Contact Interactions and Large Extra Dimensions at HERA

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for the H1 and ZEUS collaborations

General Introduction

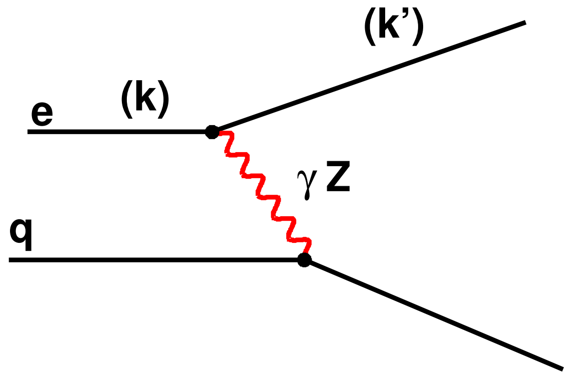
PART I: Contact Interactions (CI)

- Phenomenology
- Analysis methods
- Limits on Compositeness and Leptoquarks

PART II: Large Extra Dimensions

- Motivation from String Theory
- Low Scale Quantum Gravity
- Effective Theory
- Limits

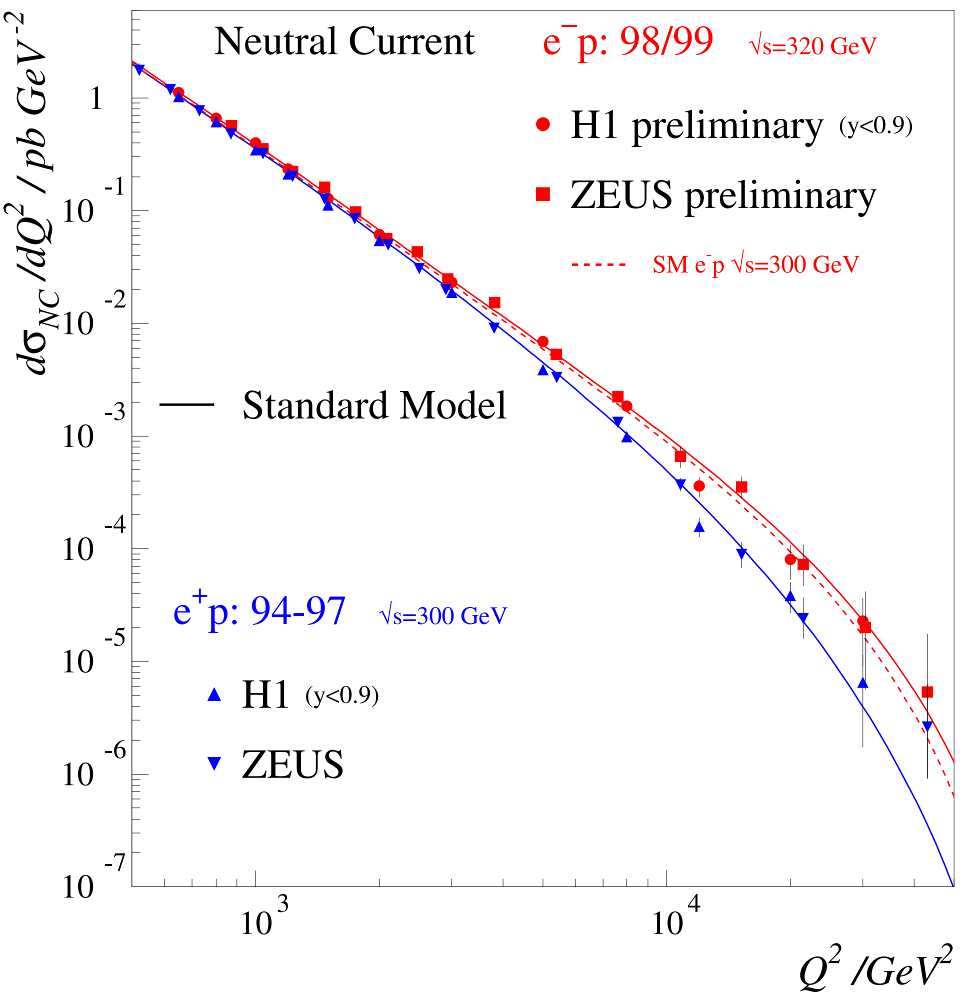
NEUTRAL CURRENT CROSS SECTIONS



exchange of SM Gauge Bosons

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

probing the proton structure at distances of 10^{-16} cm for highest momentum transfers Q^2



