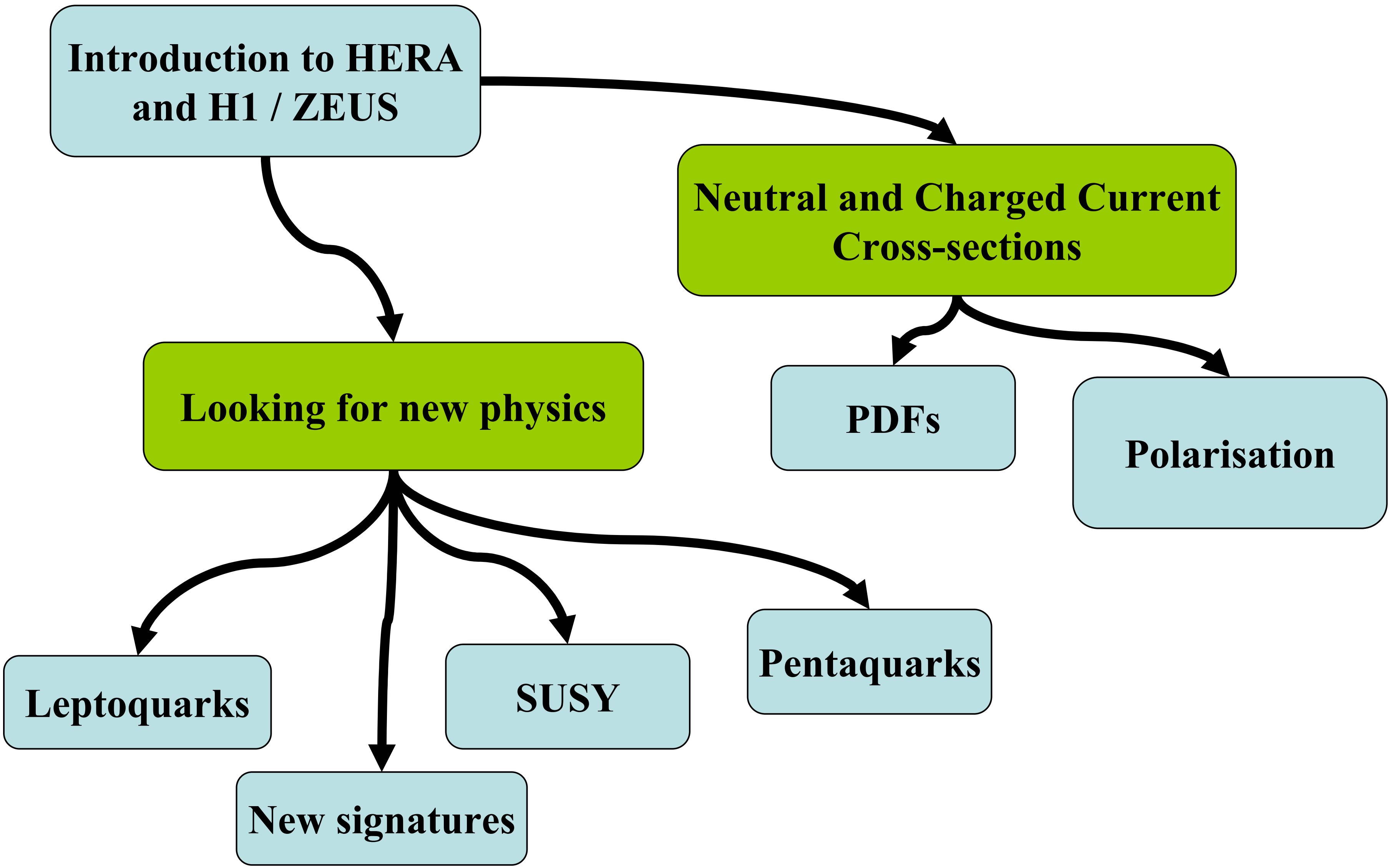
Neutral and charged current cross-section measurements and searches for new physics at HERA

Nick Malden – Manchester (UK)

HEP-MAD 04, Antananarivo, Madagascar

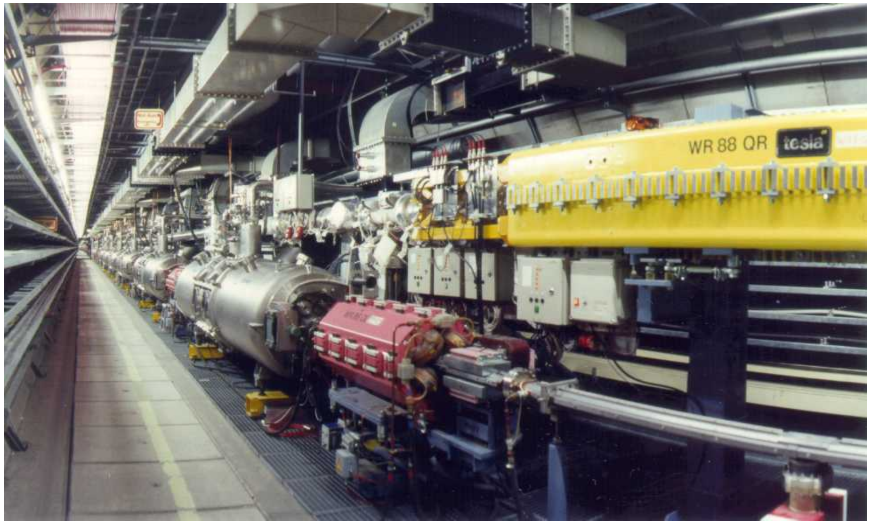
Overview


Introduction to HERA
and H1 / ZEUS
Neutral and Charged Current
Cross-sections
Looking for new physics
PDFs
Polarisation
Leptoquarks
New signatures
SUSY
Pentaquarks

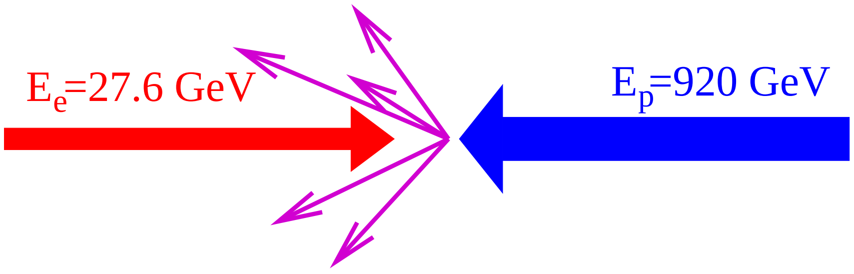
The HERA electron-proton collider

Hamburg,
Germany

The HERA Ring – 6.3km circumference



A view inside the HERA tunnel



$$\sqrt{s} = 320\,\text{GeV}$$

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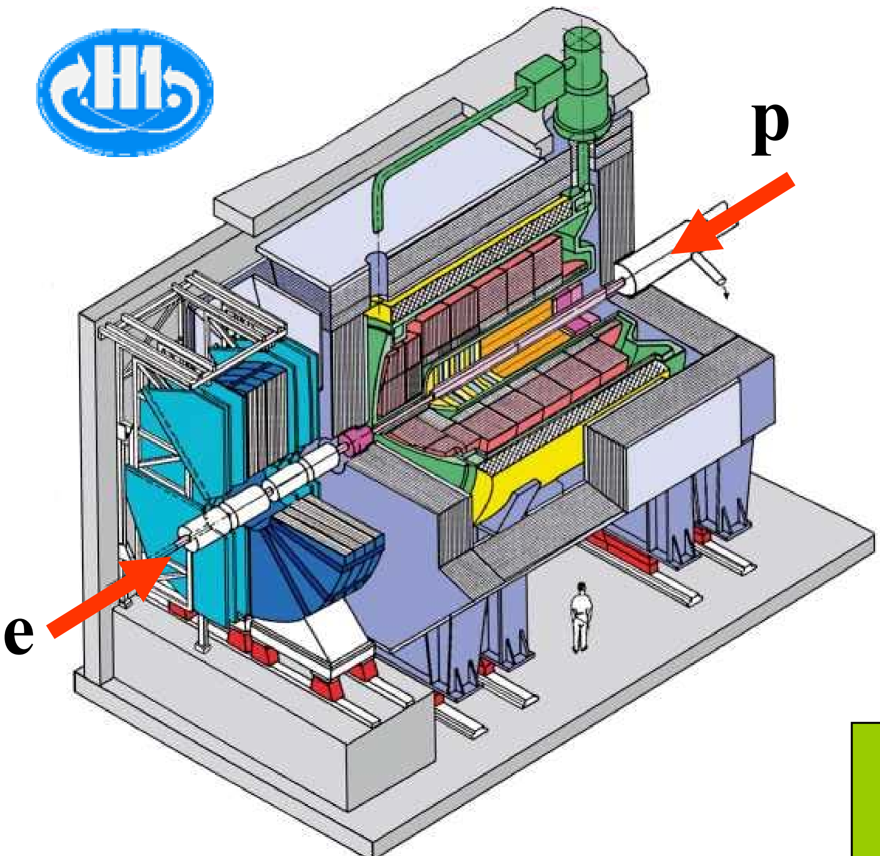
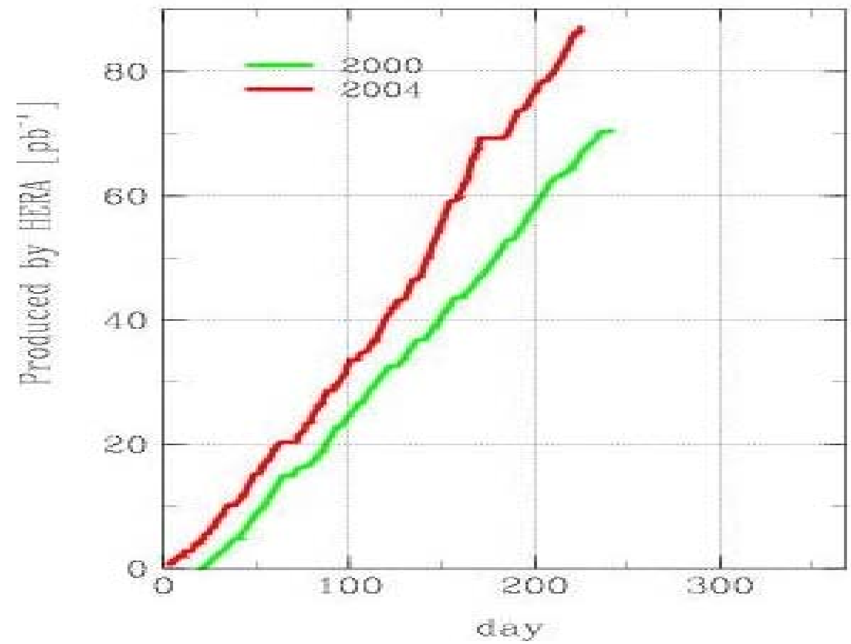
Recording the ep collisions at HERA



Integrated Luminosity



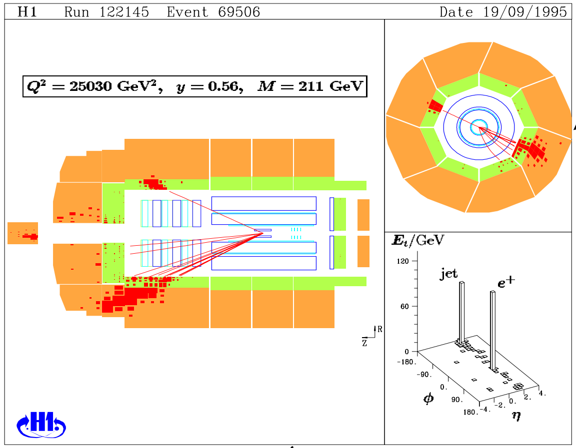
Asymmetric multi-purpose detector – vertexing, tracking, calorimetry and outer muon chambers

94-00 "HERA I" ~100 pb^{-1} e$^+$p data
~15 pb^{-1} e$^-$p data
03-04 "HERA II" ~50 pb^{-1} e$^+$p data
per experiment

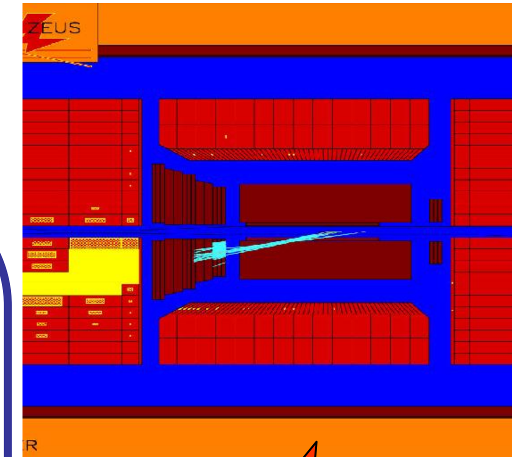
- Polarised positrons <P> $\leq$ 40%

Approx equal amount of each helicity

Deep Inelastic Scattering



Neutral Current DIS – beam electron scattered into detector



Kinematic variables

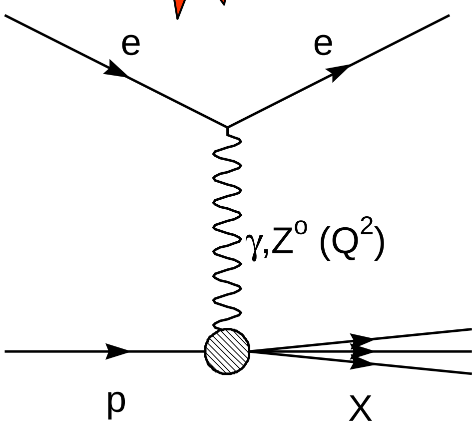
Q^2 – momentum transfer squared (“resolution”)

x – fraction of proton momentum carried by struck quark

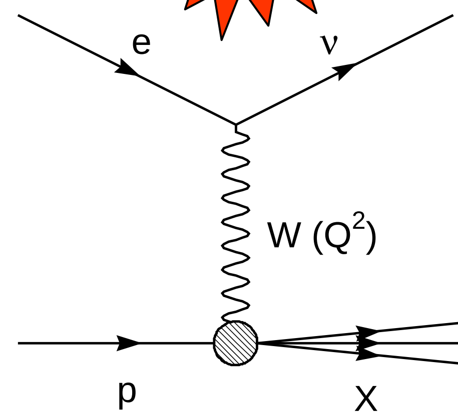
y – inelasticity (fractional electron loss)

