Collective flow measurements with HADES in Au+Au collisions at 1.23A GeV

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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

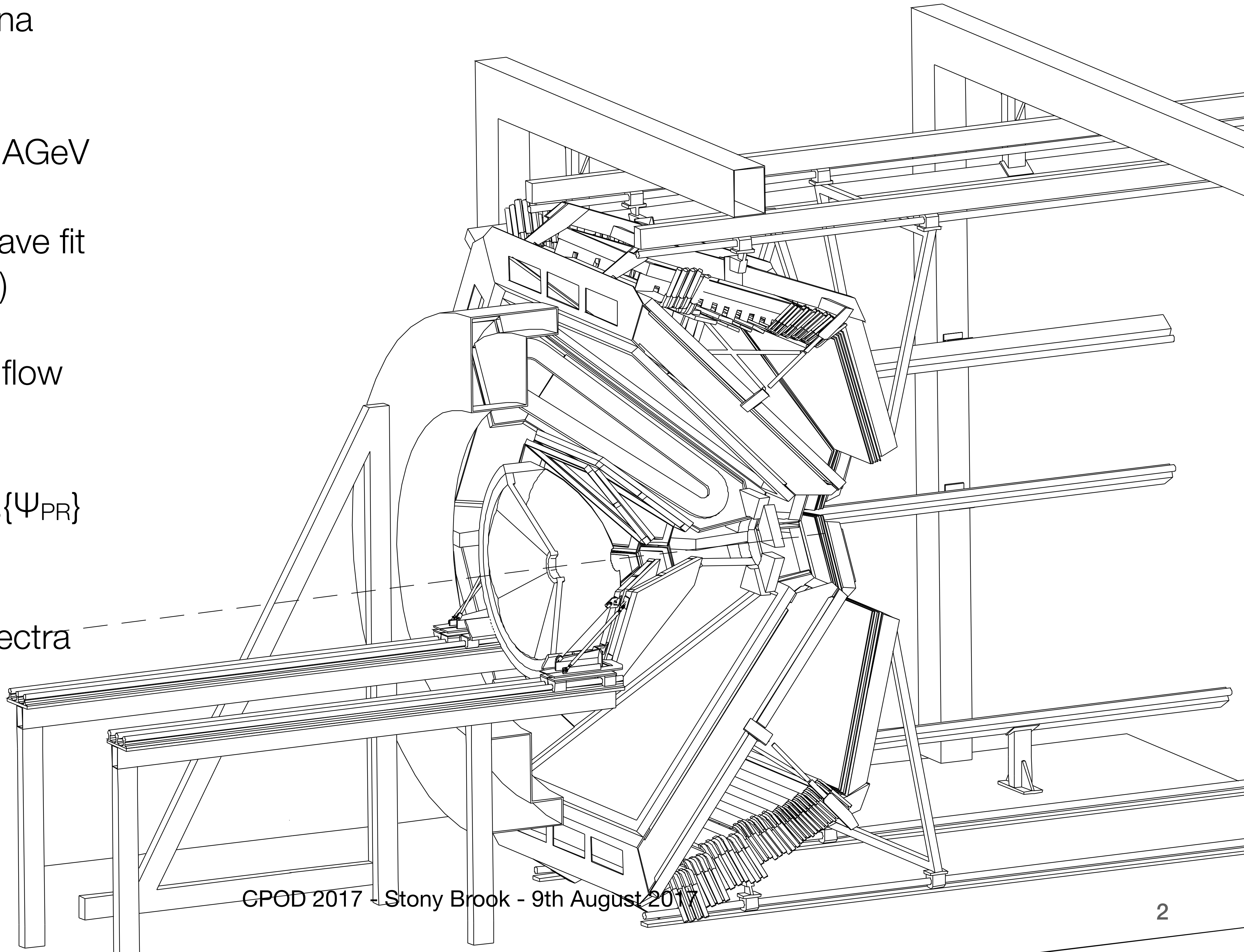
HADES

CPOD 2017 Critical Point and Onset of Deconfinement

CPOD 2017
Stony Brook
9th August 2017

Outline

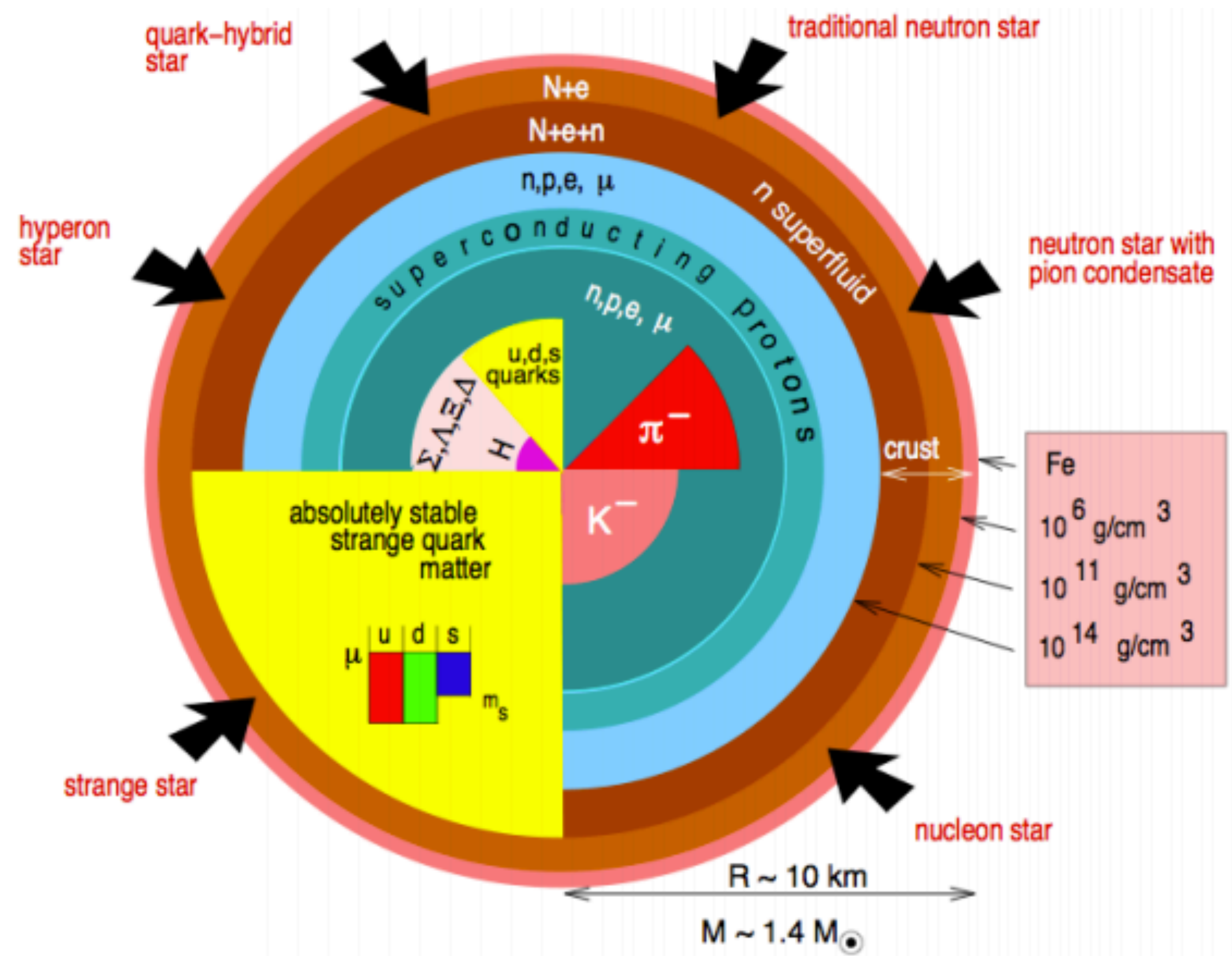
- Collective Phenomena
- HADES and
  Au+Au data at 1.23 AGeV
- Radial flow (Blast-Wave fit
  → kinetic freeze-out)
- Directed and elliptic flow
  of protons
- Higher harmonics $v_3\{\Psi_{PR}\}$
- Effect of Coulomb
  potential on pion spectra



Motivation
Collective Phenomena

- Equation-of-state
    - Understanding of astrophysical phenomena
    - Effect of mean-field potentials
- Bulk properties of extreme nuclear matter
    - Transport coefficient: shear viscosity η/s, bulk viscosity ...
- Reference v_1 v_2 measurement for multi-particle correlation analysis

Neutron Star

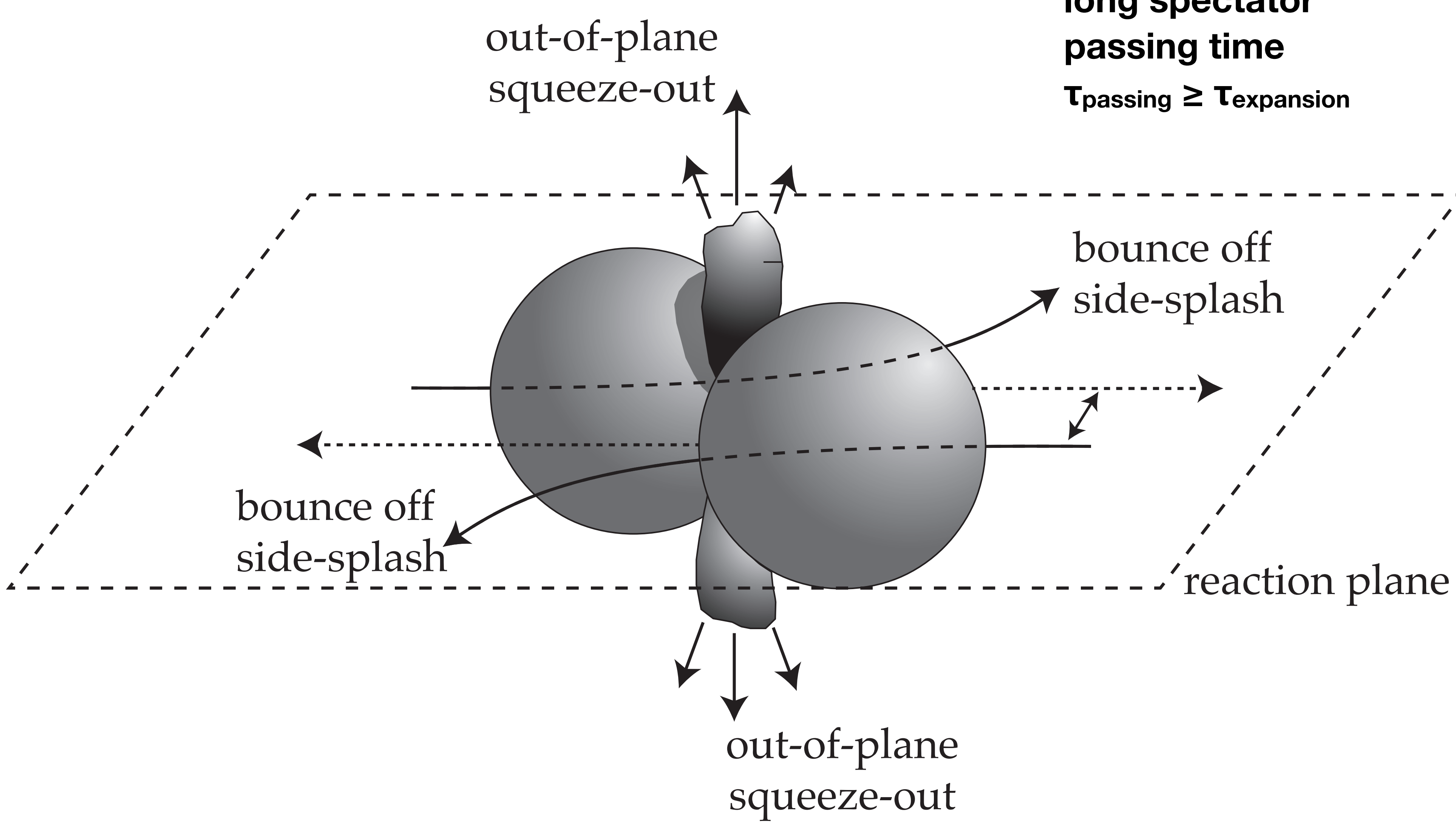


Motivation

Heavy ion collision at 1.23A GeV

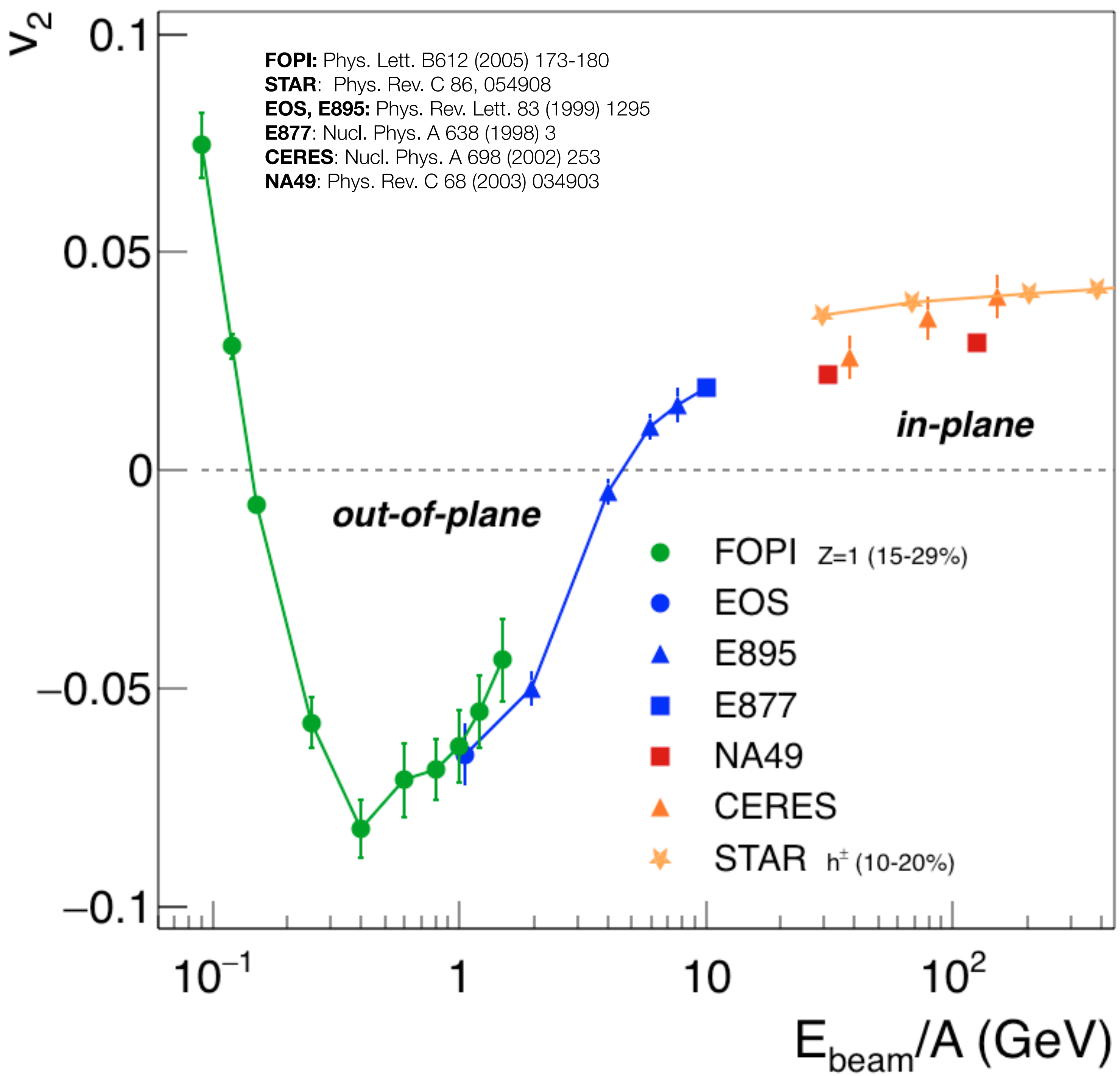
long spectator passing time

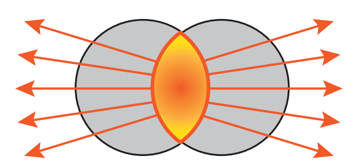
$\tau_{passing} \geq \tau_{expansion}$



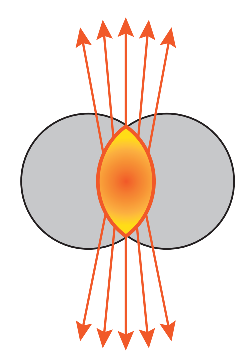
Motivation

Energy Dependence v_2





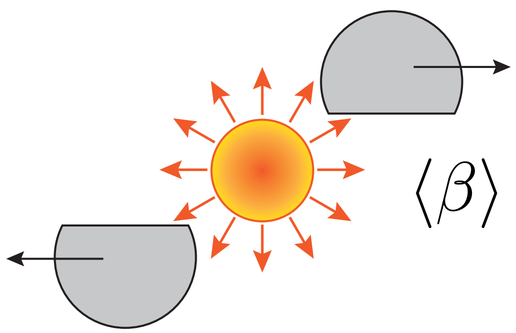
in-plane $v_2>0$
short spectator passing time
$\tau_{passing} \ll \tau_{expansion}$
pressure gradient



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

Motivation
Flow Components

radial flow



$\langle \beta \rangle$

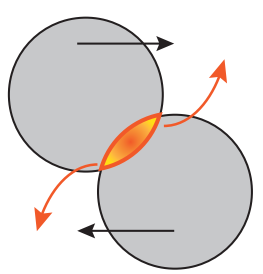
Blast wave model: Phys. Rev. C **48**, 2462

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

Linear radial flow velocity profile:

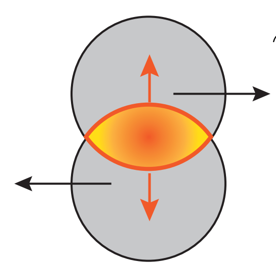
$$\beta = \beta_S (r/R)^n \qquad n = 1$$

directed flow



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

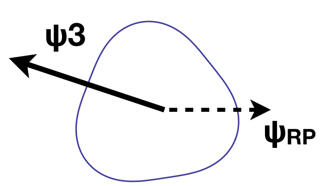
elliptic flow



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

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

triangular flow



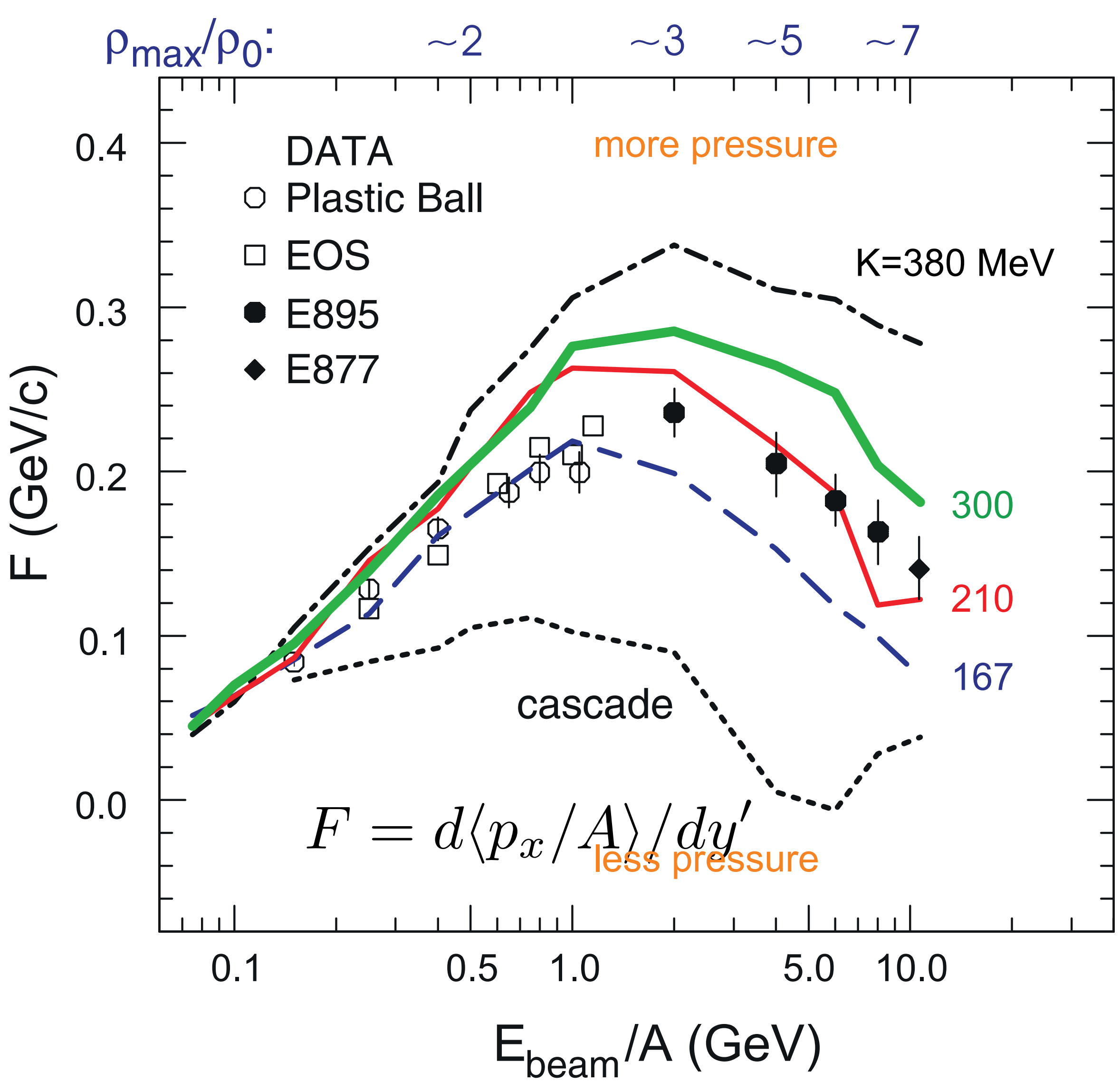
$$v_3 = \langle cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle$$

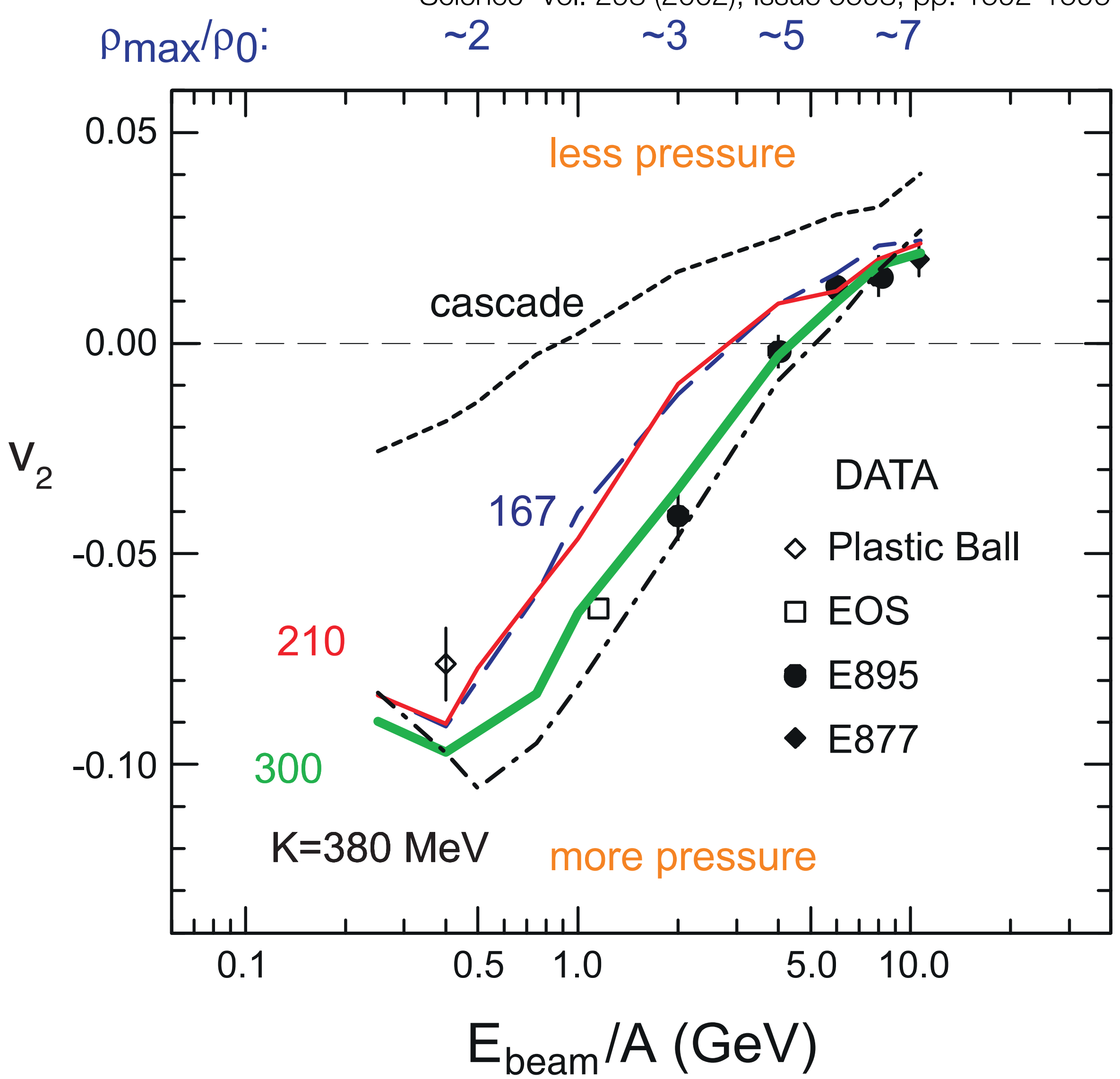
Motivation

Equation-of-state

- Effect of mean-field potentials $$\kappa = 9\rho^2 \frac{\partial^2}{\partial \rho^2}\left(\frac{E}{A}\right)$$

