Diffraction and forward physics: from HERA to LHC

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Aims of this talk

▶ point out and connect physics issues at HERA and at LHC
▶ remark on status of theory and phenomenology

...will include some criticism. This is not meant to denigrate existing work, but to trigger discussion and, hopefully, progress

1. Leading protons and rapidity gaps

2. Saturation and the dipole formalism

Special thanks to D. Ivanov and L. Motyka for discussions
Central exclusive production at LHC

\[ pp \rightarrow p + X + p \]

- SM channels:
  \[ X = \text{jets}, \gamma\gamma, \text{SM Higgs} \]

- beyond SM: any system with strong coupling to \( gg \)
  \[ X = H, h \text{ esp. SUSY at large } \tan \beta \]
  see e.g. S. Heinemeyer et al, arXiv:0708.3052

\[ X = \tilde{g}\tilde{g} \text{ longlived gluions} \]
  P. Bussey et al, hep-ph/0607264

main physics motivation: Higgs and beyond SM
study \( X \) in a clean environment

- precise measurement of \( M \) (and possibly of \( \Gamma \))
- filters out \( CP = ++ \) states

→ talks by M. Taševski, J. Forshaw, B. Cox, ...
Central exclusive production at LHC

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main physics motivation: Higgs and beyond SM

study \( X \) in a clean environment

- if get “effective \( pp \rightarrow p + gg + p \) lumi” from SM channels
  then measure
  \[ \frac{\Gamma(X \rightarrow gg) \Gamma(X \rightarrow \text{final state})}{\Gamma_{\text{tot}}(X)} \]

→ talks by M. Taševski, J. Forshaw, B. Cox, …
Leading protons and rapidity gaps

- typically lower backgrounds
- lower rate

input from theory and HERA data

- rate estimate (before measured at LHC)
- control backgrounds (→ selection cuts, triggers)
  e.g. extra radiation if $X \rightarrow$ colored particles as in $H \rightarrow b\bar{b}$
Elements of theory description

- no all-order factorization proof
  - partial NLO corrections  
  - Sudakov logarithms important
  - rescattering corrections (gap survival)

HERA input: generalized gluon distribution

- $J/\Psi$ production (theoretically quite clean, high rate)
- DVCS (very good theory control, lower rate)
Elements of theory description

![Diagram of proton interaction](image)

- no all-order factorization proof
  - partial NLO corrections
    - [V. Khoze et al](#)
  - Sudakov logarithms important
  - rescattering corrections (gap survival)

**HERA input:** generalized gluon distribution

- $J/\Psi$ production (theoretically quite clean, high rate)
- DVCS (very good theory control, lower rate)
- $\Upsilon$ production theoretically very clean (large mass scale) but limited rate at HERA
  - study $\gamma p \rightarrow \Upsilon p$ in $pp$ or $pA$ at LHC
    - motivation: proton structure from GPDs
    - also: perturbative odderon in $pp \rightarrow p\Upsilon p$, $pp \rightarrow pJ/\Psi p$

→ talks by L. Motyka, J. Nystrand, L. Favart, J. Malka
theory remarks

- different GPD formalisms:
  - integrated/collinear GPDs $H^g(x, \xi, t; \mu)$
    → factorization theorems, NLO corrections, NNLO for DVCS
  - $k_T$ dependent/unintegrated $f^g(x, \xi, t, k_T^2; \mu)$
    only partial NLO

- calculation in collinear framework:
  - for vector meson prod’n NLO corrections huge
  - problem not easily fixed by choice of factorization scale
    D.Yu. Ivanov et al. '04; M.D. and W. Kugler '07
  - resummation of small-$x$ logarithms in BFKL framework
    D.Yu. Ivanov and A. Papa, in progress
theory remarks

- different GPD formalisms:
  - integrated/collinear GPDs \( H^g(x, \xi, t; \mu) \)
    \( \rightarrow \) factorization theorems, NLO corrections, NNLO for DVCS
  - \( k_T \) dependent/unintegrated \( f^g(x, \xi, t, k_T^2; \mu) \)
    only partial NLO

- for diffractive Higgs need \( k_T \) dependent GPDs
  schematically have:

\[
\begin{align*}
\text{ep and } \gamma p \text{ reactions: } & \int \frac{d k_T^2}{k_T^2} f^g(x, \xi, k_T^2; \mu) = H^g(x, \xi, t; \mu) \\
\text{central exclusive prod'n: } & \int \frac{d k_T^2}{k_T^4} f^g(x_1, \xi_2, t_1, k_T^2; \mu) f^g(x_2, \xi_2, t_2, k_T^2; \mu) \\
\end{align*}
\]
Rescattering corrections: gap survival probability

