Minireview on diffraction

and some new results on high gluon densities

Gösta Gustafson

Department of Theoretical Physics
Lund University

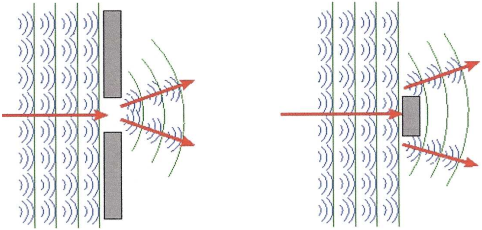
ISMD 2014
Bologna, 8 - 12 Sept. 2014

Content

1. Optical analogy and Good–Walker formalism
2. Soft diffraction
   - Reggeon theory
   - QCD and the BFKL pomeron
3. Hard diffraction
4. Effects of high gluon density

1. Optical analogy and Good–Walker

Optics: A hole equivalent to a black absorber



Forward peak

$$\theta \sim \frac{\lambda}{\text{opening width}}$$

Diffraction and rescattering more easily treated in impact parameter space

Rescattering $\Rightarrow$ convolution in $\mathbf{k}_\perp$-space $\rightarrow$ product in $\mathbf{b}$-space

Optical theorem:

$$\mathrm{Im}A_{el} = \frac{1}{2}\{|A_{el}|^2 + \sum_j |A_j|^2\}$$

Structureless projectile (*e.g.* a photon):
Diffraction = elastic scattering driven by absorption

Absorption probability in Born approx. = $2F$

Rescattering exponentiates in impact param. space:
$d\sigma_{inel}/d^2b = 1 - e^{-2F}$

Optical theorem $\Rightarrow \mathrm{Im}A_{el} = 1 - e^{-F}$

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

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

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 the righthanded photons have lower mass:

The diffractive beam contains also photons excited to a state with higher mass

Good–Walker formalism:

Projectile with a substructure: The mass eigenstates can differ from the eigenstates of diffraction

Diffractive eigenstates: Φ_n; Amplitude: T_n

Mass eigenstates: $\Psi_k = \sum_n c_{kn}\Phi_n$ $(\Psi_{in} = \Psi_1)$

Elastic amplitude: $\langle\Psi_1|T|\Psi_1\rangle = \sum c_{1n}^2 T_n = \langle T\rangle$

$d\sigma_{el}/d^2b \sim (\sum c_{1n}^2 T_n)^2 = \langle T\rangle^2$

Amplitude for diffractive transition to mass eigenstate Ψ_k:

$\langle\Psi_k|T|\Psi_1\rangle = \sum_n c_{kn} T_n c_{1n}$

$d\sigma_{diff}/d^2b = \sum_k \langle\Psi_1|T|\Psi_k\rangle\langle\Psi_k|T|\Psi_1\rangle = \langle T^2\rangle$

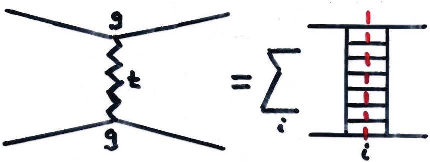
Diffractive excitation determined by the fluctuations:

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

2. Soft diffraction

2a. Reggeon theory

Pomeron exchange



$$d\sigma_{el}/dt \sim (g^2 \cdot s^{\alpha(t)})^2 = g^4 s^{2(\alpha(0)-1)} e^{2(\ln s)\alpha' t}$$

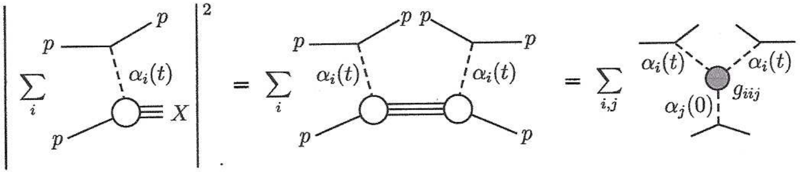
$$\sigma_{tot} \sim g^2 s^{\alpha(0)-1}$$

Note: $\alpha(0) > 1 \Rightarrow \sigma_{el} > \sigma_{tot}$ for large s:

Multi-pomeron exchange important

Inelastic diffraction

Mueller triple-Regge formalism

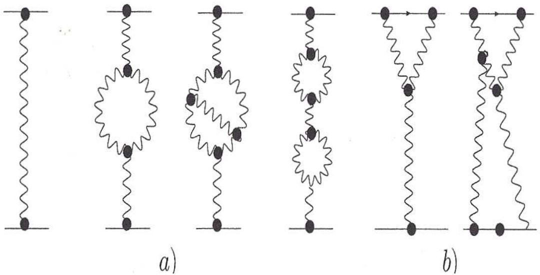


Triple pomeron coupling: g_{3P}

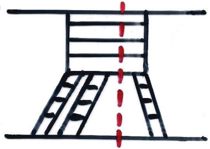
$$\sigma \sim g_{pP}^2(t) g_{pP}(0) g_{3P} \left(\frac{s}{M_X^2}\right)^{2(\alpha(t)-1)} \left(M_X^2\right)^{(\alpha(0)-1)}$$

Triple (and multiple) pomeron coupling → pomeron loops

Complicated resummation schemes



Also multi-pomeron vertices:



$= g_{n,m}$

3 dominating groups:

Tel Aviv (GLM)

Durham (KMR)

Ostapchenko (based on Kaidalov and coworkers)

Low mass diffr.: G-W, approximated by 1 excited state N^*

High mass diffraction: Cut pomerons

At low energies also Reggeon: $\alpha(0) \approx 0.5$

Fit regge intercepts and couplings to experimental data

Significantly modified after Totem data at 7 TeV:
$\sigma_{tot} = 98.6 \pm 2.2$ mb, $\sigma_{el} = 25.4 \pm 1.1$ mb

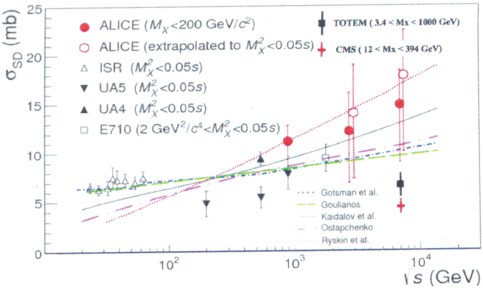
- Tel Aviv
  Single pomeron: $\Delta_P = 0.23$, $\alpha' \approx 0$
  $\Rightarrow$ pomeron propagator $\sim \delta(\mathbf{b})$, no diffusion in **b**-space
  Only 3-pomeron vertices
- Durham
  New version 2014:
  Single “effective” pomeron with couplings dep. on $k_\perp$.
  Interpolates between
  “bare $I\!P$": $\Delta \approx 0.3$ with α' small,
  “soft $I\!P$": $\Delta \approx 0.08$ with $\alpha' = 0.25$
  Multi-pomeron couplings, $g_{n,m} \sim nm\gamma^{n+m}$, large
- Ostapchenko
  Hard and soft pomeron, $\Delta_{soft} = 0.14$, $\Delta_{hard} = 0.31$
  Multi-pomeron couplings $g_{n,m} \sim \gamma^{n+m}$

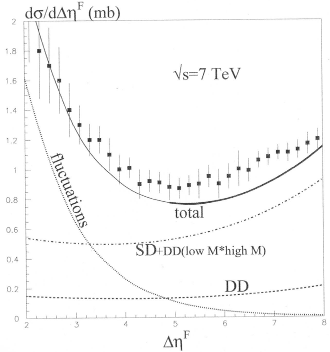
Single diffractive cross section

(Low mass diffraction difficult to measure)

$d\sigma/d\eta^F \sim d\sigma/d\ln M_X^2$

KMR result with ATLAS data





(From N. Cartiglia)

ATLAS and CMS have similar results

2b. QCD and the BFKL pomeron

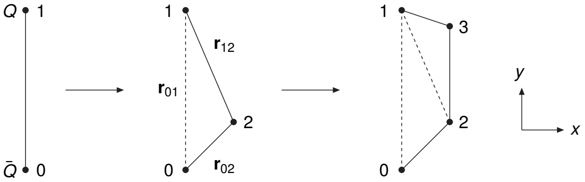
Saturation much easier in transverse coordinate space

i. Mueller's Dipol model:

LL BFKL evolution in transverse coordinate space

Colour charge always accompanied by corresponding anticharge

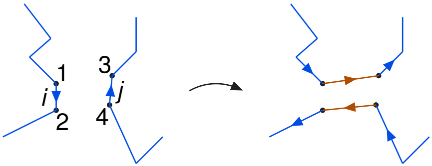
Gluon emission: dipole splits in two dipoles:



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

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

ii. The Lund cascade model, DIPSY MC

(E. Avsar, C. Flensburg, G.G., L. Lönnblad)

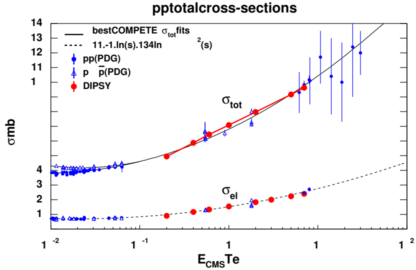
Includes:

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

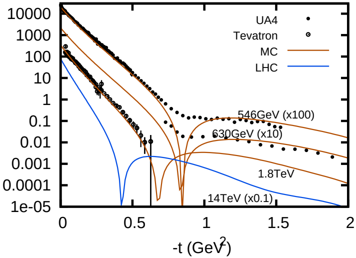
pp total and elastic cross sections

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

σ_{tot} *and* σ_{el}



$d\sigma/dt$

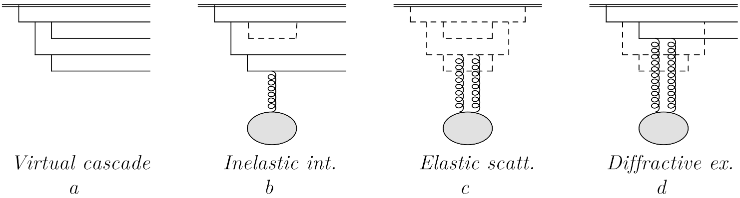


No input structure functions

iii. 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.



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

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

cf KMR and GLM: only 2 low mass eigenstates

Claim: Good–Walker and triple-pomeron are only different formulations of the same phenomenon (1206.1733, PLB 2013)

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

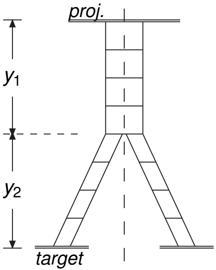
2 colliding cascades, evolved y_1 and y_2:

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

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.



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

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

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

Triple-pomeron:

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

Good–Walker: Diffr. exc. determined by the fluctuations:

$$\sigma_{\rm SD} = \langle\langle T\rangle_{\rm targ}^2\rangle_{\rm proj} - \langle\langle T\rangle_{\rm targ}\rangle_{\rm proj}^2 = f^2 e^{2\lambda Y}(1 - e^{-\lambda y_1})$$

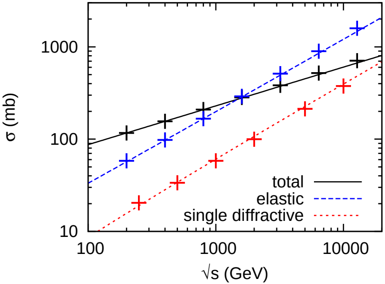
Same expression as in triple-pomeron!!

Most essential for this result is the approximate KNO scaling

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

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

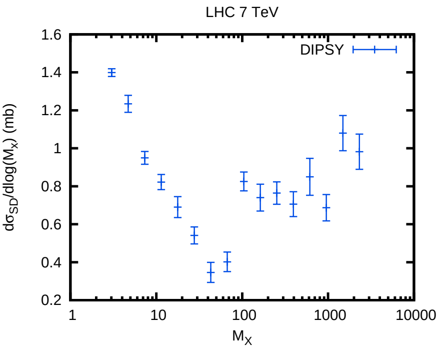
$g_{pP}(t) = (5.6\,\text{GeV}^{-1})\, e^{1.9t}, \;\; g_{3P}(t) \approx 1\text{GeV}^{-1}$ (dep. on def.)

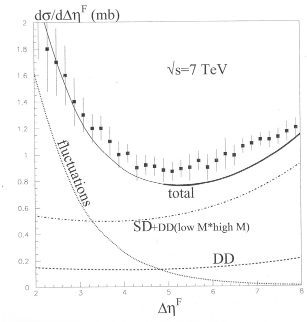
Diffractive cross sections, DIPSY

$d\sigma_{SD}/d \ln M_X$ at 7 TeV

preliminary

Cf ATLAS data





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

3. Hard diffraction

UA8 at CERN S$p\bar{p}$S collider (= UA2 central detector + roman pots at 630 GeV) observed high $p_\perp$ jets in diffractive events

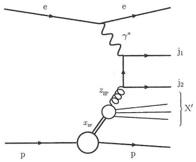
Also observed in gap events at HERA and the Tevatron.

