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

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for the
HADES Collaboration

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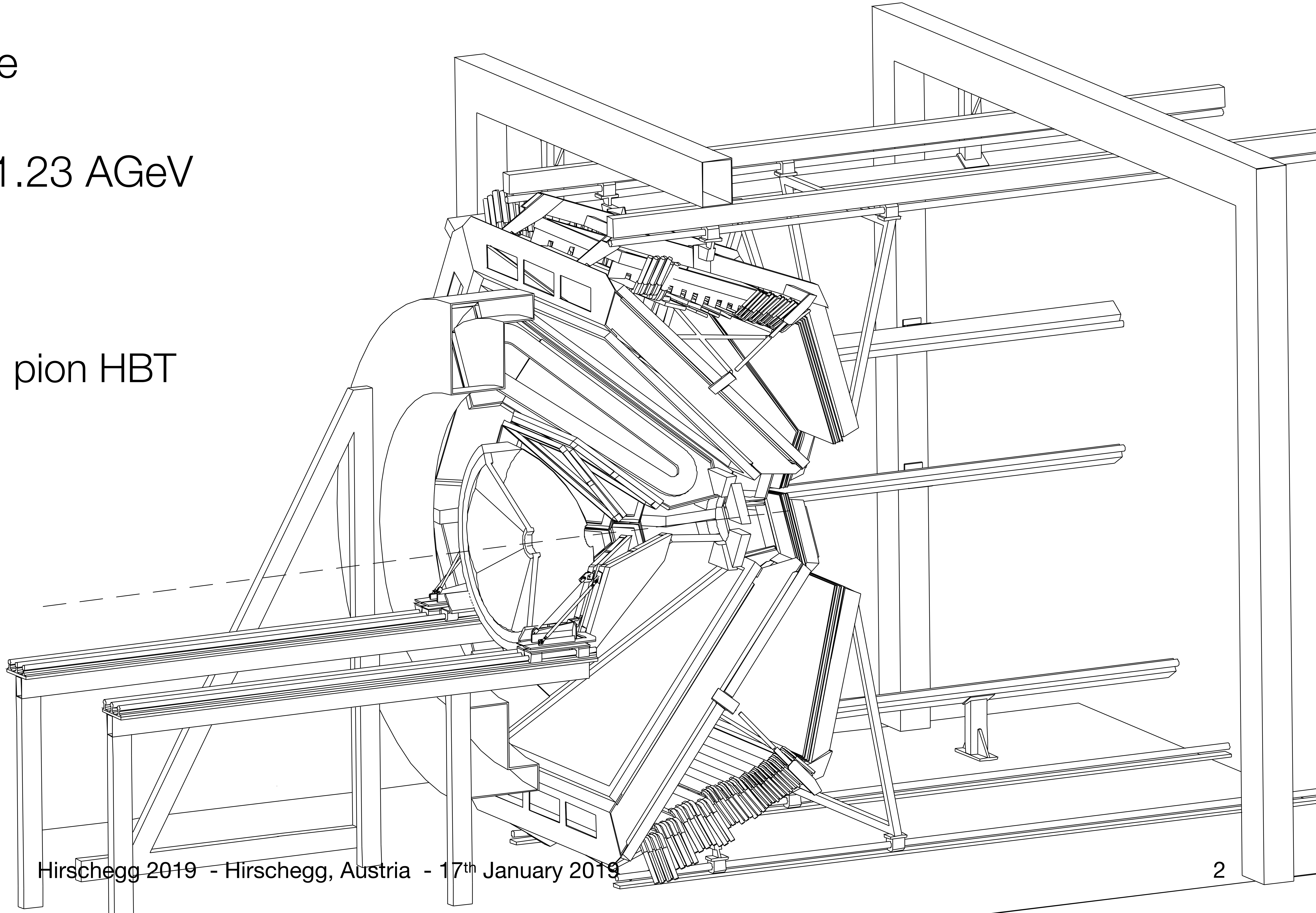
H-QM Helmholtz Research School Quark Matter Studies

HIC for FAIR
Helmholtz International Center

HADES

Outline

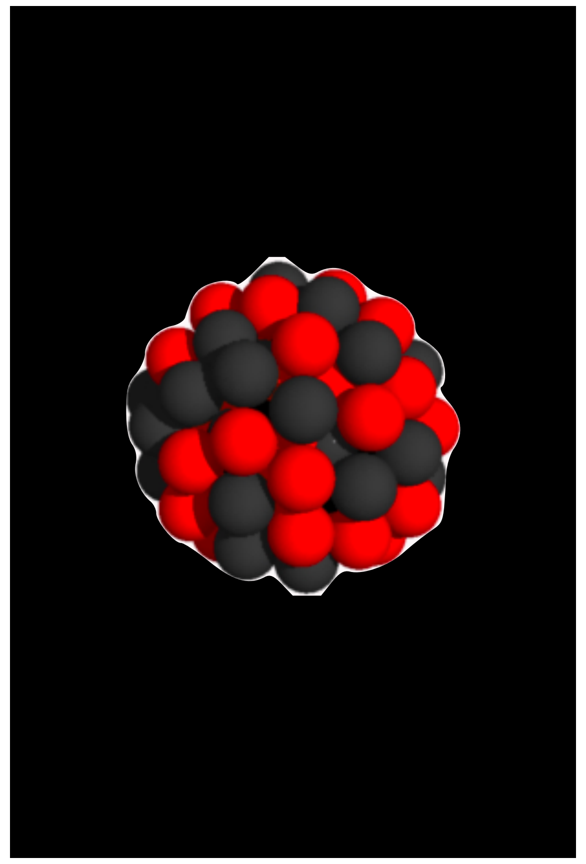
- Motivation: Equation-of-State
- HADES and Au+Au data at 1.23 AGeV
- Radial flow
  - Via Blast-Wave analysis and pion HBT
- Directed v_1, elliptic v_2, triangular $v_3\{\Psi_{RP}\}$ flow
  - Of protons, deuterons and tritons
- Quadrangular $v_4\{\Psi_{RP}\}$ flow



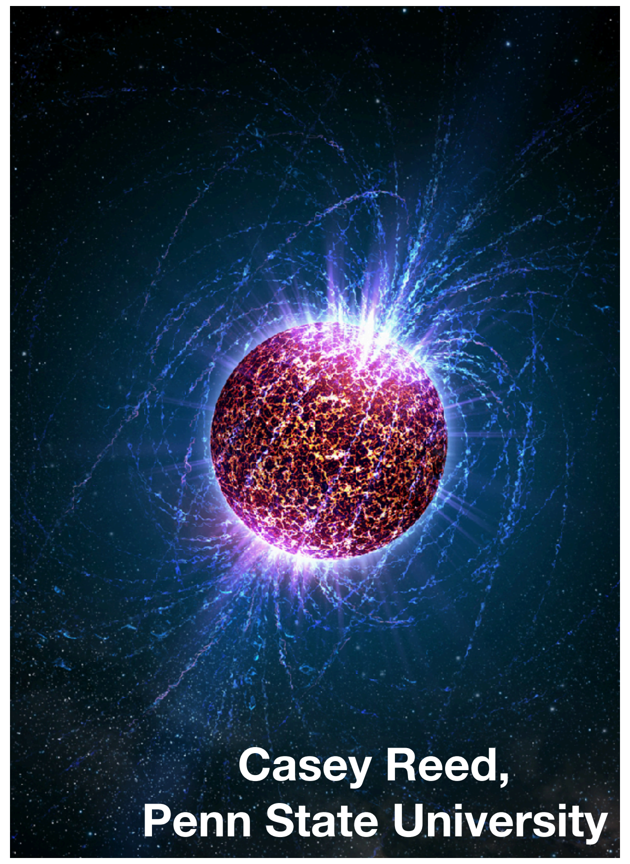
Motivation

Nuclear and Neutron Star Matter

Nuclei

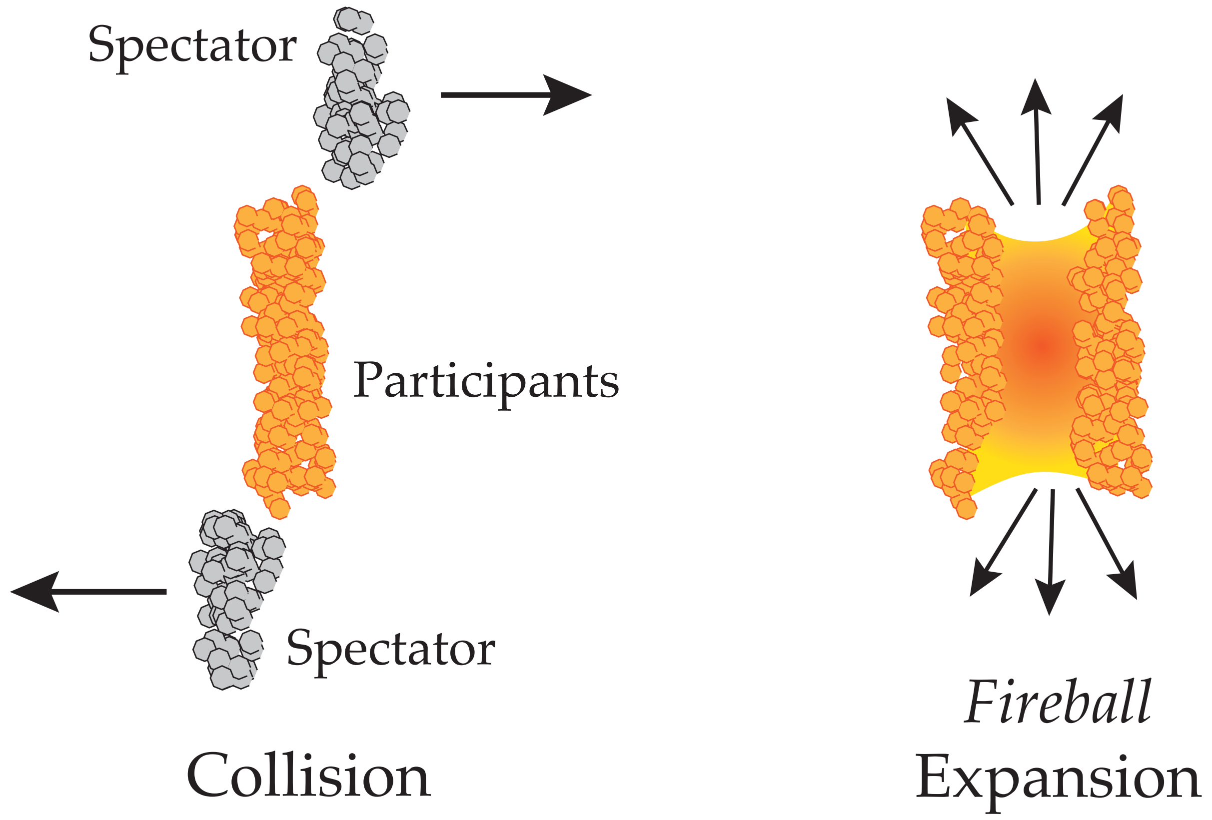


Neutron Star



Neutron Star Merger

Heavy Ion Collision



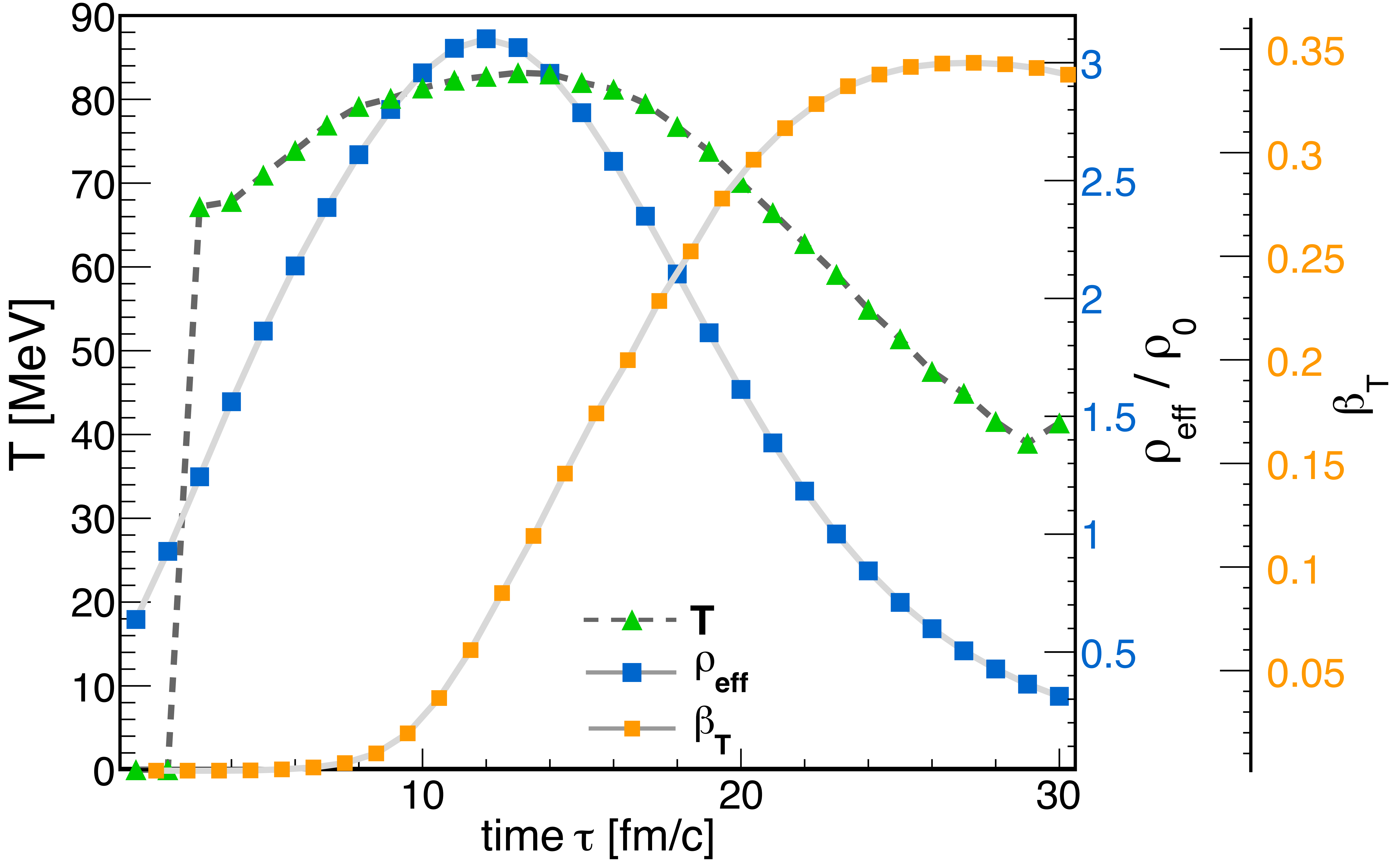
EoS

Motivation

Heavy Ion Collisions at 1.23A GeV

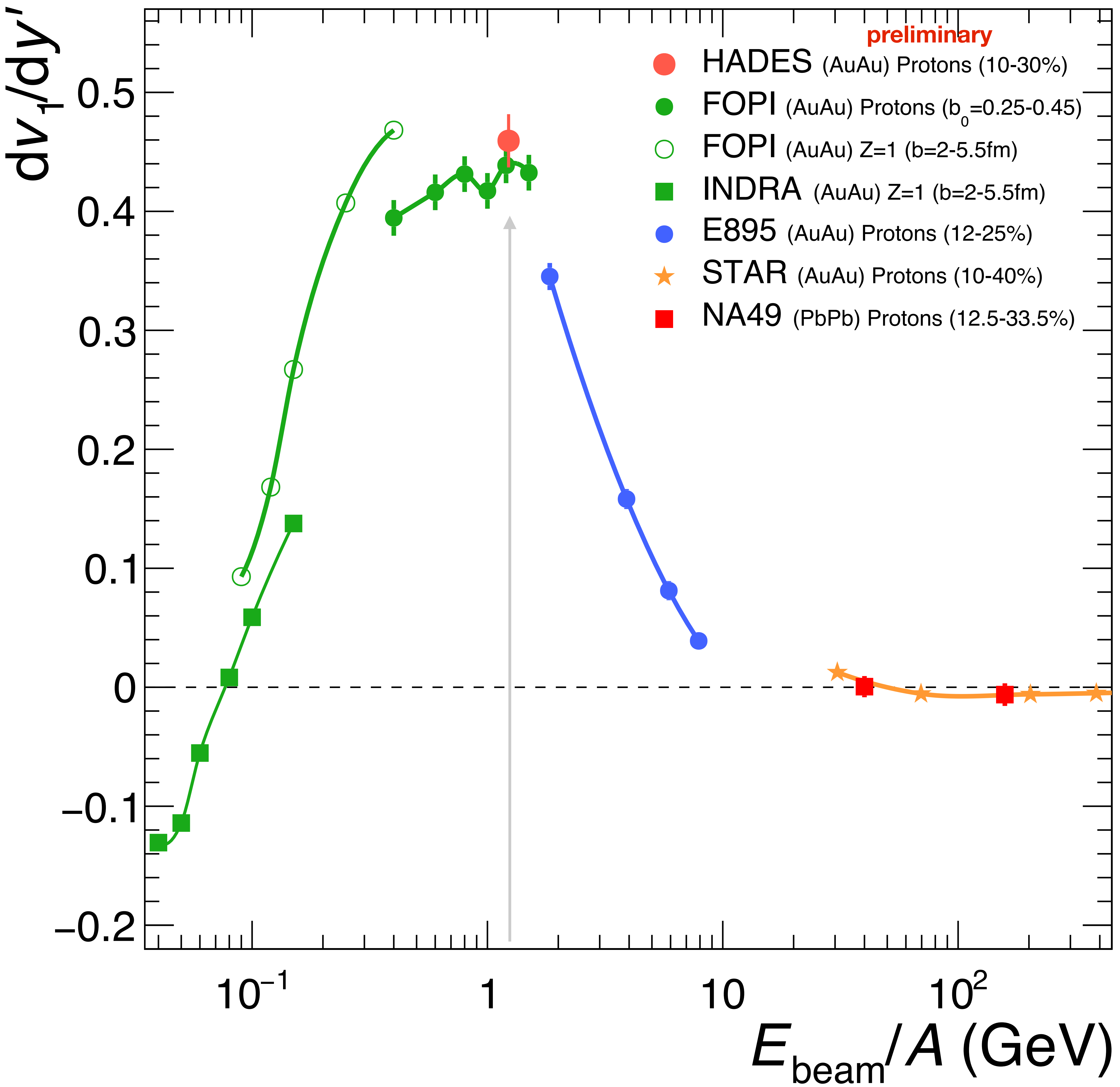
- High densities:
  ρ_{max} = 1-3ρ_0
- Moderate temperatures:
  T = 50-100 MeV
- Relatively long lifetime of fireball
- Significant transverse expansion expected

