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Initial State of Heavy Ion Collisions

Björn Schenke, Brookhaven National Laboratory

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Overview

- IP-Glasma and EKRT
- TRENTO
- 3D TRENTO
- 3D Dynamical String Model
- 3D-Glasma
- A word on strong coupling models

IP-Glasma initial state

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Initial state from an effective field theory of QCD

- Limit of high energy and high parton density
- Weak coupling limit but strongly interacting
- Non-linear effects:
  Gluon saturation at $p_T \lesssim Q_s(x, \vec{b})$
- Occupation # $\sim 1/\alpha_s$
  →Classical: Solve Yang-Mills equations!
- Leading quantum corrections can be included via small-x evolution (JIMWLK, BK)

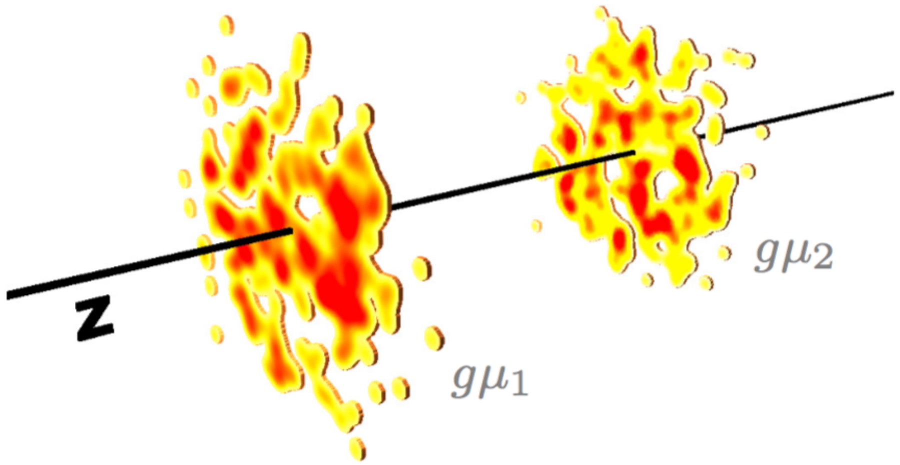
F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan
Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489 and references therein

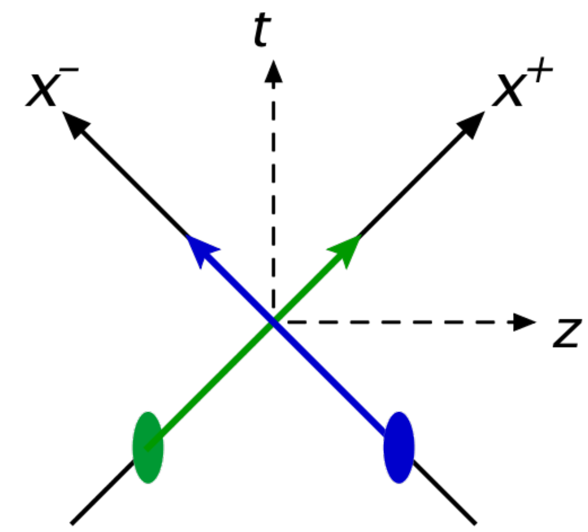
IP-Glasma initial state

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Particle production governed by the **Yang Mills equations**

$$[D_\mu, F^{\mu\nu}] = J^\nu$$





First determine incoming currents J^ν:

- IP-Sat model: Parametrize energy and spatial dependence of deep inelastic cross section - fit parameters to HERA e+p data
  Kowalski, Teaney, Phys.Rev. D68 (2003) 114005
  → energy and position dependent saturation scale $Q_s(x, \vec{b})$

- Sample nucleons and color charges $\rho(\vec{b})$ from local Gaussian with variance $g^2\mu^2(x, \vec{b}) \propto Q_s^2(x, \vec{b})$

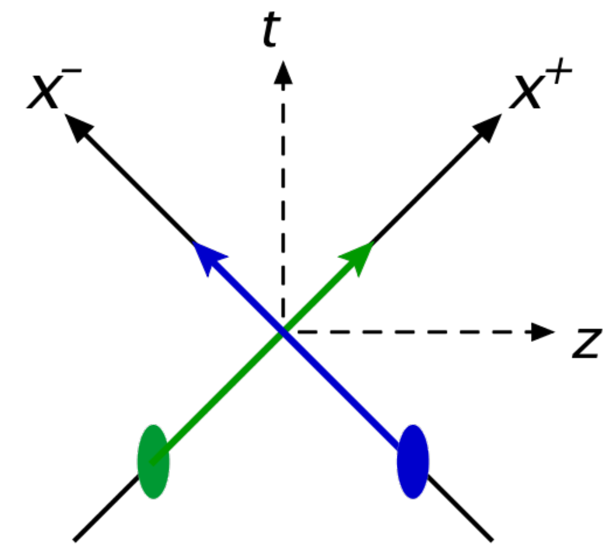
IP-Glasma initial state

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Then compute incoming gluon fields using currents J^ν:

$$J_1^\mu = \delta^{\mu +}\rho_1(x^-, \mathbf{x}_T)$$

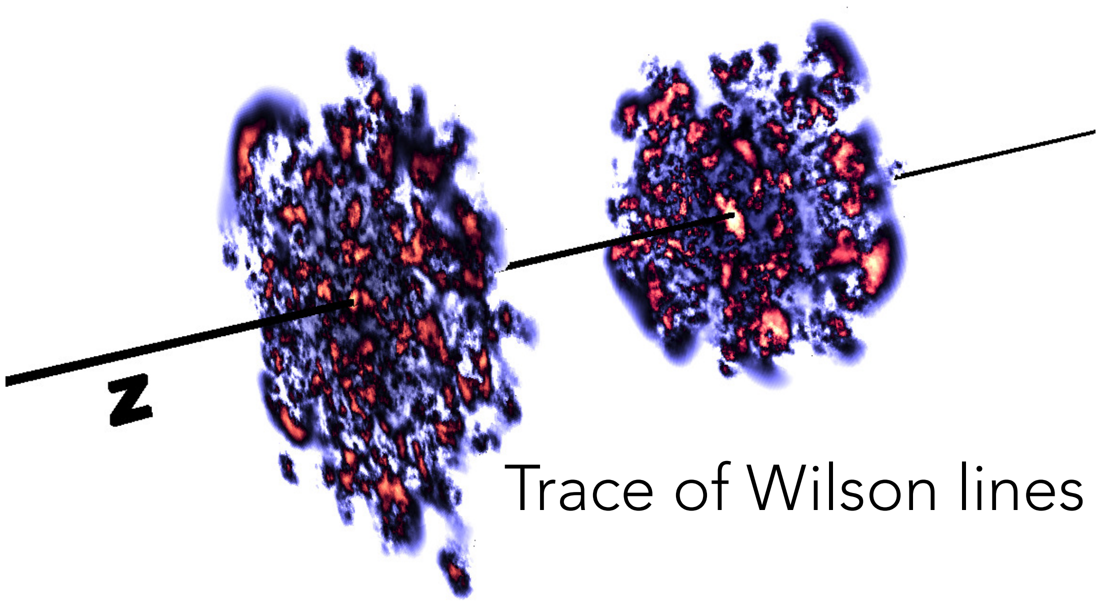
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$



$$J_2^\mu = \delta^{\mu -}\rho_2(x^+, \mathbf{x}_T)$$

$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

Solve Yang-Mills equations for the gauge fields in the incoming nuclei



Fluctuations from nucleon positions and color charges

IP-Glasma initial state

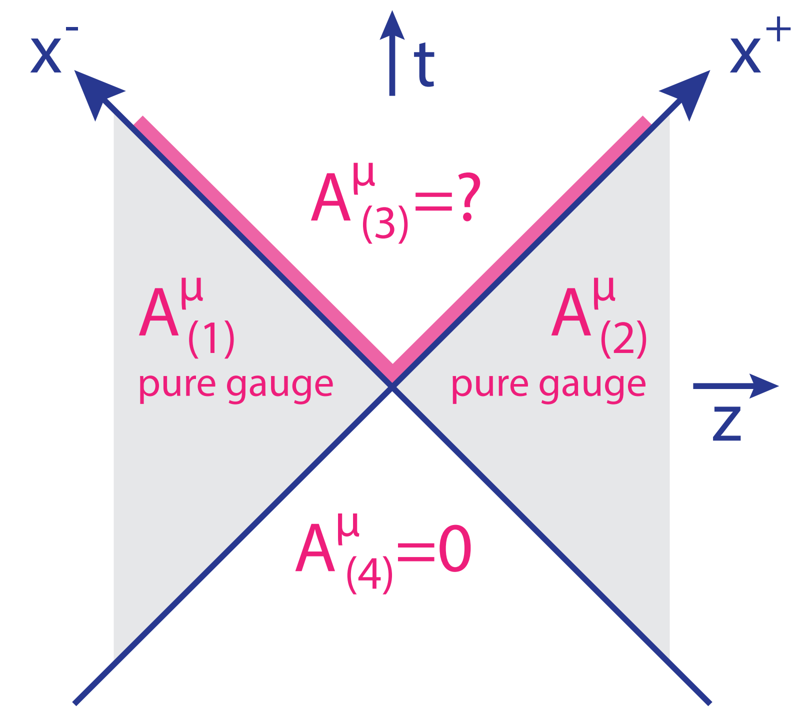
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Solutions in light cone gauge:

$$A^{+}_{(1,2)}(\vec{b}) = A^{-}_{(1,2)}(\vec{b}) = 0$$

$$A^{i}_{(1,2)}(\vec{b}) = \theta(x^{-,+})\frac{i}{g}V_{(1,2)}(\vec{b})\partial_i V^{\dagger}_{(1,2)}(\vec{b})$$

where $V_{(1,2)}(\vec{b}) = P\exp\left(-ig\int dx^{-}\frac{\rho_{(1,2)}(x^{-},\vec{b})}{\nabla_{\perp}^{2}+m^{2}}\right)$



Finally compute gluon fields in the forward light-cone:

$$A^{i}_{(3)}|_{\tau=0^{+}} = A^{i}_{(1)} + A^{i}_{(2)}$$

$$A^{\eta}_{(3)}|_{\tau=0^{+}} = \frac{ig}{2}[A^{i}_{(1)}, A^{i}_{(2)}]$$

Then evolve in time according to source-free Yang-Mills equations

Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

IP-Glasma initial state

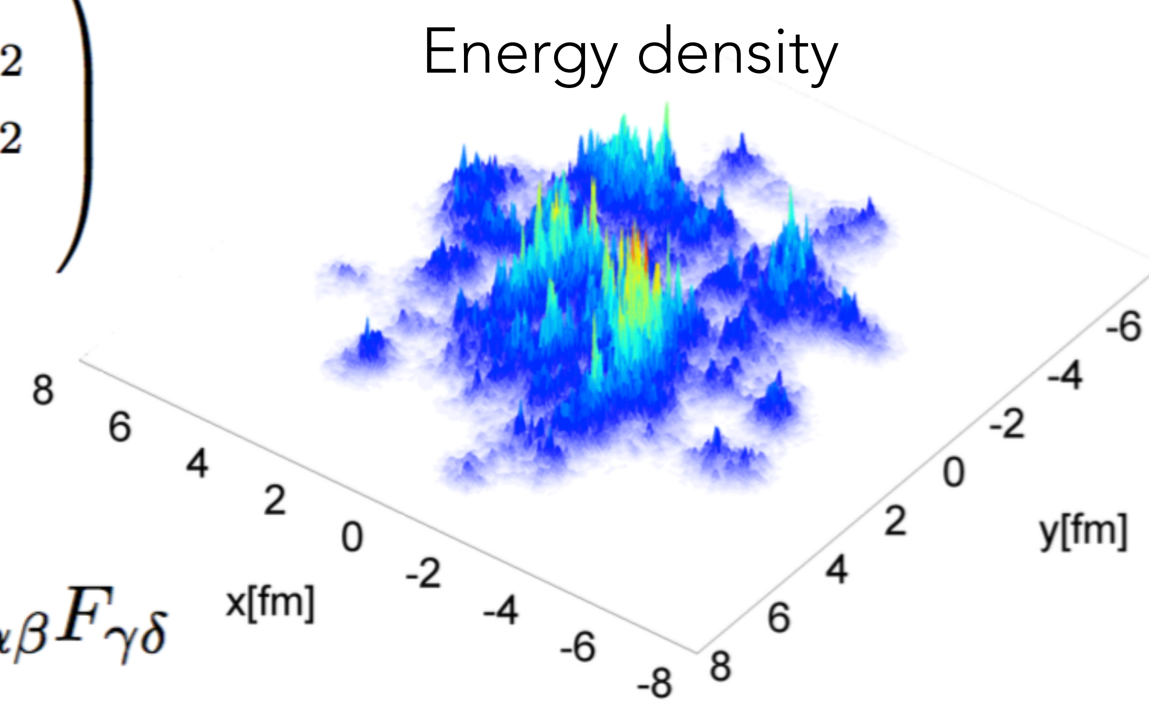
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Energy momentum tensor at every transverse position:

$$\phi = A_\eta\,, \qquad \pi = E^\eta$$

$$E_i = -\tau\partial_\tau A_i\,, \qquad E_\eta = -\tau\partial_\tau A_\eta$$

$$F^{\mu\nu} = \begin{pmatrix} 0 & -E^x/\tau & -E^y/\tau & -\pi/\tau \\ E^x/\tau & 0 & F^{xy} & (D_x\phi)/\tau^2 \\ E^y/\tau & F^{yx} & 0 & (D_y\phi)/\tau^2 \\ \pi/\tau & -(D_x\phi)/\tau^2 & -(D_y\phi)/\tau^2 & 0 \end{pmatrix}$$



$$T^{\mu\nu} = -g^{\mu\alpha}g^{\nu\beta}g^{\gamma\delta}F_{\alpha\gamma}F_{\beta\delta} + \frac{1}{4}g^{\mu\nu}g^{\alpha\gamma}g^{\beta\delta}F_{\alpha\beta}F_{\gamma\delta}$$

Solve eigenvalue problem $u_\mu T^{\mu\nu} = \varepsilon u^\nu$

to obtain energy density and flow velocities

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

EKRT initial state

K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000)
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 024907
H. Niemi, K. J. Eskola, R. Paatelainen, K. Tuominen, Phys.Rev. C93 (2016) 014912

NLO-improved pQCD + saturation

Compute minijet (=gluons, $p_T > p_0$ - a few GeV) E_T production in A+A, using NLO perturbative QCD + saturation conjecture

$$\frac{dE_T(p_0, \sqrt{s}, \Delta y, \vec{s}, \vec{b})}{d^2\vec{s}} = T_A(\vec{s} + \vec{b}/2) T_B(\vec{s} - \vec{b}/2) \sigma \langle E_T \rangle_{p_0, \Delta y}$$

T_A , T_B: nuclear thickness functions $T_A(\vec{r}) = \int_{-\infty}^{\infty} dz \rho_A(\vec{r}, z)$

$\sigma \langle E_T \rangle_{p_0, \Delta y}$: First moment of the mini-jet E_T distribution in NLO:

$$\sigma \langle E_T \rangle_{p_0, \Delta y} = \int_0^{\sqrt{s}} dE_T E_T \frac{d\sigma}{dE_T}\bigg|_{p_0, \Delta y}$$

EKRT initial state

K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000)
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 024907
H. Niemi, K. J. Eskola, R. Paatelainen, K. Tuominen, Phys.Rev. C93 (2016) 014912

Semi-inclusive E_T distribution of minijets in a rapidity interval Δy in N+N collisions:

phase-space measure

$$\left.\frac{d\sigma}{dE_T}\right|_{p_0,\Delta y} = \sum_{n=2}^{3} \frac{1}{n!} \int d[PS]_n \frac{d\sigma^{2\to n}}{d[PS]_n} S_n$$

differential NLO partonic cross sections
PDFs (NLO, MSbar scheme) and squared
spin- and color-summed/averaged matrix elements

IR/CL safe measurement functions S_2 & S_3
to define the mini-jet E_T in NLO

EKRT initial state

K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000)
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 024907
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Soft gluon production controlled by saturation of mini-jet production:

$$\frac{dE_T}{d^2\vec{r}dy}(3 \to 2) \sim \frac{dE_T}{d^2\vec{r}dy}(2 \to 2)$$

It follows for the gluon density at saturation (g = gluon PDF):

$$T_A g \sim p_0^2/\alpha_s$$

This can be written as the transversally local saturation criterion

$$\frac{dE_T}{d^2\vec{r}}(p_0, \sqrt{s}, A, \Delta y, \vec{r}, \vec{b}) = \frac{K_{\rm sat}}{\pi} p_0^3 \Delta y$$

The saturation scale p_{sat} is p_0 that solves above equation
$K_{\rm sat} \sim 1$ is a constant to be determined from data centrality dep.

