... we investigate the **fundamental forces** and **particles** in $e\,p$ collisions at highest energies – quark and gluon interactions, we verify the **Standard Model** and seek „new physics“ ...

... among the other - studying **diffractive** processes ...
Outline

- Introduction to diffraction in h-h and e-p interactions
- Recent results from HERA
  - Exclusive diffraction: vector meson production
  - Inclusive diffraction:
    - Diffractive parton distribution functions
    - QCD factorisation tests: diffractive dijet production
- Summary
Diffraction in hadron-hadron interactions (1)

Light scattering: Fraunhofer diffraction \((1/k \ll R)\)

\[ |t| = 4k^2 \sin^2(\theta/2), \]
\[ d\sigma/dt \sim \exp(-b|t|), \]
\[ b = (R/2)^2 \approx 8 - 10 \text{ GeV}^{-2} \]
Inelastic hadron diffractive dissociation $\leftrightarrow$ coherence condition:

- $\Delta I = \Delta Q = \Delta S = 0$, $\Delta P = (-1)^J$
- $\xi = M_X^2/s = \Delta p_L/p_L = 1 - |x| < m/\sqrt{s} = 0.15$
- $\Delta \eta = \ln(1/\xi) > 2$, ("large rapidity gap, LRG")

$s =$ squared CMS energy of hadrons

$\eta = -\ln(\tan(\theta/2))$, (pseudo-)rapidity

J. Figiel

Exclusive and diffractive processes... , Trento 2012
Regge model of hadronic interactions:

two-body reactions: “trajectory” exchange ($s \to \infty$)

$$\alpha(t) = \alpha_0 + \alpha' t$$

$$\frac{d\sigma}{dt} \sim F(t) \ s^{2\alpha(t)-2} = F(t) \ s^{2\alpha(0)-2} \ \exp(2\alpha' \ \log(s) \ t)$$

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

Elastic scattering (→ total cross-section):
exchange of Pomeron IP trajectory (vacuum quantum numbers)

Universal parametrisation of Donnachie-Landshoff ("soft" Pomeron):

$$\alpha_{IP}(t) = 1.08 + 0.25 \ t$$

PS: J. D. Bjorken: Regge model foundations are as solid as those of QCD, DIS1994
Diffraction in e-p interactions

HERA: $e^\pm$ (27.5 GeV) – p (820/920 GeV) → $\gamma^* p$ → hadrons

$Q^2 - \gamma^*$ virtuality (0 – $10^5$ GeV$^2$)

$s \approx E_e E_p$, $\sqrt{s} \approx 300$ GeV

$W - \gamma^* p$ CMS energy (20 -290 GeV)

$x \approx Q^2/W^2$ – Bjorken $x = \text{fractional parton momentum in proton Breit frame}$

$y \approx Q^2/(sx)$ – fractional energy transfer to $p$

Coherence condition in proton rest frame:

fluctuation length ($\gamma^* \rightarrow \text{dipol } q\bar{q}$) = $2E_\gamma/(m_{q\bar{q}}^2 + Q^2) > 1$ fm

$\rightarrow x < 0.01$

At HERA diffraction is low Bjorken-$x$ phenomenon!

Vector meson production

DVCS

inclusive diffraction

J. Figiel

Exclusive and diffractive processes... , Trento 2012
Vector meson production (1)

Vector Dominance Model + Regge

\[ \gamma^* p \to VM p = (\gamma^* \to VM) \otimes (VM p \to VM p) \]

- VM p \to VM p \Rightarrow DL IPomeron exchange
- \( d\sigma/dt \sim \exp(-b(W)t), \quad b \sim R_{int}^2 \approx 10 \text{ GeV}^{-2} \)
- \( b(W) = (b_{VM} + b_p + \alpha' \ln(W^2)) \) ("shrinkage")
- \( \sigma_{VMp} \sim W^{4(\alpha_0-1)/b(W)} \sim W^\delta, \quad \delta \approx 0.22 \)

Perturbative QCD

Large \( Q^2, M_{VM} \) or \(|t| \to \) small qq dipol

- QCD Pomeron exchange:
  \( \geq 2 \) gluons (colour singlet)
- \( \sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7} \) !!!
- \( b \ll 10 \text{ GeV}^{-2} \), weak shrinkage

