Small-x Physics at the LHC

Gatchina, April 28, 2011
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Introduction

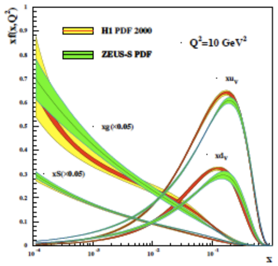
QCD at the LHC: more than background to new physics

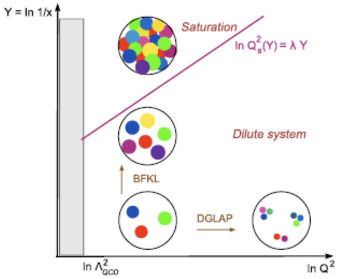
collinear factorization (DGLAP) $\longrightarrow$ BFKL $\longrightarrow$ multiple interactions, $\longrightarrow$ saturation $\longrightarrow$ Soft physics

- structure functions at small x: first step is BFKL
- BFKL at the LHC
- Beyond BFKL: theoretical aspects
- saturation at HERA
- saturation at the LHC
- multiple interactions: theoretical remarks

I.Structure functions at small x: BFKL

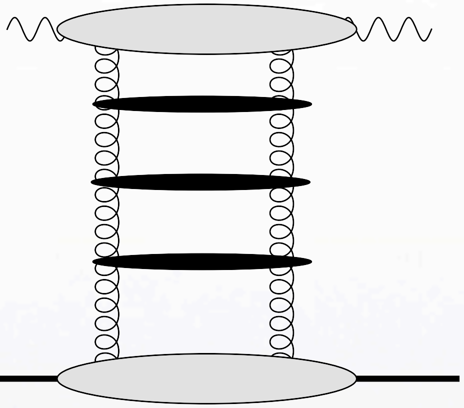
DGLAP versus BFKL:





$$\frac{\partial}{\partial \ln Q^2} f_i(x,Q^2)$$

$$= (K_{DGLAP)} \otimes f_i)(x,Q^2)$$



$$\frac{\partial}{\partial \ln 1/x} g(k_t^2,x)$$

$$= (K_{BFKL} \otimes g)(k_t^2,x)$$

ordering in Q^2

ordering in x

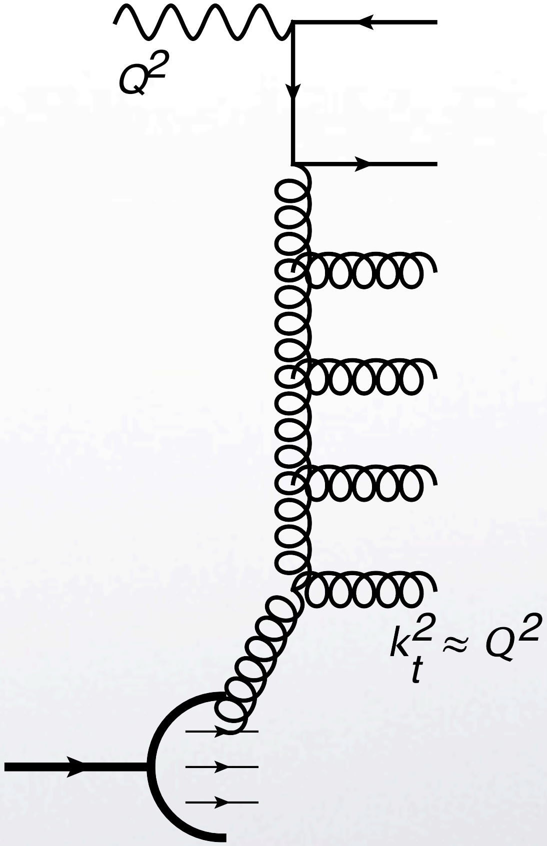
DGLAP: $\ln Q^2/\Lambda^2 \gg \ln 1/x$

BFKL: $\ln 1/x \gg \ln Q^2/\Lambda^2$

at small x and low Q^2 : BFKL takes over

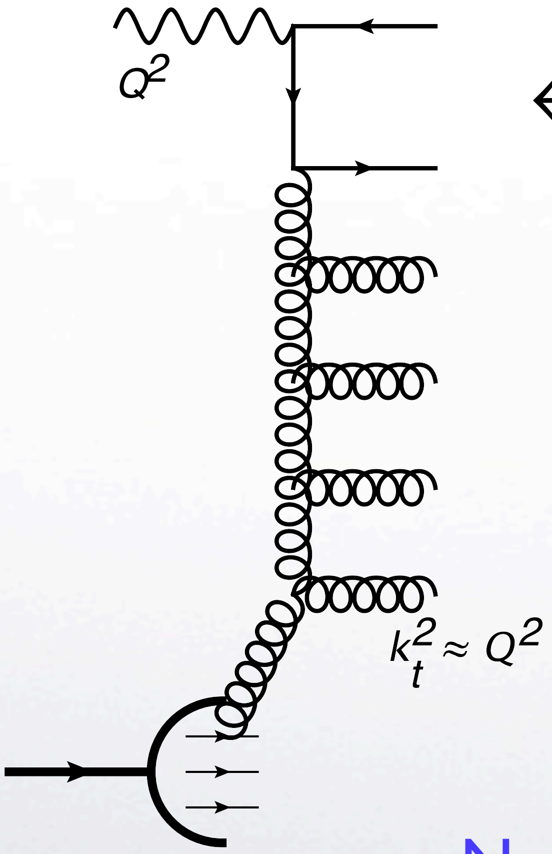
More about BFKL:

- successful fits to F_2 (e.g. Kowalski,Lipatov,Ross)
- BFKL resummation in DGLAP splitting functions (e.g. Colferai et al,; Forte et al.; Thorne at al.): improves DGLAP at small x.
- forward jets: special kinematics for BFKL test. DGLAP fails



At small x:
there is BFKL!

Status of NLO calculations:



← NLO photon impact factor

JB,Chachamis, Gieseke
Kyrieleis,Qiao;
Balitsky,Chirilli

← NLO BFKL kernel

Fadin, Lipatov

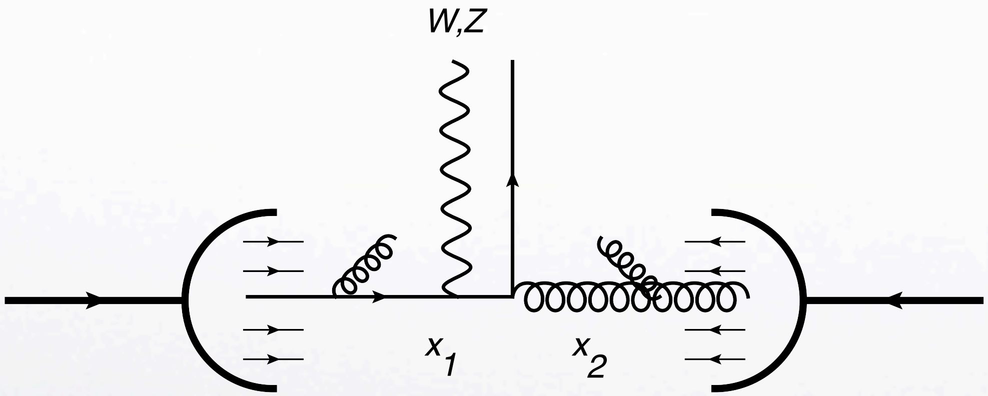
← jet vertex

JB, Colferai,Vacca

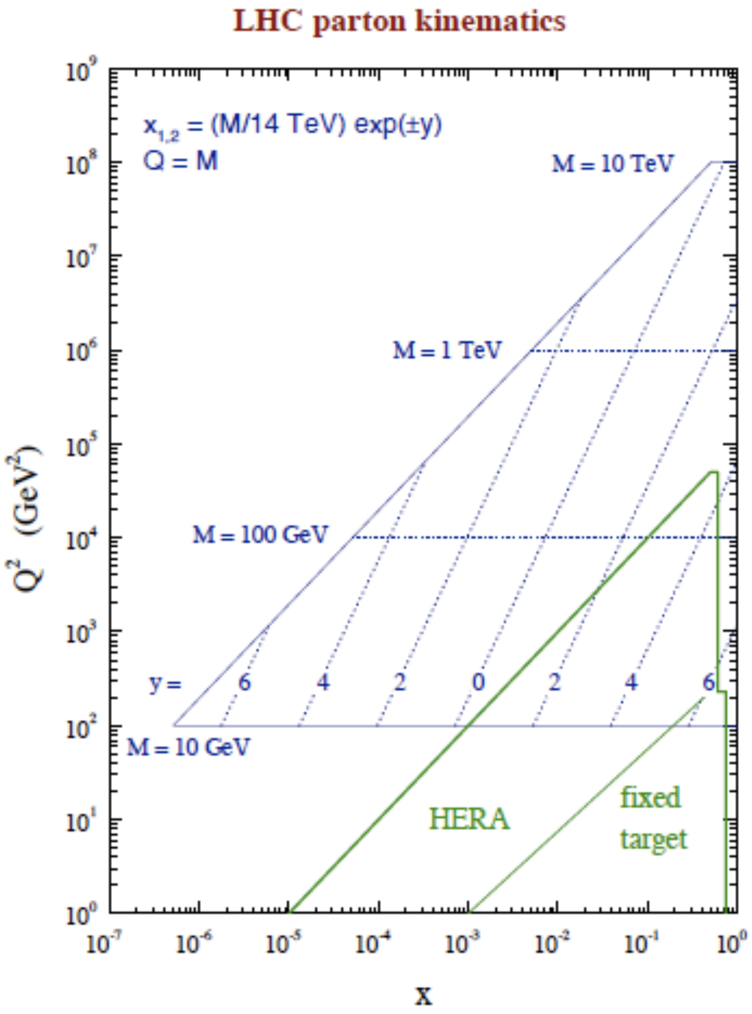
Needs numerical work!

2. Small-x sf, BFKL at the LHC

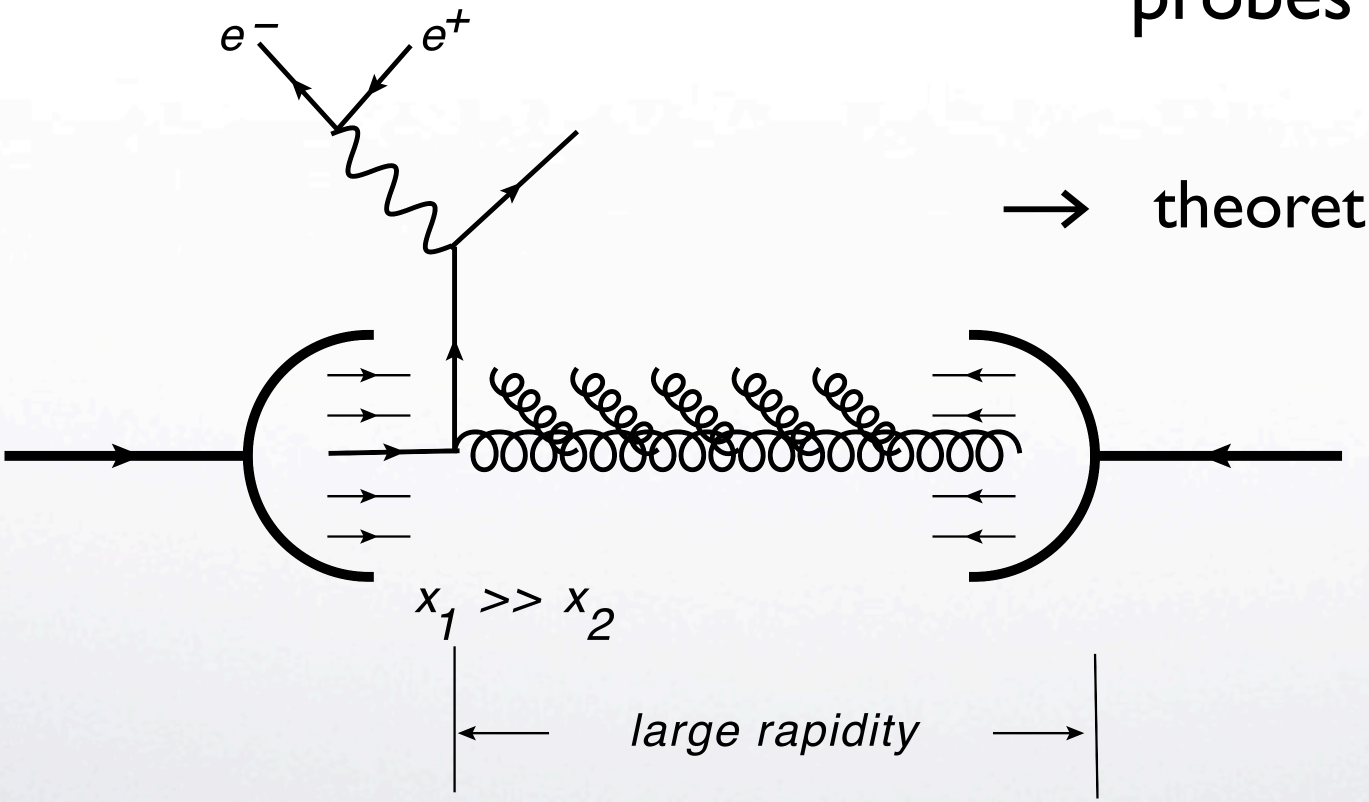
Where would we expect to see signals of small-x deviations: forward direction



$$x_1 \gg x_2$$



1) Dedicated small x: Drell-Yan near forward direction:



probes very small x_2

→ theoretical remark later

kinematic reach:

T.Shears, ISMD 2008

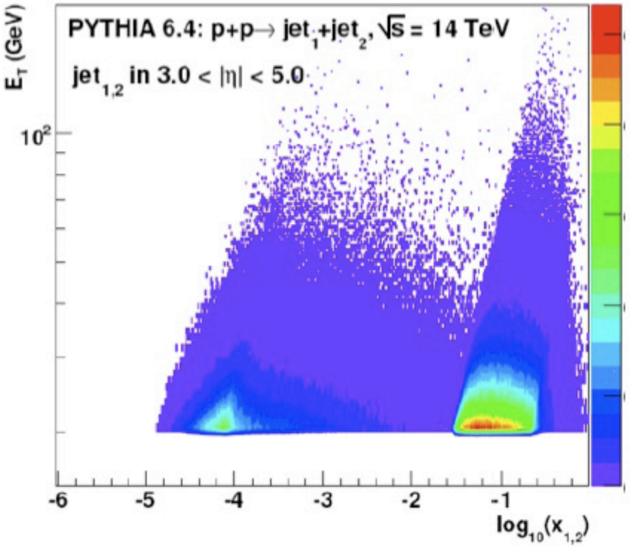


Fig. 2: Range of x probed in forward jet production with CMS, shown as a function of the transverse energy of the jet.

