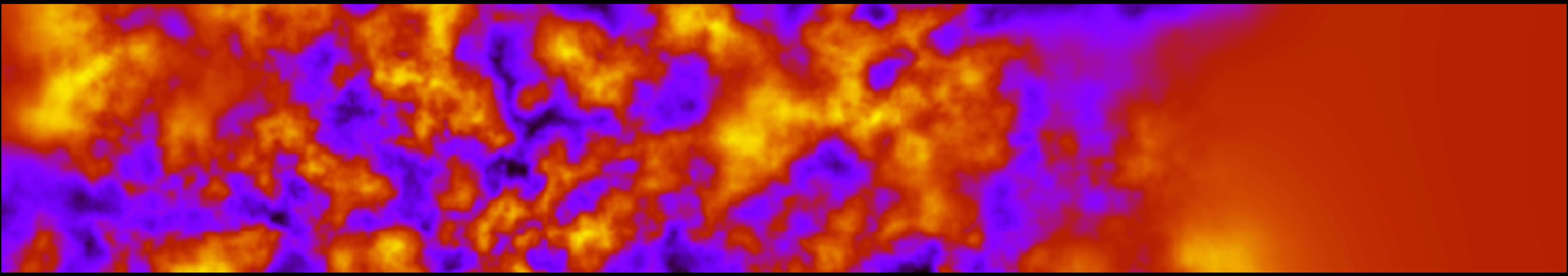
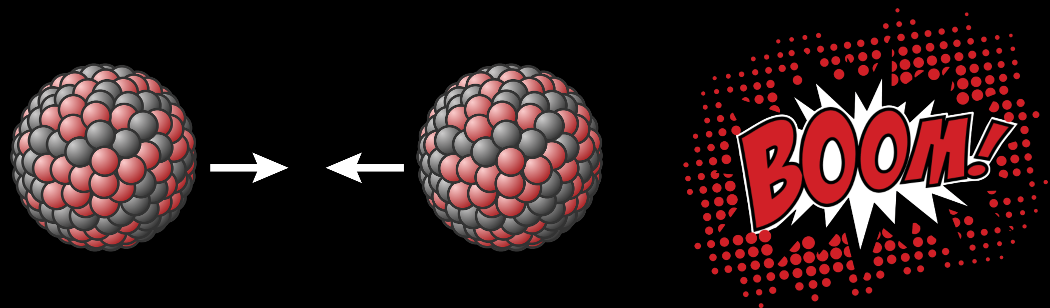
INITIAL STATE FLUCTUATIONS IN HEAVY ION COLLISIONS

Björn Schenke
Brookhaven National Laboratory

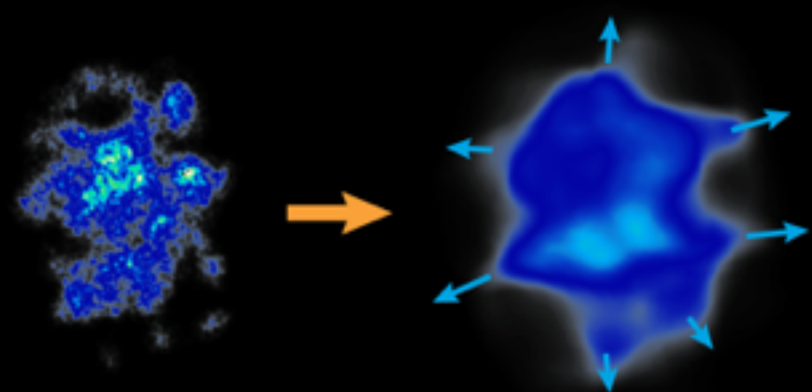


November 5, 2016
XII Polish Workshop on Relativistic Heavy-Ion Collisions
Institute of Physics, Jan Kochanowski University
Kielce, Poland

HEAVY ION COLLISIONS, FLUID DYNAMICS AND THE INITIAL STATE

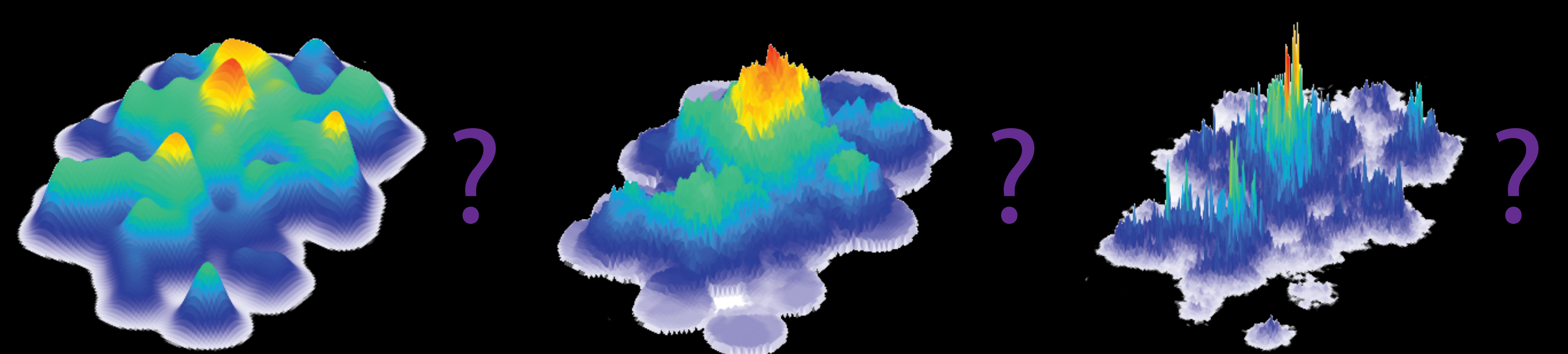


Fluid dynamics apparently describes the bulk observables in heavy ion collisions



Final results are strongly dependent on the initial state and its fluctuations

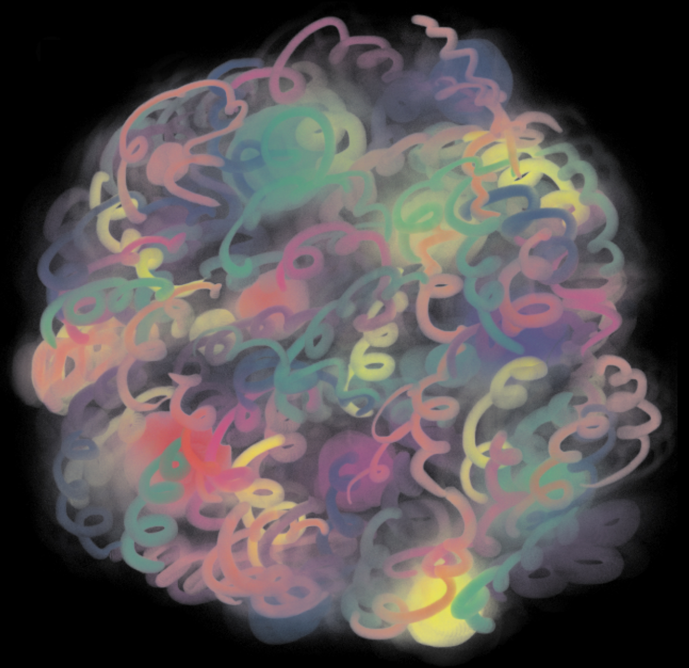
Need a rigorous understanding of the initial state



COLOR GLASS CONDENSATE INITIAL STATE

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Gluon number increases with decreasing gluon momentum
- Gluon saturation at $p_T \lesssim Q_s(\mathbf{x}, \mathbf{b})$
- Strong fields with occupation $\sim 1/\alpha_s$
  Classical description possible
- IP-Sat model parametrizes $Q_s(\mathbf{x}, \mathbf{b})$
  (simple way to include impact parameter dependence)
  KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Fit parameters to HERA diffractive data



COMPUTING THE INITIAL STATE

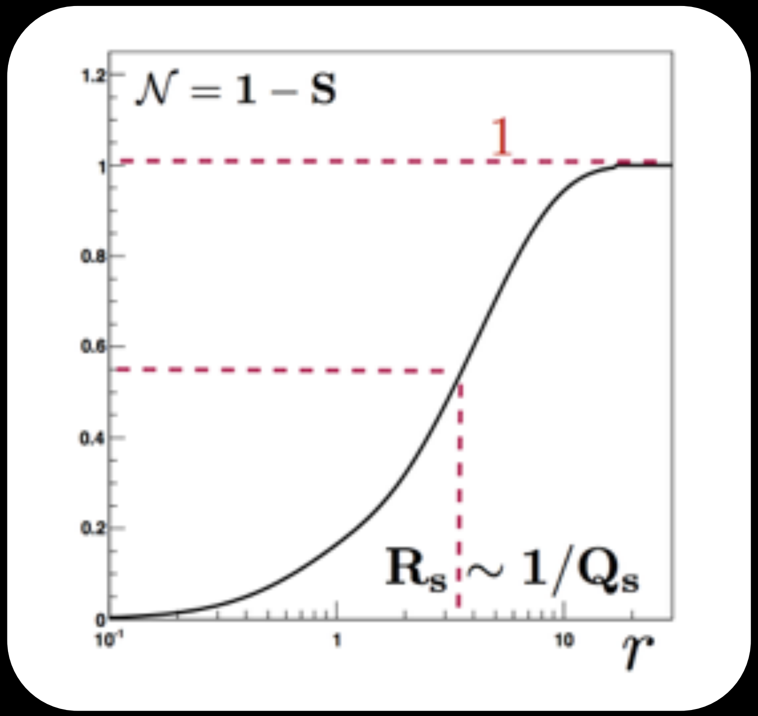
B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

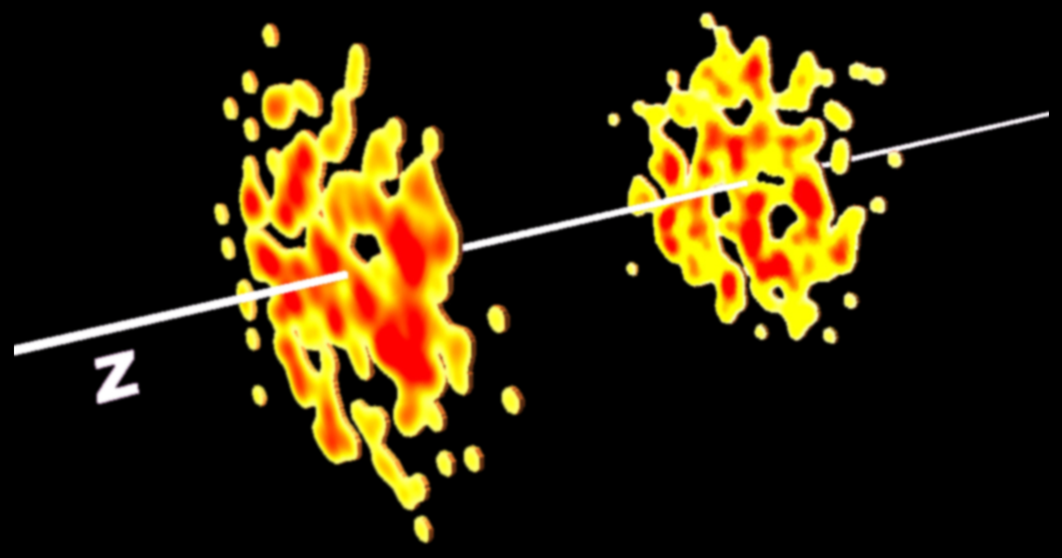
- Sample nucleon positions from Woods-Saxon distribution

- Add all (Gaussian) thickness functions

$$\frac{\mathrm{d}\sigma^{\mathrm{p}}_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{x}_T}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\,\mathcal{N}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_T^2\alpha_s(Q^2)xg(x, Q^2)\sum_{i=1}^{A} T_p(\mathbf{x}_T - \mathbf{x}_T^i)\right)\right]$$

- Extract $Q_s(x, \mathbf{x}_T)$ and get color charge density distributions





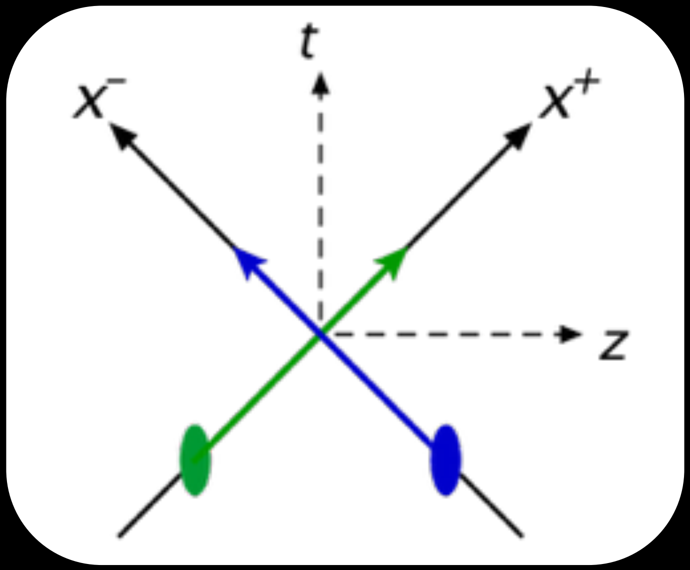
CLASSICAL GLUON FIELDS

MCLERRAN, VENUGOPALAN, PHYS.REV. D49 (1994) 3352-3355

Sample color charges $\rho_{(1,2)}(x^{\pm}, \mathbf{x}_\perp)$ - SU(3)