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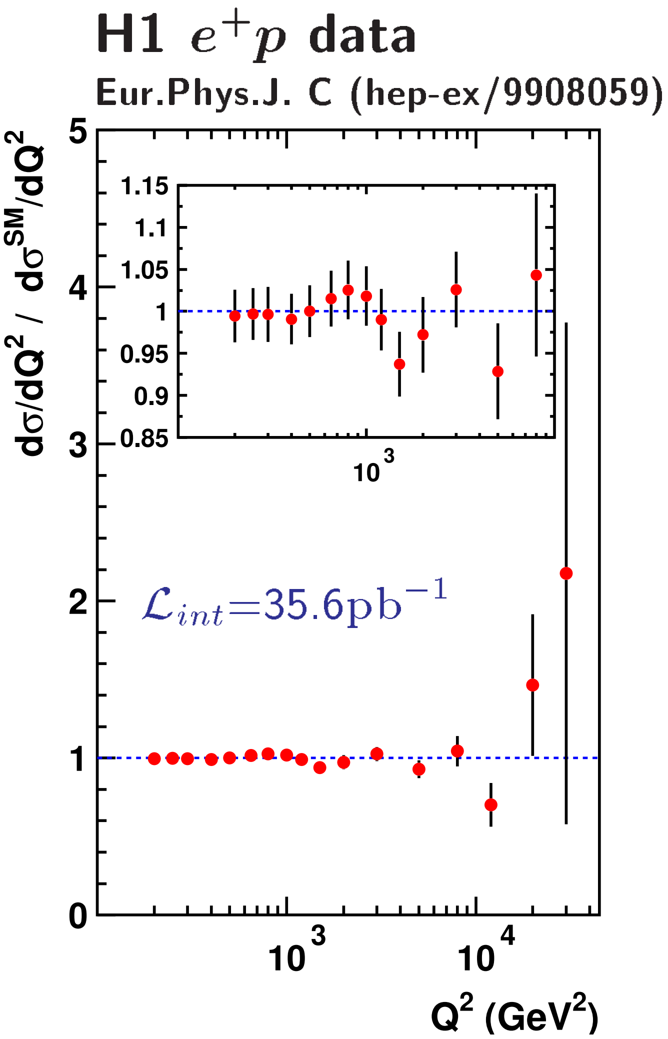
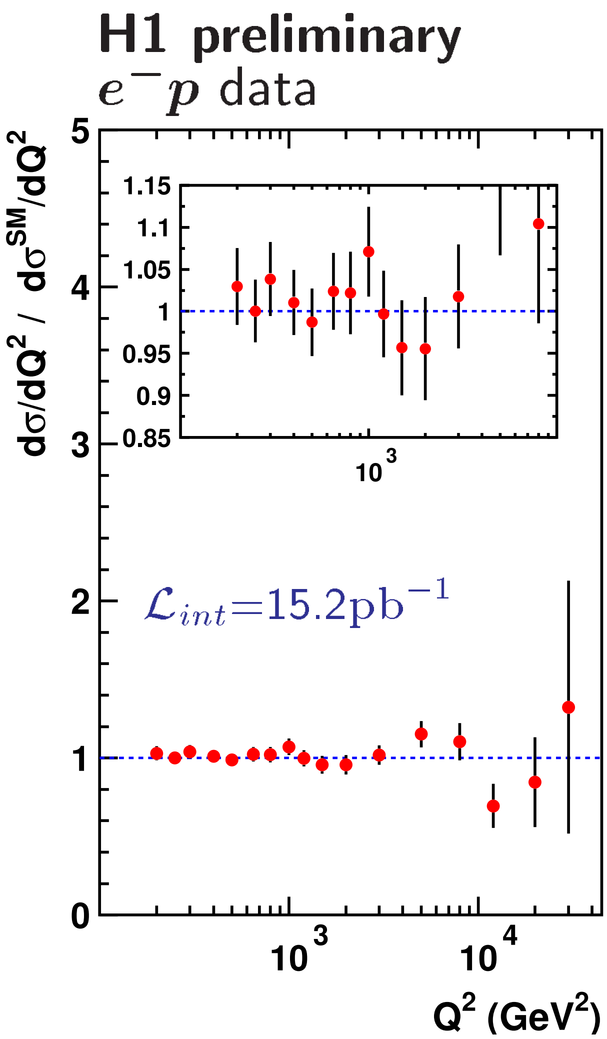
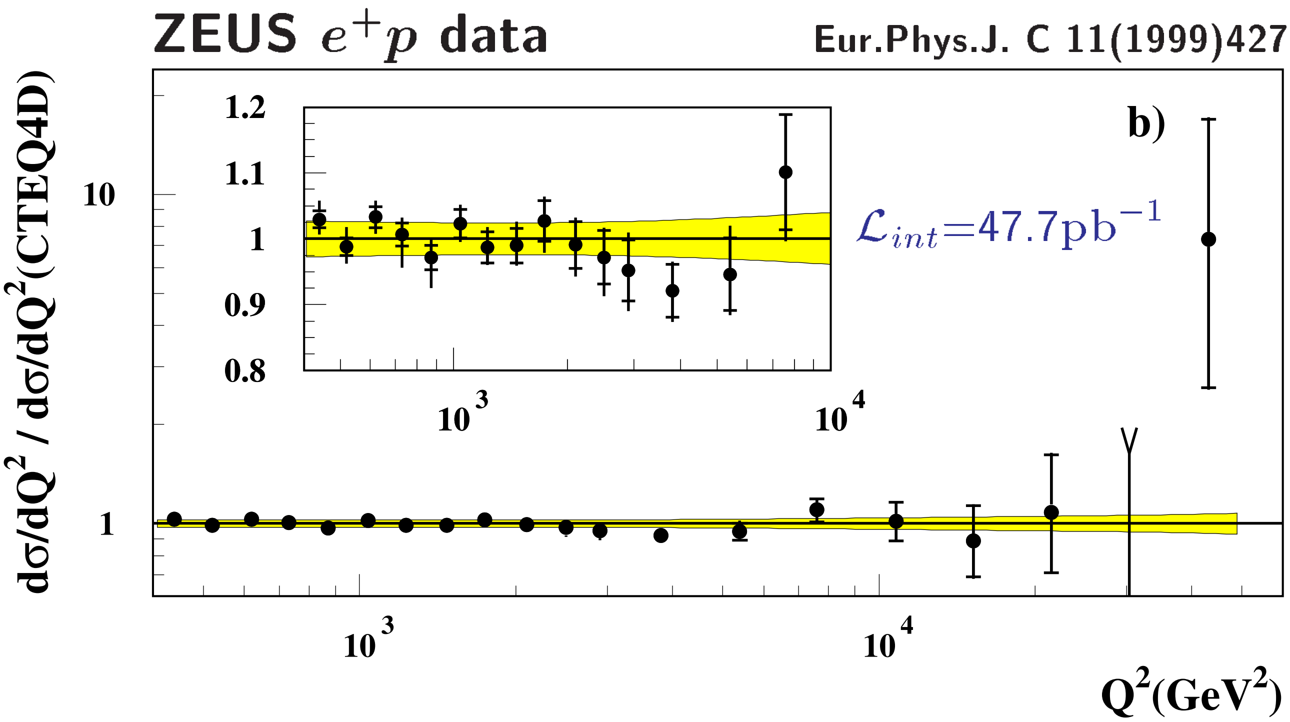






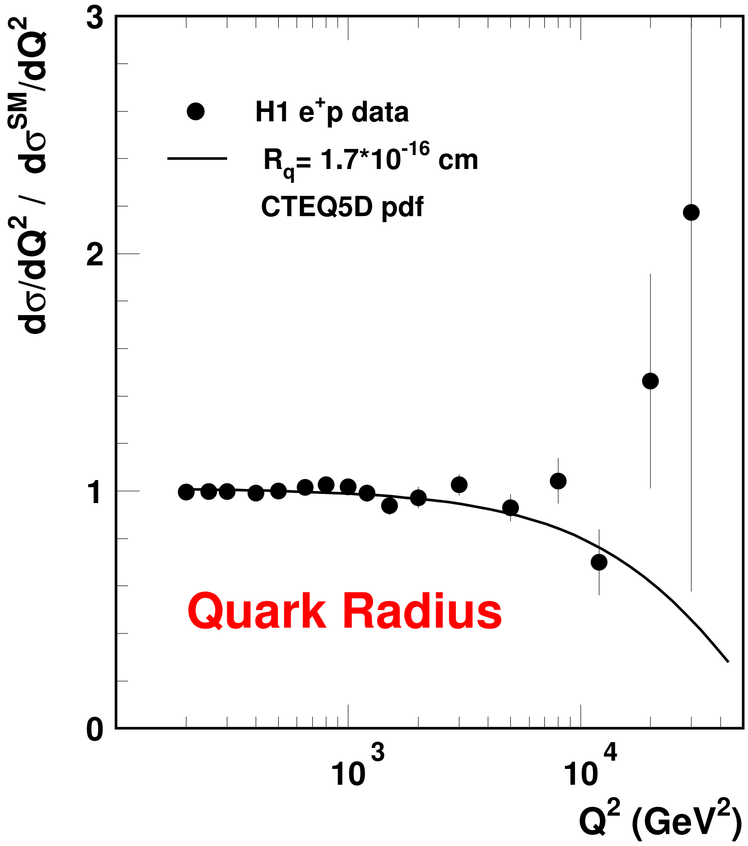
POSSIBLE NEW PHYSICS

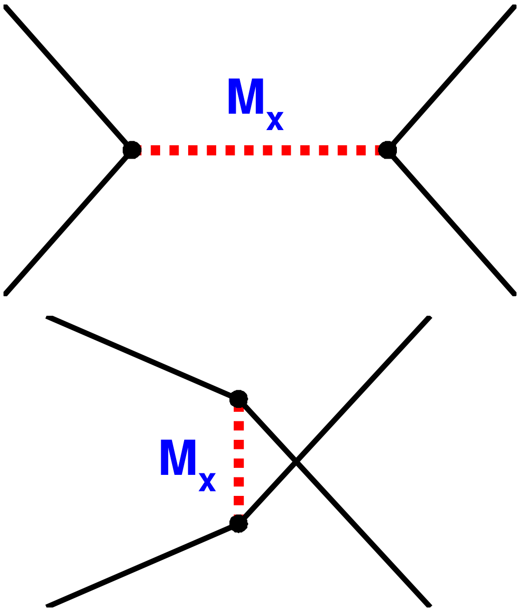
simplest interpretation of deviations in Q^2-spectrum:

QUARK RADIUS

parametrisation as form factor:

$$f(Q^2) = 1 - \frac{1}{6} \langle R_q^2 \rangle Q^2$$





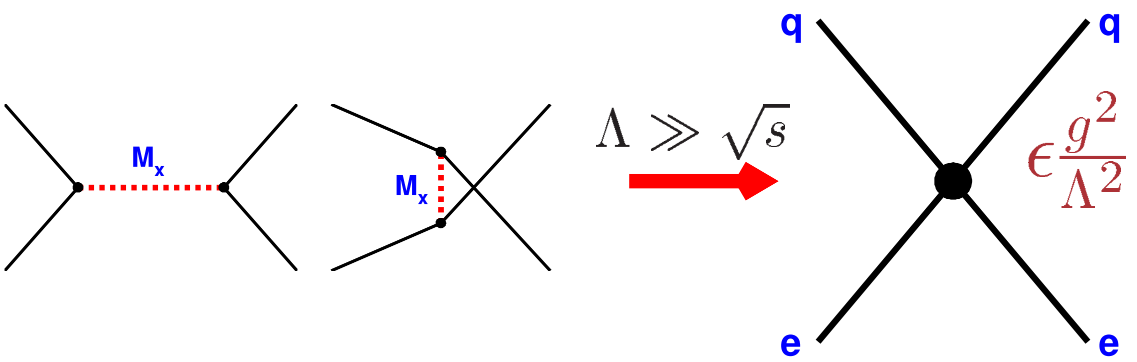
exchange of
new, heavy bosons or
composite objects

- Direct production for $M_x < \sqrt{s}$, e.g. LQ,q^*
  Mass peak: $M_x = \sqrt{xs}$
- Indirect effects at large scales $\Lambda \gg \sqrt{s}$

CONTACT INTERACTION – PHENOMENOLOGY

New Physics at large scales $\Lambda \gg \sqrt{s}$ observable as deviations from SM prediction due to virtual particle exchange
$\rightarrow$ distorsion of Q^2-spectrum at high Q^2

parametrisation as effective low energy approximation with Contact Interactions (CI):



propagators contract to pointlike FOUR FERMION CI with effective coupling g^2/Λ^2

Effective Lagrangian: (vector terms only)

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

8 vector couplings: $\eta^q_{ab} \equiv \pm (g/\Lambda^q_{ab})^2$

Scattering amplitudes for $eq \to eq$ modified in presence of CI:

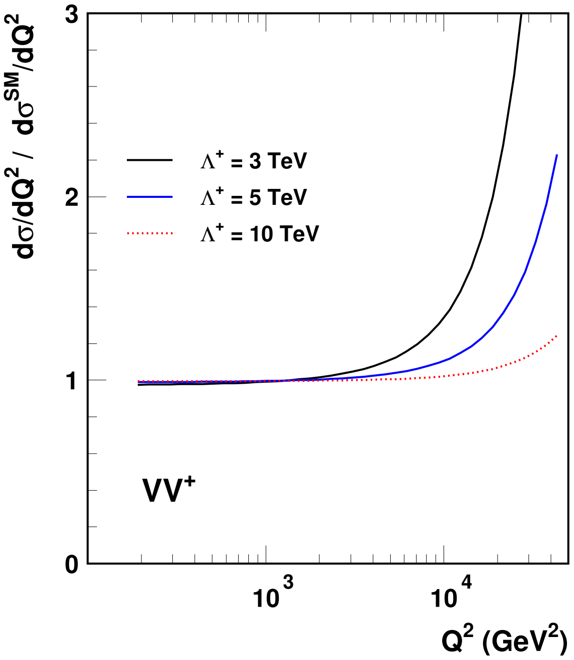
$$M^q_{ab}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2 g^e_a g^q_b}{\sin^2 \Theta_W \cos^2 \Theta_W} \cdot \frac{1}{Q^2 + M_Z^2} + \eta^q_{ab}$$

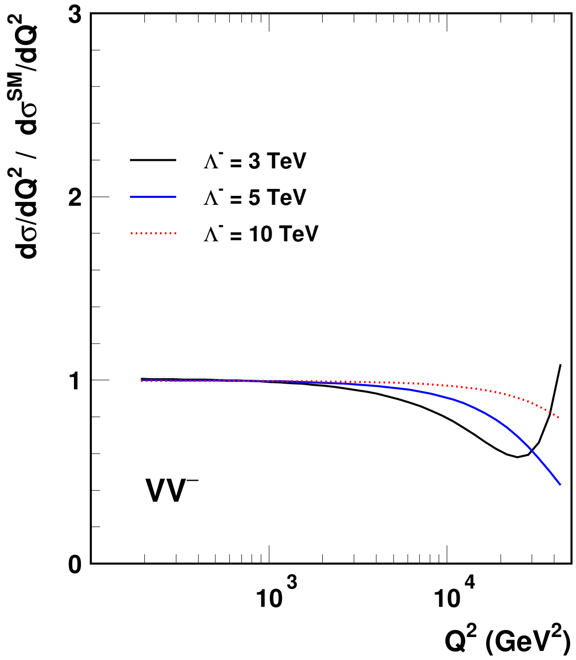
COMPOSITENESS MODELS

- assume quark flavour symmetry, i.e. (u=c, d=s=b)
- conventionally set $g^2 = 4\pi$
- consider models with fixed relative coupling strength, i.e. only scale Λ as parameter: $\eta^q_{ab} = \epsilon^q_{ab} \cdot 4\pi/\Lambda^2$
- positive and negative interference possible ($\eta^q_{ab} \rightarrow -\eta^q_{ab}$)

MODEL	$\epsilon^u_{LL}, \epsilon^d_{LL}$	$\epsilon^u_{LR}, \epsilon^d_{LR}$	$\epsilon^u_{RL}, \epsilon^d_{RL}$	$\epsilon^u_{RR}, \epsilon^d_{RR}$
VV	$+1$	$+1$	$+1$	$+1$
VA	$+1$	-1	$+1$	-1
AA	$+1$	-1	-1	$+1$
X1 = LL−LR	$+1$	-1	0	0
X2 = LL+RL	$+1$	0	$+1$	0
X3 = LL+RR	$+1$	0	0	$+1$
X4 = LR+RL	0	$+1$	$+1$	0
X5 = LR+RR	0	$+1$	0	$+1$
X6 = RL−RR	0	0	$+1$	-1
RR,RL,LR,LL	pure chiral (strong bounds from APV)			

- all models (except LL,RR,LR,RL) conserve parity: $\eta_{LL} - \eta_{RR} + \eta_{LR} - \eta_{RL} = 0$

