UNIVERSITÄT BIELEFELD

CRC-TR 211 Strong-interaction matter under extreme conditions

Exploring 3D structure of Glasma

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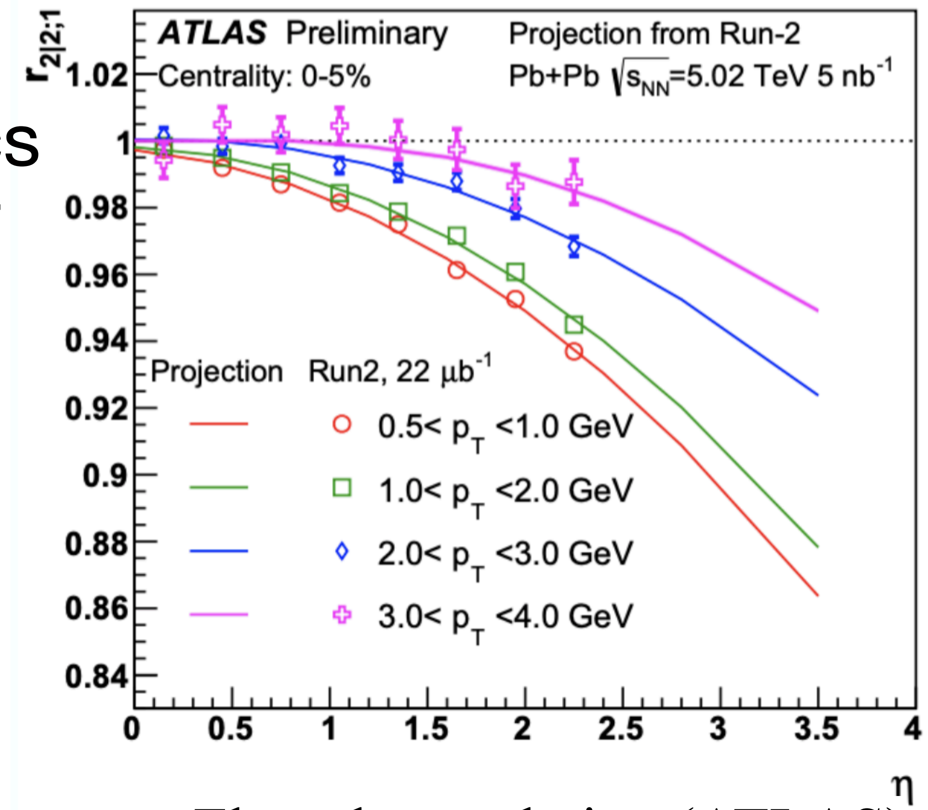
Based on S. Schlichting, P. Singh arxiv2010.11172

Motivation

• Space time dynamics dominated by hydrodynamics expansion which requires macroscopic properties of initial state as an input.



Flow decorrelation (ATLAS)
arXiv:1709.02301

•Boost invariance is a good "approximation" that have been exhaustively studied.

• New measurements at RHIC and LHC indicates towards the presence of longitudinal dynamics

•Available 3+1D models:

Generalisation of 2+1D CGC model arXiv:1605.07158 arXiv:2001.08636, ...

Phenomenological model arXiv:1506.02817 arXiv:1509.04103, ...

3D CGC (Coloured particle in cell method) arXiv:1605.07184

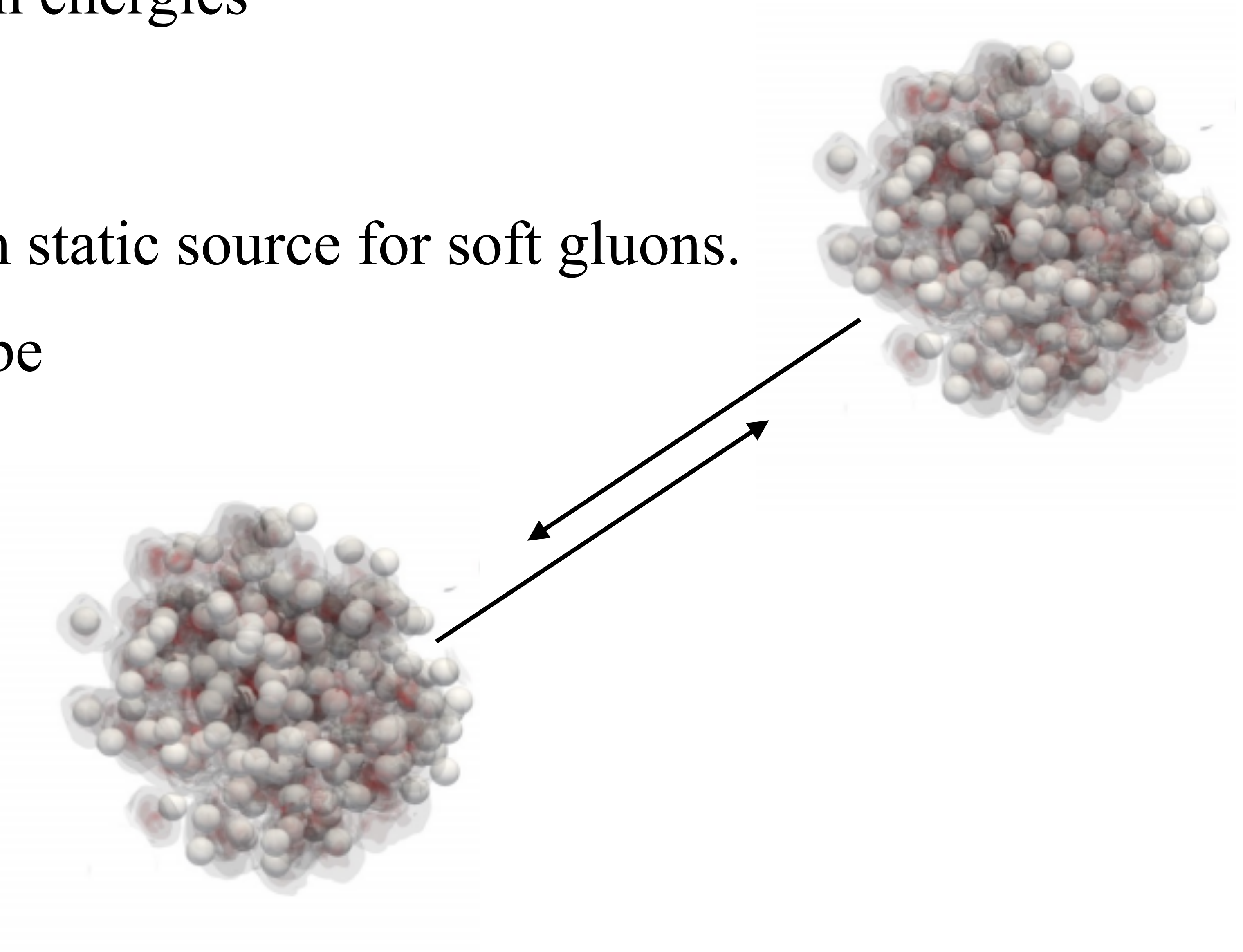
The effective theory

- Earliest stage of collision is described well using Color glass condensate, an effective theory.
  [McLerran, Venugopalan PRD49 (1994) 2233-2241, Kovner, McLerran, Weigert D52 (1995) 6231-6237]

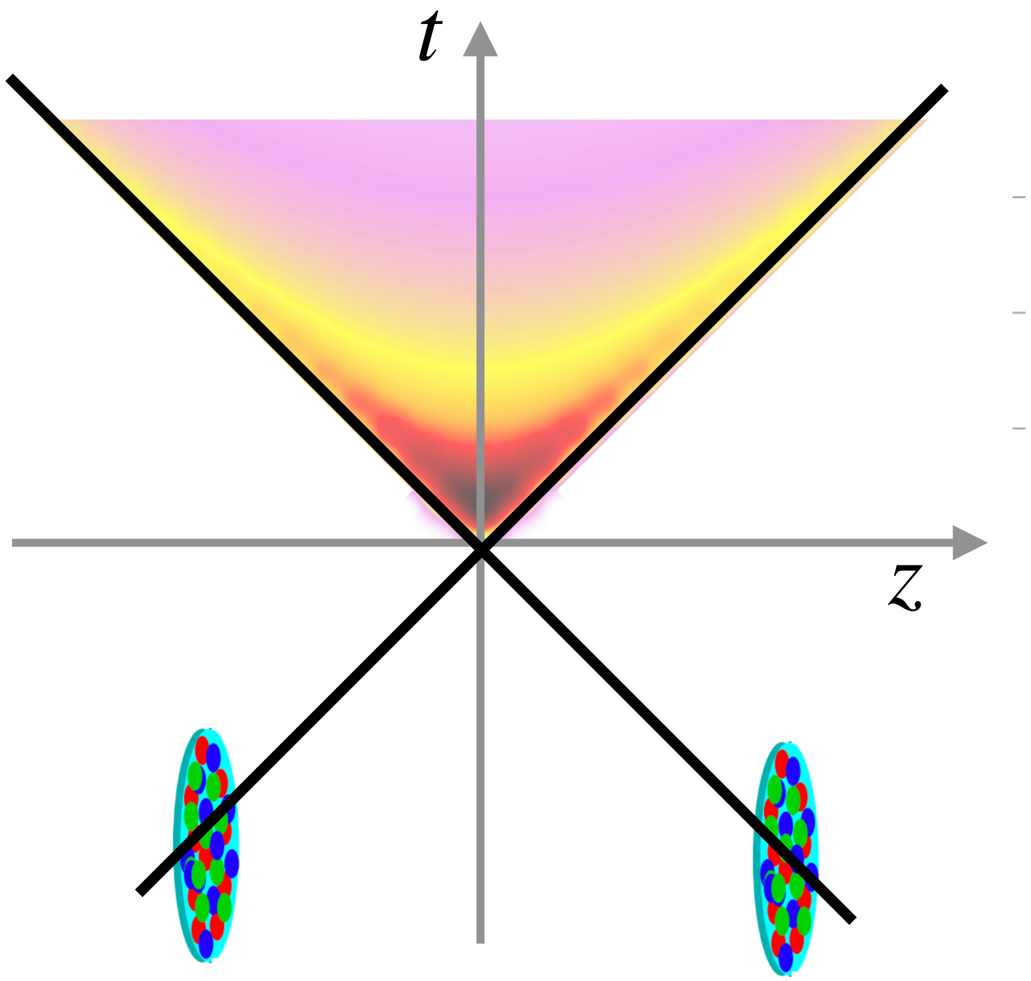
- Separation of scale at very high energies
  Hard constituents
  Soft gluons

- Hard partons acts as a random static source for soft gluons.