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

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



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

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

Solution in covariant gauge or A^-=0 gauge:

$$A^+_{\mathrm{cov}}(x^-, \mathbf{x}_\perp) = -\frac{g\rho_1(x^-, \mathbf{x}_\perp)}{\nabla_\perp^2 + m^2}$$

$m \sim \Lambda_{\mathrm{QCD}}$

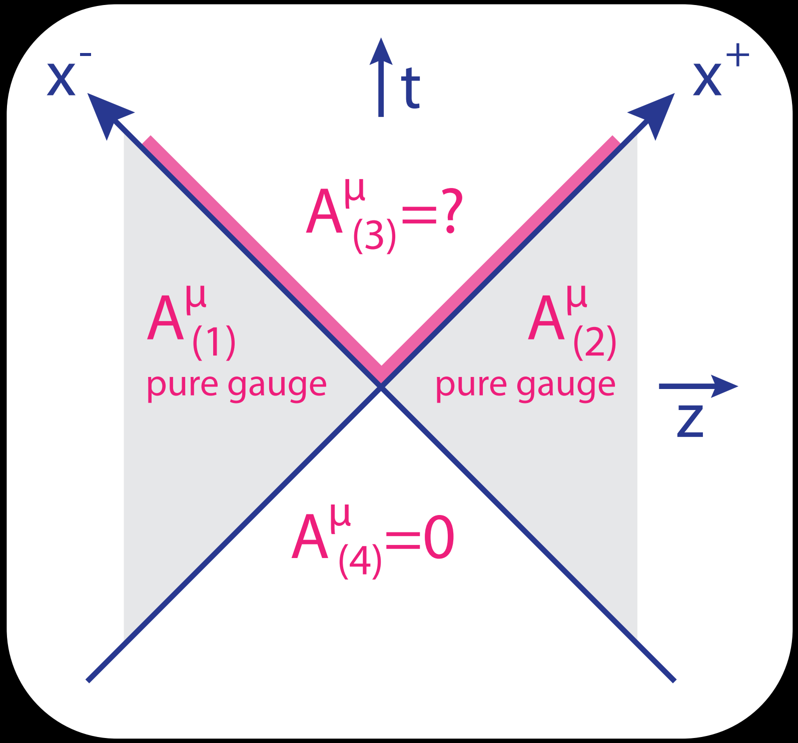
Solution in lightcone gauge:

$$A^+_{(1,2)}(\mathbf{x}_\perp) = A^-_{(1,2)}(\mathbf{x}_\perp) = 0$$

$$A^i_{(1,2)}(\mathbf{x}_\perp) = \frac{i}{g} V_{(1,2)}(\mathbf{x}_\perp)\partial_i V^\dagger_{(1,2)}(\mathbf{x})$$

GAUGE FIELDS AFTER THE COLLISION

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)



CONFIGURATION IN SCHWINGER GAUGE

Solution:

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

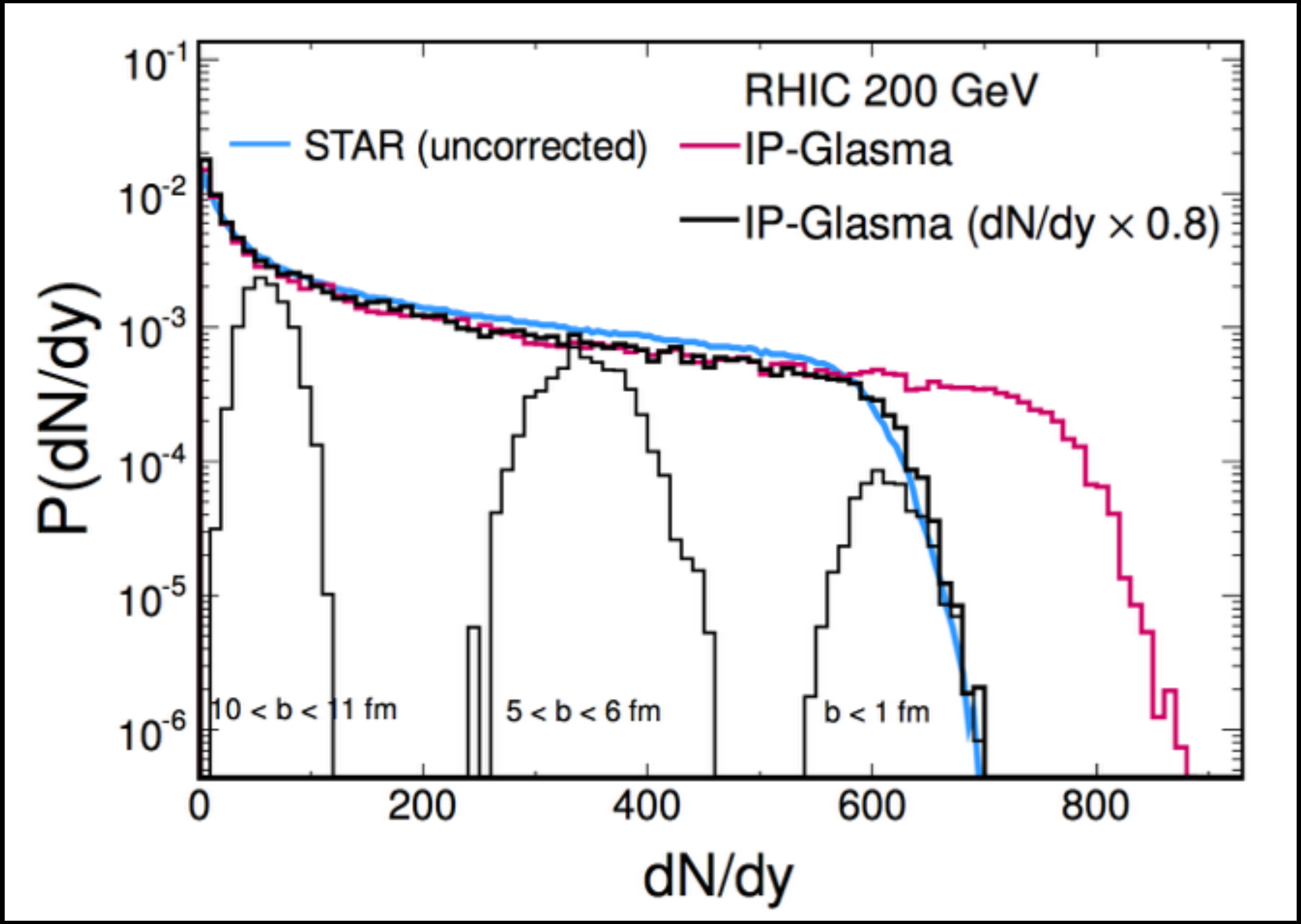
We solve for the gauge fields numerically

KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237

Time evolution follows free Yang-Mills equations

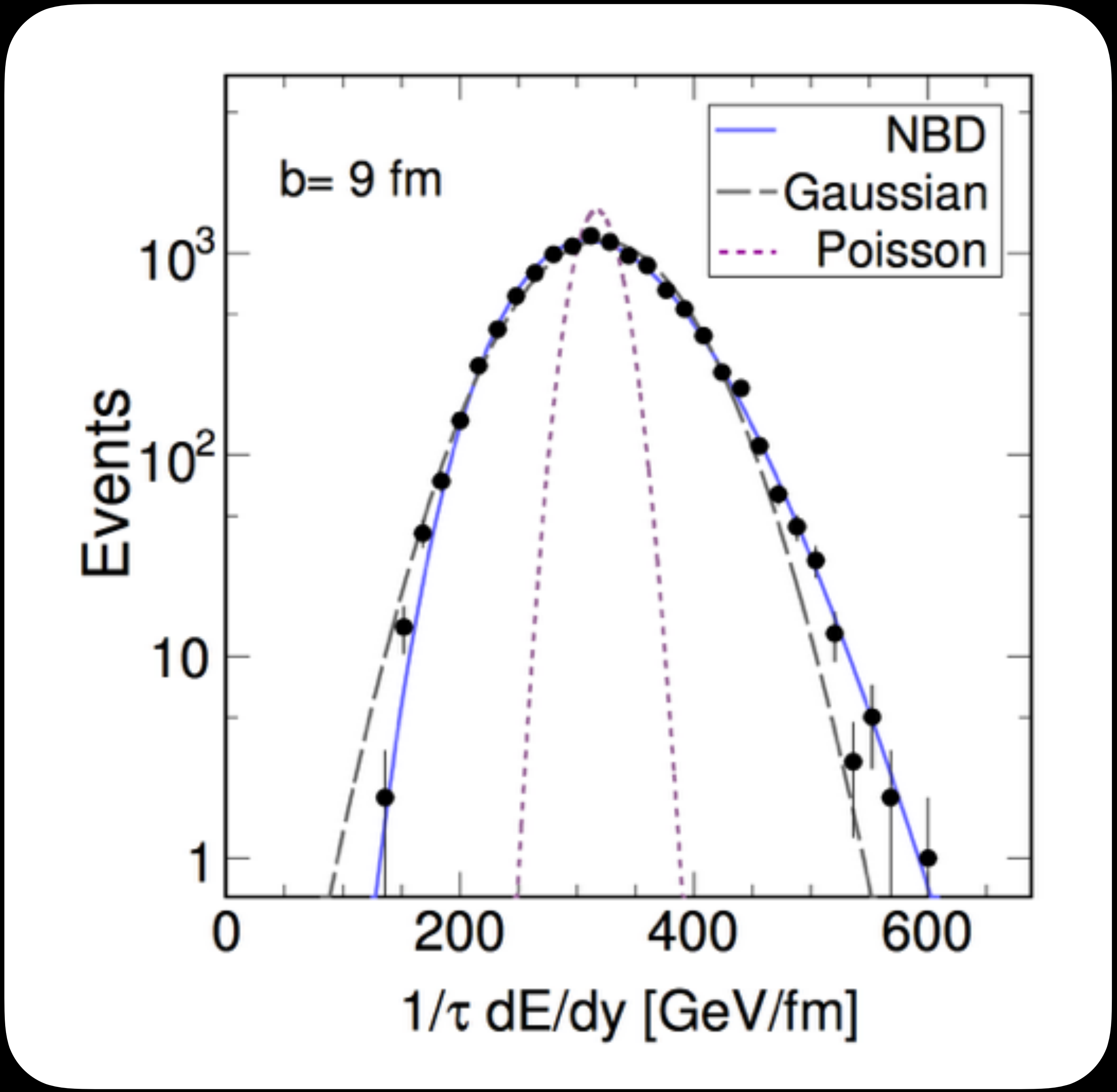
MULTIPLICITY DISTRIBUTIONS

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)



TRANSVERSE ENERGY DISTRIBUTION

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)



At fixed impact parameter, the multiplicity and energy distribution is given by a negative binomial

$$P(n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

ALSO SEE F. GELIS, T. LAPPI, L. MCLERRAN, NUCL.PHYS. A828 (2009) 149-160

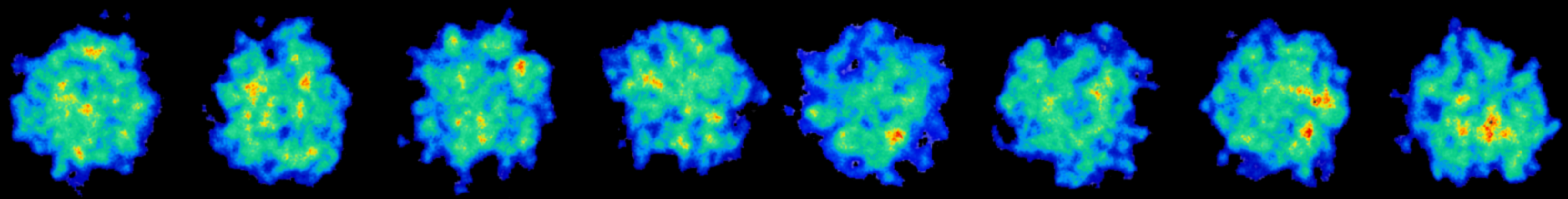
INITIAL STATE AND FLUID DYNAMICS

C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)

- Compute energy-momentum tensor $T^{\mu\nu}$ of the gluon fields
- Extract energy density and flow vector via $u_\mu T^{\mu\nu} = \varepsilon u^\nu$
- This provides the initial conditions for fluid dynamic simulations
- In first calculations used $\Pi^{\mu\nu} = 0$
- We can also match the shear viscous tensor

