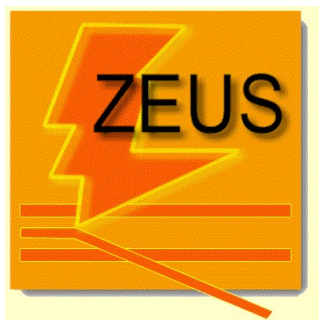
Physics at Very High Energies and Search for New Physics at HERA

Katie Oliver
On behalf of the H1 and ZEUS collaborations

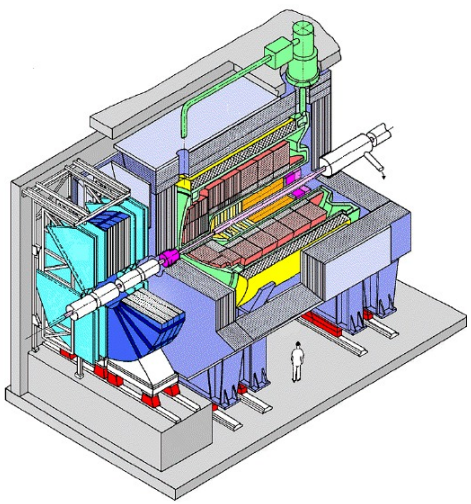
University of Oxford

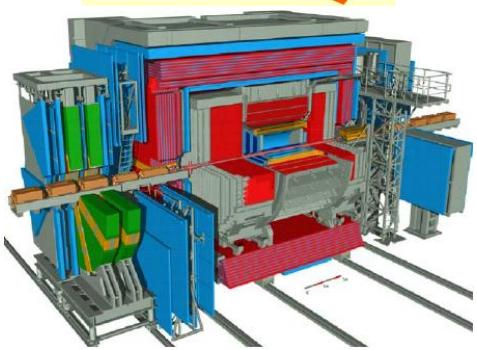
PANIC 2008, 13th November 2008



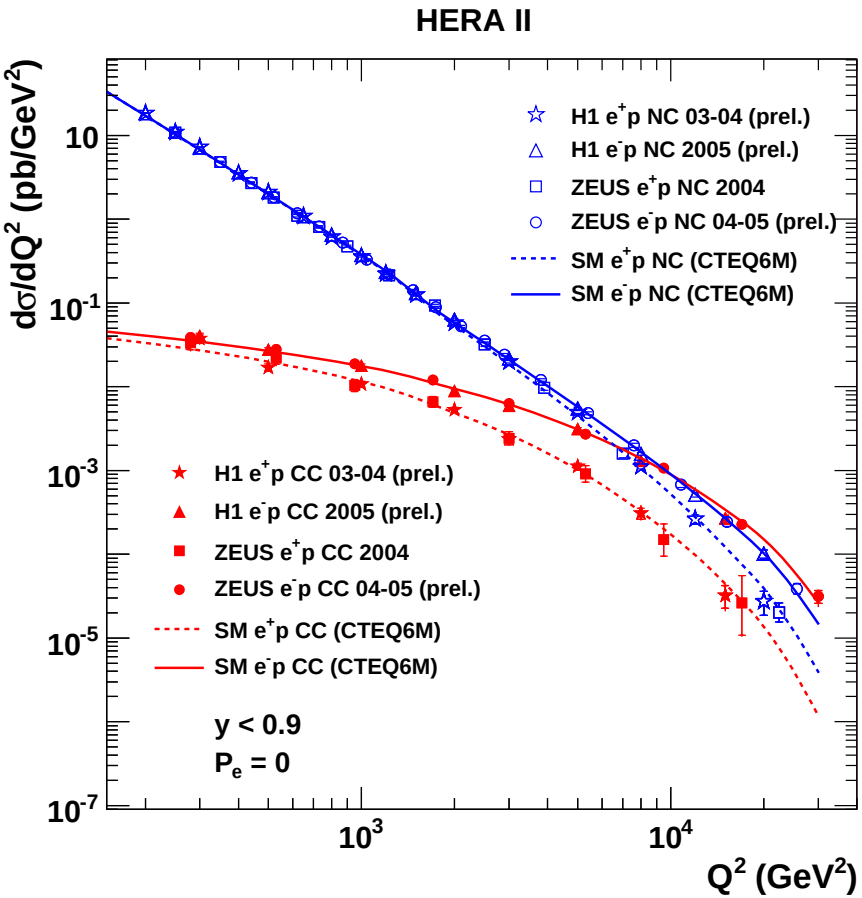
HERA, ZEUS and H1

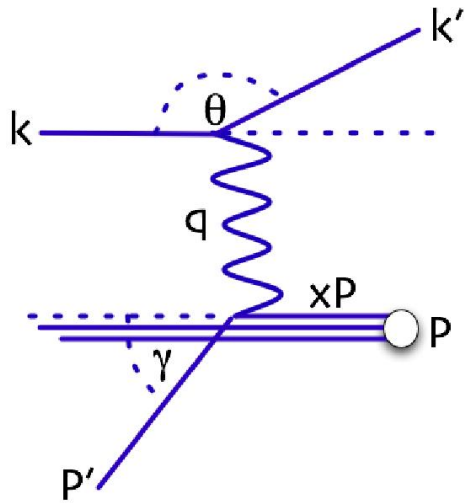
- H1 and ZEUS were multi-purpose detectors located on the *ep* collider HERA. Data taking ended on 30th June 2007
- 0.5 fb^{-1} luminosity taken by each experiment





High Q^2 Cross-Sections





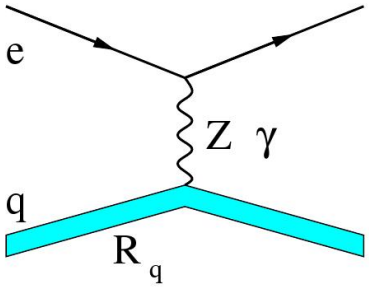
Probing power:

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

- Neutral current: γ/Z° exchange
- Charged current: $W^\pm$ exchange

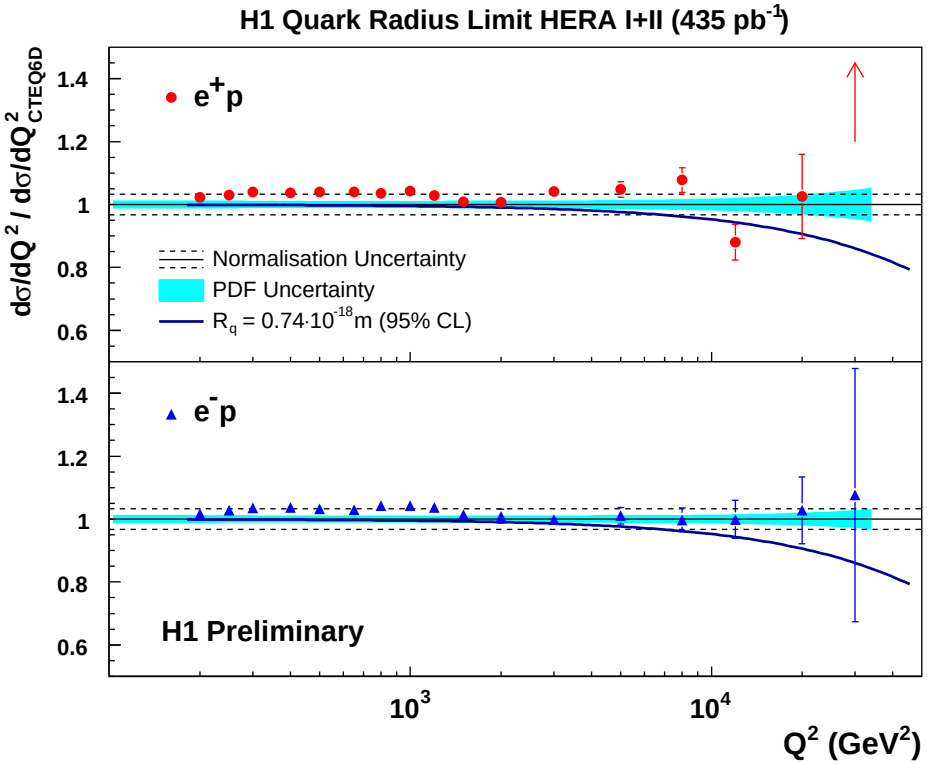
- Proton energy: 920 GeV
- Electron energy: 27.5 GeV
- $\sqrt{(s)} = 318$ GeV

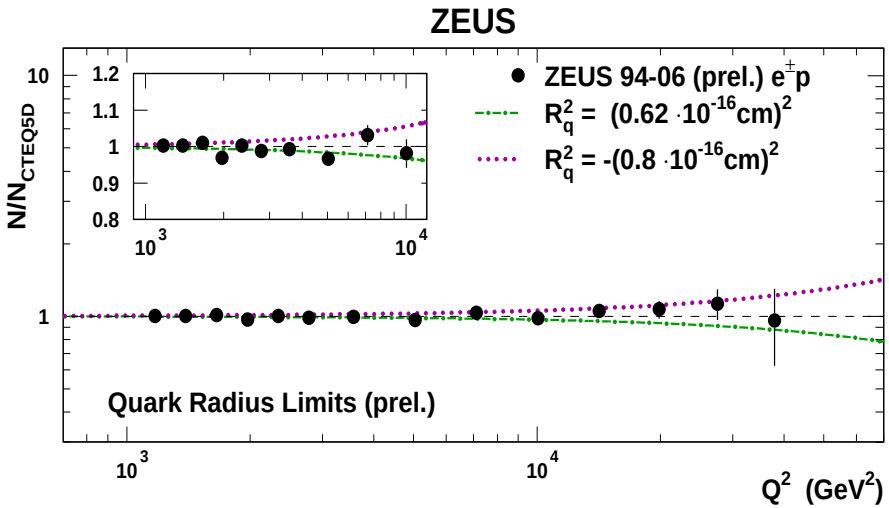
Quark Radius



Finite quark size → SM cross-section modified:

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

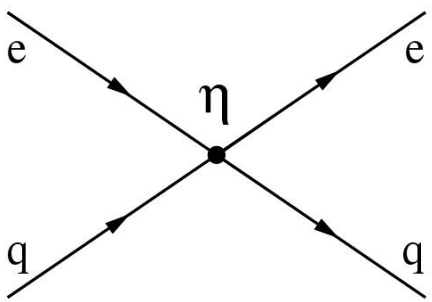




ZEUS	$R_q < 0.67 \times 10^{-18}$m
H1	$R_q < 0.74 \times 10^{-18}$m

Contact Interactions

- 4-fermion contact interactions describe effects from processes at higher scales: ($\sqrt{s} << \Lambda$):
  - Exchange of extra gauge bosons
  - Production or exchange of leptoquarks or squarks
  - Compositeness
  - Gravitational effects from extra dimensions
- Could alter the SM distributions at high-Q^2



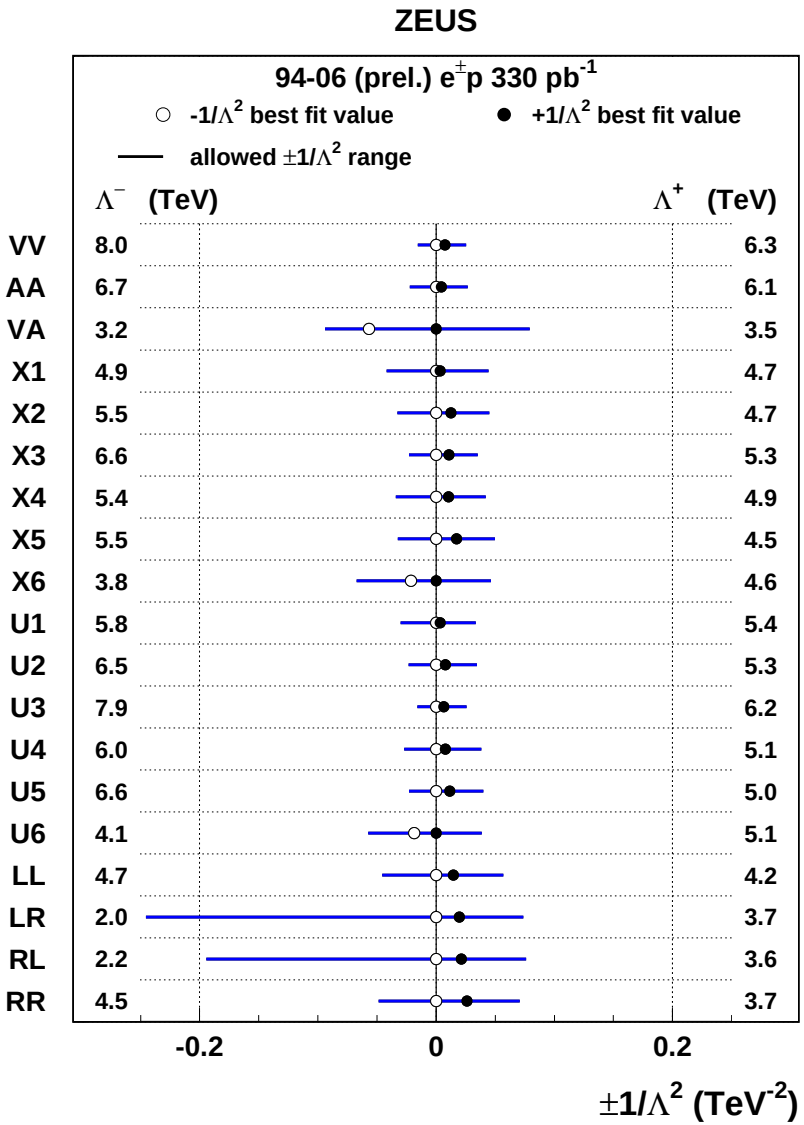
Lagrangian for vector *eeqq* contact interactions:

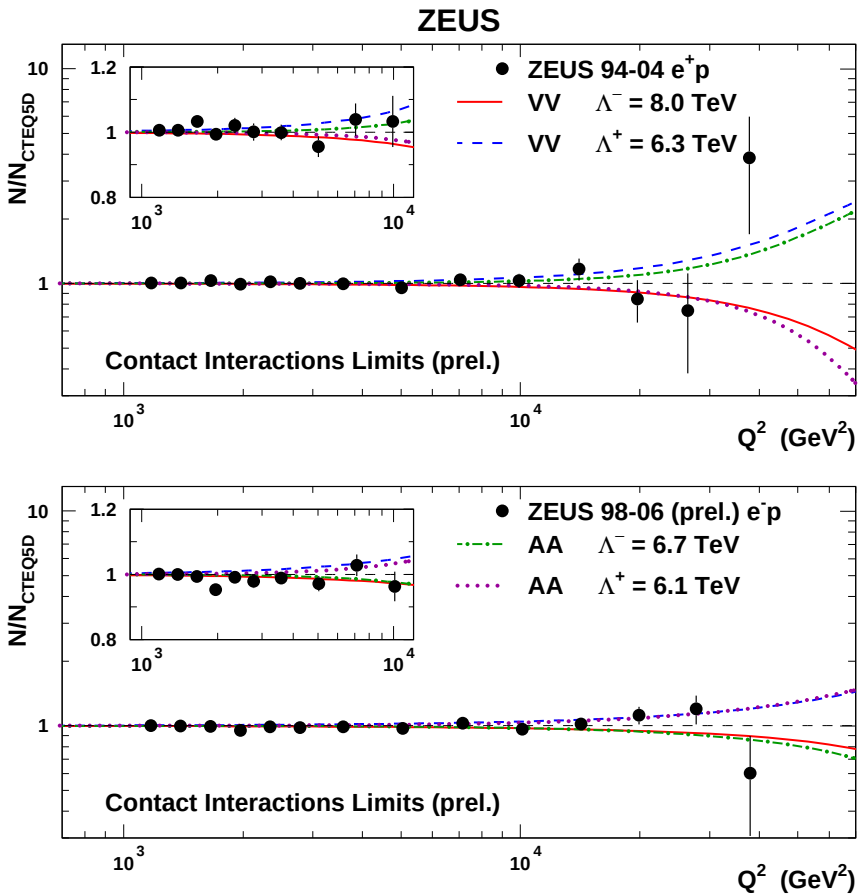
$$L_{CI} = \sum_{\substack{\alpha,\beta=L,R \\ q=u,d}} \eta^{eq}_{\alpha\beta}(\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

$\eta \propto \pm\frac{1}{\Lambda^2}$ where Λ is effective scale

Contact Interactions II

- Fit to NC data yields limits on Λ

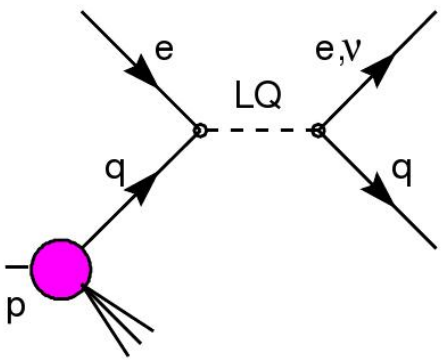




ZEUS (94-06) Λ = 2.0-8.0 TeV
H1 (HERA-I) Λ = 1.6-5.5 TeV

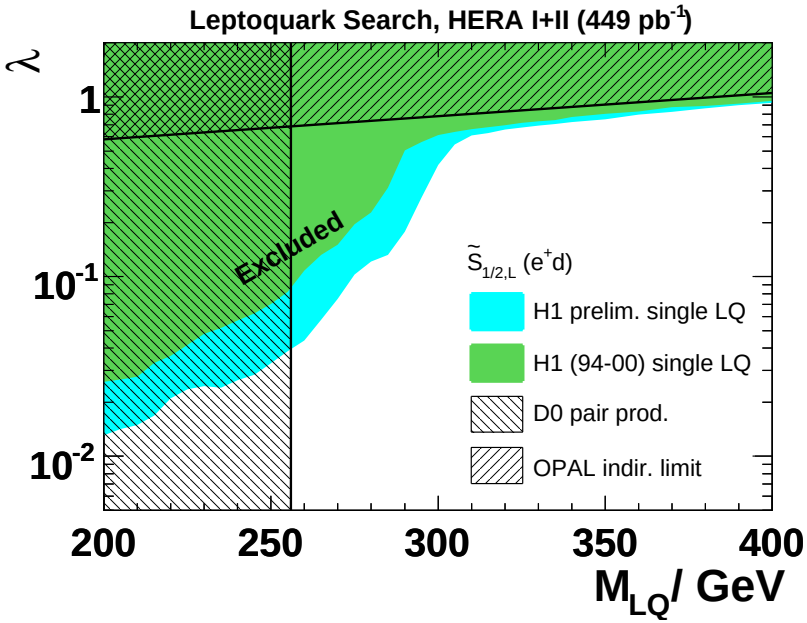
Leptoquarks

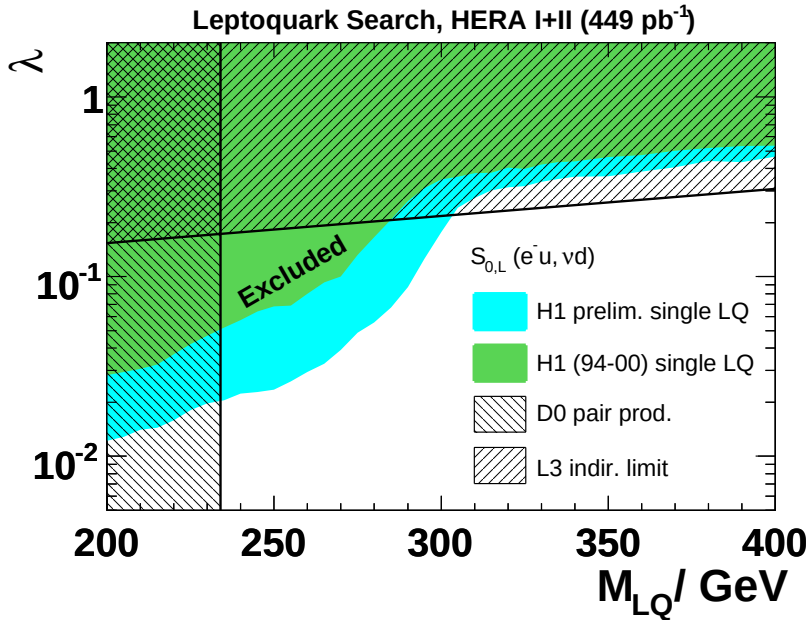
- Leptoquarks are scalar or vector colour triplet bosons
- They carry both lepton and baryon number and have fermion number $F = 3B + L$



- $M_{LQ} < \sqrt{(s)}$: s channel dominates
- Resonant production of single leptoquark
- Sensitivity to leptoquark coupling and mass
- Two searches have been performed:
  - First generation leptoquarks, no lepton flavour violation
  - First and second generation leptoquarks, allowing lepton flavour violation

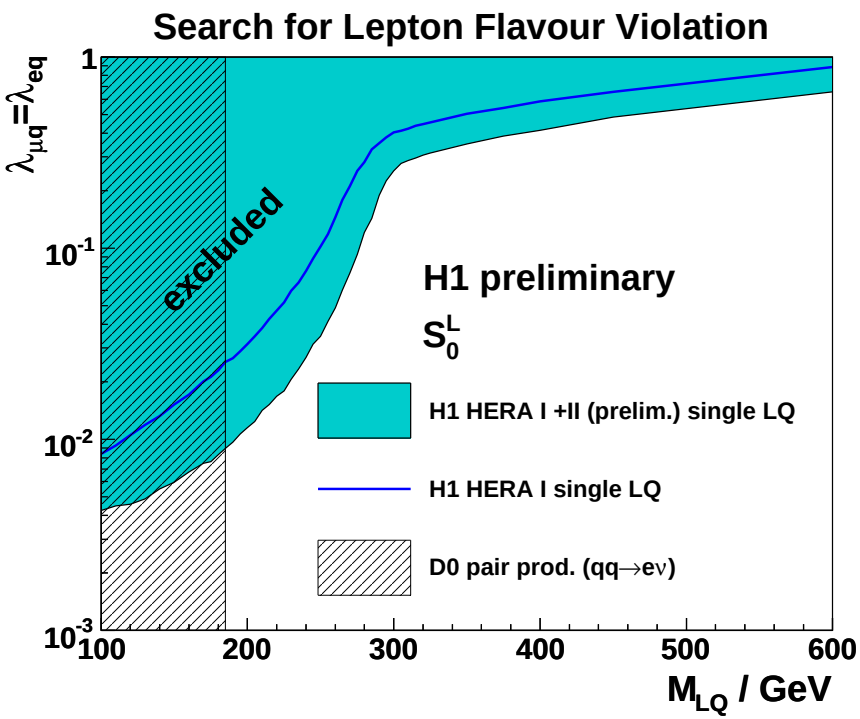
Leptoquarks: No Flavour Violation Limits





- $\tilde{S}^L_{1/2}$ and S^L_0 can be interpreted as squarks ($\tilde{u}_{j,L}$ and $\tilde{d}_{k,R}$ respectively) produced via a R-parity violating coupling
- For couplings of electromagnetic strength the production of $\tilde{S}^L_{1/2}$ and S^L_0 is excluded for masses up to 295 GeV and 310 GeV, respectively

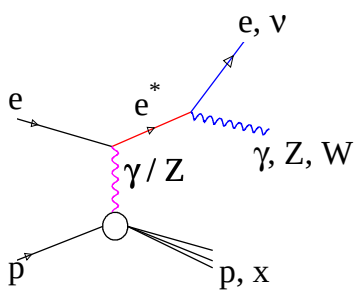
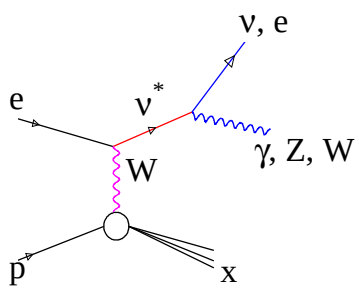
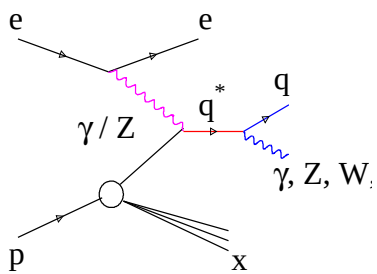
Leptoquarks: With Lepton Flavour Violation



- Search for F=2 leptoquarks coupling to 1st and 2nd generation fermions in $e^- p$ HERA-II data
- For coupling of electromagnetic strength, leptoquark masses below 291-433 GeV are ruled out

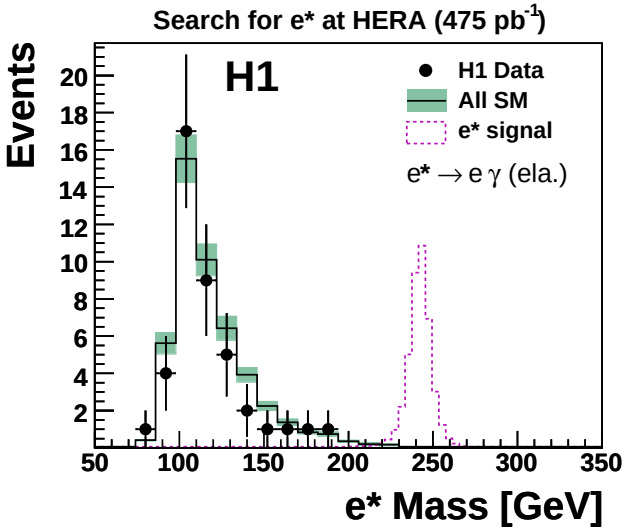
H1 Excited Leptons & Quarks

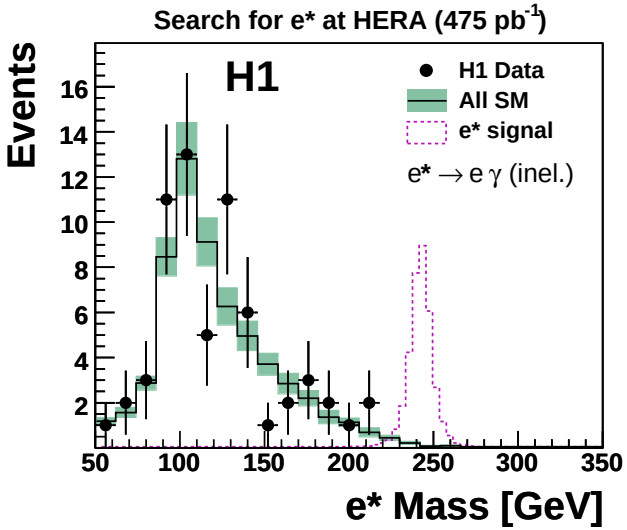
- Compositeness models allow excited states of electrons, neutrinos and quarks