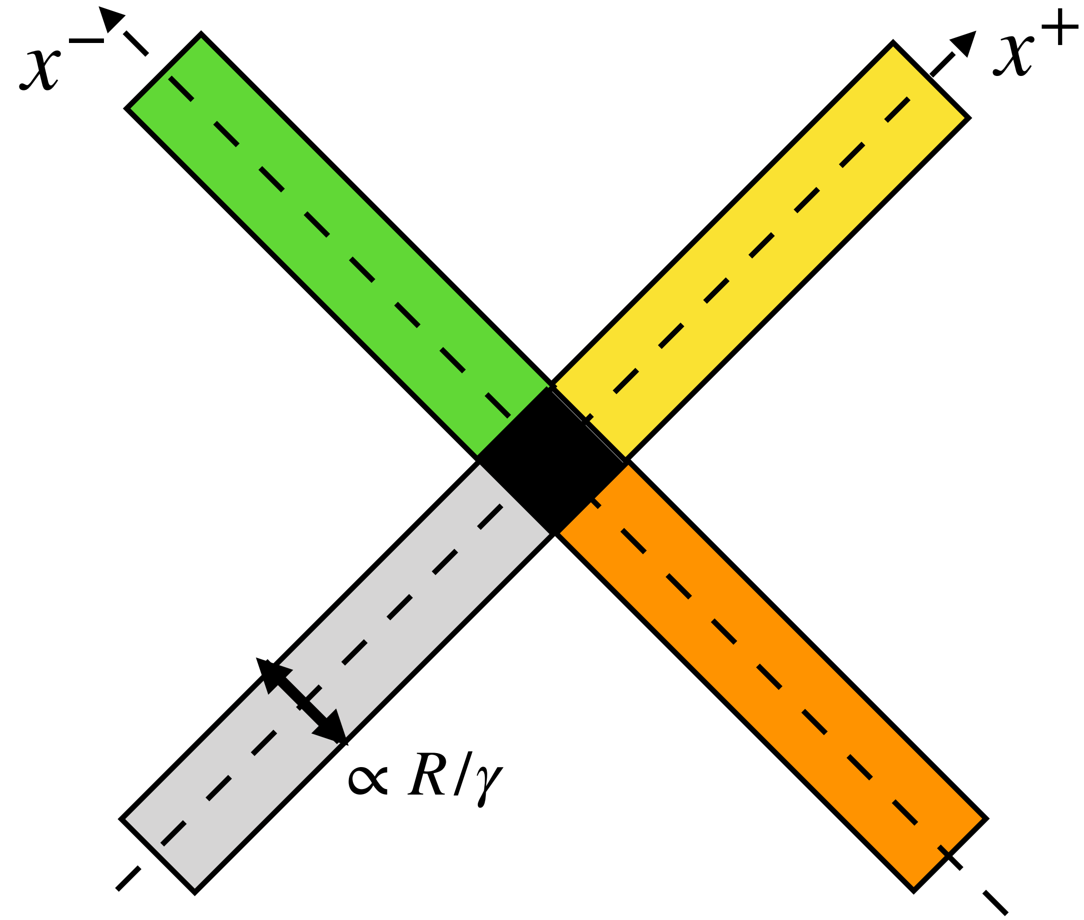
- Initial energy deposition can be obtained by solving classical Yang-Mills equation.



2+1D Vs 3+1D



“Boost-invariant collision”



“Realistic collision”

- Collisional overlap region becomes extended in t,z
- No longer have access to analytical solutions for initial conditions in the forward light-cone

3+1D Glasma simulations

Solve 3+1D classical Yang-Mills equations & evolution equations for eikonal currents, before, during and after the collision

