Electroweak Physics and Searches for New Physics at HERA

Uwe Schneekloth
DESY
On behalf of the H1 and ZEUS Collaborations

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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

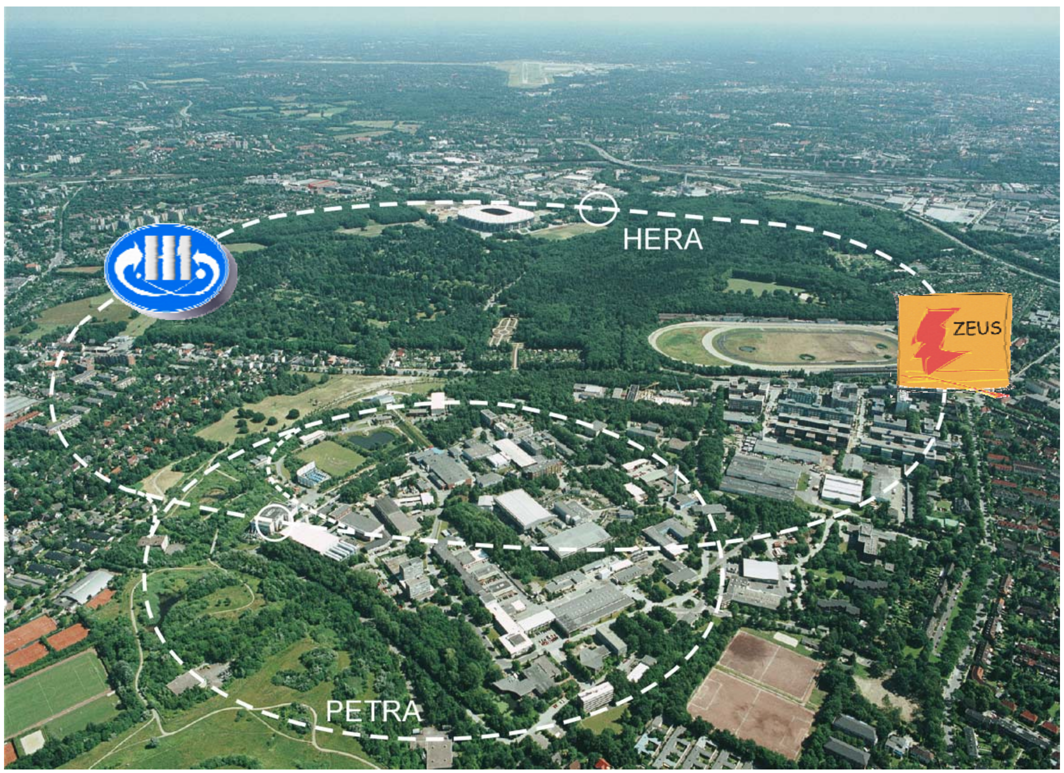
World's only electron proton collider, in operation 1992-2007

HERA-I (1992-2000)

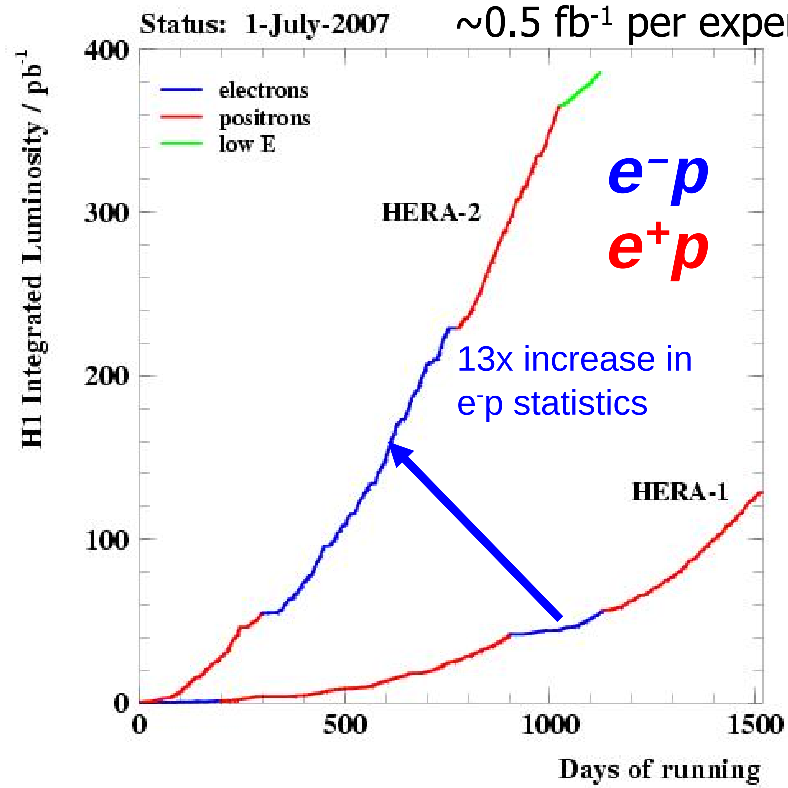
- ~130 pb^{-1} per exp., (90% e^+p)

HERA-II (2003-07)