EKRT initial state

K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000)
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 024907
H. Niemi, K. J. Eskola, R. Paatelainen, K. Tuominen, Phys.Rev. C93 (2016) 014912

Event by event implementation:

1) Use that NLO K-factor does not depend on the PDFs and employ:

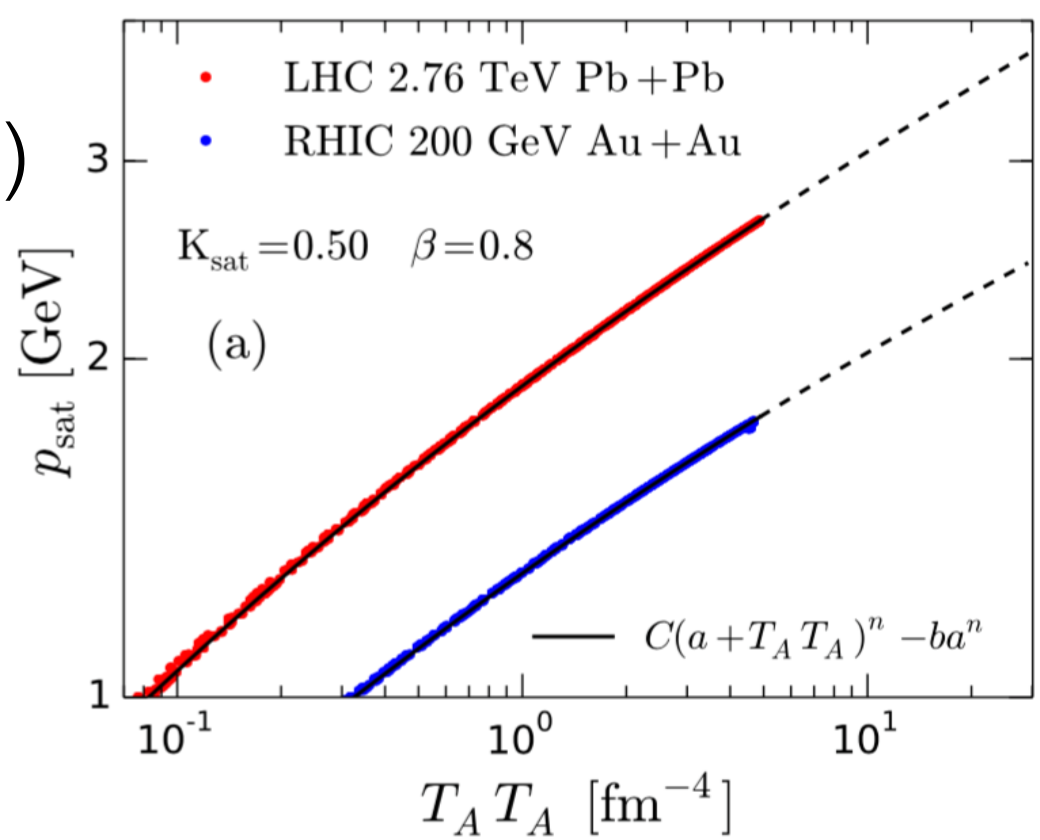
$$\sigma\langle E_T\rangle_{p_0,\Delta y,\beta}(\text{NLO,EPS09s}) \approx \sigma\langle E_T\rangle_{p_0,\Delta y,\beta}(\text{LO,EPS09s})\times K$$

2) Use that local saturation scale $p_{sat}(x,y)$ is only a function of $T_A T_B$ for a given system and energy (b-indep.)

In the naive scaling limit

$$p_{\rm sat}^2 \sim \sqrt{T_A T_B}$$

but corrections to the power 1/2 come from x– and Q^2-slopes of the small-x gluon distribution, phase-space integration and running of α_s



EKRT initial state

K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000)
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 024907
H. Niemi, K. J. Eskola, R. Paatelainen, K. Tuominen, Phys.Rev. C93 (2016) 014912

that n is a bid odd - does not go to 1 at small T_A

Energy density initialization:

Transverse profile of energy density at time τ_s=1/p_{sat} is given by

$$e(\vec{r}, \tau_s(\vec{r})) = \frac{dE_T}{d^2\vec{r}} \frac{1}{\tau_s(\vec{r})\Delta y} = \frac{K_{\rm sat}}{\pi} p^4_{\rm sat}(\vec{r})$$

All points are evolved to the maximal time τ=0.2 fm using Bjorken hydrodynamic scaling

At the edges, where pQCD is not applicable, one smoothly connects to the binary collision profile, given by

$$e = C(T_A T_B)^n \quad \text{with} \quad n = \frac{1}{2}\left[(k+1) + (k-1)\tanh\left(\frac{\sigma_{NN} T_A T_B - g}{\delta}\right)\right]$$

$$g = \delta = 0.5 fm^{-2}$$

TRENTo

Available for download at:
https://github.com/Duke-QCD/trento

J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C 92, 011901 (2015)

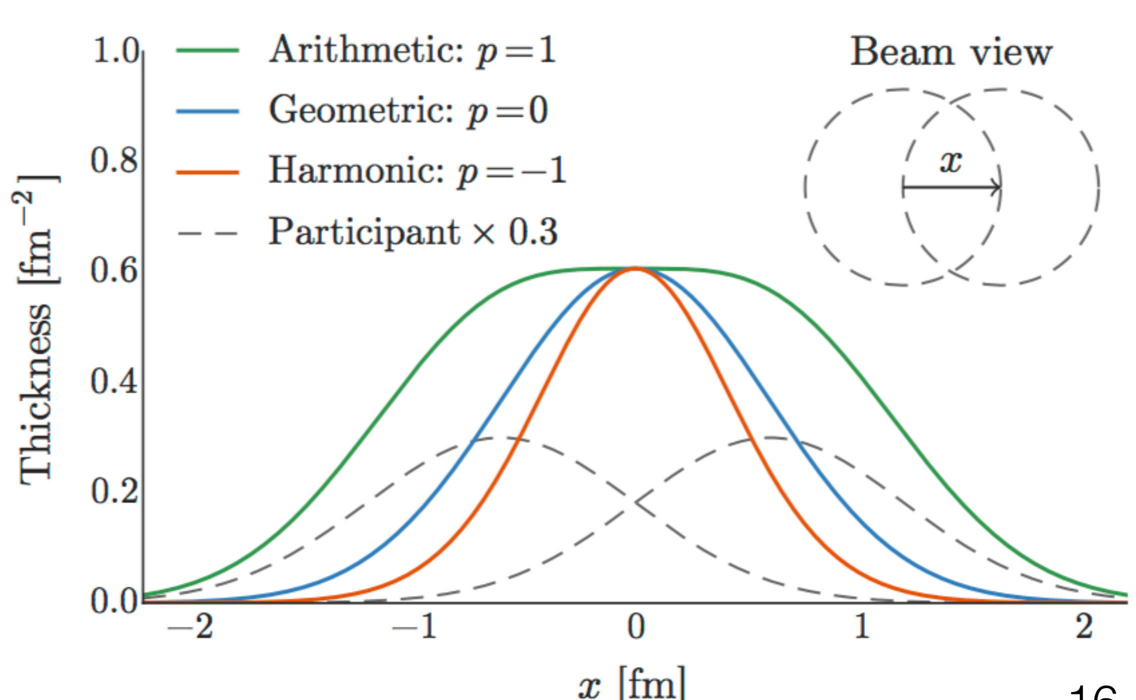
Model assumption based on observation**:**
N one-on-one nucleon collisions produce the same amount of entropy as a single N-on-N collision

It follows $f(cT_A, cT_B) = c\, f(T_A, T_B)$
where *f* is a function proportional to the entropy

Ansatz: Entropy density proportional to **generalized mean** of nuclear density

$$f = T_R(p; T_A, T_B) \equiv \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$$

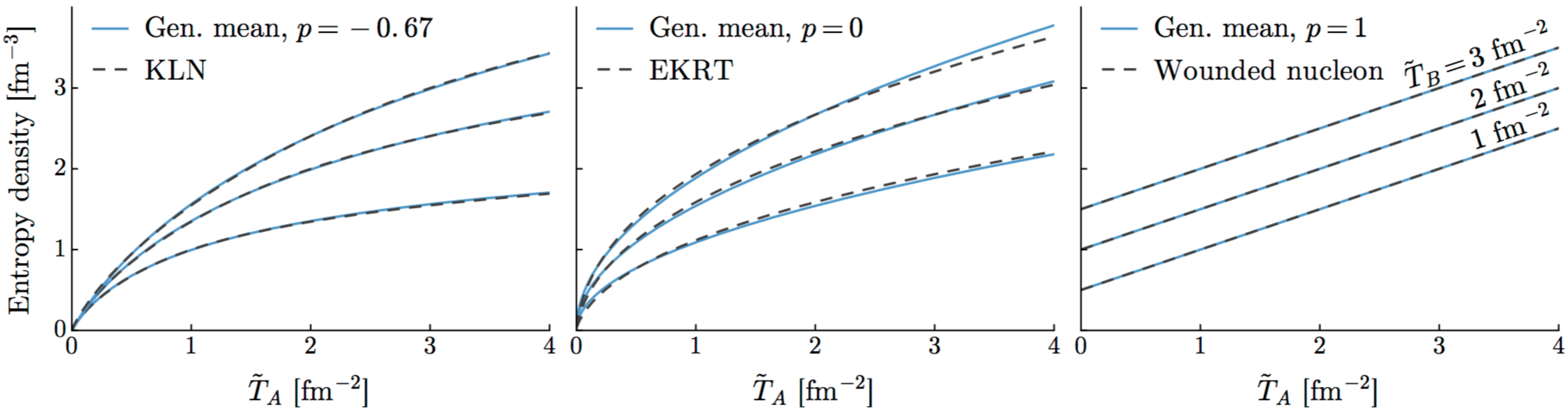
$$T_R = \begin{cases} \max(T_A, T_B) & p \to +\infty, \\ (T_A + T_B)/2 & p = +1, \quad \text{(arithmetic)} \\ \sqrt{T_A T_B} & p = 0, \quad \text{(geometric)} \\ 2\, T_A T_B / (T_A + T_B) & p = -1, \quad \text{(harmonic)} \\ \min(T_A, T_B) & p \to -\infty. \end{cases}$$



TRENTo

J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C 92, 011901 (2015)

Entropy density:



Observation:

p=0 reproduces EKRT results best - not obvious from EKRT

p=-0.67 reproduces KLN

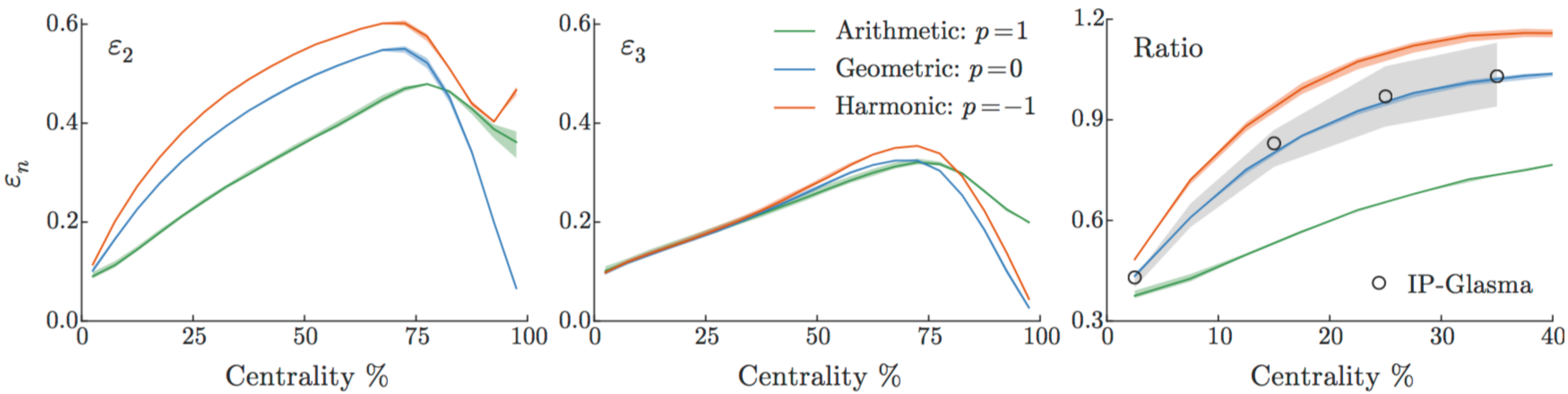
p=1 is the wounded nucleon model

Available for download at:
https://github.com/Duke-QCD/trento

TRENTo

J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C 92, 011901 (2015)

Eccentricities:



Observation: p=0 reproduces IP-Glasma eccentricities.

Trento will not reproduce all of IP-Glasma's features like fluctuations, e.g. multiplicity fluctuations

Available for download at:
https://github.com/Duke-QCD/trento

TRENTo

J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C 92, 011901 (2015)

- Bayesian analysis which finds the best parameter set to describe a selected set of experimental data yields a best fit value for the parameter p~0, compatible with EKRT and IP-Glasma results

Slide from J. Bernhard

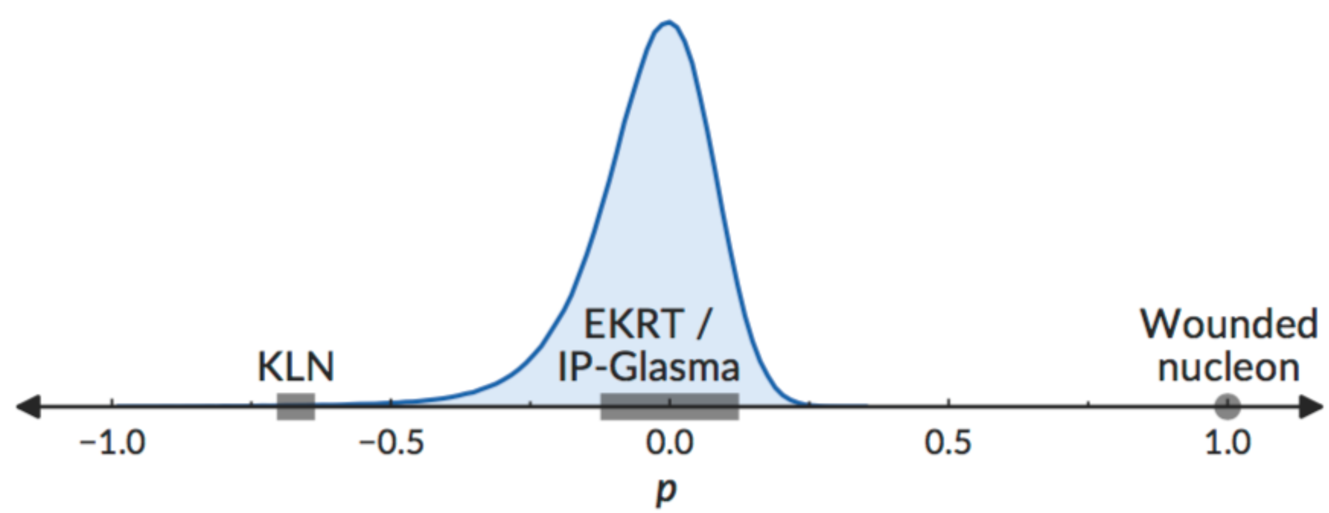
Ansatz

Entropy density proportional to **generalized mean** of local nuclear density

$$s \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$$

$p \in (-\infty, \infty)$ = tunable parameter

$p = +1$	$p = 0$	$p = -1$
$\frac{T_A + T_B}{2}$	$\sqrt{T_A T_B}$	$\frac{2 T_A T_B}{T_A + T_B}$



Available for download at:
https://github.com/Duke-QCD/trento

Going 3D

3D TRENTo

W. Ke, J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys.Rev. C96 (2017) no.4, 044912

Extend the TRENTO model by a rapidity dependent function

$$s(\mathbf{x}, \eta_s)|_{\tau=\tau_0} \propto f(\mathbf{x}) \times g(\mathbf{x}, \eta_s)$$

Assume massless free streaming particles: $\eta_s \approx \eta$

Parametrize in terms of y, then convert to pseudo-rapidity

$$s(\mathbf{x}, \eta_s)|_{\tau=\tau_0} \propto f(\mathbf{x})\, g(\mathbf{x}, y)\, \frac{dy}{d\eta}$$

Parametrize *g* using cumulants and construct the function from the inverse Fourier transform of its cumulant-generating function

$$g(\mathbf{x}, y) = \mathcal{F}^{-1}\{\tilde{g}(\mathbf{x}, k)\},$$

$$\log \tilde{g} = i\mu k - \frac{1}{2}\sigma^2 k^2 - \frac{1}{6} i\gamma\sigma^3 k^3 + \cdots$$

3D TRENTo

W. Ke, J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys.Rev. C96 (2017) no.4, 044912

Existing models use shifted or tilted rapidity distributions

P. Bozek and I. Wyskiel, Phys. Rev. C81, 054902 (2010)

- Shifted initial conditions use a Gaussian profile shifted by the local center of mass rapidity $\eta_{\rm cm} = \frac{1}{2}\log(T_A/T_B)$

- Tilted initial conditions include a local tilting factor

$$s(\mathbf{x}, \eta_s) = s(\mathbf{x})[1 + \eta_s \mathcal{A}(\mathbf{x})]$$

where $\mathcal{A}$ measures the local thickness asymmetry, fulfilling

$$\mathcal{A}(T_A, T_B) = -\mathcal{A}(T_B, T_A)$$

Shifted model alters the mean μ and tilted model the skewness γ

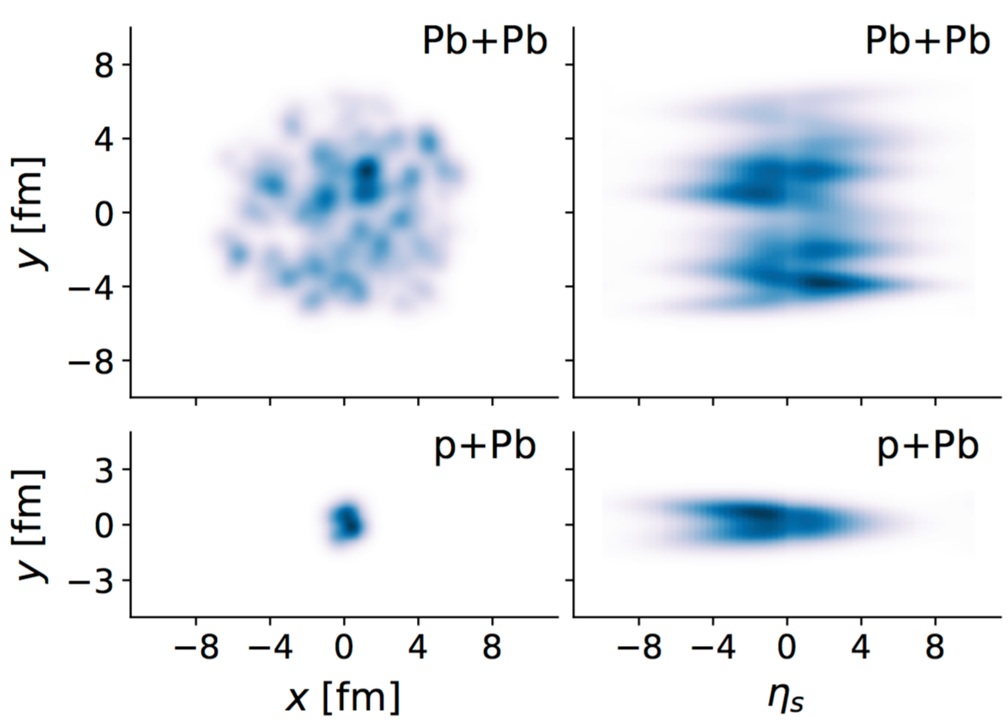
3D TRENTO allows the first few cumulants to be non-zero

