On the Collective Dynamics of Dense Baryonic Matter

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10th International Symposium on Non-Equilibrium Dynamics

Krabi, Thailand

Nov. 25. – 29., 2024

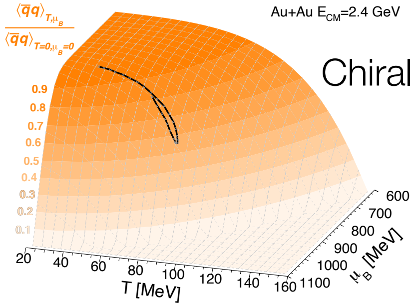
Dense Baryonic Matter

Heavy-Ion Collisions

Heavy-ion collisions

QCD phase diagram in the region of high μ_B

Rare and penetrating probes



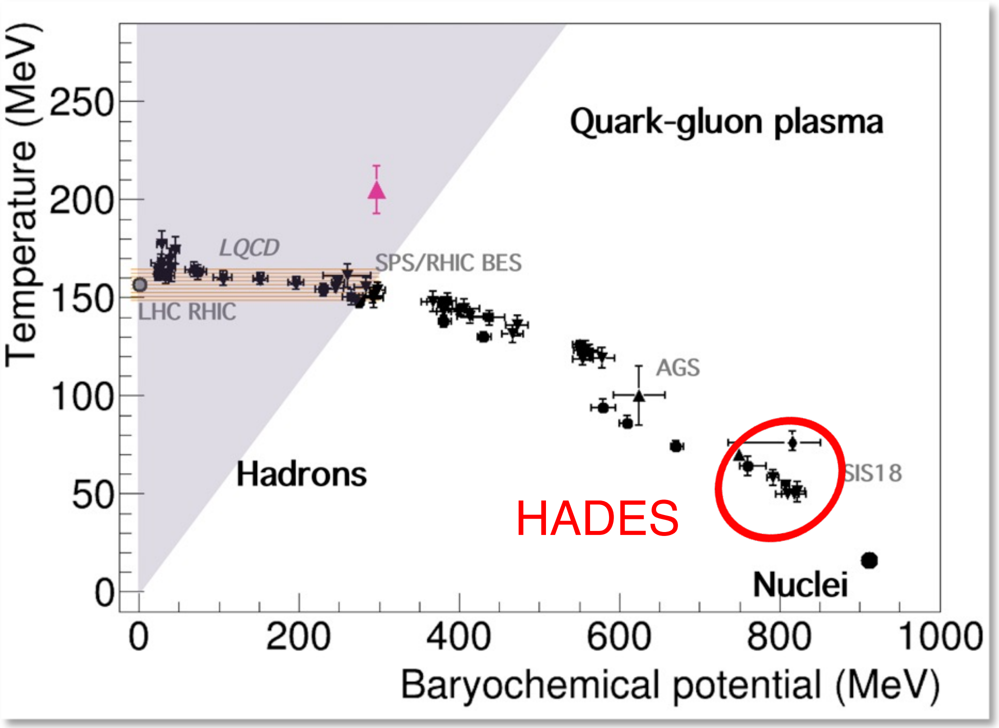
Chiral condensate

F. Seck et al.,
JPCS **024** (2018) 012011

Bulk properties of dense fireball

Pion + proton beams

Properties of baryon resonances
(vacuum, cold QCD matter)



Dense Baryonic Matter

Physics Topics

Open questions

Origin of hadron masses
Role of of condensates
QCD-Confinement
Equation-of-state (EoS) of dense matter

Super-dense matter in the laboratory

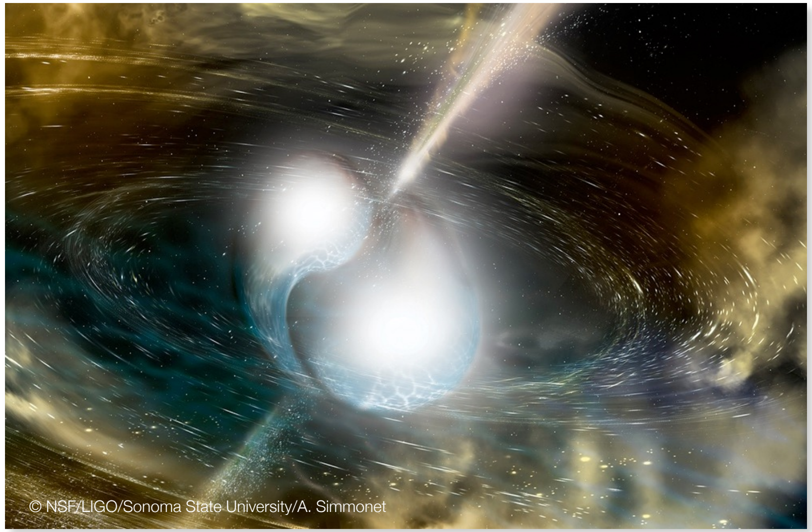
Neutron Star Merger

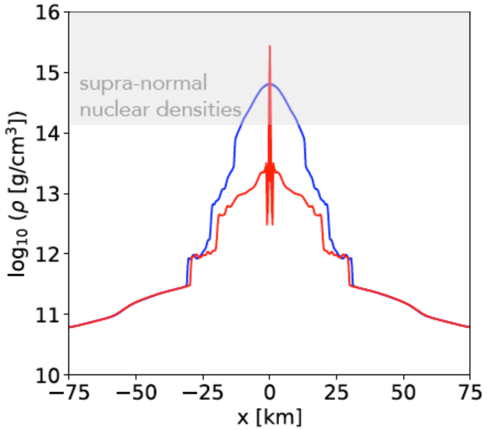
Observation via gravitational waves

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

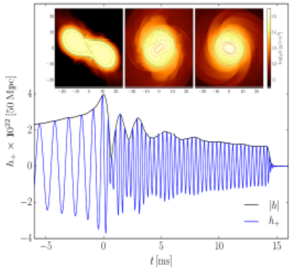
Sensitivity to EoS

Super-dense matter in the universe





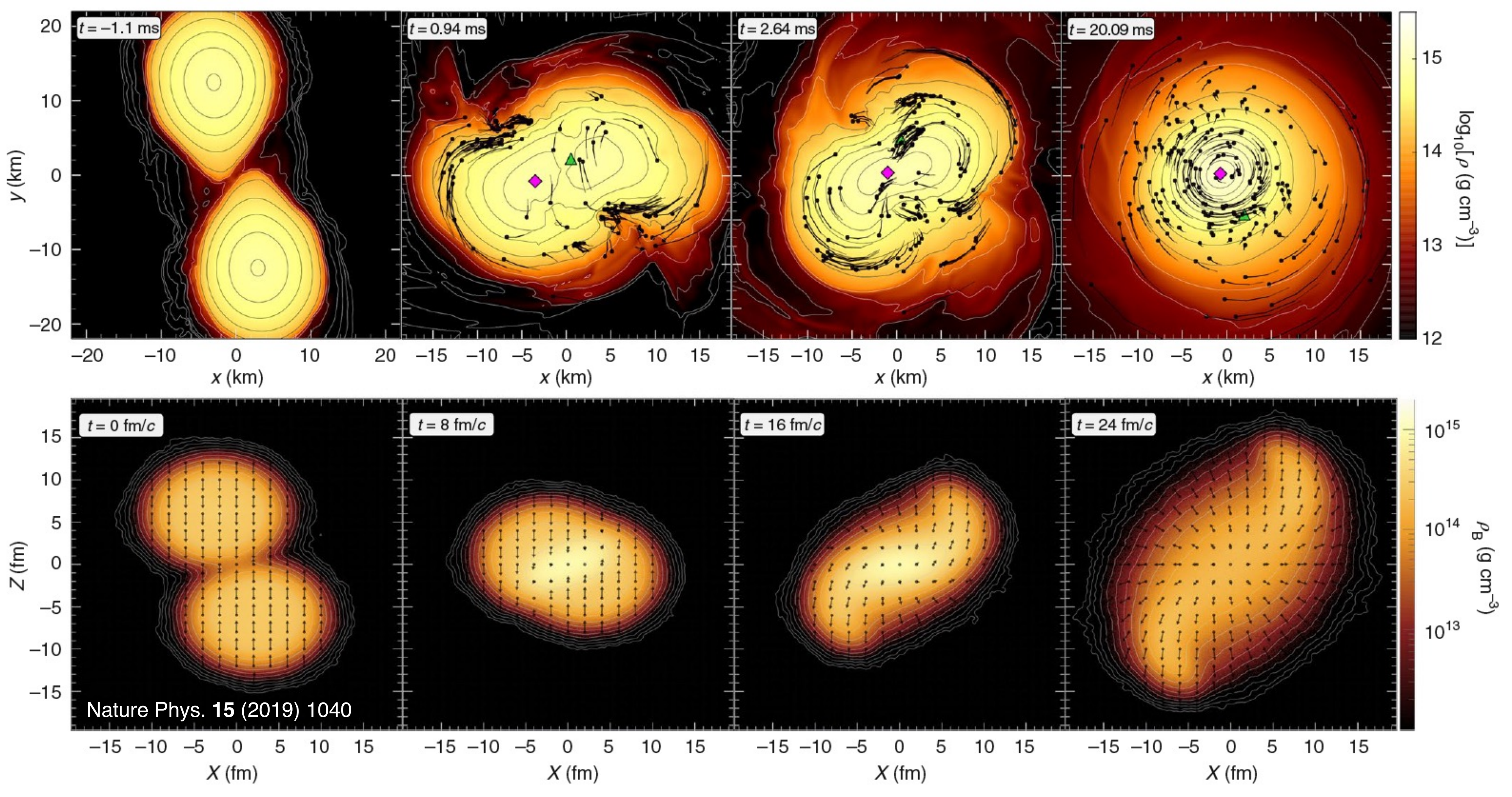
Density profile across a merging NS binary system. Taken $t = 1.4$ ms ($t = 0$ see below).



M. Hanauske, L. Rezzolla et al. J.Phys.Conf.Ser. 878 (2017) no.1, 012031

Dense Baryonic Matter

Relation to Neutron Star Mergers



Dense Baryonic Matter

Topics of this Talk

Flow Measurements

Principle of flow measurements relative to the 1st order event plane

Results for Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV

Proton, deuteron and triton flow results up to 4th order (v_1, v_2, v_3, v_4) (PhD work by B. Kardan)

Scaling Properties

Mass number and initial geometry scaling properties

Model comparisons

Comparison of various model calculations ⟹ Towards a precise determination of the EoS

Correlations

Additional information extracted from the correlations of flow coefficients

Flow Measurements

Principle

Emission relative to event plane

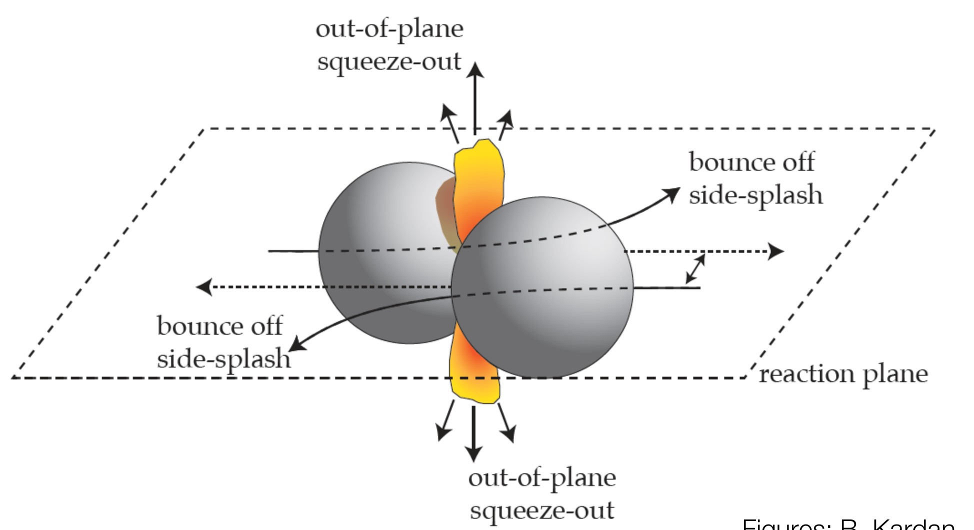
Interactions in medium
$\Longrightarrow$ different pressure gradients in different directions

Access to medium properties, e.g. viscosity
Equation-of-state (EoS)

