Charm quarks to probe Glasma in p-Pb collisions

QCD@WORK 2018

The *first* QCD conference ever held in Matera, Italy

Marco Ruggieri

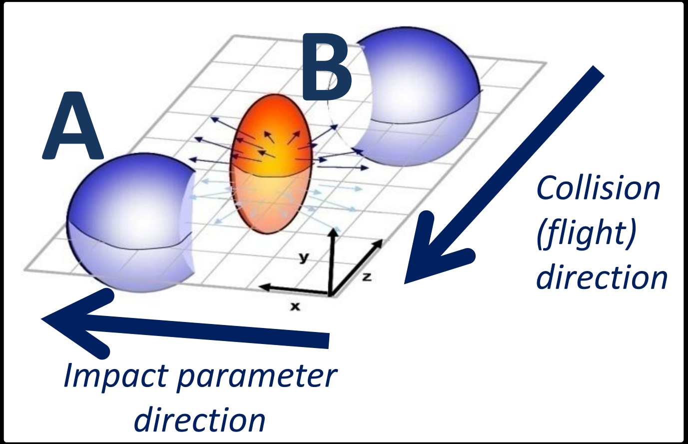
School of Nuclear Science and Technology

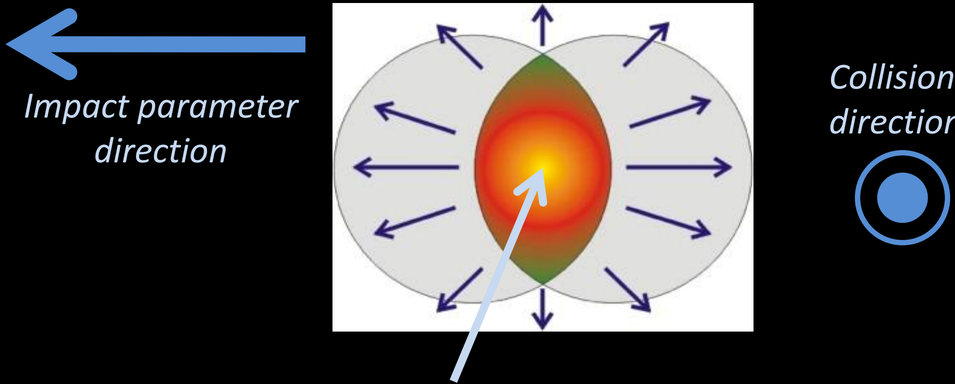
Lanzhou University

In this talk

- High energy nuclear collisions and the Glasma
- Gluon fields in p-Pb collisions
- ***Heavy quarks and the cathode tube effect***
- Conclusions

High energy nuclear collisions





In Au-Au, Pb-Pb, Cu-Cu,…..:
Hot and dense expanding
QUARK-GLUON-PLASMA (QGP)

A,B: Cu, Au (RHIC@BNL)
Pb (LHC@CERN)
p (LHC@CERN)
p-Pb collisions (LHC@CERN)
d-Au collisions (RHIC@BNL)

$$\mathrm{Au-Au}: \sqrt{s} = 200 \times A \ \mathrm{GeV} \quad \text{at RHIC}$$
$$\mathrm{Pb-Pb}: \sqrt{s} = 2.76 \times A \ \mathrm{TeV} \quad \text{at LHC}$$
$$\mathrm{p-Pb}: \sqrt{s} = 5.02 \ \mathrm{TeV} \quad \text{at LHC}$$
$$\mathrm{p-p}: \sqrt{s} = 5,\ 7 \text{ and } 13 \ \mathrm{TeV} \quad \text{at LHC}$$

QGP formation time
- RHIC $\approx$ 0.6 fm/c ≈ 10^{-24} sec
- LHC $\approx$ 0.2 fm/c

QGP lifetime
- RHIC $\approx$ 5 fm/c ≈ 10^{-23} sec
- LHC $\approx$ 10 fm/c

Is it possible to describe collisions within effective field theory?

What kind of system is created after the collision?

Which observable we can look at in order to probe this system?

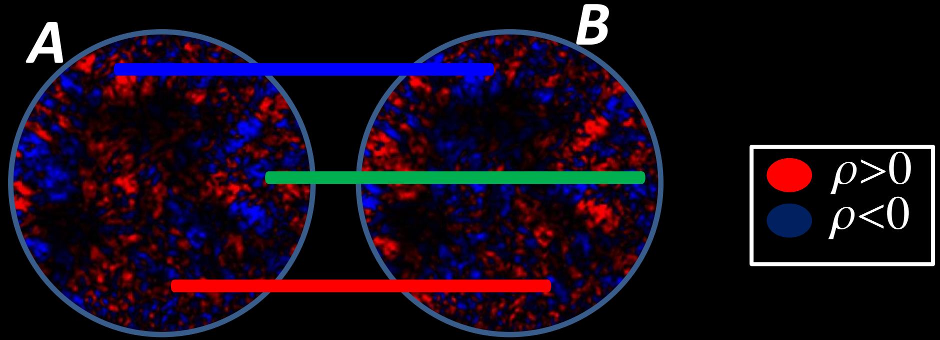
Nucleons/Nuclei at high energy:

Small-x gluons dominate the wave function.

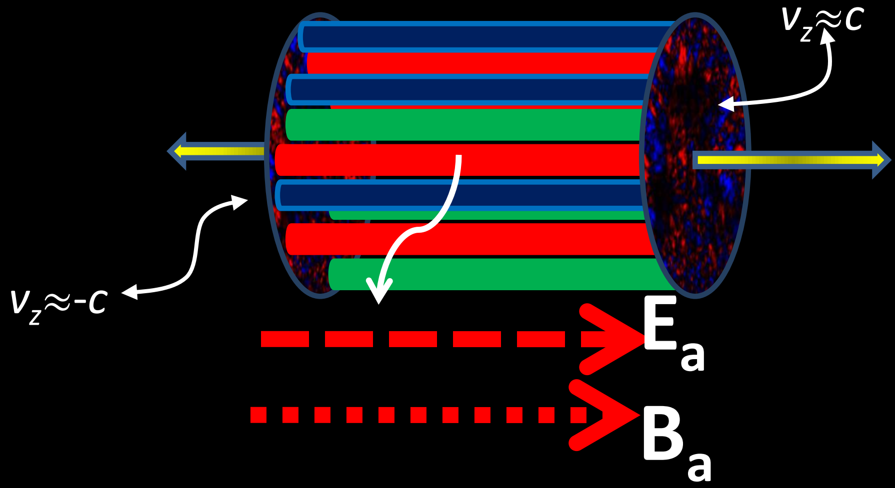
McLerran and Venugopalan (1996)
and many others

Collision within effective theory (Color-Glass-Condensate, aka CGC):

Interaction of two dense gluon systems.



$$\nabla \cdot E = ig\left[\mathcal{A}^i, \mathcal{E}^i\right]$$
$$\nabla \cdot B = ig\left[\mathcal{A}^i, \mathcal{B}^i\right]$$



Glasma

Lappi and McLerran (2006)

Due to the large density the gluon field behaves like a classical field:

Dynamics is governed by classical EoMs, namely the classical Yang-Mills (CYM) equations.

$$
\begin{aligned}
\frac{dA_i^a(x)}{dt} &= E_i^a(x), \\
\frac{dE_i^a(x)}{dt} &= \sum_j \partial_j F_{ji}^a(x) + \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x)
\end{aligned}
$$

QCD equivalent of the Maxwell Equations in vacuum space.

$$
A_\mu \to \frac{A_\mu}{g}
$$

Here:

$$
F_{ij}^a(x) = \partial_i A_j^a(x) - \partial_j A_i^a(x) + \sum_{b,c} f^{abc} A_i^b(x) A_j^c(x)
$$

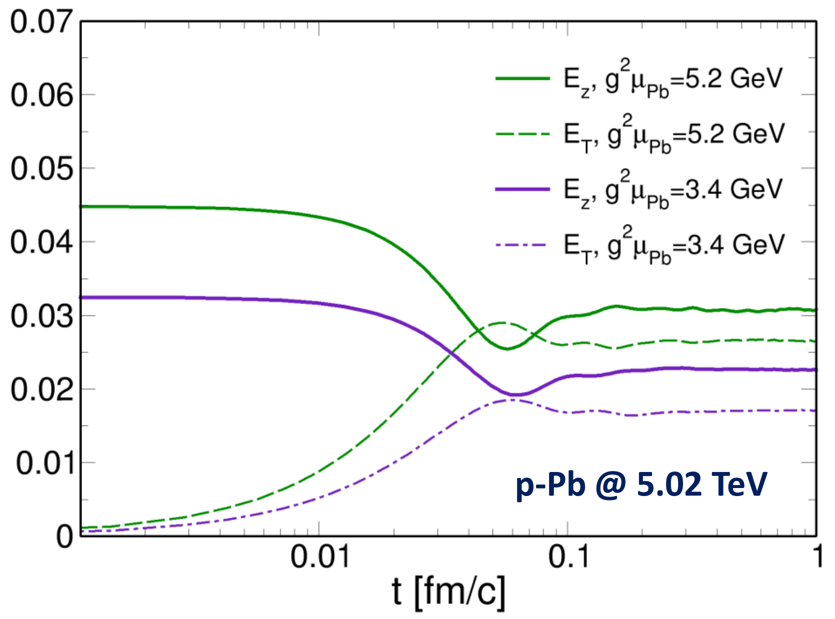
Field strength tensor

Evolution of the system is studied assuming the Glasma initial condition, and evolving this condition by virtue of the CYM equations.