3D TRENTo

W. Ke, J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys.Rev. C96 (2017) no.4, 044912

TRENTO implements models with two different parametrizations for the skewness parameter

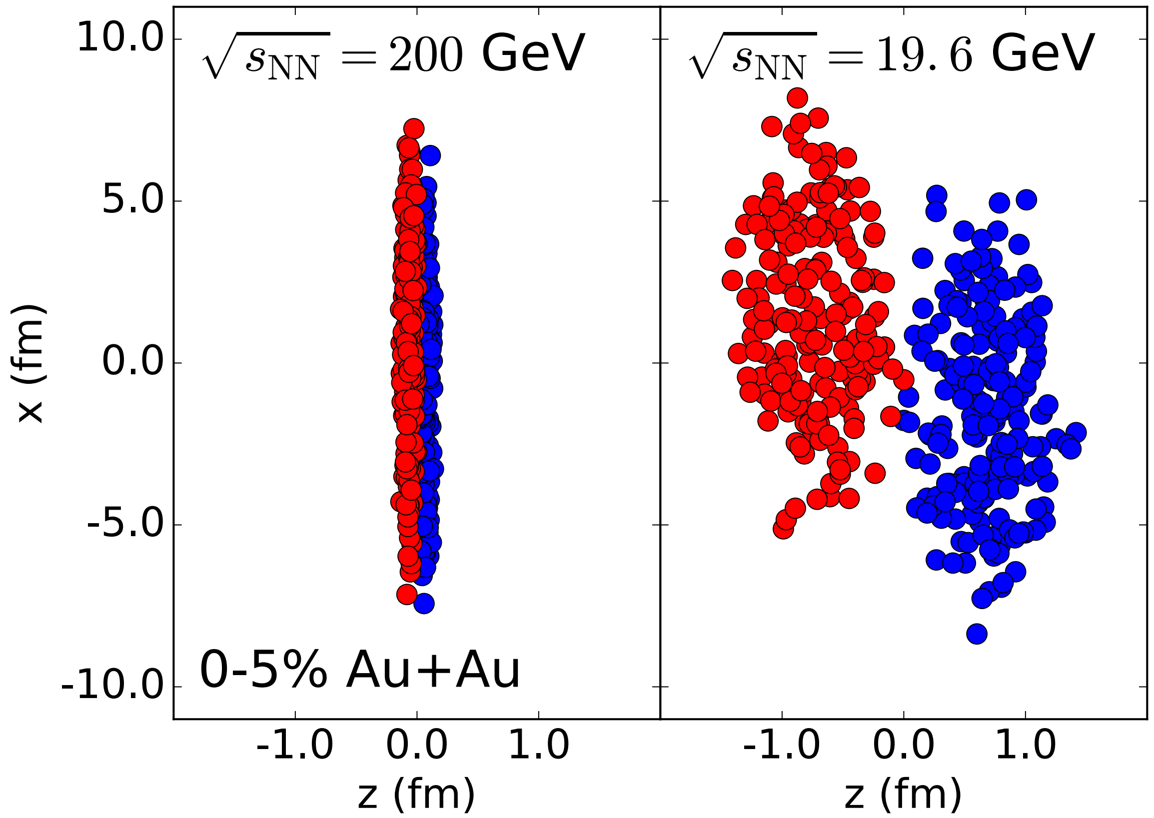
	Distribution cumulant:		
Model	mean μ	std. σ	skewness γ
Relative	$\frac{1}{2}\mu_0 \log(T_A/T_B)$	σ_0	$\gamma_0 \dfrac{T_A - T_B}{T_A + T_B}$
Absolute	$\frac{1}{2}\mu_0 \log(T_A/T_B)$	σ_0	$\gamma_0 (T_A - T_B)/T_0$

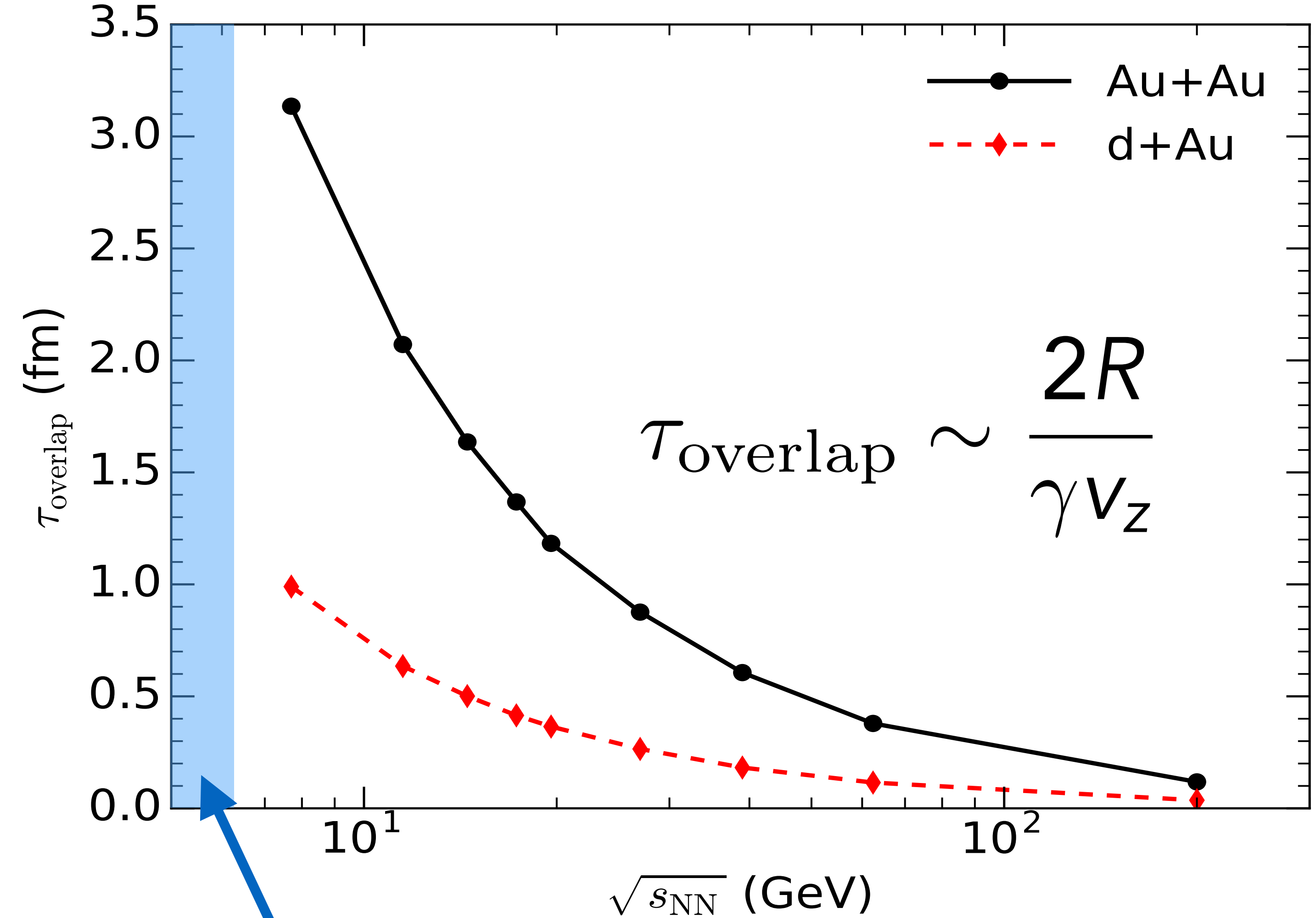


Event constructed with *relative* skewness model using $\mu_0 = 1$, $\sigma_0 = 3$ and $\gamma_0 = 6$

Both models can provide a good fit to a wide range of data

3D Dynamical Initial States for lower energies





J-PARC HI $\sqrt{s_{NN}} = 2 - 6.2\,\mathrm{GeV}$

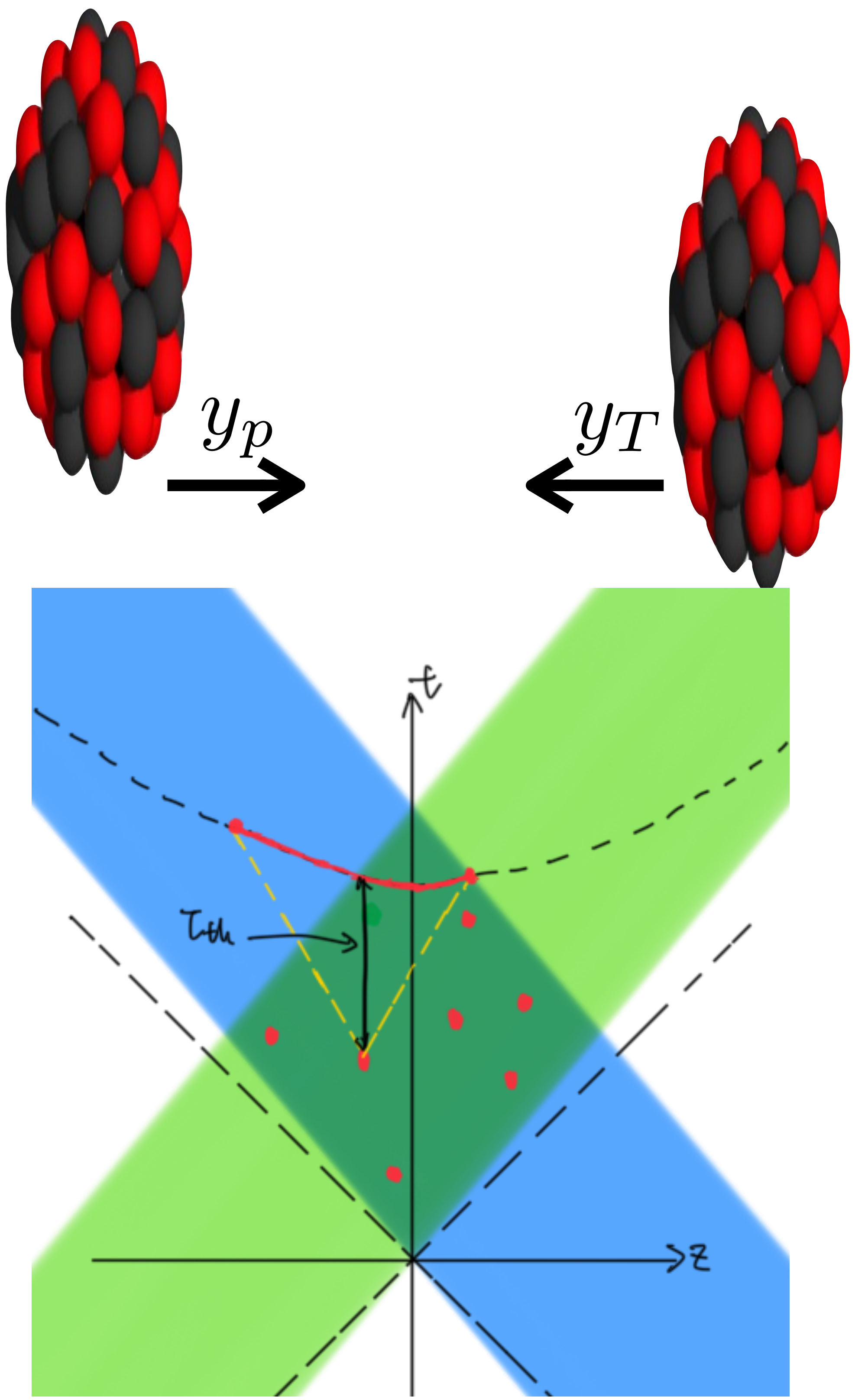
- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

$$\tau = \sqrt{t^2 - z^2}$$

$$\eta = \frac{1}{2} \ln \left(\frac{t+z}{t-z} \right)$$

Interaction geometry

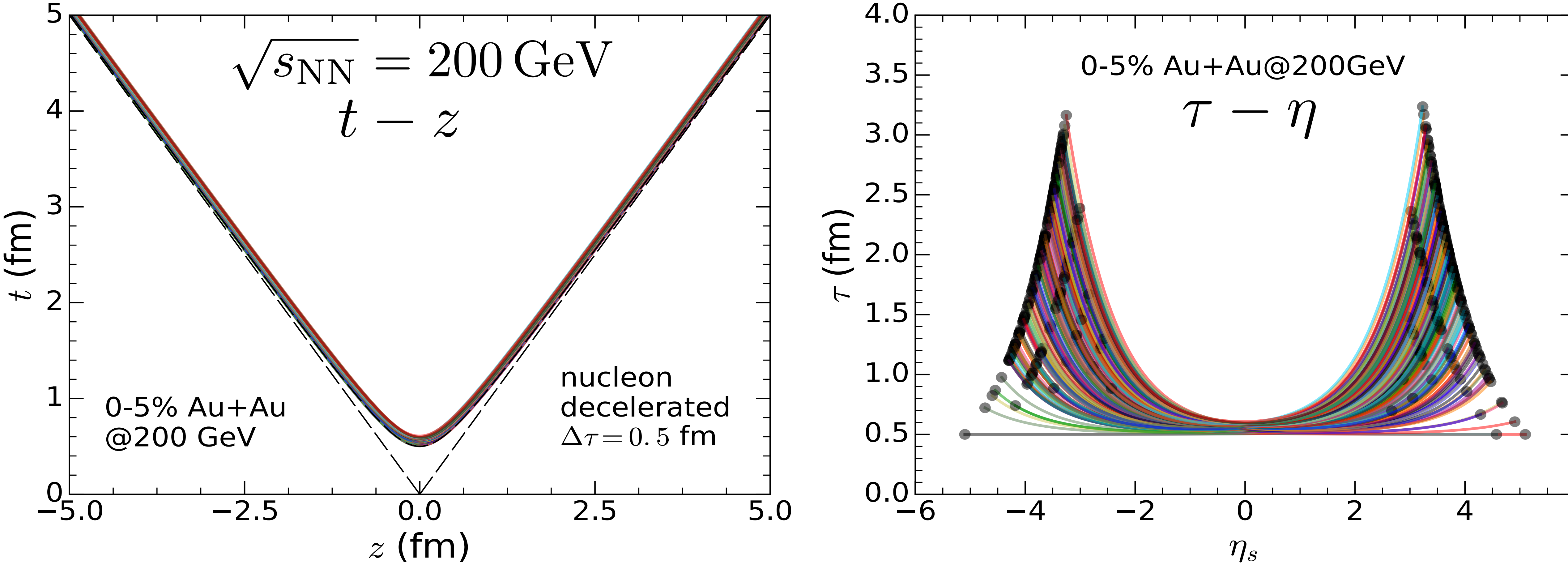
C. Shen, B. Schenke, arXiv:1710.00881



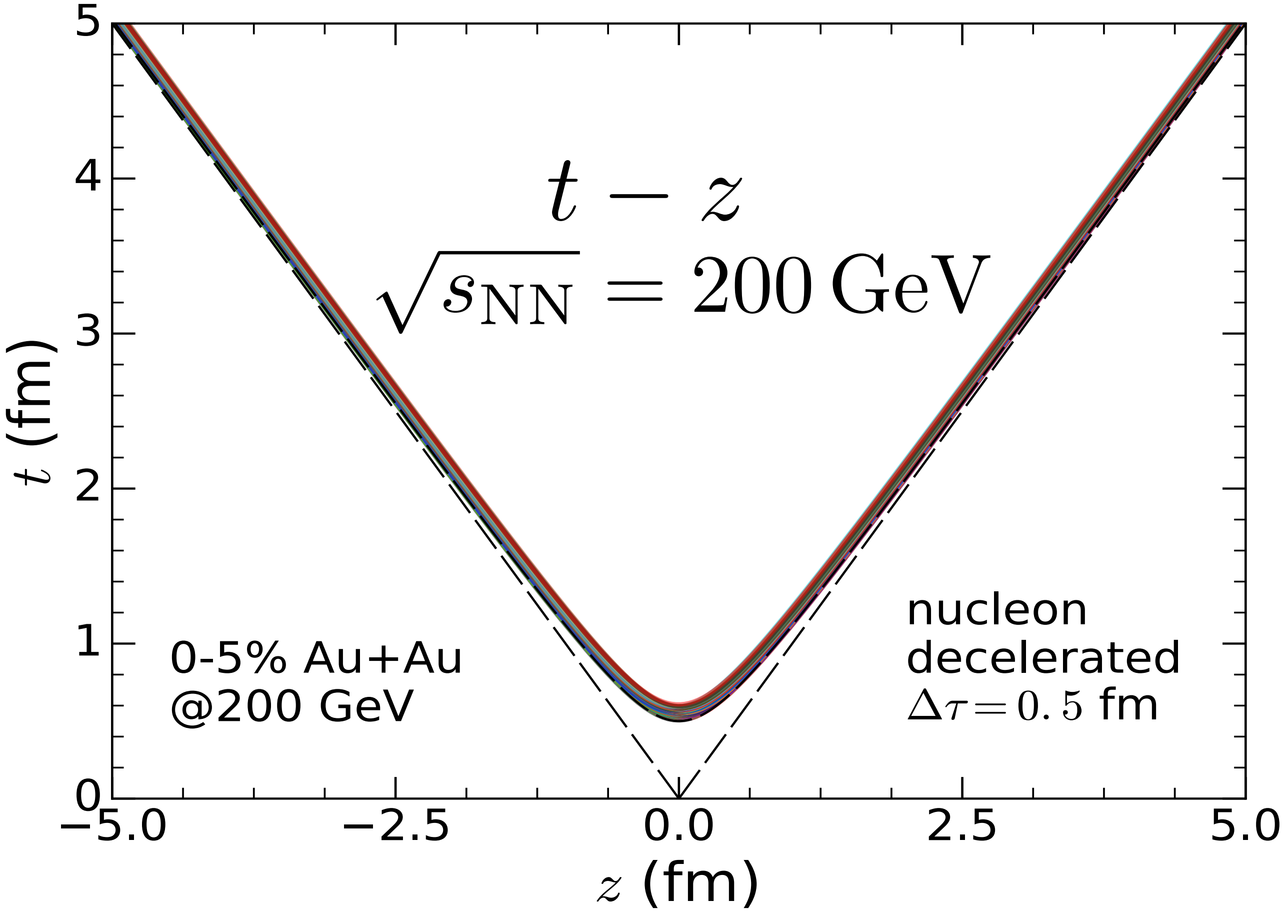
- Collision time and 3D spatial position are determined for every binary collision
- QCD strings are produced from collision points
- These strings are decelerated with a constant string tension σ=1GeV/fm before thermalizing with the medium

