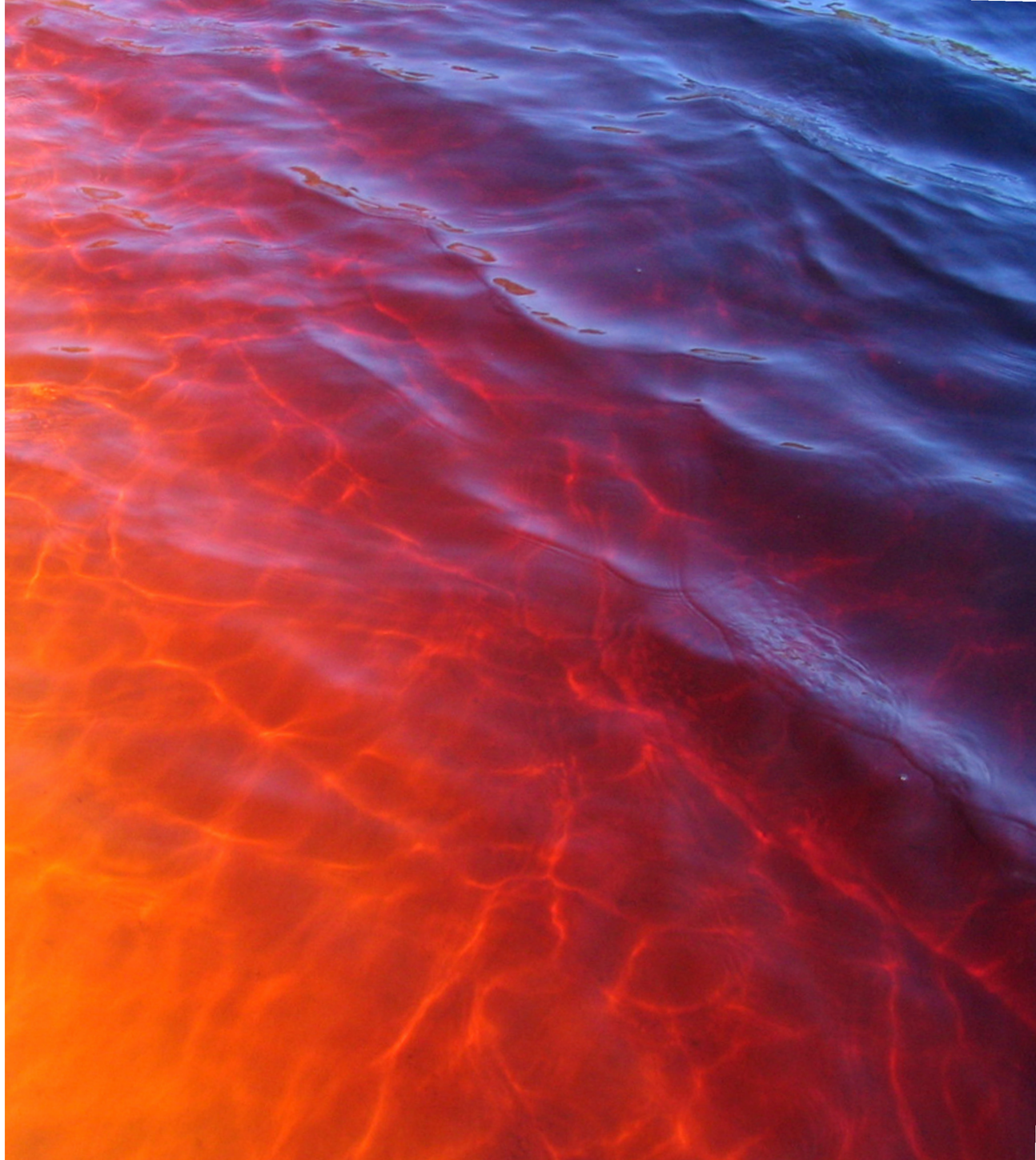
# Proton and light nuclei flow with HADES

Behruz Kardan

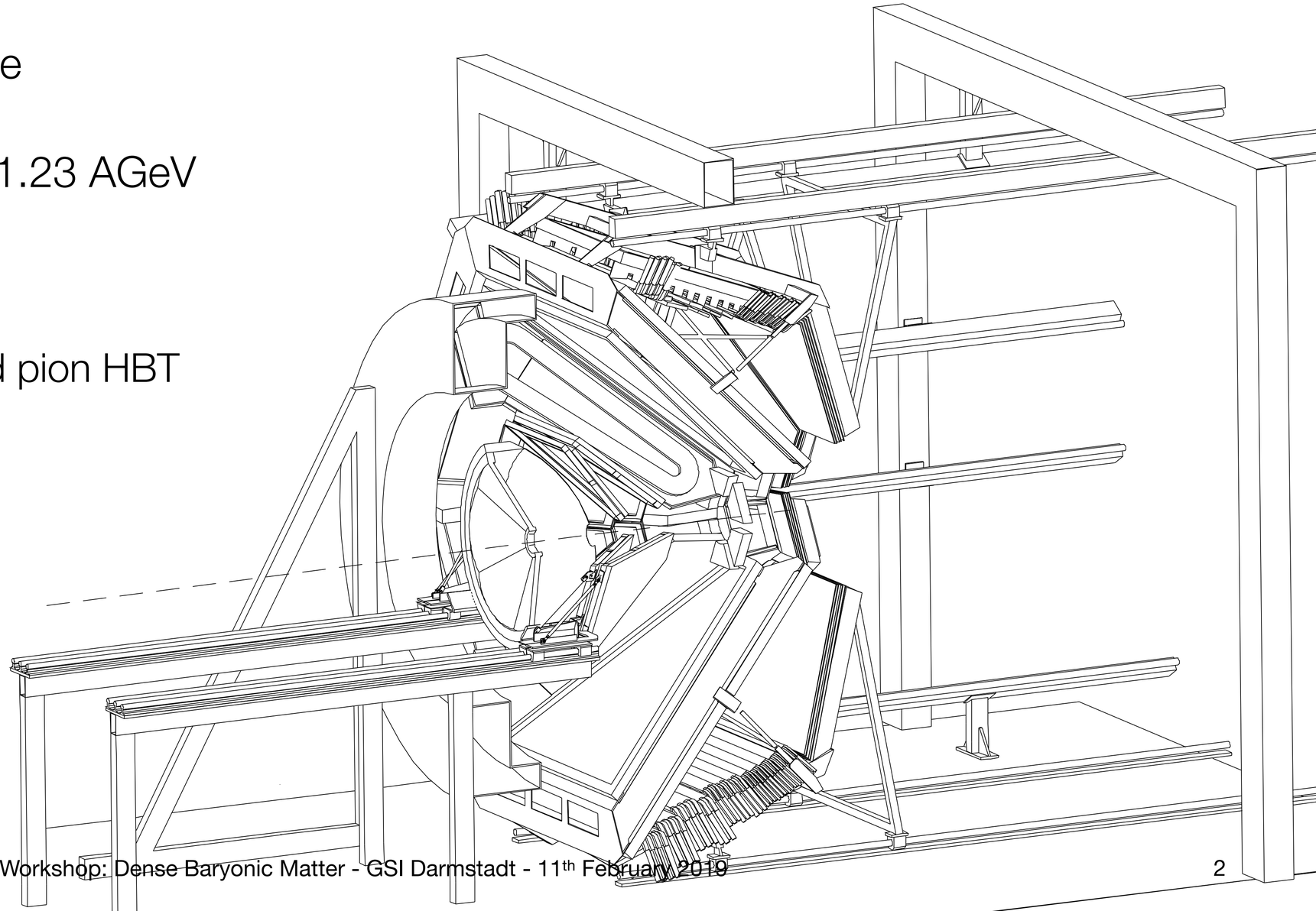
for the
HADES Collaboration

EMMI Workshop
Probing dense baryonic matter with hadrons: Status and Perspective
GSI, Darmstadt
11-13. February, 2019



# Outline

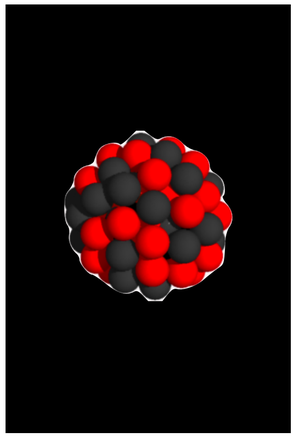
- Motivation: Equation-of-State
- HADES and Au+Au data at 1.23 AGeV
- Radial flow
  - Via Blast-Wave analysis and pion HBT
- Directed $v_1$, elliptic $v_2$, triangular $v_3\{\Psi_{RP}\}$ flow
  - Of protons, deuterons and tritons
- Quadrangular $v_4\{\Psi_{RP}\}$ flow



# Motivation

## Nuclear and Neutron Star Matter

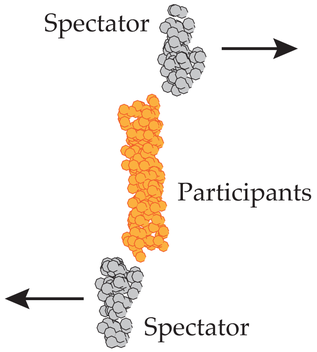
**Nuclei**

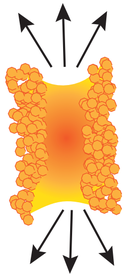


**Neutron Star**

**Neutron Star Merger**

**Heavy Ion Collision**



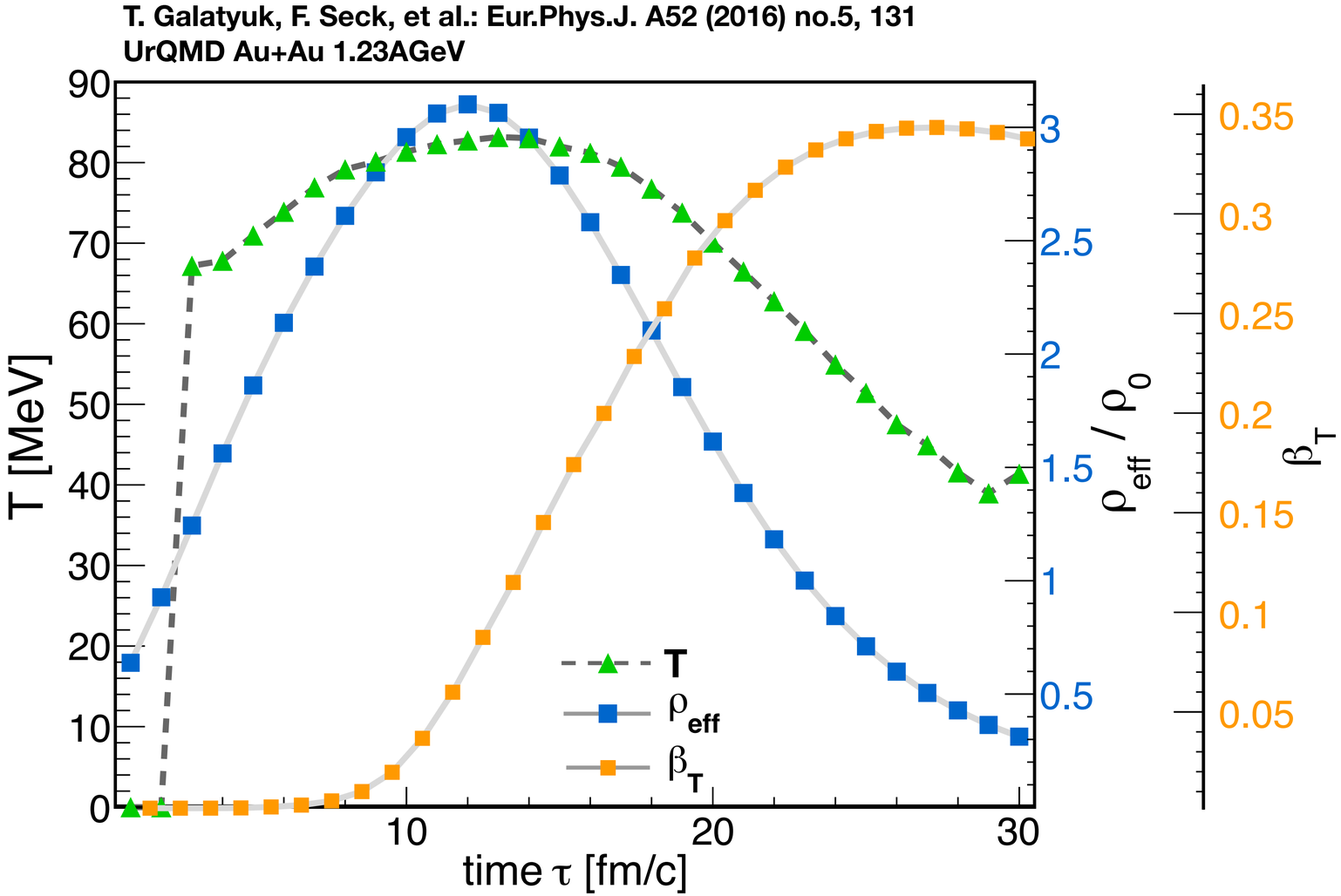




**EoS**

# Motivation

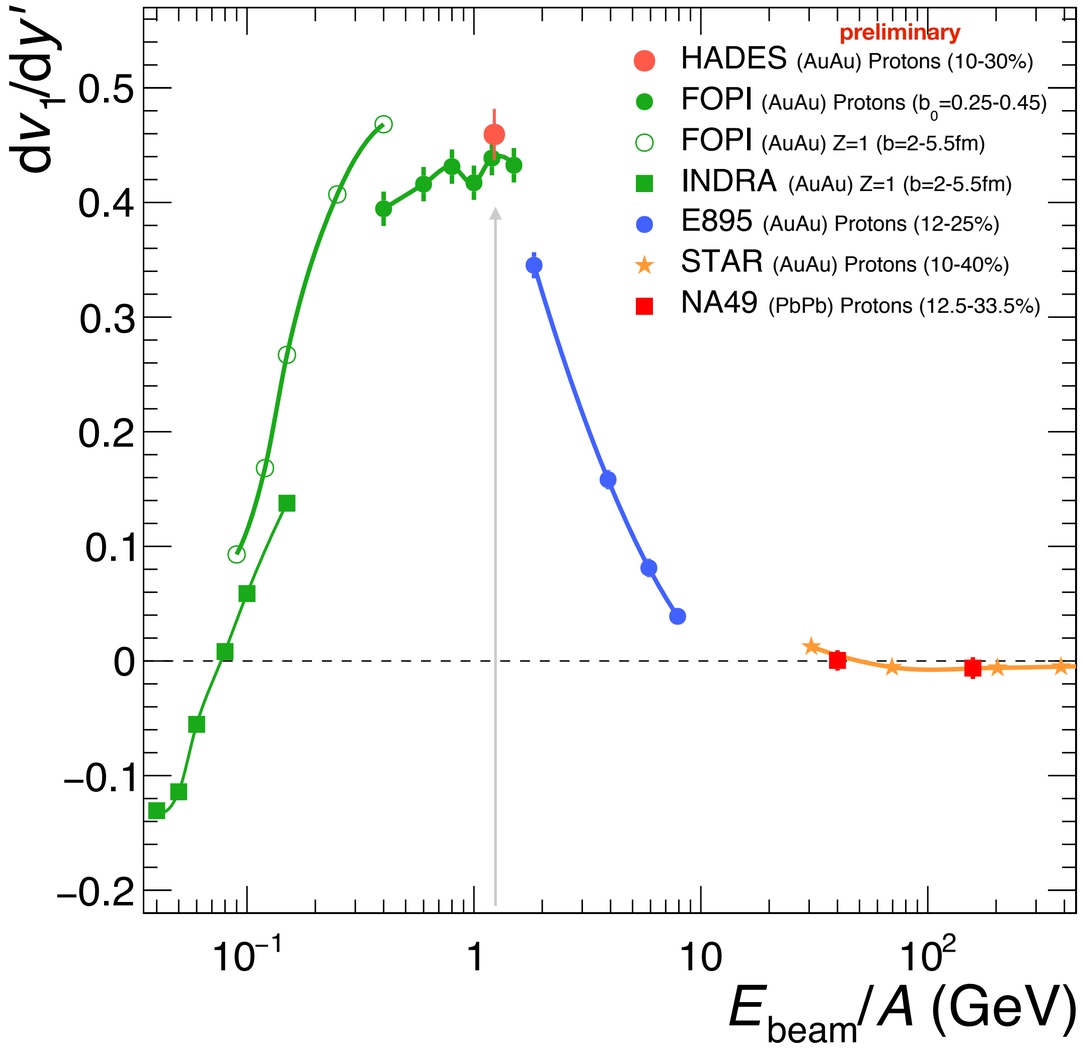
## Heavy Ion Collisions at 1.23A GeV

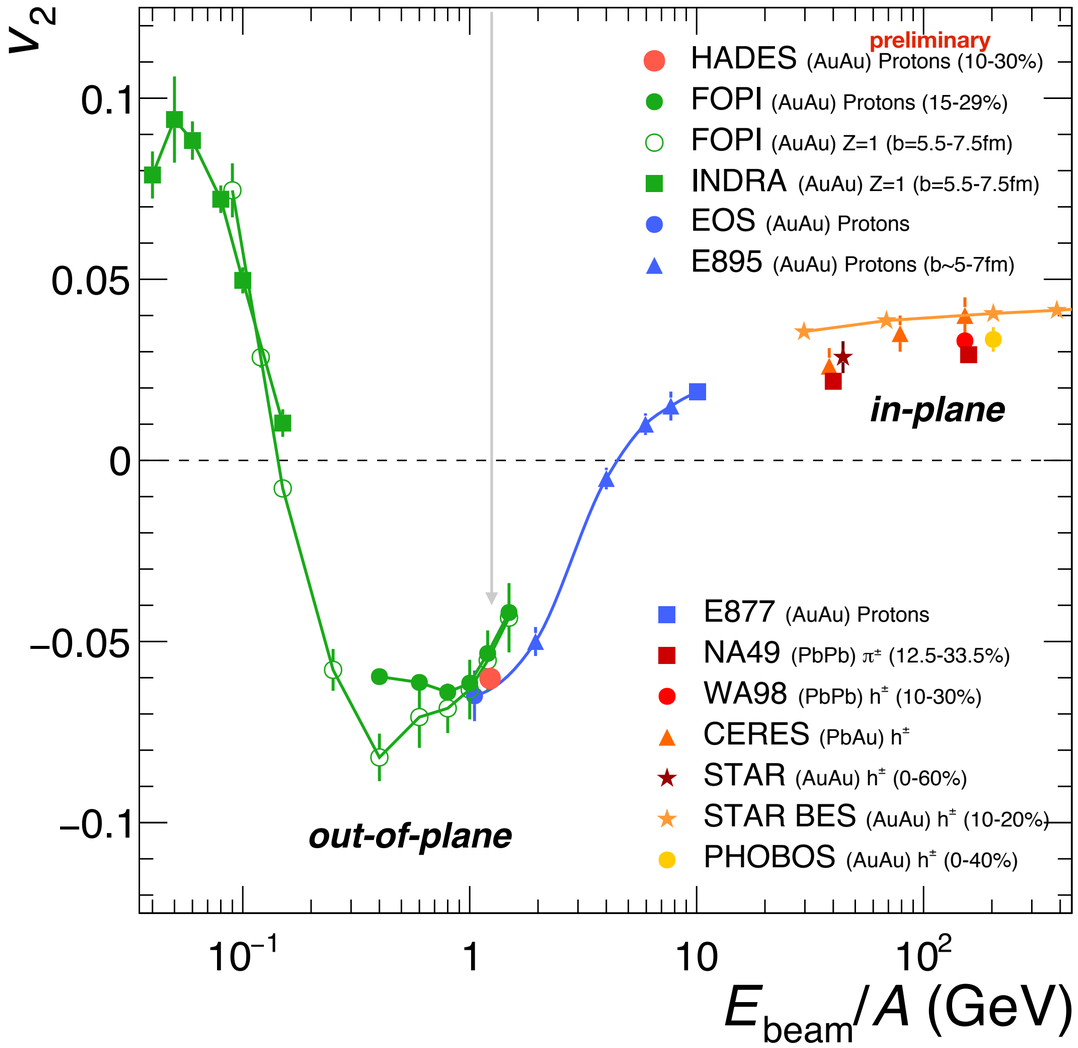
- High densities:
  $\rho_{max} = 1\text{-}3\rho_0$
- Moderate temperatures:
  T = 50-100 MeV
- Relatively long lifetime of fireball
- Significant transverse expansion expected