1. Sample 3D distribution of color charges $\rho(x^{\pm}, x_{\perp})$ in each half boxes.

2. Solve for Weizsäcker-Williams fields (WW) of the incoming nuclei.

3. Evolve gauge fields and corresponding conjugate momenta according to the discretised 3+1D YM

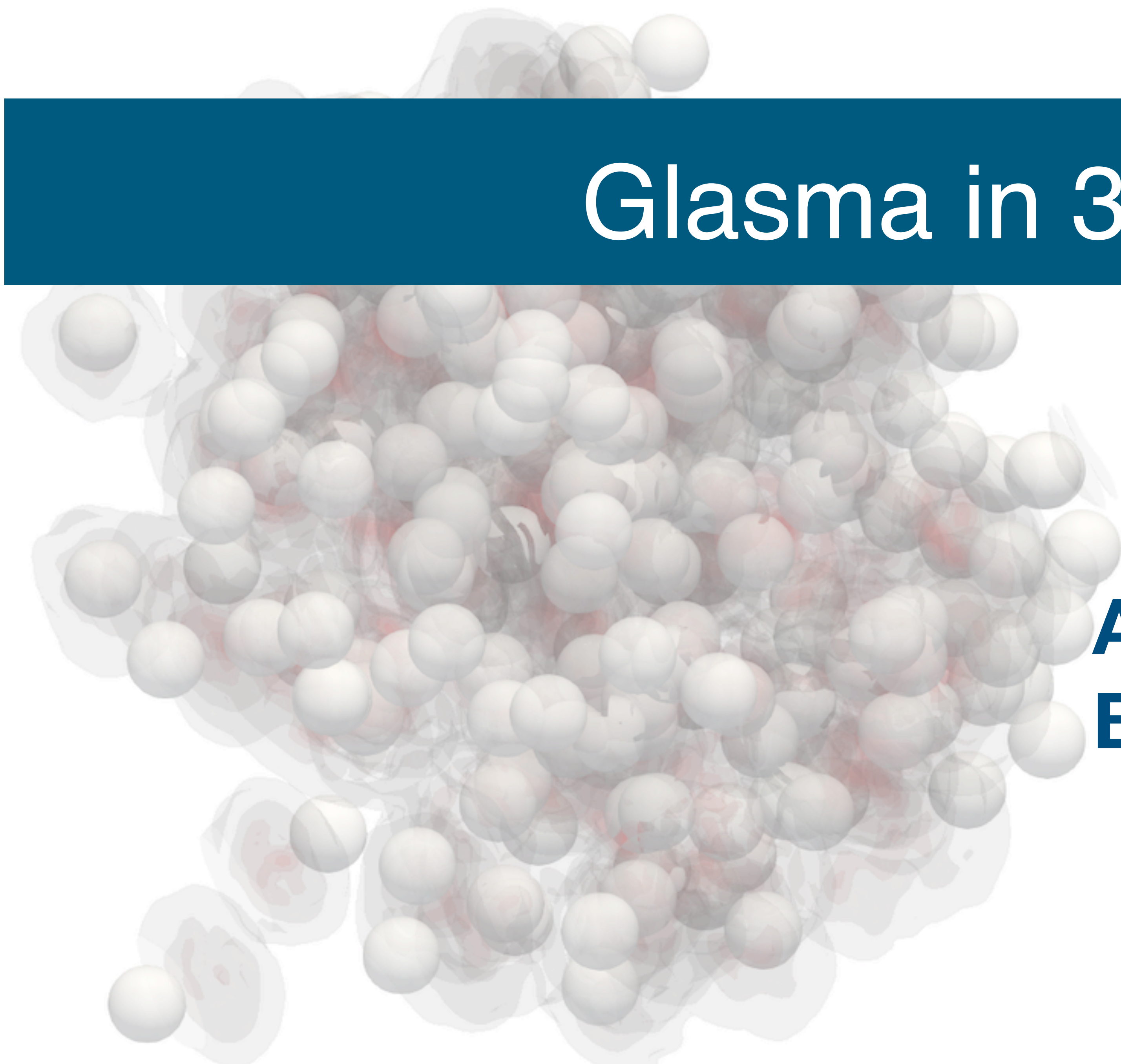
$$[D_{\mu}, F^{\mu\nu}] = J^{\nu}$$

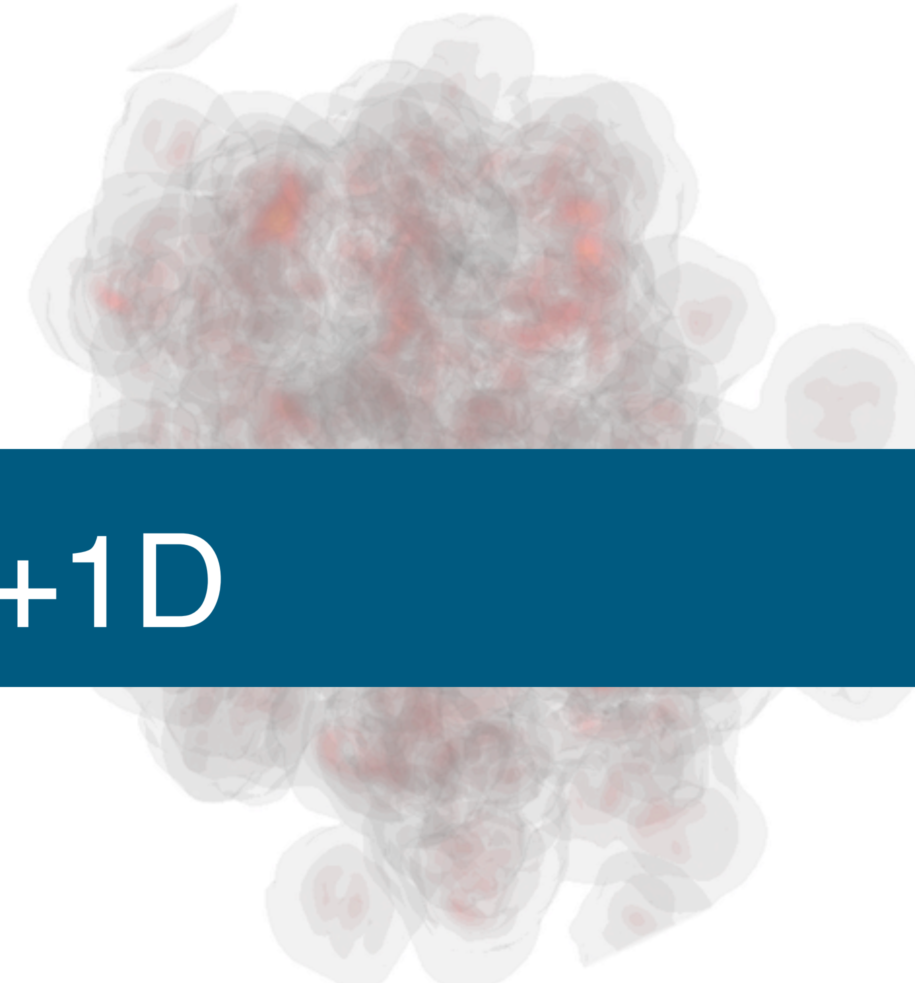
4. Evolve eikonal currents according to continuity equation.

$$[D_{\mu}, J^{\mu}] = 0$$

5. Solve 3. and 4. simultaneously to simulate early time dynamics of collision in 3+1D

Glasma in 3+1D





A. Toy Model Charges
B. Physical Charges

3+1 D Glasma simulations

Before addressing full complexity of colliding nuclei, consider a simple extension of McLerran-Venugopalan model

$$\langle \rho^a(x^+, x_\perp) \rangle = 0$$

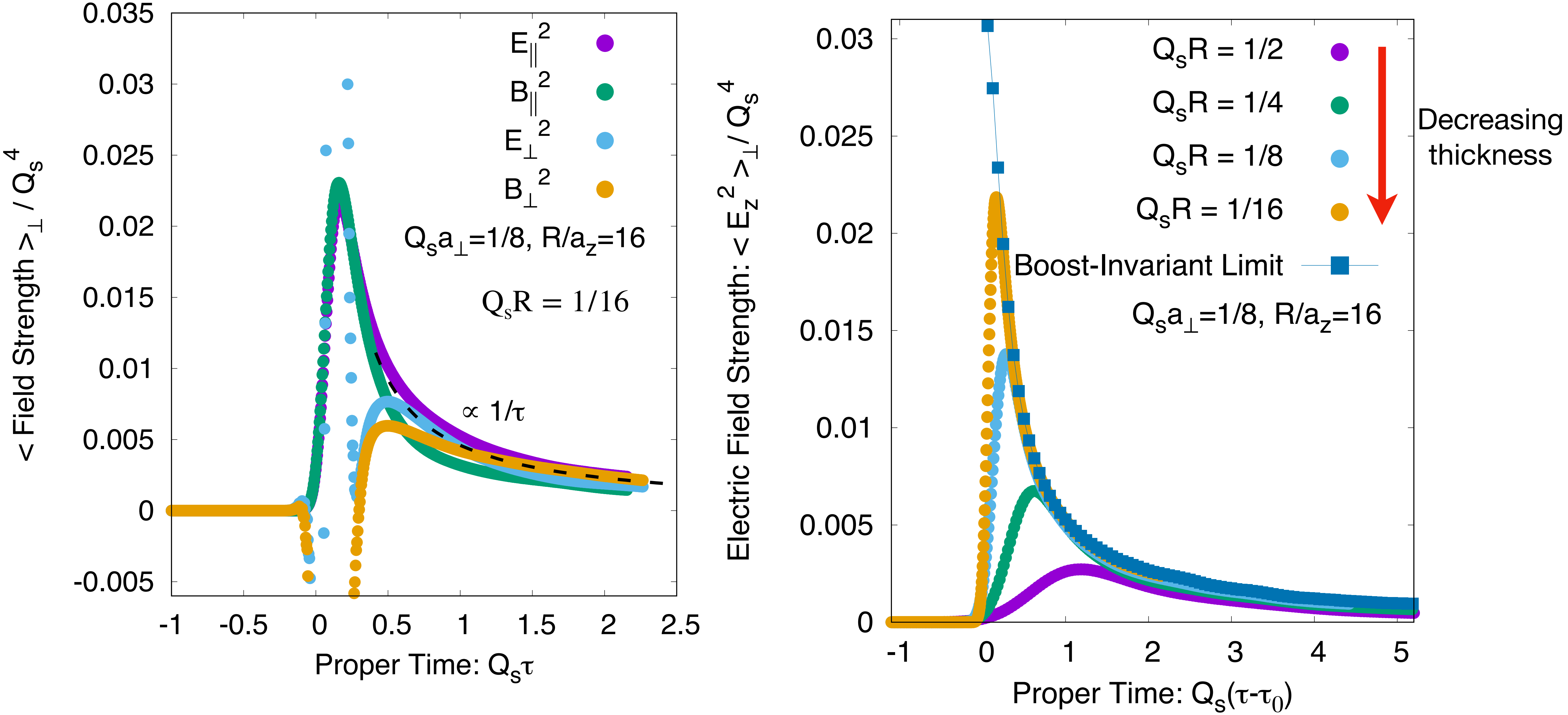
$$\langle \rho^a(x^+, x_\perp) \rho^b(y^+, y_\perp) \rangle = \delta^{ab} Q_s^2 \delta^2(x_\perp - y_\perp) f_\sigma(\frac{x^+ + y^+}{2})$$

- nuclei are transverse homogenous
- no fluctuations of longitudinal distribution of color charges, except for average Gaussian profile

$$f_\sigma(x^+) \sim \exp(-(x^+/R)^2)$$

Single scale Q_s controlling energy deposition, and dimensionless parameter Q_sR controlling thickness of Lorentz contracted nuclei

Toy Model Charges



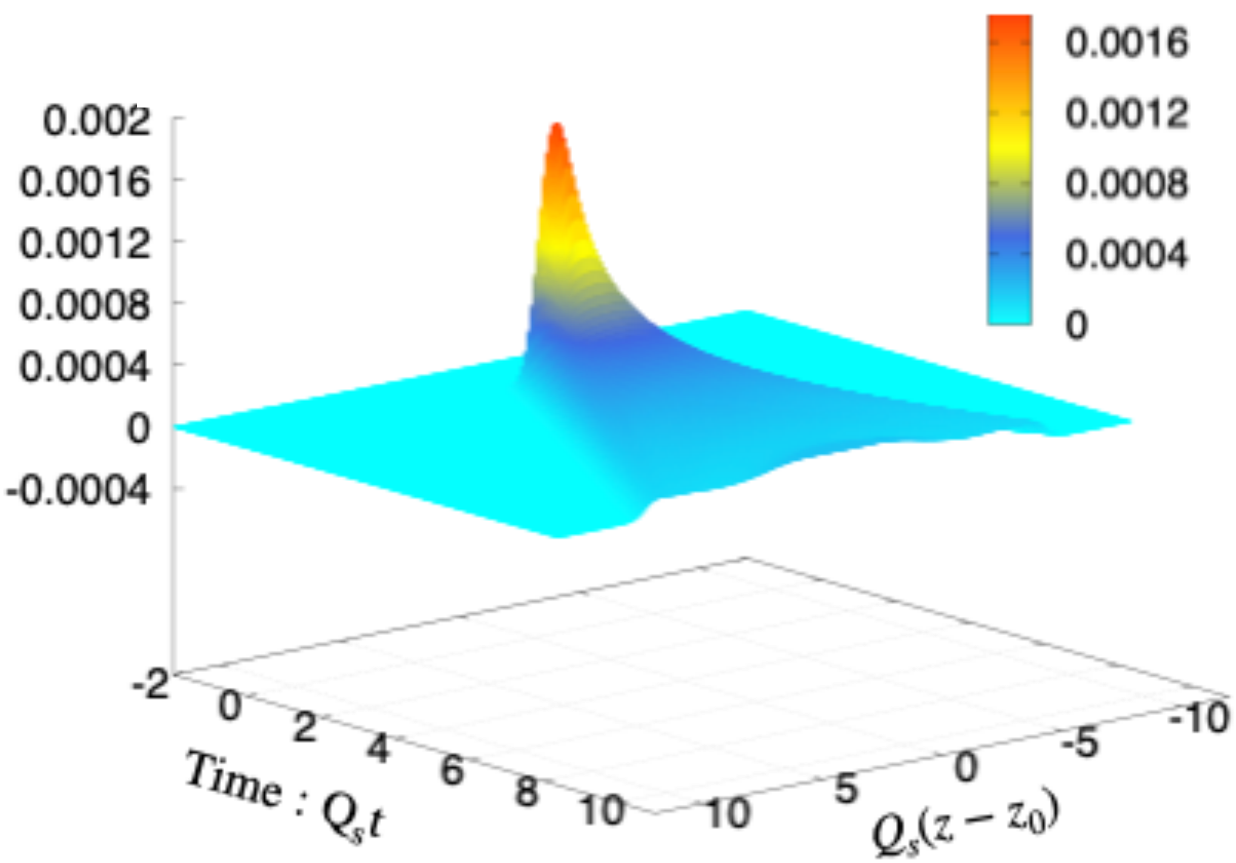
Evolution of glasma fields before and after the collision.

