Gluon saturation and its role in heavy ion collisons

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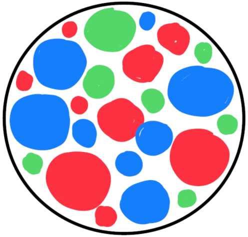
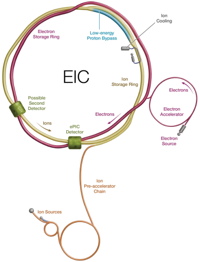
Gluon saturation

At high energies proton/nucleus becomes densely packed with gluons



Proton/Nucleus

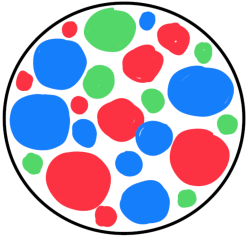


When gluon densities become large enough to “saturate” the proton/nucleus, we call it gluon saturation

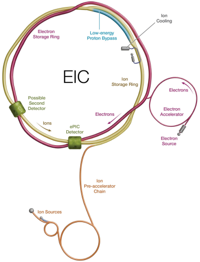
Figure from https://www.bnl.gov/eic/science.php

Gluon saturation

At high energies proton/nucleus becomes densely packed with gluons



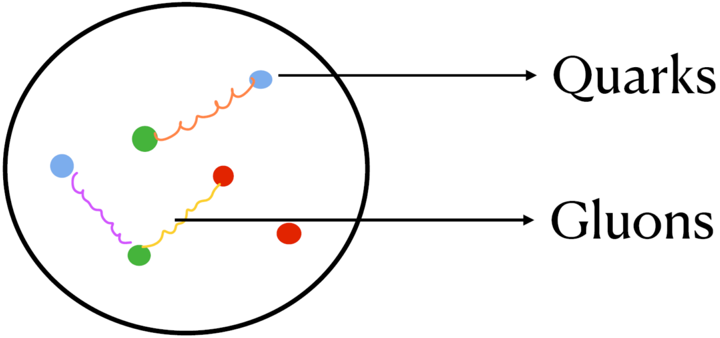
Proton/Nucleus



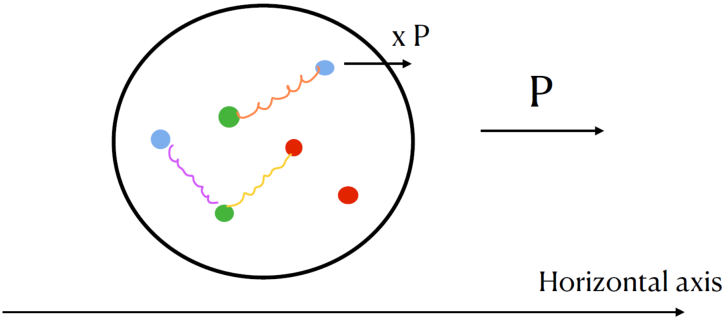
Saturation can help us understand high energy processes, heavy ion collisions, spin puzzle etc...

Figure from https://www.bnl.gov/eic/science.php

Structure of proton

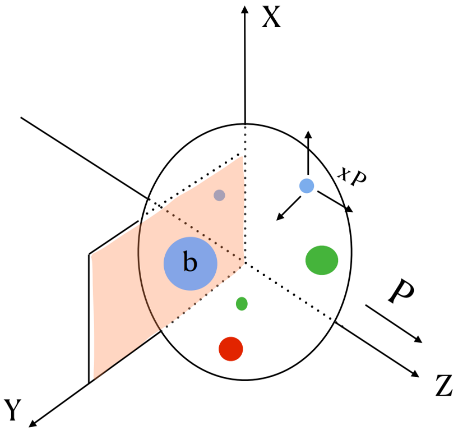


One-dimensional structure of proton



x is between 0 and 1

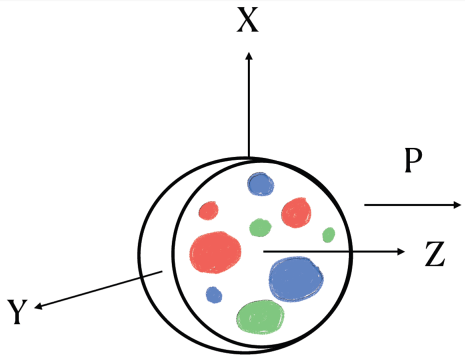
Three dimensional structure of proton



b is the transverse size (in X-Y plane)

