Measurements at High Q^2 and Searches at High ep Energy Frontier

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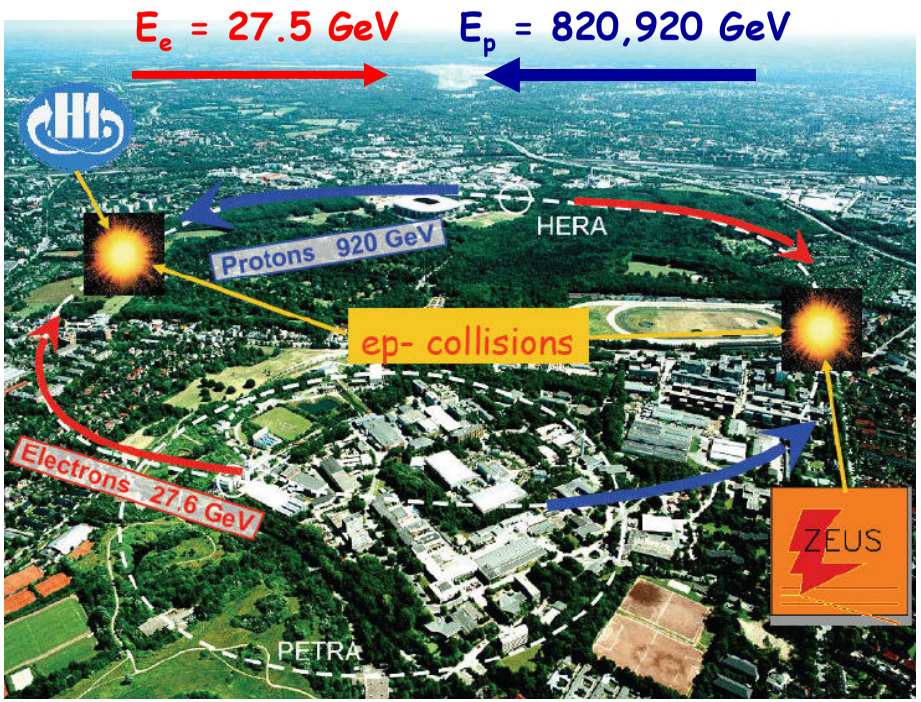
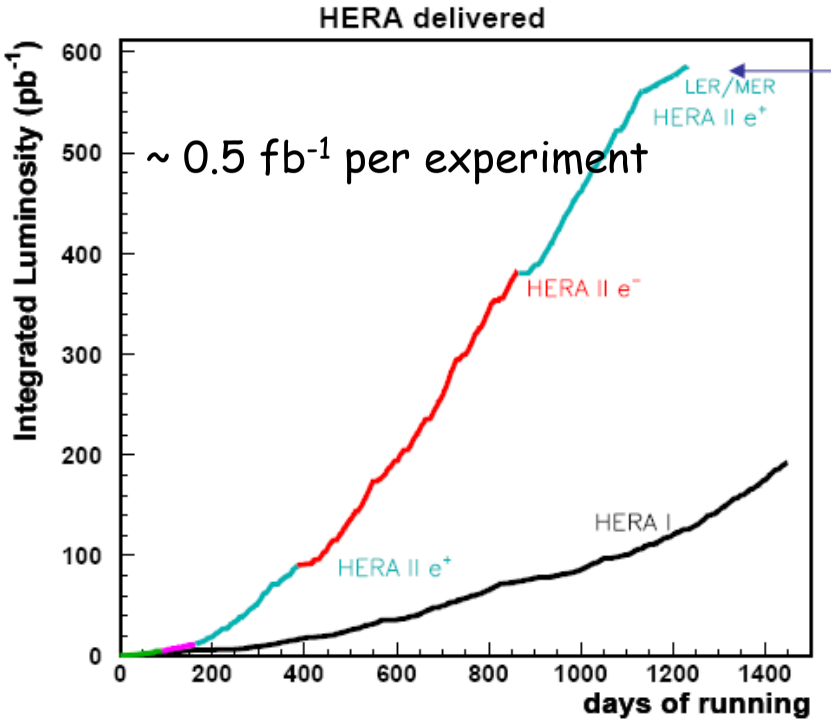
HERA and luminosity





1992 – 2000 HERA-I (E_p = 820, 920 GeV)

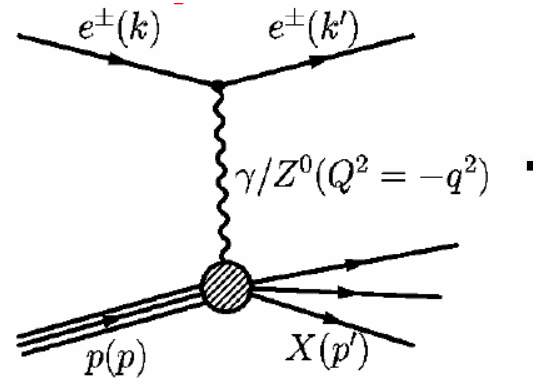
2003 – 2007 HERA-II (E_p = 920 GeV) - Increased luminosity

- Longitudinal $e^{\pm}$ polarisation

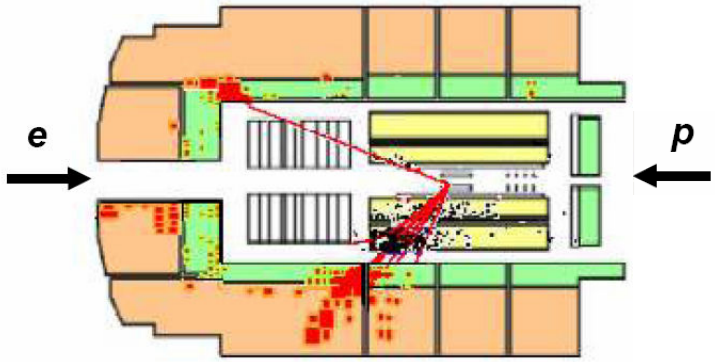
$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}} \sim 30 - 40\%$$

Inclusive Deep Inelastic Scattering (DIS)

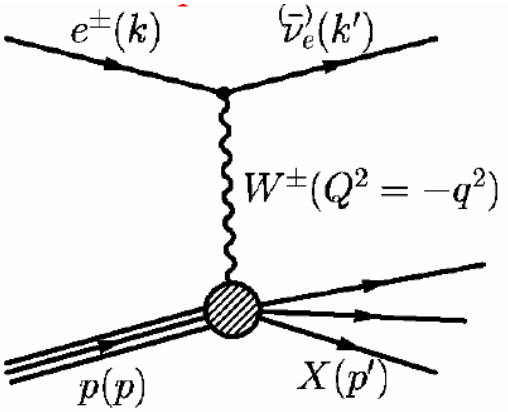
Neutral Current (NC)



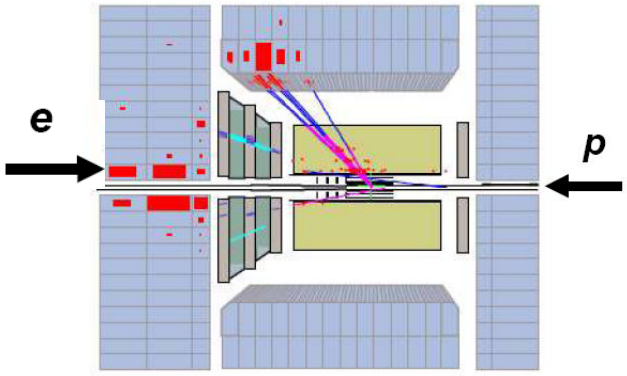
H1 NC event display



Charged Current (CC)



ZEUS CC event display



Virtuality of exchanged boson:

$$Q^2 = -q^2 = -(k-k')^2$$

Fraction of proton momentum carried by struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

Fraction of energy transferred from incoming lepton at proton rest frame

$$y = \frac{p \cdot q}{p \cdot k}$$

Cross Sections and Structure Functions

Neutral current cross section

$\tilde{\sigma}_{NC}(x,Q^2)$ - NC reduced cross-section

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ [\tilde{F}_2^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm} \mp \frac{Y_-}{Y_+} x\tilde{F}_3^{\pm}] \qquad Y_{\pm} = 1 \pm (1-y)^2$$

$$k = \frac{Q^2}{(Q^2+M_Z^2)^2}\frac{1}{4\sin^2\theta_W\cos^2\theta_W}$$

γ-exchange γZ-interference Z-exchange

$$\tilde{F}_2^{\pm} = F_2 + k(-v_e \mp P_e a_e)F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm P_e v_e a_e)F_2^Z$$

