Diffractive Phenomena

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- why we think hard diffraction is important
- newest results and theoretical ideas
Foreword

Confinement of colour: the most important open problem in QCD

QCD is what we need: a quantum field theory of strong interactions
But:
We master QCD only when perturbative methods can be applied
i.e. small distance (or, equivalently, hard scale: $p_T^2$, $Q^2$,...) processes.

$\Rightarrow$ we are unable to use QCD to compute the bulk of hadronic
interactions, i.e. the “soft” (or large distance) cross sections
$\sigma_{\text{total}}$, $\sigma_{\text{elastic}}$ and $\sigma_{\text{diffr}}$.

Indeed, at large distance the QCD coupling becomes large
and confinement changes radically the QCD radiation pattern
Confinement

Traditionally:
study the binding forces between quarks described in terms of interquark potential
⇒ calculate static properties of hadrons, like masses

In high energy hadronic scattering ⇒ HARD DIFFRACTION:
class of events in which an initial state hadron may emerge intact
Confinement wins over strong forces which tend to breakup hadrons
⇒ hope to learn about fundamental properties of the binding forces
Diffractive scattering

Large fraction of events (~30% of $\sigma_{\text{tot}}$) in which:

- beam particles emerge intact (elastic) or dissociate into low mass states $X,Y$ ($M_X, M_Y \ll s$)
- there is a $t$-channel exchange of a colourless object
- emerging systems hadronize independently

$\Rightarrow$ Large Rapidity Gap (LRG) if $s$ large enough: $y \approx \frac{1}{2} \ln \frac{s}{M_X^2}$
The Hadronic level: Regge Theory

Experimental observations in diffractive scattering:

- **weak energy dependence** of the cross-sections $\Rightarrow s^{0.16}$
- very small scattering angles $\Rightarrow$ exponential dep. of the square of the exchanged 4-mom. $|t|$: $e^{-B|t|}$
- $B = B(s)$ increases with energy

successfully parameterized by **Regge theory**

**Regge theory**: analytic theory of HADRONIC scattering described by the exchange of collective states: linear trajectories in the spin-energy $(\alpha, t)$ plane,

$$\alpha_j(t) = \alpha_j(0) + \alpha'_j \cdot t \quad (j = \pi, P, R)$$

$\pi, P, R$
Regge phenomenology: hadronic $\sigma^{\text{tot}}$

To describe the rise of $\sigma^{\text{tot}} \Rightarrow \text{pomeron (P) trajectory} \text{ with } \alpha_{P}(0) > 1$
(not associated to any real particle).

$$\sigma^{\text{tot}} = X \cdot s^{\alpha_{P}(0)-1} + Y \cdot s^{\alpha_{R}(0)-1}$$

Great success for Regge phenomenology: asymptotic behaviour of all hadronic $\sigma^{\text{tot}}$ ($pp, \pi p, Kp, \gamma p, \ldots$) described by the same $\alpha_{P}(0)$

$\Rightarrow$ Donnachie-Landshoff fit for “soft”-P: $\alpha_{P}(0) = 1.08$, $\alpha'_{P} = 0.25$
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successfully parameterized by Regge theory:

Example: elastic scattering $a+b \rightarrow a+b$ in Regge theory at high energy

$$\frac{d\sigma_{ab}^{el}}{dt} = \frac{1}{16\pi} \sum_j \beta_{aj}(0) \cdot \beta_{bj}(0) \cdot s^{2(\alpha_p(0)-1)} \cdot e^{-B(s)|t|}$$

and $B(s) = B_0 + 2\alpha'_p \ln (s/s_0)$
The parameters $\alpha_p(0)$ and $\alpha_p'$

These two are **FUNDAMENTAL parameters**, since they represent **UNIVERSAL** (i.e. independent of initial state hadrons) features of strong forces that govern the binding of hadrons

$\alpha_p(0) = 1 + \varepsilon = \text{“intercept”}$, determines the energy dependence of $\sigma^{\text{tot}} \propto s^{\alpha_p(0)-1} = \varepsilon$ and $\sigma^{\text{el}}, \sigma^{\text{diffr}} \propto s^{2\varepsilon}$

$\alpha_p' = \text{“slope”}$, determines the growth with energy of the transverse extension of the scattering system ($\Rightarrow$ colour radiation cloud), $R_{\text{int}}^2 = \langle \vec{b}^2 \rangle = 2 B(s) = b_a + b_b + 2 \alpha_p' \ln(s)$, and reflects the strength of the binding forces

$\Rightarrow$ characterizes the confinement forces in QCD

Access to $\alpha_p'$ only in diffraction
It is of primary importance to compute $\alpha_P(0)$ and $\alpha'_P$ from first principles, by using novel concepts and math. methods.