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

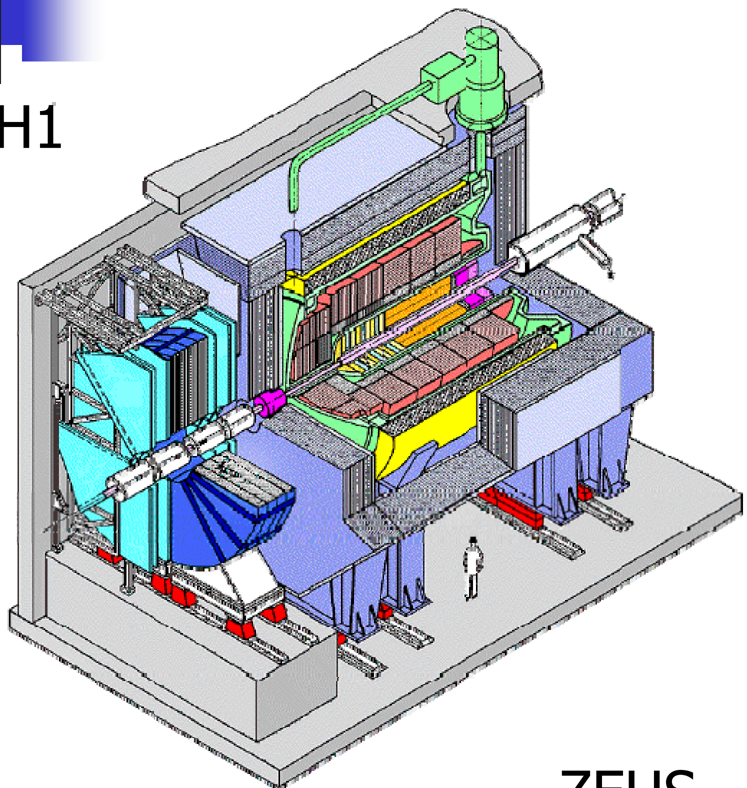


Total integrated luminosity ~0.5 fb^{-1} per experiment



H1 and ZEUS Experiments

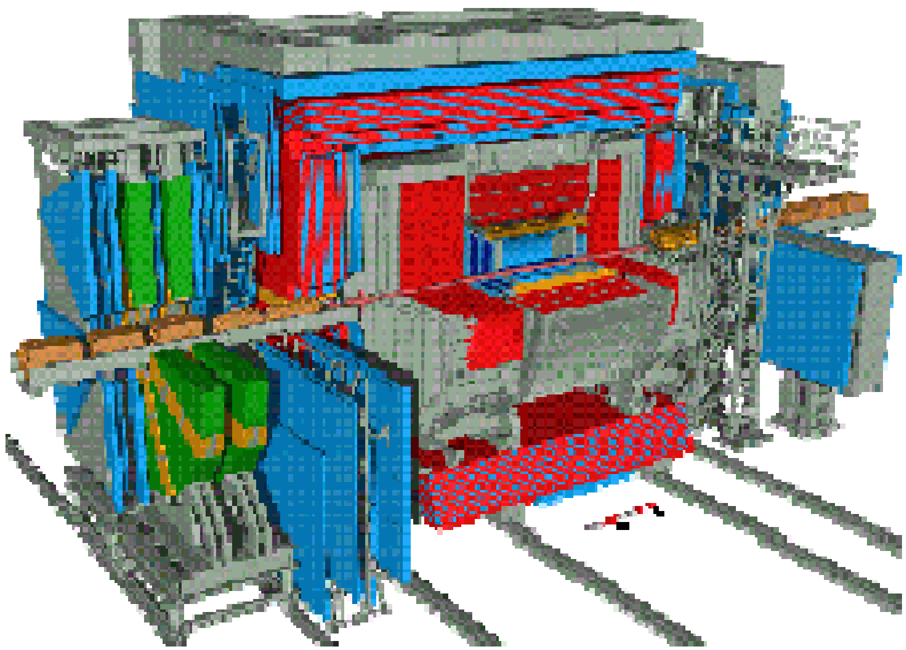
H1



Large general purpose collider experiments

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

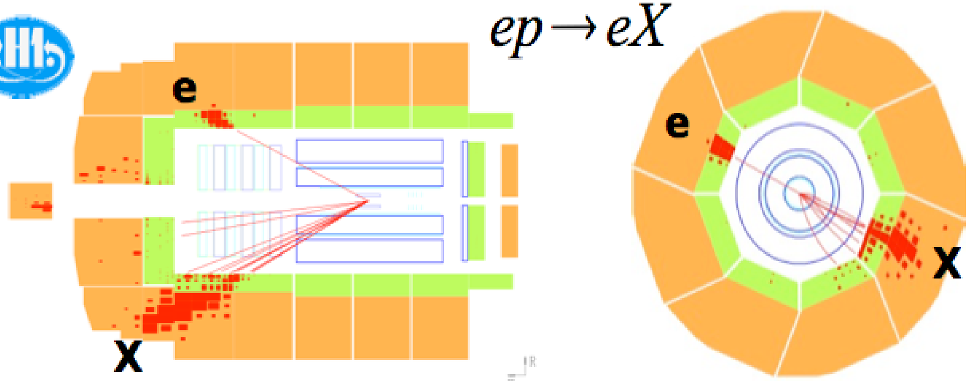
ZEUS

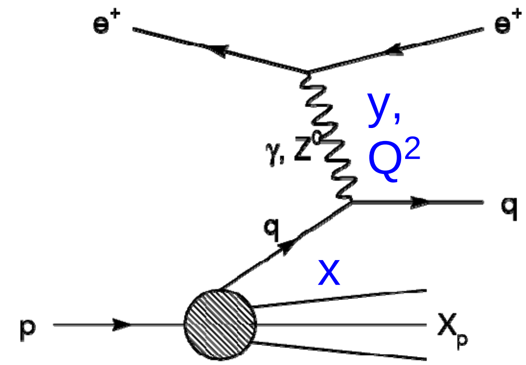


Deep Inelastic Scattering at HERA

Neutral Current

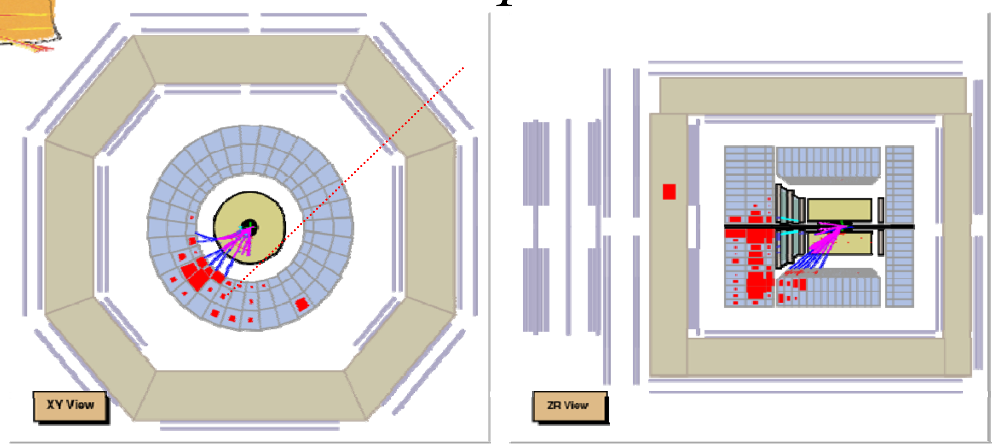
$ep \rightarrow eX$





Charged Current

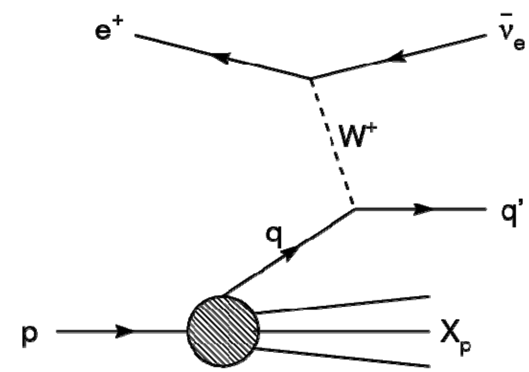
$ep \rightarrow \nu X$



Q^2 – virtuality of exchange boson

x – Bjorken scaling variable

y – Inelasticity



Unpolarized DIS Cross Sections

Neutral Current

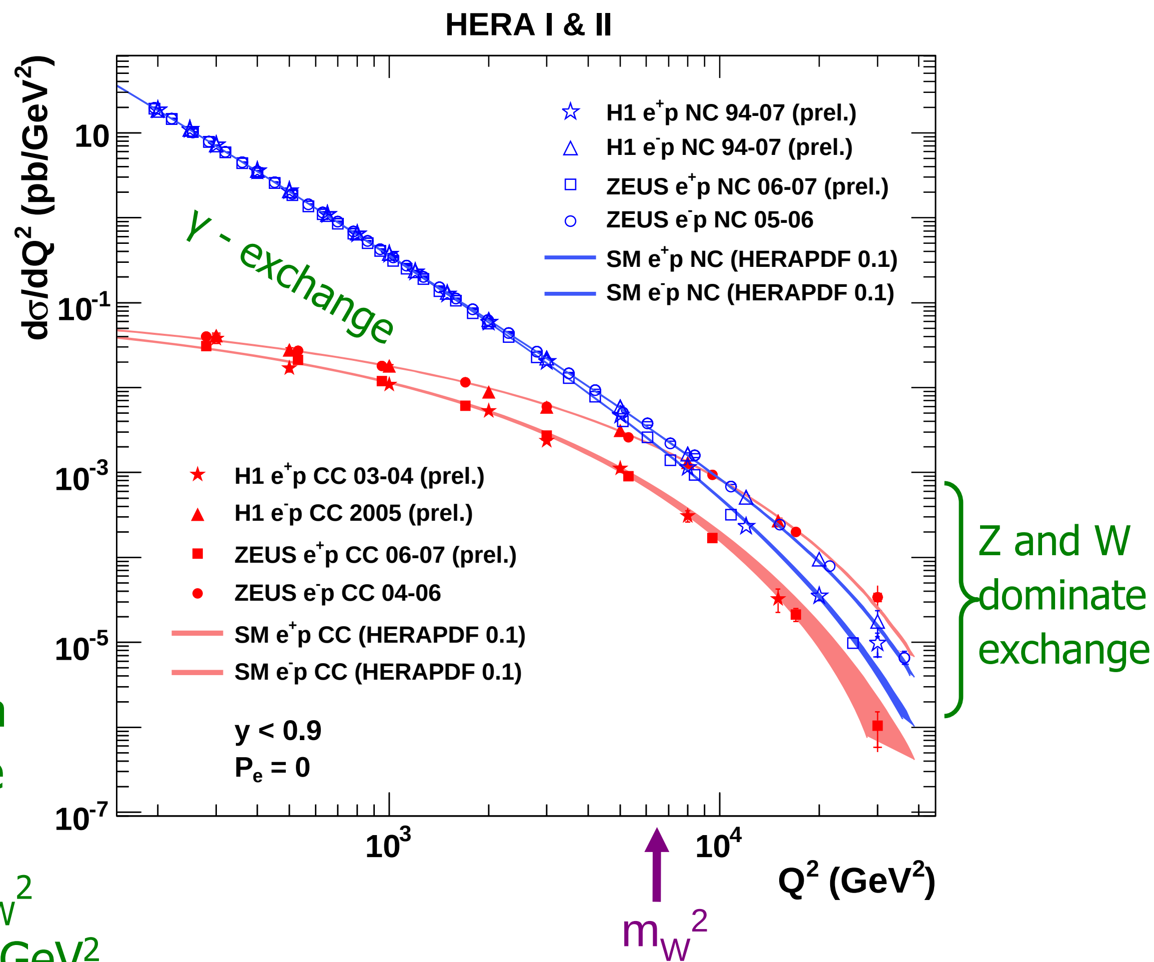
$$\frac{d^2\sigma^{e^\pm p}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

Charged Current

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

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

Electroweak unification



- 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 $1/Q \sim 10^{-18}$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)

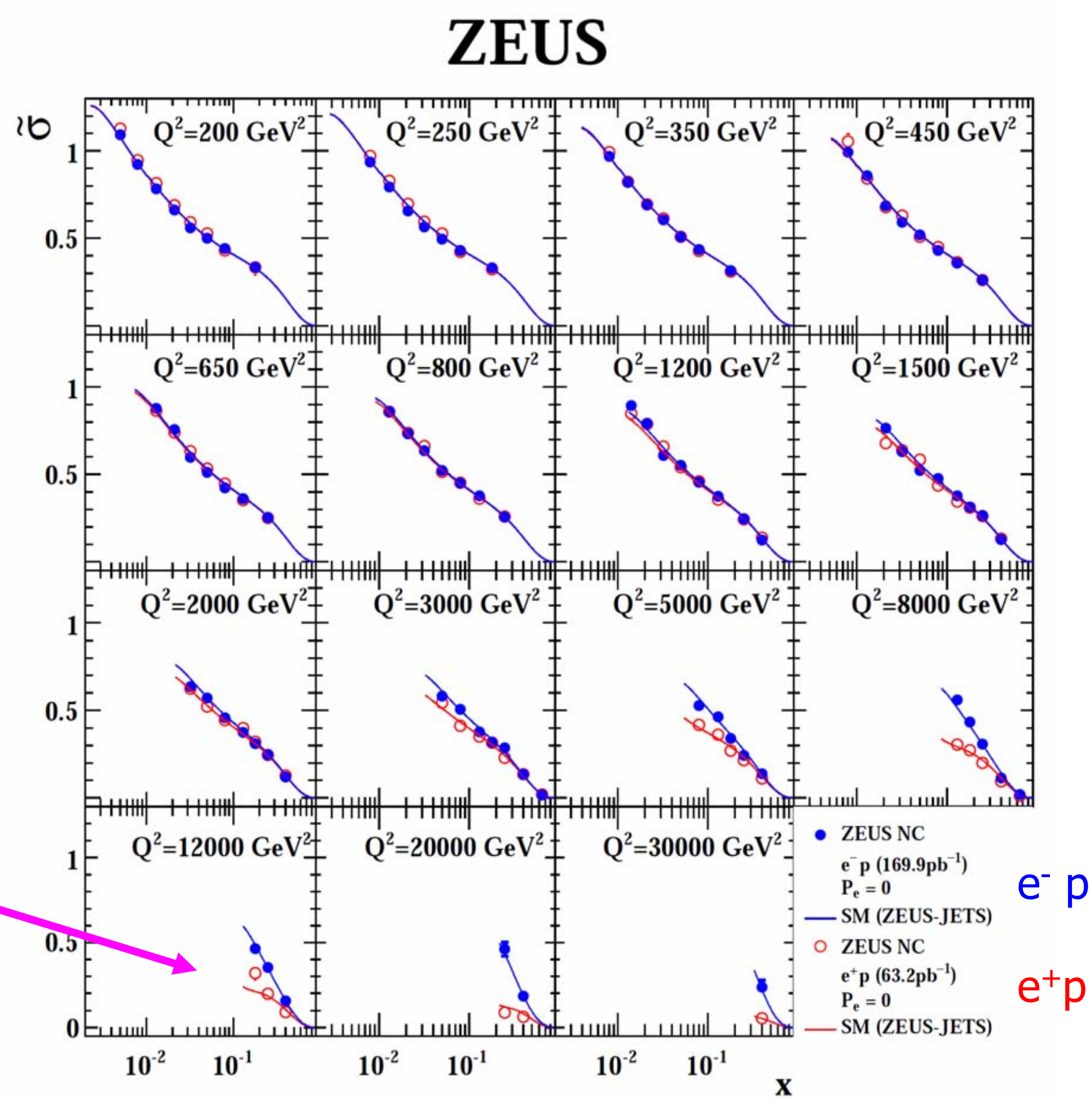
$$\tilde{F}_2^\pm = F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2+M_Z^2} F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2 v_e a_e)\kappa^2 \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z$$