- dominant contribution

$$x\tilde{F}_3^{\pm} = k(-a_e \mp P_e v_e)xF_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^Z$$

- important only at high Q^2

$$F_L = (Q^2/4\pi\alpha)\sigma_L$$

- sizable contribution for high y

Generalised Structure Functions (SF)

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

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

SFs

$v_e \sim 0$

When $P_e \neq 0$ additional constraint on v_q by $F_2^{\gamma Z}$

Charged current cross section (LO)

$$\frac{d^2\sigma_{CC}^{e^+p}}{dxdQ^2} = (1+P_e)\frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(\bar{u}+\bar{c})+(1-y)^2 x(d+s)]$$

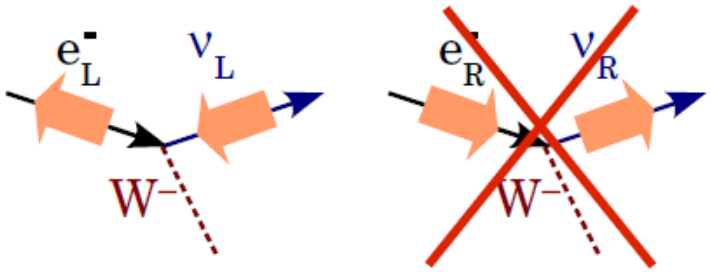
$$\frac{d^2\sigma_{CC}^{e^-p}}{dxdQ^2} = (1-P_e)\frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(u+c)+(1-y)^2 x(\bar{d}+\bar{s})]$$

d_v at high x

u_v at high x

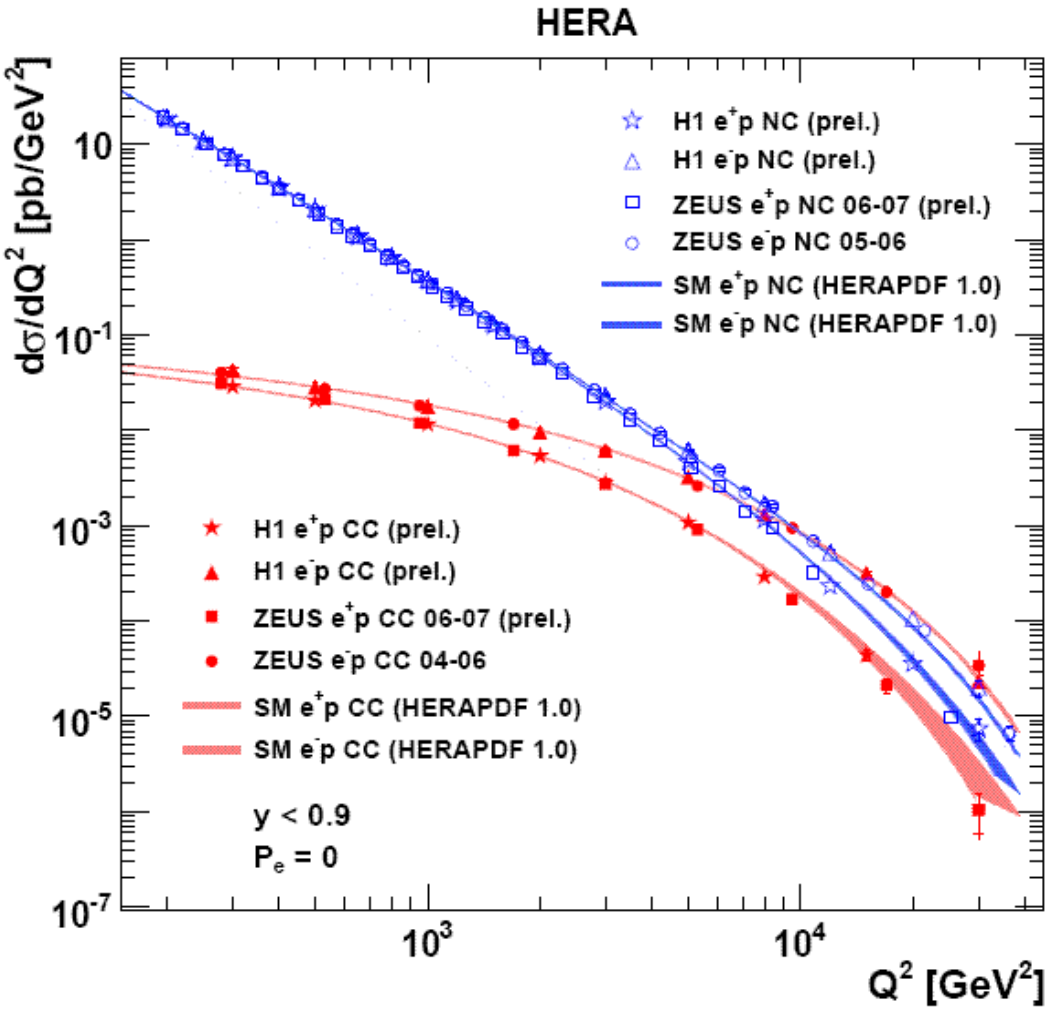
Sensitivity to the flavor of the valence distributions at high x

$\tilde{\sigma}_{CC}(x,Q^2)$ - CC reduced cross-section



- According to the Standard Model (SM), weak interactions act only on left-handed particles

Electroweak unification

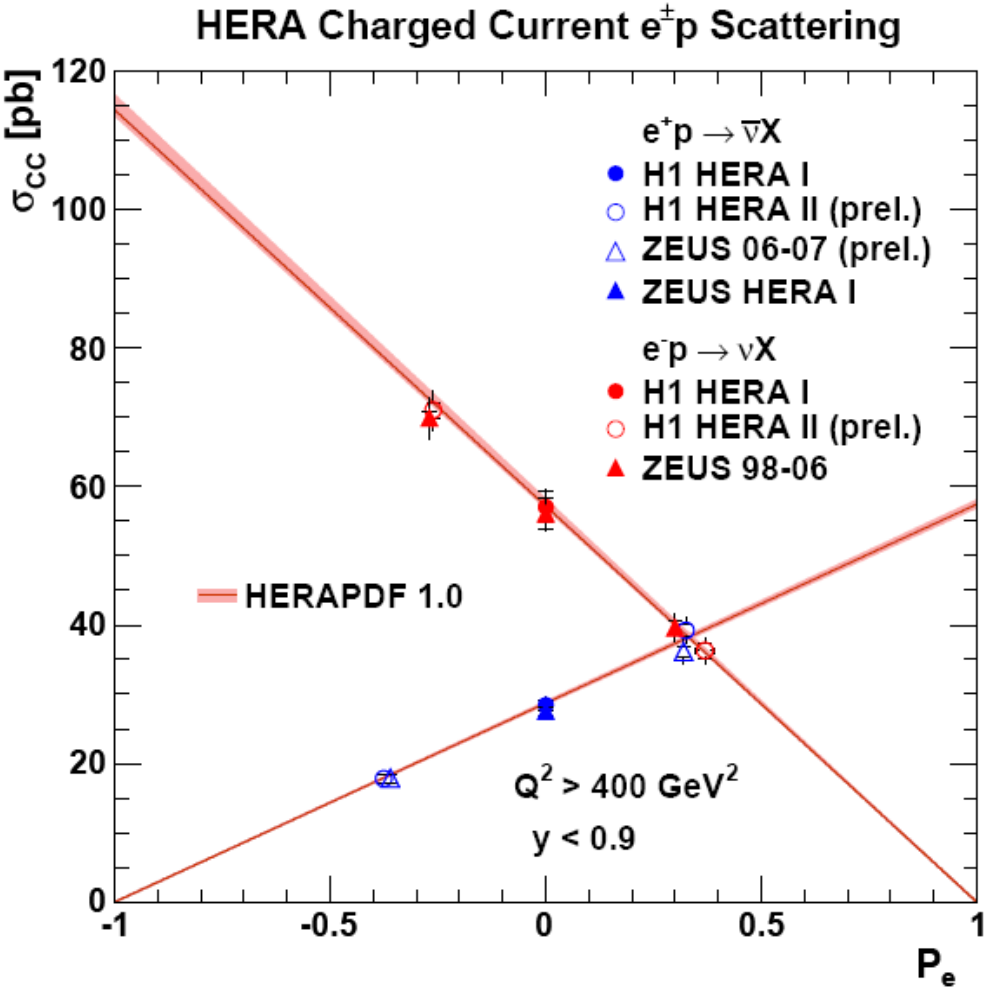


- EW unification at the $M_{W,Z}$ scale
- SM provides perfect description of data over many orders of magnitude