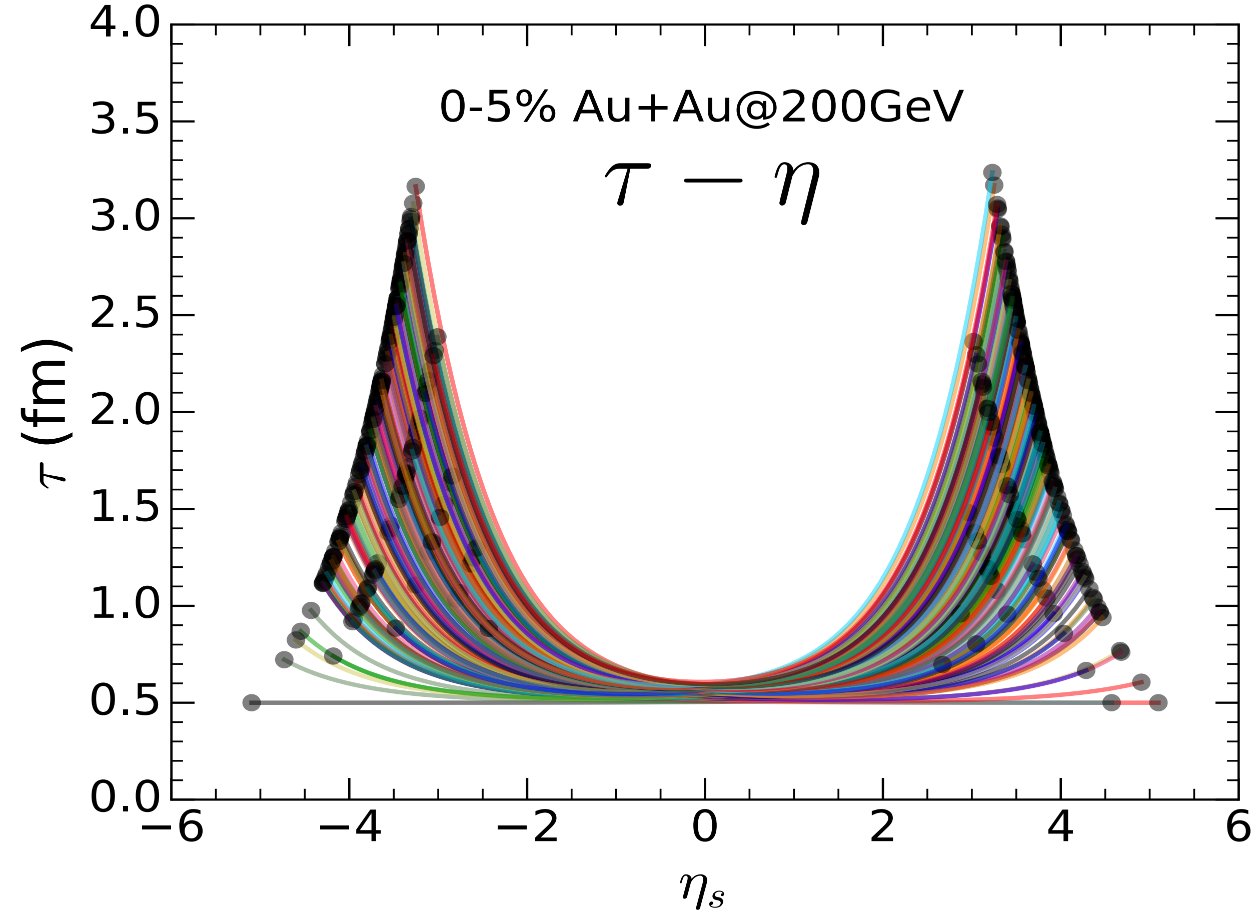
see A. Bialas, A. Bzdak and V. Koch, arXiv:1608.07041 [hep-ph]

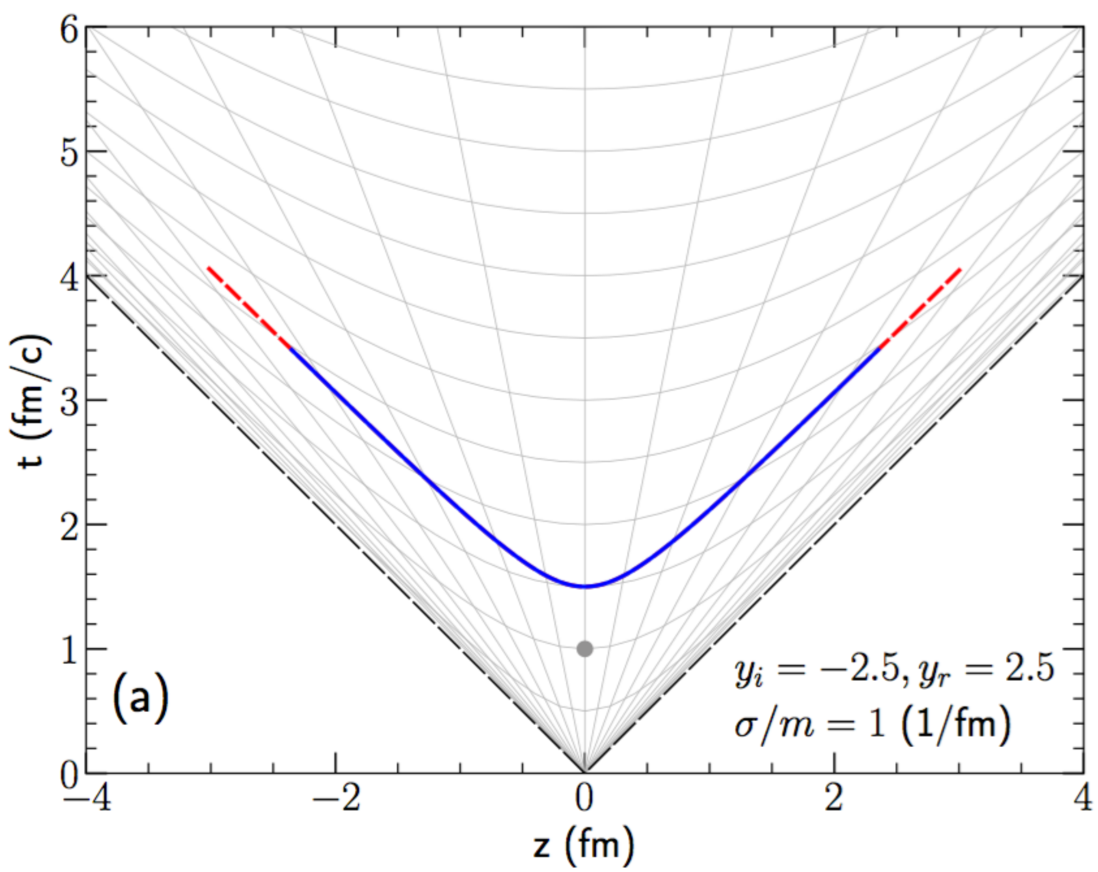
Entropy and baryon deposition in space-time

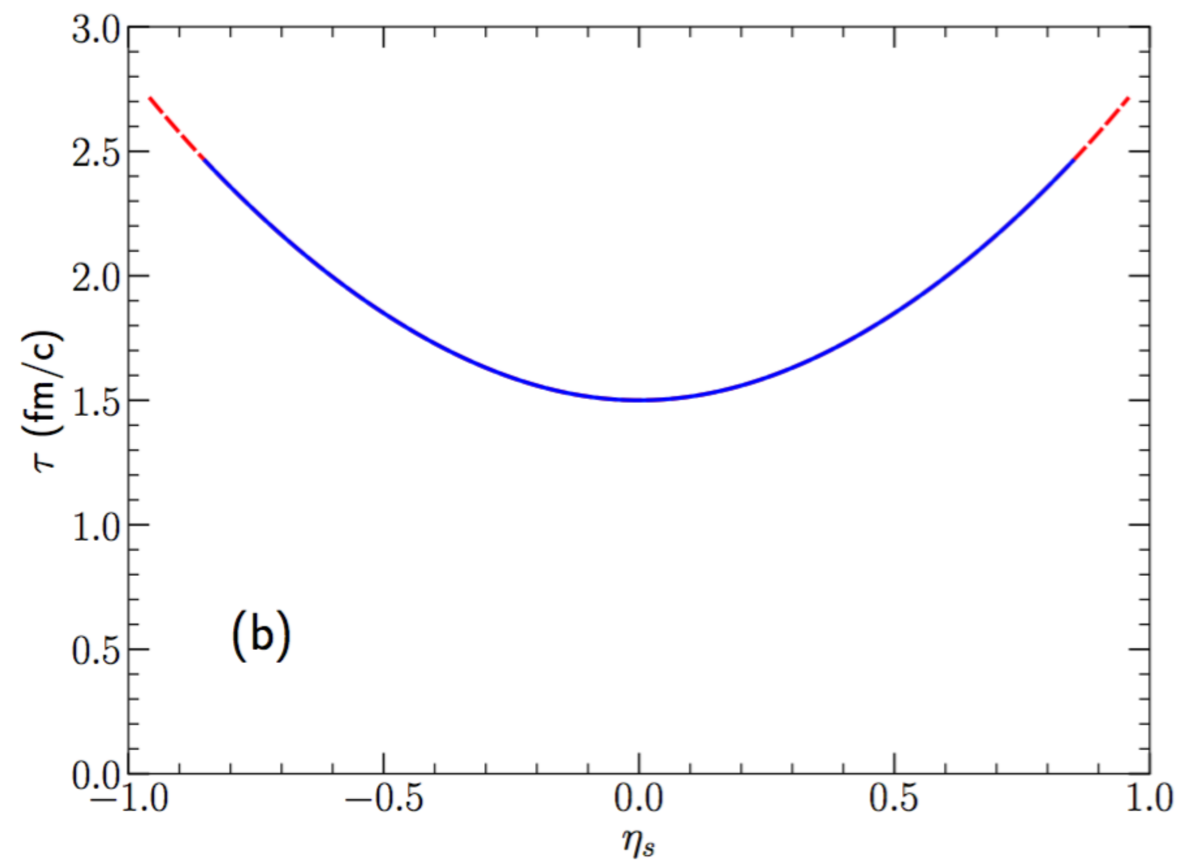


Entropy and baryon deposition in space-time

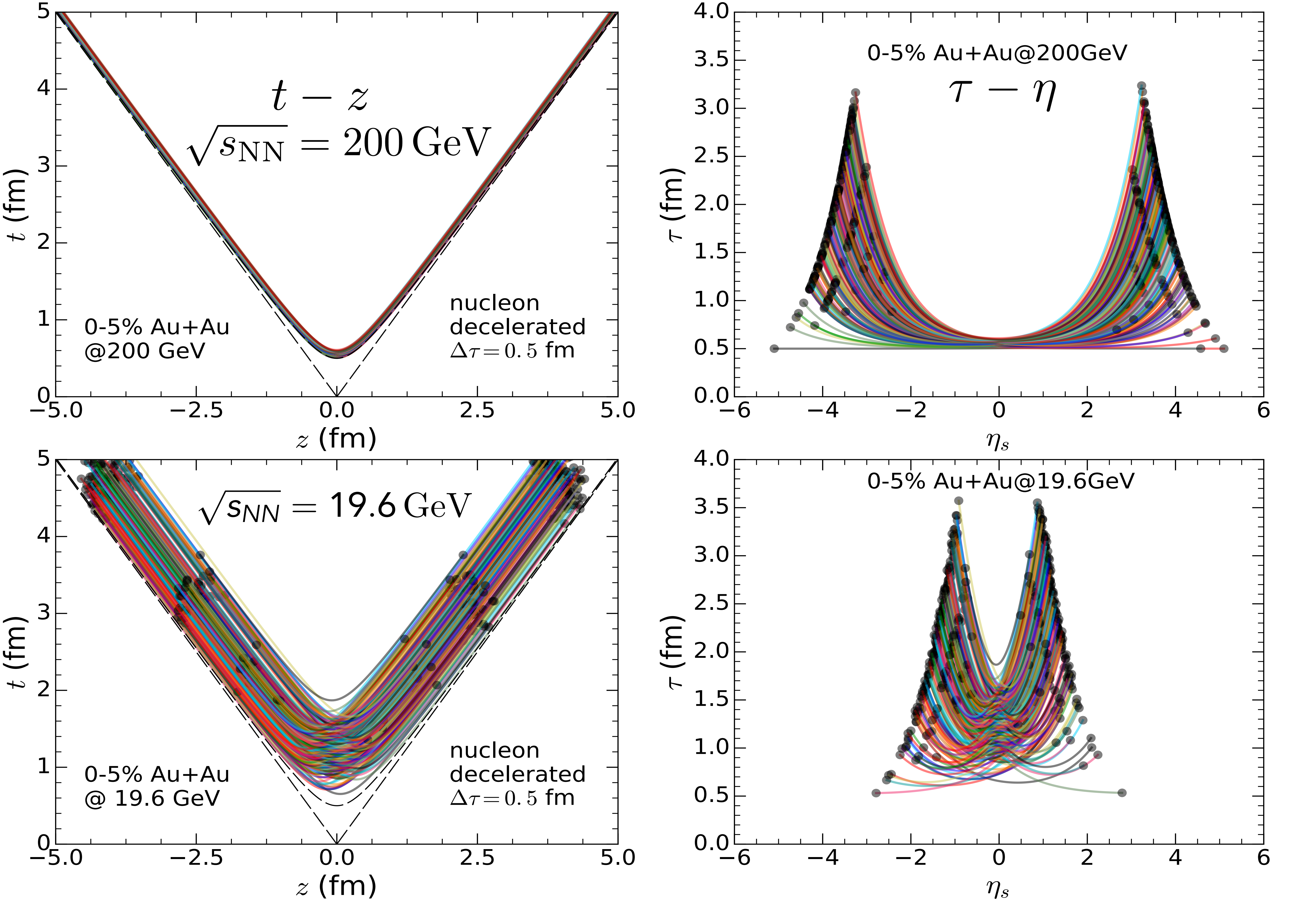








Entropy and baryon deposition in space-time



Sources of longitudinal fluctuations

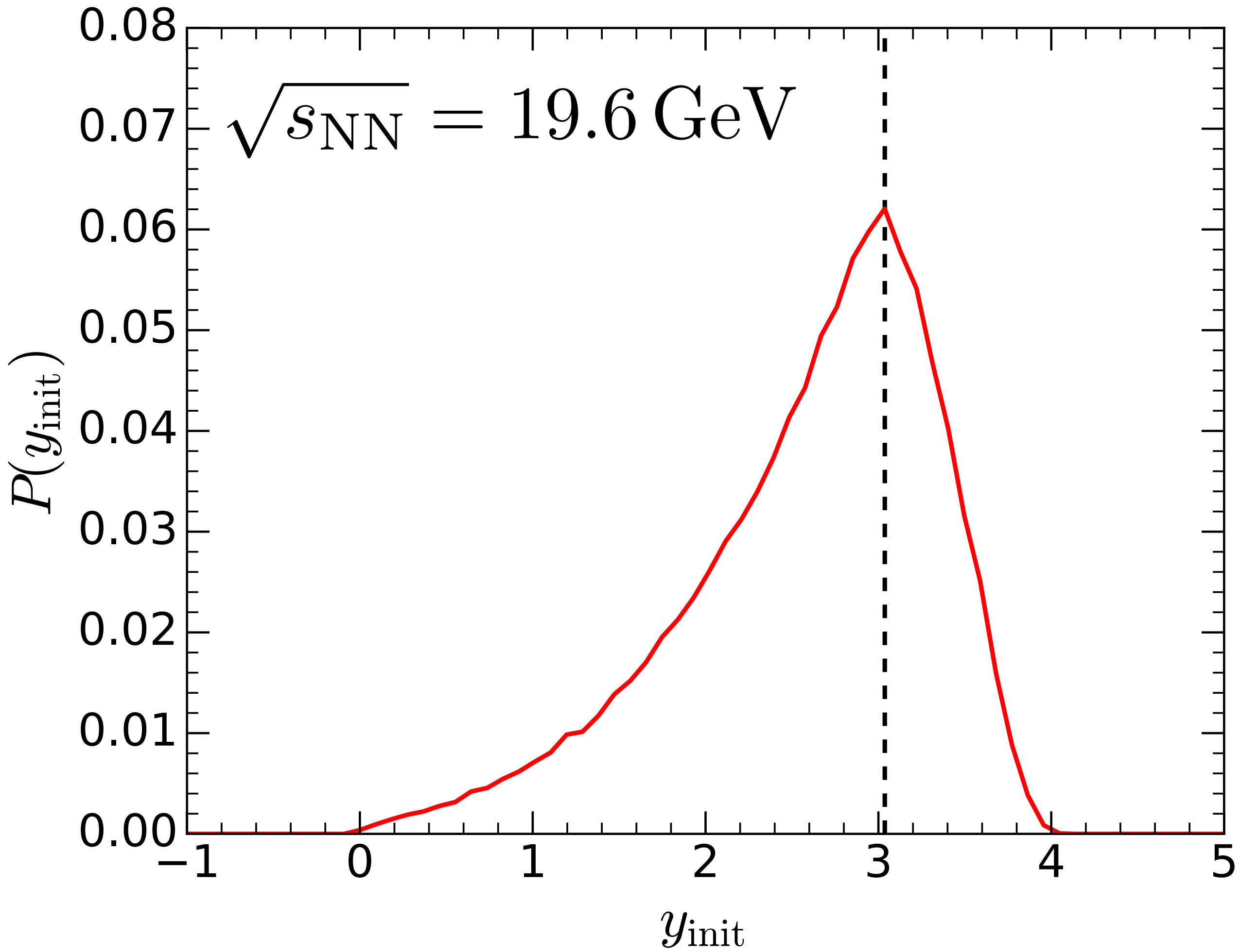
- Sample valence quarks from the incoming participants

