Exclusive final states in diffractive excitation

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Work in coll. with C. Flensburg and L. Lönnblad

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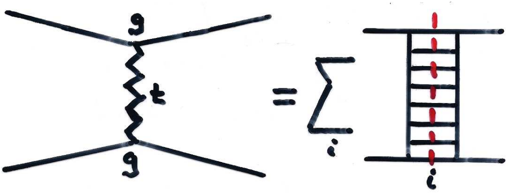
1. Introduction, Reggeon theory



Elastic scattering driven by absorption.
Analogous to diffraction in optics

Single pomeron exch.: $\sigma_{tot} \sim g^2 s^{\alpha(0)-1}$, $\frac{d\sigma_{el}}{dt} \sim (g^2 s^{\alpha(t)-1})^2$

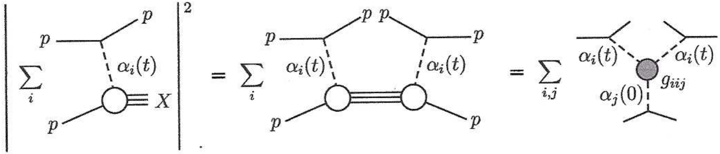
Unitarity corrections in impact parameter space:

If absorption prob. in Born approx. = $2F$:

Optical theorem $\Rightarrow d\sigma_{inel}/d^2b = 1 - e^{-2F}$

$$d\sigma_{el}/d^2b = (1 - e^{-F})^2$$

Inelastic diffraction, Mueller triple-Regge



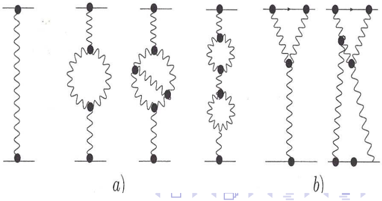
Triple pomeron coupling: g_{3P}

$$\sigma \sim g_{pP}^2(t) g_{pP}(0) g_{3P} \left(\frac{s}{M_X^2}\right)^{2(\alpha(t)-1)} \left(M_X^2\right)^{(\alpha(0)-1)}$$

Unitarity corrections

cf GLM, KMR, and others

Fit regge intercepts and couplings to exp. data



QCD

Can the known QCD dynamics and the BFKL pomeron give more information, *e.g.* determine g_{3P}?

Problems with BFKL and low x evolution

- LL BFKL not enough. Non-leading effects large
- In LL g_{3P} is singular $\sim 1/\sqrt{-t}$
- Saturation: BK works for large homogenous targets
- Soft cutoff needed in parton subcollisions
- BFKL inclusive. For exclusive states: CCFM

These problems are treated in the Lund Dipole Cascade model DIPSY

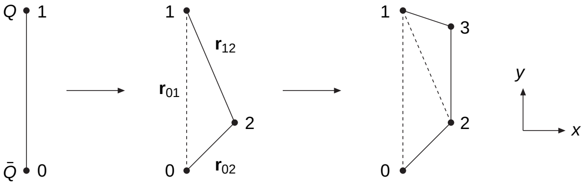
2. Dipole cascade models

a. Mueller Dipol model:

LL BFKL evolution in transverse coordinate space
Saturation effects from multiple interactions

Colour charge always accompanied by corresponding anticharge

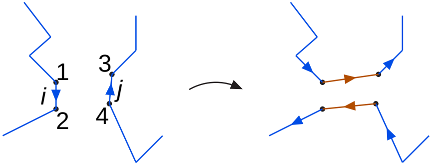
Gluon emission: dipole splits in two dipoles:



Emission probability: $\frac{d\mathcal{P}}{dy} = \frac{\bar{\alpha}}{2\pi} d^2\mathbf{r}_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2}$

Dipole-dipole scattering

Single gluon exhange $\Rightarrow$ Colour reconnection



Born amplitude:

$$f_{ij} = \frac{\alpha_s^2}{2} \ln^2\left(\frac{r_{13}r_{24}}{r_{14}r_{23}}\right)$$

Multiple subcollisions

BFKL stochastic process with independent subcollisions:

Sum over all dipole pairs: Born ampl.: $F = \sum_{ij} f_{ij}$

Uniterized ampl.: $T = 1 - e^{-\sum f_{ij}}$

b. The Lund cascade model, DIPSY MC

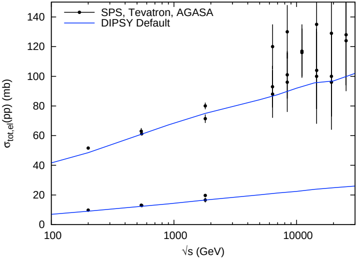
Includes:

- Important non-leading effects in BFKL evol.
- Saturation from pomeron loops in the evolution
  (Not included by Mueller or in BK)
- Confinement
- MC DIPSY
  gives also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei

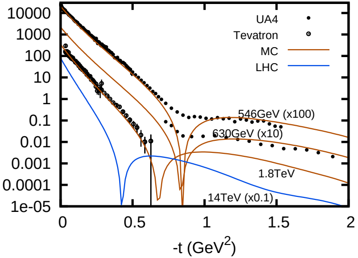
Total and elastic cross sections

pp

σ_{tot} and σ_{el}



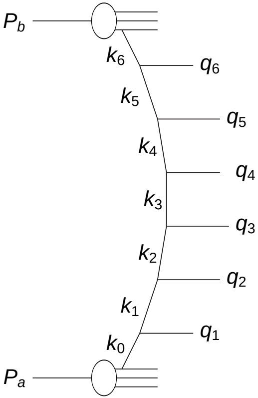
$d\sigma/dt$



Exclusive final states

BFKL: Inclusive   Exclusive: CCFM

In momentum space



Inclusive cross section determined by "hard" emissions, where $k_\perp$ gets a big kick, "$k_\perp$-changing emissions"

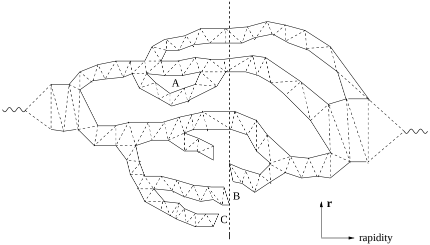
Gives initial state radiation

(Lund 1996, Salam 1999)

(either $k_{\perp i} \gg k_{\perp i-1}$; $q_{\perp i} \simeq k_{\perp i}$

or $k_{\perp i} \ll k_{\perp i-1}$; $q_{\perp i} \simeq k_{\perp i-1}$)

Schematic picture: BFKL is a stochastic process



Non-interacting branches cannot come on shell.

To get final states:

- Determine which dipoles interact
- Absorbe non-interacting chains
- Determine final state radiation
- Hadronize

Comparisons to ATLAS data

[arXiv:1103.4321]

Min bias

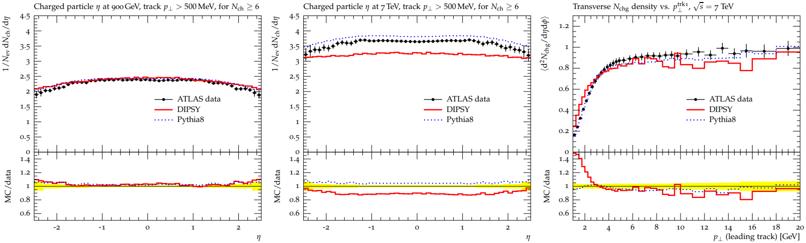
η distrib. charged particles

0.9 TeV 7 TeV

Underlying event

N_{ch} in transv. region

vs $p_\perp^{lead}$, 7 TeV



Our aim to get dynamical insight, not to give precise predictions

At present no quarks, only gluons

3. Diffractive excitation

Alternative formalism: Good–Walker

Projectile with a substructure

The mass eigenstates, Ψ_k, can differ from the eigenstates of diffraction, Φ_n, with eigenvalues T_n

Elastic amplitude: $\langle\Psi_{in}|T|\Psi_{in}\rangle = \langle T\rangle$

$d\sigma_{el}/d^2b = \langle T\rangle^2$

Ampl. for transition to state Ψ_k given by $\langle\Psi_k|T|\Psi_{in}\rangle$

Total diffractive cross section (incl. elastic):

$d\sigma_{diff}/d^2b = \sum_k\langle\Psi_{in}|T|\Psi_k\rangle\langle\Psi_k|T|\Psi_{in}\rangle = \langle T^2\rangle$

$d\sigma_{diff\ ex}/d^2b = d\sigma_{diff} - d\sigma_{el} = \langle T^2\rangle - \langle T\rangle^2 = V_T$

What are the diffractive eigenstates?