# Motivation

## Energy Dependence of Direct and Elliptic Flow



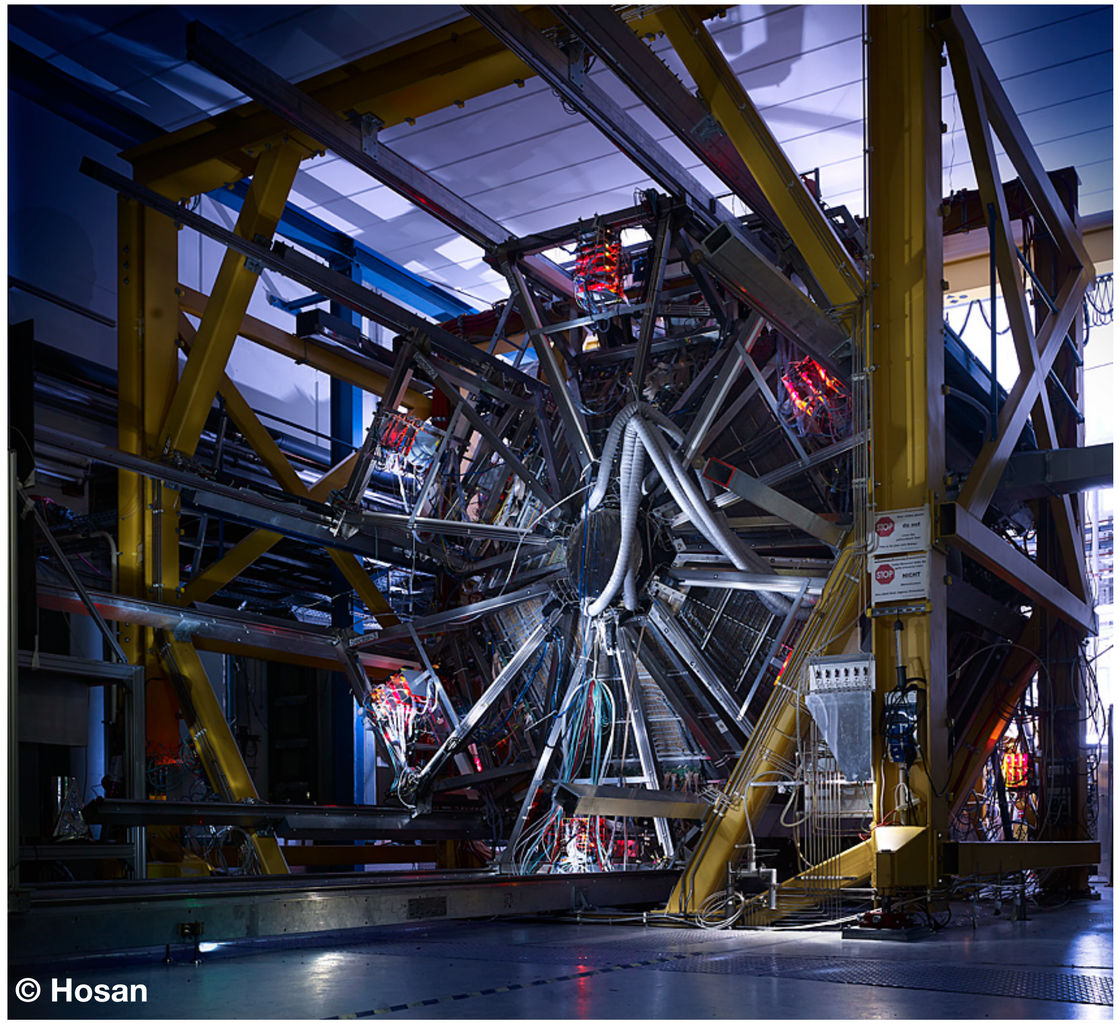




**in-plane $v_2>0$**
**short spectator passing time**
**$\tau_{passing} \ll \tau_{expansion}$**
**pressure gradient**

**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

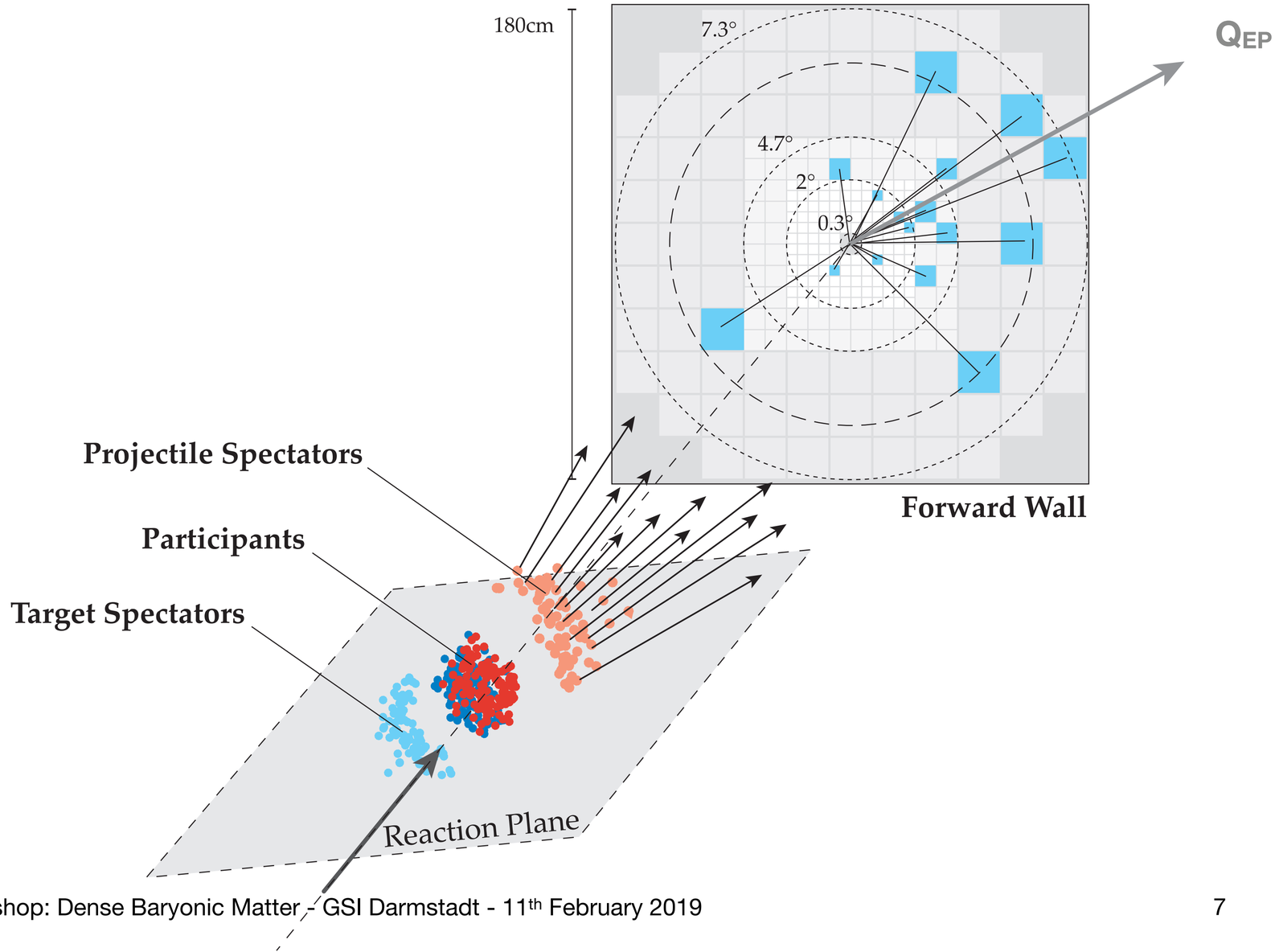


# HADES Performance

## Event Plane Reconstruction

- Based on hits of projectile spectators in the Forward Wall

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



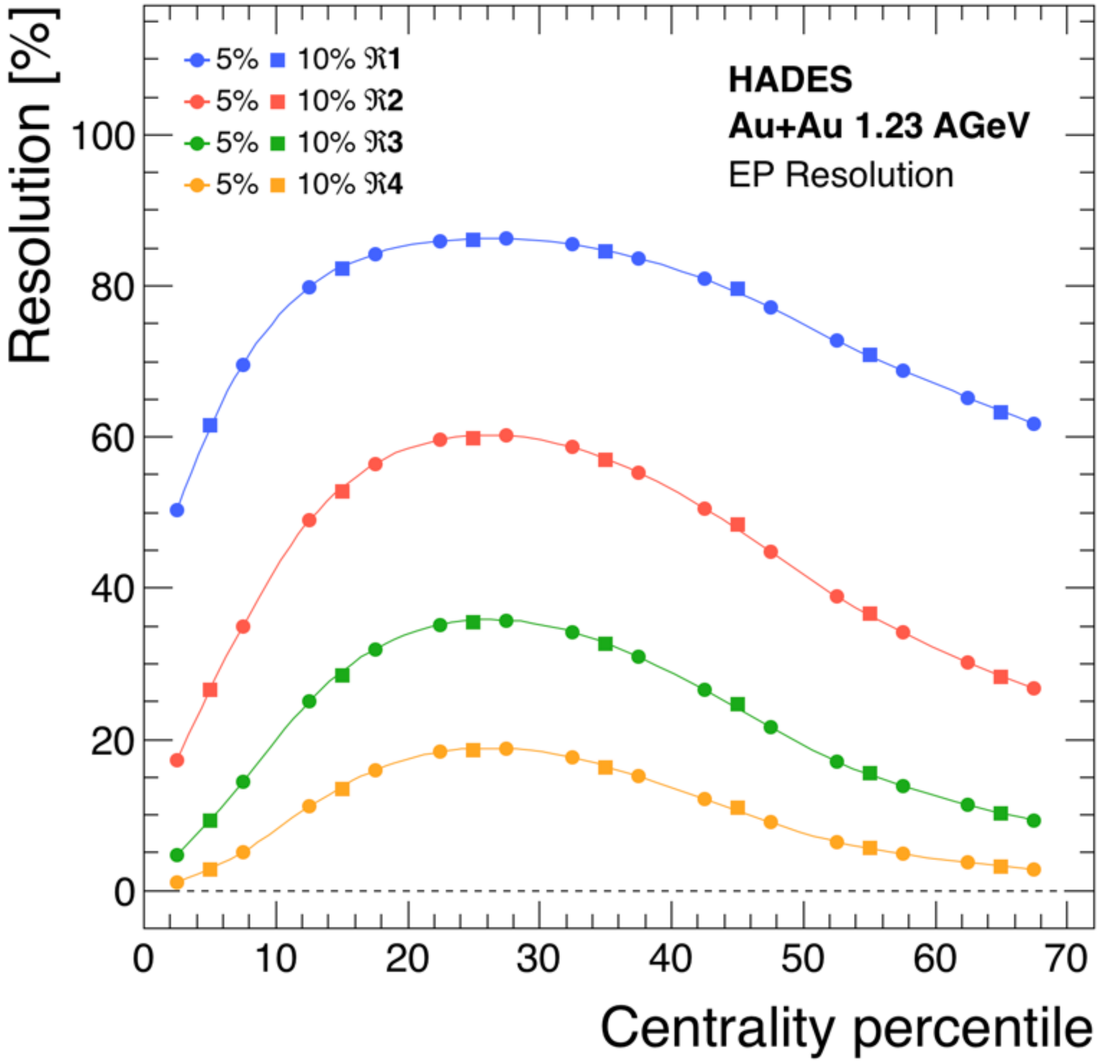
# HADES Performance

## Event Plane Resolution

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

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

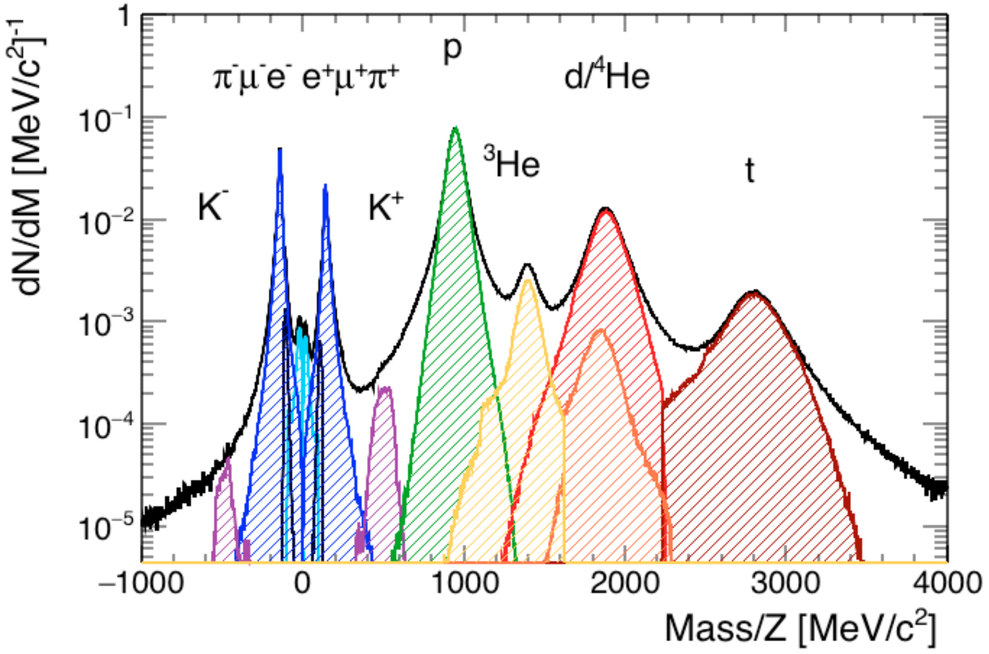
$$\mathfrak{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

