Searches for Contact Interactions, Leptoquarks and Large Extra Dimensions at HERA

DIS 2003
XI International Workshop on Deep Inelastic Scattering
St. Petersburg, 23-27 April 2003

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for the H1 collaboration

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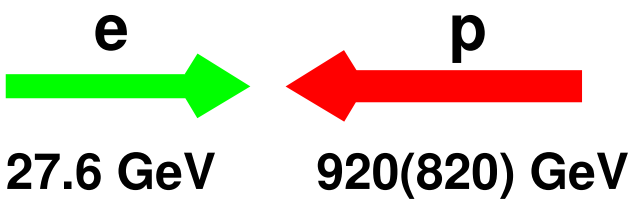
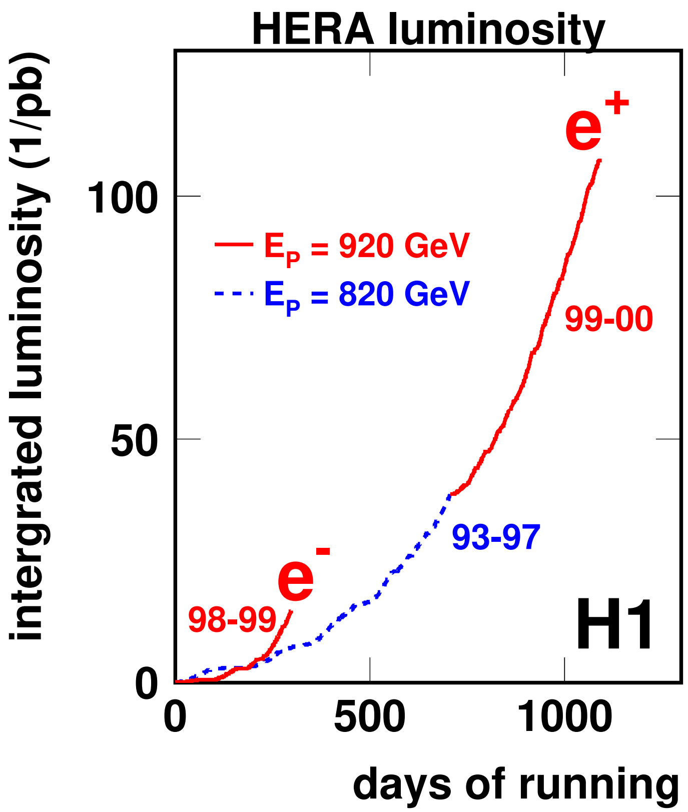
- Introduction
- NC Cross Sections
- Contact Interaction Formalism
- Leptoquarks (direct/indirect searches)
- Large Extra Dimensions
- Summary

Introduction

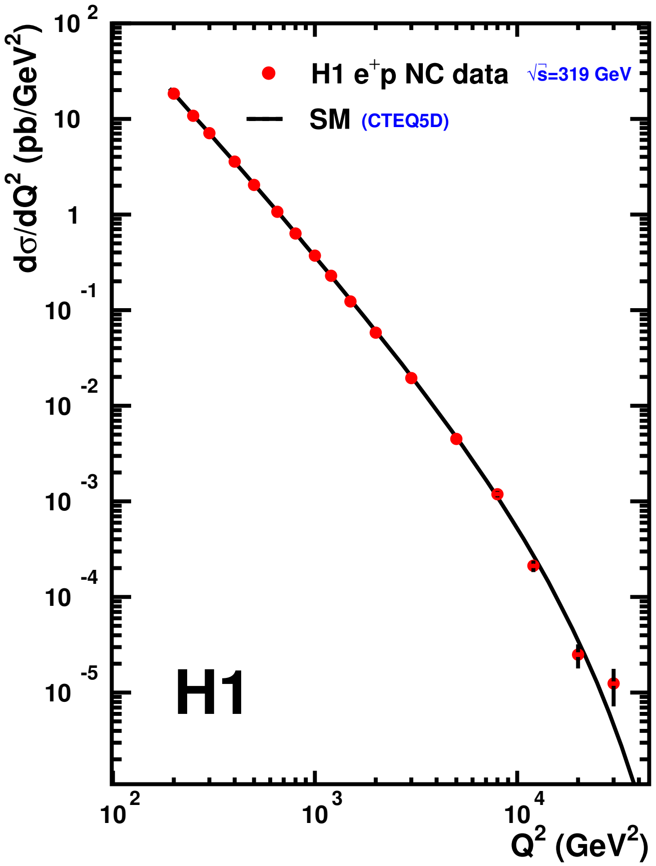


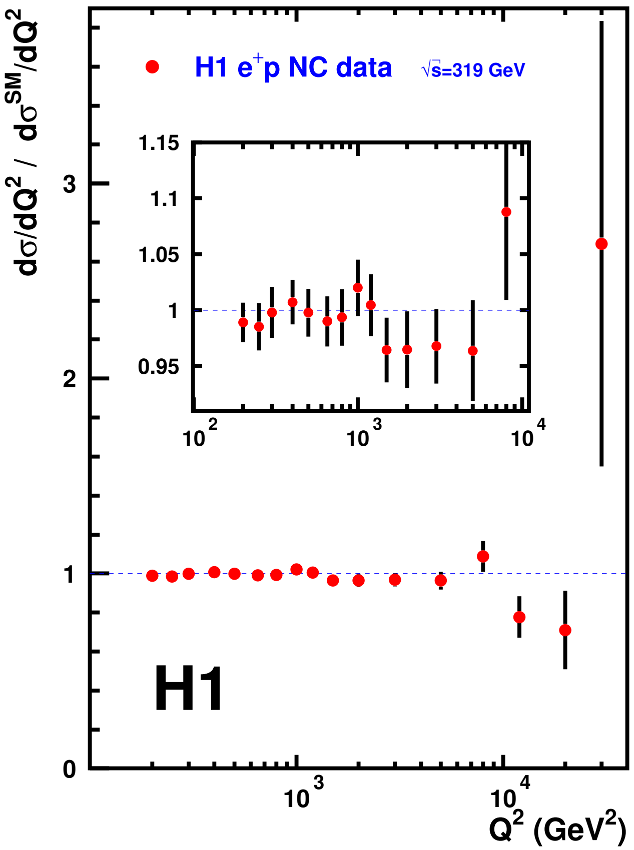


- HERA is unique in probing electron-quark interactions at high energies
  $\Rightarrow$ Ideal to look for **new particles** coupling to eq pairs
- Searches on various Scenarios like LQ, SUSY, q^*/e^*, CI, etc. have been applied
- In total $\mathbf{117.2\ pb^{-1}}$ of data in HERA I for following analysis splitted up into **3 data sets**

reaction	$\mathcal{L}_{int}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	run period
$e^+p \longrightarrow e^+X$	$\mathbf{35.6 \pm 0.5}$	301	1994 – 1997
$e^-p \longrightarrow e^-X$	$\mathbf{16.4 \pm 0.3}$	319	1998 – 1999
$e^+p \longrightarrow e^+X$	$\mathbf{65.2 \pm 1.0}$	319	1999 – 2000