As an example:
Kharzeev, Kovchegov, Levin (2000), proposed a new type of instanton induced interaction ("instanton ladder") that leads to the rise with energy $\sigma \sim s^\Delta$ typical of Regge theory, and they argue that this interaction might be responsible for the structure of the soft-Pomeron.
From Hadrons to Partons

So far, we discussed **hadronic degrees of freedom**, the soft-interactions. However, we need to describe phenomena in terms of **hadronic subcomponents** and **quantum field theories**, i.e. in terms of **QCD** ⇒ need **hard scale** to apply perturbative methods

1987: beginning of the age of **HARD DIFFRACTION**

**UA8**: First measurement of diffractive jet production, predicted by Ingelman & Schlein (1984)

**TEVATRON**: soft: SD and DD  
hard: W, dijet, beauty, J/Ψ, gaps between jets

**HERA**: soft: inclusive, vector mesons (VM)  
hard: inclusive, VM, jets, charm

In this talk, mostly HERA data. **Tevatron starting Run II**:  
much to come: CDF upgraded Forward Proton Spectrometer  
D0 installed Forward Proton Spectrometer
Main task:

deeper understanding at small (x, Q^2) in DIS of the transition from pert. QCD to non-pert. pomeron physics

**HERA**, born as a machine to study structure functions and search for some exotic processes (leptoquarks, excited electron, contact interactions), acquired a central rôle in the attempt to understand hadronic scattering:

- varying resolution power (Q^2)
  \[ \downarrow \]
- investigation of both short and long distance regions in diffractive high-energy scattering
Hard Diffraction at HERA

Several advantages:

- Diffraction in DIS is much simpler than in hadron-hadron, since only one large (~ 1 fm) non-pert. object (hadron) present.
- Virtual-\(\gamma\) provides varying resolution power: \(Q^2 : 10^{-8} \rightarrow 10^5 \text{ GeV}^2\) (corresponding to probing distances \(\Delta r : 10^3 \rightarrow 10^{-3} \text{ fm}\)) which allows to study the transition between soft and hard regimes.
- Small-\(x\) \(\Rightarrow\) high parton densities \(\Rightarrow\) saturation (confinement?)
- Excellent acceptance for diffractive dissociated system: asymmetric beams \((E_{e\pm} = 27.5, E_p = 820(920) \text{ GeV})\) open up the \(\gamma^*\)-hemisphere.

About 10% of the DIS events at HERA at small-\(x\) are diffractive.
The diffractive structure functions

Cross section for the diffractive process $ep \rightarrow eXp$ in DIS:

$$\frac{d^4\sigma_{ep}}{d\beta dQ^2 dx_P dt} = \frac{4\pi\alpha^2}{\beta Q^4} \cdot (1 - y + \frac{y^2}{2}) \cdot F_2^{D(4)}(\beta, Q^2, x_P, t)$$

where $F_2^{D(4)}(\beta, Q^2, x_P, t)$ is the diffractive structure function and (in a frame where the proton is fast):

$$\beta = \frac{Q^2}{M_X^2 + Q^2} = \frac{x}{x_P} = \text{fraction of } \mathcal{P}\text{-momentum carried by the quark coupling to the } \gamma^*$$

$$x_P = \frac{M_X^2 + Q^2}{W^2 + Q^2} = \text{fraction of proton mom. carried by } \mathcal{P}$$

Integration over $t$ gives $F_2^{D(3)}(\beta, Q^2, x_P)$
Hard Diffraction in QCD

- **Hard QCD factorization in diffractive DIS proven** (Collins, 1998) which validates the concept of:

- **Diffractive Parton Distributions** (Berera-Soper, 1994)

\[
\frac{d^4\sigma(x,Q^2,\xi,t)}{d\xi dt} = \sum_i \int_x \sigma(x,Q^2,y) \cdot \frac{df^D_i(y,\xi,t)}{d\xi dt} \quad \text{(for large enough } Q^2)\]

