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BROOKHAVEN NATIONAL LABORATORY

Moving forward to constrain the transport properties of QCD

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Santa Fe, NM

Introduction

- Viscous relativistic fluid dynamics in 3+1D available since 2011

  B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. 106, 042301 (2011)

- Fluctuations in all three dimensions only recently implemented

  P. Bozek, W. Broniowski, Phys.Rev. C85 (2012) 044910 (bulk+shear, limited long. fluctuations via torque)
  L.-G. Pang, Q. Wang, X.-N. Wang, Phys.Rev. C86 (2012) 024911 (ideal)
  L.-G. Pang, G.-Y. Qin, V. Roy, X.-N. Wang, G.-L. Ma, Phys.Rev. C91 (**2015**) 4, 044904 (ideal)
  Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys.Rev. C91 (**2015**) 6, 064901 (shear)
  A. Monnai, B. Schenke, e-Print: arXiv:1509.04103 (**2015**) (bulk+shear)

- 3D fluctuations in viscous relativistic hydrodynamics are new!

- Calculations of observables vs. rapidity are now possible

- More detailed measurements at forward rapidity can help to constrain models, in particular transport parameters and the 3-dimensional fluctuating initial state

Hydrodynamics - state of the art

Use the state of the art 3+1D viscous relativistic hydrodynamics **MUSIC** with **shear** and **bulk** viscosity and all nonlinear terms that couple bulk viscous pressure and shear-stress tensor

Solve $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu J^\mu_B = 0$ along with

bulk → Π; shear → $\pi^{\mu\nu}$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

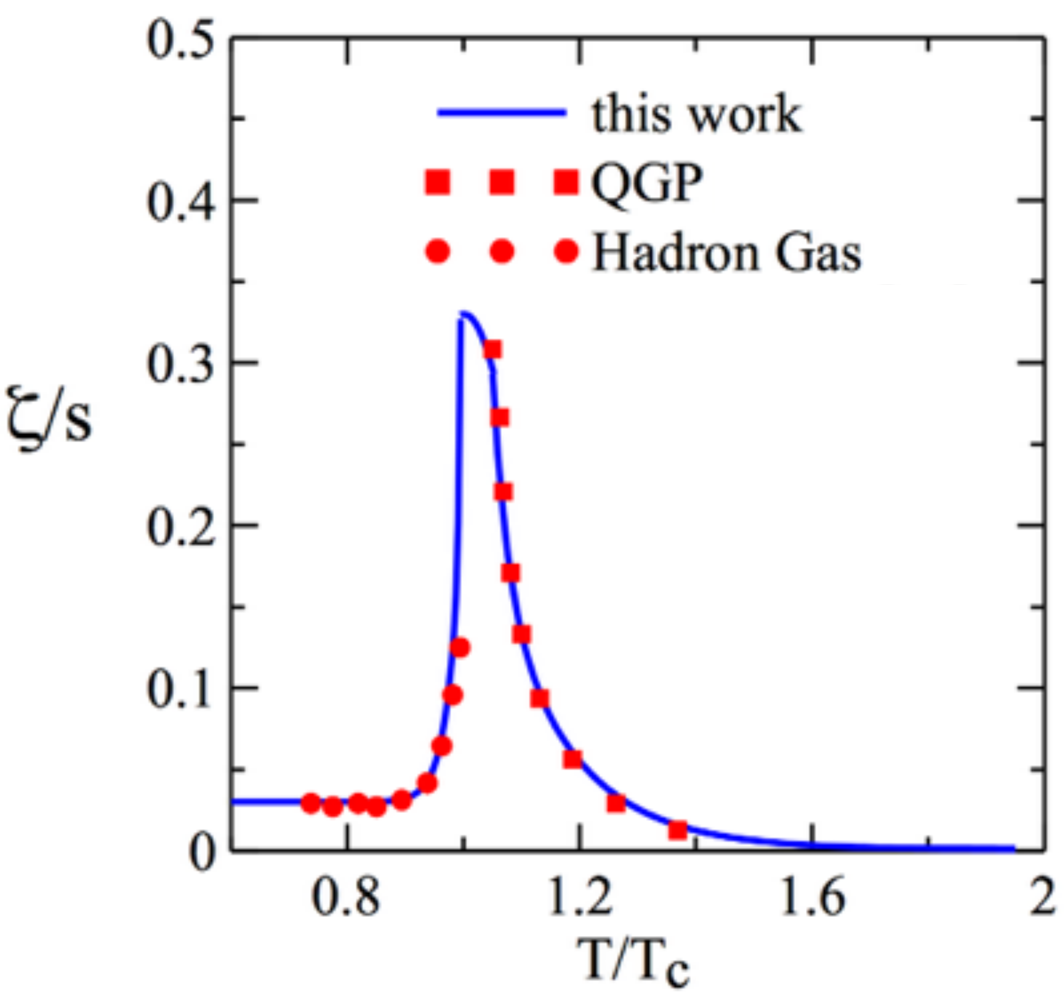
The transport coefficients $\tau_\Pi, \delta_{\Pi\Pi}, \lambda_{\Pi\pi}, \tau_\pi, \delta_{\pi\pi}, \phi_7, \tau_{\pi\pi}, \lambda_{\pi\Pi}$ are fixed using formulas derived
from the Boltzmann equation near the conformal limit

G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C 90, 024912 (2014)
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Viscosities

In the calculations presented here we use:

- shear viscosity (constant or with T dependence to be defined)
- bulk viscosity:



S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale Phys.Rev.Lett. 115 (2015) 13, 132301

G. S. Denicol, U. W. Heinz, M. Martinez, J. Noronha and M. Strickland, Phys. Rev. D 90, 125026 (2014); Phys. Rev. Lett. 113, 202301 (2014)

QGP: F. Karsch, D. Kharzeev and K. Tuchin, Phys. Lett. B 663, 217 (2008)
Hadron Gas:
J. Noronha-Hostler, J. Noronha and C. Greiner, Phys. Rev. Lett. 103, 172302 (2009)

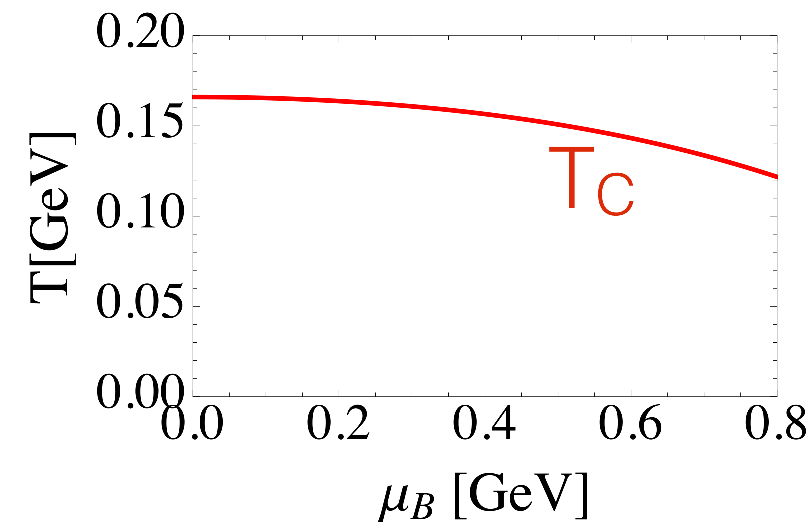
Equation of state

Construct EoS at finite μ_B using Taylor expanded lattice data:

Hadron resonance gas — interpolate — **Lattice QCD**

connect smoothly at T_C

(**c**onnecting temperature)



$$\frac{P}{T^4} = \frac{P_0}{T^4} + \frac{1}{2}\chi_B^{(2)}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{4!}\chi_B^{(4)}\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left[\left(\frac{\mu_B}{T}\right)^6\right]$$

Currently using data for parameters P_0^{lat} and $\chi_B^{(2)}$ from:

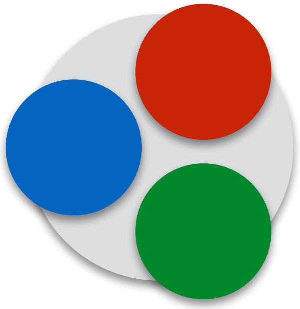
Borsanyi et al, JHEP1011, 077 (2010); JHEP1201, 138 (2012)

$\chi_B^{(4)}$ from the ratio $\chi_B^{(4)}/\chi_B^{(2)}$ in a HRG and parton gas model

Initial conditions - 3DMC-Glauber with quarks

Introduce a **simple** extension of the Monte Carlo Glauber model

We use constituent quarks



Constituent quark initial positions in the transverse plane are sampled from a 2D exponential distribution around the nucleon center (Nucleons are sampled from Woods-Saxon)

Their rapidities are sampled from nuclear parton distribution functions (here I used CTEQ10 and EPS09)

q-q cross sections determined geometrically to reproduce the nucleon-nucleon cross sections

Event-by-event baryon density

Transverse distribution:

Black disk or Gaussian wounding to determine wounded quarks

Longitudinal distribution:

Implement an MC version of the **Lexus** model

S. Jeon and J. Kapusta, PRC56, 468 (1997)

Idea: Rapidity distributions in heavy ion collisions follow via linear extrapolation from p+p collisions

Distribution in p+p collisions is parametrized and fit to data

Probability for a quark with rapidity y_P to get rapidity y after collision with another quark with rapidity y_T:

$$Q(y, y_P, y_T) = \lambda \frac{\cosh(y - y_T)}{\sinh(y_P - y_T)} + (1 - \lambda)\delta(y - y_P)$$

where we treat λ as a free parameter

(it characterizes the stopping power for quarks)

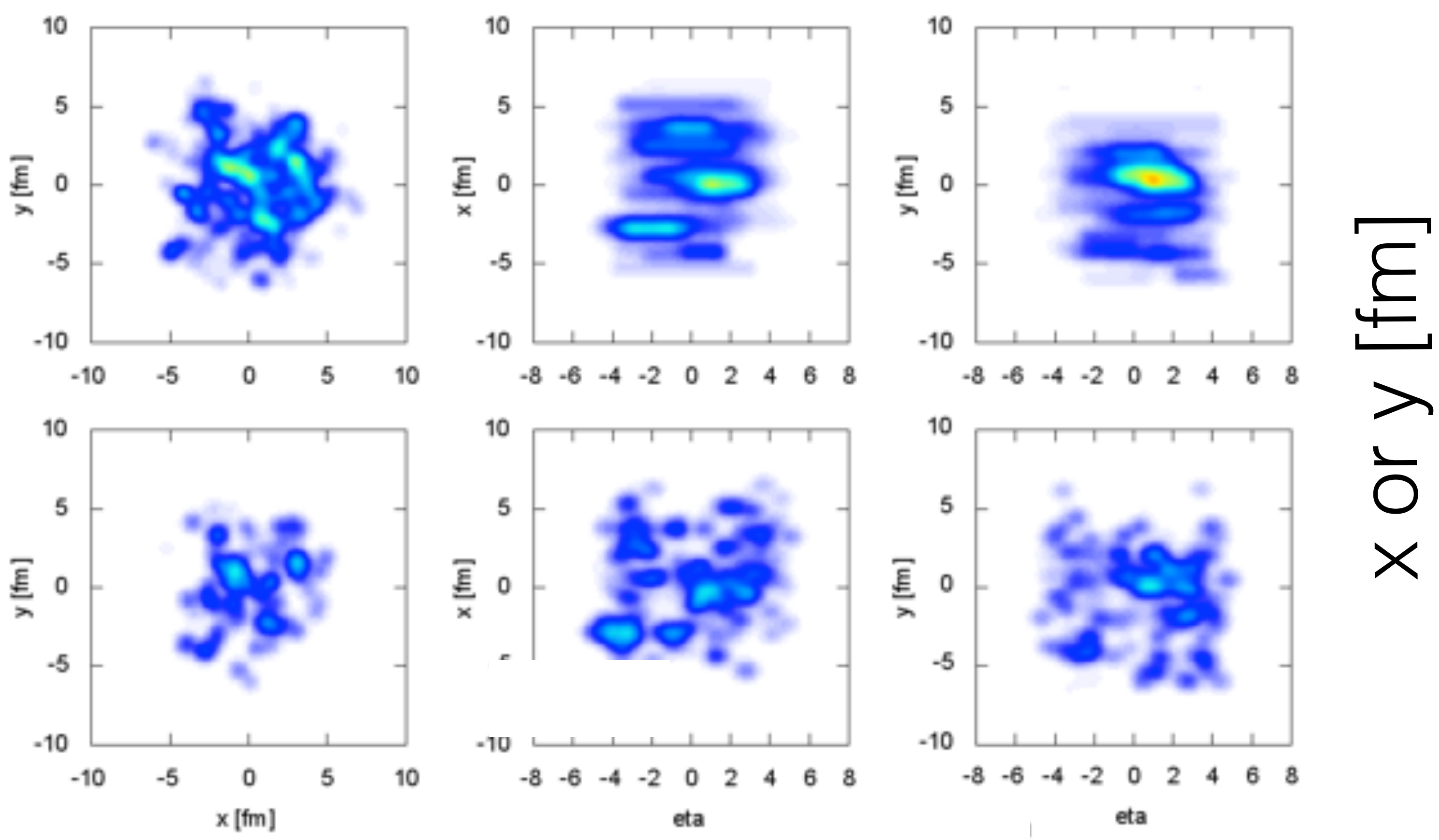
Event-by-event baryon- and entropy density

Deposit entropy density (fluctuating with NBD) between the collided constituent quarks using a Gaussian profile in the transverse plane and a constant distribution (with Gaussian edges) in rapidity

$\sqrt{s} = 200\mathrm{GeV}$

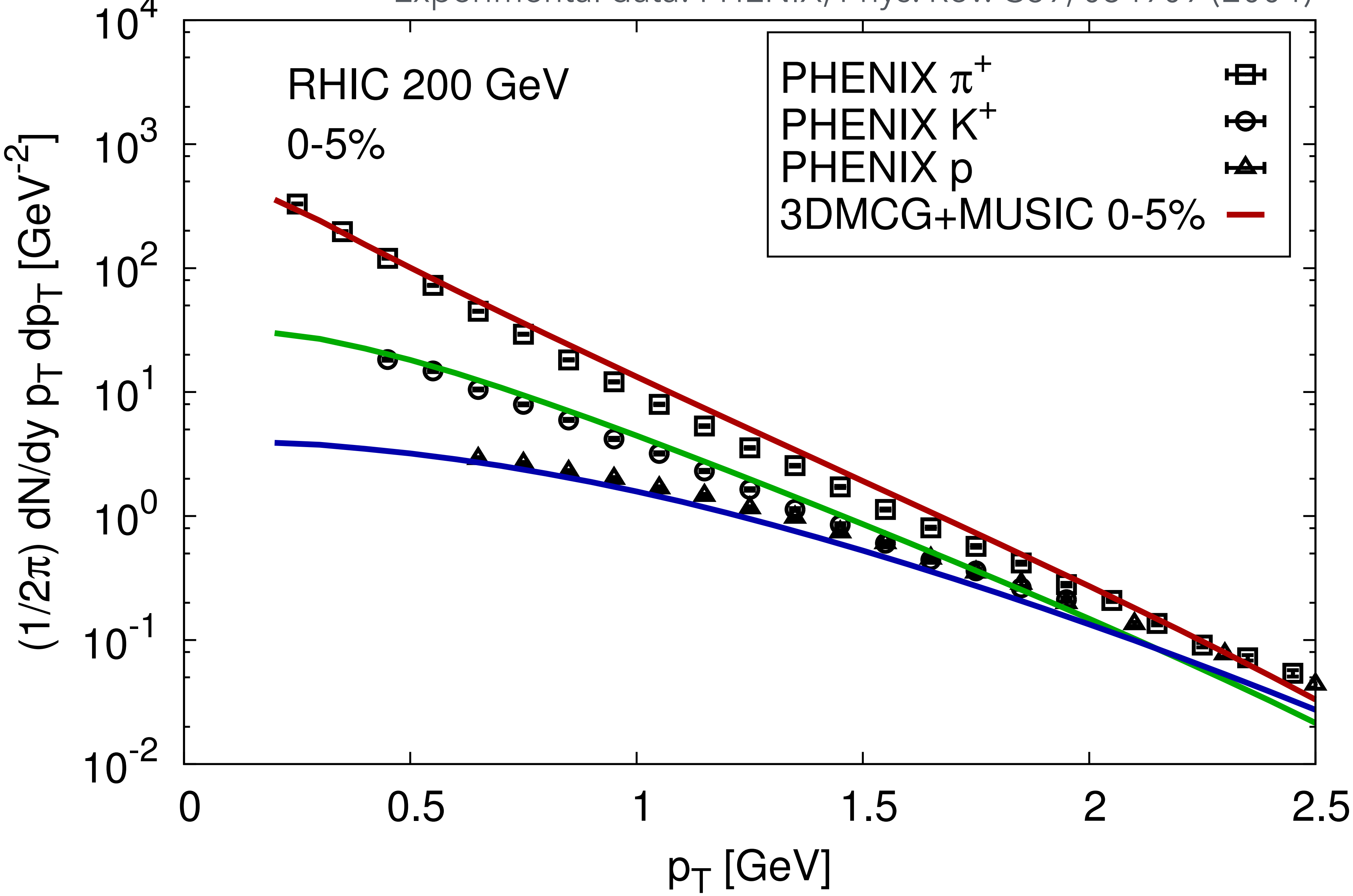
energy density

baryon density



Identified particle transverse momentum spectra

Experimental data: PHENIX, Phys. Rev. C69, 034909 (2004)

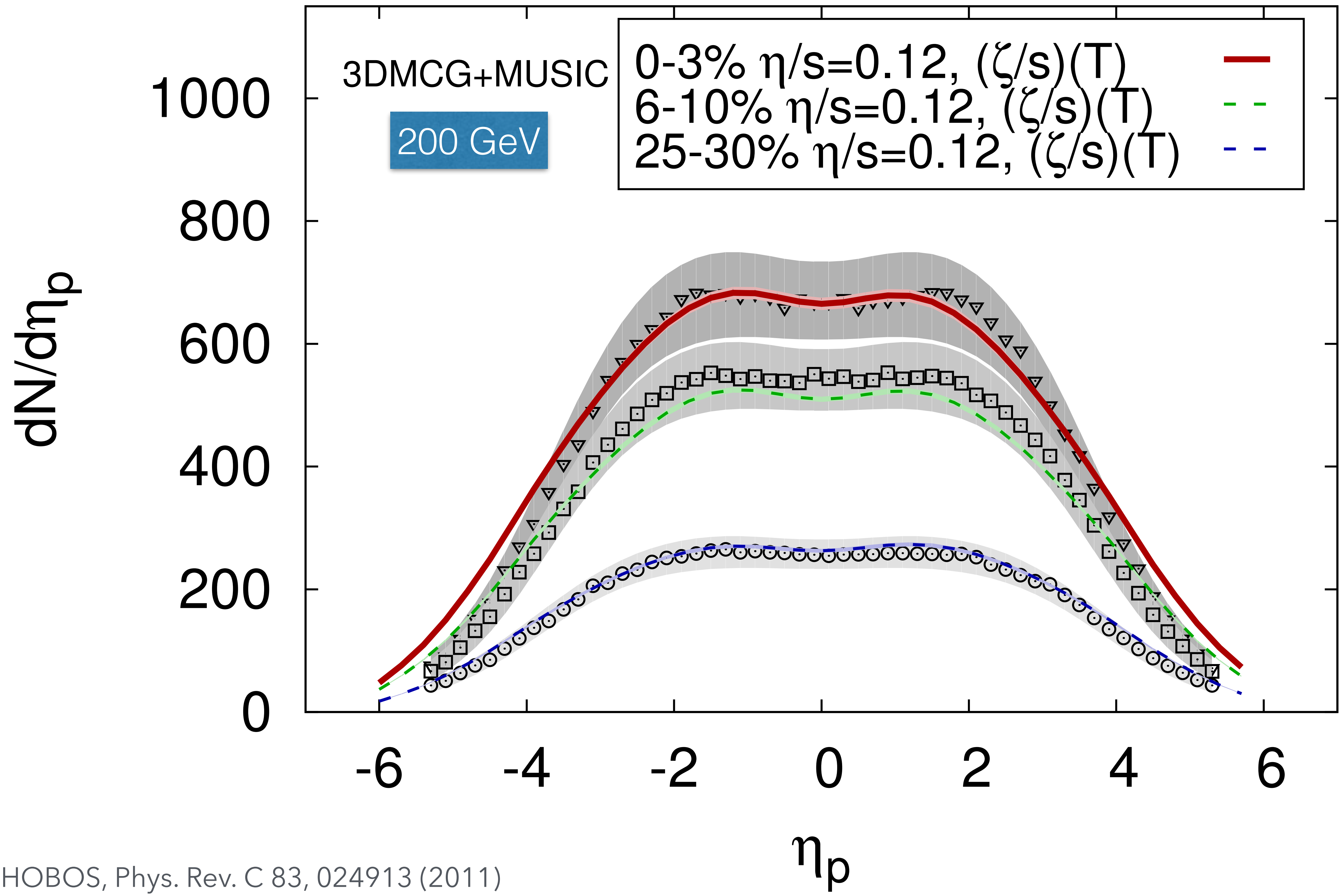


Bulk viscosity needed to get mean p_T right

Same as with IP-Glasma initial conditions:

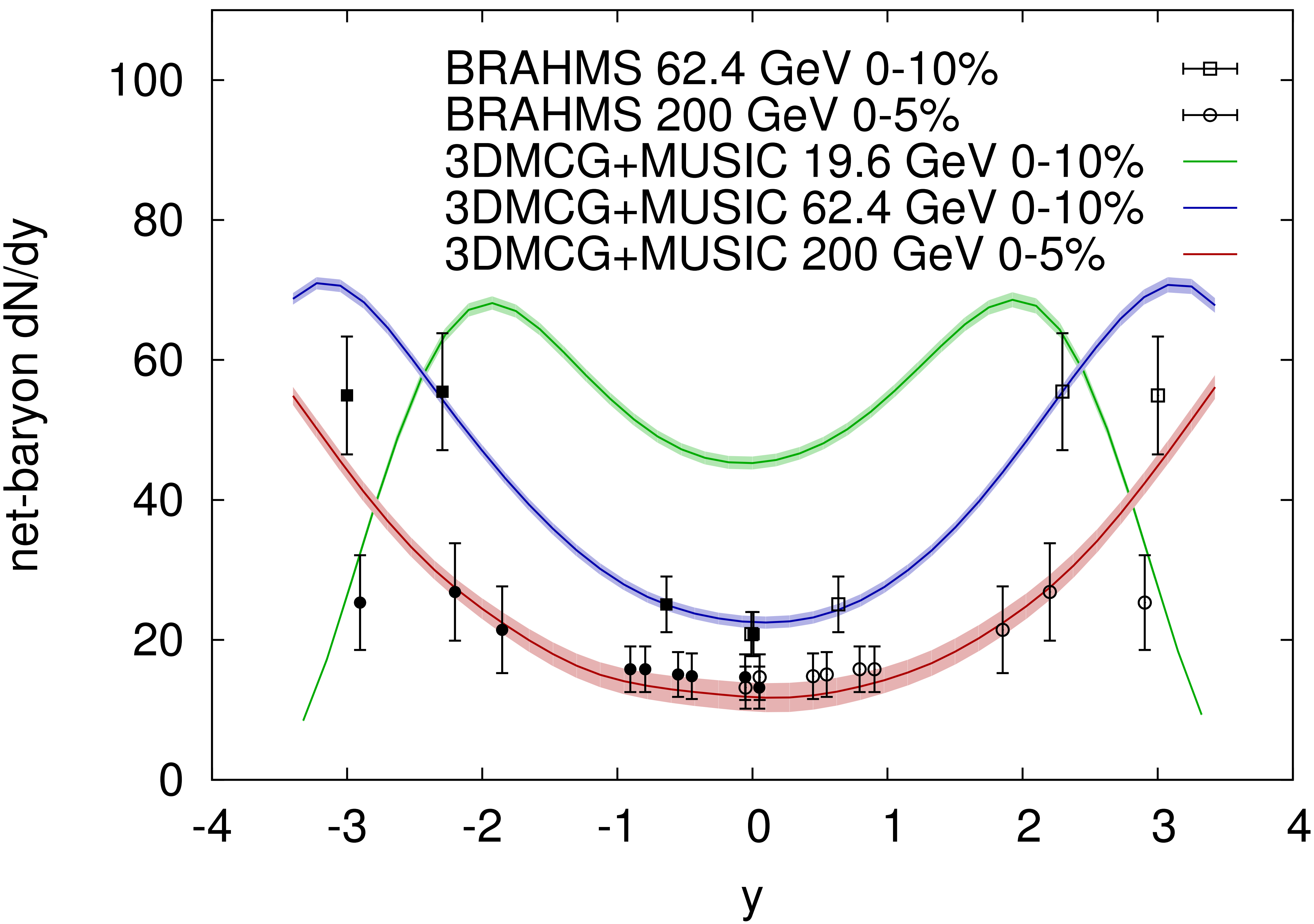
S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. 115, 132301 (2015)

Charged hadron pseudo-rapidity distributions



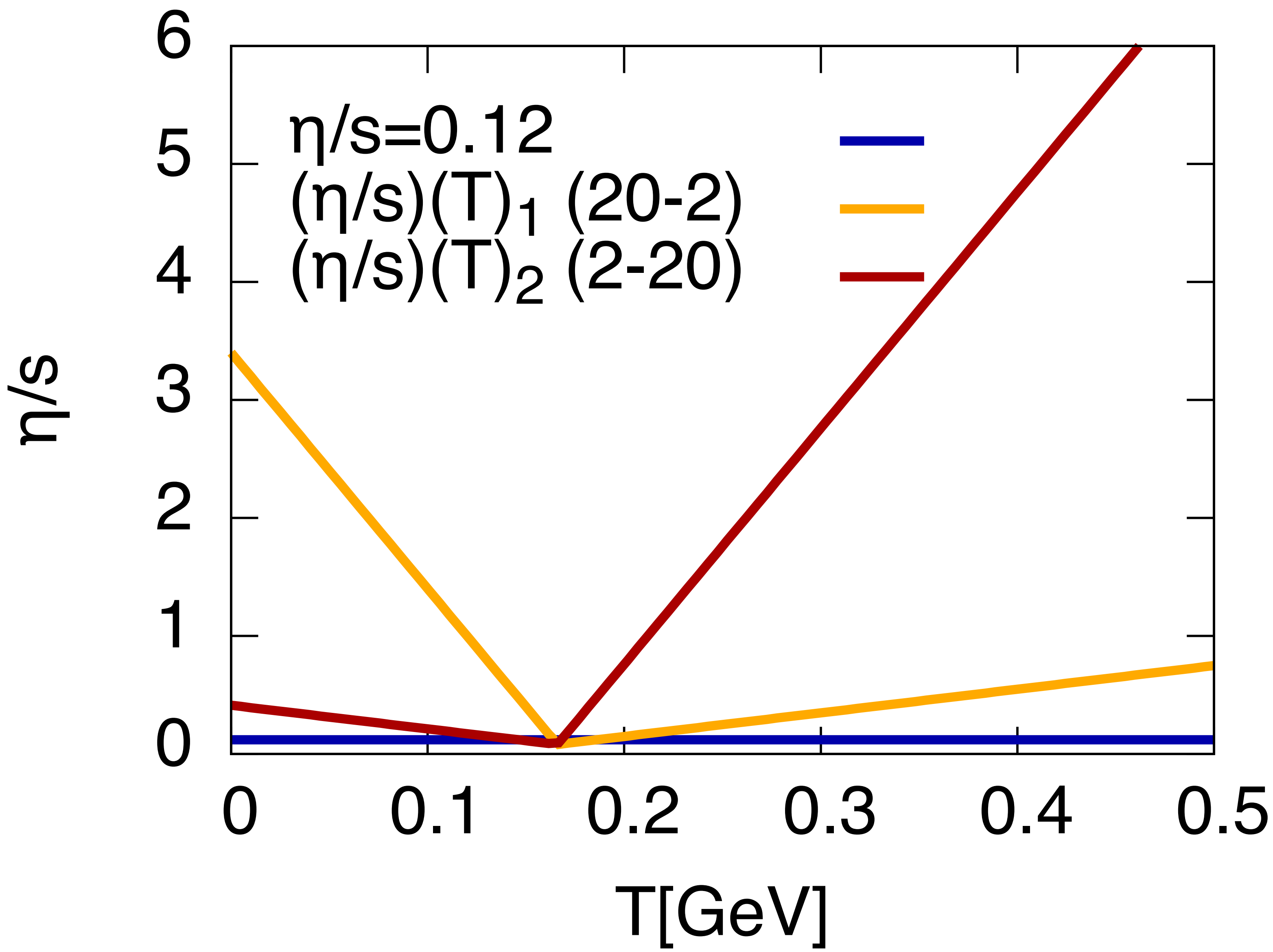
PHOBOS, Phys. Rev. C 83, 024913 (2011)

Net-baryon rapidity distributions



BRAHMS Phys. Lett. B677, 267-271 (2009), Phys. Rev. Lett. 93, 102301 (2004)

T dependent η/s from rapidity dependence

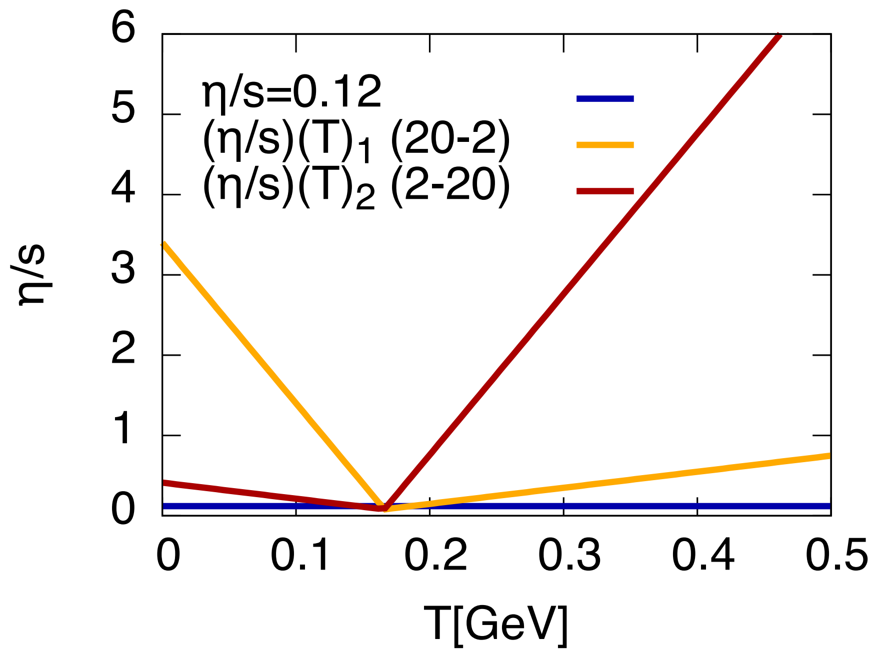


Numbers (a,b) are the slopes in [GeV^{-1}] in:

$$(\eta T/(\varepsilon + P))(T) = 0.08 + a(T_c - T)\theta(T_c - T) + b(T - T_c)\theta(T - T_c)$$

where $T_c = T_c(\mu_B)$

T dependent η/s from rapidity dependence



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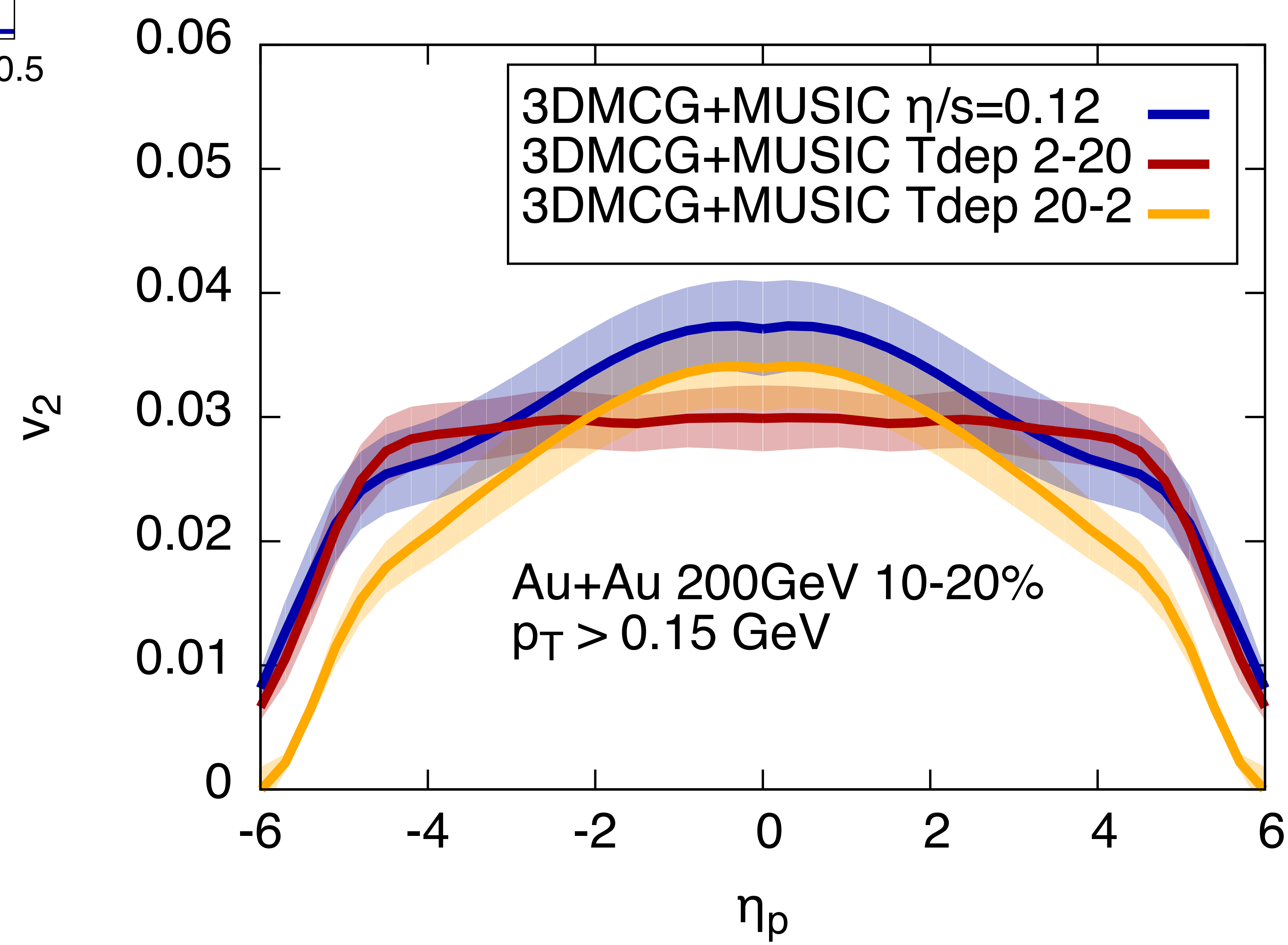
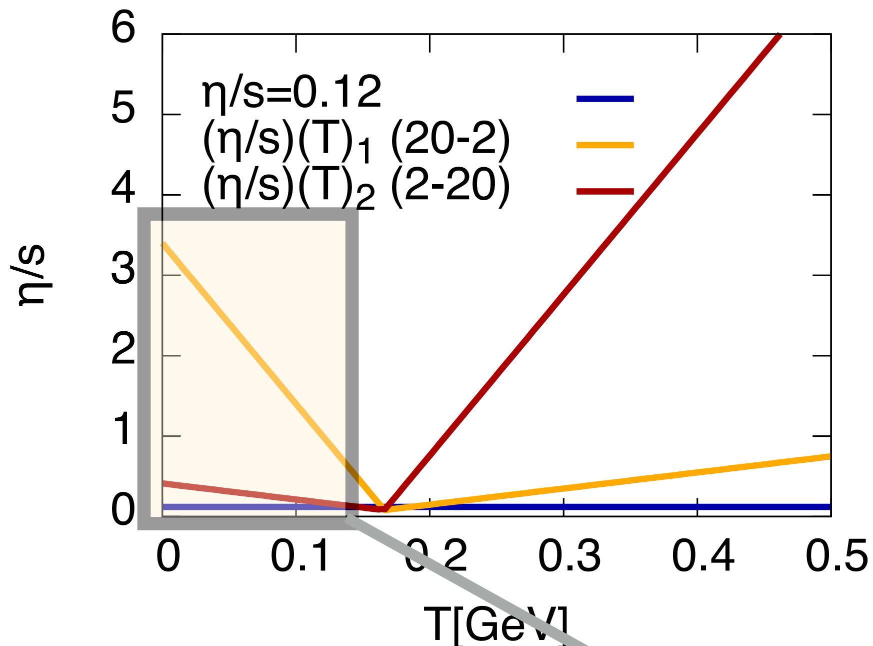


T dependent η/s from rapidity dependence



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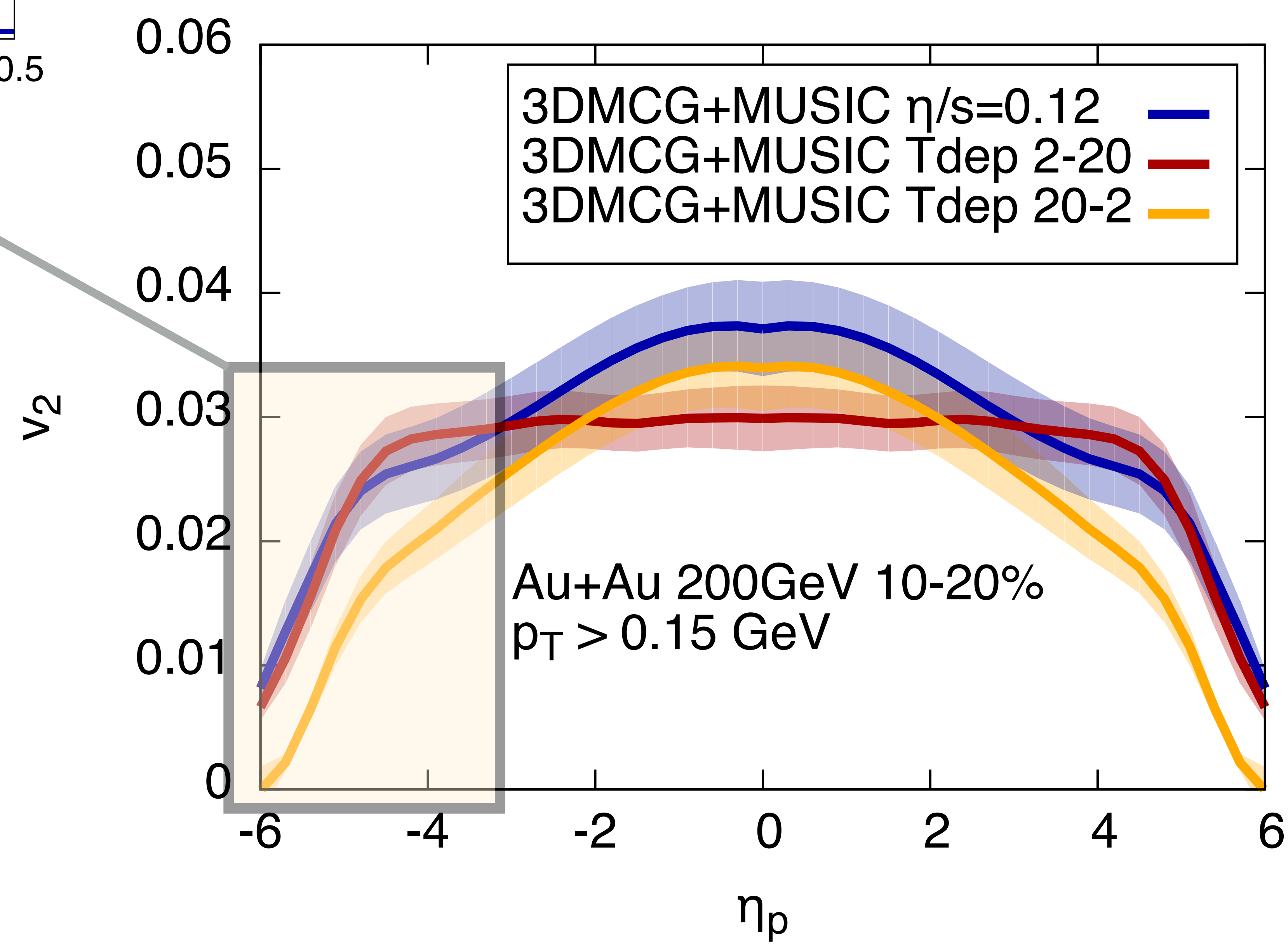