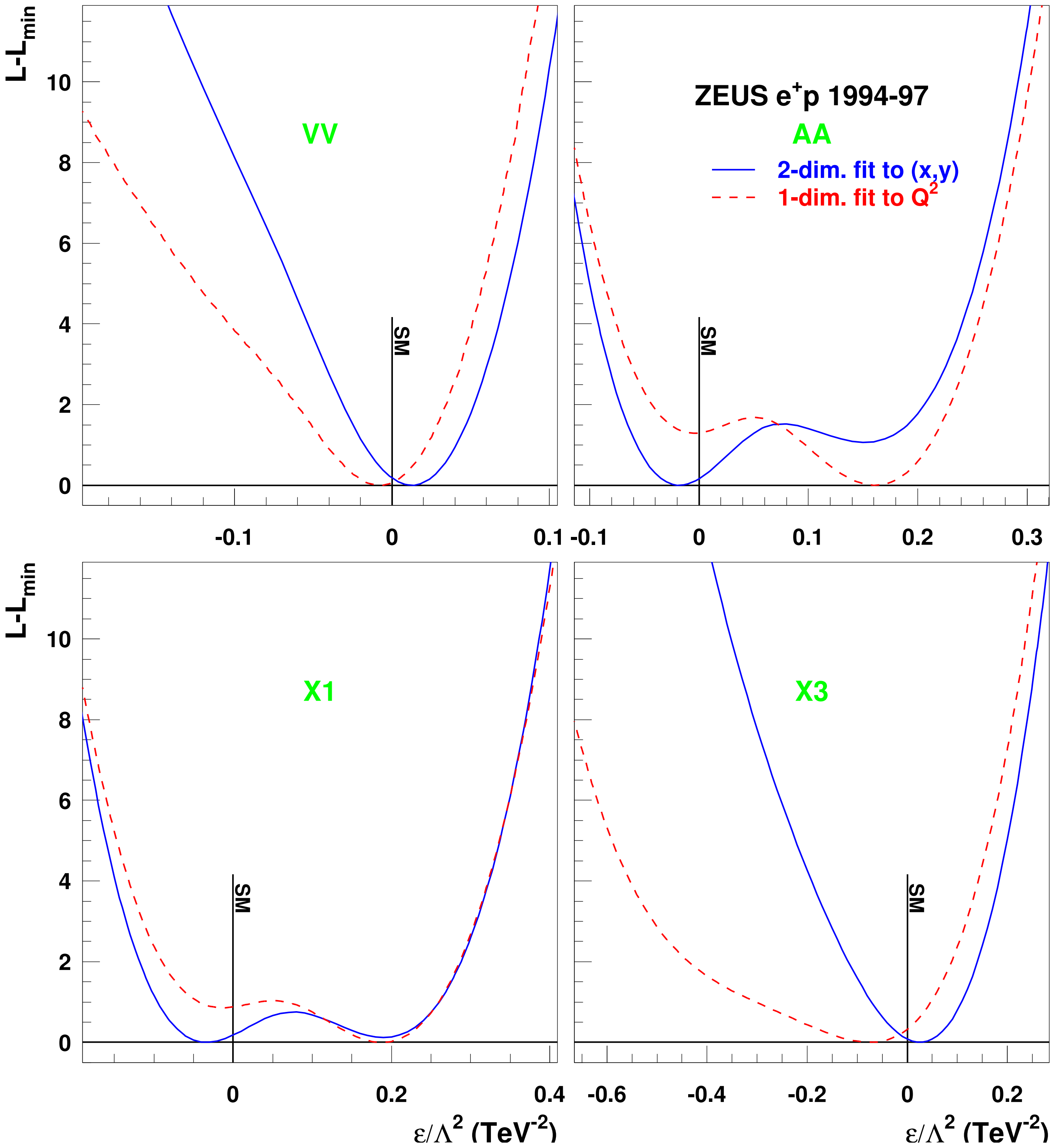




ANALYSIS METHODS

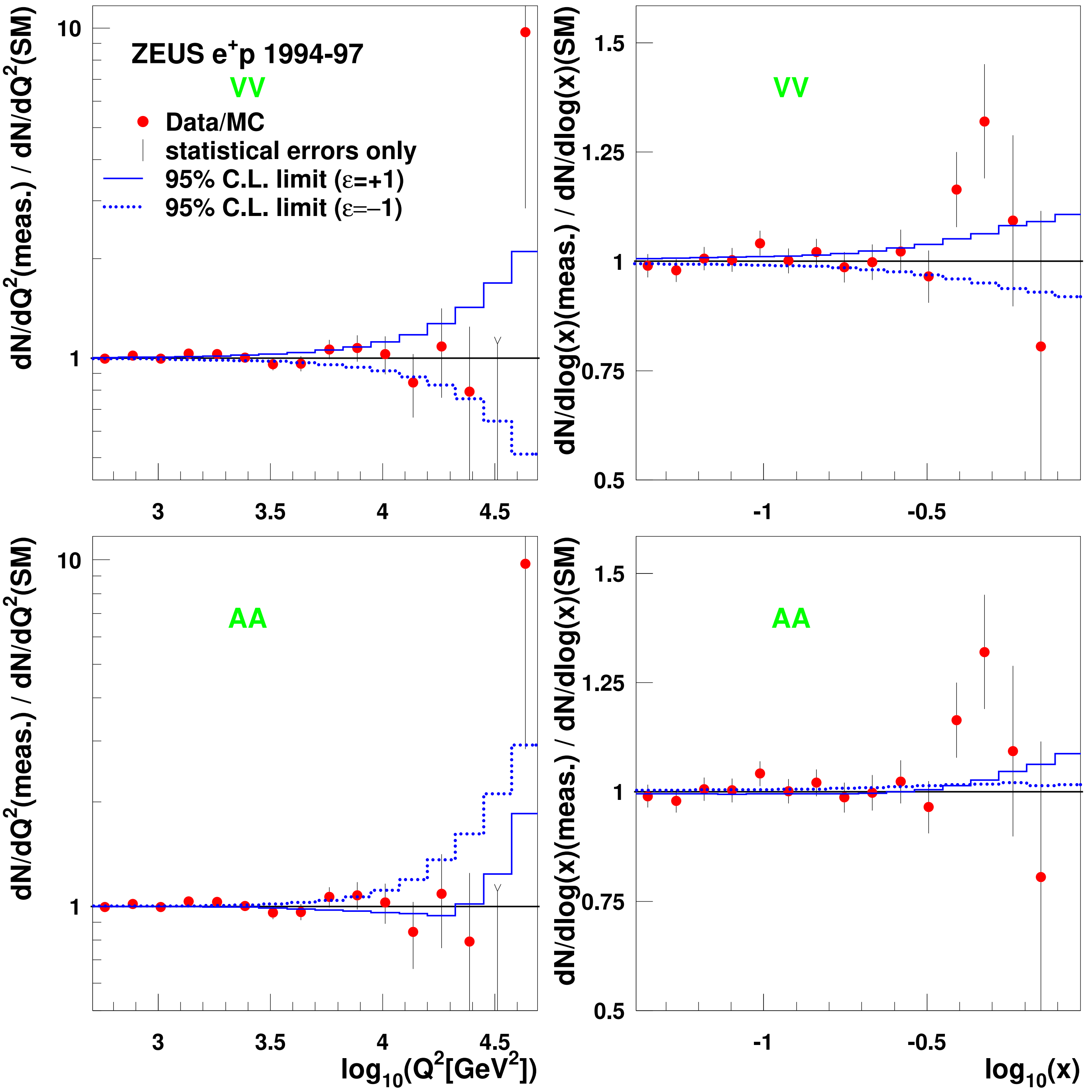
ZEUS	H1
method	
unbinned log-likelihood method 2 dimensional (x,y) $\rightarrow \frac{dN}{dx \cdot dQ^2} \cdot \frac{1}{N_{tot}}$ shape analysis	χ^2 method 1 dimensional (Q^2) $\rightarrow \frac{d\sigma}{dQ^2}$ absolute normalisation taken into account
95% CL limits	
95% of MC experiments give $\Lambda_{true} < \Lambda_{data}$ (frequentist approach)	$\chi^2(\epsilon/\Lambda_{lim}) = \chi^2_{SM} + \Delta\chi^2_{95\% CL}$
errors	
combined set of MC experiments including variations within systematic errors used for limit calculation $\rightarrow$ average over spectra of sys. effects	uncorrelated stat. & sys. errors used in χ^2 correlations considered e.g. α_s different pdf's used, quoting the most conservative limit

LOG-LIKELIHOOD (ZEUS)