$$Q^2 = s\,x\,y$$

NC

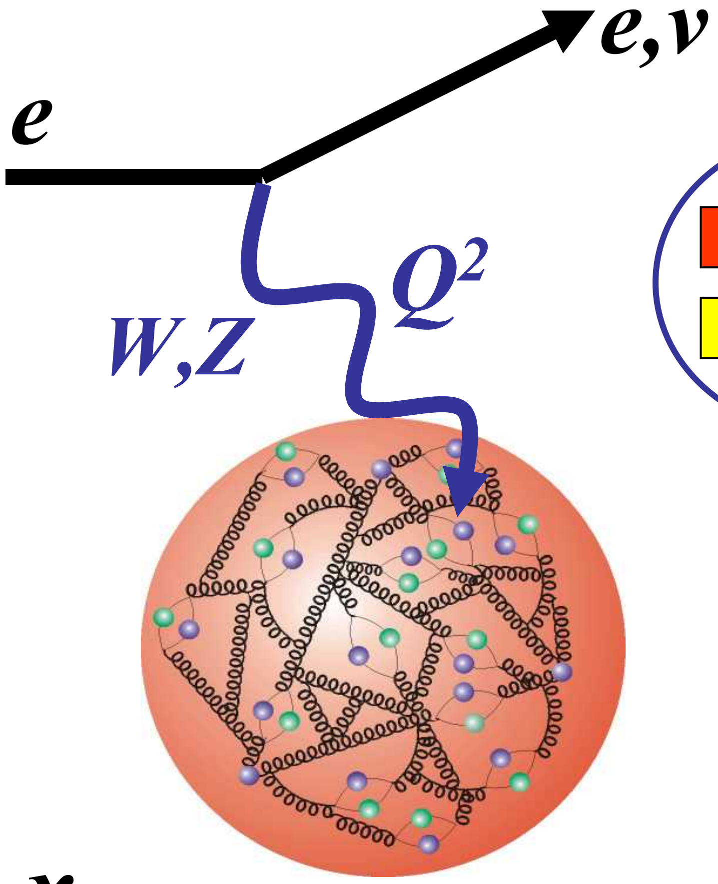


CC

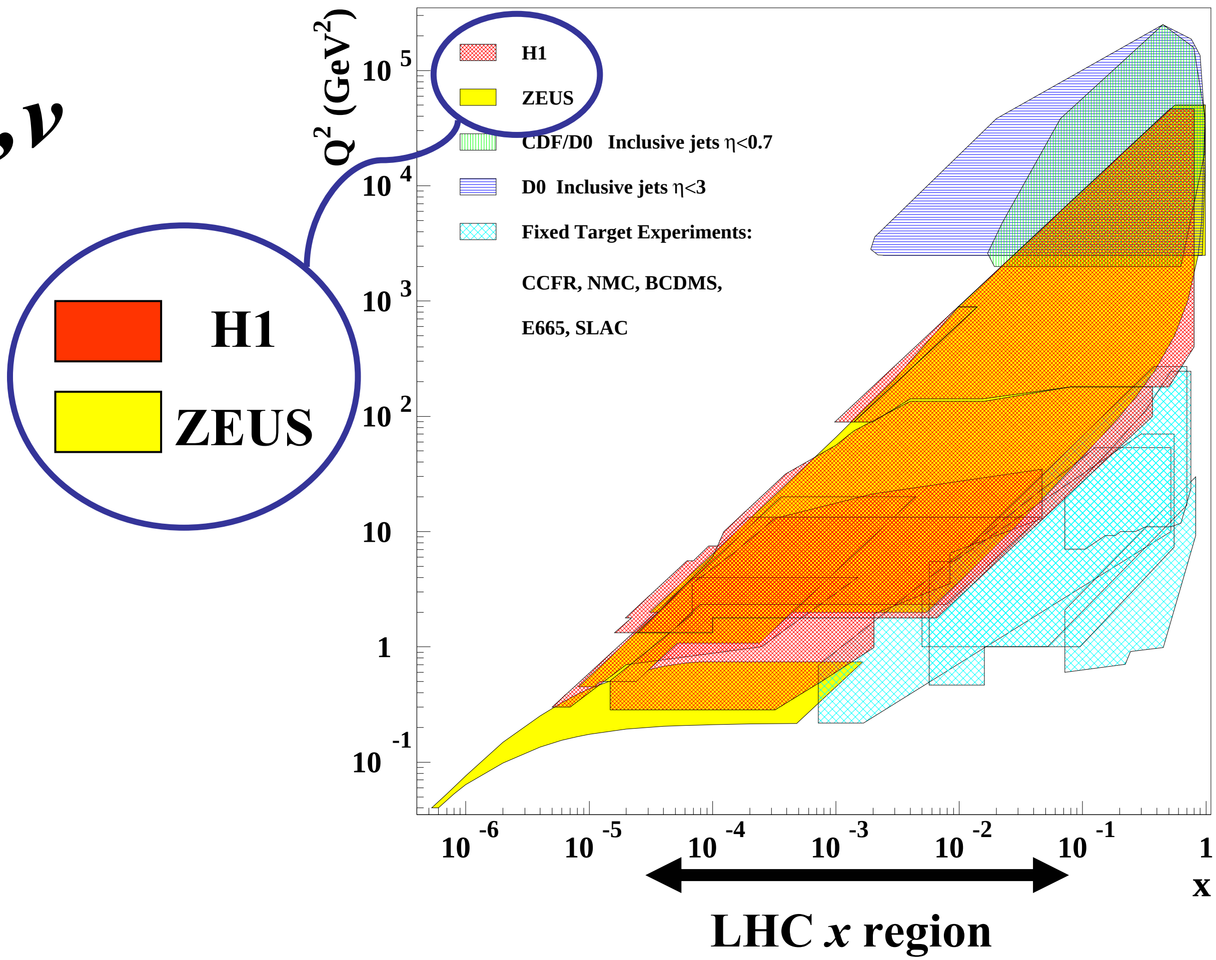


Charged Current DIS – beam electron converted to neutrino

The kinematic domain

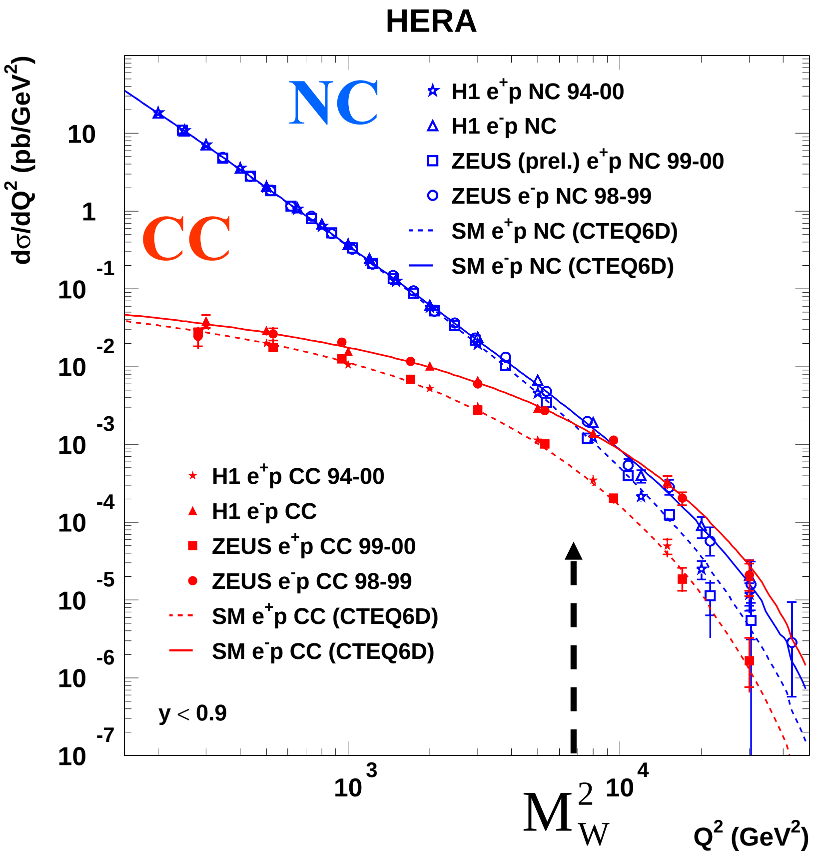


x – Fraction of proton's momentum



Proton structure investigated at HERA over an impressive kinematic range

Neutral and Charged Current Cross-sections (intro)



NC :

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} \approx \alpha^2_{\mathrm{em}} \left[\frac{1}{Q^2}\right]^2 \frac{1}{x} \tilde{\sigma}_{\mathrm{NC}}$$

Propagator terms – unification at $Q^2 > (M_W)^2$

Proton structure and QCD – that bubbling sea of quarks and gluons

CC :

$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} \approx G_F^2 M_W^4 \left[\frac{1}{M_W^2 + Q^2}\right]^2 \frac{1}{x} \tilde{\sigma}_{\mathrm{CC}}$$

Neutral and Charged Current Cross-sections (detail)

NC : $$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

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

CC : $$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2 \left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

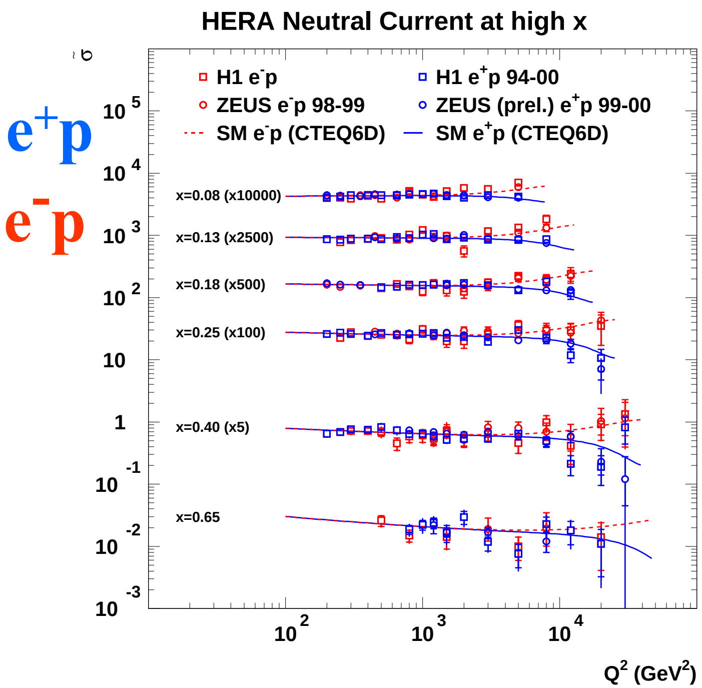
$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$ **The dominant contribution**

$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$ **Only significant at high Q^2**

$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$ **Only significant at low Q^2 and high y**

Similarly for $W_2^{\pm}$, $xW_3^{\pm}$ and W_L

$\tilde{\sigma}_{NC}$ - the reduced NC cross-section and xF_3

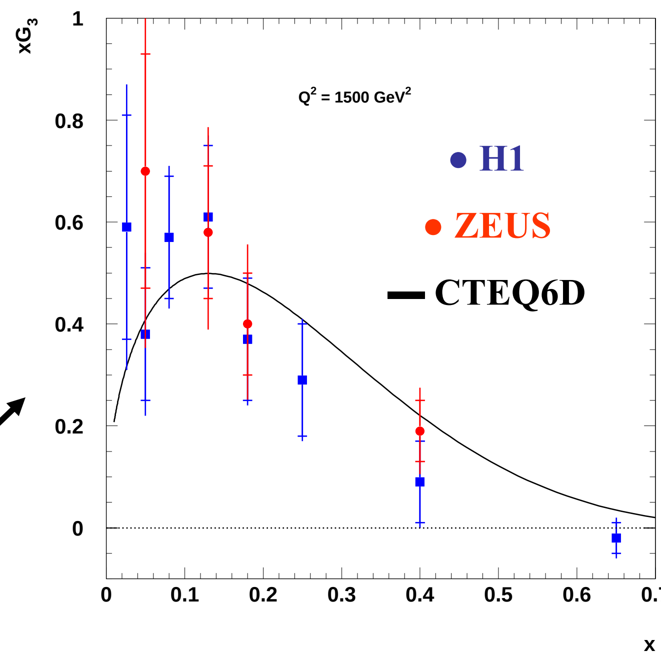


$$\tilde{\sigma}^{\pm}_{NC} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

F_2 is mainly :

$$F_2^{em} = \sum e_q^2 (q + \bar{q})$$

Access xF_3 via the difference between positron and electron cross-sections



Most of xF_3 comes from γZ interference

$$xF_3 = xF_3^{\gamma Z} + Z\,\text{exchange}$$

$$xF_3^{\gamma Z} \sim \frac{Q^2}{Q^2 + M_Z^2} xG_3$$ **where** $$xG_3 = \sum e_q a_q (q - \bar{q})$$

Valence quarks dominate - compares well to fixed target extrapolation

Reduced CC cross-sections

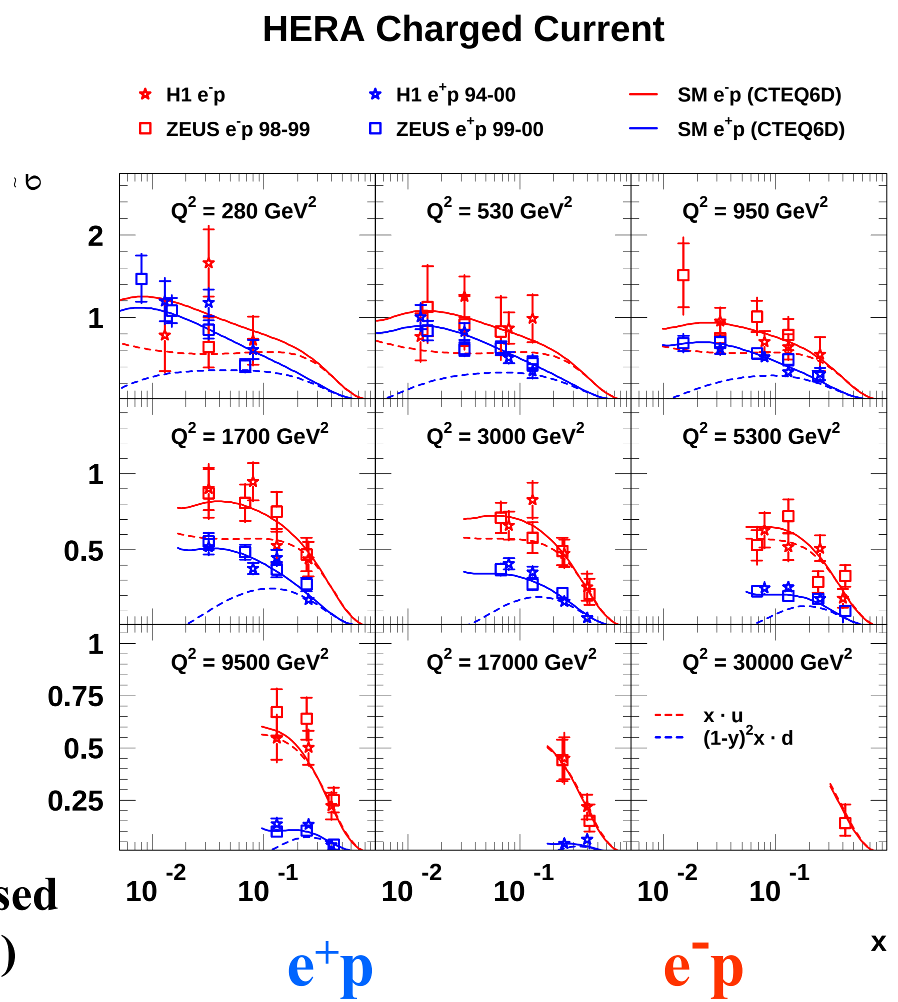
Probe the quark flavours in the proton.
Cross sections smaller than NC due to *W* mass in the propagator

