Fluctuations of the multiplicity of produced particles in pA collisions

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Based on a work to appear (Phys Rev D, 2016) with Tseh Liou and A.H. Mueller

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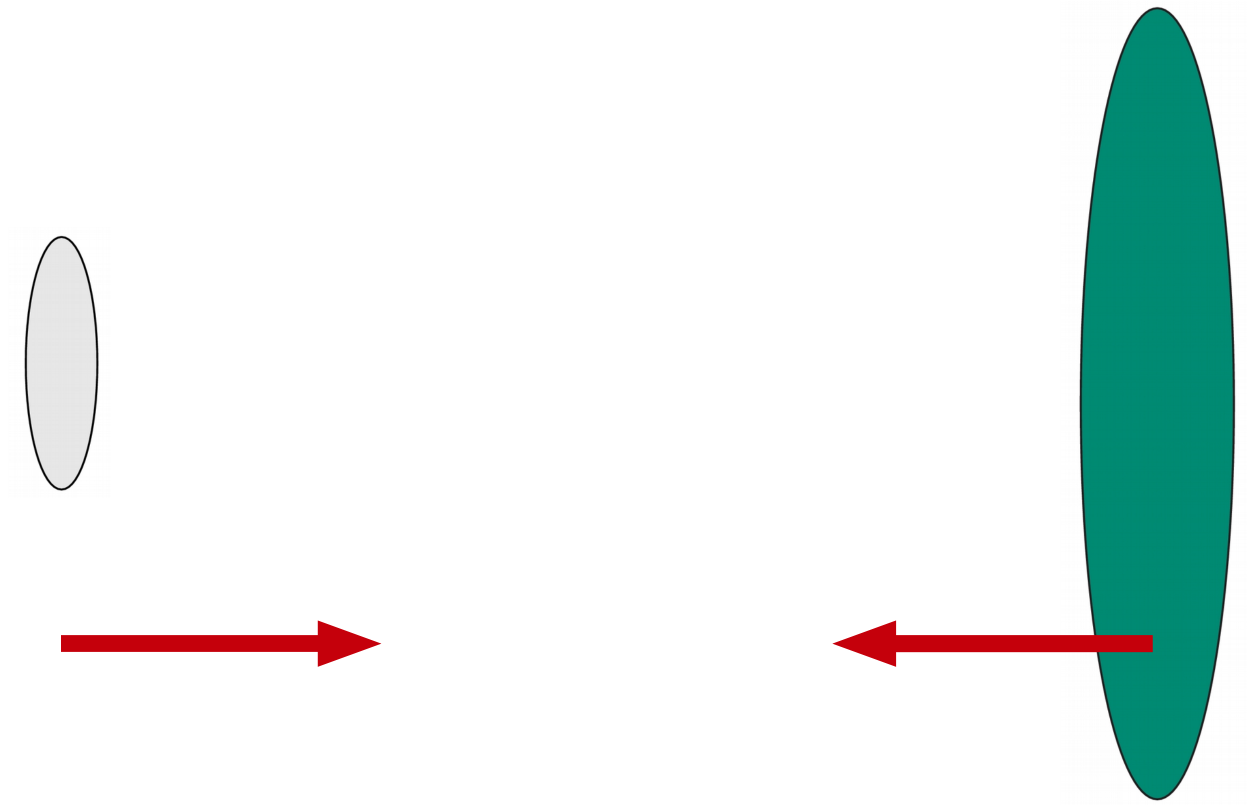
Observable

Consider proton-nucleus collisions



What is the distribution of the number of particles observed in the fragmentation region of the proton?

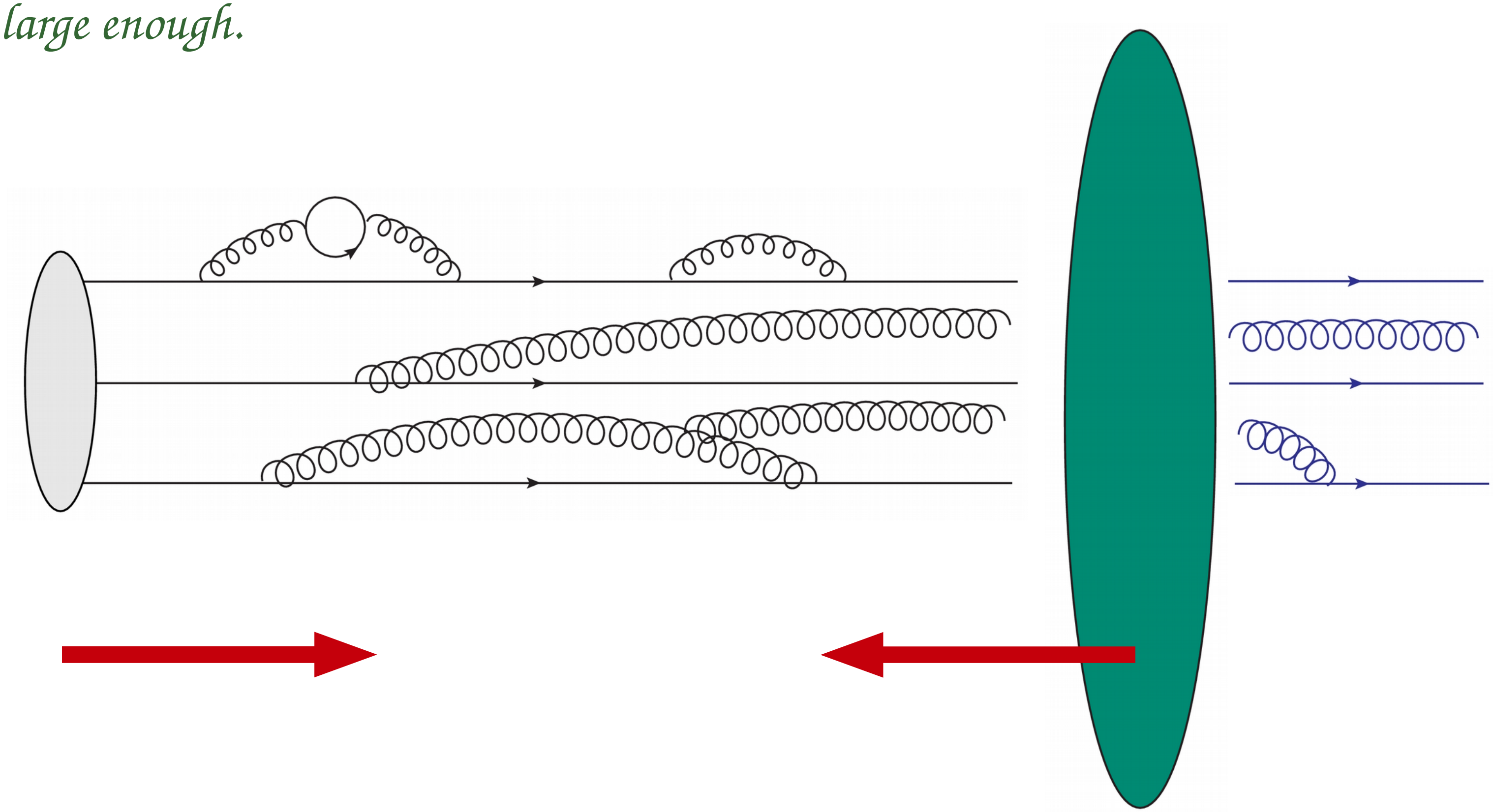
Outline

- Picture of particle production in pA collisions
- How a hadronic state dresses at high energies: the color dipole model
- Probability distribution of the particle multiplicity

