Diffraction and forward physics at HERA

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HERA: The World’s Only ep Collider

• 1998 $E_p$ upgrade: 820 $\Rightarrow$ 920 GeV
  ($\sqrt{s}$: 301 $\Rightarrow$ 319 GeV)

• 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised $e^+/e^-$
  ($\langle P \rangle = 40\%$)

HERA-1 (1993-2000) $\sim$ 120 pb$^{-1}$
HERA-2 (2003-2007) $\sim$ 380 pb$^{-1}$

Final Data samples
H1+ZEUS: $2 \times 0.5$ fb$^{-1}$
Deep-Inelastic Scattering at HERA

Neutral Current DIS: $\text{ep} \rightarrow e'X$

Charged Current DIS: $\text{ep} \rightarrow \nu X$

Kinematics: (Momentum transfer)$^2$: $Q^2 = -q^2$
Bjorken $x$: $x = Q^2/(2p \cdot q)$
Inelasticity: $y = (p \cdot q)/(p \cdot l)$
(Total hadronic energy)$^2$: $W^2 = (p + q)^2$
$W^2 \simeq Q^2/x$
Two approaches to Strong Interactions

1. Regge Pole Model $\Rightarrow$ RFT

\[ g_1(m_1, M_1, t) g_2(m_2, M_2, t) \frac{s^{\alpha(t) \pm (-s)^{\alpha(t)}}}{\sin(\pi \alpha(t))} \]

hadronic language

2. Quark-Parton Model $\Rightarrow$ QCD

$\sigma_{ab} = \int f_{i/a}(x_i, \mu^2) \cdot f_{j/b}(x_j, \mu^2) \cdot \hat{\sigma}_{ij}(x_i, x_j, \mu^2)$

sub-hadronic language

Ultimate goal: derive (1) from (2)
RFT: soft $hh$ scattering \hspace{1cm} vs \hspace{1cm} QCD: deep inelastic $ep$ scattering

- **Hadronic** degrees of freedom
- **Validity:** large $s \gg t$
- $IP$ dominates: $\alpha_{IP}(0) > \alpha_{IR}(0)$ \hspace{1cm} $\rightarrow \sigma_{\text{tot}} \propto s^{\alpha_{IP}(0)-1}$
- Unitarity corrections unavoidable \hspace{1cm} $(\sigma_{\text{tot}} \leq \ln^2(s/s_0) \text{ at } s \rightarrow \infty)$
- **When?** \hspace{0.5cm} $s_{sat} = ?$
- **First to be seen in diffraction:** $\sigma_D \propto s^{2(\alpha-1)}$

- **Partonic** degrees of freedom
- **Low $x$:** $W^2 \gg Q^2, t \left( Q^2/W^2 \simeq x \ll 1 \right)$
- gluons dominate: $xg(x) \gg xq_{\text{val}}(x)$ \hspace{1cm} $F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$
- **Saturation of the $xg(x)$** \hspace{1cm} (non-linear effects, shadowing, ...)
- $x_{sat}(Q_{sat}) = ?$
- **First to be seen in diffraction:** $\sigma_D \propto |xg(x)|^2$

$\Rightarrow$ Diffraction $\equiv$ Physics of the Pomeron, the essence of strong interactions

$\Rightarrow$ Diffraction $\equiv$ Gluodynamics, the essence of QCD

(in high energy limit)
**Diffraction at HERA**

- **Fundamental aim:** understand high energy limit of QCD (gluodynamics; CGC ?)
- **Novelty:** for the first time probe partonic structure of diffractive exchange
- **Practical motivations:** study factorisation properties of diffraction; try to transport to $hh$ scattering (e.g. predict diffractive Higgs production at LHC)

$$x_{IP} = \xi = \frac{Q^2 + M_x^2}{Q^2 + W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2 + M_x^2} = x_{q/IP} = \frac{x}{x_{IP}}$$

(fraction of exchange momentum, coupling to $\gamma^*$)

$$t = (p - p')^2$$

(4-momentum transfer squared)

