Cross sections and final states in diffractive excitation

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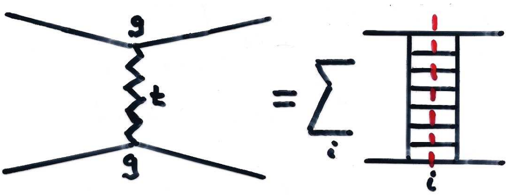
Content

1. Reggeon theory



Elastic scattering driven by absorption.
Analogous to diffraction in optics

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

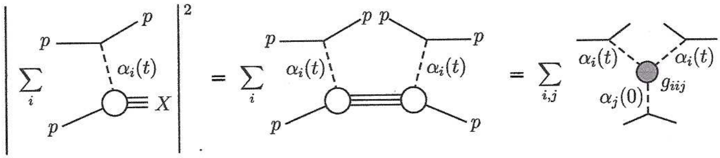
Rescattering corrections in impact parameter space:

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

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



High energy and large masses ⇒ pomeron dominance

Triple pomeron coupling: g_{3P}

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

BFKL pomeron

QCD: Hadron ladder $\rightarrow$ gluon ladder

Leading log approx.: $\alpha(0) \sim 1.5$, HERA: $\alpha(0) \sim 1.3$

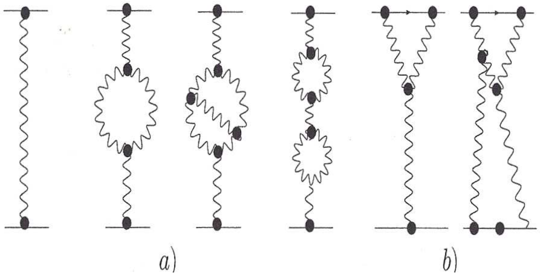
LL BFKL not enough. Non-leading effects large.

$\alpha(0) > 1 \Rightarrow$ Single pomeron exchange gives $\sigma_{el} > \sigma_{tot}$

Unitarity corrections very important

Triple (and multiple) pomeron coupling → pomeron loops

Complicated resummation schemes



Durham (KMR)

Tel Aviv (GLM)

Ostapchenko (based on Kaidalov and coworkers)

Fit regge intercepts and couplings to experimental data

2. Good-Walker formalism for diffractive excitation

Example:

A photon in an optically active medium:

Righthanded and lefthanded photons move with different velocity; they propagate as particles with different mass.

Study a beam of righthanded photons hitting a polarized target, which absorbs photons linearly polarized in the x-direction.

The diffractively scattered beam is now a mixture of right- and lefthanded photons.

If righthanded photons have lower mass:
The diffractive beam contains also photons excited to a state with higher mass

General formalism

A 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):

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

Diffractive excitation determined by the fluctuations:

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

3. BFKL pomeron in dipole formulation

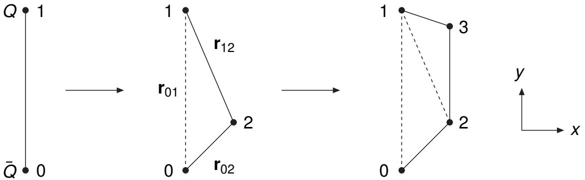
a. Mueller's Dipol model:

LL BFKL evolution in transverse coordinate space

Saturation effects from multiple interactions

Colour charge always accompanied by corresponding anticharge

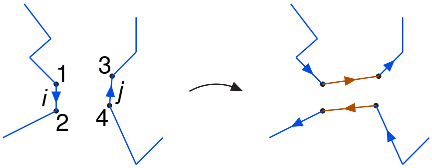
Gluon emission: dipole splits in two dipoles:



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 exchange ⇒ 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.: $T = 1 - e^{-\sum f_{ij}}$

$d\sigma_{el}/d^2b = T^2, \qquad d\sigma_{tot}/d^2b = 2T$

Problems with the BFKL pomeron:

- LL BFKL not enough. Non-leading effects large
- In LL g_{3P} is singular $\sim 1/\sqrt{-t}$
- Saturation important: BK eq. or CGC work for large homogenous targets
- Soft cutoff needed in parton subcollisions
- BFKL inclusive. For exclusive states: Add final state radiation, CCFM

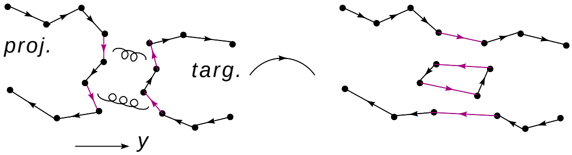
b. The Lund cascade model, DIPSY MC

Includes:

- Important non-leading effects in BFKL evol.
  (Most essential rel. to energy cons. and running α_s)
- Saturation from pomeron loops in the evolution
  (Not included by Mueller or in BK)
- Confinement: eff. gluon mass $\Rightarrow$ t-channel unitarity
- MC DIPSY
  gives also fluctuations and correlations
- Applicable to collisions between electrons, protons, and nuclei

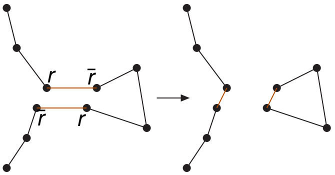
Saturation

Multiple interactions $\Rightarrow$ colour loops $\sim$ pomeron loops



Multiple interaction in one frame $\Rightarrow$
colour loop within evolution in another frame

Gluon scattering is colour suppressed compared to gluon emission $\Rightarrow$ Loop formation and saturation related to identical colors.



transv. space

Same colour ⇒ quadrupole

May be better described by recoupled smaller dipoles

⇒ smaller cross section: fixed resolution ⇒ effective $2 \rightarrow 1$ and $2 \rightarrow 0$ transitions

Thus saturation shows up in two ways:

– Multiple interactions

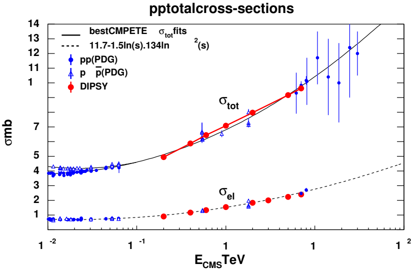
– Colour reconnection

Including the "colour swing" makes the result almost frame independent

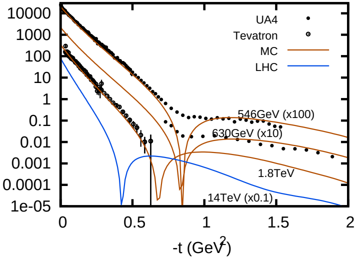
pp total and elastic cross sections

Initial proton wavefunction $\sim$ three dipoles in a triangle

σ_{tot} *and* σ_{el}



$d\sigma/dt$

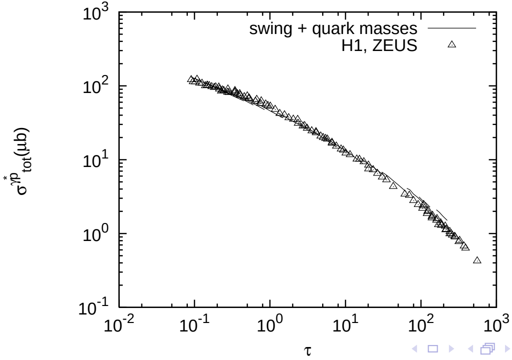


Structure functions

$F_2(x, Q^2) \sim \gamma^* p$ cross section

$\gamma^\star \to q\bar{q}$ dipole wavefunction from QED

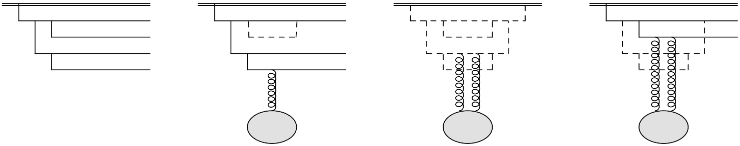
Satisfies geometric scaling. $\tau = Q^2/Q_s^2(x)$, $Q_s^2 \propto x^{-0.3}$



4. Good-Walker *vs* triple-regge

What are the diffractive eigenstates for the BFKL pomeron?

