Diffraction

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• A brief look back to pre-QCD times
• Relation to QCD
• Experimental methods
• Diffraction @ HERA
  – inclusive diffraction: F2D3, interpretation
  – final states: dijets and vector meson production
• Diffraction @ Tevatron
  – dijets and effective structure
  – exclusive production
• Summary
• Outlook to the FUTURE
The Roots

**Optics**

Diffraction of plane light waves on an absorbing disc

$$I / I_0 = 1 - \frac{R_0^2}{4} (k \cdot \Theta)$$

**High Energy Physics**

Analogy to Born approximation of high energy scattering reactions:

Elastic scattering

$$a + b \rightarrow a + b$$

$$\sigma \sim 1 - b(p \cdot \Theta)^2$$

$$\frac{d\sigma}{d\sigma_{t=0}} = e^{b \cdot t}$$

analogy:  $b = R_0^2 / 4$, „size of the hadron“

shrinkage $\equiv b = b(s)$, $b \uparrow$ für $s \uparrow$
Diffraction: a special class of hadronic interactions

Inelastic interactions:

in general a large number of single particles and/or jets are produced.

But in the early hadron-hadron collision experiments a rather large fraction of events were observed in which the incoming particles are scattered at very small angles and remain practically intact (\( \rightarrow \) diffraction pattern, elast. scatt.).

Good & Walker (1960): predict a phenomenon, in which the diffracted wave acquires a component corresponding to dissociation products of the incident particle.

Several types of processes:

Diffractive interactions \( \equiv \) hadronic interactions without exchange of quantum numbers or color (caution: photon background),

Identification : quasi-elastic scattered beam hadron with only small momentum loss, rapidity gaps due to color less exchange (regions in the detector without any signal of produced particles)
Early Hadron-Hadron Scattering

1960: enormous proliferation of strong interacting particles/hadrons

Experimental observation:
numerous hadronic resonances with rather high spin,
which are dominating the cross section

→ S-matrix is given by the sum of the resonance poles
(but not all found resonances can be fundamental)

Striking property: linear correlation between mass square $M^2$ and spin $J$

Regge Theory (Regge, Chew&Frautschi, Gribov):
introduction of complex angular momenta to quantum mechanics, poles in the
angular momentum plane determine the S-matrix in non-relativistic potential
scattering,

extension to relativistic particle physics, poles change their position with energy
→ definition of Regge trajectories.

Here we have particularly simple trajectories with linear correlation:

$$\alpha(t) = \alpha(0) + \alpha' t$$

with intercept $\alpha(0)$ and slope $\alpha'$

Summation over all poles with spin $J$ (alternating terms $(-s)^J$) (Witten String Theory)

$$A(s,t) \sim \beta(t) s^{\alpha(t)},$$

with $\beta(t)$ : coupling of the external particle to the Regge trajectory
Interpretation of Hadron-Hadron Scattering

What is the nature of this colorless exchange mediating the strong force between hadrons?

It has the quantum numbers of the vacuum, but spin 1.

Regge Phenomenology

Exchange of Regge-Trajectory

\[ \alpha(t) = \alpha(0) + \alpha' t \]

eg. IR, π, IP

Total cross section: \( \sigma_{\text{tot}} \sim s^{\alpha(0) - 1} \)

decreasing for low \( \sqrt{s} \rightarrow \alpha(0) < 1 \)

increasing for high \( \sqrt{s} \rightarrow \alpha(0) \geq (1) 1 \)

fit \( \sigma_{\text{tot}} \sim A s^{-0.45} + B s^{0.08} \rightarrow \) combination of Reggeon and a postulated Pomeron

Soft Pomeron trajectory: \( \alpha_{\text{IP}}(t) \approx 1.1 + 0.25 t \), but no particle observed so far