Drell-Yan, CMS:

$$5.2 < |\eta| < 6.5$$

$$x \geq 10^{-6}$$

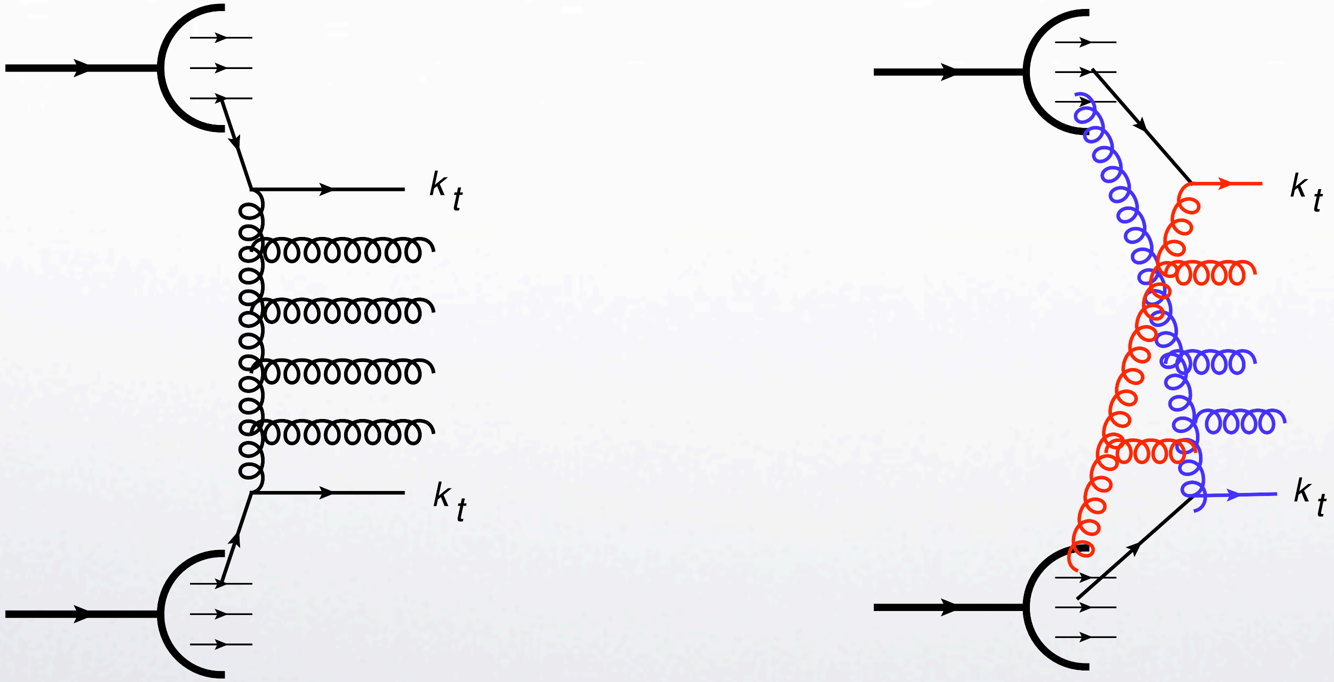
too optimistic?

2) Dedicated BFKL measurements:

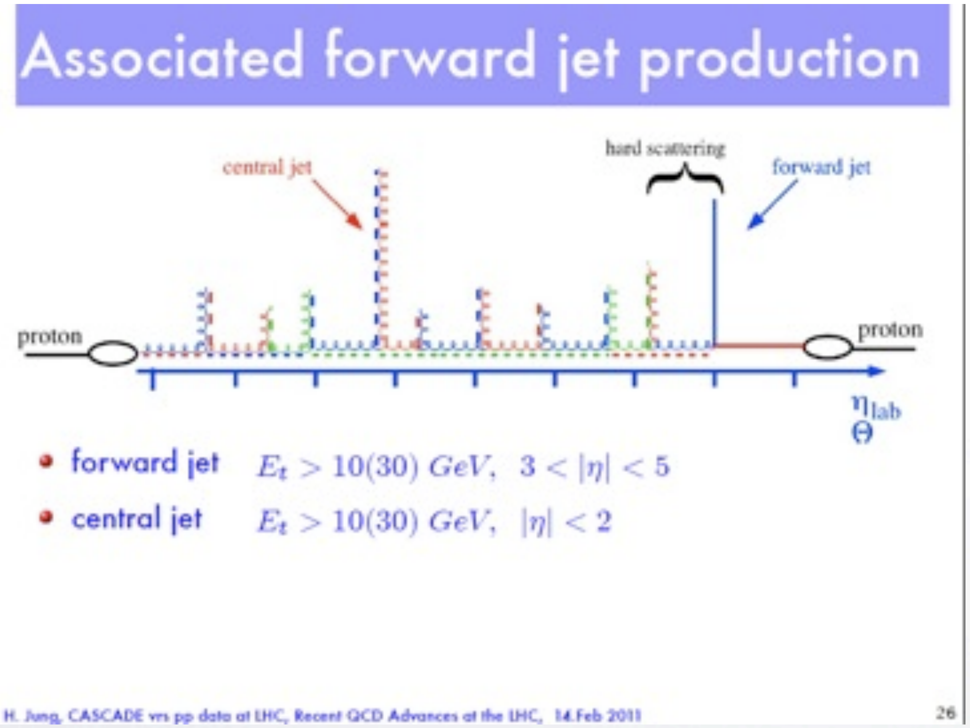
BFKL based Monte Carlo

Sabio-Vera

- Mueller Navelet jets: energy dependence, angular decorrelation



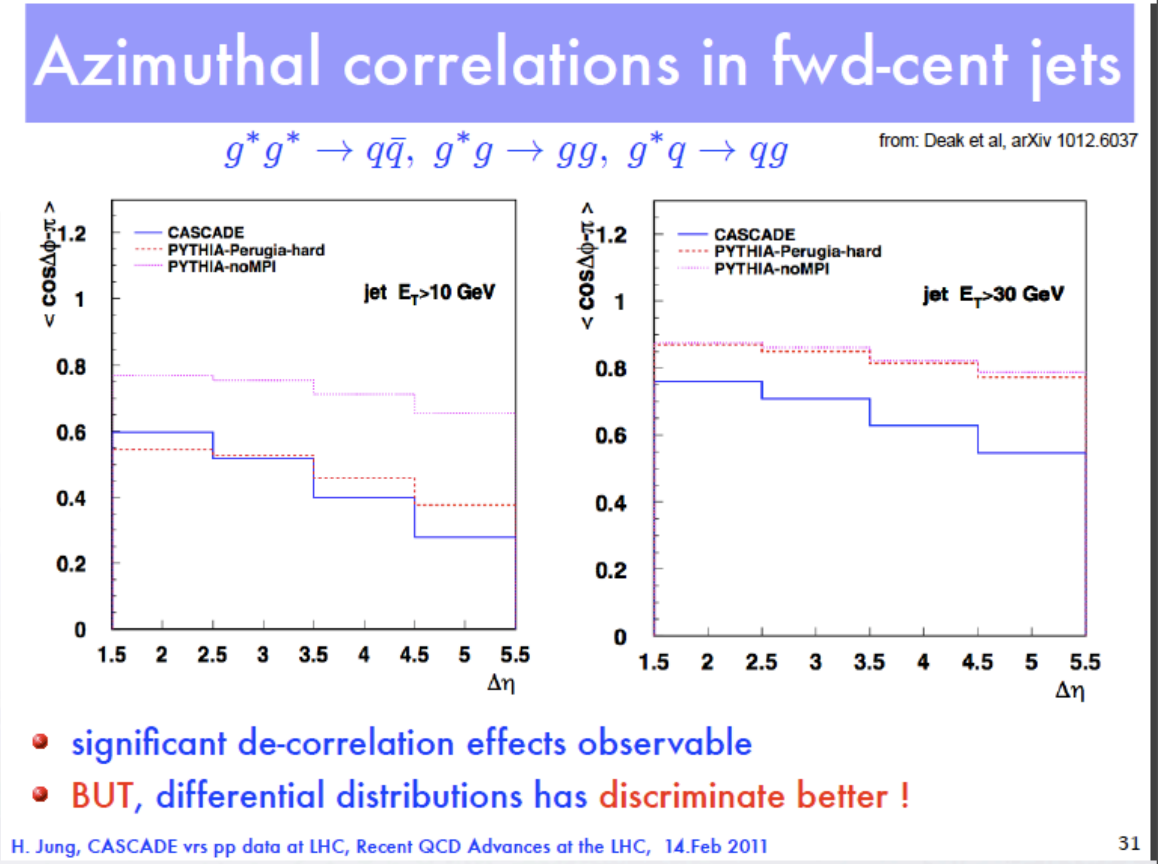
Potential importance of multiparton correction as function of E_T:



Associated forward jet production

- forward jet $E_t > 10(30)\ GeV,\ \ 3 < |\eta| < 5$
- central jet $E_t > 10(30)\ GeV,\ \ |\eta| < 2$

H. Jung, CASCADE vrs pp data at LHC, Recent QCD Advances at the LHC, 14.Feb 2011 26



Azimuthal correlations in fwd-cent jets

$g^* g^* \to q\bar{q},\ g^* g \to gg,\ g^* q \to qg$

from: Deak et al, arXiv 1012.6037

- significant de-correlation effects observable
- BUT, differential distributions has discriminate better !

H. Jung, CASCADE vrs pp data at LHC, Recent QCD Advances at the LHC, 14.Feb 2011 31

BFKL energy dependence: make use of different machine energies

Colferai et al.

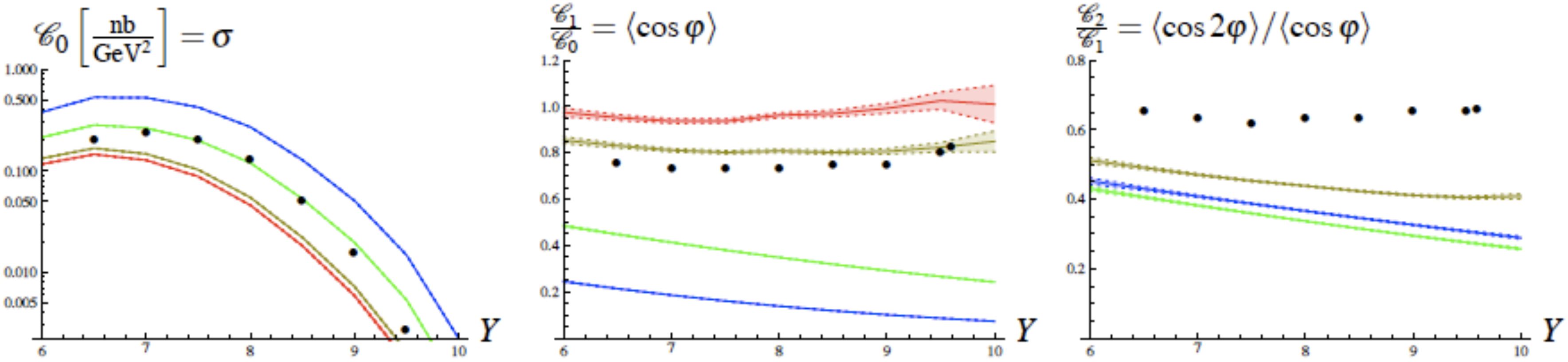


Figure 1: Differential cross section (a), azimuthal correlation $\langle\cos\varphi\rangle$ (b) and ratio $\langle\cos 2\varphi\rangle/\langle\cos\varphi\rangle$ (c) in dependence on Y for $|\mathbf{k}_{J,1}| = 35\,\text{GeV}$, $|\mathbf{k}_{J,2}| = 50\,\text{GeV}$. The errors due to the Monte Carlo integration are given as error bands. As dots are shown the results of Ref. [18] obtained with DIJET [19].

Y dependence is combination of
BFKL and parton densities:

Instead: fix x of parton densities,
vary machine energies

(Tevatron)

3. Beyond BFKL: Theoretical remarks

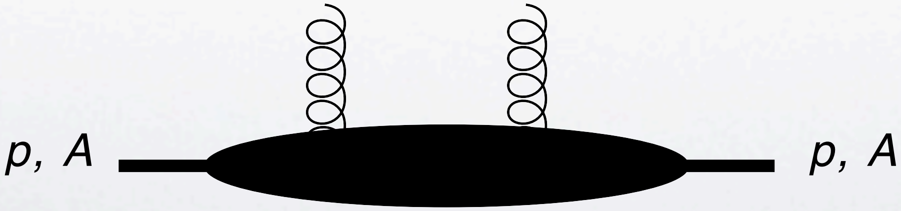
Gribov
Lipatov
JB
...

What comes beyond BFKL: QCD reggeon field theory.