xF_3 γZ 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 Q^2
- Cross section difference gives interference $xF_3^{\gamma Z}$



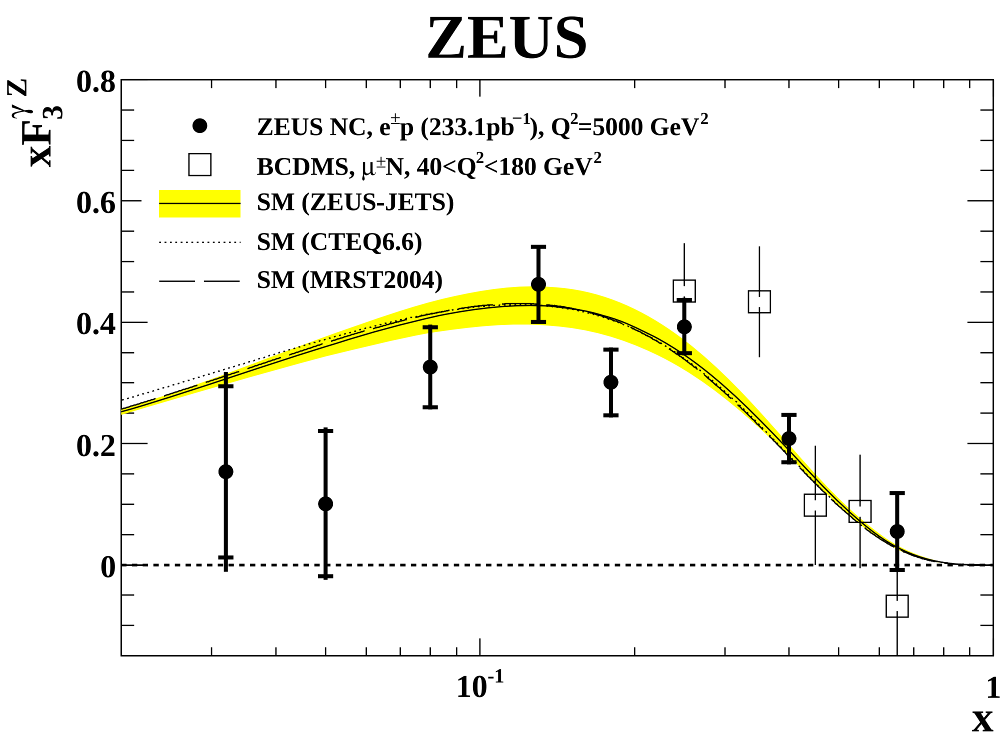
Interference Structure Function $xF_3^{\gamma Z}$

Charge asymmetry observed:
Exploit difference in e^-p/e^+p cross sections to measure xF_3

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

γZ interference dominates in HERA kinematic range:
Measure "interference structure function"

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



- All measurements extrapolated to Q^2=5000 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

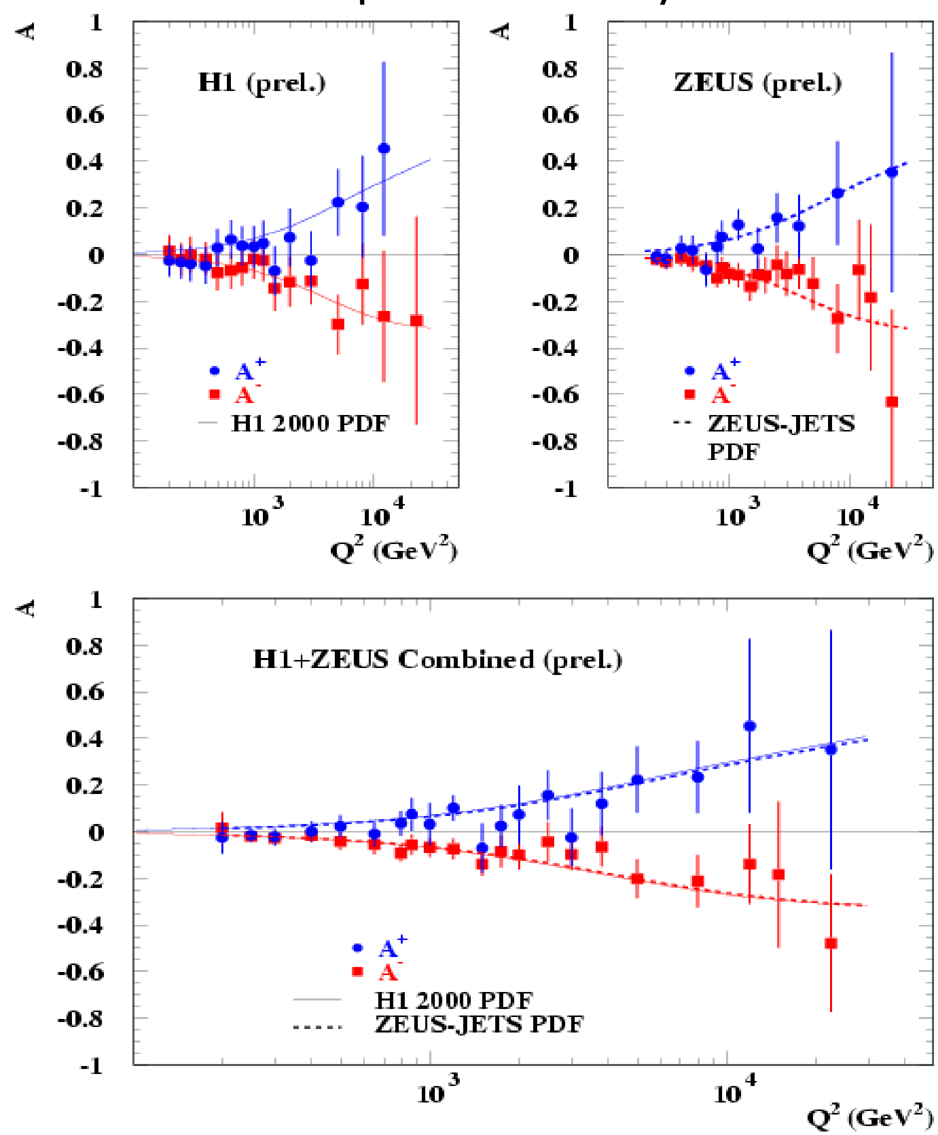
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

