Leptoquark searches in TESLA

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Outline

- Introduction
- Leptoquark models
- Current experimental constraints
  results from global analysis hep-ph/0003271
- Search methods in e^+e^- and $e\gamma$
- Expected limits
- Polarization
- Comparison with other experiments

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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:

$$\Delta Q_W^{Cs} \equiv Q_W^{meas} - Q_W^{SM} = 1.13 \pm 0.46$$

$$\text{previously :} \quad 0.71 \pm 0.84$$

$\Rightarrow$ 2.5 σ deviation from the Standard Model

Unitarity of the CKM matrix

PDG: 1999 partial update for 2000 edition

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

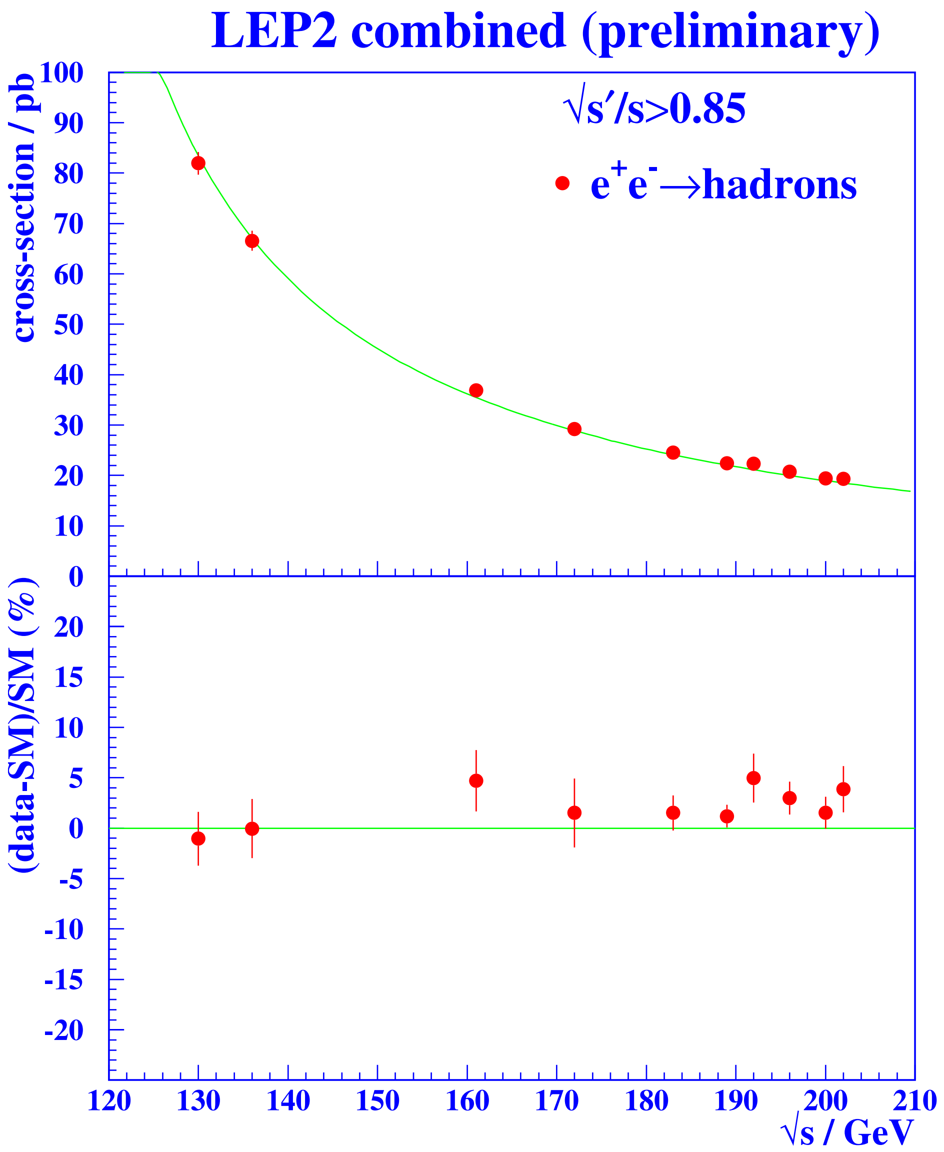
$$\text{previously :} \quad 0.9969 \pm 0.0022$$