$$\tilde{\sigma}^{-}_{CC} \sim xu + (1-y)^2 x\bar{d}$$

Dominated by the *u* quarks at high *x*

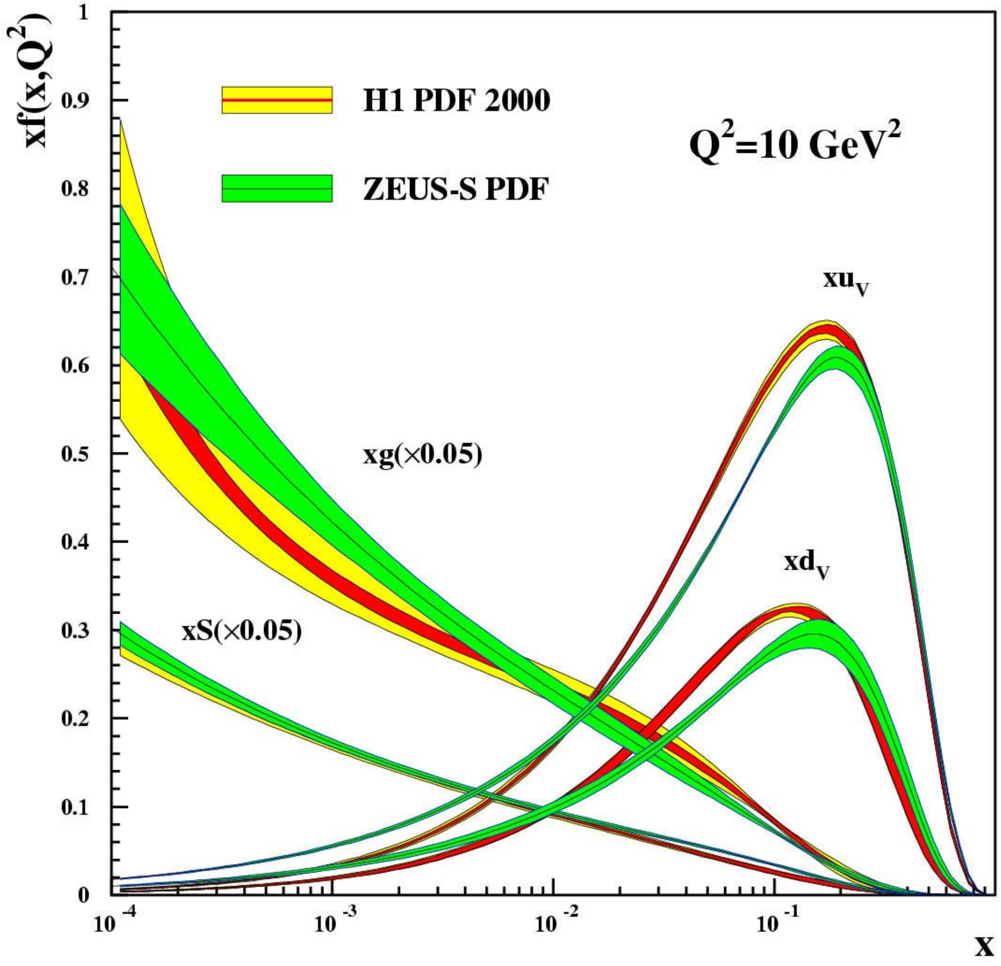
$$\tilde{\sigma}^{+}_{CC} \sim x\bar{u} + (1-y)^2 xd$$

***d* quark dominated at high *x*, but suppressed by the quark content of the proton (uud)**



Valence quarks dominate at high *x*

Parton density functions (PDFs)

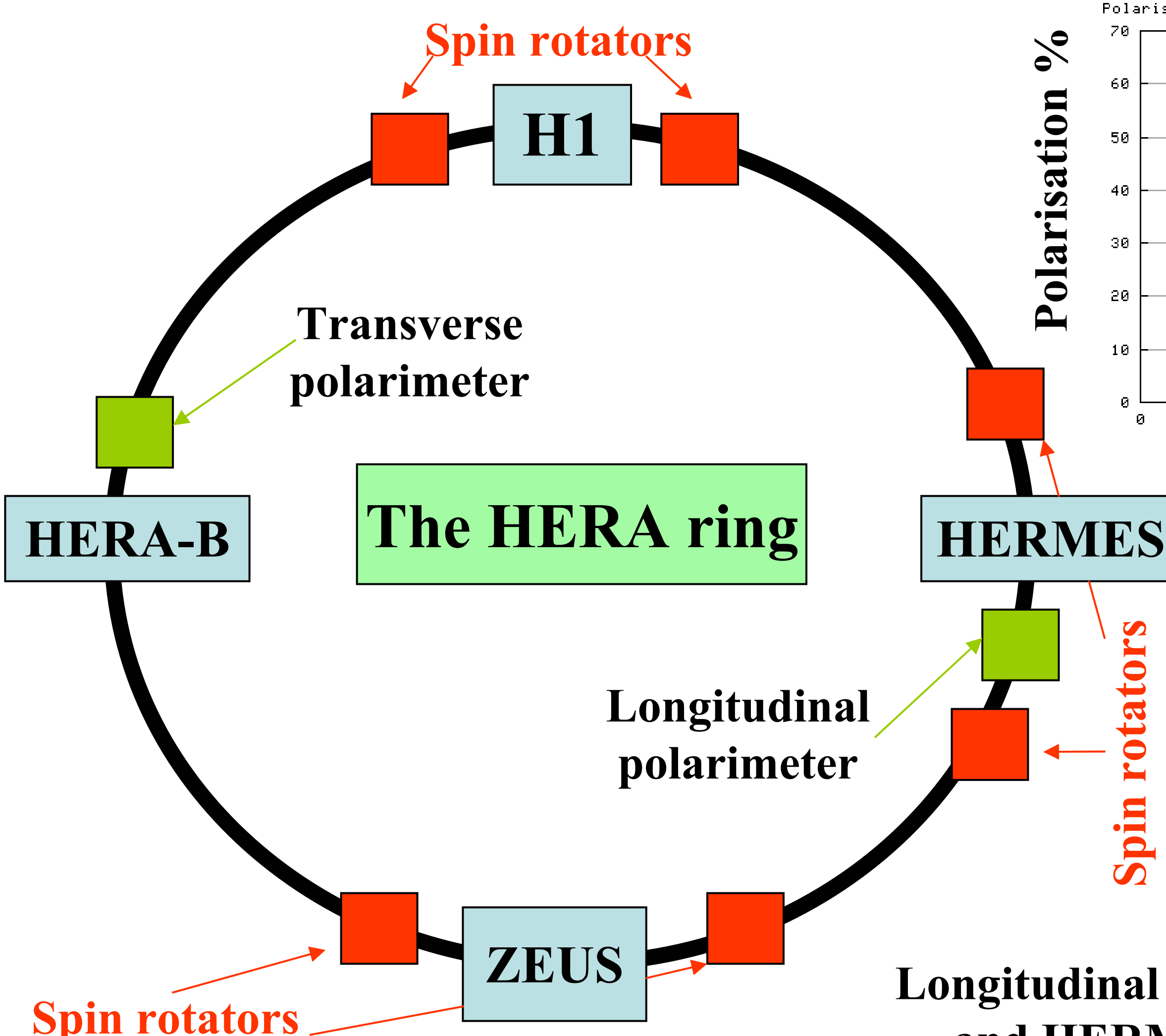


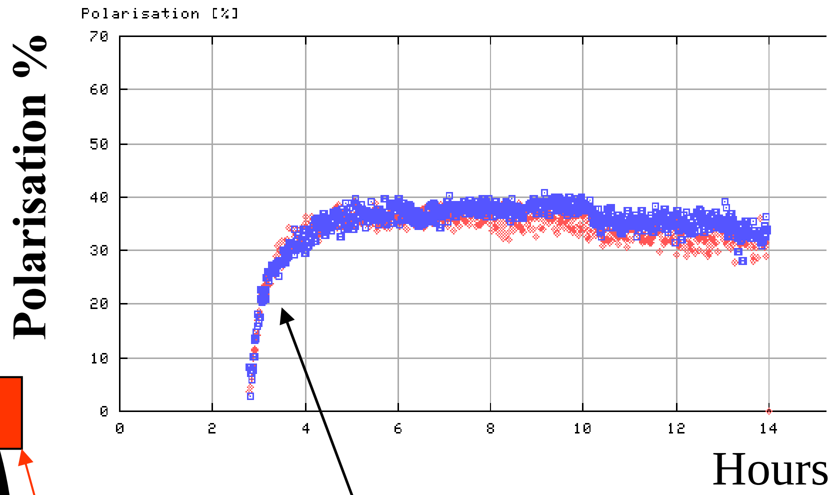
Combined fits fits allow the extraction of parton density functions (PDFs)

H1 and ZEUS pdfs are in agreement and agree with global fits

Gluon at low *x* and Q^2 the least well constrained

Polarised leptons for HERA II

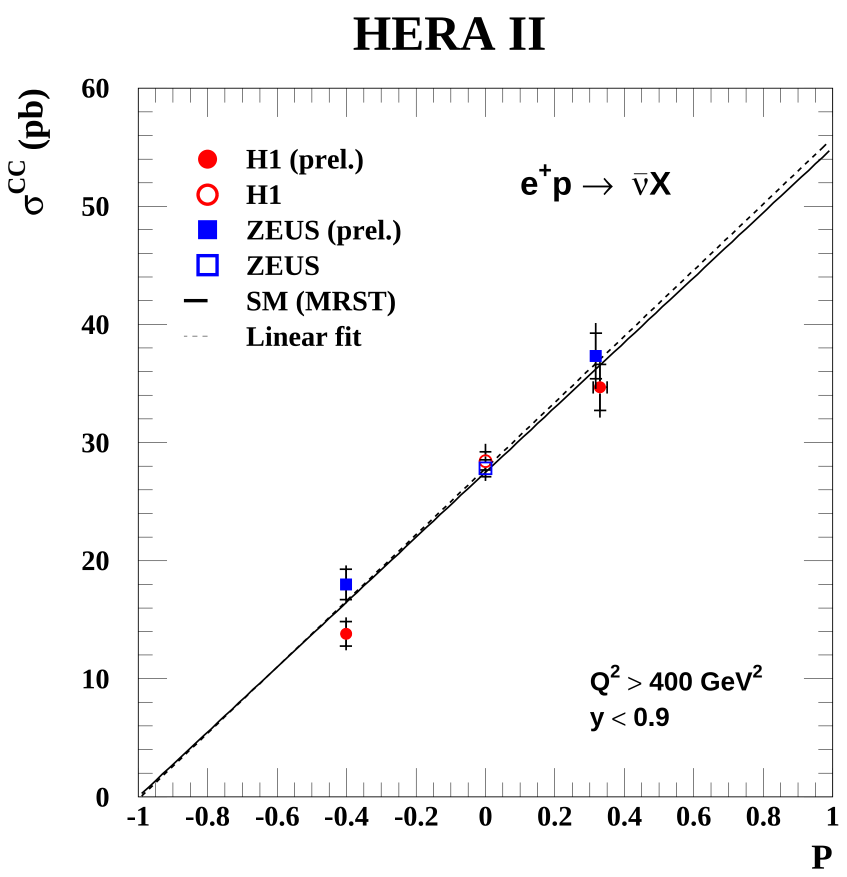




Rapid build-up of polarisation (Solokov-Turnov effect) at the beginning of the fill to ~ 40%

Longitudinal polarisation through H1, ZEUS and HERMES - transverse polarisation round the curved sections of HERA

Polarised CC cross-sections at HERA II



CC interaction depends linearly on the polarisation:

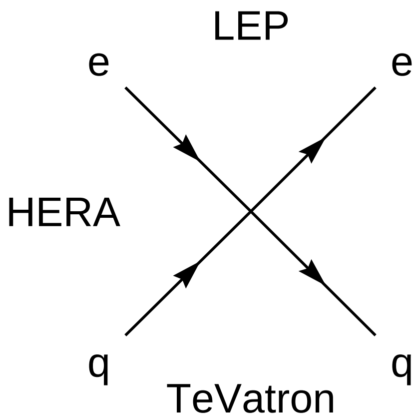
$$\sigma_{CC}^{\pm} = (1 \pm P)\ \sigma_{CC}^{(P=0)}$$

SM CC interaction is left-handed.
Deviations from the above give direct sensitivity to right-handed CC interactions

"Spin-flips" at intervals during HERA running give data sets with both polarisations

Fits are consistent with SM expectation – no hint of right handed charged currents yet…

New physics at HERA?

