Characterizing the Bulk Properties of Dense Baryonic Matter

Christoph Blume
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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Dense Baryonic Matter

Physics Topics

Open questions

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

Super-dense matter in the laboratory

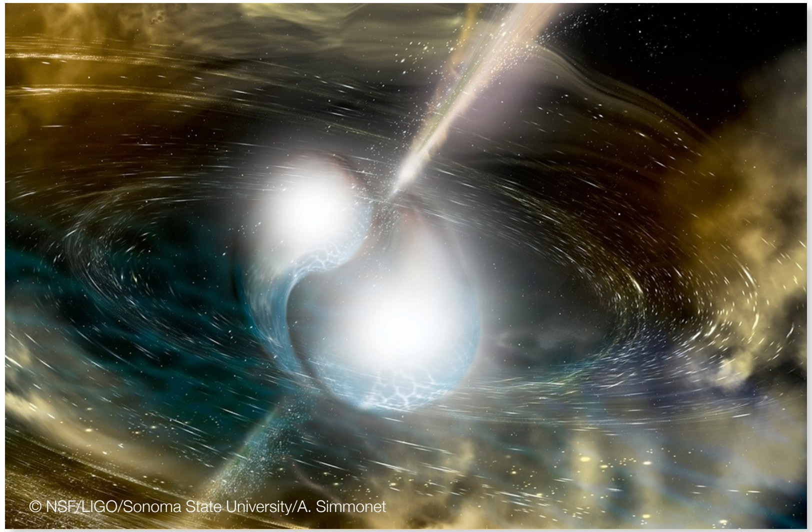
Neutron Star Merger

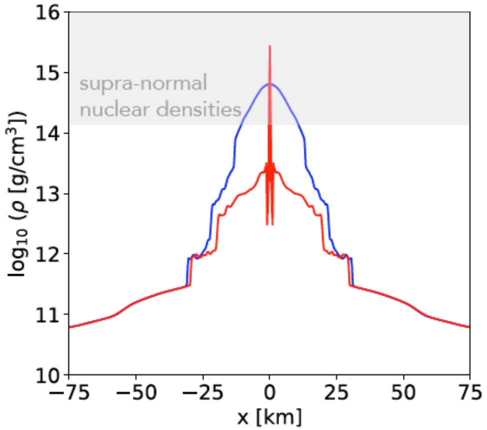
Observation via gravitational waves

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

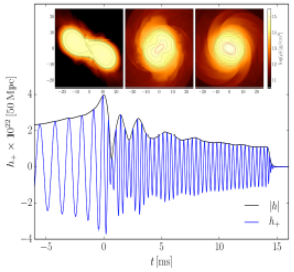
Sensitivity to equation-of-state

Super-dense matter in the universe





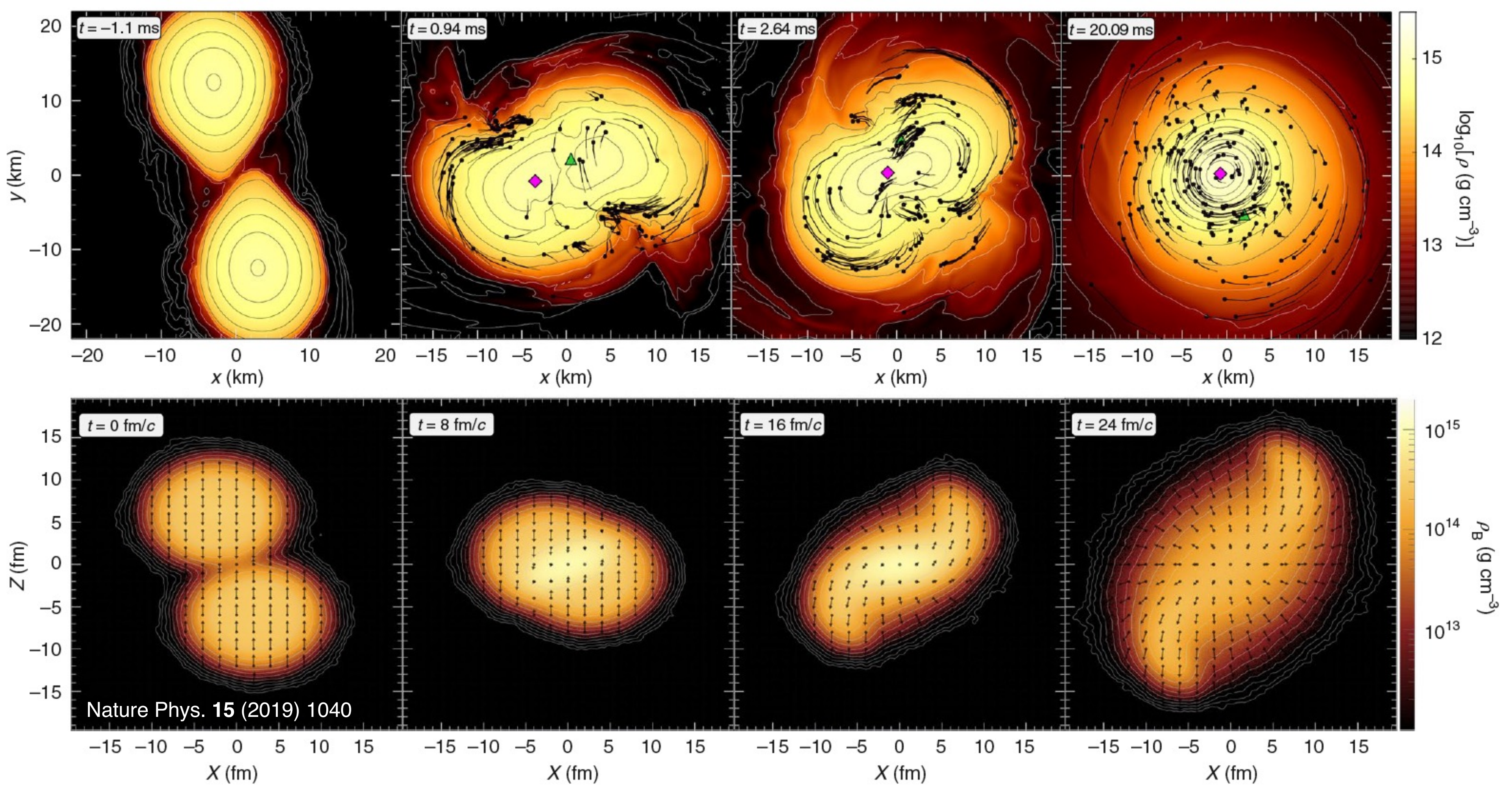
Density profile across a merging NS binary system. Taken $t = 1.4$ ms ($t = 0$ see below).



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

Collective effects

Proton, deuteron and triton flow results up to 4th order (v_1, v_2, v_3, v_4)

Femtoscopy

Fireball size and dynamics from two-pion correlations

Vorticity

Global Λ polarization

Baryon number fluctuations

Proton fluctuations at low energies

Collective Effects

Principle

Emission relative to event plane

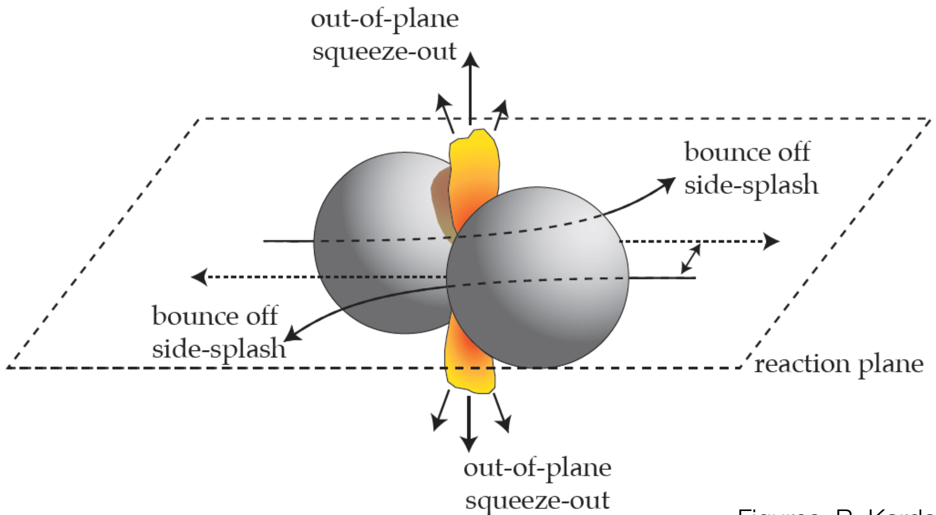
Interactions in medium $\Longrightarrow$ different pressure gradients in different directions

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

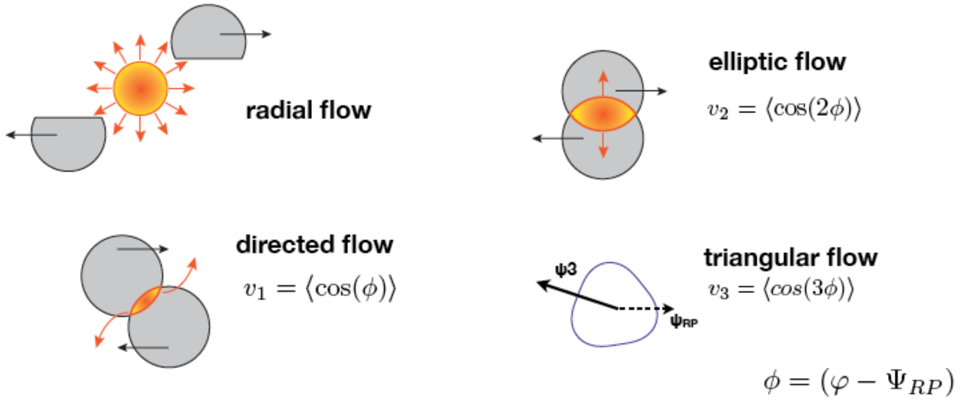
Fourier-Decomposition

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



Collective Effects

Event Plane

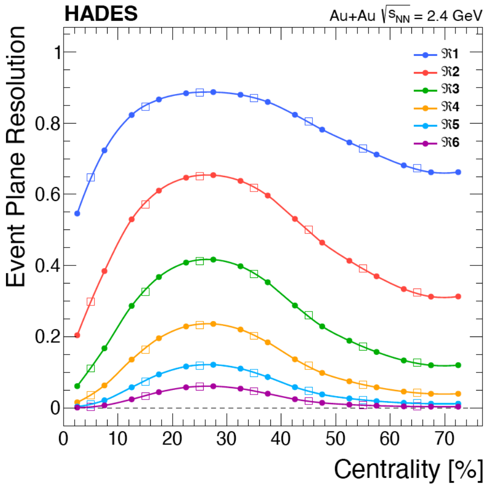
Event plane Reconstruction

1^{st}-Order event plane

Projectile spectators in Forward Wall

EP-resolution via sub-event method

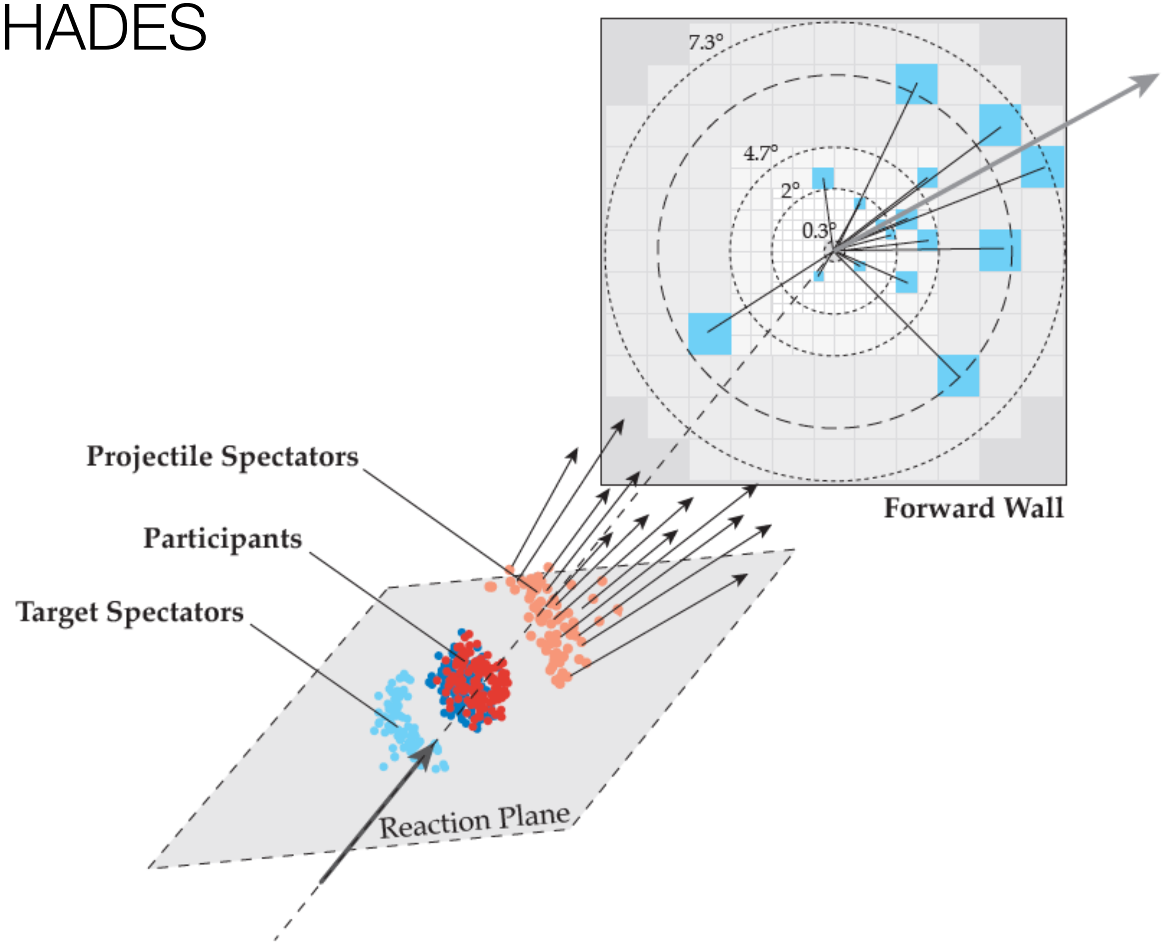
J.-Y. Ollitrault, arXiv:nucl-ex/9711003



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

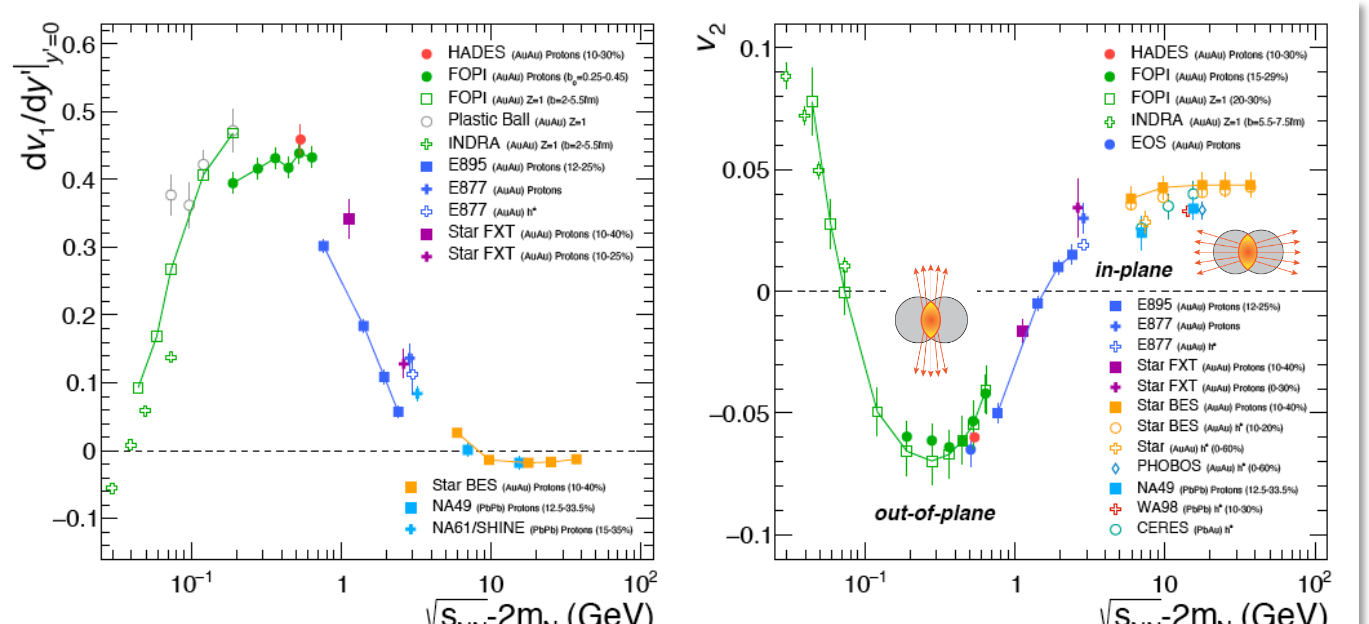
$$\mathfrak{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

