Saturation phenomenology: selected results in p+p, p+A and A+A collisions

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Contents

- Brief introduction to parton saturation

  the Color Glass Condensate (CGC) to
  approximate QCD in the saturation regime

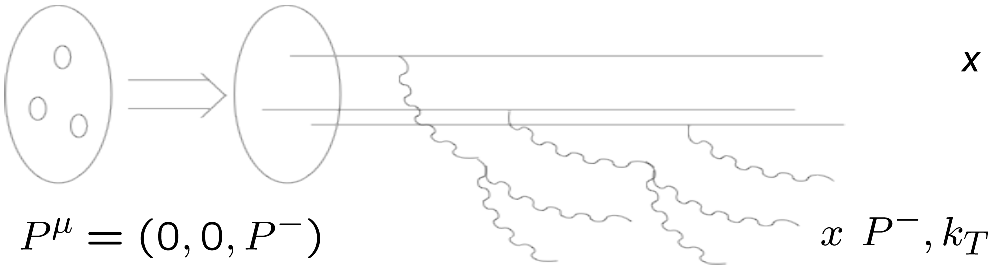
- Particle production in dilute-dense collisions

  forward rapidities in p+p and p+A collisions:
  collisions of a dilute projectile with the CGC

- Particle production in dense-dense collisions

  high-multiplicity p+p and p+A collisions, A+A collisions:
  collisions of two CGCs

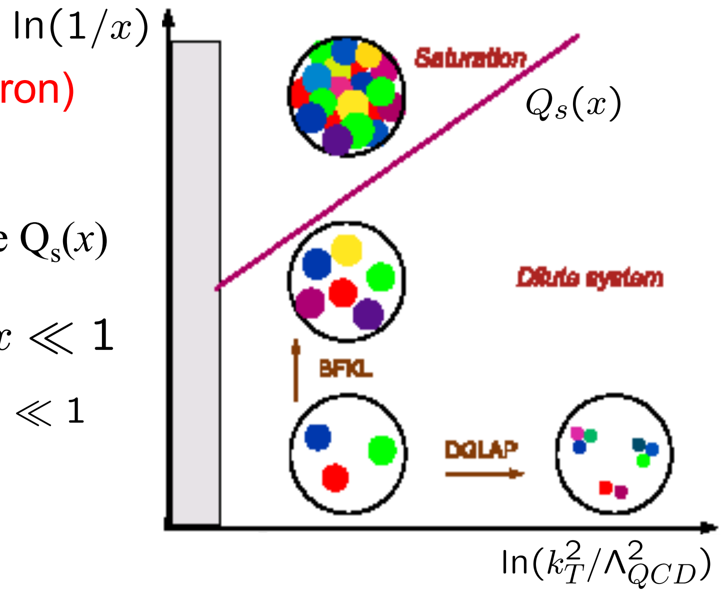
Map of parton evolution in QCD



x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a more dilute hadron)

BFKL evolution to smaller x (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

this regime is non-linear yet weakly coupled: $\alpha_s(Q_s^2) \ll 1$

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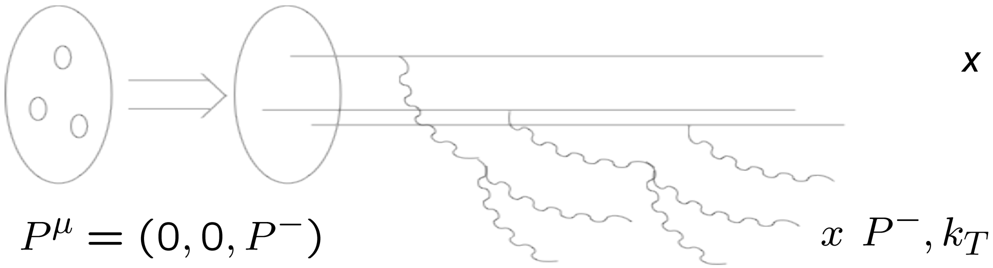

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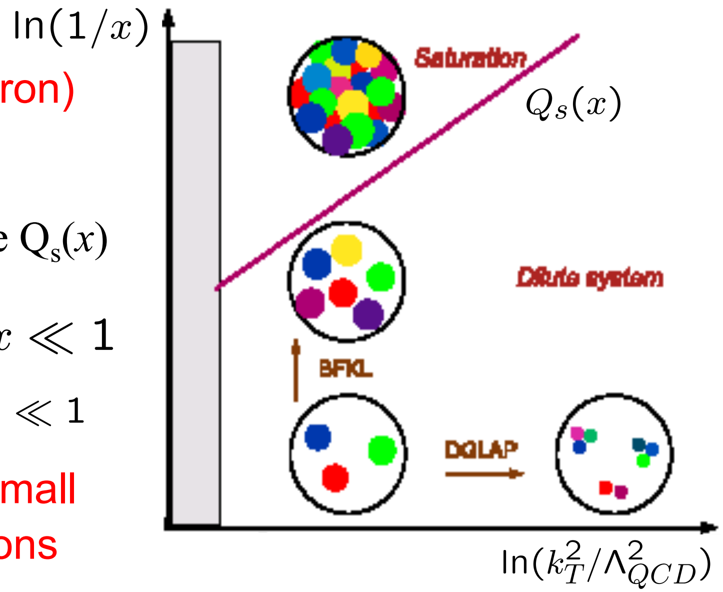

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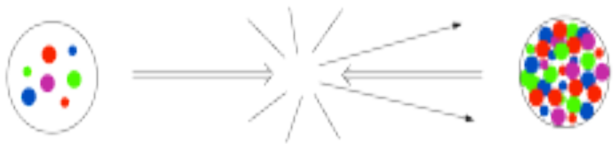
collinear factorization does not apply when *x* is too small and the hadron has become a dense system of partons

$$\sigma_{DIS}(x_{Bj}, Q^2) = \sum_{partons\ a} \int_{x_{Bj}}^{1} dx\ \varphi_{a/p}(x, Q^2)\hat{\sigma}_a(x_{Bj}/x, Q^2) + O\left(Q_0^2/Q^2\right)$$

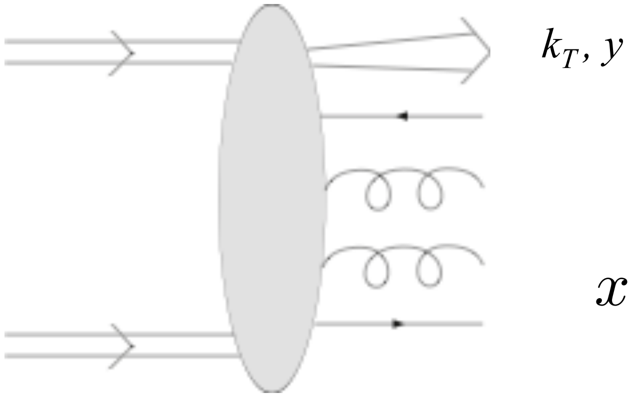
parton density ↓ partonic cross-section ↓ higher twist ↓ → $\dfrac{(A/x)^{1/3}}{Q^2}$

Forward particle production, dilute-dense collisions



Single inclusive hadron production

forward rapidities probe small values of x



transverse momentum k_T, rapidity $y > 0$

values of x probed in the process:

$$x_1 = M_T\ e^{y}/\sqrt{s} \qquad x_2 = M_T\ e^{-y}/\sqrt{s}$$

$$M_T^2 = (k_T/z)^2 + m_h^2$$

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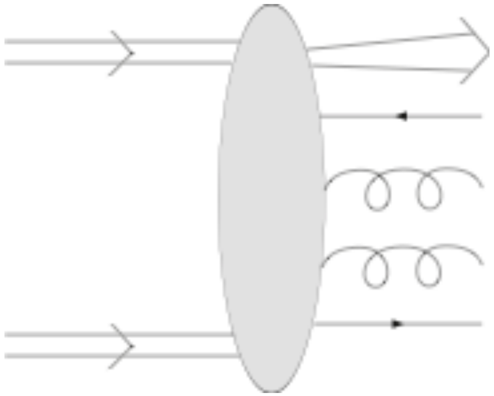

