

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

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on behalf of the H1 and ZEUS Collaborations

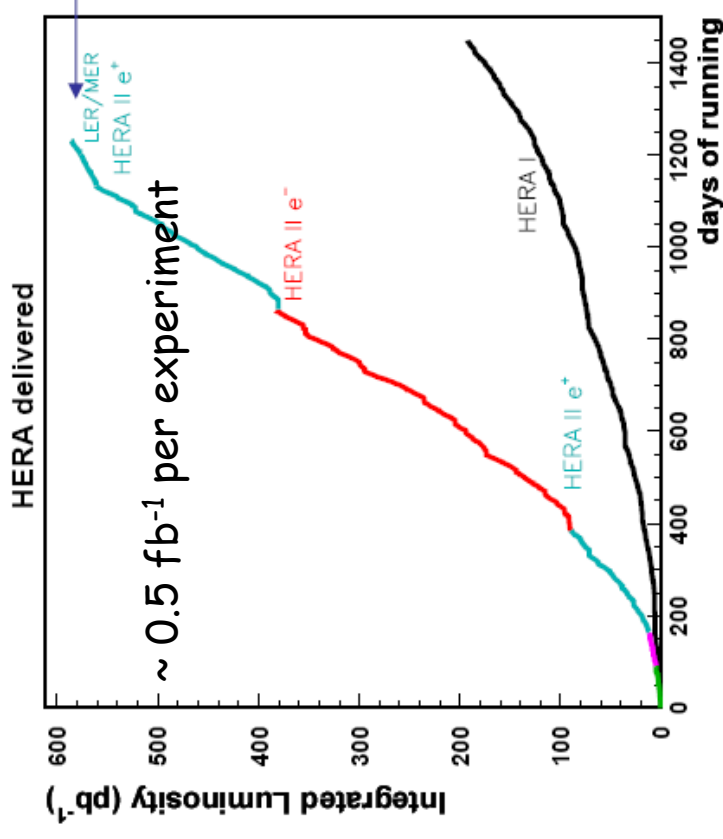
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HERA and luminosity



1992 - 2000 HERA-I ($E_p = 820, 920 \text{ GeV}$)

2003 - 2007 HERA-II ($E_p = 920 \text{ GeV}$) - Increased luminosity

- Longitudinal e[±] polarisation

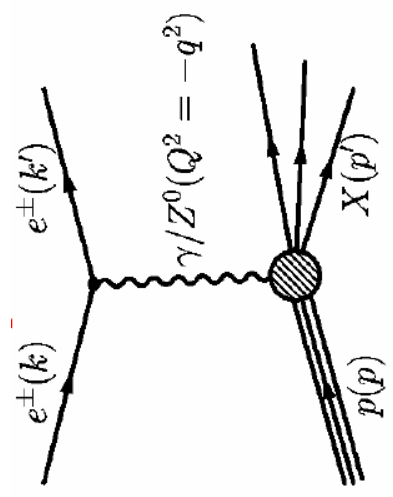
$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}} \sim 30 - 40\%$$

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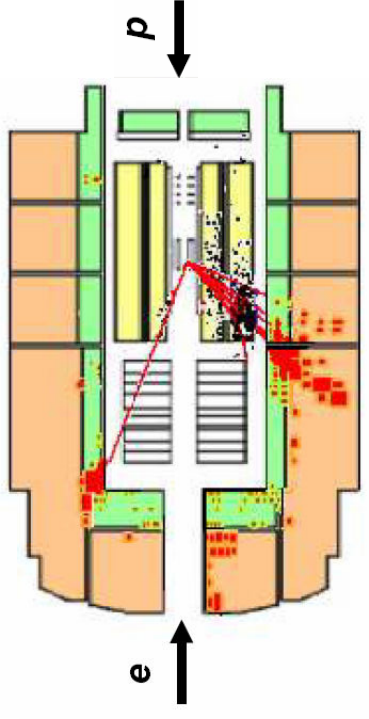
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Inclusive Deep Inelastic Scattering (DIS)

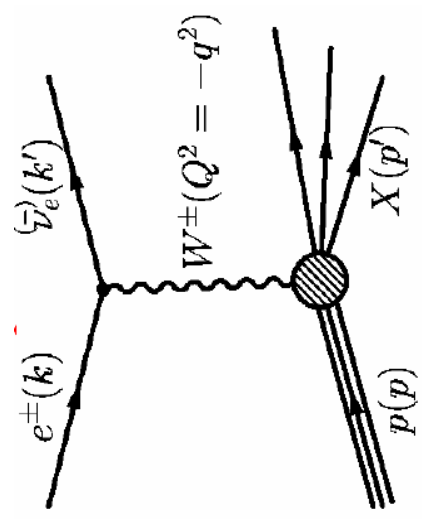
Neutral Current (NC)



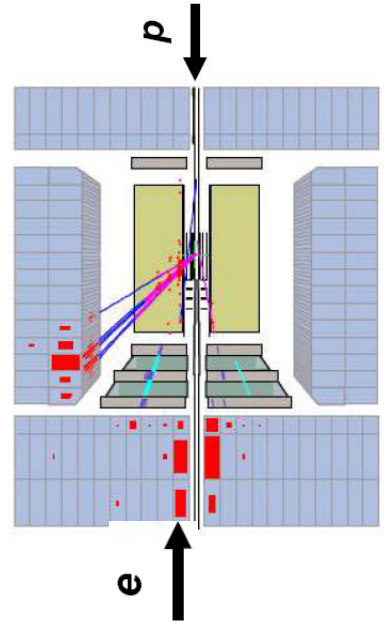
H1 NC event display



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

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

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

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

γ -exchange γ Z-interference Z-exchange

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

$$x \tilde{F}_3^\pm = k(-a_e \mp P_e v_e) x F_3^{\gamma Z} + k^2 2 v_e a_e \pm P_e (v_e^2 + a_e^2) x F_3^Z$$

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

- dominant contribution
- important only at high Q^2
Generalised Structure Functions (SF)

- sizable contribution for high γ

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

$$[x F_3^{\gamma Z}, x F_3^Z] = 2 \sum [e_q a_q, v_q a_q](x q - x \bar{q})$$

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

SFs

Charged current cross section (LO)

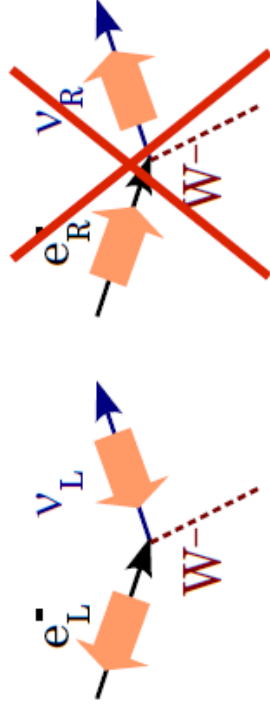
$$\frac{d^2 \sigma_{CC}^{e^+p}}{dx dQ^2} = (1 + P_e) \frac{G_F^2 M_W^4}{2\pi x(Q^2 + M_W^2)^2} [x(\bar{u} + \bar{c}) + (1 - y)^2 x(d + s)]$$

