Fizyka „do przodu”. Część I: przegląd fenomenologii

Barbara Badełek
Uniwersytet Warszawski

Seminarium Zakładu FCiOF

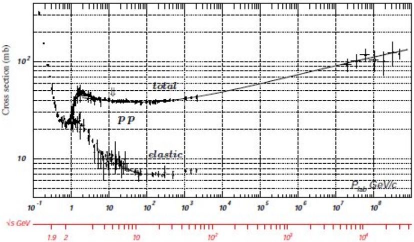
Warszawa, 16.III. 2012

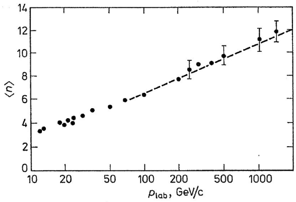
Outline

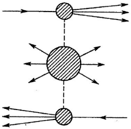
Outline

Hadron – hadron interactions

- QCD – theory of quark-quark interactions at high momentum transfers while hadron–hadron interactions involve many partons at small momentum transfers.
- Two approaches: S matrix theory (amplitudes and phases of waves analogously to optics) and Regge model (single particle exchanges).
- Features of those interactions:







- inelastic processes dominate
- average multiplicity grows logarithmically with energy
- average transverse momentum is low, $\langle p_T \rangle \sim 0.4$ GeV, and independent of energy
- most of particles emitted from the cms "central region" (low p_L); some diffractive.

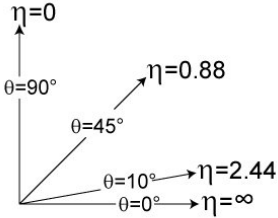
Hadron – hadron interactions,...cont'd

- Particle production is constant as a function of rapidity, y.

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

- Under a boost in z to a frame with velocityβ, $y \to y - \tanh^{-1}\beta$...
- ...hence shape of rapidity, $\mathrm{d}N/\mathrm{d}y$ is invariant as are differences in rapidity $\Longrightarrow y$ is preferred over polar angle θ in hadron collider physics.
- "Forward" in a hadron–hadron collider experiment means close to the beam axis, i.e. high pseudorapidity, $|\eta|$, where

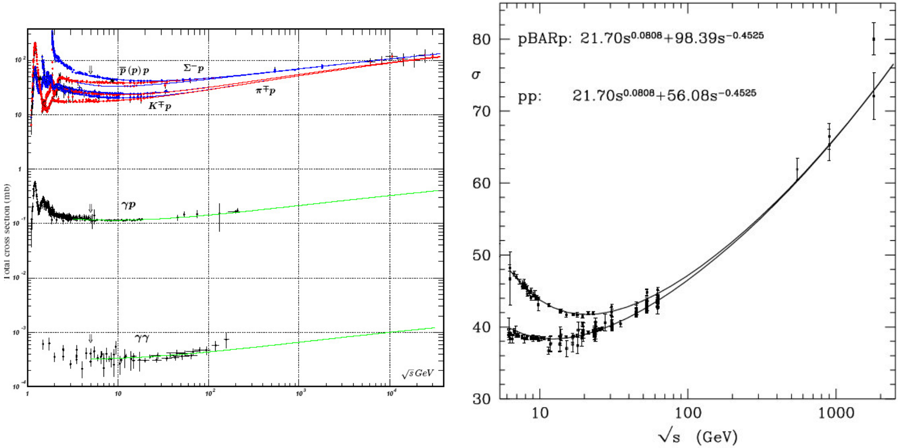
$$\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



- $\eta \Rightarrow y$ for $v \approx c$ or $m \approx 0$,
  η can be measured when m and p unknown.

Outline

Total cross section data

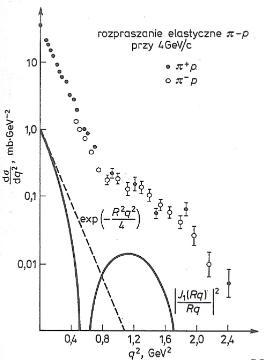


- Cross sections (slowly) grow with energy (curves: Donnachie and Landshoff).
- Particle and antiparticle cross sections equal at high energy.