HADES



Collective Effects

Energy Dependence



HADES, arXiv:2208.02740

Compilation of world data

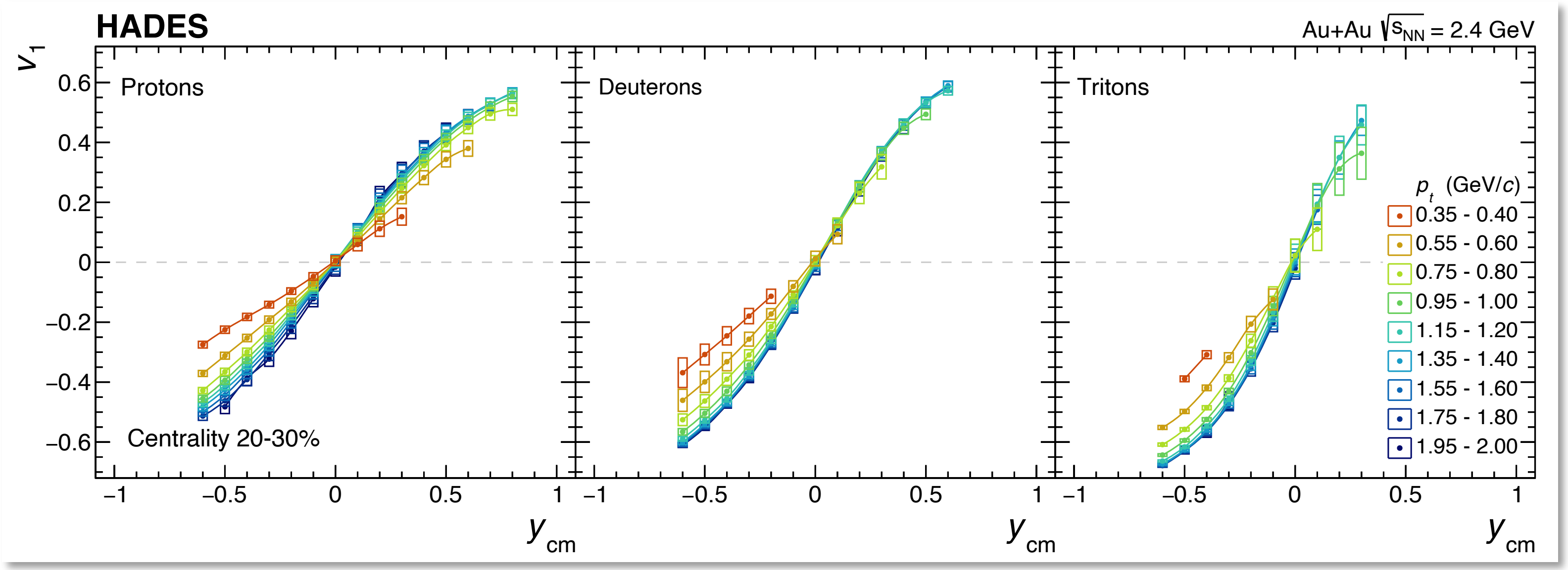
Good agreement of integrated dv_1/dy (directed flow) and v_2 (elliptic flow)

Out-of-plane v_2

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

Collective Effects

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



HADES, arXiv:2208.02740

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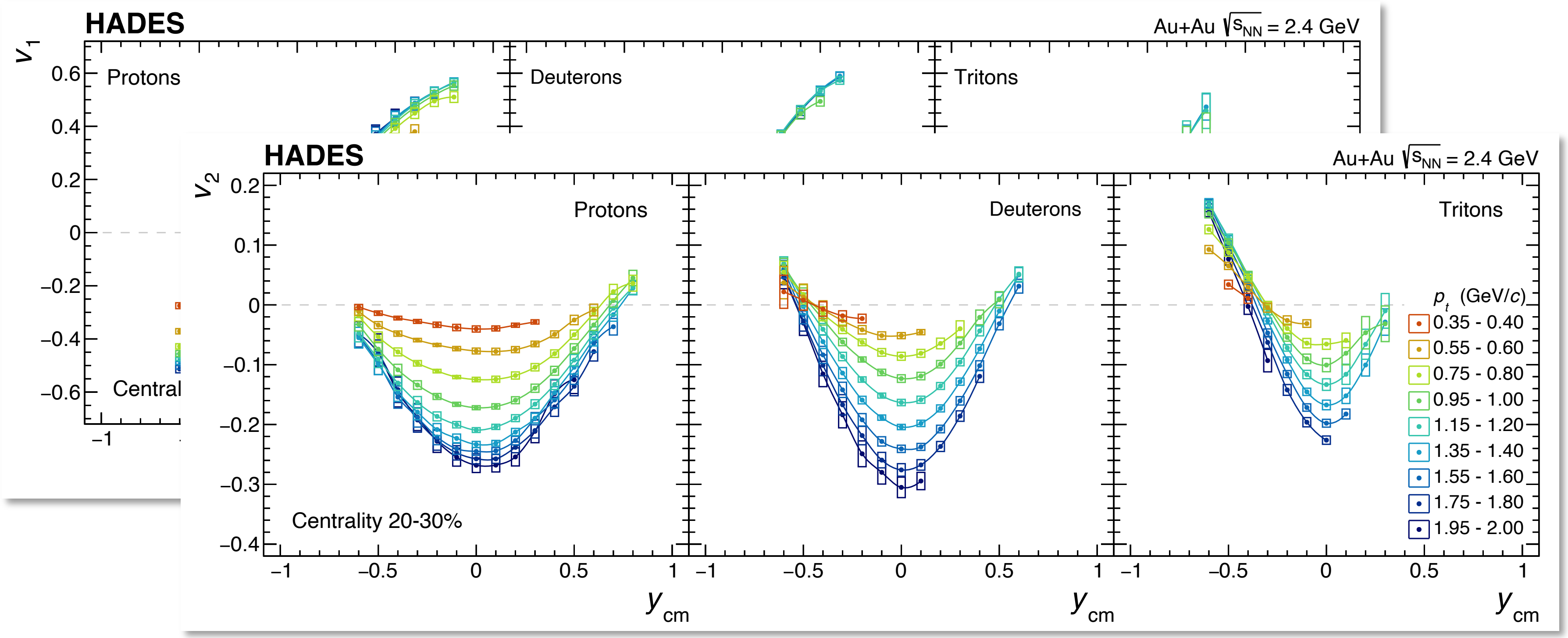

HADES, arXiv:2208.02740

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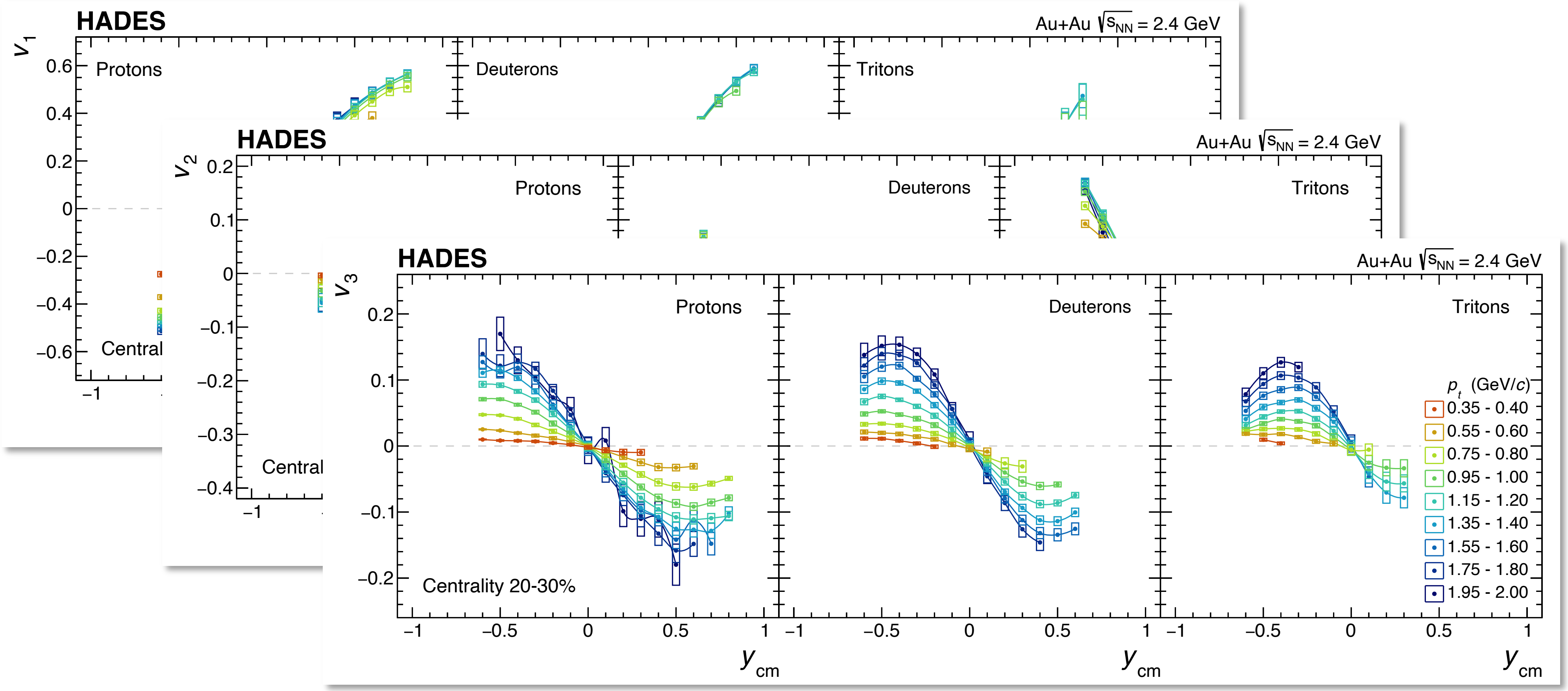
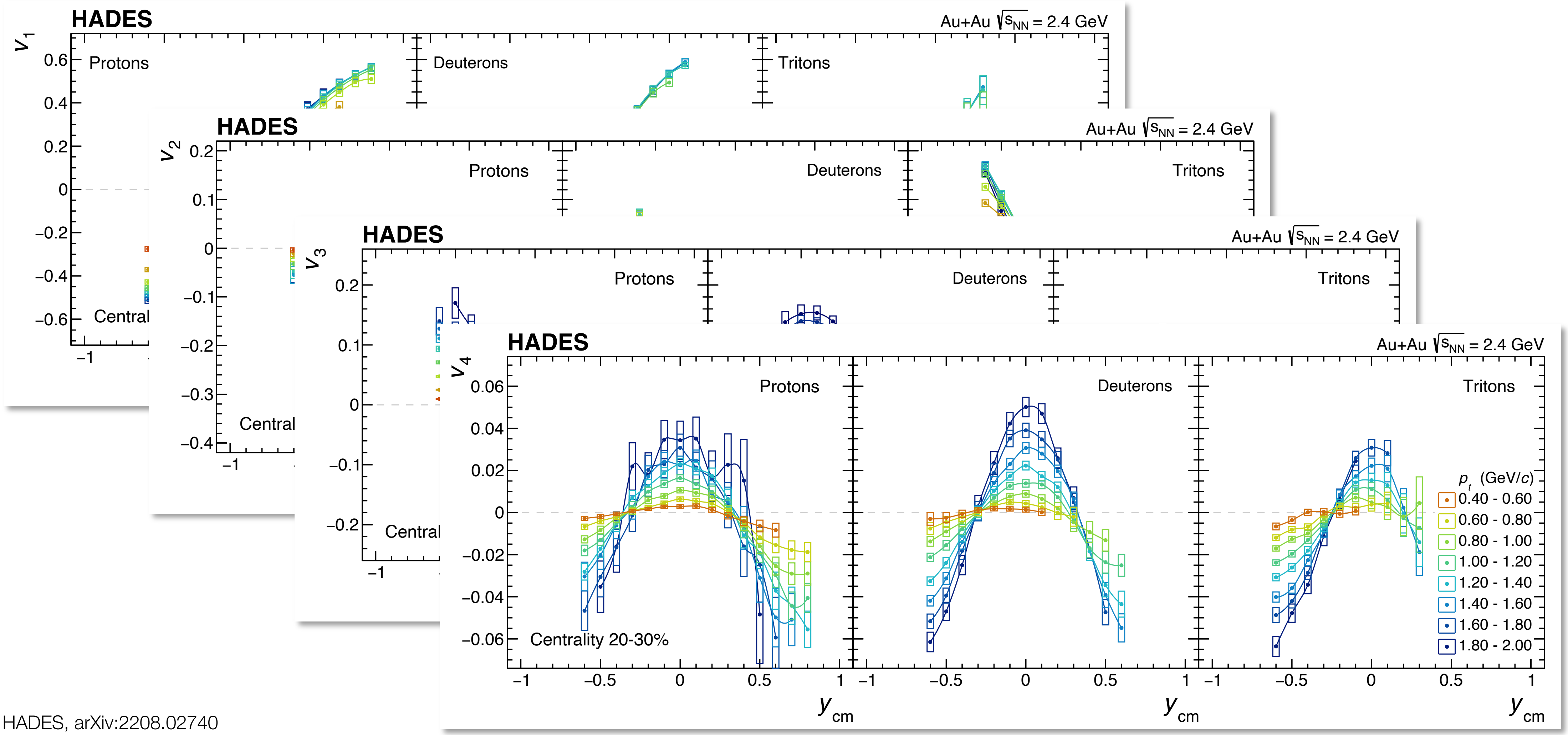


HADES, arXiv:2208.02740

Collective Effects

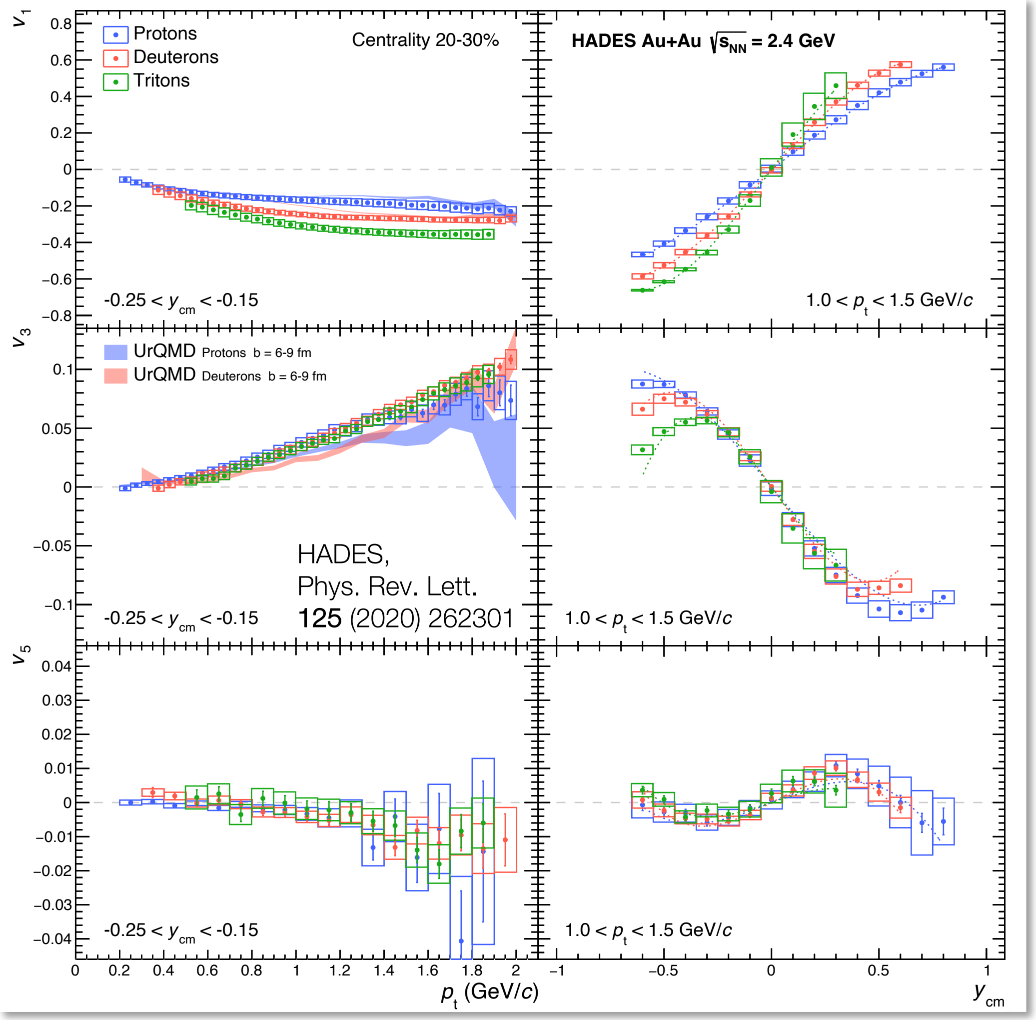
Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons

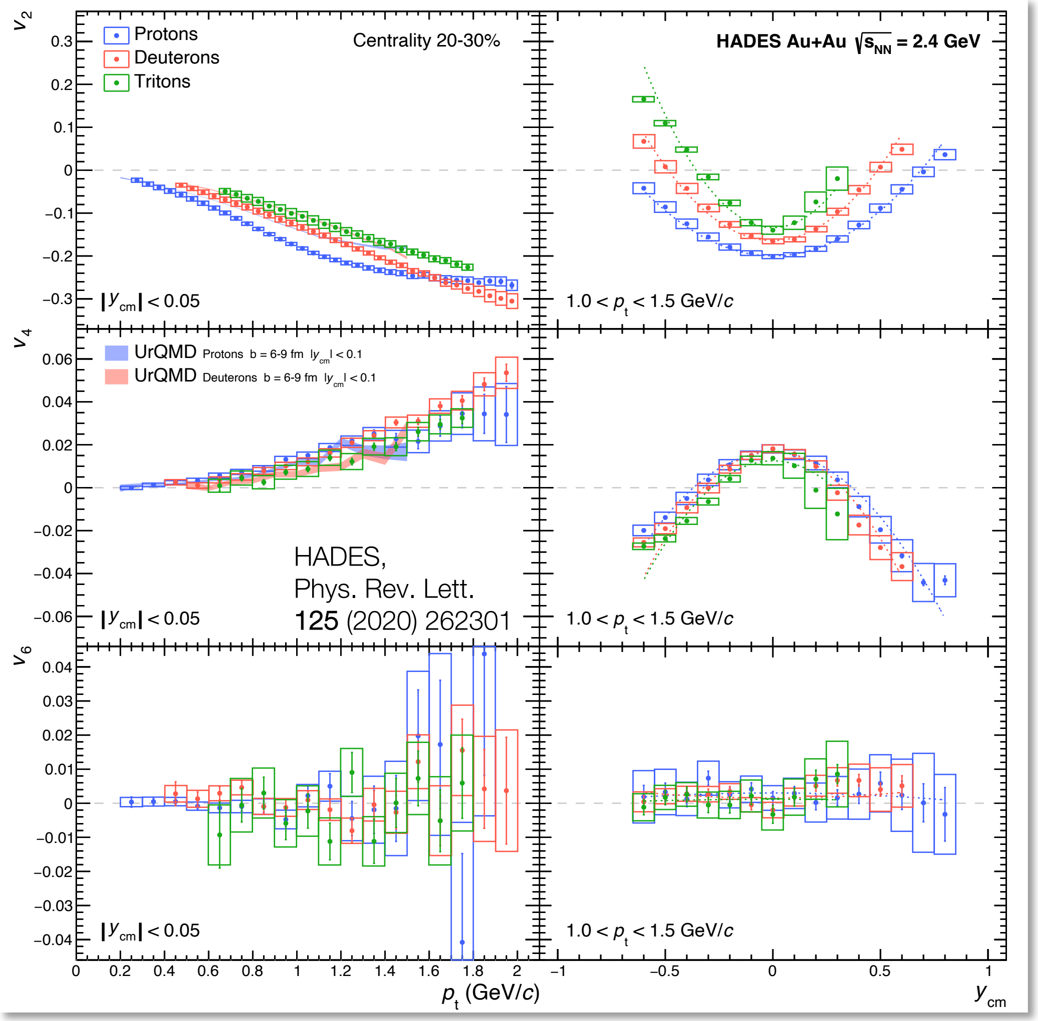


HADES, arXiv:2208.02740

Collective Effects

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





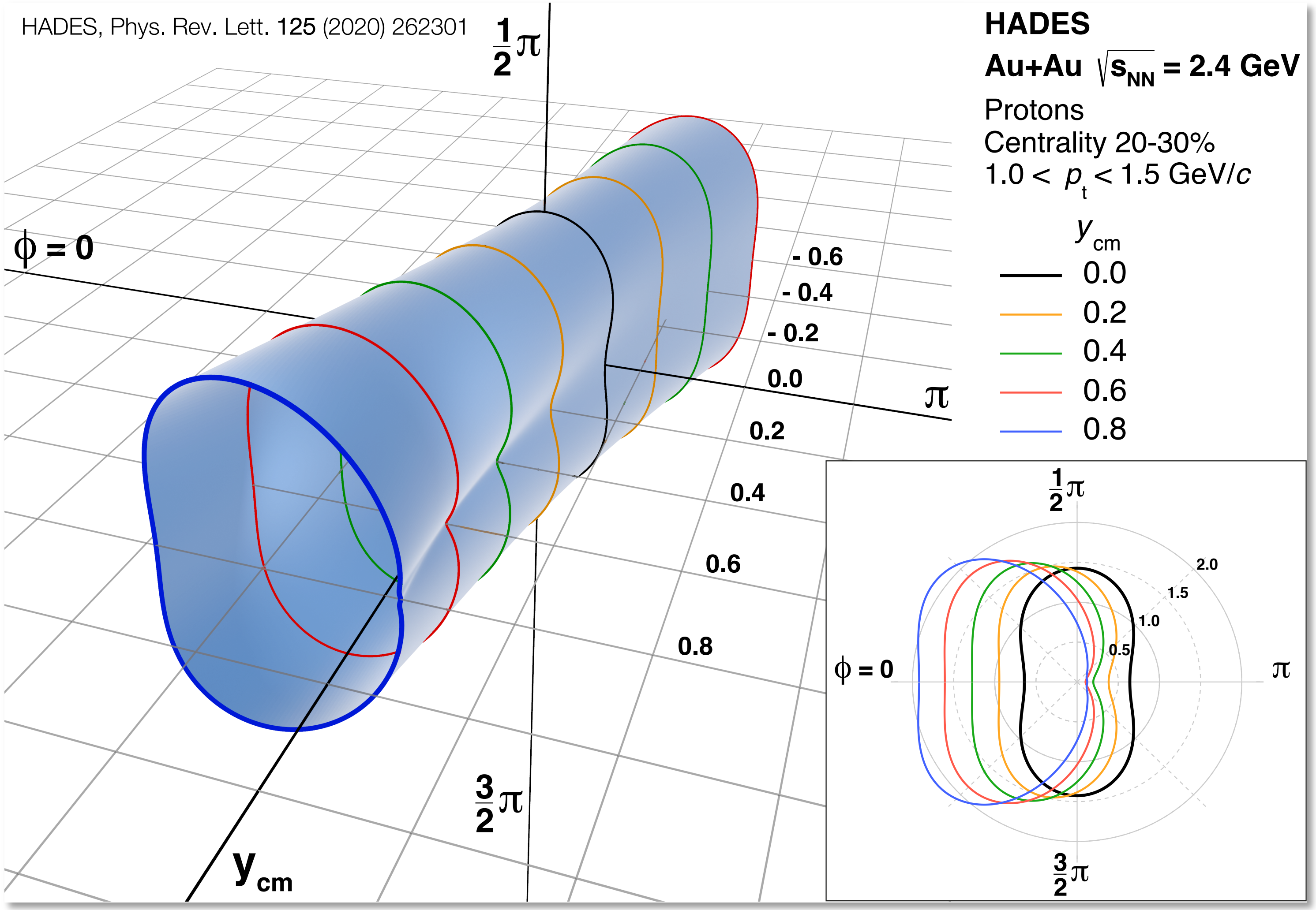
Collective Effects

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



Collective Effects

Relation between v_2 and v_4

Scaling properties

Prediction for ideal fluid:

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

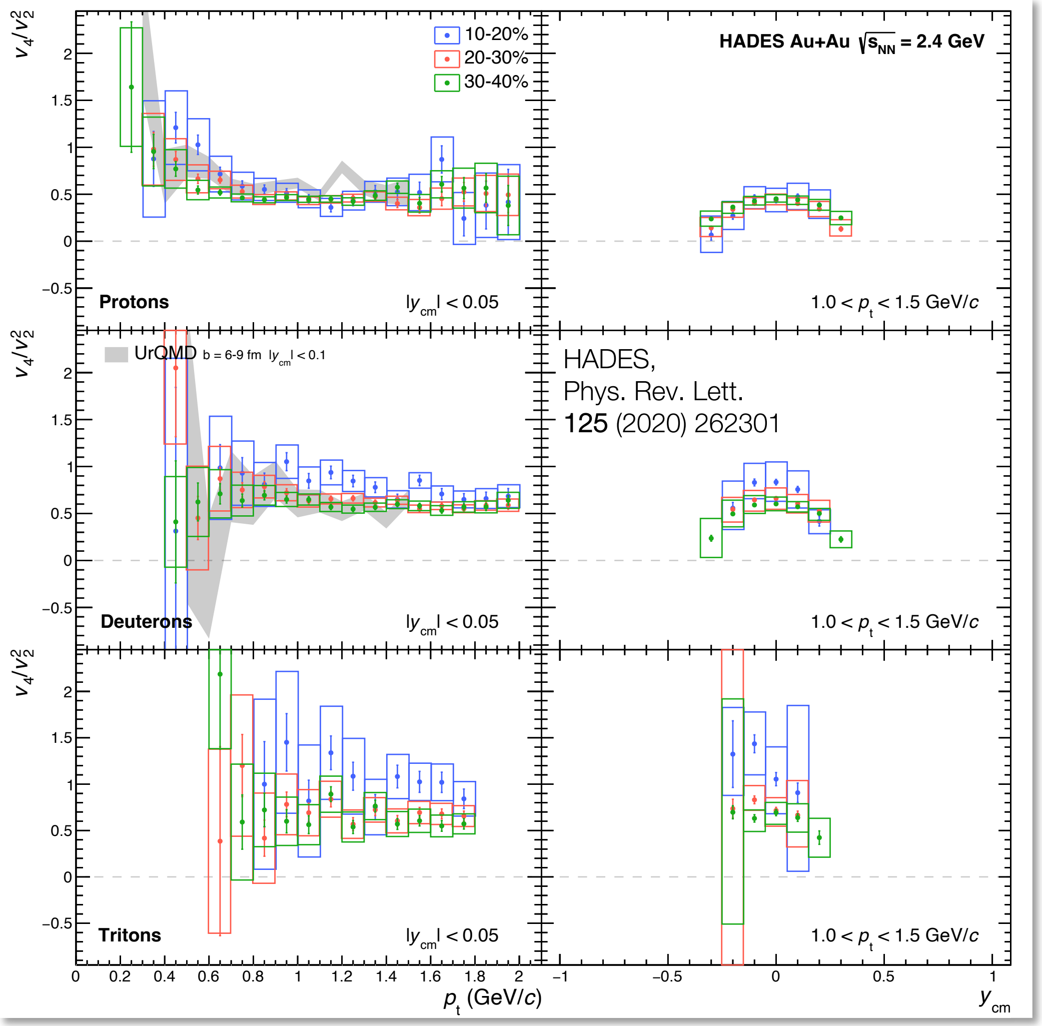
P.F. Kolb, PRC **67** (2003) 031902
N. Borghini and J.-Y. Oliitrault, PLB **642** (2006) 227
C. Gombeaud and J.-Y. Ollitrault, PRC **81** (2010) 014901

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

Observed ratios for p, d and t

Independent of p_t
Close to predicted value of ~ 0.6

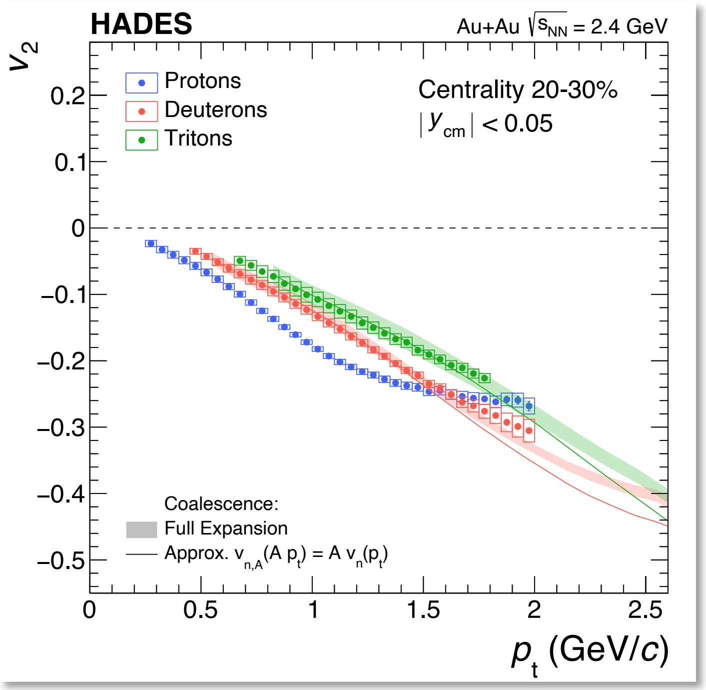
Hydro-like matter at SIS energies?

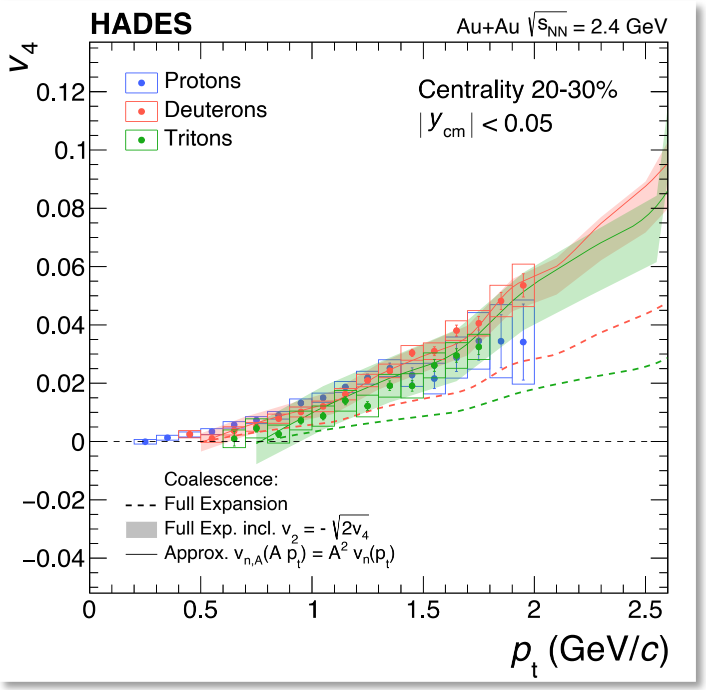


Collective Effects

Scaling Properties of v_2 and v_4 at Mid-Rapidity

HADES, arXiv:2208.02740





Nucleon Coalescence

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

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

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

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

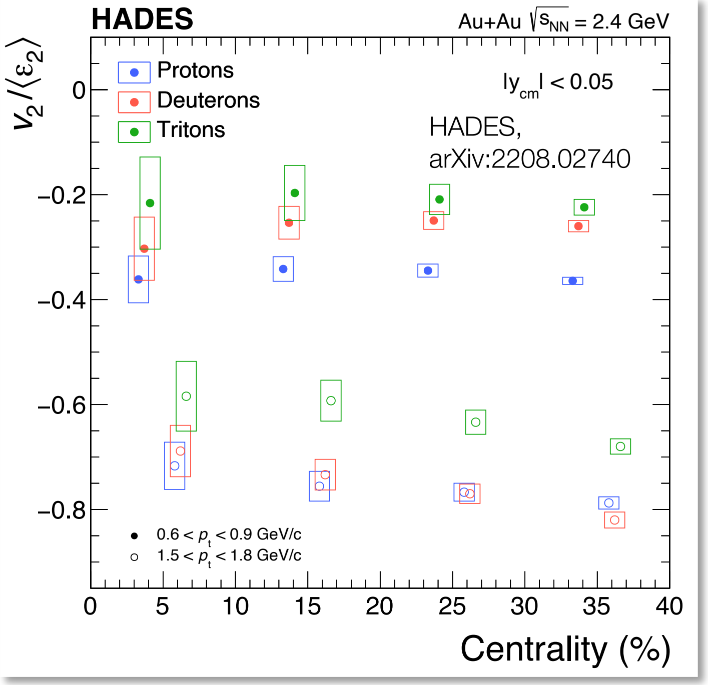
$$v_{4,A=3}(3\,p_t) = 9\,v_4(p_t)\,\frac{1}{1+12\,v_4(p_t)+6\,v_4^2(p_t)}$$

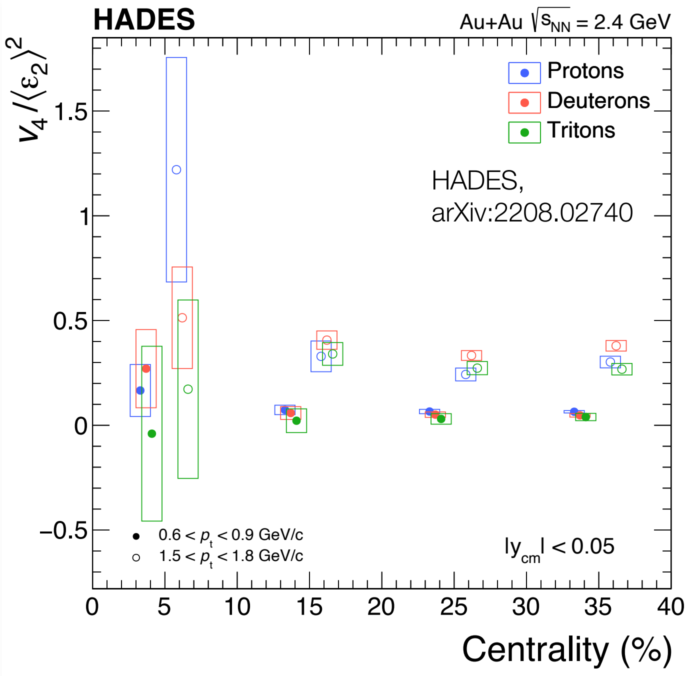
(assuming: $v_2 = -\sqrt{2\,v_4}$)

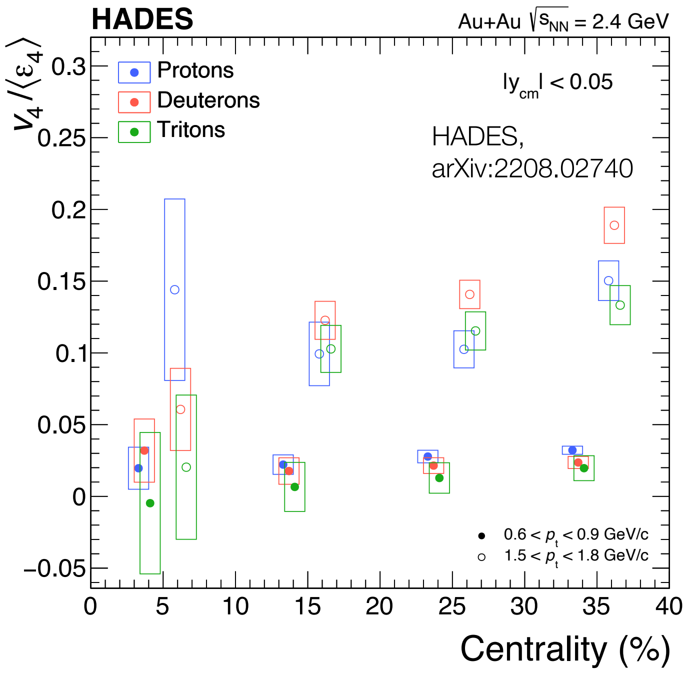
Works as expected in simple coalescence picture (only at mid-rapidity!)