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

d_v at high x

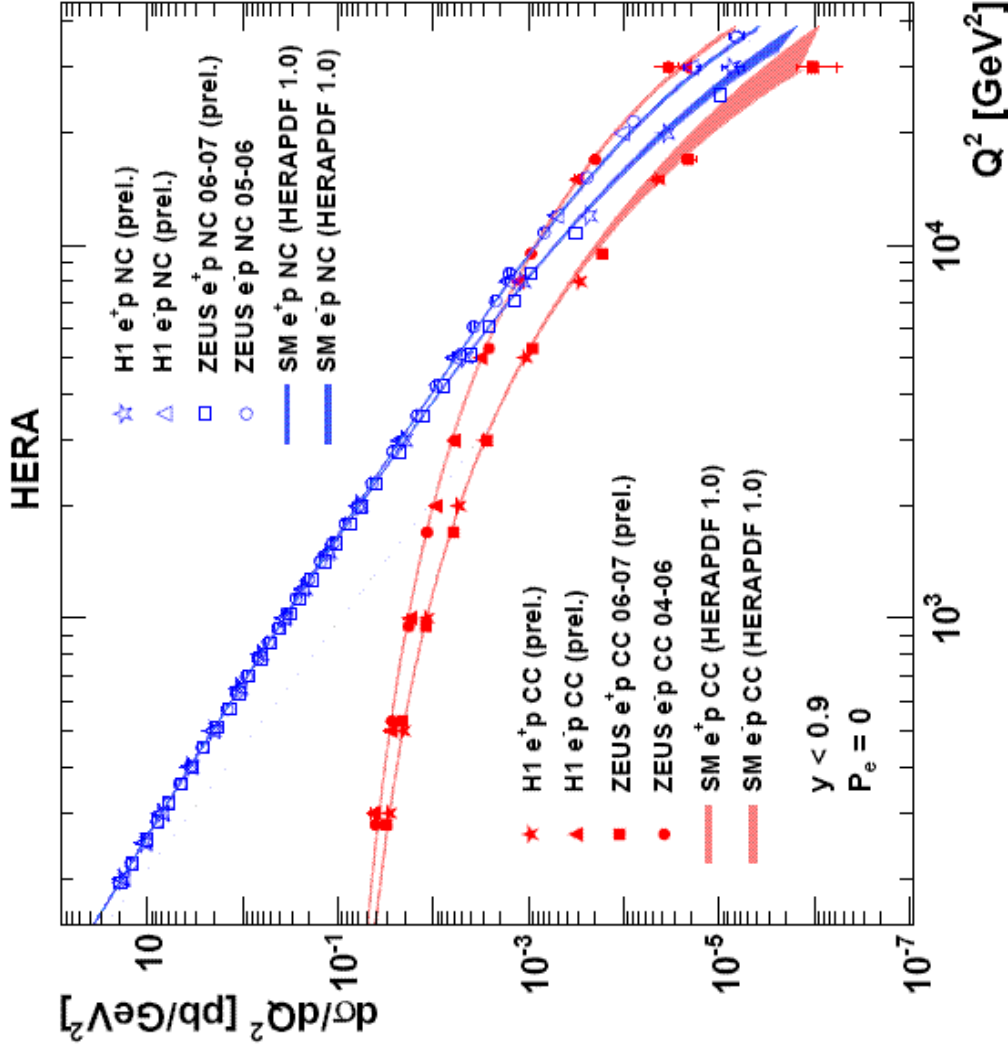
Sensitivity to the flavor of the valence distributions at high x

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



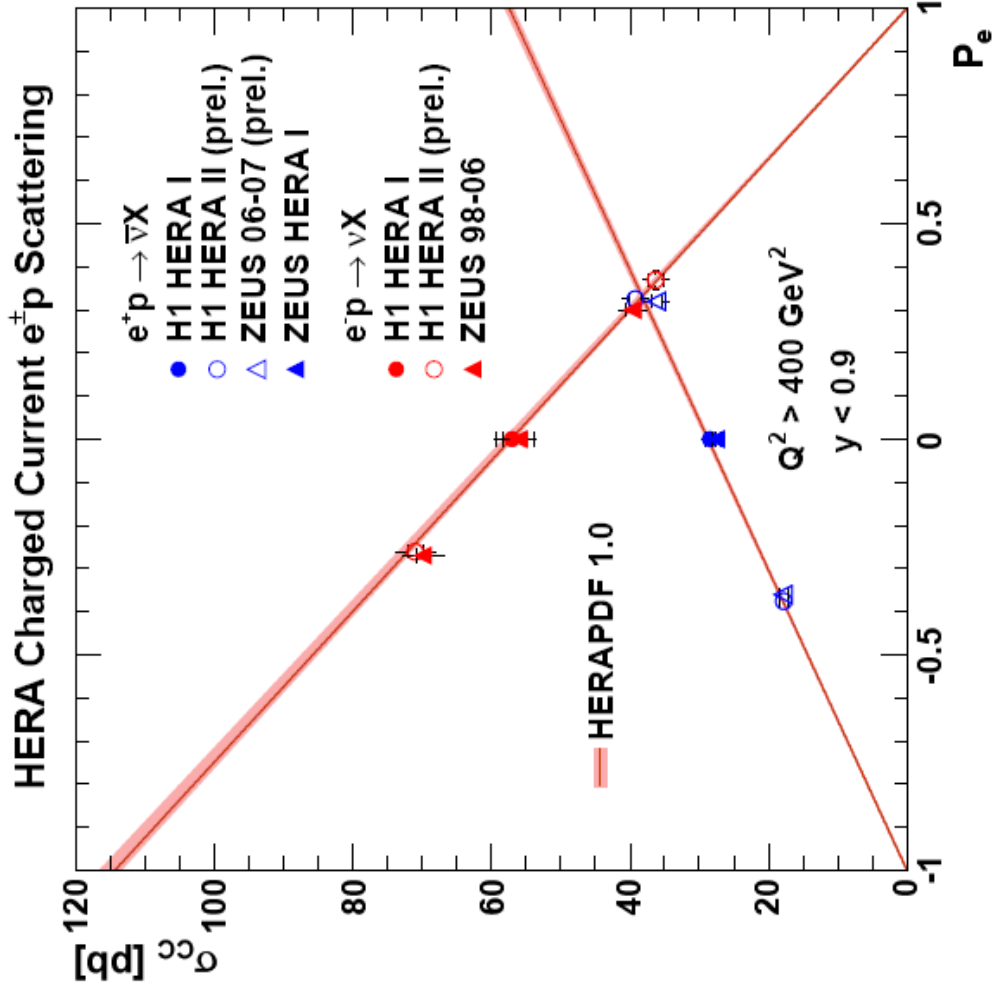
➤ According to the Standard Model (SM), weak interactions act only on left-handed particles

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



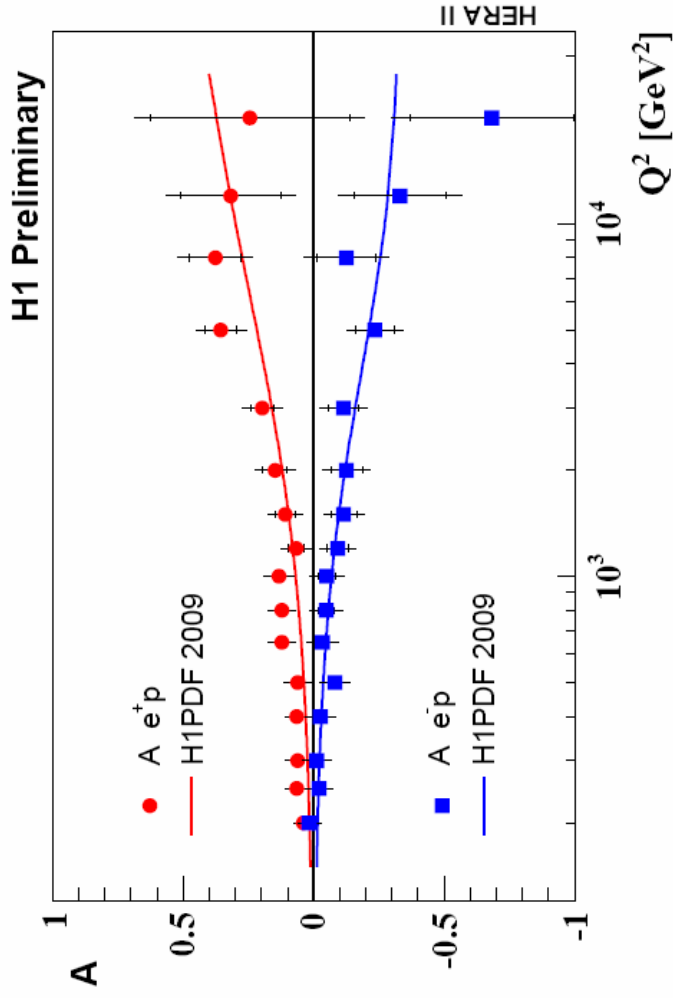
SM:
 Linear dependence of CC cross section on P_e
 $\sigma^\pm(P_e) = (1 \pm P_e) \cdot \sigma^\pm(P_e = 0)$
 → ZEUS and H1 measurements in agreement with SM
 → no right handed charged currents