Parton cascades, which can come on shell through interaction with the target.

Continuous distrib. up to high masses (with large fluctuations)

(Also Miettinen–Pumplin (1978), Hatta *et al.* (2006))

cf KMR and GLM: 2 or 3 low mass states

Claime: Good–Walker and triple-pomeron are only different formulations of the same phenomenon

a. Relation Good–Walker *vs* triple-pomeron

(For more details see arXiv:1206.1733)

Essential feature of the BFKL cascade:

prob. for a dipole split $dP/dy \sim \lambda$

$\Rightarrow$ # dipoles grows $\langle n(y)\rangle \approx e^{\lambda y}$

Large fluctuations: $V(y) \approx e^{2\lambda y} - e^{\lambda y} = \langle n\rangle^2(1 - e^{-\lambda y})$,
$(V \equiv \langle n^2\rangle - \langle n\rangle^2)$

Approximate KNO scaling

2 colliding cascades, evolved y_1 and y_2:

Dipole-dipole interaction prob. $= 2f \Rightarrow$

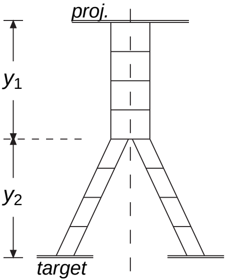
Bare pomeron: $\sigma_{inel} \propto e^{\lambda y_1}\, 2f\, e^{\lambda y_2} = 2f\, e^{\lambda Y} = 2f\, s^{\lambda}$

$$\sigma_{el} \propto f^2 e^{2\lambda Y} = f^2 s^{2\lambda}$$

Single diffr. excit.

$M_X^2 \approx \exp(y_1)$

$s \approx \exp(y_1 + y_2) = \exp(Y)$



Triple-pomeron:

$$\frac{d\sigma_{SD}}{d\ln M^2} \approx \langle n_{proj}\rangle\,\lambda\,f^2\,\langle n_{targ}\rangle^2 \approx \lambda f^2\,e^{\lambda y_1} e^{2\lambda y_2} = \lambda f^2\,(\frac{s}{M^2})^{2\lambda}\,(M^2)^{\lambda}$$

Integrated cross section, $M_X < M_{max}$:

$$\int_{(M<M_{max})} \frac{d\sigma_{SD}}{d\ln M^2} dy_1 = f^2\,e^{2\lambda Y}(1-e^{-\lambda y_1}) = f^2\,s^{2\lambda}(1-1/(M_{max}^2)^{\lambda})$$

Good–Walker

Gives integrated cross section for $M_X^2 < M_{max}^2 = \exp(y_1)$

$\sigma_{\rm SD}$ = (total diffraction for projectile and elastic target) $-\sigma_{\rm el}$

$$= \langle\langle T\rangle_{\rm targ}^2\rangle_{\rm proj} - \langle\langle T\rangle_{\rm targ}\rangle_{\rm proj}^2 =$$

$$= f^2(2e^{2\lambda y_1} - e^{\lambda y_1})(e^{2\lambda y_2}) - f^2(2e^{2\lambda y_1})(e^{2\lambda y_2}) =$$

$$= f^2 e^{2\lambda Y}(1 - e^{-\lambda y_1})$$

Same expression as in triple-pomeron!!

