Leptoquarks and Contact Interactions from a Global Analysis

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Outline

- Introduction
- Models (CI, LQ)
- Global analysis
- Contact Interaction results
- Leptoquark results
- Summary

Analysis described in	• hep-ph/0003271	LQ
and	• hep-ph/9904334, Eur. Phys. J. C 11 (1999) 539	CI

DIS'2000, Liverpool

Introduction

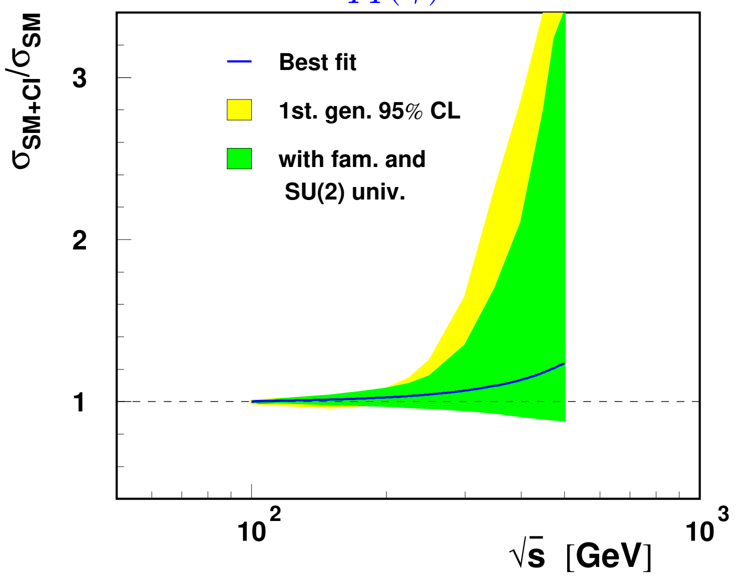
DIS'99, Zeuthen:

"Contact Interactions: Results from ZEUS and a Global Analysis "

Summary:

- Data from HERA, LEP, Tevatron and low energy experiments in good agreement with the Standard Model predictions.
- The mass scale limits obtained for different one-parameter models range from 5.1 TeV to about 18 TeV .
- Model independent limits on single CI couplings correspond to Λ limits from 2.1 to 7.8 TeV .
- Limits on possible effects to be observed in future HERA, LEP and Tevatron running are estimated.

$e^+e^- \to q\bar{q}(\gamma)$



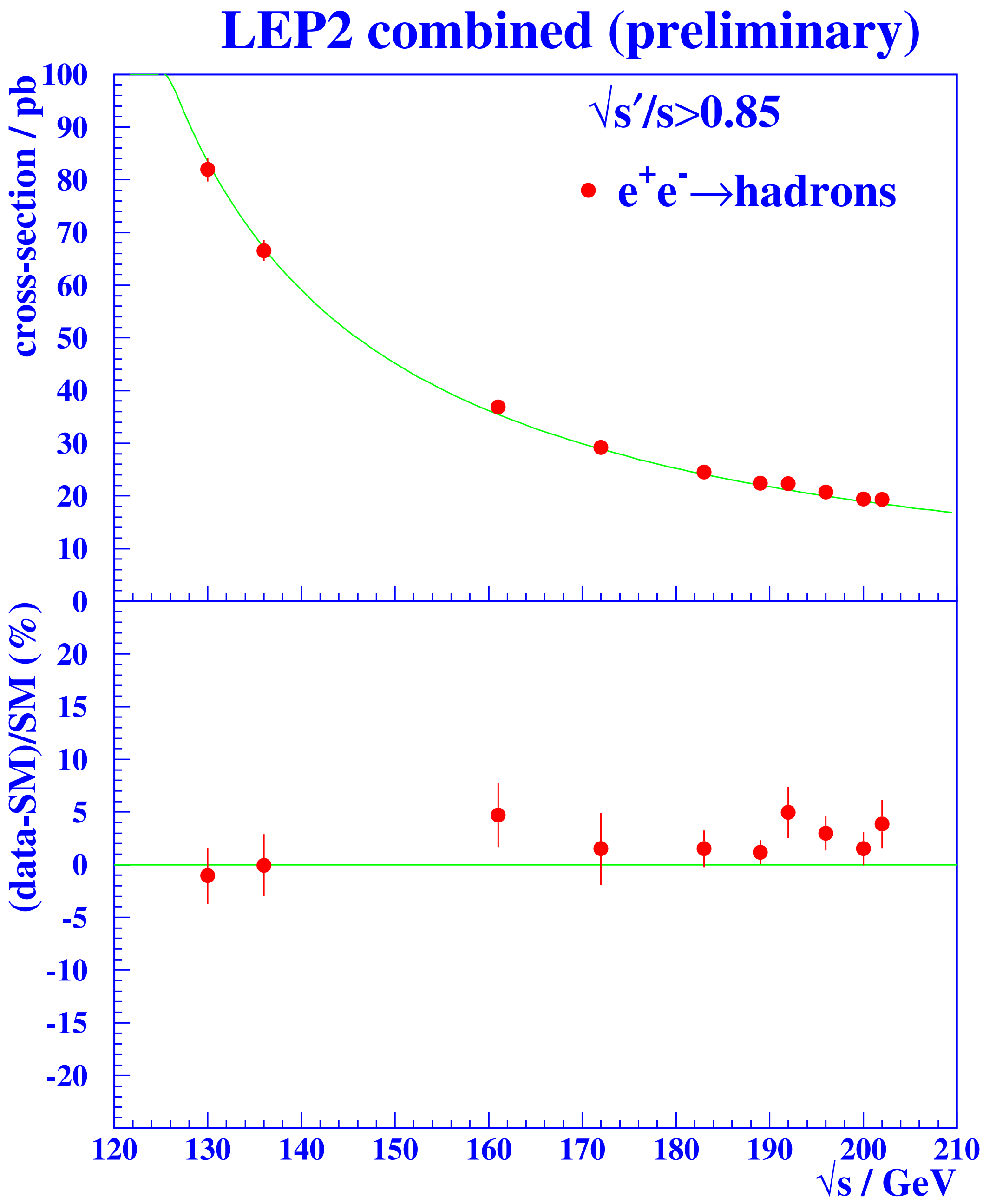
95% CL at $\sqrt{s} = 200$ GeV:

$$\frac{\Delta\sigma}{\sigma_{\rm SM}} < 8\%$$

Introduction

New results from LEP2

Hadronic cross-section measurements presented in Moriond



⇒ 2.3 σ deviation from the Standard Model

Introduction

New determination of APV in cesium

Parity non-conservation in cesium atoms caused by exchange of the Z° boson between atomic electrons and quarks in the nucleus.

New data and improved theoretical calculations:

$$\begin{aligned} \Delta Q_W^{Cs} \equiv Q_W^{meas} - Q_W^{SM} &= 1.13 \pm 0.46 \\ \text{previously :} \quad & 0.71 \pm 0.84 \end{aligned}$$

$\Rightarrow$ 2.5 σ deviation from the Standard Model

Unitarity of the CKM matrix

PDG: 1999 partial update for 2000 edition

$$\begin{aligned} |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 &= 0.9959 \pm 0.0019 \\ \text{previously :} \quad & 0.9969 \pm 0.0022 \end{aligned}$$

$\Rightarrow$ 2.2 σ deviation from the Standard Model

Introduction

Possible sign for "new physics" ???

The aim of this analysis

Use all available data to answer the following questions:

$\Rightarrow$ are new measurements consistent with each other ?

$\Rightarrow$ are they consistent with other high energy data ?

$\Rightarrow$ which model describes all the data best ?

$\Rightarrow$ what new effects can we expect ?

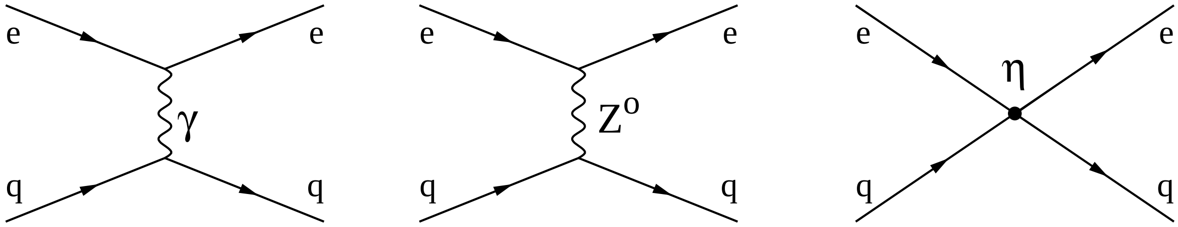
Models

Effective Lagrangian for vector $eeqq$ contact interactions:

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

Scalar and tensor terms are constrained beyond collider sensitivity

Neutral Current eq Scattering



$eq \rightarrow eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$ (at tree level):

$$M^{eq}_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{sin^2\theta_W \cdot cos^2\theta_W} \cdot \frac{g^e_\alpha g^q_\beta}{Q^2 + m_Z^2} + \eta^{eq}_{\alpha\beta}$$

$\eta^{eq}_{\alpha\beta}$ - 4 possible vector CI couplings for every flavor q

New couplings $\eta^{eq}_{\alpha\beta}$ are then related to the energy scale of "new physics" Λ by the formula:

$$\eta = \frac{\varepsilon \cdot g^2_{CI}}{\Lambda^2}$$

where g_{CI} is the coupling strength of new interactions and $\varepsilon = \pm 1$.

By convention we set $g^2_{CI} = 4\pi$.

Models

Contact interactions introduce 4 couplings for every lepton-quark pair.