**Experimental methods:**
1) selecting LRG events
2) detecting $p$ in Roman Pots
   
   ($60 - 220$ m from IP)

![Diagram]

(V)FPS
Selection of Diffractive Events

Measure the leading proton

- Forward spectrometers (H1 FPS/VFPS)
- $x_{ip}$ and t measurements
- Less statistics
- p-tagging systematics

Measure a Large Rapidity Gap

- Data integrated over $|t| < 1$ GeV$^2$
- High statistics
- Contamination from proton dissociation events
  - Needs to be controlled

Different systematics
Different kinematic coverage
Factorisation properties in diffraction

QCD versus Regge factorisation

**QCD factorisation**
(rigorously proven for DDIS by Collins et al.):

\[ \sigma^{D(4)}_r \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f^D_i(x, Q^2; x_{IP}, t) \]

- \( \hat{\sigma}^{\gamma^* i} \) – hard scattering part, same as in inclusive DIS
- \( f^D_i \) – diffractive PDF’s, valid at fixed \( x_{IP}, t \) which obey (NLO) DGLAP

**Regge factorisation**
(conjecture, e.g. RPM by Ingelman, Schlein):

\[ F^{D(4)}_2(x_{IP}, t, \beta, Q^2) = \Phi(x_{IP}, t) \cdot F^{IP}_2(\beta, Q^2) \]

- In this case shape of diffractive PDF’s is independent of \( x_{IP}, t \)
  while normalization is controlled by Regge flux \( \Phi(x_{IP}, t) \)
QCD based approaches to DDIS: Partons vs Dipoles

- Infinite momentum frame: partons

\[ F_2^{IP}(\beta, Q^2) \]

- Proton rest frame: dipoles

\[ f_{IP}(x_P, t) \]

- Factorization is assumed.

\[ F_2^D = f_{IP}(x_P, t) F_2^{IP}(\beta, Q^2) \]

\[ f_{IP} = \frac{e^{bt}}{x_P^{2\alpha_F - 1}} \]

- Diffractive parton densities can be derived.

Resolved Pomeron model

_by Ingelman, Schlein - 1985_

- Long-living quark pair interacts with the gluons from the proton.

\[ \frac{d\sigma_{\gamma^* p}}{dt} \propto \int dz dr^2 \Psi^* \sigma_{qq}^2(x, r^2, t) \Psi \]

- Direct relation to inclusive DIS.

- Incorporates saturation dynamics.

- No extra parameters for diffraction are needed.
Selected Results

- Inclusive diffraction and DPDF: Pomeron under the microscope
- Diffractive dijets and QCD factorisation tests
- Vector Mesons and DVCS: soft vs hard Pomeron
- Leading neutrons and $\gamma\pi^+$ cross sections
  - forward neutrons and photons and CR models
  - inclusive neutrons in DIS and pion structure function
  - exclusive $\rho^0$ with forward neutron in PHP
- Summary and open questions
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Inclusive diffraction in DIS
First observation of diffraction in DIS
1992 data, 24.7 nb$^{-1}$
20 years of Diffraction in DIS

Current H1 status

\[ \mathcal{L} = 95 \text{ pb}^{-1} \]

\[ 390 \text{ pb}^{-1} \]

\[ 180 \text{ pb}^{-1} \]

First observation of diffraction in DIS 1992 data, 24.7 \( \text{nb}^{-1} \)

- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range. Clear candidate for the textbook!

- Positive scaling violation up to large \( \beta \) \( \Rightarrow \) gluon dominated \( IP \)
Compare to scaling violation in Inclusive NC DIS
Diffractive PDFs as determined by H1 and ZEUS

Diffractive PDFs extracted from NLO DGLAP fit, using Regge factorisation

- DPDFs are consistent in shape, $\sim 10\%$ difference in normalisation
- Jets help to constrain high $z$ gluons
- Gluons carry $\sim (70 - 75)\%$ of the Pomeron momentum
Inclusive DDIS: LRG vs p-tagged methods