Particle production in a dilute-dense collision

*The proton is an initially **dilute** object while the nucleus is a **dense** object, characterized by a saturation scale* Q_A

***At the time of the interaction:** The proton is in a given Fock state, **essentially made of gluons** if its rapidity is large enough.*

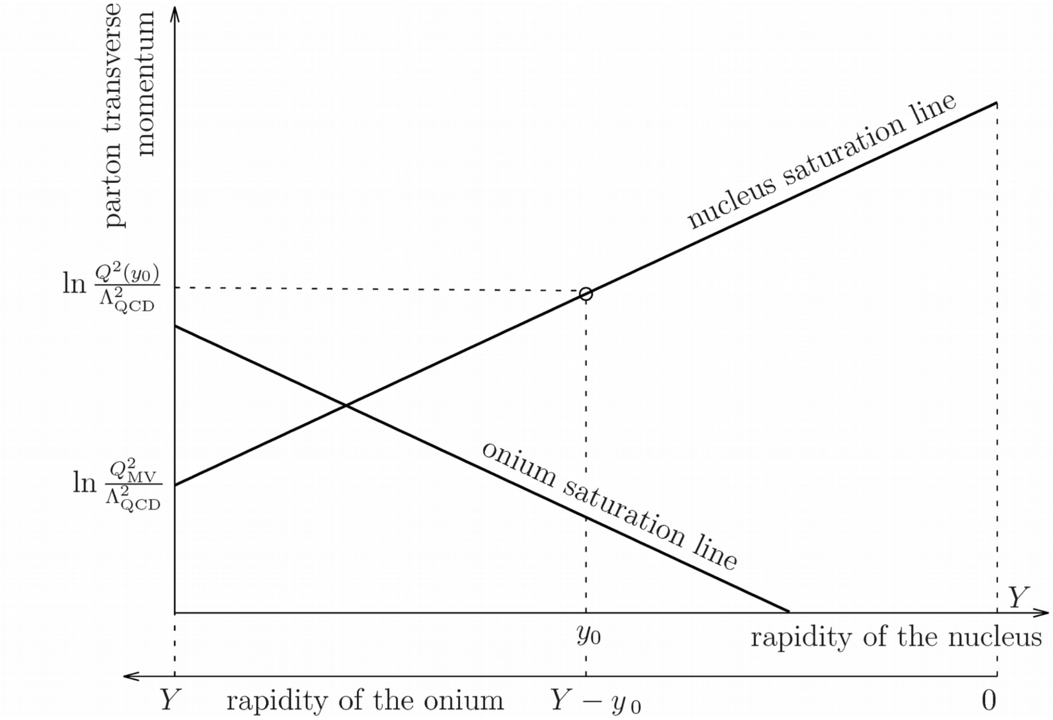


***Final state:** The gluons which have a transverse momentum less than* Q_A *are **freed** thanks to multiple scatterings with the nucleus and go the the final state (in the forward region of the proton), while the others essentially do not interact and just recombine.*

Particle production in a dilute-dense collision

As a model for a dilute system, we consider an **onium** (quark-antiquark pair in a color-singlet state)

We choose a frame in such that the saturation scale of the nucleus is much larger than that of the proton, and **look at central rapidity in that frame**.



The multiplicity of produced particles at central rapidity is related to the gluon density in the onium by

$$\frac{dN}{dy}(y \simeq 0) = x\, G(x, Q_A^2(y_0))$$

where $x = e^{-(Y-y_0)} \dfrac{Q_A(y_0)}{\text{onium mass}}$

The multiplicity measured in the onium/proton fragmentation region in an event is the gluon number density at the scale Q_A in the corresponding realization of the QCD evolution.

Let's try and understand theoretically the event-by-event fluctuations of this gluon density!

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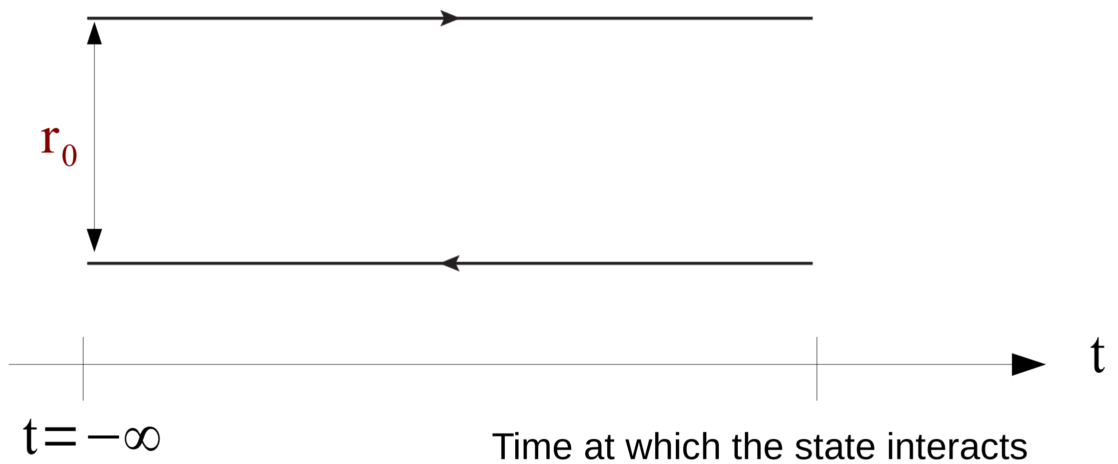
- Probability distribution of the particle multiplicity

QCD calculation: the color dipole model

*To simplify, we start with a **color neutral quark-antiquark pair** (=onium) of given transverse size.*

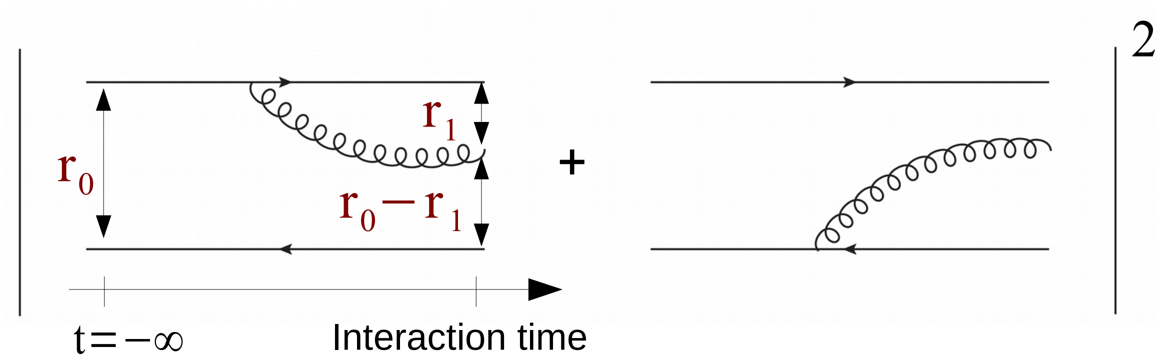


QCD calculation: the color dipole model

*To simplify, we start with a **color neutral quark-antiquark pair** (=onium) of given transverse size.*