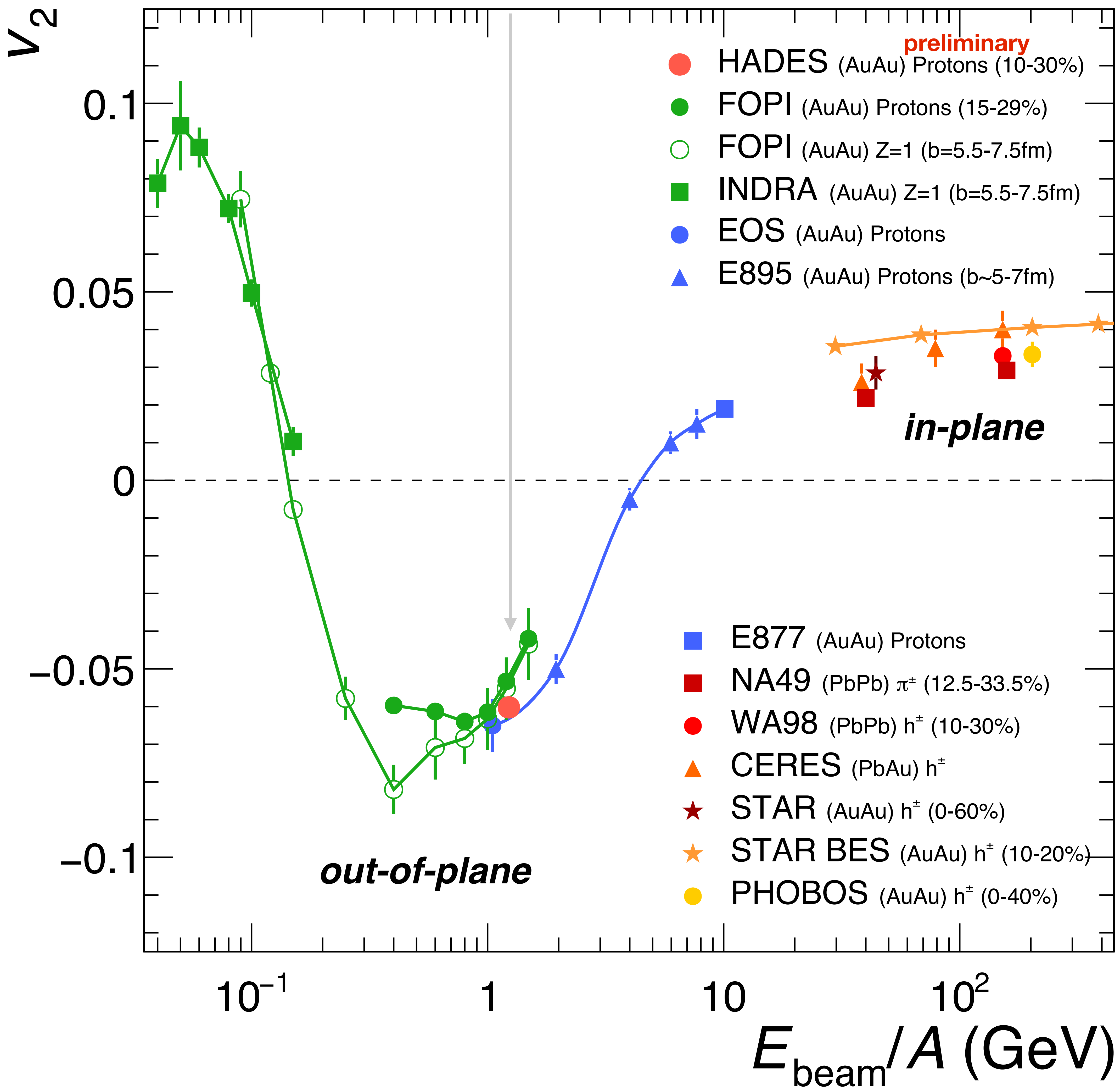
T. Galatyuk, F. Seck, et al.: Eur.Phys.J. A52 (2016) no.5, 131
UrQMD Au+Au 1.23AGeV



Motivation

Energy Dependence of Direct and Elliptic Flow



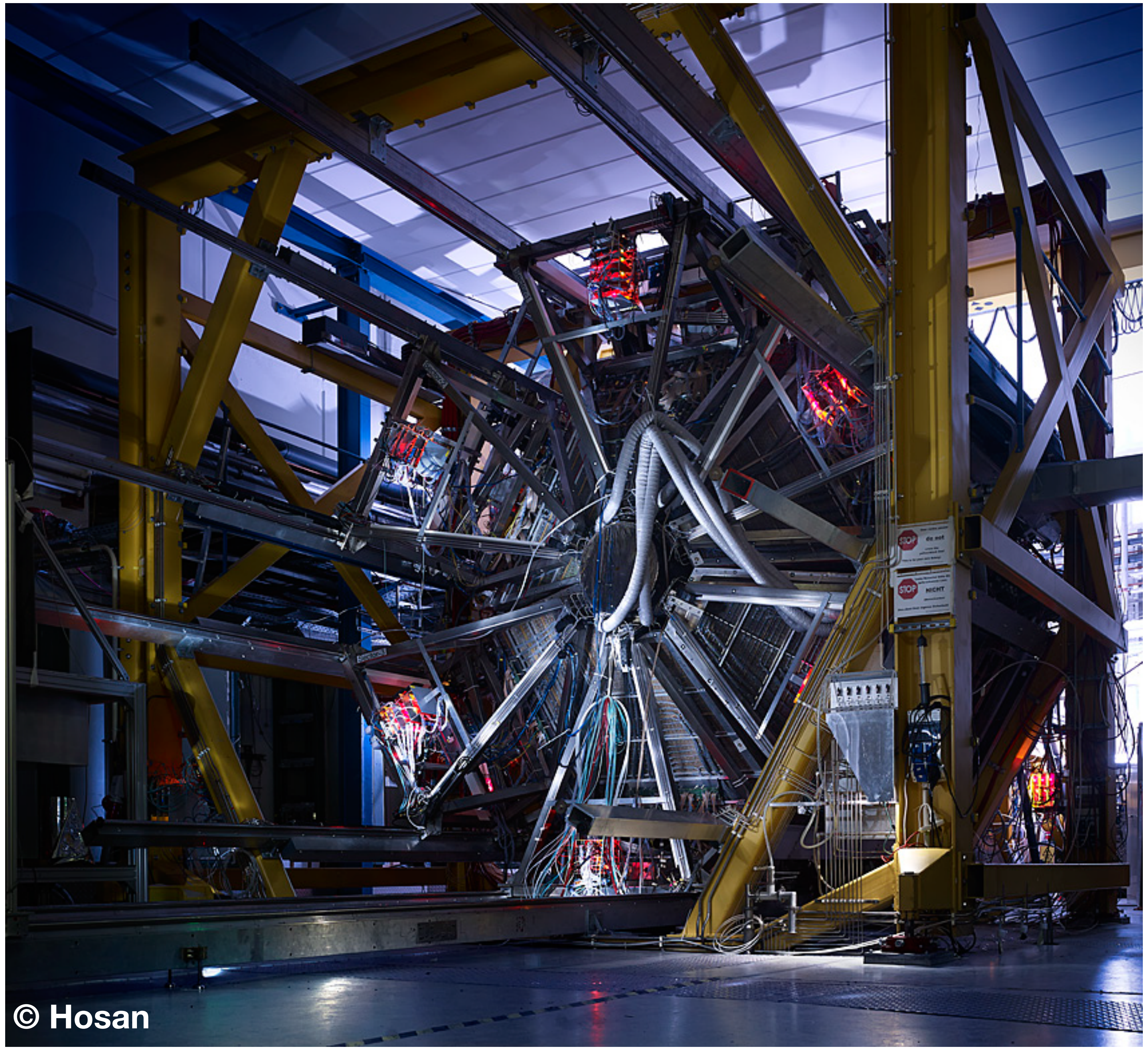


in-plane $v_2>0$
short spectator passing time
$\tau_{passing} \ll \tau_{expansion}$
pressure gradient

out-of-plane $v_2<0$
long spectator passing time
$\tau_{passing} \geq \tau_{expansion}$
squeeze-out

High Acceptance Di-Electron Spectrometer

- 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

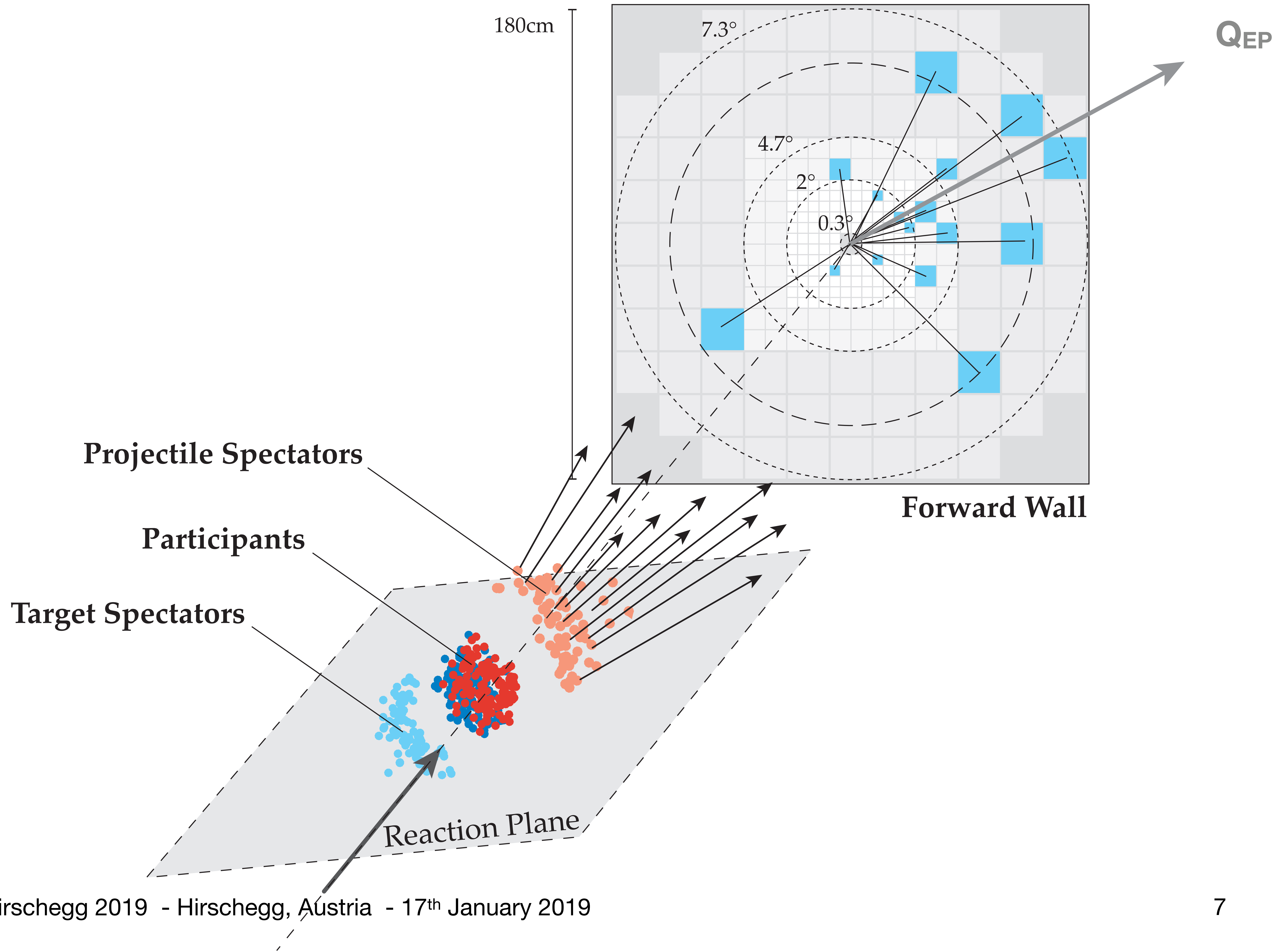


HADES Performance

Event Plane Reconstruction

- Based on hits of projectile spectators in the Forward Wall

$$\vec{Q}_{EP} = \sum_{i=0}^{N} \vec{u}_i$$



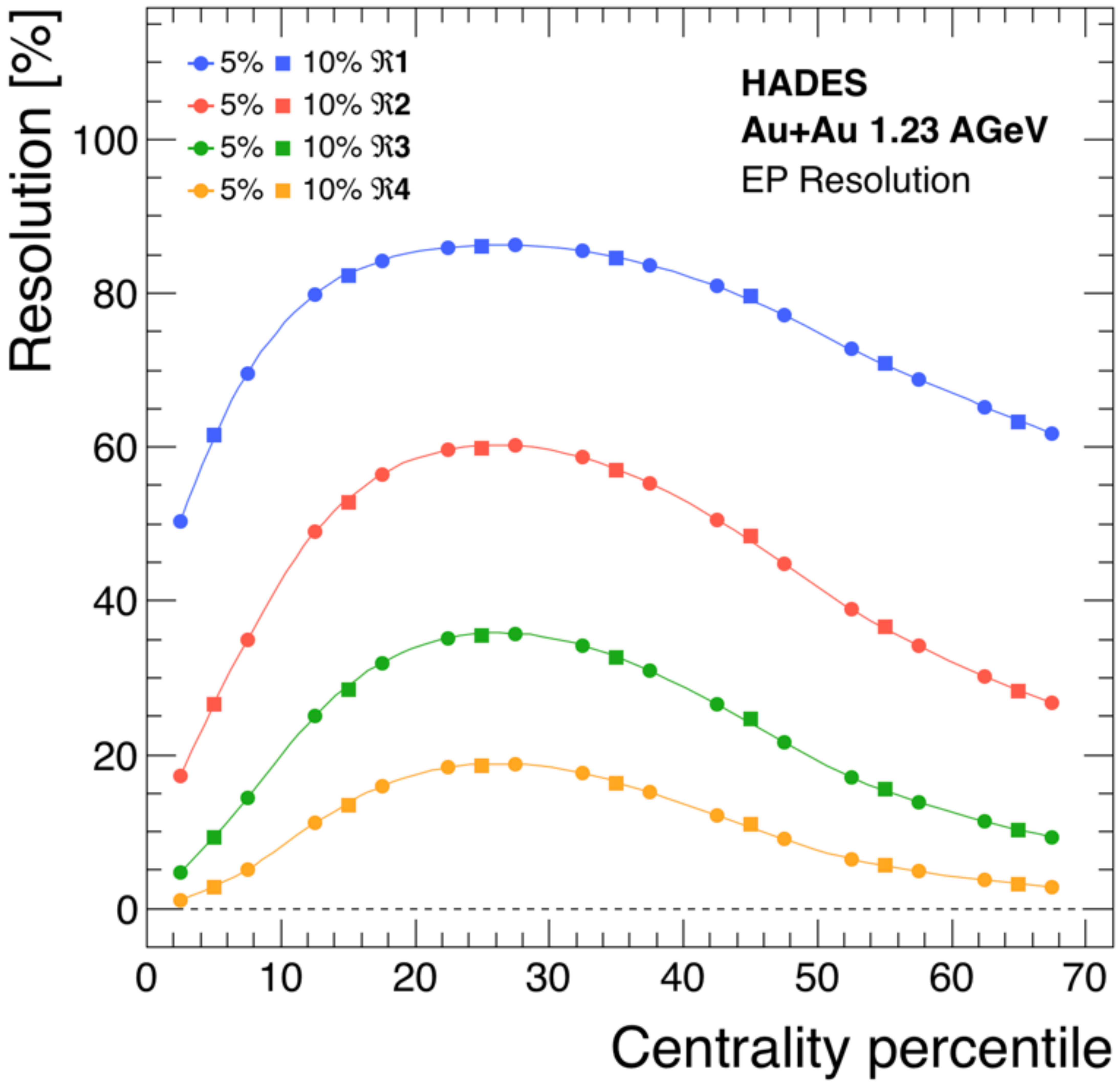
HADES Performance

Event Plane Resolution

- Calculation of full Resolution from sub-event Resolution
- Based on method described in J.-Y. Ollitrault, arXiv:nucl-ex/9711003

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

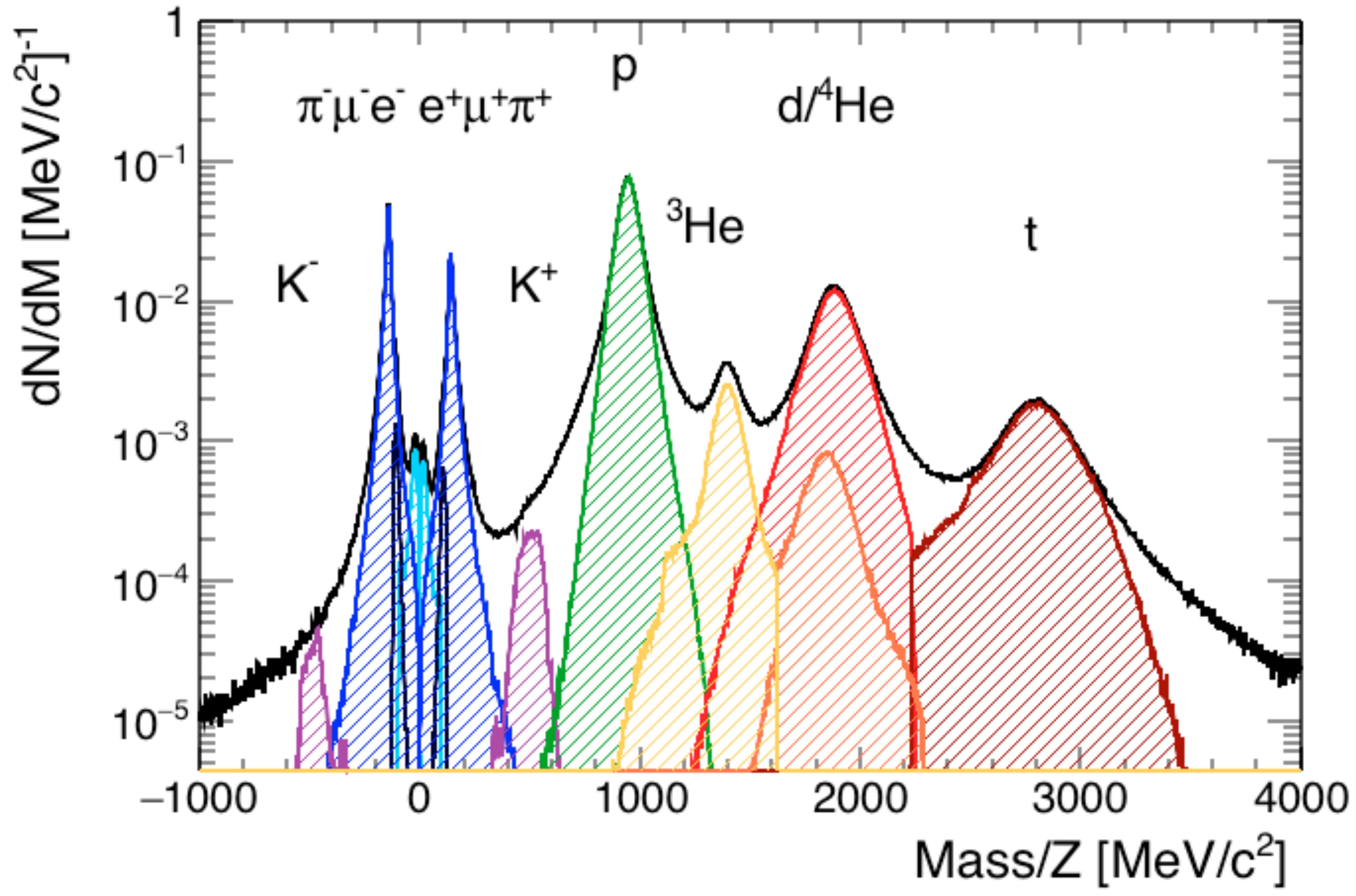
$$\boldsymbol{\mathfrak{R}_n} = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

