(Probing) The evolving Glasma

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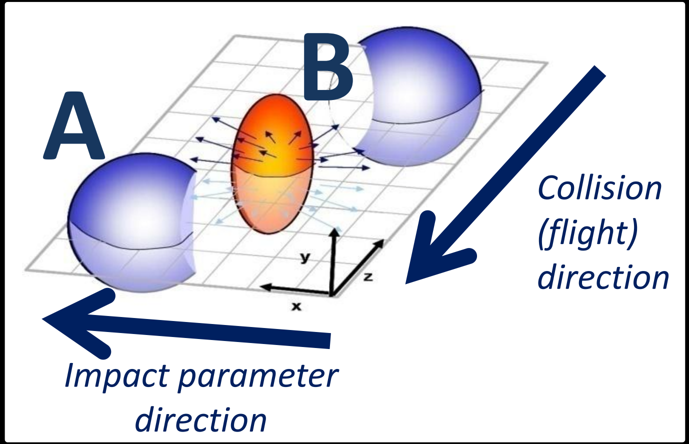
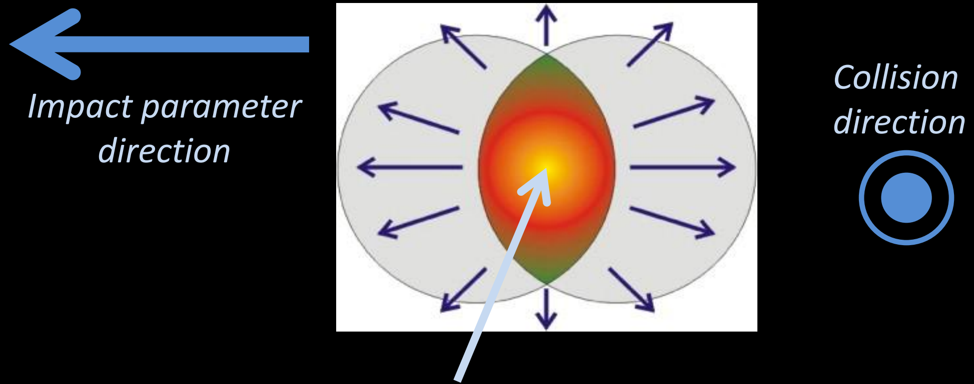
In this talk

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

Motivation: high energy nuclear collisions

High energy nuclear collisions





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

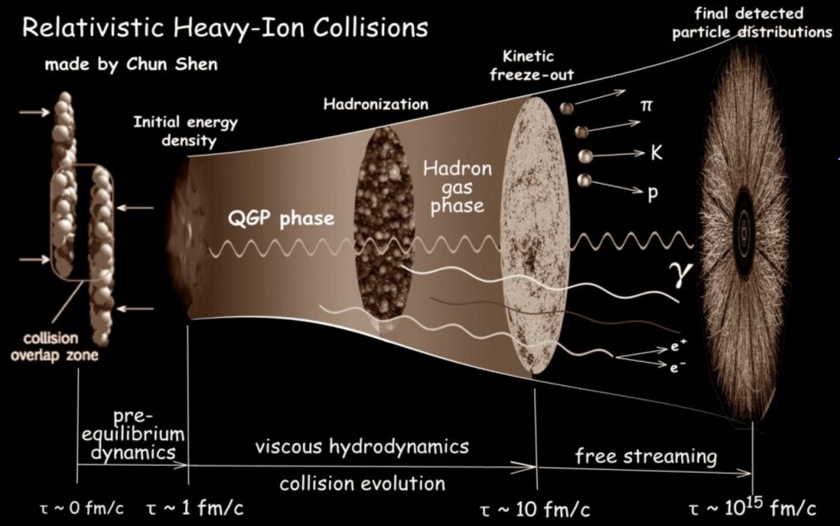
A,B: Cu, Au (RHIC@BNL)
Pb (LHC@CERN)
p (LHC@CERN)
p-Pb collisions (LHC@CERN)
d-Au collisions (RHIC@BNL)

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

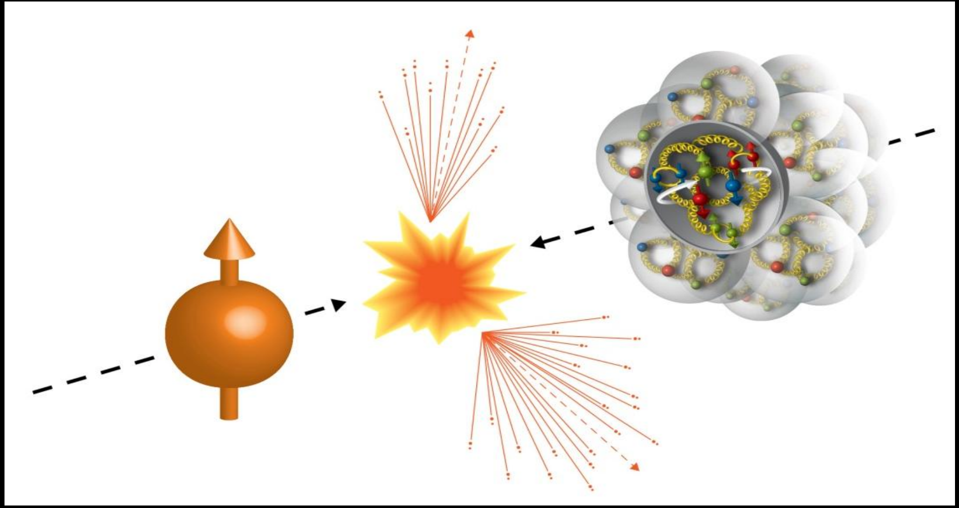
QGP formation time
- RHIC $\approx$ 0.6 fm/c ≈ 10^{-24} sec
- LHC $\approx$ 0.2 fm/c

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

Why we want to do proton-Pb collision?



While QGP is likely to be formed in Pb-Pb collisions, it is not clear if it is produced in collisions of small systems like proton-Pb (p-Pb).



p-Pb collisions can help to quantify the effects of the cold nuclear matter (i.e., not related to the QGP formation) on observables.

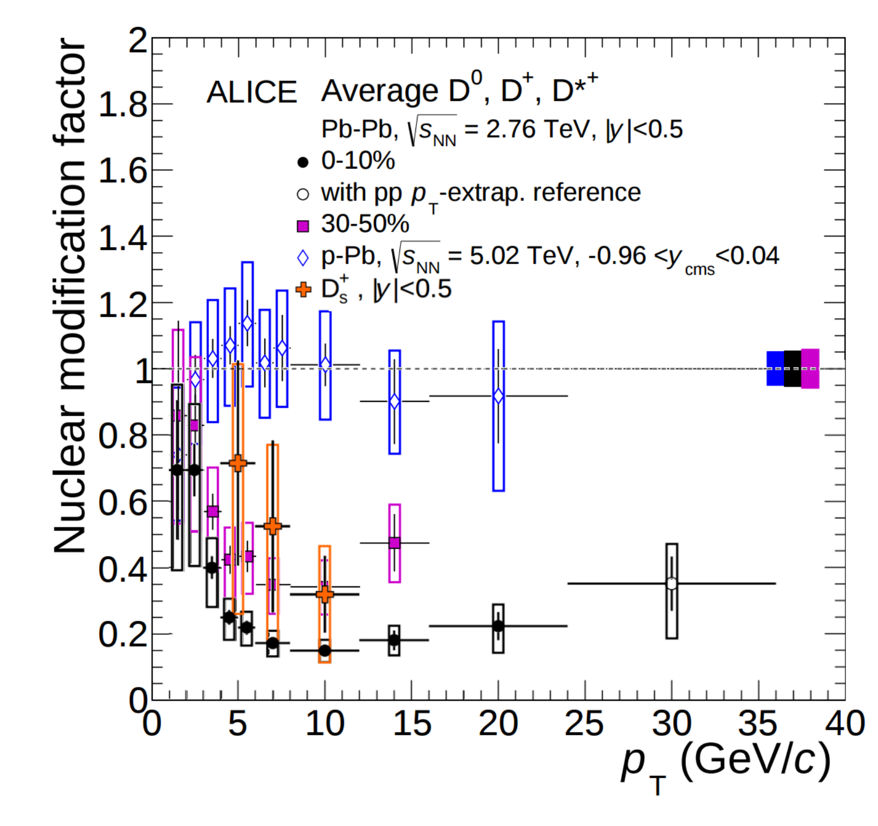
Nuclear modification factor: p-Pb versus Pb-Pb

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

pQCD: spectrum computed within perturbative QCD
It does not consider effects of propagation in a hot medium

$R_{AB} \neq 1$
Interaction with the medium created by the collision

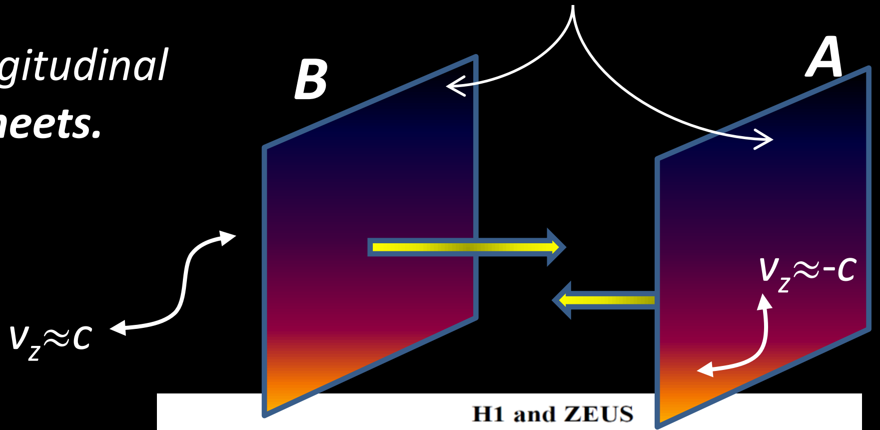
Measured energy loss is substantial for Pb-Pb
Almost no energy loss measured for p-Pb

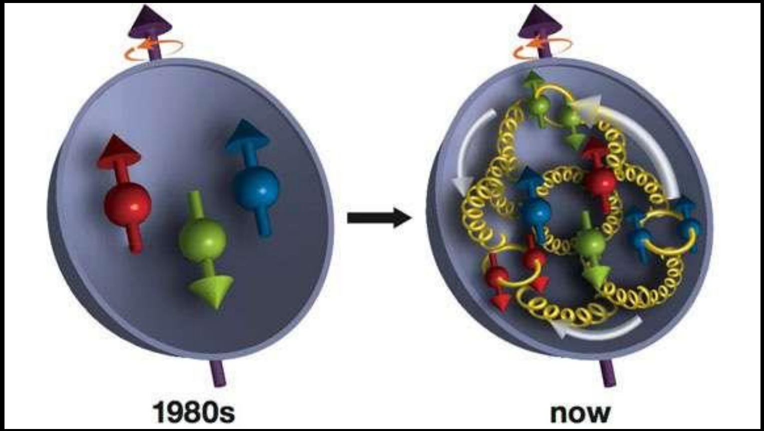


This observable suggests that most likely a hot medium is not created in p-Pb collisions.
Modification at small pT can be understood in terms of cold nuclear effects.