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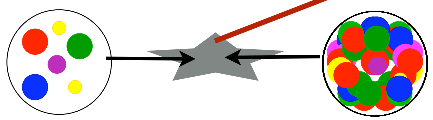

large-x parton from proj. (pdf)

small-x glue from target (CGC)

$$\frac{dN_h}{dy_h \, d^2p_t} = \frac{K}{(2\pi)^2} \sum_q \int_{x_F}^{1} \frac{dz}{z^2} \left[x_1 f_{q/p}(x_1, p_t^2) \, \tilde{N}_F\left(x_2, \frac{p_t}{z}\right) D_{h/q}(z, p_t^2) \right.$$

$$\left. + \, x_1 f_{g/p}(x_1, p_t^2) \, \tilde{N}_A\left(x_2, \frac{p_t}{z}\right) D_{h/g}(z, p_t^2) \right]$$

fragmentation

Nuclear modification factor

$R_{dA} = 1$ in the absence of nuclear effects, i.e. if the gluons in the nucleus interact incoherently as in A protons

$$R_{dA} = \frac{1}{N_{coll}} \frac{\frac{dN^{dA\to hX}}{d^2k dy}}{\frac{dN^{pp\to hX}}{d^2k dy}}$$

the suppressed production (R_{dA} < 1) was predicted in the Color Glass Condensate picture, along with the rapidity dependence

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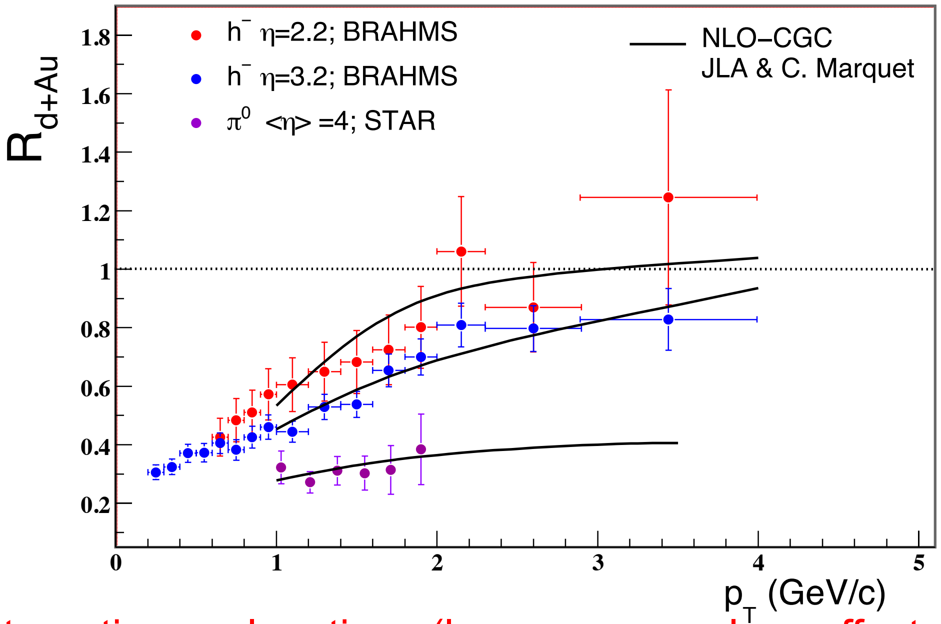


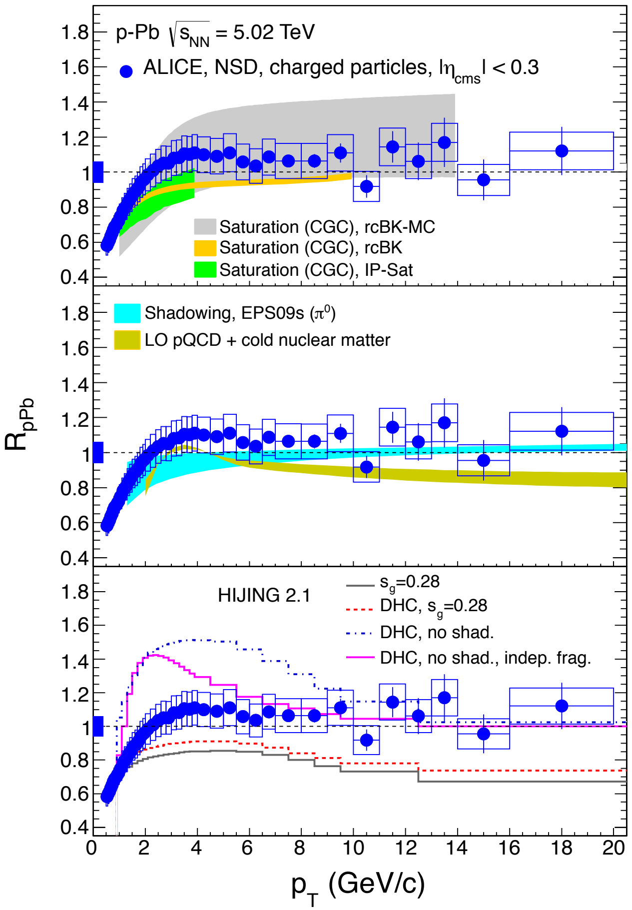
Albacete and CM (2010)

note: alternative explanations (large-x energy loss effects) have been proposed

Kopeliovich et al (2005), Frankfurt et al (2007)

p+Pb @ the LHC

- mid-rapidity data



good description but not
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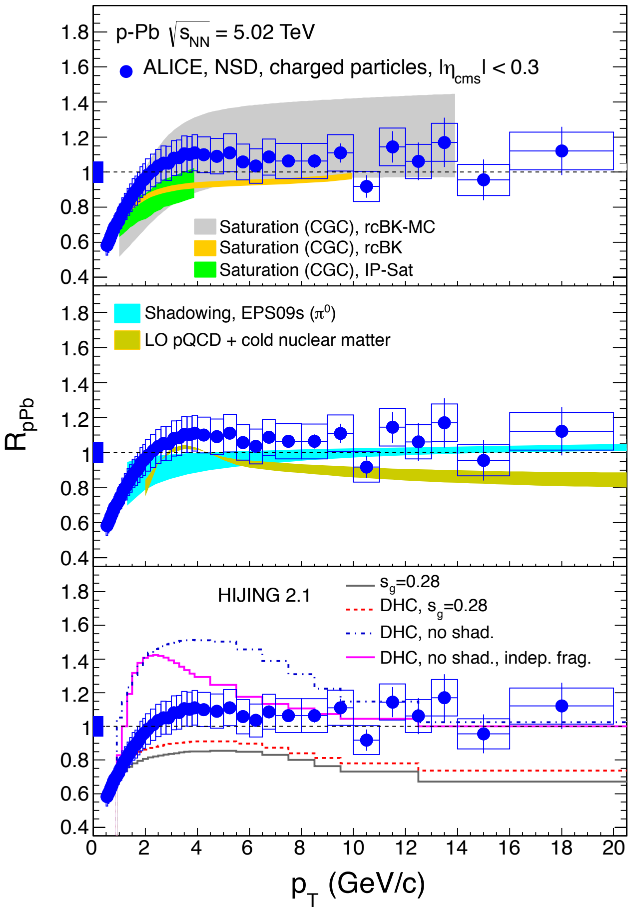