Science Vol. 298 (2002), Issue 5598, pp. 1592-1596



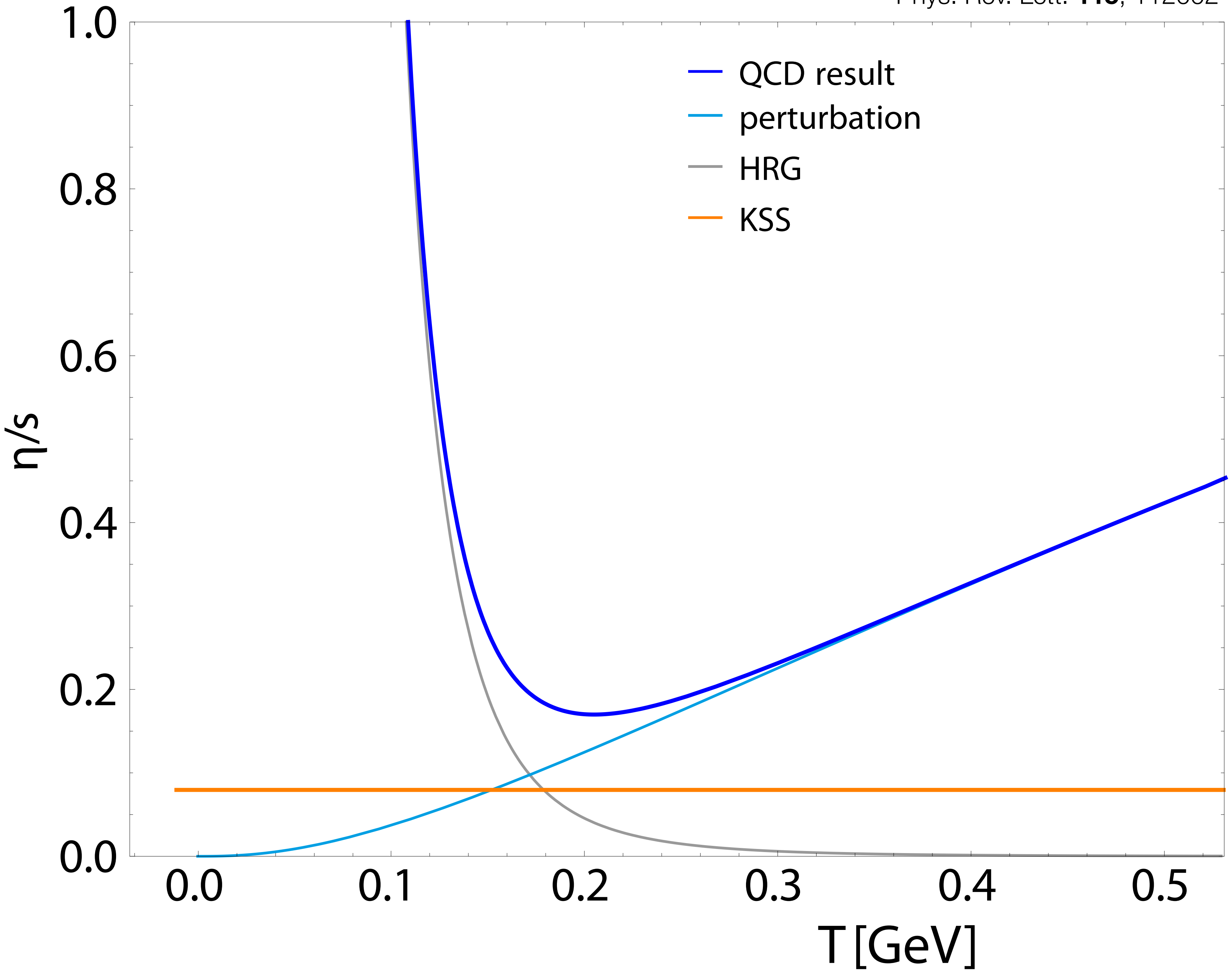


- Difficult to draw quantitative conclusion

Motivation

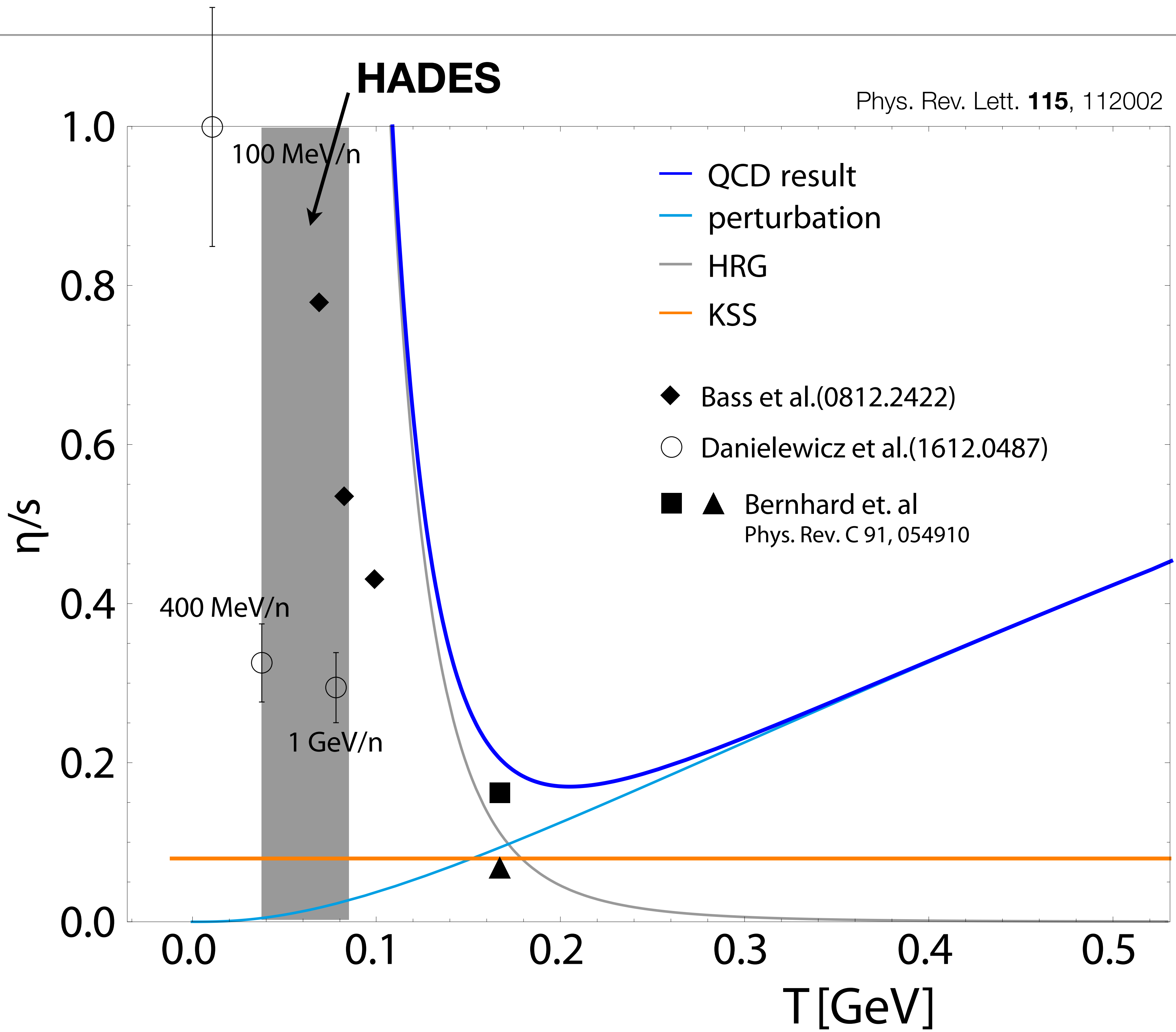
Shear-Viscosity over Entropy Density

Phys. Rev. Lett. **115**, 112002

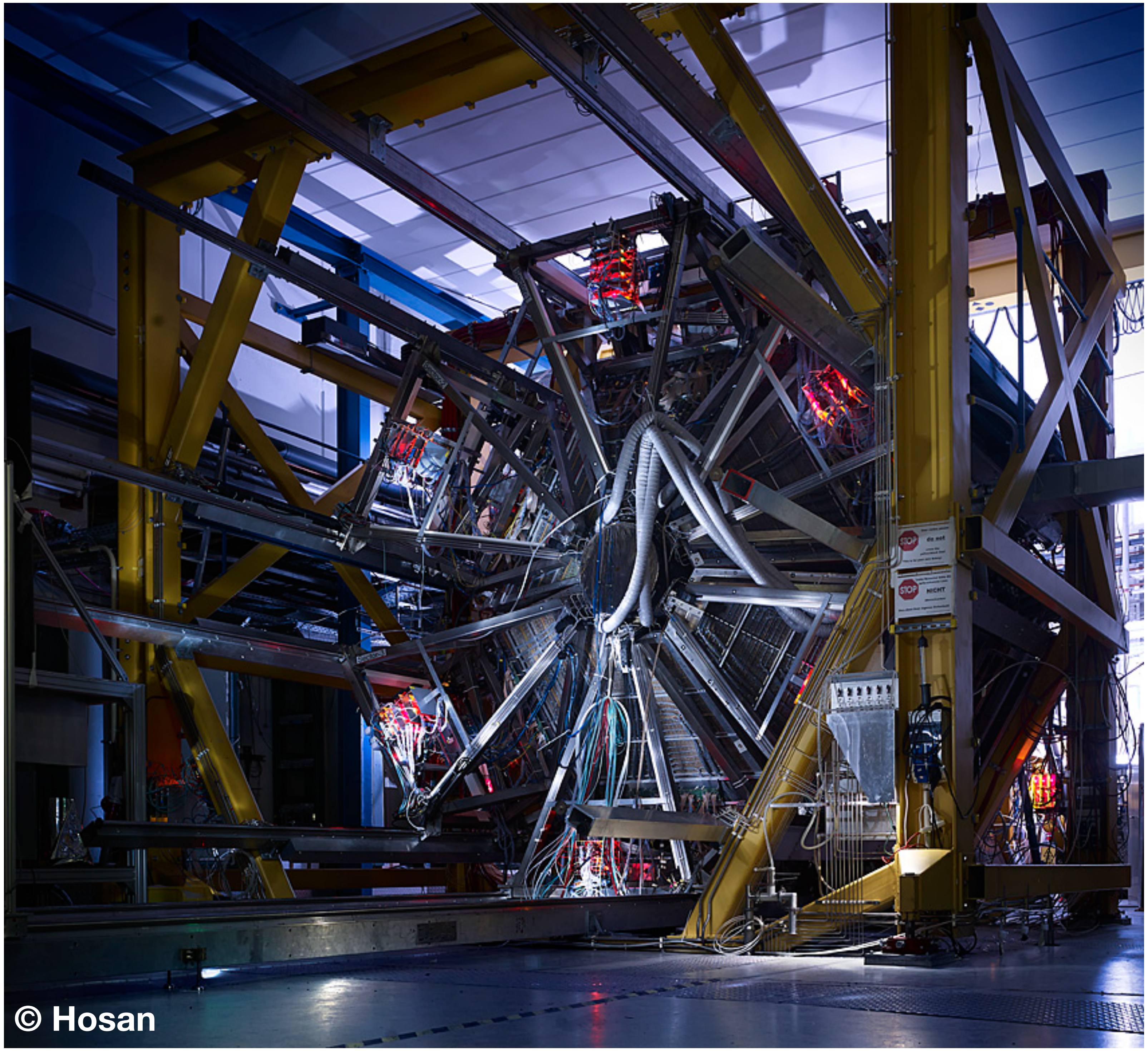


Motivation

Shear-Viscosity over Entropy Density



High Acceptance Di-Electron Spectrometer

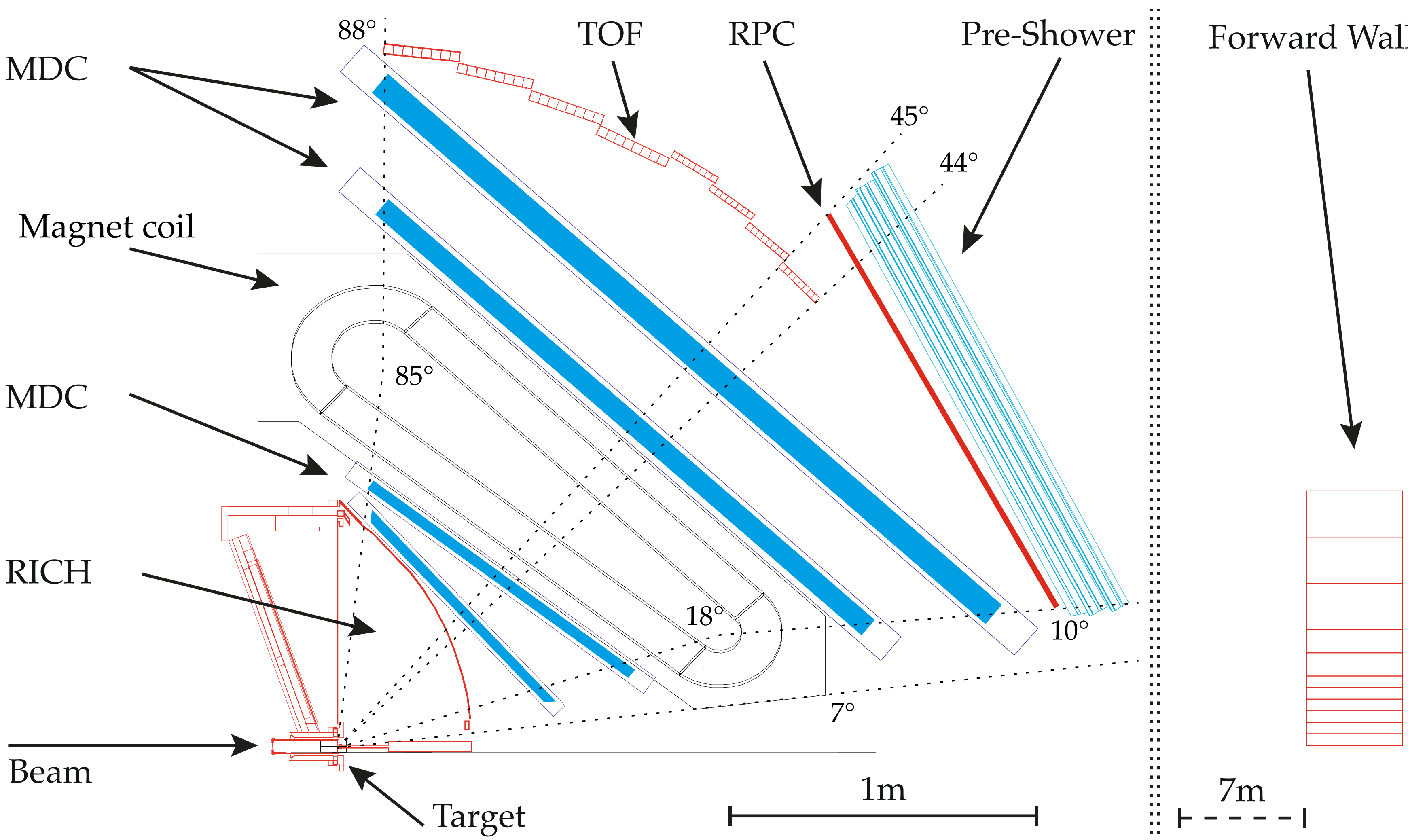


Fixed-target experiment located at SIS18 GSI

Physics program

- 2002 – 2008:
  - Light collision systems (A+A, p+p, n+p, p+A)
- 2012 – 2015:
  - **Au+Au @ 1.23A GeV** ($\sqrt{s_{NN}}$ = 2.41 GeV)
  - **π-induced** reactions
- FAIR Phase-0:
  - **π-induced** reactions
  - **Ag+Ag @ 1.65A GeV**
- SIS100

High Acceptance Di-Electron Spectrometer

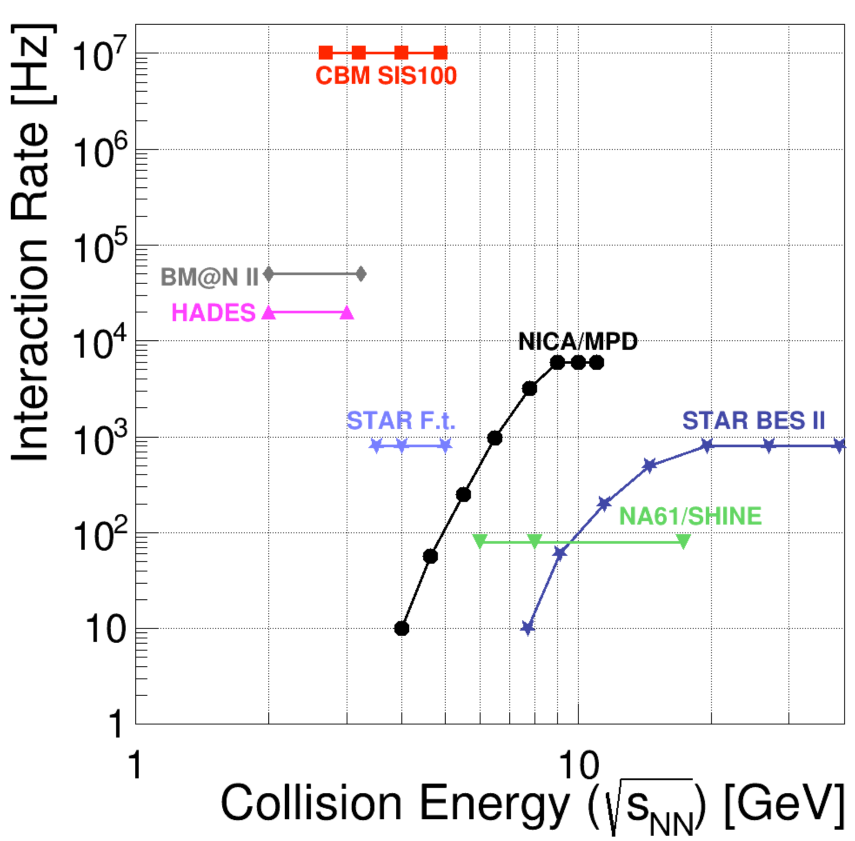


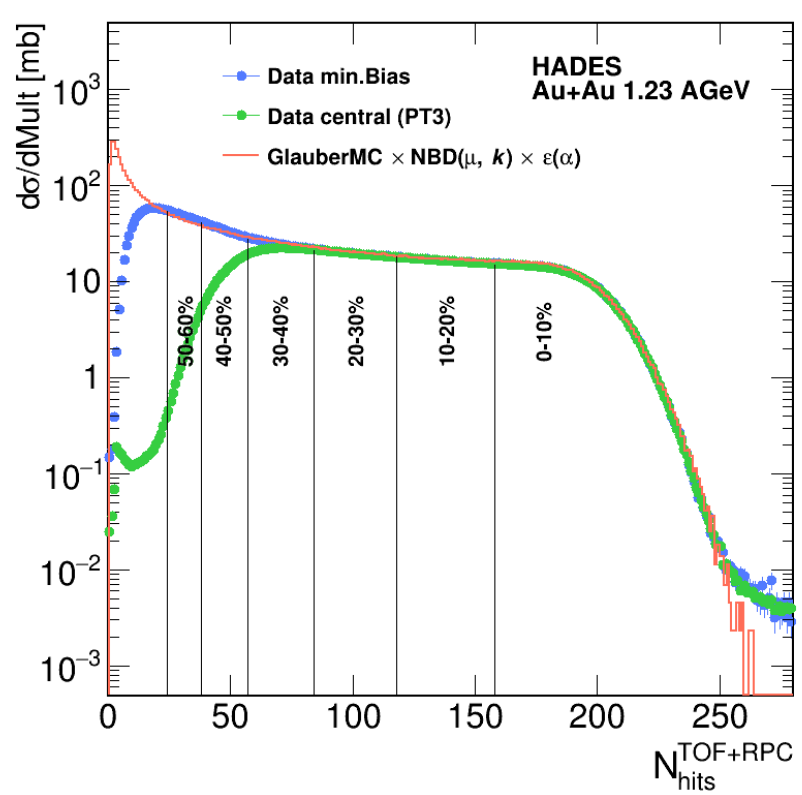
Cross section of one of six sectors

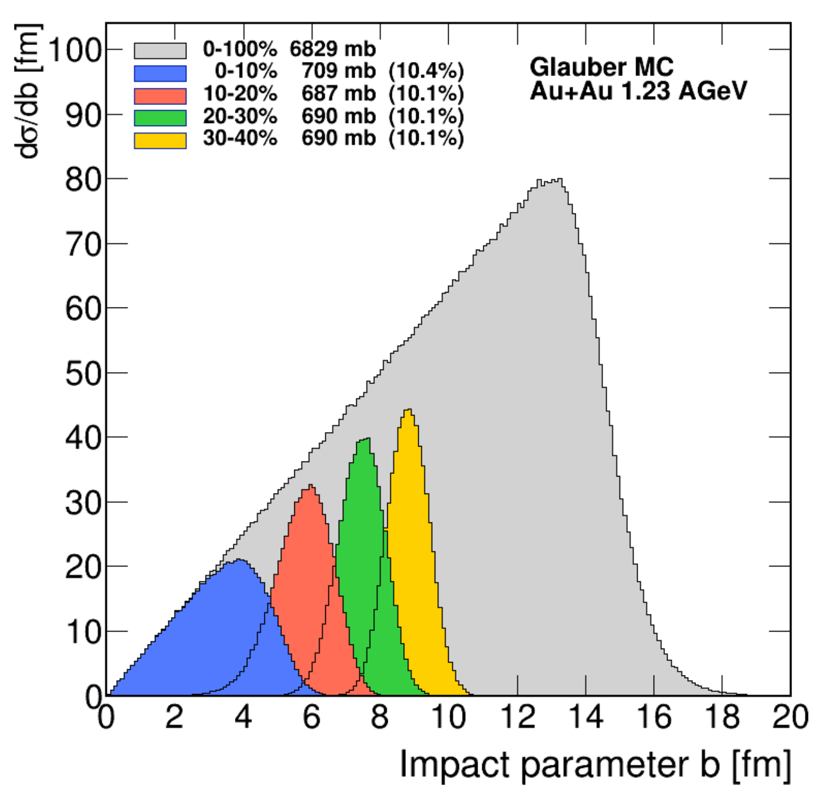
- **Large acceptance**
  - Symmetric azimuthal coverage
  - 18°-85° in polar angle
- **Tracking system and magnetic spectrometer**
  - 4 planes of low-mass mini-drift chambers (MDC)
  - Superconducting toroidal magnet
- **Forward Wall**
  - Reaction plane reconstruction

HADES Performance

- **High interaction rates**
  - Beam rate: 1.5 x 10^6 Au ions/s
  - Trigger rate of up to 8 kHz (Au+Au)
- **High 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





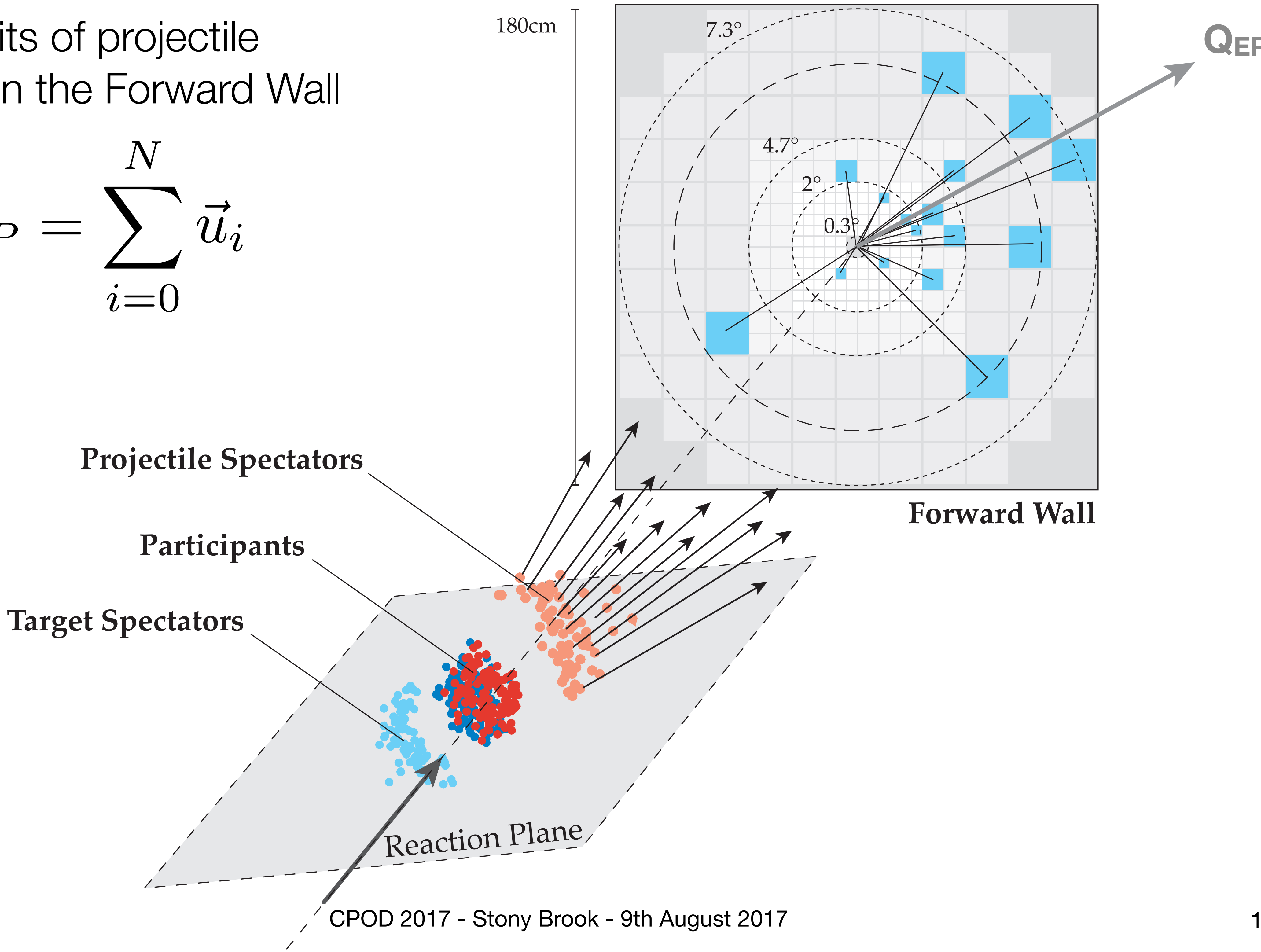


HADES Performance

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

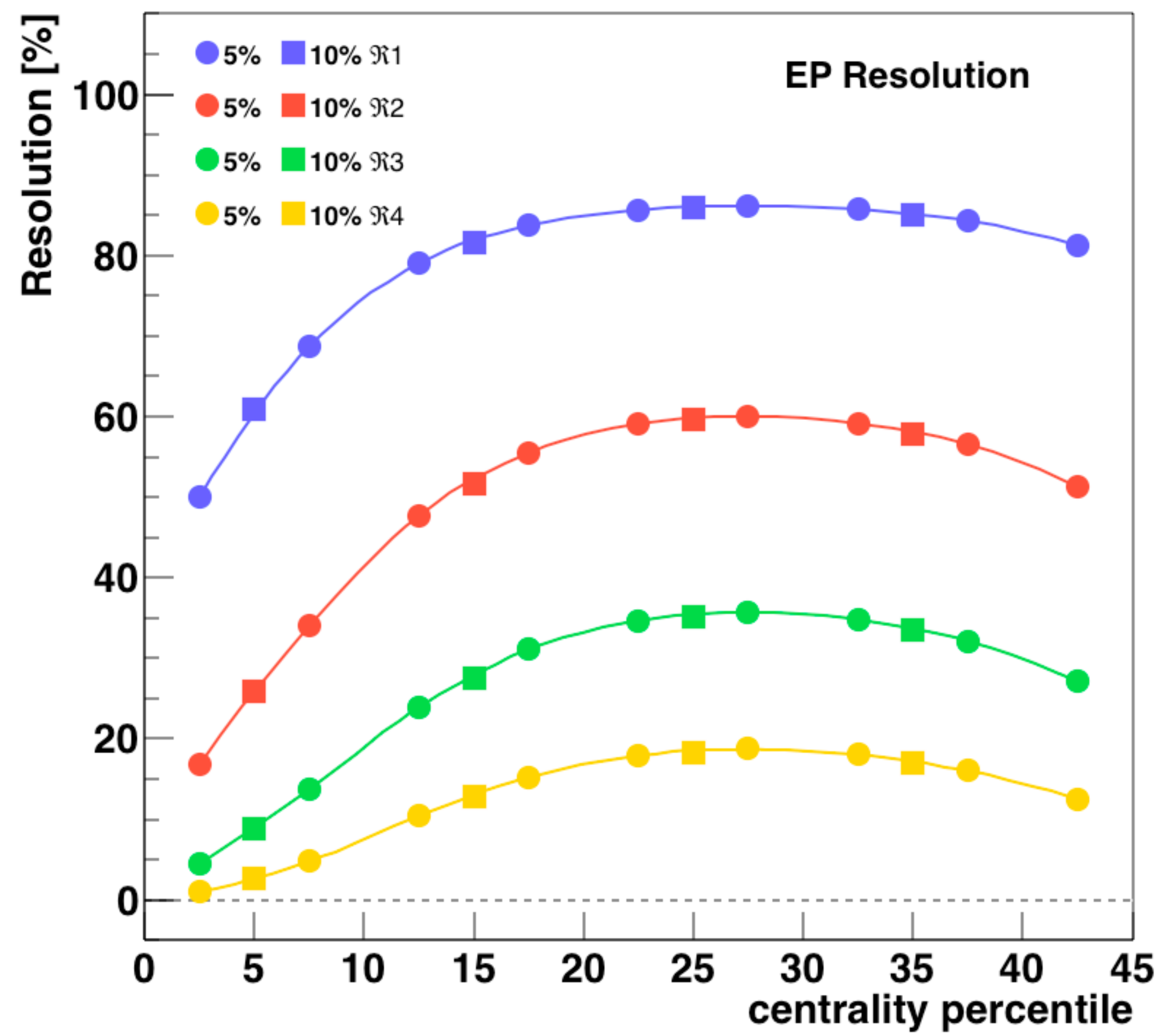
- Resolution determined with sub-event method