Total and elastic cross section

- Pomeranchuk theorem: at high energies, $\sigma_{\rm tot}(\rm ab) = \sigma_{\rm tot}(\bar{a}b)$, if $\mathrm{Re}A/\mathrm{Im}A < 1$. Manifestation of crossing symmetry. Confirmed experimentally.
- Froissart bound: asymptotically $\sigma_{\rm tot}(s)$ cannot increase faster than $\ln^2 s$ (unitarity, analyticity).
- Simplest scattering/absorption model: a black disk of radius R.
- Partial wave decomposition gives:
  $\sigma_{\rm el} = \pi R^2 \qquad \sigma_{\rm in} = \pi R^2 \qquad \sigma_{\rm tot} = 2\pi R^2$
- $\sigma_{\rm el} = \sigma_{\rm in} \Longrightarrow$ diffraction
  (seen in data albeit wrong proportions; $R \sim 1$ fm):

$$\frac{\mathrm{d}\sigma_{\rm el}(\text{black disk})}{\mathrm{d}q^2} = \pi R^4 \left| \frac{J_1(Rq)}{Rq} \right|^2 \approx \frac{\pi R^4}{4} \exp\left(-\frac{R^2 q^2}{4}\right)$$

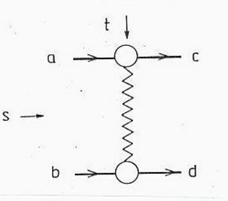


- At high energies, radius R grows slowly with energy (seen in data).
- Data: $\sigma_{\rm el}/\sigma_{\rm tot} \ll 0.5$ and decreases with energy.
- Better description $\Longrightarrow$ Regge model.

Outline

A concept of Regge exchange

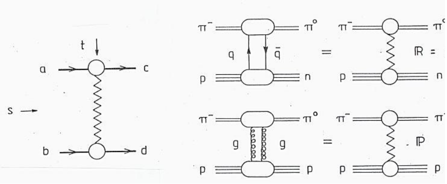
- Cross section for two-body process: ab→cd is strongly dominated by small t (or small θ).
- Successfuly described by exchange of a particle with appropriate quantum numbers.
- Regge “pole” (of given quantum numbers) exchange:
  a generalisation of a single particle exchange, where angular momentum is complex and continuous.

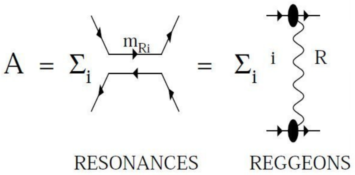


Regge model and partons

Regge poles (singularities !) exchange represented in terms of partons of different virtuality t and spin α.

DUALITY





- "pomeron", $\mathbb{P}$ = Regge pole carrying quantum numbers of vacuum ($\rightarrow$ diffractive scattering). No known particles associated with it!
- "reggeons", $\mathbb{R}$ = other Regge poles with $\mathrm{q\bar{q}}$ structure. Sometimes no known particles associated with it.

Regge trajectory

- Regge trajectory: $\alpha(t)$,
  t-dependent position of a pole of f_l
  in the (Im l, Re l)–plane in the t-channel.
  Whenever $\alpha(t) = n, \quad n = 1, 2, 3, ...$
  or $\quad n = 1/2, 3/2, ...$
  there should exist a particle
  of spin n and mass $M_n = \sqrt{t}$.

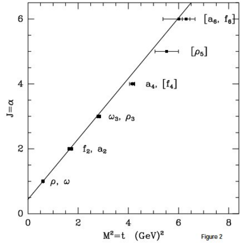
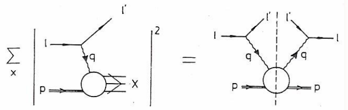


Figure 14: *The experimental ρ, f and a trajectories .*

- H.e. behaviour of a 2-body amplitude due to $\mathbb{R}$ exchange:
  $A(s,t) \sim s^{\alpha(t)}$, $\quad \alpha(0)$ = "intercept"

- Optical theorem: $\mathrm{Im}A_{\mathrm{el}}(0) = s\sigma_{\mathrm{tot}}$,
  $\sigma_{\mathrm{tot}} \sim s^{\alpha(0)-1}$ for a + b → *anything*.



- Known trajectories: $\alpha_{\mathbb{R}}(0) \lesssim$ 1/2 but $\alpha_{\mathbb{P}}(0) \approx$ 1 ???
  $\mathbb{P}$ should be able to describe h.e. cross section ($\sigma_{\mathrm{tot}} \approx \mathrm{const}, s \nearrow$)
  and the shrinkage of the pp diffractive peak.