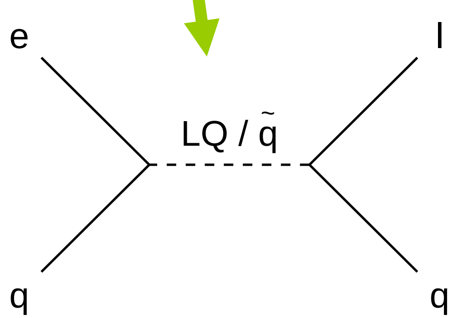


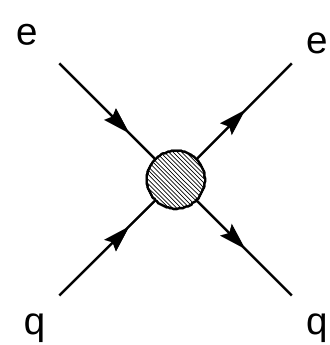
As the world's only electron-proton collider HERA can uniquely look for new physics in eq interactions

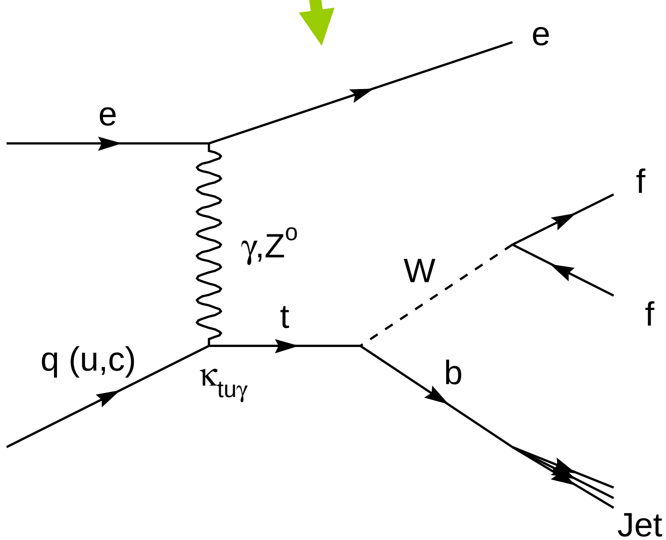
Exclusive final states – rare topologies – exotic particles or decay modes

Contact interactions – generic coupling model to probe scales beyond CoM

eq resonances – brief fusion of e and q to form leptoquark or squark







Leptoquarks

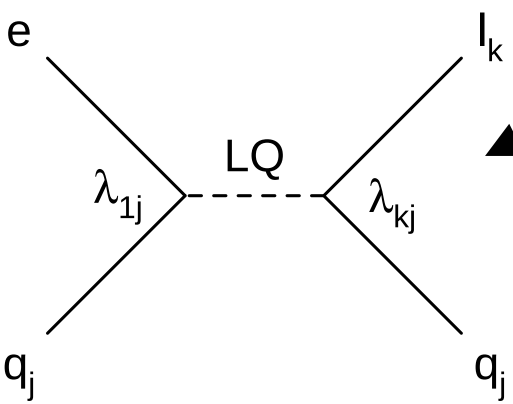
$|Q_p - Q_e|$

1 part in 10^{21}

Quarks and leptons are both point-like fermions

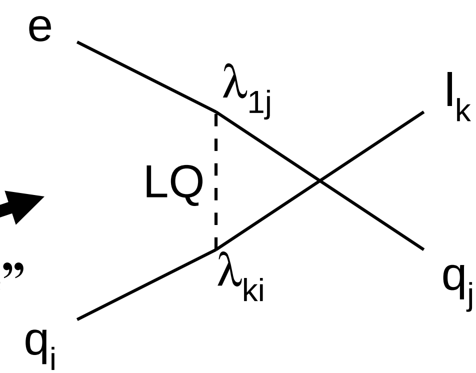
– clear symmetry between the families (3 x 2)

Is there a higher symmetry? → Leptoquarks (LQs) with B and L ≠ 0



s channel
“resonant production”

u channel
“virtual exchange”



LQs are part of many GUTs which appeal to higher symmetries – SU(5) or SU(15)

Buchmüller-Rückl-Wyler (BRW) model predicts 14 LQs (7 scalar / 7 vector)

Yukawa coupling λ_{ij} - Branching ratios fixed: β_{eq} = 1, ½ and $\beta_{\nu q}$ = 0, ½

Leptoquarks – Resonance search

Separate events from DIS data

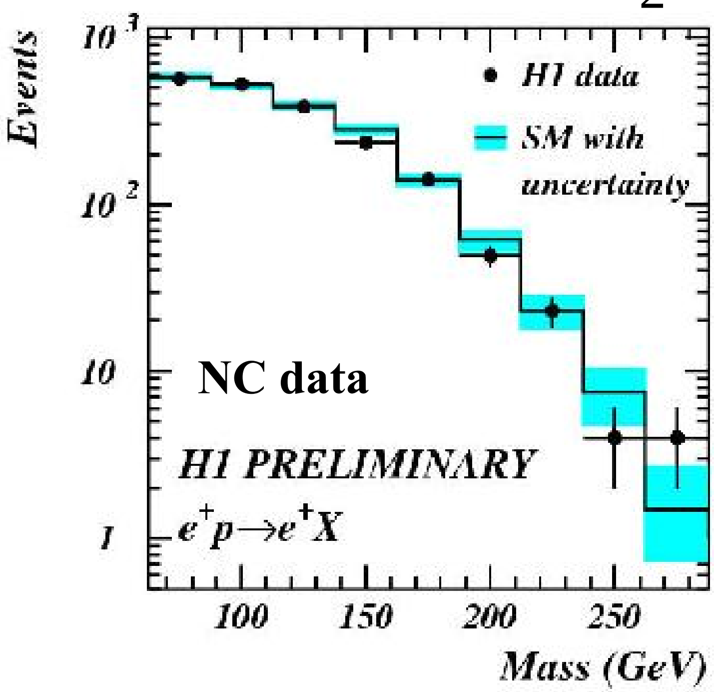
(Recall y relates to the scattered lepton polar angle)

$$y = \frac{1}{2}(1 + \cos\theta^*)$$

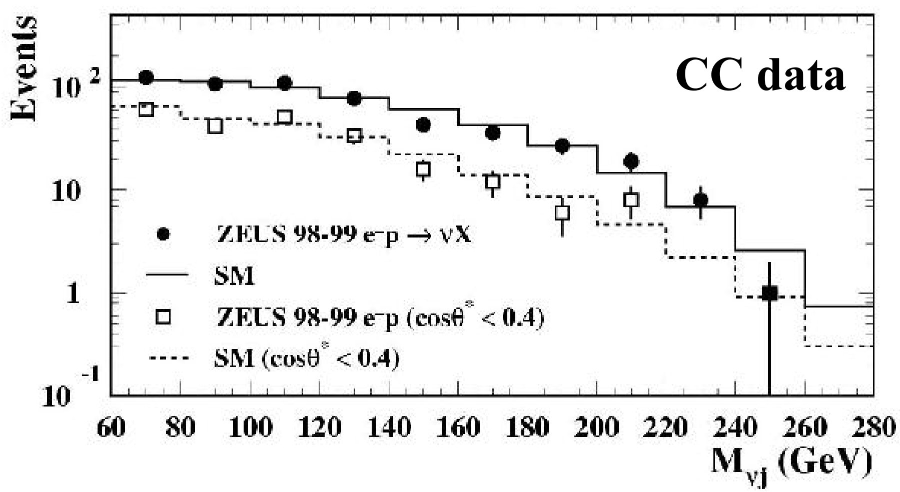
Scalar LQs produced flat in *y*

Vector LQs produced $\propto (1-y)^2$

NC DIS $\propto \frac{1}{y^2}$

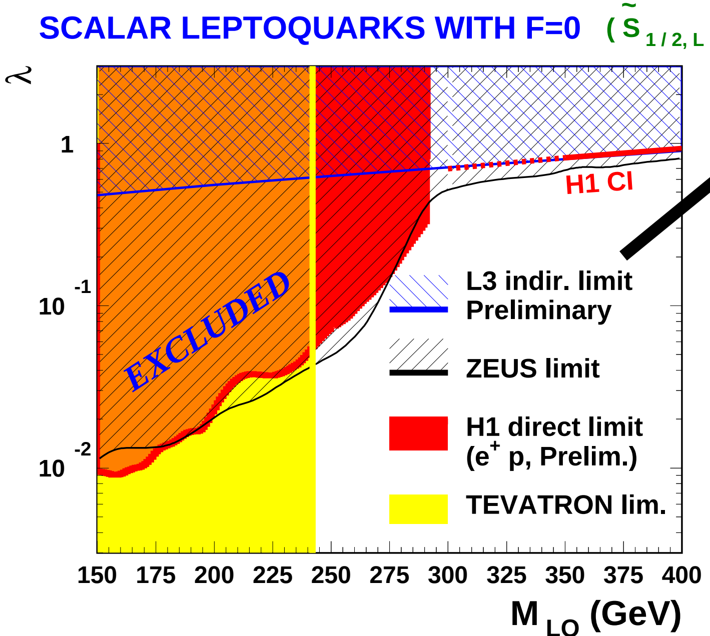


ZEUS

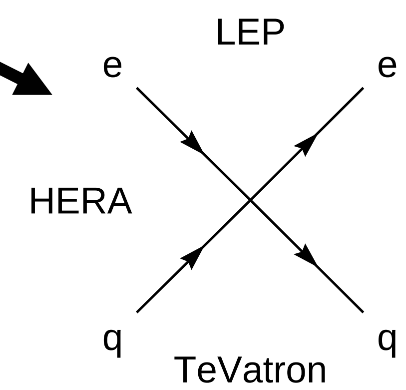


Good agreement with the Standard Model, hence derive mass and coupling exclusion limits

Leptoquarks – Mass and coupling limits



Remember "The Big 3"?



TeVatron – pair production – independent of λ

LEP – virtual effects in $e^+e^- \rightarrow$ hadrons
- strong dependence on λ

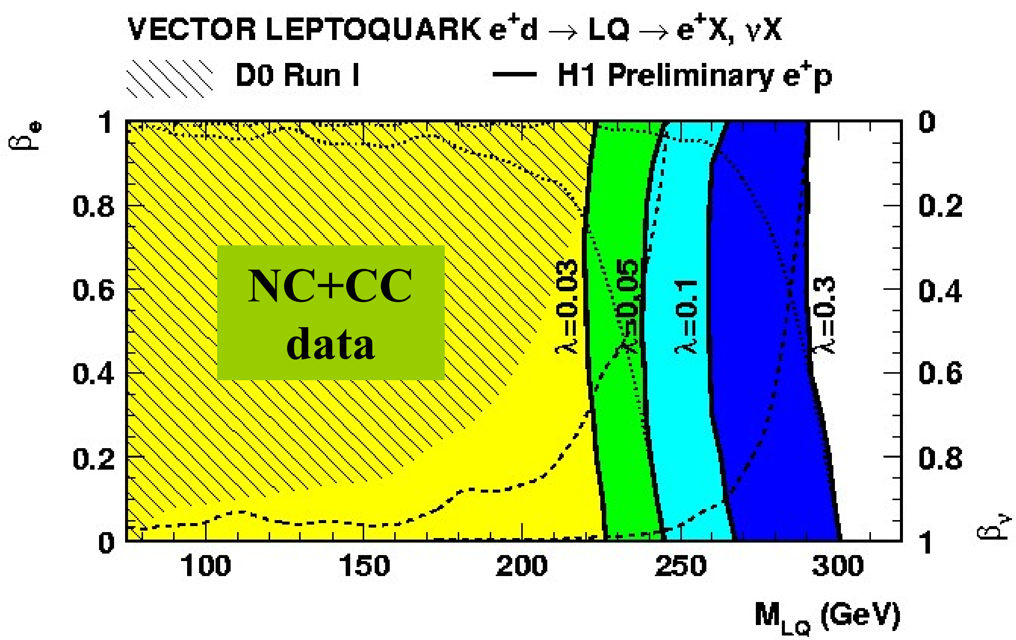
More general model :

β free – examine various choices of λ

NC+CC data : if $\beta_{eq} + \beta_{\nu q} = 1$ then

limits are almost independent of β

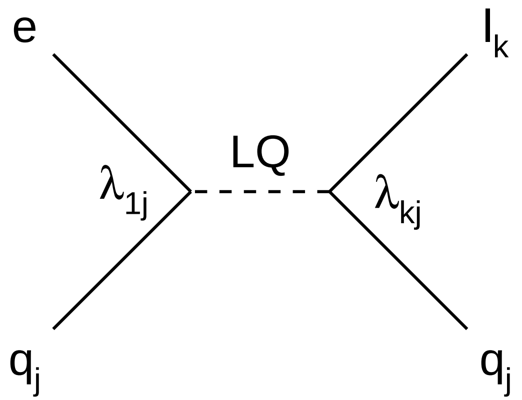
For $\lambda=\alpha_{em}$ LQs below 290GeV are ruled out



Lepton Flavour Violation

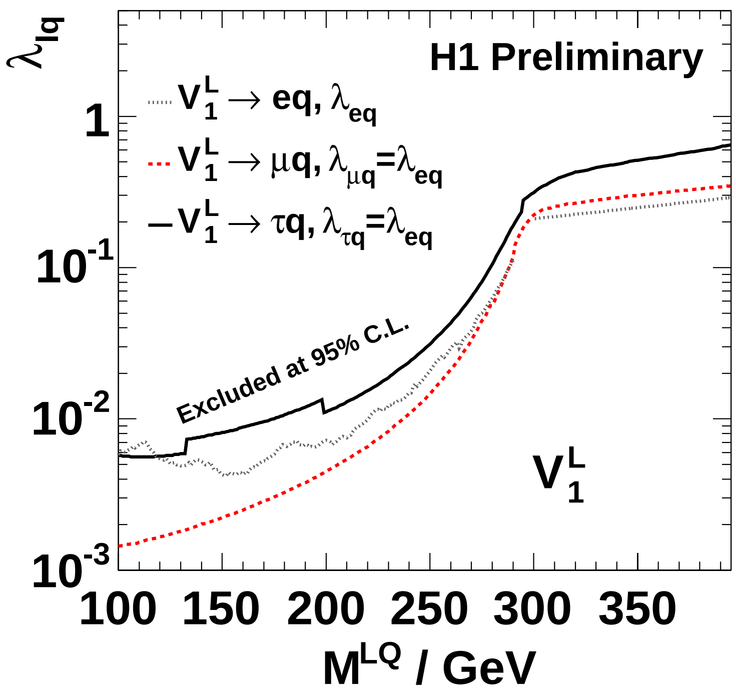
Neutrino oscillations tell us that lepton flavour is not conserved