Collective Effects

Geometry Scaling





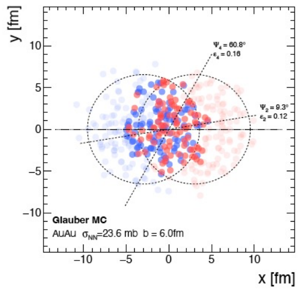


Scaling with Initial Eccentricities

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)

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



Collective Effects

Model Comparisons to Proton Data

Determination of EOS

New level of precision
Additional information from higher orders

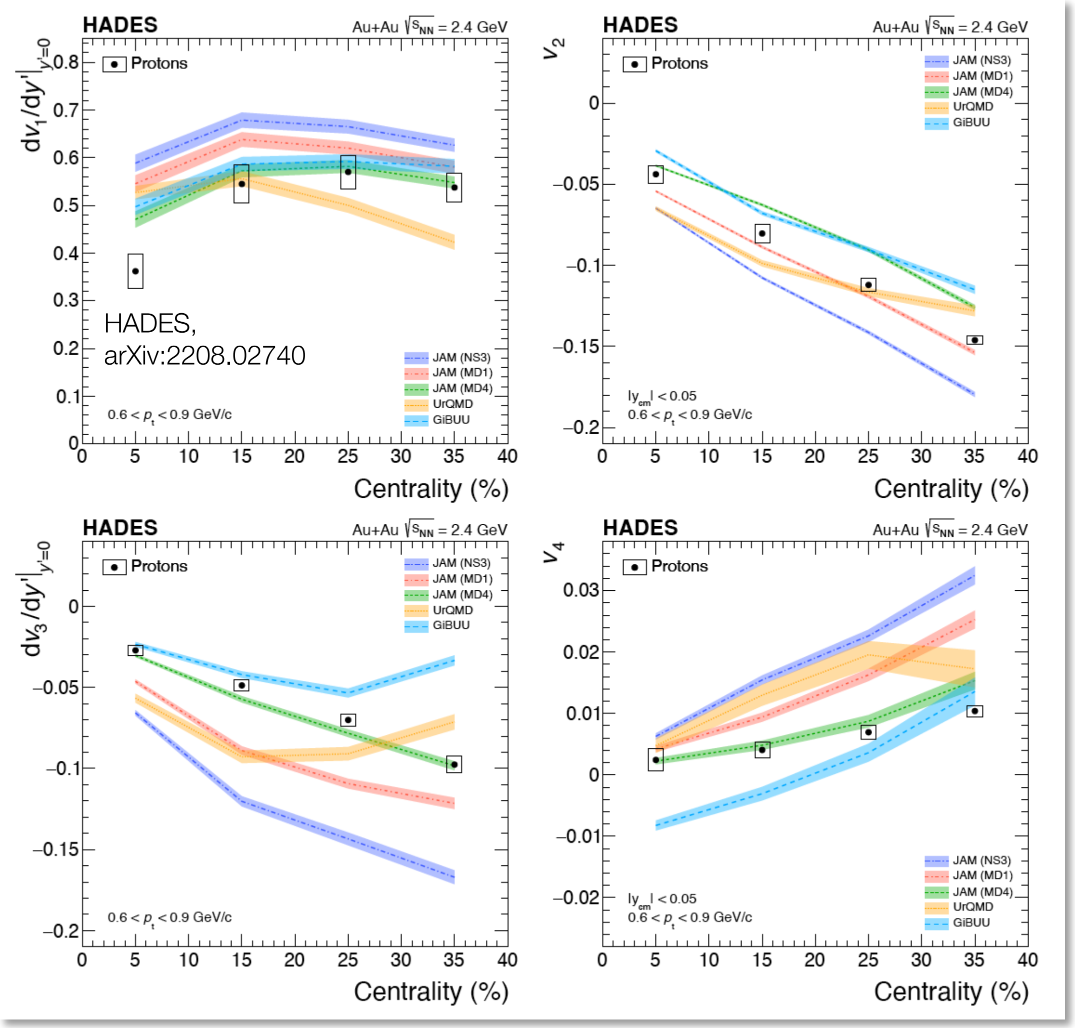
Models:
JAM 1.9 NS3 (hard EOS, mom.-indep.)
JAM 1.9 MD1 (hard EOS, mom.-dep.)
JAM 1.9 MD4 (soft EOS, mom.dep.)
UrQMD 3.4 (hard EOS, mom.-indep.)
GiBUU Skyrme 12 (soft EOS)

Conclusions

Overall trend reasonably described,
but no model works everywhere

Several systematic deviations

Unified description of cluster production missing



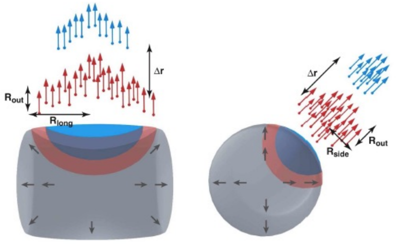
Femtoscopy
Principle

Bose-Einstein-Correlations
Pairs of identical bosons (charged pions)

Widths of correlation inversely proportional to size *R* of pion source

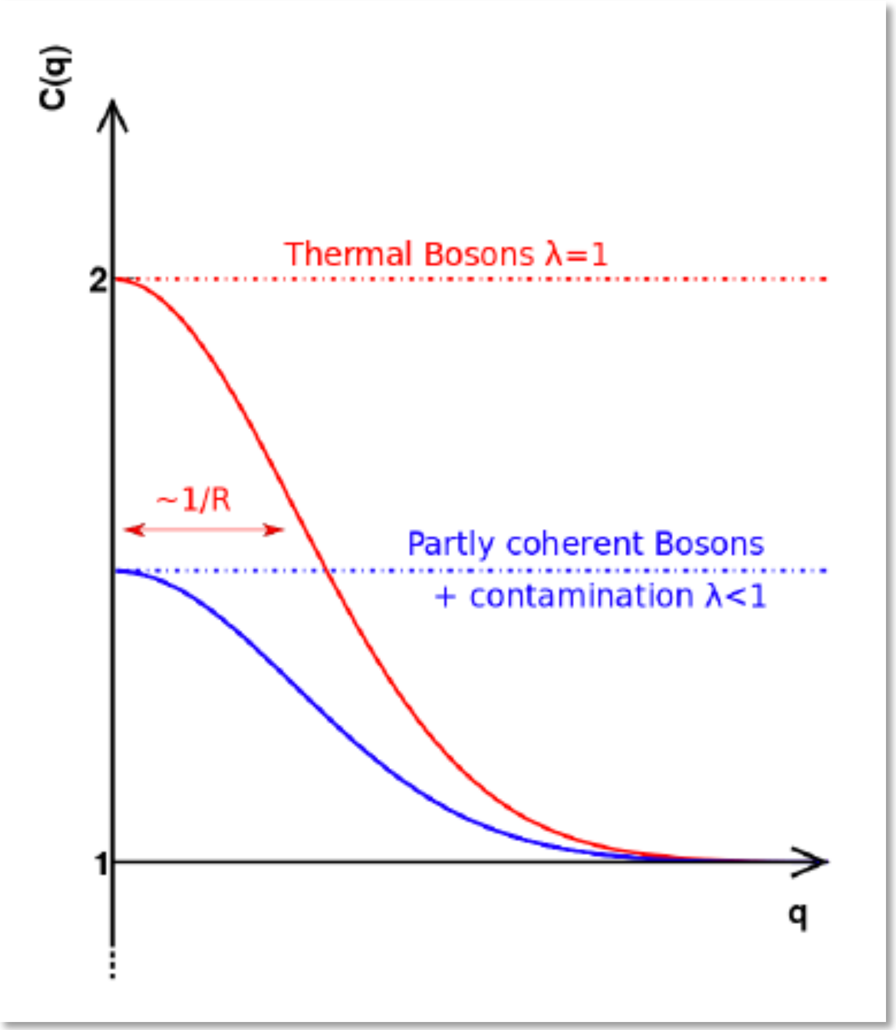
$$\Delta q = \frac{\hbar c}{R} \approx \frac{200}{R} \frac{GeV\, fm}{c}$$

Multi-dimensional analysis
Access to fireball evolution (radial flow)



M.A. Lisa and S. Pratt, arXiv:0811.1352

Analysis relative to event plane
Access to event shapes

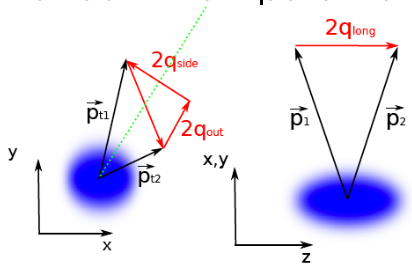


Femtoscopy

Charged-Pion Correlations

Space-time-extend of fireball

3D correlation function
Bertsch-Pratt parameterization

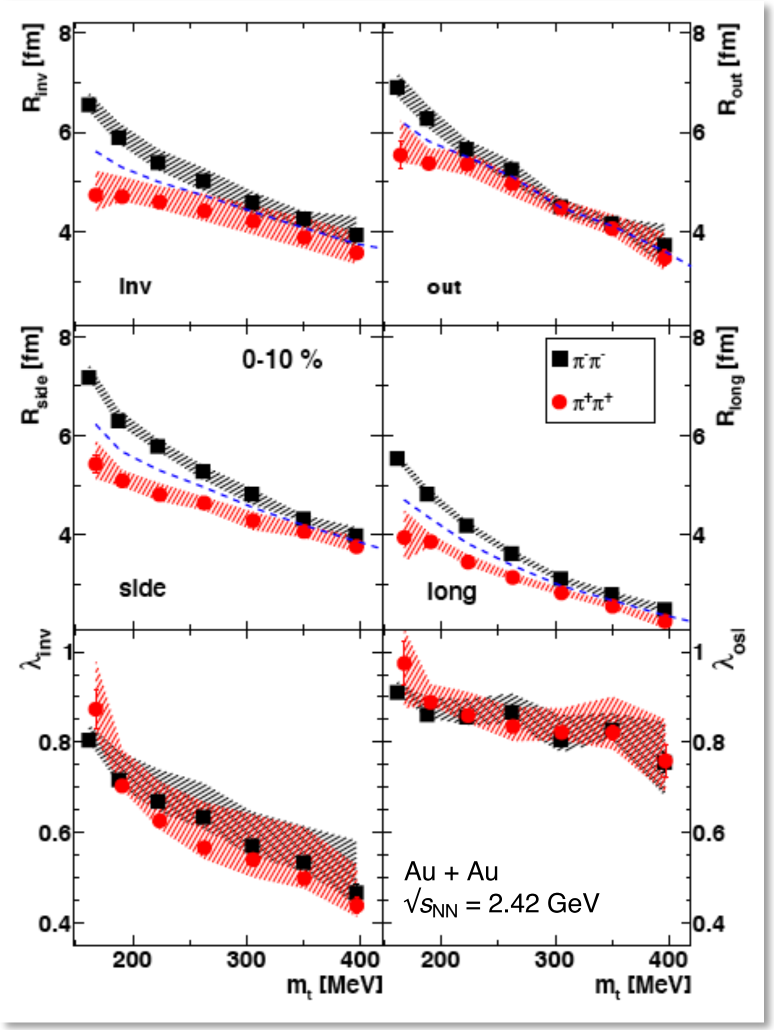


Radius parameters

Strong m_t-dependence ⟶ radial flow

1st observation of charge sign difference

R. Greifenhagen, QM19
HADES
Phys. Lett. **B795** (2019) 446
Eur. Phys. J. **A56** (2020) 140



Femtoscopy
Radius Parameters

Energy dependence
R_{out}, R_{side} and R_{long}

HADES result follows trend from higher energies (SPS, RHIC)
Room for structures at low energies as indicated by E895 data?

1st observation of charge sign difference

HADES
Phys. Lett. **B795** (2019) 446
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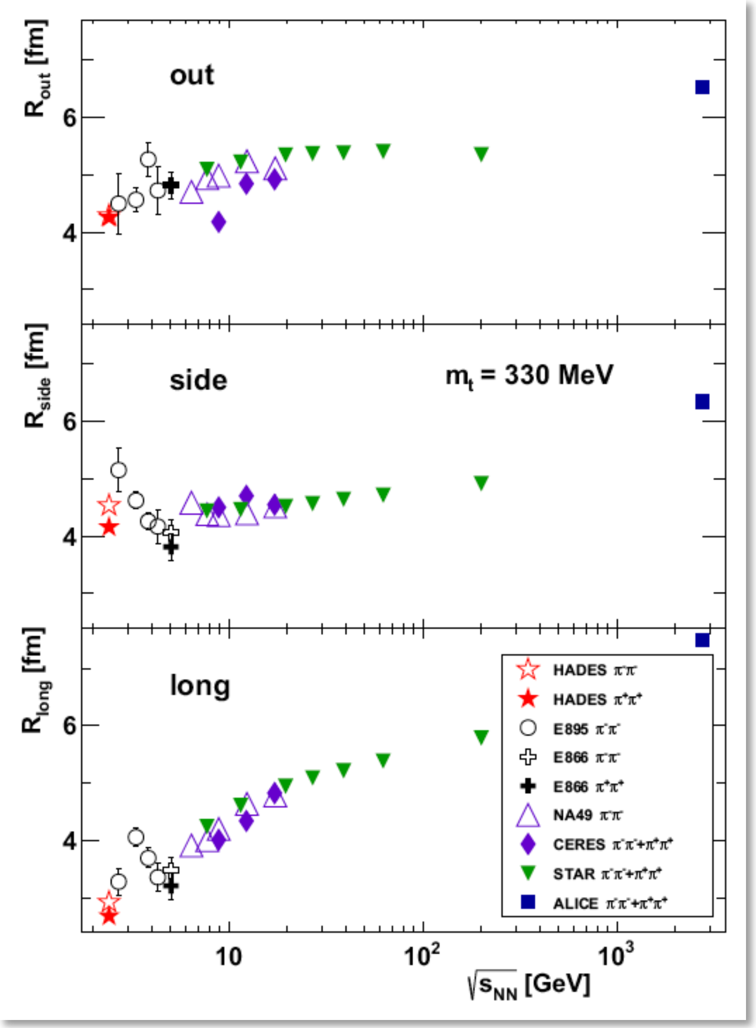
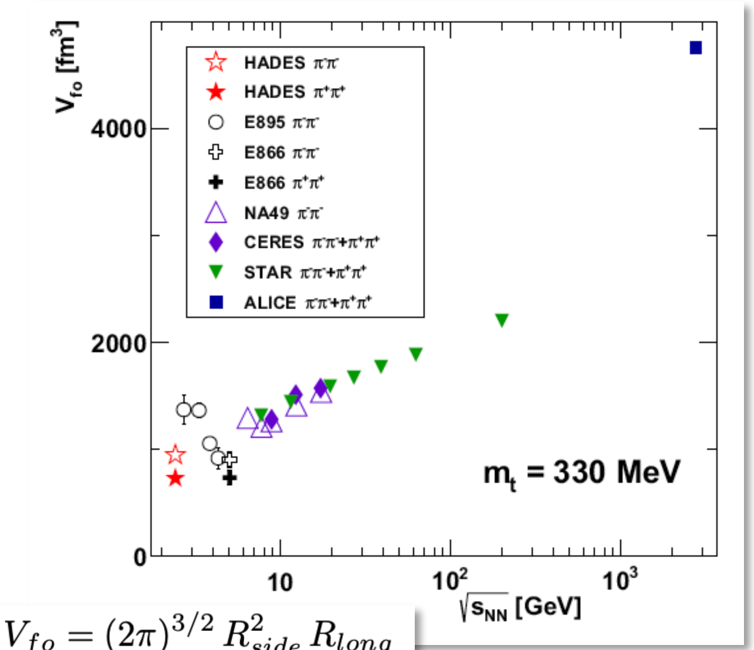
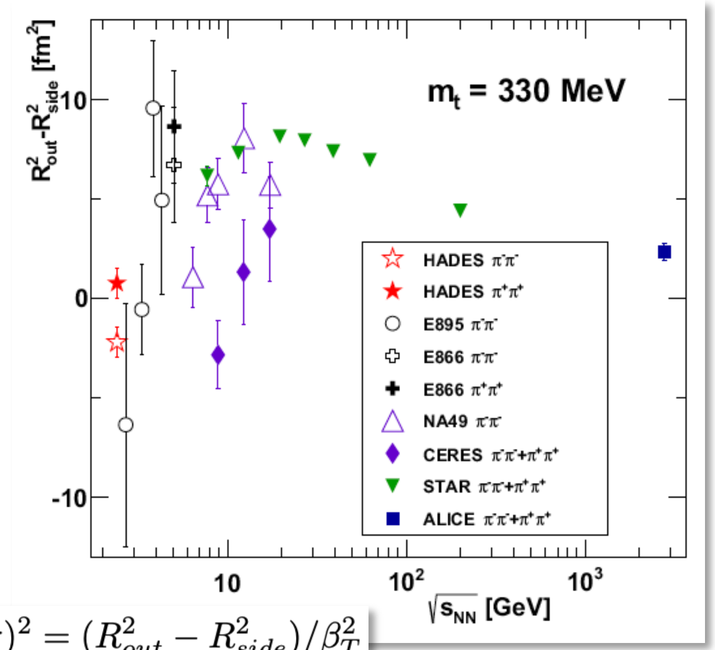


Femtoscopy
Radius Parameters



$$V_{fo} = (2\pi)^{3/2}\, R_{side}^2\, R_{long}$$



$$(\Delta\tau)^2 = (R_{out}^2 - R_{side}^2)/\beta_T^2$$

Energy dependences

Freeze-out volume: HADES result follows trend from higher energies (SPS, RHIC)
Room for structures at low energies as indicated by E895 data?

