Multi-particle production and correlations

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- Particle production in dense-dense collisions

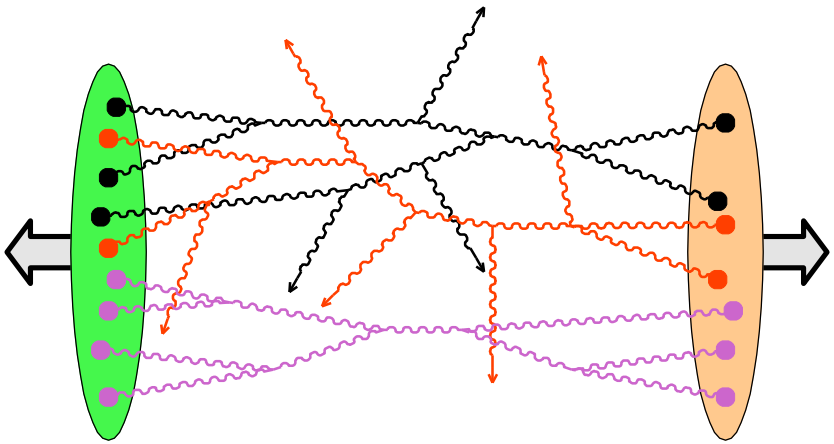
  CGC on CGC applied to A+A, high-multiplicity p+p and p+A

- Particle production in dilute-dense collisions

  dilute projectile on CGC, applied to forward rapidities in p+p and p+A

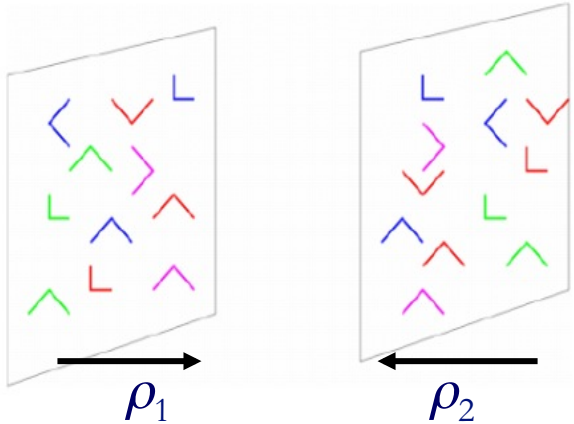
- Note: many results of this review have been or will be presented by the authors at this conference

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

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

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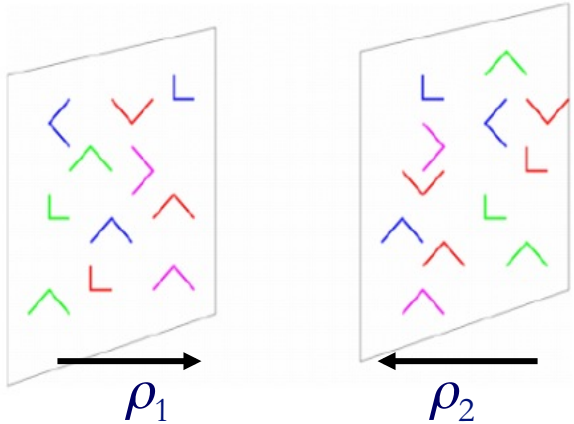

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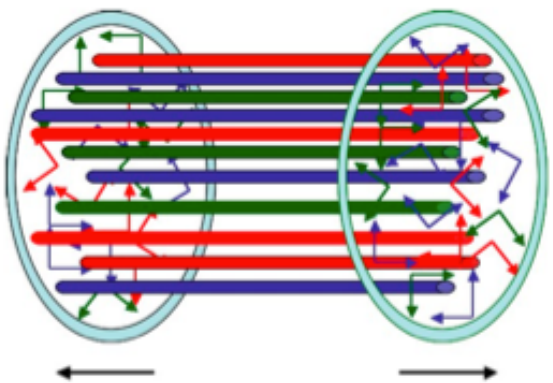
these wave functions are mainly non-perturbative, but their evolution is known

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



- after the collision: the Glasma phase

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

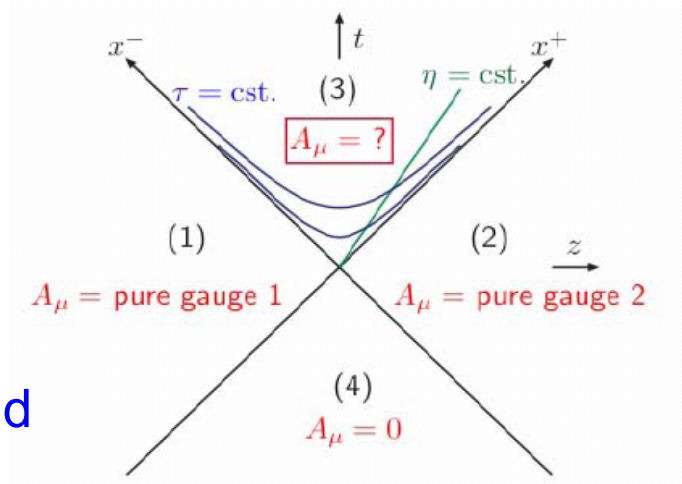
Lappi and McLerran (2006)

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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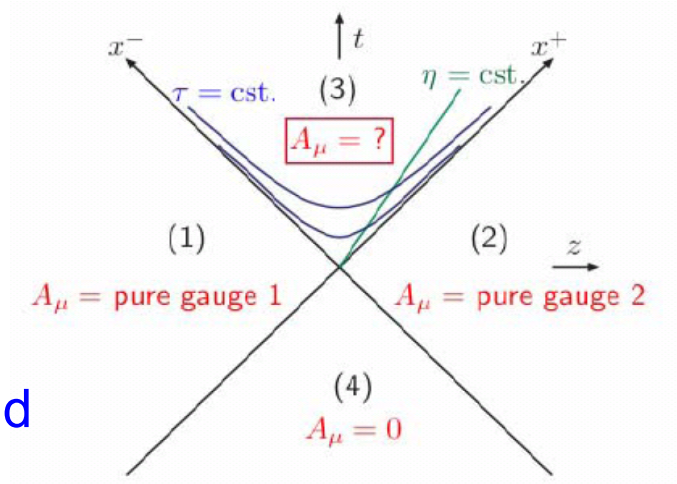

- express observables in terms of the field

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

- 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)

Single gluon production

to compute the total multiplicity, ignoring the following phases (QGP, …)

- the cross-section in terms of the field

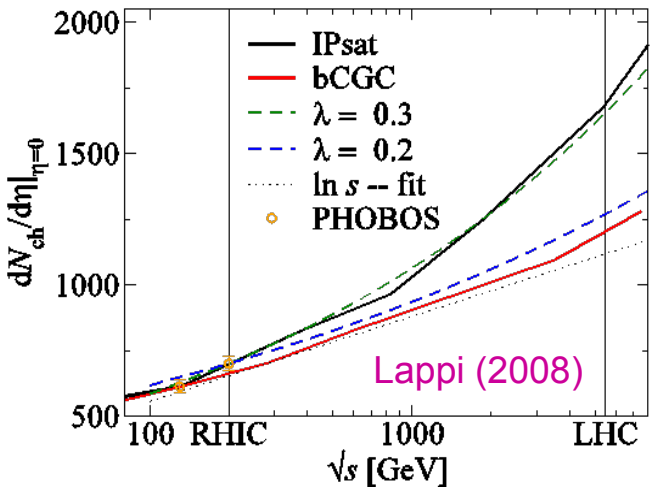
Krasnitz and Venugopalan (1998)

$$\frac{dN}{d^3p}[\mathcal{A}] = \frac{1}{16\pi^3}\int_{x,y} e^{ip.(x-y)} \sum_\lambda \varepsilon^\mu_\lambda \varepsilon^\nu_\lambda A_\mu(x) A_\nu(y)$$

- the evolution of the CGC wave functions

modeled with

$$|\Phi_x[\rho]|^2 = \exp\left(-\int d^2x \frac{\rho_c(\mathbf{x})\rho_c(\mathbf{x})}{2Q_s^2(x)}\right)$$



