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Limiting fragmentation in the dilute Glasma

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Based on
A. Ipp, M. Leuthner, D. I. Müller, S. Schlichting, K. Schmidt and P. Singh,
Energy-momentum tensor of the dilute (3+1)D Glasma
Phys.Rev.D 109 (2024) 9, 094040
and work in progress

XVIth Quark Confinement and the Hadron Spectrum Conference
Track D: Deconfinement
Cairns, Queensland, Australia

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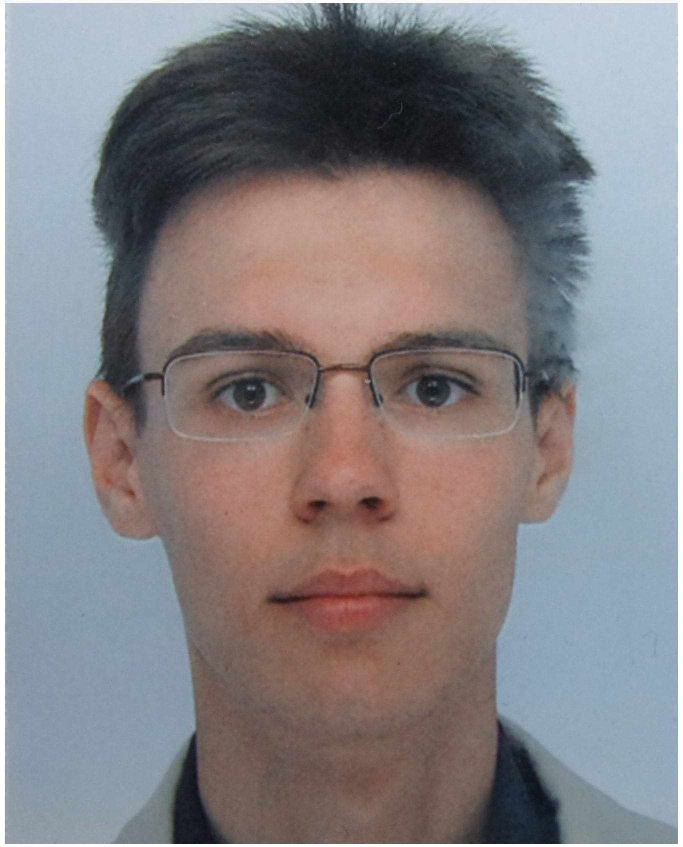
Contact information



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Don't hesitate to find me and ask questions!

Dilute Glasma in A+A collisions

Ingredients

- Nuclear model
- Realization of two full nuclei color fields
- Solution of dilute Glasma $f^{\mu\nu}$ integrals

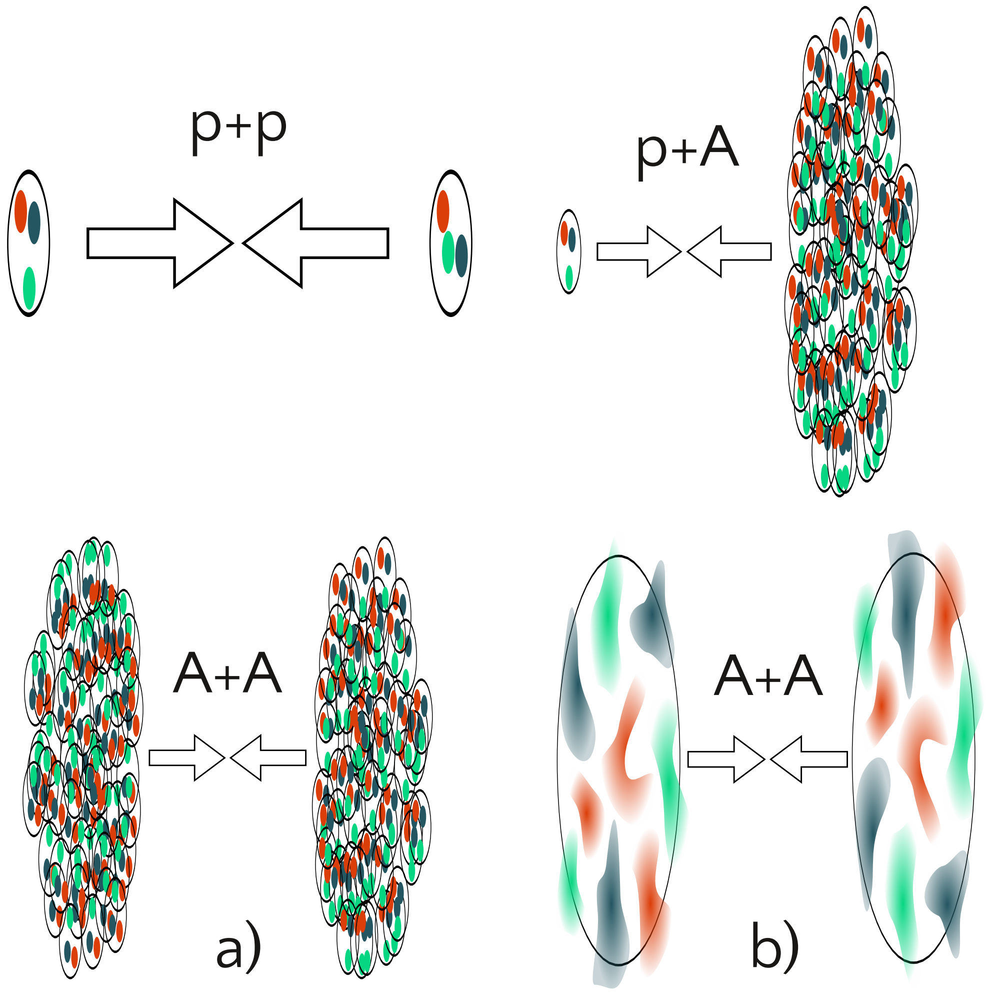
Nuclear models for A:

a) Nucleonic and subnucleonic structure:

$$A \sim N \times p$$

b) Charge fluctuations for whole nucleus:

$$A \propto \langle \rho\rho \rangle$$



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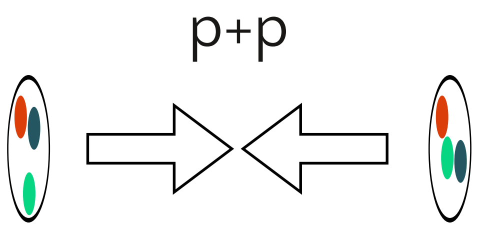
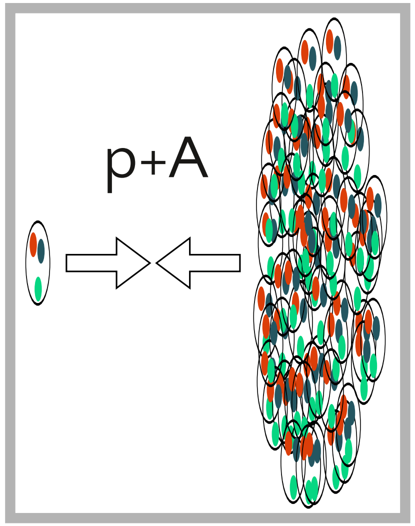




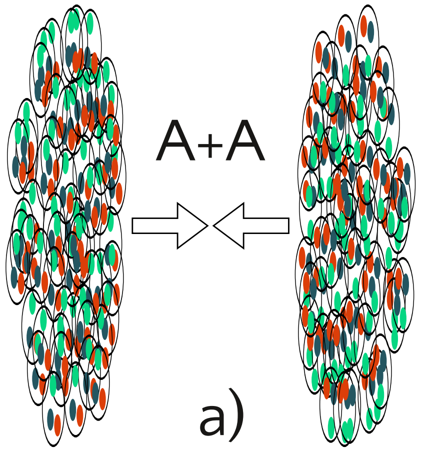
Nuclear models for A:

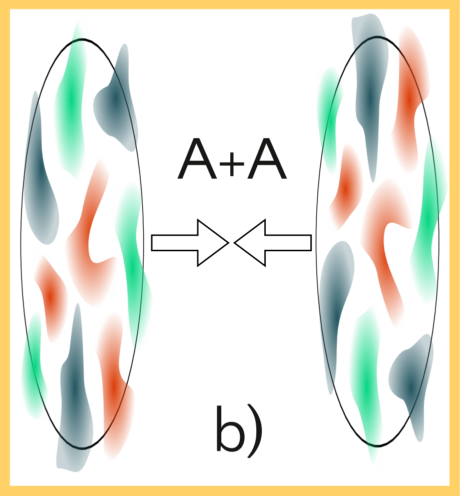
a) Nucleonic and subnucleonic structure:

$A \sim N \times p$ Previous talk by M. Leuthner

b) Charge fluctuations for whole nucleus:

$A \propto \langle \rho\rho \rangle$ **This talk**





Nuclear model

Color charges are drawn from Gaussian probability functional defined by 1-pt. function

$$\langle \rho^a(x^\pm, \mathbf{x}) \rangle = 0$$

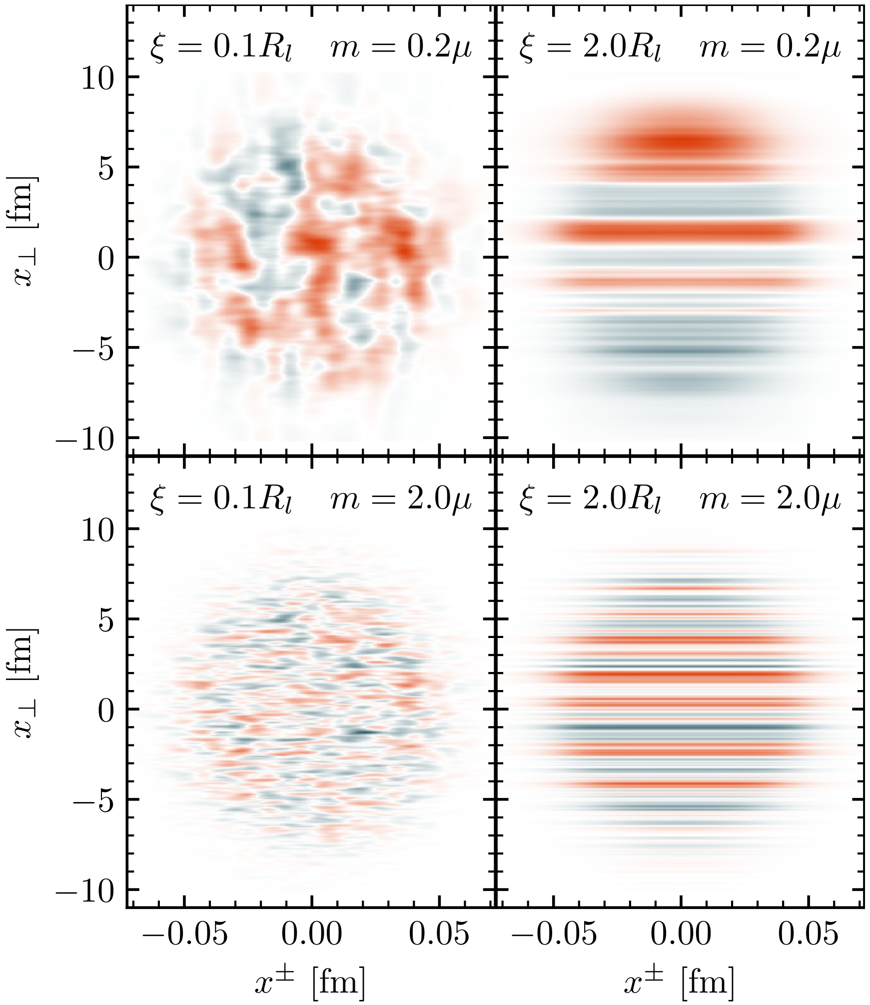
and 2-pt. function

$$\langle \rho^a(x^\pm, \mathbf{x}) \rho^b(y^\pm, \mathbf{y}) \rangle = g^2 \mu^2 \delta^{ab} \sqrt{T(x^\pm, \mathbf{x})} \sqrt{T(y^\pm, \mathbf{y})} \times U_\xi(x^\pm - y^\pm) \delta^{(2)}(\mathbf{x} - \mathbf{y})$$

with

$$T(x^\pm, \mathbf{x}) = \frac{c}{1 + \exp\left(\frac{\sqrt{2(\gamma\, x^\pm)^2 + \mathbf{x}^2} - R}{d} \right)}$$

$$U_\xi(x^\pm - y^\pm) = \frac{1}{\sqrt{2\pi\xi^2}} e^{\frac{(x^\pm - y^\pm)^2}{8R_l^2}} e^{-\frac{(x^\pm - y^\pm)^2}{2\xi^2}}$$



Nuclear model

3D Woods-Saxon envelope profile

$$T(x^\pm, \mathbf{x}) = \frac{c}{1 + \exp\left(\frac{\sqrt{2(\gamma\, x^\pm)^2 + \mathbf{x}^2} - R}{d}\right)}$$