Structure at high energies

Boosted along the Z -direction

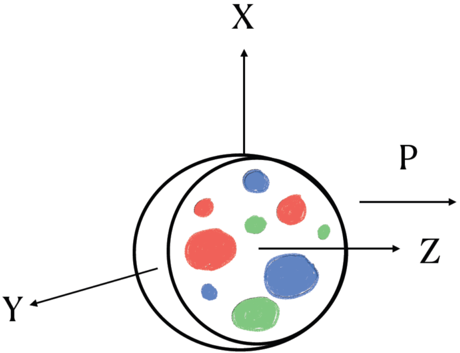


Lorentz contraction: becomes pancake like

L.McClerran (2008), A.Kovner(2005)

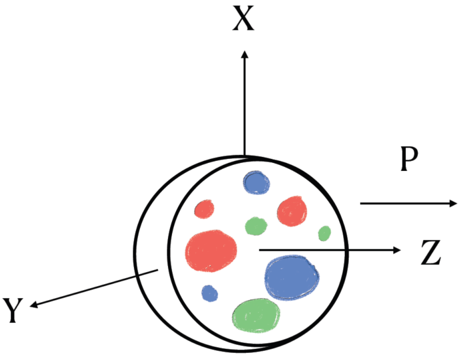
Structure at high energies

Boosted along the Z -direction

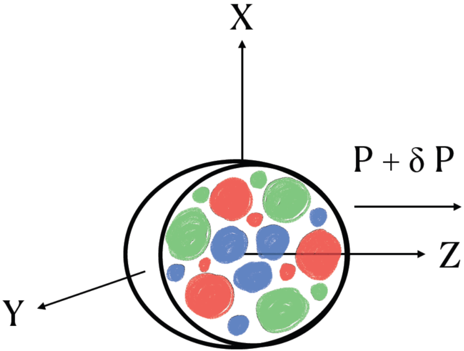


What happens if we boost it further?

Gluon radiation



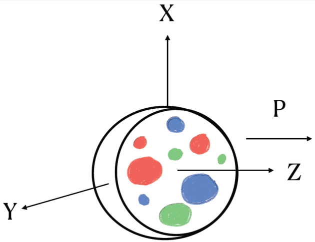
P

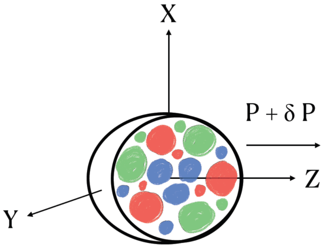


$P + dP$

L.McClerran (2008), A.Kovner(2005)

Gluon radiation

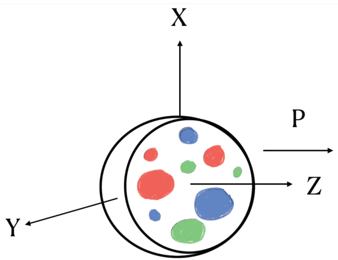




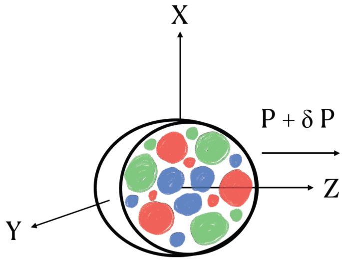
- Boosting a color charge gives rise to new gluons
- “Virtual” gluons survive longer due to time dilation

L.McClerran (2008), A.Kovner(2005)

Gluon radiation



P



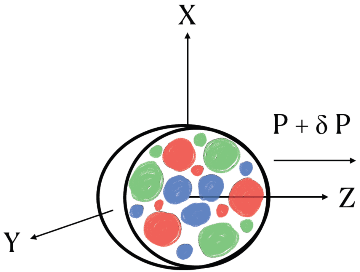
P + dP

- New gluons (or quarks) have smaller momentum fraction x
- New gluons have the same transverse size b

L.McClerran (2008), A.Kovner(2005)

What is gluon saturation?

- Size of the proton varies very slowly with energy
- Number of gluons increases much faster



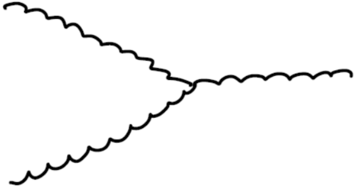
$\boxed{\text{Gluons with the same b start overlapping}}$

L.McClerran (2008), A.Kovner(2005)

What is gluon saturation?