VM at HERA: transition between soft and hard regime; testbed of QCD scales
Vector meson production (2)

H1, ZEUS

H1 \( \phi \) notag

\[
\begin{align*}
M_{\rho} & = 768 \pm 0.001 \text{ (GeV)} \\
\Gamma_{\rho} & = 154 \pm 0.003 \text{ (GeV)}
\end{align*}
\]

\( \rho^0 \rightarrow \pi^+ \pi^- \)

\( \gamma \rightarrow \mu^+ \mu^- \)

J/\psi Photoproduction

H1 Preliminary

\( \text{H1 data } J/\psi \rightarrow ee \) \( \langle \sqrt{s} = 318 \text{ GeV} \) 

Fit (N(J/\psi) = 12581)
Vector mesons: energy dependence

Photoproduction, energy dependence: $\sigma \sim W^\delta$

The heavier vector meson – the steeper $W$-dependence.

VM mass sets QCD scale
VMs: bigger “hard” scale $Q^2+M^2$ – steeper rise with $W$, $Q^2+M^2$ scale governs “soft” – “hard” interaction transition

DVCS: always steep rise with $W$ – “hard” interaction...
VM and DVCS: t-slope compilation

\[
d\sigma/dt \sim e^{-b|t|}
\]

Decreasing slope (and interaction size) with rising scale \(Q^2+M^2\) -
- transition between “soft” and “hard” interaction
Possible exchanges:

- **Pomeron** (C=+1), QCD: 2 gluons,
- **Odderon** (C=-1), QCD: 3 gluons
- **Photon γ** (C=-1),

<table>
<thead>
<tr>
<th>Type</th>
<th>Meson</th>
<th>I^G</th>
<th>J^{PC}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>f_0 / α(600), f_0(980), χ_c</td>
<td>0^-</td>
<td>0^{++}</td>
</tr>
<tr>
<td>PS</td>
<td>π^0, η_c</td>
<td>1/0^+</td>
<td>0^+</td>
</tr>
<tr>
<td>V</td>
<td>ρ^0, J/ψ</td>
<td>1^+0^-</td>
<td>1^-</td>
</tr>
<tr>
<td>T</td>
<td>f_2(1270)</td>
<td>0^+</td>
<td>2^{++}</td>
</tr>
</tbody>
</table>

~ HERA...
Central, exclusive diffraction in (anti-)pp collisions (2)

Exclusive Dimuon Production

\[ \bar{p} + p \rightarrow \bar{p} + \mu^+ \mu^- + p \]

Many Physics Processes in this data:

- Observation of exclusive \( \chi_c \) PRL 102 242001 (2009)
Central, exclusive diffraction in (anti-)pp collisions (3)

Exclusive J/ψ and ψ(2s)

J/ψ production
243 ± 21 events
\(d\sigma/dy\big|_{y=0} = 3.92 ± 0.62 \text{ nb}\)

Theoretical Predictions
2.8 nb [Szczureko7],
2.7 nb [Klein&Nystrand04],
3.0 nb [Conclaves&Machado05], and
3.4 nb [Motkya&Watto8].

ψ(2s) production
34±7 events
\(d\sigma/dy\big|_{y=0} = 0.54 ± 0.15 \text{ nb}\)

R = ψ(2s)/J/ψ = 0.14 ± 0.05
In agreement with HERA: R = 0.166 ± 0.012 in a similar kinematic region

PRL 242001 (2009)

J/ψ
Fit:
2 Gaussians + QED continuum

ψ(2s)
QED continuum

September 5-9, 2011
Christina Mesropian, Summer School Heidelberg
Central, exclusive diffraction in (anti-)pp collisions (4)

Exclusive $\chi_c \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) + \gamma$

$\rightarrow$ Allowing EM towers ($E_T > 80$ MeV)
large increase in the $J/\psi$ peak
minor change in the $\psi(2s)$ peak