Neutral Current Cross Sections (e^+p)





SM prediction:

NLO calculation with CTEQ5D pdf

$$\mathcal{L}_{\rm int} = \mathbf{65.2}\,\mathrm{pb}^{-1}$$

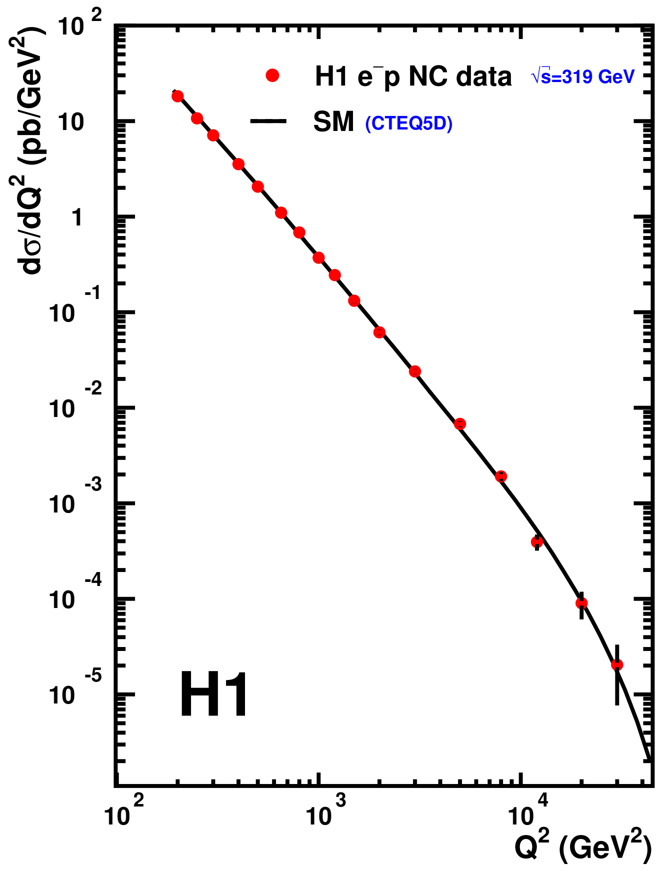
$$\boldsymbol{\chi^2/dof = 13.9/17}$$
$$\boldsymbol{f_n = 1.006}$$

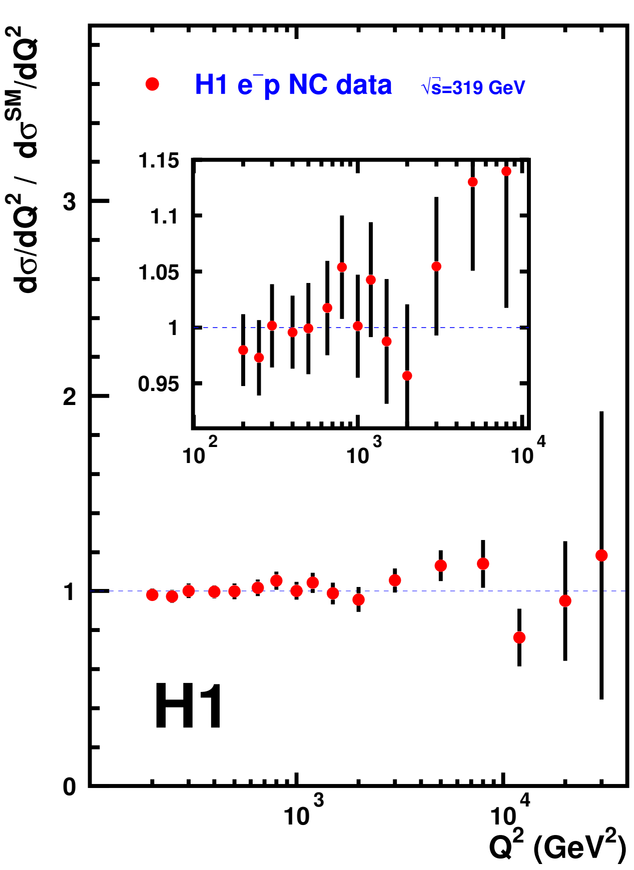
dominant correlations taken into account with functions $\Delta_{ik}(\varepsilon_k)$:

– normalisation
– electron energy & angle
– pdf uncertainty due to α_s

$$\chi^2 = \sum_i \left(\frac{\hat{\sigma}_i^{\rm exp} - \hat{\sigma}_i^{\rm th}(1 - \sum_k \Delta_{ik}(\varepsilon_k))}{\Delta\hat{\sigma}_i} \right)^2 + \sum_k \varepsilon_k^2$$

Neutral Current Cross Sections $(e^{-}p)$





SM prediction:

NLO calculation with CTEQ5D pdf

$$\mathcal{L}_{\rm int} = \mathbf{16.4}\,\mathrm{pb}^{-1}$$

$$\boldsymbol{\chi^2/dof = 10.4/17}$$
$$\boldsymbol{f_n = 0.998}$$

No significant deviations from SM prediction seen in $e^{+}p$ and $e^{-}p$ data

$\rightarrow$ Limits in terms of Quark Radius, CI, ...