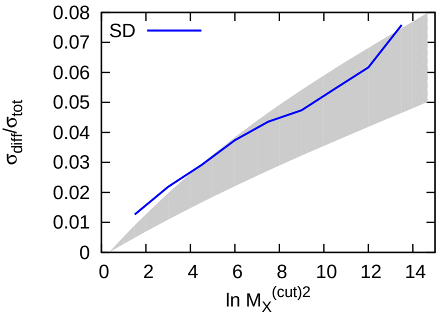
Most essential for this result is the approximate KNO scaling:

$$\frac{V(y)}{\langle n\rangle^2} = (1 - e^{-\lambda y})$$

DIPSY: *pp* 1.8 TeV

Single diffractive cross section for $M_X^2 < M_{max}^2$

Shaded area: Estimate of CDF result



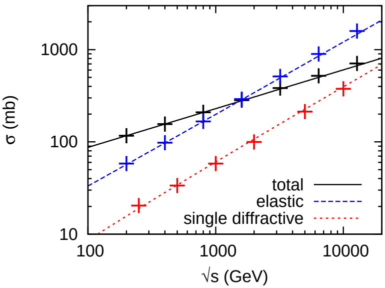
Note: Tuned only to σ_{tot} and σ_{el}. No new parameter

Saturation$\Rightarrow$ Factorization broken between *pp* and DIS

DIPSY results have the expected triple-regge form

BARE pomeron (Born amplitude without saturation effects)

Total, elastic and singel diffractive cross sections



Triple-Regge fit with a single pomeron pole

$\alpha(0) = 1.21, \ \ \alpha' = 0.2\,\text{GeV}^{-2}$

$g_{pP}(t) = (5.6\,\text{GeV}^{-1})\,e^{1.9t}, \ \ g_{3P}(t) \approx 1\text{GeV}^{-1}$ (dep. on def.)

b. Exclusive diffractive states

Diffraction is a quantum effect $\Rightarrow$ interference is important $\Rightarrow$ no probabilistic picture

But: positive and negative contributions to the amplitude can be generated by DIPSY, added, and squared.

Toy model example

System with a valence particle, which can emit a single gluon

2 states: valence only $\Psi_0 = |1, 0\rangle$

valence + gluon $\Psi_1 = |1, 1\rangle$

Probability for emission: β^2 prob. for no em.: $\alpha^2 = 1 - \beta^2$

General state $\Psi = a\Psi_0 + b\Psi_1 \equiv \begin{pmatrix} a \\ b \end{pmatrix}$

Assume an initial state Ψ which evolves to a cascade Φ at the time of interaction with the target

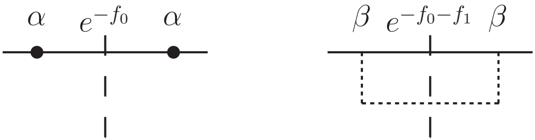
$$\Phi = U_{\rm evol}\Psi$$

Evolution operator $U_{\rm evol}$ is a unitary matrix $= \begin{pmatrix} \alpha & -\beta \\ \beta & \alpha \end{pmatrix}$

Eikonal interaction operator $U_{\rm int} = \begin{pmatrix} e^{-f_0} & 0 \\ 0 & e^{-f_0-f_1} \end{pmatrix}$

$$\Psi_{out} = S\Psi_{in} = U^{\dagger}_{\rm evol} U_{\rm int} U_{\rm evol} \Psi_{in}$$

Elastic scattering:

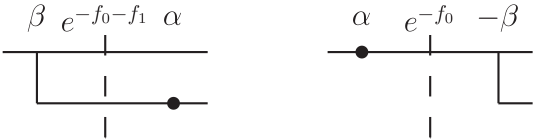


Elastic amplitude

$$T_{11} = 1 - S_{11} = 1 - \alpha^2 e^{-f_0} - \beta^2 e^{-f_0-f_1} =$$

$$\alpha^2(1 - e^{-f_0}) + \beta^2(1 - e^{-f_0-f_1})$$

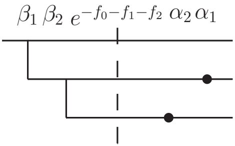
Diffractive excitation:

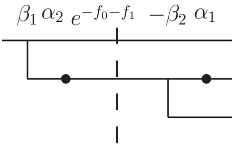


$$T_{21} = -S_{21} = -\alpha\beta e^{-f_0-f_1} - \alpha(-\beta)e^{-f_0} = \alpha\beta e^{-f_0}(1 - e^{-f_1})$$