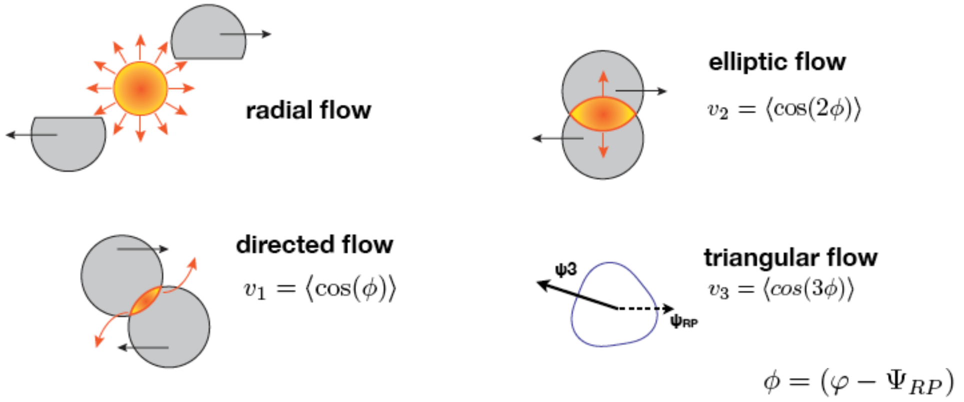
Fourier-Decomposition

Extraction of moments v_n

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$



Figures: B. Kardan



Flow Measurements

Event Plane

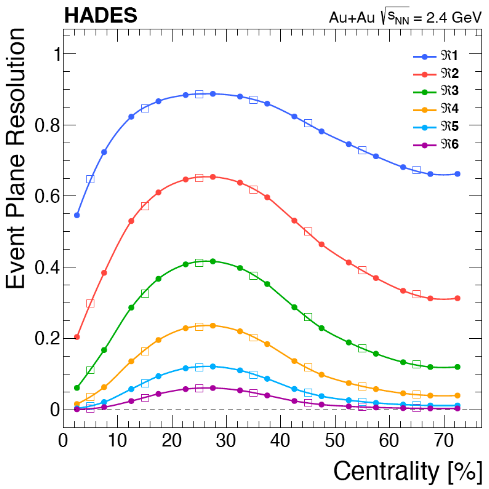
Event plane Reconstruction

1st-Order event plane

Projectile spectators in Forward Wall

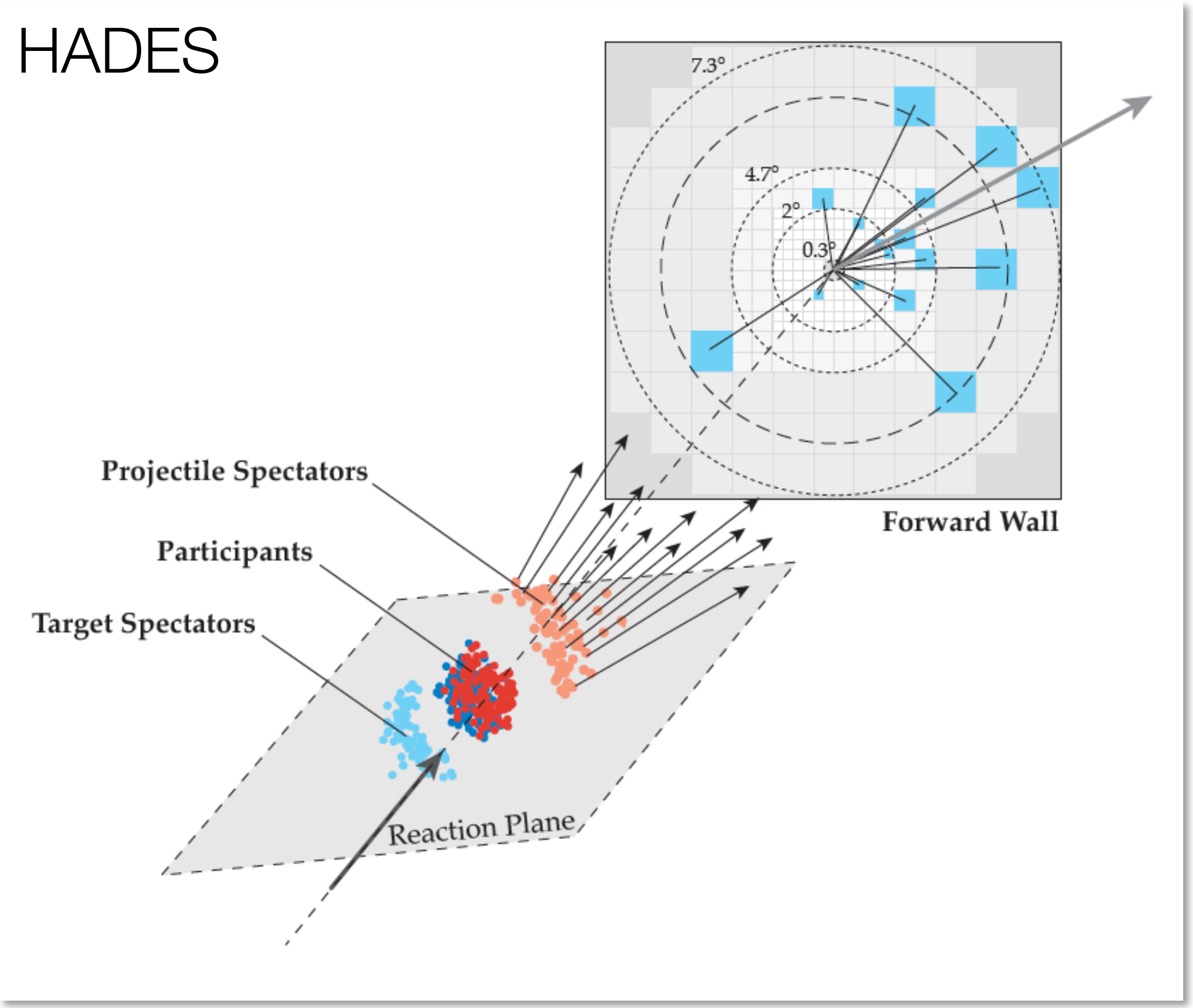
EP-resolution via sub-event method

J.-Y. Ollitrault, arXiv:nucl-ex/9711003



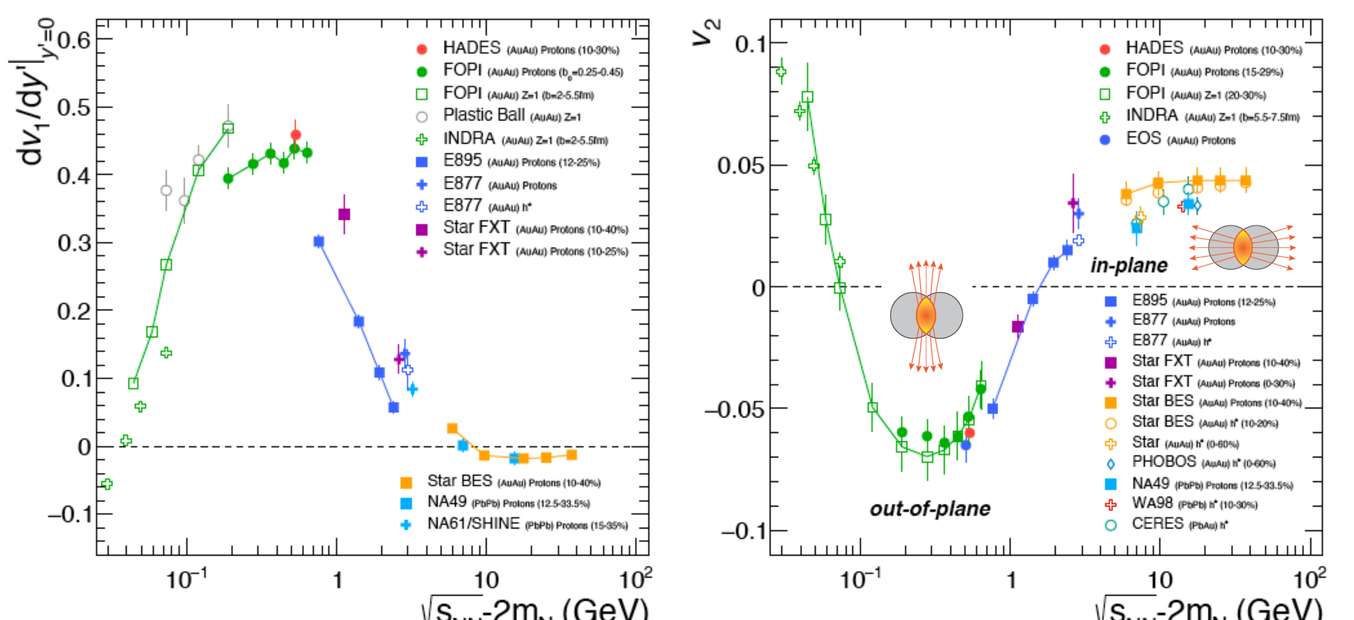
$$v_n = v_n^{obs} \,/\, \mathfrak{R}_n$$

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



Flow Measurements

Energy Dependence of Directed and Elliptic Flow



HADES, EPJ **A59** (2023) 80

Compilation of world data

Good agreement of integrated dv_1/dy (directed flow) and v_2 (elliptic flow) between experiments

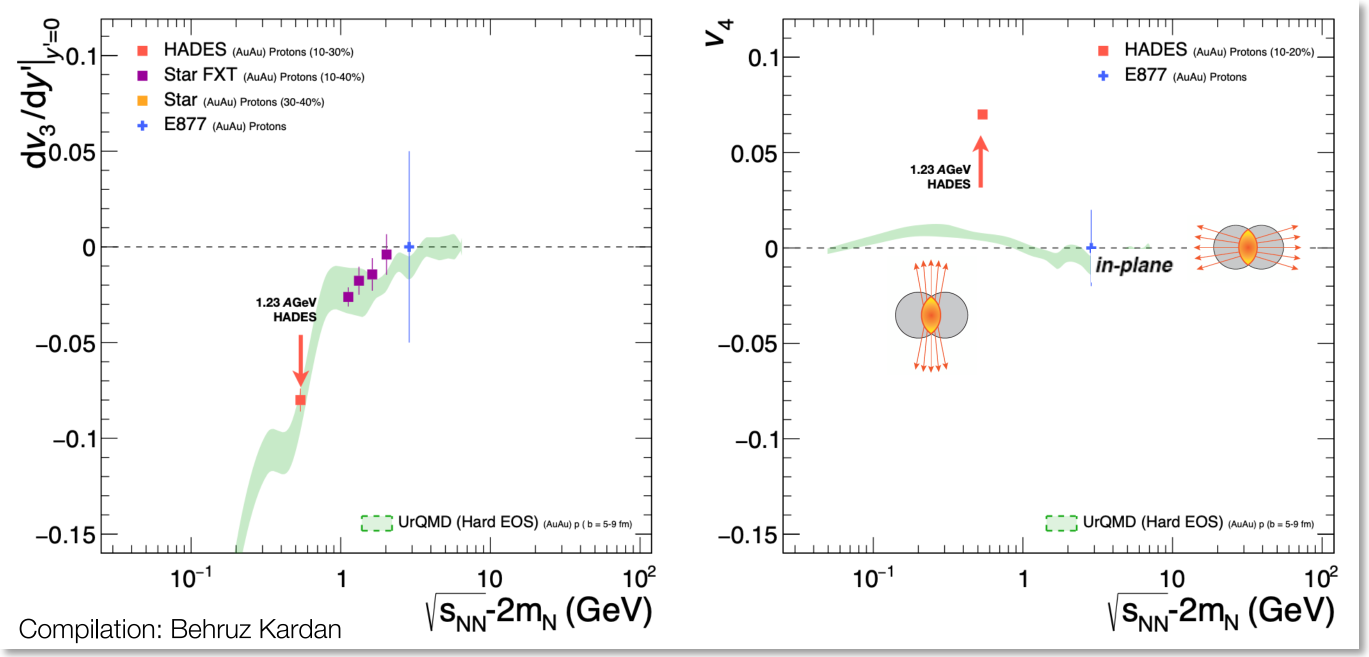
Out-of-plane v_2

Long spectator passing time $\tau_{passing} \approx \tau_{expansion} \Longrightarrow$ "squeeze-out" and/or "shadowing"

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

Flow Measurements

Energy Dependence of Higher Orders



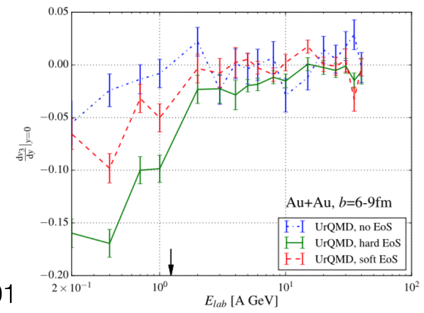
Triangular and quadrangular flow

Very scarce data at low energies

Additional source of information

Should help to narrow down EoS

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



Flow Measurements

Experiment Comparison

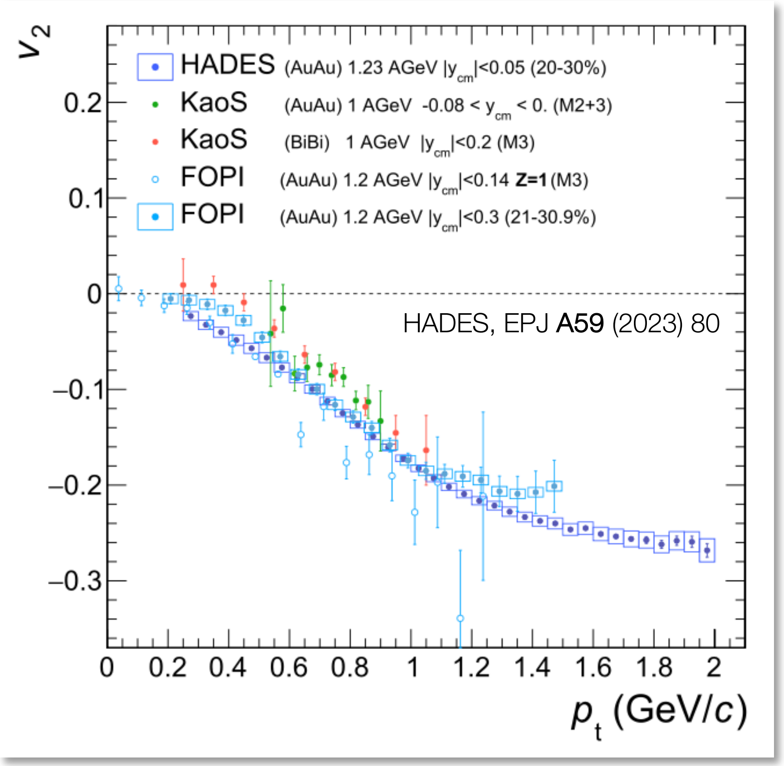
Elliptic flow of protons

Other data sets from SIS18

KaoS: Z. Phys. **A355** (1996) 61
and priv. comm.

