Recent results from HERA

Robert Ciesielski

Seminarium Zakladowe, Warszawa, 13 Listopad 2009
Outline

- Introduction to HERA and DIS
- Inclusive measurements and proton structure
- Exotic searches

... including results from first H1 and ZEUS combined analyses!

Will not cover:
Jets and Hadronic Final States, Heavy Flavours Production, Diffraction
(selected material in backup slides)
First H1-ZEUS Papers and more...

NEW for this PRC: first three H1-ZEUS papers

1. “Multi-leptons with High-Transverse Momentum at HERA”

2. “Events with an Isolated lepton and Missing Transverse Momentum and Measurement of W production at HERA”
   - arXiv:0911.0858, submitted to JHEP

3. “Combined Measurement and QCD Analysis of the inclusive ep Scattering Cross-Sections at HERA”
   - arXiv:0911.0884, submitted to JHEP

NEW for this PRC: Preliminary H1-ZEUS combined $F_2^{(charm)}$ results
HERA operation

World's only ep collider, located at DESY Hamburg.
Ended in June 2007, after 15 years of successful running.
Two colliding experiments: H1 and ZEUS.

\[ \sqrt{s} = 318 \text{ GeV} \]

p (820/920 GeV)  e (27.5 GeV)

\[ L \sim 0.5 \text{ fb}^{-1} \] per experiment

HERA I (1994-2000)
\[ L \approx 120 \text{ pb}^{-1} \] collected per experiment.
Mostly e^+p.

HERA II (2002-2007)
\[ L \approx 360 \text{ pb}^{-1} \] collected per experiment.
Similar amount of e^+p and e^-p.
Longitudinal polarisation of lepton beam (P=0.3-0.4).

L. Ciesielski, Recent Results from HERA 13/Nov/2009
H1 and ZEUS detectors

Fine-grained LAr calorimeter:
\[ \sigma_E/E = 12\% / \sqrt{E} \pm 1\% \text{ (ele)} \]
\[ \sigma_E/E = 55\% / \sqrt{E} \pm 1\% \text{ (had)} \]

Backward lead-scintillator calorimeter:
\[ \sigma_E/E = 7\% / \sqrt{E} \pm 1\% \text{ (ele)} \]

Uranium-scintillator calorimeter:
\[ \sigma_E/E = 18\% / \sqrt{E} \text{ (ele)} \]
\[ \sigma_E/E = 35\% / \sqrt{E} \text{ (had)} \]
**Deep Inelastic Scattering at HERA (1)**

**Two processes:**
- **Neutral Current (NC)** - exchange $\gamma$ and $Z^0$ \( (e^\pm p \rightarrow e^\pm X) \)
- **Charged Current (CC)** - exchange of $W^\pm$ \( (e^\pm p \rightarrow \nu X) \)

\[
Q^2 = -q^2 = (k - k')^2 \\
x = \frac{Q^2}{2p \cdot q} \\
y = \frac{p \cdot q}{p \cdot k} \\
Q^2 = s \cdot x \cdot y \\
s = (p + q)^2
\]

**Kinematic range:** \( 0 \) (photoproduction) \(< Q^2 < 40000 \text{ GeV}^2 \), \( x > 10^{-6} \)
Deep Inelastic Scattering at HERA (2)

Event selection based on:

**NC DIS**
- scattered electron

**CC DIS**
- missing $p_T$

R. Ciesielski, Recent Results from HERA  
13/Nov/2009
Deep Inelastic Scattering at HERA (3)

\[
\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dq^2} = \frac{2 \pi \alpha^2}{x q^4} \left[ Y_+ F_2(x, Q^2) + Y_- x F_3(x, Q^2) - y^2 F_L(x, Q^2) \right]
\]

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

\[F_2 \propto x \sum (q + \bar{q})\]
\[xF_3 \propto 2x \sum (q - \bar{q})\]
\[F_L \propto \alpha_s \cdot x g(x, Q^2)\]

**dominant contribution**

**only sensitive at high \(Q^2\)** (\(\gamma-Z\) interference)

**important at high \(y\)**

Similarly for CC: \(W^2\), \(xW^3\), \(W_L\)

(CC purely weak, \(xW^3\) contributes over full phase space)

\(F_2\) measured with HERA I data

\(xF_3, F_L\) – with HERA II data
HERA I Data
Low and Medium-$Q^2$ NC cross sections, $F_2$

Recently H1 measured the NC cross sections using HERA I data taken at $E_p = 920$ GeV and combined them with HERA I published results at $E_p = 820$ GeV. → H1 “final” low and medium $Q^2$ results.
History of H1 $F_2$ Measurements

- Total measurement uncertainties have been reduced to $\sim 1.3 - 2\%$ in the medium $Q^2$ domain
- At lower $Q^2$ uncertainties slightly larger with $\sim 2\%$ in most of the phase space
H1+ZEUS combined HERA I cross sections

Significantly reduced experimental uncertainties compared to the separate analyses of the ZEUS and H1 experiments. (experiments cross calibrate each other).

Complete set of published inclusive NC/CC HERA-I DIS data (1994-2000, L=240 pb$^{-1}$)

- 1400 data points, spanning 6 order of magnitude in $x$ and $Q^2$.
- 110 syst. error sources

Data show good consistency:
- $\chi^2$/ndf = 637/656
- small shifts of global normalisation.
- pull distributions are OK.
H1+ZEUS combined HERA I cross sections

1-2% precision in the medium $Q^2$ region.
New standard HERA data input for future DGLAP analyses!
NLO QCD fit to combined HERA I data

HERAPDF1.0

Parametrisation in $x$ at $Q^2 = 1.9$ GeV$^2$ and DGLAP evolution in $Q^2$.