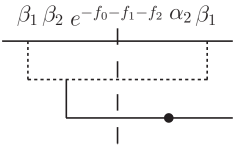
Cascade with 2 possible emissions

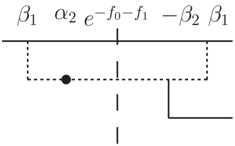
Ex.: Final state with both emissions





Final state with only the second emission





Generalizations:

Continuous cascades

Independent gluon emissions $\longrightarrow$ dipole cascade

Include target cascade

Calculations:

Collide many similar real cascades (emissions before and after interaction) which interfer

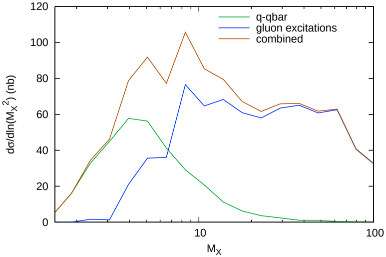
Collide with large no. of target cascades

Computationally demanding, but still possible in the MC

Preliminary results DIS

Single diffraction $W = 120\,\mathrm{GeV}, \;\; Q^2 = 24\,\mathrm{GeV}^2$

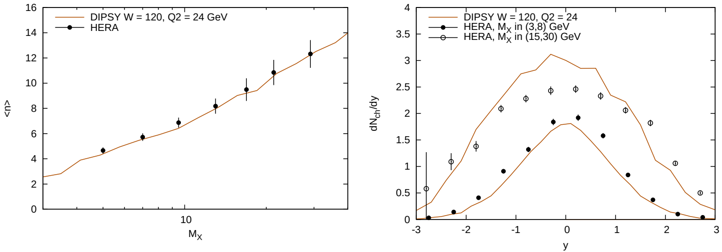
$$\frac{d\sigma}{d\ln M_X^2}$$



Curves show contributions from $q\bar{q}$ state plus 0, 1, and ≥ 2 gluons

Peak at $M_X^2 \approx Q^2$. Flatter distribution for larger M_X. Cutoff for $M_X > 50\,\mathrm{GeV}$ from the Lorentz frame used in the calculation.

DIS: $\langle n_{ch} \rangle$ *vs* M_X $\quad$ $dn_{ch}/d\eta$



pp collisions: coming soon

Future:

Double diffraction. Computationally demanding

Hard diffraction, would need a “trigger” in the MC

Might be possible to estimate the survival probability

Conclusions

The DIPSY model is based on QCD dynamics for small x evolution plus saturation

No input structure functions:

Attempt to understand underlying dynamics, not to give optimal precision

Works well for inclusive observables

Fair description of non-diffractive final states

Diffraction

Claim: Good–Walker and triple-pomeron describe the same dynamics

In both approaches: gap events analogous to diffraction in optics

Good–Walker: No extra tunable parameter

Diffractive final states:

Quantum effect: Interfering contributions to the amplitude

Still possible to calculate in the dipole cascade formalism

Preliminary results for diffractive final states in DIS

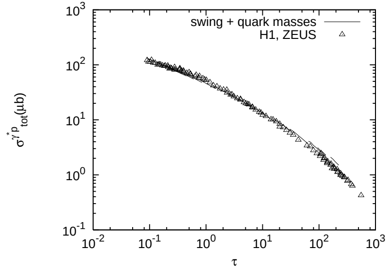
pp coll. coming soon

Extra slides

DIS, Inclusive cross sections

$\gamma^* p$ total cross section

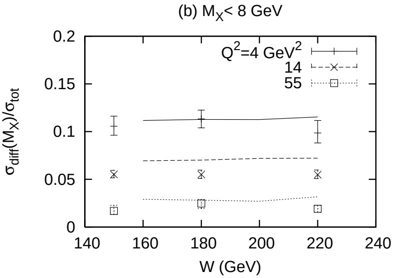
Satisfies geometric scaling.
$\tau = Q^2/Q_s^2(x)$, $Q_s^2 \propto x^{-0.3}$