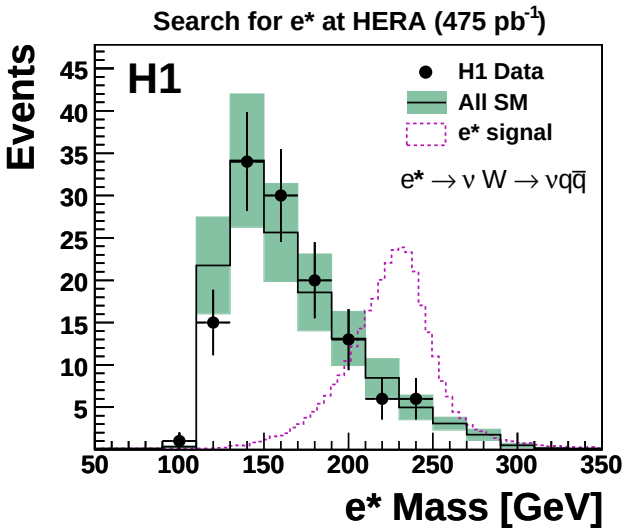
	Electrons	Neutrinos	Quarks
Lumi (pb^{-1})	475	184	475
Decays	$e^* \to e\gamma$ $e^* \to eZ^0$ $e^* \to \nu W^{\pm}$	$\nu^* \to \nu\gamma$ $\nu^* \to \nu Z^0$ $\nu^* \to eW^{\pm}$	$q^* \to q\gamma$ $q^* \to qZ^0$ $q^* \to qW^{\pm}$
Diagrams			

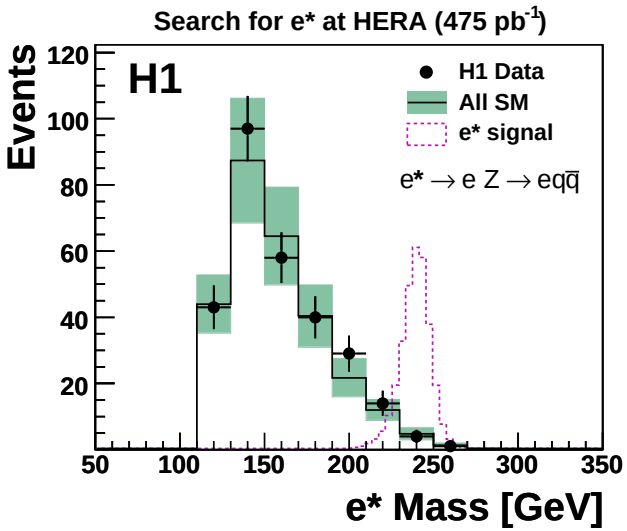
- Hadronic or leptonic decays of the $W^{\pm}$ and Z^0 considered.

H1 Excited Electrons







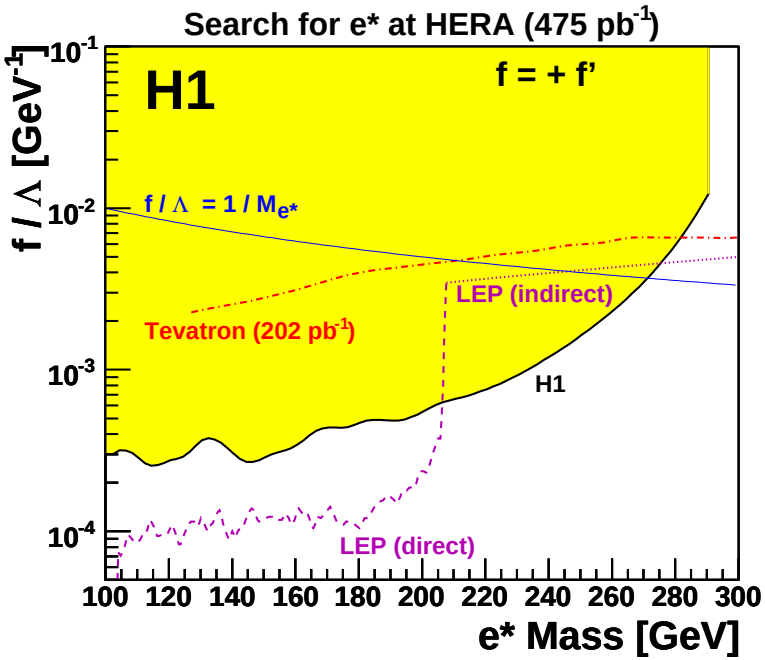


e^* signal histogram: reconstructed mass distribution of e^* events with $M_{e^*} = 240$ GeV (normalisation is arbitrary)

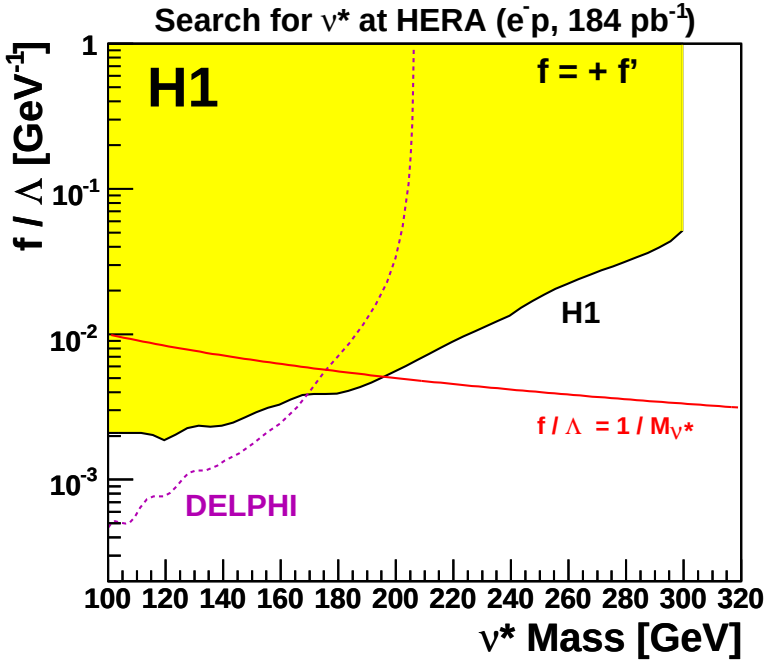
H1 Excited Leptons

- Derive mass-dependent limits on the ratio of the coupling to the compositeness scale (f/Λ)

Excited electrons

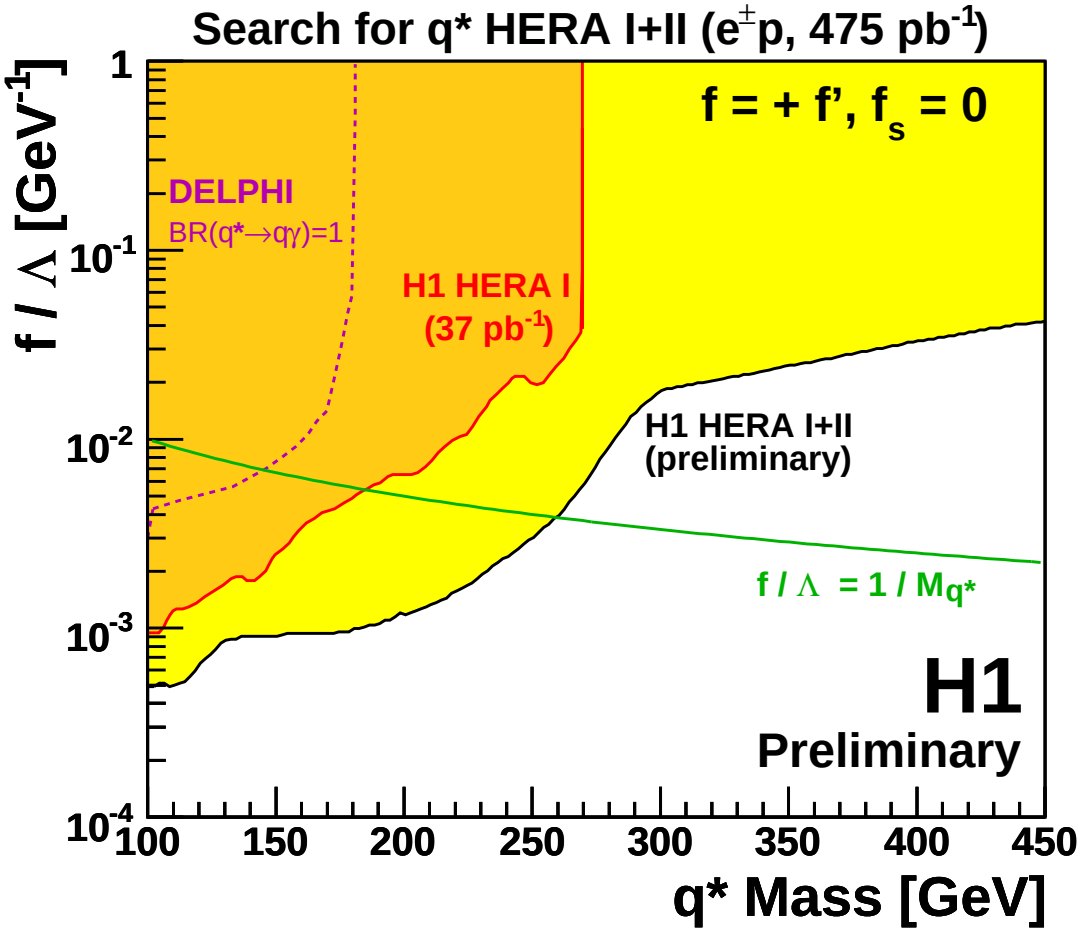


Excited Neutrinos



- No evidence for excited lepton production is found

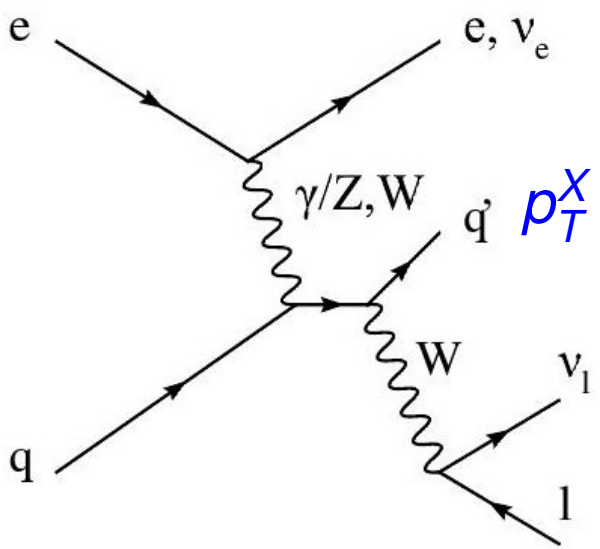
H1 Excited Quarks



- No evidence for q^* states.

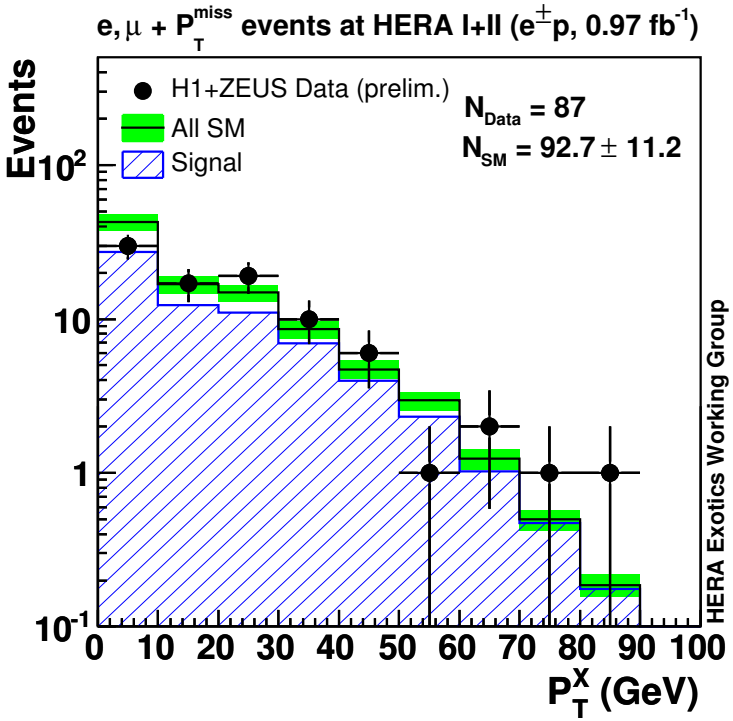
Isolated Leptons And $W^{\pm}$ Production I

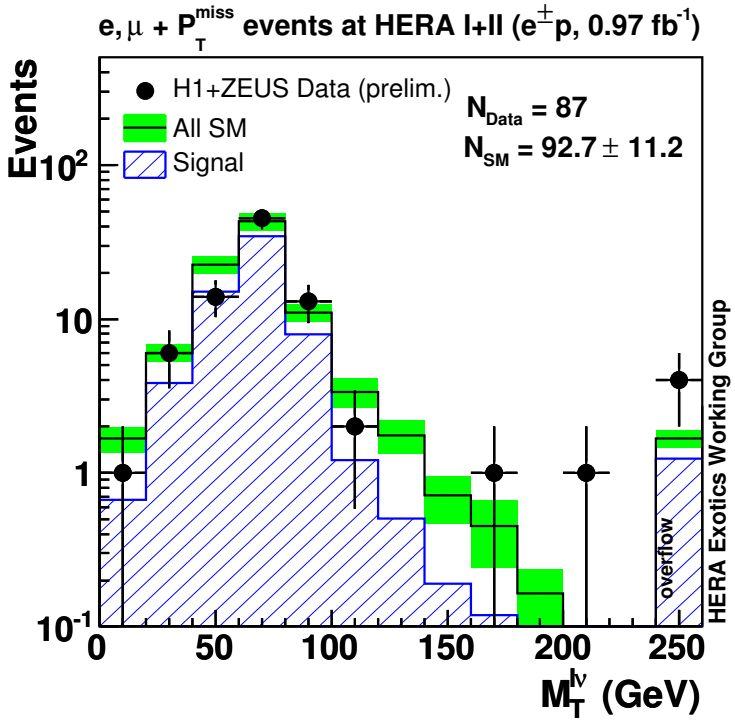
- Main SM source of isolated leptons with missing transverse momentum at HERA is single $W^{\pm}$ production ($\sigma \approx 1.3$pb)
- H1 saw excess in HERA-I data over the SM for both isolated e and isolated μ searches



