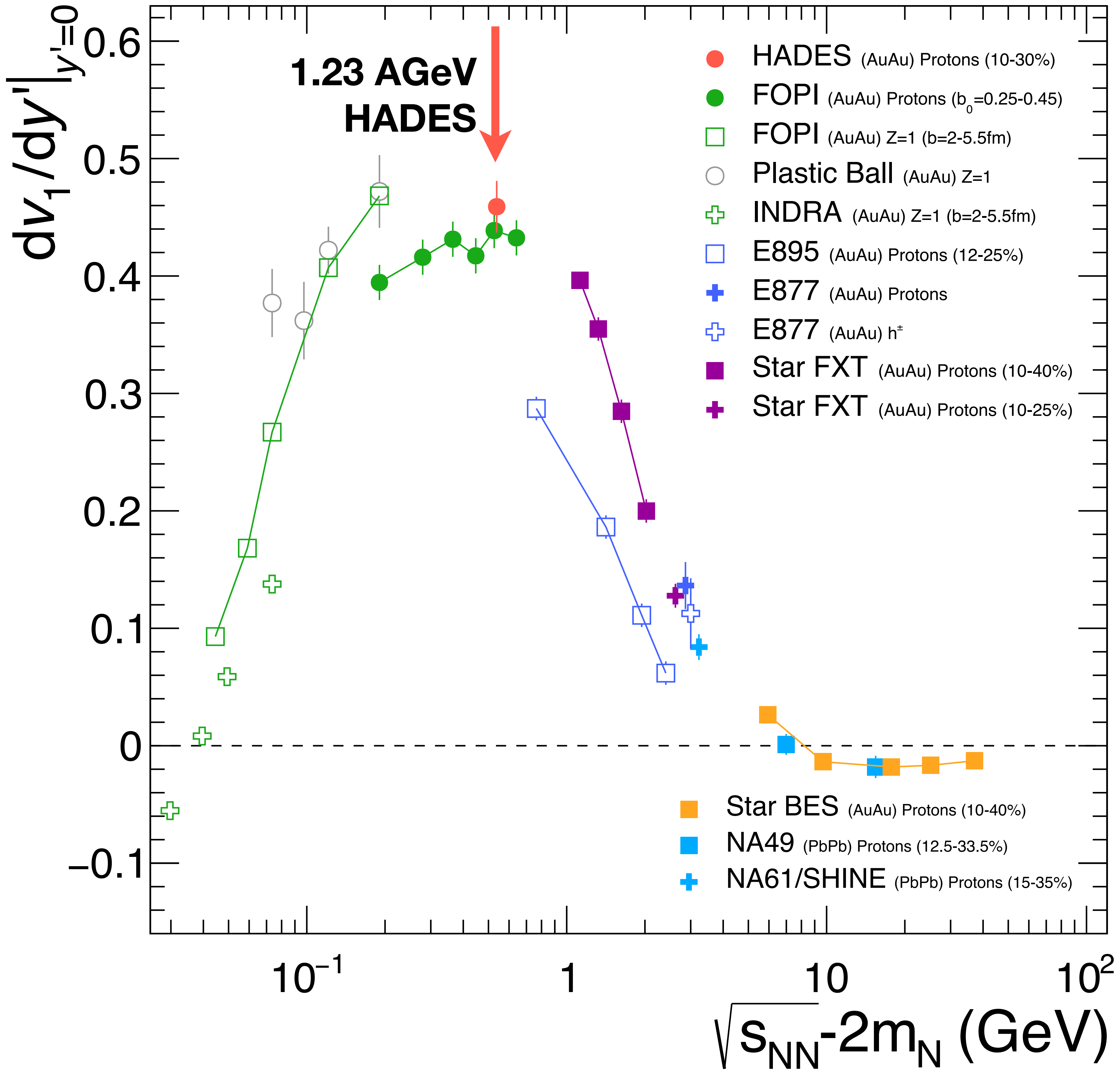


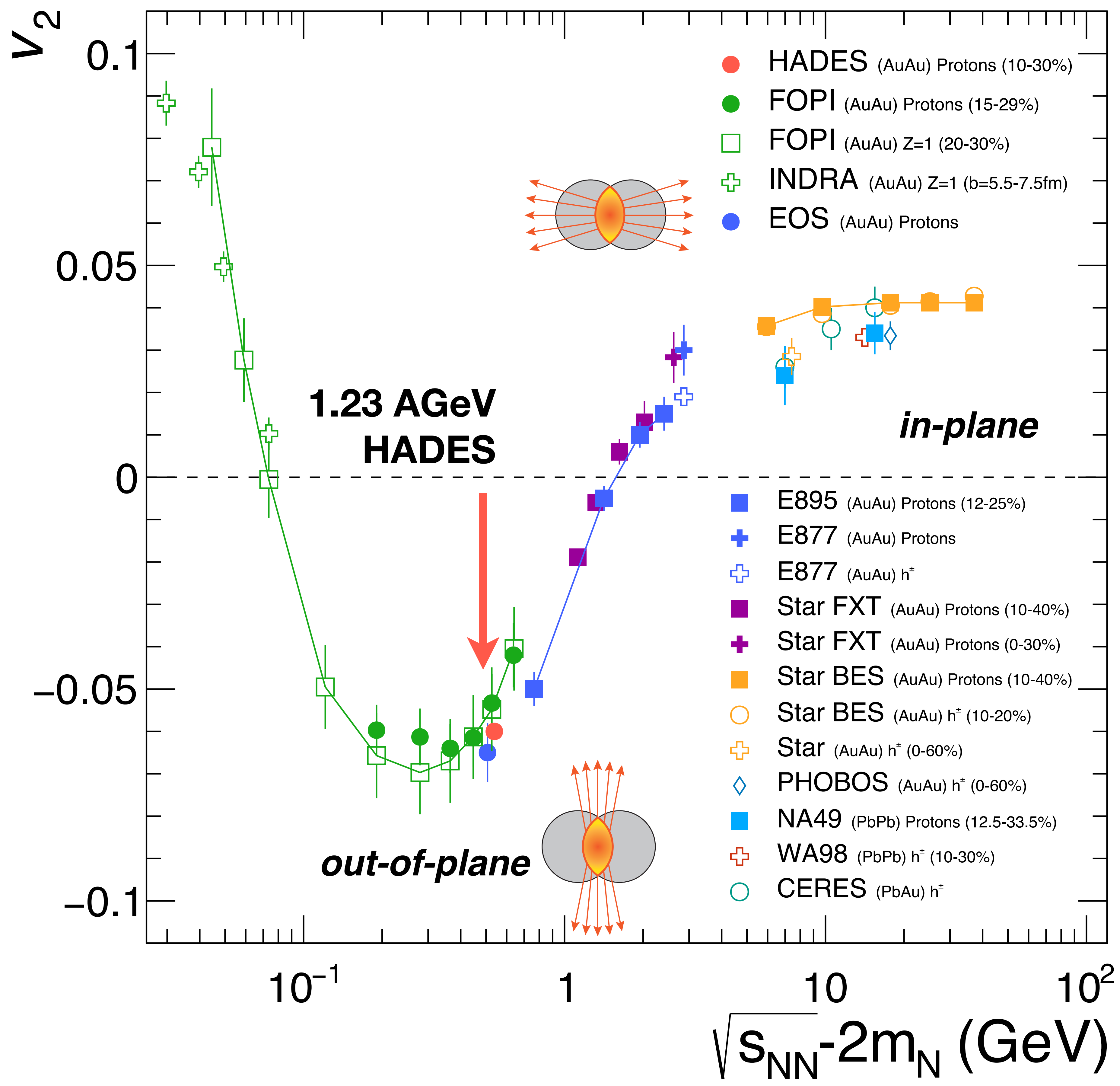
- Good agreement of integrated dv_1/dy (***directed flow***) and v_2 (***elliptic flow***) between experiments
- ***Partially stopped matter*** moves at different rapidities and results in non-uniform expanding density profile

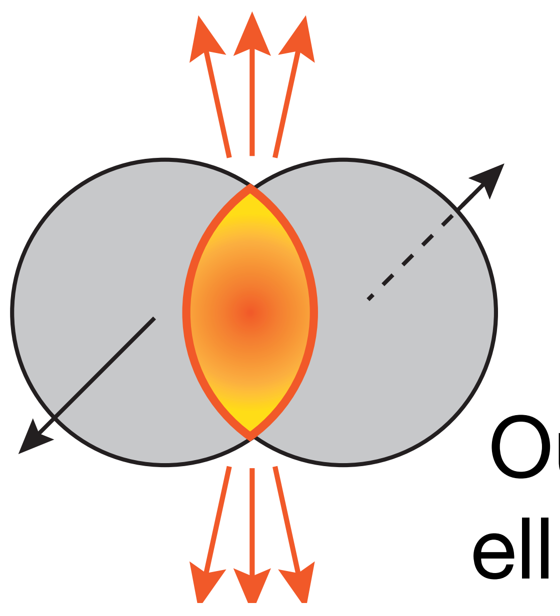
Collectivity

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

Energy dependence of directed and elliptic flow

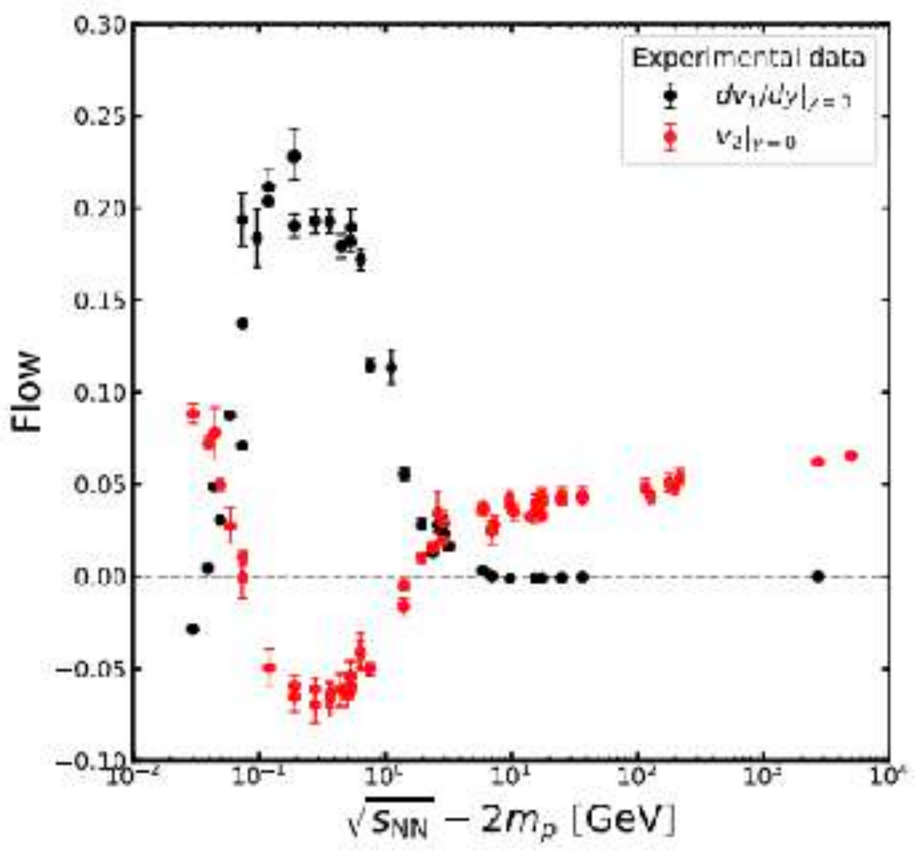






Out-of-plane elliptic flow v_2

as discussed in:
T. Reichert and J. Aichelin,
arXiv:241112908

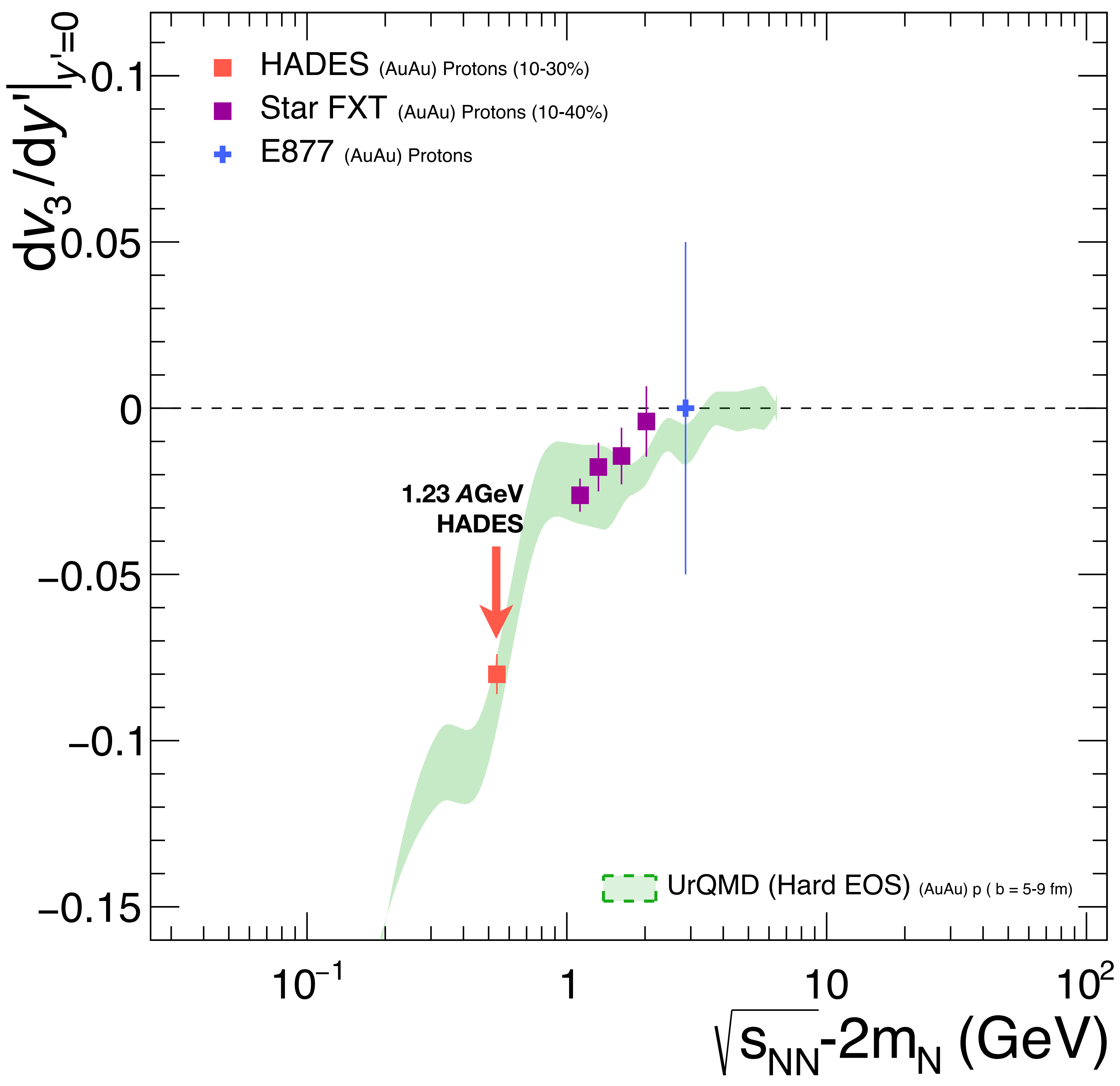


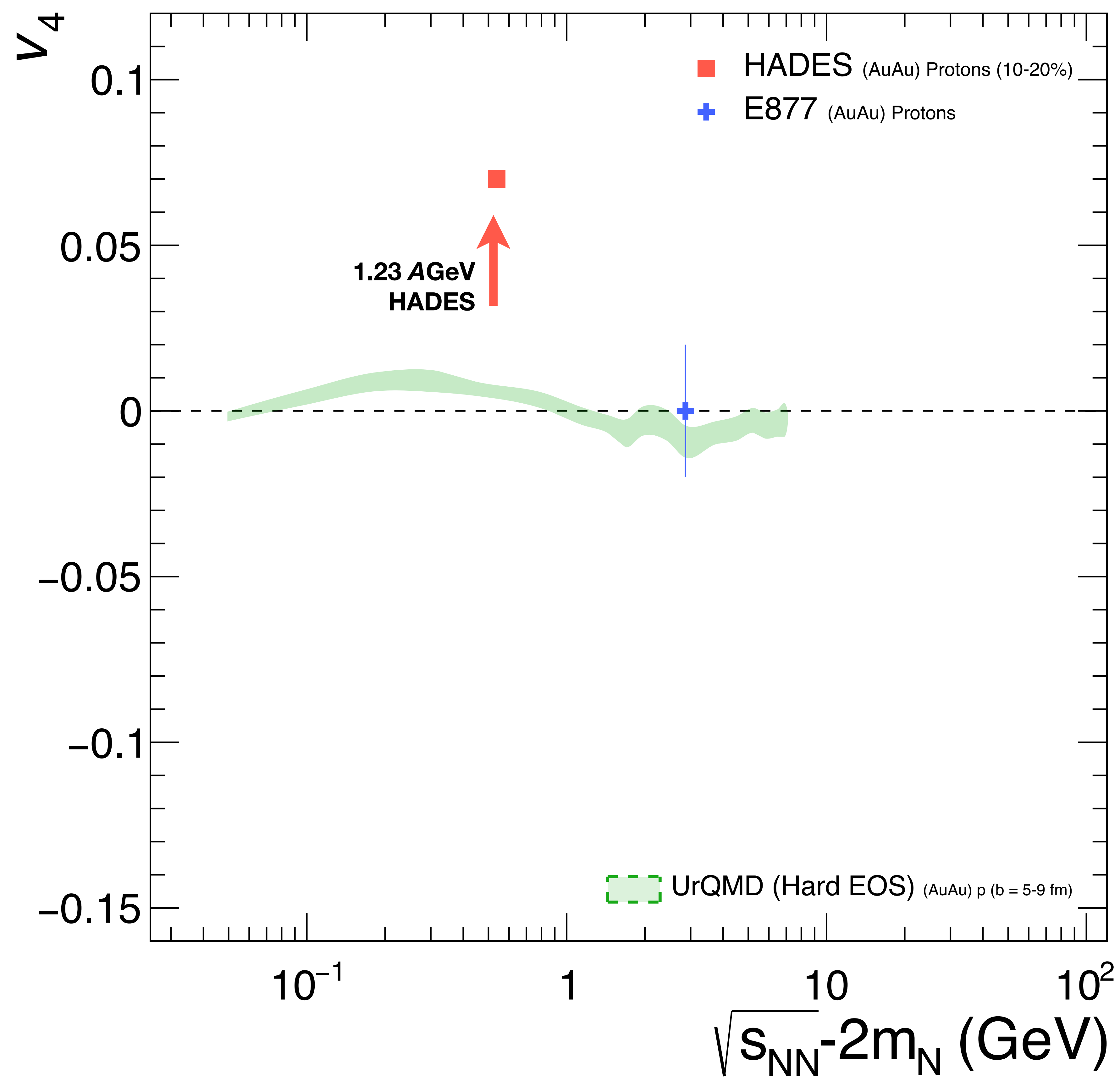
- Good agreement of integrated dv_1/dy (***directed flow***) and v_2 (***elliptic flow***) between experiments
- ***Long spectator passing time*** $\tau_{passing} \approx \tau_{expansion}$ $\Longrightarrow$ "squeeze-out" and/or "shadowing"

Collectivity

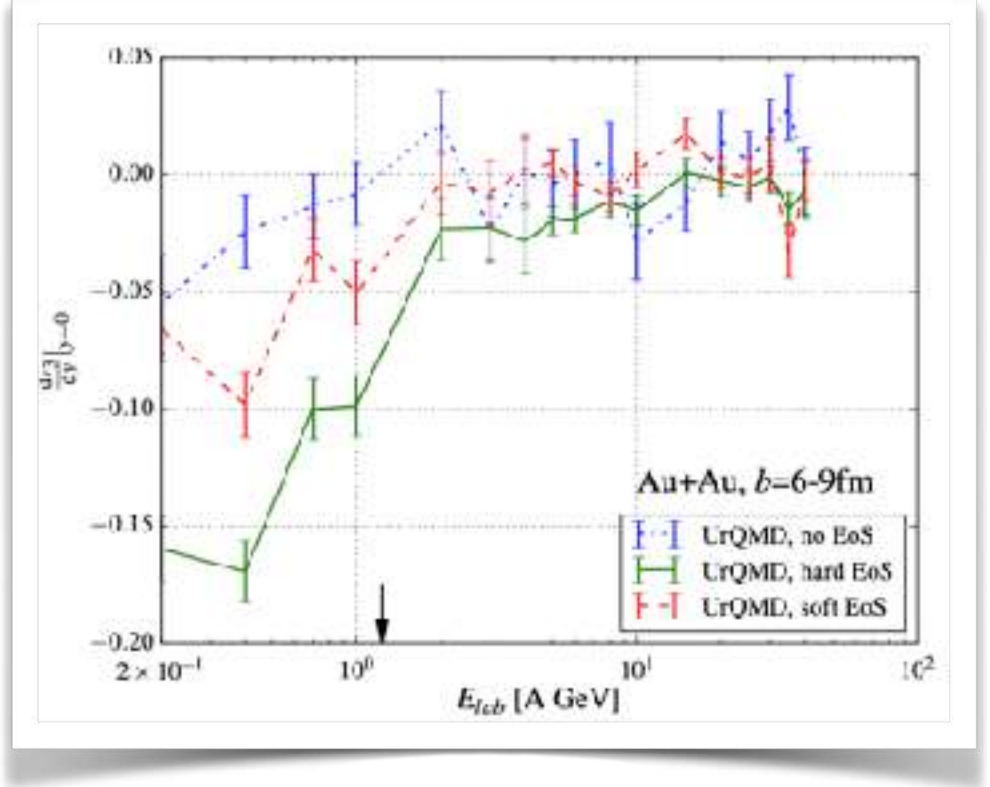
HADES, EPJ A 59 (2023) 80
E877 (AGS), PRL 73 (1994) 2532, PRC 56 (1997) 3254
STAR FXT (QM2023), Universe 10 (2024) 3, 118

Energy dependence of higher order - triangular and quadrangular flow

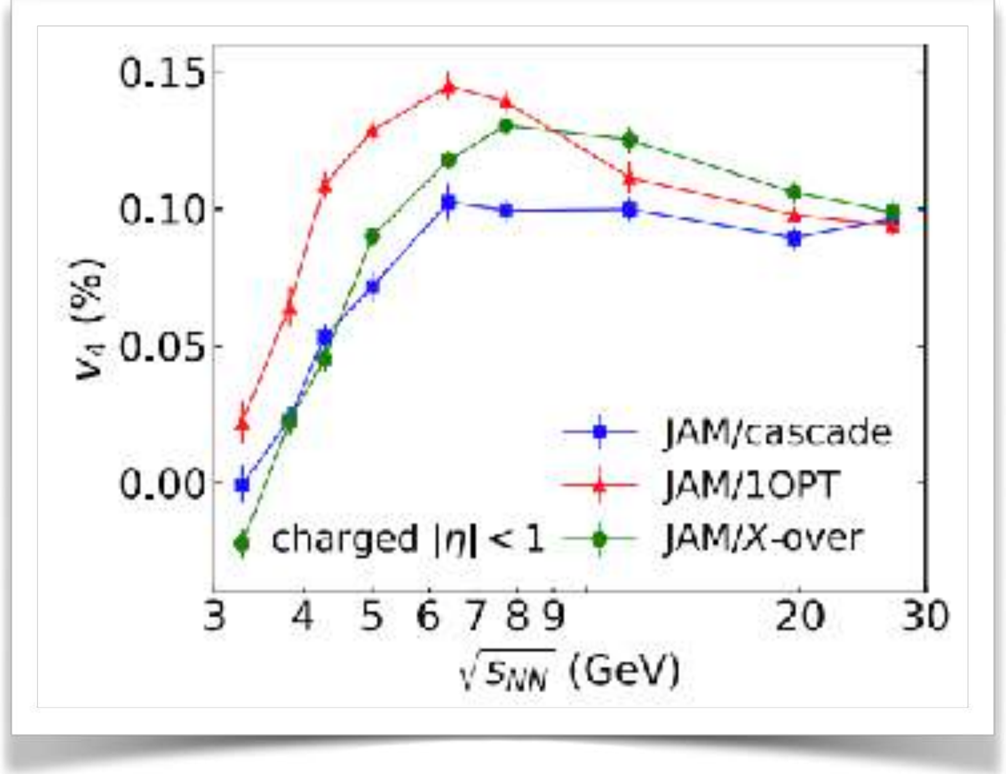




UrQMD, P. Hillmann et al.
JP **G45** (2018) 085101



JAM, Y. Nara et al.
EPJ A **54** (2018) 11

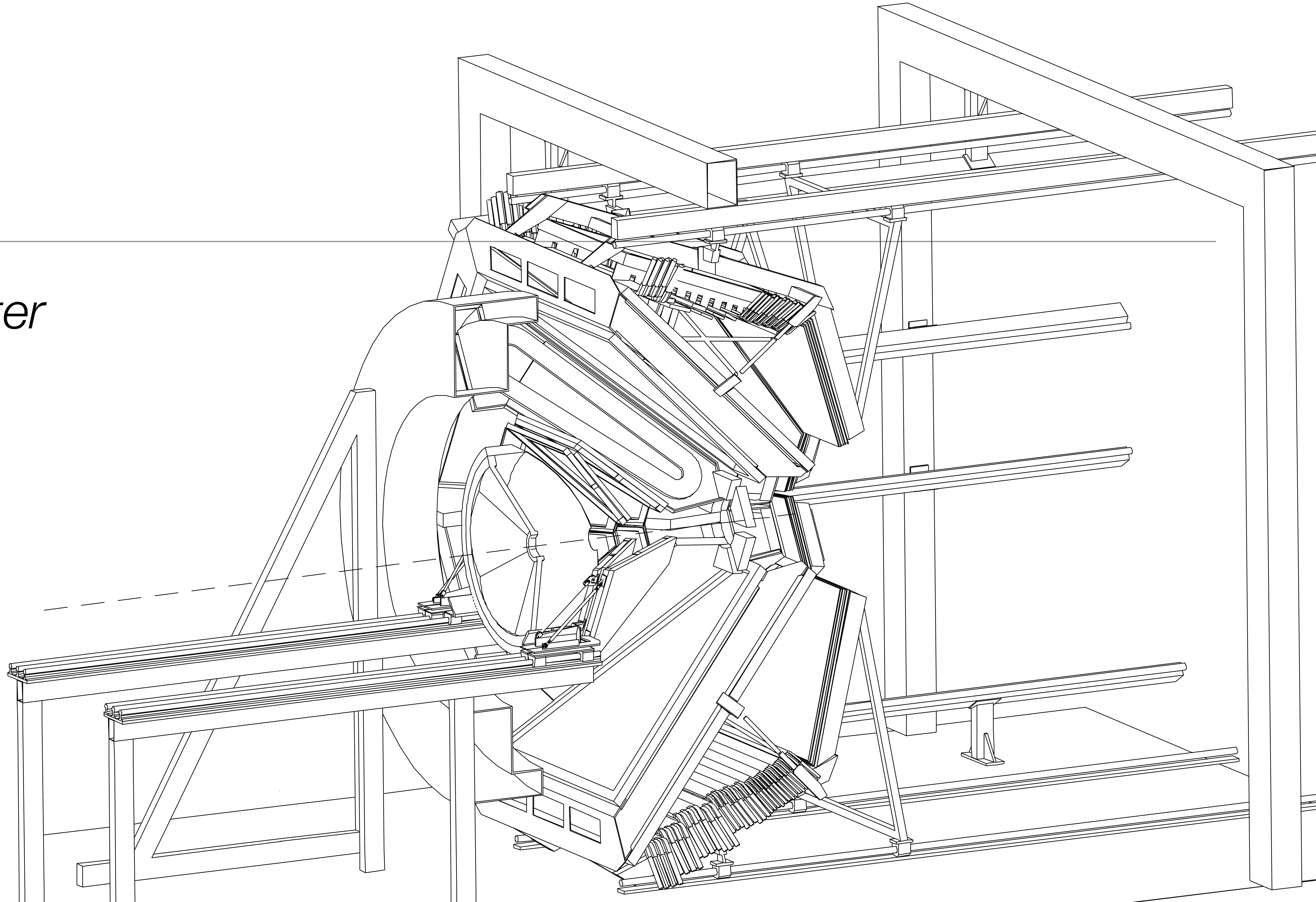


- ***Triangular*** dv_3/dy and ***quadrangular flow*** v_4
  Very scarce data at low energies