$$y_q = \mathrm{arcsinh}\left(x_q \sqrt{\frac{s}{4m_q^2} - 1}\right)$$

quark momentum fraction

$$y_q = log\left(\frac{x_q\sqrt{s}}{m_q}\right)$$

for large s



C. Shen, B. Schenke, arXiv:1710.00881

Sources of longitudinal fluctuations

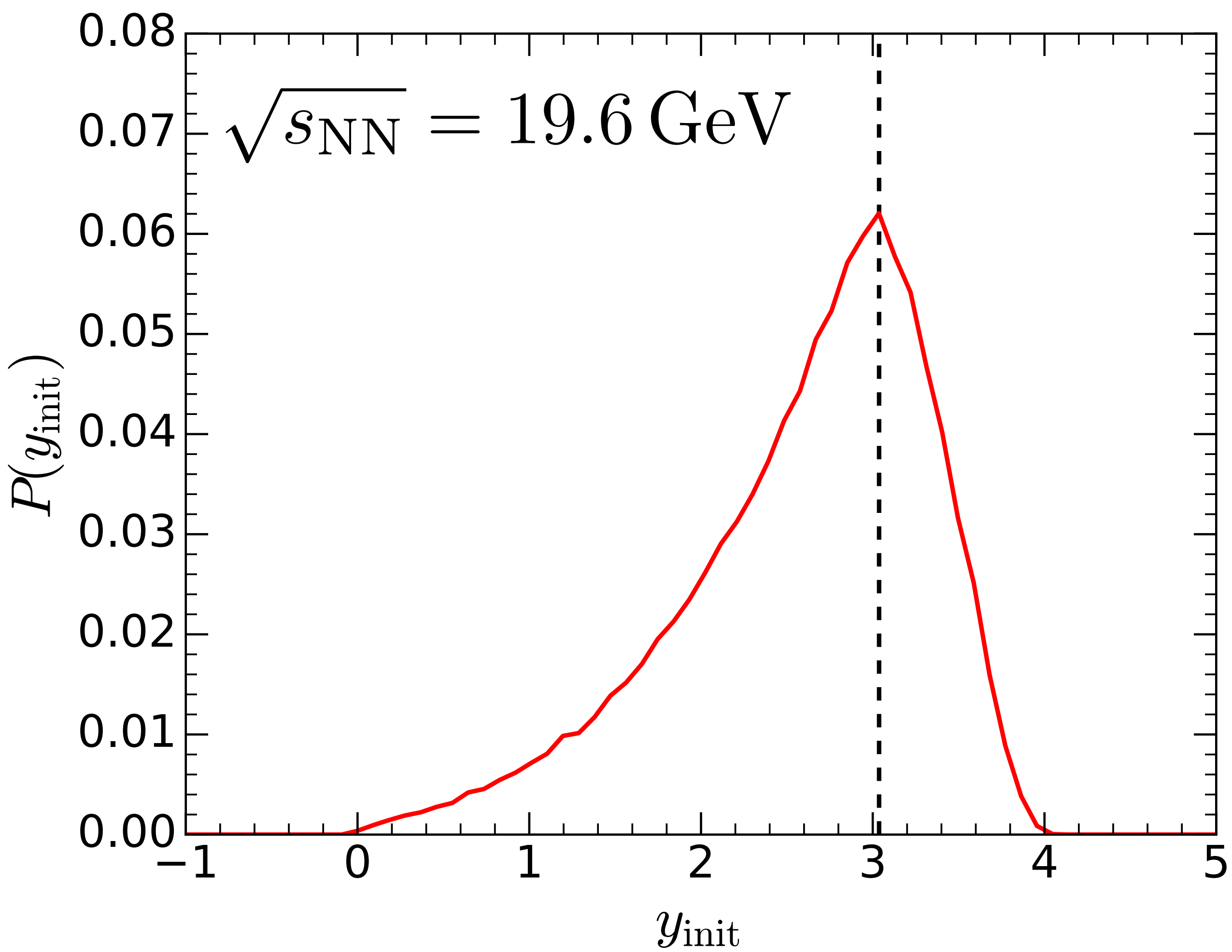
- Sample valence quarks from the incoming participants

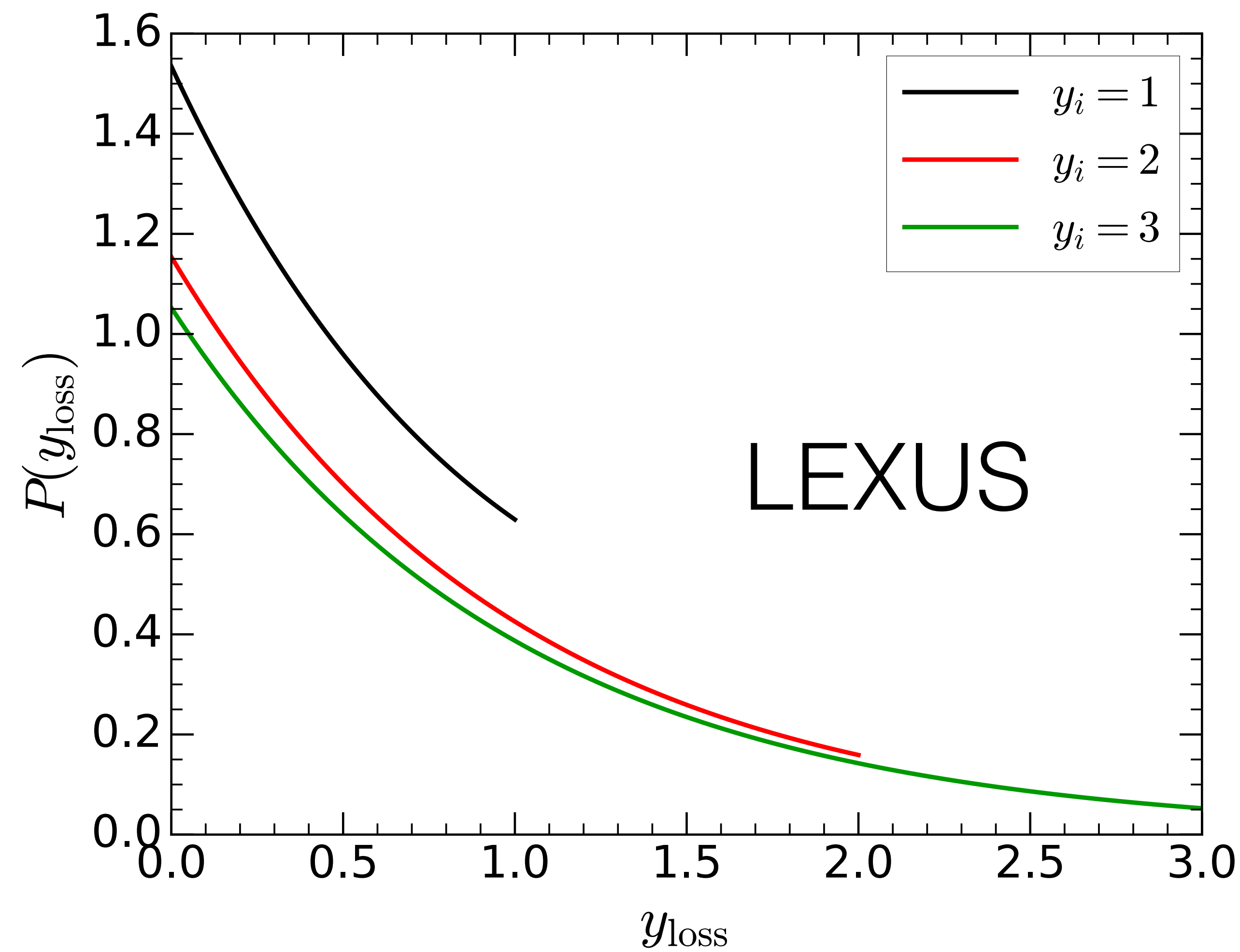
$$y_q = \text{arcsinh}\left(x_q\sqrt{\frac{s}{4m_q^2} - 1}\right)$$

- Sample the rapidity loss according to the LEXUS model

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

$$P(y_{\rm loss}) = \frac{\cosh(2y_{\rm init} - y_{\rm loss})}{\sinh(2y_{\rm init}) - \sinh(y_{\rm init})} \qquad y_{\rm loss} \in [0, y_{\rm init}]$$

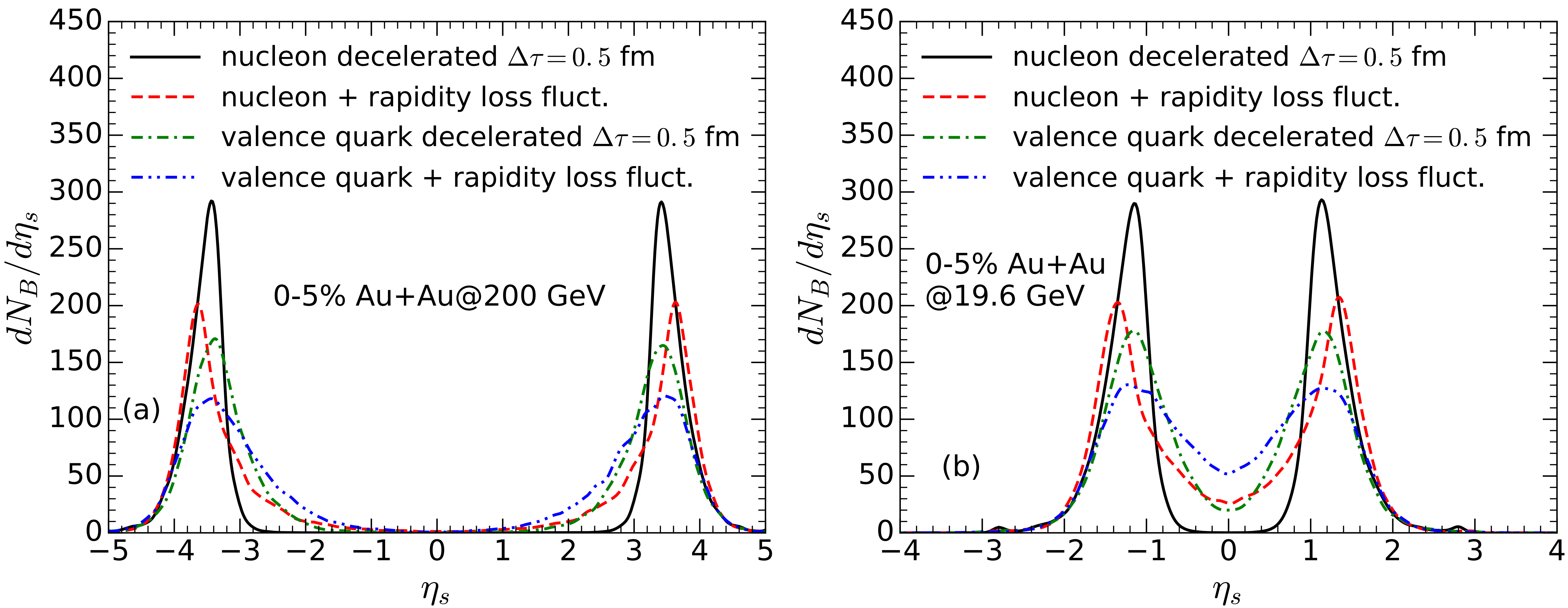




C. Shen, B. Schenke, arXiv:1710.00881

Net baryon space-time rapidity distribution

C. Shen, B. Schenke, arXiv:1711.10544



- Degree of initial-state rapidity fluctuations affect the net-baryon space-time rapidity distributions
- The valence quark + rapidity loss fluctuation model gives the largest baryon stopping in collisions

Hydrodynamics with sources

C. Shen, B. Schenke, arXiv:1711.10544

Energy-momentum current and net baryon density are fed into the hydrodynamic simulation via source terms

$$\partial_\mu T^{\mu\nu} = J^\nu_{\mathrm{source}}$$

$$\partial_\mu J^\mu = \rho_{\mathrm{source}}$$

where

$$J^\nu_{\mathrm{source}} = \delta e u^\nu + (e+P)\delta u^\nu$$

$$\delta u^\nu = \frac{\Delta^\nu_\mu J^\mu_{\mathrm{source}}}{e+P}$$

δe heats up the system; δu^ν accelerates the flow velocity

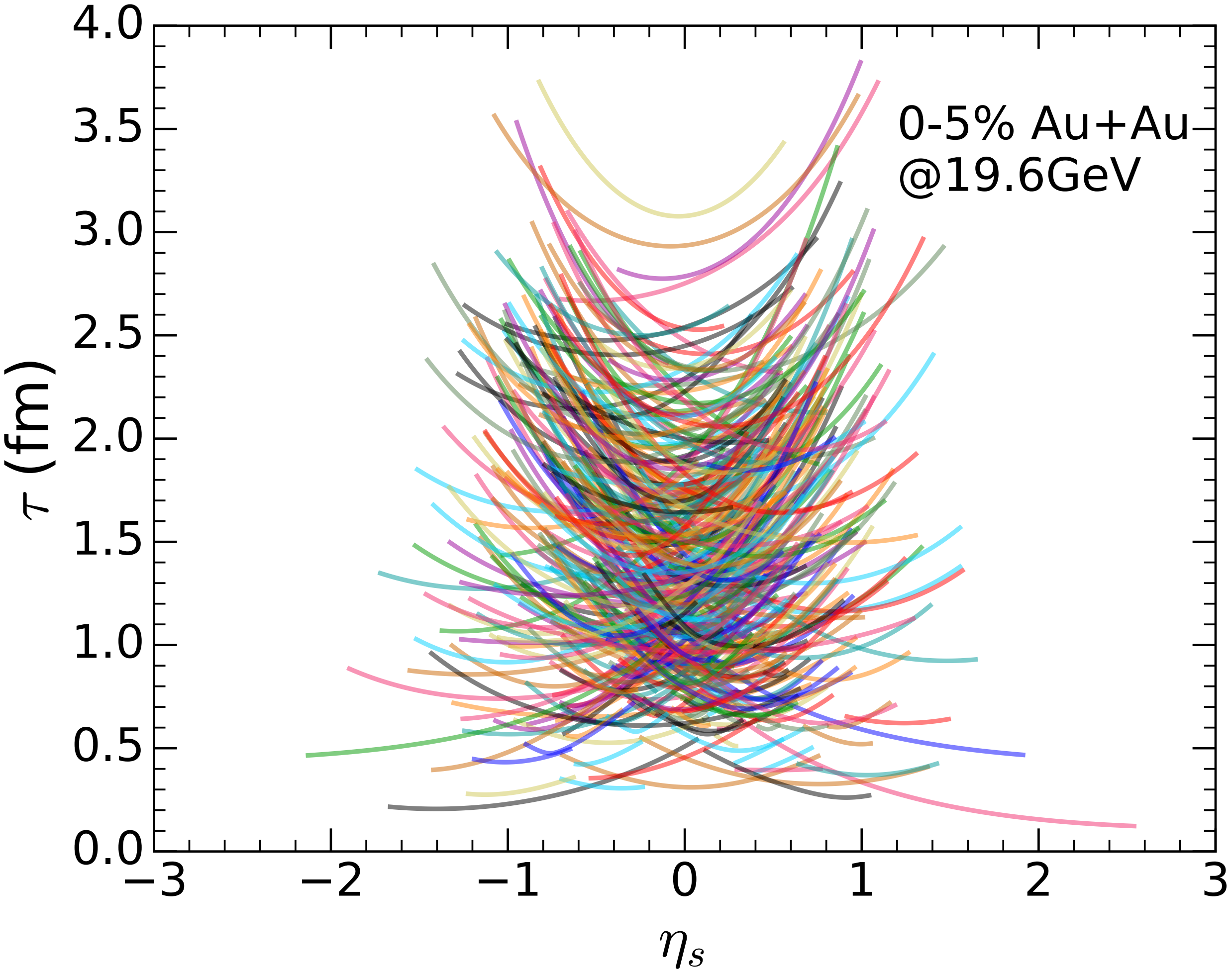
ρ_{source} dopes baryon charges into the system