$SU(2)_L \times U(1)_Y$ gauge invariance

of the model reduces number of free model parameters from 8 to 7:

$$\eta^{eu}_{RL} = \eta^{ed}_{RL}$$

Relates $eeqq$ and $\nu\nu qq$ couplings:

$$\begin{aligned} \eta^{\nu u}_{LL} &= \eta^{ed}_{LL} \\ \eta^{\nu d}_{LL} &= \eta^{eu}_{LL} \\ \eta^{\nu u}_{LR} &= \eta^{eu}_{LR} \\ \eta^{\nu d}_{LR} &= \eta^{ed}_{LR} \end{aligned}$$

Induces charged-current contact interaction $e\nu qq'$:

$$\eta^{CC} = \eta^{ed}_{LL} - \eta^{eu}_{LL}$$

Family Universality

We can impose lepton universality:

$$\eta^{eq}_{ij} = \eta^{\mu q}_{ij} = \eta^{\tau q}_{ij}$$

and quark family universality:

$$\begin{aligned} \eta^{eu}_{ij} &= \eta^{ec}_{ij} = \eta^{et}_{ij} \\ \eta^{ed}_{ij} &= \eta^{es}_{ij} = \eta^{eb}_{ij} \end{aligned}$$

Possible CI scenarios

⇒ General models : 7 u-e and d-e couplings can vary independently

⇒ One-parameter models : fixed coupling structure of new interactions

Models

One parameter models

Models violating 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}
d_{LL}	$+\eta$							
d_{LR}		$+\eta$						
d_{RL}			$+\eta$					
d_{RR}				$+\eta$				
u_{LL}					$+\eta$			
u_{LR}						$+\eta$		
u_{RL}							$+\eta$	
u_{RR}								$+\eta$
q_{LL}	$+\eta$				$+\eta$			
q_{LR}		$+\eta$				$+\eta$		
q_{RL}			$+\eta$				$+\eta$	
q_{RR}				$+\eta$				$+\eta$

d_{RL} and u_{RL} models violate $SU(2)_L \times U(1)_Y$

Parity conserving models

VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$

Models

Leptoquarks

Consider leptoquark states described by
the Buchmüller-Rückl-Wyler (BRW) effective model

BRW model

First-generation leptoquarks:

- respect $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry of the Standard Model
- only family diagonal couplings
  (to avoid FCNC processes)
- couplings conserve lepton and baryon numbers
  (to avoid rapid proton decay)
- couple either to left- or right-handed leptons
  (very strong bounds from rare decays)

$\Rightarrow$ 14 possible states
(7 scalar and 7 vector)

Additional (simplifying) assumptions:

- different states within isospin multiplets have the same mass
- only one of the leptoquark types contribute

Models

Aachen notation

Model	Fermion number F	Charge Q	$BR(LQ \to e^{\pm}q)$ β	Coupling		Squark type
$S_\circ^L$	2	$-1/3$	$1/2$	$e_L u$	νd	$\tilde{d}_R$
$S_\circ^R$	2	$-1/3$	1	$e_R u$		
$\tilde{S}_\circ$	2	$-4/3$	1	$e_R d$		
$S_{1/2}^L$	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	0		$\nu \bar{u}$	
$S_{1/2}^R$	0	$-5/3$	1	$e_R \bar{u}$		
		$-2/3$	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	$-2/3$	1	$e_L \bar{d}$		$\overline{\tilde{u}_L}$
		$+1/3$	0		$\nu \bar{d}$	$\overline{\tilde{d}_L}$
S_1	2	$-4/3$	1	$e_L d$		
		$-1/3$	$1/2$	$e_L u$	νd	
		$+2/3$	0		νd	
$V_\circ^L$	0	$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
$V_\circ^R$	0	$-2/3$	1	$e_R \bar{d}$		
$\tilde{V}_\circ$	0	$-5/3$	1	$e_R \bar{u}$		
$V_{1/2}^L$	2	$-4/3$	1	$e_L d$		
		$-1/3$	0		νd	
$V_{1/2}^R$	2	$-4/3$	1	$e_R d$		
		$-1/3$	1	$e_R u$		
$\tilde{V}_{1/2}$	2	$-1/3$	1	$e_L u$		
		$+2/3$	0		νu	
V_1	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
		$+1/3$	0		$\nu \bar{d}$	

Models

CI limit

In the limit $M_{LQ} \gg \sqrt{s}$ leptoquark production or exchange can be described by contact interactions:

$$\eta_{ij}^{eq} = a_{ij}^{eq} \cdot \left(\frac{\lambda_{LQ}}{M_{LQ}} \right)^2$$

M_{LQ} – leptoquark mass, λ_{LQ} – leptoquark-electron-quark Yukawa coupling

Model	a_{LL}^{ed}	a_{LR}^{ed}	a_{RL}^{ed}	a_{RR}^{ed}	a_{LL}^{eu}	a_{LR}^{eu}	a_{RL}^{eu}	a_{RR}^{eu}
$S_\circ^L$					$+\frac{1}{2}$			
$S_\circ^R$								$+\frac{1}{2}$
$\tilde{S}_\circ$				$+\frac{1}{2}$				
$S_{1/2}^L$						$-\frac{1}{2}$		
$S_{1/2}^R$			$-\frac{1}{2}$				$-\frac{1}{2}$	
$\tilde{S}_{1/2}$		$-\frac{1}{2}$						
S_1	$+1$				$+\frac{1}{2}$			
$V_\circ^L$	-1							
$V_\circ^R$				-1				
$\tilde{V}_\circ$								-1
$V_{1/2}^L$		$+1$						
$V_{1/2}^R$			$+1$				$+1$	
$\tilde{V}_{1/2}$						$+1$		
V_1	-1				-2			

Models

Mass effects

For $M_{LQ} \sim \sqrt{s}$ leptoquark contribution to the scattering amplitude $\eta^{eq}_{\alpha\beta}$ depends on the production/exchange channel:

⇒ u-channel exchange:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta} \frac{\lambda^2_{LQ}}{M^2_{LQ} - \hat{u}}$$

LEP, HERA, Tevatron

⇒ t-channel exchange:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta} \frac{\lambda^2_{LQ}}{M^2_{LQ} - \hat{t}}$$

LEP, Tevatron

⇒ s-channel production:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta} \frac{\lambda^2_{LQ}}{M^2_{LQ} - \hat{s} - i\hat{s}\frac{\Gamma_{LQ}}{M_{LQ}}}$$

HERA

Problem: $\boxed{\Gamma_{LQ} \sim \lambda^2_{LQ}}$

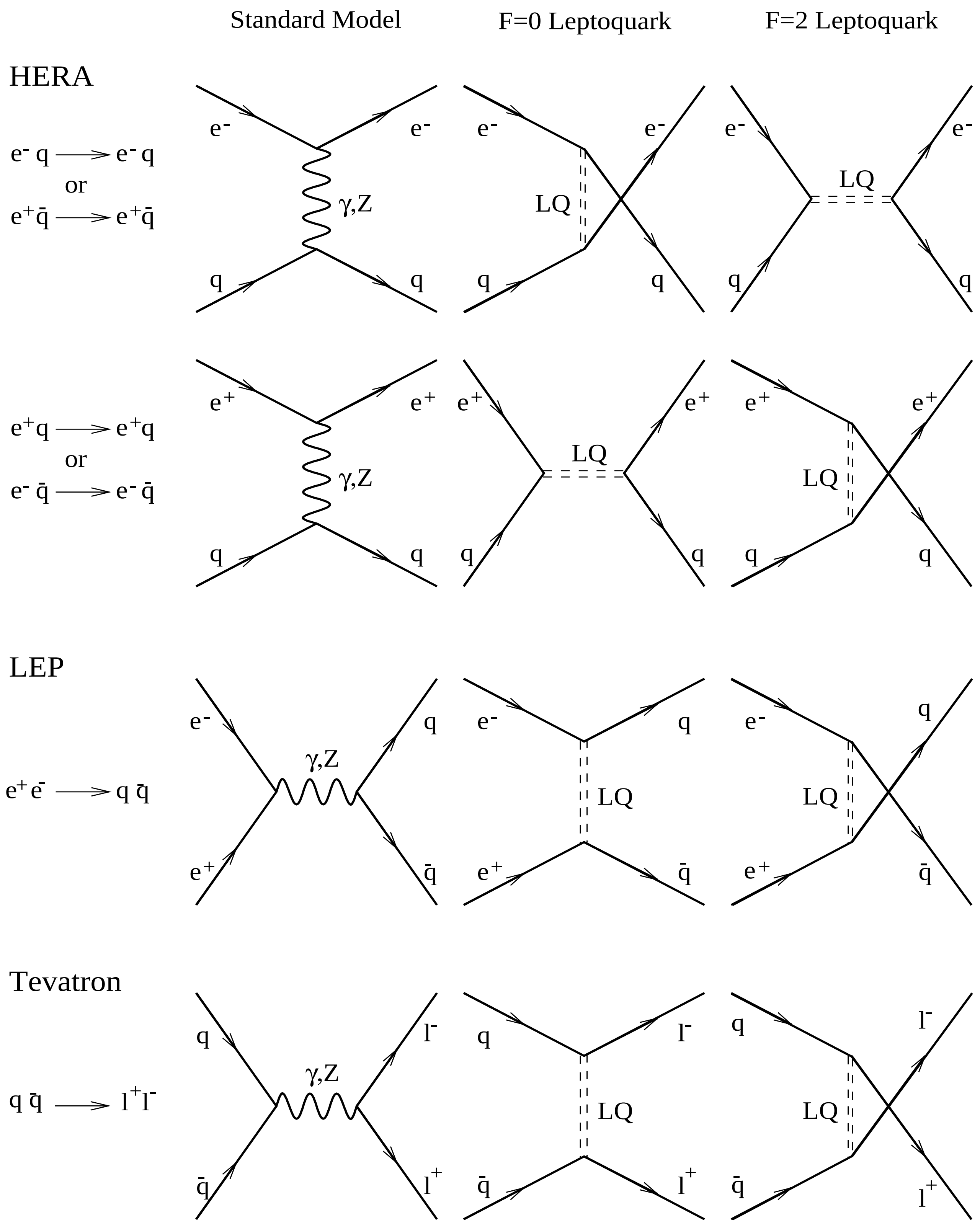
Cross section can no longer be parametrized as

$$\sigma(\lambda) = \sigma_{SM} + A \cdot \lambda^2 + B \cdot \lambda^4$$

⇒ much more CPU...