- Additional source of information
  Should help to narrow down EoS

The HADES experiment

High-Acceptance Dielectron Spectrometer



The HADES experiment

(*) center-of-mass energy in the nucleon-nucleon frame $\sqrt{s_{NN}}$

Physics Program

- Heavy ion collisions
  - Equation-of-State
  - Microscopic properties of baryon dominated matter
- Proton and pion beam
  - Reference measurement (vacuum, cold nuclear matter)
  - In-medium modifications
  - *em* structure of baryons/hyperons in time-like region

Heavy ion collisions:

Ar+KCl (2005) 2.61 GeV
Au+Au (2012) 2.42 GeV
Ag+Ag (2019) 2.55 / 2.42 GeV
Au+Au (2024/25) 2.23 - 1.96 GeV

Light ion collisions:

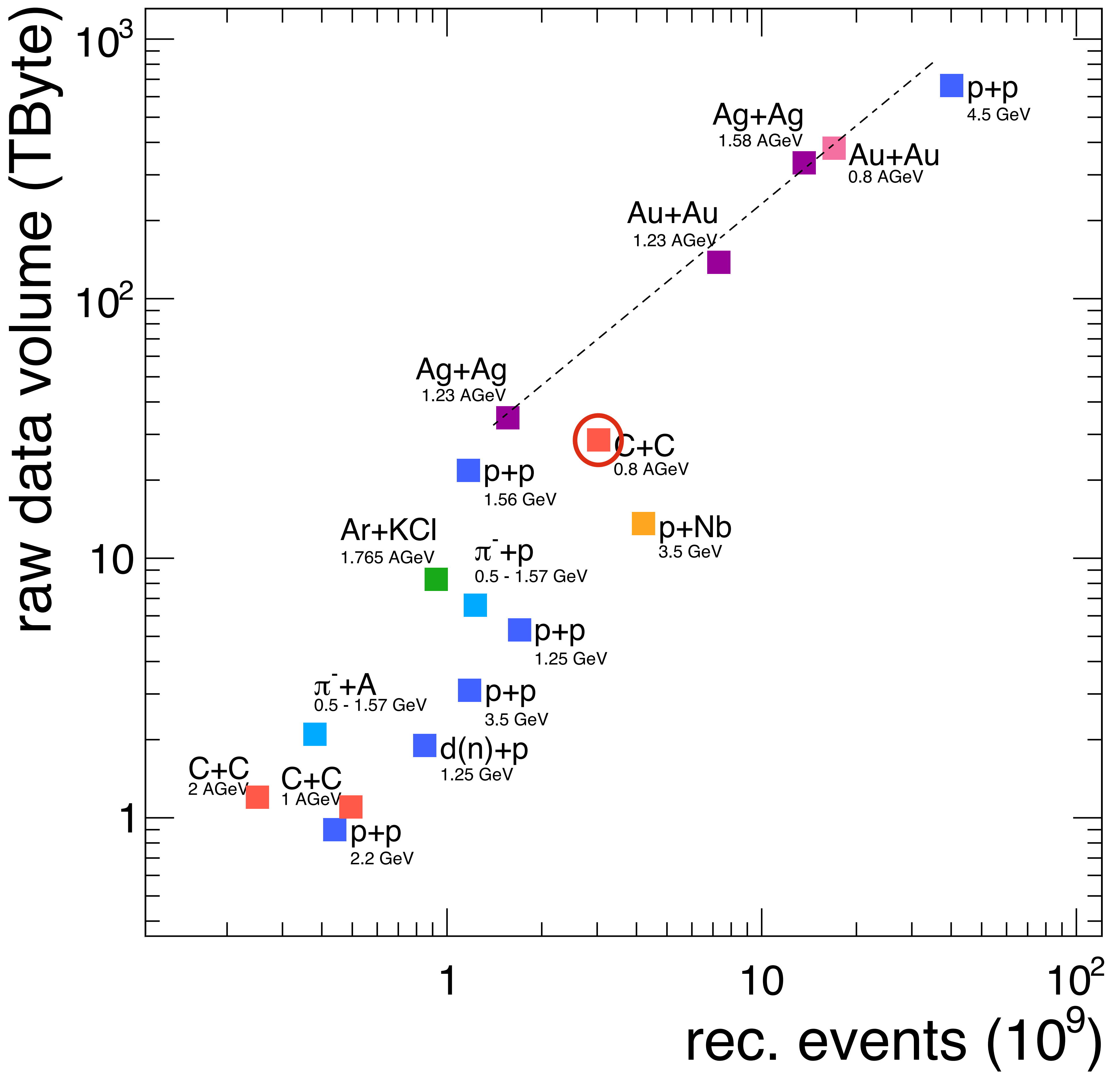
C+C (2002) 2.7 GeV
C+C (2004) 2.32 GeV
C+C (2024) 2.23 GeV

Proton/deuteron beams:

p+p (2004) 2.7 GeV
d(n)+p (2006) 2.42 GeV
p+p (2007) 3.18 GeV
p+p (2022) 3.46 / 2.55 GeV
p+Nb (2008) 3.1 GeV

Pion beams:

π^- + W / C / PE (2014) 1.5 GeV



The HADES experiment

Fixed-target experiment at SIS18(GSI, Germany)

Large acceptance in 6 identical sectors

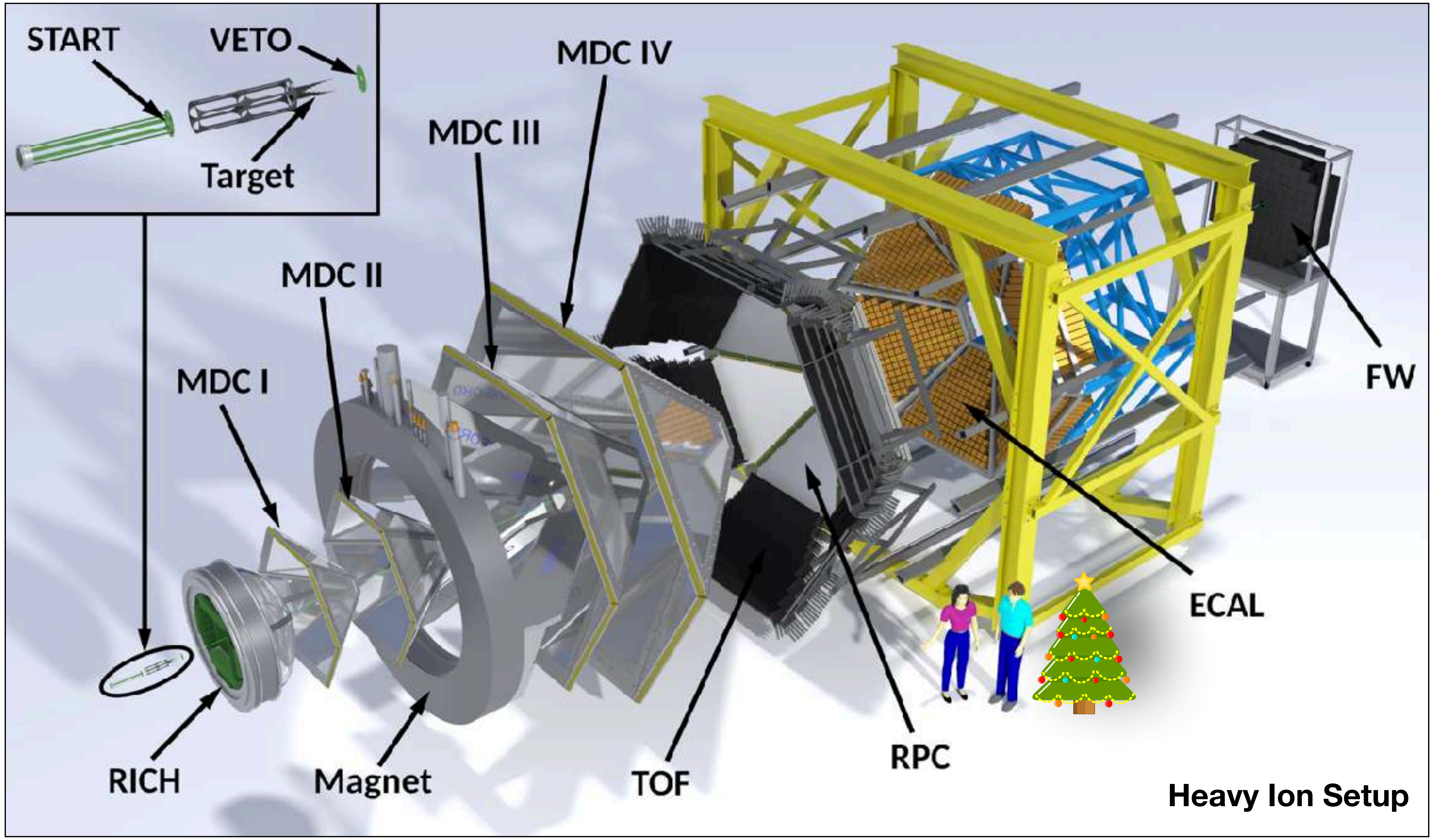
- Symmetric azimuthal coverage
- Superconducting toroidal magnets
- Low-mass Drift Chambers (MDC)

Particle identification

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

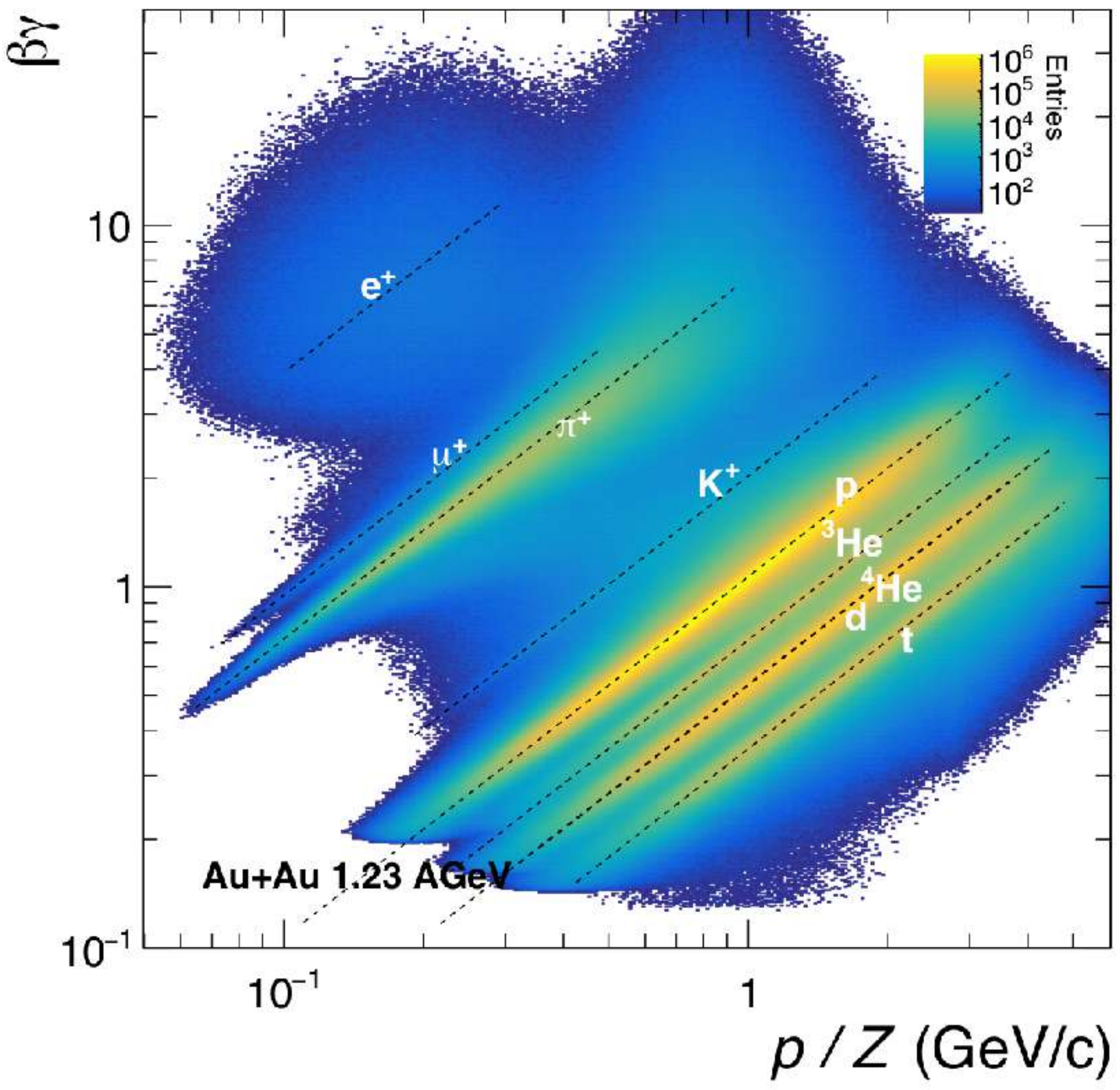
Forward Wall

- Reaction plane reconstruction

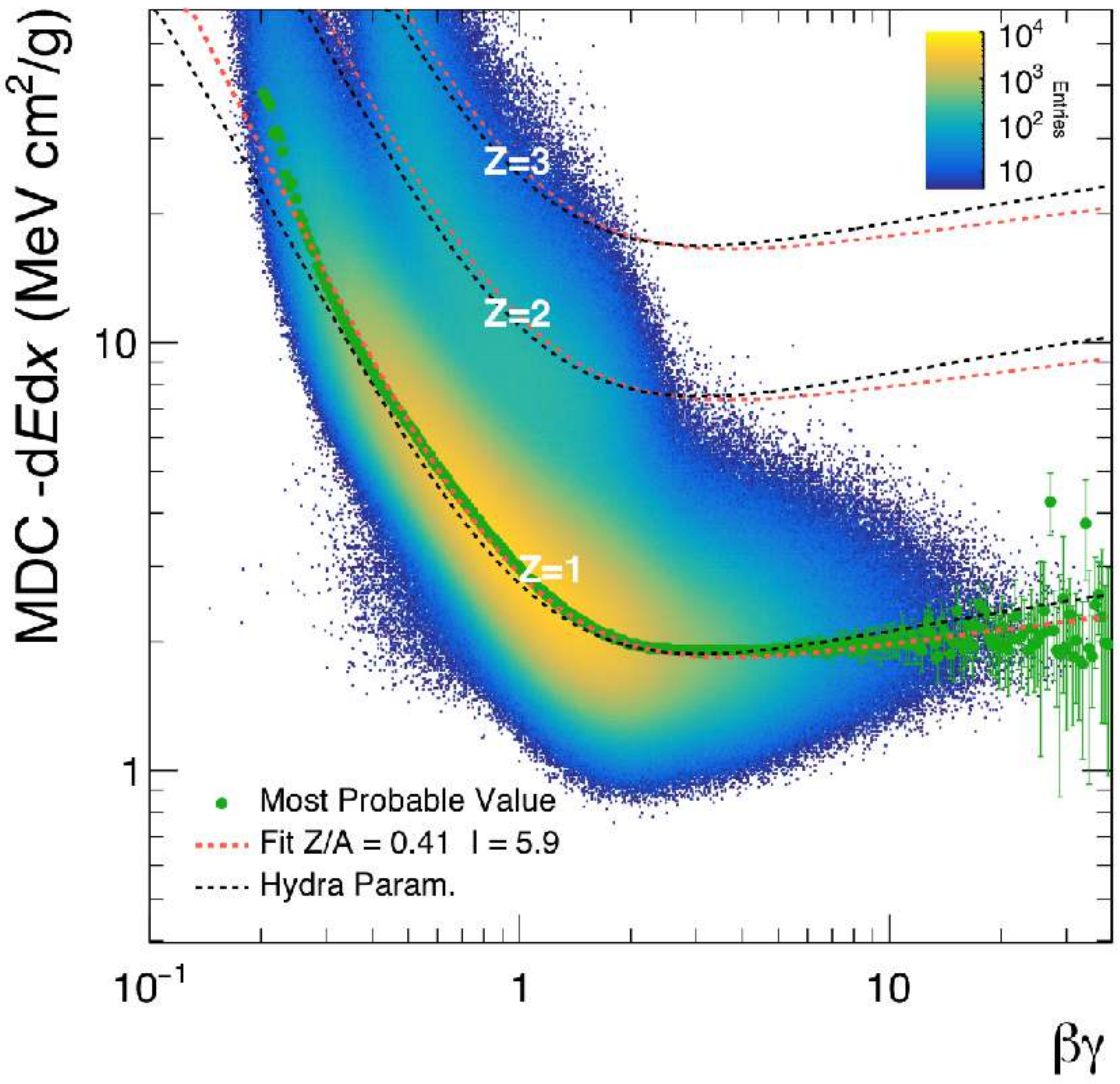


Particle Identification

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



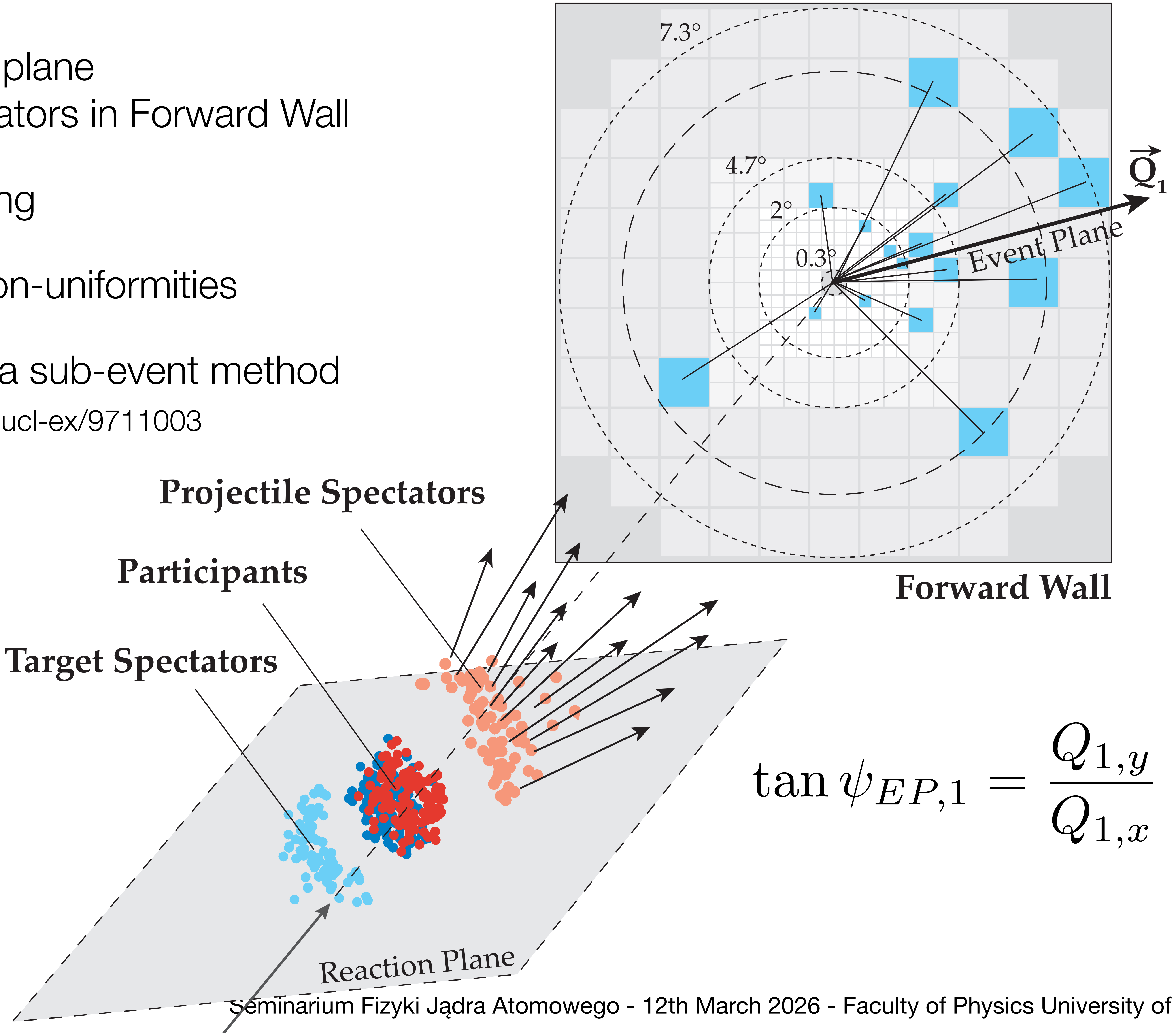
Energy loss in the MDC $-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \propto f(Z,\beta)$