EVENT-BY-EVENT FLUID DYNAMICS

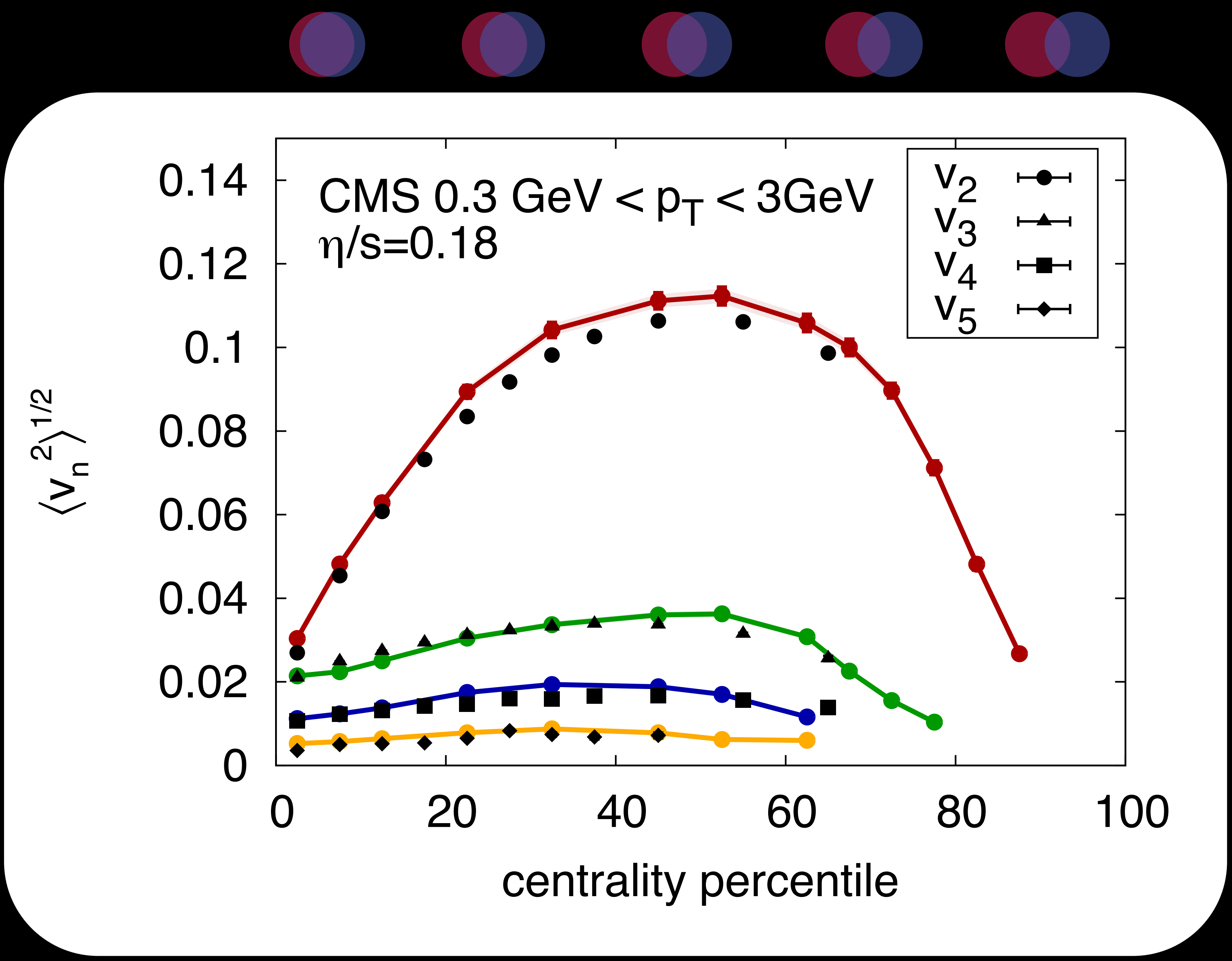
C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)



- Evolve many initial shapes using viscous fluid dynamics
- Convert energy density to particles (“freeze-out”)
- Determine v_n coefficients of particle distributions
- Average and compare to experimental data

FLOW HARMONICS v_n

CMS COLLABORATION, PRC 87(2013) 014902, ARXIV:1310.8651



EVENT-BY-EVENT FLOW

ATLAS COLLABORATION, JHEP 1311 (2013) 183

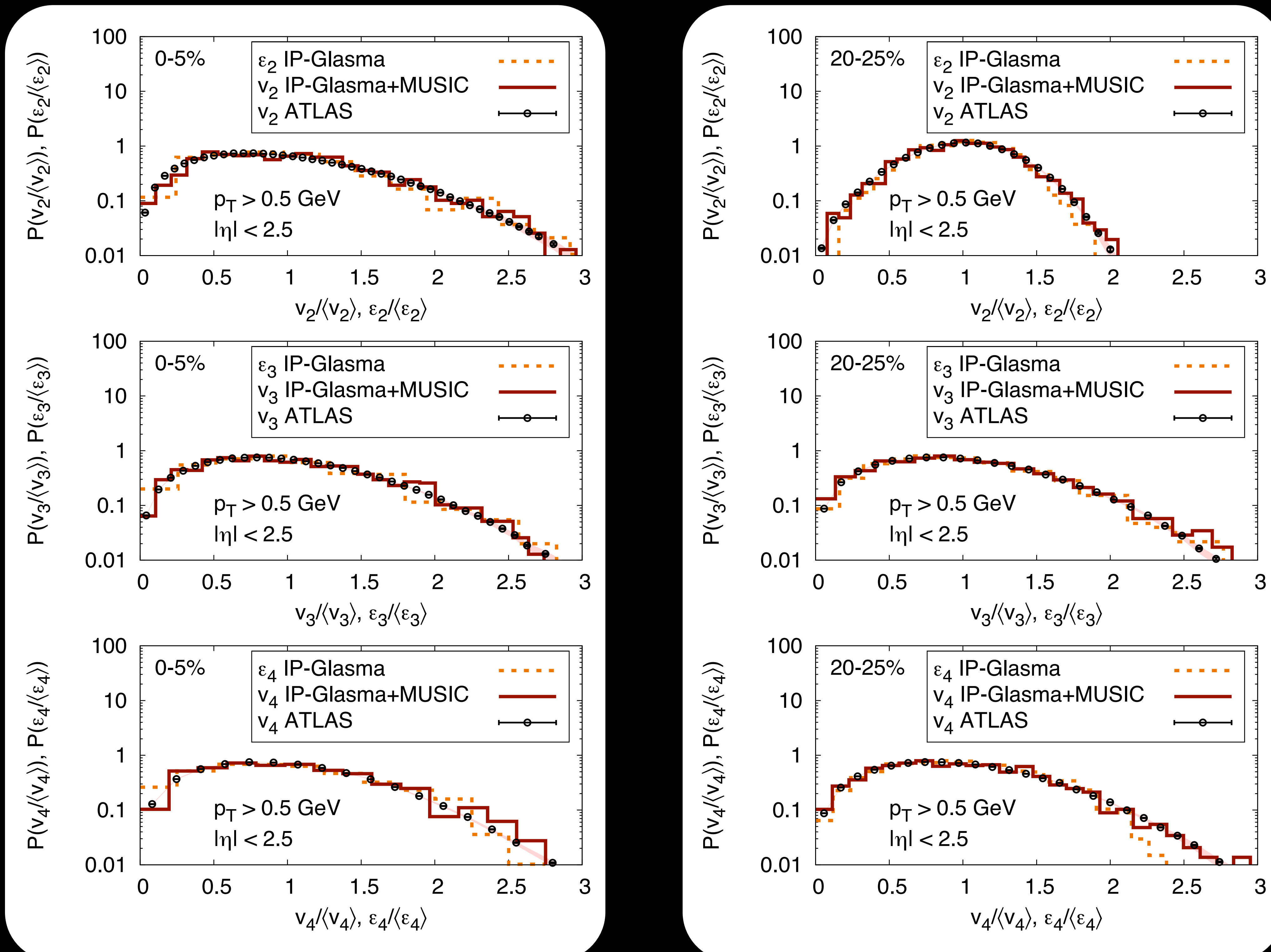
C. GALE, S. JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL110, 012302 (2013)

0-5% | 20-25%

v_2

v_3

v_4

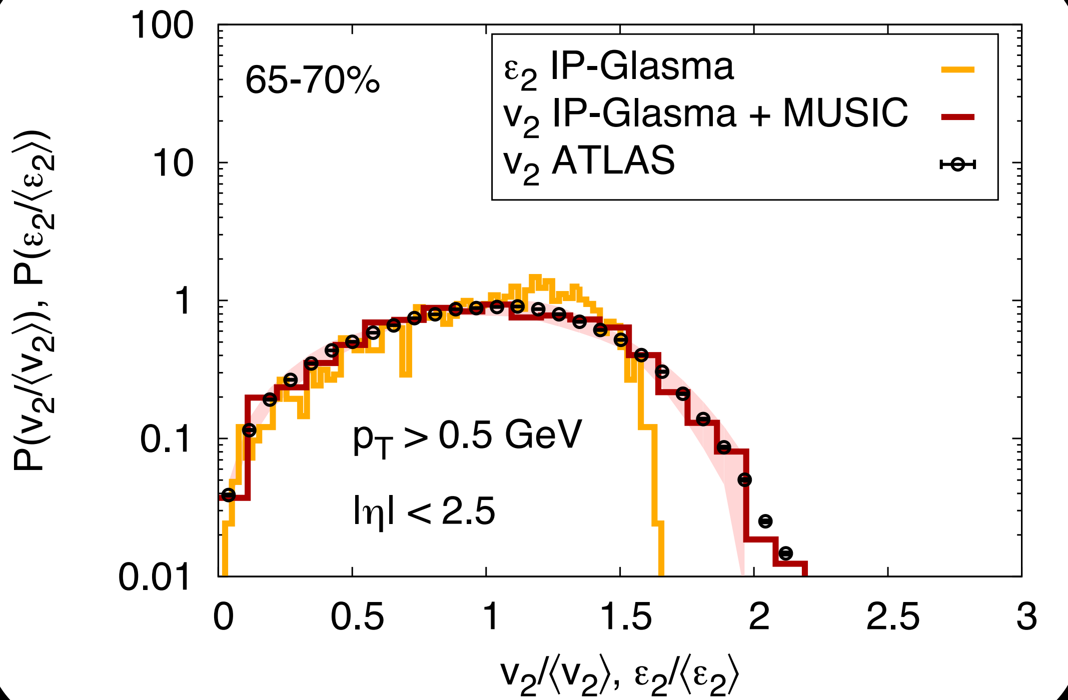


EVENT-BY-EVENT FLOW

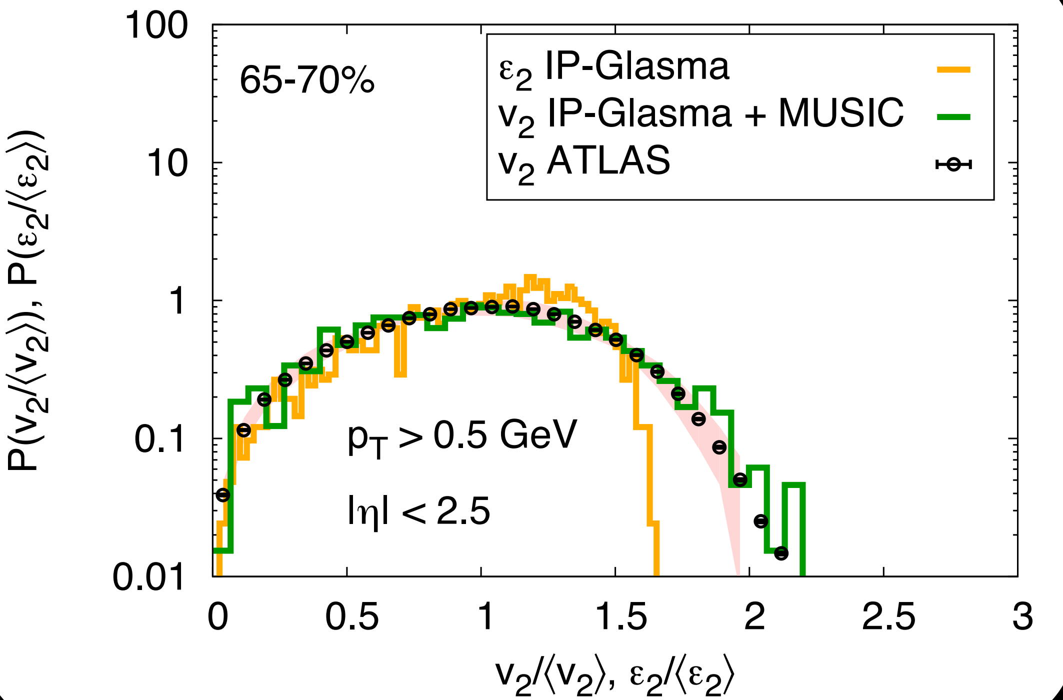
ATLAS COLLABORATION, JHEP 1311 (2013) 183