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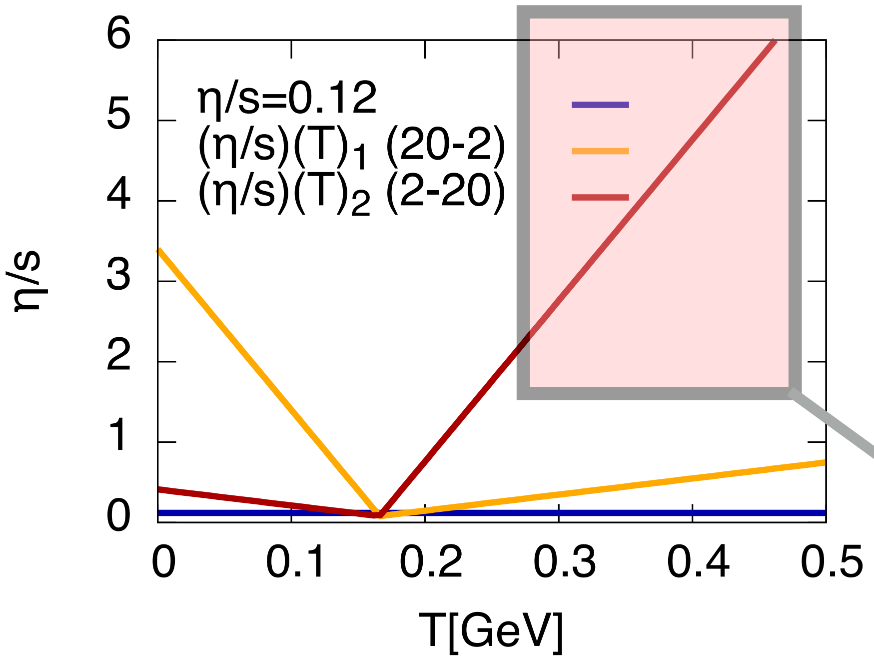

Numbers (a,b) are the slopes in [GeV^{-1}] in:

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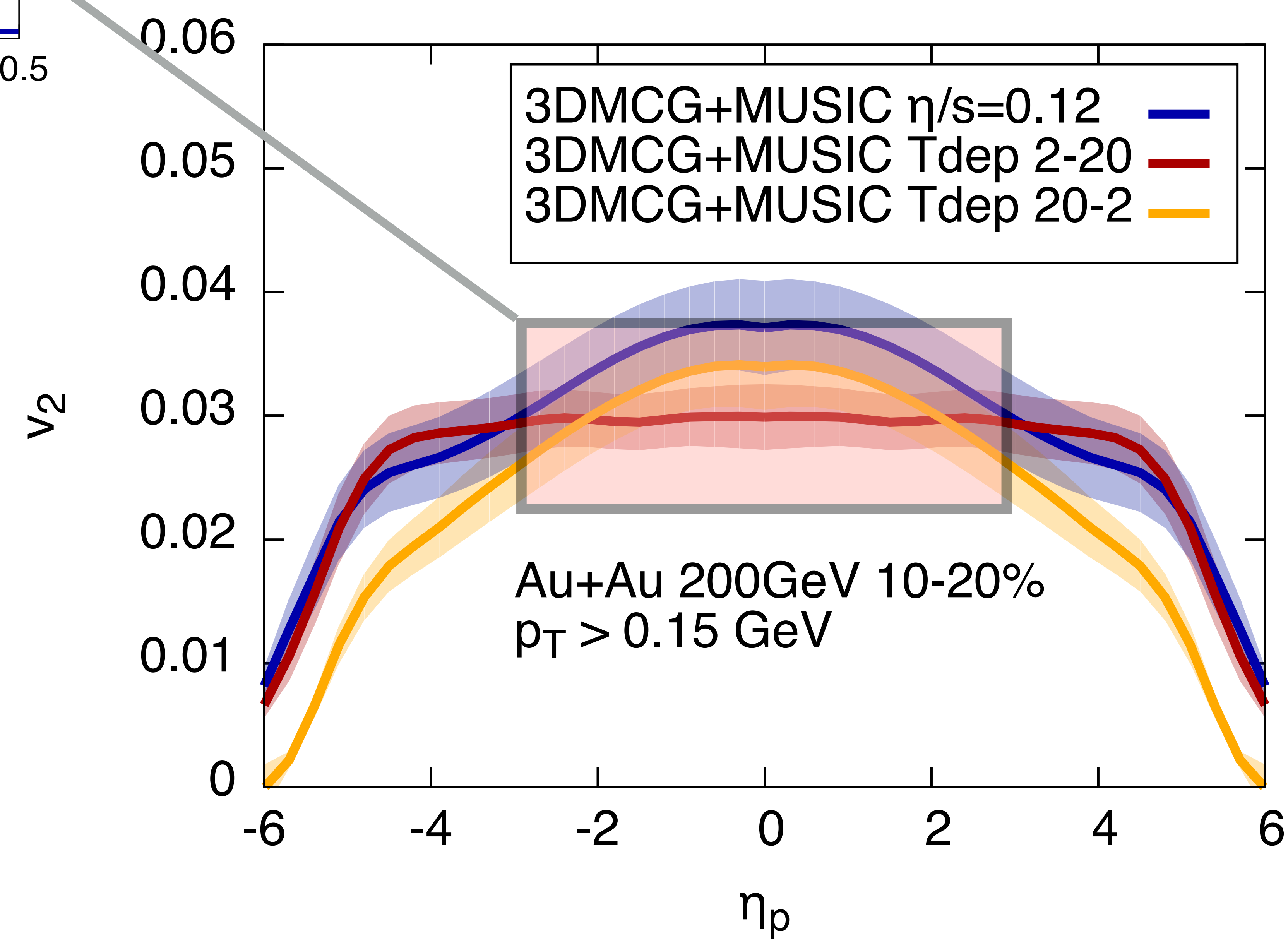
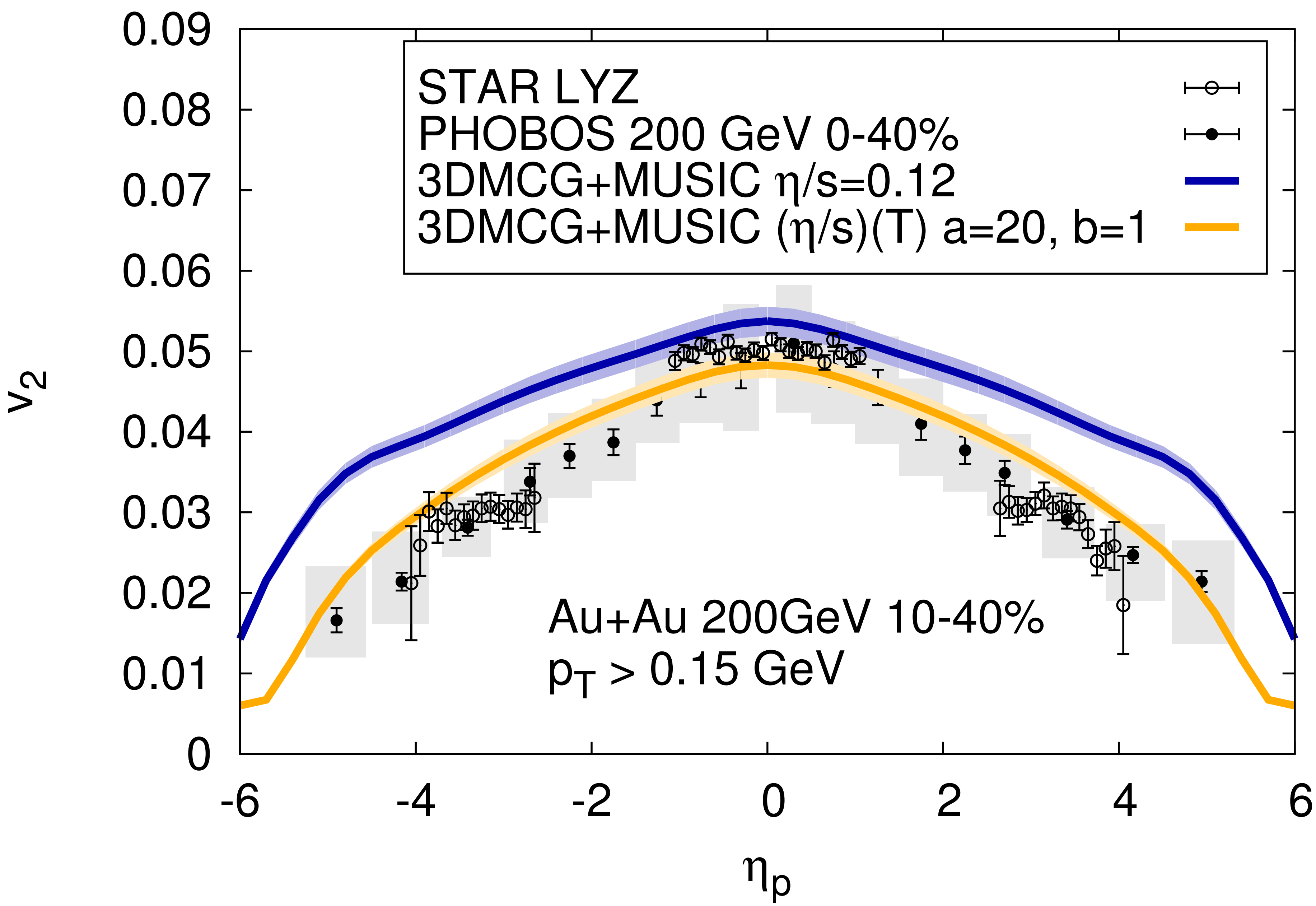
where $T_c = T_c(\mu_B)$



Pseudo-rapidity dependent flow

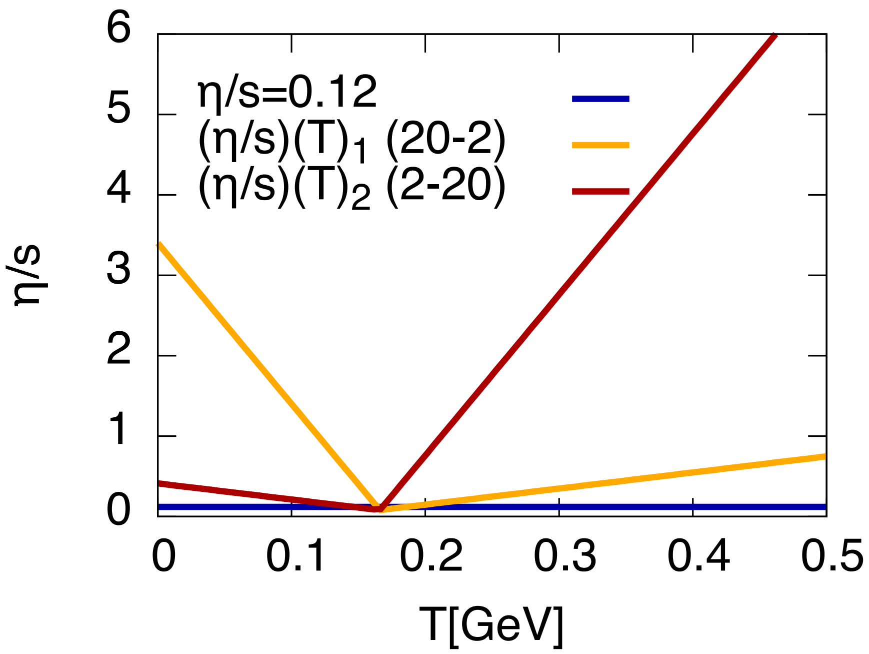


Data favors large hadronic η/s. No room for large QGP η/s.

Even constant η/s is disfavored - would not have seen that at $y=0$

PHOBOS Collaboration, Phys. Rev. Lett. 94, 122303 (2005)
STAR Collaboration, Phys. Rev. C77, 054901 (2008)

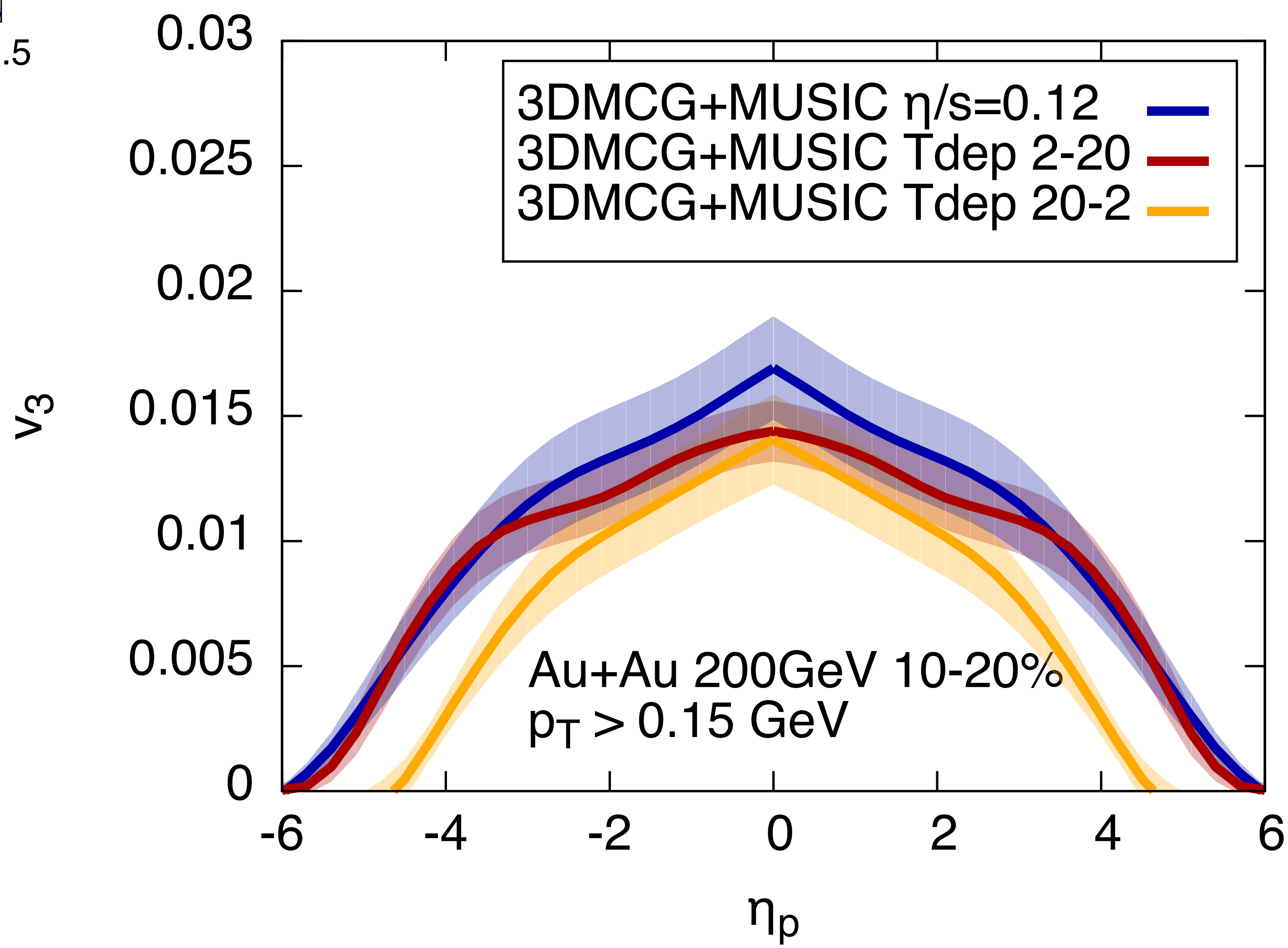
Triangular flow vs rapidity



Numbers (a,b) are the slopes in [GeV^{-1}] in:

$$(\eta T/(\varepsilon + P))(T) = 0.08 + a(T_c - T)\theta(T_c - T) + b(T - T_c)\theta(T - T_c)$$