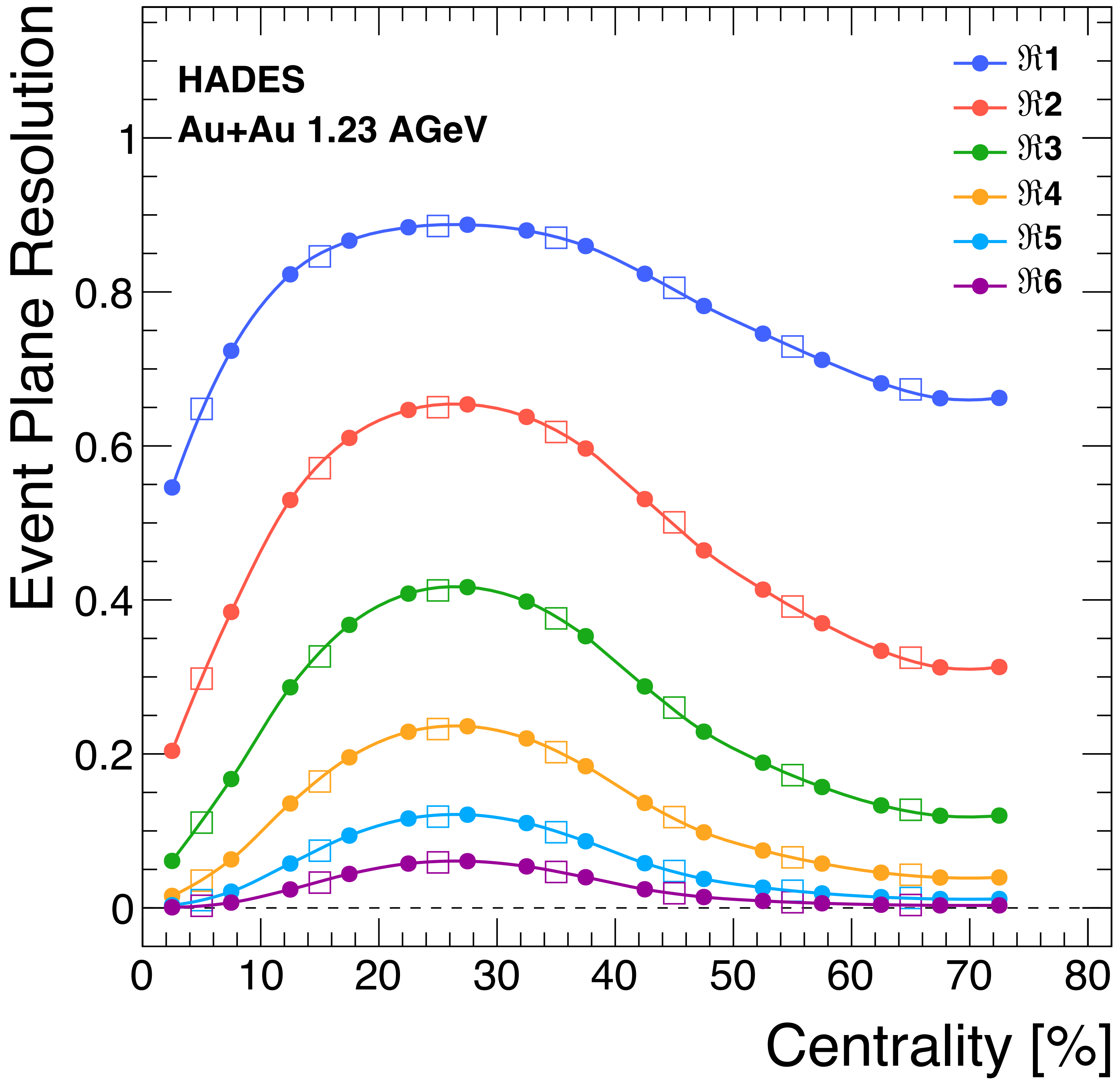


Flow Measurements

Event plane reconstruction

- 1st-Order event plane
  Projectile spectators in Forward Wall
- Charge-weighting
- Correction of non-uniformities
- EP-resolution via sub-event method
  J.-Y. Ollitrault, arXiv:nucl-ex/9711003





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

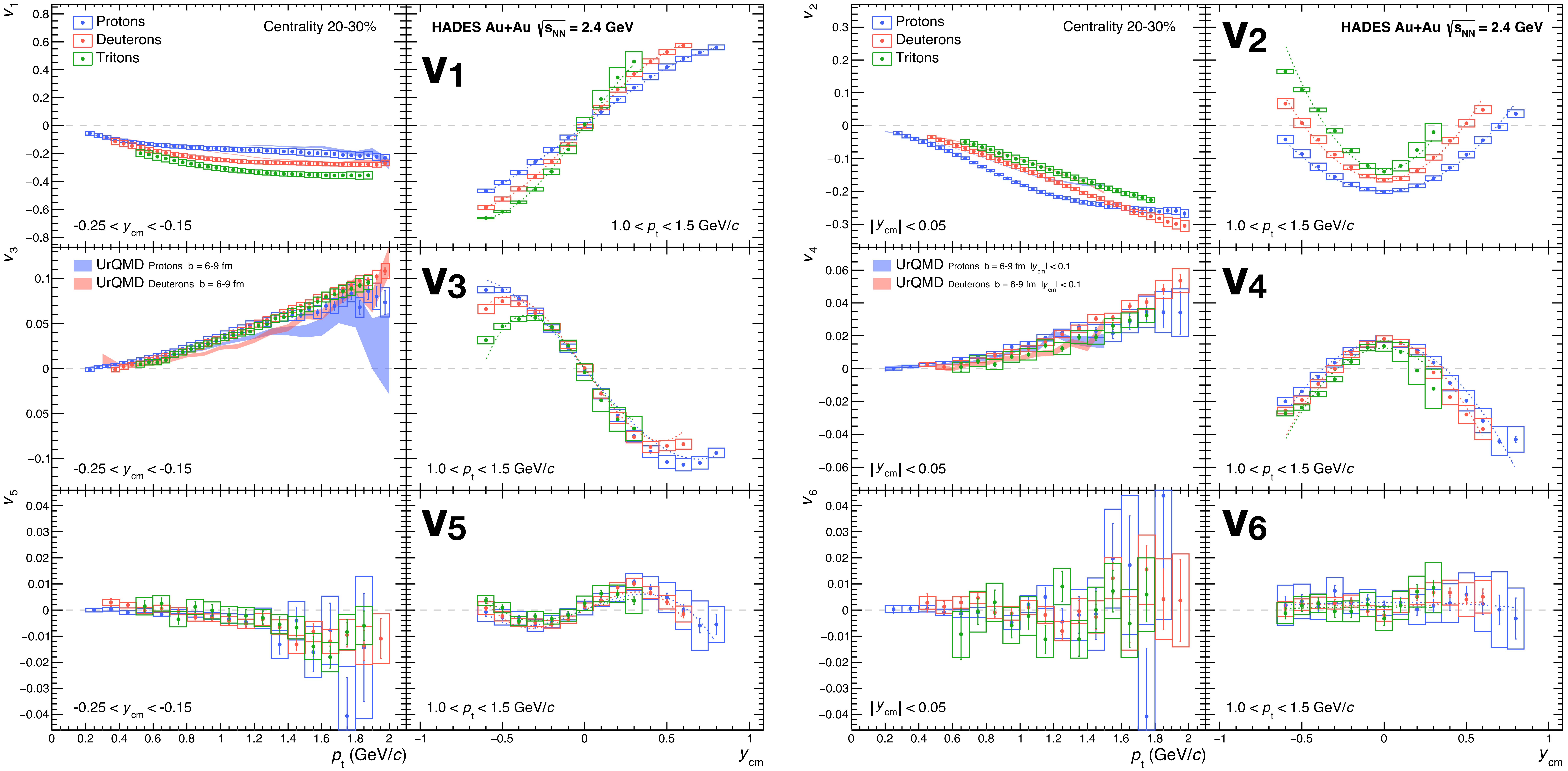
$$v_n = v_n^{obs} \,/\, \boldsymbol{\mathfrak{R}_n}$$

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

Collective Effects

Results on v1 — v6 for Protons, Deuterons and Tritons

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



Emission Pattern

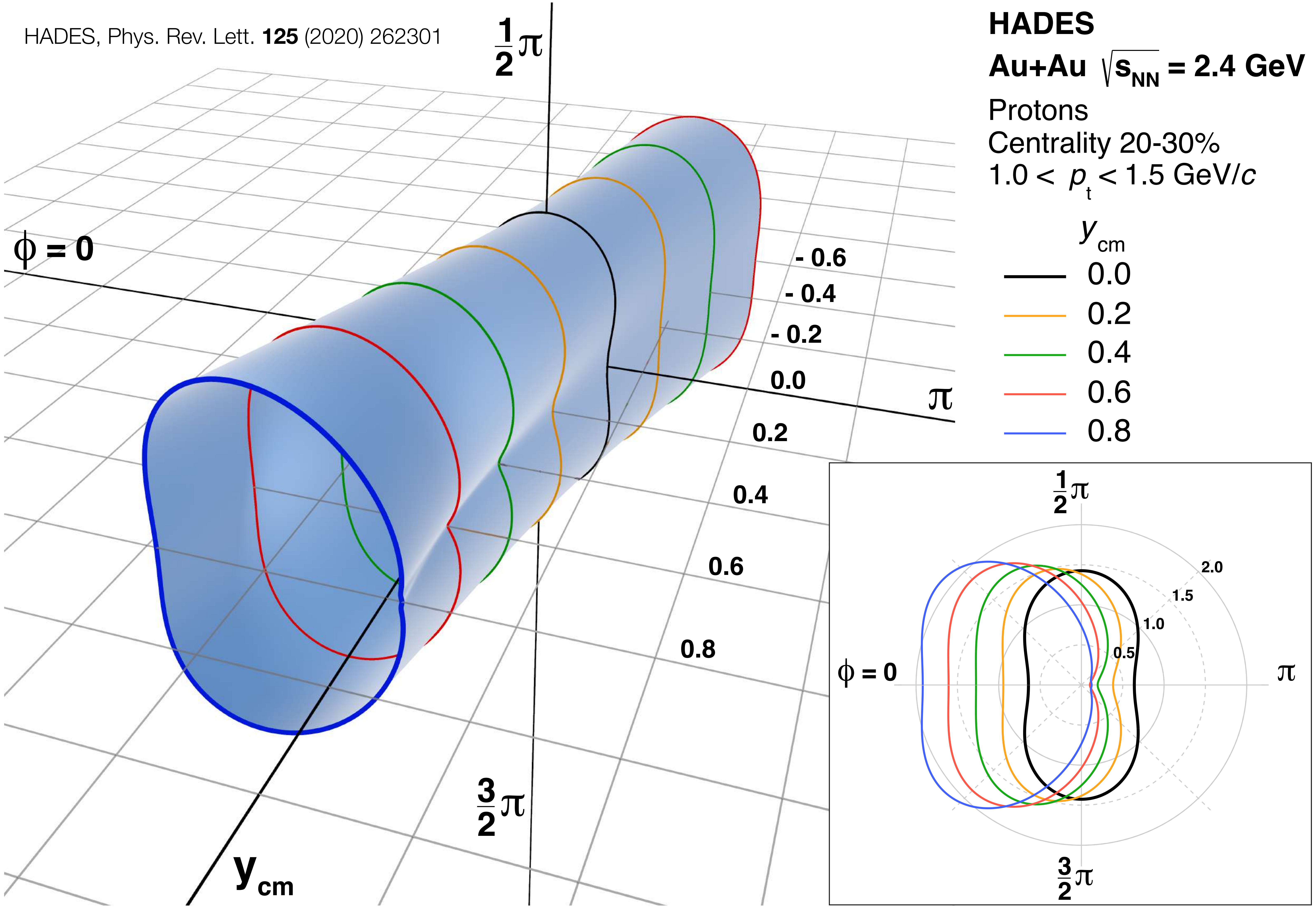
Protons

- 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

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

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

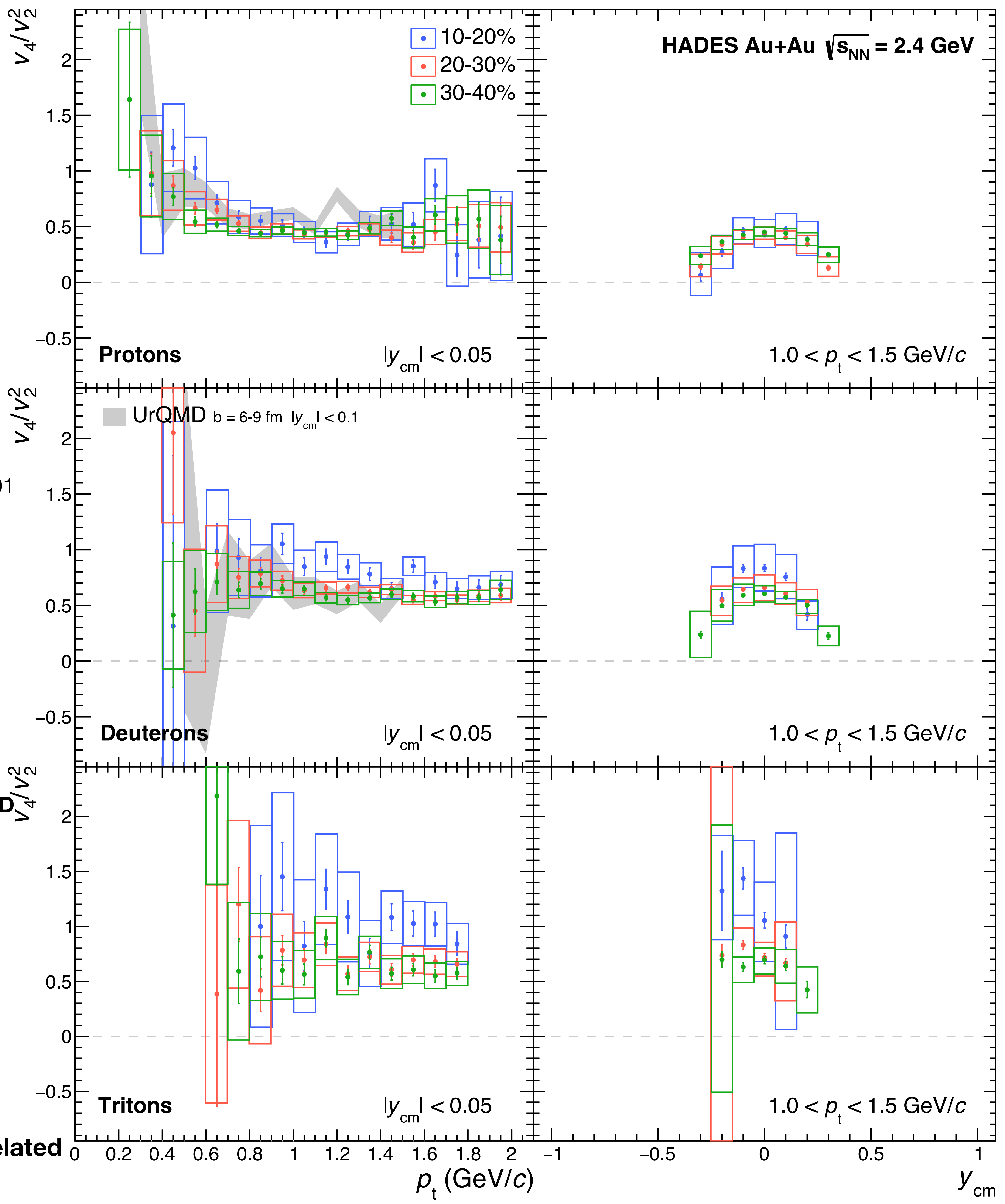
Independent of p_t and centrality
Close to predicted value of ~ 0.6

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

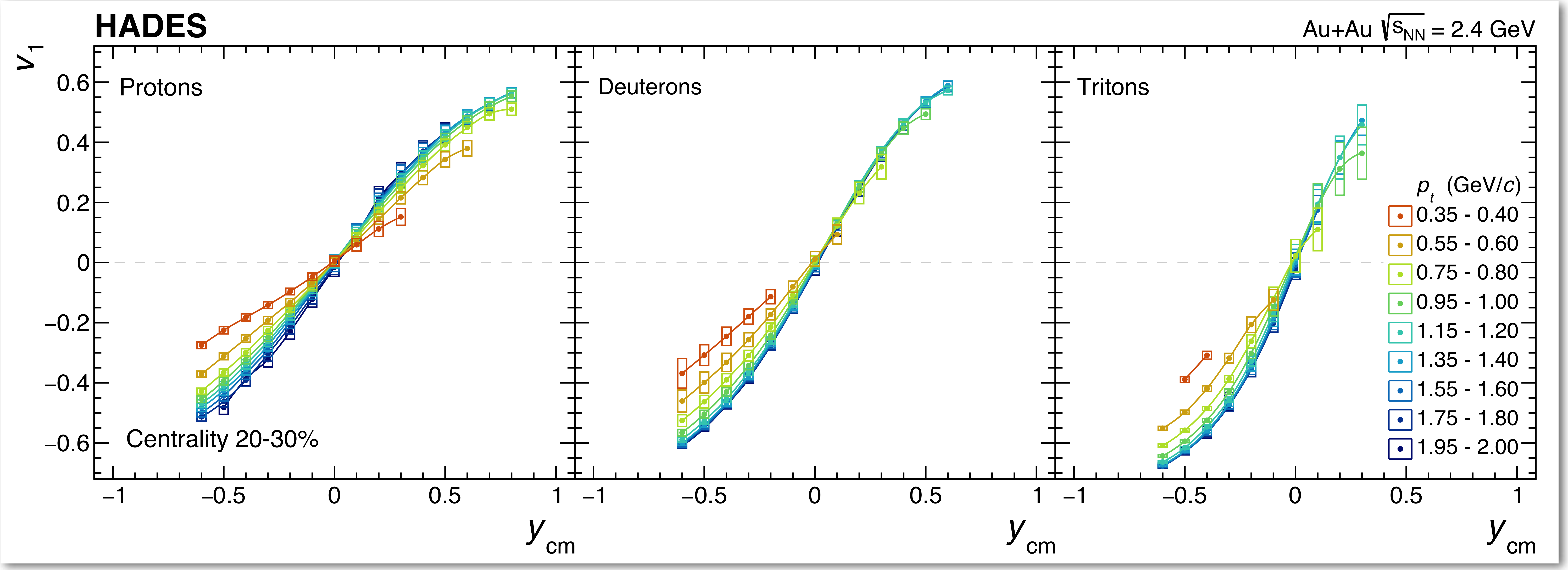


Systematic Error of v2 and v4 are treated as correlated

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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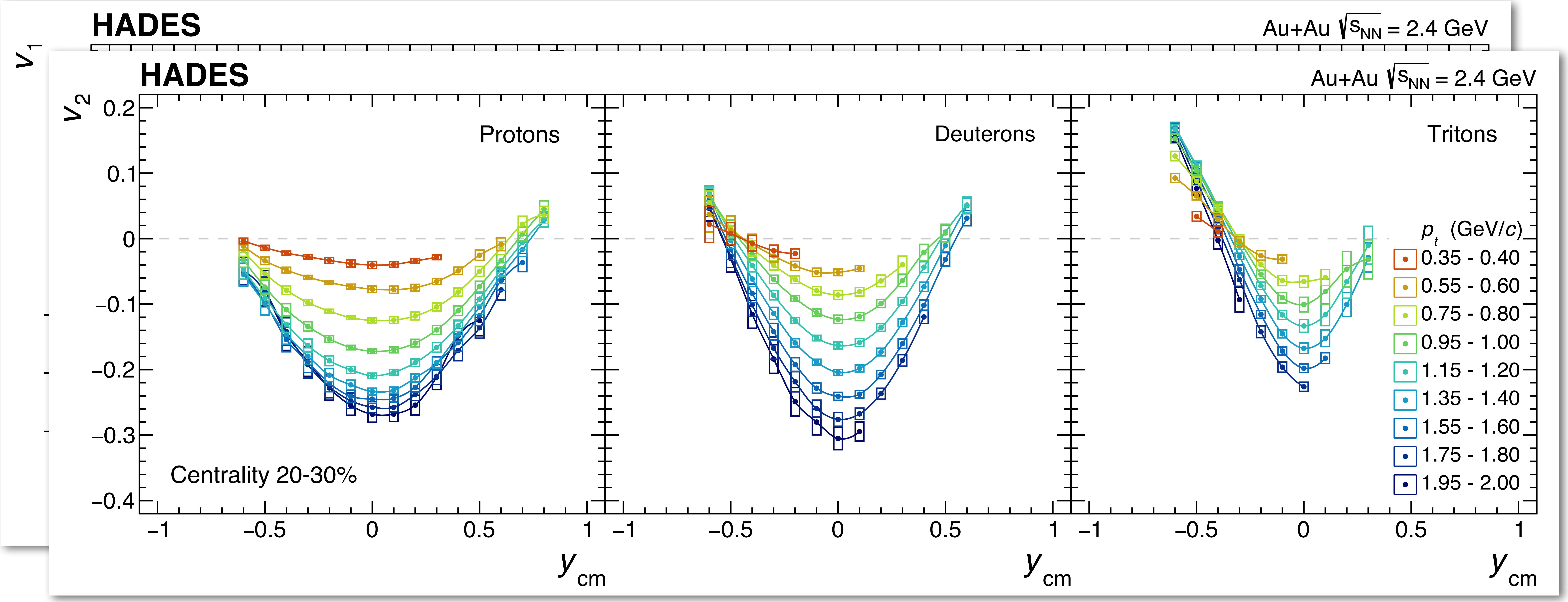

Collective Effects

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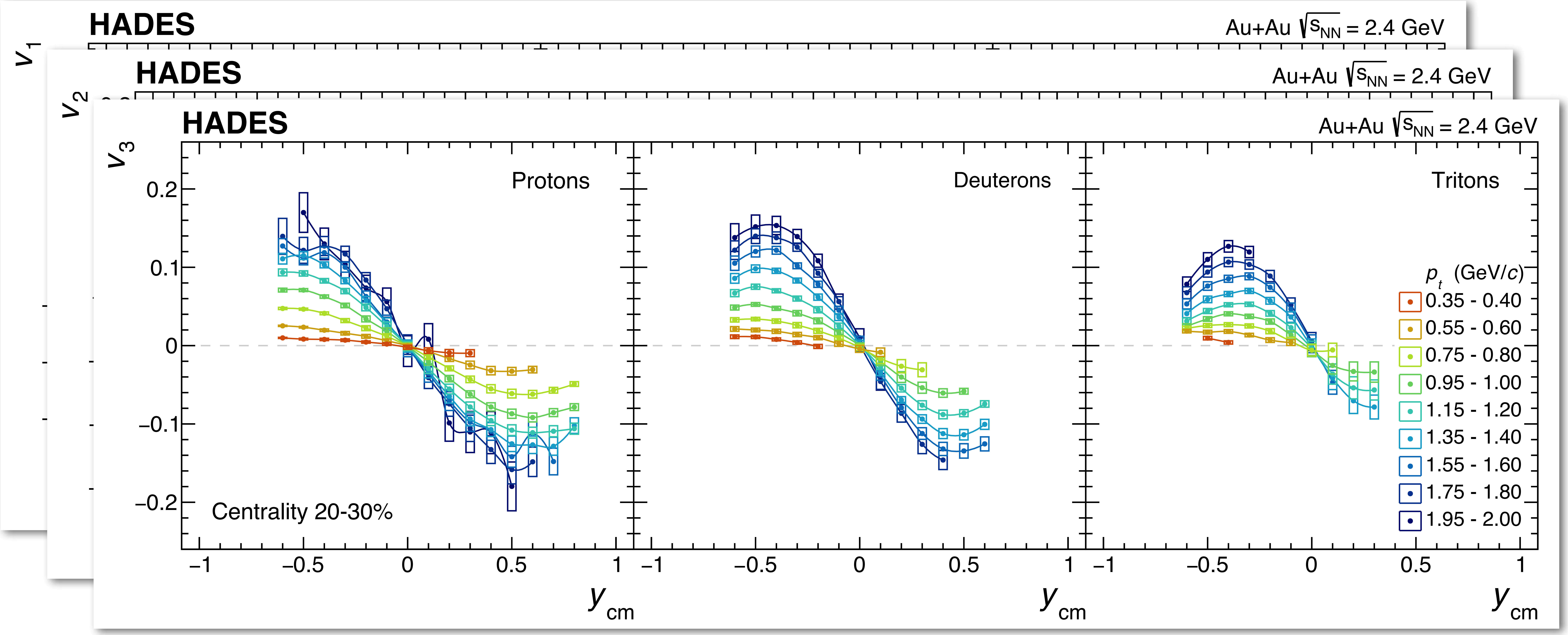

Collective Effects

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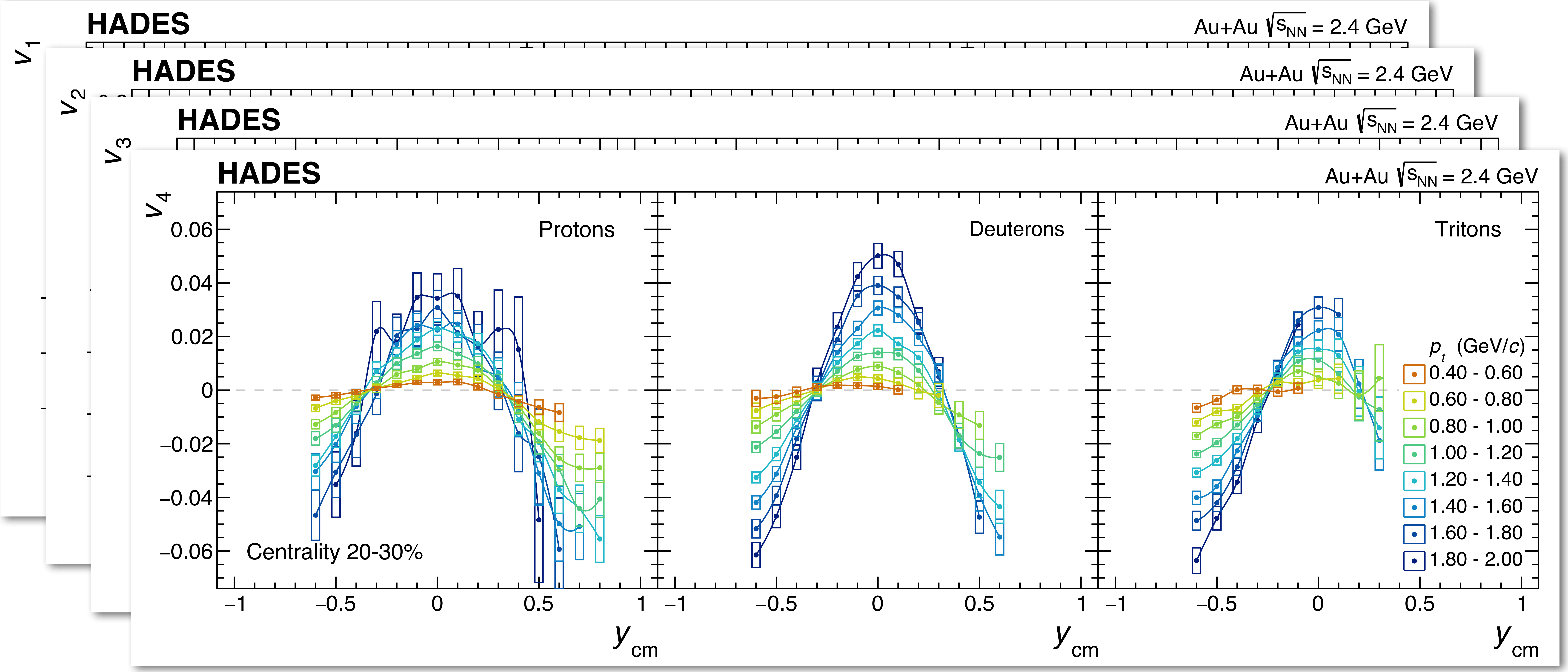