v_2

65-70%



65-70% IDEAL



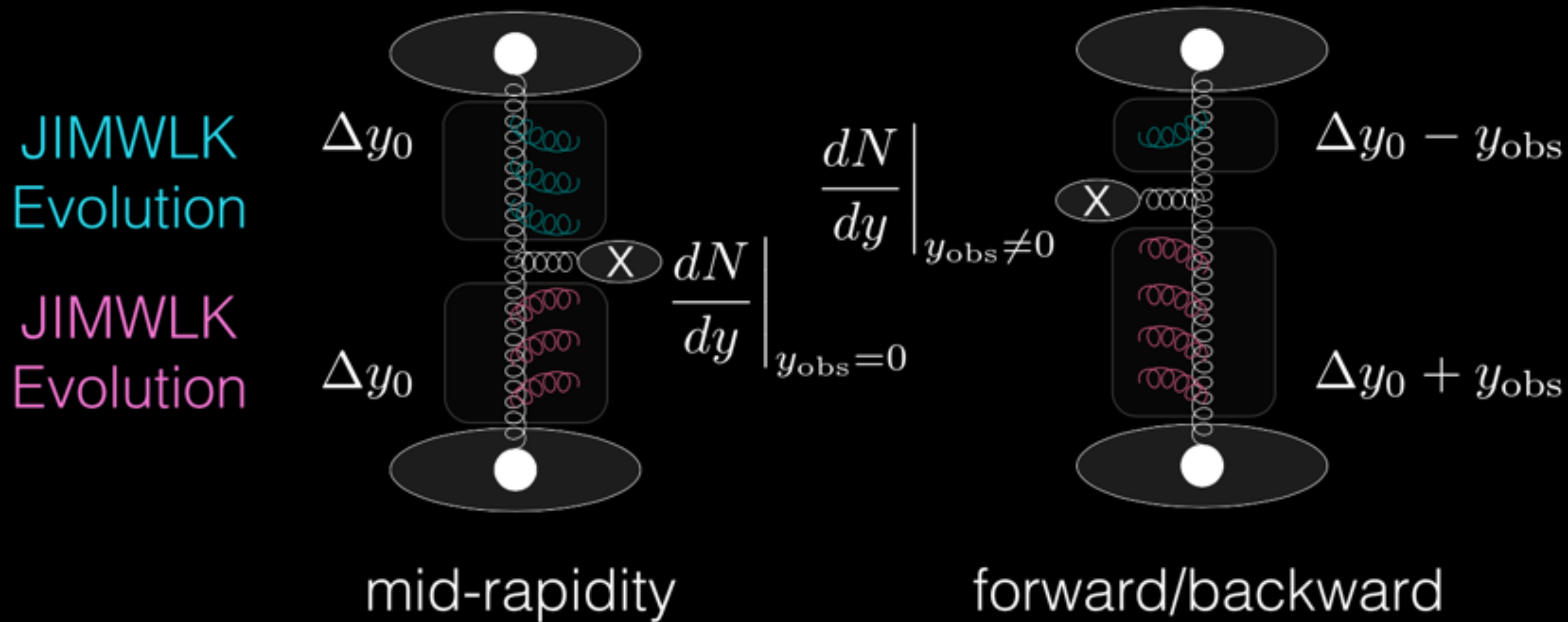
GOING 3D

EXISTING 3D INITIAL STATE MODELS ARE VERY SIMPLISTIC

NOW DO A FIRST PRINCIPLES 3D CALCULATION USING CLASSICAL YANG-MILLS + QCD JIMWLK EVOLUTION

3D GLASMA INITIAL STATE

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)



3D GLASMA INITIAL STATE

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. MANTYSAARI, EUR. PHYS. J. C 73, 2307 (2013)

$$V_{\mathbf{x}}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot(V_{\mathbf{z}}\boldsymbol{\xi}_{\mathbf{z}}V_{\mathbf{z}}^{\dagger})\right\}$$
$$\times V_{\mathbf{x}}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot\boldsymbol{\xi}_{\mathbf{z}}\right\}$$

ξ is Gaussian noise with zero average and

$$\left\langle \xi^{a}_{\mathbf{x},i}(Y)\xi^{b}_{\mathbf{y},j}(Y')\right\rangle = \delta^{ab}\delta^{ij}\delta^{(2)}_{\mathbf{xy}}\delta(Y-Y')$$

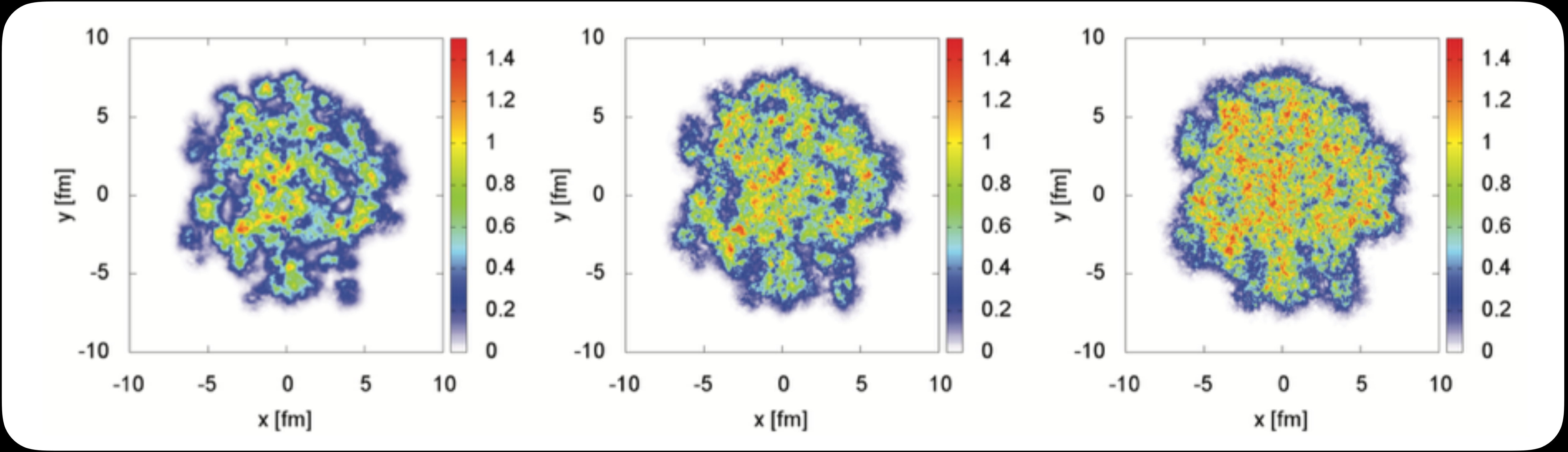
The JIMWLK Kernel is modified to avoid infrared tails:

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

3D GLASMA INITIAL STATE

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)

GLUON FIELDS IN A NUCLEUS AT DIFFERENT *x*:

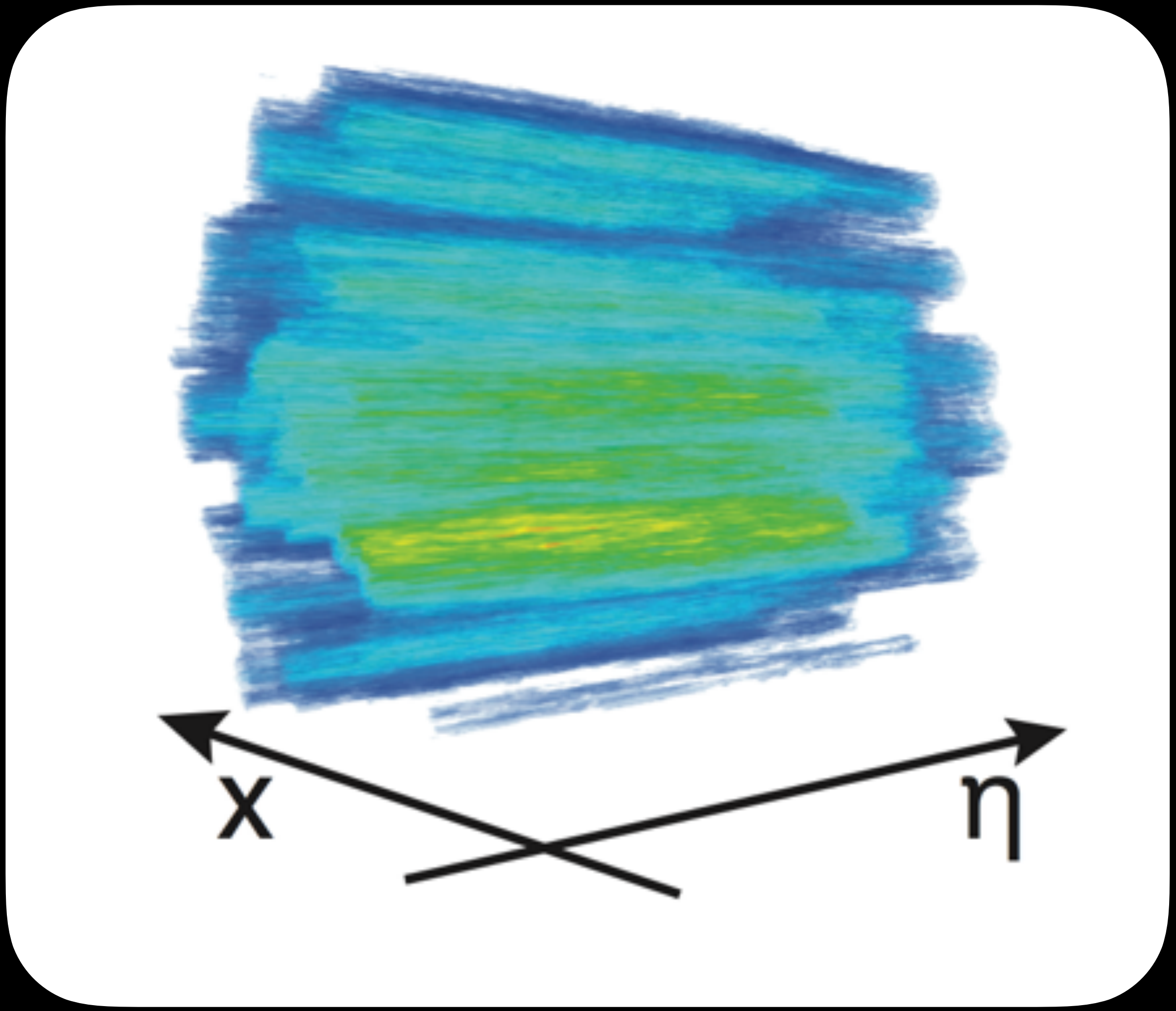


$Y = -2.4$ ($x \approx 2\times10^{-3}$) $Y = 0$ ($x \approx 2\times10^{-4}$) $Y = 2.4$ ($x \approx 1.6\times10^{-5}$)

3D GLASMA INITIAL STATE

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)

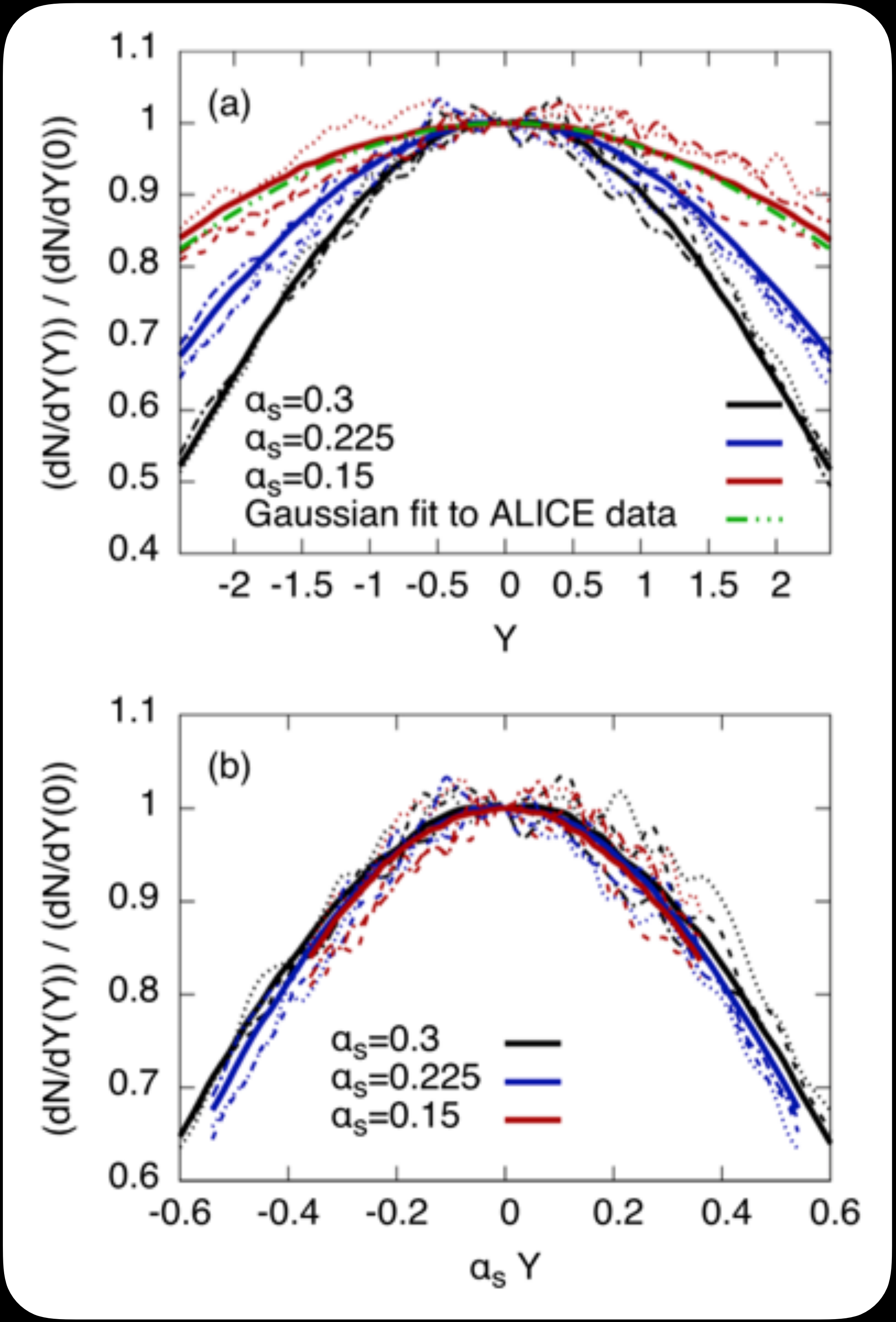
- COLLIDE TWO JIMWLK EVOLVED NUCLEI



ENERGY DENSITY

GLUON RAPIDITY DISTRIBUTION

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)