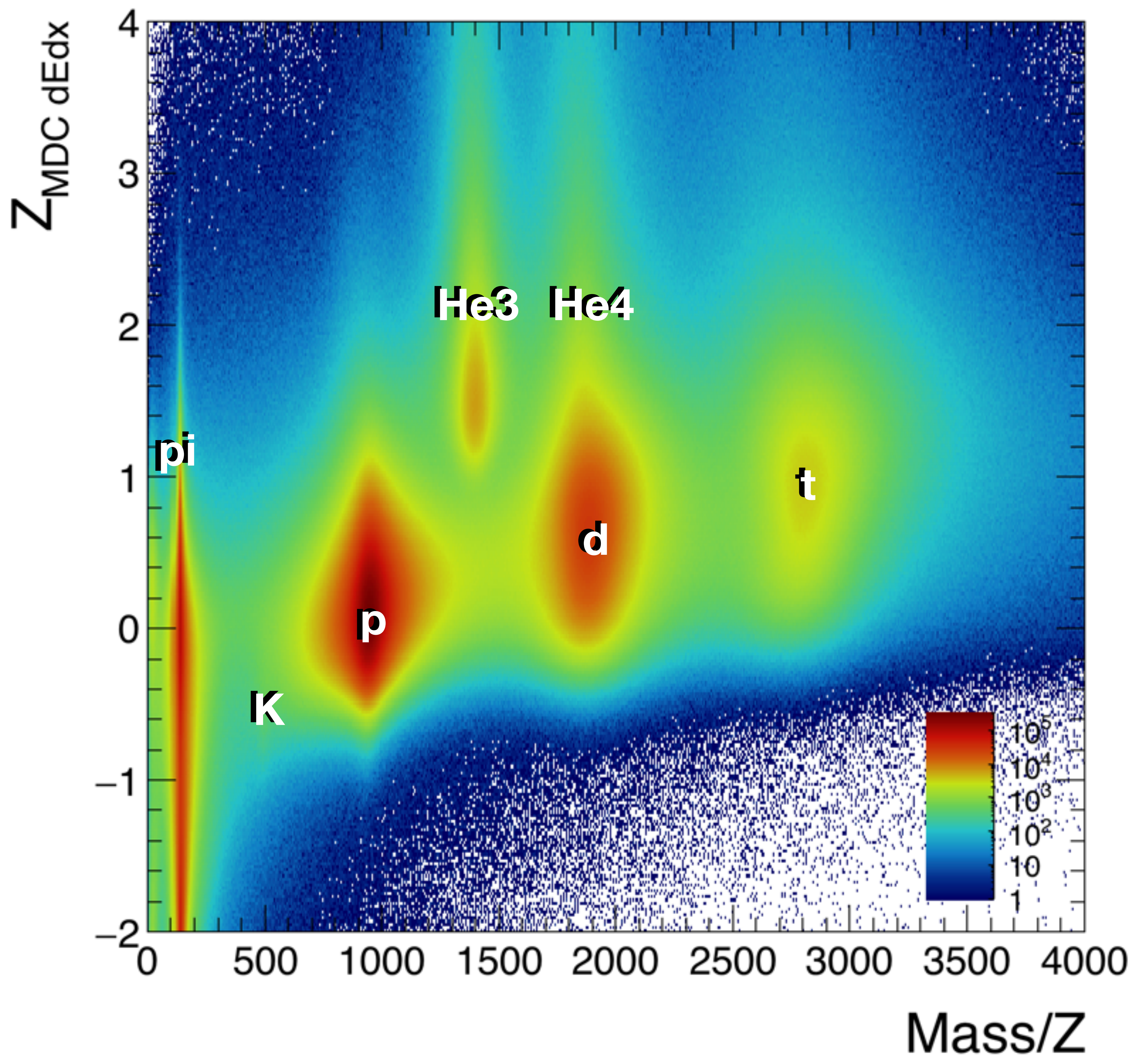


HADES Performance

Particle identification

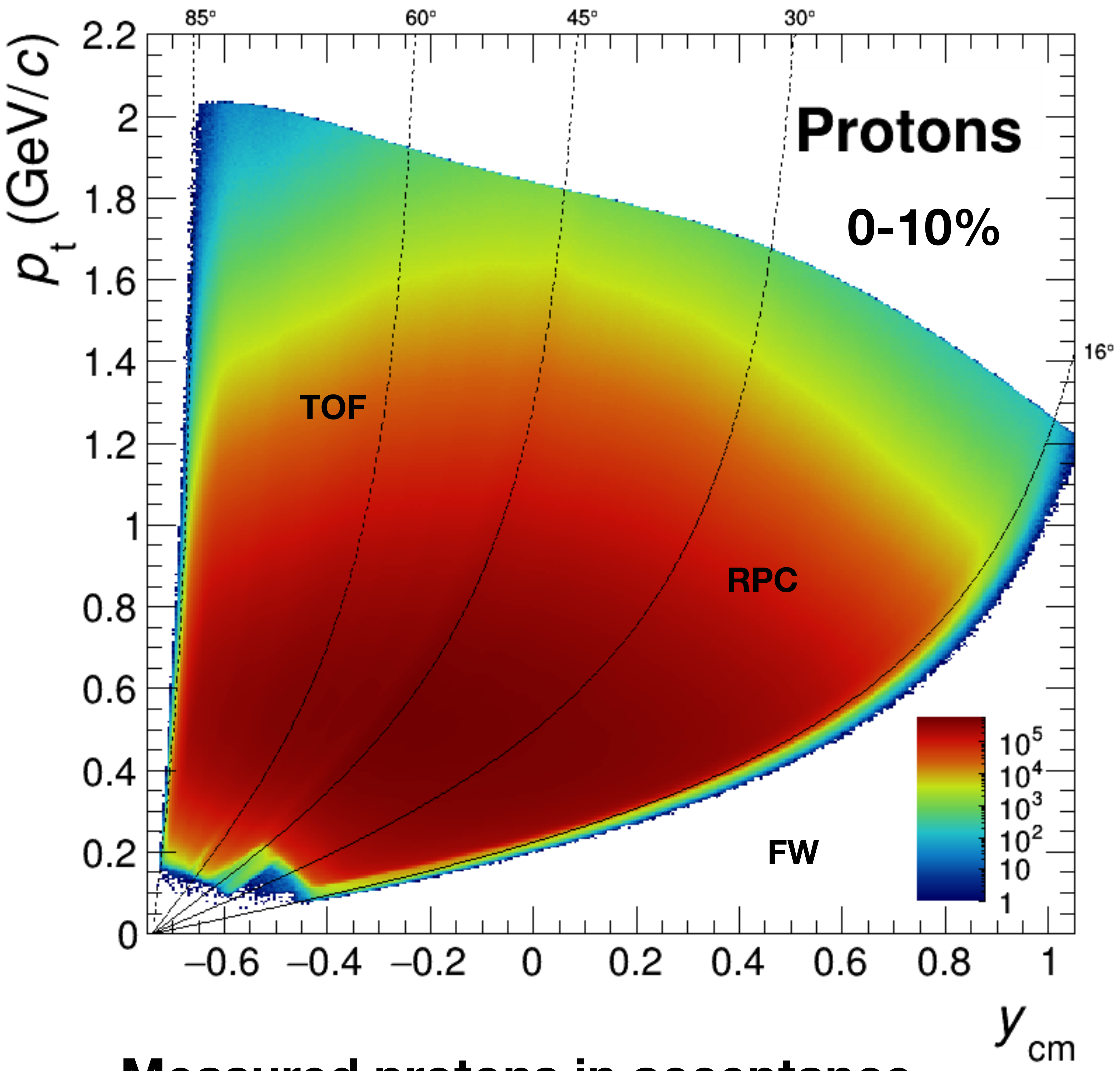
- Time-of-Flight (TOF and RPC)
- Energy loss in the MDC $Z_{MDC} = ln[\frac{(dE/dx)_{measured}}{(dE/dx)_{proton}}]$
  - Separation deuterons and He



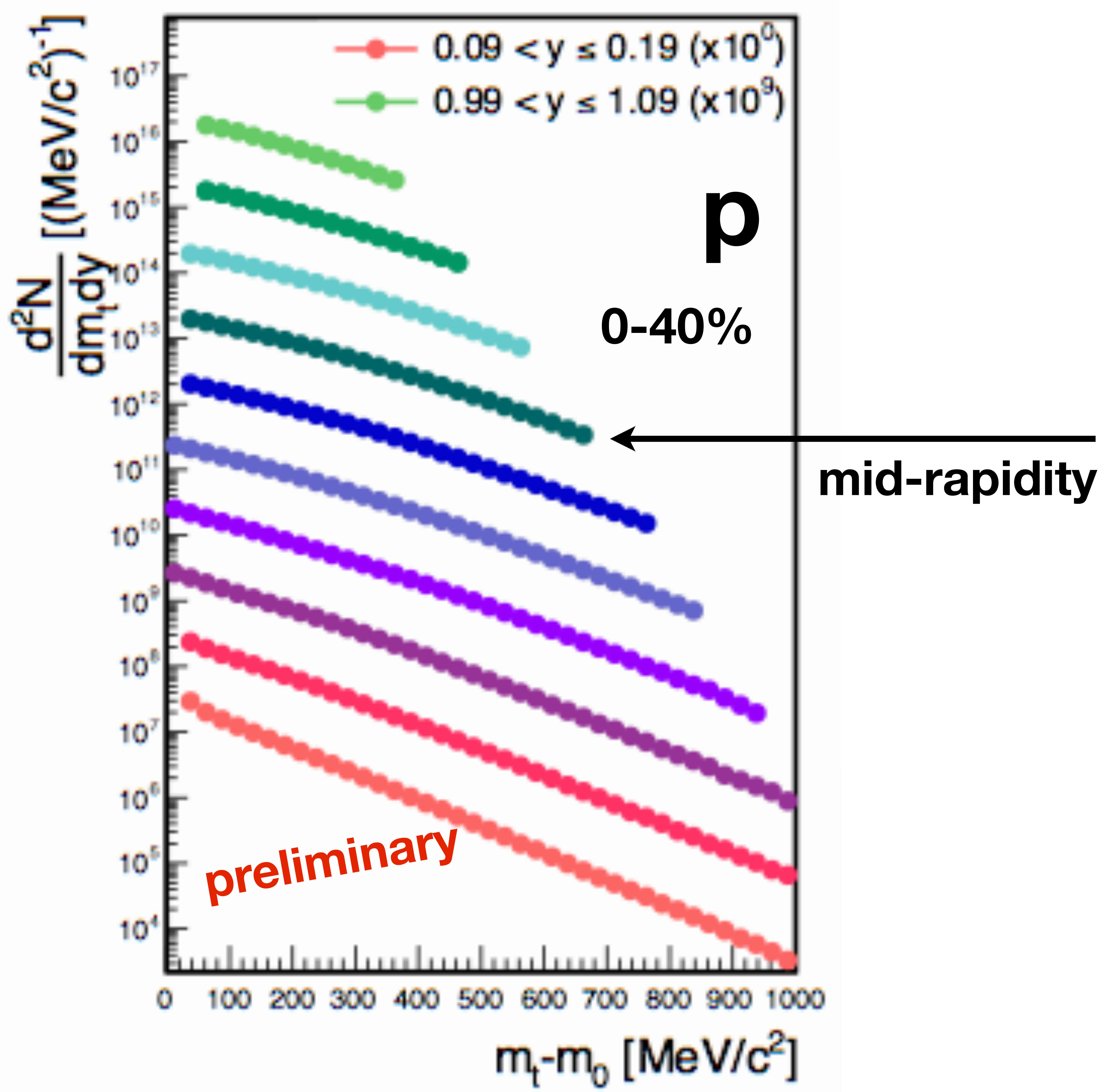


HADES Performance

Proton Spectra

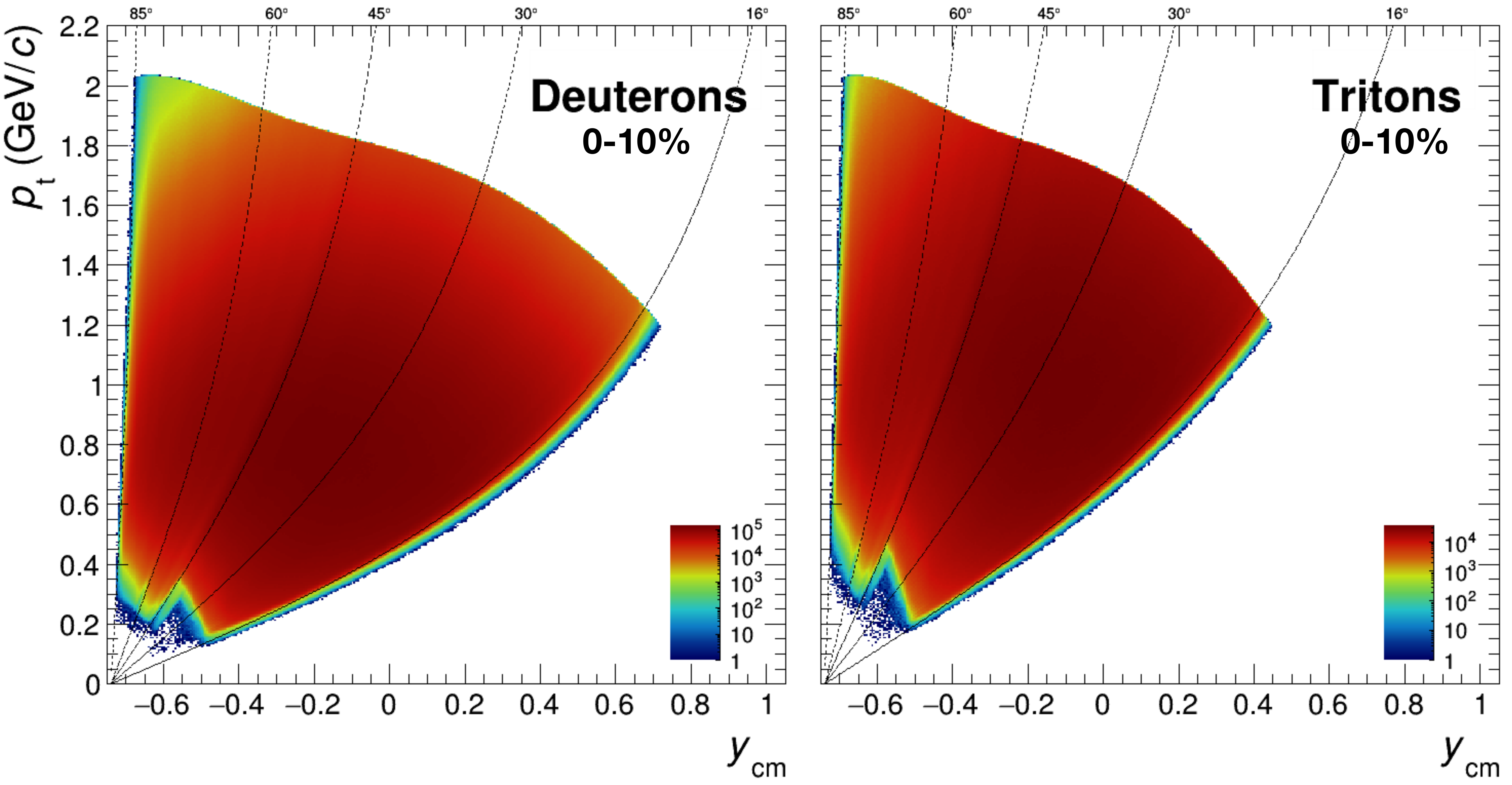


Measured protons in acceptance



HADES Performance

Acceptance for Deuterons and Tritons



Radial Flow

Transverse Momentum Spectra

Blast-Wave model:

Phys. Rev. C **48**, 2462

$$\frac{dN}{p_T\, dp_T} \propto \int_0^R r\, dr\, m_T I_0 \left(\frac{p_T \sinh \rho(r)}{T_{\rm kin}}\right) \times K_1 \left(\frac{m_T \cosh \rho(r)}{T_{\rm kin}}\right)$$

