Hipstars

Collective flow measurements with HADES in Au+Au collisions at 1.23 AGeV

Behruz Kardan

for the
HADES Collaboration

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

HIPSTARS
Workshop on Heavy Ion Physics
and Compact Stars

4th December, 2020

H-QM Helmholtz Research School
Quark Matter Studies

HIC for FAIR
Helmholtz International Center

HADES

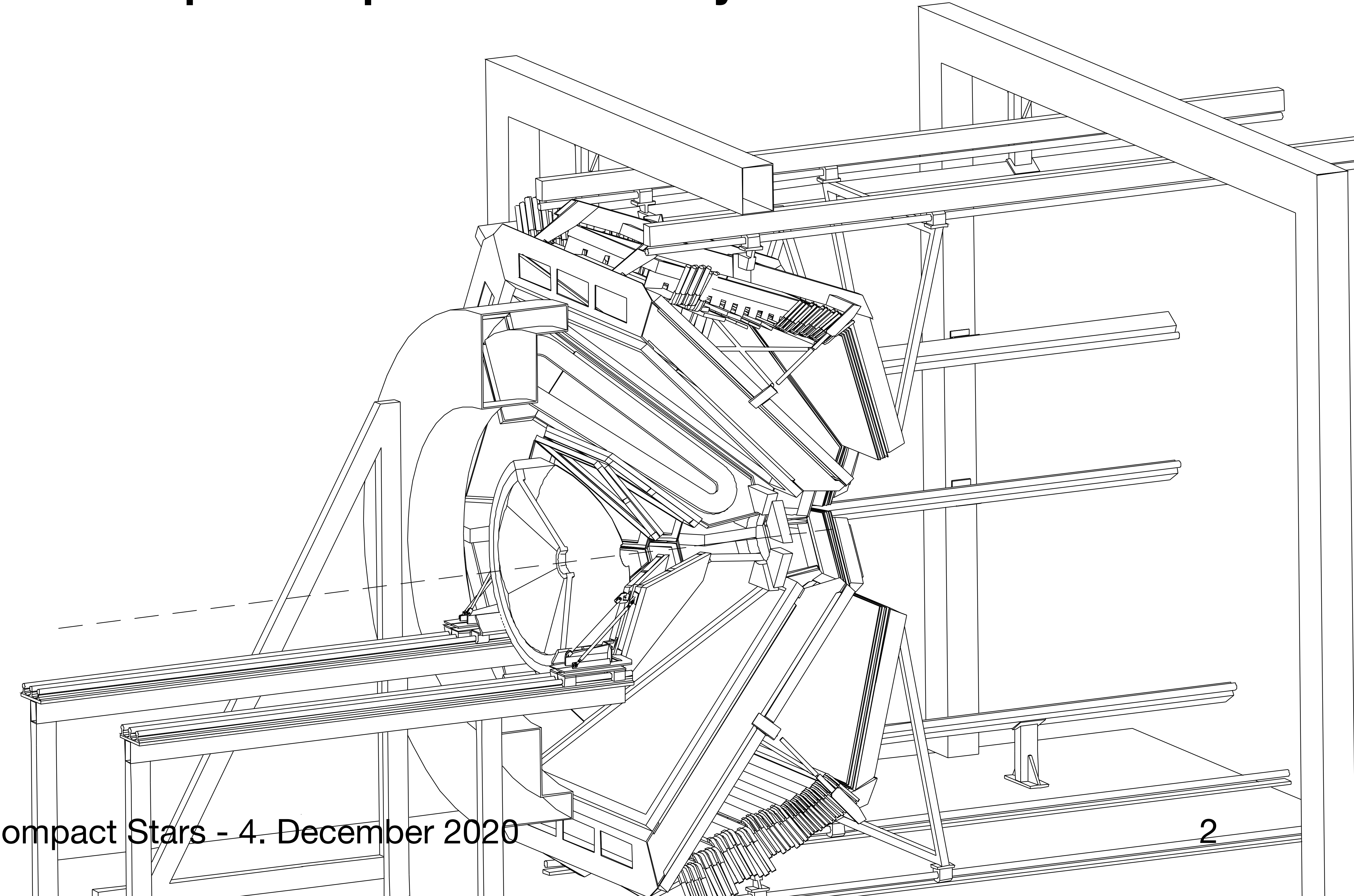
Outline

- Motivation: Properties of Dense Nuclear Matter
  - Macroscopic:
    Equation-of-State or Mean-Field Potentials
  - Microscopic:
    Transport coefficients (shear viscosity)
    or “effective in-medium” cross sections
- HADES and Au+Au data at 1.23 AGeV
- Flow harmonics v_n of order n = 1 - 6
  of protons, deuterons and tritons
- Scaling properties of Flow

Presentation based on following publication:

Directed, elliptic and higher order flow harmonics of protons, deuterons and tritons in Au+Au collisions at $\sqrt{s_{NN}}$=2.4 GeV

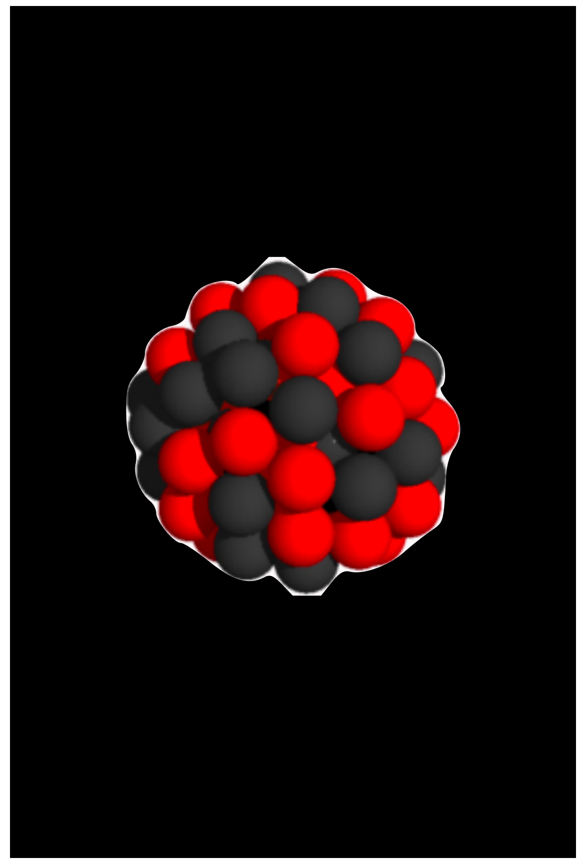
HADES, arXiv:2005.12217 [nucl-ex],
accepted for publication in Phys.Rev.Lett.



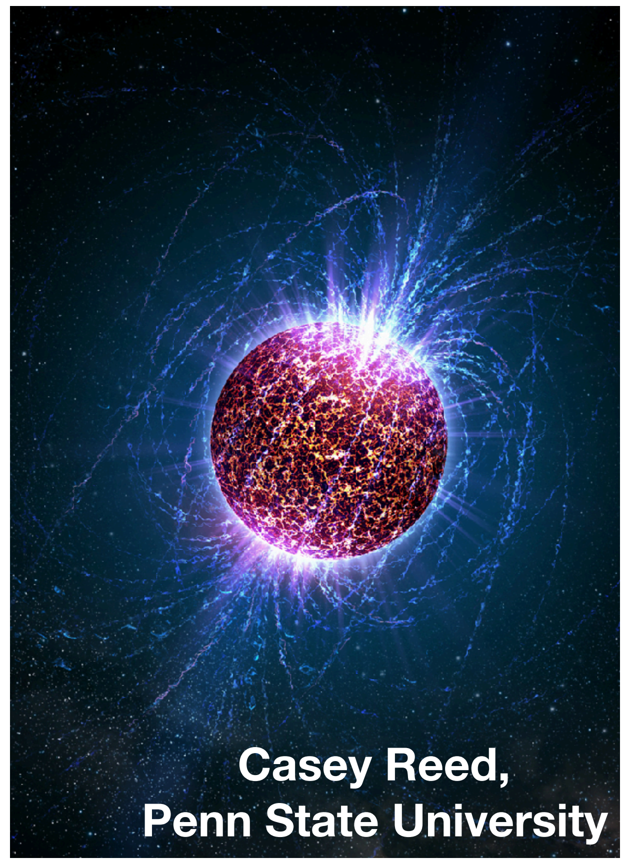
Motivation

Nuclear and Neutron Star Matter

Nuclei



Neutron Star

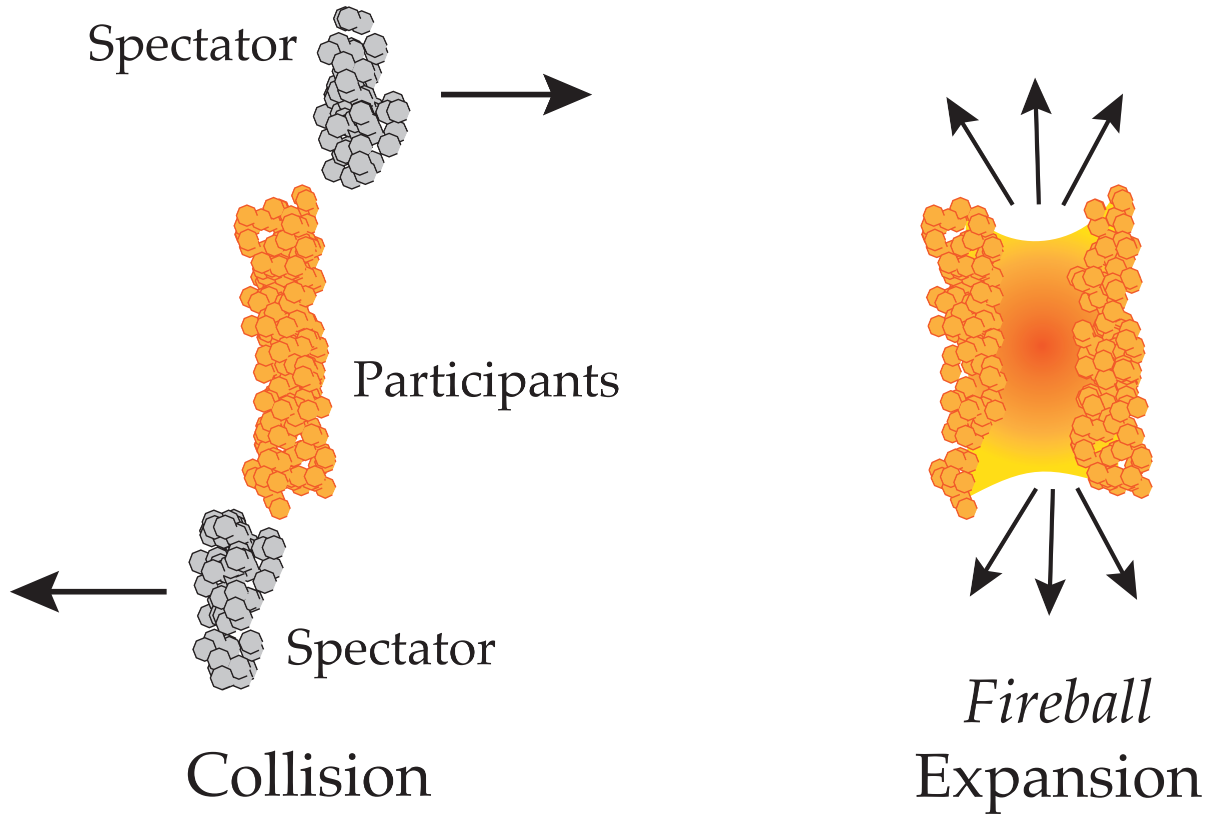


Casey Reed,
Penn State University

Neutron Star Merger

NASA/Swift/Dana Berry,
SkyWorks Digital, Inc.

Heavy Ion Collision

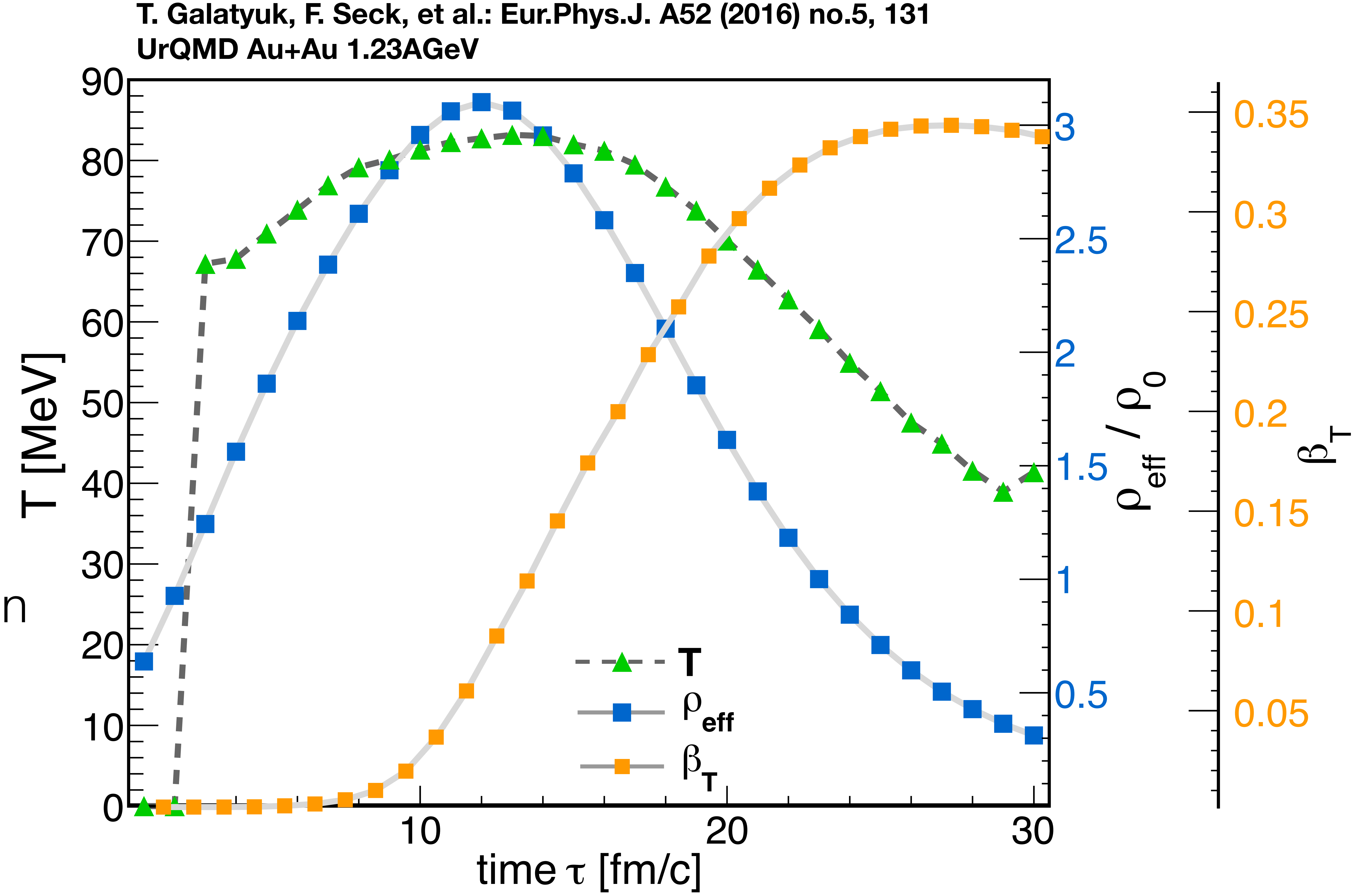


EoS

Motivation

Heavy Ion Collisions at 1.23A GeV

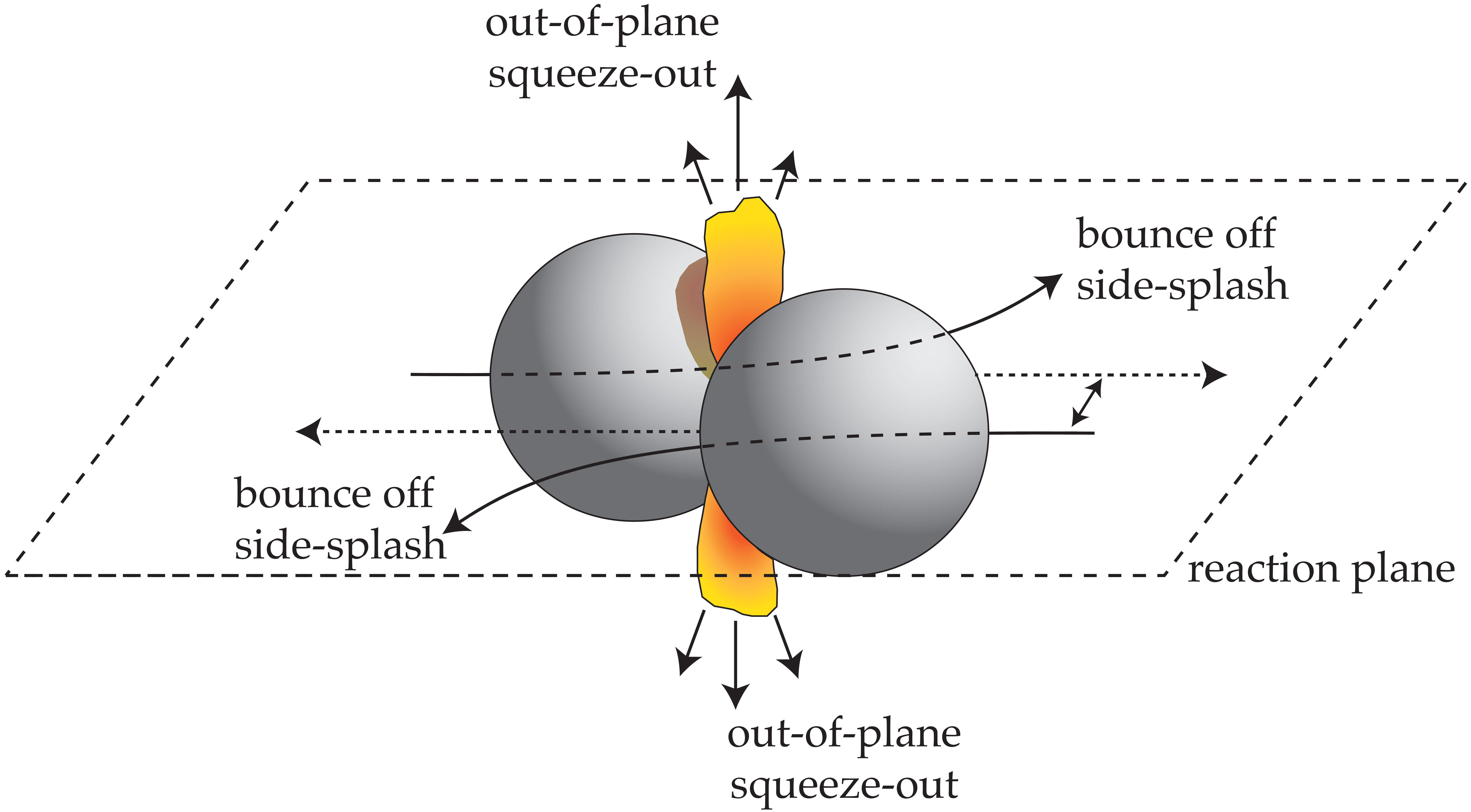
- High densities:
  $\rho_{max} = 1\text{-}3\rho_0$
- Moderate temperatures:
  T = 50-100 MeV
- Relatively long lifetime of fireball
- Significant transverse expansion expected


T. Galatyuk, F. Seck, et al.: Eur.Phys.J. A52 (2016) no.5, 131

UrQMD Au+Au 1.23AGeV

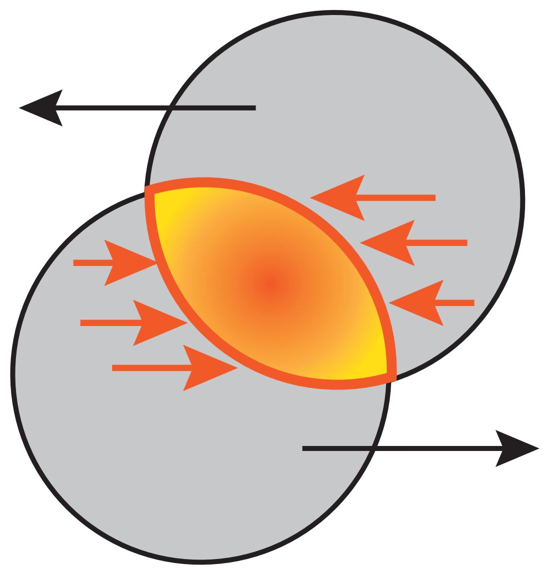
Motivation

Flow

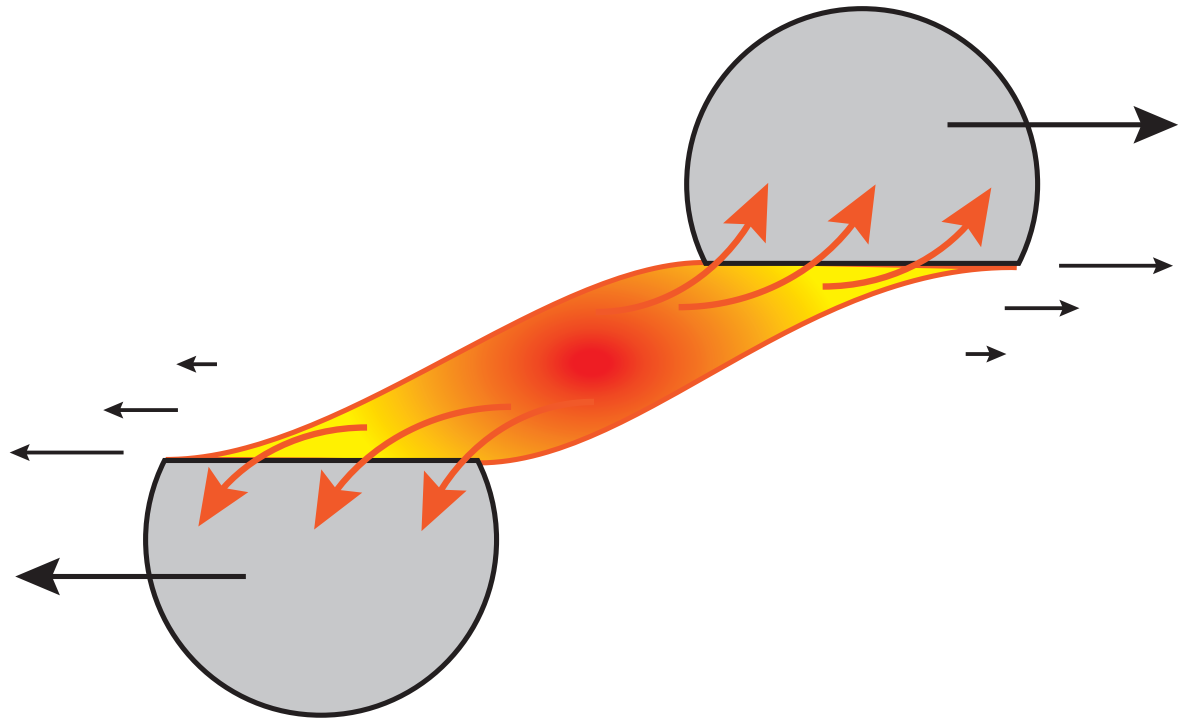


Motivation

Flow Components



top view



directed flow

V1

$$v_1 = \langle \cos(\phi) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

triangular flow

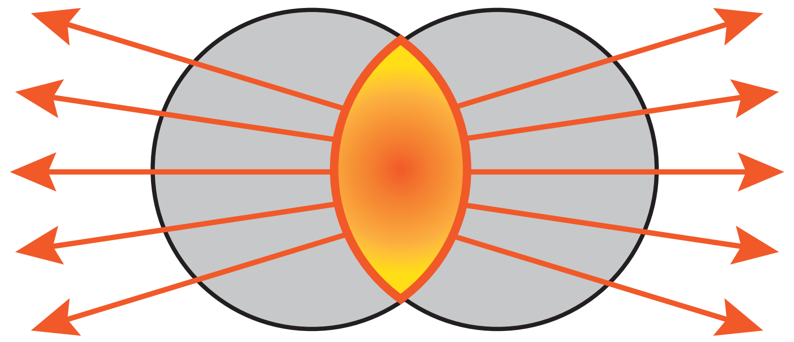
V3

$$v_3 = \langle cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle$$

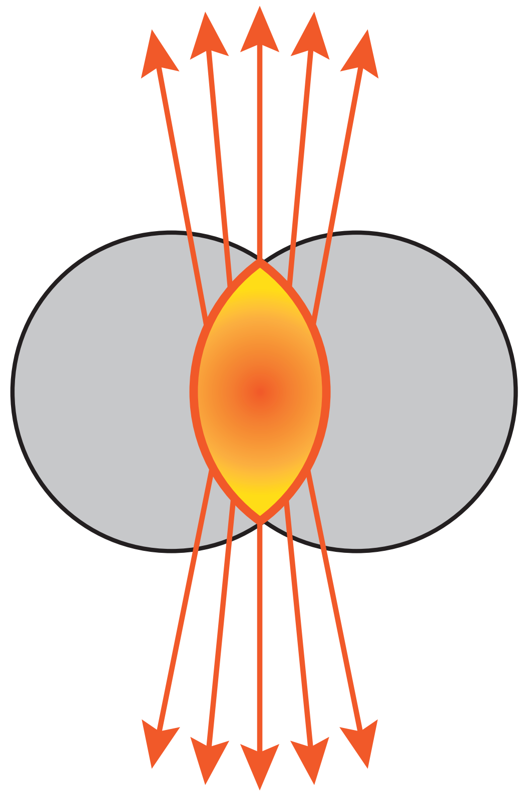
....

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

front view



in-plane



out-of-plane

elliptic flow

V2

$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

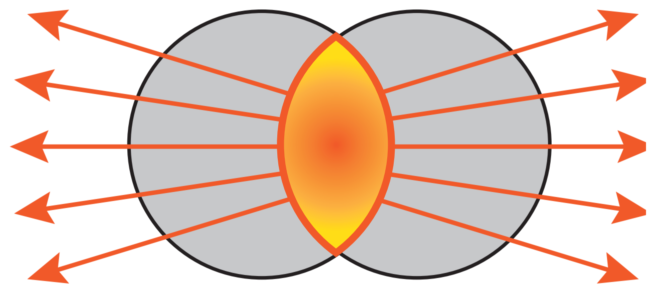
V4

....