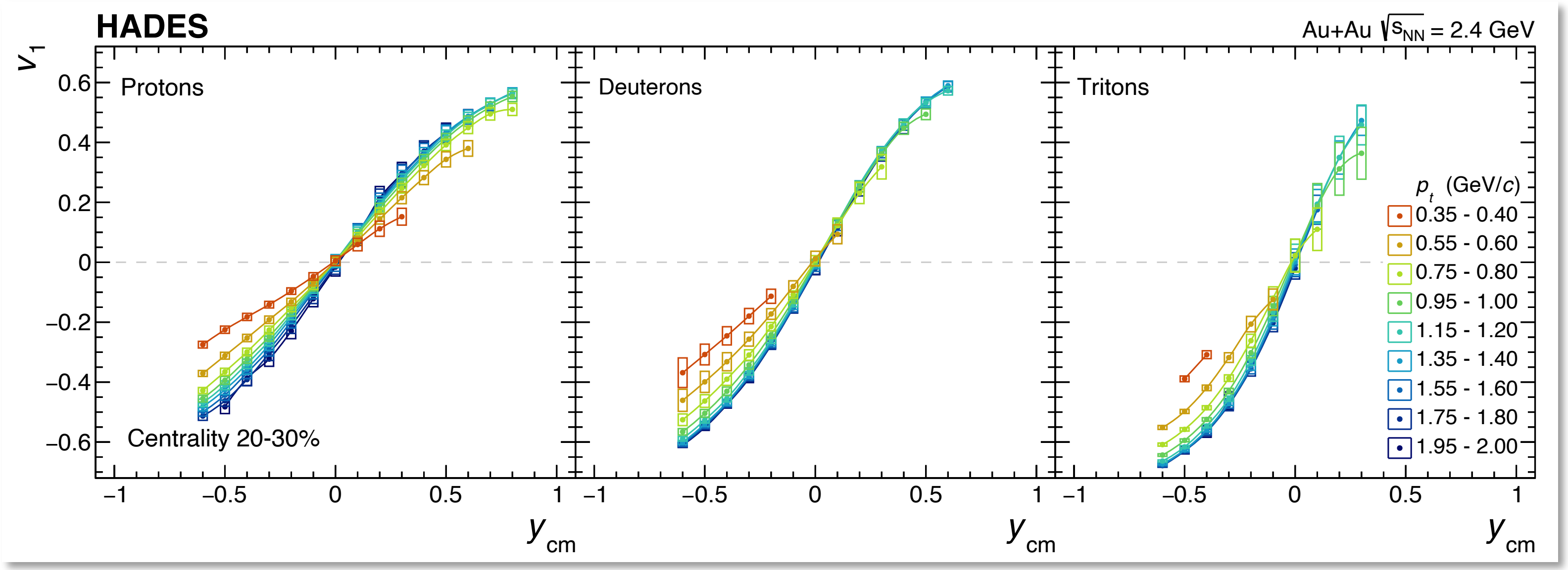
FOPI: Phys. Lett. **B612** (2005) 173
Nucl. Phys. **A876** (2012) 1

Good agreement, considering differences in beam energies and/or centrality selection



Results for Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV

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



All data points
available in HEPDATA:
https://www.hepdata.net/record/ins2132332

HADES, EPJ **A59** (2023) 80

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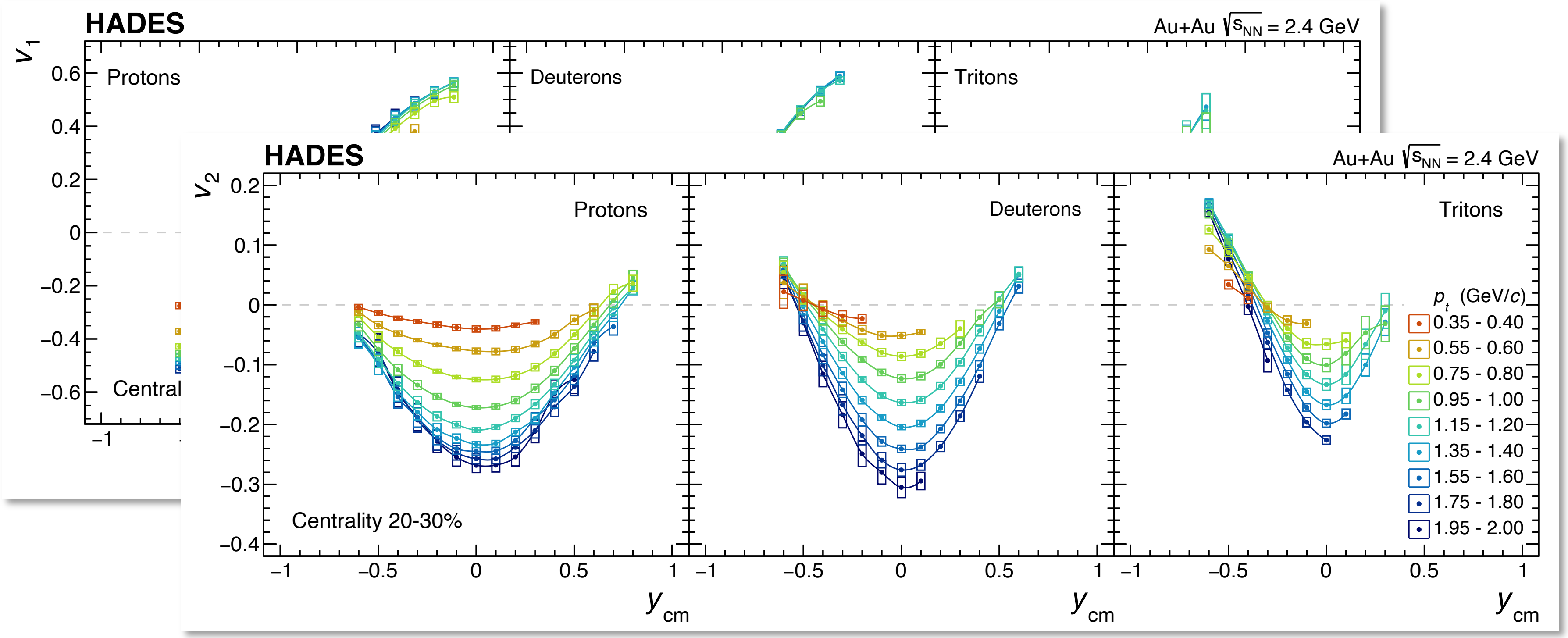

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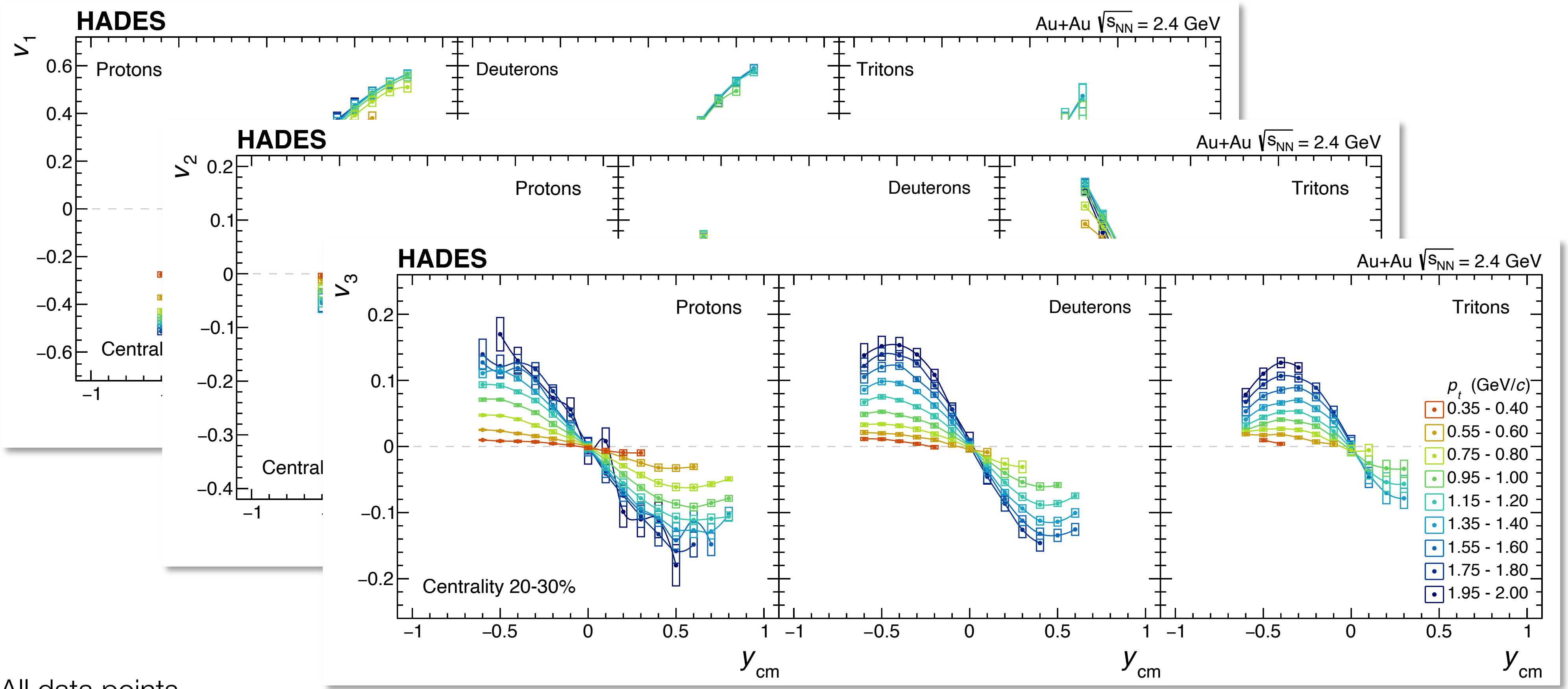

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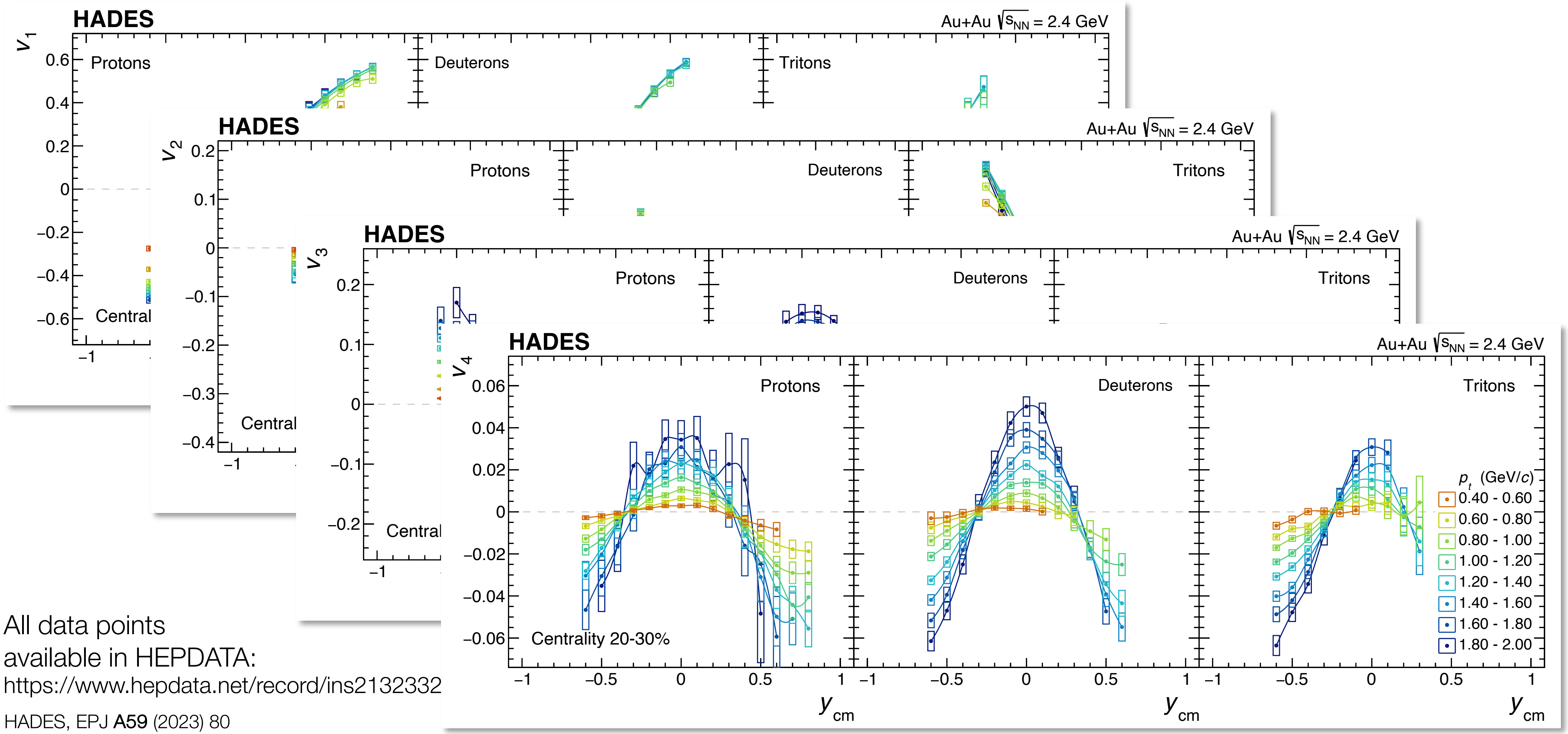