where $T_c = T_c(\mu_B)$

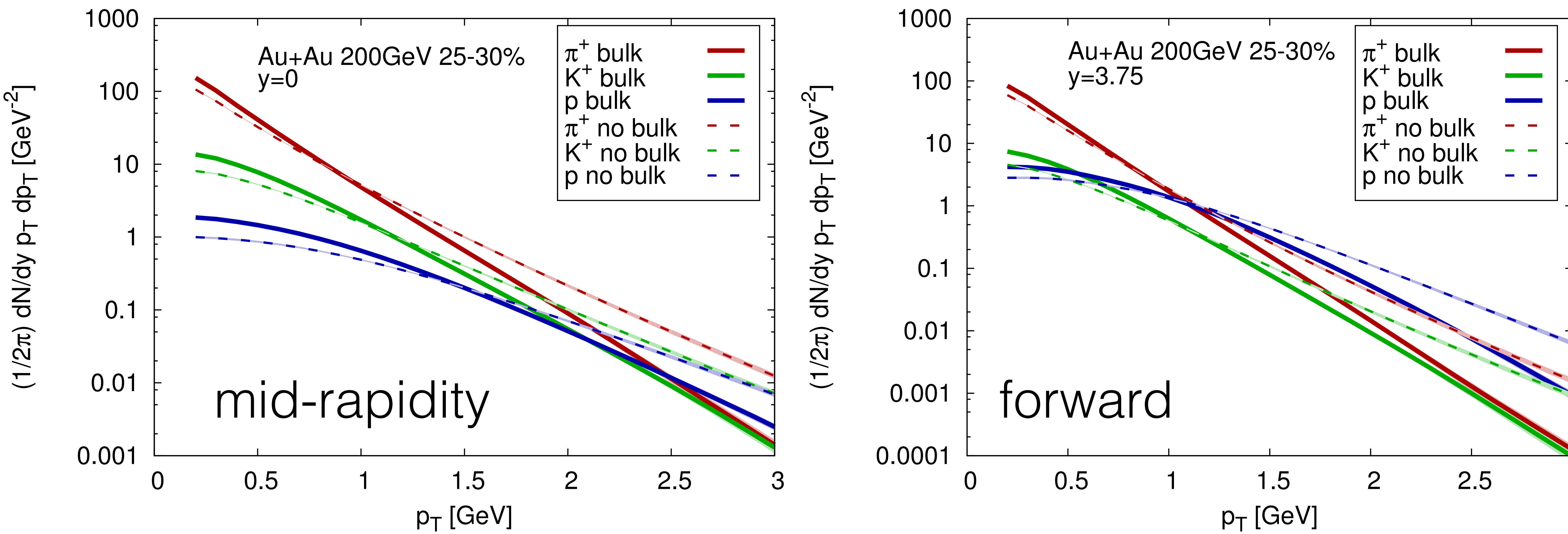


Getting more differential

Particle ID and p_T + y dependence carry information on

- η/s and ζ/s as functions of T and μ_B
- distributions of ρ_B and s

So far this is largely unexplored



solid: with bulk, dashed: no bulk

Getting more differential

Particle ID and p_T + y dependence carry information on

- η/s and ζ/s as functions of T and μ_B
- distributions of ρ_B and s

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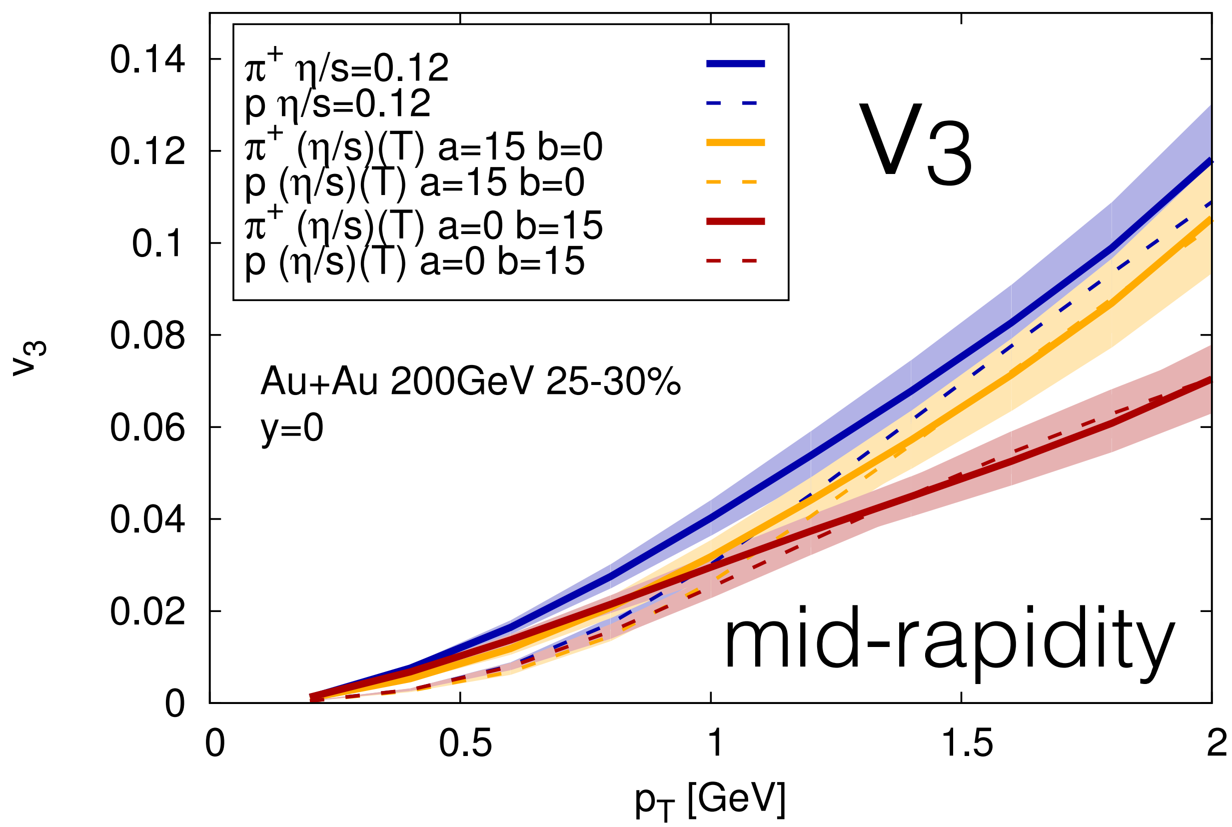
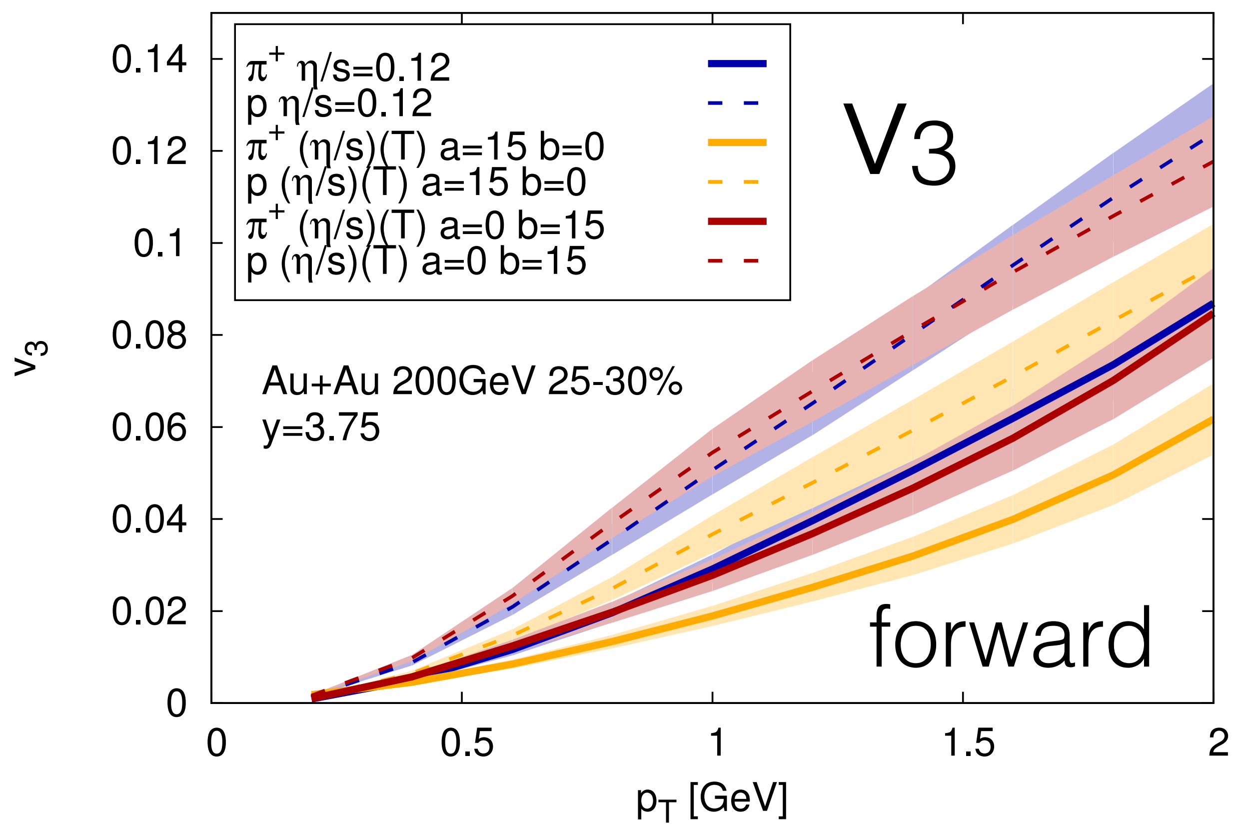
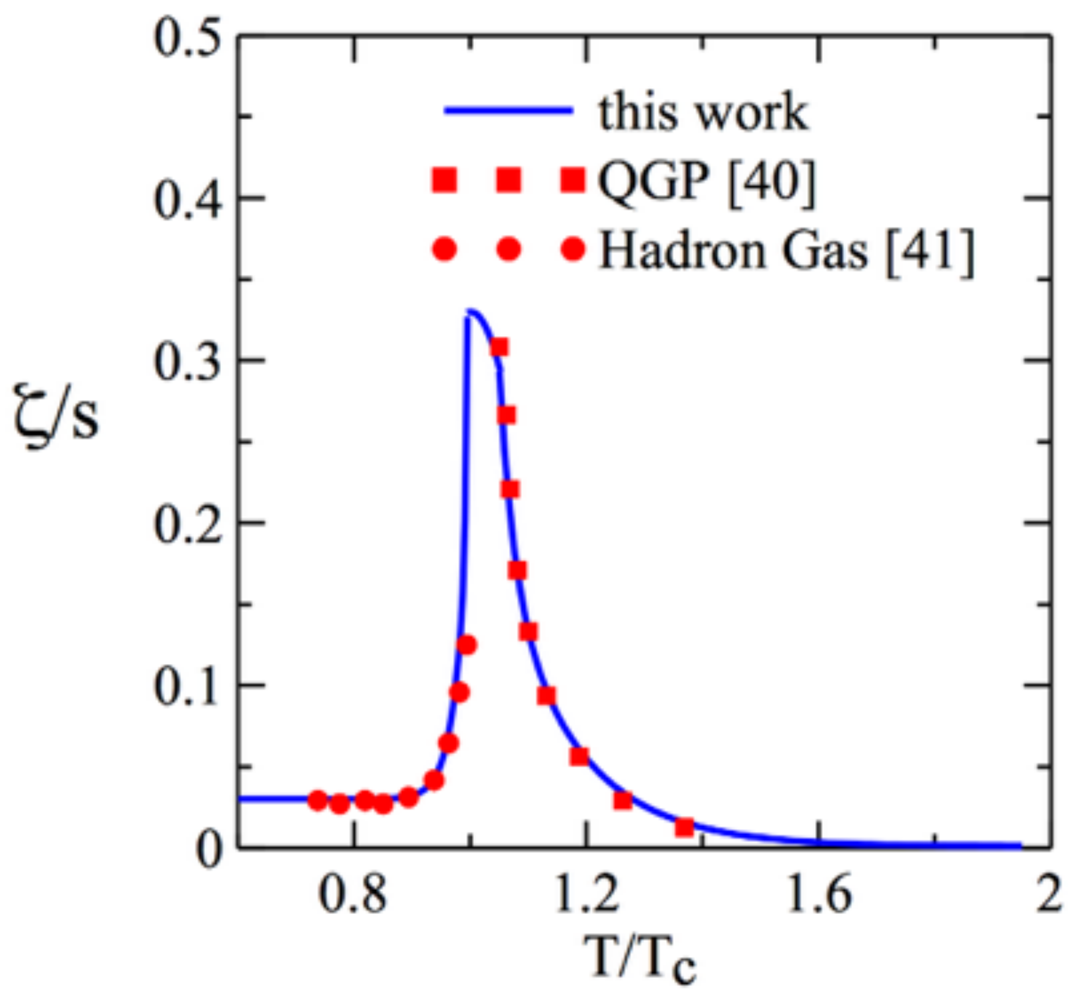




solid: pions, dashed: protons

Bulk viscosity



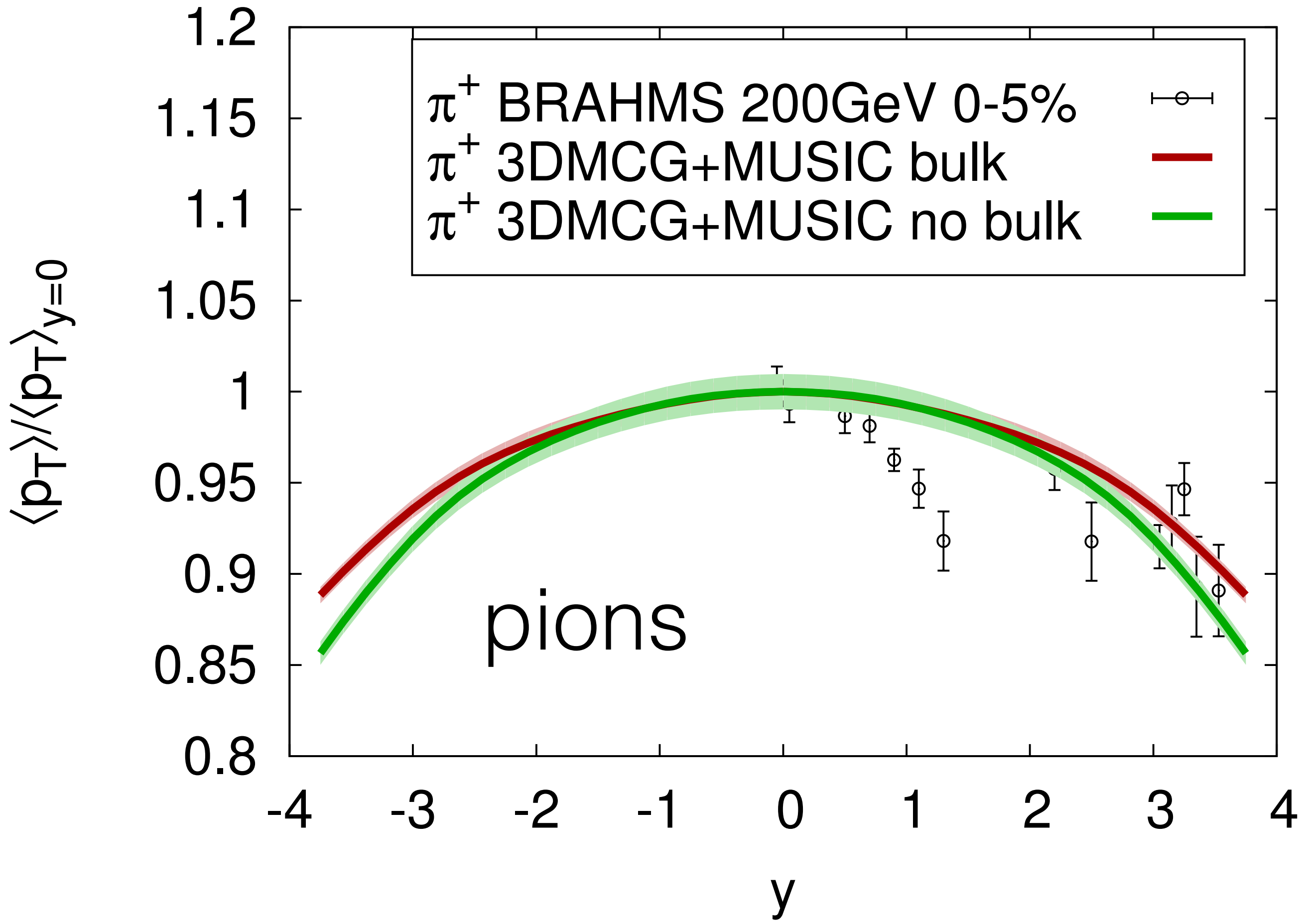
Can forward measurements help constrain this shape in T?

We know that mean-p_T is sensitive to bulk viscosity at mid-rapidity

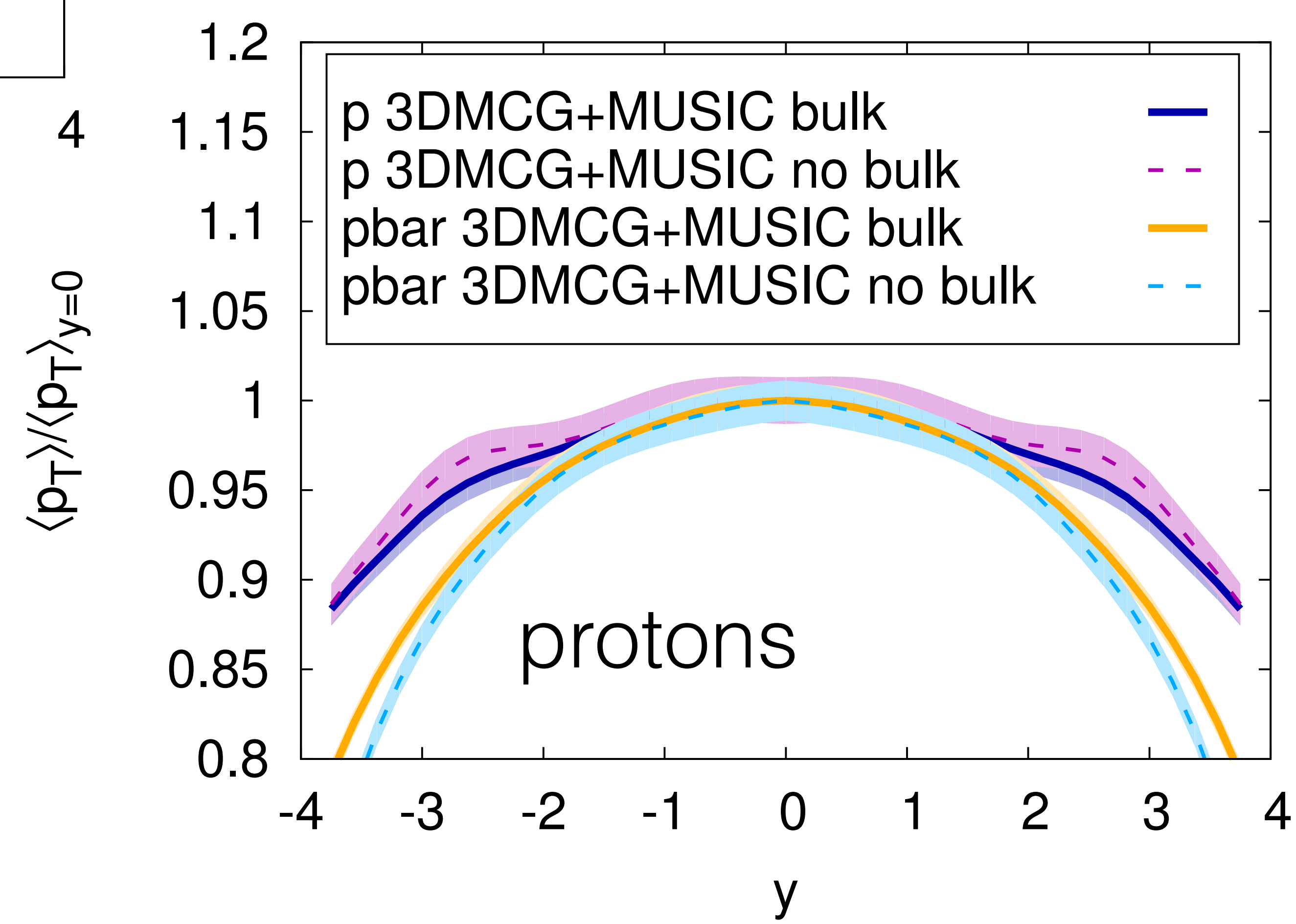
S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale
Phys. Rev. Lett. 115 (2015) 13, 132301

So let's look at mean-p_T as a function of rapidity

Effect of bulk viscosity on ⟨p_T⟩ vs rapidity



Visible but fairly weak effect at forward rapidity



Two-particle pseudo-rapidity correlations

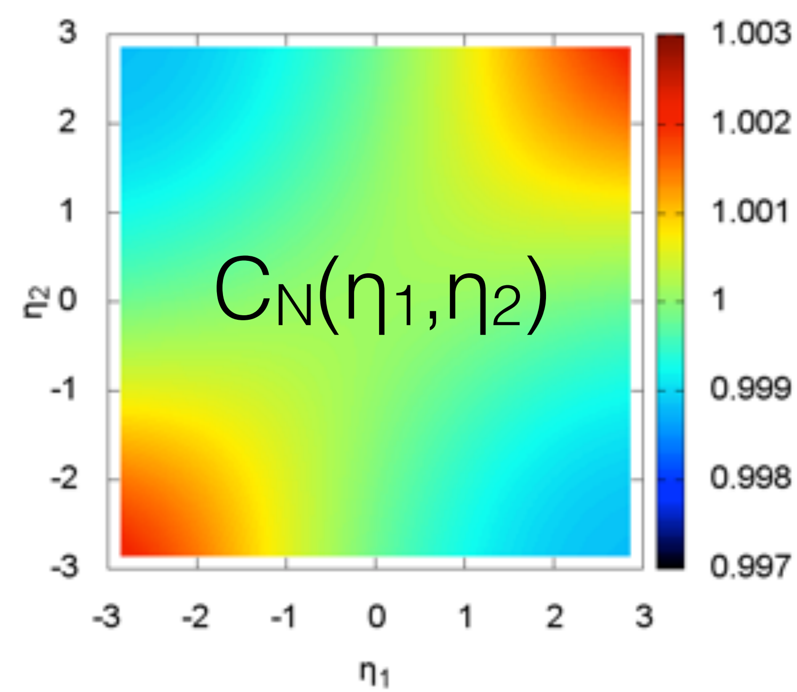
$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1)\rangle \langle N(\eta_2)\rangle}$$

to remove the effect of a residual centrality dependence in 5% bin

$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1) C_p(\eta_2)}$$

with

$$C_p(\eta_{1/2}) = \frac{1}{2Y} \int_{-Y}^{Y} C(\eta_1, \eta_2) d\eta_{2/1}$$



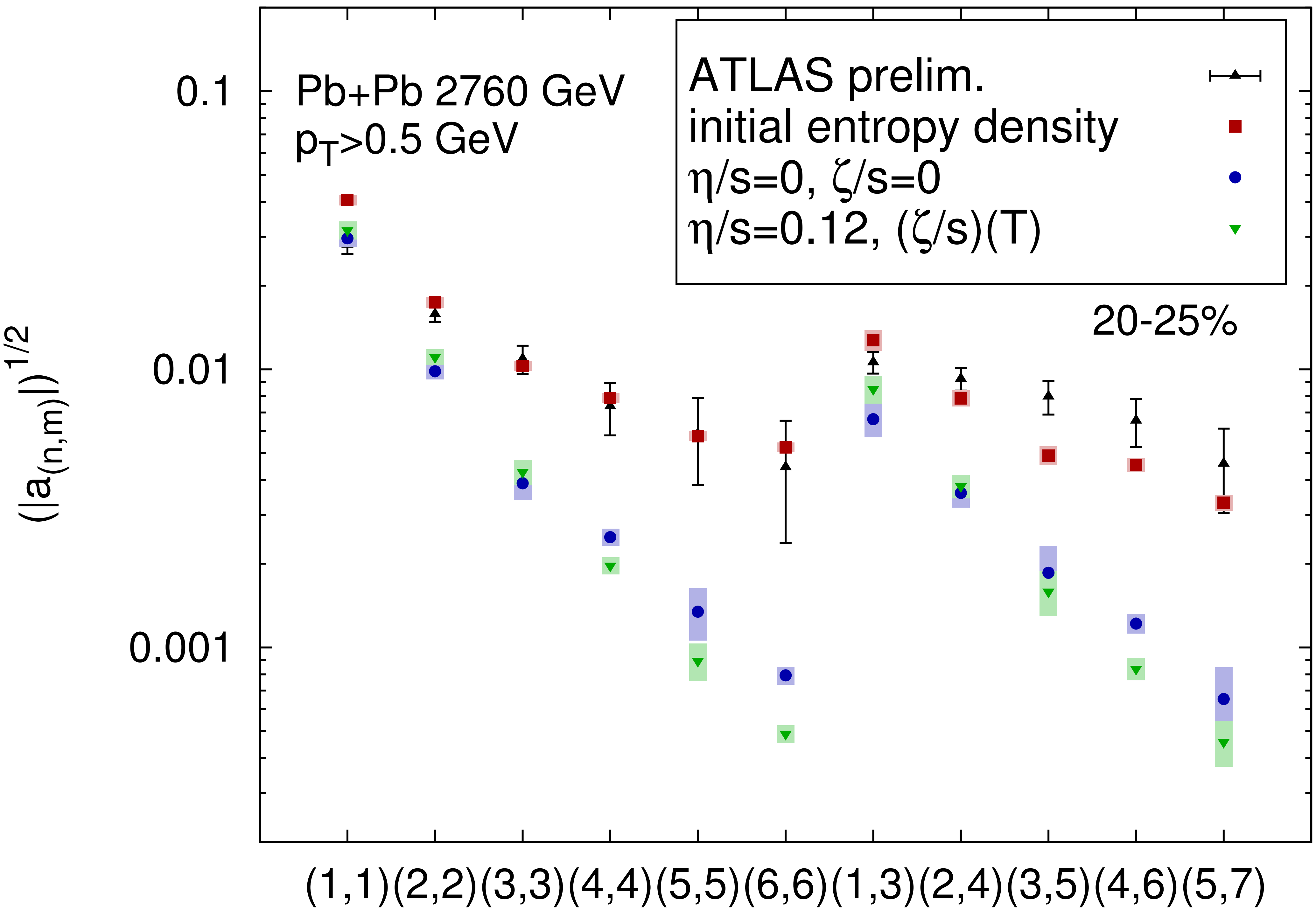
Expand in Legendre polynomials. The coefficients are given by

$$a_{n,m} = \int C_N(\eta_1, \eta_2) \frac{T_n(\eta_1) T_m(\eta_2) + T_n(\eta_2) T_m(\eta_1)}{2} \frac{d\eta_1}{Y} \frac{d\eta_2}{Y}$$

see: A. Bzdak, D. Teaney, Phys. Rev. C 87, 024906
J. Jia, S. Radhakrishnan, M. Zhou, arXiv:1506.03496, and ATLAS-CONF-2015-020,