Compare LRG and FPS cross sections

Ratio LRG/FPS:

\[
\frac{\sigma(Y < 1.6\text{ GeV})}{\sigma(Y = p)} = 1.203 \pm 0.019(\text{exp}) \pm 0.087(\text{norm}) \quad (1.6\%) \quad (7.2\%)
\]

- Experimental control on the amount of proton dissociation in LRG data
- No \( Q^2 \) or \( \beta \) dependent differences observed
Compare H1 and ZEUS LRG data to H1 DPDF Fit B and Dipole model

Normalisation difference of $\sim 10\%$ between H1 and ZEUS – within norm. uncertainties of each experiment

Dipole model describes better low $Q^2$ trend

DPDF is better at higher $Q^2$

Final precise data challenge models
To do: final QCD analysis of all H1 + ZEUS data (LRG and p-tagged) ⇒ DPDF
Diffractive dijets
QCD Factorisation Tests in Diffraction at HERA

QCD Factorisation holds in DIS regime \((EPJ, C72, 2012)\)

![Graphs showing two central jets and one central + one forward jet data and fits.](image)
QCD Factorisation holds in DIS regime \((EPJ, C72, 2012)\)

However, it breaks down at Tevatron ...
QCD Factorisation holds in DIS regime \textit{(EPJ, C72, 2012)}

\begin{align*}
\text{two central jets} & \\
\text{one central + one forward jet} & \\
\end{align*}

However, it breaks down at Tevatron ...
...due to soft remnant rescattering \((S \sim 0.15)\)
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⇒ Test it in photoproduction:

direct, \(x_\gamma = 1\) (DIS-like)
resolved, \(x_\gamma < 1\) (hadron-like)

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QCD Factorisation Tests in Diffraction at HERA

QCD Factorisation holds in DIS regime \((EPJ, C72, 2012)\)

\[
\frac{d^2 \sigma}{d x \, d y} \propto \frac{1}{(1-x)^2}
\]

\[ \Rightarrow \text{Test it in photoproduction:} \]

\[
e(k) e(k') \xrightarrow{\gamma^* (q)} \text{jet} \xrightarrow{\text{jet}} X(P_x) \]

\[
\text{direct, } x_\gamma = 1 \text{ (DIS-like)} \quad \text{resolved, } x_\gamma < 1 \text{ (hadron-like)}
\]

However, it breaks down at Tevatron ...
...due to soft remnant rescattering \((S \approx 0.15)\)

\[
\text{Tevatron vs HERA}
\]

\[
E_T^{\text{jet}1(2)} > 5.4(4) \text{ GeV} \quad E_T^{\text{jet}1(2)} > 7.5(6.5) \text{ GeV}
\]

\[
S \approx 0.6 \quad S \approx 1.0
\]
New analysis: VFPS Dijets in DIS and PHP

• 2006/07 $e^+p$ data, $\mathcal{L} \approx 30(50)\text{ pb}^{-1}$
• Leading proton measured by VFPS
• Untagged photoproduction
  ($e^+$ escapes in the beampipe)

Statistics: 3800 dijet events in PHP
  550 dijet events in DIS

Data unfolded to the level of stable hadrons using $TUnfold$ program

Results are compared to NLO QCD
• Scales: $\mu_r^2 = \mu_f^2 = \langle E_{T,\text{jet}}^2 \rangle + Q^2$
• DPDF H1 2006 Fit B and GRV-HO $\gamma$-PDF used
• Different scale choices and $\gamma$-PDF studied

<table>
<thead>
<tr>
<th>Photoproduction</th>
<th>DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event kinematics</td>
<td>$Q^2 &lt; 2 \text{ GeV}^2$</td>
</tr>
<tr>
<td>Leading proton</td>
<td>$0.2 &lt; y &lt; 0.7$</td>
</tr>
<tr>
<td>Dijets</td>
<td>$</td>
</tr>
</tbody>
</table>

$E_T^{*\text{jet1}} > 5.5 \text{ GeV}$
$E_T^{*\text{jet2}} > 4 \text{ GeV}$
$-1 < \eta^{\text{jet1,2}} < 2.5$

Table 1: Analysis phase space.
VFPS Dijets: Data vs NLO QCD

- DIS dijets in agreement with QCD factorisation

- Factorisation is broken in PHP

\[ \langle S^2 \rangle = 0.51 \pm 0.09 \]

- This is not related to \( p \) diss.