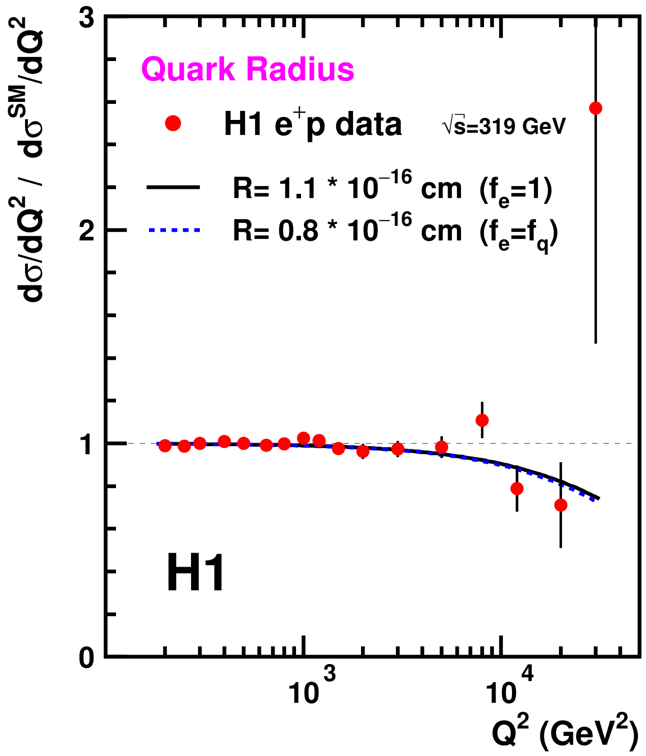
Quark Radius

- simplest model on physics beyond standard model: **Quark Radius**
- introduce **classical form factors** for non point-like quark and/or electron:

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

- would lead to reduced cross sections:

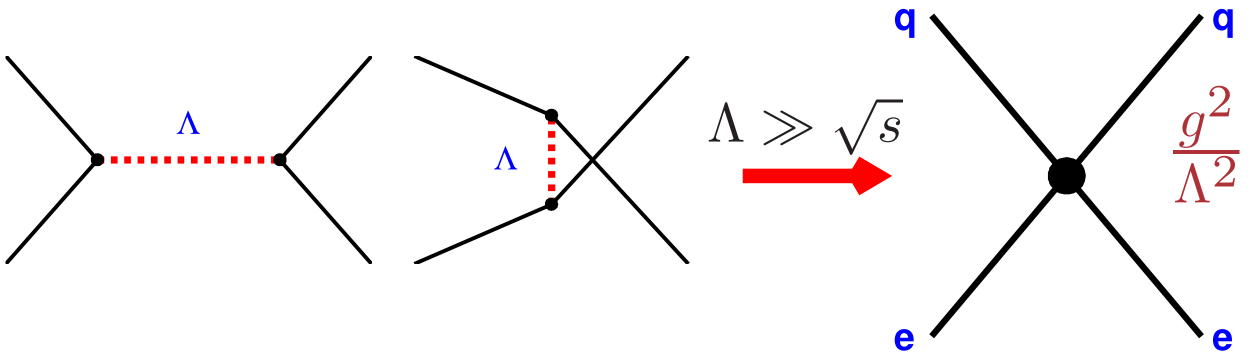
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\mathrm{SM}}}{dQ^2} f_q^2(Q^2) f_e^2(Q^2)$$



form factor	e^-p (319 GeV) R [10^{-18} m]	e^+p (319 GeV) R [10^{-18} m]	all e^+p & e^-p R [10^{-18} m]
$f_e \equiv 1$	1.1	1.1	**1.0**
$f_e = f_q$	0.8	0.8	**0.7**

Contact Interactions

- Contact Interaction formalism allows for **indirect searches** of physics beyond SM
- At large scales $\Lambda \gg \sqrt{s}$:
  New physics possibly observable as deviations from SM prediction due to
  virtual exchange of new particles $\longrightarrow$ e.g. distorsion of Q^2-spectrum at high Q^2
- Parametrisation as effective low energy approximation



propagators contract
to pointlike
four fermion CI *with*
effective coupling g^2/Λ^2

- Effective Lagrangian: (vector terms only)

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

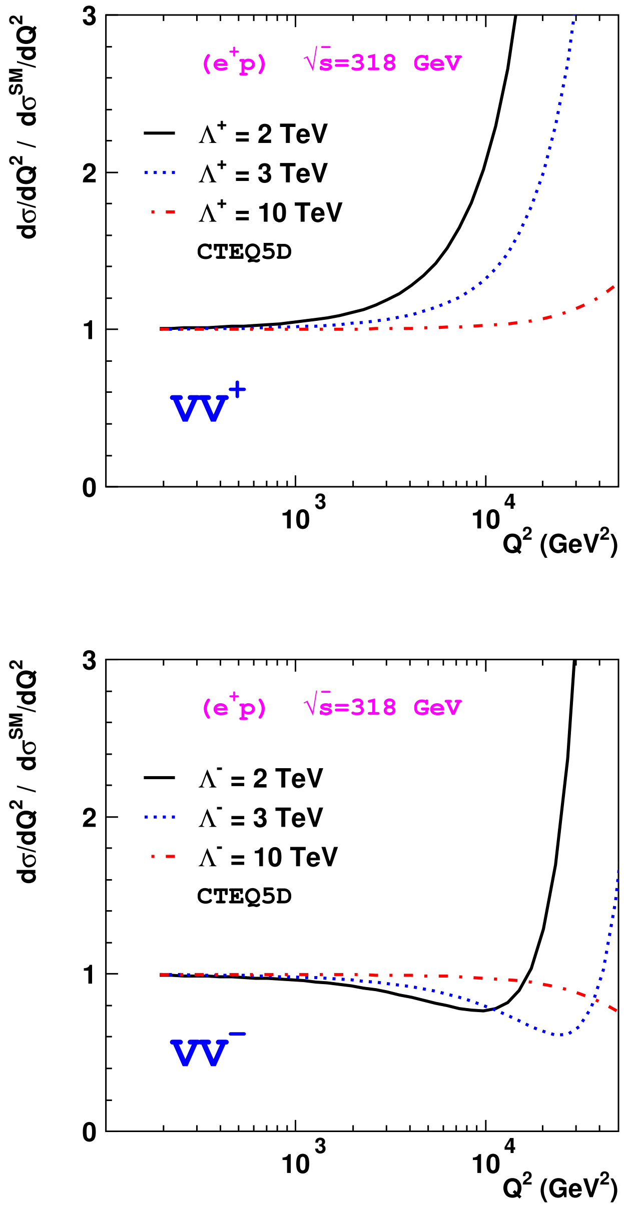
a, b=\{L,R\} denote the helicity states
8 couplings with interference sign $\pm$:
$\boldsymbol{\eta^q_{ab} \equiv \pm (g/\Lambda^q_{ab})^2}$