Two-particle pseudo-rapidity correlations

A. Monnai, B. Schenke, arXiv:1509.04103

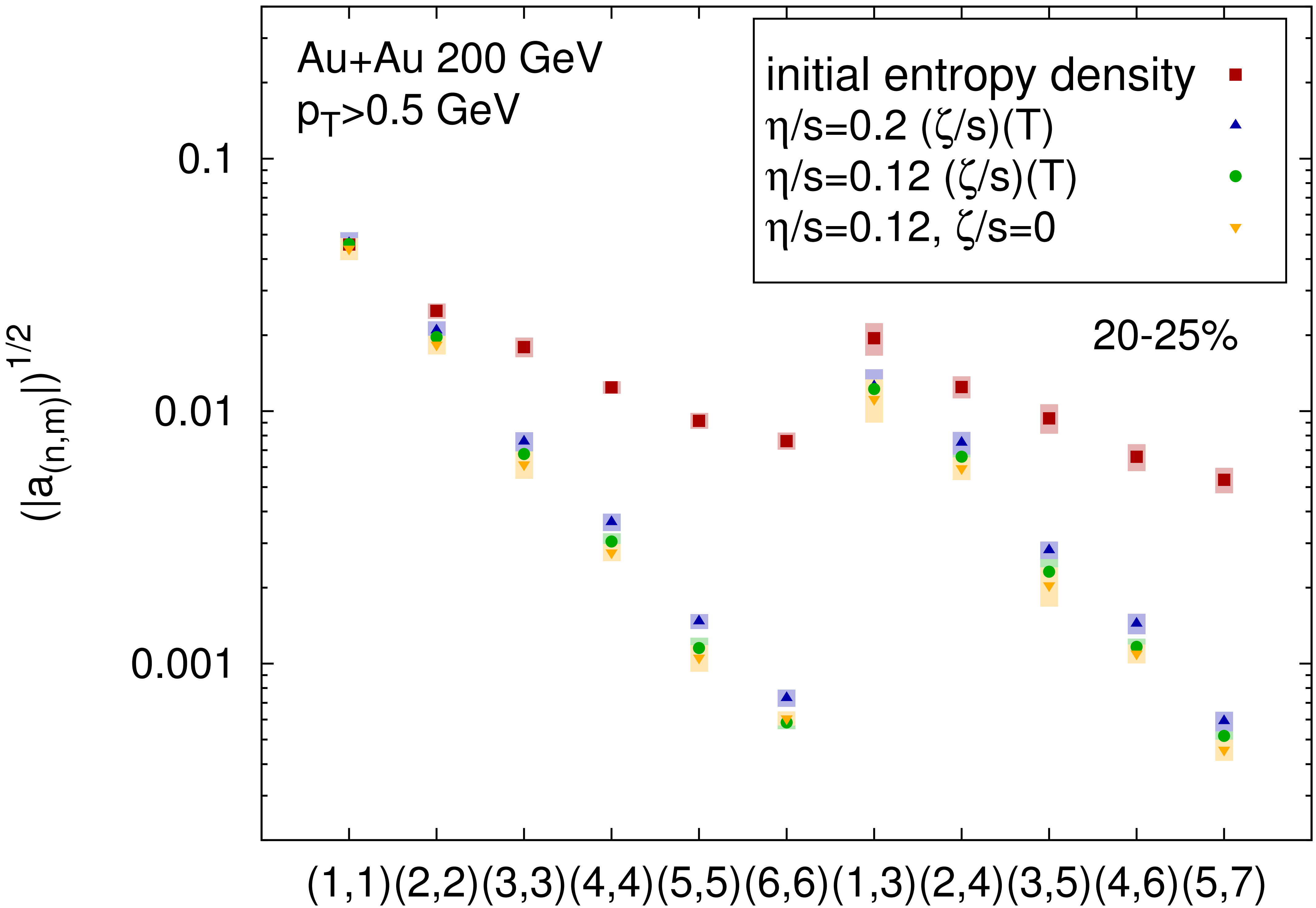


missing short range correlations

Experimental data: ATLAS-CONF-2015-020

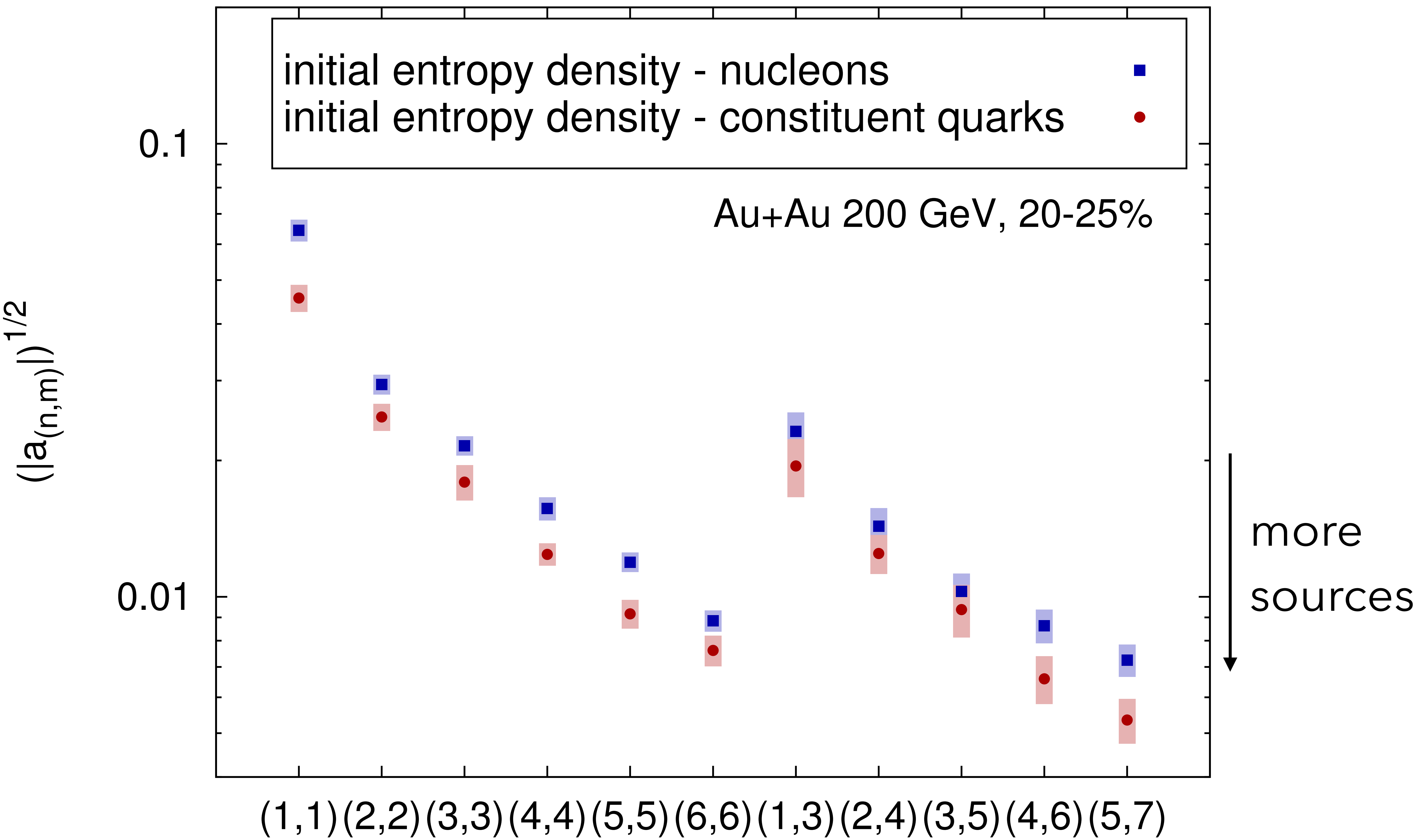
Effect of shear and bulk viscosity

A. Monnai, B. Schenke, arXiv:1509.04103



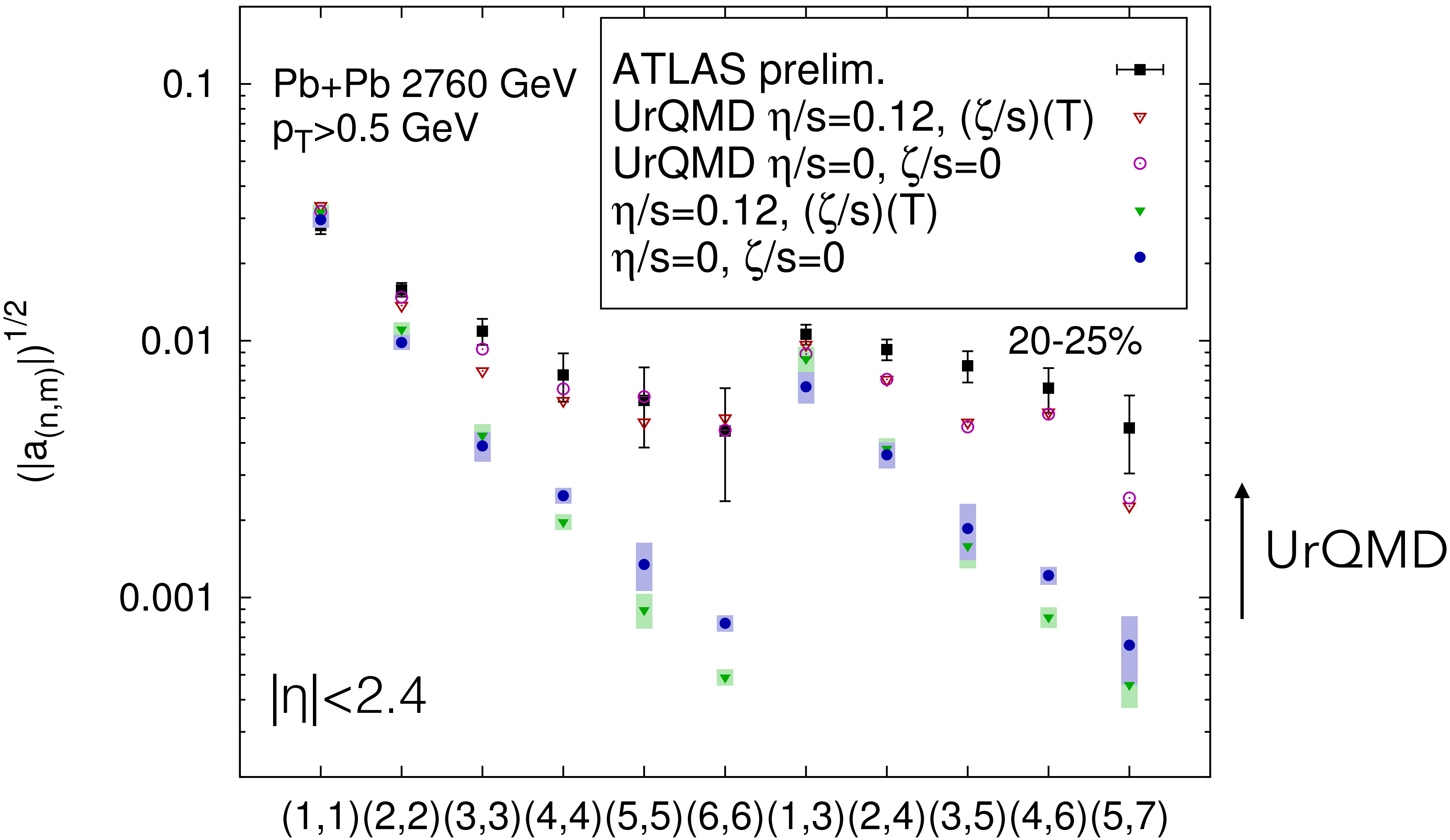
Effect of the initial number of sources

A. Monnai, B. Schenke, arXiv:1509.04103



Couple to UrQMD: short range correlations matter

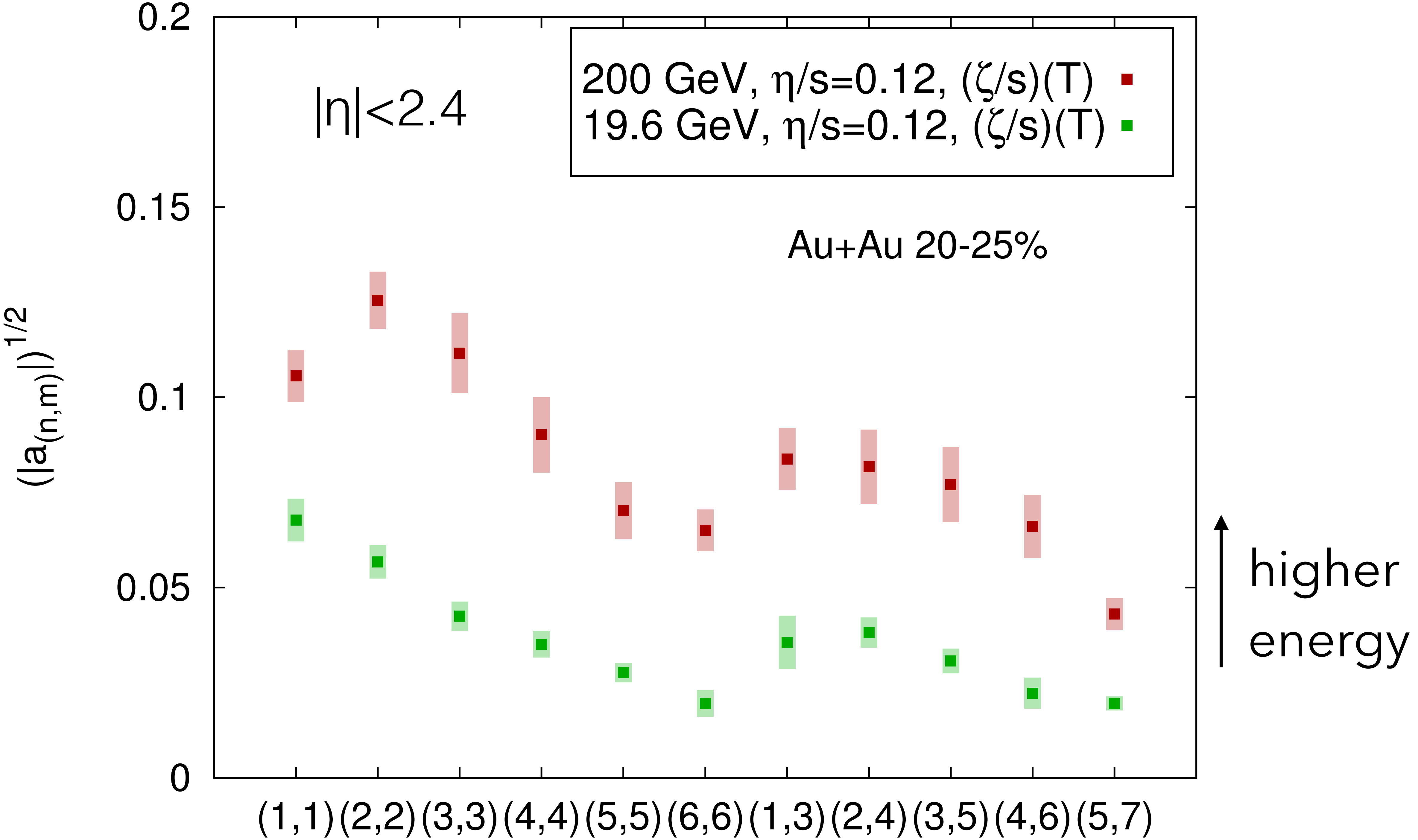
G. Denicol, C. Gale, S. Jeon, A. Monnai, S. Ryu, B. Schenke, **work in progress**



also see P. Bozek, W. Broniowski, A. Olszewski, arXiv:1509.04124

Net baryon pseudo-rapidity correlations

A. Monnai, B. Schenke, arXiv:1509.04103



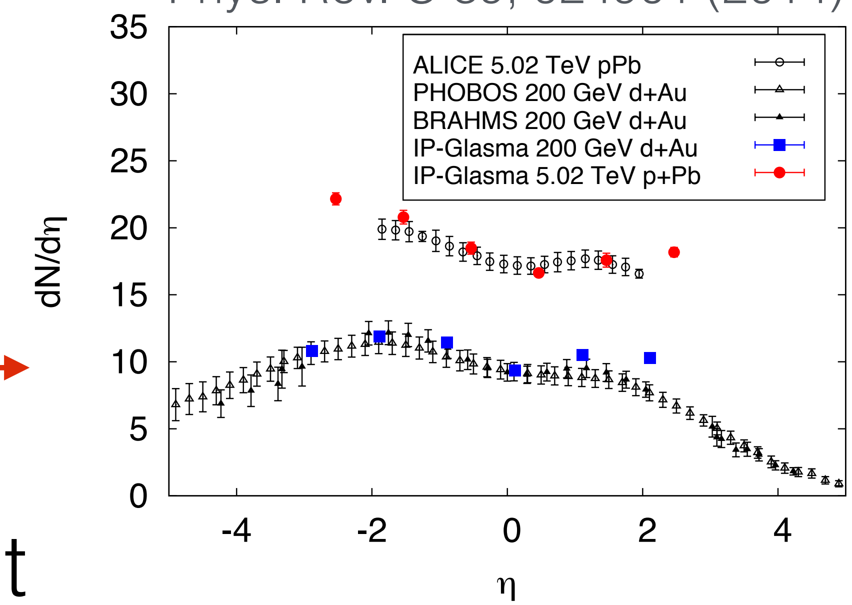
Measure this: Could help our understanding of baryon stopping

JIMWLK and IP-Glasma

IP-Glasma+JIMWLK

- IP-Glasma is boost invariant and uses a parametrization for the *x* dependence
- Changing the rapidity changes *x*, changes Q_S, changes the multiplicity