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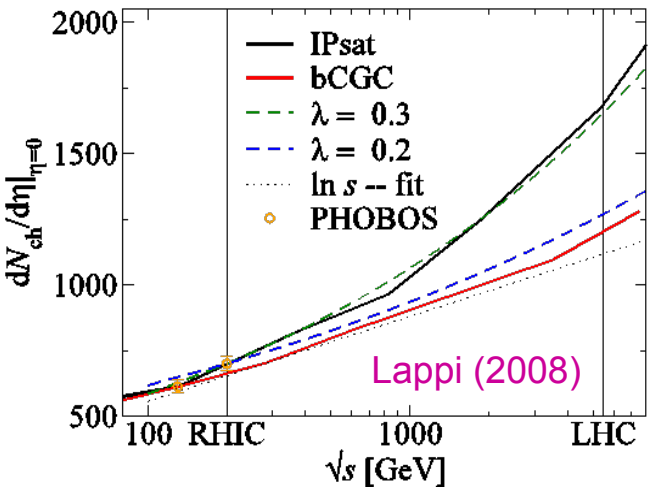
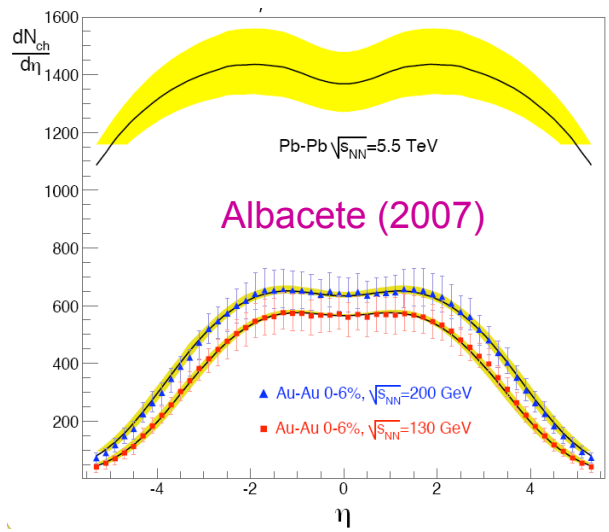


or true QCD evolution, but assuming k_T factorization



in both cases, the extrapolation from RHIC to LHC is driven by the small-x evolution

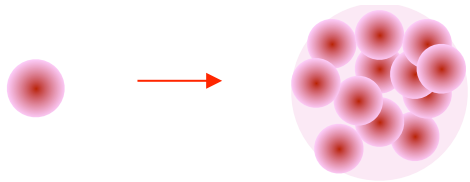
The nuclear geometry

caveat with the previous results: the nuclear geometry is not properly treated

- the impact parameter dependence of the gluon density and of Q_S

in the case of a proton, using an impact-parameter averaged saturation scale is enough most of the time, but in the case of a nucleus it is not

proper modeling of the nuclear geometry and of its fluctuations done in the rcBK and IP-Glasma MCs



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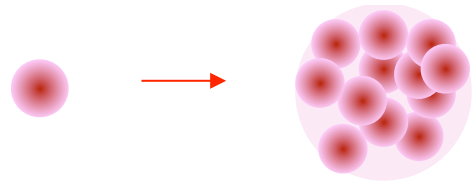
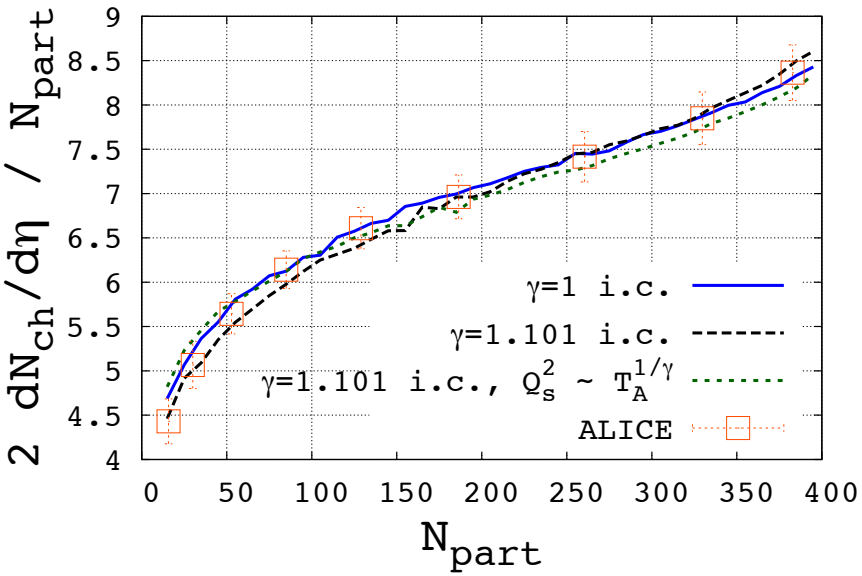
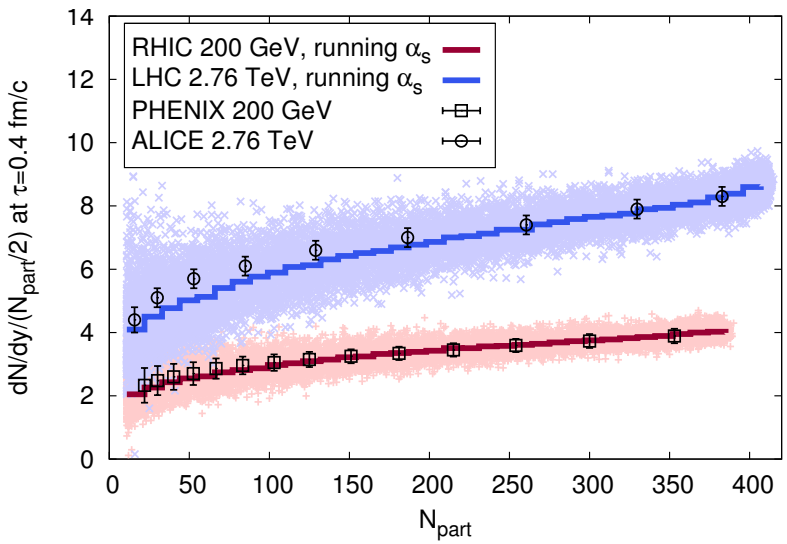


Albacete, Dumitru, Fujii and Nara (2013)



Schenke, Tribedy and Venugopalan (2012)



Multi-gluon production

- two-gluon production

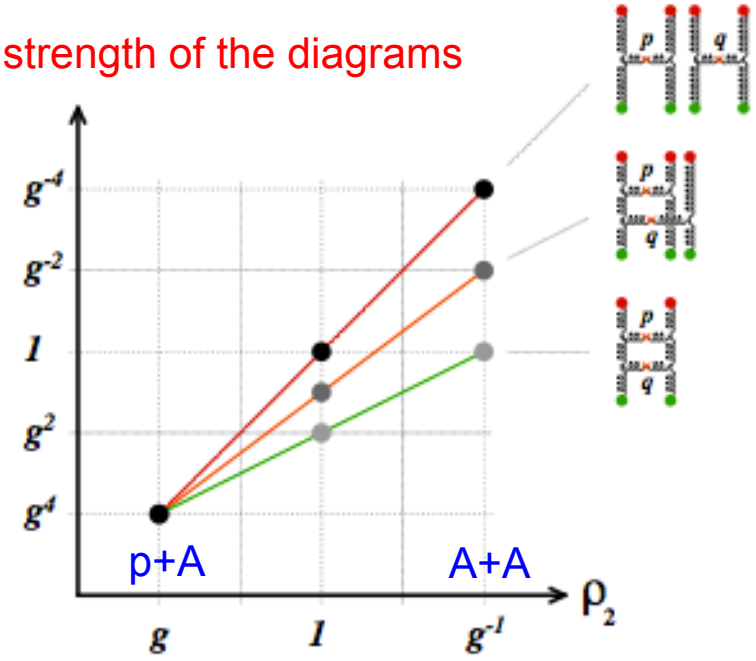
easily obtained from the single-gluon result

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

Gelis, Lappi and Venugopalan (2008)

the exact implementation of the small-x evolution is still not achieved as in the single-particle case

