Electroweak Physics and Searches for New Physics at HERA

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Outline

Introduction

Electroweak physics
- Neutral and charged current DIS cross sections
- Unpolarized and polarized DIS cross sections
- Interference structure function
- Combined Electroweak-QCD fits
- Isolated lepton events
  - single W production cross section
- Multi-lepton final states
  - $\gamma\gamma \rightarrow l^+l^-$ cross section

Physics beyond the Standard Model
- Single top production
- Quark radius, contact interactions
- Excited fermions
- Leptoquarks
- General searches

Conclusions

Individual analyses of H1 and ZEUS experiments and recently significant improvement by combining both experiments
The HERA ep Collider at DESY

World's only electron proton collider, in operation 1992-2007

HERA-I (1992-2000)
- ~130 pb\(^{-1}\) per exp. (90% e\(^+\)p)

HERA-II (2003-07)
- Luminosity upgrade
- Longitudinal e polarization (avg. 30%-40%)

Total integrated luminosity
~0.5 fb\(^{-1}\) per experiment

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

\[ p (920 \text{ GeV}) \rightarrow e (27.6 \text{ GeV}) \]
H1 and ZEUS Experiments

Large general purpose collider experiments
- Asymmetric design
- 4π coverage
- Excellent electromagnetic and hadronic calorimeters
Deep Inelastic Scattering at HERA

**Neutral Current**

\[ ep \rightarrow eX \]

**Charged Current**

\[ ep \rightarrow \nu X \]

- **Q**\(^2\) – virtuality of exchange boson
- **x** – Bjorken scaling variable
- **y** – Inelasticity
Unpolarized DIS Cross Sections

Neutral Current

\[
\frac{d^2 \sigma_{\text{NC}}^{e^p}}{dx dQ^2} = \frac{2 \pi \alpha^2}{x Q^4} \left[ Y_+ \vec{F}_2^\pm + Y_- \vec{F}_3^\pm - y^2 \vec{F}_L^\pm \right]
\]

Charged Current

\[
\frac{d^2 \sigma_{\text{CC}}^{e^p}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2 \pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{\text{CC}}^{e^p}
\]

\(~0\) \sim 1/Q^4 \text{ at } Q^2 \gg M_W^2

- Excellent agreement between data and SM over large kinematic range (many orders of magnitude)
- Electroweak unification at \(Q^2 = M_W^2\)
- \(Q^2\) (resolving) power up to 40000 GeV^2, corresponds to spatial resolution \(1/Q \sim 10^{-18} \text{m}\)
Neutral Current Cross Section

A closer look at the neutral current cross section in \((x, Q^2)\)

\[
\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- x \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right]
\]

Cross section parametrized using generalized structure functions related to quark/gluon density distributions in proton

\(F_2\) \(\gamma\) exchange dominant contribution, \(\gamma Z\) interference depends on polarization (axial-vector coupling to \(Z\) \(a_e\) large)

\[
\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + \left( v_e^2 + a_e^2 \pm P_e 2v_e a_e \right) \kappa^2 \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z
\]

\(xF_3\) \(\gamma Z\) interference / \(Z\) exchange, depends on beam lepton charge (vector coupling to \(Z\) \(v_e\) small)

\[
x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \left( 2a_e v_e \pm P_e [v_e^2 + a_e^2] \right) \kappa^2 \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 xF_3^Z
\]
Unpolarized NC Cross Sections

- Measured using 170 pb\(^{-1}\) of HERA-II data
- Good agreement with SM (ZEUS-JETS) over large kinematic range
- Dependence on beam charge apparent: e\(^-\)p cross section larger at high Q\(^2\)
- Cross section difference gives interference xF\(_3\)\(^Y\)Z
Interference Structure Function $x F_3^{\gamma Z}$

Charge asymmetry observed:
Exploit difference in $e^-p/e^+p$ cross sections to measure $x F_3$

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

$\gamma Z$ interference dominates in HERA kinematic range:
Measure “interference structure function”

$$x F_3^{\gamma Z} \simeq x \tilde{F}_3 \frac{(Q^2 + M_Z^2)}{a e \kappa Q^2}$$

ZEUS

- All measurements extrapolated to $Q^2=5000 \text{ GeV}^2$
- Measured as function of $x$
- Result in good agreement with standard model expectation

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Electroweak Physics and Searches at HERA
Polarized NC Cross Sections: Parity Violation

Polarization asymmetries:
Measurement of $\gamma Z$ interference term in $F_2$

\[ A^\pm = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \]

\[ A^\pm \approx \mp k a_e \frac{F_2^\gamma Z}{F_2} \sim a_e v_q \]

