Charged particle multiplicity in pp-collisions from the dilute Glasma

Markus Leuthner

Institute for Theoretical Physics
TU Wien
Vienna, Austria

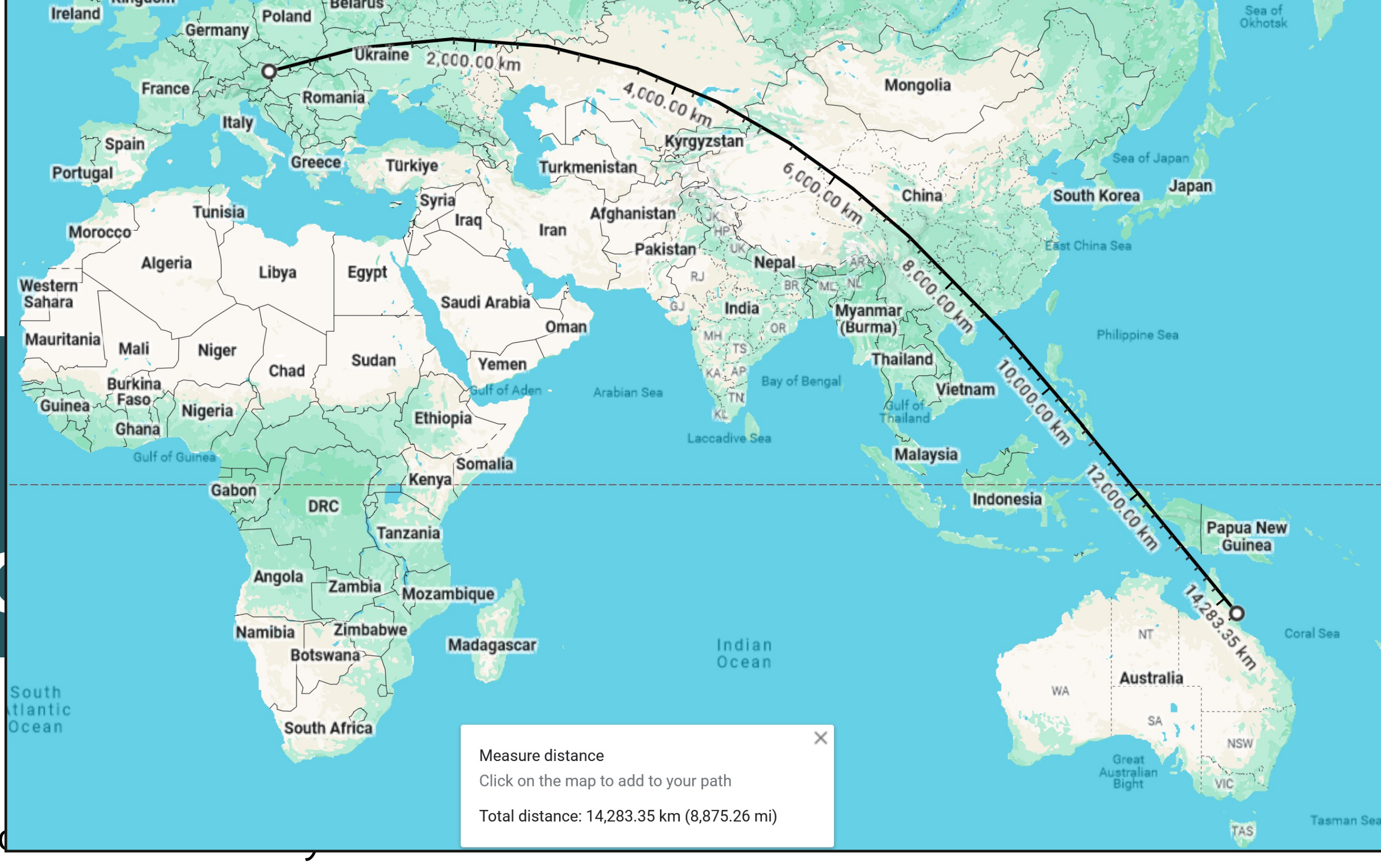
mleuthner@hep.itp.tuwien.ac.at

August 21, 2024

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 subsequent work

XVI$^{\text{th}}$ Quark Confinement and the Hadron Spectrum Conference
Track D: Deconfinement
Cairns, Queensland, Australia

Charged particle mu
from the c



Mark

Institute f

TU Wien

Vienna, **Austria**

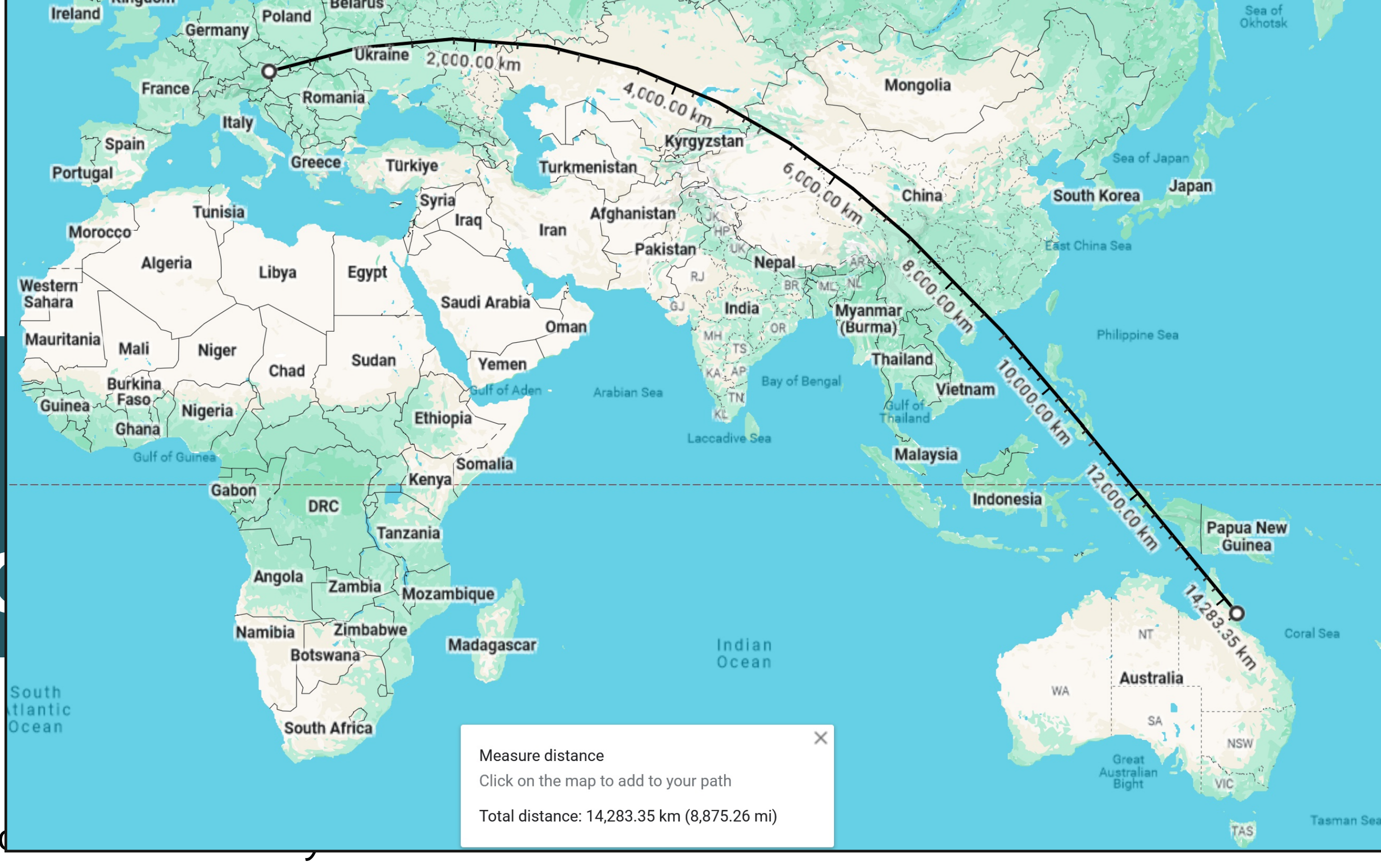
mleuthner@hep.itp.tuwien.ac.at

August 21, 2024

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 subsequent work

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



Mark

stitute fo

TU Wien
Vienna, **Austria**

euthner@hep.itp.tuwien.ac.at

August 21, 2024

Singh,

XVIth Quark Con

TECHNISCHE UNIVERSITÄT WIEN

FWF Österreichischer Wissenschaftsfonds

Doktoratskolleg Particles and Interactions

Charged particle multiplicity in pp-collisions from the dilute Glasma

Markus Leuthner

Institute for Theoretical Physics
TU Wien
Vienna, Austria

mleuthner@hep.itp.tuwien.ac.at

August 21, 2024

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 subsequent work

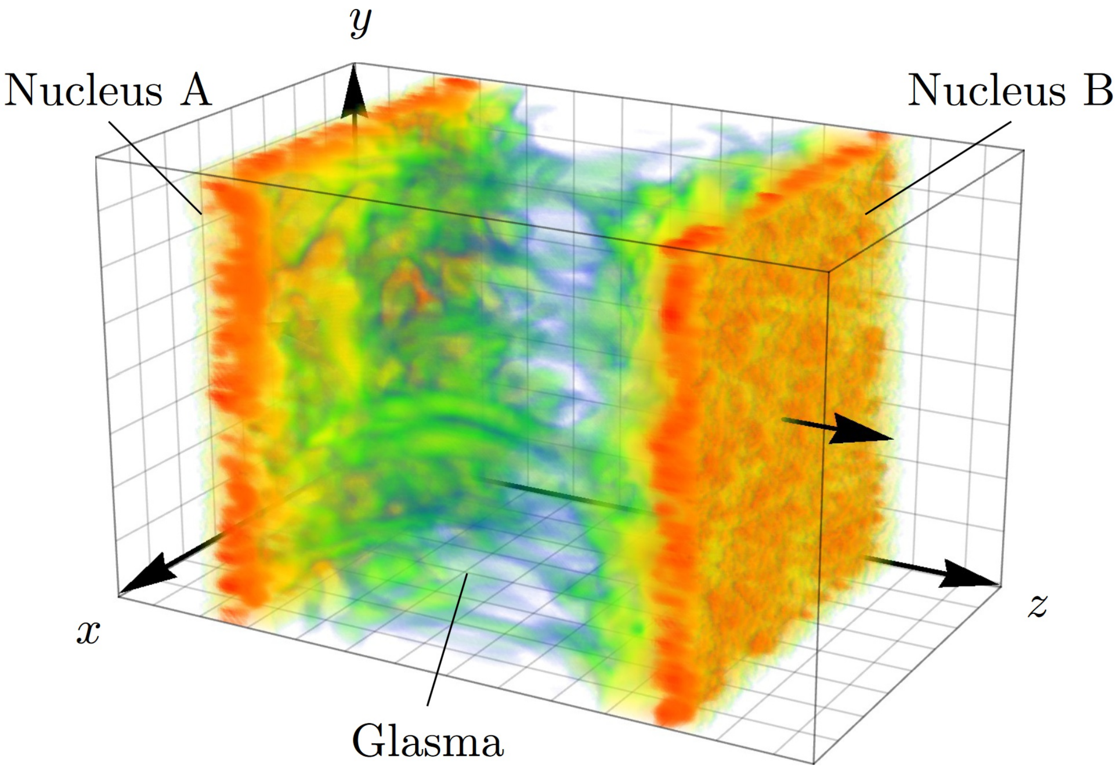
XVI$^{\text{th}}$ Quark Confinement and the Hadron Spectrum Conference
Track D: Deconfinement
Cairns, Queensland, Australia