Competing process: Recombination

Gluon splitting



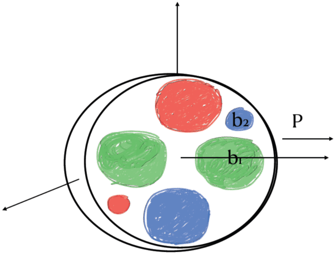
Gluon recombination

Gluon saturation: splitting rate = recombination rate

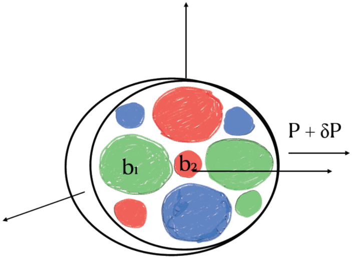
L.McClerran (2008), A.Kovner(2005)

Saturation momentum

Gluons with different b saturate at different momentum



$\mathbf{b_1}$ gluons saturated



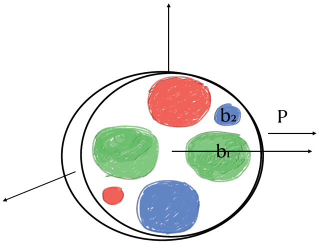
$\mathbf{b_1}$ and $\mathbf{b_2}$ gluons saturated

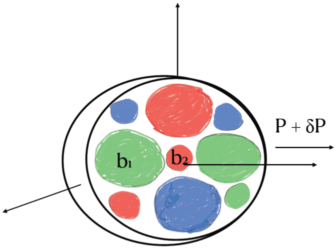
Gluons with larger b or smaller momenta saturate first

L.McClerran (2008), A.Kovner(2005)

Saturation momentum

$\boxed{\text{Saturation momentum: } Q_s(P)}$





$\mathbf{b_1}$ gluons saturated

$\mathbf{b_1}$ and $\mathbf{b_2}$ gluons saturated

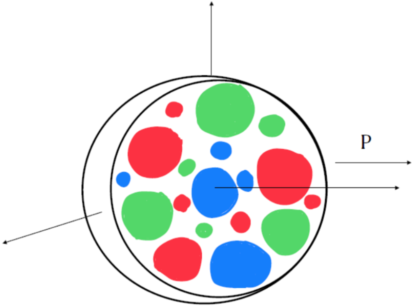
$\boxed{\text{All gluons with typical momenta less that } Q_s(P) \text{ are saturated}}$

L.McClerran (2008), A.Kovner(2005)

In nucleus

- Area of nucleus $\propto A^{2/3}$
- Number of gluons $\propto A$

$$(Q_s(P))^2 \propto \frac{\text{Number of gluons}}{\text{Area of nucleus}} \propto A^{1/3}$$



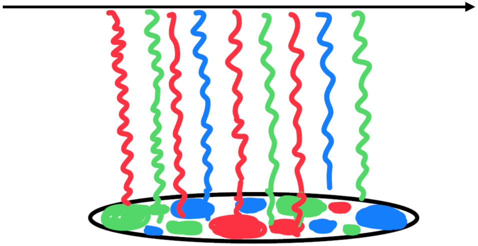
$\boxed{\text{Nuclear modes saturate faster than proton modes}}$

L.McClerran (2008), A.Kovner(2005)

How to understand saturation?

$\boxed{\text{Saturation implies multiple interactions}}$

- Interaction with multiple quarks/gluons
- Each interaction is weak but large in number



$\boxed{\text{Probes a dense but perturbative regime of QCD. Dense implies classical !}}$

L.McClerran (2008), A.Kovner(2005)

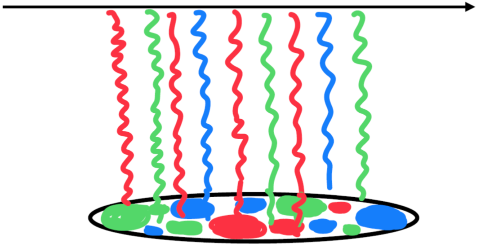
How to understand saturation?

Multiple interactions are summed!