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

- 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

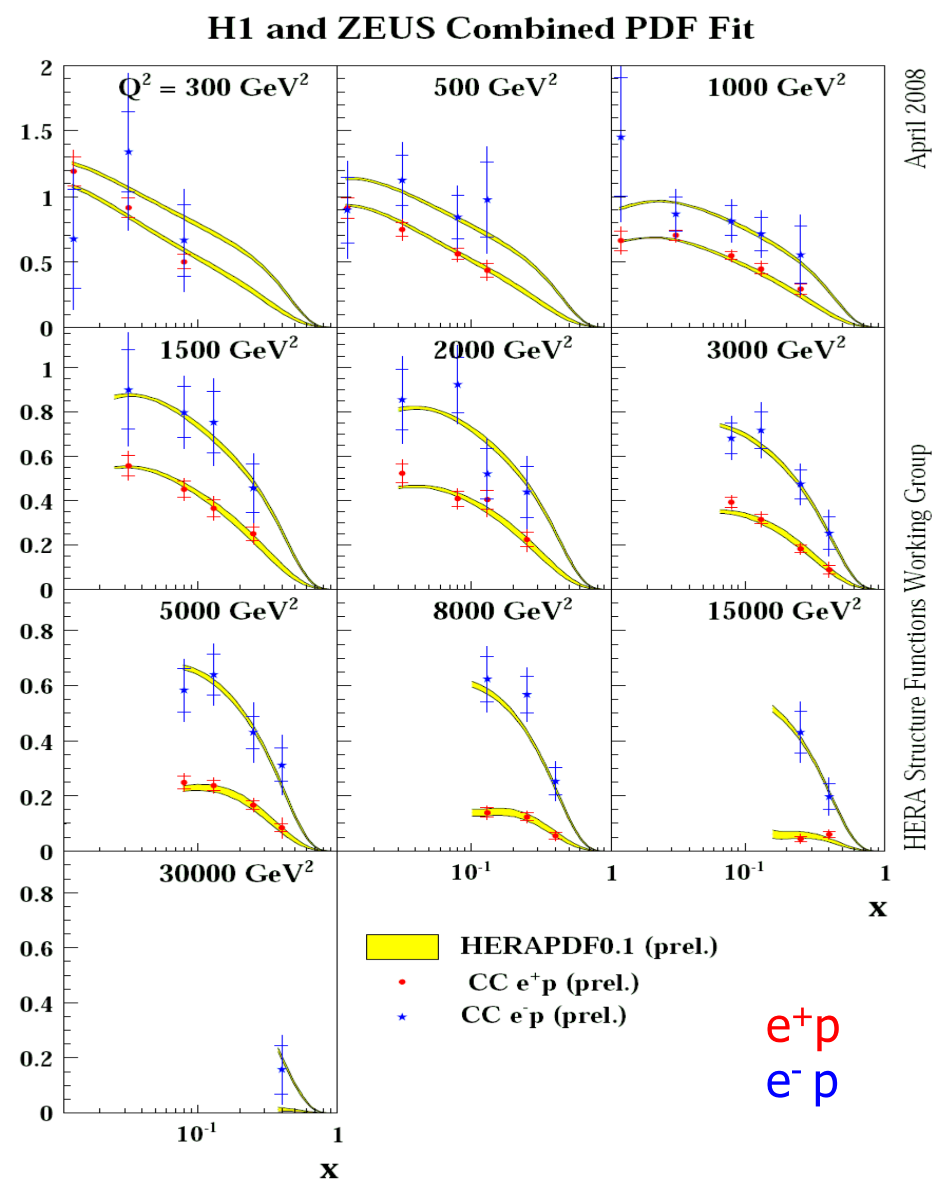


Unpolarized Charged Current Cross Section

- 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 ~ (uud) at high x

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

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

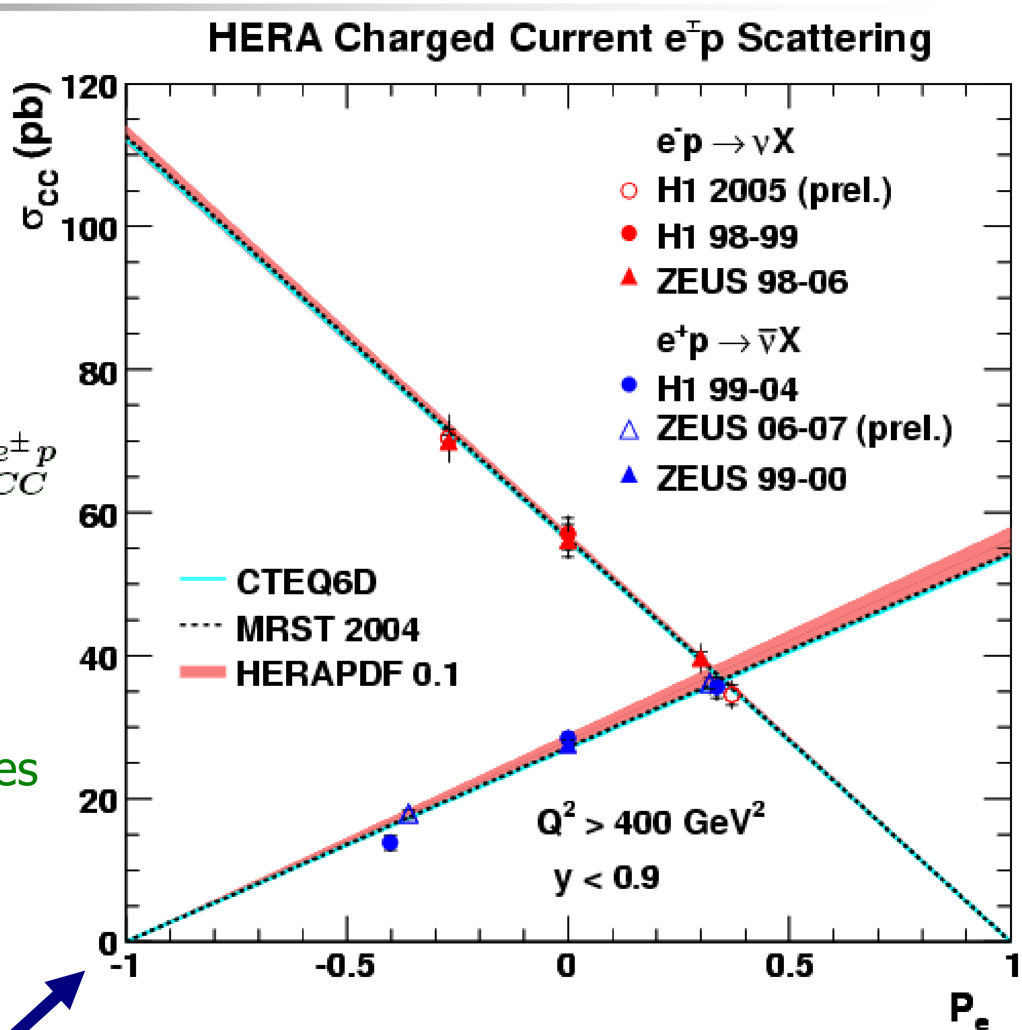


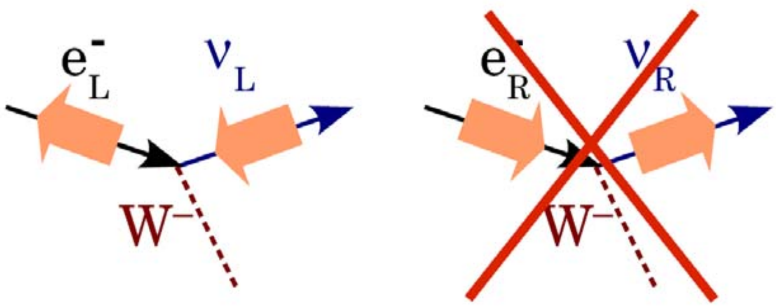
Polarized Charged Current Cross Section

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

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

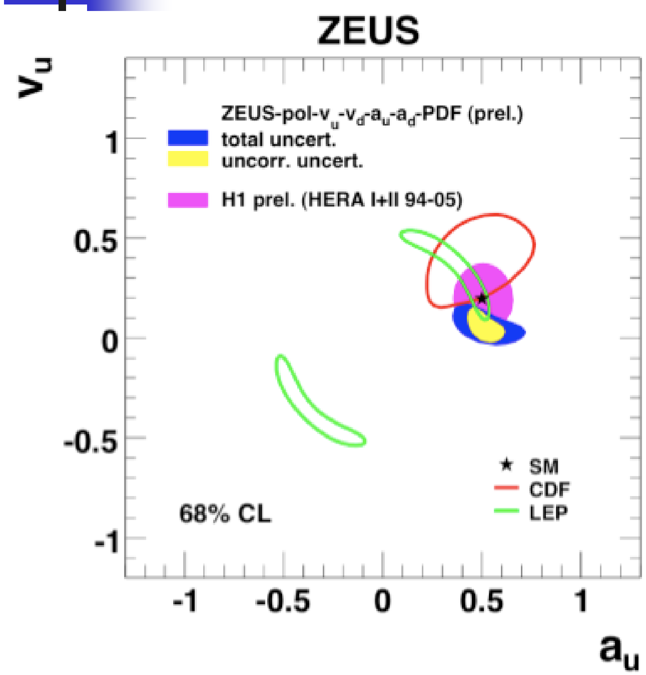
- Fundamental feature of SM directly visible:
  - Only L(R)-handed (anti)particles interact weakly

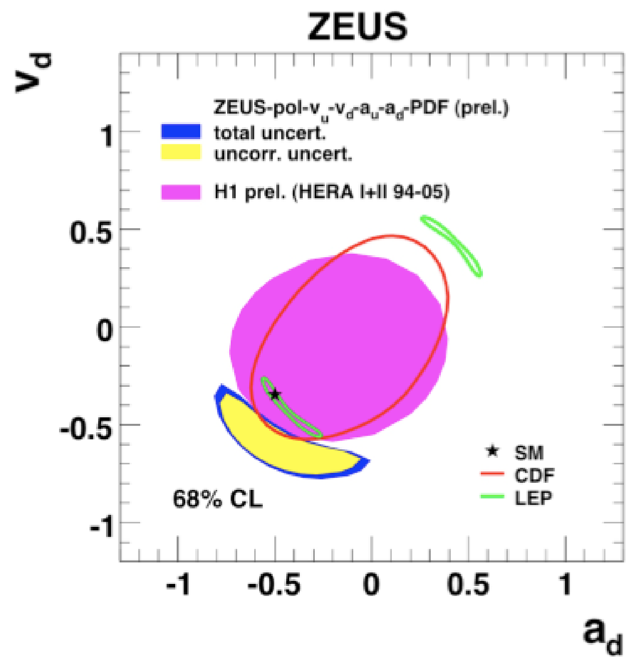


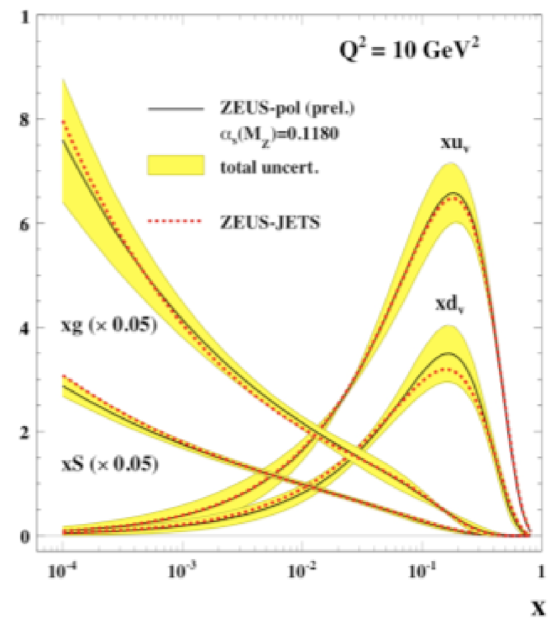


Right-handed currents forbidden in SM.
At P =-1 (extrapolated): $M_W{}^R$ > 208 GeV (H1)