NC with longitudinally polarised leptons

□ Polarisation 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

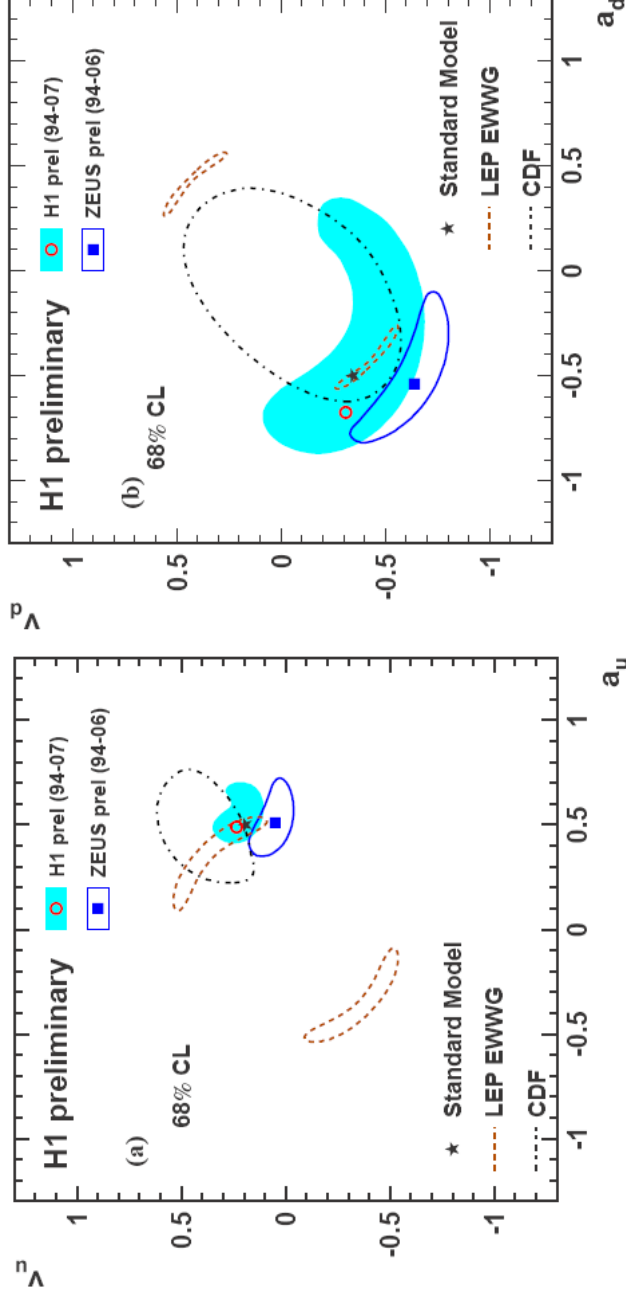
- Preliminary results for light quark vector (v_u, v_d) and axial-vector (a_u, a_d) couplings to Z-boson are obtained from H1 and ZEUS experiments using HERA-I and HERA-II data
- Combined fit of a_u, v_u, a_d, v_d and PDFs \rightarrow QCD-EW fit

Standard Model:

$$a_q = I_q^3$$

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

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

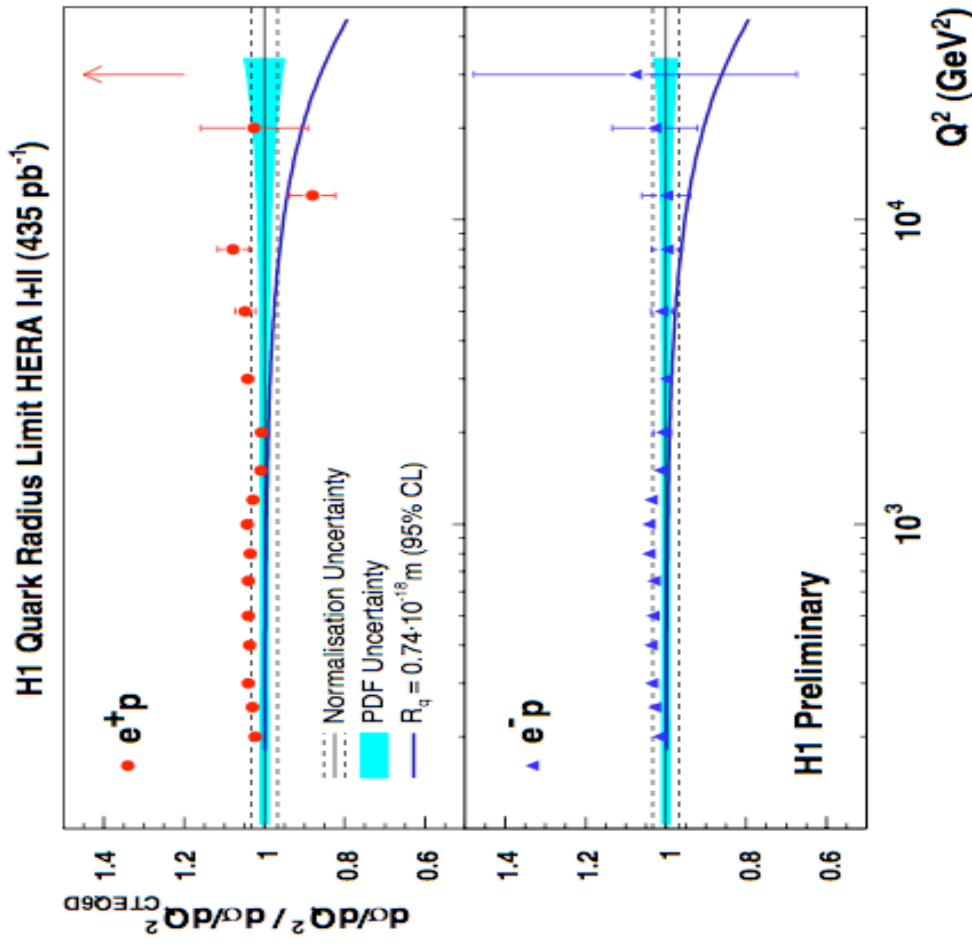
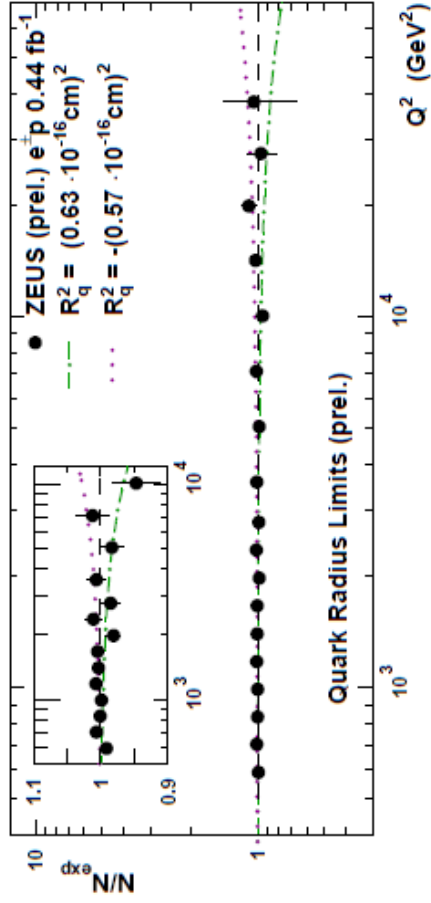


