Flow phenomena at high nuclear densities with HADES

Behruz Kardan

for the
HADES Collaboration

EMMI Workshop:
Collective phenomena and the
Equation-of-State of dense baryonic matter

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und Forschung

HFHF

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

HADES

12th November 2025 - GSI Darmstad

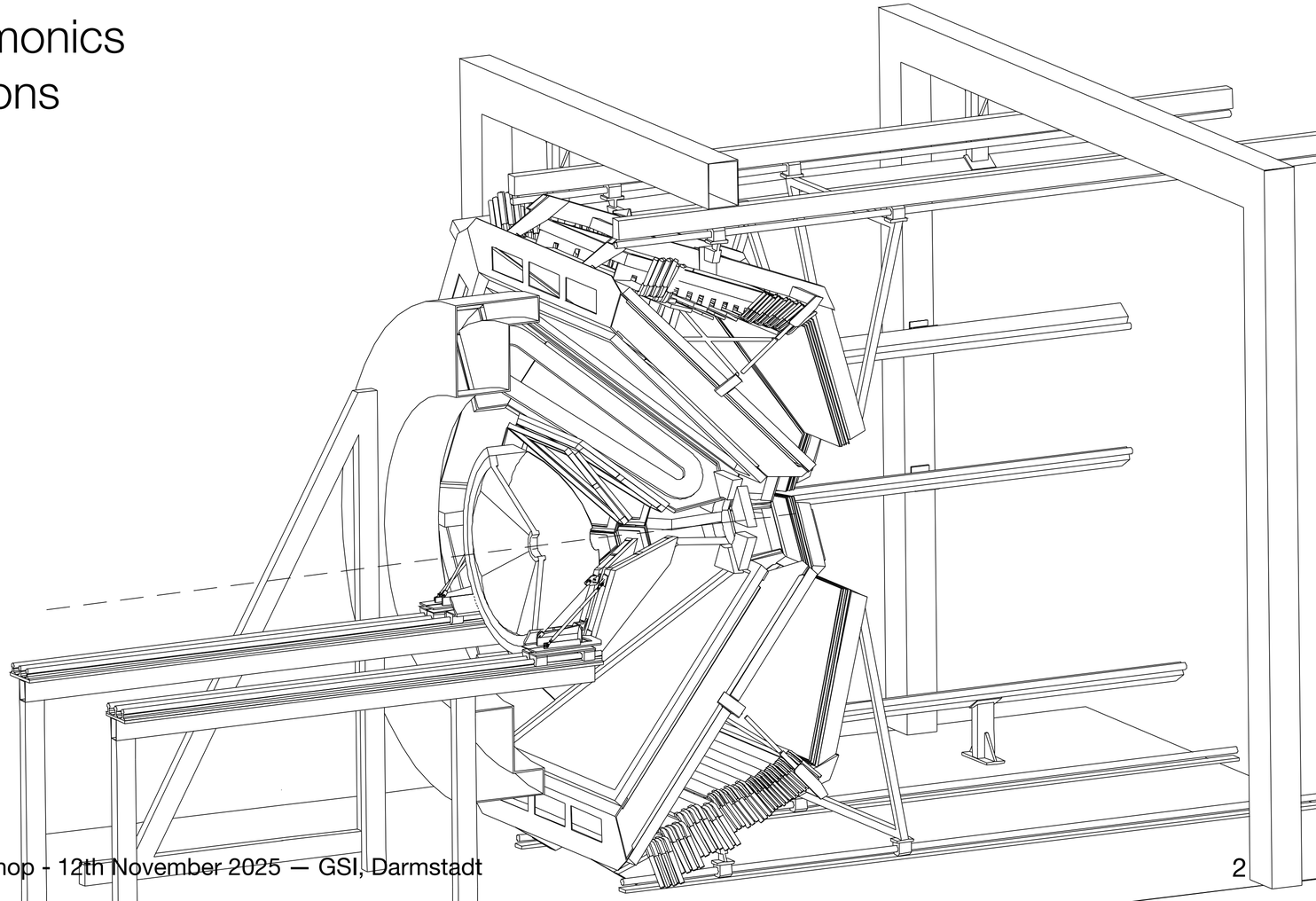
Outline

- 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]



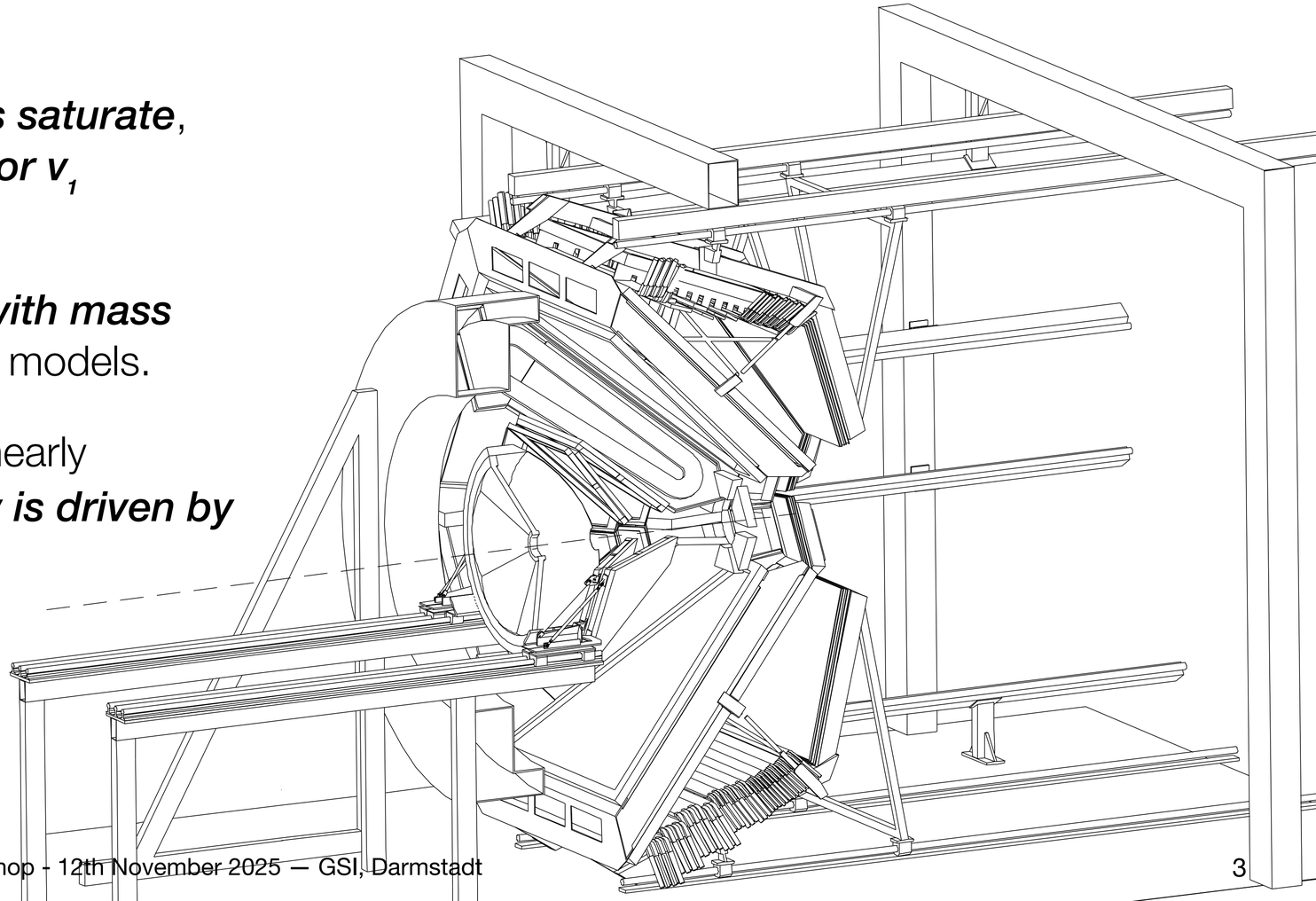
Highlights

- ***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]

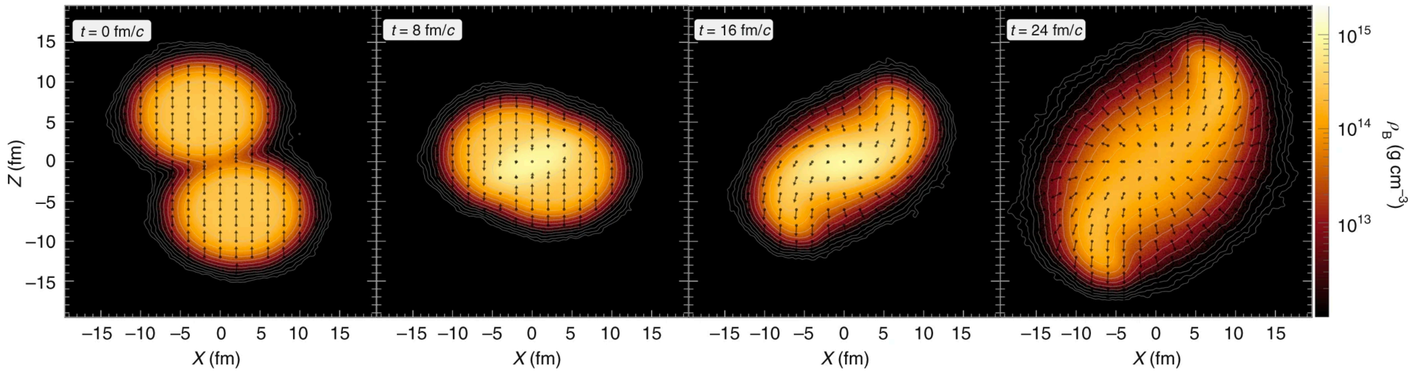


Dense nuclear matter and astrophysics

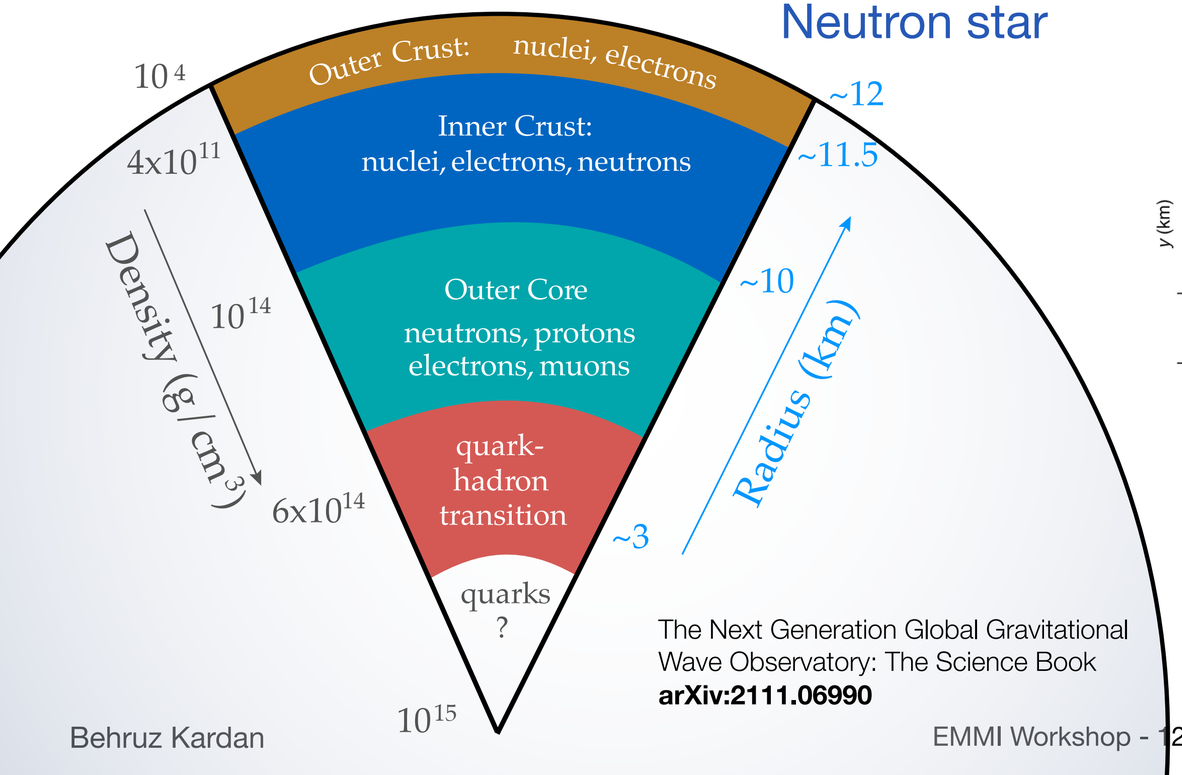
- Properties of neutron star matter and its Equation-of-State (EoS)
- Similar conditions in heavy-ion collisions at SIS18 energies than in merging neutron stars

Heavy-ion collision

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

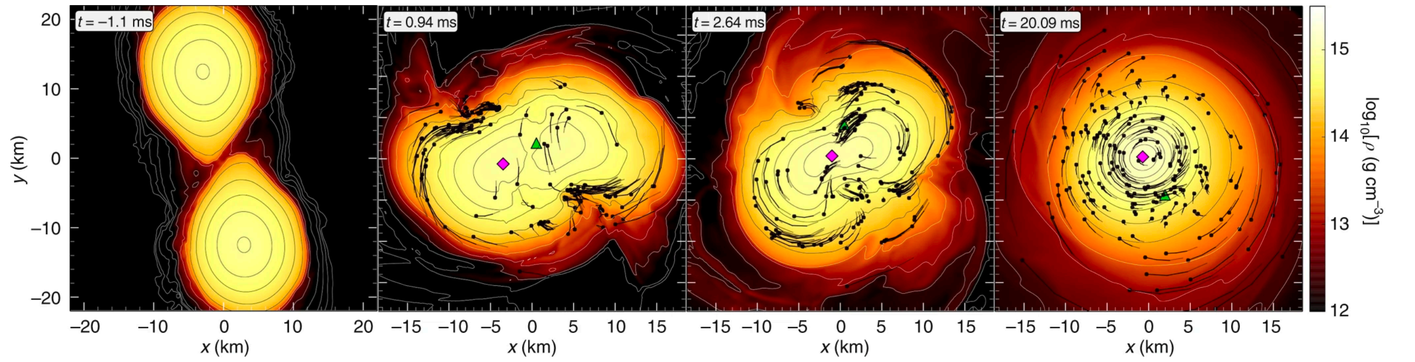


Neutron star



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

Neutron star merger

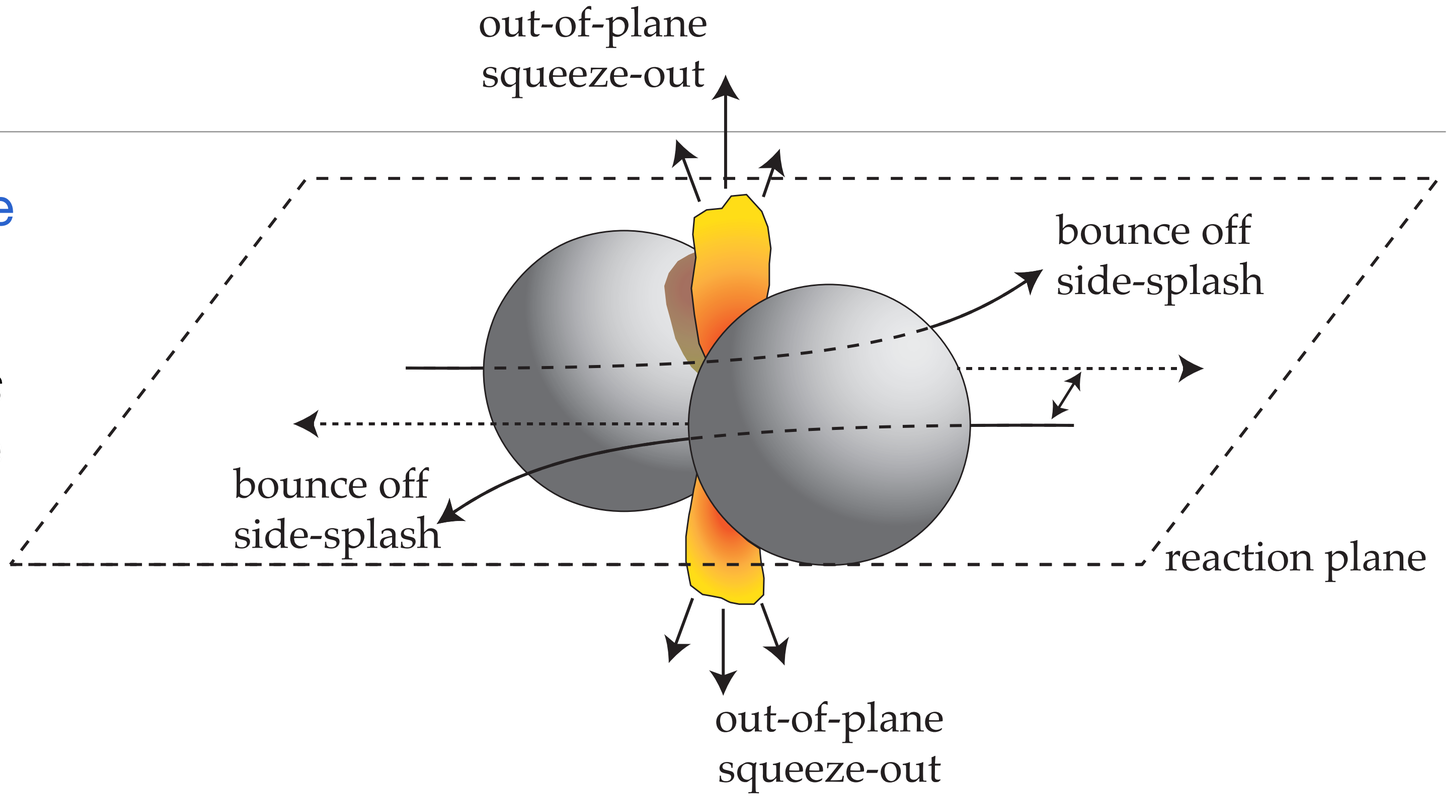


⇒ Heavy-ion collisions can provide access to equation-of-state of neutron star matter

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)*



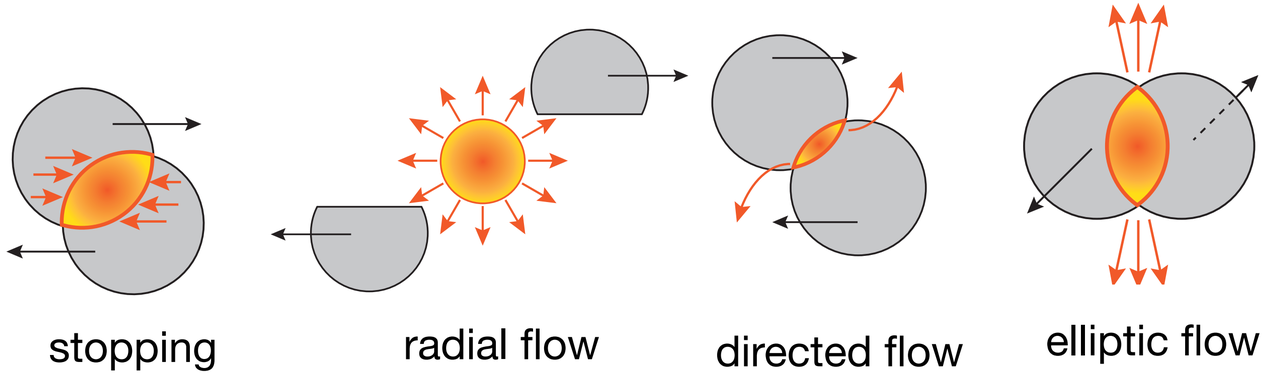
Fourier-decomposition of the triple differential invariant cross section

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

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

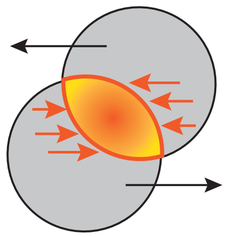
Extraction of azimuthal moments v_n

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



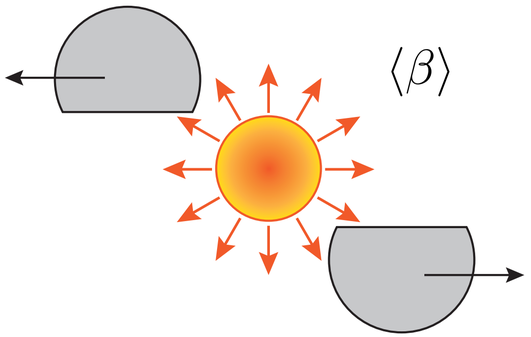
Motivation

Flow and Event Shapes

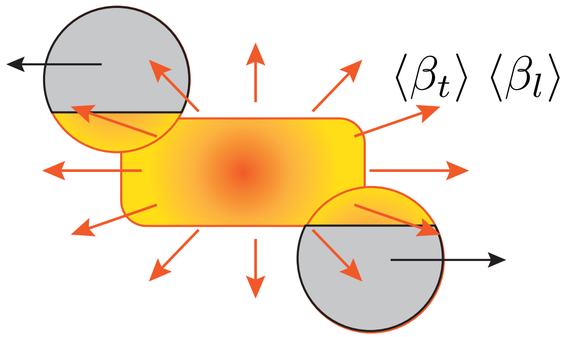


top view

radial flow

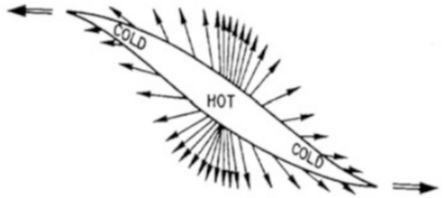


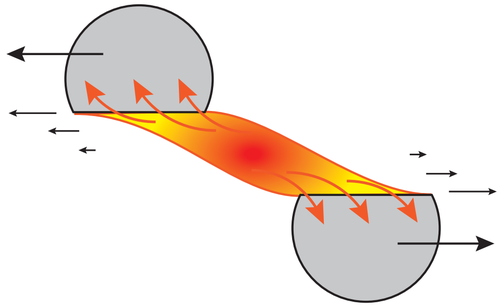
Landau scenario
total stopping



Bjorken scenario
partial stopping
initial longitudinal flow

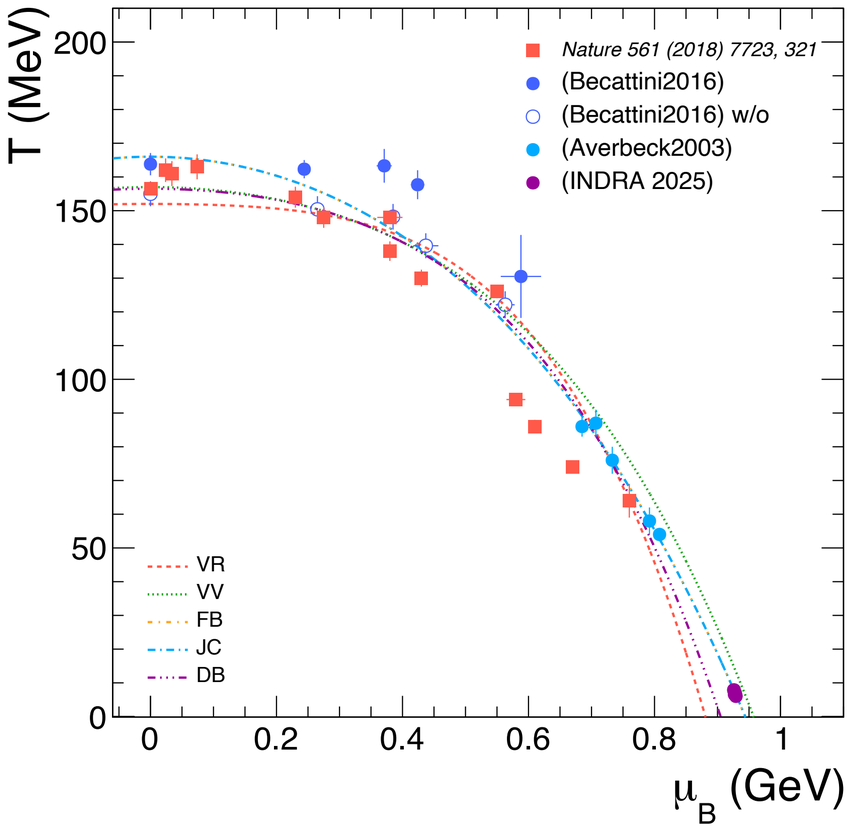
How to Deal with Relativistic Heavy Ion Collisions
R. Hagedorn (1981)

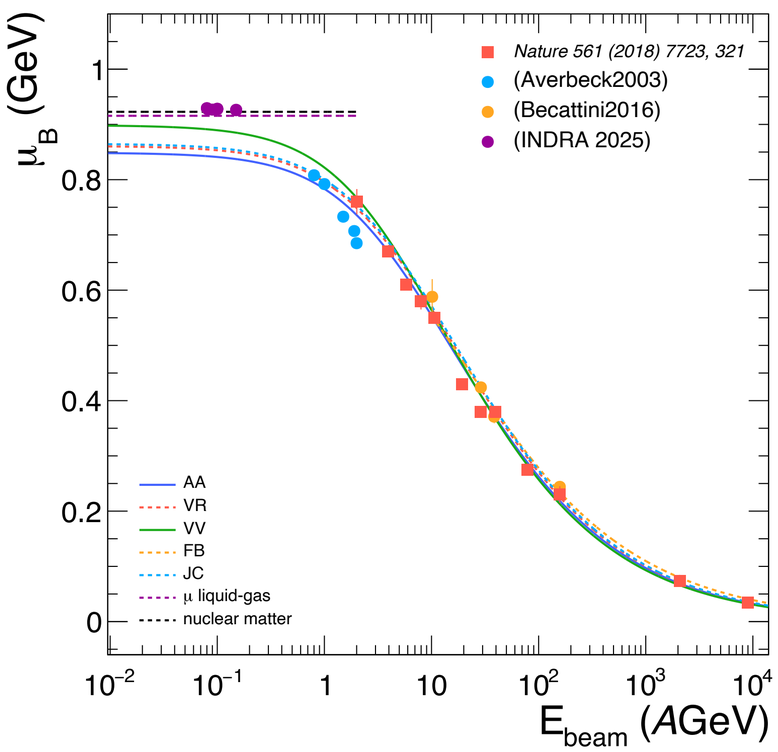


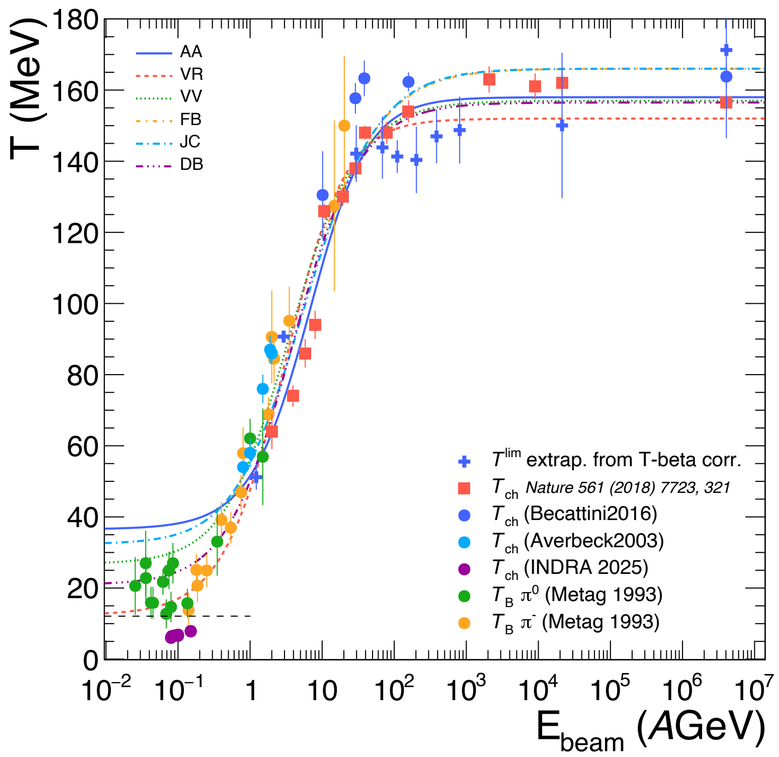


Hagedon-Myers scenario
(similar to “firestreak” model)
stopping dependent on nuclear density
partial stoped matter moves with
different rapidities

Phase diagram of QCD matter



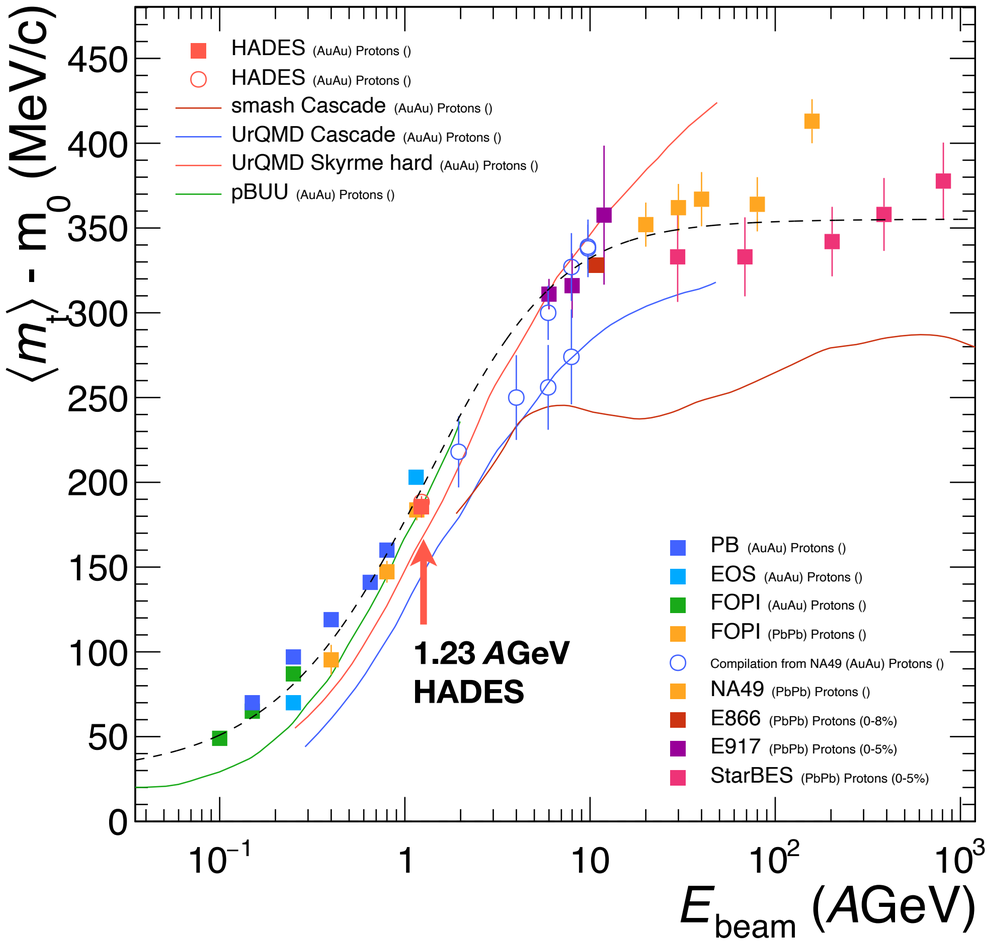


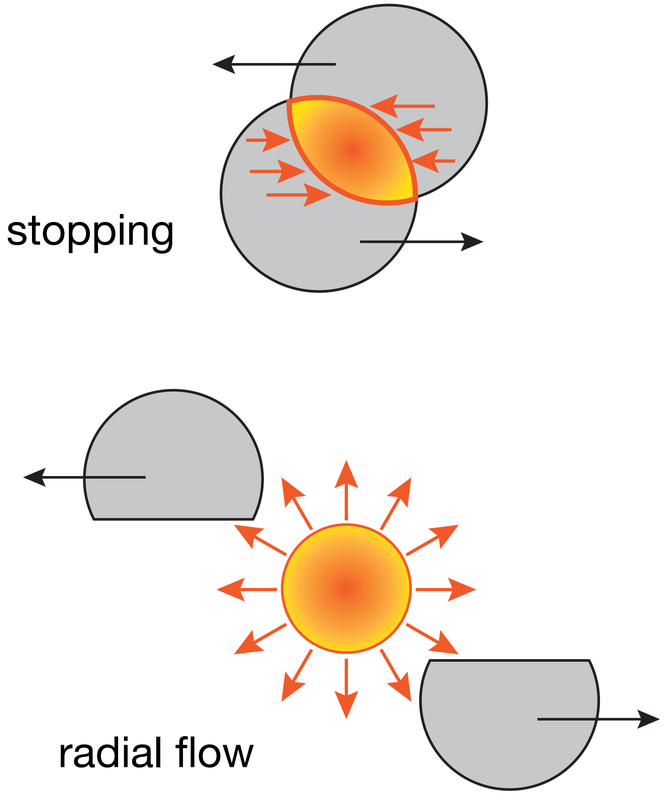


- Mapped via particle abundances fitted with the Statistical Hadronization Model (SHM) to determine temperature and chemical potential.