Color ≡ Degrees of freedom

Glass ≡ Freezing of gluons

Condensate ≡ High density



CGC formalism uses multiple scattering and saturation to study physical processes

L.McClerran (2008), A.Kovner(2005)

But how to see saturation?

Need to compare with experiments at HERA, RHIC, LHC and EIC in future!

Three directions

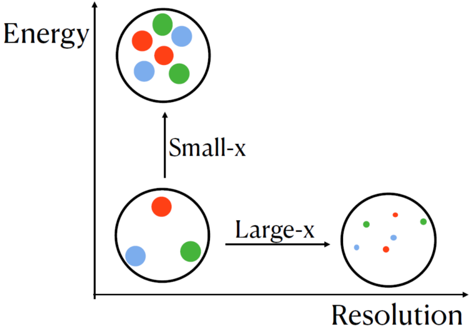
- Understand applicability of CGC formalism
- Compute processes at high accuracy using CGC formalism
- Compare robust observables with data to see signals of saturation

Applicablity of CGC formalism

Schemes

- **Large-x/collinear methods**
  Get **Large-x evolution**

- **Small-x/CGC methods**
  Get **Small-x evolution**



How do you connect the two regimes/evolutions?

New scheme with validity for all x is needed

TMD handbook
A.Kovner(2005)
S.Mukheree, V.Skokov, A.Tarasov, S.T (2024,2025)
H.Duan,A.Kovner,M.Lublinsky(2024)

MSTT scheme

$\boxed{\text{MSTT factorization is based on the background field method}}$

gluon transverse distribution function(x, b) operator

$\downarrow$ Quantum corrections

Transverse distribution function(x, b, Λ) valid for all x

Small-x limit ↙ ↘ Large-x limit

Small-x methods/CGC **Large-x methods/CSS**

S.Mukheree, V.Skokov, A.Tarasov, S.T (2024,2025)

Full result

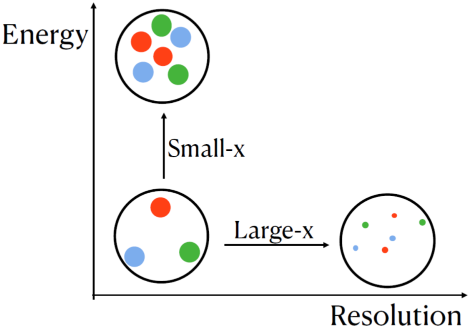
The full result contains parts of Large-x and parts of Small-x

$$
\begin{aligned}
f_{ij}(x, b_\perp, \mu^2_{\mathrm{UV}}, \zeta) &= f_{ij}(x, b_\perp, \mu^2_{\mathrm{IR}}, \rho) - 4\alpha_s N_c \int \bar{d}^2 p_\perp e^{ip_\perp b_\perp} \int_0^1 \frac{dz}{z(1-z)} \int \bar{d}^2 k_\perp \Big[\mathcal{R}^a_{ij;lm}(z, p_\perp, k_\perp) \\
&+ \mathcal{R}^b_{ij;lm}(z, p_\perp, k_\perp)\Big] \int d^2 z_\perp e^{-i(p_\perp - k_\perp)z_\perp} f_{lm}\Big(\frac{x}{z}, z_\perp, \mu^2_{\mathrm{IR}}, \rho\Big) + \boxed{\frac{\alpha_s N_c}{2\pi}\Big(- \frac{1}{2}(L_b^{\mu_{\mathrm{UV}}})^2 + L_b^{\mu_{\mathrm{UV}}} \ln \frac{\mu^2_{\mathrm{UV}}}{\zeta^2} - \frac{\pi^2}{12}\Big)} \\
&\times f_{ij}(x, b_\perp, \mu^2_{\mathrm{IR}}, \rho) - \boxed{\frac{\alpha_s N_c}{\pi} L_b^{\mu_{\mathrm{IR}}} \int_0^1 dz \Big[\frac{1}{(1-z)_+} + \frac{1}{z}\Big]} f_{ij}\Big(\frac{x}{z}, b_\perp, \mu^2_{\mathrm{IR}}, \rho\Big) - \frac{\alpha_s N_c}{2\pi} \int d^2 z_\perp \int \bar{d}^2 p_\perp e^{ip_\perp (b-z)_\perp} \\
&\times \Big(\frac{1}{2} \ln^2 \frac{\mu^2_{\mathrm{IR}}}{p^2_\perp} + \boxed{\ln \frac{\mu^2_{\mathrm{IR}}}{p^2_\perp} \ln \frac{\rho}{\zeta}} - \frac{\pi^2}{12}\Big) \frac{g_{il} p_j p_m + p_i p_l g_{mj}}{p^2_\perp} f_{lm}(x, z_\perp, \mu^2_{\mathrm{IR}}, \rho) \\
&+ \frac{\alpha_s N_c}{2\pi} \int d^2 z_\perp \int \bar{d}^2 p_\perp e^{ip_\perp (b-z)_\perp} \Big(\frac{\beta_0}{2N_c} \ln \frac{\mu^2_{\mathrm{UV}}}{p^2_\perp} + \frac{67}{18} - \frac{5N_f}{9N_c}\Big) f_{ij}(x, z_\perp, \mu^2_{\mathrm{IR}}, \rho) + O(\alpha_s^2)\,.
\end{aligned}
$$