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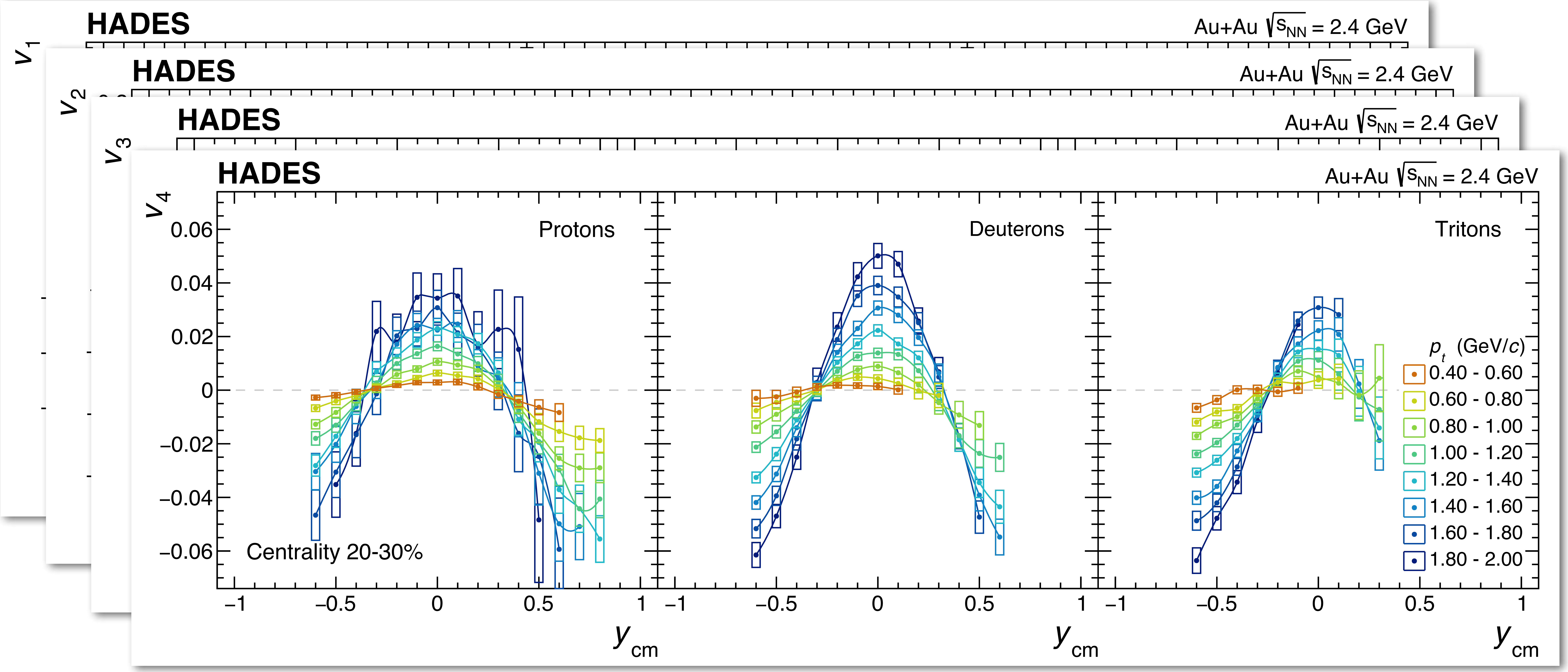
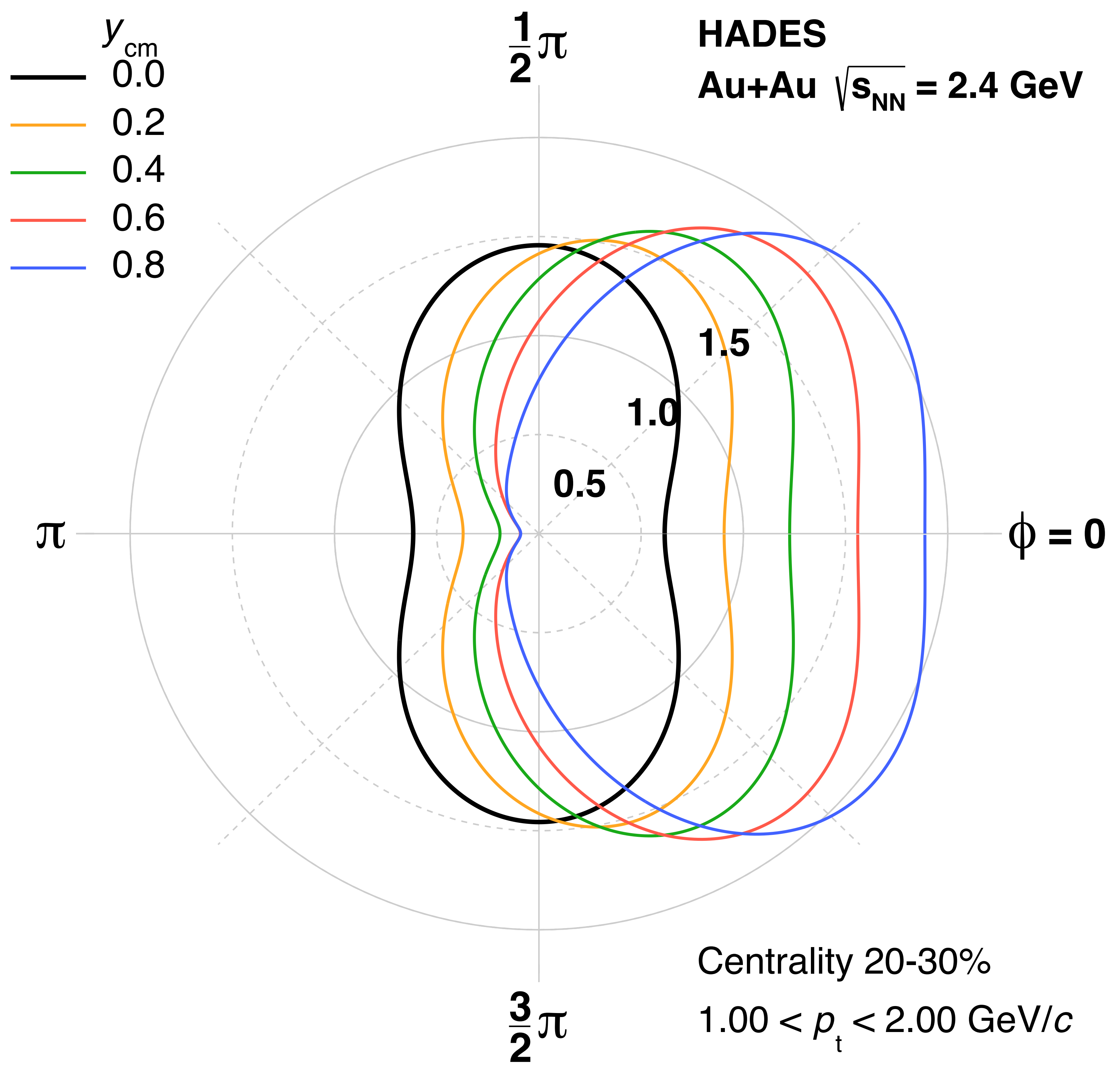


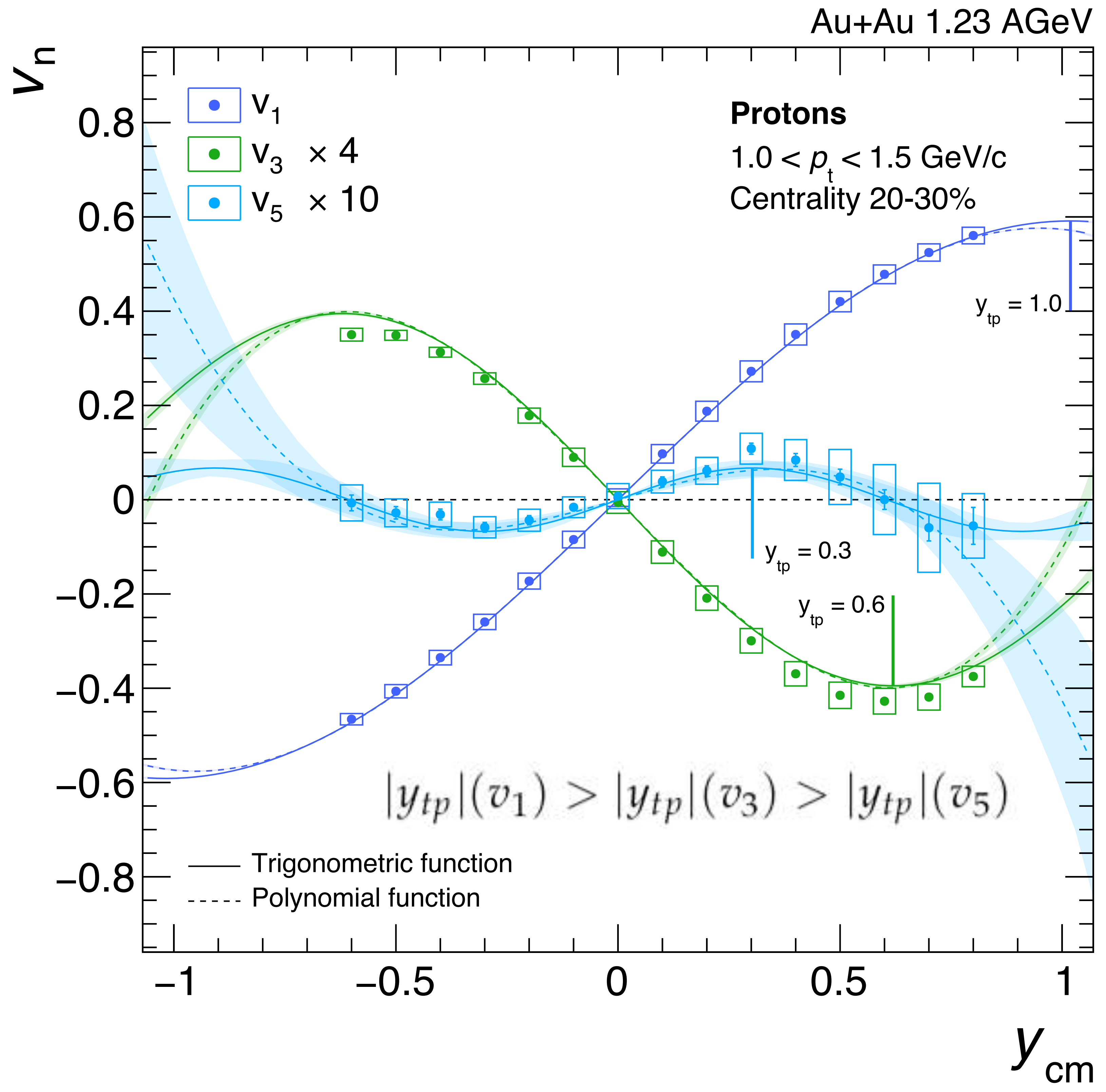
Only a fraction of the data is shown

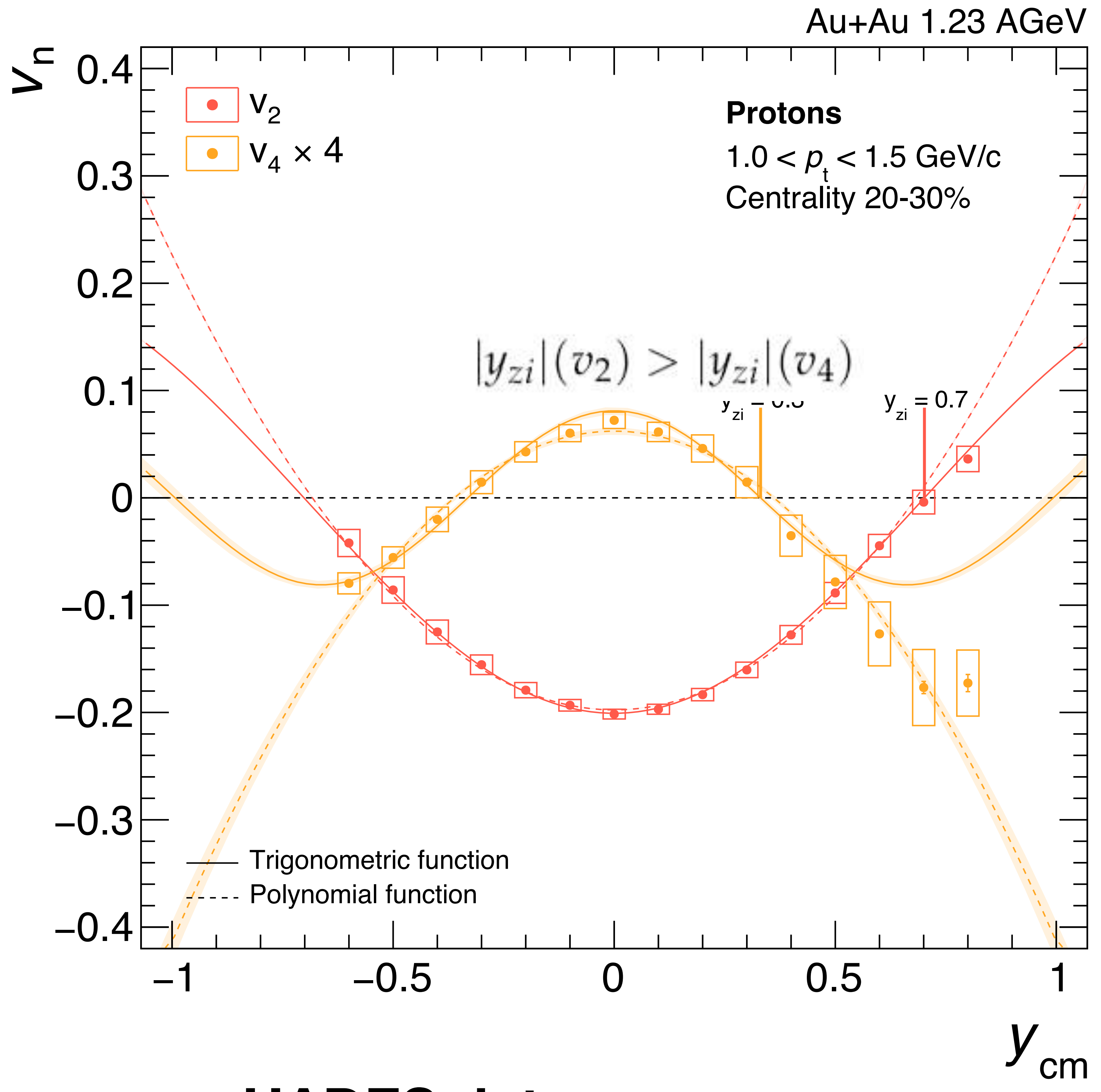
In total 17k data points with individual systematic uncertainties available: [hepdata]

Parameterisation

Rapidity-Dependence







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

Polynomial function:

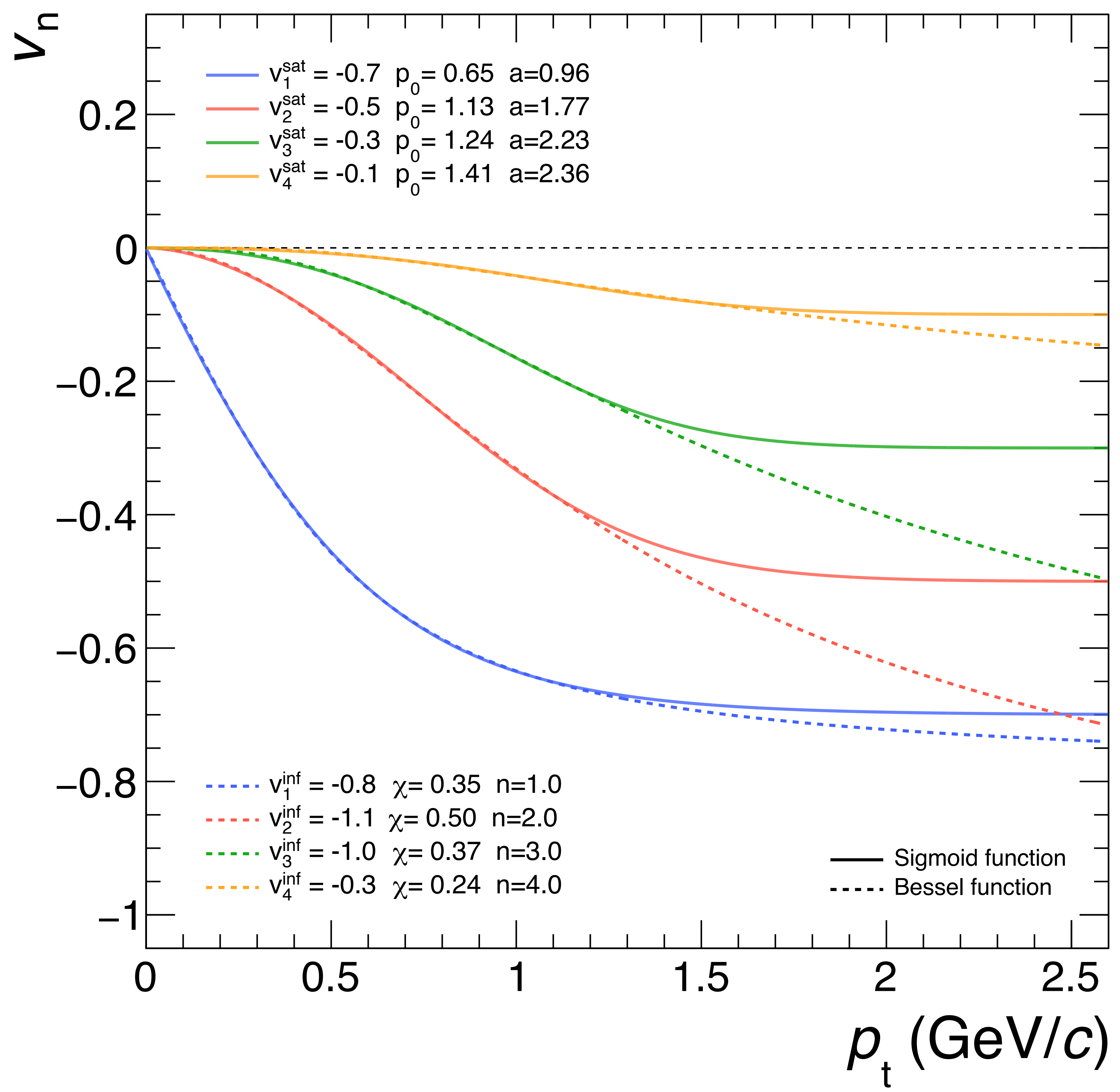
$$v_{n,\,odd}(y_{cm}) = v_{n1}\, y_{cm} + v_{n3}\, y_{cm}^3$$
$$v_{n,\,even}(y_{cm}) = v_{n0} + v_{n2}\, y_{cm}^2$$

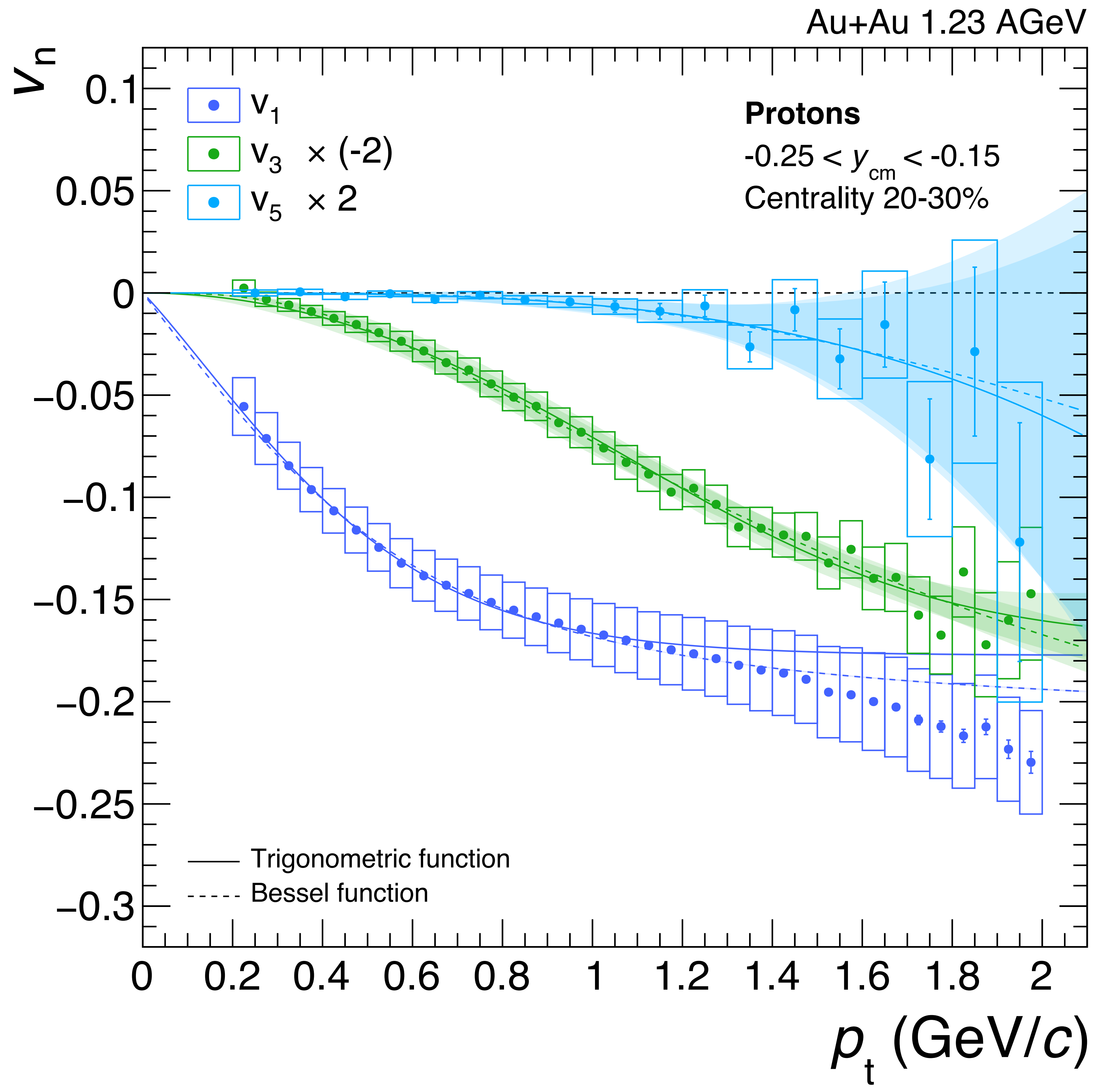
Trigonometric functions:

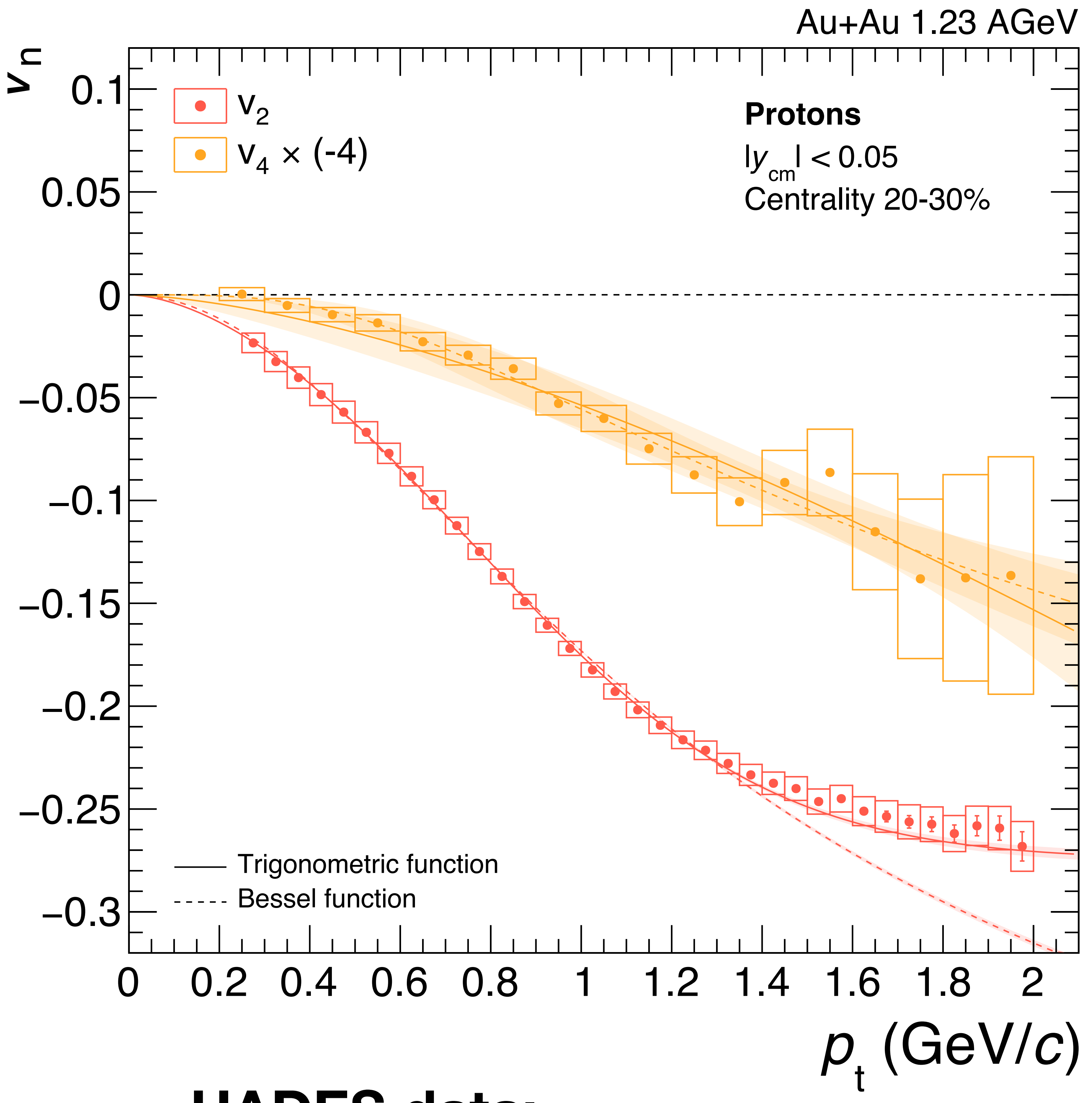
$$v_n^{odd}(y_{cm}) = v_n^{sat} \cdot \sin(y_{cm}/y_{tp} \cdot \pi/2)$$
$$v_n^{even}(y_{cm}) = v_n^{sat} \cdot \cos(y_{cm}/y_{zi} \cdot \pi/2)$$