Ingelman-Schlein model:

The pomeron has a universal parton substructure $f_{q,g}^{P}(z, Q^2)$

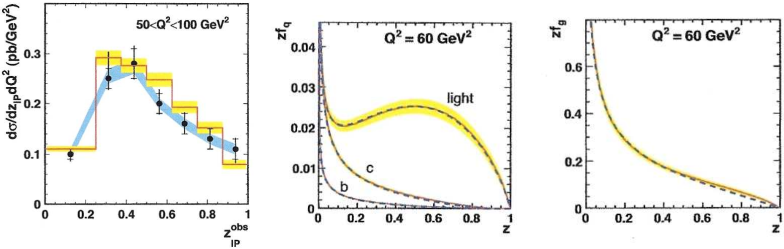
Factorization:

$\sigma^{diff} \sim \sum_i F_P^p(x_P) \otimes f_i^P(z = x_{Bj}/x_P, Q^2) \otimes \hat{\sigma}_{\gamma^* i}$



Collins: Factorization works for DIS at high Q^2

Fit with NLO DGLAP evolution to HERA DIS data for hard and soft diffraction (ZEUS)



z_P^{obs}-distr. extracted q distr. extracted g distr.

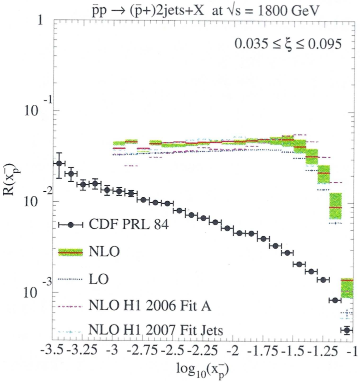
Gluon dominated

Implemented *e.g.* in MC POMPYT, PYTHIA8, and POMWIG

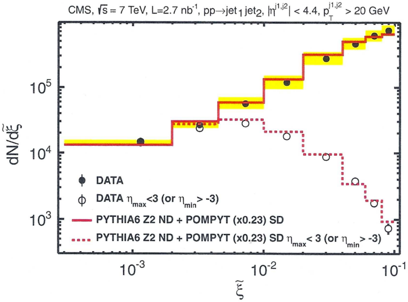
Factorization broken in *pp* and γp

Gap filled by soft interactions. Ex.: $pp \to p + 2\,jets + X$

CDF: $R = SD/ND$ vs x_P



CMS: $dN/d\tilde{\xi} \approx dN/d(M_X^2/s)$



Pomeron flux renormalized in MC

Gap survival prob. extra factor ≈ 0.2

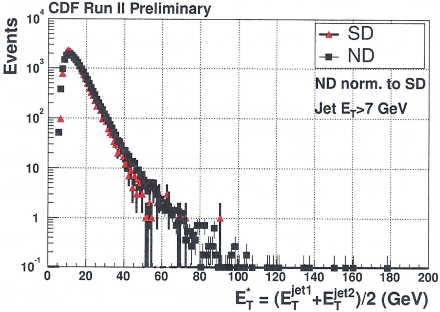
Rescaling factor 0.1–0.2

Jet distribution in SD similar to ND

CDF 2-jet events

N_{ev} vs mean E_T

red: SD
black: ND



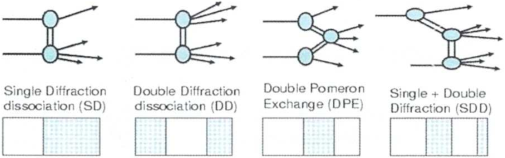
Same hard subprocess; no extra suppression $\sim 1/Q^2$

$\Rightarrow$ A soft gluon neutralizes the colour exchange

No additional gluons fills the gap with prob. S^2

Consistent with Goulianos' empirical "renormalized pomeron" and B.Z. Kopeliovich *et al.*: Hard diffr. in DIS is leading twist

Multiple gaps

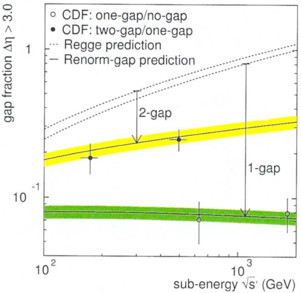


Gap survival prob. difficult to calculate

Ratio 2-gap/no-gap (SDD/SD) and one-gap/no-gap (DD/tot)