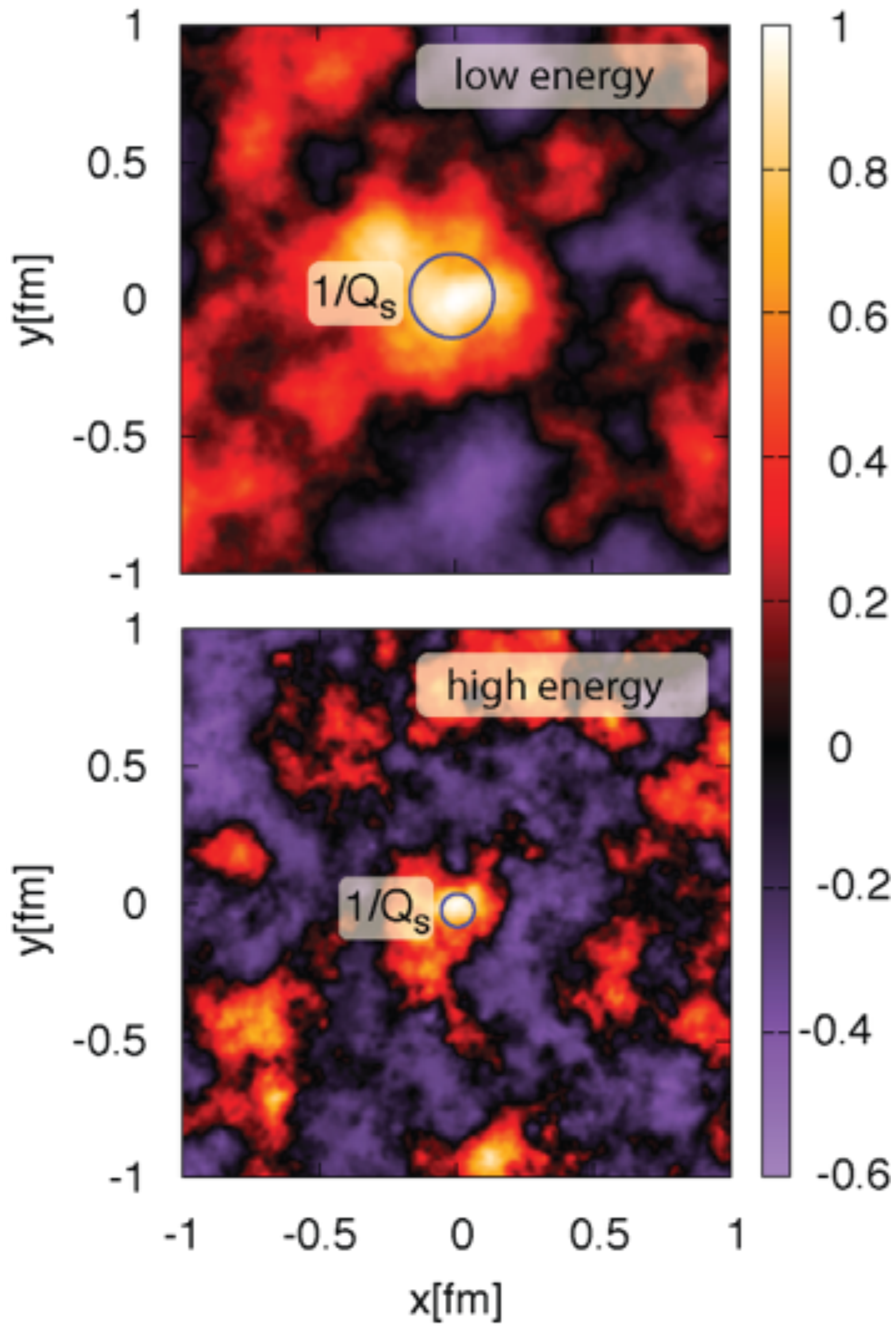
Schenke, Tribedy, Venugopalan
Phys. Rev. C 89, 024901 (2014)



- However, energy density in a single event is boost invariant - a full 3D Glasma calculation is very hard
- To do better we can replace the parametrization by JIMWLK
- Then compute energy density at different rapidities
- Will contain rapidity correlations via "geometry"
- Then combine all slices in rapidity to make 3D initial condition for hydrodynamics

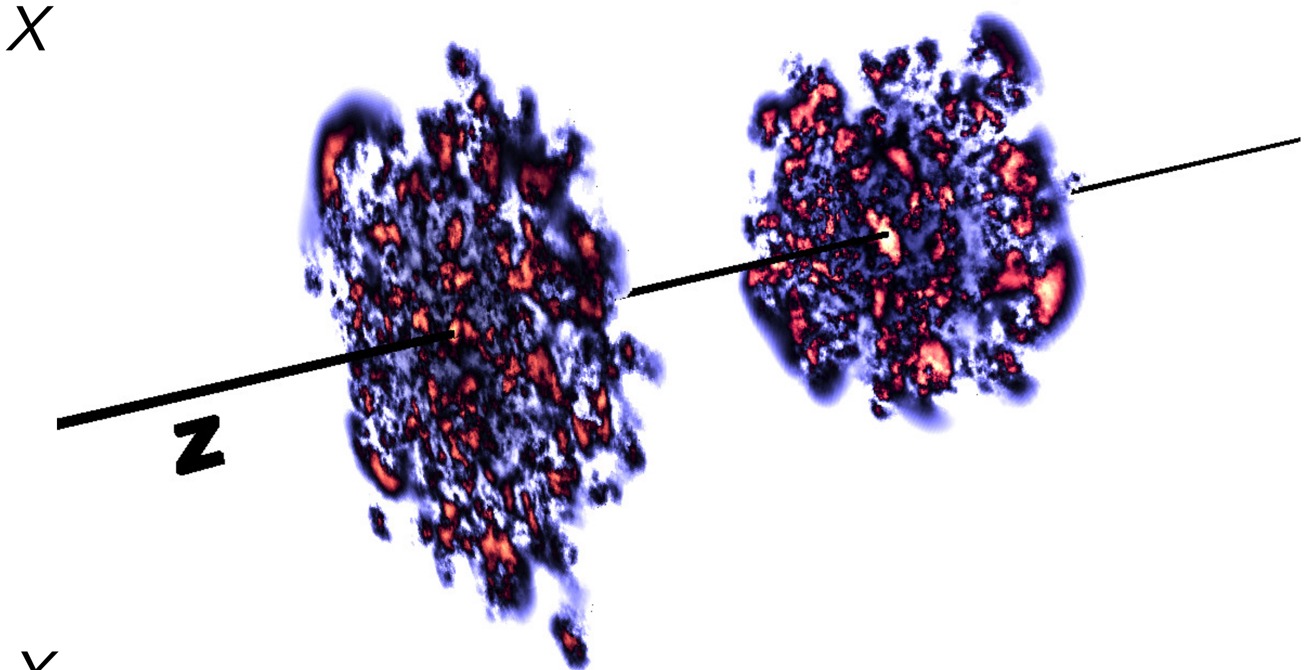
JIMWLK: Correlation length within one nucleus

A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke, R. Venugopalan, Phys. Lett. B706, 219-224 (2011)



large *x*

small *x*



At forward rapidity one should be sensitive (multi-particle correlations?) to the change in transverse structure of the two nuclei

Conclusions

- Event-by-event 3+1D viscous relativistic fluid dynamic calculations with fluctuations of baryon number and entropy density in all three dimensions are a very recent development

- Comparison to experimental data over a wide rapidity range can contribute greatly to constraining the T and μ_B dependence of transport parameters such as bulk and shear viscosities (in addition to using different beam energies)

- Net-baryon rapidity correlations can shed more light on poorly understood baryon stopping

- 3+1D Glasma initial state under development - forward data could confirm predicted *x* dependence of fluctuations - test of CGC

Backup

Calculation of pseudo-rapidity dependent flow

$$v_n\{2\}(\eta_p) = \frac{\langle v_n v_n(\eta_p) \cos[n(\psi_n - \psi_n(\eta_p))]\rangle}{\sqrt{\langle v_n^2 \rangle}}$$

v_n and ψ_n are the rapidity integrated quantities
cosine term not important in the hydro calculation

Result very similar to rms of $v_n(\eta_p)$

Constructing the equation of state (EoS)

Taylor Expansion

Cannot deal with complex Fermion determinants on lattice, so Taylor expand around zero baryon chemical potential

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \frac{1}{2}\chi_B^{(2)}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{4!}\chi_B^{(4)}\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left[\left(\frac{\mu_B}{T}\right)^6\right]$$

because of matter-anti-mater symmetry only even powers appear similarly for energy density and entropy density

For net-baryon density we have

$$\frac{n_B}{T^3} = 0 + \chi_B^{(2)}\frac{\mu_B}{T} + \frac{1}{3!}\chi_B^{(4)}\left(\frac{\mu_B}{T}\right)^3 + \mathcal{O}\left[\left(\frac{\mu_B}{T}\right)^5\right]$$

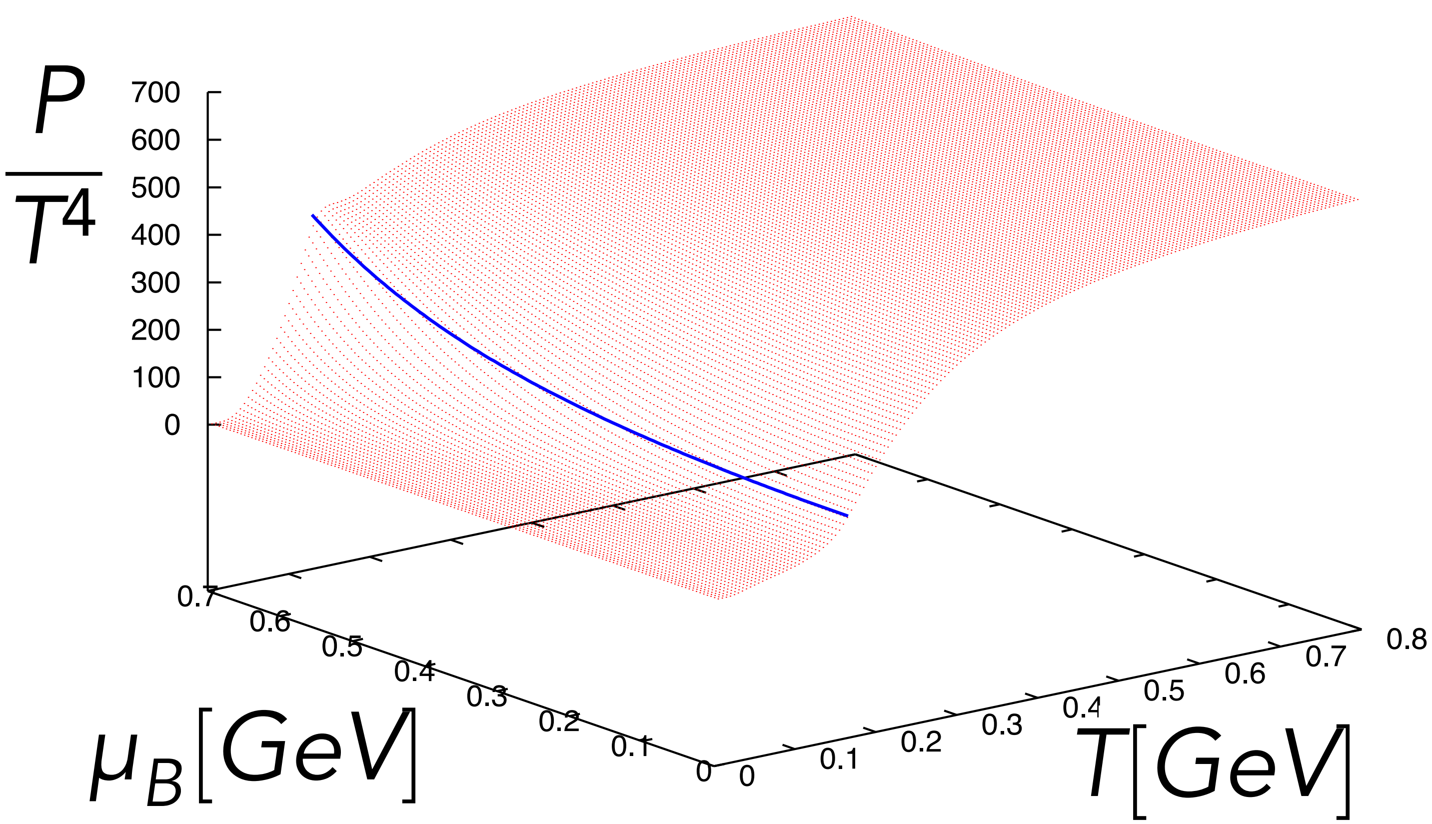
Constructing the equation of state (EoS)

Smooth matching (cross over)

As a first try, we match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\mathrm{HRG}}(T)}{T^4} + \frac{1}{2}\left[1 + \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\mathrm{lat}}(T_s)}{T_s^4}$$

In the future one can introduce a critical point here.



T_C: connecting temperature
ΔT_C: width of overlap area
T_s: temperature shift

$$T_s = T + d[T_C(0) - T_C(\mu_B)]$$

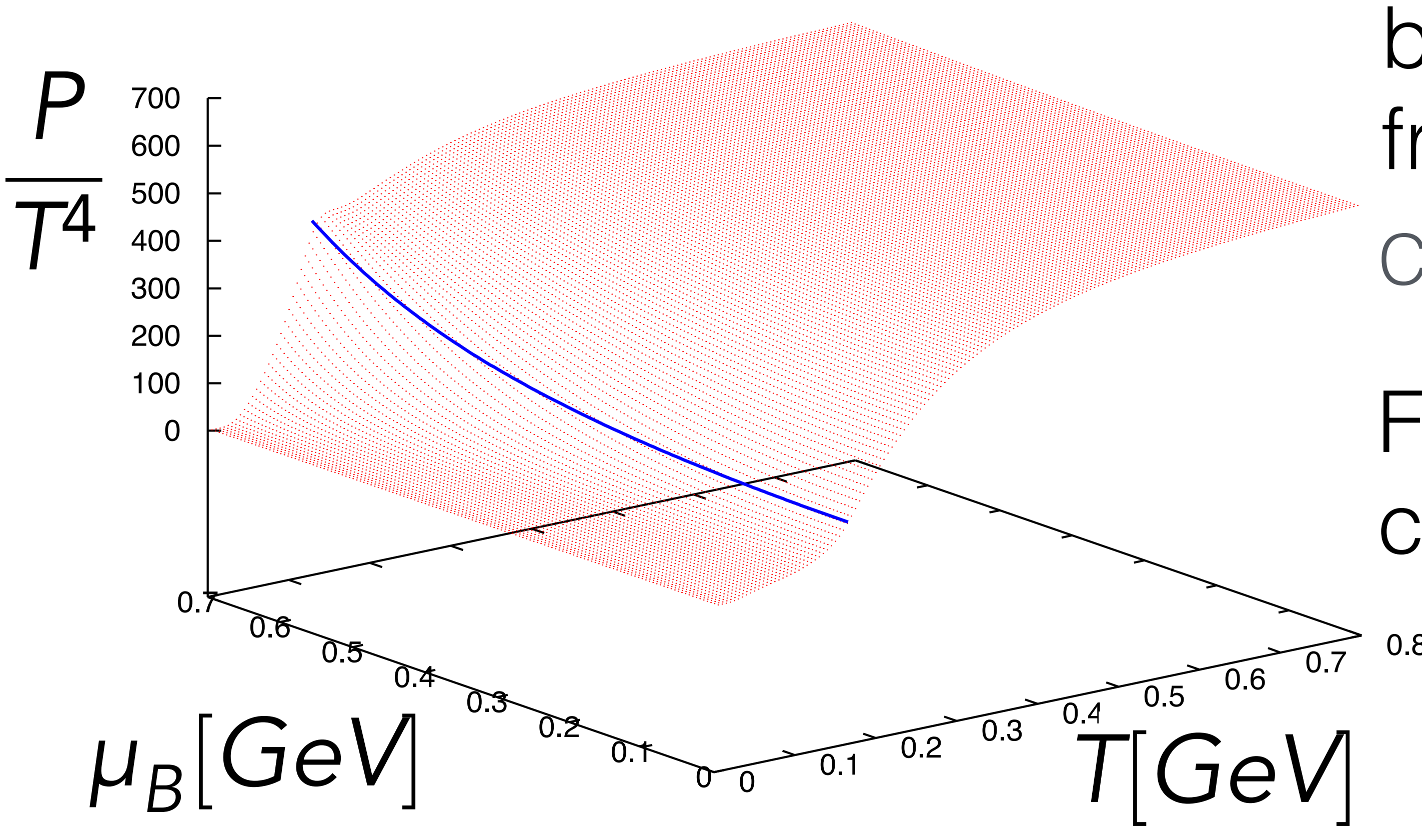
Constructing the equation of state (EoS)

Smooth matching (cross over)

As a first try, we match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\mathrm{HRG}}(T)}{T^4} + \frac{1}{2}\left[1 + \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\mathrm{lat}}(T_s)}{T_s^4}$$

$$T_C(\mu_B) = 0.166\mathrm{GeV} - c(0.139\mu_B^2 + 0.053\mu_B^4)$$



based on the chemical freeze-out line (c=1)

Cleymans et al, PRC73, 034905 (2006)

For the connecting line we use c=d=0.4, ΔT_C=0.1 $T_C(0)$

Constructing the equation of state (EoS)

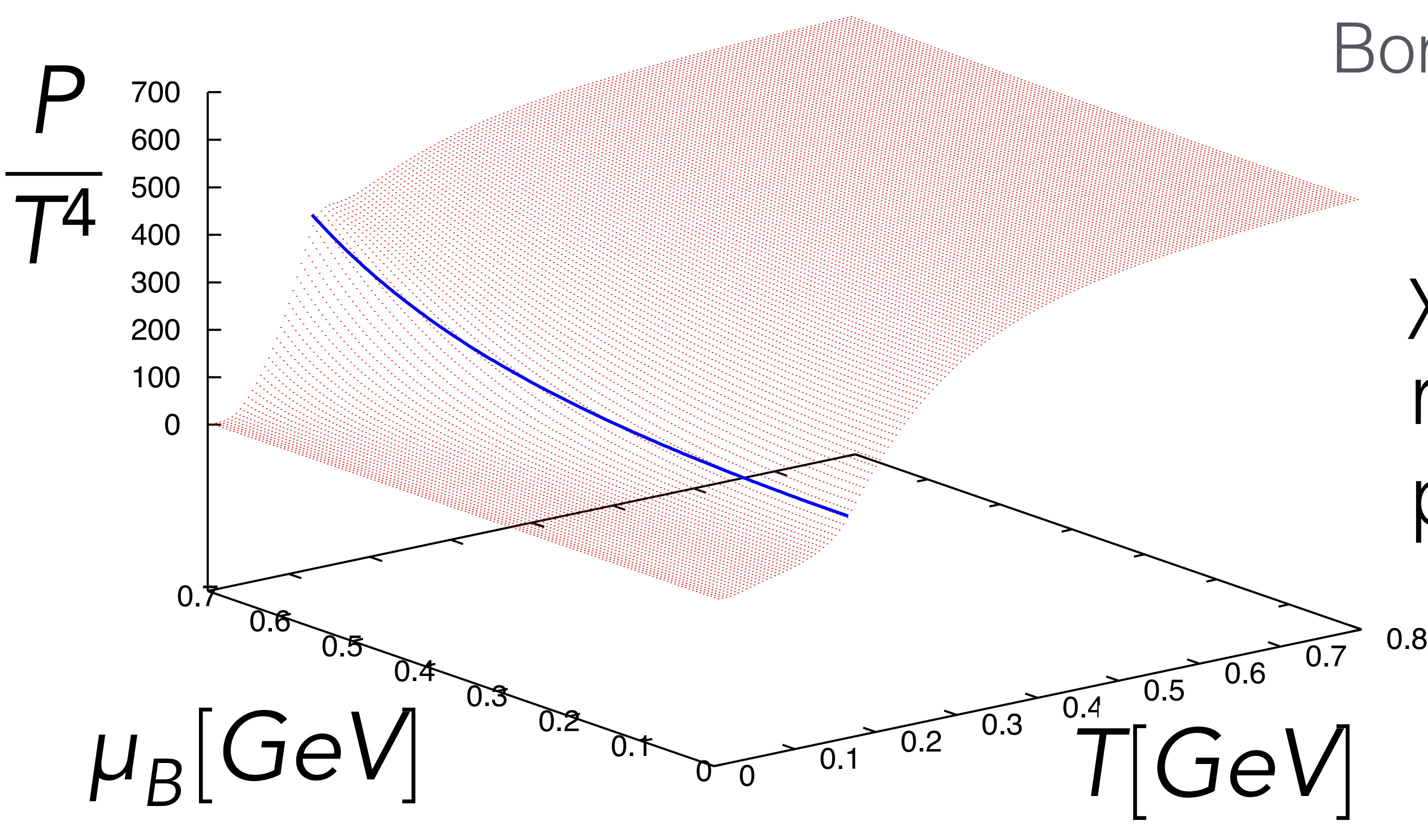
Smooth matching (cross over)

As a first try, we match the HRG and lattice EoS smoothly

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\rm HRG}(T)}{T^4} + \frac{1}{2}\left[1 + \tanh\frac{T - T_C(\mu_B)}{\Delta T_C}\right]\frac{P_{\rm lat}(T_s)}{T_s^4}$$

Parameters P_0^{lat} and $\chi_B^{(2)}$ are determined from the lattice:

Borsanyi et al, JHEP1011, 077 (2010)
Borsanyi et al, JHEP1201, 138 (2012)



$\chi_B^{(4)}$ is obtained from the ratio $\chi_B^{(4)}/\chi_B^{(2)}$ in a HRG and parton gas model