Linear radial flow velocity profile: $\beta = \beta_S (r/R)^n \quad n = 1$

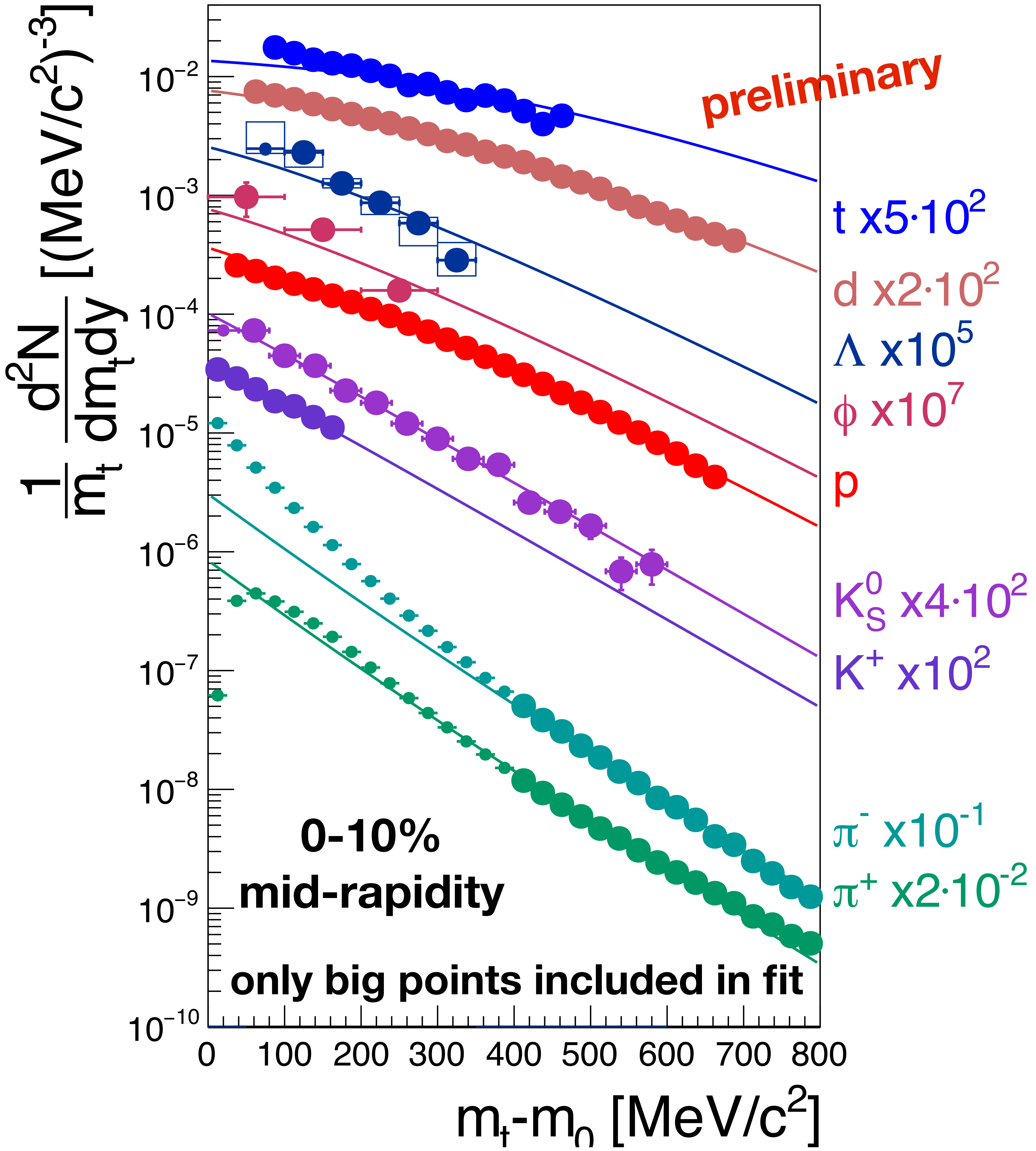
- Reasonable description of protons, light nuclei, kaons and pions (at higher mt)

$$T_{kin} = 66 \pm 8 \text{ MeV}$$

$$\langle \beta_r \rangle = 0.34 \pm 0.04$$

$$T_{chem} = 68 \pm 2(\text{stat.}) \text{ MeV}$$

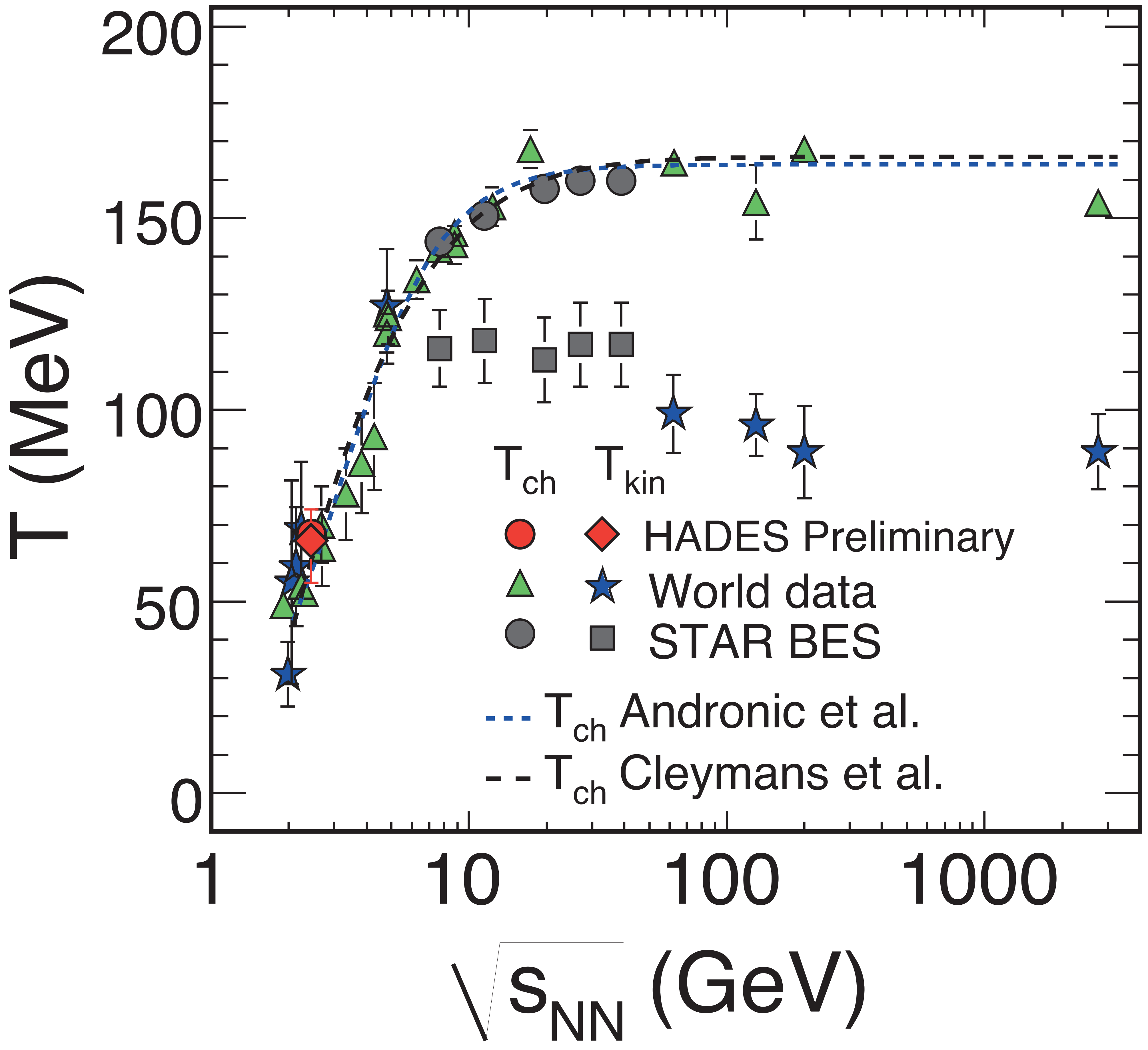
EPJ Web Conf. 171 (2018) 01001

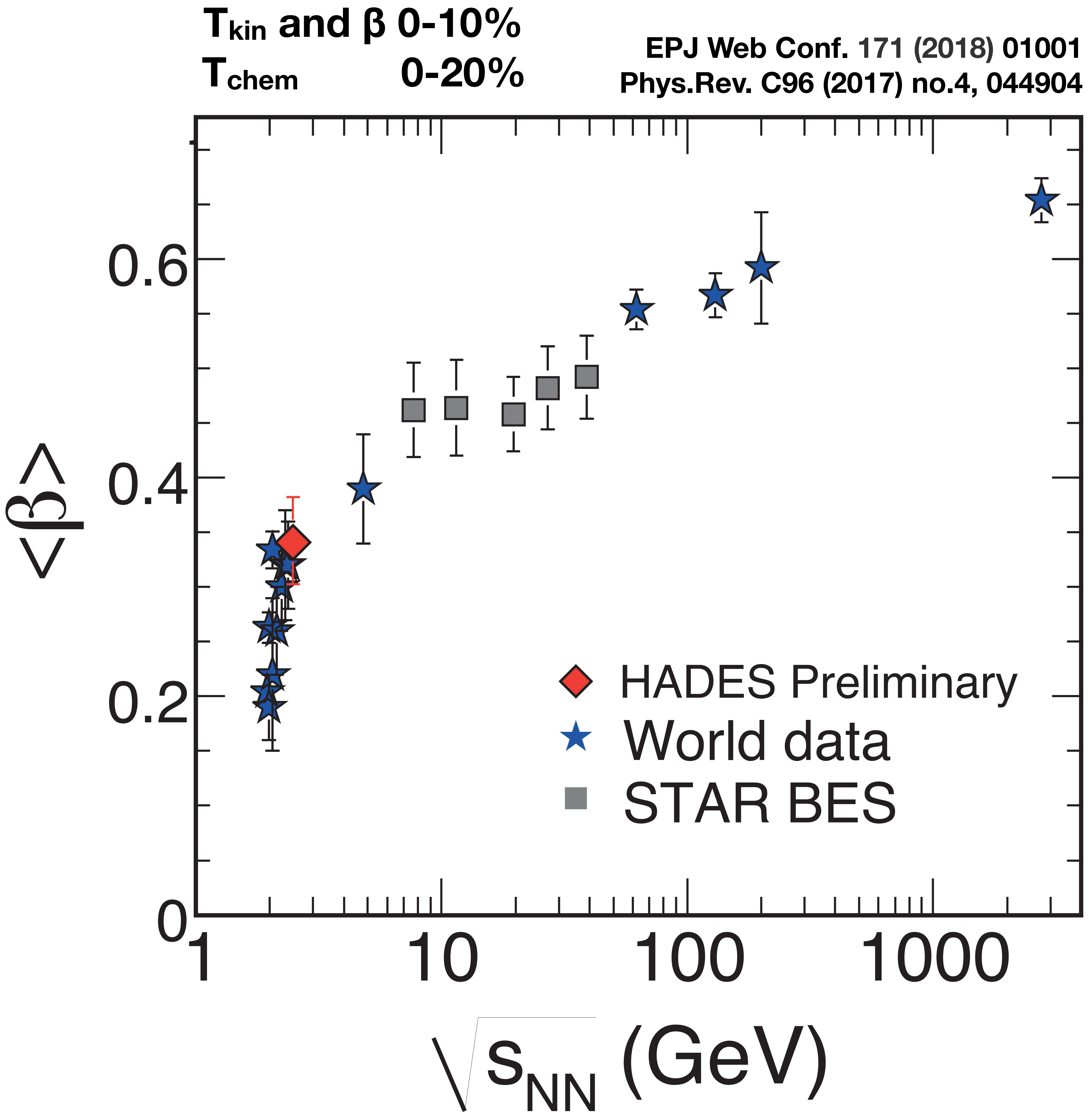


Radial Flow

Energy Dependence of Freeze-out Parameters

Parameters fit well into trend of world data





Radial Flow

HBT - Intensity Interferometry

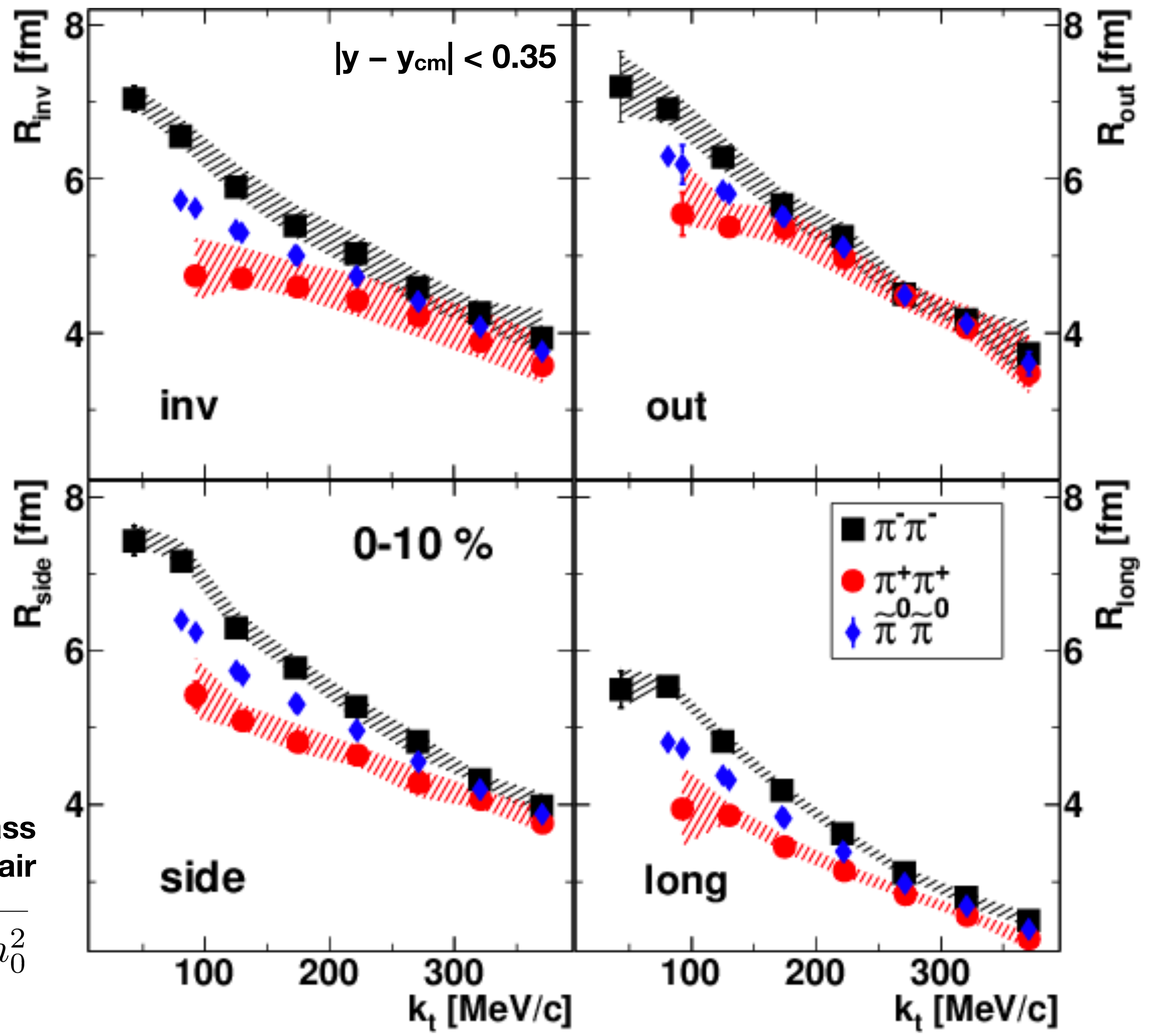
- First measurement of pion HBT in Au+Au collisions at 1.23 AGeV
- R_{side}: smaller radii for higher pair transverse momenta:

  → Radial flow

- Accounting for Coulomb potential

  → First time such substantial difference!