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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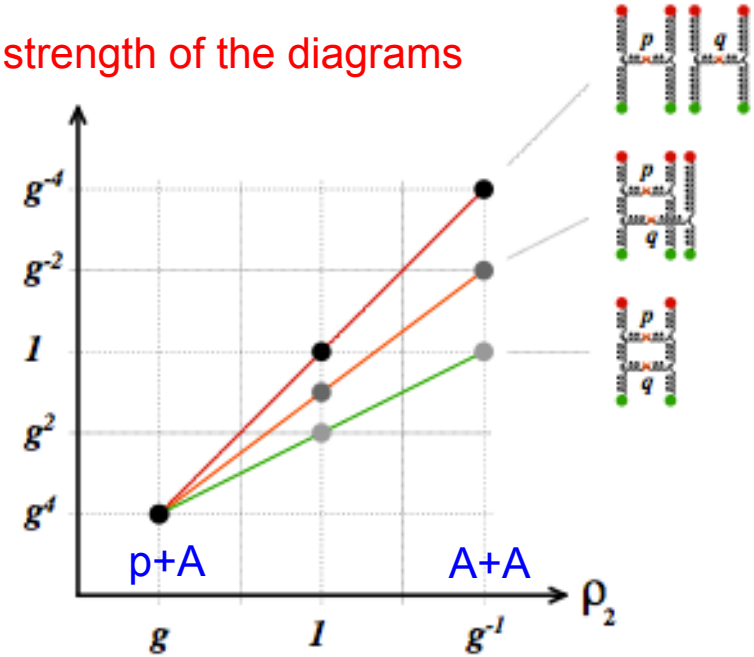

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- multi-gluon production

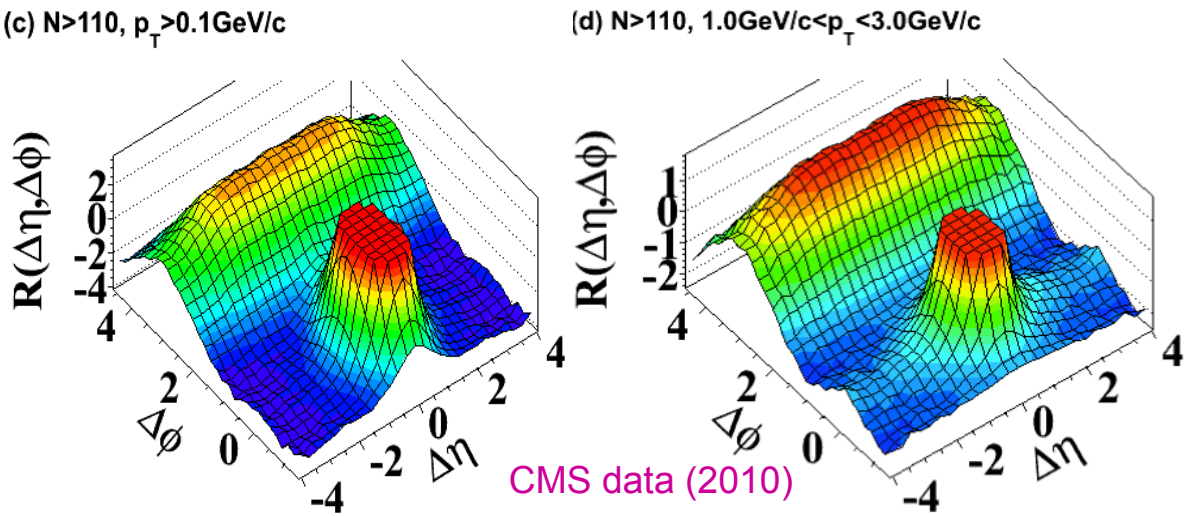
same conclusion: disconnected diagrams dominate multi-gluon production, multi-particle correlations can be calculated!

- 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:



CMS data (2010)

question to experimentalists: Fourier decomposition of the "central-pheripheral" signal?

no ridge at low p_T, there can't be much flow

ridge with p_T ~ Qs

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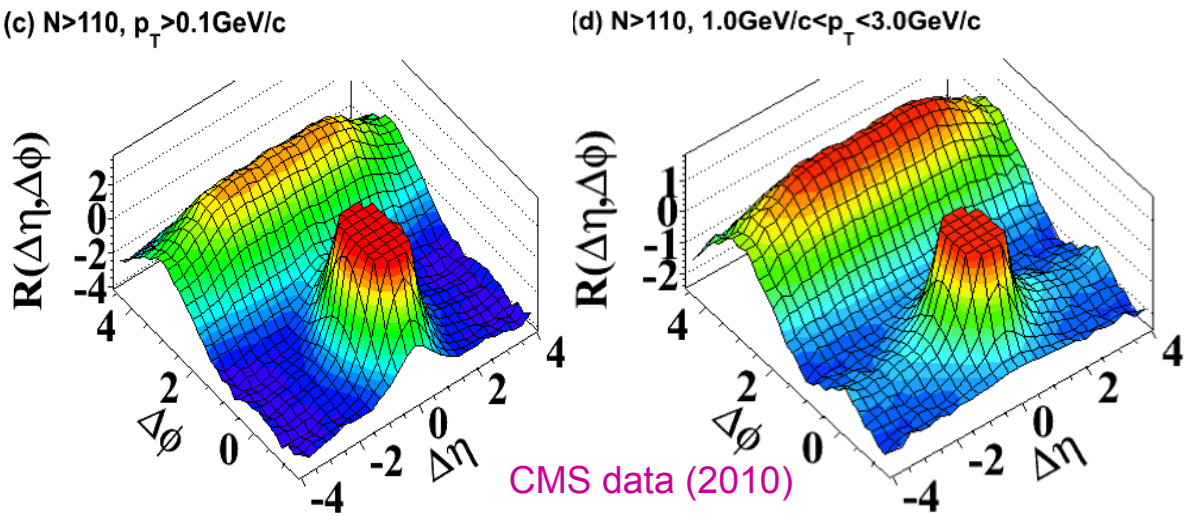

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Dumitru, Dusling, Gélis, Jalilian-Marian, Lappi and Venugopalan (2011)

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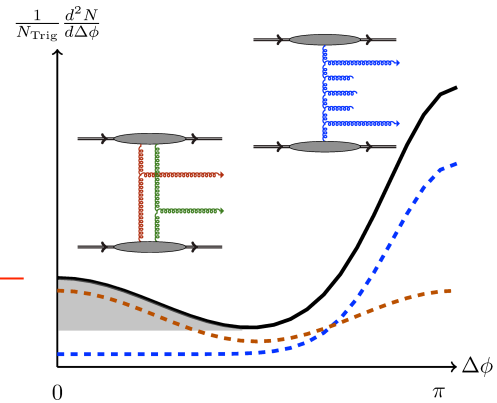


- CGC calculation after Gaussian averaging

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

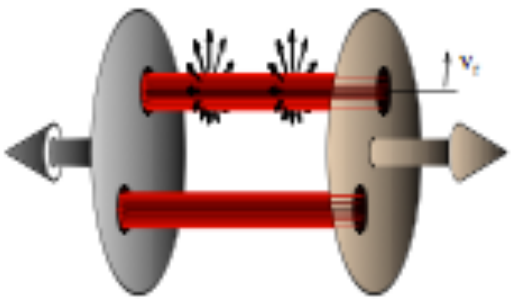
such strucutre exists independently of the assumption

Kovner and Lublinsky (2011)

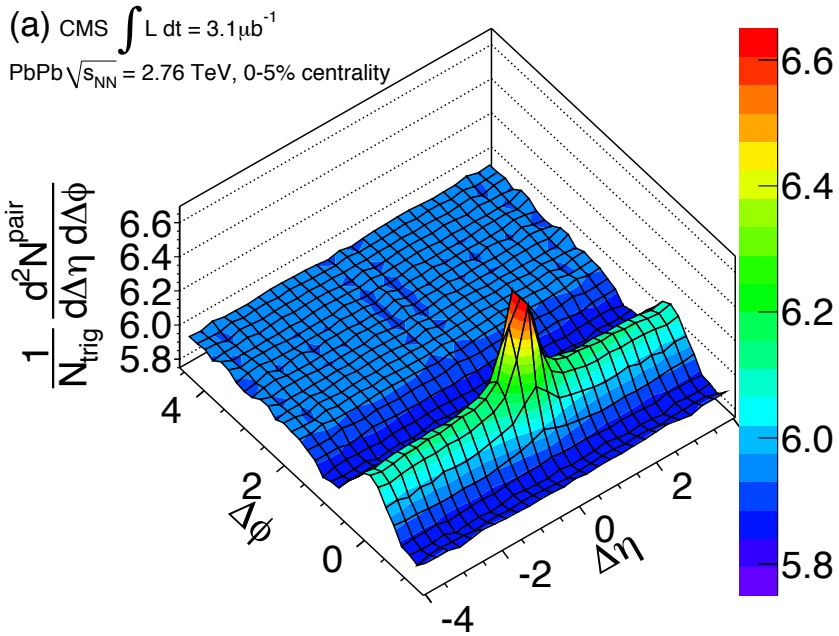
The ridge in A+A collisions

- 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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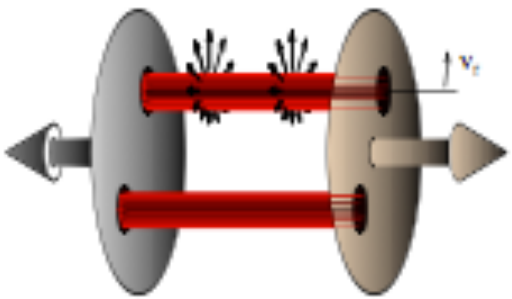