- Excess at high hadronic transverse momentum (p_T^X) $\rightarrow$ new physics?
- HERA I+II data from both experiments have now been combined

Isolated Leptons And $W^{\pm}$ Production II



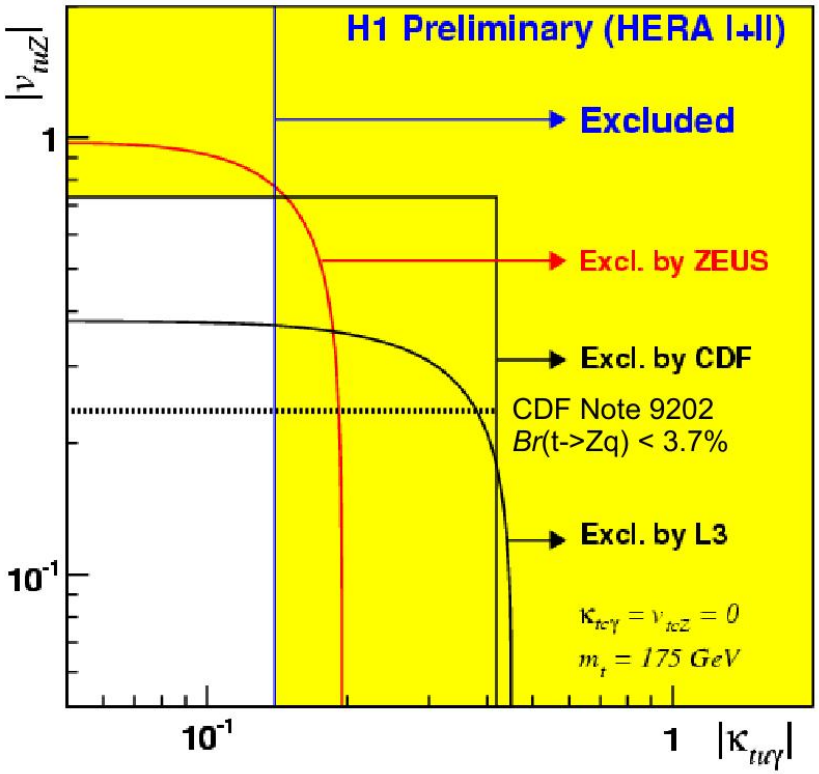


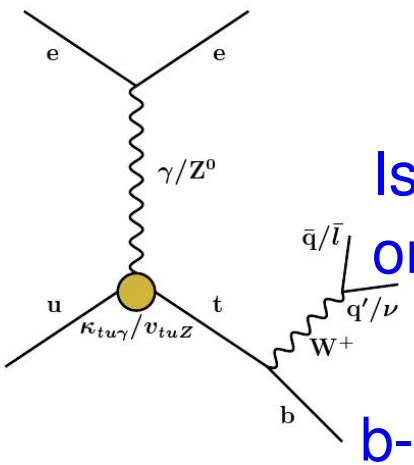
$W^{\pm}$ production cross-section:

SM	1.31 ± 0.20 (theory syst.) pb
ZEUS	$0.89^{+0.25}_{-0.22}$ (stat.) ± 0.10 (syst.) pb
H1	1.23 ± 0.25 (stat.) ± 0.22 (syst.) pb

Anomalous Top Production

- Flavour changing neutral current process
- SM single top production at HERA < 1fb
- $\kappa_{tu\gamma}$: coupling of t, u and photon
- ν_{tuZ}: vector coupling of t, u and Z^0 (assumed = 0 by H1)





Isolated lepton + p_T^{miss} or 2 light jets

b-jet

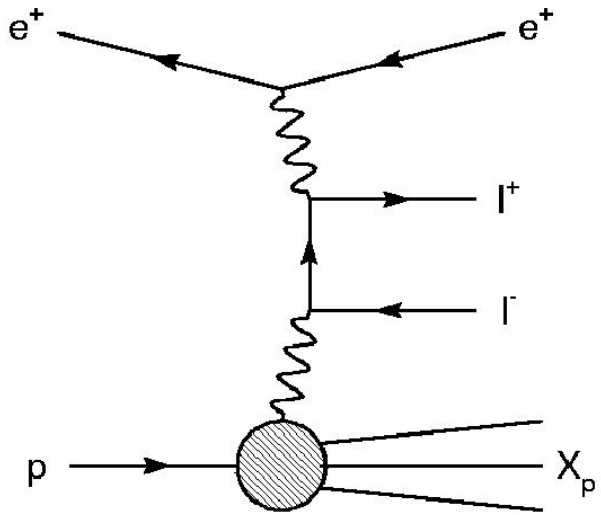
H1 limits:

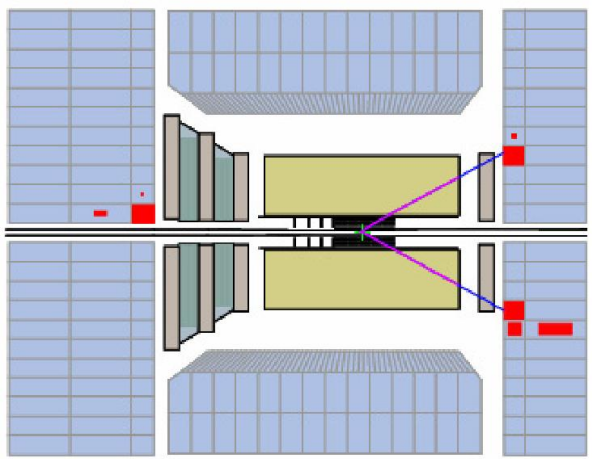
$\sigma_{ep\to etX} < 0.16$pb

$\kappa_{tu\gamma} < 0.14$

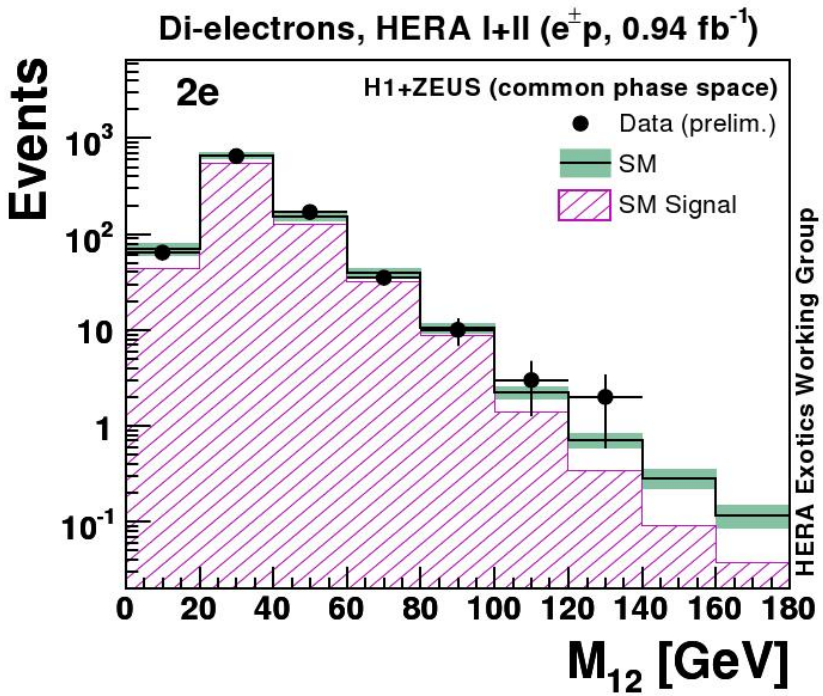
Multi-Electrons I

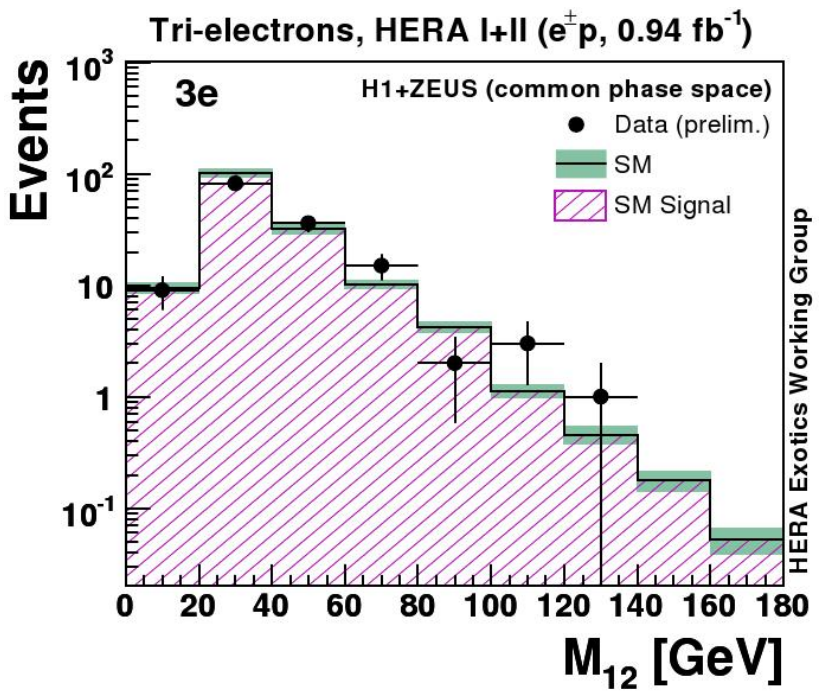
- Main production mechanism: Bethe-Heitler. $\gamma\gamma \rightarrow e^+e^-$
- QED process $\rightarrow$ precisely calculable
- SM prediction falls steeply with p_T
- Deviation from SM could be new physics
- H1 and ZEUS have combined results for the multi-electron analysis
- Multi-muon analyses not yet combined





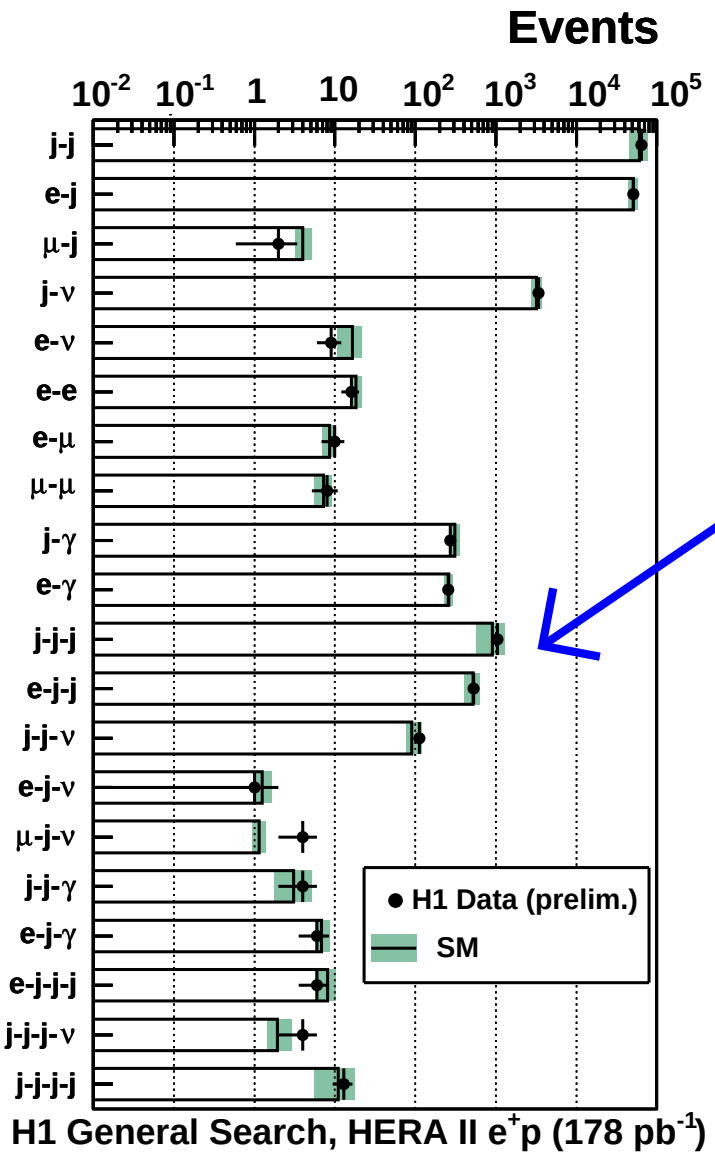
Multi-Electrons II

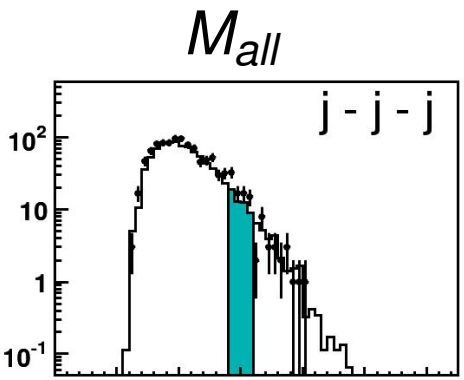


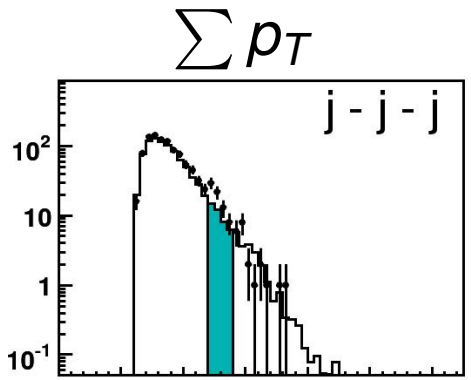


- M_{12} is the invariant mass of the two highest p_T electrons

H1 General Search I







- Look for final states with high p_T objects, $p_T > 20$GeV
- For each topology, examine $\sum p_T$ and M_{all} distributions to look for deviation from SM
- Determine the significance of deviations