Collectivity

Energy dependence of radial flow





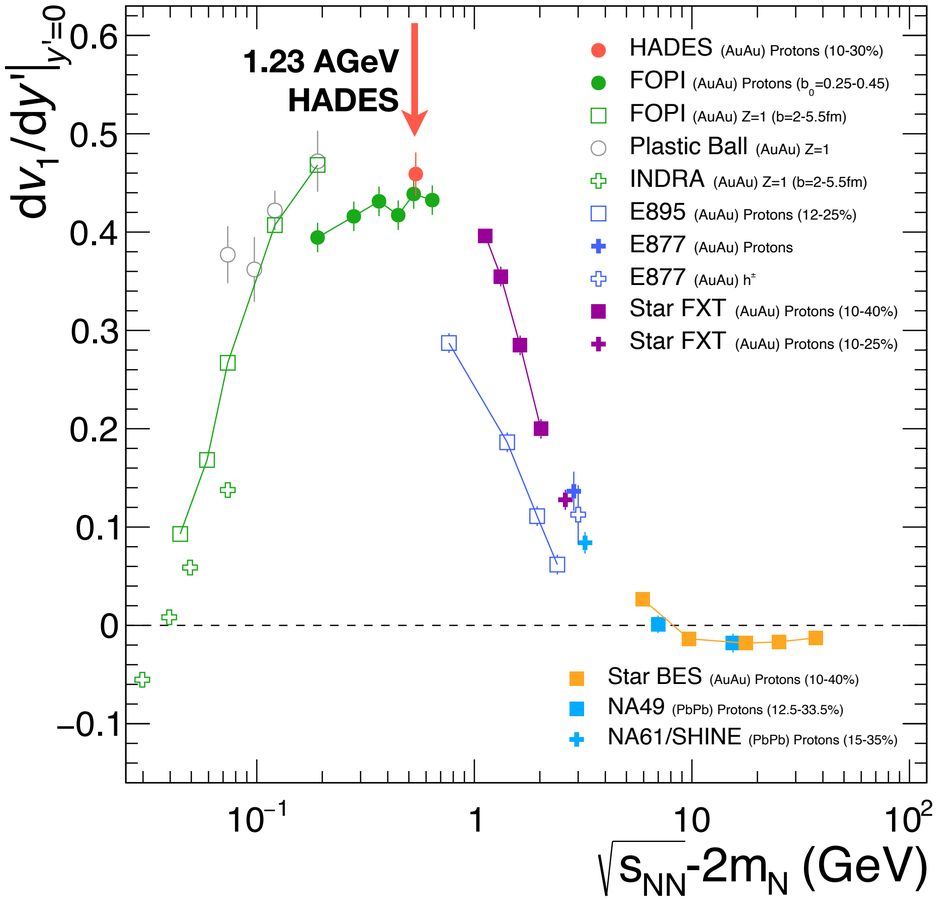
- Good agreement of the ***proton mean transverse mass*** $\langle m_t \rangle - m_0$ between experiments

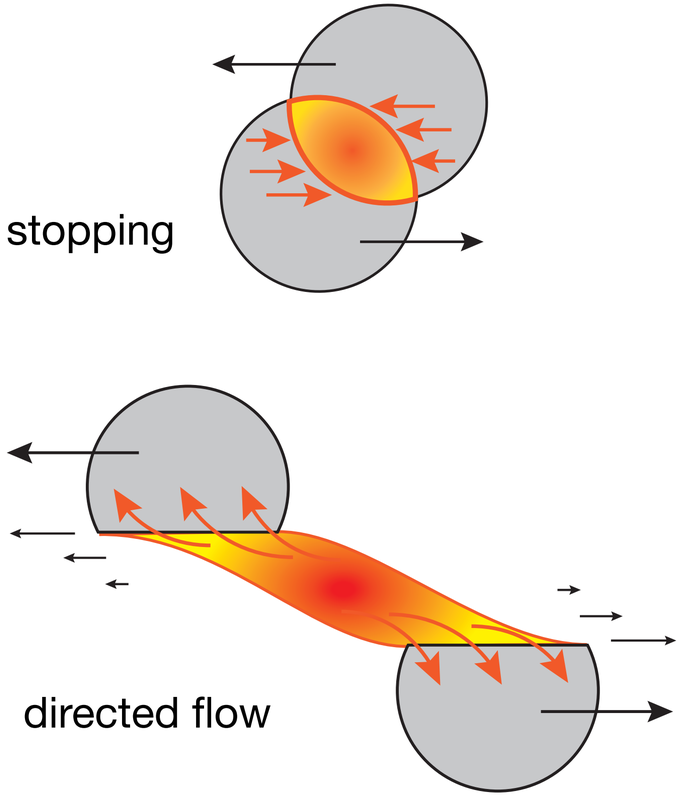
- ***Stopping*** is necessary condition for the creation of dense and hot nuclear matter

Collectivity

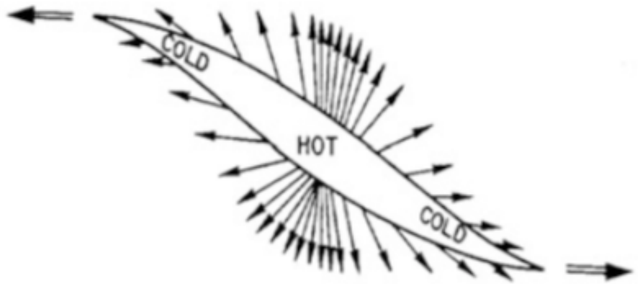
HADES, EPJ A 59 (2023) 80
STAR FXT (QM2023), Universe 10 (2024) 3, 118

Energy dependence of directed flow





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

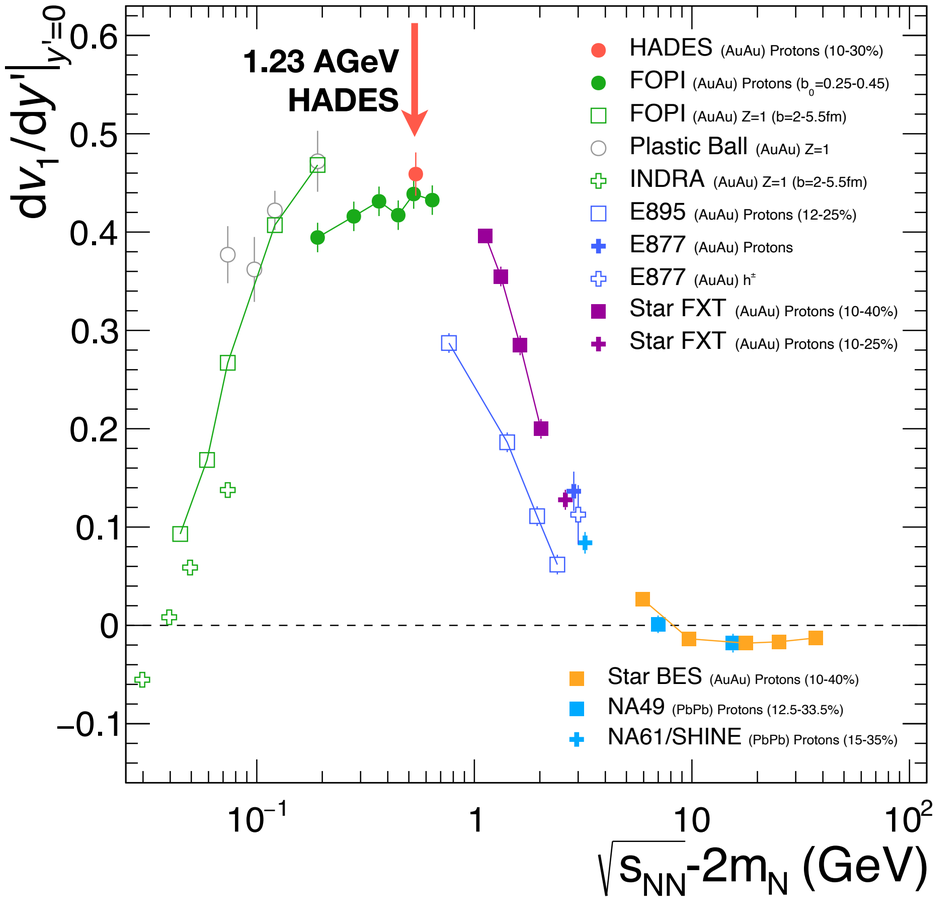


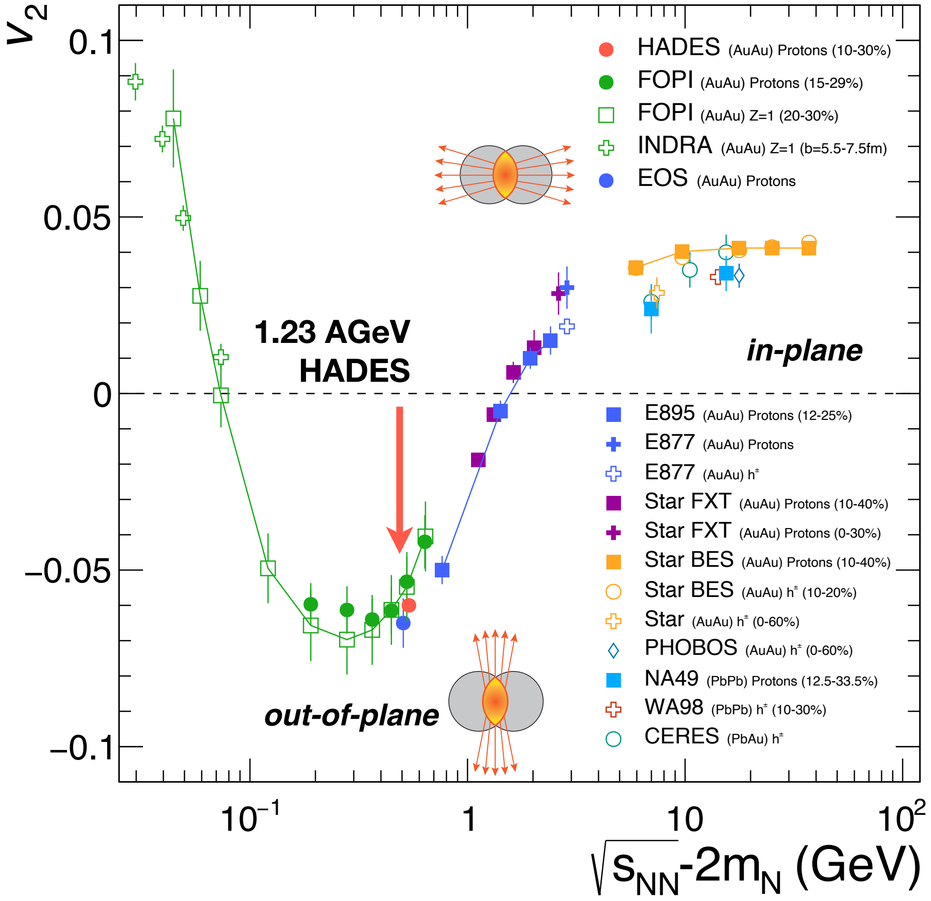
- Good agreement of integrated dv_1/dy (***directed flow***) and v_2 (***elliptic flow***) between experiments
- ***Partially stopped matter*** moves at different rapidities and results in non-uniform expanding density profile

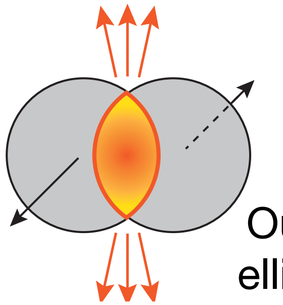
Collectivity

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

Energy dependence of directed and elliptic flow

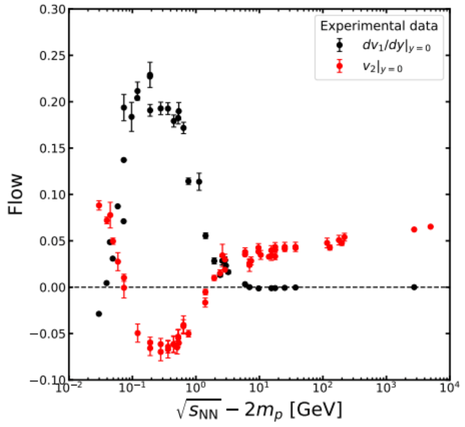






Out-of-plane elliptic flow v_2

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

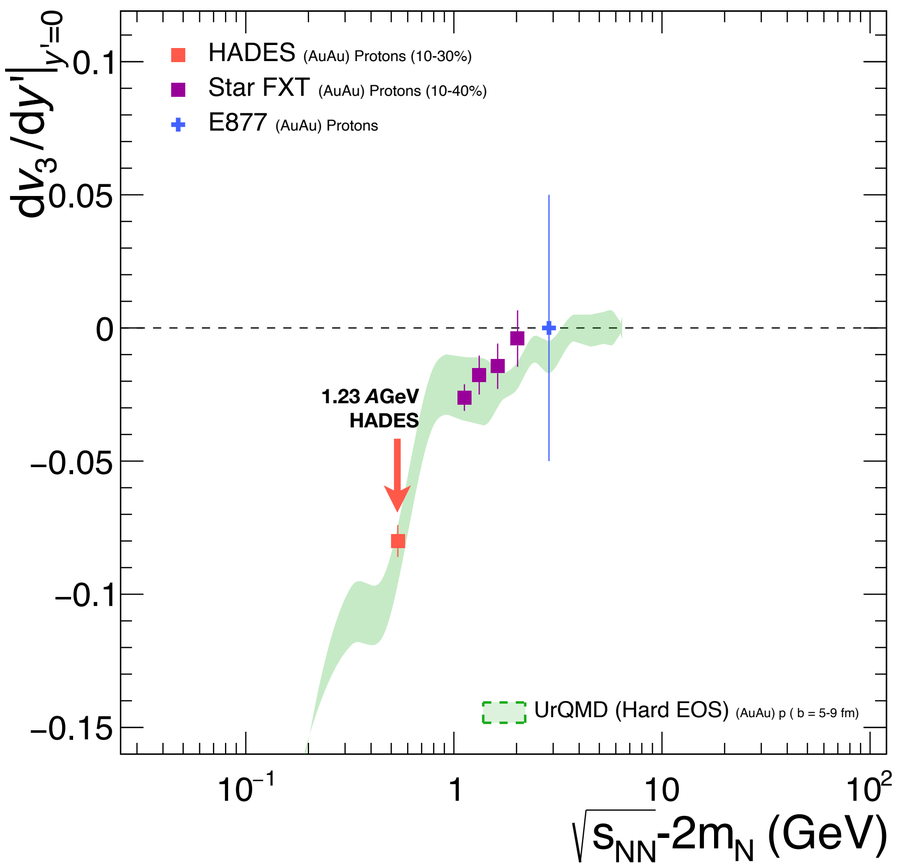


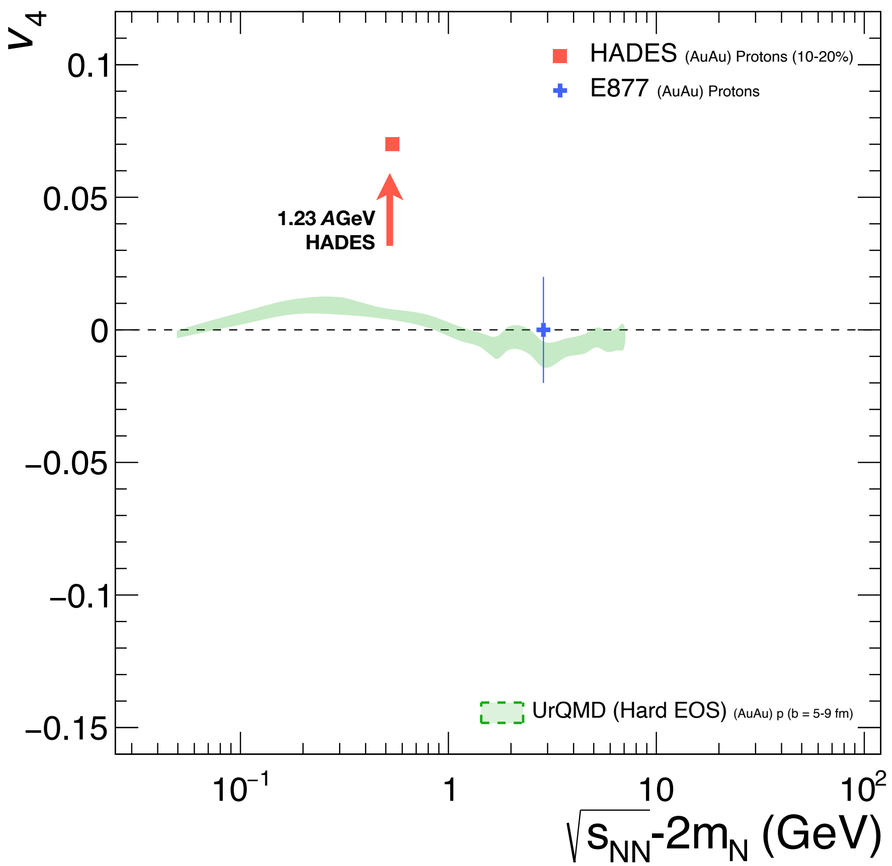
- Good agreement of integrated dv_1/dy (***directed flow***) and v_2 (***elliptic flow***) between experiments
- ***Long spectator passing time*** $\tau_{passing} \approx \tau_{expansion}$ $\Longrightarrow$ "squeeze-out" and/or "shadowing"

Collectivity

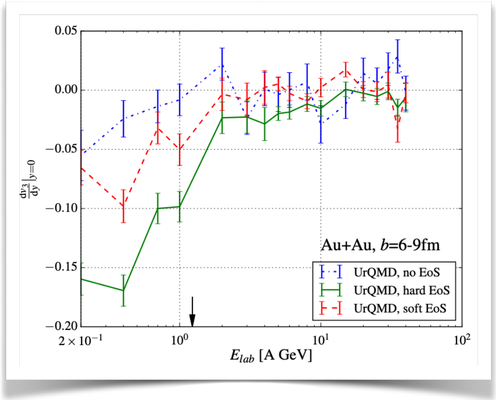
HADES, EPJ A 59 (2023) 80
E877 (AGS), PRL 73 (1994) 2532, PRC 56 (1997) 3254
STAR FXT (QM2023), Universe 10 (2024) 3, 118

Energy dependence of higher order - triangular and quadrangular flow

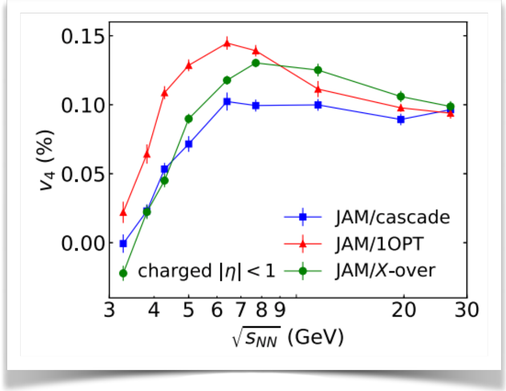




UrQMD, P. Hillmann et al.
JP **G45** (2018) 085101



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

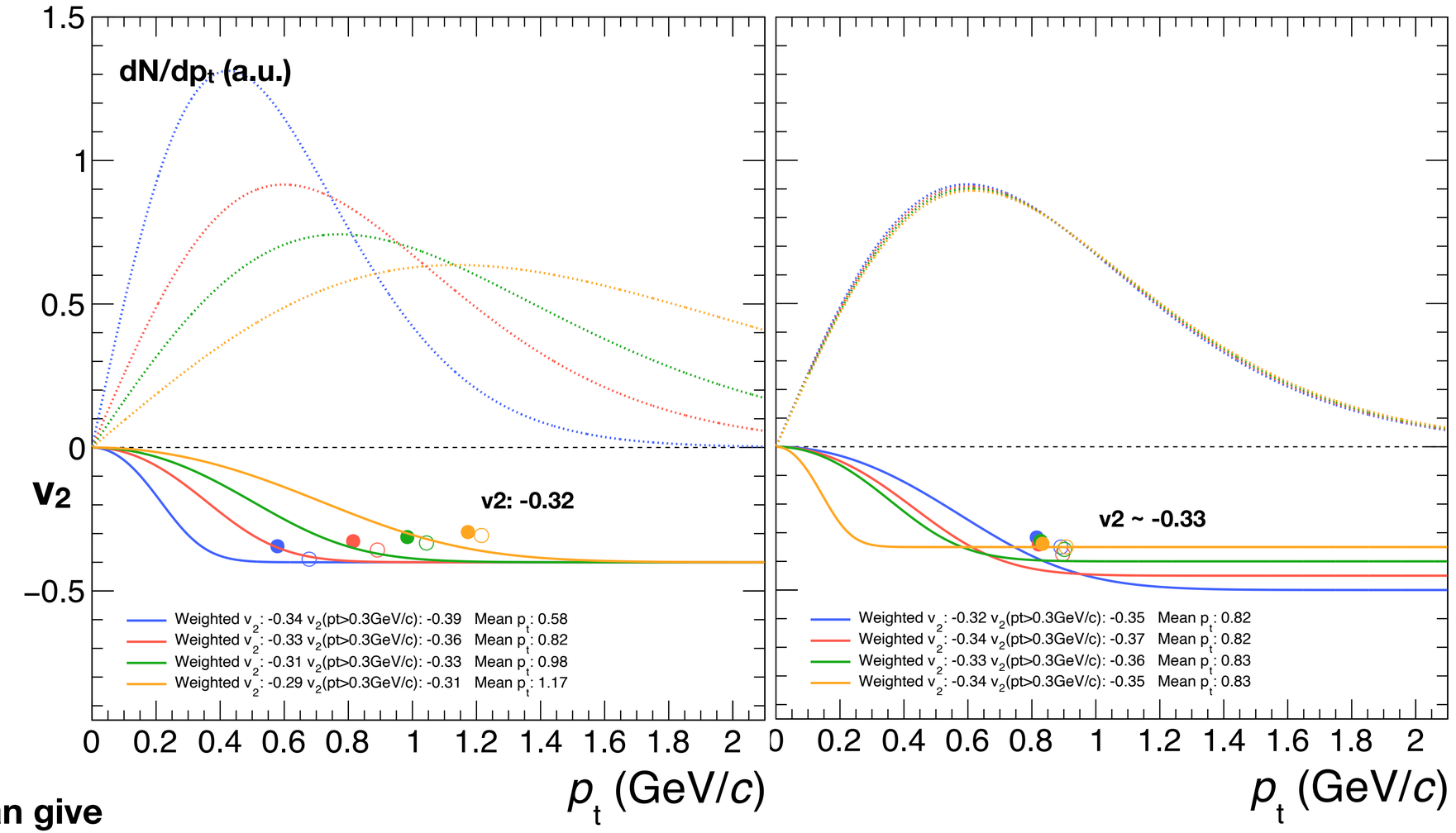


- ***Triangular*** dv_3/dy and ***quadrangular flow*** v_4
  Very scarce data at low energies

- Additional source of information
  Should help to narrow down EoS

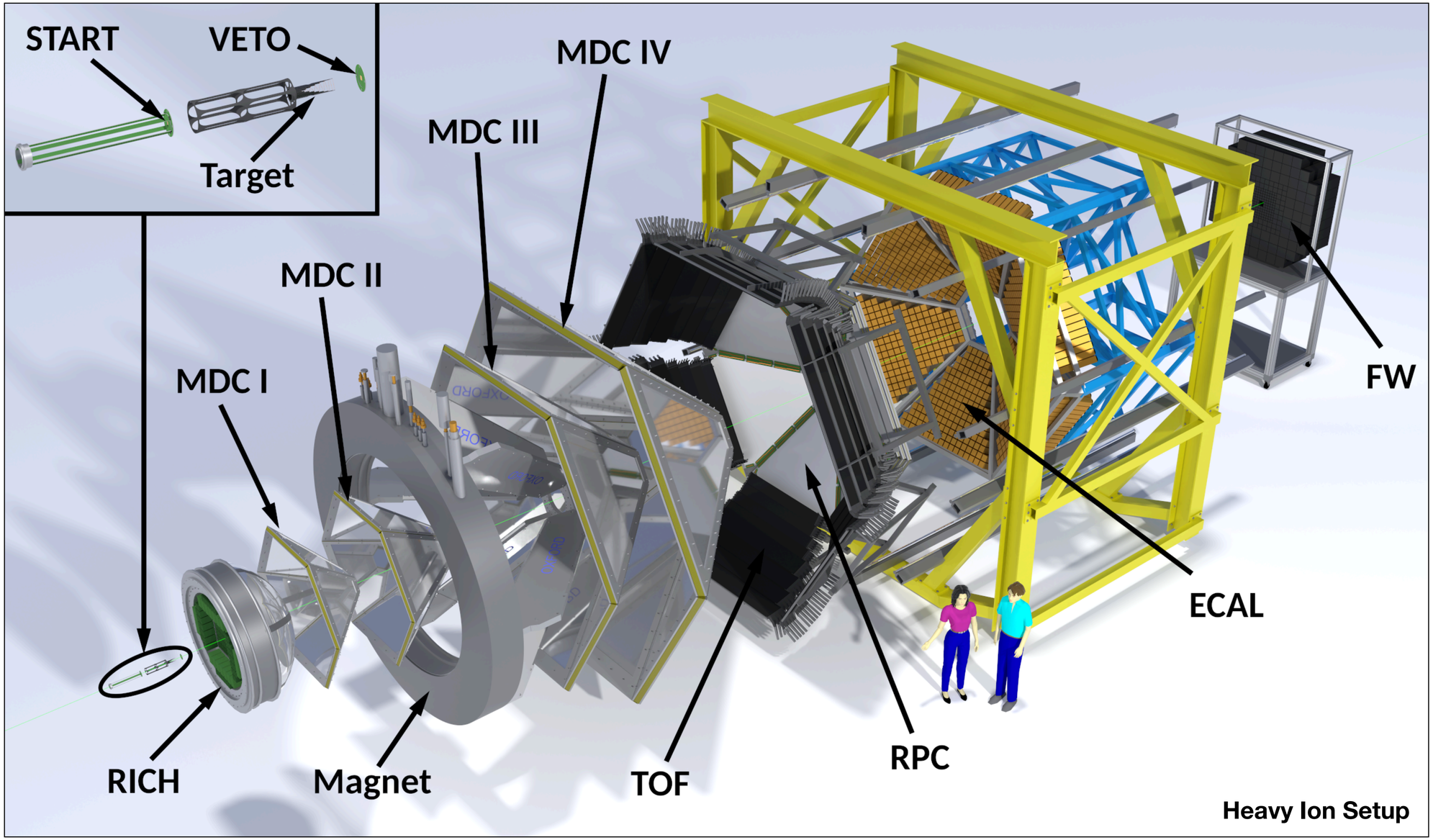
Elliptic Flow v_2

Integrated and p_t-Dependence



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

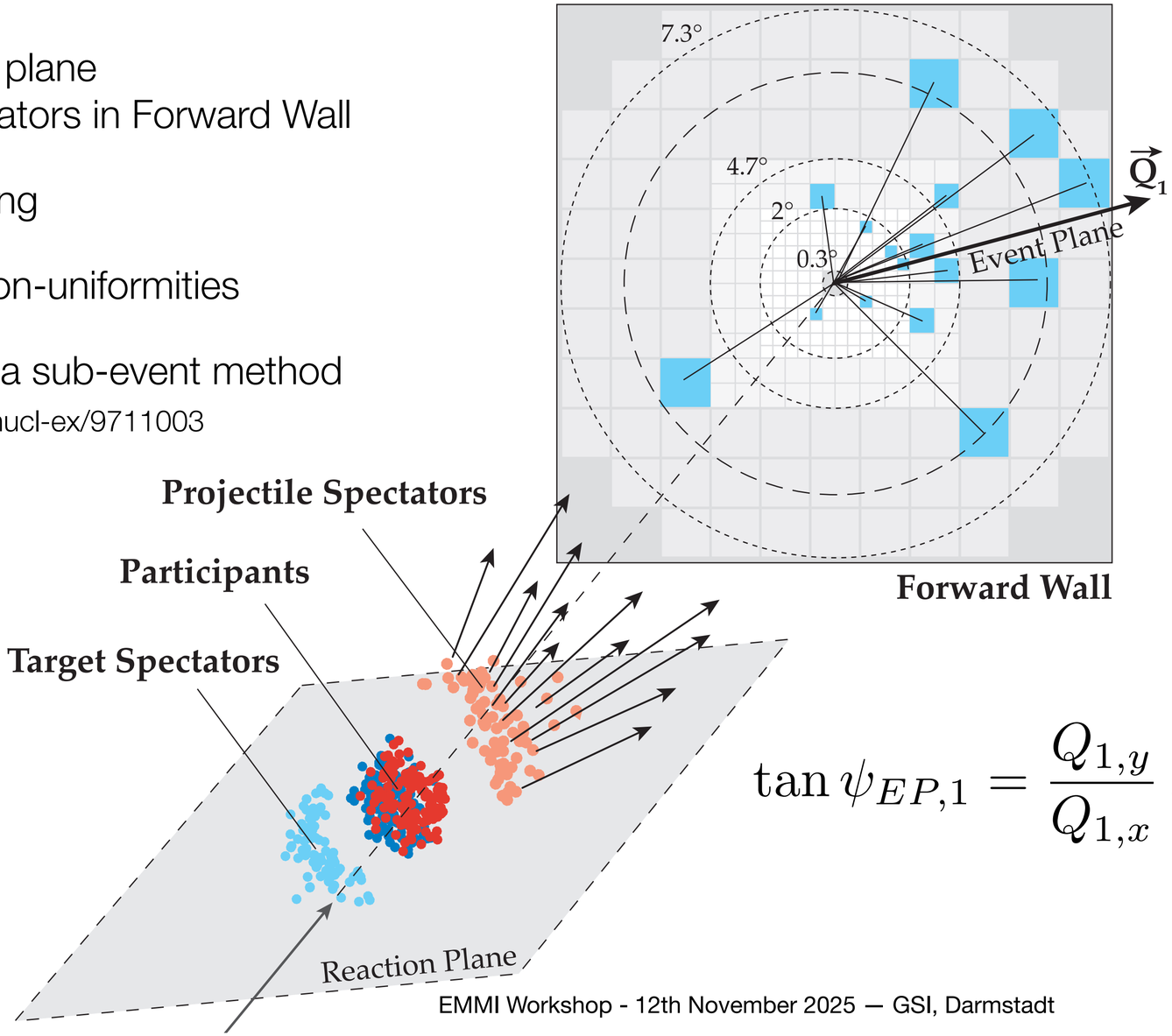
The HADES experiment

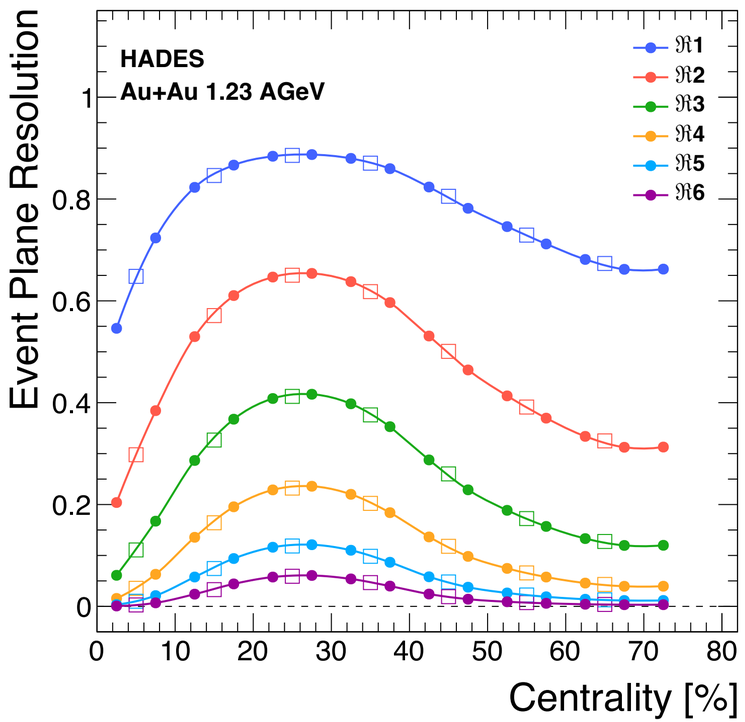


Flow Measurements

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





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

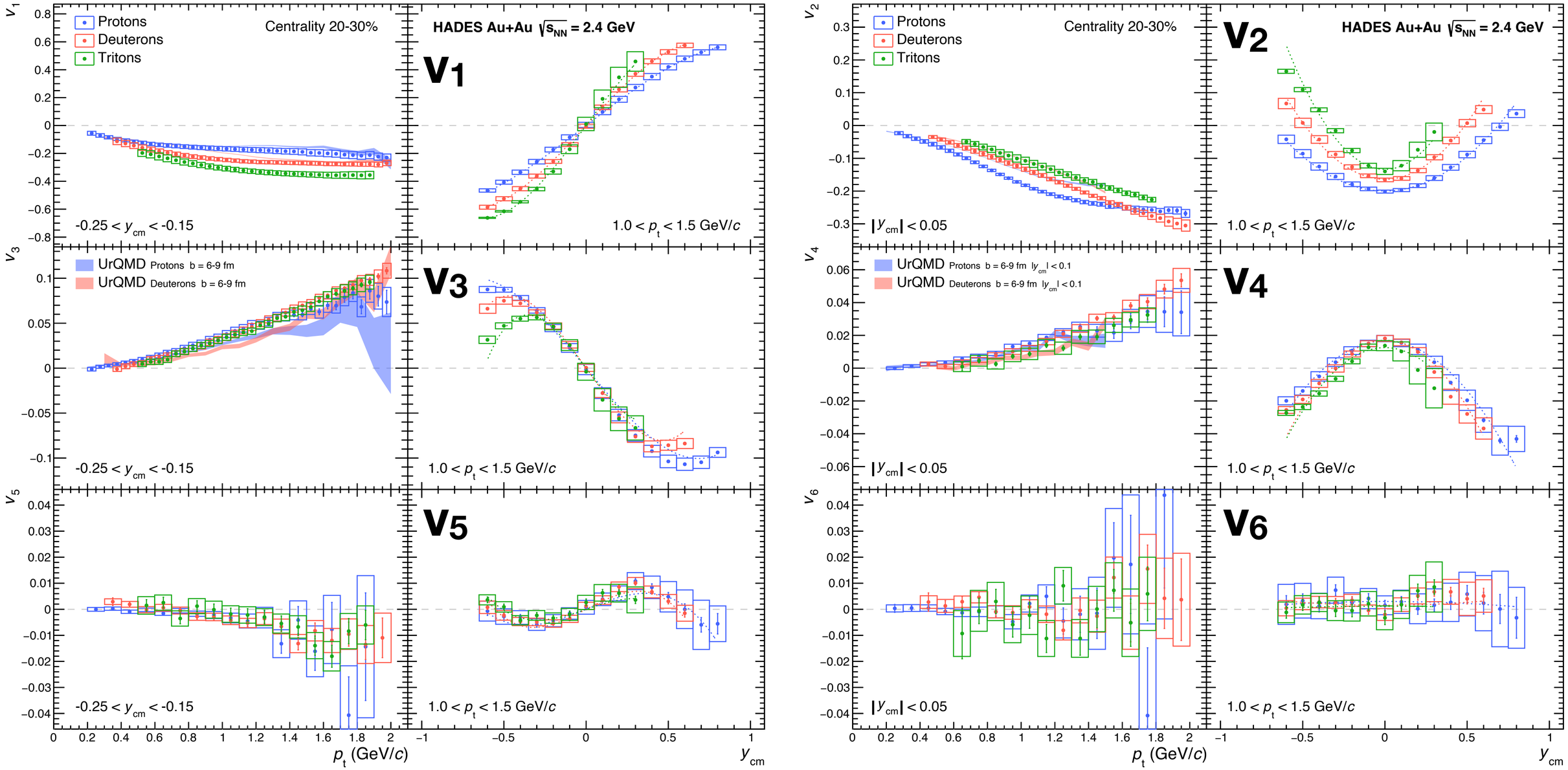
$$v_n = v_n^{obs} \,/\, \mathfrak{R}_n$$