Compositeness Models

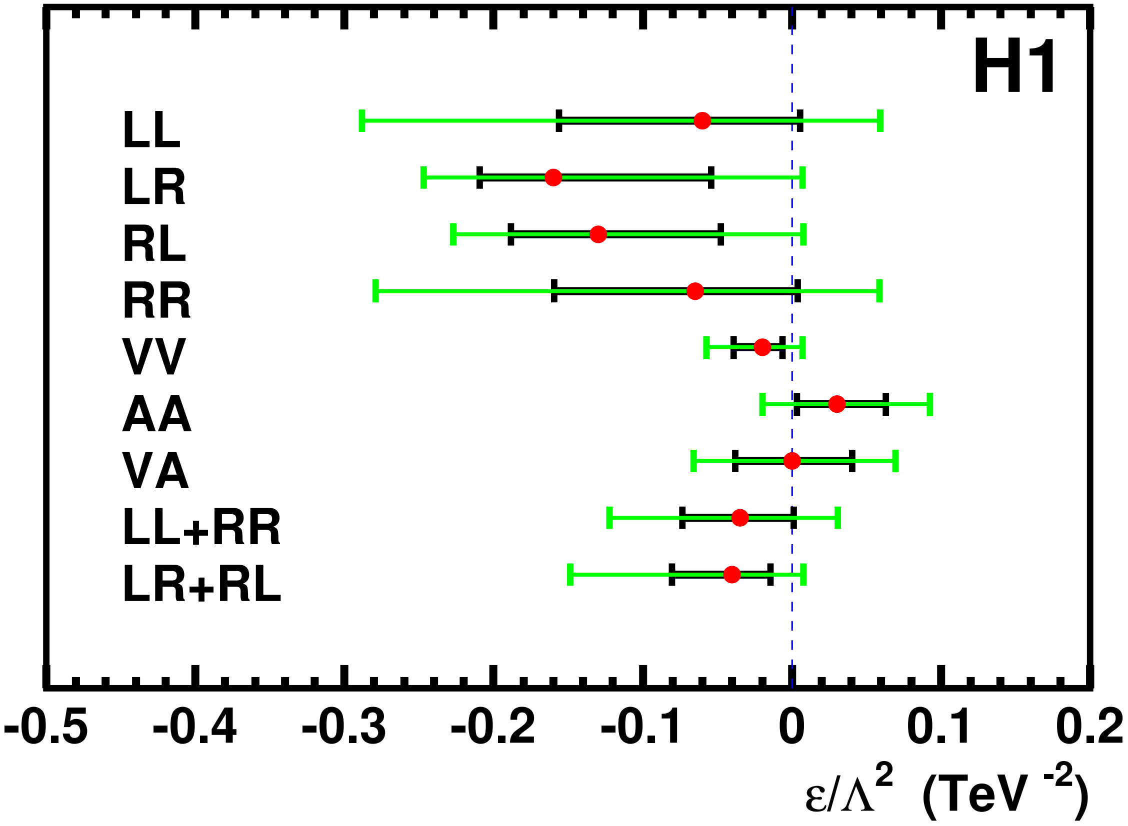
- assume quark flavour symmetry, i.e. (u=c, d=s=b)
- conventionally set $g^2 = 4\pi$
- consider models with fixed relative coupling strength, i.e. **only scale Λ as free parameter**: $\eta^q_{ab} = \epsilon^q_{ab} \cdot 4\pi/\Lambda^2$
- positive and negative interference possible ($\eta^q_{ab} \rightarrow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

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
LL+RR	+1	0	0	+1
LR+RL	0	+1	+1	0
LL	+1	0	0	0
LR	0	+1	0	0
RL	0	0	+1	0
RR	0	0	0	+1

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



Significance of Deviations for Compositeness Scenarios



Fit results of parameter ϵ/Λ^2 for **all data** combined using **experimental systematics**

Inner/outer errors bars represent one/two standard deviations

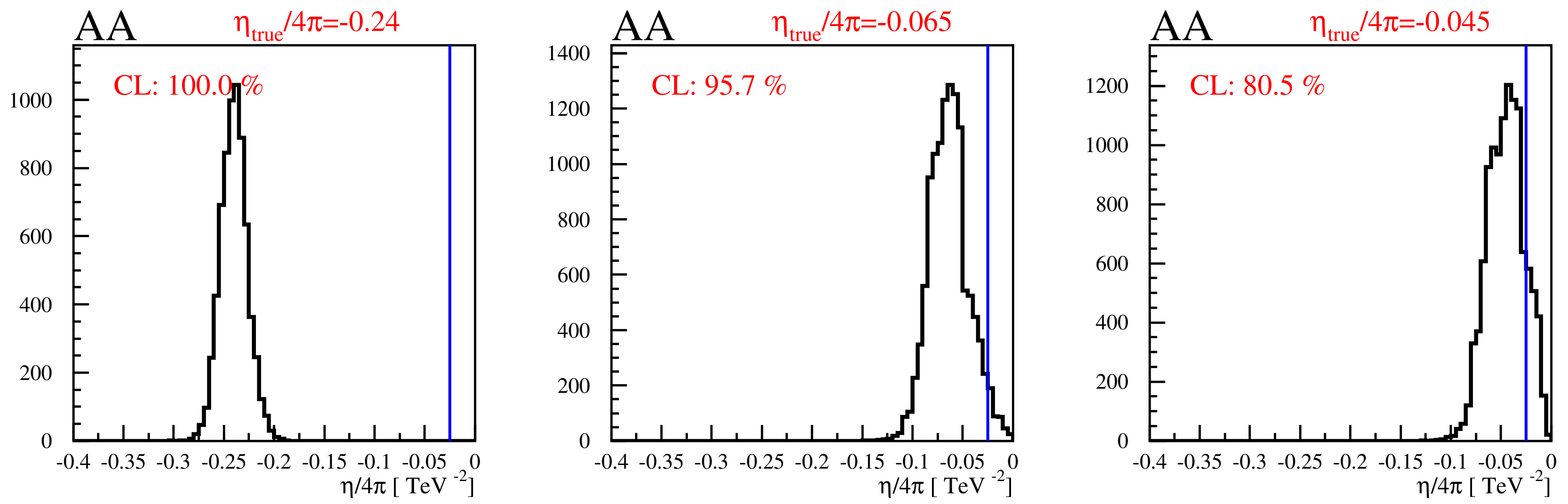
negative values for best fit (●) are prefered in most of the models

all models are consistent with SM better than the two standard deviation level

Limit Calculation with Monte Carlo Experiments

1. Generation of data samples (**M**onte **C**arlo **E**xperiments) for prediction with underlying parameter $\Lambda_{\rm true} \neq 0$ within systematics,
   i.e. predicted statistical errors for given Lumi $\oplus$ experim. systematics