H1 and ZEUS

$Q^2 = 10$ GeV$^2$

$x f = 1$

- HERAPDF1.0
- exp. uncert.
- model uncert.
- parametrization uncert.

$x g (\times 0.05)$

$x S (\times 0.05)$

$x u_f$

$x d_f$

Detailed study of the PDFs uncertainties.

Much increased precision for sea quarks and gluons.

They are < 2% at the scale relevant for Z/W production at the LHC.
**HERAPDF1.0**

### CTEQ6.6

\[ Q^2 = 10 \text{ GeV}^2 \]

Sea and Gluon densities much better determined for \( x < 10^{-2} \)

### MSTW08

\[ Q^2 = 10 \text{ GeV}^2 \]
HERA and the LHC

Centrally produced 100 GeV object

\[ x \sim 10^{-2}, \ Q^2 \sim 10000 \ \text{GeV}^2 \]
Single W Production at LHC

A. Cooper-Sarkar
E. Perez
Presented at HERA and the LHC
26 – 28 May 2008

Uncertainties \(\sim 3\%\)
HERA II Data
High-\(Q^2\) NC and CC cross sections

\[
\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dQ^2} = \frac{2 \pi \alpha^2}{xQ^4} [Y_+ F_2(x, Q^2) \mp Y_- x F_3(x, Q^2)]
\]

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

\[d^2 \sigma^{NC}(e^\pm p) = 2 x Q^4 \left[ Y_+ F_2(x, Q^2) \mp x Y_- F_3(x, Q^2) \right] \]

\[d^2 \sigma^{NC}(e^\mp p) = \frac{2 \pi \alpha^2}{xQ^4} [Y_+ F_2(x, Q^2) \mp x Y_- F_3(x, Q^2)]
\]

EW effects enhanced with polarised lepton beam.

R. Ciesielski, Recent Results from HERA 13/Nov/2009
Polarisation Effects in NC

Polarisation effects are subtle in NC DIS

Reduced cross section: $\sigma_{NC}(e^\pm p) \sim Y_+ F_2 \mp Y_- xF_3$

$F_2(\pm Pe) = F_2^\gamma - (v_e \pm Pe a_e) \kappa Z F_2^\gamma + ((v_e^2 + a_e^2) \pm Pe 2v_e a_e) \kappa Z^2 F_2^Z$

$xF_3(\pm Pe) = - (a_e \pm Pe v_e) \kappa Z xF_3^\gamma + (2v_e a_e \pm Pe (v_e^2 + a_e^2)) \kappa Z^2 xF_3^Z$

Weak parity violating effect though $\gamma Z$ interference and pure $Z \rightarrow$ high $Q_2$ only

$\gamma Z$ dominates (pure $Z$ suppressed by additional propagator i.e. $\kappa Z >> \kappa Z^2$ and $v_e \approx 0.04$)
**Polarisation Effects in NC**

### Reduced cross section:

$$\sigma_{\text{NC}}(e^\pm p) \sim Y_+ F_2 \mp Y_- xF_3$$

$$F_2(\pm Pe) = F_2^\gamma - (v_e \pm Pe a_e) \kappa_Z F_2^{\gamma Z} + \frac{1}{2} (v_e^2 + a_e^2) \kappa_Z^2 F_2^Z$$

$$xF_3(\pm Pe) = - (a_e \pm Pe v_e) \kappa_Z xF_3^{\gamma Z} + \frac{1}{2} (v_e^2 + a_e^2) \kappa_Z^2 xF_3^Z$$

### Weak parity violating effect though $\gamma Z$ interference and pure $Z$ \rightarrow high $Q^2$ only

$\gamma Z$ dominates (pure $Z$ suppressed by additional propagator i.e. $\kappa_Z \gg \kappa_Z^2$ and $v_e \approx 0.04$)

### EW structure functions in QPM ($\gamma Z$):

$$F_2^\gamma, F_2^{\gamma Z} = x \sum (e_q^2, 2 e_q v_q)(q + \bar{q})$$

$$xF_3^{\gamma Z} = 2x \sum e_q a_q (q - \bar{q})$$

### Unpolarised:

$$\sigma(e^+ p) - \sigma(e^- p) \rightarrow xF_3^{\gamma Z}$$

### Polarised:

$$\sigma(P_R) - \sigma(P_L) \rightarrow F_2^{\gamma Z}$$
Unpolarised NC Cross Sections, $x F_3$

\[ \tilde{\sigma}^{\pm p} = \frac{x Q^4}{2 \pi \alpha^2 Y_+} \frac{1}{dx dQ^2} = \tilde{F}_2(x, Q^2) = \frac{Y_-}{Y_+} x \tilde{F}_3(x, Q^2) \]

\[ x \tilde{F}_3 = \frac{Y_+}{2Y_-} (\tilde{\sigma}^{e- p} - \tilde{\sigma}^{e+ p}) \]

Sensitivity to valence quark distributions in a region where there were no previous DIS measurements with pure proton target.
Polarised NC Cross Sections: $d^2\sigma/dxdQ^2$

\[ P_e = \frac{N_R - N_L}{N_R + N_L} \]

\[ \sigma_{NC}^{e^p} \approx F_2 + P_e a_e \chi_Z \cdot F_2^{\gamma Z} + a_e \chi_Z \cdot xF_3^{\gamma Z} \]

11/09: H1prelim-09-042, New
Clear evidence of parity violation at high $Q^2$
Polarised High-$Q^2$ CC cross sections

Total cross sections as a function of lepton beam polarisation.
Demonstration of chiral structure of the Standard Model.

Cross sections depend linearly on $P_e$, vanish for right-handed particles (left-handed antiparticles).

Weak interactions left handed.