$$E^2_{Glasma}(t,z) = E^2(t,z) - E^2_{WW}(t,z)$$

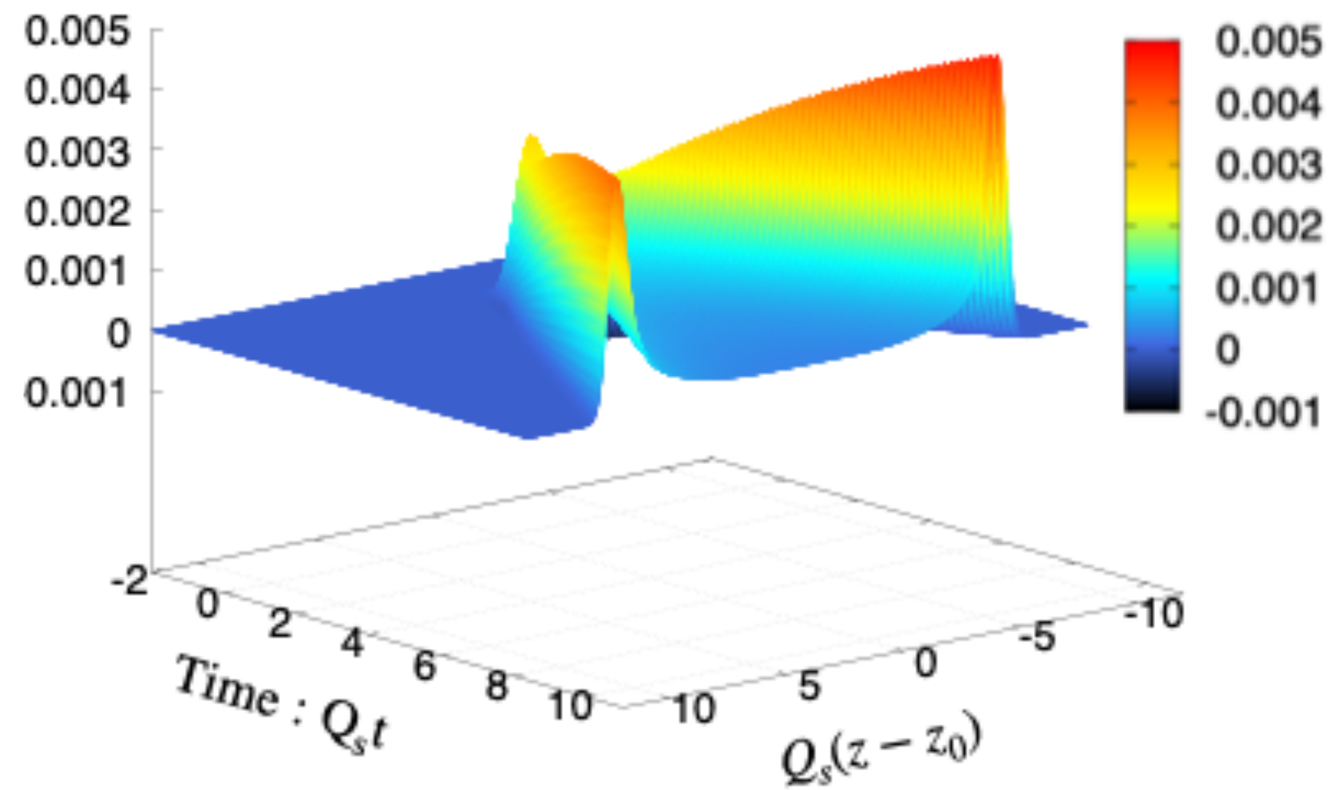
Exploring the full space-time dynamics

$Q_s R = 1/2$

Transverse Pressure : $\left\langle \frac{T^{xx} + T^{yy}}{2} \right\rangle_\perp / Q_s^4$



Energy Density : $\langle T^{00} \rangle_\perp / Q_s^4$



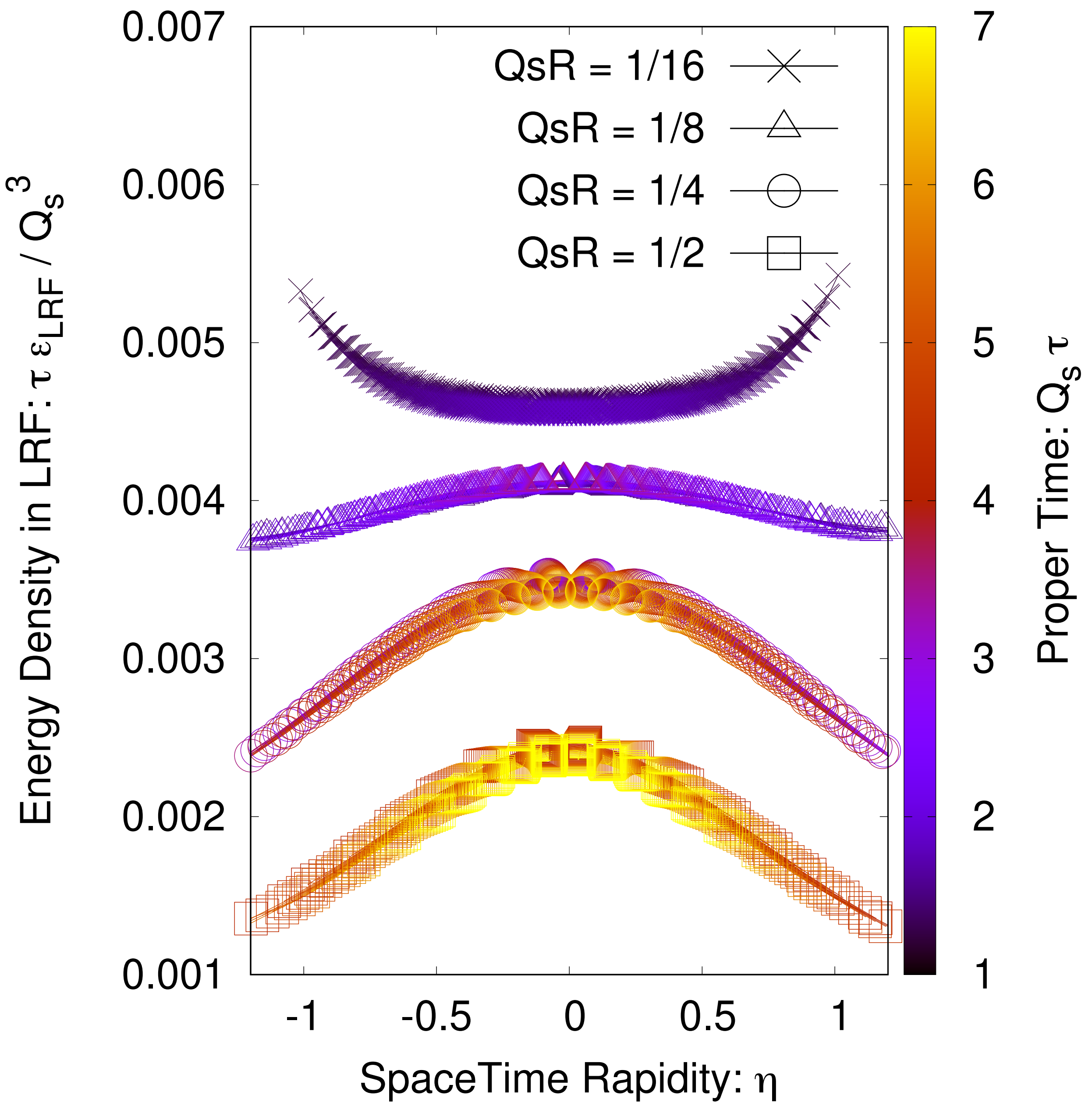
Sensible space-time profiles for transverse pressure, but surprisingly large energy density near the light-cones