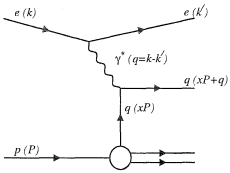
Outline

DIS and definitions of variables

- Inclusive interaction: e + p $\rightarrow$ e$^{'}$ + X *via* one γ^* exchange
- At a given energy the cross section described by 2 variables, *e.g.:* x, Q^2

$$Q^2 = -q^2 = -(k-k')^2$$

$$x = \frac{q^2}{2P \cdot q}, \quad 1 \leq x \leq 1$$



- Observe that the resolution of the γ^* sond:

$$\Delta r \sim \frac{\hbar c}{\sqrt{Q^2}}$$

- The ep$\rightarrow$ e$^{'}$X cross section:

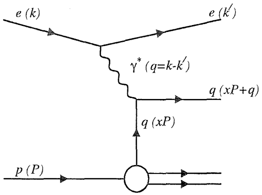
$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\mathrm{d}x}\right)_{\mathrm{ep}} = \sum_i \int_0^1 \mathrm{d}\eta f_i(\eta) \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\mathrm{d}x}\right)_{\mathrm{ei}} \sim F_1(x,Q^2) + F_2(x,Q^2)$$

  is a sum of $\gamma^* - q$ interactions.
  Observe: σ factorisation into short- and long range processes!

- “Structure functions” F_1 and F_2 taken from measurements.

- In the QPM: $F_2(x) = \sum_i e_i^2 x q_i(x)$, and $2xF_1 = F_2$.

Regge model in DIS



- $s = (P+q)^2 = W^2_{\gamma * \mathrm{p}} \equiv W^2$
- DIS: $Pq \to \infty$, $Q^2 \to \infty$,
  but $x = Q^2/(2Pq) \to$ finite and $x \sim$ O(1)
- Small x limit of DIS:
  $2Pq \gg Q^2$ (or $s \gg Q^2$) yet Q^2 is still large, $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$.
- Regge limit: scattering energy $\gg$ masses, momentum transfers.
  In DIS: $2Pq \gg Q^2$, i.e. small x limit.
- Regge behaviour of structure functions in the parton model: $F_2 \sim x^{-\lambda}$ where $\lambda \equiv \alpha(0) - 1$. Thus

$$q_{\mathrm{sea}}(x) \sim \frac{1}{x} \qquad \mathbb{P} \;\; \text{exchange,} \quad \alpha^{\mathrm{B}}_{\mathbb{P}}(0) = 1$$

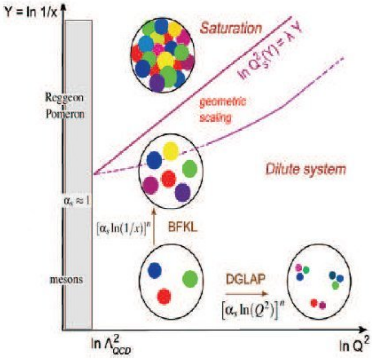
$$q_{\mathrm{val}}(x) \sim \frac{1}{\sqrt{x}} \qquad \mathbb{R} \;\; \text{exchange,} \quad \alpha_{\mathbb{R}}(0) \approx \frac{1}{2}$$

- Same processes lead to gluon and sea distr$^{\mathrm{s}}$, thus: $G(x) \sim \dfrac{1}{x}$

Outline

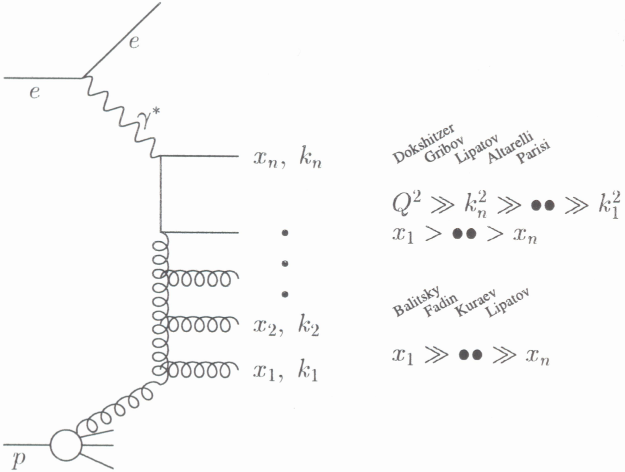
Low x region in QCD

- At low x, energy in the $\gamma^* p$ cms is large (large gluon cascades): $W^2_{\gamma^* p} = Q^2(1-x)/x$.
- Contributions from large $\alpha_s \ln \frac{1}{x}$ terms $\Rightarrow$ new evolution equations: BFKL, CCFM.