Gluon multiplicity relative to its value at Y = 0

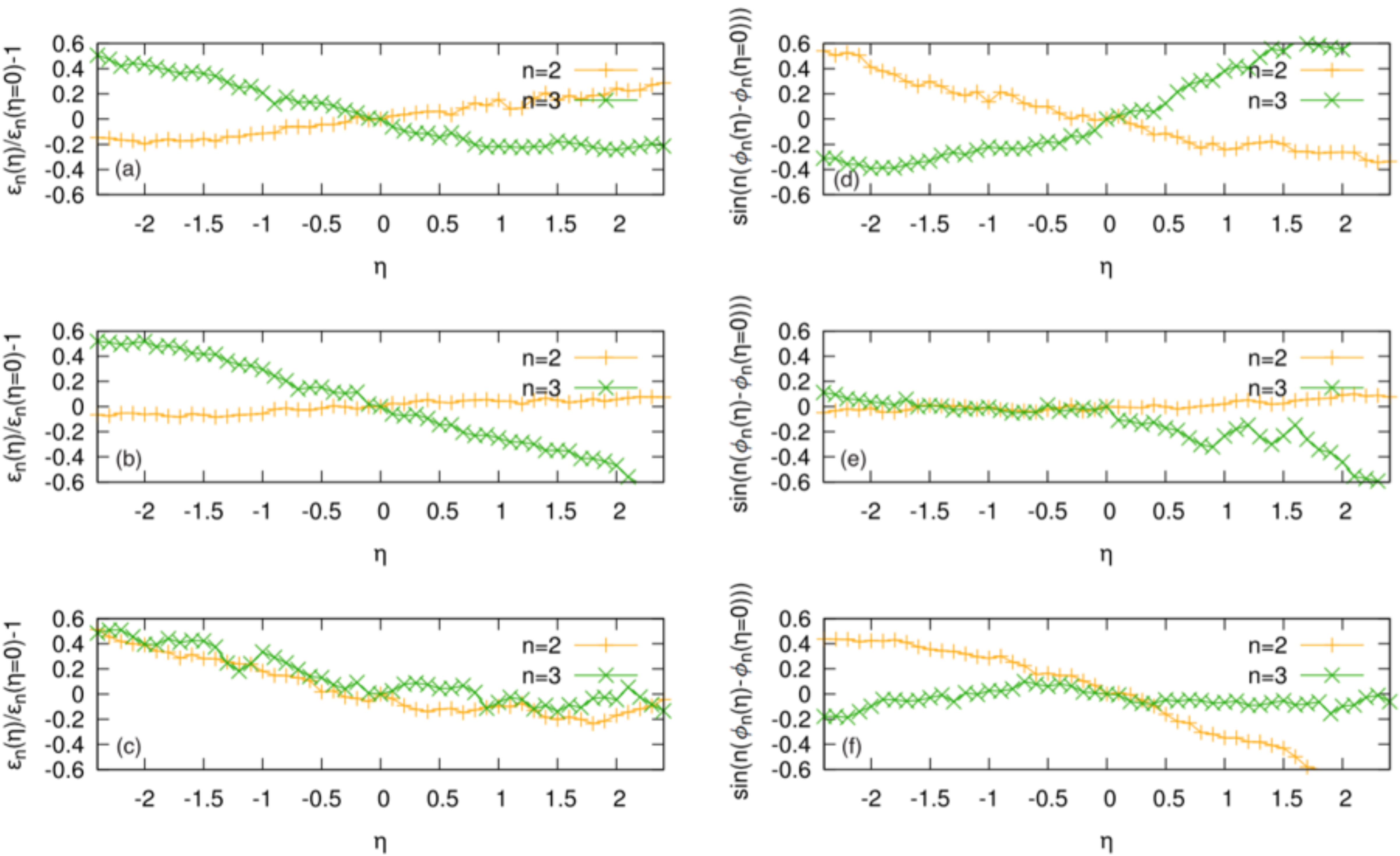
m = 0.4 GeV

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

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)

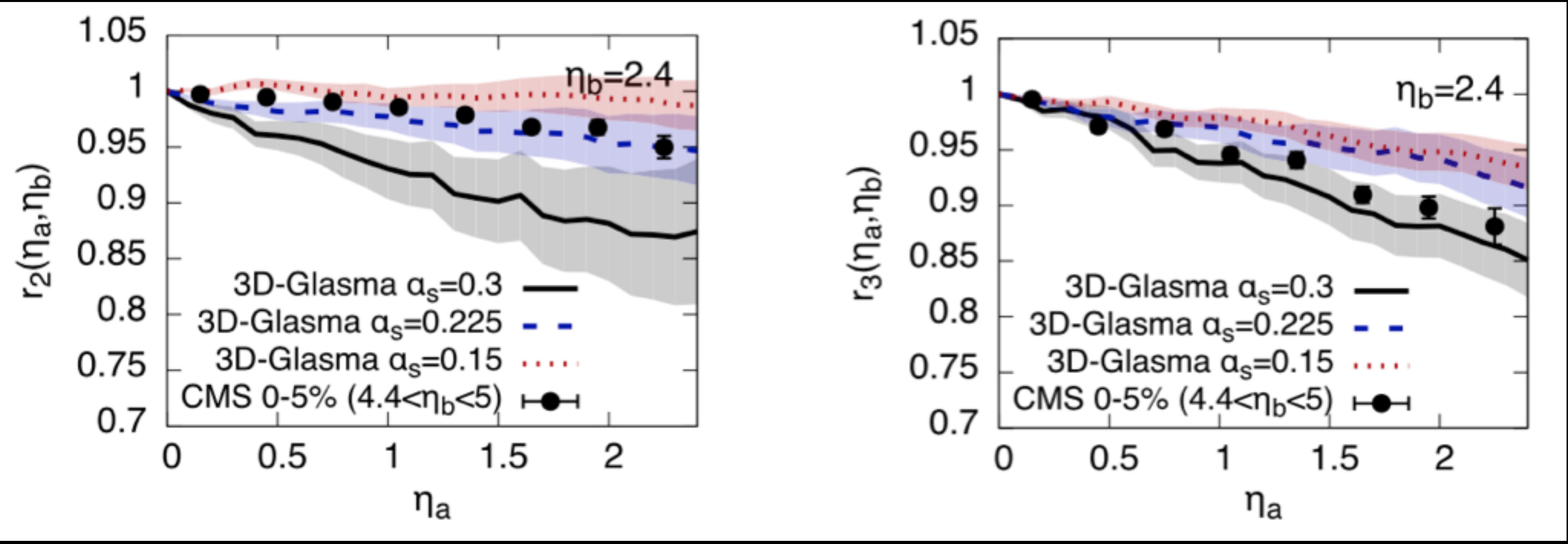


DECORRELATION MEASURE

B. SCHENKE, S. SCHLICHTING, PRC94, 044907 (2016)

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

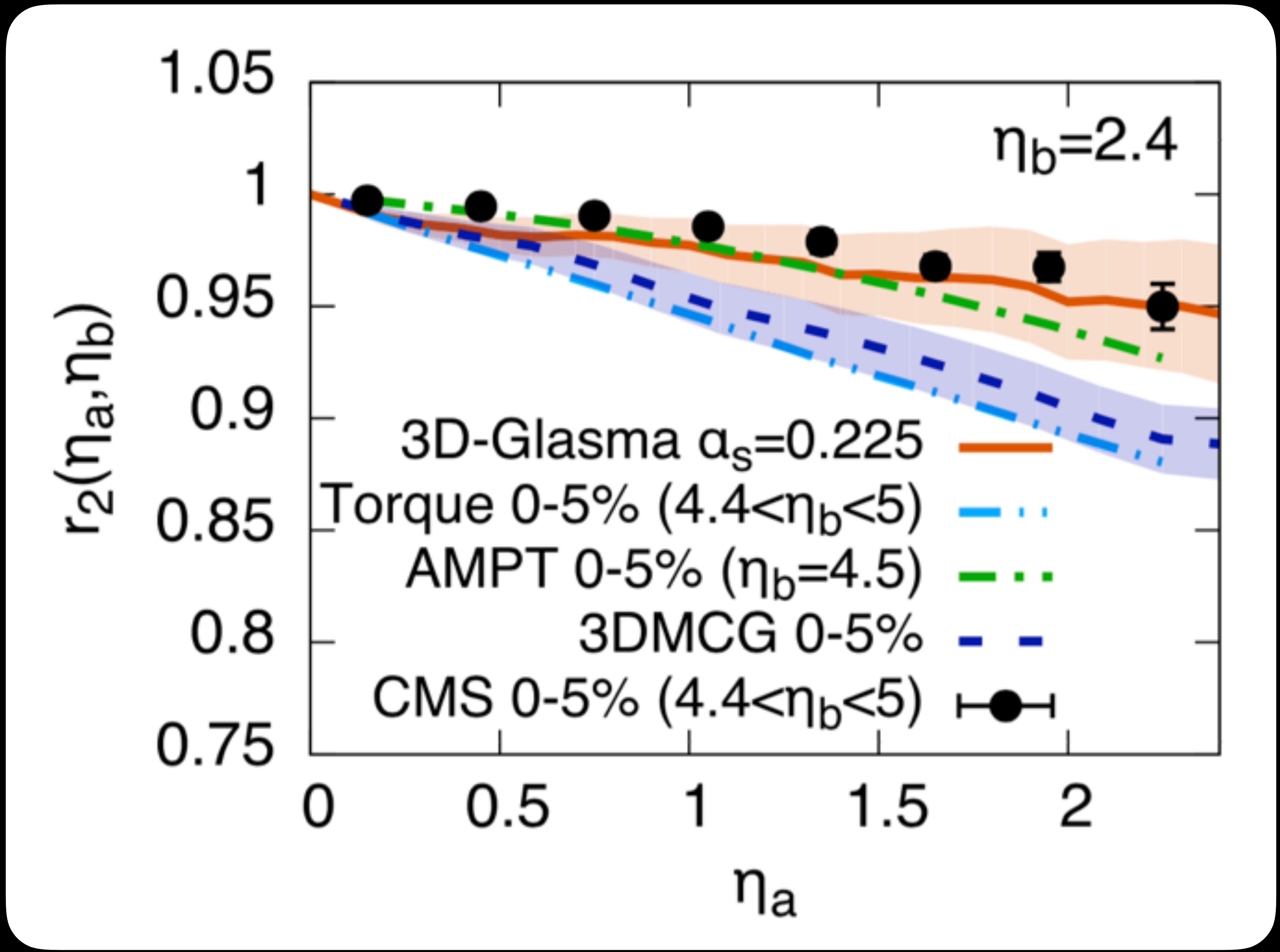
$$= \frac{\langle \epsilon_n(-\eta_a)\epsilon_n(\eta_b)\cos\{n[\phi_n(-\eta_a)-\phi_n(\eta_b)]\}\rangle}{\langle \epsilon_n(\eta_a)\epsilon_n(\eta_b)\cos\{n[\phi_n(\eta_a)-\phi_n(\eta_b)]\}\rangle}$$



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)

QUANTUM FLUCTUATIONS (NOW INSTABILITIES!)