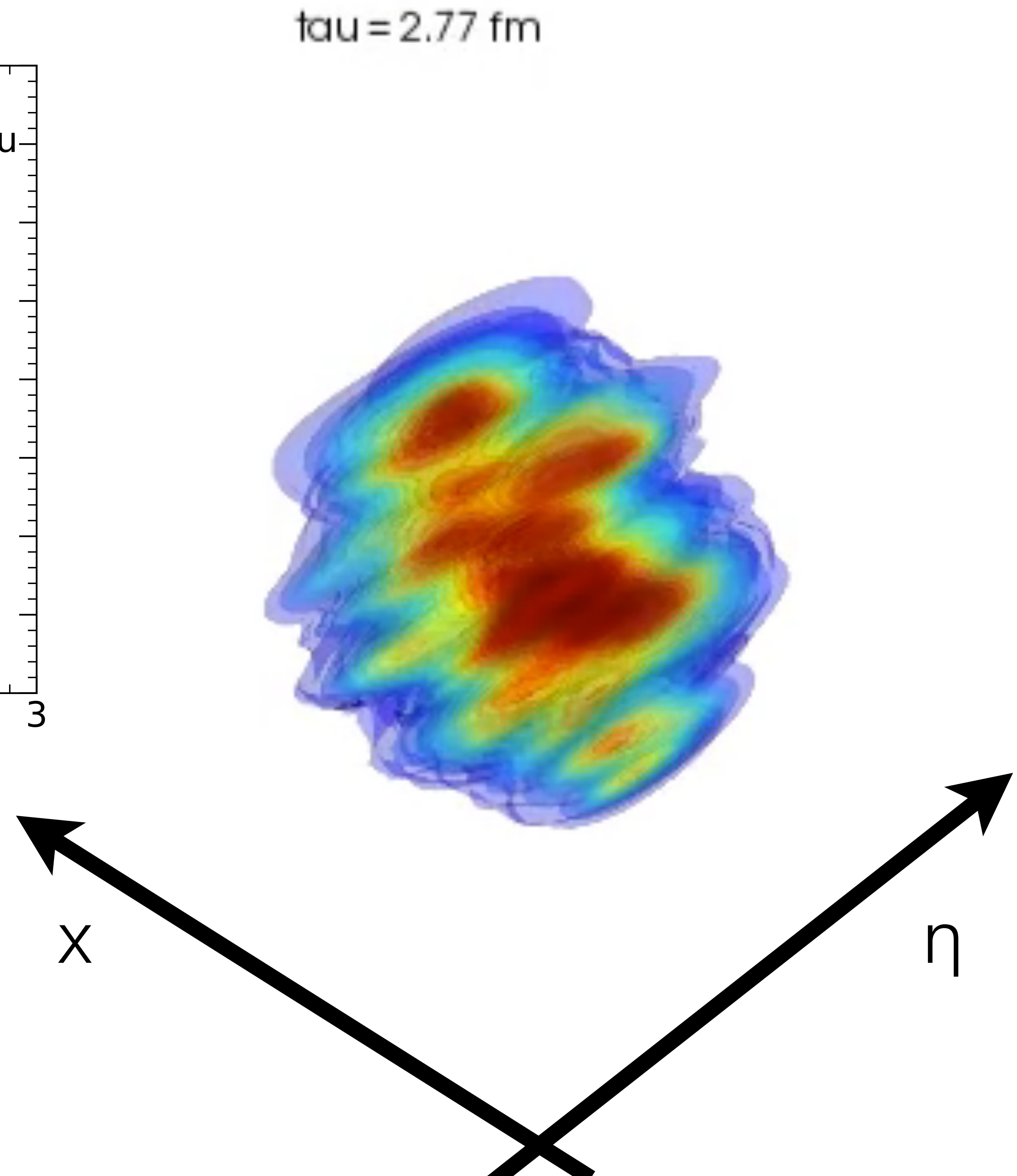
Source terms are smeared with Gaussians in space and time

Hydrodynamical evolution with sources

C. Shen, B. Schenke, arXiv:1711.10544

energy density





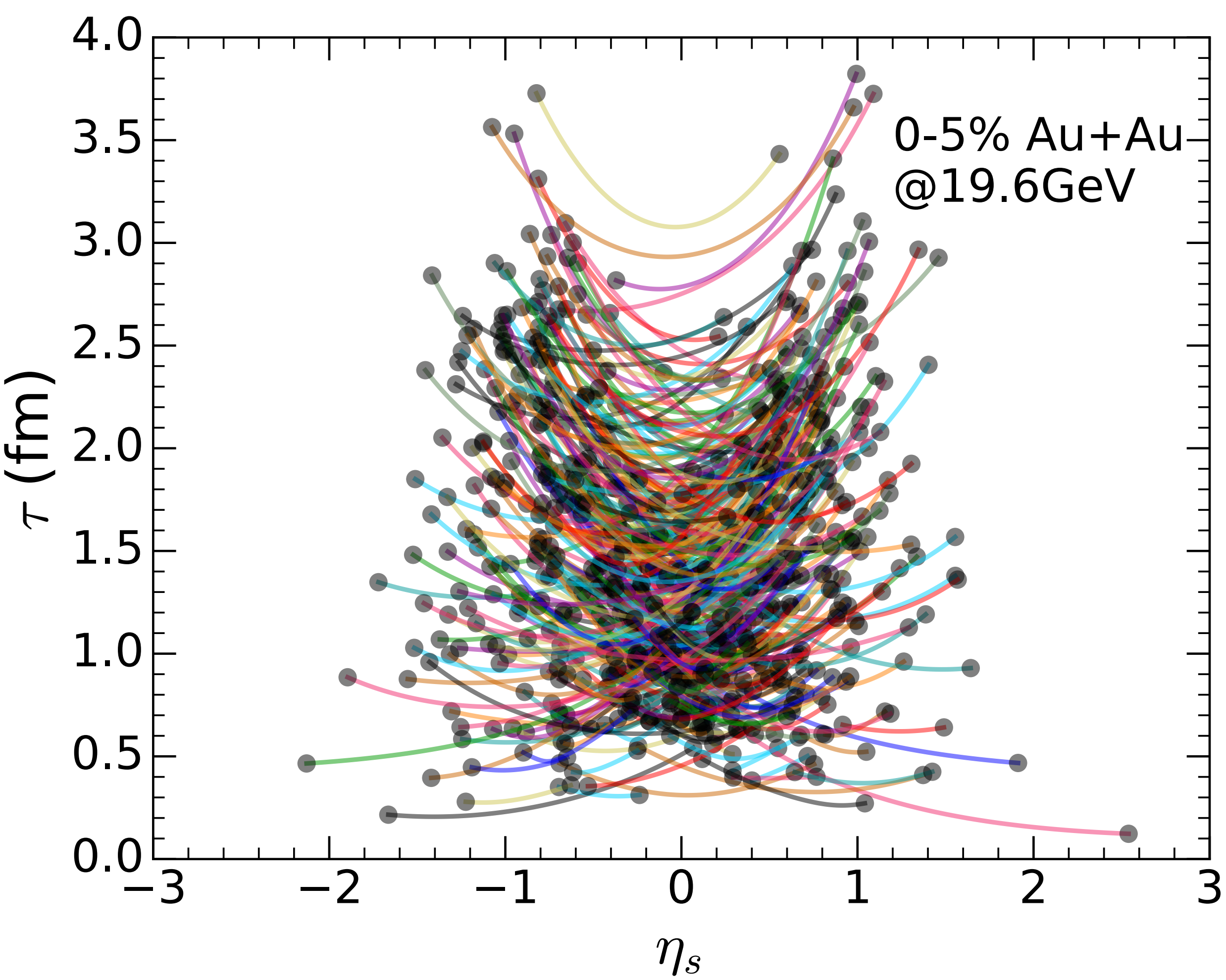
$$\sqrt{s_{\rm NN}} = 19.6\,\mathrm{GeV}$$

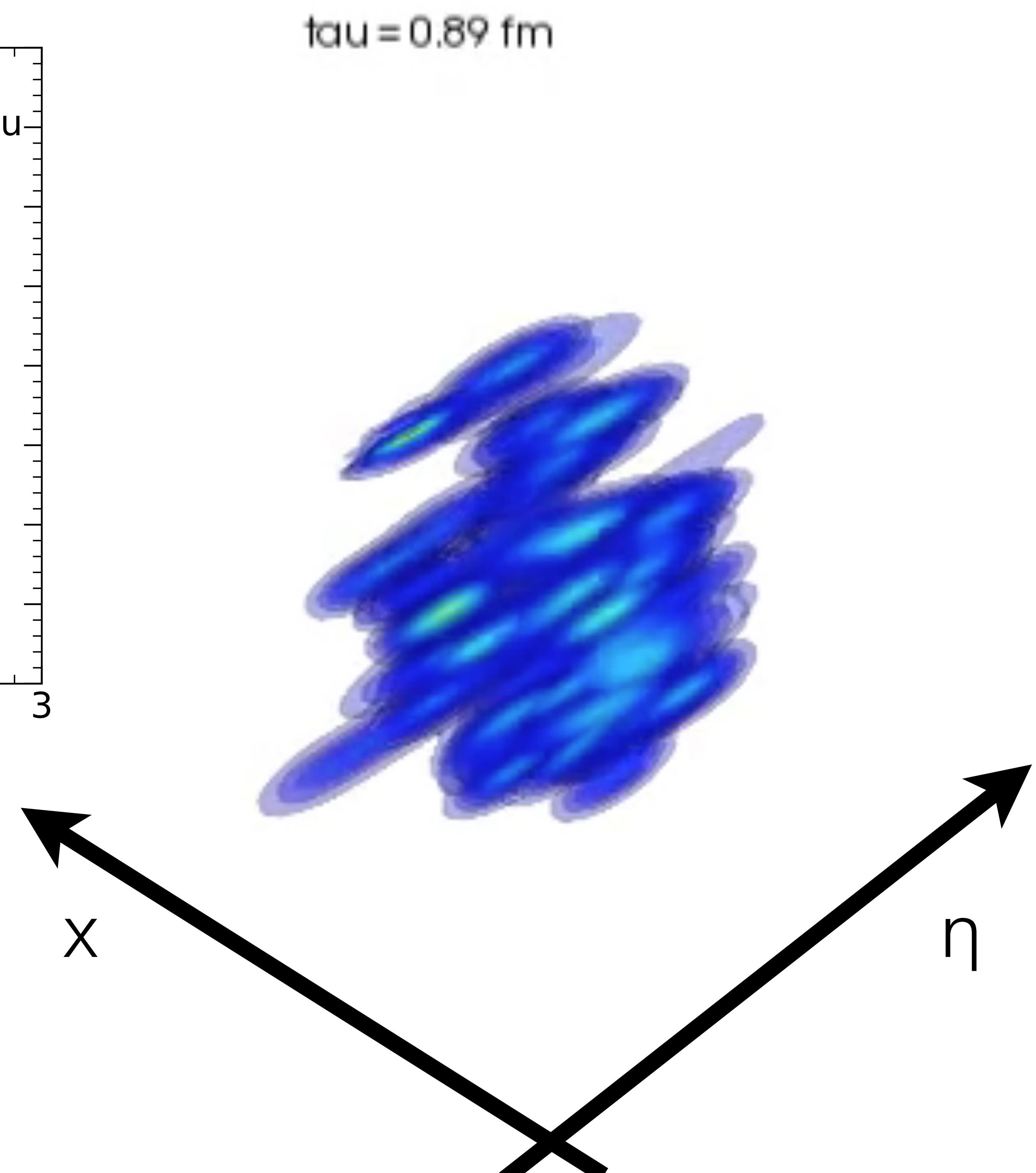
valence quark +
rapidity loss fluct.

Hydrodynamical evolution with sources

C. Shen, B. Schenke, arXiv:1711.10544

net baryon density





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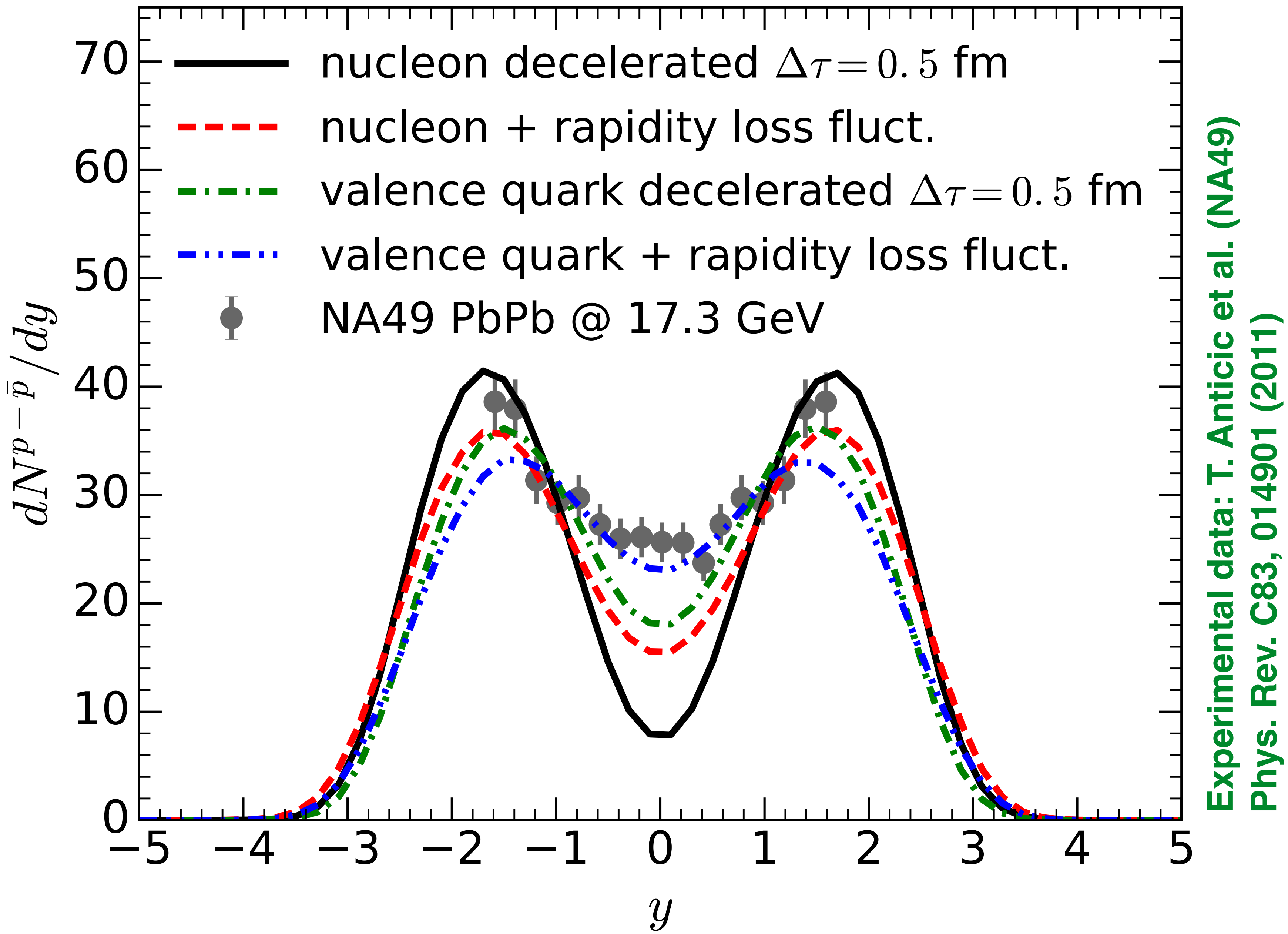
Net baryon rapidity distribution