\( \alpha_{\text{IP}}(0) = 1 + \varepsilon \)
Formalism of Regge Phenomenology

\[ \sigma_{\text{tot}}^{ab} = \frac{1}{s} \cdot \text{Im} \left[ A(s, t = 0) \right] = \sum_k \beta_{ak}(0) \beta_{bk}(0) s^{\alpha_k(0)-1} \]

\[ \frac{d\sigma_{el}}{dt} = \frac{1}{16\pi} \beta_a^2(t) \beta_b^2(t) s^{2(\alpha(t)-1)} = \frac{\sigma_{\text{tot}}^2}{16\pi} e^{bt} = \frac{\sigma_{\text{tot}}^2}{16\pi} e^{b_0 t} \cdot e^{-\alpha' \ln s \cdot t} \]

\[ \frac{\sigma_{\text{diff}}^{ab}}{dt \, dM_X^2} = \sum_{k,l} \frac{\beta_{ak}^2(t) \beta_{bl}(0)}{16\pi} g_{kk,l}(t) \left( \frac{s}{M_X^2} \right)^{2(\alpha_k(t)-1)} \left( \frac{M_X^2}{M_X^2} \right)^{\alpha_l(0)-1} \]

Triple Regge coupling

Optical Theorem

Shrinkage
Regge Fluxes / Regge Factorization

\[ \xi = \frac{M_X^2}{s} = \frac{s'}{s} \]

\[
\frac{d\sigma^{\text{diff}}}{dt \ d\xi} = \frac{N \beta_{bIP}^2(t)}{16\pi} \xi^{2\alpha_{IP}(t)-1} \cdot \left[ \beta_{aIP}(0) g_{IP} g_{IP} g_{IP}(s) \alpha_{IP}(0) - 1 \right]
\]

\[ = f_{IP/b}(\xi, t) \cdot \sigma_{\text{tot}}^{aIP}(s', t) \]

Flux \times \text{total cross section}

Regge Factorization

Triple Regge Formalism successful for description of early data, but no sound theoretical fundament.

Complications:

Predictions with standard parameterizations too large:

\[ \sigma_{\text{SD}} > \sigma_{\text{tot}} \text{ at } 40 \text{ TeV} \]

\[ \rightarrow \text{different approaches for taming the cross sections:} \]

gap survival probability (secondary interactions destroy the gap), renormalization of gap probability to unity, non-linear pomeron trajectory, ...
Diffraction in QCD

- simplest model for Pomeron: 2 gluon system

**Two gluon exchange models:**

interpret diffractive data from HERA

- inclusive diffractive DIS
- exclusive vector meson
- deeply virtual Compton scattering (DVCS)
Rapidity Gaps in DIS @ HERA

\[ y = \frac{1}{2} \log \left( \frac{E+p_z}{E-p_z} \right) \approx \eta = - \log \tan \left( \frac{\theta}{2} \right) \]

Rapidity gap:
no particle flow up to \( \eta_{\text{max}} \)

Probe the structure of the diffractive exchange in DIS using the precise tools of QCD.
Kinematic Variables

**HERA**

\[ Q^2 = \gamma \text{ virtuality} \]

\[ x = x_q / p \quad \text{or} \quad x_g / p \]

\[ x_{IP} = x_{IP} / p \]

\[ \beta = x_q / IP \quad \text{or} \quad x_g / IP \]

\[ t = (p - p')^2 \]

\[ \xi = x_{IP} = M^2 / s \]

both names \( \xi \) and \( x_{IP} \)

will be used here

\[ \eta \approx -\ln \xi = \ln s - \ln M^2 \]
QCD Factorization

**Inclusive DIS:**
- Theory: QCD Factorization holds
- \( \sigma^{\text{DIS}}(x,Q^2) \sim F_2(x,Q^2) \sim f_q(x,Q^2) \times \sigma_{pQCD} \)

**Diffractive DIS:**
- Theory: QCD Factorization holds
- \( \sigma^{\text{DDIS}}(x_{IP},t,\beta,Q^2) \sim F_2^D(x_{IP},t,\beta,Q^2) \)
  \[ \sim f_q^D(x_{IP},t,\beta,Q^2) \times \sigma_{pQCD} \]
  
  - parton densities universal
  - same QCD evolution with DGLAP
  - hard scattering in DDIS = hard scattering in DIS
  - same parton densities for other processes at the same \((x_{IP},t)\)

**Possibility for experimental tests**
QCD Factorization in $\bar{p}p$ and resolved $\gamma p$?

Theory: QCD Factorization not proven and not expected to hold:

Modeled by:

- absorption in target fragmentation,
- rapidity gap suppression via secondary interactions (calculable with multiple pomeron exchange),
- renormalization of rapidity gap probability, ...