\rightarrow HERA-II brought improvement with statistics and polarisation (which provides better sensitivity to v_q)

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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: $R_Q < 0.74 \times 10^{-18} \text{ m}$
 - ZEUS: $R_Q < 0.62 \times 10^{-18} \text{ m}$

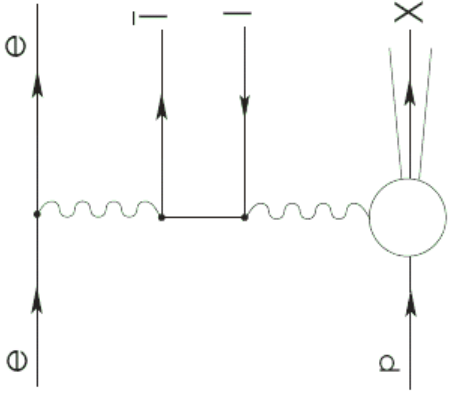
- No substructure of quarks

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

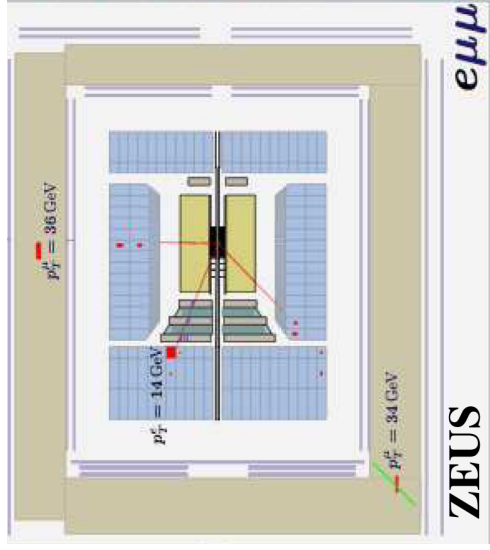
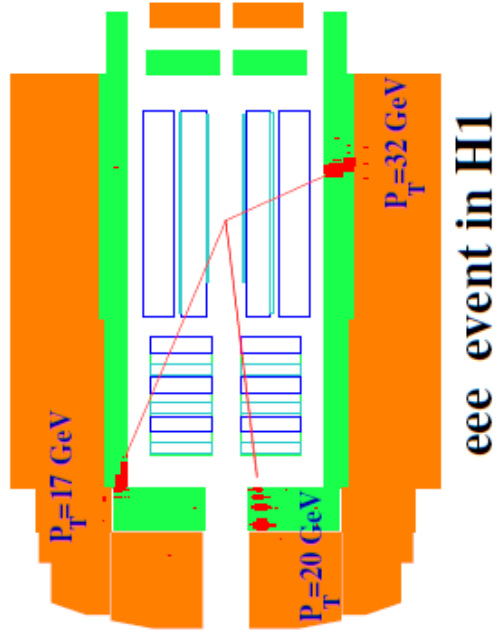
 - **Model independent searches**
 - signature based searches → looking for differences between data and SM expectation in various event topologies (do not rely on a priori definition of expected signatures for exotic phenomena)
 - Multi leptons at high P_T
 - Isolated leptons with large missing P_T
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

Events with multi-leptons with high P_T

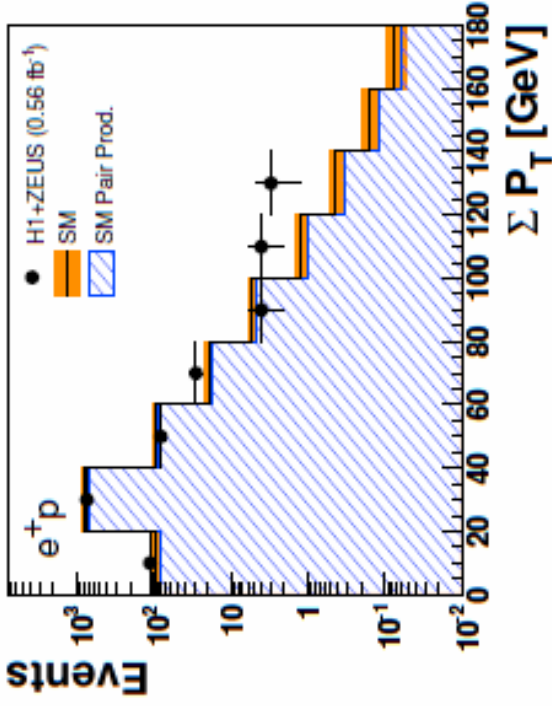


- Final word from HERA about multi-leptons (e and μ)
 - H1 and ZEUS Collaborations combined results in the common phase space ($\sim 0.94 \text{ fb}^{-1}$) (**JHEP 0910:013, 2009**)
- In SM events with multi leptons are produced in photon-photon interactions

➤ Considered topologies: $ee, \mu\mu, e\mu, eee, e\mu\mu$



Events with multi leptons with high P_T

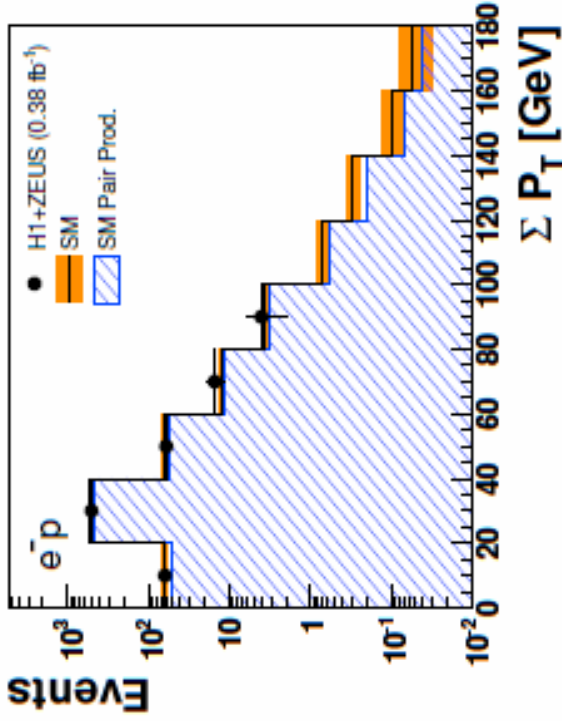


Multi-Leptons at HERA (0.94 fb^{-1})
 $\sum P_T > 100 \text{ GeV}$

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

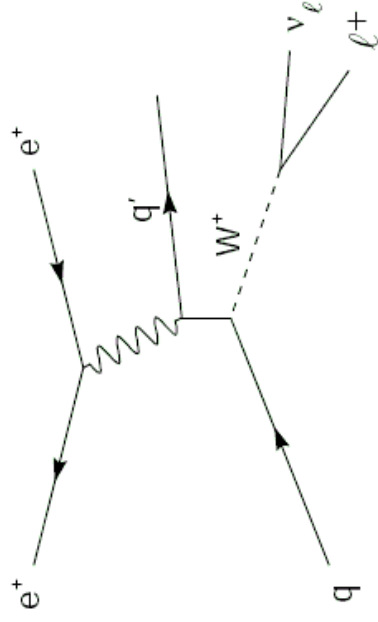
□ Events at high mass and high ΣP_T are observed by both H1 and ZEUS, but only in e^+p data

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

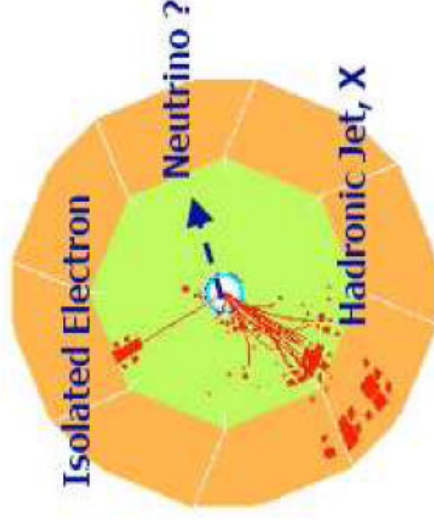


Events with isolated lepton and missing P_T

- 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**)