The evolving Glasma: fields in p-Pb collisions

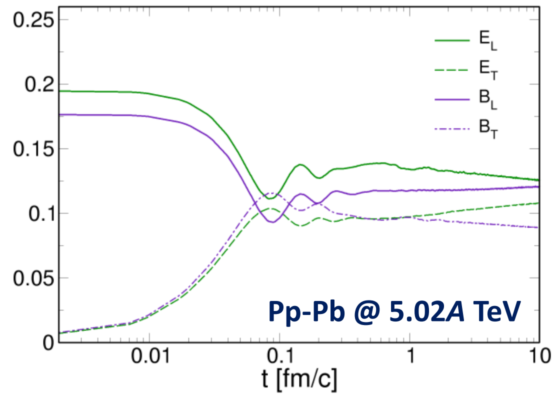
No longitudinal expansion

M. R. and S. K. Das, 1805.09617



Fields

M. Ruggieri *et al.* (2017)

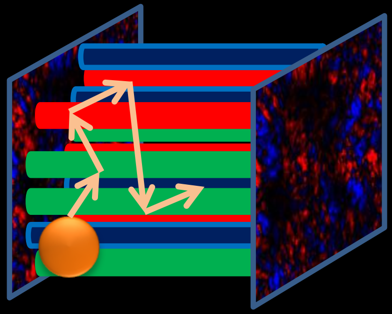


$$\left.\frac{dE_a^x}{dt}\right|_{t=0^+} = \partial_y B_z^a + f_{abc} A_y^b B_z^c$$

Formation time of transverse fields:

$\Delta t \approx 0.1$ fm/c

Heavy quarks as probes of the evolving Glasma



$$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06 \text{ fm/c}$$

HQs can probe the very early evolution of the Glasma fields

Hamilton equations of motion of c-quarks:

$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E = \sqrt{\boldsymbol{p}^2 + m^2}$$

$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu$$

$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \mathbf{A}_b \cdot \boldsymbol{p}$$

Wong (1979)

$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$$ *(Relativistic) Velocity*

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q\left(\boldsymbol{v} \times \boldsymbol{B}\right)$$ *Lorentz force*

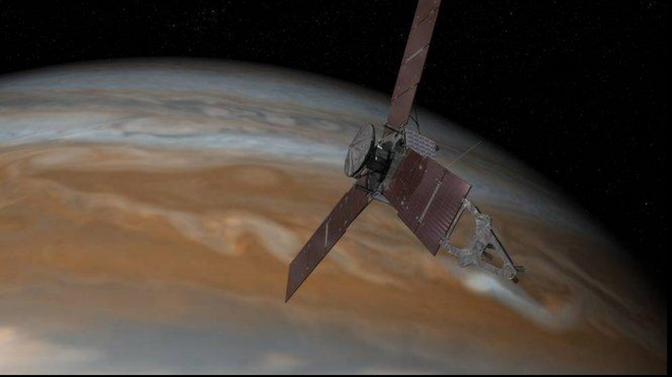
$$D_\mu J^\mu_a = 0$$

$$J^\mu_a = \bar{c}\gamma^\mu T_a c$$

Gauge-invariant conservation of the color current carried by charm quaks + gluons

Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

Heavy quarks as **probes** of the evolving Glasma



S. K. Das *et al.* (2017)
Rapp *et al.* (2014)
Mrorcinsky (2017)
Scardina *et al.* (2016)
Greiner (2018)
Goussiaux *et al.* (2015)

Heavy quarks are:
- Quite massive
- Quite diluted

- *Carry negligible color current*
- *Self-interactions occure rarely*

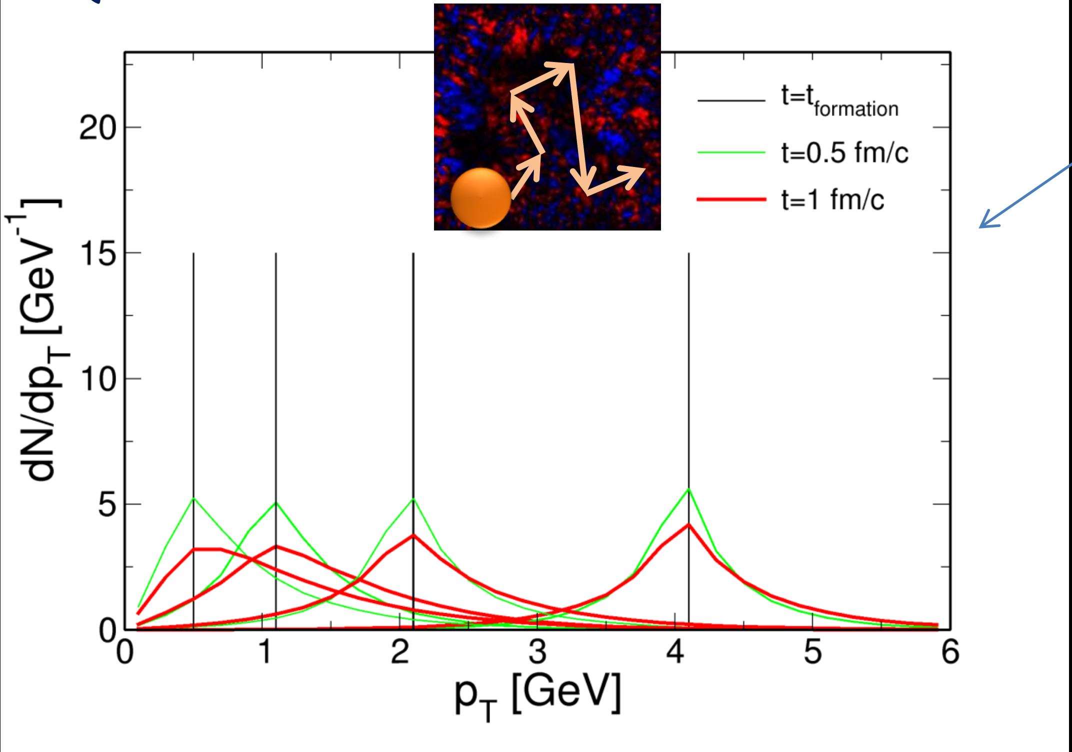
≈No disturbance to the evolving gluon fields

HQs are real probes of the evolving Glasma

Heavy quarks as **probes** of the evolving Glasma

HQs in Glasma

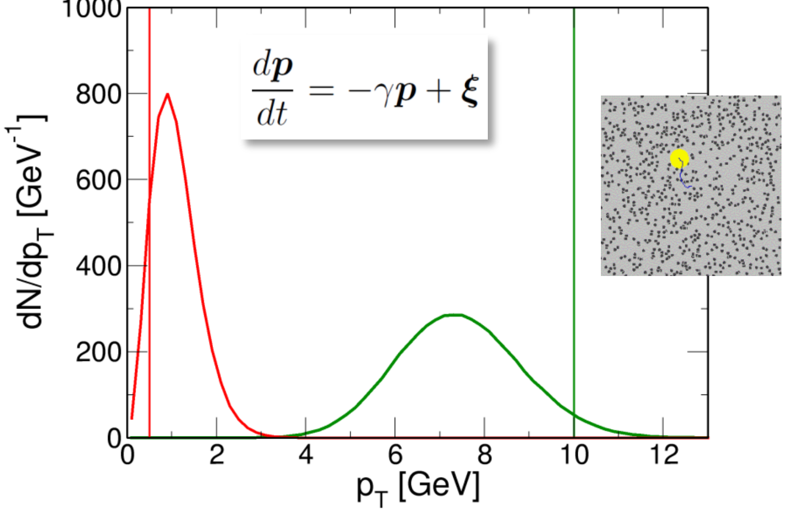
M. Ruggieri and S. K. Das, *in preparation*



(Anomalous) Diffusion in momentum space

T=500 MeV

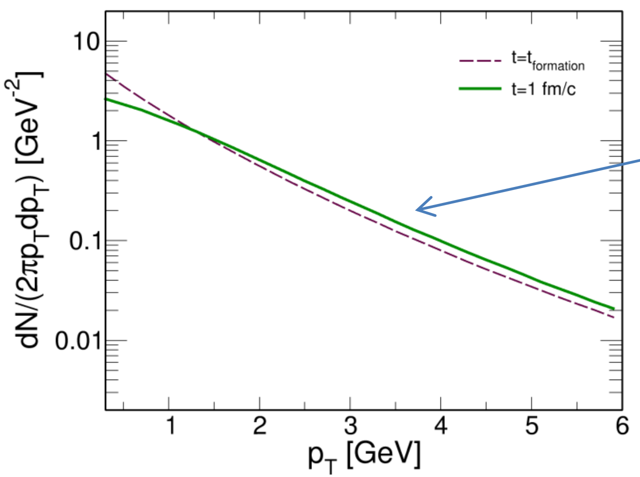
HQs in hot plasma



For anomalous diffision see Havlin and Avraham (1987)