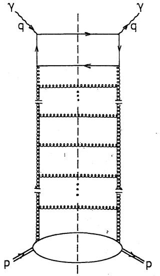
- At low x: strong increase of gluon density with decreasing x (cf. HERA data) $\Rightarrow$ gluon recombination (saturation).
- At $Q^2 \ll Q^2_{sat}$ nonlinear effects of parton saturation must be considered.

QCD cascades at low x



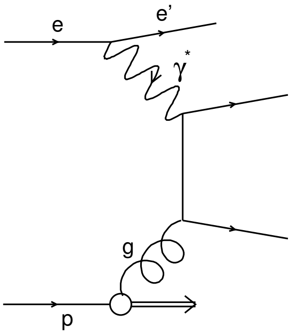
Pomeron

- Geometrically: diffraction corresponds at most to scattering on an expanding black disk with radius growing no faster than $\ln s$. At finite energies $\sigma_{\rm tot}(s) \sim s^{\alpha_{\mathbb{P}}(0)-1}$, $\alpha_{\mathbb{P}}(0) > 1$ is possible (later slowed down).
- Pomeron of Donnachie–Landshoff, $\alpha_{\mathbb{P}}(0) = 1.08$
- This is a "soft" pomeron.
- In QCD, LL$(1/x)$ ($\equiv$ LL(s)) approximation $\rightarrow$ bare pomeron, $\alpha_{\mathbb{P}}^{\rm B}(0) > 1$
  $\Longrightarrow$ violation of Froissart bound
  $\Longrightarrow$ find unitarisation procedure.
- Ladder diagrams of "reggeised" gluons.
- In the BFKL: a "hard" pomeron of $\alpha_{\mathbb{P}}^{\rm B}(0) \approx 1.5$,
  $\Longrightarrow$ $xG(x, Q^2) \sim x^{1-\alpha_{\mathbb{P}}^{\rm B}(0)}$.