Experimental and theoretical challenge!
Selection methods

**Hadronic Final State:**

**Rapidity Gap Method:**
selection on event by event basis

**Mx – Method:**
statistical extraction

**LPS Method:**
detect leading proton with leading proton spectrometer
Rapidity Gap Method

Hadronic plateau:
(Feynman Parton Model, gas model
QCD calculations eg. Dokshitzer)
particles produced uniformly in
rapidity space with an
approximately flat particle density
$\lambda$, increasing with $s$.

Probability for a rapidity gap $\Delta y$ is
given by Poisson distribution:

$$P(\Delta y) \sim e^{-\lambda \Delta y}$$

$\rightarrow$ rapidity gaps are exponentially
suppressed (see also definition of
diffraction by Bjorken).
Rapidity Gap Method

Probability for any particle to be produced in a sufficiently large rapidity gap \( \sim \exp (a \Delta y) \) with \( a \) depending on quantum numbers of the gap (Feynman).

**Regge:** \( P(\Delta y) \sim e^{2(\alpha(t)-1) \Delta y} \)

<table>
<thead>
<tr>
<th>exchange</th>
<th>intercept</th>
<th>( P(\Delta y) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pomeron</td>
<td>( \alpha_{IP} \approx 1 )</td>
<td>( \sim e^{0} ) ( \rightarrow ) flat</td>
</tr>
<tr>
<td>reggeon</td>
<td>( \alpha_{IR} \approx 0.5 )</td>
<td>( \sim e^{-\Delta y} ) ( \leftrightarrow ) QCD</td>
</tr>
<tr>
<td>pion</td>
<td>( \alpha_{\pi} \approx 0 )</td>
<td>( \sim e^{-2\Delta y} ) ( \leftrightarrow ) 2x QCD</td>
</tr>
</tbody>
</table>

**Remark:** same can be derived from Regge fluxes \( \sim 1/\xi^{2\alpha(t)-1} \)

with \( \Delta y \approx \ln 1/\xi \)
**Mx Method**

\[ \frac{d\sigma}{dM_x^2} \sim \frac{1}{(M_x^2)^{(1+\epsilon)}} \]

\[ \frac{dN}{d\ln M_x^2} \sim \frac{1}{(M_x^2)^\epsilon} \approx \text{const for } \epsilon \approx 0. \]

- same expectation from:
  - \[ M_x^2 \approx \xi W^2 \]
  - \[ \ln M_x^2 \approx \ln \xi + \ln W^2 \]
  - \[ \approx -\Delta y + \ln W^2 \]

- \( \Rightarrow \) Mx and Rapidity Gap methods closely related!

- \( \Rightarrow \) also flat \( \ln \text{Mx} \) distribution

Fit the \( \ln \text{Mx} \) distributions in bins of \( W \) and \( Q^2 \) with:

\[ \frac{dN}{d\ln M_x^2} = D + c e^{b \ln M_x^2} \]

and extract the diffractive signal statistically.

\[ \alpha_{IP}(0) = 1 + \epsilon \]
LPS Method

detect the leading proton with a leading proton spectrometer beam line

operation of Roman Pot station

\( x_L (=1-x_{IP}) \) spectrum:
- diffractive peak
- pion exchanges
- p dissociations

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**Inclusive DIS Data**

- Leading protons
- $M_X$ Method

**Rapidity gap selection** $x_{IP}$
- Large data sets available
- $\rightarrow$ high precision
- $\rightarrow$ even rapidity gaps observed in CC events
Rapidity Gaps in Charged Current Events

first observation with 9 events, data consistent with expectation

\[ \sigma_{cc,\text{diff}} (Q^2>200\text{GeV}^2, x_{IP}<0.05) = 0.49\pm0.20(\text{stat})\pm0.13(\text{syst})\text{pb} \]

\[ \sigma_{cc,\text{tot}} (Q^2>200\text{GeV}^2, x_{bj}<0.05) = 2.9\pm1.2(\text{stat})\pm0.8(\text{syst})\% \]
Inclusive Cross Section as a function of $W$

$\sigma^{\text{tot}} \sim F_2 \sim x^{-\lambda}$

$\sigma^{\text{tot}} \sim (W^2)^{\alpha_{IP,\text{tot}}(0) - 1}$

$\sigma^{\text{diff}} \sim (W^2)^{2(\alpha_{IP,\text{diff}} - 1)}$

→ expect rising ratio if $\alpha_{IP}$ are the same!