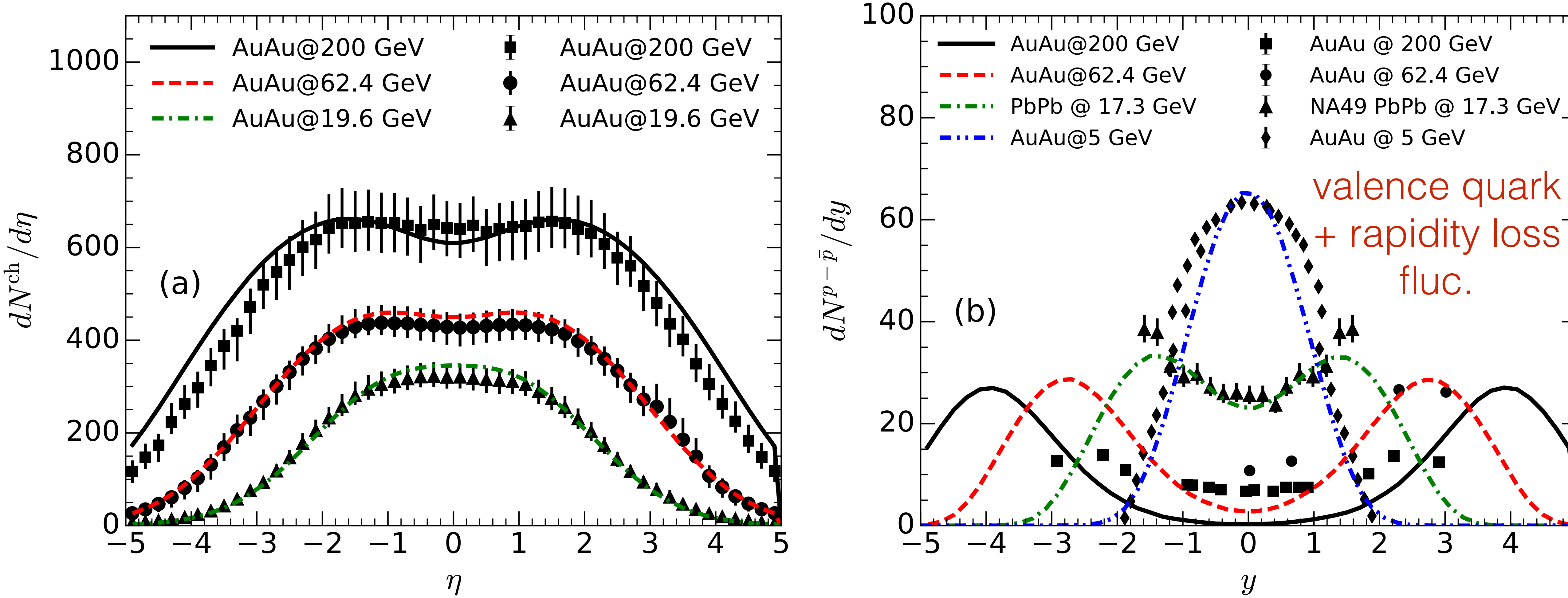
C. Shen, B. Schenke, arXiv:1711.10544



- The valence quark + rapidity loss fluctuation model provides a reasonable net baryon rapidity distribution compared to the NA49 measurement

Particle rapidity distribution

C. Shen, B. Schenke, arXiv:1711.10544



- Rapidity distribution of charged hadrons agrees fairly well with the RHIC BES measurements below 200 GeV
- The valence quark + rapidity loss fluct. model provides a reasonable net baryon rapidity distribution compared to low energy BES data; but too low for high energies

Experimental data:
PHOBOS Collaboration, Phys. Rev. C83, 024913 (2011); E-802 Phys. Rev. C57, R466–R470 (1998); E-802 Phys. Rev. C60, 064901 (1999); E-877 Phys. Rev. C62, 024901 (2000); NA49 Phys. Rev. C83, 014901 (2011)

Dynamical initial state using PYTHIA

PHYSICAL REVIEW C **95**, 054914 (2017)

New approach to initializing hydrodynamic fields and mini-jet propagation in quark-gluon fluids

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- MC-Glauber+ PYTHIA
- Rejection sampling of particles to achieve N_{part} scaling

Dynamical hydrodynamization

Utilize QGP fluid + jet model to generate QGP fluids from initial partons dynamically

<u>Initial condition</u>

$$T^{\mu\nu}_{\text{fluid}}(\tau = \tau_{00}) = 0 \quad \text{(No QGP fluid at } \tau = \tau_{00} = 0.1 \text{ fm)}$$

<u>"Production rate" of energy and momentum of the QGP fluid per parton</u>

$$J_i^{\mu}(x) = -\frac{dp_i^{\mu}}{dt}\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_i(p_i, t))$$

$$\frac{dE}{dt} = \frac{d|\boldsymbol{p}|}{dt} = 5 \text{ GeV/fm} \qquad (\tau_{00} < \tau < \tau_0)$$

Regardless of whether matter exists or not

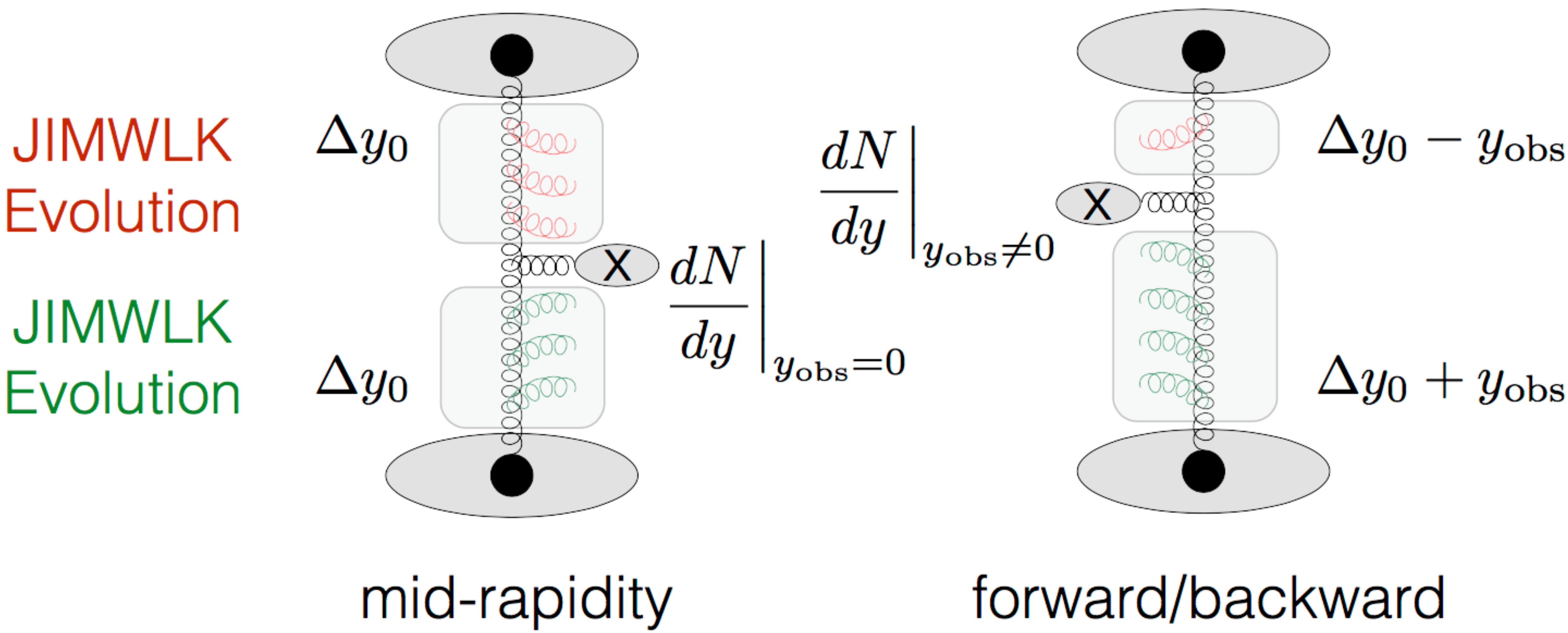
Slide from T. Hirano

3D-Glasma Initial State

B. Schenke, S. Schlichting, PRC94, 044907 (2016)

IP-Glasma usually applied to mid-rapidity

Varying x-value in both nuclei allows to compute initial state at different rapidities:



JIMWLK evolution for 3D-Glasma

B. Schenke, S. Schlichting, PRC94, 044907 (2016)

Rapidity evolution of Wilson lines in Langevin form:

H. Weigert, Nucl. Phys. A 703, 823 (2002).

T. Lappi and H. Mäntysaari, Eur. Phys. J. C 73, 2307 (2013)

$$V_x(Y+dY) = \exp\left\{ -i\frac{\sqrt{\alpha_s dY}}{\pi} \int_z \vec{K}^{\mathrm{mod}}_{x-z} \cdot (V_z \vec{\xi}_z V_z^\dagger) \right\}$$

$$\times V_x(Y) \exp\left\{ i\frac{\sqrt{\alpha_s dY}}{\pi} \int_z \vec{K}^{\mathrm{mod}}_{x-z} \cdot \vec{\xi}_z \right\}$$

ξ is Gaussian noise with zero average and

$$\langle \xi^a_{\vec{x},i}(Y) \xi^b_{\vec{y},j}(Y') \rangle = \delta^{ab} \delta^{ij} \delta^{(2)}_{\vec{x}\vec{y}} \delta(Y - Y')$$

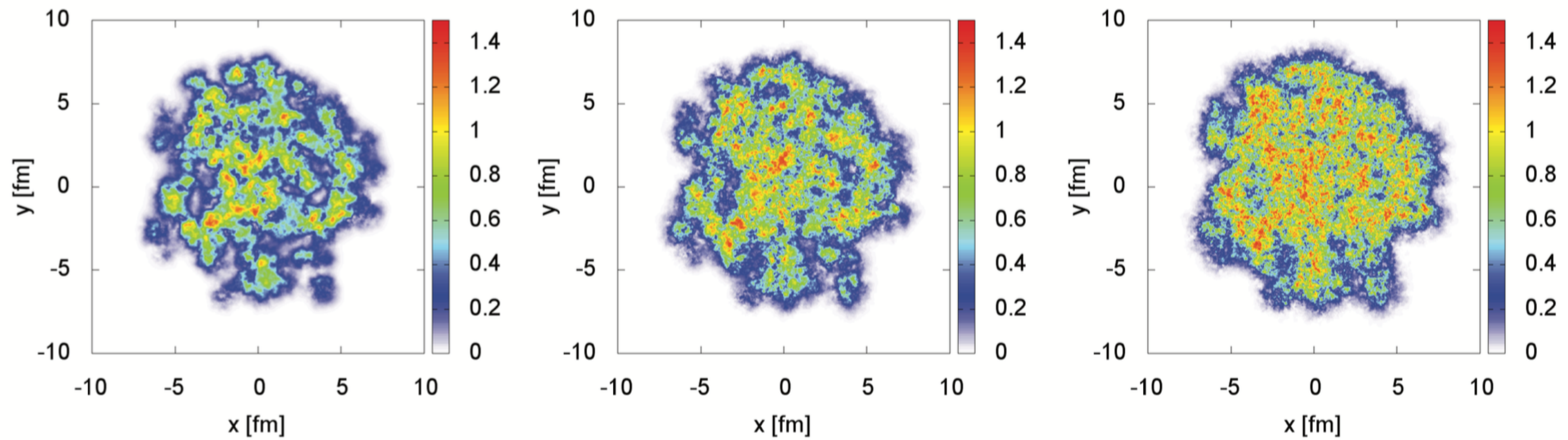
The JIMWLK Kernel is modified to avoid infrared tails:

$$K^{\mathrm{mod}}_{\mathbf{x}-\mathbf{z}} = m|\mathbf{x}-\mathbf{z}| K_1(m|\mathbf{x}-\mathbf{z}|) \frac{\mathbf{x}-\mathbf{z}}{(\mathbf{x}-\mathbf{z})^2}$$

Gluon fields in a nucleus at different x

B. Schenke, S. Schlichting, PRC94, 044907 (2016)

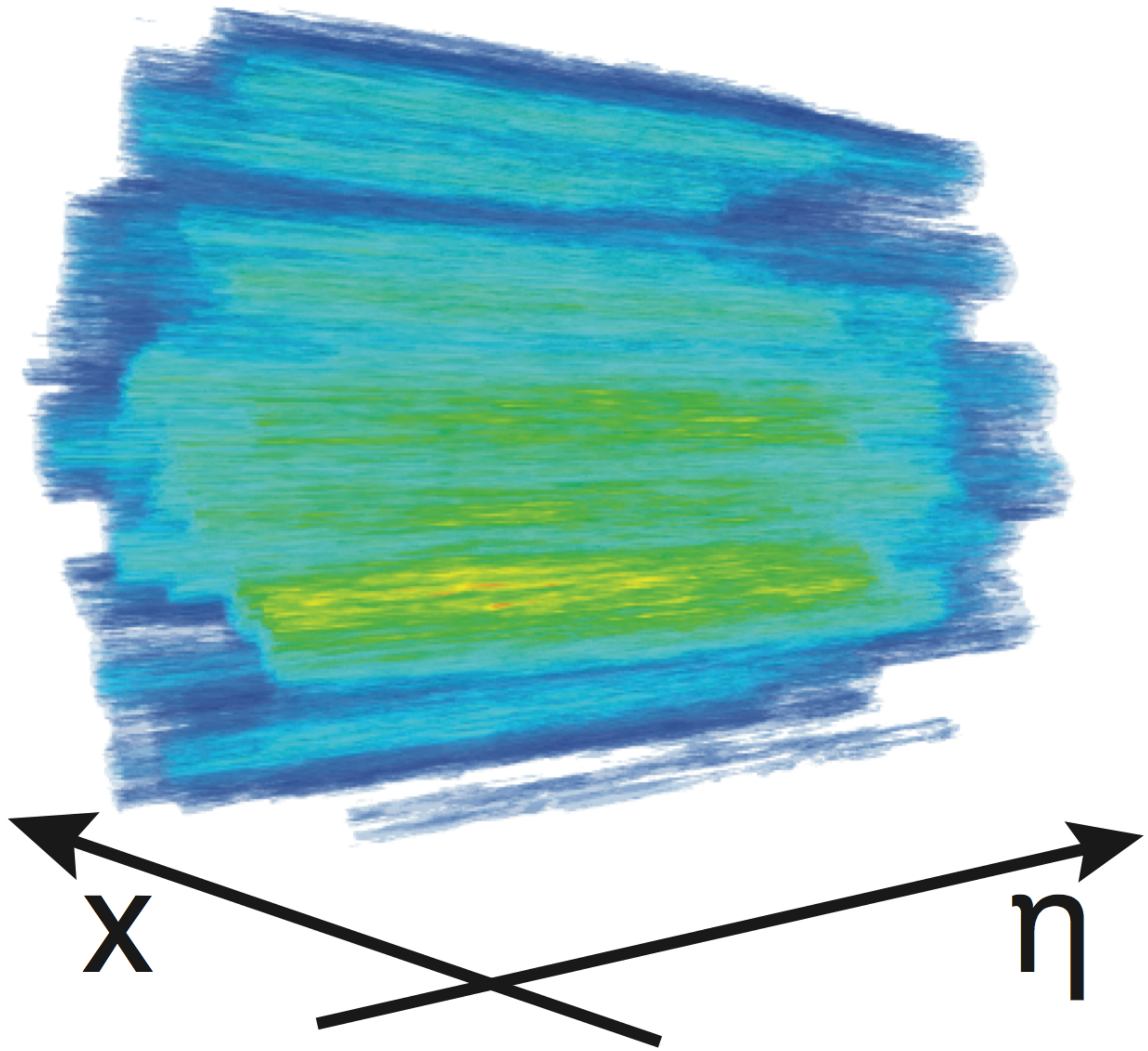
Shown is the trace of Wilson lines for illustration



$Y = -2.4$ ($x \approx 2\times10^{-3}$) $Y = 0$ ($x \approx 2\times10^{-4}$) $Y = 2.4$ ($x \approx 1.6\times10^{-5}$)