Rapidity Profiles

- Observable highly sensitive to the choice of origin.
- Use local energy rest frame.

$$\epsilon_{LRF} = \frac{1}{2}\left(T^{00} - T^{zz} + \sqrt{\left(T^{00} + T^{zz}\right)^2 - 4T^{0z}T^{0z}}\right)$$

- Limited rapidity window.
- Breaking boost invariance with increasing thickness



Collision with (semi-) realistic charge distribution

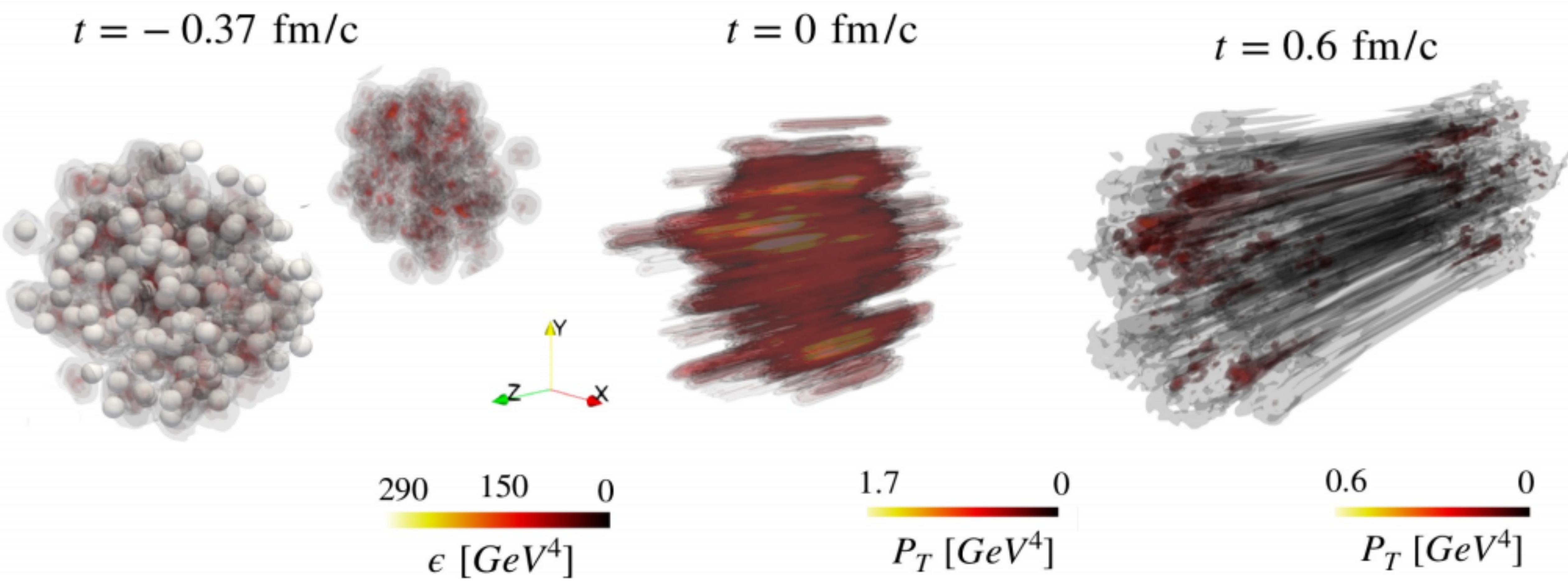
- Model of three dimensional structure of the color charge distribution based on small-x transverse momentum distribution (TMDs).

$$\left\langle \rho^a(x)\rho^b(y) \right\rangle = \delta^{ab} T\left(\frac{x+y}{2}\right)\Gamma(x-y)$$

- $\tilde{\Gamma}(x-y)$ describes the momentum dependence of color charge inside the nucleus. Parametrised by TMDs.

- $T\left(\frac{x+y}{2}\right)$ tells about the spatial structure. Obtained using Monte Carlo Glauber model.

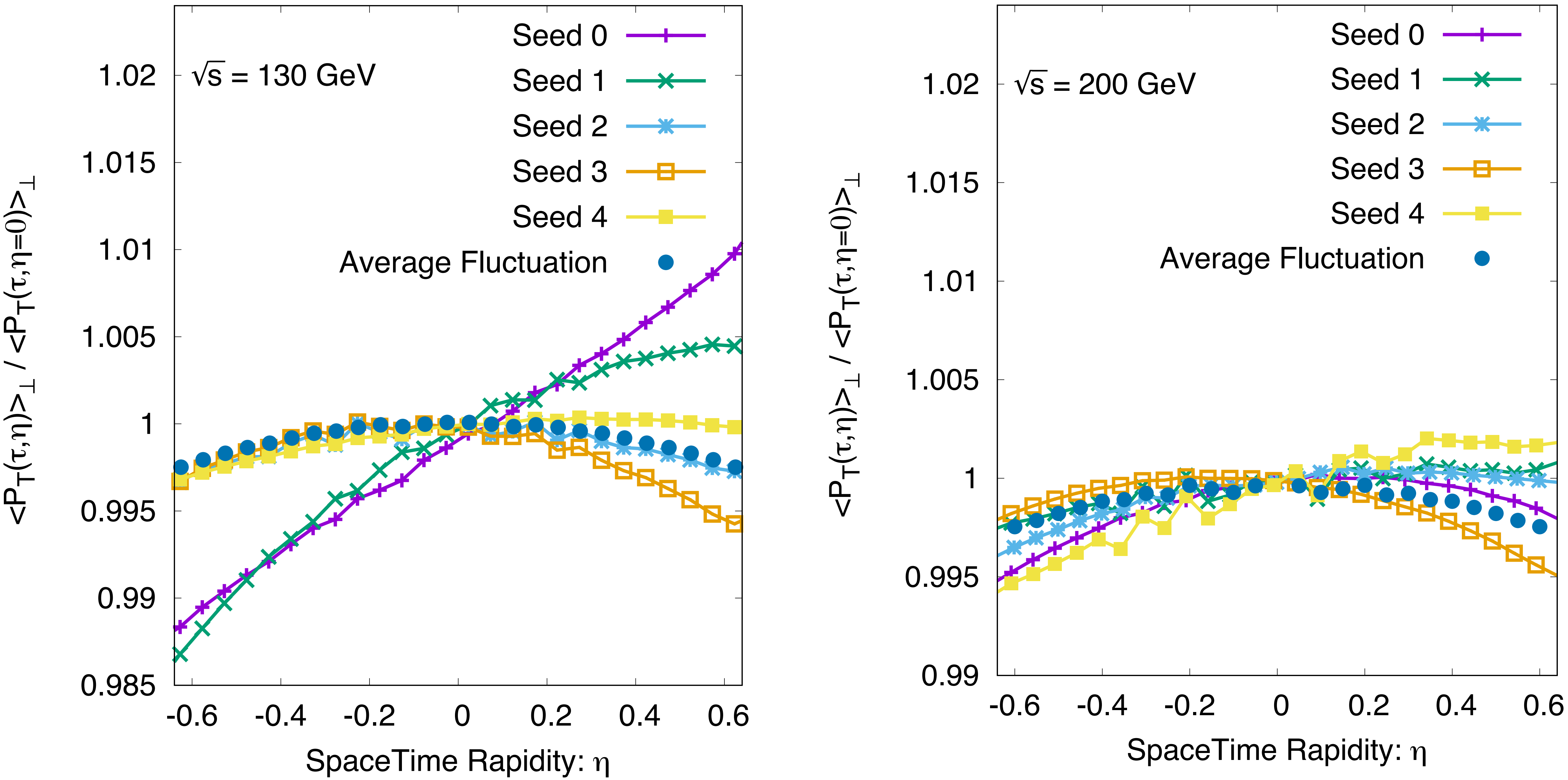
Effect of fluctuation at RHIC energies



$$Q_S a_\perp = 0.33$$

Au-Au collision at $\sqrt{s} = 200$ GeV

Effect of fluctuation at RHIC energies



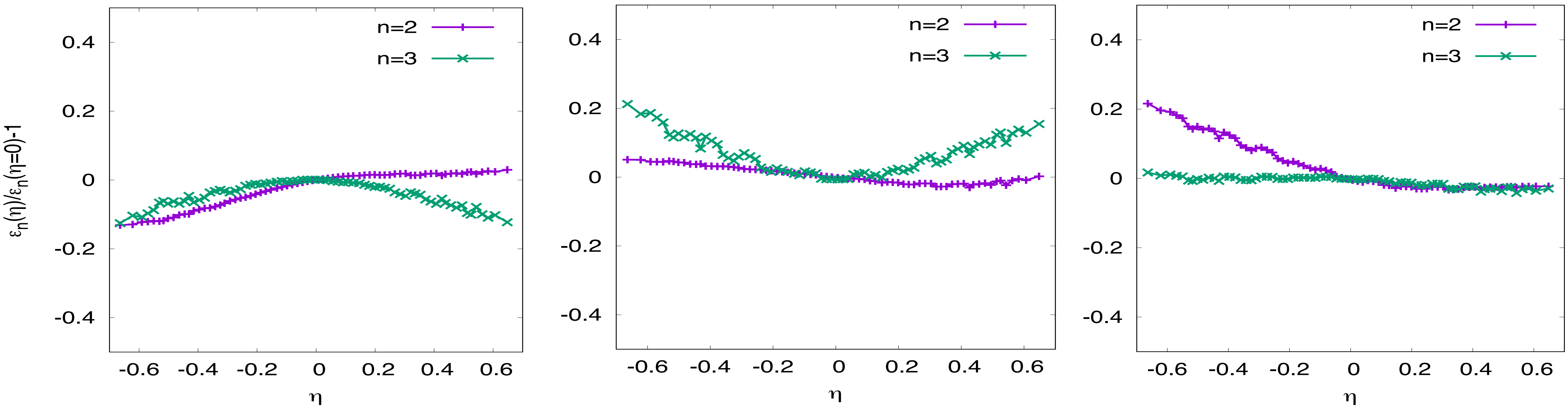
Fixed $\tau \simeq 0.75$ fm/c

Fluctuation relatively small $\leq 1\ \%$ and decreases with increasing $\sqrt{s}$

