Diffraction and Vector Meson Production

Yuji Yamazaki
KEK-IPNS / ZEUS collaboration
15 Aug 2003
The XXI International Symposium on Lepton and Photon Interactions at High Energies
Diffractive processes

- $t$-channel exchange of the vacuum quantum numbers
  - Colourless exchange
  - Small momentum transfer
    - $t \ll s$
    - Longitudinal momentum fraction $\xi (= x_p) < 0.05$
    - Large Rapidity Gap (LRG)
  - Historically described by an exchange Pomeron trajectory in the Regge theory
Aim of studying diffraction

- ... is to understand the exchange in terms of pQCD
  - 2-gluon exchange at LO
  - The exchange itself does not have hard scale: typically $t \approx \Lambda_{QCD}^2$
    Need a scale to see partons

- Probing partonic structure by **hard diffraction** e.g.
  - DIS, jet / HQ production, large $t$
The basic of hadron physics:
\[ W^2 \propto 1/x_{\text{Bj}} \] dependence

- \( F_2 \) rises steeply towards low-\( x_{\text{Bj}} \)
  
  □ This means:
  
  the cross section steeply rises with \( W \), the centre-of-mass energy of \( \gamma^{(*)}p \) system:
  
  \[
  W^2 = \left( \frac{1}{x} - 1 \right) Q^2 \approx \frac{Q^2}{x} \quad (x << 1)
  \]

  □ Or: rise in \( s \) for hadron-hadron

- Fast rise in \( W \): partons = pQCD

- Slow rise: soft collisions

\[ Q^2 = 0 \text{ GeV}^2 \]
\[ Q^2 = 0.3 \text{ GeV}^2 \]
\[ Q^2 = 15 \text{ GeV}^2 \]
\[ (x \times 8) \]
Why diffraction? a simple view

- Plenty of partons at low-$x$
  - 1-parton exchange
    - Hard scattering
  - 2-parton exchange
    - Multi-parton scattering – incoherent
    - Diffraction – coherent
  - 3 or more could occur as well
- These phenomena should be explained uniformly
  - Cannot be ignored at high energy
Diffraction is a good part of $\sigma_{tot}^{hh}$

- Diffraction expected to be dominant in high-energy hadron-hadron collisions
  - Elastic + diffraction: already $\sim 35\%$
  - $\sigma_{tot} \propto g(x)$, $\sigma_{diff} \propto |g(x)|^2$
  - $\therefore \sigma_{diff}/\sigma_{tot} \propto g(x)$, rising with $s$

- Important component for understanding the asymptotic behaviour of hadron-hadron scattering at high energies

\[ \sigma_{diff} \propto |g(x)|^2 \]
\[ \sigma_{tot} \propto g(x) \]
Outline of the talk

- Hard diffraction and its partonic structure at HERA
- Vector meson production at HERA
- Diffraction at Tevatron

The first subject:
Hard diffraction and its partonic structure at HERA
Diffractive DIS (DDIS)

- $Q^2$ provides a hard scale
  - probing partonic structure
- Main task: $F_2^{D(3)}(\beta, Q^2, x_P)$
  - Structure function for diffractive processes
    $$\int dt \frac{d^4 \sigma_{\text{diff}}^{ep}}{d\beta dQ^2 dx_P dt} \approx \frac{4\pi\alpha^2}{\beta Q^4} \left(1 - y - \frac{y^2}{2}\right) F_2^{D(3)}(\beta, Q^2, x_P)$$
  - Sensitive to quarks
- Gluons are “measured” by
  - Jet and HQ production
  - Scaling violation of DDIS using DGLAP eq.
**$F_2^D(3)$ from H1, ZEUS**

- 3 issues on $F_2^D$, in this talk

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1. Factorisation in DDIS

In normal DIS or hard scattering

\[ \sigma = \sum_i f_i(x, \mu^2) \otimes \hat{\sigma}_{i\gamma}(x, \mu^2) \]

- QCD factorisation

The factorisation theorem is also applicable for DDIS:

\[ \frac{d\sigma(x, Q^2, x_P, t)}{dx_P dt} = \sum_i \int_x^{x_P} \left[ dz \hat{\sigma}^{i\gamma}(z, Q^2, x_P) f_i^D(z, Q^2, x_P, t) \right] \]

- \( f_i^D \): pdfs with a diffractive exchange at \((x_P, t)\)
- **Q1**: Is the pdfs universal?