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$
Polarised High-$Q^2$ CC cross sections

$e^+p$

Cross sections as a function of $Q^2$, $x$ and $y$ @ $P=+0.33$ and $P=-0.36$.

Scale with polarisation independently of kinematic variables.

$$\sigma_{e^+p}^{CC}(P) = (1 \pm P) \sigma_{e^+p}^{CC}(0)$$
Unpolarised CC cross sections

\[ \tilde{\sigma}(e^- p \rightarrow \nu X) = [(u+c) + (1-y)^2(\bar{d} + \bar{s})] \]

Sensitive to \( u \), quark.

\[ \tilde{\sigma}(e^+ p \rightarrow \bar{\nu} X) = [(\bar{u} + \bar{c}) + (1-y)^2(d + s)] \]

Sensitive to \( d \), quark.

Flavour decomposition

13/Nov/2009
Combined Electroweak-QCD Fits

- All these measurements are used to extract 5 PDFs \( (g, u, \bar{u}, d, \bar{d}) \) and weak couplings to \( Z^0 \) \( (a_u, a_d, \nu_u, \nu_d) \) simultaneously
  - NC: \( \gamma Z \) interference / \( Z \) exchange sensitive to \( a_u a_d \) and can resolve signs of couplings
  - CC: flavor sensitivity helps to disentangle \( u, d \)-quarks
- Precision competitive with LEP and Tevatron results
- Most precise value for \( u \)-coupling to \( Z \) comes from HERA
\[ \sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2) \]

**F_L and gluons**

\( F_L \) is proportional to the longitudinally polarised photon – proton cross section.

In the QPM \( F_L = 0 \)

(Callan-Gross relation \( F_L(x) = F_2 - 2x F_1 = 0 \))

In QCD, a gluon radiation contribute to the non zero \( F_L \).

\[ F_L \propto \sigma_L = 0 \]

\[ F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} \sum_q z e_q^2 (q + \bar{q}) + 8 \sum_q e_q^2 \left( 1 - \frac{x}{z} \right) \cdot z g \right] \]

\( J_z \) conservation not possible

---

How to measure \( F_L \)?

For fixed \( x \) and \( Q^2 \) need different \( y \).

\( Q^2 = s y \rightarrow \) need data at different \( \sqrt{s} \).
Measurement of $F_L$

NC e+p data from dedicated running periods:

**HER:** $E_p = 920$ GeV  $\sqrt{s} = 318$ GeV  $L=44.5$ pb^{-1}

**MER:** $E_p = 575$ GeV  $\sqrt{s} = 251$ GeV  $L=7.1$ pb^{-1}

**LER:** $E_p = 460$ GeV  $\sqrt{s} = 225$ GeV  $L=13.9$ pb^{-1}

Reduced cross sections measured for $20 < Q^2 < 130$ GeV$^2$ and $5 \times 10^4 < x < 0.007$
Measurement of $F_L$

Rosenbluth plots in bins of $Q^2$ and $x$.

Straight line fit to $\sigma_r$ vs $y/Y_+$. $F_2$ - intercept, $F_L$ - slope.

\[ \sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2) \]
Measurement of $F_L$ (and $F_2$)

Non zero $F_L$.

Most precise ZEUS measurement of $F_2$ in this kinematic region.

Predictions for $F_2$ and $F_L$ (ZEUS-JETS) are consistent with data.
Measurement of $F_L$

Kinematic region of H1 measurements:

$2.5 < Q^2 < 800$ GeV$^2$ and $5 \times 10^{-5} < x < 0.005$
$F_L$ vs $Q^2$

Comparison to theory predictions.

Predictions agree well with data for $Q^2 > 10$ GeV$^2$

And slightly underestimate the measurements at lower $Q^2$. (better agreement with CTEQ6.6)

$F_L$ data are expected to further constrain the low-x theory.
ZEUS Inclusive HERA II Measurements
Where are we?

NC e+p HER, MER, LER ($F_L$ meas.), published

NC e-p, published

CC e-p, published

CC e+p, preliminary, publication imminent

NC e+p, preliminary, in progress

Impact of new data $\rightarrow$ ZEUS09 NLO QCD fit
ZEUS09 NLO QCD fit

With the approach described in the ZEUS-JETS publication study the impact of new HERA II NC $e^-p$, CC $e^-p$ on PDFs.

$xu_v$ – improved by NC and CC $e^-p$ data
With the approach described in the ZEUS-JETS publication study the impact of new HERA II NC e^−p, CC e^−p and CC e^+p on PDFs

\[ Q^2 = 10 \text{ GeV}^2 \]

- \( x_u \) – improved by NC and CC e^−p data
- \( x_d \) – improved by CC e^+p data
ZEUS09 NLO QCD fit

With the approach described in the ZEUS-JETS publication study the impact of new HERA II CC $e^+p$, NC $e^p$ and NC $e^p$ HER/MER/LER data on PDFs

Consistent with ZEUS-JETS. Slightly steeper gluons at low $x$.

$xg$ ($\times 0.05$)

$xd$ ($\times 0.05$)

$xs$ ($\times 0.05$)

Further improvement of the HERA PDFs for LHC promising
Exotic Searches

- Quark radius
- Contact Interactions
- LED, Heavy Leptoquarks
- General Searches
- Multi-leptons
- Isolated leptons and missing $p_T$
- FCNC single-top production
- Excited Fermions
- Squark production in RPV SUSY

Presented results are based on full datasets, ~0.5 fb$^{-1}$ per experiment
High-$Q^2$ NC and CC Cross Sections

Main processes studied at HERA:
- Neutral Current (NC) DIS, $e p \rightarrow e X$, mediated by $\gamma$ or $Z^0$.
- Charged Current (CC) DIS, $e p \rightarrow \nu X$, mediated by $W^\pm$.