Difference between R_{out} and R_{side} close to zero (HADES), maximal for intermediate energies (top-SPS, RHIC)

HADES
Eur. Phys. J. **A56** (2020) 140

Femtoscopy
Azimuthal Dependence

Fits relative to event plane

Rotation of osl-system relative to EP-system

Formulas: PLB **496** (2000) 1, PRC **57** (1998) 266

Corrected for EP-resolution

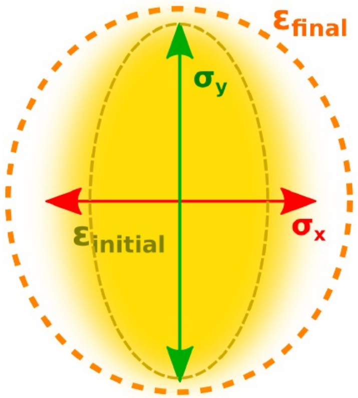
$\Longrightarrow$ Access to event shape parameters

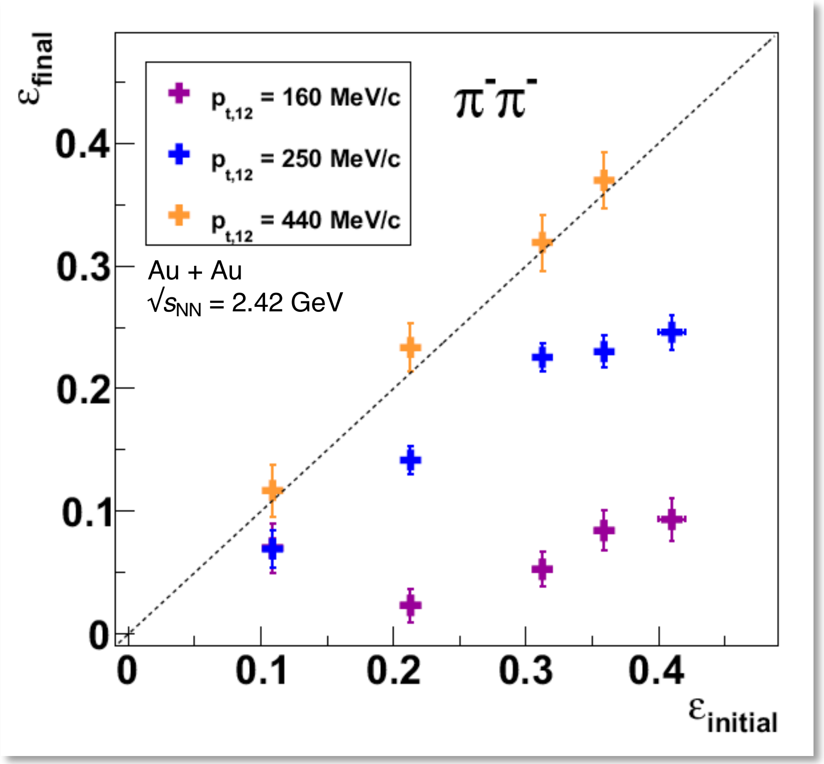
Eccentricity ε in xy-plane

Compare to initial participant eccentricity $\varepsilon_{\text{initial}}$ from Glauber MC

Early stage (high $p_{t,12}$):
$\varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}}$

Late stage (low $p_{t,12}$):
$\varepsilon_{\text{final}} \longrightarrow 0$





$$\epsilon_{final} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

HADES
Eur. Phys. J. **A56** (2020) 140

Femtoscopy
Azimuthal Dependence

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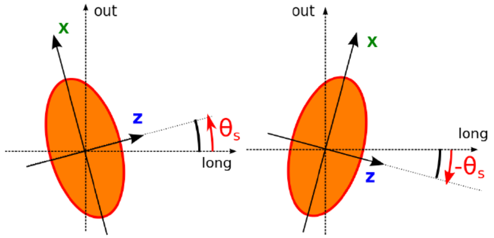
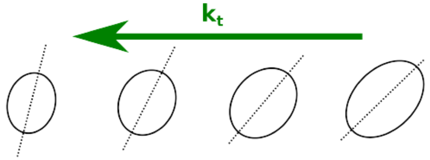
Corrected for EP-resolution

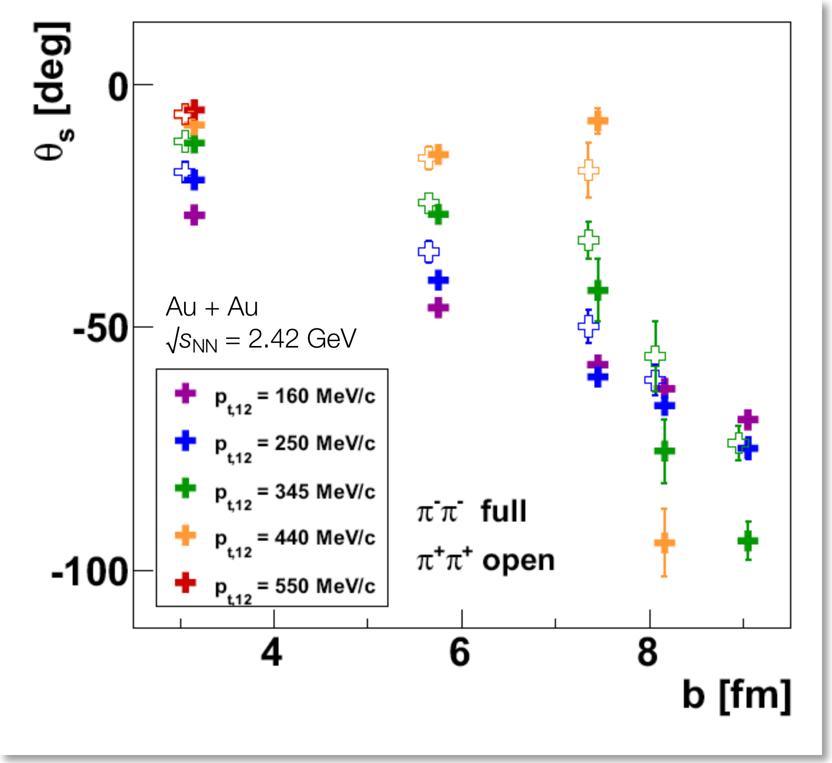
⟹ Access to event shape parameters

Tilt angle θ_s in xz-plane



$|\theta_s|$ tends to decrease with increasing $p_{t,12}$





HADES
Eur. Phys. J. **A56** (2020) 140

Vorticity

Principle of Global Λ Polarization

Global polarization

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

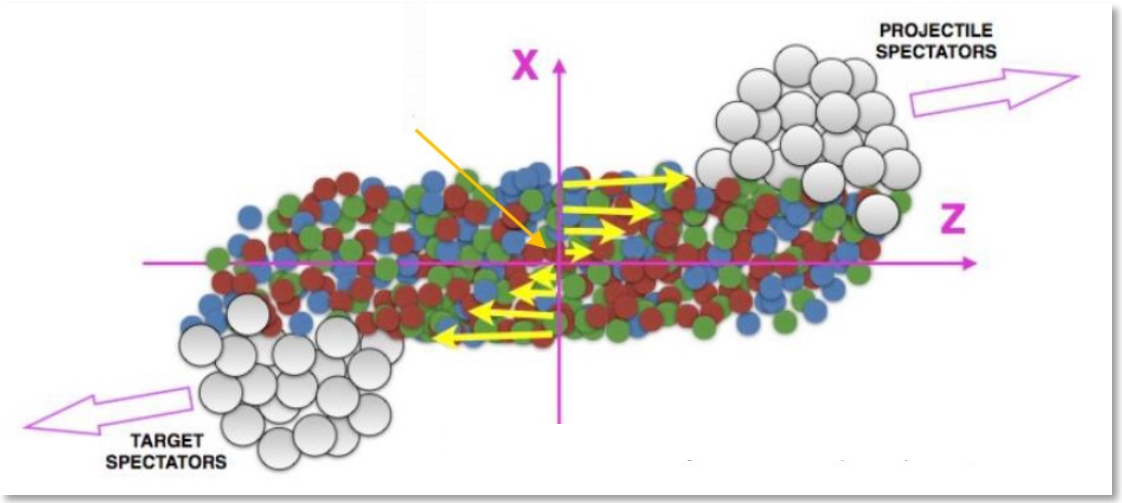
Observable via polarization of spins relative to event plane
(spin-orbit coupling, e.m.-coupling)

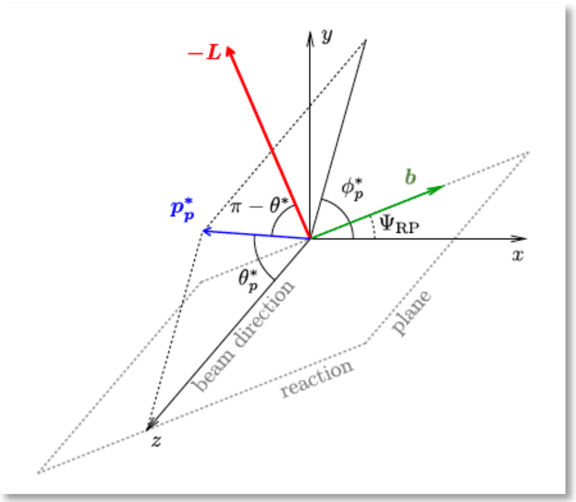
Observable

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

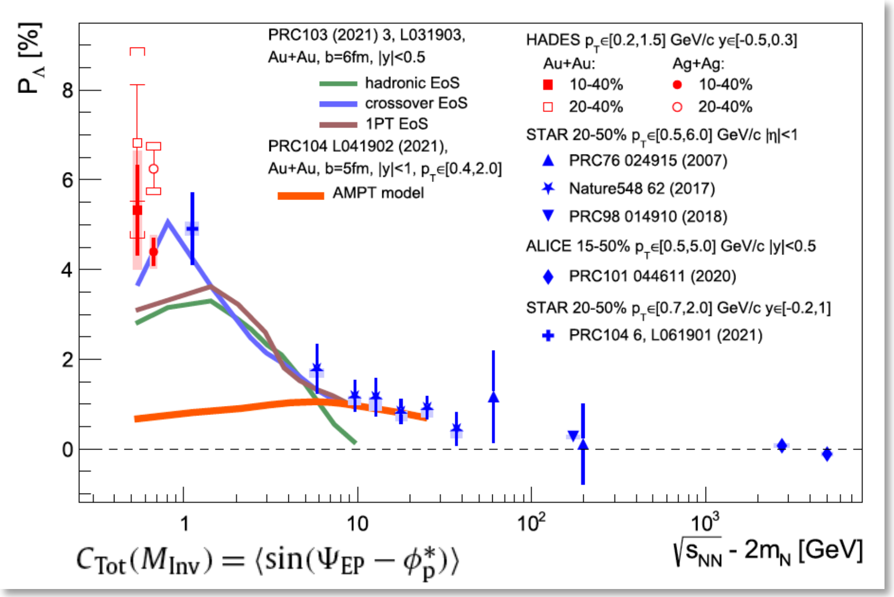
Results (10–40 % cent.)

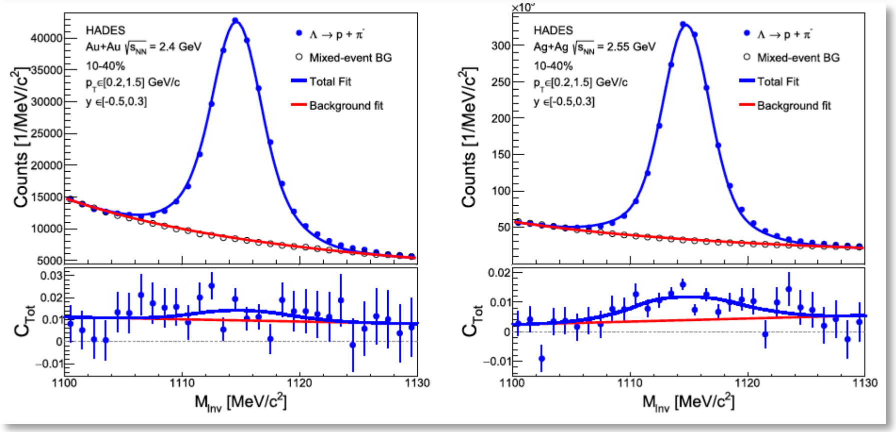
P_{Λ} (Au+Au) = (5.3 ± 1.0 (stat.) ± 1.3 (syst.)) %
P_{Λ} (Ag+Ag) = (4.4 ± 0.3 (stat.) ± 0.4 (syst.)) %

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

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





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!)

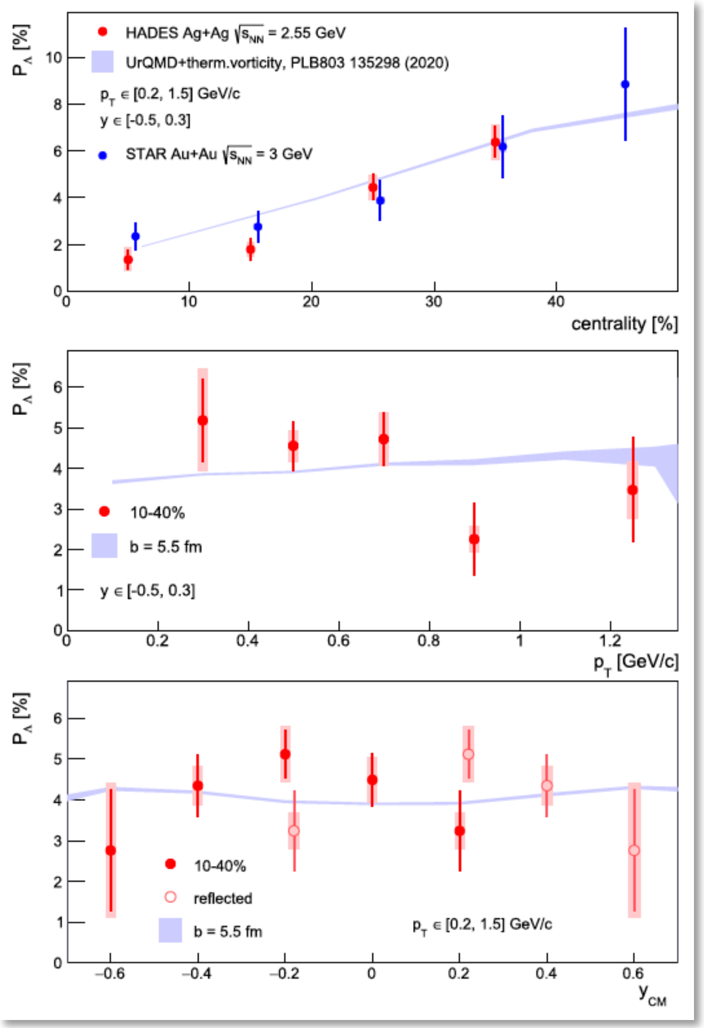
Phase space dependence

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

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



Vorticity

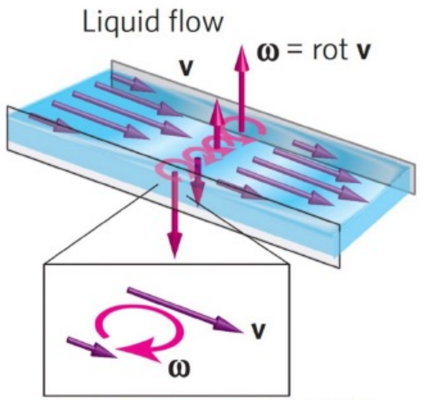
Outlook

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)