→ Lepton probe behaves as expected

- High Q^2 – region ideal for search for deviations from SM

Total CC cross section



SM:

Linear dependence of CC cross section on P_e

$$\sigma^{\pm}(P_e) = (1 \pm P_e) \cdot \sigma^{\pm}(P_e=0)$$

→ **ZEUS and H1 measurements in agreement with SM**

→ no right handed charged currents

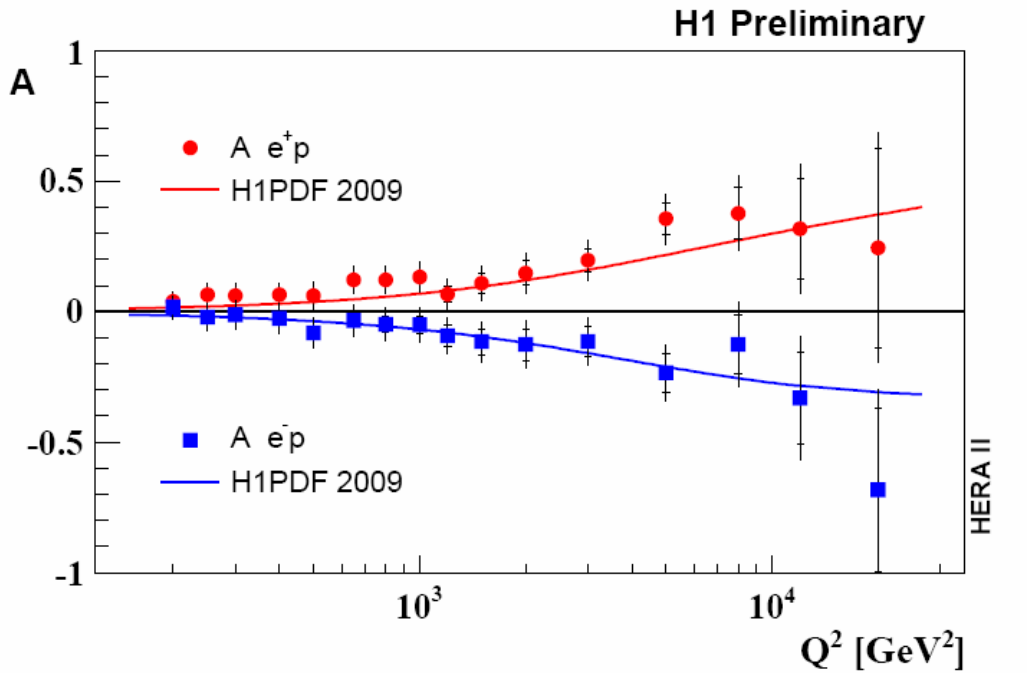
NC with longitudinally polarised leptons

- Polazrisation asymmetry $$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

  directly measures parity violation in NC

- For NC, em. contribution which dominates at low Q^2 does not depend on polarisation

- Polarisation dependence occurs via interference between γ and Z boson exchanges



Measurements well described by the SM

H1 and ZEUS Combined QCD and EW fit

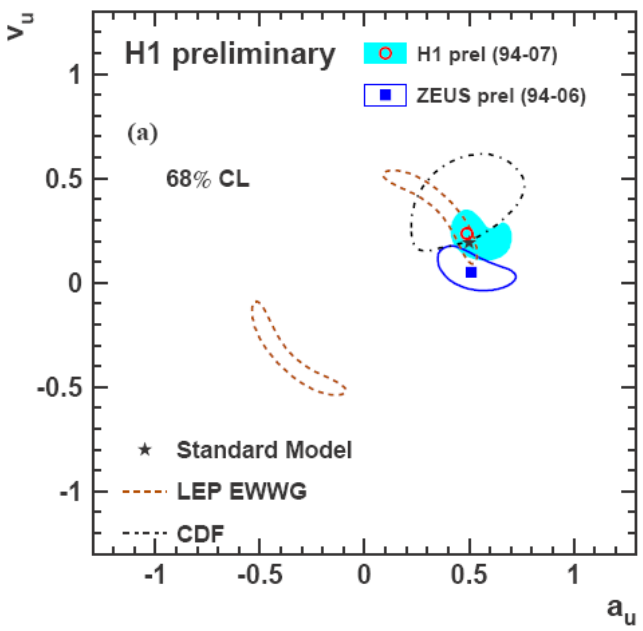
- Preliminary results for light quark vector (v_u, v_d) and axial-vector (a_u, a_d) couplings to Z-boson are obtained from H1 and ZEUS experiments using HERA-I and HERA-II data
- Combined fit of a_u, v_u, a_d, v_d and PDFs → QCD-EW fit

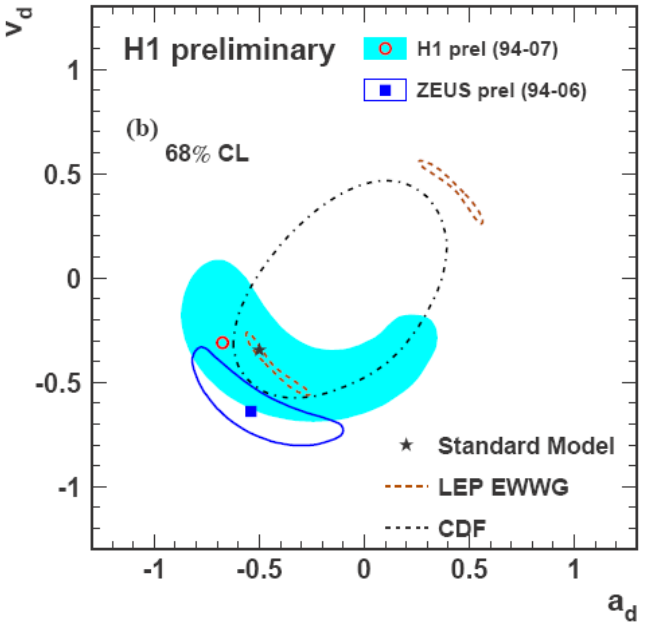
Standard Model:

$a_q = I_q^3$

$a_u = +1/2$, $a_d = -1/2$

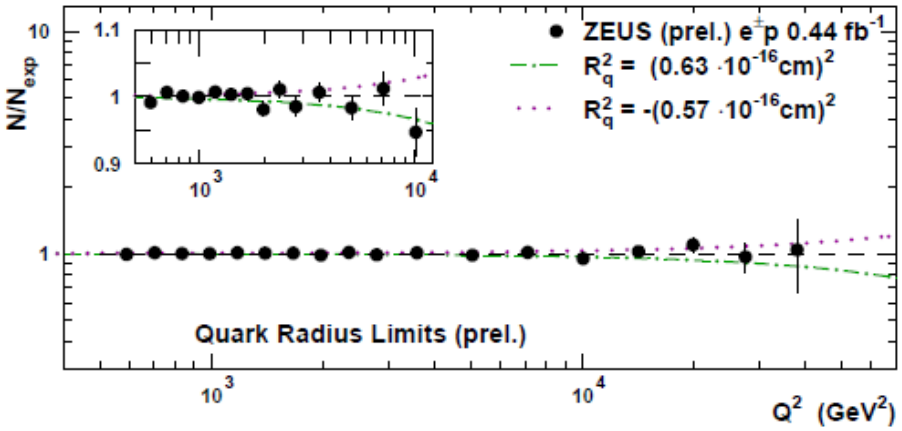
$v_q = I_q^3 - 2e_q \sin^2\theta_W$



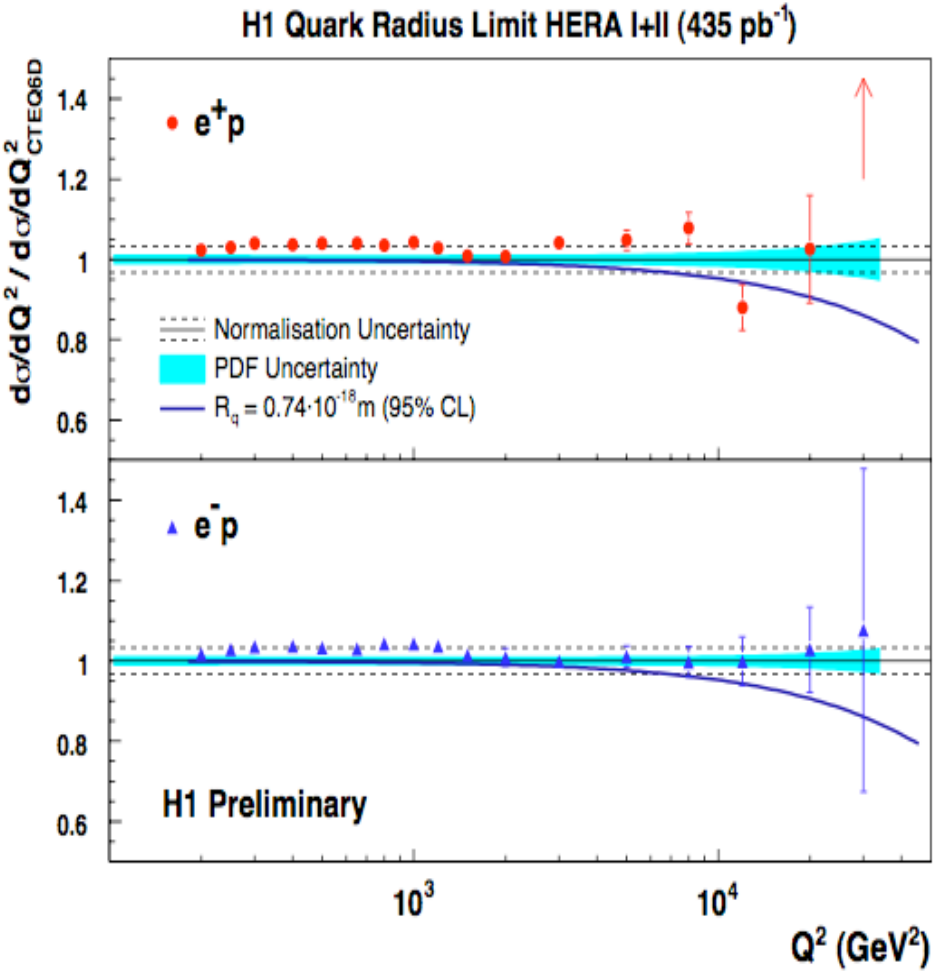


→ HERA-II brought improvement with statistics and polarisation (which provides better sensitivity to v_q)

Quark substructure



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



- Limit on quark size:
  - H1: $R_Q < 0.74 \times 10^{-18}$ m
  - ZEUS: $R_Q < 0.62 \times 10^{-18}$ m
- No substructure of quarks

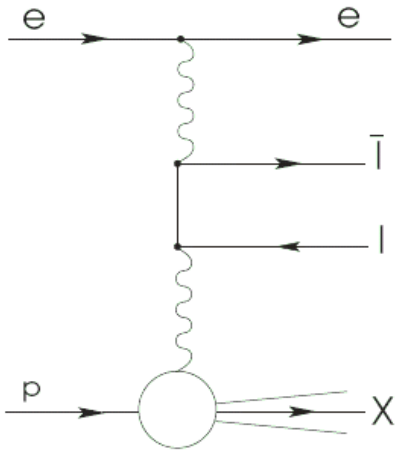
Searches at HERA

- Model dependent searches
  - test models and verify predicted signatures; if non-observation → limit set
    - Leptoquarks
    - Squarks in R-parity violating SUSY
    - Single top
    - Excited fermions
    - Contact interactions

- Model independent searches
  - signature based searches → looking for differences between data and SM expectation in various event topologies (do not rely on a priori definition of expected signatures for exotic phenomena)
    - Multi leptons at high P_T
    - Isolated leptons with large missing P_T
    - General search

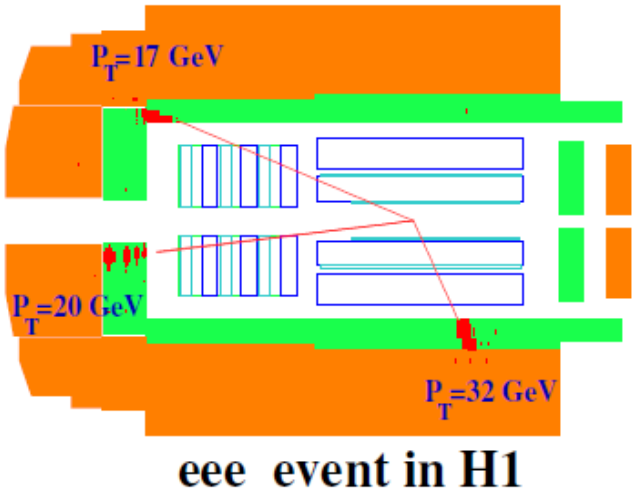
} Final results from HERA → NEXT SLIDES

Events with multi-leptons with high P_T

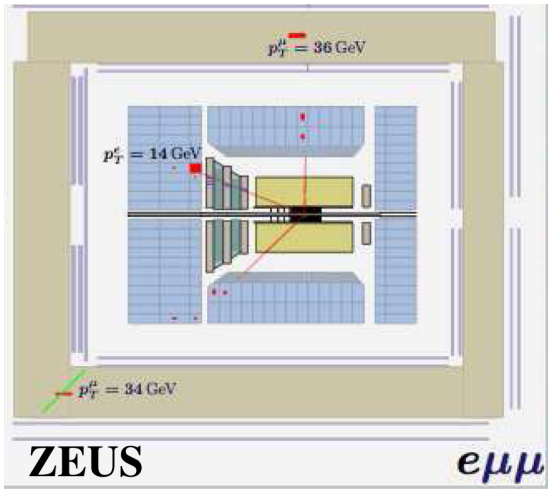


- Final word from HERA about multi-leptons (e and μ)
  - → H1 and ZEUS Collaborations combined results in the common phase space (~0.94 fb^{-1}) (**JHEP 0910:013, 2009**)
- In SM events with multi leptons are produced in photon-photon interactions

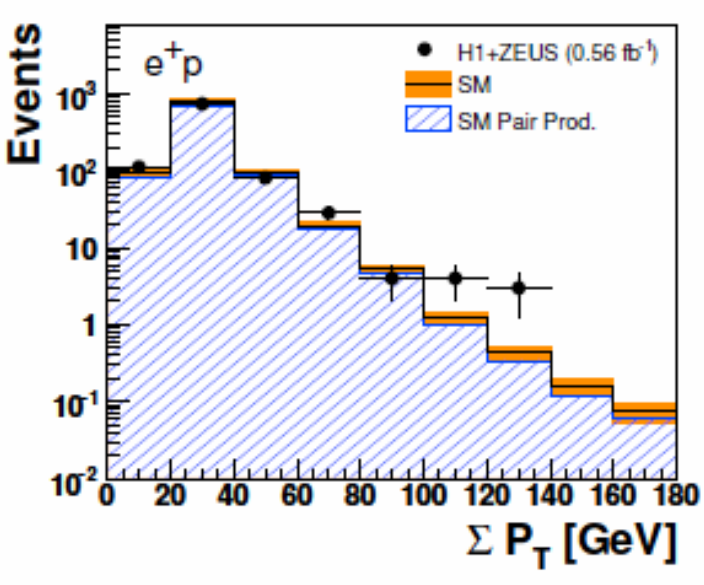
➢ Considered topologies: ee, μμ, eμ, eee, eμμ

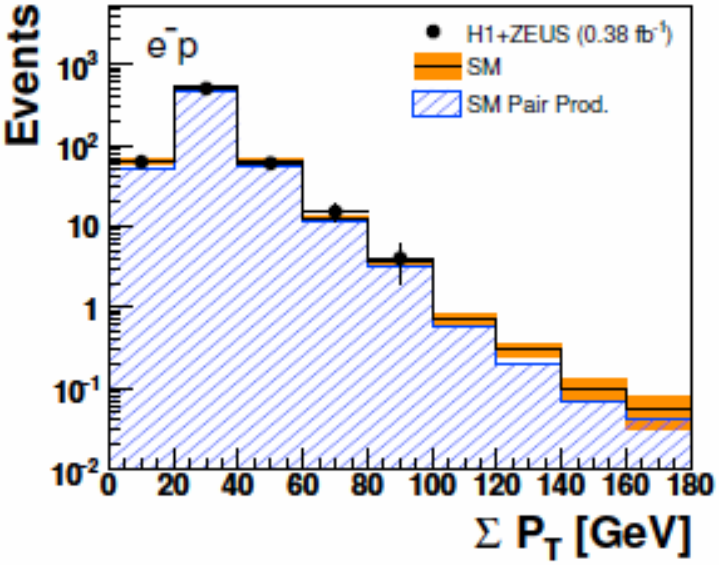


eee event in H1



Events with multi leptons with high P_T





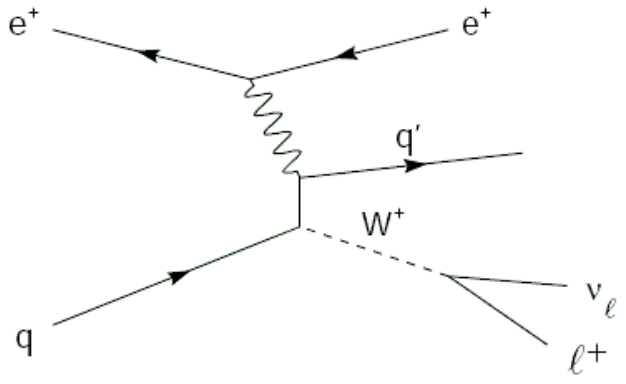
Multi-Leptons at HERA (0.94 fb^{-1}) $\sum P_T$ >100 GeV				
Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p (0.56 fb^{-1})	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e^-p (0.38 fb^{-1})	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb^{-1})	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10