Excellent agreement between data and SM predictions over many orders of magnitude.

$Q^2$ (resolving power) up to 40000 GeV$^2$.
Spatial resolution $\sim 1/Q \approx 10^{-8}$ m = $10^{-3}$ fm.
1/1000 of proton radius.

Search for Beyond SM physics by studying processes at highest $Q^2$ and/or processes with high $p_T$ objects in the final state.
Quark Radius

If a quark has a finite size, the SM cross section is expected to decrease at higher $Q^2$. Quark form-factor (electron assumed to be point-like):

$$
\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left[ 1 - \frac{R_q^2}{6 Q^2} \right]^2
$$

$R_q$ is a root-mean-square radius of the EW charge distribution in the quark. The same dependence expected for $e^-p$ and $e^+p$.

Excellent agreement with SM expectations up to highest $Q^2$.

ZEUS: $R_q < 0.63 \times 10^3$ fm

H1: $R_q < 0.74 \times 10^3$ fm

@ 95% C.L.
Contact Interactions (CI)

Reminder:
before W and Z$^0$ were discovered, weak interactions ($\Lambda \approx M_W$) were described as 4-fermion CI with Fermi constant $G_F = g^2/M_W^2$.

New interactions at higher scale ($\Lambda \gg \sqrt{s}$) can be effectively described at lower energies as 4-fermion $eeqq$ Contact Interactions (CI).

CI modify the tree level $eq \rightarrow eq$ scattering amplitudes

$$M_{\alpha\beta}^{eq}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2\theta_W \cos^2\theta_W} \frac{g_\alpha g_\beta}{Q^2 + M_Z^2} + \eta_{\alpha\beta}^{eq}$$

Search for deviations from SM cross sections at highest $Q^2$. 

R. Ciesielski, Recent Results from HERA 13/Nov/2009
Also referred to as Compositeness Models.

Couplings $\eta_{\phi}^{eq}$ are related to the effective mass scale $\Lambda$ of new interactions:

$$\eta_{\phi}^{eq} = \frac{\epsilon g_{CI}^2}{\Lambda^2}$$

$g_{\phi}$ is a coupling strength ($g_{\phi}^2 = 4\pi$), $\epsilon = \pm 1$.

Different models assume different helicity structure of new interactions (given by set of 4 couplings $\eta_{\phi}^{eq}$)

Parity conserving models fulfill the relation:

$$\eta_{LL}^{eq} + \eta_{LR}^{eq} - \eta_{RL}^{eq} - \eta_{RR}^{eq} = 0$$

Family universality assumed.

Models conserving parity:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\eta_{LL}^{eq}$</th>
<th>$\eta_{LR}^{eq}$</th>
<th>$\eta_{RL}^{eq}$</th>
<th>$\eta_{RR}^{eq}$</th>
<th>$\eta_{LL}^{LU}$</th>
<th>$\eta_{LR}^{LU}$</th>
<th>$\eta_{RL}^{LU}$</th>
<th>$\eta_{RR}^{LU}$</th>
<th>$\eta_{LL}^{RU}$</th>
<th>$\eta_{LR}^{RU}$</th>
<th>$\eta_{RL}^{RU}$</th>
<th>$\eta_{RR}^{RU}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
</tr>
<tr>
<td>AA</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
</tr>
<tr>
<td>VA</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
</tr>
<tr>
<td>X1</td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3</td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X4</td>
<td></td>
<td>+$\eta$</td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X5</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td>-$\eta$</td>
<td></td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
</tr>
<tr>
<td>U1</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U2</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U3</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U4</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U5</td>
<td></td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Models violating parity:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\eta_{LL}$</th>
<th>$\eta_{LR}$</th>
<th>$\eta_{RL}$</th>
<th>$\eta_{RR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LR</td>
<td>+$\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL</td>
<td></td>
<td>+$\eta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR</td>
<td></td>
<td></td>
<td>+$\eta$</td>
<td></td>
</tr>
</tbody>
</table>
CI, General Models

ZEUS CI analysis based on full NC sample of $L=0.44$ fb$^{-1}$. Models with 19 different helicity structure tested.

\[ \eta_{\alpha\beta}^{eq} = \frac{\epsilon g_{CI}^2}{\Lambda^2} \]

ZEUS

Contact Interactions Limits (prel.)

\[ \Lambda > 3.8 - 8.9 \text{ TeV} @95\% \text{ C.L.} \]

R. Ciesielski, Recent Results from HERA 13/Nov/2009

\[ \pm 1/\Lambda^2 \text{ (TeV}^{-2}) \]
CI, Large Extra Dimensions

Arkani-Hamed-Dimopolous-Dvali Model

If gravity propagates in $4+\delta$ dimensions, effective Plank scale $M_S$ can be as low as 1 TeV.

Contribution of graviton exchange (Kaluza-Klein tower) to $e^+p$ NC DIS:

$$\eta_G = \frac{\lambda}{M_S^4}$$

$\lambda = \pm 1$ - coupling strength.

ZEUS: $M_S^+ > 0.94$ TeV, $M_S^- > 0.94$ TeV @ 95% C.L.

CI, heavy Leptoquarks

Buchmueller-Rueckl-Wyler Model

7 scalar, 7 vector Leptoquarks at HERA.

$\lambda$ - Yukawa LQ-\(e\)-q coupling.

$M_{LQ}/\lambda > 0.41-1.88$ TeV @95% C.L.
General Searches

Analysis based on complete set of H1 $e^\pm p$ data, $L=0.46$ fb$^{-1}$.