$\alpha_{IP,\text{diff}}(0) > \alpha_{IP,\text{soft}}(0)$

$\alpha_{IP,\text{diff}} = \alpha_{IP,\text{diff}}(Q^2)$?

$\alpha_{IP,\text{tot}}(0) = 1 + \lambda$

$\alpha_{IP,\text{diff}}(0) \approx 1 + \lambda/2$

- Ratio flat with $W$
- Ratio decreasing with increasing $Q^2$

Regge Factorization?

Experimental uncertainties large
Diffractive Structure Function

Measure $F_2^D$ analog to $F_2$ with two more variables: $x_{IP}$ and $t$ (integrated):

$$F_2^{D(3)}(\beta, Q^2, x_{IP}) = \frac{\beta Q^4}{4\pi\alpha^2 (1 - y + y^2 / 2)} \frac{d\sigma_{ep \to e'Xp'}}{d\beta dQ^2 dx_{IP}}$$

Parameterizations / Interpretations:

- Resolved Pomeron
- Color Dipole Models (for example BEKW)
- Soft Color Interaction
- Deep Sea Model
Resolved Pomeron Model

Regge Factorization:

\[ F_2^{D(3)} = f_{IP}(x_{IP}) \cdot F_2^{IP}(\beta, Q^2) \]

\[ f_{IP}(x_{IP}) \propto \int \frac{e^{b \cdot t}}{x_{IP}^{\alpha_{IP}(t)-1}} dt \]

\[ \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP} \cdot t \]

assuming no \( Q^2 \) dependence

→ Need sub-leading trajectory exchange

\[ F_2^{D(3)} = f_{IP}(x_{IP}) \cdot F_2^{IP}(\beta, Q^2) + f_{IR}(x_{IP}) \cdot F_2^{IR}(\beta, Q^2) \]

Pomeron

Reggeon
Parton Densities for Pomeron Part

F_2^D \sim q^D(x) + q^D(x)
\frac{\partial F_2^D}{\partial \ln Q^2} \sim g^D(x)
DGLAP QCD fit

\begin{itemize}
  \item large gluon density
  \item large uncertainty at high β
  \item good description of data
  \item fits now finalized and in the process of being published
\end{itemize}

x: similar to proton

β = x/x_{IP} large scaling violations \rightarrow gluons
**Color Dipole Models**

**BEKW model (Bartels, Ellis, Kowalski, Wüsthoff):**
- at medium \( \beta \) \( F_{qq}^T \sim \beta (1 - \beta) \)
- at small \( \beta \) \( F_{qq}^T \sim (1 - \beta)^Y \)

**Saturation model:** \( \sigma_{qq} \propto r^2 \propto 1/Q^2 \)

for \( Q^2 \to 0 \) \( \sigma_{qq} \to \infty \)

growth tamed by requiring saturation
Soft Color Interaction

Reordering of colour strings via soft colour interactions:
(Ingelman et al)

Comparisons have to be updated with the new more precise data available now.
Deep Sea Model

(Goulianos, LaThuile 2004)

Restrict the validity of the model to the partonic sea region

small $x$, small $x_{IP}$, small $\beta$

asymptotic behavior

$$F_D(x_{IP}, x, Q^2) \sim \frac{1}{x_{IP}^{1+\varepsilon}} F(x, Q^2)$$

$$\sim \frac{1}{x_{IP}^{1+\varepsilon}} \cdot C \cdot (\beta \cdot x_{IP})^\lambda(Q^2)$$

Expectation seen in the data:

$$F_2^D / F_2 = \text{constant} \quad \text{for fixed } x_{IP}$$

$$\alpha_{IP,\text{diff}}(0) = 1 + \frac{1}{2}(\varepsilon + \lambda(Q^2))$$

$\Rightarrow$ QCD extension of Regge
QCD Factorization in DDIS

Using the extracted diffractive pdf's should reproduce other processes

Diffractive Dijet and D* production rates well reproduced by NLO calculations

Factorization holds!
Summary Diffractive DIS @ HERA

- Large amount of data analyzed
  → high precision achieved
- Models available to describe the data
- QCD Factorization holds in DDIS

