



Electroweak Physics and Searches for New Physics at HERA

Uwe Schneekloth

DESY

On behalf of the H1 and ZEUS Collaborations

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Elementary Particle Physics

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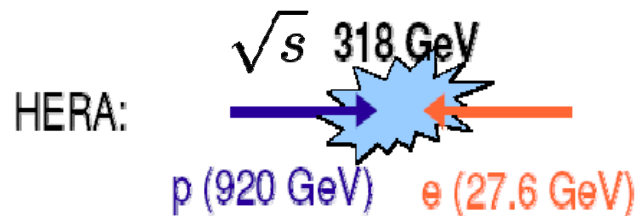
Outline

- 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)

- $\sim 130 \text{ pb}^{-1}$ per exp., (90% e^+p)

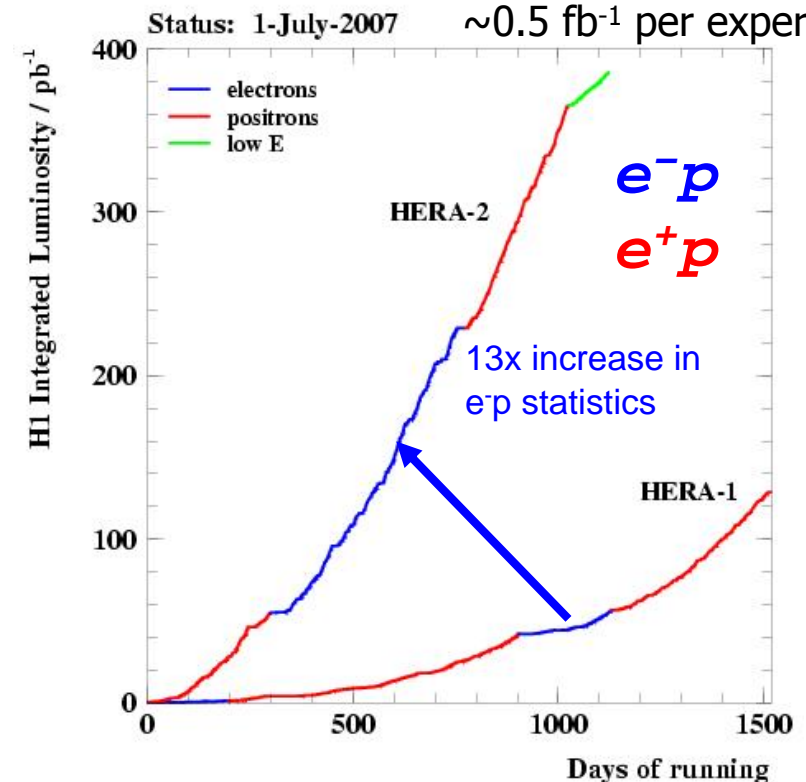
HERA-II (2003-07)

- Luminosity upgrade
- Longitudinal e polarization (avg. 30%-40%)



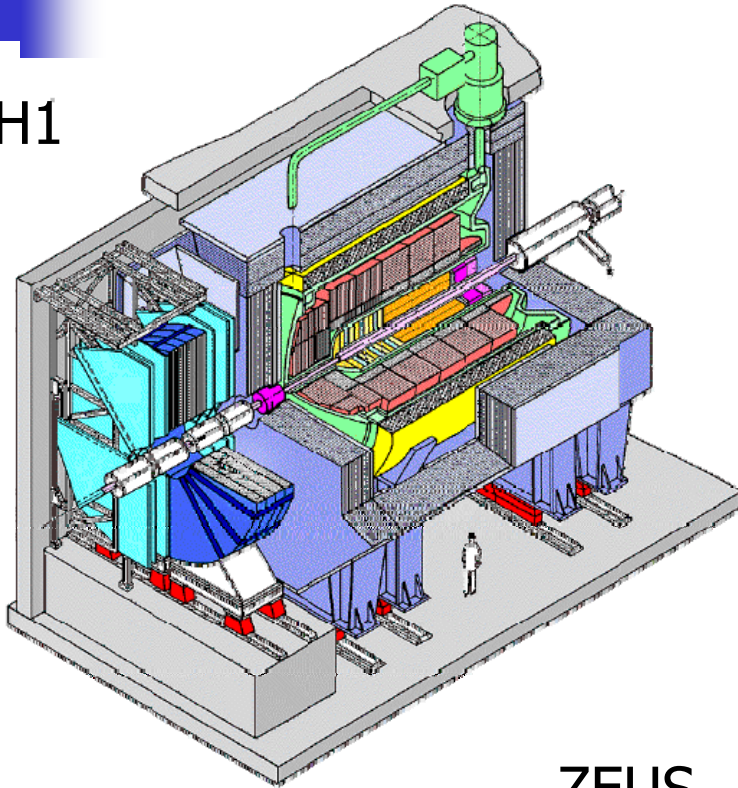
Total integrated luminosity

$\sim 0.5 \text{ fb}^{-1}$ per experiment



H1 and ZEUS Experiments

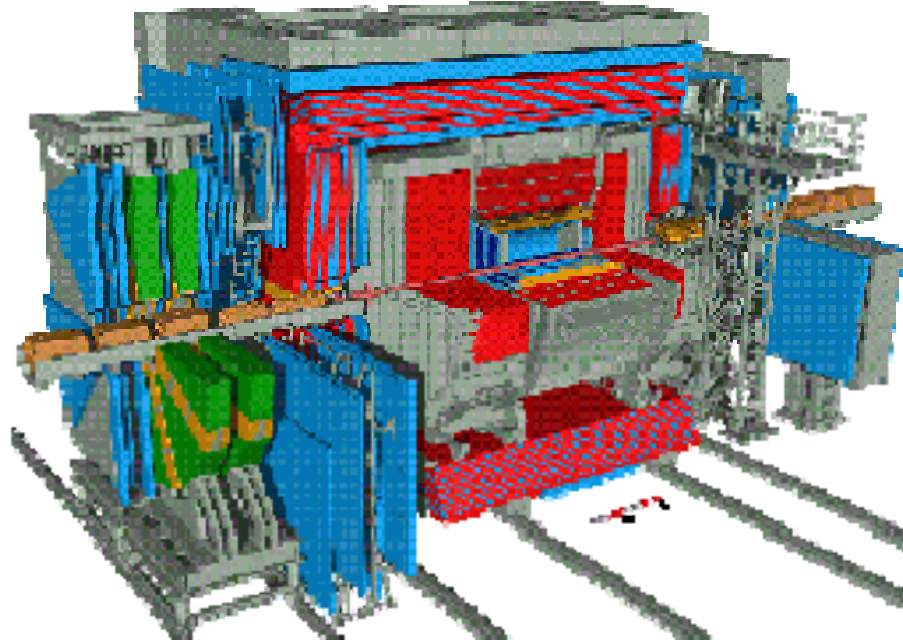
H1



Large general purpose collider experiments

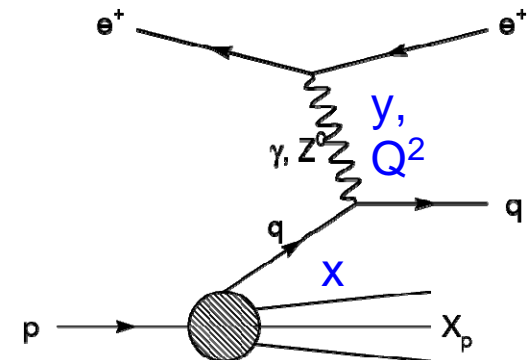
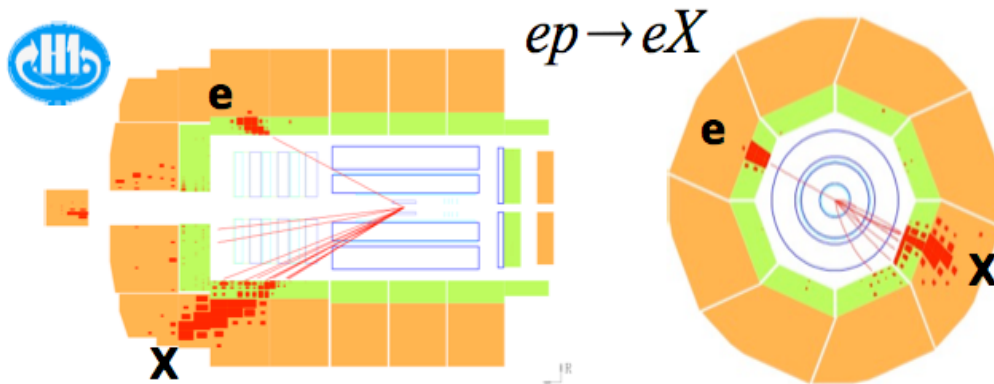
- Asymmetric design
- 4 π coverage
- Excellent electromagnetic and hadronic calorimeters