Model independent, generic search for final states with $\geq 2$ high-$p_T$ objects:

- $\gamma$, $e$, $\mu$, $\nu$, jet
- $p_T > 20$ GeV
- $10^\circ < \theta < 140^\circ$
- $D(\eta,\varphi) > 1$

Events counted in distinct channels, separately for $e^+p$ and $e^-p$ data.

Good agreement of event yields with SM expectations (NC, CC, photoproduction, lepton pair production, W production, QEDC).

Good understanding of detector and physics processes at HERA.

No indication for BSM physics.

All deviations compatible with statistical fluctuations (largest for $e^-e^-$ channel in $e^+p$ data).
Multileptons

- The main multi-lepton process at HERA is $\gamma\gamma$ process.
- Precise SM QED predictions, modelled with GRAPE.
- Cross section steeply falling with $p_T$, low at high masses
  $\Rightarrow$ any deviation is an indication of new phenomena, e.g. exotic resonances ($H^{\pm\pm}$).

Combined H1 and ZEUS analysis in the common phase-space, $L = \sim 1 \text{ fb}^{-1}$.

- Events selected by requiring at least 2 isolated, high-$p_T$ $e$ or $\mu$.
- Two leptons must satisfy: $20^\circ < \theta < 150^\circ$, $p_T > 15, 10 \text{ GeV}$
- Events classified into independent exclusive samples: $ee, \mu\mu, e\mu, eee, e\mu\mu, \ldots$

\textbf{eee event in H1 detector:}

\textbf{Inv. mass of highest $p_T$ leptons for $eee$, $e\mu\mu$ channel (examples):}
Multileptons

Overall good agreement with the SM.

For $\Sigma p_T > 100$ GeV:
7 events observed in $e^+p$ data, while 1.94 ± 0.17 expected (2.6 $\sigma$ significance).

Differential cross section for the $\gamma\gamma \rightarrow \ell\ell$ process measured as a function of $p_T$ of leading lepton and lepton-pair mass.

Measured total visible cross section:
0.66 ± 0.03 (stat.) ± 0.03 (sys.) pb
in agreement with the SM prediction of 0.69±0.02 pb (GRAPE).
Isolated Leptons & missing $p_T$

The main corresponding SM process is single $W$ production. Modelled with EPVEC (NLO corr., ~15% unc.).

- Rare process, $\sigma \sim 1.3$ pb.
- Search for new phenomena (e.g. anomalous single-top production, bosonic stop decay).

Combined H1 and ZEUS analysis in the common phase-space, $L = \sim 1$ fb$^{-1}$.

- isolated high-$p_T$ $e$ or $\mu$ ($p_T > 10$ GeV, $15 < \theta < 120$)
- missing $p_T$ ($p_T^{\text{miss}} > 12$ GeV)
- hadronic system $p_T^X$.

High purity (75%) of $W$ production, clear jacobian peak.
Overall good agreement with the SM.

For $p_T^X > 25$ GeV:
23 events observed in $e^+p$ data, while $14.02 \pm 1.94$ expected (1.9 $\sigma$ significance).

Differential cross section for W production extracted as a function of hadronic transverse momentum $p_T^X$.

Branching ratio of W leptonic decays (~10 %) used to measure full W production cross section.

Measured total single W production cross section:

\[ 1.07 \pm 0.16 \text{ (stat.)} \pm 0.08 \text{ (sys.)} \text{ pb} \]

in agreement with the SM prediction of \( 1.26 \pm 0.19 \text{ pb} \) (EPVEC).
Anomalous single-top production

- The SM single-top production negligible at HERA ($\sigma < 1 \text{ fb}$).
- FCNC single-top production predicted by several BSM theories.
- At HERA sensitivity to anomalous $t-u-\gamma$ and $t-u-Z$ couplings.

Search for $t \rightarrow bW$, with $W \rightarrow \ell\nu$: topology as for isolated lepton and missing $p_T$ but higher $p_T^{\ell'}$ (b jet)

$W \rightarrow q\bar{q}: 3$ jets

H1 analysis based on full dataset ($L=0.47 \text{ fb}^{-1}$)

No significant excess in the signal region.
Set limits on anomalous $\kappa_{uy}$ coupling ($V_{uZ}=0$).
HERA limits on $\kappa_{uy}$ most stringent.

R. Ciesielski, Recent Results from HERA 13/Nov/2009
Excited Fermions

Excited fermions would be a signature for compositeness. Explanation of 3 lepton families and mass hierarchy.

Effective lagrangian (Hagiwara et al.):

\[
\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{R} \gamma_{\mu} \gamma_{\nu} \left[ g f Y + g f' \frac{Y'}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a \right] L
\]

\[SU(2) \quad U(1) \quad SU(3)\]

\[
\begin{align*}
\text{Decay to standard fermions and gauge bosons:} & \quad f^* \rightarrow f + \gamma, Z, W \\
\text{with} \ Z & \rightarrow e e, \tau \tau, \text{qq and} \ W & \rightarrow e \nu, \mu \nu, \text{qq}'.
\end{align*}
\]

Variety of experimental signatures: isolated leptons, missing p_T, \gamma, jets.

H1 analysis based on full dataset (L=0.47 fb^{-1}). 80%-90% of decay channels looked at.
Excited Fermions

No deviation from SM observed. Limits set on $f/\Lambda$ ratio (95% C.L.).