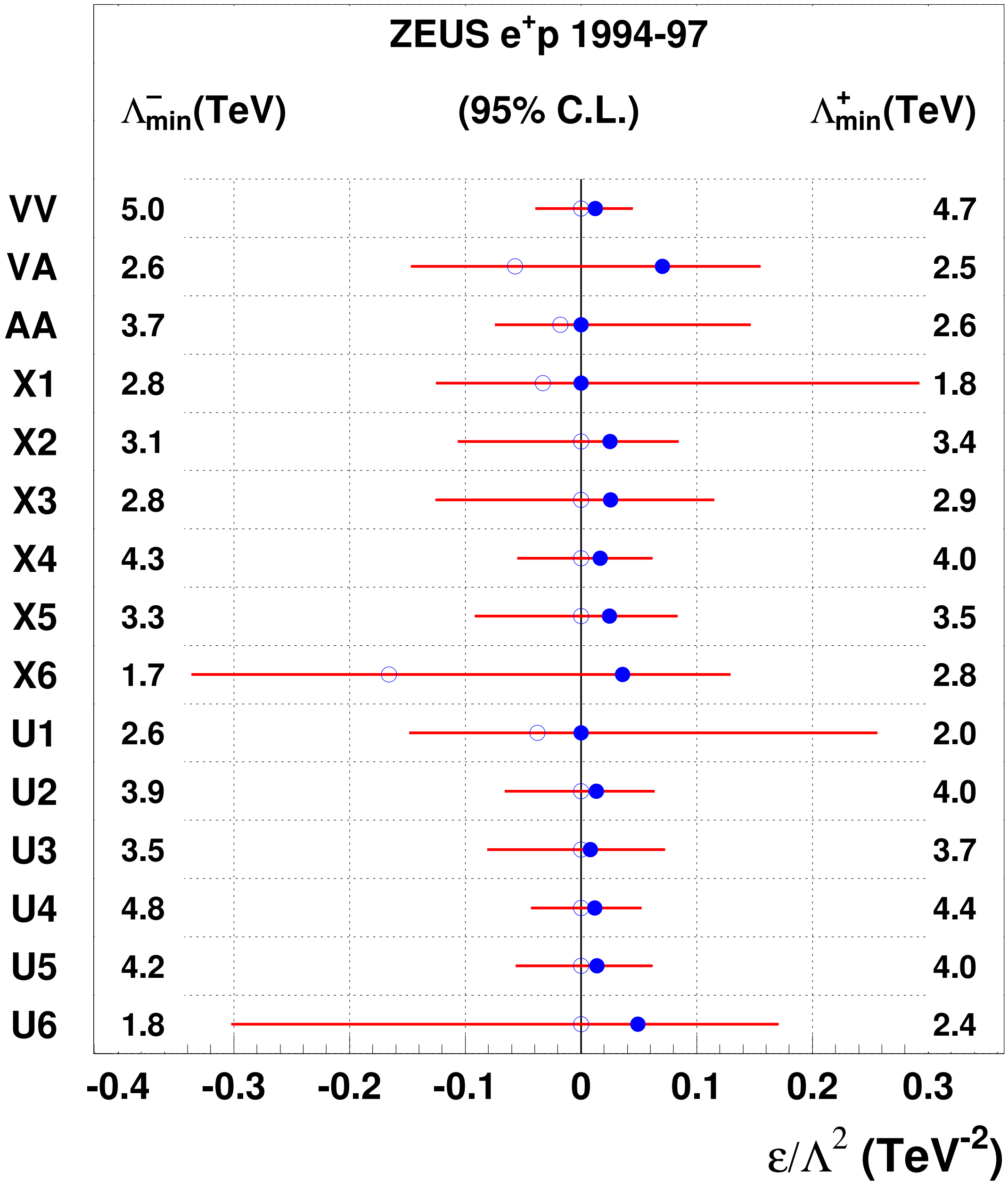


- 1-dim fit as cross check takes normalisation into account
- 2-dim fit and 1-dim fit look very similar
- minimum value often lies closer to SM for 2-dim fit, e.g. AA, X1
- for some models 2-dim fit has more narrow curves $\longrightarrow$ better limits

MODEL SENSITIVITY



COMPOSITENESS MODEL LIMITS



●(○) best fit for $\eta = +(-)1$

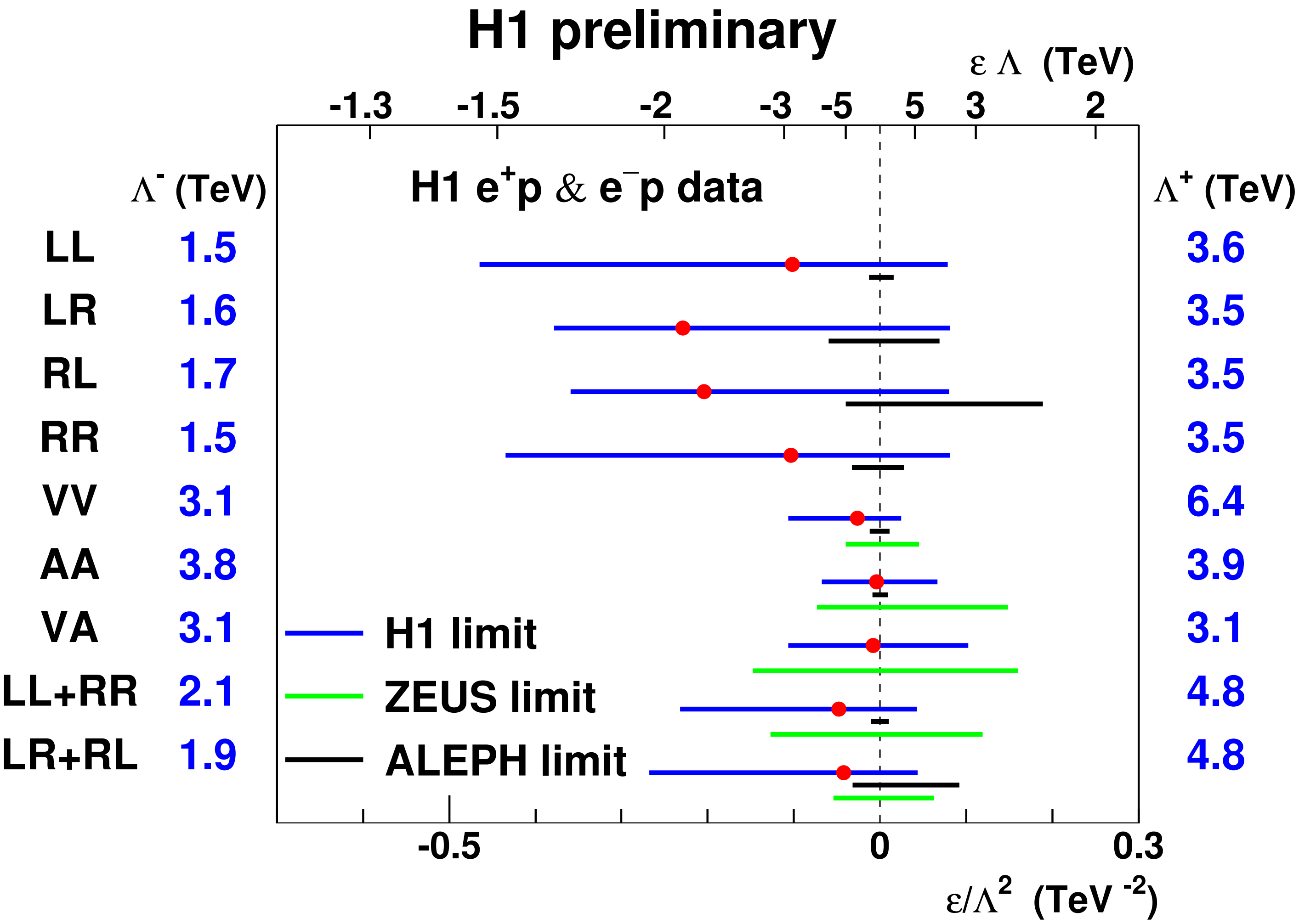
– 95% CL limit

- all models conserve parity
- for models U1-U6 only u-quarks considered

No evidence for CI signal

limits between 1.7 TeV to 5 TeV

COMPOSITENESS MODEL LIMITS



- H1 limits from combined e^+p and e^-p data
- similar results for H1 and ZEUS
- ALEPH/LEP limits often more stringent

COMPOSITENESS MODEL LIMITS

coupling	H1		H1 prelim		ZEUS			
	e^+		e^+ & e^-		e^+			
	u+d		u+d		u+d		u only	
	Λ^+ [TeV]	Λ^- [TeV]	Λ^+ [TeV]	Λ^- [TeV]	Λ^+ [TeV]	Λ^- [TeV]	Λ^+ [TeV]	Λ^- [TeV]
LL	2.3	1.2	3.6	1.5	-	-	-	-
LR	3.0	1.5	3.5	1.6	-	-	-	-
RL	3.0	1.5	3.5	1.6	-	-	-	-
RR	2.3	1.2	3.5	1.5	-	-	-	-
VV	5.0	1.9	6.4	3.1	4.7	5.0	-	-
AA	2.0	3.4	3.9	3.8	2.5	2.6	-	-
VA	2.6	2.6	3.1	3.1	2.6	4.7	-	-
LL−LR	-	-			1.8	2.8	2.0	2.6
LL+RL	-	-			3.4	3.1	4.0	3.9
LL+RR	3.1	1.3	4.8	2.1	2.9	2.8	3.7	3.5
RL+LR	4.1	1.8	4.8	1.9	4.0	4.3	4.4	4.8
LR+RR	-	-			3.5	3.3	4.0	4.2
RL−RR	-	-			2.8	1.7	2.4	1.8

ZEUS and H1 give very similar limits

strong bounds already for the pure chiral couplings (LL,RR,RL,LR) from APV exp.