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

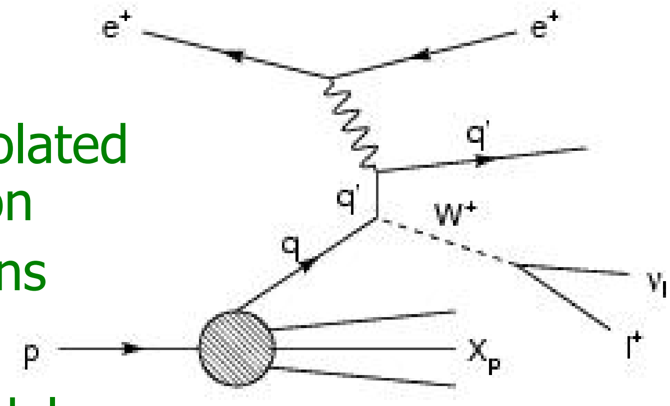
Isolated Lepton Events with Missing p_T

Motivation:

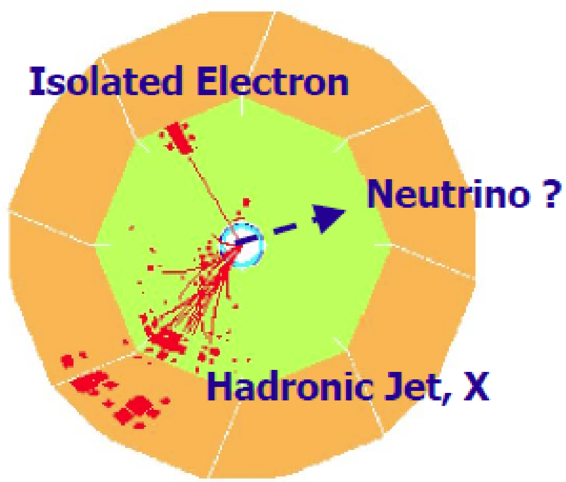
- Main Standard Model process for high P_T isolated lepton with missing P_T is single W production
- Other SM process have smaller cross sections

→ Measure single W production (σ~1.3pb)

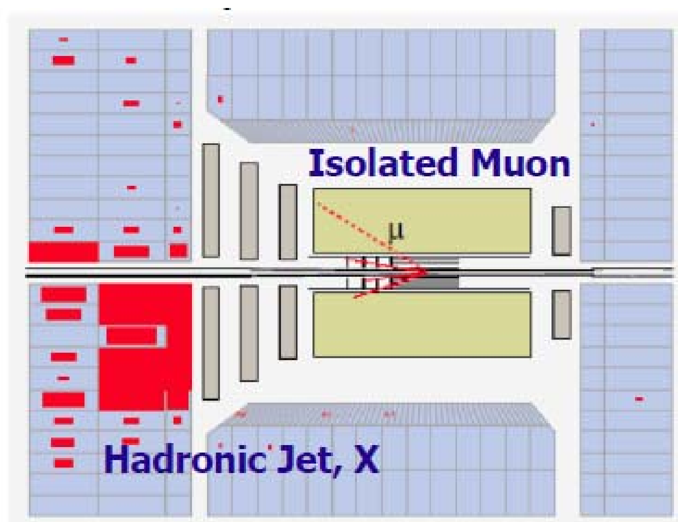
→ Search for physics beyond the Standard Model



Experimental signature:



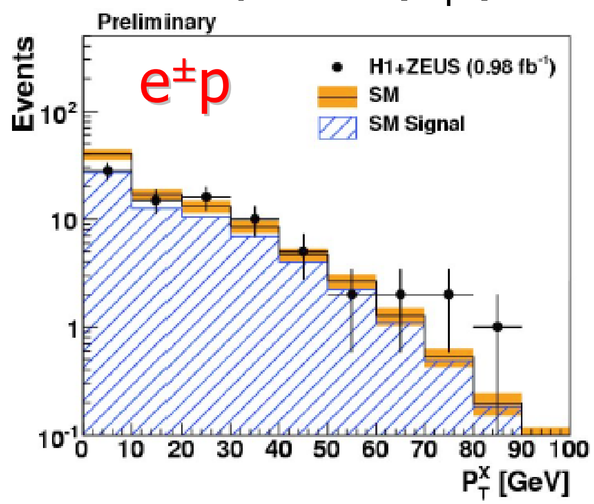
e + P_T^{Miss} event in H1



μ + P_T^{Miss} event in ZEUS

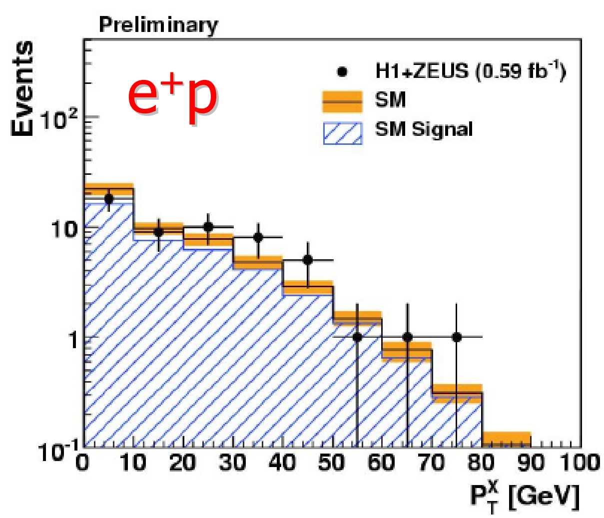
Isolated Lepton Events with Missing p_T

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 + μ total	81	87.8±10.6
p_T^X>25GeV	29	24.0±3.2

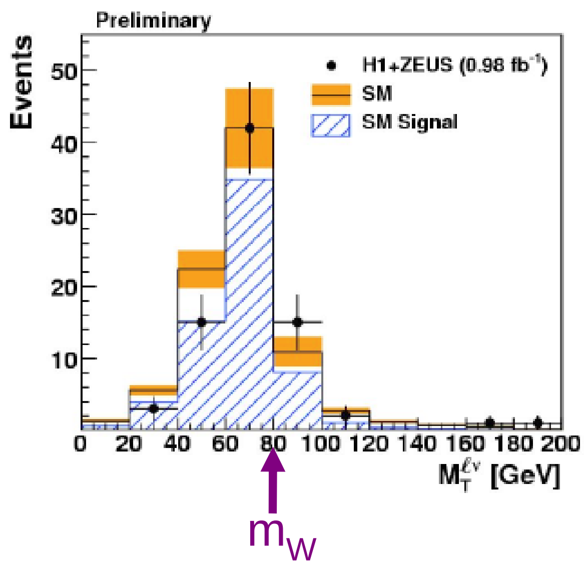
- In general, good agreement with SM prediction



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

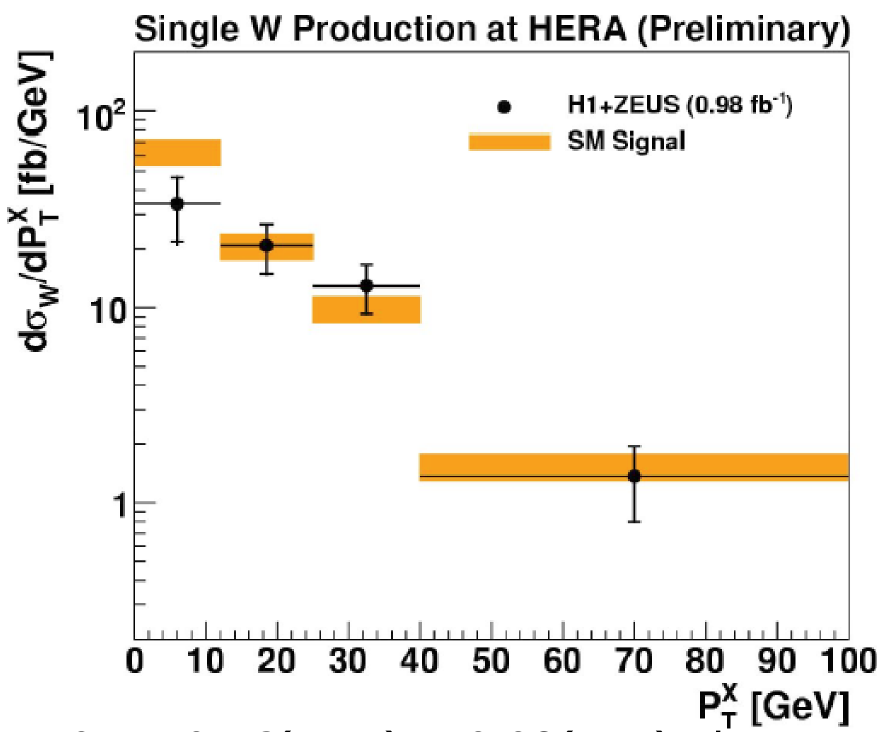
- Excess of H1 e^+p data at large P_T^X, small SM expectation
  - Not confirmed by ZEUS analysis
- Excess remains in common phase space of combined analysis (1.9σ)