Models

Contributing diagrams



Global analysis

High energy data

- LEP2 results
  - ⇒ quark-pair production cross-section $\sigma(e^+e^- \to q\bar{q})$
    sensitive to all CI couplings
  - ⇒ heavy quark production ratios R_b, R_c
    important for models with family universality
  - ⇒ forward-backward asymmetries A^b_{FB}, A^c_{FB}, A^{uds}_{FB}
    very strong constraints for models with family universality
- HERA $\frac{d\sigma}{dQ^2}$ results
  - ⇒ NC e^+p DIS data 1994-97
    most sensitive to η^{eq}_{LR} and η^{eq}_{RL} (q=u,d)
  - ⇒ NC e^-p DIS data 1998-99
    most sensitive to η^{eq}_{LL} and η^{eq}_{RR}
  - ⇒ CC $e^{\pm}p$ DIS data 1994-99
    sensitive to $\eta^{CC} = \eta^{ed}_{LL} - \eta^{eu}_{LL}$
- Tevatron results
  - ⇒ data on high-mass Drell-Yan lepton pair production
    sensitive to all $q = u, d$ couplings
  - ⇒ direct search results for first-generation leptoquarks

    $M_{LQ} > 242$ GeV for scalar LQ (CDF+DØ)

    $M_{LQ} > 245$ GeV for vector LQ (DØ)

Global analysis

Low energy data

- Atomic Parity Violation experiments

$$\begin{aligned} \Delta Q_w(Cs) &= 1.13 \pm 0.46 \\ \Delta Q_w(Tl) &= 1.9 \pm 3.6 \\ \text{CI}: \quad \Delta Q_w &\sim \sum_{\substack{q=\\u,d}} \sum_{\beta} (\eta^{eq}_{L\beta} - \eta^{eq}_{R\beta}) \end{aligned}$$

- Unitarity of the Cabibbo-Kobayashi-Maskawa matrix

$$|V_{ud}|^2 + |V_{us}|^2 \; + \; |V_{ub}|^2 = 0.9959 \pm 0.0019$$

$$\text{CI}: \quad V_{ud} = V^{SM}_{du} \cdot \left(1 - \frac{\eta^{CC}}{4\sqrt{2}G_F} \right)$$

- electron-muon universality

$$R = \frac{\Gamma(\pi^- \to e\bar{\nu})}{\Gamma(\pi^- \to \mu\bar{\nu})} = 0.9966 \pm 0.030 \; R_{SM}$$

$$\text{CI}: \quad \frac{R_{meas}}{R_{SM}} = \left(1 - \frac{\eta^{CC}}{4\sqrt{2}G_F} \right)^2$$

- Polarization Asymmetry in low energy scattering

  results from eD, eBe, eC and $\mu^{\pm}C$ scattering

  direct measurement of the parity non-conservation

- neutrino-nucleus scattering

  constraints derived from the precise measurement of

$$R^{\nu} = \frac{\sigma^{\nu N}_{NC}}{\sigma^{\nu N}_{CC}}$$

Global analysis

Method

Consider global probability function:

$$\mathcal{P}(\vec{\eta}) \;=\; \prod_i P_i(\vec{\eta})$$

where the product runs over all experimental data points i.

For low-energy experiments and LEP data:

Gaussian probability distribution is used for $P_i(\vec{\eta})$.

For HERA high-Q^2 and Tevatron results:

Poisson distribution for the observed number of events.

Probability function is normalized to the Standard Model probability:

$$\mathcal{P}(0) \equiv \mathcal{P}_{SM} \;=\; 1$$

Maximum probability value $\mathcal{P}_{max}$ is found using MINUIT

Limit setting

- 95% CL **exclusion** limits:

$$\begin{aligned} \mathcal{P}(\vec{\eta}) &< 0.05 \cdot \mathcal{P}_{SM} \\ \text{or} \quad \ln \mathcal{P}(\vec{\eta}) &< -3.0 \end{aligned}$$

For $\mathcal{P}_{max} \gg 1$:

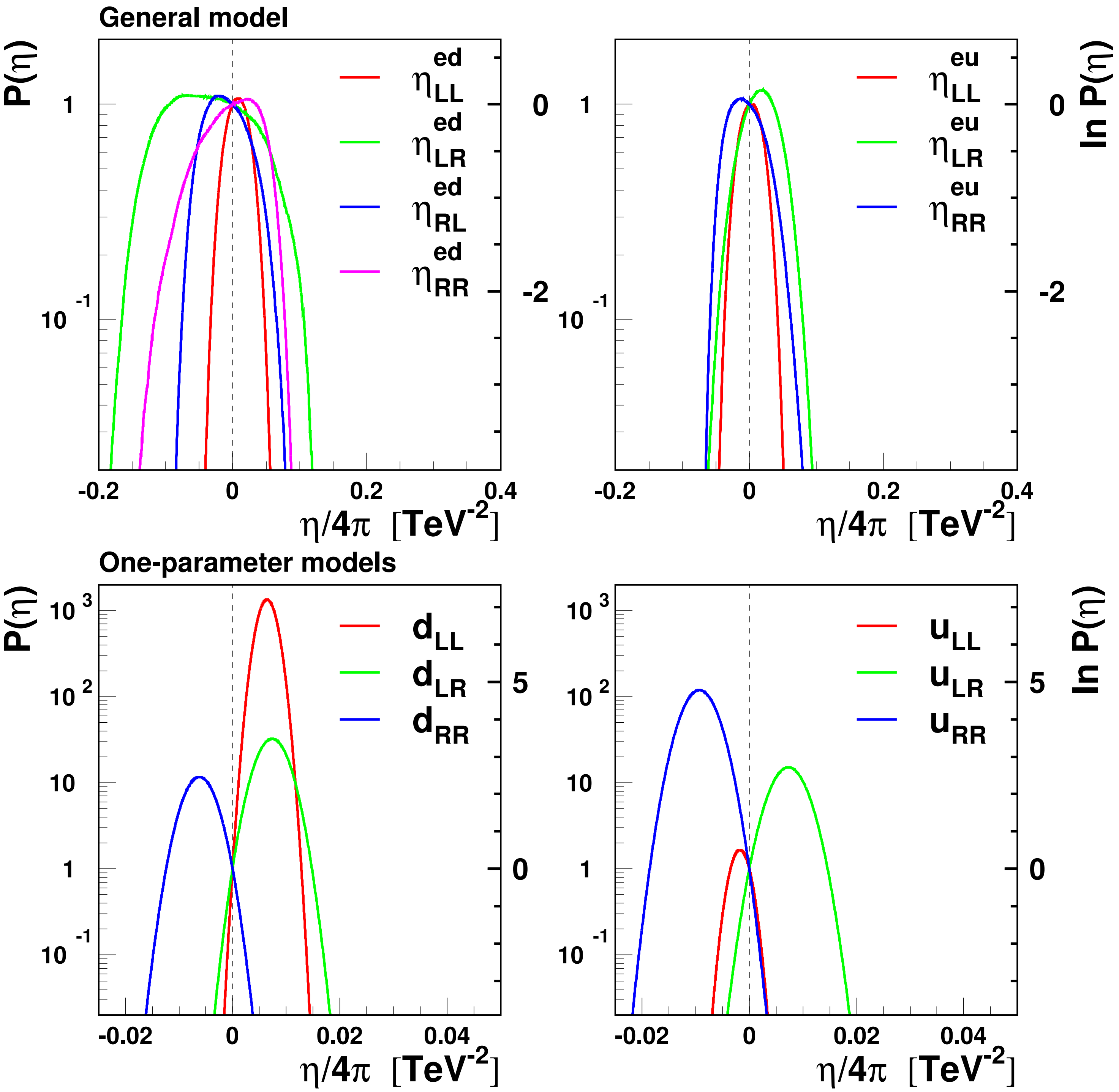
- 95% CL **signal** limits:

$$\begin{aligned} \mathcal{P}(\vec{\eta}) &> 0.05 \cdot \mathcal{P}_{max} \\ \text{or} \quad \ln \mathcal{P}(\vec{\eta}) &< \ln \mathcal{P}_{max} - 3.0 \end{aligned}$$

Contact Interaction Results

Probability functions

For first-generation Contact Interactions:



Contact Interaction Results

Exclusion limits

95% CL exclusion limits for the CI mass scale Λ [TeV]

Model	General models				One-parameter models			
	1^{st} gen.		3 gen.		1^{st} gen.		3 gen.	
	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
η^{ed}_{LL}	5.3	4.4	6.7	7.2	28.6	8.4	30.5	8.9
η^{ed}_{LR}	2.4	3.0	3.6	3.8	19.2	7.6	19.5	7.5
η^{ed}_{RL}	3.5	3.7	4.3	4.2				
η^{ed}_{RR}	2.8	3.5	4.0	5.9	8.0	18.1	8.8	17.4
η^{eu}_{LL}	4.9	4.6	6.0	8.2	12.5	18.7	11.8	21.4
η^{eu}_{LR}	4.3	3.4	5.0	4.8	17.4	7.5	17.3	7.8
η^{eu}_{RL}	3.5	3.7	4.3	4.2				
η^{eu}_{RR}	4.0	3.8	4.9	4.7	6.9	19.7	7.0	21.2

VV					6.5	11.1	8.2	15.1
AA					5.7	6.3	10.5	11.7
VA					4.5	4.6	5.7	7.8

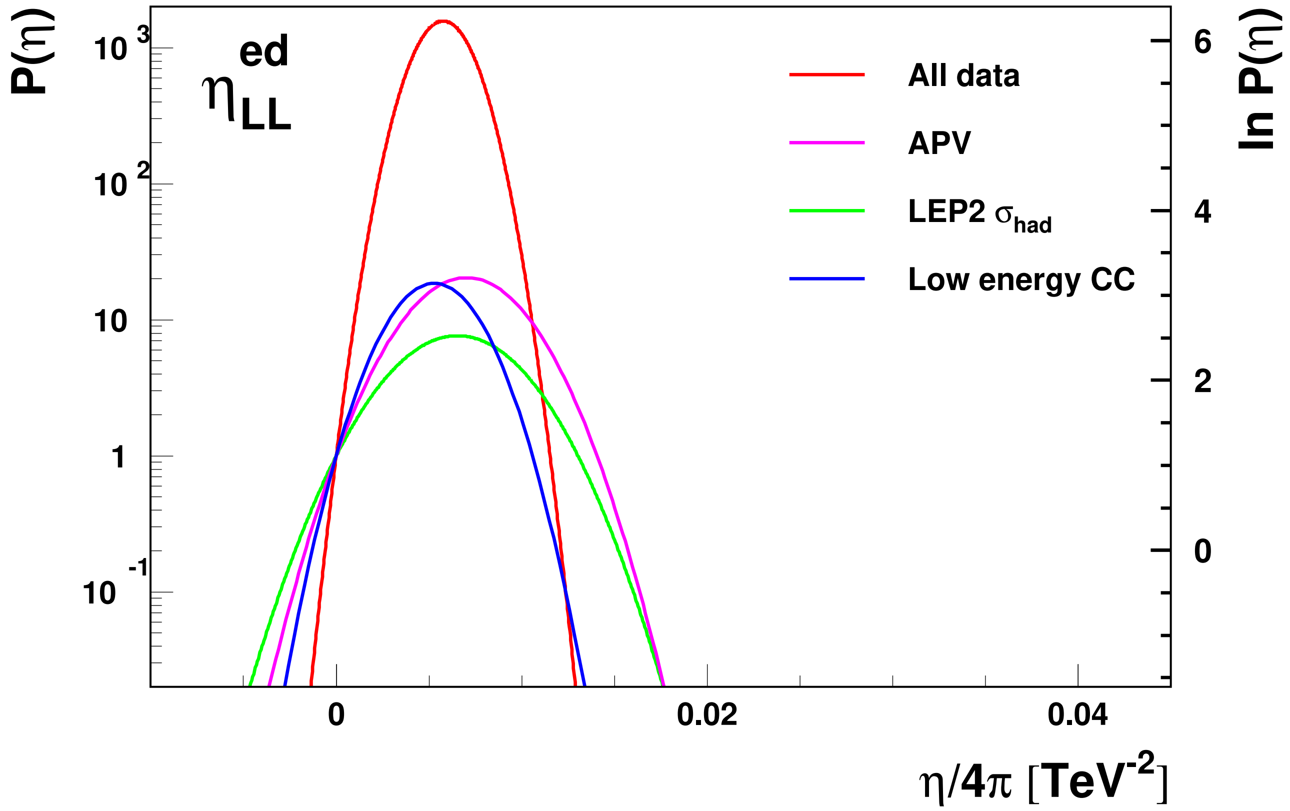
Contact Interaction Results

Possible CI signal

Best description of all data –

d_{LL} model with family universality

Contributions to the probability function:



Maximum probability $\mathcal{P}_{max} = 1570.$ $(\ln \mathcal{P}_{max} = 7.4)$ corresponds to $3.8\ \sigma$ deviation from the Standard Model:

$\Rightarrow$ APV measurement: $P = 21.1$ $2.5\ \sigma$

$\Rightarrow$ LEP σ_{had}: $P = 7.4$ $2.0\ \sigma$

$\Rightarrow$ Low energy CC (CKM and e/μ): $P = 18.1$ $2.4\ \sigma$

For first-generation d_{LL} model: $\mathcal{P}_{max} = 1300.$

Contact Interaction Results

Possible CI signal

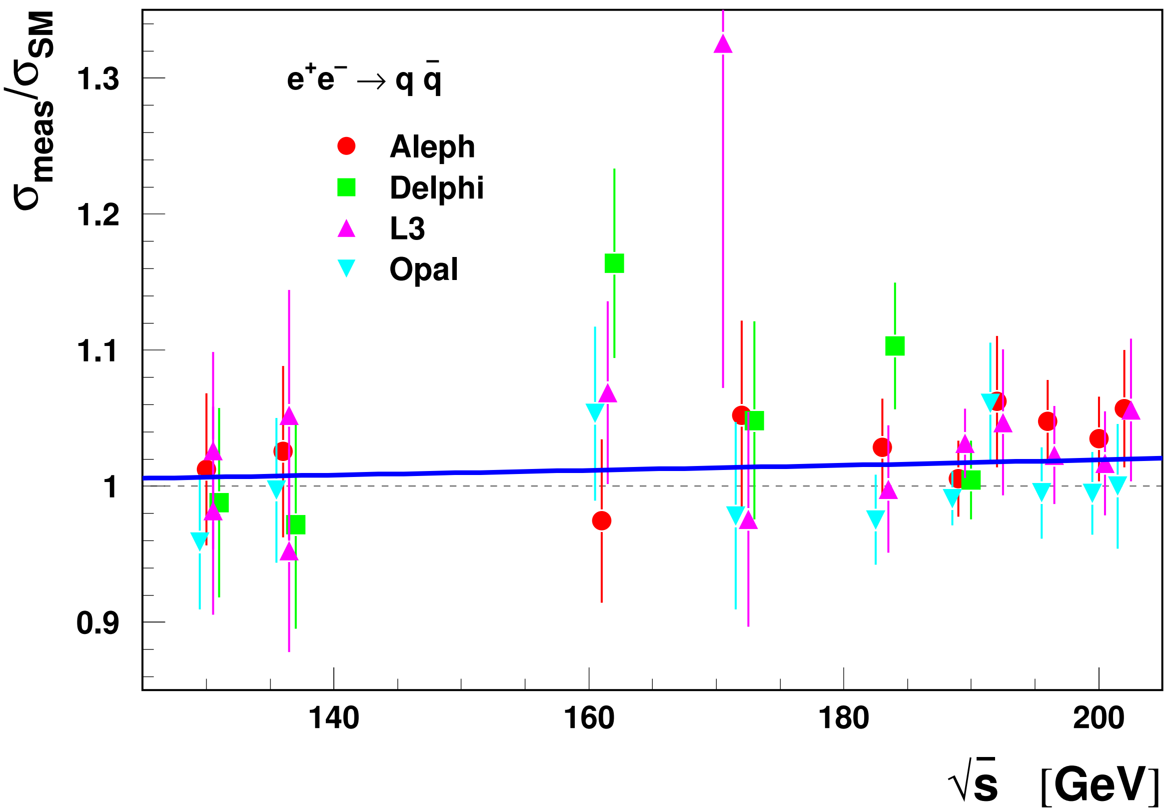
d_{LL} model with family universality

$$\boxed{\Lambda_{max} = 13.2 \text{ TeV}}$$

95% CL signal limits:

$$10.3 \text{ TeV} < \Lambda < 21.9 \text{ TeV}$$

comparison with LEP2 σ_{had} results



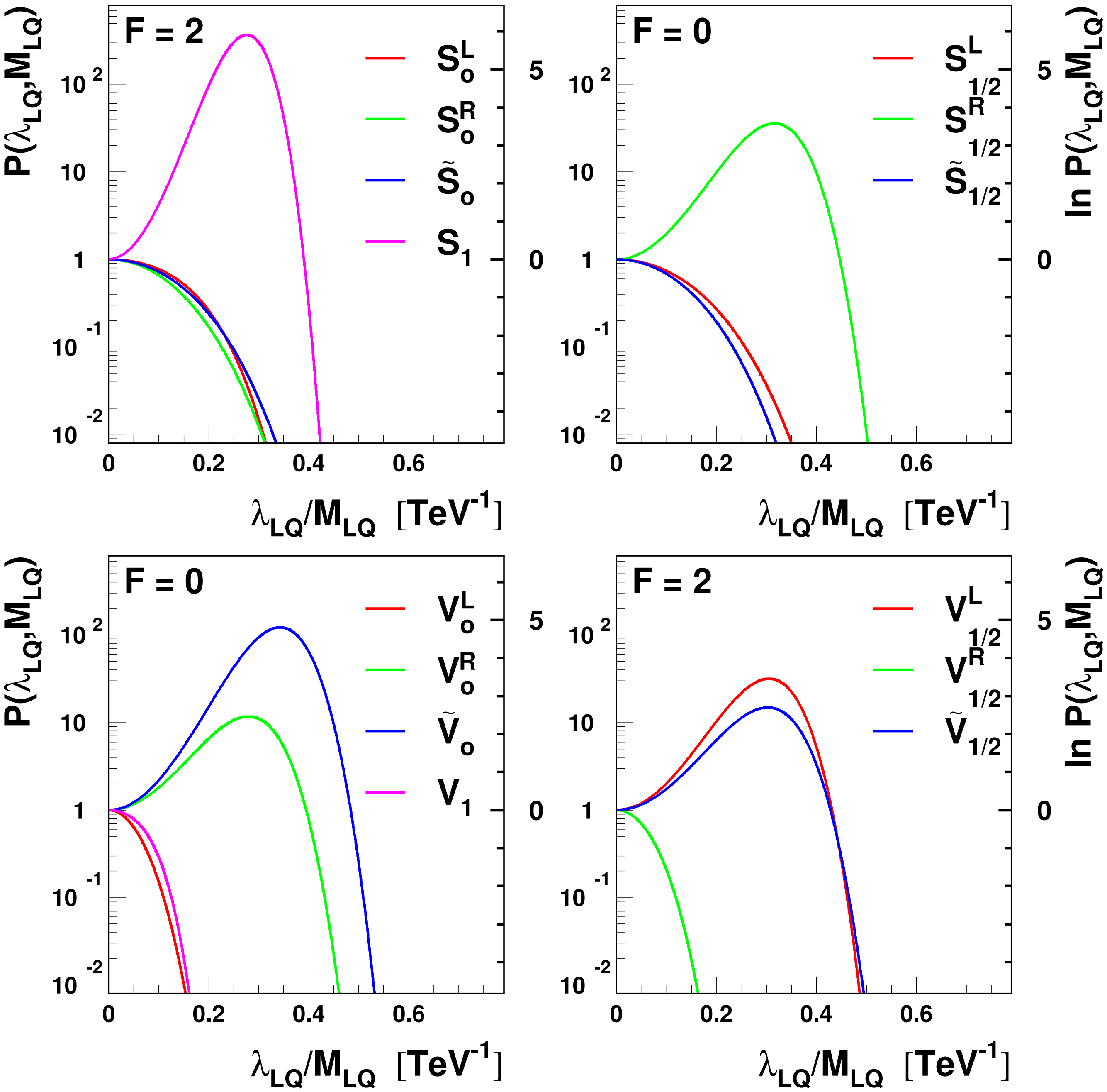
$\Rightarrow$ 1.9% increase at $\sqrt{s} = 200$ GeV

$\Rightarrow$ $\sim 0.1\%$ effect at $\sqrt{s} = M_Z$

Leptoquark Results

Probability functions

For BRW leptoquark models, in the limit $M_{LQ} \gg \sqrt{s}$



Leptoquark Results

CI approximation

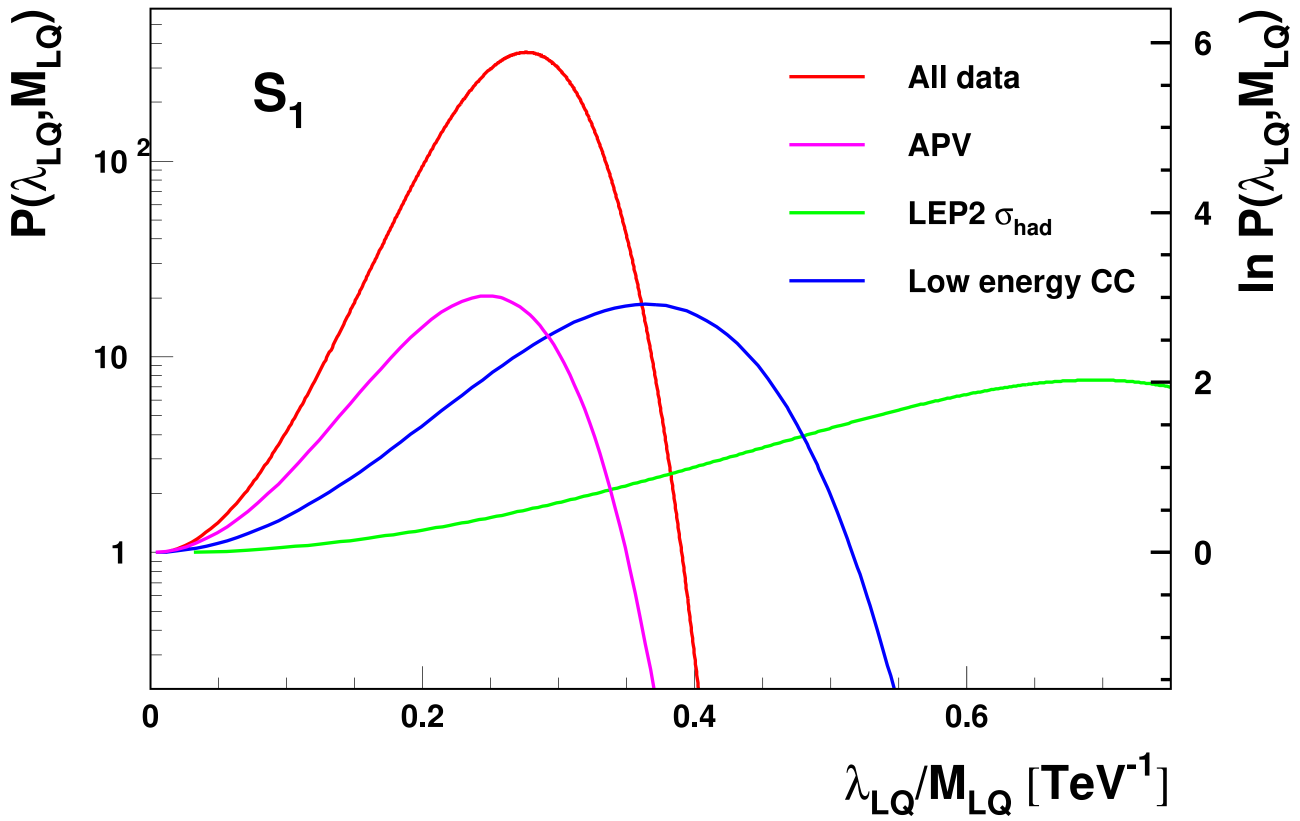
Best solution parameters and λ/M limits for $M_{LQ} \gg \sqrt{s}$