Parameterisation based on Blast-Wave Model

p_t-Dependence







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

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

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

Bessel functions:

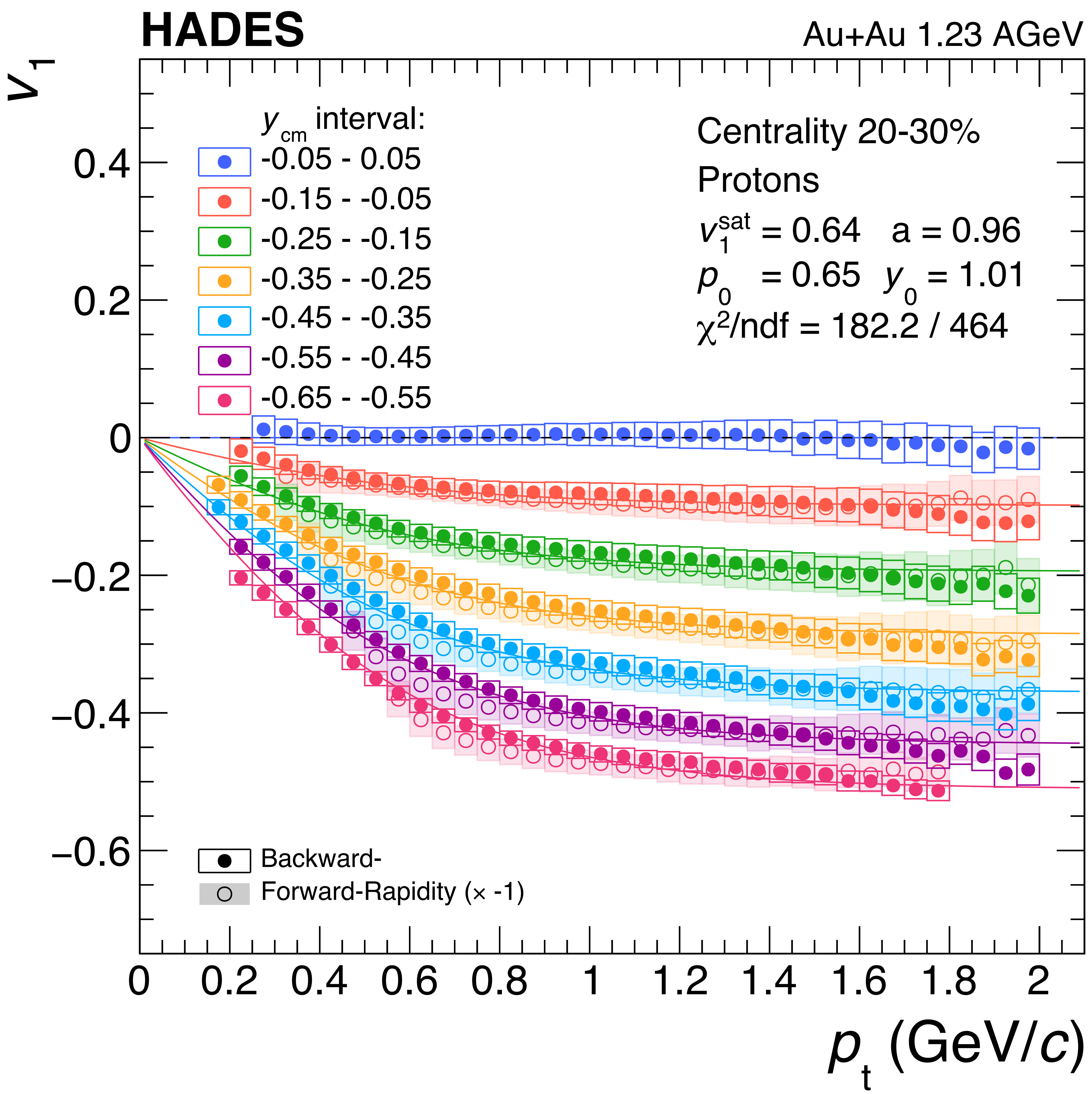
$$v_n(p_t) = v_n^{\text{inf}}\ I_n(p_t/\chi)/I_0(p_t/\chi)$$

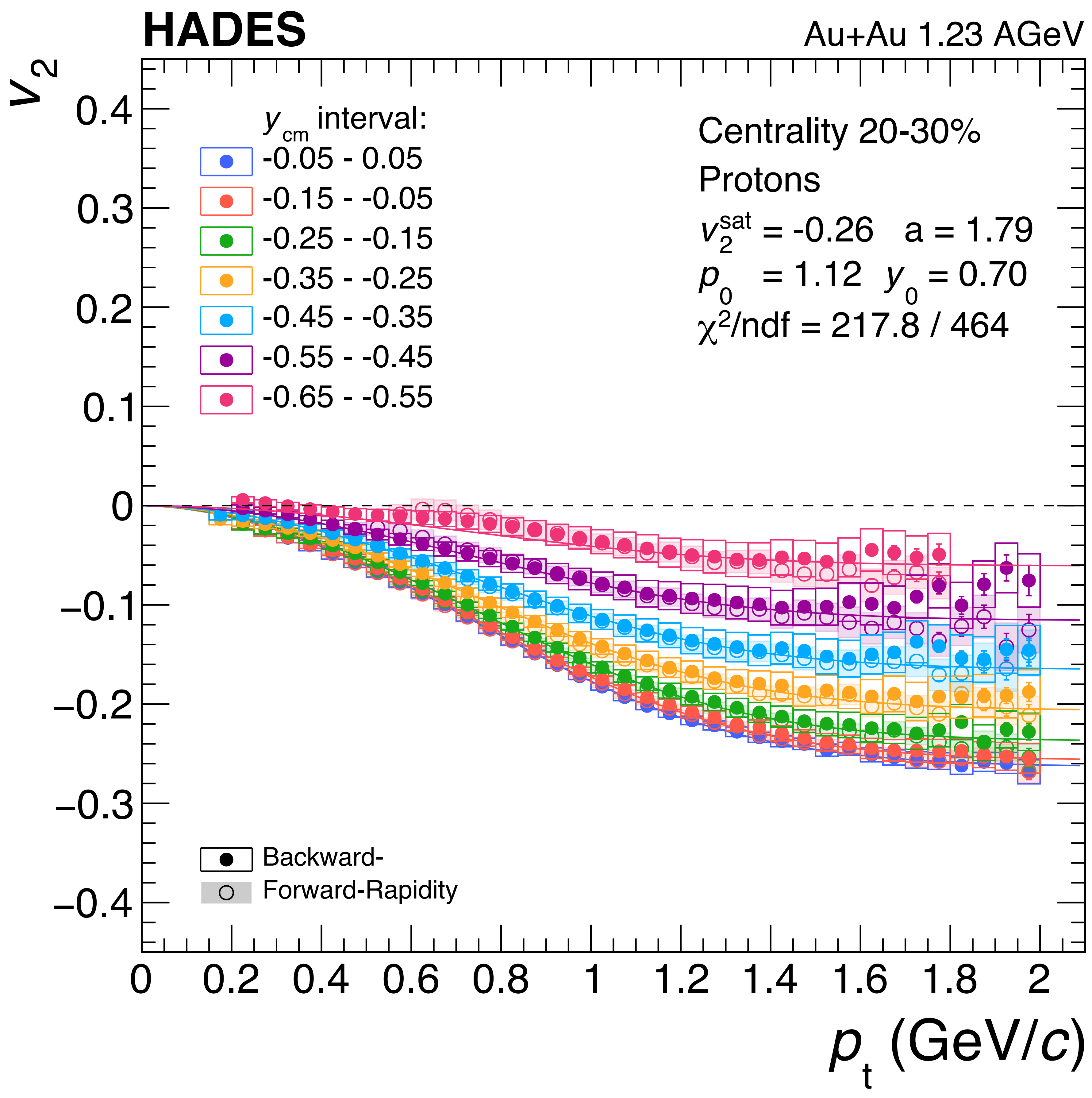
Trigonometric functions:

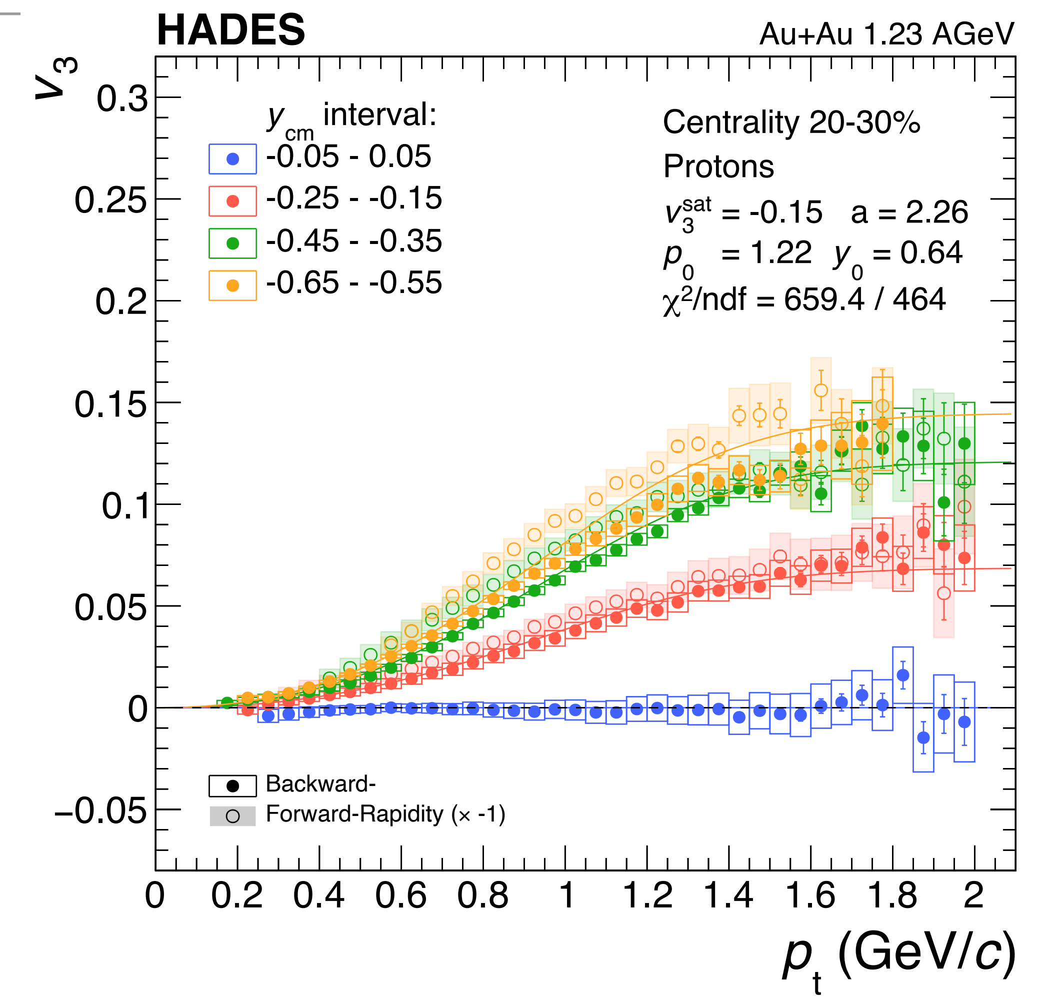
$$v_n(p_t) = v_n^{\text{sat}} \cdot \tanh(p_t/p_0)^a$$

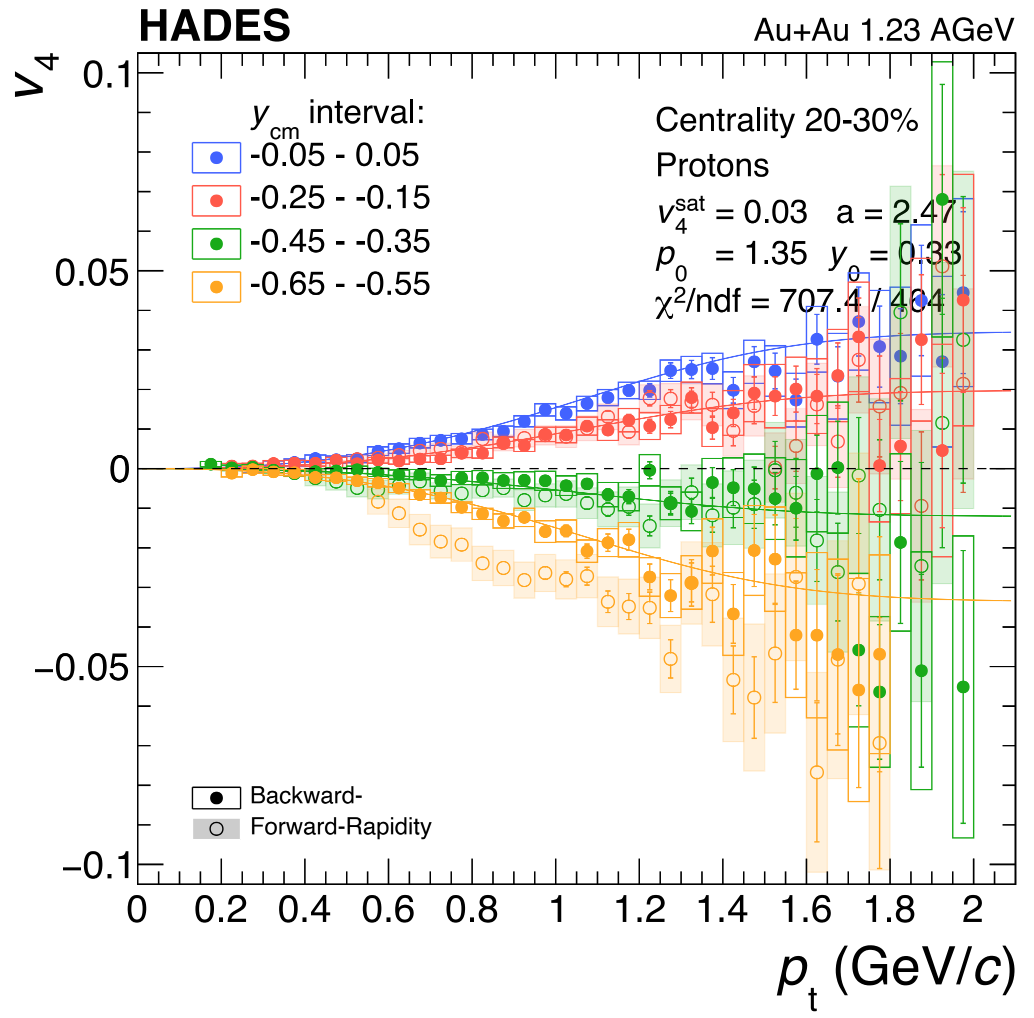
Global Parameterisation

Rapidity- and p_t-Dependence









Combined Trigonometric functions (y, pt):

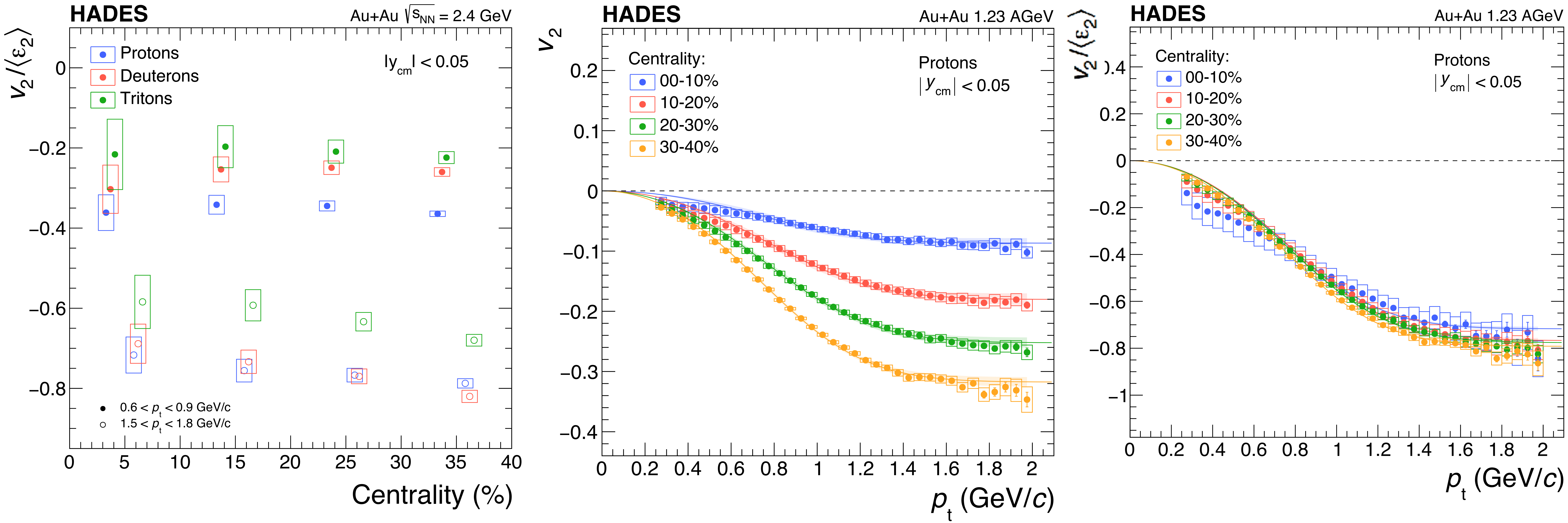
$$v_n^{odd}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \sin(y_{cm}/y_{tp} \cdot \pi/2)$$

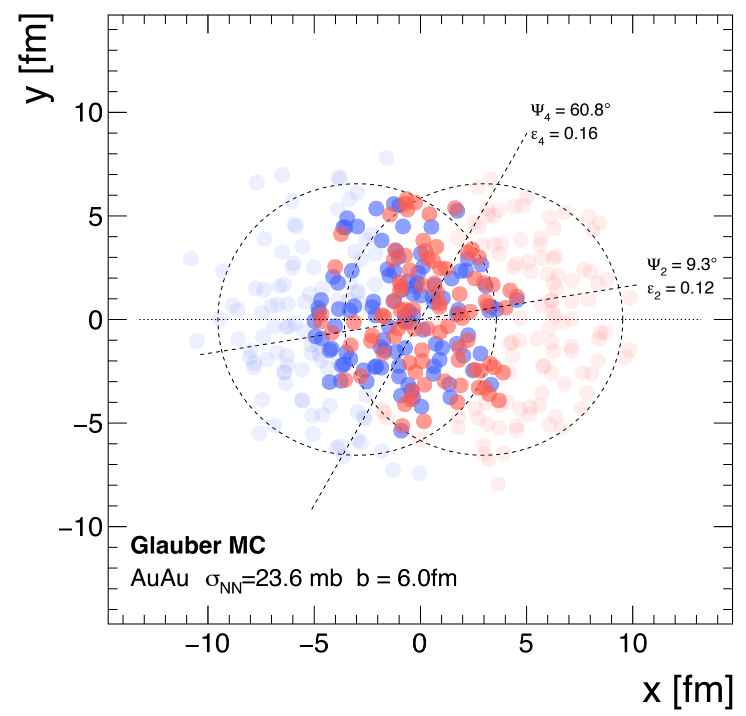
$$v_n^{even}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \cos(y_{cm}/y_{zi} \cdot \pi/2)$$

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

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

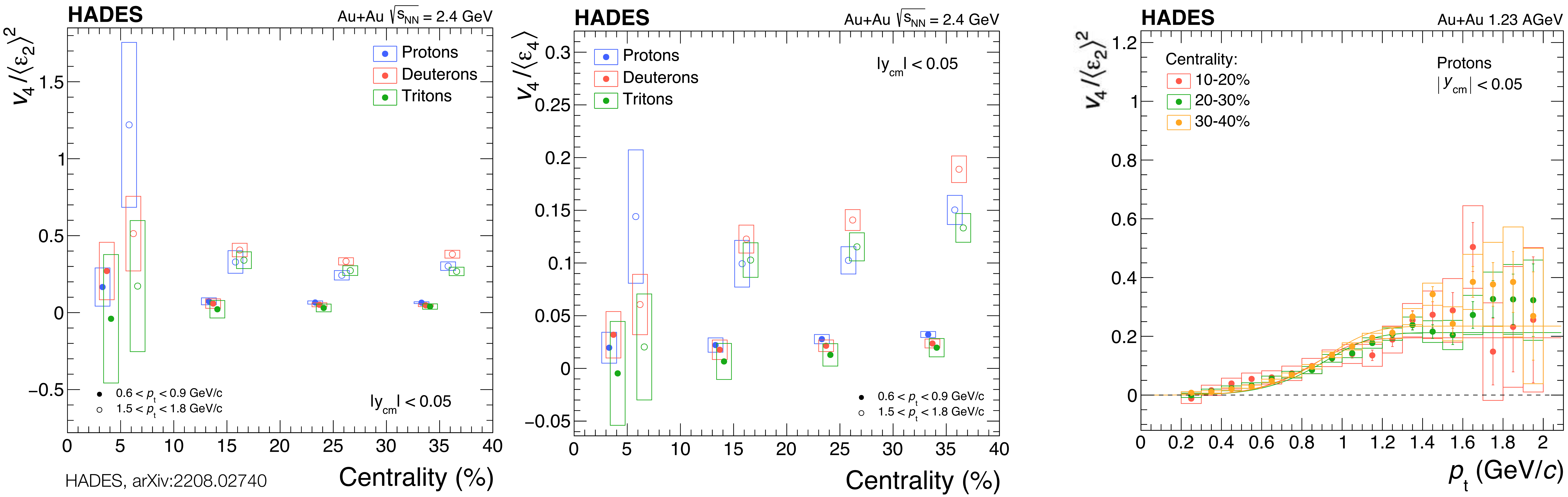
Orientation of symmetry-planes

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 $\langle\varepsilon_2\rangle^2$

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)