All data points
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https://www.hepdata.net/record/ins2132332

HADES, EPJ **A59** (2023) 80

Results for Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons vs. Centrality

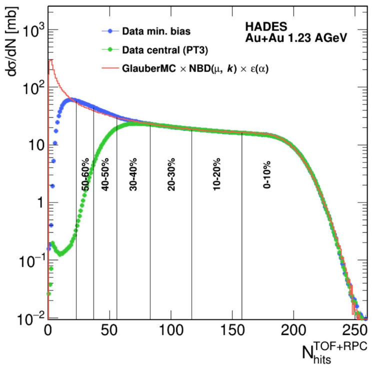
Four centrality classes available

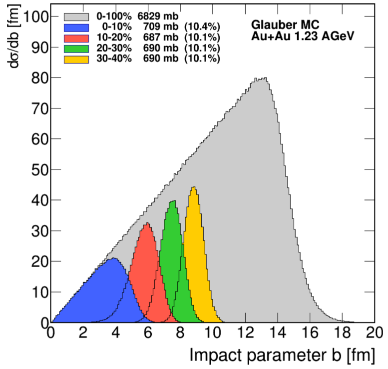
0 – 10 %, 10 – 20 %, 20 – 30 %, 30 – 40 %

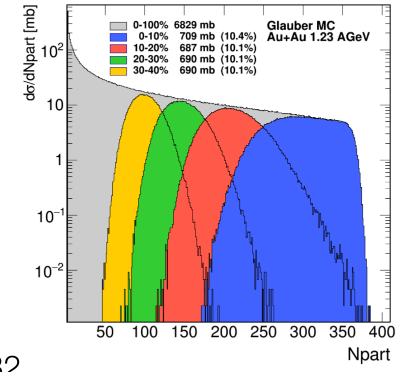
Centrality selection

Charged particle multiplicities

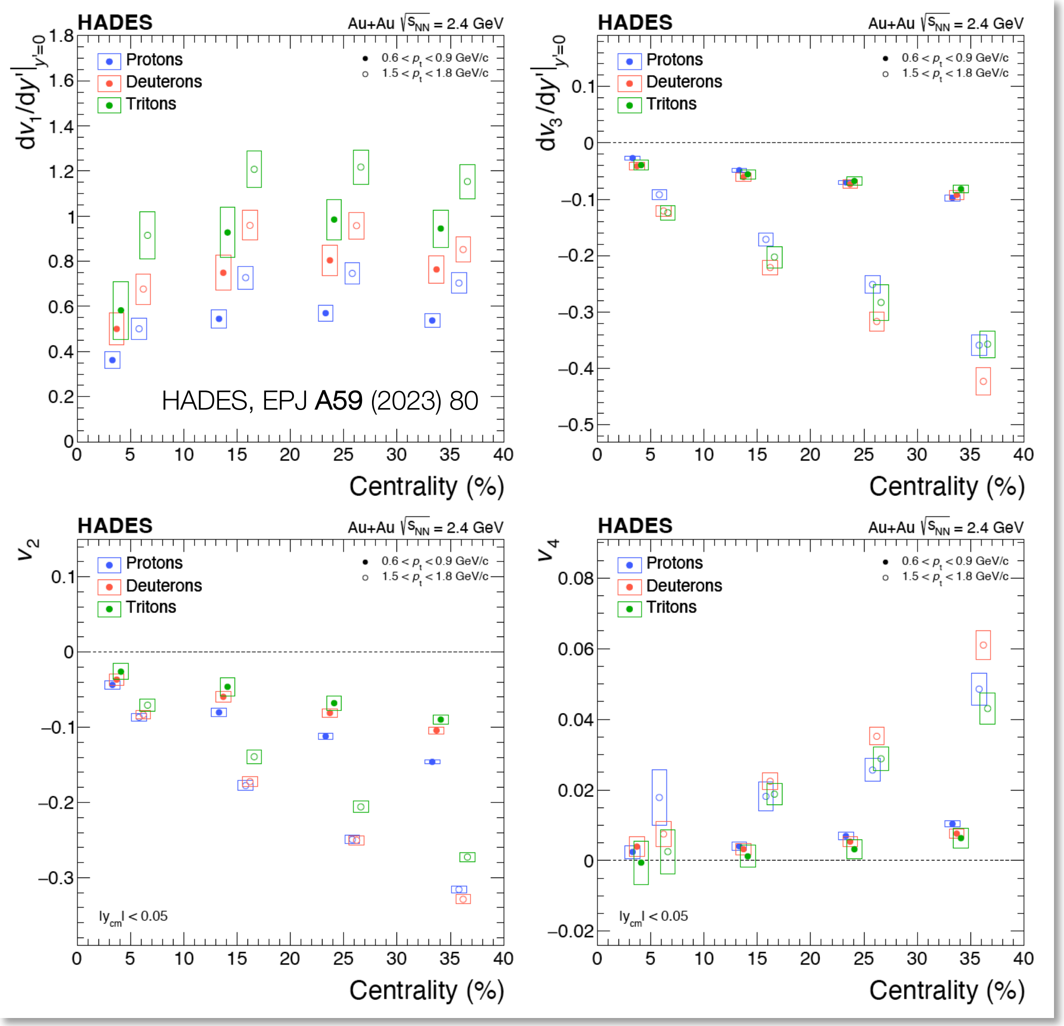
HADES, EPJ **A54** (2018) 85





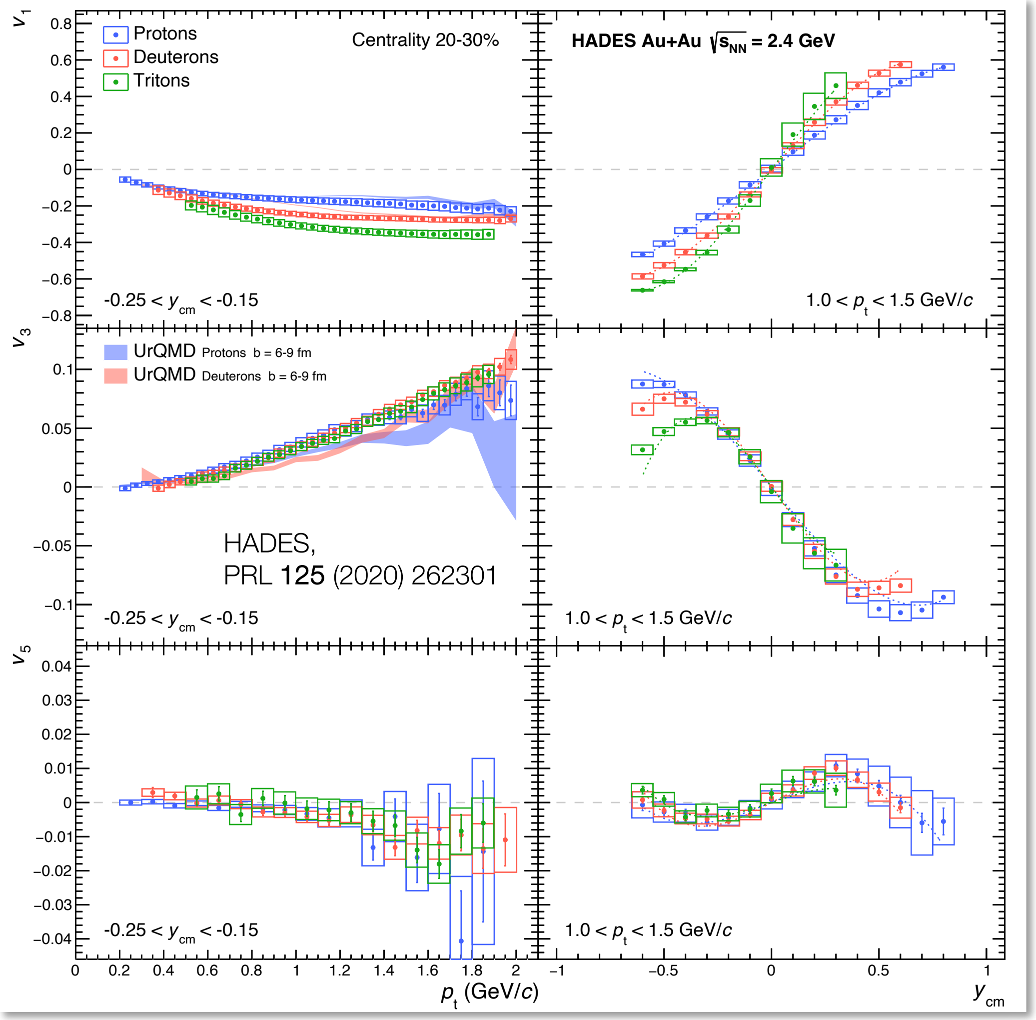


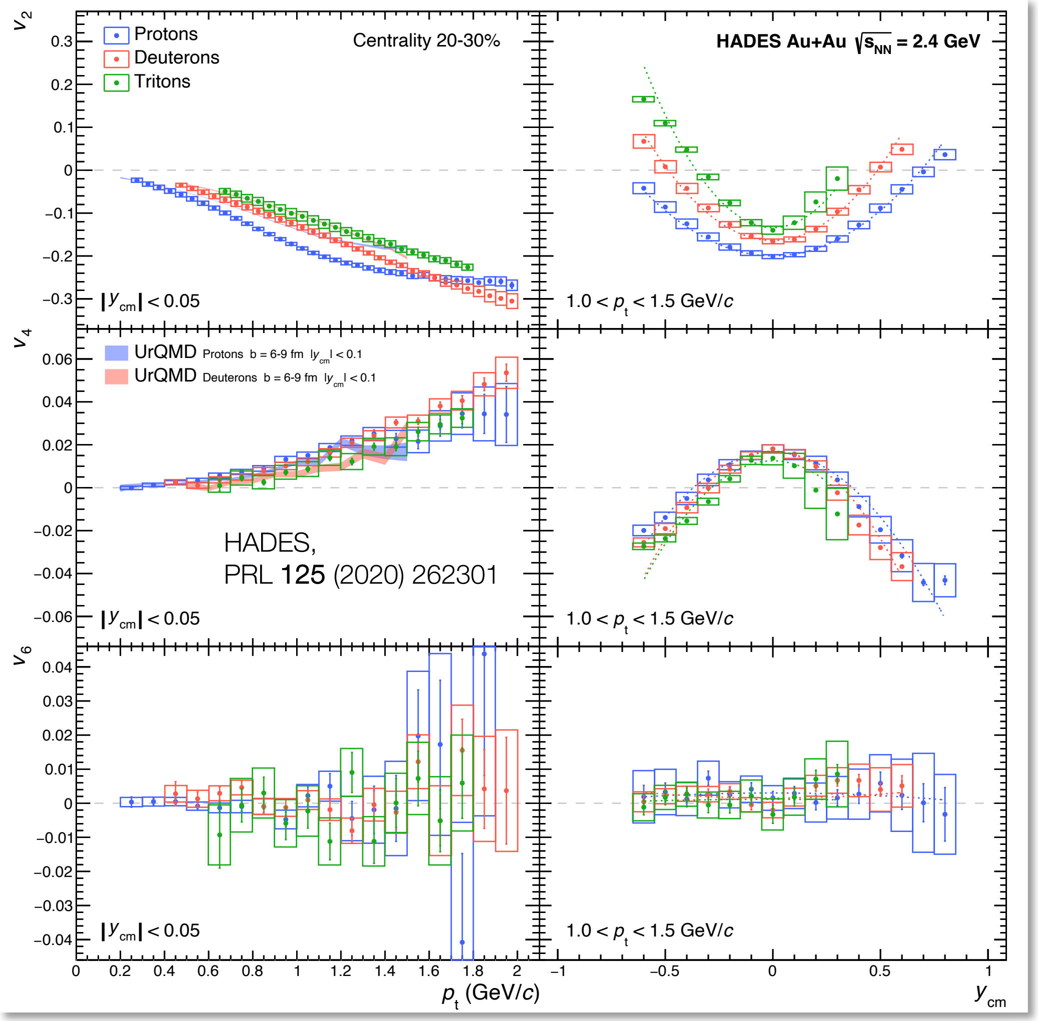
Data points for all centralities available in HEPDATA:
https://www.hepdata.net/record/ins2132332