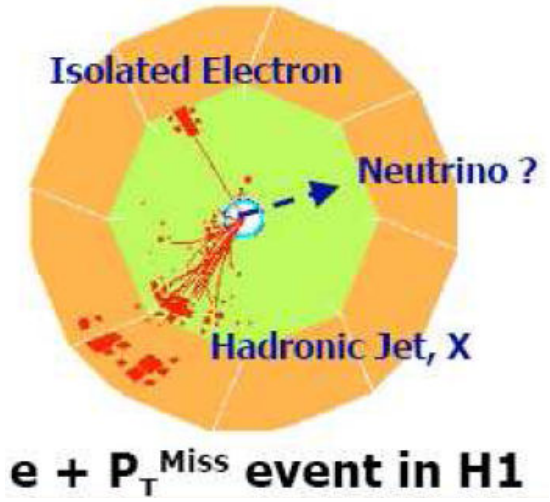
- Events at high mass and high ΣP_T are observed by both H1 and ZEUS, but only in e^+p data

- The production cross section of e^+e^- and $\mu^+\mu^-$ pairs measured in photoproduction regime ($Q^2 < 1$ GeV^2):
  0.66 ± 0.03(stat.) ± 0.03(sys.) pb
  in good agreement with SM prediction
  0.69 ± 0.02 pb (from GRAPE MC)

Events with isolated lepton and missing P_T

- Final word from HERA about isolated electron or muon and missing P_T in the common phase space of the combined H1+ZEUS analysis (**JHEP 1003:035, 2010**)

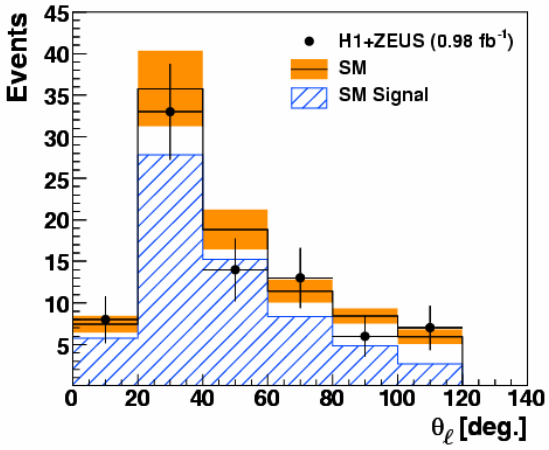


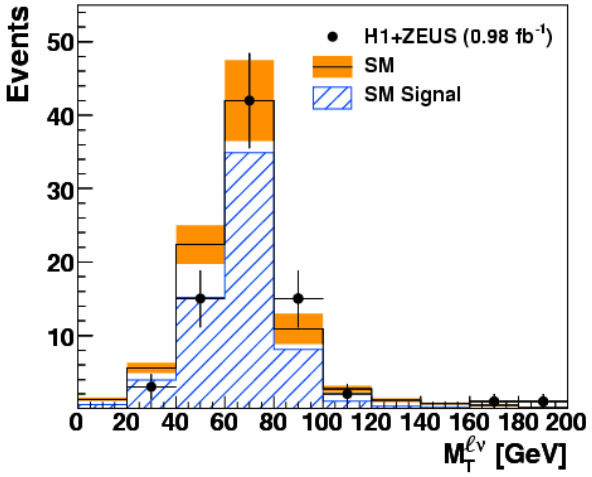


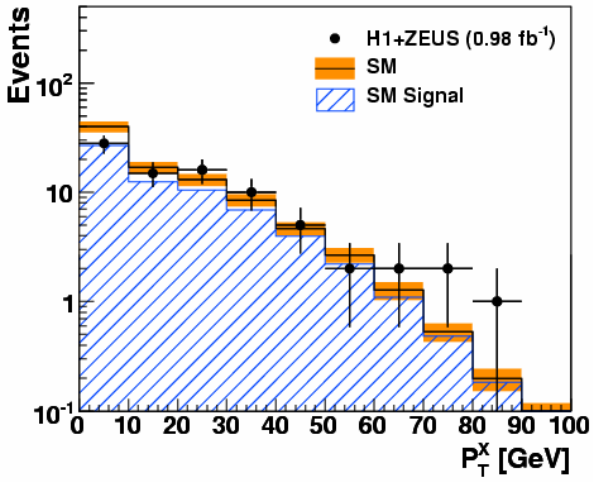
e + P_T^{Miss} event in H1

- The main SM process in ep interactions leading to the event topology with high P_T isolated lepton and at least one high P_T neutrino is single W production with subsequent leptonic decay
- Main SM backgrounds are NC-DIS, CC-DIS and lepton pair production
- For hadronic transverse momentum, $P_T^X > 25$ GeV, previously an excess in e and μ has been reported by the H1 collaboration (2.4σ) but not confirmed by ZEUS

Events with isolated lepton and missing P_T







H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	Total	81	87.8 ± 11.0	64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

Overall good agreement is observed with the SM expectation

→ Determination of σ_W

- The single W cross section: **1.06 ± 0.16(stat.) ± 0.07(sys.) pb** in good agreement with SM **1.26 ± 0.19 pb** (from EPVEC at NLO)

General search for new phenomena

- Complete HERA $e^{\pm}p$ data (~ 0.5 fb^{-1}): final result by H1 (**PL B674 257-268, 2009**)

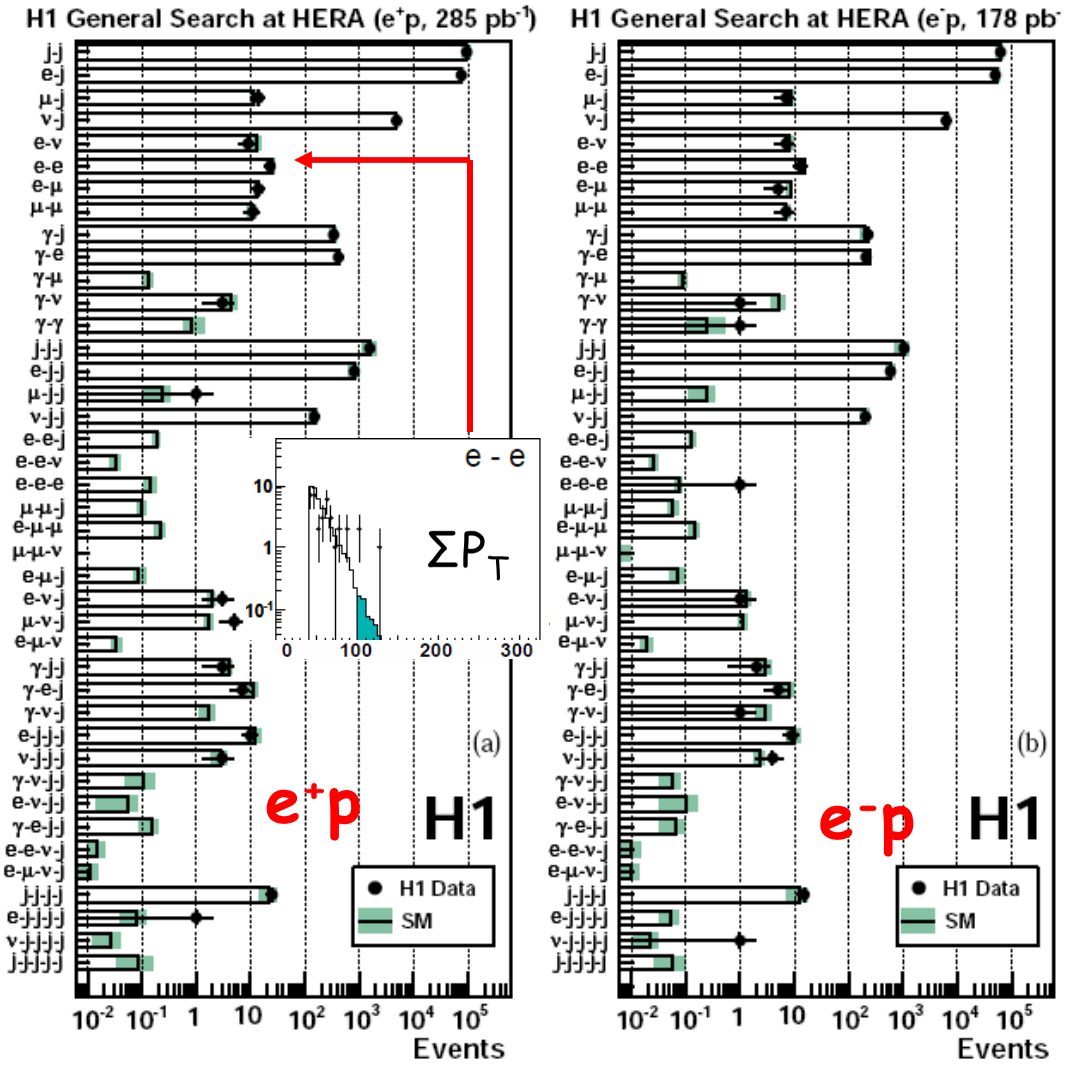
- Considered final state configurations:
  e, μ, jets (j), γ, ν