DPD's are **conditional probabilities** of finding, in a fast proton, a parton \( i \) with momentum fraction \( y \), while the proton (intact) is scattered with mom. transfer \( t \) and losing \( \xi \equiv x_P \)

**DPD's obey the usual DGLAP evolution equations.**

⇒ **diffractive DIS is firmly rooted in QCD, like inclusive DIS.**

**Notice:** in hard-diffractive processes it is still possible to use the \( \mathbb{P} \) language. However, it is only one way to look at it. I will continue to use “\( \mathbb{P} \)”, but remember it is **not** the soft \( \mathbb{P} \)
Models for Hard Diffraction: the DIS Frame

**Ingelman-Schlein model** (born for hadron-hadron, 1984)
Apply concept of soft-pomeron to hard scattering, **assuming**:

1) \( P \) has a partonic structure, like for real hadrons

2) Regge factorisation,
   \( P \) structure function
   factorizes from \( P \)-flux:

\[
F_2^{D(4)}(\beta, Q^2, x_P, t) = \Phi_{p/p}(x_P, t) \cdot F_2^{D(2)}(\beta, Q^2)
\]

\( P \)-flux factor:
\[
\left( \frac{1}{x_P} \right)^{2\alpha_p(t) - 1}
\]
in Regge approach
diffractive structure function
Hard Diffraction in the Breit-frame

Thus, in a frame where the proton is fast (Breit or Bjorken frame):

The hard scale in diffractive scattering solves only part of the problem by making the upper part of the diagram calculable in pQCD, while the soft (lower) part of the interaction occurs over a large space-time and perturbative treatment is not possible.
Models for Hard Diffraction: the target frame

Physical picture of DIS most easily seen in the proton rest frame: $\gamma^* \rightarrow q\bar{q}$ fluctuations ($+q\bar{q}g$, ...).

At small-$x$, the lifetime $\tau_{osc} \approx 1/(xM_p)$ large, up to 1000 fm at HERA,

$\Rightarrow$ interaction between a colour-dipole (the $q\bar{q}$ state) and the proton:

$$\sigma^{Diffr}_{T,L} (x, Q^2) = \int d^2rdz \left| \Psi_{T,L} (r, z, Q^2) \right|^2 \cdot \sigma^2_{dipole} (x, r)$$

$$\begin{align*}
\Psi_{T,L} &= \gamma^*_{T,L} \rightarrow q\bar{q} \text{ wave function} \\
\sigma_{dipole} &= \text{dipole-proton cross-section} \\
z &= E_q/E_{\gamma^*} \\
r &= \text{transverse separation of } q\bar{q}.
\end{align*}$$

Diffraction: colour-singlet exchange

$\Rightarrow \sigma_{dipole}$ modelled at lowest order in pQCD by two gluon exchange.
Remark

Many models for hard diffraction, can be grouped in **two main approaches**, according to the ref. frame:

**DIS picture**
(Breit frame: proton is fast)

parton cascade seen as emitted from the proton

**Dipole picture**
(target frame: proton at rest)

parton cascade seen as emitted from the $q\bar{q}$ decomposition of the $\gamma^*$

The point is: **different time ordering in different frames, but the physics must be the same!!!**

**Ongoing theor. effort to establish this connection at NLO/large $r^2$**
List of exp. & theor. results

1. Structure functions and jets measurements in diffraction + predictions for Tevatron

2. Elastic VM production

3. Selection of new topics:
   - Deeply Virtual Compton Scattering
   - Skewed Parton Distributions calculation at large $\beta$ and $Q^2$
   - Searches for Odderon exchange
Structure Functions
and jets measurements
in Diffractive DIS
New $F_2^{D(3)}$

New measurement of $x_P F_2^{D(3)}$ by H1 based on LRG requirement:
- factor $\sim 5$ in statistics ($\sim 10$ pb$^{-1}$)
- higher precision
- wider kinematic range:
  - $6.5 < Q^2 < 120$ GeV$^2$
  - $0.01 < \beta < 0.9$
  - $0.0001 < x_P < 0.05$
  - $|t| < 1$ GeV$^2$

H1 fit based on $P + R$ terms and hard-QCD + Regge factorisation describes $x_P$ dependence well ($\chi^2/\text{ndf} = 0.95$) and gives:

$$\alpha_P(0) = 1.173 \pm 0.018 \text{(stat)} \pm 0.017 \text{(syst)} + 0.063 \text{ (model)} - 0.035$$
Models for Hard Diffraction: the target frame