\((p \text{ tagged in VFPS})\)

- Independence on \( x_\gamma \) confirmed

No jet \( E_T \) dependence observed
Vector Mesons and DVCS
Vector Mesons at HERA

\[ \alpha_{\Pi}(t) = \alpha(0) + \alpha' t \]

soft Pomeron exchange

hard Pomeron diagrams

LO 2 gluons

LL1/x ladder
Vector Mesons at HERA

Exclusive VM production at HERA – a nice tool to study ‘soft’ vs ‘hard’ Pomeron regimes

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

\[ \sigma \propto W_{\gamma p}^{4(\alpha_P-1)} \]

Hard scales: \( Q^2, M_V, t \)

Predictions

\[ \alpha_P(0) \simeq 1.08 / 1.20 \]

\[ \alpha'_P \simeq 0.25 / 0.0 \]

Universal scale \( \mu^2 = (Q^2 + M_V^2)/4 \)

\[ \sigma \propto [xg(x, Q^2)]^2 \]
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transition from soft to hard regime at $\mu^2 \simeq 4 \div 5$ GeV$^2$
Diffractive scattering of $\gamma$ at large $|t|$ and DVCS

PHP ($Q^2 < 0.01$ GeV$^2$)

$$\sigma(W) \propto W^{4\omega_0} \quad \omega_0 = 4N_c\frac{\alpha_s^{BFKL}}{\pi} \ln 2 \quad \frac{d\sigma}{dt} \propto |t|^{-n}$$

DIS ($Q^2 > 2$ GeV$^2$)

Hard Pomeron at work
Vector Mesons at HERA: \( t \)—dependence

\[
d\sigma/dt \sim e^{-b|t|} \rightarrow \text{diffractive peak (approximated from Bessel function)}
\]

\[
b = (R/2)^2 \rightarrow \text{transverse size of the target (geometric picture)}
\]

Predictions:

\[
b = b_0 + 4\alpha'_P \ln(W/W_0);
\]

soft \( \mathcal{P} \): shrinkage of diffractive peak \( (\alpha'_P = 0.25) \); large \( b_0 \approx 10 \text{ GeV}^{-2} \)

hard \( \mathcal{P} \): no (or small) shrinkage \( (\alpha'_P < 0.1) \); small \( b_0 \approx 5 \text{ GeV}^{-2} \)
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\[ b = b_0 + 4\alpha'_IP \ln(W/W_0); \]

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**Example:** shrinkage in $\gamma^*p \rightarrow J/\psi p$

\[ Q^2 < 1 \text{ GeV}^2: \]

\[ \alpha'_IP = 0.164 \pm 0.028 \pm 0.030 \]

\[ Q^2 = 2 - 80 \text{ GeV}^2: \]

\[ \alpha'_IP = 0.019 \pm 0.139 \pm 0.076 \]
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Dipole picture interpretation:

\[ b = b_{VM} + b_p \]

\[ b_{VM} \sim \frac{1}{(Q^2 + M_{VM}^2)} \]

\[ b_p \rightarrow \text{size of the gluons area:} \]

\[ \langle r^2 \rangle = 2b_p \cdot (\hbar c)^2 \approx 0.6 \text{ fm} \]

Gluons confinement area (0.6 fm) is smaller than the proton size (0.8 fm)
Simultaneous unfolding of EL and PD channels

Use high $E_p = 920$ GeV and low $E_p = 460$ GeV data thus extending $W_{\gamma p}$ range

Both $e^+e^-$ and $\mu^+\mu^-$ decay channels $\Rightarrow$ cross check of systematics, better statistics

$t$ dependence:
EL – exponential; $b_{el} = 4.9 (4.3)$ GeV$^{-2}$ for HE(LE)
PD – $d\sigma/dt \propto (1 + (b_{pd}/n)|t|)^{-n};$