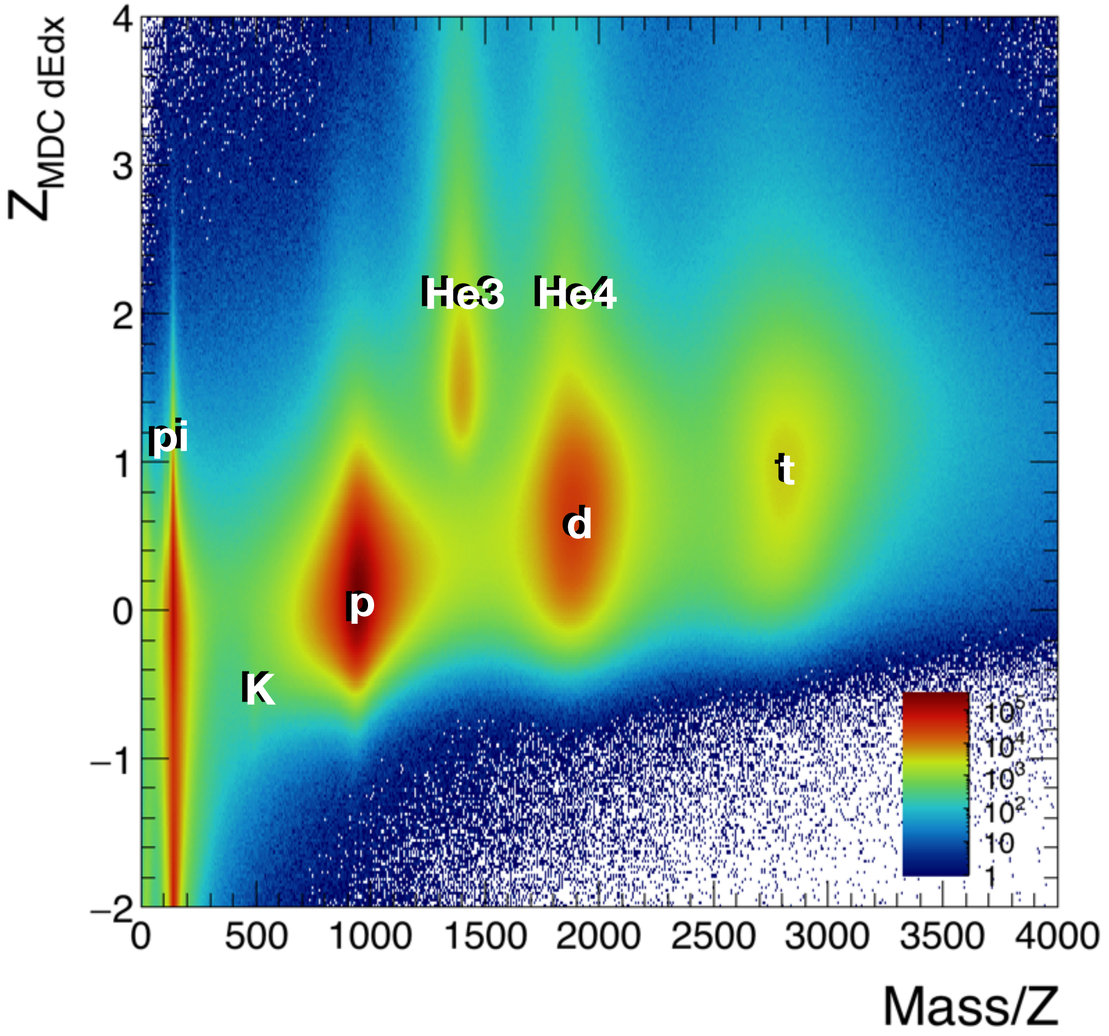


# HADES Performance

## Particle identification

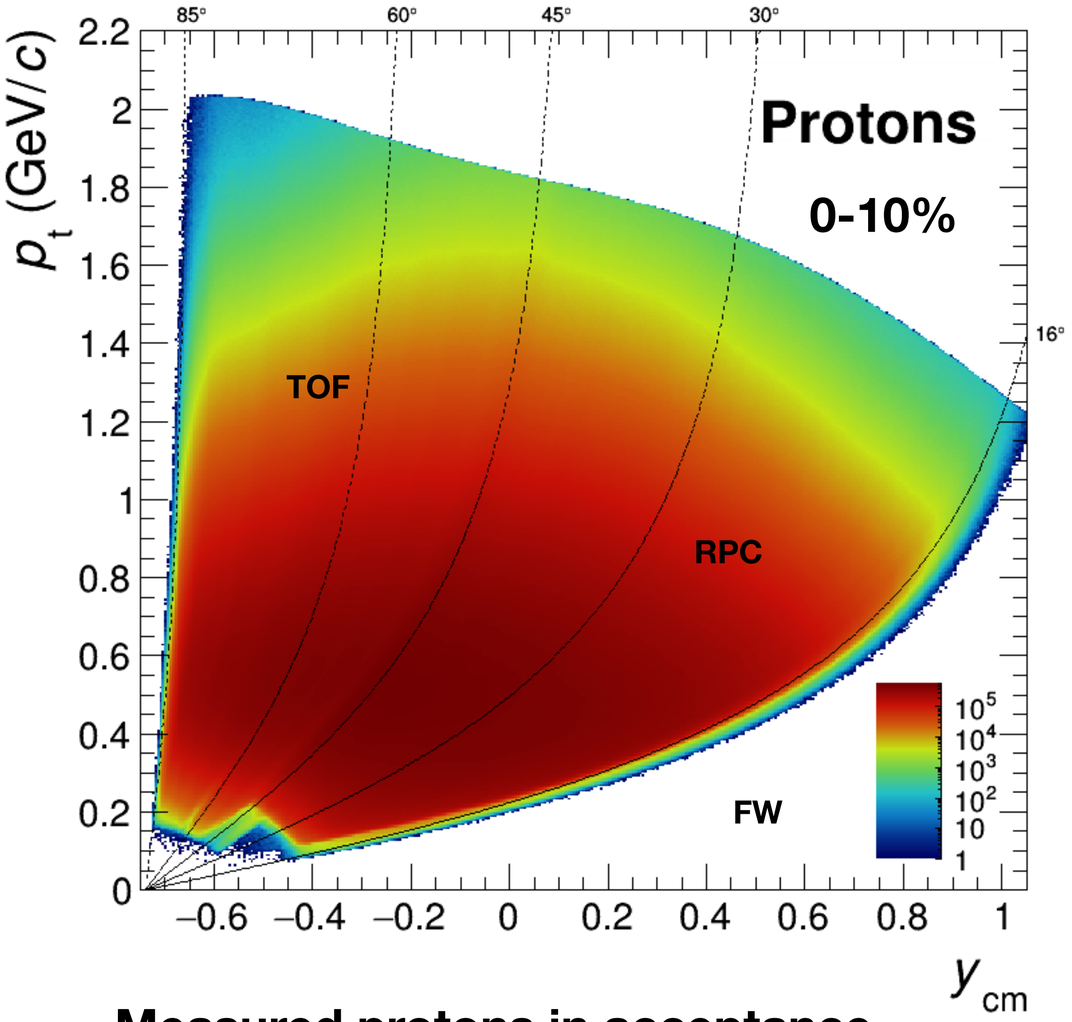
- Time-of-Flight (TOF and RPC)
- Energy loss in the MDC $Z_{MDC} = ln[\frac{(dE/dx)_{measured}}{(dE/dx)_{proton}}]$
  - Separation deuterons and He



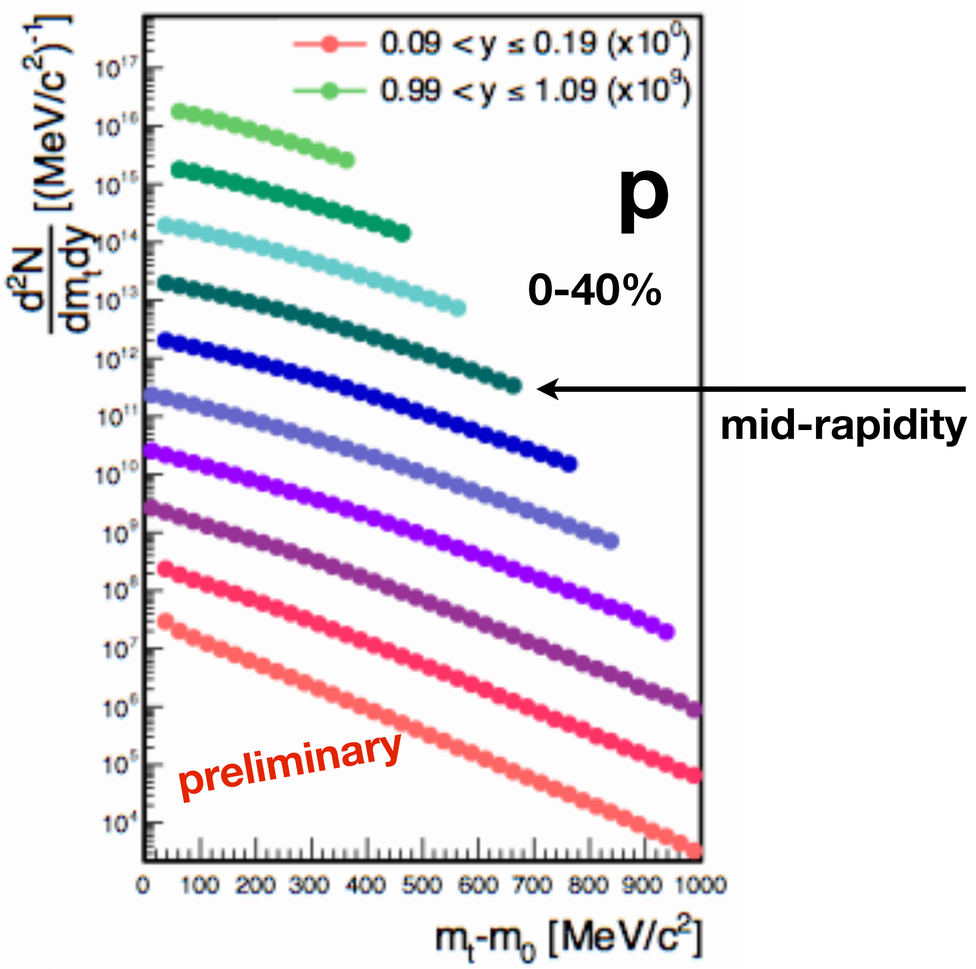



# HADES Performance

## Proton Spectra

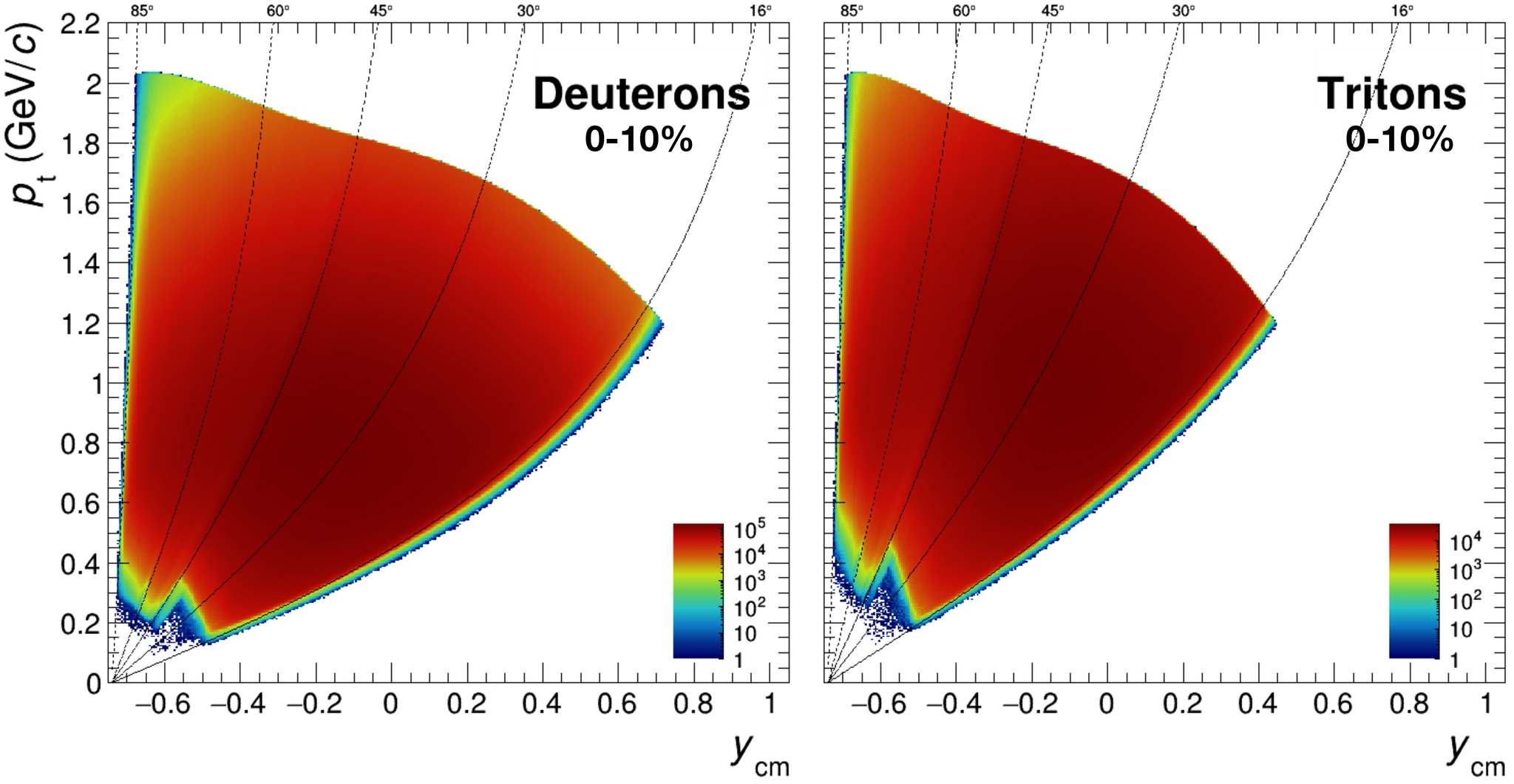



**Measured protons in acceptance**



# HADES Performance

## Acceptance for Deuterons and Tritons



# Radial Flow

## Transverse Momentum Spectra

**Blast-Wave model:**

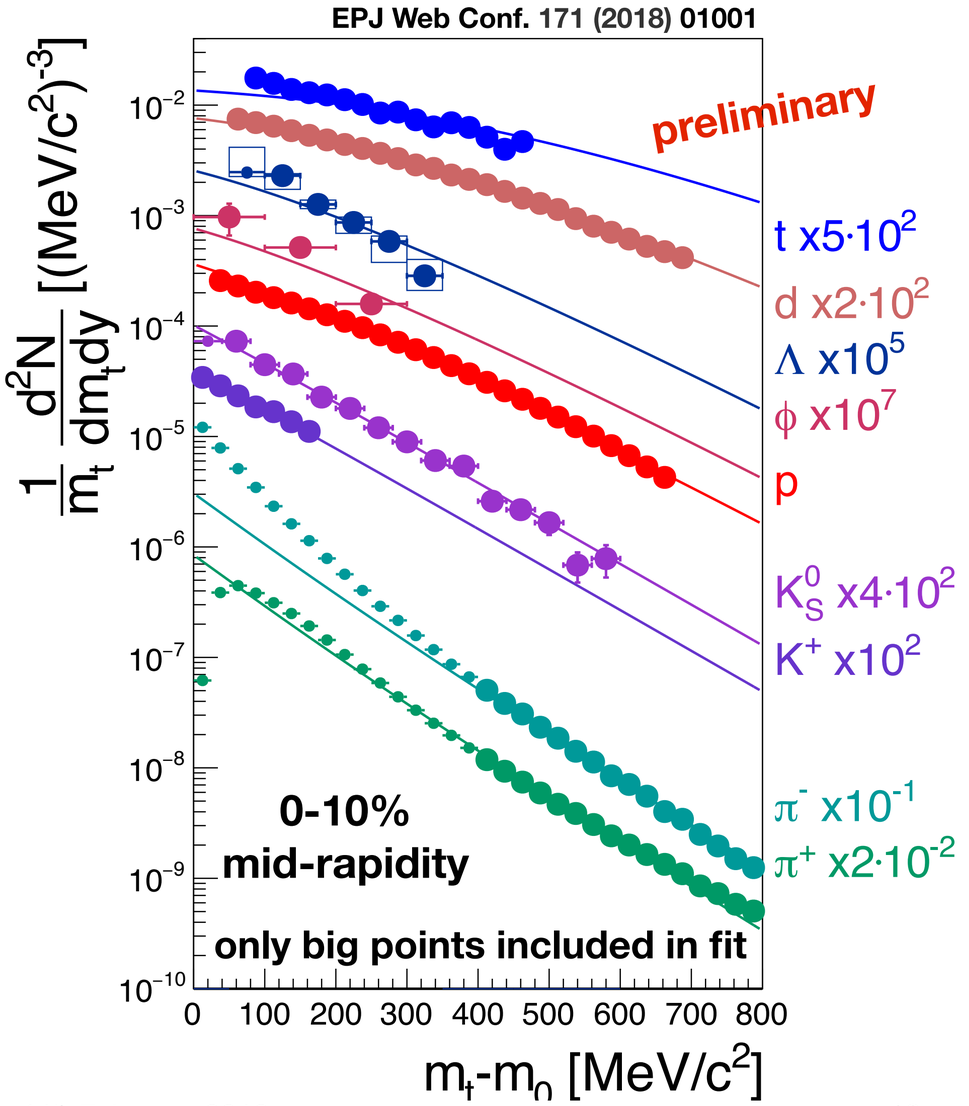
Phys. Rev. C **48**, 2462

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

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

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

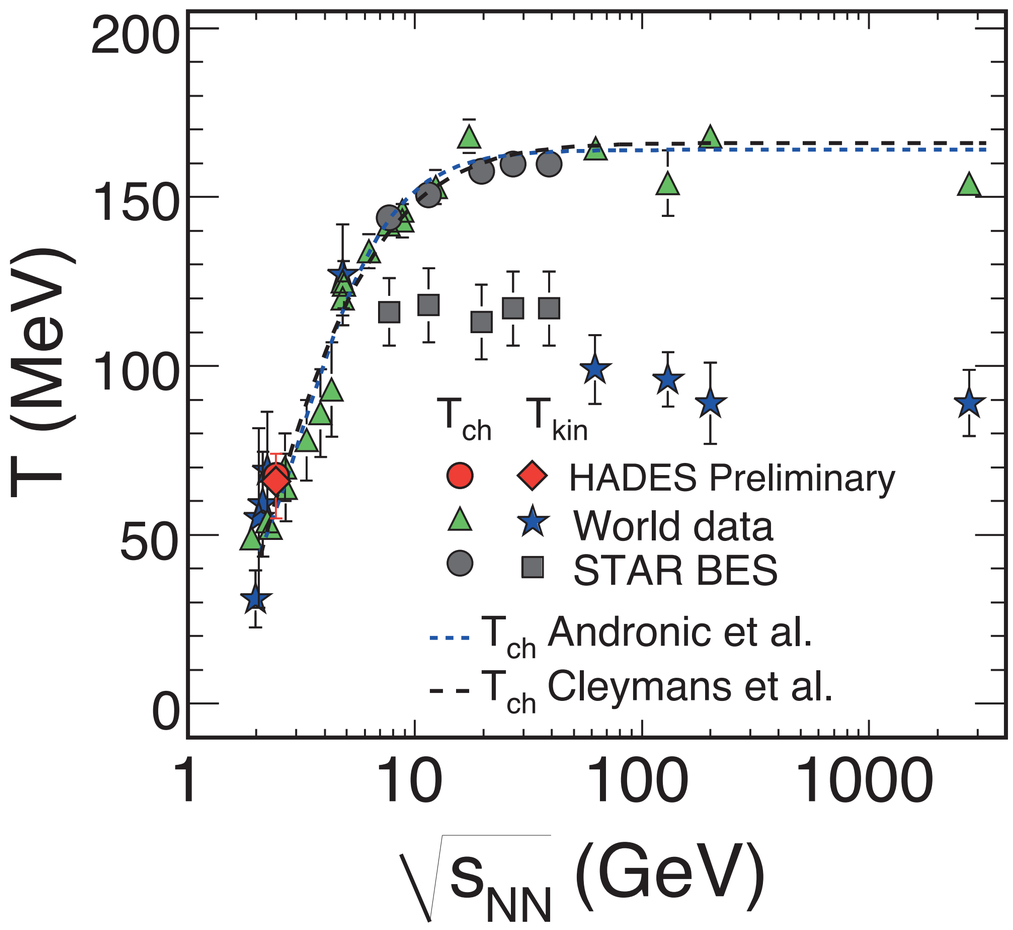
$$T_{kin} = 66 \pm 8 \text{ MeV}$$
$$\langle \beta_r \rangle = 0.34 \pm 0.04$$
$$T_{chem} = 68 \pm 2(\text{stat.}) \text{ MeV}$$