$f/\Lambda$ limits can be translated into mass limits assuming $f/\Lambda = 1/M^*$:

- $M_{e^*} > 272$ GeV
- $M_{\nu^*} > 213$ GeV
- $M_{q^*} > 252$ GeV  (for $f_s = 0$, HERA unique)

Best sensitivity achieved for masses beyond LEP reach.
Squark Production in RPV SUSY

R parity: \( R_p = (-1)^{\text{BLM}} \)
(+1 for SM, -1 for SUSY particles)

\[ W_R = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \]

- \( L \): left-handed (s)leptons,
- \( Q \): left-handed (s)quarks,
- \( D \): right-handed down-type (s)quarks

\( i, j, k \) generation indices (27 couplings)

Production:
\( e^+ p : \lambda'_1 j_1 \)
\( \tilde{u}_L, \tilde{c}_L \)

\( e^- p : \lambda'_{11k} \)
\( \tilde{d}_R, \tilde{s}_R \)

RPV

Decays:
Gauge coupling
(neutralinos or charginos)

Many final states:
DIS-like or multi-jets with isolated lepton(s), missing \( p_T \)

R. Ciesielski, Recent Results from HERA

13/Nov/2009
Squark Production in RPV SUSY

No deviations from SM observed. Limits set (SUSYGEN3).

Photino-like neutralino

\( \tan \beta = 2 \)
\( \mu = -200 \text{ GeV} \)
\( M_2 = 80 \text{ GeV} \)

Parameter scan

\( \tan \beta = 2 \)
\(-300 < \mu < 300 \text{ GeV} \)
\( 70 < M_2 < 350 \text{ GeV} \)

For \( \lambda = \sqrt{4\pi\alpha} = 0.3 \):
\( M_{\text{squark}} < 290 \text{ GeV} \)
\( M_{\text{squark}} < 275 \text{ GeV} \)
excluded @95% C.L.
Summary

- HERA still provides a wealth of data.
- Inclusive/High-Q2/EW/Exotics measurements are getting to their final shape.
- Precision on PDF fits is still improving.
- H1+ZEUS start to combine analyses (~1 fb⁻¹) in order to further improve statistical precision.

Thank you for your attention.
Contact Interactions

4-fermion CI at HERA:

\[ M_{\alpha\beta}^{eq}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2 \theta_W \cos^2 \theta_W} \frac{g_{\alpha}^{e} g_{\beta}^{q}}{Q^2 + M_Z^2} + \eta_{\alpha\beta}^{eq} \]

\(\alpha, \beta\) - electron, quark helicities (L,R).

NC e⁻p scattering:

\[
\frac{d^2 \sigma(e^- p)}{dx dy} = \frac{sx}{16 \pi} \sum q(x) \left[ P_- M_{LL}^2 + P_+ M_{RR}^2 + (1-y)^2 \right] 
\]

\[ \left[ P_- M_{LR}^2 + P_+ M_{RL}^2 \right] + \bar{q}(x) \left[ P_- M_{LL}^2 + P_+ M_{RL}^2 + (1-y)^2 \right] \]

NC e⁺p scattering:

\[
\frac{d^2 \sigma(e^+ p)}{dx dy} = \frac{sx}{16 \pi} \sum q(x) \left[ P_+ M_{LR}^2 + P_- M_{RL}^2 + (1-y)^2 \right] 
\]

\[ \left[ P_+ M_{LL}^2 + P_- M_{RR}^2 \right] + \bar{q}(x) \left[ P_+ M_{LL}^2 + P_- M_{RR}^2 + (1-y)^2 \right] \]

At high \(Q^2\) and high \(x\) quark distribution dominate (valence quarks).

Some contributions are suppressed by helicity factor \((1-y)^2\).

NC e⁻p sensitive to LL and RR, NC e⁺p sensitive to LR and RL configurations.

\[
P_\pm = 1 \pm P
\]

SM MEs modified by quark form-factor:

\[
M_{\alpha\beta}^{eq}(Q^2) = M_{\alpha\beta}^{eq}(Q^2)^{SM} (1 - R_q^2 Q^2 / 6)
\]
**Leptoquarks Production**

The Buchmueller-Rueckl-Wyler Model

- Leptoquarks (LQ) - hypothetical bosons connecting lepton and quark sectors.
- Carry SU(3) colour, fractional charge, lepton (L), barion (B) and fermion number \( F = 3B + L = 0, 2 \).
- Chiral objects i.e. either left- or right-handed coupling to lepton, but not both.

At HERA:
7 scalar and 7 vector LQs coupling to \( e \bar{q} \).
4 LQs couple also to \( \nu q \).

LQs can be resonantly produced in s-channel \( (M_{LQ} < \sqrt{s}) \) or exchanged in u-channel.

\( \lambda \) is the Yukawa LQ-\( e-q \) coupling.
Limit setting on \( M_{LQ}/\lambda \).

---

<table>
<thead>
<tr>
<th>( F = 2 )</th>
<th>Prod./Decay</th>
<th>( \beta_e )</th>
<th>( F = 0 )</th>
<th>Prod./Decay</th>
<th>( \beta_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e^+p</td>
<td>Scalar Leptoquarks</td>
<td>e^+p</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_{0,L} )</td>
<td>( e^-_Lu_L \to e^-u )</td>
<td>1/2</td>
<td>( S_{1/2,L} )</td>
<td>( e^+_Ru_R \to e^+u )</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( \to \nu d )</td>
<td>1/2</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>( S_{0,R} )</td>
<td>( e^-Ru_R \to e^-u )</td>
<td>1</td>
<td>( S_{1/2,R} )</td>
<td>( e^+_Lu_L \to e^+u )</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( e^-_Rd_R \to e^-d )</td>
<td>1</td>
<td></td>
<td>( e^+_Ld_L \to e^+d )</td>
<td>1</td>
</tr>
<tr>
<td>( S_{1,L} )</td>
<td>( e^-_Ld_L \to e^-d )</td>
<td>1/2</td>
<td>( S_{1/2,L} )</td>
<td>( e^+_Rd_R \to e^+d )</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( e^-_Lu_L \to e^-u )</td>
<td>1/2</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