$\Rightarrow$ 2.2 σ deviation from the Standard Model

Introduction

New results from LEP2

Hadronic cross-section measurements presented in Moriond



⇒ 2.3 σ deviation from the Standard Model

Possible sign for "new physics" ???

Leptoquark Models

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

Leptoquark 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		$\nu \bar{d}$	

Global analysis

High energy data

- LEP2 results

  $\Rightarrow$ quark-pair production cross-section $\sigma(e^+e^- \to q\bar{q})$
  sensitive to all CI couplings

  $\Rightarrow$ heavy quark production ratios $R_b,\ R_c$
  important for models with family universality

  $\Rightarrow$ 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

  $\Rightarrow$ NC e^+p DIS data 1994-97
  most sensitive to η^{eq}_{LR} and η^{eq}_{RL} (q=u,d)

  $\Rightarrow$ NC e^-p DIS data 1998-99
  most sensitive to η^{eq}_{LL} and η^{eq}_{RR}

  $\Rightarrow$ CC $e^\pm p$ DIS data 1994-99
  sensitive to $\eta^{CC} = \eta^{ed}_{LL} - \eta^{eu}_{LL}$

- Tevatron results

  $\Rightarrow$ data on high-mass Drell-Yan lepton pair production
  sensitive to all $q = u, d$ couplings

  $\Rightarrow$ 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:

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

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

- 95% CL **signal** limits:

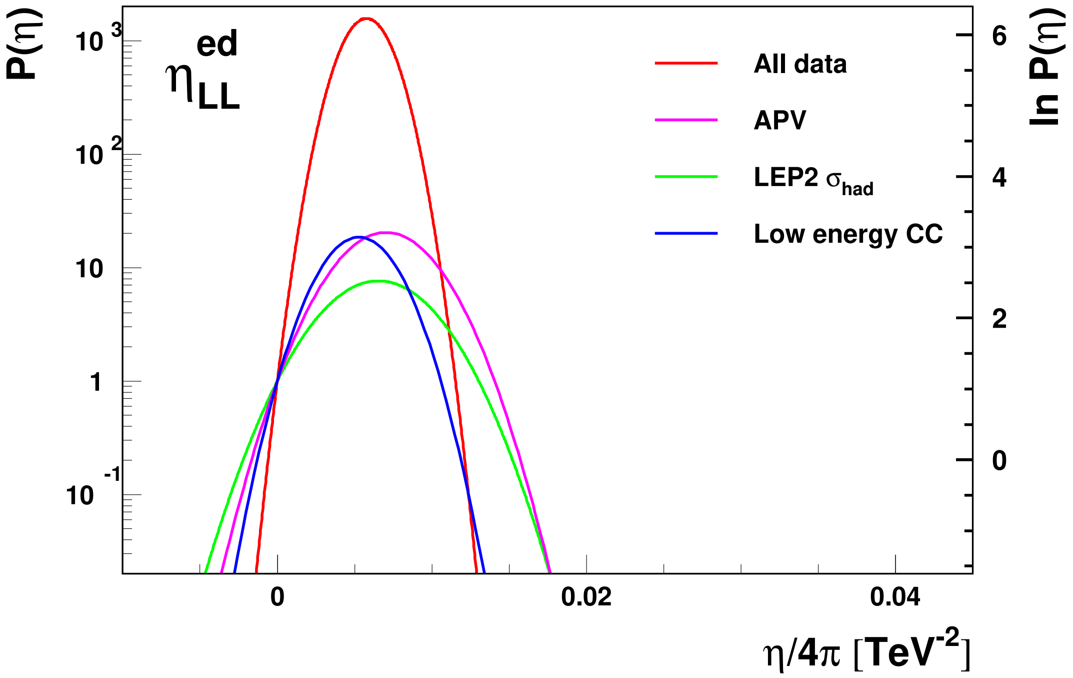
$$\mathcal{P}(\vec{\eta}) \;>\; 0.05 \cdot \mathcal{P}_{max}$$
$$\text{or} \quad \ln \mathcal{P}(\vec{\eta}) \;<\; \ln \mathcal{P}_{max} \;-\; 3.0$$

