

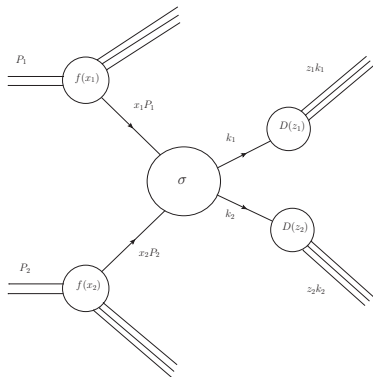
# Multiple Particle Production in the Presence of Saturation

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IPhT - Saclay

Excited QCD 2012  
Peniche, Portugal

# Particle Production in Hadronic Collisions

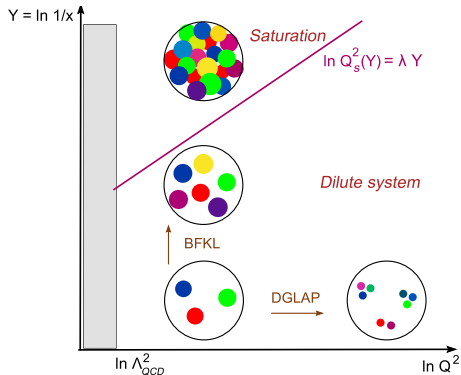


- Factorization of perturbative and non-perturbative regimes
- Assumptions:
  - All energy scales (except for masses) are of the same order
  - Mostly inclusive processes
  - Single large momentum transfer

# Problems with Collinear Factorization

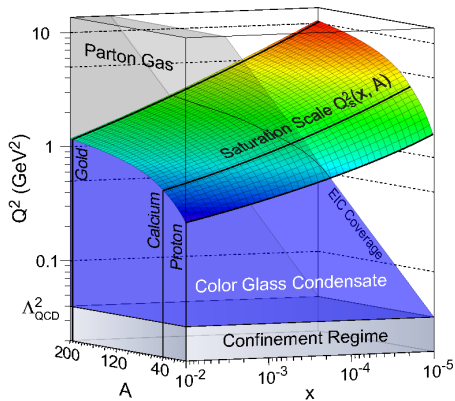
- Transverse momentum dependence:
  - Less inclusive processes
  - Wider range for transverse momentum of produced particles
- Enhancement of factorization breaking terms:
  - Very high energies
  - Nuclear effects
  - High densities in the small- $x$  regime

# High Densities at Small- $x$



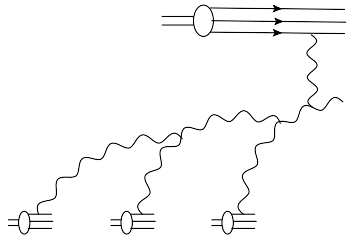
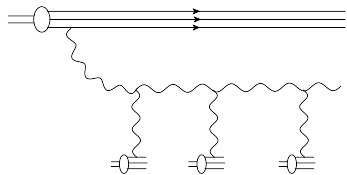
- Soft gluon emission is enhanced at large rapidities
- BFKL dynamics predicts a large growth in gluon densities at small- $x$
- Nonlinear dynamics predicts the generation of a semi-hard momentum scale which justifies the use of perturbative techniques

# Saturation in Nuclei



- Nuclear enhancement factor  $A^{1/3}$
- Saturation region is available at lower energies and in the perturbative regime

## Factorization at Small $x$ (in nuclei)



- Covariant gauge:
  - Resummation of multiple scatterings
  - Transverse momentum broadening
- Light-cone gauge:
  - Appropriate choice of boundary conditions turns off final (initial) state interactions
  - Modified distribution function
- Transverse momentum of partons can no longer be ignored

## Resummation of Multiple Scatterings

- Eikonal approximation  $\rightarrow$  Representation in coordinate space
- Choose a covariant gauge
- Take high density target as a strong static color field
- Effect of multiple scatterings can be resummed into a Wilson line

$$U(x) = \mathcal{P} \exp \left\{ ig \int dz^+ \alpha_a(z^+, x) T^a \right\}$$

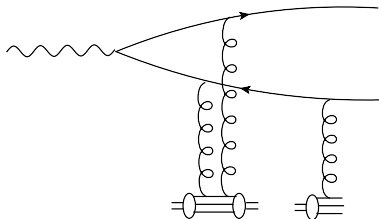
## Medium Average

$$\langle \mathcal{O} \rangle_Y = \int \mathcal{D}\alpha W_Y[\alpha] \mathcal{O}[\alpha]$$

- Weight function is given by non-perturbative physics
- Quantum dynamics determined by CGC effective theory
- Fundamental piece to understand the color correlations among the partons participating in a given process



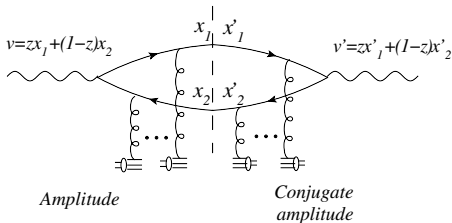
## Deep Inelastic Scattering at Small- $x$



$$\propto \psi(x_1 - x_2) \left[ 1 - U(x_1)U^\dagger(x_2) \right]$$

- Light-cone wave function
- Multiple scattering in the eikonal approximation in terms of Wilson lines