The Glasma

- ...is mostly discussed in the context of HIC
- ...is something between a glass (CGC) and a plasma (QGP)

therefore

- ...is the precursor to the quark-gluon plasma
- ...is a classical state characterized by large gluon occupation numbers
- ...provides initial conditions for hydro simulations of the QGP



A. Ipp, D. I. Müller, Phys. Lett. B771 (2017) 74–79

Color glass condensate

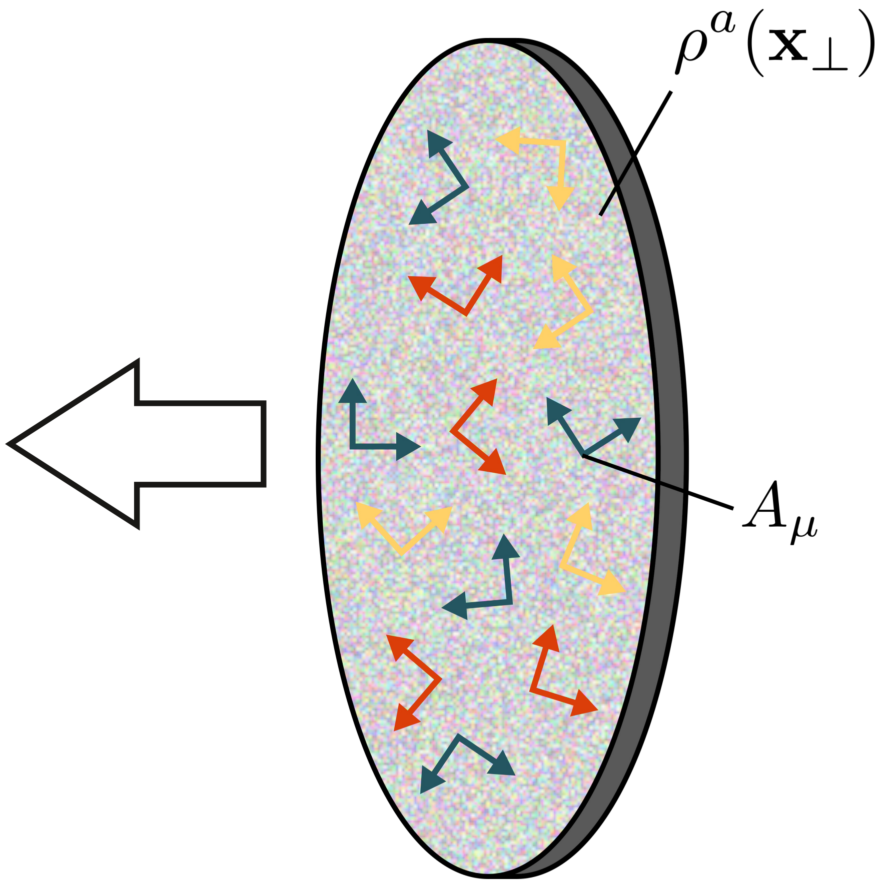
Effective theory for high energy QCD

Separation of scales into

- Hard partons – color charges ρ
- Soft partons – gauge field A_μ

Moving ρ leads to current J

$$D_\mu F^{\mu\nu} = J^\nu$$



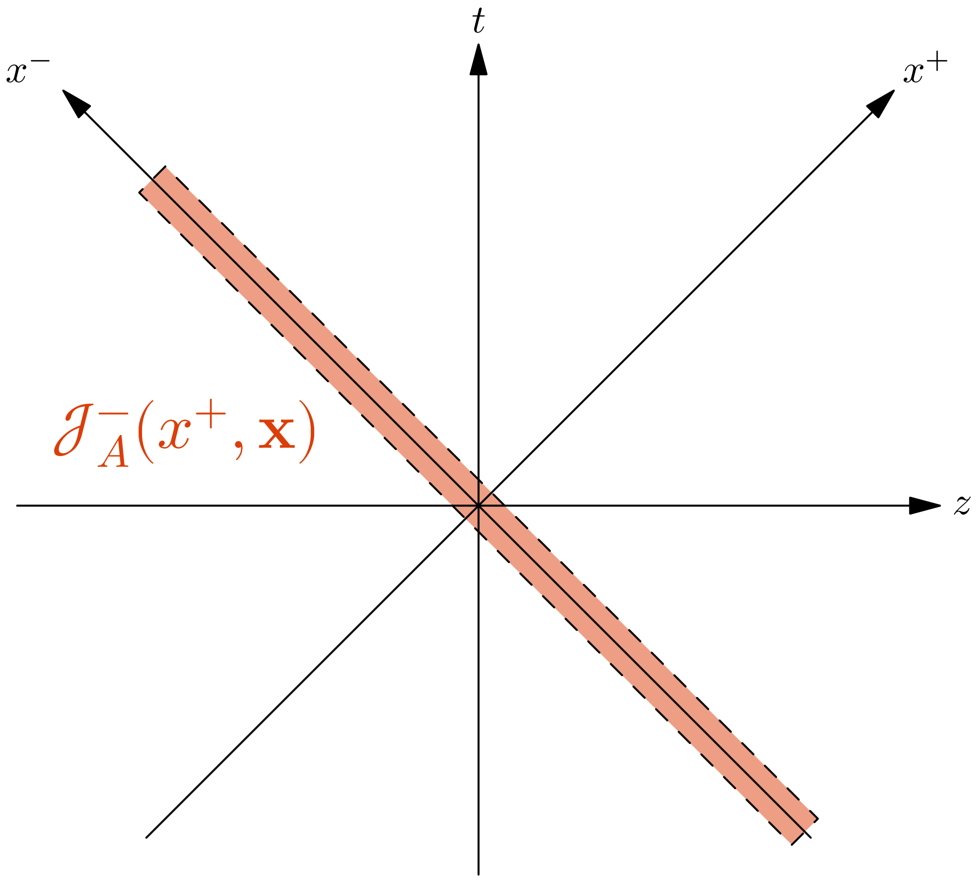
Color glass condensate

Consider nucleus A moving to the left

Color current $\mathcal{J}^-_A$ is a stochastic variable

Classical Yang–Mills equations $\mathcal{D}_\mu \mathcal{F}^{\mu\nu} = \mathcal{J}^\nu$ in covariant gauge $\partial_\mu \mathcal{A}^\mu_A = 0$ gives gauge field $\mathcal{A}_A$ via

$$-\Delta_\perp \mathcal{A}^-_A(x^+, \mathbf{x}) = \mathcal{J}^-_A(x^+, \mathbf{x})$$



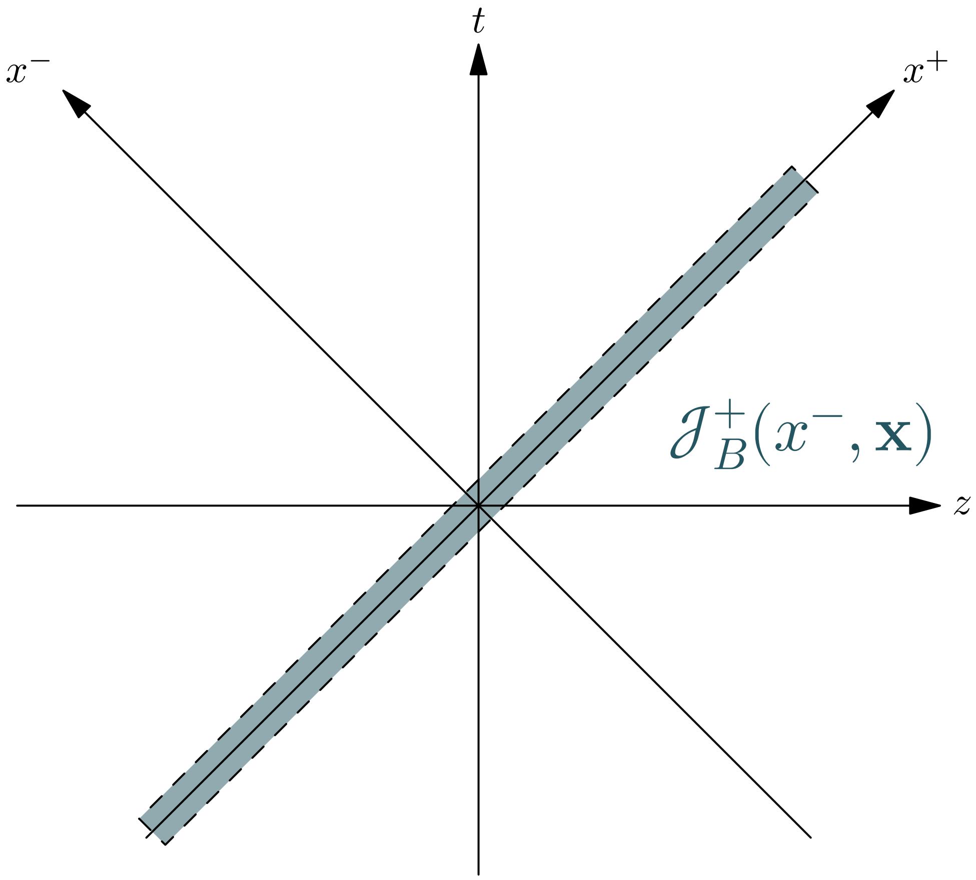
Color glass condensate

Consider nucleus B moving to the right

Color current $\mathcal{J}_B^+$ is a stochastic variable

Classical Yang–Mills equations $\mathcal{D}_\mu \mathcal{F}^{\mu\nu} = \mathcal{J}^\nu$ in covariant gauge $\partial_\mu \mathcal{A}_B^\mu = 0$ gives gauge field $\mathcal{A}_B$ via

$$-\Delta_\perp \mathcal{A}_B^+(x^-, \mathbf{x}) = \mathcal{J}_B^+(x^-, \mathbf{x})$$