ZEUS



Deep Inelastic Scattering at HERA

Neutral Current



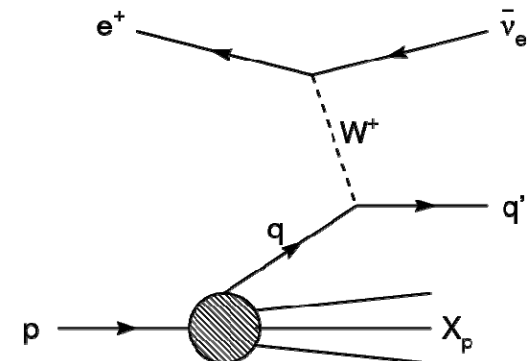
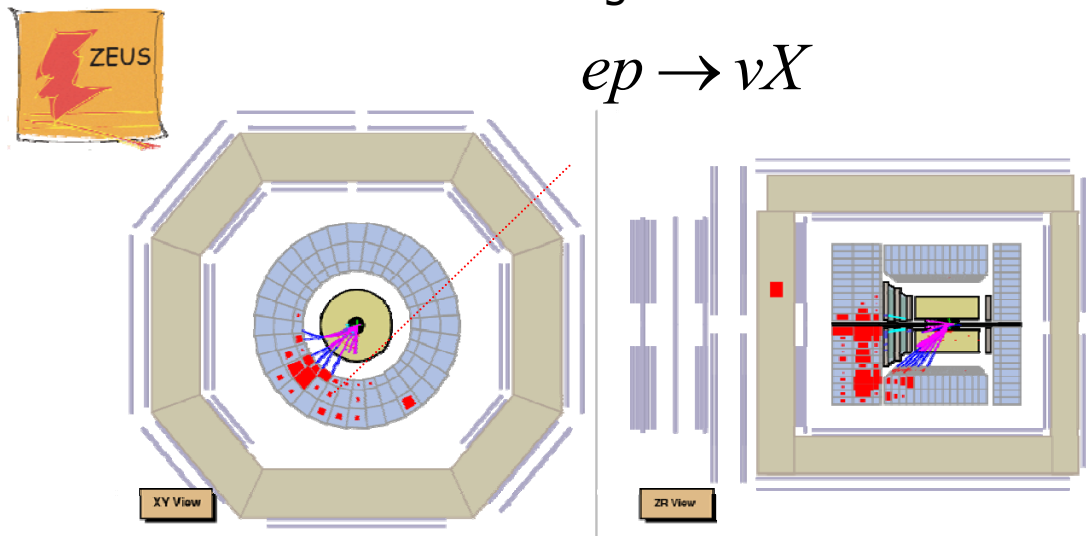
Q^2 – virtuality of exchange boson

x – Bjorken scaling variable

y – Inelasticity

Charged Current

$ep \rightarrow \nu X$



Unpolarized DIS Cross Sections

Neutral Current

Electroweak unification

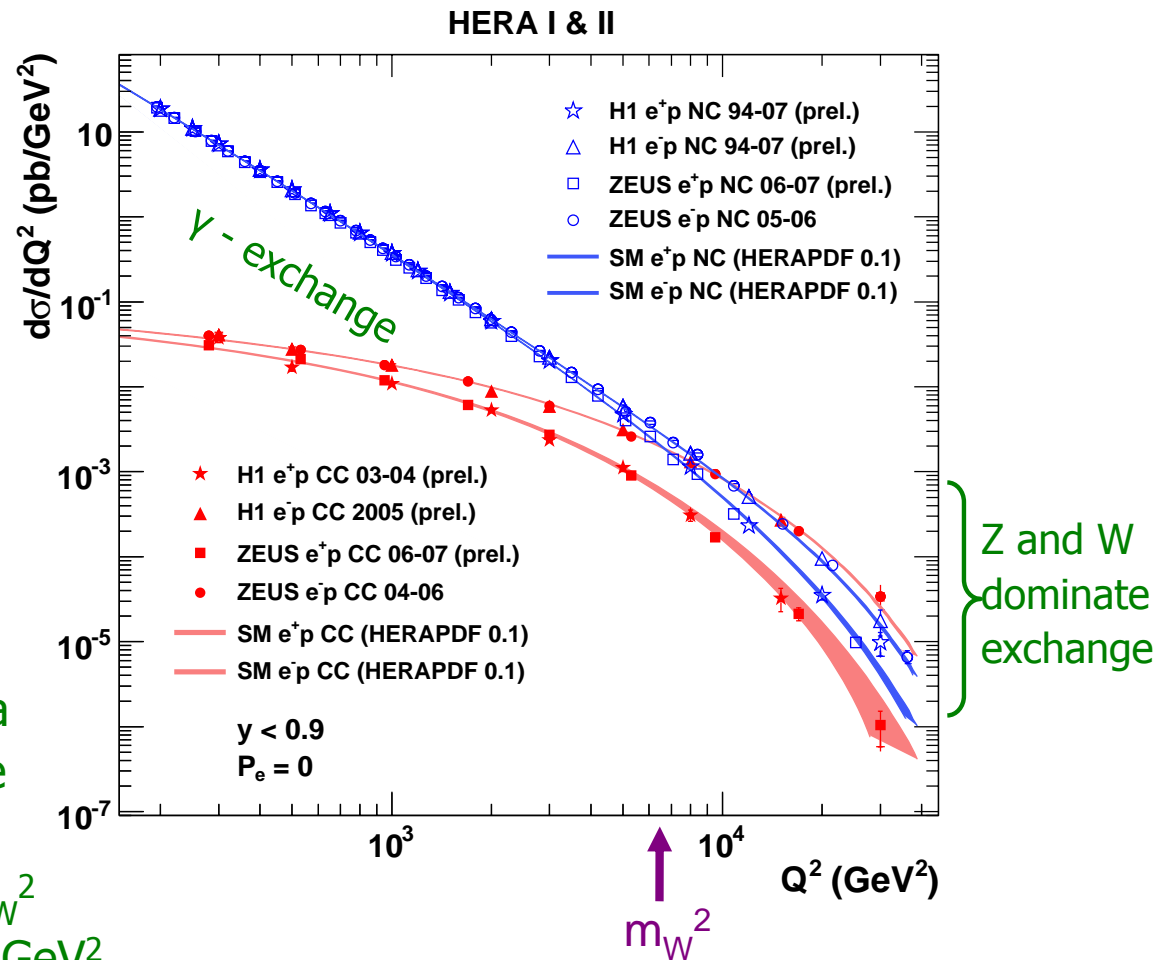
$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+ \tilde{F}_2^\pm \mp Y_- x \tilde{F}_3^\pm - y^2 \tilde{F}_L^\pm \right]$$

Charged Current

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

~ 0 $\sim 1/Q^4$ at $Q^2 > M_W^2$

- 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 GeV², corresponds to spatial resolution $1/Q \sim 10^{-18}$ m



Neutral Current Cross Section

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

$$Y_{\pm} = 1 \pm (1 - y)^2$$

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

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

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

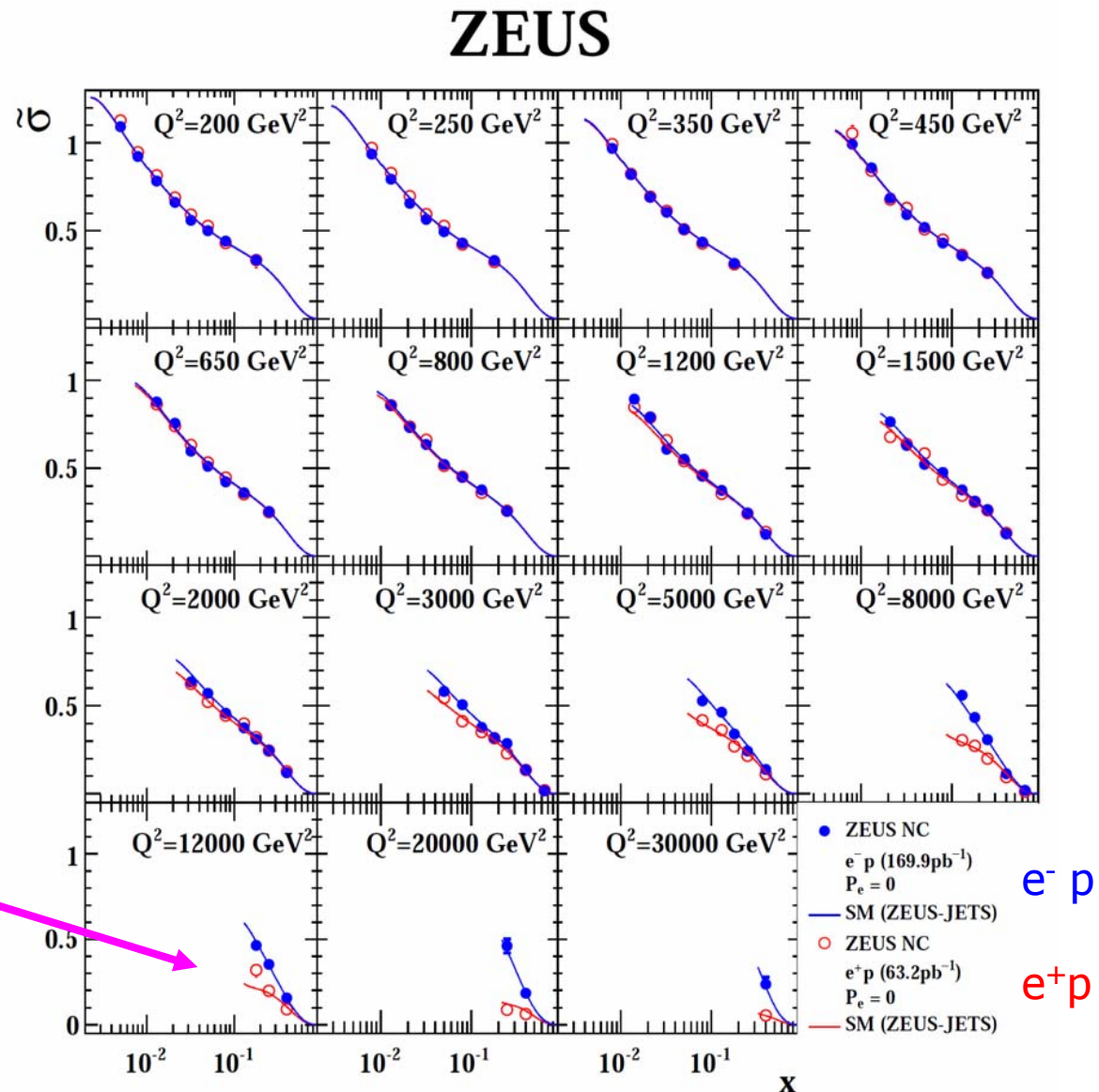
$$\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2v_e a_e) \kappa^2 \left[\frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z$$