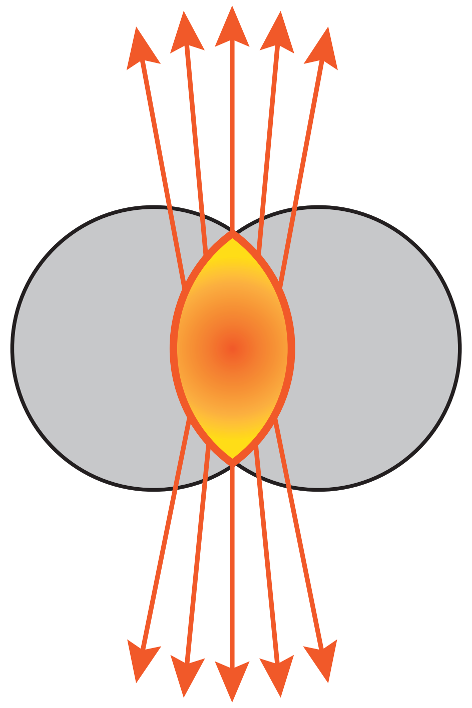
Motivation

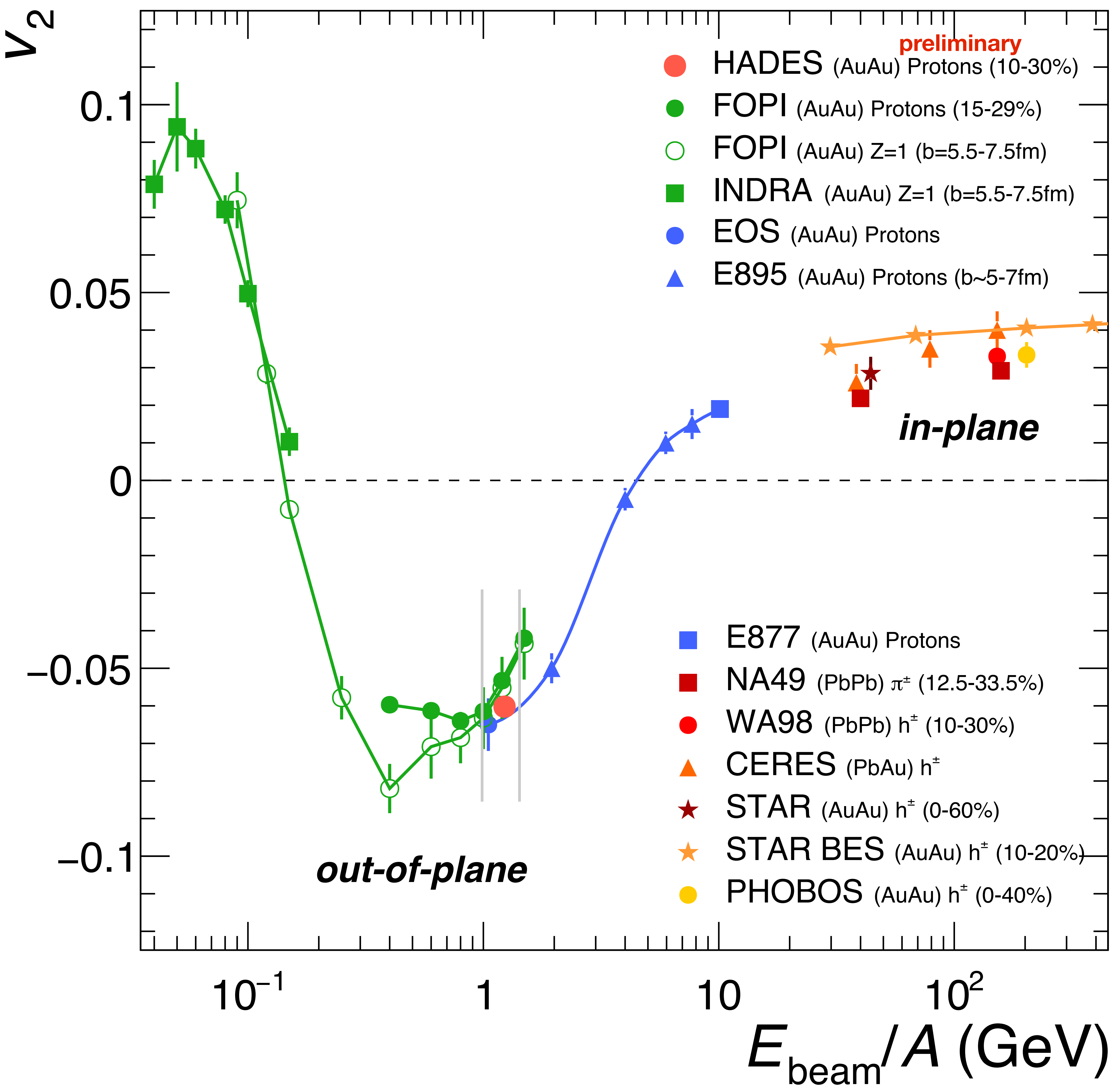
Energy Dependence of Elliptic Flow

- In-plane $v_2>0$
    - Short spectator passing time
      $\tau_{passing} \ll \tau_{expansion}$
    - Pressure gradient



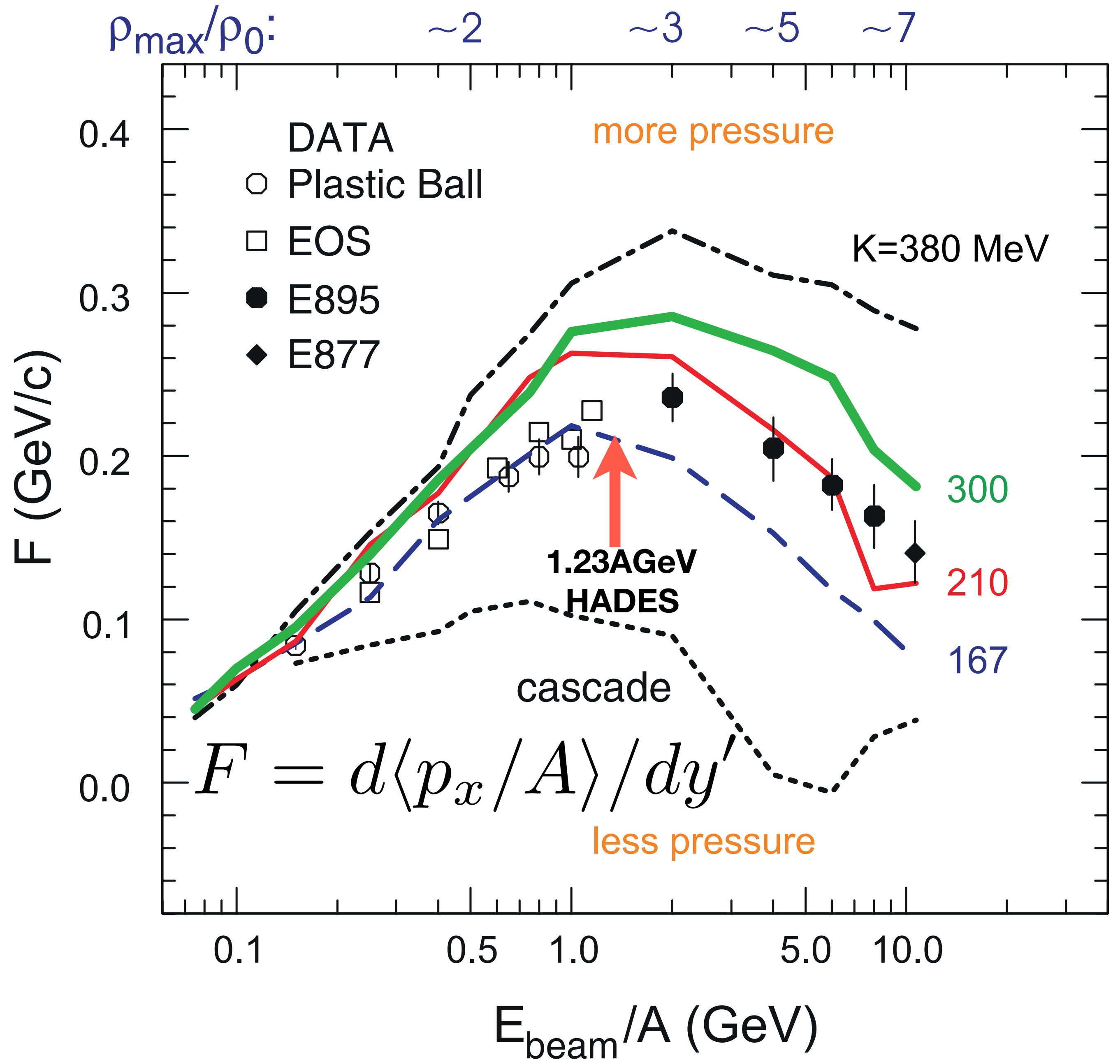
- Out-of-plane $v_2<0$
    - Long spectator passing time
      $\tau_{passing} \geq \tau_{expansion}$
    - Squeeze-out

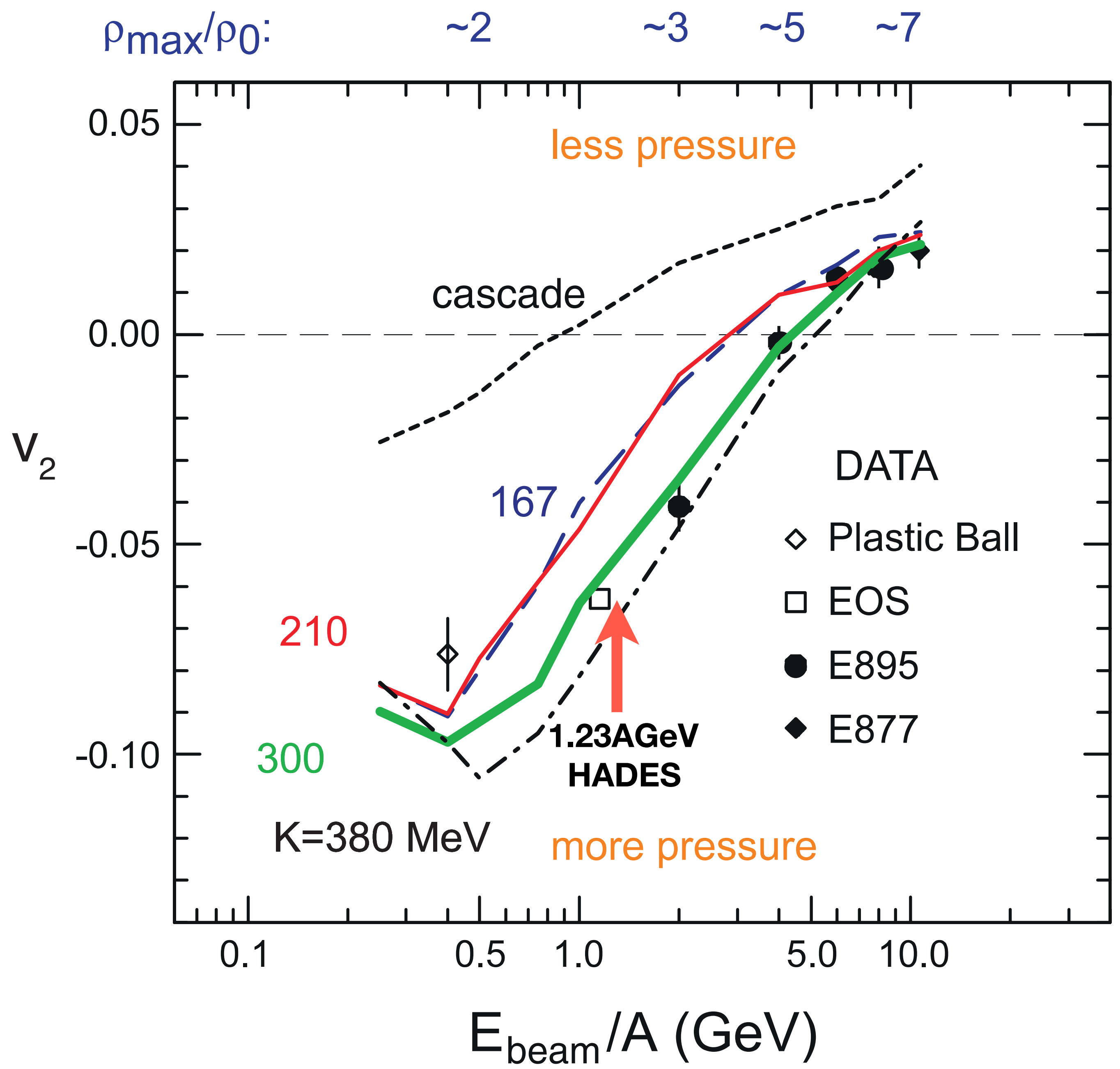




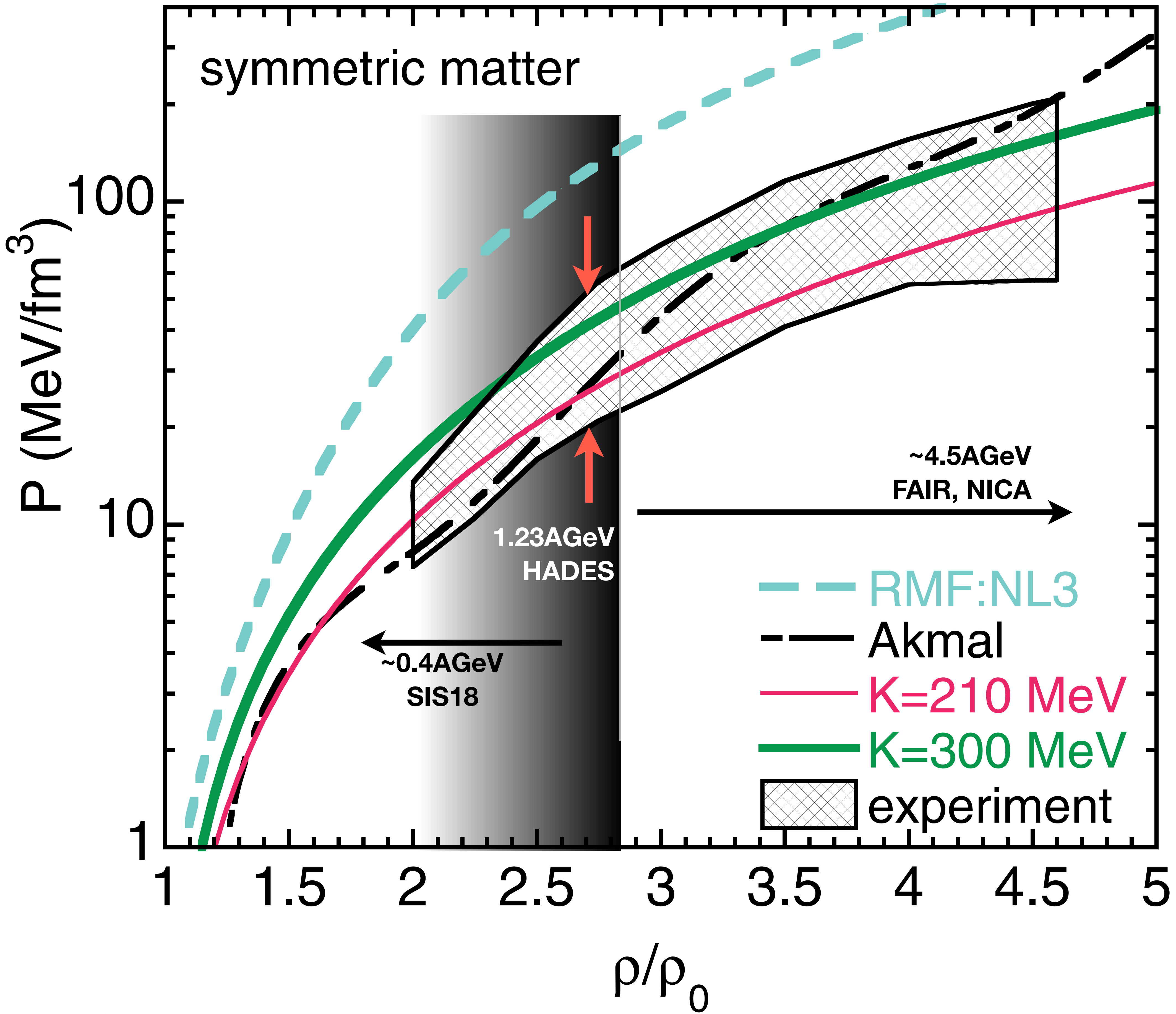
Equation of State of Dense Matter

- EoS is the *equilibrium* property of Hydrodynamical simulations
- *Non-equilibrium dissipative* effects described by transport coefficients (shear viscosity ***η***)
- In microscopic transport models implemented via *averaged mean-field potentials* (Skyrme-like or RMF)





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

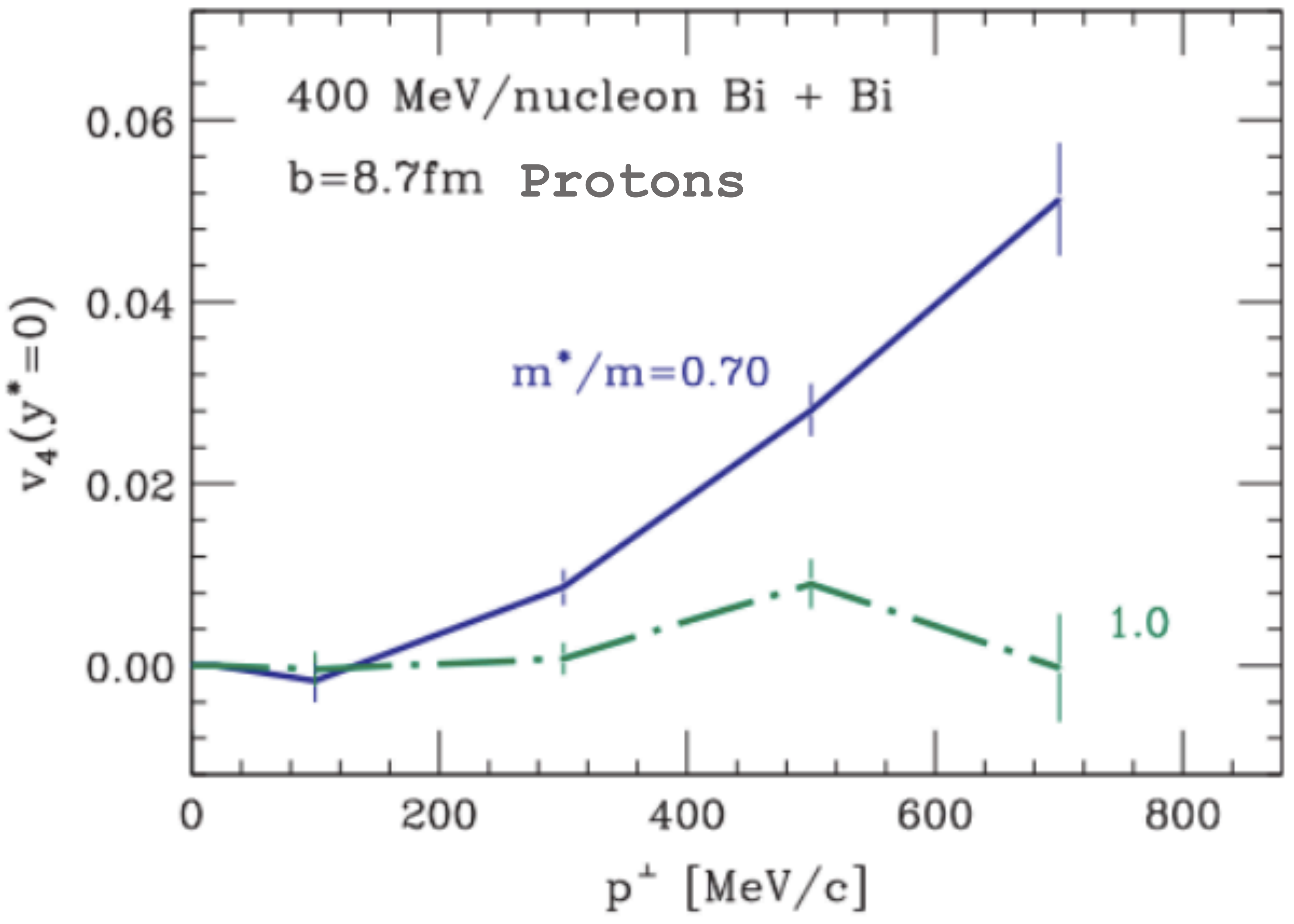


Equation of State of Dense Matter

Momentum Dependence of the mean fields

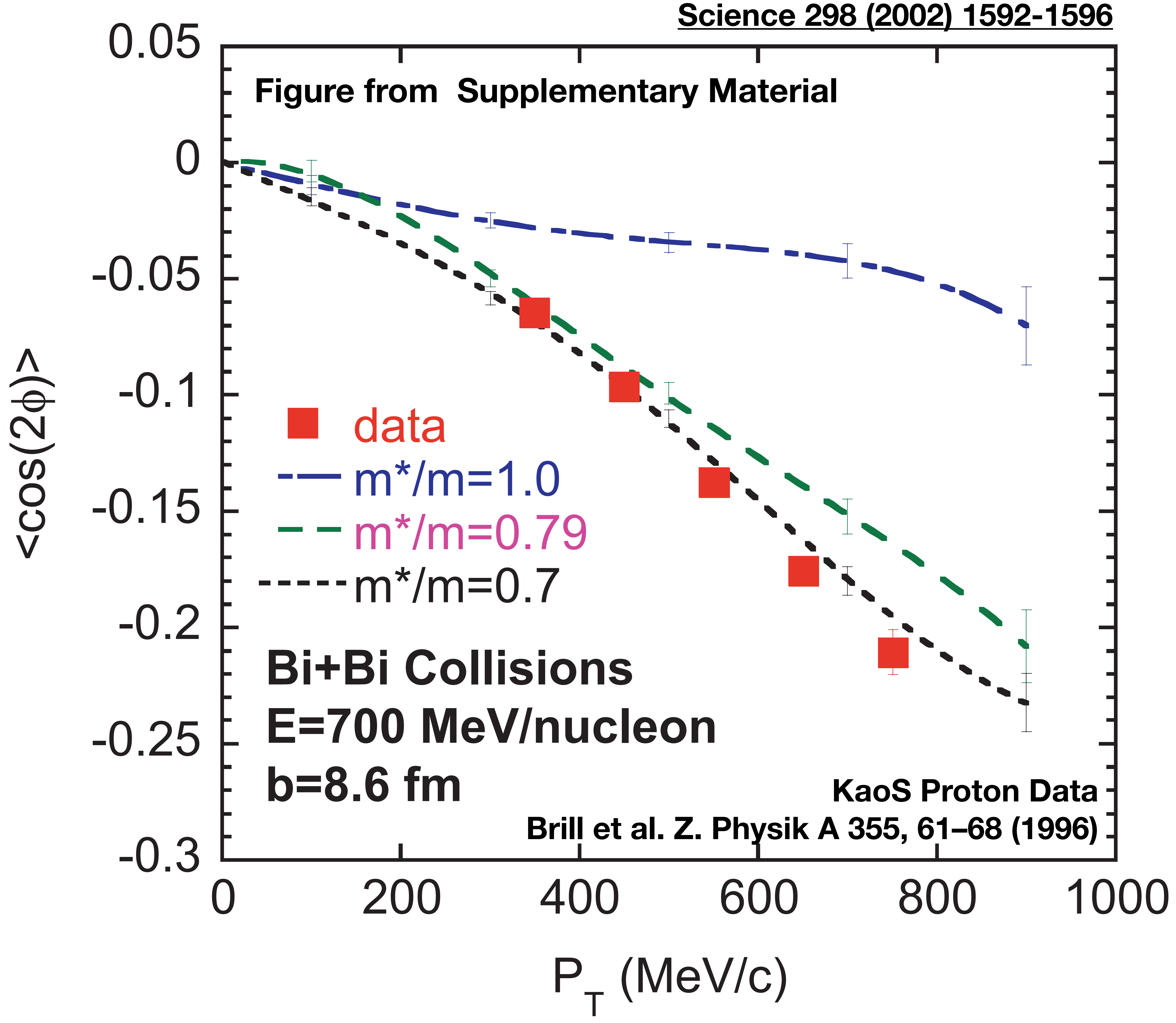
- Momentum dependence characterized by **m^*=0.7m_N**

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



First prediction of v_4{RP} in 2000!

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

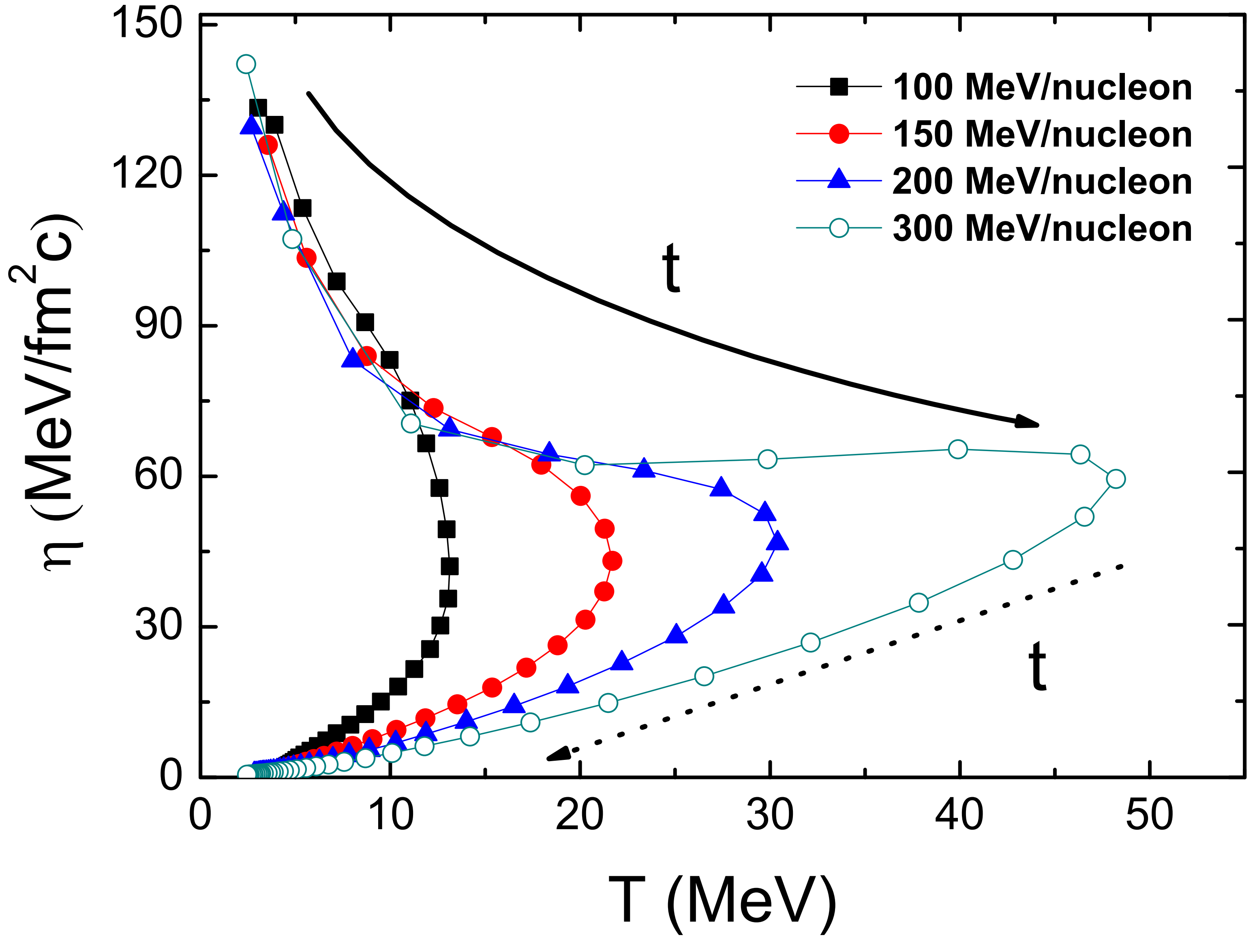


Properties of Dense Nuclear Matter

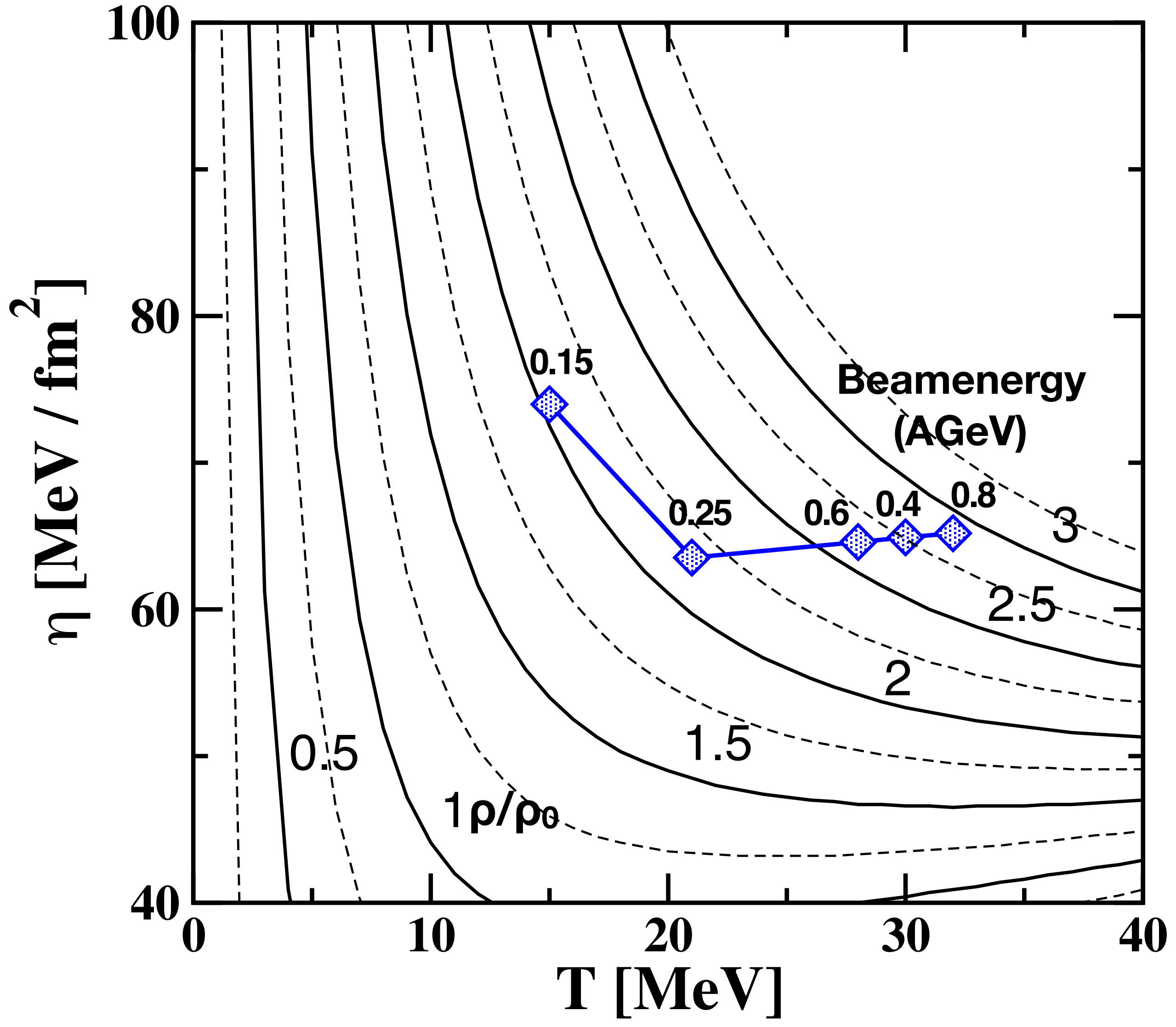
Shear viscosity

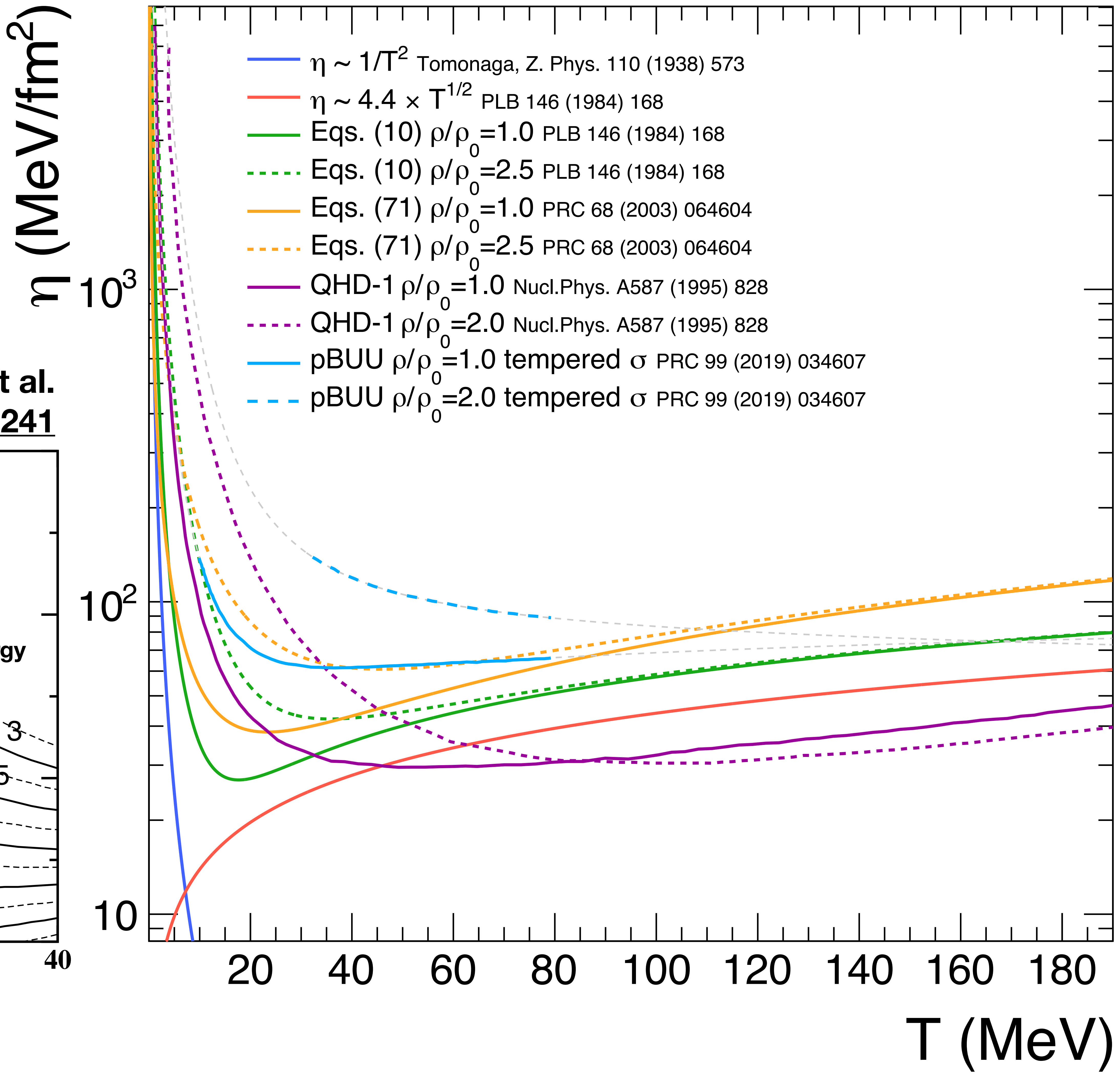
- Nuclear shear viscosity extracted from transport models
- Mean-field potentials and in-medium cross section are constrained by stopping and flow observables