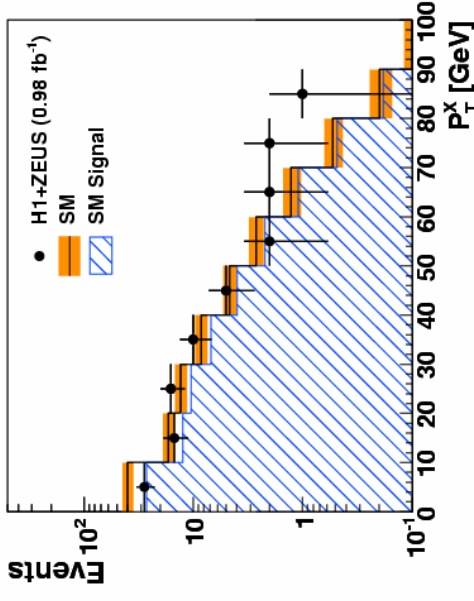
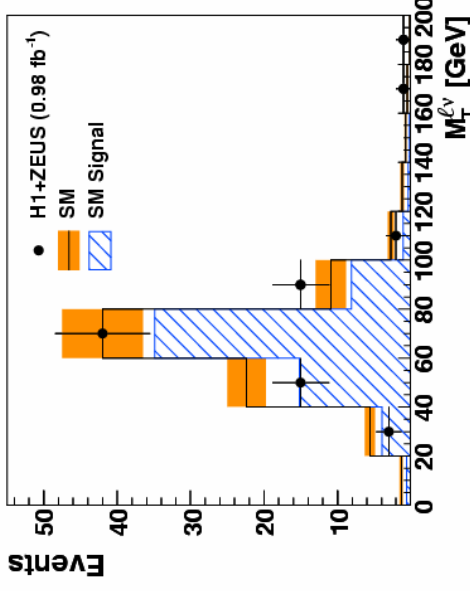
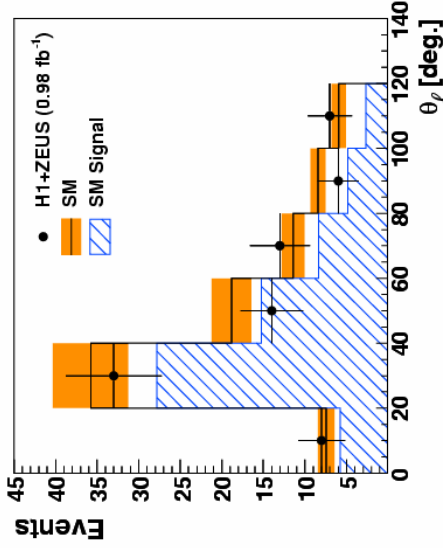


- The main SM process in ep interactions leading to the event topology with high P_T isolated lepton and at least one high P_T neutrino is single W production with subsequent leptonic decay
- Main SM backgrounds are NC-DIS, CC-DIS and lepton pair production
- For hadronic transverse momentum, $P_{T^X}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



$e + P_{T^{\text{Miss}}}$ event in H1

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

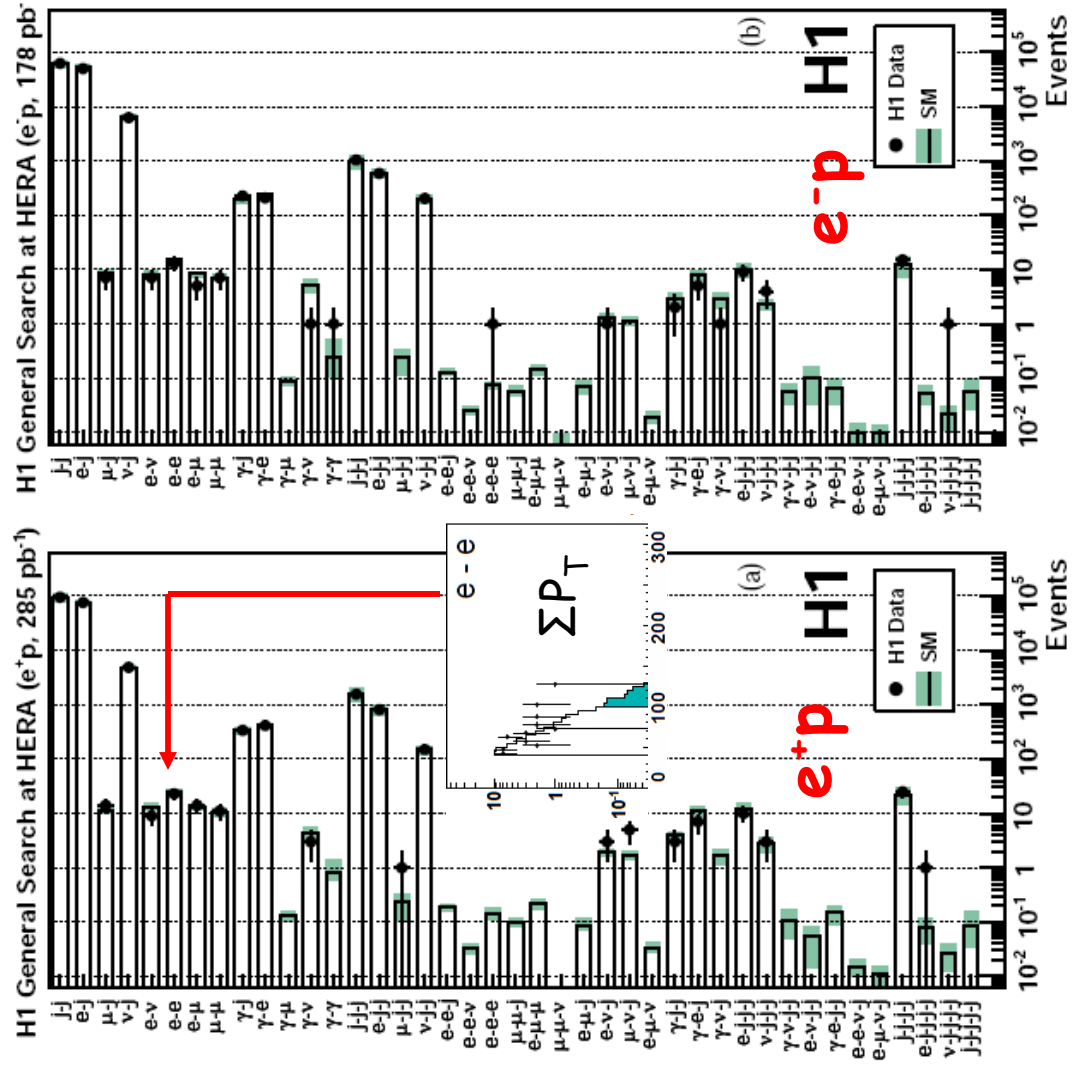
➤ The single W cross section: $1.06 \pm 0.16(\text{stat.}) \pm 0.07(\text{sys.})$ pb in good agreement with SM 1.26 ± 0.19 pb (from EPVEC at NLO)

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General search for new phenomena

- Complete HERA $e^{\pm}p$ data ($\sim 0.5 \text{ fb}^{-1}$): final result by H1 (PL B674 257-268, 2009)
- Considered final state configurations:
 $e, \mu, \text{jets (j)}, \gamma, \nu$
- At least 2 particles with $P_T > 20 \text{ GeV}$
- Deviations searched in $\Sigma P_T, M_{\text{all}}$ with dedicated algorithm
- Good agreement with SM
- High P_T phenomena well understood at HERA