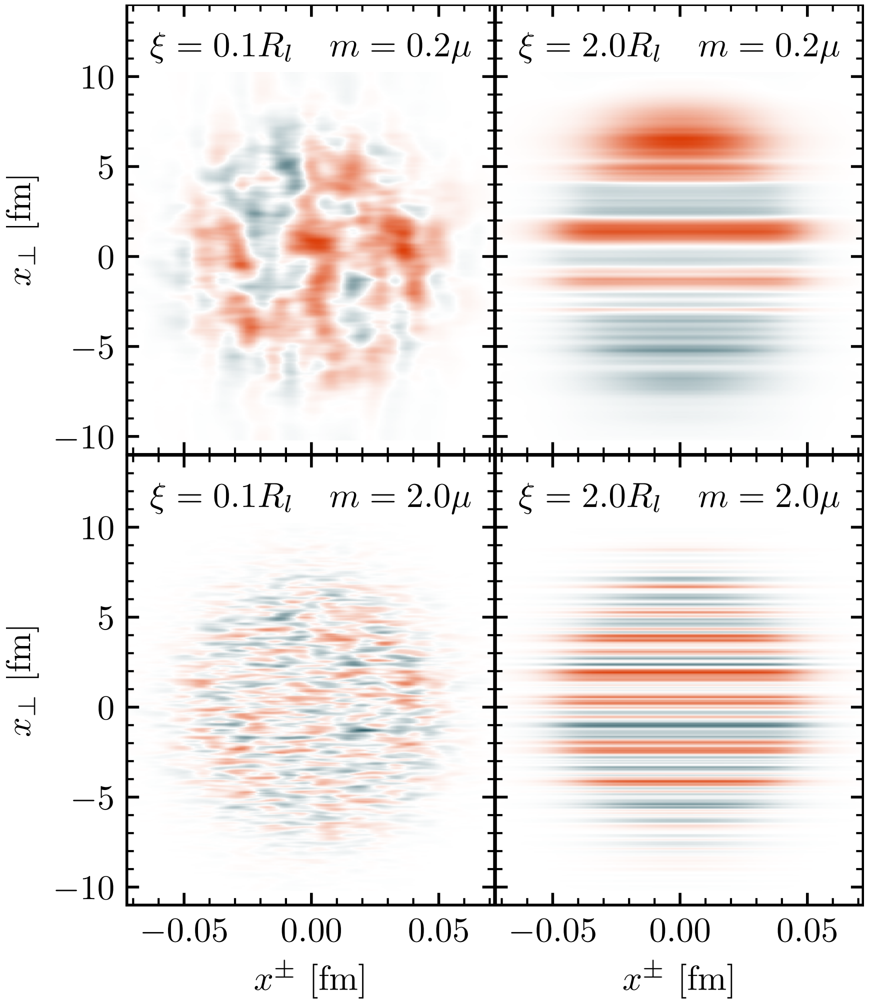
with parameters

Nuclear radius: R

Skin depth: d

Lorentz gamma: γ

that depend on collider energy and nucleus species.



Observables

Using the dilute Glasma field strength tensor $f^{\mu\nu}$

- Energy-momentum tensor

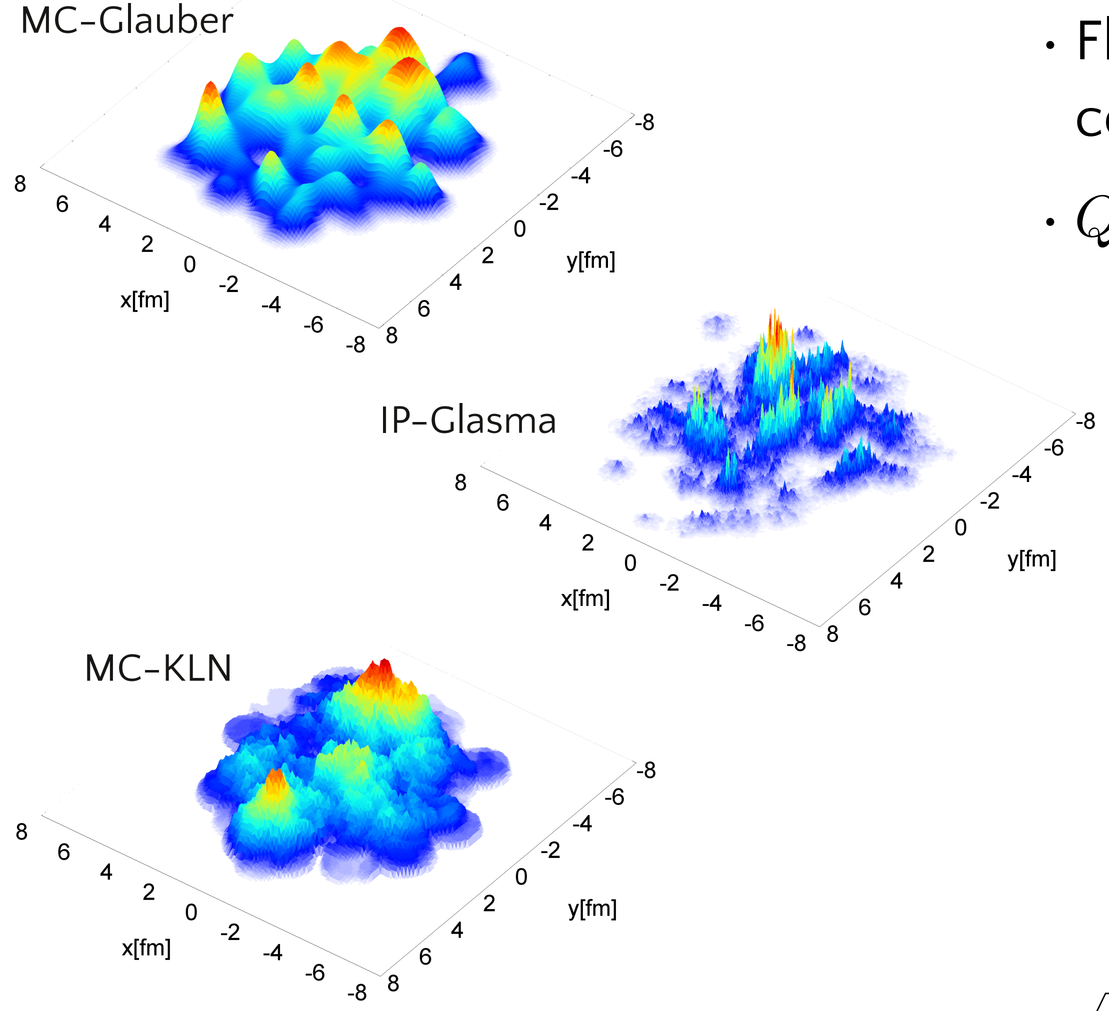
$$T^{\mu\nu} = 2\,\mathrm{Tr}\left[f^{\mu\rho} f_{\rho}^{\ \nu} + \frac{1}{4} g^{\mu\nu} f^{\rho\sigma} f_{\rho\sigma}\right]$$

- Local rest frame energy density ϵ_{LRF}

$$T^{\mu}_{\ \nu} u^{\nu} = \epsilon_{\mathrm{LRF}} u^{\mu}$$

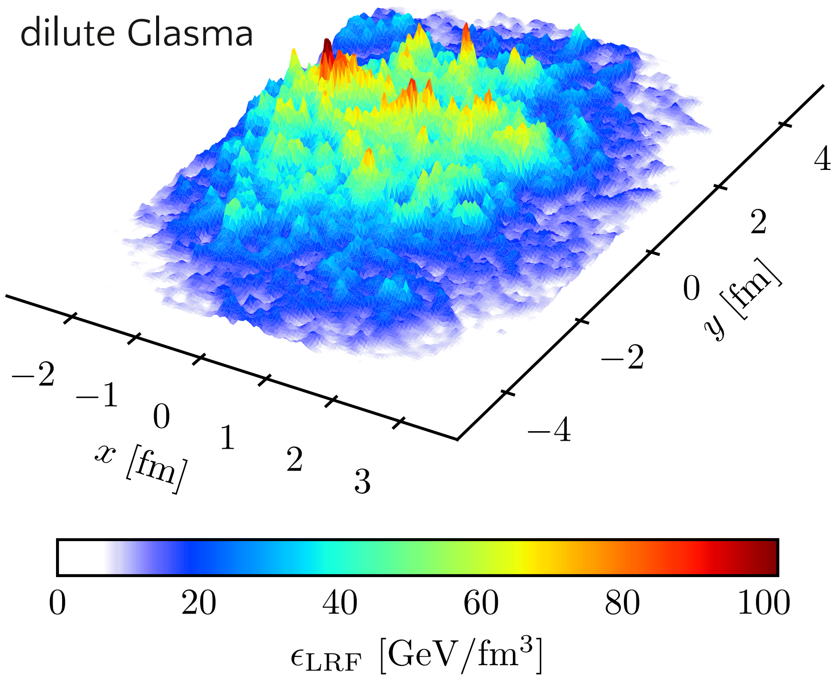
(u^{μ} is the only timelike eigenvector of $T^{\mu}_{\ \nu}$ with $u^{\mu} u_{\mu} = 1$)

Initial energy density comparison



B. Schenke, P. Tribedy, and R. Venugopalan,
Fluctuating Glasma Initial Conditions and Flow in Heavy Ion Collisions
Phys. Rev. Lett. 108 (2012), 252301

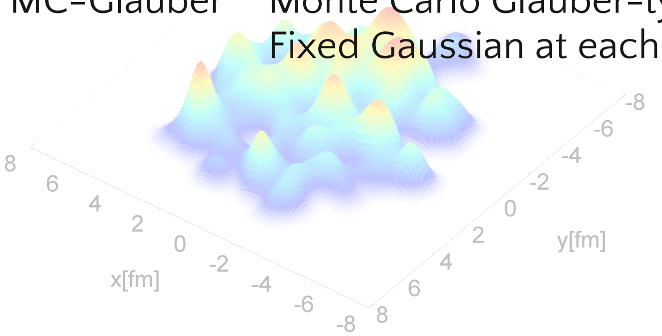
- Fluctuating domains on similar scales compared to IP-Glasma
- Q_s equivalent parameter m (IR regulator)



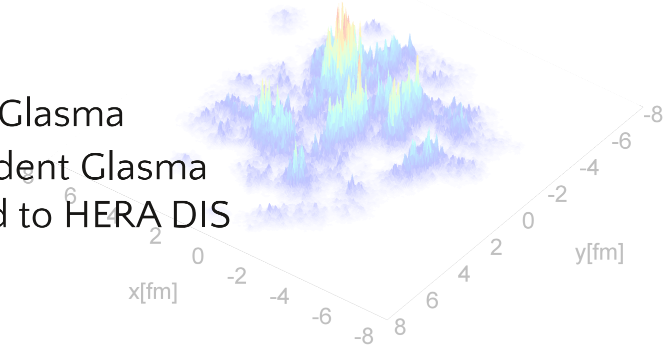
$\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c with impact parameter $b = R$

Initial energy density comparison

MC-Glauber   Monte Carlo Glauber-type
Fixed Gaussian at each participant

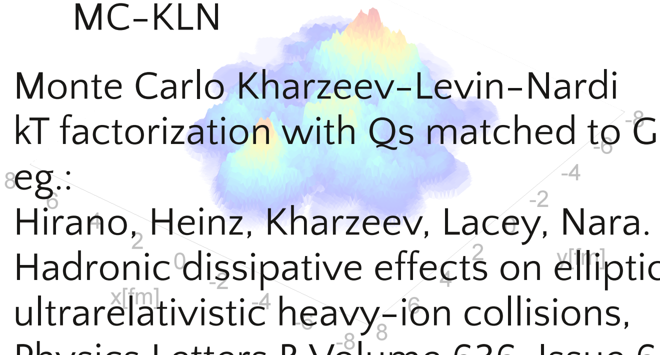


IP-Glasma
Impact parameter dependent Glasma
IP-Saturation model fitted to HERA DIS



MC-KLN

Monte Carlo Kharzeev-Levin-Nardi
kT factorization with Qs matched to G(x, Qs)
eg.:
Hirano, Heinz, Kharzeev, Lacey, Nara.
Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions,
Physics Letters B Volume 636, Issue 6 (2006), 299-304