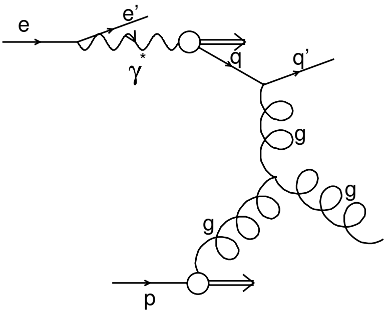


Resolved photon

Direct γ^*



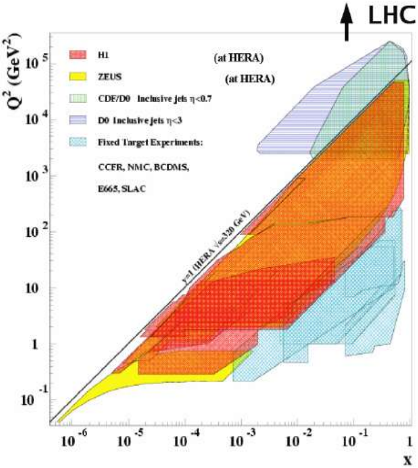
Resolved γ^* $(k_t^2 \gg Q^2)$

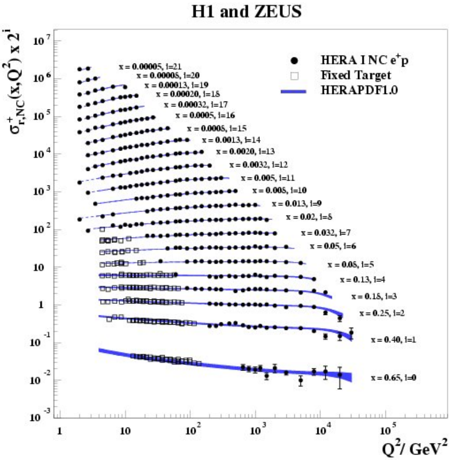


$$t_{\text{fluct}} = \frac{2E_\gamma}{m^2_{q\bar{q}} + Q^2}$$

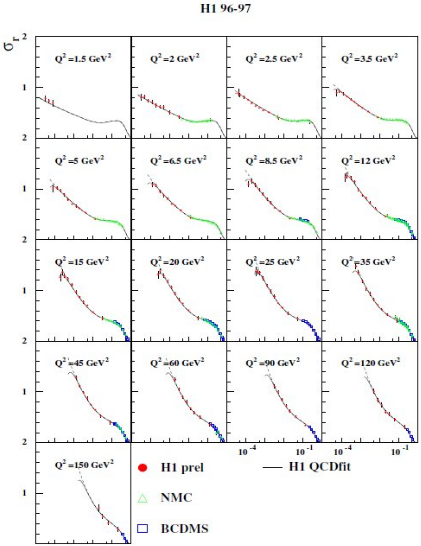
When $Q^2 \to \infty$, $t_{\text{fluct}} \to 0$ BUT $t_{\text{fluct}} = \dfrac{1}{2Mx}$ = large at low x !!

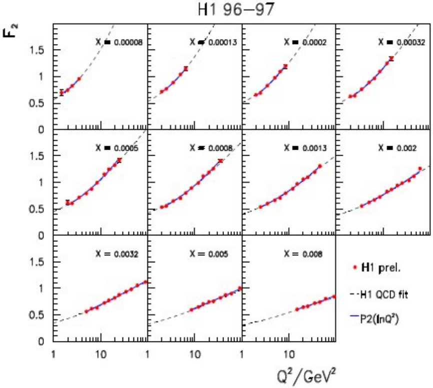
HERA data at low x. Inclusive measurements



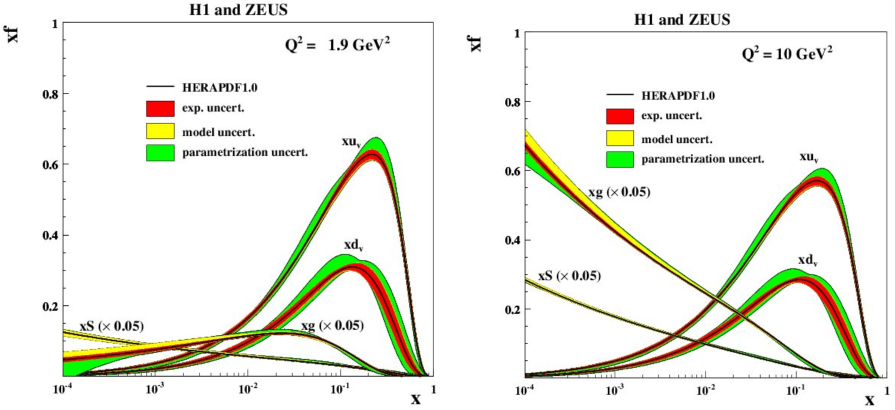


HERA data at low x. Inclusive measurements

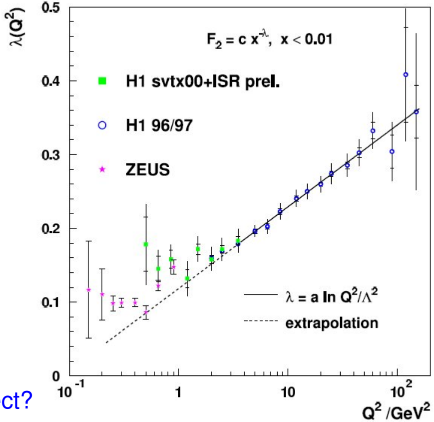




HERA data at low x. Inclusive measurements..cont'd



HERA data at low x. Inclusive measurements..cont'd



What should we expect?

- From DGLAP (DLLA approximation): $xg(x)$ grows faster than any power of $\ln\frac{1}{x}$; partons do not necessarily overlap.
- From BFKL: $xg(x) \sim x^{-\lambda} \Rightarrow F_2 \sim x^{-\lambda}, \quad \lambda \approx 0.5$

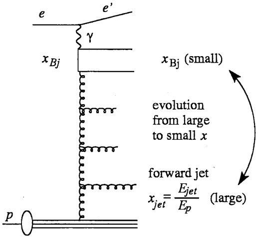
HERA data at low x. Hadron final states

- At low x parton probed by γ^* comes from a cascade initiated by a parton of a large longitudinal momentum.
- No k_t ordering of this cascade in BFKL
  $\Longrightarrow$ more hard gluons ($\rightarrow$ hadrons) in the forward and central region.
- Measured: transverse energy flow, $p_{\rm T}$ hadrons, forward hadrons and jets, multijets, azimuthal correlations between energetic jets,...
- Conclusions:

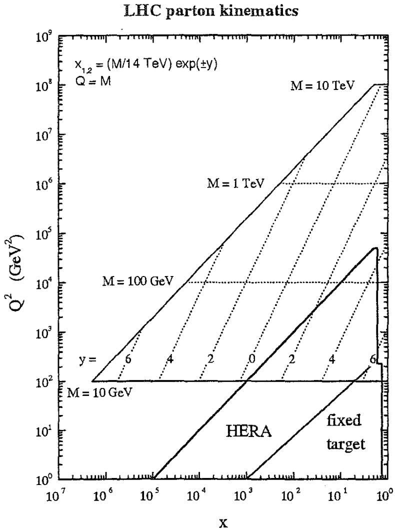
  NLO DGLAP + resolved photon describe data fairly well.

  BFKL effects not conclusive (too short cascade?)

Mueller's jet



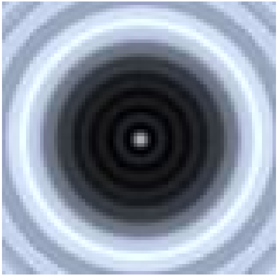
Low x @ LHC

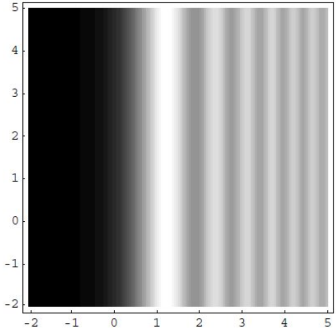

LHC parton kinematics
$x_{1,2} = (M/14\ \text{TeV})\ \exp(\pm y)$
$Q = M$
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
HERA
fixed target
Q^2 (GeV^2)
x
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0}

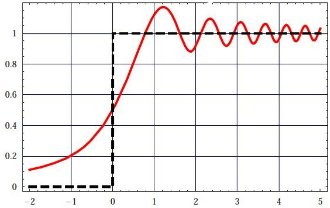
Outline

Diffraction in optics...

Fresnel difffraction on an opaque disk and edge







...and in the scattering theory

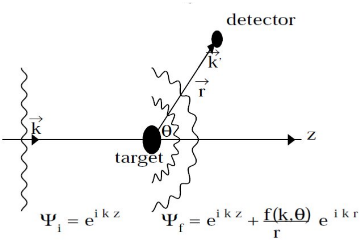


Figure 1: *The elastic scattering.*

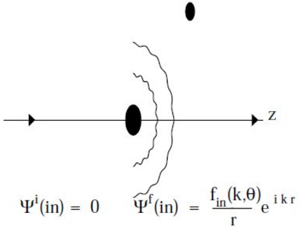


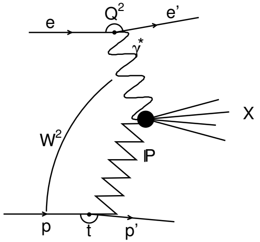
Figure 5: *Elastic and inelastic scattering.*

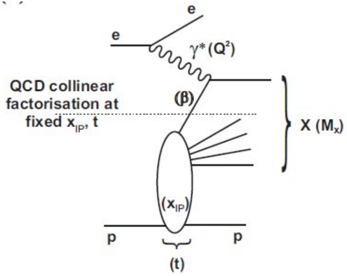
Diffraction = a purely geometric effect
$\Longrightarrow \sigma_{\rm el} \neq 0$

In a black disk limit: $\sigma_{\rm el} = 0.5\ \sigma_{\rm tot}$

Definition of diffraction

- No quantum number exchange in a process (no $\mathbb{R}$ or γ^* exchange). Target (or both hadrons) emerges intact. Pomeron exchange.
- Cross section not decreasing with energy.
- Secondary features: small t and large Δy in final state hadrons.