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

Collective Effects

Results on v_1—v_6 for Protons, Deuterons and Tritons

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



Emission Pattern

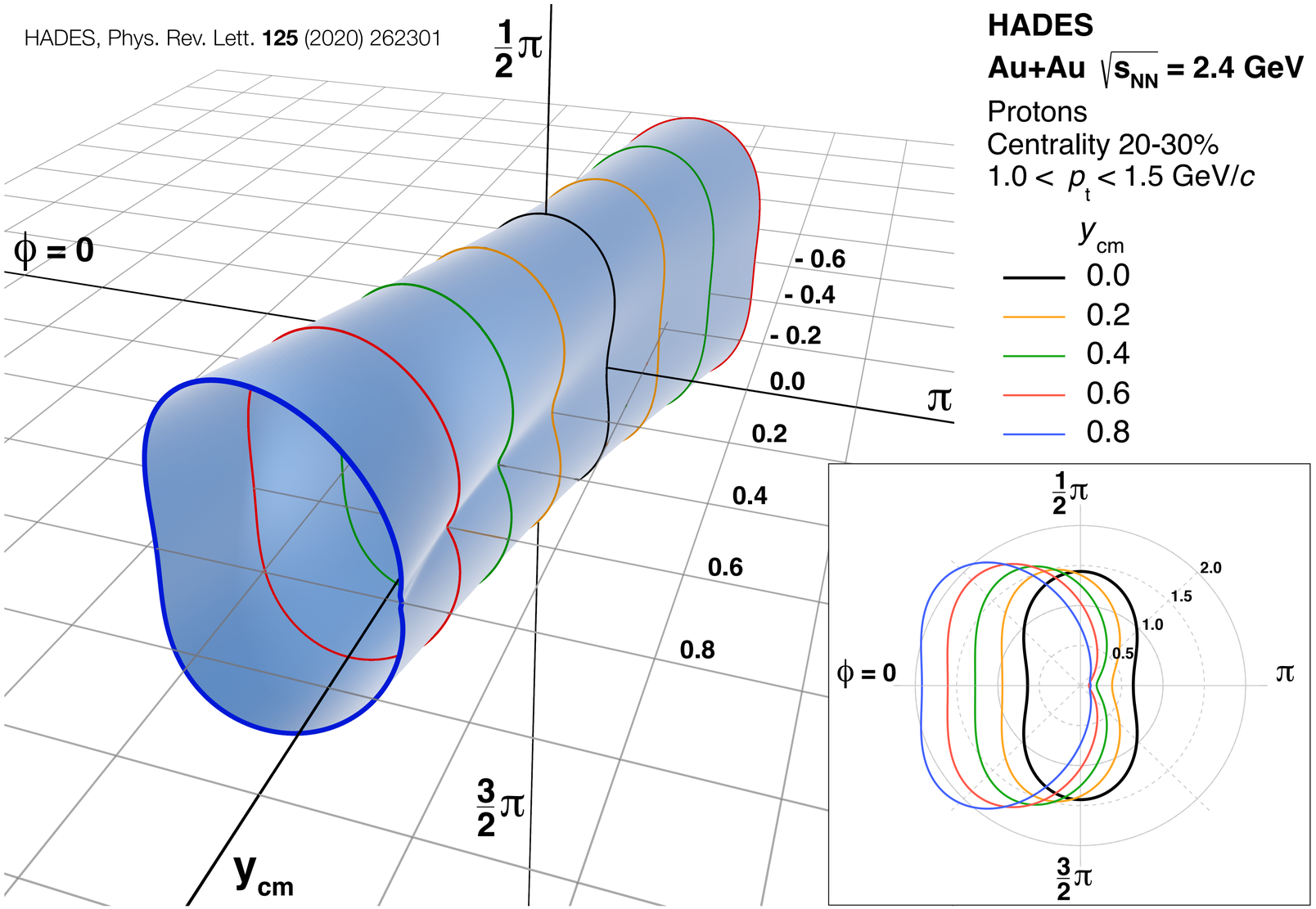
Protons

- 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

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

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

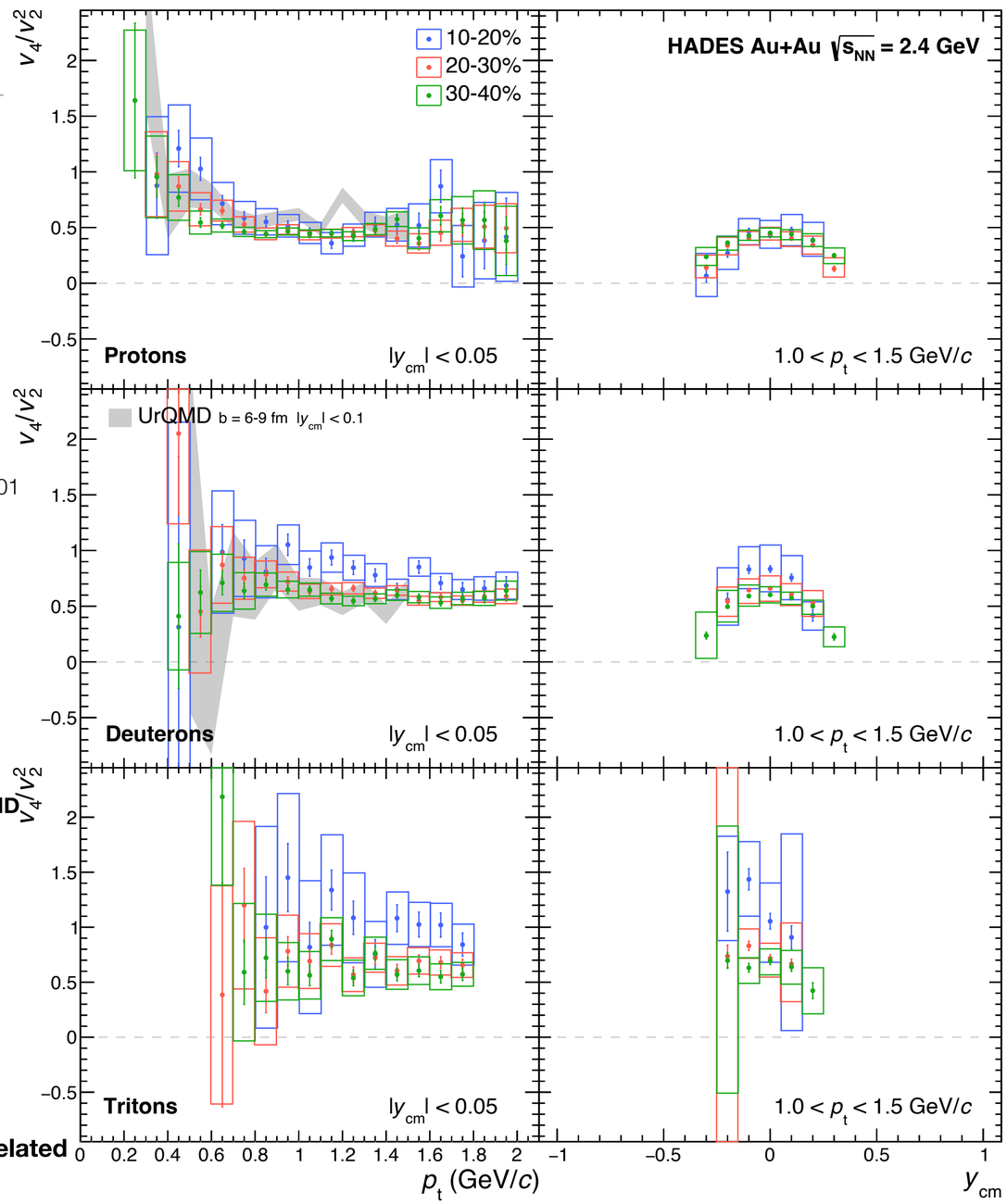
Independent of p_t and centrality
Close to predicted value of ~ 0.6

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



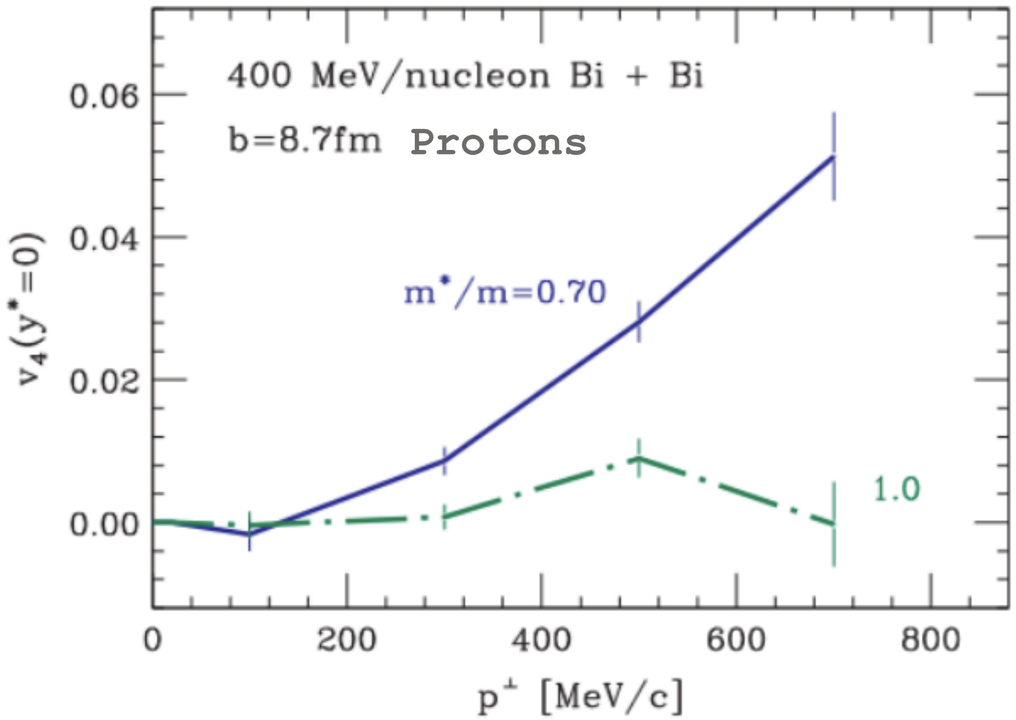
Systematic Error of v2 and v4 are treated as correlated

Equation of State of Dense Matter

Momentum Dependence of the mean fields

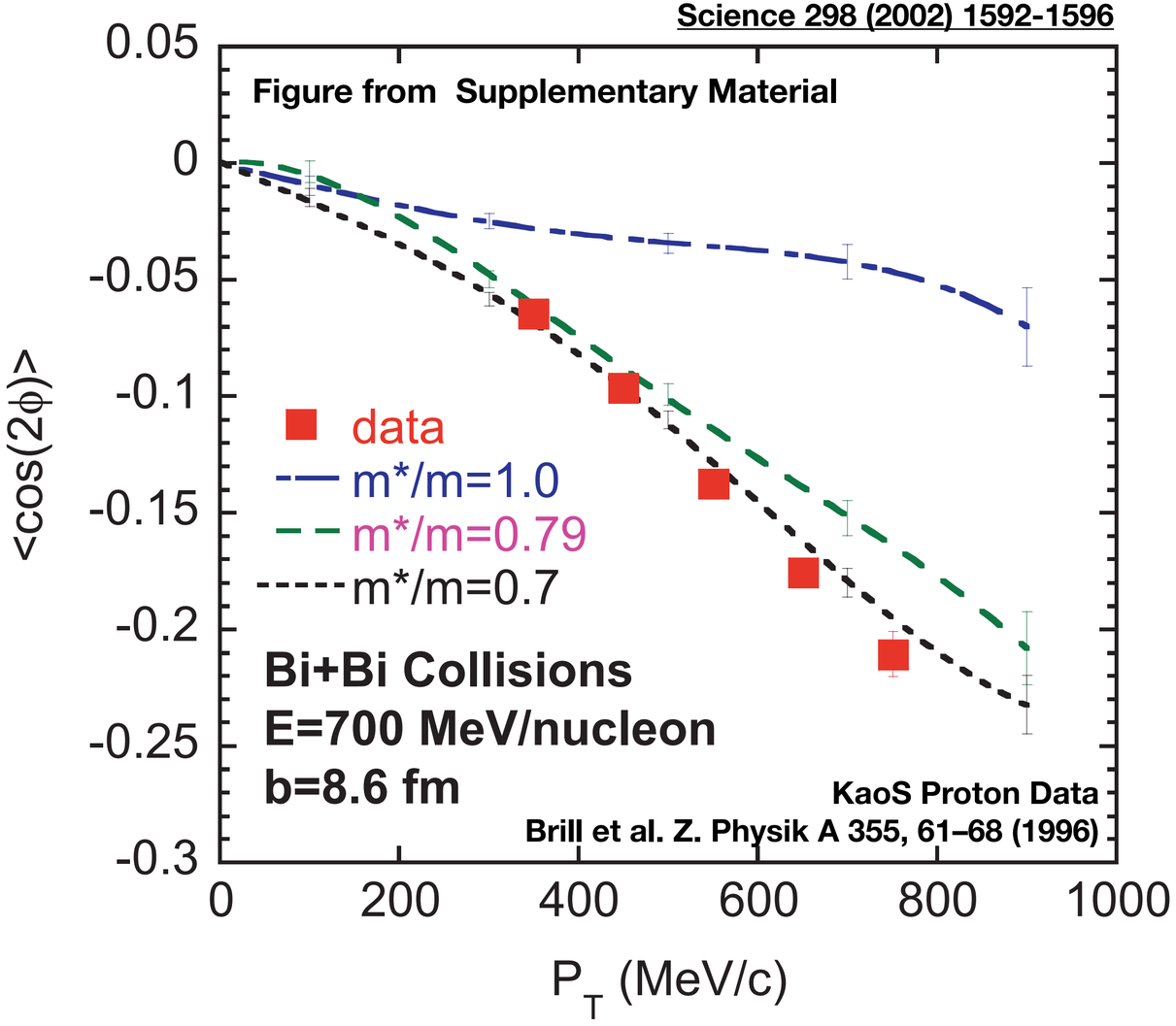
Momentum dependence characterized by **$m^*=0.7m_N$**

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



First prediction of v_4{RP} in 2000!

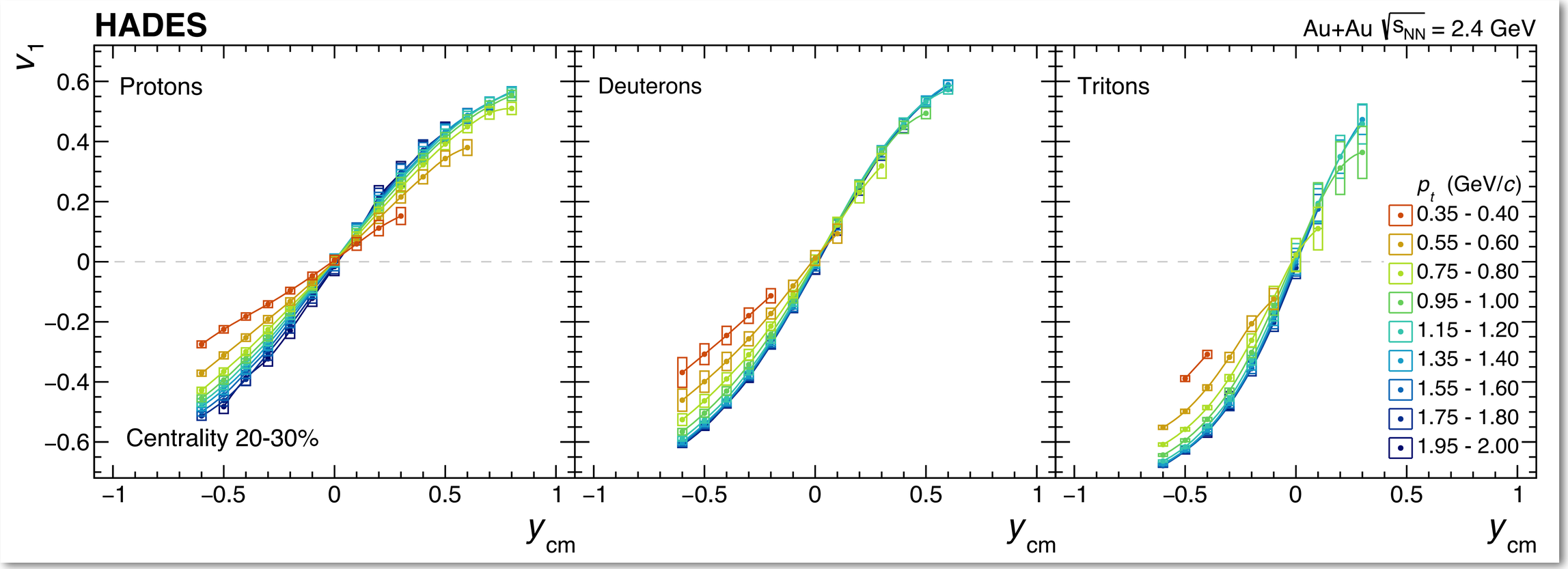
P. Danielewicz, R. Lacey, W.G. Lynch
Science 298 (2002) 1592-1596



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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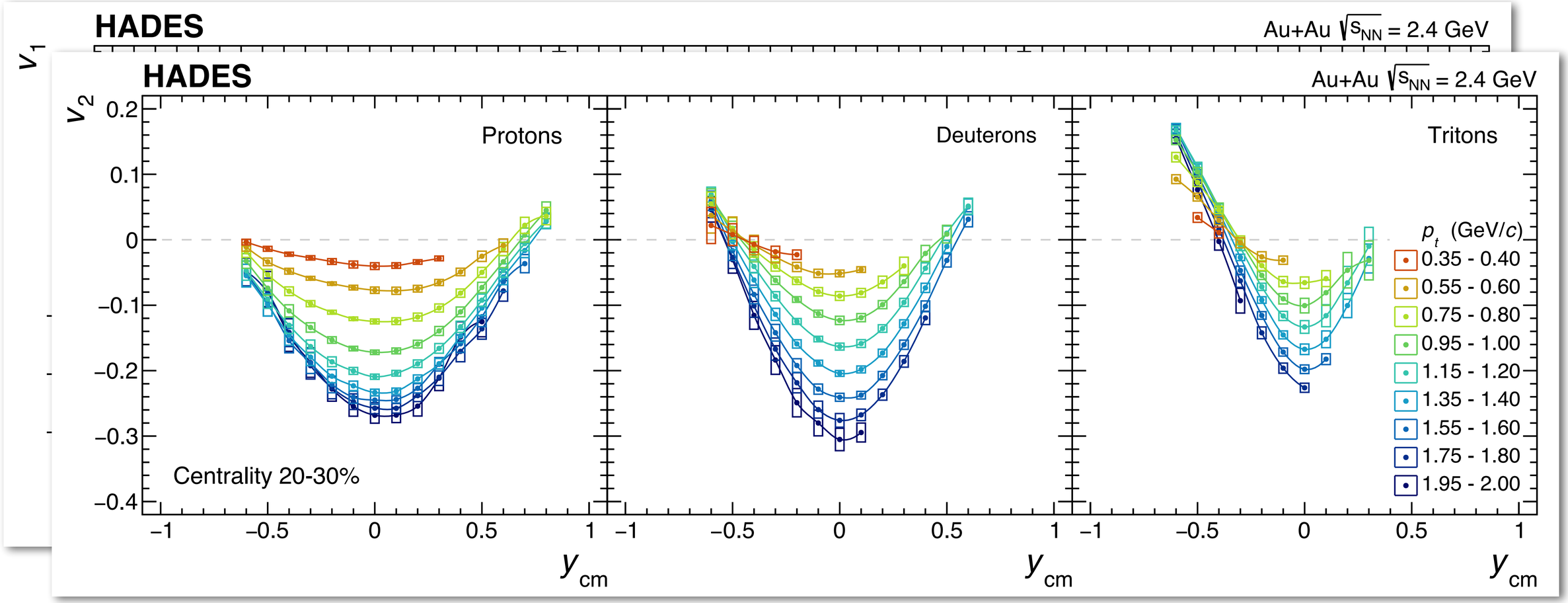

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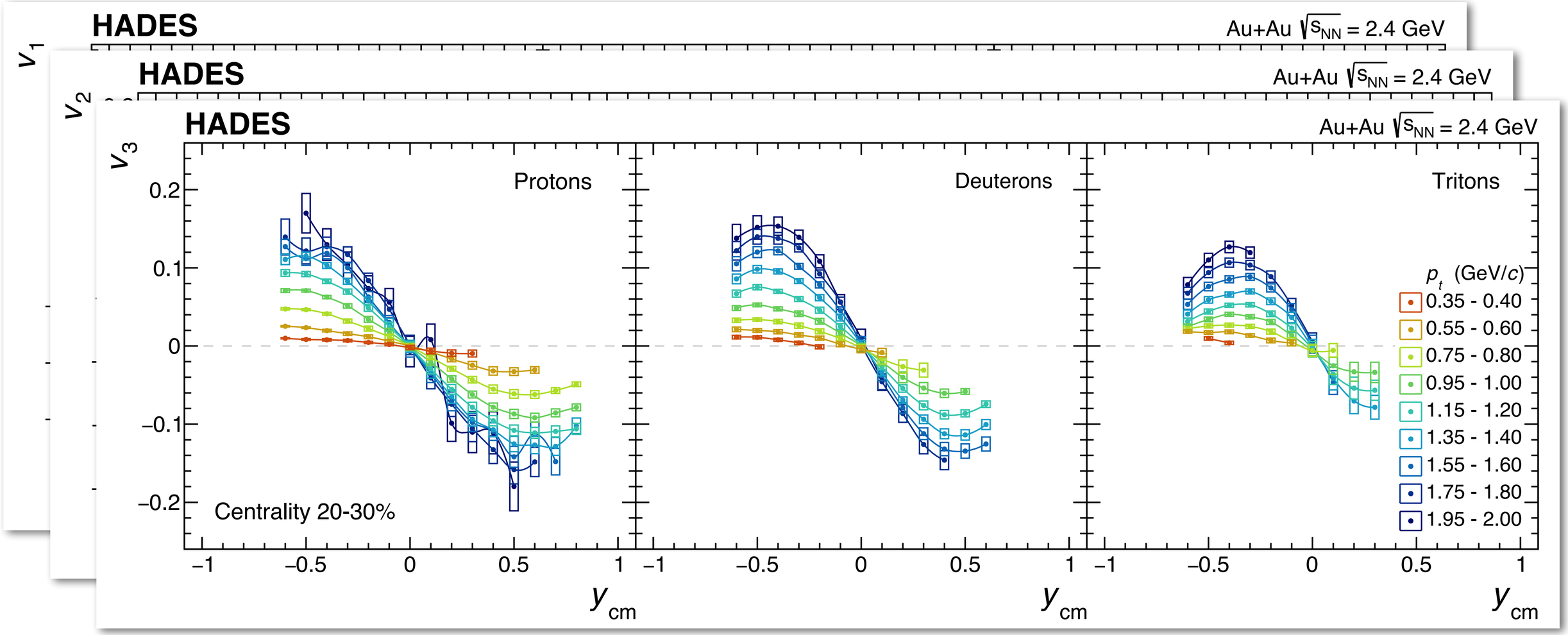

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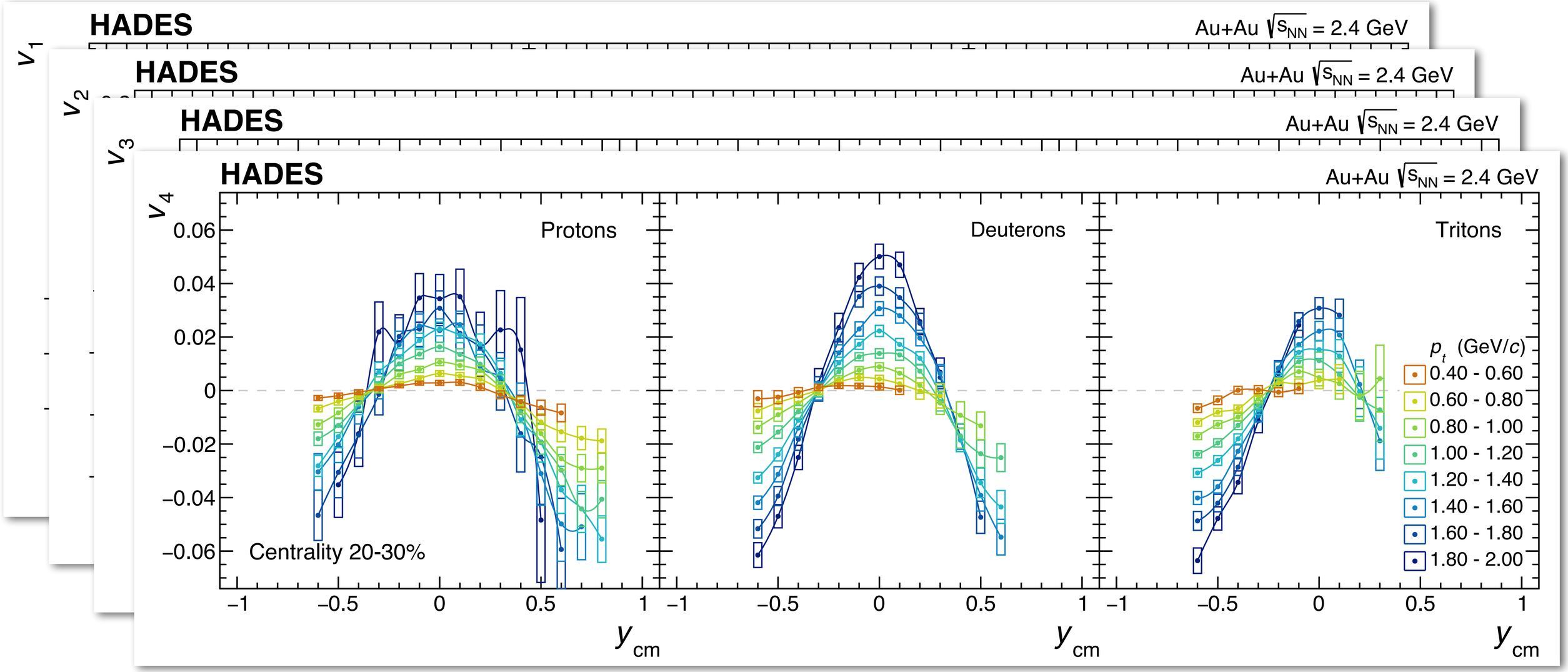

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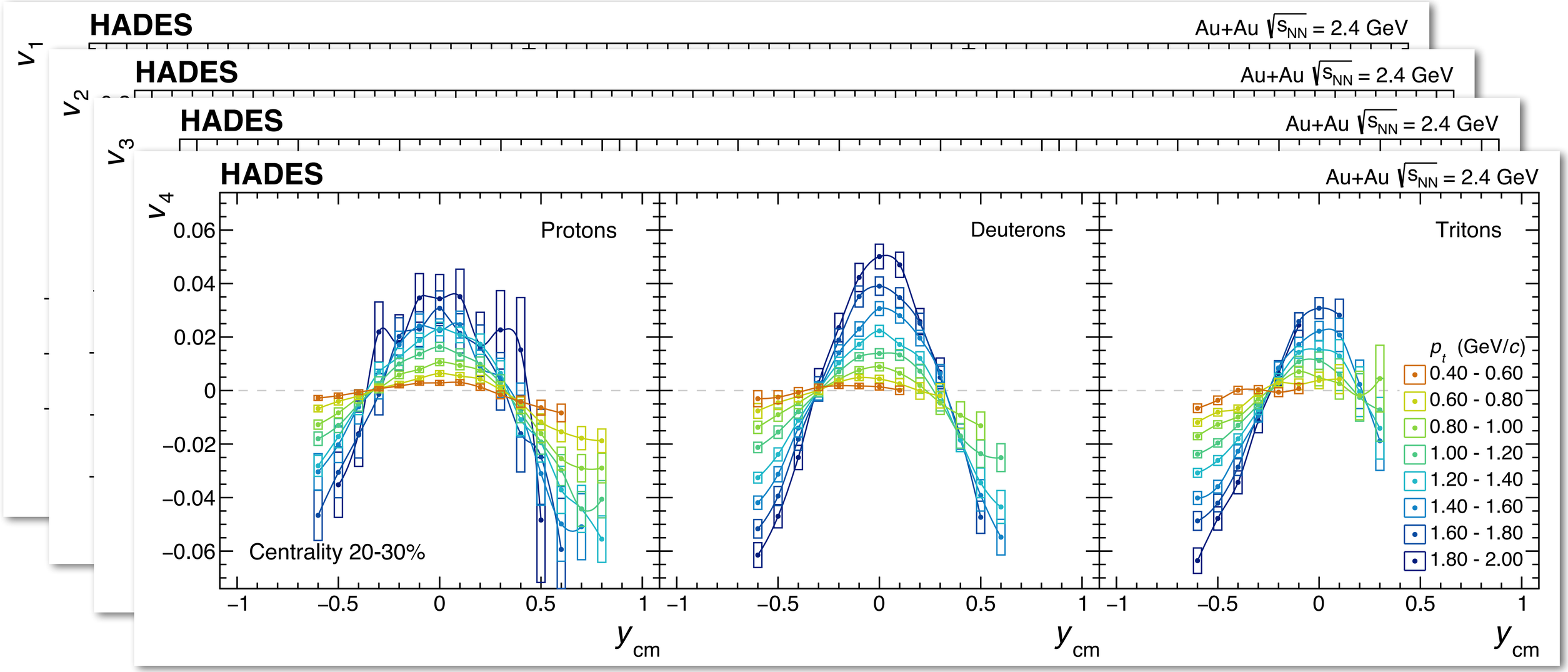
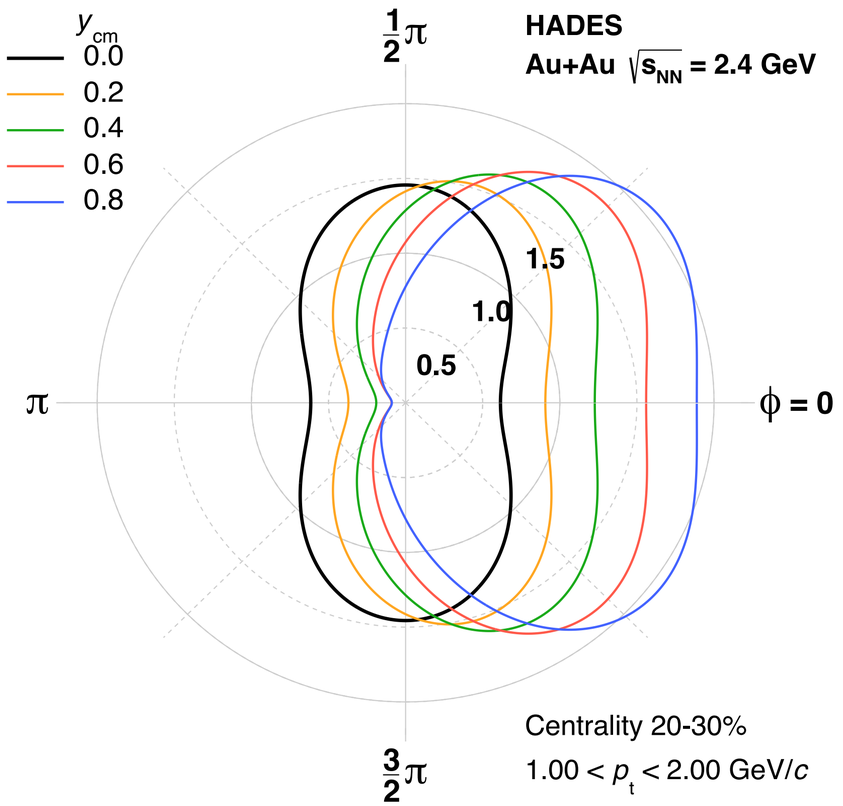


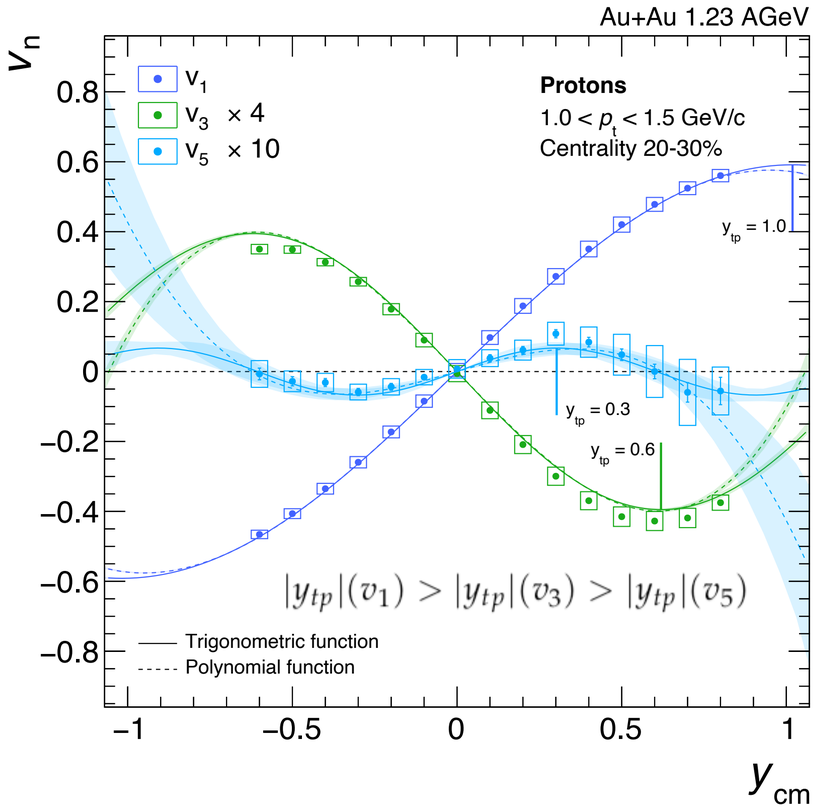
Only a fraction of the data is shown

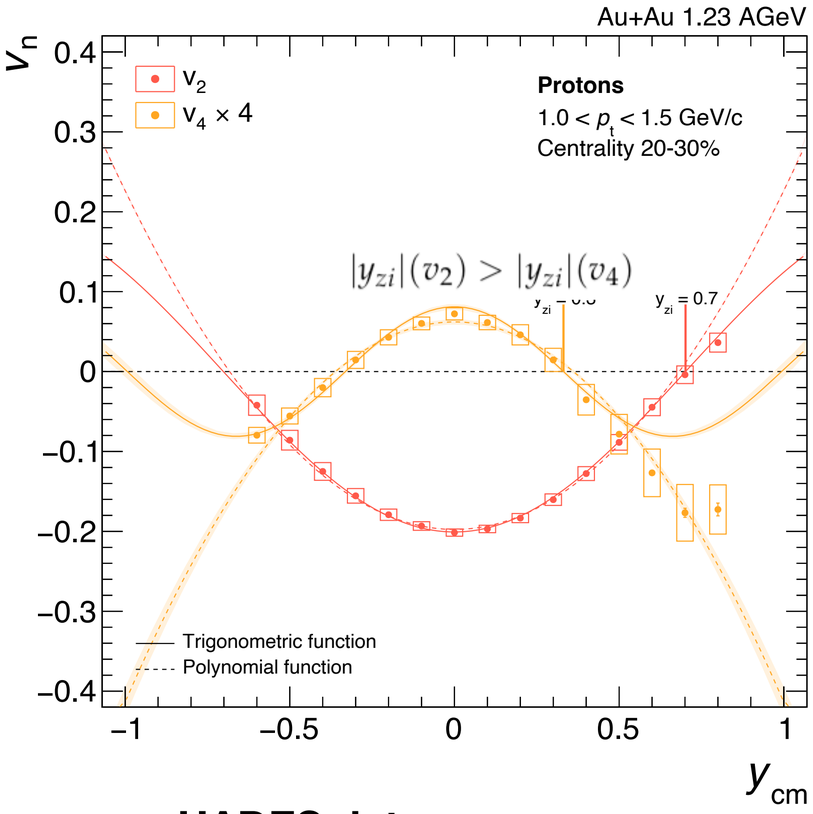
In total 17k data points with individual systematic uncertainties available: [hepdata]