S.Mukheree, V.Skokov, A.Tarasov, S.T (2024,2025)

Small-x evolution or JIMWLK

Given an initial condition evolve by implementing a random walk (langevin equation)

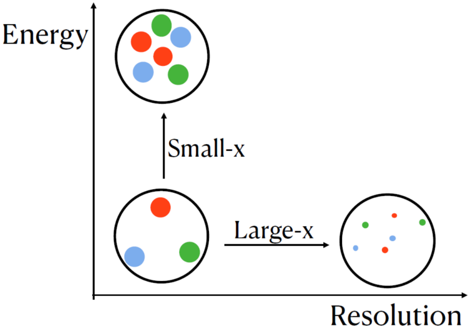


Y.Kovchegov, H.Weigert(2013), I.Balitsky, G.Chirilli (2013)
Y.Hatta, E.Iancu (2016)

Evolution at high energies

Small-x evolution or JIMWLK

- Not all observables can be evolved
- Computationally expensive
- Method does not work at higher orders

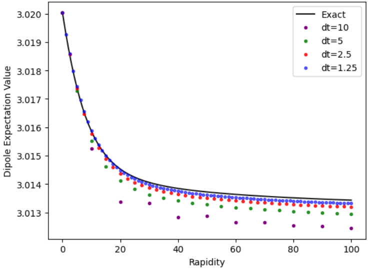


Y.Kovchegov, H.Weigert(2013), I.Balitsky, G.Chirilli (2013)
Y.Hatta, E.Iancu (2016)

Evolution at high energies

JIMWLK using quantum computers

- Using open quantum system methods
- Using lattice gauge theory methods



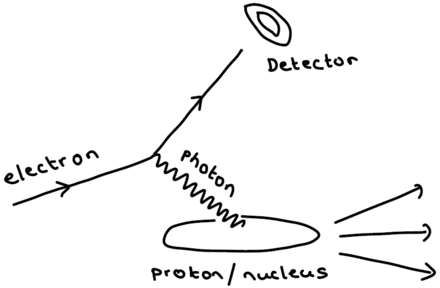
Quantum mechanical system with a few points. Early stages!

A. Agrawal, E. Budd, A. Kemper, V. Skokov, A. Tarasov, S.T (to appear)

Process I

Electron - proton scattering

- Quantum corrections to **photon**
- Quantum corrections to **proton/nucleus**

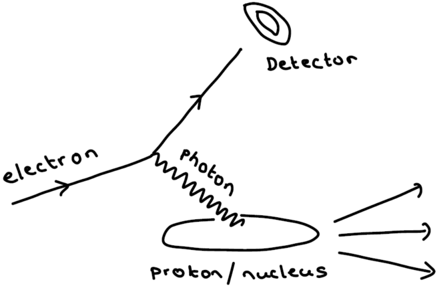


Balitsky, Chirilli (2008, 2015)
Beuf, Lappi, Paatelainen (2021, 2022)
Kovchegov, Weigert (2007)

Process I

Electron - proton scattering

- Measure outgoing hadron
- Proton survives
- Ultraperipheral collisons ...