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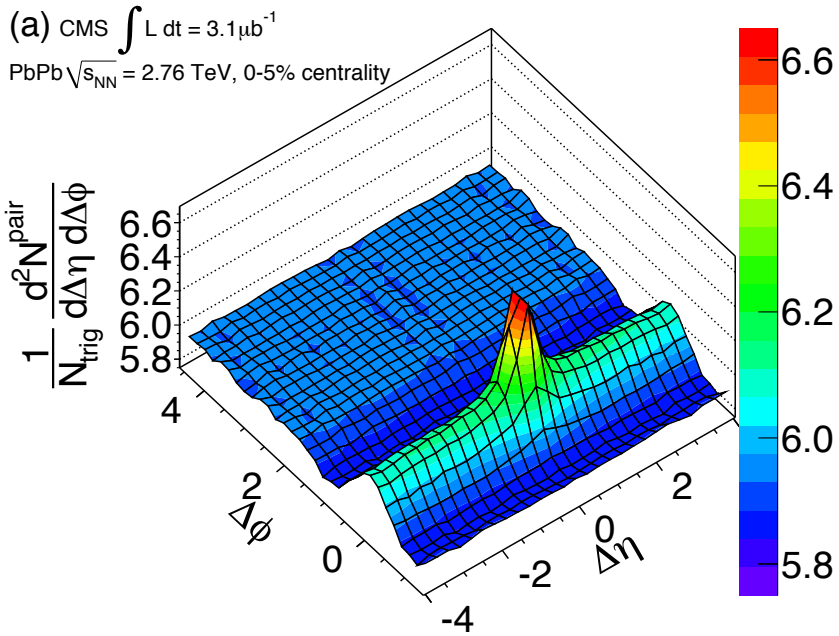


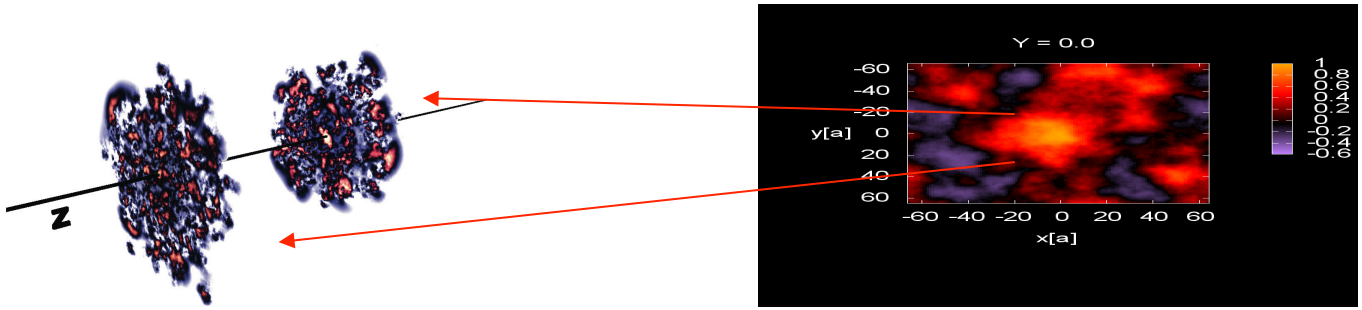
a proper treatment of the nuclear geometry and of it's fluctuation becomes crucial

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

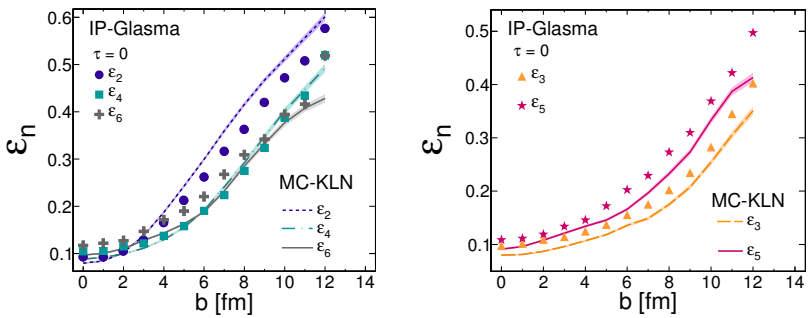
QGP properties cannot be precisely extracted from data without a proper understanding of the initial state

Glasma+hydro approach

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



eccentricity harmonics



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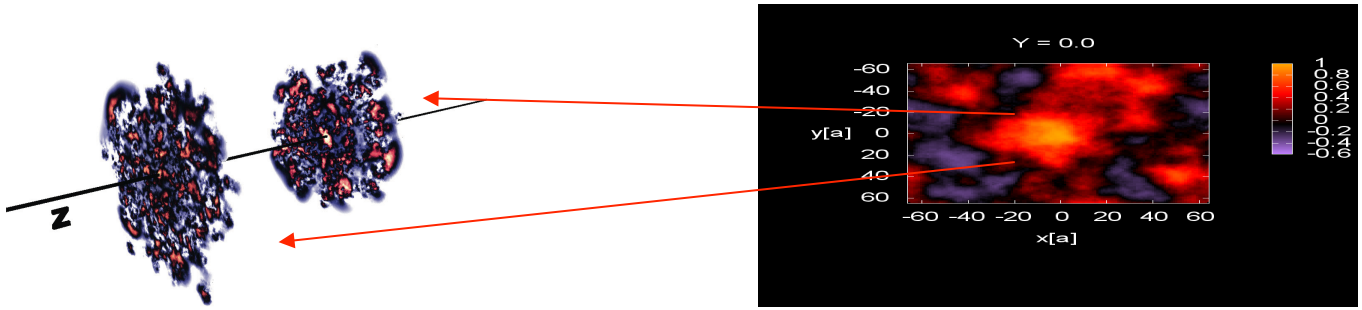

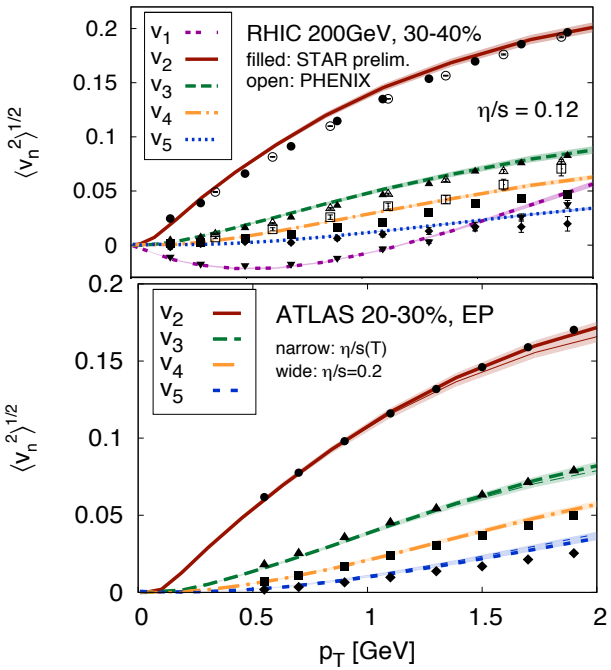

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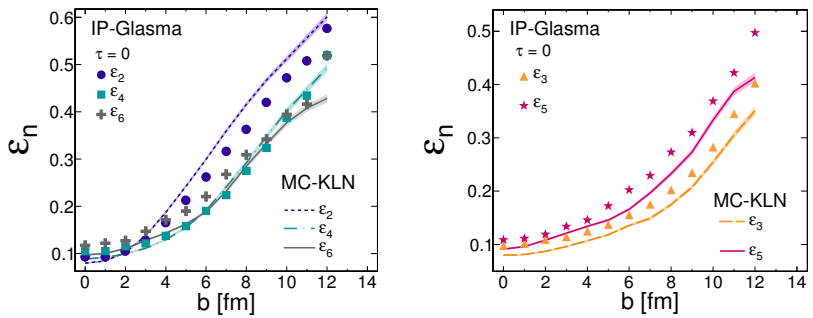
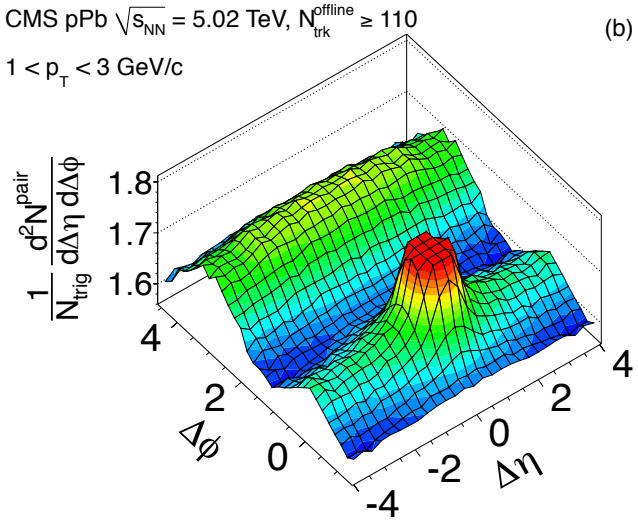