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- Fluctuating domains on similar scales compared to IP-Glasma
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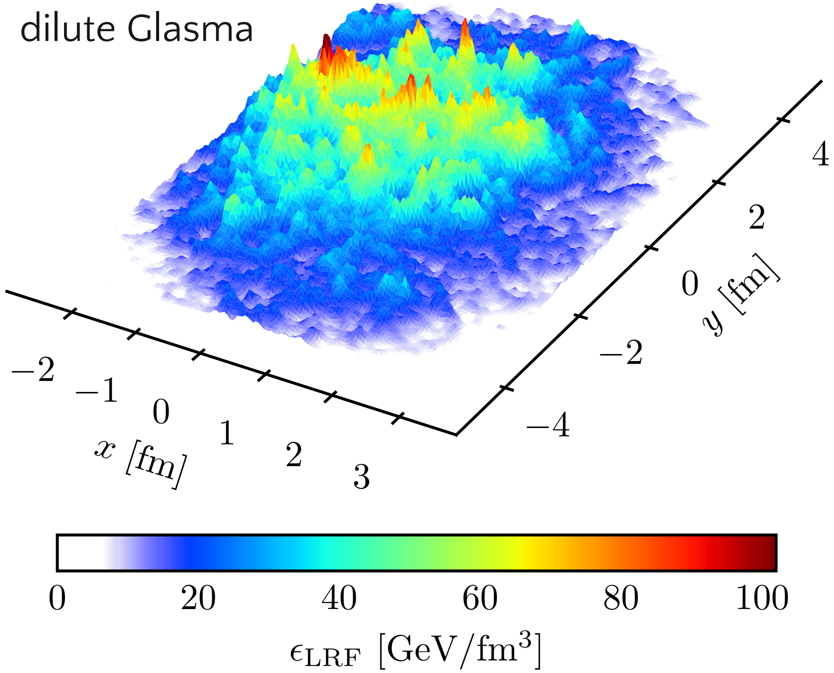
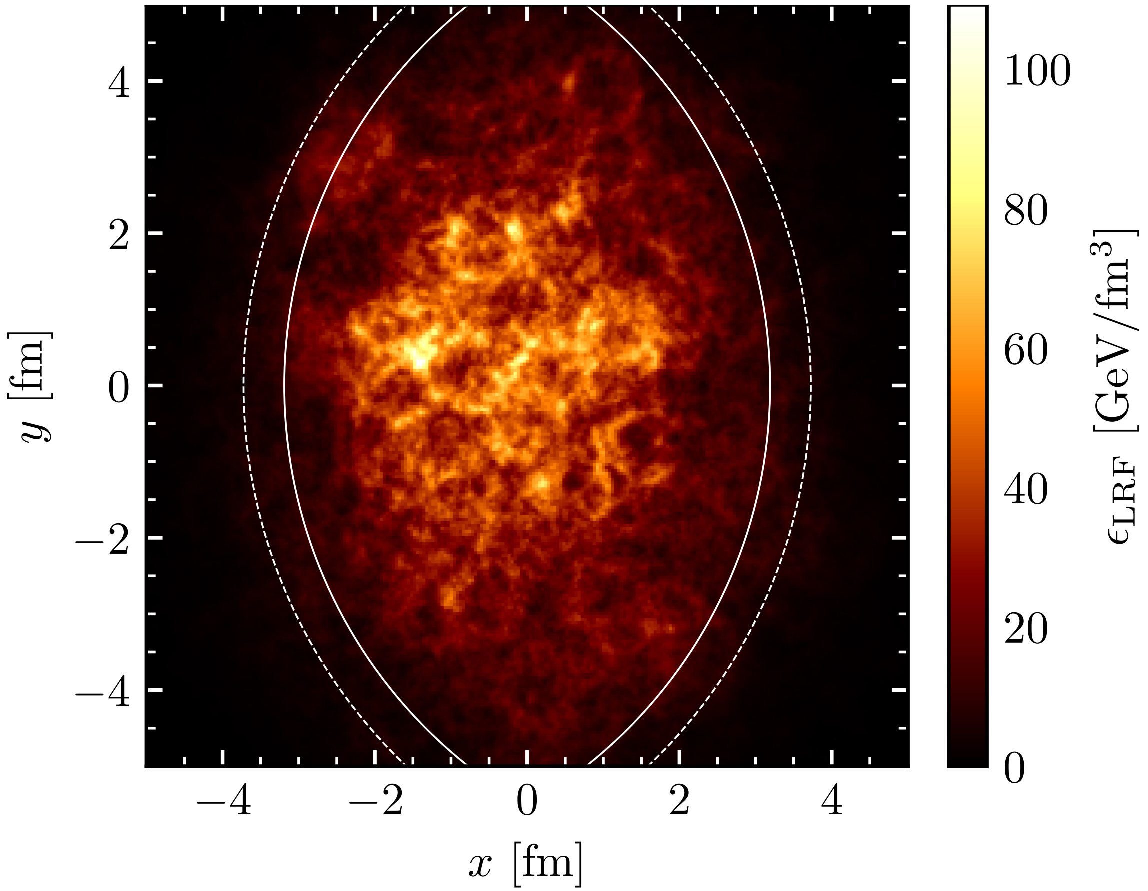
dilute Glasma



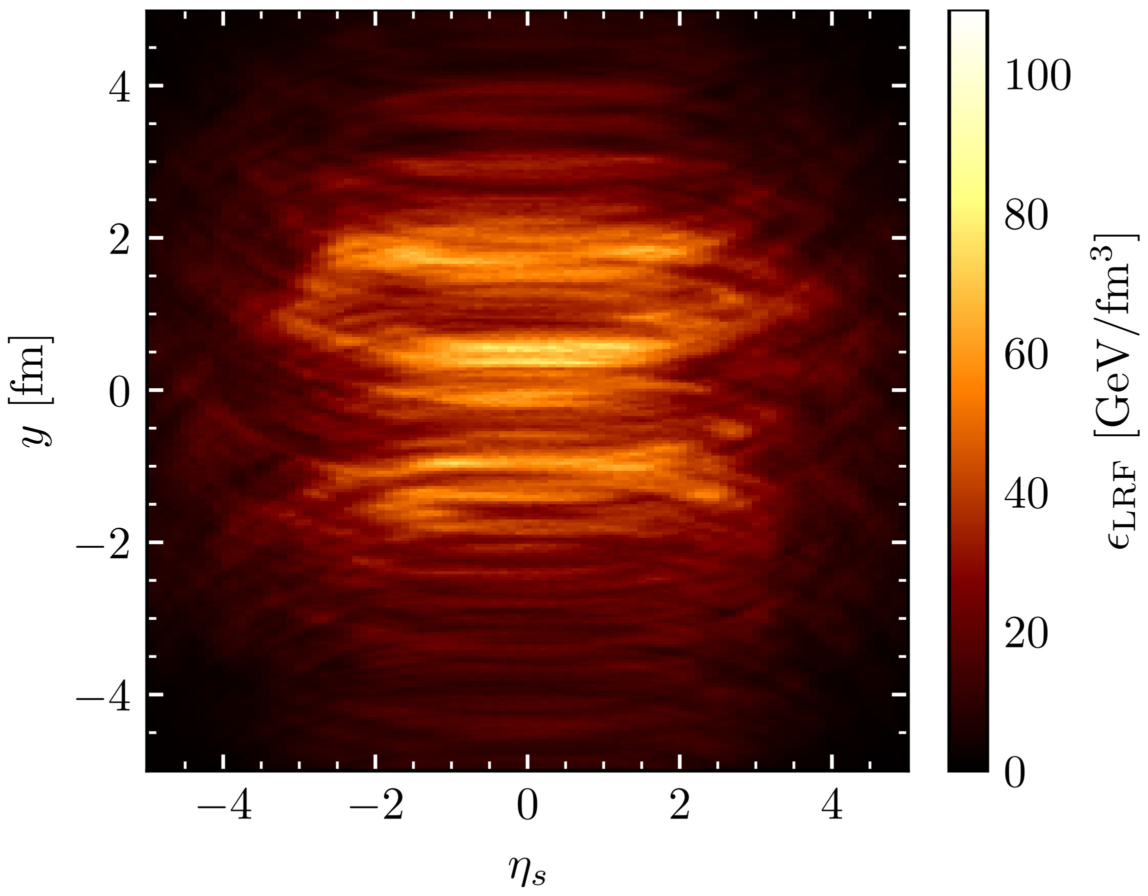
$\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c with impact parameter $b = R$

3D structure

$\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c with impact parameter $b = R$



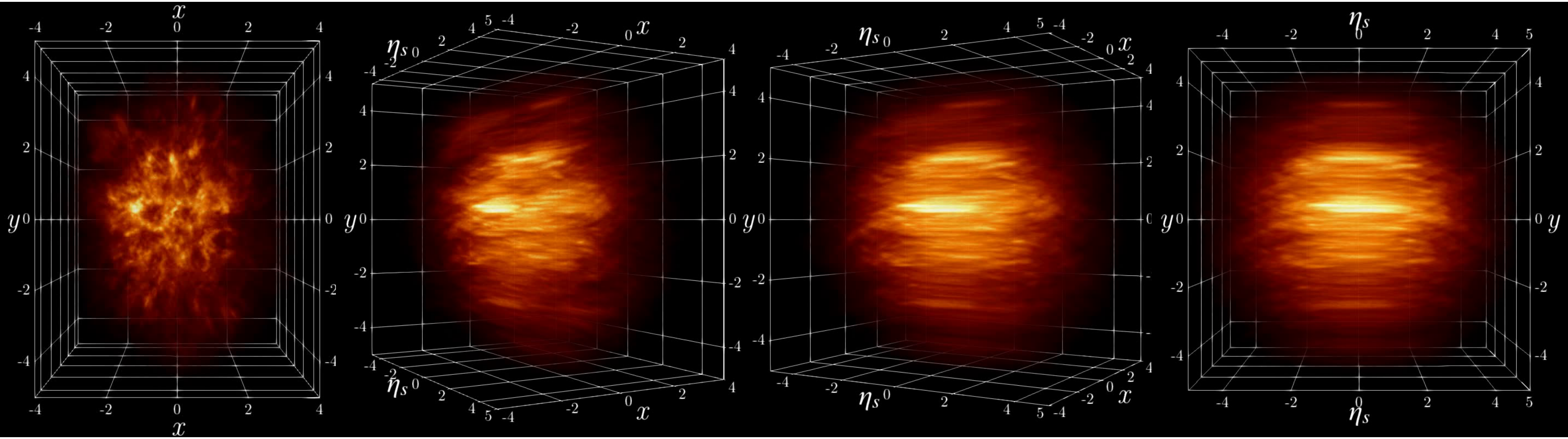
Almond shape



"Flux tube" structure

3D structure

$\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c with impact parameter $b = R$



Full video available online: PhysRevD.109.094040 or [2401.10320]

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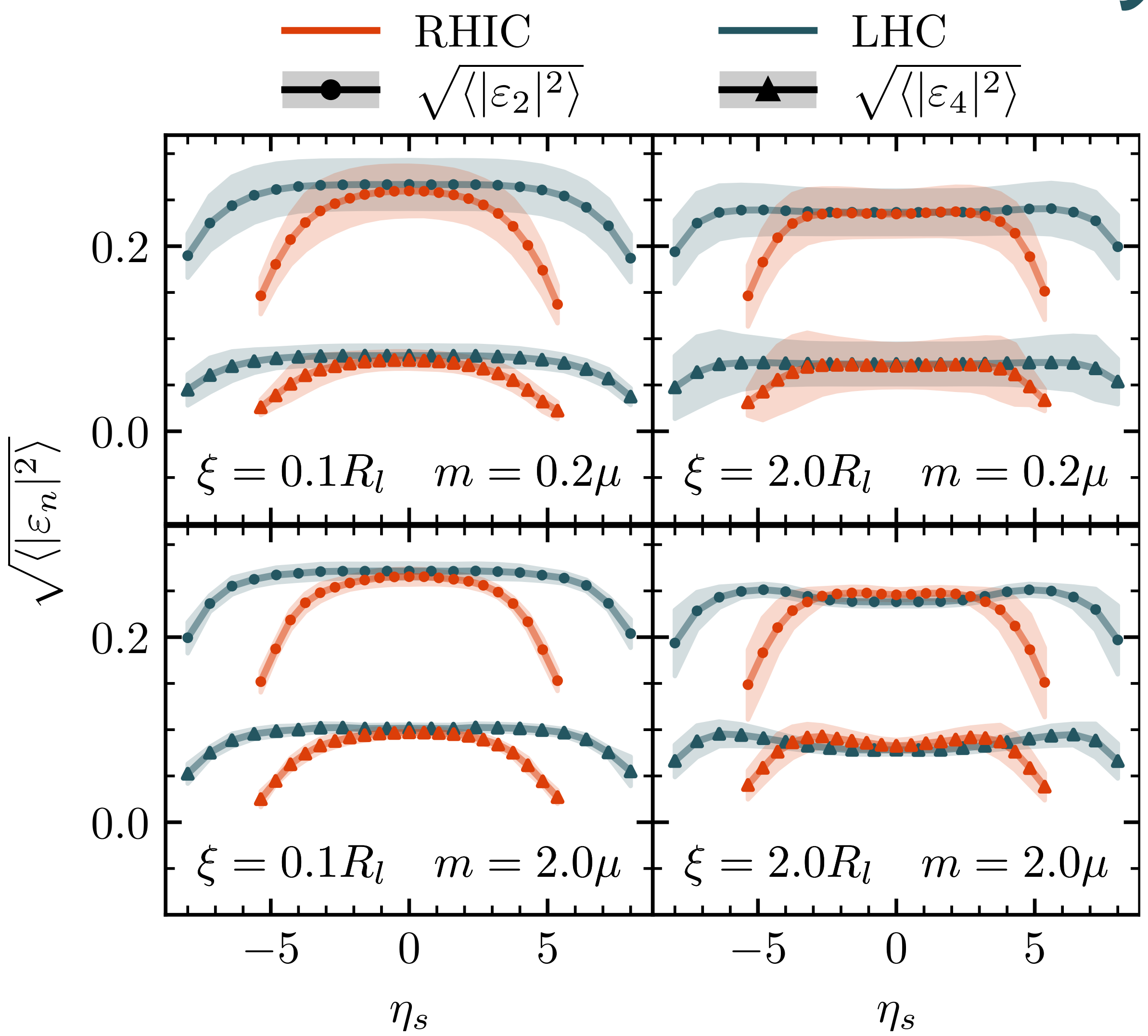
Eccentricity