Model	$\left(\frac{\lambda_{LQ}}{M_{LQ}}\right)_{max}$ [TeV^{-1}]	$\mathcal{P}_{max}$	$\ln \mathcal{P}_{max}$	95% CL limit [TeV^{-1}] signal	exclusion
$S_\circ^L$	0	1.0	0.0		0.27
$S_\circ^R$	0	1.0	0.0		0.25
$\tilde{S}_\circ$	0	1.0	0.0		0.28
$S_{1/2}^L$	0	1.0	0.0		0.29
$S_{1/2}^R$	0.32 ± 0.06	35.8	3.6	0.09–0.44	0.49
$\tilde{S}_{1/2}$	0	1.0	0.0		0.26
S_1	0.28 ± 0.04	367.	5.9	0.15–0.36	0.41
$V_\circ^L$	0	1.0	0.0		0.12
$V_\circ^R$	0.28 ± 0.07	11.7	2.5		0.44
$\tilde{V}_\circ$	0.34 ± 0.06	122.	4.8	0.16–0.46	0.52
$V_{1/2}^L$	0.30 ± 0.06	31.7	3.5	0.08–0.42	0.47
$V_{1/2}^R$	0	1.0	0.0		0.13
$\tilde{V}_{1/2}$	0.30 ± 0.07	14.8	2.7		0.47
V_1	0	1.0	0.0		0.14

Leptoquark Results

Possible S_1 signal

Contributions to the probability function, $M_{LQ} \gg \sqrt{s}$



Maximum probability $\mathcal{P}_{max} = 367.$ $(\ln \mathcal{P}_{max} = 5.9)$
corresponds to $3.4\ \sigma$ deviation from the Standard Model:

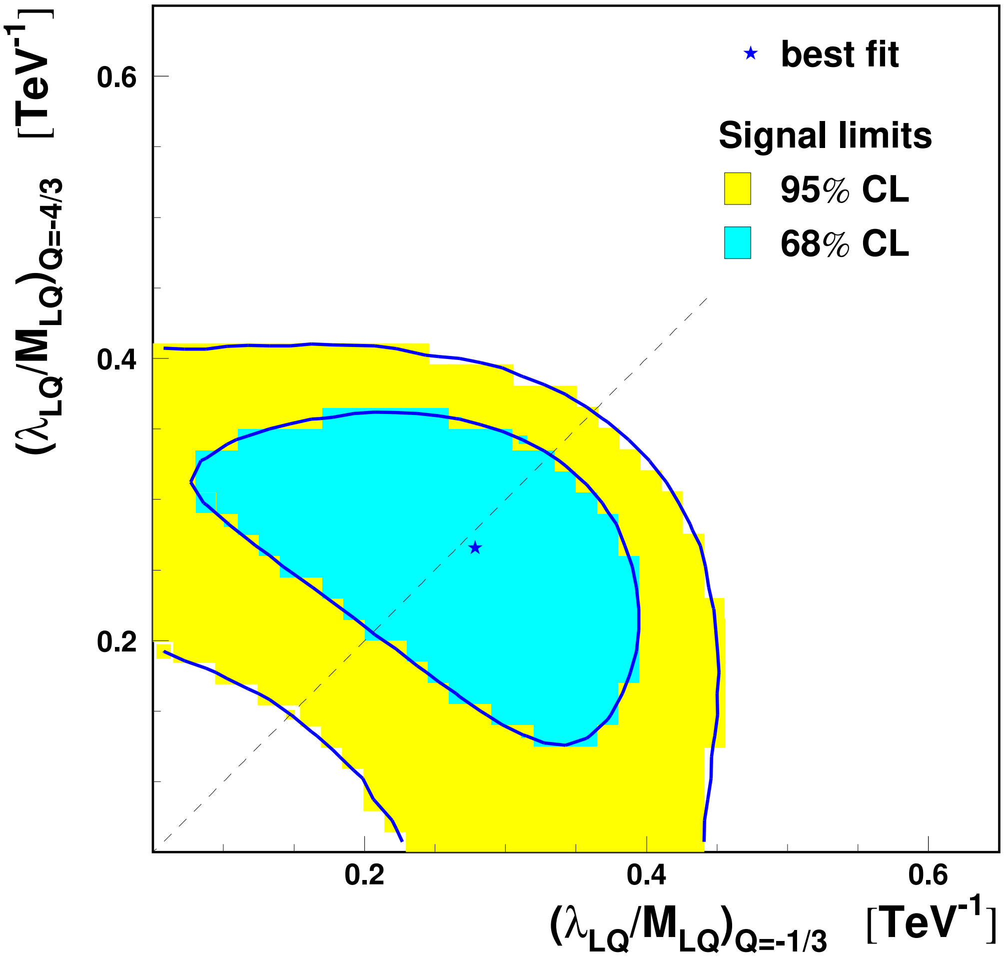
$\Rightarrow$ APV measurement:	$P = 19.5$	$2.4\ \sigma$
$\Rightarrow$ LEP σ_{had}:	$P = 1.7$	$1.0\ \sigma$
$\Rightarrow$ Low energy CC (CKM and e/μ):	$P = 10.9$	$2.2\ \sigma$

Leptoquark Results

Possible S_1 signal

S_1 – isospin triplet:
$Q = -4/3(ed)$, $Q = -1/3(eu, \nu d)$ or $Q = +2/3(\nu u)$

Varying masses of $Q = -4/3$ and $Q = -1/3$ states:



Maximum probability for:

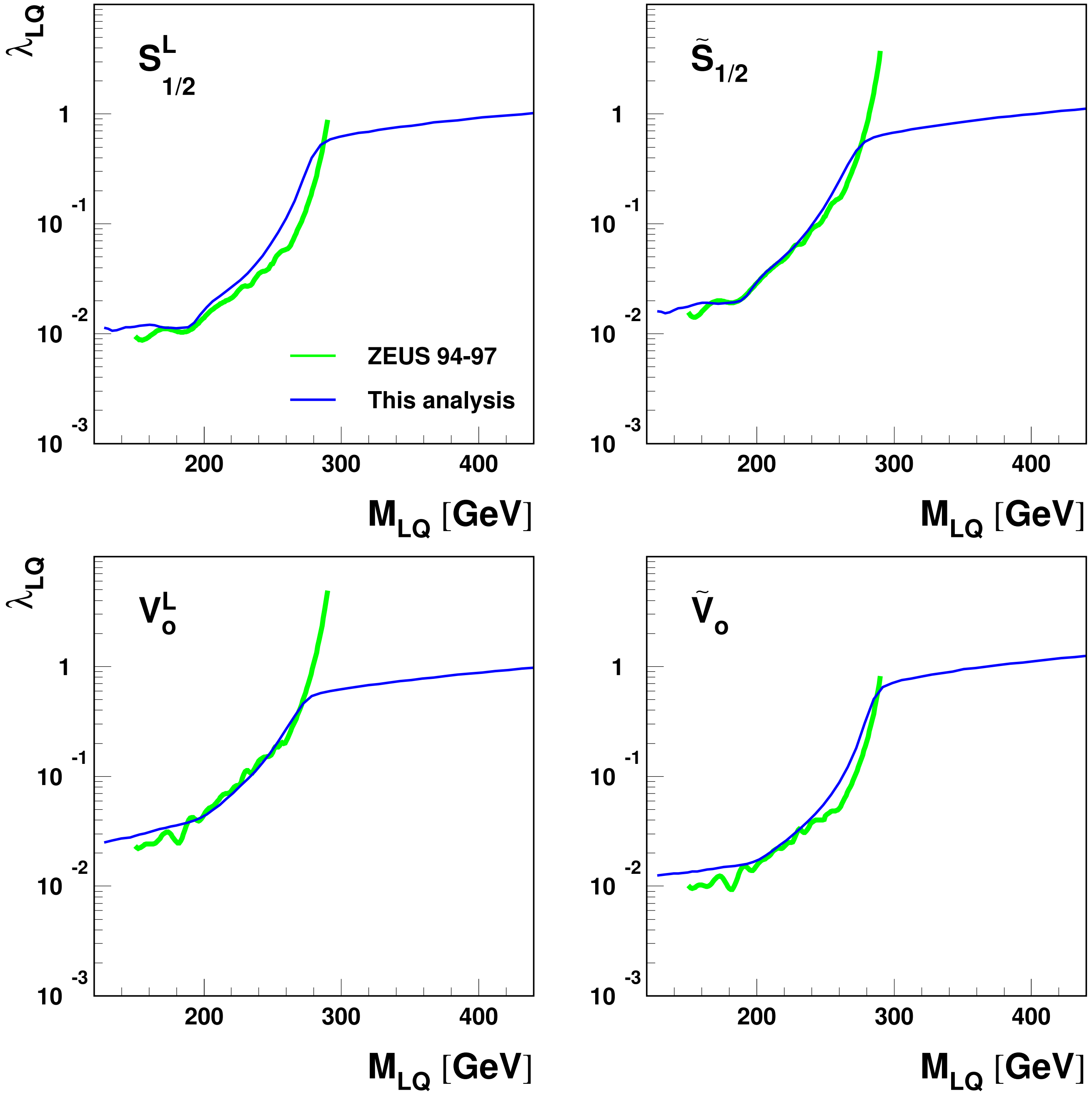
$$M_{eu} \approx M_{ed}$$

$\Rightarrow$ not consistent with d_{LL} model $(M_{eu} \gg M_{ed})$

Leptoquark Results

Direct production limits

Comparison of limits for ZEUS e^+p NC DIS data:

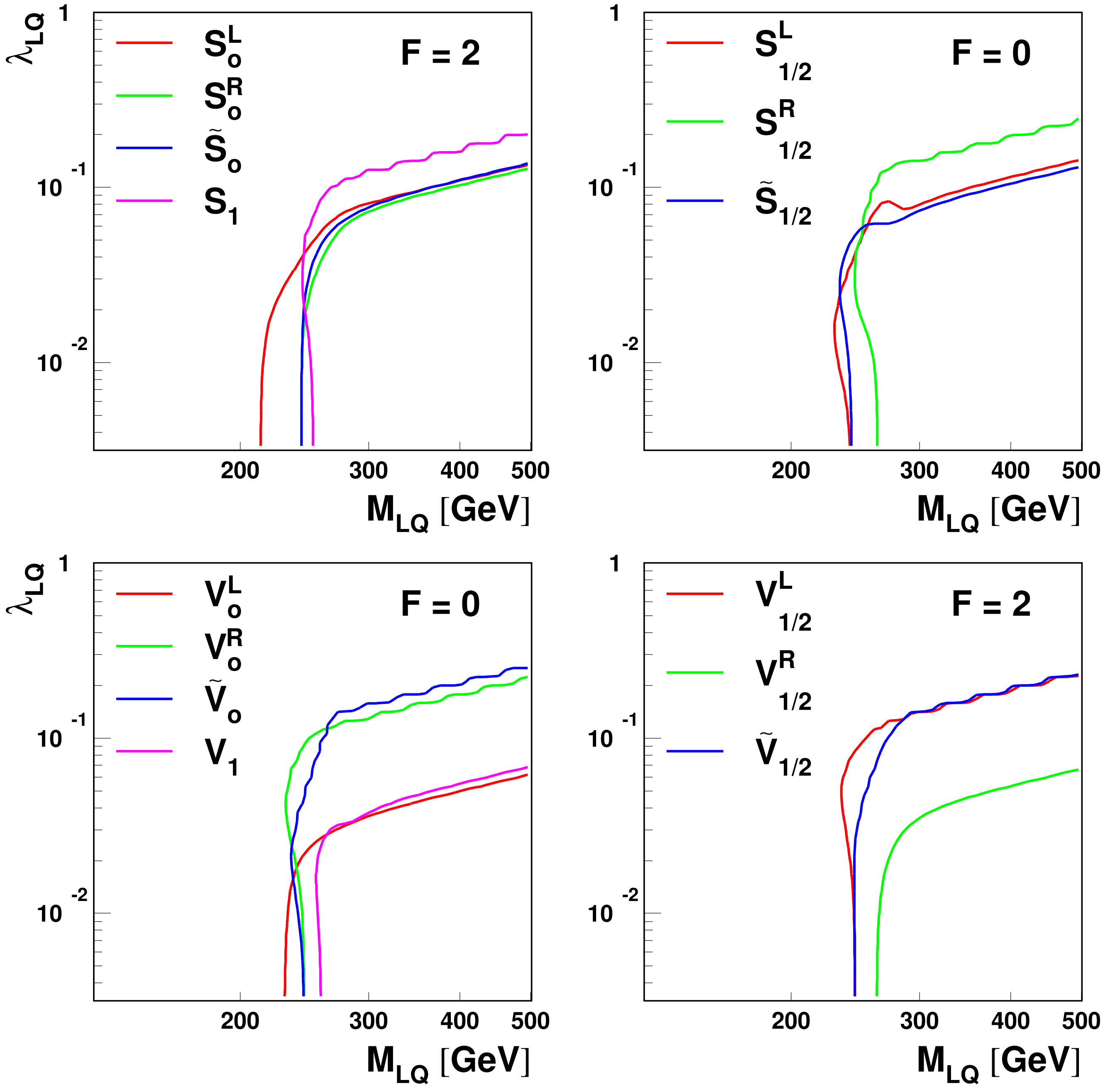


$\Rightarrow$ Limits from $\frac{d\sigma}{dQ^2}$ are very close to the direct search results.

Leptoquark Results

Exclusion limits

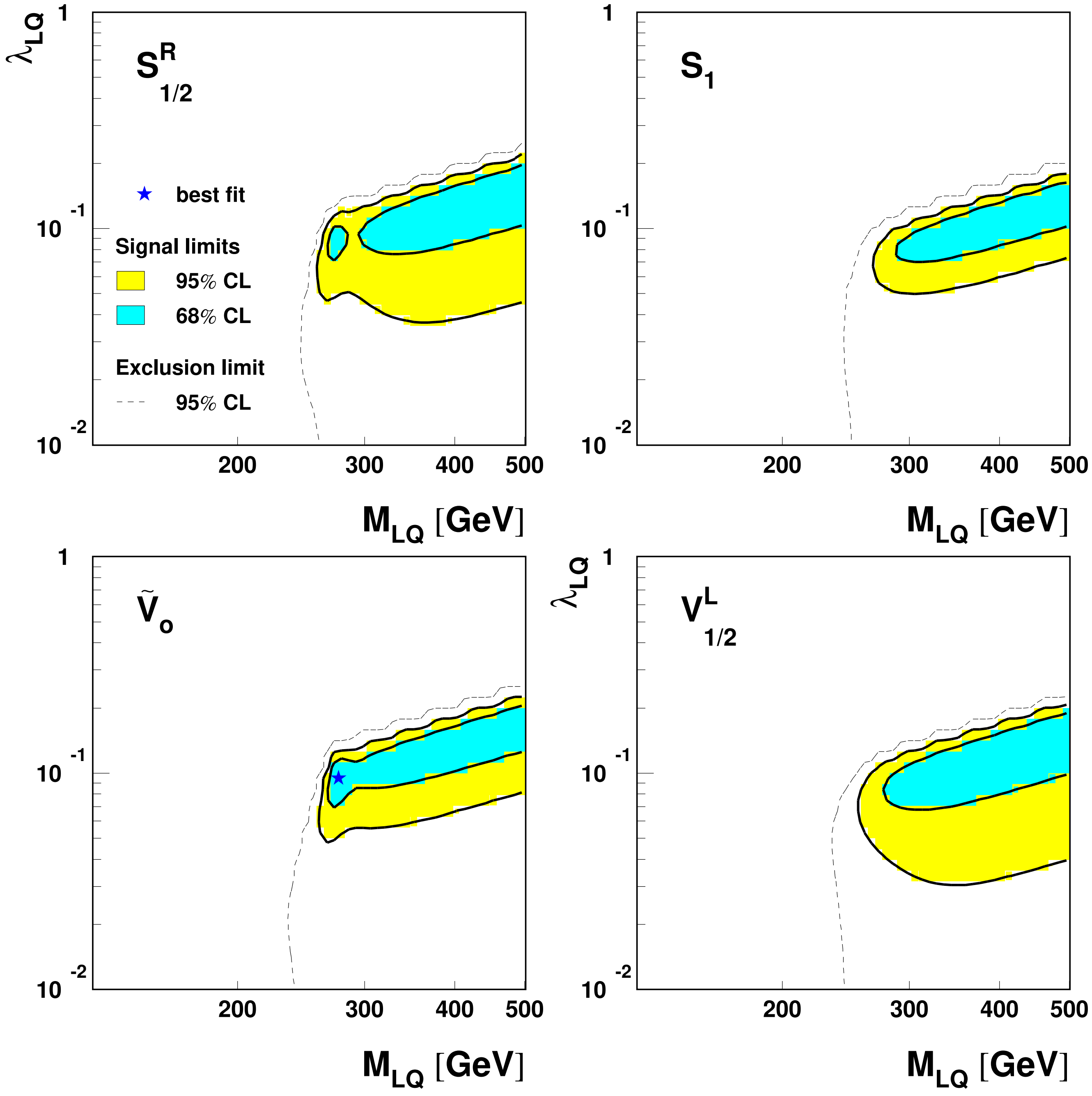
For leptoquark masses $M_{LQ} \sim \sqrt{s}$



Leptoquark Results

Signal limits

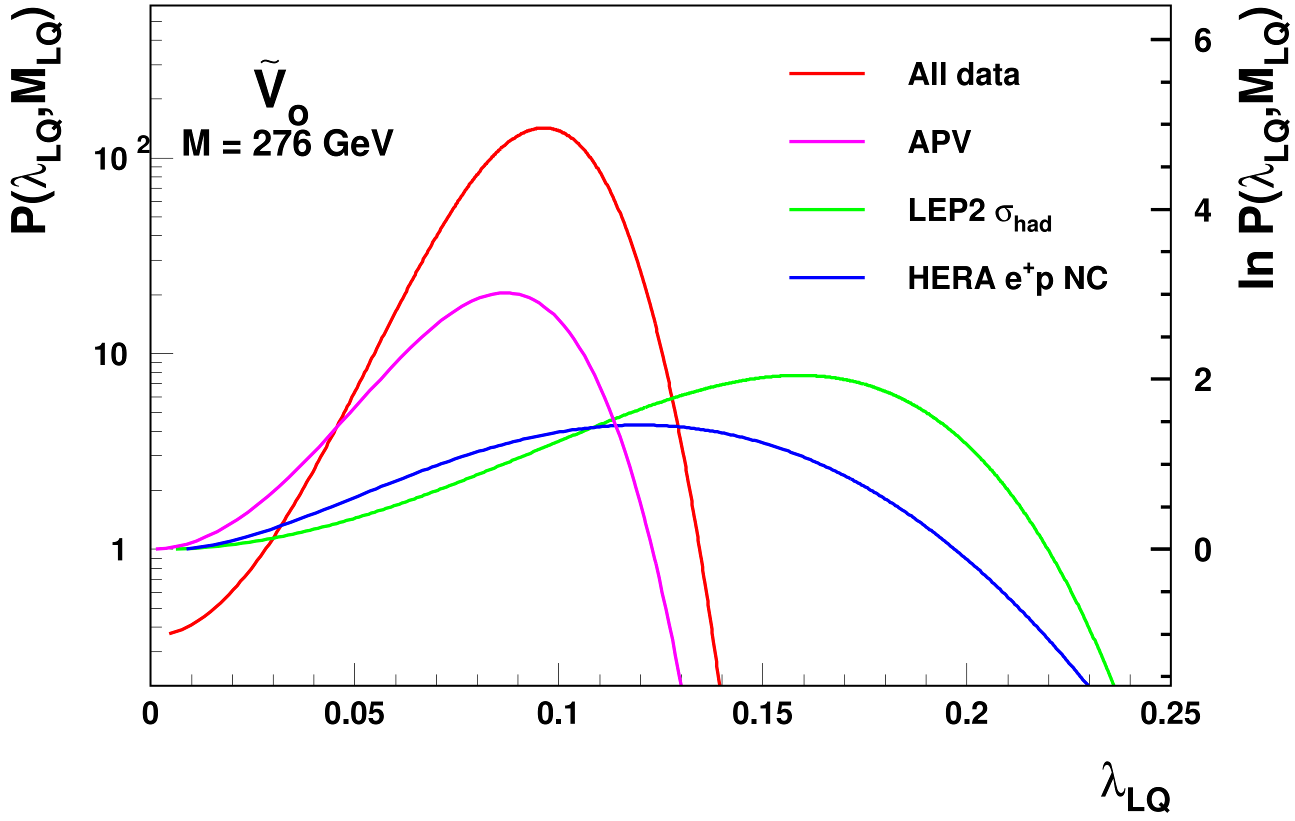
For leptoquark masses $M_{LQ} \sim \sqrt{s}$