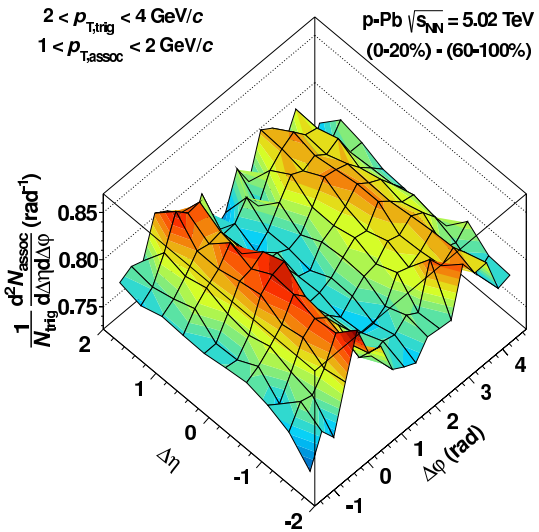
Gale, Jeon, Schenke, Tribedy and Venugopalan (2013)

- 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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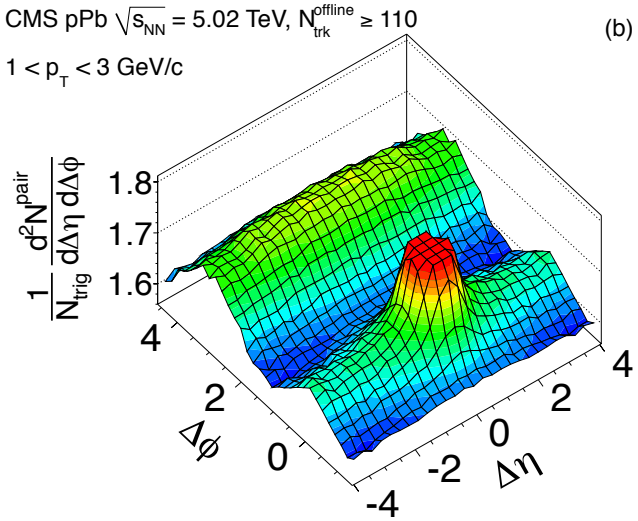
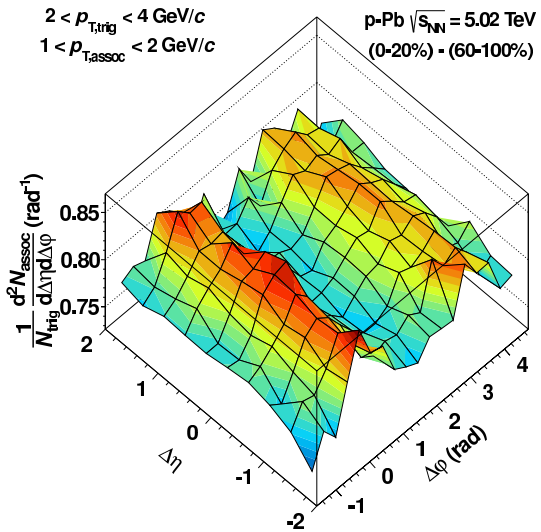




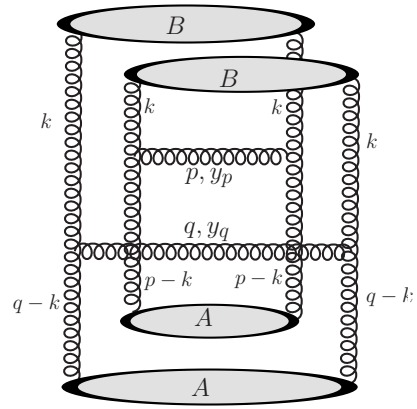


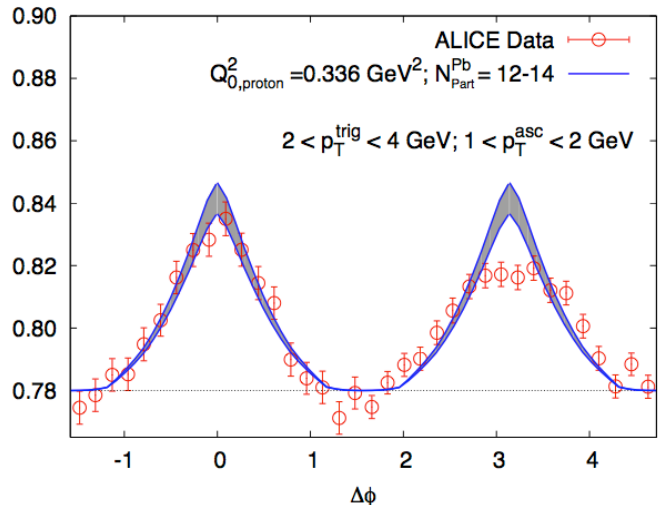
diagram which gives the $\Delta\phi$ dependence

- in the absence of 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

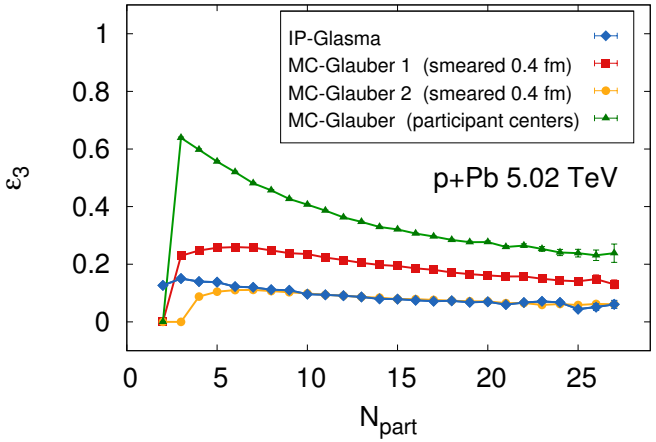


CGC or CGC+hydro ?

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

- in the presence of the flow

MC-Glauber 1 MC-Glauber 2



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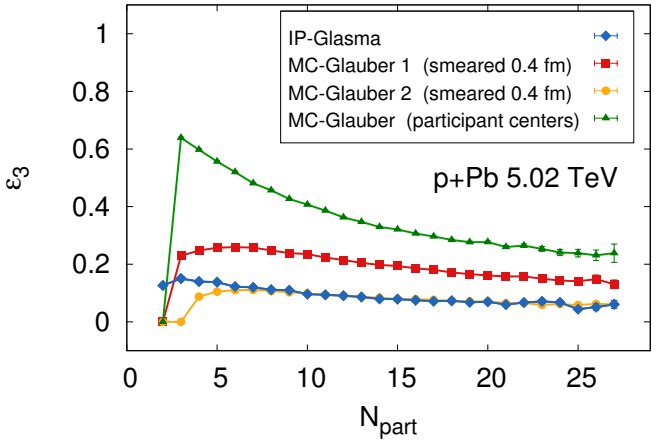
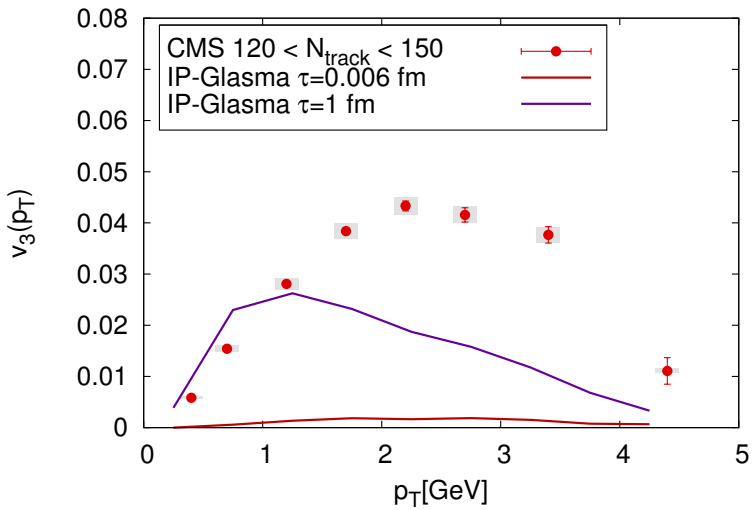


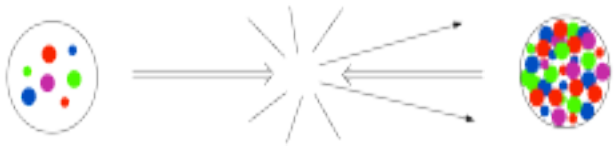


Bzdak, Schenke, Tribedy and Venugopalan (2013)

- other options to access the QCD momentum correlations ?