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



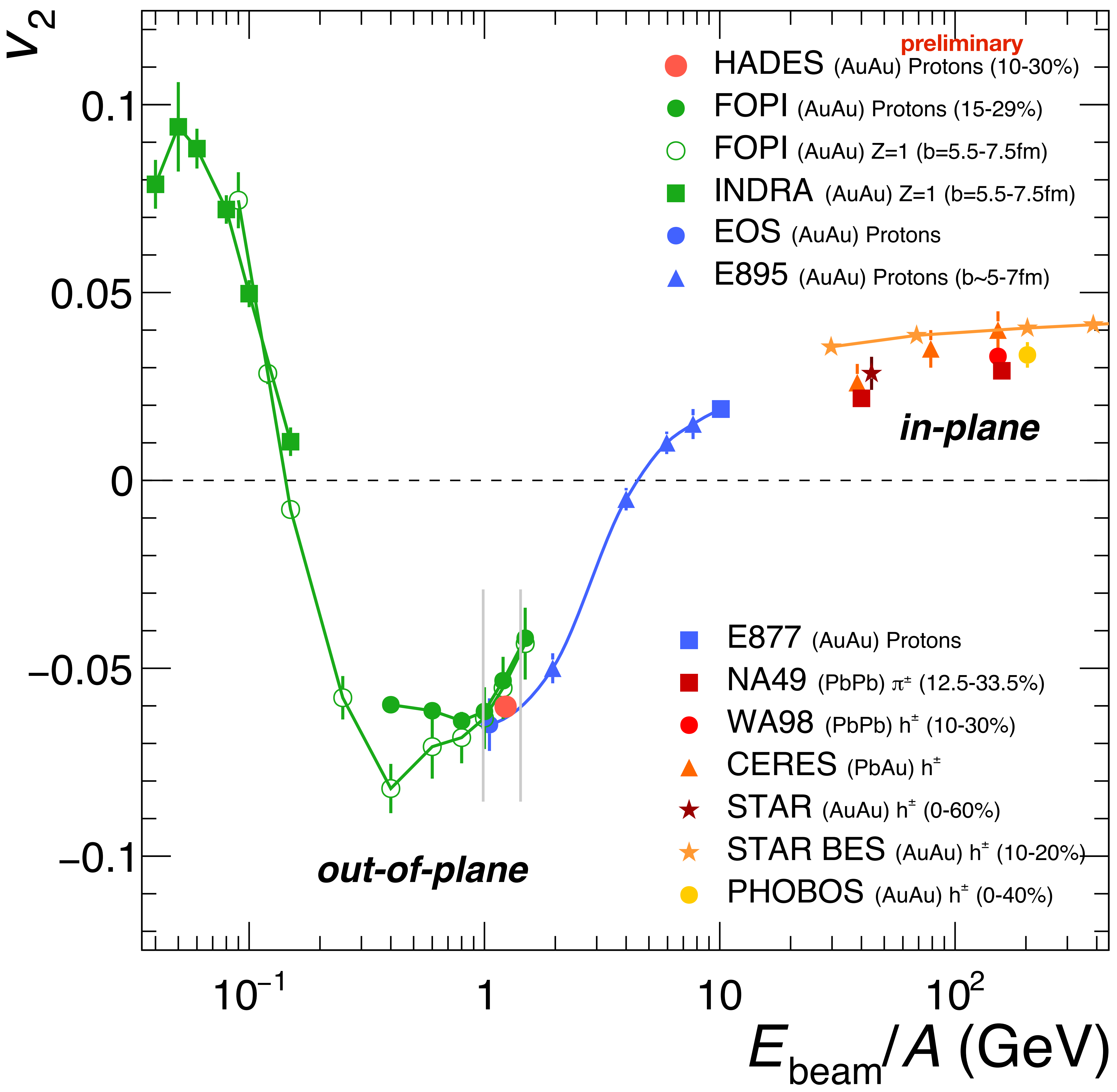
T. Gaitanos et al.
Phys.Lett.B 609 (2005) 241

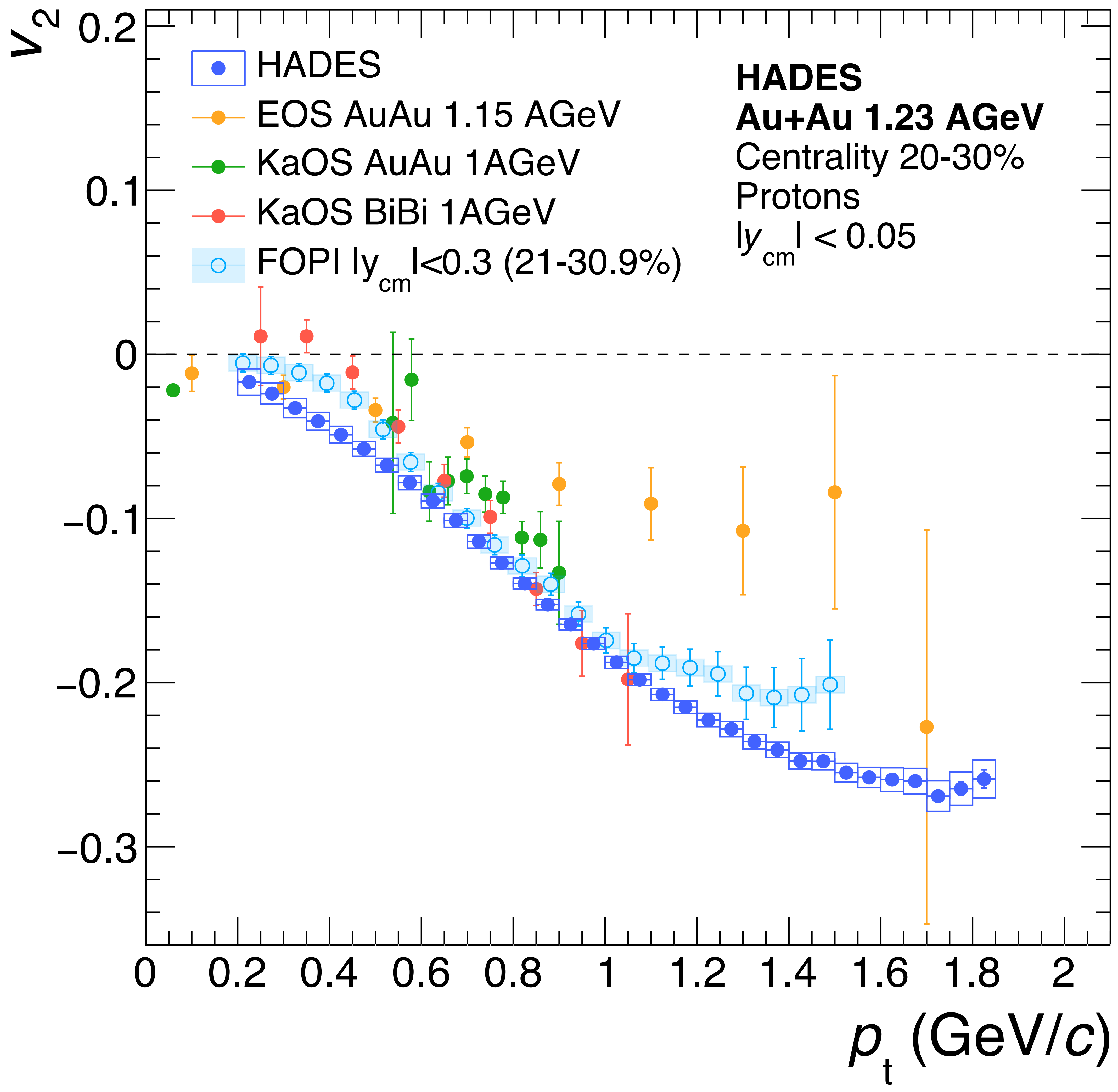




Elliptic Flow v_2

Energy- and p_t-Dependence





EOS:
J. Kintner, Squeeze-Out and Flow of Pions from 1.5 GeV/Nucleon Au+Au. Dissertation, University of California Davis (1993)

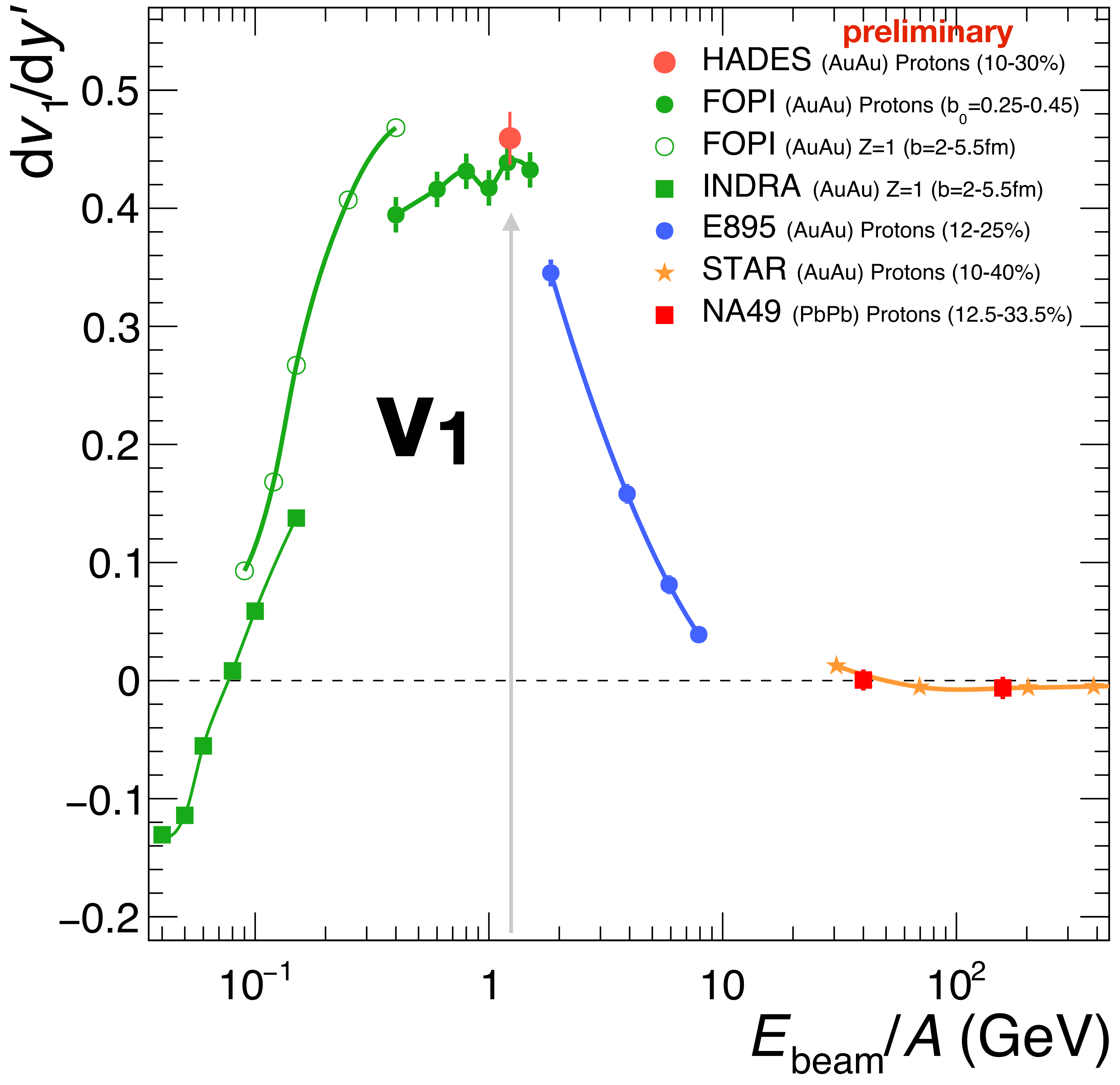
KaoS AuAu:
D. Brill, Azimutal anisotrope Teilchenemission in relativistischen Schwerionenstössen. Dissertation, Goethe-University, 1993

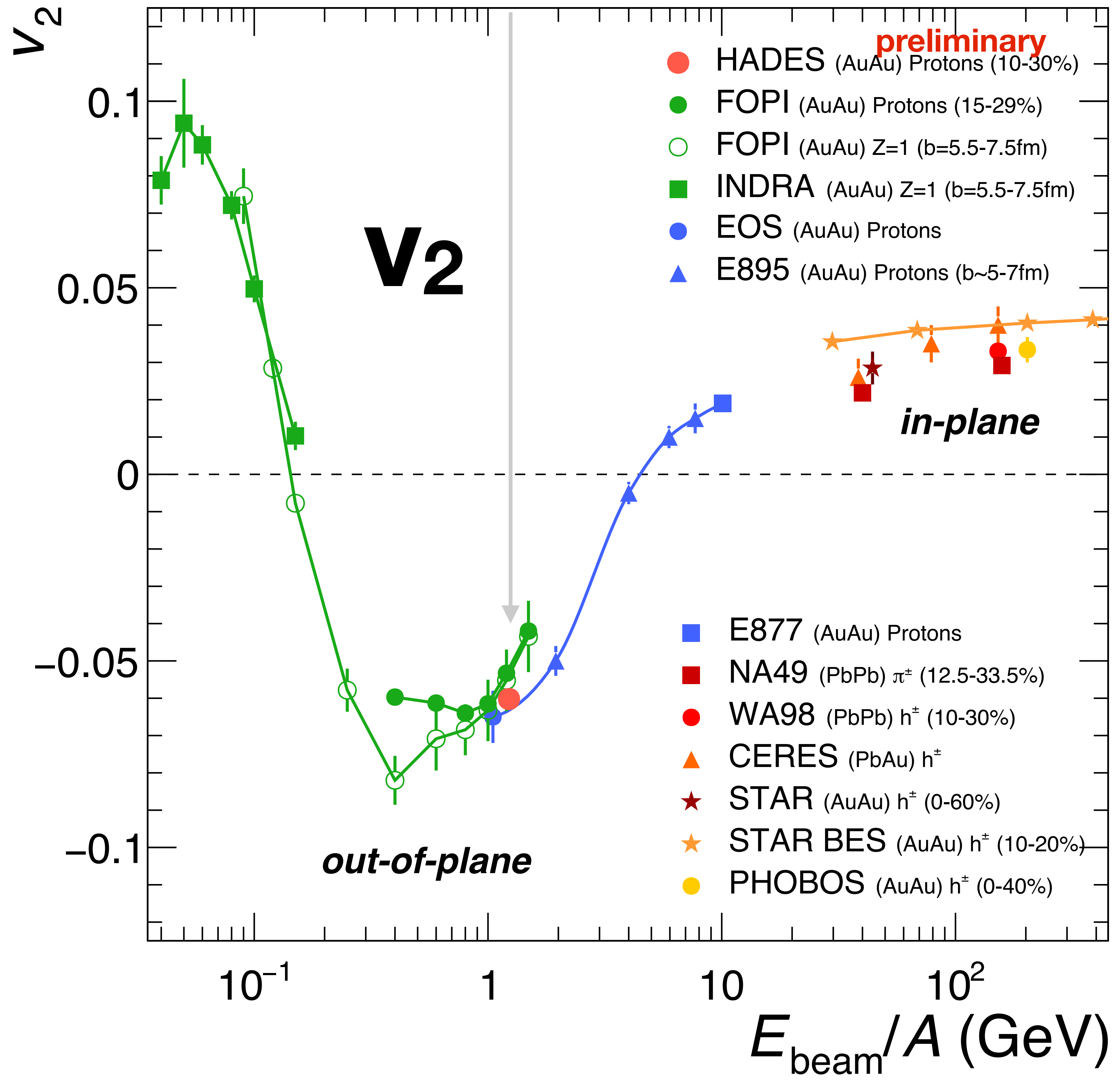
KaoS BiBi:
D. Brill, et al., Z. Phys. A355, 61 (1996).

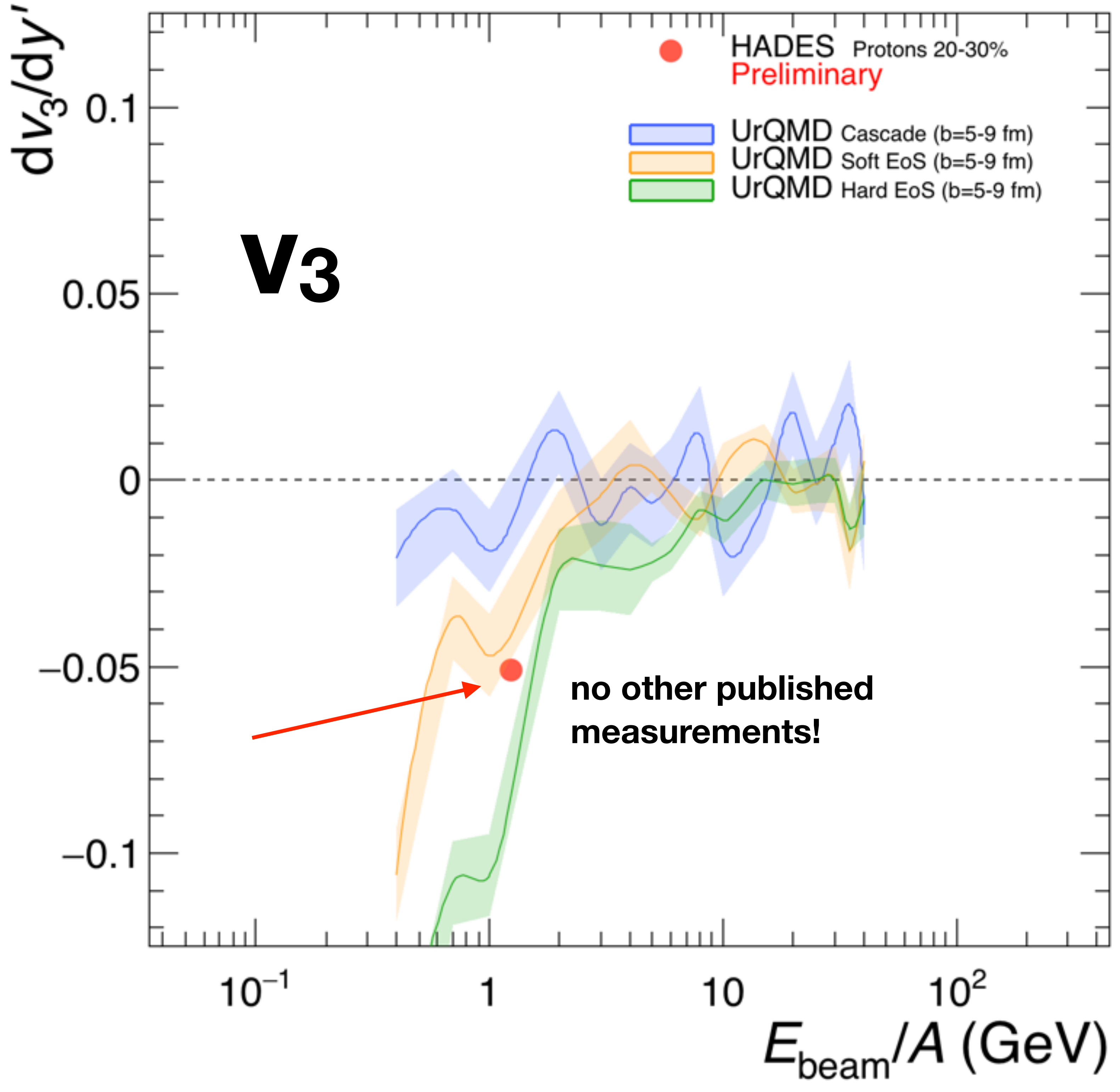
FOPI:
Nucl.Phys. A876 (2012) 1-60

Motivation

Energy Dependence and Systematics of Flow



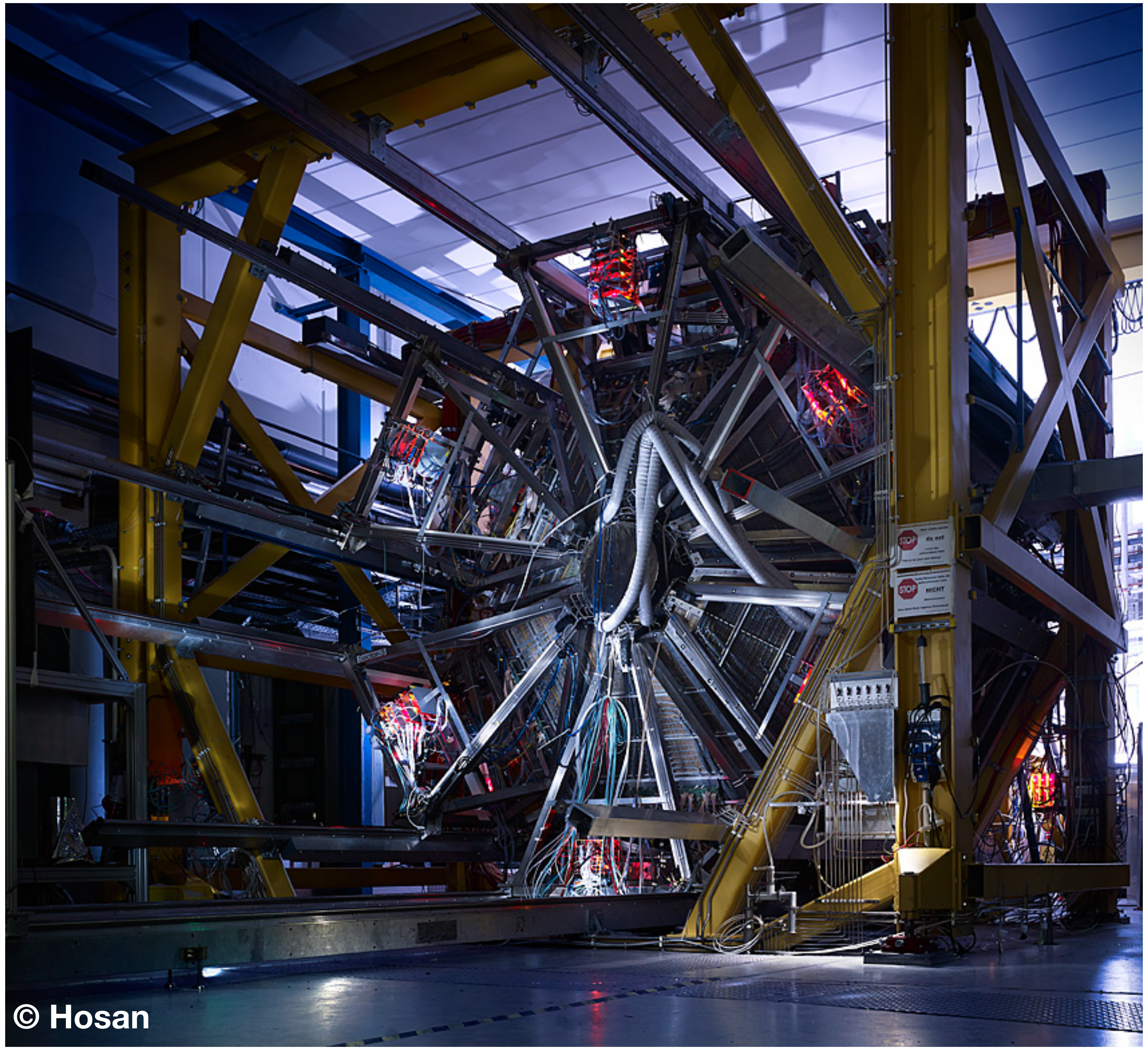




- Fully multi-differential measurement in Centrality and Phase Space (Pt and Rapidity)
  - Directed $v_1\{\Psi_{RP}\}$ and Elliptic $v_2\{\Psi_{RP}\}$
- First measurement at SIS energies of
  - Triangular $v_3\{\Psi_{RP}\}$ and higher flow harmonics