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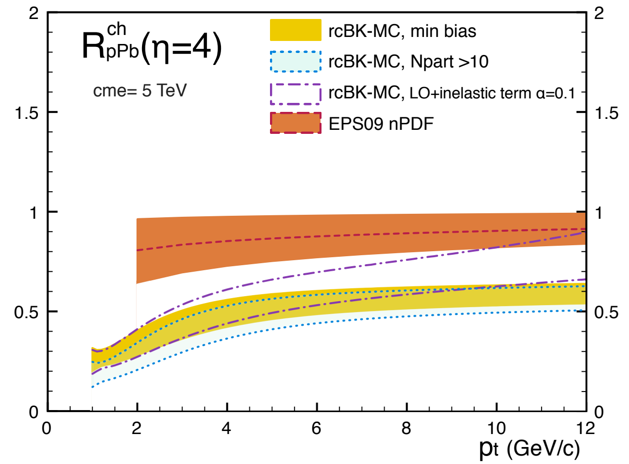
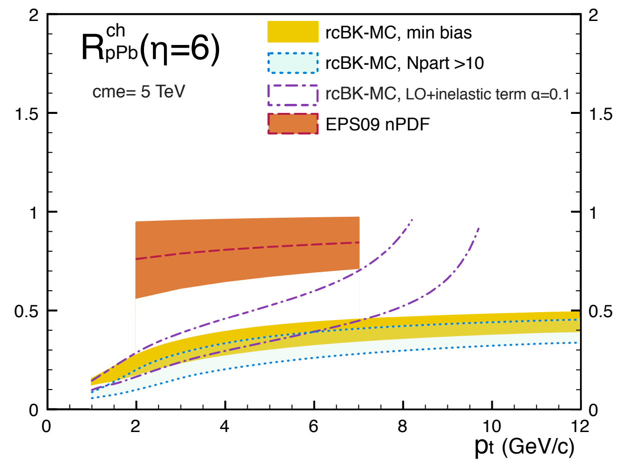
- predictions for forward rapidities





strong non-linear effects

Best way to confirm R_{pA} suppression at the LHC

- isolated photons at forward rapidities

  - no isospin effects in p+Pb vs p+p (contrary to d+Au vs p+p at RHIC)

  - smallest possible x reach: no mass, no fragmentation

  - no cold matter final-state effects (E-loss, …)

  - large EPS09 / CGC difference in forward rapidity predictions

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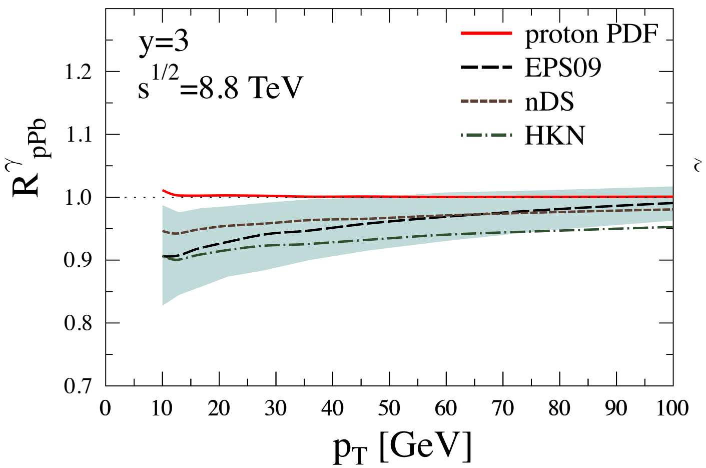
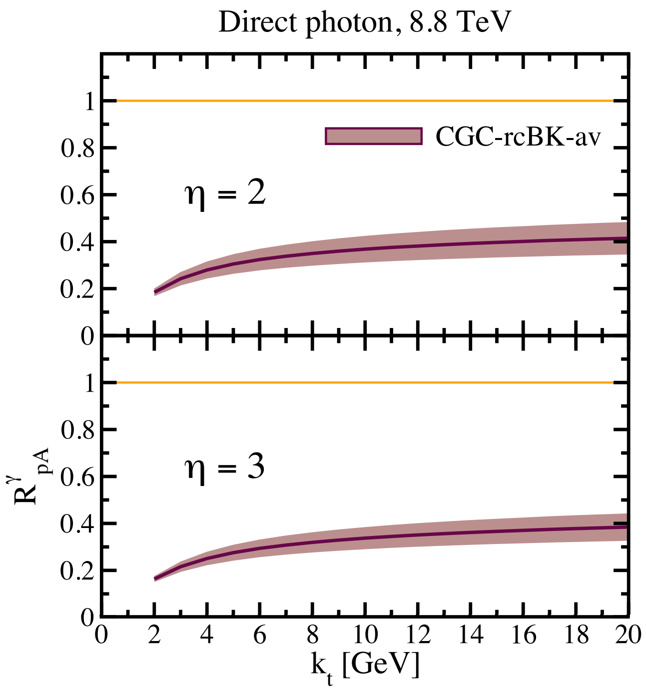


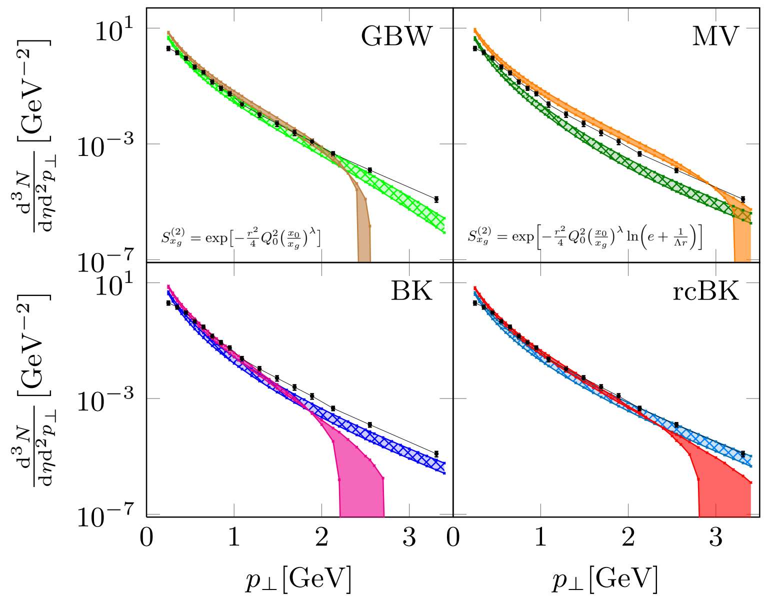
Arleo, Eskola, Paukkunen and Salgado (2011)

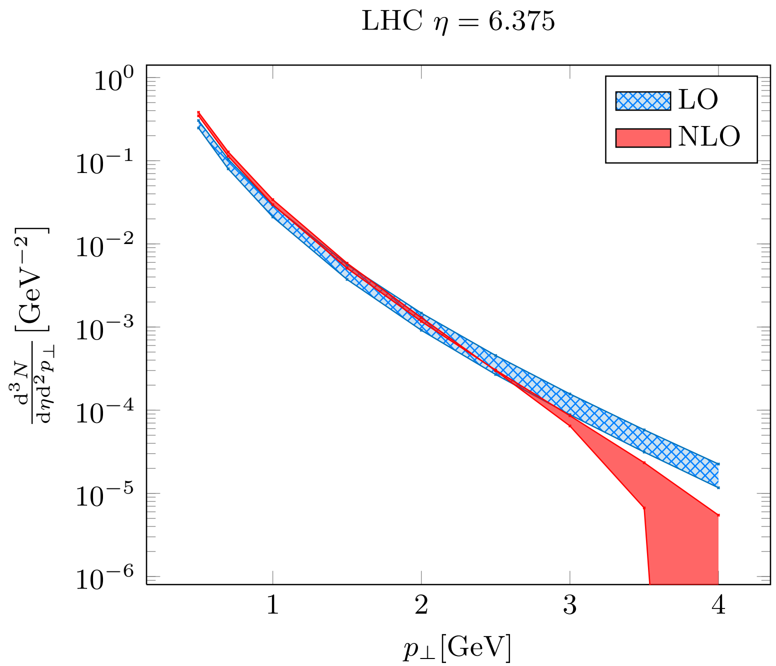


Jalilian-Marian and Rezaeian (2012)