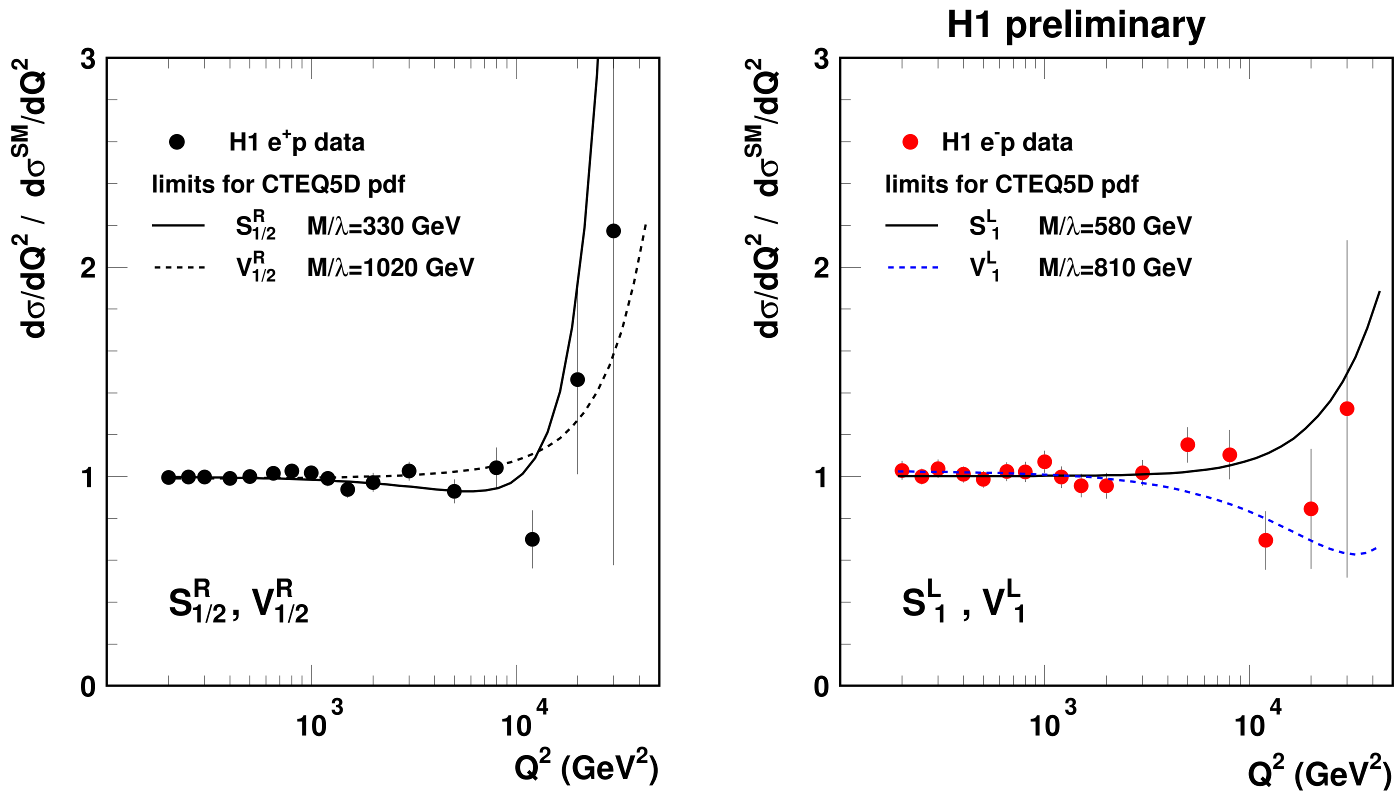
sensitivity at HERA comparable to that at LEP and Tevatron

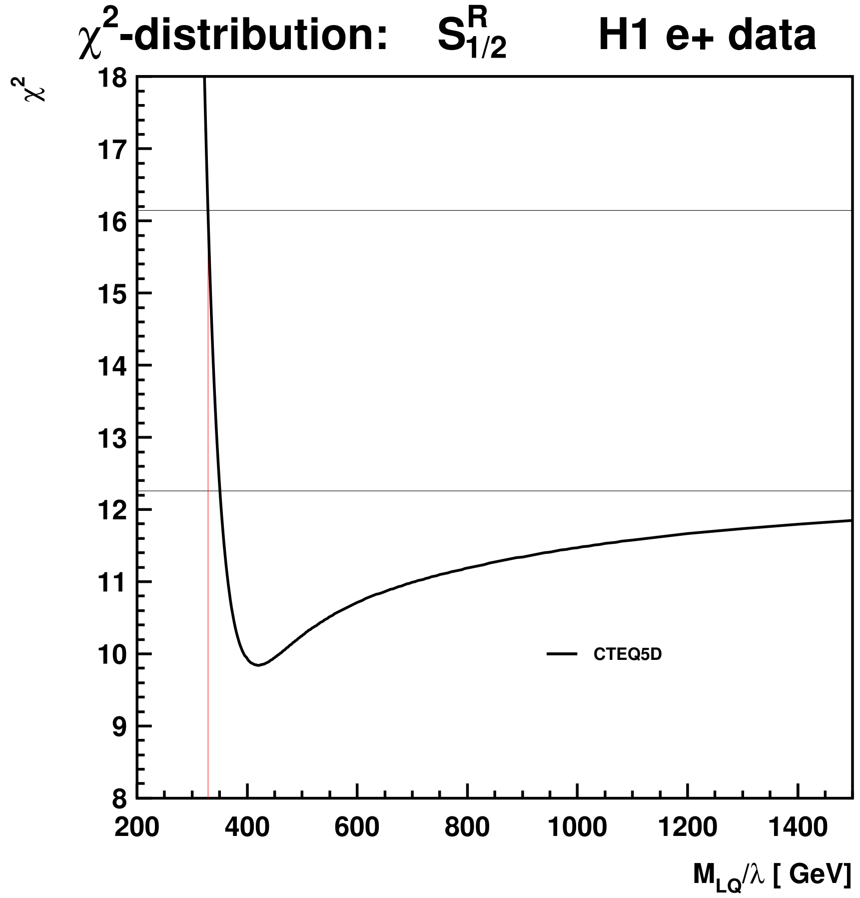
LEPTOQUARKS

- colour triplet bosons with $B \neq 0$, $L \neq 0$ predicted by certain extensions of SM
- $\eta^q_{ab} = \epsilon \left(\frac{g}{\Lambda}\right)^2 \quad \rightarrow \quad \eta^q_{ab} = \zeta^q_{ab} \left(\frac{\lambda}{M_{LQ}}\right)^2$
- Buchmüller-Rückl-Wyler framework:
  L,B conserving
  NO flavour changing neutral currents

leptoquark	coupling to u quarks	coupling to d quarks	$F = 3B + L$
S_0^L	$\zeta^u_{LL} = +\frac{1}{2}$		2
S_0^R	$\zeta^u_{RR} = +\frac{1}{2}$		2
$\tilde{S}_0^R$		$\zeta^d_{RR} = +\frac{1}{2}$	2
$S_{1/2}^L$	$\zeta^u_{LR} = -\frac{1}{2}$		0
$S_{1/2}^R$	$\zeta^u_{RL} = -\frac{1}{2}$	$\zeta^d_{RL} = -\frac{1}{2}$	0
$\tilde{S}_{1/2}^L$		$\zeta^d_{LR} = -\frac{1}{2}$	0
S_1^L	$\zeta^u_{LL} = +\frac{1}{2}$	$\zeta^d_{LL} = +1$	2
V_0^L		$\zeta^d_{LL} = -1$	0
V_0^R		$\zeta^d_{RR} = -1$	0
$\tilde{V}_0^R$	$\zeta^u_{RR} = -1$		0
$V_{1/2}^L$		$\zeta^d_{LR} = +1$	2
$V_{1/2}^R$	$\zeta^u_{RL} = +1$	$\zeta^d_{RL} = +1$	2
$\tilde{V}_{1/2}^L$	$\zeta^u_{LR} = +1$		2
V_1^L	$\zeta^u_{LL} = -2$	$\zeta^d_{LL} = -1$	0