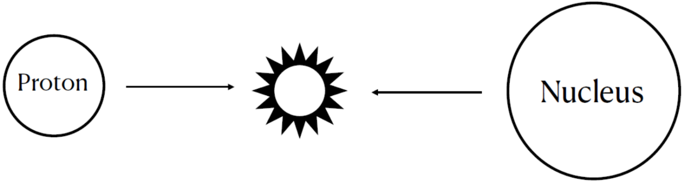


Beuf, Lappi, Mantysaari, Paatalainen, Penttala (2024)
Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon (2016)
Mantysaari, Penttala (2021, 2022)
Roy, Venugopalan (2019)
Caucal, Salazar, Schenke, Stebel, Venugopalan (2024)

Process II

$\boxed{\text{Proton- Nucleus collisons}}$

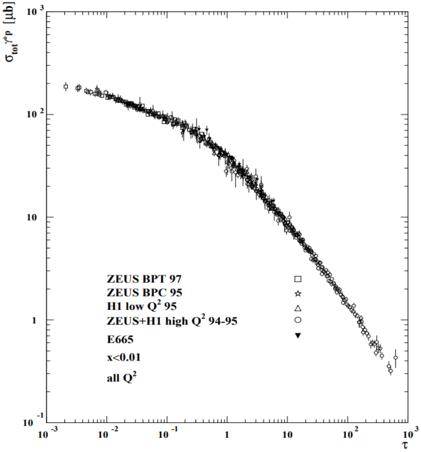
- Proton: Not saturated
- Nulceus: Saturated



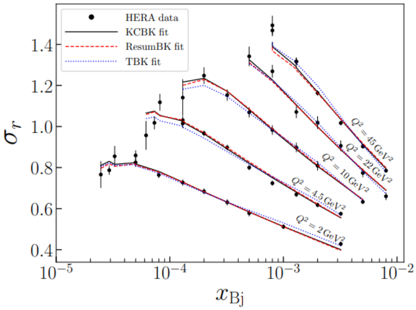
Chirilli, Xiao, Yuan (2012)
Mantysaari, Tawabutr (2023)
Liu, Xie, Kang, Liu (2022)
Taels (2023)

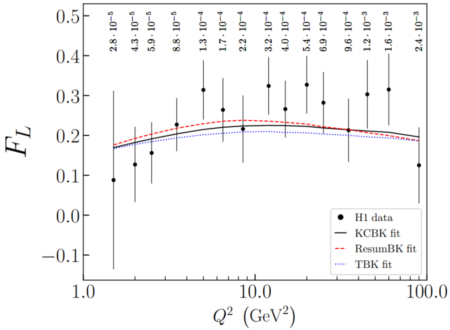
Fits to Deep inelastic scattering

Geometric scaling at high energy: Function of $\tau = Q^2/Q_s^2$



Fits to Deep inelastic scattering



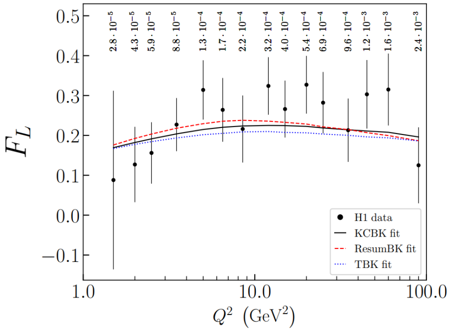


Beuf, Lappi, Hanninen, Mantysaari (2020)

Fits to Deep inelastic scattering

$\boxed{\text{At EIC}}$

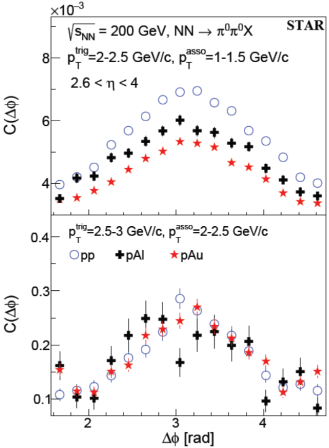
- Fits with nucleus
- Better luminosity
- Polarized scattering



Beuf, Lappi, Hanninen, Mantysaari (2020)