TECHNISCHE UNIVERSITÄT WIEN

Color glass condensate

In forward lightcone full Yang–Mills equations

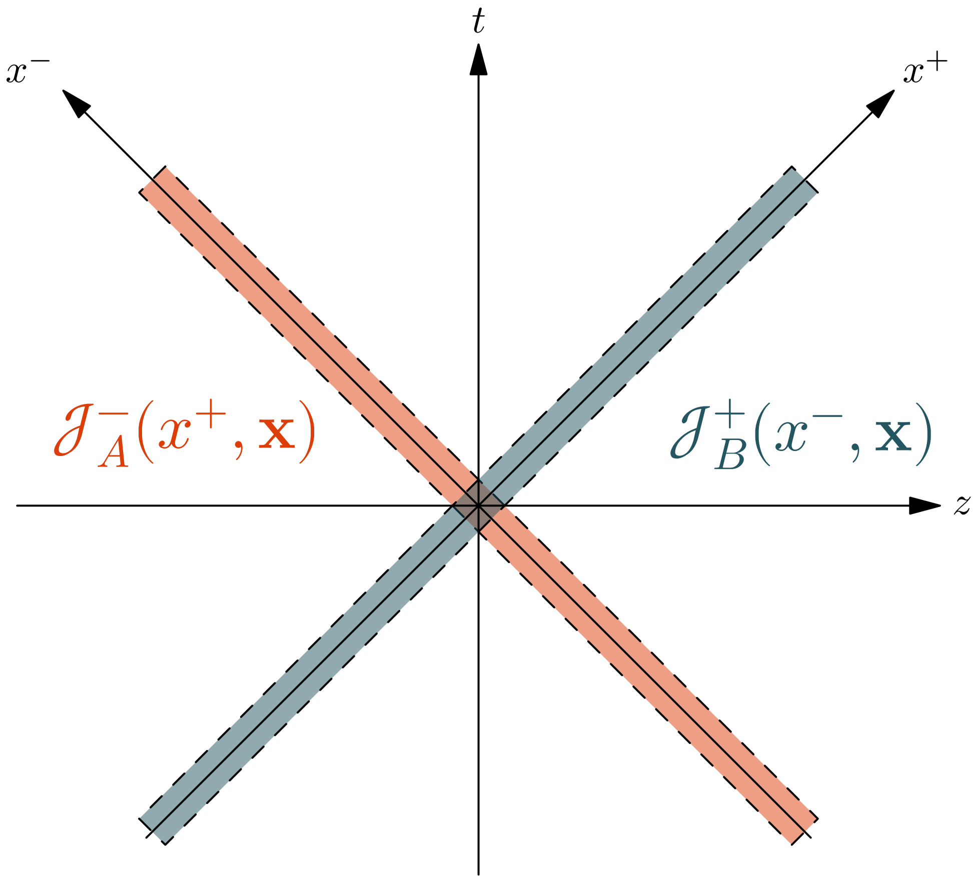
$$D_\mu F^{\mu\nu} = J^\nu$$

with

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

must hold. Also,

$$D_\mu J^\mu = 0.$$



Color glass condensate

In forward lightcone full Yang–Mills equations

$$D_\mu F^{\mu\nu} = J^\nu$$

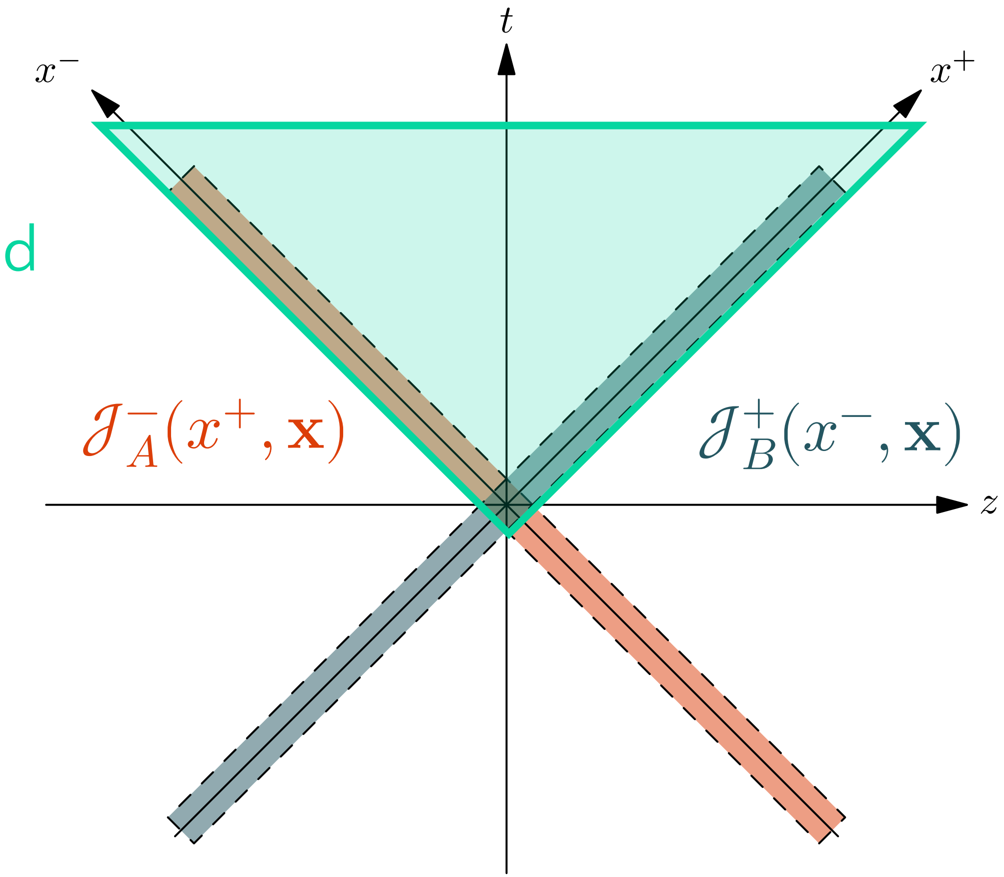
with

Glasma field

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

must hold. Also,

$$D_\mu J^\mu = 0.$$



Color glass condensate

In forward lightcone full Yang–Mills equations

$$D_\mu F^{\mu\nu} = J^\nu$$

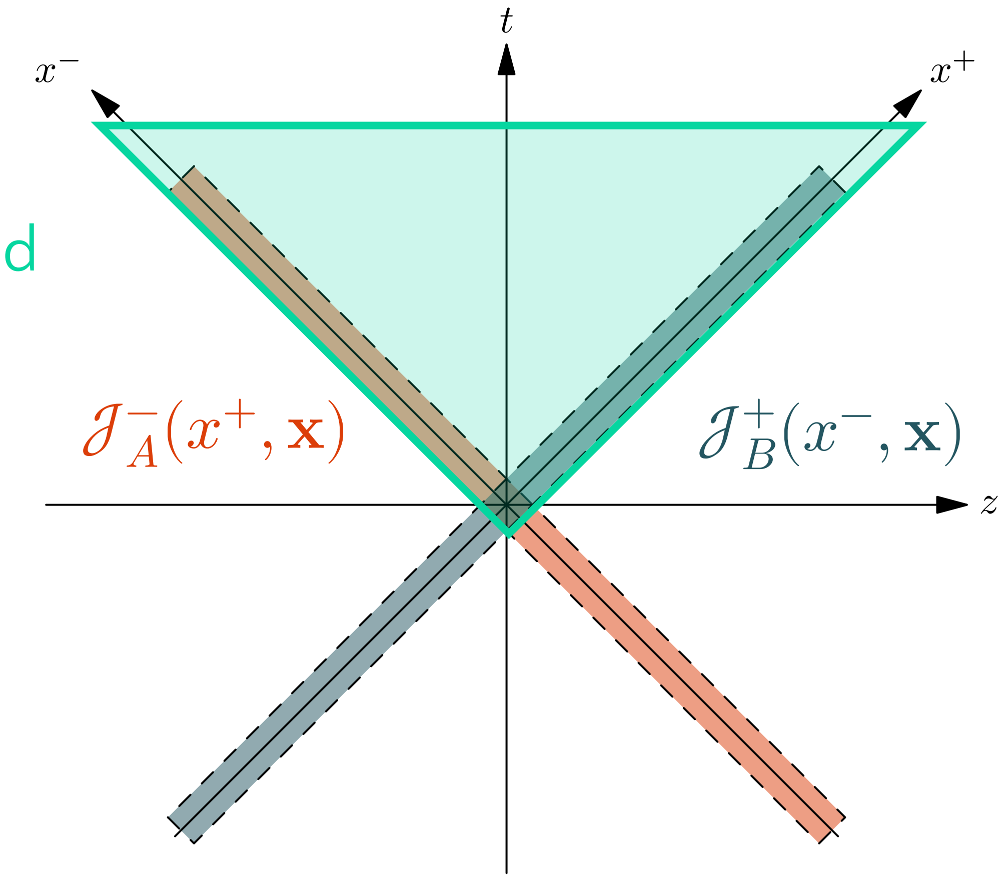
with

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

Glasma field

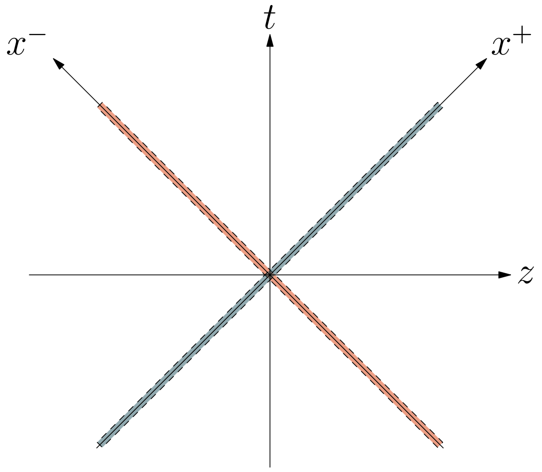
must hold.

No analytic solution for this system!



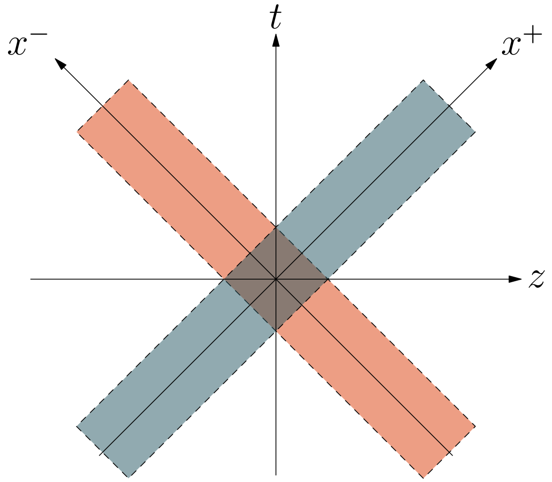
Breaking boost-invariance

2D nuclei
infinitely Lorentz-contracted



no info about rapidity dependence
of observables (boost-invariance)