Problem: NLO corrections are not under control at high p_T

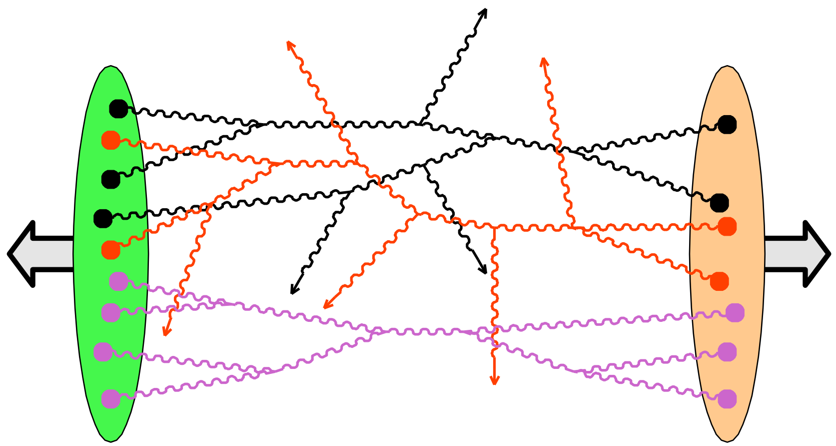
- importance of NLO at high-p_T Altinoluk and Kovner (2011)
- full NLO calculation Chirilli, Xiao and Yuan (2012)
- first numerical results Stasto, Xiao and Zaslavsky (2013)





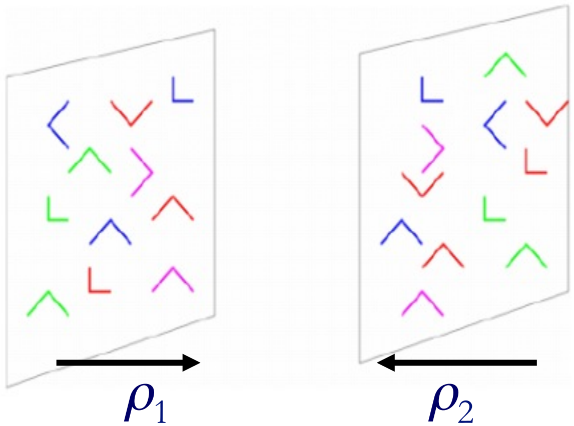
solution : Iancu et al. see next talk

Particle production in dense-dense (CGC on CGC) collisions



Collision of two CGCs

- the initial condition for the time evolution in heavy-ion collisions, and high-multiplicity p+p and p+A



before the collision:

$$J^{\mu} = \delta^{\mu +}\delta(x^-)\rho_1(x_\perp) + \delta^{\mu -}\delta(x^+)\rho_2(x_\perp)$$

$$\rho_1 \sim 1/g \qquad \rho_2 \sim 1/g$$

the distributions of ρ contain the small-x evolution of the nuclear wave functions

$$|\Phi_{x_1}[\rho_1]|^2 \quad |\Phi_{x_2}[\rho_2]|^2$$

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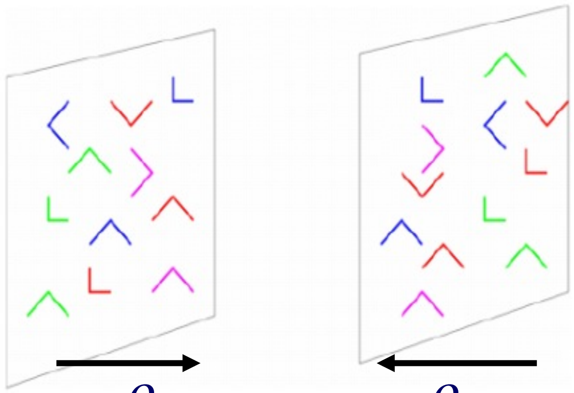

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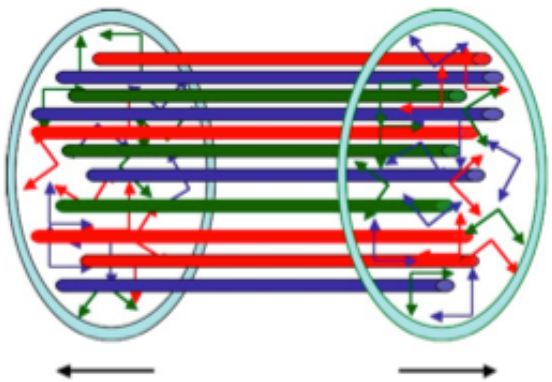
these wave functions are mainly non-perturbative, but their evolution is known



$$\frac{d}{d\ln(1/x)}\left|\Phi_x[\alpha]\right|^2 = H^{JIMWLK} \otimes \left|\Phi_x[\alpha]\right|^2$$

- after the collision: the Glasma phase

the gluon field is a complicated function of the two classical color sources

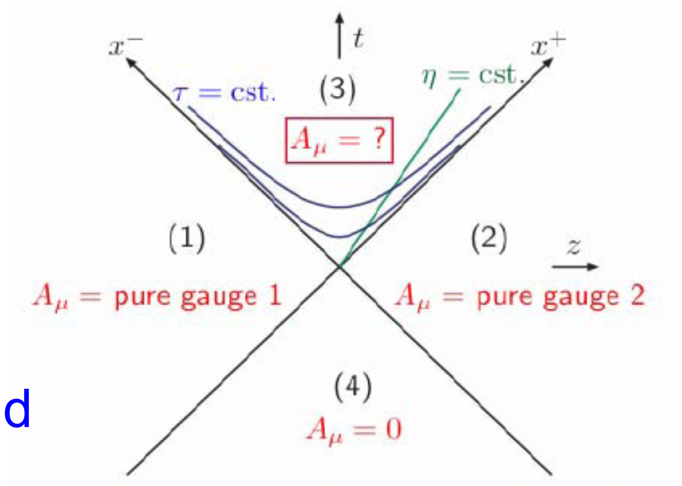
Lappi and McLerran (2006)

Computing observables

- solve Yang-Mills equations

$$[D_\mu, F^{\mu\nu}] = J^\nu \longrightarrow \mathcal{A}_\mu[\rho_1, \rho_2]$$

this is done numerically (it could be done analytically in the p+A case)



- express observables in terms of the field

determine $O[\mathcal{A}_\mu]$, in general a non-linear function of the sources

examples on next slide : single- and double-inclusive gluon production

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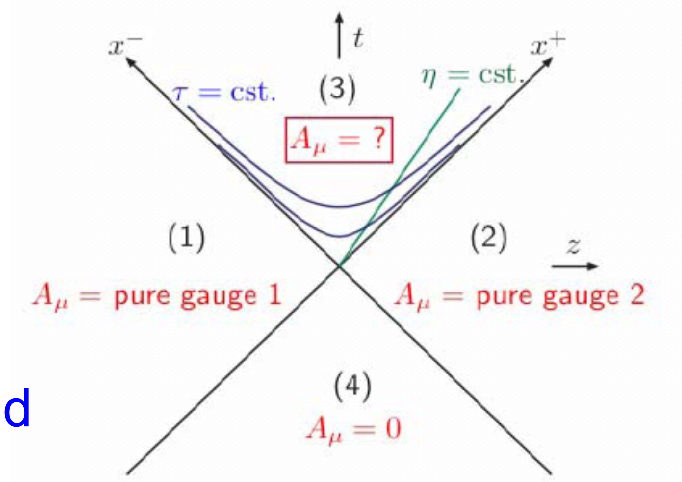

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- perform the CGC averages

$$\langle O \rangle = \int D\rho_1 D\rho_2 |\Phi_{x_1}[\rho_1]|^2 |\Phi_{x_2}[\rho_2]|^2 O[\mathcal{A}_\mu]$$

rapidity factorization proved recently at leading-order for (multi-)gluon production