The recent saturation model (Golec-Biernat et al.) postulates a dipole cross-section form:

\[
\sigma_{\text{dipole}}(x, r) = \sigma_0 \left[ 1 - \exp \left( \frac{-r^2}{4R_0^2(x)} \right) \right]
\]

with the “saturation radius” \( R_0 \) given by:

\[
R_0(x) = \frac{1}{Q_0^2} \cdot (x / x_0)^{\lambda/2}
\]

The results of the (good) fit to the DIS inclusive data of the 3 free parameters, \( \sigma_0, x_0 \) and \( \lambda \), describe well the diffractive data too. Phenomenological model \( \Rightarrow \) completely theoretical framework would include non-linear QCD evolution equations.

Notice: \( \sigma_{\text{dipole}} \) expected to be the same in several processes, inclusive, charm, VM jets \( \Rightarrow \) experimental goal
\( F_2^{D(3)} \): comparison with GB-W model

Comparison with perturbative dipole model by Golec-Biernat & Wüsthoff:
3-parameters fit to \( F_2 \) to predict \( F_2^{D(3)} \)

- Good description at high \( \beta \)
- Lies above data at lowest \( \beta \)
- Addition of DGLAP evolution worsens the description of the data

Impressive success of saturation model: this is not a fit to diffr. data
Models for Hard Diffraction: the target frame

In the semiclassical approach (Buchmüller et al.) the proton is seen as a superposition of soft colour-fields:

Diffraction occurs if both target and $\bar{q}q$ pair from $\gamma^*$ remain in a colour-singlet state after traversing the proton colour-field. Both diffractive and inclusive DIS can be calculated if a model for the proton wave-function is available. Interesting attempt: this is a non-perturbative model which made the prediction: $\sigma_{\text{Diffr.}}/\sigma_{\text{incl}}$ independent of $W$, found in data.
Comparison with non-perturbative dipole model of Büchmuller et al., based on four-parameter fit to previous $F_2$ and $F_2^D$ data. Valid for $M_X > 4$ GeV (left of green line) ($M_X = \text{mass of the diffractive system}$)

- General features of data well reproduced
- Predictions exceed data at lowest $\beta$
New $F_{2}^{D(4)}(\beta,Q^{2},x_{p},t)$ with the ZEUS LPS

**Leading Proton Spectrometer:**
measure scattered proton
⇒ small LPS acceptance, but
- measure $t$
- cleanest selection of diffr. evts,
  free of p-dissociation and
  unbiased by hadr. final state

**Kin. range:**
- $5.3 < Q^{2} < 31 \text{ GeV}^{2}$
- $0.027 < \beta < 0.43$
- $0.00046 < x_{p} < 0.029$
- $0.075 < |t| < 0.35 \text{ GeV}^{2}$

**Fit $x_{p}$-dependence assuming**
factorisable $P$-flux $\propto (1/x_{p})^{2\alpha_{p}(t)-1}$
gives good description of data and
$\alpha_{p}(0) = 1.13 \pm 0.03(\text{stat})^{+0.03}_{-0.01} (\text{syst})$
QCD-fit to inclusive diffractive cross-section

\[ P_{i/P} = \text{mom. density of parton } i \text{ in the } P \]

\[ Z_P = \text{long. mom. fraction of parton in pomeron} \]

\[ Z_P \equiv \beta \text{ if } i \equiv \text{quark} \]

\[ \Rightarrow \text{Gluon dominated pomeron} \]

\[ (90 \rightarrow 80\% \text{ at } Q^2 = 4.5 \rightarrow 75 \text{ GeV}^2) \]

Both fits giving similar \( \chi^2 \)

Notice: inclusive measurements not particularly sensitive to shape of the gluon at large \( Z_P \) (or \( \beta \)). Jet measurements do much better \( \rightarrow \)
Diffractive Dijet Cross Sections

<table>
<thead>
<tr>
<th>cone (R=1) γ*p cms</th>
<th>( p_T^* &gt; 4 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4 \leq Q^2 \leq 80 \text{ GeV}^2 )</td>
<td>( 23 \leq M_x \leq 40 \text{ GeV} )</td>
</tr>
<tr>
<td>( 90 \leq W \leq 260 \text{ GeV} )</td>
<td>( x_P \leq 0.05 )</td>
</tr>
<tr>
<td>( \eta_{\text{hadr}}^{\text{max(LAB)}} \leq 3.2 )</td>
<td>(-1 \leq \eta_{\text{jets}}^{\text{LAB}} \leq 2.2 )</td>
</tr>
</tbody>
</table>