3D nuclei
with longitudinal extent



gives rapidity profile of observables

Dilute approximation

In forward lightcone full Yang-Mills equations

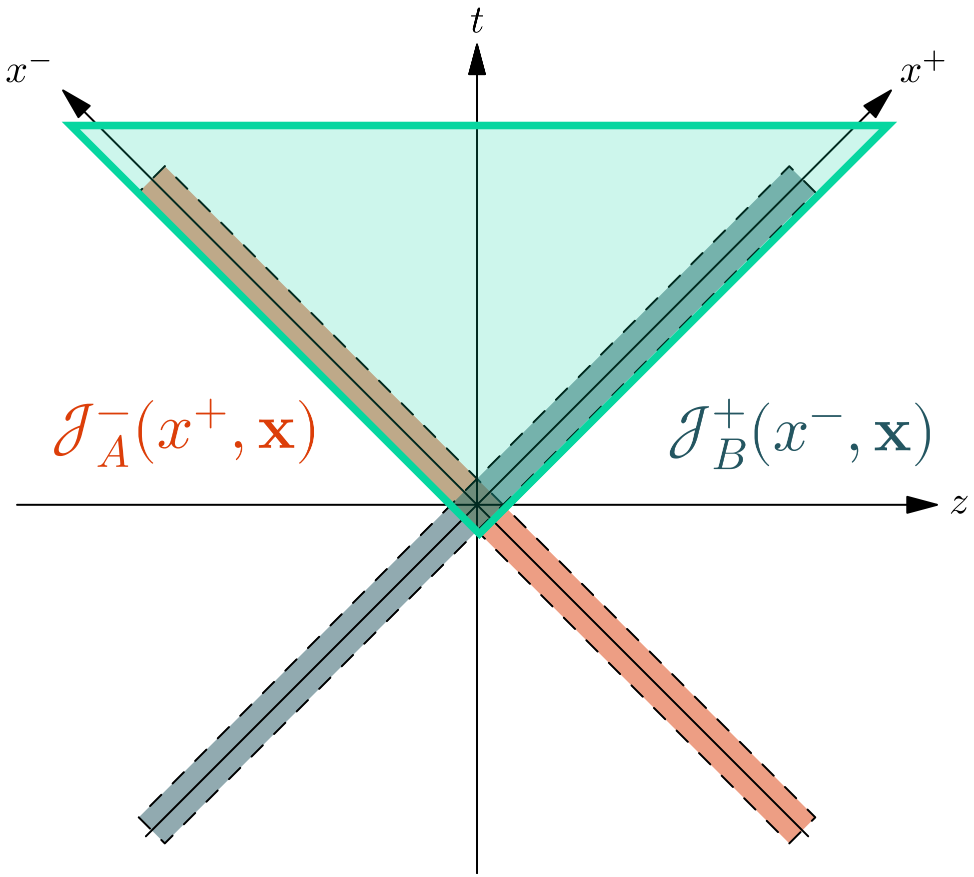
$$D_\mu F^{\mu\nu} = J^\nu$$

with

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

must hold. Also,

$$D_\mu J^\mu = 0.$$



TECHNISCHE UNIVERSITÄT WIEN

Dilute approximation

In forward lightcone full Yang–Mills equations

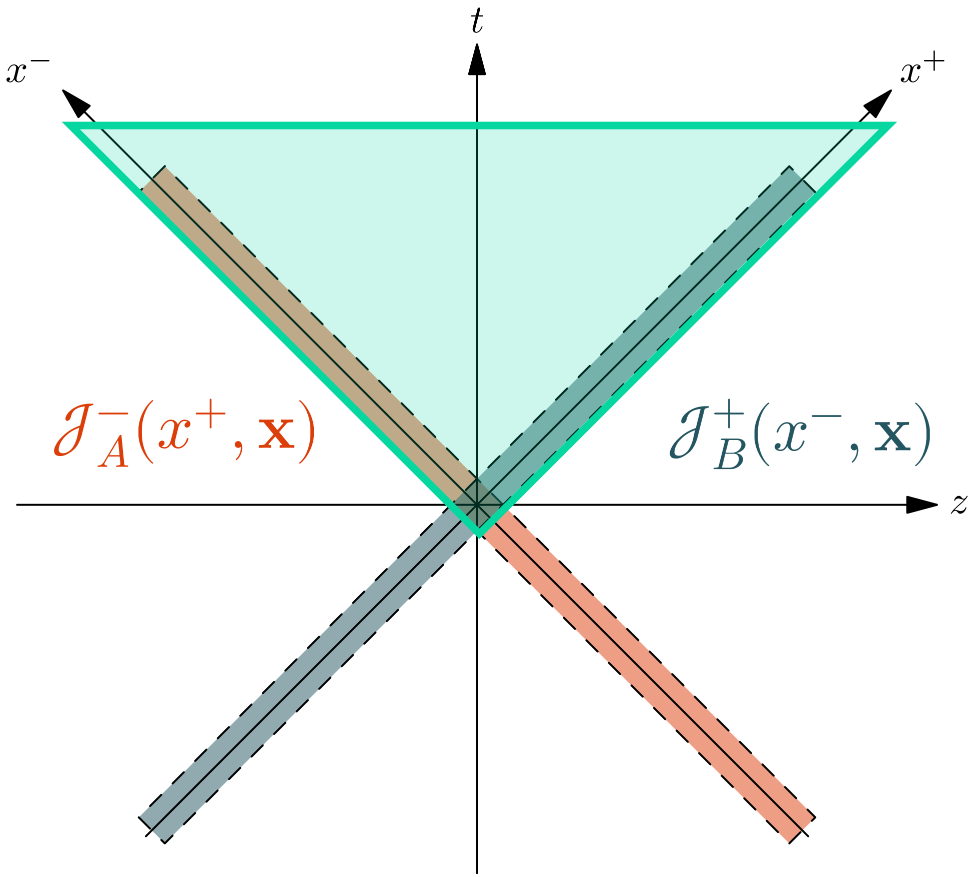
$$D_\mu F^{\mu\nu} = J^\nu$$

with **We assume weak sources!**

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

must hold. Also,

$$D_\mu J^\mu = 0.$$



Dilute approximation

In forward lightcone full Yang–Mills equations

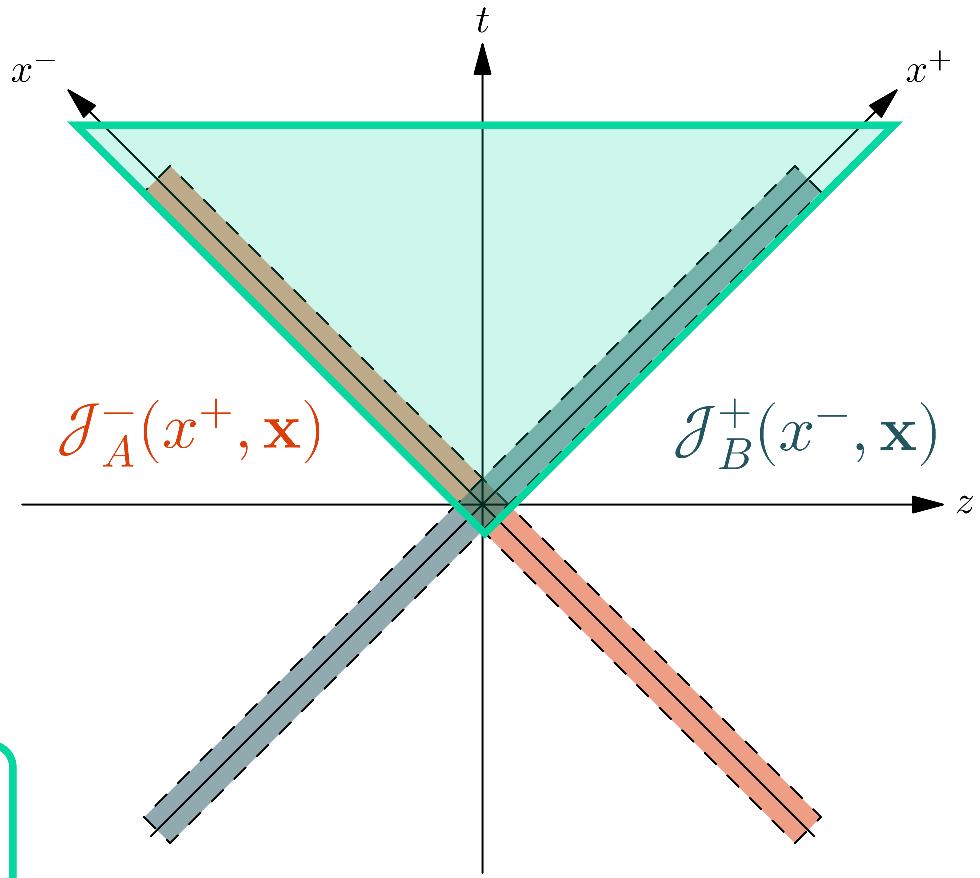
$$D_\mu F^{\mu\nu} = J^\nu$$

with **We assume weak sources!**

$$A^\mu(x) = \mathcal{A}^\mu_A(x) + \mathcal{A}^\mu_B(x) + a^\mu(x),$$
$$J^\mu(x) = \mathcal{J}^\mu_A(x) + \mathcal{J}^\mu_B(x) + j^\mu(x)$$

must hold.

→ power series expansion in $\mathcal{J}_A$ and $\mathcal{J}_B$
keep $\mathcal{O}(\mathcal{J}_A \mathcal{J}_B)$, drop higher orders



Dilute approximation

Covariant conservation of current:

$$D_\mu J^\mu = \partial_\mu J^\mu - \mathrm{i}g[A_\mu, J^\mu]$$
$$= \mathcal{D}_{A,\mu}\mathcal{J}^\mu_A + \mathcal{D}_{B,\mu}\mathcal{J}^\mu_B + \partial_\mu j^\mu - \mathrm{i}g[\mathcal{A}_{A,\mu}, \mathcal{J}^\mu_B] - \mathrm{i}g[\mathcal{A}_{B,\mu}, \mathcal{J}^\mu_A] = 0$$

$$\partial_- j^- = \mathrm{i}g\left[\mathcal{A}^+_B, \mathcal{J}^-_A\right]$$
$$\partial_+ j^+ = \mathrm{i}g\left[\mathcal{A}^-_A, \mathcal{J}^+_B\right]$$

TECHNISCHE UNIVERSITÄT WIEN

Dilute approximation

Yang-Mills equations:

$$
\begin{aligned}
[D_\mu, F^{\mu\nu}] &= [\mathcal{D}_{A,\mu}, \mathcal{F}_A^{\mu\nu}] + [\mathcal{D}_{B,\mu}, \mathcal{F}_B^{\mu\nu}] + \partial_\mu(\partial^\mu a^\nu - \partial^\nu a^\mu - \mathrm{i}g[\mathcal{A}_A^\mu, \mathcal{A}_B^\nu] - \mathrm{i}g[\mathcal{A}_B^\mu, \mathcal{A}_A^\nu]) \\
&\quad - \mathrm{i}g[\mathcal{A}_{A,\mu}, \partial^\mu \mathcal{A}_B^\nu - \partial^\nu \mathcal{A}_B^\mu] - \mathrm{i}g[\mathcal{A}_{B,\mu}, \partial^\mu \mathcal{A}_A^\nu - \partial^\nu \mathcal{A}_A^\mu] \\
&= \mathcal{J}_A^\nu + \mathcal{J}_B^\nu + j^\nu .
\end{aligned}
$$

$$
\begin{aligned}
\partial_\mu \partial^\mu a^+ &= \mathrm{i}g[\mathcal{A}_A^-, \partial_- \mathcal{A}_B^+] + j^+ \\
\partial_\mu \partial^\mu a^- &= \mathrm{i}g[\mathcal{A}_B^+, \partial_+ \mathcal{A}_A^-] + j^- \\
\partial_\mu \partial^\mu a^i &= \mathrm{i}g[\mathcal{A}_A^-, \partial_i \mathcal{A}_B^+] + \mathrm{i}g[\mathcal{A}_B^+, \partial_i \mathcal{A}_A^-]
\end{aligned}
$$

Glasma field

$$a^+(x) = \frac{g}{2} f_{abc} t^c \int\limits_{\mathbf{p},\mathbf{q}} \int\limits_0^\infty dz^+ \int\limits_0^\infty dz^- \tilde{A}_A^{-a}(x^+ - z^+, \mathbf{p}) \tilde{A}_B^{+b}(x^- - z^-, \mathbf{q}) \times \frac{\left(-(\mathbf{p}+\mathbf{q})^2 + 2\mathbf{q}^2 \right) z^+}{|\mathbf{p}+\mathbf{q}|\tau_z} J_1(|\mathbf{p}+\mathbf{q}|\tau_z) e^{-i(\mathbf{p}+\mathbf{q})\cdot\mathbf{x}},$$

$$a^-(x) = \frac{g}{2} f_{abc} t^c \int\limits_{\mathbf{p},\mathbf{q}} \int\limits_0^\infty dz^+ \int\limits_0^\infty dz^- \tilde{A}_A^{-a}(x^+ - z^+, \mathbf{p}) \tilde{A}_B^{+b}(x^- - z^-, \mathbf{q}) \times \frac{\left(+(\mathbf{p}+\mathbf{q})^2 - 2\mathbf{p}^2 \right) z^-}{|\mathbf{p} + \mathbf{q}|\tau_z} J_1(|\mathbf{p}+\mathbf{q}|\tau_z) e^{-i(\mathbf{p}+\mathbf{q})\cdot\mathbf{x}},$$