$x\tilde{F}_3$ γ Z interference / Z exchange,
depends on beam lepton charge (vector coupling to Z v_e small)

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

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 Q²
- Cross section difference gives interference $\chi F_3^{\gamma Z}$



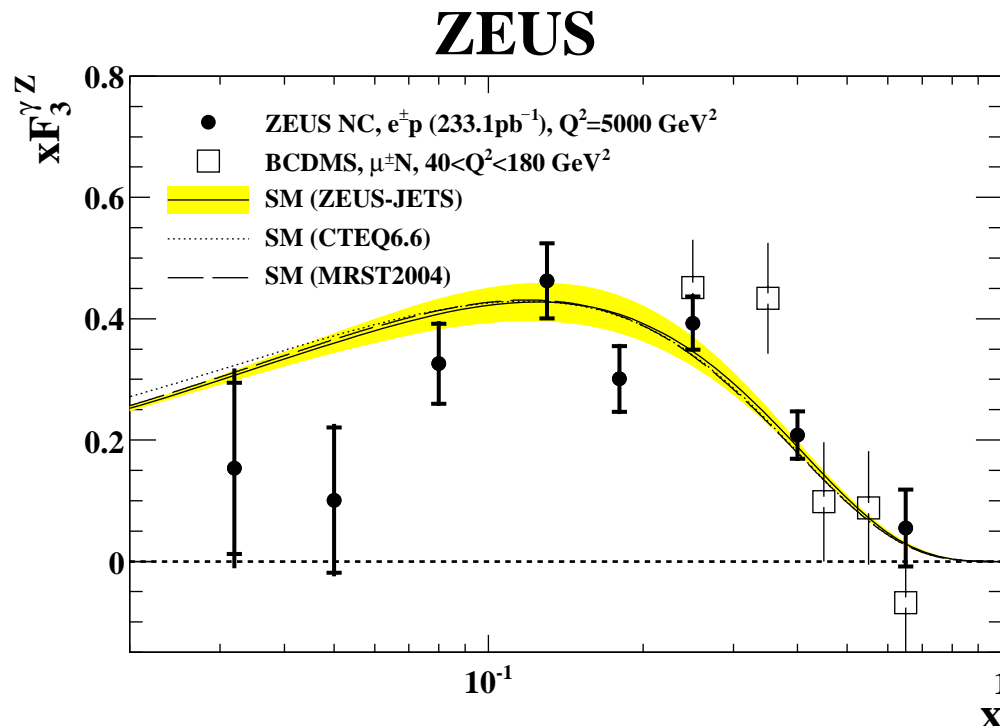
Interference Structure Function $x\tilde{F}_3^{\gamma Z}$

Charge asymmetry observed:
Exploit difference in e^-p/e^+p
cross sections to measure $x\tilde{F}_3$

γZ interference dominates in
HERA kinematic range:
Measure “interference structure function”

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

$$xF_3^{\gamma Z} \simeq x\tilde{F}_3 \frac{(Q^2 + M_Z^2)}{a_e \kappa Q^2}$$



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

Polarized NC Cross Sections: Parity Violation

Polarization asymmetries:

Measurement of γZ interference term in F_2

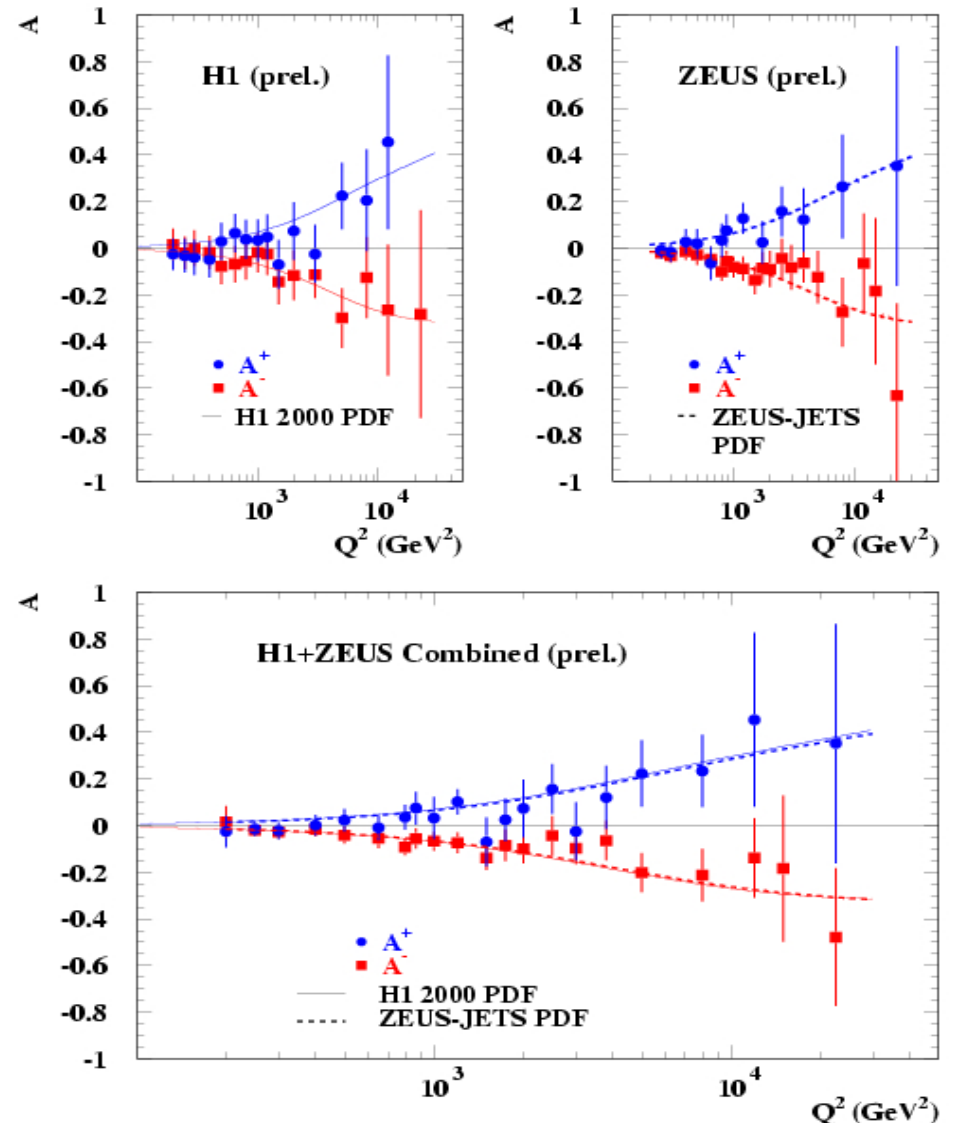
$$A^\pm = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)}$$

$$A^\pm \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \sim a_e v_q$$

- 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.)

