Physics at HERA

Summer Student Lectures
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Overview Part 2

- High $Q^2$ and Electroweak Physics
- Polarization
- Exotics
- Jet Physics
- Heavy Quarks
- Diffraction

personal selection!
many more analyses are done!
High $Q^2$ & Electroweak Physics
More Structure Functions

\[ F_L = F_2 - 2xF_1 = 0 \] in the QPM

\[
\frac{d^2 \sigma_{NC}^\pm}{dx \, dQ^2} = \frac{2 \pi \alpha^2}{Q^4} \frac{1}{x} Y + \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} \left( F_L(x, Q^2) \mp \frac{Y}{Y_+} x F_3(x, Q^2) \right) \right]
\]

\[ F_3 : y - Z^0 - \text{interference} \]

\[ Y_\pm = 1 \pm (1 - y)^2 \]

- \( F_L \) relevant only at large \( y \)
- \( F_3 \) relevant only at large \( Q^2 \), different sign for \( e^+ \) and \( e^- \)
High $Q^2$ Neutral Current

- difference between $e^+p$ and $e^-p$ only at large $Q^2 \approx M_Z^2$
- $\gamma - Z^0$ interference

$Q^2 \approx M_Z^2$

$\gamma - Z^0$ interference

$\sqrt{s} = 319$ GeV
$P_e = 0$
$y < 0.9$
High $Q^2$ Neutral Current

HERA Neutral Current at high $x$

\[ \tilde{\sigma} = \frac{x Q^4}{2 \pi \alpha^2} \frac{1}{Y} \frac{d^2 \sigma_{NC}^\pm}{dx dQ^2} \]

- $e^-$ positive interference
- $e^+$ negative interference

\[ x F_3 \propto x \sum e_q^2 (q - \bar{q}) \]

direct handle on valence quark distribution!
high $Q^2$ NC DIS allows the determination of the vector and axial-vector couplings of up- and down-type quarks to the $Z^0$
Charged Current Interactions

CC: $Q^2 = 83656 \text{ GeV}^2; y=0.83; P_T=118$

neutrino not visible in detector

imbalance in transverse plane
Charged Current Cross Section

\[\frac{d^2 \sigma^{\pm}_{CC}}{dx \, dQ^2} = \frac{G_F^2}{4 \pi x} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ W^2_+ - \frac{y^2}{Y_+} W^2_- + \frac{Y_-}{Y_+} x W^2_3 \right] \]

- \( W \) bosons couple differently to \textit{up}- and \textit{down}-type quarks
- in the QPM:
  \[ W^-_2 = x (U + D), \quad x W^-_3 = x (U - D) \]
  \[ W^+_2 = x (U + D), \quad x W^+_3 = x (D - U) \]
  \[ W^+_L = 0 \]
  \[ \Rightarrow \sigma^-_{CC} \propto x \left[ U + (1 - y)^2 D \right] \]
  \[ \sigma^+_{CC} \propto x \left[ U + (1 - y)^2 D \right] \]
Comparison NC vs. CC

- at low $Q^2$: different dependences because of photon in NC

- at high $Q^2 \approx M_Z^2$: „electroweak unification“: electromagnetic and weak interactions have similar strength
Polarization
Polarization @ HERA

\[ P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}} \]

- transverse polarization builds up in \(~40\) minutes through synchrotron radiation (Sokolov-Ternov effect)
- spin rotators flip transverse \rightarrow \text{longitudinal} before experiments and back after
Polarization @ HERA

spin rotator
CC & Polarization

- CC cross section depends on longitudinal electron/positron polarization $P_e$

$$\frac{d^2 \sigma_{CC}^\pm}{dx \, dQ^2}(P_e) \approx (1 \pm P_e) \frac{G_F^2}{4 \pi x} \cdot \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \cdot Y + W^\pm$$

- reason: $W$ boson couples only to left-handed (LH) particles and right-handed (RH) antiparticles:
CC: Polarization Dependence