Compare data to RAPGAP MC (implementation of Ingelman-Schlein “partonic-pomeron” model):

- Parton-densities from QCD-fit to \( F_2^D \) describe diffractive-jets well
- Highly sensitive to gluon-density in the \( P \): “flat-gluon” favoured

Strong support for fully-factorizable diffractive PDFs in DIS which are gluon dominated
Diffractive Dijet Cross Section

Double differential cross-sections:

- DGLAP evolution holds (left-side plots)
- consistent with Regge-factorisation assumed in MC (right-side plots)
- in both cases preference for “flat-gluon” confirmed

in bins of $Q^2+p_T^2$

in bins of $\log_{10} x_P$
Three-jets diffractive cross-sections

$k_T$ algorithm in $\gamma^*P$ c.m. system: $\eta_{jet}^*$ and $p_{T,jet}^*$ w.r.t. the $\gamma^*P$ axis

I.S. partonic $P$ (RAPGAP) \{ Dipole (saturation) (SATRAP) \} models describe data equally good

indeed they must contain same physics seen in different ref.frames

$5 \leq Q^2 \leq 100 \text{ GeV}^2$

$23 \leq M_X \leq 40 \text{ GeV}$

$200 \leq W \leq 250 \text{ GeV}$

$\eta_{\text{hadr}}^{\text{max(LAB)}} \leq 3.0$

$-2.3 \leq \eta_{\text{jets}}^{\text{LAB}} \leq 2.3$
New precise data on $F_2^D$ and jets in diffraction:

1. data consistent with fully factorisable "partonic-$\mathcal{P}$"
   i.e. Regge-inspired I.-S. model in QCD
   - $\mathcal{P}$ mostly made by gluons (~80-90% at HERA)
   - DGLAP evolution equations work well

2. recent dipole models (pert. and non-pert.)
   in target-frame also able to describe data

How do these results compare to what has been measured in diffraction at the Tevatron?
The Tevatron results

$F_{jj}^D(\beta)$, the Tevatron diffractive structure function from dijets:

Breakdown of (ep ↔ pp) factorisation?

Concept of

**LRG survival probability:**

secondary emissions might fill the LRG with particles ⇒ rescattering corrections

Gotsman et al. (1999), Khoze et al., (2000)
Very recently, Kaidalov, Khoze, Martin and Ryskin (2001) used **LRG survival probability & HERA data** to estimate dijet production at the Tevatron: "Estimates in surprising agreement with CDF data"

- essentially parameter-free prediction: use survival prob. they obtained from soft h-h data (from ISR to Tevatron)
- uncertainty dominated by available $P$ struct. functions
Exclusive (or Elastic) production of Vector mesons
\[ \gamma^* p \rightarrow \text{VM} \rightarrow \text{p} \]
Vector Mesons production at HERA

Elastic (or exclusive)

\[ e + \gamma^* \rightarrow p + VM \]

proton dissociative

\[ e + \gamma^* \rightarrow p + Y \]

Notice: in ep we use \( W_{\gamma p} \) instead of \( s \)

Experimentally: very clean processes in wide kinematic range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q^2 )</td>
<td>( \gamma^* ) virtuality</td>
<td>( 0 &lt; Q^2 &lt; 100 \text{ GeV}^2 )</td>
</tr>
<tr>
<td>( W_{\gamma p} )</td>
<td>c.m. energy of ( \gamma^*p ) system</td>
<td>( 20 &lt; W_{\gamma p} &lt; 290 \text{ GeV} )</td>
</tr>
<tr>
<td>( t )</td>
<td>4-mom. transfer squared at p-vertex</td>
<td>( 0 &lt;</td>
</tr>
<tr>
<td>VM</td>
<td>Vector Meson</td>
<td>( \rho^0, \omega, \phi, J/\psi, \psi', \Upsilon )</td>
</tr>
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</table>

HERA \( \Rightarrow \) simultaneous control of different scales: \( Q^2, t, M_{VM} \)
Models for Elastic VM production

Elastic Photoproduction $(Q^2 \sim 0)$ of light Vector Mesons (VM) is a soft process. No hard scale $\Rightarrow$
Vector Dominance Model $\times$ Regge theory: $\gamma^*$ fluctuates into VM before the interaction