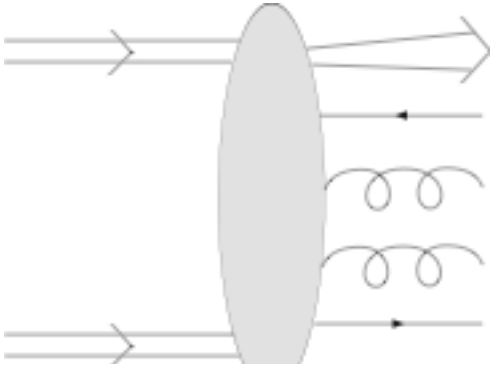
e+A collisions, and maybe p+A in the forward region

Forward particle production, dilute-dense collisions



Single inclusive hadron production

forward rapidities probe small values of *x*

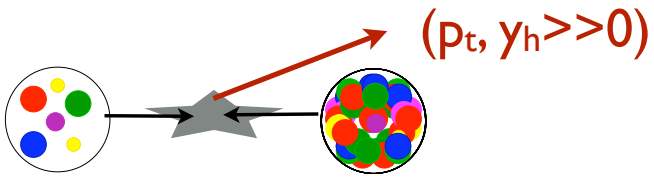


k_T, y

transverse momentum k_T, rapidity $y > 0$

values of x probed in the process:

$$x_1 \sqrt{s} = k_T\, e^{y} \qquad x_2 \sqrt{s} = k_T\, e^{-y}$$



large-x parton from proj. (pdf)

small-x glue from target (CGC)

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

fragmentation

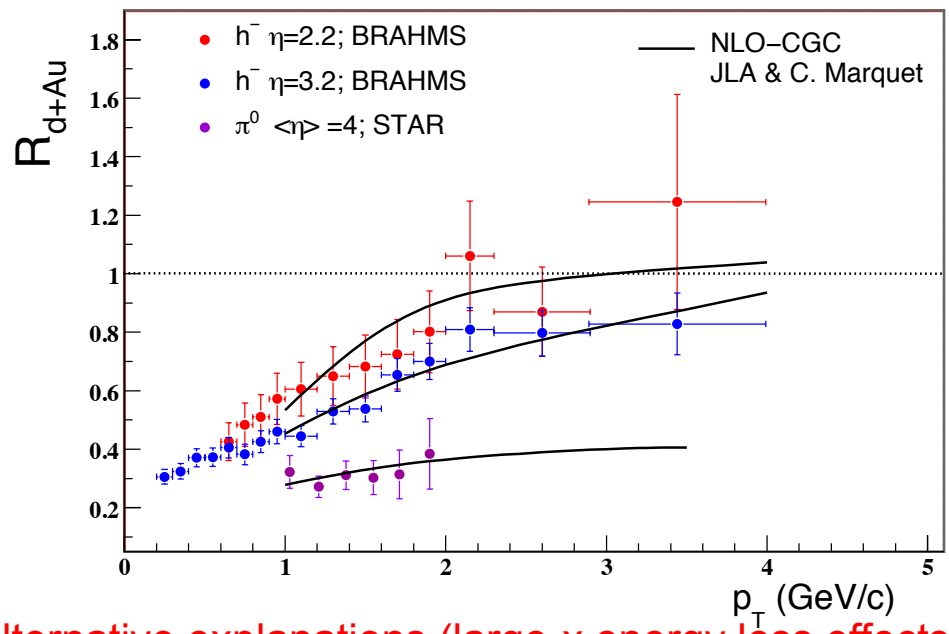
Dumitru, Hayashigaki and Jalilian-Marian (2006)

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

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

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



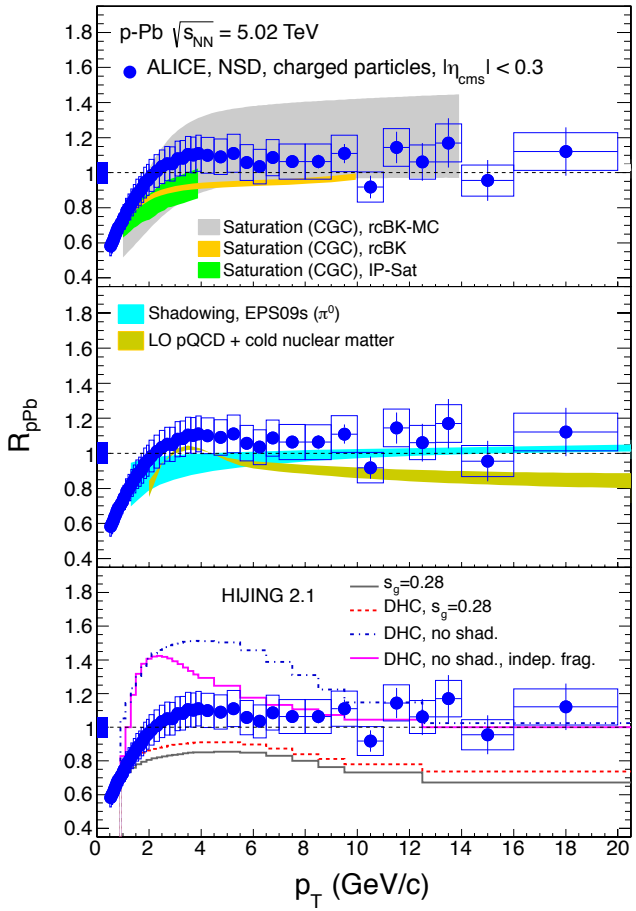
Albacete and CM (2010)

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

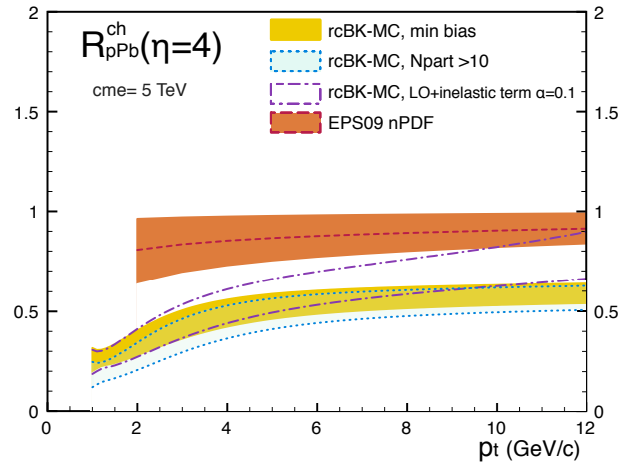
Kopeliovich et al (2005), Frankfurt et al (2007)

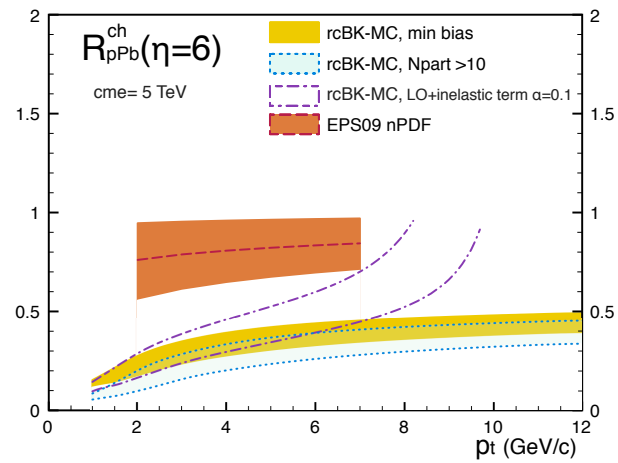
p+Pb @ the LHC

- mid-rapidity data



- predictions for forward rapidities





a proper treatment of the nuclear geometry and of it's fluctuation is indeed crucial

Next : phenomenology at NLO ?