- Correction based on method described in J.-Y. Ollitrault, arXiv:nucl-ex/9711003

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

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

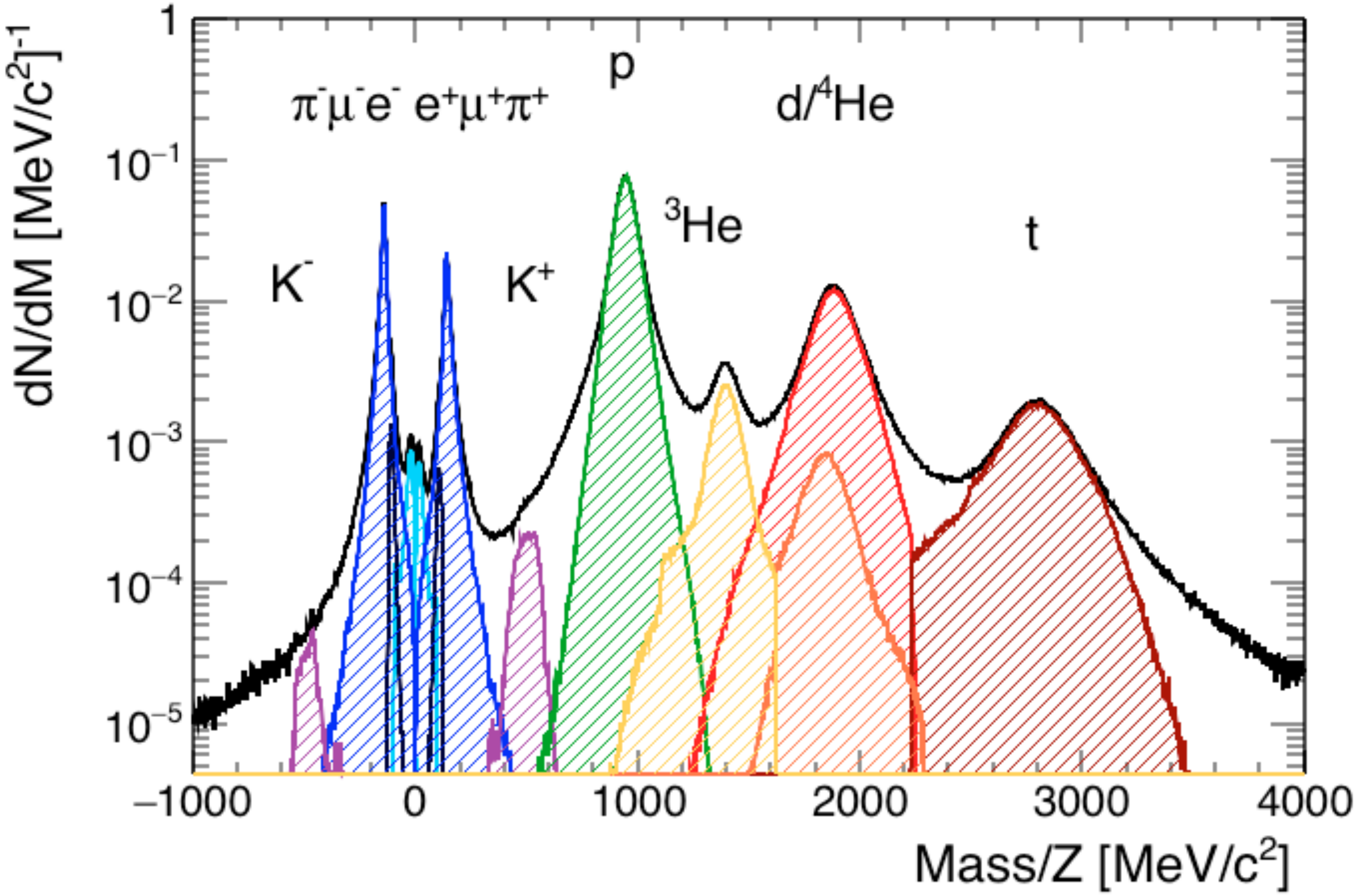
$$= \sqrt{2 \, \langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$