Diffractive cross section

(Data from ZEUS)

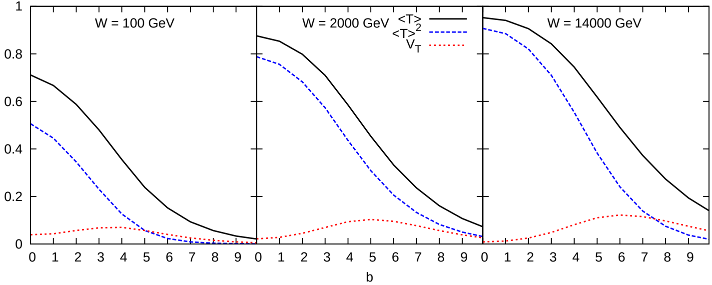
$M_X < 8$ GeV, $Q^2 = 4, 14, 55\,\mathrm{GeV}^2$



Impact parameter profile

Central collisions: $\langle T \rangle$ large $\Rightarrow$ Fluctuations small

Peripheral collisions: $\langle T \rangle$ small $\Rightarrow$ Fluctuations small

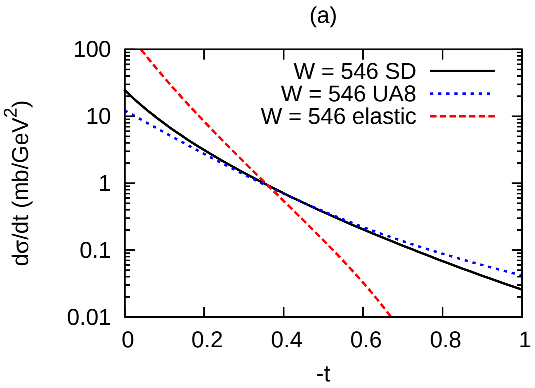


Largest fluctuations when $\langle F \rangle \sim 1$ and $\langle T \rangle \sim 0.5$

Circular ring expanding to larger radius at higher energy

t-dependence

Single diffractive and elastic cross sections



Agrees with fit to UA8 data

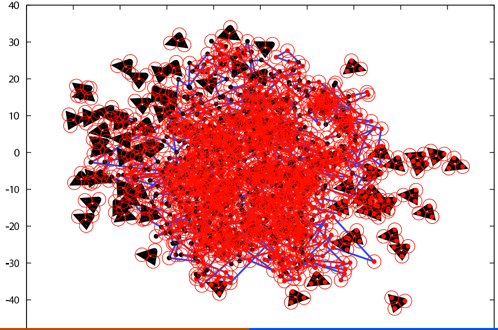
Nucleus collisions

Gives full partonic picture:

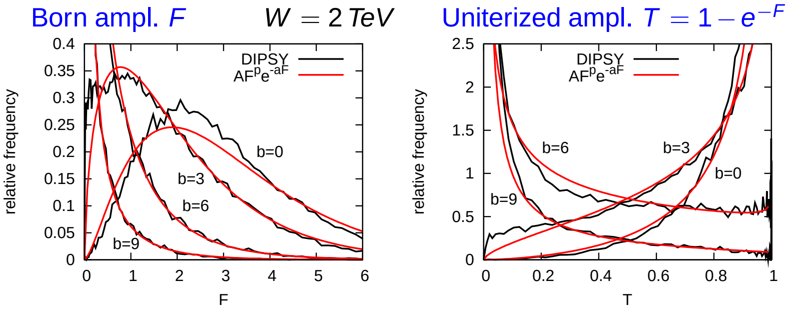
Energy & momentum density $\sim$ initial conditions in hydro

Fluctuations $\Rightarrow$ *e.g.* v_3

Ex.: $Pb - Pb$ 200 GeV/N



Prob. distrib. for *pp* amplitudes



Born approximation: large fluctuations

$\langle F \rangle$ is large $\Rightarrow$ Unitarity effects important

$\sim$ enhanced diagrams in triple-regge formalism

Fluctuations strongly reduced for central collisions

Exclusive diffractive excitation

- A single real final state cascade is collided with a large number of virtual cascades.
- Collide several similar real final states, to calculate fluctuations.
  - Takes time, but possible to calculate at amplitude level.
- No extra parameters! Exclusive diffractive excitation predicted from inclusive and non-diffractive minimum bias.