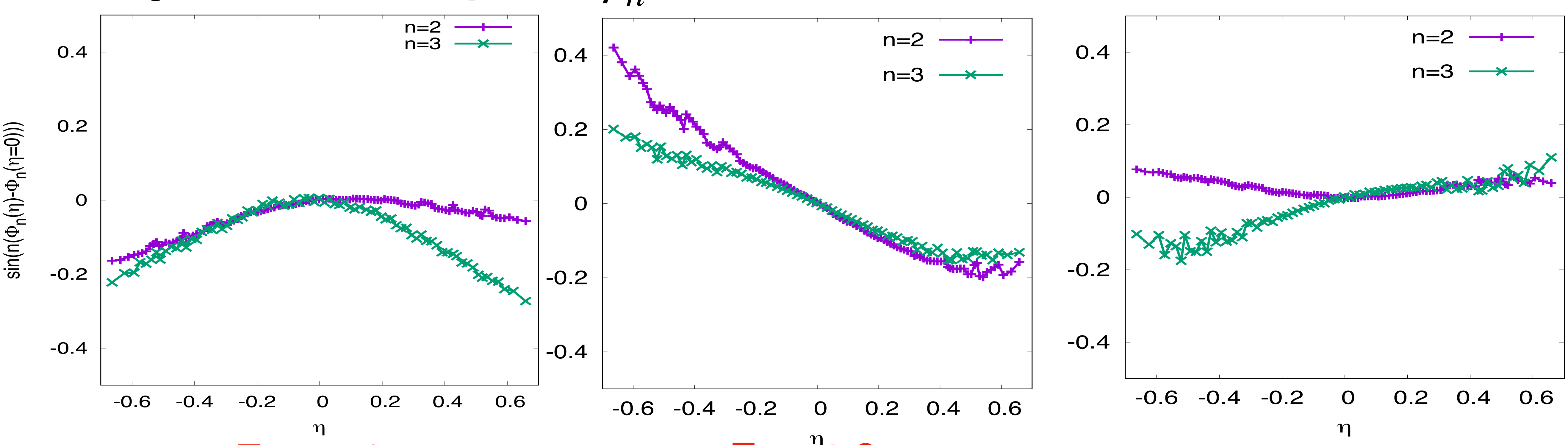
Characterising transverse geometry

Relative change in the eccentricity ε_n

Au-Au collision at $\sqrt{s} = 130$ GeV



Change in the event plane ϕ_n orientation



Event 1 Event 2 Event 3

Conclusion and Outlook

- Developed a framework to perform 3+1D simulation based on CGC.
- Significant violation of boost invariance for finite thickness.
- Physical model which includes the spatial structure and fluctuations of the colliding nuclei.

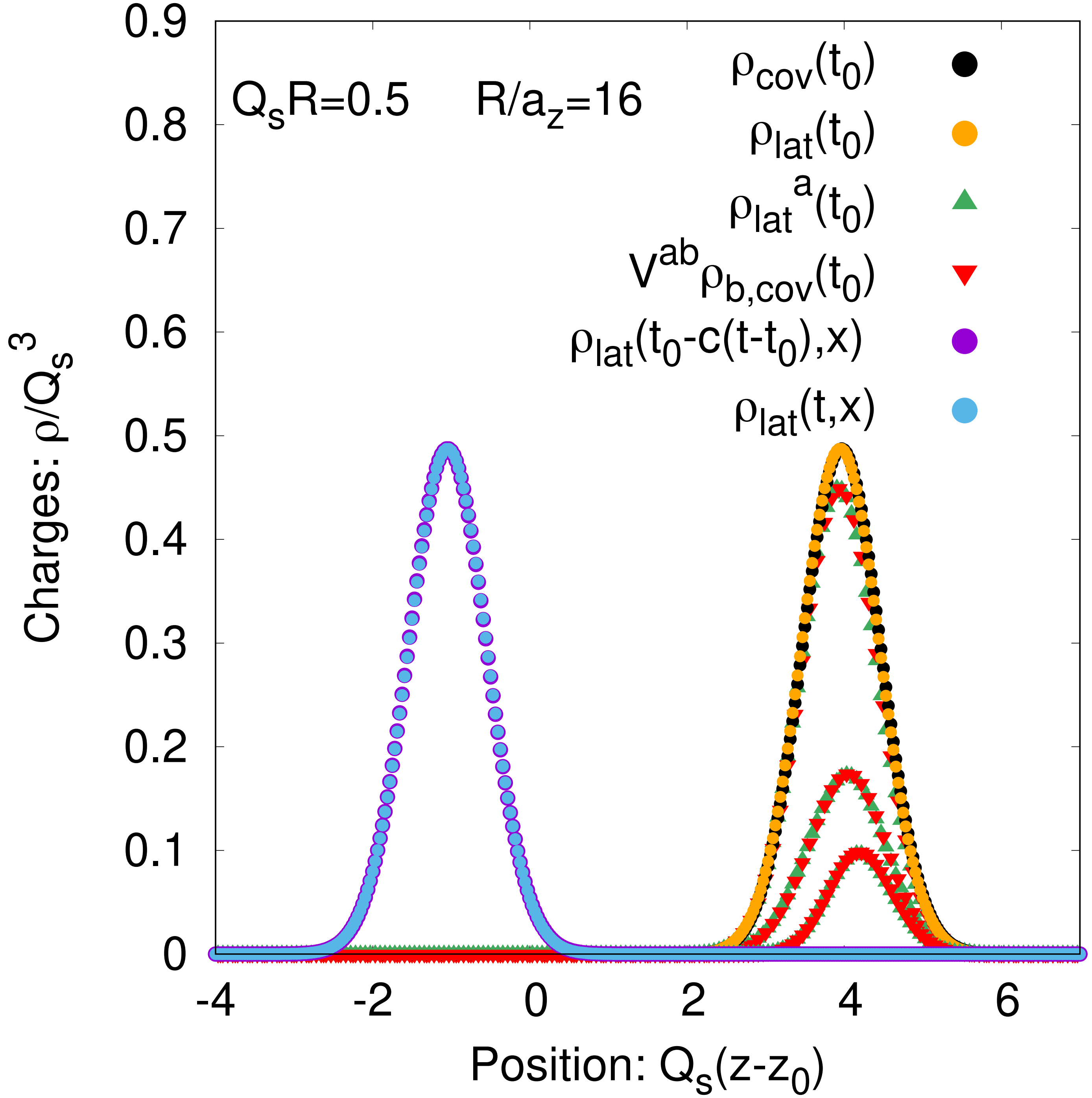
Future Plans

- Include physical SU(3) gauge group to compare against experiments.
- Reduce the computational cost and explore larger rapidity window.
- Collision at LHC energies.