Global Analysis

Possible CI signal

Best description of all data –
model with $e_L d_L$ contact interaction

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): $P = 18.1$ $2.4\ \sigma$

Contact Interaction mass scale:

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

95% CL signal limits:

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

Global Analysis

Leptoquark limits

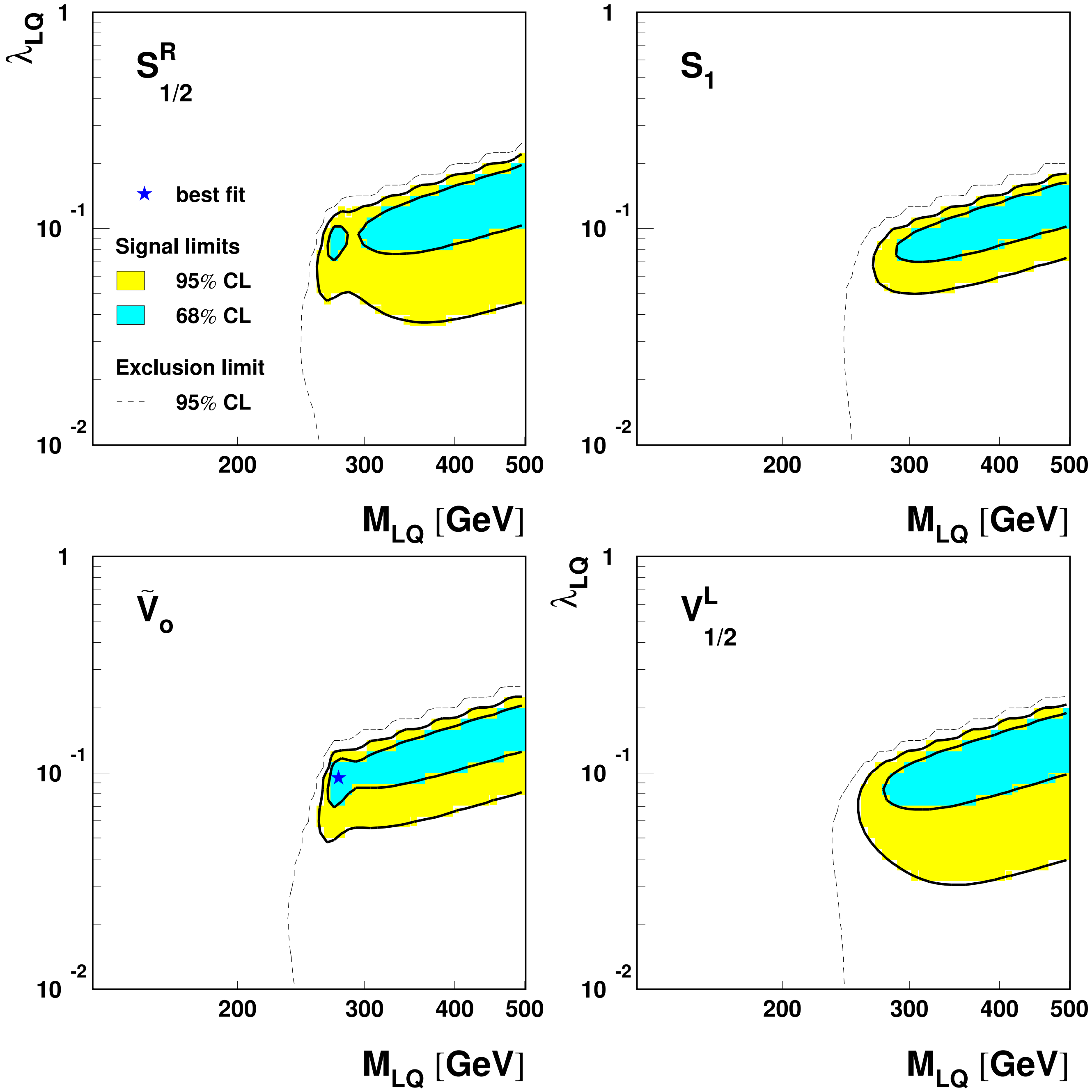
Best solution parameters and λ/M limits for $M_{LQ} \gg \sqrt{s}$