- Transverse structure

$$\varepsilon_n(\tau, \eta_s) = \frac{\int_{\mathbf{x}} \gamma \epsilon_{\mathrm{LRF}}\, \bar{r}^n \exp(in\bar{\phi})}{\int_{\mathbf{x}} \gamma \epsilon_{\mathrm{LRF}}\, \bar{r}^n}$$

- Connected to flow coefficients v_n
  $\Rightarrow$ Hydro evolution

10 events with impact parameter $b = R$ at $\tau = 0.4$ fm/c
RHIC: $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, LHC: $\sqrt{s_{\mathrm{NN}}} = 2700$ GeV



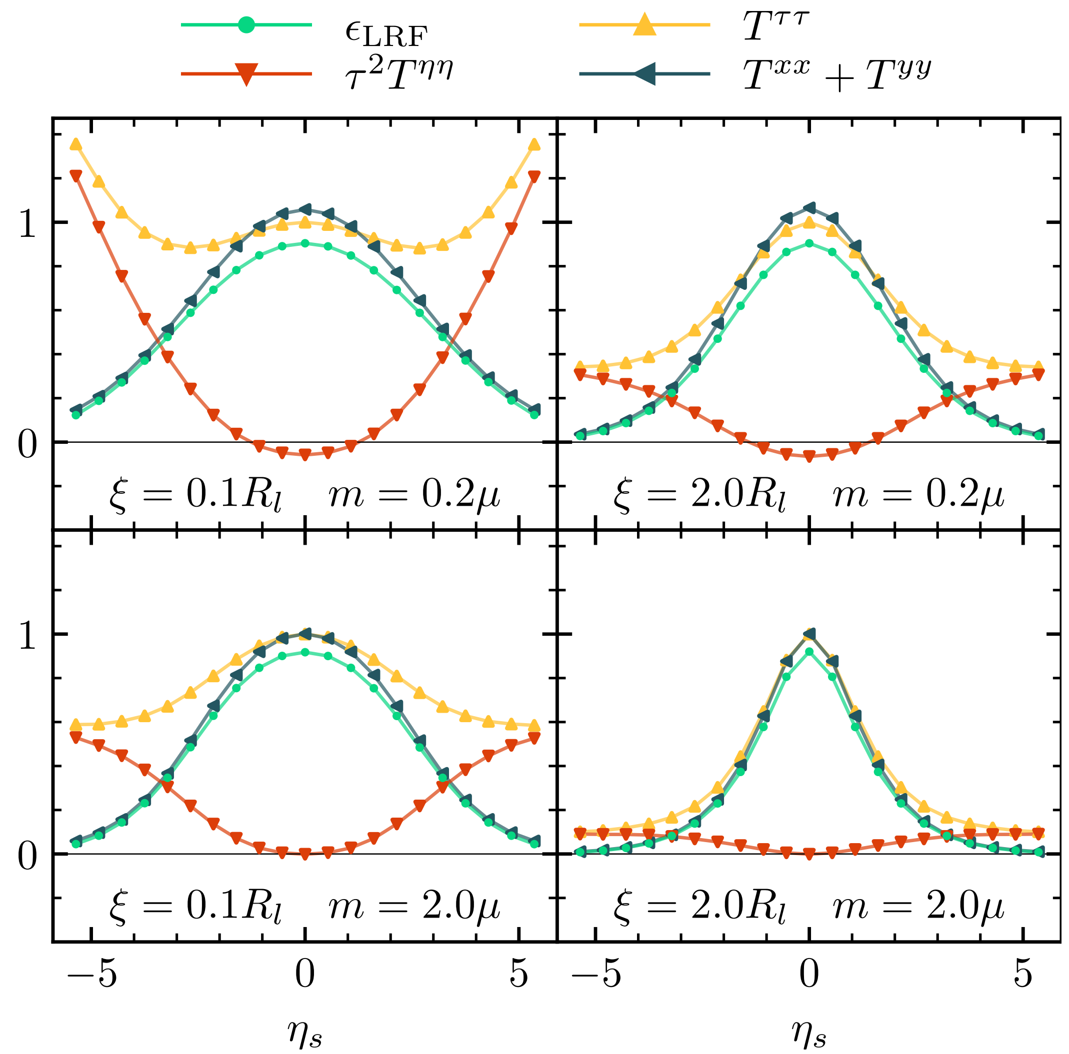
Rapidity profiles

- Transverse integrals

  $\tau \int_{\mathbf{x}} T^{\mu\nu}$

  $\tau \int_{\mathbf{x}} \epsilon_{\mathrm{LRF}}$

- Normalized to $T^{\tau\tau}(\eta_s = 0)$
- τ and η tensor components are problematic
- Tracelessness $T^{\mu}{}_{\mu} = 0$



10 central events at $\tau = 0.4$ fm/c at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

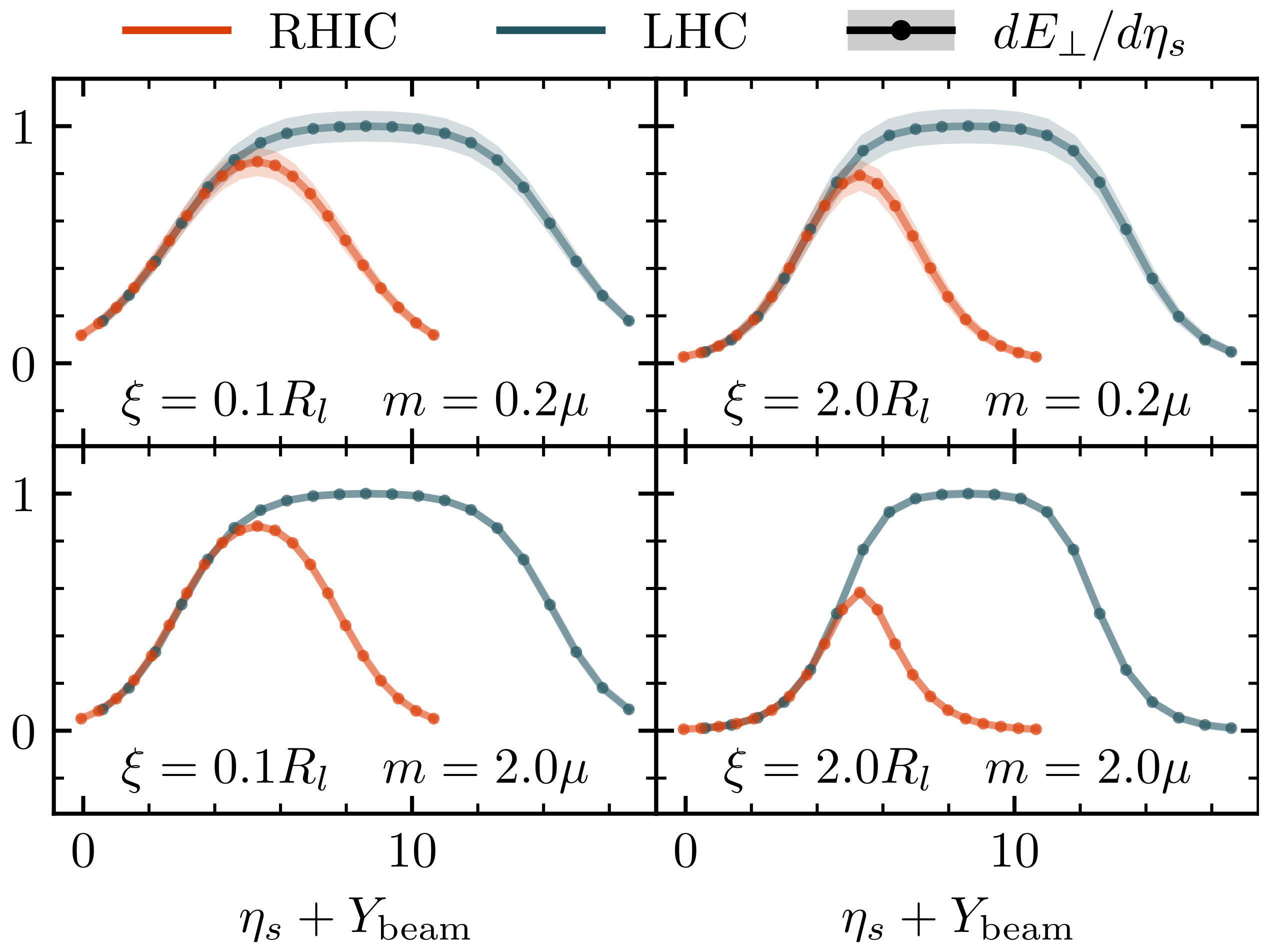
Limiting fragmentation

- Differential transverse energy

$$\frac{dE_\perp}{d\eta_s} = \tau \int_{\mathbf{x}} \left(T^{xx}(\tau, \eta_s, \mathbf{x}) + T^{yy}(\tau, \eta_s, \mathbf{x}) \right)$$

- Normalized to LHC at $\eta_s = 0$
- Shifted by beam rapidity Y_{beam}

$\Rightarrow$ Curves at large η_s overlap

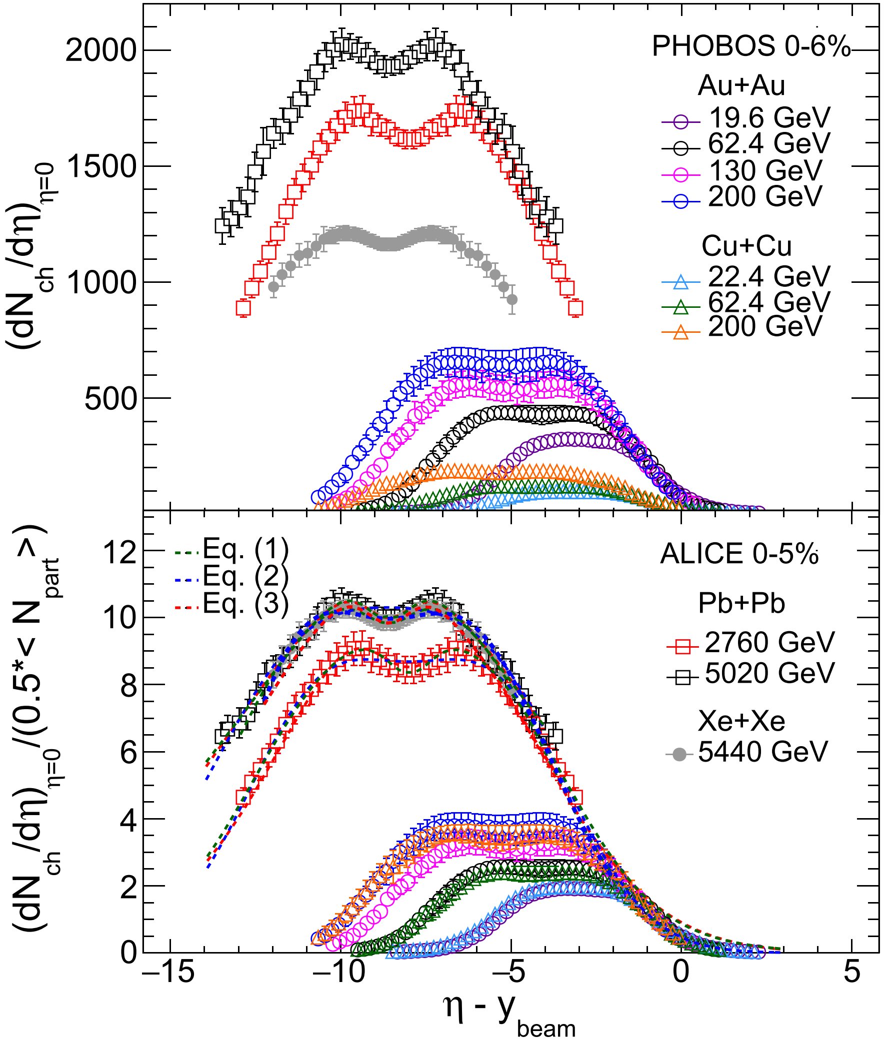


10 central events at $\tau = 0.4$ fm/c

RHIC: $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, LHC: $\sqrt{s_{\mathrm{NN}}} = 2700$ GeV