▶ assumption in current models: (quasi) elastic rescattering independent of hard scattering part

\[ \text{gap survival factor: } \sigma = \sigma_{\text{hard}} \otimes |S|^2 \]

input from (quasi) elastic \( pp \) scattering
Rescattering corrections: gap survival probability

▶ assumption in current models: (quasi) elastic rescattering independent of hard scattering part

\[ \sigma = \sigma_{\text{hard}} \otimes |S|^2 \]

input from (quasi) elastic \( pp \) scattering

▶ more complicated rescattering mechanisms

connection with multiple scattering

Bartels, Bondarenko, Kutak, Motyka ’06

\[ \rightsquigarrow \text{test rescattering models} \]
Testing rescattering models

various possible channels in $pp$ and $p\bar{p}$:
- inclusive hard diffraction with one or two rap. gaps
- central exclusive production

▶ HERA input:
  - diffractive parton densities, generalized parton dist’s
▶ compare with Tevatron data:
  - several inclusive channels e.g. $\bar{p}p \rightarrow \bar{p} + \text{dijet} + X$
  - exclusive dijets $\bar{p}p \rightarrow \bar{p} + \text{dijet} + p$
  - diphotons $\bar{p}p \rightarrow \bar{p} + \gamma\gamma + p$

→ talks K. Goulianos, J. Pinfold

▶ possible measurements at LHC

→ talk V. Khoze
Testing rescattering models

various possible channels in $pp$ and $p\bar{p}$:
- inclusive hard diffraction with one or two rap. gaps
- central exclusive production

▶ HERA input:
  diffractive parton densities, generalized parton dist’s
▶ rescattering at HERA $\leadsto \gamma p$ diffraction
  tricky theory issues resolved vs. direct $\gamma$ ambiguous beyond LO

data situation: wait for talks

W. Slominski, K. Cerny
Parton saturation

nonlinear effects when parton densities become large
breakdown of DGLAP formalism

relevance:

▶ nonlin. eff. would limit precision of PDF extractions at HERA

study by Bartels, Golec-Biernat, Peters using GBW dipole model
at $Q^2 = 5 \text{ GeV}^2$ and $x_B = 2.5 \times 10^{-4}$ found

$$\frac{F_2^{\text{full}}}{F_2^{\text{twist}}} \approx 0.94$$

$$\frac{F_L^{\text{full}}}{F_L^{\text{twist}}} \approx 0.66$$

calls for an update

▶ of interest by itself: strongly coupled theory at small $\alpha_s$
Parton saturation

nonlinear effects when parton densities become large
breakdown of DGLAP formalism

possible studies at LHC:

- forward processes
  esp. Drell-Yan: formulation in dipole picture
  Kopeliovich et al. ’95, ’98; Brodsky et al. ’96
  Gelis, Jalilian-Marian ’02
  precise DGLAP “baseline predictions” (NNLO)

- continuation of HERA studies at higher energy: \( \gamma p \rightarrow J/\Psi p \)

- heavy-ion collisions: RHIC and LHC
Theoretical framework: color dipole formalism

description of

- inclusive DIS: $F_2$, $F_2^{c\bar{c}}$, $F_L$
- inclusive diffraction: $F_2^D$, $F_L^D$

  diffract. $q\bar{q}$ state simple, $q\bar{q}g$ more complicated

- exclusive channels: DVCS, $J/\Psi$, $\Upsilon$, $\rho$, $\phi$, $\omega$

with same non-perturbative input: dipole scatt. amp. $N(x, r, b)$

  plus meson wave function for $\rho$, $\phi$, $\omega$
Theoretical framework: color dipole formalism

description of

- inclusive DIS: $F_2$, $F_2^{cc}$, $F_L$
- inclusive diffraction: $F_2^D$, $F_L^D$

  diffract. $q\bar{q}$ state simple, $q\bar{q}g$ more complicated

- exclusive channels: DVCS, $J/\Psi$, $\Upsilon$, $\rho$, $\phi$, $\omega$

with same non-perturbative input: dipole scatt. amp. $N(x, r, b)$

but: formalism essentially at LO

- $\gamma^* \to q\bar{q}$, but not $\gamma^* \to q\bar{q}g$ in general
- $x$ dependence of $\sigma_{\text{dip}}$ in principle from theory
  evolution equations: BFKL, Balitsky-Kovchegov, . . .
  in practice fitted to data

- appropriate energy variable of $\sigma_{\text{dip}}$: $x_B$, $W^2$, . . .?
- skewness factor in dipole formalism?

outstanding task: cast NLO BFKL into dipole form
Evidence for saturation effects at HERA?