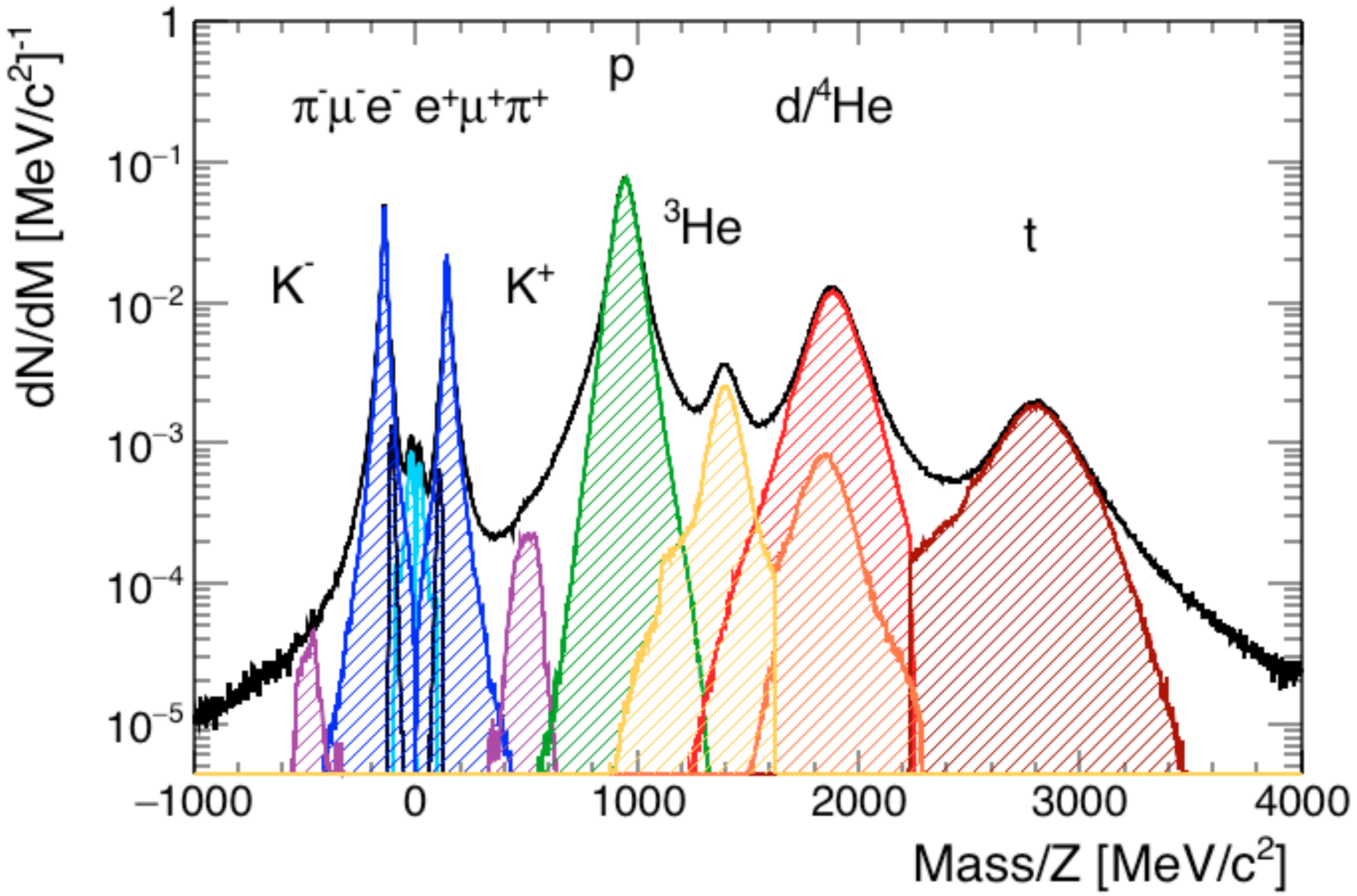
High Acceptance Di-Electron Spectrometer

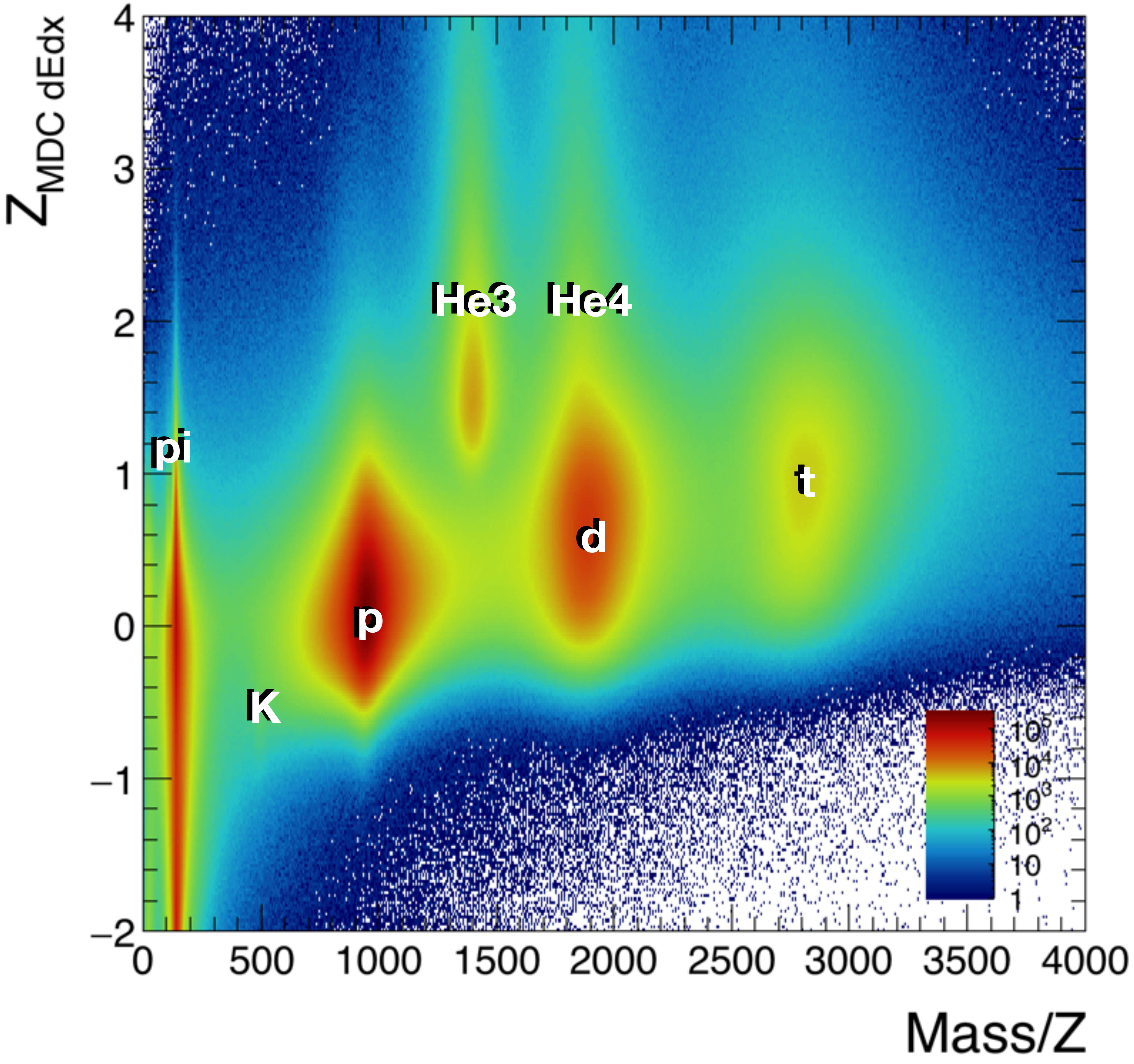
- High interaction rates and statistics
  - 5 weeks of beamtime with 558.3 hours of data taking
  - Beam intensities between 1.2 - 2.2 x 10^6
  - Total number of events recorded: 7 × 10^9
- Large acceptance
  - Symmetric azimuthal coverage
  - 18°-85° in polar angle
- Tracking system and magnetic spectrometer
  - 4 planes of low-mass mini-drift chambers (MDC)
  - Superconducting toroidal magnet
- Forward Wall
  - Reaction plane reconstruction


© Hosan

Particle identification

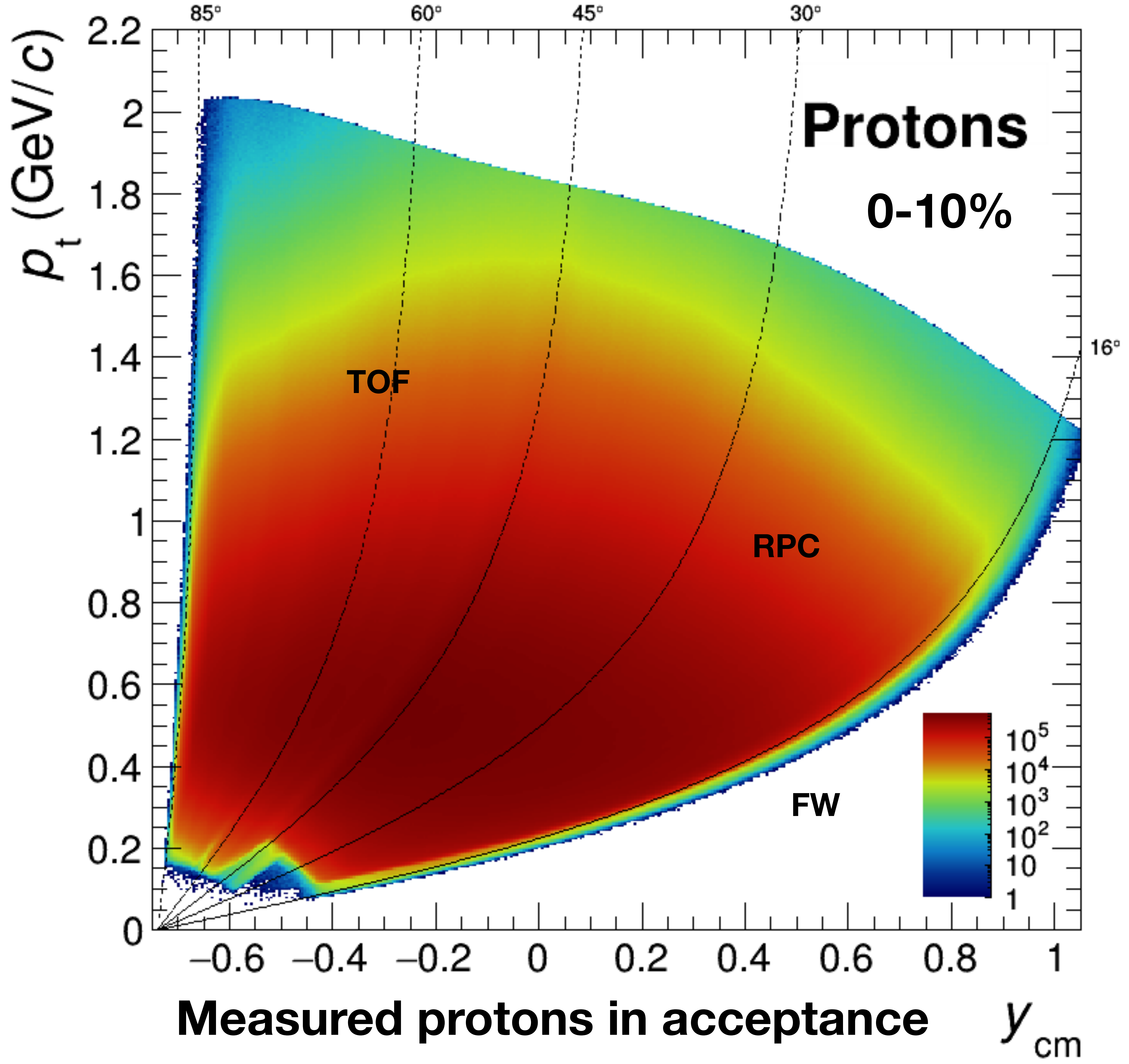
- Time-of-Flight (TOF and RPC)
- Energy loss in the MDC $Z_{MDC} = ln[\frac{(dE/dx)_{measured}}{(dE/dx)_{proton}}]$
  - Separation deuterons and He





HADES Performance

Multidifferential Analysis

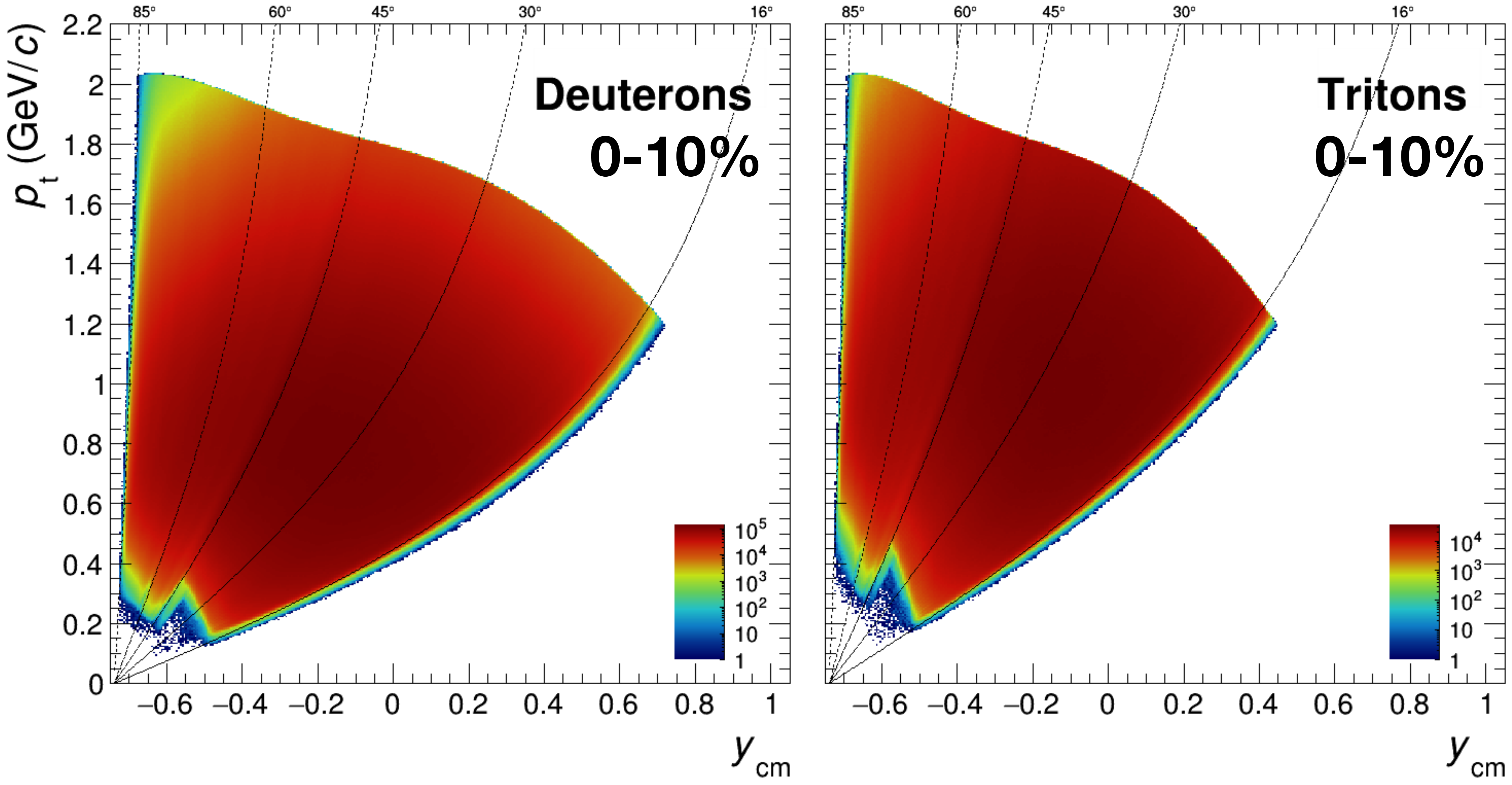


Measured protons in acceptance

4x 10% Centrality Classes
6x Flow Harmonics
Total yield of individual p_t-y bins:

8k protons, 6k deuteron, 5k tritons

with ~20 systematic variations
to estimate uncertainties



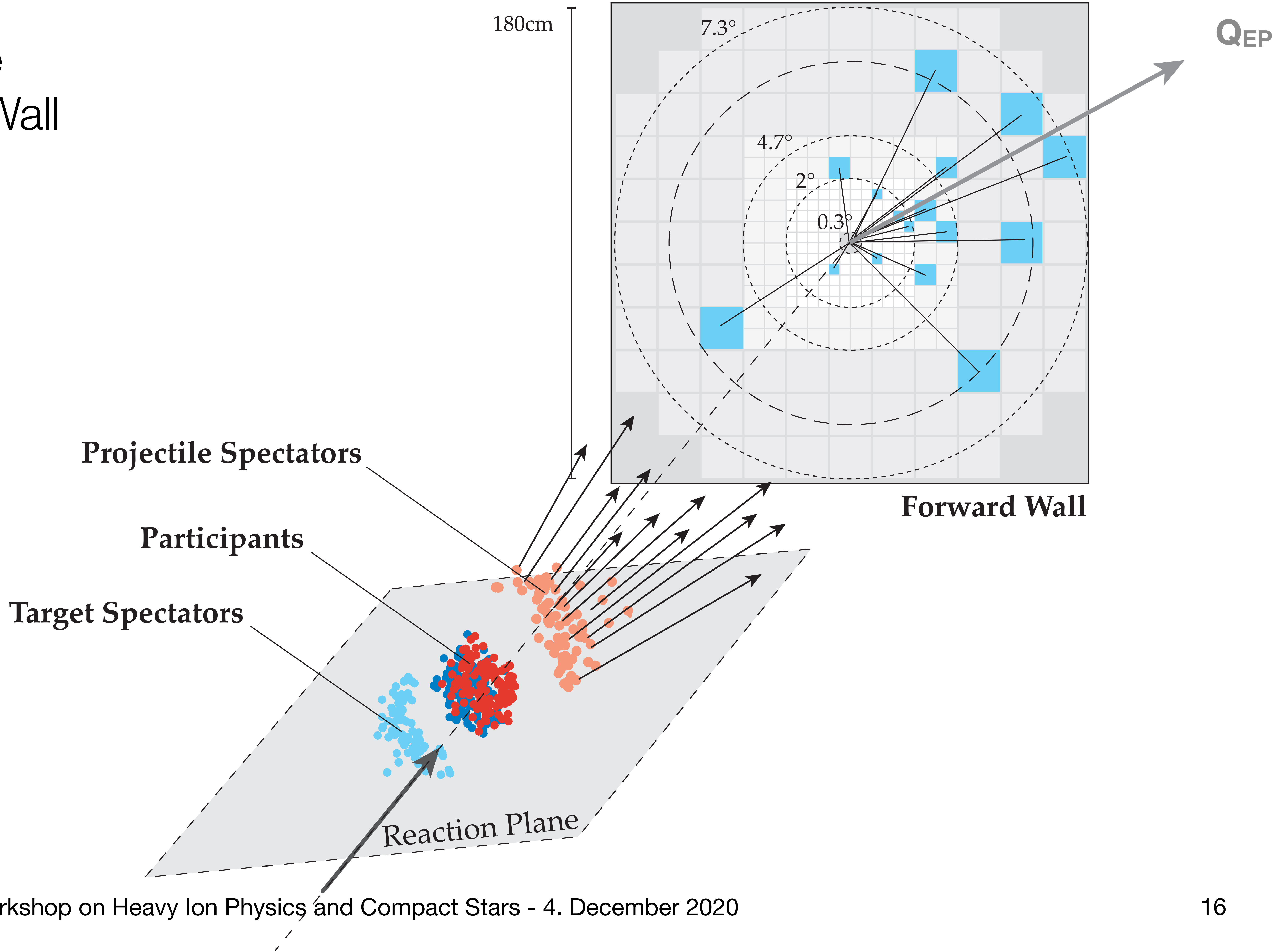
Event Plane Reconstruction

- Based on the angle of projectile spectators hits in the Forward Wall

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

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

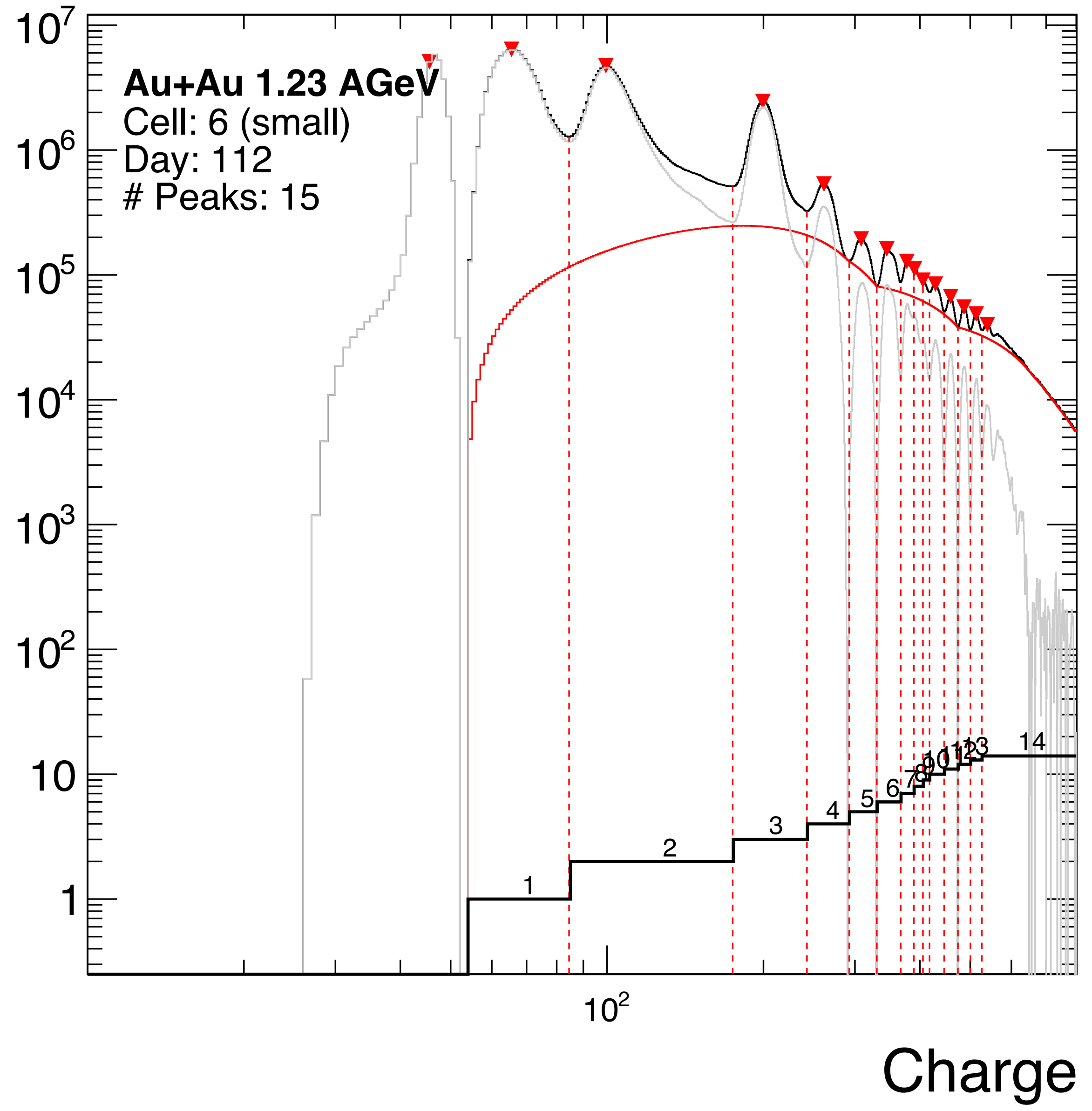
$$\tan\psi_{EP,1} = \frac{Q_{1,y}}{Q_{1,x}}$$



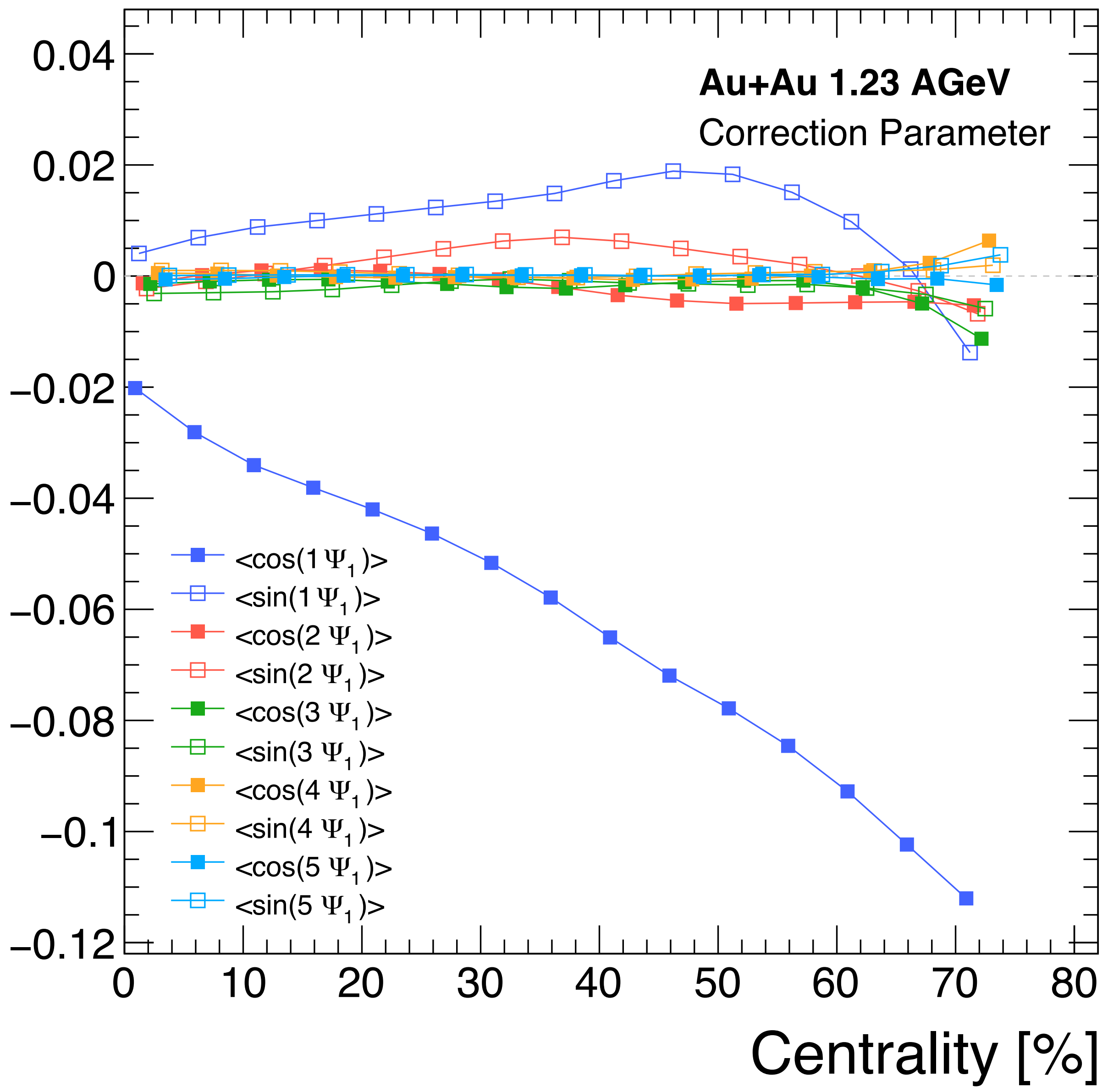
Event Plane Determination

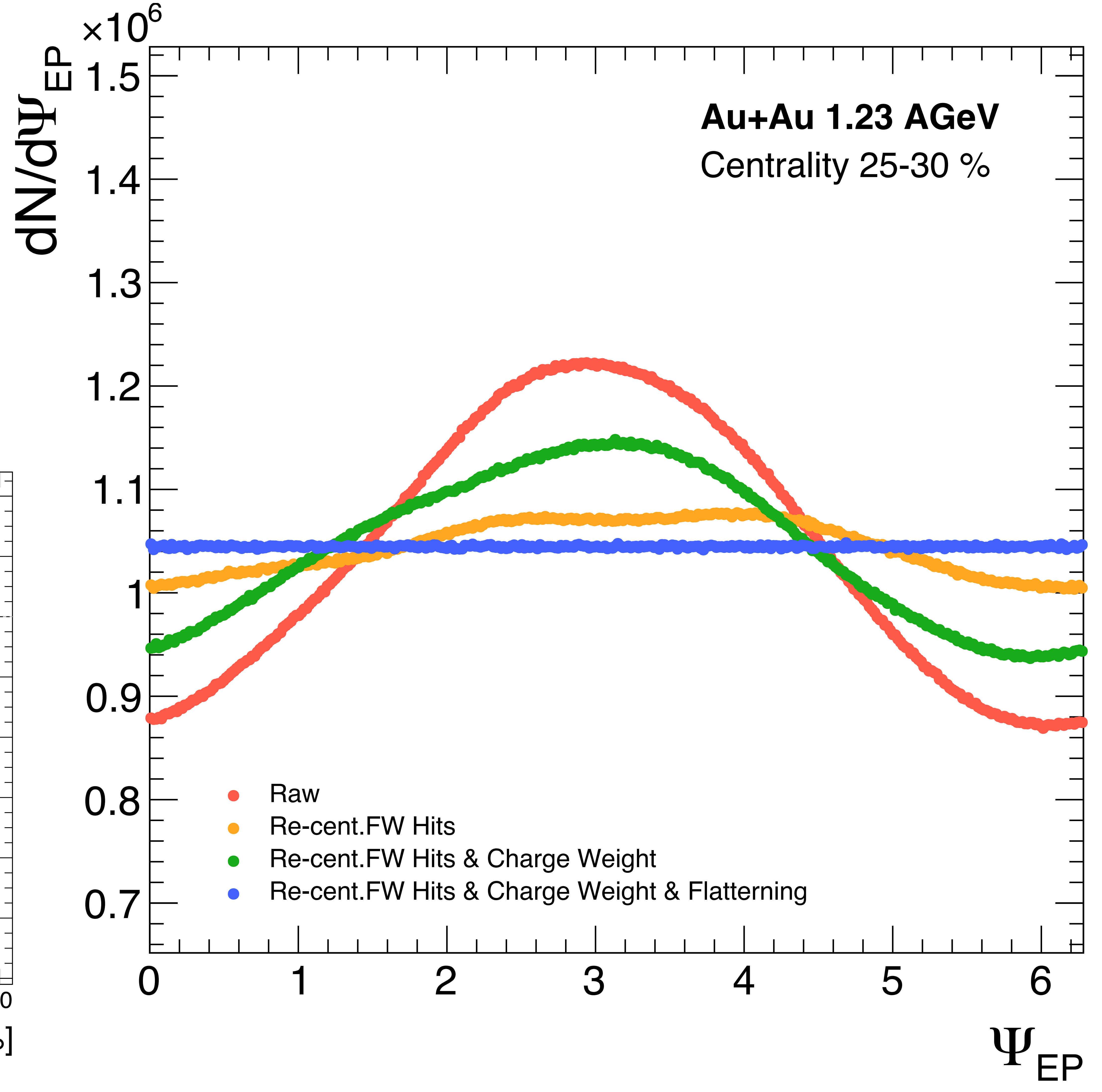
- Re-Centering of X and Y of all FW hits (day-by-day and Centrality)
- Z-Weighting up to Charge 14
- Flattening of residual Fourier components with 8x Cos- and 8x Sin-Terms