Nuclear modification factor (R_{pPb}) for p-Pb collisions

p-Pb @ 5.02 TeV



*Initial distribution: from perturbative QCD, aka **prompt***

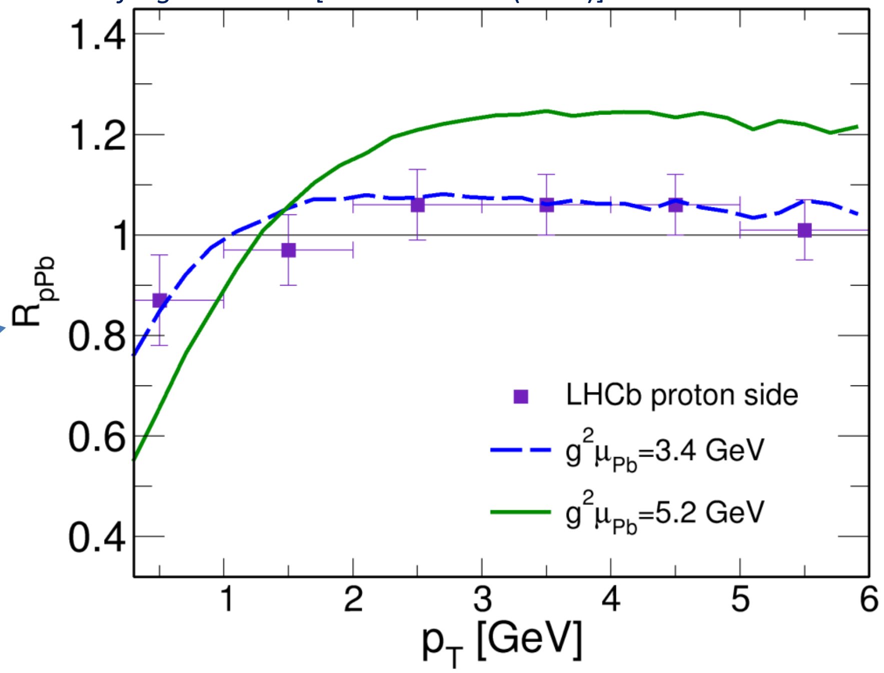
Evolution: interaction with the Glasma

$$R_{pPb} = \frac{(dN/d^2p_T)_{final}}{(dN/d^2p_T)_{pQCD}}$$

D-mesons R_{pPb}

M. Ruggieri and S. K. Das, 1805.09617

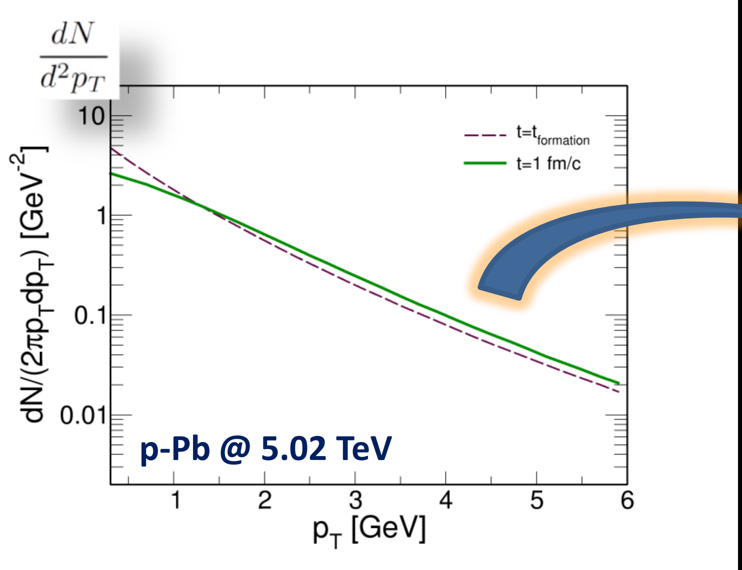
Standard fragmentation [Peterson *et al.*(1983)]



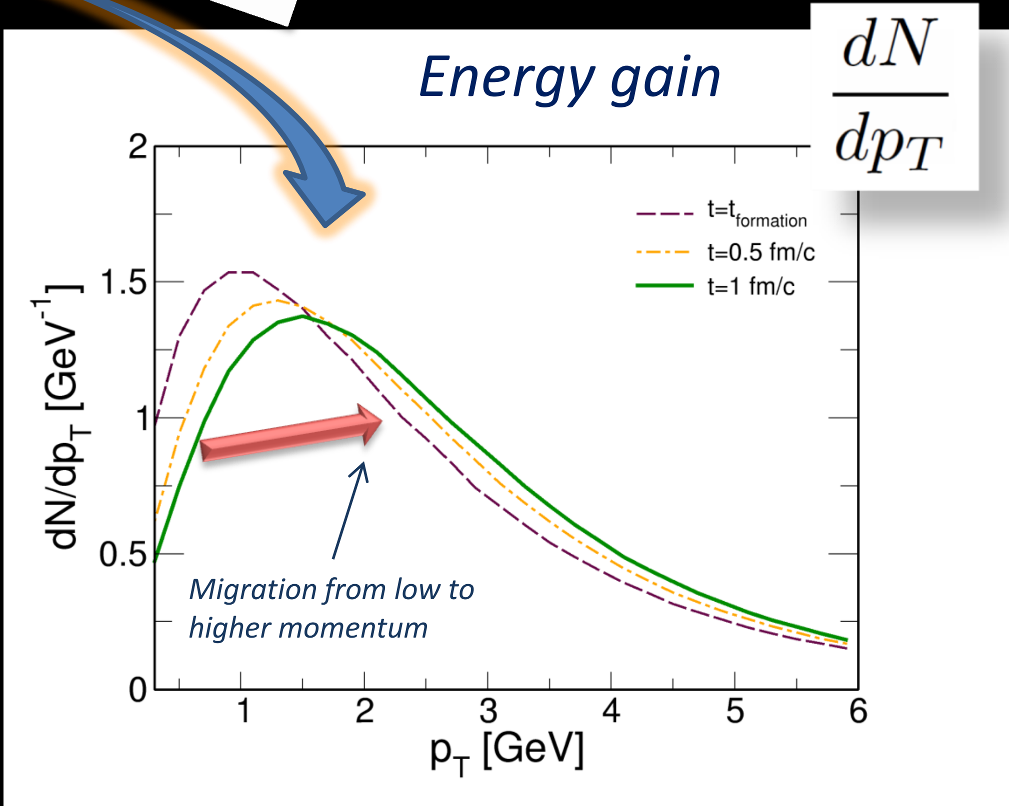
$R_{pPb} \neq 1$

Interaction with the fields created by the collision

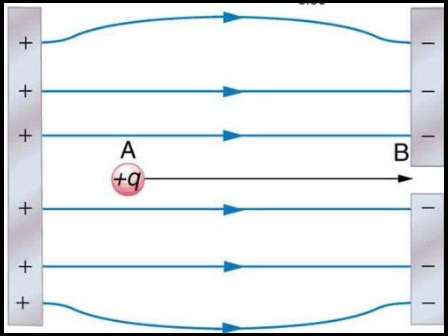
Diffusion results in acceleration



$\times p_T (\times 2\pi)$

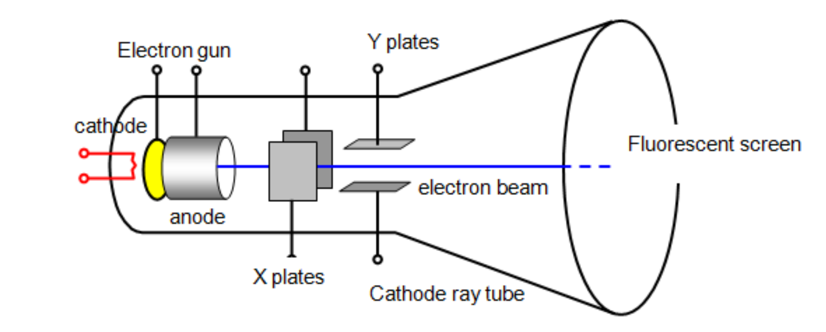


*Heavy quarks seem to be **accelerated** by the **transverse** (color-)electric field*



$$\frac{\Delta \boldsymbol{p}}{\Delta t} = q\boldsymbol{E}$$

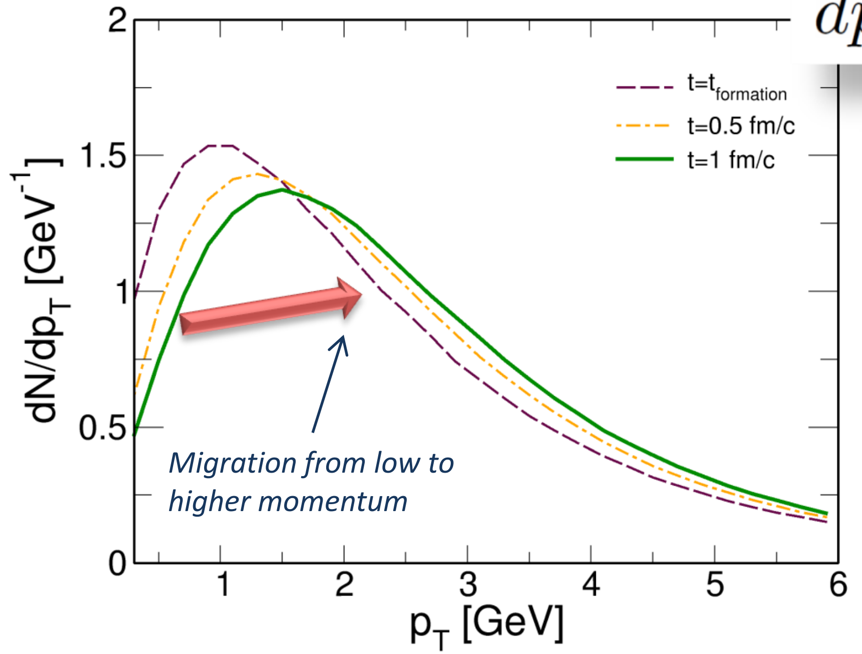
Why cathode tube?