# DIS at Small- $x$



$$\begin{aligned}
 \frac{d\sigma^{\gamma_T^* A \rightarrow q\bar{q}X}}{d^3k_1 d^3k_2} &= N_c \alpha_{em} e_q^2 \delta(p^+ - k_1^+ - k_2^+) \int \frac{d^2x_1}{(2\pi)^2} \frac{d^2x'_1}{(2\pi)^2} \frac{d^2x_2}{(2\pi)^2} \frac{d^2x'_2}{(2\pi)^2} \\
 &\times e^{-ik_{1\perp} \cdot (x_1 - x'_1)} e^{-ik_{2\perp} \cdot (x_2 - x'_2)} \sum \psi_T^*(x_1 - x_2) \psi_T(x'_1 - x'_2) \\
 &\times [1 + \mathcal{Q}_{x_g}(x_1, x_2; x'_2, x'_1) - S_{x_g}(x_1, x_2) - S_{x_g}(x'_1, x'_2)]
 \end{aligned}$$

$$\mathcal{Q}_{x_g}(x_1, x_2; x'_2, x'_1) = \frac{1}{N_c} \left\langle \text{Tr} U(x_1) U^\dagger(x'_1) U(x'_2) U^\dagger(x_2) \right\rangle_{x_g} \quad S_{x_g}(x_1, x_2) = \frac{1}{N_c} \left\langle \text{Tr} U(x_1) U^\dagger(x_2) \right\rangle_{x_g}$$

## SIDIS and Total Cross Section

- Integrating over momenta identifies coordinates in the amplitude and conjugate amplitude
- SIDIS

$$1 + S_{x_g}(x_2, x'_2) - S_{x_g}(x_1, x_2) - S_{x_g}(x_1, x'_2)$$

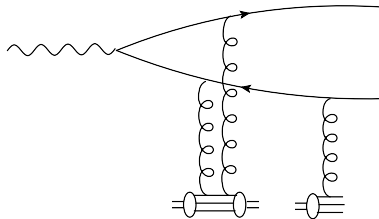
- Total cross section

$$2(1 - S_{x_g}(x_1, x_2))$$

- Quadrupole disappears and cross sections are written in terms of only dipole amplitudes
- Gluon distribution related to Fourier transform of dipole amplitude

## Gluon Distribution from DIS Dijet

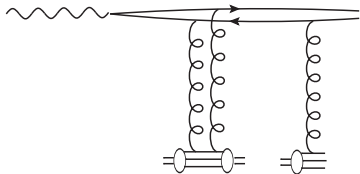
- Consider limit where two final particle are almost back-to-back
- Make separation between quark and antiquark small
- Singlet pair looks like a colorless object
- Octet pair looks like a gluon



FD, C. Marquet, B. Xiao, F. Yuan, 2011

## Gluon Distribution from DIS Dijet

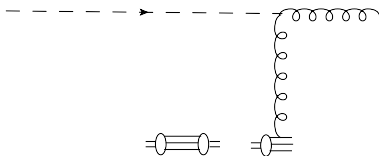
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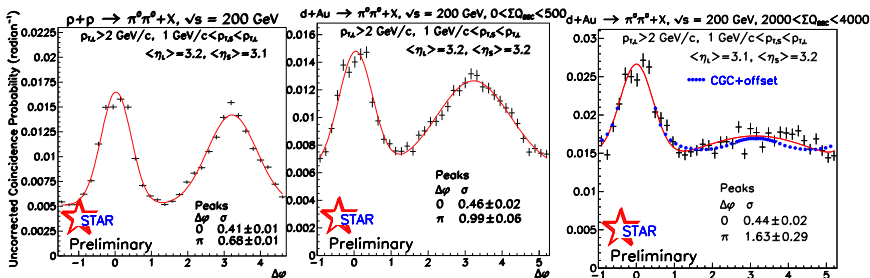
FD, C. Marquet, B. Xiao, F. Yuan, 2011

# pA Collisions

- Data available from RHIC (soon LHC)
- Single hadron production
  - Cronin effect
  - Suppression at large rapidities as compared to pp
- Di-hadron correlations

# Di-hadron correlations

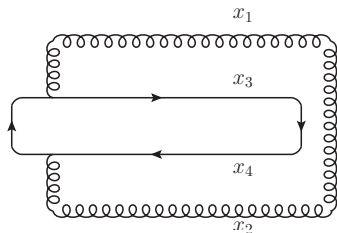
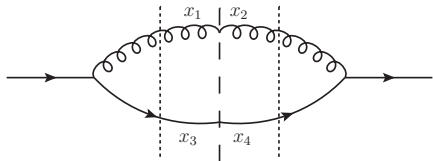
- Observed suppression of away side peak in azimuthal correlation in the forward region
- Considered strongest evidence of saturation so far