Saturation: quantity of interest ='dipole cross sections'

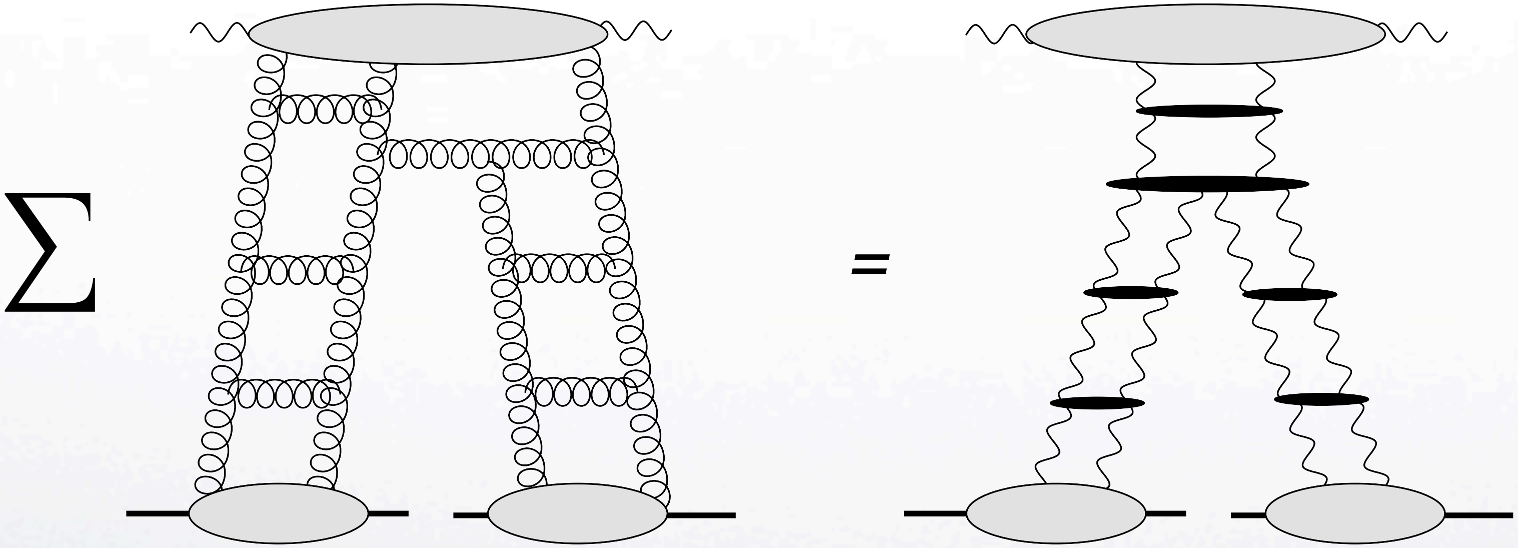
$$< p|A(y,p_1)A(y,p_2)|p >$$

$$< nucleus|A(y,p_1)A(y,p_2)|nucleus >$$



Why so simple?

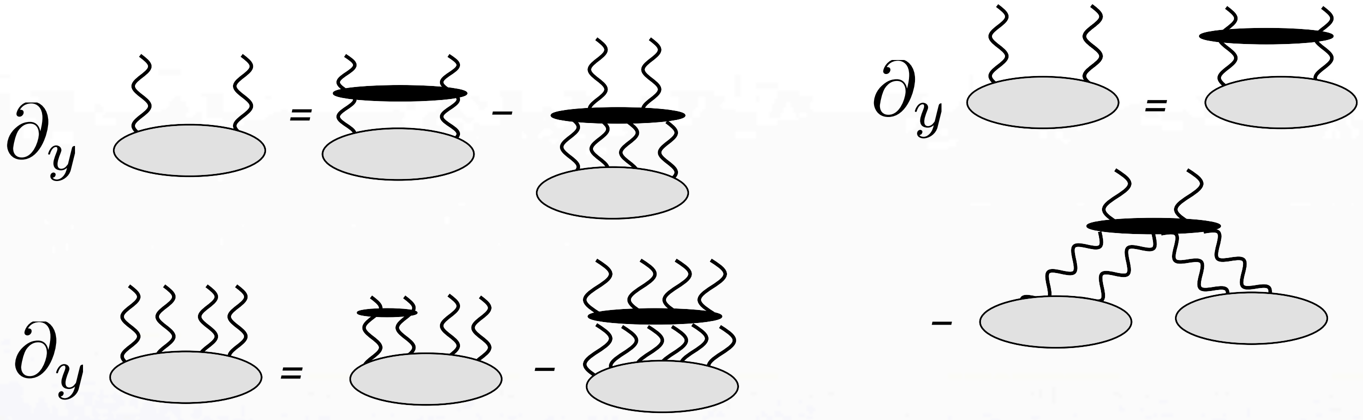
1. Stimulated by DIS → color dipoles



coupling to dipole (quark loop) only through two gluons
reggeization of gluon - unclear in color dipole approach

II. Mean field approximation

Coupled system of equations:



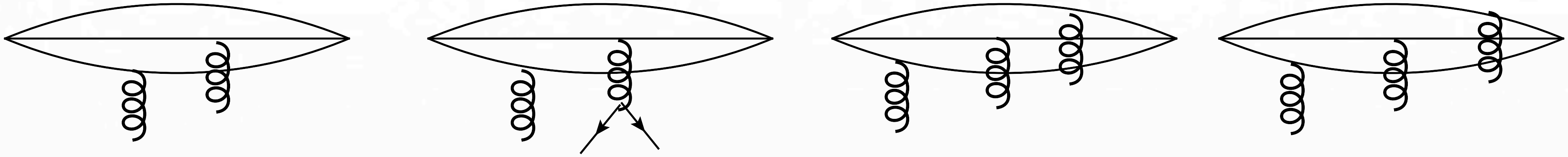
. . .

Mean field approximation leads to nonlinear equation (BK-equation):

$$< p|A(y,p_1)A(y,p_2)A(y,p_3)A(y,p_4)|p >=$$
$$< p|A(y,p_1)A(y,p_2)|p >< p|A(y,p_3)A(y,p_4) >$$

Where do we need higher correlators:

1. Baryons: not only dipoles (diquarks) JB, Motyka



dipole

dipole +reggeization

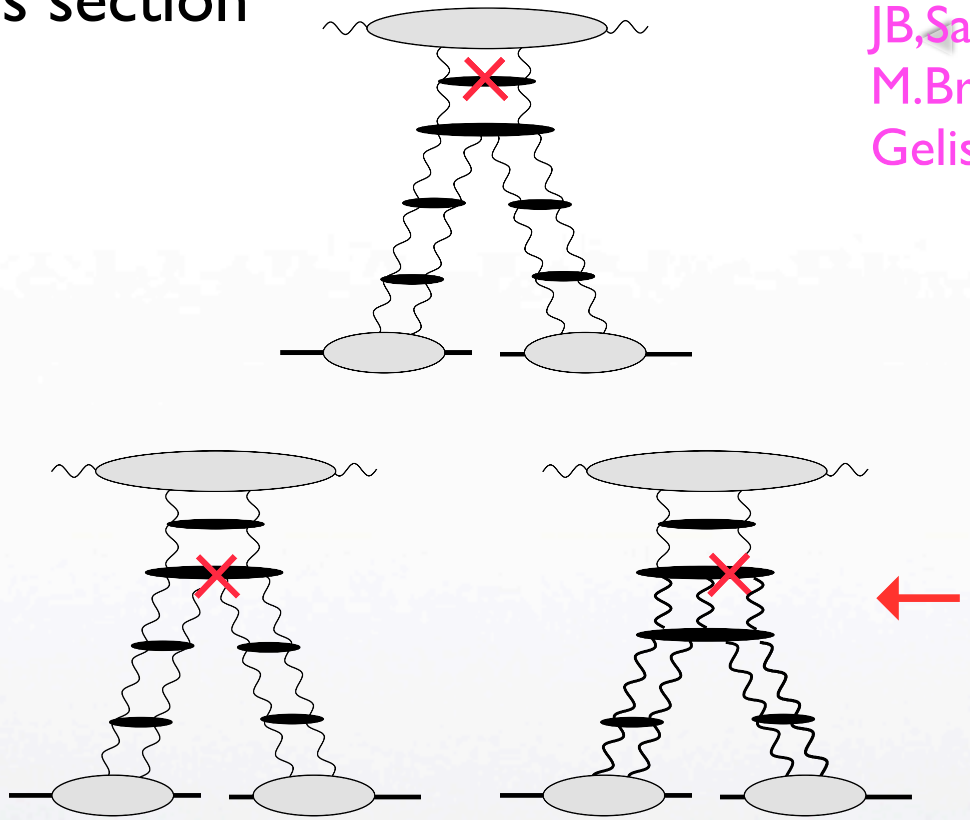
C even: new baryonic confg.

C odd: Odderon

→ need 3 gluon correlator, not obtained within JIMWLK/Balitsky

II. Inclusive cross section

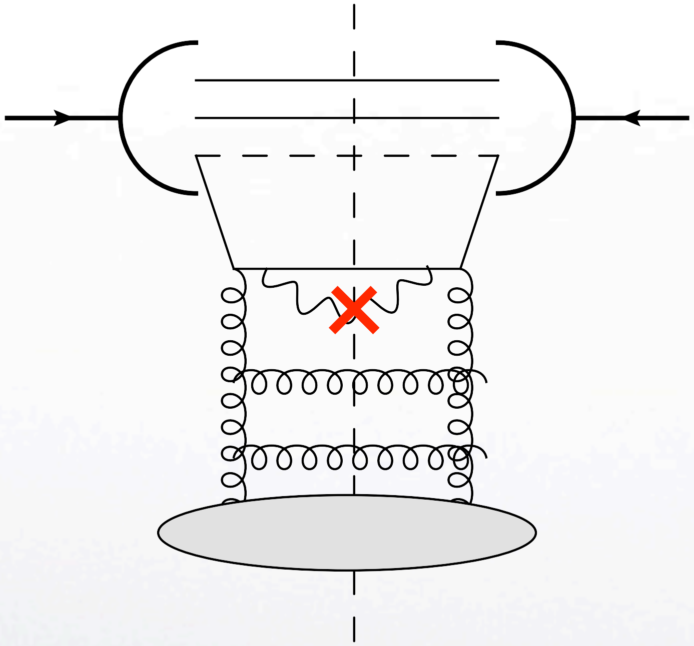
Kovchogov, Tuchin;
JB, Salvadore, Vacca;
M.Braun;
Gelis, Venogopalan



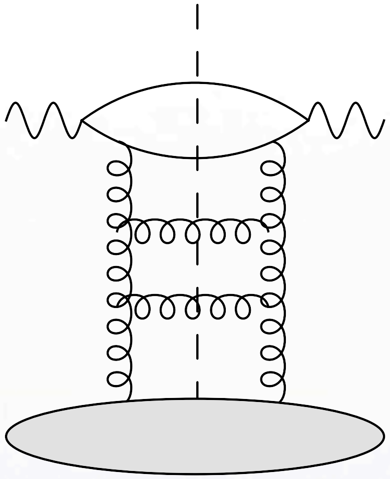
→ inclusive gluon destroys coherence, new correlator appears
‘breaking of factorization’

III. Drell-Yan: most promising small-x signals at LHC

Standard picture:



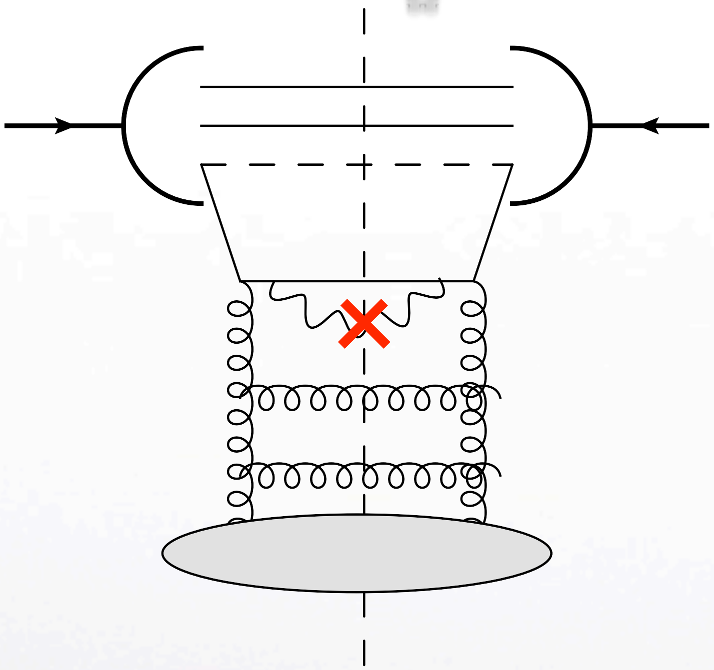
Drell Yan



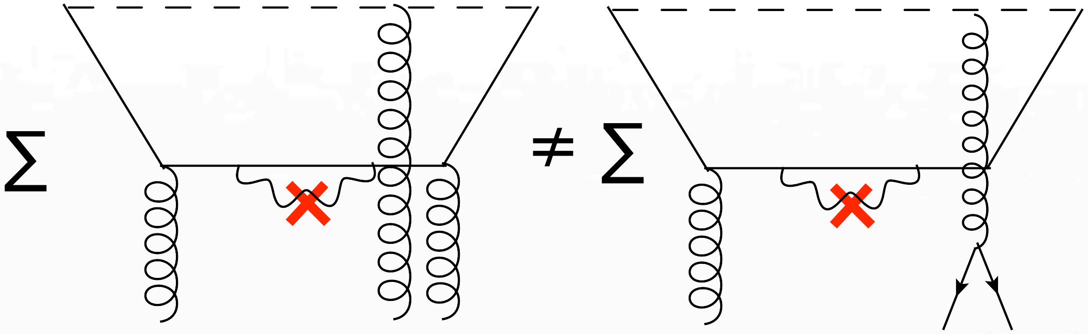
DIS

Suggest: use the same dipole cross section for the lower part

A closer look shows that there is more:



Drell Yan



Again: need higher order gluon correlators

Resume of this part:

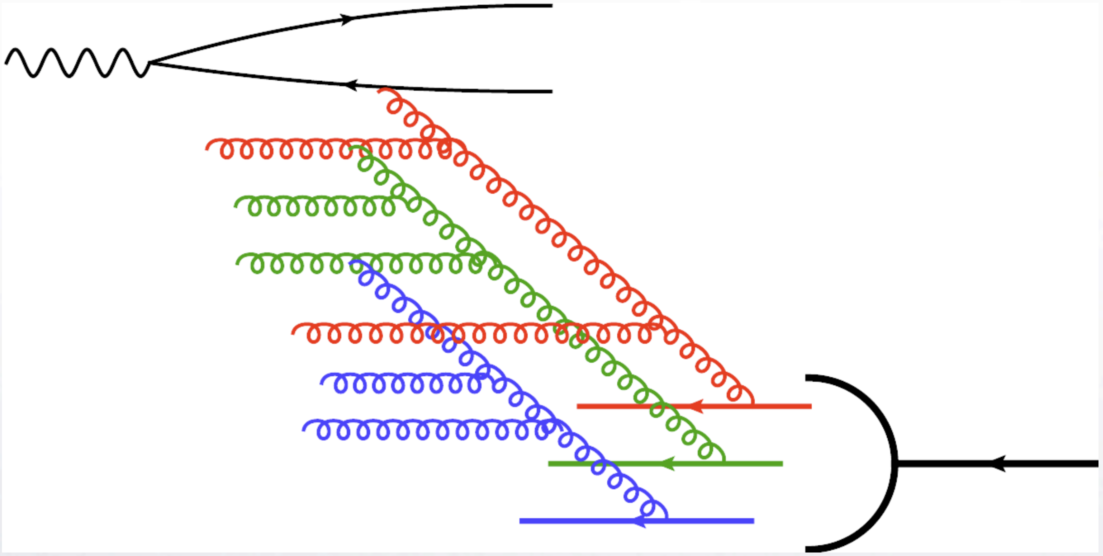
Need to study higher order correlator
= deeper into QCD reggeon field theory

4. Saturation at HERA

Gribov, Levin, Ryskin 1979

First discussed: in the context of small-x observations at HERA.