Electrons are produced by the electron gun, then accelerated by the electric field

Heavy quarks seem to be ***accelerated*** *by the (color-)electric field*

$$\frac{dN}{dp_T}$$



- Borrowing the Glasma picture, the ***evolution*** of the system after the collision can be probed by ***heavy quarks observables.***

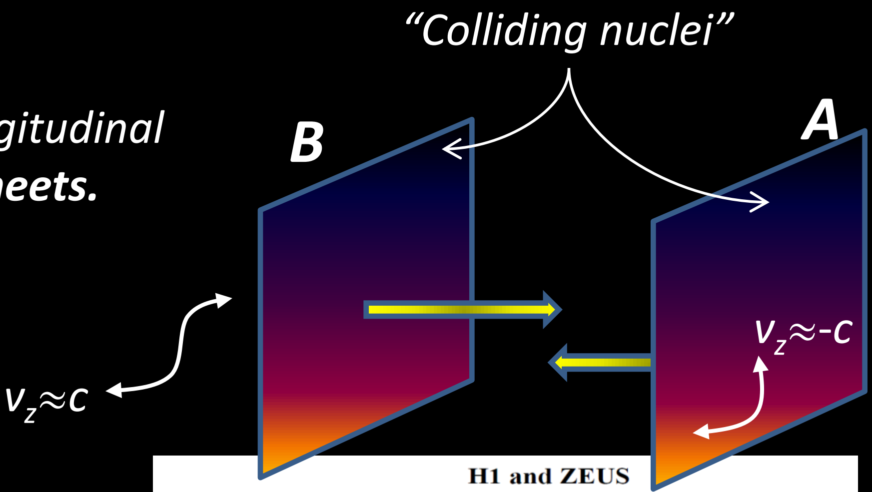
- (At least part of) the measured nuclear modification factor in p-Pb can be understood as the (anomalous) diffusion of heavy quarks in the evolving Glasma: ***Cathode Tube Effect.***

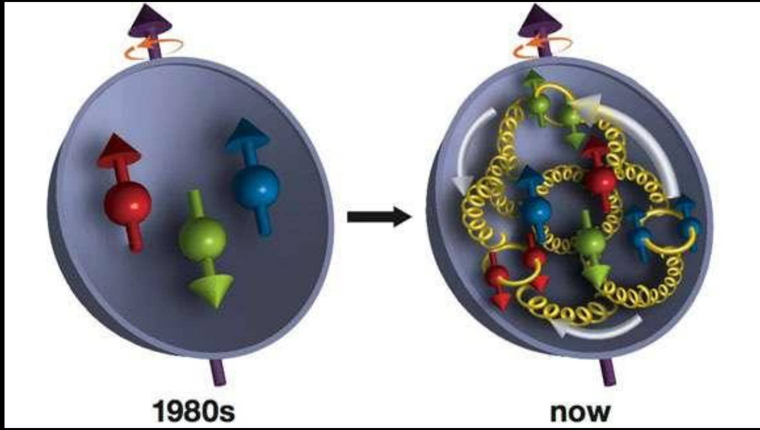
- *J/ψ survival in the Glasma*
- *Diffusion coefficient of c and b quarks*
- *Anomalous vs standard diffusion*
- *v2, v3,………..*
- *p-Pb, p-p, Pb-Pb*

Appendix

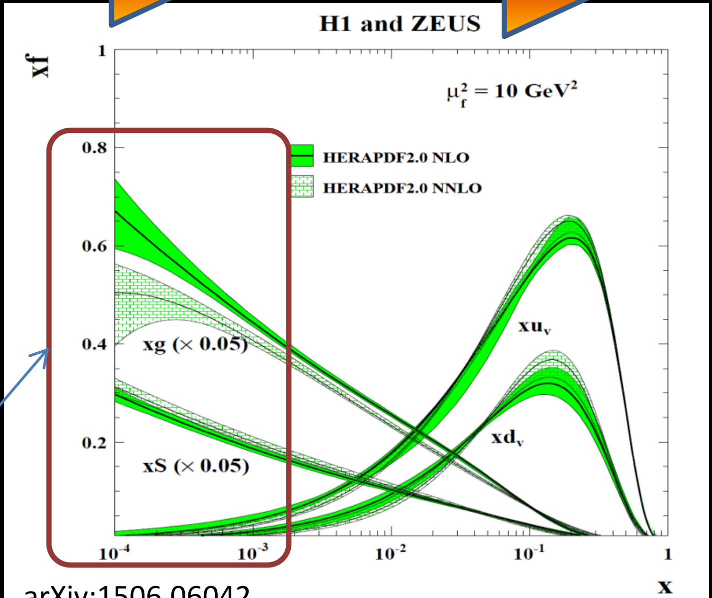
Cold nuclear matter effects: gluon saturation

The two nuclei are Lorentz contracted along the longitudinal direction: ***in Lab frame they appear like two thin sheets.***



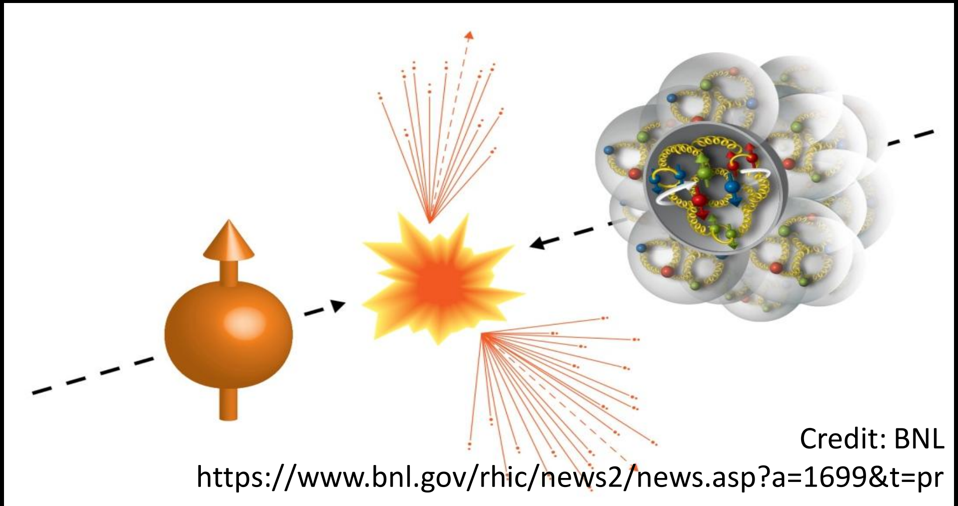


x: parton momentum/nucleon momentum

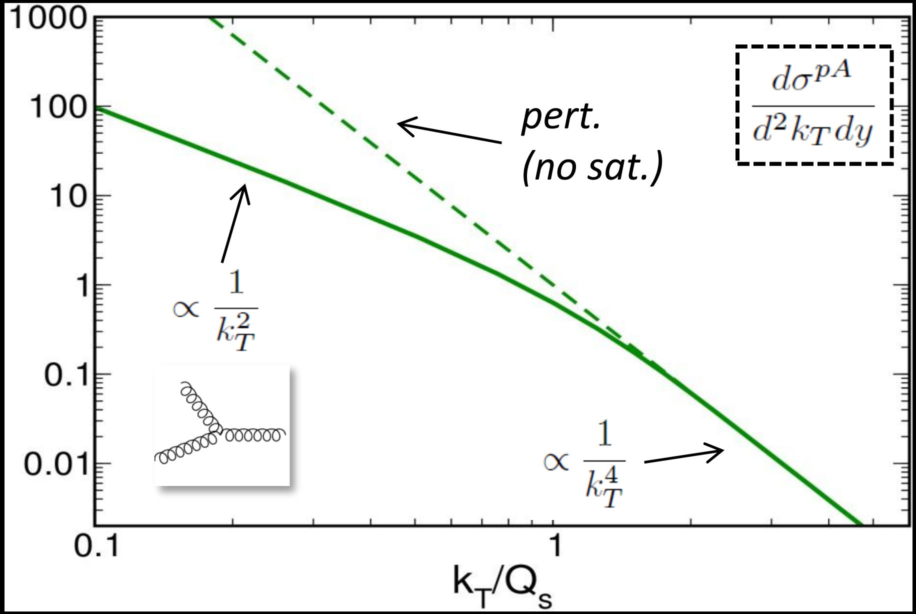


arXiv:1506.06042

The small-x proton wave function is dominated by the sea of virtual gluons.



High gluon density:
Gluon recombination



Saturation

Gluon production is suppressed due to the abundance of the 2 → 1 processes.