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

Nucleon Coalescence

Scaling Properties of v_2 at Mid-Rapidity

Scaling of v_2 and p_t with nuclear mass number A

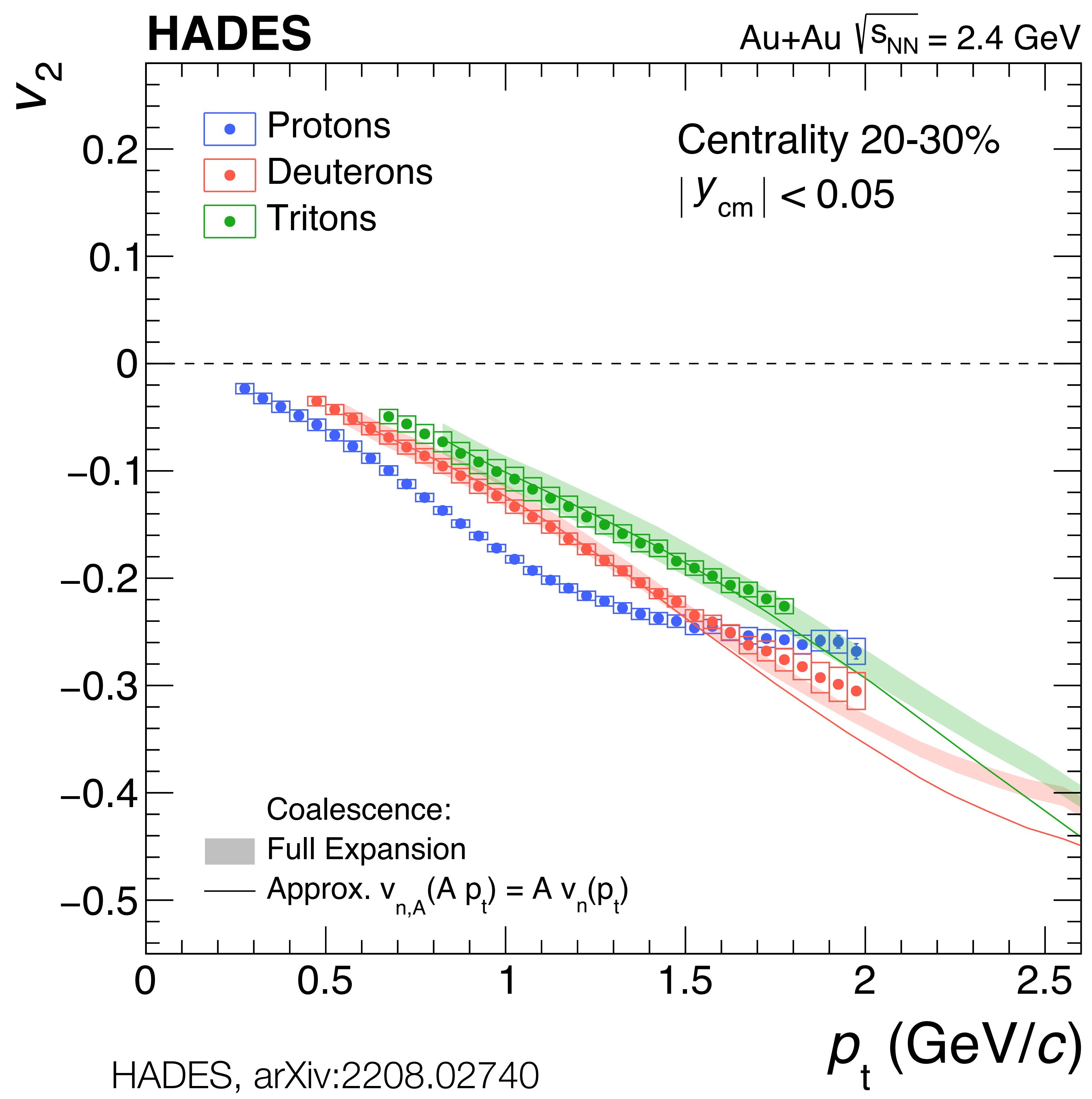
Inclusion of higher order terms

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

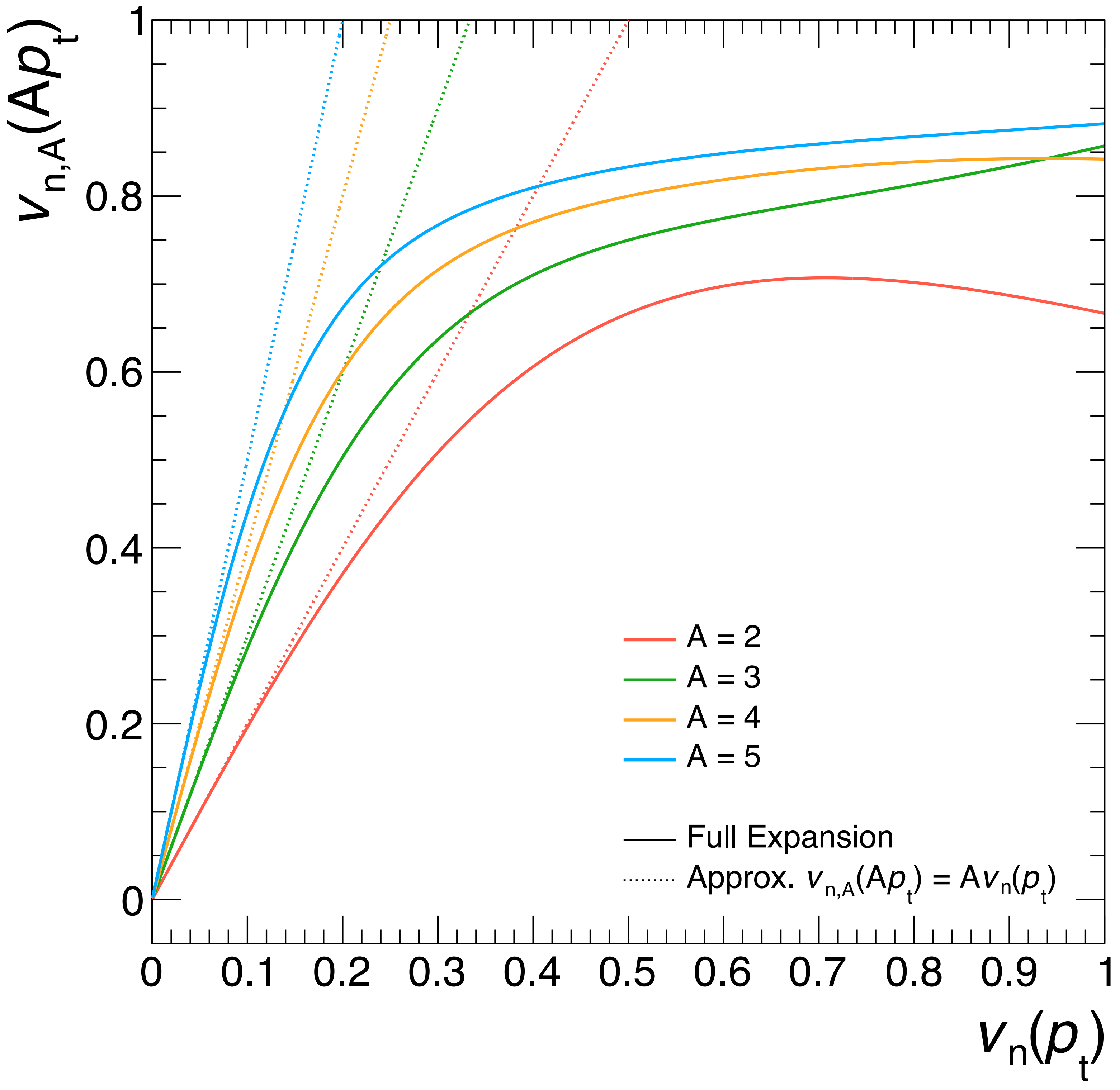
Odd flow coefficients vanish at mid-rapidity and v_4 contribution is negligible

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

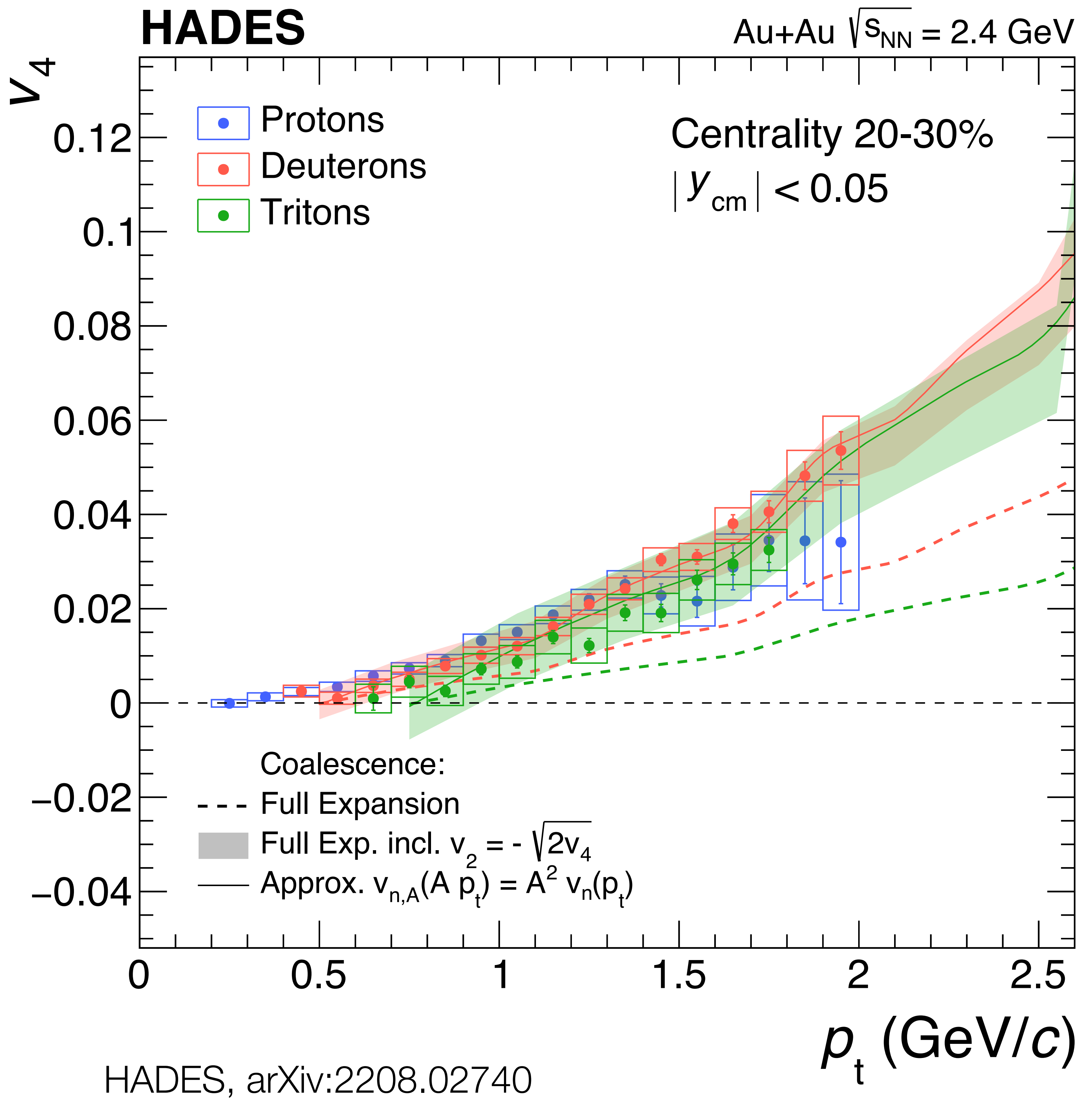
Scaling of v_4 and p_t with nuclear mass number A

Inclusion of higher order terms and contribution of v_2

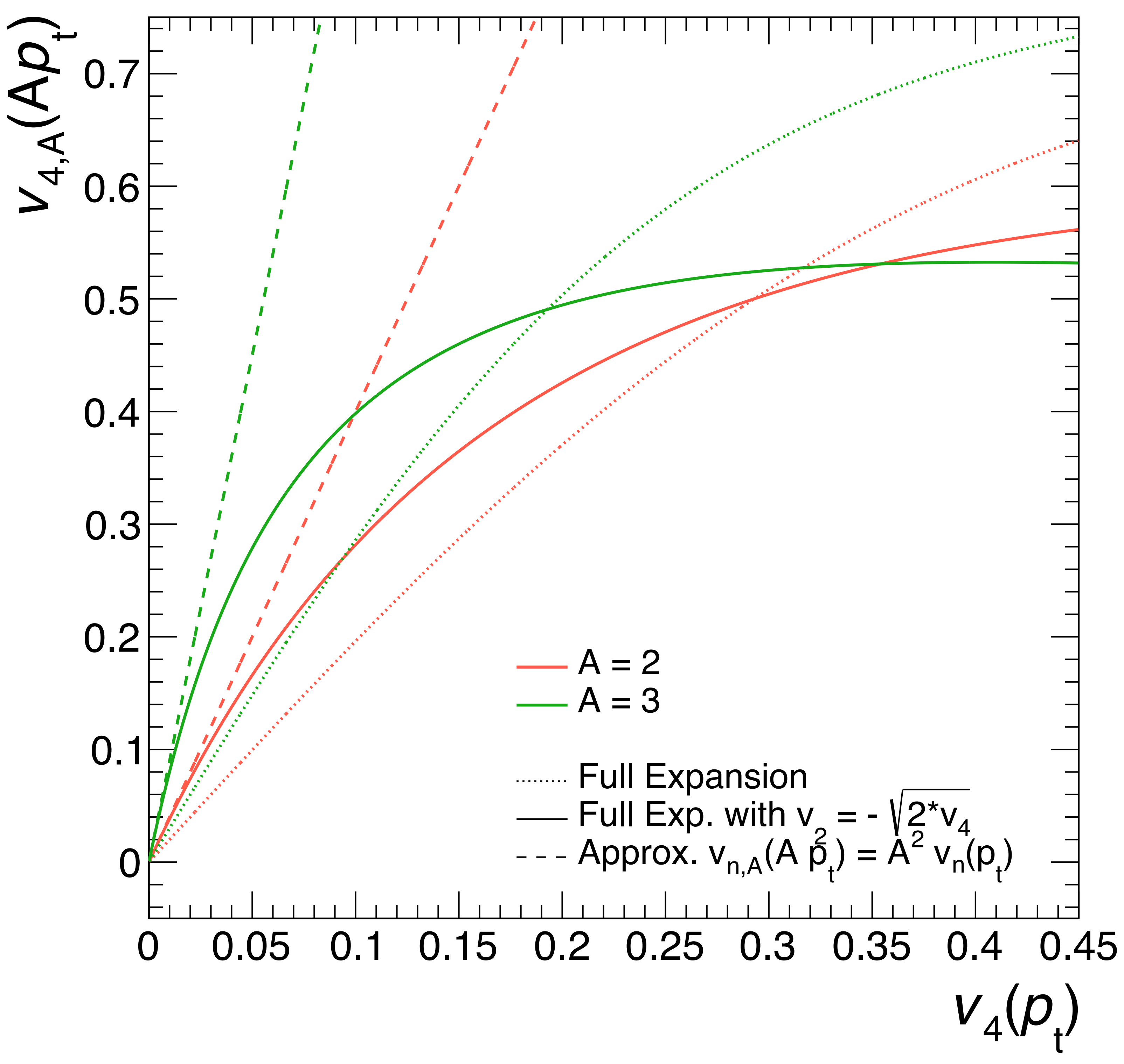
Works as expected in simple coalescence picture if contribution of dominant flow coefficient is included

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



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

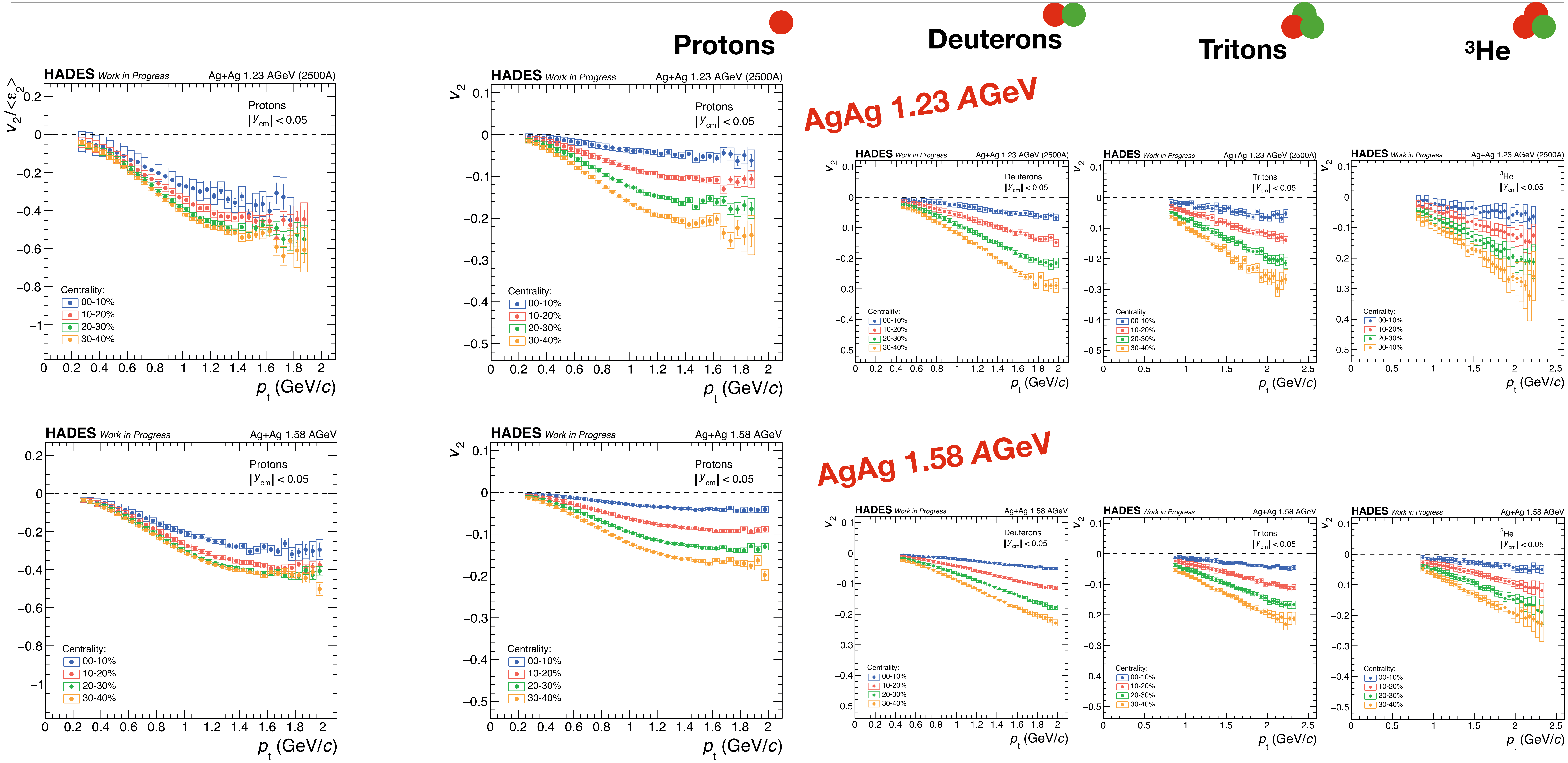
$$v_{4,A=3}(A\,p_t) = 9\,v_4(p_t)\,\frac{1}{1+12\,v_4(p_t)+6\,v_4^2(p_t)}$$

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

Elliptic Flow v_2

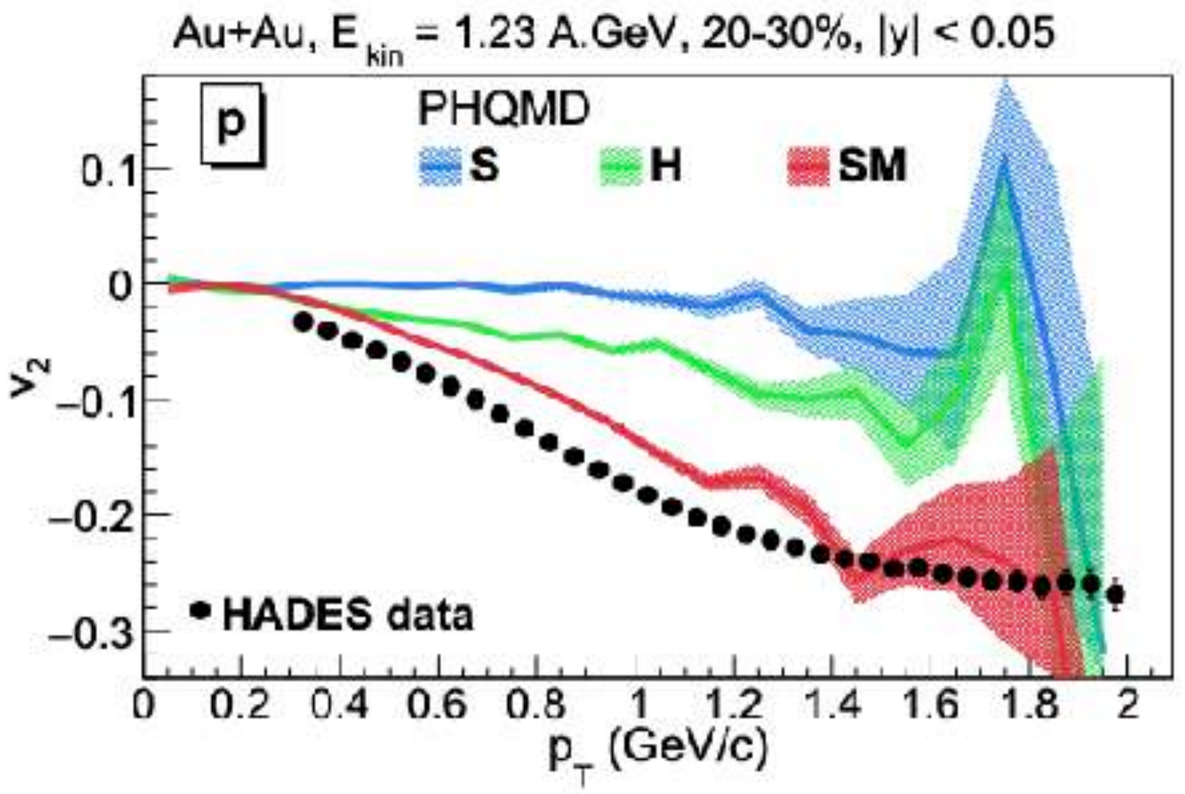
Protons, Deuterons, Tritons and ^{3}He in Ag+Ag collisions at 1.23 and 1.58 AGeV



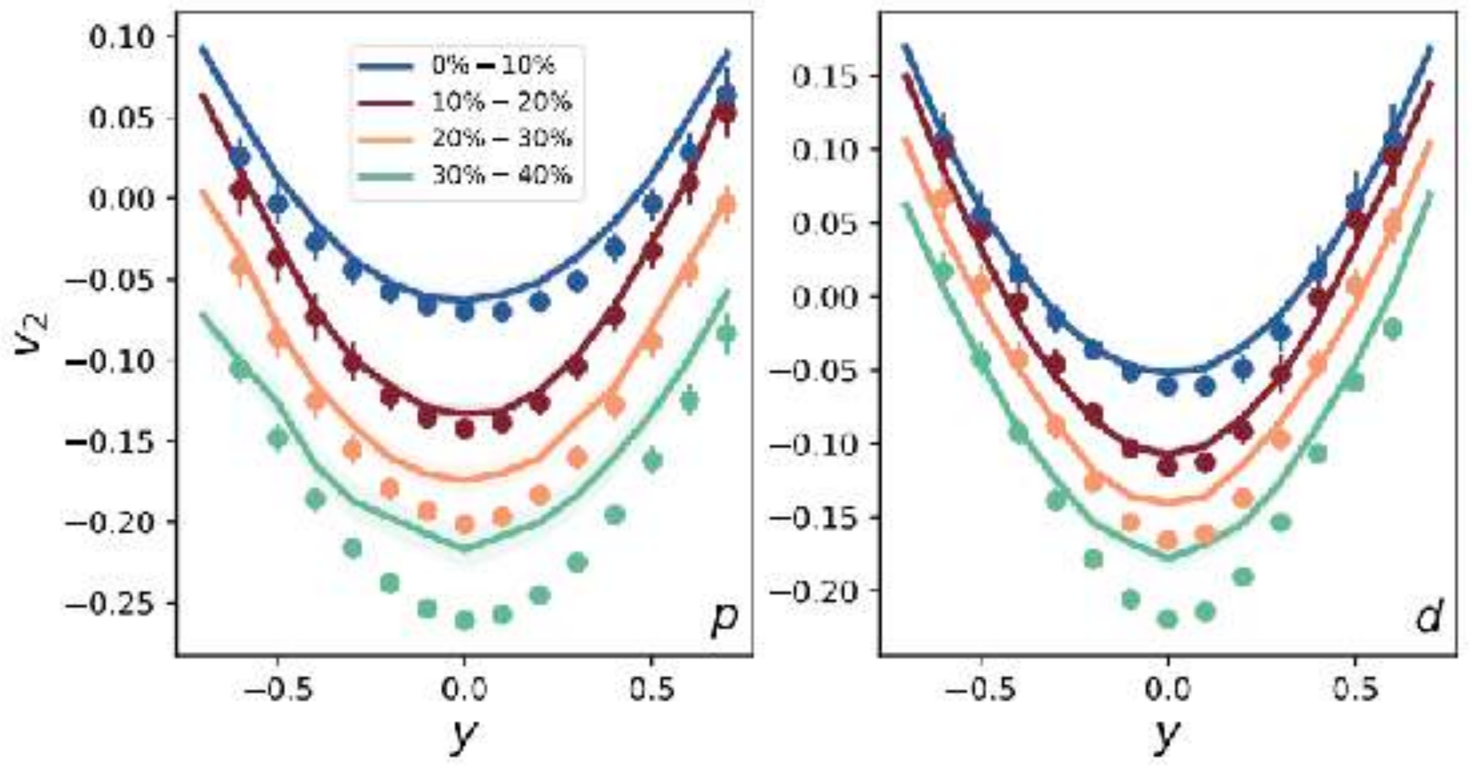
Model Comparisons

Extracting the EoS

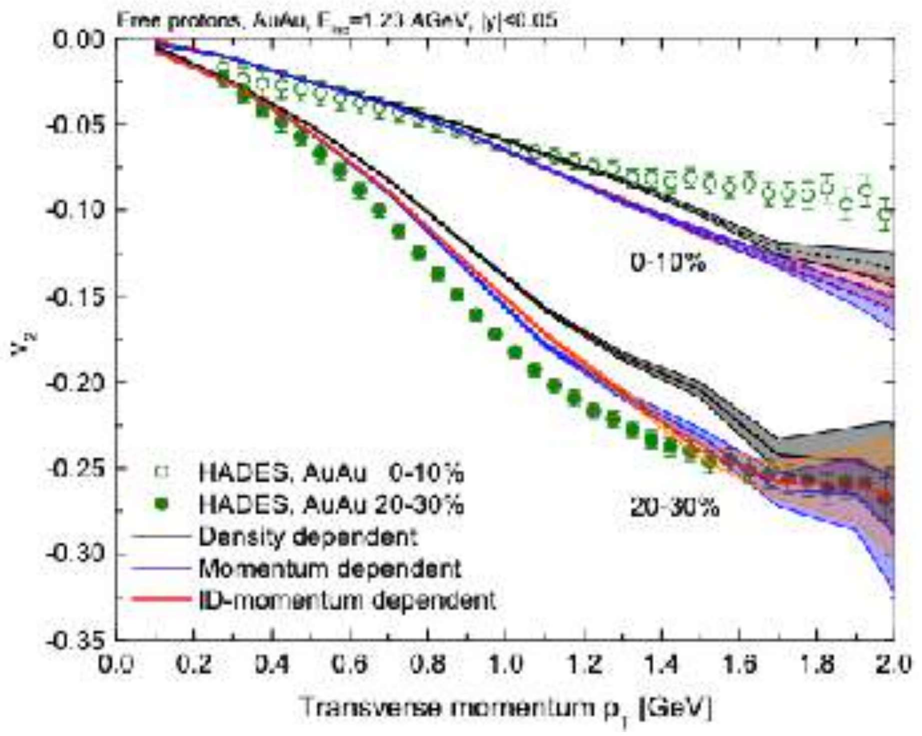
- Overall good description of data (directed and elliptic flow) by different models
- Momentum dependent soft EoS generally favoured
- Importance of the mechanism of light nuclei production
- Possibilities of available data set not yet fully exploited (higher order)
- Move to Bayesian analyses (first attempts)