Thank you…

BACKUP

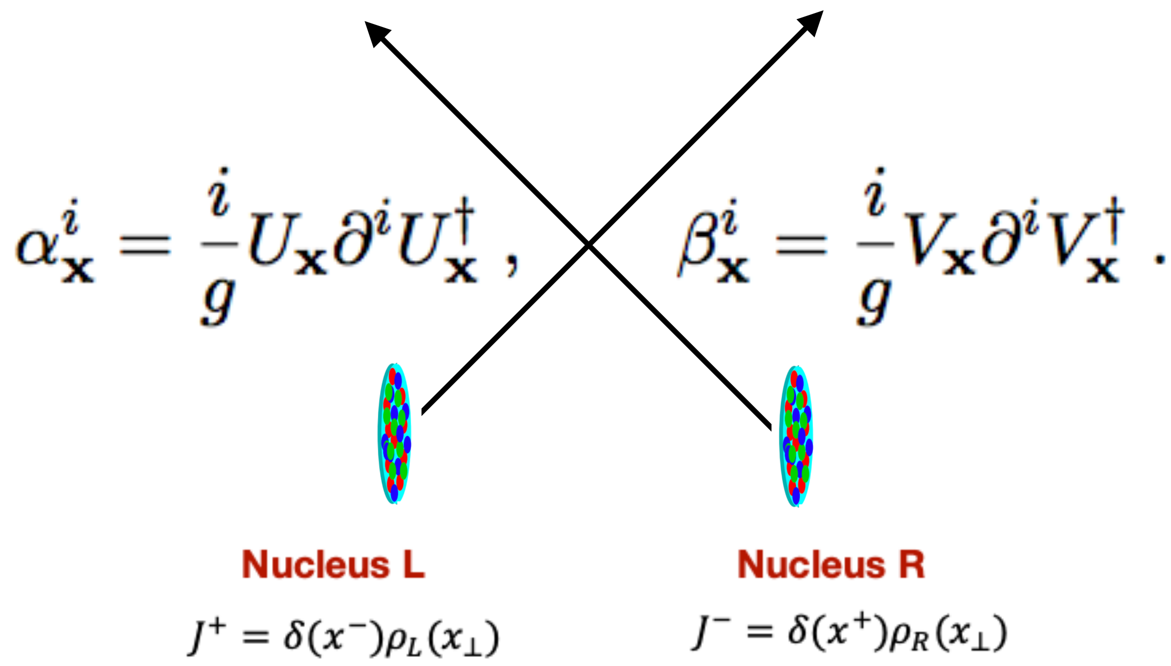
Stable Propagation of color charges

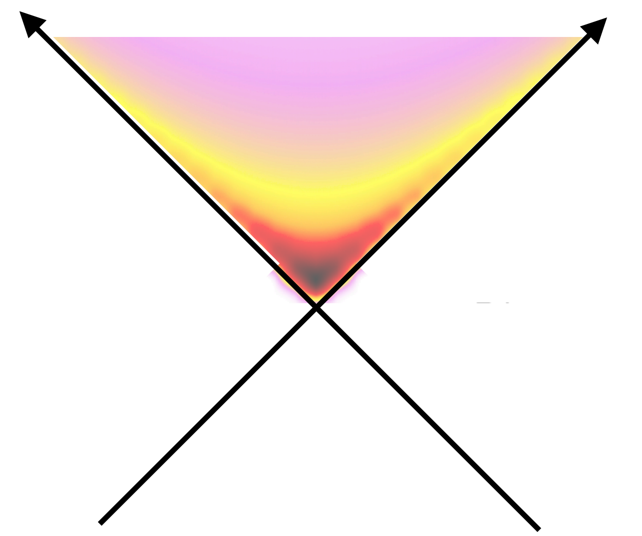


Numerical dispersion of current is small

Boost-invariant high energy limit

Based on Color Glass Condensate description of high-energy QCD, colliding nuclei are described as infinitely thin sheets of static color charges





Before the collision

Creation of boost invariant transverse chromo-electric and chromo-magnetic fields

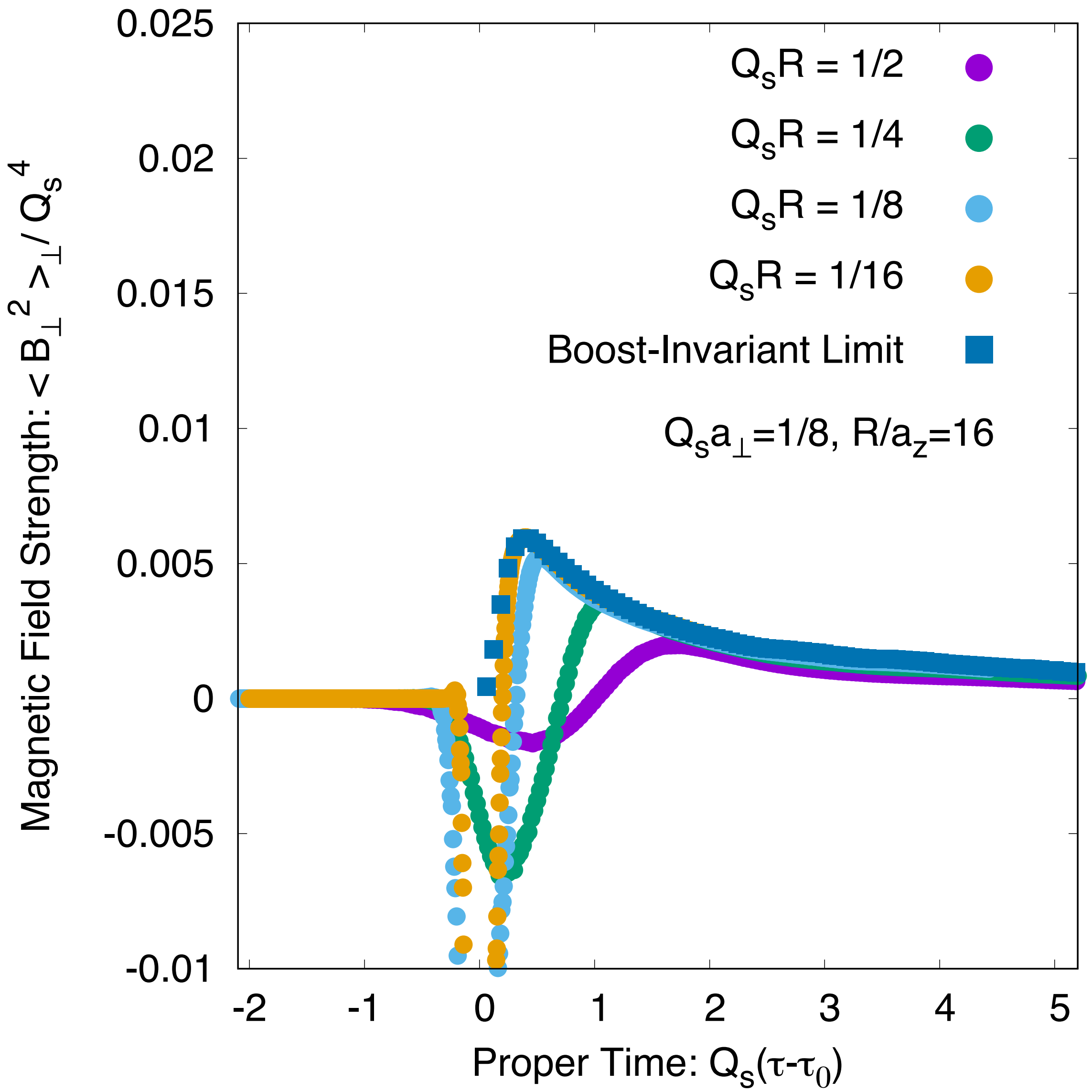
Immediately after collision

$$E^\eta_x = -ig\delta^{ij}[\alpha^i_x, \beta^j_x]$$

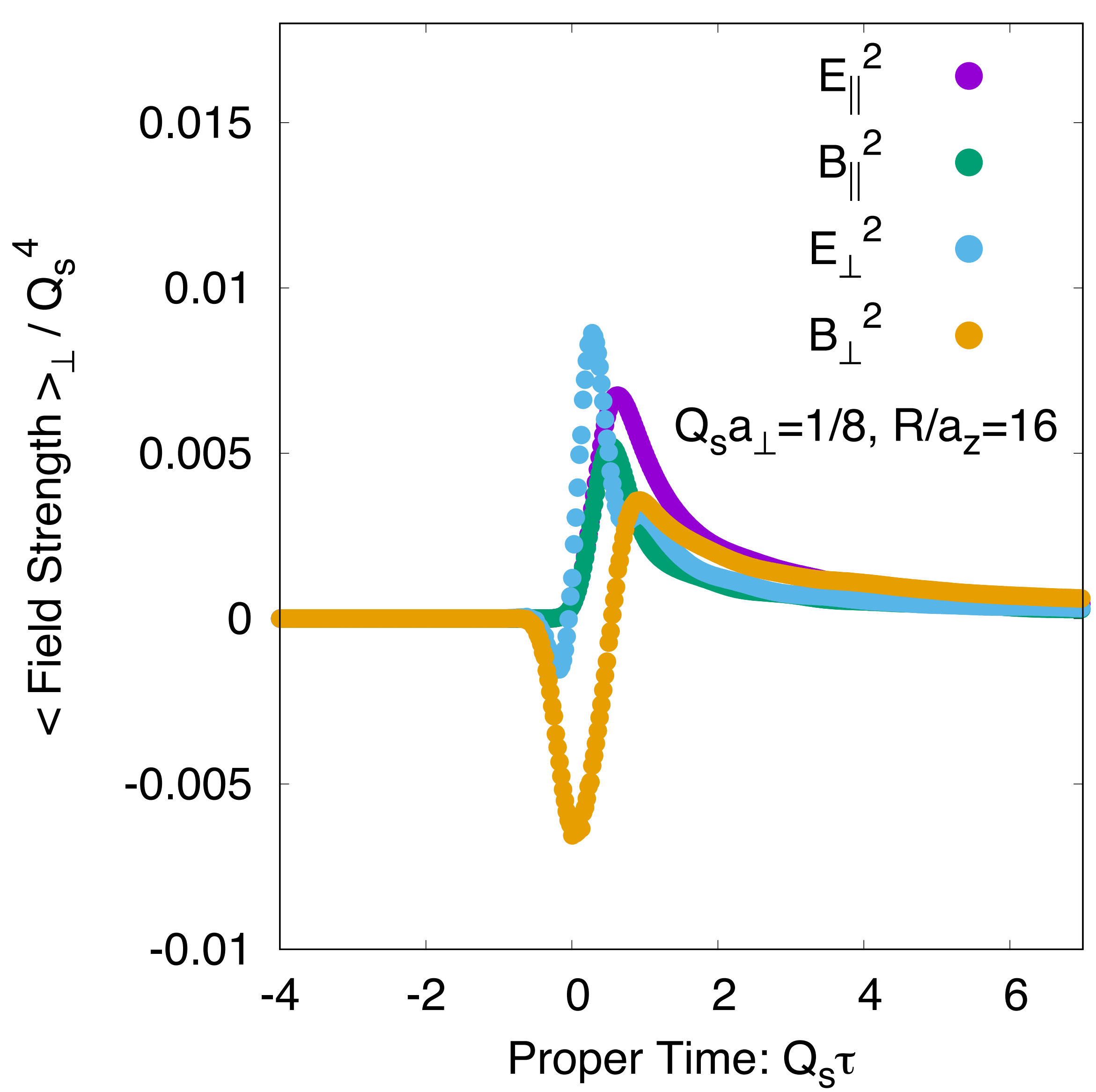
$$B^\eta_x = -ig\epsilon^{ij}[\alpha^i_x, \beta^j_x]$$