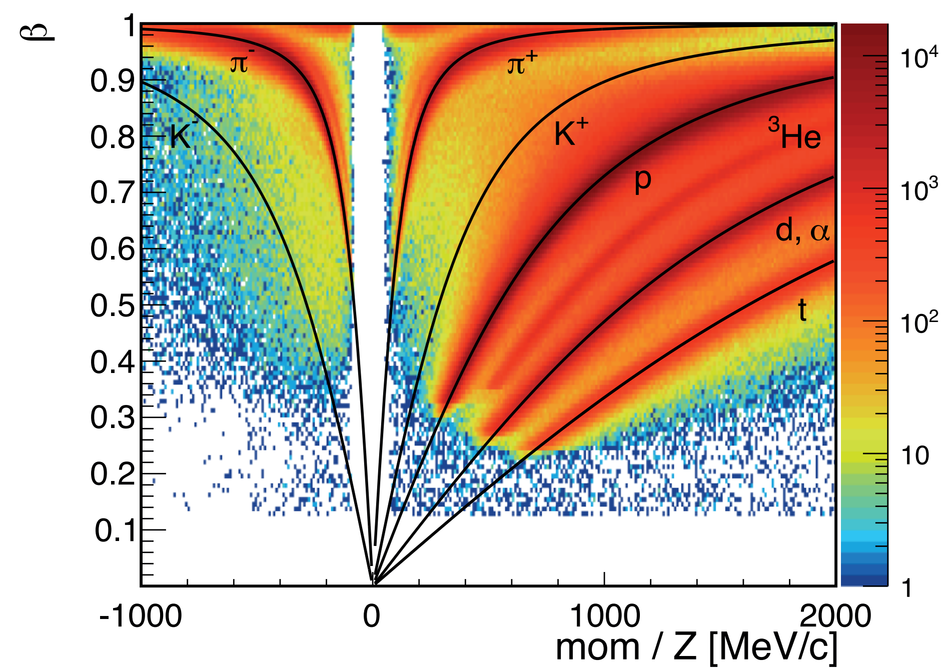
HADES Performance

Particle identification

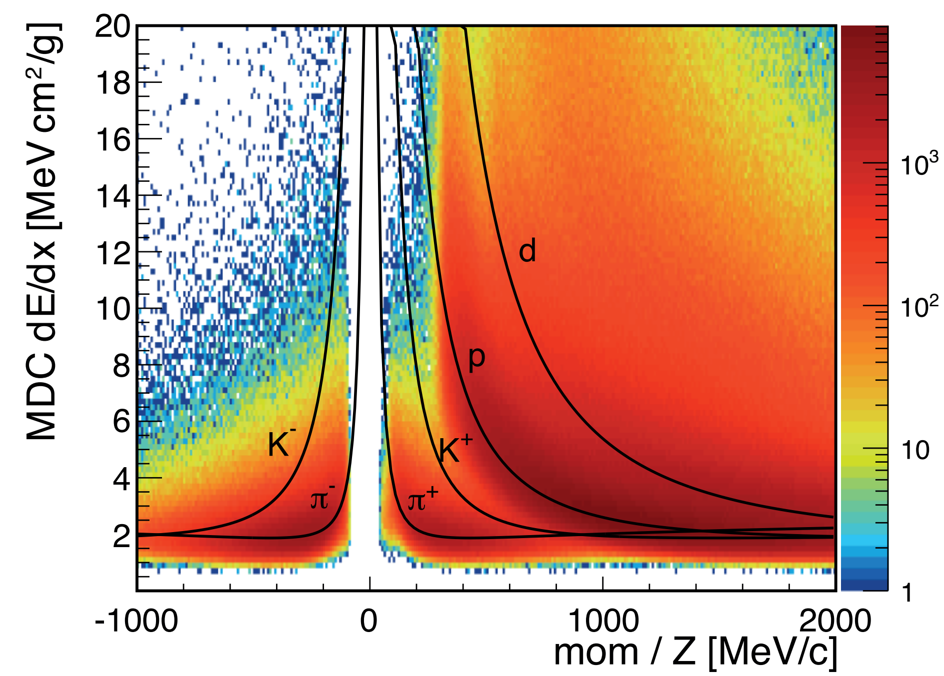
- Via TOF & momentum and dE/dx



Velocity vs. Rigidity



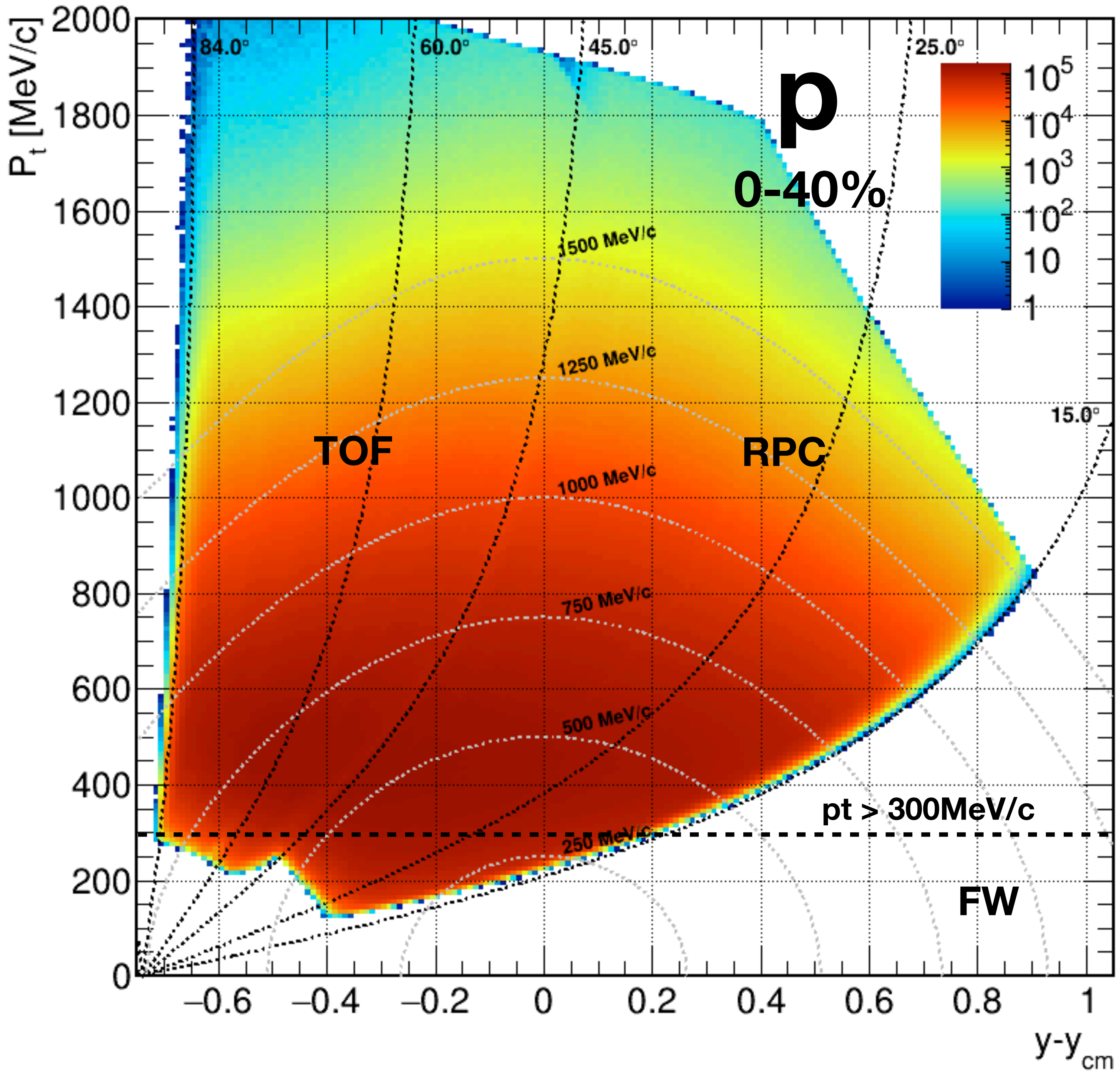
dE/dx in the MDC

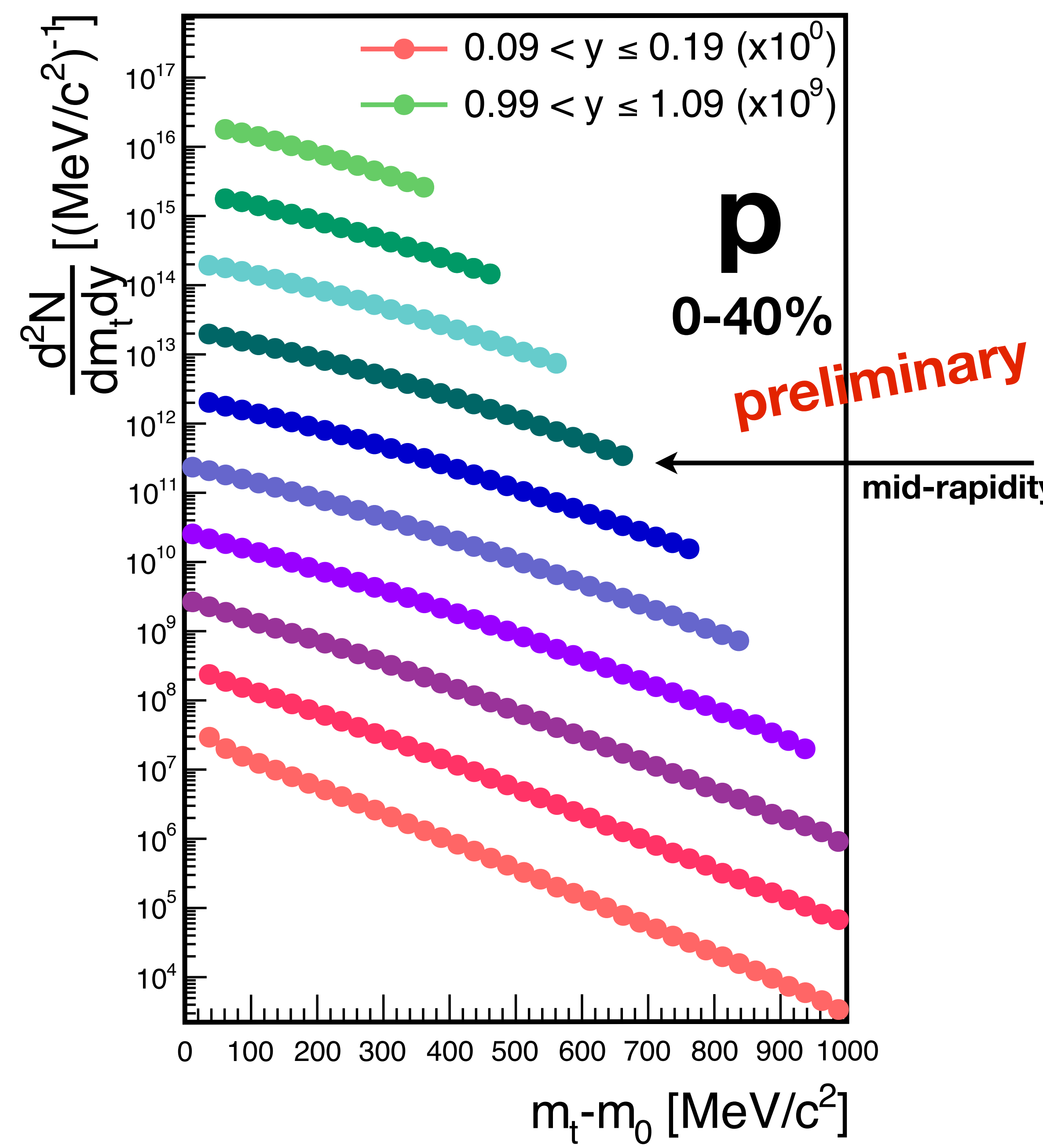


HADES Performance

Proton Spectra

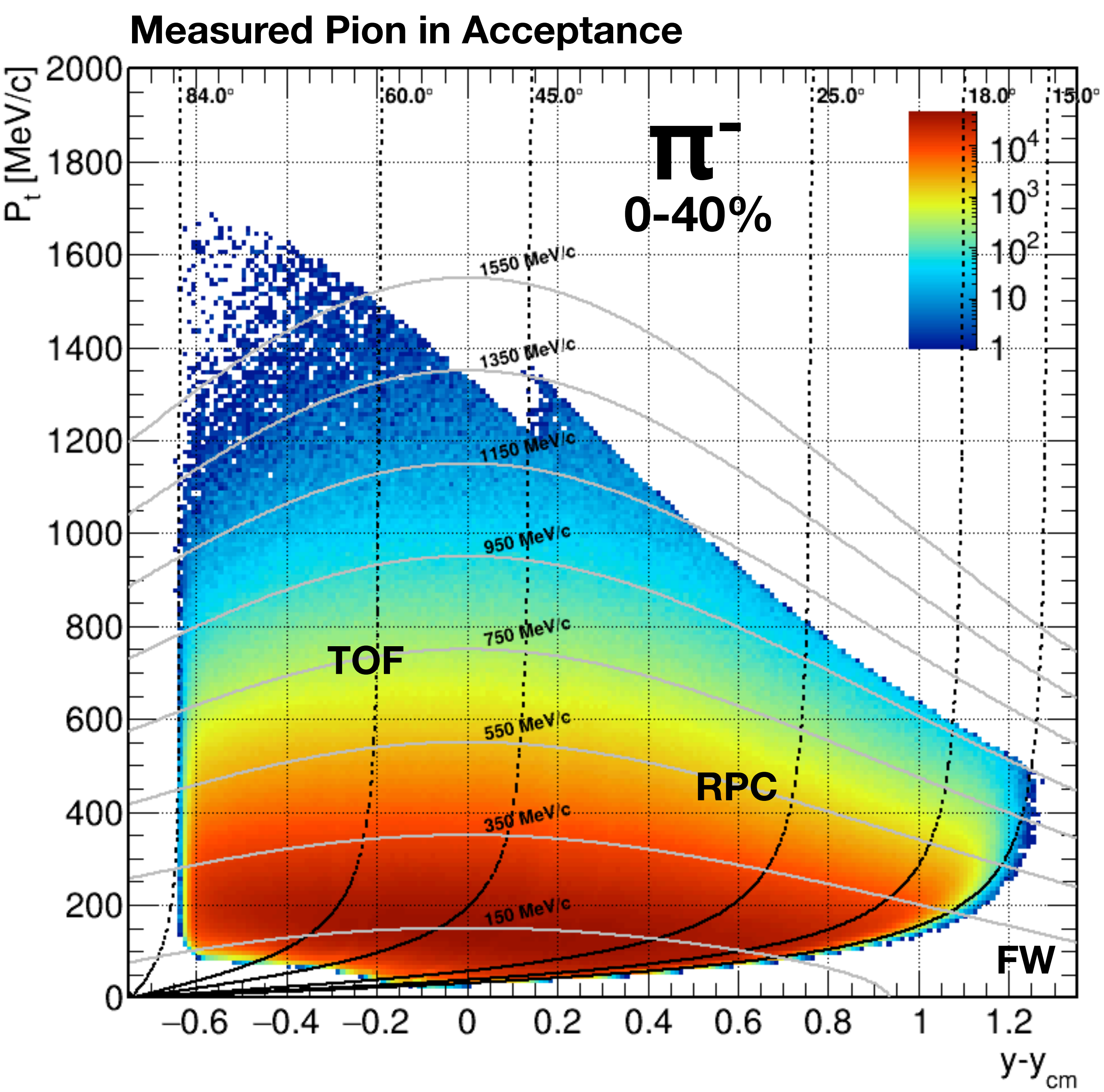
Measured Protons in Acceptance

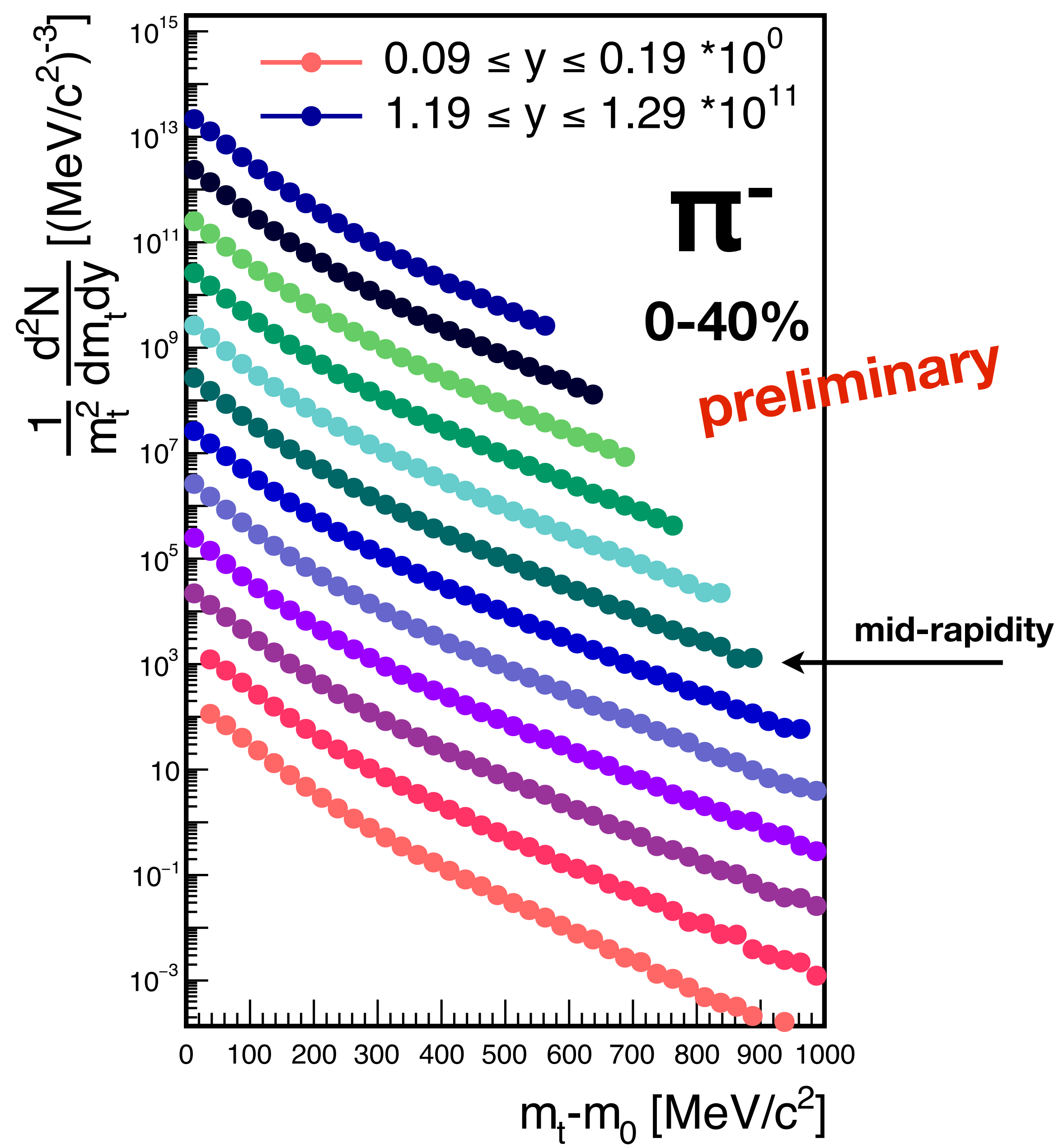




HADES Performance

Pion Spectra

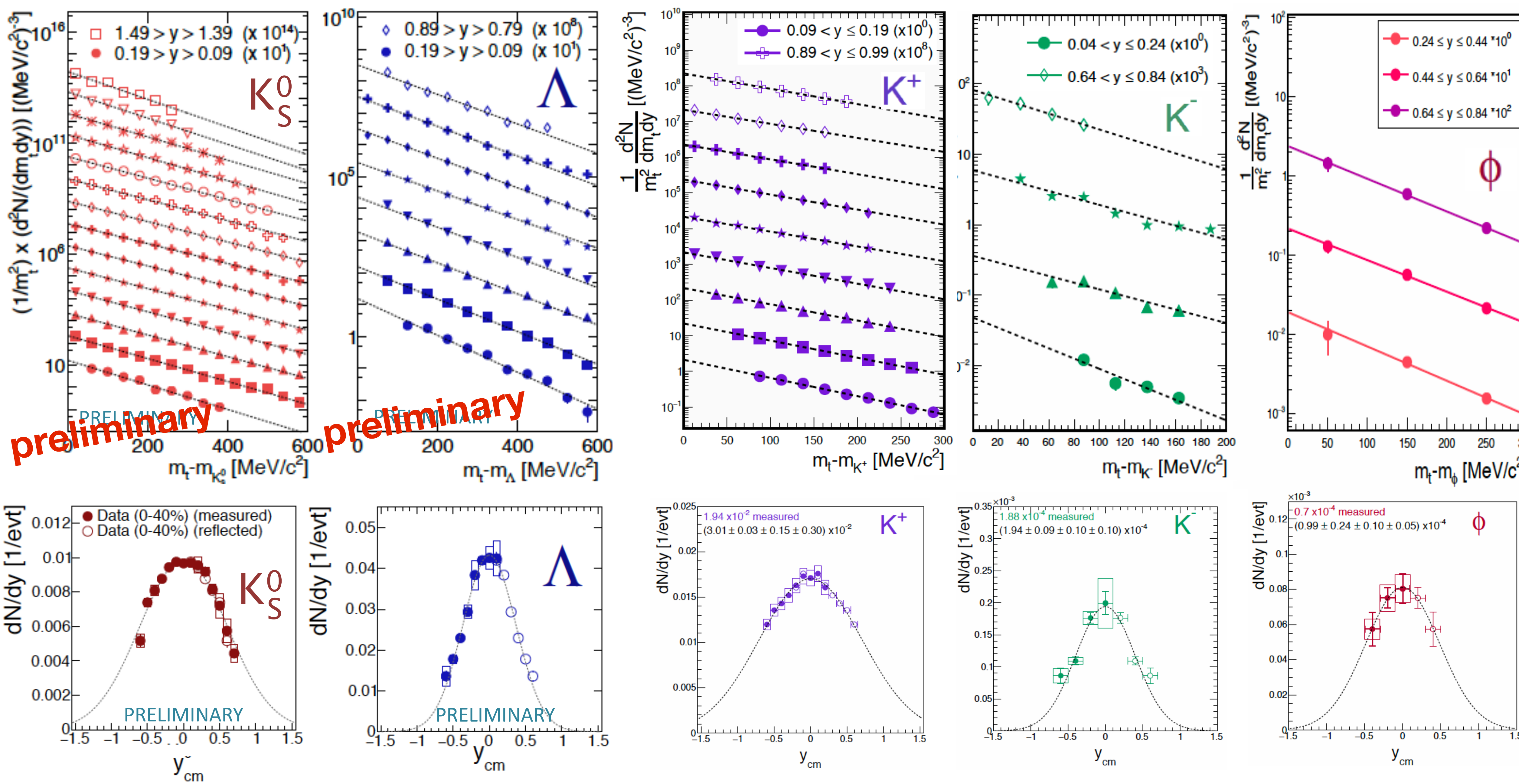




HADES Performance

Strange Hadrons (0-40%)

arXiv:1703.08418



Extrapolation in m_t: $\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$

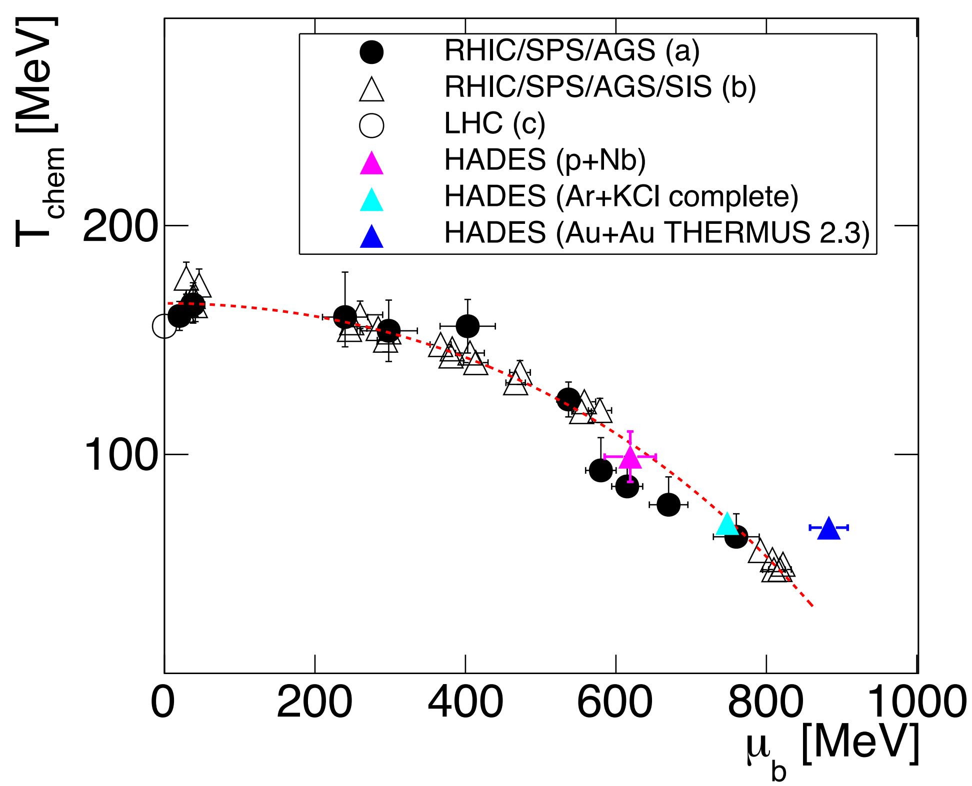
Freeze-out Parameters

Chemical Freeze-out

- Hadron yields well described by SHM with global parameters: T, μ_B, R_V, R_C

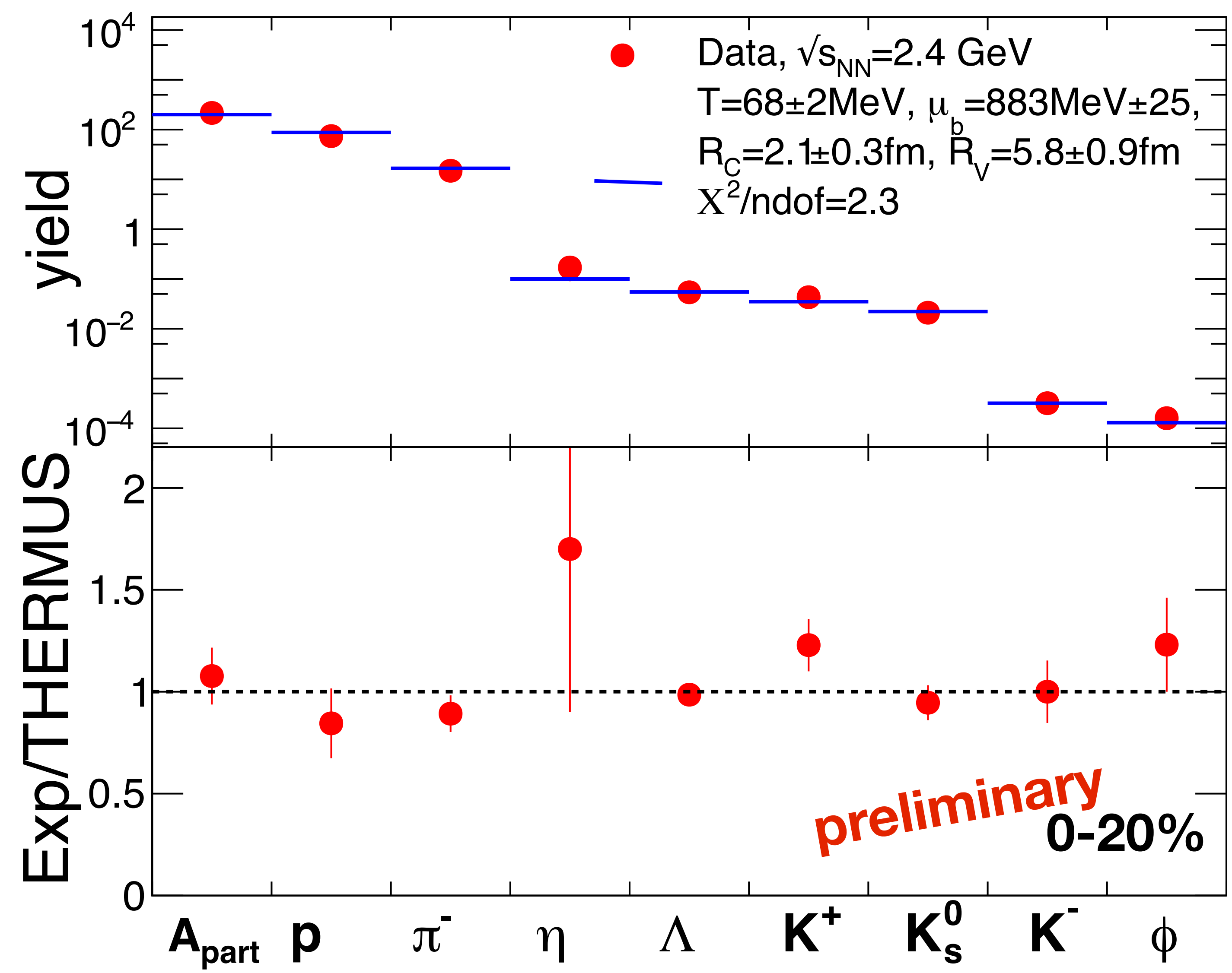
$$\mu_B = 883 \pm 25 \text{ MeV}$$

$$T_{chem} = 68 \pm 2 \text{ MeV}$$



THERMUS V2.3

S. Wheaton, J.Cleymans Comput.Phys.Commun.180:84-106,2009



Freeze-out Parameters

Kinetic Freeze-out

Blast-Wave model: Phys. Rev. C **48**, 2462

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

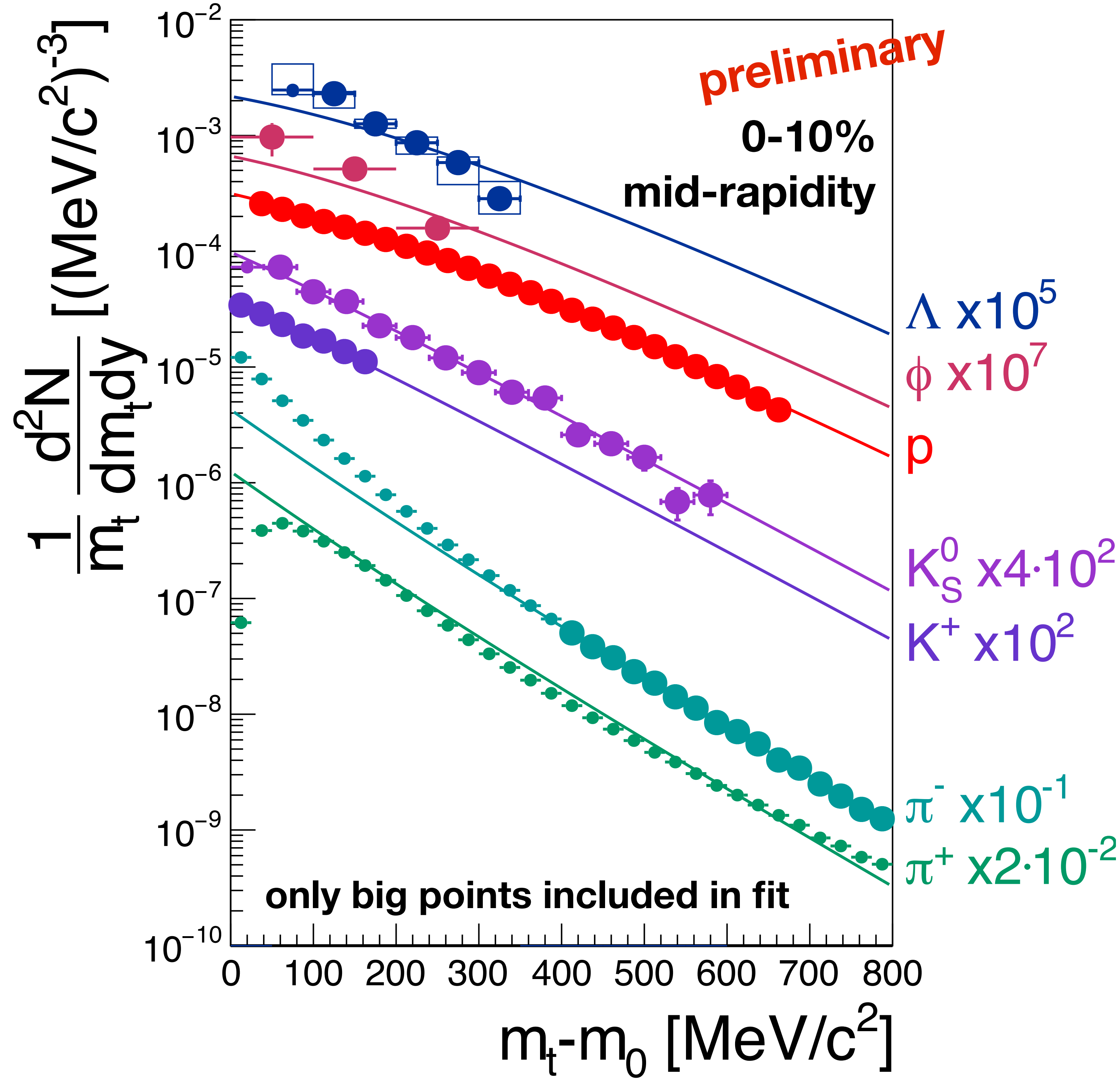
Linear radial flow velocity profile:

$$\beta = \beta_S (r/R)^n \qquad n = 1$$

- Good description of protons, kaons and pions (higher m_t)

$$T_{kin} = 62 \pm 10\ \mathrm{MeV}$$
$$\langle \beta_r \rangle = 0.36 \pm 0.04$$
$$T_{kin} < T_{chem} = 68 \pm 2\ \mathrm{MeV}$$