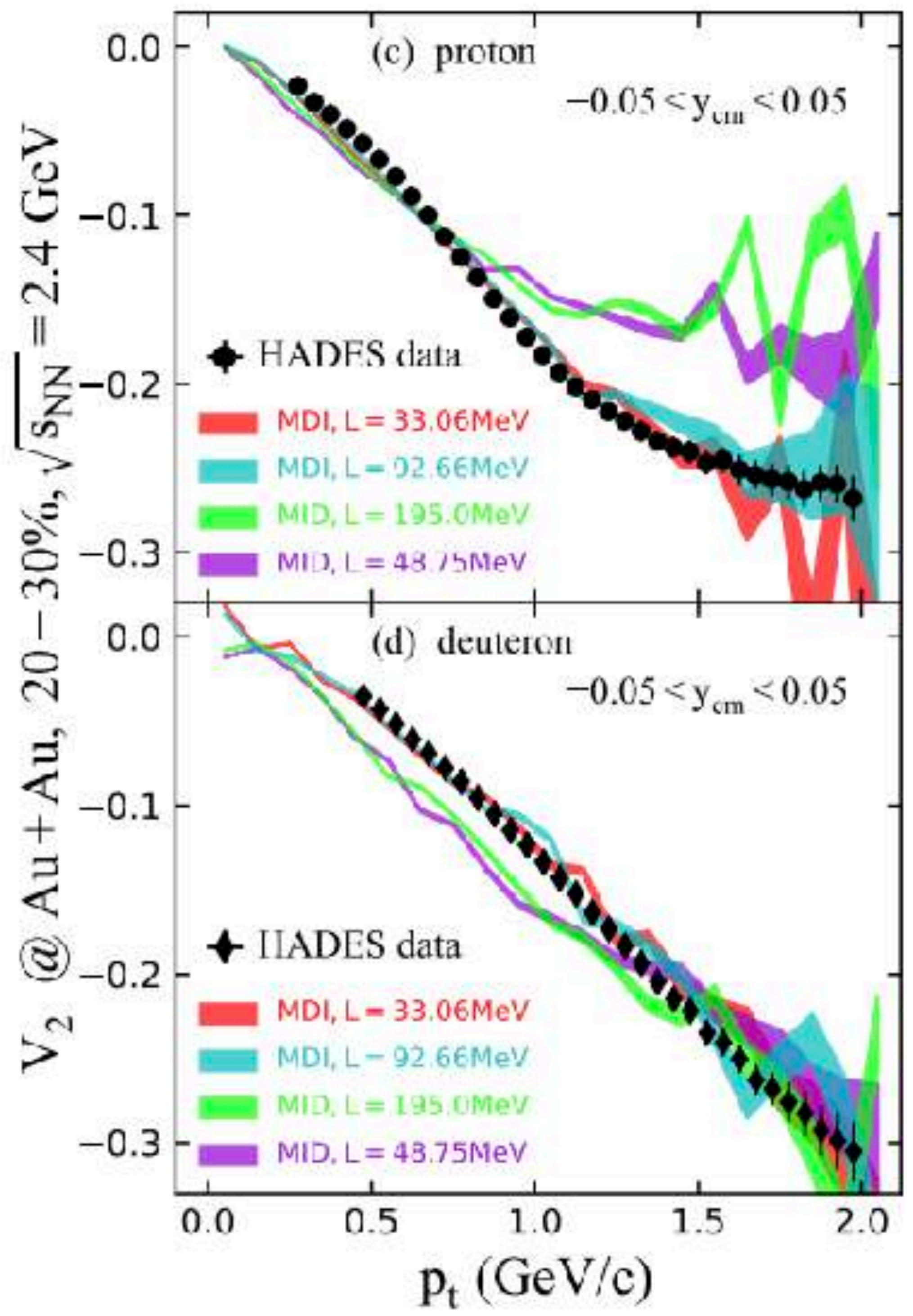
PHQMD: V. Kireyeu et al., arXiv:2411.04969

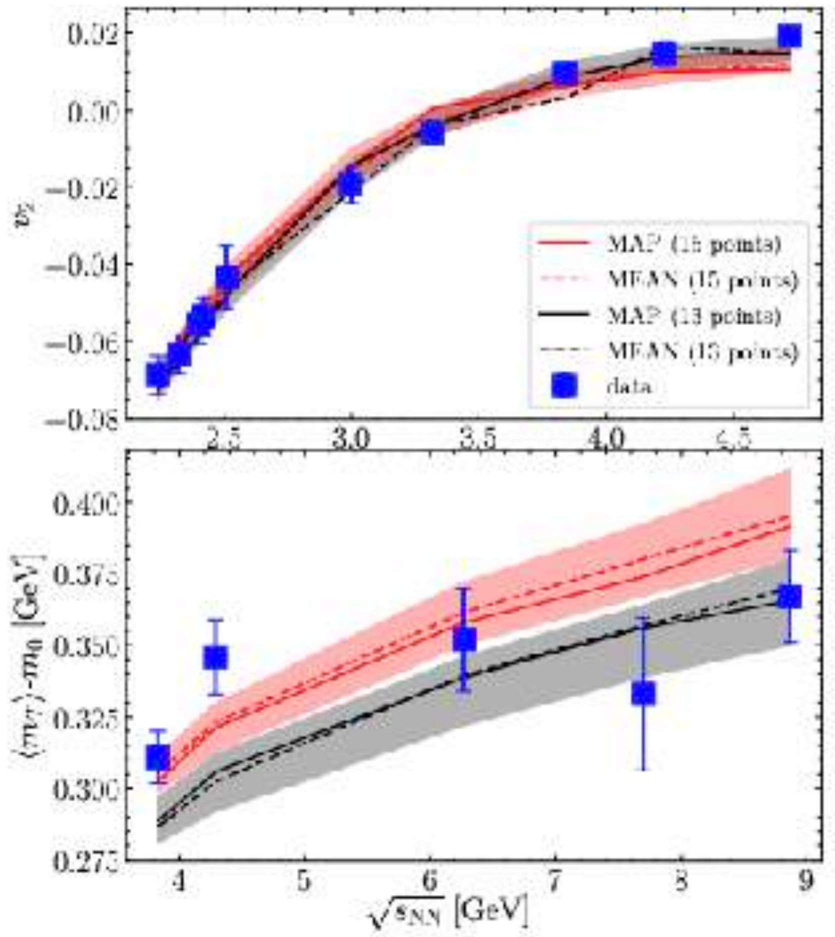


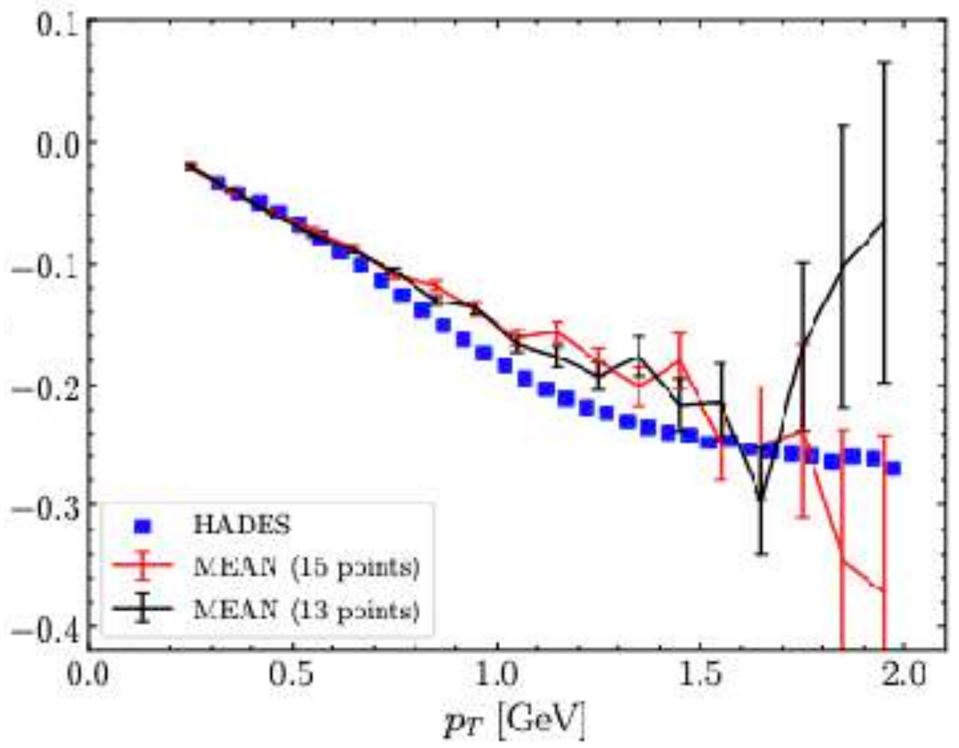
SMASH: J. Mohs et al., arXiv:2409.16927



UrQMD: J. Steinheimer et al. arXiv:2410.01742





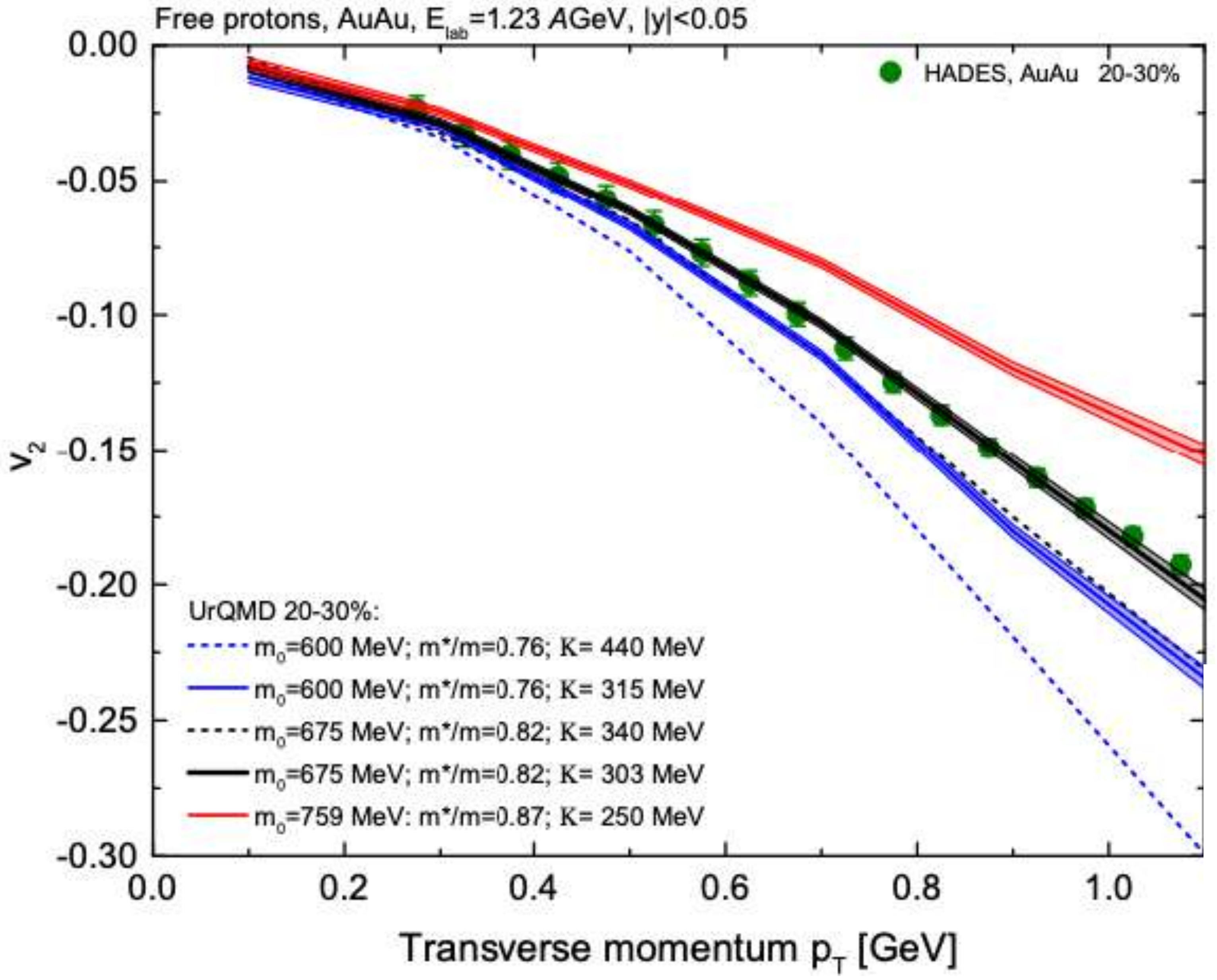


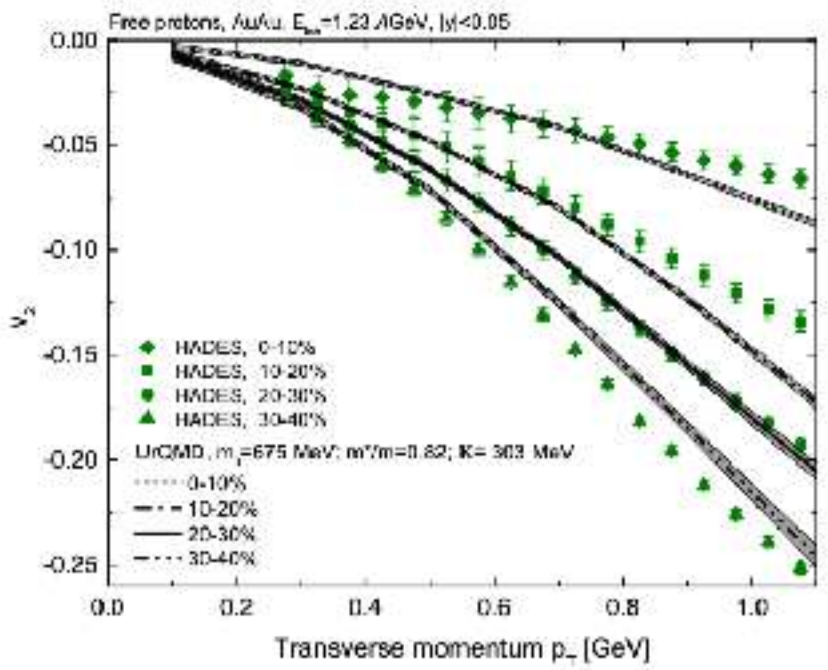
UrQMD: M.O. Kuttan et al., PRL **131** (2023) 202303

IBUU: H. Du et al., PLB 839 (2023) 137823

Model Comparisons

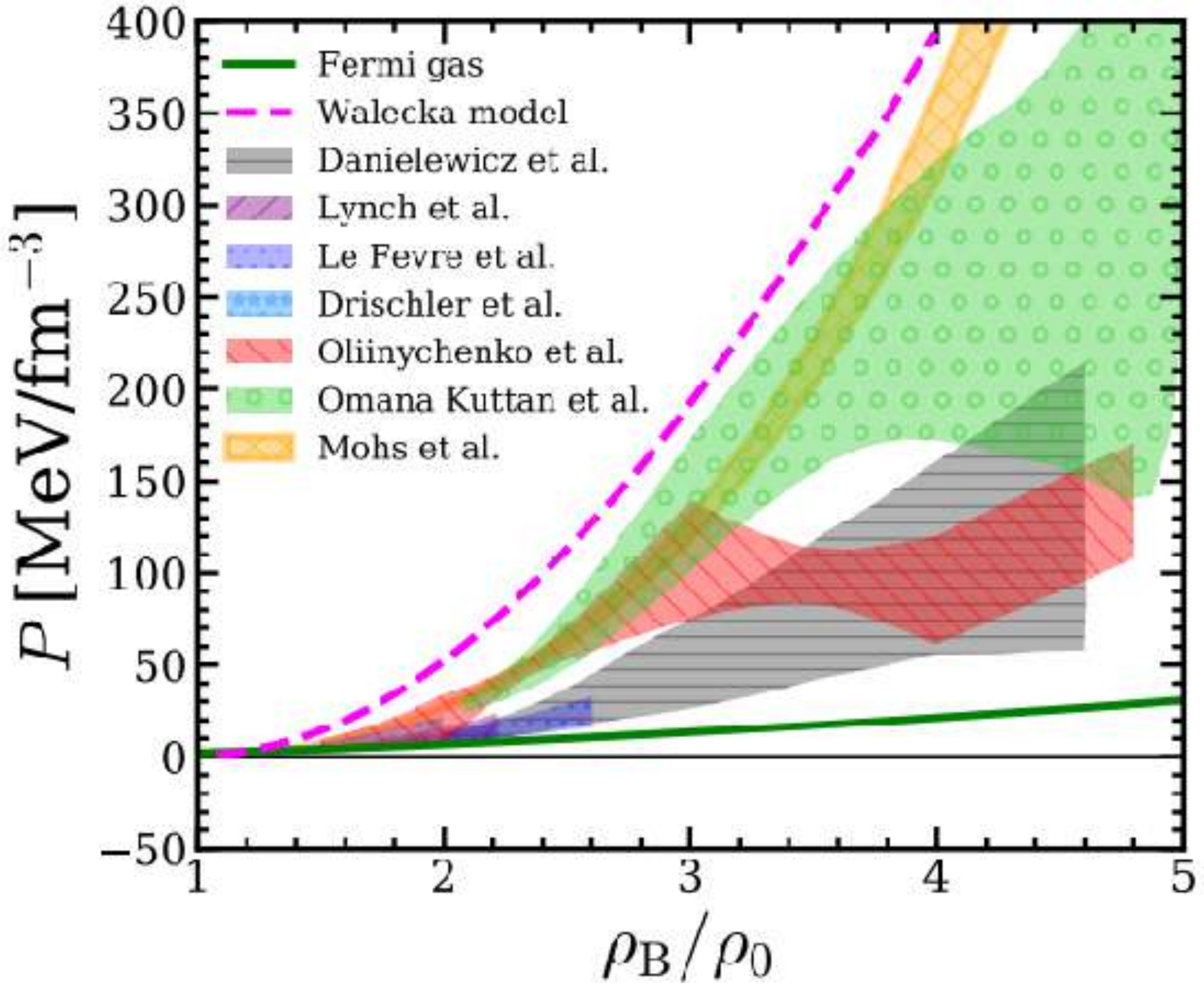
Data - Transport Model Comparison (UrQMD)



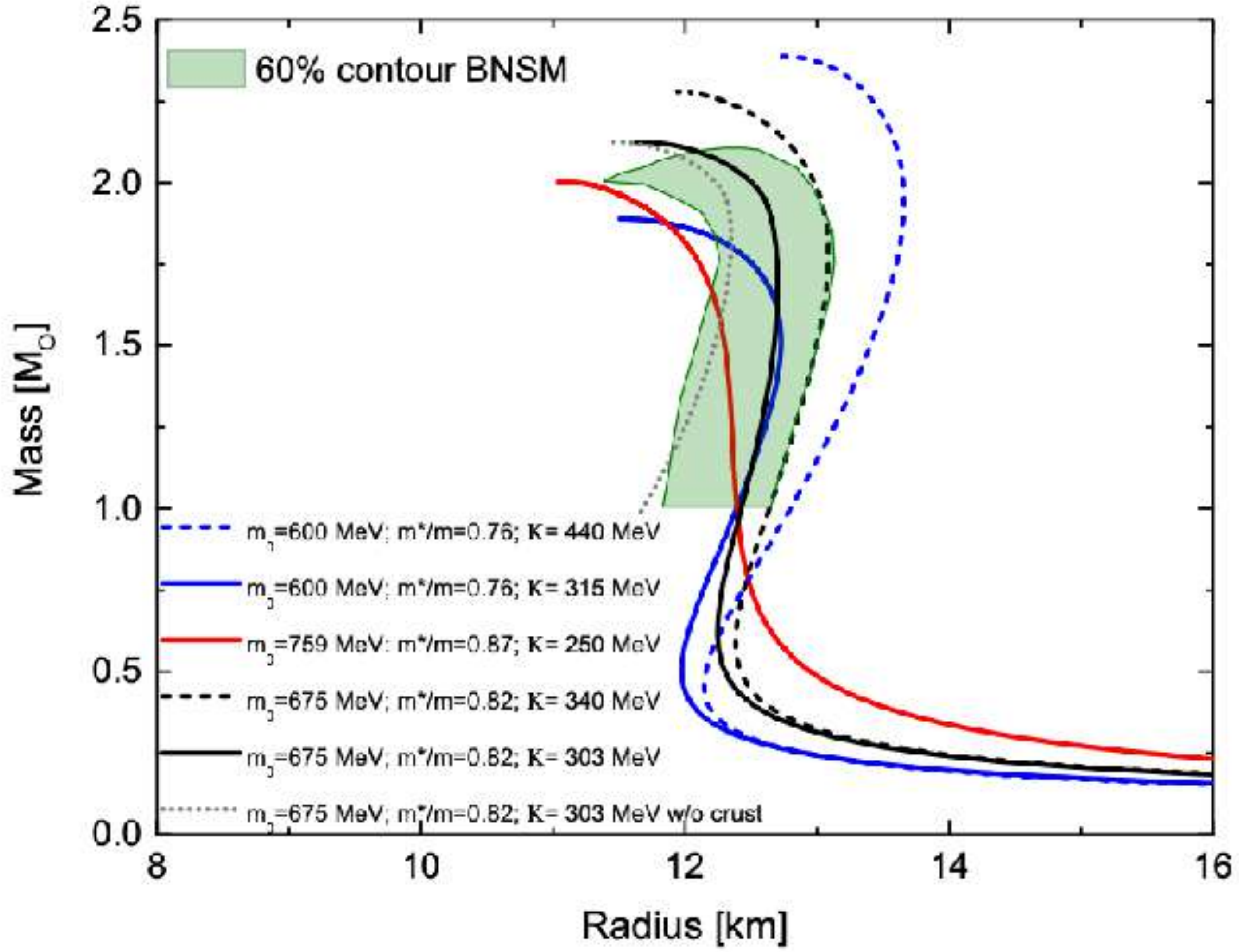


UrQMD: J. Steinheimer et al.
Phys.Lett.B 867 (2025) 139605

Equation-of-State



Tolman–Oppenheimer–Volkoff (TOV) equation



Toward a Unified Understanding of the Dense Matter Equation of State
Kshitij Agarwal, B.K. et al.
arXiv:2511.20378

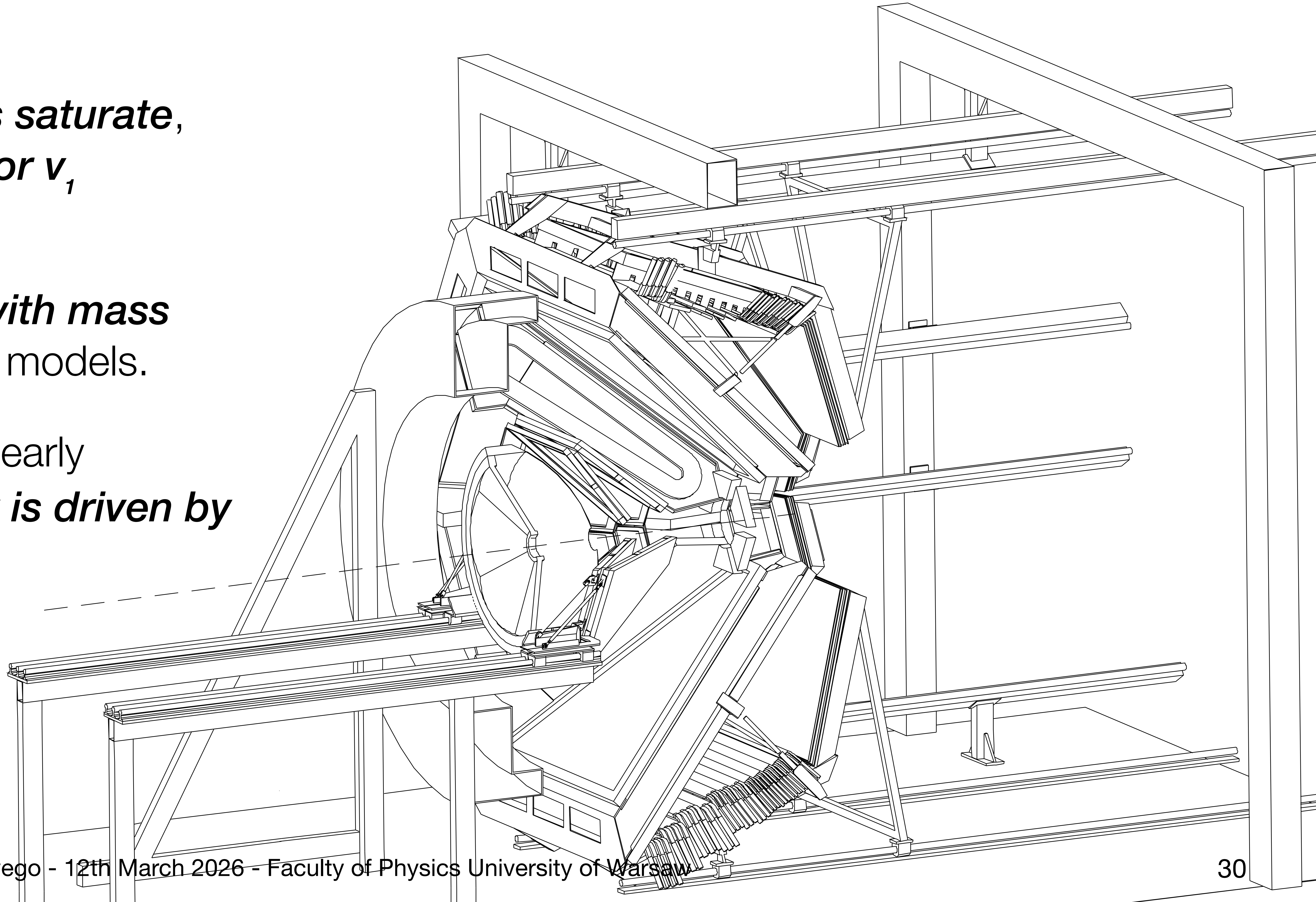
Highlights

- ***First observation*** of flow harmonics up to v_6 at these energies.
- Ratio v_4 / v_2^2 for protons, deuterons, and tritons approaches ~0.5 at high transverse momentum, indicating *"hydrodynamic behaviour"*.
- At large transverse momenta, ***flow coefficients saturate***, while at low momenta they show a ***linear rise for v_1*** and ***quadratic rise for v_2***.
- Flow values and transverse momentum ***scale with mass number A***, consistent with simple coalescence models.
- Dividing v_2 by $\langle\varepsilon\rangle$ and v_4 by $\langle\varepsilon\rangle^2$ makes results nearly independent of centrality, showing that the ***flow is driven by initial geometry***.