arXiv:1811.06213



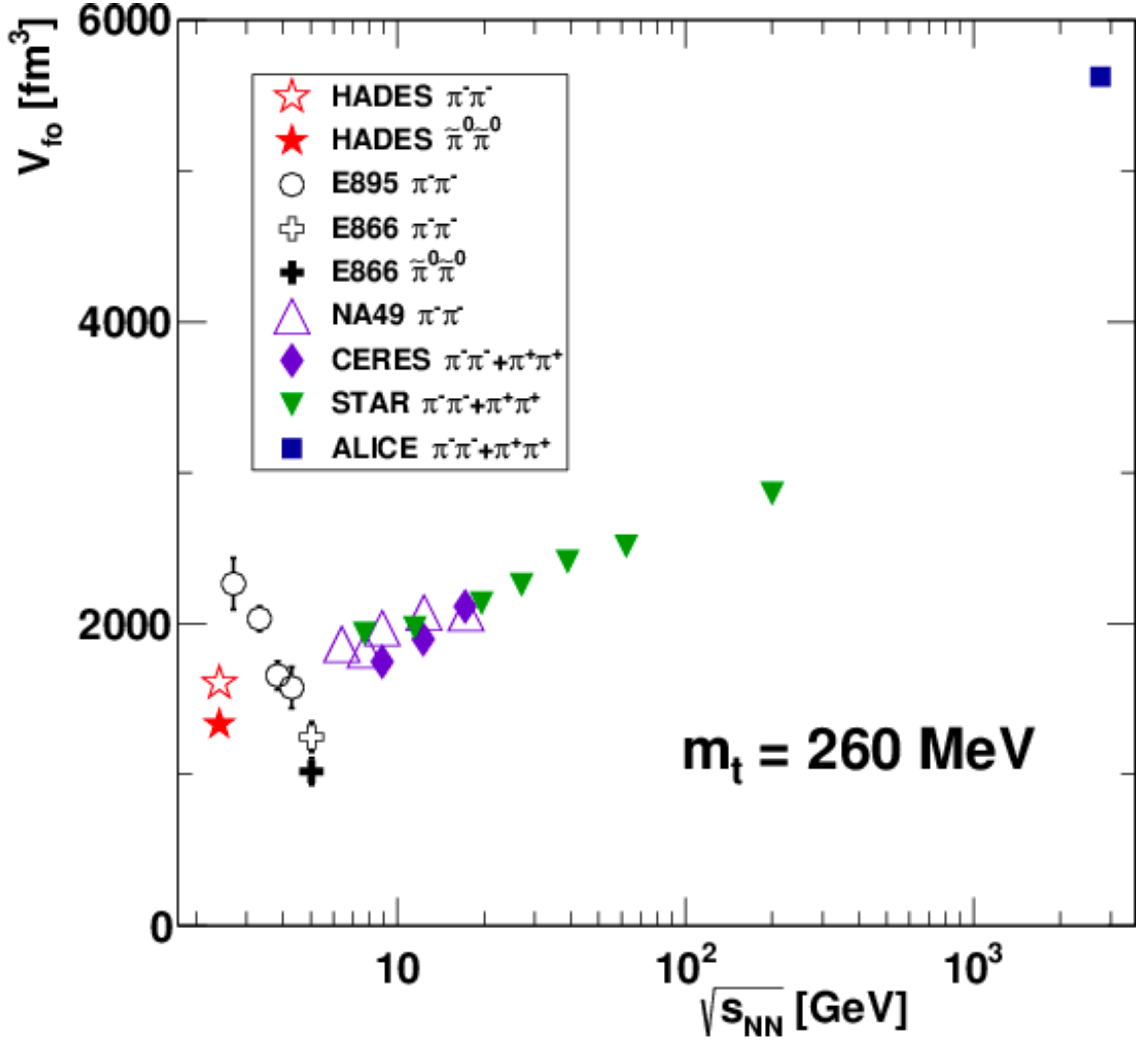
m_T: transverse mass of the pair

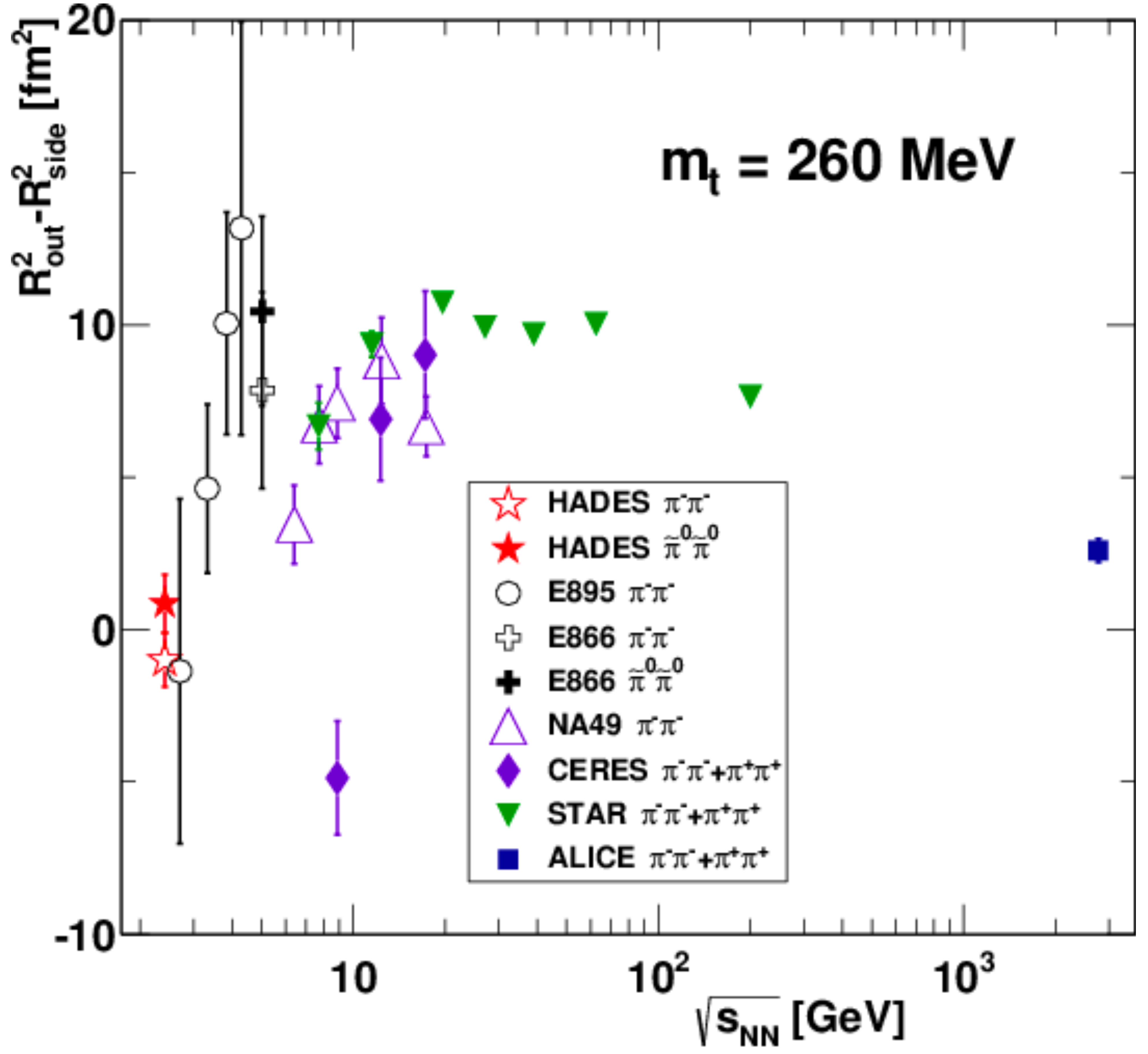
$$m_T = \sqrt{k_t^2 + m_0^2}$$

Radial Flow

HBT - Intensity Interferometry

arXiv:1811.06213



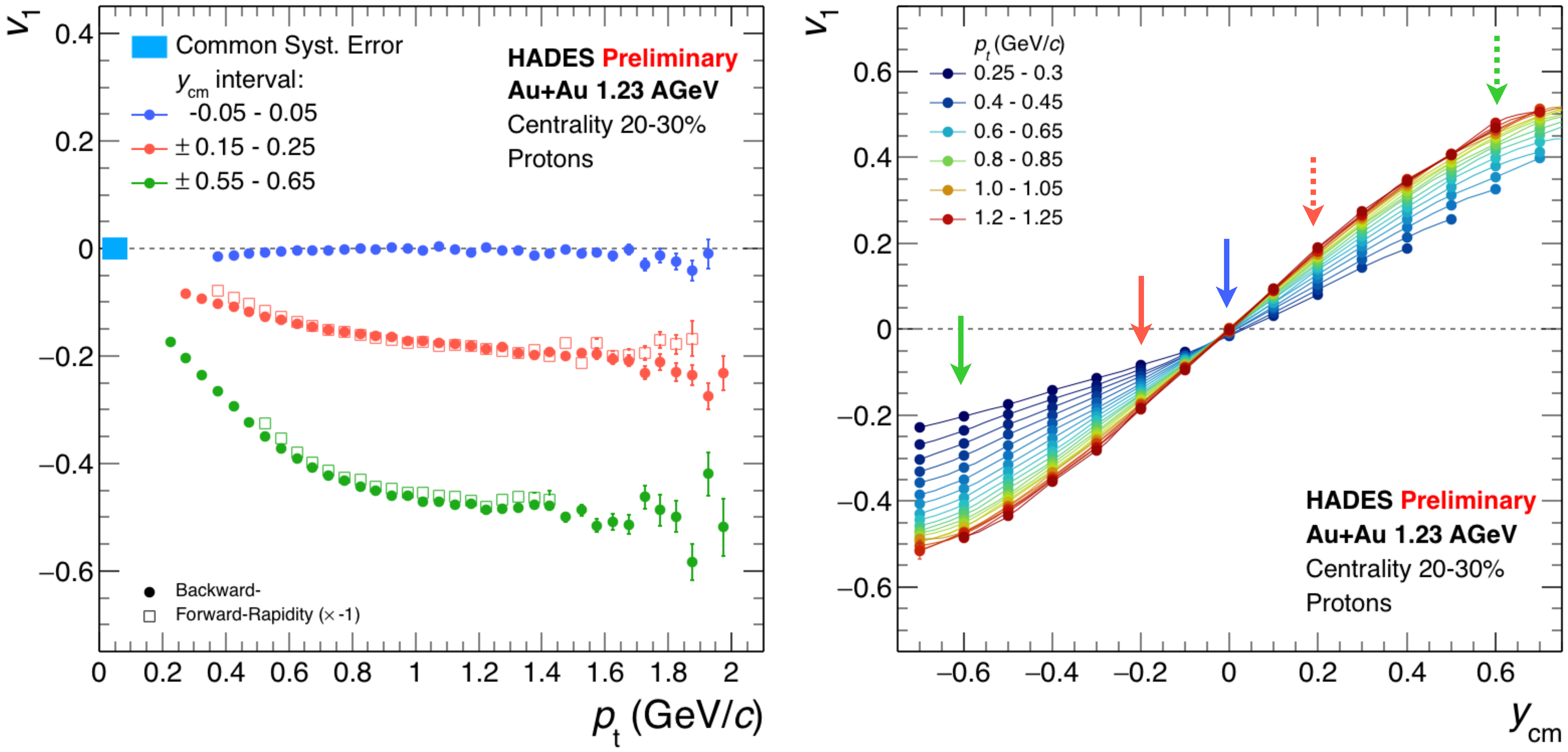


$$V_{\text{fo}} = (2\pi)^{3/2} R^2_{\text{side}} R_{\text{long}} \approx 1300\ \text{fm}^3$$

Directed Flow v_1: Protons

p_t-Dependence

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

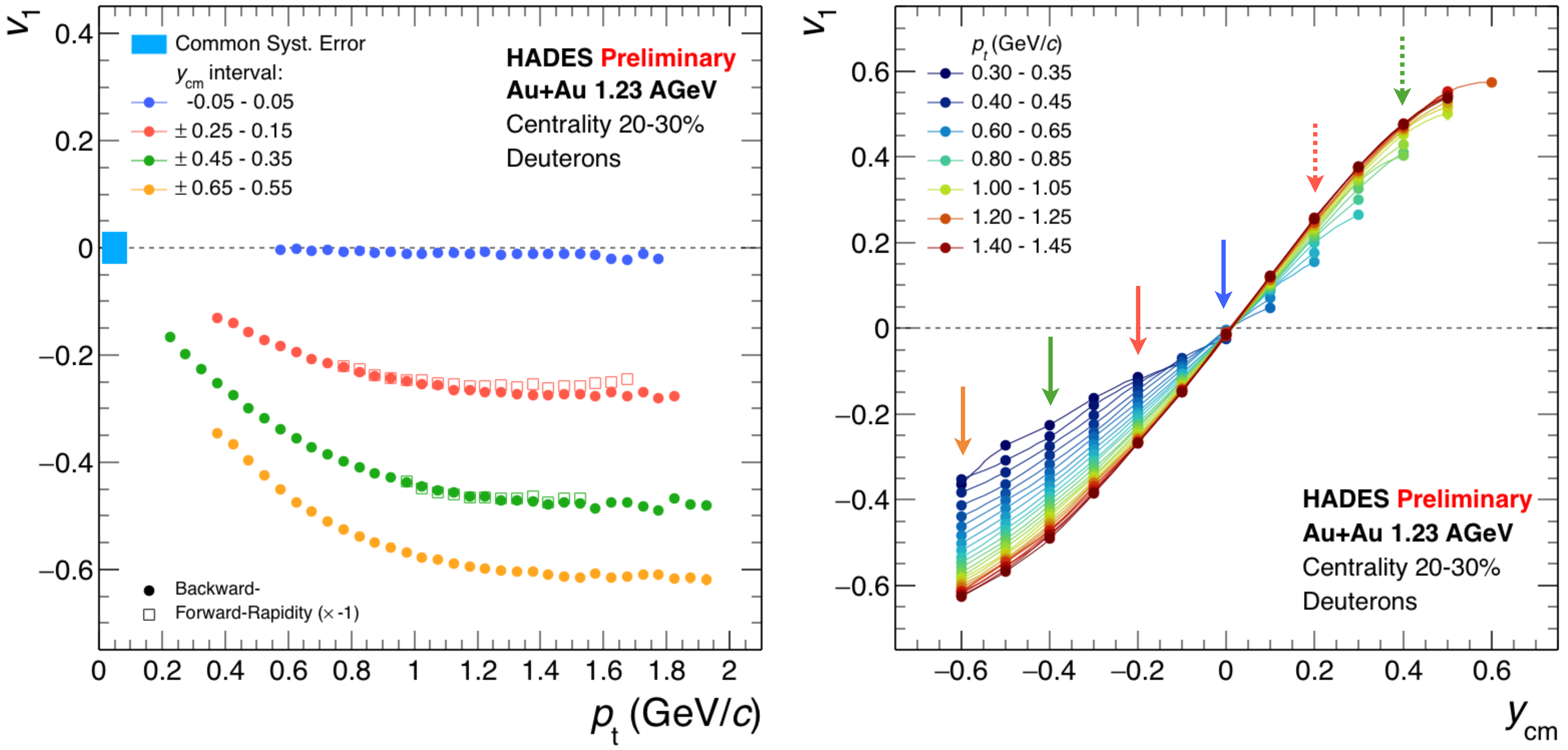


Good agreement between backward and forward rapidity bins

Directed Flow v_1: Deuterons

p_t-Dependence

QM18, arXiv:1809.07821

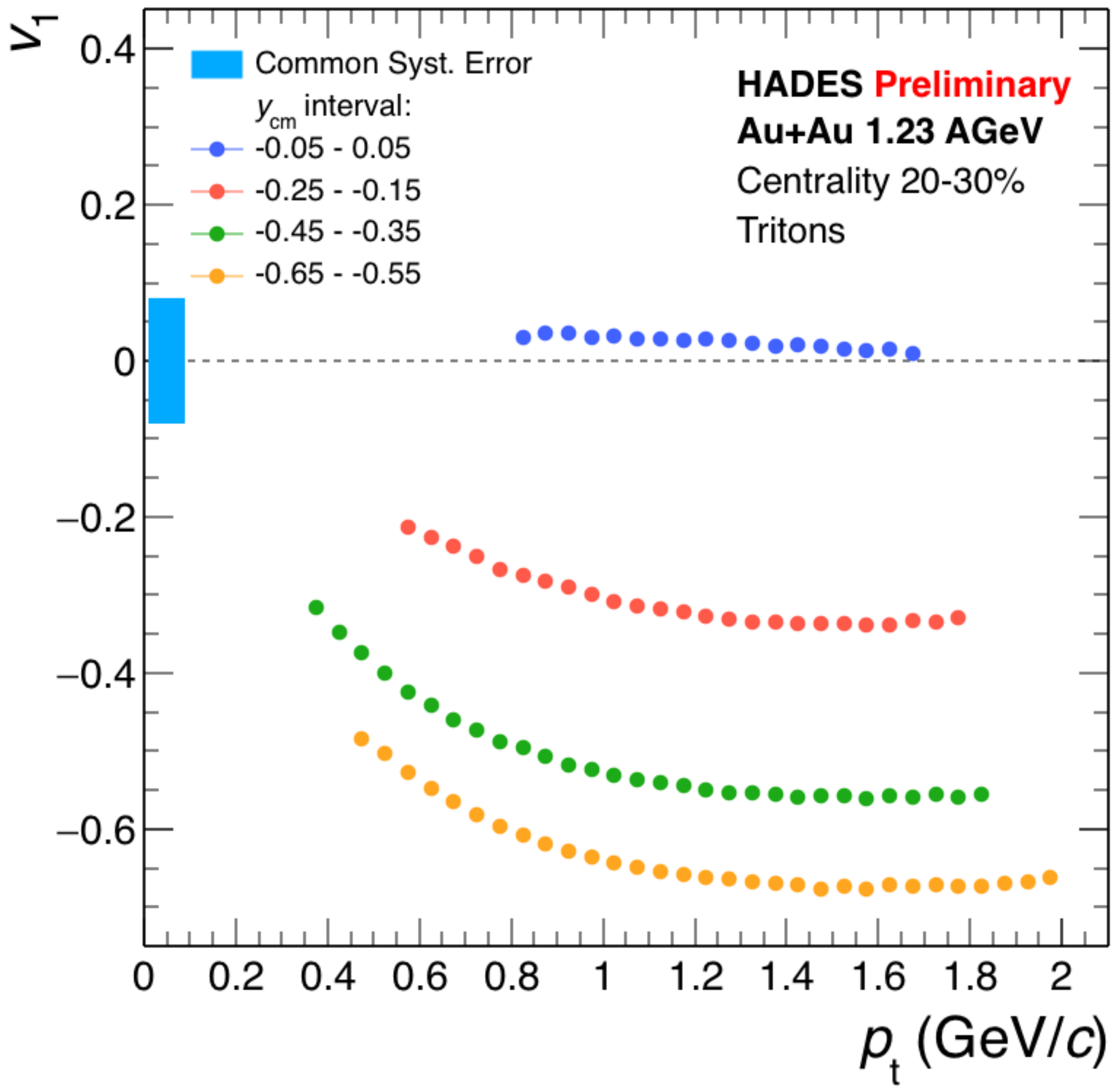


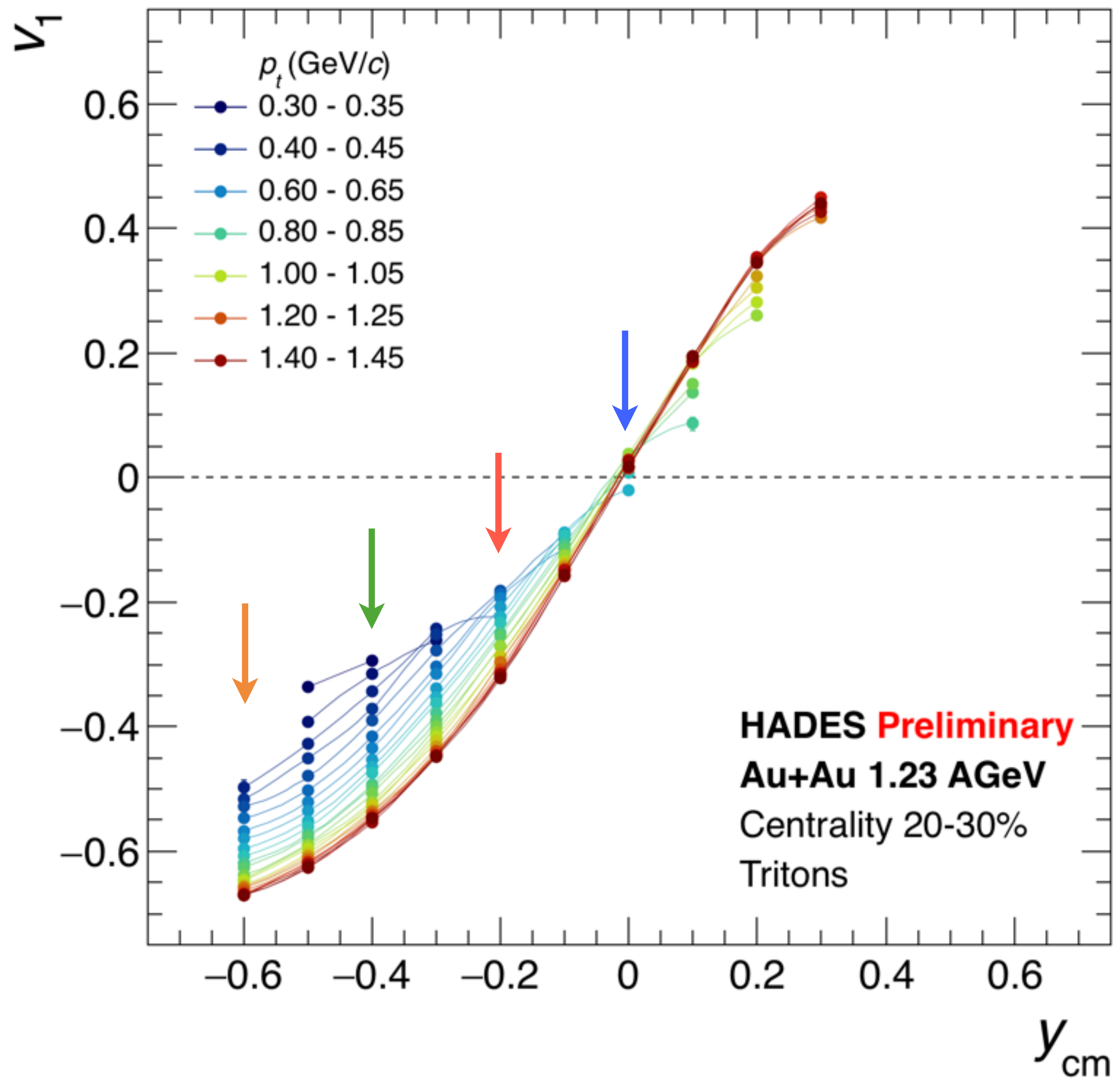
Good agreement between backward and forward rapidity bins