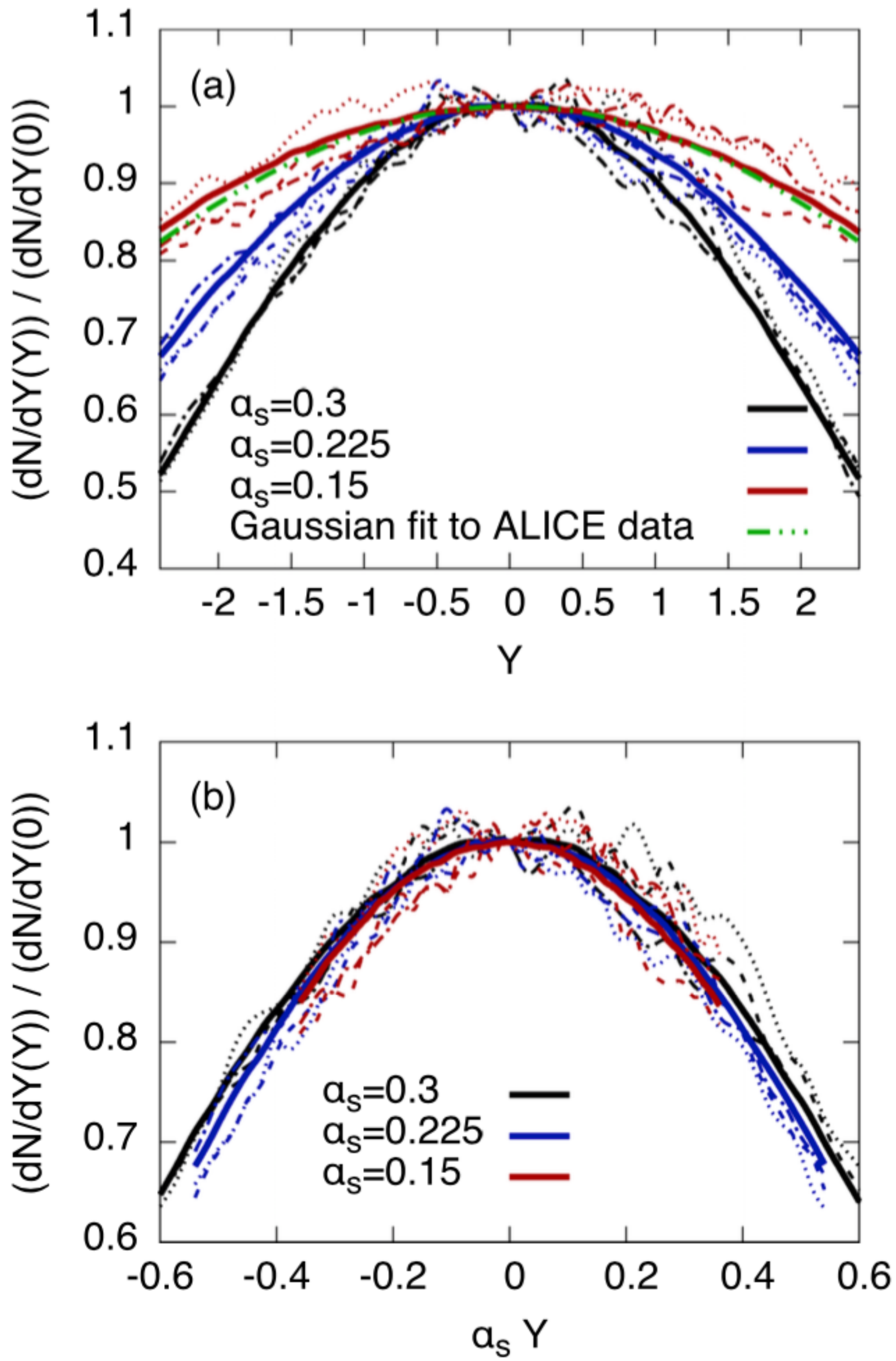
Energy density after the collision

B. Schenke, S. Schlichting, PRC94, 044907 (2016)



Gluon rapidity distribution

B. Schenke, S. Schlichting, PRC94, 044907 (2016)



Gluon multiplicity relative to its value at $Y = 0$

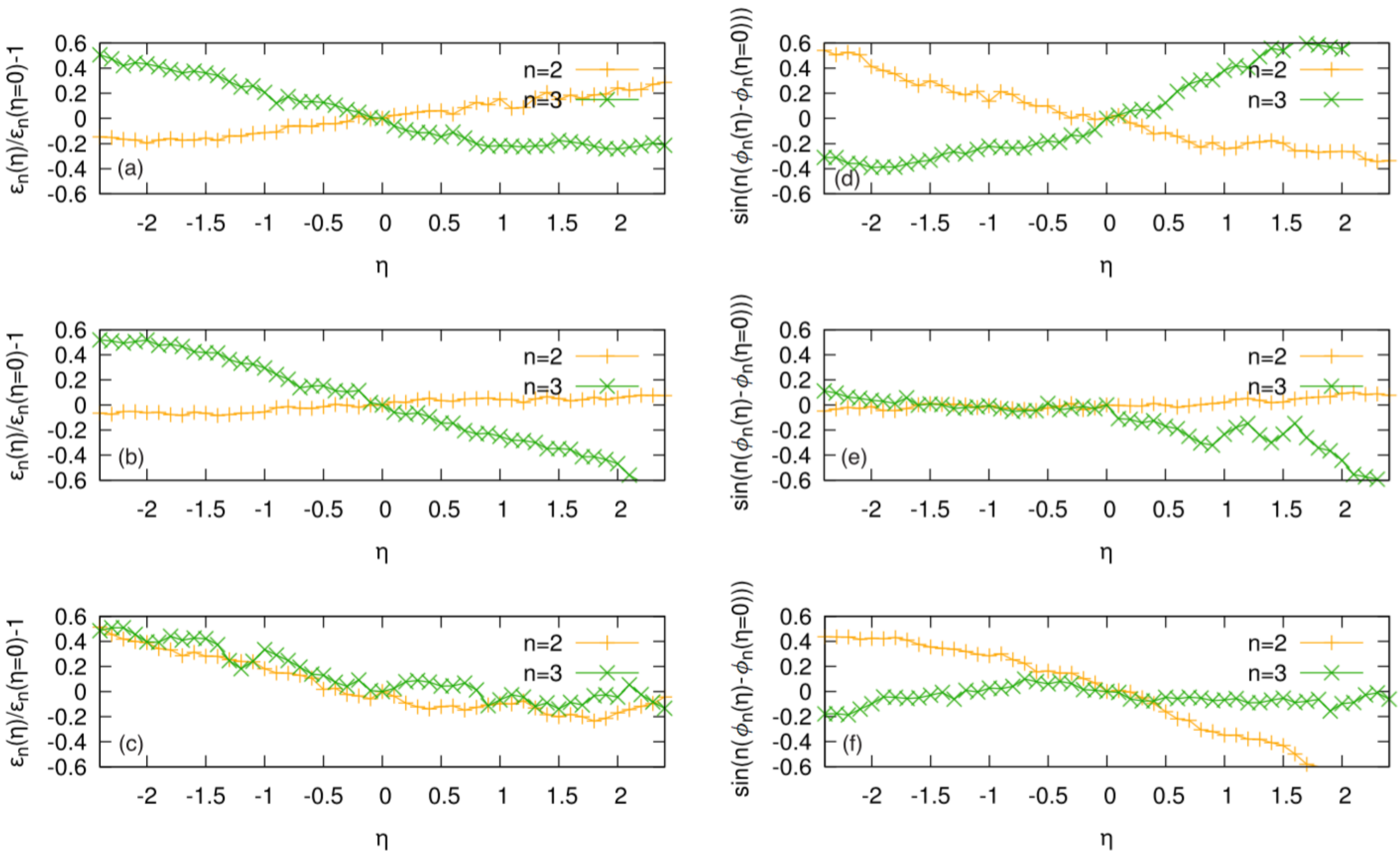
$m = 0.4$ GeV

Dashed lines show results from three single events for each value of the coupling constant.

Experimental Data:
ALICE, Phys. Lett. B 726, 610 (2013)

3D Geometry (eccentricities and angles)

B. Schenke, S. Schlichting, PRC94, 044907 (2016)

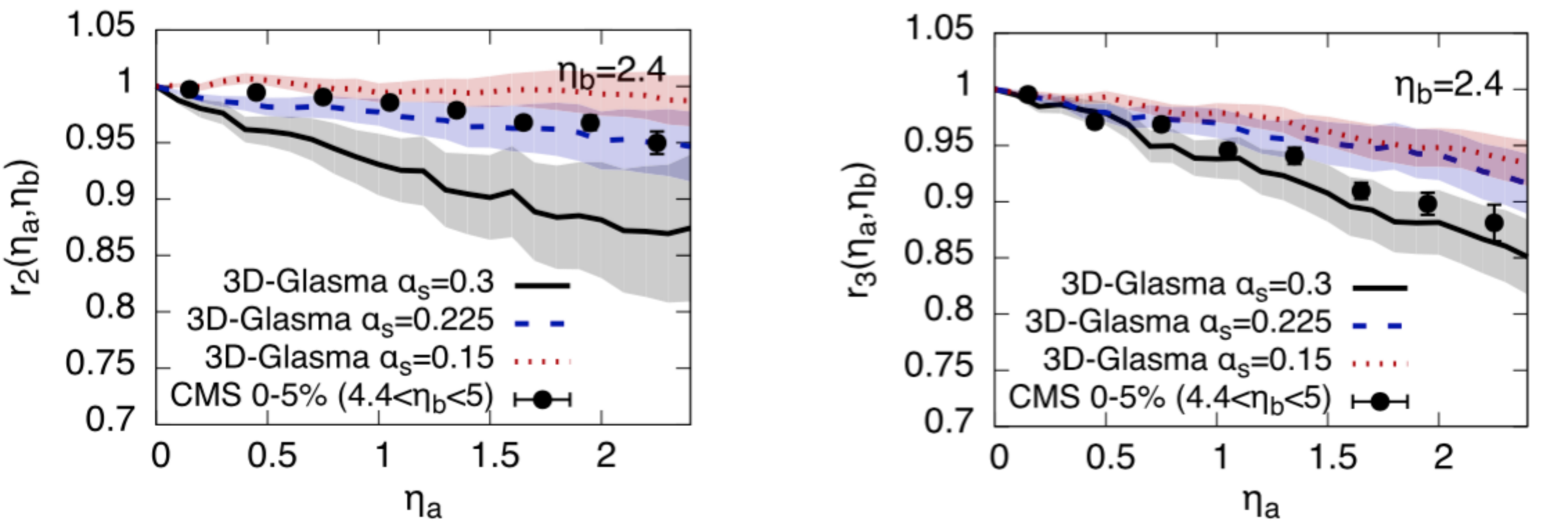


Rapidity decorrelation

B. Schenke, S. Schlichting, PRC94, 044907 (2016)

$$r_n(\eta_a,\eta_b) = \frac{\langle \mathrm{Re}[\boldsymbol{\epsilon}_n(-\eta_a)\cdot\boldsymbol{\epsilon}_n^*(\eta_b)]\rangle}{\langle \mathrm{Re}[\boldsymbol{\epsilon}_n(\eta_a)\cdot\boldsymbol{\epsilon}_n^*(\eta_b)]\rangle}$$

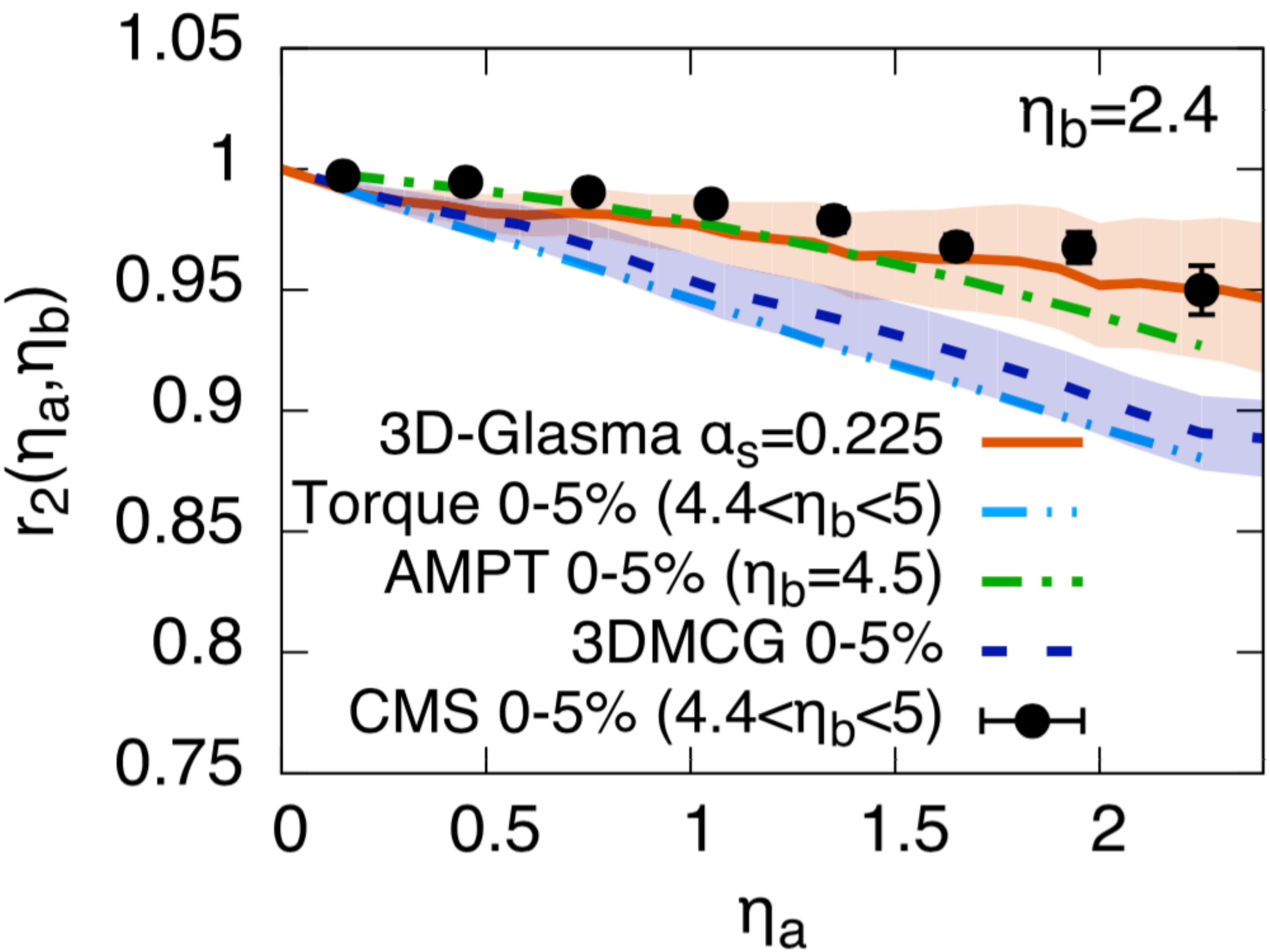
$$= \frac{\langle \epsilon_n(-\eta_a)\epsilon_n(\eta_b)\cos[n(\phi_n(-\eta_a)-\phi_n(\eta_b))]\rangle}{\langle \epsilon_n(\eta_a)\epsilon_n(\eta_b)\cos[n(\phi_n(\eta_a)-\phi_n(\eta_b))]\rangle}$$



Experimental Data: CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

Decorrelation measure

B. Schenke, S. Schlichting, PRC94, 044907 (2016)



Torque: P. Bozek and W. Broniowski, Phys. Lett. B 752, 206 (2016)
AMPT: L.G. Pang, H. Petersen, G.Y. Qin, V. Roy, and X.N. Wang, Eur.Phys.J.A52, 97
3DMCG: A. Monnai and B. Schenke, Phys. Lett. B 752, 317 (2016)
Experimental Data: CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

Strong coupling limit

Initial conditions can be computed using AdS/CFT correspondence by solving Einstein's equations for the collision of two shock-waves

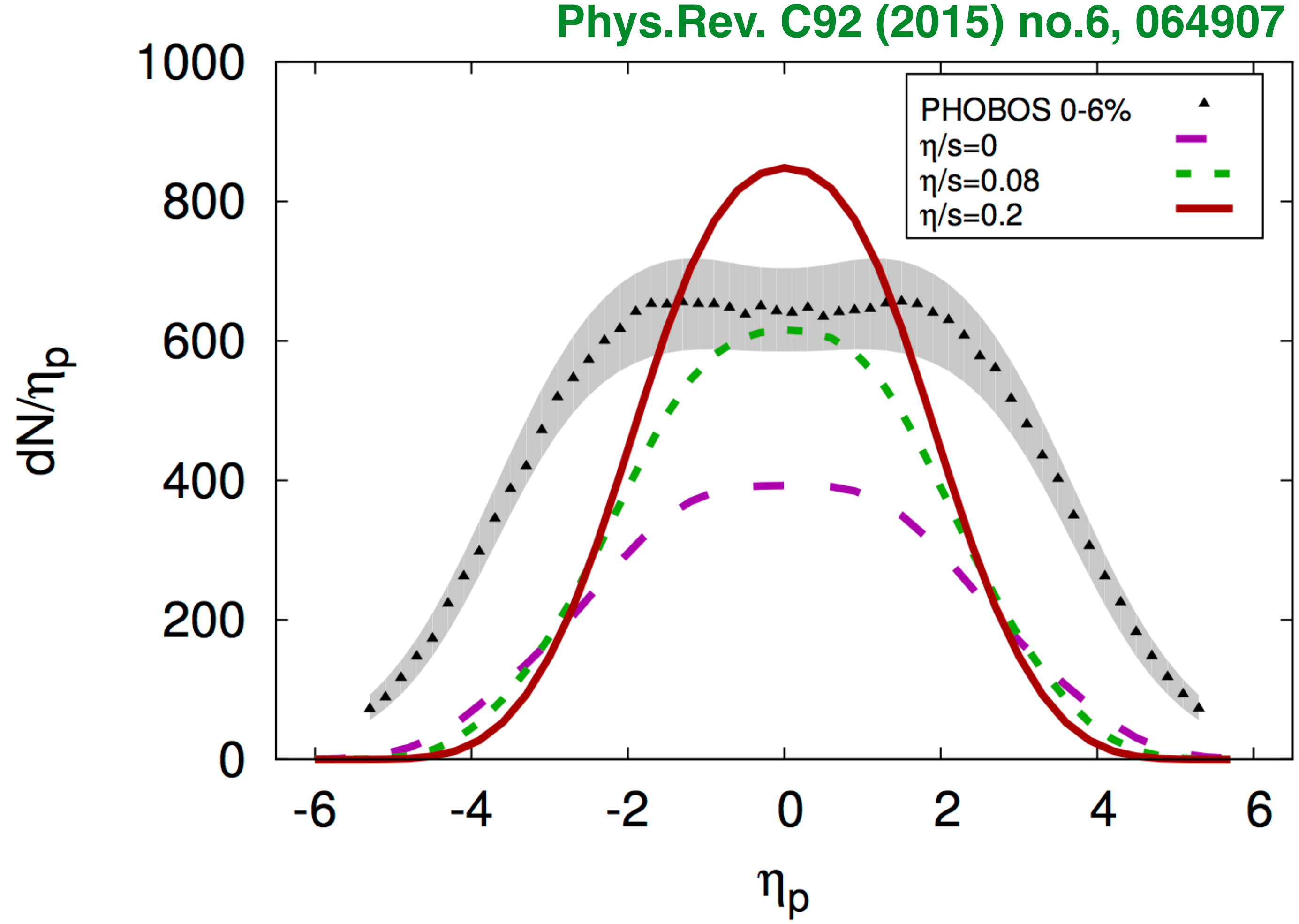
Energy momentum tensor is obtained from the near-boundary expansion (in coordinate z) of the line-element

Results are not boost-invariant in fact - typically have too strong a rapidity dependence:

See e.g. the recent review:
P. Romatschke, U. Romatschke, arXiv:1712.05815

No time to go into more detail here

W. van der Schee, B. Schenke
Phys.Rev. C92 (2015) no.6, 064907



Summary and Outlook

- Most successful initial states at high energies:
  IP-Glasma and EKRT
- TRENTO is a fast and convenient parametrization reproducing some of the two models features - and verifying that they are compatible with data
- More recently models for 3D spatial structures are emerging
- Dynamical 3D initial state with source term is highly relevant for lower collision energies in e.g. the RHIC Beam Energy Scan
- Also IP-Glasma can be extended to 3 dimensions using JIMWLK evolution of the colliding nuclei