Gelis, Lappi and Venugopalan (2008)

Gluon production

- two-gluon production

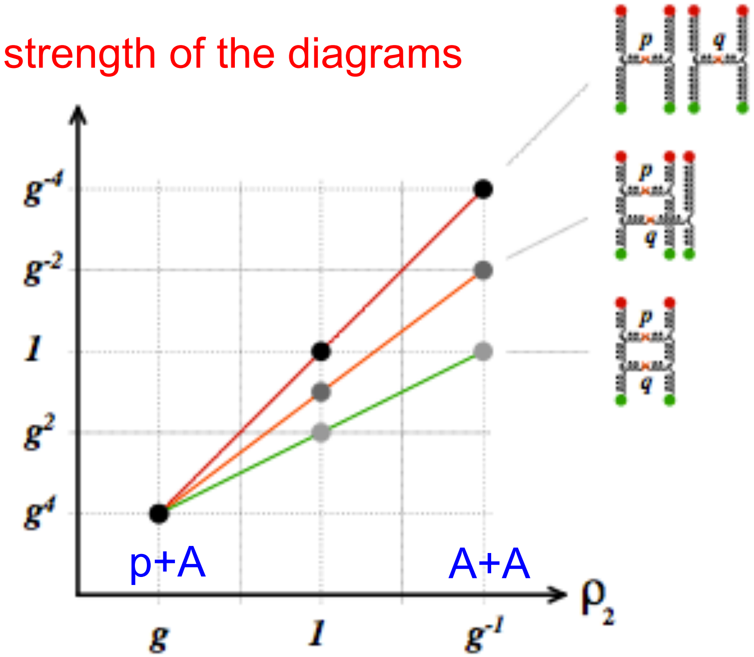
easily obtained from the single-gluon result

$$\frac{dN}{d^3p d^3q}[\mathcal{A}] = \frac{dN}{d^3p}[\mathcal{A}] \times \frac{dN}{d^3q}[\mathcal{A}]$$

Gelis, Lappi and Venugopalan (2008)

the exact implementation of the
small-x evolution is still not achieved

strength of the diagrams



strength of the color charge of the projectile

the target is always dense $\rho_1 \sim 1/g$

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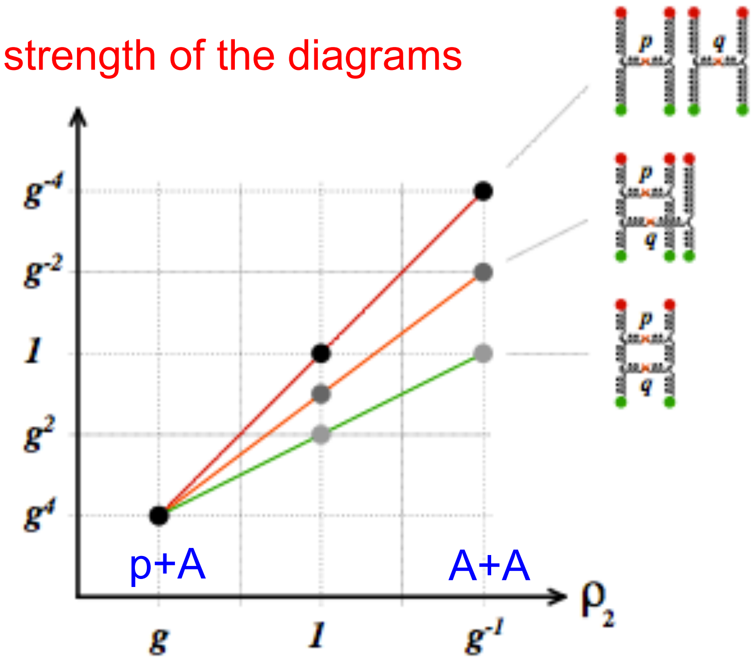

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the target is always dense $\rho_1 \sim 1/g$

- multi-gluon production

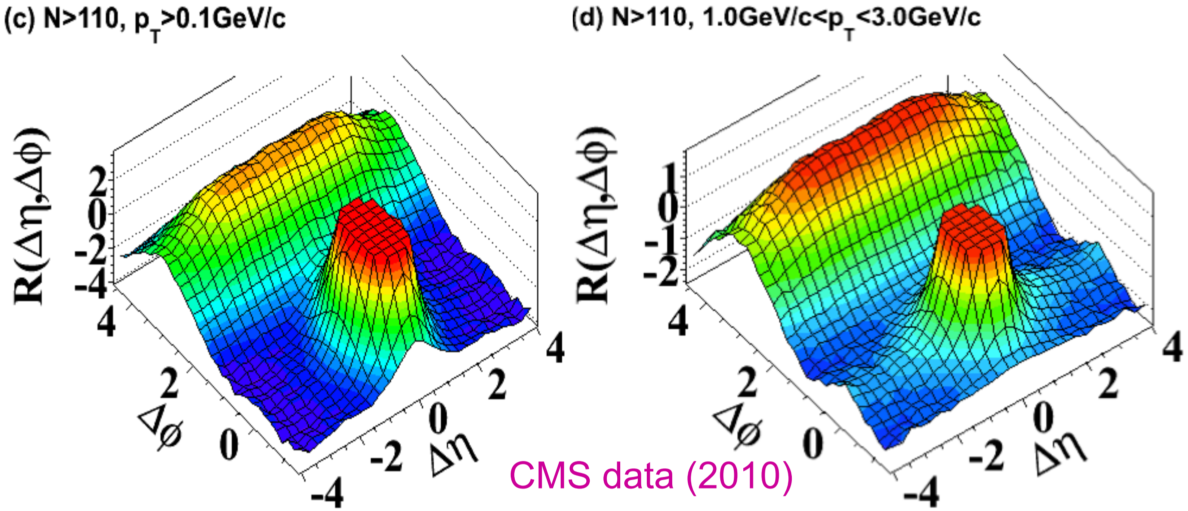
same conclusion: disconnected diagrams dominate multi-gluon production, multi-particle correlations can be calculated!

- however the following phases cannot be ignored

if the system later becomes a perfect fluid, those initial QCD momentum correlations will be washed away

The ridge in p+p collisions

- in the absence of flow, the ridge reflect the actual QCD momentum correlations of the early times, like in p+p collisions:



ridge with p_T ~ Qs

no ridge at low p_T,
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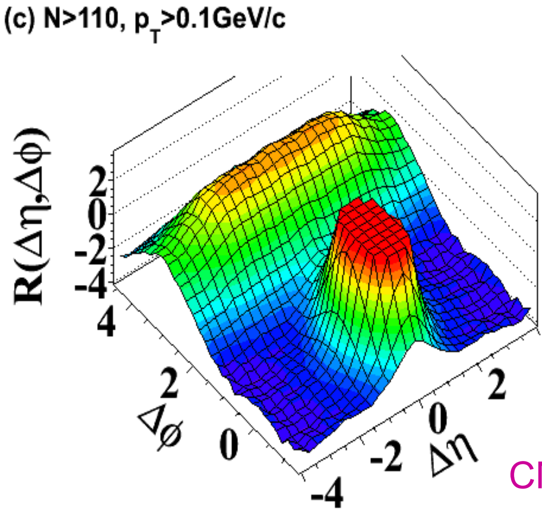