Directed Flow v_1: Tritons

p_t-Dependence

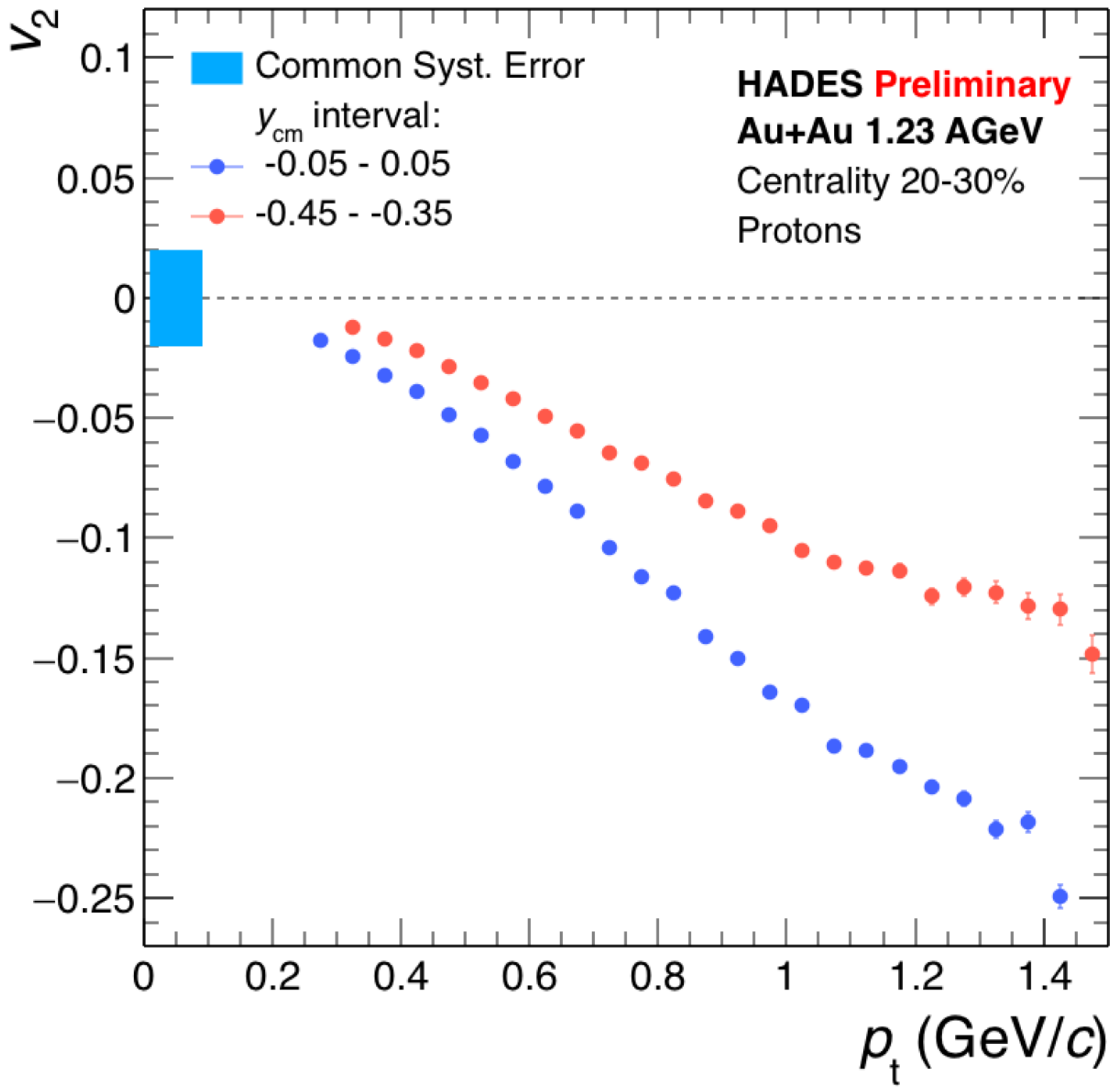
QM18, arXiv:1809.07821



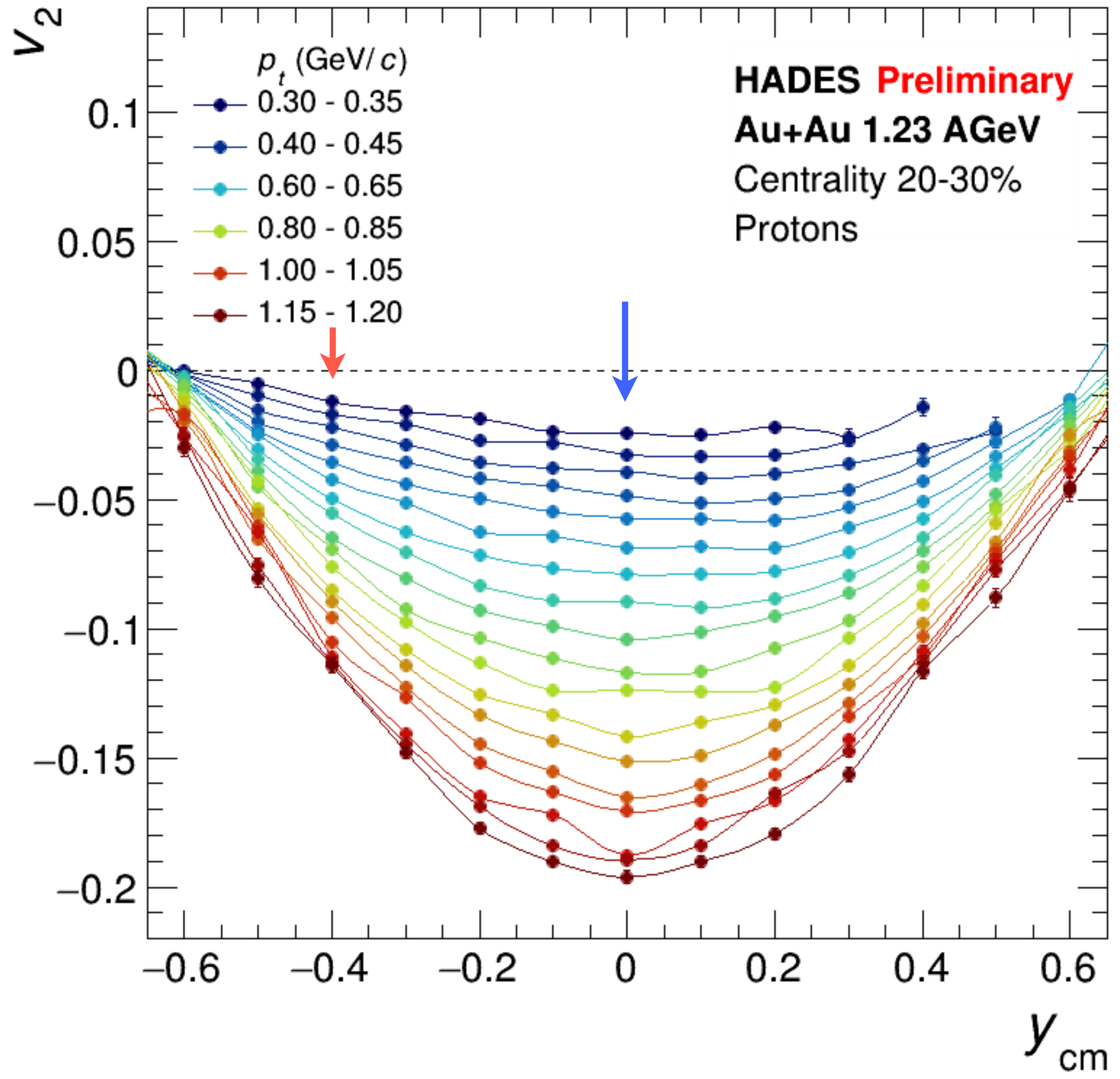


Elliptic Flow v_2: Proton

p_t-Dependence

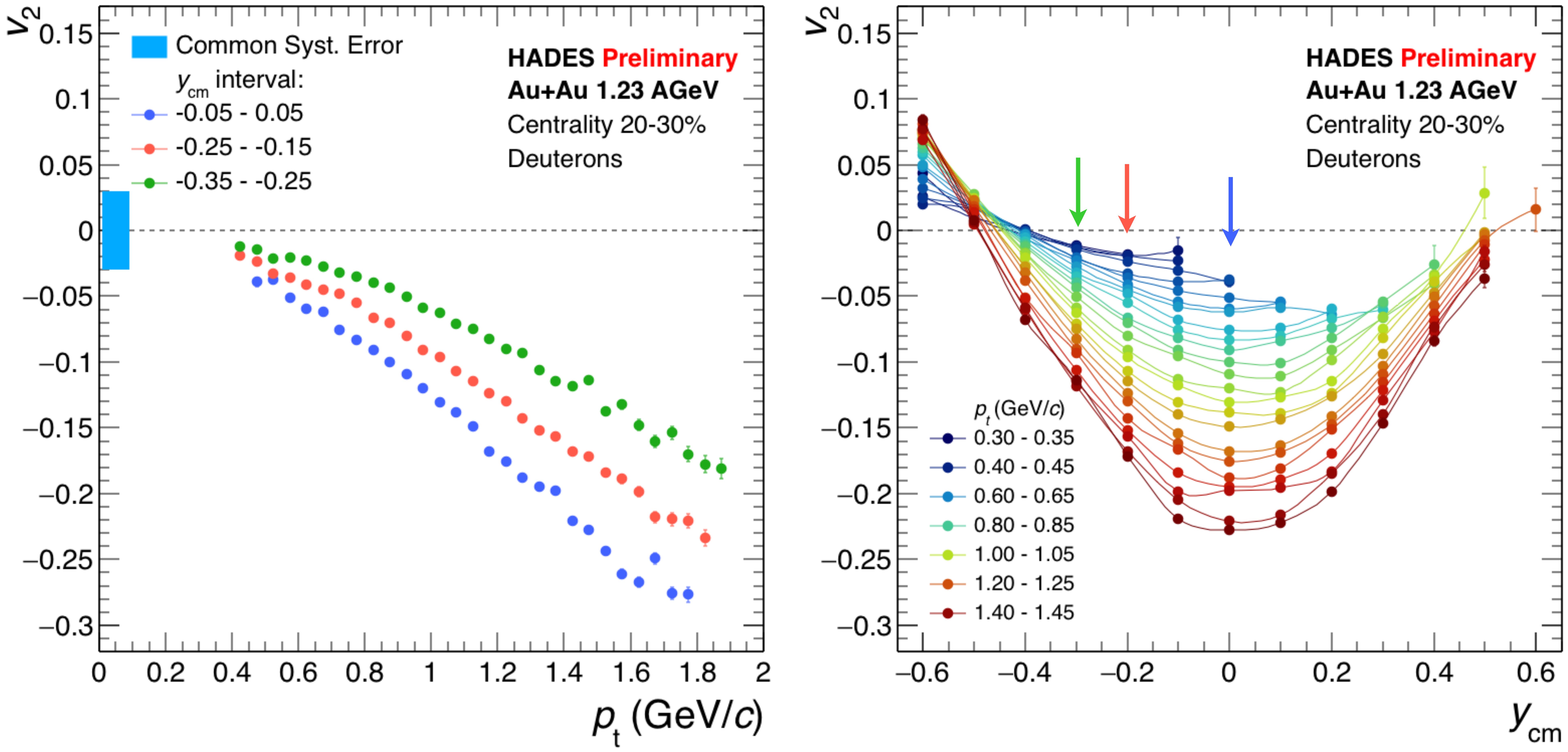


QM17, Nucl.Phys. A967 (2017) 812-815



Elliptic Flow v_2: Deuterons
p_t-Dependence

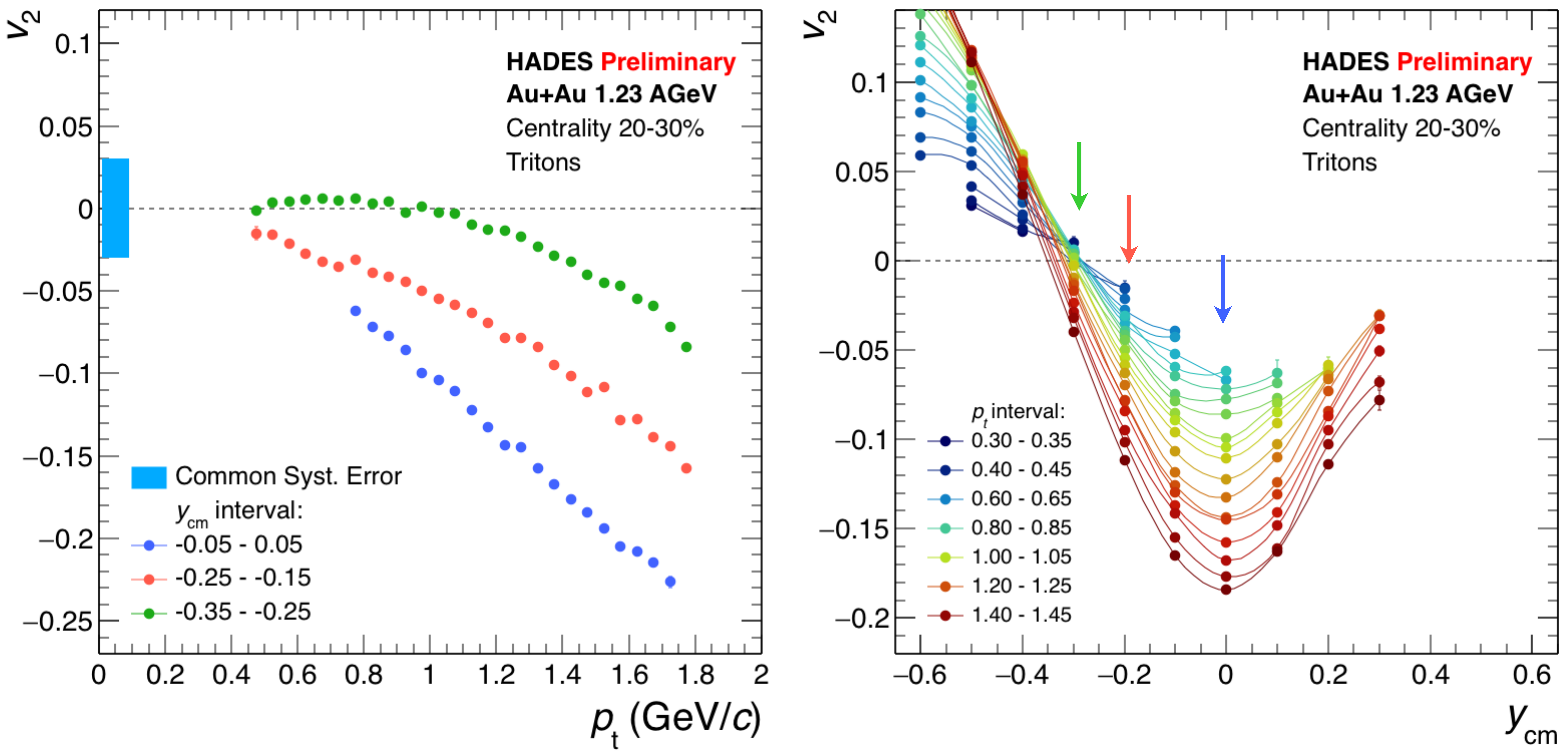
QM18, arXiv:1809.07821



Elliptic Flow v_2: Tritons

p_t-Dependence

QM18, arXiv:1809.07821

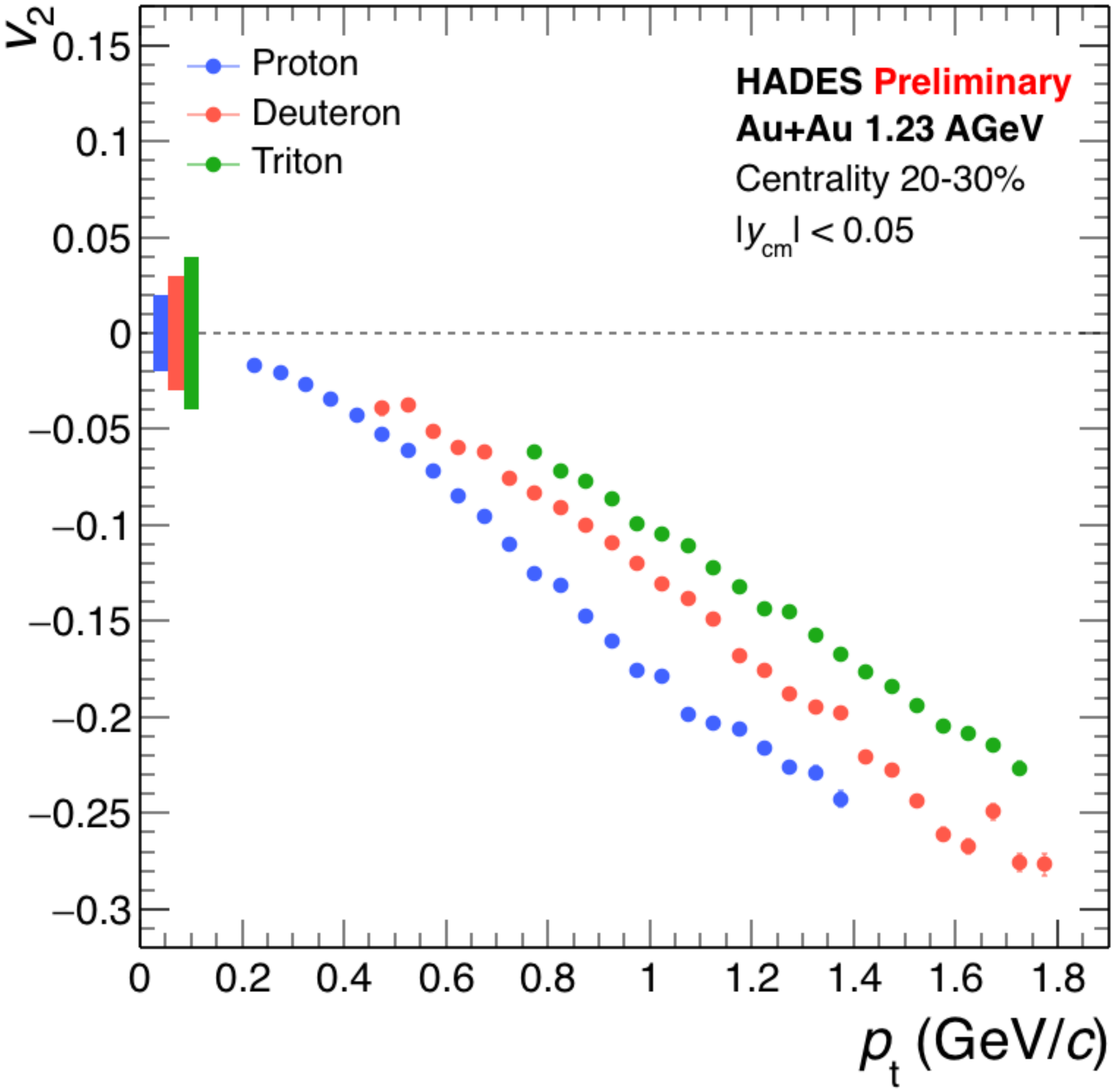


Elliptic Flow v_2: Light Nuclei

Nucleon Coalescence

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

QM18, arXiv:1809.07821

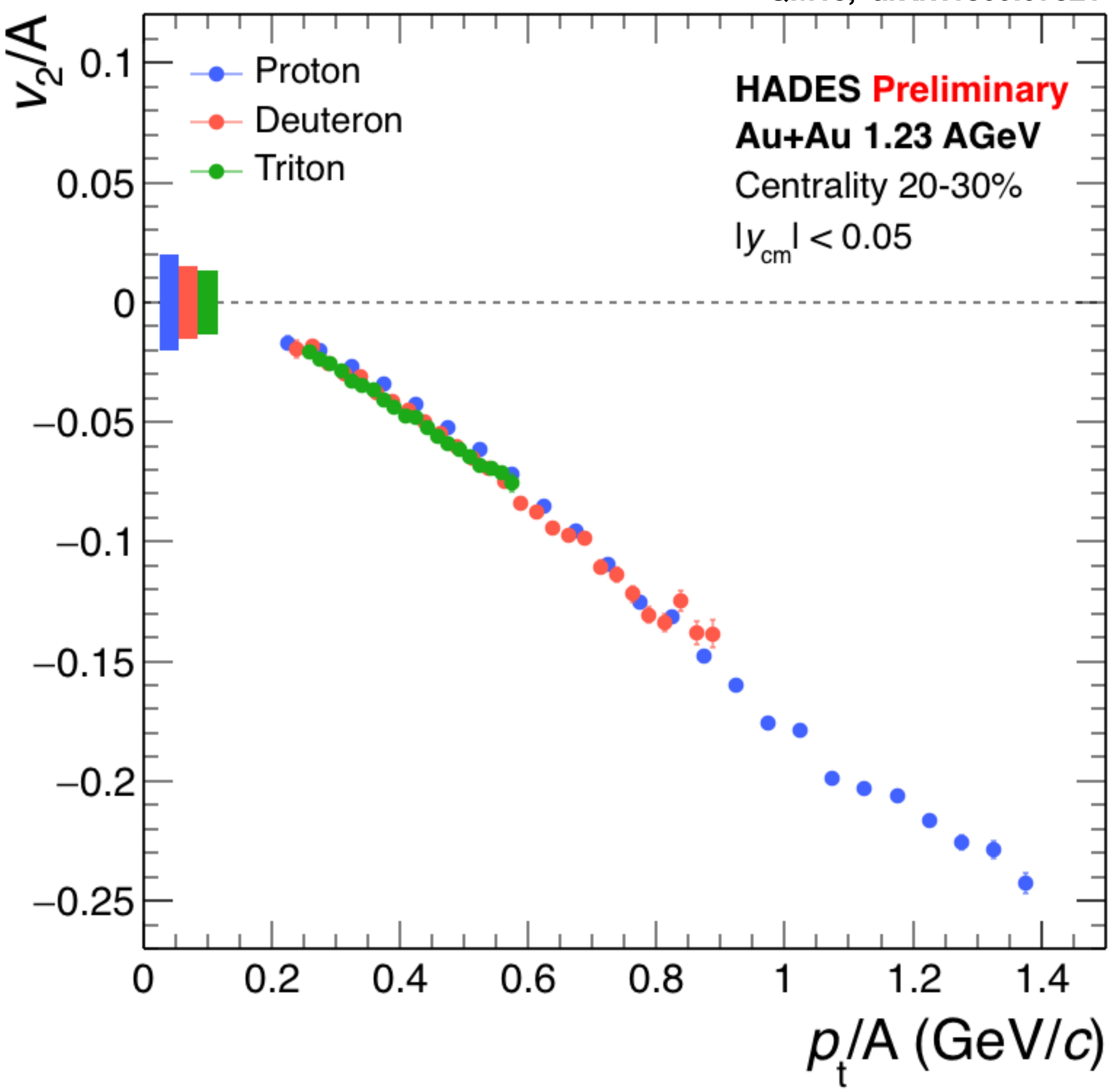


Elliptic Flow v_2: Light Nuclei