Charge Weighting



Flattening Parameter



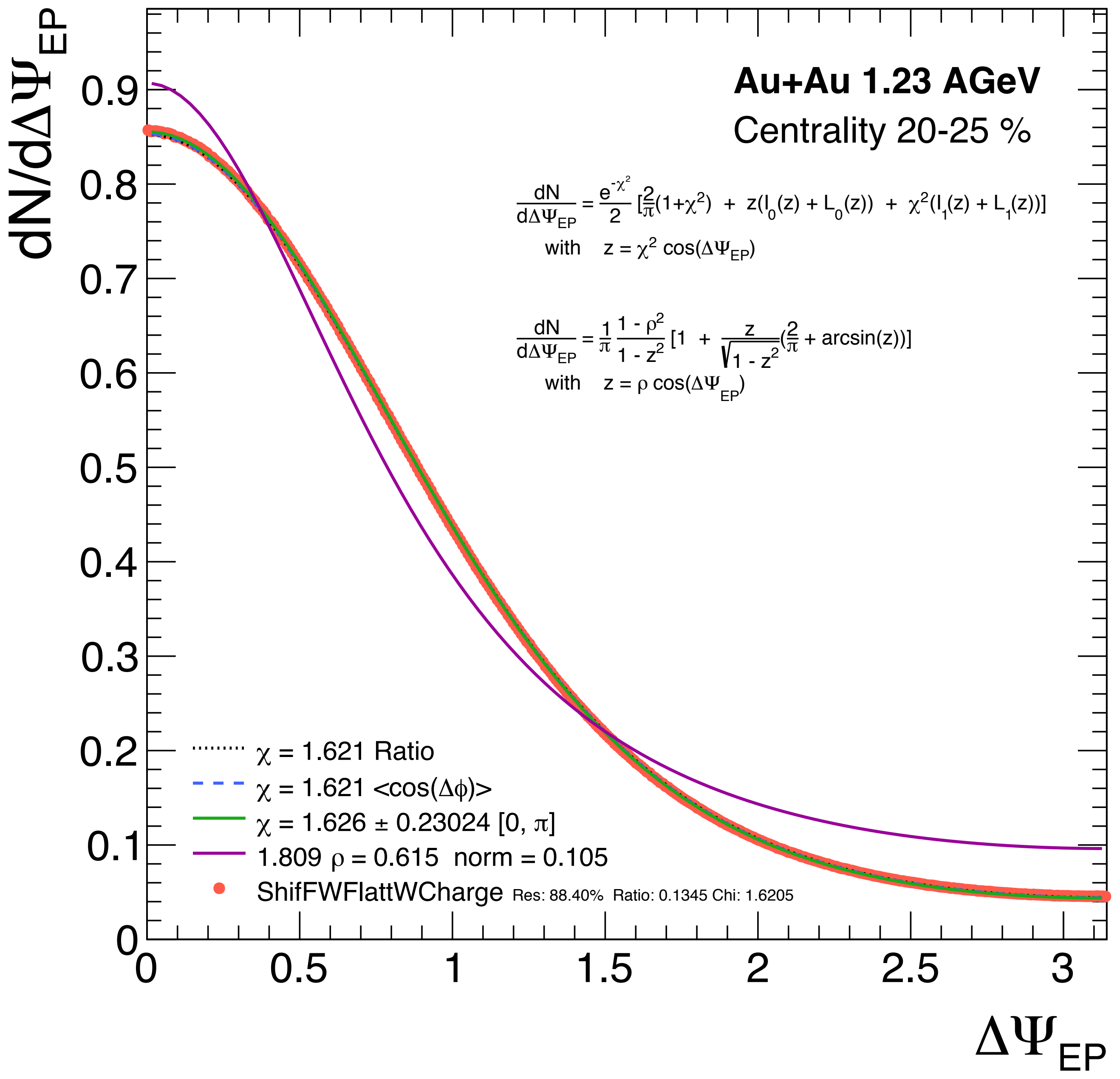


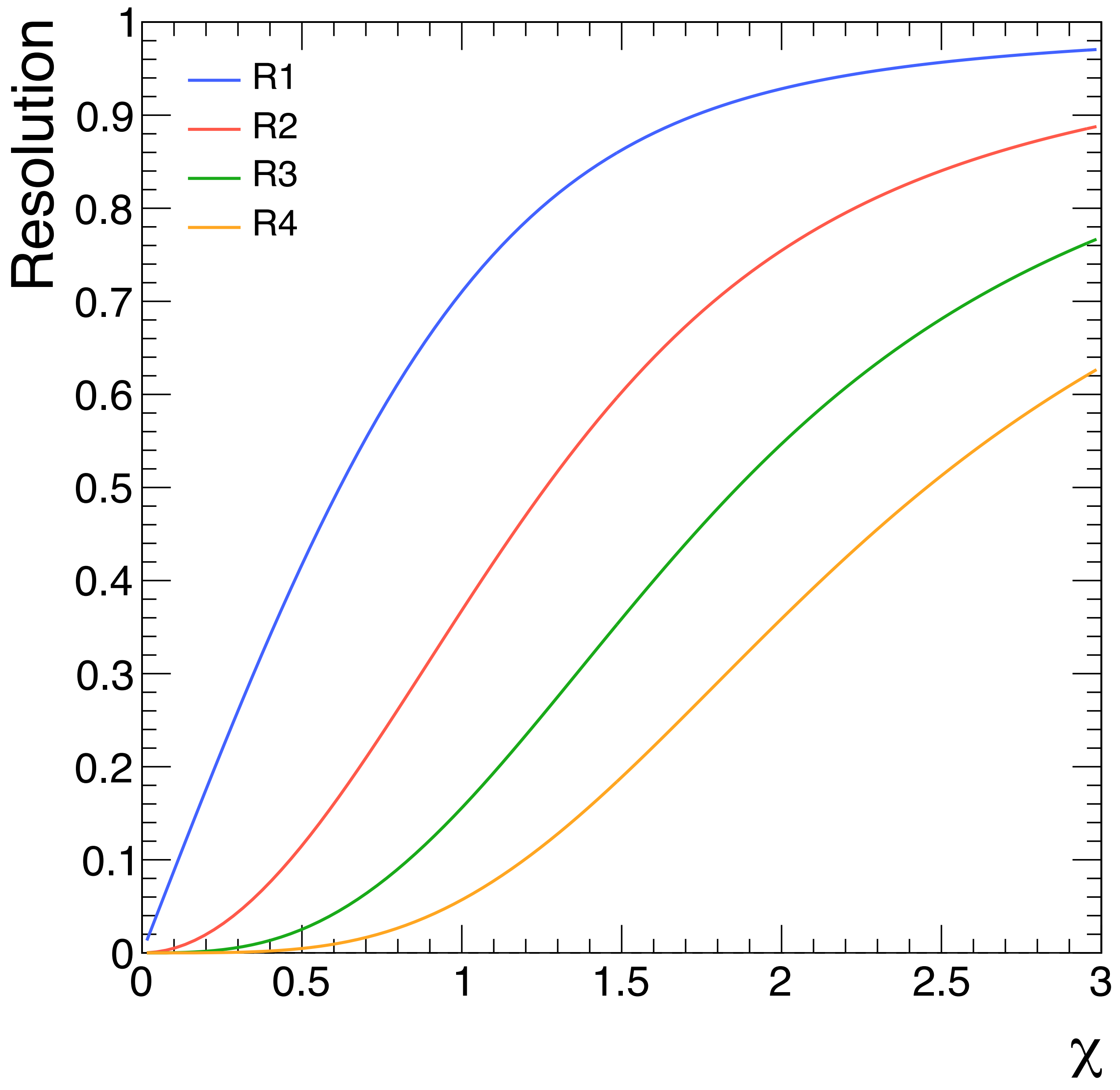
Event Plane Resolution

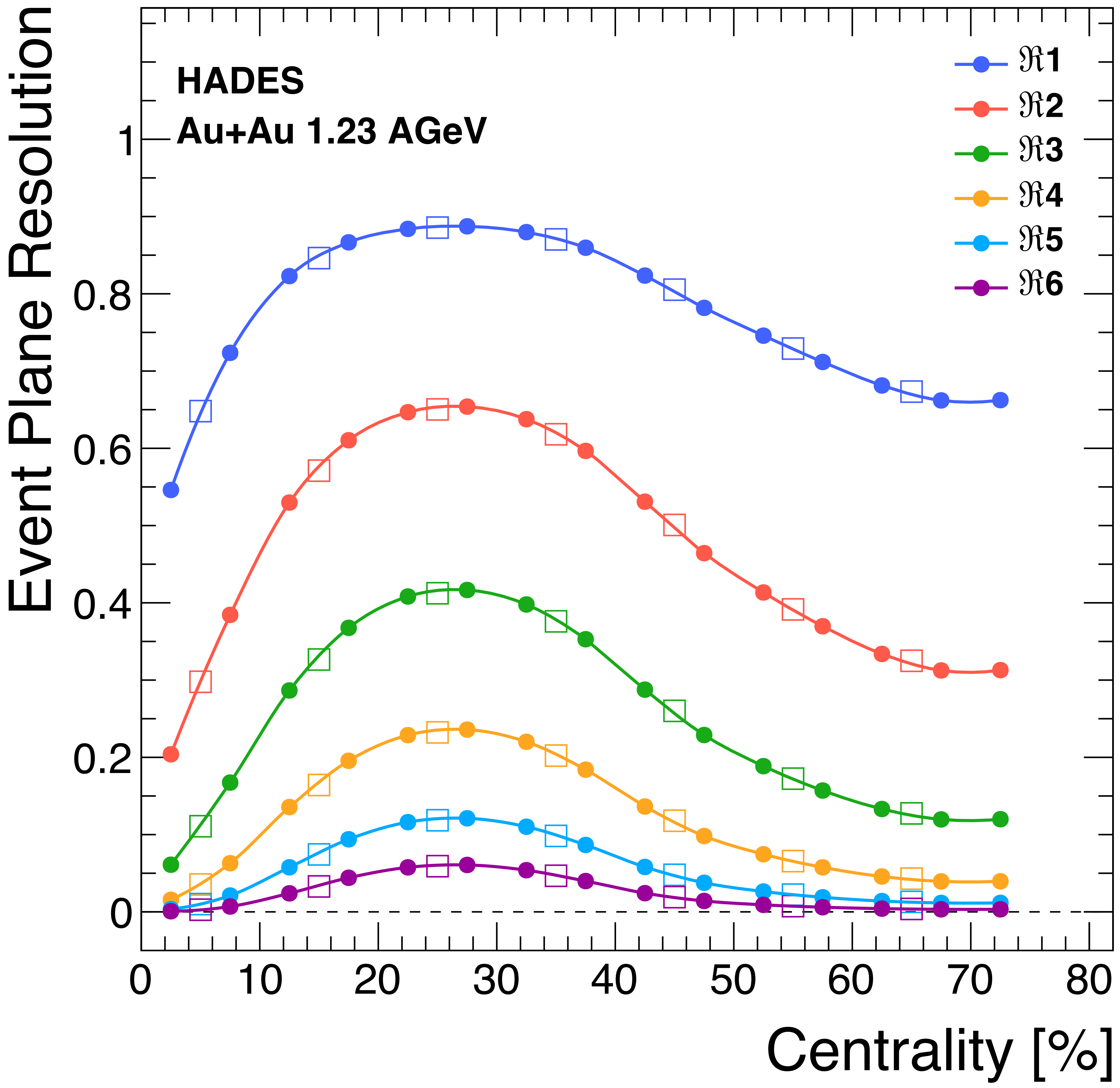
- EP-Resolution determined by Ratio-, <cos (ΔΦ)> and Fit-Method in Sub-Events

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

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





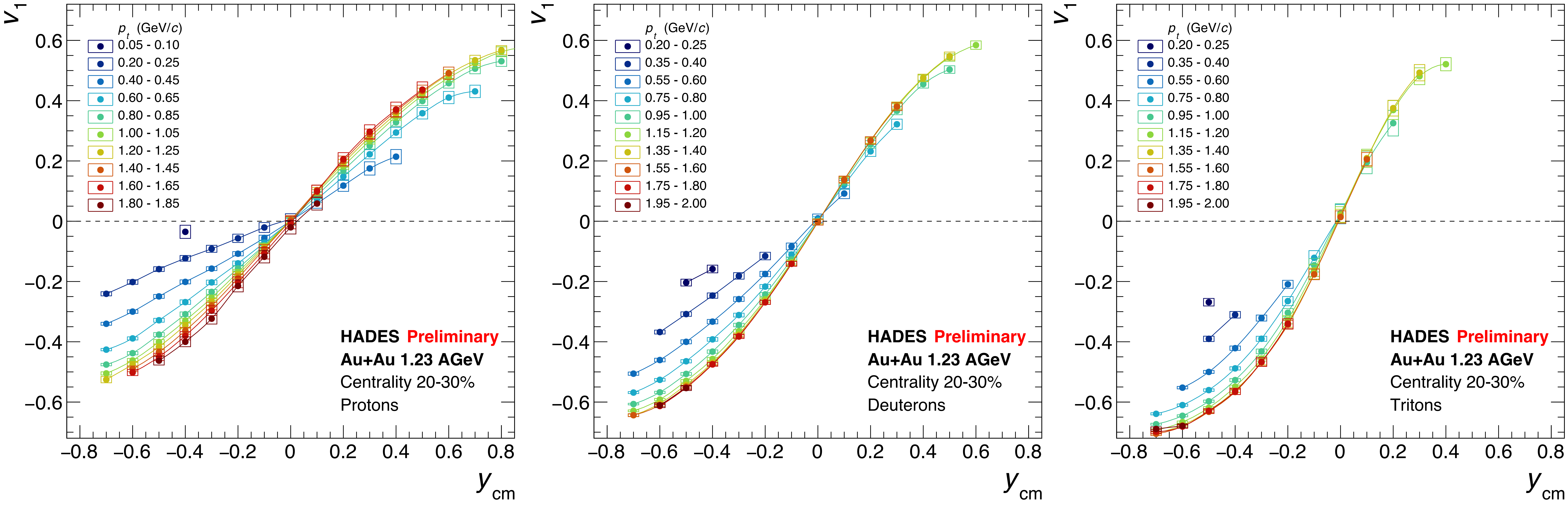


Directed Flow v_1: Protons and Light Nuclei

p_t-Dependence

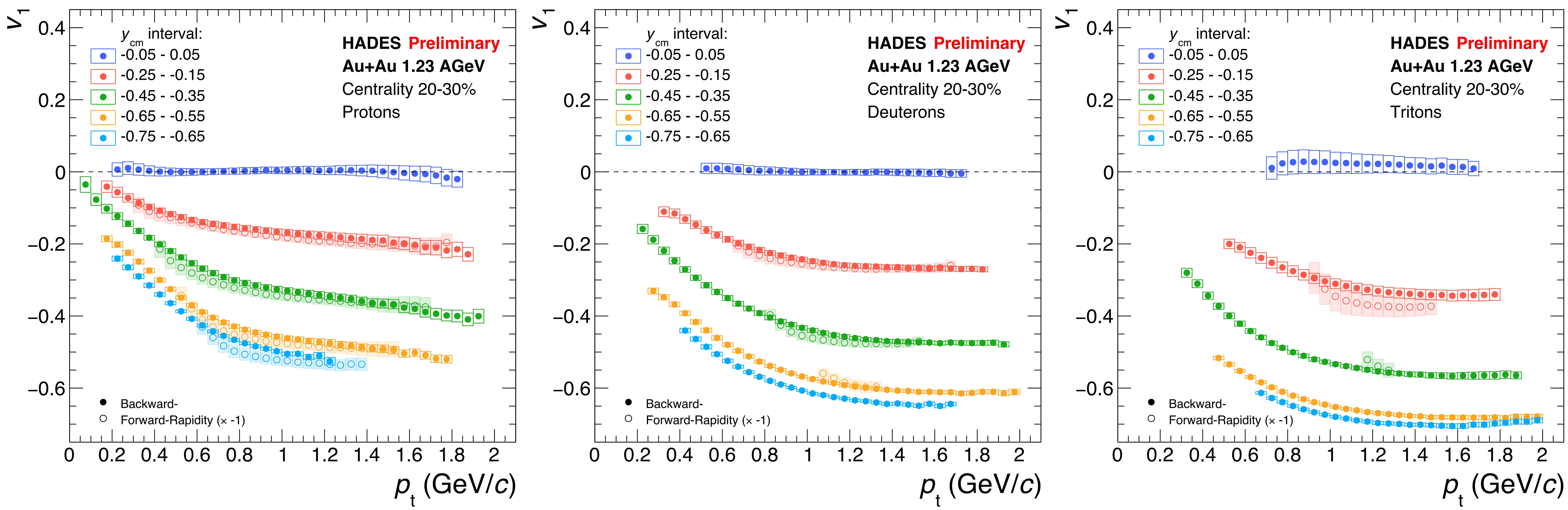
QM17, Nucl.Phys. A967 (2017) 812-815

QM18, Nucl.Phys. A982 (2019) 431-434, arXiv:1809.07821



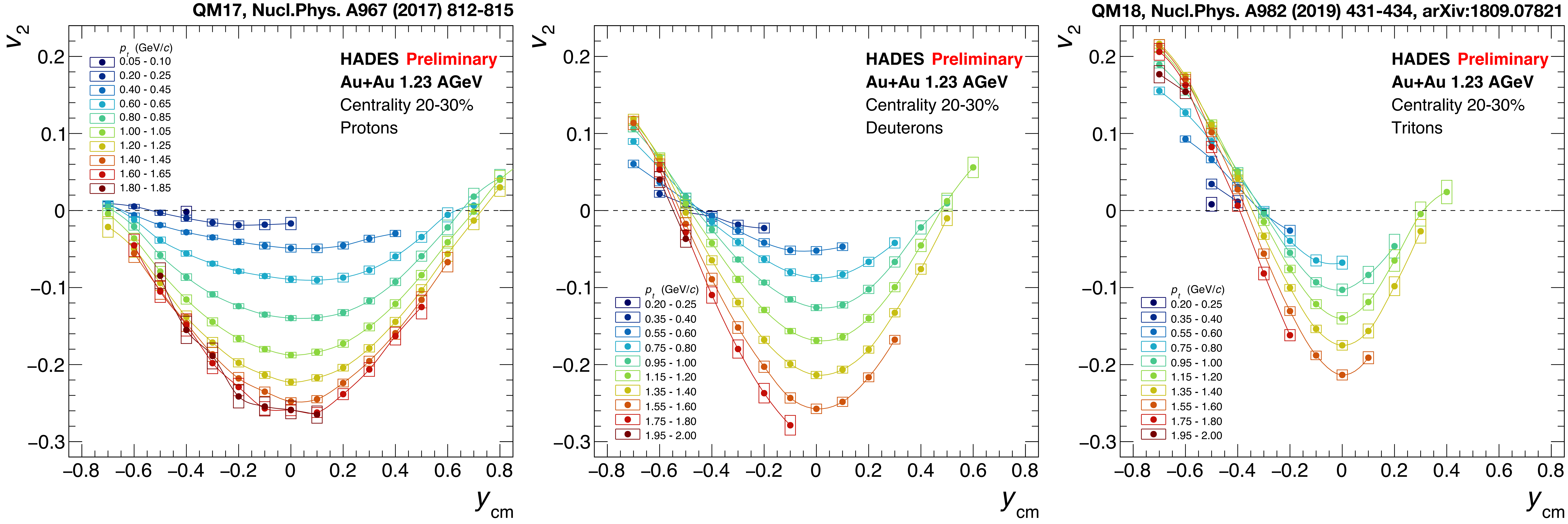
Directed Flow v_1: Protons and Light Nuclei

p_t-Dependence



Elliptic Flow v_2: Proton and Light Nuclei

p_t-Dependence



QM17, Nucl.Phys. A967 (2017) 812-815

QM18, Nucl.Phys. A982 (2019) 431-434, arXiv:1809.07821

Elliptic Flow v_2: Proton and Light Nuclei

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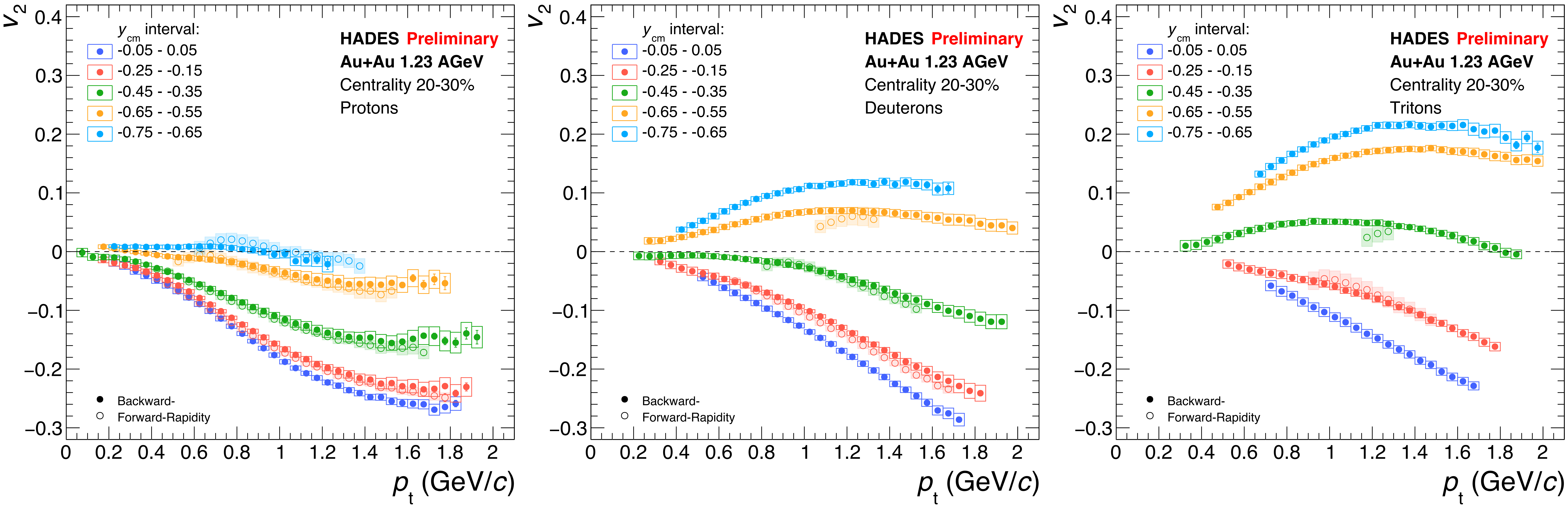
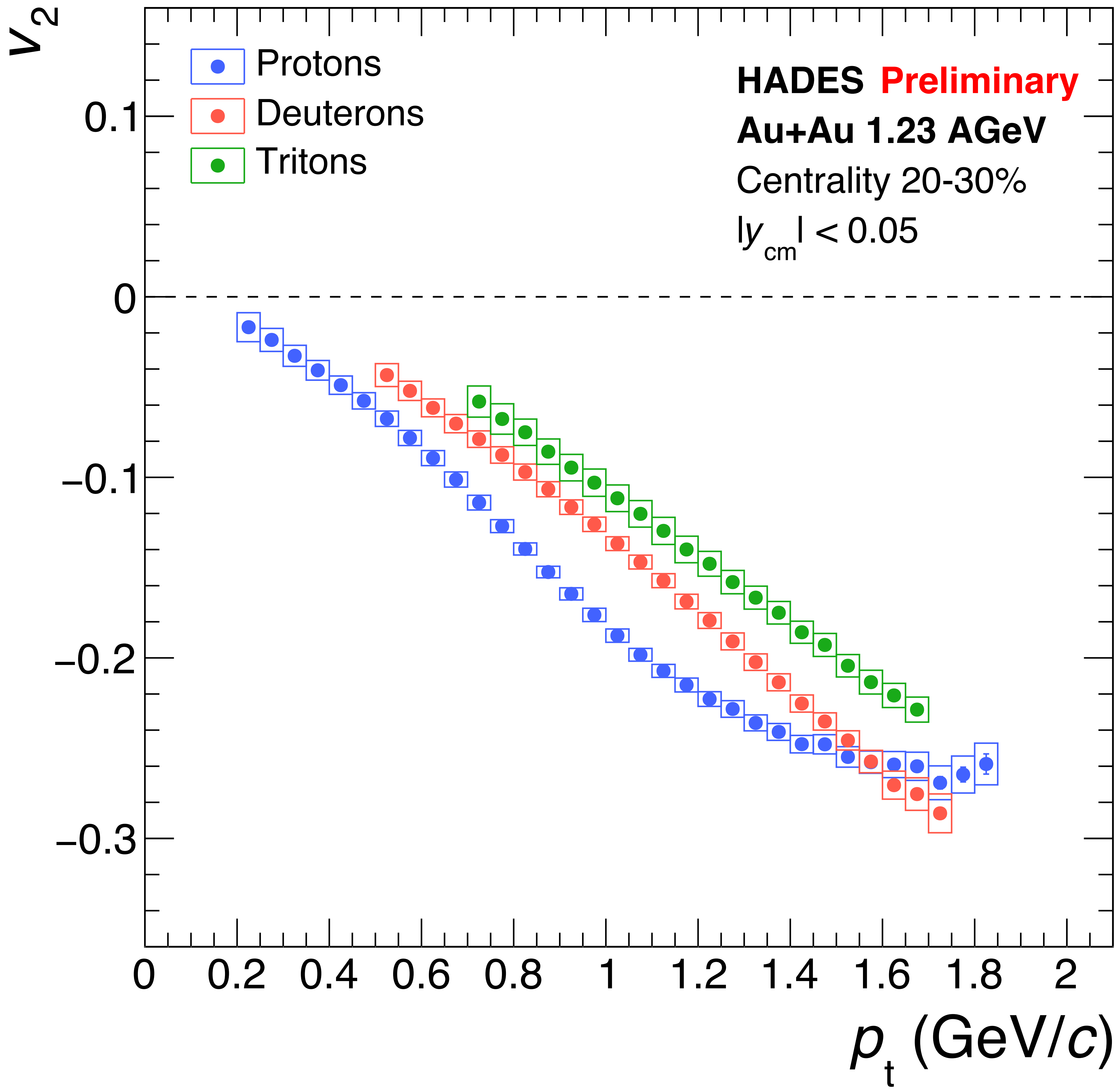


Elliptic Flow v_2: Light Nuclei

Nucleon Coalescence

- Comparison of p, d, t v_2 at mid-rapidity

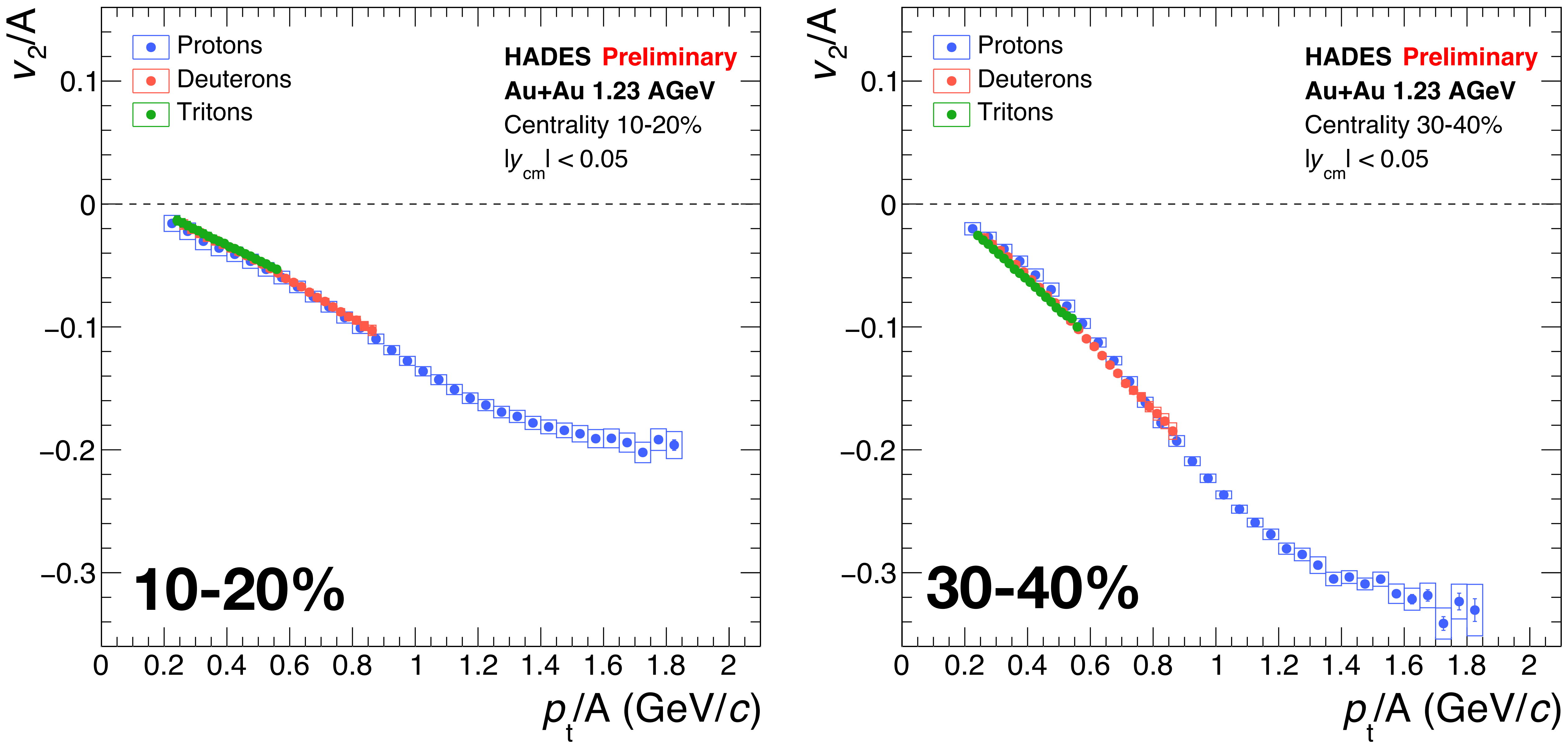
QM18, Nucl.Phys. A982 (2019) 431-434, arXiv:1809.07821