Summary and outlook

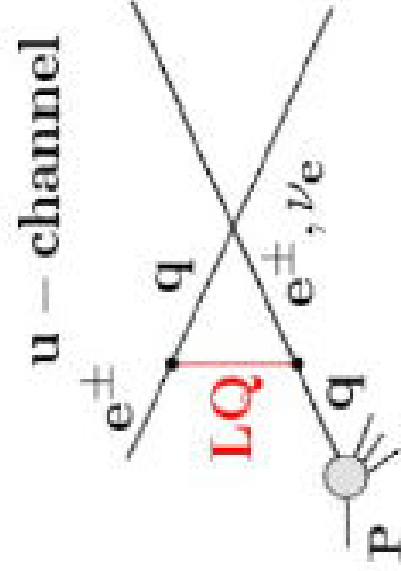
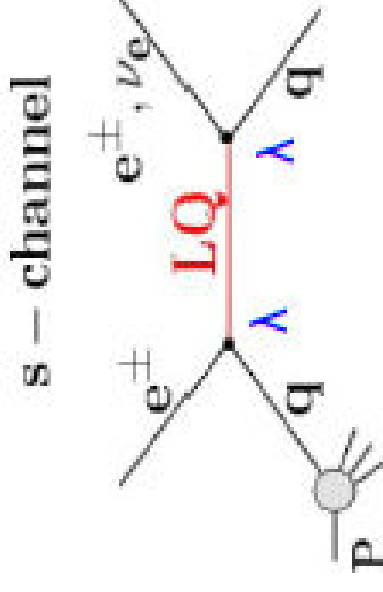
- ❖ Full power of HERA data collected over 15 years of operation at high Q^2 is revealed - 1 fb^{-1}
- ❖ New preliminary results from full HERA data obtained for high Q^2
 - CC cross section measurement
 - NC cross section measurement
 - Extraction of electroweak parameters
- ❖ H1 and ZEUS Collaborations 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 $P_{T,\text{miss}}$

→ 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 \rightarrow Fermion number $F = 3B + L = 0, 2$
- Buchmuller-Ruckl-Wyler Model
 - Lepton and baryon number conserved
 - Chiral particles: either left or right-handed couplings
- \rightarrow 7 scalar and 7 vector LQs
- Resonance width: $\Gamma \sim \lambda^2 \cdot M_{LQ}$
 - LQ mass - M_{LQ}
 - LQ-l-q Yukawa coupling, λ

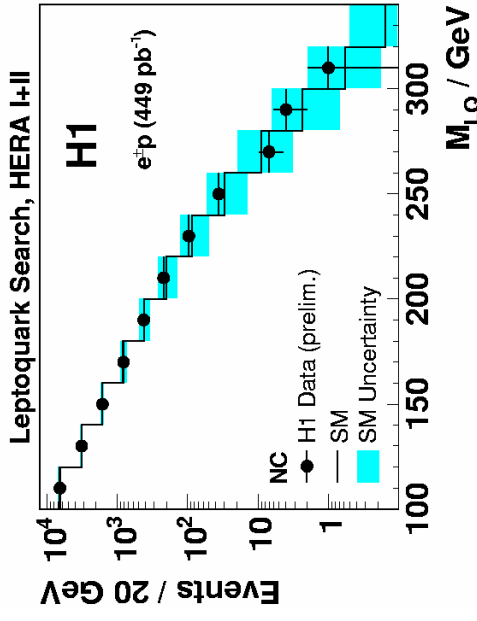


➤ 1st generation LQs:
 LQ \rightarrow eq - Lepton Flavor Conservation (LFC)

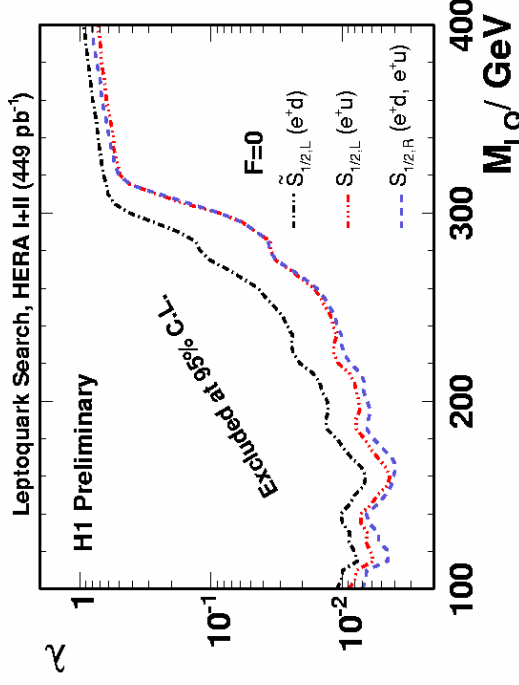
➤ 2nd/3rd generation LQs:
 LQ \rightarrow $\mu q / \tau q$ - Lepton Flavor Violation (LFV)
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Search for 1st generation Leptoquarks

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



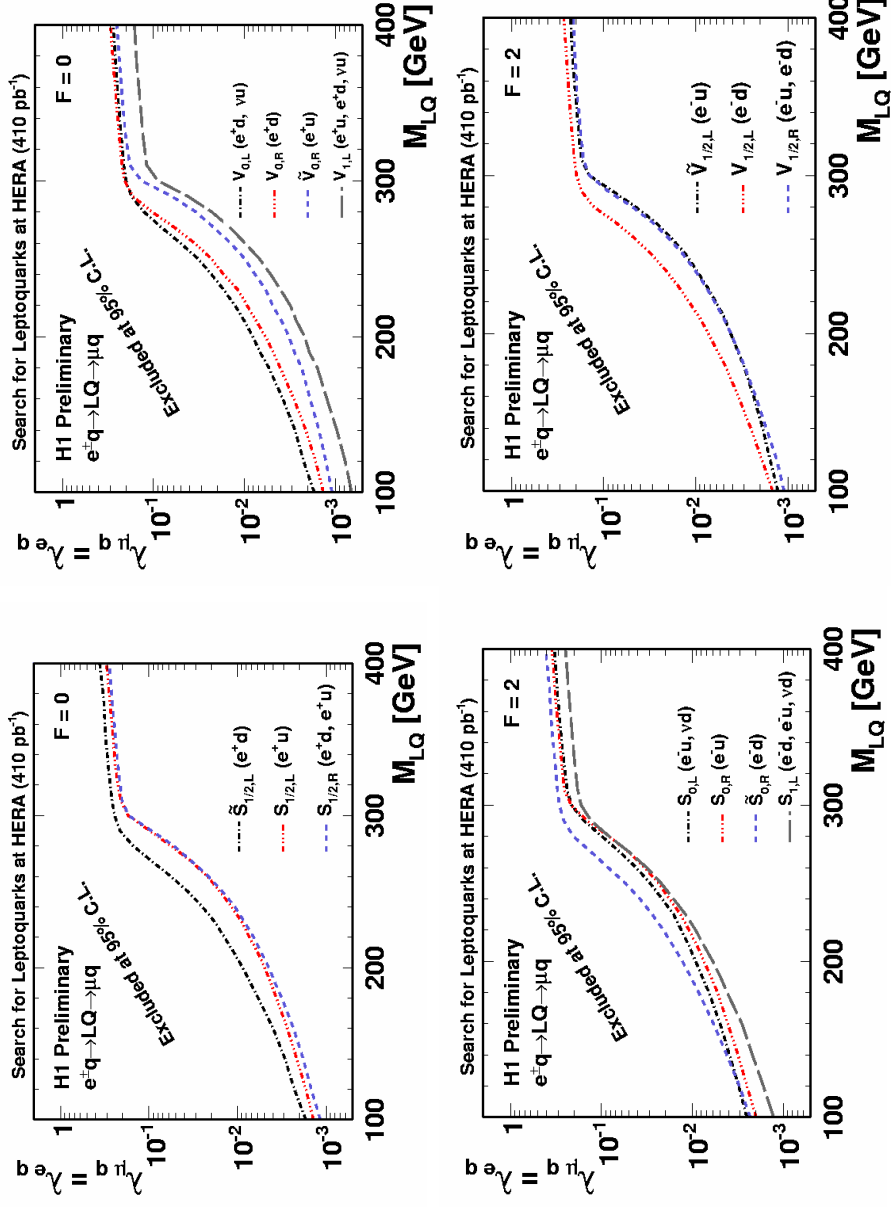
- Good description of data by SM prediction in both NC and CC processes
- No evidence of signal \rightarrow interpretation in terms of exclusion limits