- Observation of parity violation in NC $e^\pm p$ scattering down to $10^{-18}$m
- Direct measurement of electroweak SM effects

Combined measurement increases statistics (prelim.)
Unpolarized Charged Current Cross Section

- Measured charged current cross sections for $e^+p/e^-p$ data (HERA-I, unpolarized)

- Good agreement with SM over large kinematic range (shown here: HERAPDF0.1)

- Sensitive to flavors of partons in proton $p \sim (uud)$ at high $x$

\[
\tilde{\sigma}_{CC}^{e^+p} = x[\bar{u} + \bar{c}] + (1 - y)^2 x[d + s]
\]

\[
\tilde{\sigma}_{CC}^{e^-p} = x[u + c] + (1 - y)^2 x[\bar{d} + \bar{s}]
\]
Polarized Charged Current Cross Section

- Different HERA-II data sets allow measuring CC cross section as function of polarization
- $P_e$ positive, negative and zero

$$\frac{d^2\sigma_{CC}^{\pm\mp},}{dxdQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{CC}^{\pm\mp}$$

- Fundamental feature of SM directly visible:
  - Only L(R)-handed (anti)particles interact weakly

Right-handed currents forbidden in SM. At $P = -1$ (extrapolated): $M_W^R > 208$ GeV (H1)
All these measurements are used to extract 5 PDFs \((g,u,\bar{u},d,\bar{d})\) and weak couplings to \(Z^0\) \((a_{ur}a_{dr}v_{ur}v_{dr})\) simultaneously

- **NC**: \(\gamma Z\) interference / \(Z\) exchange sensitive to \(a_{ur}a_{dr}\)
  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
Isolated Lepton Events with Missing $p_T$

Motivation:
- Main Standard Model process for high $P_T$ isolated lepton with missing $P_T$ is single $W$ production
- Other SM process have smaller cross sections
  - Measure single $W$ production ($\sigma \sim 1.3\text{pb}$)
  - Search for physics beyond the Standard Model

Experimental signature:
Isolated Lepton Events with Missing $p_T$

Look for events with isolated, high-$P_T$ lepton (e, $\mu$), missing $P_T$ and hadronic system ($P_T^X$) in high-$p_T$ lepton (e, $\mu$) events.

| H1+ZEUS prel. $e^\pm p$ | Data | SM prediction |
|--------------------------|------|---------------|
| e + $\mu$ total $p_T^X>$25GeV | 81   | 87.8±10.6     |
|                           | 29   | 24.0±3.2      |

- In general, good agreement with SM prediction

Excess of H1 $e^+p$ data at large $P_T^X$, small SM expectation
- Not confirmed by ZEUS analysis
- Excess remains in common phase space of combined analysis (1.9$\sigma$)
Single W Production Cross Section

- High purity of ~75% of W production
- Clear Jacobian peak
- Strong evidence for W production

Cross section measurement in common (H1, ZEUS) phase space
W branching ratio of leptonic decays used to calculate full cross section
Measurement done differentially as function of hadronic transverse momentum

→ Inclusive single W production \( \sigma = 1.07 \pm 0.16 \text{ (stat.)} \pm 0.08 \text{ (sys.)} \) pb
In good agreement with SM prediction 1.26 ± 0.19 pb (EPVEC at NLO)
Multi-Lepton Production

Motivation
- Main Standard Model process with multi-lepton is $\gamma\gamma$ process
- QED cross section well known, modelled using GRAPE
- Any deviation, indication of new phenomena

Signature
- Events with 2 or more isolated high-$P_T$ leptons ($e$ or $\mu$)

Results
- H1 and ZEUS combined results (0.94 fb$^{-1}$)
- In general, observed number of events in good agreement with SM expectation

\[ \Sigma P_T > 100 \text{ GeV}: \]
- $e^+p$ data:
  7 obs/1.94±0.17 exp
  (excess of 2.6 $\sigma$)
- $e^-p$ data:
  0 obs/1.19±0.12 exp
Measurement of $\gamma\gamma \rightarrow l^+l^-$ Cross Section

Two-photon channels used to measure the H1 + ZEUS weighted average cross section for e and $\mu$ pair production

- Differential cross sections measured as function of $P_T$ of leading lepton and invariant mass of lepton pair
- Total visible cross section $0.66\pm0.03$ (stat.) $\pm0.03$ (sys.) pb in good agreement with SM prediction $0.69\pm0.02$ pb (GRAPE)
Search for Single-top Production