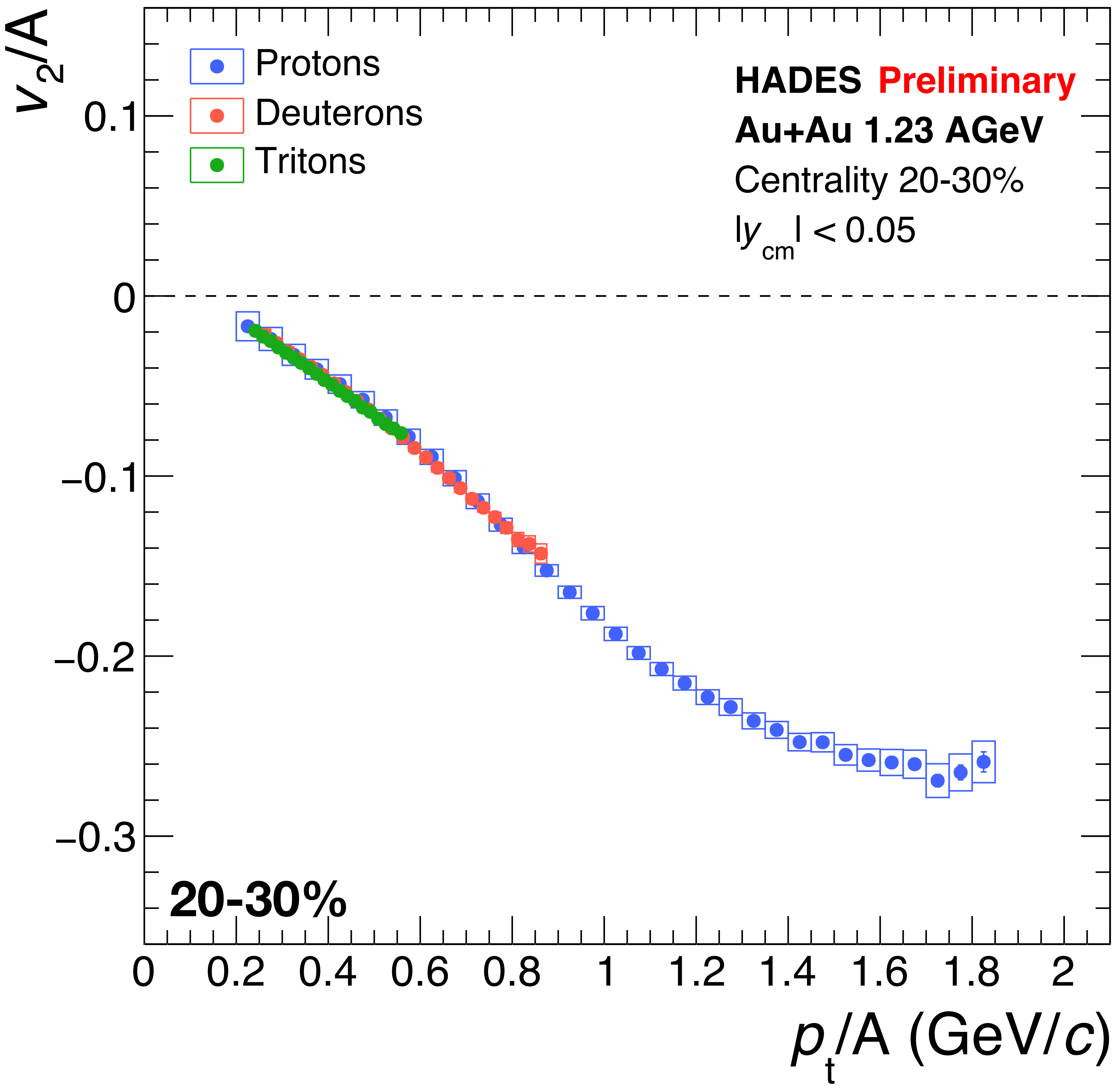
Elliptic Flow v_2: Light Nuclei

Nucleon Coalescence

- Comparison of p, d, t v_2 at mid-rapidity
- Scaling of v_2 and p_t with nuclear mass number A
- As expected for nucleon coalescence



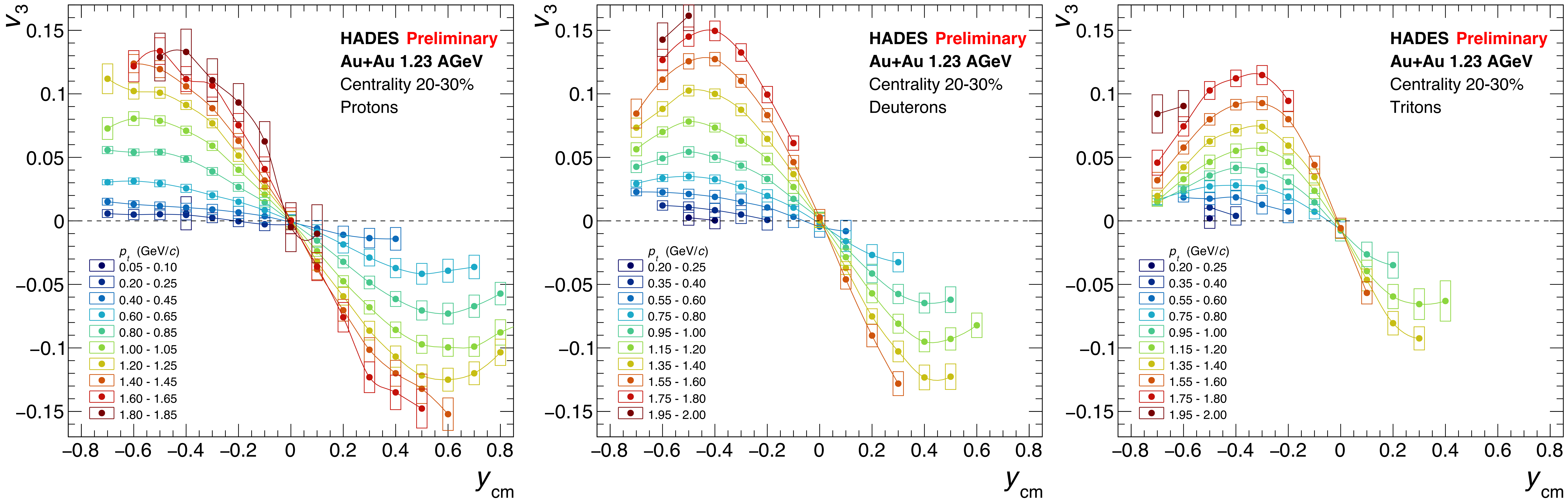
QM18, Nucl.Phys. A982 (2019) 431-434, arXiv:1809.07821



Triangular Flow $v_3\{\Psi_{RP}\}$

Protons and Light Nuclei

QM18, Nucl.Phys. A982 (2019) 431



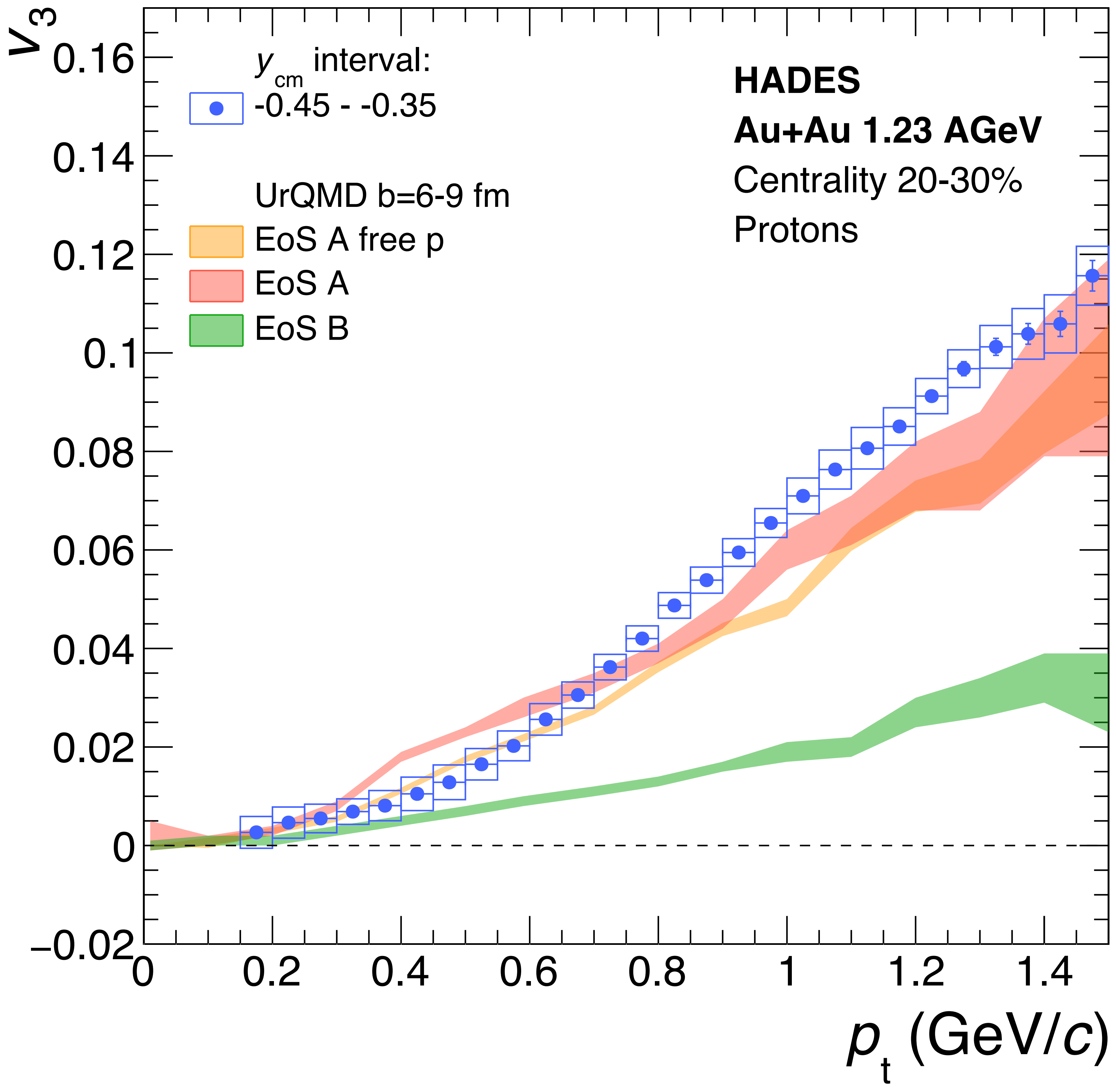
Note: $v3\{\Psi_{RP}\}$ w.r.t reaction plane $v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$

Triangular Flow $v_3\{\Psi_{RP}\}$

Comparison of Protons and Deuterons to UrQMD

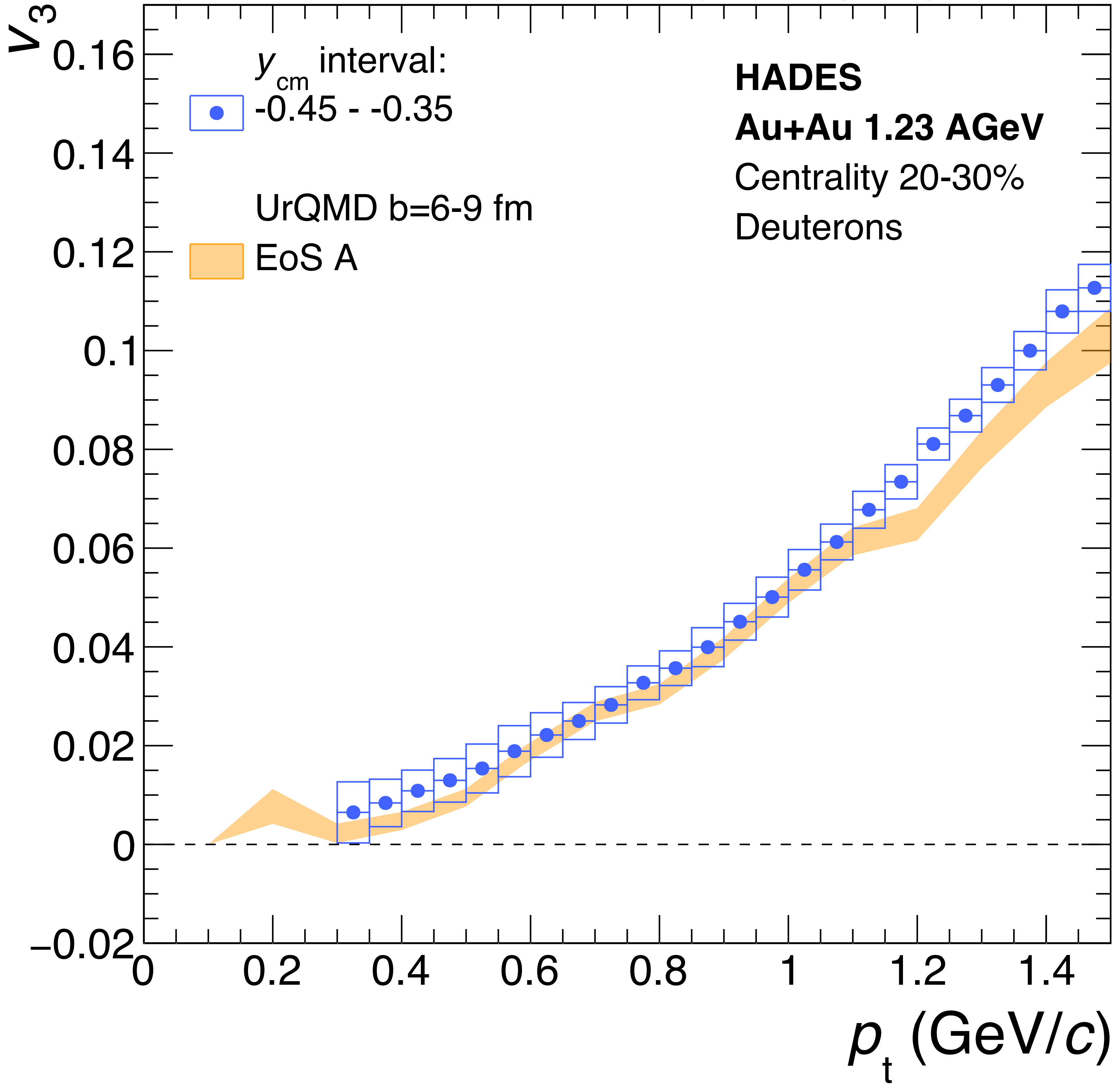
UrQMD predicts high sensitivity of v_3 to EoS

P. Hillmann, J. Steinheimer, M. Bleicher, J.Phys. G45 (2018) no.8, 085101



Parameters	hard EoS	soft EoS
α [MeV]	-124	-356
β [MeV]	71	303
γ	2.00	1.17

P. Hillmann et al. J.Phys. G47 (2020) 5, 055101



UrQMD (hard EoS) with a coalescence in space-coordinates and momentum-space $\Delta r = 3.575 fm^{-3}$ and $\Delta pmax = 0.285$ GeV

Odd Flow Harmonics v1 v3 v5

Protons and light nuclei

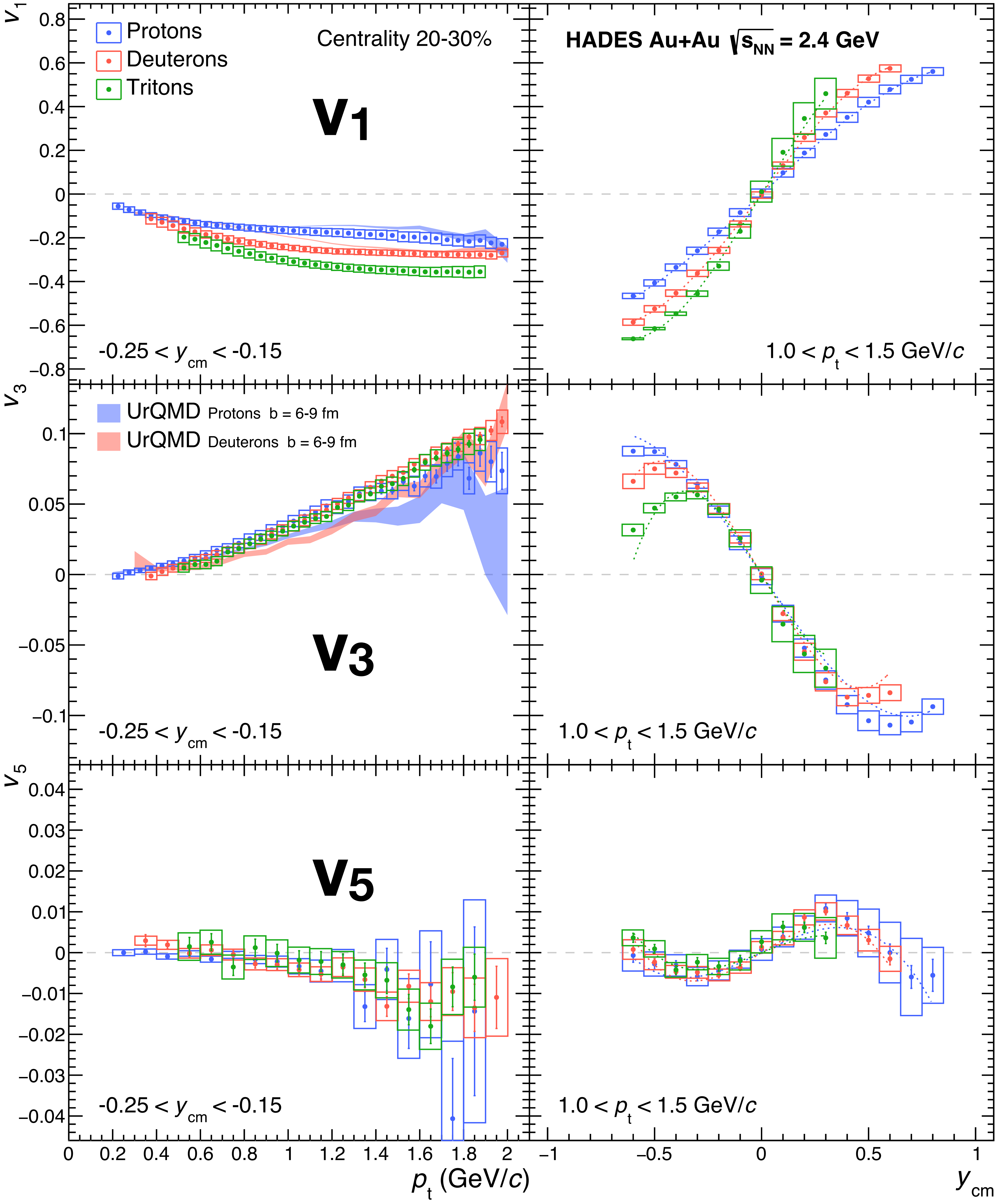
- v1 develops a strong mass dependence when moving away from mid-rapidity, not in the case of v3 and v5

- UrQMD model with hard EOS provides a general good description of v1 and v3, but discrepancies can be observed

Rapidity dependence of odd harmonic parameterised with:

$$v_{1,3,5}(y_{cm}) = a\, y_{cm} + b\, y_{cm}^3$$

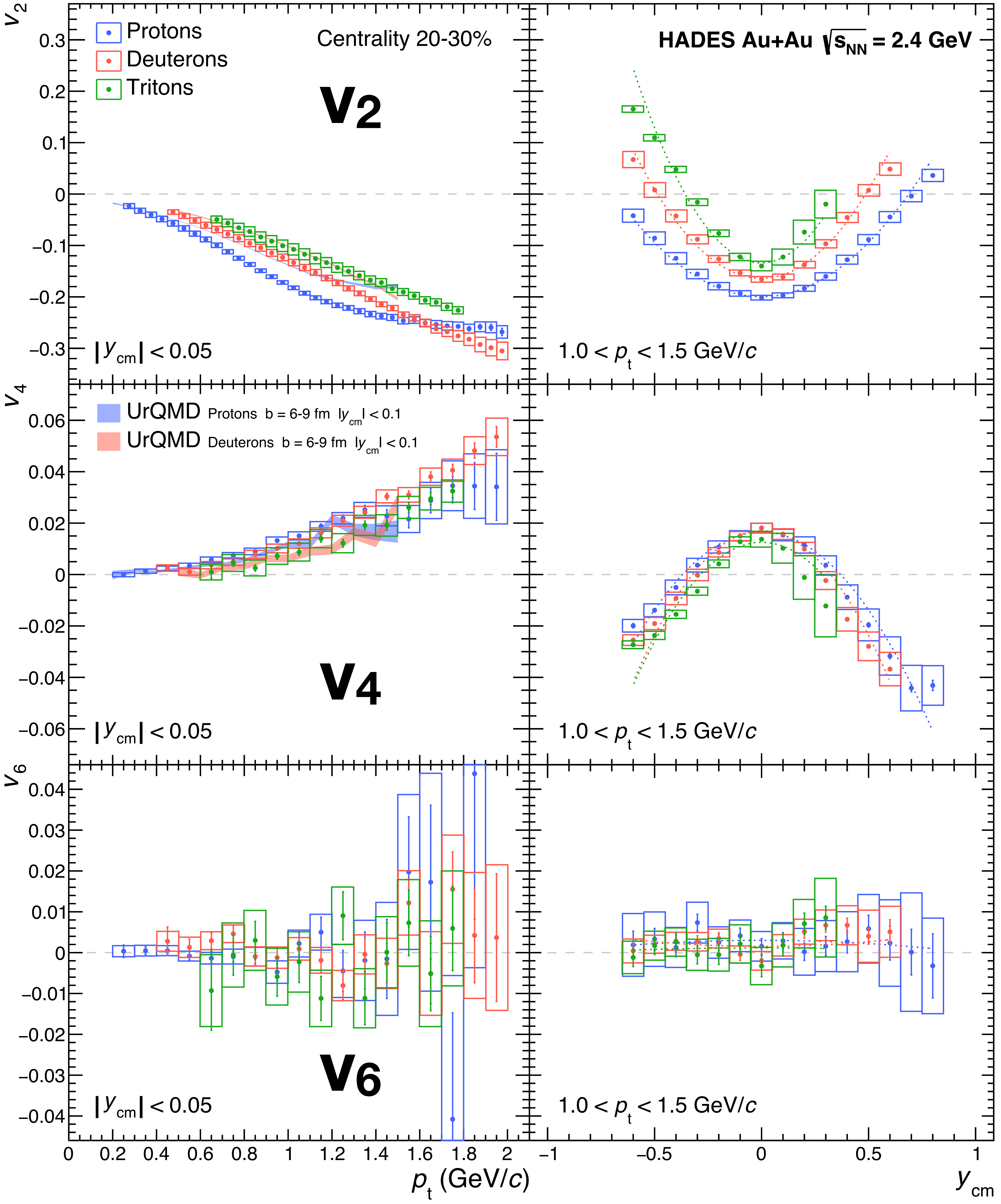
UrQMD calculation:
P. Hillmann et al.
J.Phys. G47 (2020) 5, 055101



Even Flow Harmonics v_2 v_4 v_6

Protons and light nuclei

- v2 around mid-rapidity a clear mass ordering can again be observed, not so strong for v4
- good description of v4 with UrQMD with hard EOS, but deviation of v2 at high momenta
- Upper limit for v6 values



Rapidity dependence of even harmonic parameterised with:

$$v_{2,4,6}(y_{cm}) = c + d\, y_{cm}^2$$

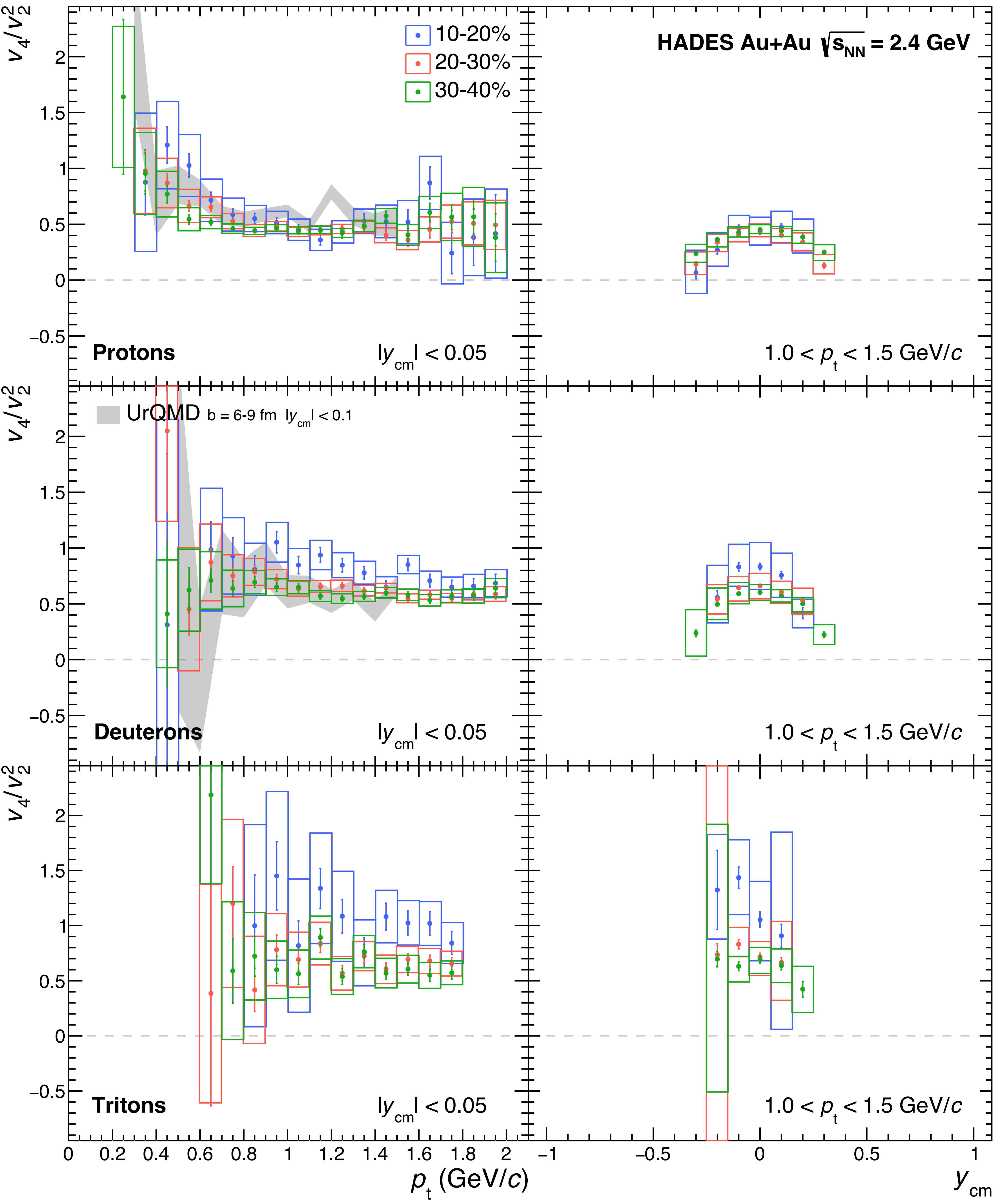
UrQMD calculation:
P. Hillmann et al.
J.Phys. G47 (2020) 5, 055101