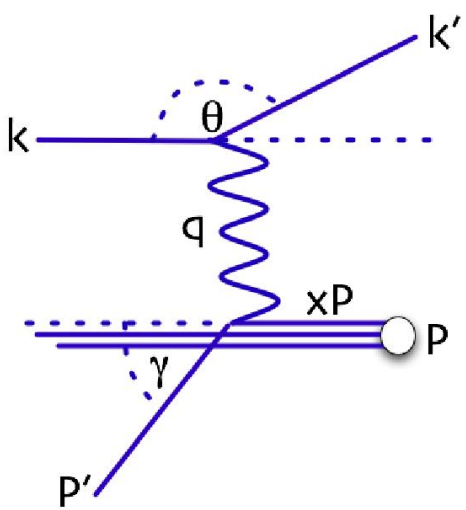
Overall, compatible with SM

Summary

- No evidence for physics beyond the standard model at HERA
- H1 and ZEUS are working to combine more results
- There is much still to analyse at HERA

Back-up Slides

Energy, Kinematics & Deep Inelastic Scattering



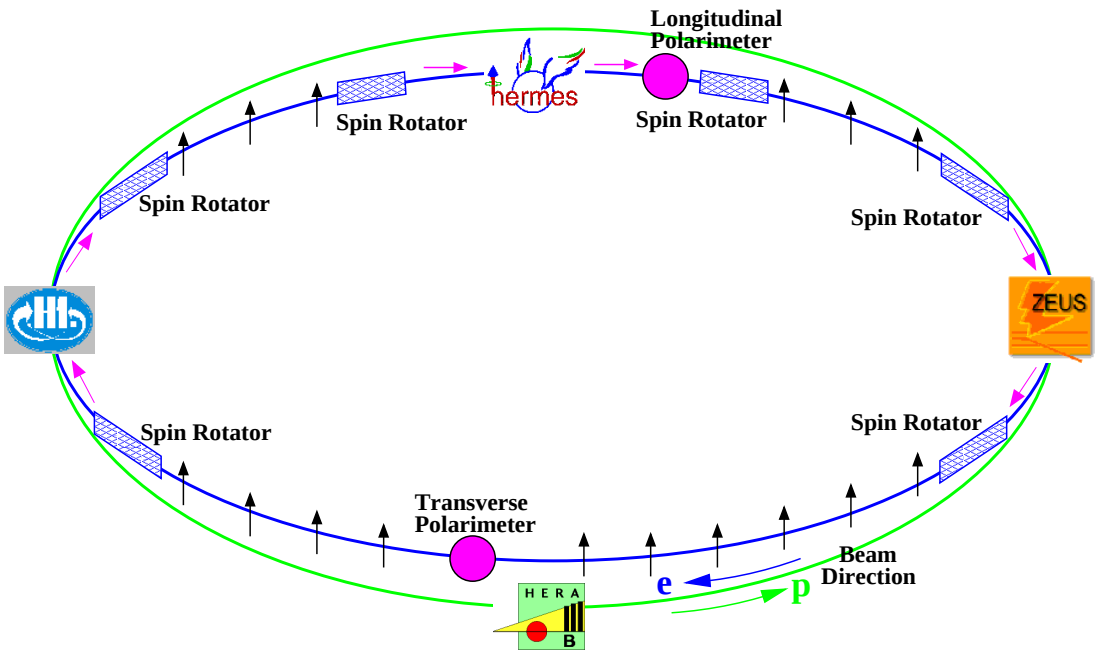
Q^2	=	$-q^2$	Probing power
	=	$-(k-k')^2$	
x	=	$\frac{Q^2}{2p.q}$	Bjorken scaling variable
y	=	$\frac{p.q}{p.k}$	Inelasticity
s	=	$(p+k)^2$	Centre of mass energy
Q^2	=	sxy	

Neutral current
exchange of γ or Z°
Charged current
exchange of $W^{\pm}$

- Proton energy: 920 GeV
- Electron energy: 27.5 GeV
- $\sqrt{(s)} = 318$ GeV

HERA: Polarised Lepton Beam

- e beam becomes transversely polarized through emission of synchrotron radiation
- Spin rotators were installed during the HERA upgrade to obtain longitudinal polarization at both IPs
- Polarization measured by polarimeters
- Mean (lumi weighted) polarization achieved: 30 - 40%



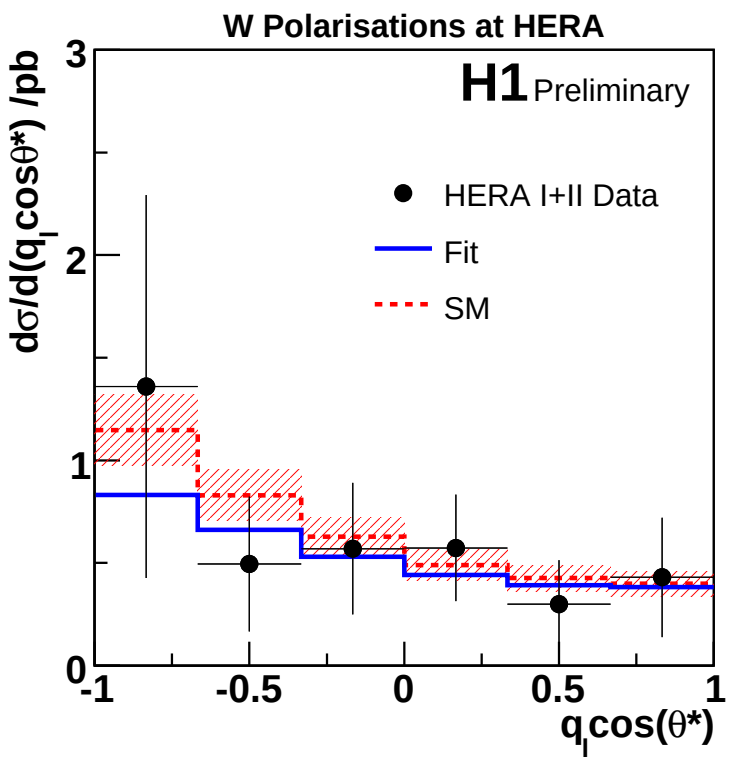
W$^{\pm}$ Polarisation I

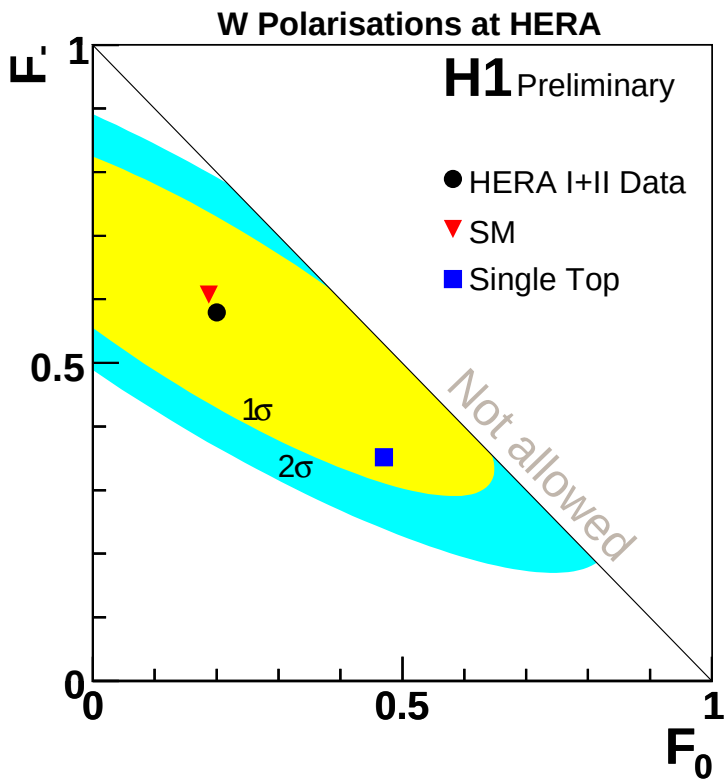
- Longitudinal polarisation fraction: F_0
- Left handed polarisation fraction: F_-
- Right handed polarisation fraction: $F_+ = 1 - F_- - F_0$
- θ^* is the angle between the $W^{\pm}$ momentum in the lab frame and the charged decay lepton in the $W^{\pm}$ rest frame

$$\begin{aligned}\frac{dN_{W^+}}{dcos\theta^*} &\propto (1 - F_- - F_0) \times \frac{3}{8}(1 + \cos\theta^*)^2 \\ &+ F_0 \times \frac{3}{4}(1 - \cos^2\theta^*) \\ &+ F_- \times \frac{3}{8}(1 - \cos\theta^*)^2\end{aligned}$$

- Fit data to $\cos\theta^*$ distribution. Extract best values of F_- & F_0

W± Polarisation II





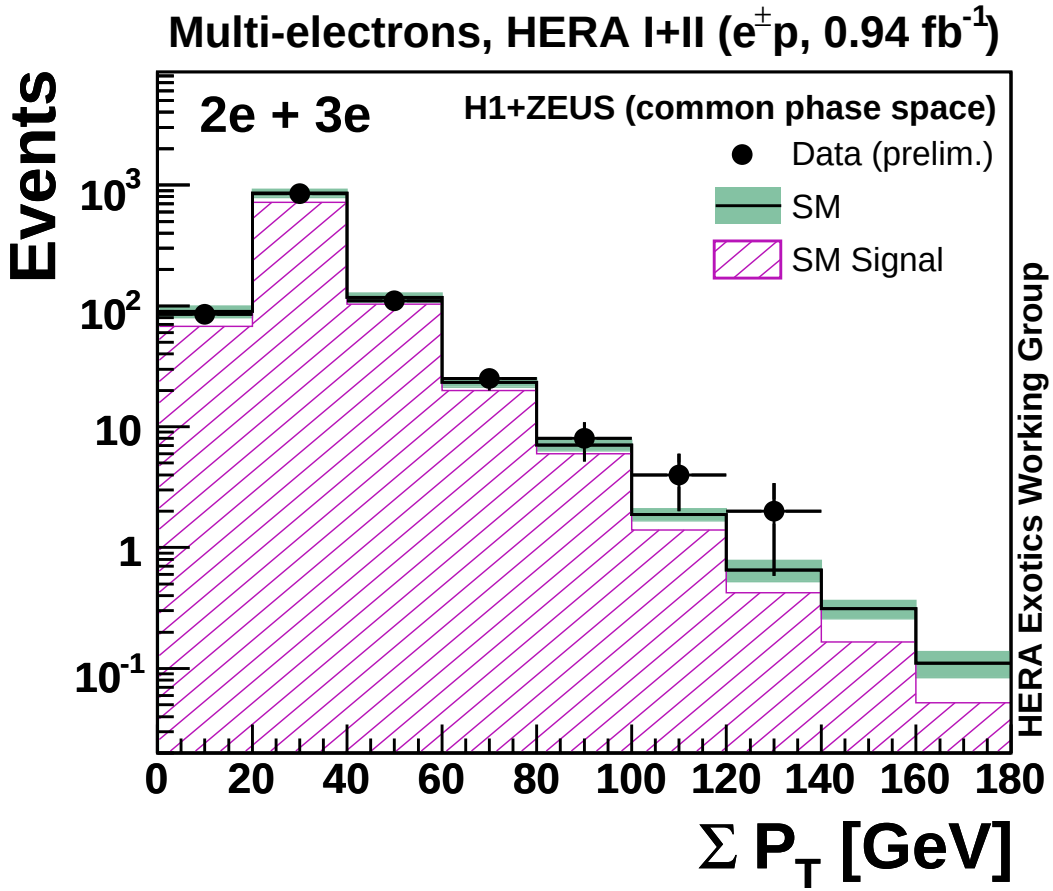
$F_- = 0.58 \pm 0.15\,(\text{stat}) \pm 0.12\,(\text{sys})$ SM: 0.61 ± 0.01 (stat)

$F_0 = 0.15 \pm 0.21\,(\text{stat}) \pm 0.09\,(\text{sys})$ SM: 0.19 ± 0.01 (stat)

Isolated Leptons: Table

H1+ZEUS Preliminary l+P_T^{miss} events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2007 e^+p 0.58 fb^{-1}	Full Sample	39 / 41.3 $\pm$ 5.0 (70%)	18 / 11.8 $\pm$ 1.6 (85%)	57 / 53.1 $\pm$ 6.4 (73%)
	$P_T^X > 25$ GeV	12 / 7.4 $\pm$ 1.0 (78%)	11 / 7.2 $\pm$ 1.0 (85%)	23 / 14.6 $\pm$ 1.9 (81%)
1998-2006 e^-p 0.39 fb^{-1}	Full Sample	25 / 31.6 $\pm$ 4.1 (63%)	5 / 8.0 $\pm$ 1.1 (86%)	30 / 39.6 $\pm$ 5.0 (68%)
	$P_T^X > 25$ GeV	4 / 6.0 $\pm$ 0.8 (67%)	2 / 4.8 $\pm$ 0.7 (87%)	6 / 10.6 $\pm$ 1.4 (76%)
1994-2007 $e^{\pm}p$ 0.97 fb^{-1}	Full Sample	64 / 72.9 $\pm$ 8.9 (67%)	23 / 19.9 $\pm$ 2.6 (85%)	87 / 92.7 $\pm$ 11.2 (71%)
	$P_T^X > 25$ GeV	16 / 13.3 $\pm$ 1.7 (73%)	13 / 12.0 $\pm$ 1.6 (86%)	29 / 25.3 $\pm$ 3.2 (79%)