Quantum fluctuations beyond the logarithmically enhanced contribution should be taken into account

At one-loop level these fluctuations only enter in the initial state, not the time evolution

Full 3-dimensional Yang-Mills simulations can be performed - they will include instabilities and a possible way to isotropization

CLASSICAL STATISTICAL SIMULATIONS

Initial condition: T. Epelbaum, F. Gelis, Phys.Rev.Lett. 111 (2013) 232301

Sum of the LO classical field A^μ and a fluctuating part

$$A^{\mu a}(x) = \mathcal{A}^{\mu a}(x) + \sum_{\lambda,c} \int \frac{d^3\boldsymbol{k}}{(2\pi)^3 2|\boldsymbol{k}|} \left[c_{\boldsymbol{k}\lambda c}\, a^{\mu a}_{\boldsymbol{k}\lambda c}(x) + \text{c.c.} \right] ,$$

$$\langle c_{\boldsymbol{k}\lambda c} \rangle = 0 \, , \quad \langle c_{\boldsymbol{k}\lambda c} c^*_{\boldsymbol{k}'\lambda' c'} \rangle = \frac{1}{2}\, 2|\boldsymbol{k}|\, (2\pi)^3 \delta(\boldsymbol{k} - \boldsymbol{k}')\, \delta_{\lambda\lambda'}\, \delta_{cc'} \, .$$

Alternative: J. Berges, K. Boguslavski, S. Schlichting, and R. Venugopalan, Phys. Rev. D89, 074011 (2014)

Classical gluon gas with distribution f(k)

no non-fluctuating part

$$A^{\mu a}(x) = \sum_{\lambda,c} \int \frac{d^3\boldsymbol{k}}{(2\pi)^3 2|\boldsymbol{k}|} \left[c_{\boldsymbol{k}\lambda c}\, a^{\mu a}_{\boldsymbol{k}\lambda c}(x) + \text{c.c.} \right] ,$$

$$\langle c_{\boldsymbol{k}\lambda c} \rangle = 0 \, , \quad \langle c_{\boldsymbol{k}\lambda c} c^*_{\boldsymbol{k}'\lambda' c'} \rangle = f(\boldsymbol{k})\, 2|\boldsymbol{k}|\, (2\pi)^3 \delta(\boldsymbol{k} - \boldsymbol{k}')\, \delta_{\lambda\lambda'}\, \delta_{cc'}$$

CLASSICAL STATISTICAL SIMULATIONS

The two initial states describe very different systems, despite their similarity:

- The flat spectrum of fluctuations on top of a classical field describes a quantum coherent state
  Combined with classical time evolution leads to results that are very sensitive to the ultraviolet cutoff
  T. Epelbaum, F. Gelis, Phys.Rev.Lett. 111 (2013) 232301

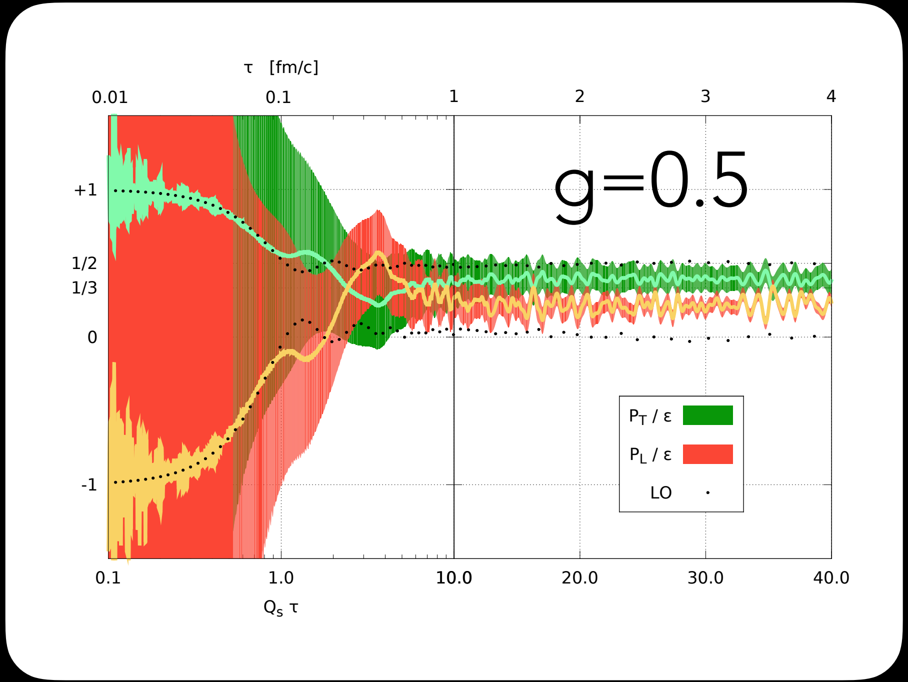
- The compact spectrum describes an incoherent classical state
  J. Berges, K. Boguslavski, S. Schlichting, and R. Venugopalan, Phys. Rev. D89, 074011 (2014)

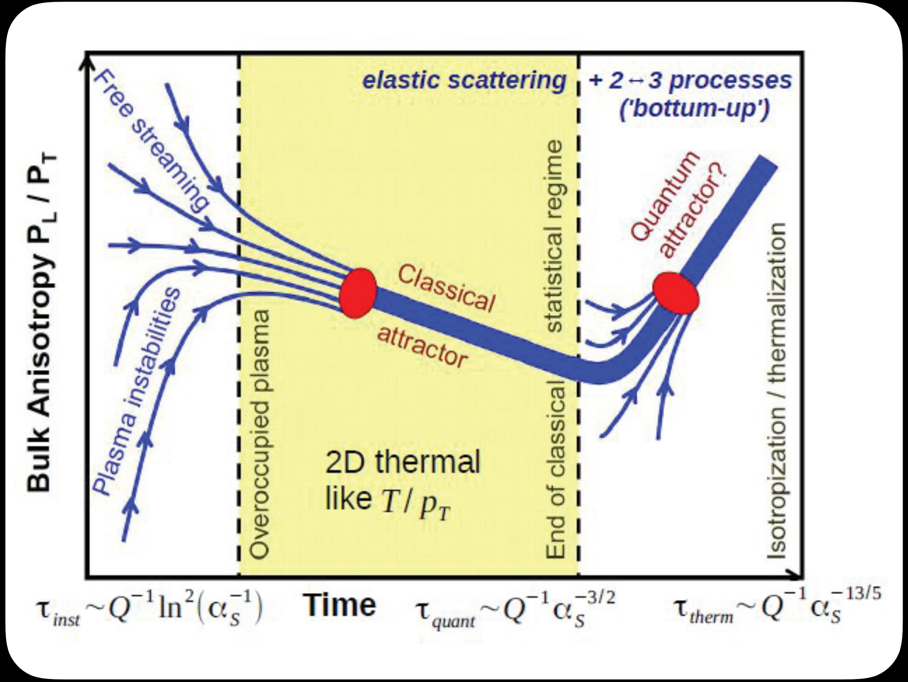
PLASMA INSTABILITIES

First approach at coupling g=0.5 leads to fast isotropization, but strong dependence on UV cutoff

Second prescription has been used at much smaller coupling and extrapolated - no fast isotropization seen

Generally issues with renormalizability





T. Epelbaum, F. Gelis, and B. Wu, Phys. Rev. D90, 065029 (2014)
T. Epelbaum, F. Gelis, N. Tanji, and B. Wu, Phys. Rev. D90, 125032 (2014)
J. Berges, K. Boguslavski, S. Schlichting, and R. Venugopalan, Phys. Rev. D89, 074011 (2014)

SUMMARY

- Fluctuating initial state for high energy collisions well described in classical Yang-Mills picture

- Extension to non-boost-invariant framework underway

- Simulation of fully 3+1 dimensional dynamics including quantum fluctuations not conclusive
due to issues with ultraviolet cutoff dependence

- Should include quantum fluctuations without sacrificing renormalizability. 2-particle irreducible approximation of the Kadanoff-Baym equations can achieve this. Also kinetic theory can be used to study effect of quantum fluctuations.
Y. HATTA AND A. NISHIYAMA, NUCL. PHYS. A873, 47 (2012)
A. KURKELA AND Y. ZHU, PHYS. REV. LETT. 115, 182301 (2015)

HAPPY BIRTHDAY, STANISŁAW!

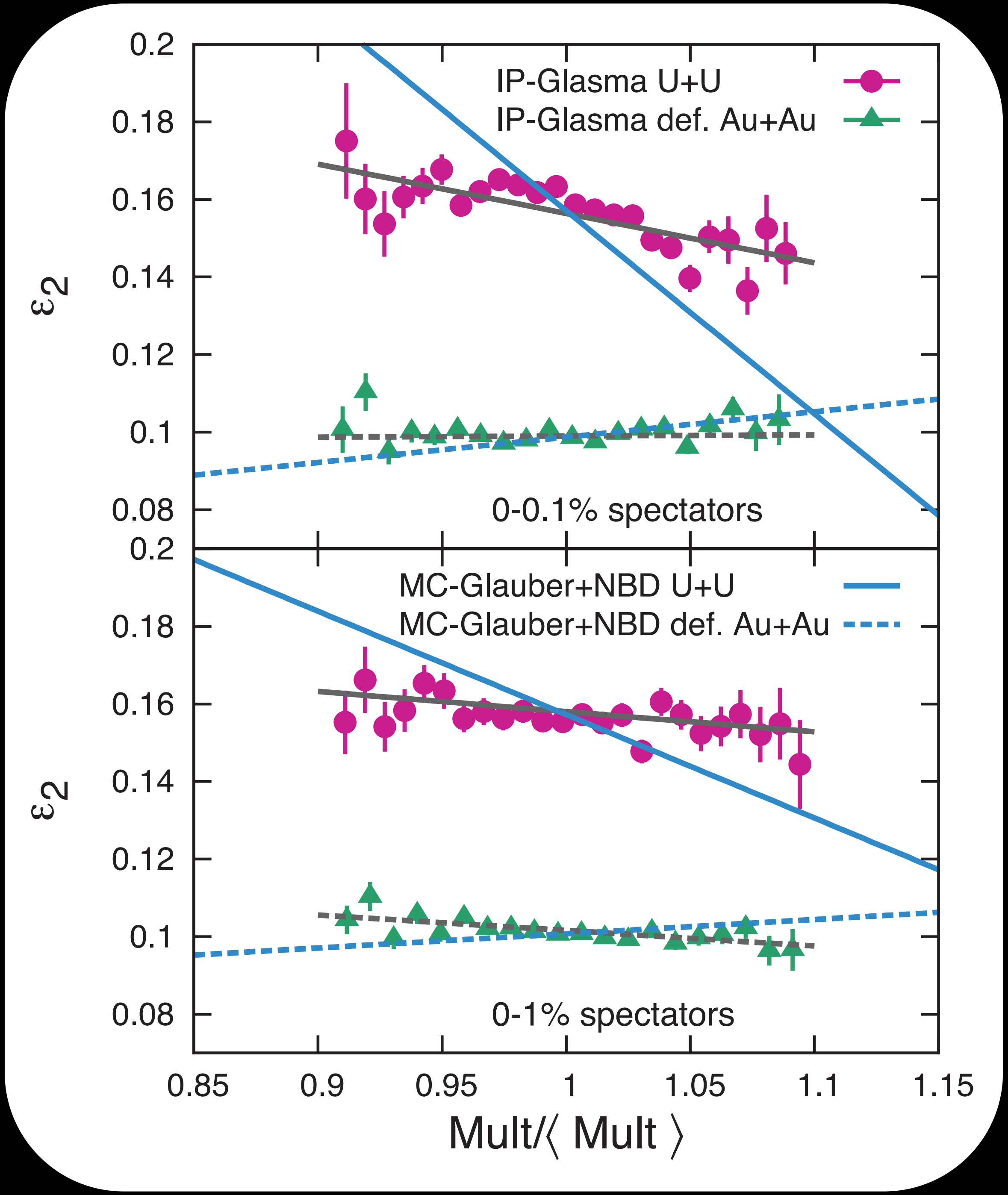
BACKUP

DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232

- Select ultra-central events based on neutrons in the ZDC
- Study correlation between v_2 and multiplicity
- MC-Glauber gets (anti-)correlation because of $N_{\rm coll}$ in

$$\frac{dN}{d\eta} = n_{\rm pp}\left(xN_{\rm coll} + (1-x)\frac{N_{\rm part}}{2}\right)$$