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



Virtual cascade a | *Inelastic int.* b | *Elastic scatt.* c | *Diffractive ex.* d

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

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

Essential feature of the BFKL cascade:

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

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

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

Approximate KNO scaling

2 colliding cascades, evolved y_1 and y_2:

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

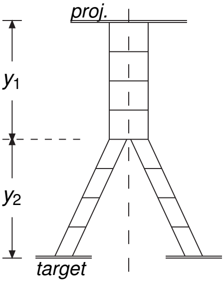
Bare pomeron: $\sigma_{inel} \propto e^{\lambda y_1}\, 2f\, e^{\lambda y_2} = 2f\, e^{\lambda Y} = 2f\, s^{\lambda}$

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

Single diffr. excit.

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

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



a) 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, $M_X < M_{max}$:

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

b) Good–Walker

Diffractive excitation determined by the fluctuations:

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

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:

$\frac{V(y)}{\langle n\rangle^2} = (1 - e^{-\lambda y})$ (arXiv:1206.1733, PLB 2013)

Diffractive cross sections, DIPSY

(JHEP 1010, 014, arXiv:1004.5502)

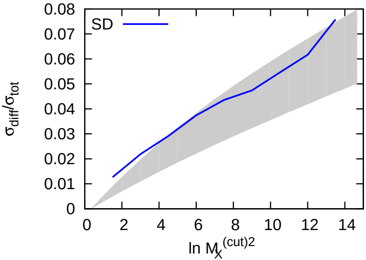
pp at 1.8 TeV

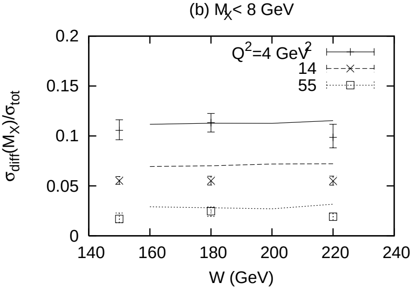
Single diffr., $M_X^2 < M_{max}^2$

Shaded area: CDF estimate

DIS: ZEUS data

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





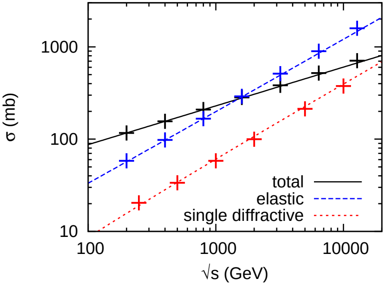
Note: Tuned only to $\sigma_{\rm tot}$ and $\sigma_{\rm el}$. No new parameter

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.)

Compare with triple-regge fits:

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

GLM: $\alpha(0) = 1.23, \quad \alpha' \approx 0$

KMR: $\alpha(0) = 1.12, \quad \alpha' \approx 0$ (“effective” pomeron traj.)

Kaidalov *et al.*: $\alpha(0) = 1.12, \alpha' = 0.22$

Goulianos: $\alpha(0) = 1.21, \quad \alpha' = 0.2$ (renorm. pomeron flux)

Note:

Fit $\sim$ single pomeron pole (not a cut)

$g_{3\text{P}}$: magnitude $\sim$ pert. QCD estimate by Bartels-Ryskin-Vacca ($\pi g_{3\text{P}} \sim 0.2 - 1.7\ \text{GeV}^{-1}$)