Multi-Electrons: 2e and 3e Samples Combined



Multi-Leptons: Tables I

H1+ZEUS Multi-electron analysis HERA I+II (0.94 fb^{-1}, preliminary)

Selection	Data	SM	Pair Production	NC-DIS + Compton
2e	937	937 ± 67	756 ± 48	181 ± 39
3e	148	161 ± 10	160 ± 10	0.4 ± 0.01
All	1085	1098 ± 75	916 ± 58	182 ± 39

H1+ZEUS Multi-electron analysis HERA I+II (0.94 fb^{-1}, preliminary)

ΣP_T >100 GeV				
Data sample	Data	SM	Pair Production	NC-DIS + Compton
e^+p (0.56 fb^{-1})	5	1.82 ± 0.21	1.28 ± 0.16	0.54 ± 0.10
e^-p (0.38 fb^{-1})	1	1.19 ± 0.14	0.79 ± 0.09	0.40 ± 0.08
$e^{\pm}p$ (0.94 fb^{-1})	6	3.00 ± 0.34	2.07 ± 0.24	0.94 ± 0.16

Multi-Leptons: Tables II

H1+ZEUS Multi-electron analysis HERA I+II (preliminary)

M_{12} >100 GeV				
Selection	Data	SM	Pair Production	NC-DIS + Compton
e^+p collisions (0.56 fb^{-1})				
2e	4	1.97 ± 0.22	1.10 ± 0.21	0.87 ± 0.18
3e	4	1.10 ± 0.12	1.10 ± 0.12	—
e^-p collisions (0.38 fb^{-1})				
2e	1	1.44 ± 0.15	0.77 ± 0.10	0.67 ± 0.12
3e	0	0.75 ± 0.08	0.75 ± 0.08	—
$e^{\pm}$ collisions (0.94 fb^{-1})				
2e	5	3.41 ± 0.37	1.87 ± 0.25	1.54 ± 0.29
3e	4	1.85 ± 0.24	1.85 ± 0.24	—

Electron Radius

- Classical radius: 2.82 $\times 10^{-15}$m
- Bhabha scattering at LEP: 2.8 $\times 10^{-19}$m
- Drell-Yan at TeVatron: 5.6 $\times 10^{-19}$m
- Single electron in a Penning Trap: $< 10^{-22}$m

Contact Interactions II

- Effective Lagrangian for vector *eeqq* contact interactions:

$$L_{CI} = \sum_{\substack{\alpha,\beta=L,R \\ q=u,d}} \eta^{eq}_{\alpha\beta}(\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

- Different models assume different helicity structure of new interactions, given by set of couplings $\eta^{eq}_{\alpha\beta}$
- 4 couplings for every flavour q

Models conserving parity:

Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$		
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$	
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$	
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$
U1					$+\eta$	$-\eta$		
U2					$+\eta$		$+\eta$	
U3					$+\eta$			$+\eta$
U4						$+\eta$	$+\eta$	
U5						$+\eta$		$+\eta$
U6							$+\eta$	$-\eta$

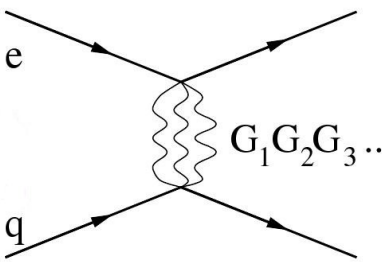
Models violating parity:

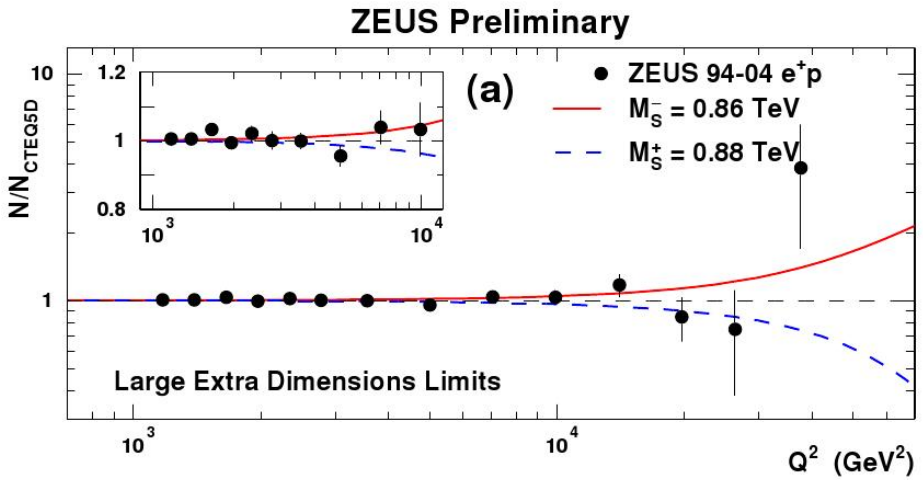
LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$

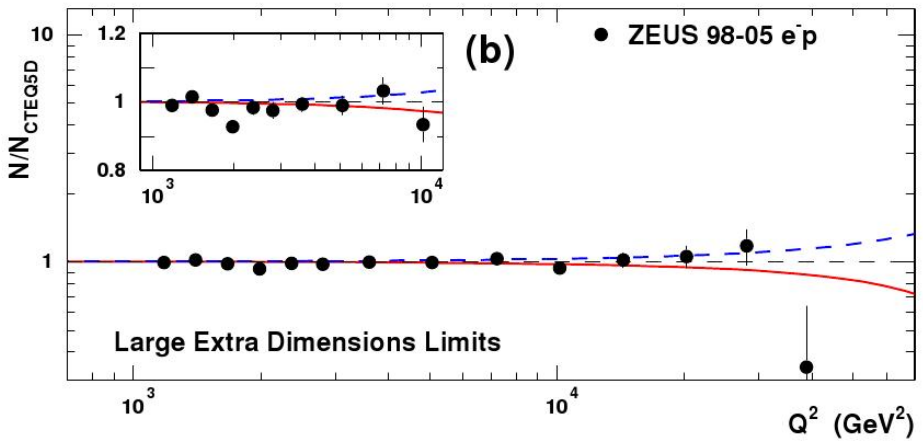
Extra Dimensions

- Extra dimensions have size R≈1mm in the Arkani- Hamed-Dimopoulos- Dvali model (4+n dimension string theory)

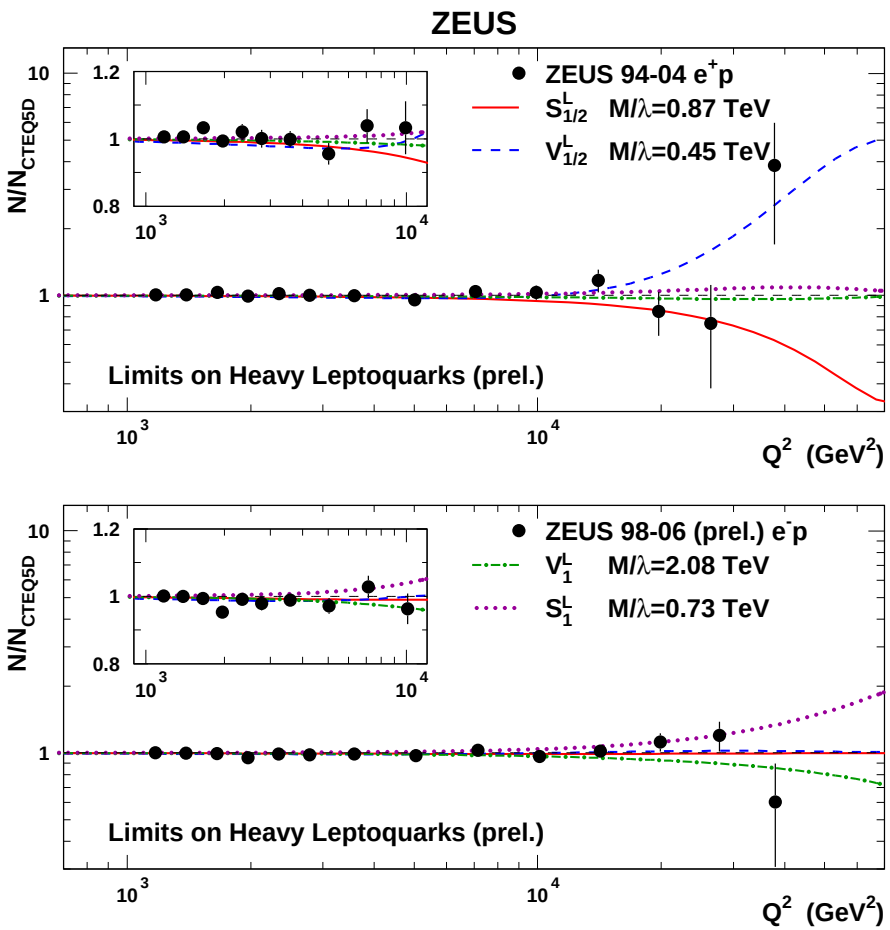
- Gravity is comparable in strength to EW f effective mass scale $M_S \approx 1$TeV
- Contributions from graviton exchange to NC DIS cross-section.
- Contact interaction parameterization: $\eta^G = \frac{\lambda}{M_S^4}$



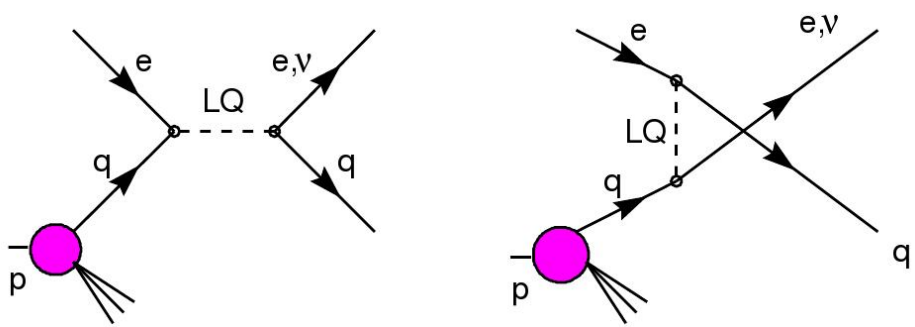




Heavy Leptoquarks



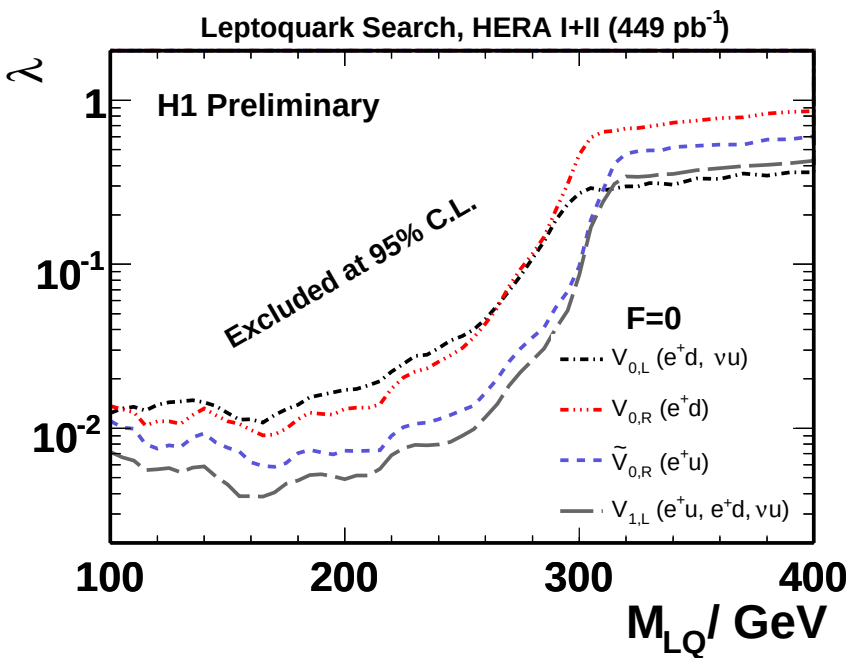
- Leptoquarks are scalar or vector colour triplet bosons
- They carry both lepton and baryon number
- Fermion number F = 3B + L
- Model: RPV SUSY for example

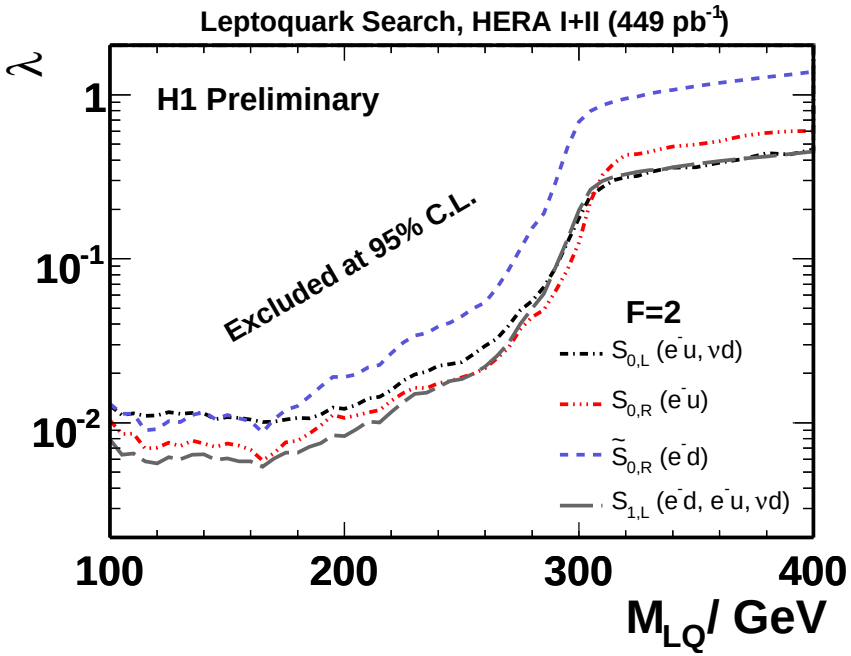


Leptoquarks: The Buchmüller-Rückl-Wyler model

- Standard model symmetries are conserved (lepton and baryon number conserved)
- Leptoquark couplings are flavor diagonal ($\rightarrow$ no FCNC)
- Couple either to left-handed or to right-handed leptons
- 7 scalar and 7 vector leptoquarks
- All 14 LQs couple to eq, 2 scalar and 2 vector LQs also to νq
- For $e^- p$, F=2 is preferred (produced from valence quarks), LQs with F=0 produced from antiquarks (sea quarks)
- For $e^+ p$, F=0 is preferred (produced from valence quarks), LQs with F=2 produced from antiquarks (sea quarks)