HERA polarization asymmetries

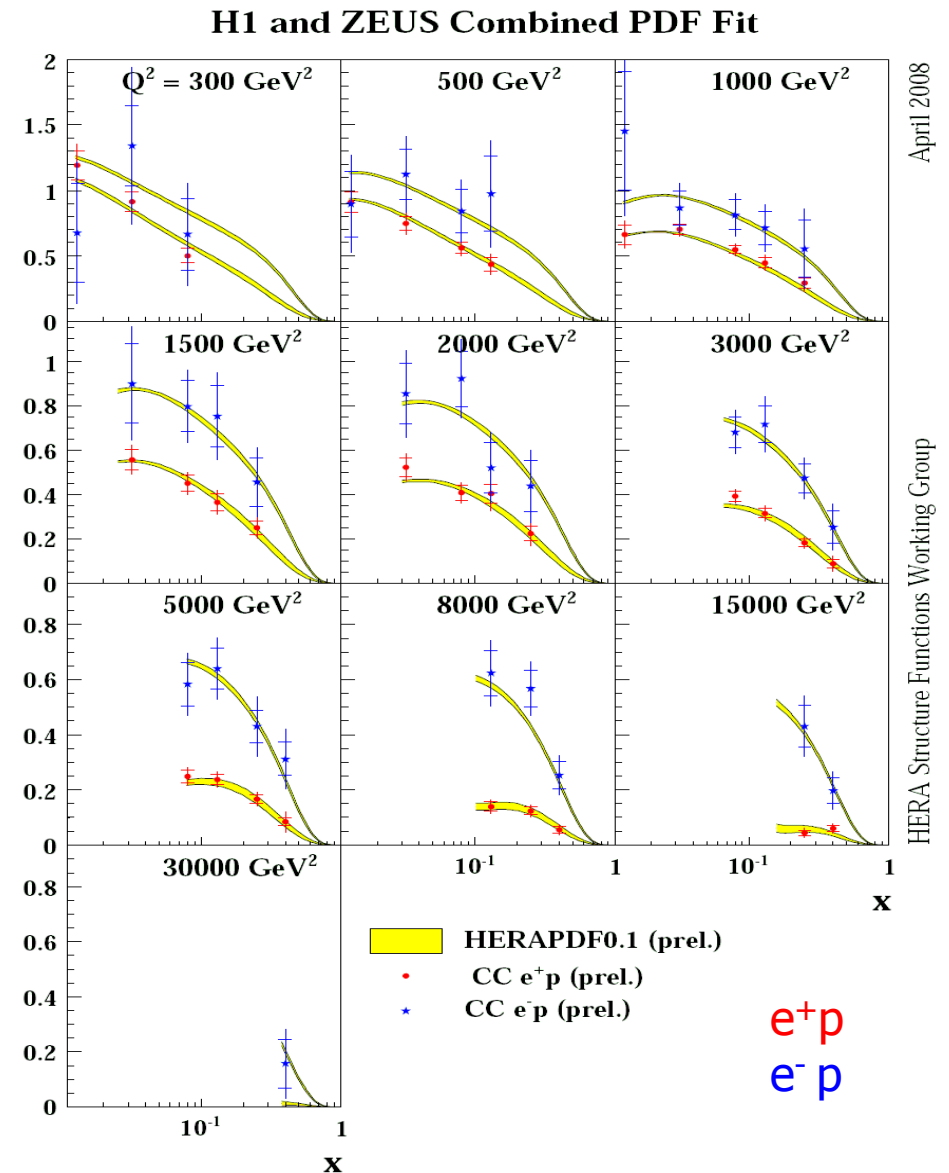


Unpolarized Charged Current Cross Section

- 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

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

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

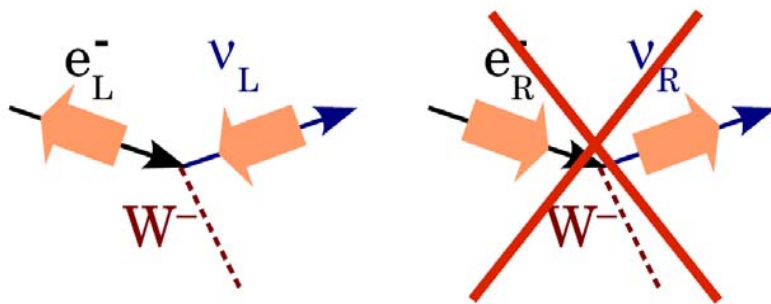


Polarized Charged Current Cross Section

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

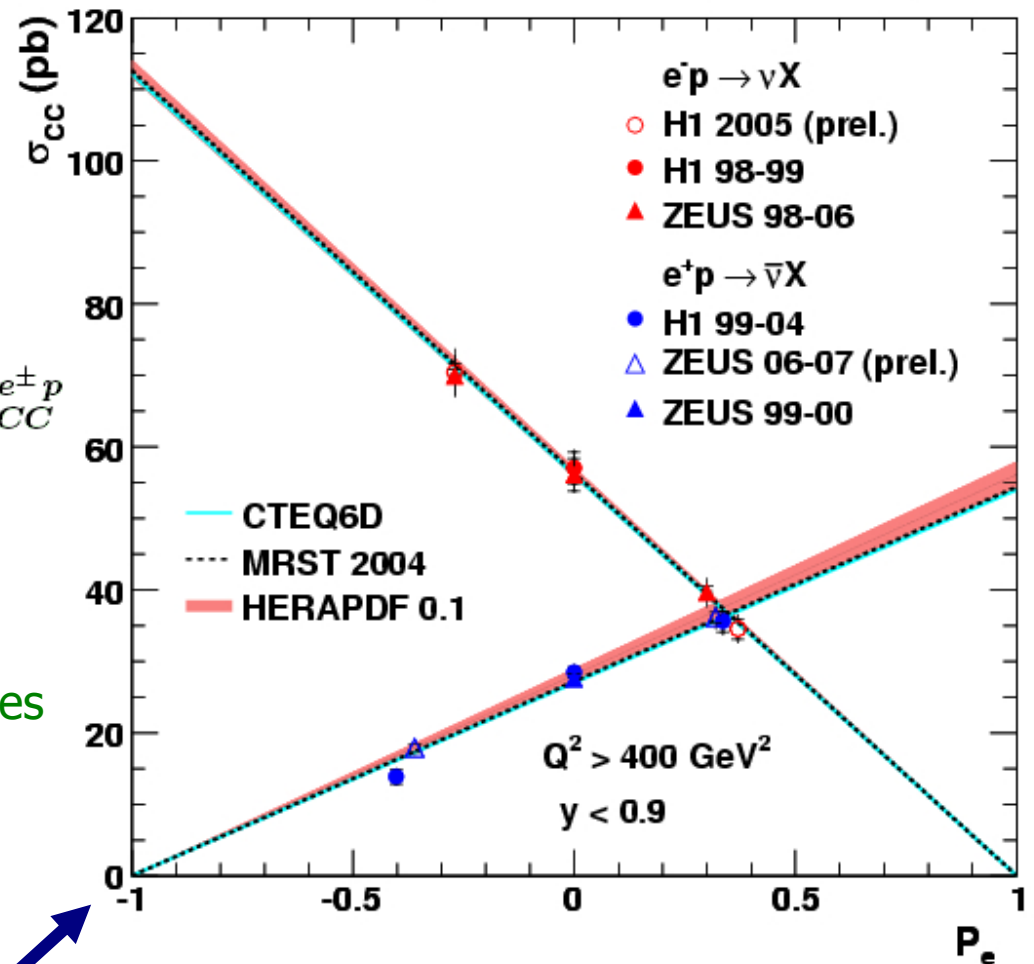
$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

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

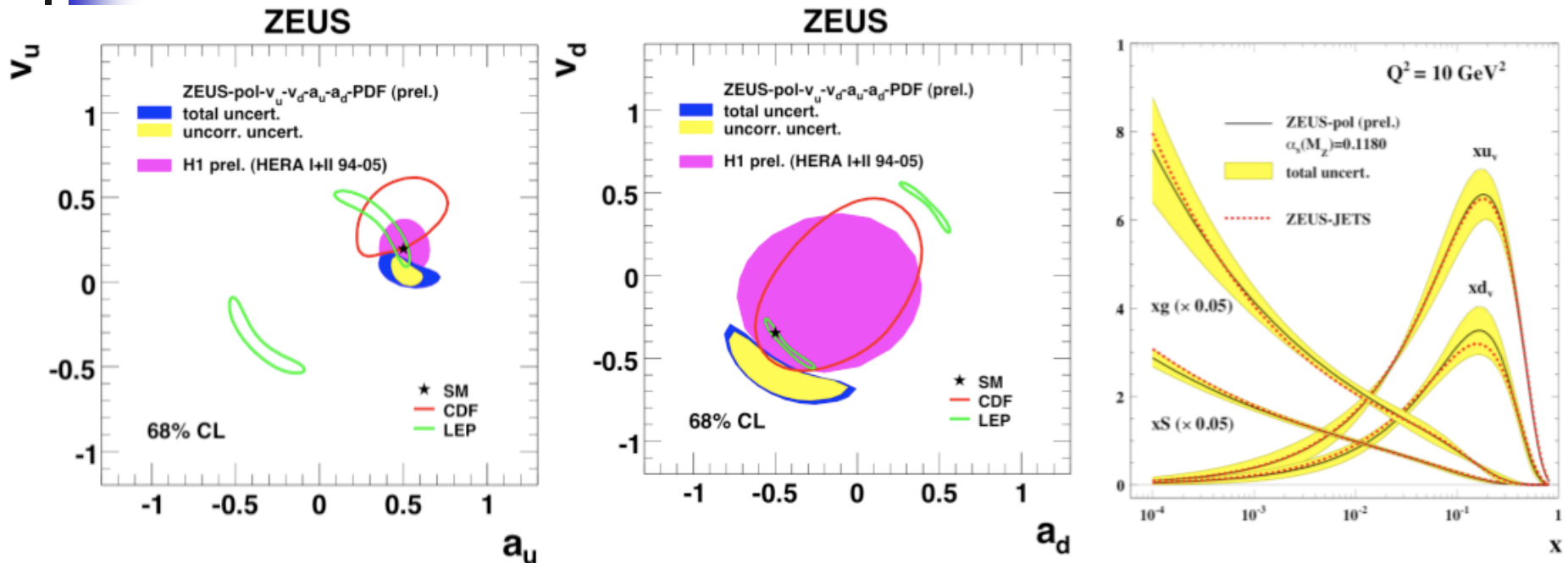


Right-handed currents forbidden in SM.
At $P = -1$ (extrapolated): $M_W^R > 208 \text{ GeV}$ (H1)

HERA Charged Current $e^\pm p$ Scattering



Combined Electroweak-QCD Fits

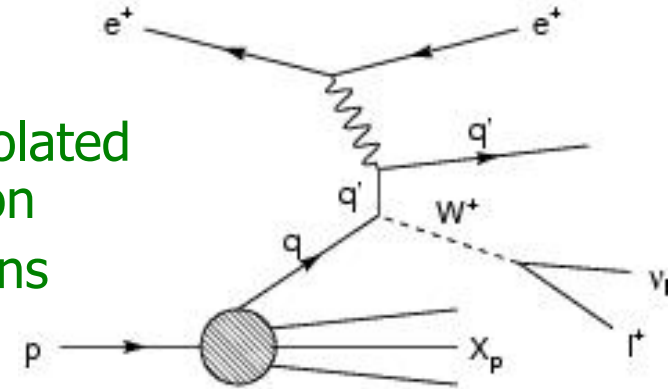


- All these measurements are used to extract 5 PDFs ($g, u, \bar{u}, d, \bar{d}$) and weak couplings to Z^0 (a_u, a_d, v_u, v_d) simultaneously
 - NC: γ Z interference / Z exchange sensitive to a_u, a_d and can resolve signs of couplings
 - CC: flavor sensitivity helps to disentangle u, d-quarks
- Precision competitive with LEP and Tevatron results
- Most precise value for u-coupling to Z comes from HERA