---

| \( V_{1/2,R} \) | \( \bar{e}^-_Rd_L \to e^-d \) | 1 | \( V_{0,R} \) | \( \bar{e}^-_Rd_L \to e^-d \) | 1 |
| | \( \bar{e}^-_Lu_L \to e^-u \) | 1 | \( V_{0,L} \) | \( \bar{e}^-_Rd_L \to \bar{\nu}d \) | 1/2 |
| | \( \to \nu d \) | 1 | | | 1/2 |
| \( V_{1/2,L} \) | \( \bar{e}^-_Rd_L \to e^-d \) | 1 | \( V_{0,R} \) | \( e^+_Lu_L \to e^+u \) | 1 |
| | \( \bar{e}^-_Lu_L \to e^-u \) | 1 | \( V_{1,L} \) | \( e^+_Rd_R \to e^+d \) | 1/2 |
| | \( \to \nu d \) | 1/2 | | | 1/2 |
1st Generation Leptoquarks

H1 analysis based on full NC and CC samples of $L=0.45 \text{ fb}^{-1}$

$\text{LQ} \rightarrow \text{eq}$

Large SM background from NC and CC processes.
Good description of data by SM prediction.
No LQ signal observed.

Limits set for all 14 LQs.

H1: For $\lambda = \sqrt{4\pi\alpha} = 0.3$
$M_{\text{LQ}} < 291-330 \text{ GeV}$ are excluded at 95\% C.L.

LEP (OPAL, L3): indirect constraints from $ee \rightarrow \text{qq}$.
Tevatron (D0): LQ+LQ pair production from $qq$ annihilation
or $gg$ fusion ($\lambda$ independent).

ZEUS CI (94-07 data):
$\eta_{\alpha\beta} \propto \left( \frac{\lambda}{M_{\text{LQ}}} \right)^2$
$M_{\text{LQ}} / \lambda > 0.41-1.88 \text{ TeV} @95\%$ C.L.
Search for Lepton Flavour Violation mediated by LQs.

Experimentally clear process. Background dominated by lepton pair production.
No evidence for signal.

Limits set for 7 LQs (F=2), under assumption:
\[ \lambda_{\mu q} = \lambda_{\tau q} = 0. \]

For \[ \lambda = \sqrt{4\pi\alpha} = 0.3 \]
\[ M_{LQ} < 291-433 \text{ GeV} \] are excluded at 95\% C.L.
Form of the chi^2

Described in detail in arXiv:0904.0929

Additive error sources:

\[ \chi^2_{\text{exp}}(m, b) = \sum_i \left[ \frac{m^i - \sum_j \Gamma_j^i b_j - \mu^i}{\Delta_i^2} \right]^2 + \sum_j b_j^2. \]

For multiplicative error sources small biases to lower cross sections values may occur. This can be avoided modifying the \( \chi^2 \) definition as follows:

\[ \chi^2_{\text{exp}}(m, b) = \sum_i \frac{\left[ m^i - \sum_j \gamma_j^i m^i b_j - \mu^i \right]^2}{\delta_{i,\text{stat}}^2 (m^i - \sum_j \gamma_j^i m^i b_j) + \left( \delta_{i,\text{uncor}} m^i \right)^2} + \sum_j b_j^2. \]

with \( \gamma_j^i = \Gamma_j^i / \mu^i \), \( \delta_{i,\text{stat}} = \Delta_{i,\text{stat}} / \mu^i \), \( \delta_{i,\text{uncor}} = \Delta_{i,\text{uncor}} / \mu^i \).
DGLAP Analysis and HERA PDFs

- DGLAP equations at NLO in the MS scheme:
  - QCDNUM17.02 (M. Botje) (NB: $Q_0 < m_c$)
  - $Q_0^2 = 1.9 \text{ GeV}^2$ ; $m_c = 1.4 \text{ GeV}$, $m_b = 4.75 \text{ GeV}$
  - $\alpha_s(M_Z) = 0.1176$; $\mu_r = \mu_f = Q$
  - $f_s = 0.31$ (di-muon production)

- PDFs at the starting scale parametrised as:
  \[
x_f(x, Q_0^2) = A x^B (1-x)^C (1+Dx+Ex^2)
  \]

where $x_f = x_u, x_d, x_g, x_U, x_D$

Nr of param. chosen by saturation of $\chi^2$

- Heavy Quarks coeff. func. calculated in the GM-VFNS of Thorne-Roberts

- Results:
  \[
  \Rightarrow 10 \text{ parameters for central fit} \\
  \Rightarrow \chi^2/\text{ndof} = 574/582
  \]
Diffractive NLO QCD fit and dPDFs

Data with $Q^2 > 5$ GeV$^2$ fitted within the combined framework of DGLAP evolution and proton-vertex factorisation. TR-VFNS treatment of heavy quarks.

Inclusive data constrain the quark PDFs,

Diffractive di-jet data (BGF) constrain the gluon PDFs od the diffractive exchange

R. Ciesielski, Recent Results from HERA 13/Nov/2009
Diffractive NLO QCD fit and dPDFs

Predictions based on extracted dPDFs satisfactory describe:
- diffractive charm production
- diffractive di-jet photoproduction cross sections

R. Ciesielski, Recent Results from HERA 13/Nov/2009
Jet production in NC DIS

HERA II e⁺p data (L=188 pb⁻¹)

Breit frame

Measurement of \( \alpha_s(M_Z) \)

Input to PDFs

R. Ciesielski, Recent Results from HERA 13/Nov/2009
New measurements of $\alpha_s(M_Z)$

**HERA II NC DIS inclusive jets:**

$$\alpha_s(M_Z) = 0.1192 \pm 0.0009 \, \text{(stat.)} + 0.0035 \, \text{(exp.)} + 0.0020 \, \text{(th.)}$$

3.5% (total)

First measurement from ZEUS HERAII data

Re-analysis of HERA I inclusive jets PhP (reduced theoretical unc., the same data):

$$\alpha_s(M_Z) = 0.1223 \pm 0.0001 \, \text{(stat.)} + 0.0023 \, \text{(exp.)} + 0.0029 \, \text{(th.)}$$

3.1% (total)

Two most precise single ZEUS measurements of $\alpha_s(M_Z)$.