Leptoquarks: No Lepton Flavour Violation

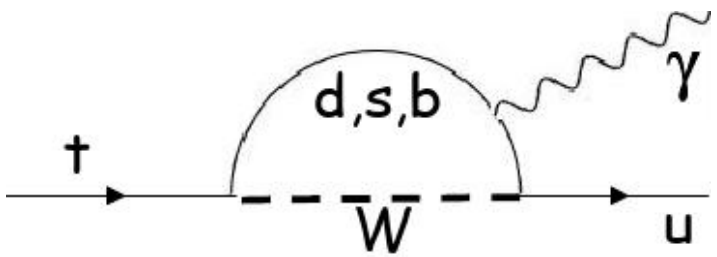




FCNC: SM & BSM

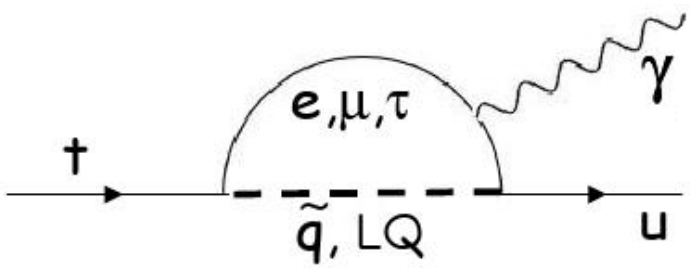
Standard Model

- FCNC one-loop process mediated by W-boson.
- Strongly suppressed by GIM mechanism

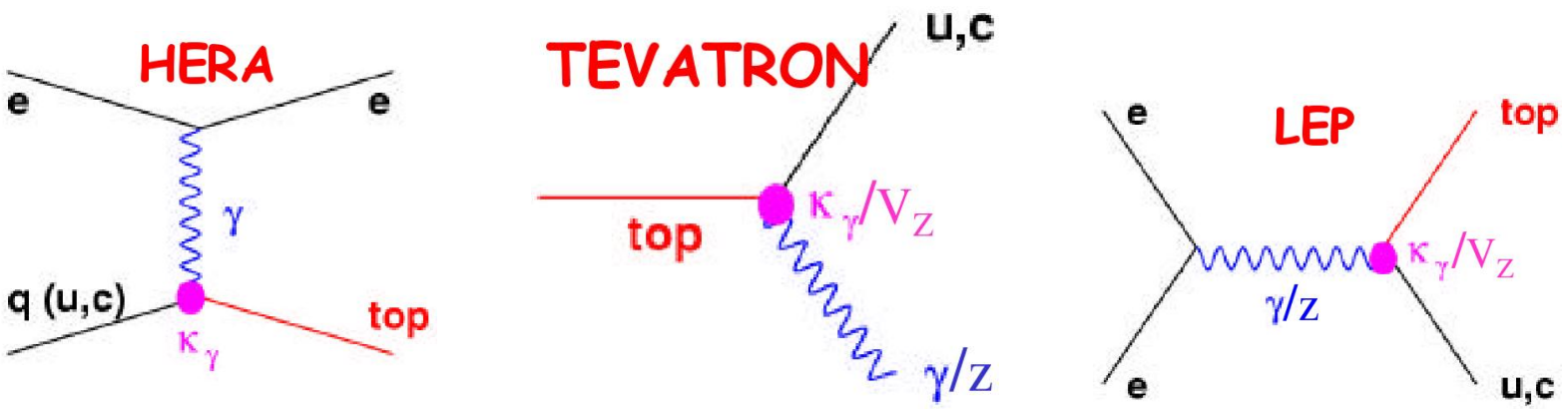


Beyond Standard Model

- Leptoquarks or squarks enter the loop
- Enhance FCNC beyond the SM expectation

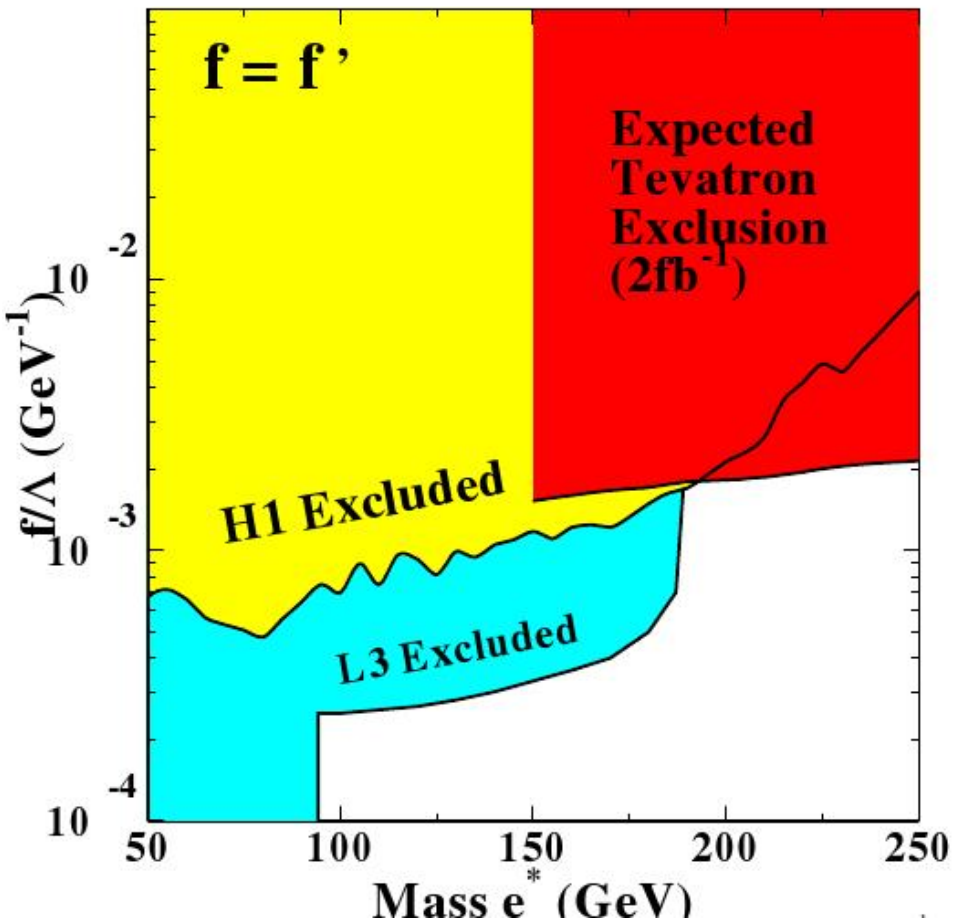


FCNC: HERA, TeVatron & LEP

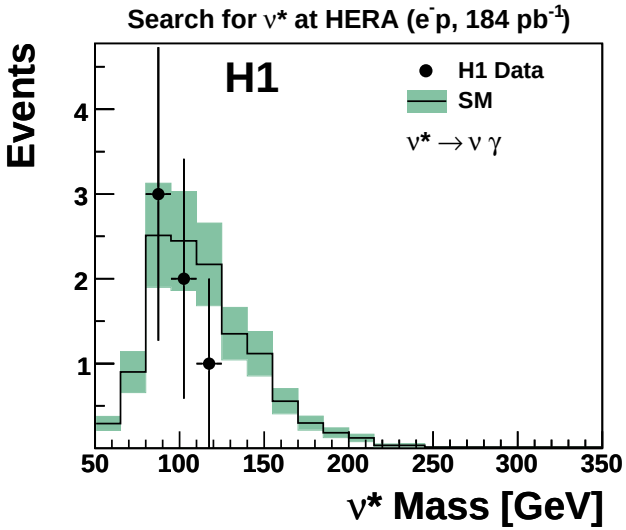


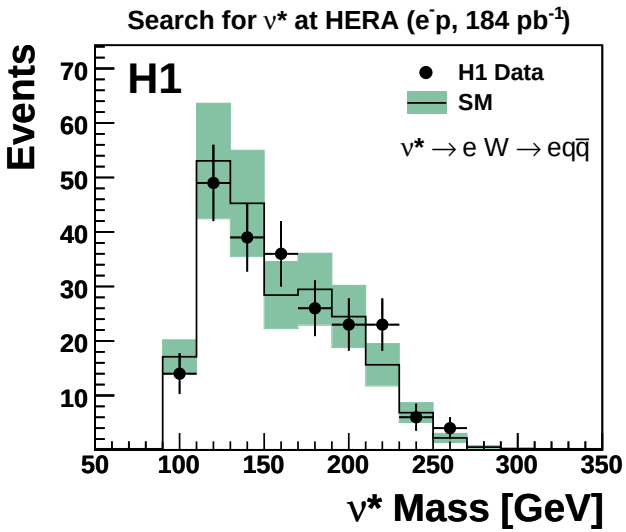
- LEP and TeVatron have sensitivity to $\kappa_{tc\gamma}$
- HERA has low sensitivity to ν_{tuZ}

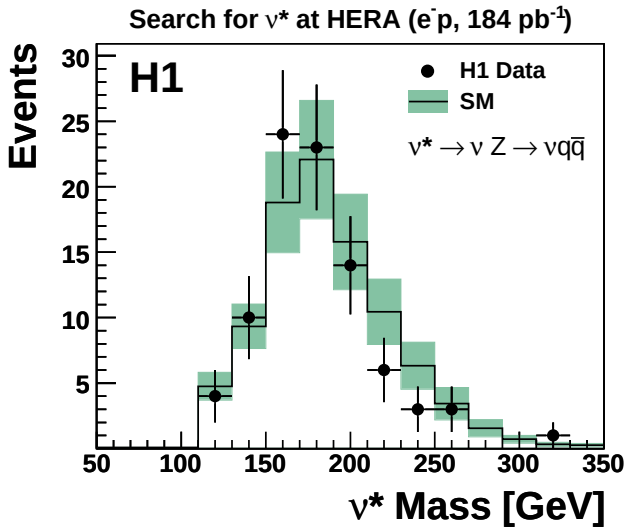
Expected TeVatron Run II Excited Electron Limit