2. For each MCE with underlying $\Lambda_{\rm true}$ determine $\Lambda_{\rm min}$ (Λ of best fit) from χ^2 fit
   $\longrightarrow$ fill histograms: **CL as function of $\Lambda_{\rm true}$**

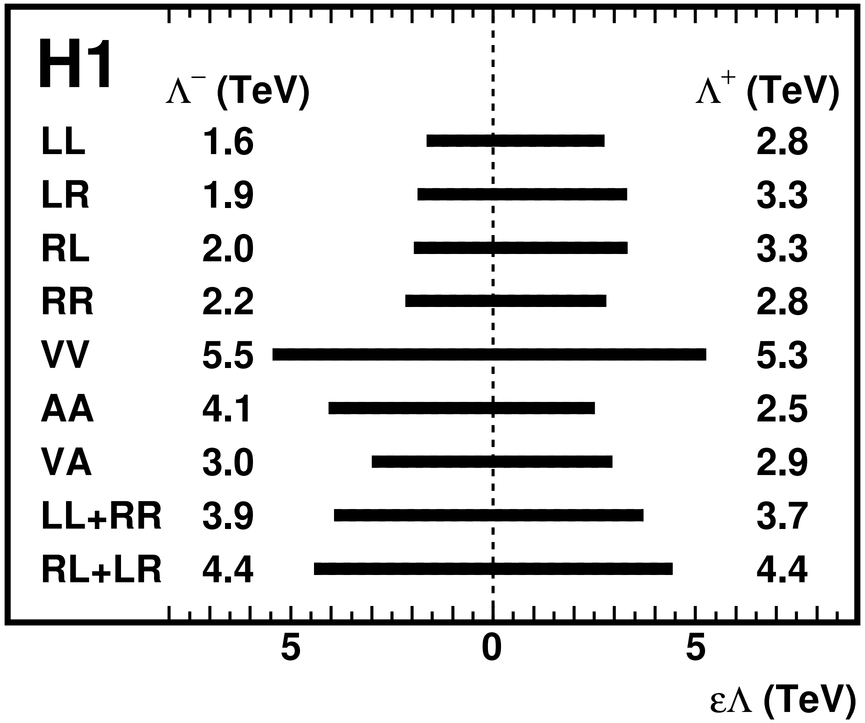


3. 95% CL Limit:
   $\Lambda_{95\%} \equiv \Lambda_{\rm true}$, where 95% of MCE produce values with $\Lambda_{\rm min} < \Lambda_{\rm DATA}$

95 % CL Limits of Compositeness Models

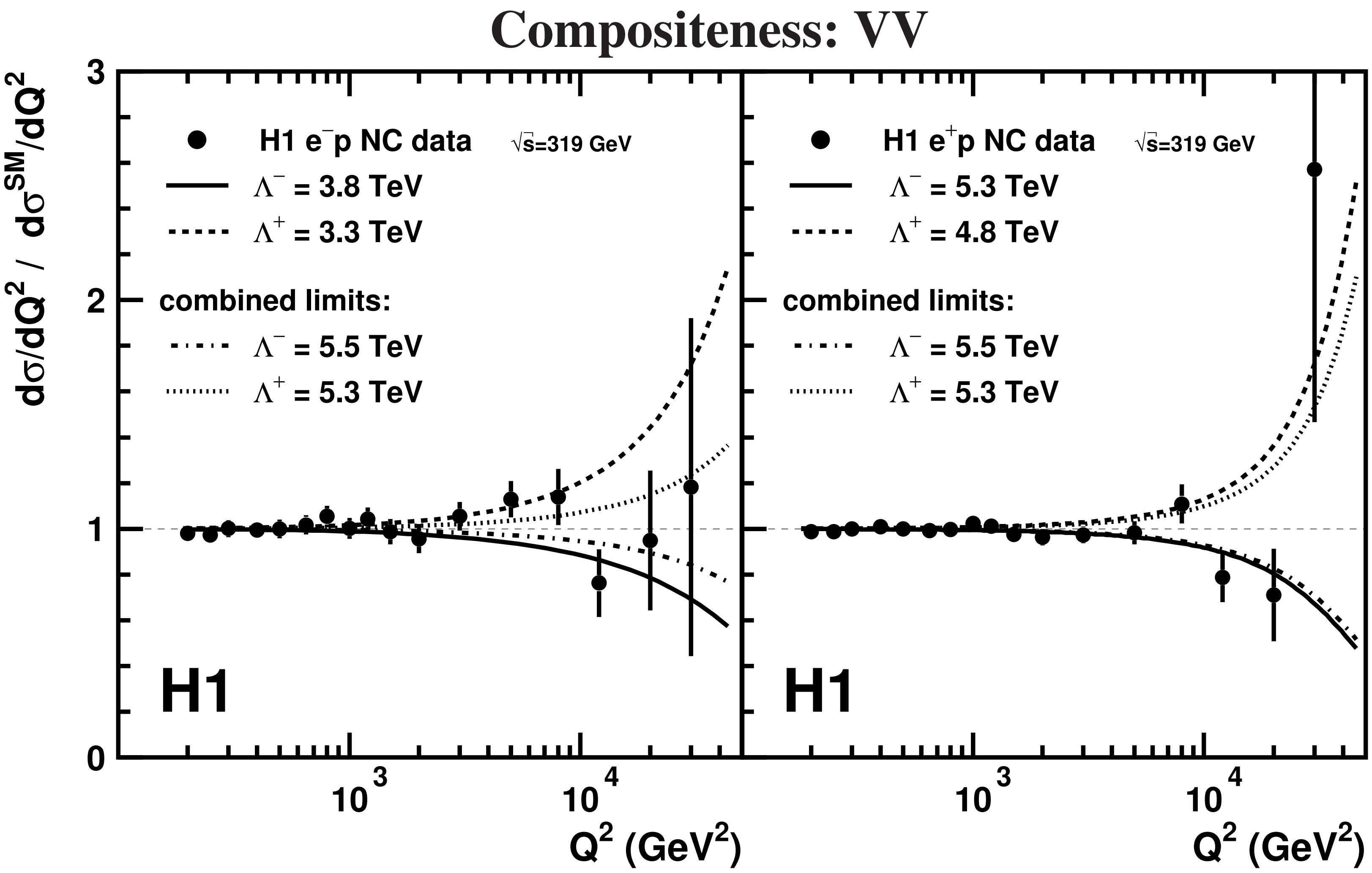
coupling	e^-p (319 GeV) Λ^+ [TeV]	e^-p (319 GeV) Λ^- [TeV]	e^+p (319 GeV) Λ^+ [TeV]	e^+p (319 GeV) Λ^- [TeV]
LL	2.4	1.3	2.3	1.3
RR	2.4	1.4	2.4	1.3
LR	1.4	1.2	3.1	1.8
RL	1.4	1.2	3.1	1.9
VV	3.3	3.8	4.8	5.3
AA	3.2	1.6	2.3	3.7
VA	2.4	2.3	2.8	2.9
$LL+RR$	3.1	**3.4**	3.1	**2.3**
$RL+LR$	1.8	1.4	4.2	4.0