Parameterisation

Rapidity-Dependence







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

Polynomial function:

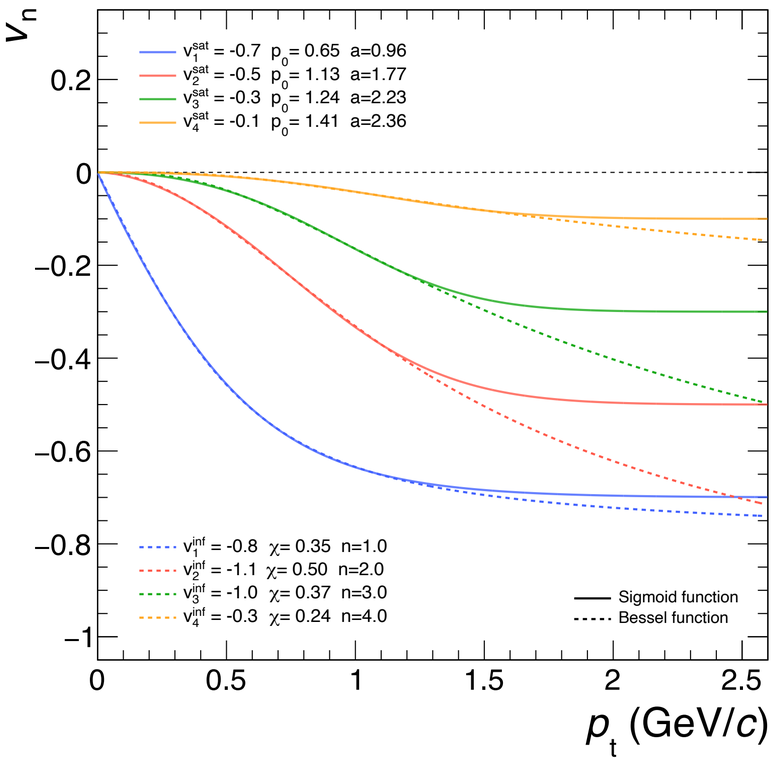
$$v_{n,\,odd}(y_{\rm cm}) = v_{n1}\, y_{\rm cm} + v_{n3}\, y_{\rm cm}^3$$
$$v_{n,\,even}(y_{\rm cm}) = v_{n0} + v_{n2}\, y_{\rm cm}^2$$

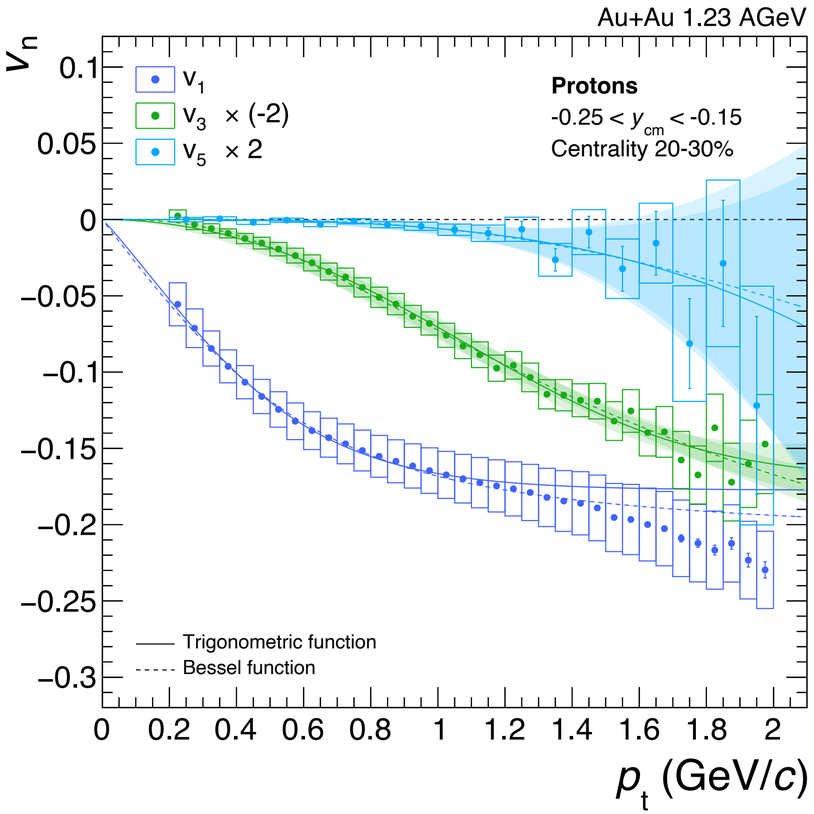
Trigonometric functions:

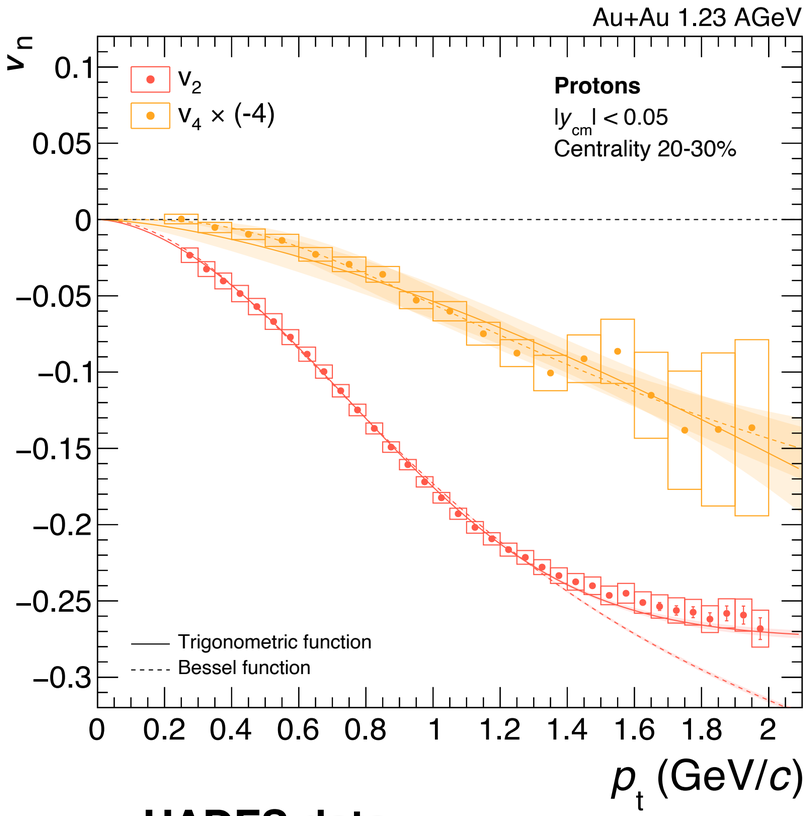
$$v_n^{odd}(y_{\rm cm}) = v_n^{\rm sat} \cdot \sin(y_{\rm cm}/y_{tp} \cdot \pi/2)$$
$$v_n^{even}(y_{\rm cm}) = v_n^{\rm sat} \cdot \cos(y_{\rm cm}/y_{zi} \cdot \pi/2)$$

Parameterisation based on Blast-Wave Model

p_t-Dependence







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

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:

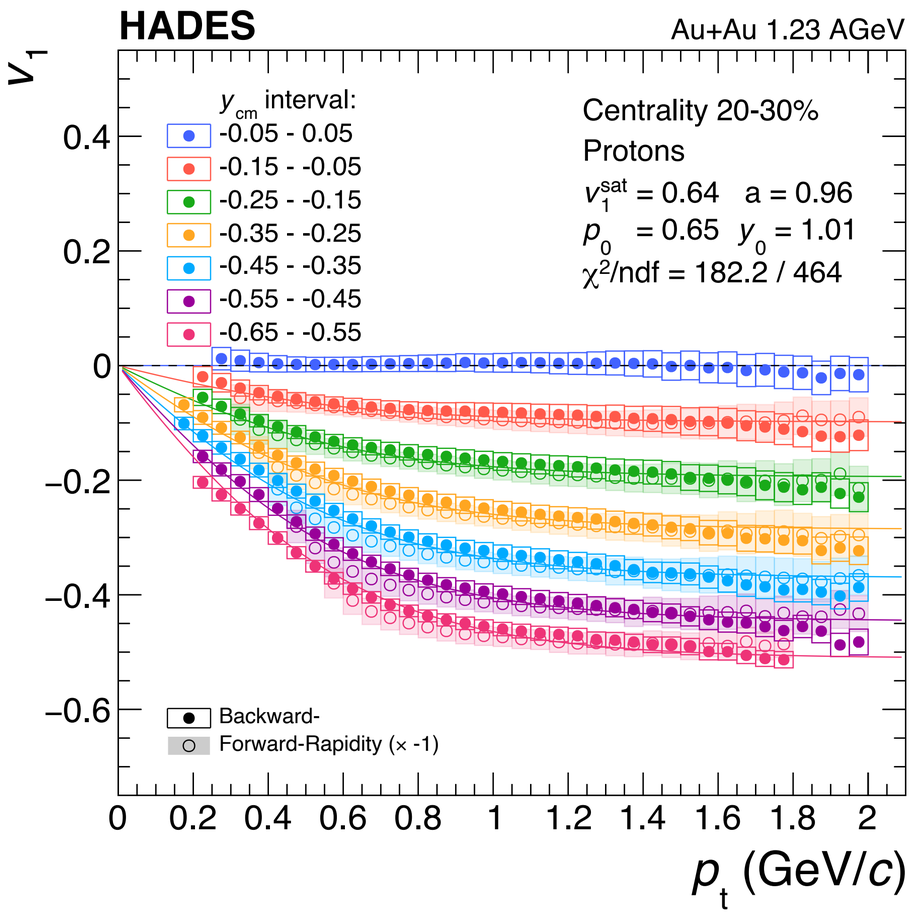
$$v_n(p_t) = v_n^{\mathrm{inf}}\ I_n(p_t/\chi)/I_0(p_t/\chi)$$

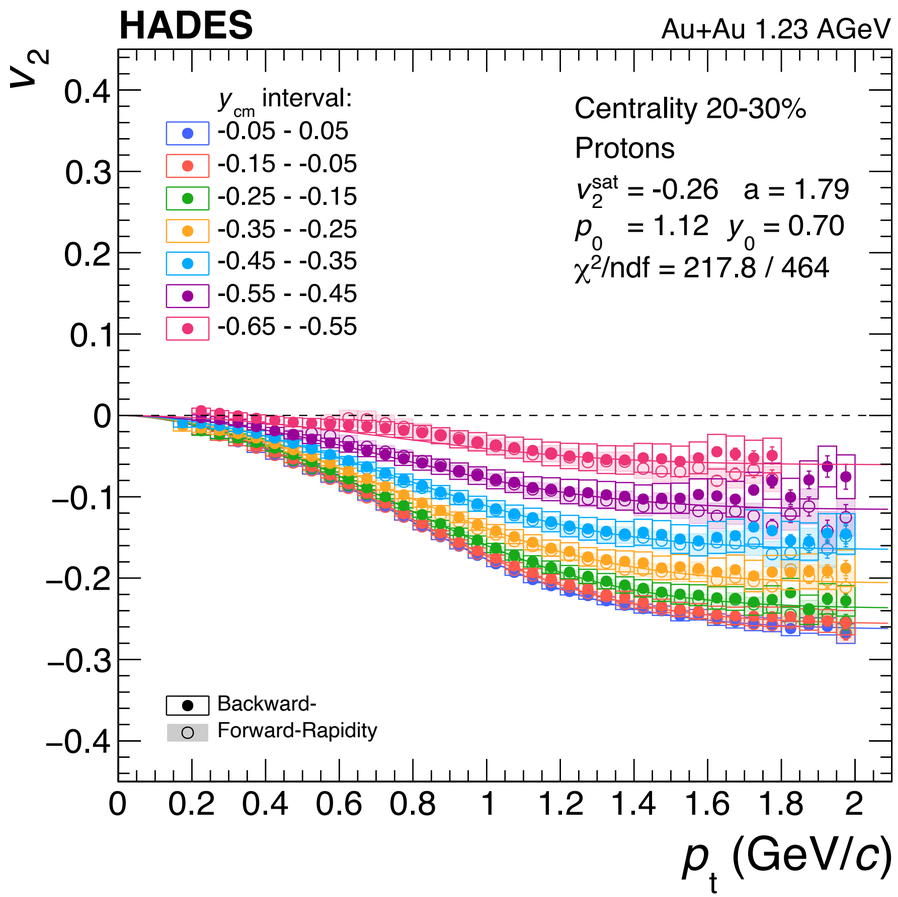
Trigonometric functions:

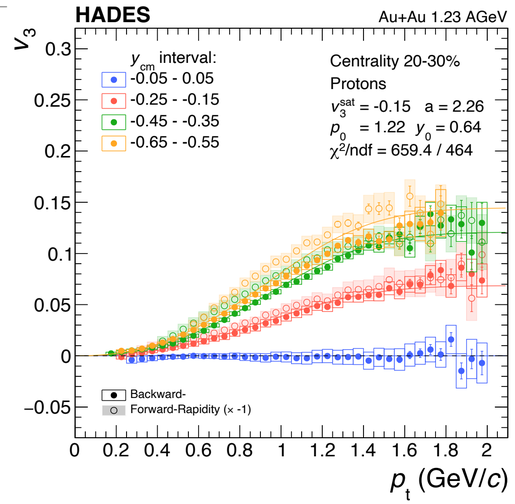
$$v_n(p_t) = v_n^{\mathrm{sat}} \cdot \tanh(p_t/p_0)^a$$

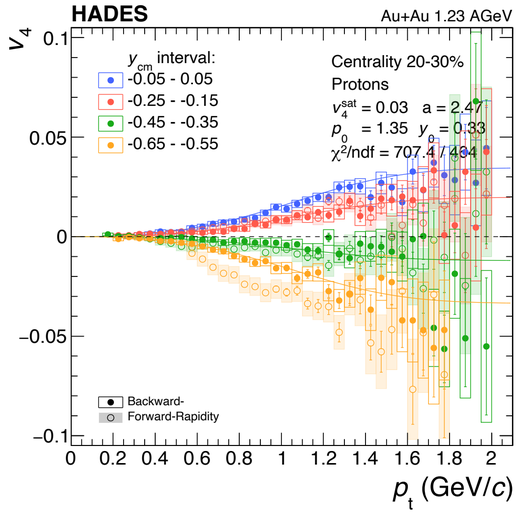
Global Parameterisation

Rapidity- and p_t-Dependence









Combined Trigonometric functions (y, pt):

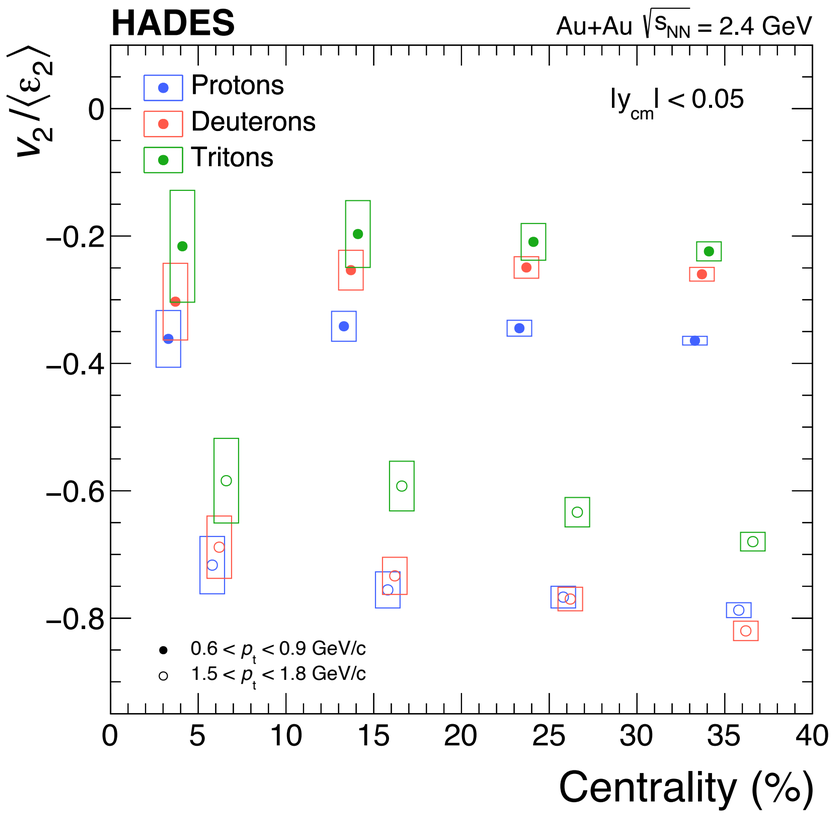
$$v_n^{odd}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \sin(y_{cm}/y_{tp} \cdot \pi/2)$$

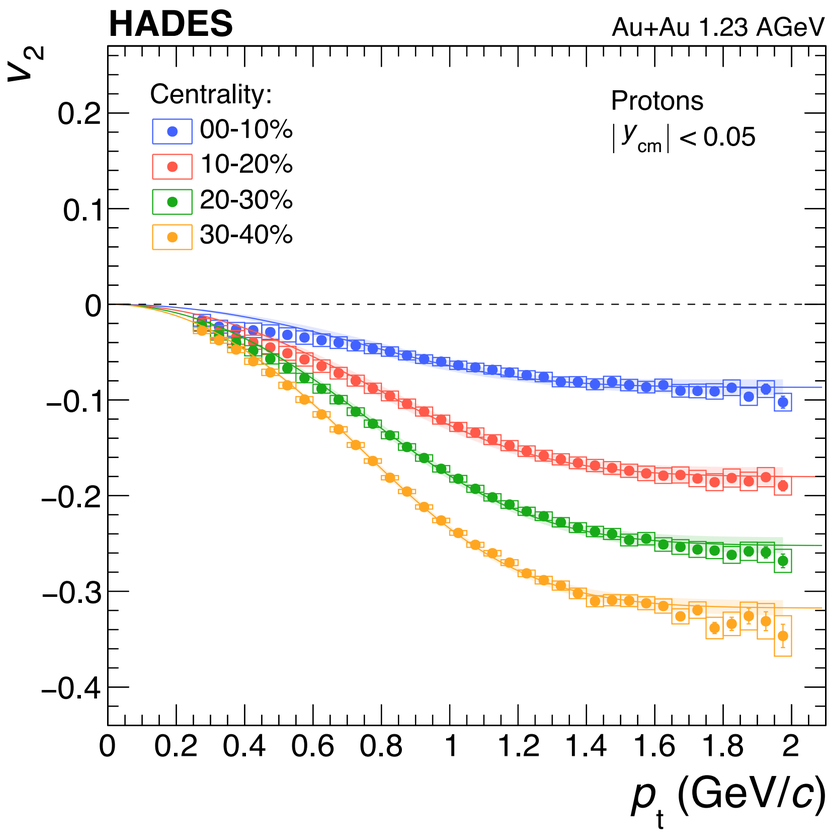
$$v_n^{even}(p_t, y_{cm}) = v_n^{sat} \cdot \tanh(p_t/p_0)^a \cdot \cos(y_{cm}/y_{zi} \cdot \pi/2)$$

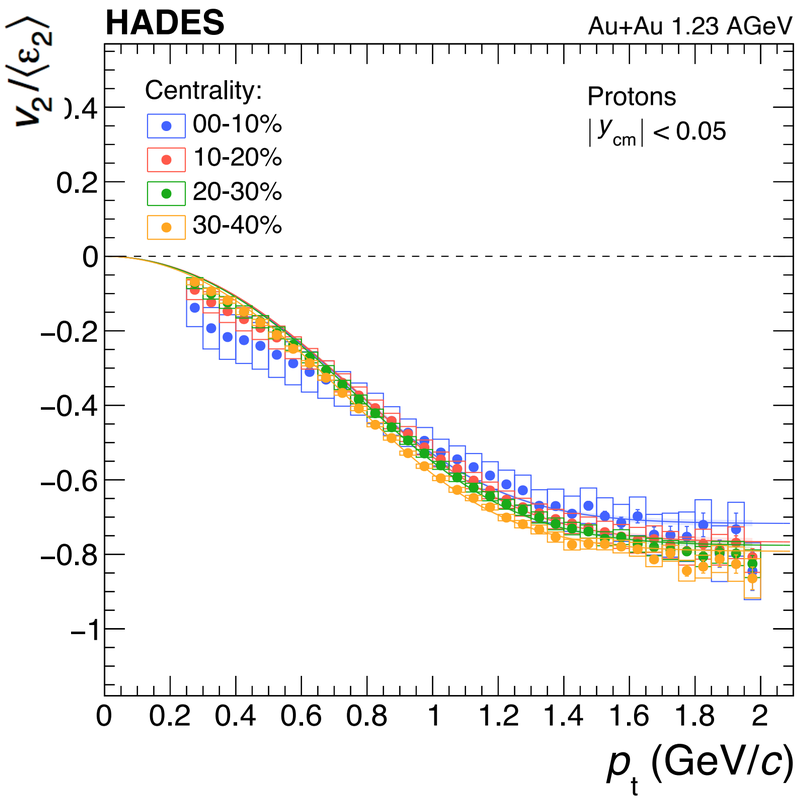
Simultaneous description of the rapidity and transverse momentum dependence with only 4 parameters for each centrality class, particle type and flow harmonic

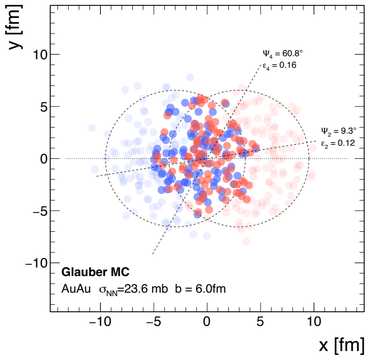
Geometry Scaling

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

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

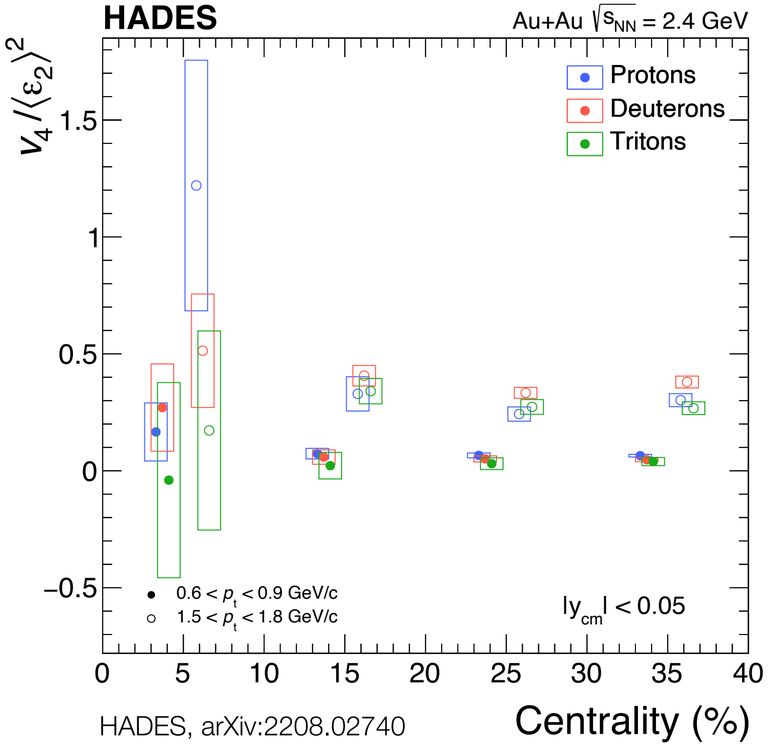
Orientation of symmetry-planes

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

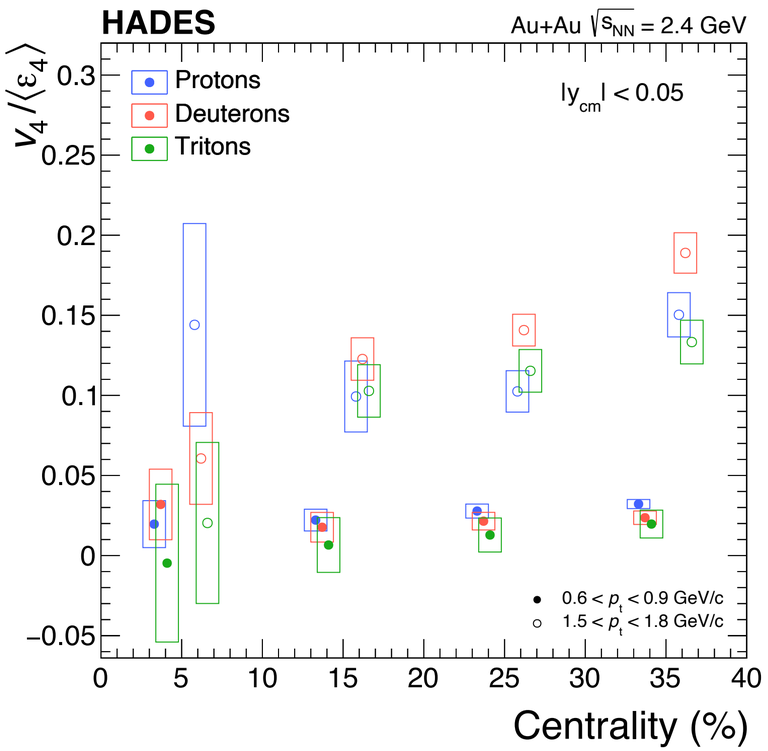
Similar scaling for v_4 with $\langle\varepsilon_2\rangle^2$

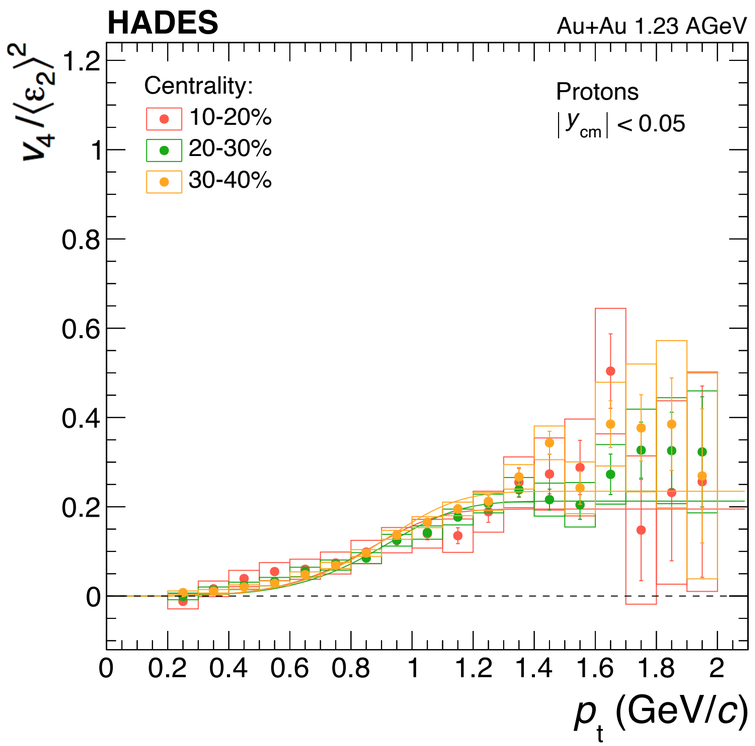
Geometry Scaling

Quadrangular Flow v_4



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)

Nucleon Coalescence

Scaling Properties of v_2 at Mid-Rapidity

Scaling of v_2 and p_t with nuclear mass number A

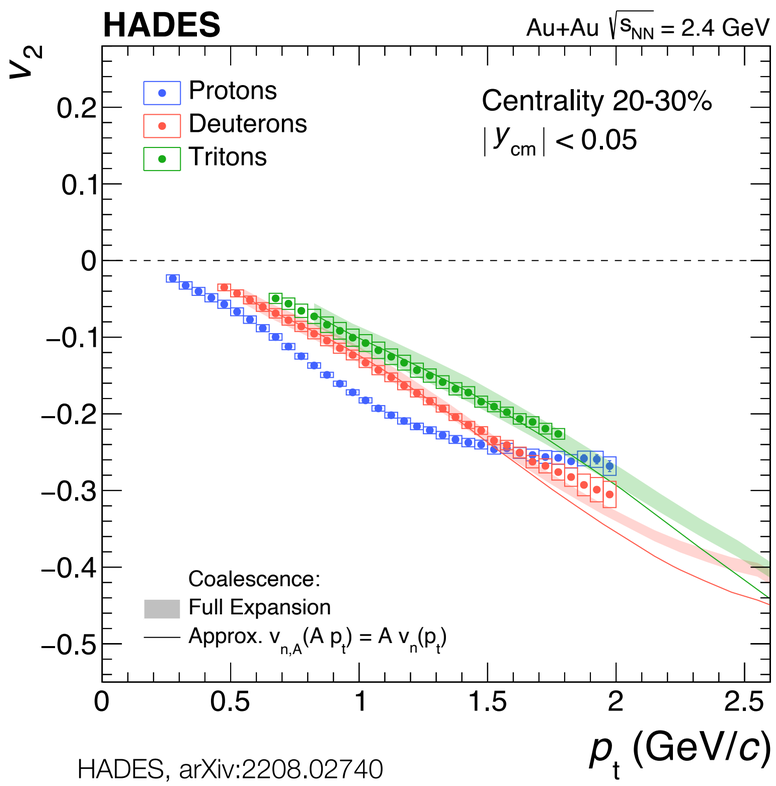
Inclusion of higher order terms

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

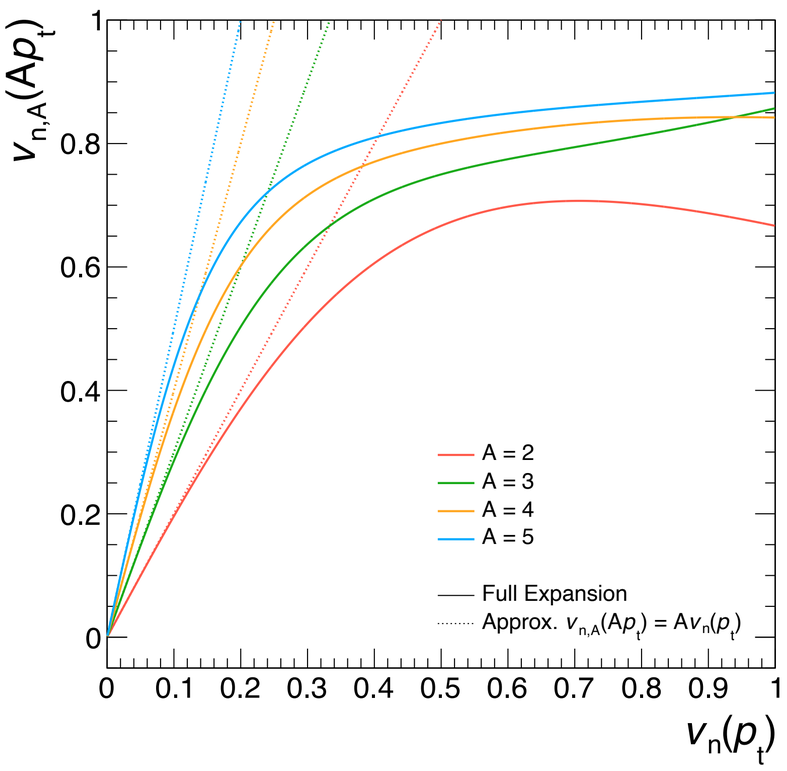
Odd flow coefficients vanish at mid-rapidity and v_4 contribution is negligible

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

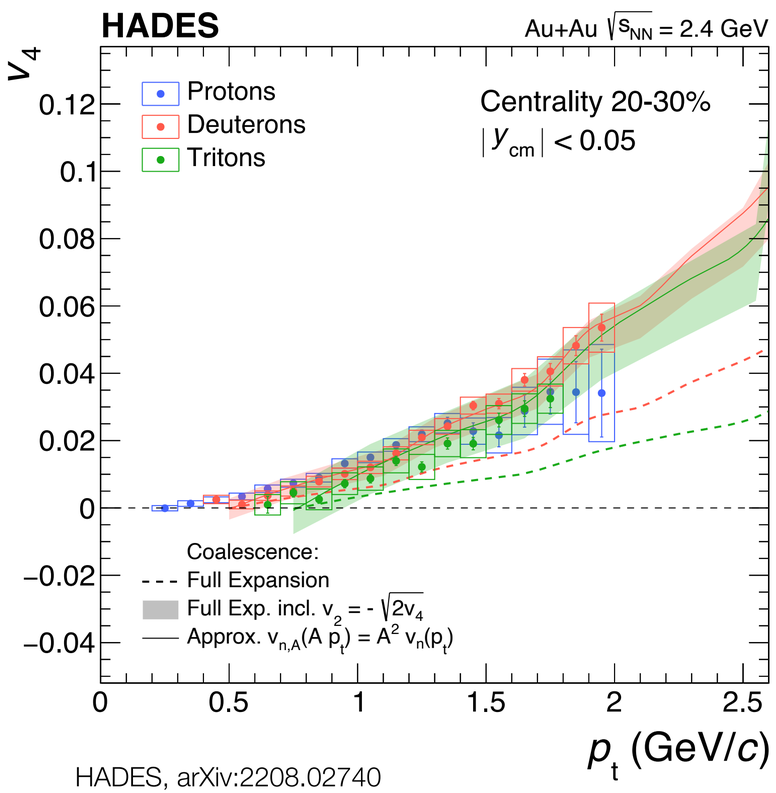
Nucleon Coalescence

Scaling Properties of v_4 at Mid-Rapidity

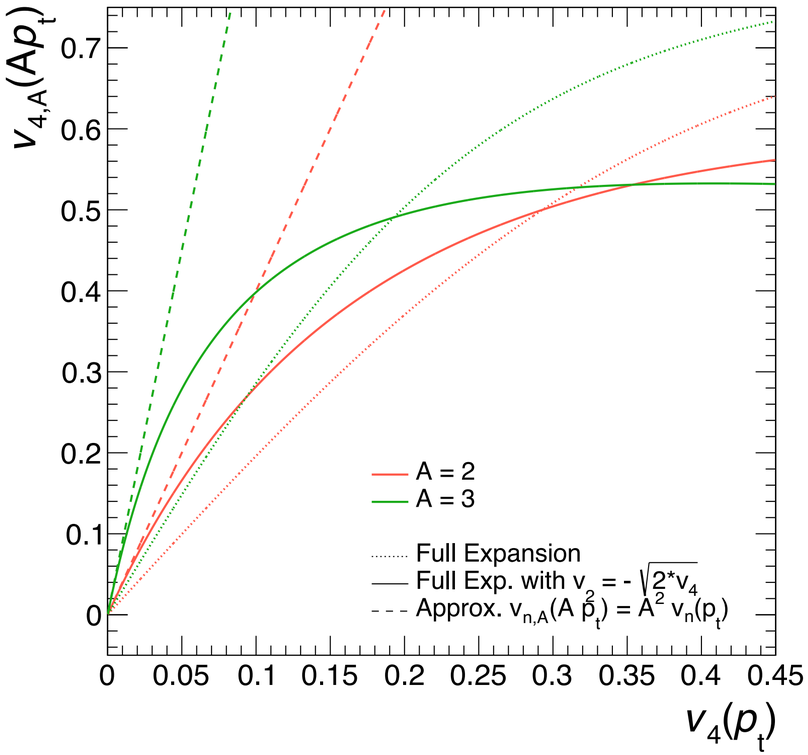
Scaling of v_4 and p_t with nuclear mass number A