Saturation scale, **Qs**

Momentum scale at which saturation becomes important

McLerran and Venugopalan (1994)
and many others

Proton: GBW fit

Golec-Biernat and Wusthoff (1999)

$$Q_s^2 = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$$

x_0=4.1x10^{-5}
λ=0.277

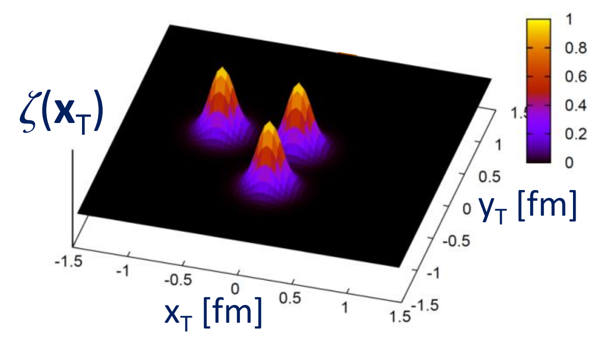
Q_0=1 GeV

x ≈10^{-2} RHIC energy: Qs ≈ 0.46 GeV [In agreement with Dumitru *et al.* (2013)]

x ≈10^{-4} LHC energy: **Qs ≈ 0.80 GeV**

valence quarks *assumption*

$$\langle g^2\mu(\boldsymbol{x}_T)\rangle \stackrel{\text{valence quarks}}{=} g^2\mu\cdot\langle\zeta(\boldsymbol{x}_T)\rangle \stackrel{\text{assumption}}{=} Q_s$$



Averaging over events:

$g^2\mu$ ≈ 1.6 GeV @ 5.02 TeV

Pb: GBW fit again

Freund *et al.* (2002)
Albacete *et al.* (2004)
Armesto *et al.* (2005)
Kowalski *et al.* (2006)
Kowalski *et al.* (2008)
Lappi (2008)

$$Q_s^2 = f(A) Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

$f(A) = A^{1/3}$, *naive*

$f(A) = cA^{1/3}\log(A)$, *IP-Sat*

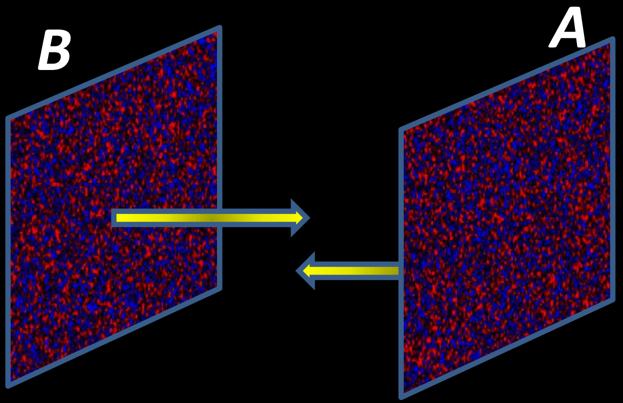
naive
- $x \approx 10^{-2}$ RHIC energy: $Q_s \approx 1.7$ GeV, $g^2\mu \approx 3$ GeV
- $x \approx 10^{-4}$ LHC energy: **$Q_s \approx 3$ GeV, $g^2\mu \approx 5.3$ GeV**

IP-Sat
- $x \approx 10^{-2}$ RHIC energy: $Q_s \approx 1.1$ GeV, $g^2\mu \approx 2$ GeV
- $x \approx 10^{-4}$ LHC energy: **$Q_s \approx 1.90$ GeV, $g^2\mu \approx 3.3$ GeV**

We consider

$g^2\mu_{Pb} \approx$ in the range 3.3 GeV – 5.3 GeV @ 5.02 TeV

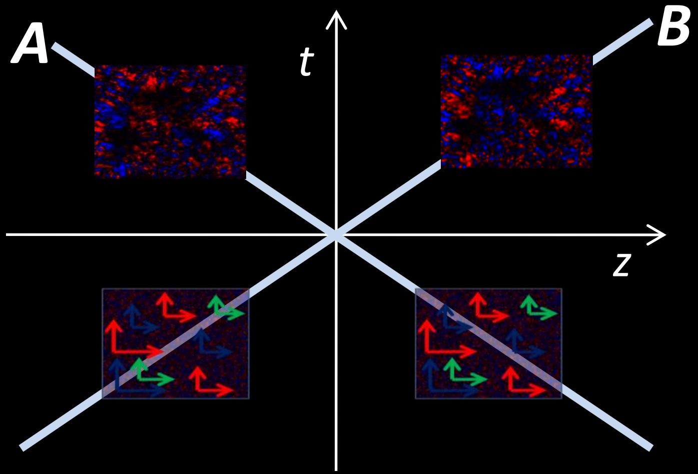
Building up the Glasma fields



$$-\partial_\perp^2 \Lambda^{(A)}(\boldsymbol{x}_T) = \rho^{(A)}(\boldsymbol{x}_T)$$

$$V^\dagger(\boldsymbol{x}_T) = e^{i\Lambda^{(A)}(\boldsymbol{x}_T)}, \quad W^\dagger(\boldsymbol{x}_T) = e^{i\Lambda^{(B)}(\boldsymbol{x}_T)}$$

$$\alpha_i^{(A)} = iV\partial_i V^\dagger, \quad \alpha_i^{(B)} = iW\partial_i W^\dagger$$



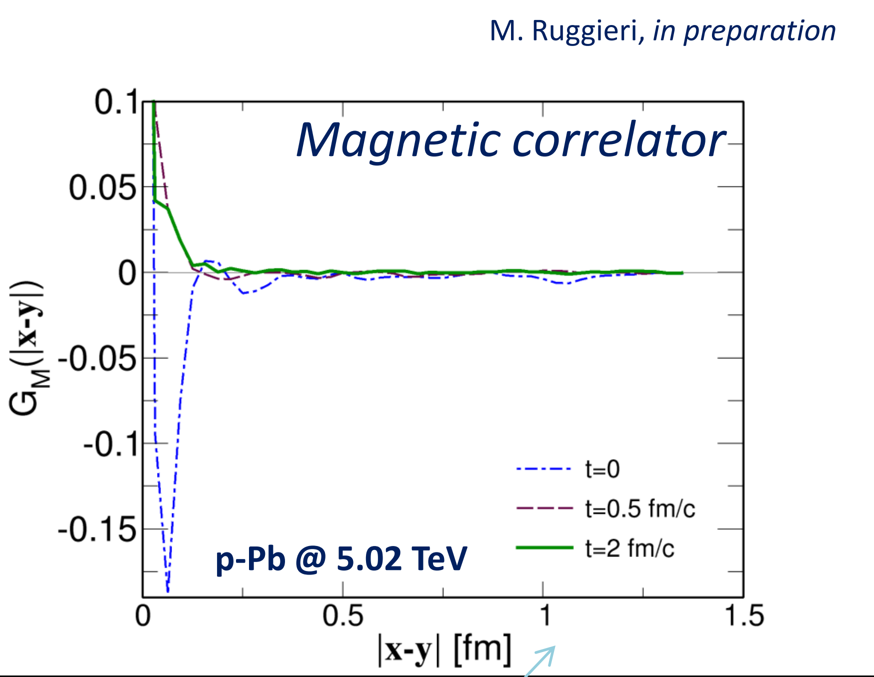
Glasma color fields

$$E^z = i \sum_{i=x,y} \left[\alpha_i^{(B)}, \alpha_i^{(A)}\right],$$

$$B^z = i\left(\left[\alpha_x^{(B)}, \alpha_y^{(A)}\right] + \left[\alpha_x^{(A)}, \alpha_y^{(B)}\right]\right)$$

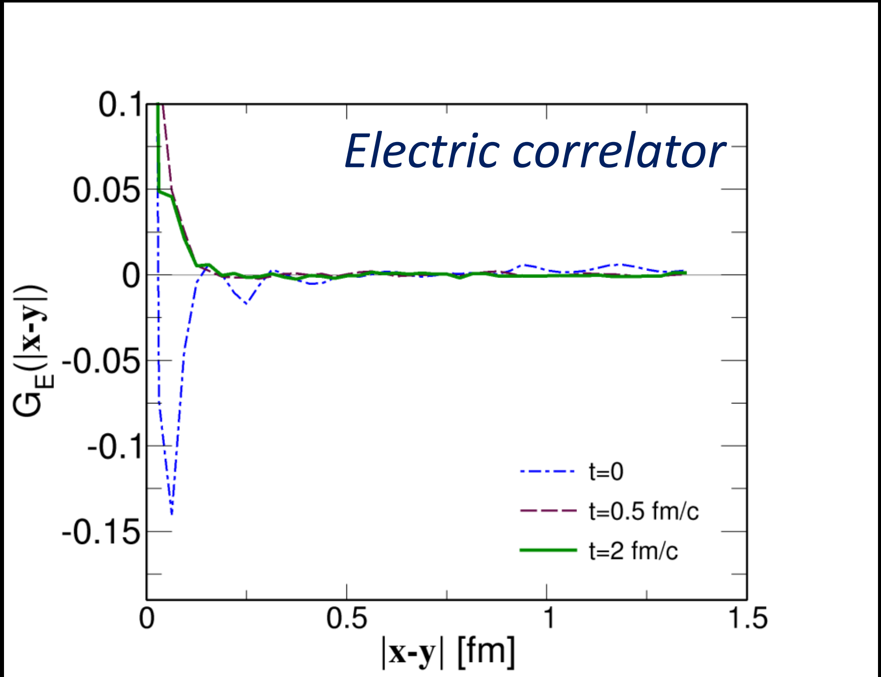
Lappi and McLerran (2006)

Correlation domains in p-Pb



Initial time:

Anticorrelation

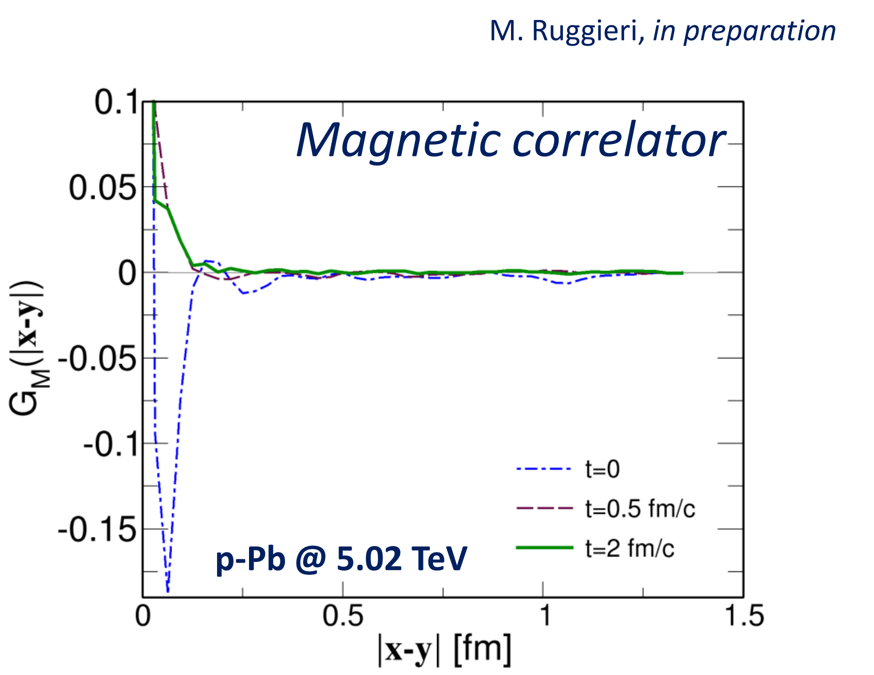


t ≈ 0.5 fm/c:

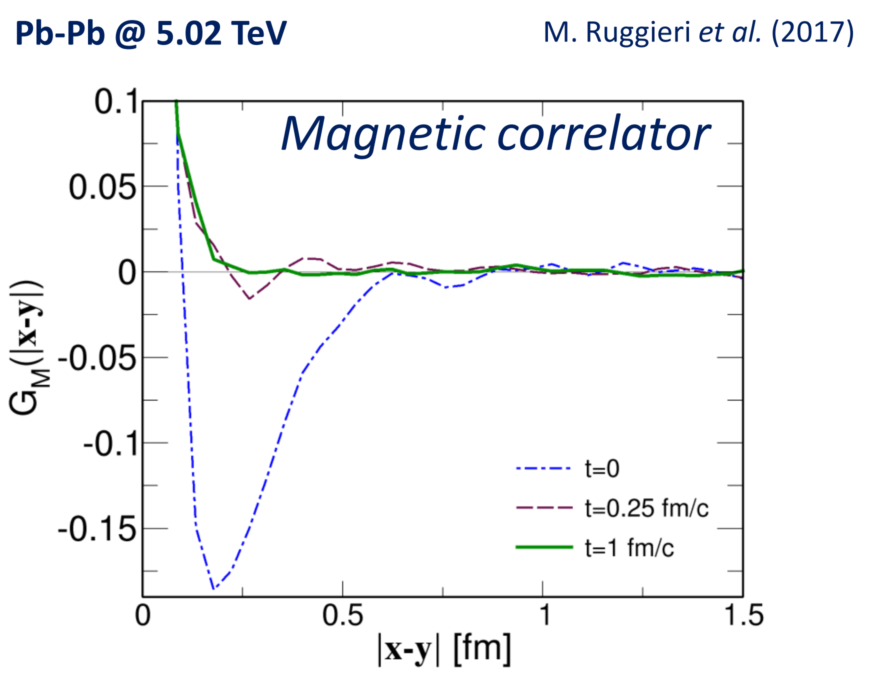
Correlation length ≈ 0.2 fm

Correlation domains

Correlation domains: p-Pb versus Pb-Pb



p-Pb



Pb-Pb

In agreement with Dumitru *et al.* (2014)
Dumitru *et al.* (2013)

Fluctuations appear at the *next-to-leading order in the QCD coupling*:

•*Longitudinal electric fields* (E_z): break longitudinal invariance.

•*Transverse electric fields* (E_x,E_y): added on the top of the longitudinal Glasma fields.

$$\langle \xi_i^a(\boldsymbol{x}_T)\xi_j^b(\boldsymbol{y}_T)\rangle = \delta_{ab}\delta_{ij}\delta^{(2)}(\boldsymbol{x}_T-\boldsymbol{y}_T);$$

$$g^2\mu\langle F(z)F(z')\rangle = \Delta^2\delta(z-z').$$

No correlation in:

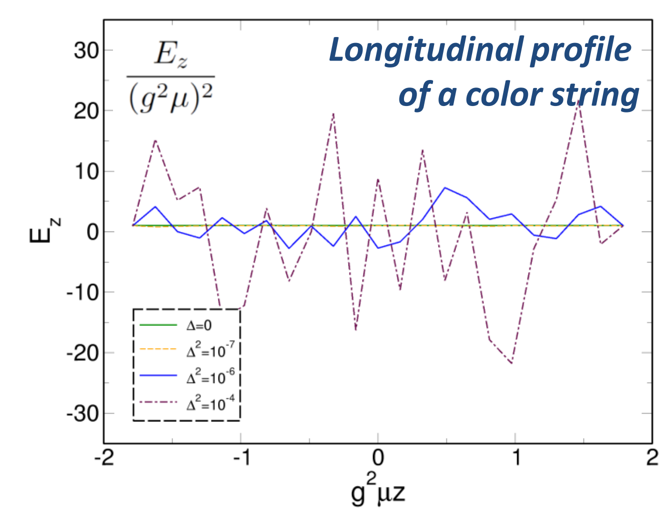
•*Transverse plane*

•*Longitudinal direction*

Fluctuations of the electric field:

$$\begin{aligned}\delta E_i^a(\boldsymbol{x}_T,z) &= \partial_z F(z)\xi_i^a(\boldsymbol{x}_T),\\ \delta E_z^a(\boldsymbol{x}_T,z) &= -F(z)D_i\xi_i^a(\boldsymbol{x}_T).\end{aligned}$$

White noise



See:

Romatschke and Venugopalan (2006)

Ohnishi *et al.* (2014)

Fukushima and Gelis (2012)

Fukushima (2013)

Berges and Schlichting (2013)

A more rigorous treatement is also possible:

Epelbaum and Gelis (2013)

Fluctuations appear at the *next-to-leading order in the QCD coupling*:

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$$g^2\mu\langle F(z)F(z')\rangle = \Delta^2\delta(z-z').$$

No correlation in:

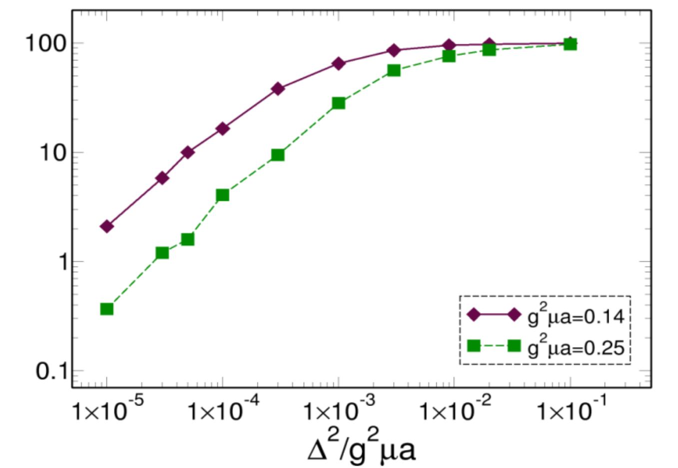
- *Transverse plane*
- *Longitudinal direction*

With these the fluctuations of the electric field are computed as:

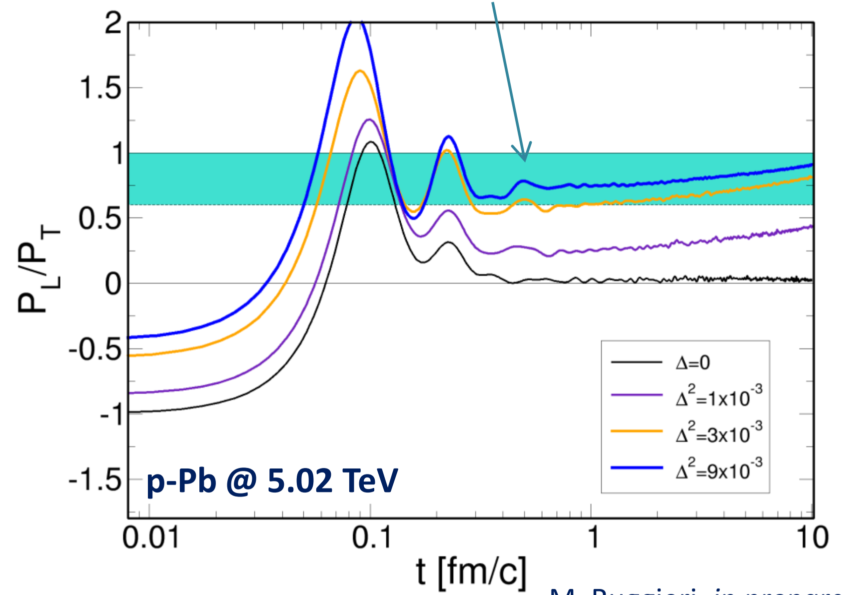
$$\delta E_i^a(\boldsymbol{x}_T, z) \;=\; \partial_z F(z)\xi_i^a(\boldsymbol{x}_T),$$
$$\delta E_z^a(\boldsymbol{x}_T, z) \;=\; -F(z)D_i\xi_i^a(\boldsymbol{x}_T).$$

$$\Delta \sim g$$

% of energy carried by fluctuations



The evolving Glasma: pressures



M. Ruggieri, *in preparation*

$$P_T = \frac{E_z^a E_z^a + B_z^a B_z^a}{2},$$

$$P_L = -P_T + \frac{\mathbf{E}_T^a \mathbf{E}_T^a + \mathbf{B}_T^a \mathbf{B}_T^a}{2},$$