↓

Evidence for

$\chi_c \rightarrow J/\psi + \gamma$ production

$\frac{d\sigma}{dy}|_{y=0} = 75 \pm 14$ nb,
compatible with theoretical predictions
160 nb (Yuan 01)
90 nb (KMR01)
Inclusive diffraction in e-p interactions (1)

\[ M_x \] – mass of diffractive system (without \( p' \))
\[ \chi_{IP} = \frac{(Q^2 + M_x^2)}{(Q^2 + W^2)} \], relative momentum \( IP/p \)
\[ \beta = \frac{Q^2}{(Q^2 + M_x^2)} \approx x/x_{IP} \], relative momentum \( q/IP \)
\[ t \] – squared 4-momentum transfer \( p - p' \)

Diffractive structure functions →
→ (“hard” factorisation + QCD fit) → diffractive PDFs

\[
\frac{d^4 \sigma^{DP}_{y*P}}{dQ^2 d\beta dx_{IP} dt} = \frac{2 \pi \alpha^2_{em}}{\beta Q^4} \left( 1 + (1 - y)^2 \right) F^{D(4)}_{2}(Q^2, \beta, x_{IP}, t)
\]

If \( t \) not measured →
\[ F^{D(3)}_{2}(Q^2, \beta, x_{IP}) \]

“reduced” cross section
\[ \sigma^D_r = F^D_2 - \frac{y^2}{1 + (1 - y)^2} F^D_L \approx F^D_2, \ y < 1 \ (F^D_L = 0 \text{ at LO}) \]

Proton vertex factorization (?):
\[ F^{D(4)}_{2}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) F^{IP}_{2}(\beta, Q^2) \]

Regge inspired...
\[ f_{IP}(x_{IP}, t) = A \frac{1}{x_{IP}}^{2\alpha(t)-1} \exp(Bt) \]
\[ F^I_{2}(z, Q^2) = A z^B (1-z)^C \]

IPomeron flux (Regge form)
IPomeron structure function !!!

J. Figiel
Exclusive and diffractive processes... , Trento 2012
Inclusive diffraction in e-p interactions (2)

Diffractive selection:

- proton tagging, LPS(\textit{ZEUS}), FPS, VFPS(\textit{H1})
- Large Rapidity Gap (p-dissociation ..!)
- \(M_X\) method (p-dissociation ..!)

3.3 < \(\eta\) < 7.5, \(\eta_{\text{max}} < 3\)
Inclusive diffraction in e-p interactions (3)

**ZEUS** (Nucl. Phys. **B800** (2008) 1) FPC II results (\(M_X\) method):

- Diffraction yield (fixed \(M_X, Q^2\)) \(\approx\) const \(W\)
- Diffraction yield (\(0.28 < M_X < 35 \text{ GeV}\)) \(\approx a - b \ln(1+Q^2)\)

![Graphs showing diffraction yield for different intervals of \(M_X\) and \(Q^2\).](image)

J. Figiel

Exclusive and diffractive processes... , Trento 2012
Inclusive diffraction in e-p interactions (4)

**ZEUS: LRG vs $M_X$ method (FPC I, FPC II)**

Different methods are consistent
Inclusive diffraction in e-p interactions

ZEUS vs LRG method

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$\beta$</th>
<th>$\sigma_{D(3)}$ (LPS) / $\sigma_{D(3)}$ (LRG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.020</td>
<td>1</td>
</tr>
<tr>
<td>3.9</td>
<td>0.031</td>
<td>0.98</td>
</tr>
<tr>
<td>7.1</td>
<td>0.019</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>0.037</td>
<td>0.94</td>
</tr>
</tbody>
</table>

- LRG data contain $\sim$20% of p-diss.
- No significant dep. on $Q^2$, $\beta$, $x_{IP}$

J. Figiel

Exclusive and diffractive processes... , Trento 2012
\( \sigma_r^{D(3)} : \) VFPS vs FPS vs LRG

H1 PRELIMINARY

VFPS \approx\ FPS within the errors...
Inclusive diffraction in e-p interactions

$\sigma^D_{(3)}$: H1 FPS vs ZEUS LPS

Reasonable agreement of H1 and ZEUS data $\Rightarrow$

$\Rightarrow$ Combine!
extend phase space, reduce uncertainties

J. Figiel
Exclusive and diffractive processes... , Trento 2012
Inclusive diffraction in e-p interactions (8)

$\sigma^{D(3)}_r$: H1 FPS and ZEUS LPS combination...