- importance of NLO at high-p_T Altinoluk and Kovner (2011)

  the coupling α_s does not appear in the hybrid formula because it is compensated by the strong color field of the nucleus $A \sim 1/g_s$

  at high-pt the color field becomes $O(1)$ and the cross section $\mathcal{O}(\alpha_s)$

  then another $\mathcal{O}(\alpha_s)$ contribution (which is an NLO contribution when $A \sim 1/g_s$) is needed to fully recover to correct high-p_T limit

- full NLO calculation Chirilli, Xiao and Yuan (2012)

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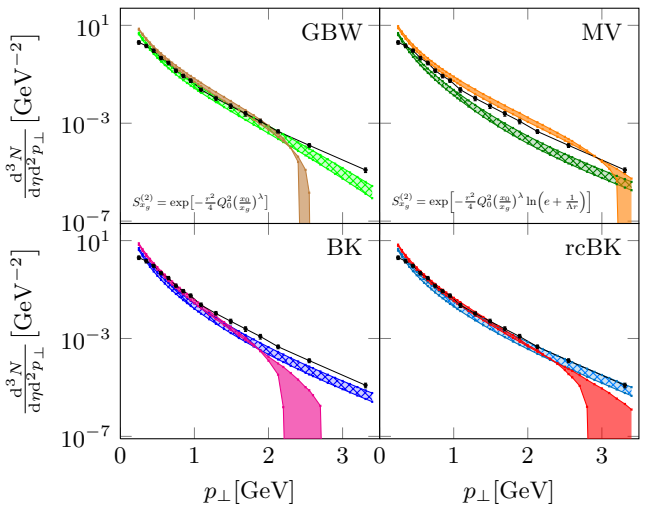
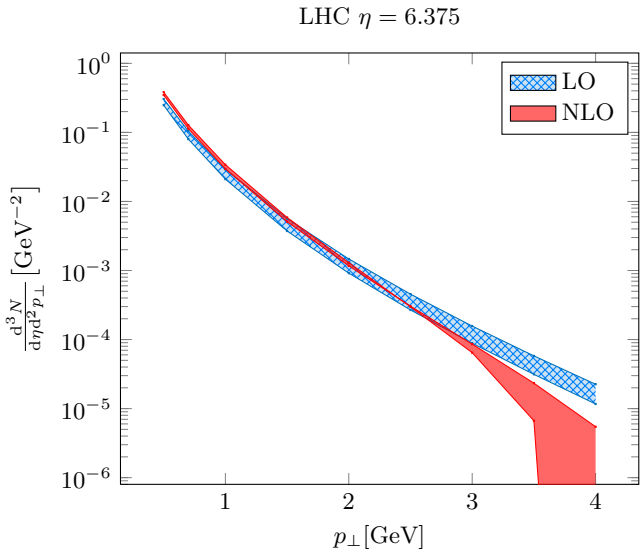
- numerical results Stasto, Xiao and Zaslavsky (2013)

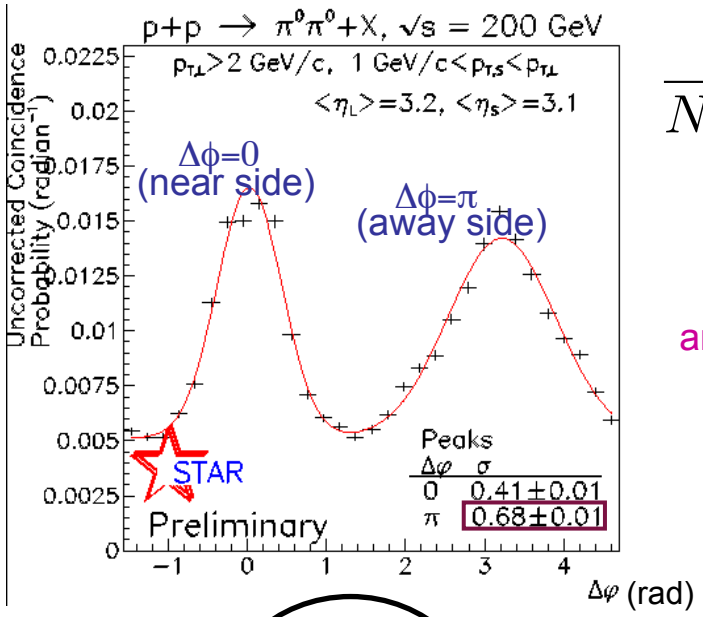




Di-hadron angular correlations

comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X

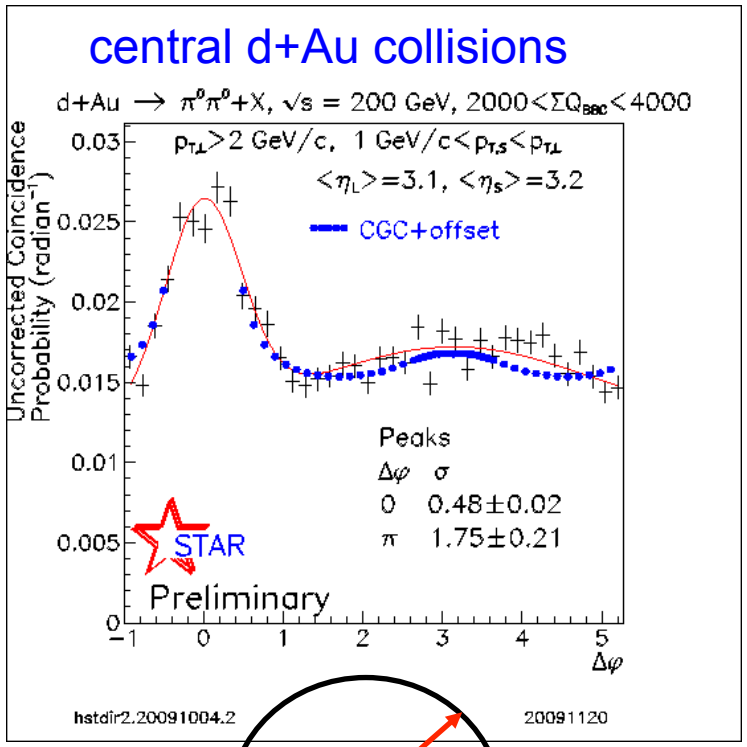
p+p collisions

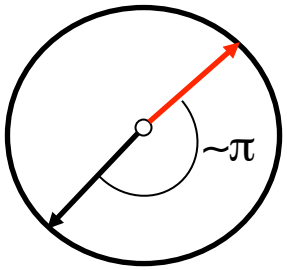


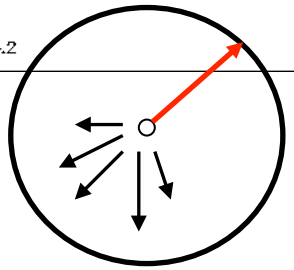
$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

Albacete
and CM (2010)

central d+Au collisions







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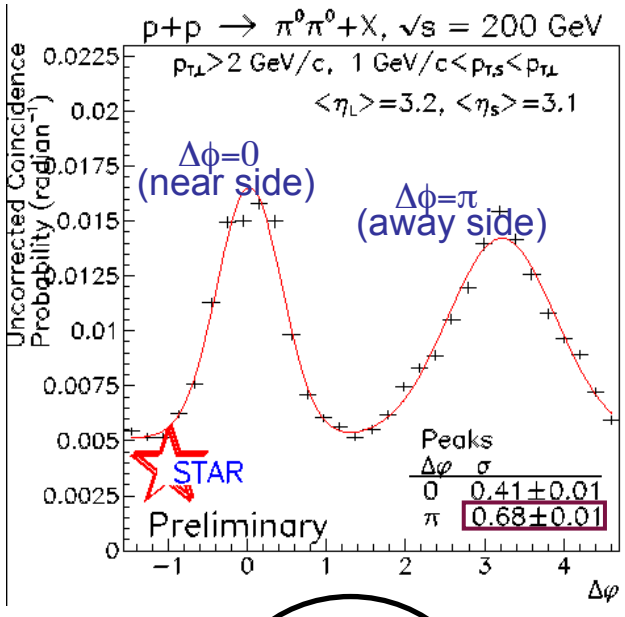