*Probability of observing 1 gluon fluctuation when one increases the rapidity from **0** to **dy**:*

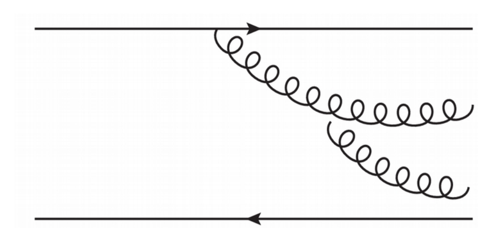
$dP =$



$r_1 =$ position of the gluon with respect to the quark

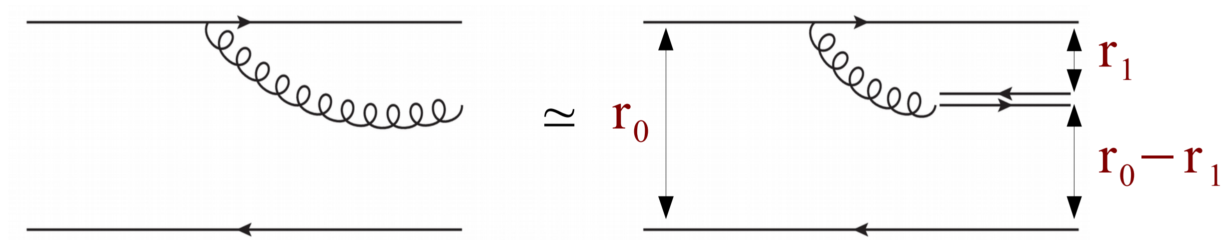
$$= \quad dy \, \frac{\alpha_s (N_c^2 - 1)}{\pi N_c} \, \frac{r_0^2}{r_1^2 (r_0 - r_1)^2} \, \frac{d^2 r_1}{2\pi}$$

For finite rapidities, one needs to consider higher-orders:



QCD calculation: the color dipole model

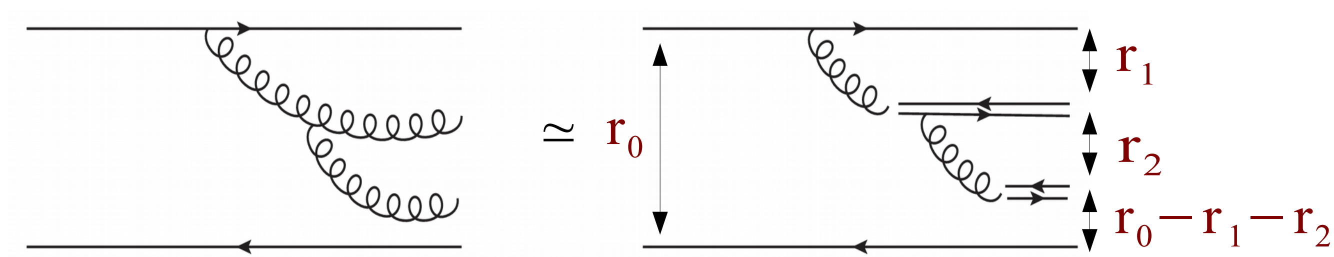
Trick: ***large number-of-color limit!***



Gluon emission is interpreted as a color-dipole splitting, with proba.

$$dP = dy \, \frac{\alpha_s N_c}{\pi} \, \frac{r_0^2}{r_1^2 (r_0 - r_1)^2} \, \frac{d^2 r_1}{2\pi}$$

Higher-order fluctuations are generated by a branching process:

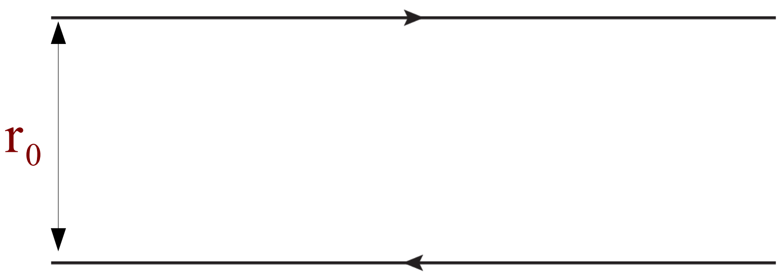


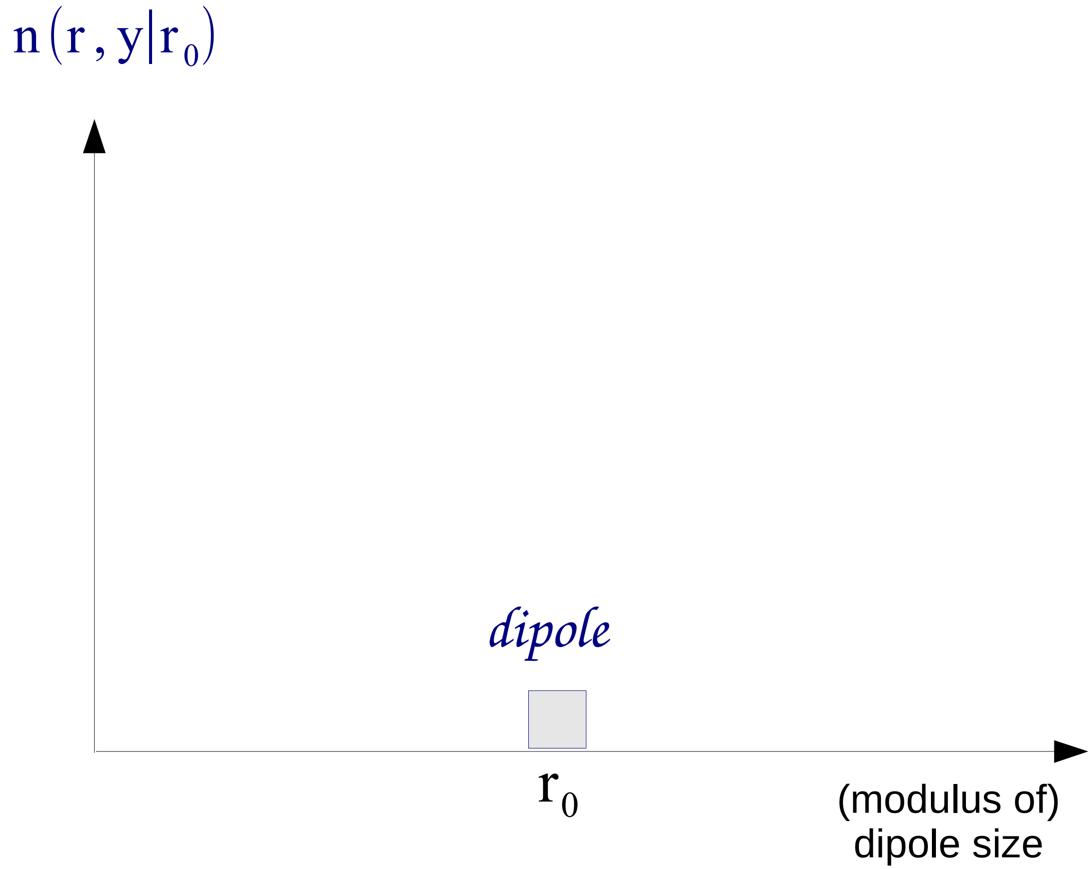
Two successive dipole branchings

$x\,G(x, k^2) \sim$ ***density of dipoles of size*** $1/k$ ***after evolution over the rapidity*** $y = \log 1/x$