Combined data have \(\sim 20\%\) smaller uncertainties than H1 or ZEUS data

J. Figiel

Exclusive and diffractive processes... , Trento 2012
Compared H1 LRG (HERA-1, HERA-2) and ZEUS LRG (HERA-1) data → reasonable agreement
Inclusive diffraction in e-p interactions (10)

\[ x_{IP} \sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t) \]

H1, EPJ C71 (2011) 1578,

**H1 FPS**

| \[ |t|=0.2 \text{ GeV}^2 \] | \[ |t|=0.4 \text{ GeV}^2 \] | \[ |t|=0.6 \text{ GeV}^2 \] |
|----------------|----------------|----------------|

\[ \beta = 0.0018 \quad 5.1 \text{ GeV}^2 \]  
\[ \beta = 0.0056 \]  
\[ \beta = 0.018 \]  
\[ \beta = 0.056 \]  
\[ \beta = 0.18 \]  
\[ \beta = 0.56 \]

\[ f_{IP}(x_{IP}, t) = A \left(1/x_{IP}\right)^{2\alpha(t)-1} \exp(B t) \]

\[ B = B_{IP} + 2\alpha'_{IP} \ln(1/x_{IP}) \]

\[ F_2^{IP}(z, Q^2) = A z^B (1-z)^C \]

Regge...

Proton vertex factorization. Regge flux approximation (7):

\[ F_2^{D(4)}(\beta, Q^2, x_{IP}, t) = f_{IP}(x_{IP}, t) F_2^{IP}(\beta, Q^2) \]

(Sub-leading IR term omitted...)

J. Figiel

Exclusive and diffractive processes... , Trento 2012

25
Inclusive diffraction in e-p interactions (10)

J. Figiel

Exclusive and diffractive processes... , Trento 2012

H1, EPJ C71 (2011) 1578, ZEUS, NP B816 (2009) 1

\[ x_{IP} \sigma^D_r (\beta, Q^2, x_{IP}, t) \]

- \( \alpha_{IP} (0) \approx 1.10 \) in agreement with \( \alpha_{IP} \) (soft)~1.08
- \( \alpha' \approx 0 \rightarrow \) no “shrinkage” < \( \alpha' \) (soft)~0.25 GeV-2
  (\( B_{IP} \) consistent with hard process)
- no strong dependence of \( \alpha_{IP} (0), \alpha', B_{IP} \) on \( Q^2 \)
- Proton vertex factorization holds within uncertainties
QCD factorisation tests

Collinear **factorization** theorem (lepton-proton, DIS, **perturbative QCD**)

\[ \sigma^D = \sum f_i^D \otimes \sigma_i^{\gamma^*} \]

- \( f_i^D \) – universal diffractive **Parton Distribution Function** (dPDF)
- \( \sigma_i^{\gamma^*} \) – universal (**\gamma^*** parton) cross-section

**Basic strategy:**

- **Inclusive diffraction:**
  - Measure diffractive structure function \( F_2^D \)
  - Extract dPDFs (quarks and gluons) from \( F_2^D \),
    - NLO DGLAP fit to \( F_2^D \) (polynomials at \( Q_0^2 \)),
    - proton vertex factorisation, Regge approximation,

- **Semi-inclusive diffractive process:**
  - Calculate partonic \( \sigma_i^{\gamma^*} \),
  - convolute with dPDFs \( \rightarrow \) cross-section

⇒ compare the calculations with experiment...