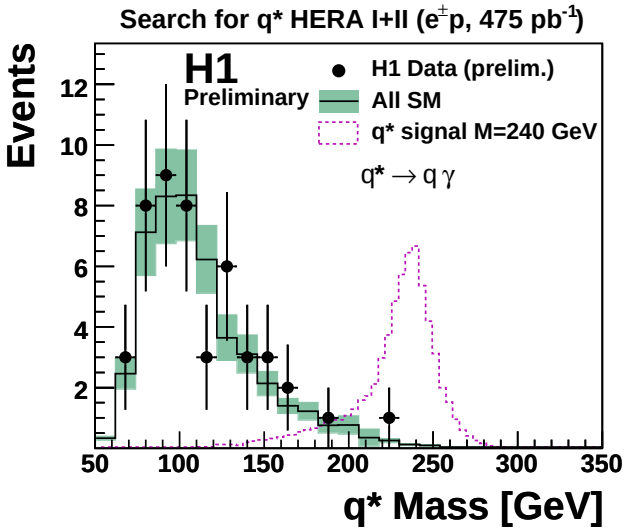
H1 Excited Neutrinos

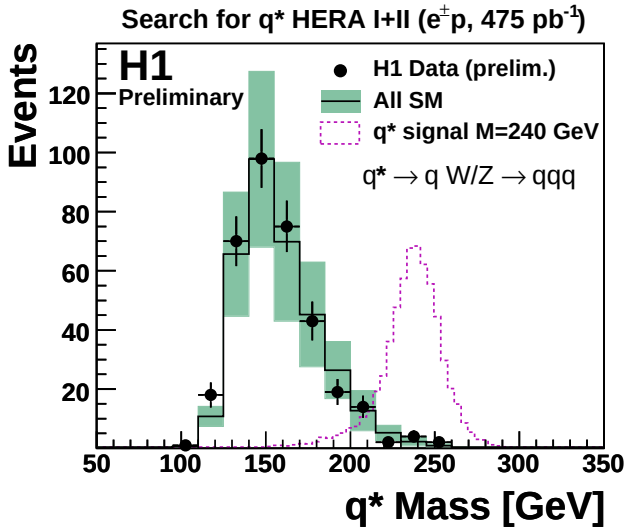


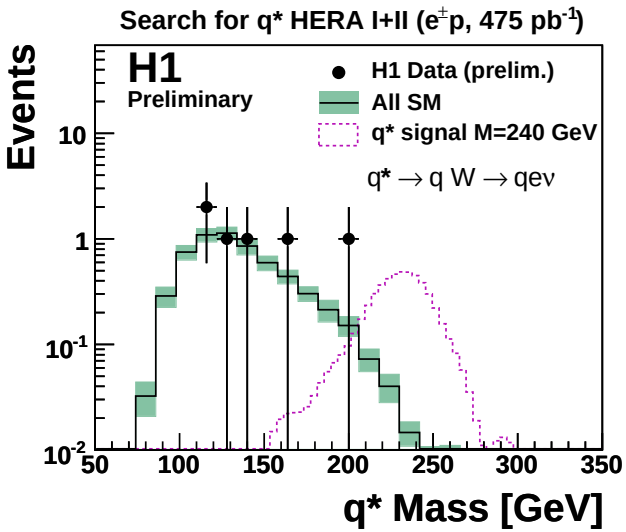


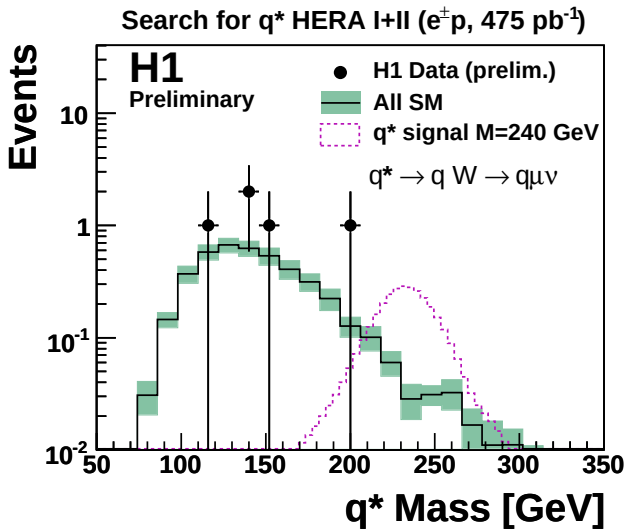


H1 Excited Quarks

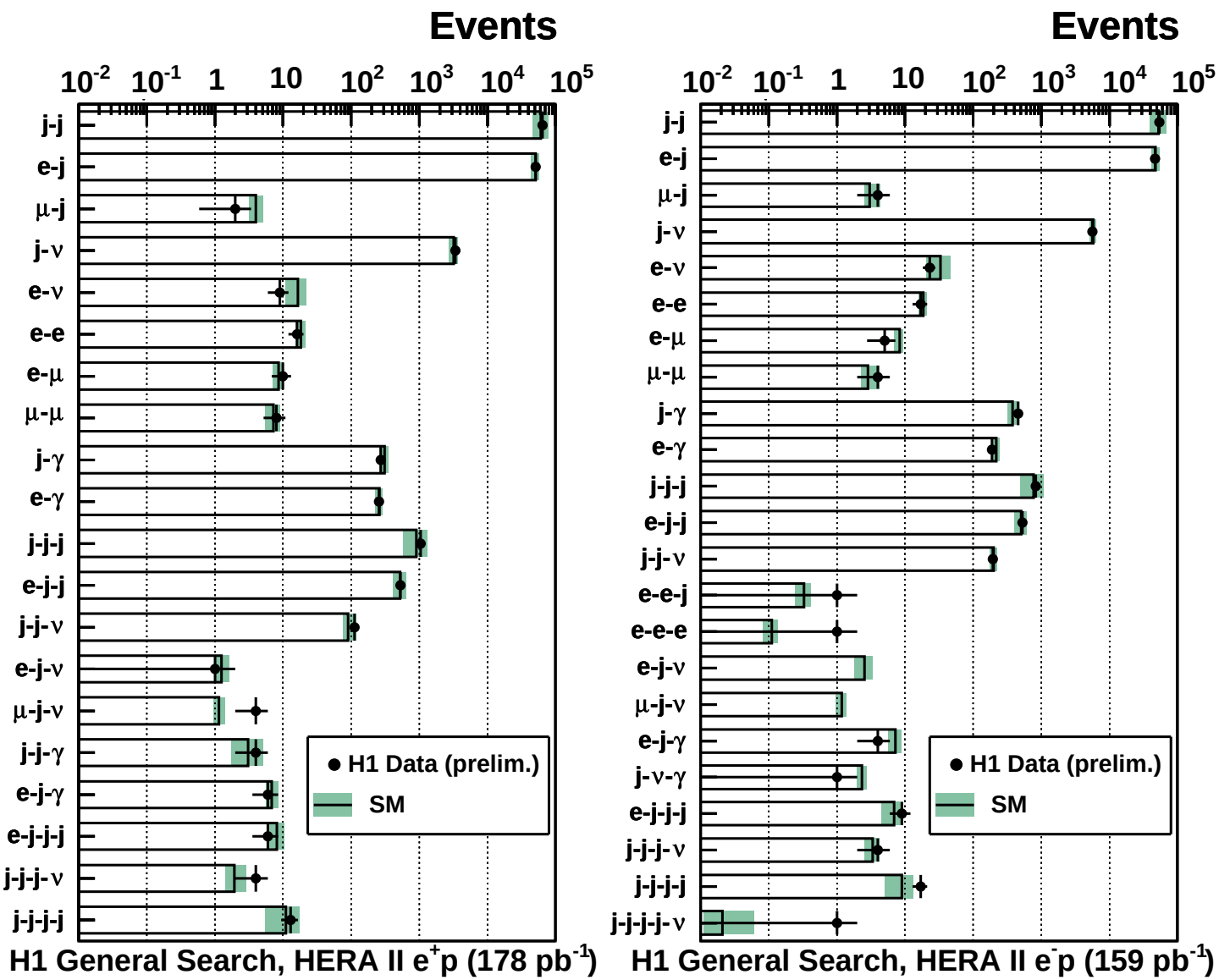








H1 General Search I

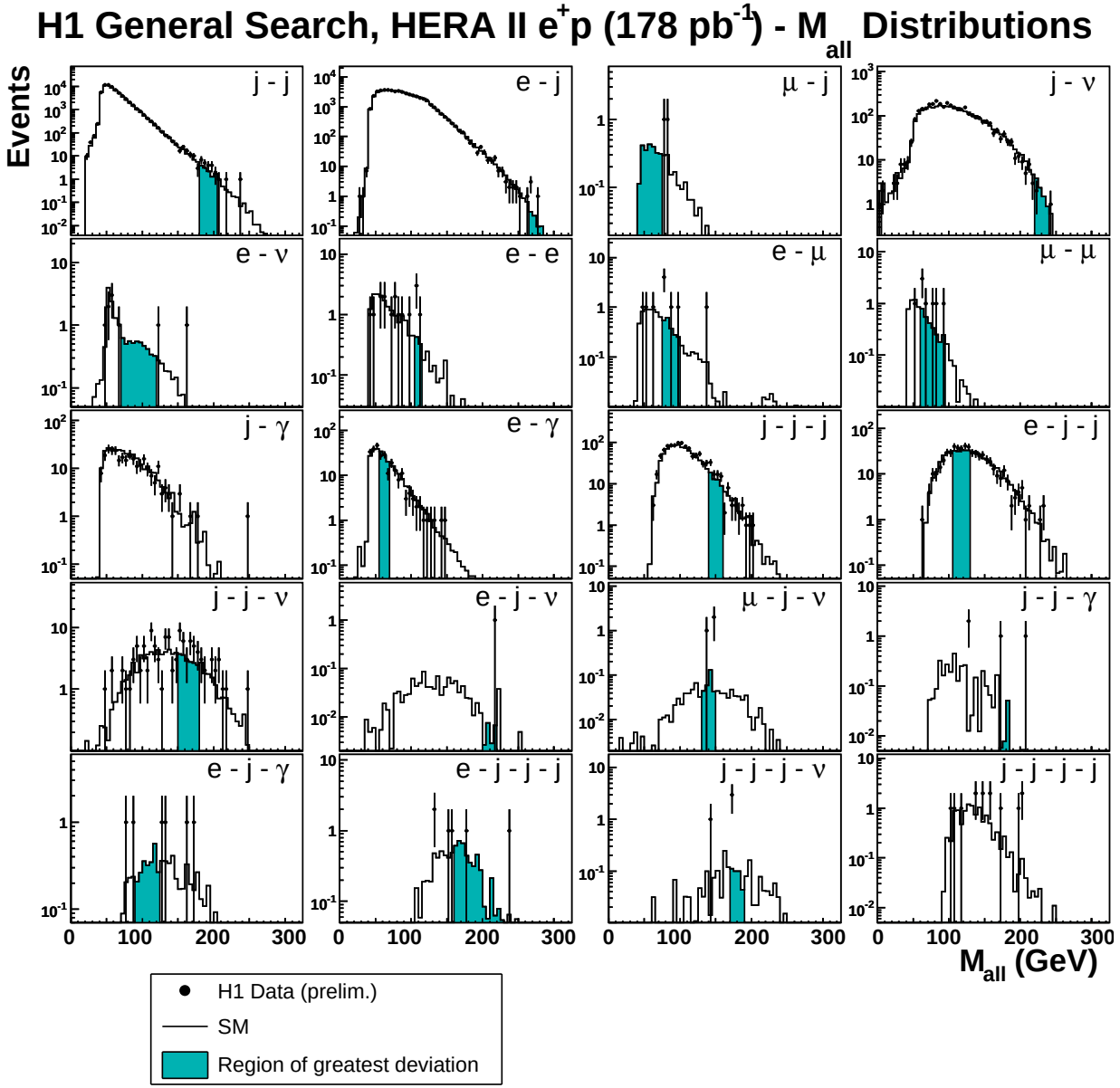


- Final states with high p_T objects, $p_T > 20$GeV
- Overall good agreement with SM

H1 General Search II

- Look at invariant mass and $\sum p_T$ distributions for each channel
- Select window with largest deviation from SM using statistical estimator, p. The region of greatest interest (largest deviation) has the smallest p value, p_{min}^{data}
- Determine the significance of this fluctuation:
  - Randomly fill many hypothetical data histograms from the probability density function of the SM prediction
  - Find the region of greatest deviation and p_{min}^{SM} for each hypothetical SM histogram
  - $\hat{P}$ is the fraction of data histograms with $p_{min}^{SM} < p_{min}$

H1 General Search: Region of Greatest Deviation



H1 General Search: Statistical Estimator p

$$p = A \int_0^{\infty} dbG(b; N_{SM}, \delta N_{SM}) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!} \quad \text{if } N_{obs} > N_{SM}$$

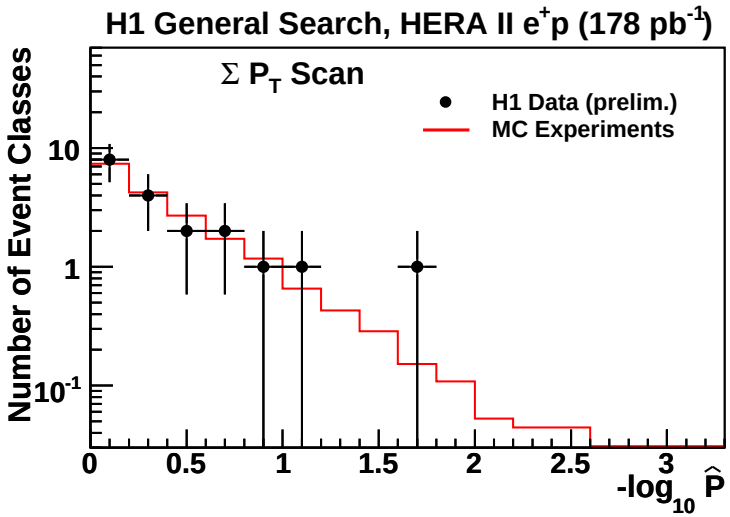
$$p = A \int_0^{\infty} dbG(b; N_{SM}, \delta N_{SM}) \sum_{0}^{i=N_{obs}} \frac{e^{-b} b^i}{i!} \quad \text{if } N_{obs} < N_{SM}$$

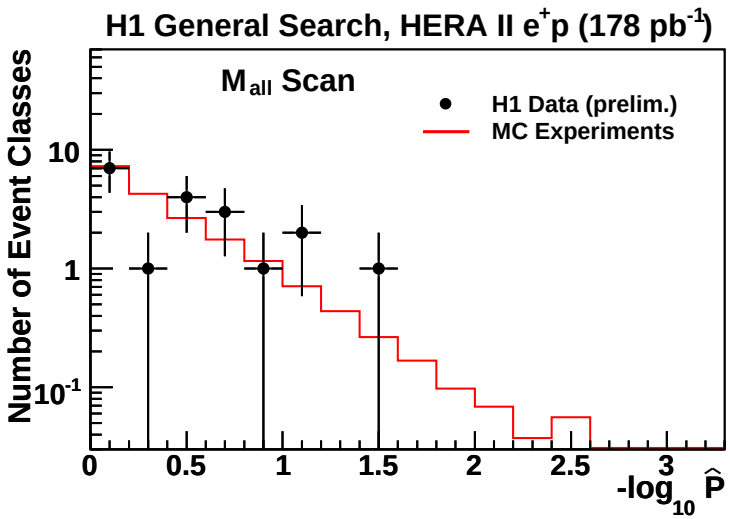
$$A = \left(\int_0^{\infty} dbG(b; N_{SM}, \delta N_{SM}) \sum_{i=0}^{\infty} \frac{e^{-b} b^i}{i!} \right)^{-1} \quad \text{(normalise to 1)}$$

Convolution of:

- Poisson probability density function to account for statistical errors
- Gaussian probability density function to account for non-negligible systematic uncertainties

H1 General Search: $\hat{P}$





- $\hat{P}$: a measure of the statistical significance of the deviation observed in the data
- A p_{min} value of 5.7×10^{-7} (a 5σ effect) corresponds to $-\log_{10} \hat{P}$ between 5 and 6