Energy dependence: $\sigma \propto W_{\gamma p}^{\delta_{el}}$
$\delta_{el} = 0.67 \pm 0.03; \quad \delta_{pd} = 0.42 \pm 0.05$
(possible explanation: $S_{gap}(W) < 1$ for PD case)
Exclusive Photoproduction of $J/\psi$ Mesons

- Extrapolating HERA fit describes LHCb
- Low $x$ gluon, based on old HERA data (A. Martin et al, 2008). NLO too steep
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- New QCD analysis (A. Martin et al, 2013) skewed $g(x, x', k_T)$, abs.corr. for LHC
- New LHCb data (930pb$^{-1}$) [arXiv:1401.3288]
Leading Neutrons at HERA
Physics with Forward Neutral Particles

HERA-I

- Similar H1 and ZEUS calorimeters, only $n$, located at $z = 106$ m from IP
- $\langle A \rangle \simeq 30\%$ for $\theta_n < 0.8$ mrad

HERA-II

- Improved H1 FNC: distinguish ($\langle P \rangle = 98\%$) and measure $n$ and $\gamma/\pi^0$
- Preshower: $60X_0$, Main Calo: $8.9\lambda$
Motivation and Challenges

- Extreme forward region in particle collisions is still poorly understood
  - Theory: No (or few) firm predictions from first principles
  - Experiment: Difficult to measure due to detector acceptance limitations

- Important for correct analysis of (ultra-high energy) Cosmic Rays
  - Two pieces of the puzzle:
    - Sources/Propagation (prime interest)
    - Interaction/Detection (extensive air shower)
  - To understand the former one needs good MC models for the latter

(Ralf Ulrich, PANIC-2014)
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- **Current situation (from PANIC summary):**
  - Recent LHC data are very valuable for CR MC tuning but still no fully consistent picture yet
  - UHECR data becomes more precise and require also better precision of hadronic interaction modelling

- **Specifics of HERA**
  - Additional constraints for different kinematical regimes wrt hadron colliders (smaller collision energy can be "compensated" by studying scaling properties and transporting the measurements to higher energies)
  - Some observables are unique (e.g. possible extraction of $\gamma\pi$ cross sections)
Inclusive forward $\gamma$, $n$ production in DIS

$$e^+ + p \rightarrow e^+ \left( \frac{n}{\gamma} \right) X$$

**Data**

$$\mathcal{L} = 131 \text{ pb}^{-1}, \quad \sqrt{s} = 319 \text{ GeV}$$

$$6 < Q^2 < 100 \text{ GeV}^2$$

$$70 < W < 245 \text{ GeV}$$

$$\eta_{\text{lab}} > 7.9, \quad x_F = \frac{2p^*_t}{W} > 0.1$$

$$\gamma : 83000 \text{ ev.} \quad n : 230000 \text{ ev.}$$

**MC models**

DIS: LEPTO/CDM ($\gamma$, $n$)

RAPGAP-$\pi$ ($n$)

CR: EPOS LHC

SYBILL 2.1

QGSJET (3 versions)
$W$ dependence

- ($\gamma, n$) yields are independent on $W$
- DIS MC overestimate photon rate by $\sim 70\%$
- and describe neutrons
- CR MC overestimate photon rate by $30 - 40\%$
- EPOS LHC is best for $n$
None of the models describes simultaneously $\gamma$ and $n$.

- EPOS LHC gives best shape description for $\gamma$ and reasonable for $n$. 
Pion structure function from LN DIS

\[ F_2^{LN(4)}(x, Q^2, x_L, t) = f_{\pi/p}(x_L, t)F_2^\pi\left(x/(1-x_L), Q^2, t\right)(1 - \Delta_{abs}(Q^2, x_L, t)) \]

\[ \Delta_{theo} = (0.1 \div 0.4) \]

Important to determine absorptive corrections experimentally
HERA as a ‘4P’ facility