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.***





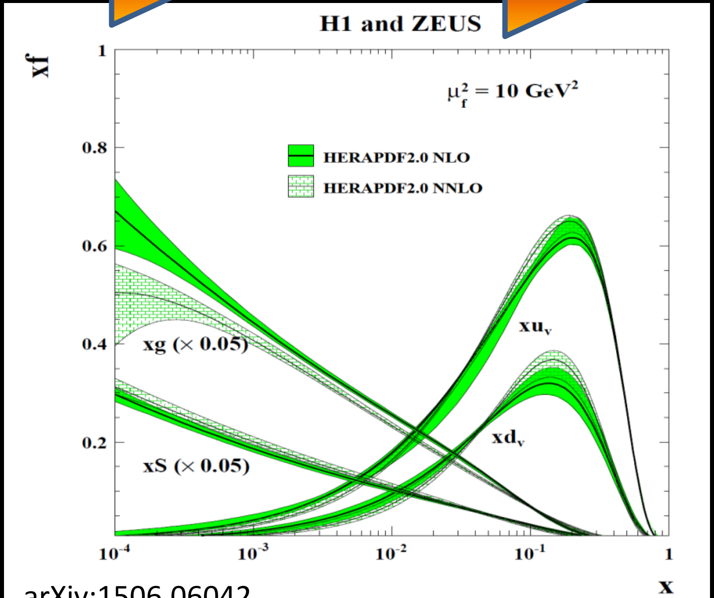
x: parton momentum/nucleon momentum

Valence quarks (uud): x ≈ 1

Small-x content of the proton

Sea quarks+antiquarks

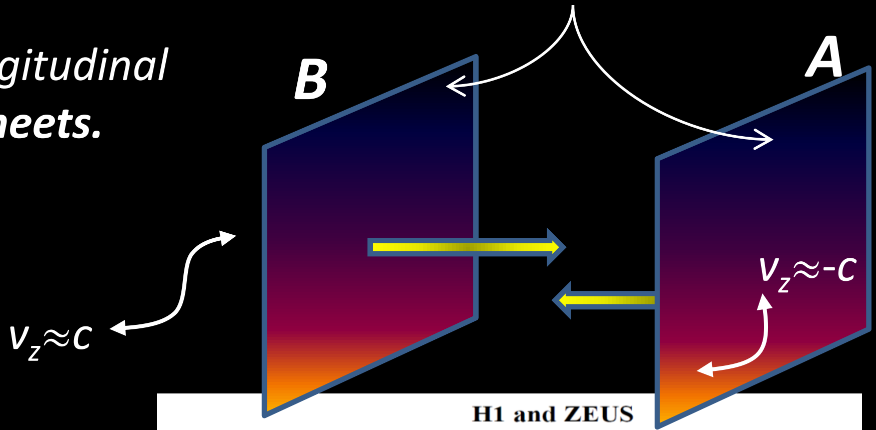
Sea gluons

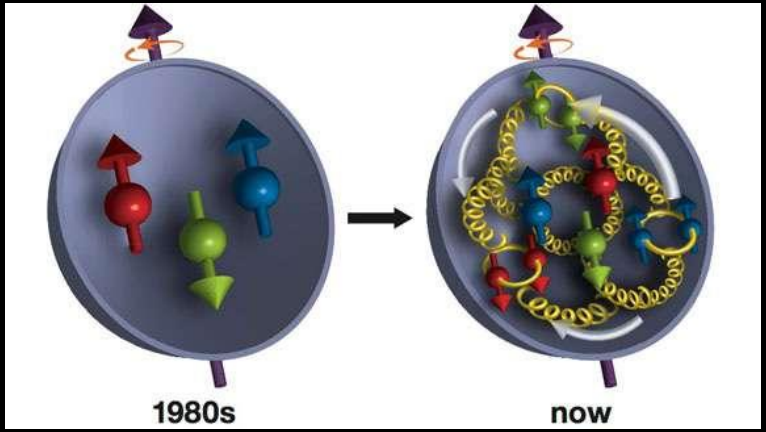


arXiv:1506.06042

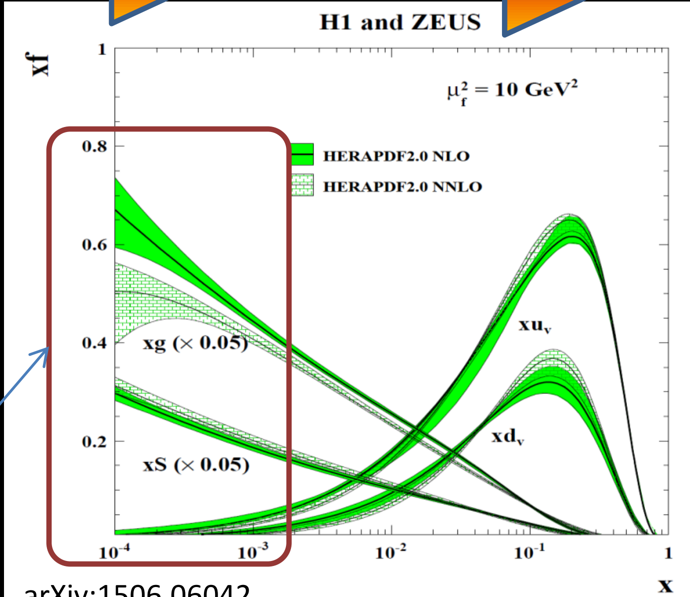
Cold nuclear matter effects: gluon saturation

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





x: parton momentum/nucleon momentum



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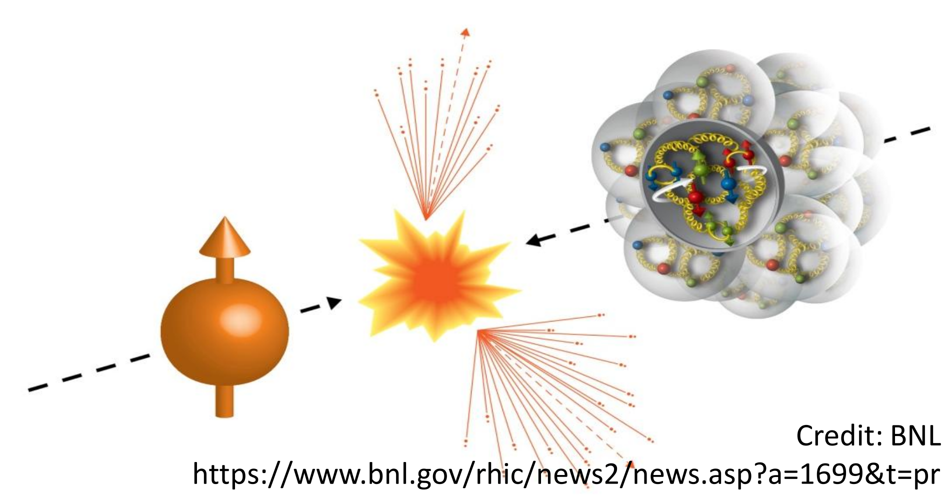
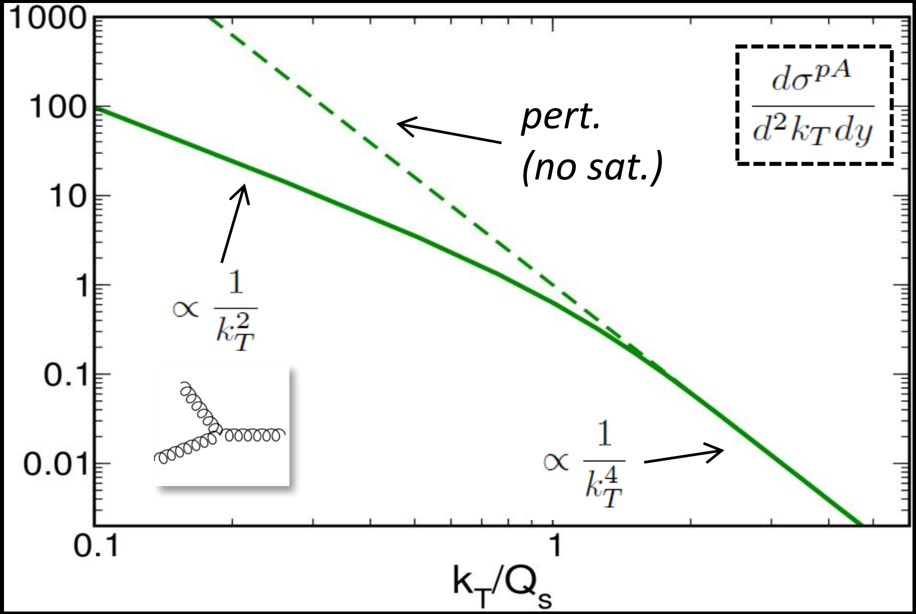
The small-x proton wave function is dominated by the sea of virtual gluons.



High gluon density:
Gluon recombination



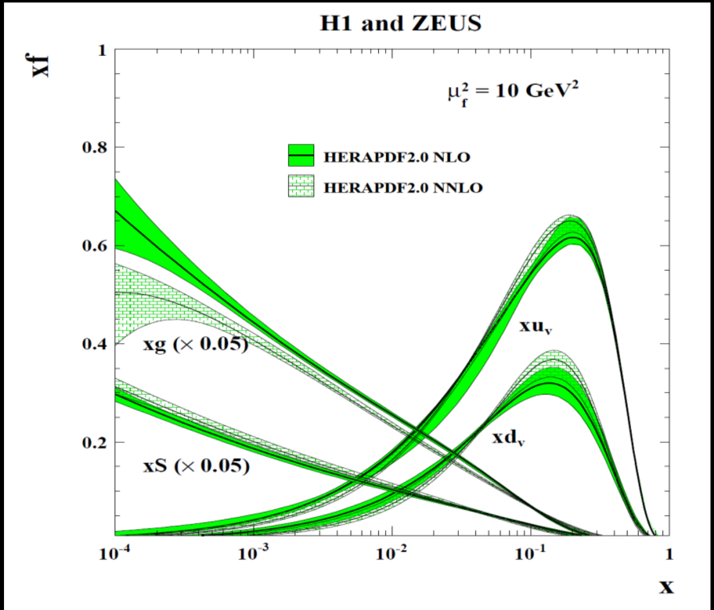
Saturation

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



Many body effects: Color-Glass-Condensate (CGC)

Color

Gluons carry a color

Condensate

Many small-x gluons: *classical field* like in a condensate

Glass

Partons (quarks and gluons) with x ≈ 1 are very fast (v ≈ c):

- Substantial Lorentz time dilation
- Dynamics in the lab system slows down

The x ≈ 1 appear frozen in lab, like molecules in glasses

The dynamical evolution of the CGC:

Yang-Mills equation

$$D^{\mu} F_{\mu\nu} = -J_{\nu}$$

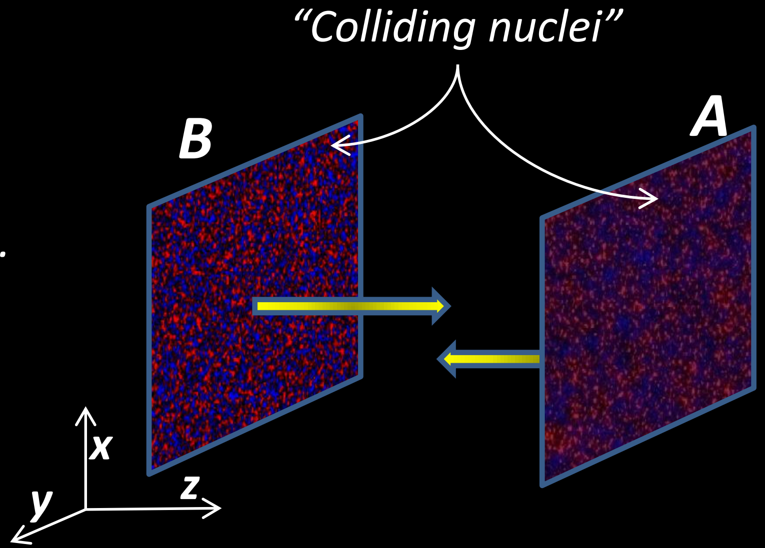
Condensate

(x ≈ 0)

Glass

(x ≈ 1)

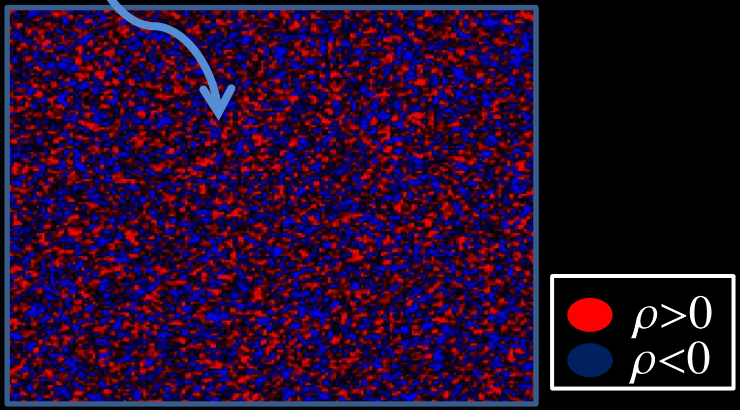
Building up the Glasma fields: static color sources



Model of static sources (MV)

Uncorrelated color density fluctuations on the two sheets.

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



$g^2\mu \approx$ Qs: saturation scale

Lappi (2007)

McLerran and Venugopalan (1996)
Kovchegov (1996)

$$D^{\mu} F_{\mu\nu} = -J_{\nu}$$

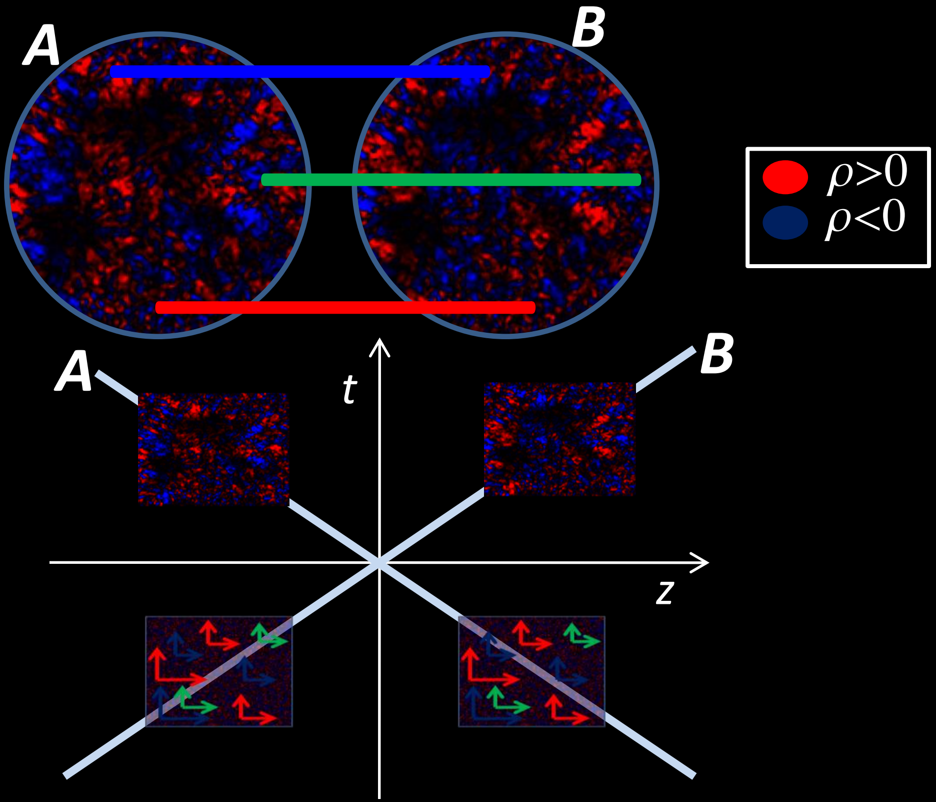
Condensate
($x \approx 0$)

Glass
($x \approx 1$)

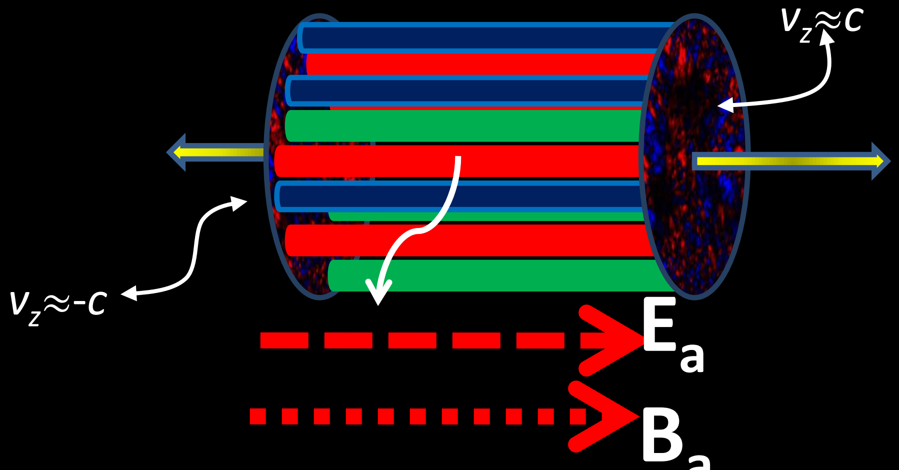
Assuming gluon saturation picture:
What kind of system is created in the p-Pb collision?

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

CGC fields ***interact*** and form two sets of opposite ***effective color charges*** on the light cone of the two nuclei.

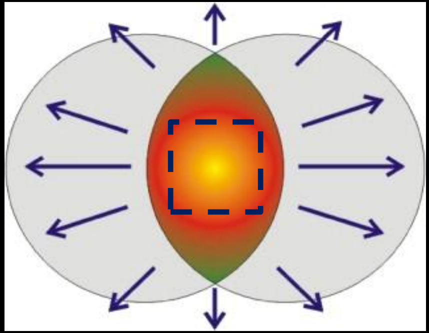


$$\nabla \cdot \boldsymbol{E} = ig\left[\mathcal{A}^i, \mathcal{E}^i\right]$$
$$\nabla \cdot \boldsymbol{B} = ig\left[\mathcal{A}^i, \mathcal{B}^i\right]$$



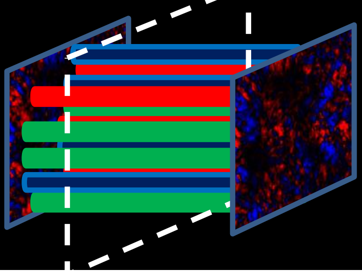
Lappi and McLerran (2006)