Results for Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV

$v_1 - v_6$ for Protons, Deuterons and Tritons





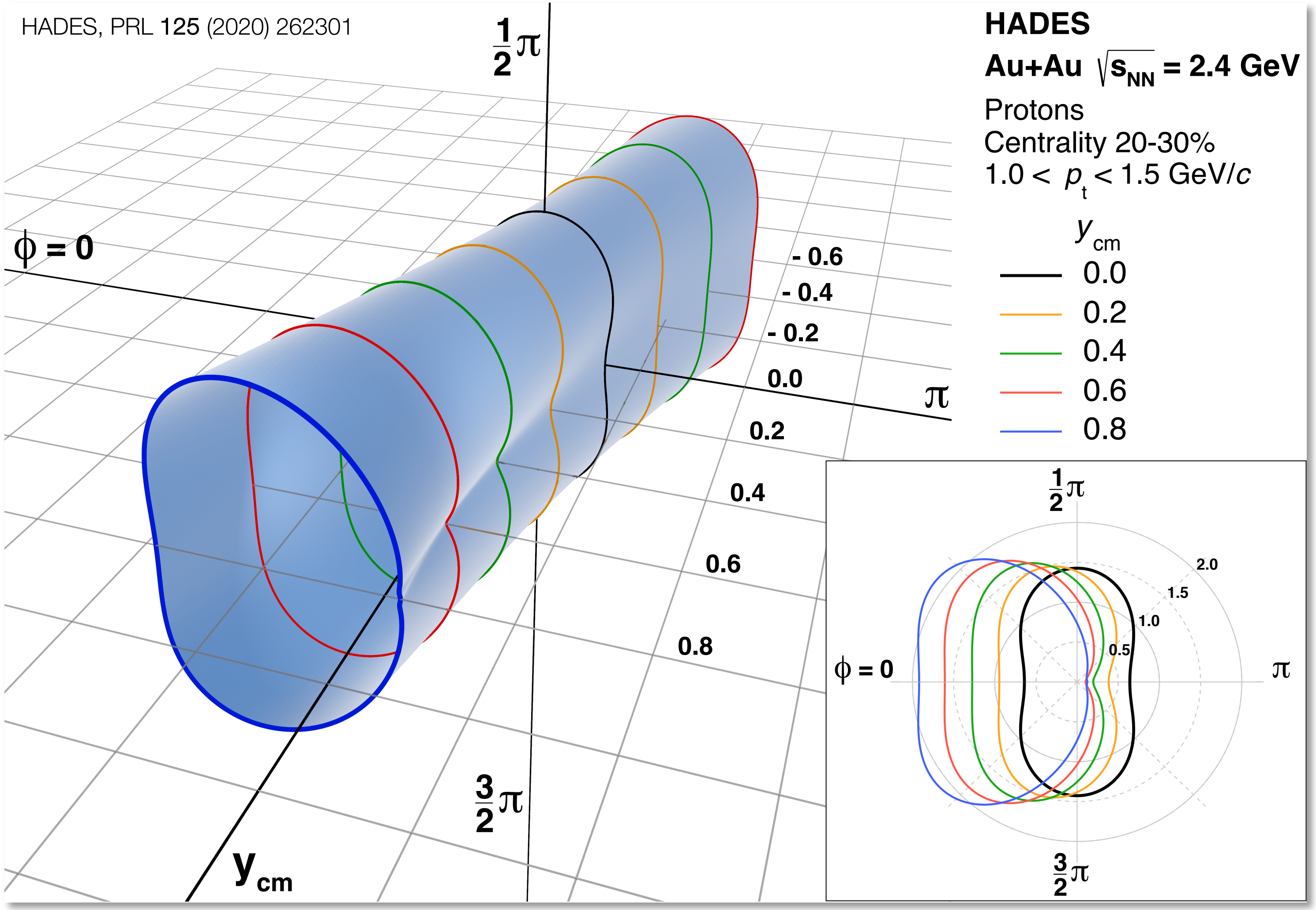
Results for Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

3D-Representation

Complete picture of flow pattern in three dimensions

Shape determined by flow coefficients $v_1 - v_6$

Complex evolution of shape as function of rapidity



Scaling Properties

Relation between v_2 and v_4

Elliptic and quadrangular flow

Prediction for ideal fluid:

$$\frac{v_4(p_t)}{v_2^2(p_t)} = \frac{1}{2}$$

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

Slightly higher values (~ 0.6) expected in more realistic scenario

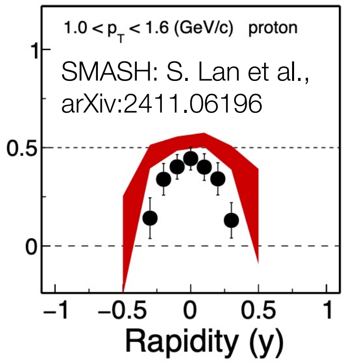
Measured for p, d and t

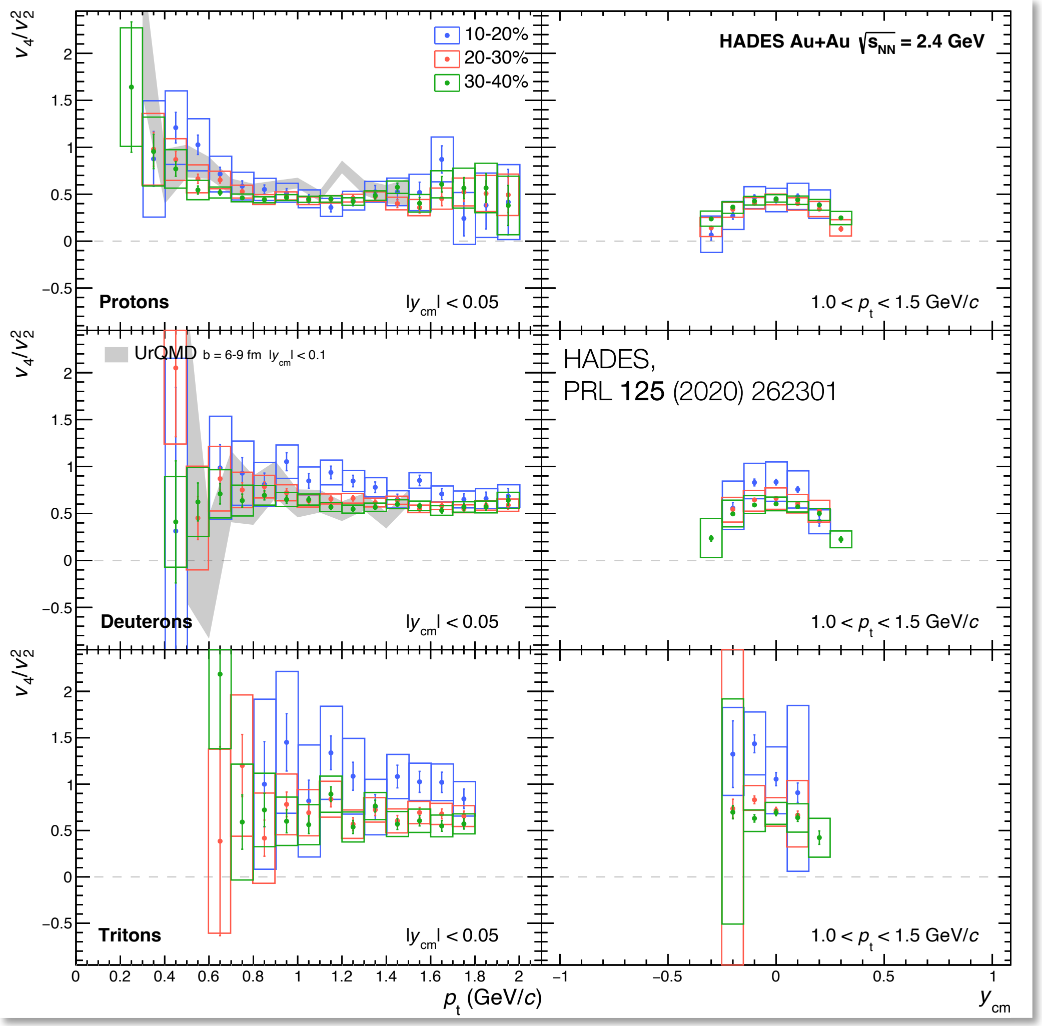
Independent of p_t
Close to predicted value of ~ 0.6

Hydro-like matter at SIS energies?

Transport models matches data

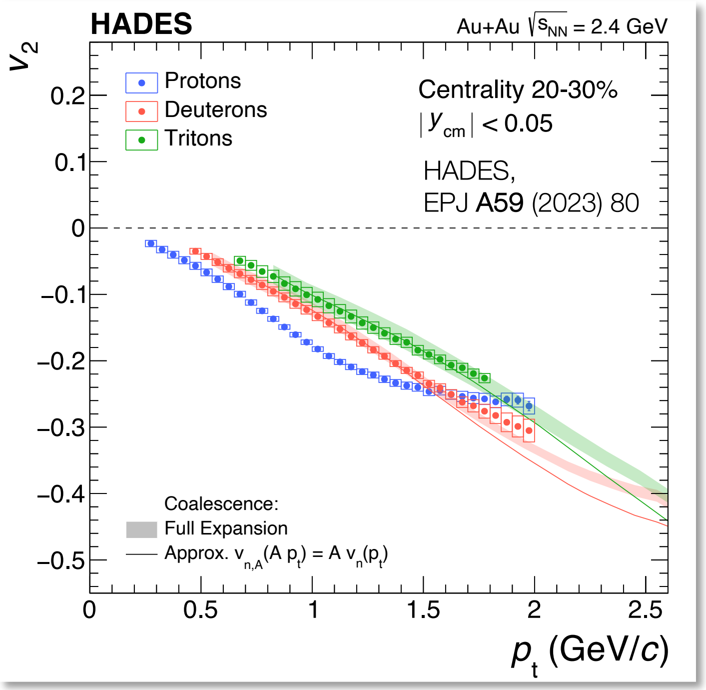
Also IQMD: L.-M. Gang et al., PRC **107** (2023) 044904

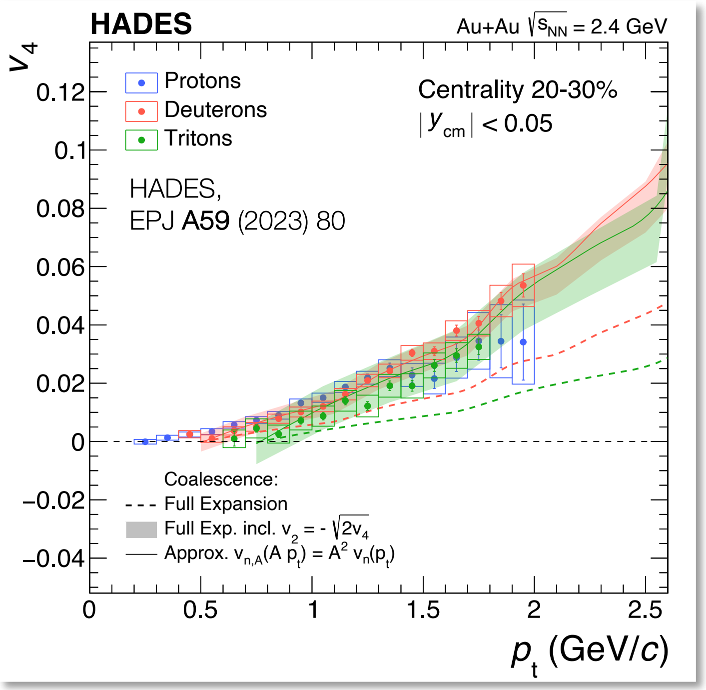




Scaling Properties

Mass Number Scaling of v_2 and v_4 at Mid-Rapidity





Nucleon Coalescence

Scaling of v_2 (v_4) and p_t with nuclear mass number A (including higher terms)

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

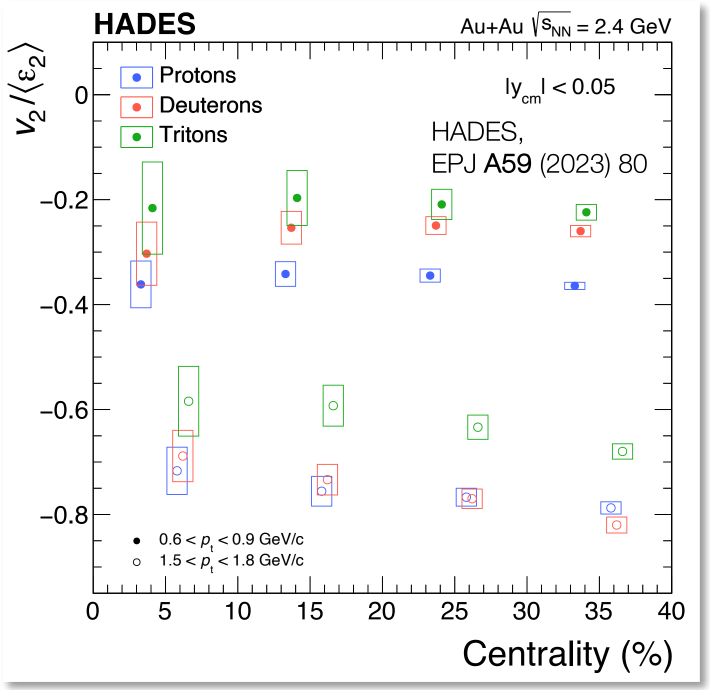
$$v_{n,A=3}(3\,p_t) = 3\,v_n(p_t)\,\frac{1+v_n^2(p_t)}{1+6\,v_n^2(p_t)} \qquad v_{4,A=3}(3\,p_t) = 9\,v_4(p_t)\,\frac{1}{1+12\,v_4(p_t)+6\,v_4^2(p_t)}$$