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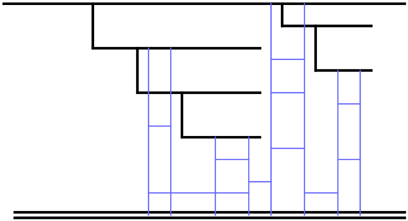

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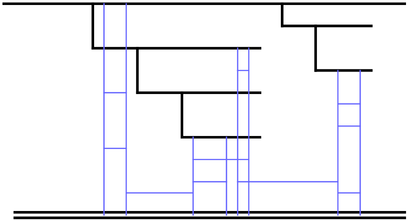

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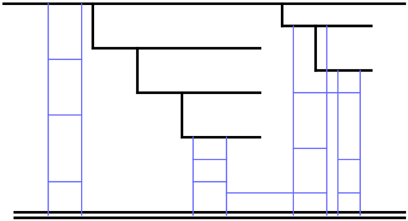

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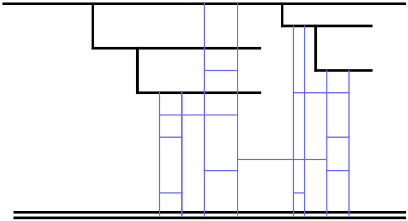

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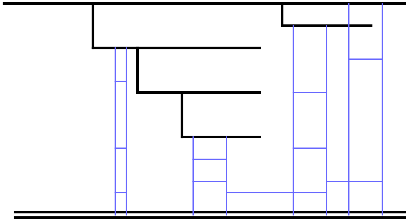
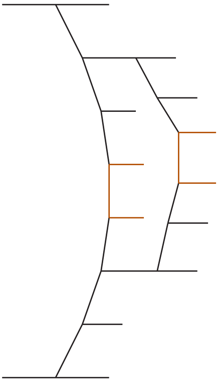


Assume: High energy collisions driven by parton-parton subcollisions (à la PYTHIA)



Low x: BFKL evolution

High $p_\perp$ also within evolution

Multiple int. $\Rightarrow$ saturation

Pomeron loops
MC $\longrightarrow$ Fluctuations
Diffractive excit., Correlations
e, p, and A collisions

The Lund model includes also nonleading effects in the evolution

- Energy conservation ($\sim$ non-sing. terms in $P(z)$)

  small dipole — high $p_\perp \sim 1/r$

  Cascade ordered in p_+

  $\Rightarrow$ small dipoles suppressed for small δy

- "Energy scale terms" $\sim$ "consistency constraint"

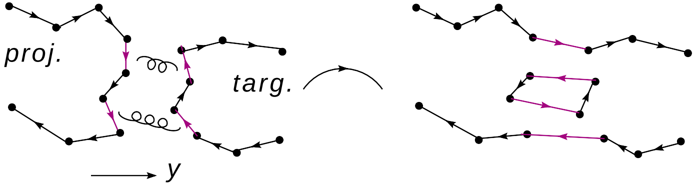
  $\Rightarrow$ Cascade ordered in p_-

  A single chain is left-right symmetric

- Running α_s

Saturation

Multiple interactions ⇒ colour loops



Multiple interaction in one frame

⇒ colour loop within evolution in another frame

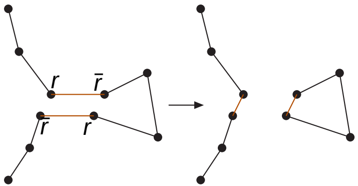
Colour swing

Gluon emission $\sim \bar{\alpha} = \frac{N_C}{\pi}\alpha_s$

Gluon scattering $\sim \alpha_s^2$. Color suppressed
$\Rightarrow$ Loop formation color suppressed. Related to identical colors.

Two dipoles with same colour form a quadrupole

May be better described by recoupled smaller dipoles



Weight favouring small dipoles $\Rightarrow$ near frame indep. result