A hard scale is often present at HERA $\Rightarrow$ perturbative QCD applicable
In target frame, VM production is a 3-step process:
1. $\gamma^* \rightarrow q\bar{q}$ oscillation
2. $q\bar{q}$ scatters off the proton by two-gluon exchange (at lowest order) in colour singlet state
3. VM is formed (well after the interaction)

If dipole size: $r = 1/[z(1-z)Q^2 + m_q^2]^{1/2}$ is small (large $m_q$ or $\gamma^*_L$ at high $Q^2$) $\Rightarrow$ qq pair resolves gluons $\Rightarrow$ pQCD
Elastic VM: pQCD predictions

1. Fast rise with energy, $W^2(\alpha_P(<t>-1)$:

$$\sigma_L \propto \left[ \frac{1}{Q^6} \right] \cdot \alpha_s^2 (Q_{\text{eff}}^2) \cdot [xg(x,Q_{\text{eff}}^2)]^2 \approx [x^{-0.2}]^2 \approx W^{0.8} \ (x \approx 1/W^2)$$

2. Universality of $t$-dependence: $e^{-b_2g|t|}$,

$$\Rightarrow b_2g \sim 4 \ \text{GeV}^{-2} \ \text{independent of} \ W \ \Rightarrow \alpha'_p = 0$$

3. Approximate restoration of flavour-independence:

$\gamma^*$ couples directly to constituent quarks $\Rightarrow \rho^0 : \omega : \phi : J/\psi = 9 : 1 \cdot 0.8 : 2 \cdot 1.2 : 8 \cdot 3.5$

Questions:

☐ Do these pQCD-based models describe HERA VM data?

☐ At which scale $Q_{\text{eff}}^2$ should $xg$ be evaluated?

i.e. which (or which combination) of $Q^2$, $M_{\text{VM}}^2$ and $|t|$ is the scale of the process?

For example, in Ryskin model

$$Q_{\text{eff}}^2 = \frac{1}{4} \cdot (Q^2 + M_{\text{VM}}^2 + |t|)$$
Elastic VM in photoproduction ($Q^2 = 0$)

Fit $\sigma^\text{el} \propto W^\delta$ ($\delta \approx 2(\alpha_p(<t>))$ gives:

$\delta \approx 0.22$ “soft” $W$-dep. for $\rho^0$, $\omega$, $\phi$

$\delta \approx 0.8$ “hard” $W$-dep. for $J/\Psi$

$J/\Psi$ described by pQCD models (below) if steep gluon from fits to $F_2$ scaling violations are used:
$W$-dependence of elastic $\rho^0$ vs. $Q^2$

Fit $\rho^0$ elastic cross sections with $W^\delta$:

$$\sigma_{\gamma^* p \rightarrow \rho p} [\text{nb}]$$

<table>
<thead>
<tr>
<th>$Q^2 [\text{GeV}^2]$</th>
<th>$\delta$ (± stat.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.16±0.06</td>
</tr>
<tr>
<td>0.47</td>
<td>0.12±0.03</td>
</tr>
<tr>
<td>0.76</td>
<td>0.33±0.05</td>
</tr>
<tr>
<td>1.4</td>
<td>0.38±0.05</td>
</tr>
<tr>
<td>2.5</td>
<td>0.56±0.10</td>
</tr>
<tr>
<td>3.5</td>
<td>0.52±0.09</td>
</tr>
<tr>
<td>6.0</td>
<td>0.46±0.10</td>
</tr>
<tr>
<td>8.0</td>
<td>0.88±0.28</td>
</tr>
</tbody>
</table>

Energy dep. steepens with $Q^2$ ⇒ reaching hard-regime (like for $M_{J/\psi}$)
HERA results quite precise:

\[(1.198 \pm 0.012) + (0.114 \pm 0.025) \cdot t\]

for \(J/\psi\) mesons

\[(1.096 \pm 0.021) + (0.125 \pm 0.038) \cdot t\]

for \(\rho^0\) mesons

\[\Rightarrow\]

Pomeron trajectories different than in soft h-h

For the \(J/\psi\):

not only \(\alpha'_{\rho}(0) > DL\)-soft,

but also \(\alpha''_{\rho} < DL\)-soft

\[\Rightarrow\]