Consistent description in the framework of QCD achieved
Hard Diffraction in $\bar{p}p$ Collisions

Results from rapidity gaps:
- $W / Z$, beauty, $J/\Psi$, jets

Tevatron: 1% diffraction
HERA: 10% diffraction

Factorization tests with leading proton data:
- $\text{SD dijet } F_{jj} \leftrightarrow F_{jj} \text{ from HERA}$
- $\text{SD dijets: } @ 1800 \text{ GeV} \leftrightarrow @ 630 \text{ GeV}$
- $\text{SD dijets } \leftrightarrow J/\Psi \@ 1800 \text{ GeV}$
- $\text{SD dijets } \leftrightarrow \text{DPE dijets}$
- $\text{DPE dijet } F_{jj} \leftrightarrow F_{jj} \text{ from HERA}$
Tevatron: SD dijets @ 1800 GeV

\[ x = \frac{1}{\sqrt{s}} \sum_i E_{T,i} e^{-\eta_i} \]

\( \xi (x_{IP}) \) from RPS

\( \beta = x/\xi \)

Effective structure function for dijet production:

\[ F_{jj}(x) = x \left[ g(x) + \frac{4}{9} \sum (q(x)+\overline{q}(x)) \right] \]

\( R_{SD}^{ND} \sim F_{jj}^D / F_{jj} \)

Tevatron: gluon dominated

(HERA: diffractive pdf's from \( F_2 \) \( \rightarrow \) quark dominated, gluon extracted indirectly through scaling violations)

Ratio: power law behavior, independent from (\( \xi = x_{IP} \))
Effective structure function for dijet production:

\[ F_{jj}(x) = x \left[ g(x) + \frac{4}{9} \sum q(x) + \overline{q}(x) \right] \]

Tevatron: unfold from ratio

\[ R_{ND}^{SD} \sim F_{jj}^D / F_{jj} \]

& \( F_{jj} \) from proton pdf

HERA: use diffractive pdf \( (x_{ip}<0.05 \rightarrow 0.035<\xi<0.095) \)

\[ F_{jj} \sim 1/ \beta^n \] with \( n=1.0\pm0.1 \) for \( \beta<0.5 \)

Tevatron ↔ HERA: shape similar → same evolution,

normalization off by a factor \( \approx 10 \) → Factorization broken!

\( \xi (=x_{IP}) \) from RPS

\[ \beta = x / \xi \]
• No estimate of uncertainties yet: large at high $\beta$ (no coverage !)
  result stable at low $\beta$

• Smaller discrepancy with respect to CDF than suggested by H1 estimate

• CDF data close to Reggeon contribution – does this mean something? **NO !**

• Difference with respect to H1:
  - a small contribution (10% ?) possibly due to proton-dissociative background in H1 data.
  - Where does the rest come from ?? (in particular for the Reggeon part)
  - Different $x_{IP}$ coverage (LPS up to $x_{IP}=0.07$) ?
Reggeon and pion contributions in diffractive processes


Note from KB: Expect IR contributions to dominate in the CDF region, but when folding the above flux with the hard cross section, where the dijet production at Tevatron is dominated by gluons → the reggeons and pions (containing mostly quarks) are in the end suppressed in the CDF diffractive dijets.
Diffractive Characteristics

\[ F_{jj}^D(\beta, \xi) \sim 1/ \beta^n \text{ independent of } \xi \]

\[ F_{jj}^D(\beta=0.1, \xi) \sim 1/ \xi^m, \quad m=1.0 \pm 0.1, \quad m > m_{\text{soft}} \]

\[ F_{jj}^D(\beta, \xi) \sim 1/ \beta^n \cdot 1/ \xi^m ? \]

(\[ F_2 \sim 1/x^\lambda, \quad f_{IP/p} \sim 1/ \xi^{(2\alpha-1)} \])

\[ F_{jj}^D(\beta, \xi) \sim 1/ \beta^n \cdot 1/ \xi^m \text{ for } \beta < 0.5 \]

Although \(0.035<\xi<0.095\): no 50% reggeon contribution

\(m_{IP} \approx 1.1, \quad m_{IR} \approx 0, \quad m_\pi \approx -1\)

Similar \(\xi\) dependence at HERA ('94 data, \(x_{IP} < 0.05\)) and CDF (0.035<\(\xi<0.095\))
Puzzling situation:
all measurements have their own uncertainties:

- CDF: large uncertainty in the jet energy scale and in the treatment of the third jet in case of radiation → not simple LO anymore
- HERA: extracted parton densities differ quite a lot, maybe ZEUS LPS and new H1 pdf's now more in agreement, differences between Mx and rapidity gap data still to be resolved → might lead to new insights, other peoples fits look then again different to those from the experiments ….