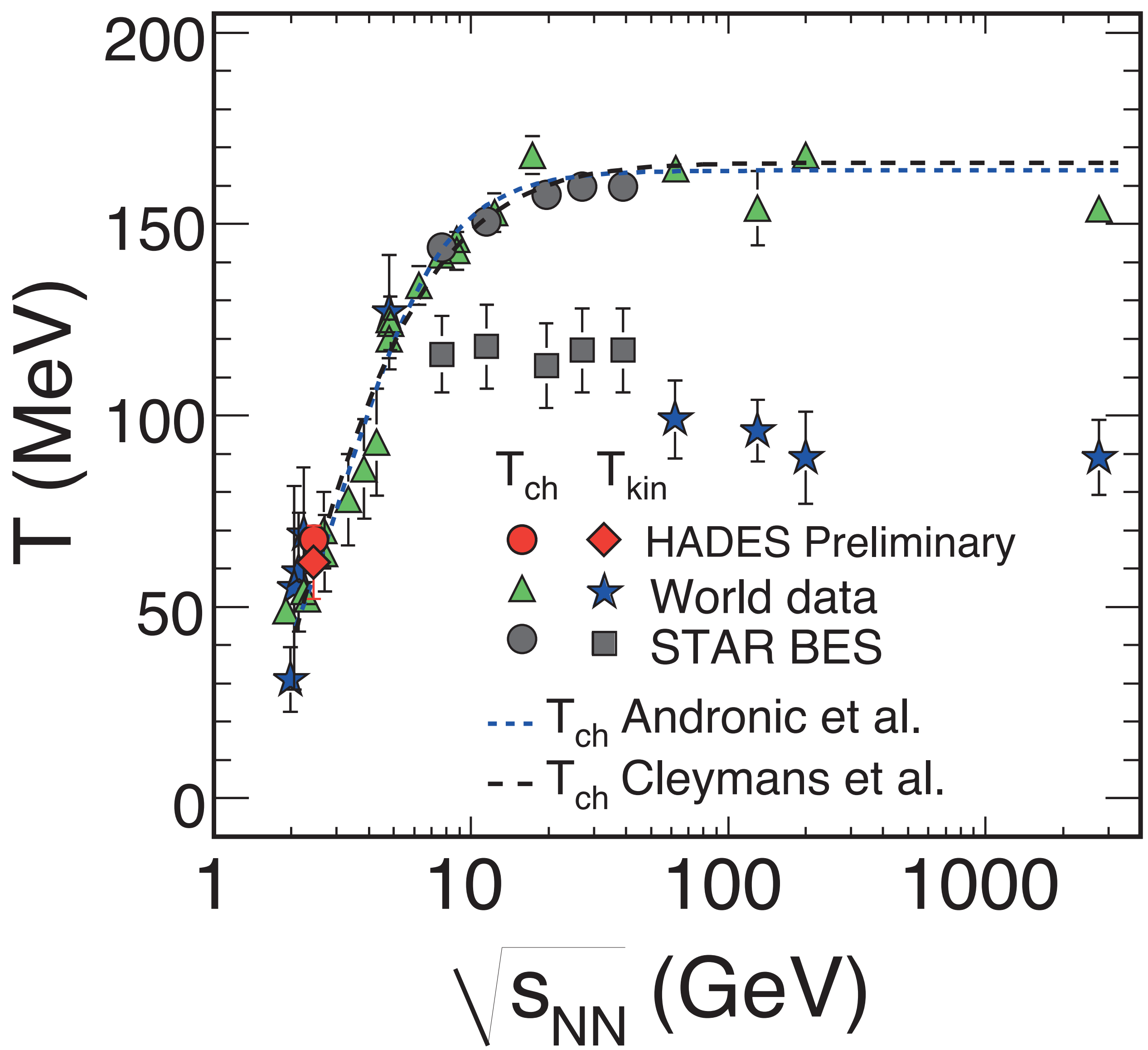
- **Λ** and **Φ** spectra steeper than expected from Blast-Wave
- **π^-** and **π^+** difference at low m_t due to Coulomb interaction

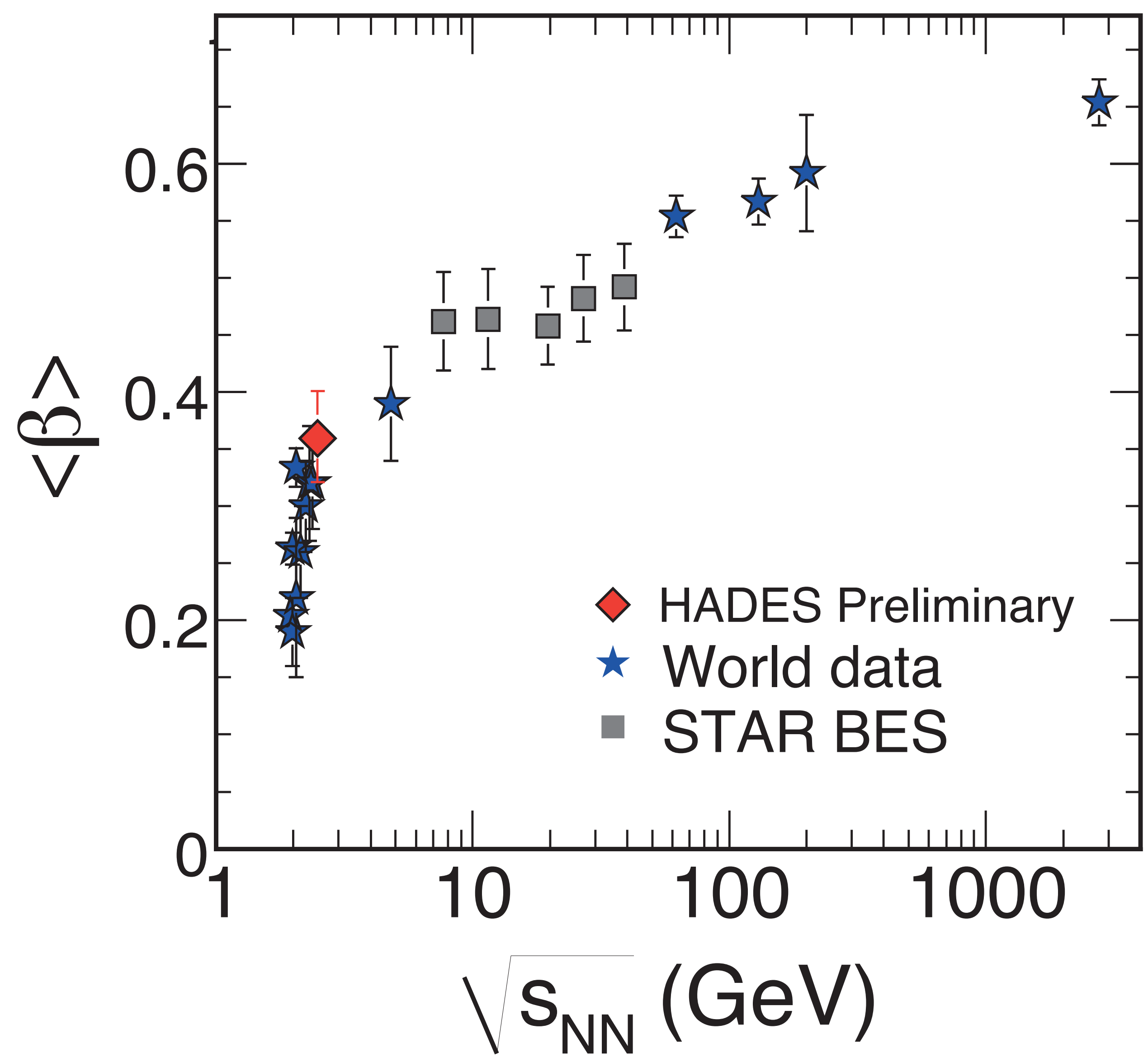


Freeze-out Parameters

Energy Dependence

STAR arXiv:1701.07065



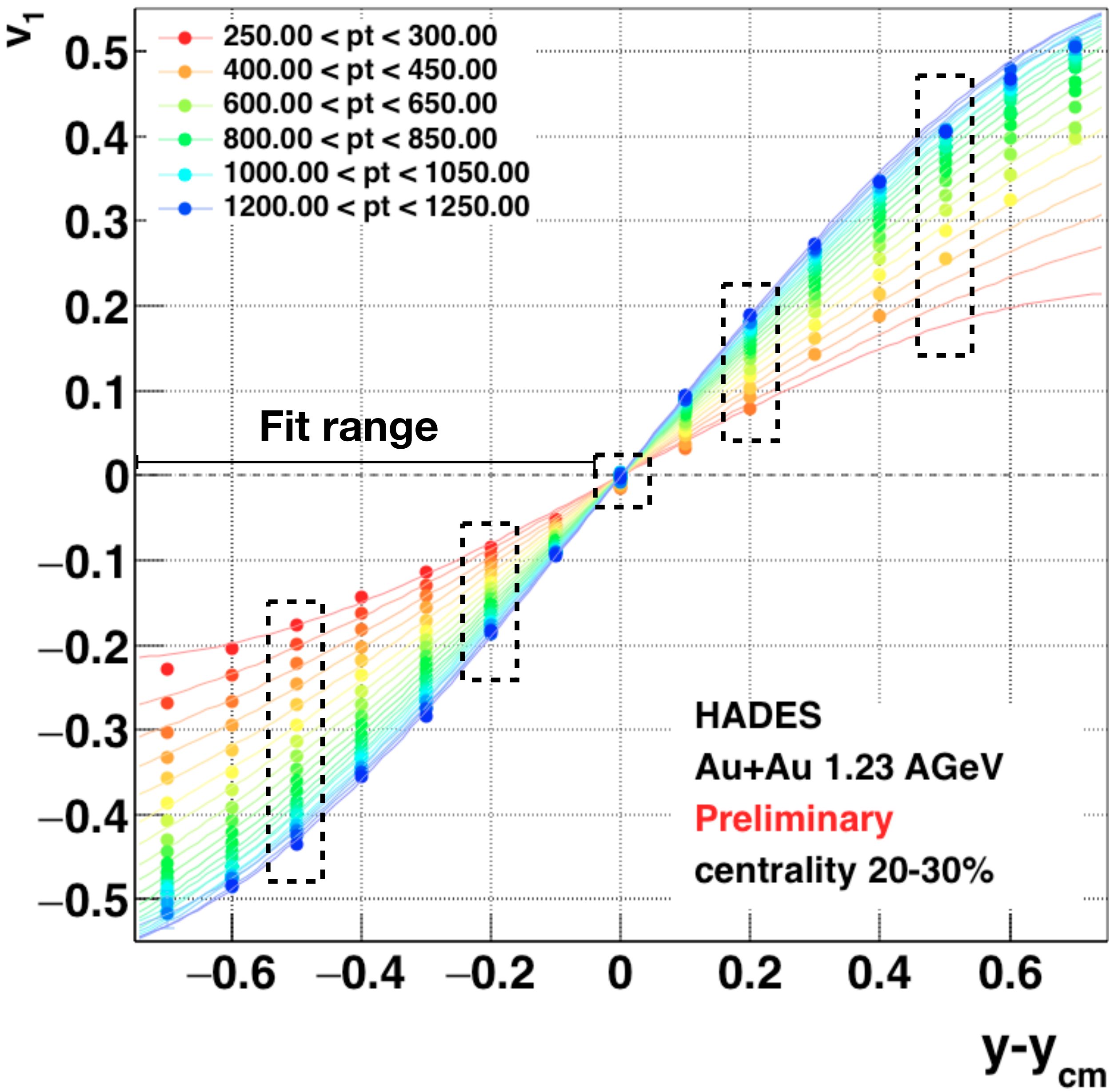


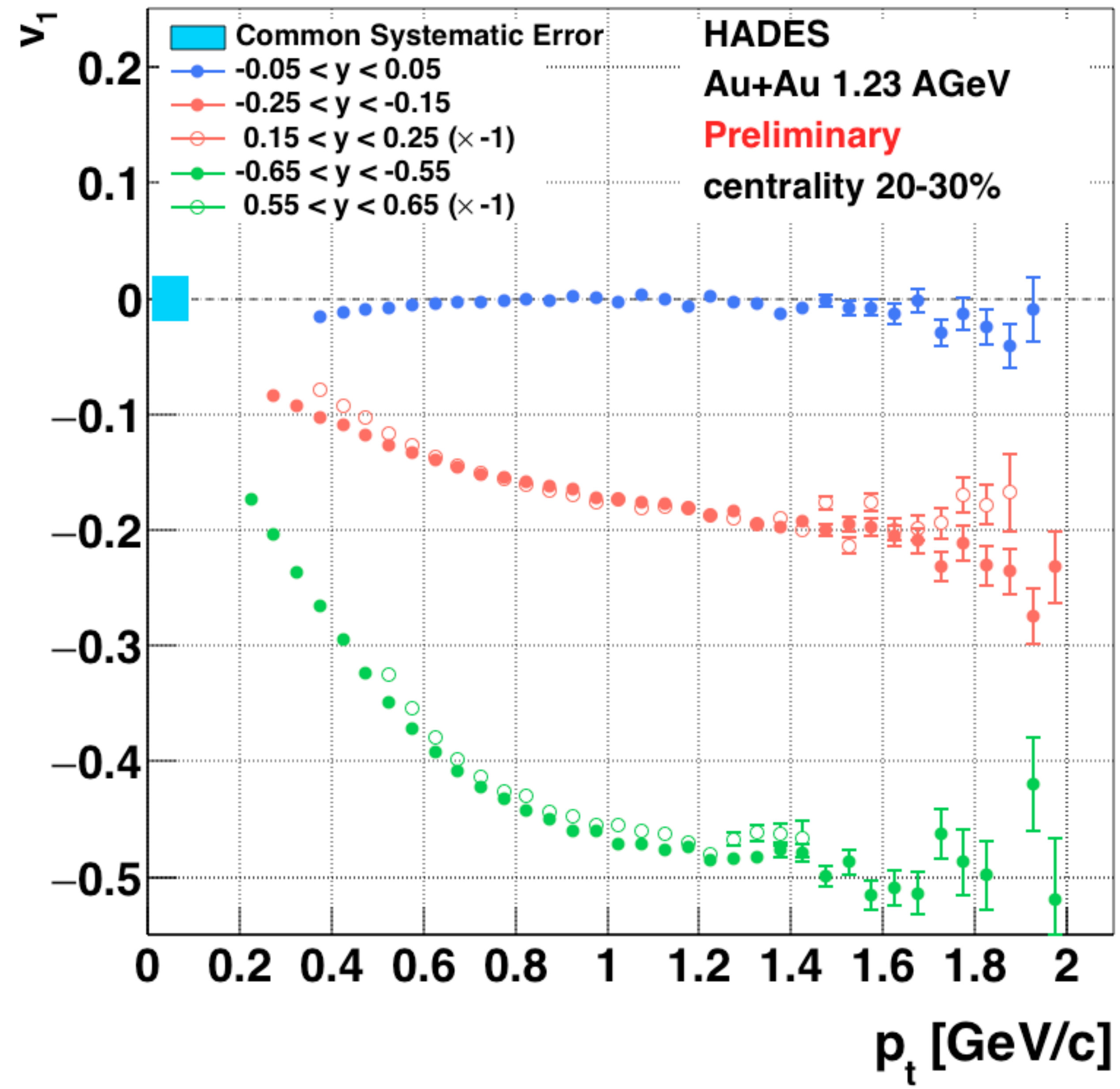
- Parameters fit well into trend of world data