Limiting fragmentation

S. Basu, S. Thakur, T.K. Nayak and C.A. Pruneau,
Multiplicity and pseudo-rapidity density distributions of charged particles produced in pp, pA and AA collisions at RHIC & LHC energies
J. Phys. G: Nucl. Part. Phys. 48 (2020) 025103



Observed in experiment, e.g. for

$$\text{Charged particle multiplicity:} \quad \frac{dN_{ch}}{d\eta}$$

Studied in theory

- J. Jalilian-Marian,
  Limiting fragmentation from the color glass condensate.
  Phys. Rev. C 70 (2004), 027902
- F. Gelis, A. M. Stasto and R. Venugopalan,
  Limiting fragmentation in hadron–hadron collisions at high energies.
  Eur. Phys. J. C 48 (2006) 489–500
- …

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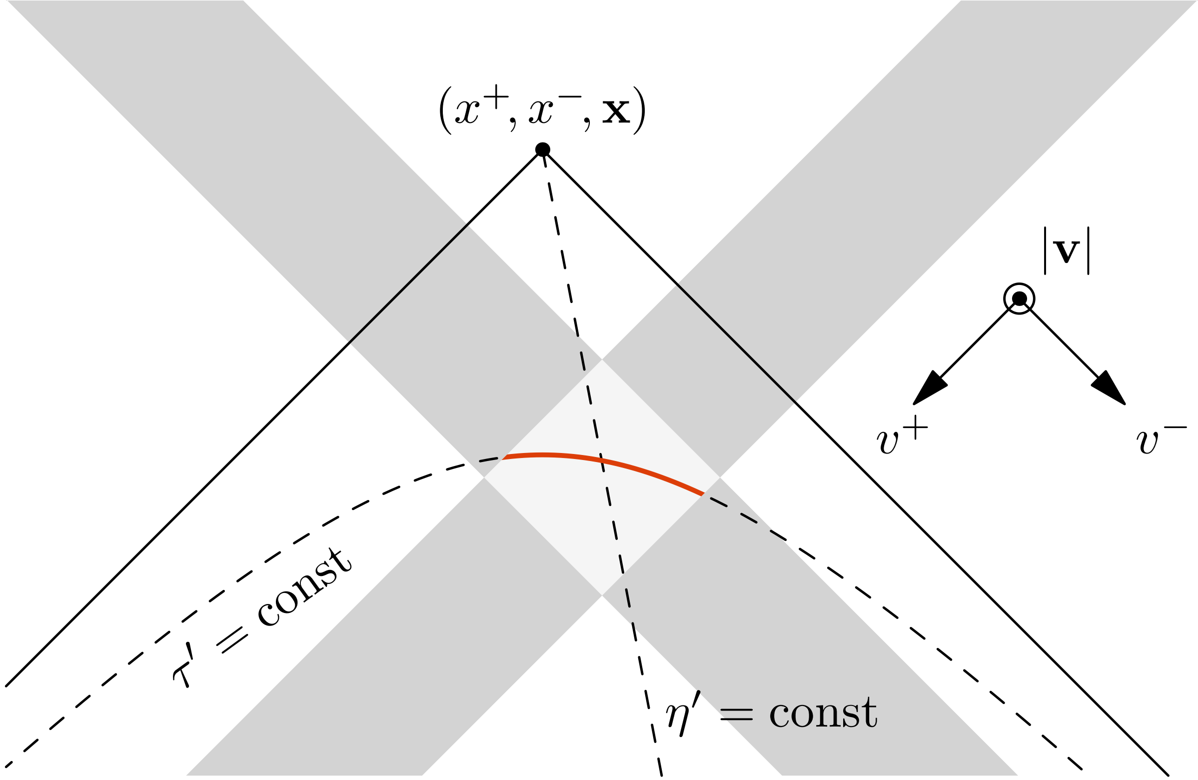
Glasma field strength tensor

$$f^{+-} = -\frac{g}{2\pi} \int\limits_{\mathbf{v}} \int\limits_{-\infty}^{\infty} d\eta' \, V$$

$$f^{\pm i} = \frac{g}{2\pi} \int\limits_{\mathbf{v}} \int\limits_{-\infty}^{\infty} d\eta' \, (V^{ij} \mp \delta^{ij} V) \frac{v^j}{|\mathbf{v}|} \frac{e^{\pm\eta'}}{\sqrt{2}}$$

$$f^{ij} = -\frac{g}{2\pi} \int\limits_{\mathbf{v}} \int\limits_{-\infty}^{\infty} d\eta' \, V^{ij}$$



$$V := f_{abc} t^c \partial^i \mathcal{A}_A^{-a}\left(x^+ - \frac{|\mathbf{v}|}{\sqrt{2}} e^{+\eta'}, \mathbf{x} - \mathbf{v}\right) \partial^i \mathcal{A}_B^{+b}\left(x^- - \frac{|\mathbf{v}|}{\sqrt{2}} e^{-\eta'}, \mathbf{x} - \mathbf{v}\right)$$

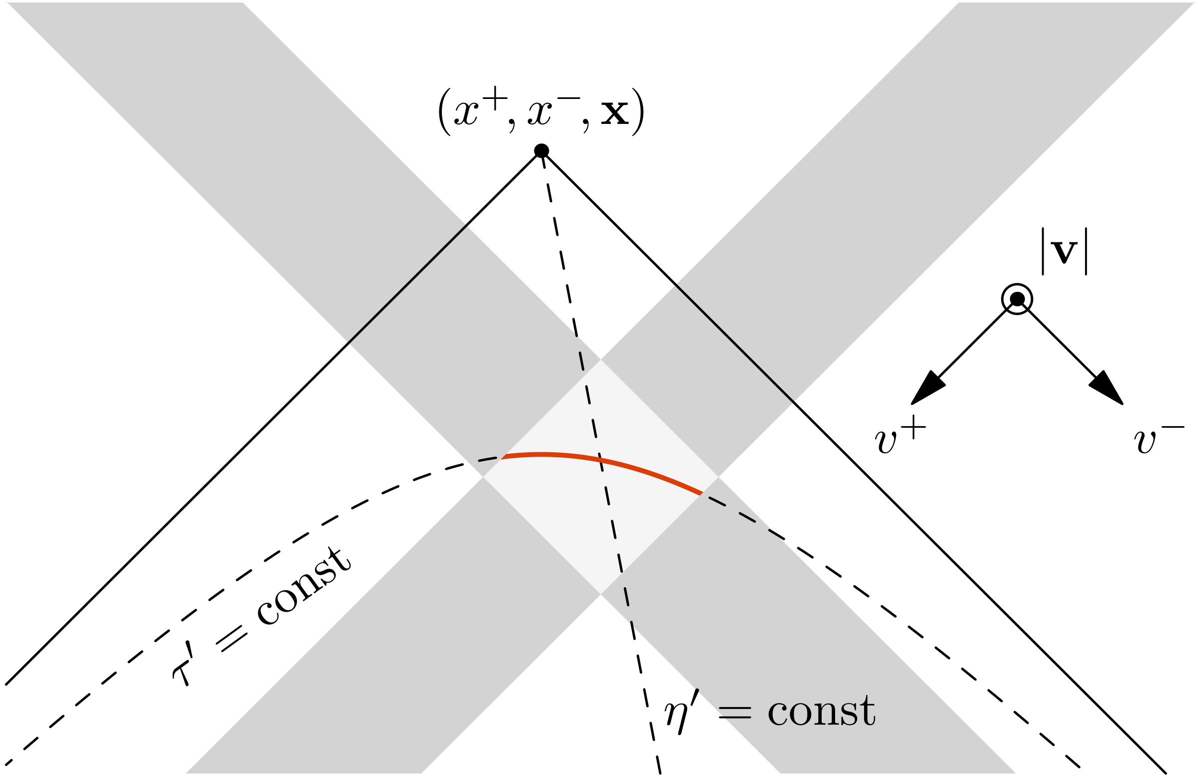
$$V^{ij} := f_{abc} t^c \left(\partial^i \mathcal{A}_A^{-a}(\dots) \partial^j \mathcal{A}_B^{+b}(\dots) - \partial^j \mathcal{A}_A^{-a}(\dots) \partial^i \mathcal{A}_B^{+b}(\dots) \right)$$

Structure of the integrand

- Pick a spacetime point $x = (x^+, x^-, \mathbf{x})$
- Integrate over past lightlike trajectories

  $v = (\frac{\tau'}{\sqrt{2}} e^{+\eta'}, \frac{\tau'}{\sqrt{2}} e^{-\eta'}, \mathbf{v}), \quad \tau' = |\mathbf{v}|$

- The integrand depends on $x - v$



$$V := f_{abc} t^c \partial^i \mathcal{A}_A^{-a}(x^+ - \frac{|\mathbf{v}|}{\sqrt{2}} e^{+\eta'}, \mathbf{x} - \mathbf{v}) \partial^i \mathcal{A}_B^{+b}(x^- - \frac{|\mathbf{v}|}{\sqrt{2}} e^{-\eta'}, \mathbf{x} - \mathbf{v})$$

$$V^{ij} := f_{abc} t^c \left(\partial^i \mathcal{A}_A^{-a}(\dots) \partial^j \mathcal{A}_B^{+b}(\dots) - \partial^j \mathcal{A}_A^{-a}(\dots) \partial^i \mathcal{A}_B^{+b}(\dots) \right)$$

Limiting fragmentation approximation

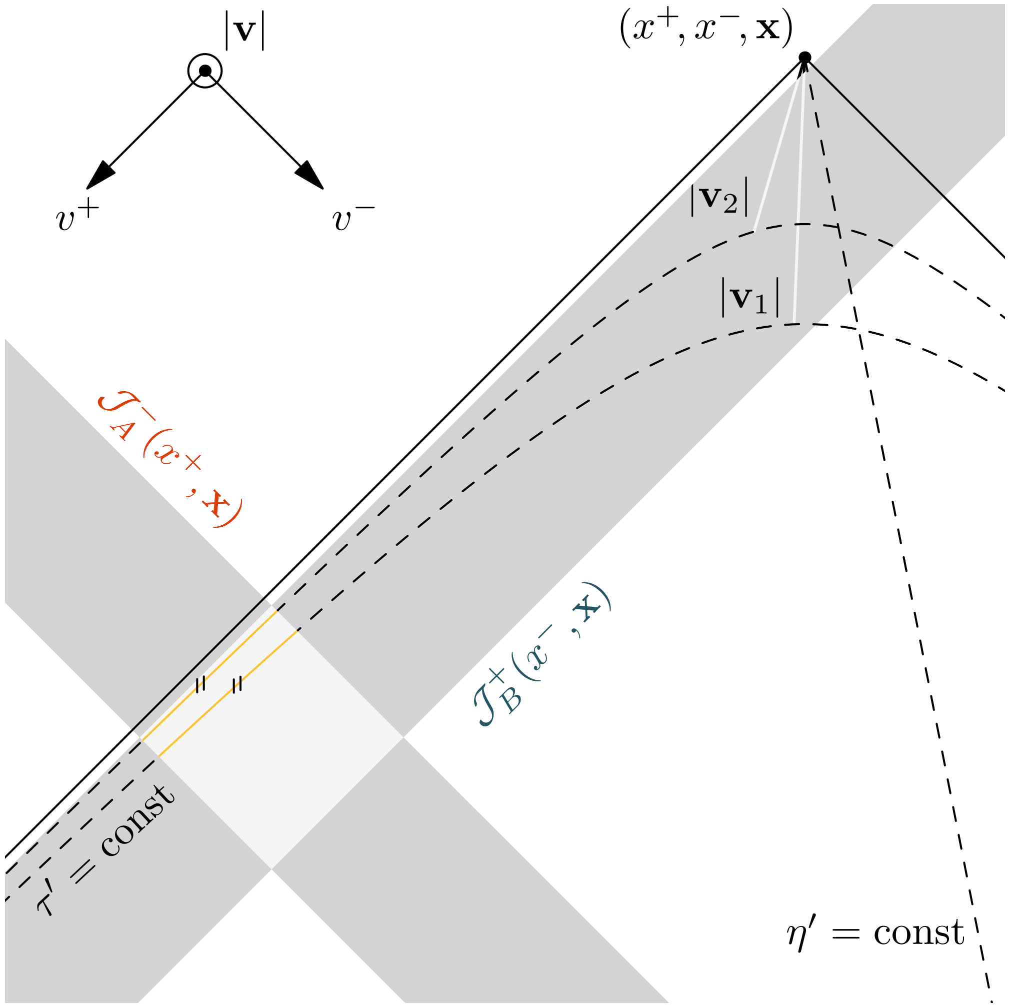
In the fragmentation region

- Contributions only where $\eta' \gg 1$
- For fixed $\tau'(= |\mathbf{v}|)$:
  - $\mathcal{A}_B$ only evaluated along $v^- =$ const.