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



HADES, arXiv:2208.02740



Approximation for small v_4 with v_2 contribution:

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

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

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

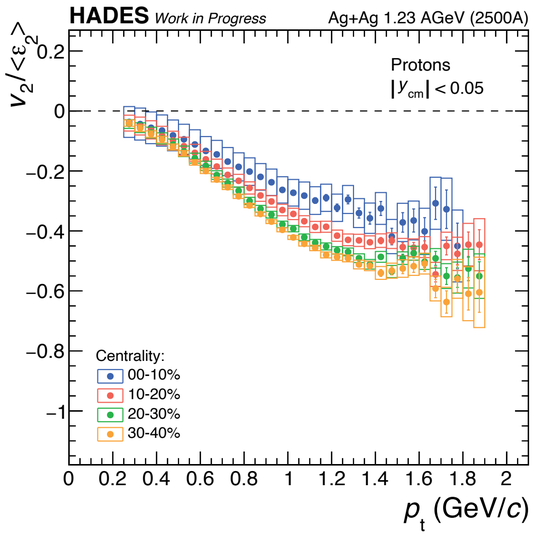
assuming: $v_4(p_t)/v_2^2(p_t) = 1/2$

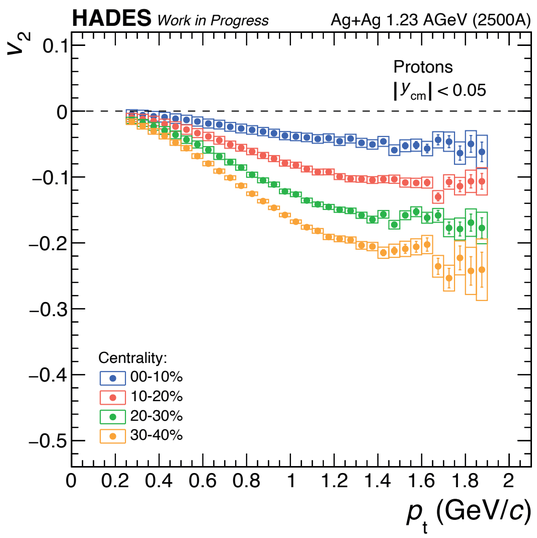
D. Molnar and S.A. Voloshin PRL **91** (2003) 092301
P.F. Kolb et al., PRC **69** (2004) 051901

Elliptic Flow v_2

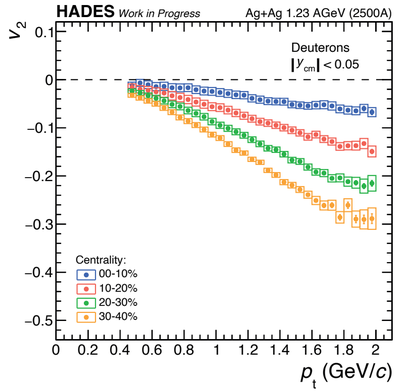
Protons, Deuterons, Tritons and ^{3}He in Ag+Ag collisions at 1.23 and 1.58 AGeV

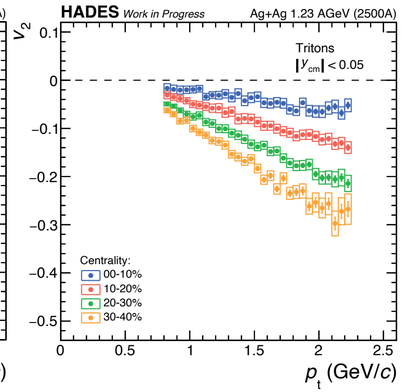
Protons **Deuterons** **Tritons** **^{3}He**

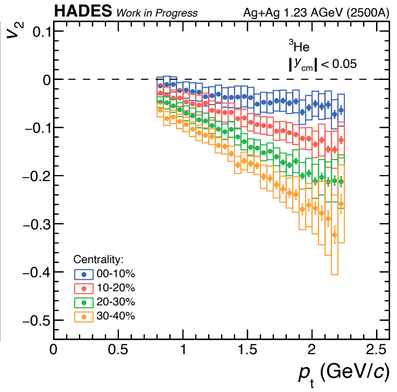


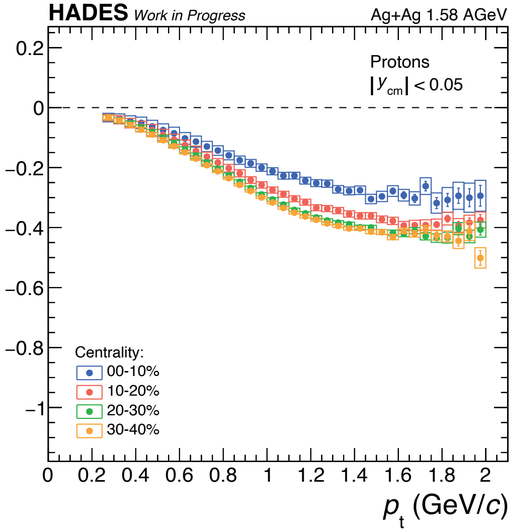


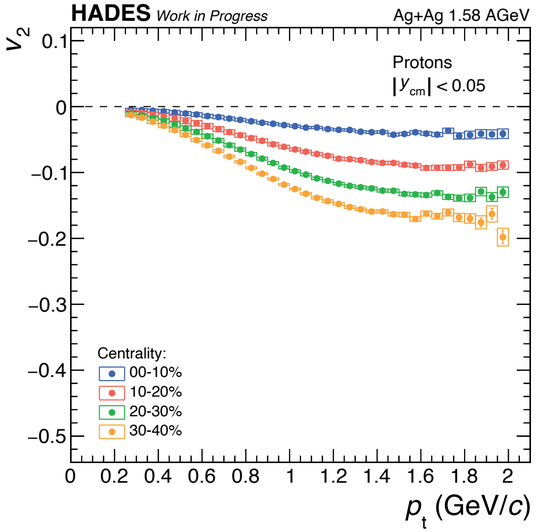
AgAg 1.23 AGeV



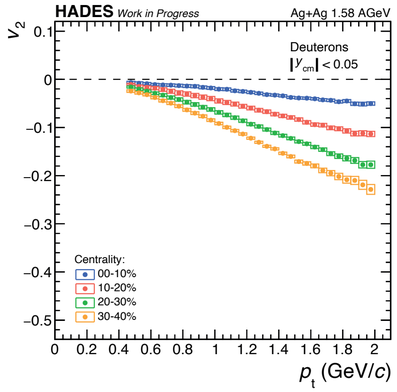


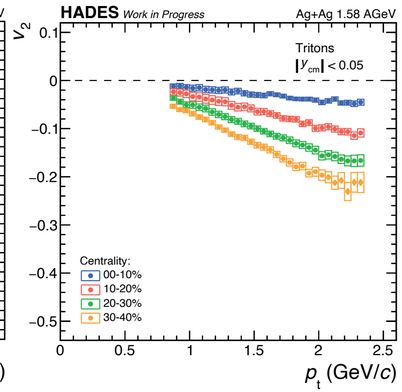


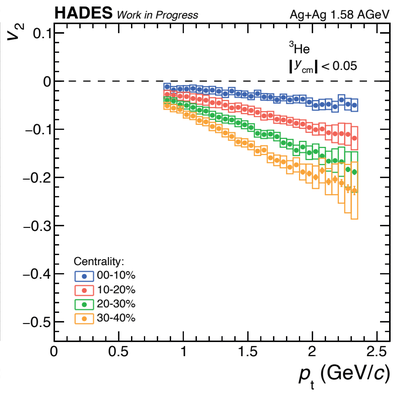




AgAg 1.58 AGeV

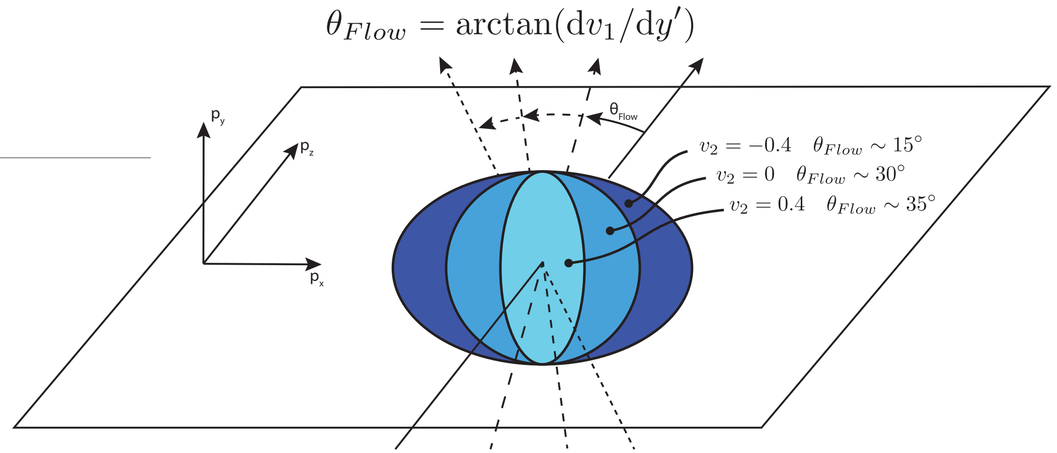


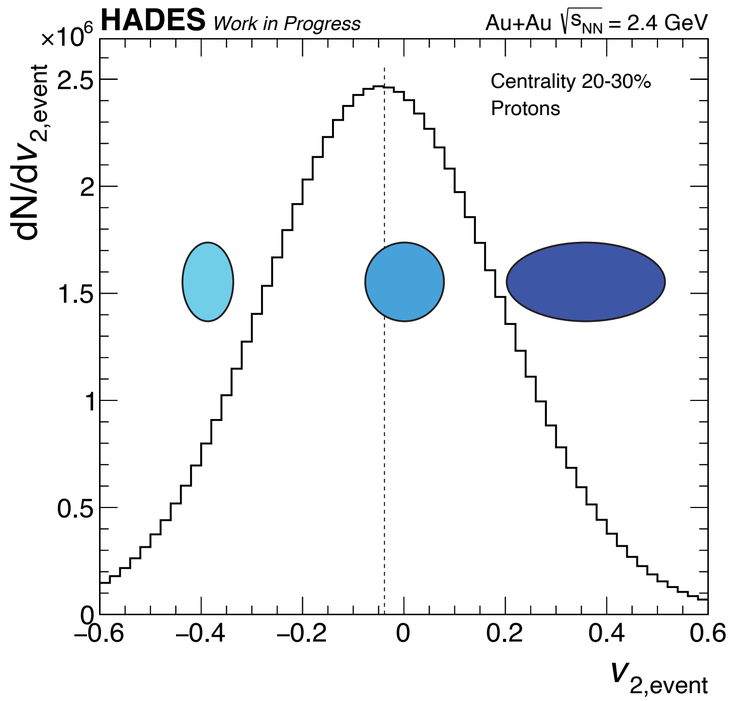


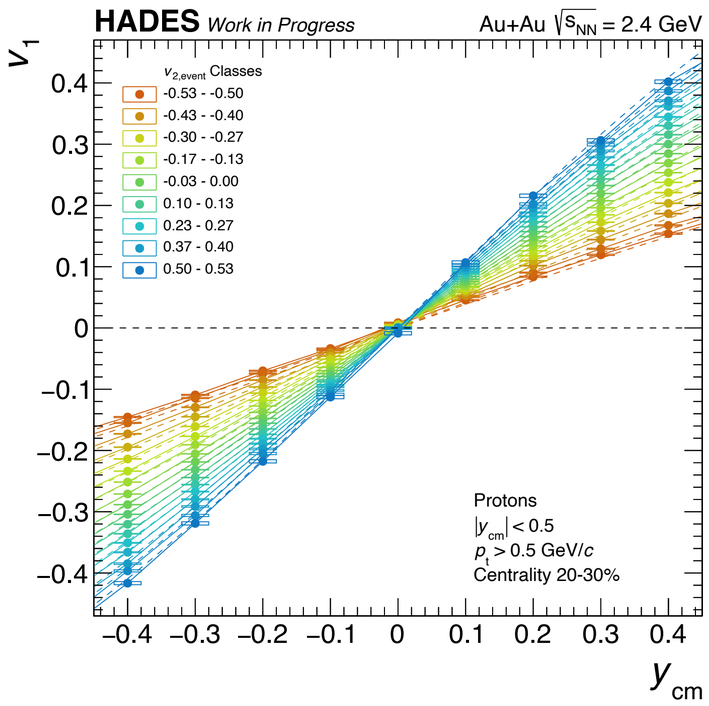


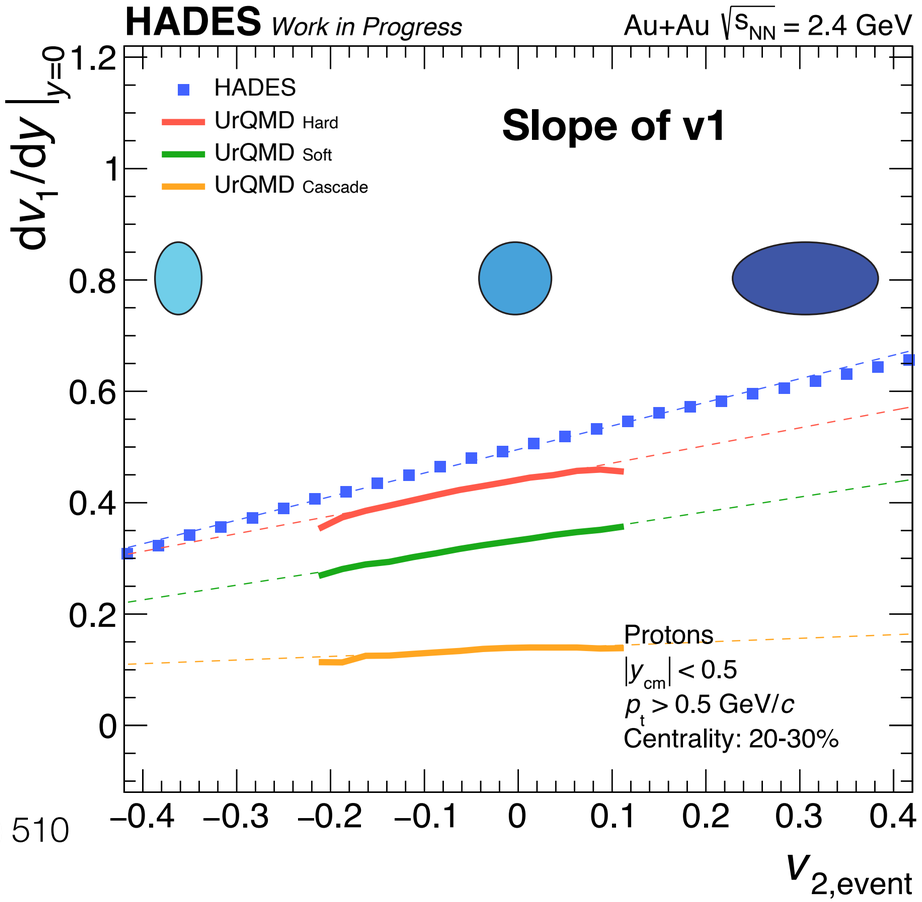
Event-wise Flow Correlations

- Events can be 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}



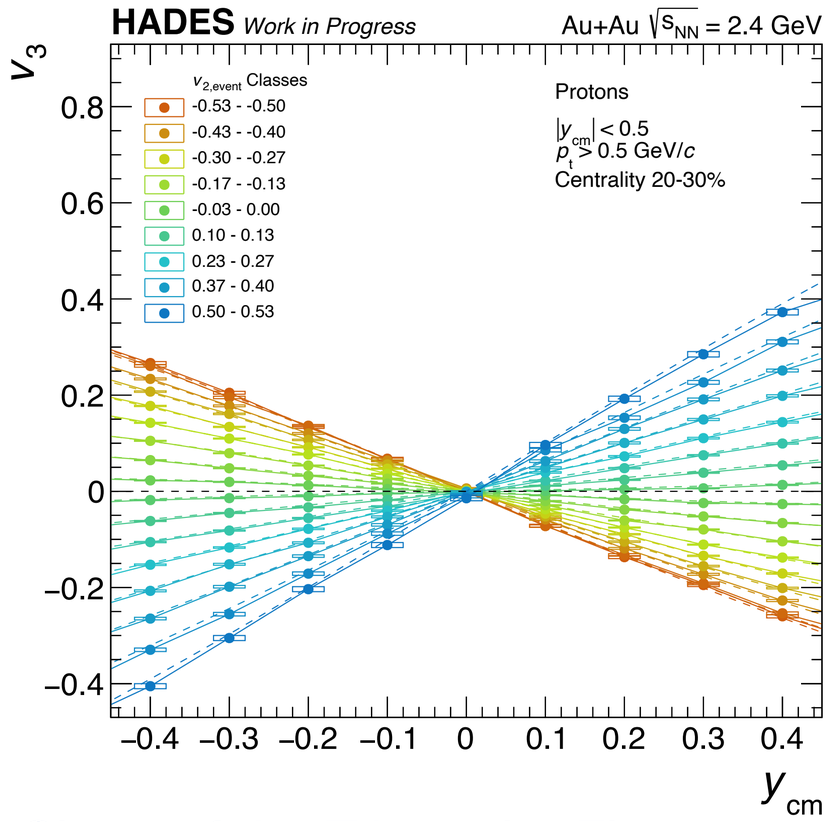


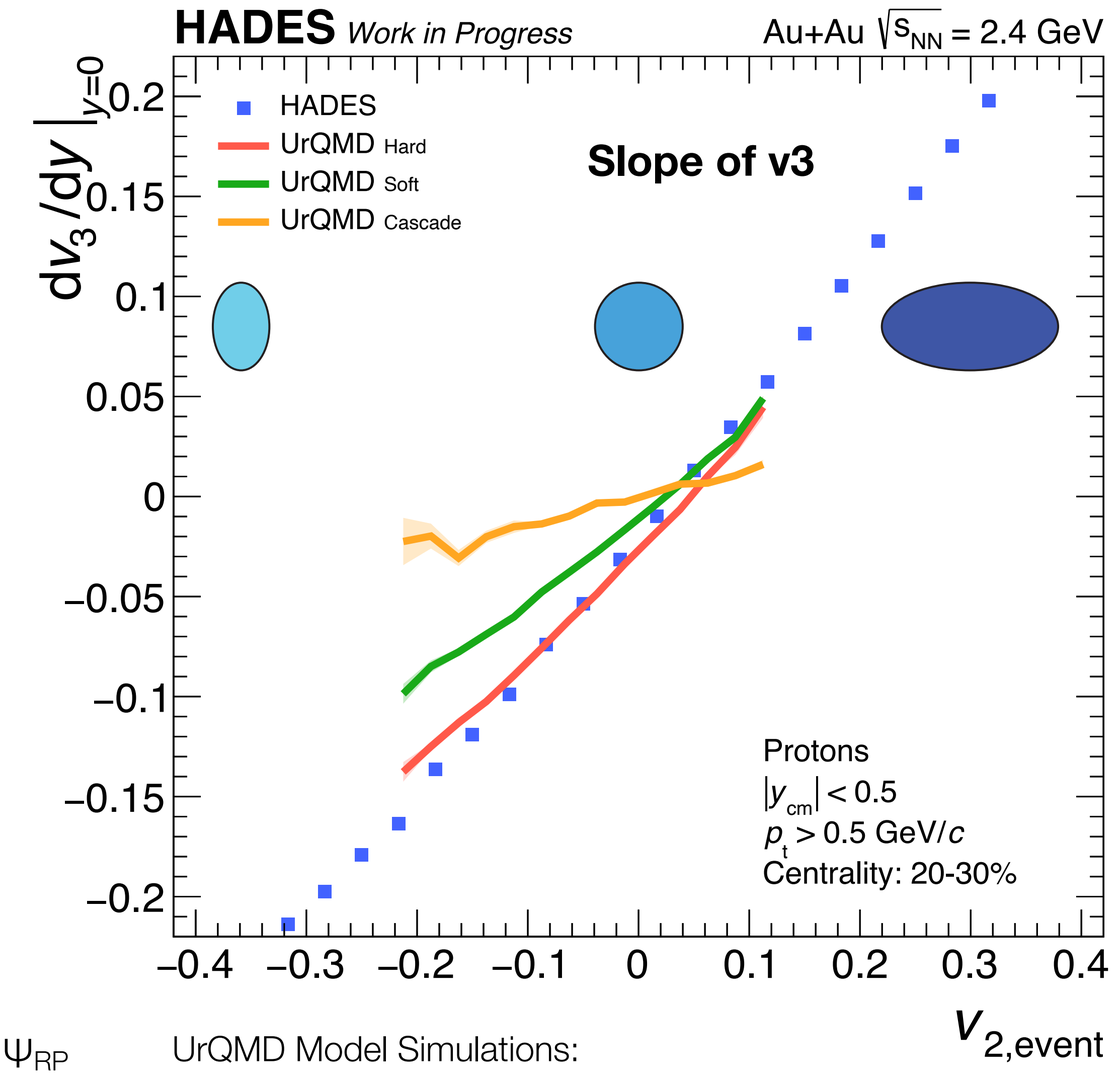




UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

Event-wise Flow Correlations





Slope of the Triangular Flow v_3

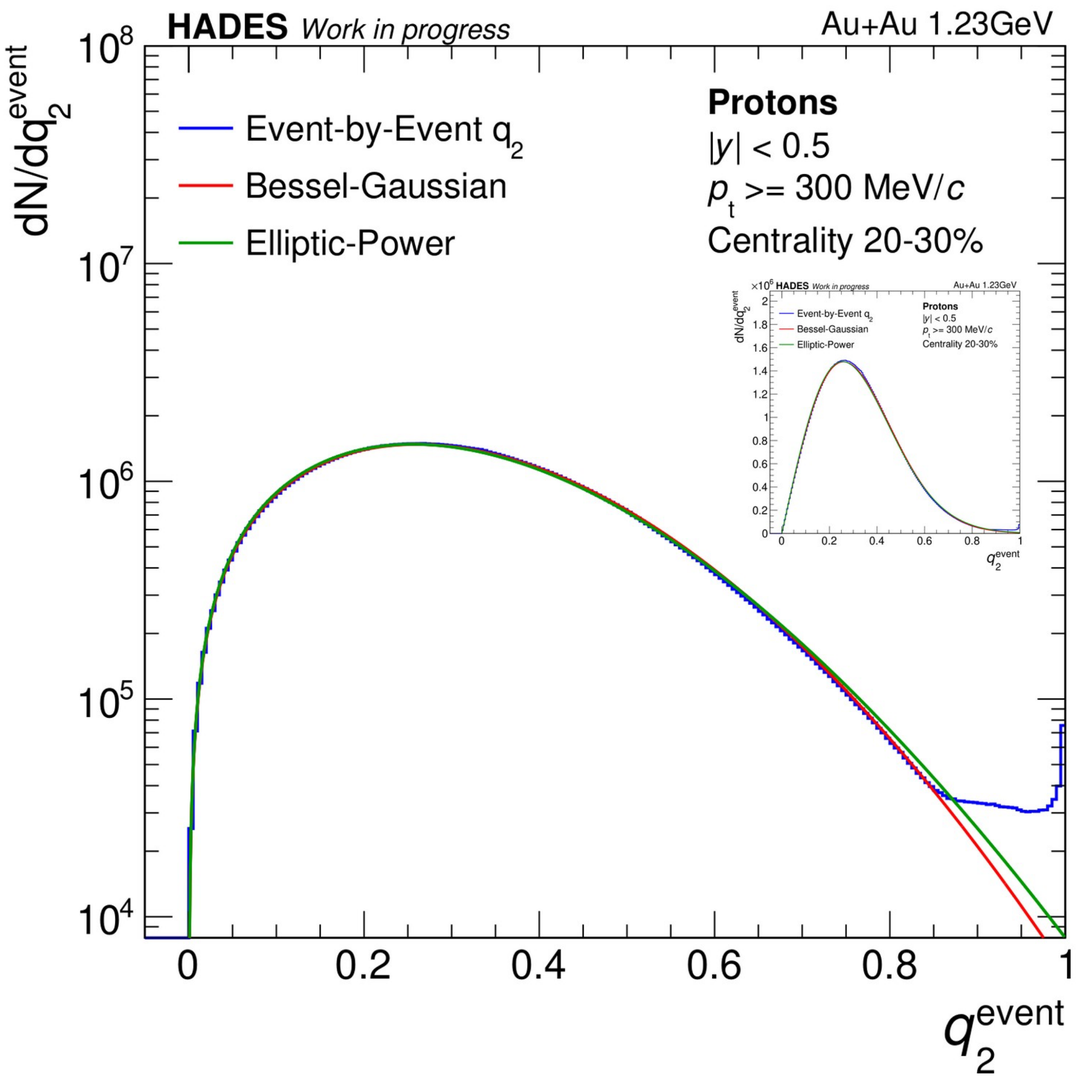
A strong sensitivity to the EoS is seen

Caveats:

- Not corrected the underlying **multiplicity fluctuations**
- **Event-plane resolution** – dispersion between Ψ_{EP} and Ψ_{RP}
- Ψ_2 **resolution and decorrelation** to Ψ_{RP}

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

Event-wise Flow Vector Magnitude q_2



Not corrected for non-uniformities expected due to detector in-efficiencies and multiplicity fluctuations

L. Yan, J.-Y. Ollitrault, A. M. Poskanzer

Bessel-Gaussian:

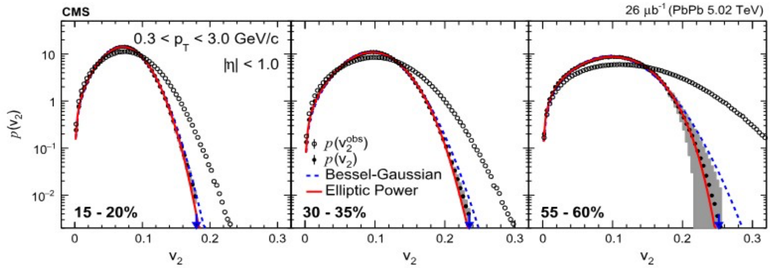
$$BG(q_2) = \frac{q_2}{\sigma^2} \exp\left(-\frac{q_2^2 + \mu^2}{2\sigma^2}\right) I_0\left(\frac{q_2 \mu}{\sigma^2}\right)$$

Power-Elliptic:

$$P(q_2) = \frac{2\alpha q_2}{\pi(1-\varepsilon^2)} \int_0^\pi d\phi \exp\left(\frac{-\alpha q_2^2}{(1-\varepsilon^2 cos(\phi))}\right) \frac{1}{(1-\varepsilon^2 cos(\phi))^2}$$

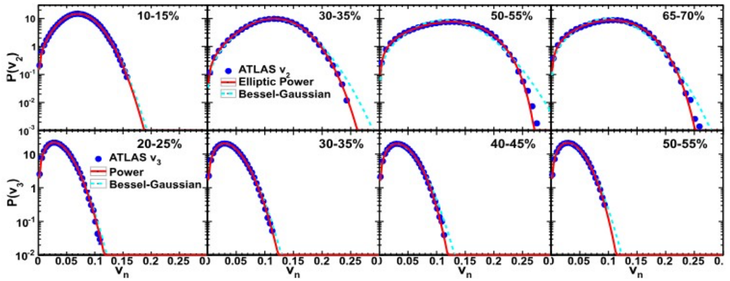
Physics Letter B 742 (2015) 290-295

CMS Collaboration: Pb+Pb Collisions at S_{NN}= 5.02 TeV



Physics Letters B 789 (2019) 643–665

ATLAS data: Pb+Pb Collisions at S_{NN}= 2,76 TeV

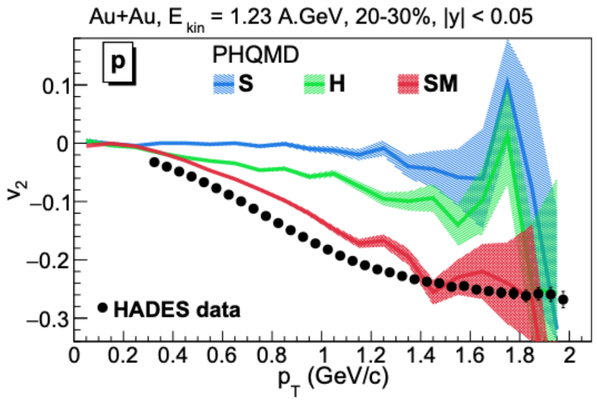


Physics Letter B 742 (2015) 290-295

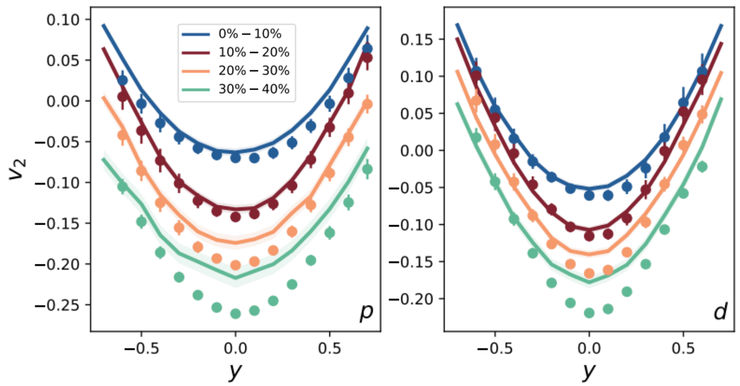
Model Comparisons

Extracting the EoS

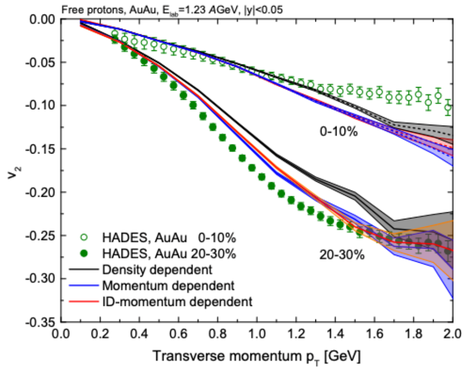
- Overall good description of data (directed and elliptic flow) by different models
- Momentum dependent soft EoS generally favoured
- Importance of the mechanism of light nuclei production
- Possibilities of available data set not yet fully exploited (higher order)
- Move to Bayesian analyses (first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



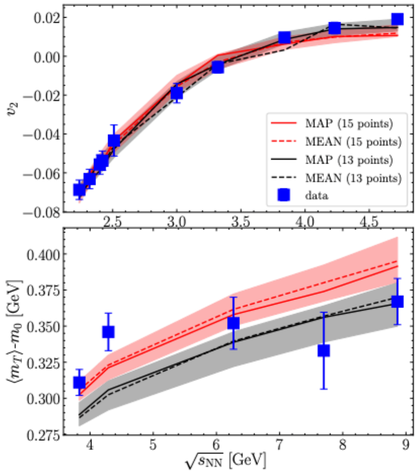
PHQMD: V. Kireyeu et al., arXiv:2411.04969

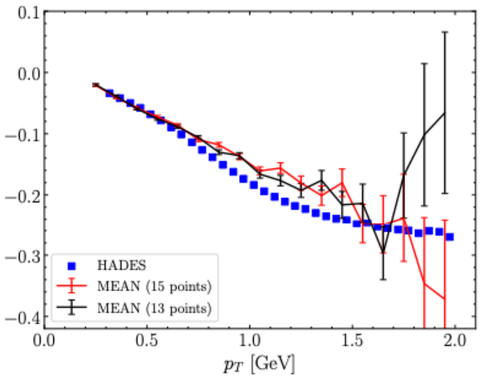


SMASH: J. Mohs et al., arXiv:2409.16927

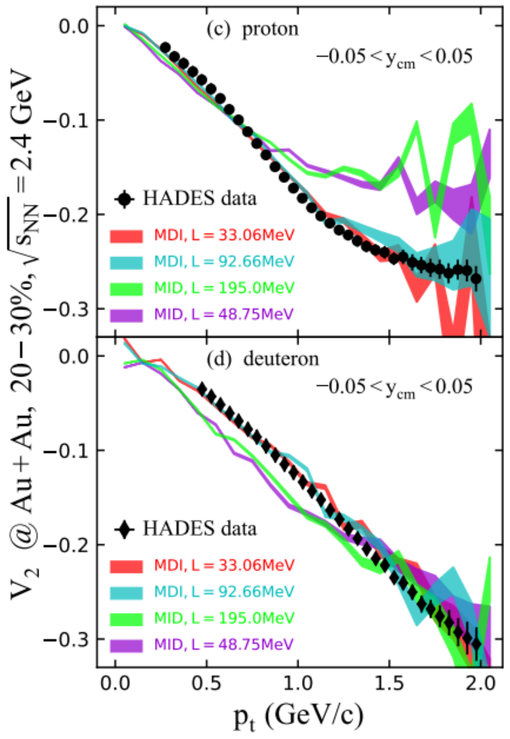


UrQMD: J. Steinheimer et al. arXiv:2410.01742





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



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

Conclusions

General Parameterisation

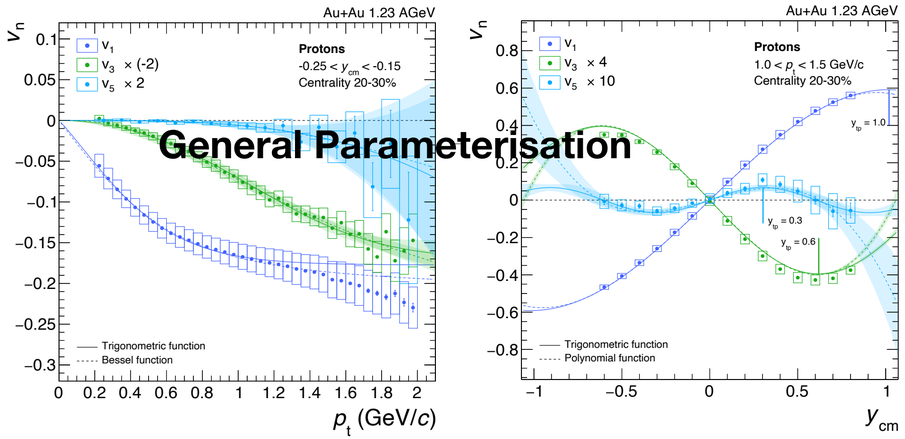
- Phenomenological approach based on hydrodynamic inspired Blast Wave model