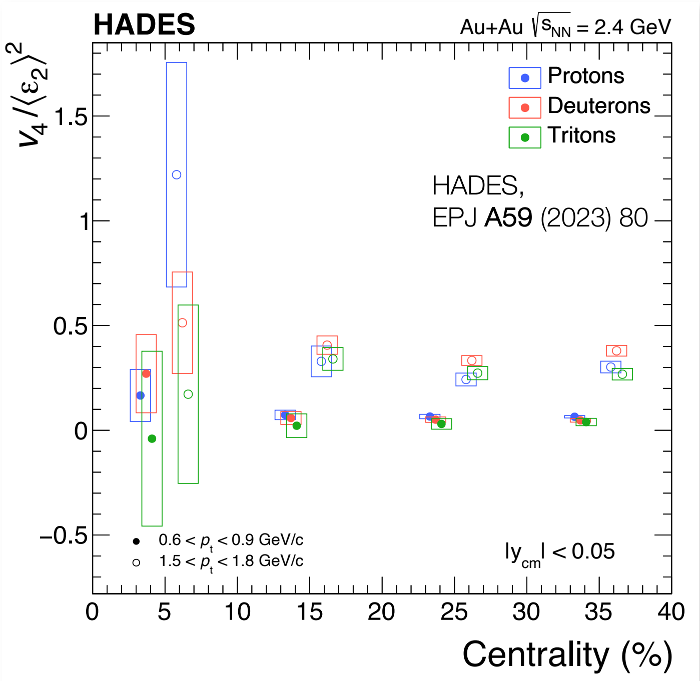
(assuming: $v_2 = -\sqrt{2\,v_4}$)

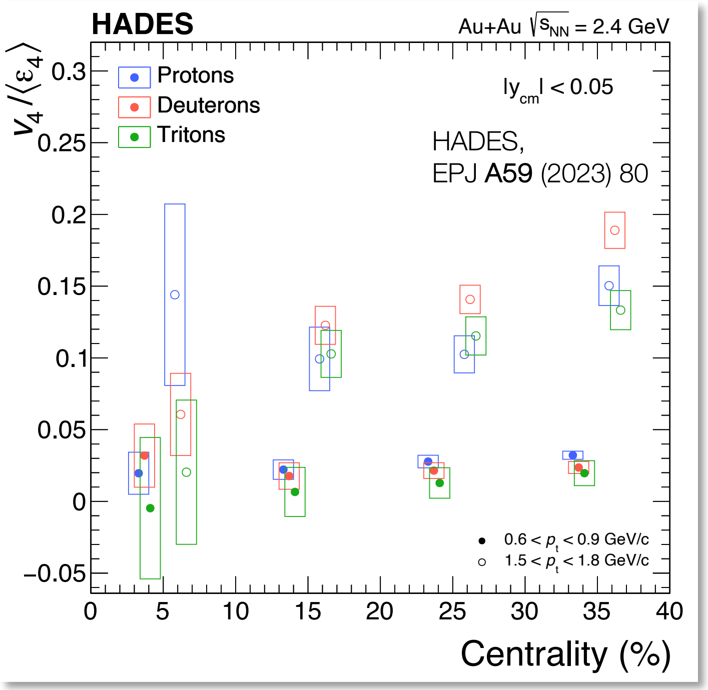
Works as expected in simple coalescence picture (only at mid-rapidity!)

Scaling Properties

Initial Geometry





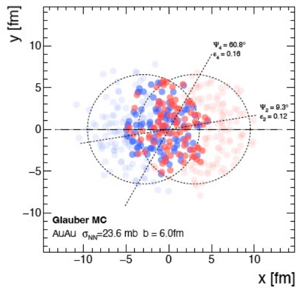


Scaling with Initial Eccentricities

Calculated for overlap zone with Glauber MC

$v_2 / \langle\varepsilon_2\rangle$ and $v_4 / \langle\varepsilon_2\rangle^2$ almost independent of centrality ($v_4 / \langle\varepsilon_4\rangle$ is not)

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



Model Comparisons

Proton Data

Determination of EoS

New level of precision

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.)

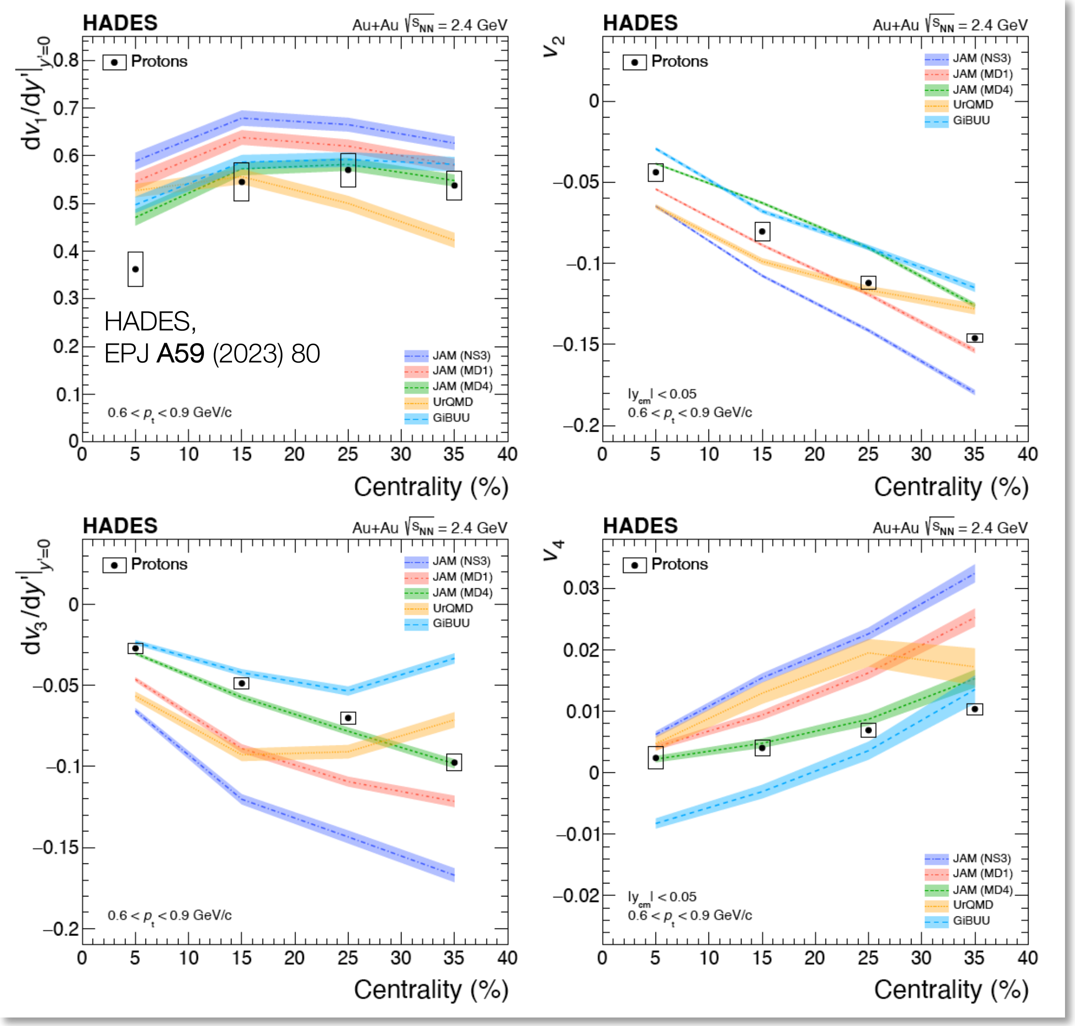
GiBUU Skyrme 12 (soft EOS)

Conclusions

Overall trend reasonably described, but no model works everywhere

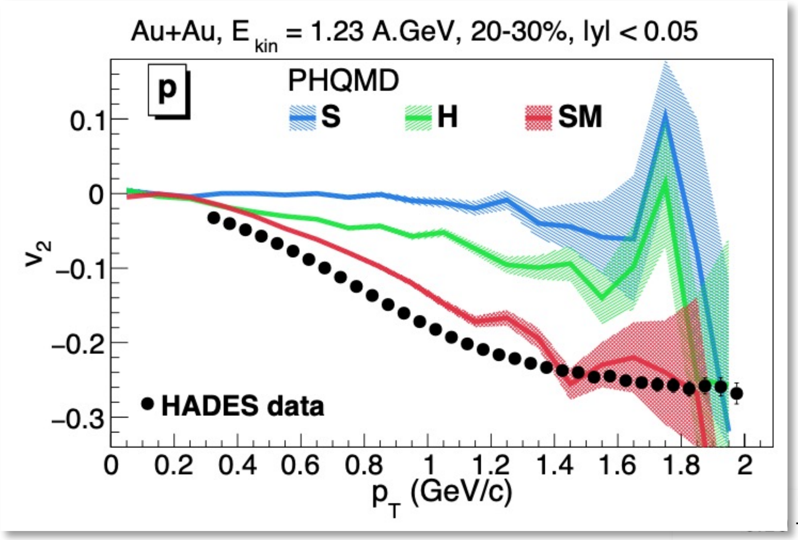
Several systematic deviations

Unified description of cluster production missing

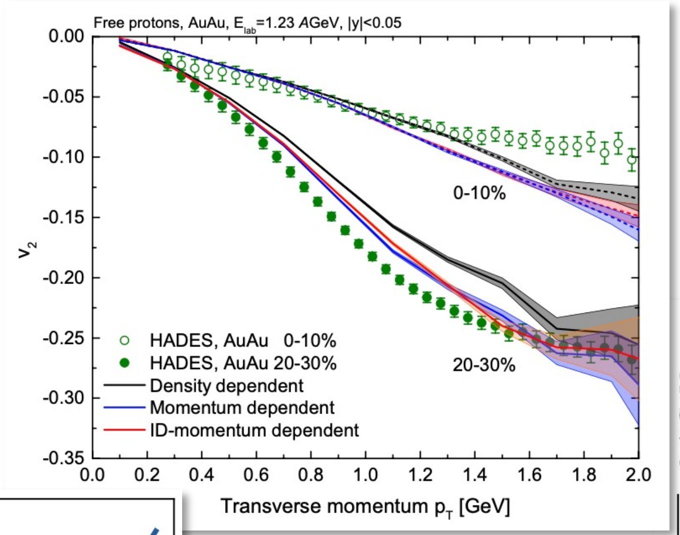


Model Comparisons

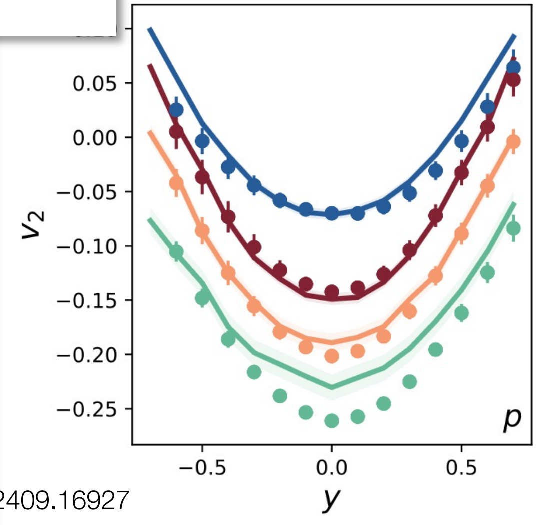
Extracting the EoS



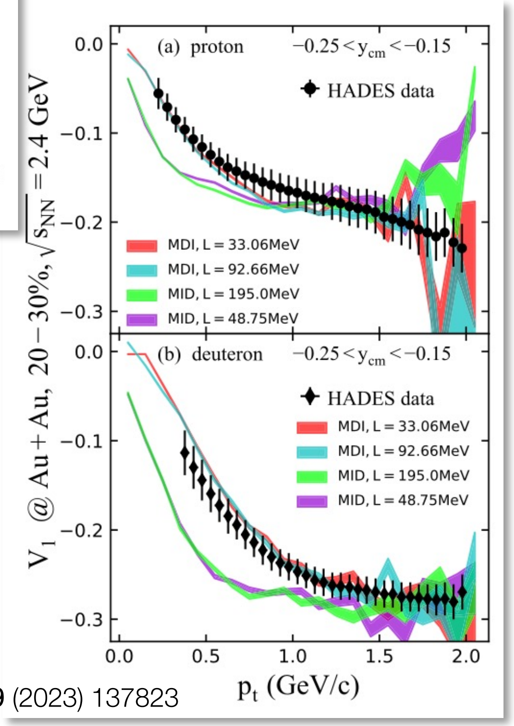
PHQMD: V. Kireyeu et al., arXiv:2411.04969