$$\beta^i_B(x, \mathbf{v}) = \partial^i \mathcal{A}^+_B\left(x^- \left(1 - \frac{\mathbf{v}^2}{\tau^2}\right), \mathbf{x} - \mathbf{v}\right)$$

  - $\mathcal{A}_A$ enters via v^+ average

$$\zeta^i_A(\mathbf{x} - \mathbf{v}) = \partial^i \int \mathrm{d}y^+ \mathcal{A}^-_A(y^+, \mathbf{x} - \mathbf{v})$$



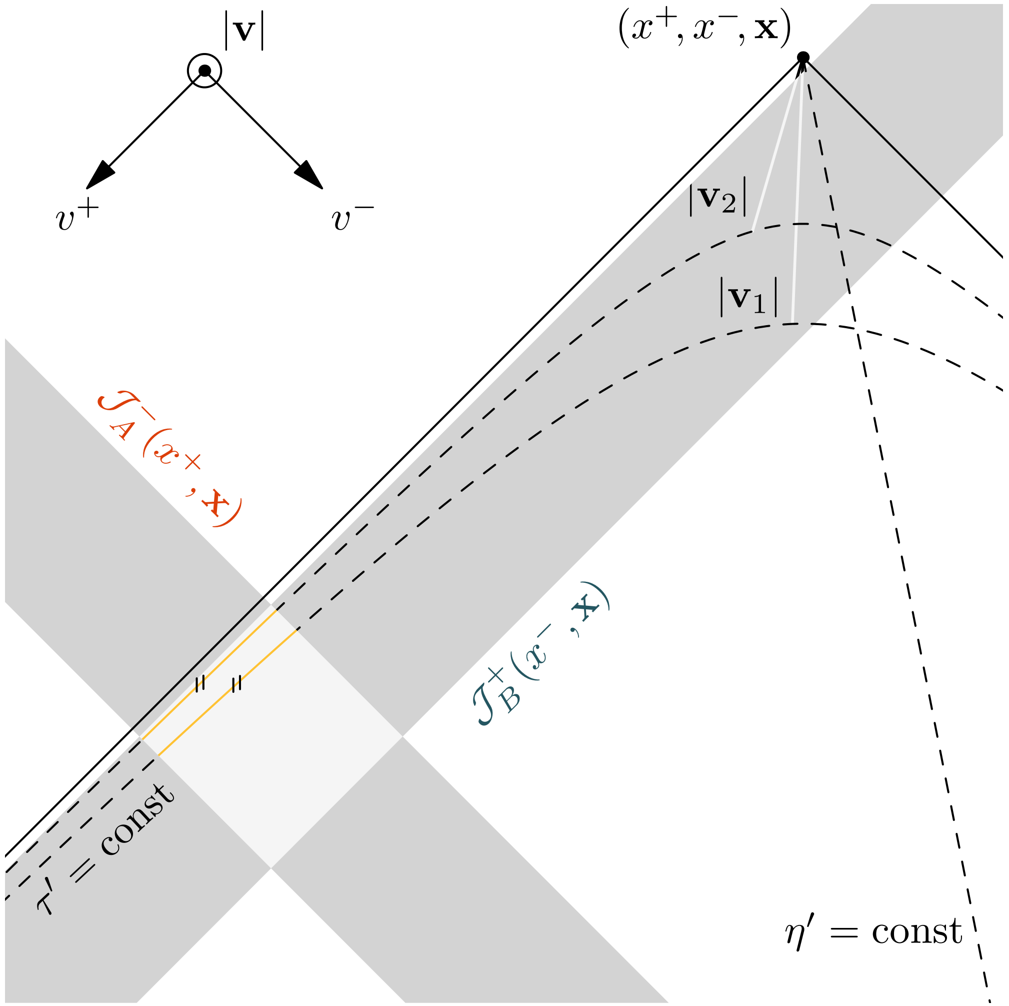
Limiting fragmentation approximation

$$f^{+-} = -\frac{g}{2\pi}\frac{1}{x^+}\int_{\mathbf{v}} Y(x,\mathbf{v})$$

$$f^{ij} = -\frac{g}{2\pi}\frac{1}{x^+}\int_{\mathbf{v}} Y^{ij}(x,\mathbf{v})$$

$$f^{+i} = \frac{g}{2\pi}\int_{\mathbf{v}} \left(Y^{ij}(x,\mathbf{v}) - \delta^{ij}Y(x,\mathbf{v})\right)\frac{v^j}{\mathbf{v}^2}$$

$$f^{-i} = \frac{g}{2\pi}\frac{1}{(x^+)^2}\int_{\mathbf{v}} \left(Y^{ij}(x,\mathbf{v}) + \delta^{ij}Y(x,\mathbf{v})\right)\frac{v^j}{2}$$



$$Y(x,\mathbf{v}) := f_{abc}t^c\,\zeta_A^{i,a}(\mathbf{x}-\mathbf{v})\,\beta_B^{i,b}(x,\mathbf{v})$$

$$Y^{ij}(x,\mathbf{v}) := f_{abc}t^c\left(\zeta_A^{i,a}(\dots)\,\beta_B^{j,b}(\dots) - \zeta_A^{j,a}(\dots)\,\beta_B^{i,b}(\dots)\right)$$

Limiting fragmentation approximation

Inserting nuclei at higher $e^{w}\sqrt{s}$ with $\gamma \sim e^{w}$:

$$\mathcal{A}^{\mp}_{A/B}(x^{\pm}, \mathbf{x}) \to e^{+w}\mathcal{A}^{\mp}_{A/B}(e^{+w}x^{\pm}, \mathbf{x})$$

$$\zeta^i_A(\mathbf{x}-\mathbf{v}) = \partial^i \int \mathrm{d}y^+ \mathcal{A}^-_A(y^+, \mathbf{x}-\mathbf{v})$$

$$\to \partial^i \int \mathrm{d}(y^+ e^{+w})\, \mathcal{A}^-_A(y^+ e^{+w}, \mathbf{x}-\mathbf{v}) = \zeta^i_A(\mathbf{x}-\mathbf{v})$$

$$\beta^i_B(x, \mathbf{v}) = \partial^i \mathcal{A}^+_B\left(x^-\left(1-\frac{\mathbf{v}^2}{\tau^2}\right), \mathbf{x}-\mathbf{v}\right)$$

$$\to \partial^i e^{+w} \mathcal{A}^+_B\left(e^{+w}x^-\left(1-\frac{\mathbf{v}^2}{\tau^2}\right), \mathbf{x}-\mathbf{v}\right) = e^{+w}\beta^{i,b}_B(e^{+w}x^-, \ldots)$$

$$Y(x, \mathbf{v}) := f_{abc}t^c\, \zeta^{i,a}_A(\mathbf{x}-\mathbf{v})\, \beta^{i,b}_B(x, \mathbf{v})$$

$$\to f_{abc}t^c\, \zeta^{i,a}_A(\mathbf{x}-\mathbf{v})\, e^{+w}\beta^{i,b}_B(e^{+w}x^-, \tau, \mathbf{x}-\mathbf{v})$$

$$Y^{ij}(x, \mathbf{v}) := f_{abc}t^c\left(\zeta^{i,a}_A(\ldots)\, \beta^{j,b}_B(\ldots) - \zeta^{j,a}_A(\ldots)\, \beta^{i,b}_B(\ldots)\right)$$

$$\to f_{abc}t^c e^{+w}\left(\zeta^{i,a}_A(\ldots)\, \beta^{j,b}_B(e^{+w}x^-, \ldots) - \zeta^{j,a}_A(\ldots)\, \beta^{i,b}_B(e^{+w}x^-, \ldots)\right)$$

$$f^{+-} = -\frac{g}{2\pi}\frac{1}{x^+}\int_{\mathbf{v}} Y(x, \mathbf{v})$$

$$\to f^{+-}(e^{-w}x^+, e^{+w}x^-, \mathbf{x}_\perp)$$

$$f^{ij} = -\frac{g}{2\pi}\frac{1}{x^+}\int_{\mathbf{v}} Y^{ij}(x, \mathbf{v})$$

$$\to f^{ij}(e^{-w}x^+, e^{+w}x^-, \mathbf{x}_\perp)$$

$$f^{+i} = \frac{g}{2\pi}\int_{\mathbf{v}} \left(Y^{ij}(x, \mathbf{v}) - \delta^{ij}Y(x, \mathbf{v})\right)\frac{v^j}{\mathbf{v}^2}$$

$$\to e^{+w} f^{+i}(e^{-w}x^+, e^{+w}x^-, \mathbf{x}_\perp)$$

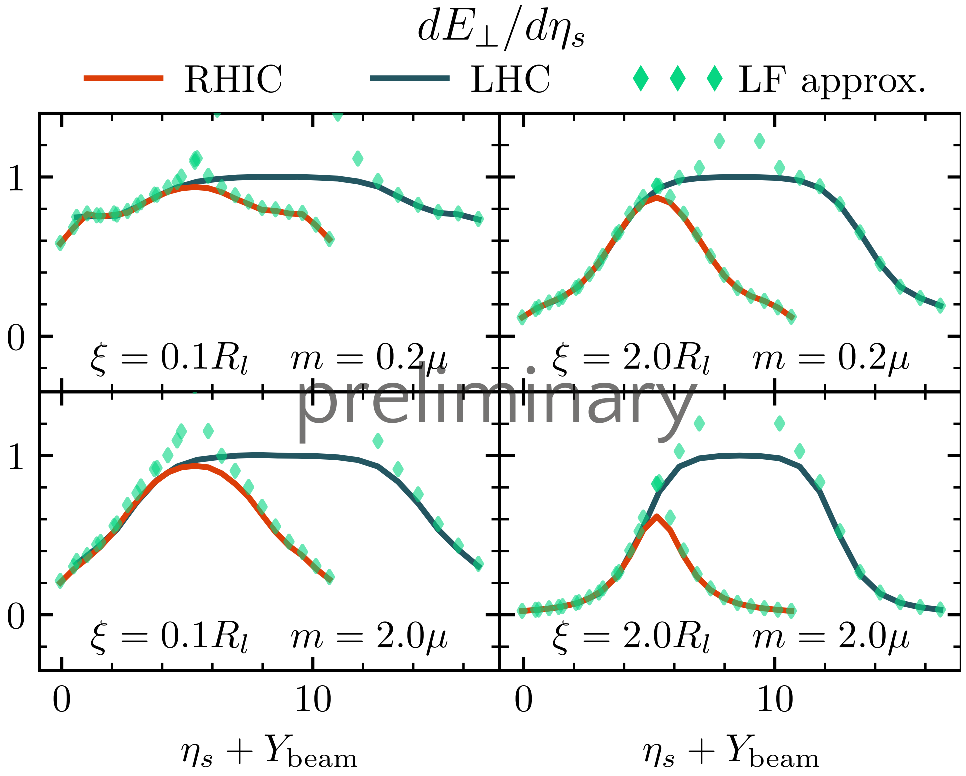
$$f^{-i} = \frac{g}{2\pi}\frac{1}{(x^+)^2}\int_{\mathbf{v}} \left(Y^{ij}(x, \mathbf{v}) + \delta^{ij}Y(x, \mathbf{v})\right)\frac{v^j}{2}$$

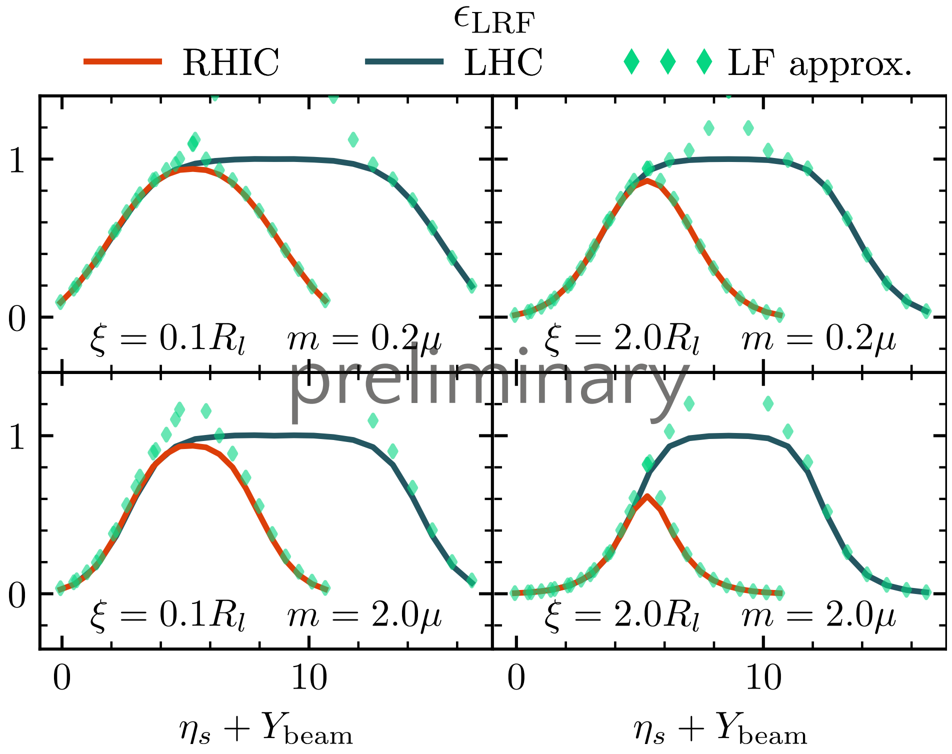
$$\to e^{-w} f^{-i}(e^{-w}x^+, e^{+w}x^-, \mathbf{x}_\perp)$$

$$f^{\mu\nu} \to \Lambda^{\mu}{}_{\rho}(w)\Lambda^{\nu}{}_{\sigma}(w) f^{\rho\sigma}(\Lambda^{-1}(w)x)$$