HERA enables us to study structure of

Proton – $F_2, F_L$, ...
Photon – $g/\gamma$
Pomeron – $F_2^D, F_L^D$
Pion – $F_2^\pi$
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Here for the first time we investigate the reaction involving all these objects simultaneously:

\[ \gamma + p \rightarrow \rho^0 \pi^+ n \]
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\[ \text{Photon} - g/\gamma \]
\[ \text{Pomeron} - F_2^D, F^D_L \]
\[ \text{Pion} - F_2^\pi \]

Here for the first time we investigate the reaction involving all these objects simultaneously:

\[ \gamma + p \rightarrow \rho^0 \pi^+ n \]

- \( Q^2 < 2 \text{ GeV}^2 \) \( \langle Q^2 \rangle = 0.04 \)
- \(|t'| < 1 \text{ GeV}^2 \) \( \langle |t'| \rangle = 0.20 \)
- \( 0.35 < x_L < 0.95 \)
- \( \theta_n < 0.75 \text{ mrad} \)
- \( p_{t,n} < 0.2 \text{ GeV (OPE)} \)

\[ \frac{d^2\sigma_{\gamma p}(W_{\gamma p},x_L,t)}{dx_L dt} = f_{\pi/p}(x_L, t) \sigma_{\gamma\pi}(W_{\gamma\pi}) \]
Constraining pion flux

\[ d\sigma_{g} / dx_{L} \text{ [\mu b]} \]

\[ \rho^0 \text{ with Forward Neutron} \]

\[ H1 \]

\[ 0.35 < x < 0.50 \ (j=3) \]

\[ 0.50 < x < 0.65 \ (j=2) \]

\[ 0.65 < x < 0.80 \ (j=1) \]

\[ 0.80 < x < 0.95 \ (j=0) \]

\[ p_{T,n}^2 \text{ [GeV}^2\text{]} \]

\[ H1 \]

\[ b_{n} \text{ [GeV]} \]

\[ H1 \]

\[ 0.4 \ 0.6 \ 0.8 \ 0.0 \]

\[ 0.2 \ 0.4 \ 0.6 \ 0.8 \ 1 \]

\[ 0 \ 0.5 \ 1 \ 10 \ 100 \]
Estimate of absorption corrections

\[ r_{el} = \frac{\sigma_{\gamma\pi^+\rho^0\pi^-}}{\sigma_{\gamma p\rho^0 p}} = \begin{cases} 0.25 \pm 0.06 \text{ (exp.extracted)} \\ 0.57 \pm 0.03 \text{ (theo.expected)} \end{cases} \]

\[ K_{abs} = 0.44 \pm 0.11 \]

Look into other processes. What do we see there?
Cross sections ratio

**H1 (2015)**

\[ \sigma_{el}^{\gamma\pi} (W=24 \text{ GeV}) \]

\[ \frac{\sigma_{el}^{\gamma\pi}}{\sigma_{el}^{\gamma p}} = 0.25 \pm 0.06 \]

Exp.result: \[ r_{el} \simeq 0.57 \]

OT+eikonal approach+data: \[ r_{el} \simeq 0.57 \]

**ZEUS (2002)**

\[ \sigma_{tot}^{\gamma\pi} (W=107 \text{ GeV}) \]

\[ \frac{\sigma_{tot}^{\gamma\pi}}{\sigma_{tot}^{\gamma p}} = 0.32 \pm 0.03 \]

AQM: \[ r_{tot} \simeq 2/3 \]

Large absorption effects!

Optical Theorem: [\[ \frac{d\sigma_{el}}{dt} \bigg|_{t=0} = b_{el}\sigma_{el} \propto \sigma_{tot}^2 \] \[ r_{el} = \left( \frac{b_{\gamma p}}{b_{\gamma\pi}} \right) \cdot \left( \frac{\sigma_{tot}^{\gamma\pi}}{\sigma_{tot}^{\gamma p}} \right)^2 \]

Eikonal approach: \[ b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2 \]

World data: \[ (b_{pp} \simeq 11.7, \quad b_{\pi^+p} \simeq 9.6, \quad b_{\gamma p} \simeq 9.75) \text{ GeV}^{-2} \]
Absorptive factors, $K_{abs}$, in different PHP reactions

Unofficial private summary!
Summary

- Diffraction is an important area of HERA physics landscape. It represents a complicated interplay of soft and hard phenomena.