Motivation

- Strongly suppressed within Standard Model (< 1fb GIM mechanism).
  Any observation clear indication of new physics.
- Single-top production through flavor-changing neutral current (FCNC)
- Several theories beyond the SM predict FCNC
- Most sensitive to tuV (charm PDF of proton small at high x)
- Effective anomalous coupling at t-u-γ or t-u-Z vertex

\[
\Delta L_{\text{eff}} = ee_t \frac{-i\sigma_{\mu\nu}q}{\Lambda} \kappa_{tu\gamma} uA^\mu + \frac{g}{2\cos\theta_W} \gamma \mu \nu_{tuZ} uZ^\mu + h.c.
\]

magnetic vector coupling
Search for Single-top Production

Decay modes:

- **Standard Model**
  - leptonic (BR 32%): \( t \rightarrow bW, W \rightarrow l\nu \) _isol.lepton, jet, p_{miss}^{T}_,
  - hadronic (BR 68%): \( t \rightarrow bW, W \rightarrow q\bar{q} \) 3 jets, \( m_{W}, m_{t} \)

- **Flavor Changing Neutral Currents**
  - \( \kappa_{tu\gamma} \) \( t \rightarrow u\gamma \) _n-jets (+lepton pairs)_,
  - \( \nu_{tuZ} \) \( t \rightarrow uZ^{0} \)

No significant excess in the signal region, upper limits are set on anomalous coupling \( \kappa_{tu\gamma} \)
Are Quarks Elementary?

- Quark substructure can be detected by measuring spatial distribution of quark charge.
- If quark has finite radius, cross section will decrease as probe penetrates into it.

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

- Limit on quark size (95%CL), assuming point-like electron
  - ZEUS: \( R_q < 0.62 \ 10^{-18} \text{m} \)
  - H1: \( R_q < 0.74 \ 10^{-18} \text{m} \)

- Use similar fit for limits on contact interactions and large extra dimensions
  ZEUS prel.: \( \Lambda > 3.8 - 8.9 \ \text{TeV} \ (95\% \text{C.L.}) \)
Excited Fermions

- Excited fermions would be signature of compositeness
- Compositeness could explain 3 families and mass hierarchy
- Excitation/de-excitation described by effective Lagrangian:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \vec{F}_R^* \sigma^{\mu\nu} \left[ g f \frac{\tau^\alpha}{2} W_{\mu\nu}^\alpha + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\chi^\alpha}{2} G_{\mu\nu}^\alpha \right] F_L$$

[f, f' and f_s are the couplings to the SM gauge groups]

Example: production and decay of e*
Excited Fermions

H1: all possible decay channels studied. No deviation from SM expectation ➔ limits set on $f/\Lambda$ (@ 95% CL)

- $f/\Lambda$ limits can be translated into mass limits assuming $f/\Lambda = 1/M_{f^*}$
  - $M_{e^*} > 272$ GeV
  - $M_{\nu^*} > 213$ GeV
  - $M_{q^*} > 252$ GeV (assuming $f_s = 0$)
**Leptoquarks**

- Leptoquarks appear in many SM extensions
- Couple to both electrons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) number
  - Fermion number: \( F = 3B + L = 0, 2 \)
- LQs model are explored in Buchmüller-Rückl-Wyler (BRW) framework (14 different LQ types, which couple to electron)
- We search for LQ decaying into e-jet or \( \nu \)-jet:
Leptoquarks

- Full statistics analyzed by H1 (prel. results)
- Search for all 14 LQ types
- No deviation from SM
- limits set on coupling at 95% CL

Example: Exclusion limits on scalar F=0 and F=2 LQs

HERA limits are complementary to LEP and Tevatron
General Searches

- H1 performed a model independent, generic search in final states with $\geq 2$ high-$P_T$ objects:
  - $e, \mu, \text{jets}, \gamma, \nu$
  - $P_T > 20\text{GeV}$
  - $10^\circ < \theta < 140^\circ$

- Classified by final state
- Standard model predictions for all HERA processes considered: NC and CC DIS, photoproduction, lepton pair production, W-production, QEDC

Good agreement of event yields with SM expectation. All deviations compatible with statistical fluctuations.
Summary

Full HERA data (1994-2007) being analyzed
Recently, combined analysis in order to improve errors/sensitivity
- Study of deep inelastic scattering processes
  - NC/CC cross sections
  - Precision of tests of Standard Model
  - Observation of electroweak effects
  - Combined QCD and EW fits performed
- Rare electroweak processes investigated
  - Single W production cross section
  - Lepton-pair production cross section
- Search for new physics
  - Single top production
  - Quark radius
  - Excited fermions
  - Leptoquarks
  - General searches

Overall good agreement with the SM:
- Exclusion limits set, competitive to LEP and TEVATRON
- Stringent limits on excited fermions, anomalous productions