The physical picture:



several chains

recombinations

high gluon density

saturation scale

nonlinear BK-equation

Predicted signal: flattening of structure function (gluon density at) small x

flattening of gluon density not seen at HERA
current estimate:

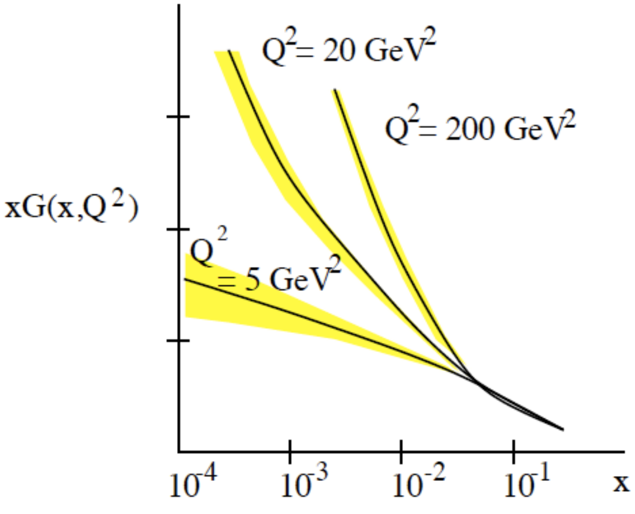
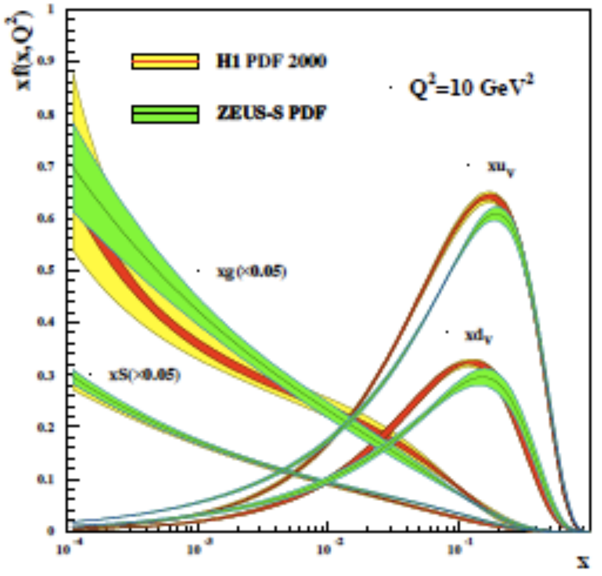
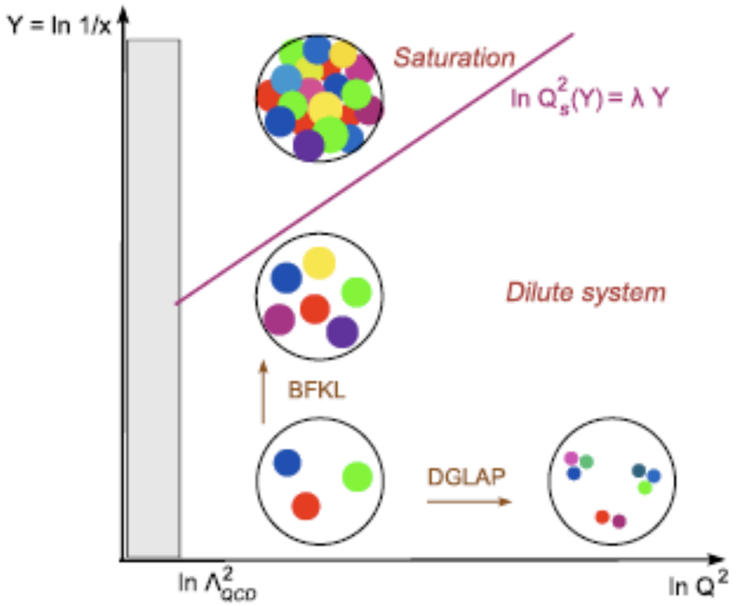


Figure 4: The distribution of gluons as a function of x as seen in the Hera deep inelastic experiments.

$Q_s \approx 1 GeV$ at $x = 10^{-5}$

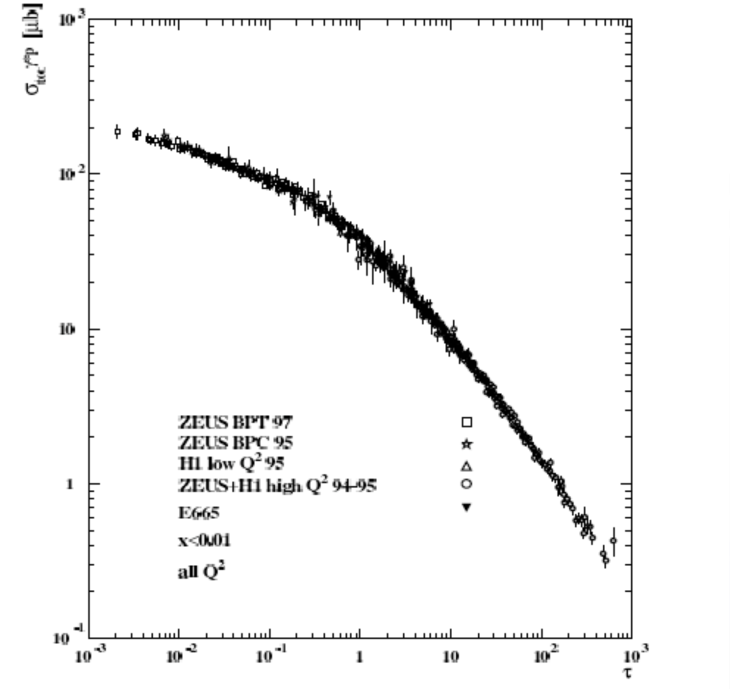
(b-averaged)





No direct evidence for saturation in F_2

Indirect signals for saturation:



$$Q_s^2 = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda} \qquad \tau = Q^2/Q_s^2$$

geometric scaling

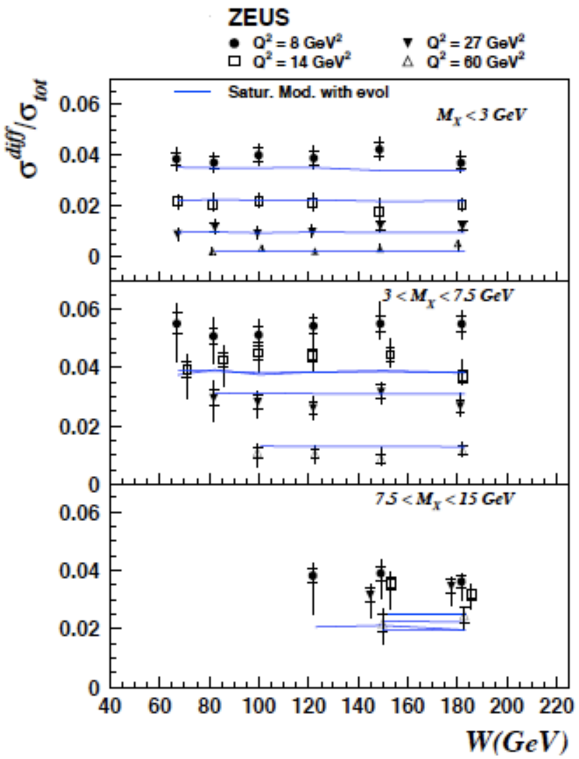
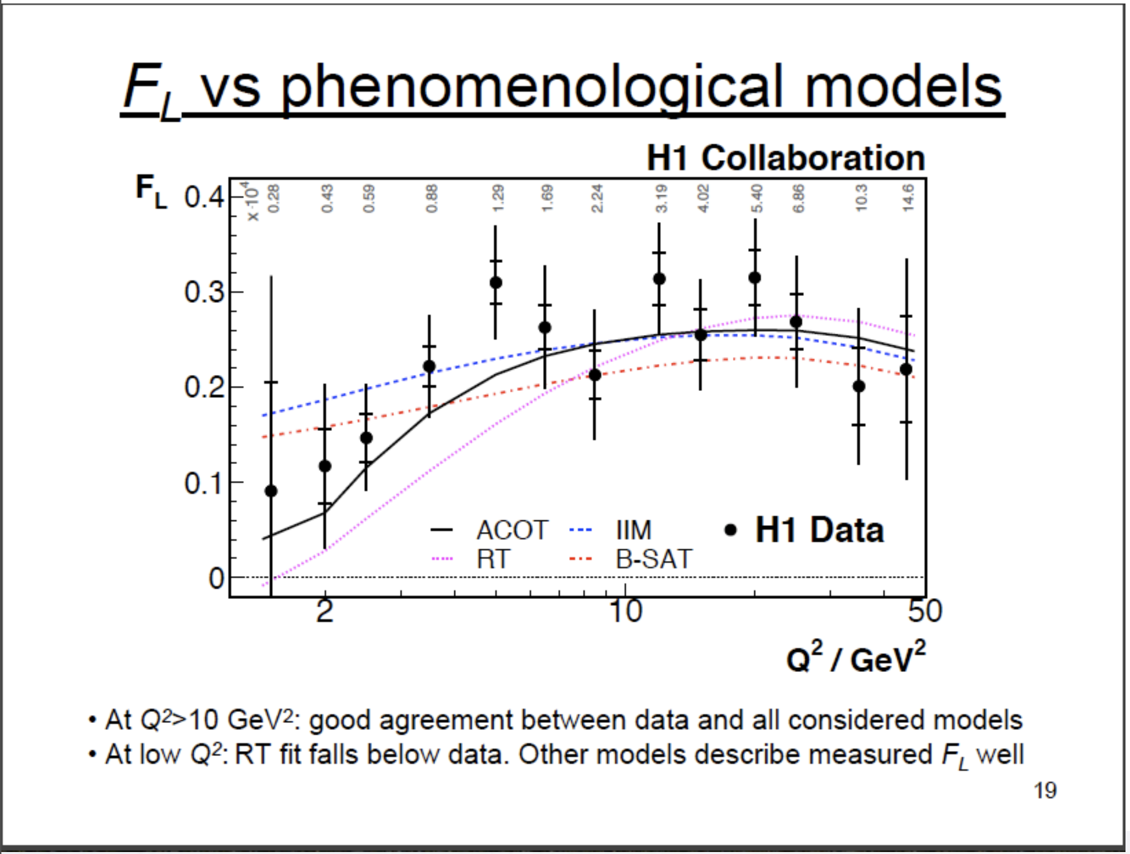


Figure 9. *ZEUS data for the ratio $\sigma_{\mathrm{diff}}/\sigma_{\mathrm{tot}}$ together with the respective prediction of the saturation model in Ref. [55].*

ratio of diffractive and total cross section



F_L vs phenomenological models

- At $Q^2 > 10$ GeV^2: good agreement between data and all considered models
- At low Q^2: RT fit falls below data. Other models describe measured F_L well

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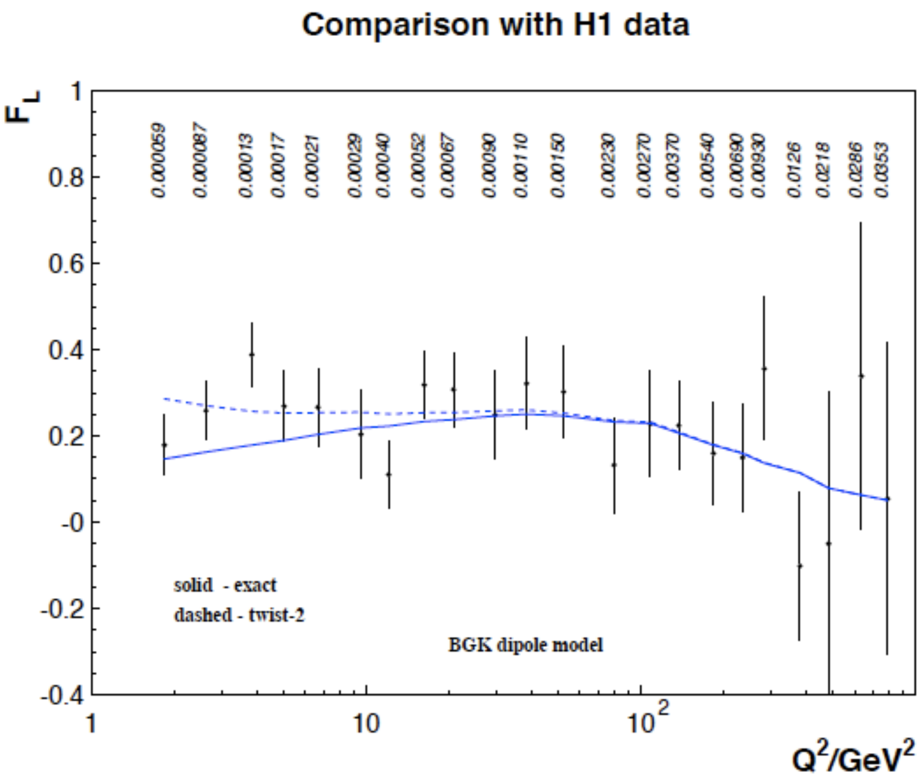
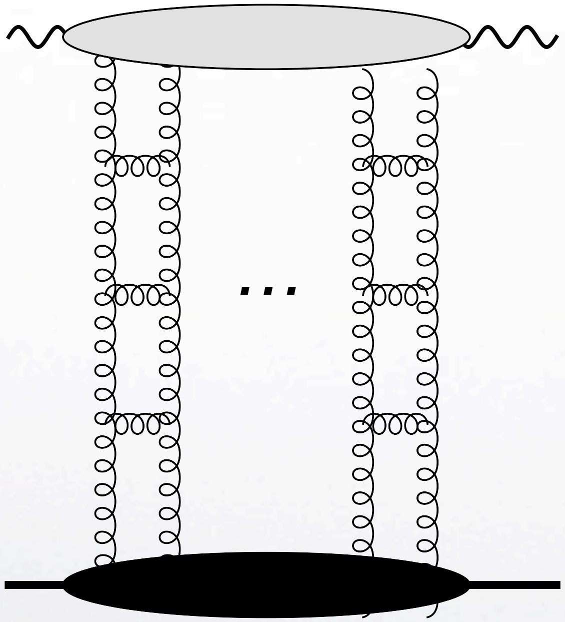


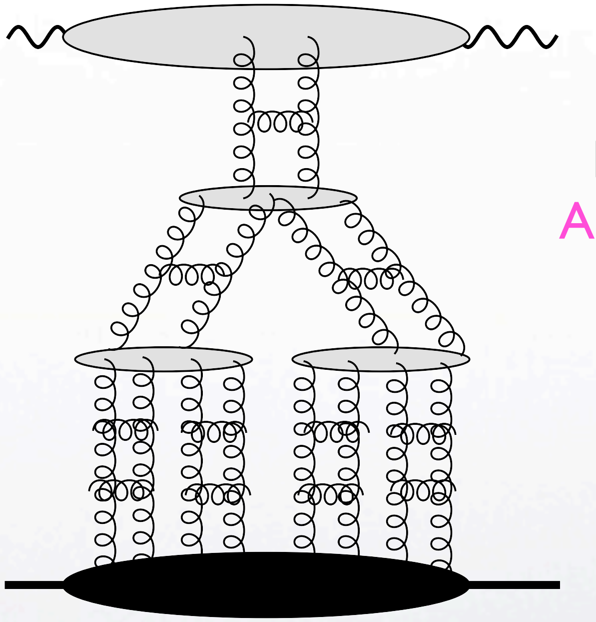
leading twist vs higher twist

Saturation models at HERA:

GBW: eikonal

BK equation: recombination





Recent fits:
Albacete et al.