Hard regime
R = \sigma_L / \sigma_T \text{ for elastic } \rho^0 \text{ electroproduction}

Early pQCD prediction: different Q^2 dep. for \(\sigma_L\) and \(\sigma_T\)
⇒ R expected to increase with Q^2

\[ R = \frac{\sigma_L}{\sigma_T} \]

ZEUS fit:
\[ \frac{\sigma_L}{\sigma_T} = \left( \frac{Q^2}{M^2} \right)^\kappa \xi \]
\[ \xi = 2.16 \pm 0.05, \quad \kappa = 0.74 \pm 0.02 \]

in agreement with data
dσ/|t| \propto e^{-b_{\psi(2S)}|t|}

In Vector Dominance Model:
VM scatters off the proton
\[ \Rightarrow b_{\psi(2S)} \propto r_p^2 + r_{VM}^2 \]
\[ \Rightarrow b_{\psi(2S)} > b_{J/\psi} \]
due to different wave-functions

In pQCD: q\bar{q} scatters off the proton
\[ \Rightarrow b_{\psi(2S)} \propto r_p^2 + r_{q\bar{q}}^2 \]
\[ \Rightarrow b_{\psi(2S)} \approx b_{J/\psi} \]

H1 measurements:
\[ b_{\psi(2S)} = (4.5 \pm 1.2^{+1.4}_{-0.7}) \text{ GeV}^{-2} \]
\[ b_{J/\psi} = (4.73 \pm 0.25^{+0.30}_{-0.39}) \text{ GeV}^{-2} \]
Elastic VM dependence on $Q^2 + M_{VM}^2$

VM cross-sections scaled by SU(4) factors:

$$\rho^0 : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$$

New (more precise) ZEUS data:

$$J/\psi /\rho^0$$ or $$\phi$$ larger than expected by SU(4). Predicted by pQCD (Frankfurt et al.)

However, SU(4) relation not expected to hold. Indeed $\rightarrow$
Ratios of Vector Mesons

pQCD prediction for $Q^2 \gg M_{VM}^2$:

[Diagram of pQCD process]

- flavour independence
- Expectations (found in the data) ⇒
  - VM ratios increase with $Q^2$
  - asymptotically reaching:
    - $\rho : \omega : \phi : J/\psi = 9 : 1 \cdot 0.8 : 2 \cdot 1.2 : 8 \cdot 3.5$
  - faster rise for $\sigma_\phi / \sigma_{\rho^0}$ than $\sigma_{J/\psi} / \sigma_{\rho^0}$

ZEUS Prelim. measurements vs. $|t|$ for \textbf{p-dissociation}, $\gamma^* p \rightarrow VY$:
1. ratios rising with increasing $|t|$
   ⇒ indication that $t$ is a scale
2. $Q^2$ and $|t|$ are NOT equivalent
Photoprod. of proton-dissoc. $J/\psi$ at high $|t|$

$$\gamma^* p \rightarrow J/\psi Y \text{ at } Q^2 \sim 0$$

- LO BFKL-model (Bartels et al.) describes the $|t|$ behavior $\propto |t|^{-n}$ (large uncertainty on magnitude)

- energy dependence "hard": $W^{\delta \approx 1}$ like for elastic (not shown)
Great success of pQCD:
small systems ($J/\psi, \gamma_L$) provide a hard scale and $W_{\gamma p}, Q^2, R=\sigma_L/\sigma_T$, VM-ratios are well described

Large luminosities gave access to large values of $|t|$
• $|t|$ as well is a hard scale for VM production,
• indication that $|t|$ and $Q^2$ are not equivalent scales
Selection of recent developments:

Deeply Virtual Compton Scattering
Skewed Parton Distributions
Searches for Odderon exchange
Deeply Virtual Compton Scattering (DVCS)

is the diffractive production of real-$\gamma$ in DIS: $ep \rightarrow ep\,\gamma\,(\gamma*p \rightarrow \gamma p)$

- theoretically pure: no VM wave-function (non-pert.) involved
- particularly interesting, since it gives access to:
  - $\text{Re}(M_{\gamma^*p \rightarrow \gamma p})$
  - Skewed Parton Distributions (SPD) which are fundamental quantities for exclusive processes in QCD
Skewed Parton Distributions