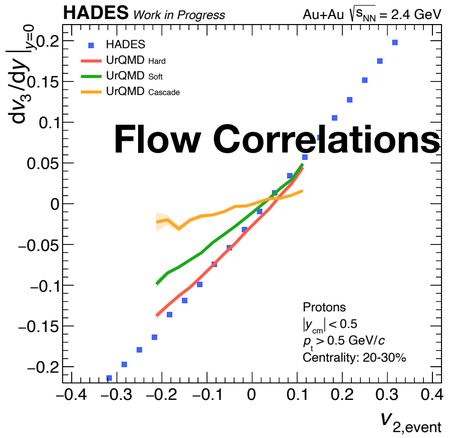
Scaling Properties

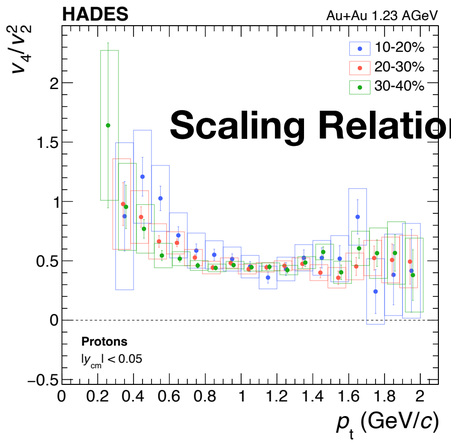
- Scaling relation between flow coefficients
  Hydro-like matter at SIS energies?
- Correlation between Flow coefficients event-wise
- Geometrical Scaling to initial overlap eccentricities

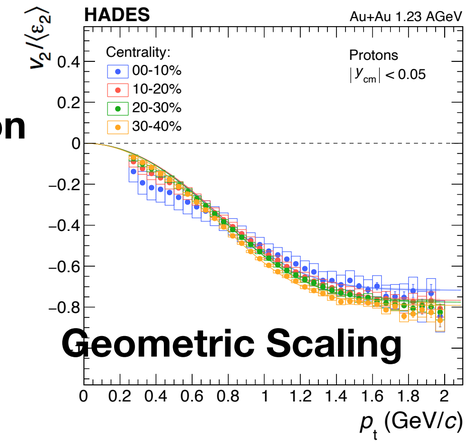
Model Comparison

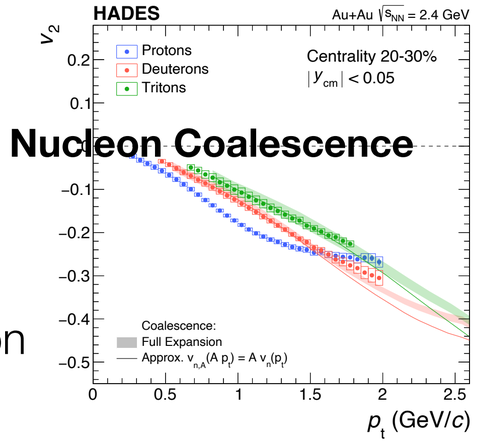
- Multi-differential analysis including higher orders
  New level of precision
- Importance of the mechanism of light nuclei production

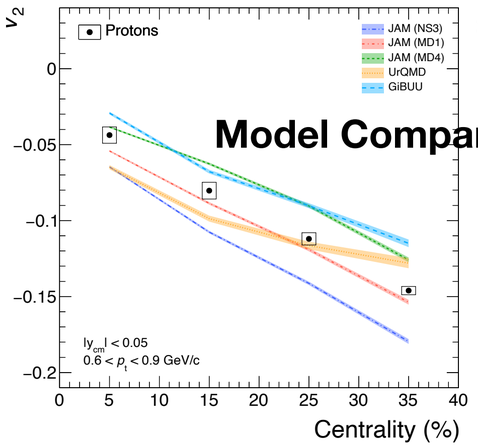


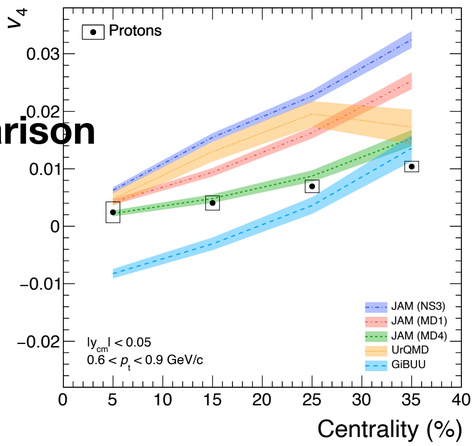












Outlook

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

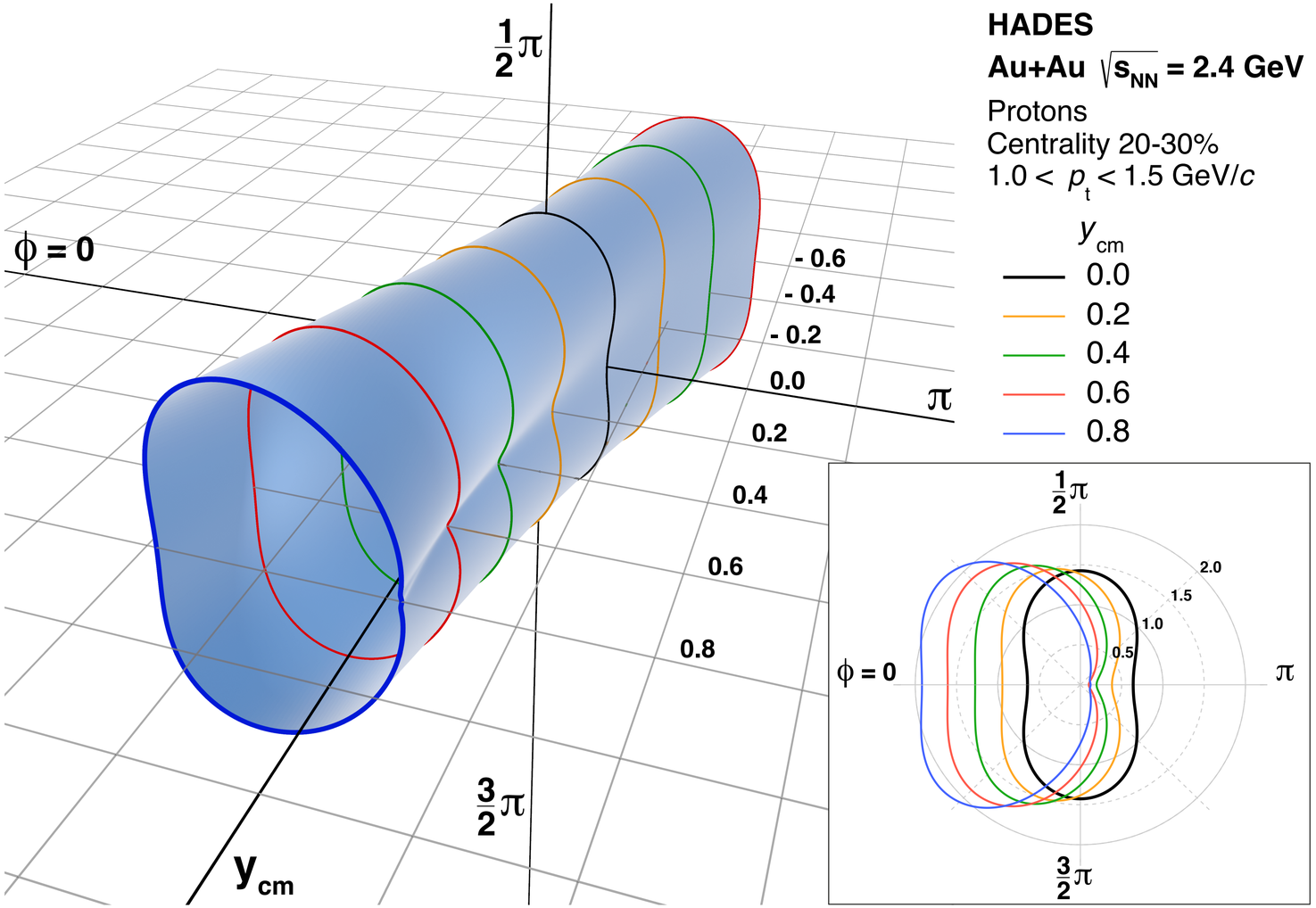
Correlations of flow coefficients for protons in Ag+Ag and Au+Au collisions

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!

The HADES experiment

Fixed-target experiment at SIS18 at GSI, Germany

Large acceptance in 6 identical sectors

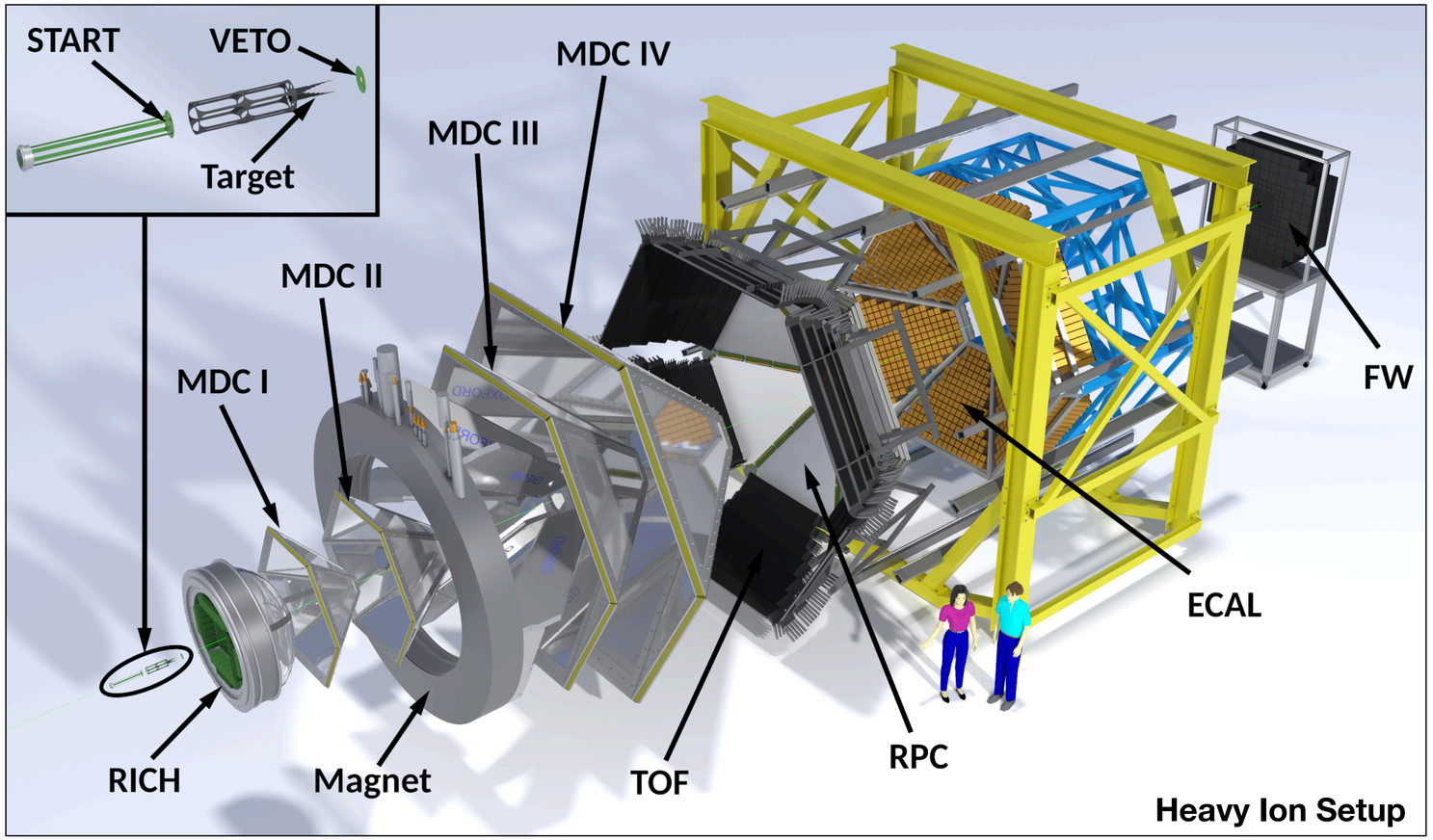
- Symmetric azimuthal coverage
- Superconducting toroidal magnets
- Low-mass Drift Chambers (MDC)

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



Size of Gold?

- **nuclear density distribution**
  parameterized by Woods-Saxon

$$\rho(r) = \rho_0 \cdot \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

RMS-Size electron scattering:

$$\langle r^2 \rangle^{1/2} = 5.33 \ fm$$

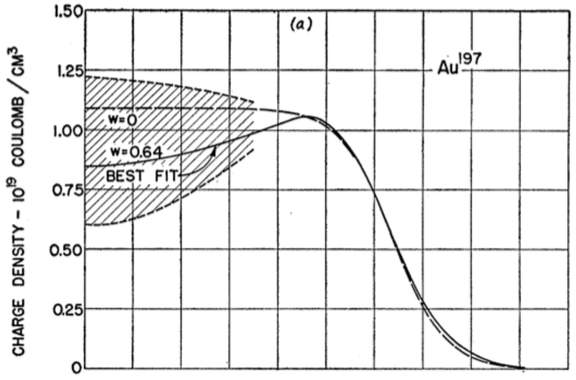
Hofstadter et al.
Phys. Rev. 101 (3 Feb. 1956)

- comparison to very precise muonic atoms measurements underestimated by **~2%**

$$\langle r^2 \rangle^{1/2} = 5.4358 \pm 0.0037 \ fm$$

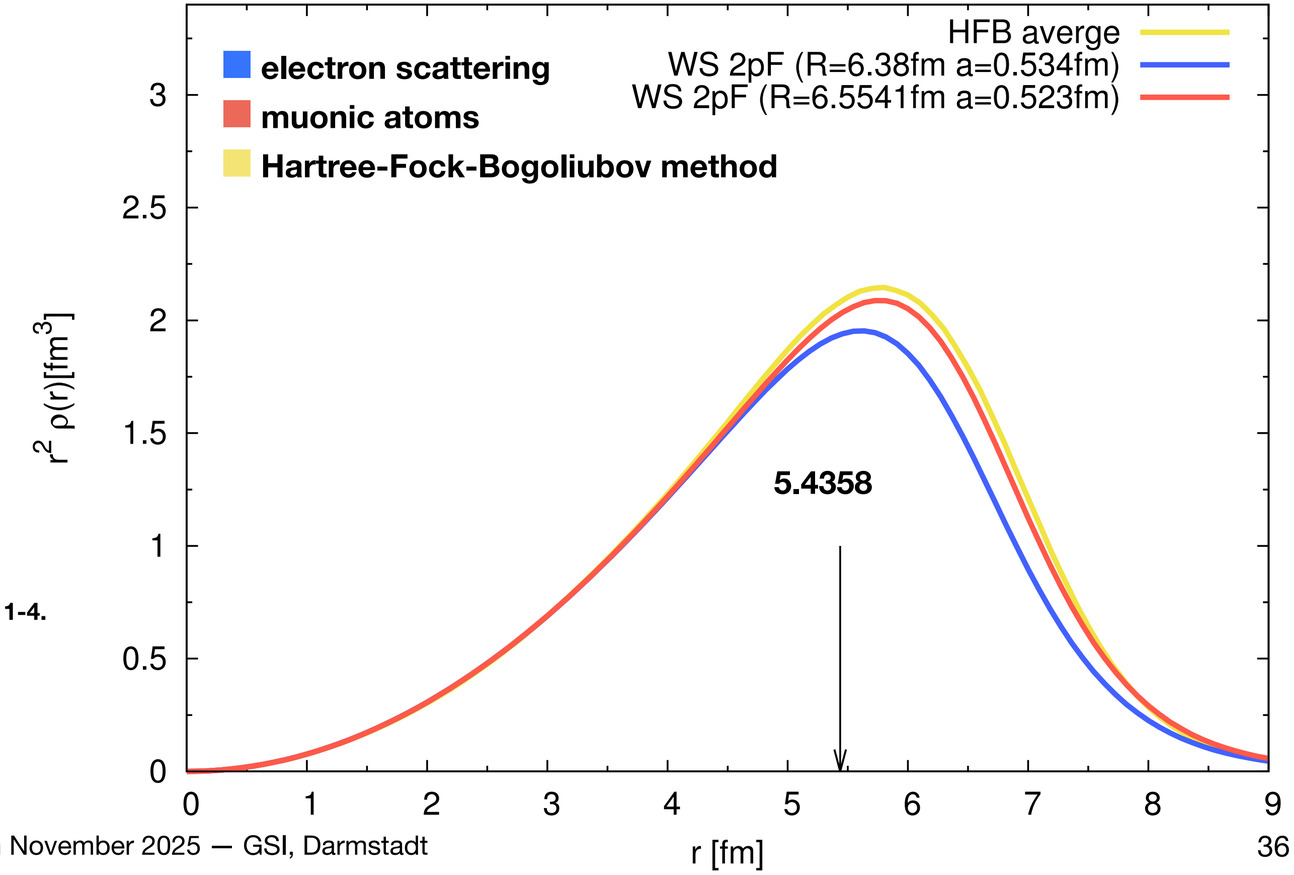
G. Fricke, K. Heilig, Nuclear Charge Radii
Landolt-Börnstein
Vol. 20 (Springer Berlin Heidelberg, 2004) pp. 1-4.

electron scattering on Au^{197}



Hofstadter et al.
Phys. Rev. 101 (3 Feb. 1956)

quoted error of R and a: ±1%



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Landolt-Börnstein
Vol. 20 (Springer Berlin Heidelberg, 2004) pp. 1-4.

Eur. Phys. J. A (2023) 59:58
https://doi.org/10.1140/epja/s10050-023-00955-3

Regular Article - Theoretical Physics

The shape of gold

B. Bally[1,2,a], G. Giacalone[3,b], M. Bender[4,c]

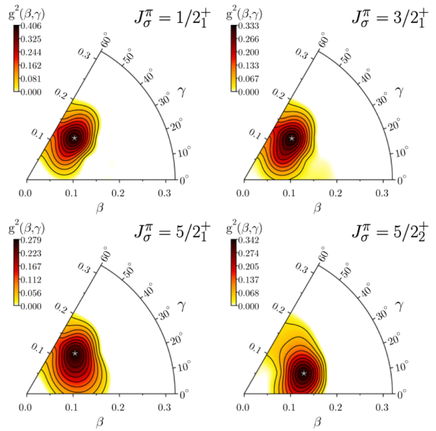
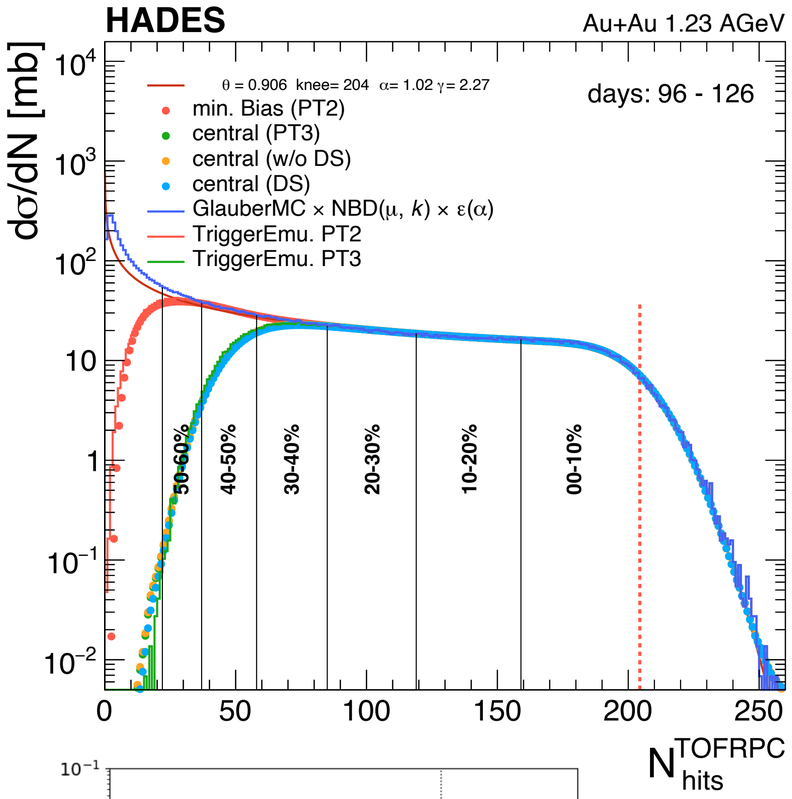


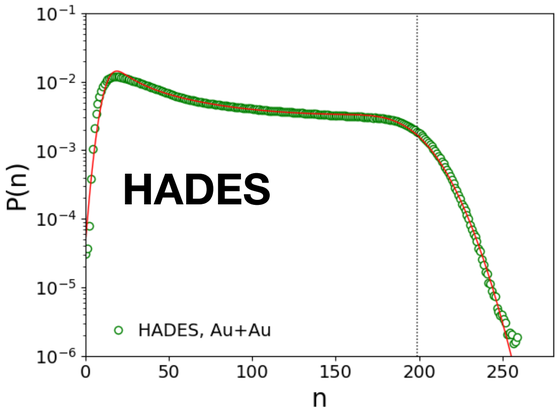
Table 3 Parameters for the point-proton, point-neutron and point-nucleon densities defined as in Eq. (1) and fitted to reproduce the one-body densities of a quasi-particle state constrained to have, on average, $\beta = 0.13$ and $\gamma = 40°$; see the body of the text for more details

Parameter	Proton	Neutron	Nucleon
ρ_0	0.067	0.090	0.157
R_0	6.44	6.65	6.56
a	0.46	0.49	0.48
β_2^{WS}	0.134	0.137	0.135
γ^{WS}	43°	43°	43°
β_4^{WS}	− 0.024	− 0.023	− 0.023

The parameters R_0 and a are given in units of fm, whereas ρ_0 is given in units of fm^{-3}

Centrality Determination

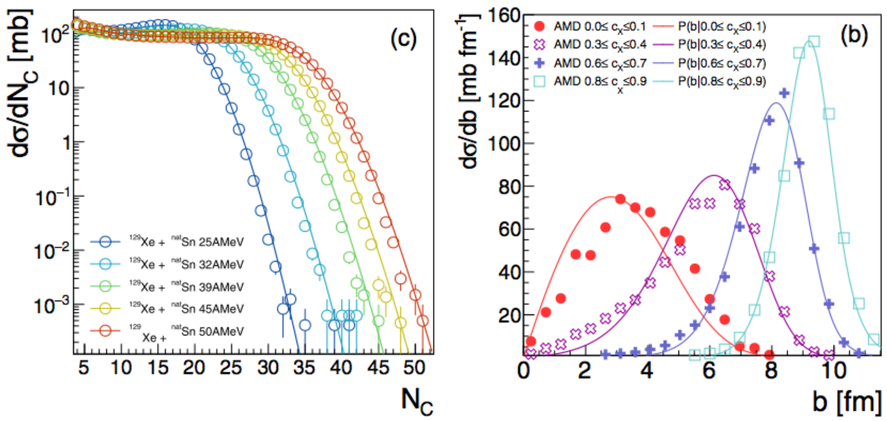


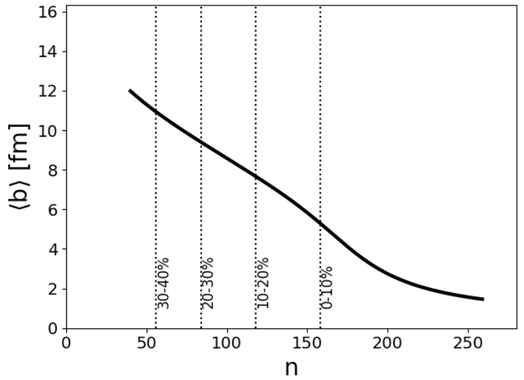


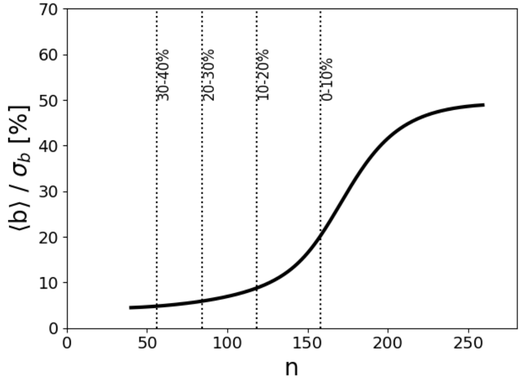
INDRA

PHYSICAL REVIEW C **104**, 034609 (2021)

Model independent reconstruction of impact parameter distributions for intermediate energy heavy ion collisions

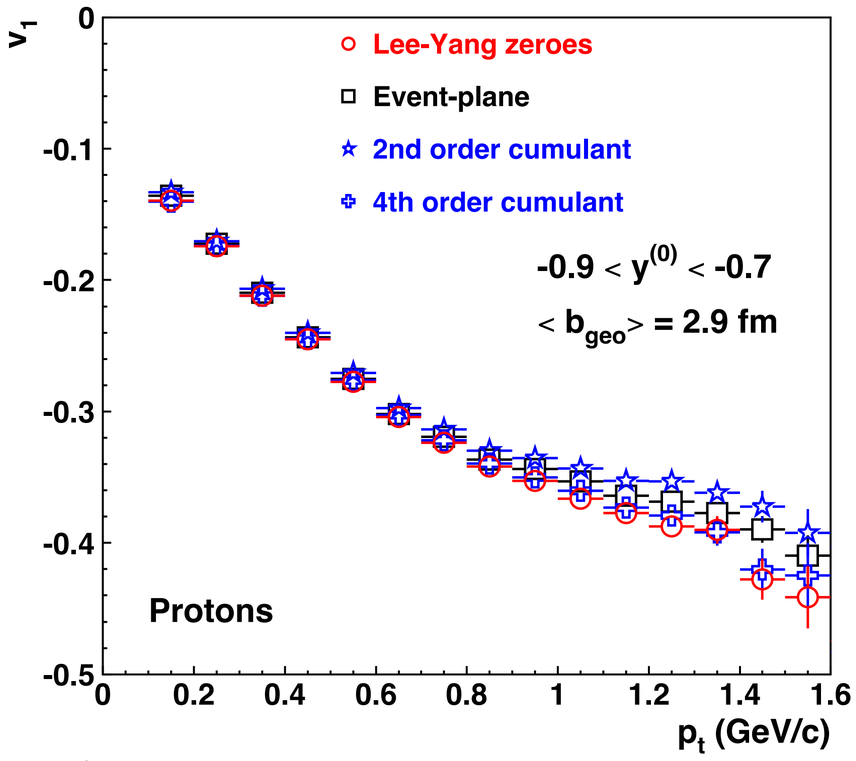


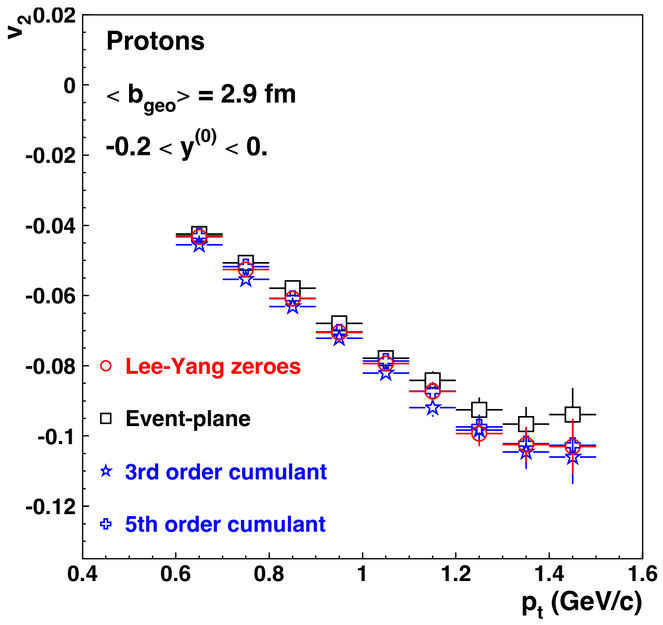




First successful test of the code in 2018 provided by Ollitrault und Giacalone:

Multi-particle Flow Correlation





FOPI
Ru+Ru 1.69A GeV
centrality: 2-12%
2.9 x 10^6 events

N. Bastid et al. (**FOPI**)
Phys. Rev. C 72, 011901(R)

PHYSICAL REVIEW C **72**, 011901(R) (2005)

First analysis of anisotropic flow with Lee–Yang zeros

N. Bastid,[1,*] A. Andronic,[2] V. Barret,[1] Z. Basrak,[3] M. L. Benabderrahmane,[4] R. Čaplar,[3] E. Cordier,[4] P. Crochet,[1] P. Dupieux,[1] M. Dželalija,[3] Z. Fodor,[5] I. Gašparić,[3] A. Gobbi,[2] Y. Grishkin,[6] O. N. Hartmann,[2] N. Herrmann,[4] K. D. Hildenbrand,[2] B. Hong,[7] J. Kecskemeti,[5] Y. J. Kim,[7,2] M. Kirejczyk,[2,8] P. Koczon,[2] M. Korolija,[3] R. Kotte,[9] T. Kress,[2] A. Lebedev,[6] Y. Leifels,[2] X. Lopez,[1] A. Mangiarotti,[4] V. Manko,[10] M. Merschmeyer,[4] D. Moisa,[11] W. Neubert,[9] D. Pelte,[4] M. Petrovici,[11] F. Rami,[12] W. Reisdorf,[2] A. Schuettauf,[2] Z. Seres,[5] B. Sikora,[8] K. S. Sim,[7] V. Simion,[11] K. Siwek-Wilczyńska,[8] M. M. Smolarkiewicz,[8] V. Smolyankin,[6] I. J. Soliwoda,[8] M. R. Stockmeier,[4] G. Stoicea,[11] Z. Tyminski,[2,8] K. Wiśniewski,[8] D. Wohlfarth,[9] Z. Xiao,[2] I. Yushmanov,[10] and A. Zhilin[6]
(FOPI Collaboration)

J.-Y. Ollitrault and N. Borghini†
Service de Physique Théorique, CEA-Saclay, Gif-sur-Yvette, France
(Received 4 April 2005; published 19 July 2005)

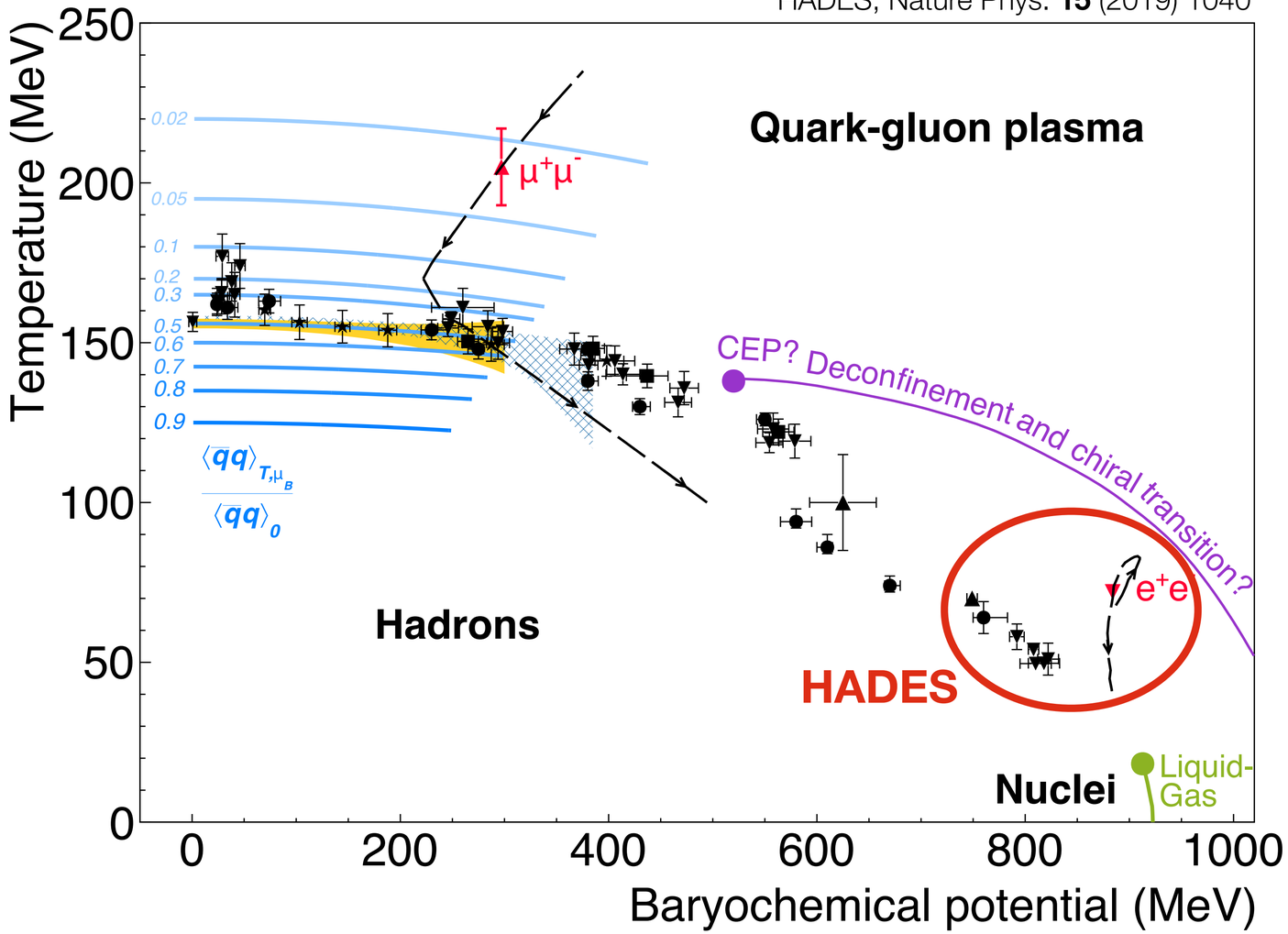
- other methods differ to event-plane results
  - Lee-Yang Zero and 4-particle cumulant compatible
  - non-flow effects seen but small