  → At least 2 particles with P_T > 20 GeV

→ Deviations searched in ΣP_T, M_{all} with dedicated algorithm

- Good agreement with SM

- High P_T phenomena well understood at HERA



Summary and outlook

- Full power of HERA data collected over 15 years of operation at high Q^2 is revealed – 1 fb^{-1}
- New preliminary results from full HERA data obtained for high Q^2
  - CC cross section measurement
  - NC cross section measurement
  - Extraction of electroweak parameters
- H1 and ZEUS Collaborations have combined their data to obtain measurements from the full HERA data with great precision
- Final results from HERA concerning searches obtained by combining H1 and ZEUS data on
  - Multi-leptons with high P_T
  - Isolated lepton and P_T^{miss}

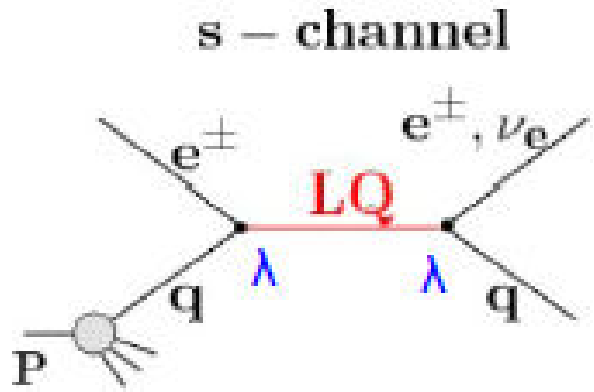
  → A good agreement with the Standard Model is observed (also for many other search results not shown here)

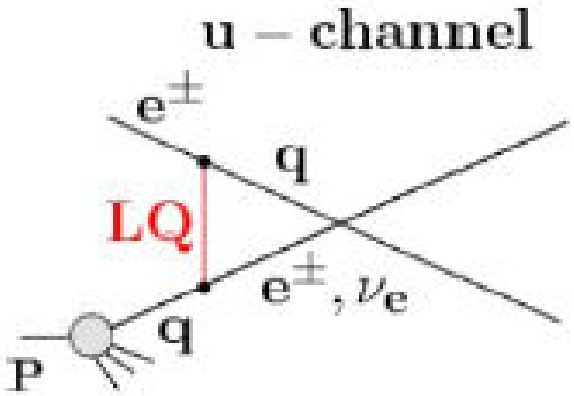
Standard Model is surviving full HERA dataset

Leptoquarks

- Leptoquarks – hypothetical bosons which appear in many SM extensions to explain symmetry between leptons and quarks
- LQs are coupled to both leptons and quarks and carry colour, fractional electric charge, baryon (B) and lepton (l) numbers → Fermion number F = 3B + L = 0, 2
- Buchmuller-Ruckl-Wyler Model
  - Lepton and baryon number conserved
  - Chiral particles: either left or right-handed couplings

  → 7 scalar and 7 vectot LQs
- Resonance width: $\Gamma \sim \lambda^2 \cdot M_{LQ}$
  - LQ mass – M_{LQ}
  - LQ-l-q Yukava coupling, λ



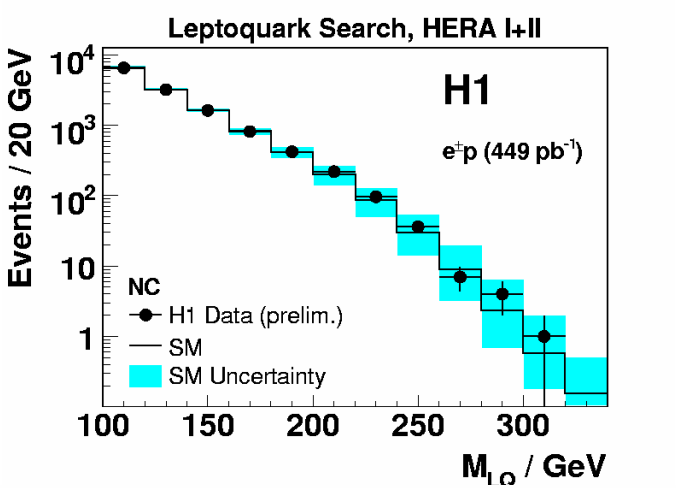


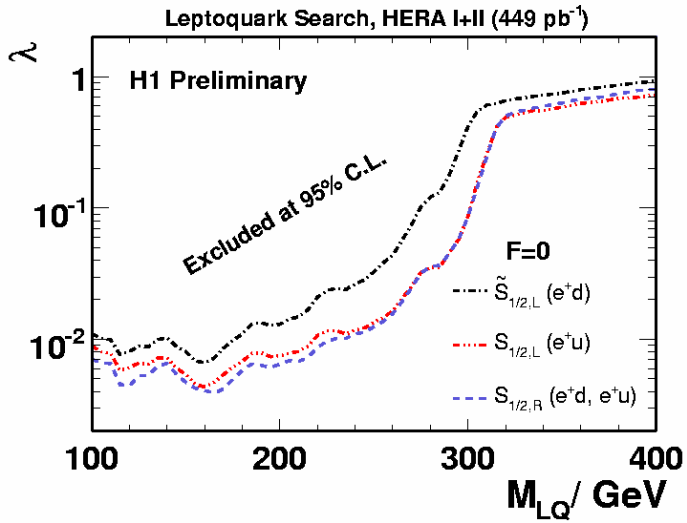
➢ 1st generation LQs:
LQ → eq - Lepton Flavor Conservation (LFC)

➢ 2nd/3rd generation LQs:
LQ→ μq/τq – Lepton Flavor Violation (LFV)

Search for 1st generation Leptoquarks

- Final state indistinguishable from SM NC/CC DIS for 1st generations LQs
- Complete HERA data analysed, L~0.45 fb^{-1}