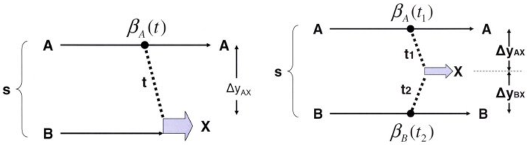




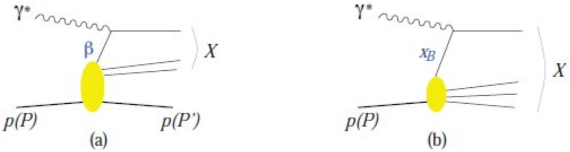
- Soft/hard diffraction $\Longrightarrow$ diffractive parton distributions! Universality? Rapidity gap survival probability for hadron–hadron.
- Diffractive PDF, $f_i^D = f_i^D(x, Q^2, x_{\mathbb{P}}, t)$. Within "vertex factorisation", $f_i^D(x, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot f_i(\beta = x/x_{\mathbb{P}}, Q^2)$

Diffraction: brief experimental status

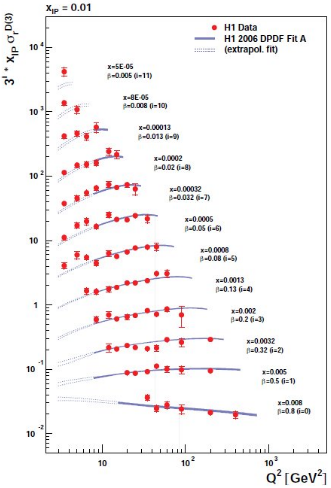
- ISR (pp, $\sqrt{s}$ = 23 – 63 GeV): σ_{el} had exponential slope and diffractive minimum; shrinkage; pomeron/double pomeron exchange.

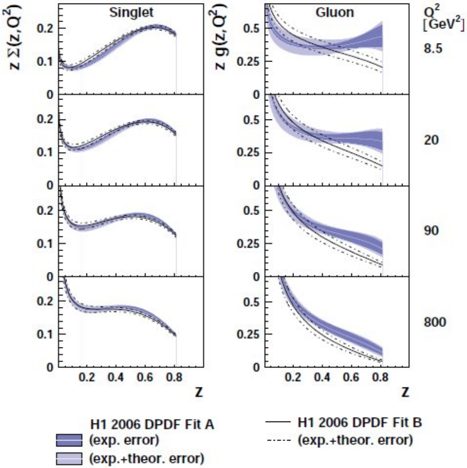


- Sp$\bar{\mathrm{p}}$S/UA8 ($\sqrt{s}$ = 630 – 900 GeV): first observation of hard diffraction.
- HERA (ep, $\sqrt{s}$ = 320 GeV): factorisation(s) holds; DPDFs.



Diffraction: brief experimental status,...cont'd

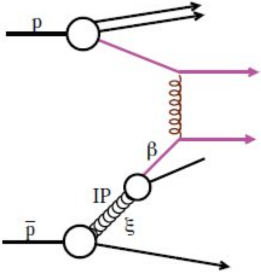


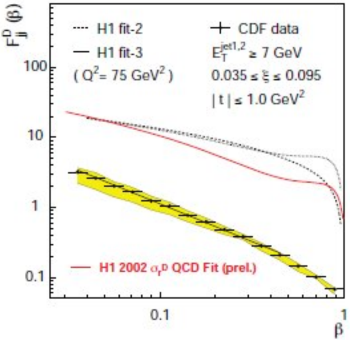


From this analysis: $\alpha_{\mathbb{P}}(0)$ = 1.118±0.008 (exp.)

Diffraction: brief experimental status,...cont'd

- Tevatron ($p\bar{p}$, $\sqrt{s}$ = 550 – 1960 GeV): diffraction in hadron–hadron scattering more complicated; hard diffractive factorisation broken by multiple interactions.





Gap survival problem??

- LHC predictions (pp, $\sqrt{s}$ = 14 000 GeV): inclusive single diffraction and double pomeron exchange also with dijets, vector bosons, heavy quarks.

Expectations for LHC in the area of forward physics

- Signatures for the BFKL evolution.
- Parton saturation taming (two nucleon scales?)...
- ...enhanced in collisions of nuclei ($Q^2_{\rm sat} \sim A^{1/3}$).
- Meaning of the (soft, hard) pomeron, also in diffraction.
- Colour Glass Condensates.
- Meaning of geometric scaling.
- Diffraction, predicted to amount up to 50% of $\sigma_{\rm tot}$ together with elastic scattering: an interplay between soft and hard physics.

How to probe the PDF structure, evolution and diffraction?

via: jets, dijets, Drell-Yan process, prompt γ, heavy quarks, vector bosons,...

$\Longrightarrow$ p. dr G.Brona.