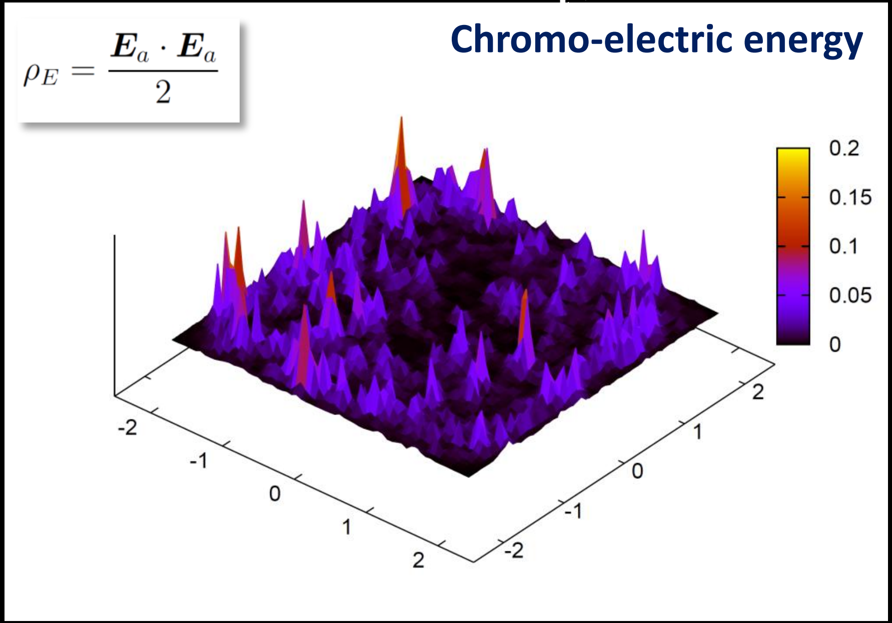
Initial fields for Pb-Pb

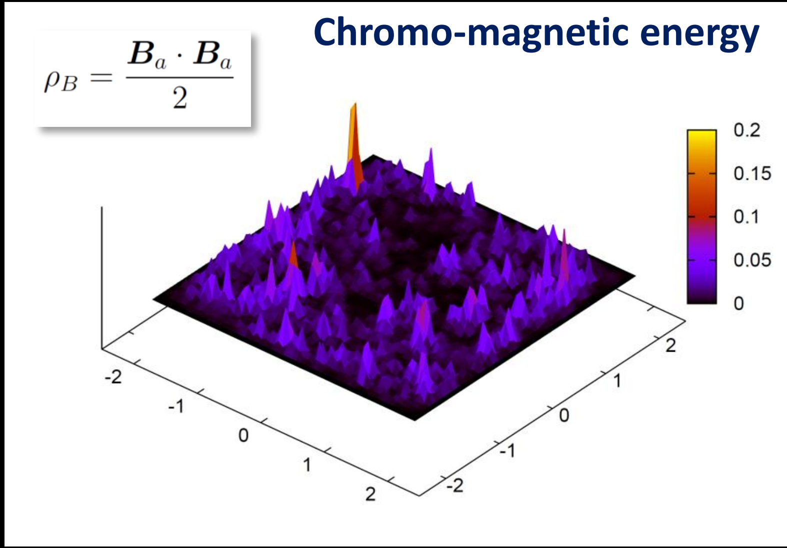


- Transverse area ≈ (4 fm)^2
- Periodic boundary conditions

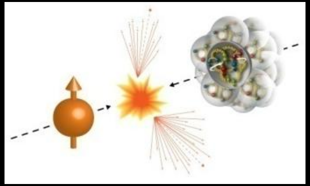
Infinite system

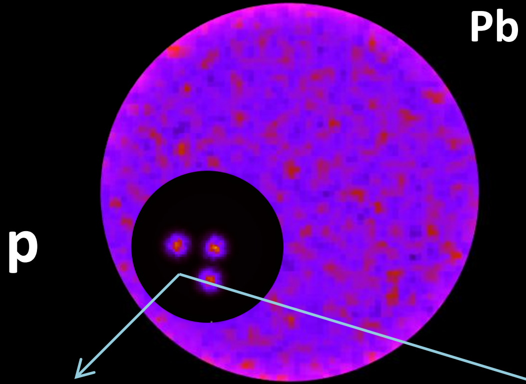






Implementation of p-Pb





Valence quarks

Sources of the x ≈ 1 gluon fields

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

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

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

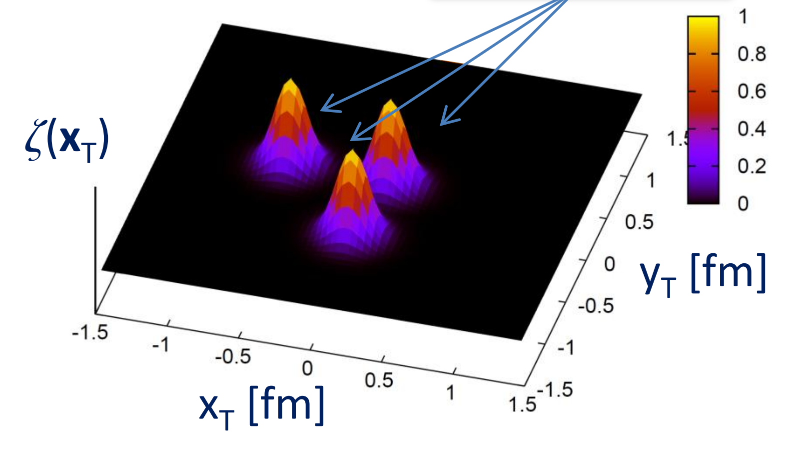
$$\psi(\boldsymbol{x}_i) = e^{-\frac{\boldsymbol{x}_i^2}{2B_{\mathrm{cq}}}}$$

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

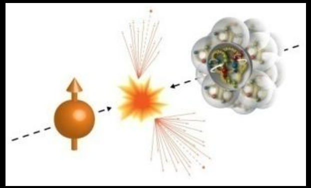
Bcq = 3 GeV^{-2} ≈ 0.12 fm^2
B = 0.3 GeV^{-2} ≈ 0.01 fm^2

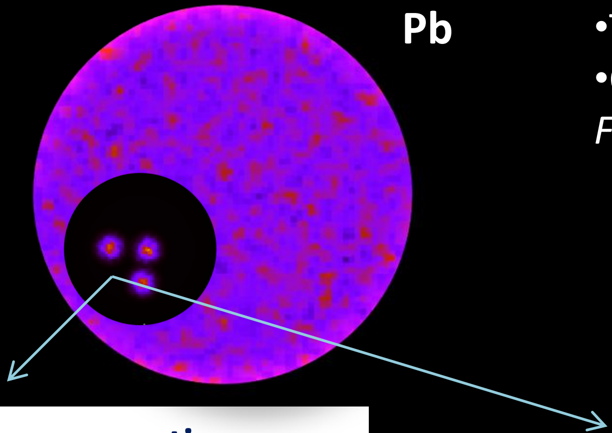
Valence quarks

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



Initial fields for p-Pb

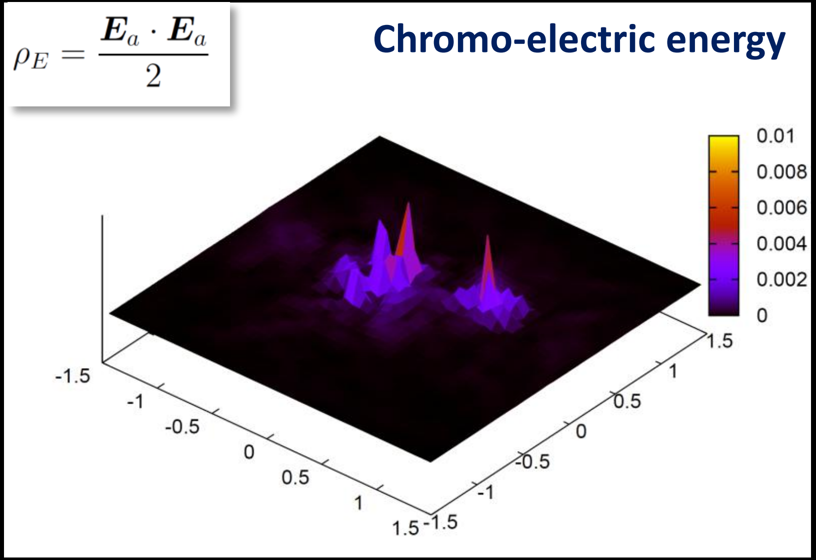




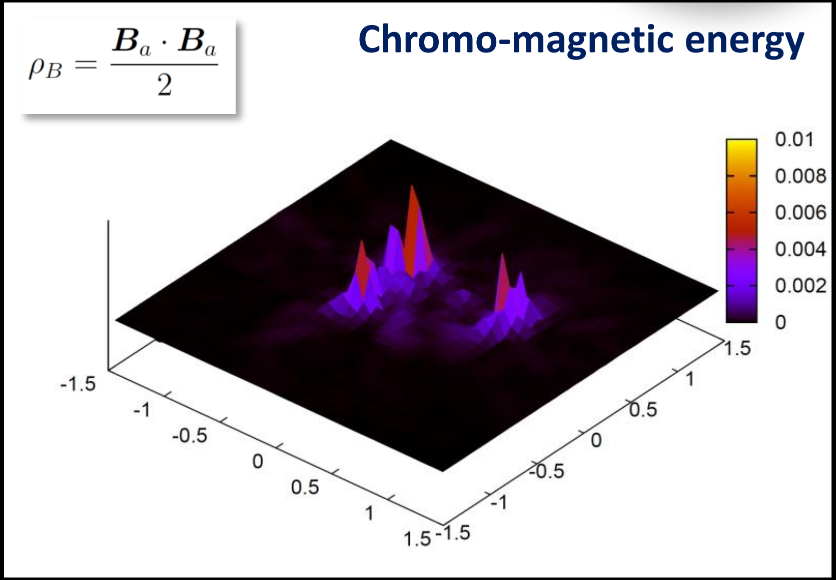
- Transverse area ≈ $(4\ \text{fm})^2$
- Overlap of color charges of proton and nucleus

Finite size system

$$\rho_E = \frac{\boldsymbol{E}_a \cdot \boldsymbol{E}_a}{2}$$



$$\rho_B = \frac{\boldsymbol{B}_a \cdot \boldsymbol{B}_a}{2}$$



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.

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

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.

(Probing) The evolution of Glasma

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)]

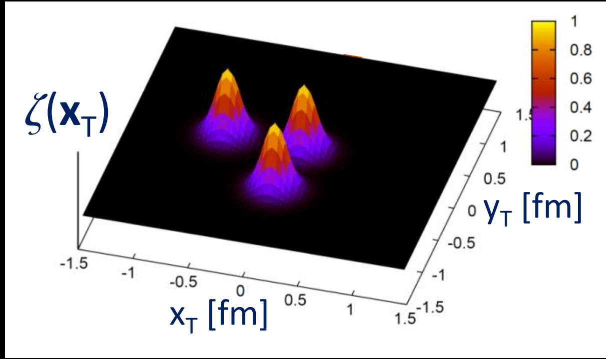
x ≈10^{-4} LHC energy: **Qs ≈ 0.80 GeV**

valence quarks *assumption*

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

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**

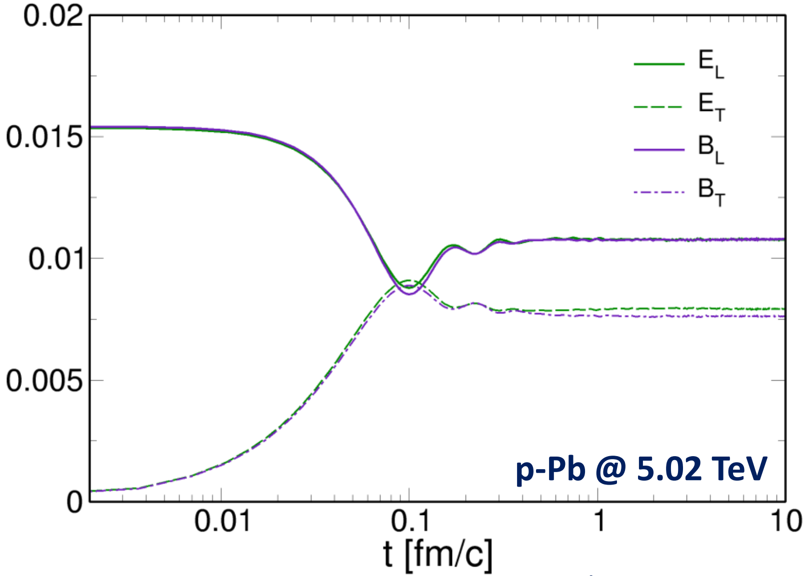
IP-Sat
- $x \approx 10^{-2}$ RHIC energy: $Q_s \approx 1.1$ GeV, $g^2\mu \approx 2$ GeV
- $x \approx 10^{-4}$ LHC energy: **$Q_s \approx 1.90$ GeV, $g^2\mu \approx 3.3$ GeV**