combined data



- complementary results from e^+/e^- data (e.g. LL+RR, Λ^-
- best limits for VV model (all couplings contribute with same interference sign)
- mostly combined data ($\mathcal{L} \approx 117\text{pb}^{-1}$) give best constraints
- 95% CL limits for combined data range from **1.6 TeV - 5.5 TeV**

Illustration of the VV model



Leptoquarks

- colour triplet bosons with $B \neq 0$, $L \neq 0$ predicted by certain extensions of SM
- Buchmüller-Rückl-Wyler framework:
  - $SU(3) \times SU(2) \times U(1)$ invariance
  - LQs only couple to chiral SM fermions
  - 14 species, **7 scalars and 7 vectors**, distinguished via $F{=}3B + L$
  - BR fixed: $\beta_{eq} = 1, \frac{1}{2}$, $\beta_{\nu q} = 0, \frac{1}{2}$
- $\eta^q_{ab} = \epsilon \left(\frac{g}{\Lambda}\right)^2 \quad \longrightarrow \quad \eta^q_{ab} = \zeta^q_{ab} \left(\frac{\lambda}{M_{LQ}}\right)^2$ Indirect search via CI

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

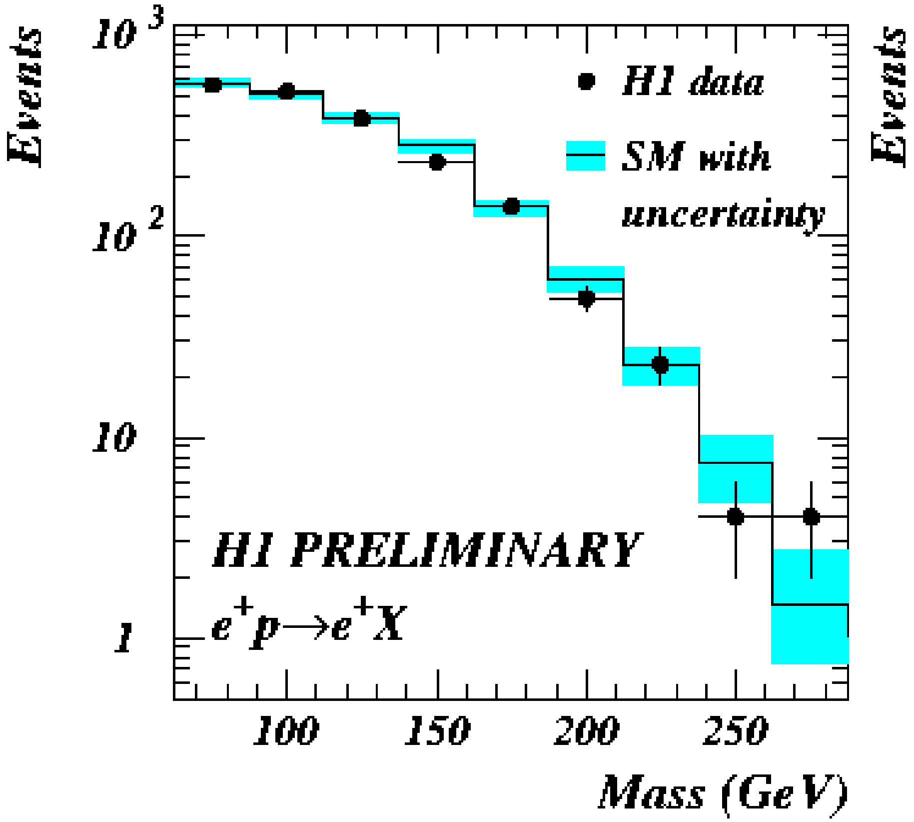
Leptoquarks – 95% CL Limits

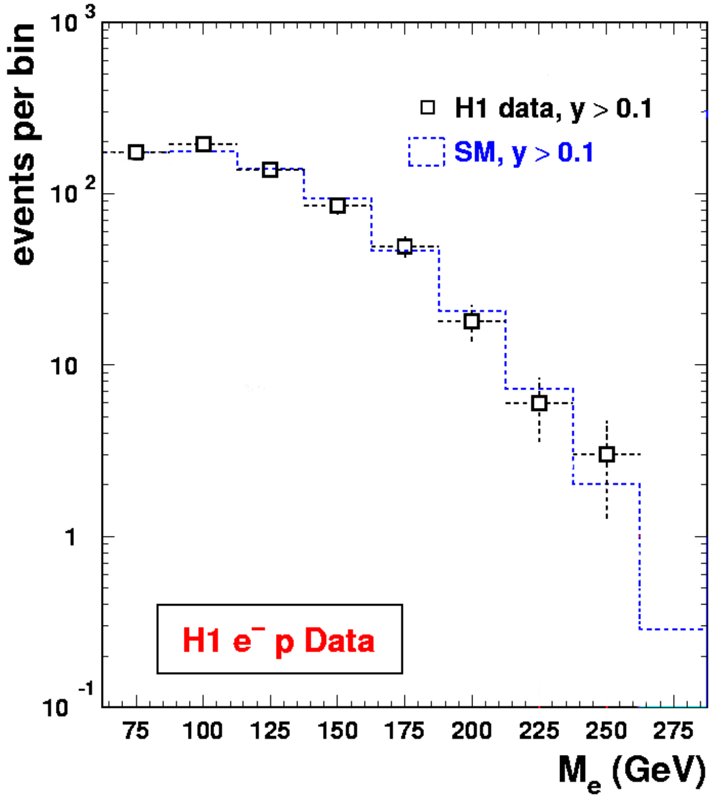