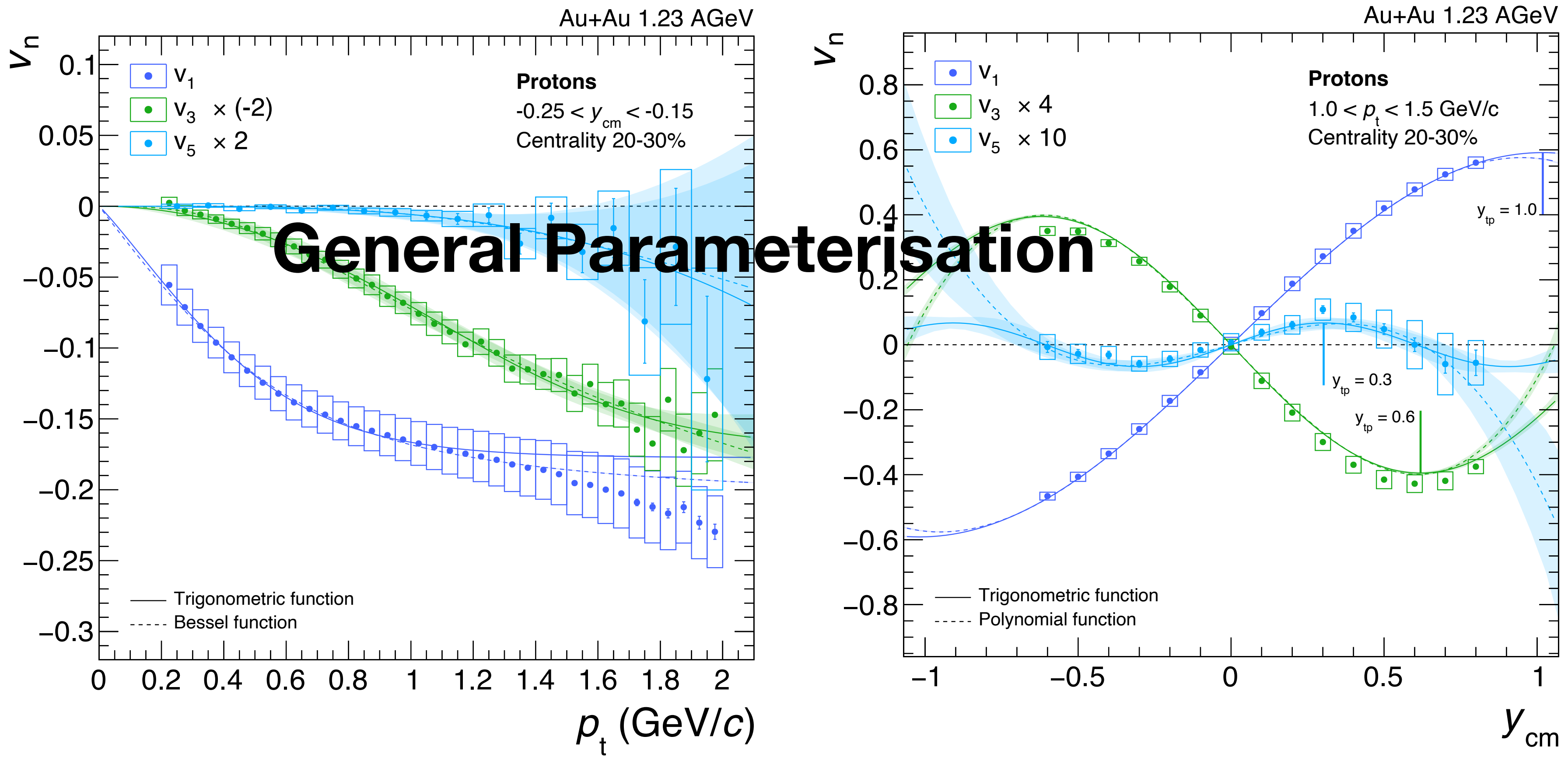
Talk based on following publications:

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

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



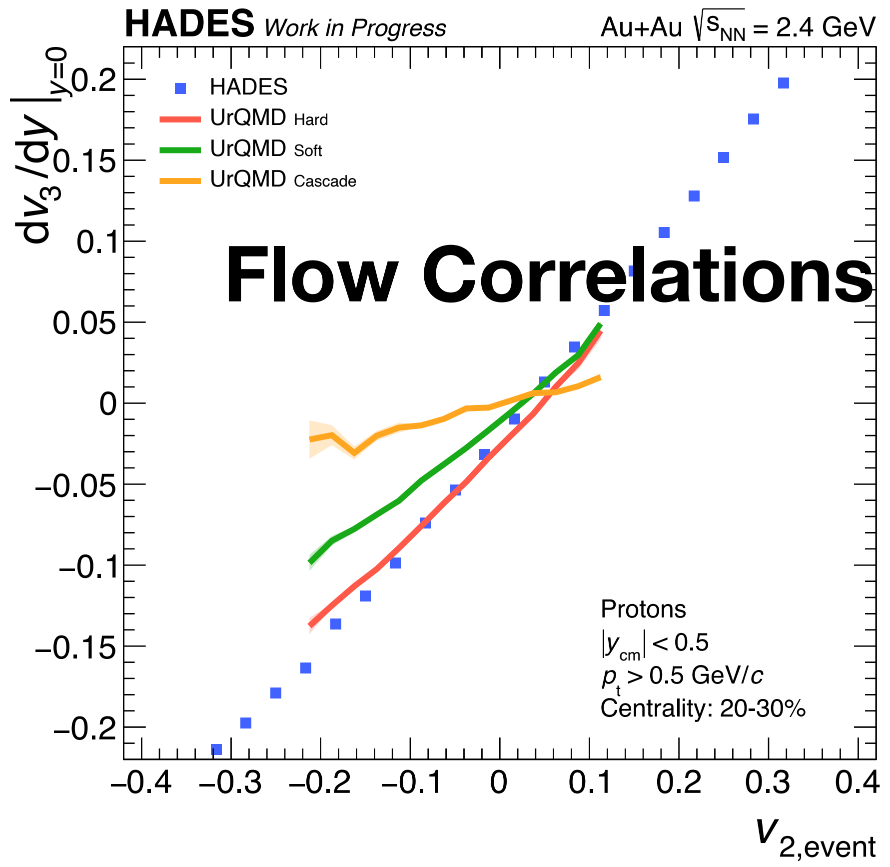
Conclusions

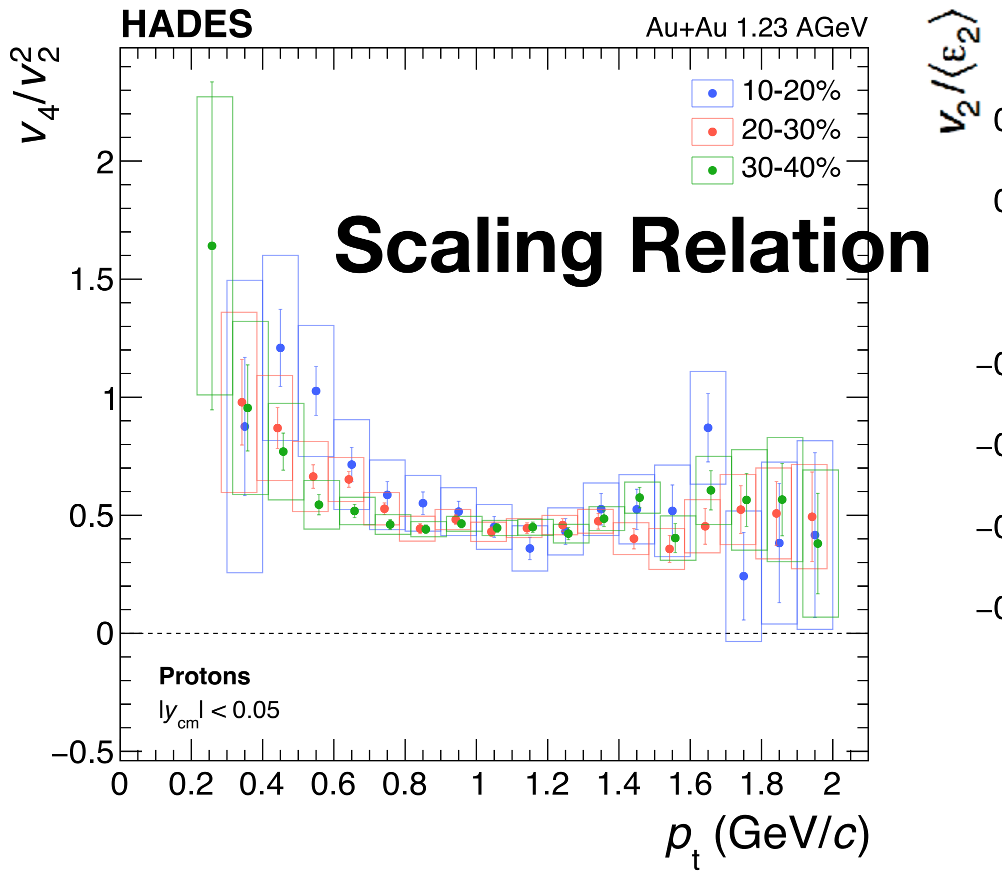


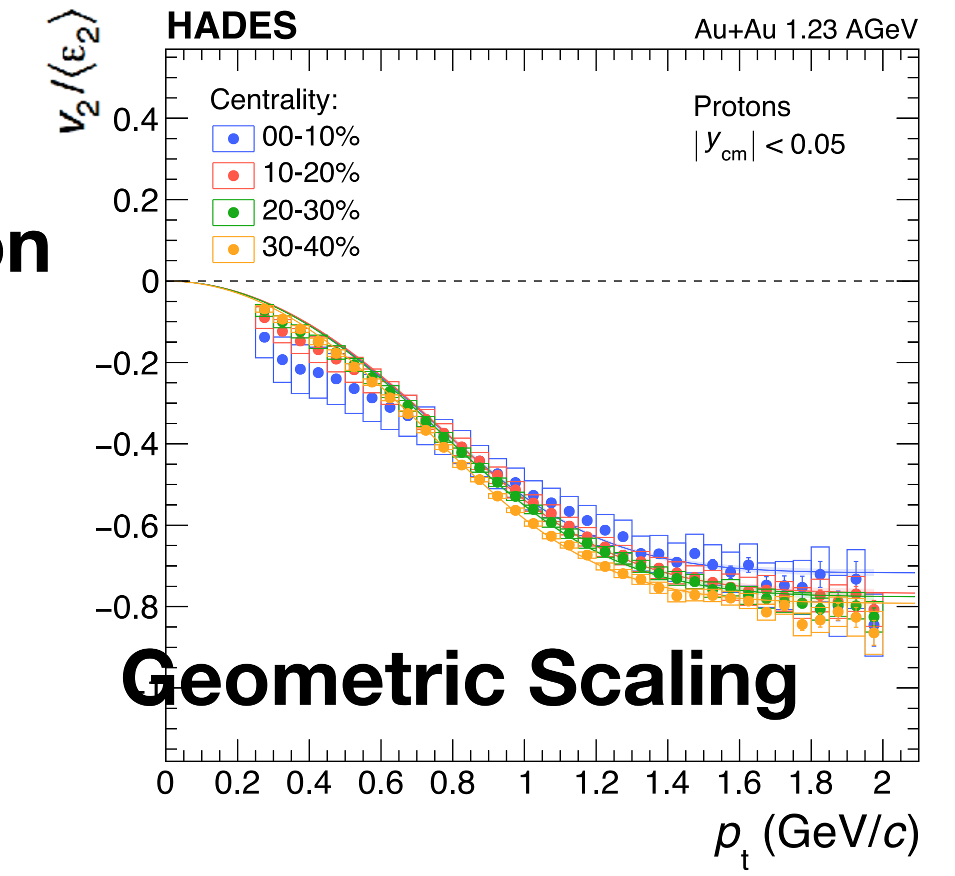
General Parameterisation

- Phenomenological approach based on hydrodynamic inspired Blast Wave model

Scaling Properties





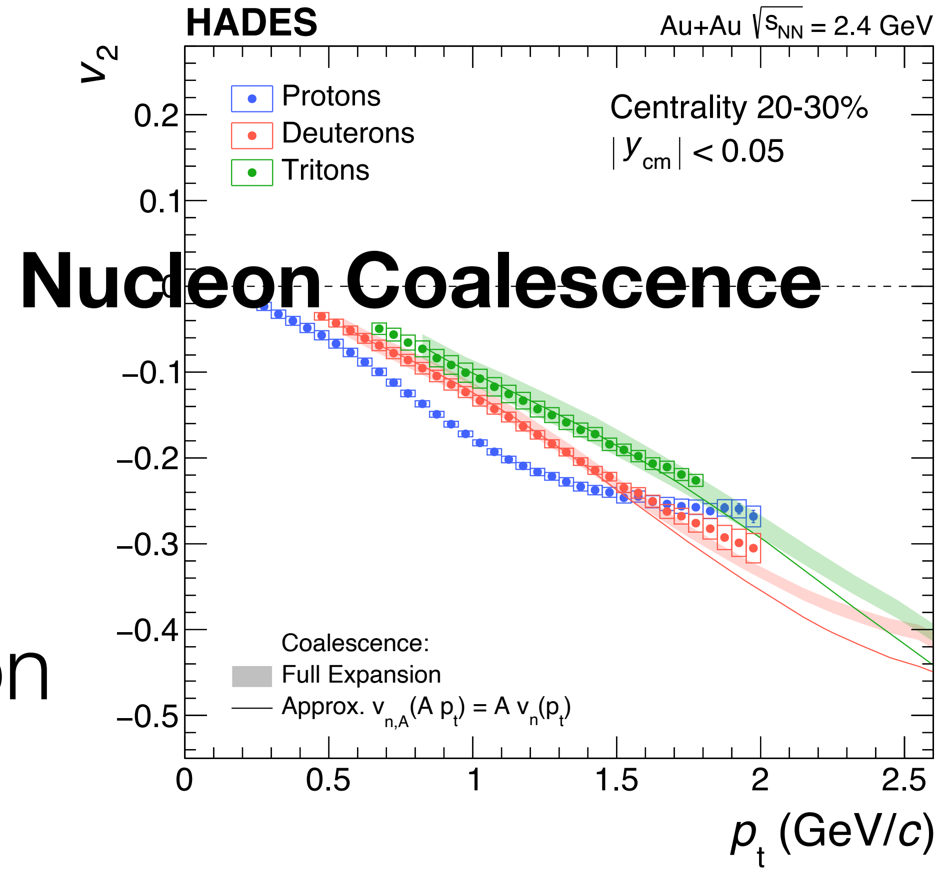


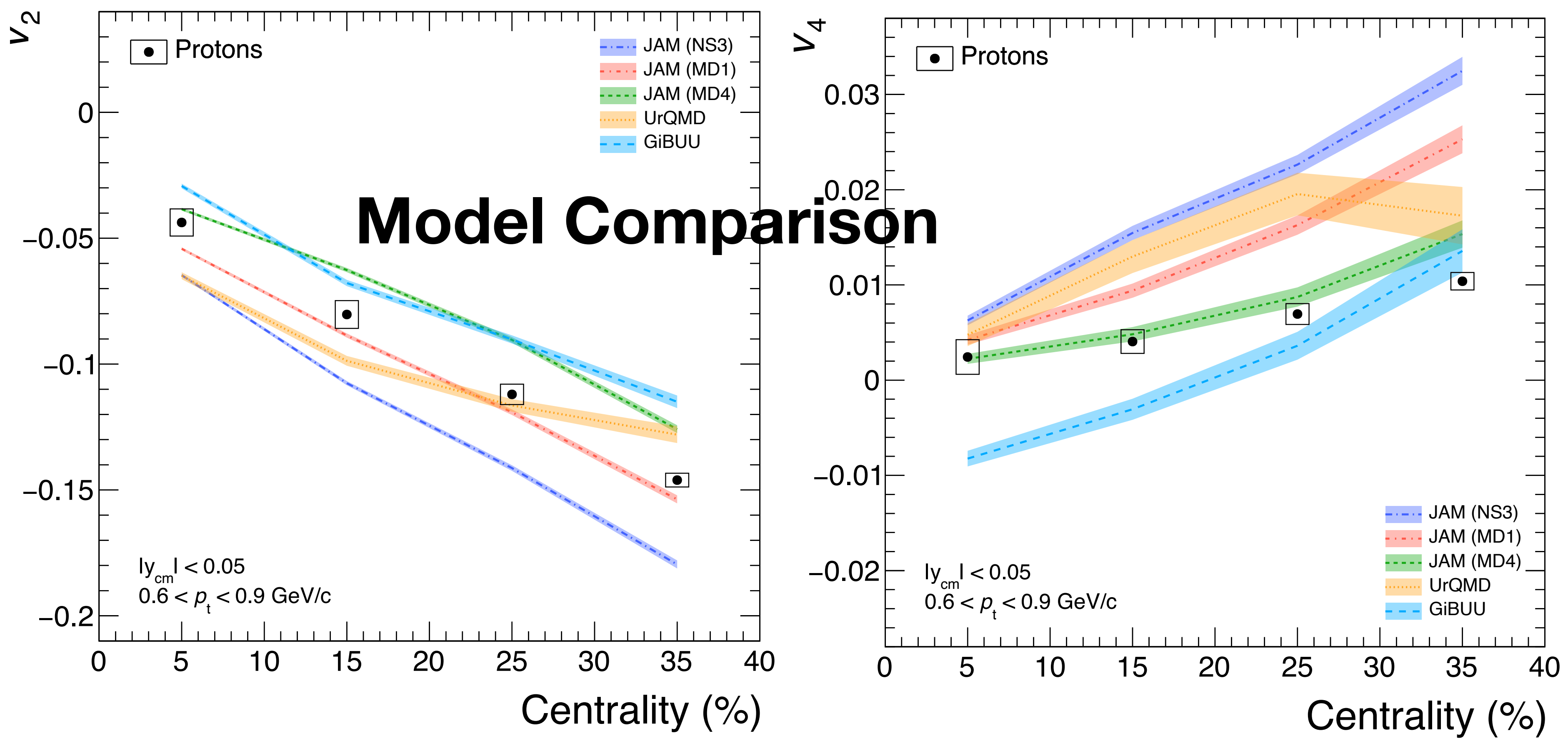
- Scaling relation between flow coefficients
  Hydro-like matter at SIS energies?

- 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

Outlook

HADES data publications in the pipeline

Flow of p, d, t and ^{3}He flow in Ag+Ag collisions at 1.23 and 1.58 AGeV

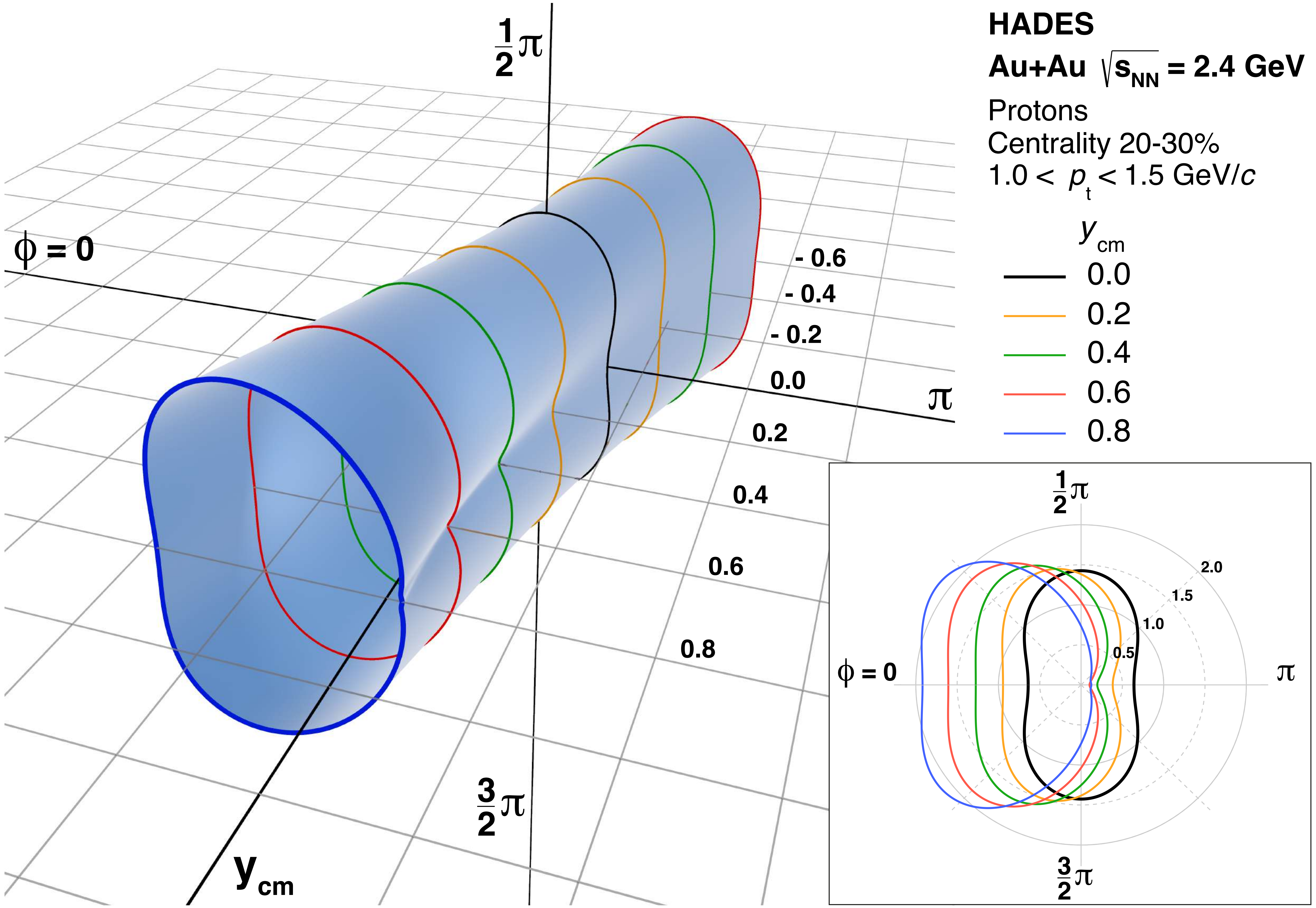
Correlations of flow coefficients for protons in Ag+Ag and Au+Au collisions

Flow of charged pions, kaons and lambda in Au+Au collisions

System-size and energy-dependence

SIS beam energy scan
C+C at 0.8 AGeV (Feb. 2024)

Au+Au at 0.2, 0.4, 0.6 and 0.8 AGeV
(March 2024 & Mai 2025)



HADES Collaboration

Thank you for your attention!