- successful dipole models with and without saturation in $\sigma_{\text{dip}}$
  
  Forshaw, Sandapen, Shaw ’06; talk G. Watt

NB: at very low $Q^2$ become sensitive to non-perturb. effects in $\gamma^*$ wave function $\rightarrow$ stronger model dependence

- recent estimates of $Q_s^2(x)$ at $b = 0$

| $x$ | $Q^2$ (GeV$^2$) | Ref.                                             |
|-----|-----------------|-------------------------------------------------|
| $10^{-4}$ | 0.6 1.0         | G. Watt, arXiv:0712.2670                        |
| $10^{-6}$ | 0.7 1.9         | G. Soyez, arXiv:0705.3672                       |
| 0.8   | 4.0             | H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272 |
| 0.8   | 2.0             | K. Golec-Biernat, S. Sapeta, hep-ph/0607276     |

numbers read off from graphs

$\sim$ at HERA must go to rather low $Q^2$
Evidence for saturation effects at HERA?

- successful dipole models with and without saturation in $\sigma_{\text{dip}}$
  
  Forshaw, Sandapen, Shaw ’06; talk G. Watt
  
  NB: at very low $Q^2$ become sensitive to non-perturb. effects in $\gamma^*$ wave function $\rightarrow$ stronger model dependence
  
- provides natural explanation why $F_2^{D}/F_2$ flat in $x$ (at given $Q^2$ and $\beta$)
  
  K. Golec-Biernat, M. Wüsthoff, '99 $\rightarrow$ plot calls for an update
Geometric scaling

\[ \sigma_{\text{tot}}(x, Q^2) = \sigma(\tau) \quad \text{with} \quad \tau = \tau(x, Q^2) \]

various forms of \( \tau(x, Q^2) \) from different evolution eqs.

\[
\ln \tau = \ln \left( \frac{Q^2}{Q_0^2} \right) - \lambda \ln \left( \frac{x_0}{x} \right)
\]

\[
\ln \tau = \ln \left( \frac{Q^2}{Q_0^2} \right) - \lambda \sqrt{\ln \left( \frac{x_0}{x} \right)}
\]

and other forms \hspace{1cm} \text{cf. e.g. G. Boef et al, arXiv:0803.2186}

\[ \text{seen in wide range of HERA small-}x \text{ data} \]

\[ \text{also for diffractive channels} \quad \text{C. Marquet, L. Schoeffel '06} \]

\[ \text{requires inclusion of } b \text{ dependence, assumption of VM wave fcts.} \]
Geometric scaling

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seen in wide range of HERA small-\( x \) data

NB: restricted lever arm

F. Caola, S. Forte, arXiv:0802.1878
Geometric scaling

- naturally emerges in dipole formulation for deeply saturated regime
  \[ 1/x \to \infty \text{ at fixed } Q^2 \]
  but also find approx. scaling from BFKL and DGLAP eqs.
  Iancu, Itakura, McLerran ’02; Kwieciński, Staśto ’02
  Avsar, Gustafson ’07, Caola, Forte ’08

NB: even \( \sigma_{\text{tot}} = \sigma_0 x^{-\lambda} Q^{2(1-\gamma)} \) satisfies geom. sc.

- if want to probe saturation then should restrict to \( x, Q^2 \)
  where expect nonlin. effects
  \[ \sim \text{ low } Q^2 \text{ but at very low } Q^2 \text{ uncertainties from } \gamma^* \text{ wave fct.} \]

- for precision should subtract charm contrib’n from \( F_2 \),
  which does not scale except if \( Q^2 \to Q^2 + n m_c^2 \) with \( n \geq 4 \)
Geometric scaling

- naturally emerges in dipole formulation for deeply saturated regime \( \frac{1}{x} \to \infty \) at fixed \( Q^2 \)

but also find approx. scaling from BFKL and DGLAP eqs.

Iancu, Itakura, McLerran '02; Kwieciński, Stasto '02
Avsar, Gustafson '07, Caola, Forte '08

NB: even \( \sigma_{tot} = \sigma_0 x^{-\lambda} Q^{2(1-\gamma)} \) satisfies geom. sc.

- if want to probe saturation then need change in paradigm?

(approx.) geometric scaling

\rightarrow deviations from geometric scaling

\rightarrow should be different in linear and nonlinear regimes

\rightarrow can theory quantify this sufficiently?

\rightarrow can HERA data distinguish?

\leadsto kinematic lever arm, precision of data
No summary

► diffraction is among the highlight results of HERA should yield interesting physics at LHC

► there are several open ends, both for theory and measurement

⇝ I look forward to a fruitful meeting