Limiting fragmentation approximation

Comparison to full dilute Glasma results





$$\frac{dE_\perp}{d\eta_s} = \tau \int_{\mathbf{x}} \left(T^{xx}(\tau, \eta_s, \mathbf{x}) + T^{yy}(\tau, \eta_s, \mathbf{x}) \right)$$

* not covering the entire $\mathbf{x}$ plane

- Remarkable agreement over broad η_s intervall
- Prediction of plateau generally fails

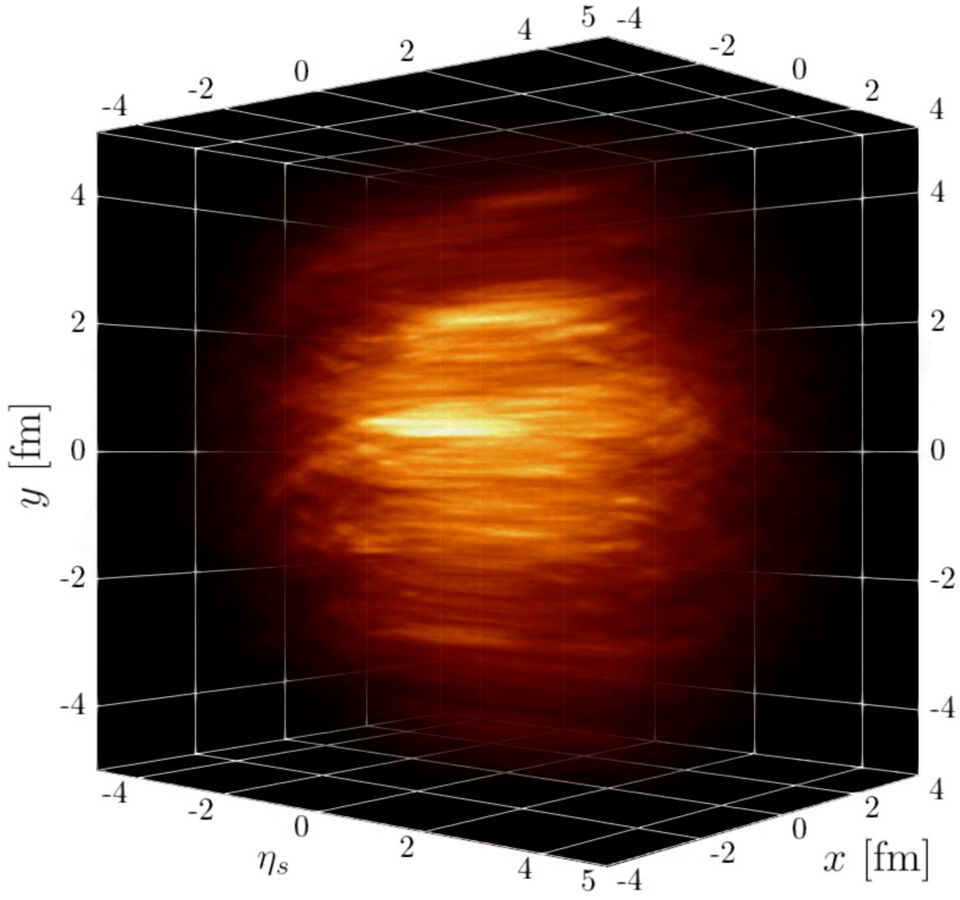
Summary

Nuclear model

- 3D nuclear model with longitudinal correlations
- Collider energy enters via Lorentz γ

Our results

- 3D energy-momentum tensor of the Glasma
- Rich longitudinal and transverse structure
- Limiting fragmentation



ϵ_{LRF} for $\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c

Outlook

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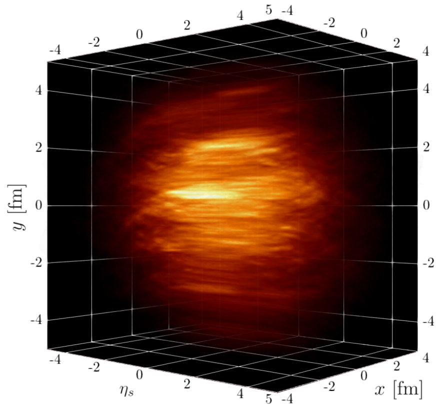
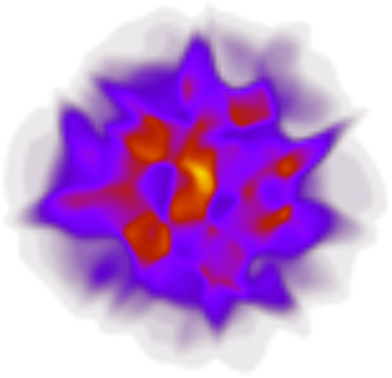
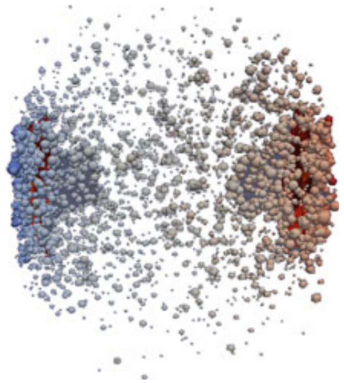
Modeling all stages



$$\mathcal{T}^{\mu\nu}_{\text{hydro}} = \mathcal{T}^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu} - (g^{\mu\nu} - u^\mu u^\nu)\Pi$$

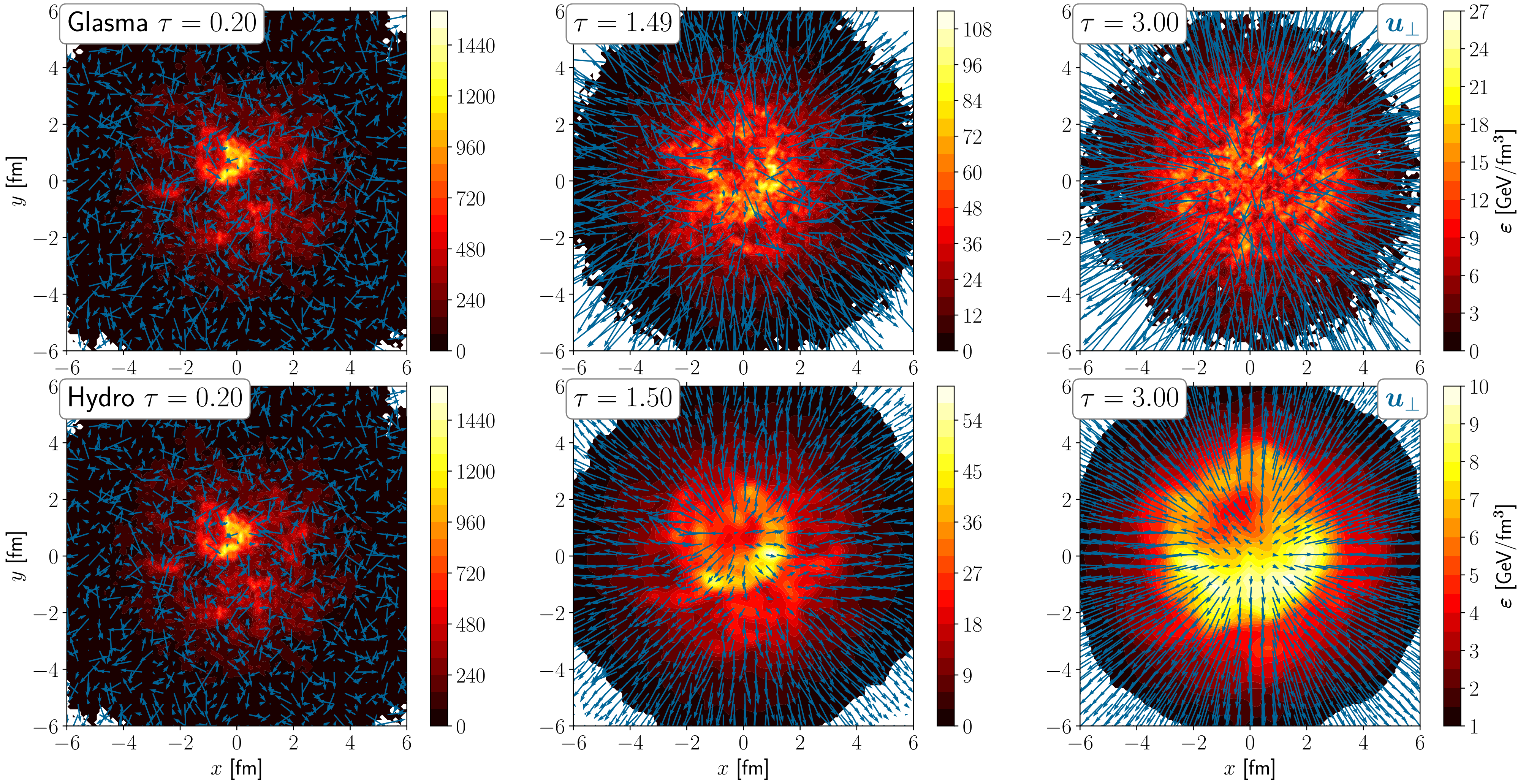
$$\mathcal{T}^{\mu\nu}_{\text{ideal}} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$





Dilute Glasma	Landau matching	Equilibrium QGP	Hadron gas
$\tau \lesssim 0.2\,\frac{\text{fm}}{c}$	$\tau = \tau_{\text{switch}}$	$1\,\frac{\text{fm}}{c} \lesssim \tau \lesssim 10\,\frac{\text{fm}}{c}$	$10\,\frac{\text{fm}}{c} \lesssim \tau$
Classical Yang-Mills	$T^\mu{}_\nu u^\nu = \epsilon u^\mu$	Rel. viscous hydrodynamics	Kinteic theory
Our code	$\pi^{\mu\nu} = \mathcal{T}^{\mu\nu}_{\text{glasma}} - \mathcal{T}^{\mu\nu}_{\text{ideal}}$, $\Pi = \frac{\epsilon}{3} - P_{\text{EOS}}(\epsilon)$	MUSIC	UrQMD

Time evolution at mid-rapidity



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Backup slides

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Simulation parameters

Param.	Name	Value(s)	Unit
N_c	No. of colors	3	–
γ	Lorentz factor	100 (R), 2700 (L)	–
$\sqrt{s_{NN}}$	c.m. energy	200 (R), 5400 (L)	GeV
R	WS radius	6.38 (R), 6.62 (L)	fm
d	WS skin depth	0.535 (R), 0.546 (L)	fm
g	YM coupling	1	–
μ	MV scale	1	GeV
m	IR cutoff	0.2, 2.0	GeV
Λ_{UV}	UV cutoff	10	GeV
ξ	correlation length	0.1, 0.5, 2.0	R_l
b	impact parameter	0, 1	R
τ	proper time	0.2, 0.4, 0.6, 0.8, 1.0	fm/c

McLerran–Venugopalan nuclear model

Gaussian distribution set by expectation values

$$\langle \rho(x^\pm, \mathbf{x}) \rangle = 0$$
$$\langle \rho^a(x^\pm, \mathbf{x})\, \rho^b(y^\pm, \mathbf{y}) \rangle = \delta^{ab} g^2 \mu^2(x^\pm) \delta(x^\pm - y^\pm) \delta^{(2)}(\mathbf{x} - \mathbf{y})$$

Extension to non-trivial longitudinal structure

$$\langle \rho^a(x^\pm, \mathbf{x})\, \rho^b(y^\pm, \mathbf{y}) \rangle =$$
$$\delta^{ab} \underbrace{g^2\mu^2}_{\text{strength of color charges}} \underbrace{T_R\left(\frac{x^\pm + y^\pm}{2}\right)}_{\text{longitudinal profile of width } R} \underbrace{U_\xi\left(x^\pm - y^\pm\right)}_{\text{correlations of width } \xi} \underbrace{T_S\left(\mathbf{x} - \mathbf{y}\right)}_{\text{transverse profile of width } S} \underbrace{\delta^{(2)}\left(\mathbf{x} - \mathbf{y}\right)}_{\text{uncorrelated}}$$