δf corrections in the presence of net baryons

A. Monnai, T. Hirano, PRC80, 054906 (2009); Nucl. Phys. A847, 283 (2010)

Grad's 14 moment method

$$\delta f^i = -f_0^i(1 \pm f_0^i)(b_i \varepsilon_\mu^B p_i^\mu + \varepsilon_{\mu\nu} p_i^\mu p_i^\nu)$$

4 10

particle i's baryon quantum number

ε_μ^B and $\varepsilon_{\mu\nu}$ are determined by the self-consistency conditions

$$\delta T^{\mu\nu} = \sum_i \int \frac{g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p_i^\nu \delta f^i = -\Pi \Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\delta N_B^\mu = \sum_i \int \frac{b_i g_i d^3p}{(2\pi)^3 E_i} p_i^\mu p_i^\nu \delta f^i = V_B^\mu$$

=0 (no baryon diffusion)

δf corrections in the presence of net baryons

A. Monnai, T. Hirano, PRC80, 054906 (2009); Nucl. Phys. A847, 283 (2010)

Grad's 14 moment method

$$\delta f^i = -f_0^i(1 \pm f_0^i)(b_i \varepsilon_\mu^B p_i^\mu + \varepsilon_{\mu\nu} p_i^\mu p_i^\nu)$$

After tensor decomposition and one finds

$$\varepsilon_\mu^B = D_\Pi \Pi u_\mu$$

$$\varepsilon_{\mu\nu} = (B_\Pi \Delta_{\mu\nu} + \tilde{B}_\Pi u_\mu u_\nu)\Pi + B_\pi \pi_{\mu\nu}$$

where the coefficients are computed in kinetic theory

We parametrize them as functions of T and μ_B

Note: Results of net baryon density are very sensitive to accuracy of the bulk-δf parametrization

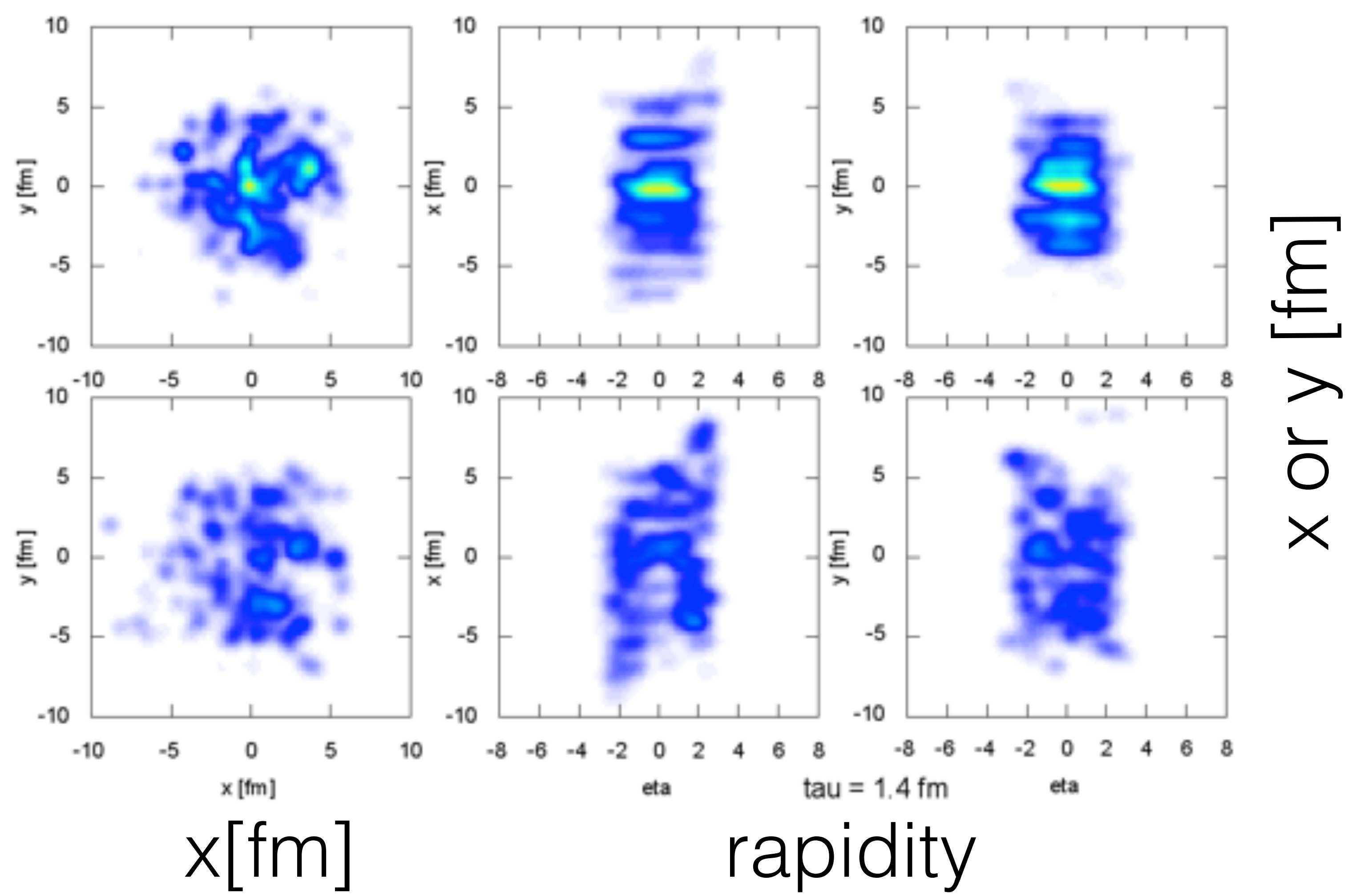
Event-by-event baryon- and entropy density

Deposit entropy density (fluctuating with NBD) between the collided constituent quarks using a Gaussian profile in the transverse plane and a constant distribution (with Gaussian edges) in rapidity

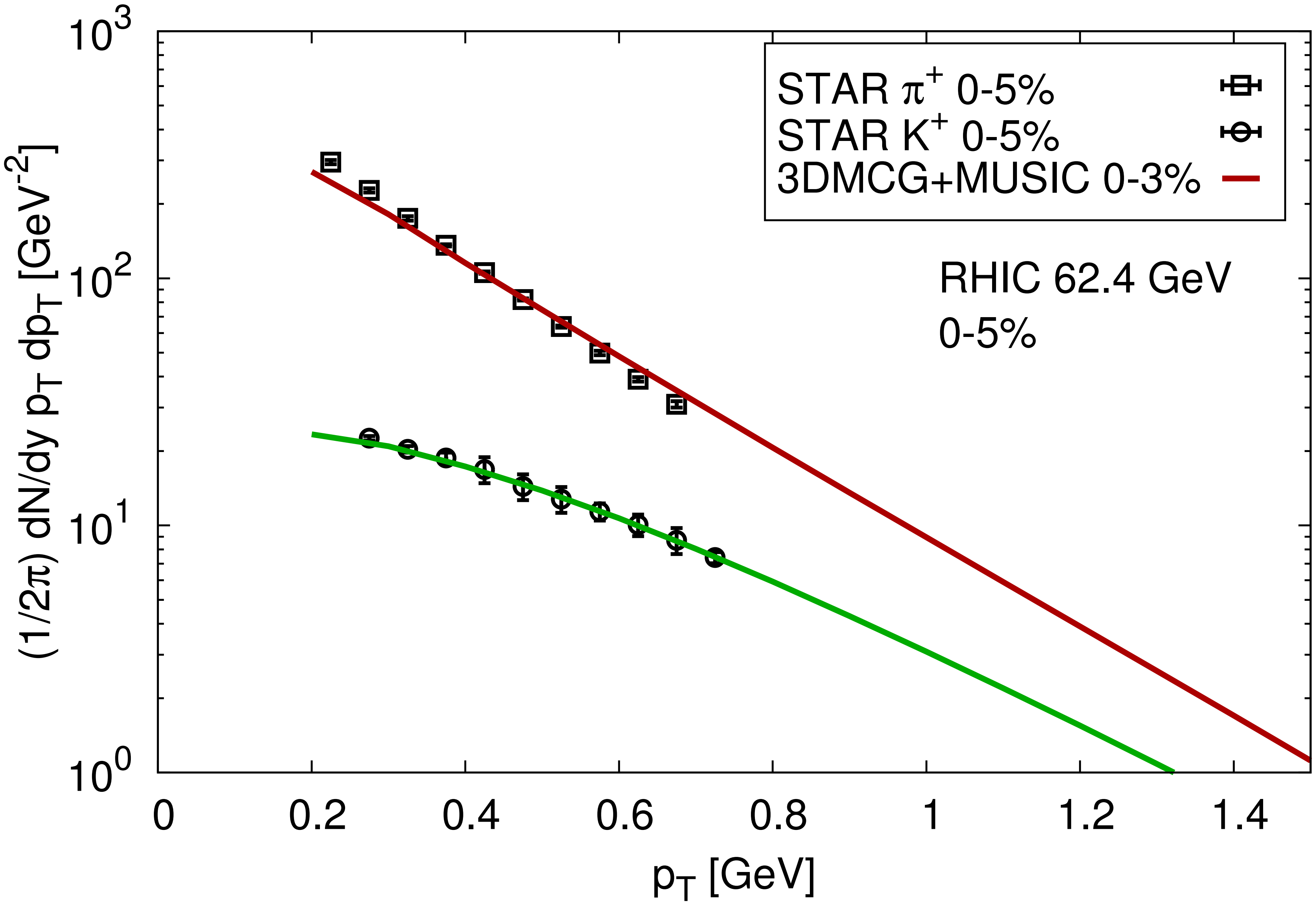
$\sqrt{s} = 19.6\mathrm{GeV}$

energy density

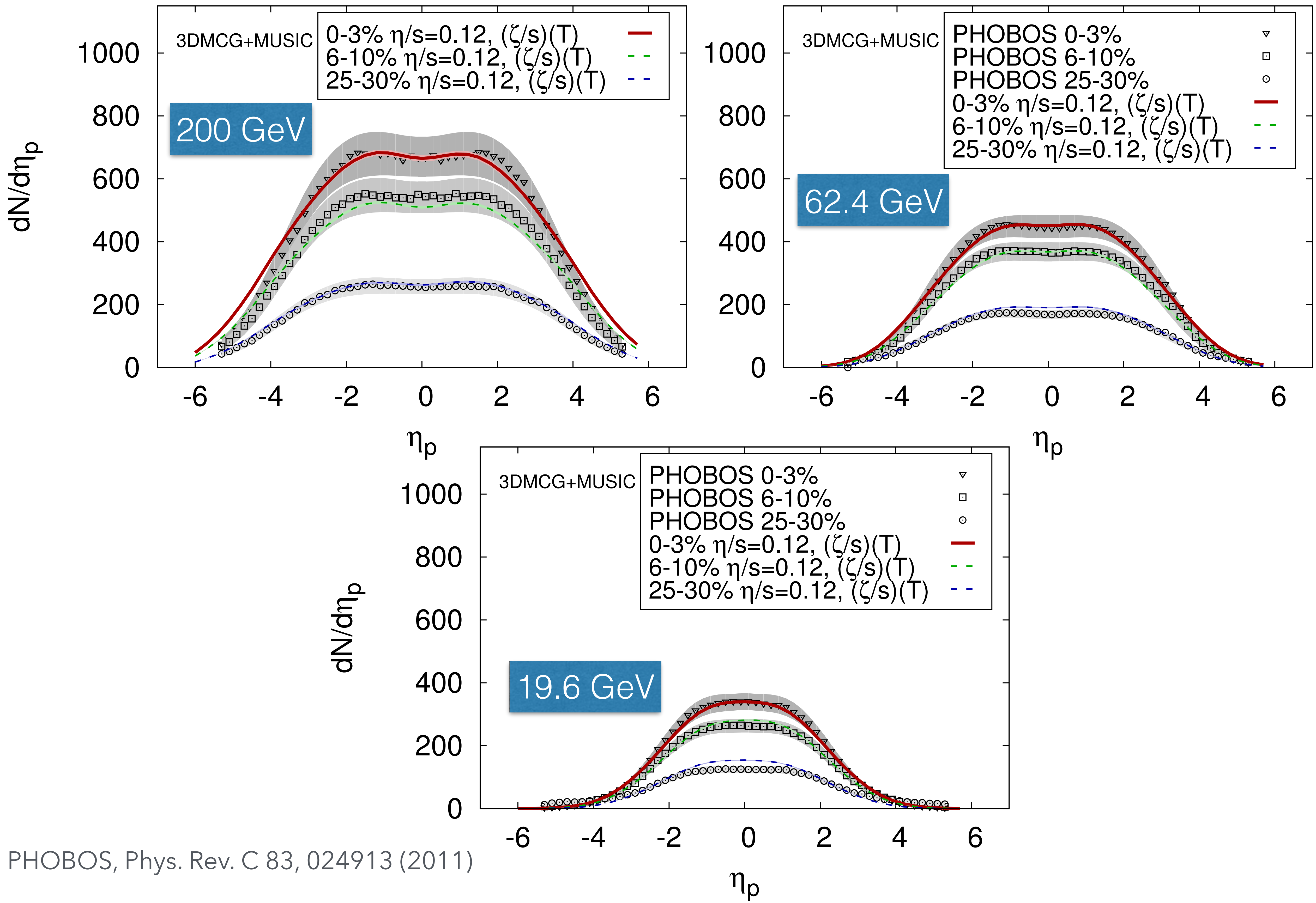
baryon density



Transverse momentum spectra at 62.4 GeV

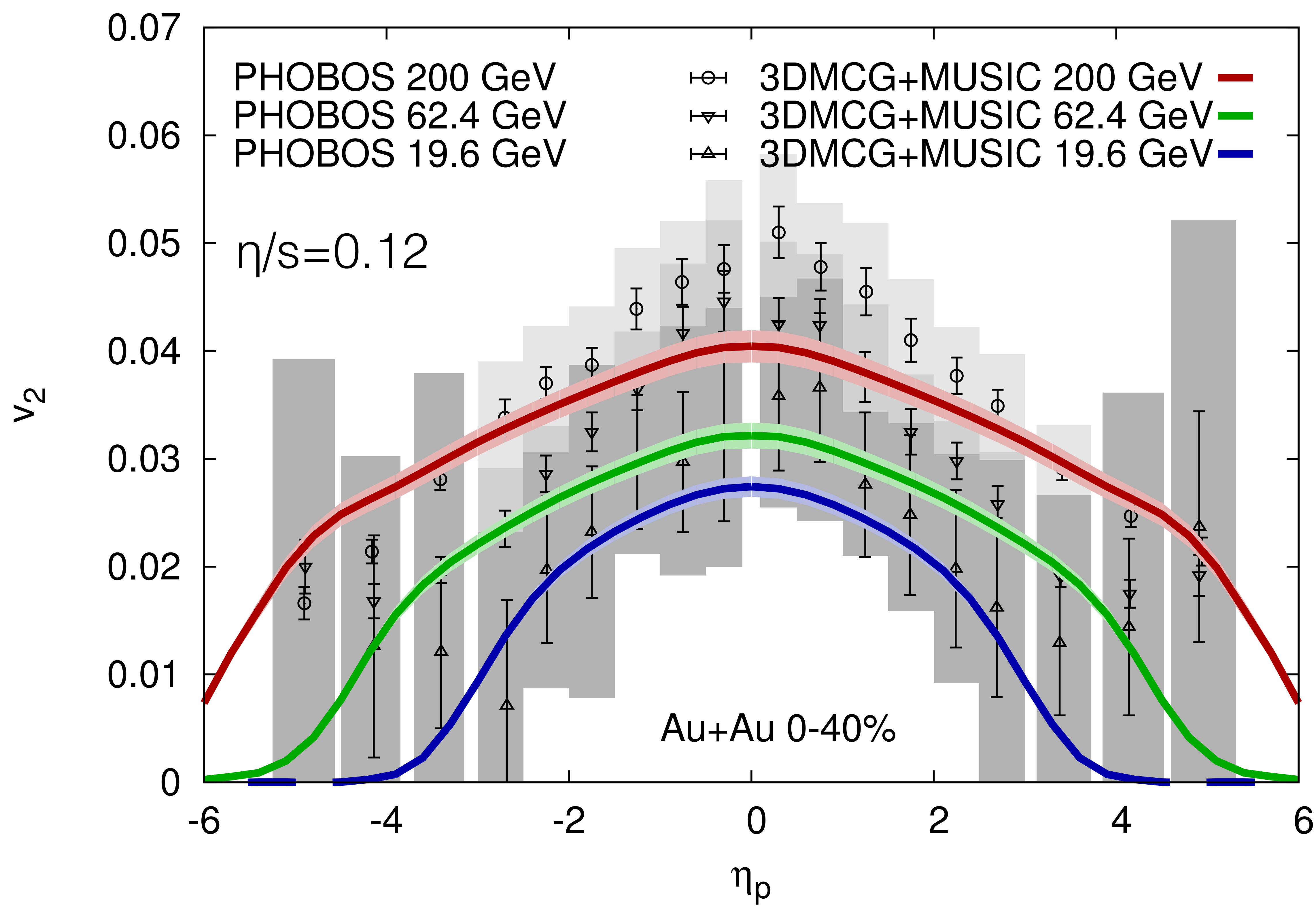


Charged hadron pseudo-rapidity distributions



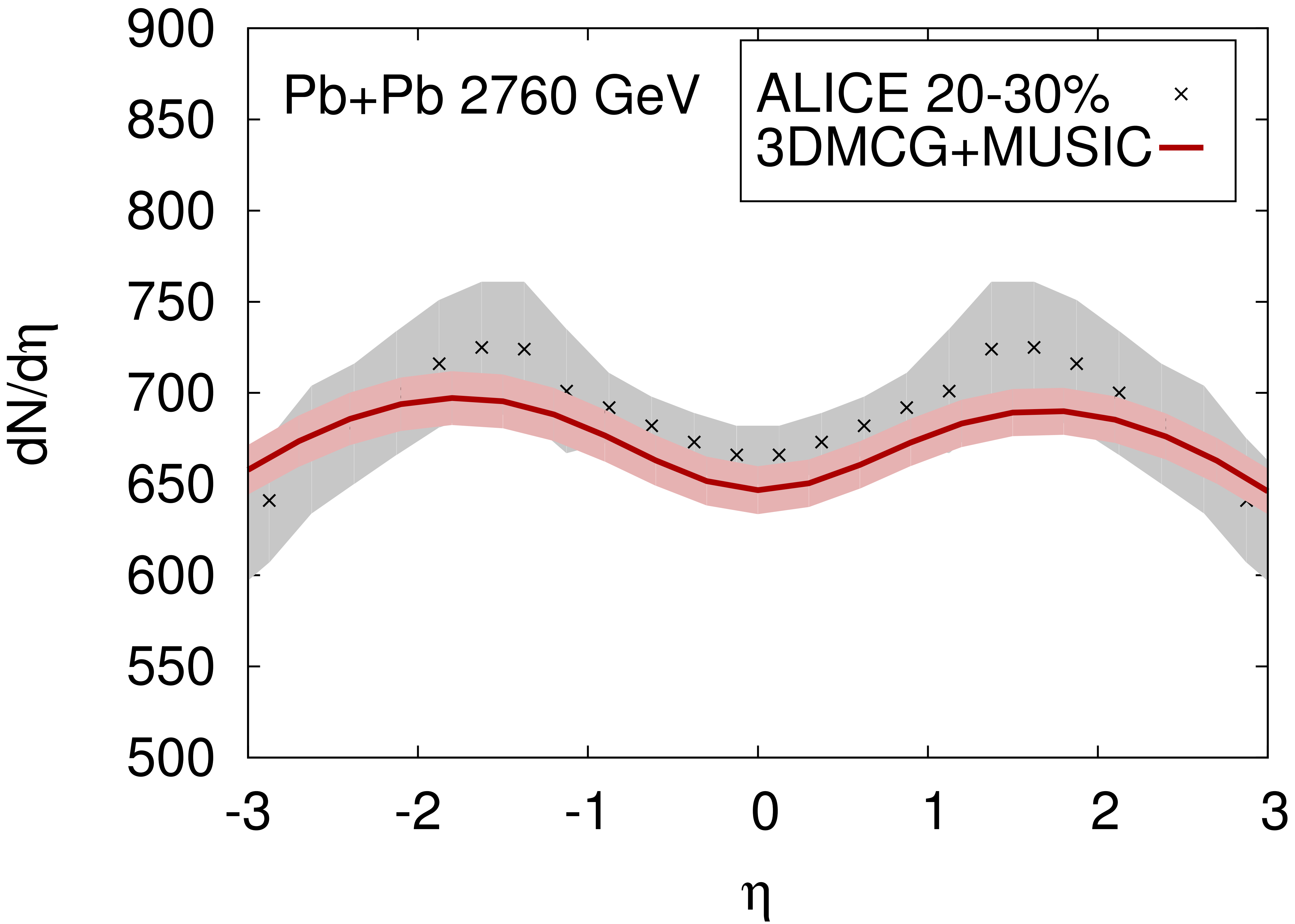
PHOBOS, Phys. Rev. C 83, 024913 (2011)

v_2 vs pseudo-rapidity at different energies

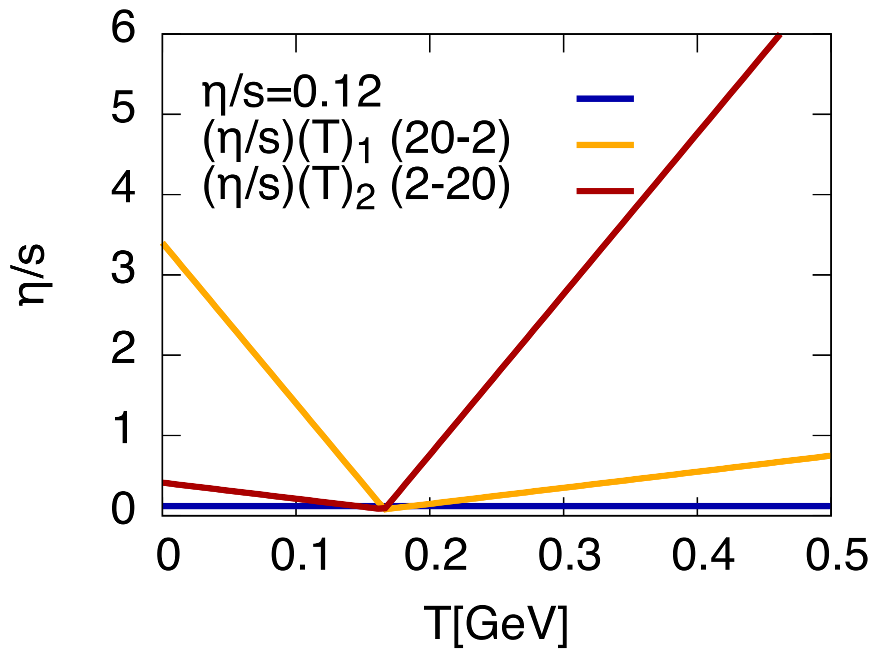


PHOBOS, Phys. Rev. Lett. 94, 122303 (2005)