J. Albacete, C. Marquet, 2010



# Quark Initiated Processes



$$\text{Tr}[U(x_3)U^\dagger(x_4)T^a T^b]\tilde{U}_{ac}(x_1)\tilde{U}_{cb}^\dagger(x_2)$$

# Quark Initiated Processes - Large- $N_c$

Use Fierz identities

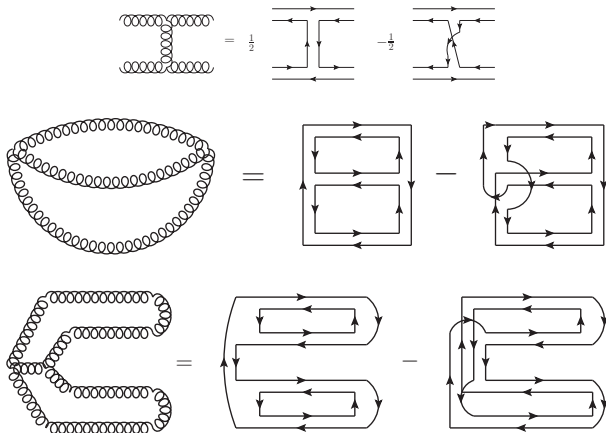
A diagrammatic equation showing the Fierz identity for two quark lines with a gluon exchange. On the left, two horizontal quark lines are connected by a vertical gluon loop (represented by a vertical line with five circles). This is equal to  $\frac{1}{2}$  times the sum of two diagrams: one where the quark lines cross each other, and another where they do not cross. The second diagram is multiplied by  $-\frac{1}{2N_c}$ .

A diagrammatic equation showing the Fierz identity for a rectangular loop with a gluon exchange. On the left, a rectangle with vertices  $x_1$  (top),  $x_2$  (bottom),  $x_3$  (right), and  $x_4$  (left). The top and bottom edges are gluon lines (represented by wavy lines), and the left and right edges are quark lines (represented by straight lines with arrows). This is equal to  $\frac{1}{2}$  times the sum of two diagrams: one where the quark lines cross each other, and another where they do not cross. The second diagram is multiplied by  $-\frac{1}{2N_c}$ .

Leading term:

$$\text{Tr}[U(x_1)U^\dagger(x_2)]\text{Tr}[U^\dagger(x_1)U(x_3)U^\dagger(x_4)U(x_2)]$$

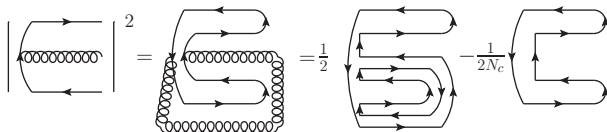
# Gluon Initiated Processes



# More Complicated Processes

Increasing the number of particles in the final state increases the complexity of the correlators?

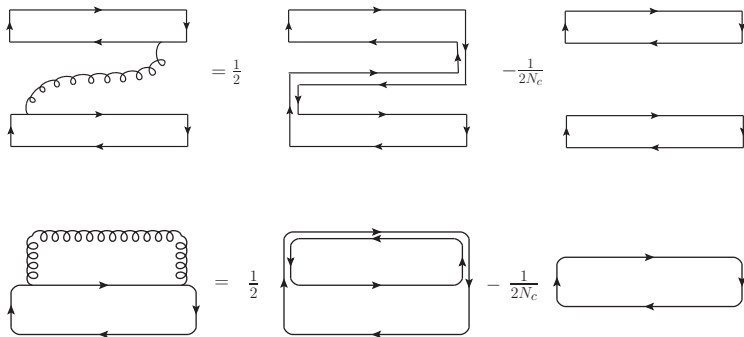
For example, look at DIS with one extra gluon:



The diagram shows a sequence of four Feynman diagrams representing the expansion of a correlator for DIS with one extra gluon. The first diagram is a simple electron-proton scattering diagram with a gluon loop. This is squared. The second diagram is a more complex diagram with multiple gluon lines. The third diagram is a diagram with a large number of gluon lines, and the fourth diagram is a diagram with a large number of gluon lines and a factor of  $-\frac{1}{2N_c}$ .

$$\left| \text{Diagram 1} \right|^2 = \text{Diagram 2} = \frac{1}{2} \text{Diagram 3} - \frac{1}{2N_c} \text{Diagram 4}$$

# Additional Gluons in Large- $N_c$ Limit



## Additional Gluons in Large- $N_c$ Limit

- Leading contribution comes from attaching both gluon legs to the same fermion loop
- Adding a gluon to either a dipole or a quadrupole gives only dipoles and quadrupoles in the large- $N_c$  limit
- In the large- $N_c$  limit, the only correlators needed to describe production of an arbitrary number of particles are the dipole and the quadrupole

FD, C. Marquet, B. Xiao, In preparation

## Conclusions

- The study of multi-particle production in asymmetric collisions can provide valuable information to determine the dynamics of the small- $x$  degrees of freedom in nuclei
- The large- $N_c$  limit greatly simplifies the description of such processes
- Further studies of the quadrupole amplitude are desirable
- Simplification of correlators in the large- $N_c$  limit is not a property of the CGC set-up and can be generalized to other cases of particles scattering in a background field configuration