→ still a lot has to be understood before firm conclusions can be drawn on factorization breaking.

Now have a closer look to Tevatron data themselves.
Further Factorization Tests @ Tevatron

**Different process, same $\sqrt{s}$:**

$J/\Psi \rightarrow \mu^+ \mu^- (+\text{jet})$

**Dijets at different center of mass energy:**

$1800\text{GeV} \leftrightarrow 630\text{GeV}$

**Ratio $jj / J/\Psi = 1.17 \pm 0.27$ (stat)**

Factorization holds

**Similar structure $1/\beta^n$**

$n(630)=1.4 \pm 0.2$, $n(1800)=1.23 \pm 0.04$

**Ratio $630 / 1800 = 1.3 \pm 0.2$ (stat) $\pm 0.3$ (syst)**

Factorization?
Factorization Test with DPE

Lower effective $\sqrt{s} \leftrightarrow$ multiple rap. gaps

Factorization:
$$F_{jj}\left[ R_{\text{SD}} \right] = F_{jj}\left[ R_{\text{DPE}} \right]$$

Ratio: $\approx$ factor 5

$F_{jj} \approx$ factor 10 between SD and DPE, but DPE similar to HERA

(similar $\sqrt{s}$ or 2nd gap survival)
Results from Run II

Non diffractive background is exponentially suppressed

Results from Run I confirmed

No \( Q^2 \) dependence seen

\( \Rightarrow F_{jj_D} \) similar evolution as \( F_{jj} \)
Summary Tevatron

- Precise data available, statistic even more increasing with Run II data
- QCD Factorization not expected to hold:
  - Factorization breaking in normalization between Tevatron and HERA seems established only in differing sizes, but similar diffractive characteristics seen
  - Factorization holds, when changing processes
  - Factorization broken between SD/ND and DPE/SD
  - Factorization re-established between DPE/SD and HERA

  Factorization breaking found, but re-established under certain circumstances (same $\sqrt{s}$ or multiple rapidity gaps)

$\rightarrow$ different observations are a challenge for the various models which usually succeed to describe only few features of the data but not all
Going back to PHP @ HERA

Factorization in resolved PHP not expected to hold:

Calculation by KKMR (Kaidalov, Khoze, Martin, Ryskin) using multiple IP exchange for modelling the additional interactions:

PHP(resolved) suppressed by 0.34 compared to DIS

Experimental smearing has to be applied
Going back to PHP @ HERA

- In LO rescaling of MC by \( \approx 0.6 \) independent of \( xy \) needed
- Same is true for NLO calculations
- Additional suppression for resolved part by 0.34 has worse description
Equivalent: Leading Baryons

Absorption for Leading Neutrons:

Dijet PHP with Leading Neutron:

Evidence for factorization breaking

Production of Leading Neutrons and Leading Protons is Q2 dependent

Models with multiple pomeron exchange or rescattering in target fragmentation describe tendency, but not yet the full effect
Unitarity Effects in hard diffraction at HERA

Further calculations from KKMR:

\[ R = \frac{\sigma_D}{\sigma_{jj}} = \frac{\int \int_{t,x_l} F_{IP}^g(x_g, \mu^2)}{x_g f_p^g(x_g, \mu^2)} \]

increases quickly for \( x \to 0 \), but should be \(<1\) by definition

**Pumplin bound:**

\[ \frac{\sigma^D}{\sigma} \leq 0.5 \Rightarrow R \leq 0.5 \]

violated even at low scale \( \mu^2 \) for \( x_g < 10^{-3} \)

\( \Rightarrow \) unitarity violation, saturation

\( \Rightarrow \) To be checked experimentally

One possibility: exclusive vector meson production probing the gluon density
Exclusive Vector Meson Production @ HERA