How to test:

- Diffractive pdfs extracted from DGLAP NLO fit of inclusive DIS
- Data of Jet / HQ production cross section (sensitive to gluons!) compared to the calculation using THE pdfs

\[ z = p_L / p \]

\[ f_i^D(z, Q^2, x_P, t) \]

\[ \hat{\sigma}_{i\gamma}(x, Q^2, z) \]

\[ \sum \otimes = \gamma x f_{xQ} \]

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Extraction of the diffractive pdfs

- NLO QCD fit performed to $F_2^{D(3)}$
  - Strong scaling violation up to high-$\beta$, origin from a boson (cf. $F_2^{\gamma}$)
  - the exchange contains more gluons than quarks

$\sigma_r^D / f_{IP}(x_{IP})$

$Q^2$ [GeV$^2$]

$Z \Sigma(Z, Q^2)$
Comparison with Jets and D* production

- Jets and D*: sensitive to gluons
- Both jets and D* agrees well with NLO
- A1. QCD factorisation holds in DDIS
  - PDFs are universal within DDIS

\[ \frac{d\sigma}{dz} \] for jets and D* production

**Diagram:**
- **Electron Emission:** 
  - $e^+ e^-$ production
  - $q$ (jet, HQ)
  - $\bar{q}$
  - $p$ to $p'$

**Equations:**
- \[ q(x_P, \beta, Q^2) \]
- \[ g(x_P, \beta, Q^2) \]
2. Test of the resolved Pomeron model

- If the exchange is a pseudo-particle
  - $\sigma = (\text{flux of } \text{Pomeron}) \otimes (F_2 \text{ of } P)$
  - $F_2^D \propto f_{P/P}(x_P, t) \cdot F_2^P(\beta, Q^2)$
- $Q^2$: Does the “resolved Pomeron” model describe data?

- This means
  - The $x_P$ shape is independent of ($\beta$, $Q^2$) values (“Pomeron flux” shape)

- Flux fit: $x_P$ or $W$ dependence
  - $F_2^D \propto \frac{1}{x_P^{a/2}} \cdot b(\beta, Q^2)$
  - $= W^a \cdot \left(\frac{\beta}{Q^2}\right)^{a/2} b(\beta, Q^2) \cdot W^2 \cong \frac{Q^2}{\beta x_P}$
$W$ slope of the diffraction

\[ F_2^D \propto \frac{1}{x_P^{a/2}} b(\beta, Q^2) \]

\[ = W^a \left( \frac{\beta}{Q^2} \right)^{a/2} b(\beta, Q^2) \]

\[ \therefore W^2 \approx \frac{Q^2}{\beta x_P} \]

- An indication of the slope rising with $Q^2$
- Shape of the flux differs in $Q^2$

A2. The exchange is not single pseudo-particle state
3. pQCD models and W dependence

- Colourless exchange of a $q\bar{q}$ dipole and proton: how?
  - Two perturbative gluons (+HO)
    \[
    \sigma_{\text{inel}} \propto g(x), \quad \sigma_{\text{diff}} \propto |g(x)|^2
    \]
    i.e. $\sigma_{\text{inel}} \propto W^a \Rightarrow \sigma_{\text{diff}} \propto W^{2a}$
  - If softer gluons are exchanged e.g.
    - Soft-colour interaction (SCI) model
      = 1 hard + 1 soft
    - Saturation model:
      two gluons, but somewhat softer
      \(\rightarrow \sigma_{\text{diff}} \) rises less steep than $|g(x)|^2$ or $W^{2a}$
  - Q3: how fast is the rise in W?
W slopes: $\sigma_{\text{tot}}$ and $\sigma_{\text{diff}}$