At HERA LFV can be mediated by LQs coupling to different generations



μ or τ

Signal : μ or τ signature back-to-back with a powerful jet

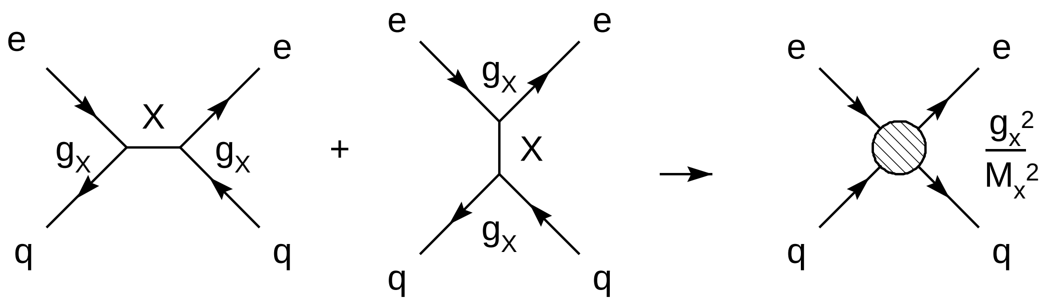


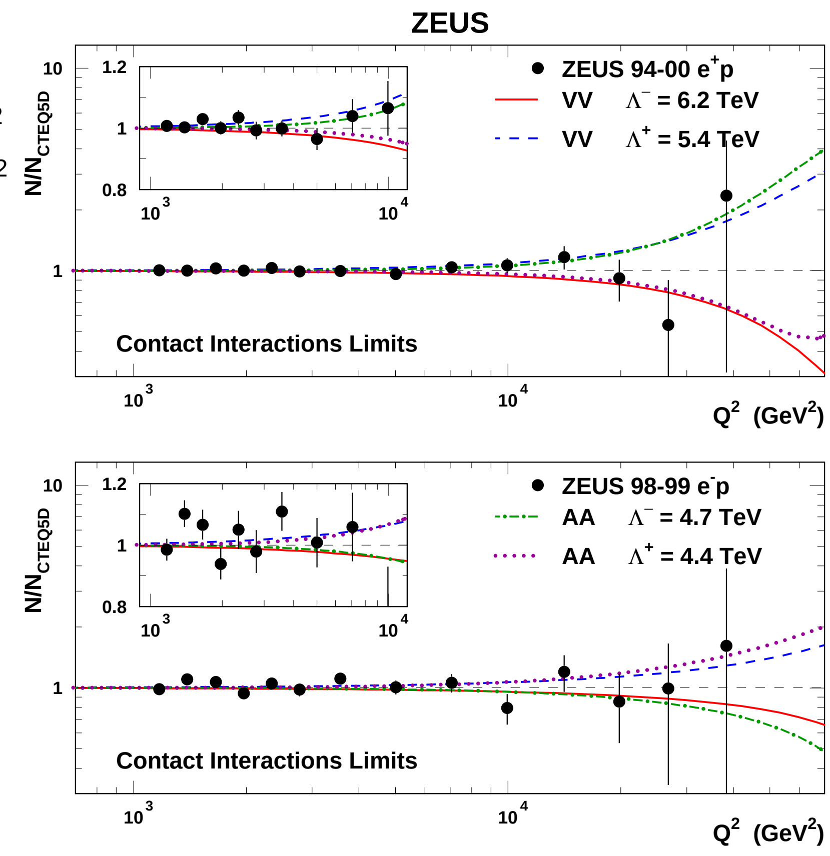
Results	LQ→μ+q	LQ→τ+q
H1 Data	0	1
Total SM	0.74±0.25	0.56±0.16

Similar results from ZEUS

Contact Interactions

For very heavy particles ($M_X >> \sqrt{s}$) parameterise a coupling for exchanges which will interfere with the "regular" HERA exchanges (γ, Z^0 and $W^\pm$)





Examine high Q^2 data → highest energies and smallest distances. No significant deviations seen (upwards or downwards depending on the sign of the interference term.

Mass scale limits 1.7→6.2 TeV (depending on the chirality of the interaction)

Also set limits on quark radius (finite radius has same effect as Λ^-)

$R_q < 0.85 \times 10^{-18}$ m

Similar results from H1

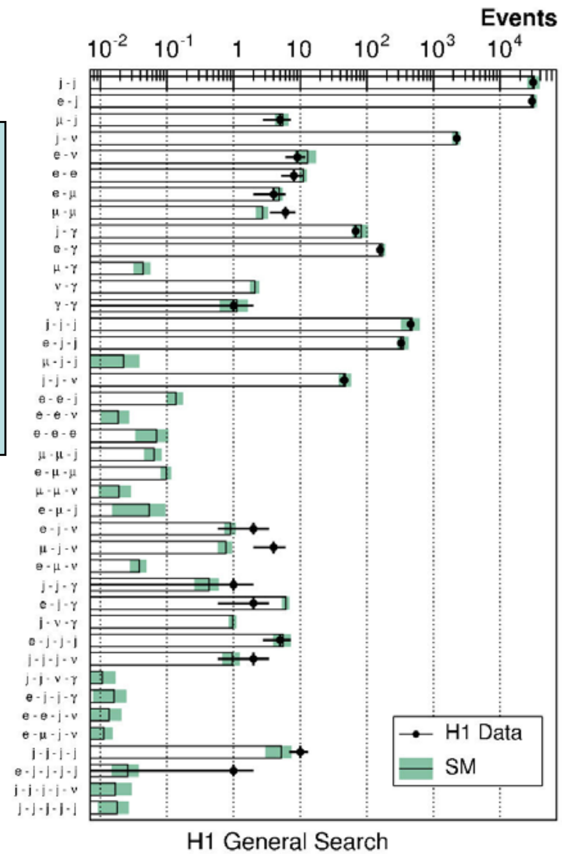
Generic search for new physics

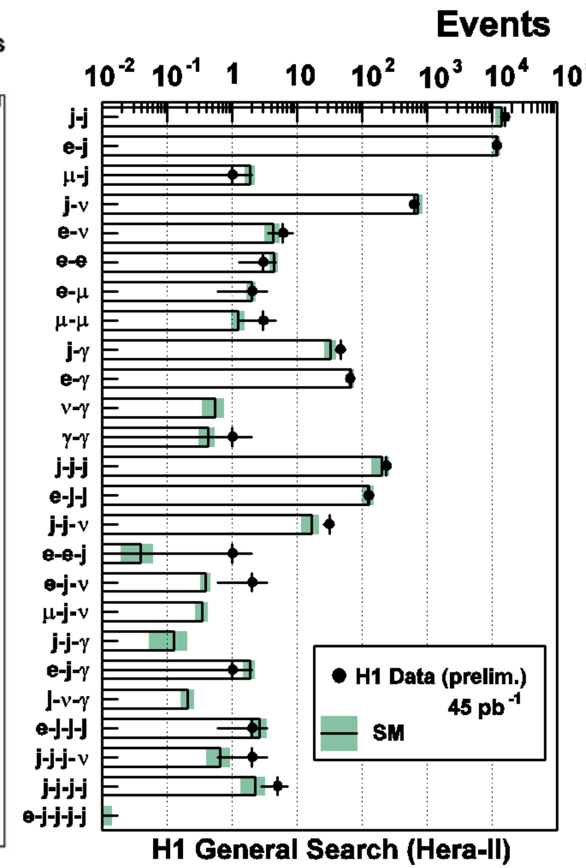
Aim is to investigate many high P_T topologies in a coherent way, looking for deviations from the Standard Model in a model independent way

Define objects *e, μ, γ, jet* and *ν* each with P_T > 20 GeV and in the central detector.

Define event classes with at least two of these objects

Compare to the SM and look for devations

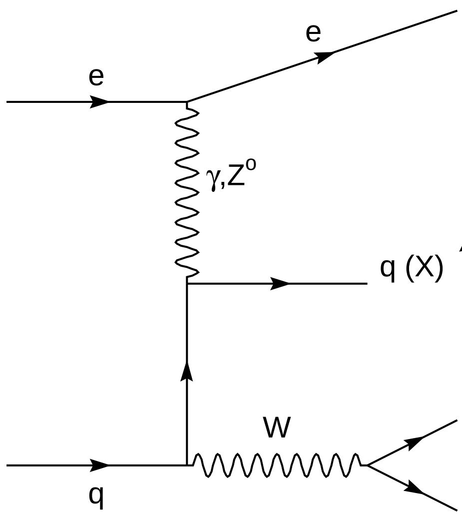




Nick Malden (Manchester) HEP-MAD 2004

Isolated leptons and missing P_T

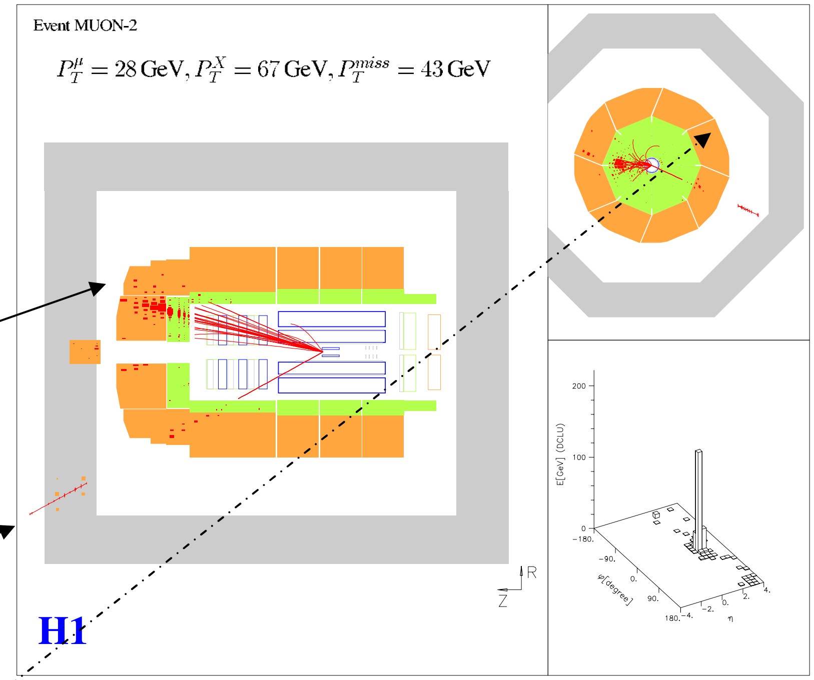
H1 observe an excess of events with a high P_T isolated lepton and missing P_T at high $P_T(X)$ (Phys.Lett.B561 (2003) 241)



Jet

Isolated lepton

Missing P_T



Only significant contribution to this signal in SM is W production with leptonic decay, particularly at high P_T (X)

Anomalous single top production? R-parity violating SUSY? (see later)

Isolated leptons – The HERA I results

H1 1994-2000 *Lumi* = 118 pb^{-1}	Electron obs./exp.	Muon obs./exp.	Tau (prel.) obs./exp.	*W* contrib. $e\mu(\tau)$
All data	11 / 11.5 ± 1.5	8 / 2.94 ± 0.51	5 / 5.81 ± 1.36	≈ 75 (15) %
$P_T(X) > 25$ GeV	5 / 1.76 ± 0.29	6 / 1.68 ± 0.30	0 / 0.53 ± 0.10	≈ 85 (50) %
$P_T(X) > 40$ GeV	3 / 0.66 ± 0.13	3 / 0.64 ± 0.14	0 / 0.22 ± 0.05	≈ 90 (55) %
ZEUS 1994-2000 *Lumi* = 130 pb^{-1}	**Electron obs./exp.**	**Muon obs./exp.**	**Tau obs./exp.**	***W* contrib. $e\mu(\tau)$**
All data	24 / 20.6 ± 3.2	12 / 11.9 ± 0.6	3 / 0.4 ± 0.12	≈ 17 (48) %
$P_T(X) > 25$ GeV	2 / 2.9 ± 0.46	5 / 2.75 ± 0.21	2 / 0.2 ± 0.05	≈ 50 (50) %
$P_T(X) > 40$ GeV	0 / 0.94 ± 0.11	0 / 0.95 ± 0.12	1 / 0.07 ± 0.02	≈ 60 (70) %

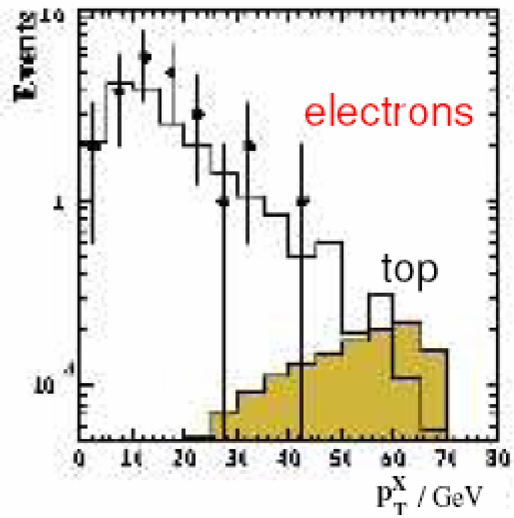
SM *W* prediction is NLO (*Diener et al.)*

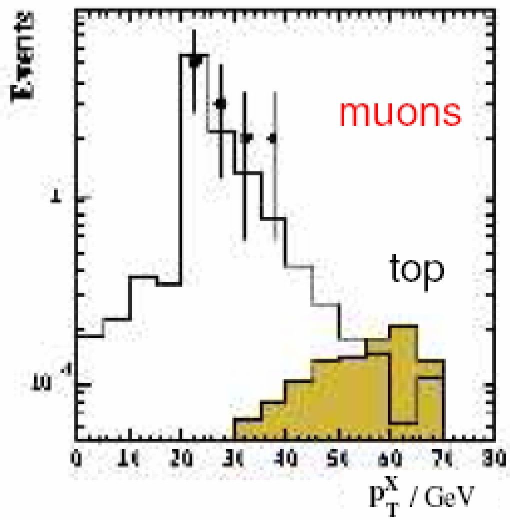
H1 and ZEUS channel excesses do not match

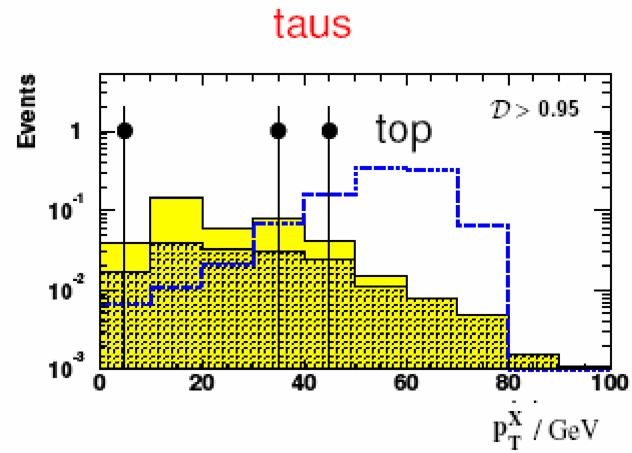
Note the difference in purities in the selections