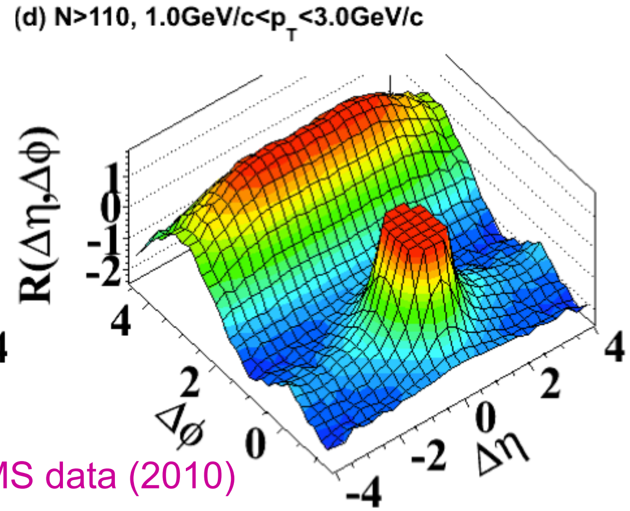

CMS data (2010)

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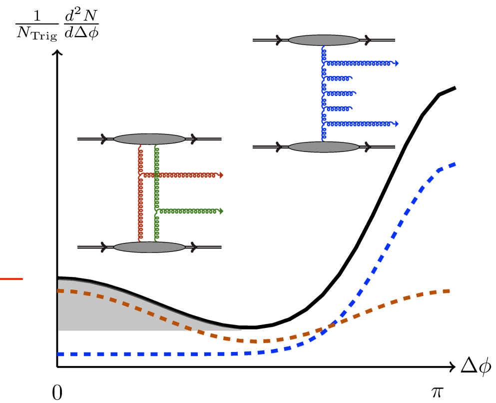
Dumitru, Dusling, Gélis, Jalilian-Marian, Lappi and Venugopalan (2011)



- CGC calculation after Gaussian averaging

additionnal double ridge in the correlation function compared to standard QCD di-jets

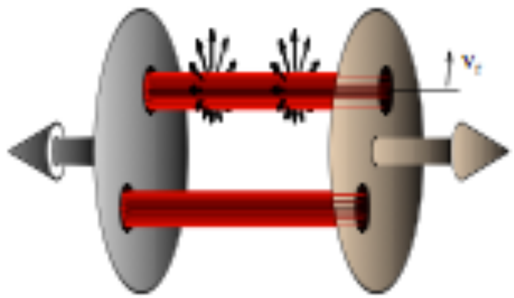
such strucutre exists independently of the assumption

Kovner and Lublinsky (2011)

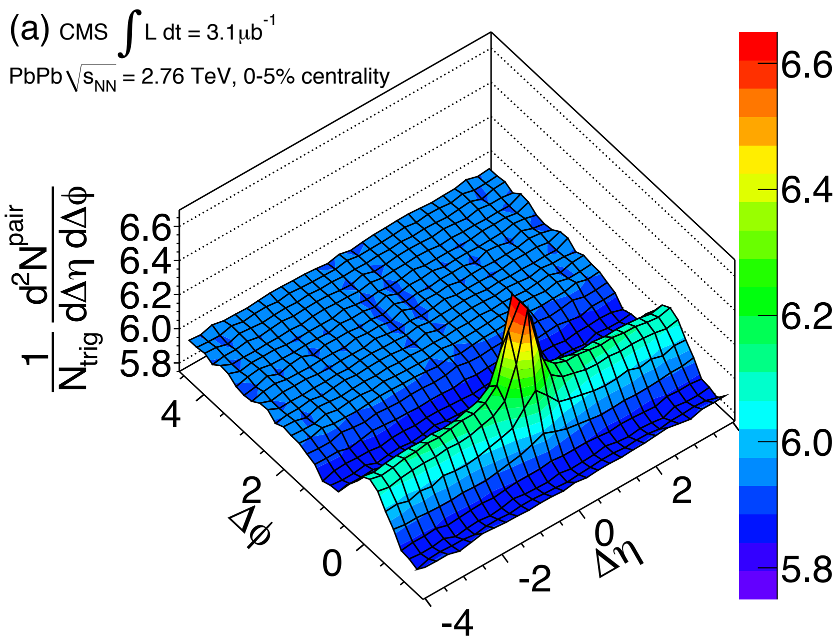
The ridge in A+A collisions

- if in the presence of flow, the initial momentum correlations are lost

instead, those created by the fluid behavior reflect the initial spatial distribution and fluctuations of the QCD matter



example with an initial Glasma field



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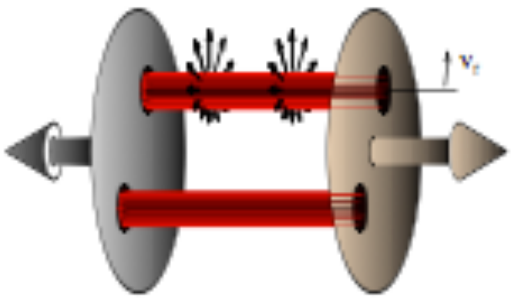

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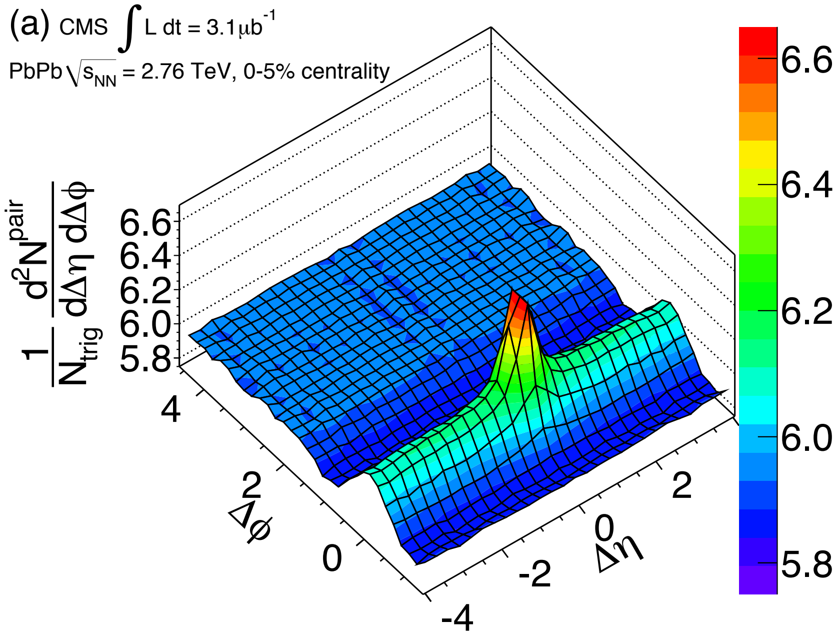


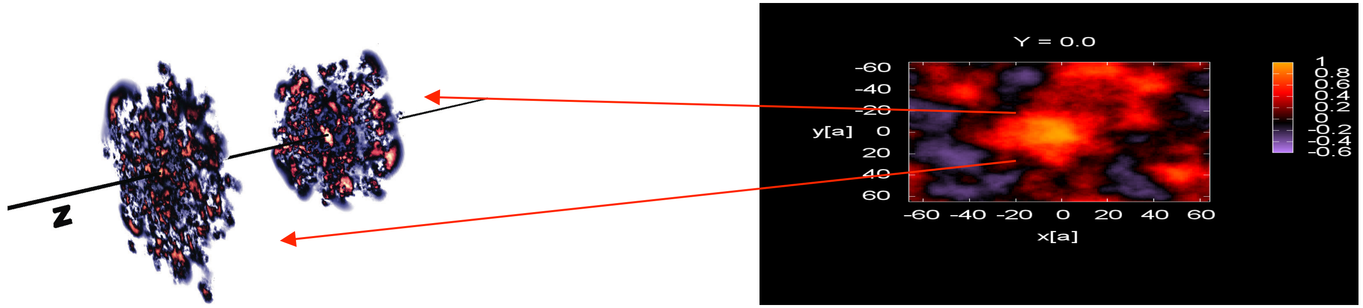
a proper treatment of the nuclear geometry and of it’s fluctuation becomes crucial

- bulk observables in heavy-ion collisions reflect the properties of the initial state as much as those of the hydro evolution of the QGP