LQ	e^-p (319 GeV) M_{LQ}/λ [GeV]	e^+p (319 GeV) M_{LQ}/λ[GeV]	all e^+p & e^-p M_{LQ}/λ[GeV]
S_0^L	530	610	**710**
S_0^R	480	560	**640**
$\tilde{S}_0^R$	220	220	**330**
$S_{1/2}^L$	290	760	**850**
$S_{1/2}^R$	220	370	**370**
$\tilde{S}_{1/2}^L$	200	410	**430**
S_1^L	**510**	**410**	**490**
V_0^L	480	660	**730**
V_0^R	420	550	**580**
$\tilde{V}_0^R$	**810**	**750**	**990**
$V_{1/2}^L$	280	410	**420**
$V_{1/2}^R$	390	890	**950**
$\tilde{V}_{1/2}^L$	400	970	**1020**
V_1^L	**1150**	**960**	**1360**

- 95% CL limits are only valid for $M_{\mathrm{LQ}} \gg \sqrt{s}$
- complementary information from e^+/e^- data
- best 95% CL limits are mostly given for the combination of all data;

  limits range from **330-1360 GeV**

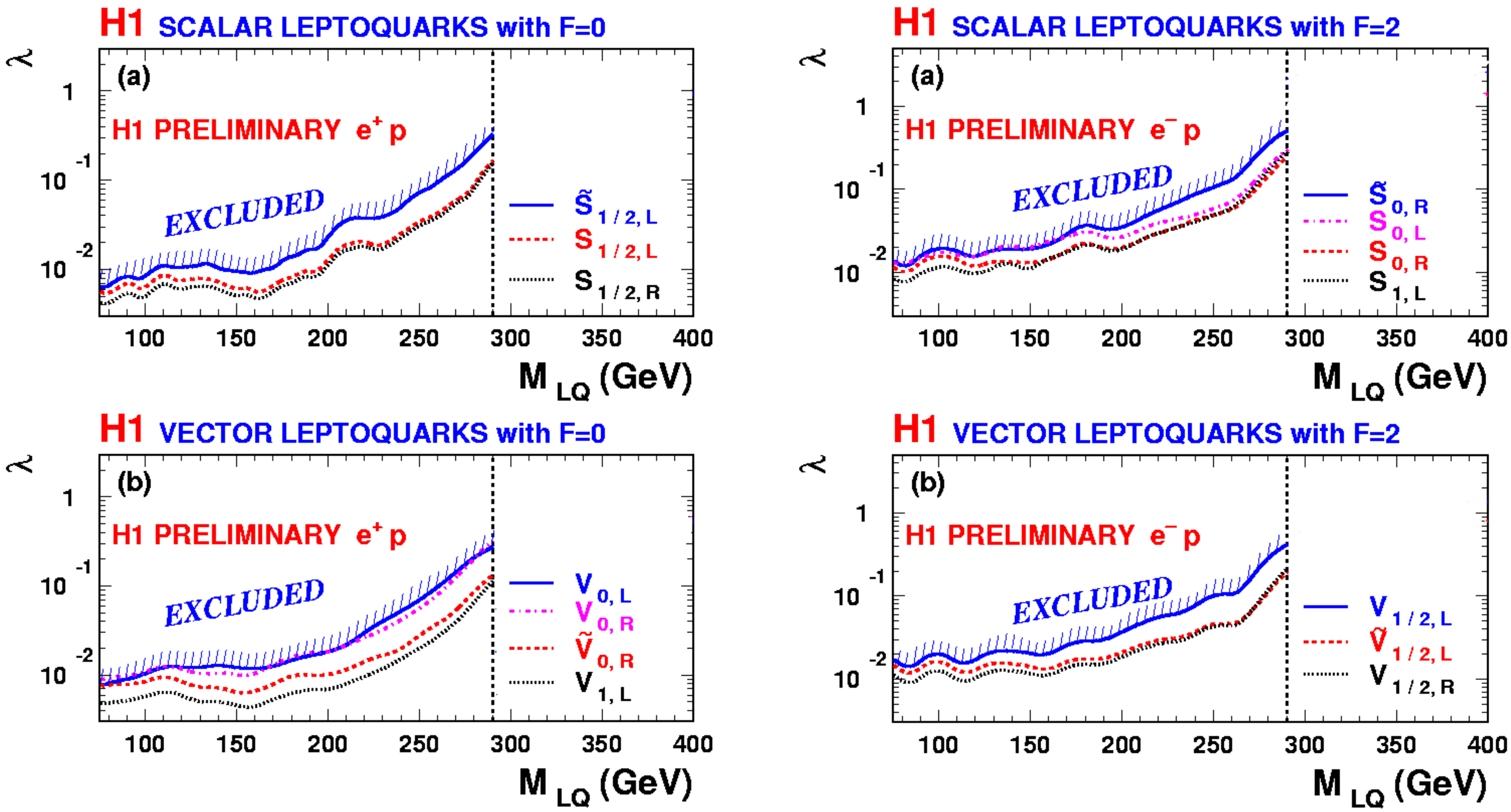
Leptoquarks – Direct Search for Resonances





- direct search of resonant production of LQ in mass spectrum
- no significant deviations from SM found in the mass distributions of e^+p and e^-p data
- $\Longrightarrow$ Direct Limits on LQs for example on couplings λ