“Ideal fluid scaling”

Protons and light nuclei

- Ideal fluid dynamics predicts contribution to v_4 from v_2 at large p_t by $v_4 = 0.5(v_2)^2$
- Realistic hydro calculation at RIHC $v4/(v2)^2 \sim 0.63$
- Good agreement with UrQMD simulations with “hard” mean-field potential

N. Borghini and J.-Y. Ollitrault
Phys.Lett. B642 (2006) 227-231



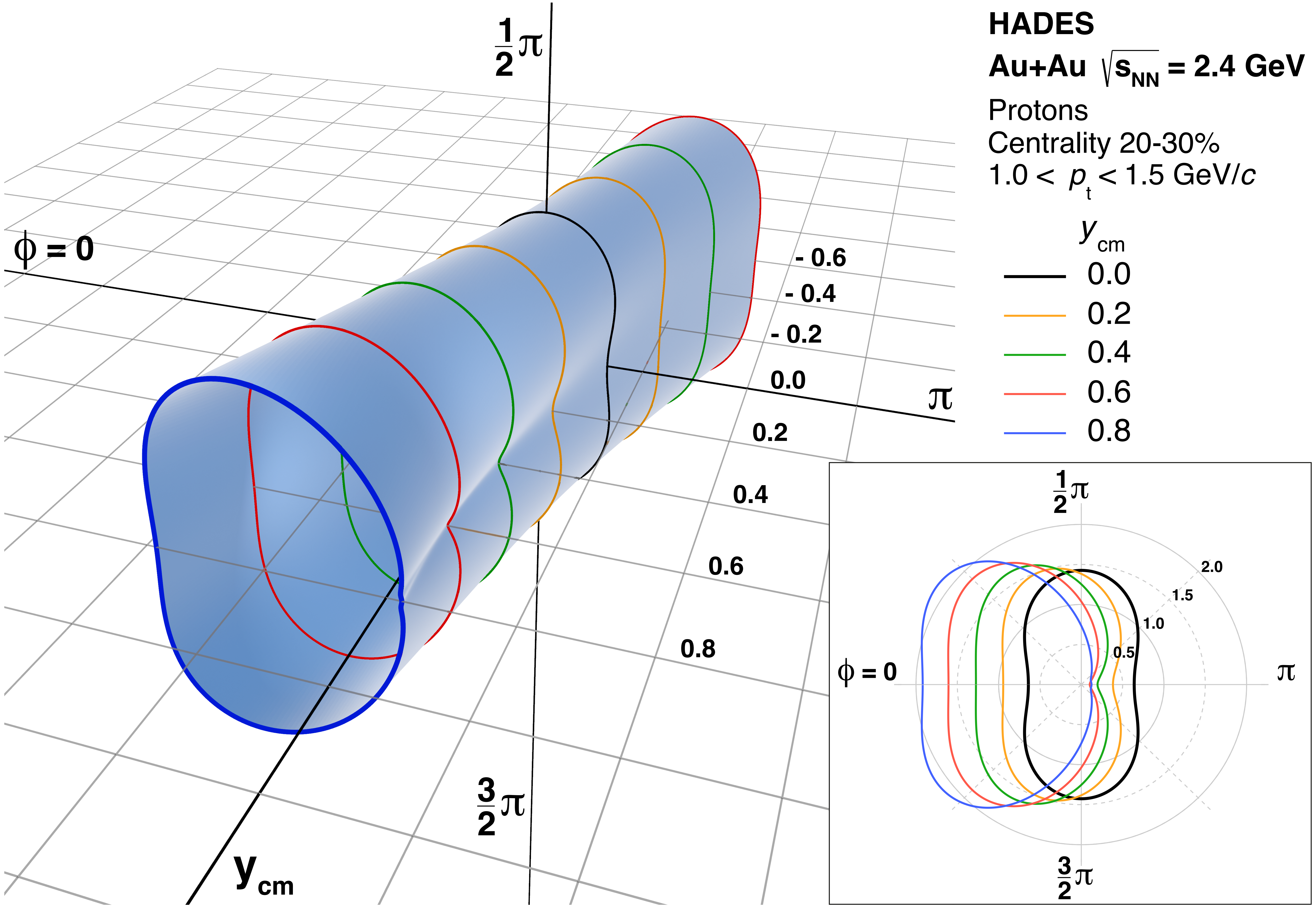
Systematic Error are evaluated for each individual Variation Calculation (errors treated as correlated)

UrQMD calculation:
P. Hillmann et al.
J.Phys. G47 (2020) 5, 055101

Emission Pattern

Protons

- Enables to reconstruct a full 3D-picture of the emission pattern in momentum space



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

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

with rapidity depend parameterisation n=1-6

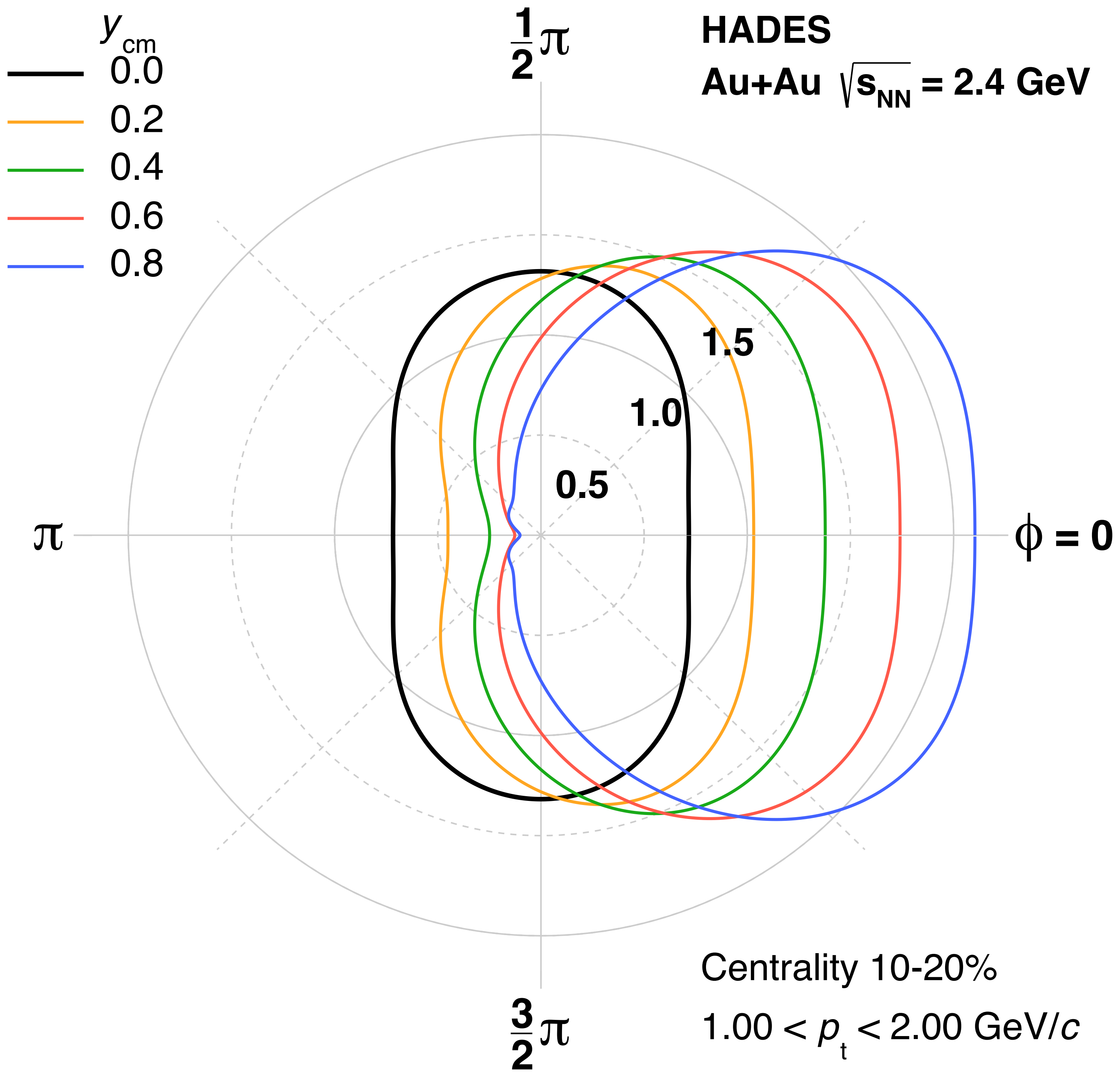
$$v_{1,3,5}(y_{cm}) = a\, y_{cm} + b\, y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d\, y_{cm}^2$$

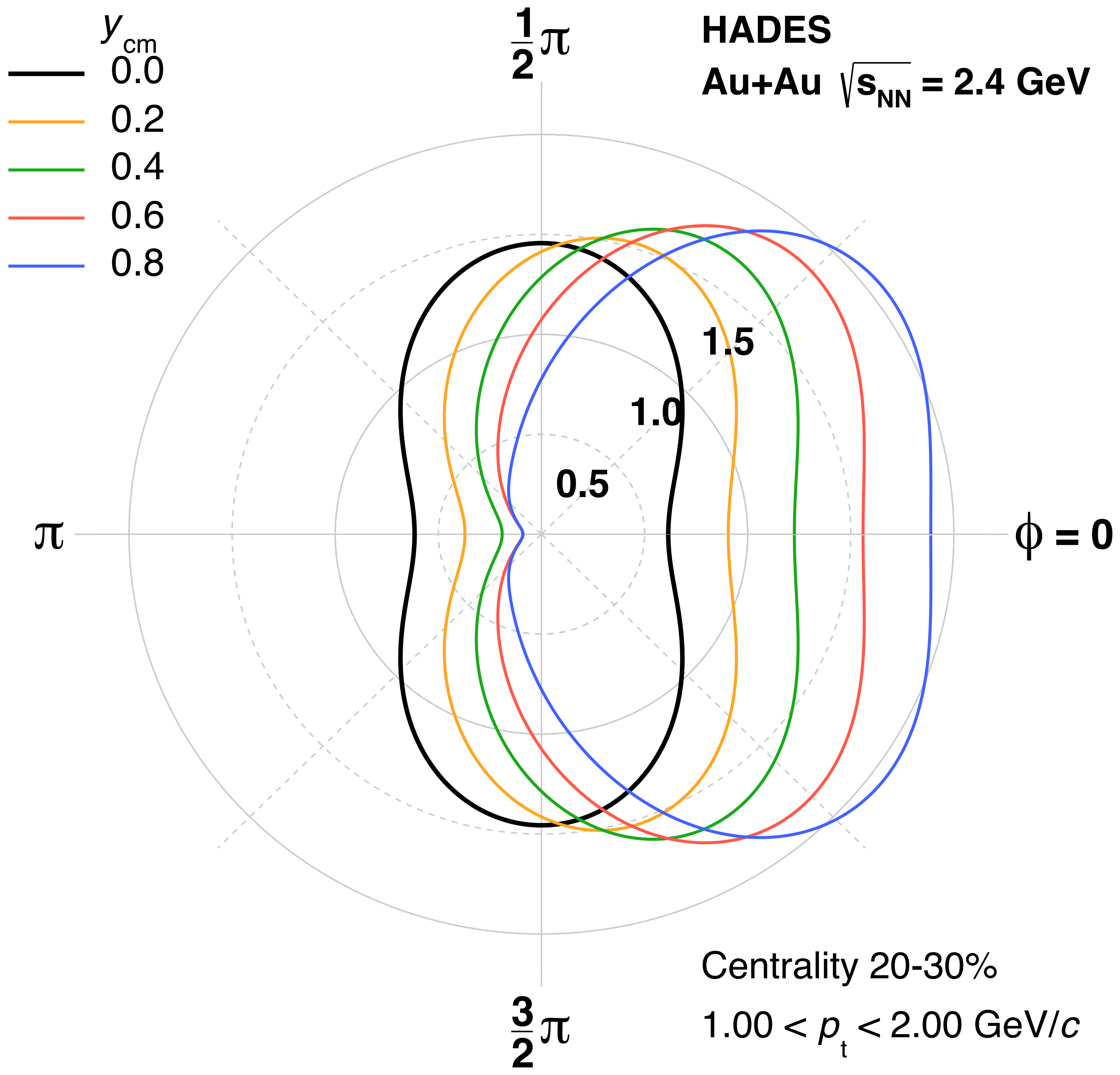
Emission Pattern

Protons

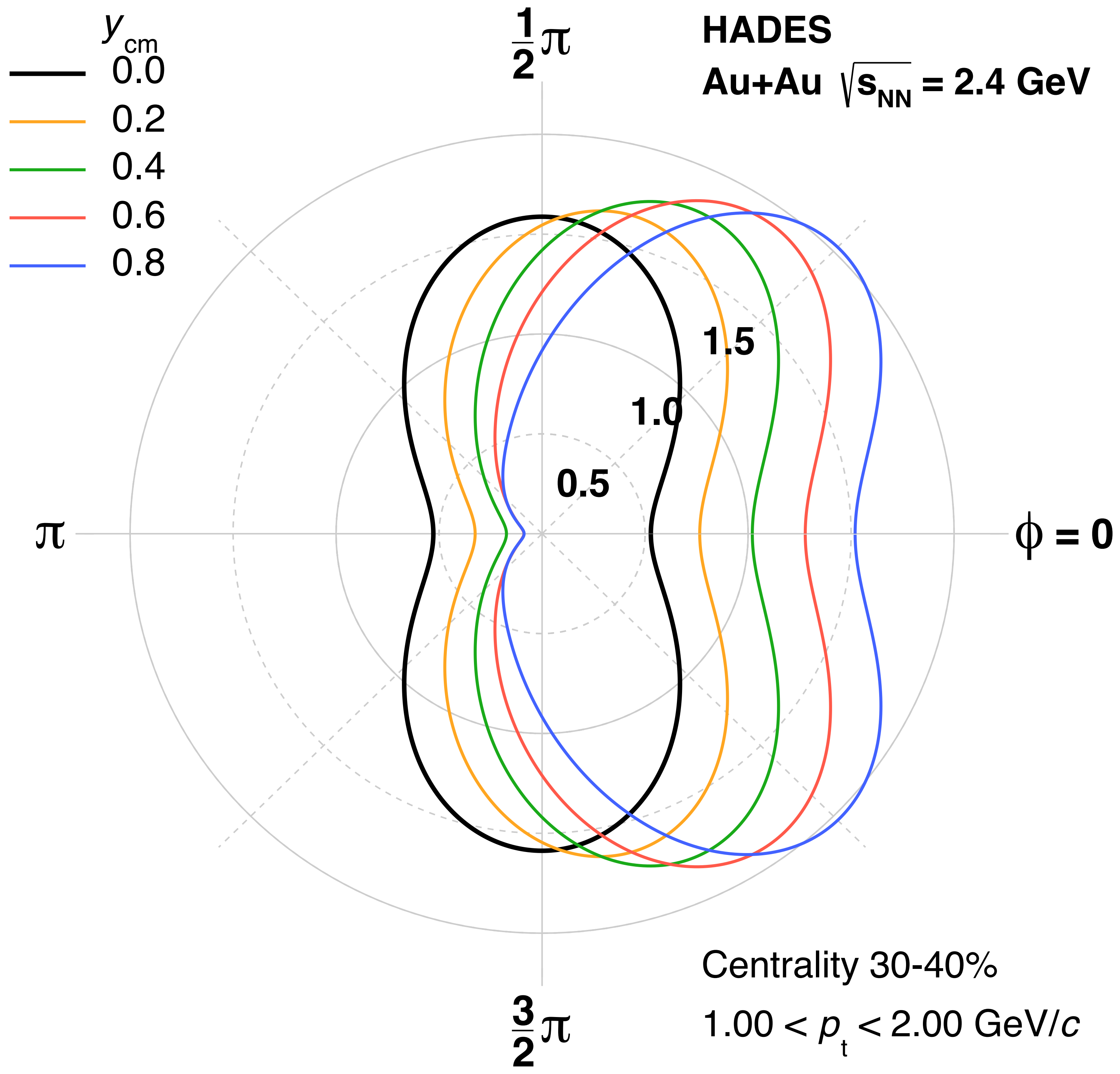
10-20%



20-30%



30-40%



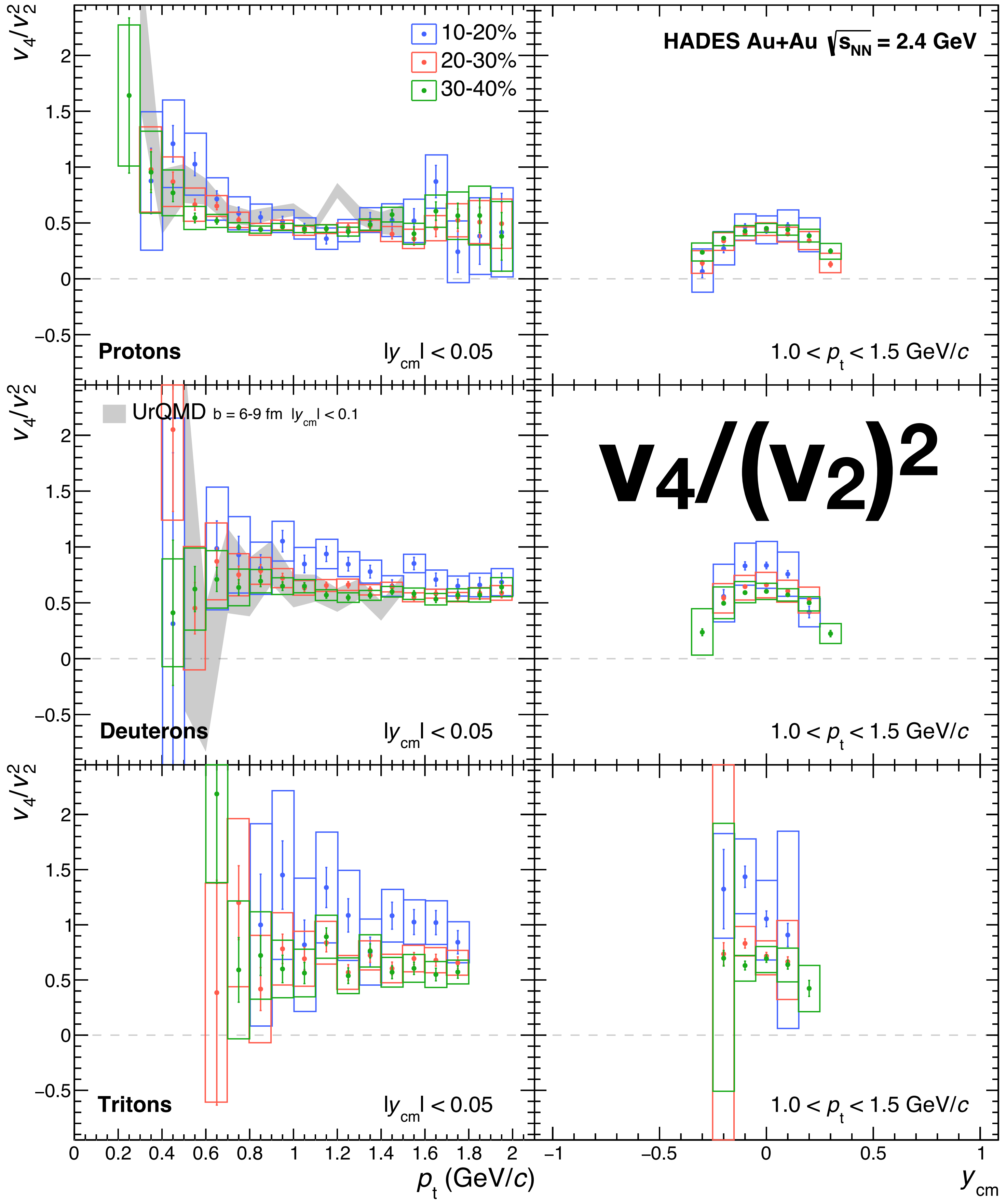
Conclusions

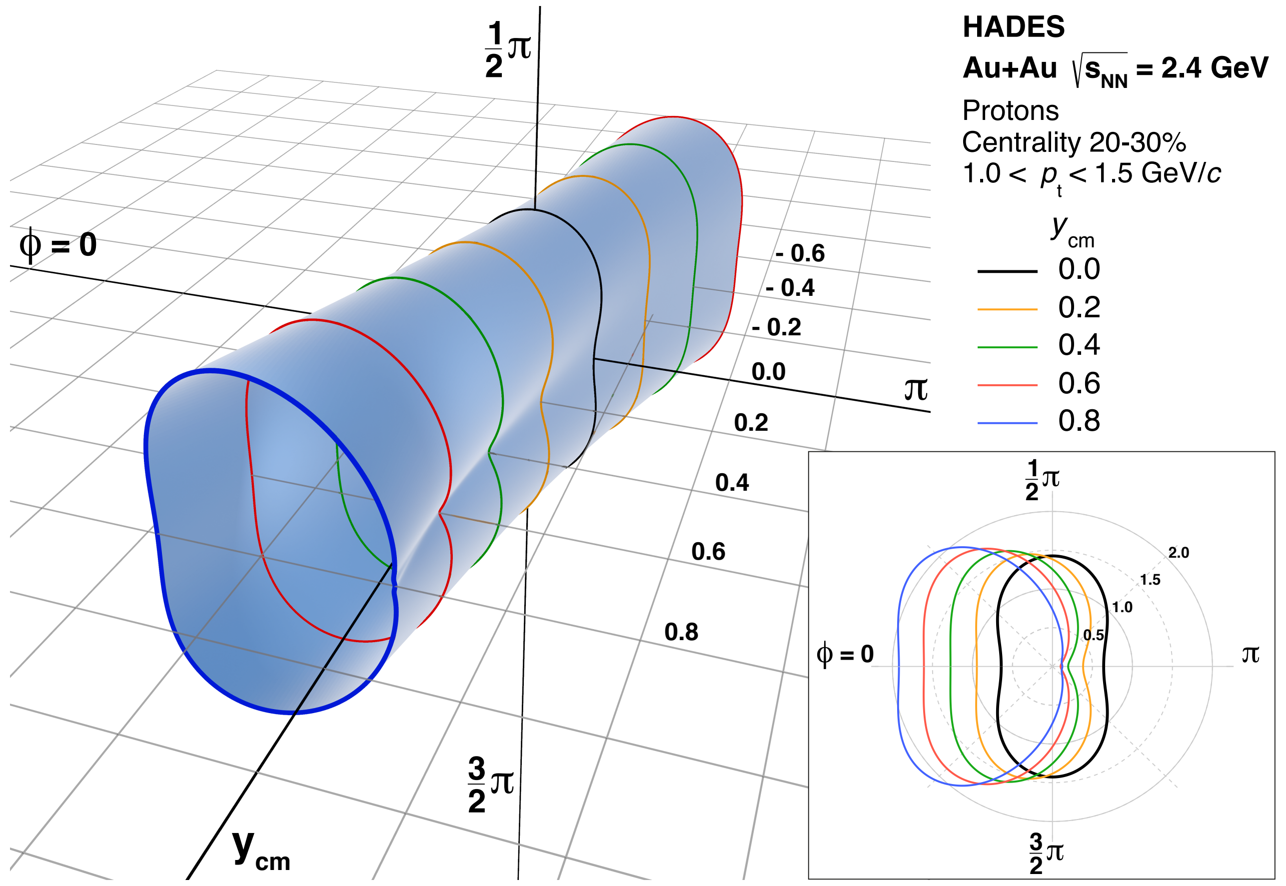
- Precision data on higher order flow is a major step forward in constraining the EOS and transport properties of dense matter

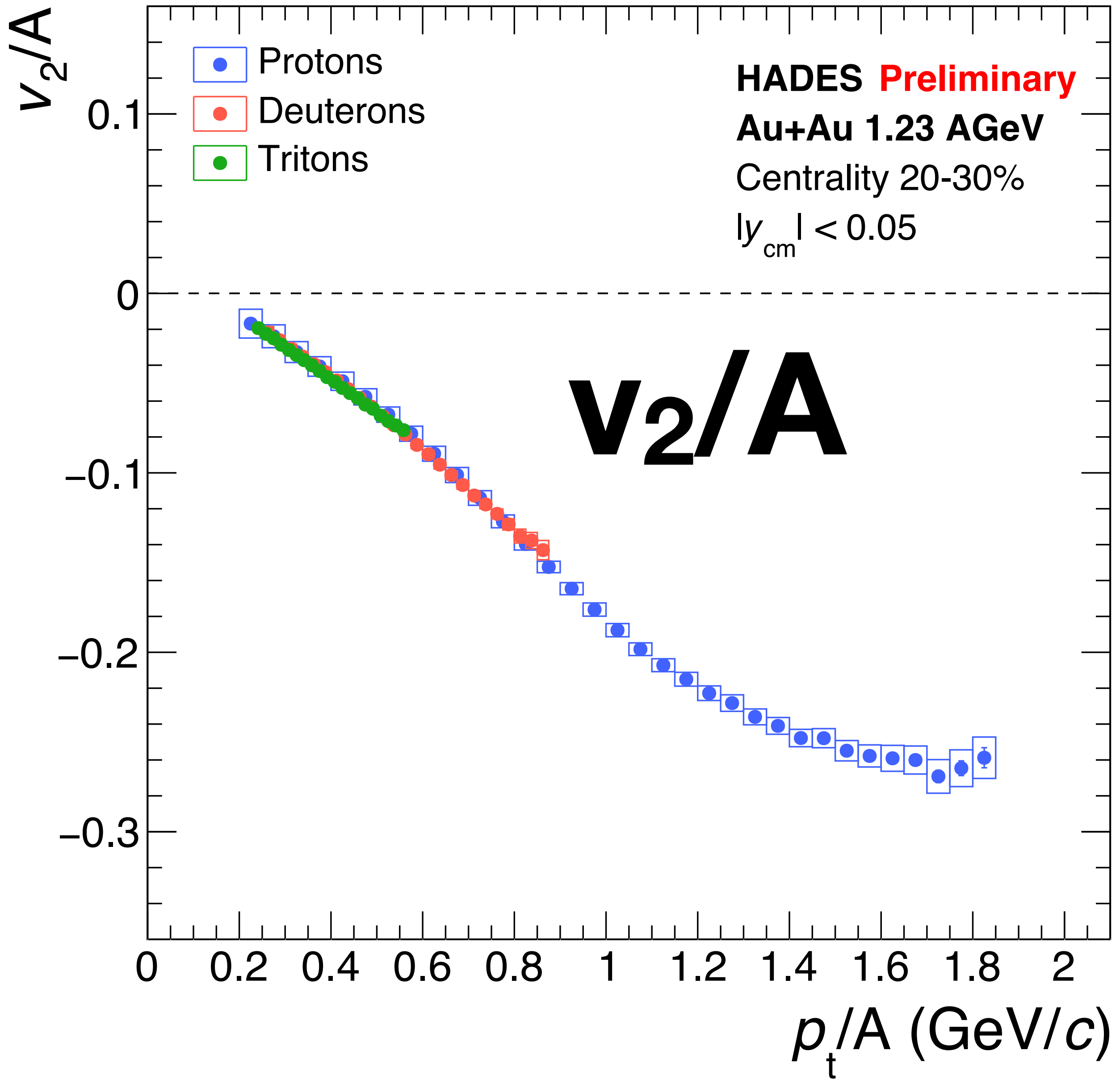
- Fully multi-differential measurement in Centrality and Phase Space (Pt and Rapidity)

- First measurement at SIS energies of
  - Triangular $v_3\{\Psi_{RP}\}$, quadrangular $v_4\{\Psi_{RP}\}$ and higher flow harmonics of protons, deuterons and tritons

- Scaling properties observed
  - Elliptic flow at mid-rapidity scales with A
  - Ratio $v_4/(v_2)^2$ shows constant scaling








Dresden 2020

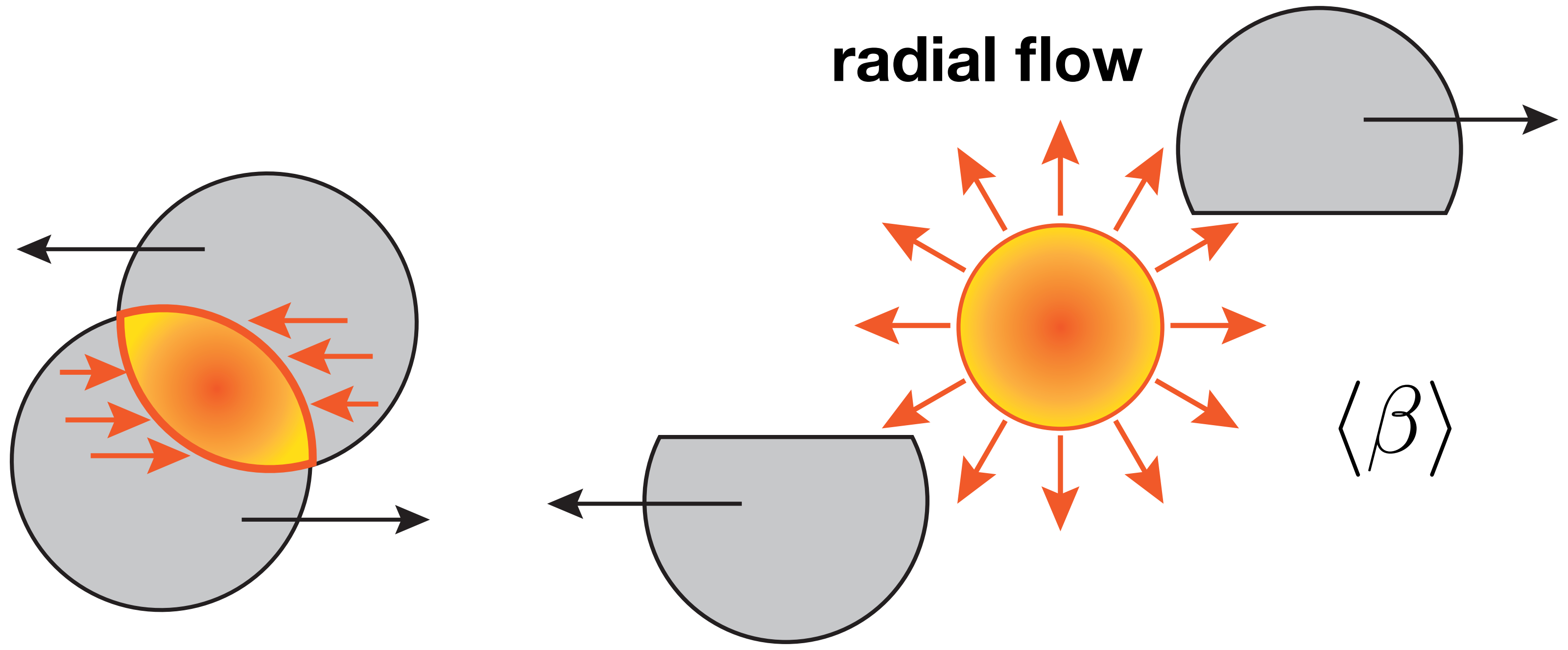
HADES Collaboration

Thank you for your attention!