LEPTOQUARKS





Minimum in χ^2-distribution at 400 GeV
(well below 2σ)

all other LQ types show less deviations from SM

LEPTOQUARK LIMITS

LQ	$M/\lambda[\,\mathrm{GeV}]$		$M/\lambda[\,\mathrm{GeV}]$		
	H1 e^+p	H1 preliminary e^+p & e^-p	ALEPH	L3	OPAL
S_0^L	620	870	1020	1210	640
S_0^R	570	780	300	610	-
$\tilde{S}_0^R$	220	270	430	570	590
$S_{1/2}^L$	340	370	390	540	460
$S_{1/2}^R$	320	330	390	630	630
$\tilde{S}_{1/2}^L$	450	460	-	490	370
S_1^L	420	610	1200	850	930
V_0^L	670	820	1380	1760	?
V_0^R	550	660	460	500	450
$\tilde{V}_0^R$	410	550	1150	1040	1100
$V_{1/2}^L$	380	400	460	740	660
$V_{1/2}^R$	960	1000	820	740	600
$\tilde{V}_{1/2}^L$	1060	1100	360	600	550
V_1^L	450	720	1950	1430	1530

limits M/λ only valid for $M \gg \sqrt{s}$

e^- data improves some scenarios

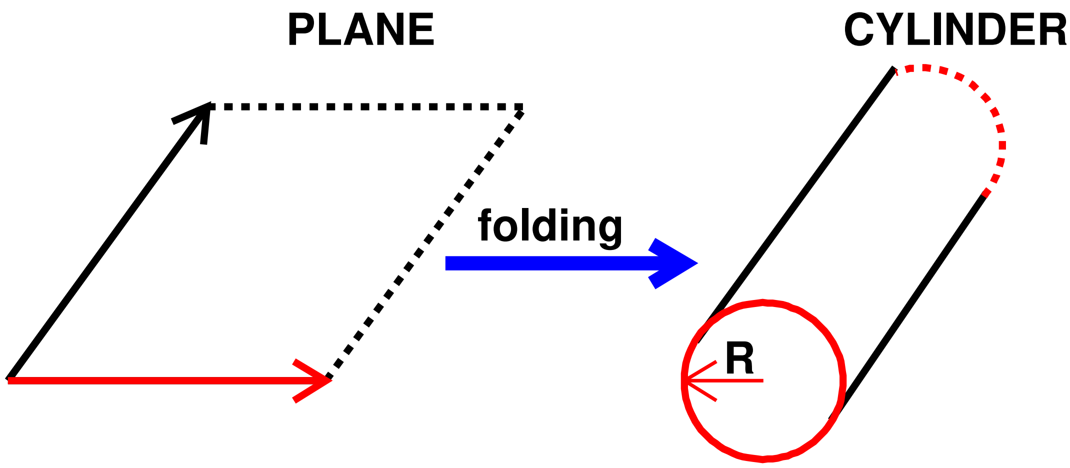
LEP limits in many cases more stringent

EXTRA DIMENSIONS AND GRAVITY

- string theory implies the existence of 7 extra spatial dimensions

  (concept of additional dimensions first used by Kaluza & Klein 1920)

- extra dimensions must be small/compactified due to (up to now) NON-observation



- periodic spatial dimensions related to quantized momentum in that dimension: $p = \frac{k}{R}$ k=0,1,2,...

  $\Longrightarrow$ graviton in 4+n dimensions projected to spectrum of massive states (Kaluza Klein states) in 4 dimensions: $m^2 = k^2/R^2$ (KK tower)

- <u>conventional string theory:</u>

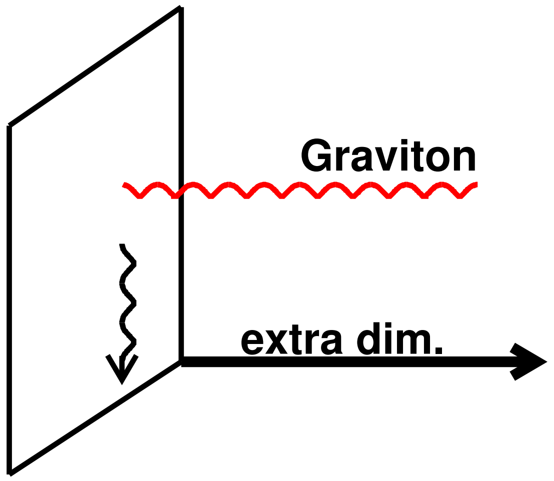
  $M_s < M_{Pl} \sim 10^{19}\,\mathrm{GeV}$ implies $R < 1/M_{Pl} \sim 10^{-32}$cm

  NO oberservation possible

LOW SCALE QUANTUM GRAVITY

exciting proposal by Arkani-Hamed, Dimopoulos, Dvali:

- n LARGE extra dimensions compactified down to size R
  M_s=O(1 TeV), $R \sim 1/M_s$
- SM fields/particles are confined to known four-dimensional world (3-brane)
- gravitation propagates into the 'bulk', i.e. 4+n dimensions



Gauss's Law: modification of gravitational potential

$$V(r) \quad \sim \quad \frac{m_1 \cdot m_2}{M_{Pl(4+n)}^{2+n}} \cdot \frac{1}{r^{n+1}} \qquad r \ll R$$

$$V(r) \quad \sim \quad \frac{m_1 \cdot m_2}{M_{Pl(4+n)}^{2+n}} \cdot \frac{1}{R^n} \cdot \frac{1}{r} \qquad r \gg R$$

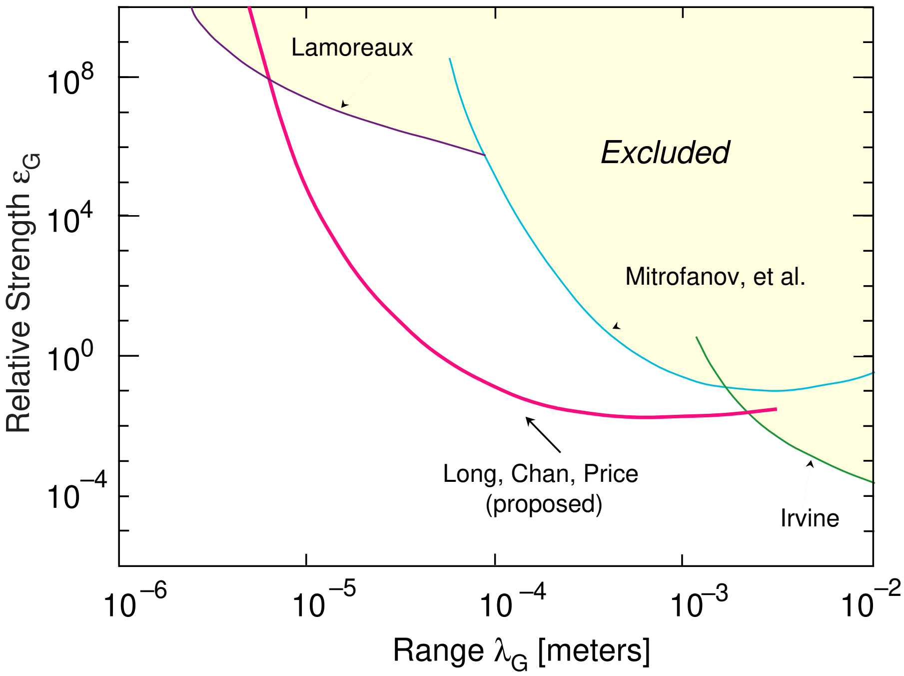
2 fundamental scales
R,$M_{pl(4+n)}$, but not M_{Pl}