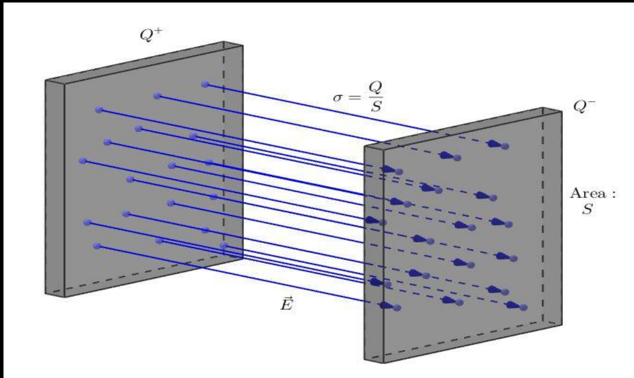
Romatschke and Venugopalan (2006)
Berges (2012)
Epelbaum and Gelis (2012)
Fukushima (2014)
M. R. *et al.* (2017)

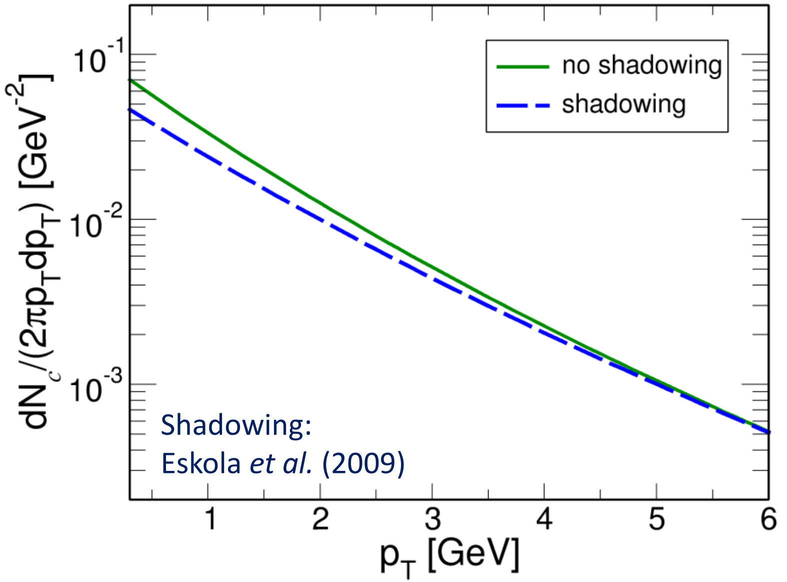
<u>Negative pressure</u>

Attraction among the two nuclei.

Energy has to be given *by the environment* to allow for the expansion of the system.

In realistic collisions *this energy is given by the kinetic energy of the colliding nuclei.*

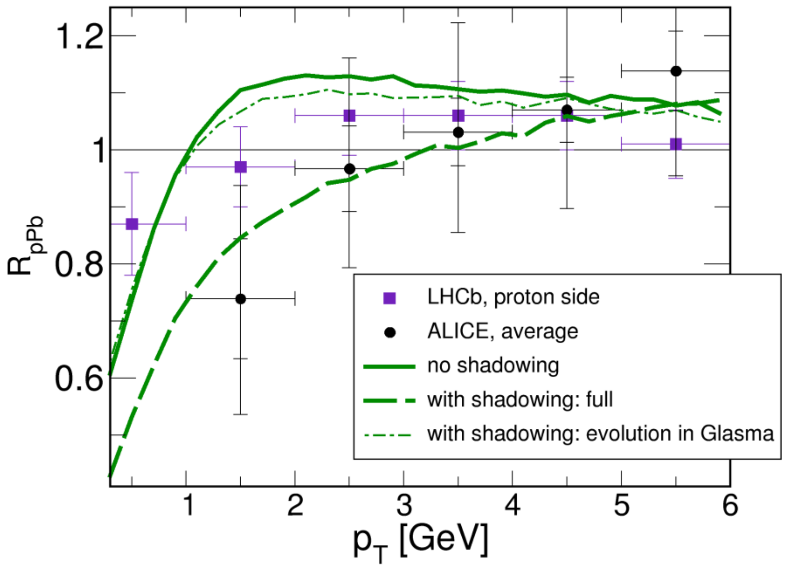




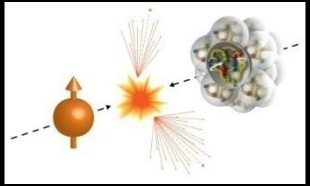
Nuclear shadowing does not affect the cathod tube

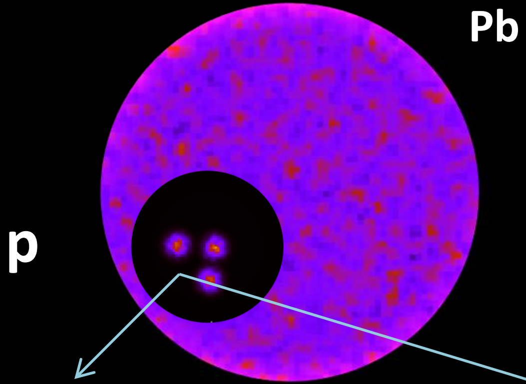
$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

p-Pb @ 5.02 TeV M. Ruggieri and S. K. Das, *in preparation*



Implementation of p-Pb





Valence quarks

Sources of the x ≈ 1 gluon fields

Mantysaari *et al.* (2017)
Mantysaari and Schenke (2016)
Schlichting and Schenke (2014)

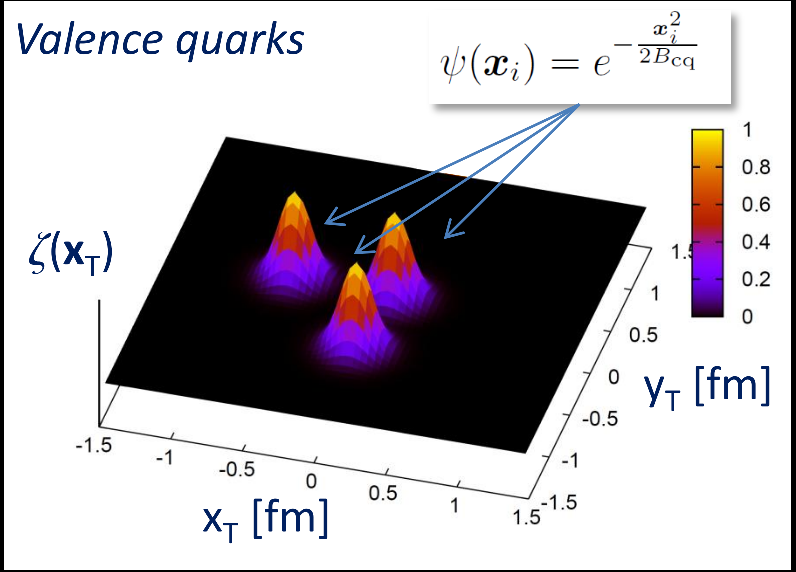
$$\langle \rho_a(\boldsymbol{x}_T)\rho_b(\boldsymbol{y}_T)\rangle = (g^2\mu(\boldsymbol{x}_T))^2\delta_{ab}\delta^2(\boldsymbol{x}_T-\boldsymbol{y}_T)$$

$$g^2\mu(\boldsymbol{x}_T) = g^2\mu\cdot\zeta(\boldsymbol{x}_T)$$

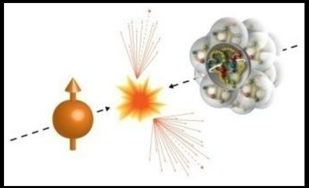
$$\psi(\boldsymbol{x}_i) = e^{-\frac{\boldsymbol{x}_i^2}{2B_{\mathrm{cq}}}}$$

$$\zeta(\boldsymbol{x}_T) = \frac{1}{3}\sum_{i=1}^{3} e^{-\frac{(\boldsymbol{x}_T-\boldsymbol{x}_i)^2}{2B}}$$

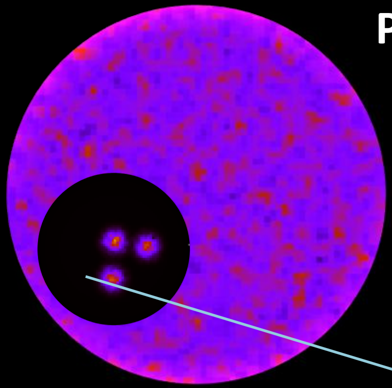
Bcq = 3 GeV^{-2} ≈ 0.12 fm^2
B = 0.3 GeV^{-2} ≈ 0.01 fm^2