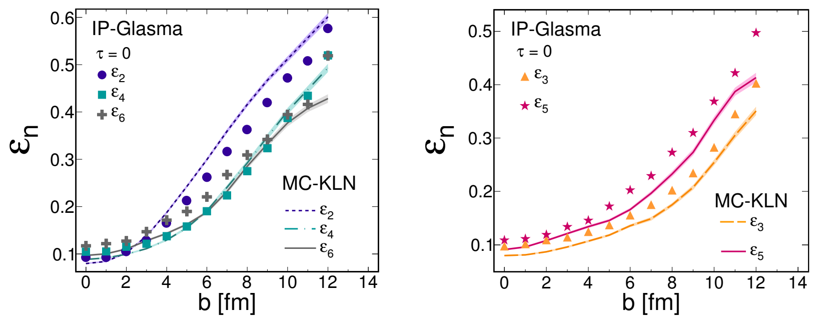
QGP properties cannot be precisely extracted from data without a proper understanding of the initial state

Glasma+hydro approach

- CGC/glasma to describe the pre-hydro spatial fluctuations



eccentricity harmonics



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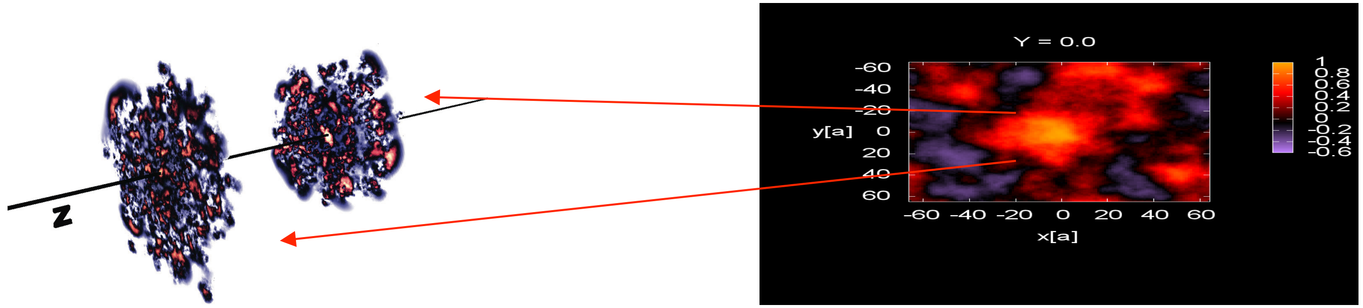

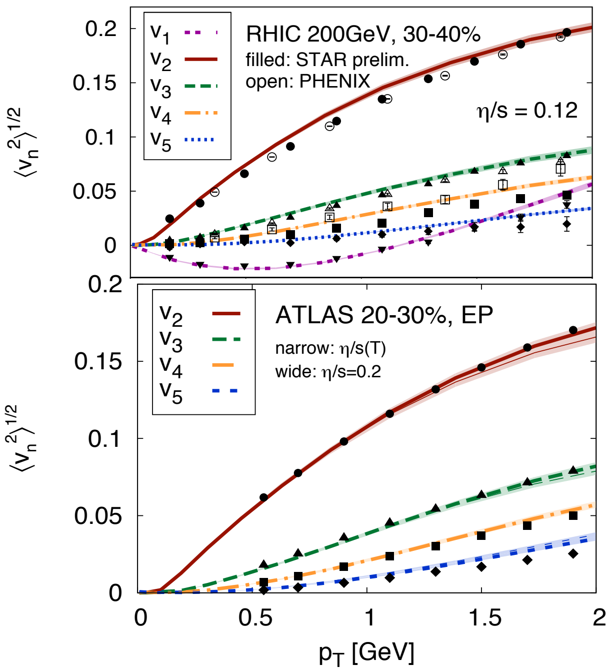

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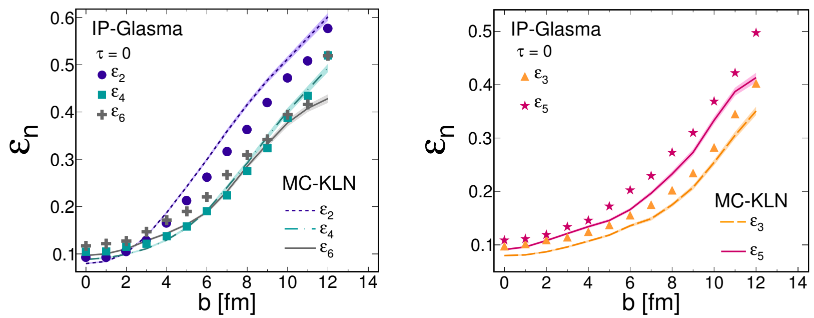
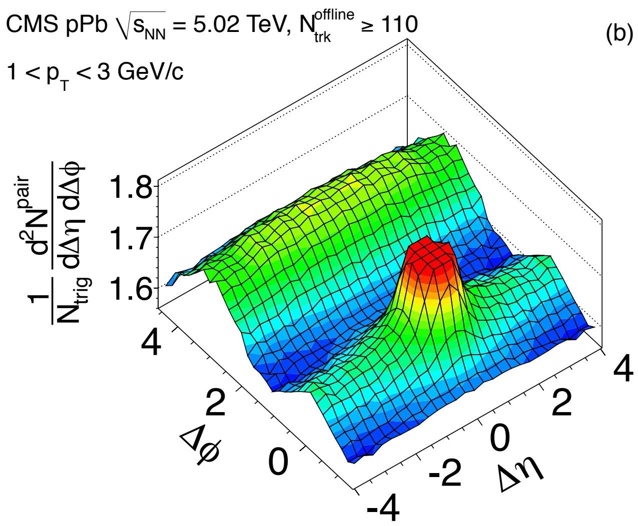


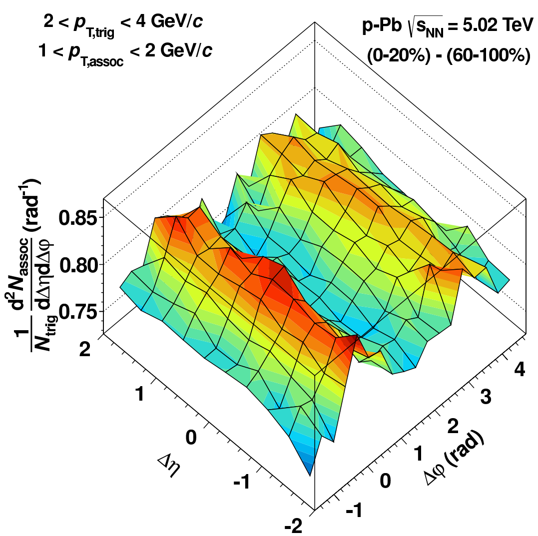
Gale, Jeon, Schenke, Tribedy and Venugopalan (2013)