J. Figiel
Exclusive and diffractive processes..., Trento 2012
Diffractive PDFs (1)

**H1**: $\sigma_{R}^{D(3)} \rightarrow$ NLO DGLAP fits (+proton vtx factorisation) $\rightarrow$ diffractive PDFs

EPJ C48 (2006) 715

- Gluons weakly constrained, esp. at large $z$

\[ z = \text{fraction of parton momentum in hard scattering/IPomeron} \quad (\beta) \]
**Diffractive PDFs (2)**

**H1, diffractive di-jets in DIS:**

JHEP 0710:042,2007

4 < \( Q^2 \) < 80 GeV\(^2\), 0.1 < \( y \) < 0.7, \( x_{IP} \) < 0.03

\[
z_{IP} = \frac{(Q^2 + M_{JJ}^2)}{(Q^2 + M_J^2)}
\]

- H1 2006 DPDF fit B gives better agreement with the data
H1: diffractive di-jets in DIS

Combined QCD fit to dijets and inclusive diffraction to constrain gluon distribution at high $z$ → H1 2007 Jets dPDFs
H1 2007 Jets dPDFs

- H1 2007 Jets DPDF close to H1 2006 DPDF fit B
- Common diffractive DIS and diffractive dijets PDFs → factorisation holds
Diffractive PDFs (5)

**ZEUS DPDF fits (ZEUS-prel-09-004):**

LRG & LPS & diffractive Dijet DIS

**ZEUS** and **H1** 2006B DPDF fits are consistent up to normalisation

---

**Figure:**
- **ZEUS** DPDF fits for different values of $Q^2$ (6, 20, 60, 200 GeV$^2$).
- **H1** 2006B DPDF fits for different values of $Q^2$ (20, 60, 200 GeV$^2$).

---

**ZEUS, NP B831(2010)1**

**Gluons/quarks**

**ZEUS**

<table>
<thead>
<tr>
<th>$Q^2 = 6$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 = 20$ GeV$^2$</td>
</tr>
<tr>
<td>$Q^2 = 60$ GeV$^2$</td>
</tr>
<tr>
<td>$Q^2 = 200$ GeV$^2$</td>
</tr>
</tbody>
</table>
QCD factorization test: dijets in D-DIS

**H1**: 2 jets in diffractive DIS with leading proton VFPS (H1 prel-11-013)

**NLO** predictions using **H1** Jets 2007 DPDFs describe dijet production in DIS with tagged proton → QCD factorisation holds...
**Diffractive dijets in photoproduction (1)**

**Direct photon (like DIS)**

\[ x_\gamma \approx 1 \]

**Resolved photon**

\[ x_\gamma = \frac{\Sigma(E-p_\gamma^2)\text{jets}}{\Sigma(E-p_\gamma^2)\text{hadr.}} \]

= fraction of photon mom. in hard scattering

Resolved photon may behave as a hadron → factorization may be broken
(as in p-p, secondary re-scattering, multi-pomeron exchanges)

→ “gap survival probability...”
**Diffractive dijets in photoproduction (2)**

**ZEUS**: diffractive (LRG+LPS) dijets in photoproduction (NP B831 (2010) 1)

![Graph](image)

- No suppression $\Rightarrow$ QCD factorization holds?
- Inconsistency with H1 DPDF...

$E_T^{jet} > 7.5$ GeV

---

J. Figiel

Exclusive and diffractive processes... , Trento 2012
H1: diffractive (LRG) dijets in photoproduction (EPJ C70 (2010) 15)

- Weak dependence on $x_γ$ (?)
- Hint of jet $E_T$ dependence
- Dependence on DPDF...

$E_T$ jet $> 5$ GeV

```
~ Gap survival probability
H1-data/NLO = 0.58±0.12(exp.) ±0.14(scale)±0.09(DPDF)
```

- Data / theory
- H1 data / theory
- NLO H1 2006 Fit B $\times (1+\delta_{\text{had}})$
- Data correlated uncertainty
- NLO H1 2007 Fit Jets $\times (1+\delta_{\text{had}})$
- NLO ZEUS SJ $\times 1.23 (1+\delta_{\text{had}})$
● Still new, precise measurements of diffraction at HERA
● Consistent picture of VM production within QCD framework
● New diffractive PDFs from inclusive and semi-inclusive measurements, with several methods - consistent
● First combination of H1 and ZEUS diffractive data with tagged proton gives consistent results
● QCD hard factorization holds in diffractive dijet production in DIS but may be broken in PHP, H1 - ZEUS comparison inconclusive
● Theoretical uncertainties of QCD calculations are larger than experimental errors...
● Diffractive analyses at HERA are still ongoing...