Glasma in p-Pb collisions



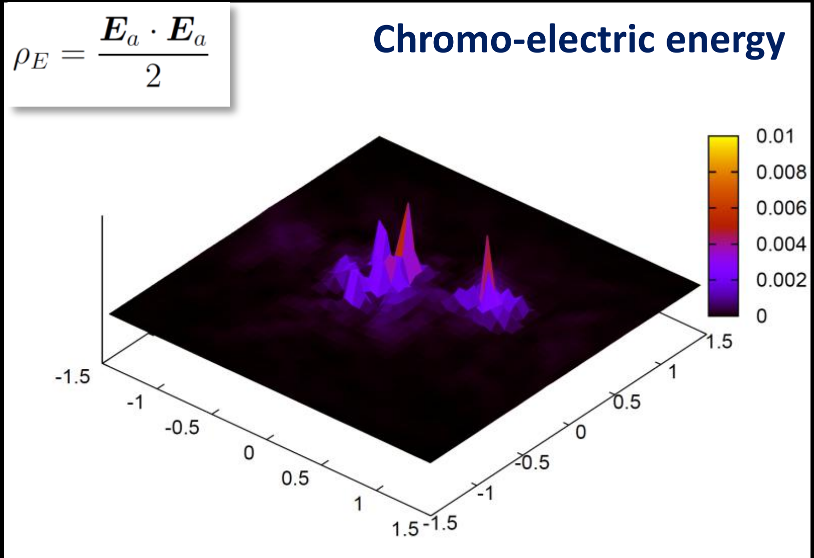
Pb



p

- Transverse area ≈ (4 fm)^2
- Overlap of color charges of proton and nucleus

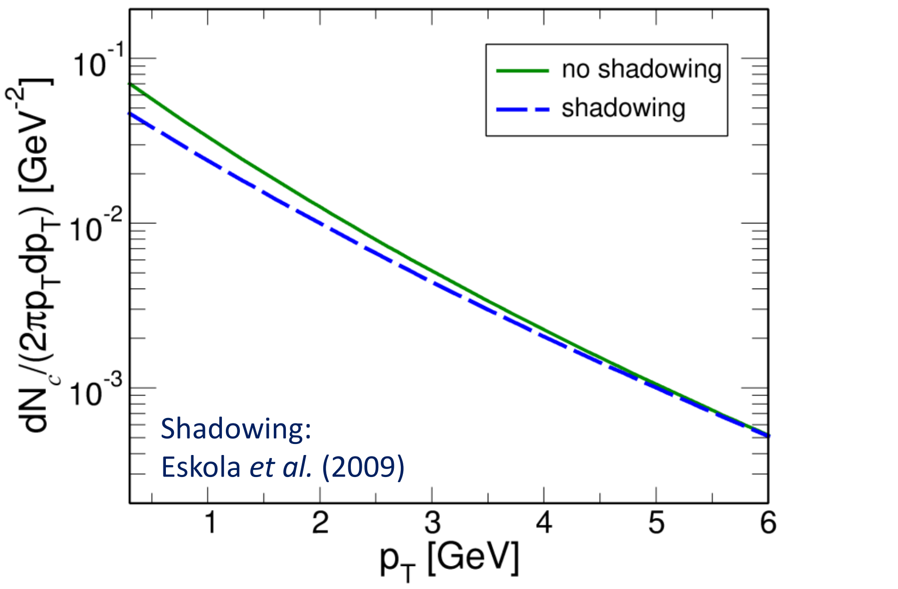
Finite size system



Energy distribution depends on the model.

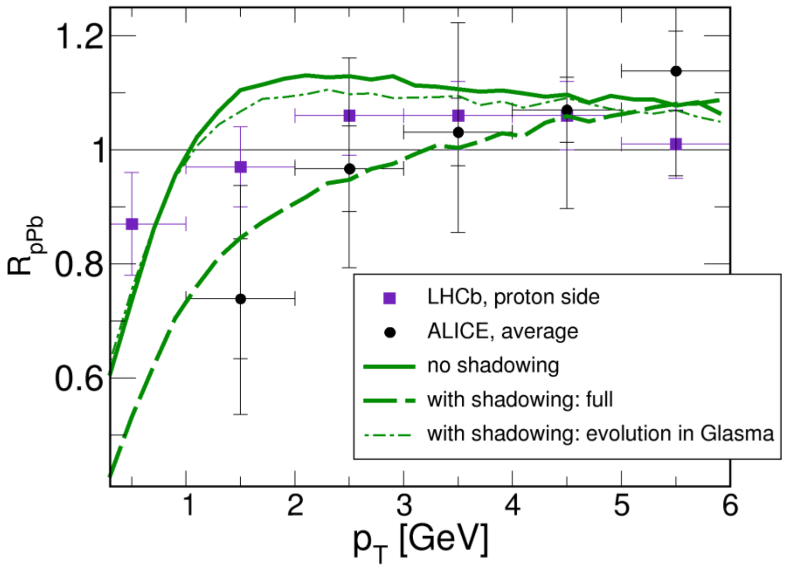
It concentrates around the peaks of the color charges (valence + sea) in the proton.

Nuclear shadowing does not affect the cathode tube



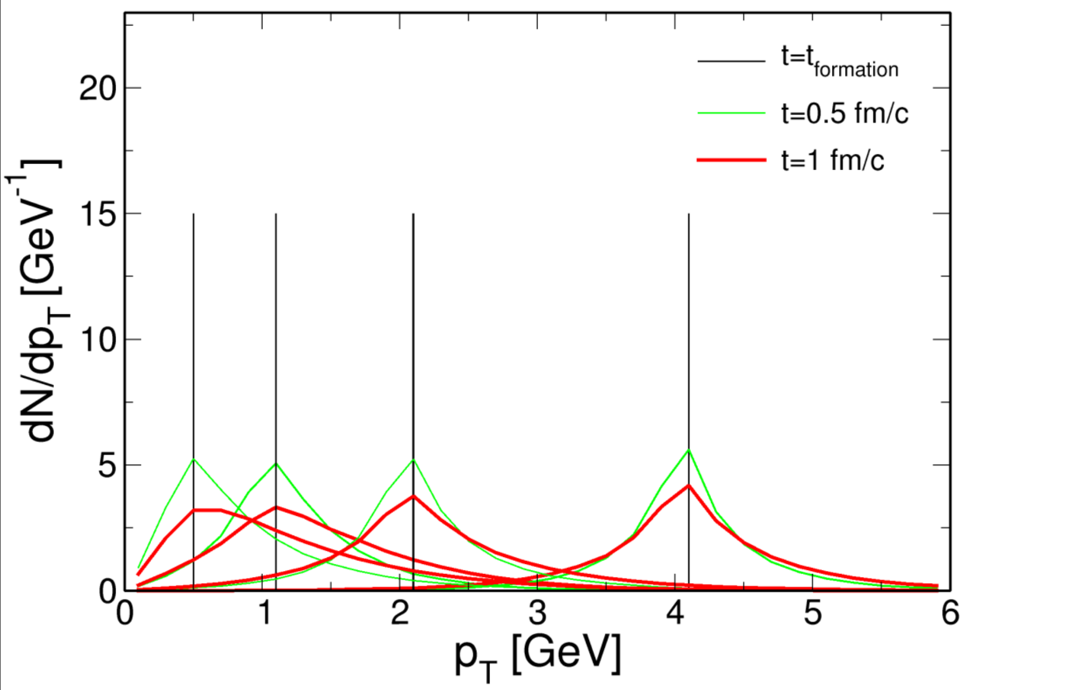
$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

p-Pb @ 5.02 TeV M. Ruggieri and S. K. Das, *in preparation*



HQs in Glasma

M. Ruggieri and S. K. Das, *in preparation*



Standard Brownian motion:
Random walk with fixed probability

$$\langle p^2 - \langle p \rangle^2 \rangle = 2Dt$$

Anomalous diffusion:
Random walk in disordered structures

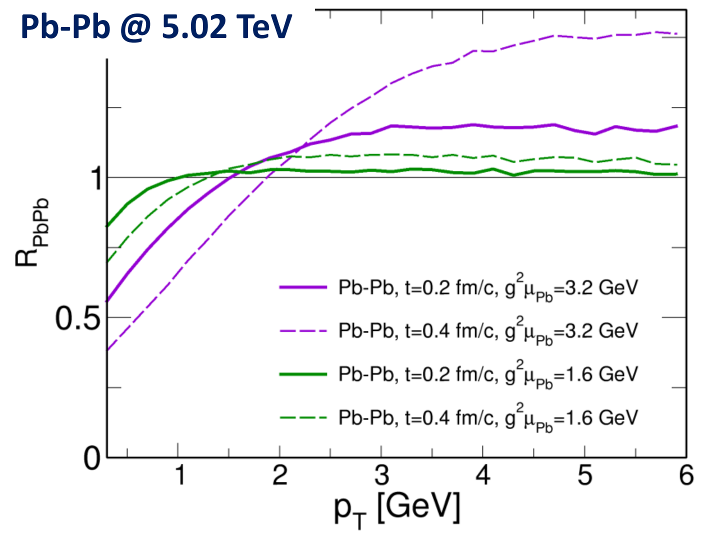
$$\langle p^2 - \langle p \rangle^2 \rangle = 2Dt^{1/d_W}$$

For HQs in Glasma:
$d_W \approx 1.66$

See Havlin and Avraham (1987)

Interaction with Glasma affects the spectrum of c in Pb-Pb

M. Ruggieri and S. K. Das, *in preparation*



$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

M. Ruggieri and S. K. Das, 1805.09617