We consider

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

The evolving Glasma: fields

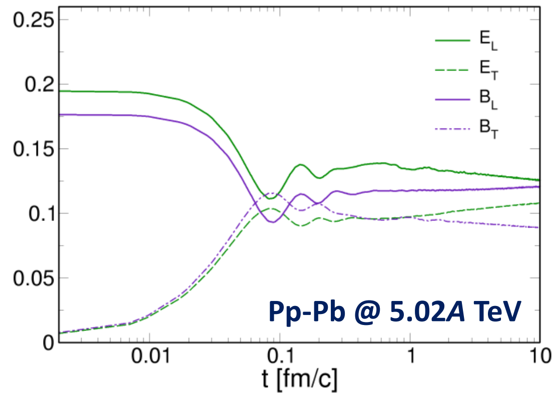
No longitudinal expansion



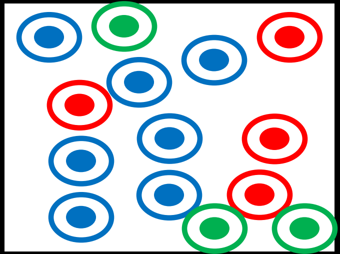
M. Ruggieri and S. K. Das, 1805.09617

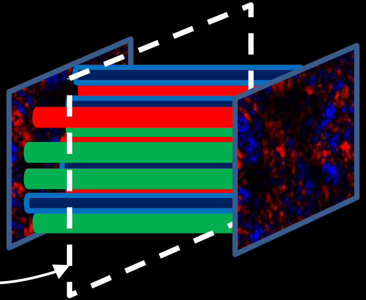
Fields

M. Ruggieri *et al.* (2017)



$t = 0^+$ *Fields are purely longitudinal*

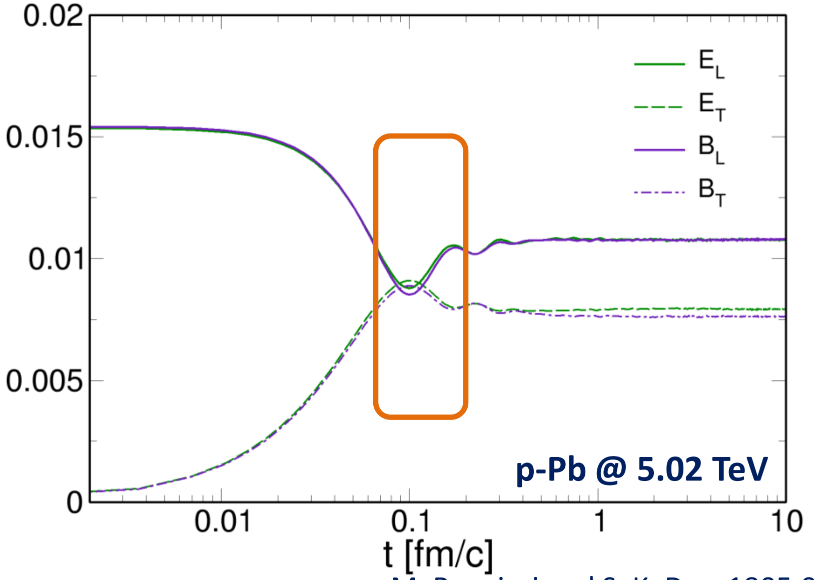




Unfaithful representation:
Only ingoing fields are shown

The evolving Glasma: fields

No longitudinal expansion



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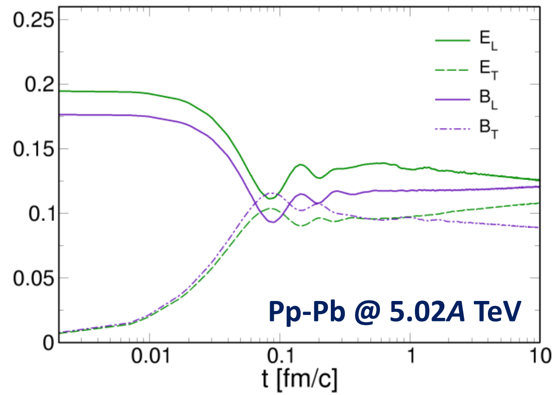
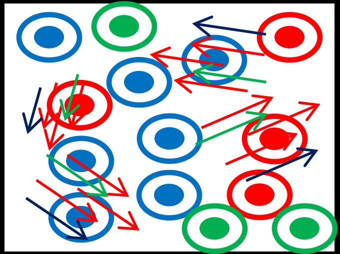
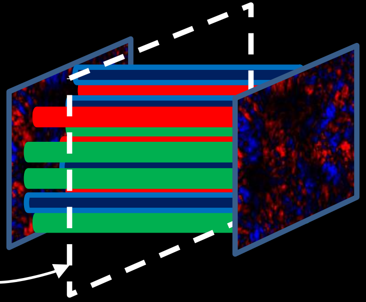
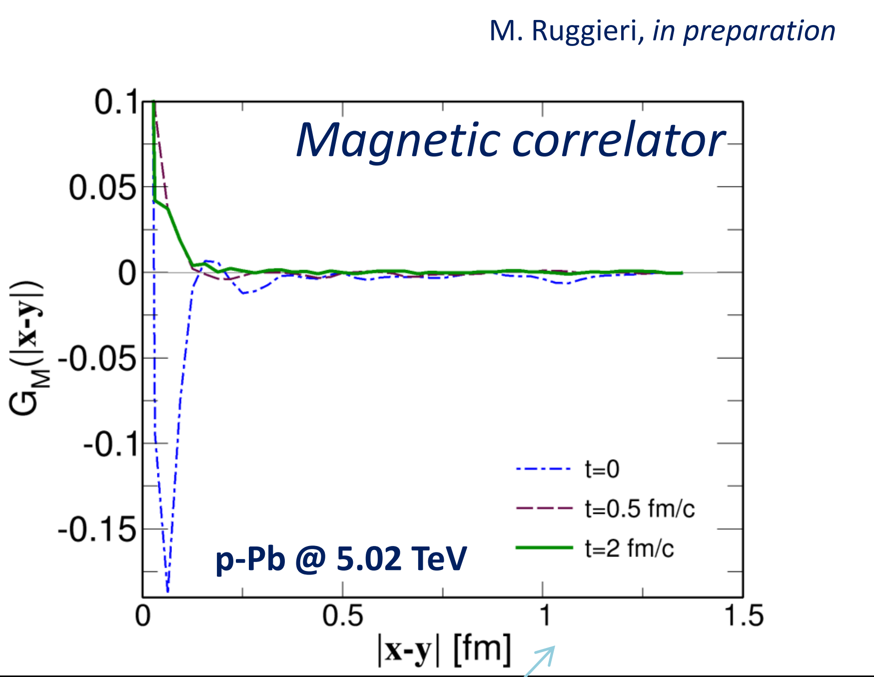


Bulk structure of fields formed within t≈0.1 fm/c:

energy is stored both in transverse and longitudinal fields.

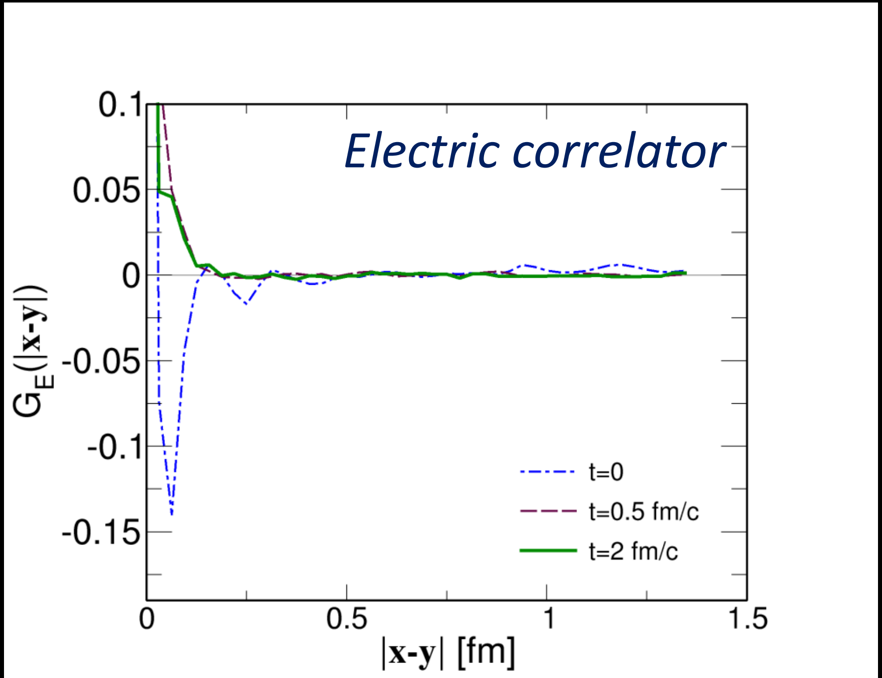






Initial time:

Anticorrelation

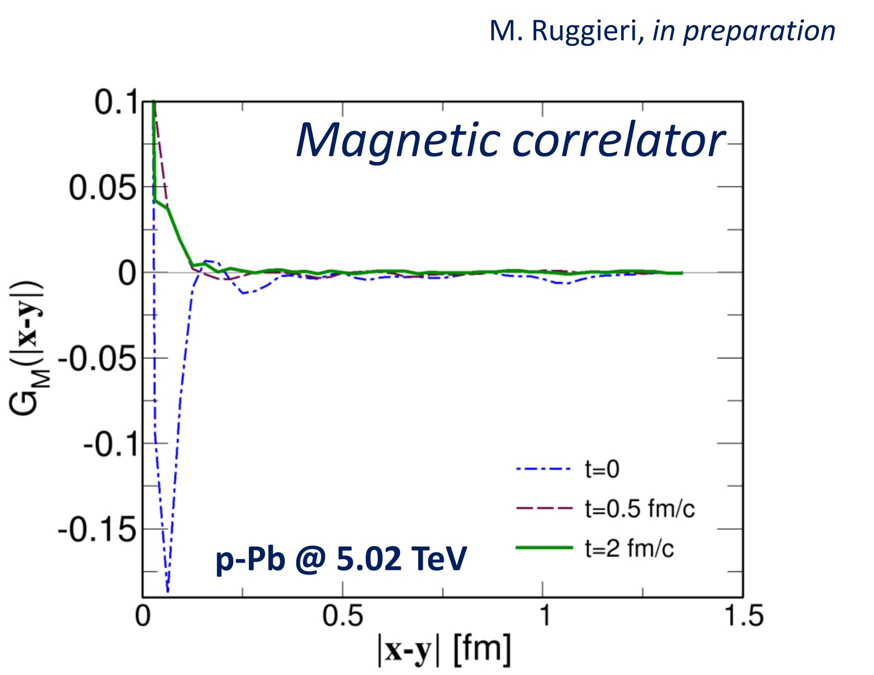


t ≈ 0.5 fm/c:

Correlation length ≈ 0.2 fm

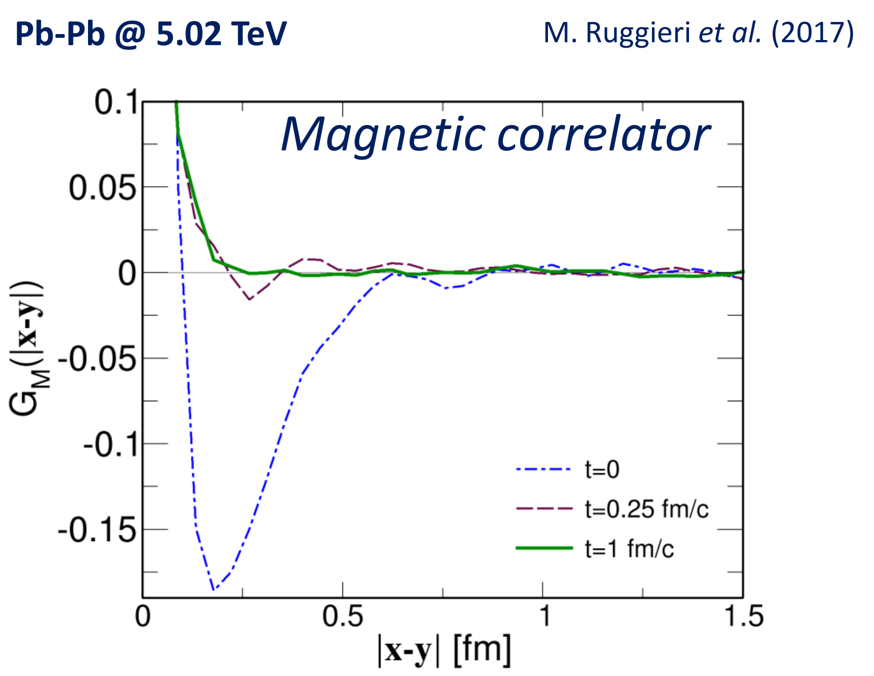
Correlation domains

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.