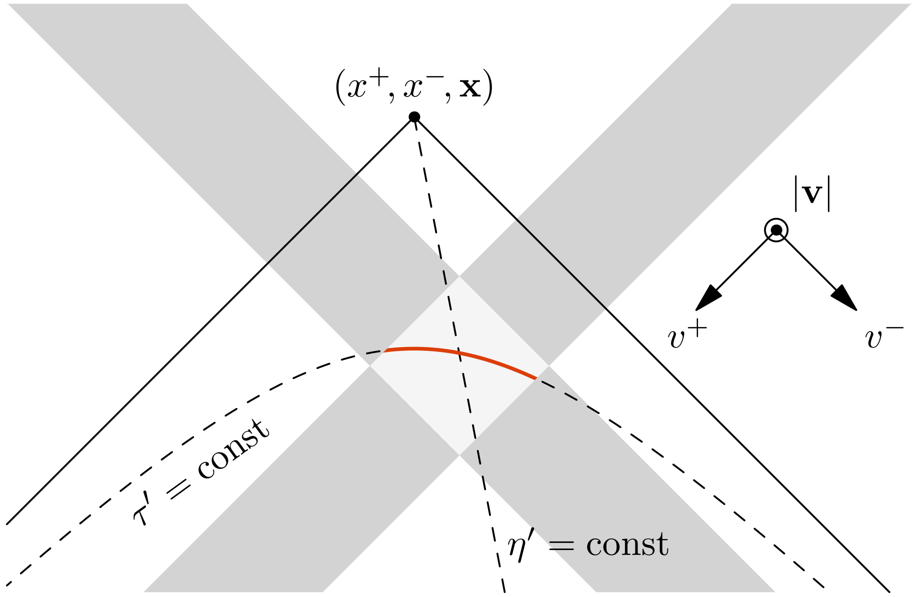
$$a^i(x) = \frac{g}{2} f_{abc} t^c \int\limits_{\mathbf{p},\mathbf{q}} \int\limits_0^\infty dz^+ \int\limits_0^\infty dz^- \tilde{A}_A^{-a}(x^+ - z^+, \mathbf{p}) \tilde{A}_B^{+b}(x^- - z^-, \mathbf{q}) \times i(\mathbf{p}^i - \mathbf{q}^i)\, J_0(|\mathbf{p}+\mathbf{q}|\tau_z) e^{-i(\mathbf{p}+\mathbf{q})\cdot\mathbf{x}}.$$

Glasma field strength tensor

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

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

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



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

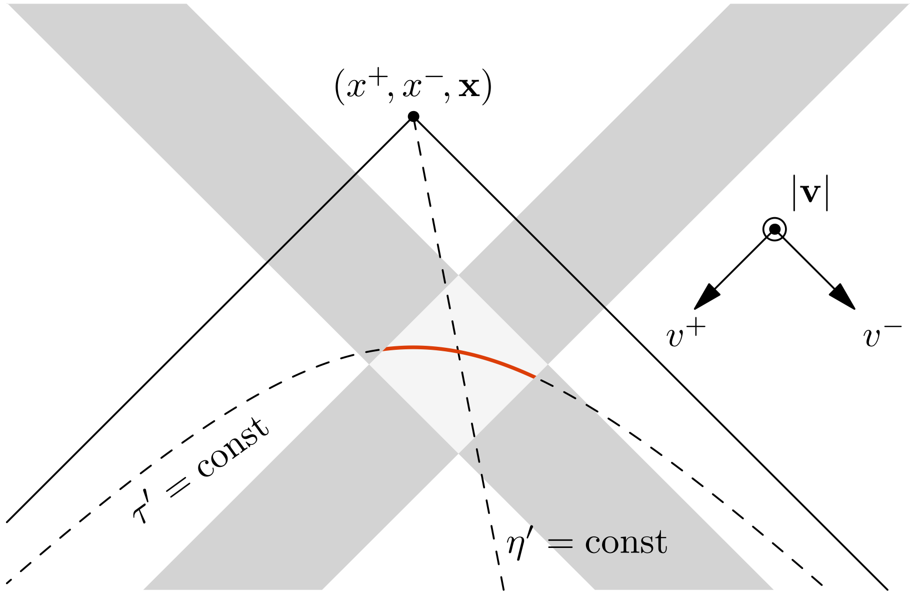
$$V^{ij} := f_{abc} t^c \left(\partial^i \mathcal{A}_A^{-a}(\dots)\partial^j \mathcal{A}_B^{+b}(\dots) - \partial^j \mathcal{A}_A^{-a}(\dots)\partial^i \mathcal{A}_B^{+b}(\dots)\right)$$

Glasma field strength tensor

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

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

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



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

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

See K. Schmidt's talk!

Color charge correlator

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

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

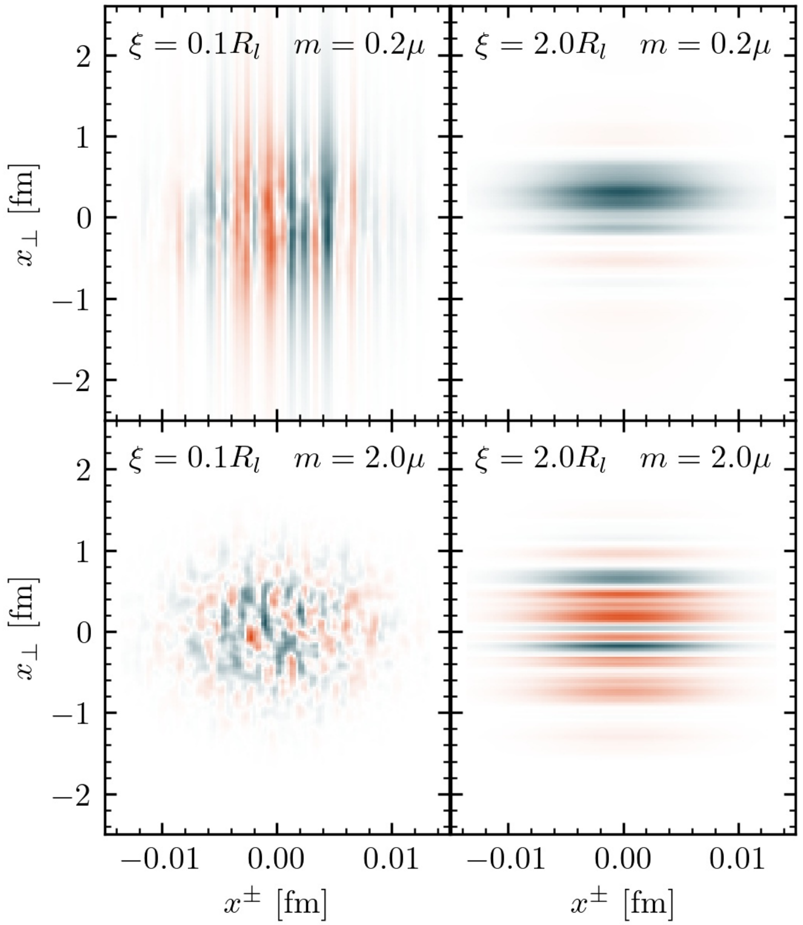
and 2-pt. function

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

with

$$T(x^\pm, \mathbf{x}) = \frac{1}{\sqrt{2\pi} R_l} e^{-\frac{(x^\pm)^2}{2R_l^2}} e^{-\frac{\mathbf{x}^2}{2R^2}}$$

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



Color charge correlator

Color ch[...]al
defined b[...]

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

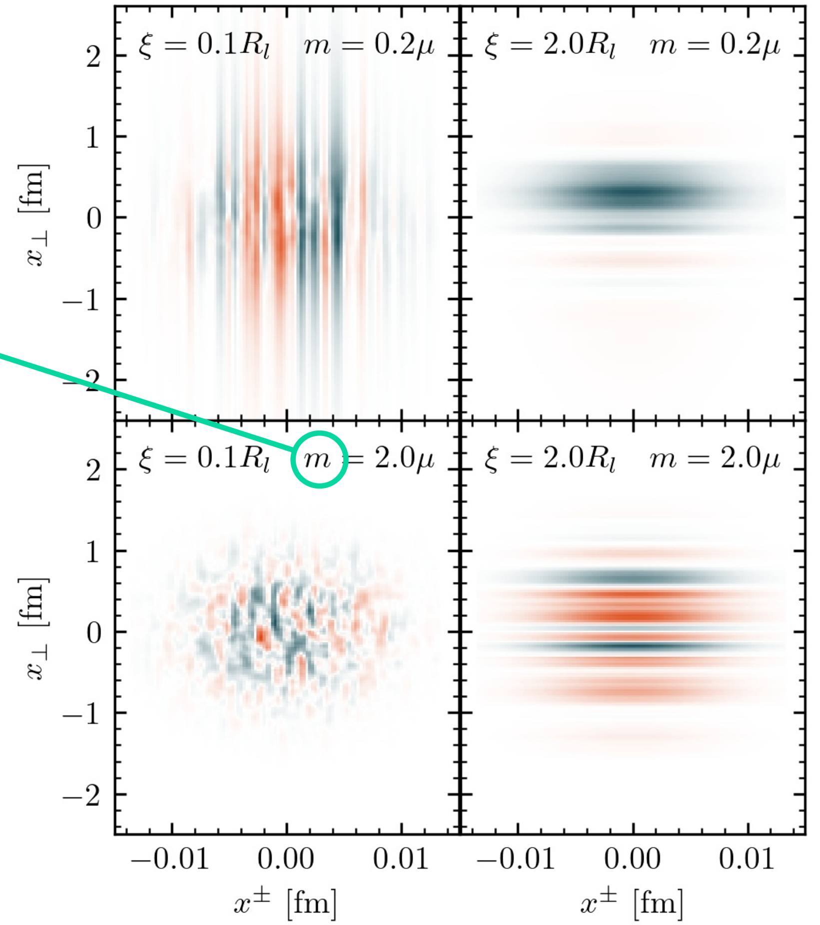
and 2-pt. function

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

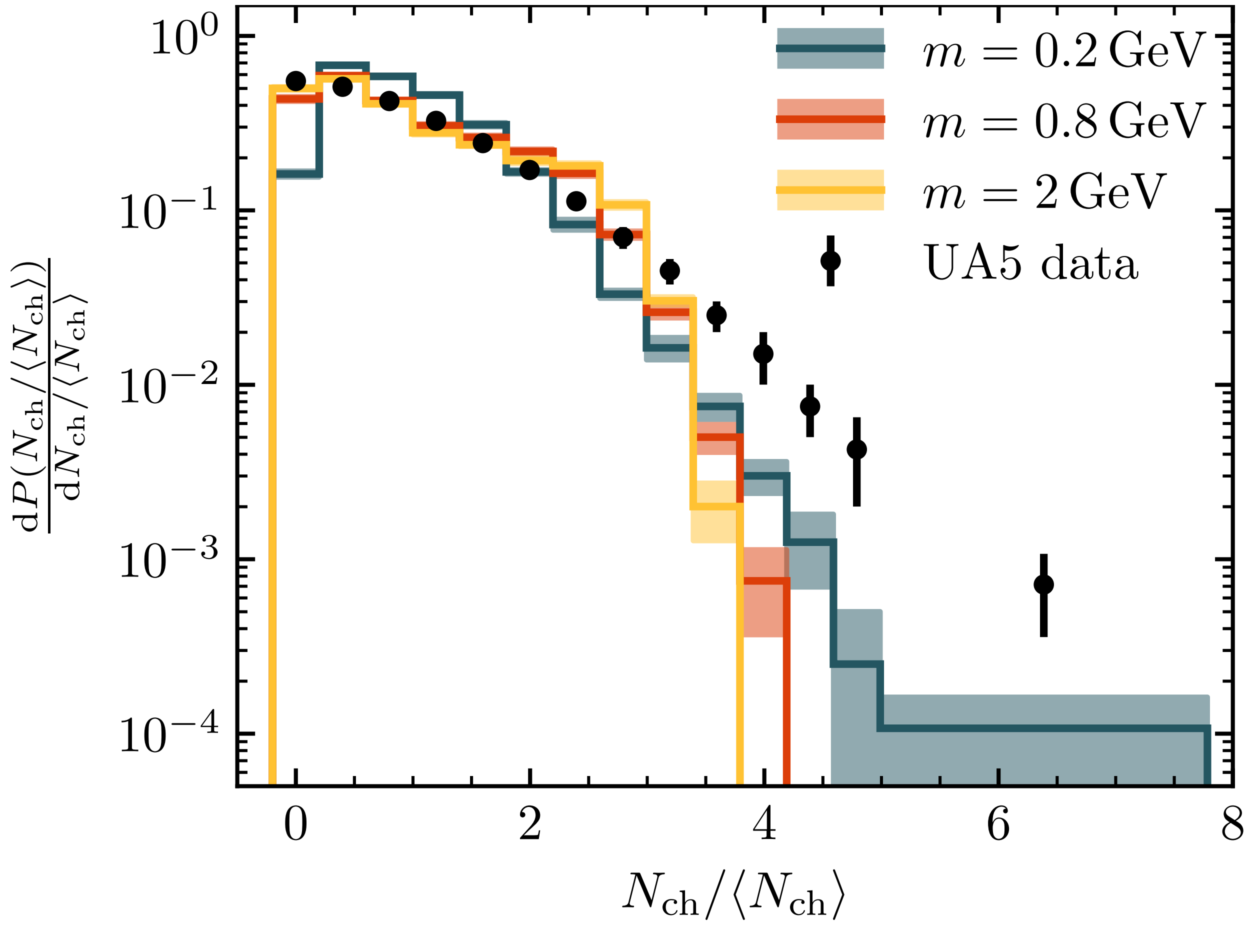
with

$$T(x^\pm, \mathbf{x}) = \frac{1}{\sqrt{2\pi}R_l} e^{-\frac{(x^\pm)^2}{2R_l^2}} e^{-\frac{\mathbf{x}^2}{2R^2}}$$

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



pp-collisions: results



$\sqrt{s} = 200\,\mathrm{GeV}$, $\eta \approx 0$

Large multiplicity events are severely underestimated!