Isolated leptons – The HERA I results

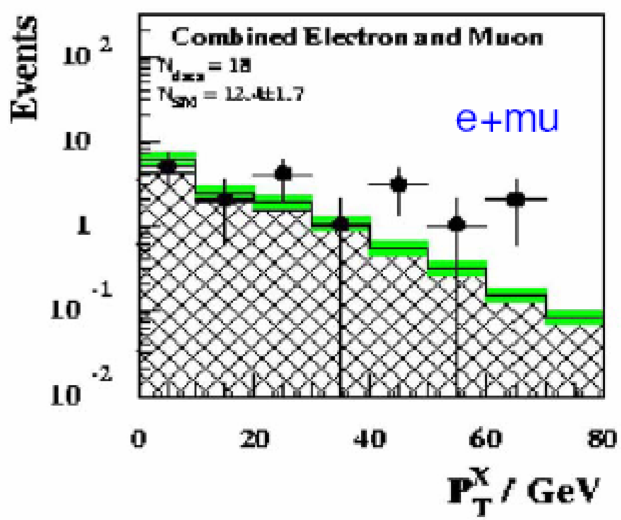
ZEUS

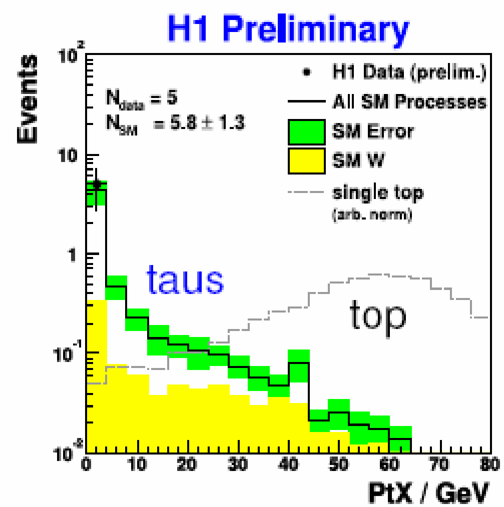






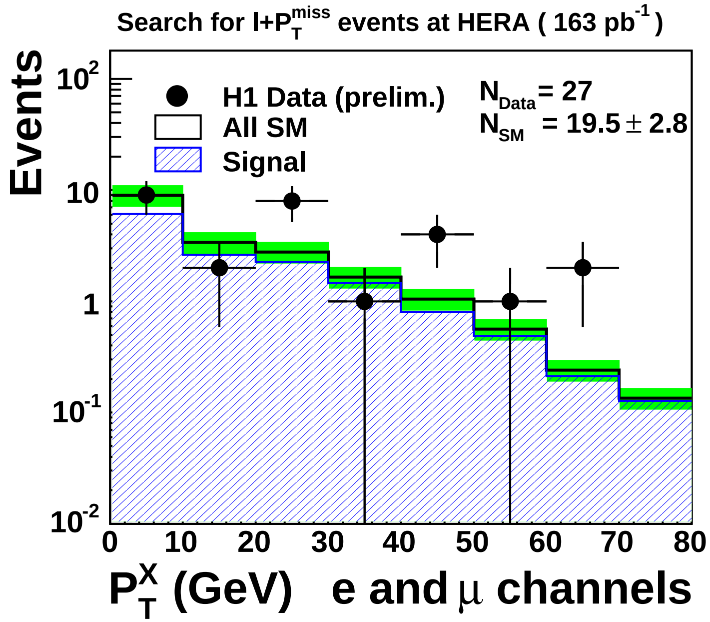
H1





H1 Isolated Leptons HERA I & HERA II

The $P_T(X)$ distribution for HERA I & II



Electron and muon channels updated for ICHEP '04 to include HERA II data

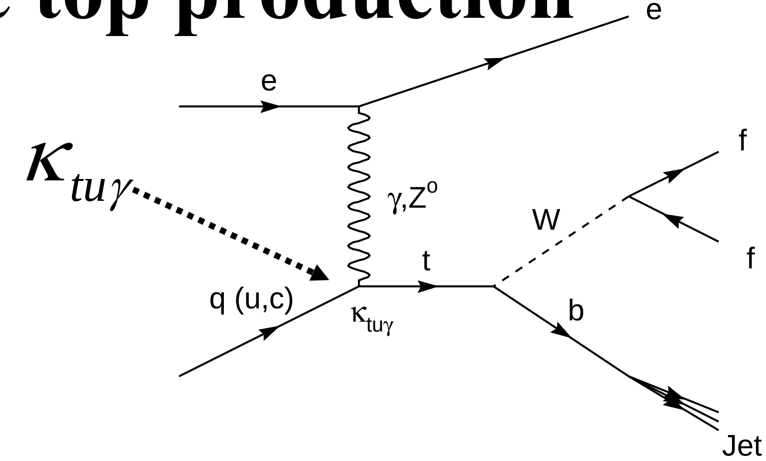
H1 1994-2004 *Lumi* = 163 pb^{-1}	Electron obs./exp.	Muon obs./exp.		Combined Obs./exp.
All data	18 / 15.4 ± 2.1	9 / 4.1 ± 0.7		27 / 19.5 ± 2.8
$P_T(X) > 25$ GeV	8 / 2.6 ± 0.5	6 / 2.5 ± 0.5		14 / 5.1 ± 1.0

The effect persists… We eagerly await more data later this year

Anomalous (FCNC) single top production

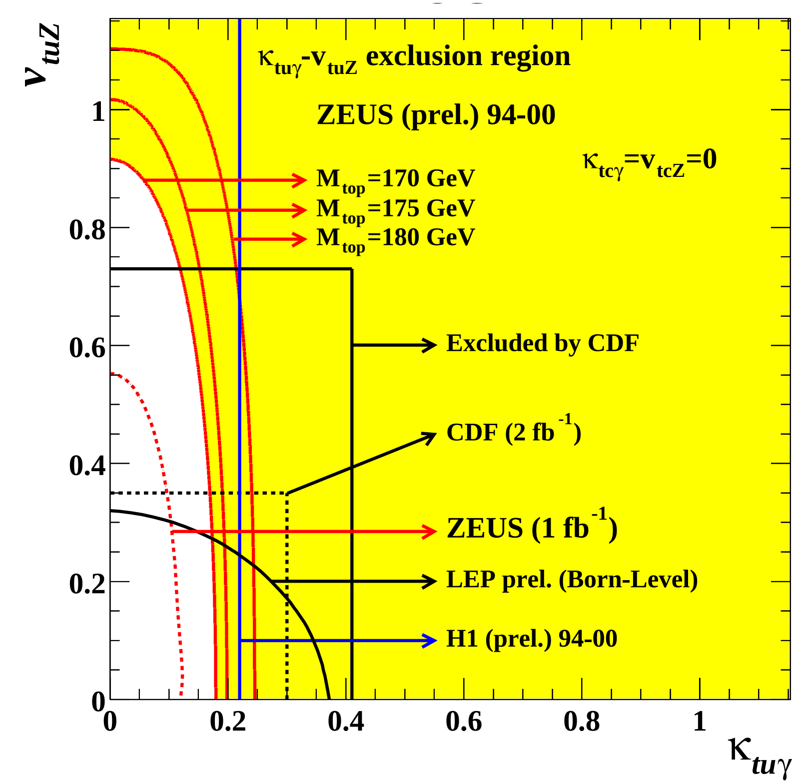
Isolated lepton, missing p_T and a hard jet also the signature for $t \to bW \to bl\nu$

SM expectation negligible due to FCNC vertex $\kappa_{tu\gamma}$



HERA is very sensitive to this coupling ($\kappa_{tu\gamma}$) and only slightly sensitive to κ_{tuZ}

Cross-section Limits:
($\sqrt{s}$=318 GeV ; CL 95%)
H1 : σ ($ep \to etX$) < 0.55 pb
ZEUS: σ ($ep \to etX$) < 0.225 pb



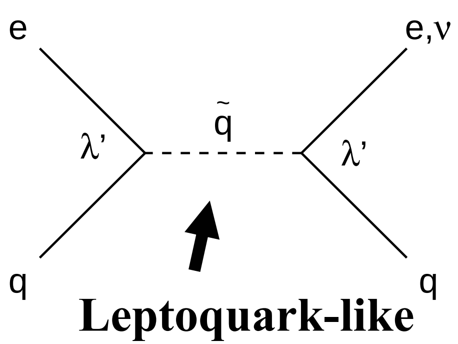
Comparable to limits from LEP ($e^+e^- \to \gamma, Z \to tu$) and TeVatron (rare top decays : $t \to \gamma q$, Zq)

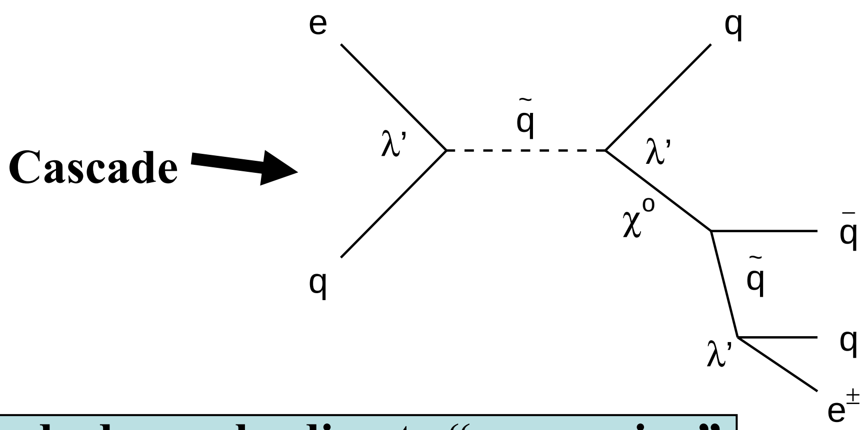
R-parity violating SUSY

SUSY is a higher symmetry between bosons and fermions – each gains a SUSY partner – fermions (bosons) gain scalar (fermionic) SUSY partners. And funny names.

$R_p = (-1)^{L+3B+2S}$ is "even" for all known particles and "odd" for their supersymmetric partners

Violating $R_p \rightarrow$ SUSY particles can be singly produced and the LSP is not stable

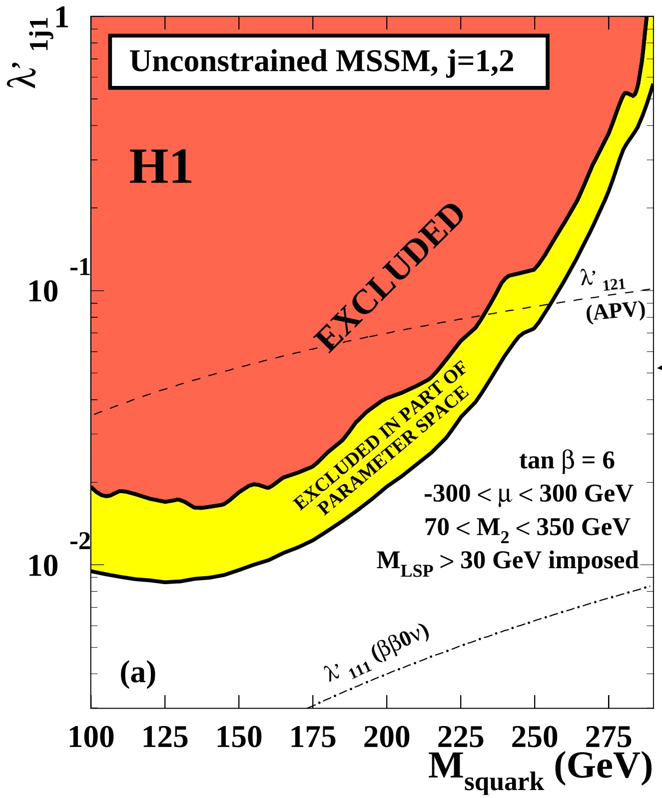




Search for resonant particle production. Cascade decays leading to "wrong sign" leptons give background free channels

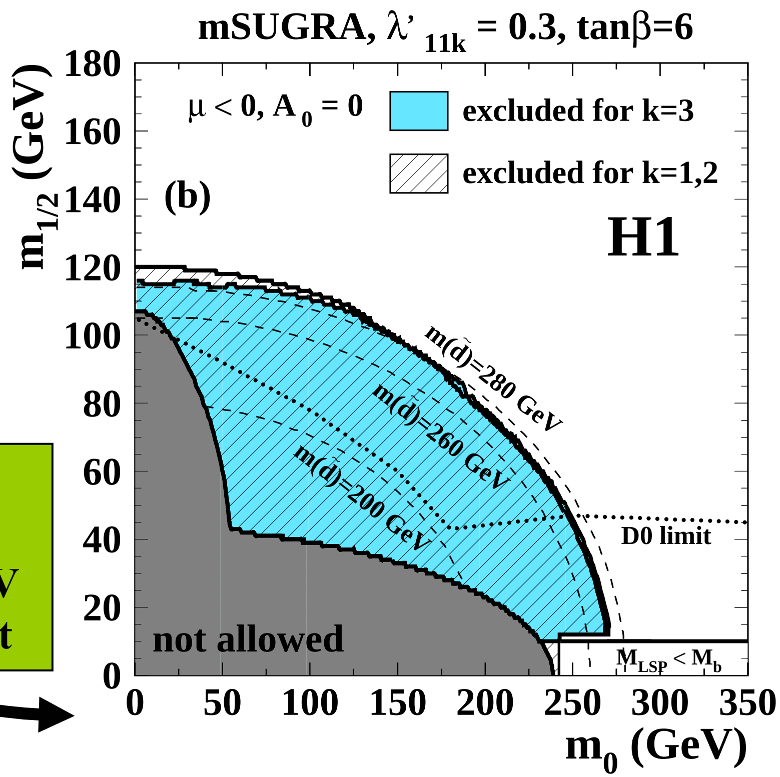
No excess seen in all channels. Set exclusion limits for unconstrained MSSM (squark mass independent of μ, M_2 and tan β) and for mSUGRA

R-parity violating SUSY limits



For $\lambda'_{1j1}=\alpha_{em}$ squarks below ~275 GeV are ruled out

sbottom masses less than 280 GeV are ruled out



MSSM – free variation of μ, M_2 and tan β – yellow band shows the variation of these parameters

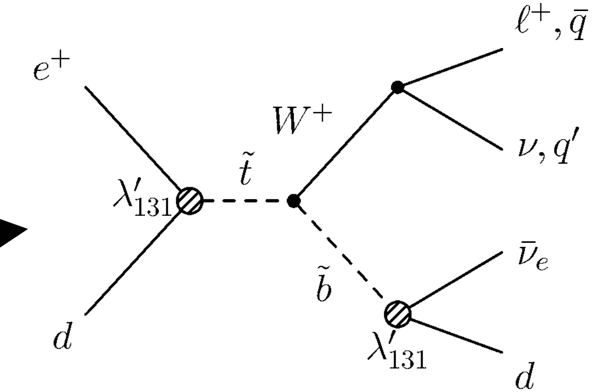
mSUGRA constrained by (amongst others):

- **m_0 (universal mass parameter for sfermions at the GUT scale)**
- **assumption that EW symmetry breaking is driven by radiative corrections**

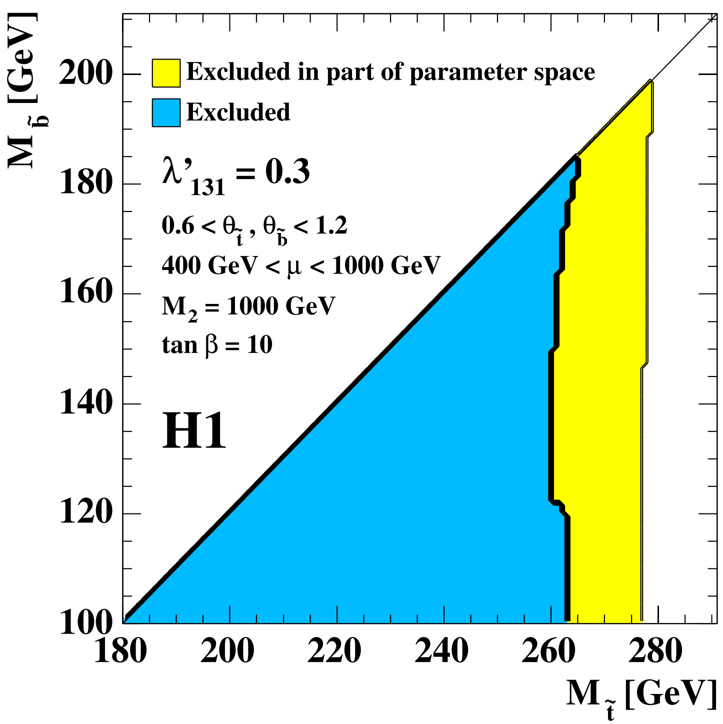
Bosonic stop decays in R-parity violating SUSY