- Pomeron is a gluon dominated object. Diffractive DIS is fairly well described by both RP model and CD approach.

- QCD factorisation holds in DDIS, but is broken in PHP regime. The exact mechanism still to be revealed ($x_\gamma$ independence).

- Very forward neutral particle production is still a challenge for Cosmic Ray models.

- Absorptive effects in Leading Neutron production are essential both in DIS and PHP regimes. They have to be taken into account when extracting $F_2^{\pi}$ from LN in DIS and for $\gamma\pi$ cross section extraction from LN in PHP.
Open questions

- $F_2^{D(4)}$ from HERA-II VFPS data and final DPDF determination without assumption on Regge factorisation.

- Explain factorisation breaking mechanism in PHP, in particular independence of Gap Survival Probability on $x_\gamma$.

- Multiscale problem: $(Q^2, E_T, M_V, t)$.

- Where is an Odderon?

- Can one observe Glueball in a double Pomeron reaction in PHP?

\[ \gamma_p \rightarrow (IPIP) \rightarrow M_X \quad (M_X = \sqrt{x_{IP_1}x_{IP_2}}W_{\gamma_p} = 2 \div 4 \text{ GeV}) \]

HERA has finished, but not DIS physics. What’s next? eRHIC? LHeC?
Backup Slides
Deep Inelastic Scattering (DIS)

particle flow

current jet
colour flow
proton remnant

27.5 GeV

920 GeV

Inclusive vs Diffractive DIS

Diffractive Scattering (DDIS)

particle flow

current jet
no colour flow
p -> beam pipe

RAPIDITY GAP
Interplay of soft and hard contributions

\[ \gamma_L \quad \gamma_T \]

\[ \langle r_t^2 \rangle \simeq (z(1 - z)Q^2 + m_q^2)^{-1} \simeq 1/[(Q/2)^2 + m_q^2] \]

\[ \gamma_T \quad \langle r_t^2 \rangle \simeq (z(1 - z)Q^2 + m_q^2)^{-1} \simeq 1/m_q^2 \]

Small dipole

Large dipole

| Table I: Interplay between the probabilities of hard and soft fluctuations in a highly virtual photon and the cross section of interaction of these fluctuations. | 
|---|---|---|---|---|
| \(|C_\alpha|^2\) | \(\sigma_\alpha\) | \(\sigma_{tot} = \sum_{\alpha=soft} |C_\alpha|^2 \sigma_\alpha\) | \(\sigma_{sd} = \sum_{\alpha=soft} |C_\alpha|^2 \sigma_{\alpha}^2\) | 
| Hard | \(\sim 1\) | \(\sim \frac{1}{Q^2}\) | \(\sim \frac{1}{Q^4}\) | 
| Soft | \(\sim \frac{m_q^2}{Q^2}\) | \(\sim \frac{1}{m_q^2}\) | \(\sim \frac{1}{m_q^2 Q^2}\) |
Inclusive DDIS: Extracting Pomeron trajectory

- Regge fit to LRG cross section:

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

\[ f_{IP/p,IR/p}(x_{IP}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{IP,IR}t}}{x_{IP}^{2 \alpha_{IP,IR}(t)-1}} dt \]

- Mean value of the Pomeron intercept:

\[ \alpha_{IP}(0) = 1.113 \pm 0.002(\text{exp})^{+0.029}_{-0.015}(\text{model}) \]

- No \(Q^2\) dependence observed
- Consistent with other determinations
- Supports proton-vertex factorisation hypothesis

\[ \alpha_{IP}(0) \] – consistent with ‘soft IP’

\[ \alpha_{IP}' \leq 0.1 \] is typical for ‘hard IP’

Complicated interplay of hard and soft phenomena
Exclusive dijets in DDIS

\[ Q^2 > 25 \text{ GeV}^2, \ x_F < 0.01, \ N_{jet} = 2, \ P_T^{jets} > 2 \text{ GeV} \]