T_{kin} and β 0-10%
T_{chem} 0-20%

Directed Proton Flow v_1

p_t-Dependence

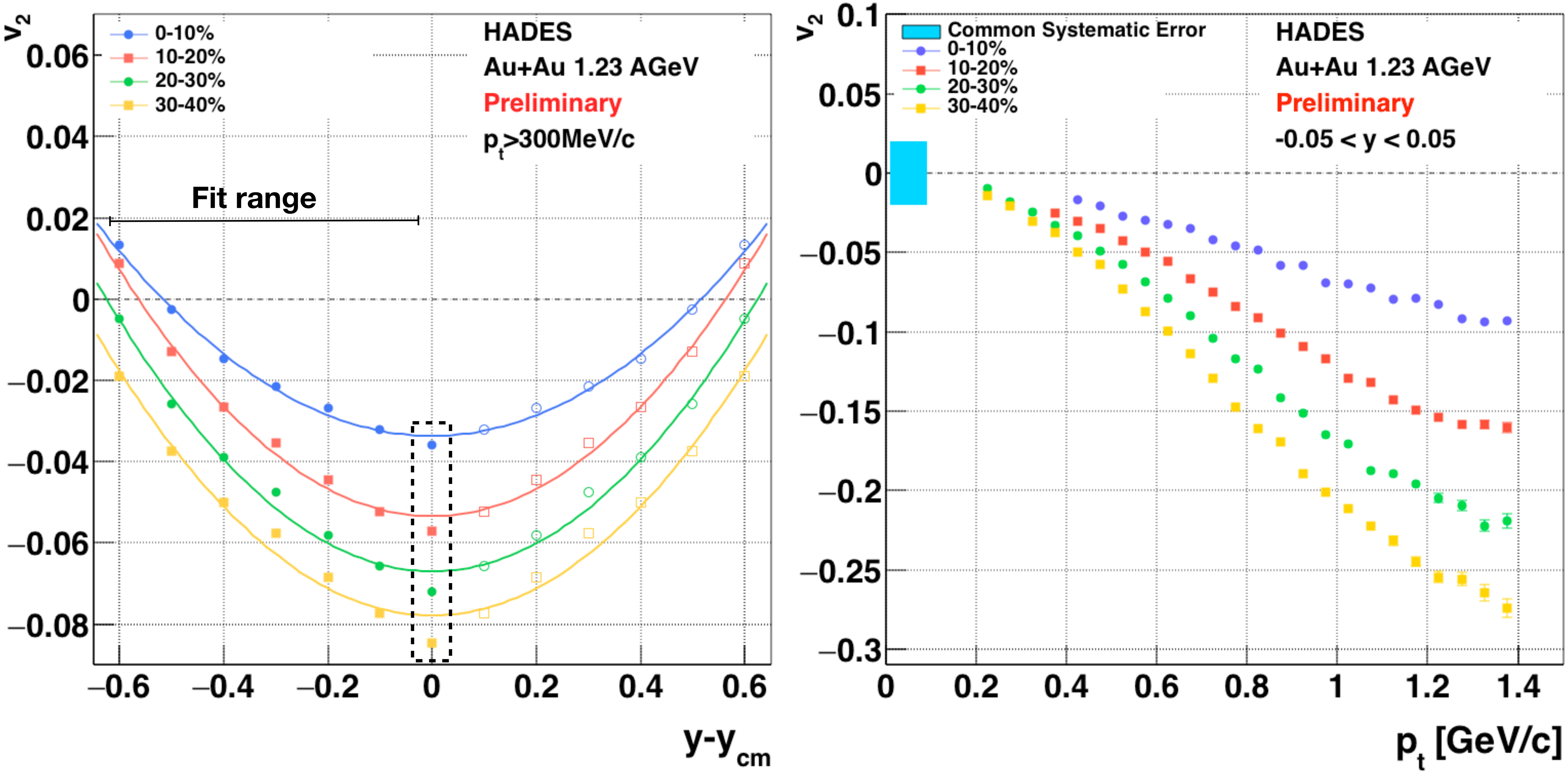




- Good agreement between backward and forward rapidity bins

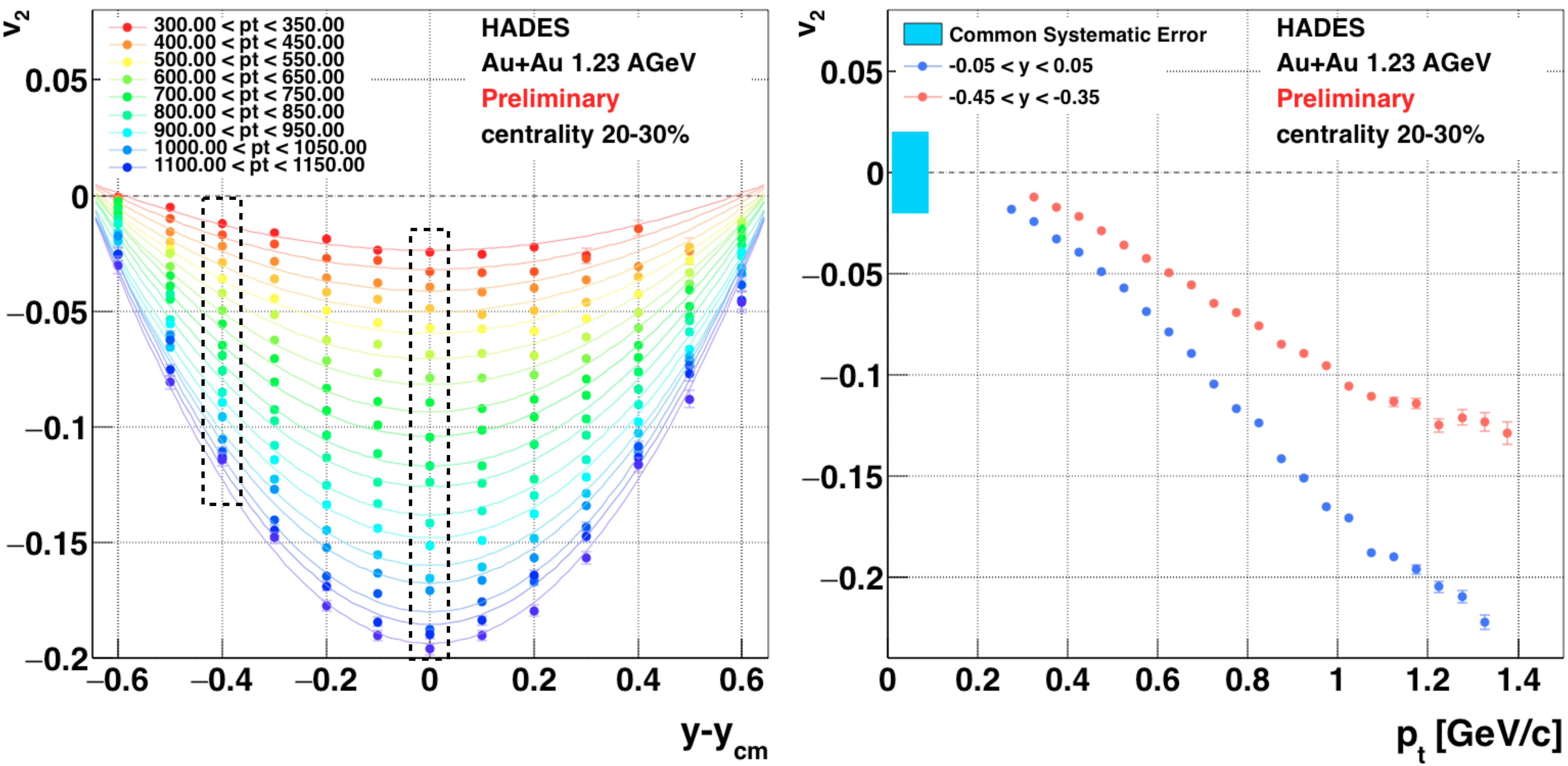
Elliptic Proton Flow v_2

Centrality-Dependence



Elliptic Proton Flow v_2

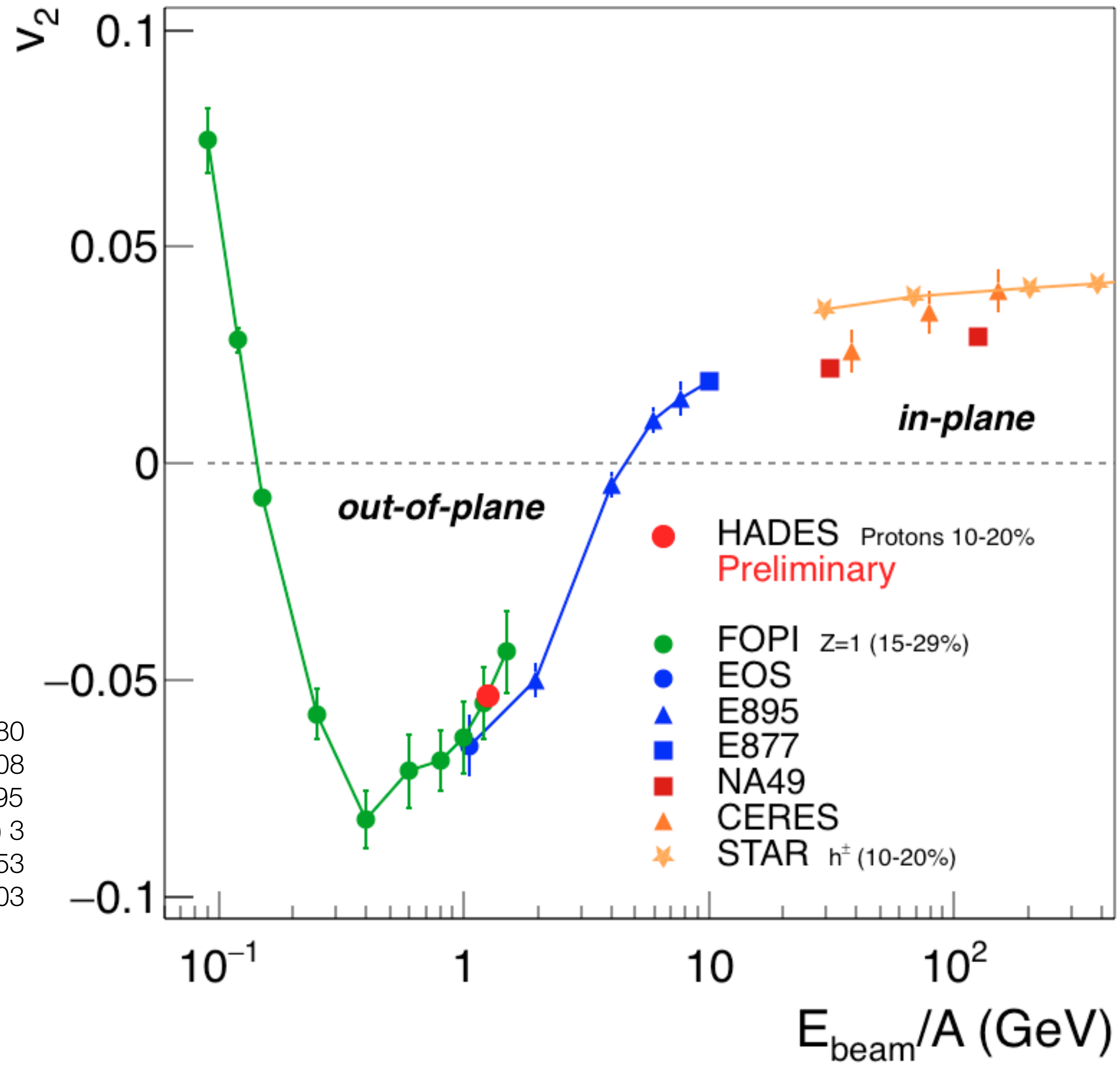
p_t-Dependence



Elliptic Flow - v_2

Energy Dependence

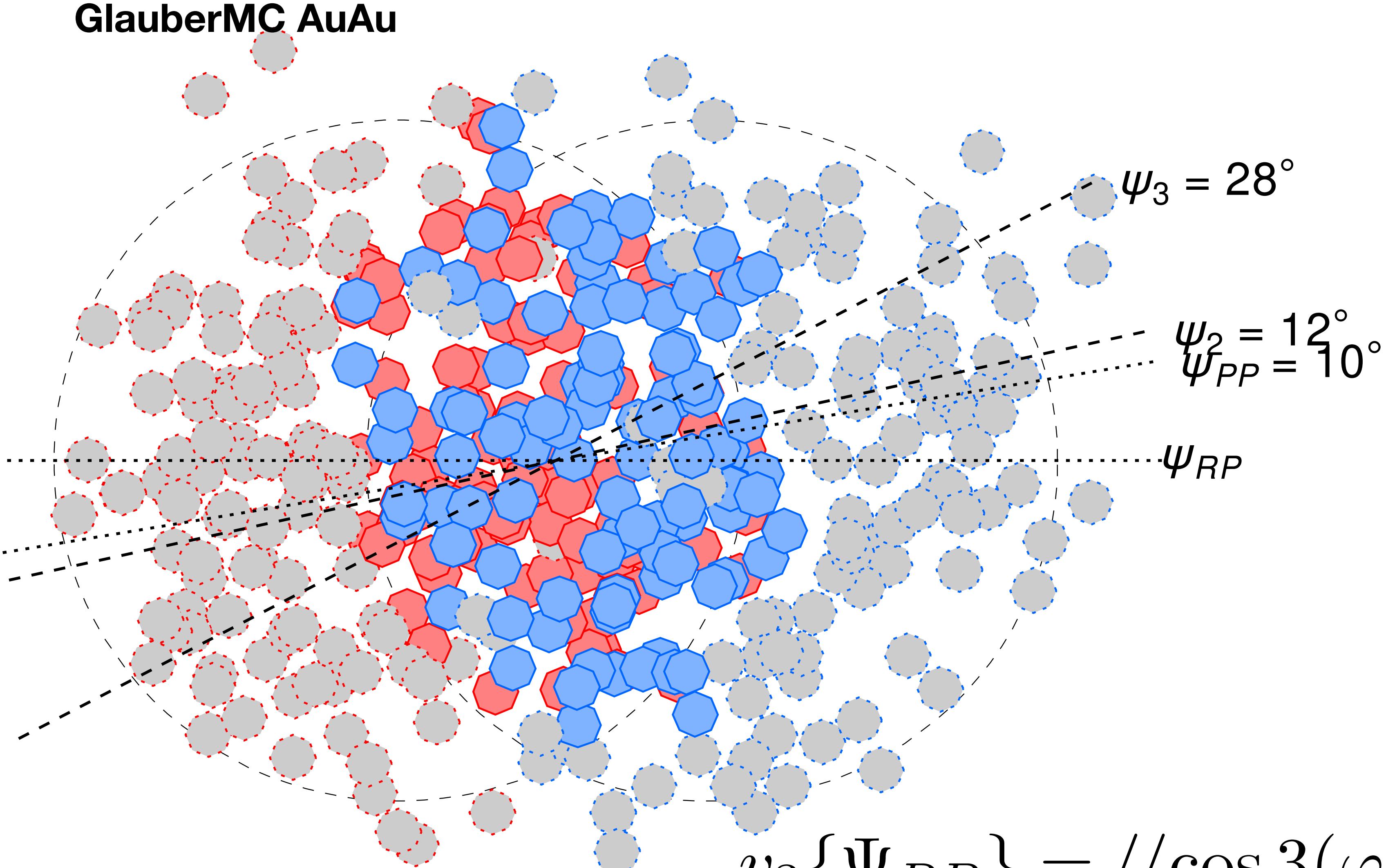
- Elliptic proton flow fits well to world data



FOPI: Phys.Lett. B612 (2005) 173-180
STAR: Phys. Rev. C 86, 054908
EOS, E895: Phys. Rev. Lett. 83 (1999) 1295
E877: Nucl. Phys. A 638 (1998) 3
CERES: Nucl. Phys. A 698 (2002) 253
NA49: Phys. Rev. C 68 (2003) 034903

Triangular Flow

$v_3\{\Psi_{RP}\}$

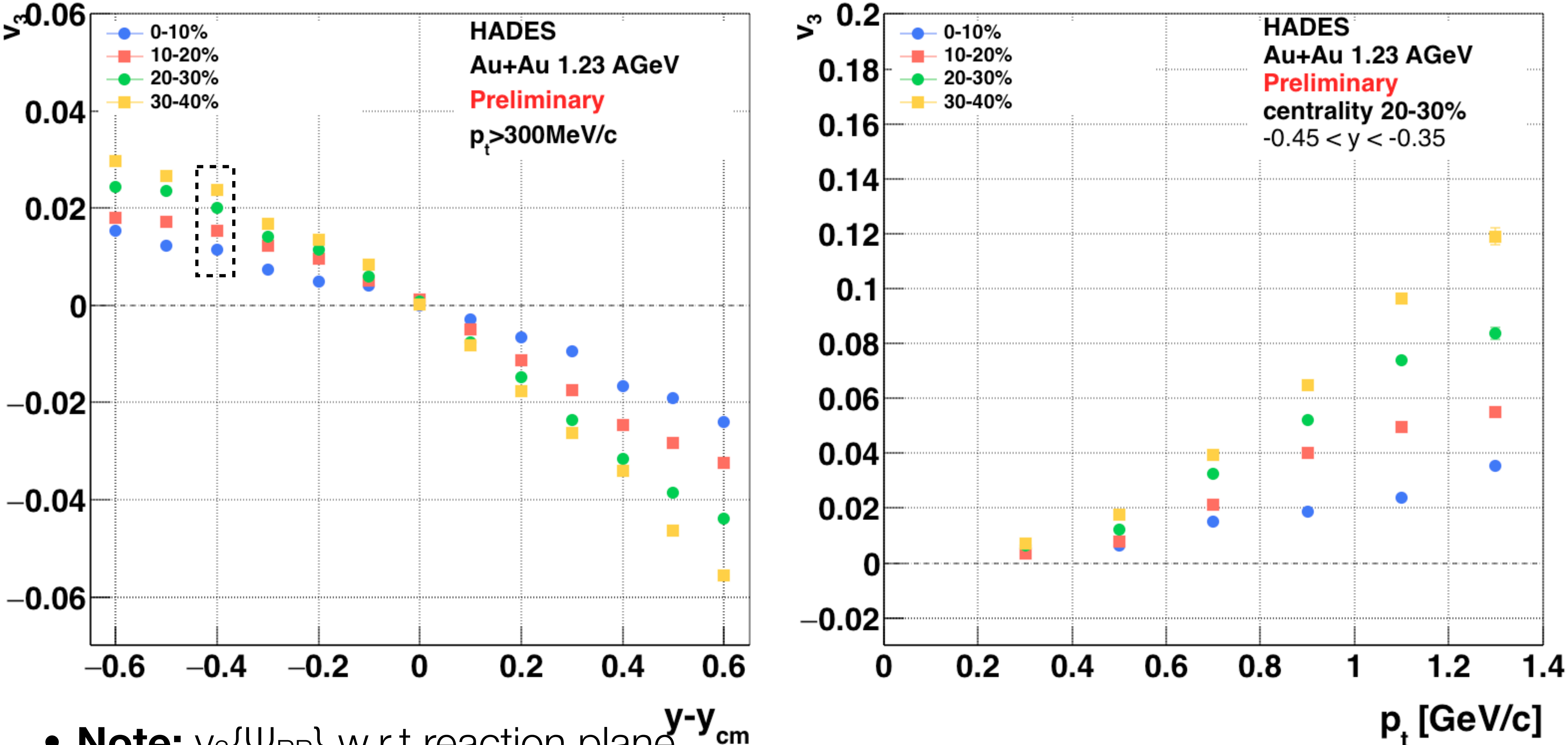


- $v_3\{\Psi_{RP}\}$ w.r.t reaction plane
- Fluctuation convoluted:
  - Symmetry plane (Ψ_3) rel. to RP
  - Measured spectator plane rel. to RP

$$
\begin{aligned}
v_3\{\Psi_{RP}\} &= \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle \\
&= \langle\langle \cos 3(\varphi - \Psi_3)\cos 3(\Psi_3 - \Psi_{RP})\rangle\rangle \\
&= \langle v_3\{\Psi_3\} \quad \langle \cos 3(\Psi_3 - \Psi_{RP})\rangle\rangle
\end{aligned}
$$