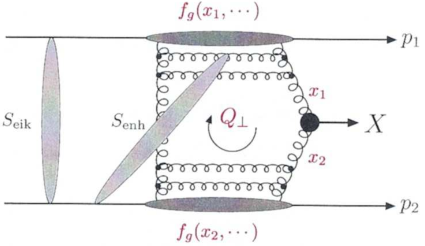
CDF: Multiple gaps not multiply suppressed

Also consistent with renorm. pomeron



Central exclusive production

Many schemes proposed for gap survival



from KMR

Experimentally determined for exclusive $Q\bar{Q}$ or two-jet production

Rule of thumb: $\sim 0.1 - 0.2$ at the Tevatron

reduced to ~ 0.03 at LHC

(Future: Survival probability in DIPSY)

Interesting processes include:

- *Cf* W^+W^- and jet-jet states
  $\rightarrow$ relation between quarks and gluons in the pomeron
- jet–gap–jet in double diffr.: study BFKL evolution
- $\gamma\gamma \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow W^+W^-$
  $\rightarrow$ possible anomalous weak couplings
- Higgs search

Specialized MC: FPMC (Boonekamp *et al.*)

based on Ingelman–Schlein and HERWIG
See following talks

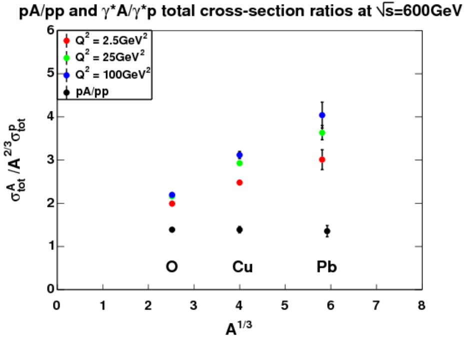
4. Some new results on high gluon densities

DIPSY applicable to collisions with nuclei

Examples: *pA* coll.: almost black: $\sigma_{pA} \propto A^{2/3}$

DIS: High Q^2 transparent: $\sigma_{pA} \propto A$,   lower Q^2: in between

$\sigma^A_{tot}/(A^{2/3}\sigma^p_{tot})$
vs $A^{1/3}$



(G.G., L. Lönnblad, A. Ster, in preparation)

High energy collisions have many strings or cluster chains in final state

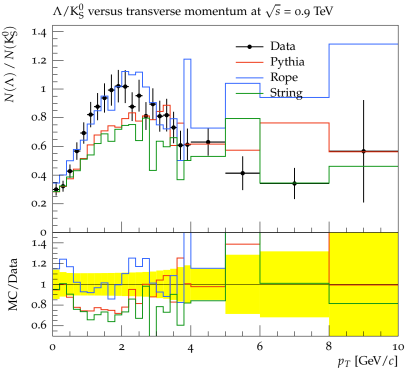
Ought to affect each other: coherent hadronization, ropes?

Gives higher strangeness and baryon ratios

Λ/K_0 ratio *vs* p_T

CMS data, 0.9 TeV

preliminary



(G.G., L. Lönnblad, Ch. Bierlich, A. Tarasov, in preparation)

Conclusions

Soft diffraction:

High mass: BFKL pomeron dynamics $\Rightarrow$
Reggeon and Good–Walker describe the same physics.

Good–Walker has the advantage that no new tunable parameters are needed for diffraction

Low mass: Low-lying reggeons contrib.; difficult to measure

Hard diffraction:

Factorization broken for *pp* and γp due to soft exchange in *pp*

Survival probability $\sim 0.1 - 0.2$ at the Tevatron, ~ 0.03 at LHC

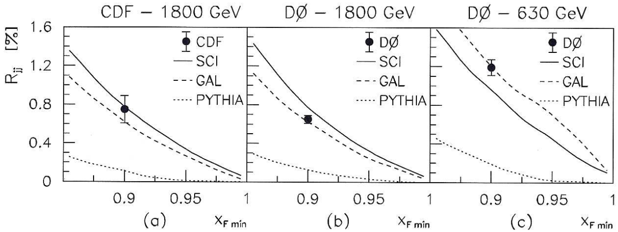
LHC: larger acceptance in *y*, than at HERA or the Tevatron