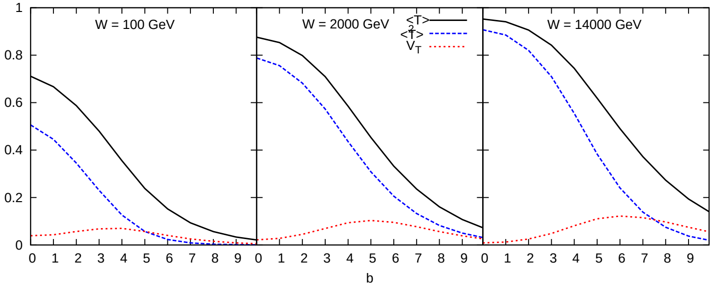
Saturation effects

Saturation ⇒ Fluctuations suppressed in central collisions

Diffr. excit. largest in a circular ring,

expanding to larger radius at higher energy

Impact parameter profile

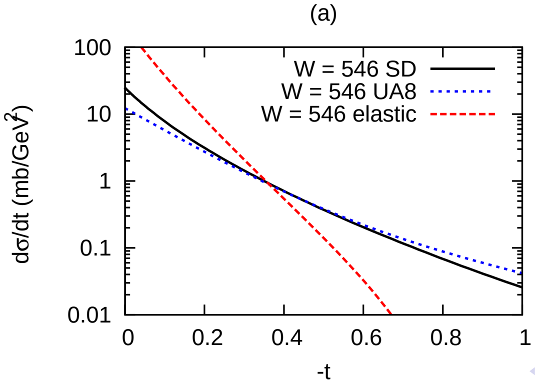


Factorization broken between *pp* and DIS

t-dependence

Amplitude purely real ⇒ possible to make Fourier transform to momentum space

Single diffractive and elastic cross sections



5. Exclusive diffractive final states

If gap events are analogous to diffraction in optics $\Rightarrow$

Diffractive excitation fundamentally a quantum effect

Different contributions interfere destructively,
no probabilistic picture

Still, different components can be calculated in a MC,
added with proper signs, and squared

Possible because opt. th. $\Rightarrow$ all contributions real

(JHEP 1212 (2012) 115, arXiv:1210.2407)

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

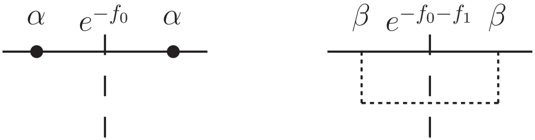
$$\Phi = U_{\text{evol}} \Psi$$

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

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

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

Elastic scattering:

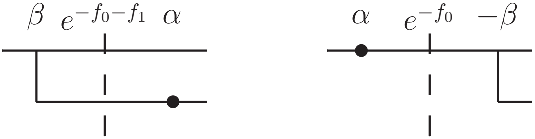


Elastic amplitude

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

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

Diffractive excitation:

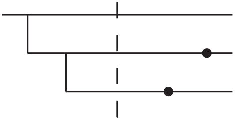


$$T_{21} = -S_{21} = -\alpha\beta e^{-f_0-f_1} - \alpha(-\beta)e^{-f_0} = \alpha\beta e^{-f_0}(1 - e^{-f_1})$$

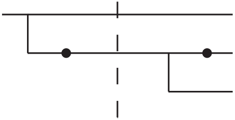
Cascade with 2 possible emissions

Ex.: Final state with both emissions

$$\beta_1\,\beta_2\,e^{-f_0-f_1-f_2}\,\alpha_2\,\alpha_1$$

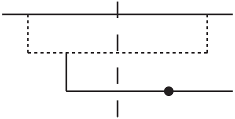


$$\beta_1\,\alpha_2\,e^{-f_0-f_1}\;-\beta_2\,\alpha_1$$

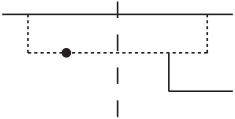


Final state with only the second emission

$$\beta_1\,\beta_2\,e^{-f_0-f_1-f_2}\,\alpha_2\,\beta_1$$



$$\beta_1\;\;\alpha_2\,e^{-f_0-f_1}\;-\beta_2\;\beta_1$$



Generalizations:

Continuous cascades

Independent gluon emissions $\rightarrow$ dipole cascade

Include target cascade

Calculations:

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

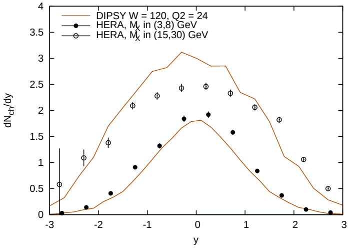
Collide with large no. of target cascades

Computationally demanding, but still possible in the MC

Early results for DIS and *pp*

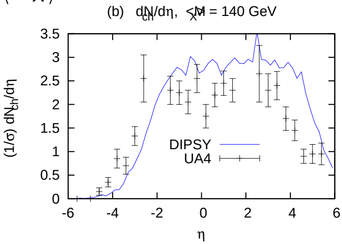
H1: $W = 120$, $Q^2 = 24$

$dn_{ch}/d\eta$ in 2 M_X-bins



UA4: $W = 546$ GeV

$\langle M_X \rangle$= 140 GeV



Too hard in proton fragmentation end. Due to lack of quarks in proton wavefunction

Note: Based purely on fundamental QCD dynamics

(JHEP 1212 (2012) 115, arXiv:1210.2407)

Future:

Include quarks

Double diffraction. Computationally demanding

Hard diffraction

Include the Odderon

Might be possible to estimate the survival probability

Is there any relation to the probabilistic approaches by Ingelman-Schlein or color reconnection?

Conclusions

The BFKL pomeron, with non-leading log corrections and saturation, gives a fair description of data, without input structure functions

Good–Walker and triple-pomeron describe the same dynamics for diffractive excitation

In both approaches: gap events are analogous to diffraction in optics

Reggeon formalism: Many parameters

Good–Walker: No extra tunable parameter

Diffractive final states:

Analogy to optics ⇒

Quantum effect: Interfering contributions to the amplitude

Reggeon theory: No predictions presented

Good–Walker: Although no semiclassical probabilistic picture, still possible to calculate in the dipole cascade formalism

Early results are encouraging

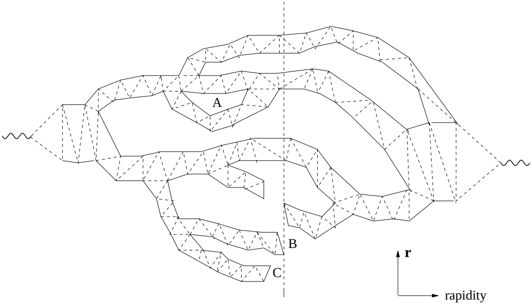
Question: Is there any relation to probabilistic schemes like Ingelman–Schlein or color reconnection?

Extra slides

Exclusive final states in non-diffractive events

BFKL is a stochastic (probalistic) process

Prob. for interaction $= 1 - e^{-2f_{ij}}$



Non-interacting branches cannot come on shell.

Virtual and reabsorbed.

How to get final states:

- Generate cascades for projectile and target
- Determine which dipoles interact
- Absorbe non-interacting chains
- BFKL is inclusive; final state radiation must be added in apropriate regions (see Nucl.Phys. B467 (1996) 443)
- Hadronize

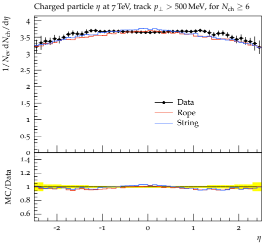
Comparisons to ATLAS data at 7 TeV

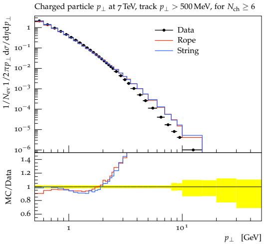
Min bias

Charged particles

η-distrib.

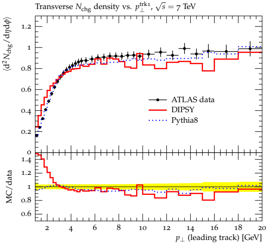
p_T-distrib.





Underlying event

N_{ch} in transv. region vs $p_{\perp}^{lead}$



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

At present no quarks, only gluons