This is a known effect!

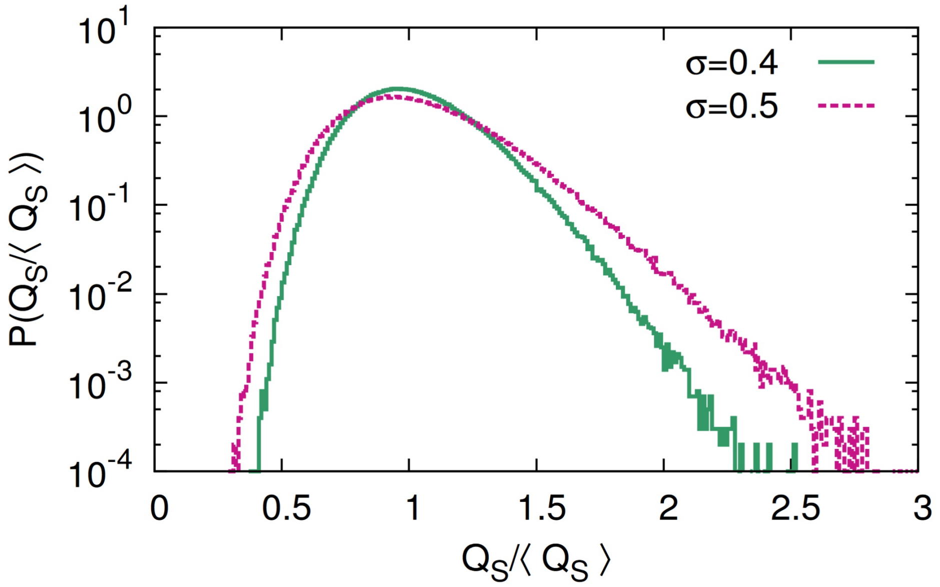
B. Schenke, P. Tribedy, R. Venugopalan
Phys. Rev. C 89.2 (2014), p. 024901

L. McLerran, P. Tribedy
Nucl. Phys. A 945 (2016), pp. 216–225

Saturation momentum fluctuations

Let Q_s (i.e. color charge) fluctuate on event-by-event basis with factor drawn from

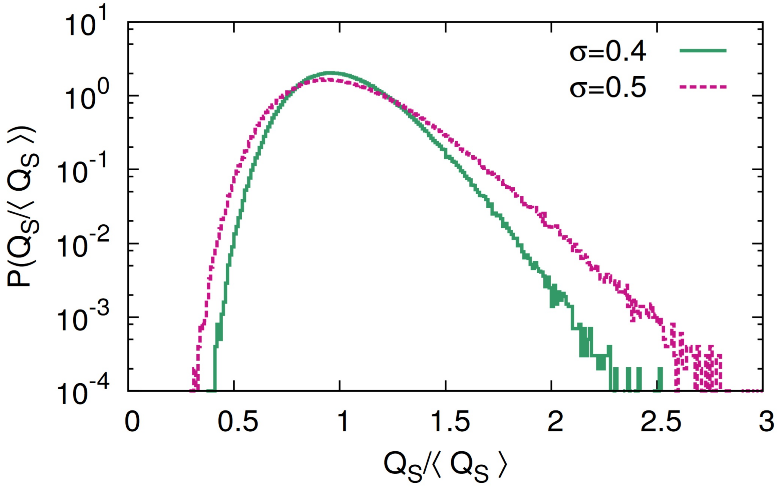
$$P(\ln(Q_s^2/\langle Q_s^2\rangle)) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\ln^2(Q_s^2/\langle Q_s^2\rangle)}{2\sigma^2}\right).$$



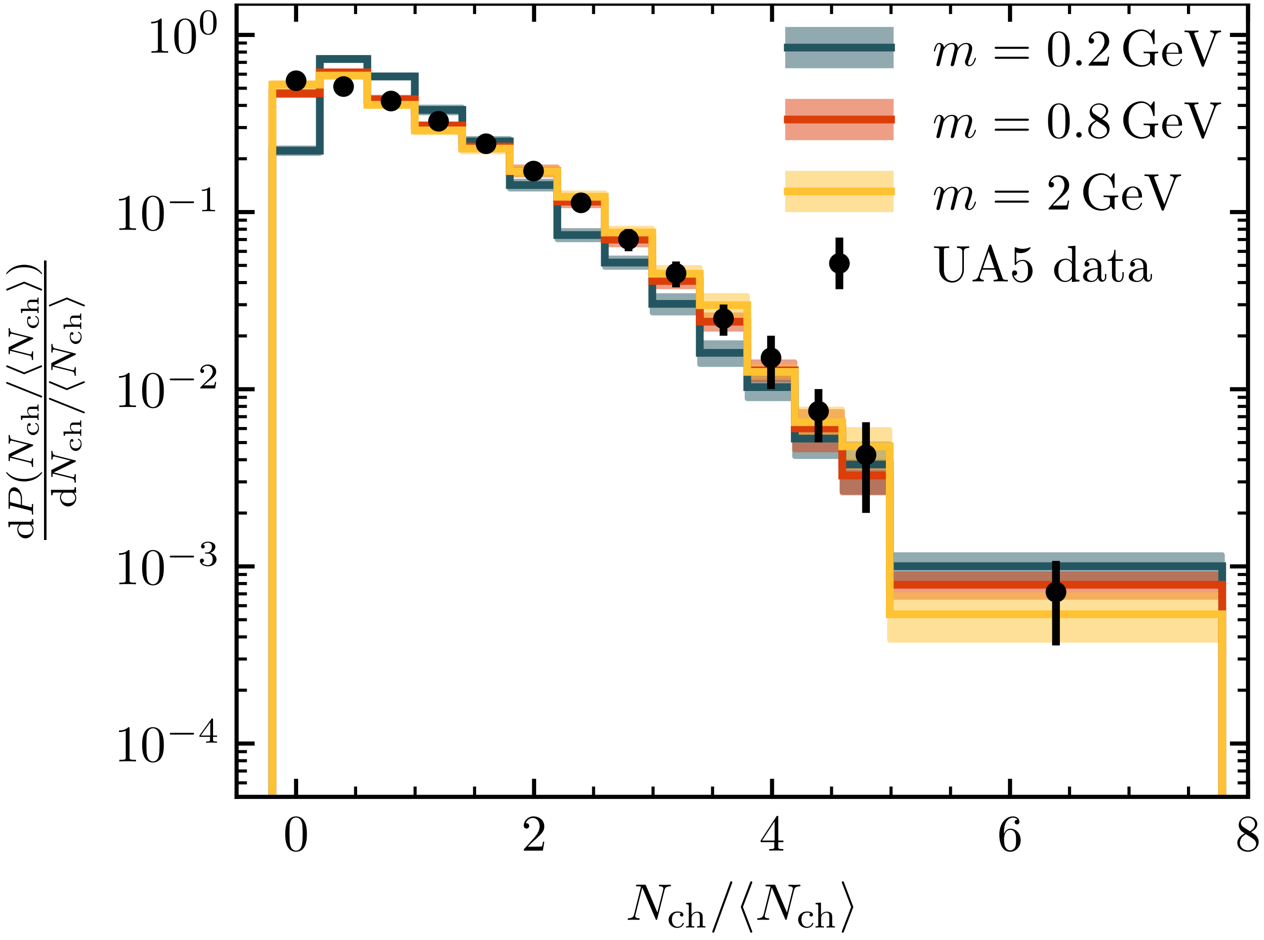
L. McLerran, P. Tribedy, Nucl. Phys. A 945 (2016), pp. 216–225