How the dipole model works

$$dP = dy\,\frac{\alpha_s N_c}{\pi}\,\frac{r_0^2}{r_1^2 (r_0 - r_1)^2}\,\frac{d^2 r_1}{2\pi}$$



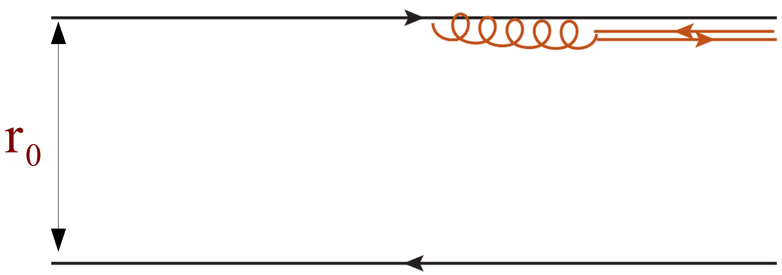


$y = 0$

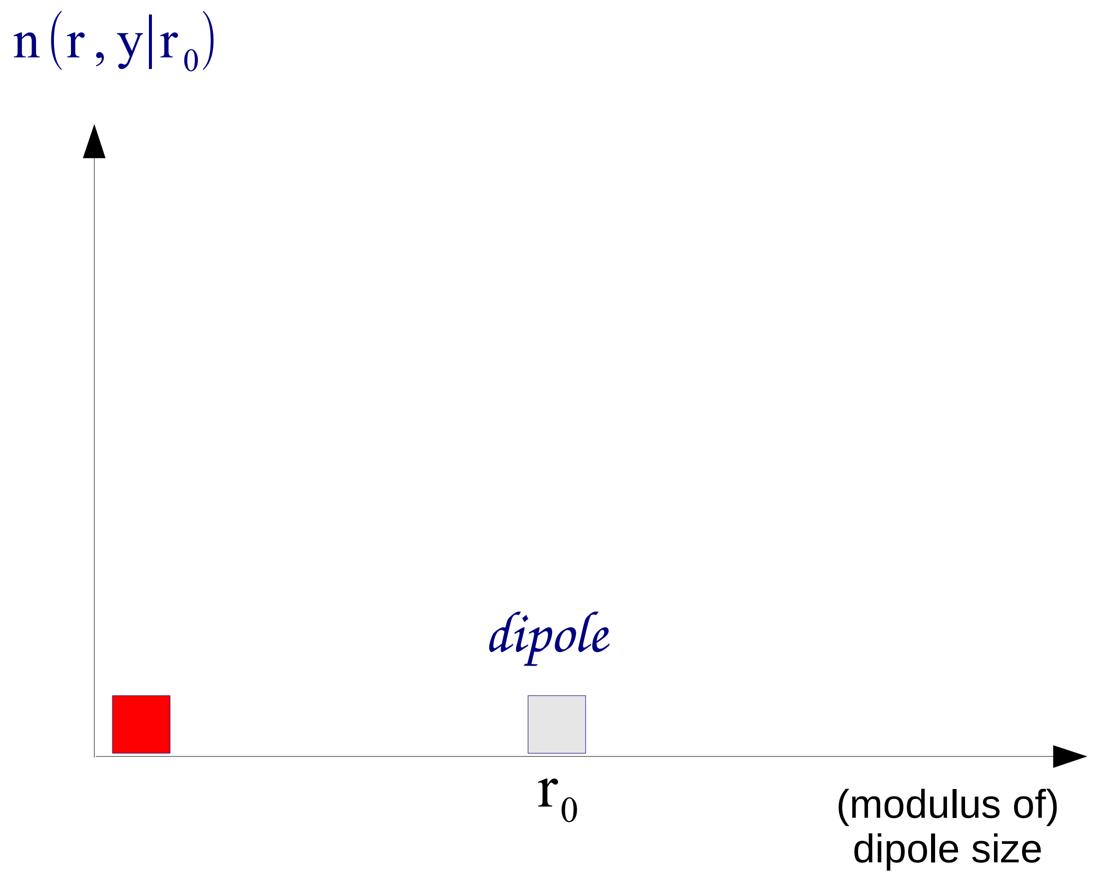
How the dipole model works

$$dP = dy\,\frac{\alpha_s N_c}{\pi}\,\frac{r_0^2}{r_1^2 (r_0 - r_1)^2}\,\frac{d^2 r_1}{2\pi}$$

Singular when the gluon is close
to the quark or to the antiquark
Collinear singularity



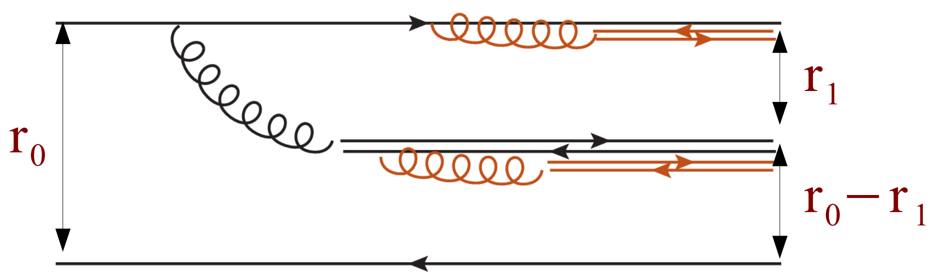
The small-dipole size region gets very easily populated