- Result:
  
  $\sigma_{\text{diff}} / \sigma_{\text{tot}}$ flat in $W$

- A3. Diffraction and inclusive has the same energy behaviour
  
  □ Not consistent with “two hard parton” model

```
ZEUS 98-99 (prel.)

0 < M_X < 2 GeV

8 < M_X < 15 GeV

2 < M_X < 4 GeV

15 < M_X < 25 GeV

4 < M_X < 8 GeV

25 < M_X < 35 GeV

W(GeV)

Q^2 = 2.7 GeV^2  Q^2 = 4 GeV^2  Q^2 = 6 GeV^2  Q^2 = 8 GeV^2
Q^2 = 14 GeV^2  Q^2 = 27 GeV^2  Q^2 = 55 GeV^2

0 0.02 0.04 0.06
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0 0.02 0.04 0.06
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0 0.02 0.04 0.06
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0 0.02 0.04 0.06
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Conclusions from DDIS at HERA

- Diffractive pdfs are universal within DIS
  - QCD factorisation holds
- Diffractive exchange is not single pseudo-particle state
  - The “flux” depend on $Q^2$: onset of pQCD
- $\sigma_{\text{diff}} / \sigma_{\text{tot}}$ is flat in $W$
  - Softer than pure 2-gluon exchange

Next:
Vector meson (VM) production at HERA
pQCD framework of the VM production

- Hard scale given by
  - $Q^2$, $M_V^2$, or $t$
- 2-gluon exchange
  - $\sigma_L \sim |g(x)|^2$ i.e. steep rise in $W$
- The concept works!
  - $J/\psi$ photoproduction:
    steep rise in $W$, agree with pQCD predictions

\[ \sigma_{\gamma p \rightarrow J/\psi} [\text{nb}] \]

\[ W [\text{GeV}] \]

- H1 99-00 $J/\psi \rightarrow \mu^+\mu^-$ (prelim.)
- H1 96-97 $J/\psi \rightarrow e^+e^-$ (BR corr.)
- ZEUS
- E401
- E516
Another example: DVCS
(Deeply virtual Compton Scattering)

- Elastic process in $\gamma^*p$
  - No uncertainty in the VM wave function
- Steep rise in $W$
  - $\sigma \propto W^\delta$
    - $\delta = 0.98 \pm 0.44$ (H1)
    - $= 0.75 \pm 0.15^{+0.08}_{-0.06}$ (ZEUS)
    - Similar to $J/\psi$ value ($\sim 0.7$)
    - Larger than soft ($\sim 0.22$)
- $Q^2$ dependence also described
Forward slope ($B$) for VMs

- **Slope of the scattering angle of the proton**:
  
  \[ \sigma \propto \exp(Bt) \]
  
  $B$ is the size of the interaction

- **$B \sim 4.5 \text{ GeV}^{-2}$**
  
  at $\rho$ in high $Q^2$ and $J/\psi$

  Similar to proton size $\rightarrow$ VM production is point-like if a hard scale

  ![Graph depicting $B$ in $\rho$ production vs $Q^2$]

- **High $Q^2$**

  ![Diagram of proton with $4.5 \text{ GeV}^{-2}$ annotation]

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Conclusions from VM production

- Steep $W$ dependence for VM and DVCS
  - Agrees with pQCD prediction
- $B$-slope $\sim 4.5 \text{ GeV}^{-2}$
  - VM with a hard scale is point-like production

Pure-pQCD approach is successful in VM, unlike in DDIS

Next:
Tevatron results and comparison with HERA
Run 1 results: hard diffraction

- Extensive survey
  - $W$ – sensitive to quarks
  - Dijet, $b$-quark, $J/\psi$ – gluons

- Hard diffraction is suppressed w.r.t. the prediction using pdfs measured at HERA
  - by about factor 5-10 (depending on diffractive pdfs)

- Diffraction seems lost by re-scattering between two remnants
  - Gap survival probability $S^2$ is small

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Recent theoretical development on $S^2$

- Various approach for multi-exchange effect:
  - Rapid progress in last several years
  - Renormalised Pomeron flux: Goulianos