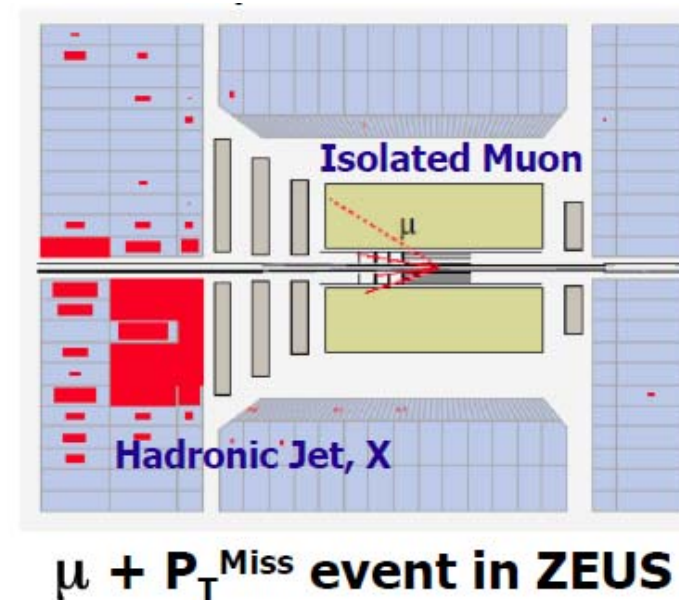
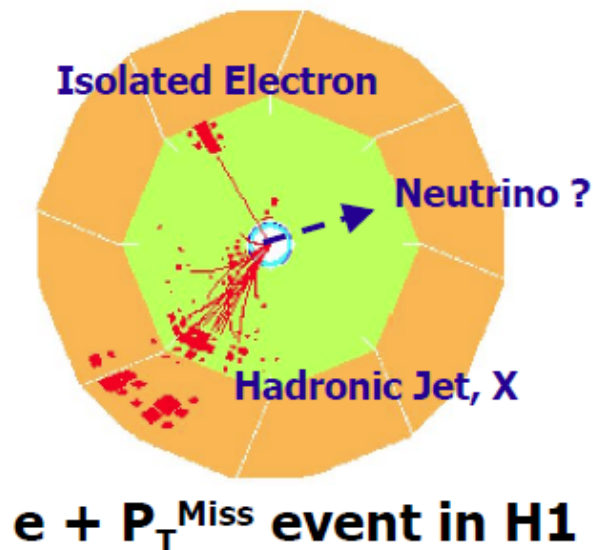
Isolated Lepton Events with Missing p_T

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

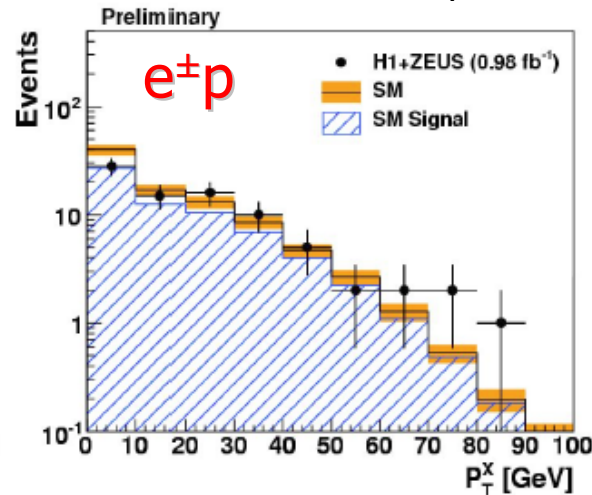


Experimental signature:



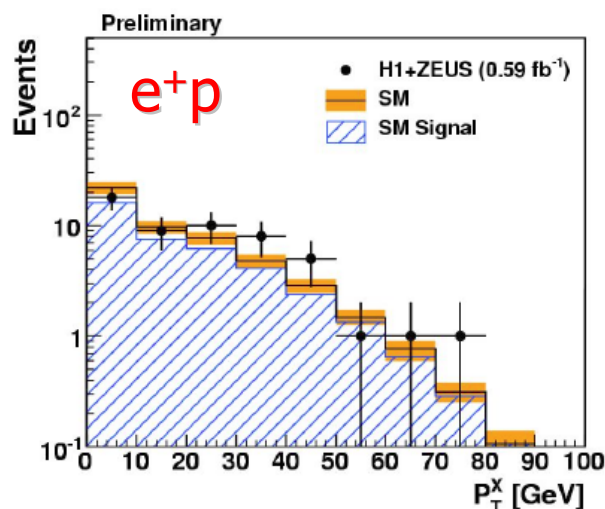
Isolated Lepton Events with Missing p_T

Look for events with isolated, high- P_T lepton (e, μ), missing P_T and hadronic system (P_T^X)



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

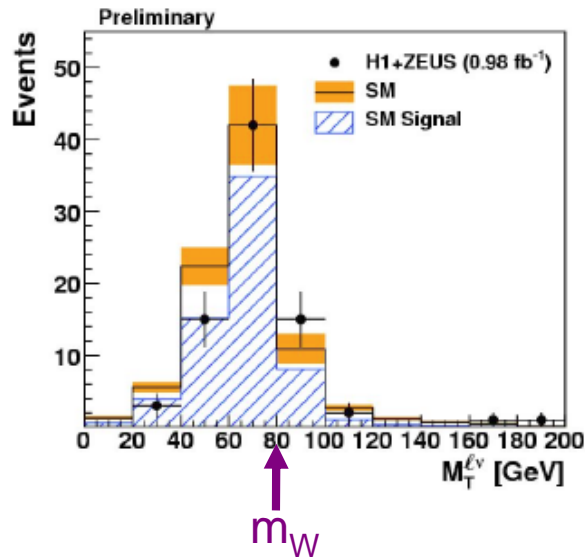
- In general, good agreement with SM prediction



H1+ZEUS prel. $e^+ p$	Data	SM prediction
$e + \mu$ total	53	49.8 ± 6.2
$p_T^X > 25 \text{ GeV}$	23	14.0 ± 1.9

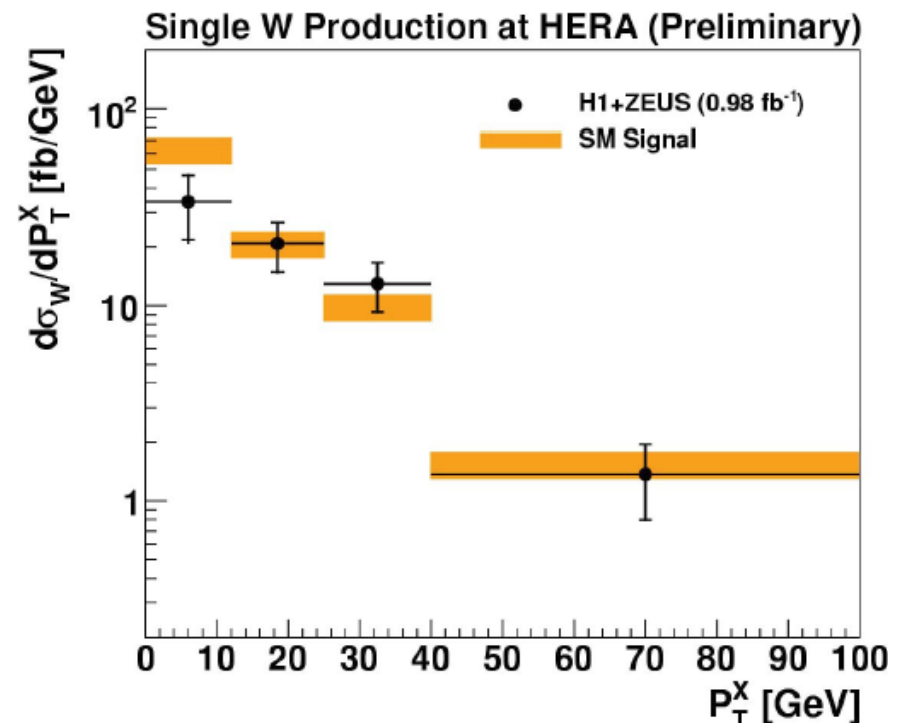
- Excess of H1 $e^+ p$ data at large P_T^X , small SM expectation
 - Not confirmed by ZEUS analysis
- Excess remains in common phase space of combined analysis (1.9σ)

Single W Production Cross Section



- High purity of $\sim 75\%$ 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