An extension of the search for R-parity violating SUSY, assuming that the "stop" is heavier than the "sbottom"

Resonantly produce the stop via the fusion of a positron and (mainly) a *u*-quark. The stop then decays "bosonically" to a sbottom and a *W* boson



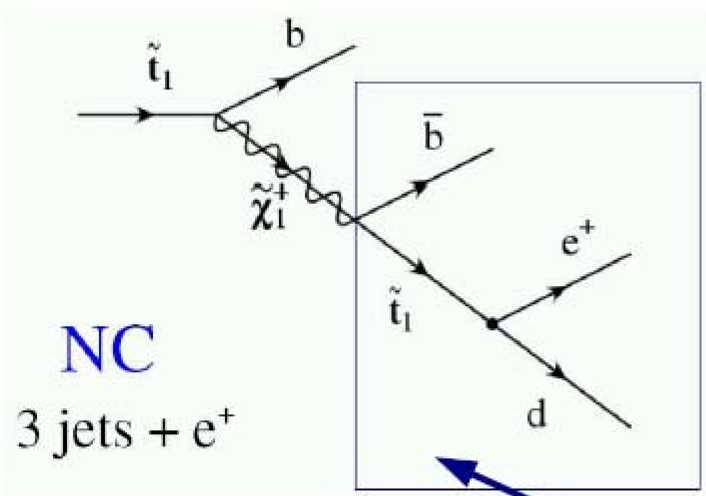
A possible explanation for the H1 isolated lepton excess? Not really – only the isolated muons survive the selection criteria



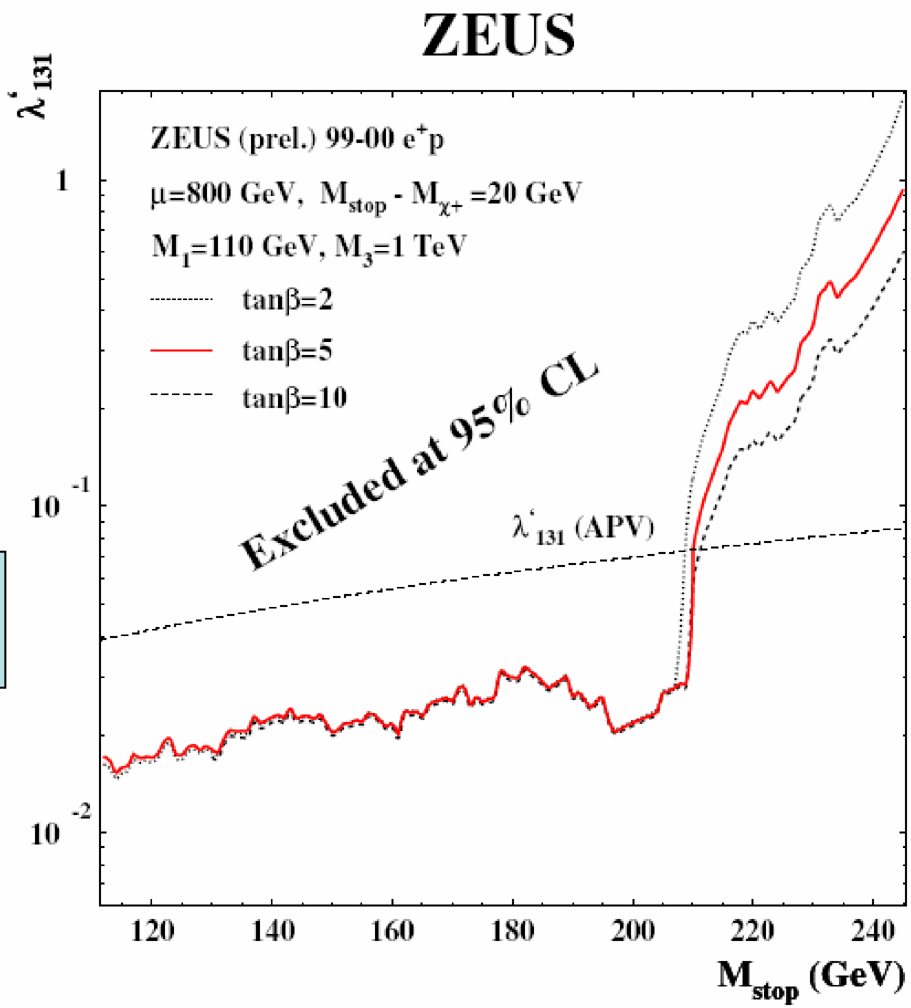
Set limits on the stop and sbottom masses and the relevant Yukawa coupling

Stops up to 260 (275) GeV are ruled out

Gauge stop decays in R-parity violating SUSY



CC channel to come



Assume : λ'_{131} is dominant

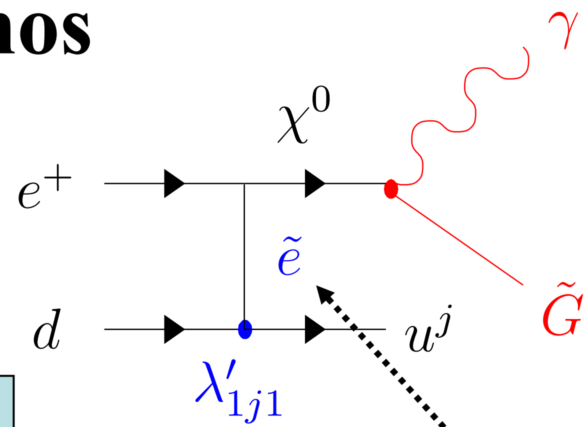
Mass of all other sfermions ~ 1TeV

stop heavier than chargino by 10 GeV

Limits on λ'_{131} improved for stop masses < 210 GeV

Superlight Gravitinos

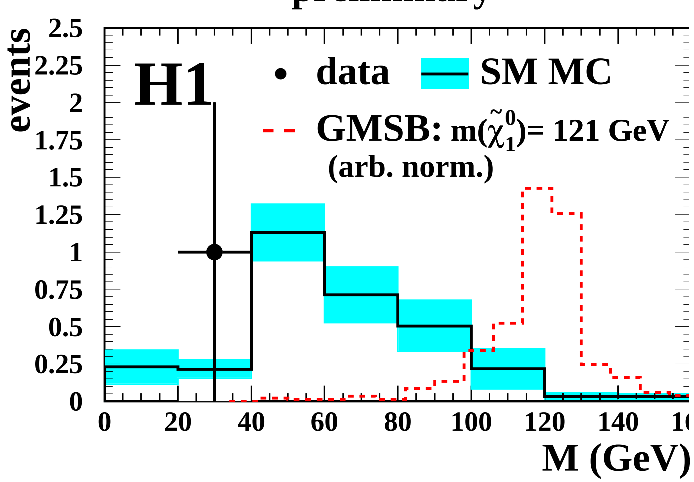
GMSB (Gauge mediated SUSY breaking) – an extension of R_P-violating SUSY, with the gravitino as the LSP (< 1 GeV). NLSP is the neutralino (short lifetime)

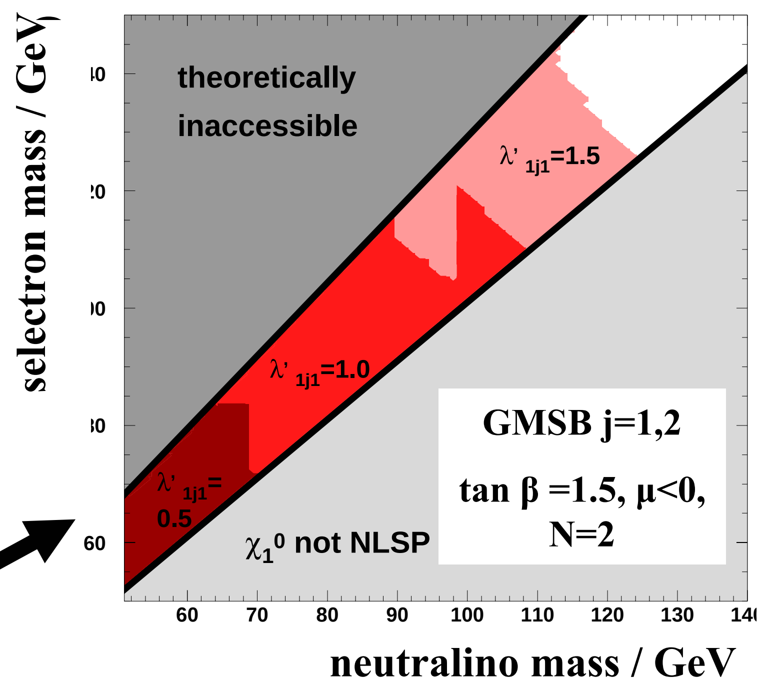


t-channel selectron exchange

Signature: An isolated photon, a jet and missing P_T

preliminary





One candidate event – derive limits on GMSB parameters

For λ'=1.0 :

m_χ > 108 GeV

& m_e > 138 GeV

First time at HERA indep. of squark mass

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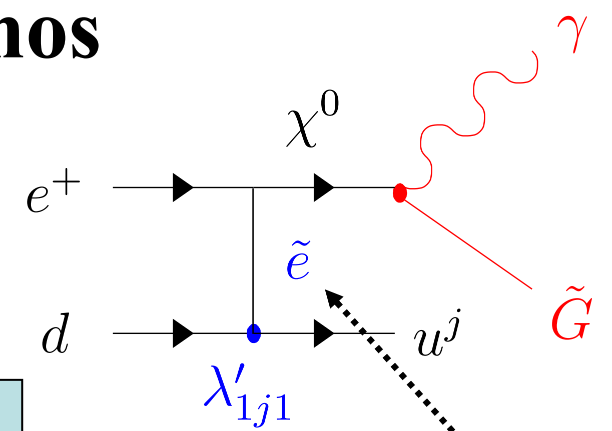

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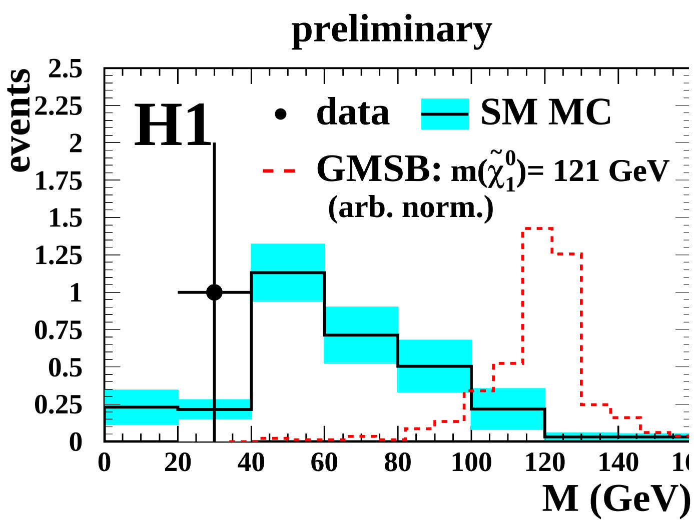

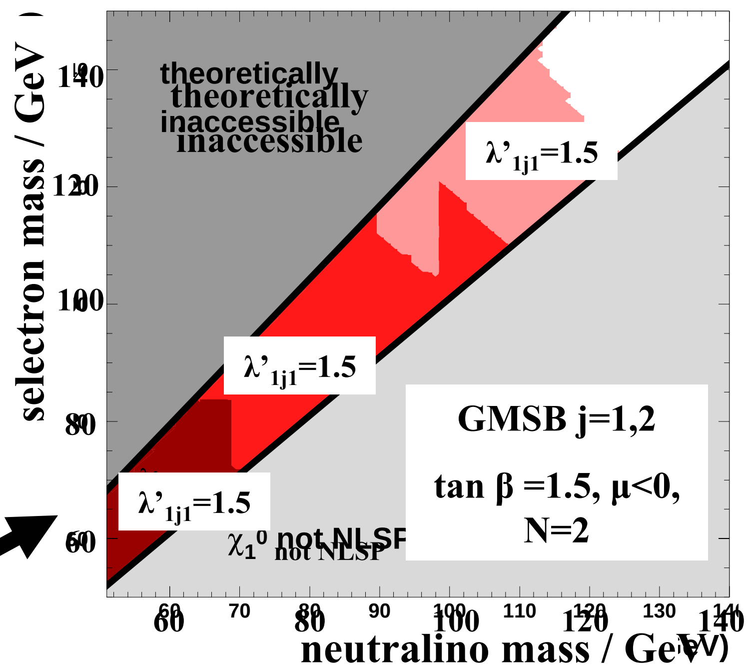

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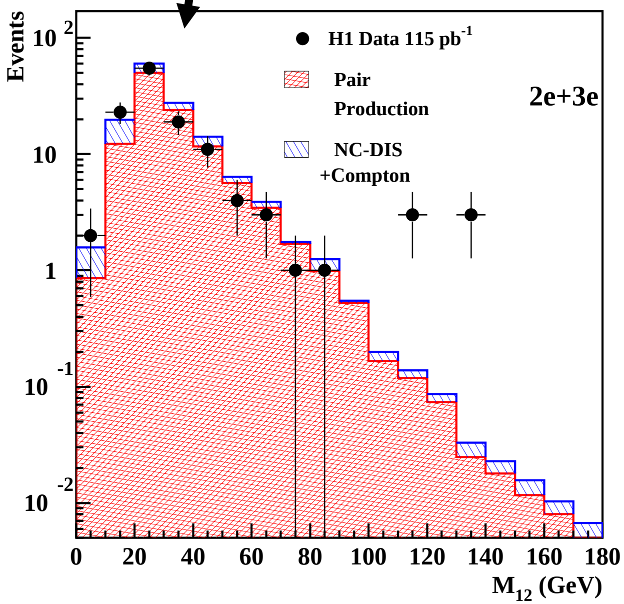
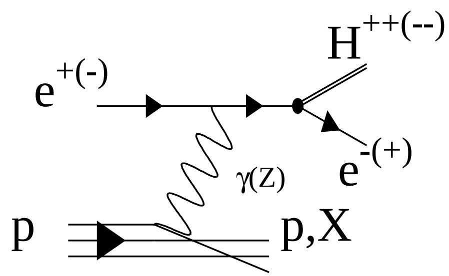
Multi-electron final states