  - Estimation from the soft hh cross sections:
    - Kaidalov, Khoze, Martin, Ryskin
    - Gotzman, Levin, Maor
    - Bialas, Peschanski
  - Soft colour interactions: Ingelman, Enberg et al.
  - Overlapping with hard multi-parton scattering:
    - Cox, Forshaw, Lönnblad …
  - …(not complete)

- Which model is more universal? (e.g. applicability to LHC)
  - more data needed to check models


Enberg et al., Phys. Rev. D 64 (2001) 114015
Suppression within HERA?

- Photoproduction: scatter of a real photon and the proton
  - Resolved photon can be regarded as a hadron $\Rightarrow$ possible re-scattering between the photon and proton remnant
  - suppression for resolved?

- Result:
  - The shape described by MC
    - No evidence of the suppression of resolved $\gamma$
  - No significant of factorisation breaking in photoproduction
RunII results from CDF

- Upgrade in CDF:
  - new MiniPlugs
  - new Cerenkov LUMI Counters
  - new Beam Shower Counters
  - More coverage in large rapidity
    Better detection of rapidity gaps

- Already reproducing run1 results
From CDF run II: exclusive dijet

- Two colourless exchange fusion to dijet, nothing else
- Resonance in $M_{p-p}$ can be detected by Roman pots
  - clean signal for diffractive Higgs production
- Cross section: difficult to calculate
  - Cannot use diffractive pdfs
  - QCD radiation to be estimated
  - Gap survival probability $S^2$ on top:
- The dijet measurement gives ...
  - the normalisation of the calculation
    $\rightarrow$ better estim. for Higgs production
Dijet spectrum in $R_{jj}$

- No peak in dijet mass observed
  - No evidence for the exclusive dijet
  - The measured cross section for $R_{jj} > 0.8$ gives upper limit of the exclusive cross section

<table>
<thead>
<tr>
<th>Minimum $E_T^{jet1}$</th>
<th>Cross section: $\sigma^{excl.dijet}<em>{DPE} (R</em>{jj} &gt; 0.8)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>$970 \pm 65(stat) \pm 272(syst)$ pb</td>
</tr>
<tr>
<td>25 GeV</td>
<td>$34 \pm 5(stat) \pm 10(syst)$ pb</td>
</tr>
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Conclusions on Tevatron – HERA comparison

- Factorisation breaking Tevatron-HERA
  - Rapid development in the theoretical framework
- Factorisation test HERA photoproduction: no breaking
- RunII data + results coming
  - Further data from DØ soon (next slide)
Future direction (1): upgrade in DØ

- New forward detectors
- New Roman pots
  - very large acceptance in $(\xi, t)$
- Status
  - alignment just finished
  - Observing right $t$-shape
  - results in coming months
Future direction (2) H1 VFPS

- Tagging scattered proton at very high acceptance
  > 90 % for 0.005 < $x_P$ < 0.02, $|t| < 0.2$

- HERA has just restarted after shutdown
  □ New data in coming months
Summary

The aim of studying diffraction was to understand the exchange in terms of pQCD

Was it successful?

The answer is “Quite well, but some homework.”

✓ The exchange is not a pseudo-particle: we need pQCD
✓ Diffractive pdfs is universal within HERA

? Factorisation breaking at Tevatron – soft re-scattering
? $\sigma_{\text{diff}} / \sigma_{\text{tot}}$ flat in $W$ at HERA

⇒ need non-perturbative phenomenology

Huge effort in building the theoretical framework

□ Experiments should provide data to “distinguish” models