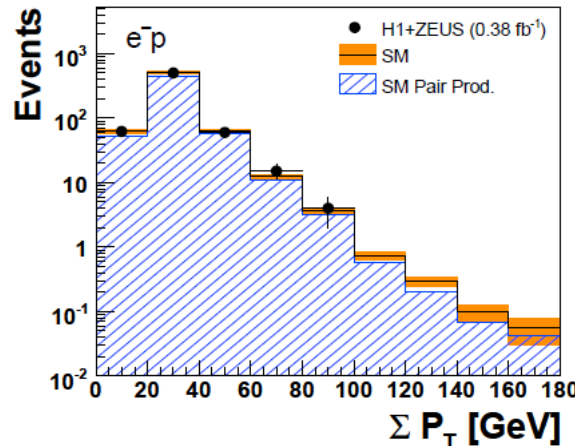
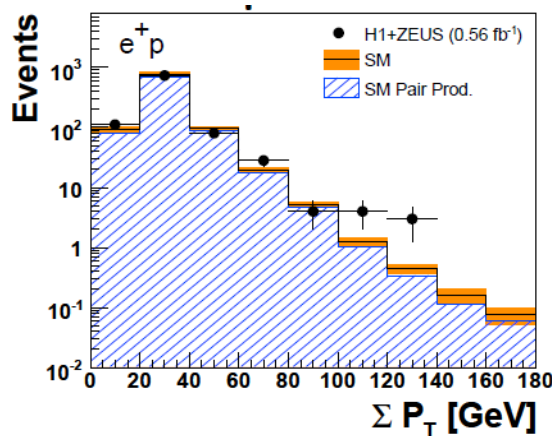
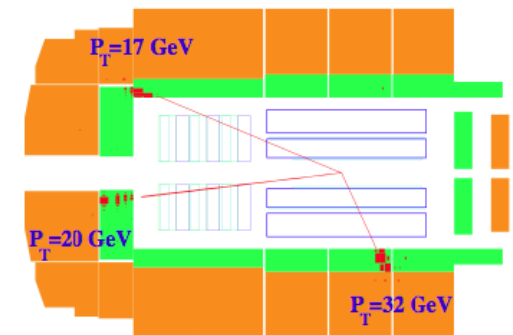
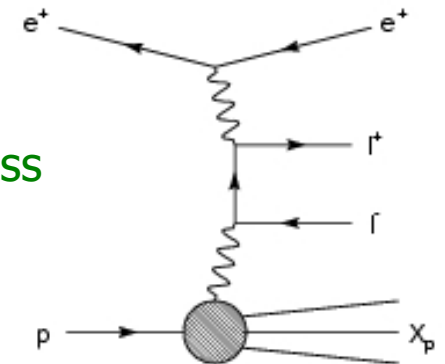
- Main Standard Model process with multi-lepton is $\gamma\gamma$ process
- QED cross section well known, modelled using GRAPE
- Any deviation, indication of new phenomena

Signature

- Events with 2 or more isolated high- P_T leptons (e or μ)

Results

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

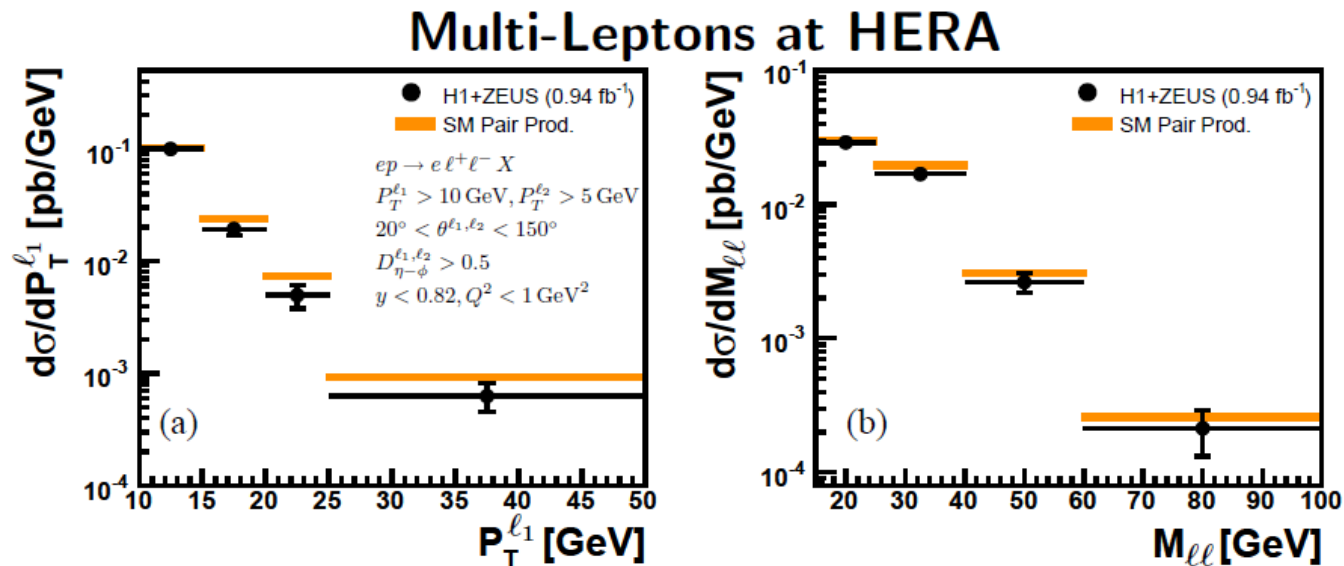


$\Sigma P_T > 100 \text{ GeV}$:

- e^+p data:
7 obs/ 1.94 ± 0.17 exp
(excess of 2.6σ)
- 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 μ pair production

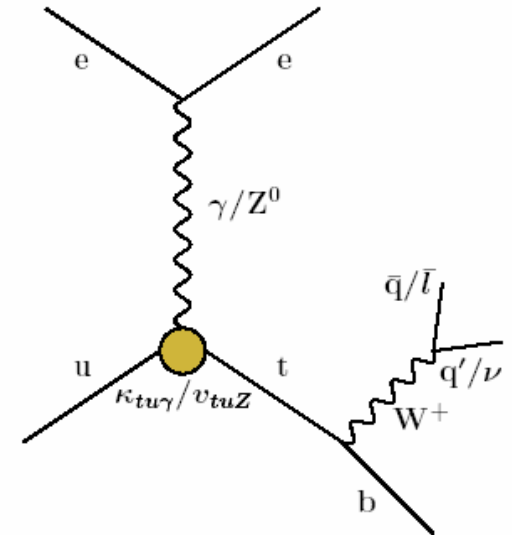


- Differential cross sections measured as function of P_T of leading lepton and invariant mass of lepton pair
- Total visible cross section $0.66 \pm 0.03(\text{stat.}) \pm 0.03(\text{sys.})$ pb in good agreement with SM prediction 0.69 ± 0.02 pb (GRAPE)

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 $t\bar{u}V$ (charm PDF of proton small at high x)
- Effective anomalous coupling at $t\bar{u}\gamma$ or $t\bar{u}Z$ vertex



$$\Delta L_{eff} = e e_t \bar{t} \frac{i \sigma_{\mu\nu} q}{\Lambda} \kappa_{t\bar{u}\gamma} u A^\mu + \frac{g}{2 \cos \theta_W} \bar{t} \gamma_\mu v_{t\bar{u}Z} u Z^\mu + h.c.$$

magnetic

vector coupling

Search for Single-top Production

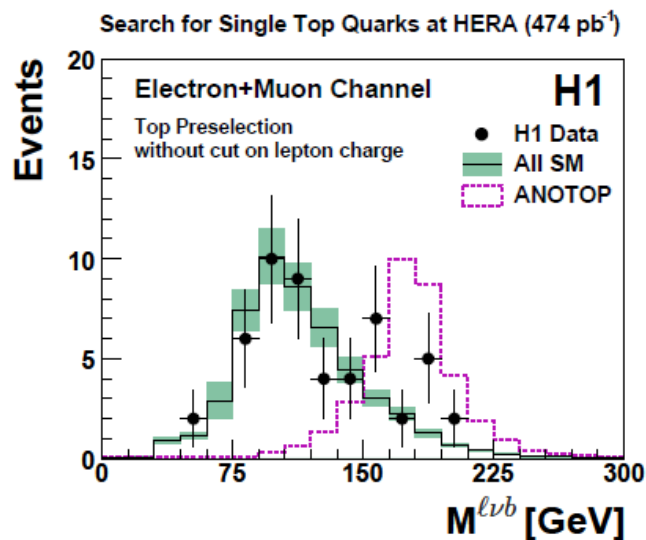
Decay modes:

- **Standard Model**

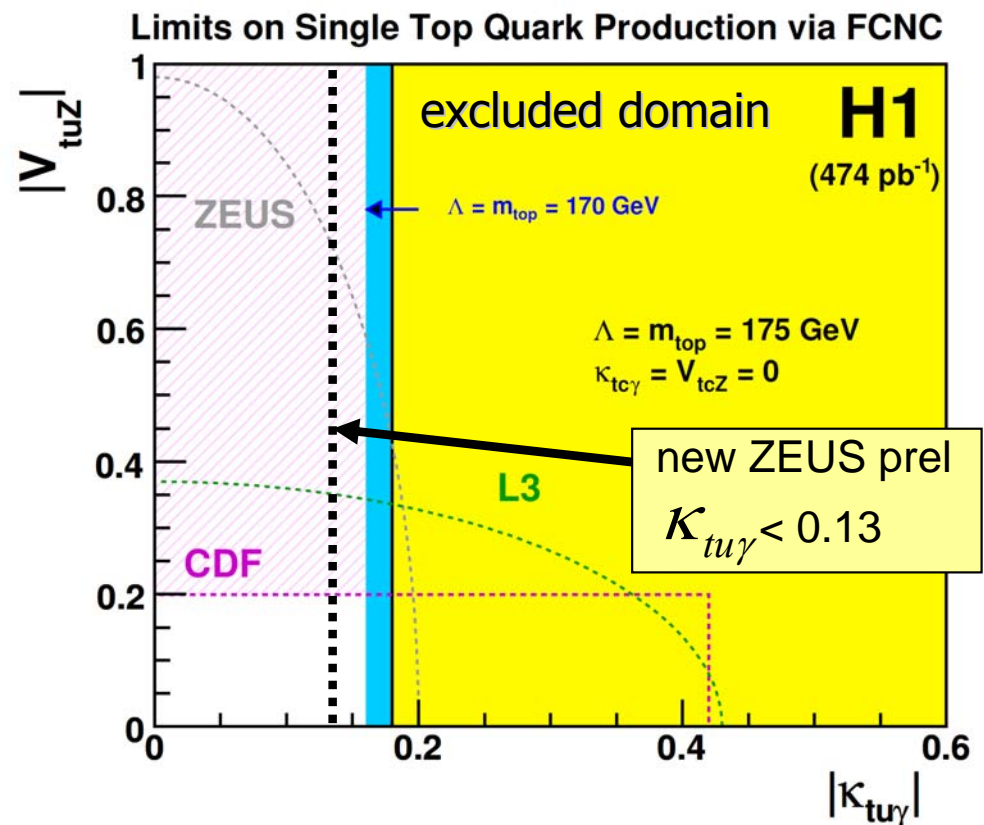
- leptonic (BR 32%): $t \rightarrow bW, W \rightarrow l\nu$ isol.lepton, jet, p_T^{miss}
- hadronic (BR 68%): $t \rightarrow bW, W \rightarrow q^- \bar{q}$ 3 jets, m_W, m_{top}