Advantage:
- Few particles in final state → clear signal
- Different hard scales available:
  - $Q^2 \quad 0 < Q^2 < 100 \text{ GeV}^2$
  - $W_{\gamma p} \quad 20 < W_{\gamma p} < 290 \text{ GeV}$
  - $t \quad 0 < |t| < 20 \text{ GeV}^2$
  - $\text{VM} \quad \rho^0, \omega, \phi, J/\psi, \psi', \Upsilon$

**Soft production: Regge+VDM**

$$\gamma^* \rightarrow V \rightarrow \gamma \rightarrow V$$

$$\rho^0, \omega, \phi$$

$$\sigma_{\gamma p \rightarrow V_p} = f^2_{\gamma \rightarrow V} \otimes \sigma_{V_p \rightarrow V_p}$$

$$d\sigma_{V_p \rightarrow V_p} / dt = e^{-b_0 t} \cdot W^{4(\alpha_{IP}(t) - 1)}$$

$$\sigma_{V_p \rightarrow V_p} \sim W^{4(\alpha_{IP}(0) - 1)} \sim W^{0.22}$$

**Production with hard scale: pQCD**

$$\sigma_{\gamma^* p \rightarrow V_p} \sim \frac{1}{Q^6} [x G(x, Q^2)]^2$$

-fast increase with $W^{0.8}$

$Q^2$ dependence slower than $1/Q^6$

Universality of $t$ dependence:

$$b_{2g} \approx 4 \text{ GeV}^{-2} \text{ and } \alpha' \approx 0$$

small $q\bar{q}$ configuration

$\rightarrow$ resolve gluons

$\rightarrow \gamma^*_L$ or VM=$c\bar{c}, bb$

Kerstin Borras (DESY)
Vector Meson Production in PHP

Increasingly harder scale by mass of the vector meson

QCD derived value reached
W Dependence for VM in DIS in pQCD

$\rho$  

$\Phi$  

$J/\Psi$

$\sigma \sim W^\delta$

$\delta$ increasing with $(Q^2+M^2)$
Vector Meson Production in pQCD

Φ : $\sigma_L$ dominates at high $Q^2$

Effective size of $\gamma^*$ becomes smaller with $Q^2$

pQCD calculations for $J/\Psi$
describe data:

ZEUS

Fit: $R = a (Q^2/M^2_Y)^b$

Effective size of $\gamma^*$ becomes smaller with $Q^2$

b$_{2g}$
Vector Meson Production in pQCD

\[ \frac{d\sigma_{Vp\rightarrow Vp}}{dt} = e^{-b_0 t} \cdot W^4(\alpha_{IP}(t) - 1) \]

Vector Meson Production is well reproduced by pQCD calculations → possibility to look for saturation effects.
Exclusive States in $\bar{p}p$ Collisions

**Diffractive Higgs production hot topic for LHC**

$\rightarrow$ Something to learn from Tevatron?

More and more exclusive states measured. Predictions for exclusive dijets within the order of magnitude, for di-photon production (brand new result) about a factor of 3 too low $\rightarrow$ gives hope for the LHC!
Summary

- Data have reached a high level of precision

- HERA:
  - Models for diffractive structure function available
  - Factorization holds in diffractive DIS, under study in PHP
  - Exclusive Vector Meson production described by pQCD calculations

- Tevatron:
  - Factorization breaking found:
    Fjj (SD 1800) ↔ HERA, dijets in SD ↔ DPE
  - But factorization also holds:
    SD 1800: Fjj ↔ J/Ψ, DPE ↔ HERA
  - Models exist to calculate features of the data

A lot of progress has been achieved so far, but still a lot remains to be understood.

What is the future?
Future HERA & Tevatron

- **HERA II:**
  - higher statistics, different kinematic range
    (high Q2, heavy vector mesons, DVCS, ...)