UrQMD: J. Steinheimer et al.
arXiv:2410.01742



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



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

Model Comparisons

Bayesian Analyses

EoS from Bayesian Analysis

Extract precise parameterizations of EoS

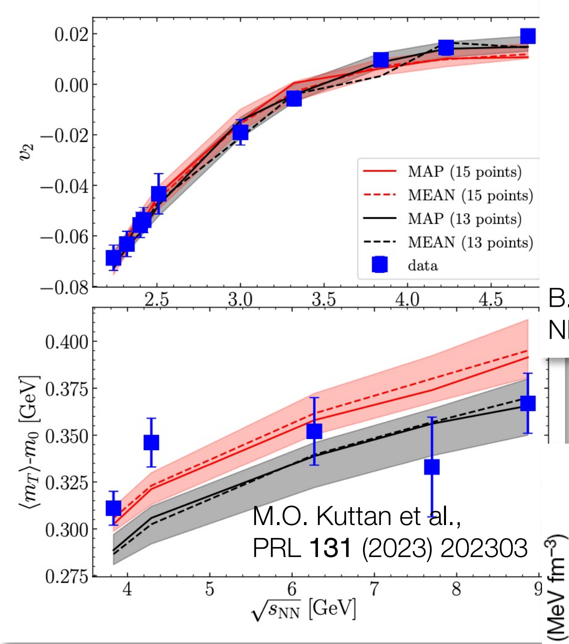
Next Steps

Make use of multi-differential data

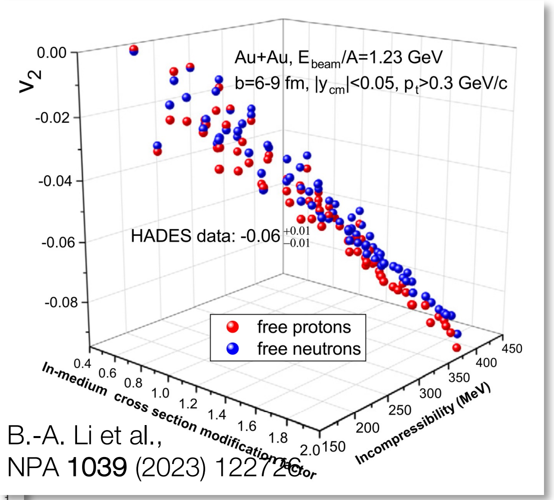
Exploit also information from higher flow harmonics

Use same recipe for cluster formation
⟹ Exploit also data on d and t in unified manner

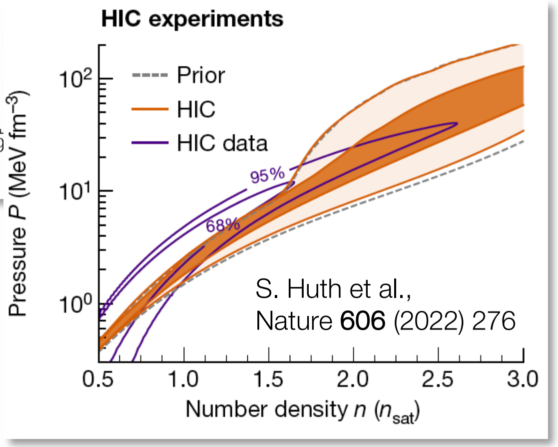
Consistent implementation of EoS in different models (momentum dependence)



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



B.-A. Li et al., NPA **1039** (2023) 122726



S. Huth et al., Nature **606** (2022) 276

Flow Correlations

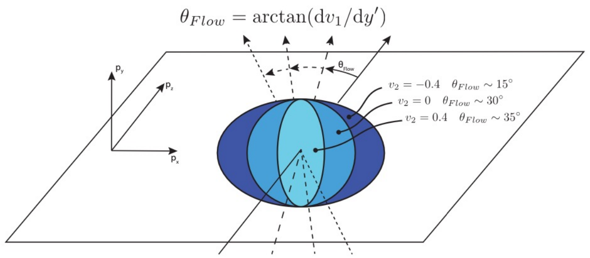
Event Selection

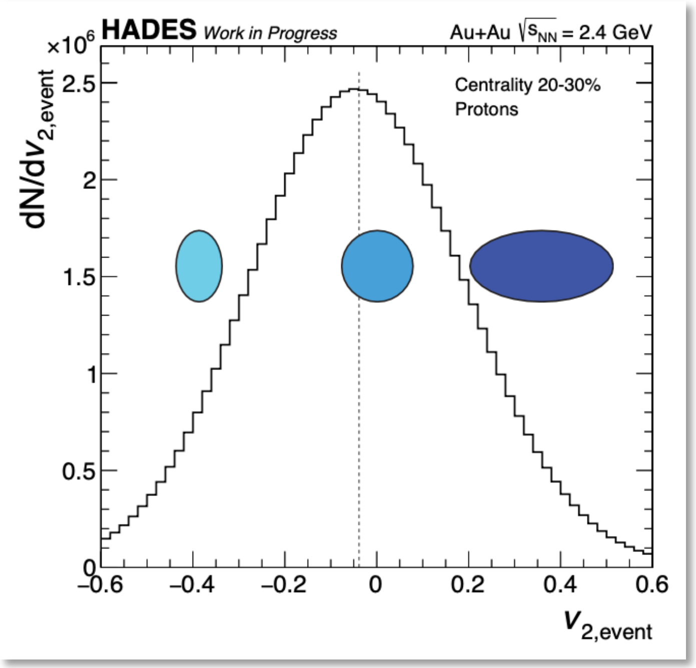
Event-by-event $v_{2,\text{event}}$

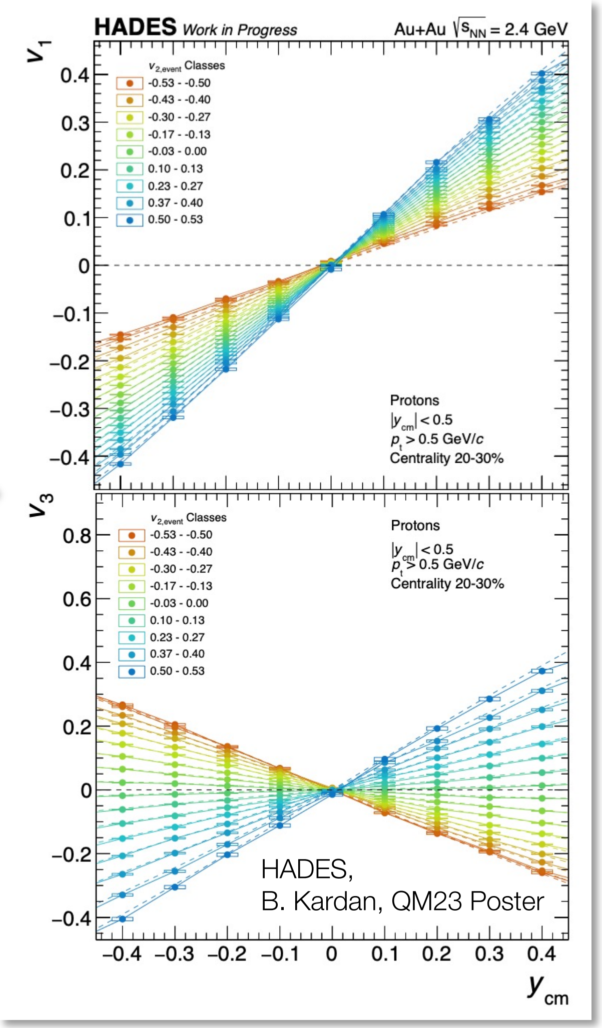
Select events according to their elliptic flow magnitude

Directed and triangular flow as function of $v_{2,\text{event}}$

(caveat: autocorrelations still to be evaluated)







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Directed and Triangular Flow

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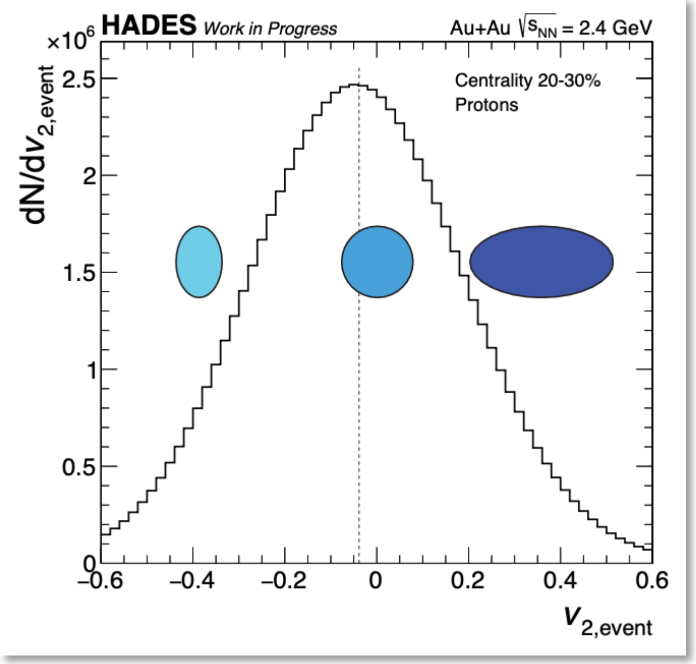
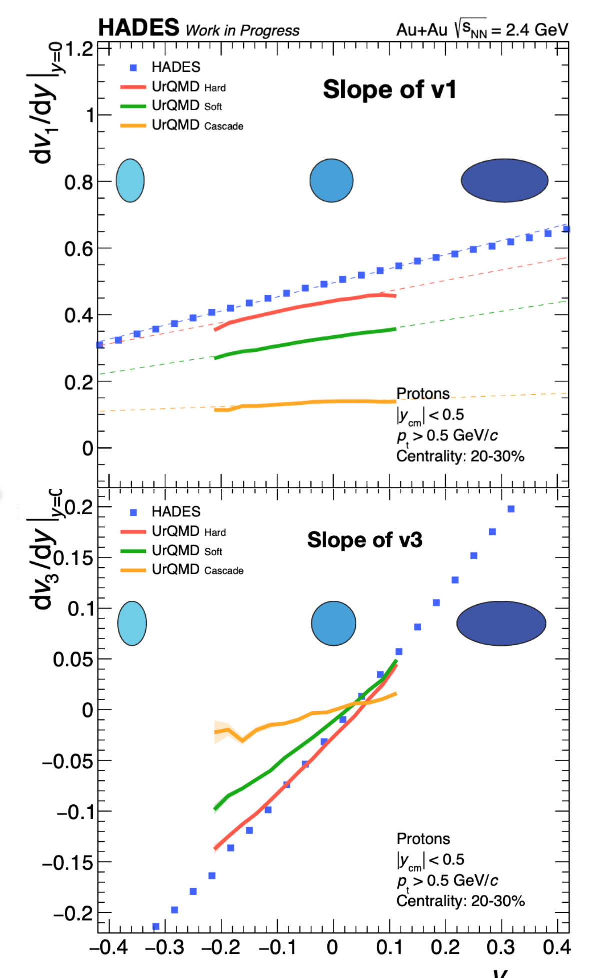
(caveat: autocorrelations still to be evaluated)

UrQMD predictions:
T. Reichert et al.,
EPJ **C82** (2022) 510

Enhanced sensitivity to EOS in $dv_3/dy|_{y=0}$ vs $v_{2,\mathrm{event}}$





HADES, B. Kardan, QM23 Poster

Conclusions + Outlook

High precision flow data available

Multi-differential data on p, d and t flow coefficients ($v_1 - v_4$) in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.42 GeV

Extraction of EoS

Overall good description of data (directed and elliptic flow) by different models
Momentum dependent soft EoS generally favored
Possibilities of available data set not yet fully exploited
Move to Bayesian analyses (first attempts)

HADES data publications in the pipeline

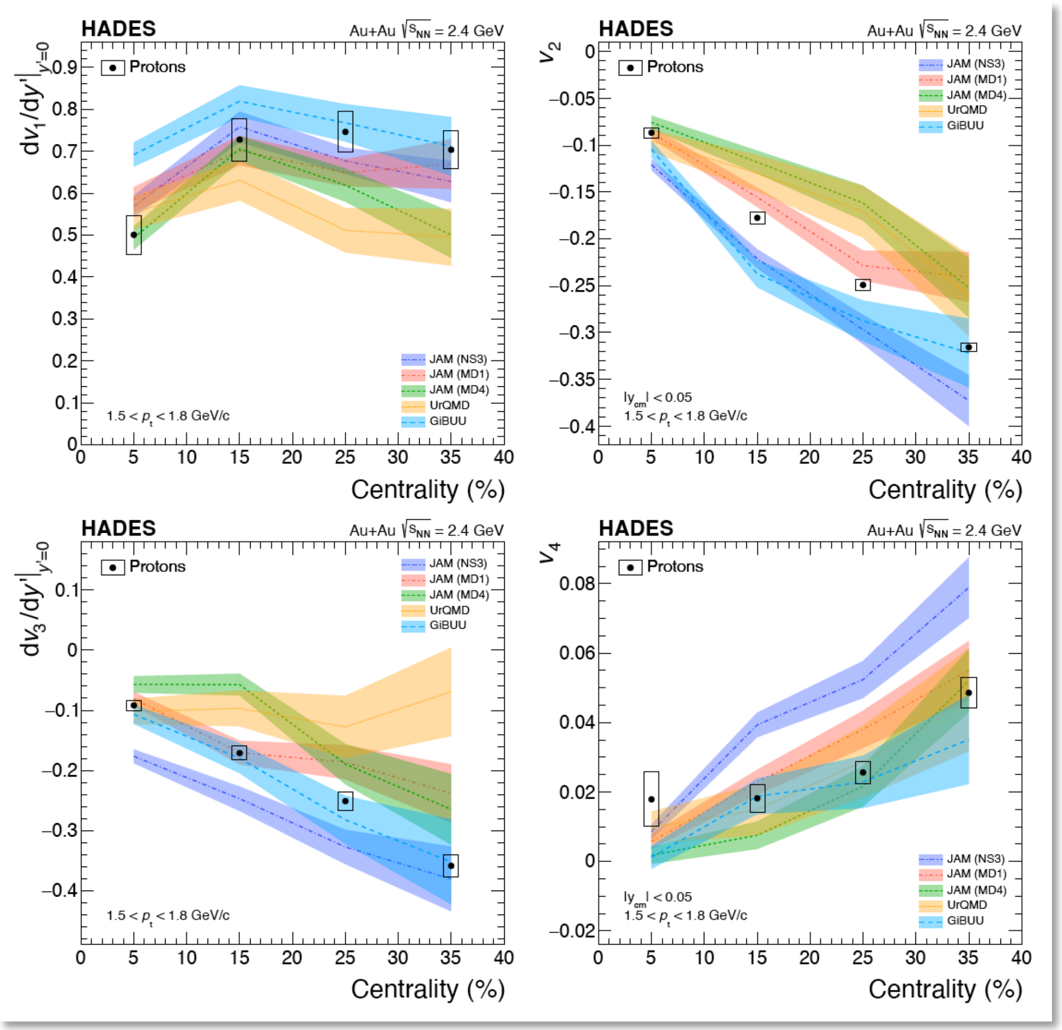
Flow of p, d, t and ^{3}He flow in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.42 GeV and $\sqrt{s_{NN}}$ = 2.55 GeV
Correlations of flow coefficients for protons in Ag+Ag and Au+Au
Flow of charged pions and kaons in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.42 GeV


Many Thanks !