$$\Rightarrow M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{2+n}$$

POSSIBLE SIZE OF EXTRA DIMENSIONS

$M_{pl(4+n)} \rightarrow$ O(1 TeV): $\boxed{R \sim 10^{\frac{30}{n}-17} \text{ m}}$

n	R	
1	10^8 km	excluded: no deviations from gravitational law in solar system
2	~ 1 mm	experiment in sub-mm range in prep. but excluded: cosmological bound from supernovae
3 . .	~ 0.1 nm . .	**No contradiction to any experiment** . .
6	$\sim$ fm	**No contradiction to any experiment**



$$V(r) = -G\frac{m_1 m_2}{r_{12}} \cdot \left[1 + \alpha e^{-r_{12}/\lambda}\right]$$

EFFECTIVE THEORY

1) coupling of KK states to all SM particles on strongly suppressed by Planck Mass M_{pl}:

$$\mathcal{L}_G = -\frac{\sqrt{8\pi}}{M_{Pl}} G^{(j)}_{\mu\nu} T^{\mu\nu}$$

graviton fields $G^{(j)}_{\mu\nu}$ couple via the energy-momentum tensor $T_{\mu\nu}$

2) large R $\rightarrow$ high density of massive KK states (KK towers)

1) & 2) $\rightarrow$ Sum over all KK states only suppressed by $M_{Pl(4+n)}$

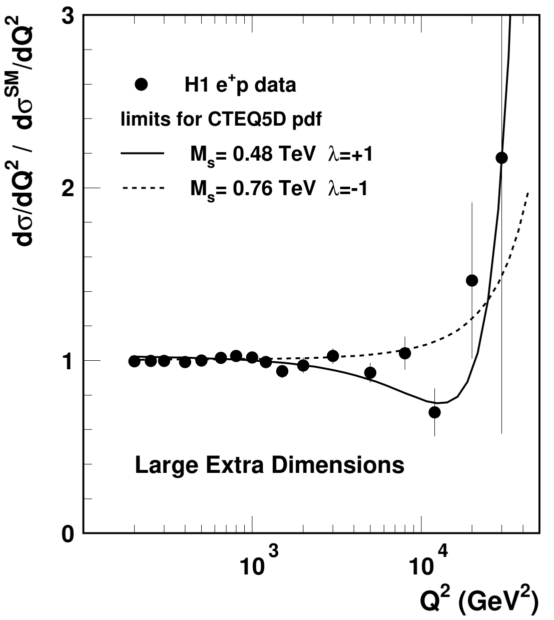
effective coupling: $\eta_G = \frac{\lambda}{M_s^4}$ $\qquad M_s \equiv M_{Pl(4+n)}$

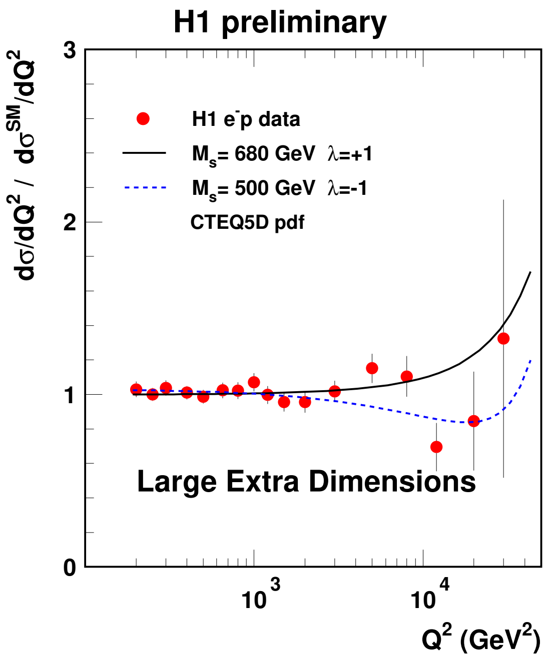
λ coupling strength/Interference sign

$\Longrightarrow$ gravitation could be visible at TeV scale (!?)
sizeable cross section:

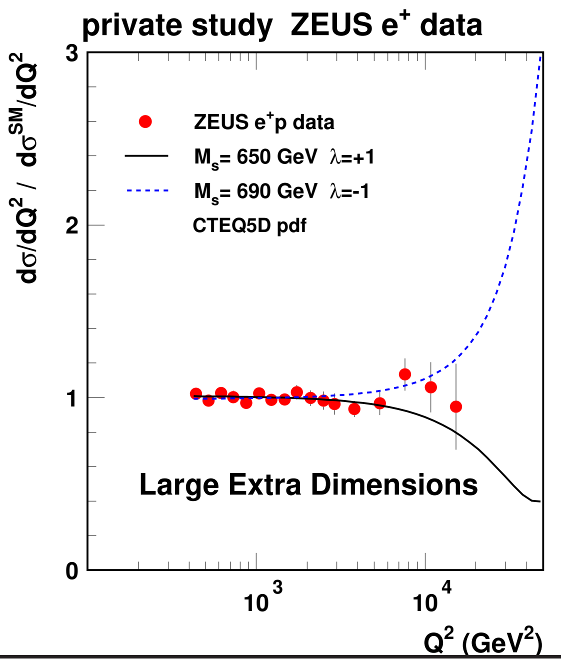
$$\begin{aligned}
\frac{d\sigma(e^+q \rightarrow e^+q)}{dt} &= \frac{d\sigma^{SM}}{dt} + \frac{d\sigma^{G}}{dt} + \frac{d\sigma^{\gamma G}}{dt} + \frac{d\sigma^{ZG}}{dt} \\
\frac{d\sigma^{G}}{dt} &\sim \lambda^2/M_s^8 \\
\frac{d\sigma^{\gamma G}}{dt}, \frac{d\sigma^{ZG}}{dt} &\sim \lambda/M_s^4 \\
\frac{d\sigma(e^+g \rightarrow e^+g)}{dt} &\sim \lambda^2/M_S^8
\end{aligned}$$

LIMITS ON LARGE EXTRA DIMENSIONS





data set	M_s [GeV] $\lambda = +1$	M_s [GeV] $\lambda = -1$
H1 e^+p	480	720
H1 preliminary e^-p	680	480
H1 preliminary e^+p & e^-p	**670**	**730**
private fit to ZEUS e^+ data	650	690
private fit to HERA	720	750



HERA limits well competetive to LEP:

500 GeV - 1000 GeV depending on process (Bhabba,...) and $\lambda = \pm 1$

CONCLUSIONS AND OUTLOOK

- no evidence for Contact Interactions in $\approx 2 \cdot 40\mathrm{pb}^{-1}$ of e^+p data and in $\approx 15\mathrm{pb}^{-1}$ of e^-p data

- competetive HERA limits for compositeness, leptoquarks and large extra dimension have been presented

- some leptoquark limits best constrained by HERA

- after lumi upgrade (summer 2001):
  $170\mathrm{pb}^{-1}/\mathrm{year}$ and $1\mathrm{fb}^{-1}$ until 2005 expected

....interesting new data will come....