No recombination; allows twist expansion

Recombination; 'leading twist shadowing'

Conclusions for saturation at HERA:

- models,
- attractive explanation for scaling,
- diffractive cross section
- probable but not proven

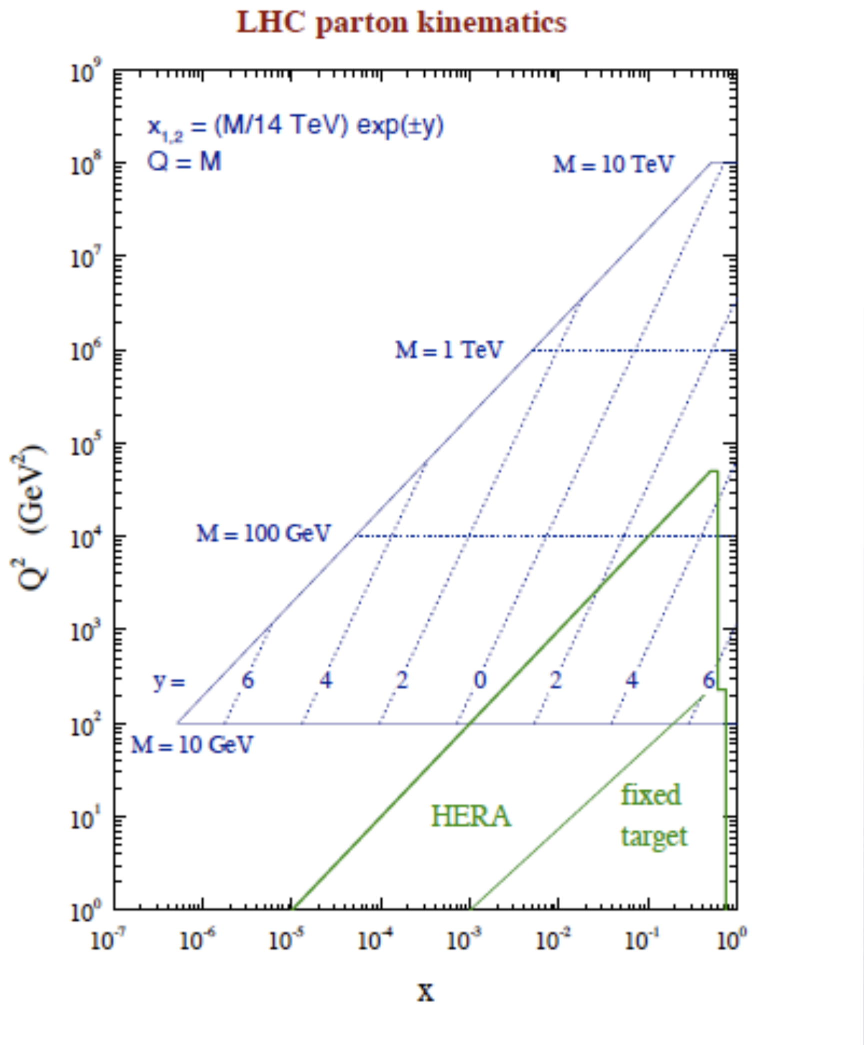
Need higher energies
or heavy ion: $Q_s^2 \sim A^{1/3}$
or LHC

5. Saturation at the LHC

Larger kinematic region:

Potential signals:

- $< p_t >, < n_c >, \dfrac{dN_{ch}}{dy dp_t^2}$
- Ridge effect?
- Drell Yan in forward region
- Angular decorrelation



At mid-rapidity:

McLerran, Praszalowicz

$$Q_s^2 = Q_0^2 \left(\frac{p_t}{W}\right)^{\lambda}$$

$$\frac{1}{\sigma}\frac{dN}{d\eta} \sim Q_s^2 \sim E^{\lambda}$$

$$< p_t > \sim Q_s \sim E^{\lambda/2}$$

$$\frac{dN}{dy\,dp_t^2} = \frac{F(\tau)}{Q_0^2}$$

$$\tau = \frac{p_t^2}{Q_s^2}$$

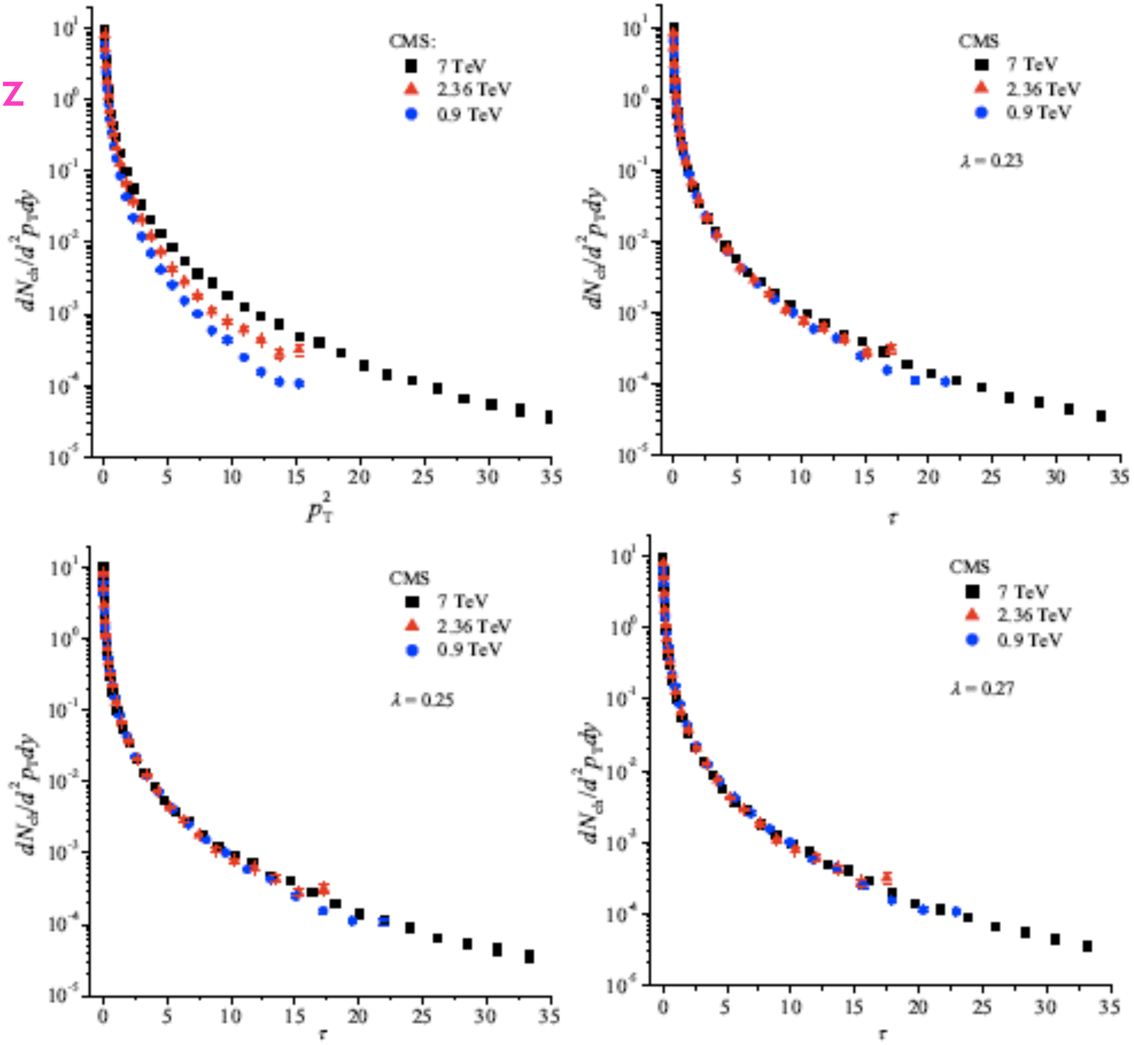
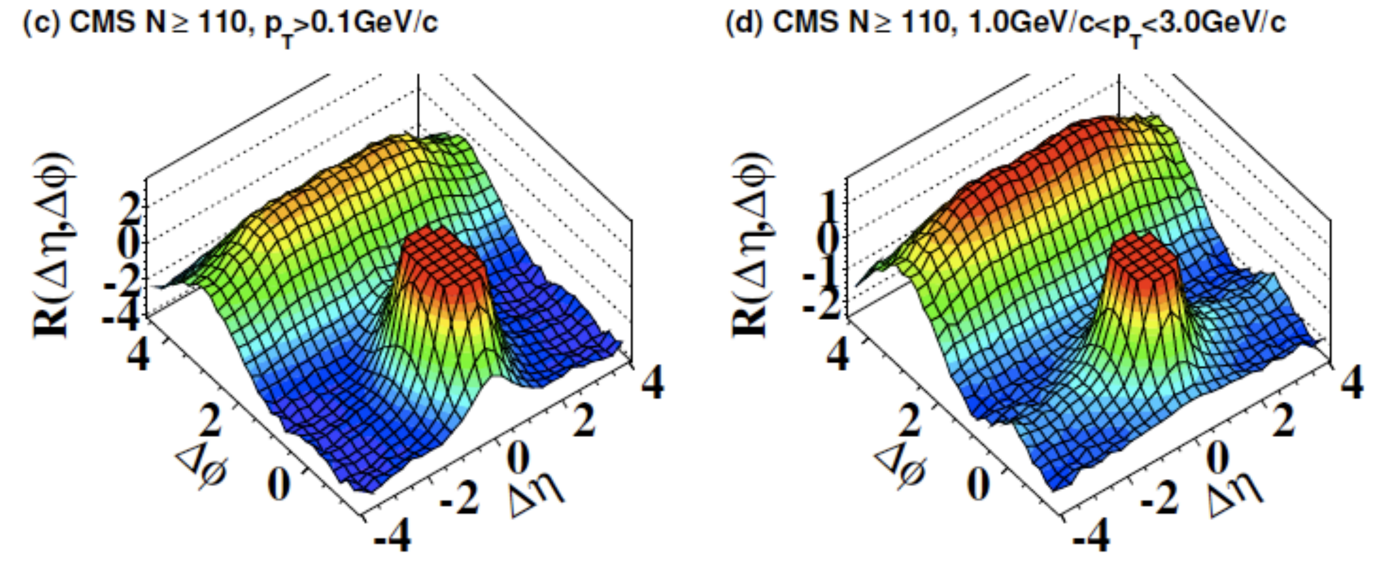


Fig. 1. Geometric scaling of the transverse momentum spectra that are plotted in terms of p_T^2 and scaling variable τ for three choices of $\lambda = 0.23$, 0.25 and 0.27.

Ridge effect: saturation?