- **Standard Modell expectation:**
  \[ \sigma^{-}_{CC}(P_{e}=+1) = 0 \]
  \[ \sigma^{+}_{CC}(P_{e}=-1) = 0 \]

- **experimental result: (H1)**
  \[ \sigma^{-}_{CC}(+1) = -0.9 \pm 2.9_{\text{stat}} \pm 1.9_{\text{syst}} \pm 1.9_{\text{pol}} \text{ pb} \]
  \[ \sigma^{+}_{CC}(-1) = -3.9 \pm 2.3_{\text{stat}} \pm 0.7_{\text{syst}} \pm 0.8_{\text{pol}} \text{ pb} \]
Exotics or Beyond the Standard Model
New Particles

many theories predict more particles than the SM:

• SUSY

• leptoquarks
  – particle with lepton and quark properties
  – can be produced resonantly in $ep$ collisions

• ... exited fermions, contact interactions, large extradimensions ...

but experimentally search also model-independent!
Leptoquarks

- can look the same as NC or CC process
- $M_{LQ}^2 = (xP + k)^2 = xs$
- compare measured cross section with SM expectation
- derive limits on coupling $\lambda$

$\lambda$ \hspace{1cm} $\lambda$
\hline
\hline
$e, \nu, (\mu)$ \hspace{1cm} $e, \nu, (\mu)$
\hline
\hline
$k$ \hspace{1cm} $k$
\hline
\hline
$q, q'$ \hspace{1cm} $q, q'$
Contact Interactions

- New interactions at higher scale ($\Lambda >> \sqrt{s}$) can be effectively described at lower energies as 4-fermion $eeqq$ Contact Interactions
- Reminder: before $W$ and $Z^0$ were discovered, weak interactions ($\Lambda \approx M_W$) were described as 4-fermion Contact Interactions with Fermi constant $G_F = g^2/M^2_W$
  - Contact Interactions would modify the DIS cross section
Contact Interactions

- No sign for Contact Interactions found
- masses much larger than $\sqrt{s}$ excluded

Zeus (94-05) $e^p$
- $\Lambda^- = 8.0 \text{ TeV}$
- $\Lambda^+ = 8.9 \text{ TeV}$

Zeus (94-07) $e^p$
- $\Lambda^- = 7.0 \text{ TeV}$
- $\Lambda^+ = 6.7 \text{ TeV}$

Zeus (94-06) $e^p$
- $\Lambda^- = 6.0 \text{ TeV}$
- $\Lambda^+ = 8.9 \text{ TeV}$

Zeus (94-07) $e^p$
- $\Lambda^- = 5.6 \text{ TeV}$
- $\Lambda^+ = 6.6 \text{ TeV}$

Zeus (94-07) $e^p$
- $\Lambda^- = 5.7 \text{ TeV}$
- $\Lambda^+ = 7.5 \text{ TeV}$
Quark Radius

- if quarks have a size, a quark Form Factor would modify the NC cross section at high $Q^2$
- limit on quark size: $< 0.6 \cdot 10^{-18}$ m
Isolated Leptons and Missing $P_T$  

- spectacular events
- excess in HERA1 data at large transverse momenta of the hadronic system ($P_T^X$) seen by H1
Isolated Leptons and Missing $P_T$

- no excess in $e^-$ data
- $e^+$: H1+ZEUS combined: 1.9 $\sigma$ excess
- H1 alone: 2.4 $\sigma$ excess

<table>
<thead>
<tr>
<th>H1+ZEUS</th>
<th>Data</th>
<th>SM Expectation</th>
</tr>
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<tbody>
<tr>
<td>1994–2007 $e^+p$ 0.59 fb$^{-1}$</td>
<td>53 49.8 $\pm$ 6.2</td>
<td></td>
</tr>
<tr>
<td>Combined $P_T^X &gt; 25$ GeV</td>
<td>23 14.0 $\pm$ 1.9</td>
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Jet Physics & the Strong Coupling $\alpha_s$
What are Jets?