- For electromagnetic strength $\lambda = 0.3$
 $M_{LQ} < 291\text{-}330 \text{ GeV}$ can be ruled out

Search for 2nd generation Leptoquarks

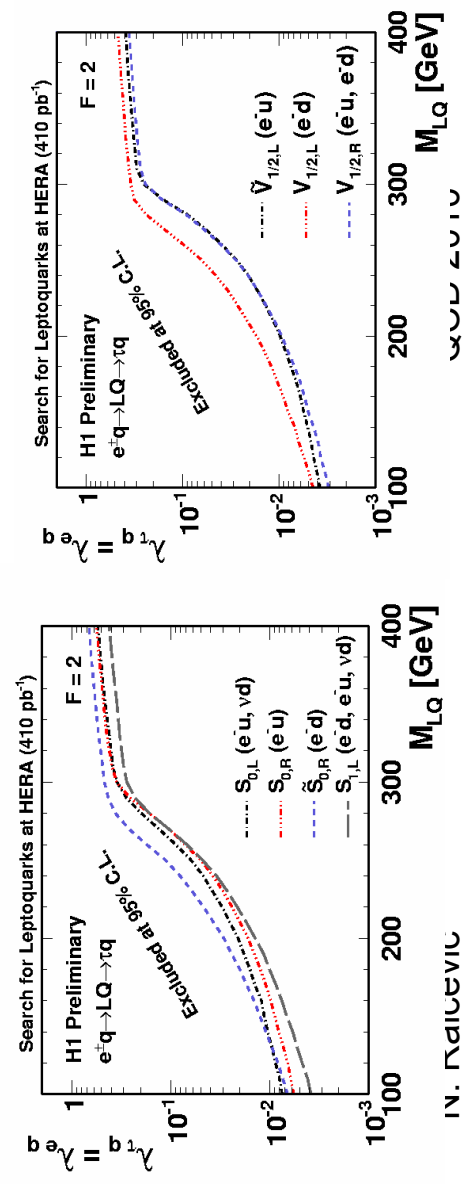
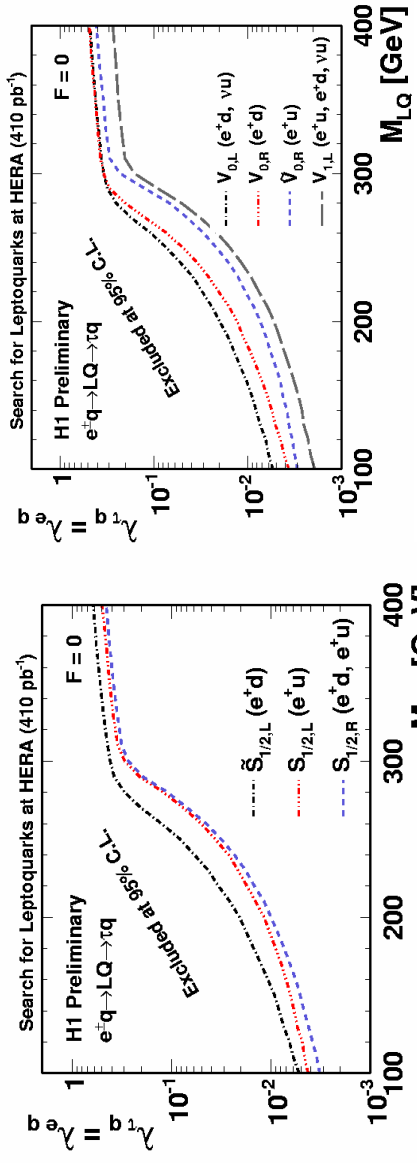
- No evidence for signal → Limits set for all 14 LQs under assumption $\Lambda_{\mu q} = \Lambda_{eq}, \Lambda_{Tq} = 0$
- H1 (98-07) sample → 1 event seen / 1.6 ± 0.5 expected



For em strength $\lambda = 0.3$
 $M_{LQ} < 304\text{-}530$ GeV
 can be ruled out

Search for 3rd generation Leptoquarks

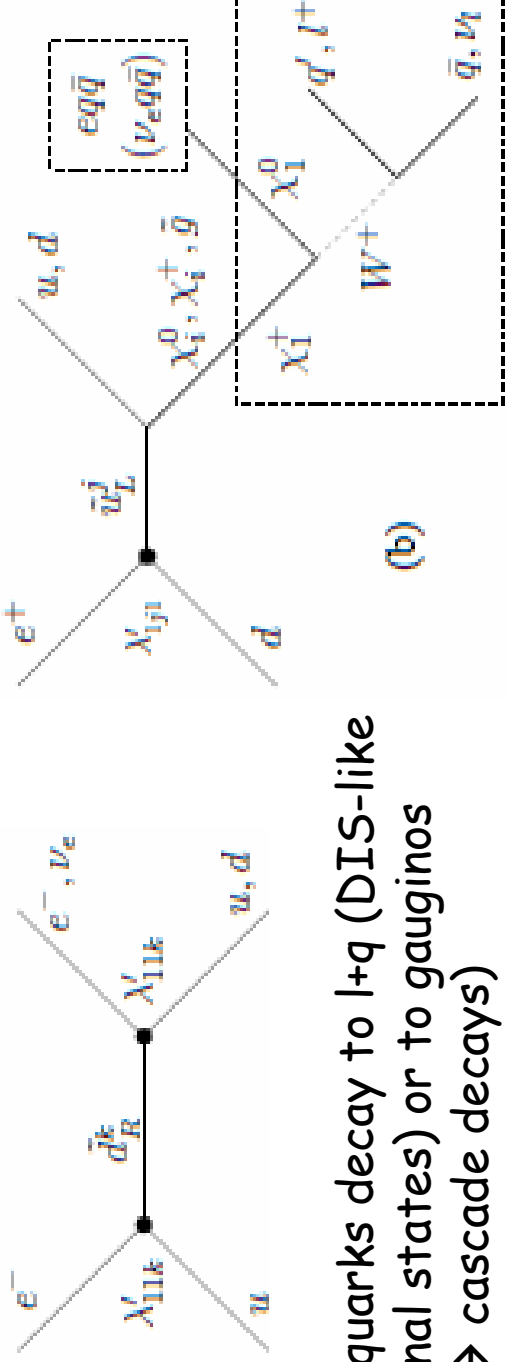
- No evidence for signal → Limits set for all 14 LQs under assumption $\Lambda_{\tau q} = \Lambda_{eq}, \Lambda_{\mu q} = 0$
- H1 (98-07) sample → 12 event seen / 10.6 expected



For em strength $\lambda = 0.3$
 $M_{LQ} < 272\text{-}450 \text{ GeV}$
 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