Motivation

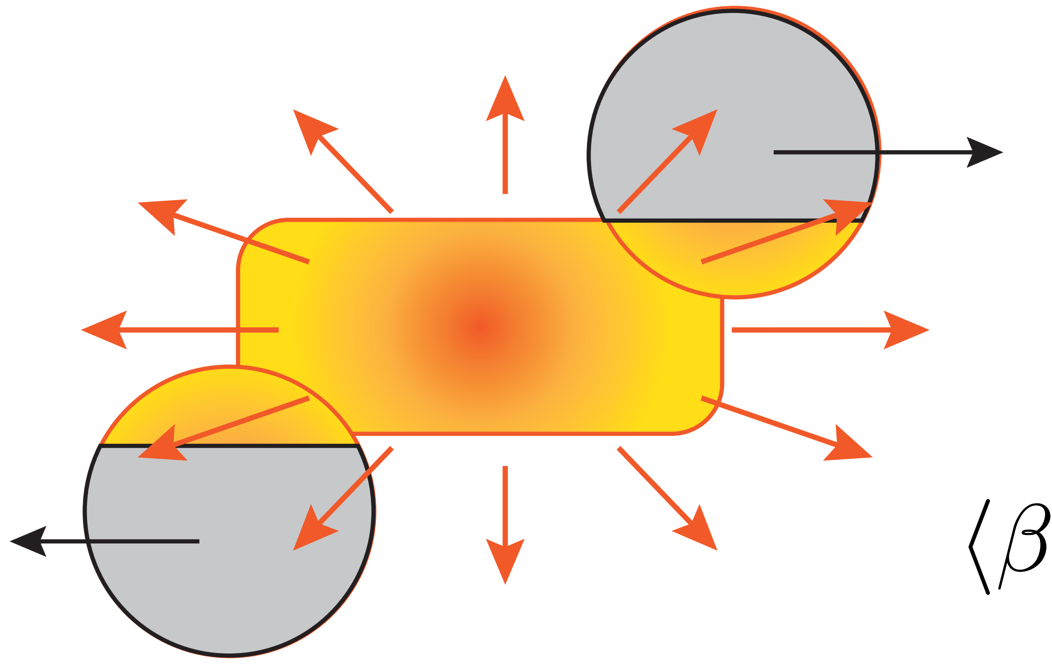
Flow and Event Shapes

top view



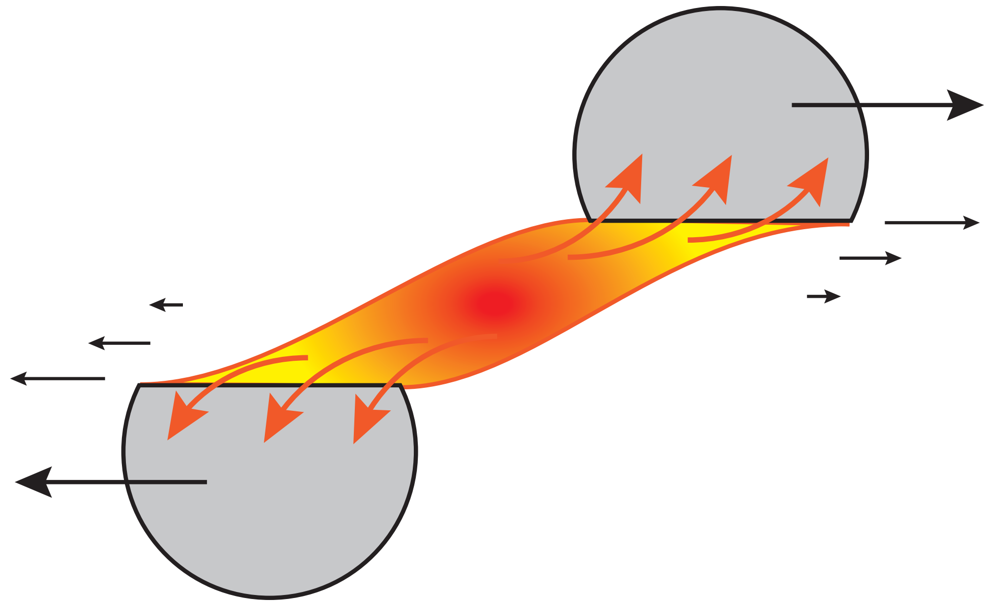
$\langle\beta\rangle$

Landau scenario
total stopping

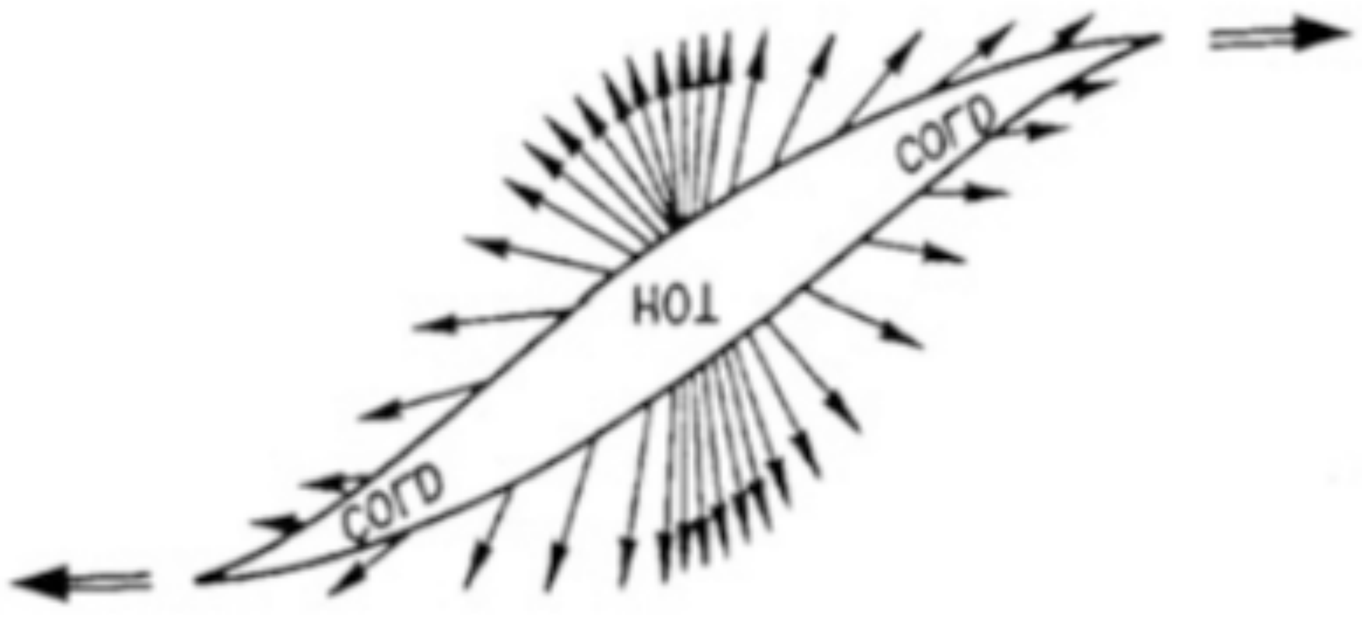


$\langle\beta_t\rangle \ \langle\beta_l\rangle$

Bjorken scenario
partial stopping
initial longitudinal flow



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

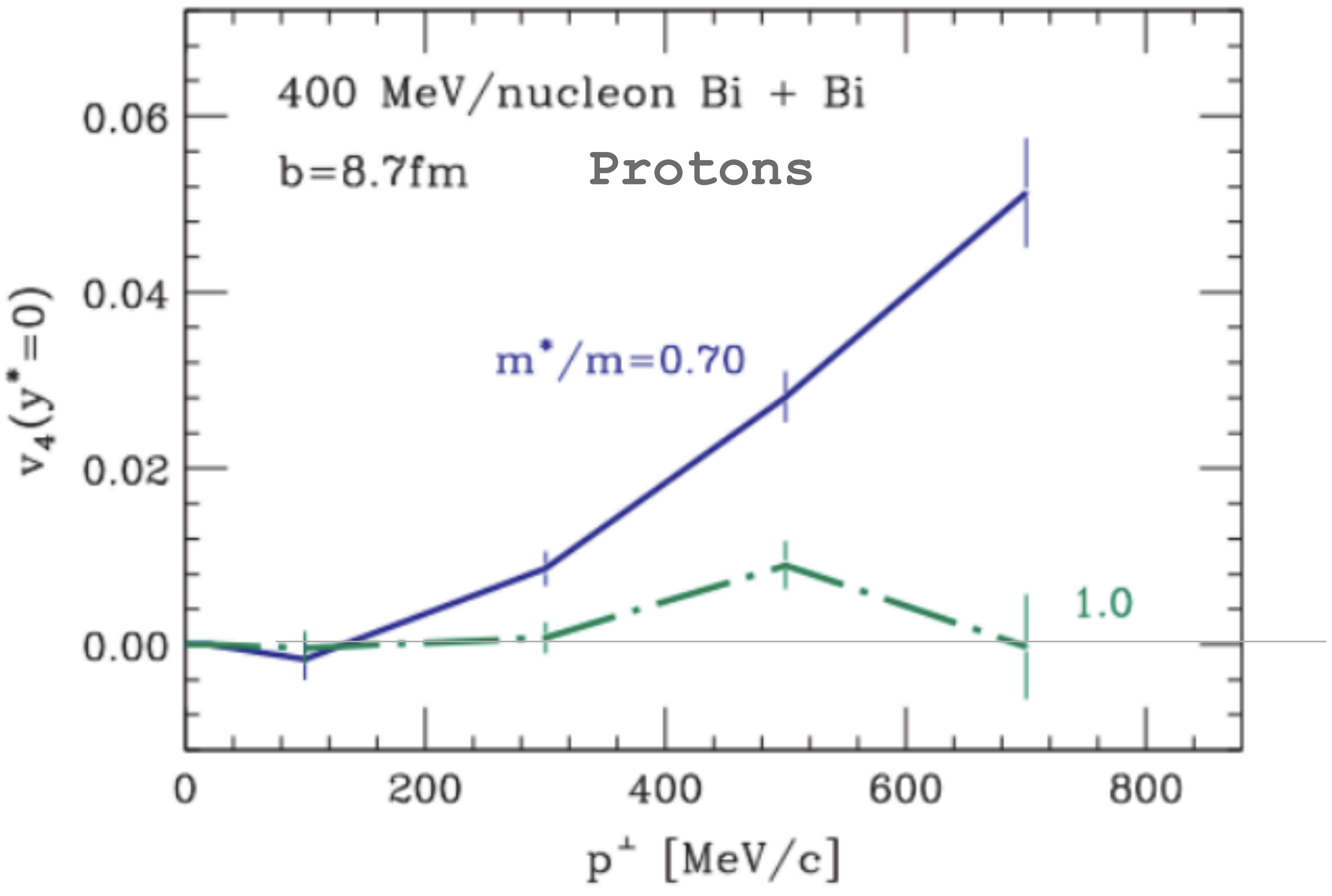


How to Deal with Relativistic Heavy Ion Collisions
R. Hagedorn (1981)

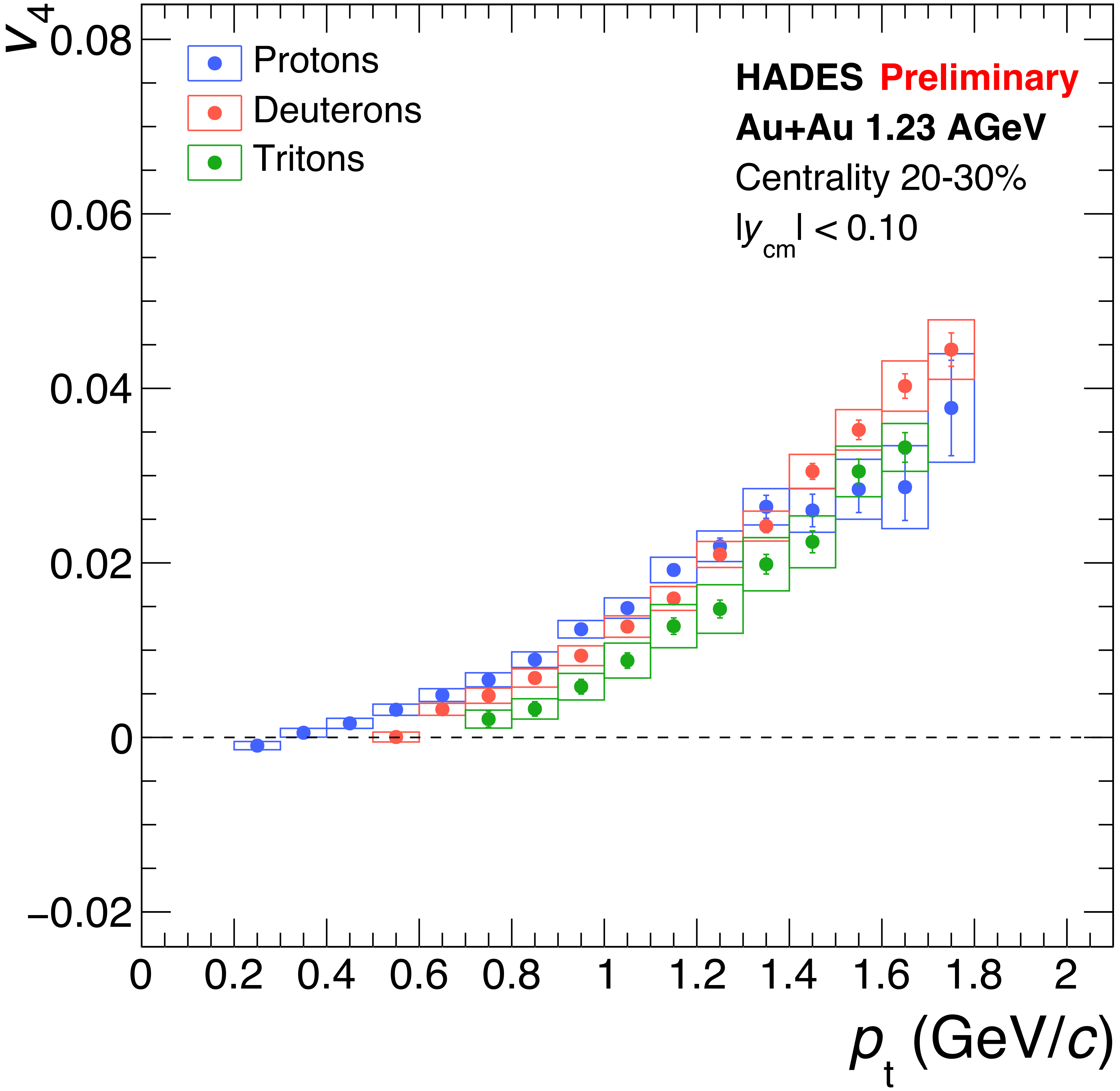
Quadrangular Flow $v_4\{\Psi_{RP}\}$

Protons and Light Nuclei

P. Danielewicz
Nucl.Phys. A673 (2000) 375-410



First prediction of v_4 with sensitive to EoS

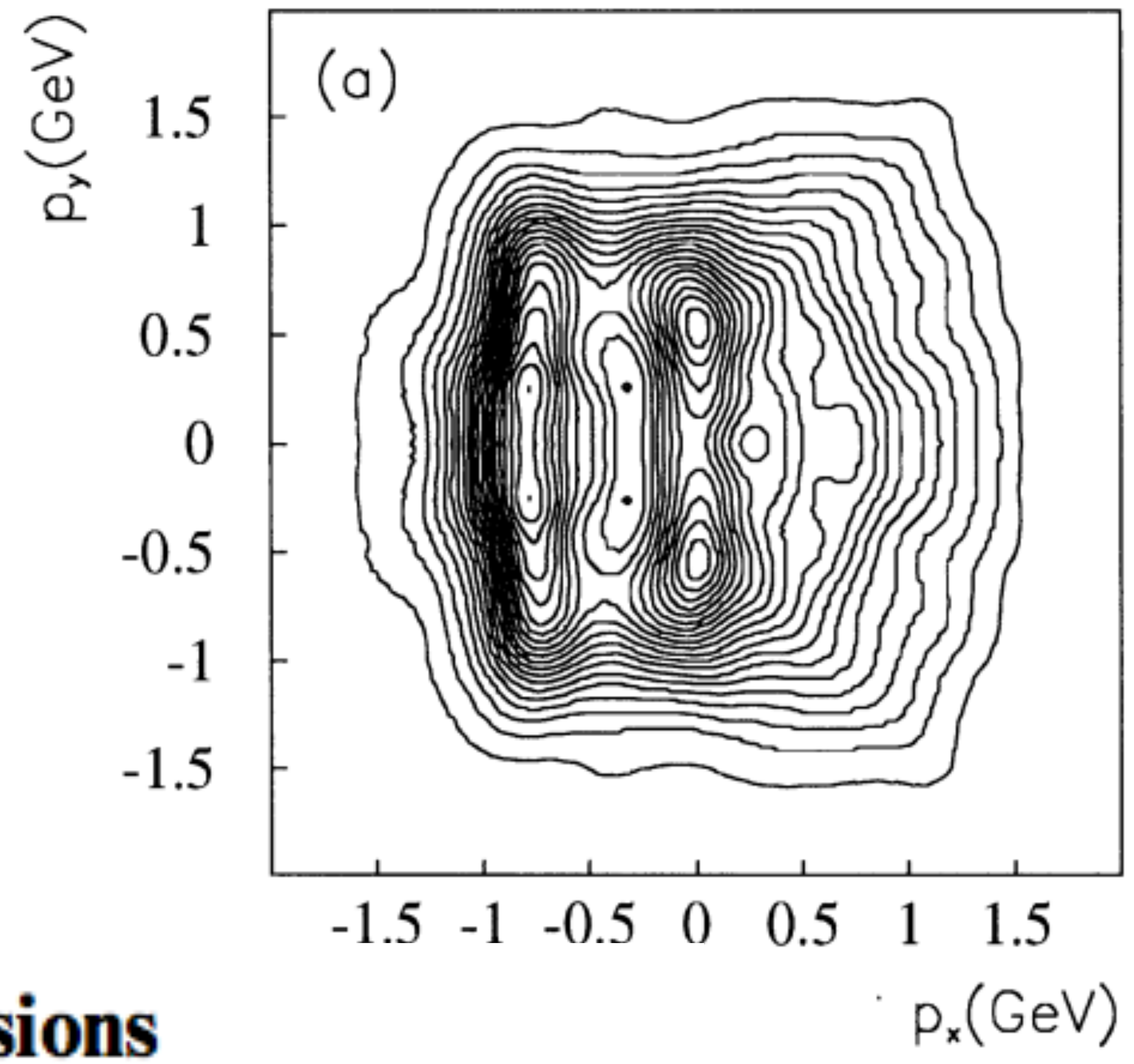


$$v_4\{\Psi_{RP}\} = \langle\langle \cos 4(\varphi - \Psi_{RP})\rangle\rangle$$

Note: $v4\{\Psi_{RP}\}$ w.r.t reaction plane

Quadrangular Flow v4{Ψ_{RP}}

Protons and Light Nuclei

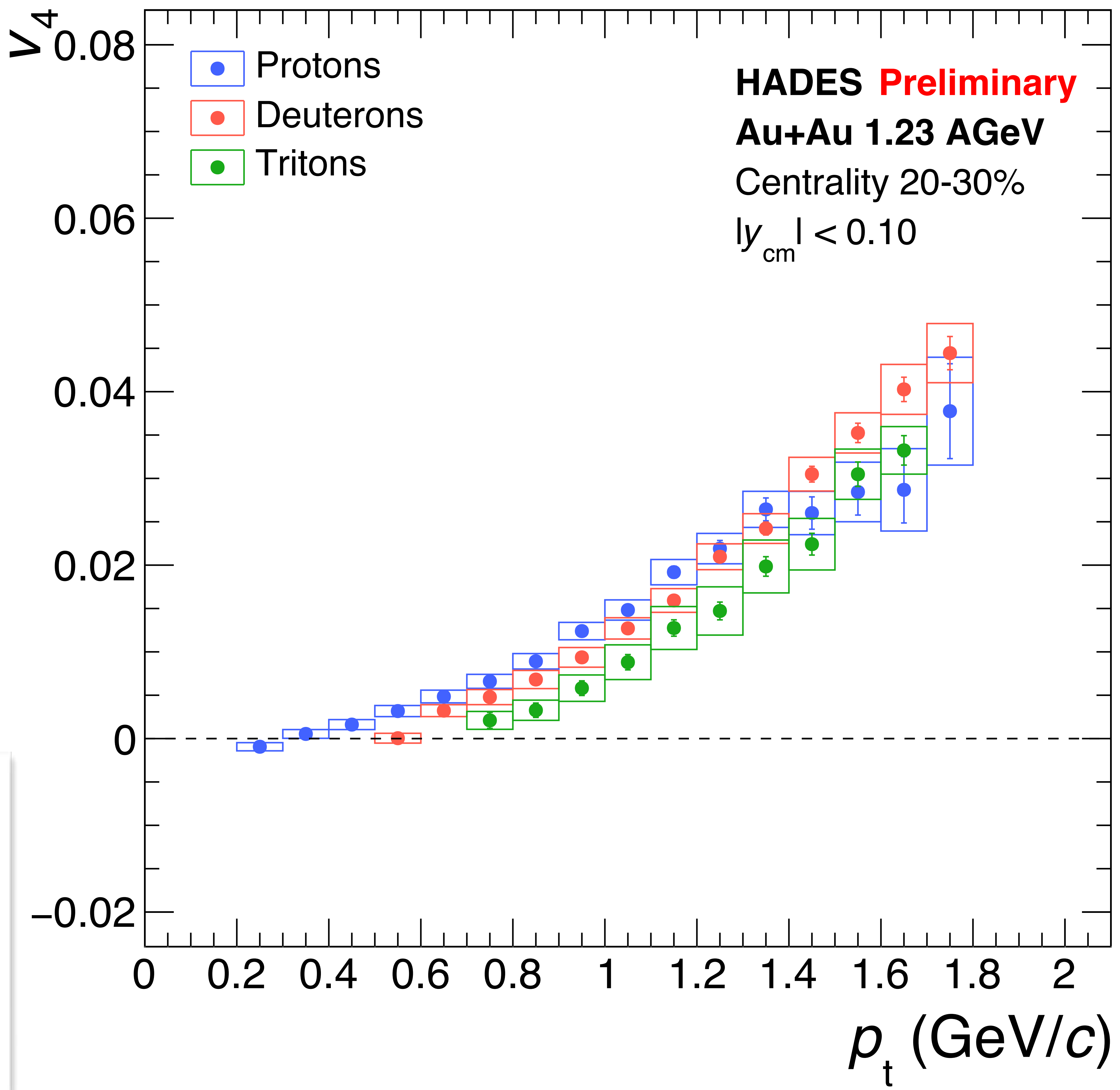


Z. Phys. C 70, 665–671 (1996)

Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions

S. Voloshin[1,★], Y. Zhang[2]

> The rectangle-type deformation amplitude v_4 could be non-zero, for example, for rapidity windows close to the center of mass, where both squeeze-out emitting preferentially more particles in the direction perpendicular to the reaction plane, and "side-splash" effects can be important.

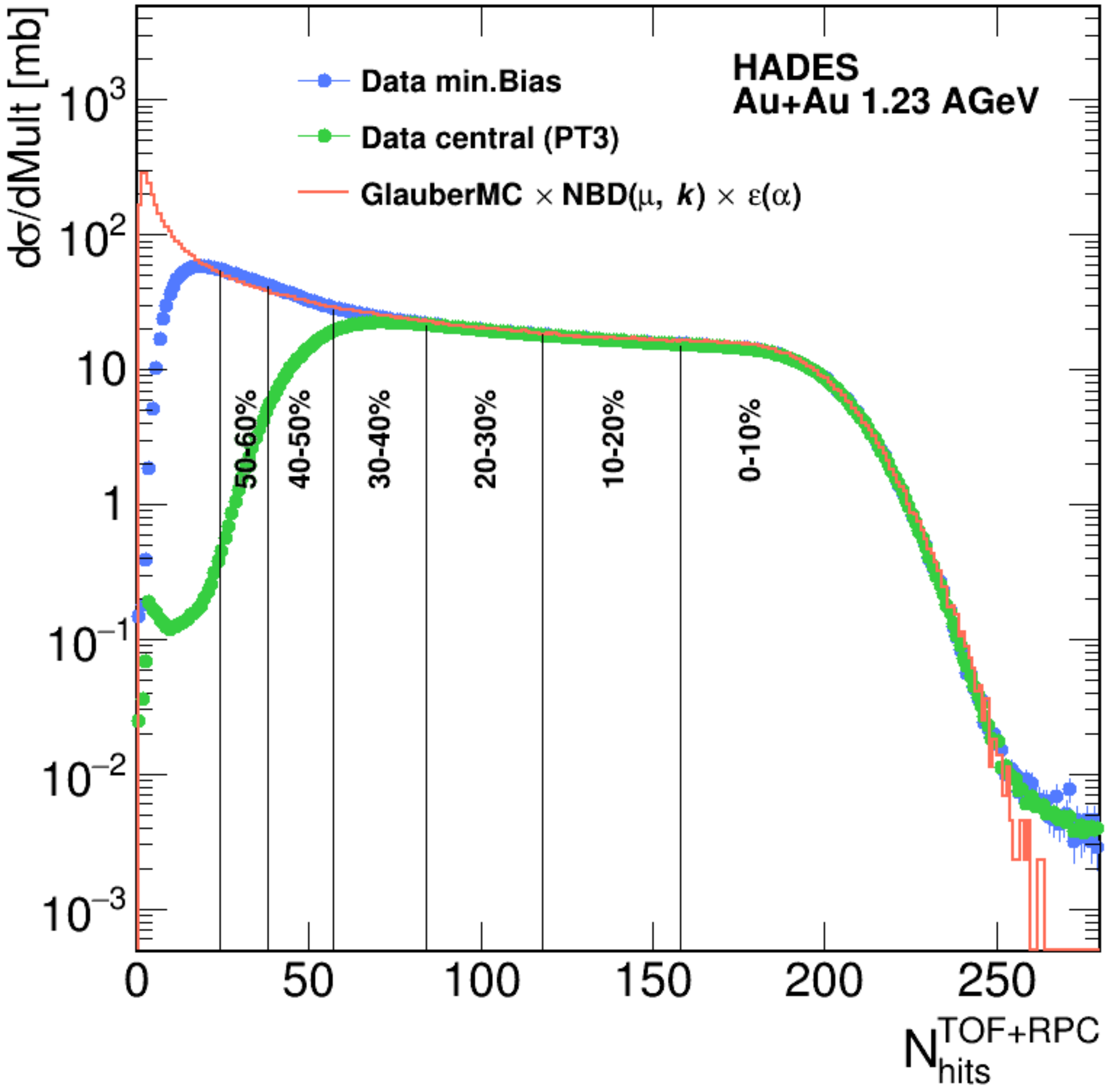


$$v_4\{\Psi_{RP}\} = \langle\langle \cos 4(\varphi - \Psi_{RP})\rangle\rangle$$

Note: v4{Ψ_{RP}} w.r.t reaction plane

HADES Performance

- High interaction rates and statistics
    - Total number of events rec 10^9
    - 2.1×10^9 most central eve analysed
- Centrality
    - 0-40% most central
    - Deduced from a Glauber MC model



HADES centrality: arXiv:1712.07993