# Radial Flow

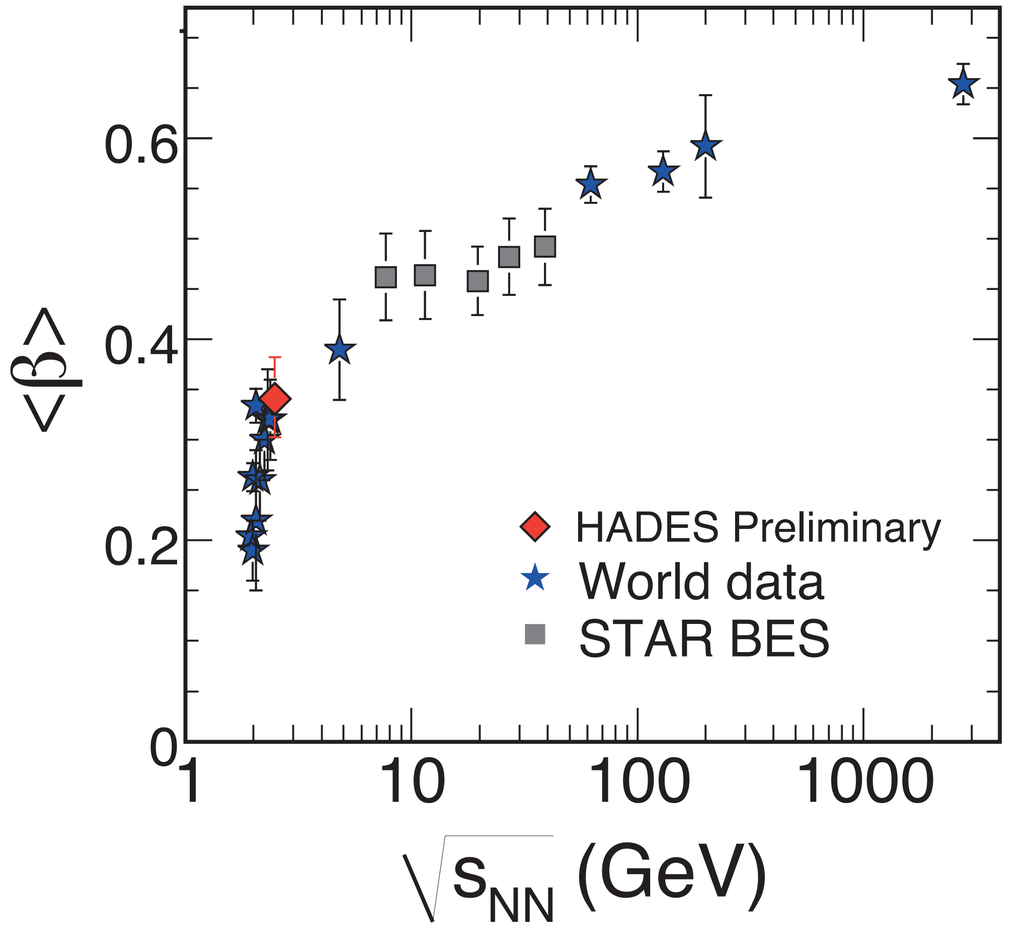
## Energy Dependence of Freeze-out Parameters

**Parameters fit well into trend of world data**




**$T_{kin}$ and β 0-10%**
**$T_{chem}$ 0-20%**

**EPJ Web Conf. 171 (2018) 01001**
**Phys.Rev. C96 (2017) no.4, 044904**



# Radial Flow

## HBT - Intensity Interferometry

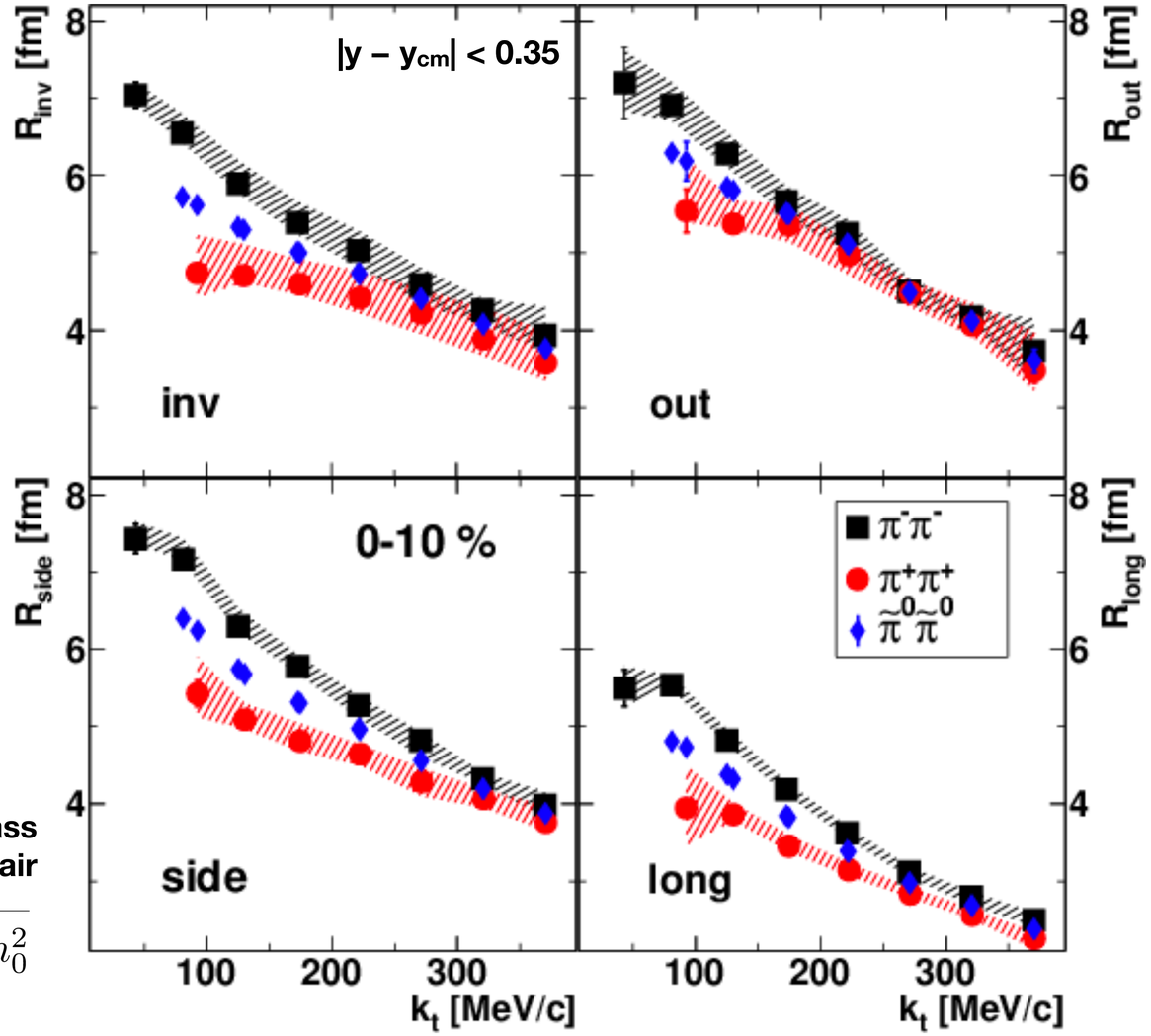
- First measurement of pion HBT in Au+Au collisions at 1.23 AGeV
- $R_{side}$: smaller radii for higher pair transverse momenta:

  → **Radial flow**

- Accounting for Coulomb potential

  → **First time such substantial difference!**

**arXiv:1811.06213**

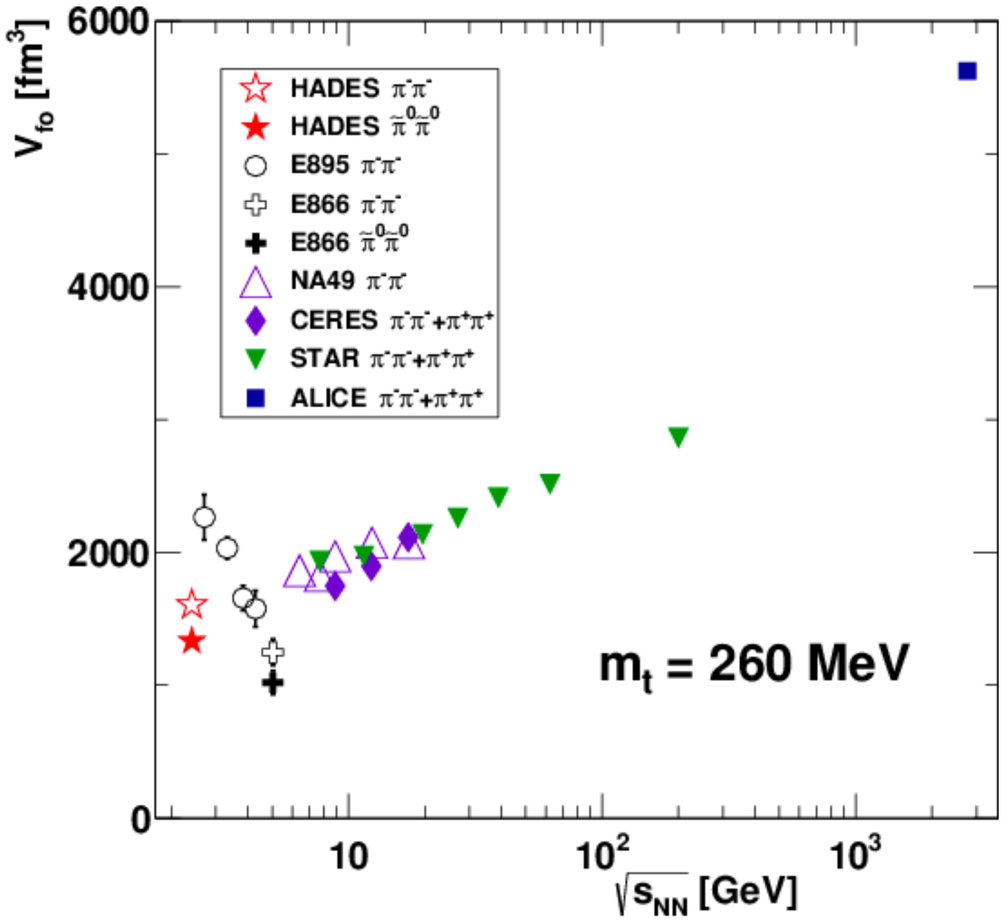



**$m_T$: transverse mass of the pair**

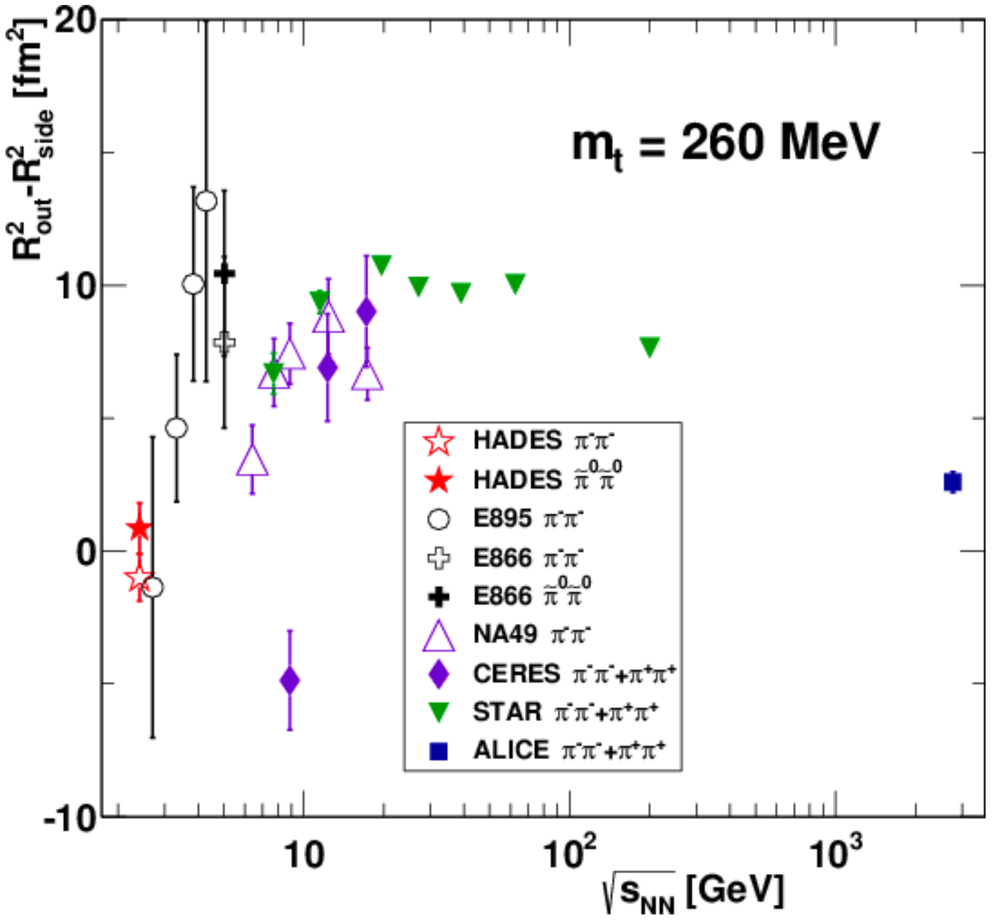
$$m_T = \sqrt{k_t^2 + m_0^2}$$

# Radial Flow

## HBT - Intensity Interferometry




arXiv:1811.06213

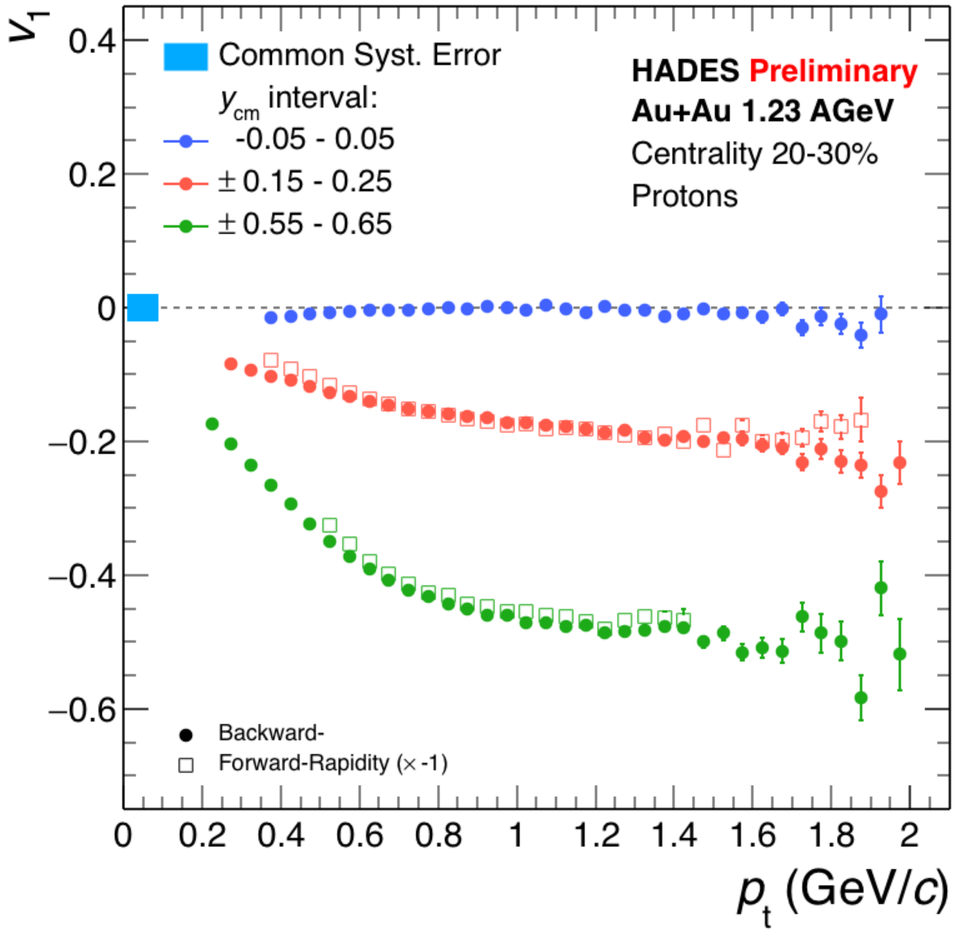


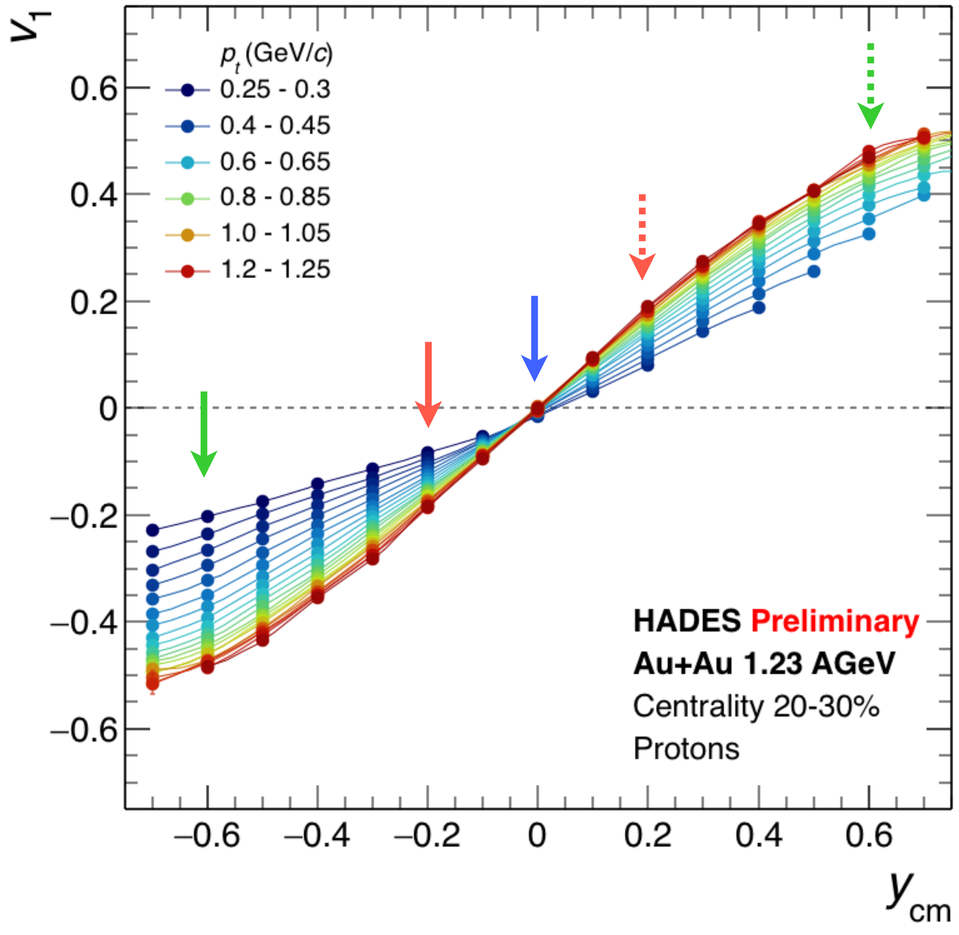

$$V_{\mathrm{fo}} = (2\pi)^{3/2} R^2_{\mathrm{side}} R_{\mathrm{long}} \approx 1300 \ \mathrm{fm}^3$$