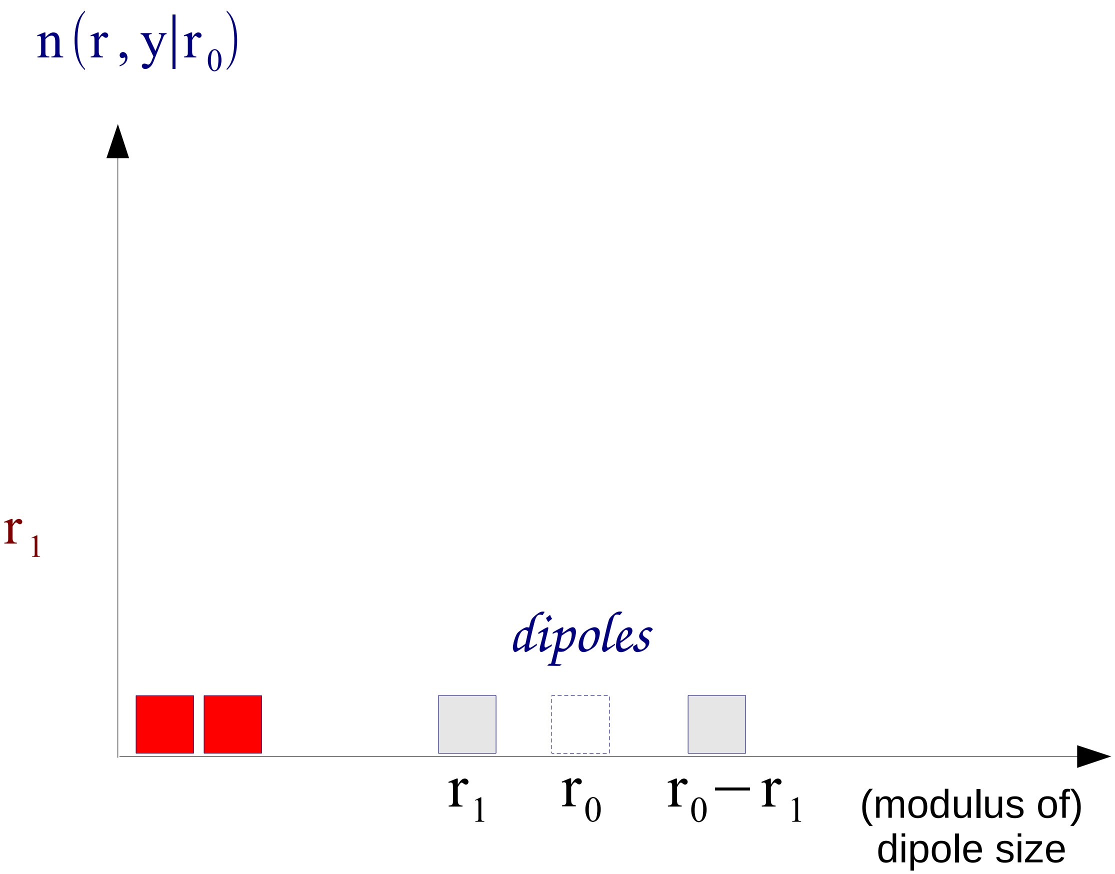
$y \geq 0$

How the dipole model works

$$dP = dy\,\frac{\alpha_s N_c}{\pi}\,\frac{r_0^2}{r_1^2 (r_0 - r_1)^2}\,\frac{d^2 r_1}{2\pi}$$



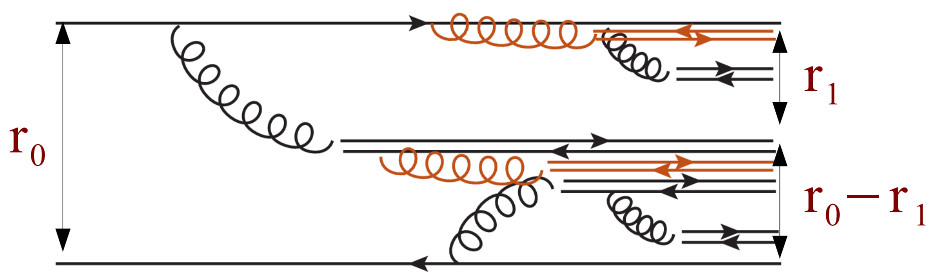
Dipoles of size of the order of the size of the initial dipole (are larger) need sone finite rapidity to get produced



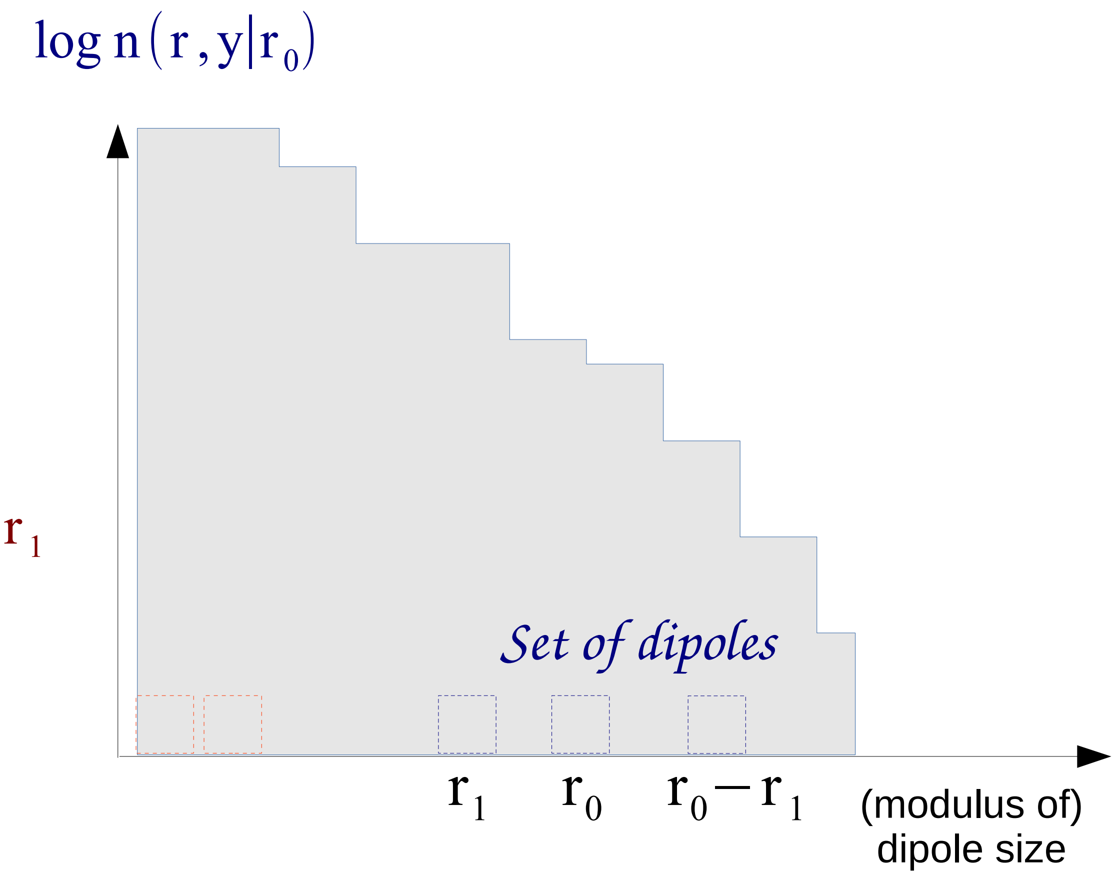
$$y \sim \frac{1}{\alpha_s N_c / \pi}$$

How the dipole model works

$$dP = dy\,\frac{\alpha_s N_c}{\pi}\,\frac{r_0^2}{r_1^2 (r_0 - r_1)^2}\,\frac{d^2 r_1}{2\pi}$$



The total number of dipoles grows exponentially with rapidity through a branching process