- **Tevatron RUN II:**
  - more forward detectors → different studies
  - much higher statistics → better precision and more exclusive states
Run II detectors

CDF

RP2  BSC4  BSC3  BSC2
RP3  D     S     Q_2  Q_3  Q_4
57    32    23    0

MP  3.5<\eta<5.5
BSC1  5.5<\eta<7.5
23    32

~57 m

DO

D2  D1  D  A_2  A_1  Q_2  Q_3  Q_4
59  57  33  23    0

LM  2.5<\eta<4.4
VC  5.2<\eta<5.9
23    33
Future LHC

LHC:
- total cross section and elastic scattering (TOTEM)

Current models predictions: 90-130 mb
Aim of TOTEM: ~1% accuracy (~1 mb)

COMPETE Collaboration fits all available hadronic data and predicts:

\[ \sigma_{tot} = 111.5 \pm 1.2 \quad \text{mb} \]

\[ \pm 4.1 \quad \text{mb} \]
Future LHC

- LHC:
  - total cross section and elastic scattering (TOTEM)
  - luminosity measurements (ATLAS)
  - diffractive soft and hard phenomena (CMS & TOTEM)
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

**CMS Castor $5.25 < \eta < 6.5$**

**Experimental Apparatus**

**TOTEM + CMS**

- RP1 (147 m)
- RP2 (180 m)
- RP3 (220 m) (later option)

**CASTOR (CMS)**

**10.5 m**

**~14 m**

**Q1 Q2 Q3**

**T1**

**Q5 Q6**

**RP1 (147 m) RP2 (180 m) RP3 (220 m) (later option)**
Future LHC

• LHC:
  – total cross section and elastic scattering (TOTEM)
  – luminosity measurements (ATLAS)
  – diffractive soft and hard phenomena (CMS & TOTEM)
  – small-x phenomena (ATLAS & CMS)
Future LHC

- **LHC:**
  - total cross section and elastic scattering (TOTEM)
  - luminosity measurements (ATLAS)
  - diffractive soft and hard phenomena (CMS & TOTEM)
  - small-x phenomena (ATLAS & CMS)

LHC: due to the high energy can reach small values of Bjorken-x in structure of the proton $F(x,Q^2)$

**Processes:**
- Drell-Yan
- Prompt photon production
- Jet production
- $W$ production

If rapidities below 5 and masses below 10 GeV can be covered $\Rightarrow x$ down to $10^{-6}$-$10^{-7}$
Possible with T2 upgrade in TOTEM (calorimeter, tracker) $5<\eta<6.7$!

**Proton structure at low-x !!**
Parton saturation effects?
Future LHC

- LHC:
  - diffractive Higgs production (FP420 for both ATLAS & CMS)
  - Installation of Roman Pots at 420m in the cold section of the beam line → special challenge!
  - Although extremely small cross section (~O(3fb)) important advantages compared to Higgs measurement in the main detectors:

Motivation from KMR calculations (e.g. hep-ph 0111078)

- Selection rules mean that central system is (to a good approx) 0++
- $H \rightarrow b\bar{b}$: QCD $b\bar{b}$ background suppressed by $J_z=0$ selection rule
- If you see a new particle produced exclusively with proton tags you know its quantum numbers
- Tagging the protons means excellent mass resolution (~ GeV) irrespective of the decay products of the central system
- Proton tagging may be the discovery channel in certain regions of the MSSM
Future LHC

- **LHC:**
  - total cross section and elastic scattering (TOTEM)
  - luminosity measurements (ATLAS)
  - diffractive soft and hard phenomena (CMS & TOTEM)
  - small-x phenomena (ATLAS & CMS)
  - diffractive Higgs production (FP420 for both ATLAS & CMS)
  - connection to cosmic rays (LHCF @ ATLAS)

![Cosmic Ray Fluxes](image1)

![Cosmic Ray Fluxes](image2)

Figure 36: Cosmic ray flux as a function of energy showing the familiar knee structure appearing somewhere between Tevatron and LHC energies.
Future

• HERA II:
  – higher statistics, different kinematic range (high Q2, heavy vector mesons, DVCS, ...)

• Tevatron RUN II:
  – more forward detectors $\rightarrow$ different studies
  – much higher statistics $\rightarrow$ better precision and more exclusive states

• LHC:
  – total cross section and elastic scattering (TOTEM)
  – luminosity measurements (ATLAS)
  – diffractive soft and hard phenomena (CMS & TOTEM)
  – small-x phenomena (ATLAS & CMS)
  – diffractive Higgs production (FP420 for both ATLAS & CMS)
  – connection to cosmic rays (LHCF @ ATLAS)

Numerous mysteries left to be solved in the present data
more HERA II and Tevatron Run II data rolling in and to be understood
new data in unexplored kinematic regions from LHC ahead of us
$\rightarrow$ the era of exciting analyses is continuing ......