TECHNISCHE UNIVERSITÄT WIEN

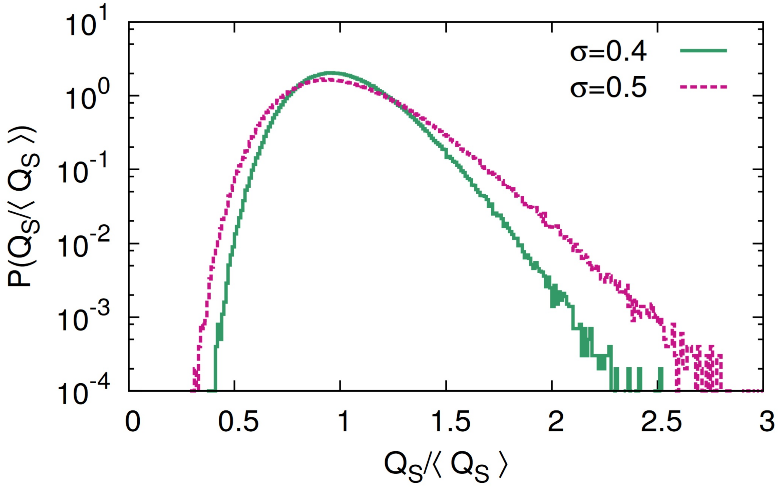
Saturation momentum fluctuations



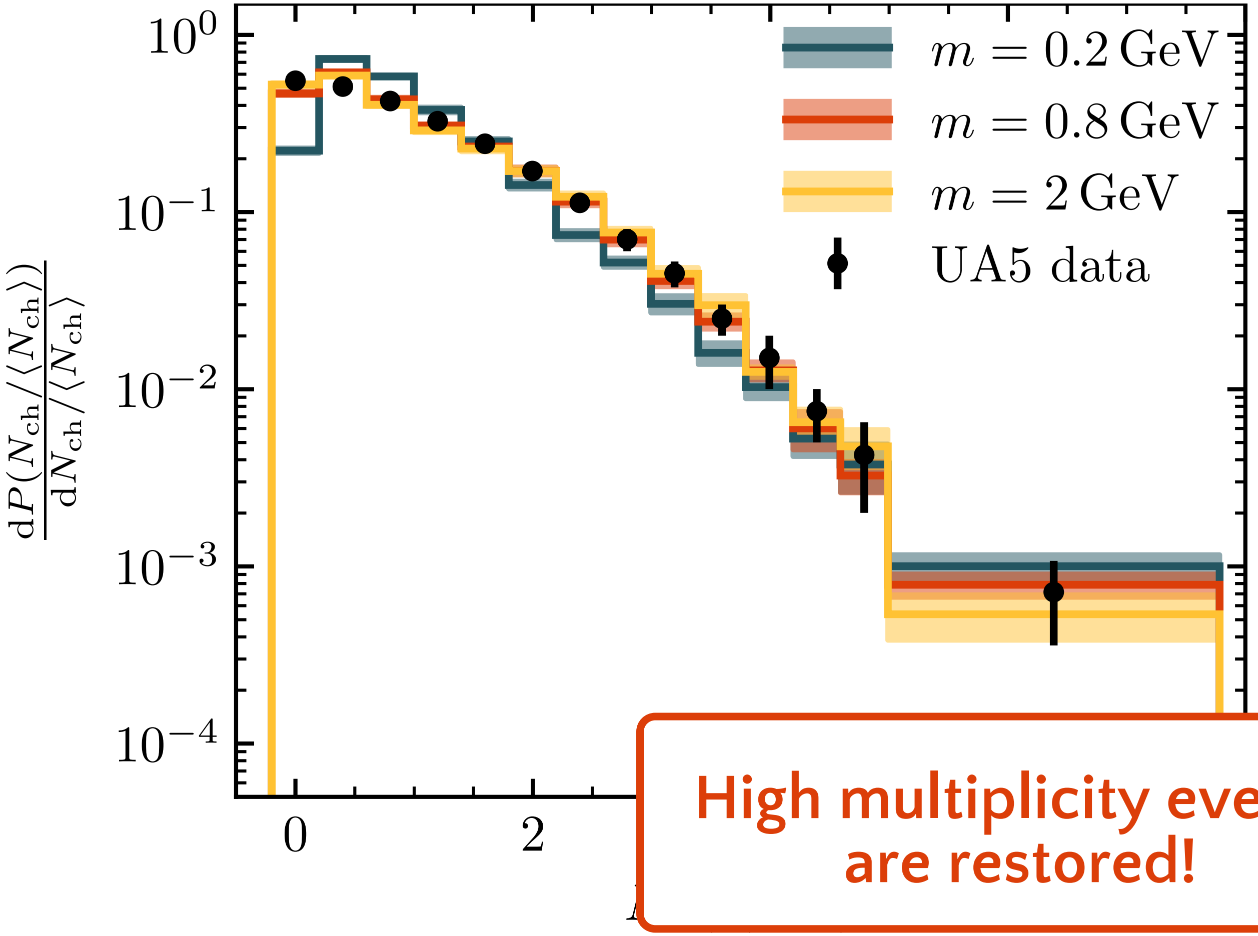
m	0.2 GeV	0.8 GeV	2 GeV
σ_{opt}	0.26	0.22	0.21



Saturation momentum fluctuations



m	0.2 GeV	0.8 GeV	2 GeV
σ_{opt}	0.26	0.22	0.21



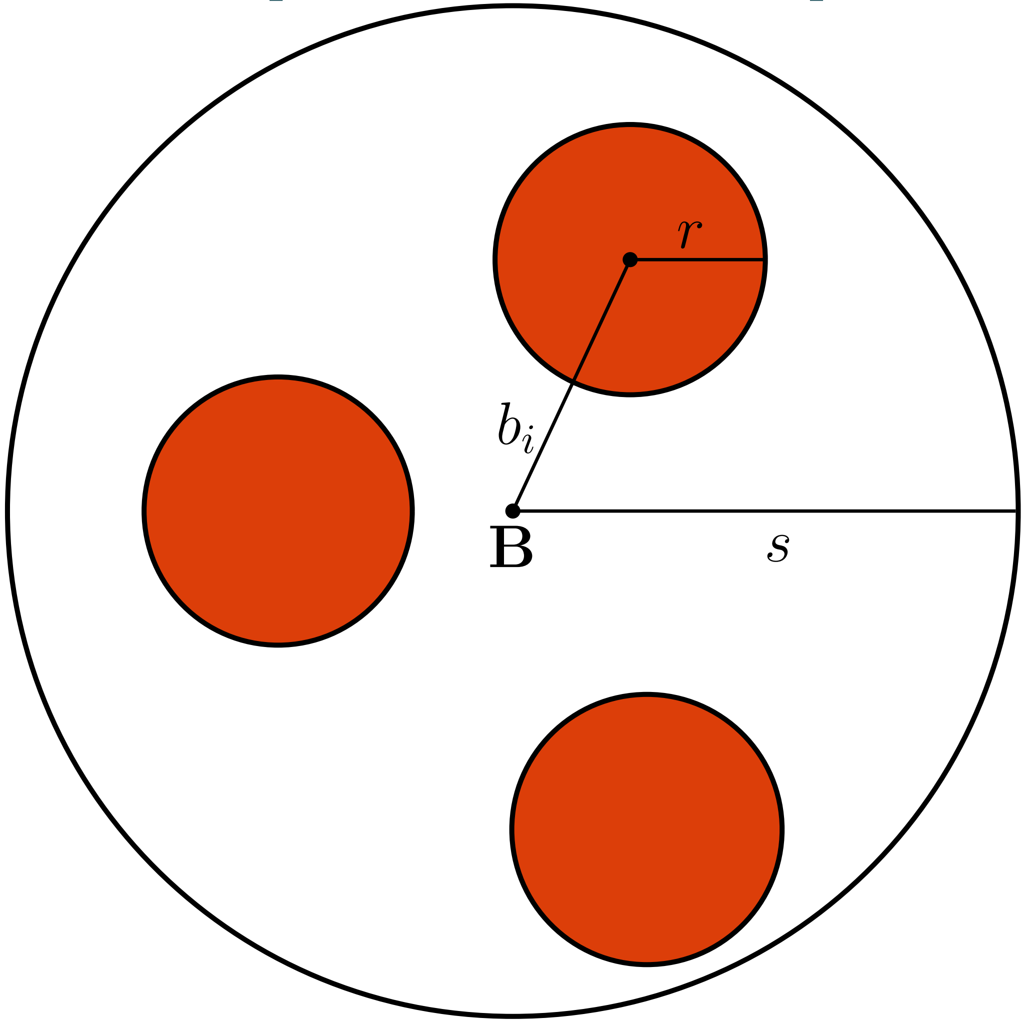
High multiplicity events are restored!

Valence quark hot spots

Alternatively:
let nucleon consist of distinct hot spots

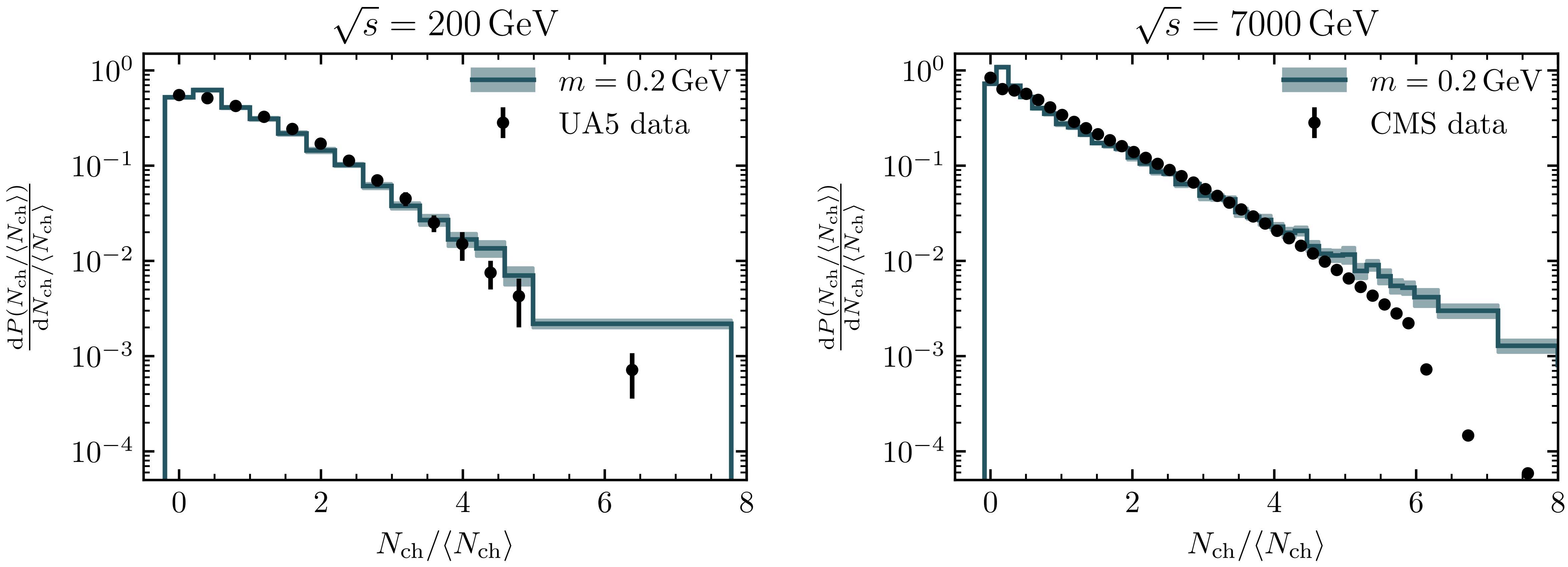
$n_v = 3$ (valence quarks)

- are modeled as Gaussians with width r
- their positions are drawn from Gaussian dist. with width s (proton size)