McLerran–Venugopalan nuclear model

$$\langle \rho^{a,-}(x^\pm, \mathbf{x}) \rangle = 0$$

$$\langle \rho^{a,-}(x^\pm, \mathbf{x})\, \rho^{b,-}(y^\pm, \mathbf{y}) \rangle = \delta^{ab}\, g^2 \mu^2\;\, T_R\left(\frac{x^\pm + y^\pm}{2}\right) U_\xi\left(x^\pm - y^\pm\right) T_S\left(\mathbf{x} - \mathbf{y}\right) \delta^{(2)}\left(\mathbf{x} - \mathbf{y}\right)$$

Single nuclei separation ansatz for gaussian T_R, T_S:

$$\langle \rho^{a,-}(x^\pm, \mathbf{x})\, \rho^{b,-}(y^\pm, \mathbf{y}) \rangle = \delta^{ab}\, g^2 \mu^2\;\, \sqrt{T_R\left(x^\pm\right)} \sqrt{T_S\left(\mathbf{x}\right)} \sqrt{T_R\left(y^\pm\right)} \sqrt{T_S\left(\mathbf{y}\right)} \times U_\xi^{\mathrm{mod}}\left(x^\pm - y^\pm\right) \delta^{(2)}\left(\mathbf{x} - \mathbf{y}\right)$$

$$U_\xi^{\mathrm{mod}}\left(x^\pm - y^\pm\right) = \frac{1}{\sqrt{2\pi\xi^2}} \exp\left[-(x^\pm - y^\pm)^2 \left(\frac{1}{2\xi^2} - \frac{1}{8R^2}\right)\right]$$

Nuclear model details

$$\langle \rho^a(x^\pm, \mathbf{x}) \rangle = 0$$

$$\langle \rho^a(x^\pm, \mathbf{x}) \rho^b(y^\pm, \mathbf{y}) \rangle = g^2 \mu^2 \delta^{ab} \sqrt{T(x^\pm, \mathbf{x})} \sqrt{T(y^\pm, \mathbf{y})} U_\xi(x^\pm - y^\pm) \delta^{(2)}(\mathbf{x} - \mathbf{y})$$

$$T(x^\pm, \mathbf{x}) = \frac{c}{1 + \exp\left(\frac{\sqrt{2(\gamma\, x^\pm)^2 + \mathbf{x}^2} - R}{d} \right)}$$

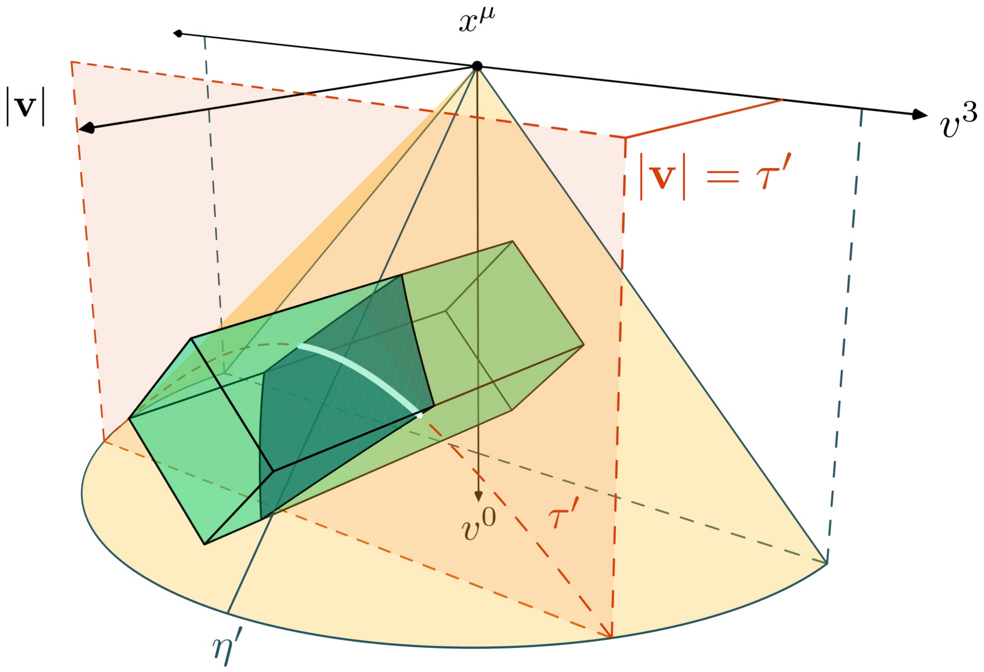
$$U_\xi(x^\pm - y^\pm) = \frac{1}{\sqrt{2\pi\xi^2}} \mathrm{e}^{\frac{(x^\pm - y^\pm)^2}{8R_l^2}} \mathrm{e}^{-\frac{(x^\pm - y^\pm)^2}{2\xi^2}}$$

$$\mathcal{A}^{\mp a}_{A/B}(x^\pm, \mathbf{x}) = \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\tilde{\rho}^a_{A/B}(x^\pm, \mathbf{k})}{\mathbf{k}^2 + m^2} \mathrm{e}^{-\mathbf{k}^2/(2\Lambda^2_{\mathrm{UV}})} \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{x}},$$

Structure of the integral

- Pick a spacetime point $x = (x^+, x^-, \mathbf{x})$
- Integrate over past lightlike trajectories

  $v = (\frac{\tau'}{\sqrt{2}}e^{+\eta'}, \frac{\tau'}{\sqrt{2}}e^{-\eta'}, \mathbf{v})$, $\tau' = |\mathbf{v}|$
- The integrand depends on $x - v$



$$V := f_{abc}t^c \partial^i \mathcal{A}_A^{-a}(x^+ - \frac{|\mathbf{v}|}{\sqrt{2}}e^{+\eta'}, \mathbf{x} - \mathbf{v}) \partial^i \mathcal{A}_B^{+b}(x^- - \frac{|\mathbf{v}|}{\sqrt{2}}e^{-\eta'}, \mathbf{x} - \mathbf{v})$$

$$V^{ij} := f_{abc}t^c \left(\partial^i \mathcal{A}_A^{-a}(\dots)\partial^j \mathcal{A}_B^{+b}(\dots) - \partial^j \mathcal{A}_A^{-a}(\dots)\partial^i \mathcal{A}_B^{+b}(\dots)\right)$$

Shifted Milne coordinates

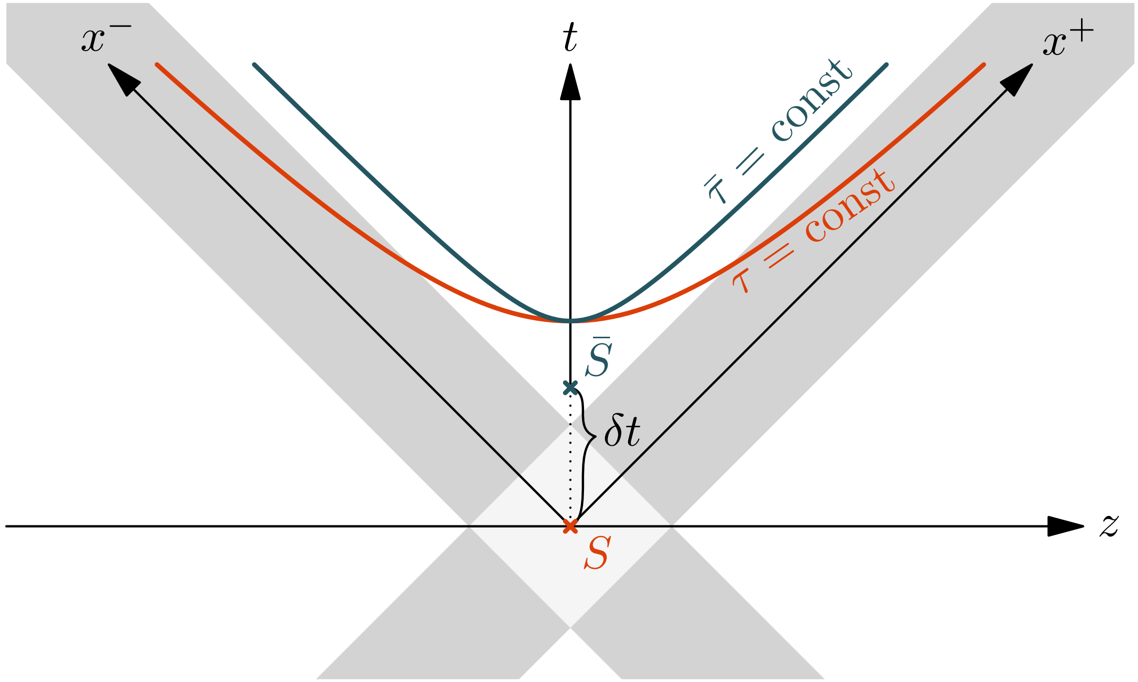
Milne coordinates

$$\tau = \sqrt{2x^+x^-} = \sqrt{t^2 - z^2}$$
$$\eta_s = \frac{1}{2}\ln\left(\frac{x^+}{x^-}\right) = \text{artanh}\left(\frac{z}{t}\right)$$

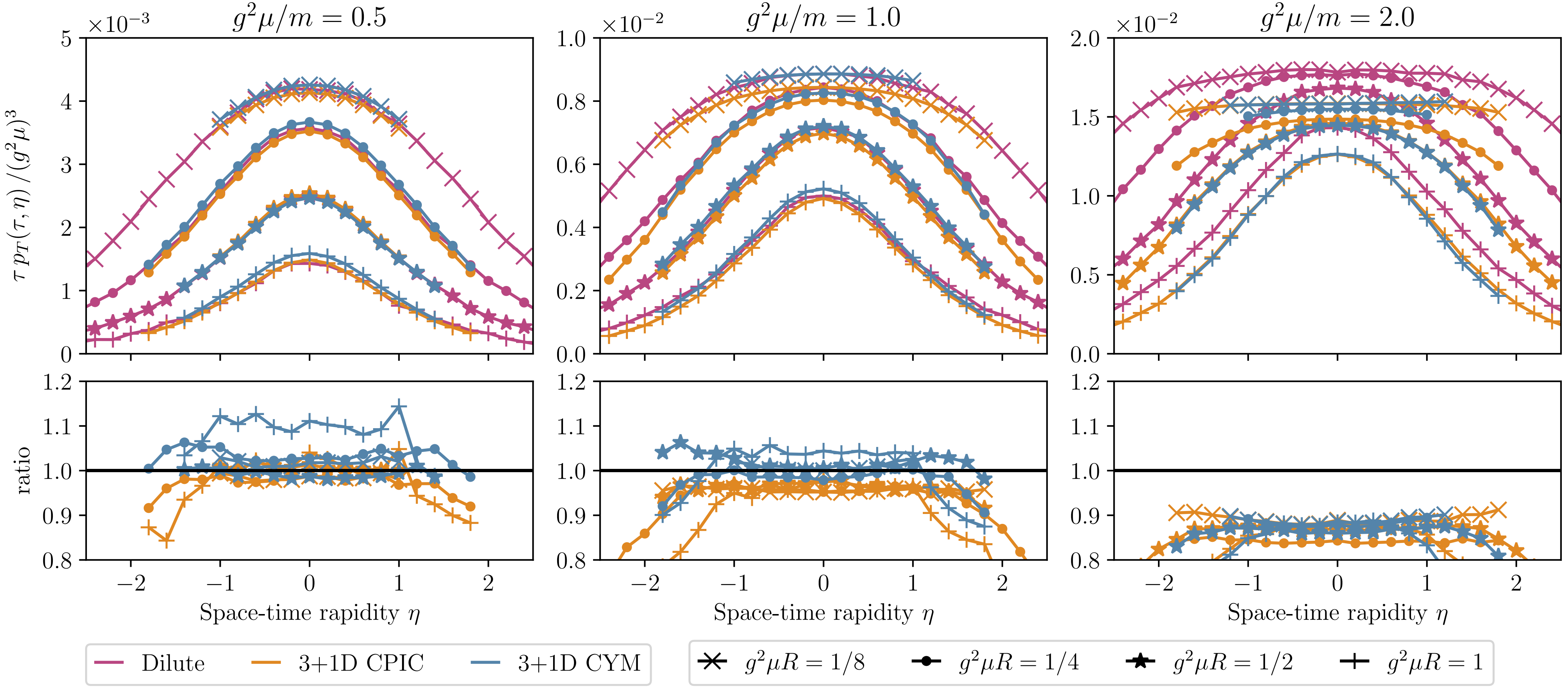
are used to parametrize observables of the Glasma.

For extended collision region it is not obvious where to put the origin!

We shift the origin to avoid $\bar{\tau} = \text{const}$ hyperbolas entering the nuclei!



Comparison to lattice simulations



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Coordinate systems

- $\mathbf{x} = (x, y)$ … transverse plane
- z … beam axis
- $\phi \in [0, 2\pi)$ … azimuthal angle
- $\theta \in [0, \pi)$ … polar angle
- η … pseudorapidity
  $\eta = -\ln\left[\arctan(\theta/2)\right]$
- y … rapidity
  $\mathrm{y} = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \approx \eta$ for $p \gg m$