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

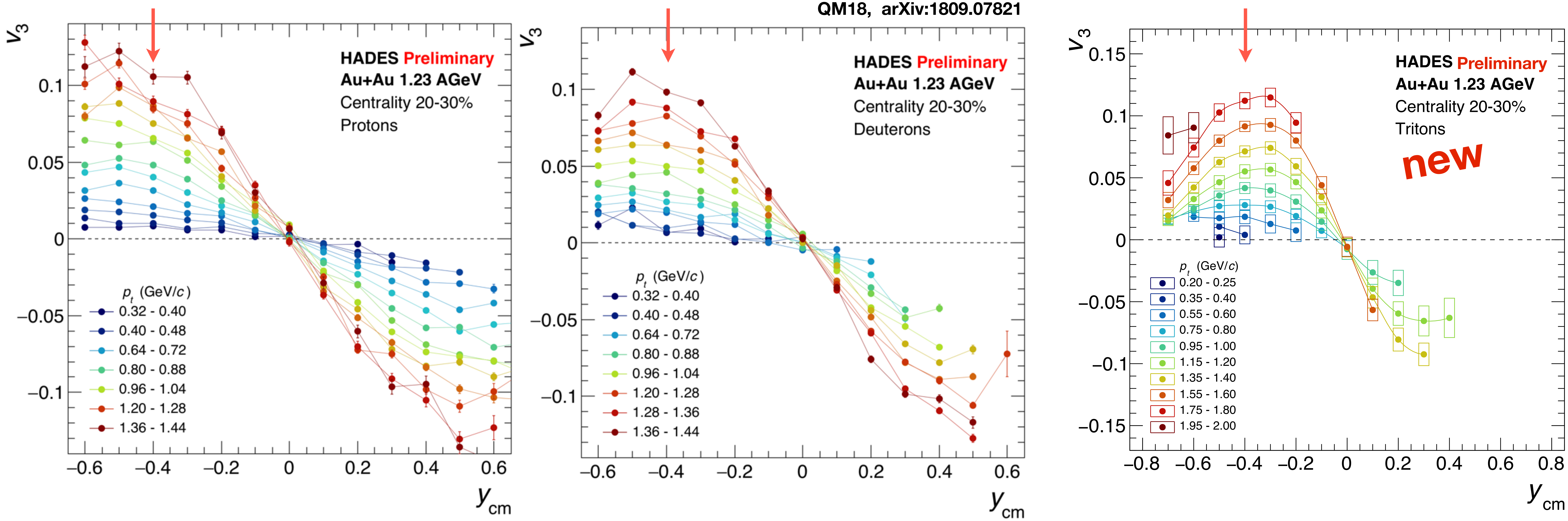
QM18, arXiv:1809.07821



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

Protons and Light Nuclei

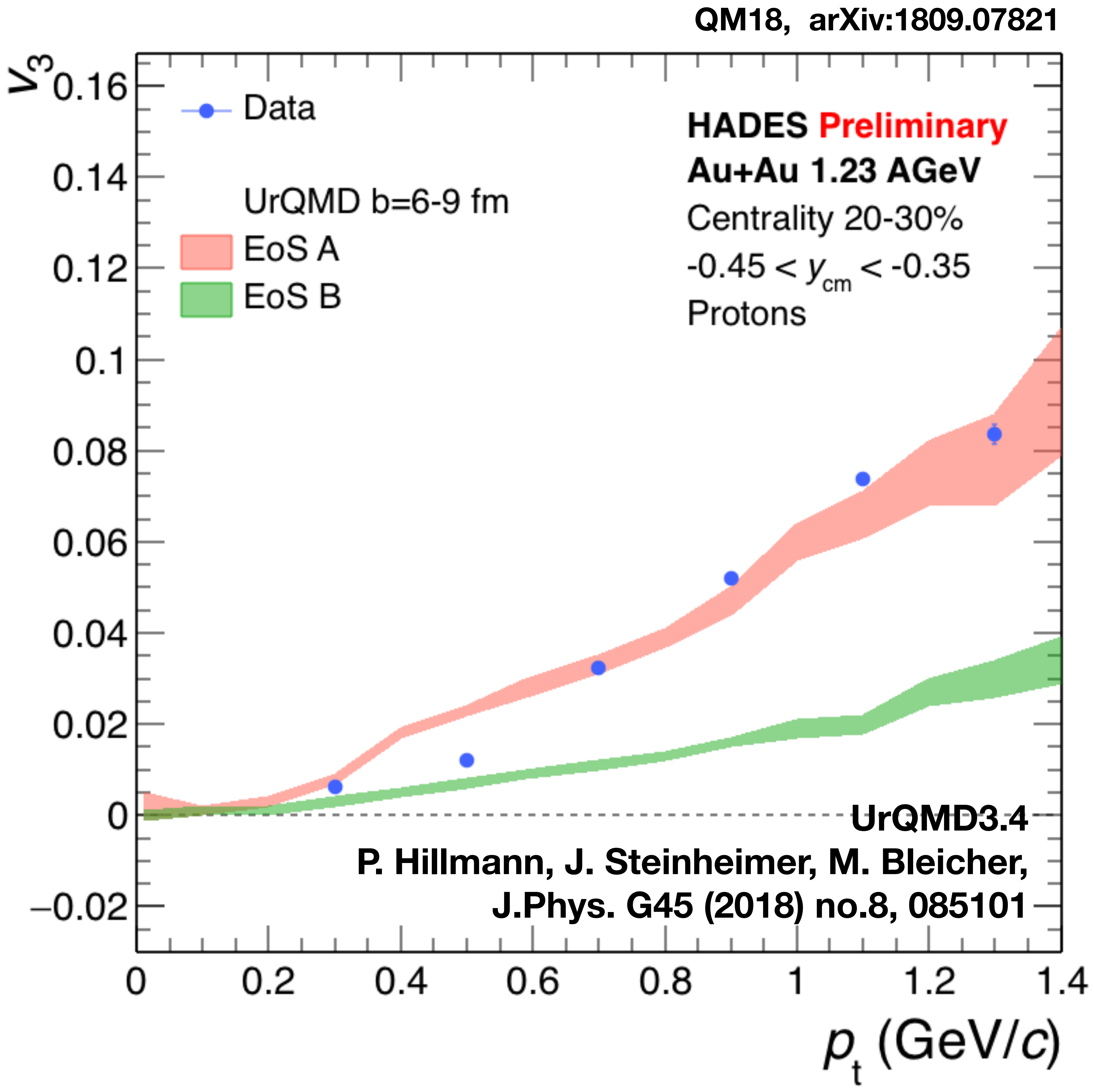
QM18, arXiv:1809.07821



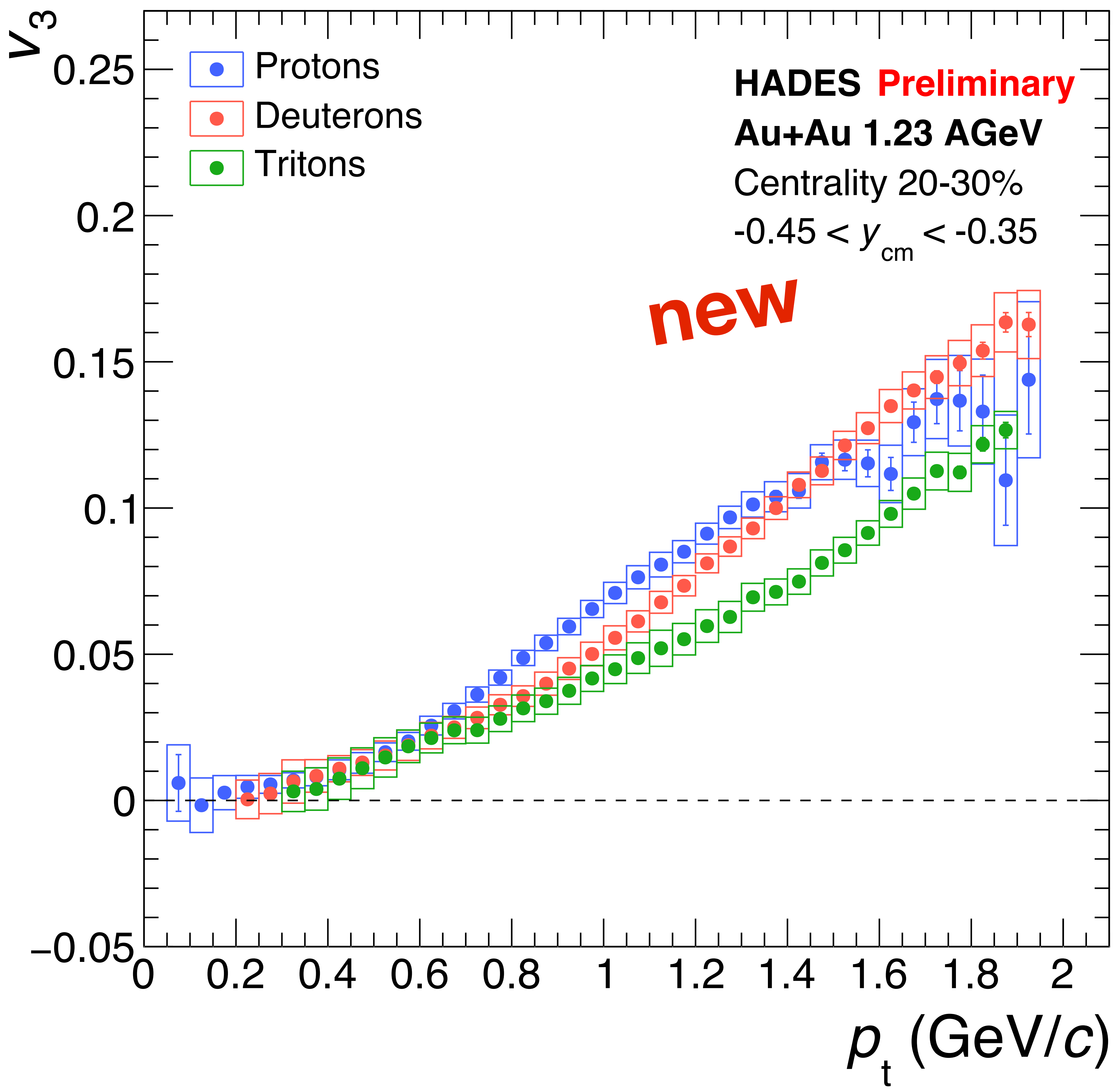
Note: $v3\{\Psi_{RP}\}$ w.r.t reaction plane $v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$

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

Protons and Light Nuclei



UrQMD predicts high sensitivity of v_3 to EoS

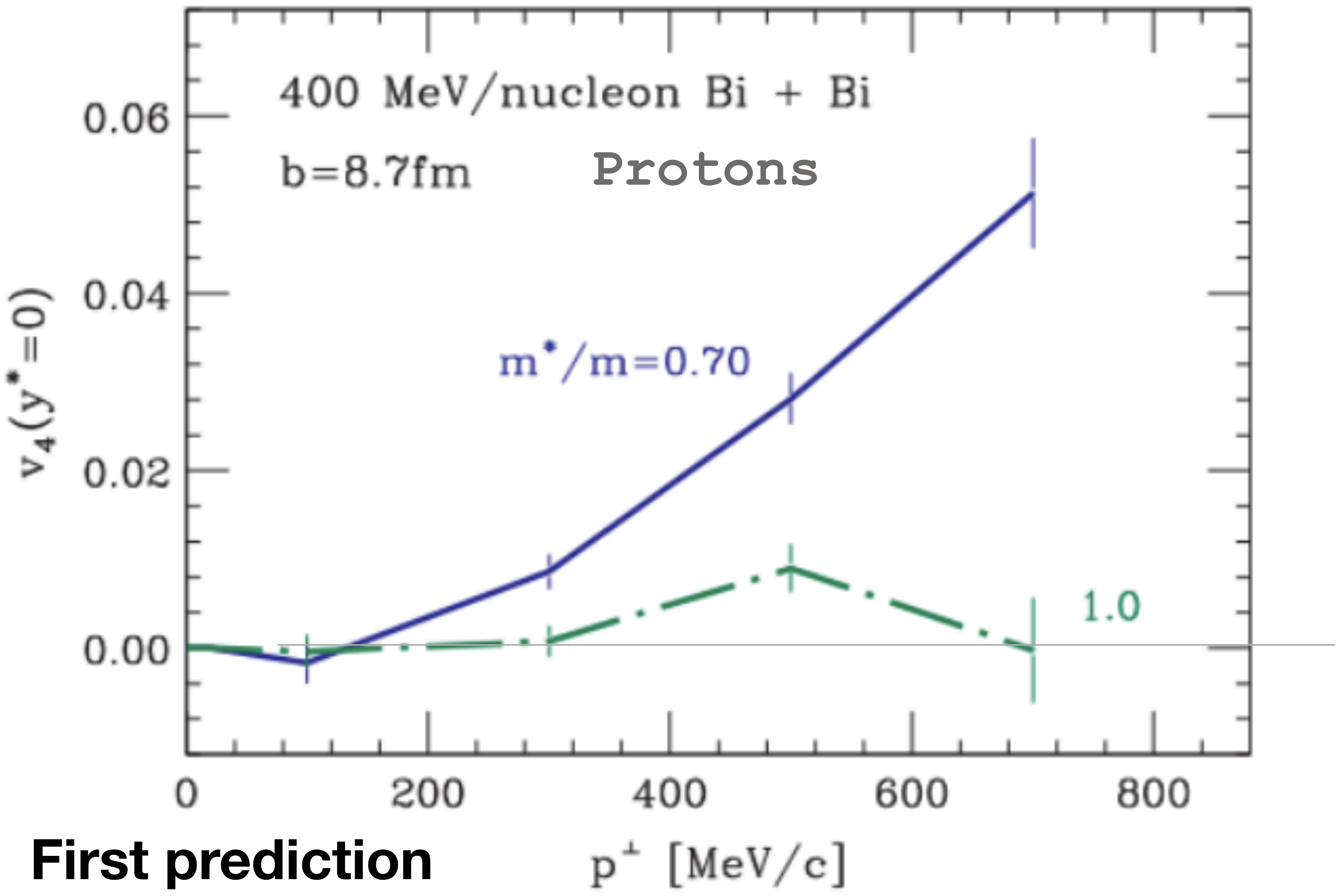


Note: $v3\{\Psi_{RP}\}$ w.r.t reaction plane $v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$