$$y \gg \frac{1}{\alpha_s N_c / \pi}$$

How the dipole model works

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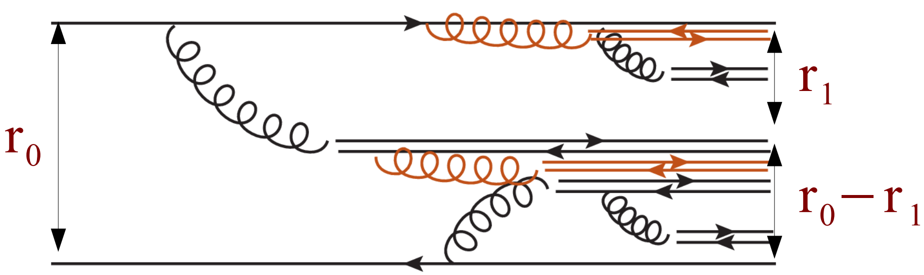
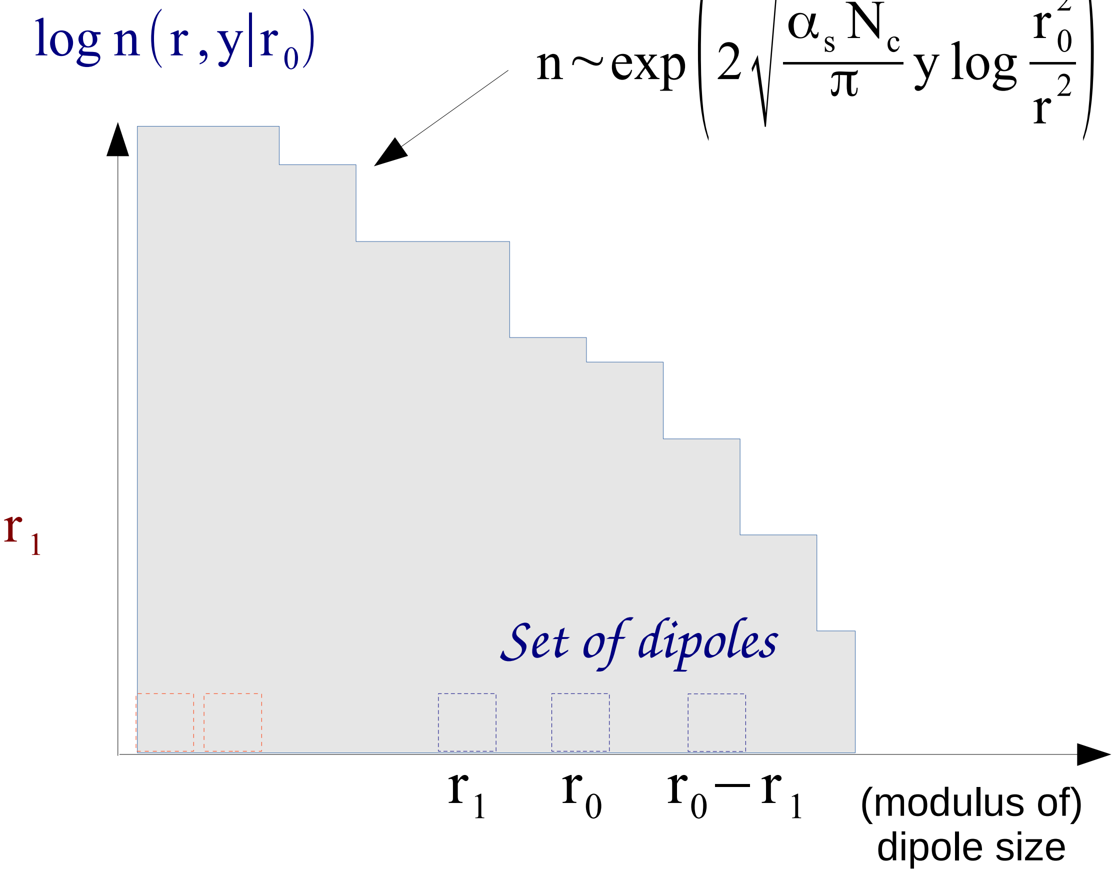


The total number of dipoles grows exponentially with rapidity through a branching process

$$n \sim \exp\left(2\sqrt{\frac{\alpha_s N_c}{\pi}\, y \log\frac{r_0^2}{r^2}}\right)$$



$$y \gg \frac{1}{\alpha_s N_c/\pi}$$

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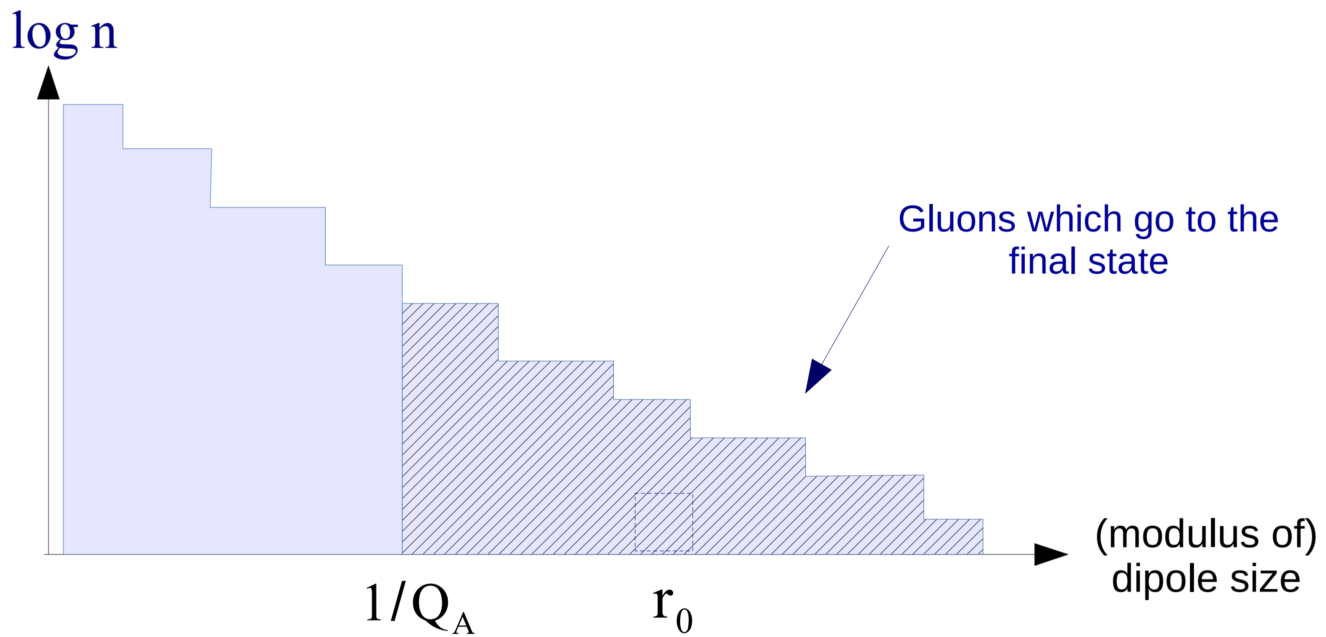
Dipole-nucleus scattering: total multiplicity

$$\frac{dN}{dy}(y \simeq 0) = x\,G\left(x, Q_A^2(y_0)\right) \quad \text{where} \quad x = e^{-(Y-y_0)} \frac{Q_A(y_0)}{\text{onium mass}}$$



*The **gluons which go to the final state**, i.e. which are freed in the scattering, correspond to **dipoles which have a size larger than the inverse saturation scale of the nucleus.***