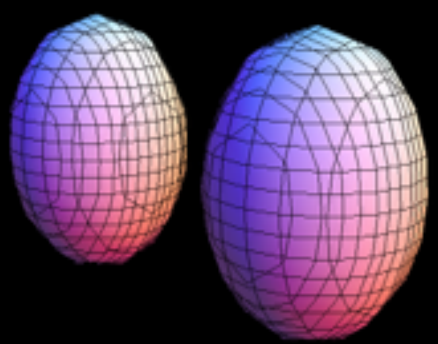


- IP-Glasma finds weaker anti-correlation

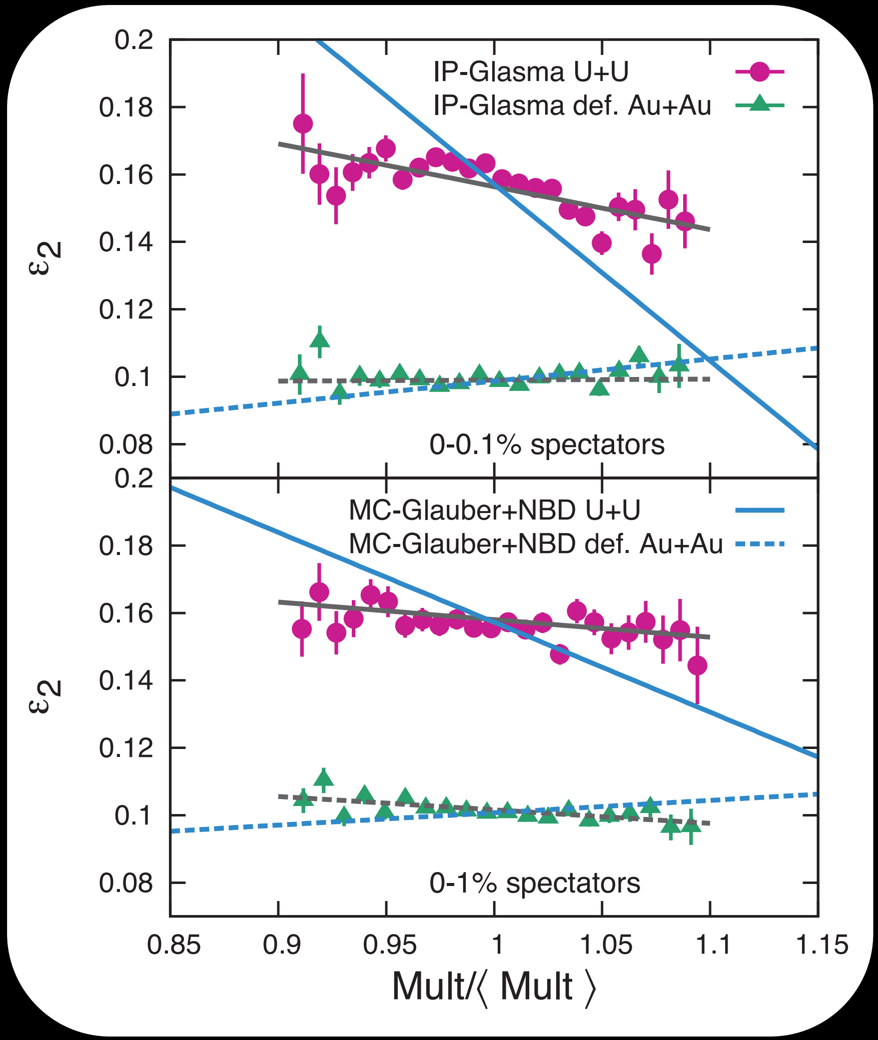
DEFORMED NUCLEI

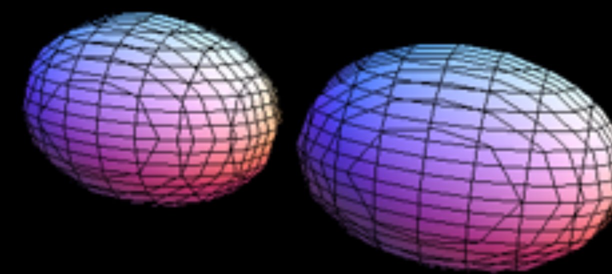
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232

- Uranium: prolate
- Gold: oblate

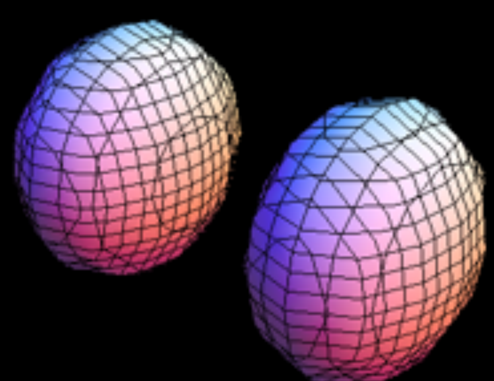


U+U, side-side

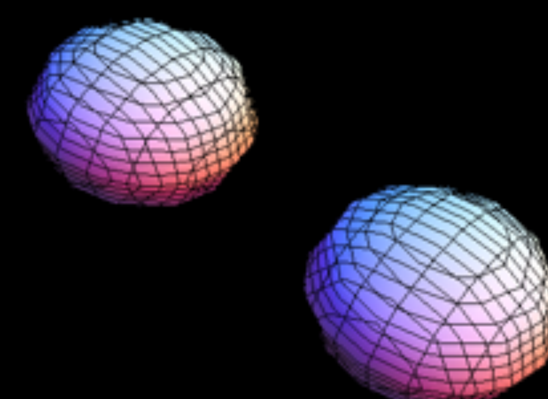




U+U, tip-tip



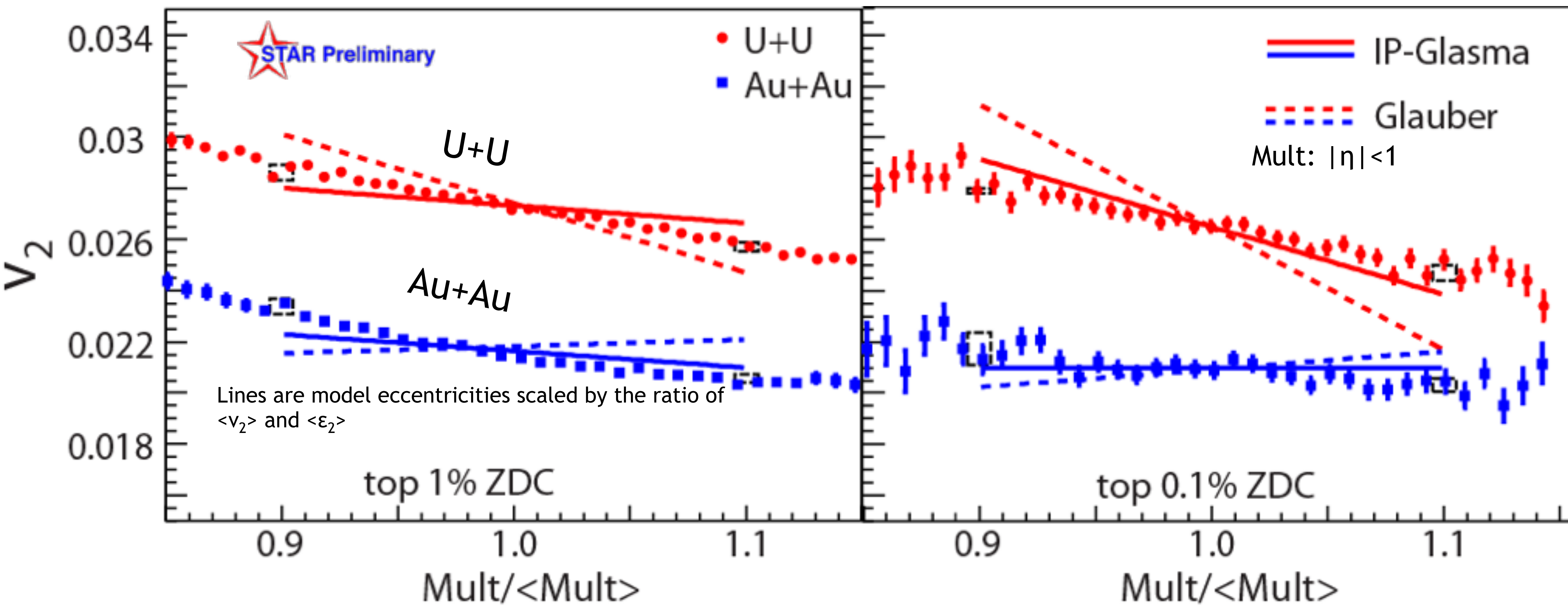
Au+Au, side-side



Au+Au, "tip-tip"

DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232
EXPERIMENTAL DATA: STAR, HUI WANG AT QUARK MATTER 2014



LONGITUDINAL STRUCTURE

A. MONNAI, B. SCHENKE, PHYS. LETT. B752, 317-321 (2015)

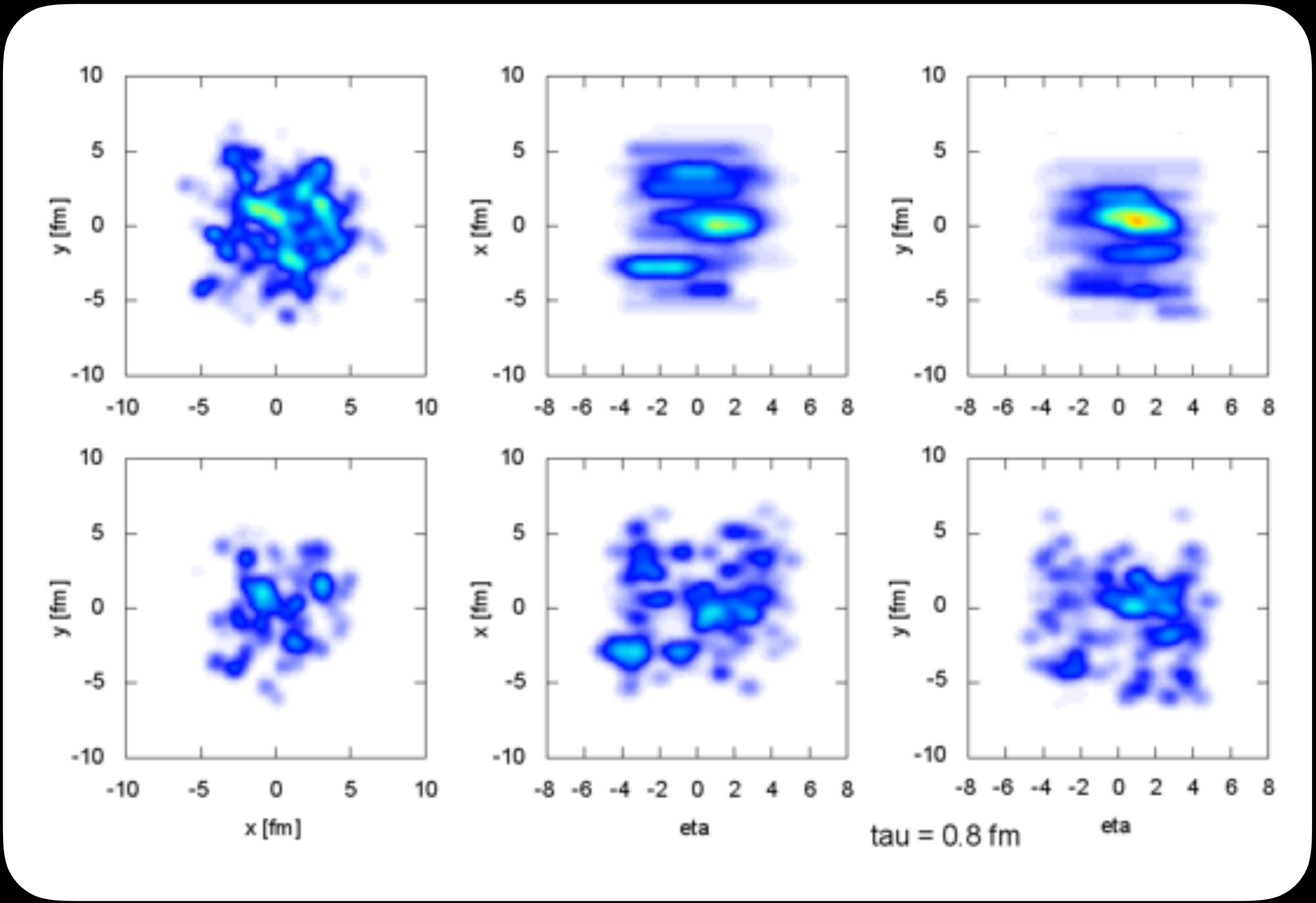
- INCLUDE 3D FLUCTUATING INITIAL STATE
- STUDY v_n AS FUNCTION OF RAPIDITY
- CAN CONSTRAIN RAPIDITY DEPENDENCE OF η/s
- WILL NEED THIS FOR SIMULATIONS OF BES@RHIC