- jets are narrow bundles of hadrons originating from quarks or gluons
- can be used to study QCD and the strong coupling
How Are Jets Produced?

- do analysis in a frame where photon and proton collide head-on (e.g. Breit frame)

→ LO DIS cannot produce transverse momentum

→ jets with transverse momentum can originate from boson-gluon fusion (BGF) or QCD-Compton (QCDC) processes
Jet Cross Sections

- theory curve:
  - NLO QCD calculation
  - PDFs
  - $\alpha_s$
  - hadronisation

- very good agreement of theory and data, PDFs extracted from $F_2$ describe jet prod.

- uncertainty on PDF and theory input leads to uncertainty on $\alpha_s$
$\alpha_s$ from Jets

- running of $\alpha_s$ visible in one experiment
- theory uncertainties larger than experimental uncertainties
HERA measurements often dominated by systematic and theoretical uncertainties

→ HERA value very competitive
Improved Parton Densities

- $F_2$ is only indirectly sensitive to the gluon

$\Rightarrow$ global fits (MRST, CTEQ) use Tevatron jet data

$\Rightarrow$ alternative: use HERA (di-)jet data

![Diagram showing gluon fractional error at different $Q^2$ values]

improvement at medium to large $x$
Heavy Quarks
Production of Heavy Quarks

predominantly via boson gluon fusion

large quark mass allows pQCD calculations
directly sensitive to gluon density in the proton

heavy quark contribution to structure function

\[
\frac{d^2 \sigma^{b\bar{b}}}{dx \, dQ^2} = \frac{2 \pi \alpha_s^2}{x \, Q^4} Y_+ \left[ F_2^{b\bar{b}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x, Q^2) \right]
\]
charm Signals

**ZEUS**

(a) 
- ZEUS (82 pb$^{-1}$)
- $D^0$
- Gauss$^{mod}$ + Backgr.

Without $\Delta M$ tag
Reflection subtracted

$1.5 < Q^2 < 1000$ GeV$^2$
$0.02 < y < 0.7$
$p_T(D^0) > 3$ GeV
$|\eta(D^0)| < 1.6$

$N^{integ}(D^0) = 7996 \pm 488$

(b) 
- ZEUS (82 pb$^{-1}$)
- $D^\pm$

$p_T(D_s^\pm) > 2$ GeV

$N(D_s^\pm) = 773 \pm 96$
Tagging of *beauty* Quarks

- large transverse momenta due to large mass
- semileptonic decay
- long lifetime (*beauty* ~500 µm, *charm* ~100-300 µm)
charm contribution to $F_2$

- good experimental precision by combining measurements with different methods
- charm data in agreement with predictions with PDF from $F_2$
Contribution to the Cross Section

- large charm fraction (up to ~30%)
- small beauty fraction (‰ to few %)
- charm and beauty thresholds
- reasonable description by theory
Diffraction
What is Diffraction?

- in general: in DIS events the proton breaks up
- in diffraction: the proton stays intact
  (but nevertheless $W>M_P$)

**surprise:** ~10% of all events at HERA are diffractive!
Diffraction

- idea: interaction between photon and proton by a „Pomeron“
  - colourless
  - already used to describe low energy hadron-hadron scattering
  - no particle!
Physics in Diffraction

• many things similar to inclusive DIS
  – diffractive parton densities
  – jets in diffraction
  – heavy flavour in diffraction

• test of factorization
  – are the parton densities the same for all diffractive processes?
  – or: does the Pomeron know what happens at the photon vertex?
Diffractive Parton Densities

Singlet = Quark

H1 2006 DPDF Fit A
- (exp. error)
- (exp.+theor. error)

H1 2006 DPDF Fit B
- (exp.+theor. error)
Diffractive Dijet Cross Sections

- shape of the QCD theory prediction agrees with the data
- normalization is wrong
  → factorization broken?!
Summary

- HERA offered unique possibilities to study the structure of the proton
- perturbative QCD is a big success to describe HERA data
- no significant deviation from the Standard Model found
- always prepare for the unexpected!