Leptoquark Results

Possible $\tilde{V}_\circ$ signal

Contributions to the probability function, $M_{LQ} = 276$ GeV



Maximum probability $\mathcal{P}_{max} = 142.$ $(\ln \mathcal{P}_{max} = 5.0)$
corresponds to $3.1\ \sigma$ deviation from the Standard Model:

$\Rightarrow$ APV measurement: $P = 20.1$ $2.4\ \sigma$

$\Rightarrow$ LEP σ_{had}: $P = 3.3$ $1.5\ \sigma$

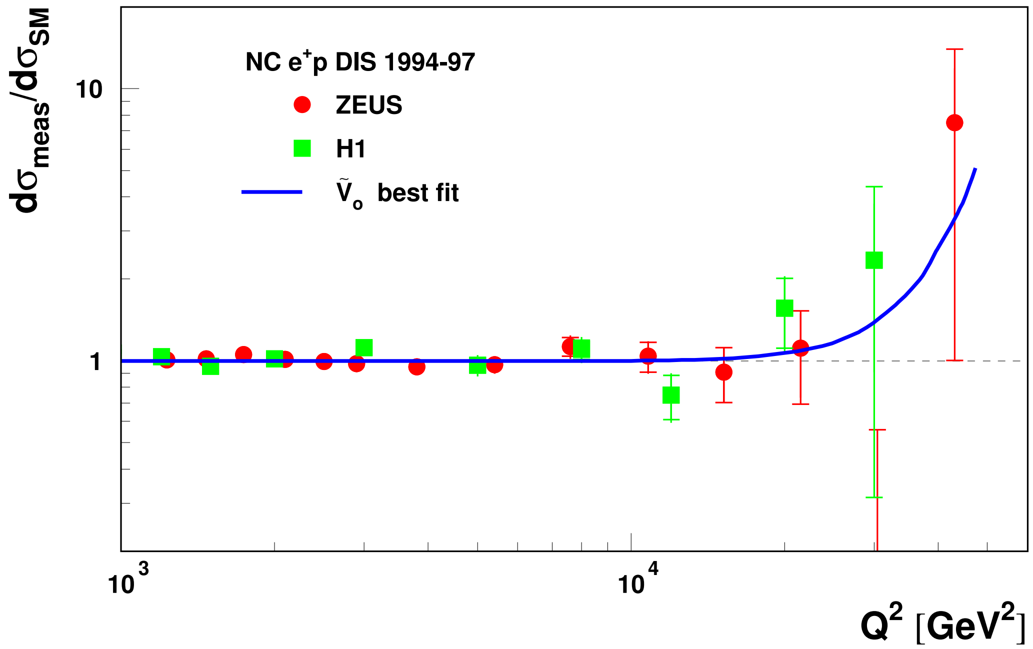
$\Rightarrow$ HERA NC e^+p DIS: $P = 3.9$ $1.7\ \sigma$

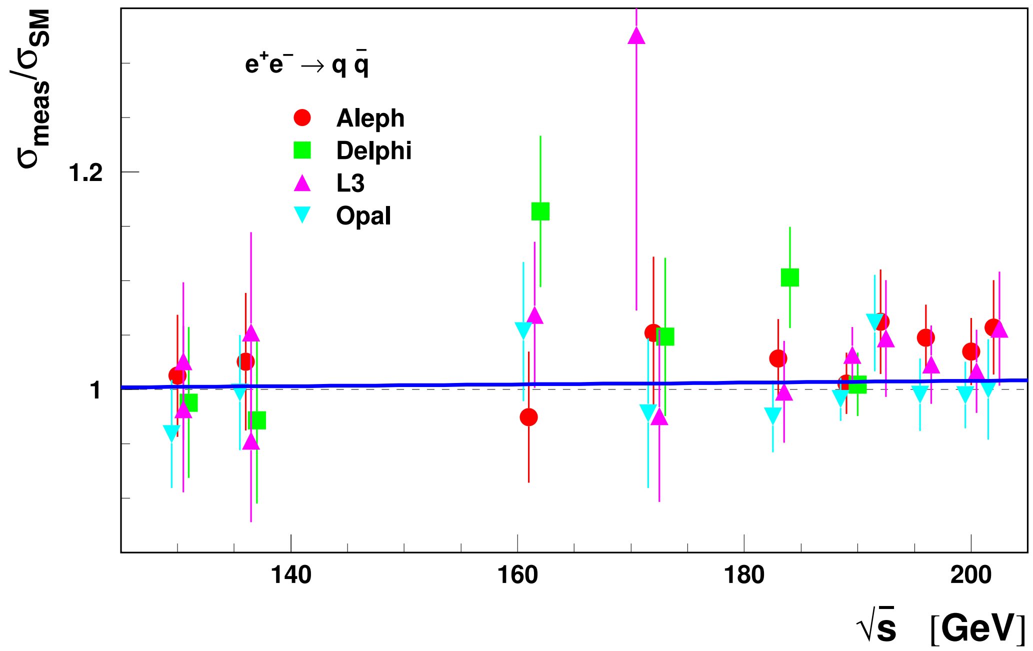
$\Rightarrow$ Tevatron direct search: $P = 0.36$

Leptoquark Results

Possible $\tilde{V}_\circ$ signal

$$\boxed{\begin{array}{l} M = 276 \pm 7\ \text{GeV} \\ \lambda = 0.095 \pm 0.015 \end{array}}$$



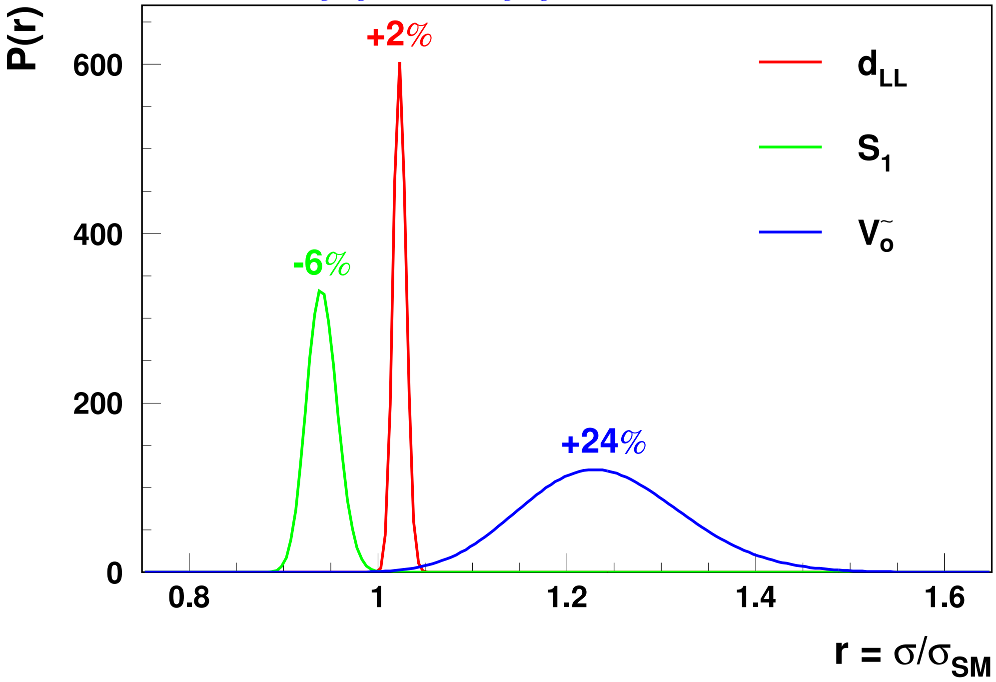


Leptoquark Results

Expected signal

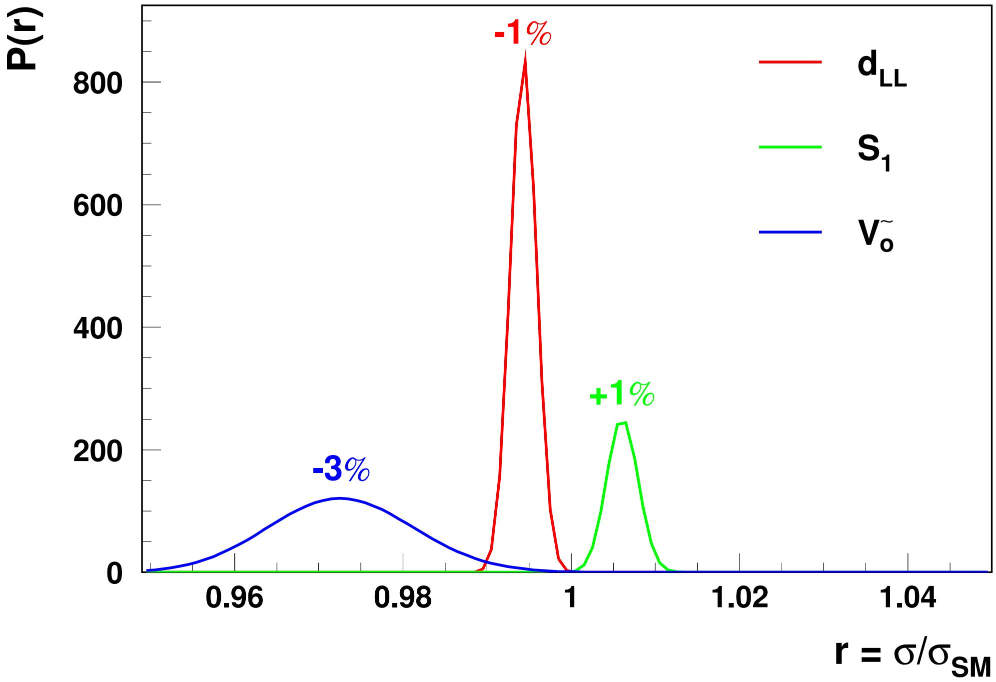
- Drell-Yan lepton pair production at the Tevatron:

$\sigma_{e^+e^-}$ at $M_{e^+e^-} = 500$ GeV

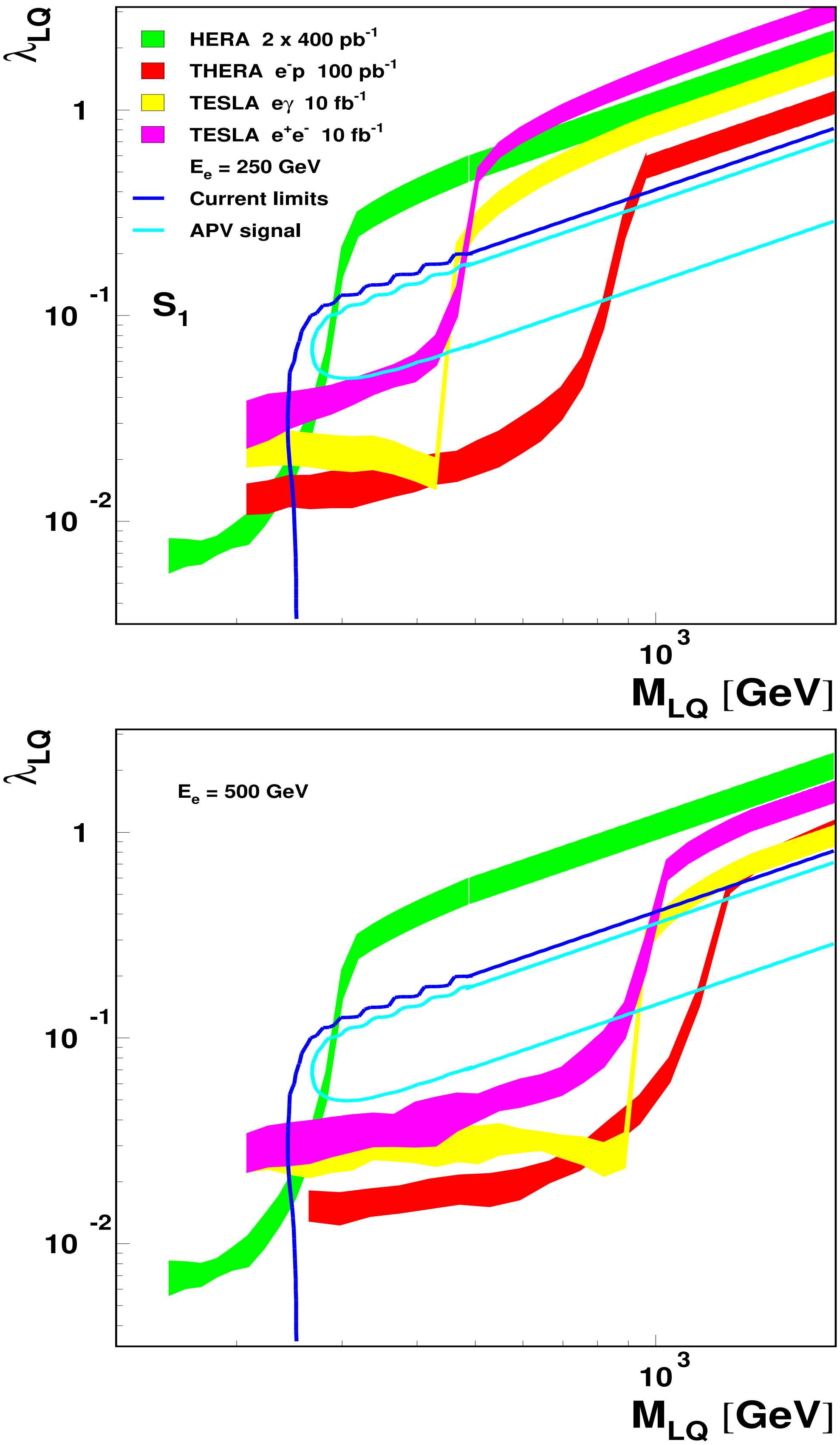


- NC e^-p DIS at HERA:

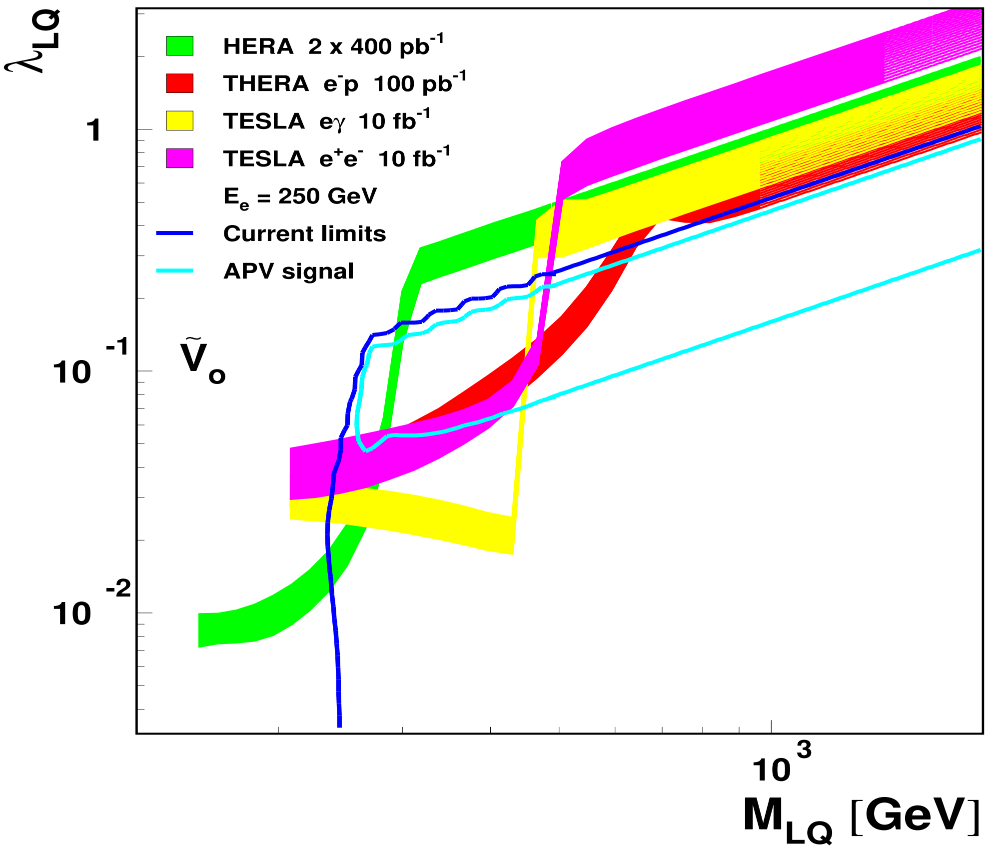
$\frac{d\sigma}{dQ^2}$ at $Q^2 = 30000$ GeV^2

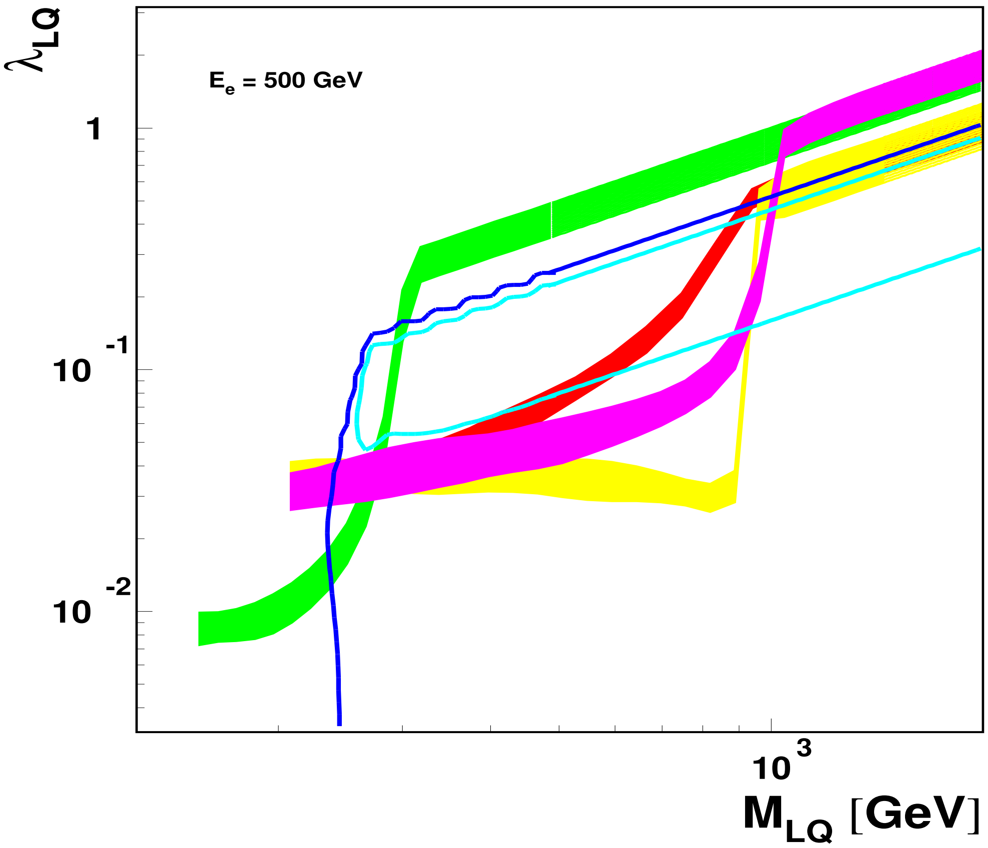


Limits from future experiments



Limits from future experiments





Summary

- Some recent data indicate possible deviations from the Standard Model predictions...
- Data from HERA, LEP, Tevatron and low energy experiments were combined in search for:
  - $\Rightarrow$ electron-quark contact interactions,
  - $\Rightarrow$ first-generation leptoquarks.
- Excluded are all models with $\Lambda < 2.4$ TeV
- For one-parameter models scale limits up to 30 TeV
- Possible signal for "new physics" observed for:
  - $\Rightarrow$ d_{LL} contact interaction model
    $\Lambda \sim 13.2$ TeV
  - $\Rightarrow$ S_1 leptoquark model
    $\lambda/M \sim 0.28$ TeV^{-1}
  - $\Rightarrow$ $\tilde{V}_\circ$ leptoquark model
    $M = 276 \pm 7$ GeV
    $\lambda = 0.095 \pm 0.015$
- If the observed leptoquark signal is real, it will be accessible at TESLA/THERA up to $M_{LQ} \sim 1$ TeV