Pb+Pb 2760 GeV pseudo-rapidity distribution



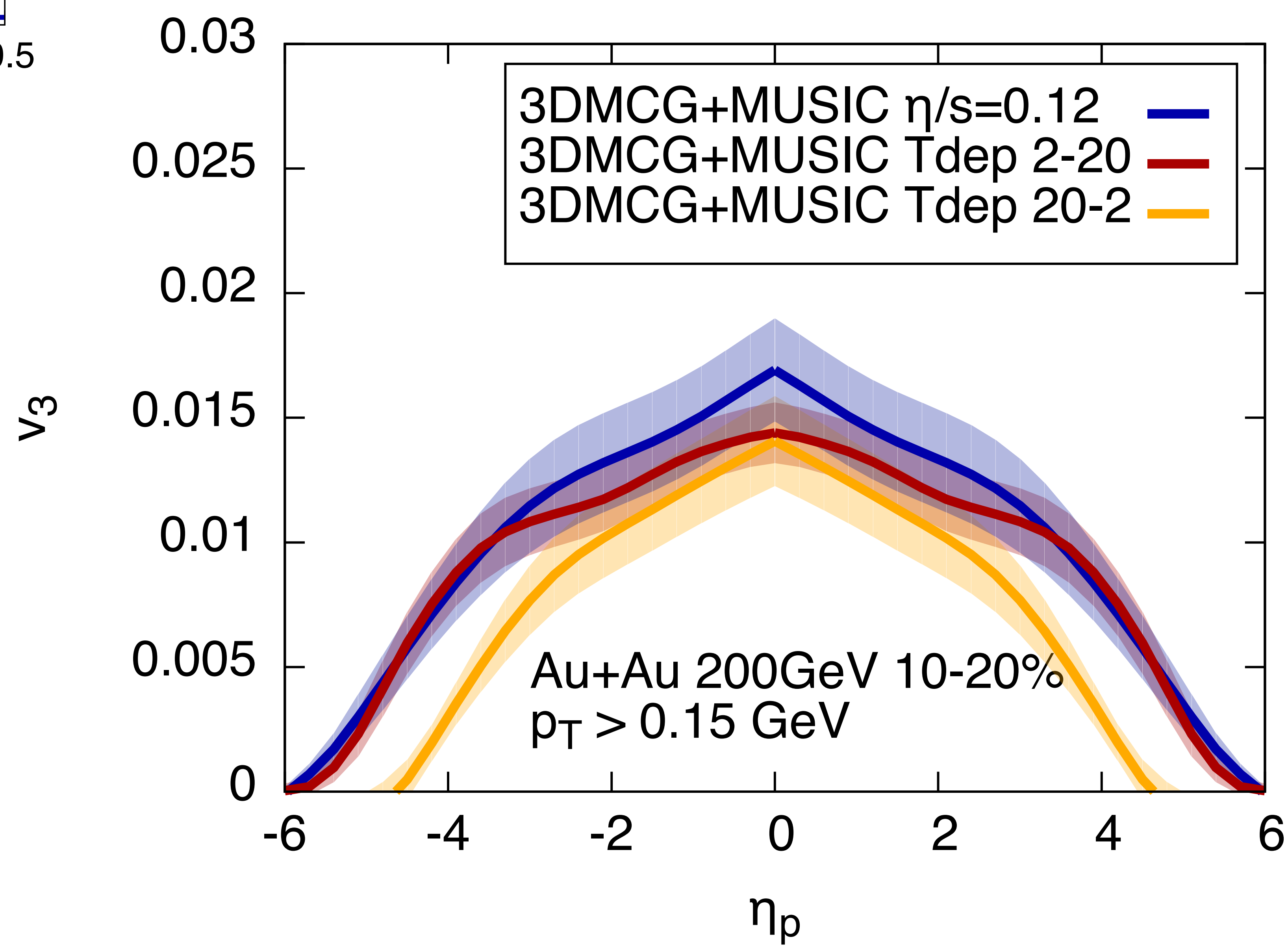
T dependent η/s from rapidity dependence



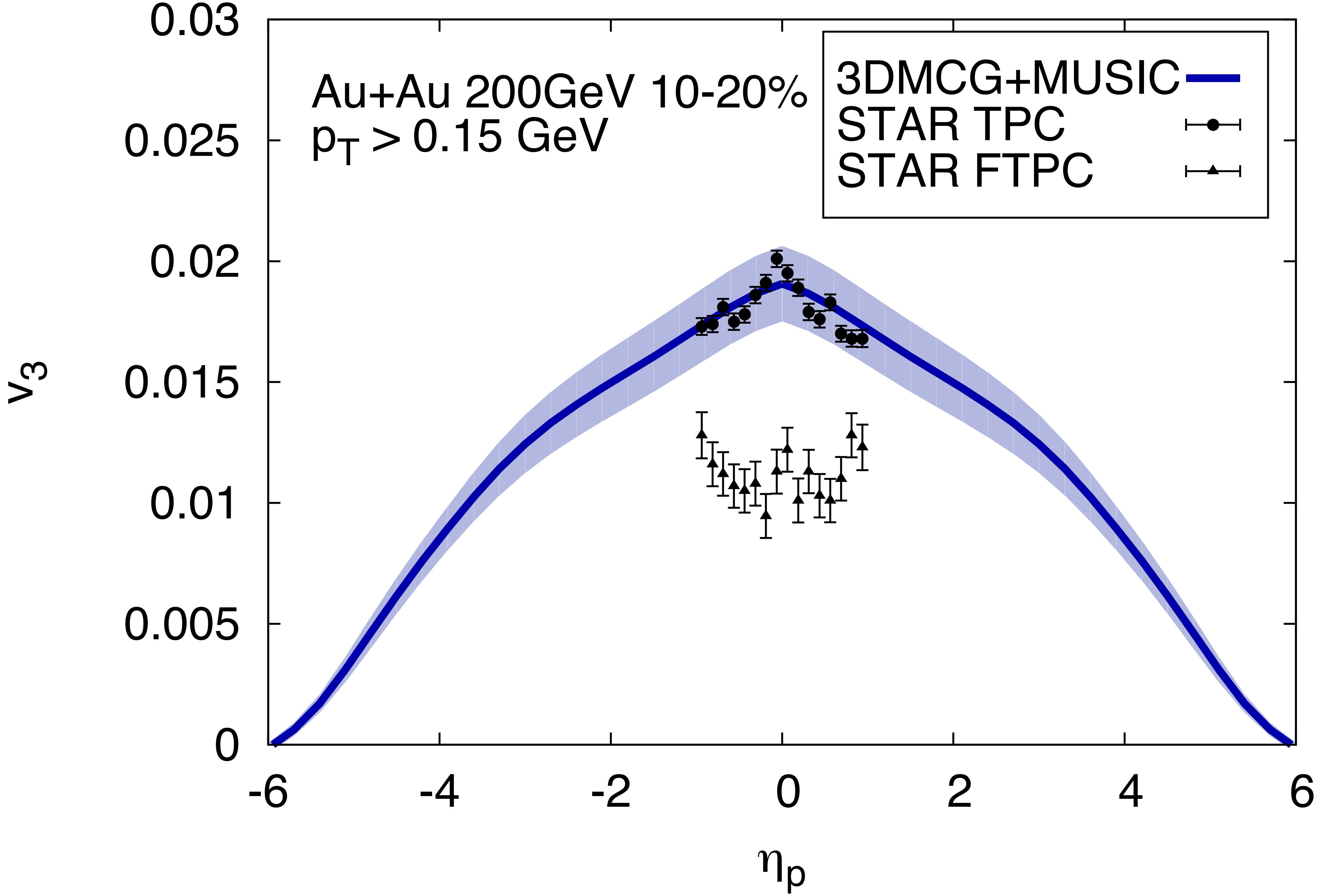
Numbers (a,b) are the slopes in [GeV^{-1}] in:

$$(\eta T/(\varepsilon + P))(T) = 0.08 + a(T_c - T)\theta(T_c - T) + b(T - T_c)\theta(T - T_c)$$

where $T_c(\mu_B)$



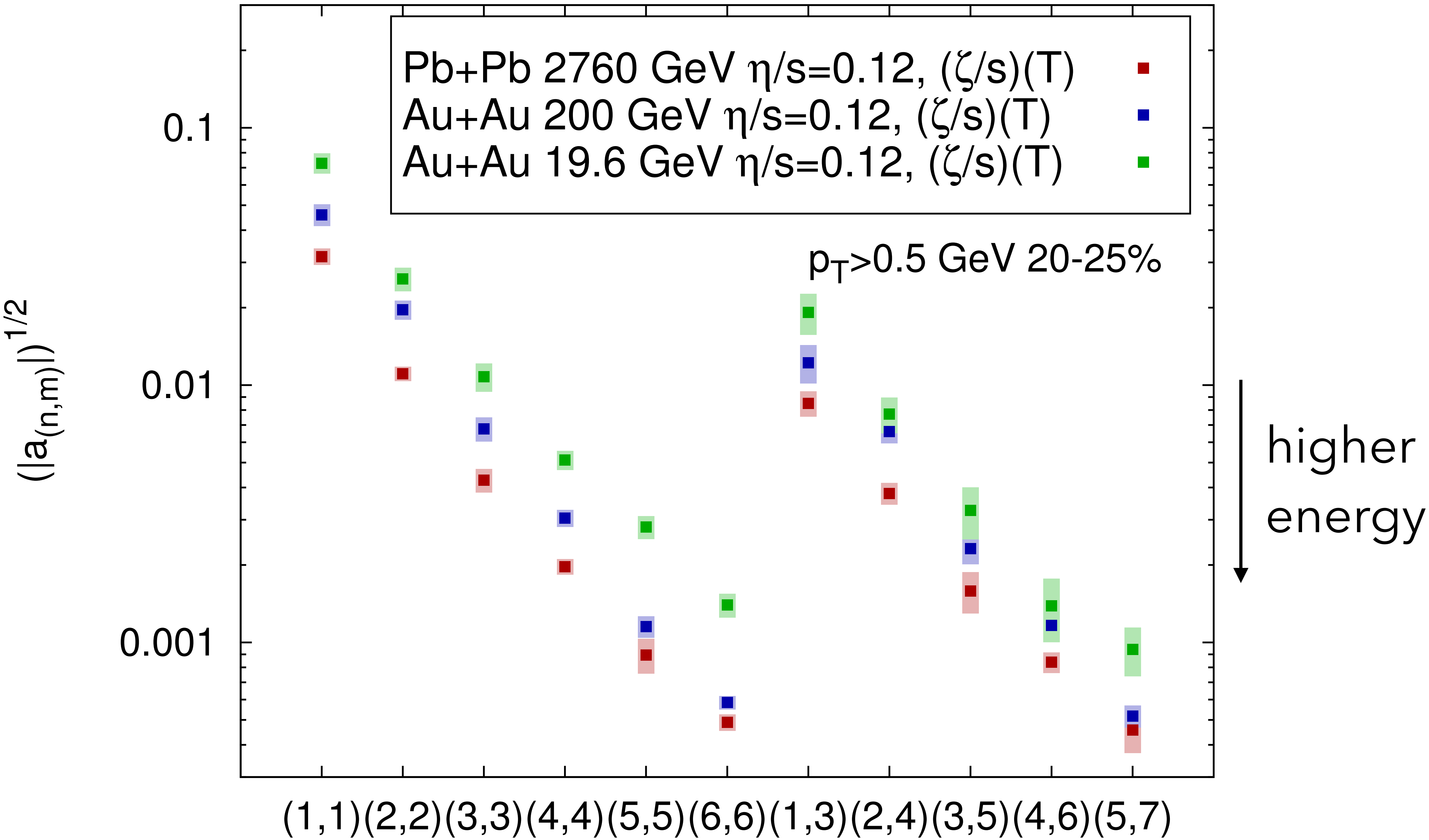
Pseudo-rapidity dependent flow



STAR Collaboration, Phys. Rev. C88, 014904 (2013)

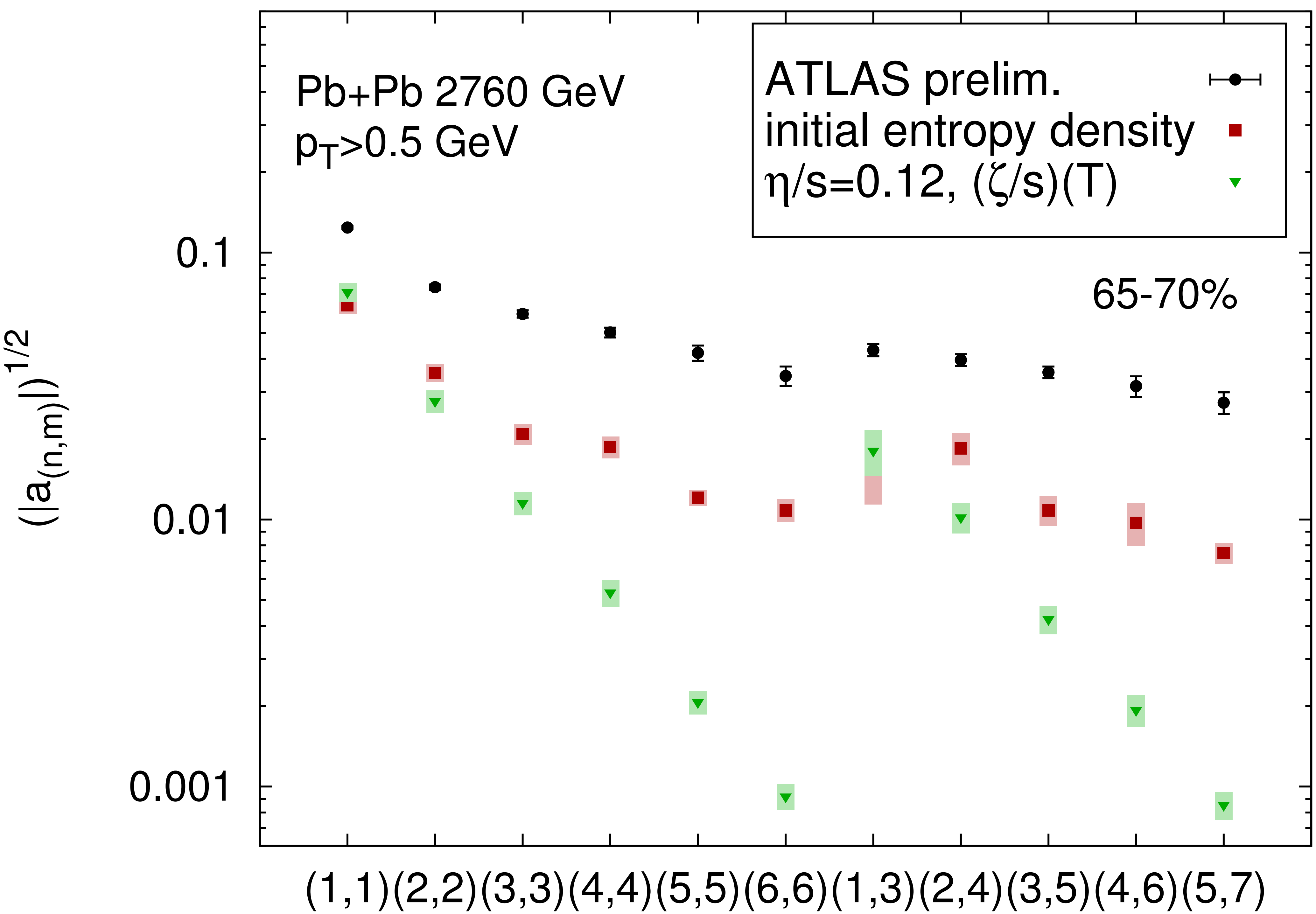
Collision energy dependence

A. Monnai, B. Schenke, arXiv:1509.04103



Two-particle pseudo-rapidity correlations

A. Monnai, B. Schenke, arXiv:1509.04103



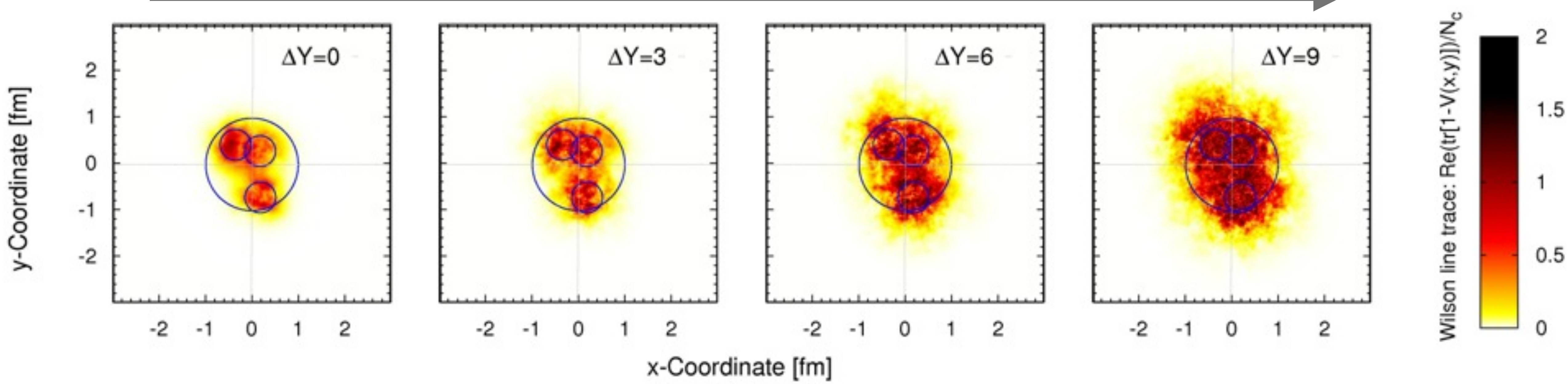
Experimental data: ATLAS-CONF-2015-020

IP-Glasma+JIMWLK

- Then combine all slices in rapidity to make 3D initial condition for hydrodynamics

- *What needs to be done before all that:*
  Constrain parameters (in particular running coupling) in JIMWLK-Glasma calculation using DIS data just like in IP-Glasma

JIMWLK evolution: decreasing *x*



S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)