Important features:

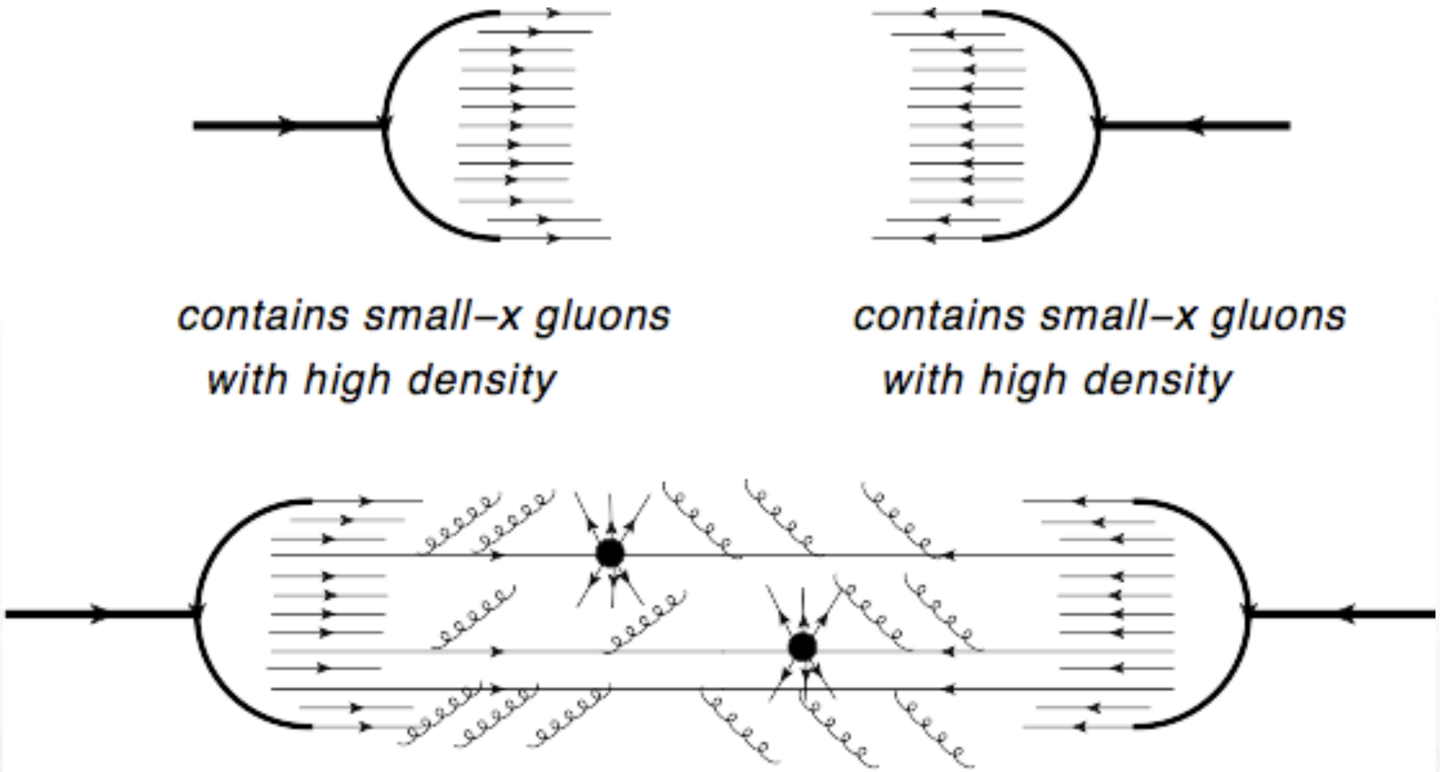
high multiplicity, $1GeV \le p_T \le 3GeV$, $\Delta\varphi \approx 0$ at $4 \le \Delta\eta \le 4$

Saturation is a strong candidate:

- strong field: high density
- low p_T: saturation momentum

$$x = 10^{-5} \to Q_s \approx 1GeV$$

- angular correlation: need extra ingredient

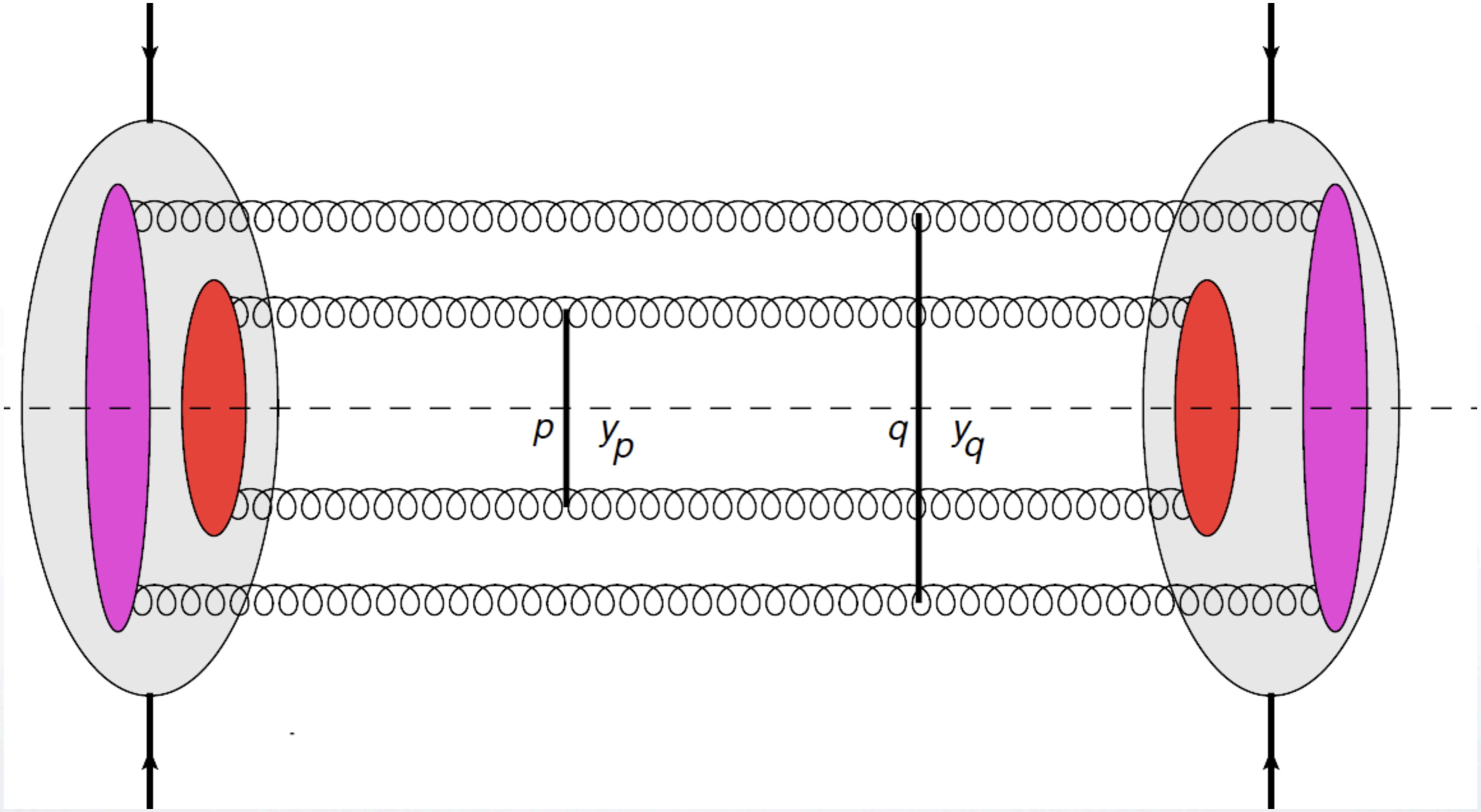


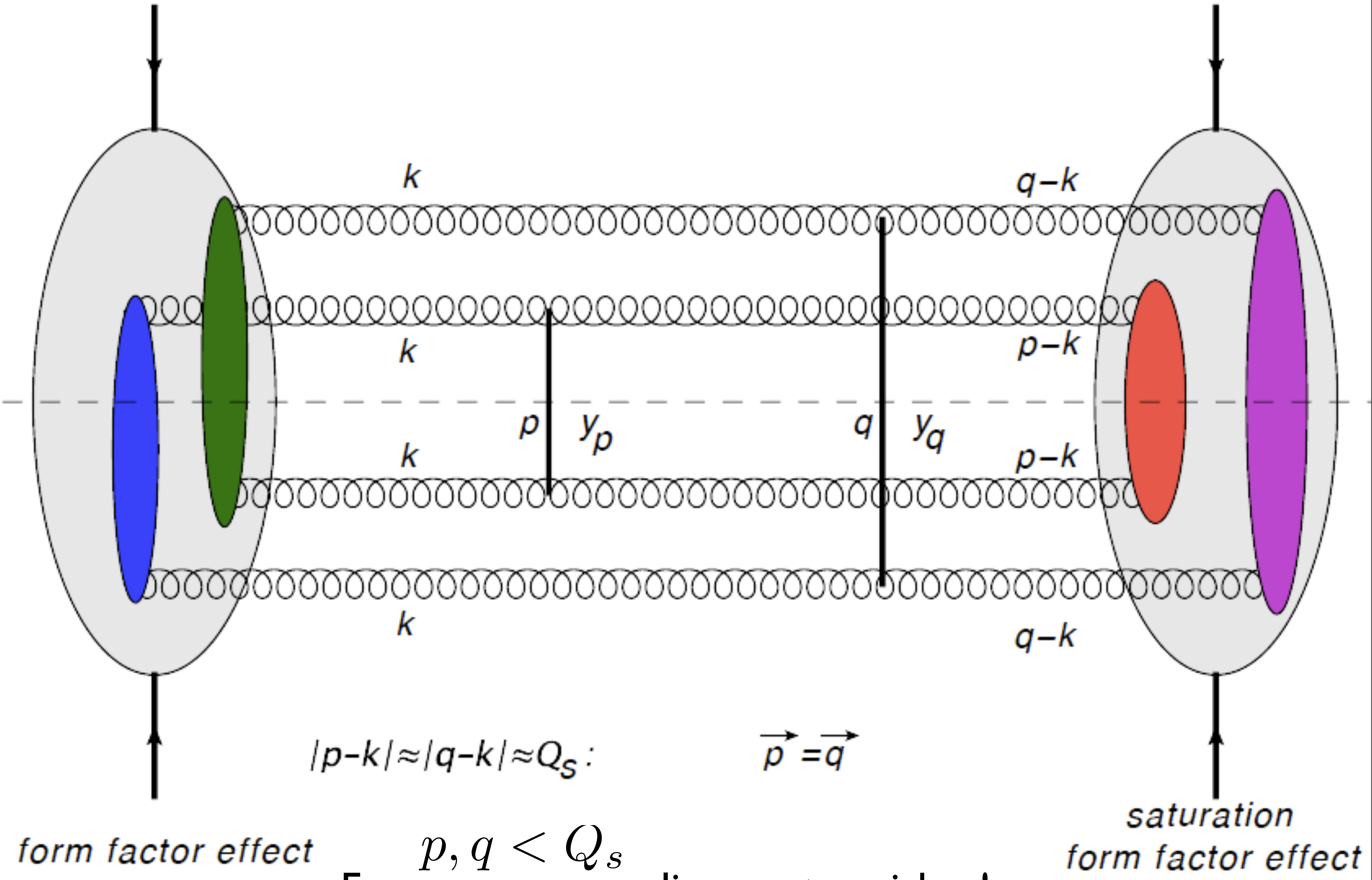
contains small–x gluons with high density

contains small–x gluons with high density

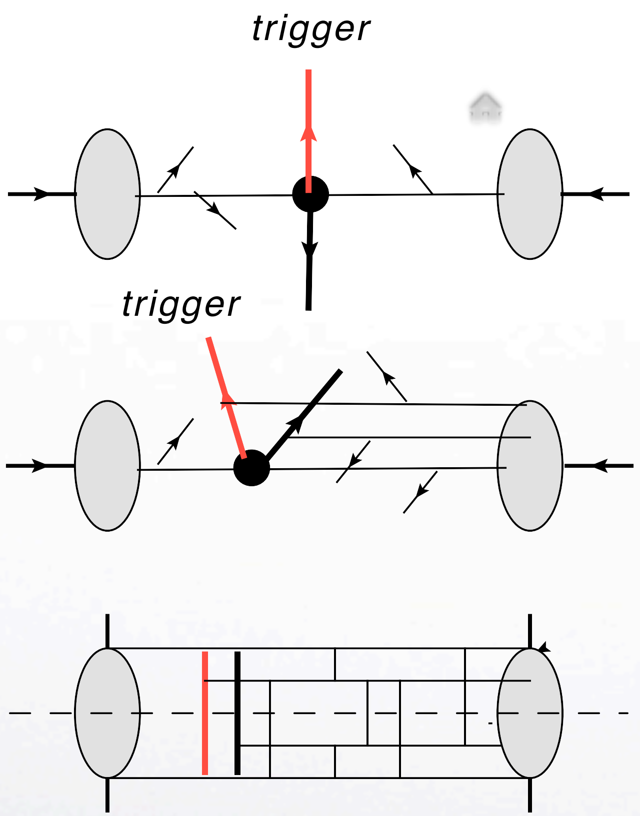
could explain high multiplicity, long rapidity correlations

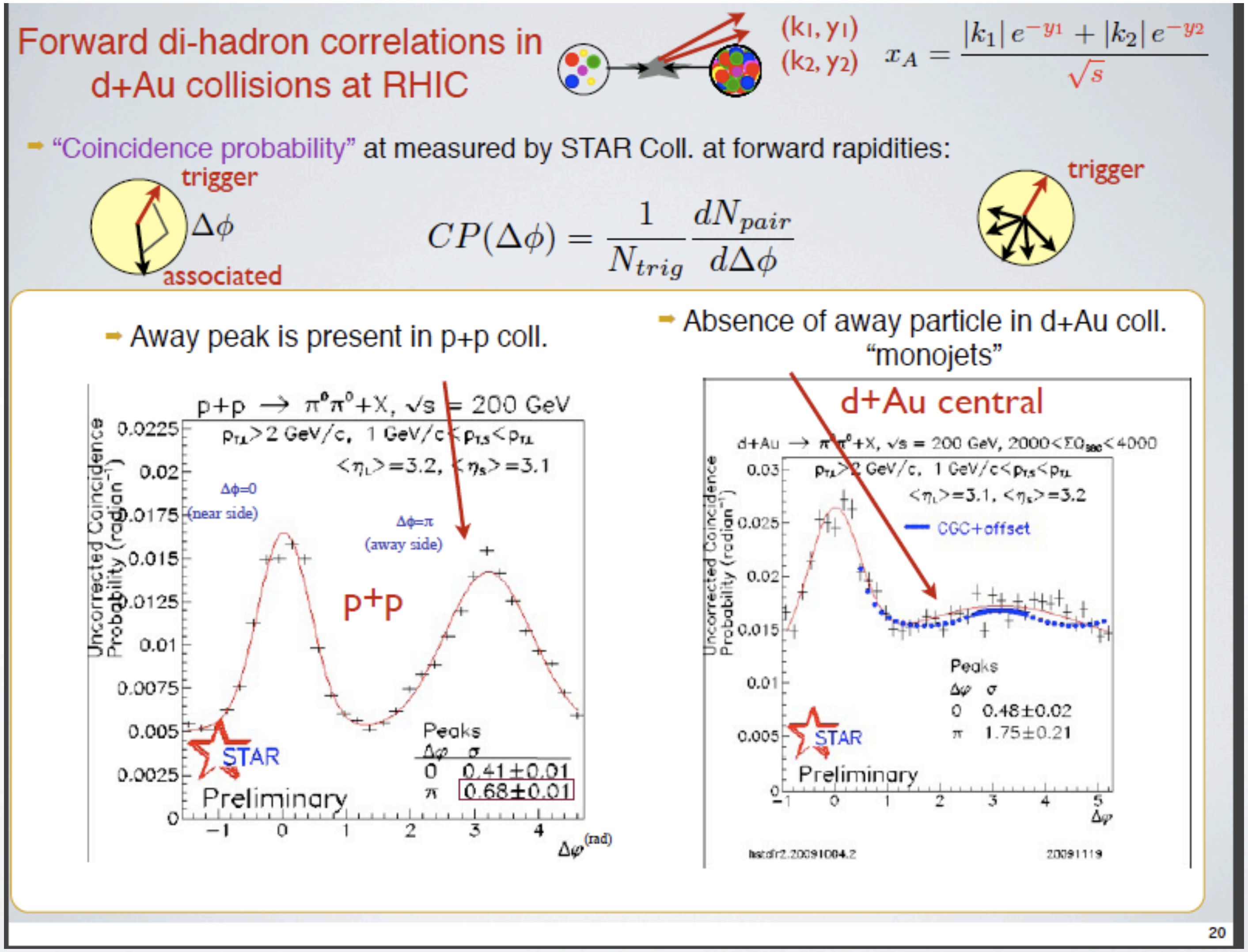
but not delta $\Delta\phi$ *enhancement*


p
y_p
q
y_q



For $\begin{matrix} p,q < Q_s \\ p,q > Q_s \end{matrix}$ alignment vanishes!