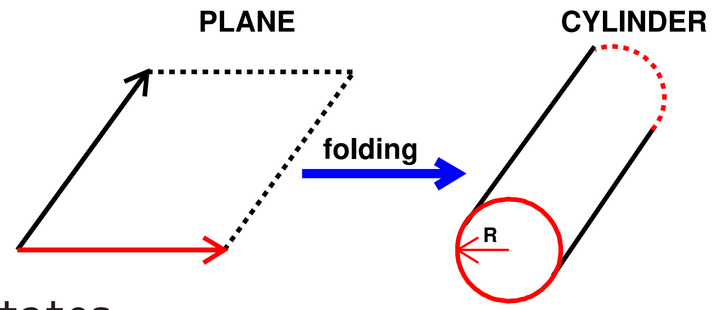
Leptoquarks – 95% CL Limits on Couplings λ



- $e^- p$ data specifically sensitive to LQs with $F = 2$
- direct/indirect searches supplement each other
- for couplings $\lambda = \sqrt{4\pi\alpha_{\rm em}} \approx 0.3$: $M_{\rm LQ} < 280$ GeV excluded on 95% CL

Large Extra Dimensions

- Space time with (4+n) dimensions (Arkani-Hamed et al.):
  - SM particles are confined in 4D world
  - Gravitions propagate also in n extra dimensions which are compactified to radius R



  - in 4 dimensions described as massive Kaluza Klein states with level spacing $\Delta m = \frac{1}{R}$

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

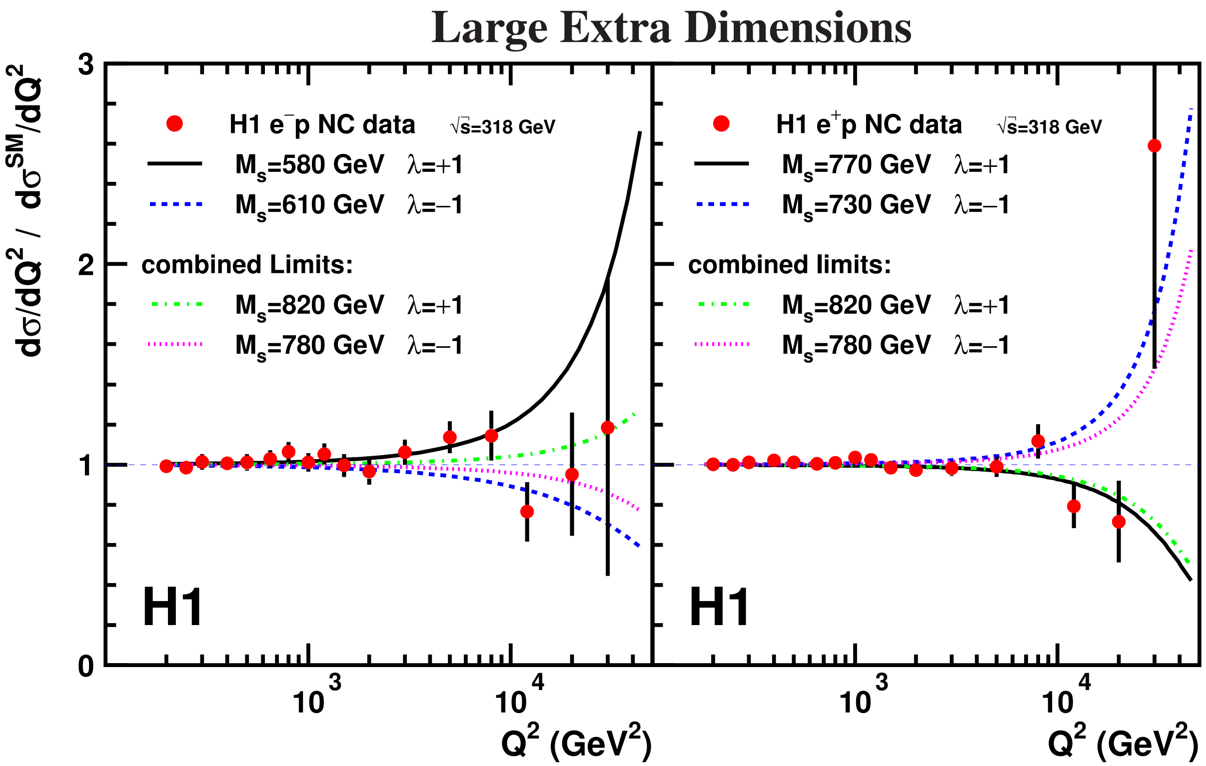
graviton states $G^{(j)}_{\mu\nu}$ couple via the energy-momentum tensor $T_{\mu\nu}$

  - R could be large (!): $R \sim 1/M_s$ with $M_s \sim \mathcal{O}(1\,TeV)$ $\Longrightarrow$ high density of KK states

- Summation over all KK states leads to an effective CI with dependence $\eta_s = \lambda/M_s^4$ and M_s as cut-off scale

- Limits are derived on scale M_s for $\lambda = \pm 1$

Large Extra Dimensions



- complementary information for e^+p and e^-p data
- strongest limits (95% CL) from combination of all data
- values $M_s < 0.8$ TeV are excluded

coupling	e^-p (319 GeV) M_S [TeV]	e^+p (319 GeV) M_S [TeV]	all e^+p & e^-p M_S [TeV]
$\lambda = +1$	0.58	0.77	**0.82**
$\lambda = -1$	0.61	0.73	**0.78**

Summary

- **final CI analysis** including all HERA I data corresponding to $\mathcal{L}_{\text{int}} \approx 115\,\text{pb}^{-1}$ has been presented

- **no evidence** for new physics has been found in the various scenarios

- 95% CL Limits have been derived:
  - Compositeness: $\Lambda > 1.6 - 5.5$ TeV
  - Leptoquarks: $M_{\text{LQ}} > 330 - 1400$ GeV
  - Quark Radius: $R_q < 1.0 \cdot 10^{-18}$ m
  - Large Extra Dimensions: $M_s > 0.8$ TeV

- limits are well **competetive** compared to other experiments ($\rightarrow$ see following talks)

- after finishing the recent shutdown, data with **polarised beams** will be available
  $\longrightarrow$ especially interesting for chiral structures of CI scenarios