LONGITUDINAL DISTRIBUTION: IMPLEMENT AN MC VERSION OF THE **LEXUS** MODEL

RAPIDITY DISTRIBUTIONS IN HEAVY ION COLLISIONS FOLLOW VIA LINEAR EXTRAPOLATION FROM P+P COLLISIONS

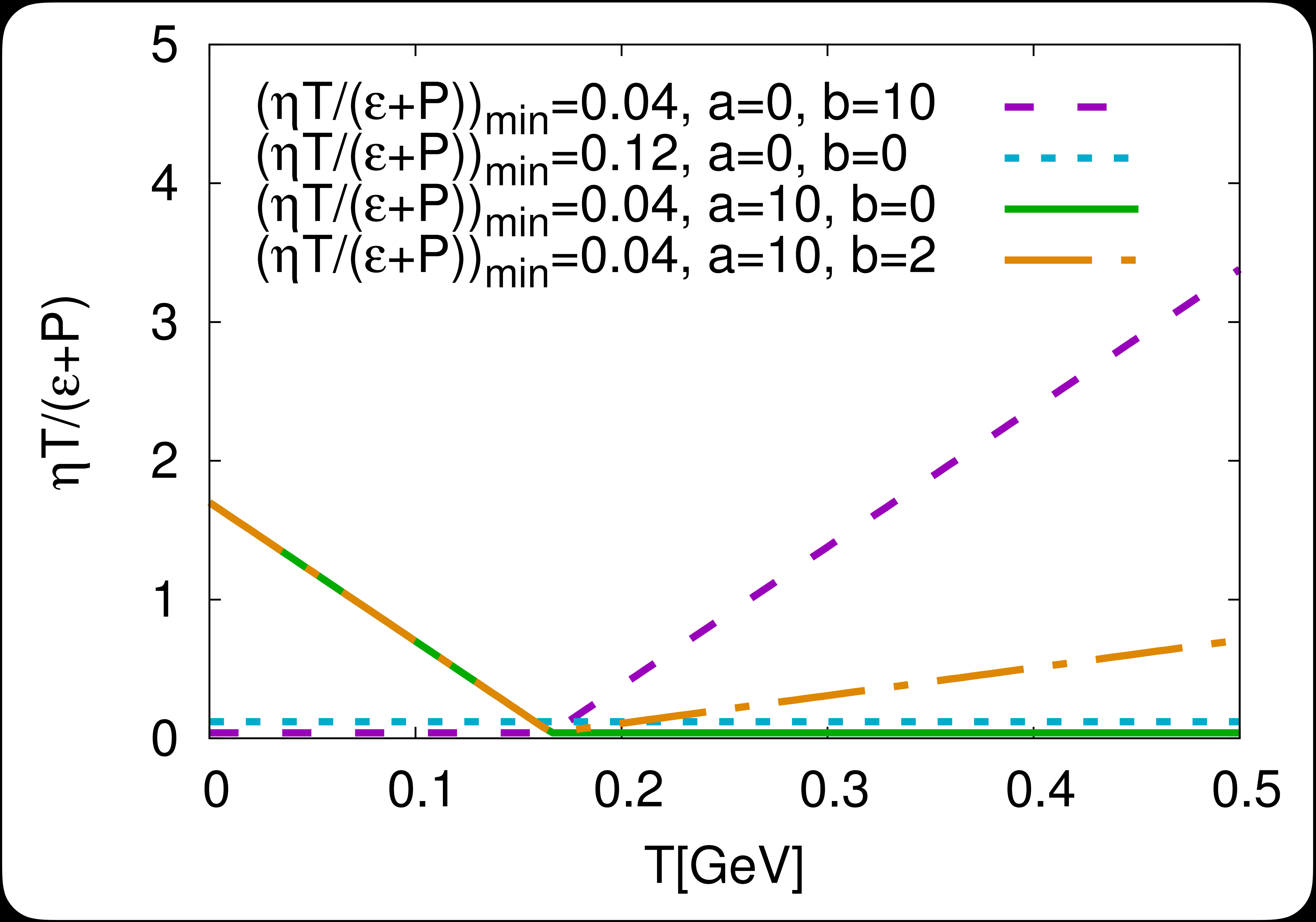
S. JEON AND J. KAPUSTA, PRC56, 468 (1997)

ENERGY DENSITY (UPPER)
BARYON DENSITY (LOWER)



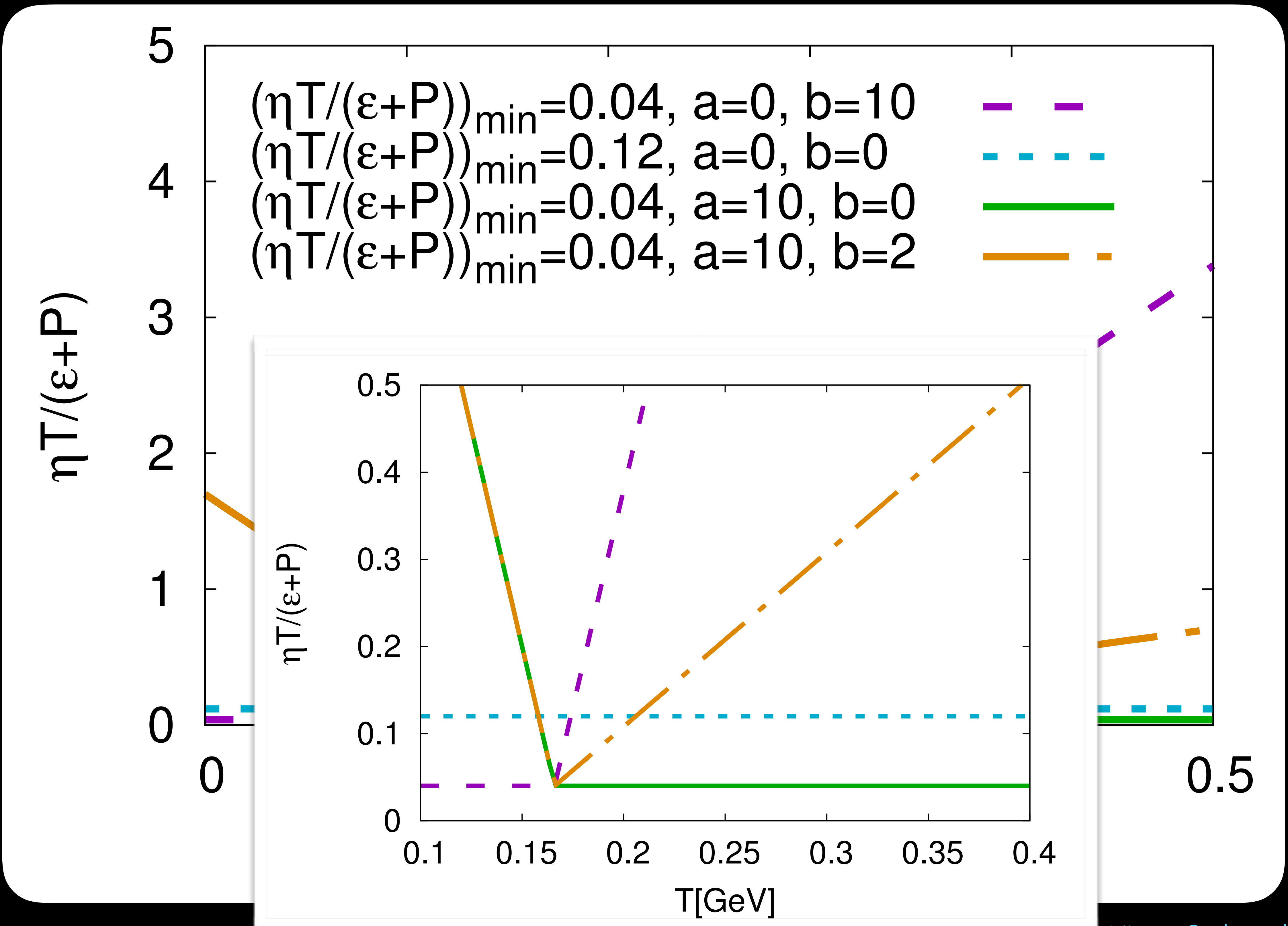
CONSTRAINING η/s vs. TEMPERATURE

G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)



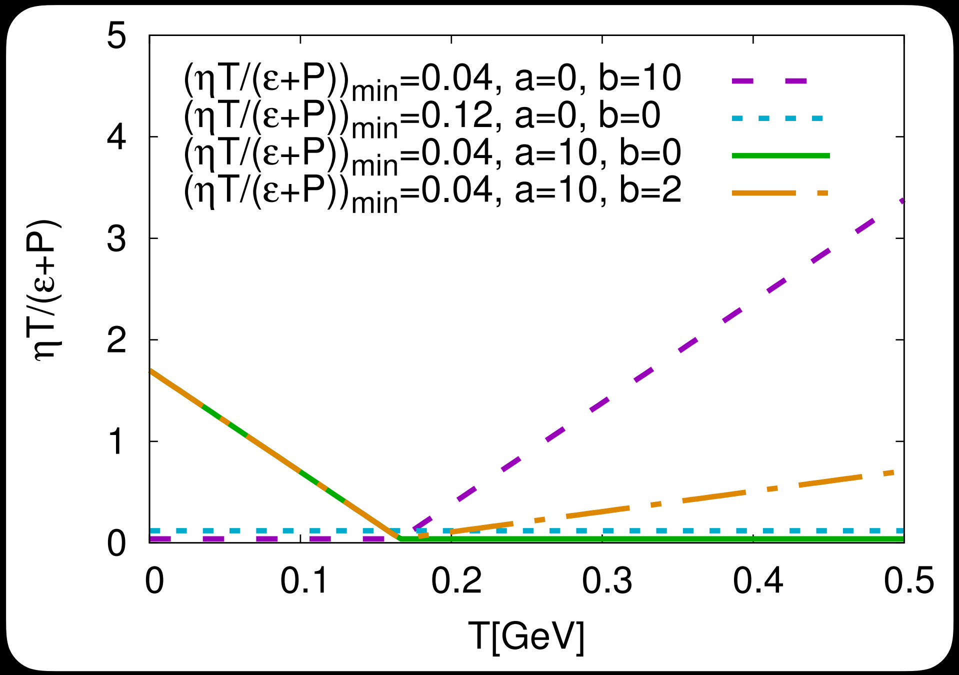
CONSTRAINING η/s vs. TEMPERATURE

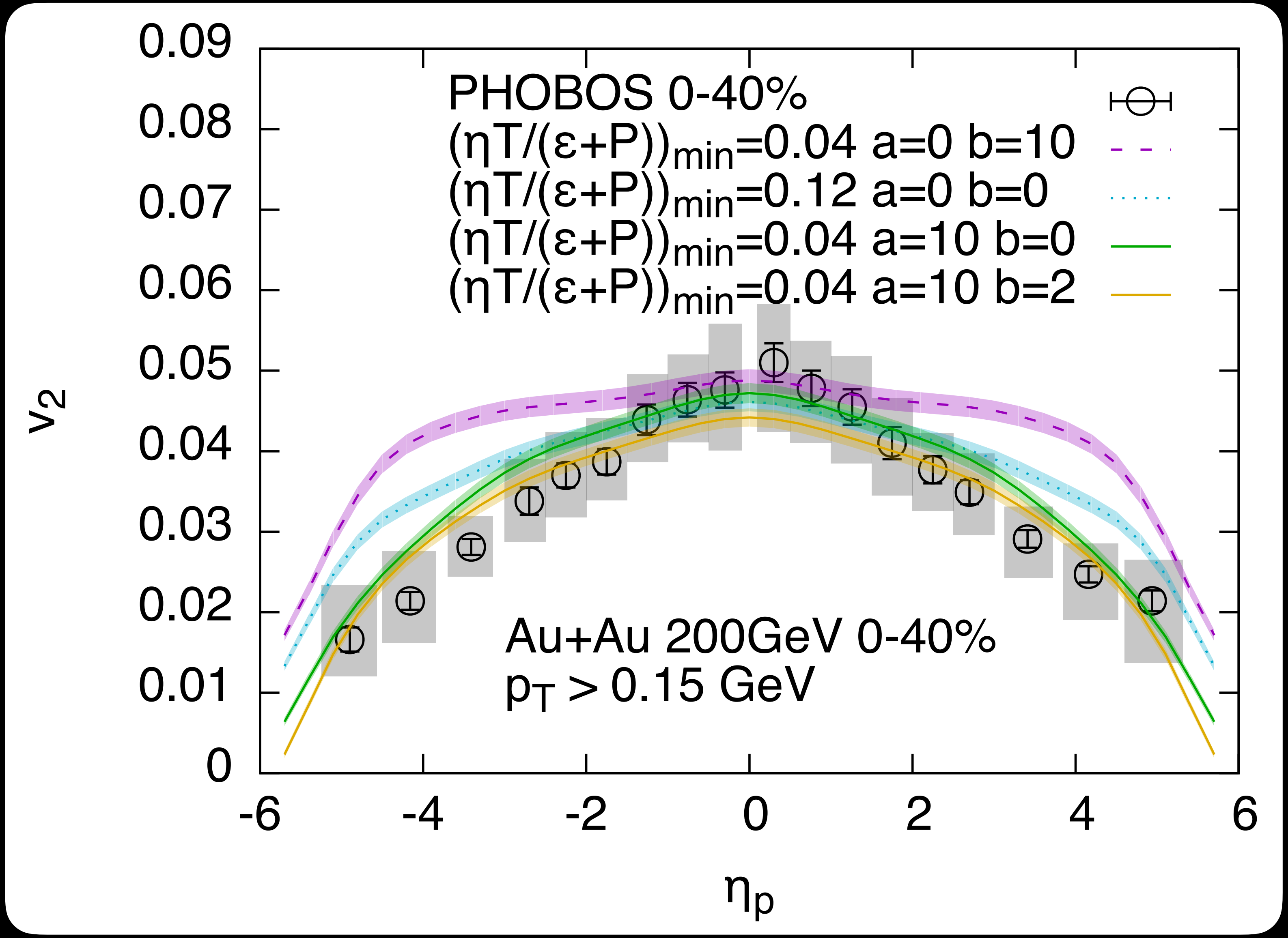
G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)



CONSTRAINING η/s vs. TEMPERATURE

G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)





EXP DATA: PHOBOS COLL., B.B. BACK,ET AL., PHYS.REV. LETT. 94 (2005) 122303

CONCLUSIONS:

η/s IS NOT CONSTANT HADRONIC η/s IS LARGE QGP η/s CANNOT RISE QUICKLY

EVENT-BY-EVENT FLOW

ATLAS COLLABORATION, JHEP 1311 (2013) 183

40-45% 55-60%

v_2

v_3

v_4