- using Durham jet algorithm in $\gamma^* - IP$ rest frame in exclusive mode (all objects are in jets), $y_{cut} = 0.15$.
- test the nature of the exchanged object in diffractive interactions
- reconstruct $\phi$ angle between lepton and jet planes

\[ \frac{d\sigma}{d\phi} \sim 1 + A(P_T^{jet}) \cos 2\phi \quad [\text{J.Bartels et al., PLB386, (1996)389}] \]

$A > 0$ for $q\bar{q}$ produced from single gluon

$A < 0$ two gluons exchange.
Exclusive dijets in DDIS

**ZEUS**

- $d\sigma/d\phi$ fitted in each $\beta$ bin

**ZEUS**

- normalisation discrepancy of factor two (NLO large?)
- $A$ vs $\phi$: good description by the two gluon model for $\beta > 0.3$ (i.e. towards exclusive dijets).
Exclusive $\rho^0$ with Forward Neutron

\[ t' = \frac{E}{E_L} \]

\[ g_p + p^- 0_t' p^+ n \]

\[ g_p + p^- 0_t' p^+ p^+ p^- n \]

\[ g_p + p^- 0_t' p^+ p^- n \]

\[ W(\rho^0) \]

Signal (DHD model)

Bgr (DIFFVM MC)

\[ dN/dM \ (\text{GeV}^{-1}) \]

\[ \pm 3.2 \text{ GeV}^{-2}, \quad b_2 = 3.62 \pm 0.32 \text{ GeV}^{-2} \]

H1 data

Fit: $a_1 e^{b_1 t'} + a_2 e^{b_2 t'}$

$b_1 = 25.7 \pm 3.2 \text{ GeV}^{-2}, \quad b_2 = 3.62 \pm 0.32 \text{ GeV}^{-2}$

Analysis region
Taking an estimate of $K_{abs}$ seriously

- Optical Theorem (plus exponential $t$ dependence):
  \[
  \frac{d\sigma_{el}}{dt} \bigg|_{t=0} = b_{el}\sigma_{el} \propto \sigma_{tot}^2; \quad \Rightarrow \sigma_{el} \propto \sigma_{tot}^2/b_{el}
  \]

- Relations between elastic slopes ($b \propto \langle R^2 \rangle$; $b_{ij} = b_i + b_j$):
  \[
  r_b \equiv \frac{b_{12}}{b_{13}} = \frac{b_1 + b_2}{b_1 + b_3} = \frac{b_1 + b_2}{(b_1 + b_2) + (b_2 + b_3) - 2b_2} = \frac{b_{12}}{b_{12} + b_{23} - b_{22}} = \frac{1}{1 - \frac{b_{22} - b_{23}}{b_{12}}}
  \]

- Data at $\sqrt{s} \simeq 24$ GeV (for $\gamma p \rightarrow \rho^0 p$ an interpolated value of $b_{\gamma p}$ is given):
  $b_{pp} = (11.7 \pm 0.2)$ GeV$^{-2}$; $b_{\pi^+ p} = (9.6 \pm 0.25)$ GeV$^{-2}$; $b_{\gamma p} = (9.75 \pm 0.50)$ GeV$^{-2}$

- Ratio $r_{el}$ ($1 = \gamma$, $2 = p$, $3 = \pi^+$):
  \[
  r_{el} = \left(\frac{b_{\gamma p}}{b_{\gamma \pi}}\right) \cdot \left(\frac{\sigma_{tot}^{\gamma \pi}}{\sigma_{tot}^{\gamma p}}\right)^2 = \left(\frac{1}{1 - (2.1/9.75)}\right) \cdot \left(\frac{2}{3}\right)^2 = (0.57 \pm 0.03)
  \]

- Absorption factor:
  \[
  K_{abs} = \frac{r_{el}(\text{measured})}{r_{el}(\text{estimated})} = \frac{0.25 \pm 0.06}{0.57 \pm 0.03} = 0.44 \pm 0.11
  \]