Forward di-hadron correlations in d+Au collisions at RHIC

(k_1, y_1)
(k_2, y_2)

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

- "Coincidence probability" at measured by STAR Coll. at forward rapidities:

$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$

- Away peak is present in p+p coll.

- Absence of away particle in d+Au coll. "monojets"

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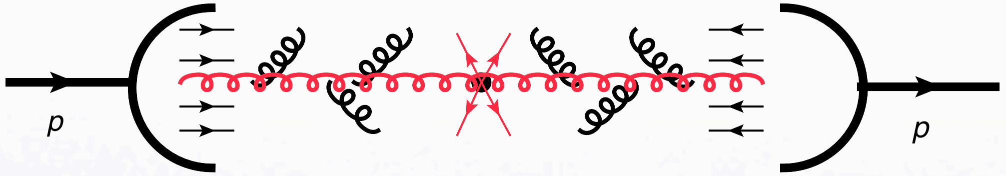
Albacete, Marquet

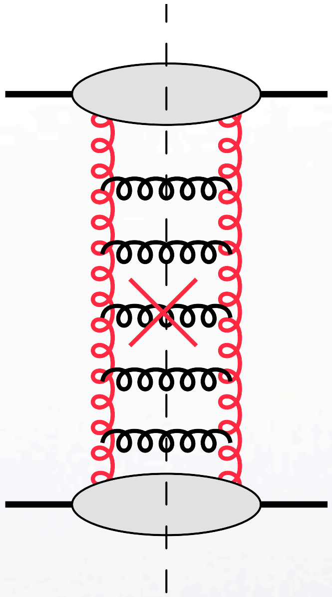
Again:

Evidence for saturation,
look for further signals

6. Multiple Interactions

Single inclusive cross section: collinear factorization (DGLAP evolution)
single chain process

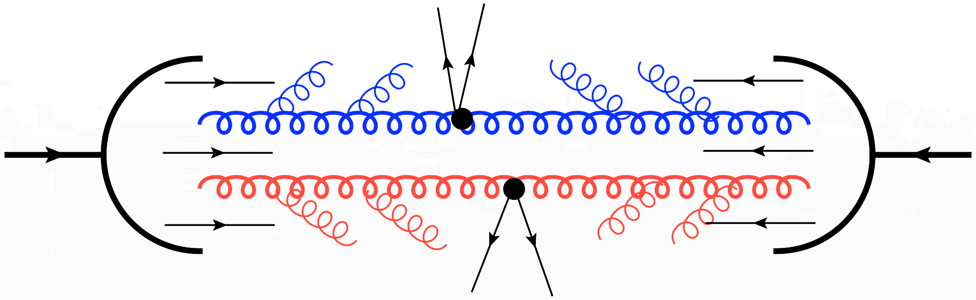


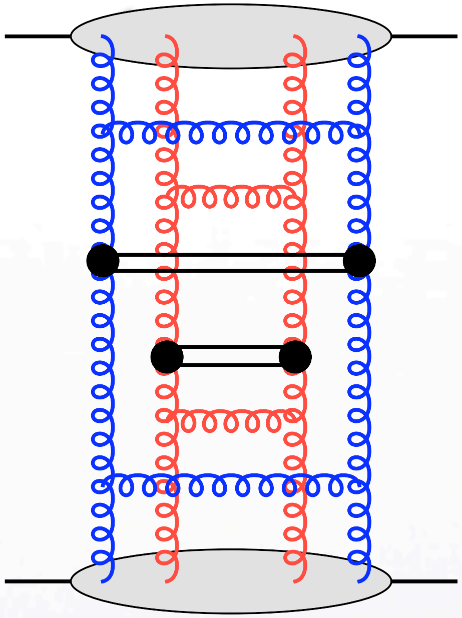


$$\begin{aligned}\sigma_{pp\to X} \;&=\; \sum_{ijk}\int dx_1\,dx_2\,dz\; f_i(x_1,\mu^2)\,f_j(x_2,\mu^2)\\ &\times\hat{\sigma}_{ij\to k}\left(x_1,x_2,z,Q^2,\alpha_s(\mu^2),\mu^2\right)\,D_{k\to X}(z,\mu^2)\end{aligned}$$

No doubt that we need more chains

A two-chain process: seen at the Tevatron (R.Field)





$$\sigma_{pp\to X} = \sum \int dx_1 dy_1 dx_2 dy_2 f_{ij}(x_1, y_1) f_{kl}(x_2, y_2) \hat{\sigma}_{ij,kl}(x_1, y_1, x_2, y_2)$$

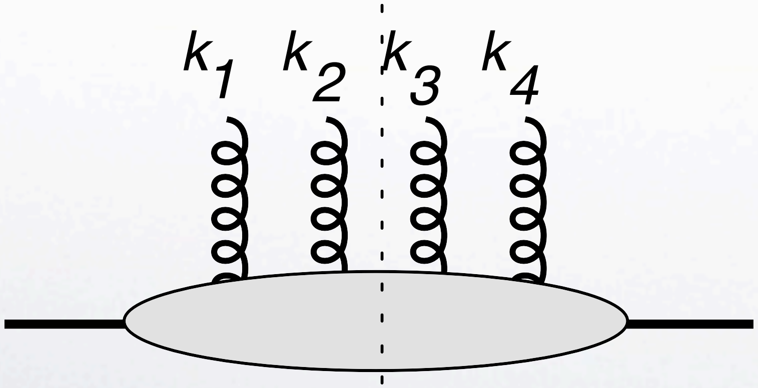
contributes to double inclusive cross section, correlation functions. Double parton densitities. How to handle theoretically?

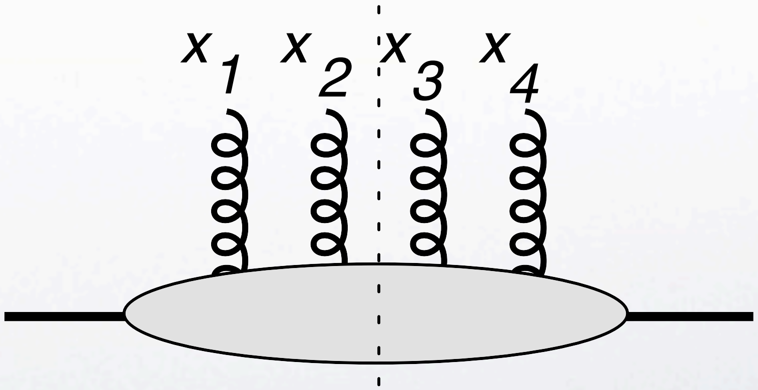
Evolution equations: two options

- evolution in rapidity (BKP; JIMWLK)
- evolution in momentum scale (B'F'KL; higher twist)

$$\partial_y \varphi_4(k_1,...k_4;y) = \left(\sum_{ij} H_{ij}\otimes\varphi_4\right)(k_1,...k_4;y)$$

$$\partial_{lnQ^2}\psi_4(x_1,...x_4;y) = \left(\sum_{ij} P_{ij}\otimes\psi_4\right)(x_1,...x_4;y)$$

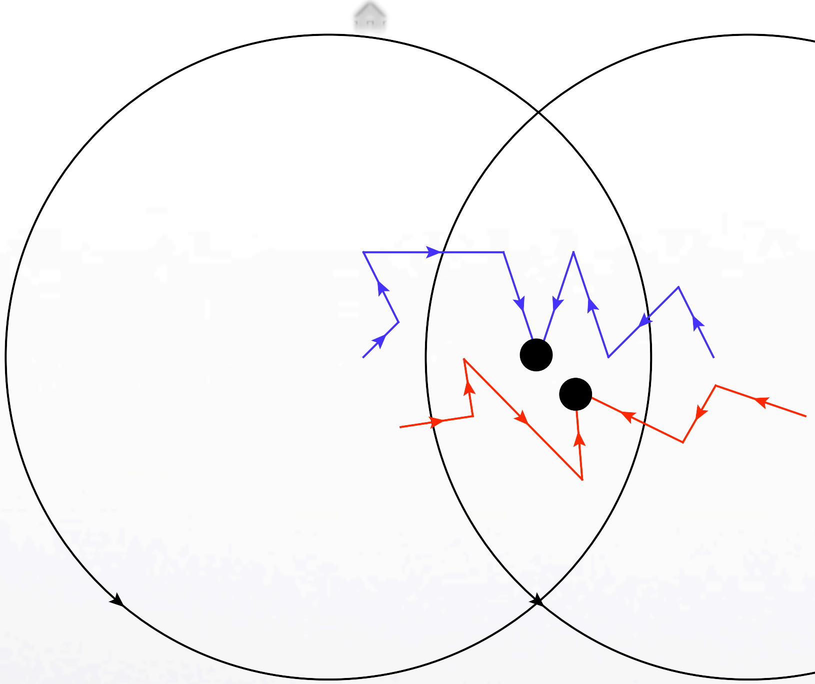


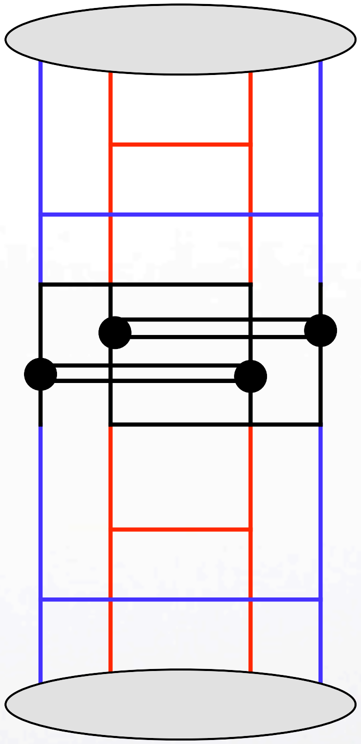


At each step of evolution: sum over all pairwise interactions.
Approximation: Double DGLAP - no cross talk between the chains

In transverse space:

JB, M.Ryskin

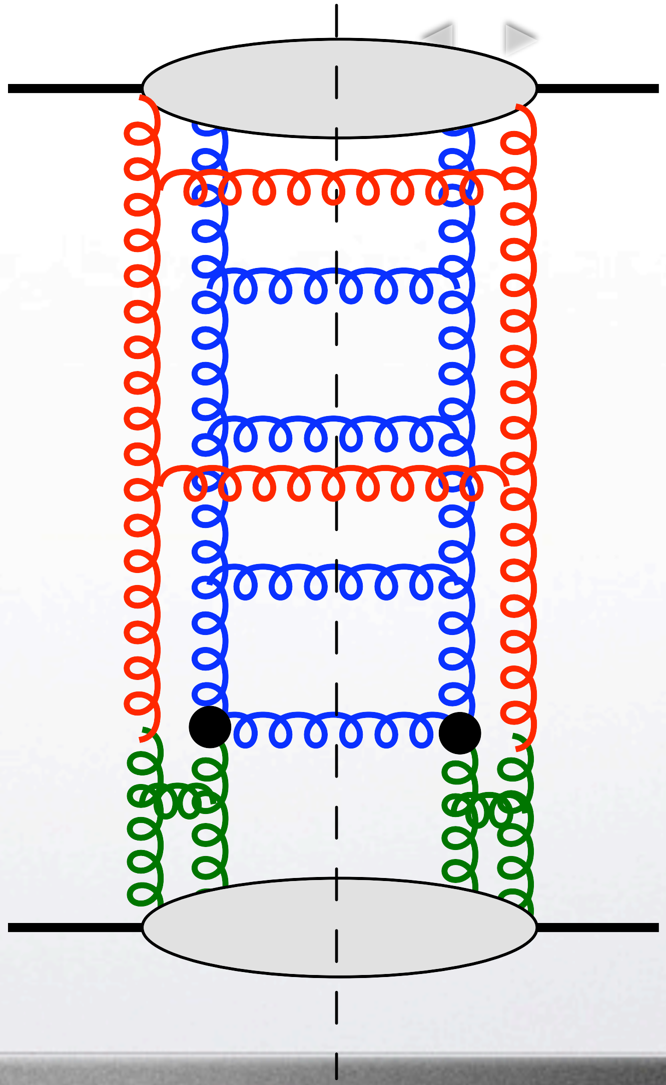




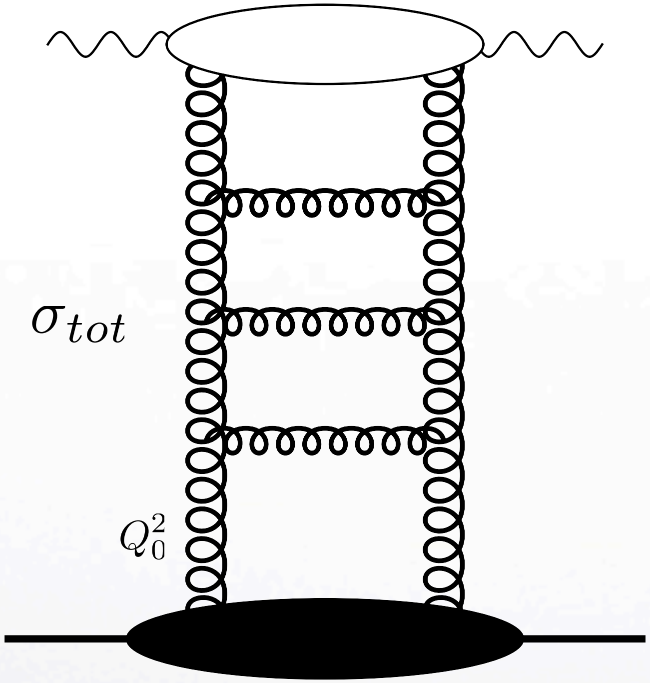
not small if n>4

Rapidity gaps: on the partonic level need color singlet

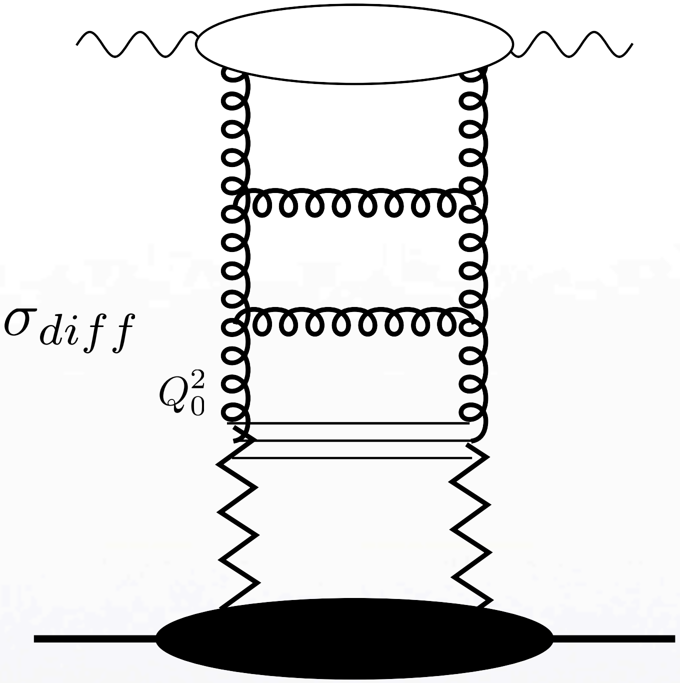
Simplest possibility:
recombination



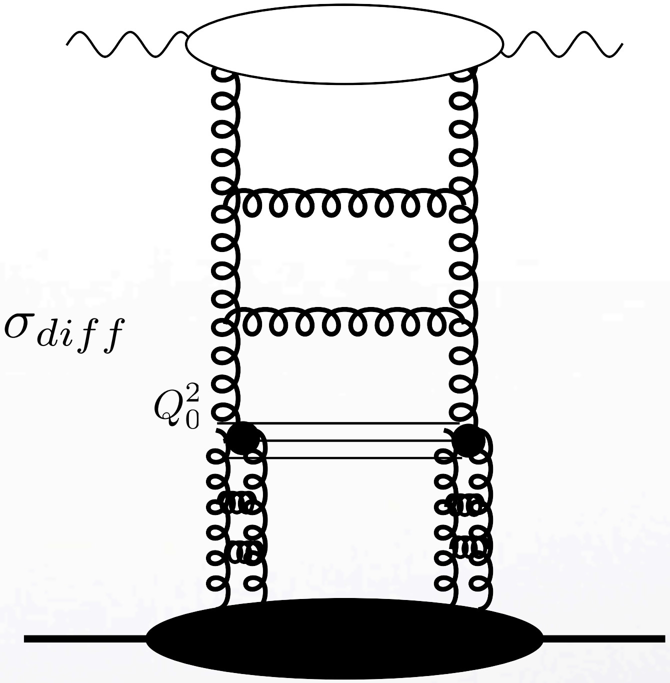
The HERA picture:



parton density,
DGLP/BFKL



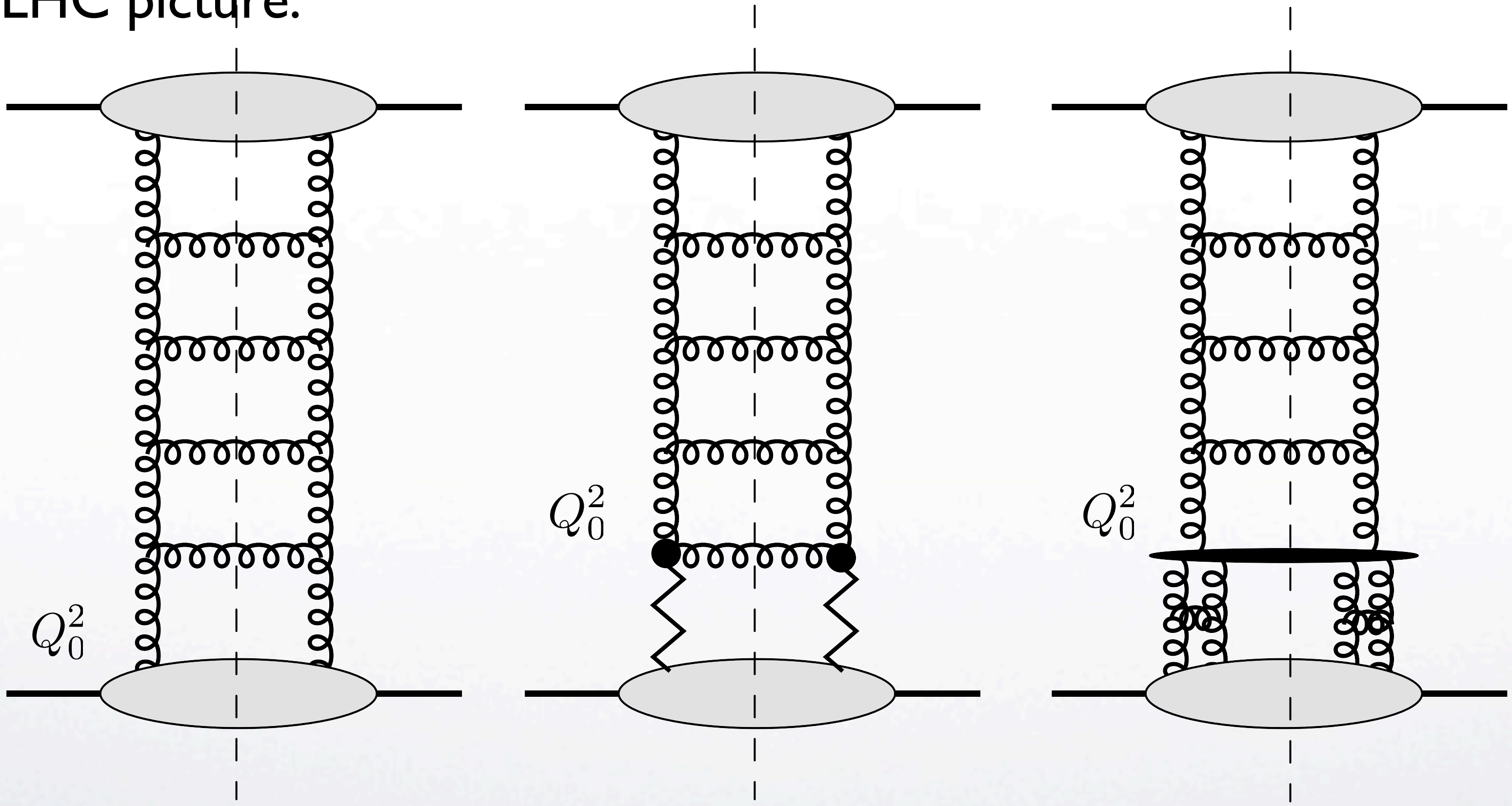
diffractive parton density,
soft Pomeron



diffractive parton density,
hard Pomeron

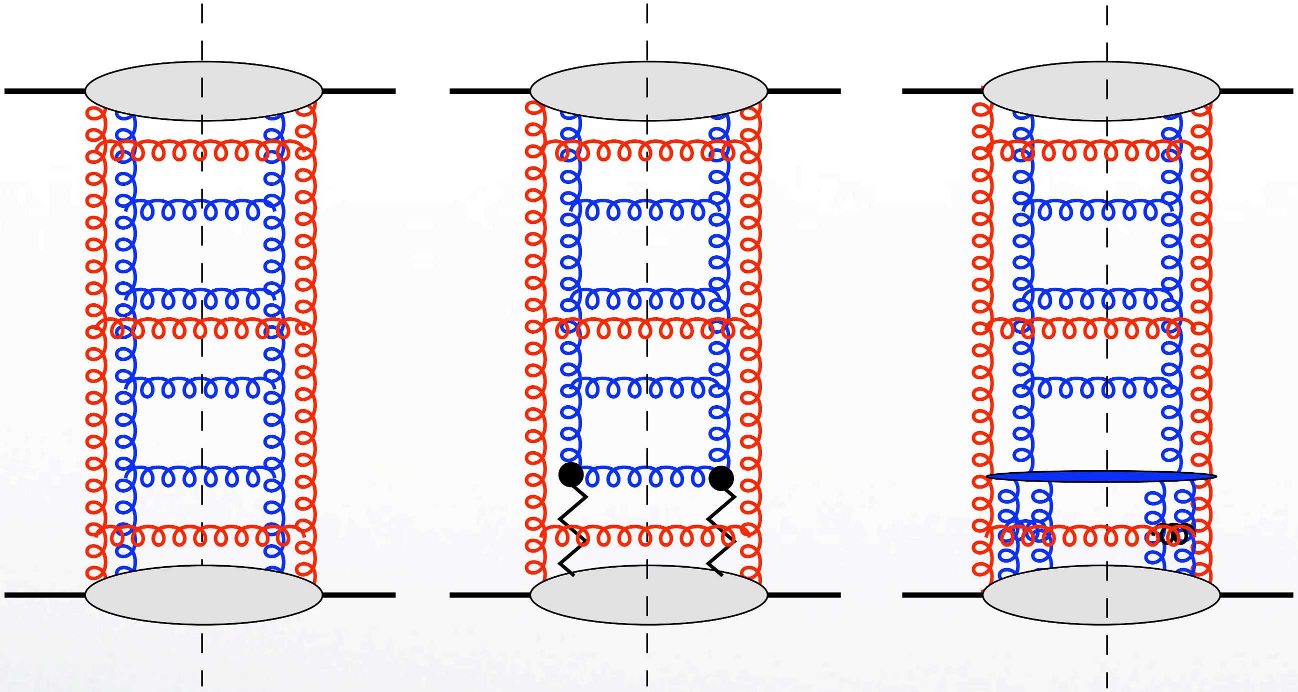
Counting problem: how much diffraction is inside the initial condition of DGLAP?
parton density does not contain hard diffraction. Best: unify the two description.

The LHC picture:

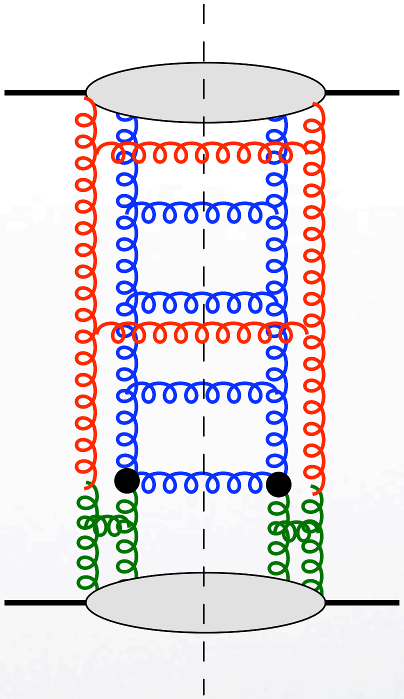


Again the same counting problem. In addition: need the survival probability

Survival probability:



Second (and third..) chain fills the gap.



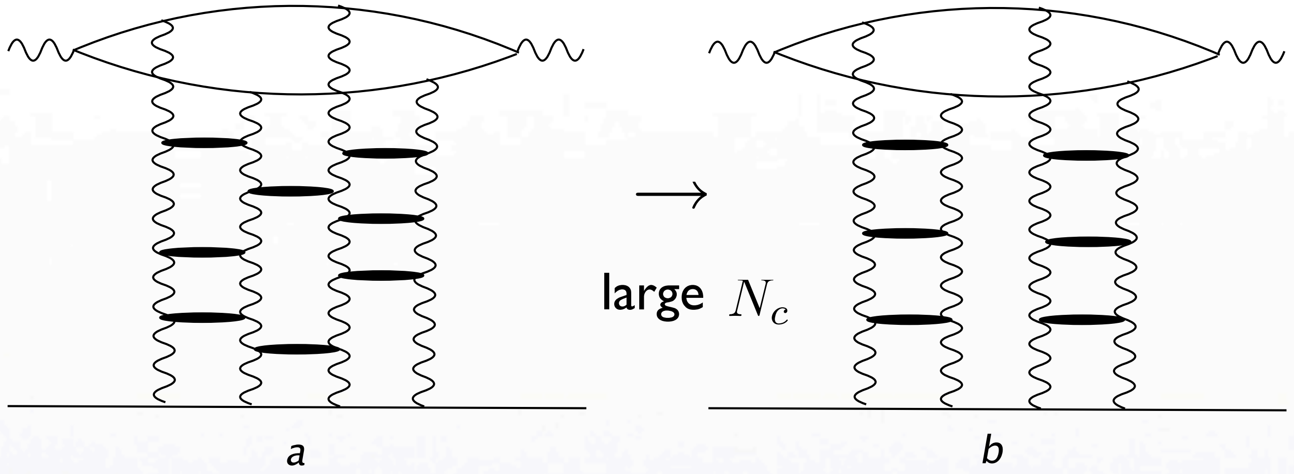
Simplest possibility:
recombination

Conclusions

- small-x physics at the LHC is essential
- importance of higher order correlators
  (‘more than dipole cross section’)
- understanding QCD dynamics:
  small-x is step towards (nonperturbative) strong interactions
- most important for the search for new physics:
  multiple interactions, needs theoretical work!

Next step: more chains, higher twist

JB, Golec-Biernat, Motyka



Most striking: twist 4 corrections (in LLA)

$\Delta F_L, \quad \Delta F_T$ have opposite sign: cancellation in $F_2 = F_L + F_T$

Warning for other applications: higher twist corrections maybe larger!

Introduction

1) Main goal of LHC: search for new physics
However: the near future may be dominated by
studies of the QCD/strong interaction background
2) QCD important by itself.

Main tool: QCD parton picture (collinear factorization)

- parton densities
- subprocesses

But: these tools cover only a small part of the phase space
Small-x physics: extension, cross section become large
New dynamics: nonlinear extensions of BFKL, saturation
Beyond small-x/saturation: strong interactions