Triangular Flow

Proton $v_3\{\Psi_{RP}\}$



- **Note:** $v_3\{\Psi_{RP}\}$ w.r.t reaction plane
- Model comparisons on-going

Pion m_t-Spectra

Coulomb Potential Analysis

Coulomb Potential

$$E_f = E_i \pm V_C$$

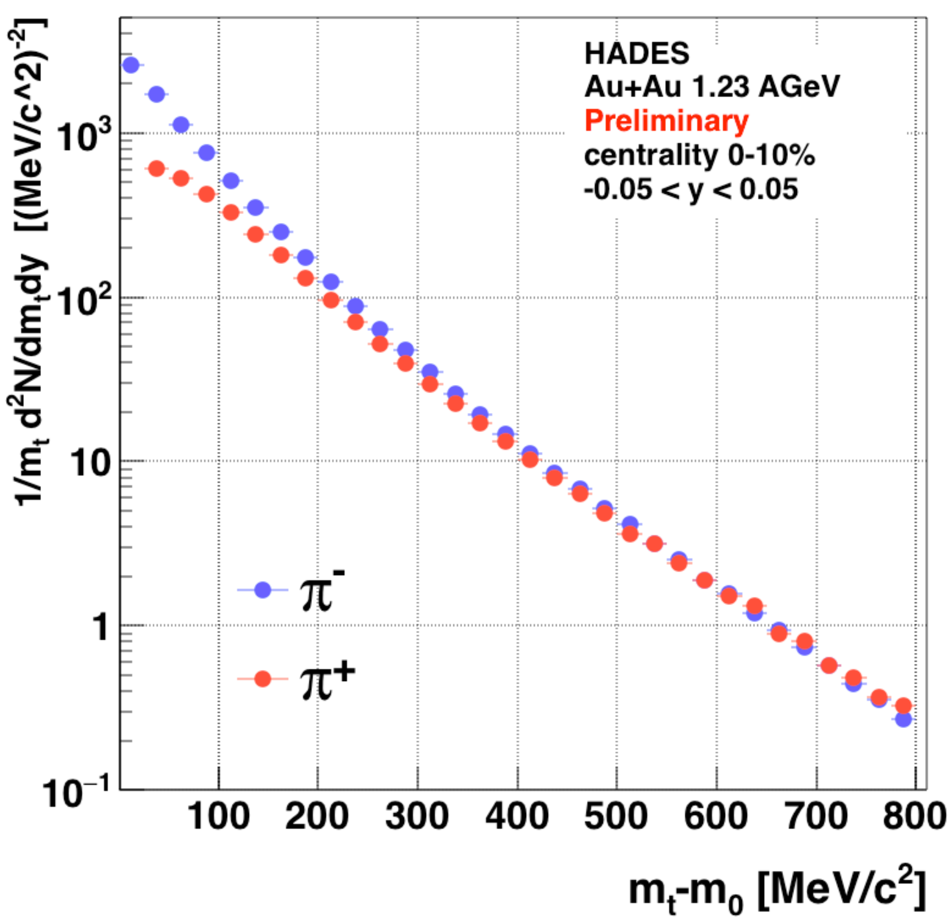
$$R_f(E_f) = \frac{E_f - V_C}{E_f + V_C}\frac{\sqrt{(E_f - V_C)^2 - m^2}}{\sqrt{(E_f + V_C)^2 - m^2}} \frac{A^+(e^{(E_f+V_C)/T_\pi} - 1)}{A^-(e^{(E_f-V_C)/T_\pi} - 1)}$$

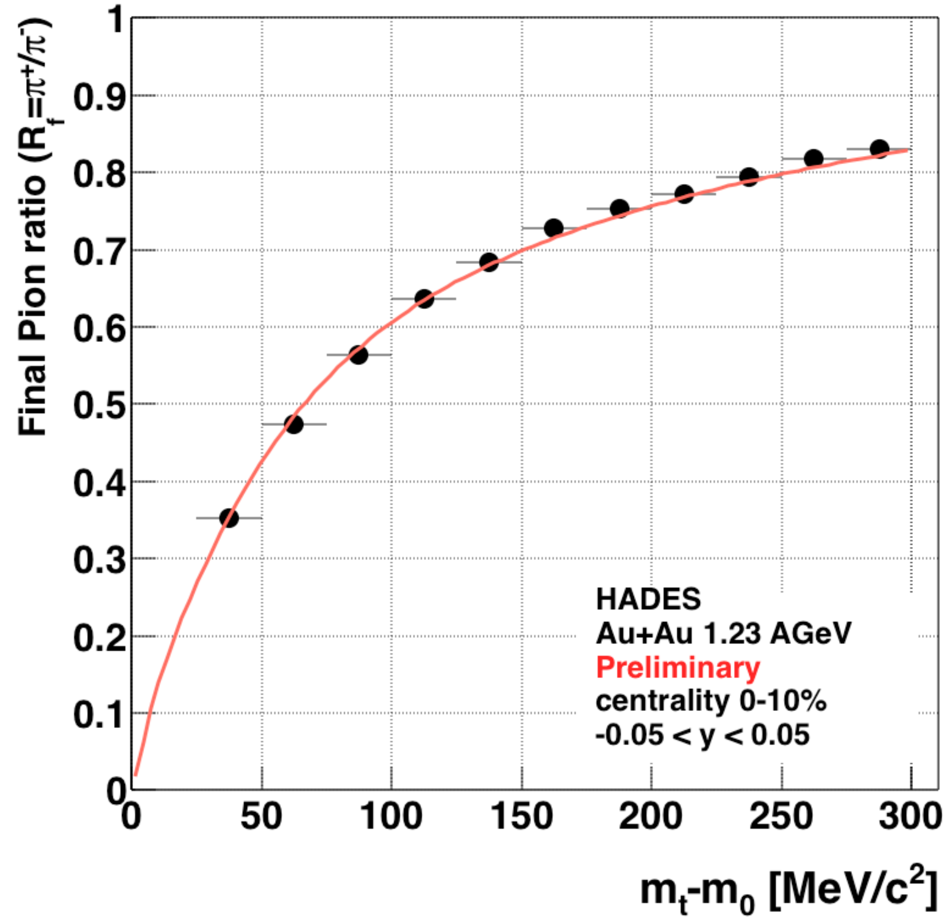
Jacobian — Bose-Einstein Formula

Recipe followed from:
Cebra et. al
arXiv:1408.1369

$$V_{\text{eff}} = V_C(1 - e^{-E_{\max}/T_p})$$

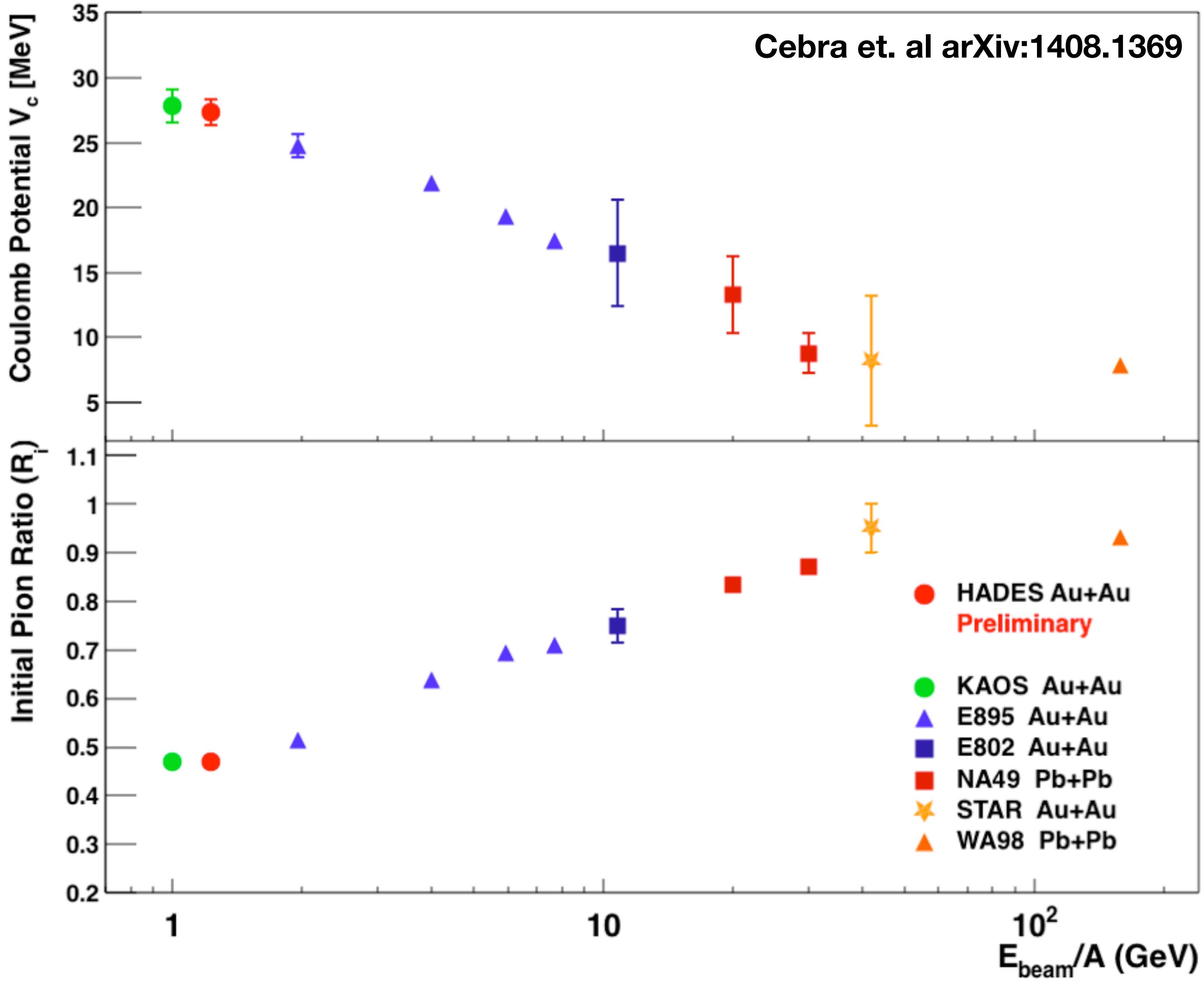
$$E_{\max} = \sqrt{(m_p p_\pi/m_\pi)^2 + m_p^2} - m_p$$





Pion m_t-Spectra

Coulomb Potential Analysis

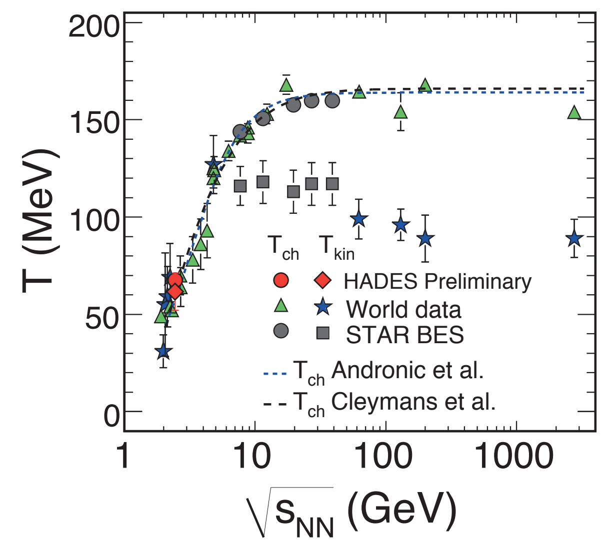


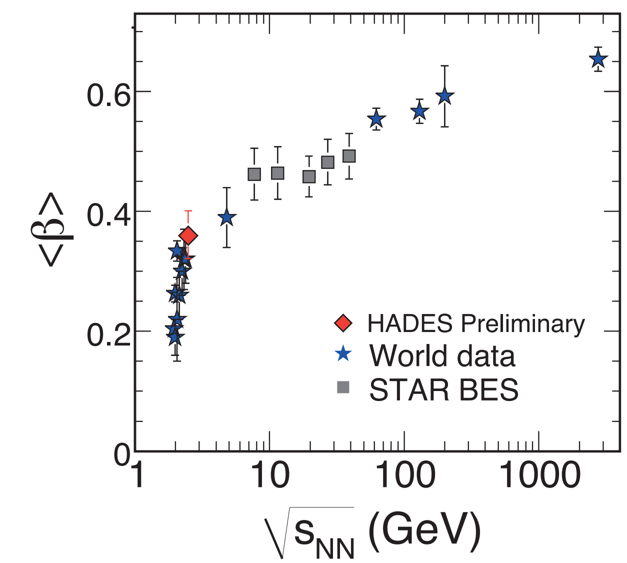
Conclusion ...

- Freeze-out parameters

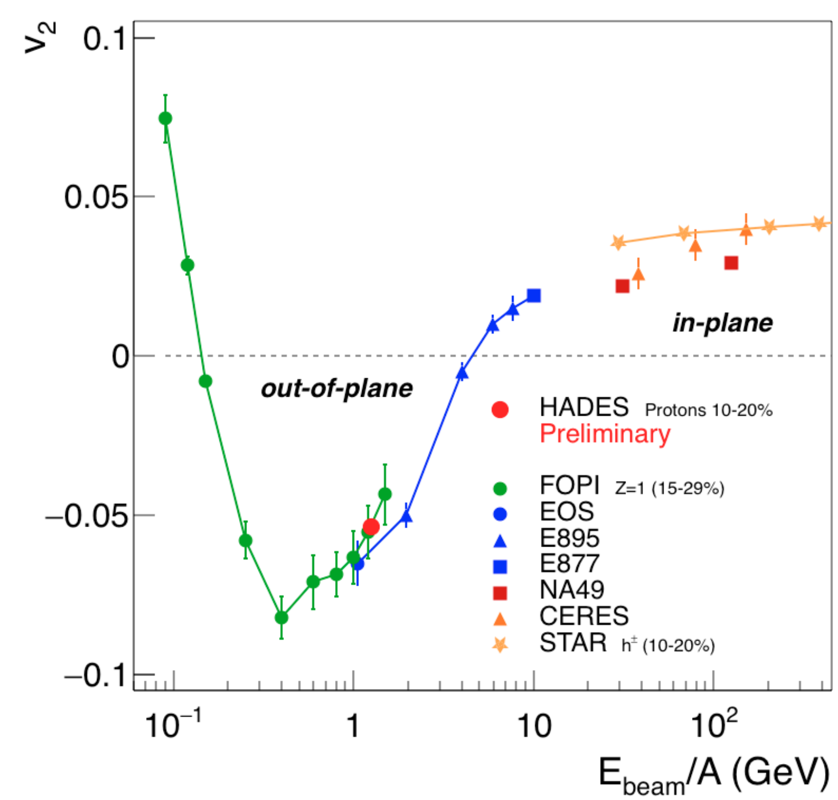
$$T_{chem} = 68 \pm 2\ \mathrm{MeV}$$
$$T_{kin} = 62 \pm 10\ \mathrm{MeV}$$
$$\langle \beta_r \rangle = 0.36 \pm 0.0$$

  - Fits into systematic of world data





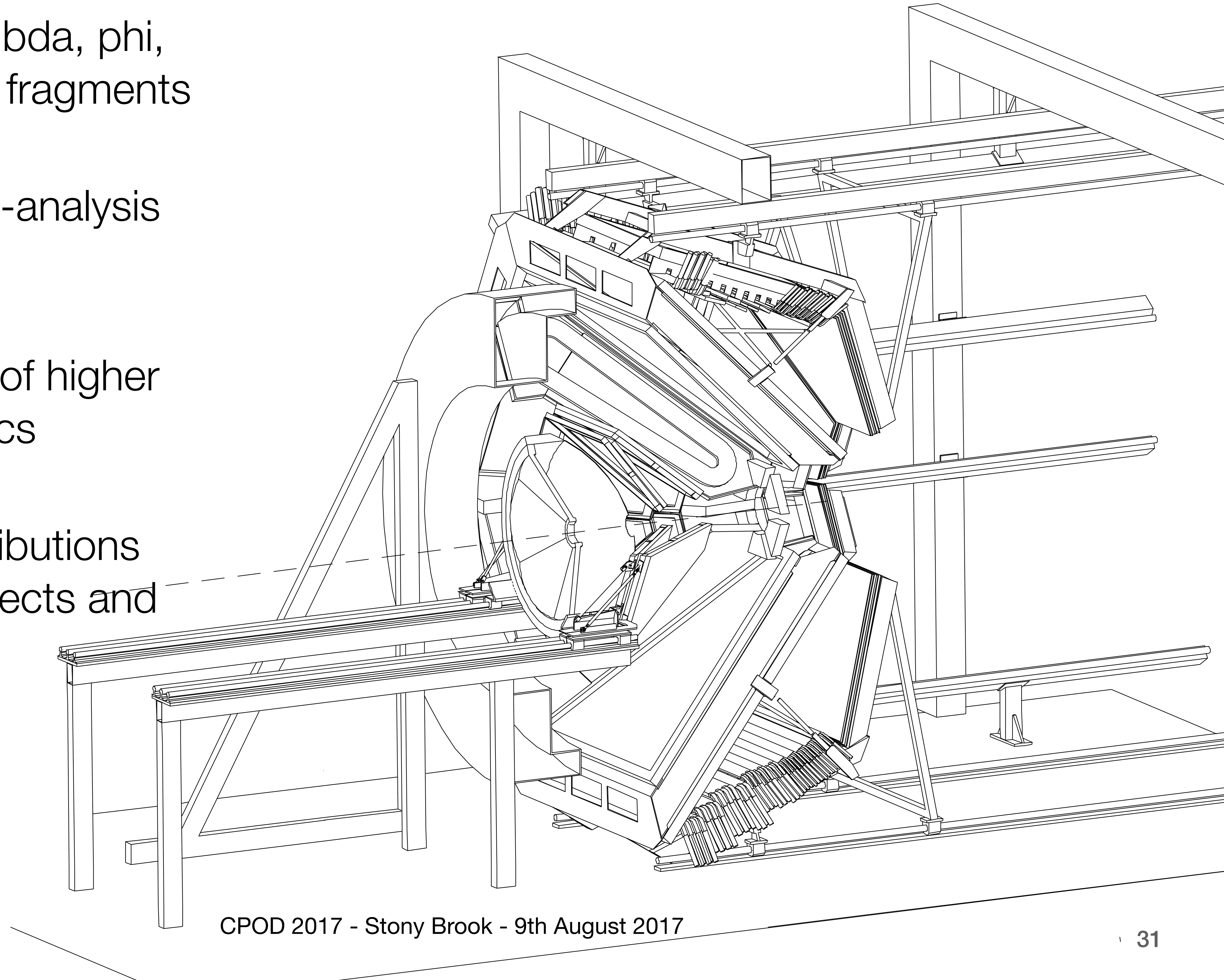
- Directed and elliptic flow of protons v_1 and v_2
  - Large phase-space coverage and high statistics
  - Multi-differential analysis (p_t, rapidity, centrality)



- Higher order harmonics
  - First look of $v_3\{\Psi_{RP}\}$ at SIS energies
- Pion Coulomb potential analysis

... Outlook

- Flow-analysis lambda, phi, kaons, pions and fragments
- Multi-particle flow-analysis methods
  - Measurement of higher order harmonics
  - Study of contributions of non-flow effects and fluctuations



HADES Collaboration

Thank you for your attention!