- in A+A, Glauber does a good job as well

but still one should aim for a QCD-based description

The ridge in p+A collisions





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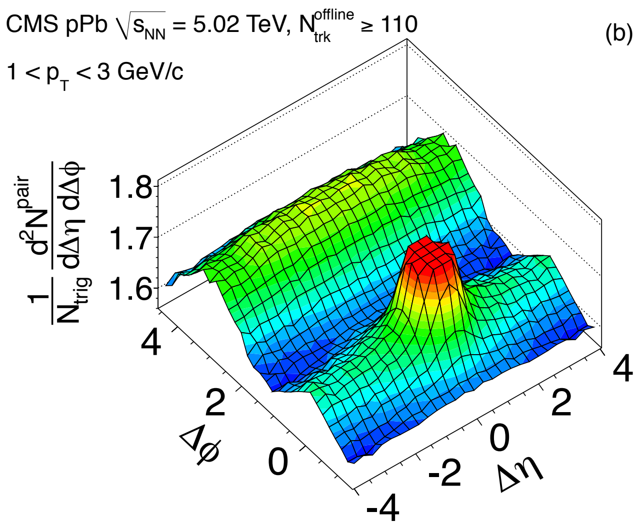
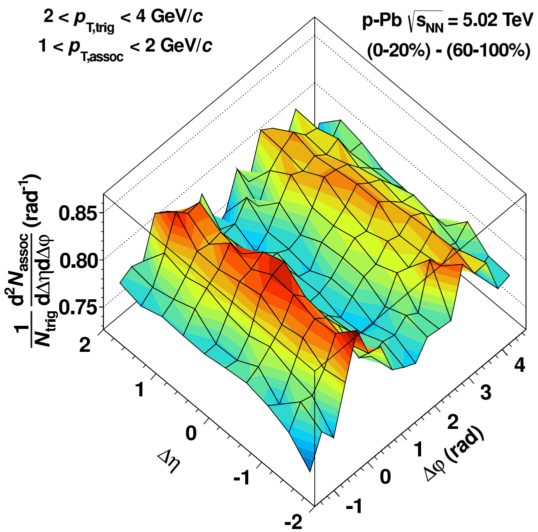




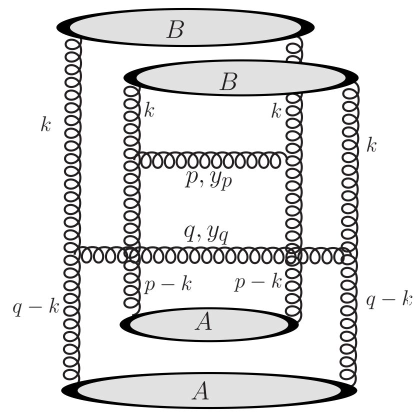


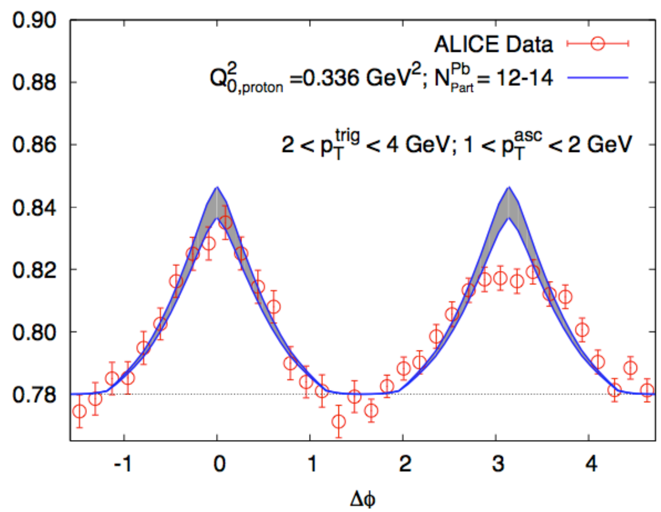
diagram which gives the $\Delta\phi$ dependence

- in the absence of hydro flow

then like in p+p, one sees the QCD momentum correlations

Dusling and Venugopalan (2013)

but the CGC should reproduce also the large higher cumulants – not clear that the glasma phase alone can do that

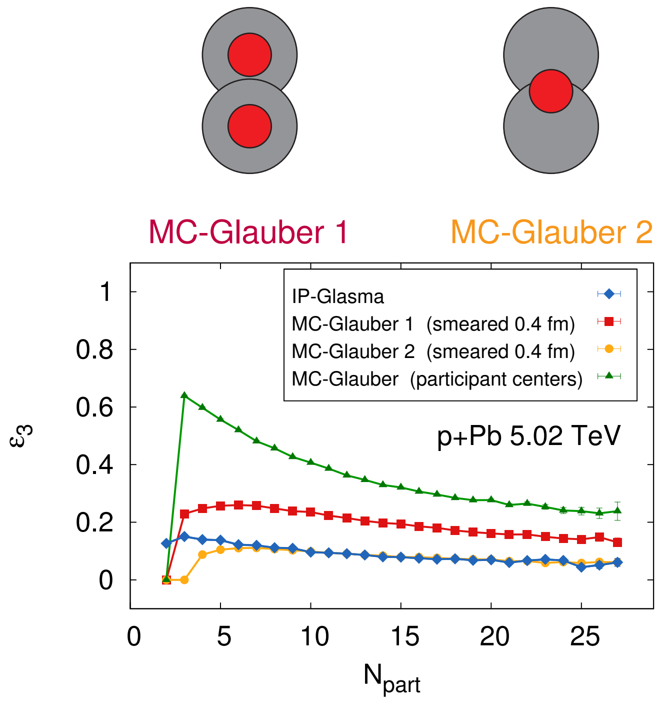


CGC or CGC+hydro ?

the question is not CGC or hydro, the question is CGC only, or CGC+hydro ?

- in the presence of the flow

one still needs to describe the nature and dynamics of the pre-hydro fluctuations, and the Glauber model is not enough anymore, QCD cannot be ignored



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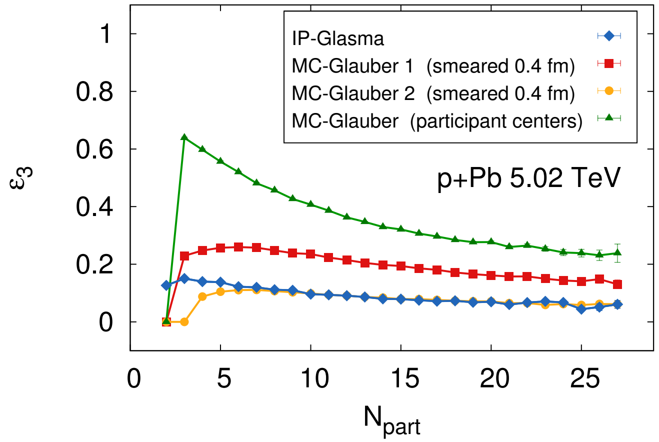
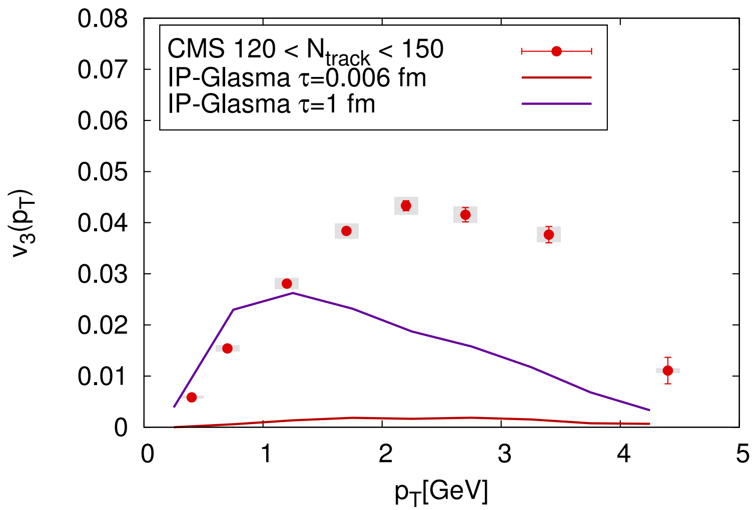
MC-Glauber 1   MC-Glauber 2





Bzdak, Schenke, Tribedy and Venugopalan (2013)

- other options to access the QCD momentum correlations ?

e+A collisions, and maybe p+A in the forward region

Conclusions

- dilute-dense p+p and p+A collisions:

  - single-inclusive: CGC works well but first NLO results raise questions

  - di-hadrons: see last talk today

- dense-dense p+p, p+A and A+A collisions:

  - in the absense of final-state hydro flow, small-x high-density QCD momentum-space correlations are seen, and qualitatively understood

  - in the presence of flow, what is relevant is the initial spatial distributions, and the CGC picture is also necessary and successful

  - if flow in p+A at LHC, e+A collisions become the only way to directly probe the nuclear gluon distribution