The DVCS process is also a two-parton exchange

- usual parton distributions are diagonal: \( x_1 \equiv x_2 \Rightarrow p = p' \Rightarrow t = 0 \)
- Skewed Parton Distributions are non-diagonal:
  \[ x_1 \neq x_2 \ (x_1 - x_2 = x) \Rightarrow p \neq p' \Rightarrow \text{allow } t \neq 0 \]

Very useful concept since they account for:
- parton \( k_T \) (in addition to long. momenta)
- two-particle correlations in the proton

Notice: most of the data shown above are at small-\(|t|\), where the SPD can be approximated by the conventional parton distributions
Deeply Virtual Compton Scattering (DVCS)

Measurements by H1 and ZEUS. Results: **DVCS seen**

Background given by Bethe-Heitler processes:

- **ZEUS prelim.**
- **Bethe-Heitler**
DVCS measurements at HERA

pQCD predictions (Frankfurt et al., Donnachie et al.)
in agreement with data

Warning: very recent NLO calc. (Freund et al.) show large corrections
Hebecker & Teubner (2001): $F_2^{D(3)}$ is perturbatively calculable (given the SPD) when $\beta \to 1$ and $Q^2$ large (LO + estimate of NLO)

- $F_L^D$ large, calculable
- $F_T^D$ estimated to be small if $\beta \to 1$

Confront to ZEUS data:
1. calc. agree with data
2. discriminate between $xg(x)$
3. SPD very important: skewing effect $\approx 2$

Need more precise data and K-factor for extraction of model indep. SPD at small $x$
The Odderon

Odderon: $C = P = -1$ companion of the Pomeron ($C = P = +1$) with similar intercept $\alpha_\sigma(0) \approx 1$

In QCD:
- $P$ seen as exchange of 2 gluons
- $O$ seen as exchange of 3 gluons

Important prediction of QCD:
- Odderon solutions found in pQCD (Lipatov 1997, Janik et al. 1999)
  $\Rightarrow$ in presence of a hard scale ($m_c$ or $Q^2$) Bartels et al. (2001) predict: $\sigma(\gamma p \rightarrow \eta_c p) = 50$ pb at $Q^2=0$, and 1.3 pb at $Q^2=25$ GeV$^2$
- Non-perturbative Odderon model (Berger et al. 1999) realised, based on "stochastic vacuum model".
  It predicts: $\sigma(\gamma p \rightarrow \pi^0 N^*) = 300$ nb at HERA
O and P induced multi-γ final states

H1 searched for multi-photon final states:

\[ Q^2 = 0 \text{ GeV}^2 \]

**P-exchange: odd # of γ**
\[ \omega \rightarrow \pi^0 \gamma \rightarrow 3\gamma \]
\[ (b_1 \rightarrow) \omega \pi^0 \rightarrow \pi^0 \gamma \gamma \rightarrow 5\gamma \]

**O-exchange: even # of γ**
\[ \pi^0 \rightarrow \gamma \gamma \]
\[ f_2(1270) \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma \]
\[ a_2(1320) \rightarrow \eta \pi^0 \rightarrow 4\gamma \]

Number of photons fixes C-parity of the exchange

QCD test with purely electromagnetic final state
Experimentally easily accessible
**Pomeron-exchange:**
signals seen

- \( \omega \) SIGNAL
- \( 3\gamma \)

**Odderon-exchange:**
no signal seen

- \( \pi^0 \) MC
- \( 2\gamma \)
- \( \alpha_2 \) MC
- \( 4\gamma \)
Odderon searches

\[ C = \begin{array}{cccccc}
\pi^0_{(135)} & \omega_{(782)} & f_2_{(1275)} & a_2_{(1318)} & \omega\pi^0 \\
+1 & -1 & +1 & +1 & -1 \\
2\gamma & 3\gamma & 4\gamma & 4\gamma & 5\gamma
\end{array} \]

H1 preliminary:

if odd number of $\gamma$ in final state (Pomeron-exchange) \[\Rightarrow\] signals found, cross sections computed

if even number of $\gamma$ in final state (Odderon-exchange) \[\Rightarrow\] no signal found, limits @ 95% C.L.
Conclusions

Quite unique situation: we know the story at both ends!

The matter now is to understand the radiation of colour between the two ends.

To shed new light on hadronic interactions we must:
- experimentalists: precisely measure diffractive phenomena at all scales
- theorists: continue in the effort to compute $\alpha_{P}(0)$ and $\alpha_{P}'$ from first principles