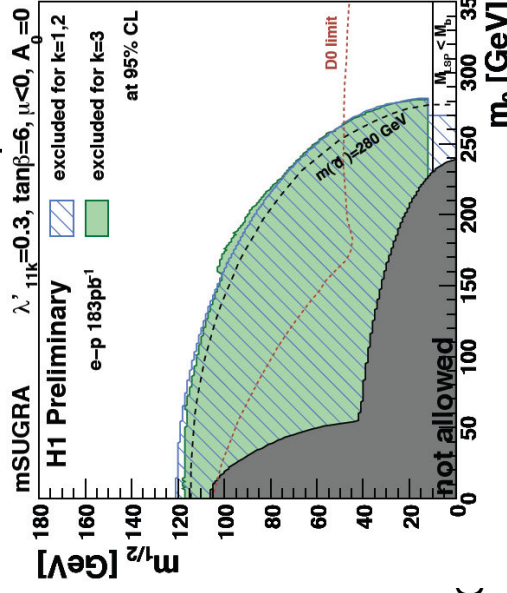
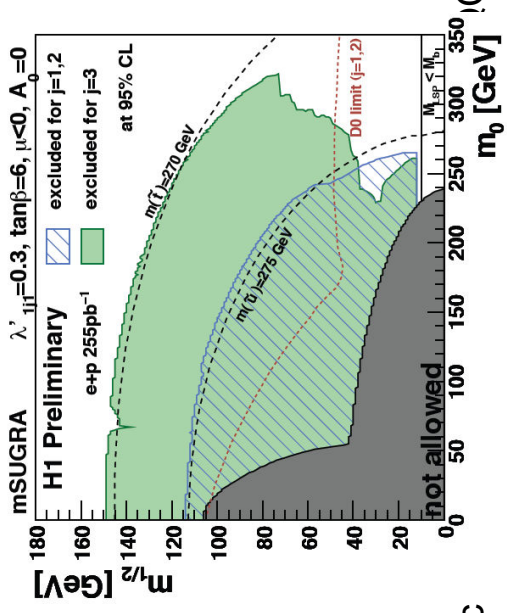
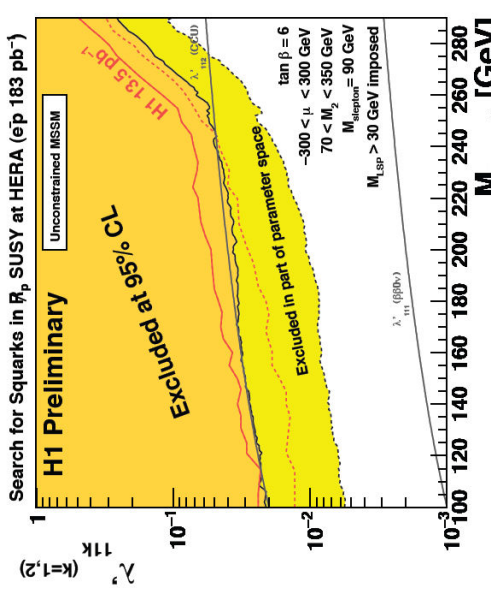
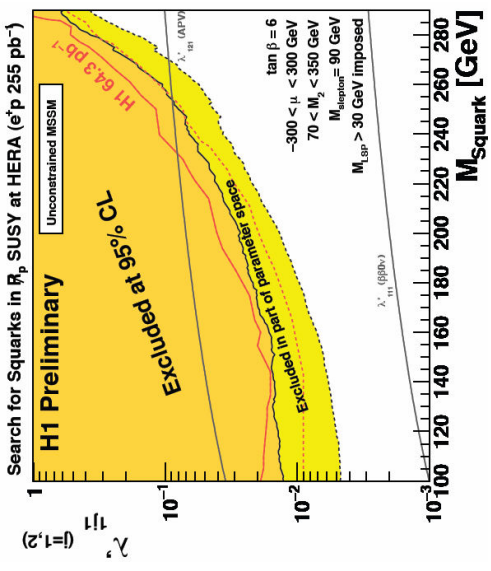


- Squarks decay to $l+q$ (DIS-like final states) or to gauginos (\rightarrow cascade decays)

- Interpretation of search results in phenomenological MSSM and mSUGRA model for a Yukawa coupling of electromagnetic strength $\lambda'_{1j1}, \lambda'_{11k} = 0.3$
 \rightarrow Limits set using full H1 data

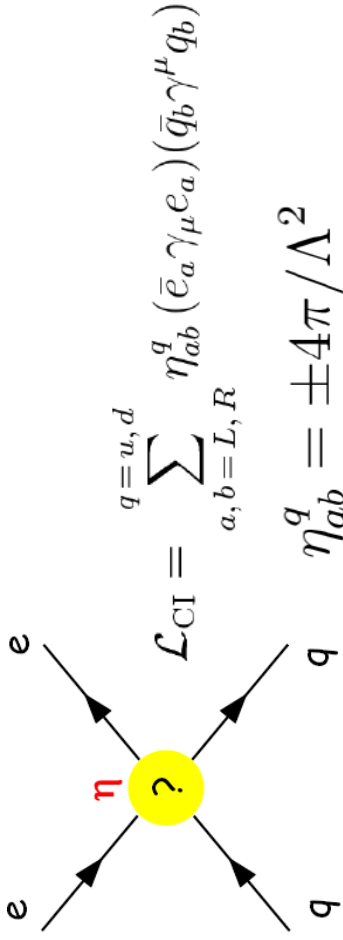
Squark production in RPV SUSY

- 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

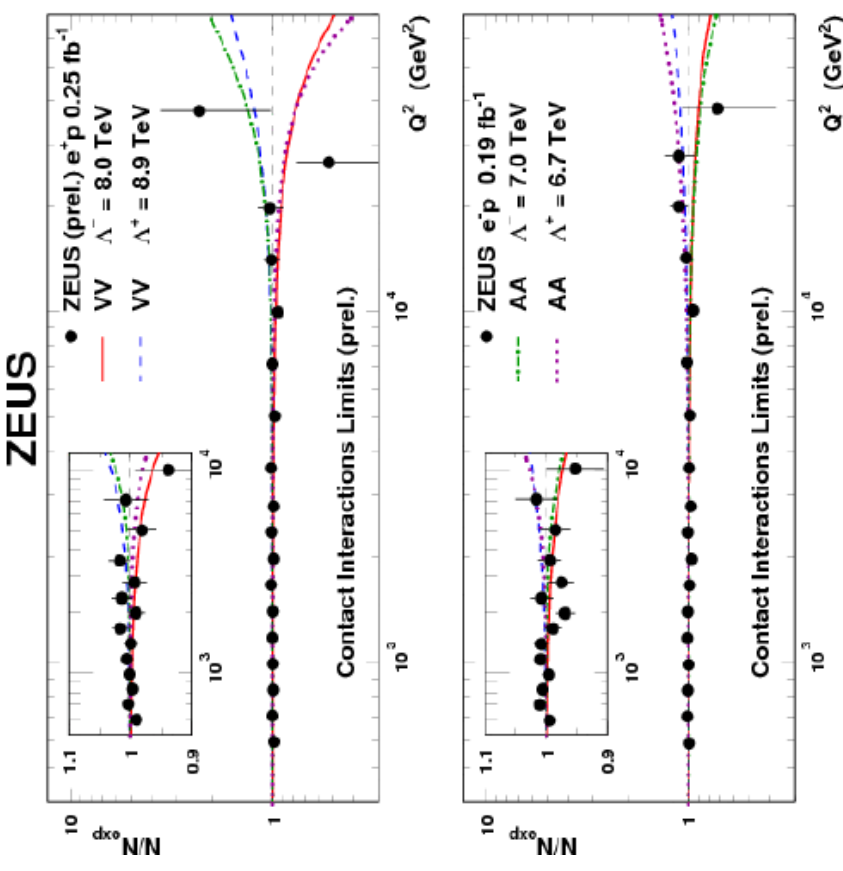


Contact interactions

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



- Could alter SM DIS distributions at high Q^2
- Many models possible depending on chiral structure



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

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

Large extra dimensions

- ADD (Arkani-Hamed, Dimopoulos, Dvali) model \rightarrow space time is 4+n dimensional
- SM particles confined to 4 dimensions, gravity can propagate into the extra dimensions
- Fundamental Planck scale M_5 in 4+n dimensions can be of the order of 1 TeV \rightarrow Strength of gravitational and electroweak interactions comparable at high energies
- Virtual graviton exchange contribution to eq \rightarrow eq scattering can be described by a contact interaction with effective coupling $\eta_G \sim \pm 1/M_5$
- ZEUS limit ($L = 0.44 \text{ fb}^{-1}$) $M_5^+, M_5^- > 0.94 \text{ TeV}$ independent on n