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

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

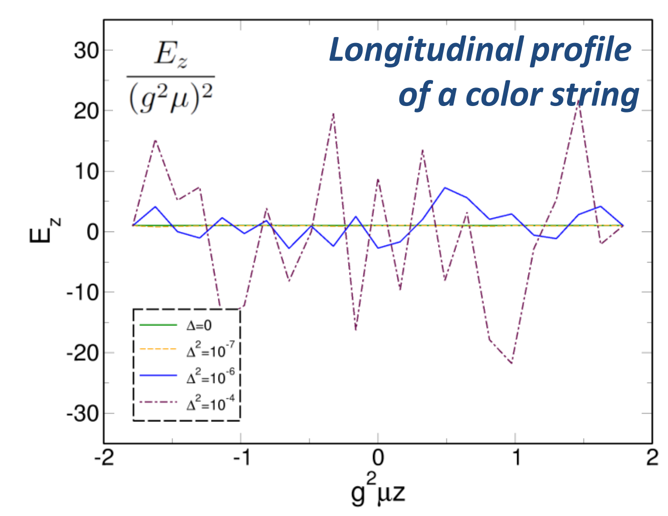
No correlation in:

- *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:

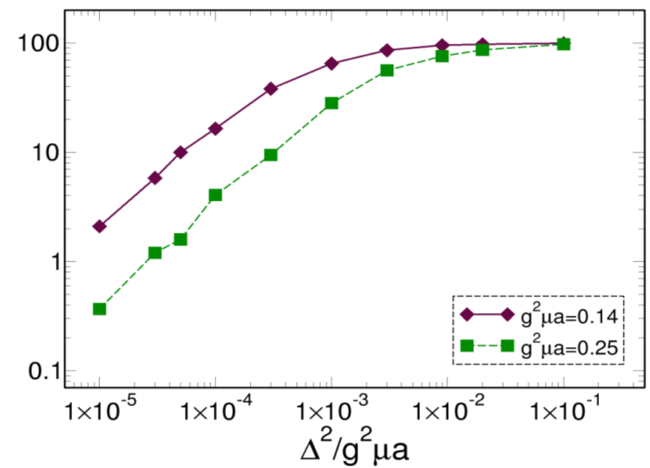
- *Transverse plane*
- *Longitudinal direction*

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

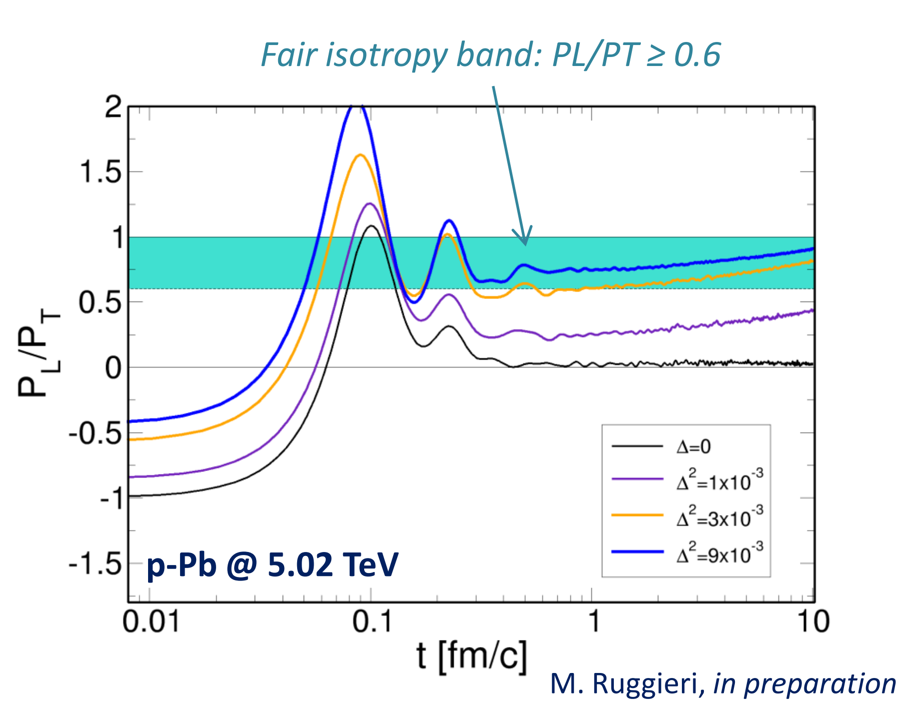
$$\delta E_i^a(\boldsymbol{x}_T, z) = \partial_z F(z)\xi_i^a(\boldsymbol{x}_T),$$
$$\delta E_z^a(\boldsymbol{x}_T, z) = -F(z)D_i\xi_i^a(\boldsymbol{x}_T).$$

$$\Delta \sim g$$

% of energy carried by fluctuations



The evolving Glasma: pressures



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

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

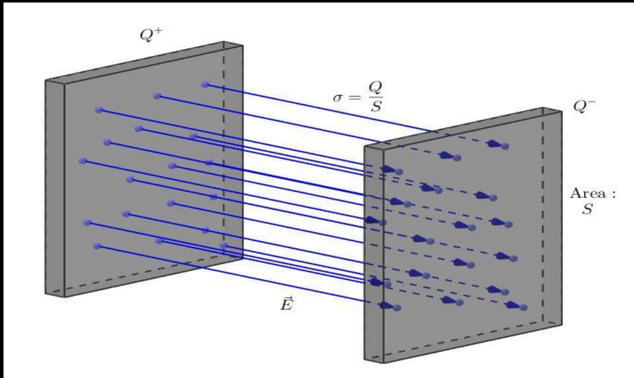
Romatschke and Venugopalan (2006)
Berges (2012)
Epelbaum and Gelis (2012)
Fukushima (2014)
M. R. *et al.* (2017)

<u>Negative pressure</u>

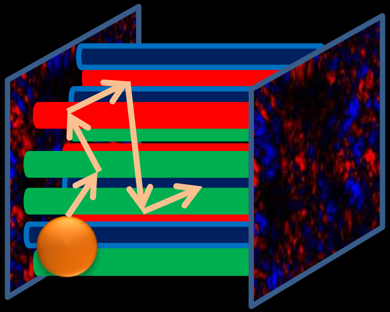
Attraction among the two nuclei.

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.*



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:

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

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

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

Wong (1979)

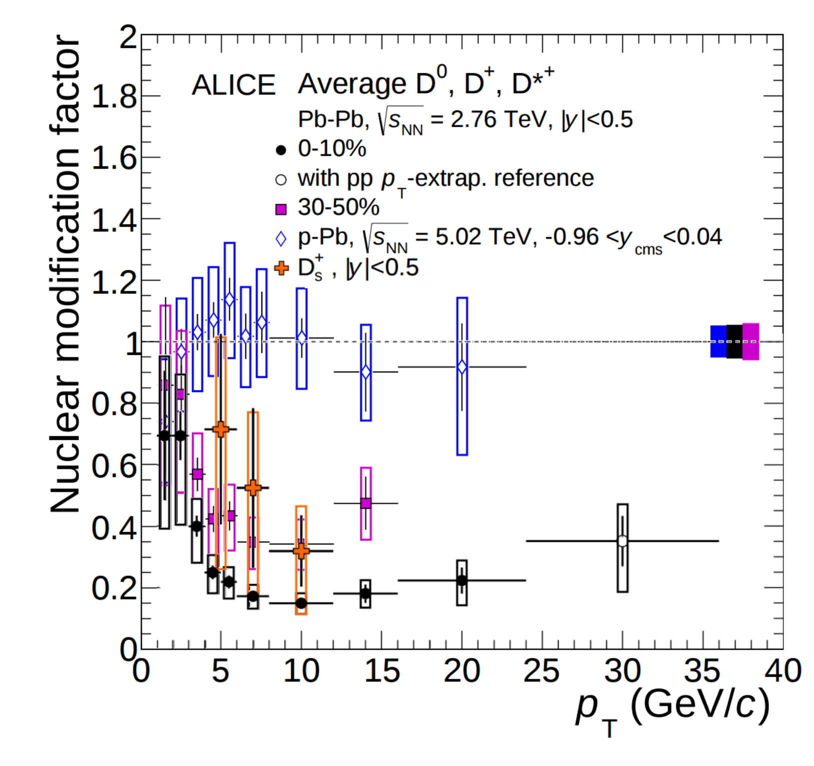
$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$$ *(Relativistic) Velocity*

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

$$D_\mu J^\mu_a = 0$$ *Gauge-invariant conservation of the color current carried by charm quaks + gluons*

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

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

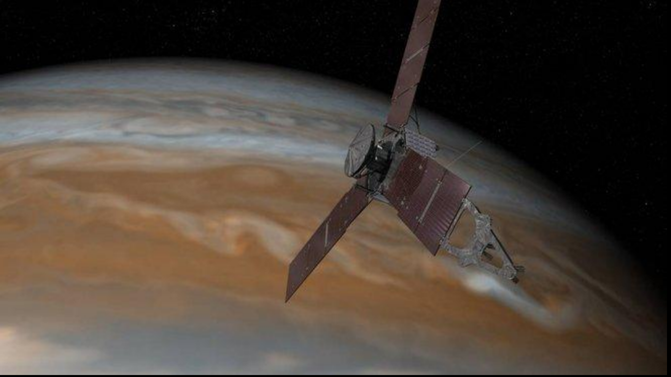


Measured R_{pPb} suggest that a hot QGP might not form in p-Pb collisions

<u>Assumption</u>

Bulk consists of gluons from the evolving Glasma.

This assumption will be relaxed in a forthcoming study.