Multi-lepton analyses



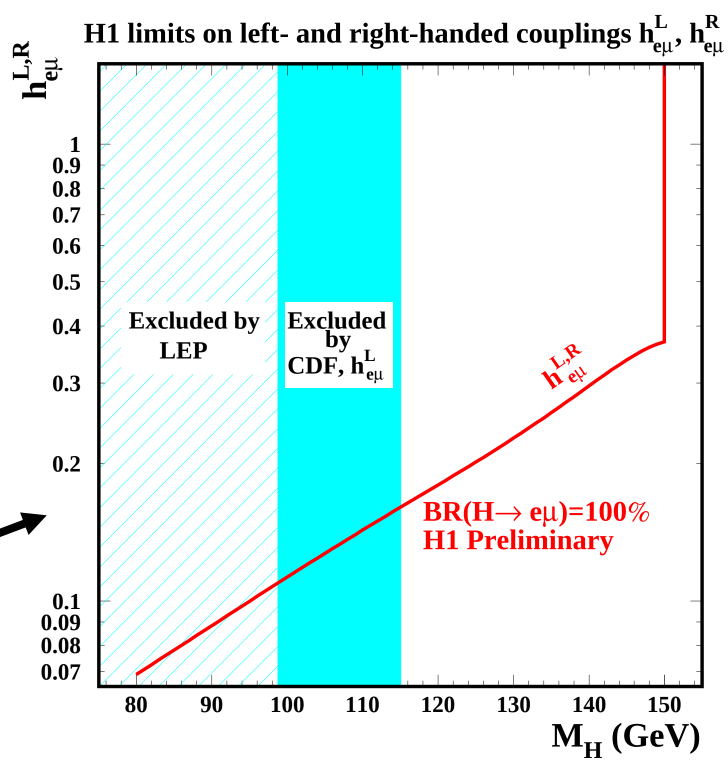
H1 observe an interesting class of events with multiple leptons in the final state

One BSM explanation is a doubly charged Higgs which decays $H^{\pm} \rightarrow l^{\pm} l^{\pm}$ (e, μ, τ)

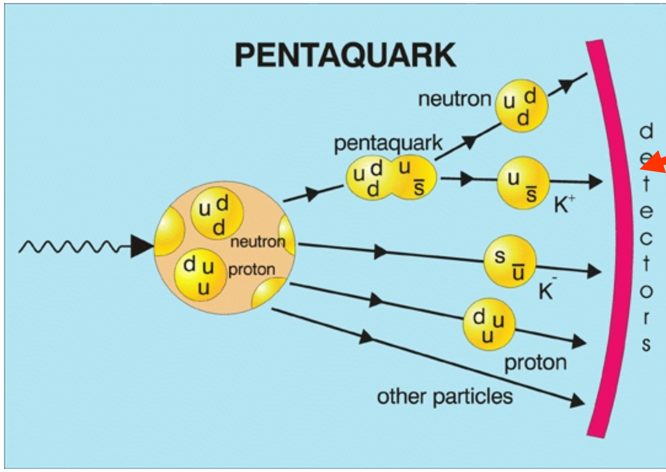


Doubly charged Higgs appear in various SM extensions where the Higgs sector has one or more charged triplets

Best limits come from eμ final state. Alone, this channel sets a lower limit of 140 GeV for a $h_{e\mu}$ coupling of 0.3



And finally… Strange pentaquark searches (ZEUS)

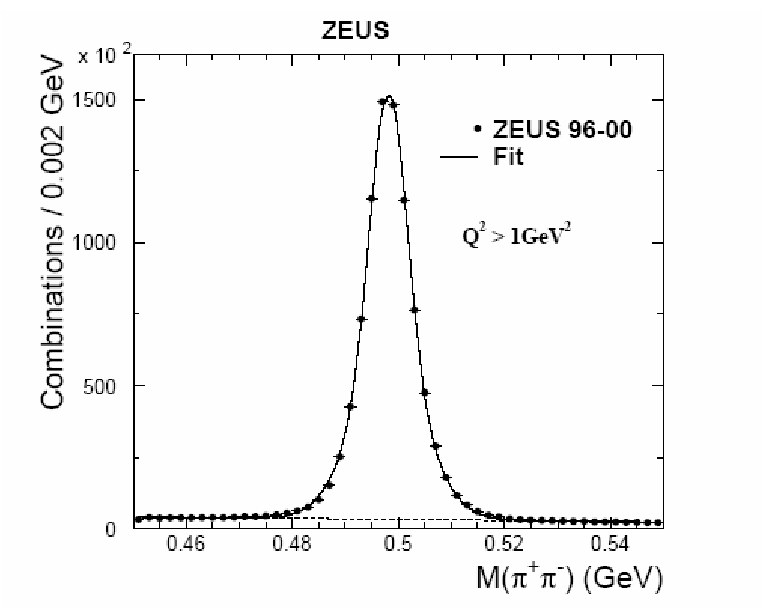


Several experiments around the world have reported observation of a Θ^+ (uudd$\hat{s}$)

Combined mass = 1530.5 ± 2.0 MeV

Look at the decay channel : $\Theta^+ \rightarrow K_S^0\, p$

Identify Kaon from reconstructed mass (decay to $\pi^+\pi^-$)



Peak = 498.12 ± 0.01 MeV

Background < 6%

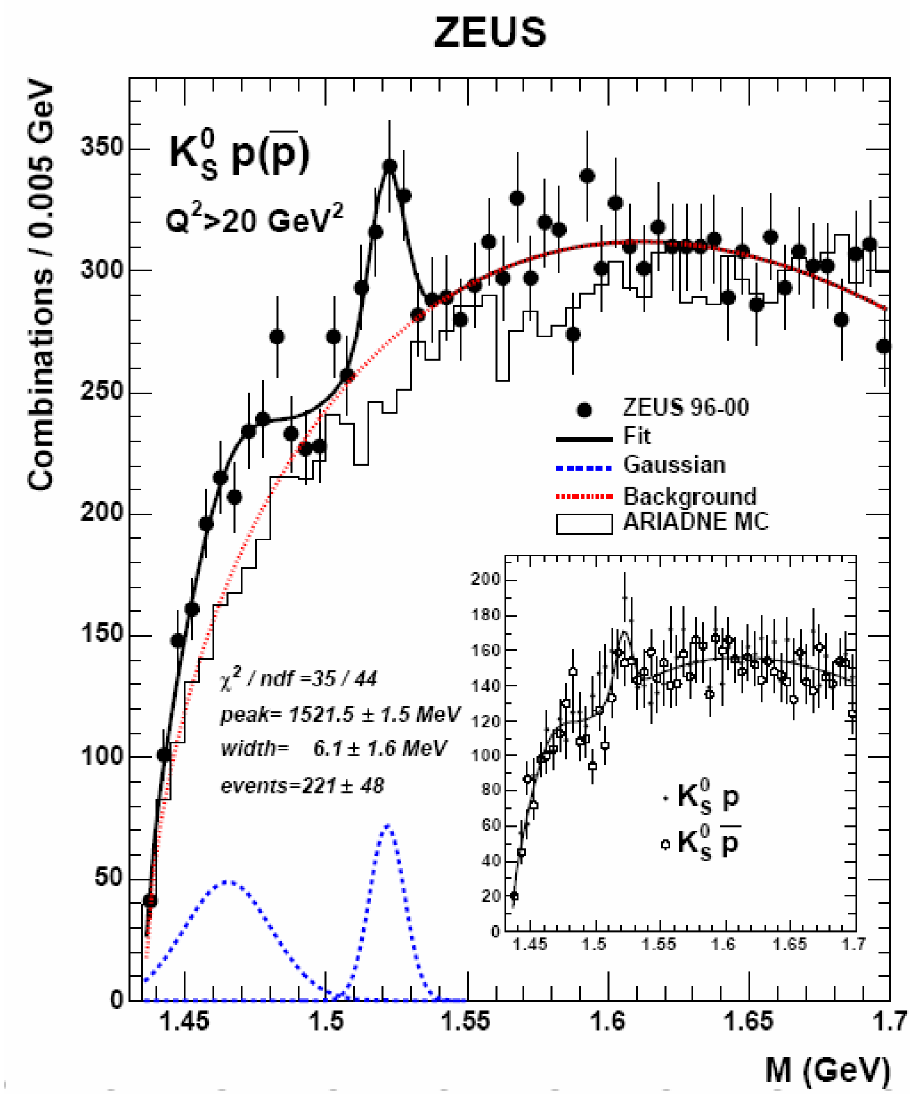
~ 870,000 candidates

Strange pentaquark (ZEUS)

Mass = 1521.5 ± 1.5 (stat) $^{+2.8}_{-1.7}$ (syst)

Gaussian width = 6.1 ± 1.5 MeV

→ compatible with experimental resolution



Fit 3rd order polynomial + double Gaussian

→ 4.6 σ

Observation not yet confirmed by H1…

Evidence for an anti-charmed pentaquark (H1)

Motivated by numerous reports of

$$uudd\bar{s}$$

Search for similar state

$$uudd\bar{c}$$

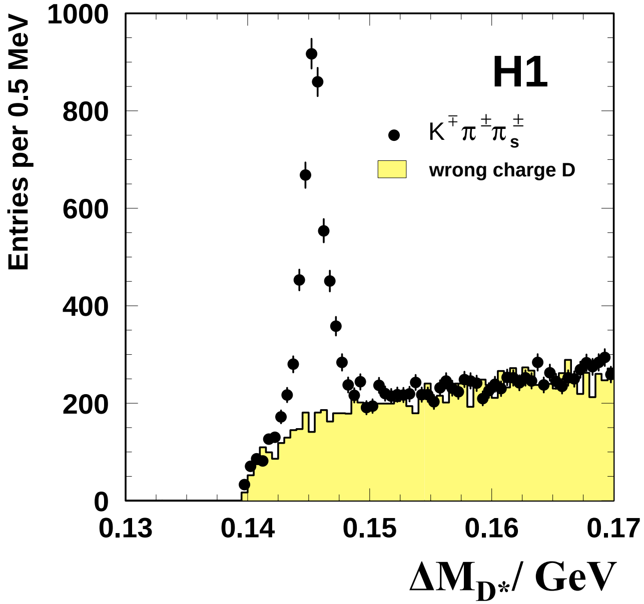
Examine the decay channel $\theta_c^0 \to D^* p$

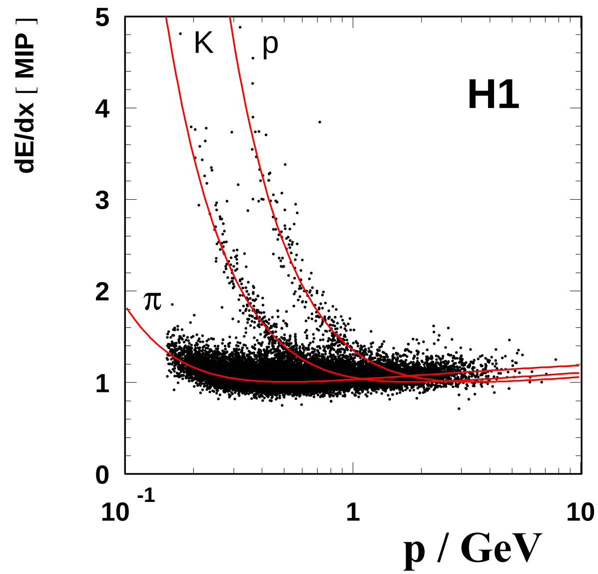
Identified via the "golden channel"

$$D^{*+} \to D^0 \pi_s^+$$

$$(K^- \pi^+)\pi_s^+$$

Identified via dE/dx measurements





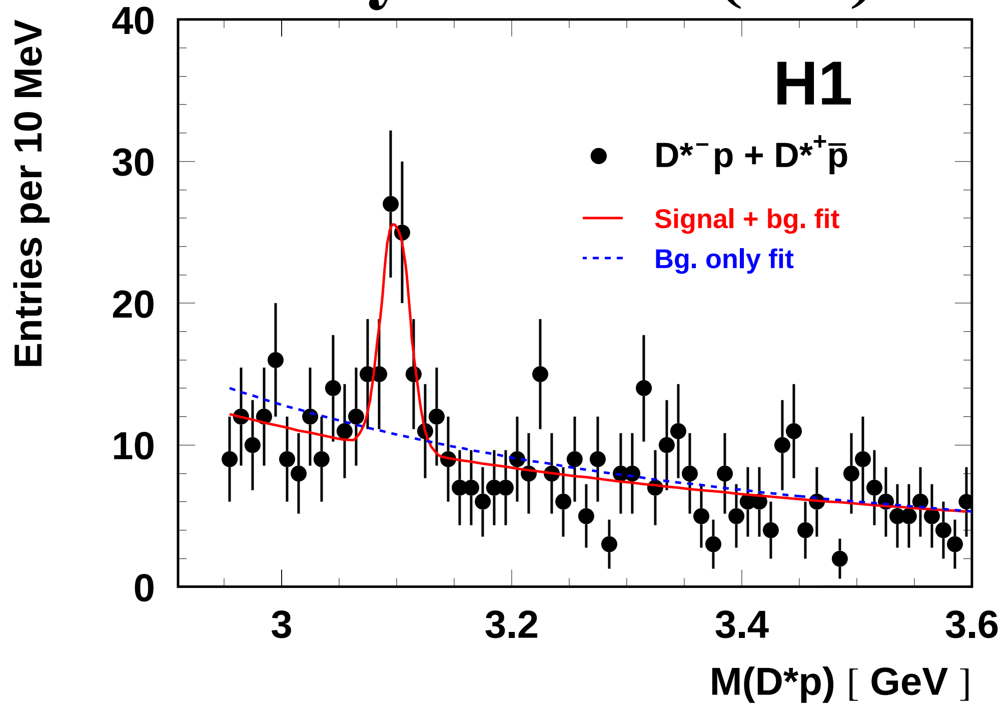
Nick Malden (Manchester) HEP-MAD 2004

Narrow anticharmed baryon state (H1)

Signal only present for oppositely charged D* & p

Signal present for both charge combinations

Extensive studies of wrong mass assignments give no indication of significant reflections



Signal + background fit (Gaussian + power law) gives

Mass = 3099 ± 3 (stat.) ± 5 (syst.) MeV   Width = 12 ± 3 MeV

Background only fit gives N_B=51.7

Poisson prob. (4×10^{-8}) to fluctuate to ≥ 95 events corresponds to 5.4 σ

Observation not yet confirmed by ZEUS…

Summary

HERA, the only electron-proton collider in the world, plays a unique and important role in global particle physics

H1 and ZEUS can study the structure of the proton with unprecedented precision – crucial in the preparation for the LHC

Searches for signs of physics beyond the Standard Model can explore unchartered regions of phase space…

…and indeed fascinating hints of potential signals are seen.