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



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

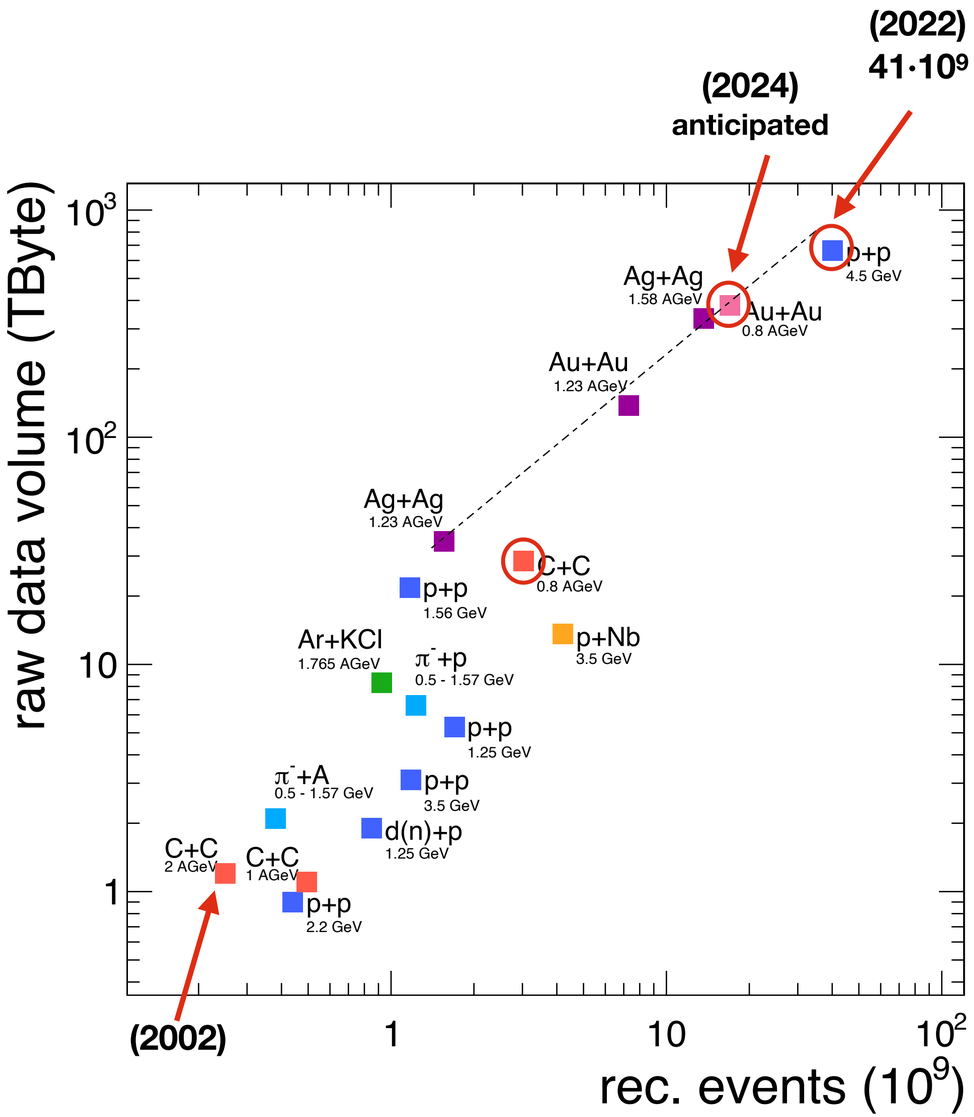
Heavy ion collisions:
Ar+KCl (2005) 2.61 GeV
Au+Au (2012) 2.42 GeV
Ag+Ag (2019) 2.55 / 2.42 GeV
Au+Au (2024) 2.23 - 1.96 GeV

Light ion collisions:
C+C (2002) 2.7 GeV
C+C (2004) 2.32 GeV
C+C (2024) 2.23 GeV

- Proton and pion beam
  - Reference measurement (vacuum, cold nuclear matter)
  - In-medium modifications
  - *em* structure of baryons/hyperons in time-like region

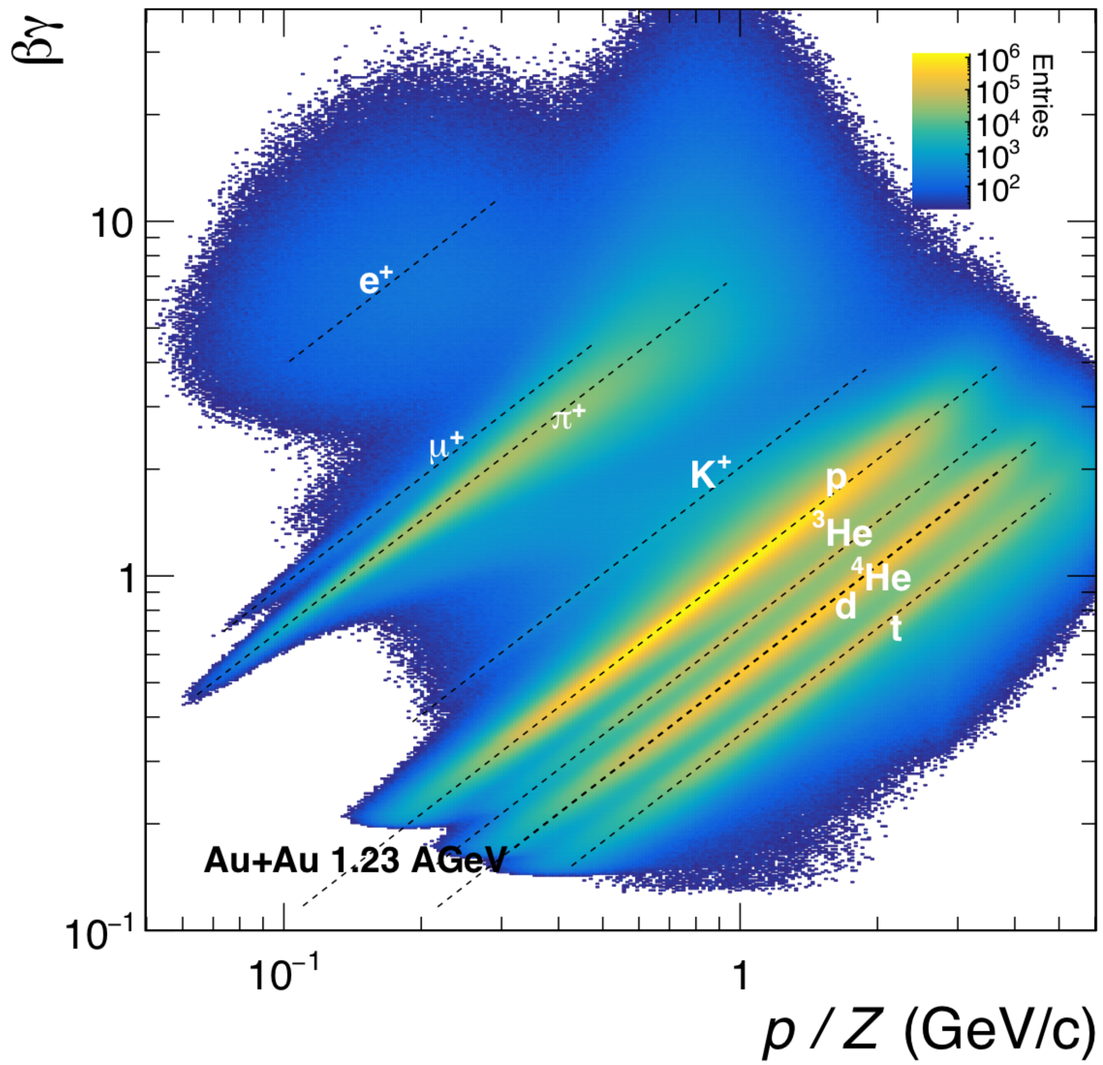
Proton/deuteron beams:
p+p (2004) 2.7 GeV
d(n)+p (2006) 2.42 GeV
p+p (2007) 3.18 GeV
p+p (2022) 3.46 / 2.55 GeV
p+Nb (2008) 3.1 GeV

Pion beams:
π^- + W / C / PE (2014) 1.5 GeV

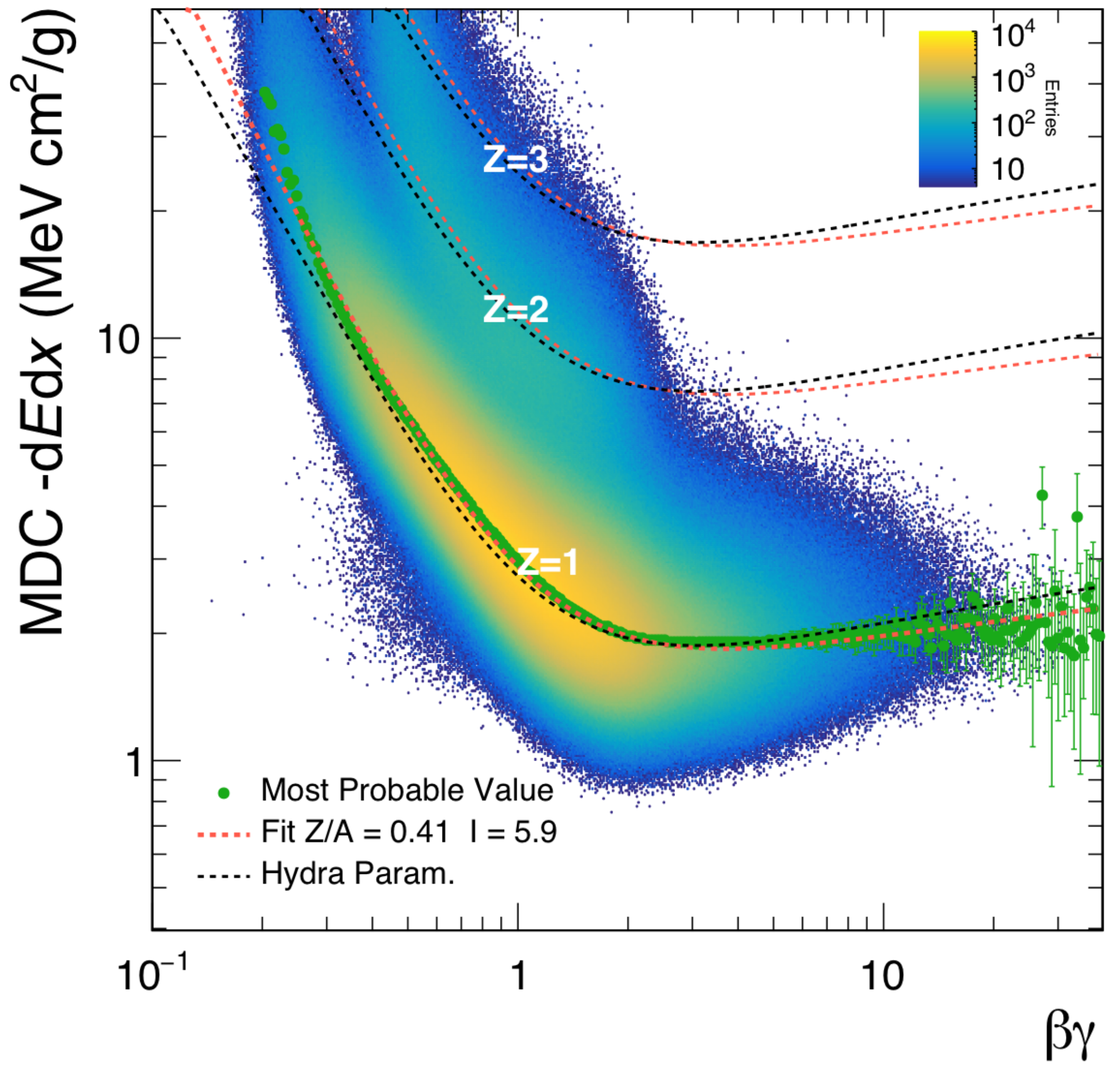


Particle Identification

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



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

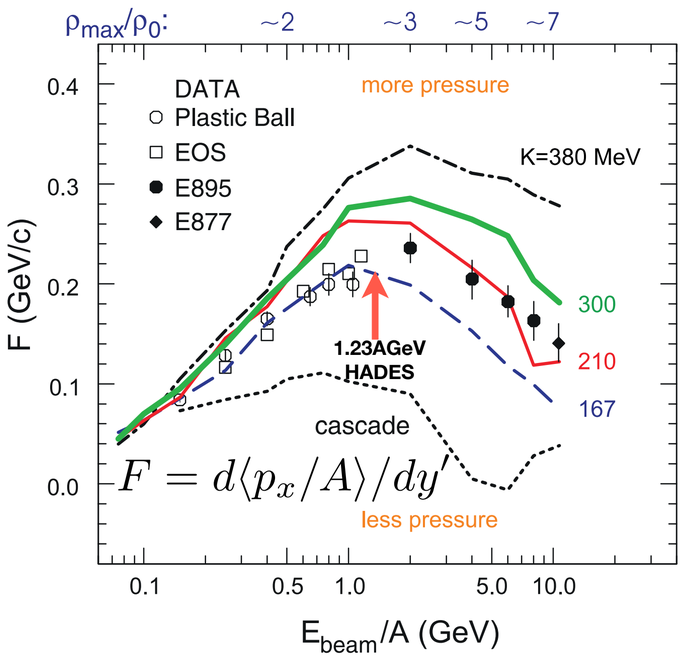


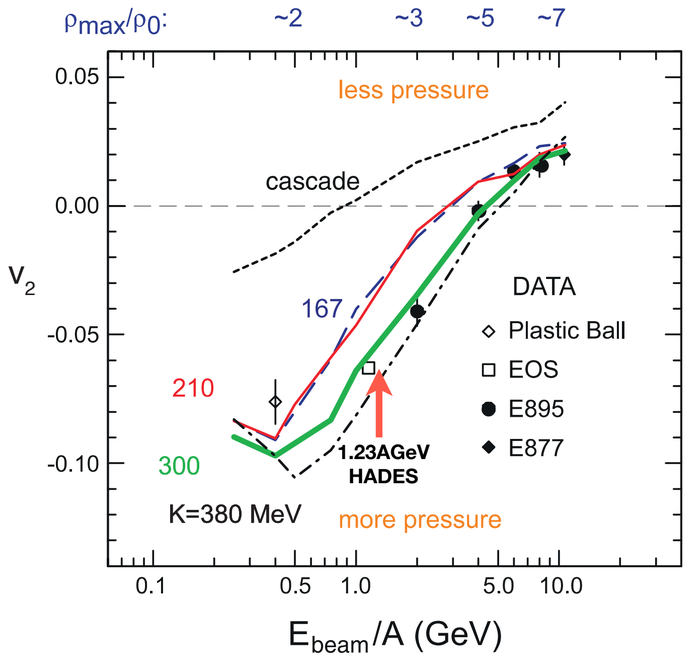
Equation of State of Dense Matter

- EoS is the *equilibrium* property of Hydrodynamical simulations

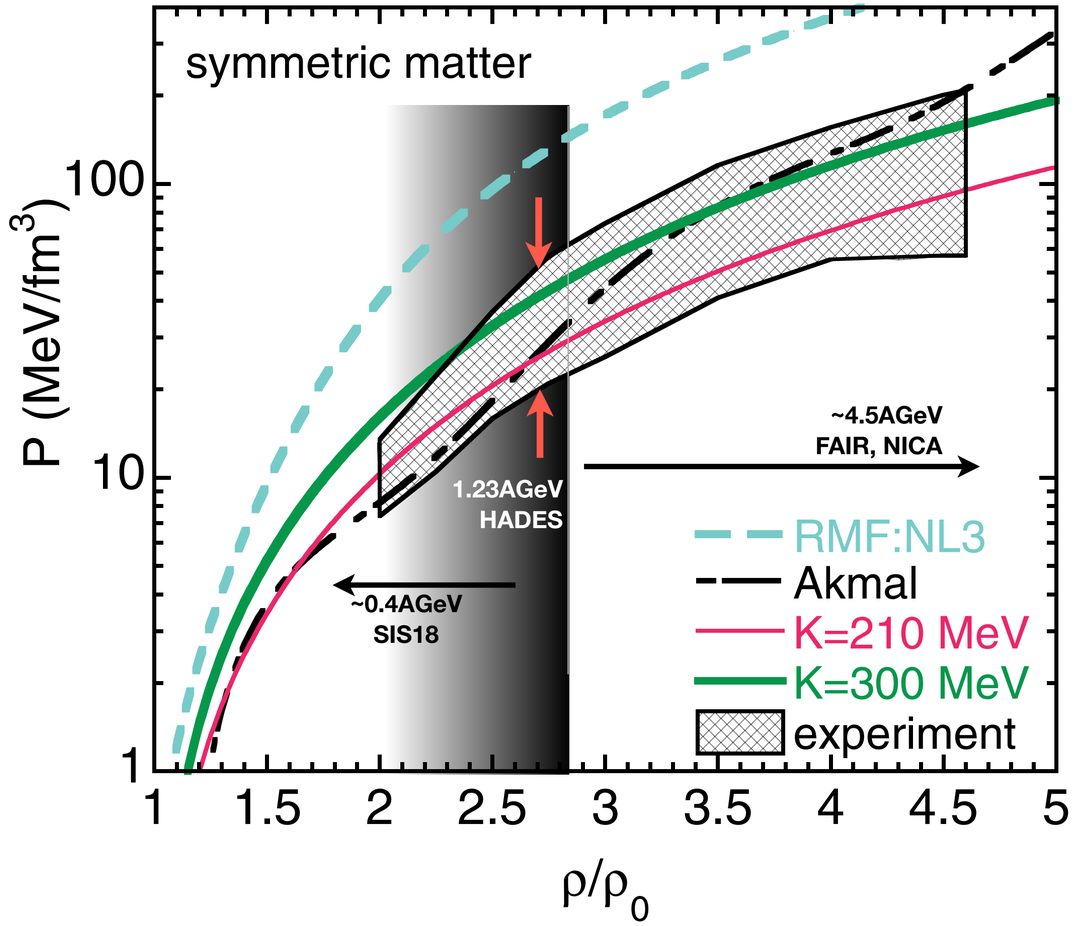
  Non-equilibrium dissipative effects are described by transport coefficients (shear viscosity $\boldsymbol{\eta}$)

- 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



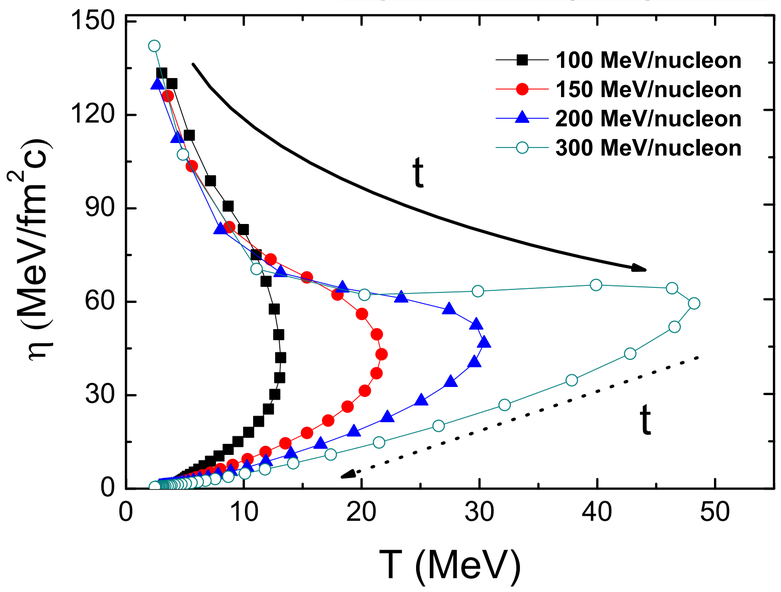
Properties of Dense Nuclear Matter

Shear viscosity

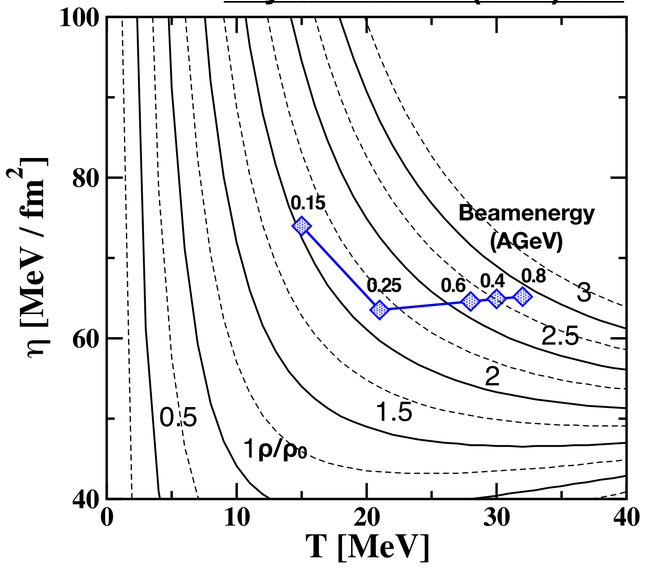
Nuclear shear viscosity extracted from transport models

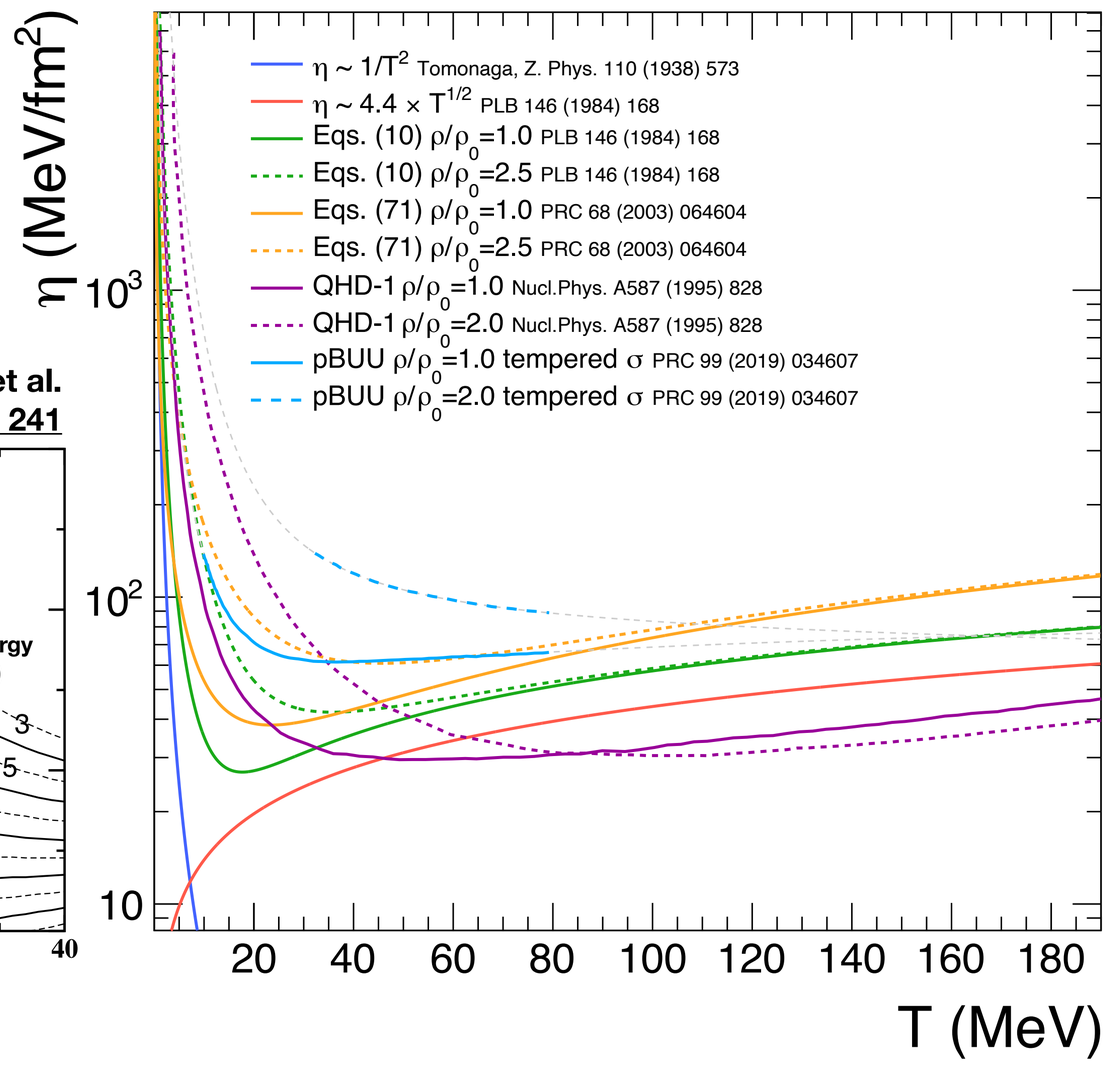
Mean-field potentials and in-medium cross section are constrained by stopping and flow observables

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



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





Model Comparisons to Proton Data

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

Determination of EOS

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

Models:

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

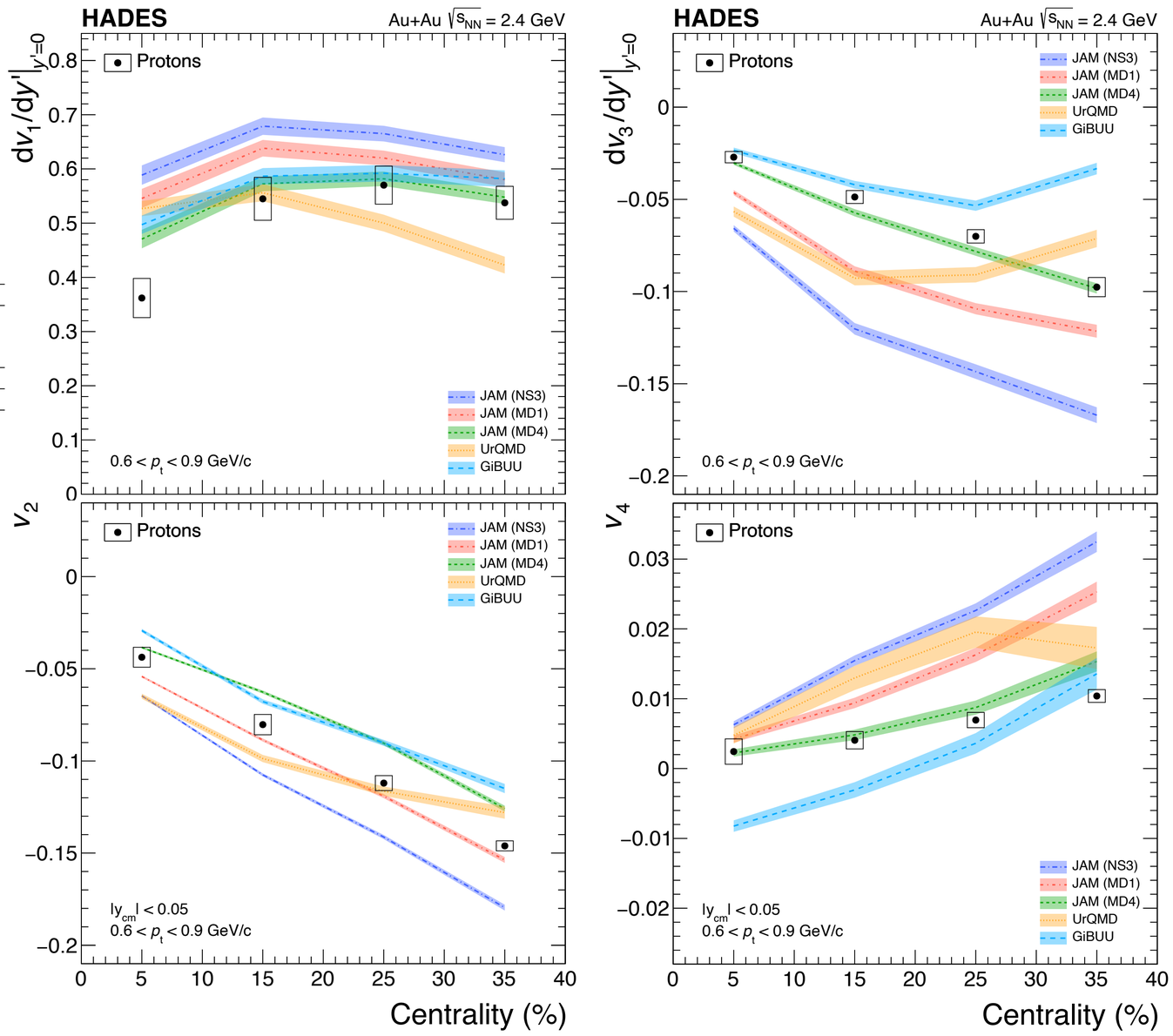
Model	EOS	K (MeV)	m^*/m	mom-dep.
JAM 1.90591	NS1	380	0.83	no
	MD1	380	0.65	yes
	MD4	210	0.83	yes
UrQMD 3.4	Hard	380		no
GiBUU 2019 (patch7)	Skyrme 12	240	0.75	no

Conclusions

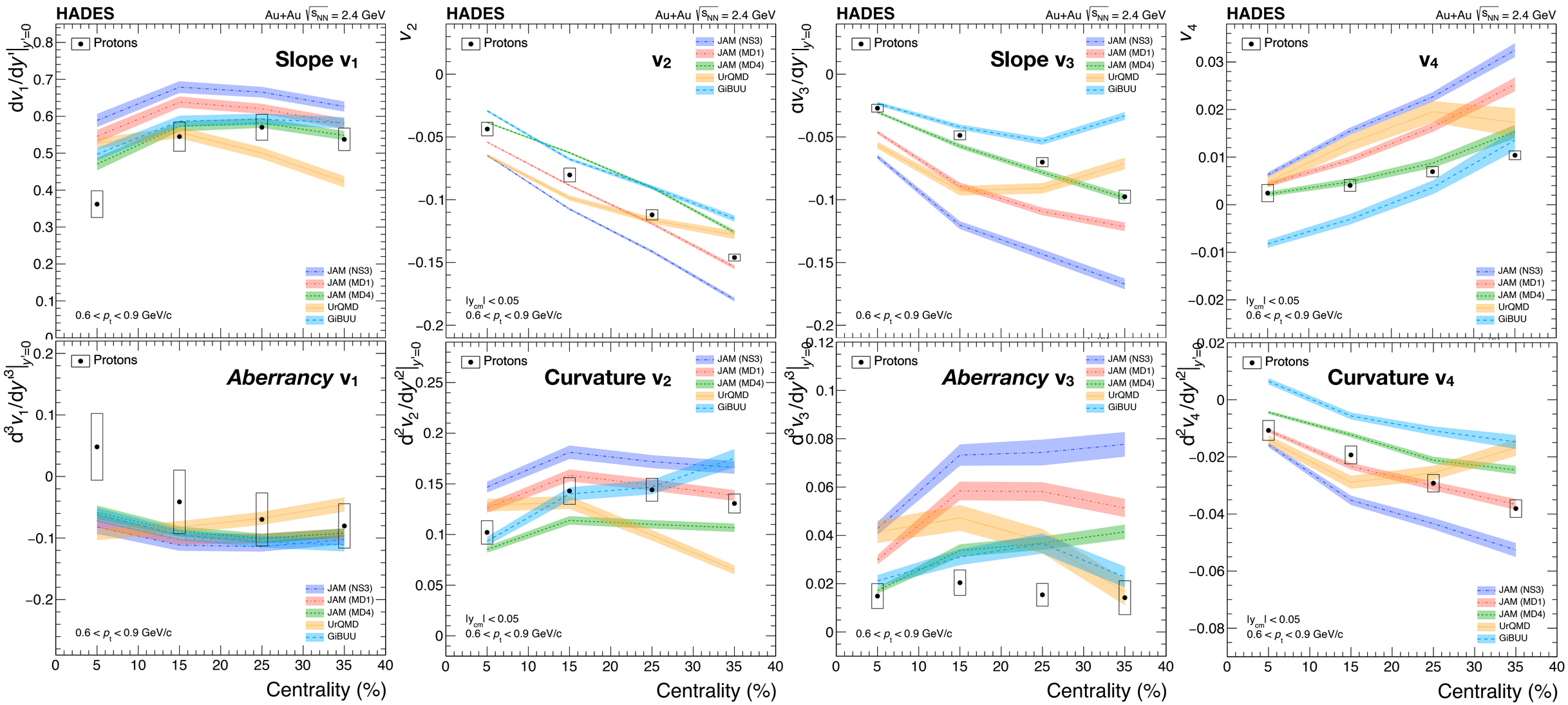
Overall trend reasonably described, but no model works everywhere

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

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



Model Comparisons to Proton Data



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

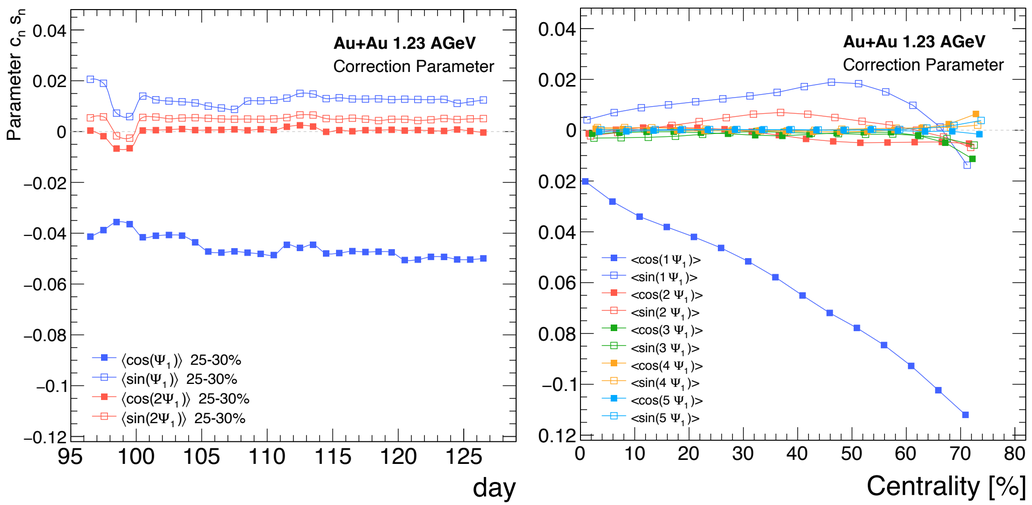
Event Plane Determination

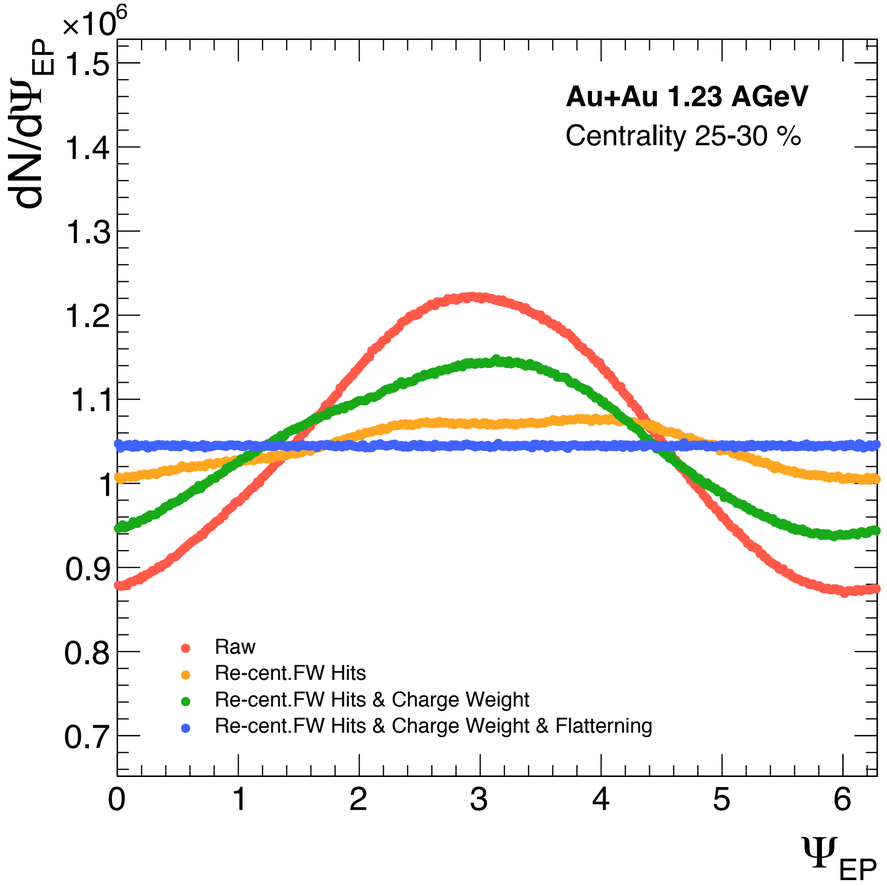
Correction of non-uniformities in the EP distribution (day-by-day and centrality)