- **Flavor Changing Neutral Currents**

- $K_{tu\gamma}$ $t \rightarrow u\gamma$ n-jets (+lepton pairs)
- V_{tuZ} $t \rightarrow uZ^0$



No significant excess in the signal region, upper limits are set on anomalous coupling $K_{tu\gamma}$



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.

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

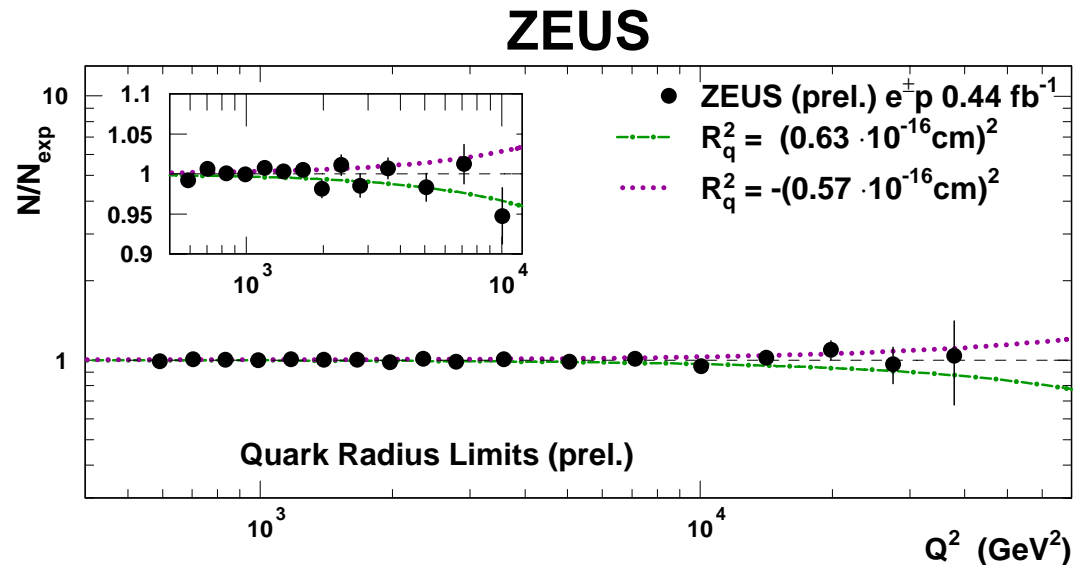
- Limit on quark size (95%CL), assuming point-like electron

- ZEUS: $R_q < 0.62 \cdot 10^{-18} \text{m}$
- H1: $R_q < 0.74 \cdot 10^{-18} \text{m}$

- Use similar fit for limits on contact interactions and large extra dimensions

ZEUS prel.: $\Lambda > 3.8 - 8.9 \text{ TeV (95\%C.L.)}$

R_q is rms of electroweak charge



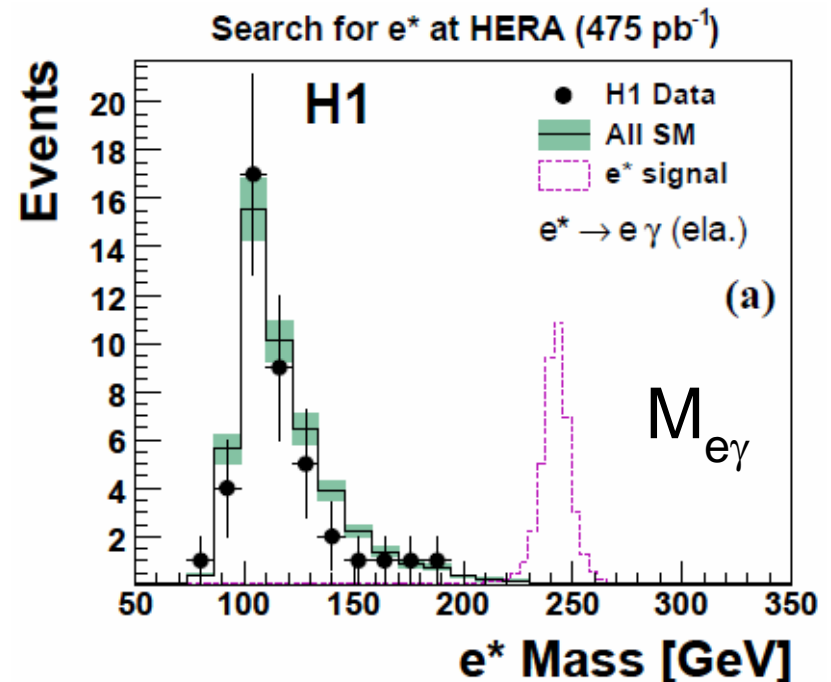
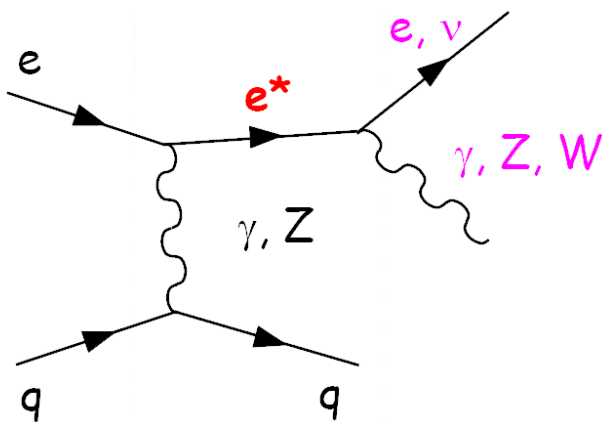
Excited Fermions

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

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

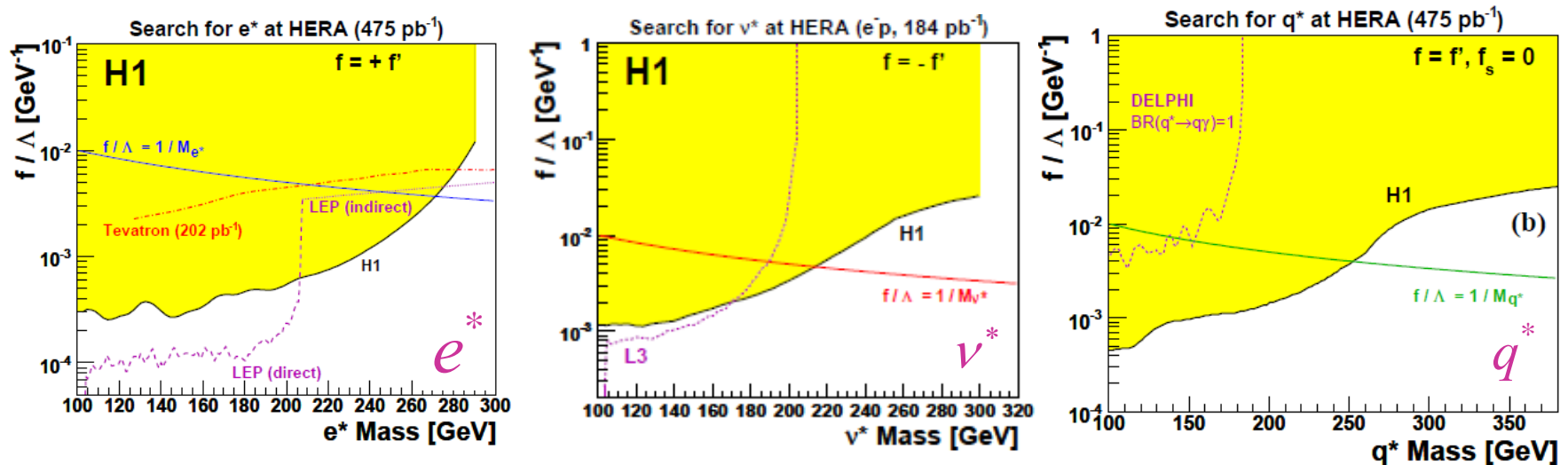
[f, f' and f_s are the couplings to the SM gauge groups]