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

Heavy quarks are:
- Quite massive
- Quite diluted

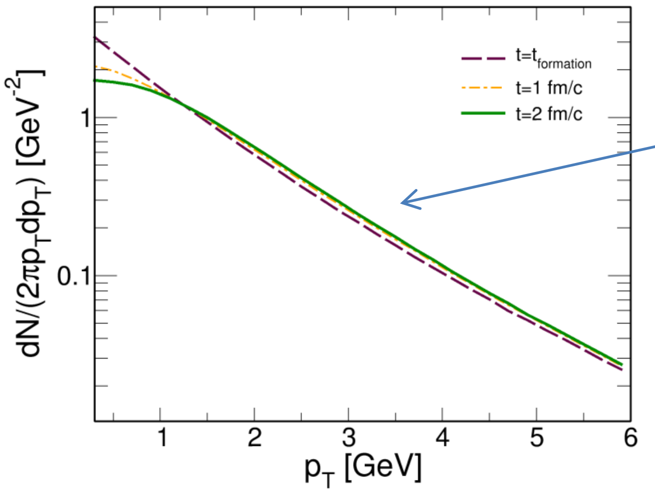
- *Carry negligible color current*
- *Self-interactions occure rarely*

≈No disturbance to the evolving gluon fields

HQs are real probes of the evolving Glasma

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

p-Pb @ 5.02 TeV



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

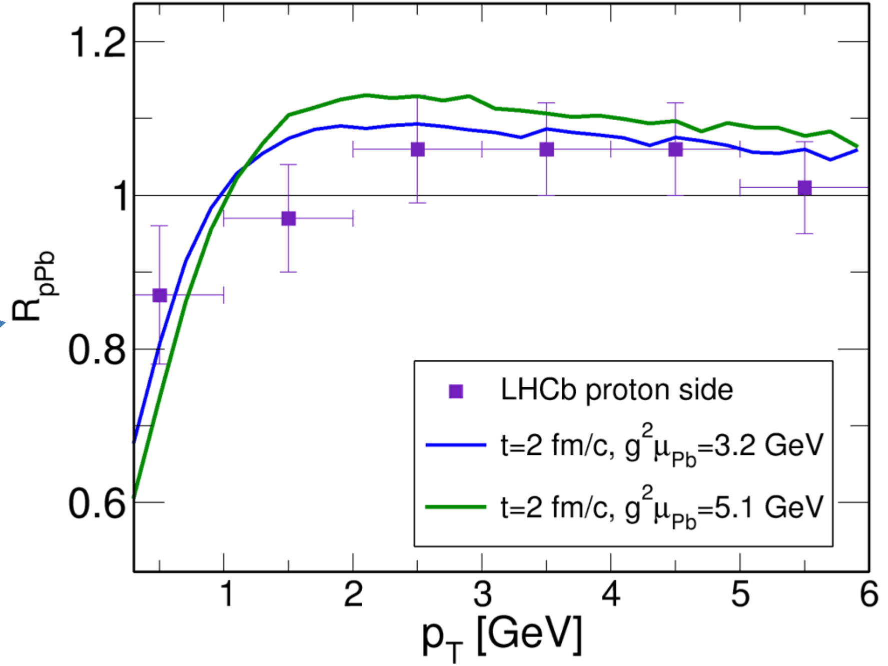
Evolution: interaction with the Glasma

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

D-mesons R_{pPb}

M. Ruggieri and S. K. Das, 1805.09617

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

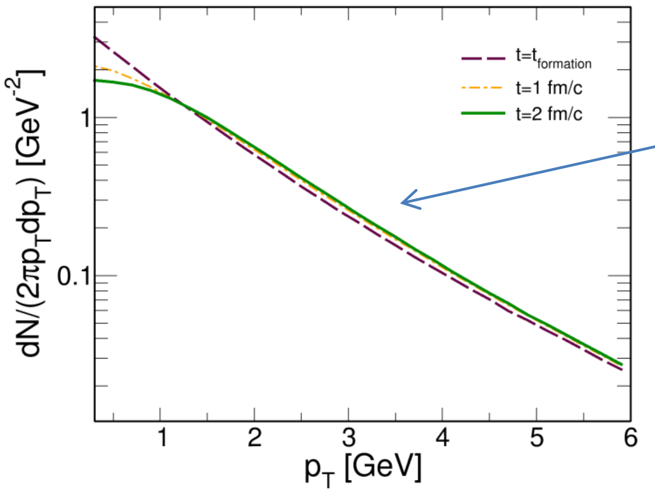


$R_{pPb} \neq 1$

Interaction with the fields created by the collision

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

p-Pb @ 5.02 TeV



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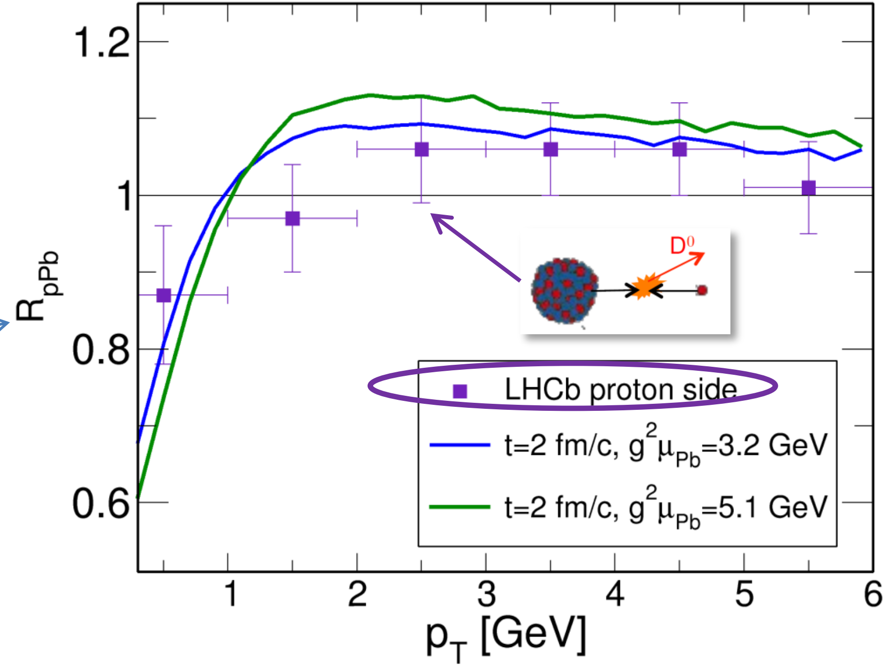
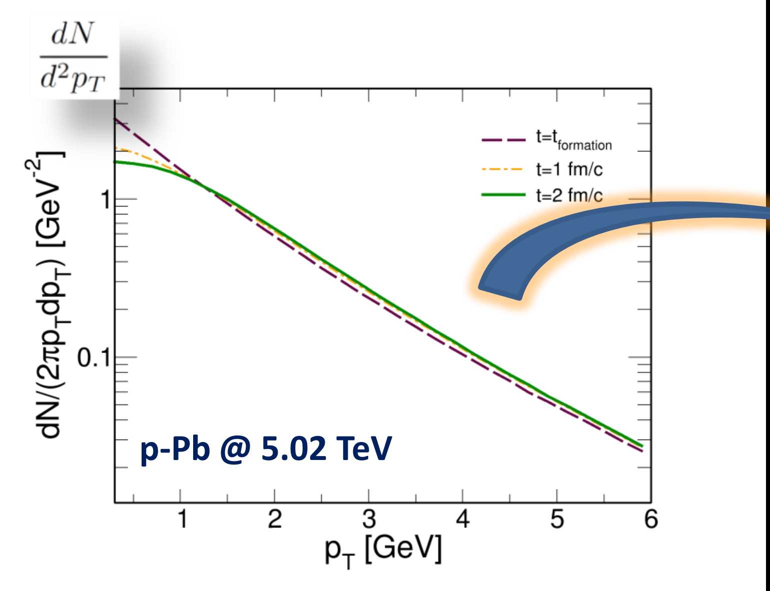


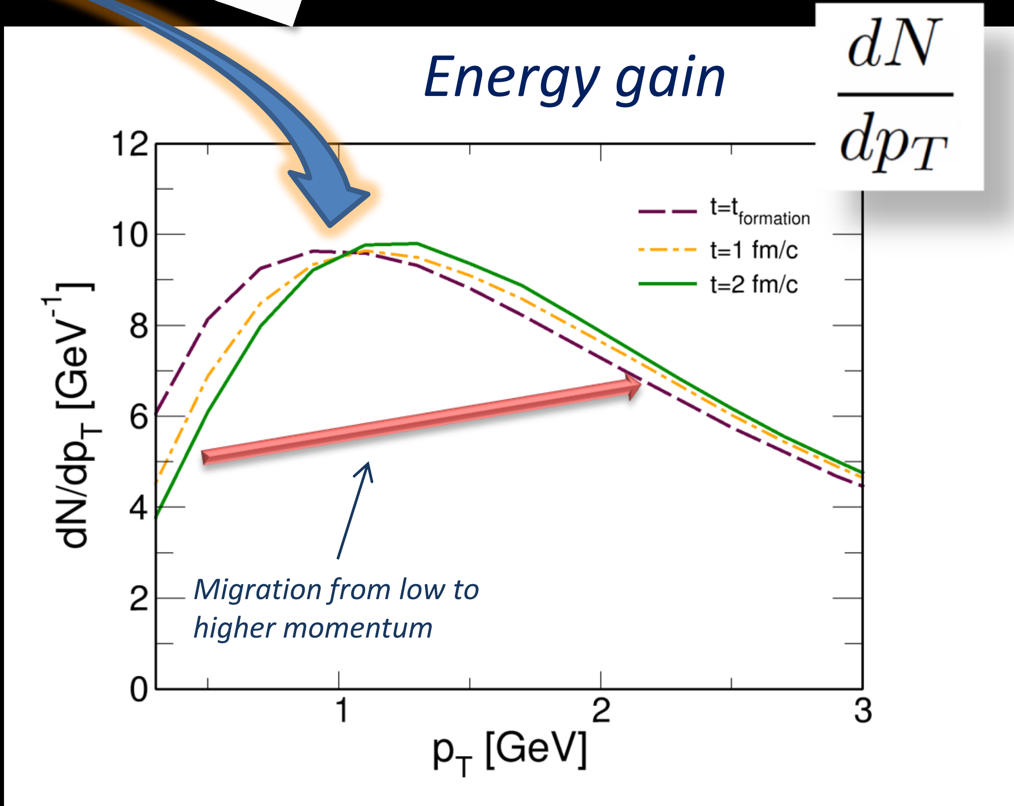
$R_{pPb} \neq 1$

Interaction with the fields created by the collision

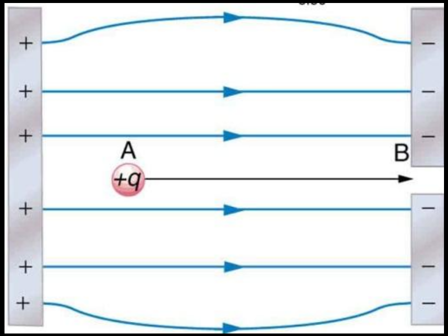
The cathode tube effect



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



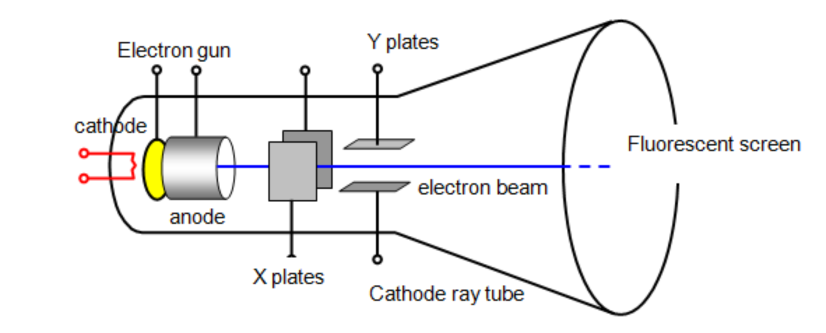
*Heavy quarks are **accelerated** by the (color-)electric field*



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

The **cathode tube** effect

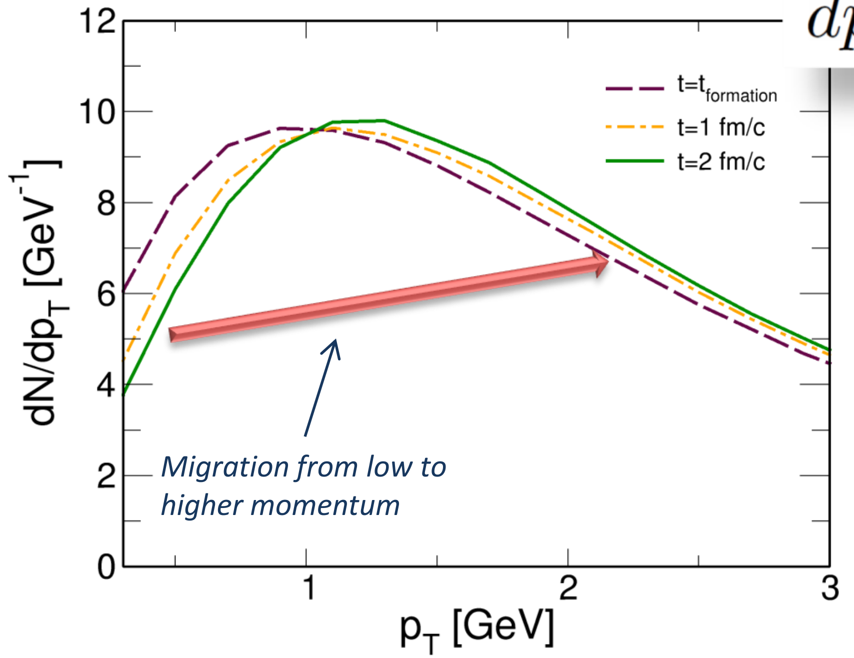
Why cathode tube?