Re-Centering of X and Y of all FW hits

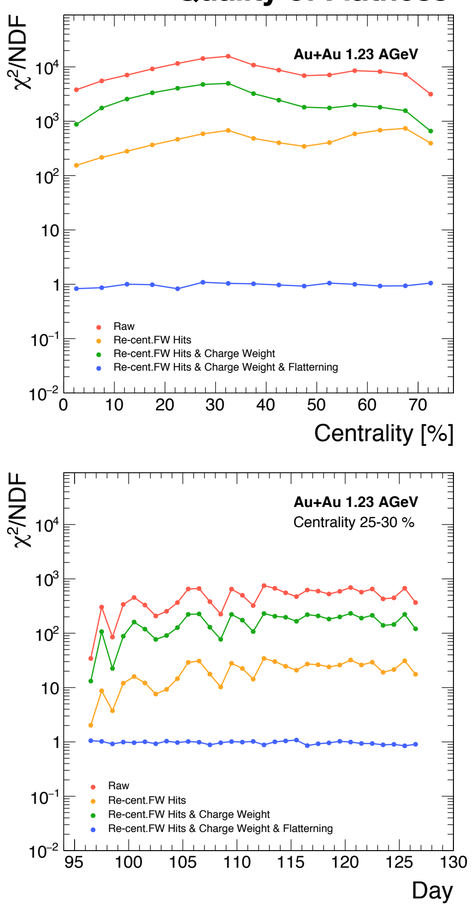
Flattening of residual Fourier components with 8 cos- and 8 sin-terms

Flattening Parameter





Quality of Flatness

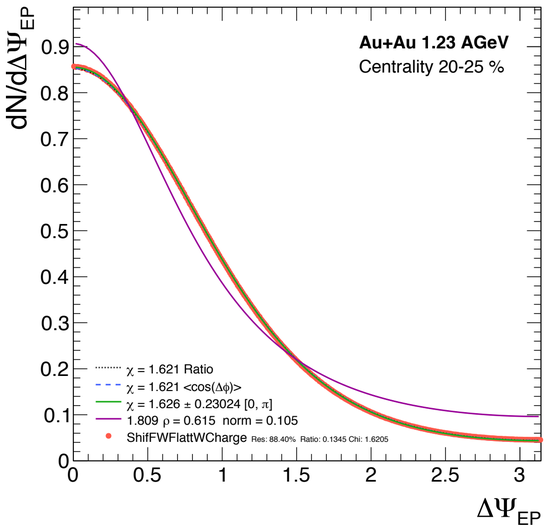


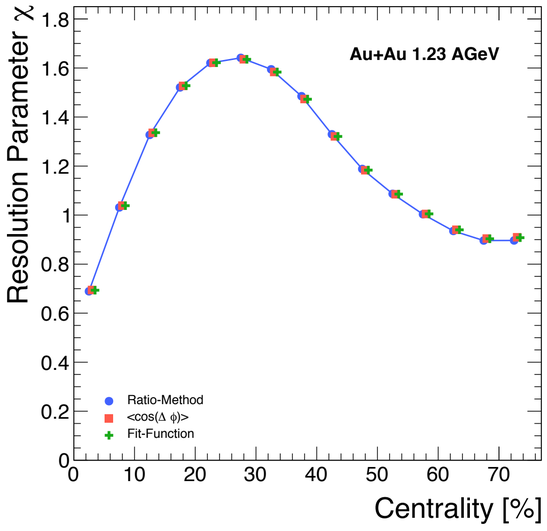
Event Plane Resolution

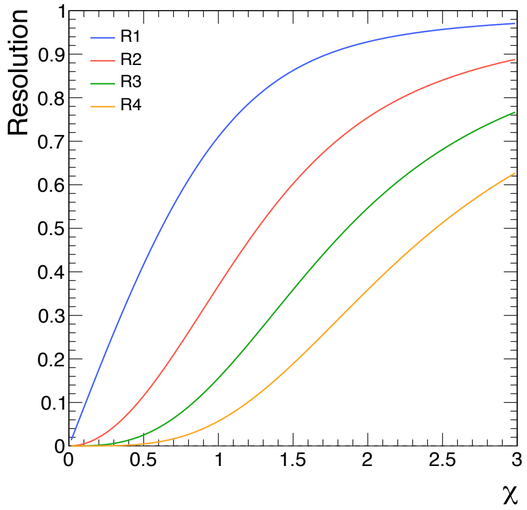
EP-resolution via sub-event method with three implementations

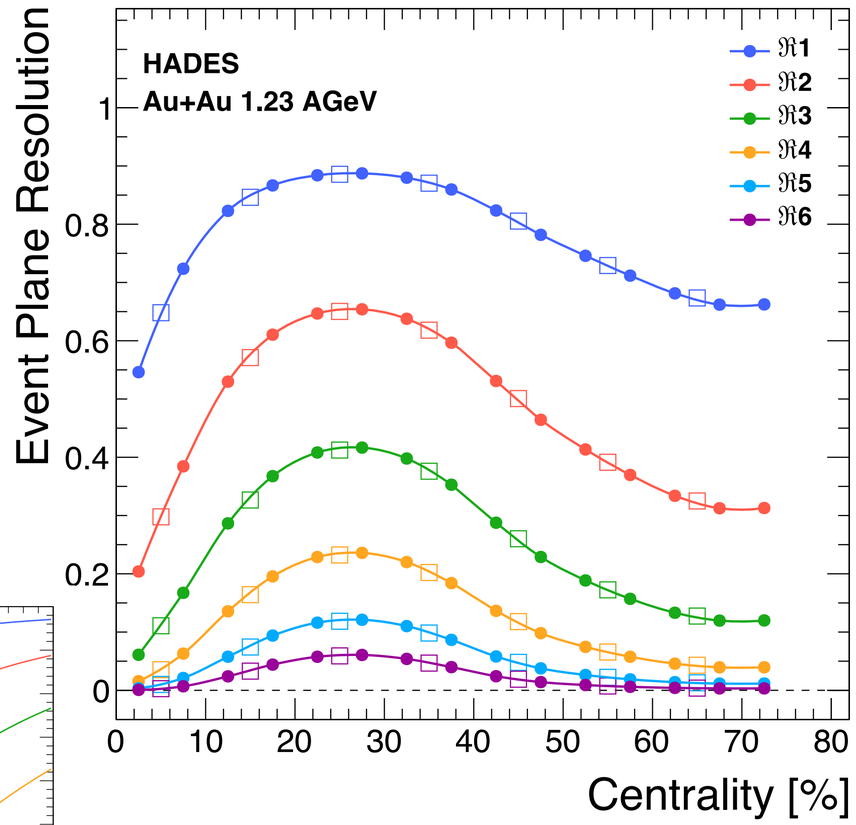
- Determination of resolution parameter χ
  - directly via <cos (ΔΦ)>
  - Approximation via Fraction of Events with ΔΦ > π/2
  - Fit-Method

Calculation of EP-Resolution of different order









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

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

Systematic Uncertainties

Validation and Consistency Checks

Sources of uncertainties

- Track selection and PID
- Occupancy correction
- Non-uniform acceptance

Toy MC study

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

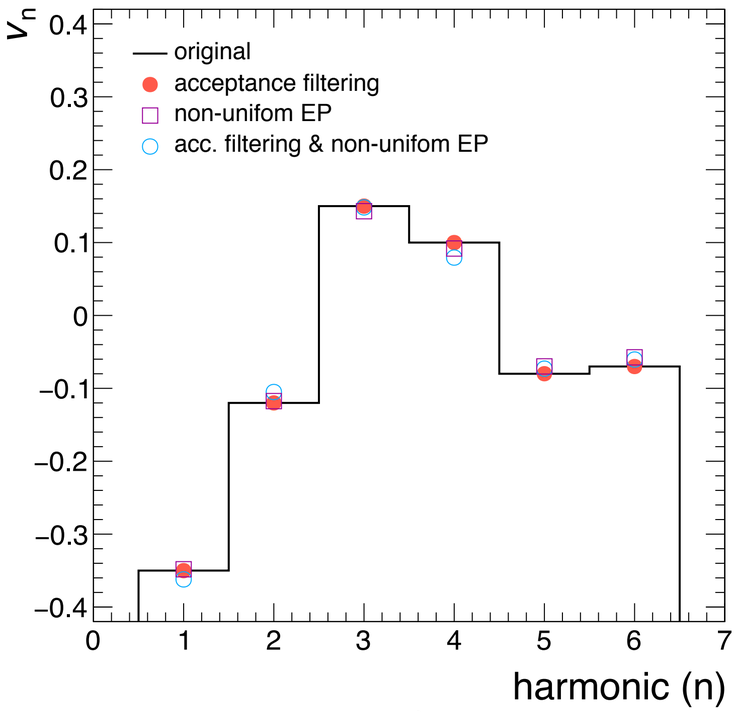
Consistency checks:

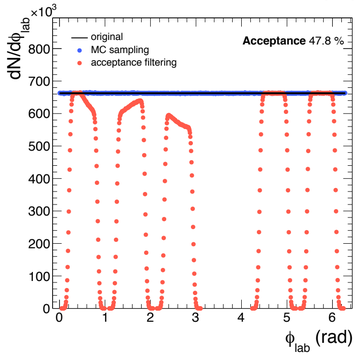
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at $y_{cm}=0$
- Vanishing residual sine-terms
- Time-dependent systematic effects

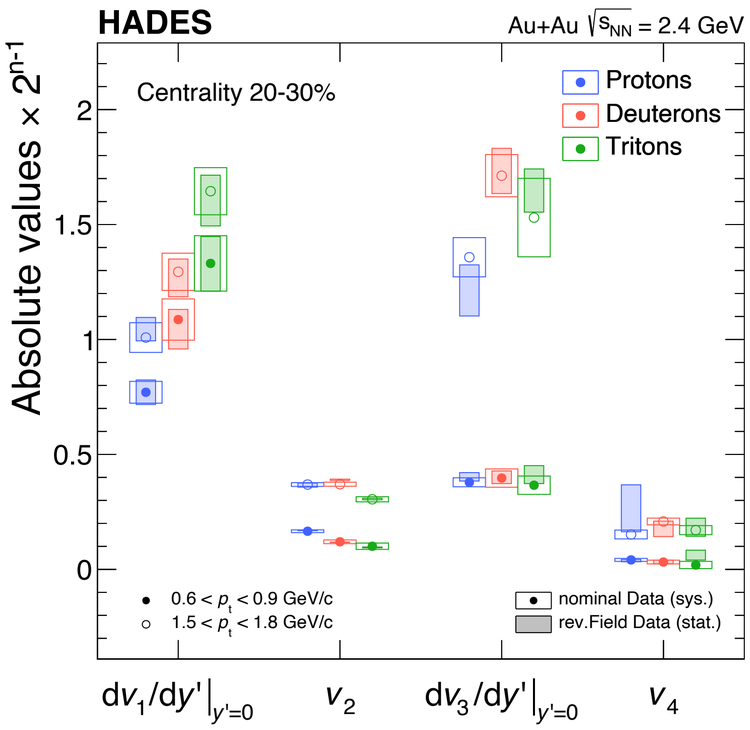
Reversed field polarity

Comparison with flow coefficients from the full data set

HADES, arXiv:2208.02740

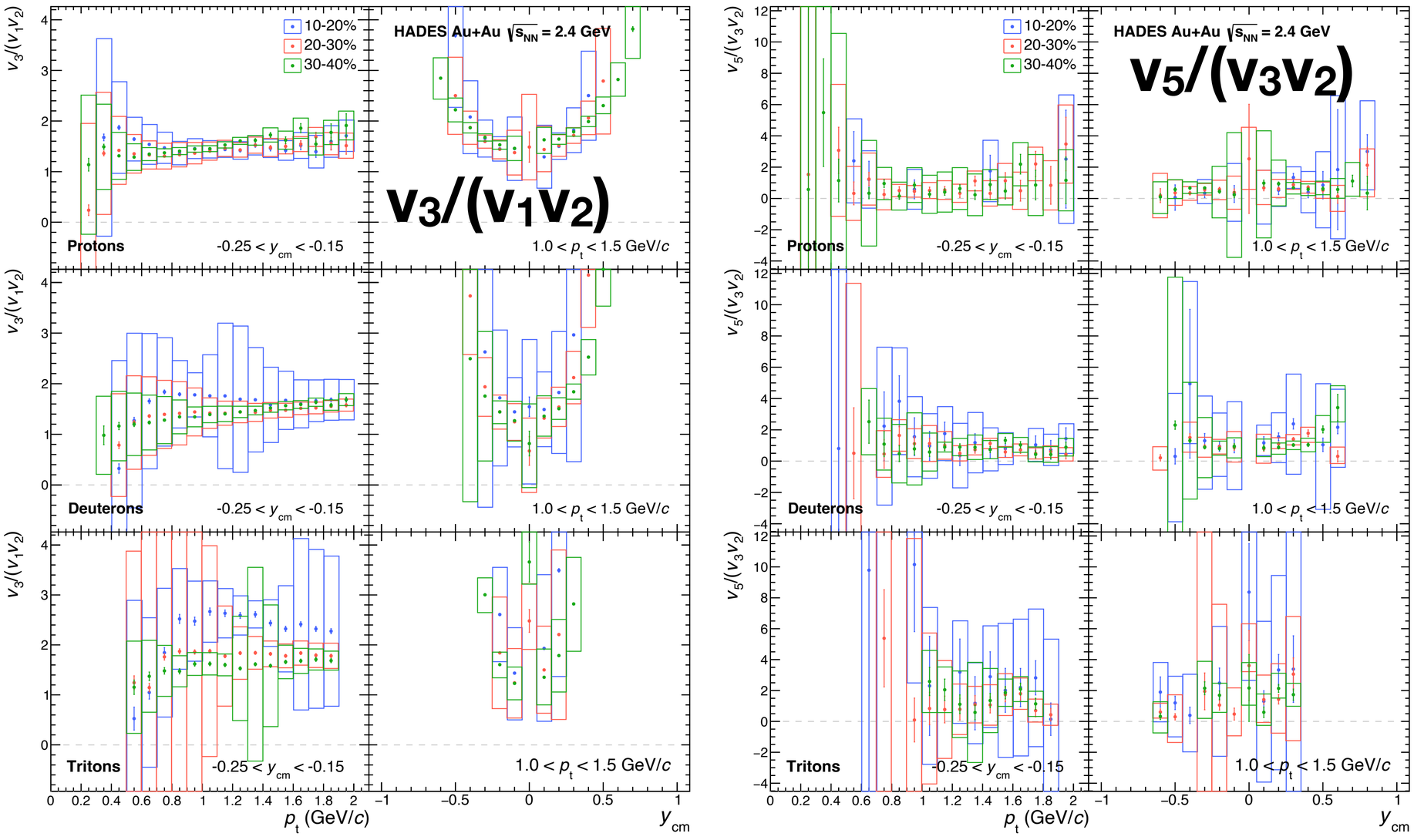






Other Ratio-Scalings?

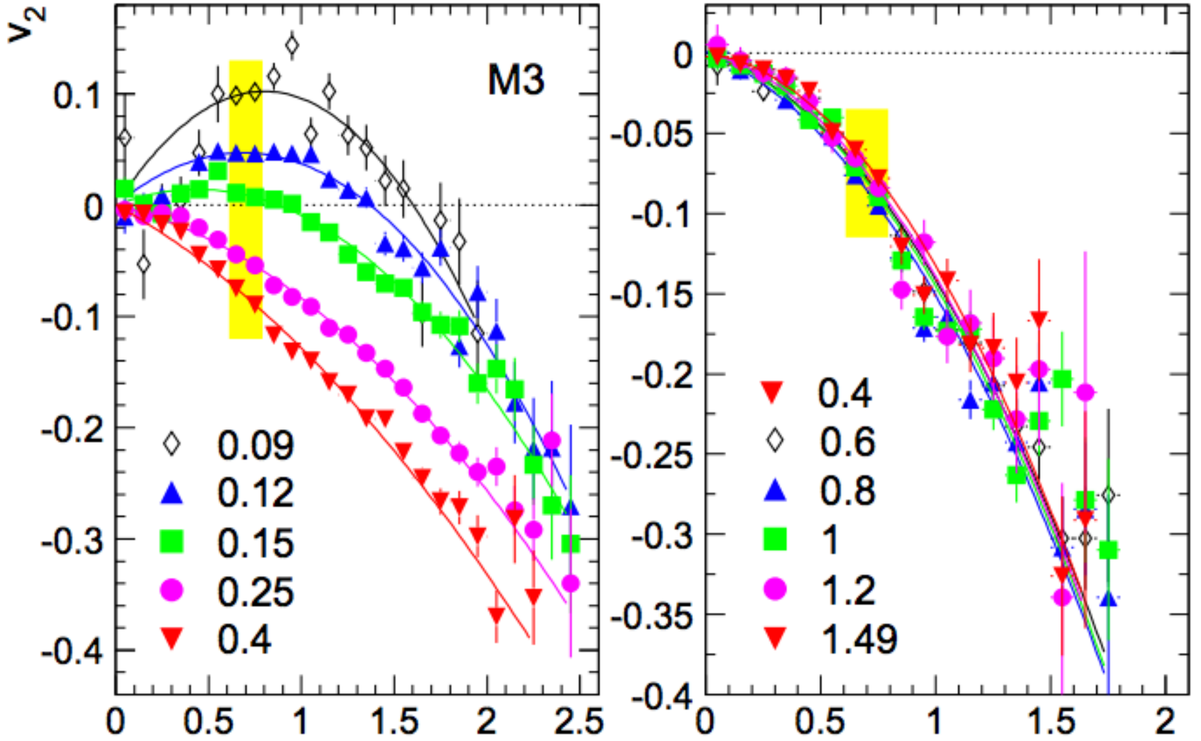
Protons and light nuclei



Elliptic Flow v_2

Energy- and p_t-Dependence

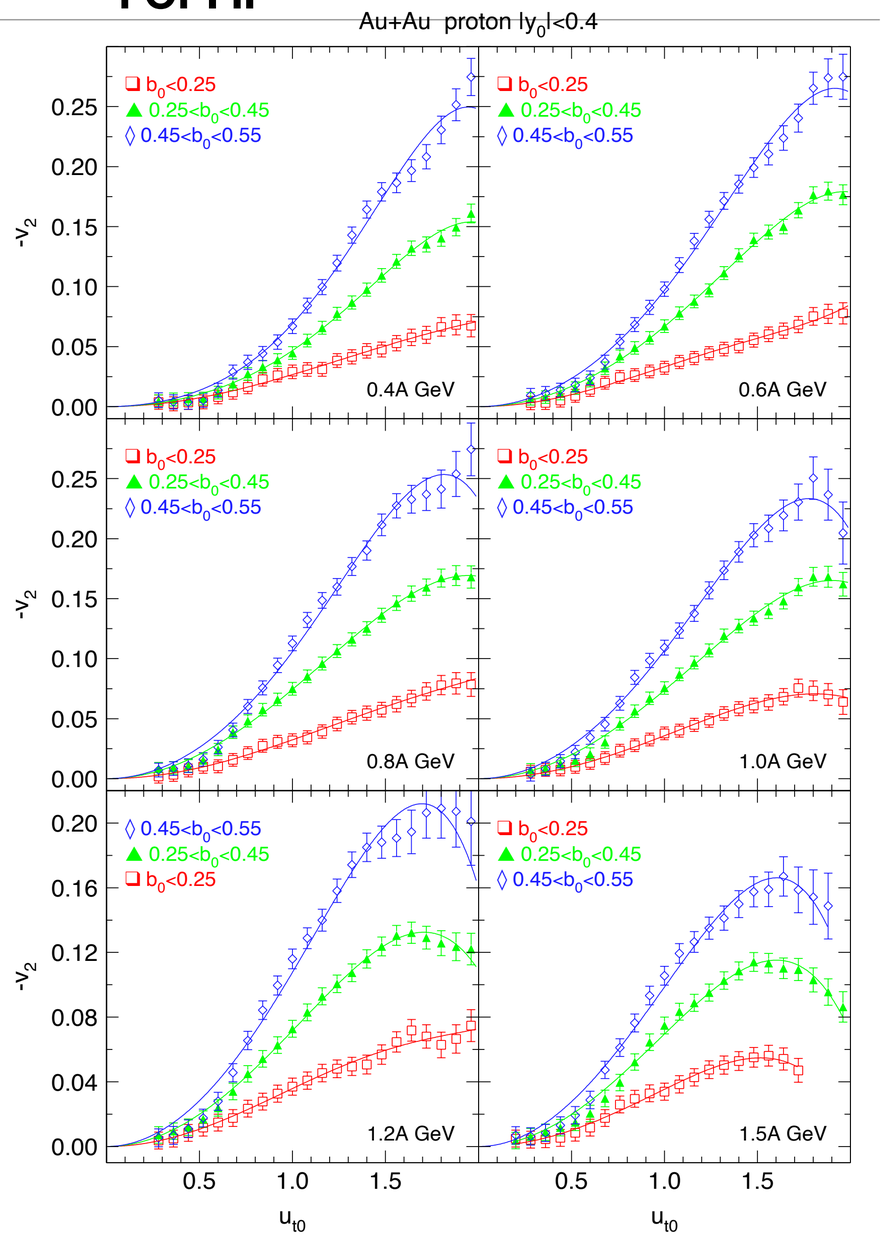
FOPI I



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

Parameterization with Polynomial

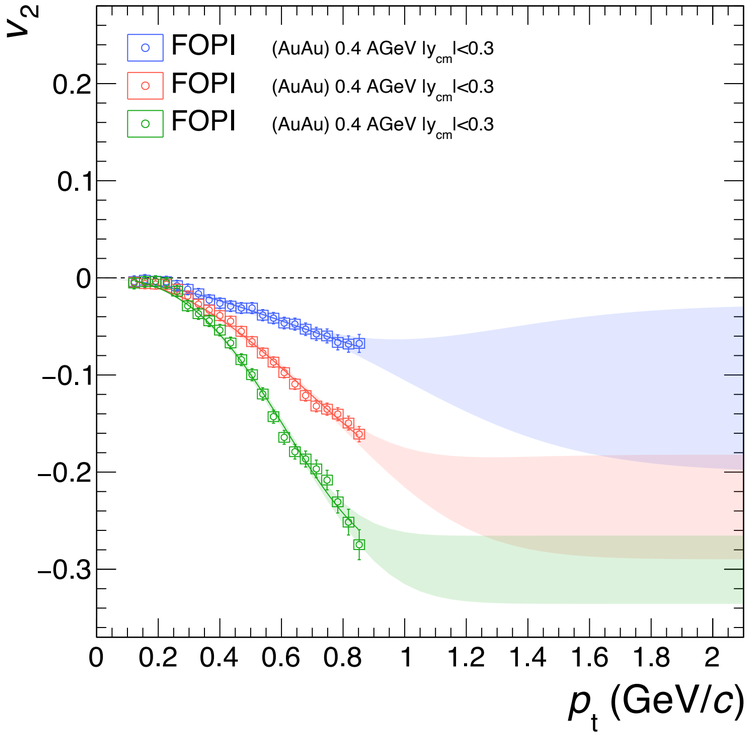
FOPI II



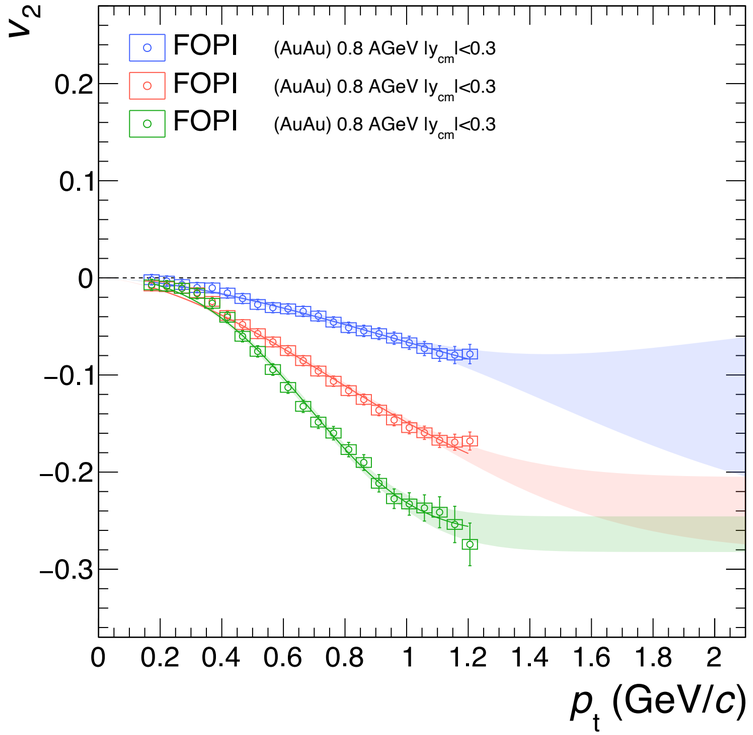
Elliptic Flow v_2

Energy- and p_t-Dependence

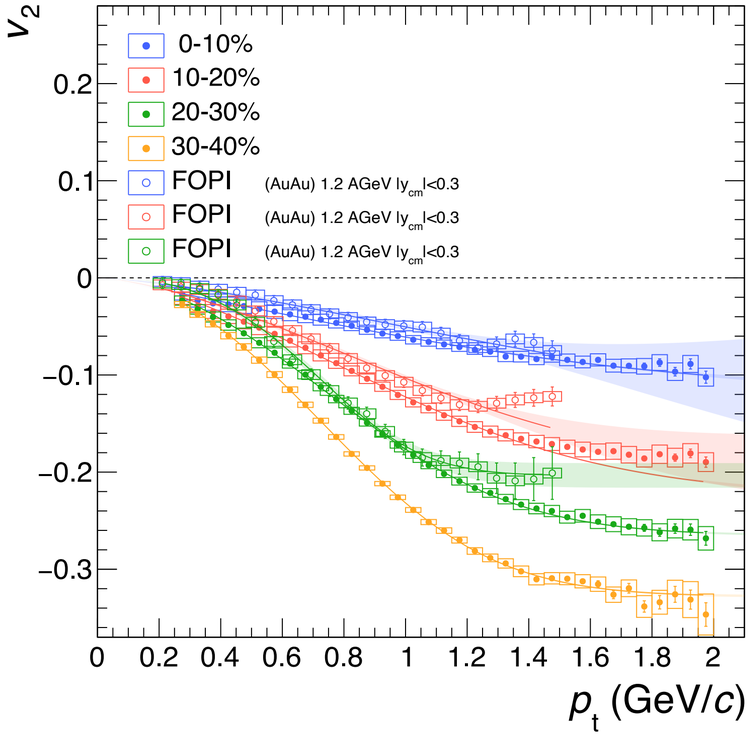
Au+Au 0.4 AGeV



Au+Au 0.8 AGeV



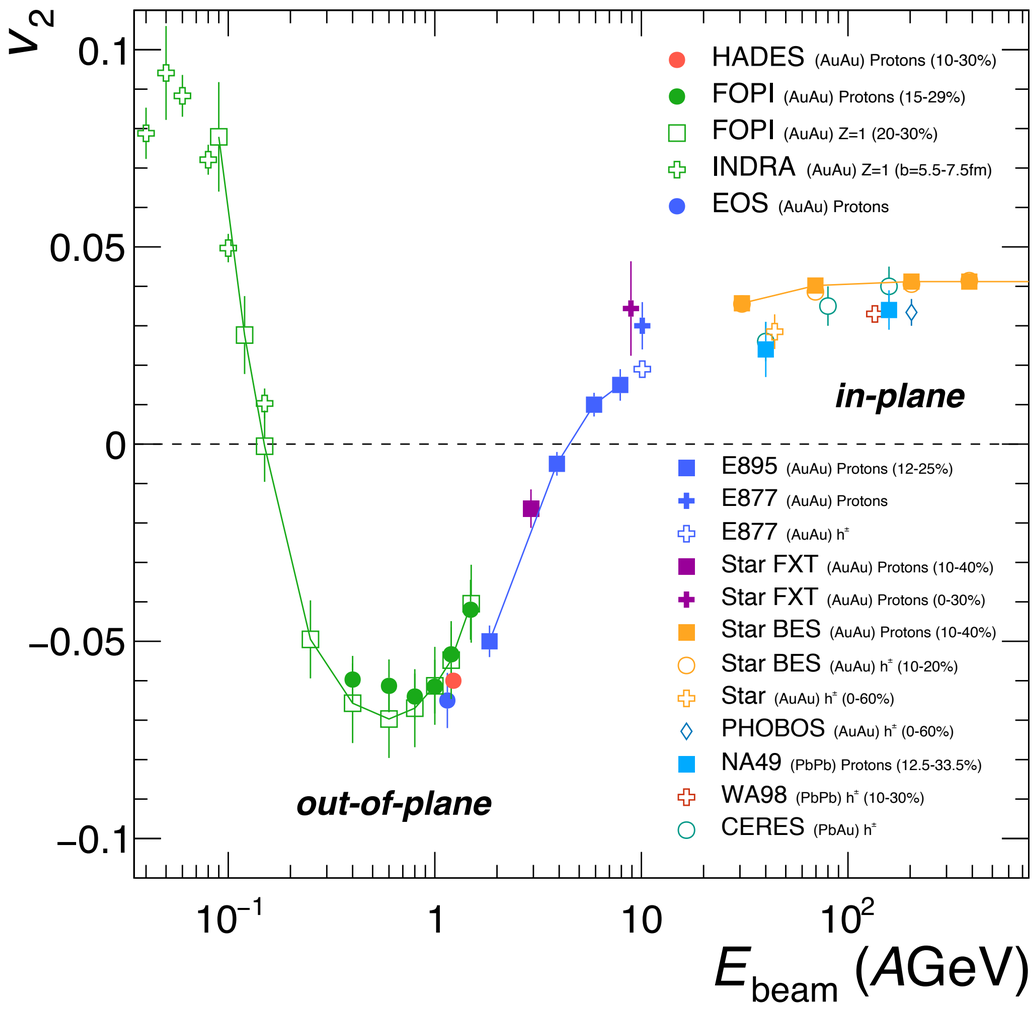
Au+Au 1.23 AGeV

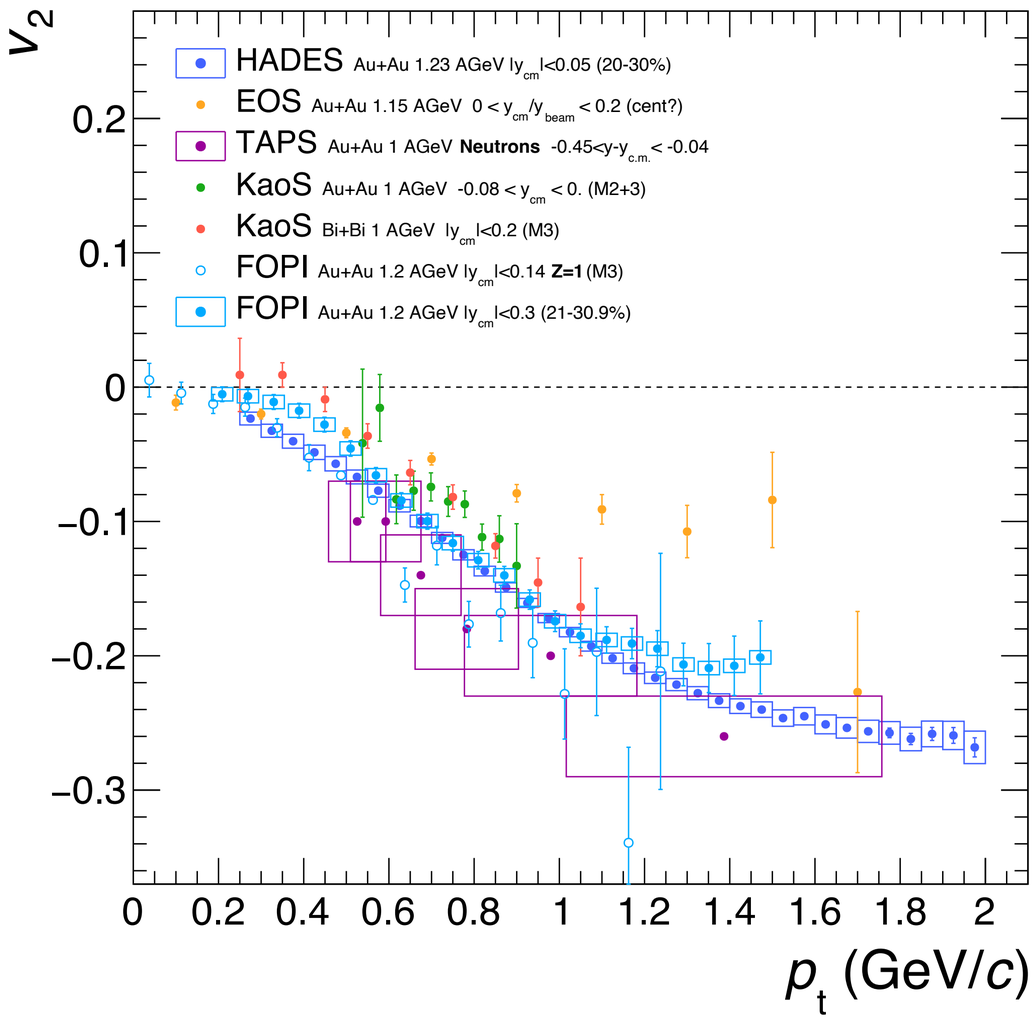


Comparison to FOPI data

Elliptic Flow v_2

Energy- and p_t-Dependence





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Nucl.Phys. A876 (2012) 1-60