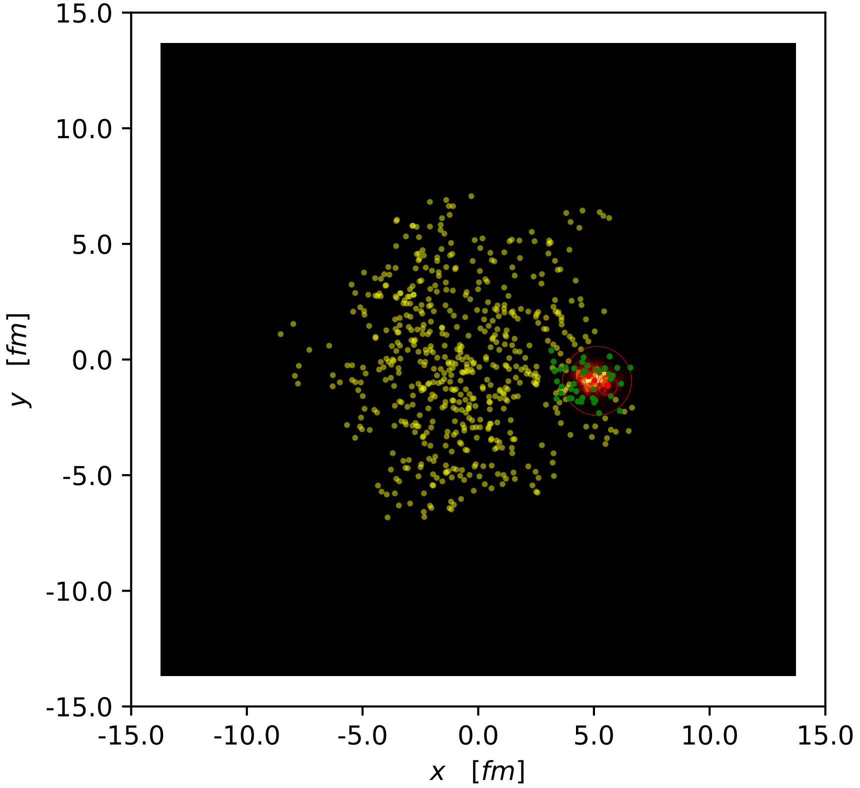
TECHNISCHE UNIVERSITÄT WIEN

Valence quark hot spots



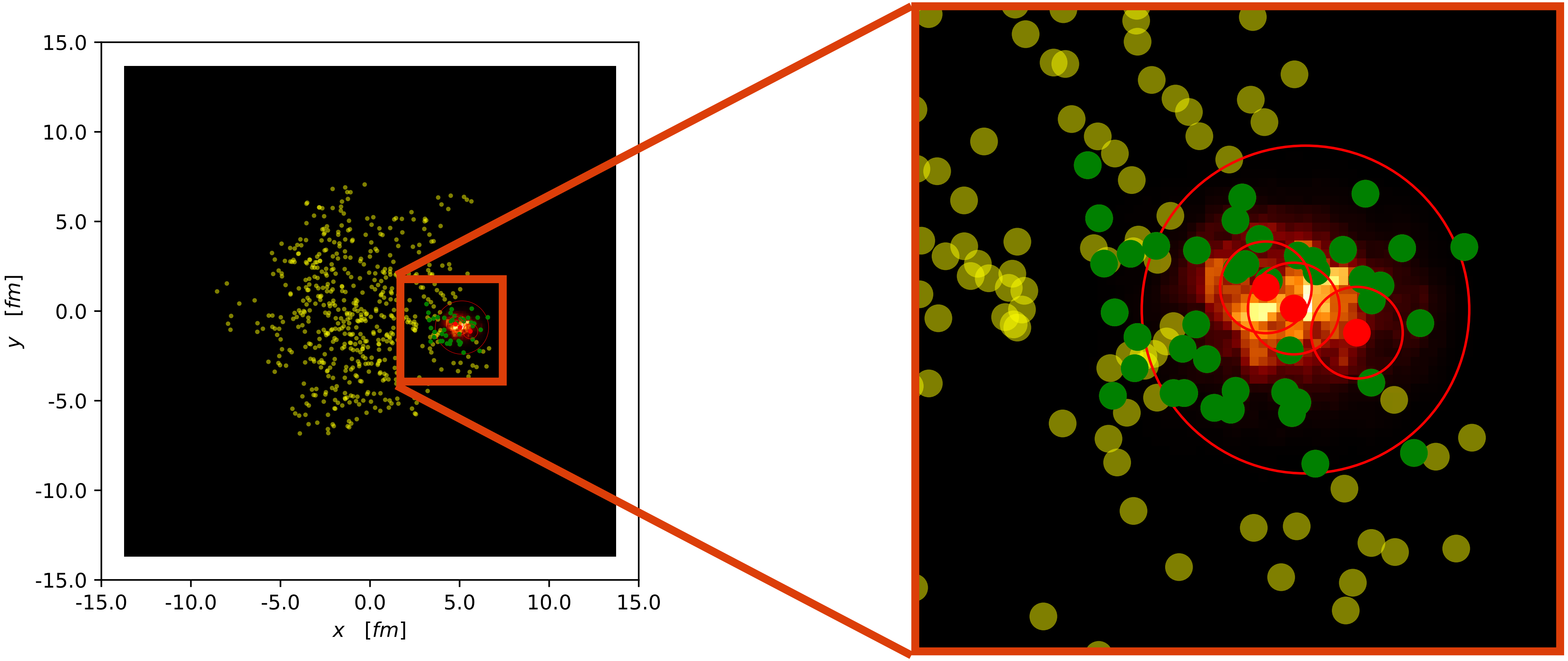
pA-collisions

Use these nucleons to build heavy nuclei and study i.e. pA-collisions



pA-collisions

Use these nucleons to build heavy nuclei and study i.e. pA-collisions



pA-collisions: outlook

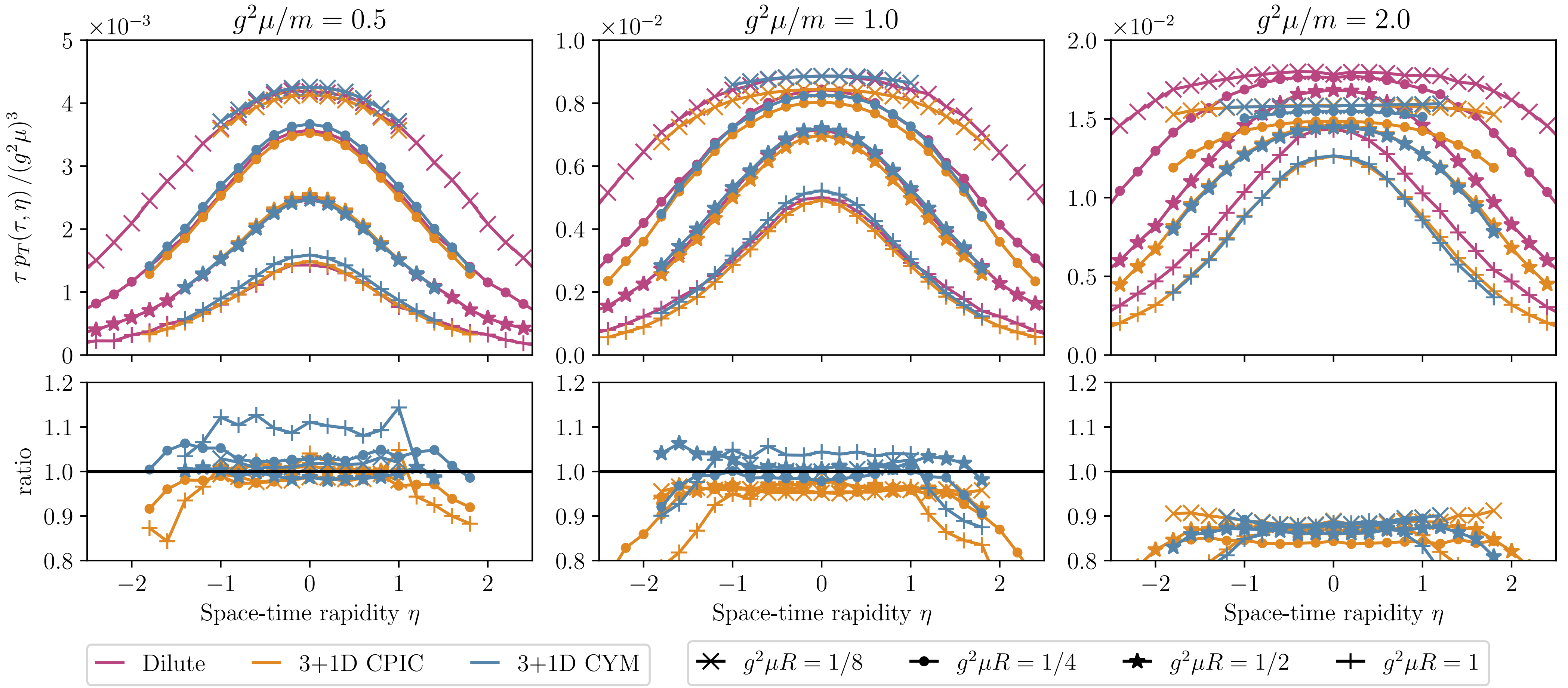
WIP coming up:

- simulate many events at $\eta = 0$
- select highest energy ($\sim$ multiplicity) pA events
- simulate these events over large η range
- study event plane decorrelations with η through violations of $V_{n\Delta} = v_n^a v_n^b$
  - $\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_n v_n \cos(n(\phi - \Psi_n))$
  - $\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} \propto 1 + 2\sum_n V_{n\Delta} \cos(n\Delta\phi)$
- Event plane fluctuations depend mostly on initial state
- $\rightarrow$ constrain model parameters and learn about longitudinal structure of nucleons and nuclei

TECHNISCHE UNIVERSITÄT WIEN

Backup slides

Comparison to lattice simulations



A. Ipp, D. I. Müller, S. Schlichting, P. Singh
Phys.Rev.D 104 (2021) 11, 114040

Shifted Milne coordinates

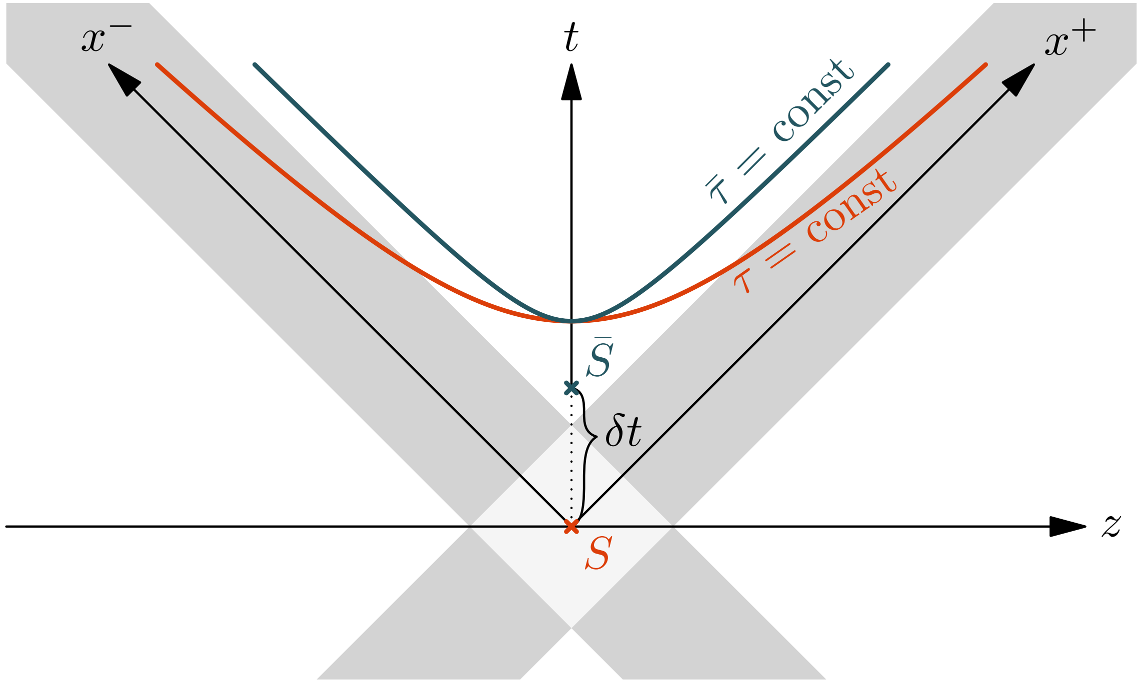
Milne coordinates

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

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!



Observables

Energy-momentum tensor

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

τ- and η-components depend on (arbitrary) origin $\rightarrow$ also look at

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 $T^{\mu}{}_{\nu}$)

pp-collisions: rejection sampling

1. define the thickness function

$$t(\mathbf{x}) = \frac{1}{2\pi s^2} \exp\left(-\frac{\mathbf{x}^2}{2s^2}\right)$$

2. define the overlap function

$$T(b) = \int \mathrm{d}^2\mathbf{x}\ t(\mathbf{x} + \mathbf{b}/2)t(\mathbf{x} - \mathbf{b}/2) = \frac{1}{4\pi s^2} \exp\left(-\frac{b^2}{4s^2}\right)$$

3. define the (average) number of parton-parton collisions

$$N_{gg} := N_g^2 \sigma_{gg} T(b).$$

4. the probability of at least 1 interaction is

$$P_{\mathrm{ia}}(b) = 1 - \exp\left(-N_g^2 \sigma_{gg} T(b)\right).$$

TECHNISCHE UNIVERSITÄT WIEN

pp-collisions: rejection sampling

5. define the effective nucleon-nucleon cross section

$$\sigma_{NN} = \int \mathrm{d}^2\mathbf{b}\, P_{\mathrm{ia}}(b).$$

6. the differential interaction probability is

$$\frac{\mathrm{d}^2 P}{\mathrm{d}\mathbf{b}^2} = \frac{1 - \exp\left(-N_g^2 \sigma_{gg} T(b)\right)}{\int \mathrm{d}^2\mathbf{b}\left(1 - \exp\left(-N_g^2 \sigma_{gg} T(b)\right)\right)}.$$

7. we simulate protons as Gaussian blobs and randomly sample impact parameters