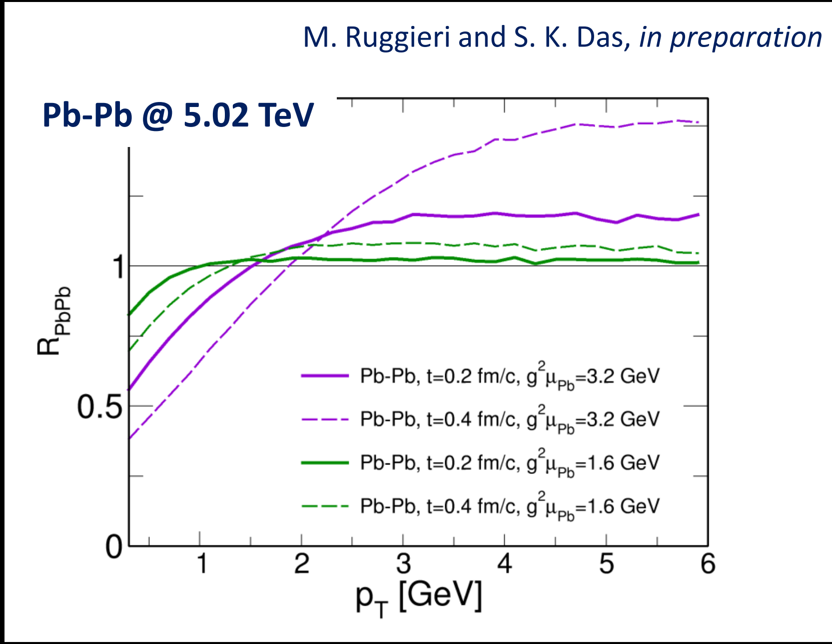
Electrons are produced by the electron gun, then accelerated by the electric field

*Heavy quarks are **accelerated** by the (color-)electric field*

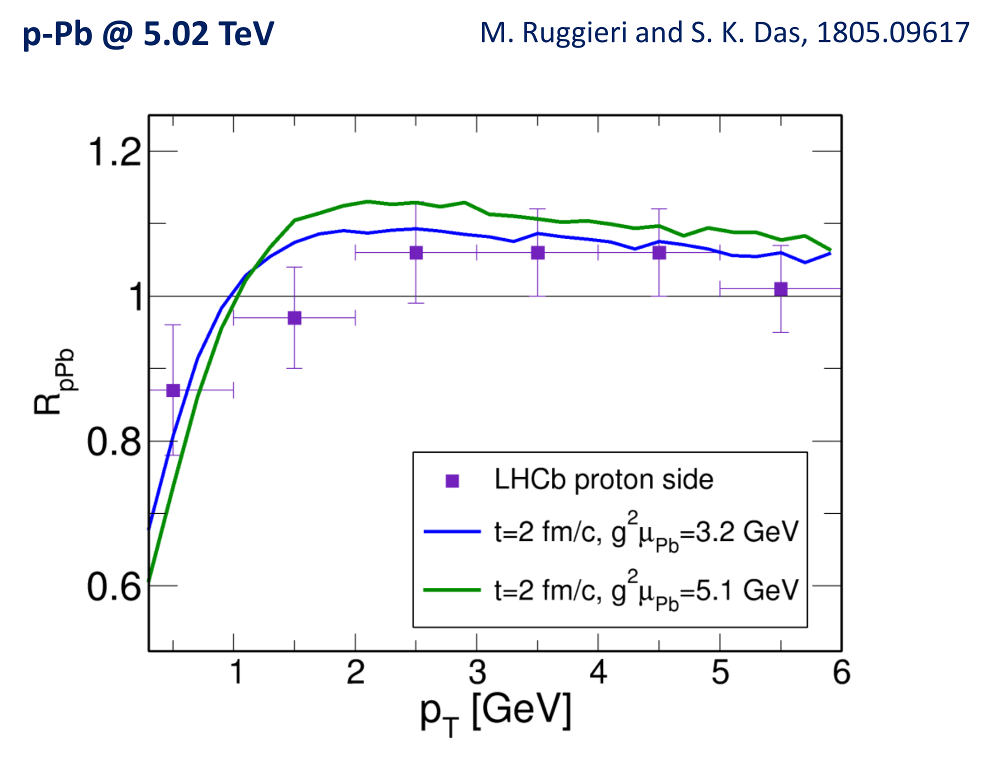
$$\frac{dN}{dp_T}$$

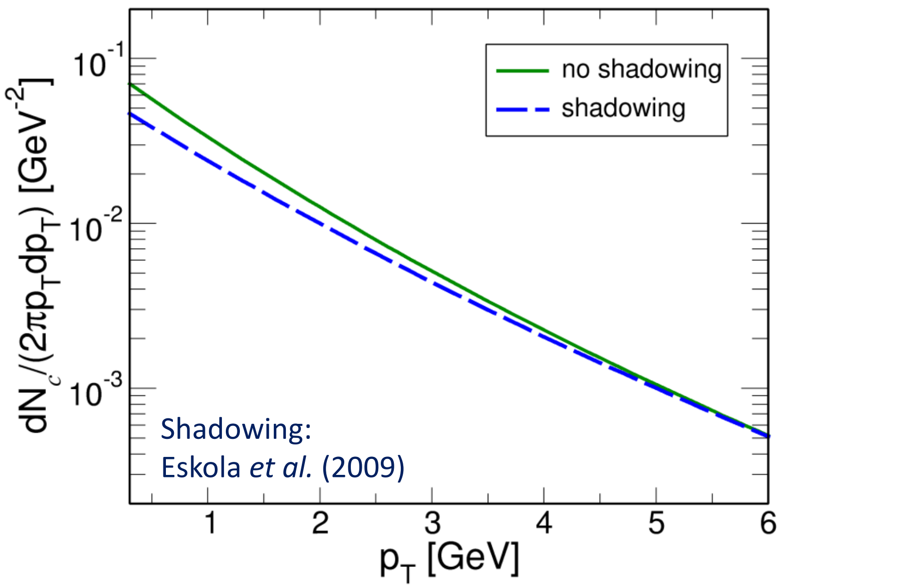


Interaction with Glasma affects the spectrum of c in Pb-Pb



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

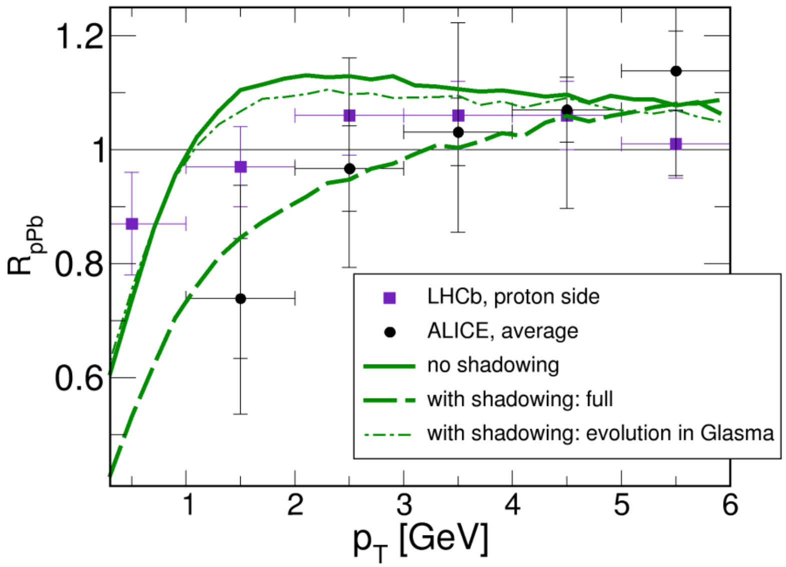




Nuclear shadowing does not affect the cathode tube

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

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



- Proton-Pb (p-Pb) collisions at relativistic energy can be used to study cold matter effects:
  - *Gluon saturation*
  - *Shadowing*

- Borrowing the gluon saturation picture, the evolution of the system after the collision (evolving Glasma) can be probed by heavy quarks observables.

- We have suggested that (at least part of) the measured nuclear modification factor in p-Pb can be understood as the propagation of heavy quarks in the evolving Glasma: ***Cathode Tube Effect.***

Concluding remarks

- What we do not claim:

All the measured R_{pPb} comes from the interaction with Glasma.

- What we do claim:

Interaction with Glasma might give a contribution to the measured R_{pPb}.

- What we do not claim:

All the measured R_{pPb} comes from the interaction with Glasma.

- What we do claim:

Interaction with Glasma might give a contribution to the measured R_{pPb}.

- Cathode Tube Effect: propagation of *c*-quarks in Glasma

The measured R_{pPb} might be a signature of the Glasma itself.

IP-Glasma [Schenke et al. (2014)]

- Successful fit of data
- No smoking gun about Glasma production

Concluding remarks

- What we do not claim:

All the measured R_{pPb} comes from the interaction with Glasma.

- What we do claim:

Interaction with Glasma might give a contribution to the measured R_{pPb}.

- The Cathod Tube Effect results from propagation of *c*-quarks in Glasma:

The measured R_{pPb} might be a signature of the Glasma itself.

- Cathode Tube: *zero-th order effect.*

•It does not depend on the specific distribution of the fields in the transverse plane.
•It is there as soon as gluon dynamics produces transverse chromo-electric fields.
•It depends on the *strength of these fields*, hence on the *saturation scale*.

Outlook

Interaction of heavy quarks with Glasma in p-Pb and Pb-Pb has been only barely studied.

Interesting situation:
many topics can be investigated

In preparation:

- v2-v3-v4 of heavy mesons.
- Multi-particle correlations.
- Charmonium and Bottomonium survival probability in Glasma.

Thank You!