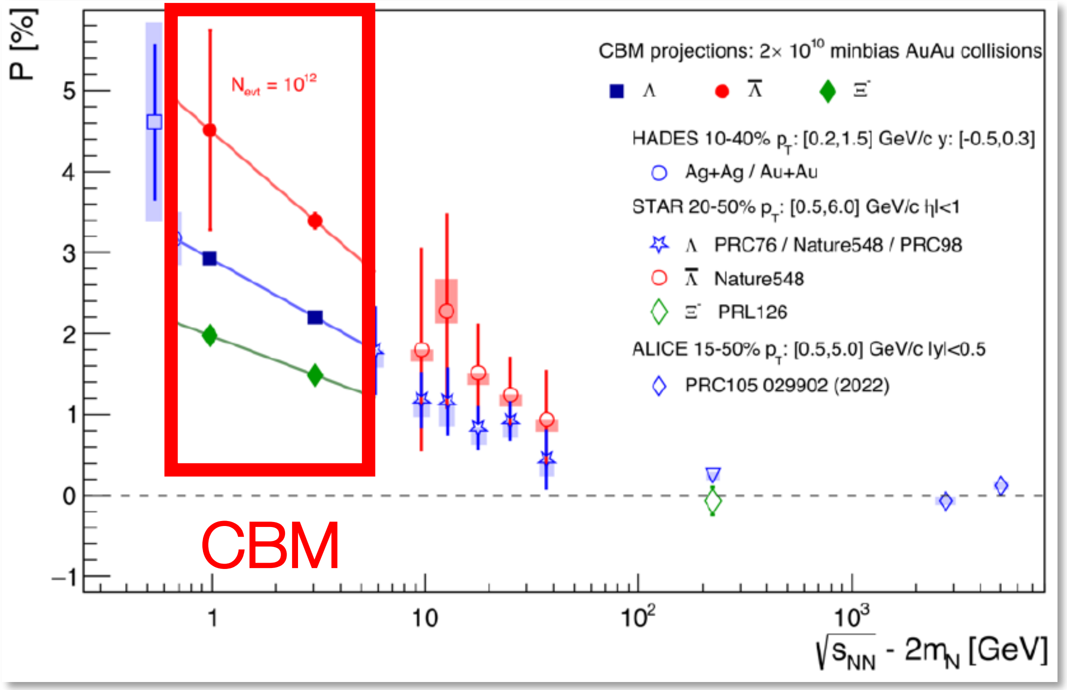
Systematic measurements at low energies needed

CBM physics program:

Λ and Ξ^- polarization with 5% precision

Mapping of Λ excitation function

($\geq 10^{13}$ event required)

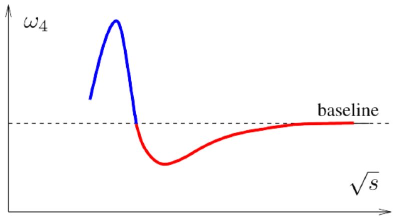


Baryon Number Fluctuations
Motivation

Search for critical point
⟶ Susceptibilities diverge
⟶ Enhanced fluctuations

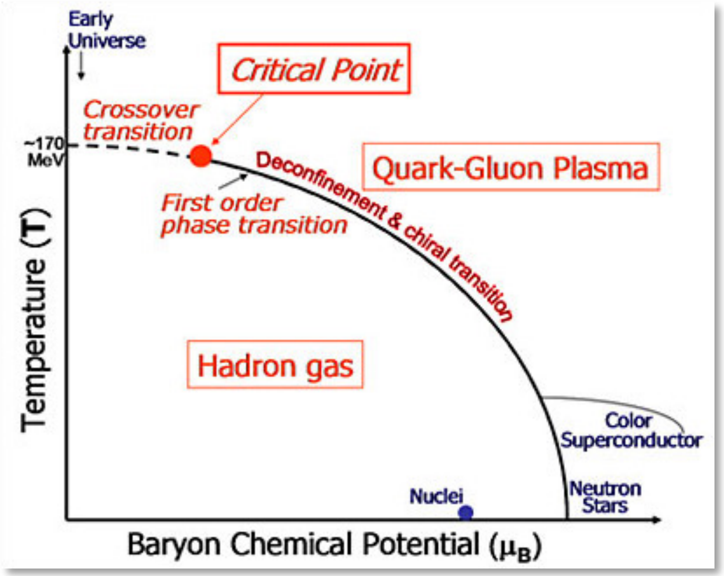
Fluctuations of conserved quantities (strangeness, baryon number, charge)
Higher moments should be more sensitive

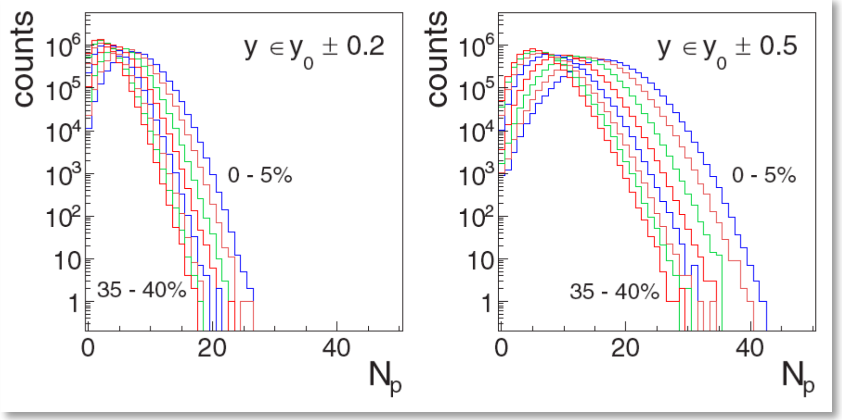
Vary freeze-out conditions via energy scan



M. Stephanov

Observable
Moments of net-proton distributions (proxy for baryon number)





Baryon Number Fluctuations

Corrections

Observable (HADES)

Moments of proton multiplicity distributions
Centrality selection with Forward Wall (5%)

Efficiency correction

Track density dependent efficiency
Evaluated via different methods

Binomial E-by-E: A. Bzdak and V. Koch, PRC **86** (2012) 044904
S. He and X. Luo, Chin. Phys. **C42** (2018) 104001
Unfolding: P. Garg et al., J. Phys. **G40** (2013) 055103
Moment expansion: T. Nonaka et al., NIM **A906** (2018) 10

Volume corrections

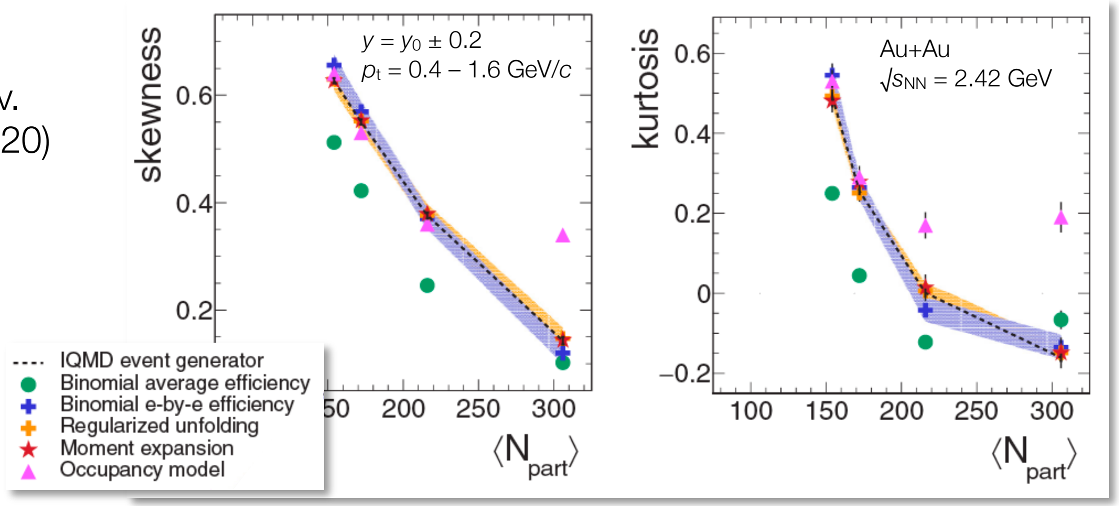
Extension of assumption of constant reduced cumulants $\kappa_n(V) = K_n/V = const.$

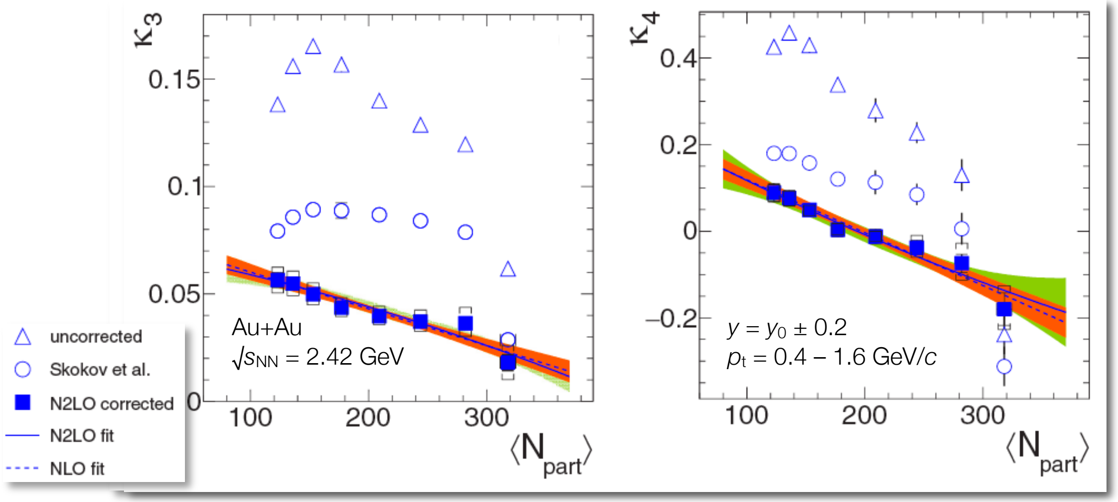
V. Skokov et al., PRC **88** (2013) 034911
P. Braun-Munzinger et al., NPA **960** (2017) 114

Here: 2nd-order approach:

$$\kappa_n(V) = \kappa_n + \kappa_n'(V - \langle V \rangle) + \kappa_n''(V - \langle V \rangle)^2$$

HADES, Phys. Rev. C102 (2020) 024914





Baryon Number Fluctuations

Energy Dependence of Scaled Cumulants

Extension of STAR-BES results

Skewness (K_3 / K_2): smooth trend

Kurtosis (K_4 / K_2): change of sign (0-10(5)%)

Contribution from spectators

Fluctuation sources: fireball ⟷ spectators

Relative admixture energy dependent!

⟹ Two rapidity intervals shown:

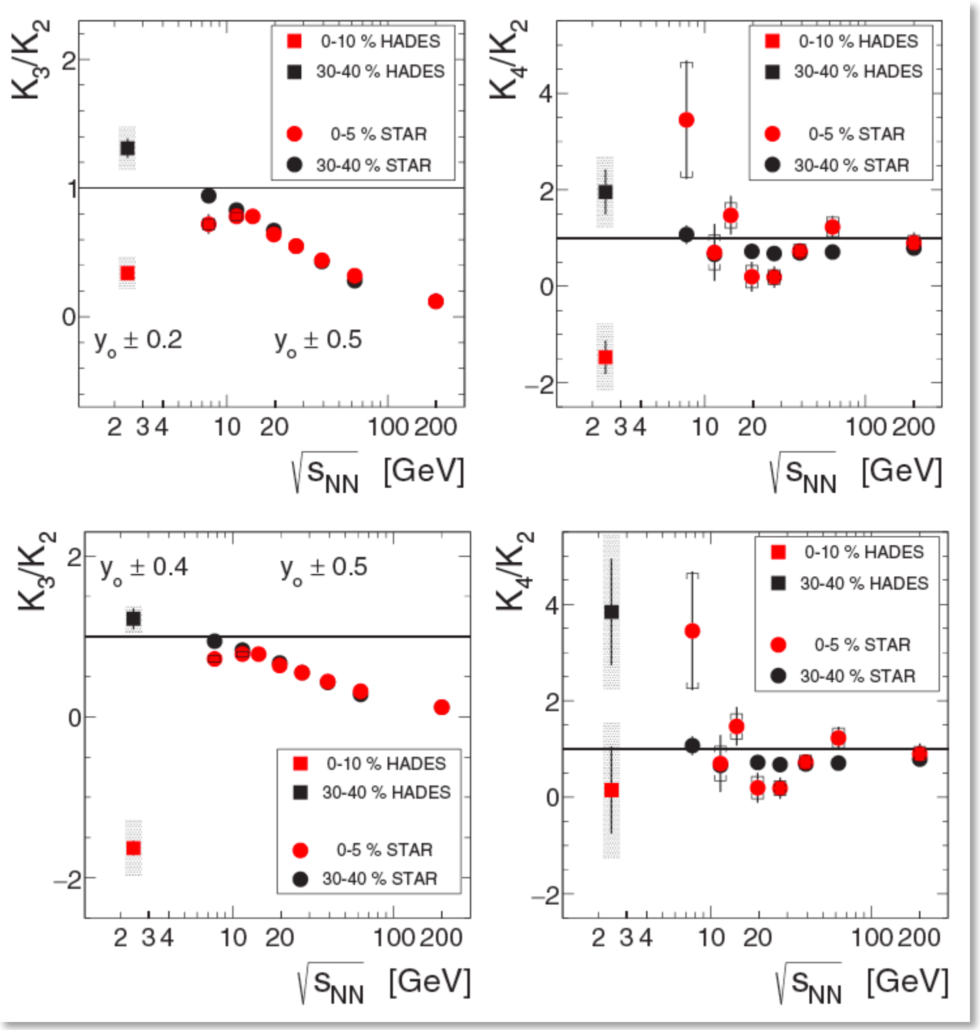
$y_0 \pm 0.2$ and $y_0 \pm 0.4$ (STAR: $y_0 \pm 0.5$)

HADES,
Phys. Rev. **C102** (2020) 024914

Outlook

Include bound protons (d, t, He)

Ag+Ag data



Baryon Number Fluctuations

Energy Dependence of Scaled Cumulants

Extension of STAR-BES results

Kurtosis (K_4 / K_2): change of sign (0-10(5)%)

Agrees with STAR fixed target result at $\sqrt{s_{NN}}$ = 3 GeV

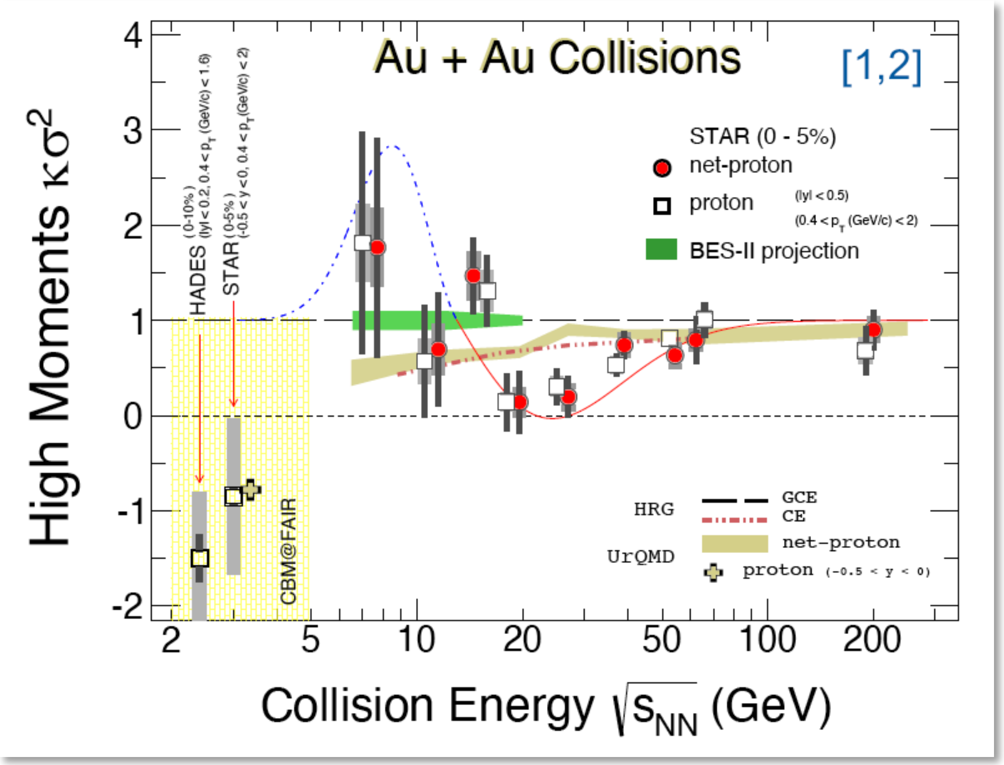
Current situation

Non-monotonous vs. smooth behavior?
Evidence for critical point?