Single W Production Cross Section



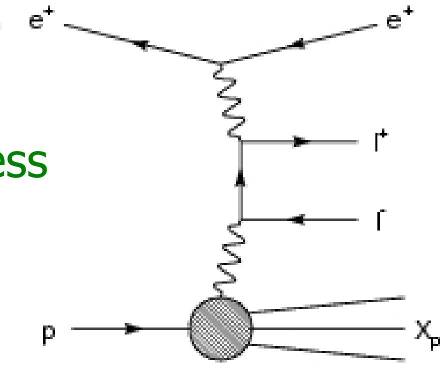
- High purity of ~75% of W production
- Clear Jacobian peak
- Strong evidence for W production

- 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 σ = 1.07 ± 0.16(stat.) ± 0.08(sys.) pb
In good agreement with SM prediction 1.26 ± 0.19 pb (EPVEC at NLO)

Multi-Lepton Production



Motivation

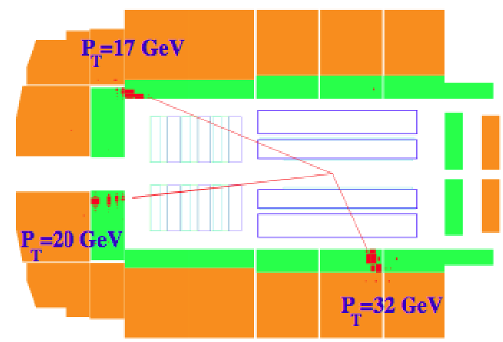
- Main Standard Model process with multi-lepton is γγ process
- QED cross section well known, modelled using GRAPE
- Any deviation, indication of new phenomena

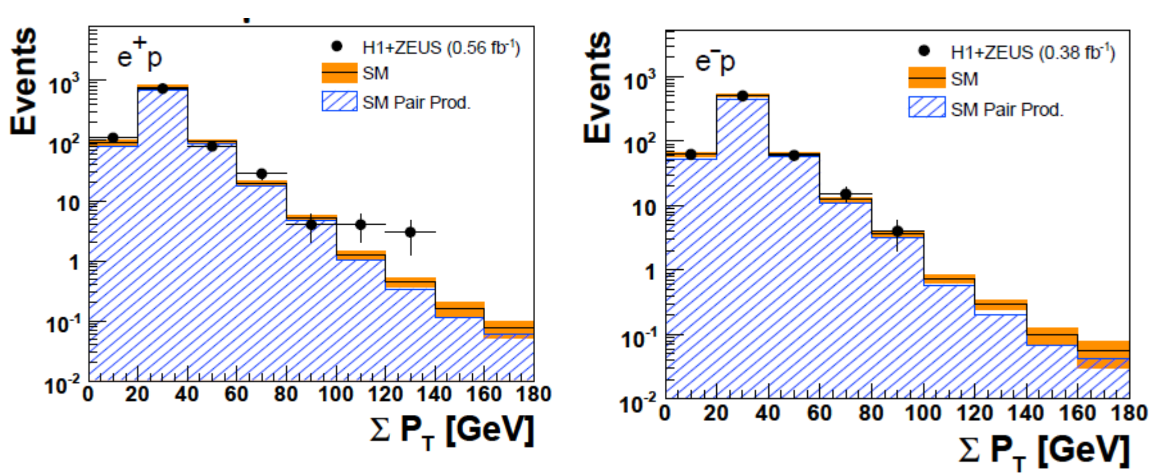
Signature

- 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



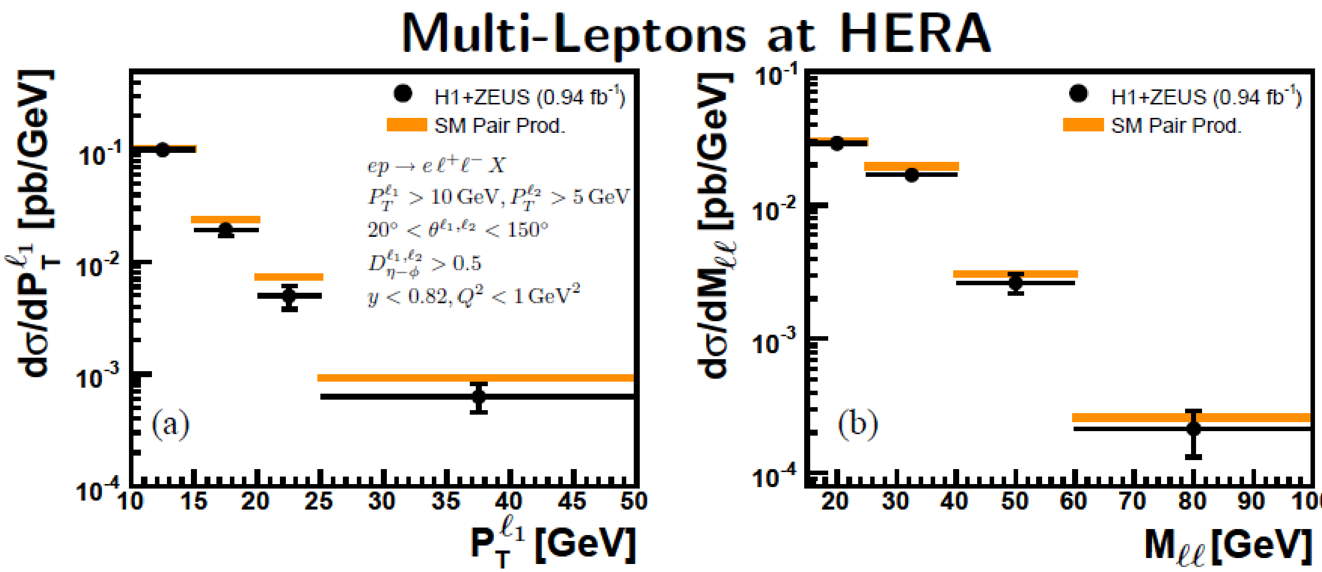


$\Sigma P_T > 100$ GeV:

- e^+p data: 7 obs/1.94±0.17 exp (excess of 2.6 σ)
- e^-p data: 0 obs/1.19±0.12 exp

Measurement of $\gamma\gamma \to l^+l^-$ Cross Section

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

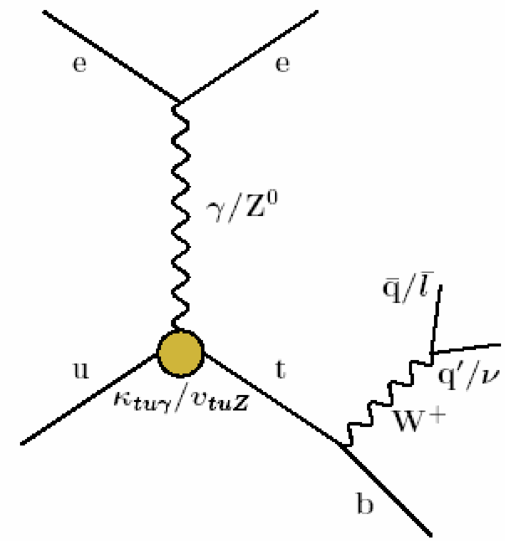


- Differential cross sections measured as function of P_T of leading lepton and invariant mass of lepton pair
- Total visible cross section 0.66±0.03(stat.)±0.03(sys.) pb in good agreement with SM prediction 0.69±0.02 pb (GRAPE)

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 tuV (charm PDF of proton small at high x)
- Effective anomalous coupling at t-u-γ or t-u-Z vertex



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

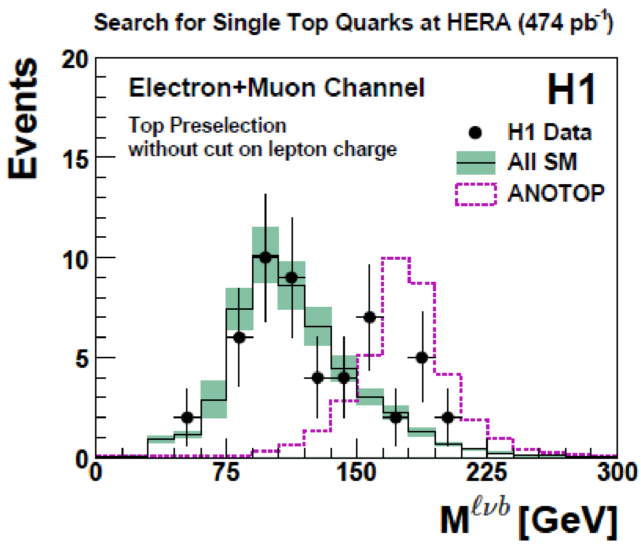
magnetic

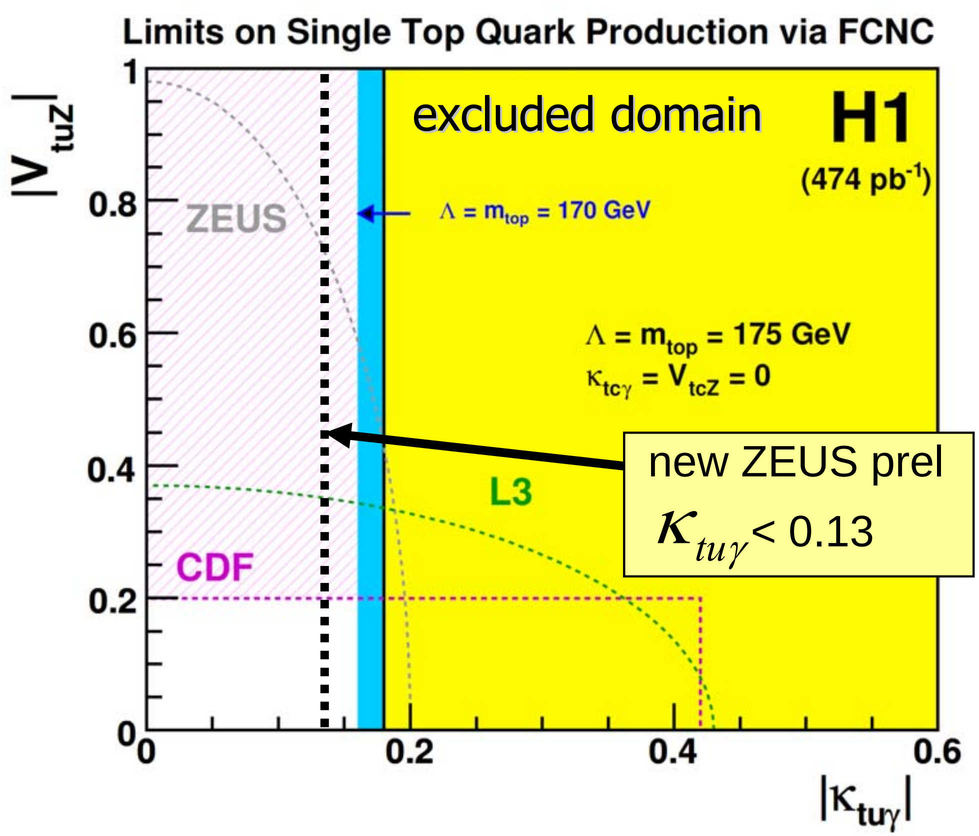
vector coupling

Search for Single-top Production

Decay modes:

- Standard Model
  - leptonic (BR 32%): t→bW, W→lν   isol.lepton, jet, p_T^{miss}
  - hadronic (BR 68%): t→bW, W→q‾q 3 jets, m_W, m_{top}
- Flavor Changing Neutral Currents
  - $\kappa_{tu\gamma}$ t→uγ   n-jets (+lepton pairs)
  - v_{tuZ} t→uZ^0





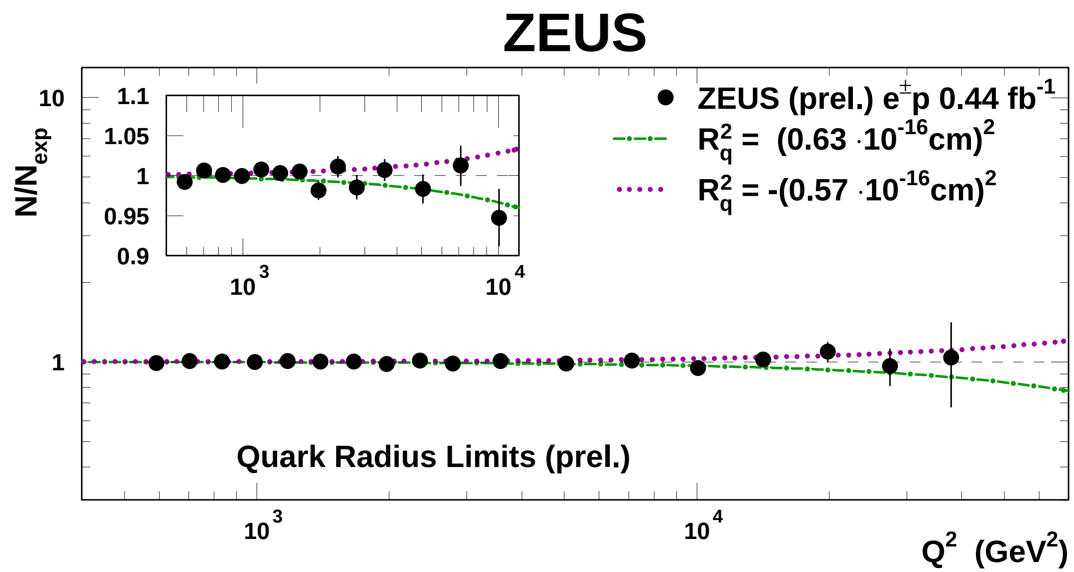
No significant excess in the signal region, upper limits are set on anomalous coupling $\kappa_{tu\gamma}$

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.

R_q is rms of electroweak charge

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



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

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

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

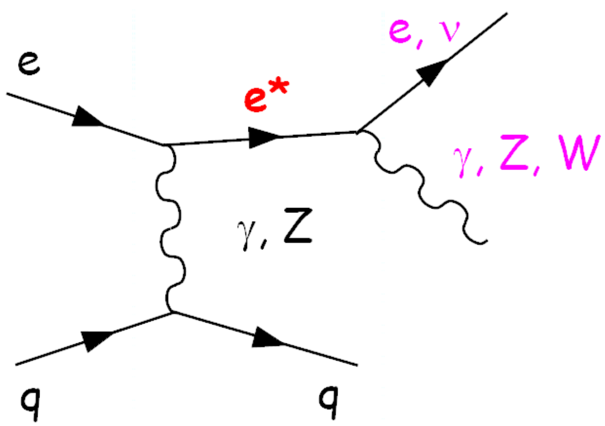
Excited Fermions

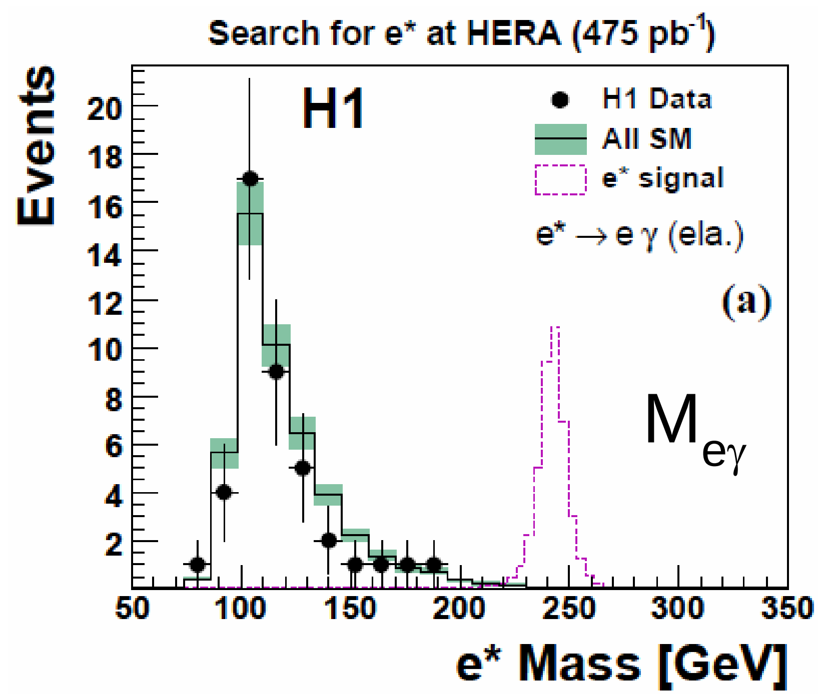
- Excited fermions would be signature of compositeness
- Compositeness could explain 3 families and mass hierarchy
- Excitation/de-excitation described by effective Lagrangian:

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

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

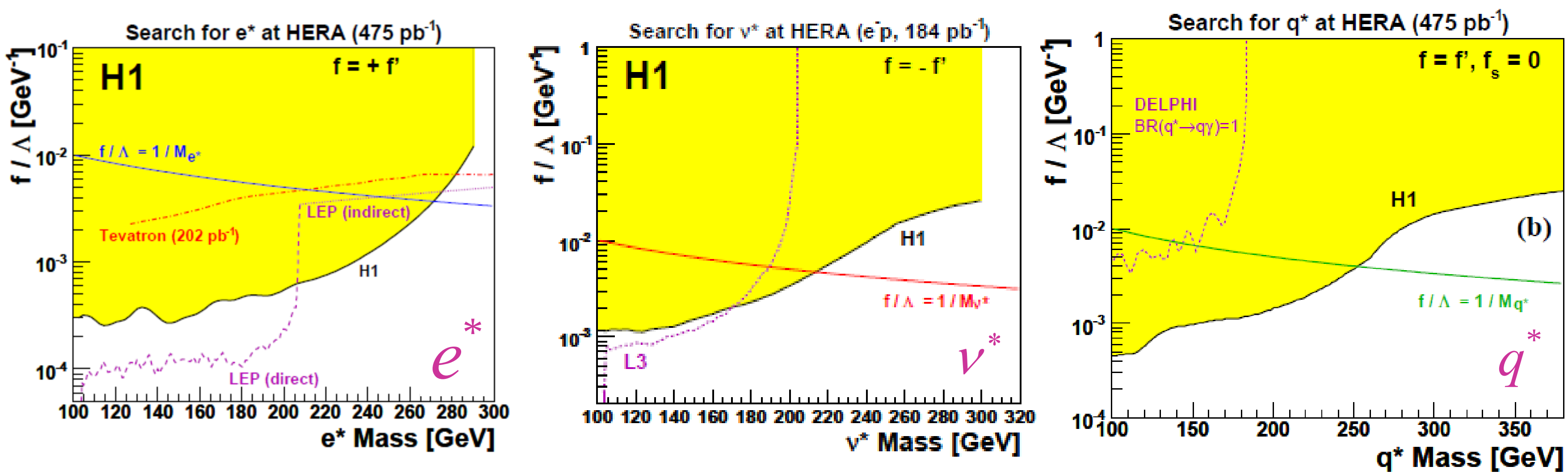
Example: production and decay of e*





Excited Fermions

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

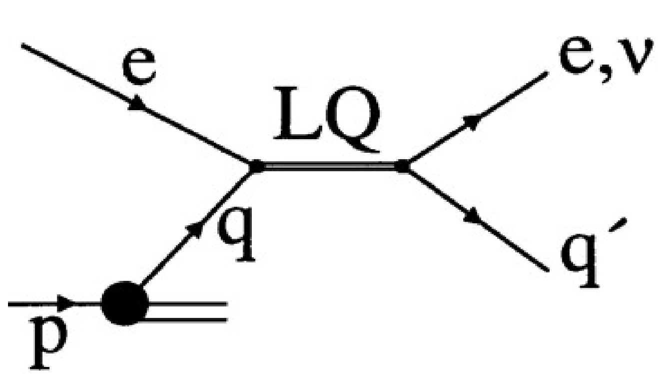


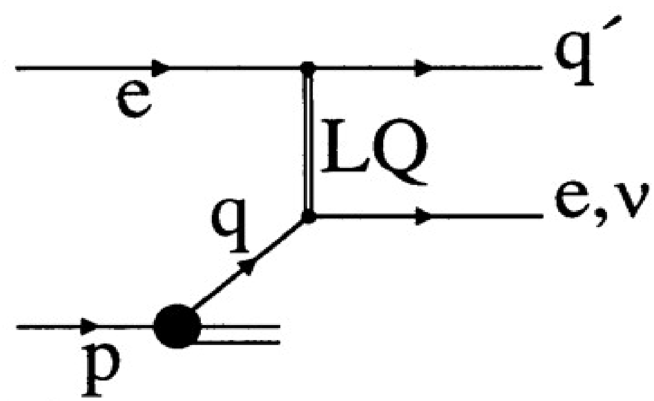
f/Λ limits can be translated into mass limits assuming $f/\Lambda = 1/M_{f^*}$