Proton-nucleus scattering

Suppression is a good signal for **saturation**



Higher order effects need to be included

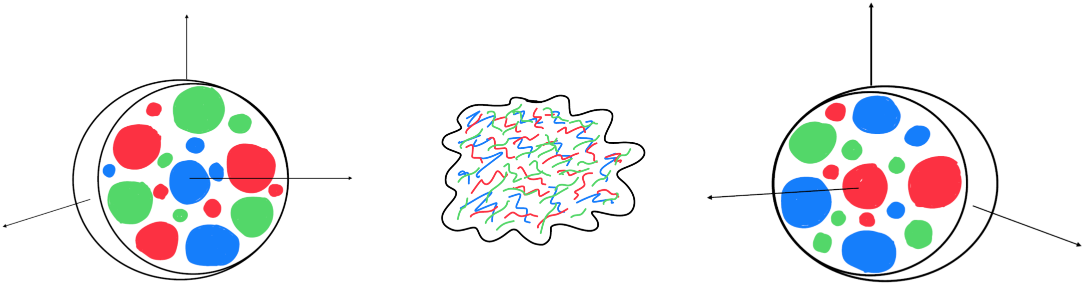
Dihadron correlations

Evidence for Nonlinear Gluon Effects in QCD and their A Dependence at STAR(2022)

Other observables

- Exclusive vector meson production
  - Mantysaari, Schenke (2016.2018)
  - Mantysaari, Salazar, Schenke (2022,2024)
  - Penttala, Royon (2024)
  - Kesler, Ikbal Sheikh, Ma, Tu, Ullrich, Xu (2025)
- Energy - energy correlators
  - Liu,Pan,Yuan, Zhu (2023)
  - Kang, Penttala, Zhao, Zhu (2024)
- Spin-dependent observables
  - Kovchegov,Sievert,Pitonyak (2012 - present)

Heavy ion collisons



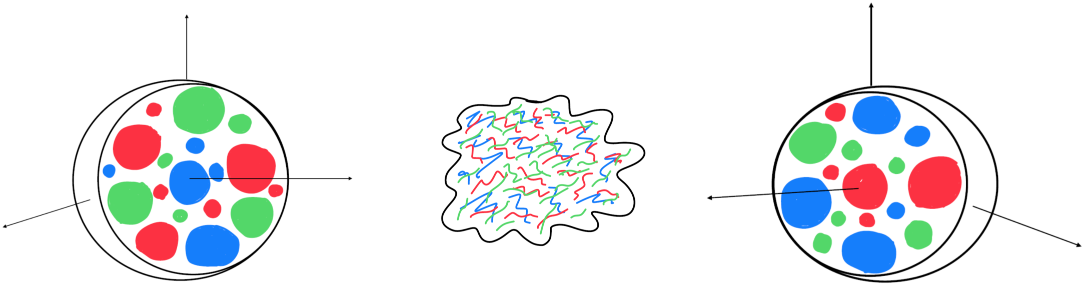
Nucleus

Quark gluon plasma

Nucleus

Busza, Rajagopal, Schee(2018), Mclerran (2008), Schenke (2021)

Heavy ion collisons



Nucleus

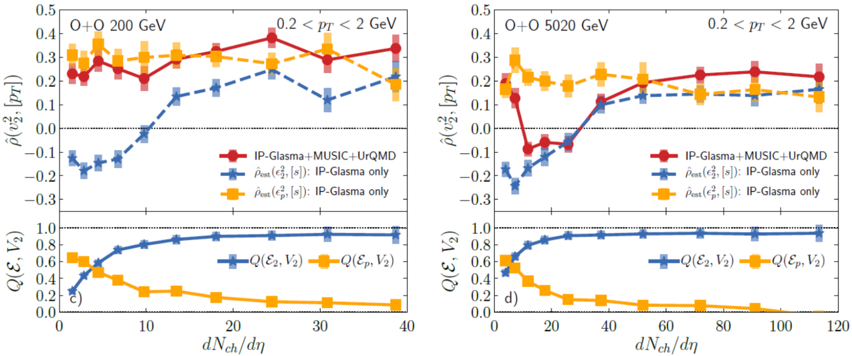
Quark gluon plasma

Nucleus

Initial condition for QGP: Saturated nucleus

Busza, Rajagopal, Schee (2018), Mclerran (2008), Schenke (2021)

Heavy ion collisons



Saturation based models make predictions for future experiments!

Giacalone, Schenke, Shen (2020)

Summary

- Search for gluon saturation is an ongoing theoretical and experimental (EIC/foCAL) effort

- Theoretical calculations need to be upgraded to higher orders

- Understand/construct observables which can provide clear signals of saturation

- Make robust predictions for high energy observables, spin and heavy ion collisons

For more information please look at the recently concluded CFNS-INT workshop on small-x