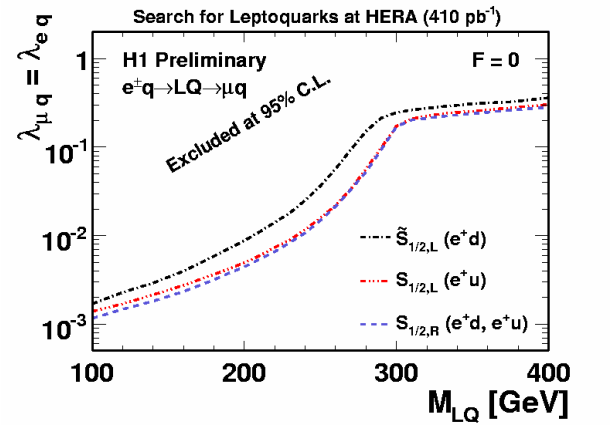


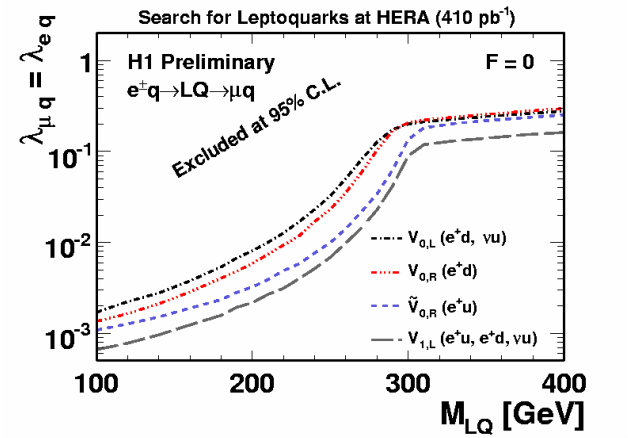


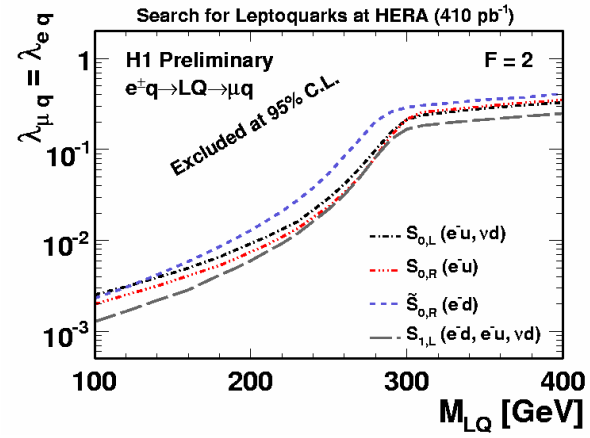
- Good description of data by SM prediction in both NC and CC processes
- No evidence of signal → interpretation in terms of exclusion limits
- For electromagnetic strength λ = 0.3 M_{LQ} < 291-330 GeV can be ruled out

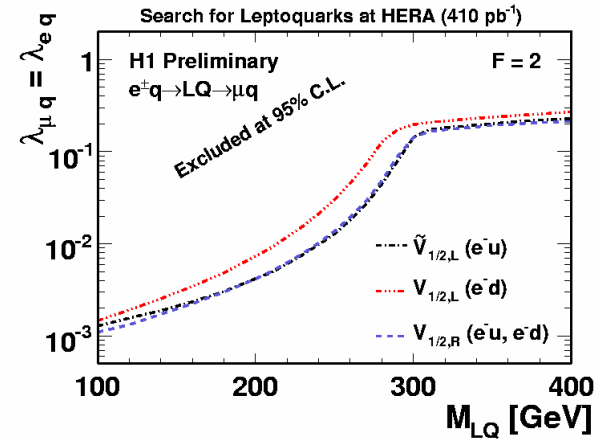
Search for 2nd generation Leptoquarks

- No evidence for signal → Limits set for all 14 LQs under assumption
  $\lambda_{\mu q} = \lambda_{eq}$, $\lambda_{\tau q} = 0$
- H1 (98-07) sample → 1 event seen / 1.6±0.5 expected







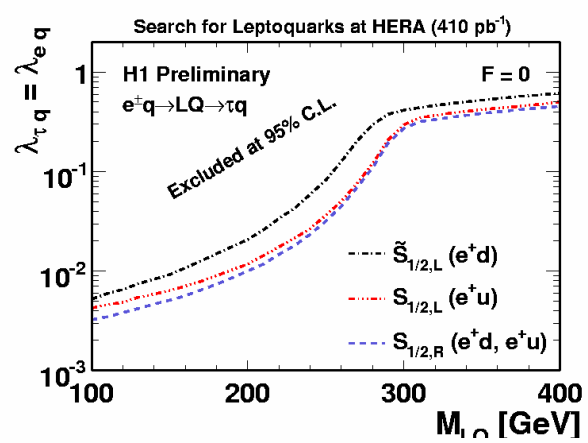


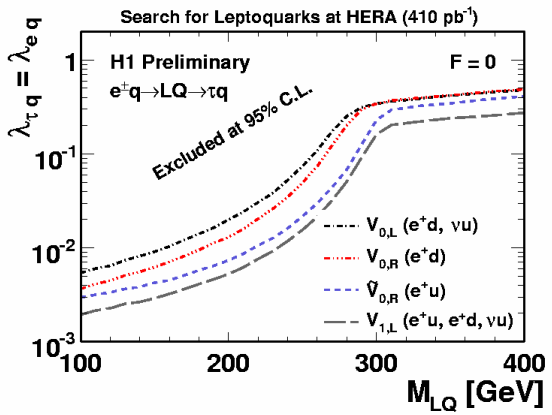
For em strength $\lambda = 0.3$

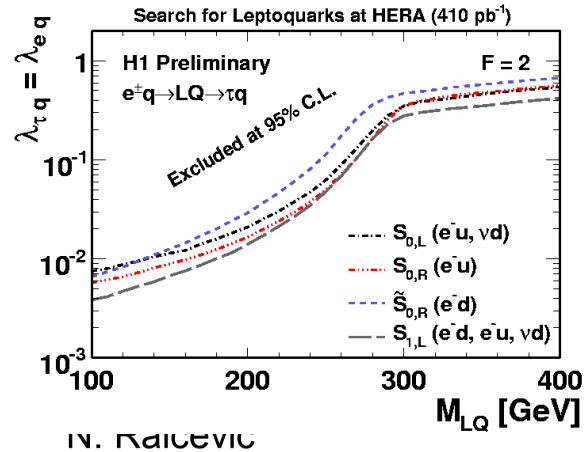
M_{LQ} < 304-530 GeV can be ruled out

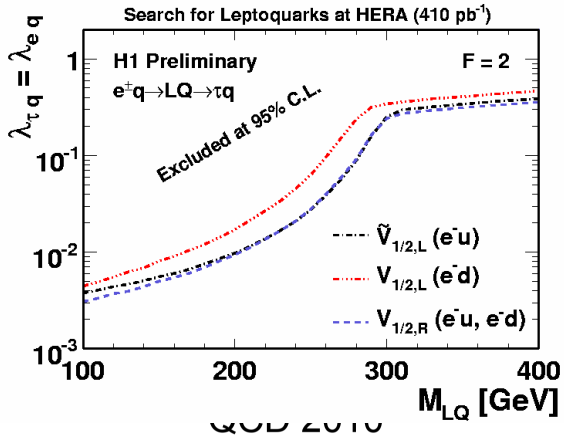
Search for 3rd generation Leptoquarks

- No evidence for signal → Limits set for all 14 LQs under assumption
  $\lambda_{\tau q} = \lambda_{eq}$, $\lambda_{\mu q} = 0$
- H1 (98-07) sample → 12 event seen / 10.6 expected







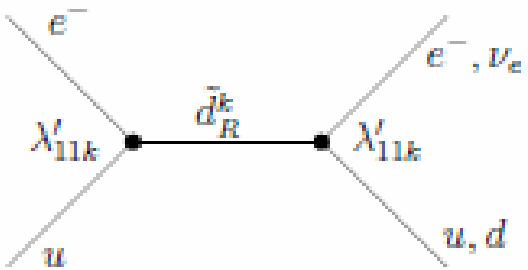


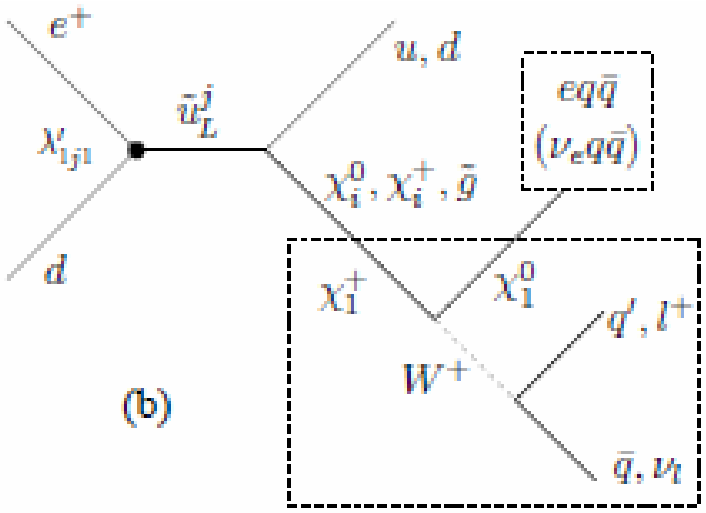
For em strength $\lambda = 0.3$

M_{LQ} < 272-450 GeV can be ruled out

Squark production in RPV SUSY

- R-parity: $R_p = (-1)^{L+3B+2S}$
- R_p = +1 for SM particles, -1 for SUSY particles
- IF RPV: single resonant squark production possible in ep collisions