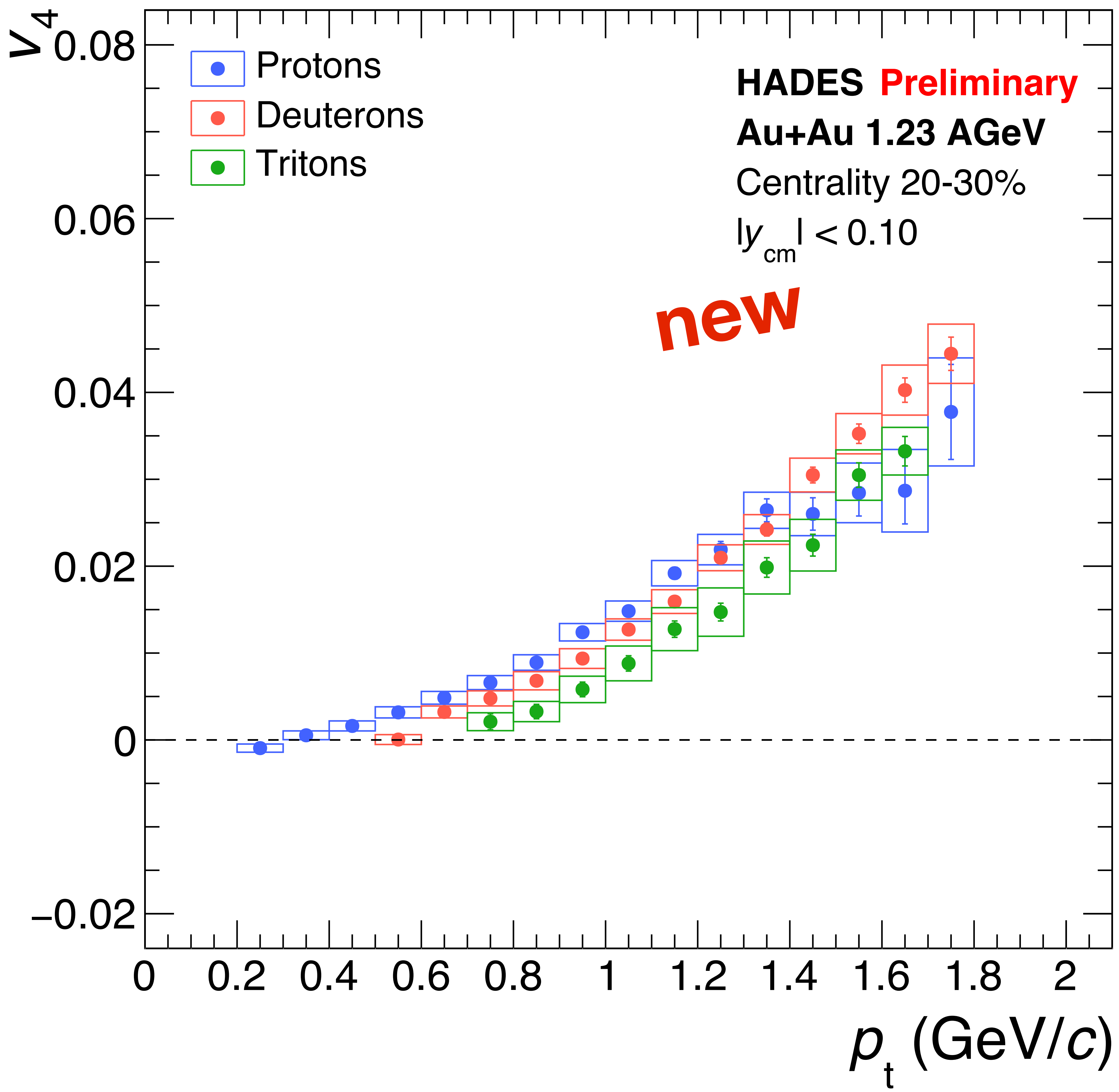
Quadrangular Flow $v_4\{\Psi_{RP}\}$

Protons and Light Nuclei

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



First prediction of v_4 with sensitive to EoS



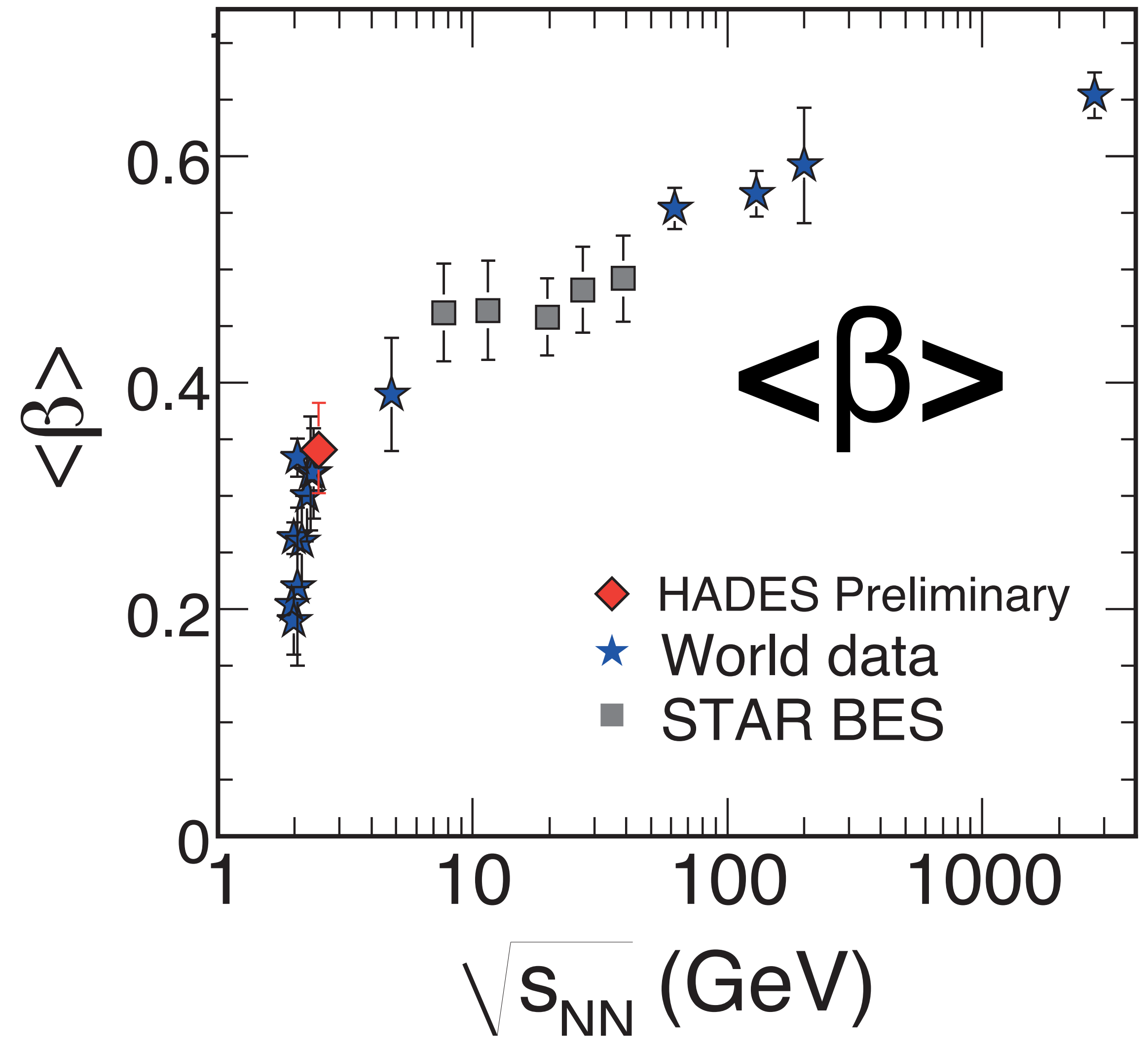
Note: $v4\{\Psi_{RP}\}$ w.r.t reaction plane $v_4\{\Psi_{RP}\} = \langle\langle \cos 4(\varphi - \Psi_{RP})\rangle\rangle$

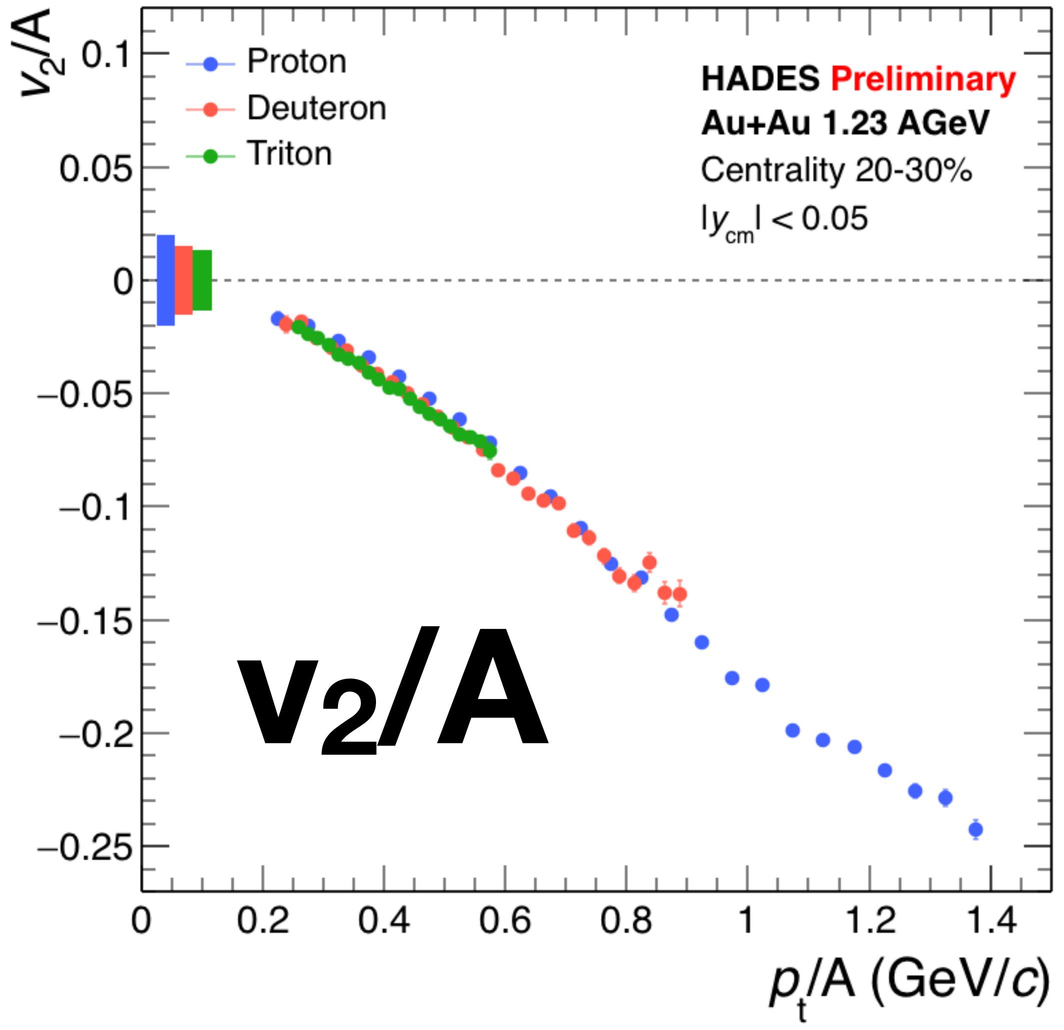
Conclusions

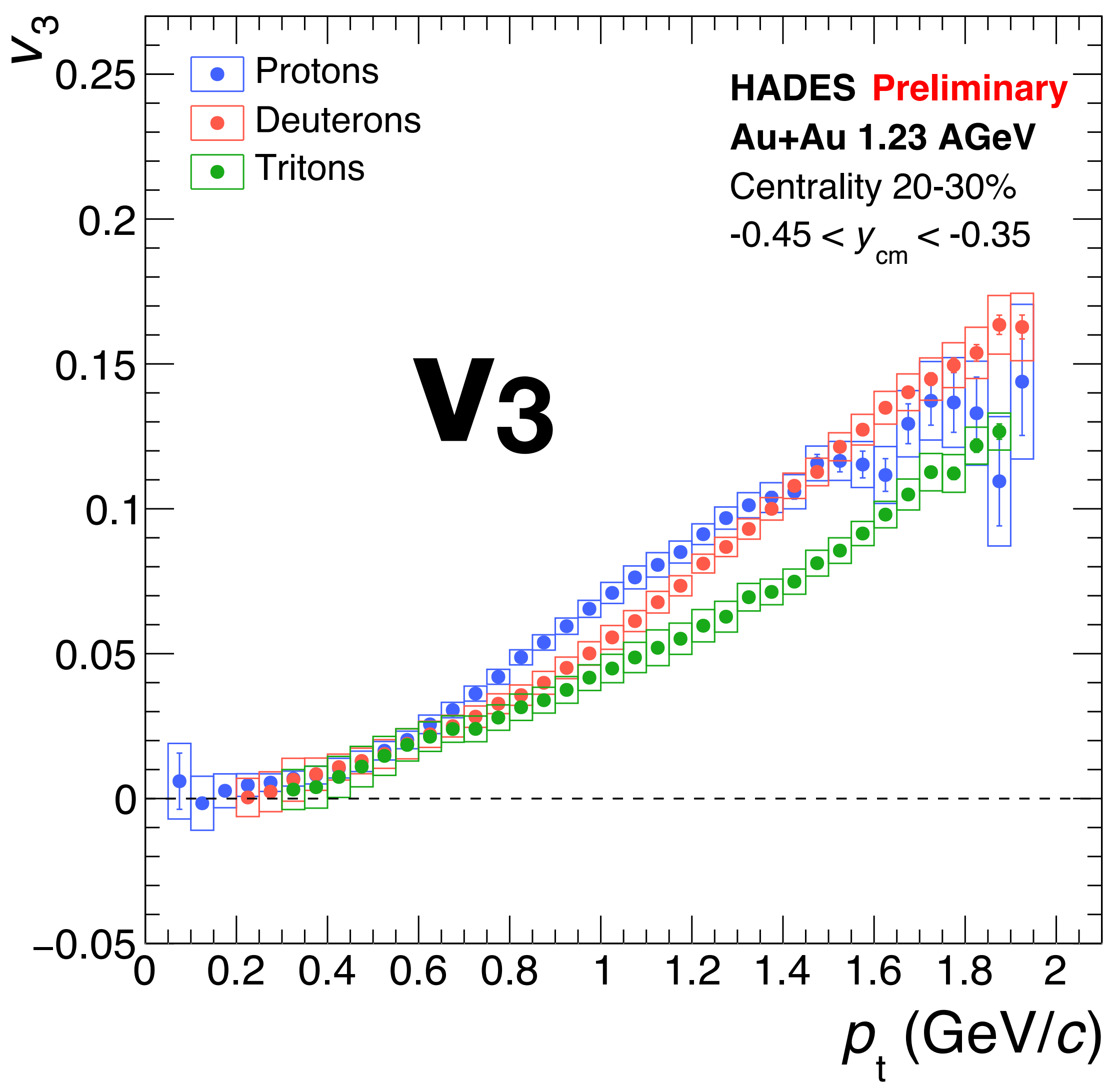
- Freeze-out parameters via Blast-Wave fit:

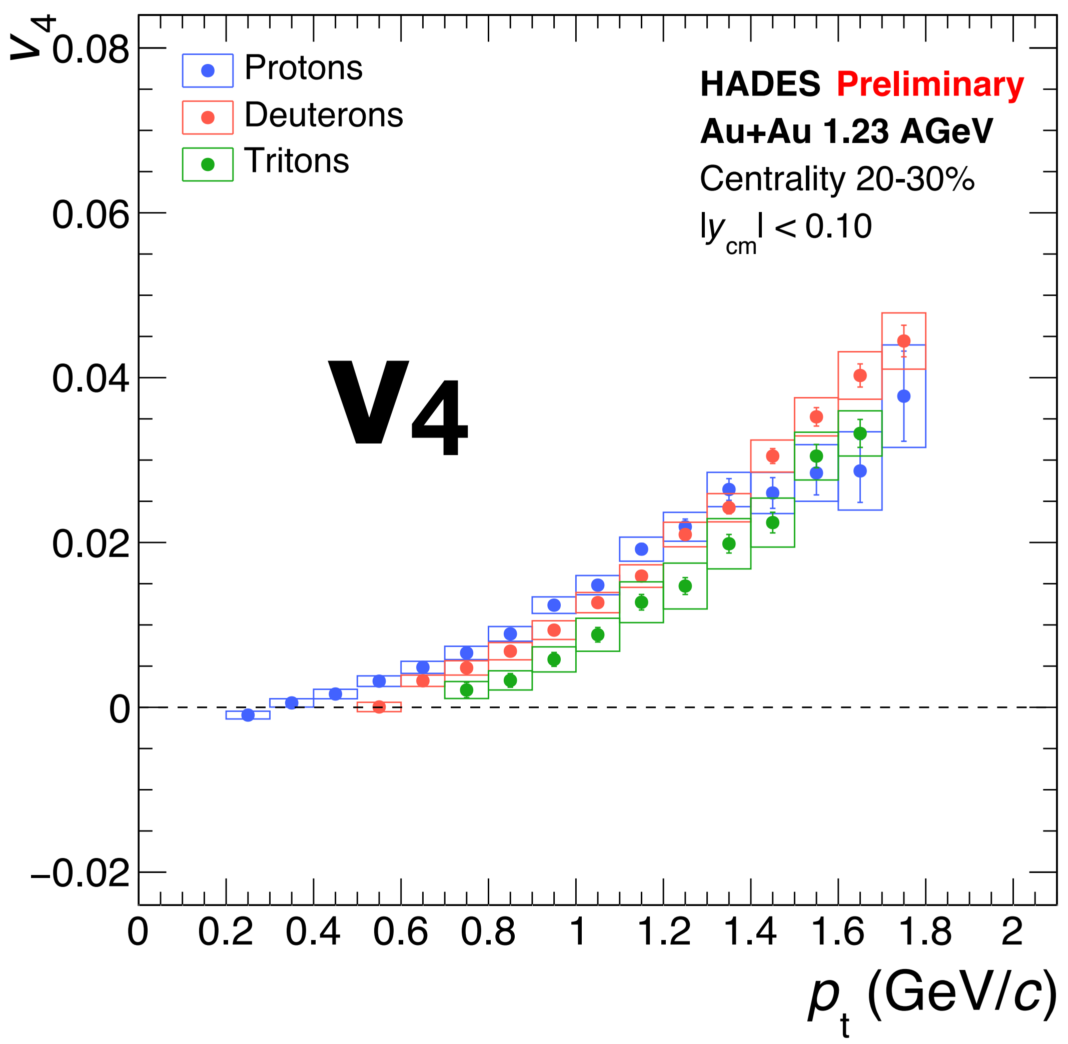
$$T_{kin} = 66 \pm 8 \text{ MeV}$$
$$\langle \beta_r \rangle = 0.34 \pm 0.04$$

- Directed v_1 and elliptic v_2 flow of protons, deuterons and tritons
  - Elliptic flow at mid-rapidity scales with A
- First measurement at SIS energies of
  - Triangular $v_3\{\Psi_{RP}\}$ and quadrangular $v_4\{\Psi_{RP}\}$ of protons, deuterons and tritons
  - Substantial difference in Pion HBT in Au+Au due Coulomb potential









HADES Collaboration

HADES Performance

- High interaction rates and statistics
  - Total number of events recorded: 7×10^9
  - 2.1×10^9 most central events analysed
- Centrality
  - 0-40% most central
  - Deduced from a Glauber MC model

HADES centrality: arXiv:1712.07993