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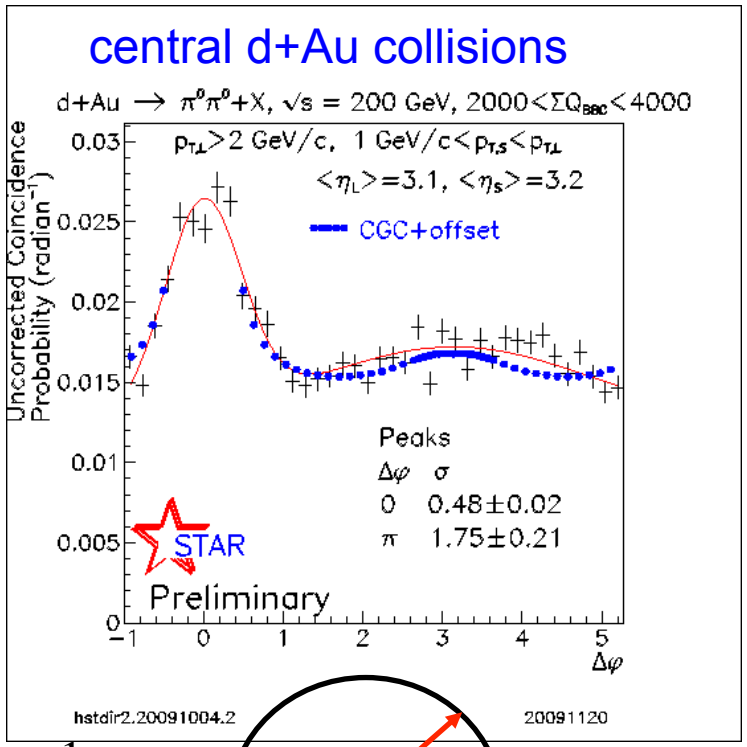
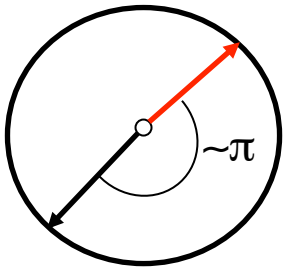
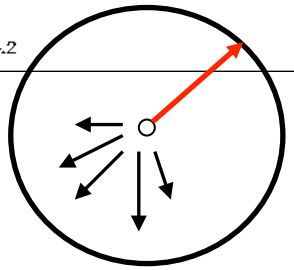




$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$



however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

Recent progress and LHC data

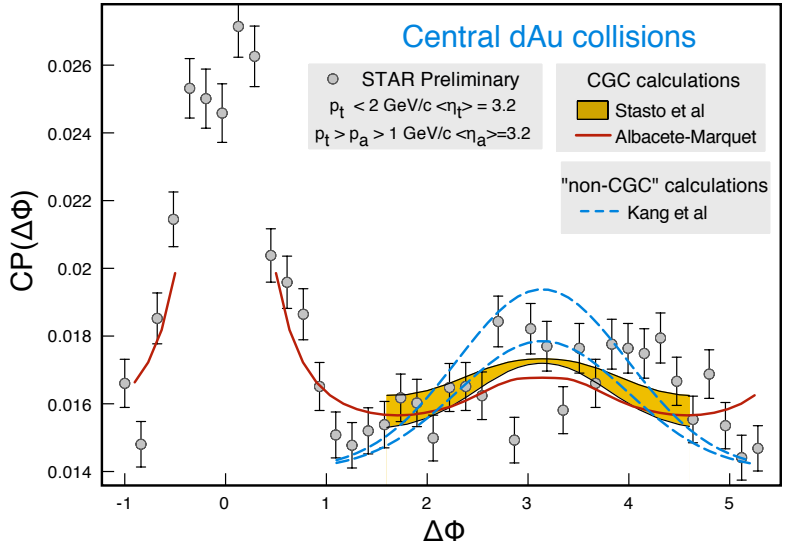
- improved CGC calculations

  Stasto, Xiao and Yuan (2012)

  Lappi and Mantysaari (2013)

- first non-CGC description

  Kang, Vitev and Xing (2012)



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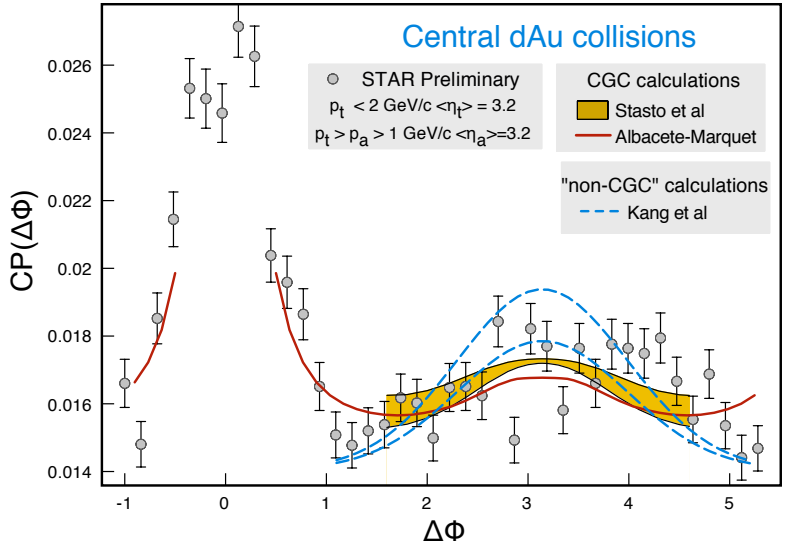
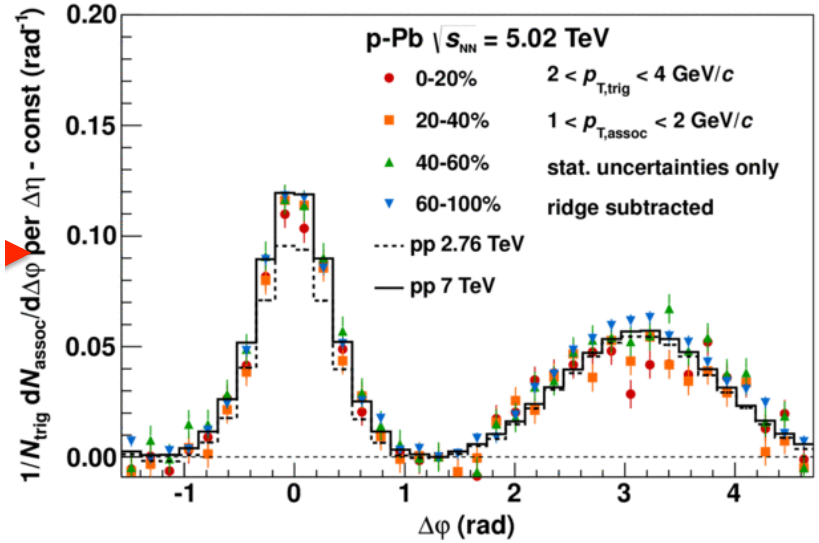
- recent ALICE mid-rapidity data





after subtracting from the data the contribution of dense-dense diagrams (at mid-rapidity, they also contribute), there is little away-side suppression with increasing centrality

Multi-particle production

- in the large-Nc limit

Kovner and Lublinsky (2006) Dominguez, CM, Stasto, and Xiao (2013)

2-point and 4-point functions are sufficient to compute multi-particle production in dilute-dense collisions, all higher-order correlators are suppressed at least by $1/Nc^2$

worth to put some effort to accurately solve the evolution equation for the 4-point function

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- at finite Nc Iancu and Triantafyllopoulos (2013)

generalization of the Langevin formulation of the JIMWLK equation

- the theory is slightly ahead of the experiments here, but it will not get much further without experimental input

in particular to determine additional initial conditions to the QCD evolution

alternatively, collective flow may again hide everything

Conclusions

- correlation measurements can probe very interesting features of QCD in the strong field regime
  - ridge-like momentum correlations
  - corrections to the Gaussian model for the color charge distribution
- when a perfect liquid is created, the dominant momentum correlations are those created by the fluid behavior
  - what becomes crucial about the initial state are the spatial correlations
  - bulk observables in A+A are very sensitive to those, as much as to medium properties
  - one should aim for a QCD understanding of these, and the CGC/ glasma effective theory is a good place to start
- if there is collective flow in p+A, e+A collisions become even more desirable to explore the strong field regime of QCD in a direct way
- forward rapidity in p+A: a lot of theory activity, hoping for LHC data