Subsequent evolution studied numerically using 2+1D classical Yang-Mills simulations

Field Strengths

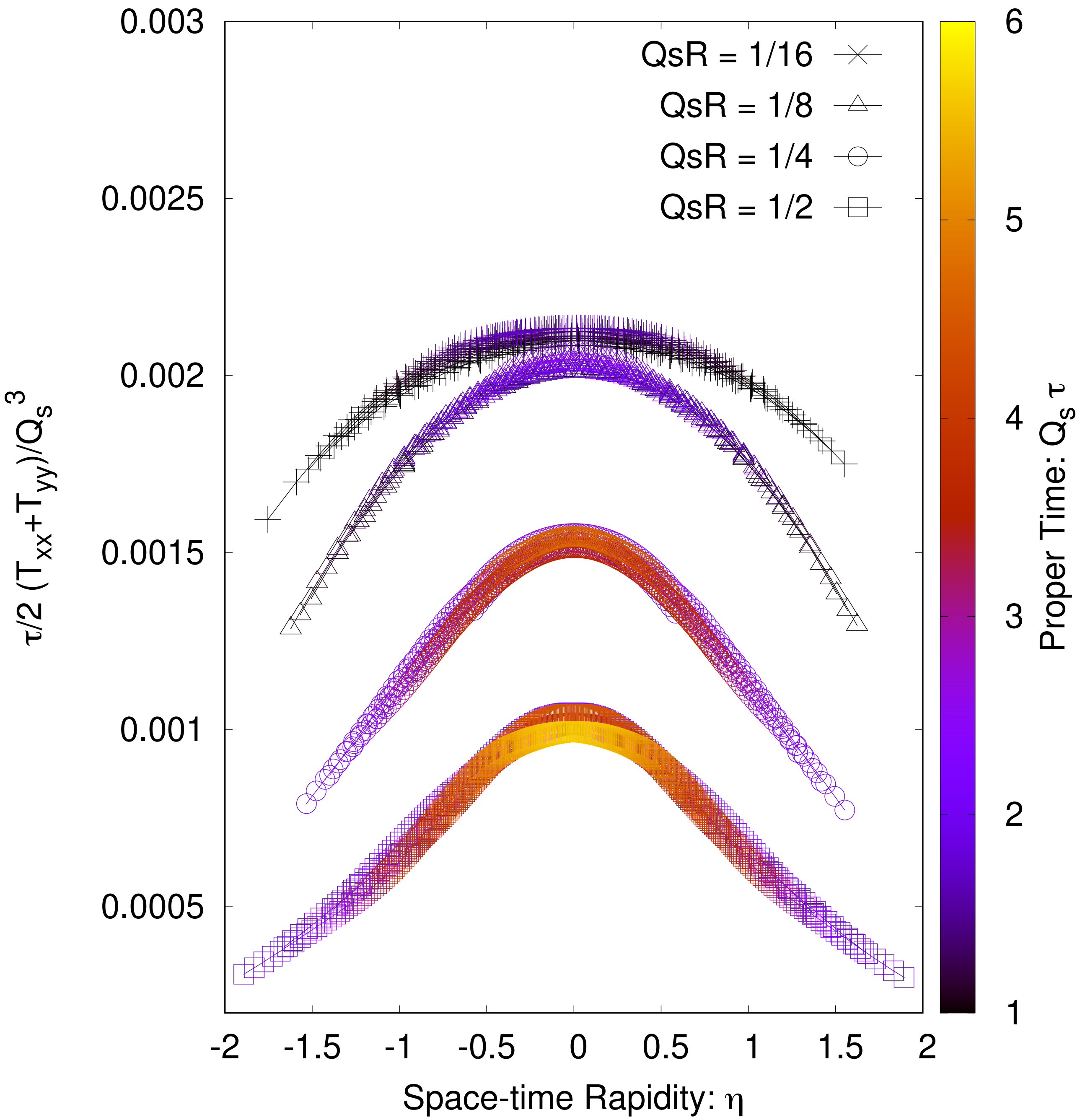


Magnetic Field Strength

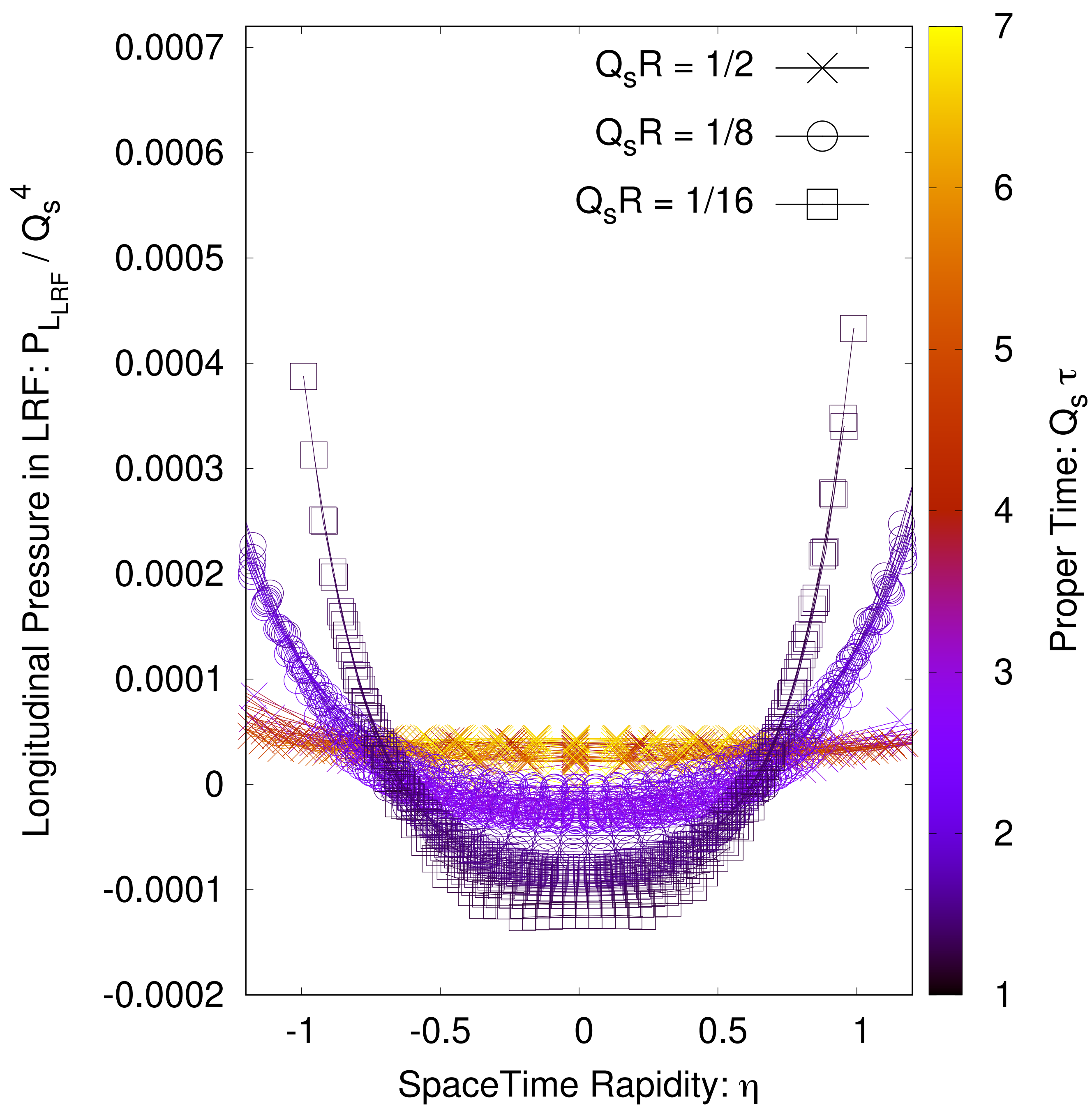


Thick Nucleus

Rapidity profile



Transverse Pressure



Longitudinal Pressure in LRF

Effect of fluctuation at RHIC energies

- Au-Au collision at $\sqrt{s} = 130$ GeV
- Fixed $\tau \simeq 0.4$ fm/c
- Flux tubes of varying lengths.
- Limited rapidity window

$$\eta \in [-0.8, 0.8]$$

Exploring the full space-time dynamics

$$T^{00}(t,x) = \frac{1}{2}\left(E^2(t,x) + B^2(t,x)\right) - \underbrace{\frac{1}{2}\left(E^2(t,x) + B^2(t,x)\right)}_{Nucleus\ L} - \underbrace{\frac{1}{2}\left(E^2(t,x) + B^2(t,x)\right)}_{Nucleus\ R}$$