# Directed Flow $v_1$: Protons

## $p_t$-Dependence

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



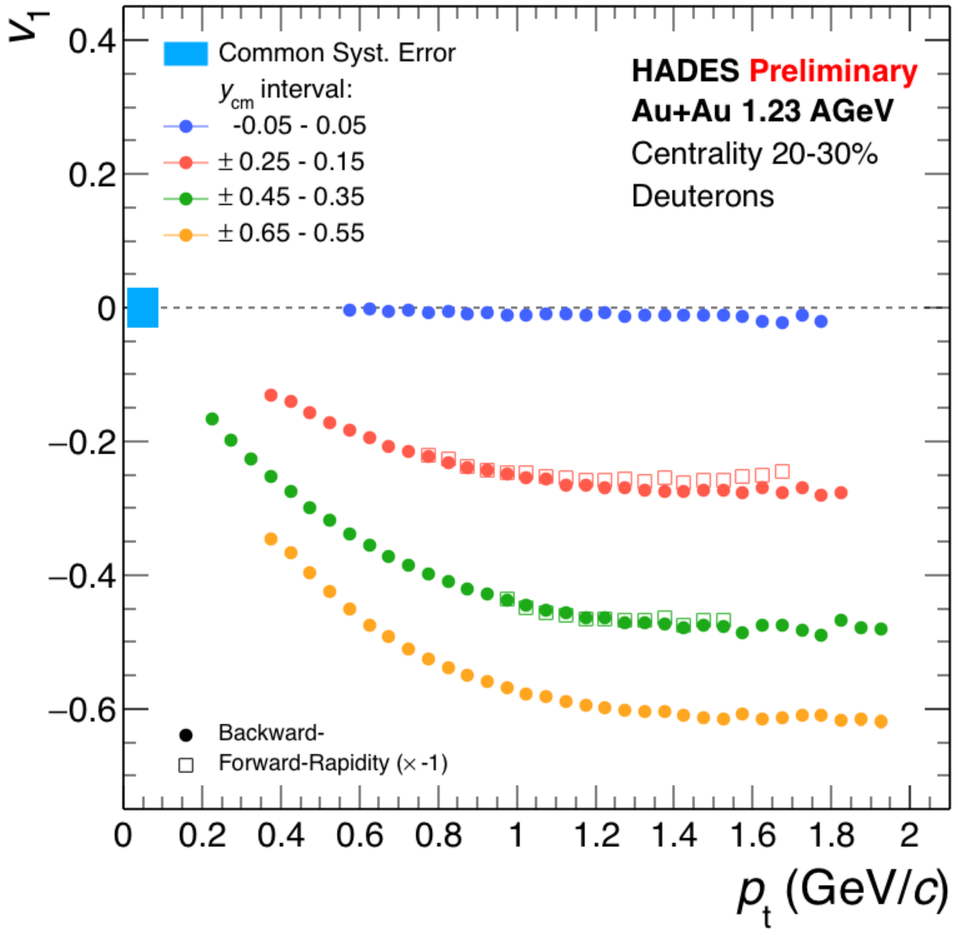



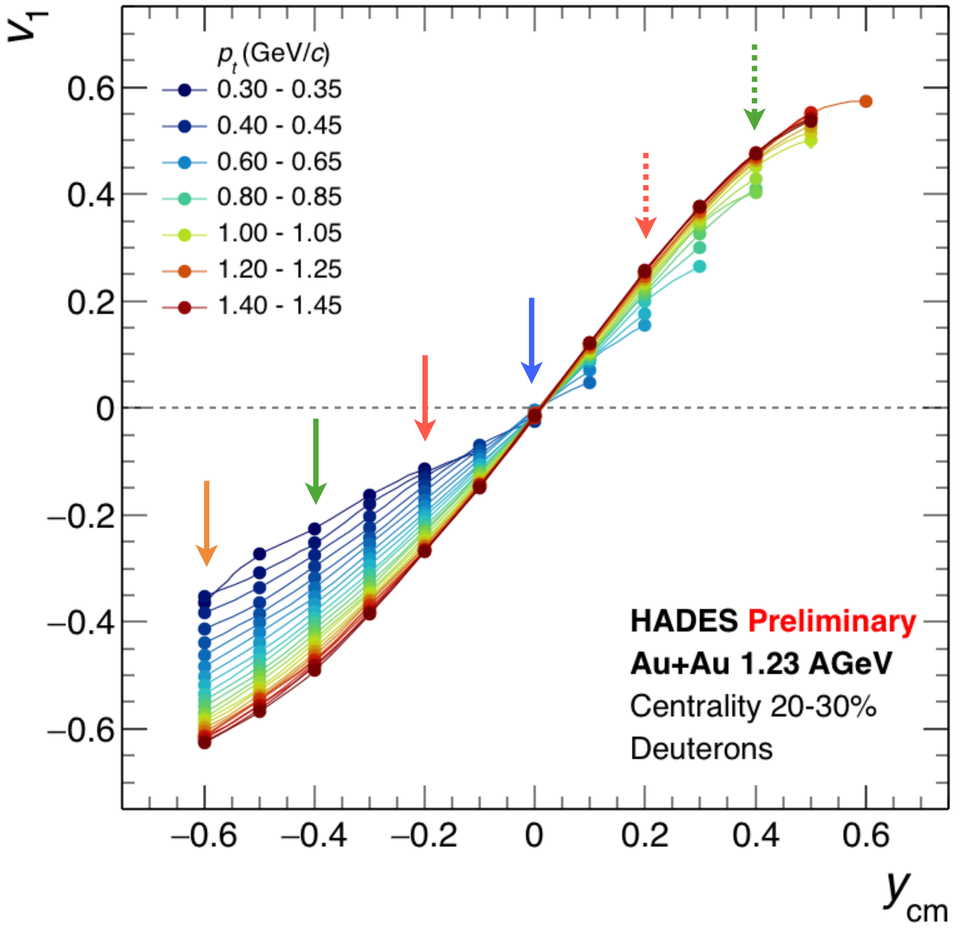

**Good agreement between backward and forward rapidity bins**

# Directed Flow $v_1$: Deuterons

## $p_t$-Dependence

QM18, Nucl.Phys. A982 (2019) 431



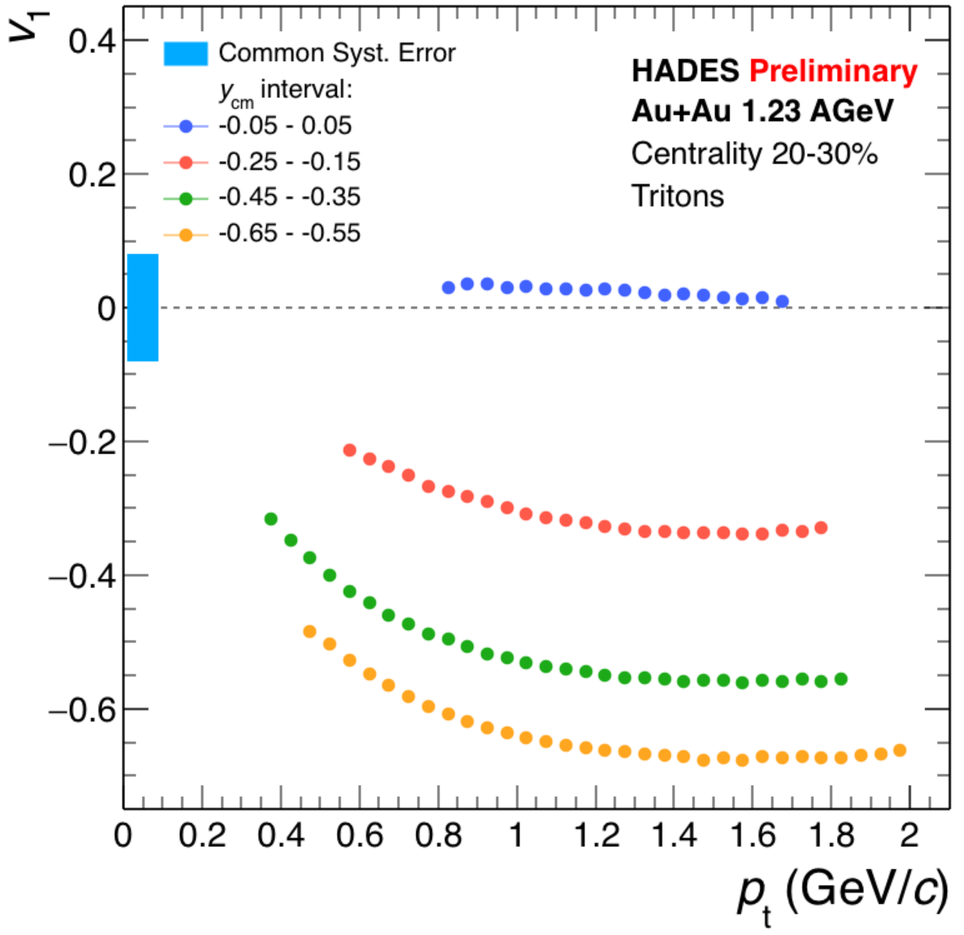



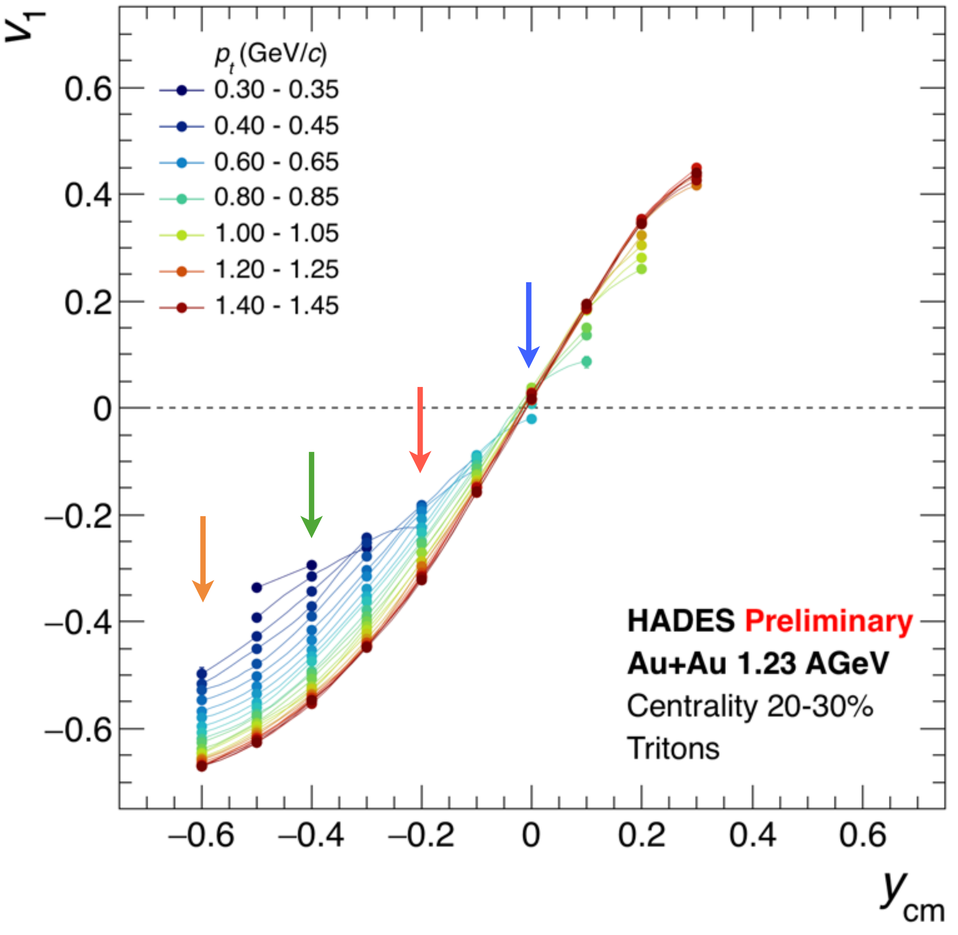

**Good agreement between backward and forward rapidity bins**

# Directed Flow $v_1$: Tritons

## $p_t$-Dependence

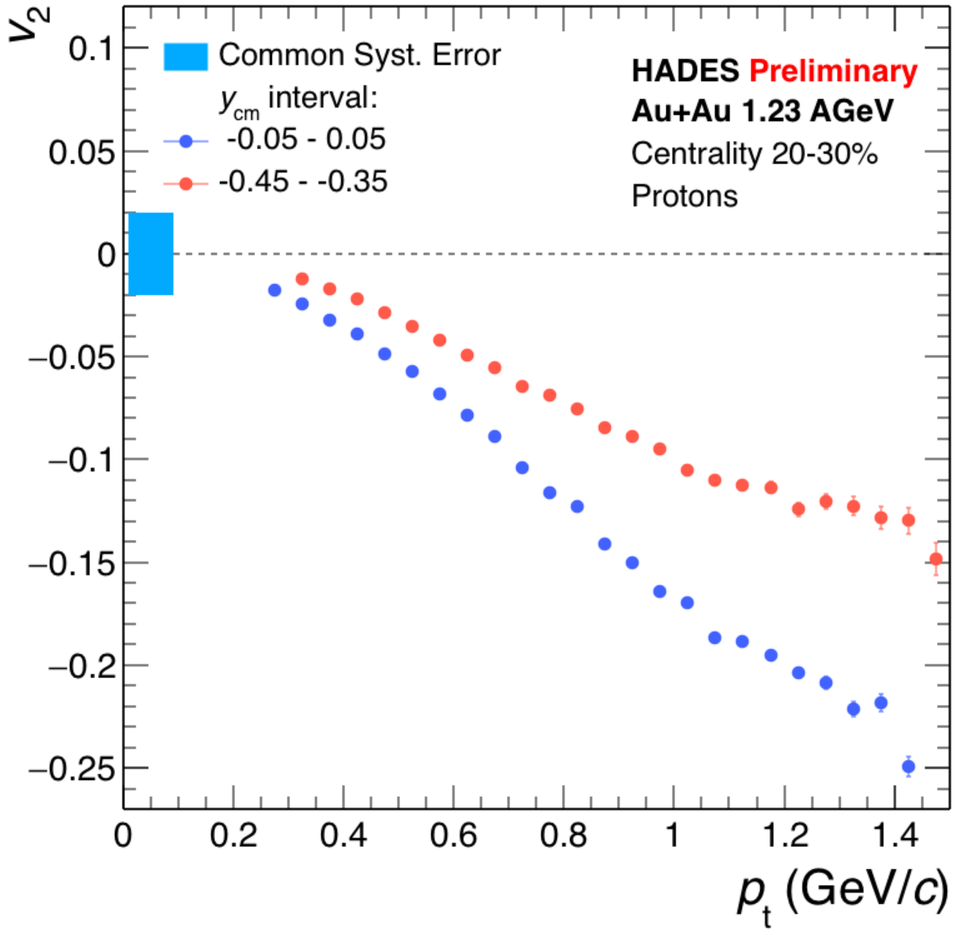
QM18, Nucl.Phys. A982 (2019) 431



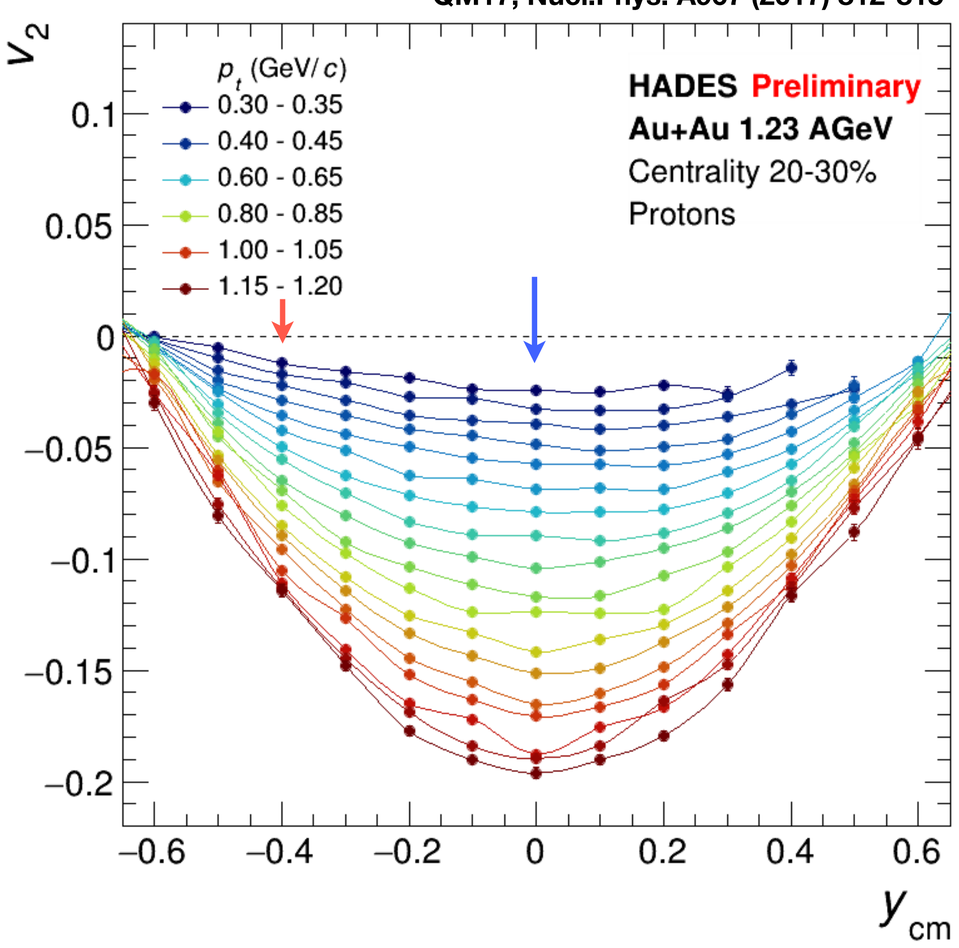