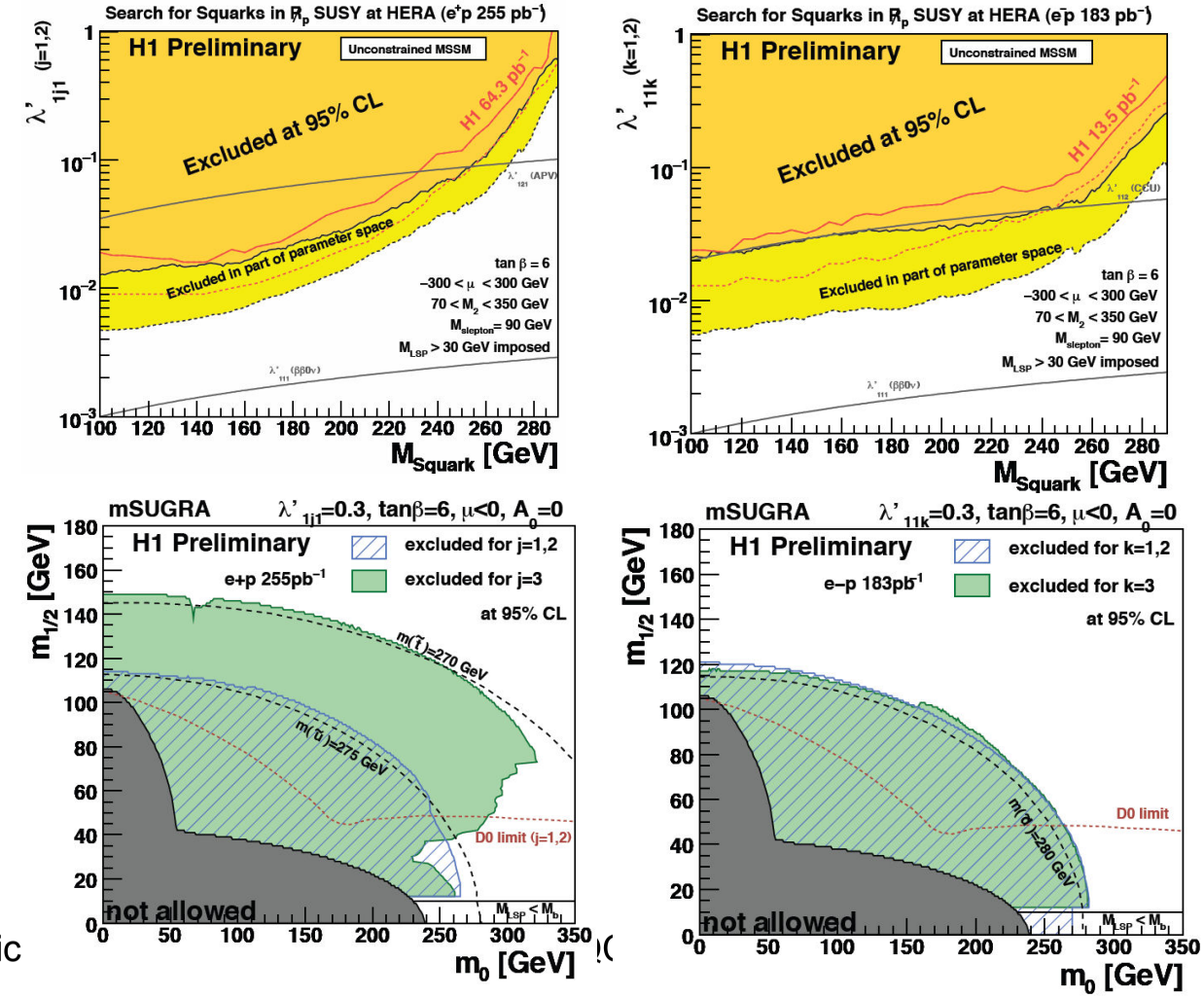
- Squarks decay to l+q (DIS-like final states) or to gauginos (→ cascade decays)

- Interpretation of search results in phenomenological MSSM and mSUGRA model for a Yukawa coupling of electromagnetic strength λ'_{1j1}, λ'_{11k} = 0.3

  → Limits set using full H1 data

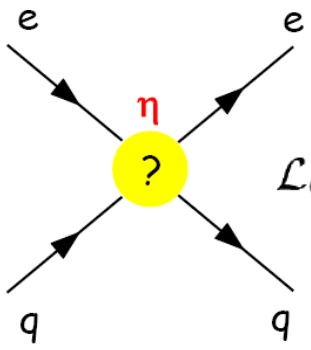
Squark production in RPV SUSY

- Up-type Squarks can be excluded up to 275 GeV at 95% CL
- Down-type Squarks can be excluded up to 290 GeV at 95% CL



Contact interactions

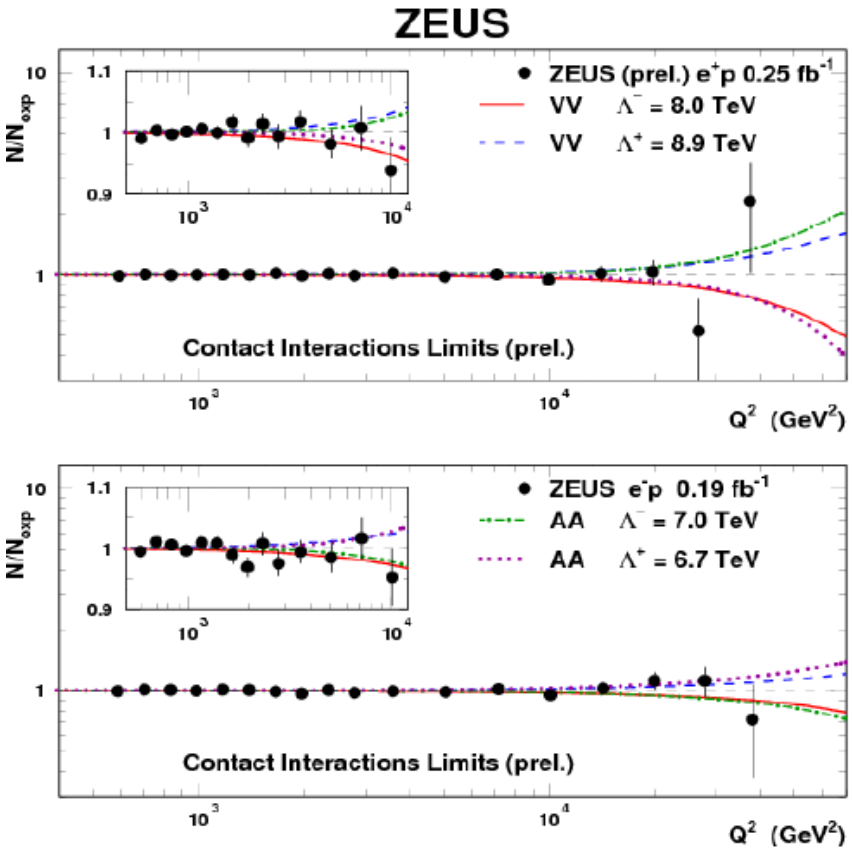
- New interactions at higher scales ($\Lambda \gg \sqrt{s}$) can be effectively described at lower energies as 4-fermion eeqq Contact Interaction



$$\mathcal{L}_{\mathrm{CI}} = \sum_{a,b=L,R}^{q=u,d} \eta^{q}_{ab} \, (\bar{e}_a \gamma_\mu e_a)(\bar{q}_b \gamma^\mu q_b)$$

$$\eta^{q}_{ab} = \pm 4\pi/\Lambda^2$$

- Could alter SM DIS distributions at high Q2
- Many models possible depending on chiral structure



- Using full dataset ZEUS set limits on 19 models with different helicity structure (L = 0.44 fb^{-1})

$\Lambda > 3.8 - 8.9$ TeV (95% CL)

Large extra dimensions

- ADD (Arkani-Hamed, Dimopoulos, Dvali) model → space time is 4+n dimensional
- SM particles confined to 4 dimensions, gravity can propagate into the extra dimensions
- Fundamental Planc scale M_S in 4+n dimensions can be of the order of 1 TeV

  → Strength of gravitational and electroweak interactions comparable at high energies
- Virtual graviton exchange contribution to eq → eq scattering can be described by a contact interaction with effective coupling $\eta_G \sim \pm 1/M_S$
- ZEUS limit (L = 0.44 fb^{-1})
  M_s^+, M_S^- > 0.94 TeV independent on n