Example: production and decay of e*



Excited Fermions

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

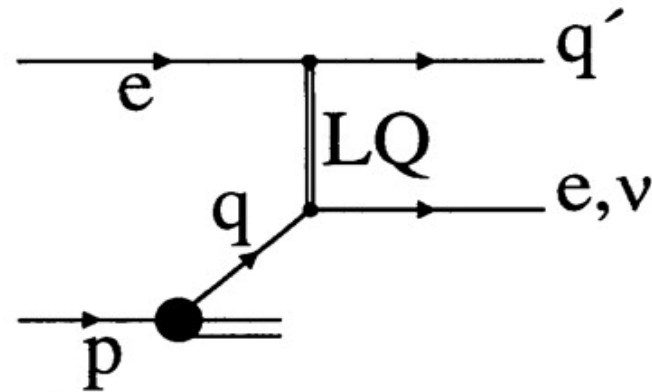
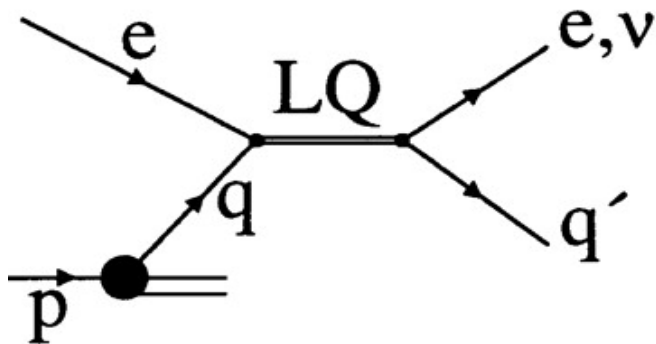


f/Λ limits can be translated into
mass limits assuming $f/\Lambda = 1/M_{f^*}$

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

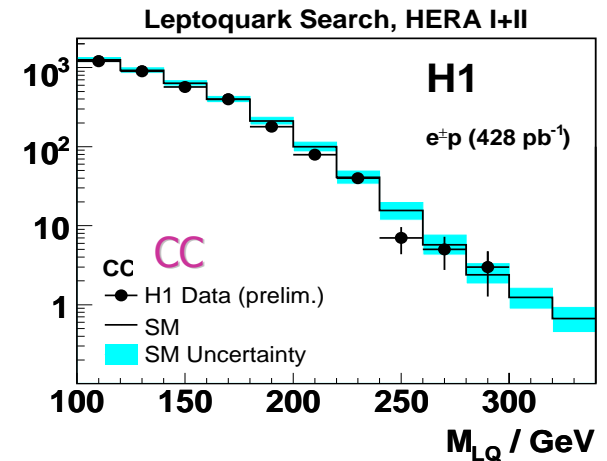
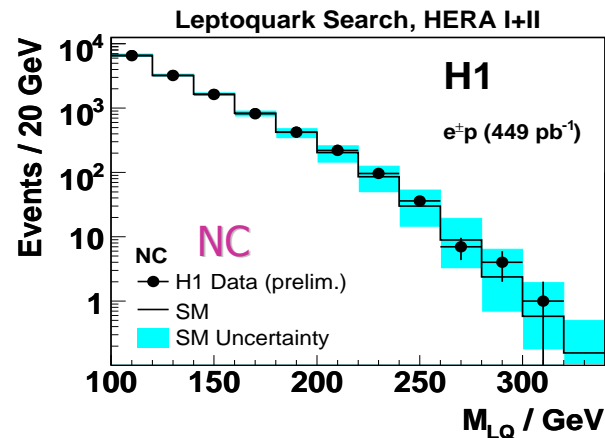
Leptoquarks

- 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 ν -jet:

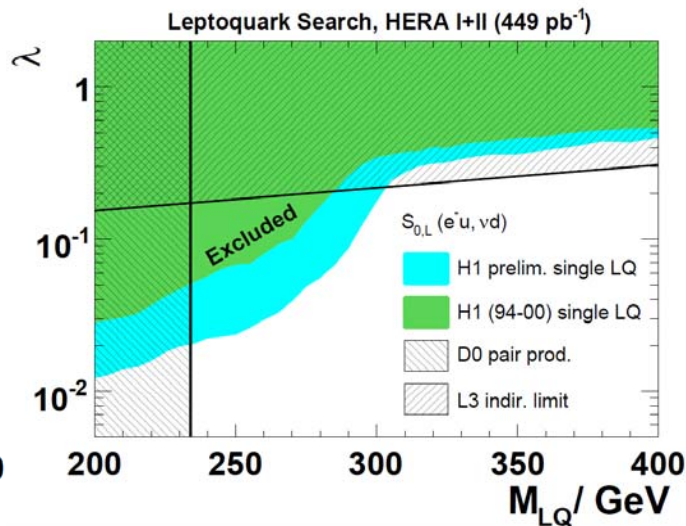
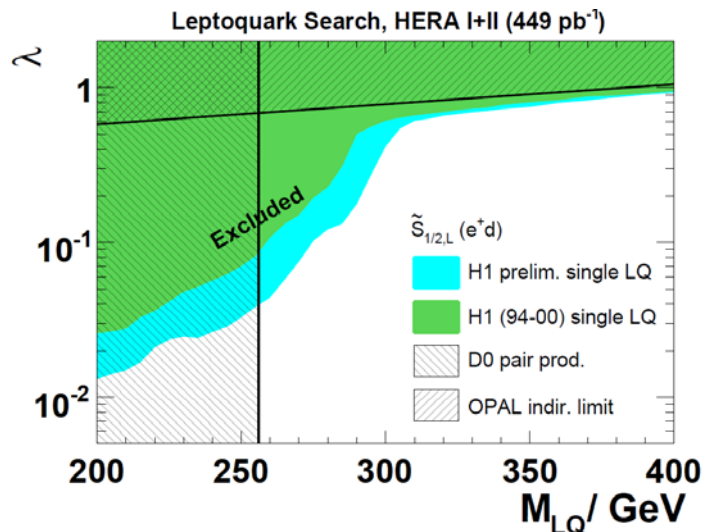


Leptoquarks

- 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 ≥ 2 high- P_T objects:

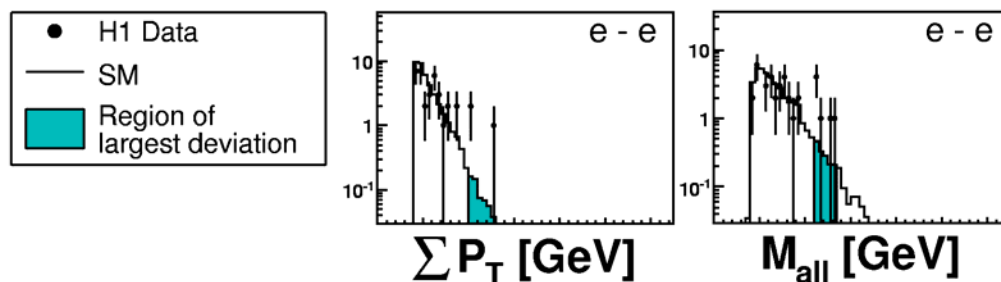
$e, \mu, \text{jets}, \gamma, \nu$

$P_T > 20 \text{ GeV}$

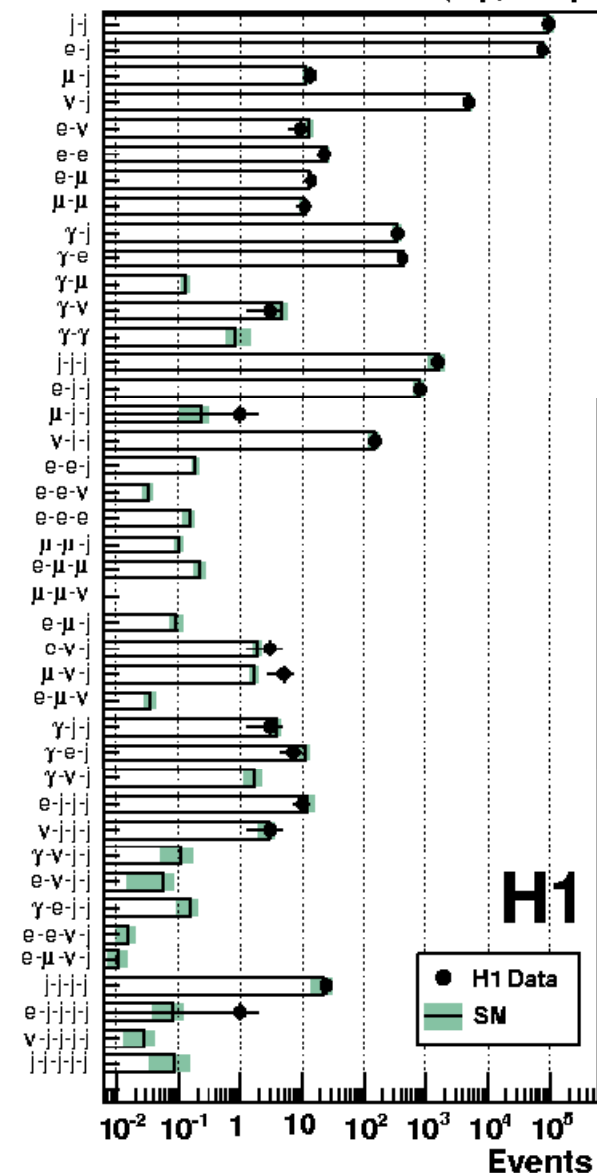
$10^\circ < \theta < 140^\circ$

- 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.



H1 General Search at HERA (e^+p , 285 pb^{-1})





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