# Elliptic Flow $v_2$: Proton

## $p_t$-Dependence



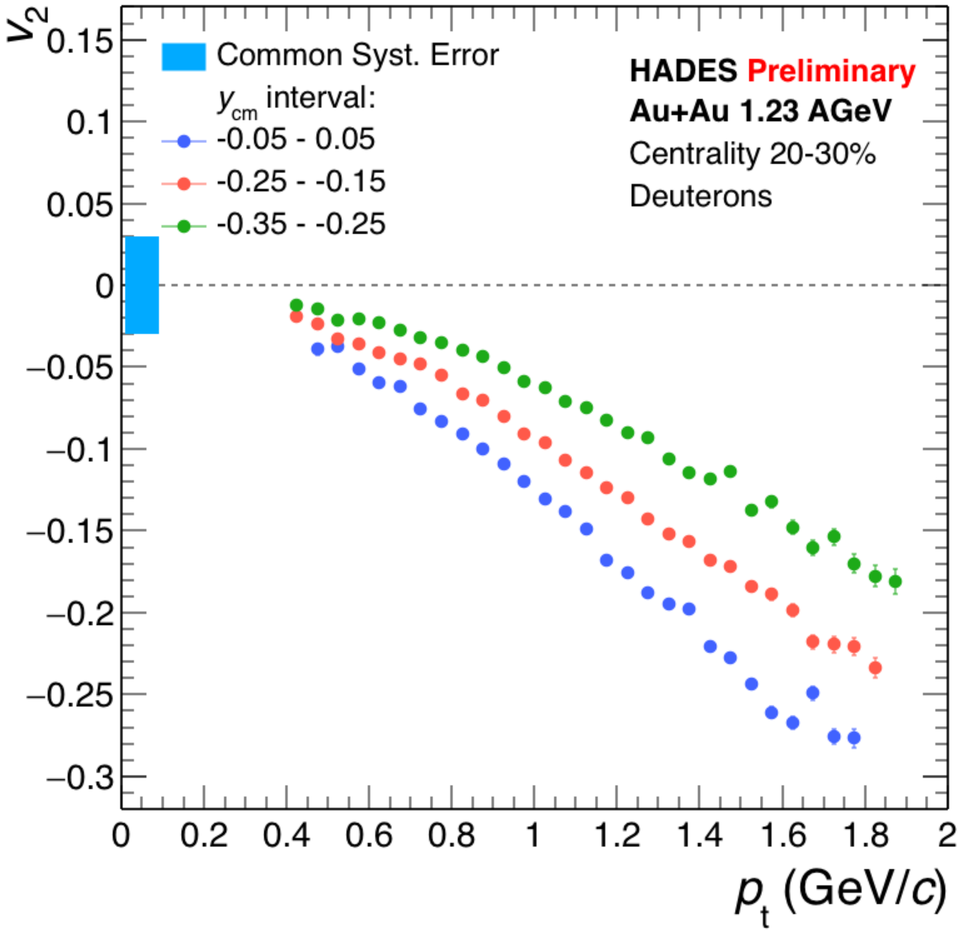

QM17, Nucl.Phys. A967 (2017) 812-815

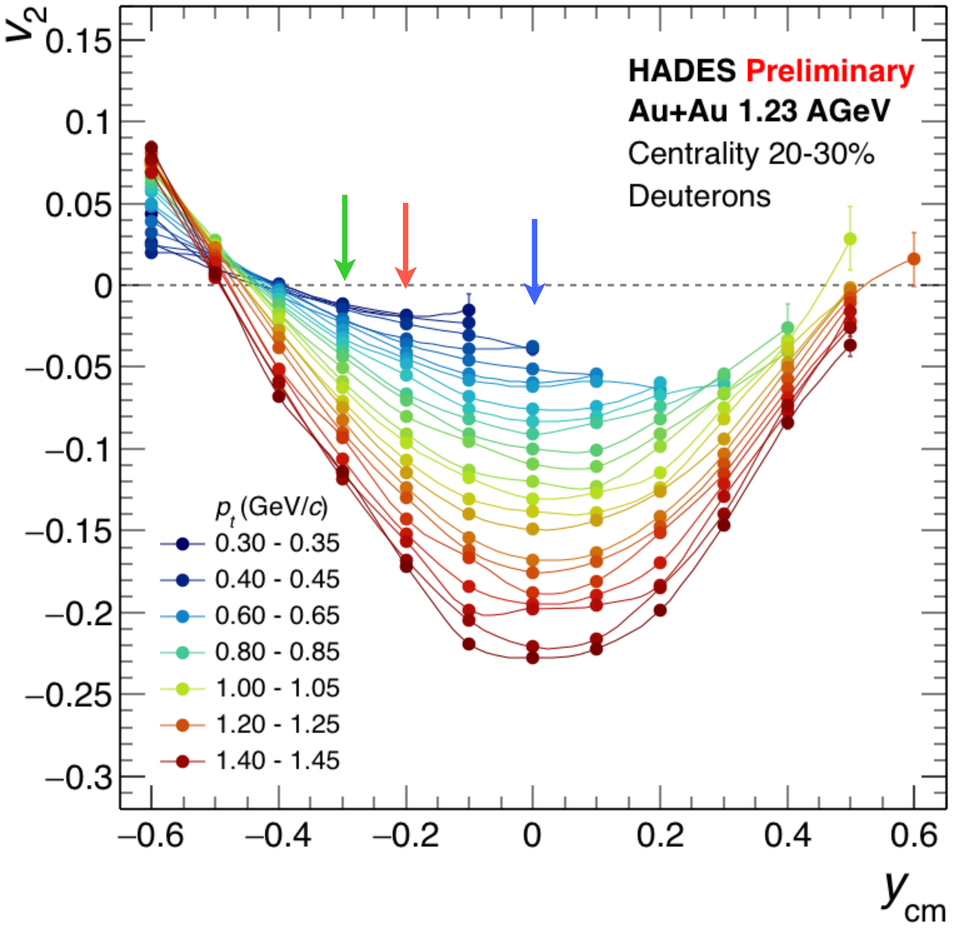


# Elliptic Flow $v_2$: Deuterons

## $p_t$-Dependence

QM18, Nucl.Phys. A982 (2019) 431

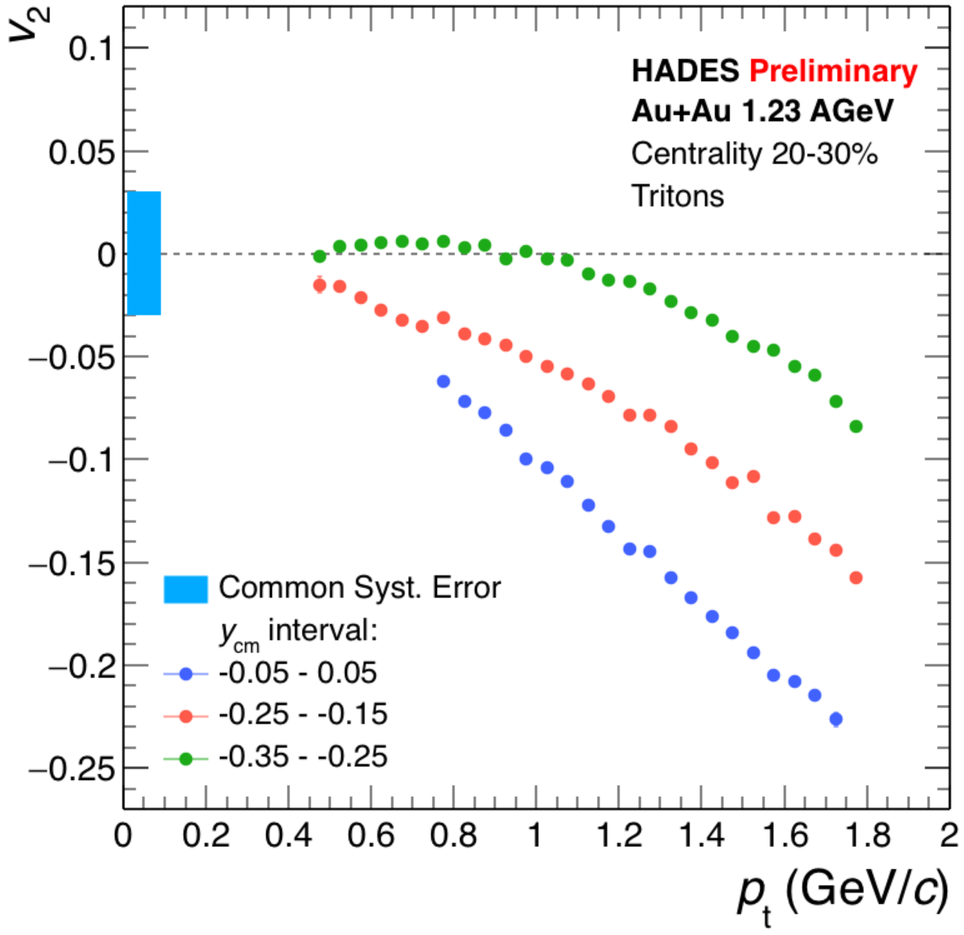


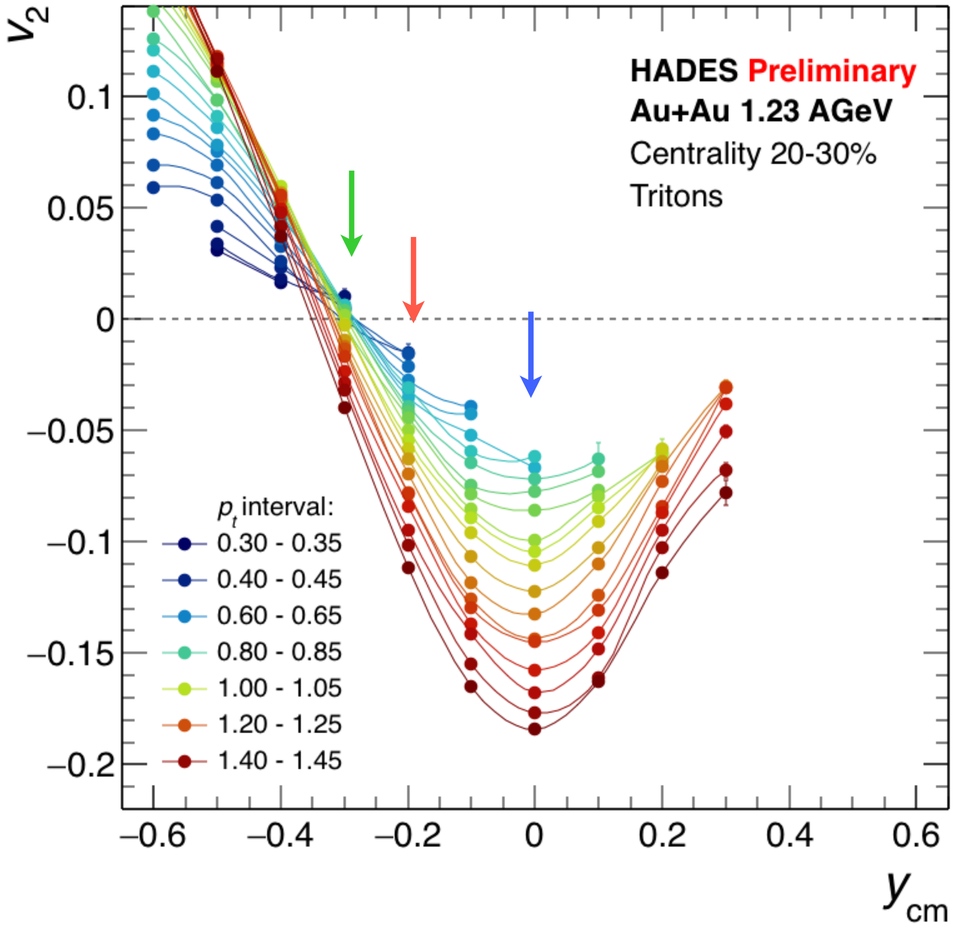



# Elliptic Flow $v_2$: Tritons

## $p_t$-Dependence

QM18, Nucl.Phys. A982 (2019) 431

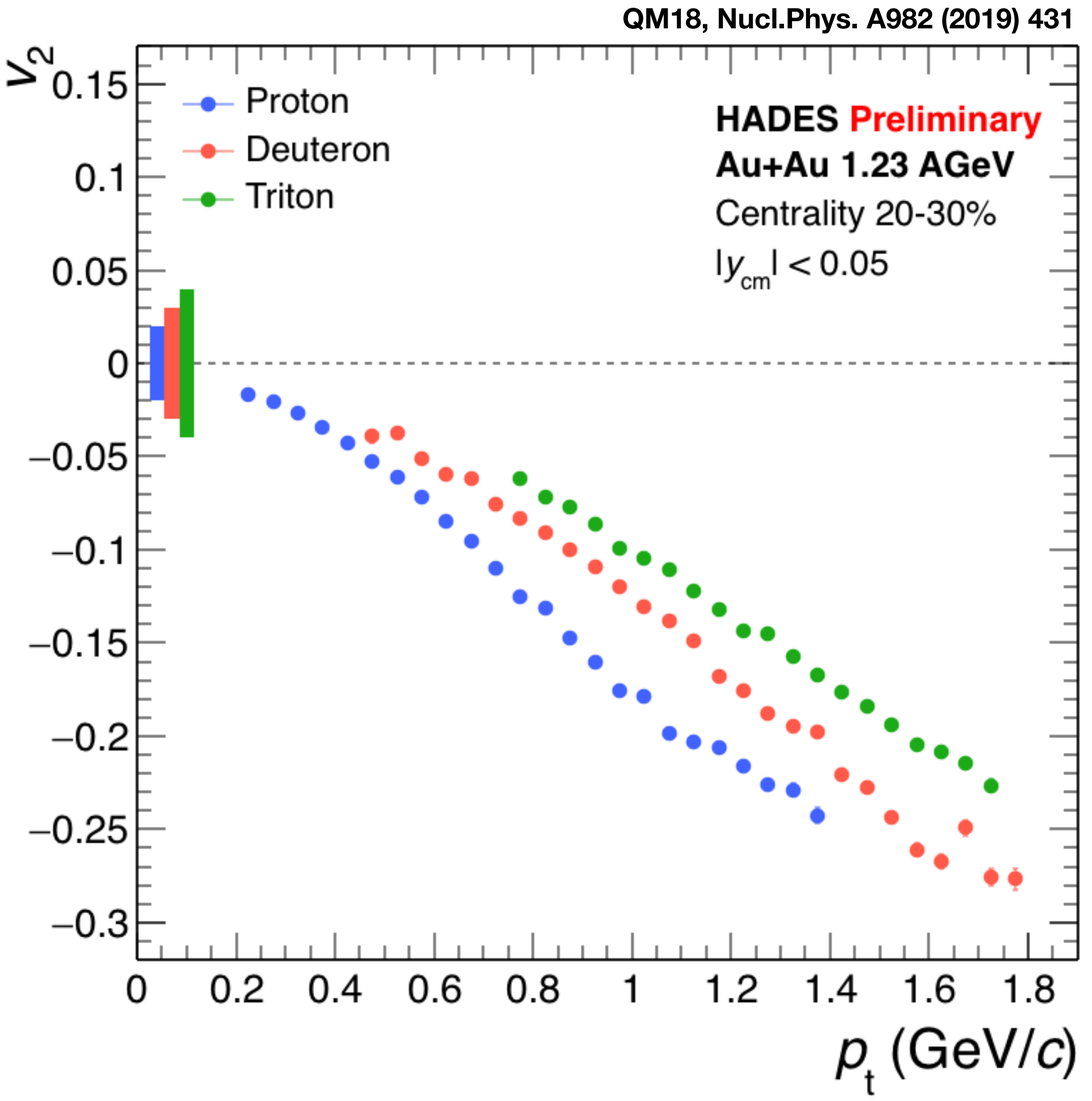


# Elliptic Flow $v_2$: Light Nuclei

## Nucleon Coalescence

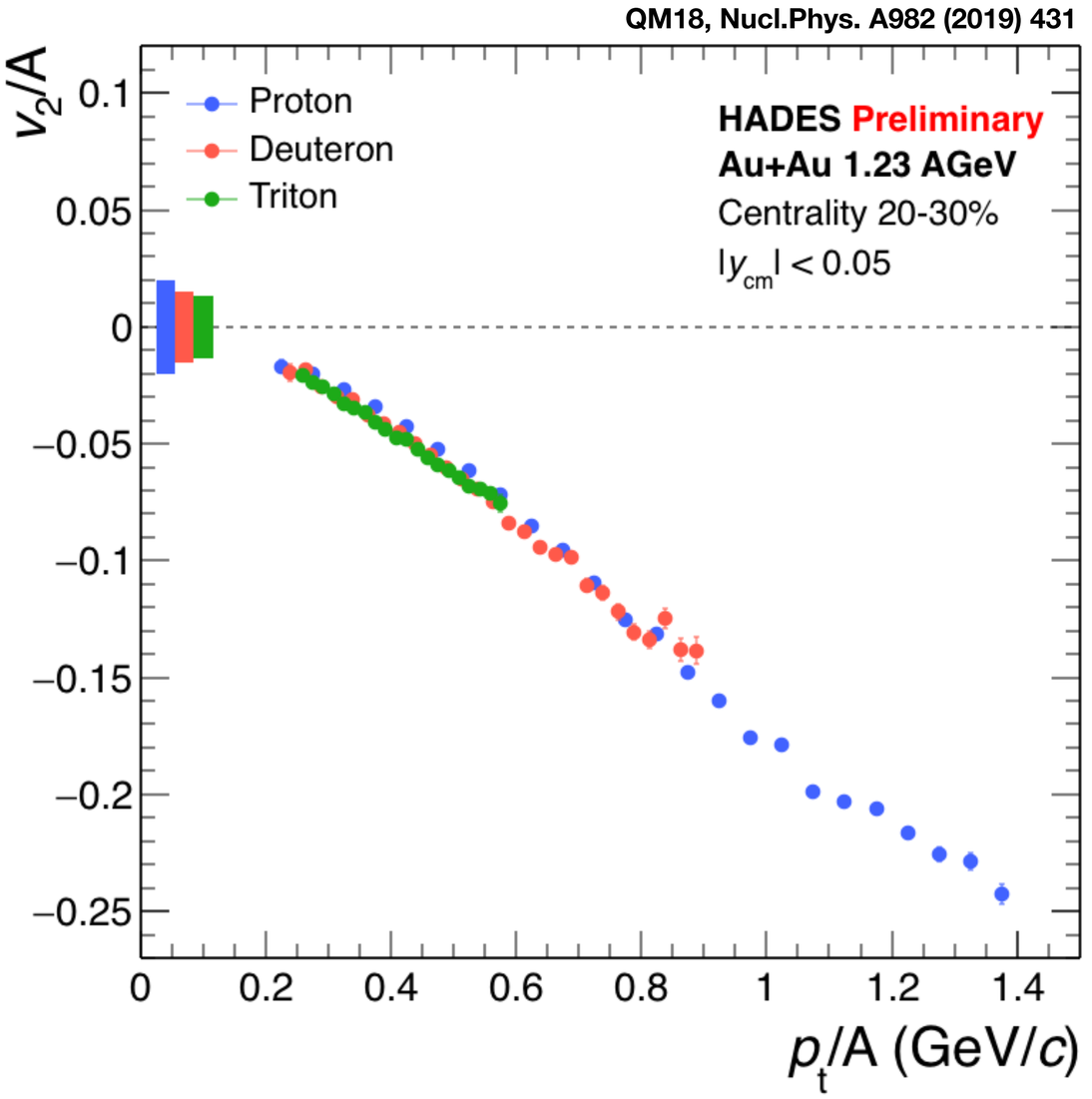
- Comparison of p, d, t $v_2$ at mid-rapidity