Large corrections ⟹ large systematic uncertainties
Systematic measurements at low energies needed

CBM physics program (first three years):

Complete excitation function of κ_4(p),
First results on κ_6(p),
Extension into strangeness sector $\kappa_4(\Lambda)$



HADES,
Phys. Rev. **C102** (2020) 024914

STAR,
Phys. Rev. Lett. **128** (2022) 202303

Conclusions

High precision flow data will provide constraints on EOS

Bayesian analysis (similar to: Kuttan et al., arXiv:2211.11670 or Huth et al., Nature **606** (2022) 276) ?
Consistent modeling of cluster formation essential

Smooth evolution of femtoscopic radius parameter

Difference between R_{out} and R_{side} close to zero at low energies

Vorticity maximal close to strangeness threshold

Effect measured via global Λ polarization
Driving mechanism for the coupling of orbital momentum to spin not yet fully understood

Baryon number fluctuations: kurtosis negative at low energies

Evidence for any non-monotonic behavior?

Precision measurements at low energies needed $\Longrightarrow$ CBM physics program

BACKUP

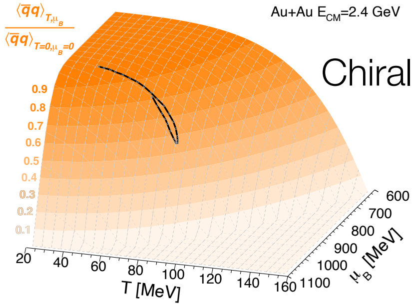
Dense Baryonic Matter

Heavy-Ion Collisions

Heavy-ion collisions

QCD phase diagram in the region of high μ_B

Rare and penetrating probes



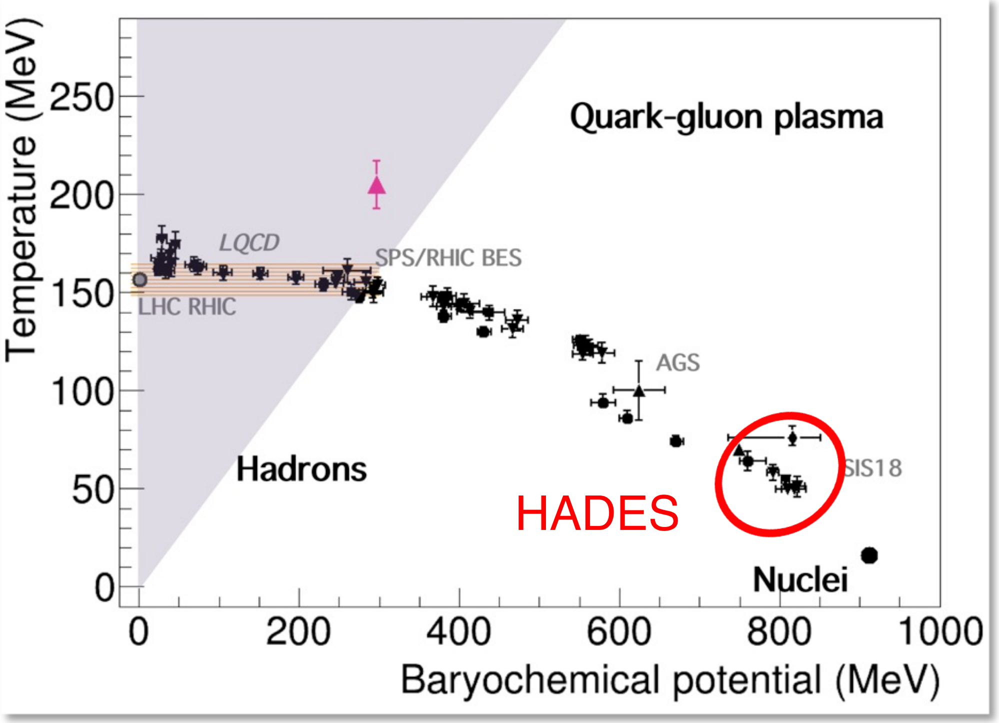
Chiral condensate

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

Bulk properties of dense fireball

Pion + proton beams

Properties of baryon resonances
(vacuum, cold QCD matter)



Collective Effects

Model Comparisons to Proton Data

Determination of EOS

New level of precision
Additional information from higher orders

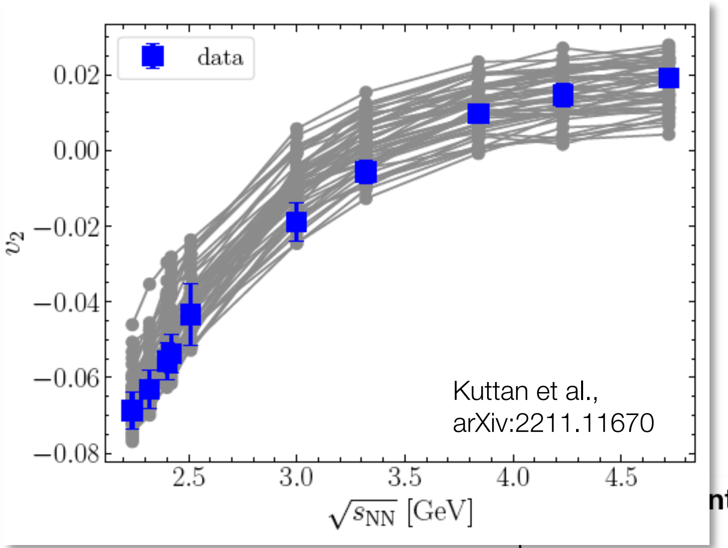
Next Steps towards EOS

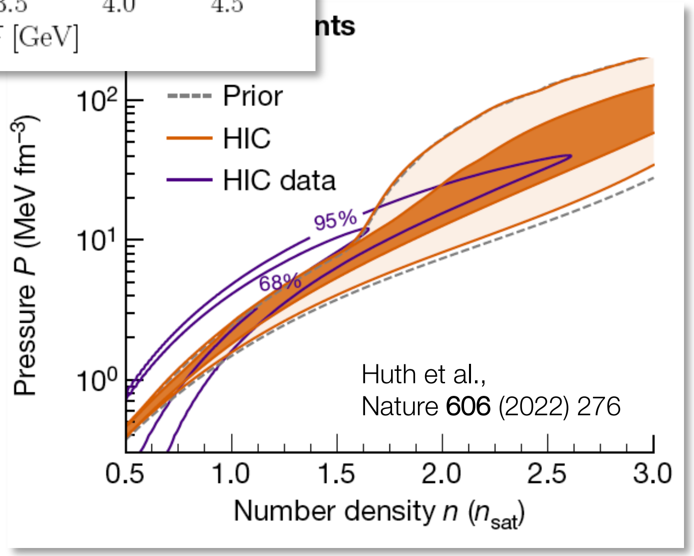
More detailed comparisons
⟹ Bayesian analysis

Other models, e.g. PHQMD

Same recipe for cluster formation (?)
Exploit also data on d and t in unified manner

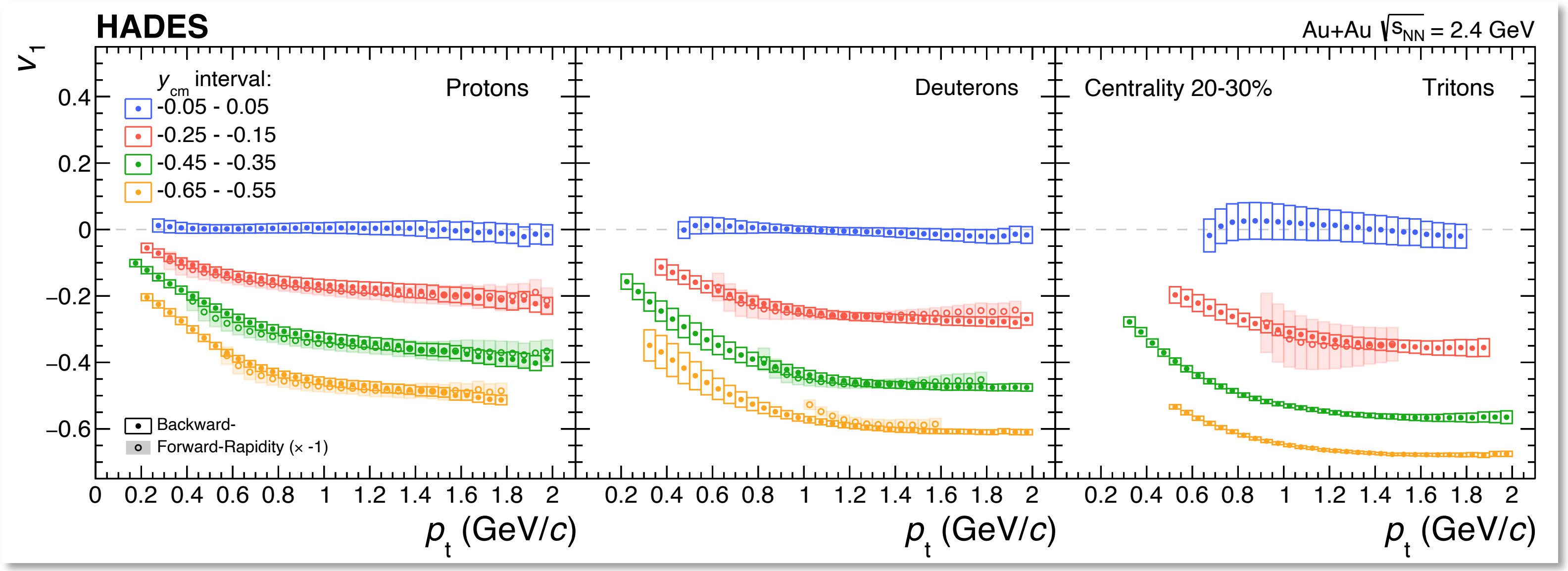
Combination with other observables and results from astrophysics





Collective Effects

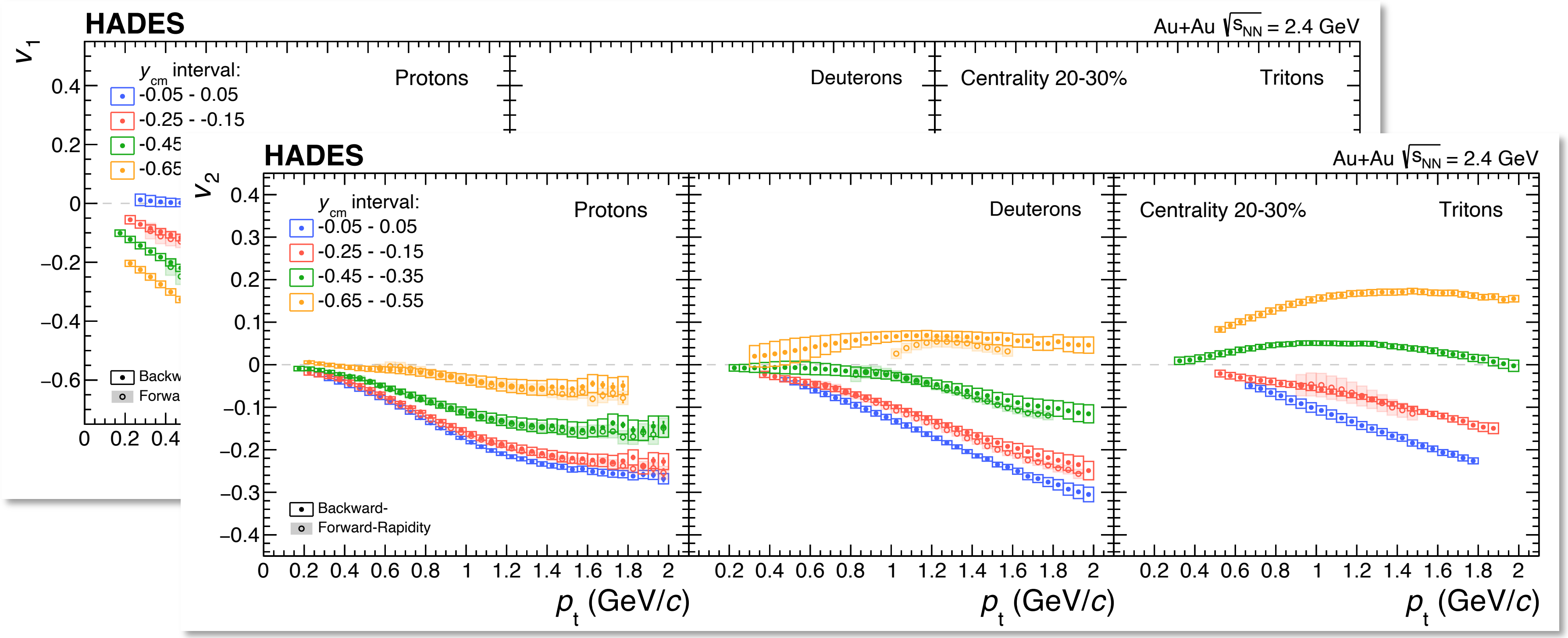
Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons



HADES, arXiv:2208.02740

Collective Effects

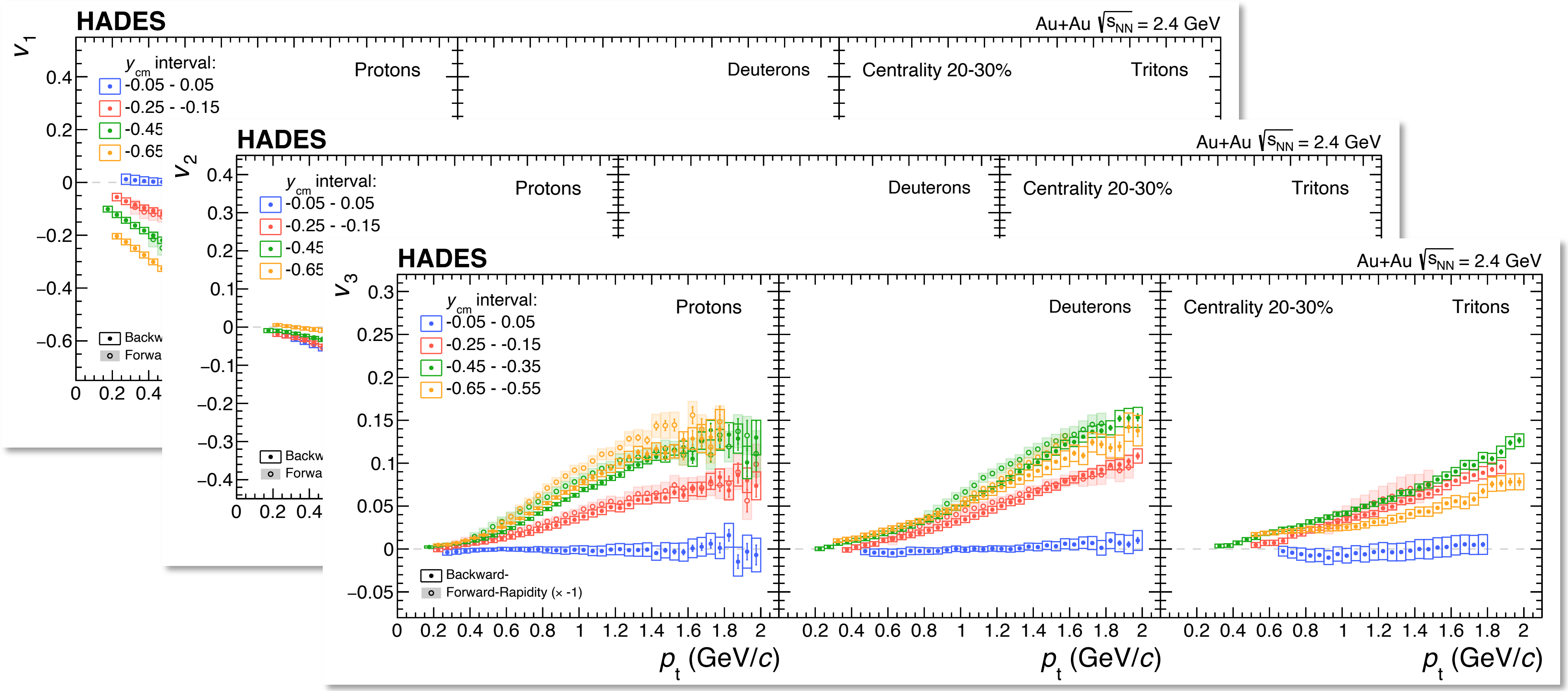
Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons



HADES, arXiv:2208.02740

Collective Effects

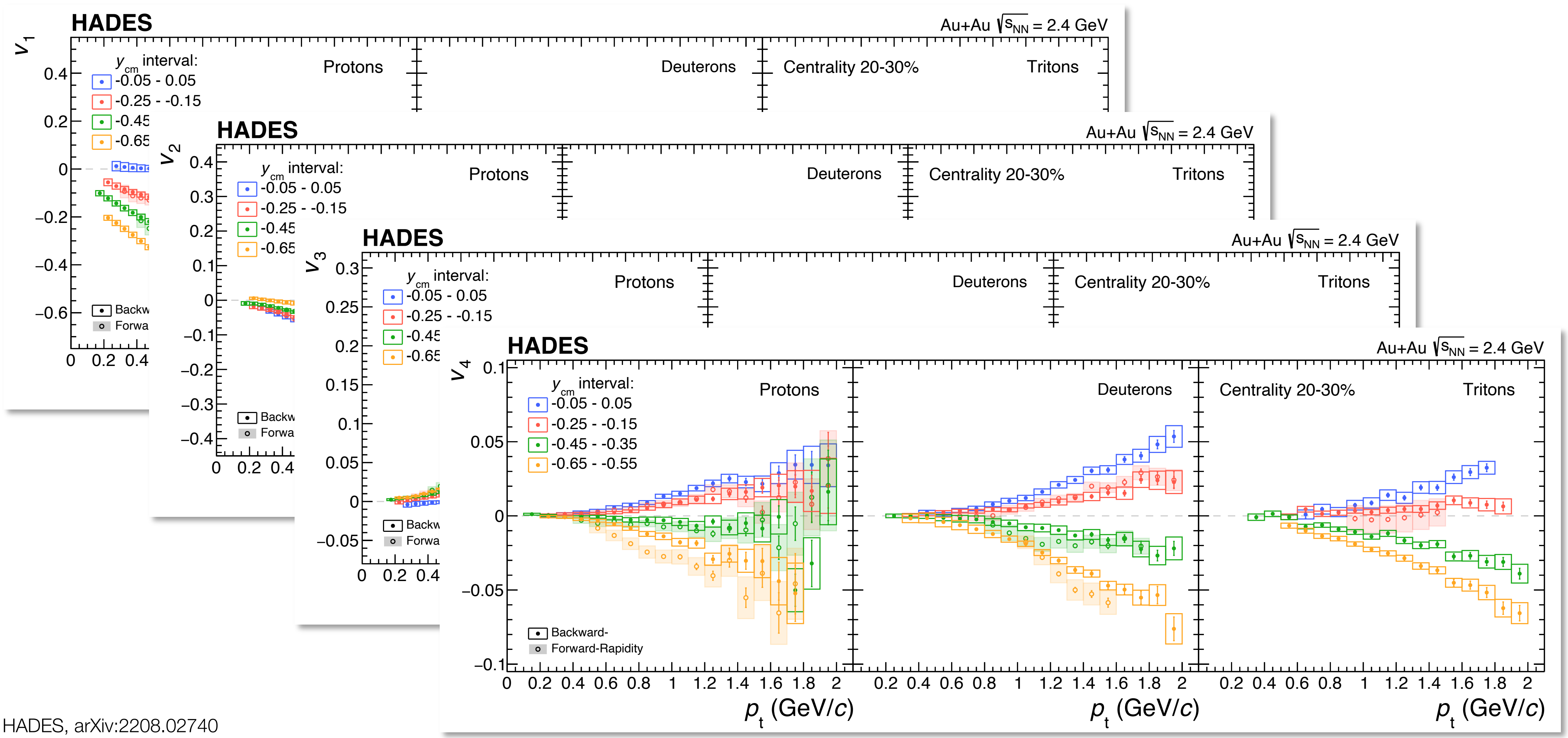
Results on v_1, v_2, v_3 and v_4 for Protons, Deuterons and Tritons



HADES, arXiv:2208.02740

Collective Effects

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

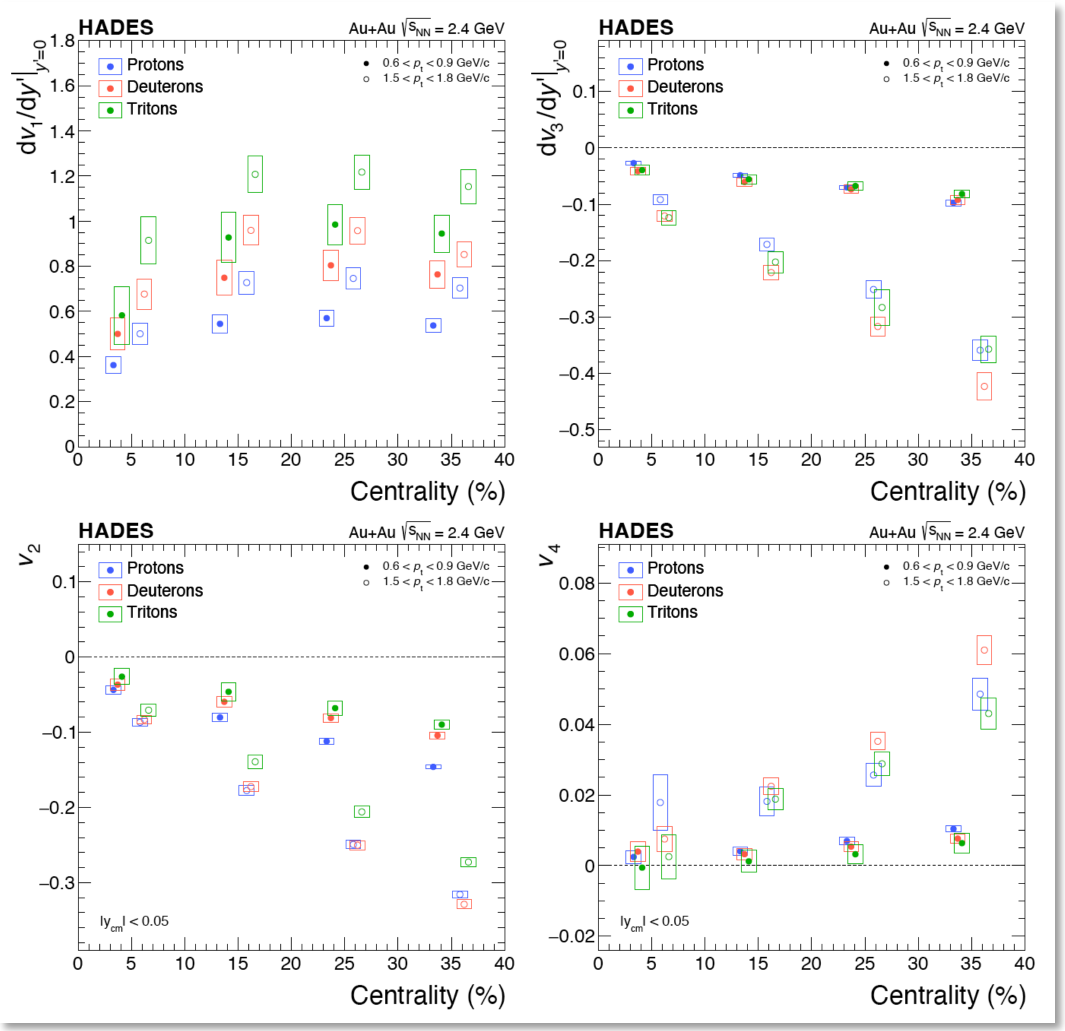


HADES, arXiv:2208.02740

Collective Effects

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

Centrality Dependence

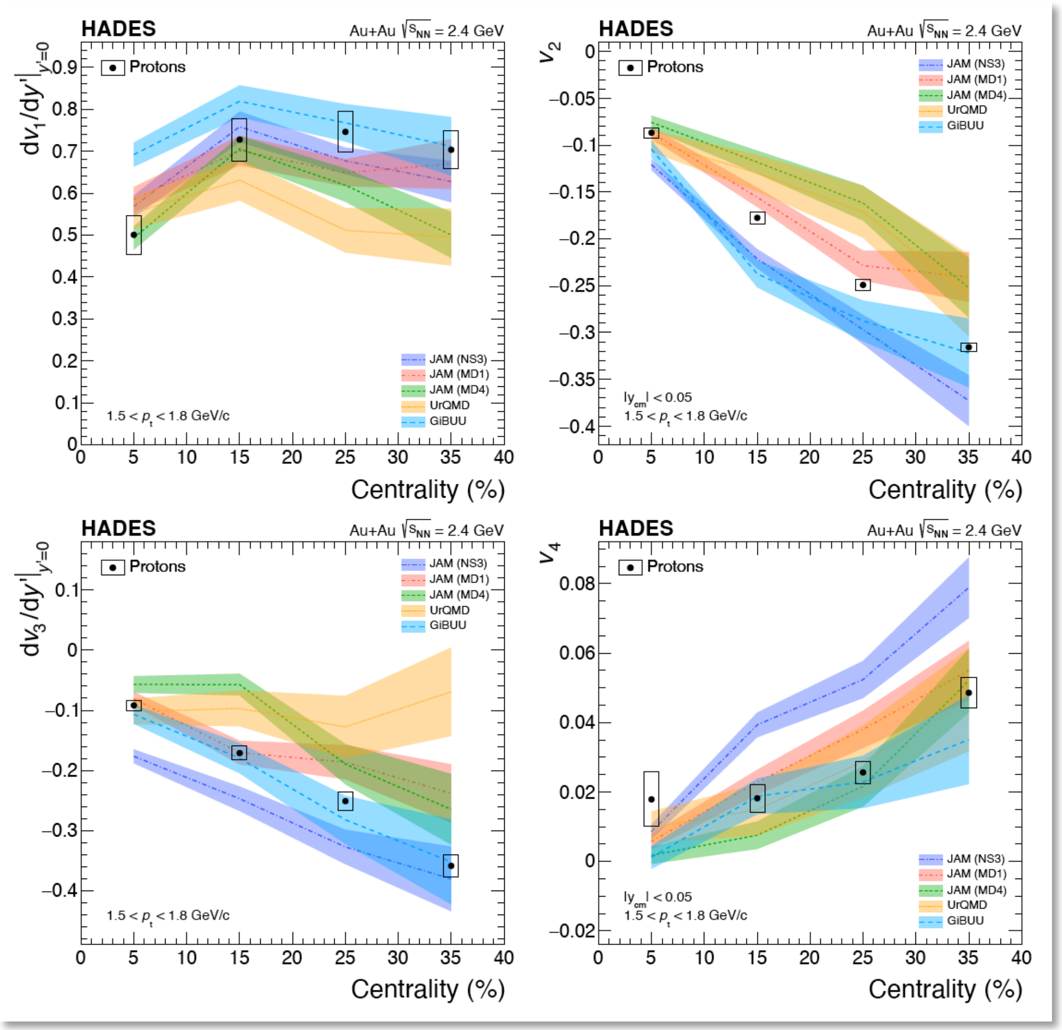


HADES, arXiv:2208.02740

Collective Effects

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

Model Comparisons



HADES, arXiv:2208.02740

Proton Number Fluctuations

NNLO Volume Corrections

$$
\begin{aligned}
\tilde{\kappa}_1 &= \kappa_1 + \upsilon_2 \kappa_1' \,, \\
\tilde{\kappa}_2 &= \kappa_2 + \kappa_1^2 \upsilon_2 + \kappa_2' \upsilon_2 + 2\kappa_1 \kappa_1' V_2 + 2\kappa_1 \kappa_1' \upsilon_3 + 2\kappa_1'^2 \upsilon_2 V_2 + \kappa_1'^2 V_1 V_2 + 2\kappa_1'^2 V_3 + \kappa_1'^2 \upsilon_4 \,, \\
\tilde{\kappa}_3 &= \kappa_3 + \kappa_1^3 \upsilon_3 + 3\kappa_1 \kappa_2 \upsilon_2 + 3(\kappa_1 \kappa_2' + \kappa_1' \kappa_2)\upsilon_3 + 6\kappa_1'(\kappa_1^2 + \kappa_2')\upsilon_2 V_2 + 3\kappa_1'(\kappa_1^2 + 2\kappa_2')V_3 \\
&\quad + 3\kappa_1'(\kappa_1^2 + \kappa_2')\upsilon_4 + 12\kappa_1\kappa_1'^2 V_2^2 + 3\kappa_1\kappa_1'^2 V_1 V_3 + 24\kappa_1\kappa_1'^2 \upsilon_2 V_3 + 6\kappa_1\kappa_1'^2 V_4 + 3\kappa_1\kappa_1'^2 \upsilon_5 \\
&\quad + 3(\kappa_1\kappa_2' + \kappa_1'\kappa_2)V_2 + 8\kappa_1'^3 \upsilon_2 V_2^2 + 6\kappa_1'^3 V_1 V_2^2 + 10\kappa_1'^3 \upsilon_3 V_3 + \kappa_1'^3 V_1^2 V_3 + 24 V_2 V_3 \kappa_1'^3 \\
&\quad + 3\kappa_1'^3 V_1 V_4 + 12\kappa_1'^3 \upsilon_2 V_4 + 3\kappa_1'^3 V_5 + \kappa_1'^3 \upsilon_6 + 3\kappa_1'\kappa_2' V_1 V_2 + \kappa_3' \upsilon_2 \,, \\
\tilde{\kappa}_4 &= \kappa_4 + \kappa_1^4 \upsilon_4 + 6\kappa_1^2 \kappa_2 \upsilon_3 + (4\kappa_1\kappa_3 + 3\kappa_2^2)\upsilon_2 + 24(\kappa_1^3\kappa_1' + 4\kappa_1\kappa_1'\kappa_2' + 2\kappa_1'^2\kappa_2)\upsilon_2 V_3 \\
&\quad + 4(\kappa_1^3\kappa_1' + 6\kappa_1\kappa_1'\kappa_2' + 3\kappa_1'^2\kappa_2)V_4 + 2(2\kappa_1^3\kappa_1' + 6\kappa_1\kappa_1'\kappa_2' + 3\kappa_1'^2\kappa_2)\upsilon_5 \\
&\quad + 48(\kappa_1^2\kappa_1'^2 + \kappa_1'^2\kappa_2')\upsilon_2 V_2^2 + 12(4\kappa_1^2\kappa_1'^2 + 5\kappa_1'^2\kappa_2')\upsilon_3 V_3 + 72(\kappa_1^2\kappa_1'^2 + 2\kappa_1'^2\kappa_2')V_2 V_3 \\
&\quad + 6(\kappa_1^2\kappa_1'^2 + 3\kappa_1'^2\kappa_2')V_1 V_4 + 72(\kappa_1^2\kappa_1'^2 + \kappa_1'^2\kappa_2')\upsilon_2 V_4 + 6(2\kappa_1^2\kappa_1'^2 + 3\kappa_1'^2\kappa_2')V_5 \\
&\quad + 6(\kappa_1^2\kappa_1'^2 + \kappa_1'^2\kappa_2')\upsilon_6 + 2(6\kappa_1^2\kappa_2' + 12\kappa_1\kappa_1'\kappa_2 + 4\kappa_1'\kappa_3' + 3\kappa_2'^2)\upsilon_2 V_2 \\
&\quad + 2(3\kappa_1^2\kappa_2' + 6\kappa_1\kappa_1'\kappa_2 + 4\kappa_1'\kappa_3' + 3\kappa_2'^2)V_3 + 2(3\kappa_1^2\kappa_2 + 2\kappa_1\kappa_3' + 2\kappa_1'\kappa_3 + 3\kappa_2\kappa_2')\upsilon_3 \\
&\quad + (6\kappa_1^2\kappa_2' + 12\kappa_1\kappa_1'\kappa_2 + 4\kappa_1'\kappa_3' + 3\kappa_2'^2)\upsilon_4 + 96\kappa_1\kappa_1'^3 V_2^3 + 96\kappa_1\kappa_1'^3 V_3^2 + 288\kappa_1\kappa_1'^3 \upsilon_3 V_2^2 \\
&\quad + 72\kappa_1\kappa_1'^3 V_1 V_2 V_3 + 4\kappa_1\kappa_1'^3 V_1^2 V_4 + 144\kappa_1\kappa_1'^3 V_2 V_4 + 128\kappa_1\kappa_1'^3 \upsilon_3 V_4 + 12\kappa_1\kappa_1'^3 V_1 V_5 \\
&\quad + 72\kappa_1\kappa_1'^3 \upsilon_2 V_5 + 12\kappa_1\kappa_1'^3 V_6 + 4\kappa_1\kappa_1'^3 \upsilon_7 + 24(2\kappa_1\kappa_1'\kappa_2' + \kappa_1'^2\kappa_2)V_2^2 + 6(2\kappa_1\kappa_1'\kappa_2' + \kappa_1'^2\kappa_2)V_1 V_3 \\
&\quad + 2(2\kappa_1\kappa_3' + 2\kappa_1'\kappa_3 + 3\kappa_2\kappa_2')V_2 + 48\kappa_1'^4 \upsilon_2 V_2^3 + 48\kappa_1'^4 V_1 V_2^3 + 48\kappa_1'^4 V_1 V_3^2 + 240\kappa_1'^4 \upsilon_2 V_3^2 \\
&\quad + 32\kappa_1'^4 \upsilon_4 V_4 + 288\kappa_1'^4 V_2^2 V_3 + 24\kappa_1'^4 V_1^2 V_2 V_3 + \kappa_1'^4 V_1^3 V_4 + 144\kappa_1'^4 \upsilon_4 V_2^2 + 72\kappa_1'^4 V_1 V_2 V_4 \\
&\quad + 128\kappa_1'^4 V_3 V_4 + 4\kappa_1'^4 V_1^2 V_5 + 72\kappa_1'^4 V_2 V_5 + 56\kappa_1'^4 \upsilon_3 V_5 + 6\kappa_1'^4 V_1 V_6 + 24 V_2 V_6 \kappa_1'^4 \upsilon_2 V_6 + 4\kappa_1'^4 V_7 \\
&\quad + \kappa_1'^4 \upsilon_8 + 36\kappa_1'^2\kappa_2' V_1 V_2^2 + 6\kappa_1'^2\kappa_2' V_1^2 V_3 + 4\kappa_1'\kappa_3' V_1 V_2 + 3\kappa_2'^2 V_1 V_2 + \kappa_4' \upsilon_2 \,.
\end{aligned}
$$

Proton Number Fluctuations

Reduced Proton Cumulants (Fully Corrected)