NNLO calculations needed.

R. Ciesielski, Recent Results from HERA

13/Nov/2009
New NC DIS inclusive jet cross sections with the anti-kt and SIScone jet algorithms

**ZEUS**

- Anti-kt ($x \times 10$)
  - ZEUS (prelim.) 82 pb$^{-1}$
  - NLO ⊕ hadr ⊕ Z$^0$

- $Q^2 > 125 \text{ GeV}^2$
- $2 < \eta_t < 1.5$
- $|\cos \gamma| < 0.65$

**ZEUS**

- Anti-kt ($x \times 10$)
  - ZEUS (prelim.) 82 pb$^{-1}$
  - NLO ⊕ hadr ⊕ Z$^0$

- $E_{T,B}^t > 8 \text{ GeV}$
- $2 < \eta_t < 1.5$
- $|\cos \gamma| < 0.65$

**Good description by NLO calculations (DISENT)**
Larger hadronisation corrections for the SIScone algorithm
New Jet Algorithms: anti-kt and SIScone

Good agreement with NLO calculations (DISENT). Comparison with $K_T$ published results. Final paper (to be released soon) will also contain $\alpha_s$ determinations.
**Subjets in NC DIS**

**Subjets: - pattern of parton radiation - colour coherence**

Two resolved subjets ($y_{\text{cut}}=0.05$) $L= 82 \text{ pb}^{-1}$

Predictions:
- soft gluon radiation to be emitted towards proton direction
- subjet with lower $E_T$ emitted predominantly towards proton direction

Three resolved subjets ($y_{\text{cut}}=0.03$) $L= 344 \text{ pb}^{-1}$

- gives a handle on underlying colour dynamics
- angular correlations are sensitive to different colour configurations.

NLO QCD describes the data adequately.
Isolated and Prompt Photons in DIS

NLO calculations needed
Heavy Quarks

- Charm: 20 - 30%, Beauty: few percent
- Important check of QCD
- HERA results at high $Q^2 \Rightarrow bb \rightarrow H$ at LHC
Beauty in photoproduction

HERA II data, 2006/07 $e^+p$ ($L=128$ pb$^{-1}$)

First ZEUS inclusive di-jet measurement with secondary vertexing.

Greatly improved precision compared to HERA I result
In agreement with NLO QCD (FMNR)

Fraction of $b$ extracted from decay length significance, after reconstructing the decay vertices of $B$ hadrons

Invariant mass at the reconstructed vertices ($m_{vtx}$) used to distinguish beauty-enriched regions
Beauty in photoproduction

Newest ZEUS results in red.
Good overall agreement of ZEUS and H1 data with NLO QCD (FMNR).
More precise theory would be useful.
Semileptonic charm and beauty in DIS

HERA II data, 2005 e-p (L=126 pb$^{-1}$) Di-jets with muons $Q^2>20 \text{ GeV}^2$, $0.01<y<0.7$ $p_T^\mu > 1.5 \text{ GeV}$, $-1.6<\eta^\mu<2.3$

The $c$ and $b$ fractions extracted simultaneously using $p_T^{rel}$, impact parameter $\delta$ and $p_T^{miss}^\mu$ ($p_T$ balance from neutrinos)

Charm: good agreement with HVQDIS and RAPGAP. Beauty: good agreement in shape, HVQDIS predictions scaled by a factor of 2.
F2cc and F2bb

Good agreement between ZEUS and H1 measurements.
Results well described by theory.
Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using the H1 Vertex Detector

$5 \leq Q^2 \leq 2000 \text{ GeV}^2$

- Measurement exploits lifetime information to separate heavy flavours from light quarks using the H1 vertex detector

- Important test of QCD
  - Provide unique constraints: input to theory
  - Check PDFs from inclusive data describe charm
  - Cross check of exclusive ($D^*$) analyses

- Contribution of charm and beauty structure functions to the total ep cross section:
  - Charm: on average 17%
  - Beauty: 0.2% ($Q^2 = 5 \text{ GeV}^2$) to 1% ($Q^2 \geq 60 \text{ GeV}^2$)

10/09: DESY-09-096, accepted by Eur. Phys. J. C
Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using the H1 Vertex Detector
$F_2^{\text{(charm)}}$  

Heavy Flavour production in DIS: a very interesting topic in pQCD  
(e.g. Treatment of HF in the DGLAP evolution: FFNS vs GMVFNS)

Combine the H1 and ZEUS $F_2^{\text{(charm)}}$ results obtained from the published or preliminary HERA-I,-II  
D-mesons, Lifetime tag and semileptonic analyses

Extraction of $F_2^{\text{(charm)}}$:  

$$F_2^{\text{c,meas}}(x, Q^2) = \frac{\sigma_{\text{vis,bin}}}{\sigma_{\text{mod,bin}}}$$

Detailed study of the correlations, and additional uncertainties introduced in the extrapolation

Combination procedure as in the inclusive case  
(cross checked with alternative bayesian combination)

Precision: 6-10% , currently mostly H1 driven  
Big impact expected from adding ZEUS HERA-II charm results
- These results triggered interesting discussions at the last PDF4LHC workshop
- Important input to further theoretical developments...