- M_e^* >272 GeV
- M_ν^* >213 GeV
- M_q^* >252 GeV (assuming f_s=0)

Leptoquarks

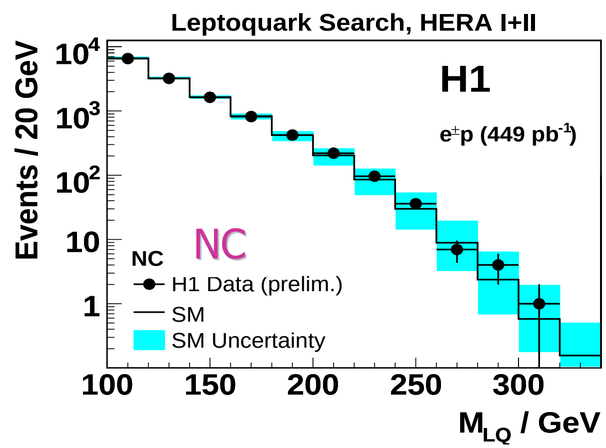
- Leptoquarks appear in many SM extensions
- Couple to both electrons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) number
  - Fermion number: F= 3B+L = 0, 2
- LQs model are explored in Buchmüller-Rückl-Wyler (BRW) framework (14 different LQ types, which couple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

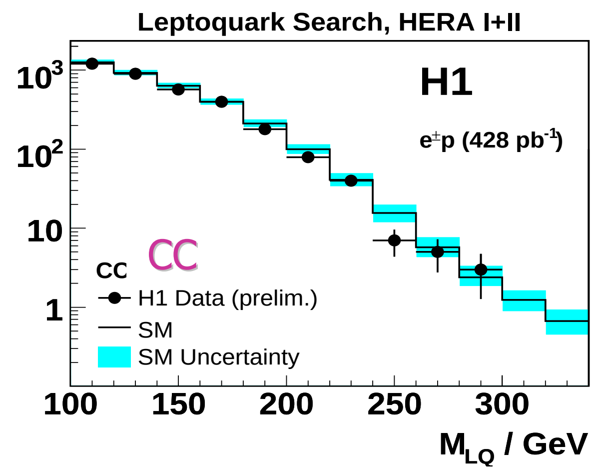




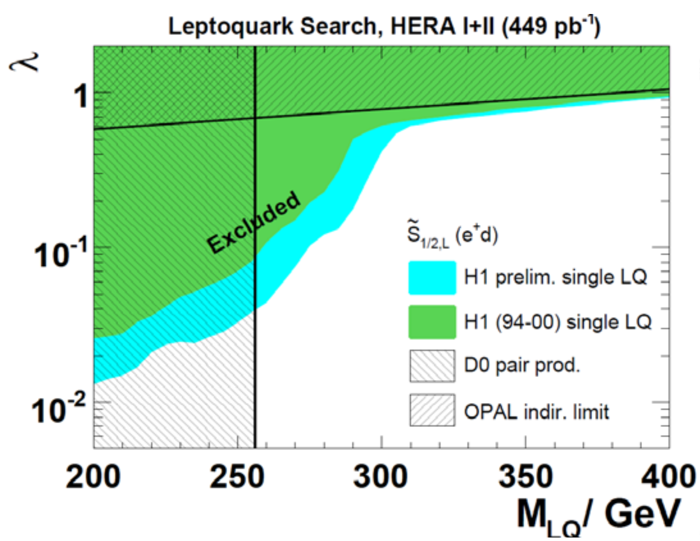
Leptoquarks

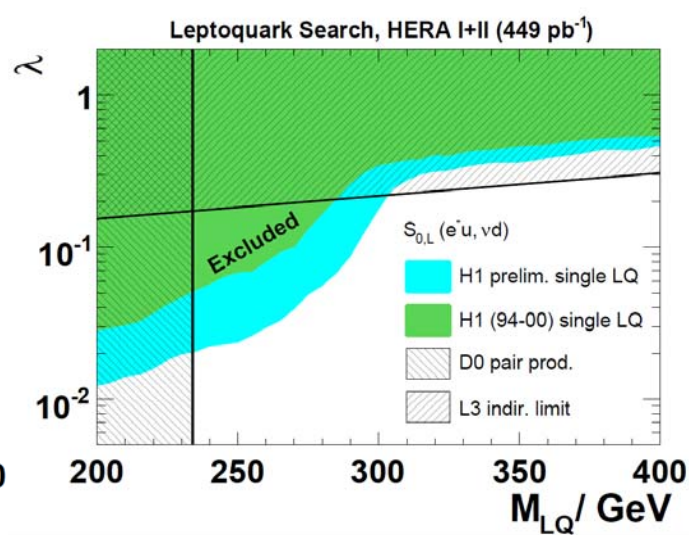
- Full statistics analyzed by H1 (prel. results)
- Search for all 14 LQ types
- No deviation from SM
- → limits set on coupling at 95% CL





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:

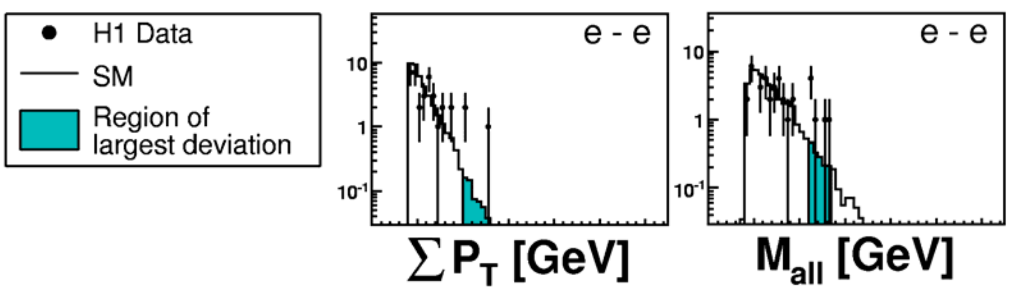
  e,μ,jets,γ,ν

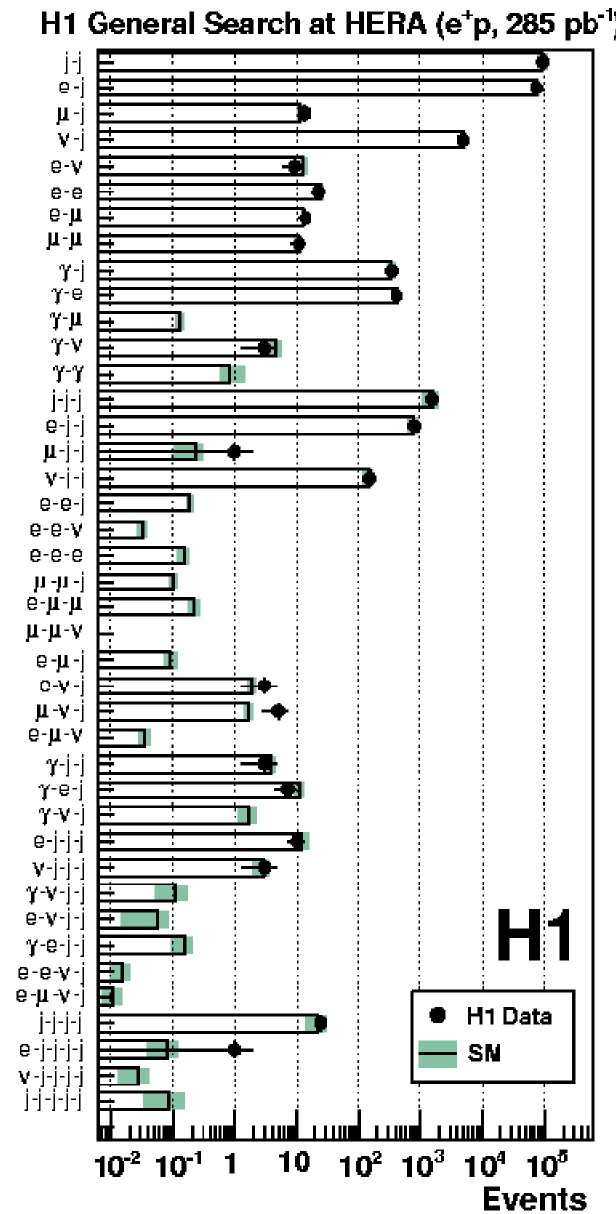
  $P_T > 20$GeV

  $10^o < \theta < 140^o$

- 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