Collective Effects

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

Model Comparisons



HADES, arXiv:2208.02740

Vorticity

Principle of Global Λ Polarization

Global polarization

Large angular momenta $|L| \sim 10^5\,\hbar$
Extreme vorticities possible ($\omega \approx 10^{21}\ s^{-1}$)

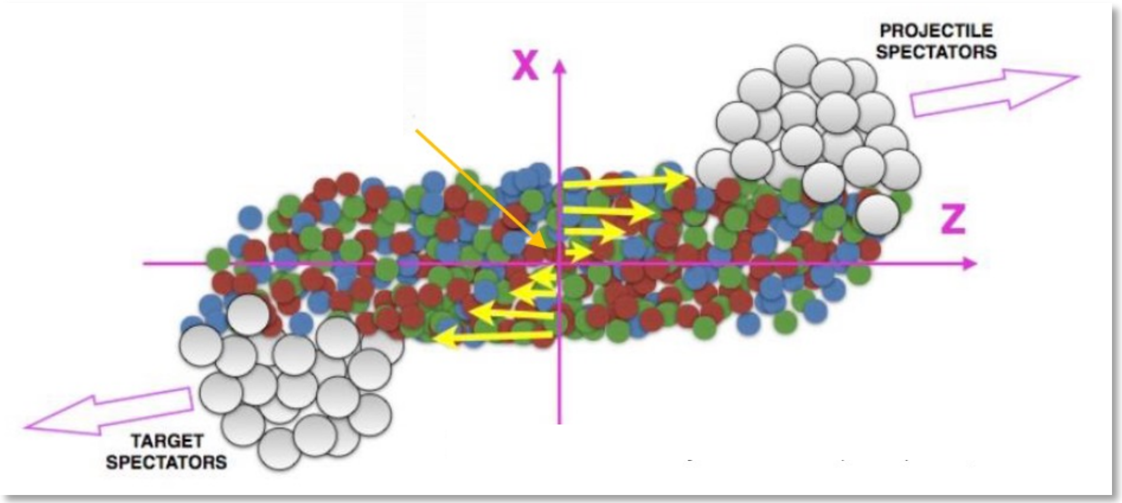
Observable via polarization of spins relative to event plane (spin-orbit coupling, e.m.-coupling)

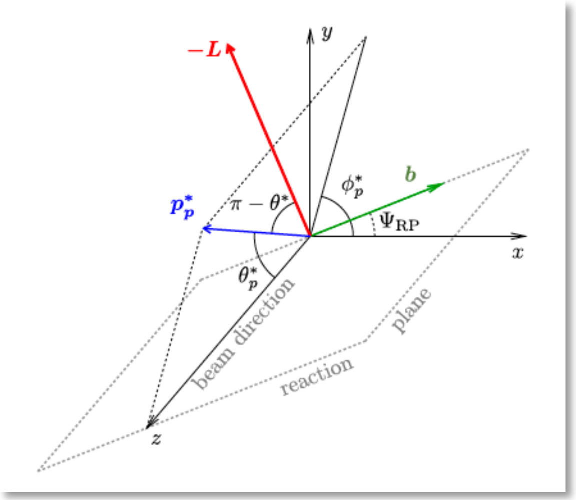
Observable

Weak decay: $\Lambda \longrightarrow p + \pi^-$
Proton preferentially in spin direction
$\Longrightarrow$ Polarization P_Λ:

$$P_\Lambda = \frac{8}{\pi\,\alpha_\Lambda} \frac{\langle \sin(\Psi_{EP} - \phi_p^*) \rangle}{R_{EP}}$$

Λ decay parameter: $\alpha_\Lambda = 0.643 \pm 0.013$
Ψ_{EP} = event plane angle, R_{EP} = EP-resolution
Φ^*_p = proton azimuth angle relative to EP





Z. Liang and X.N. Wang, PRL **94** (2005) 102301

F. Becattini et al, PRC **95** (2017) 054902

STAR Collaboration, PRC **76** (2007) 024915

HADES Collaboration PLB **835** (2022) 137506

Vorticity

Measurements in Au+Au ($\sqrt{s_{NN}}$ = 2.42 GeV) and Ag+Ag ($\sqrt{s_{NN}}$ = 2.55 GeV)

Analysis procedure

EP estimation from spectators
Optimized Λ reconstruction with ANN

Results (10–40 % cent.)

P_Λ (Au+Au) = (5.3 ± 1.0 (stat.) ± 1.3 (syst.)) %
P_Λ (Ag+Ag) = (4.4 ± 0.3 (stat.) ± 0.4 (syst.)) %

Highest values measured at strangeness production threshold $\sqrt{s_{NN}}$ = 2.55 GeV
(should vanish around $\sqrt{s_{NN}} \sim 2\, m_N \approx$ 1.9 GeV)

Agrees with 3D-fluid-dynamical model
AMPT underestimates data

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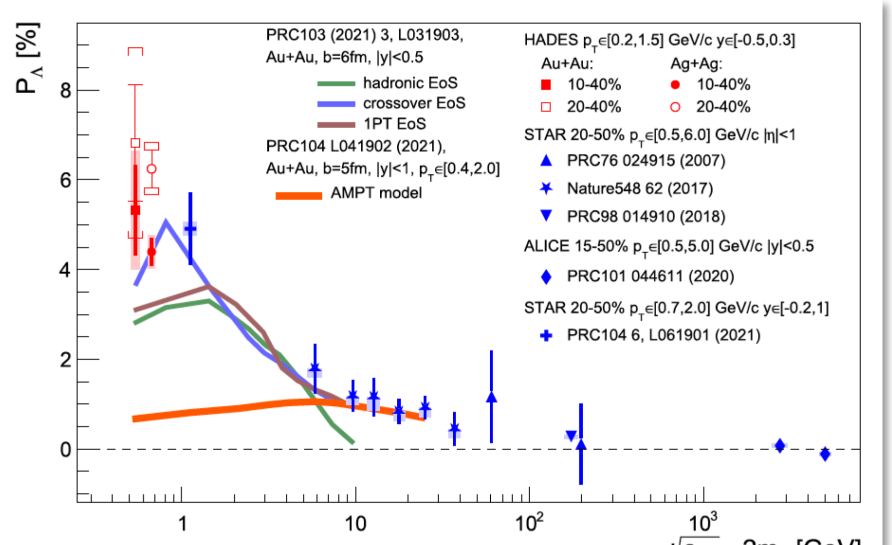
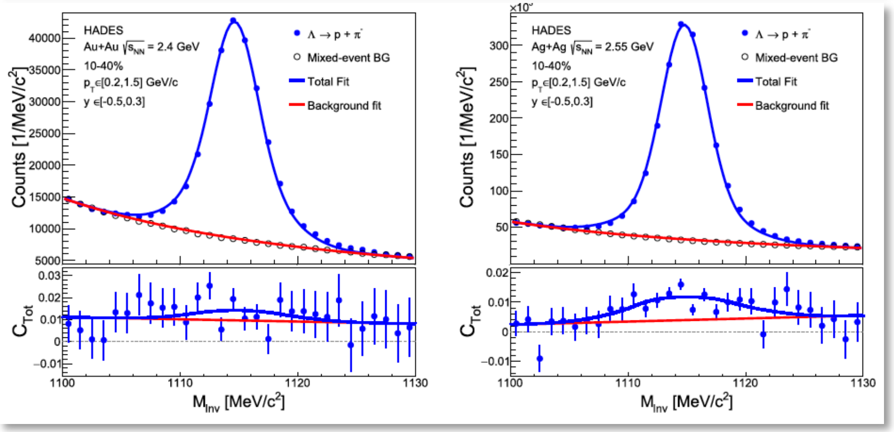


$C_{\text{Tot}}(M_{\text{Inv}}) = \langle \sin(\Psi_{\text{EP}} - \phi^*_p) \rangle$



Vorticity

Measurements in Au+Au ($\sqrt{s_{NN}}$ = 2.42 GeV) and Ag+Ag ($\sqrt{s_{NN}}$ = 2.55 GeV)

Centrality dependence

Increase towards less central events
Same trend as in STAR data (different phase space!)

Phase space dependence

No strong dependence on *pt* and *y* observed

Model comparison

Good agreement with UrQMD + thermal vorticity
O. Vitiuk et al., Phys. Lett. **B803** (2020) 135298

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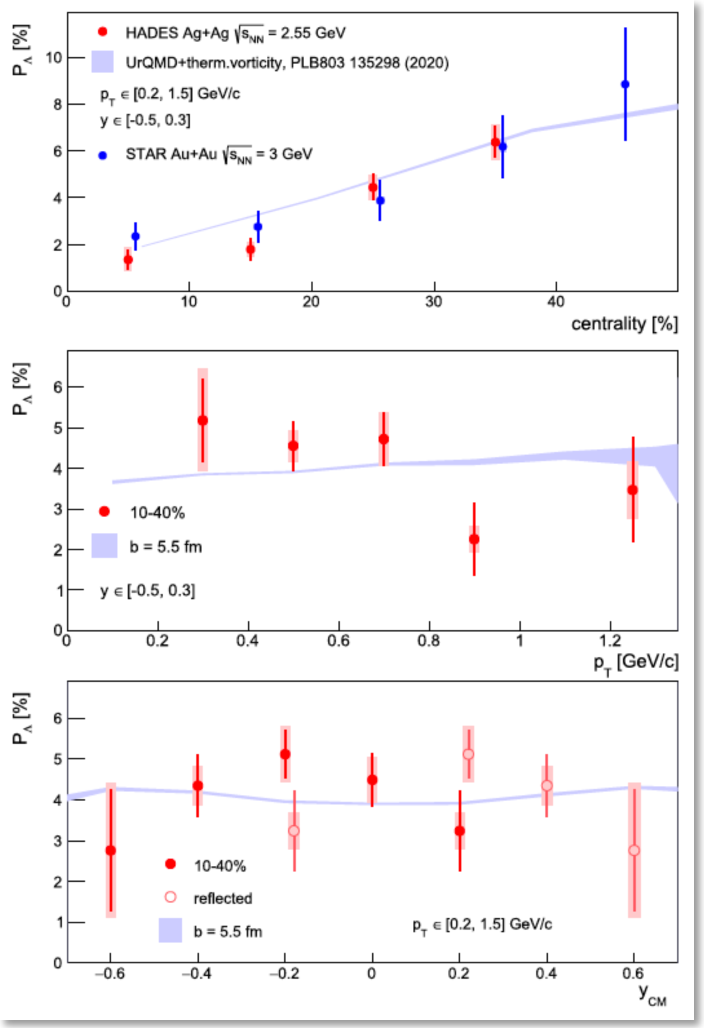
Phys. Lett. **B835** (2022) 137506

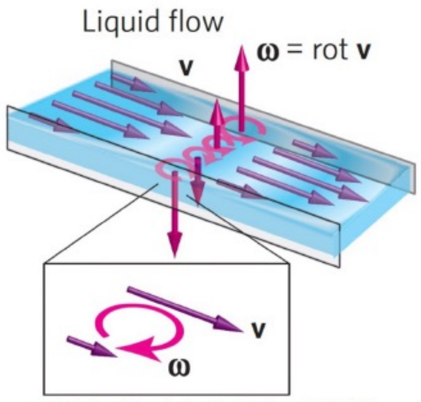


Vorticity
Outlook

Vorticity at low energies
Large effect

Where is the onset?

Driving mechanism for the coupling of orbital momentum to spin not yet understood



Takahashi, et al. Nat. Phys. (2016)

Systematic measurements at low energies needed

CBM physics program:
Λ and Ξ⁻ polarization with 5% precision

Mapping of Λ excitation function
(≥ 10^{13} event required)