Dipole-nucleus scattering: total multiplicity

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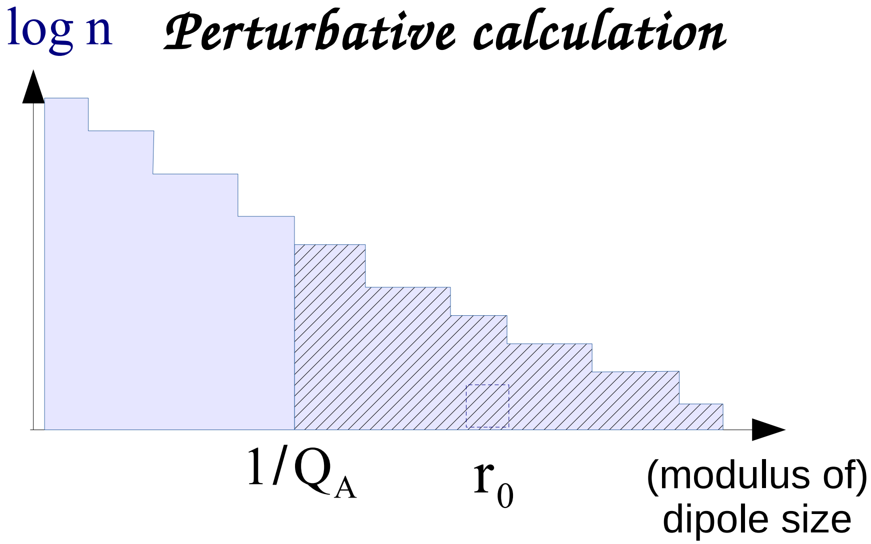

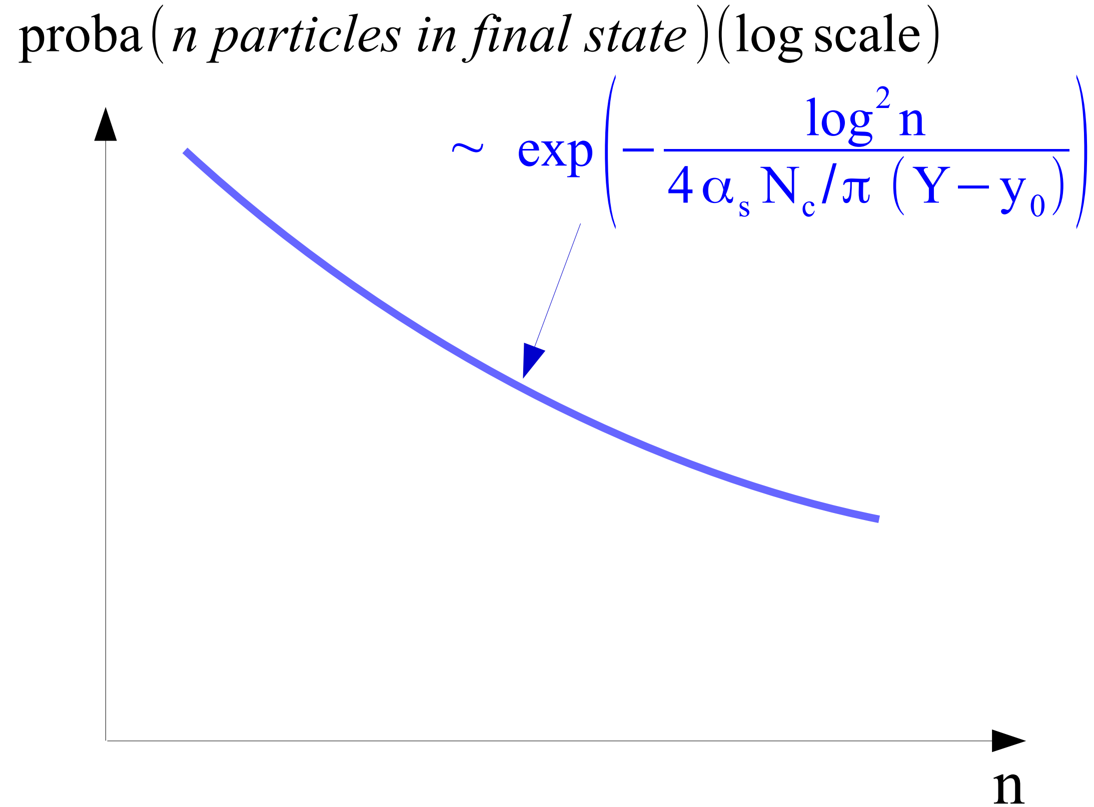

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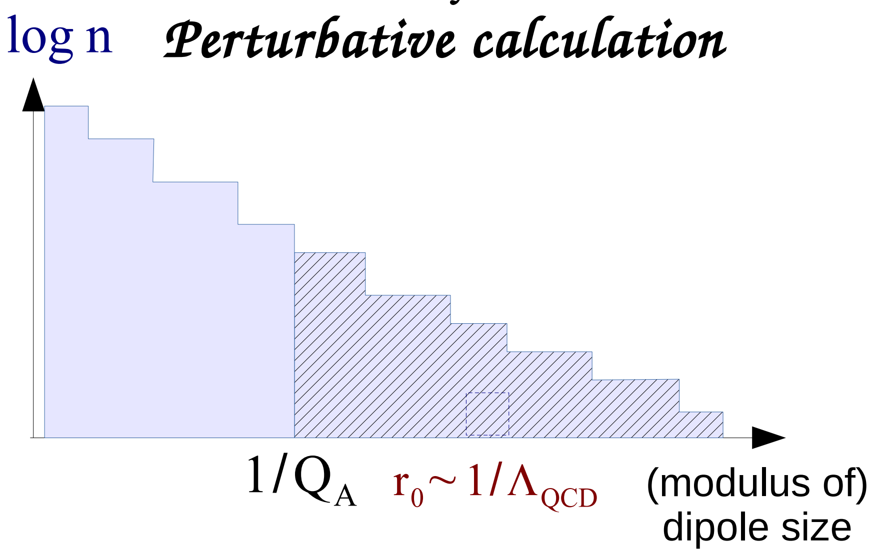
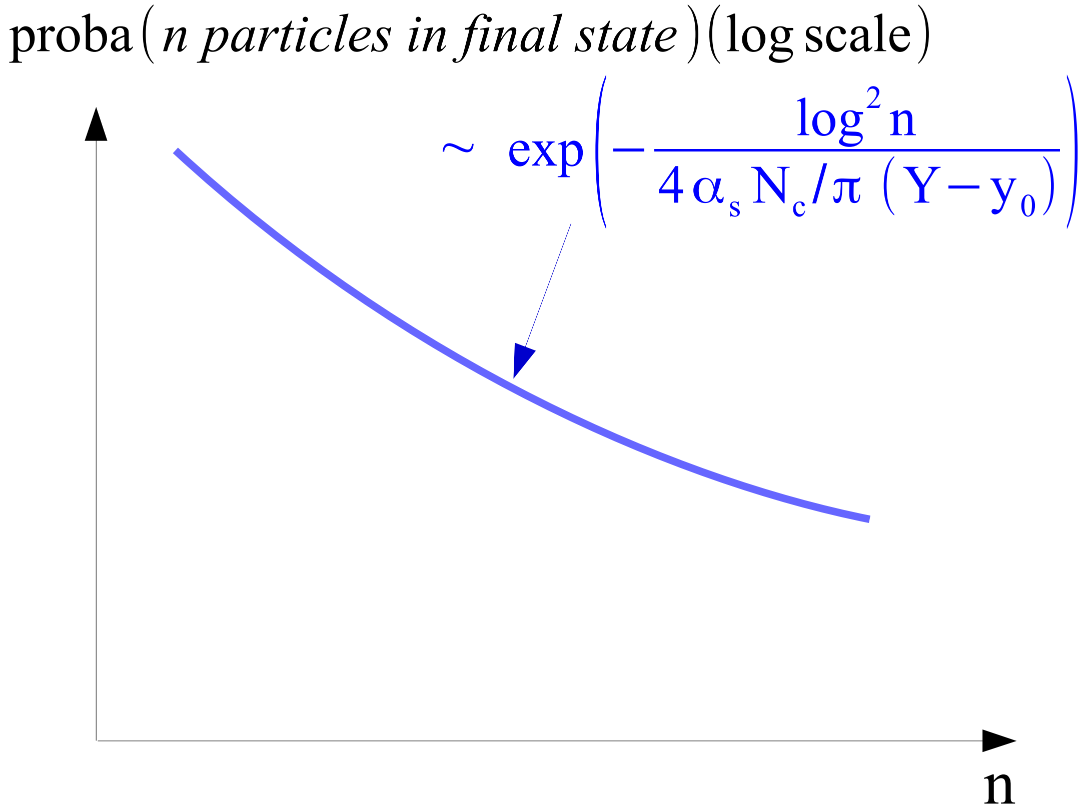
Perturbative calculation



But in pA, the "dipole" is a proton!