# Elliptic Flow $v_2$: Light Nuclei

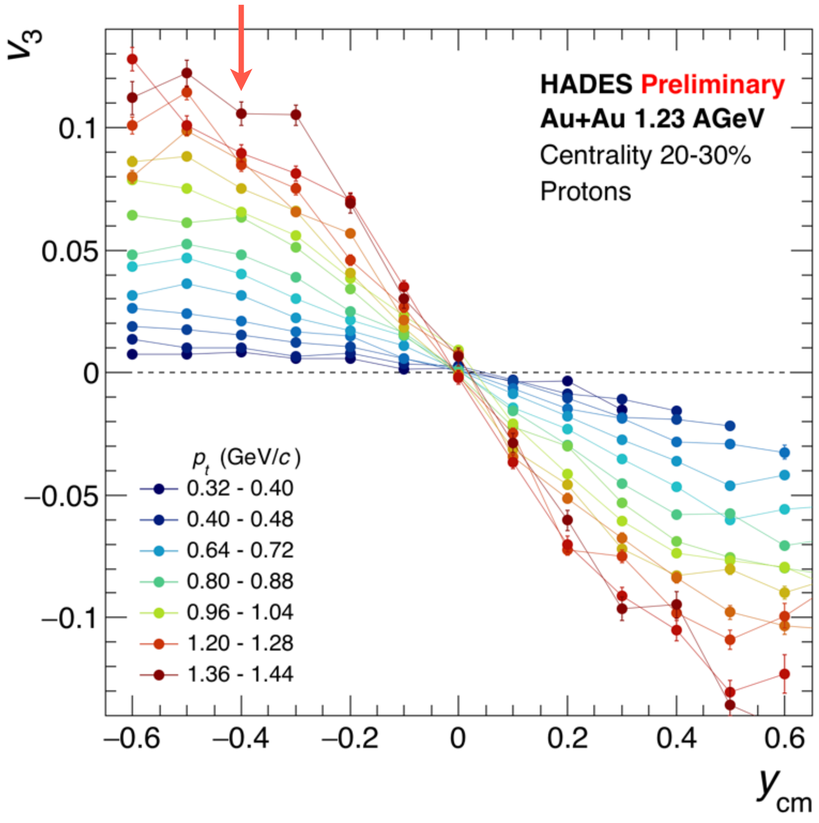
## Nucleon Coalescence

- 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

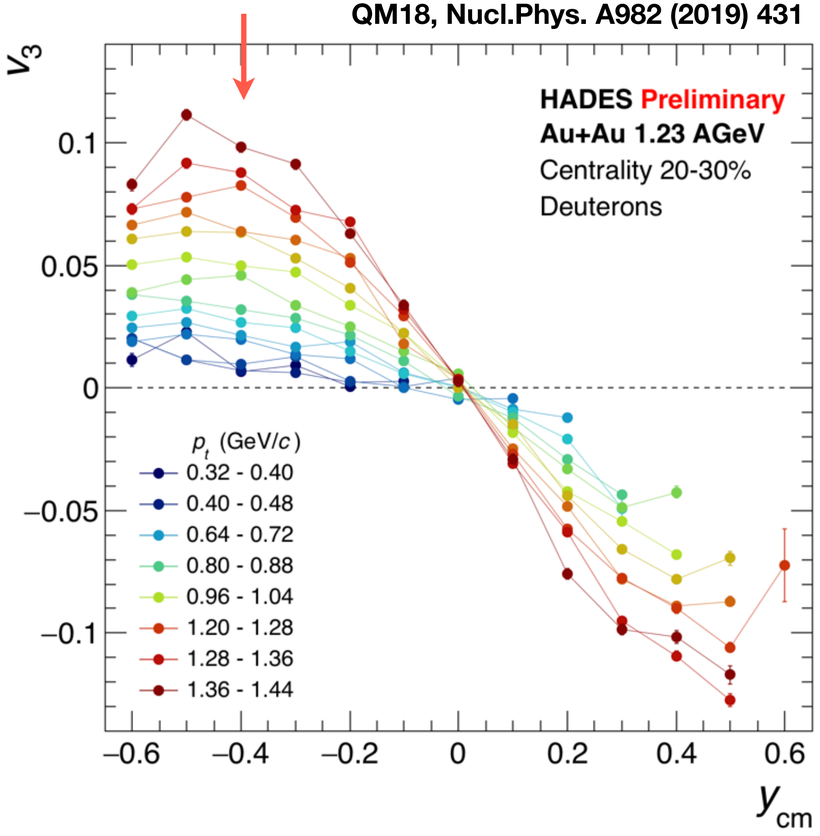


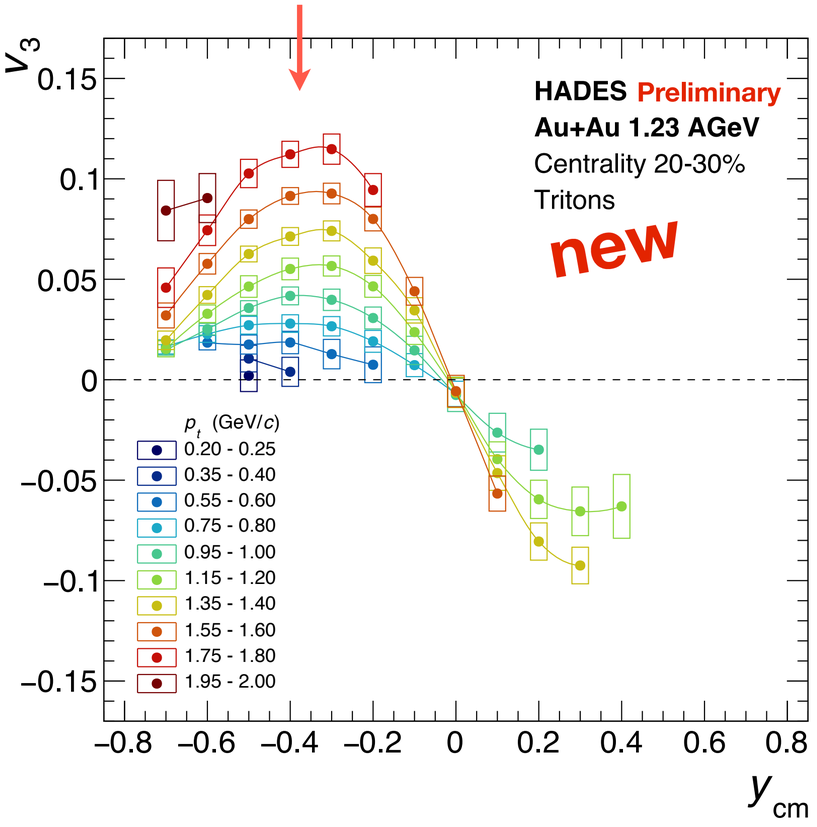
# Triangular Flow $v_3\{\Psi_{RP}\}$

## Protons and Light Nuclei




QM18, Nucl.Phys. A982 (2019) 431

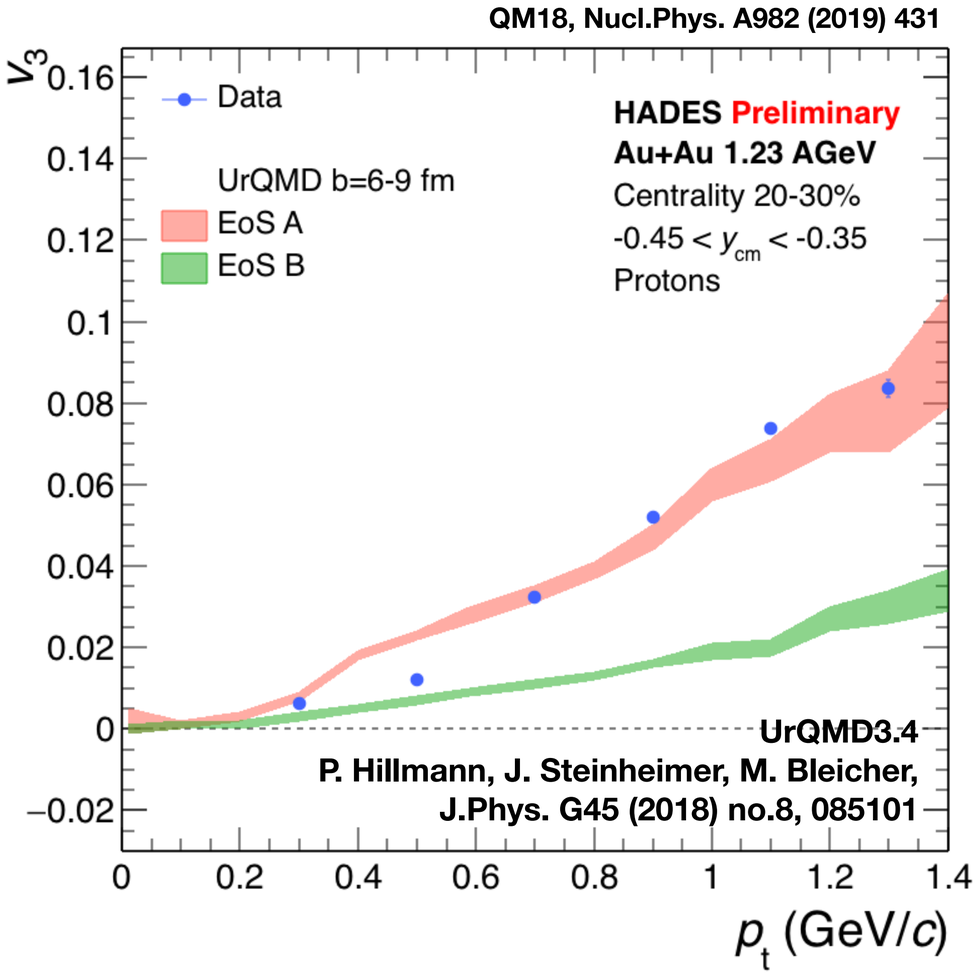


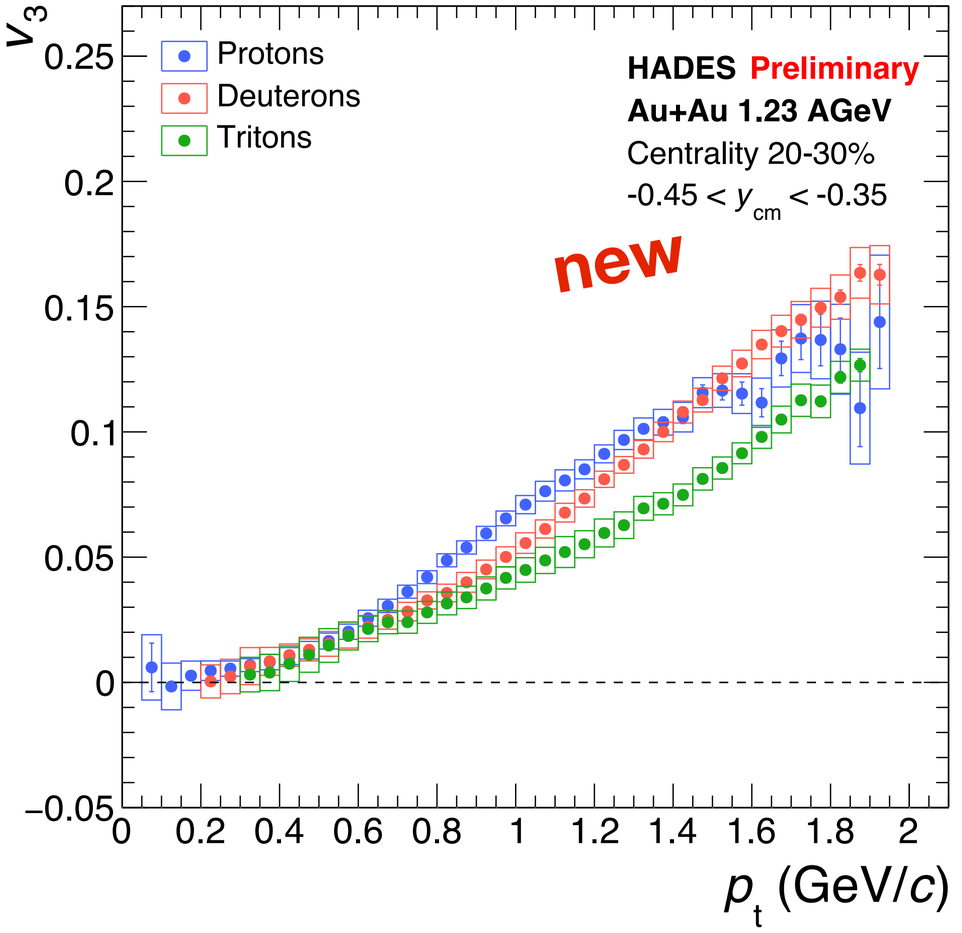

**Note: v3{$\Psi_{RP}$} w.r.t reaction plane** $v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$

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

## Protons and Light Nuclei




**UrQMD predicts high sensitivity of $v_3$ to EoS**

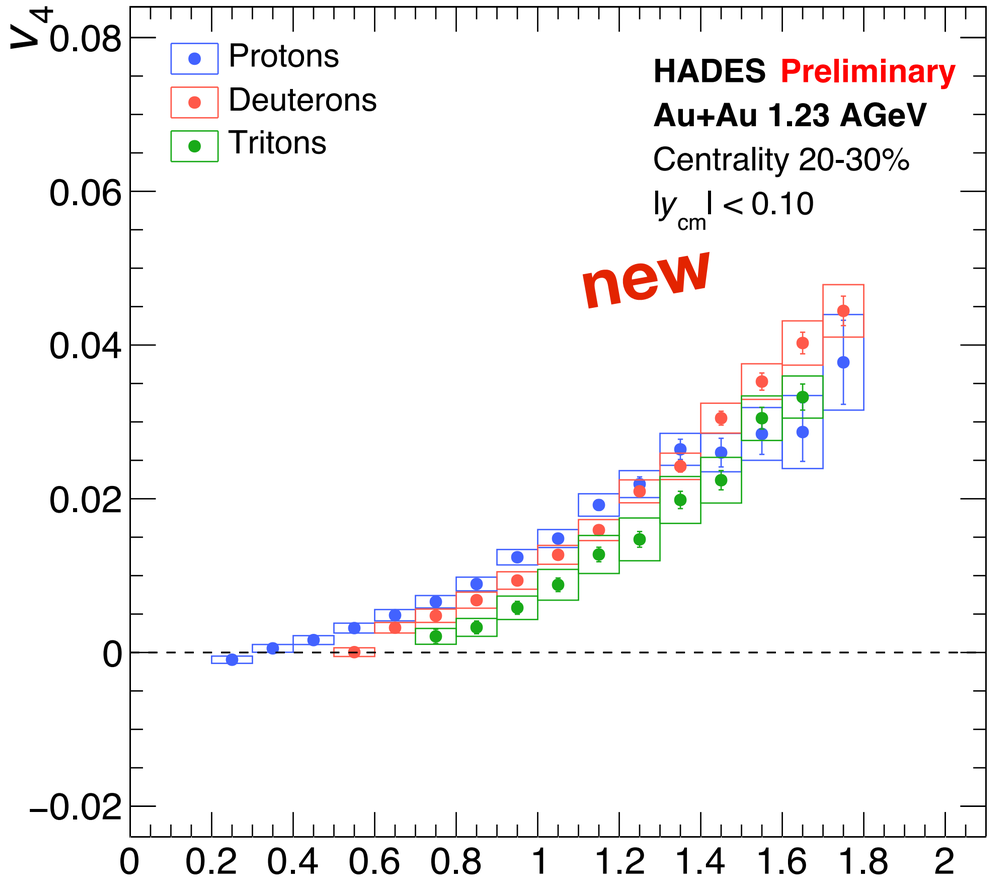



**Note: v3{$\Psi_{RP}$} w.r.t reaction plane** $v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$

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

Protons and Light Nuclei

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

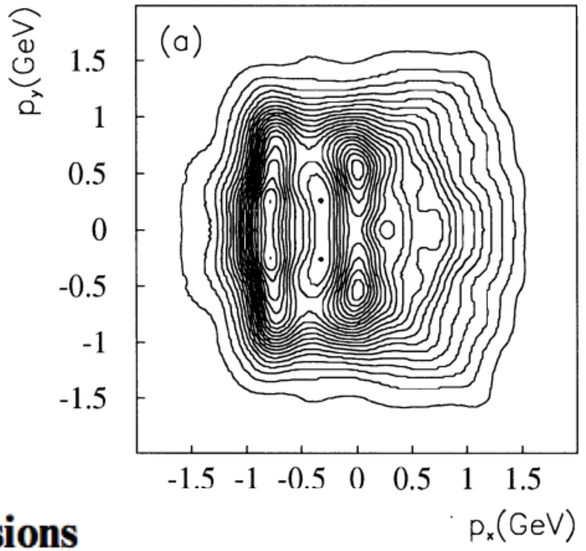



$$v_4\{\Psi_{RP}\} = \langle\langle \cos 4(\varphi - \Psi_{RP})\rangle\rangle$$

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

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