Many interesting analyses at LHC with roman pots

Extra slides

Alternative description of gap events

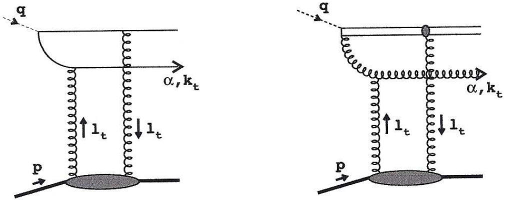
Soft color reconnection or soft rescattering can give rapidity gaps in “normal” inelastic events (Ingelman and coworkers)



Diffraction in DIS

Events with a large rapidity gap are observed by H1 and ZEUS at HERA

Dipole model, Golec-Biernat – Wüsthoff



The photon fluctuates into a $q\bar{q}$ or $q\bar{q}g$ state

Elastic scattering of this state gives a hadronic state with a gap to the target proton

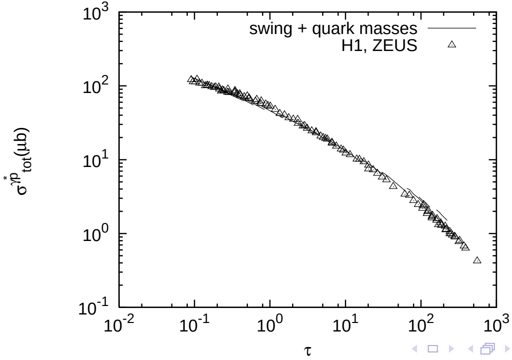
optical theorem $\Rightarrow \sigma^D$

Structure functions in DIPSY

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

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

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



Exclusive diffractive final states

If gap events are analogous to diffraction in optics ⇒

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

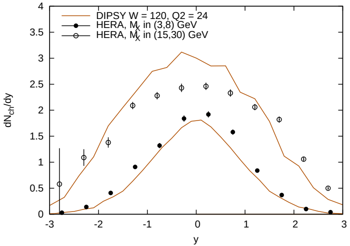
Possible because opt. th. ⇒ all contributions real

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

Early results for DIS and *pp*

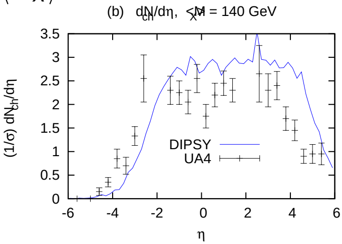
H1: $W = 120$, $Q^2 = 24$

$dn_{ch}/d\eta$ 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

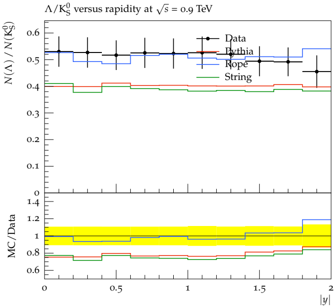
Note: Based purely on fundamental QCD dynamics

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

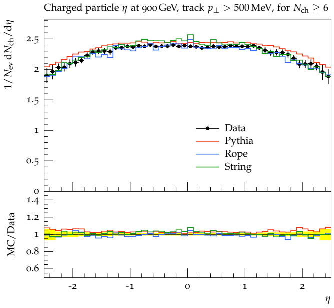
More results for ropes from DIPSY

pp at 0.9 TeV   preliminary

CMS: Λ/K_0 ratio *vs* y



ATLAS: n_{ch} *vs* η



(G.G., L. Lönnblad, Ch. Bierlich, A. Tarasov, in preparation)

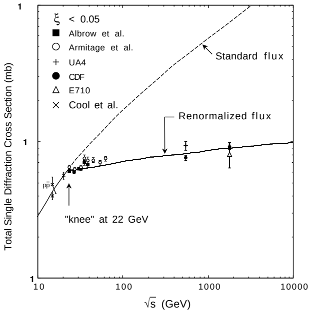
Goulianos' renormalized pomeron

$$M_X^2 \frac{d\sigma_{SD}}{dt\, d(M_X^2)} = \left\{ \frac{1}{16\pi} g_{pP}^2(t) g_{pP}(0) g_{3P} \left(\frac{s}{M_X^2} \right)^{2(\alpha(t)-1)} \right\} (M_X^2)^{(\alpha(0)-1)}$$

Saturation $\Rightarrow$ Renormalization of pomeron flux:

divide by $\quad const. \cdot \int dt\, d\ln M_X^2 \{\ldots\}$

pp scatt.



Suppresses diffraction

in *pp*, but not in $\gamma^\star p$

DIS: ZEUS data

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