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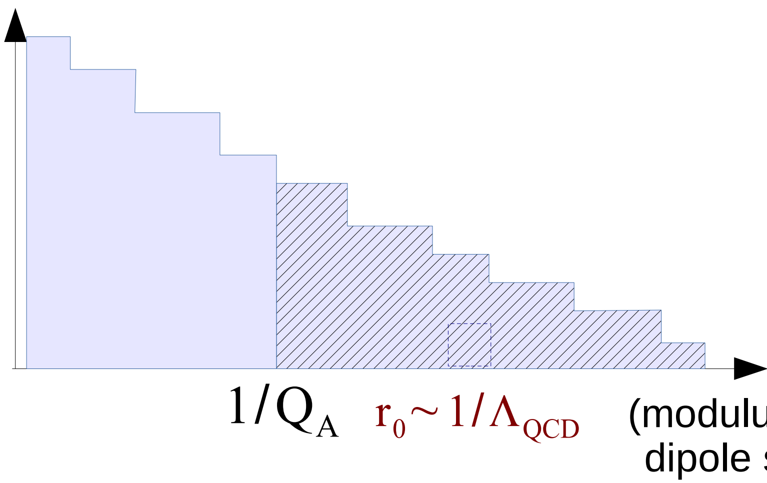
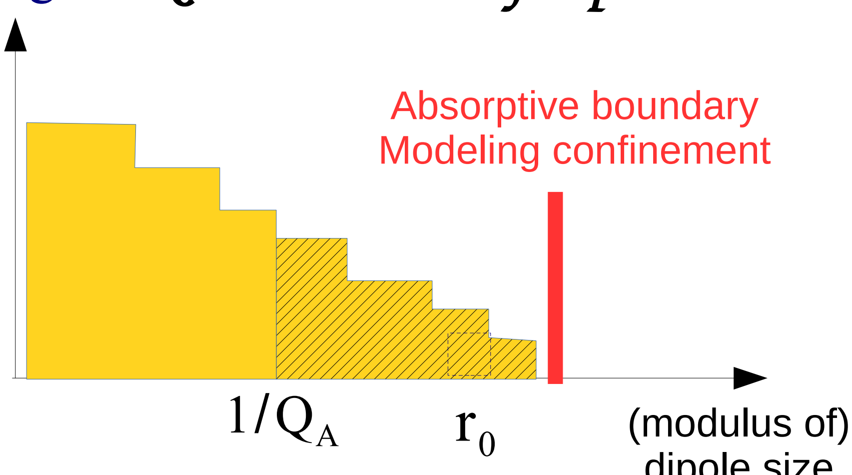
log n ***Perturbative calculation***

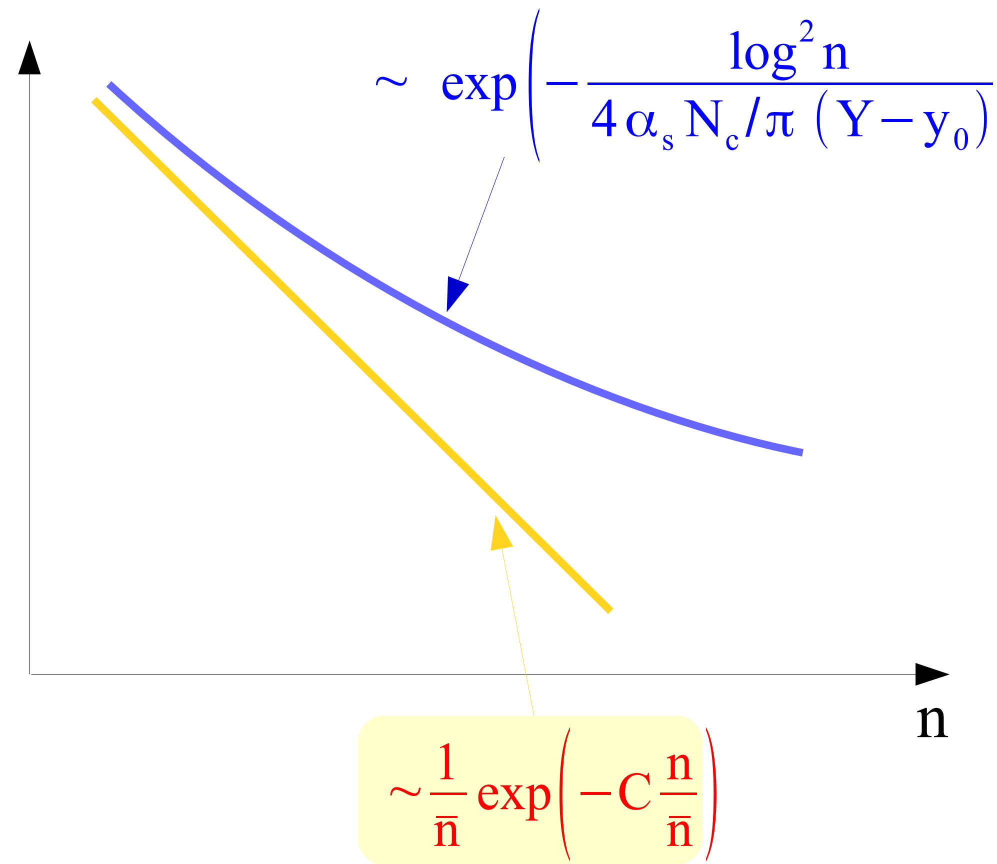


But in pA, the "dipole" is a proton!

log n ***Realistic model for pA***



proba(*n particles in final state*)(log scale)



Consistent with the data?

Work in progress: How much does C depend on the details of confinement?

Summary

- At high energies, **hadrons look like dense states of gluons** (sometimes called "color glass condensates"), very far from the valence picture. This is a property of QCD.
- The (stochastic) evolution of hadronic wave functions towards high energy can be computed in QCD. The **color dipole model** is a convenient implementation of this evolution.
- **Fluctuations of the multiplicity in pA scattering in the proton fragmentation region can be related to the *event-by-event fluctuations of the total integrated gluon density in the proton*!** pA data at the LHC is a great opportunity to study these fluctuations!

Outlook

- Better understand the fluctuations in the dipole model+confinement - test robustness of our solution
- Try and build a realistic model for phenomenology (proton instead of onium etc...)