Protons and Light Nuclei

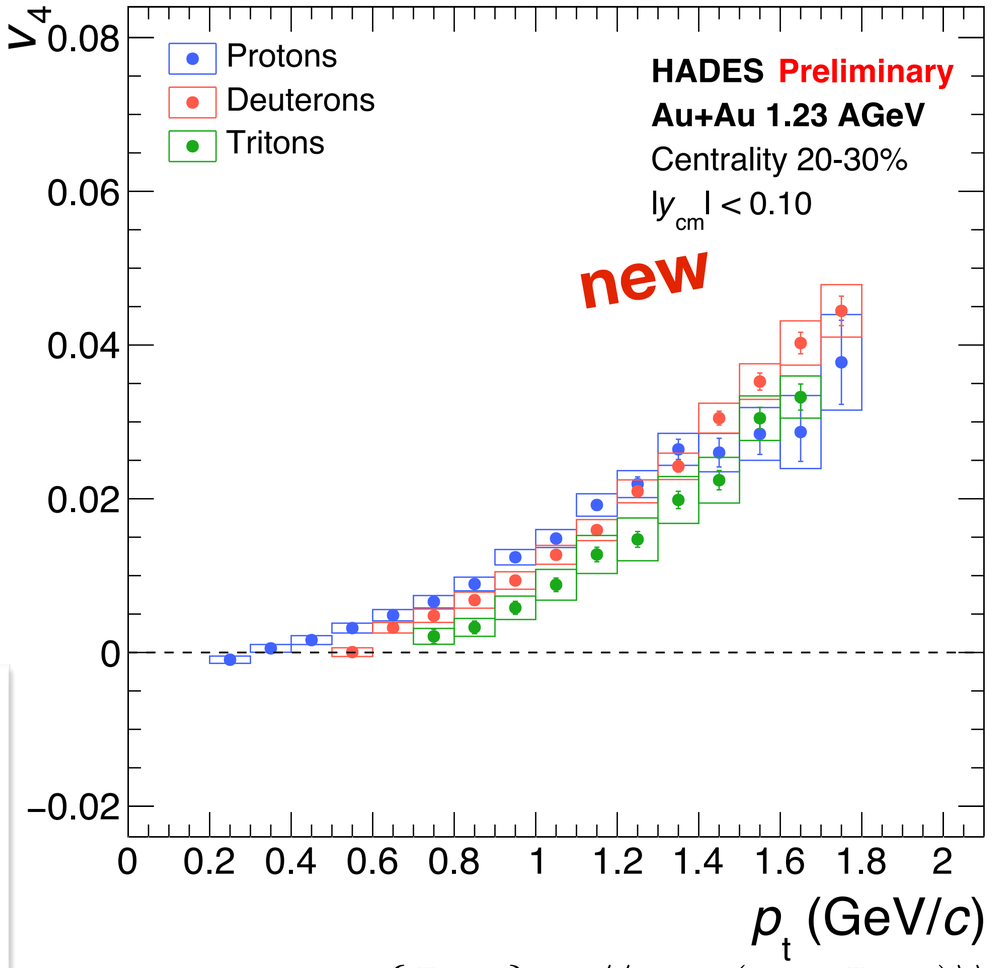



Z. Phys. C 70, 665–671 (1996)

**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.



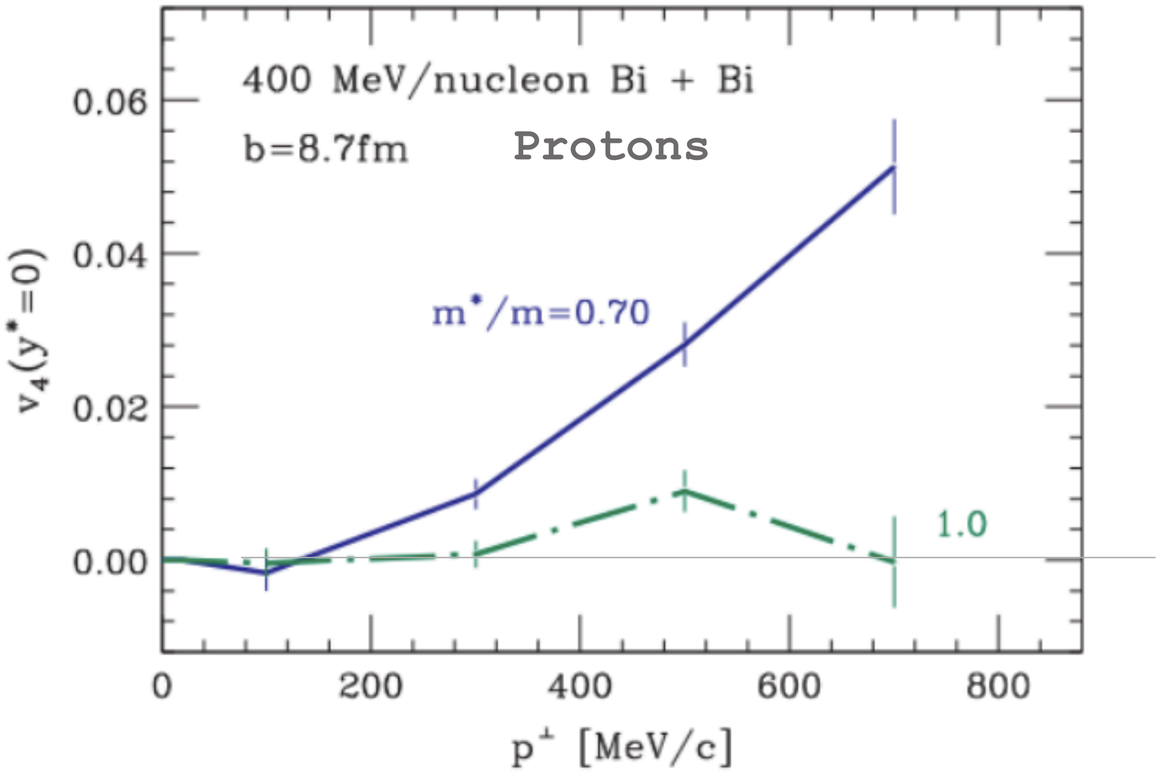

$$v_4\{\Psi_{RP}\} = \langle\langle \cos 4(\varphi - \Psi_{RP})\rangle\rangle$$

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

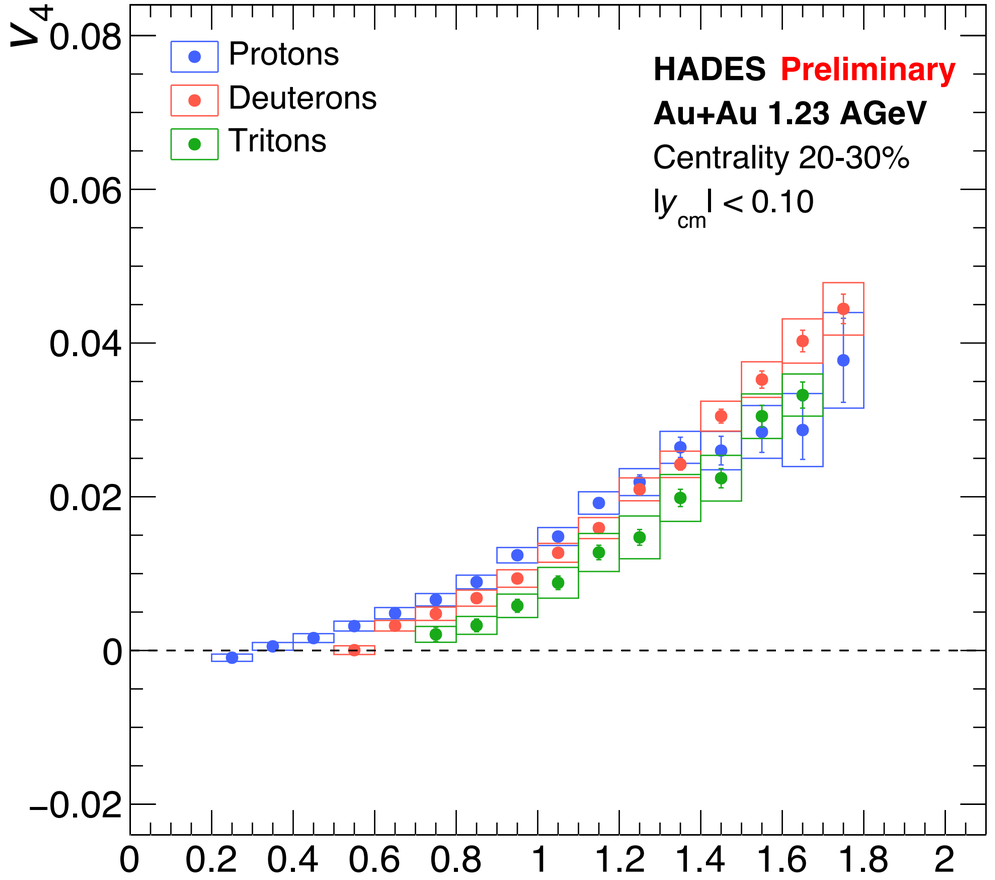
# Quadrangular Flow $v_4\{\Psi_{RP}\}$

## 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**

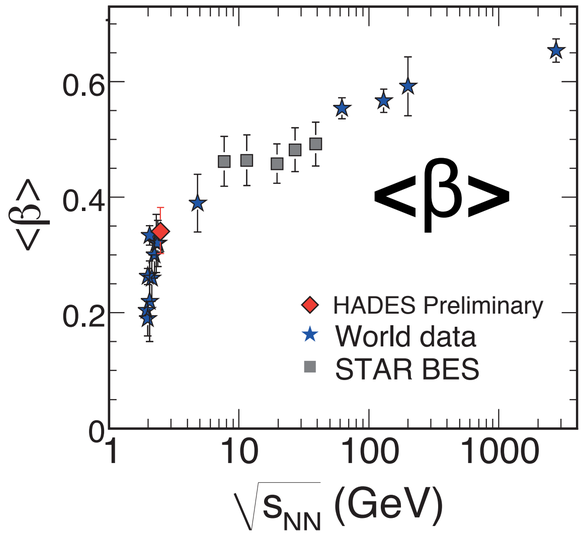
# Conclusions

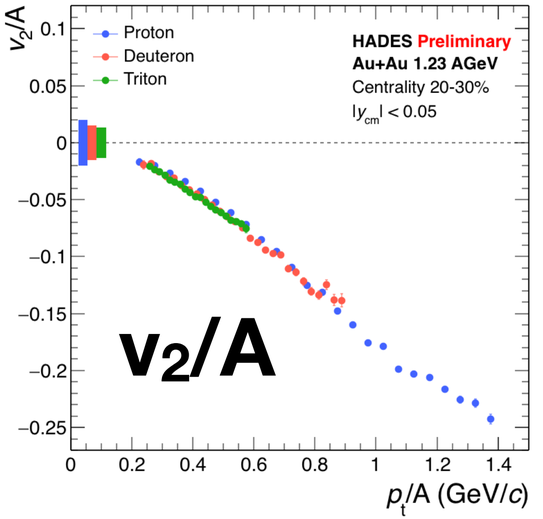
- Freeze-out parameters via Blast-Wave fit:

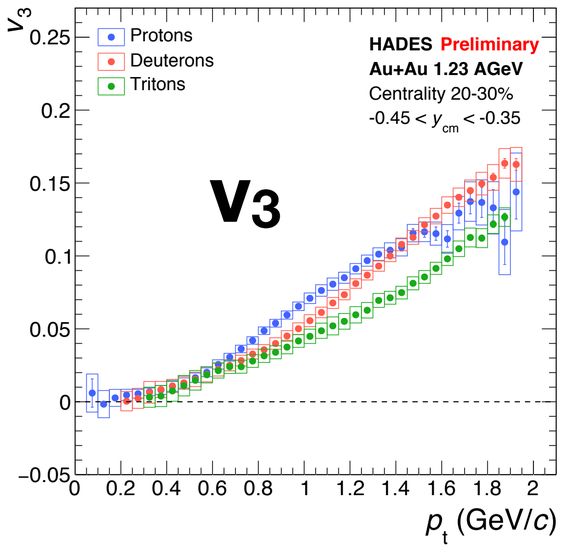
$$T_{kin} = 66 \pm 8 \text{ MeV}$$
$$\langle \beta_r \rangle = 0.34 \pm 0.04$$

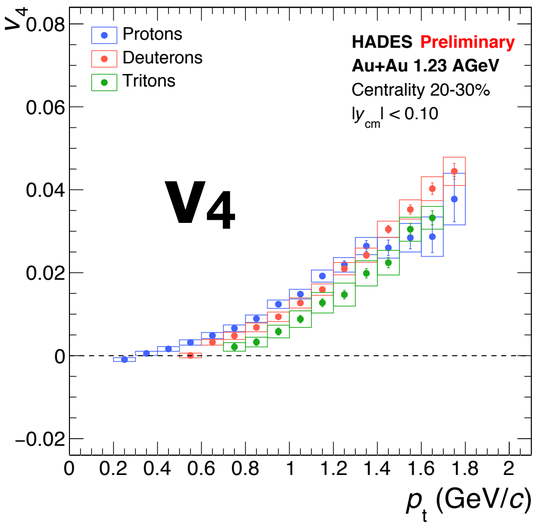
- Directed $v_1$ and elliptic $v_2$ flow of protons, deuterons and tritons
  - Elliptic flow at mid-rapidity scales with A

- 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

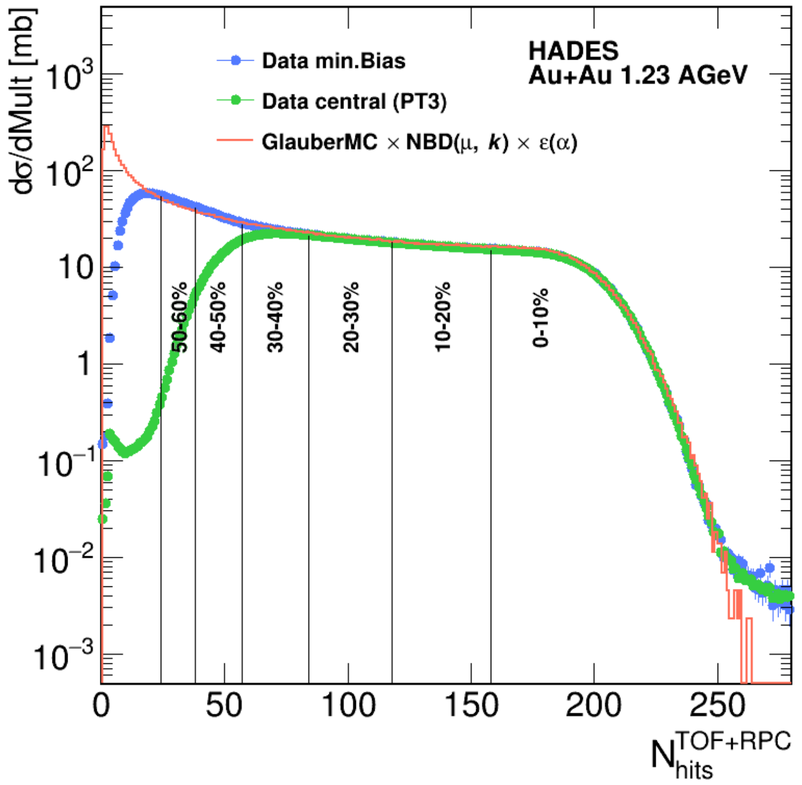
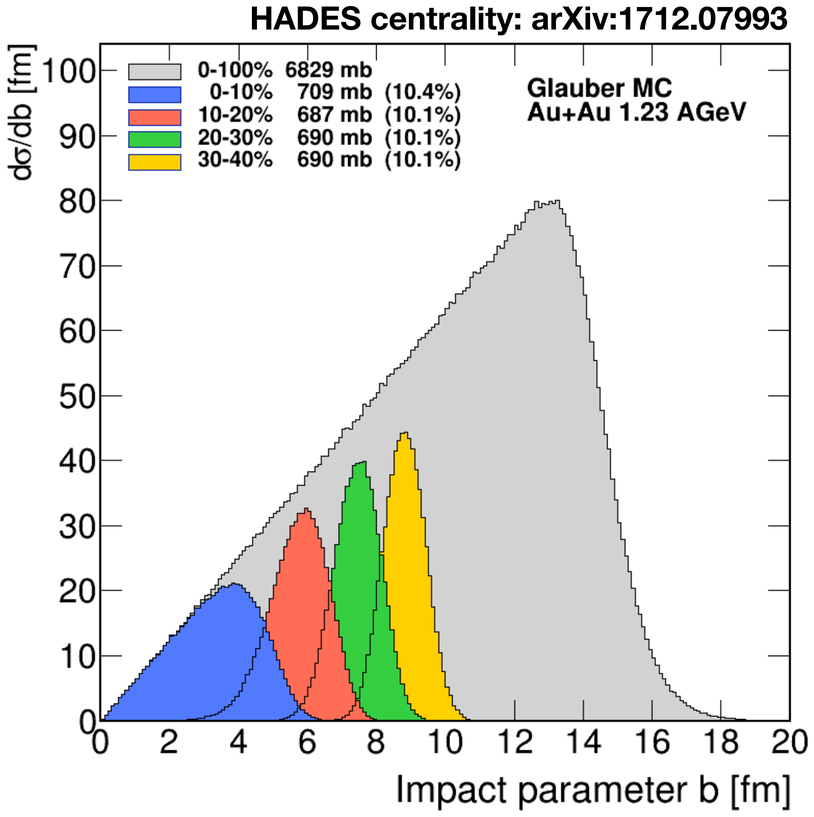


# HADES Collaboration

# HADES Performance

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