Model	$\left(\frac{\lambda_{LQ}}{M_{LQ}}\right)_{max}$ [TeV^{-1}]	$\mathcal{P}_{max}$	$\ln \mathcal{P}_{max}$	95% CL limit [TeV^{-1}] signal	95% CL limit [TeV^{-1}] 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

Global Analysis

Leptoquark limits

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

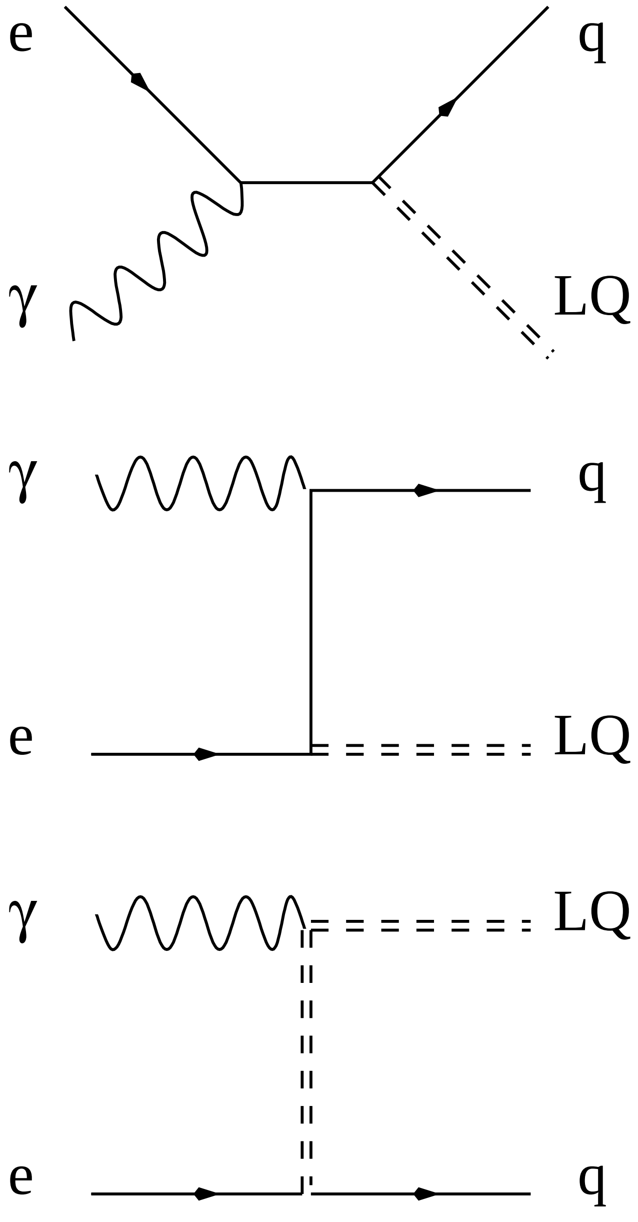


Leptoquark search methods

Direct production

For F=0 leptoquark production

$e\,\gamma \rightarrow q\,LQ$

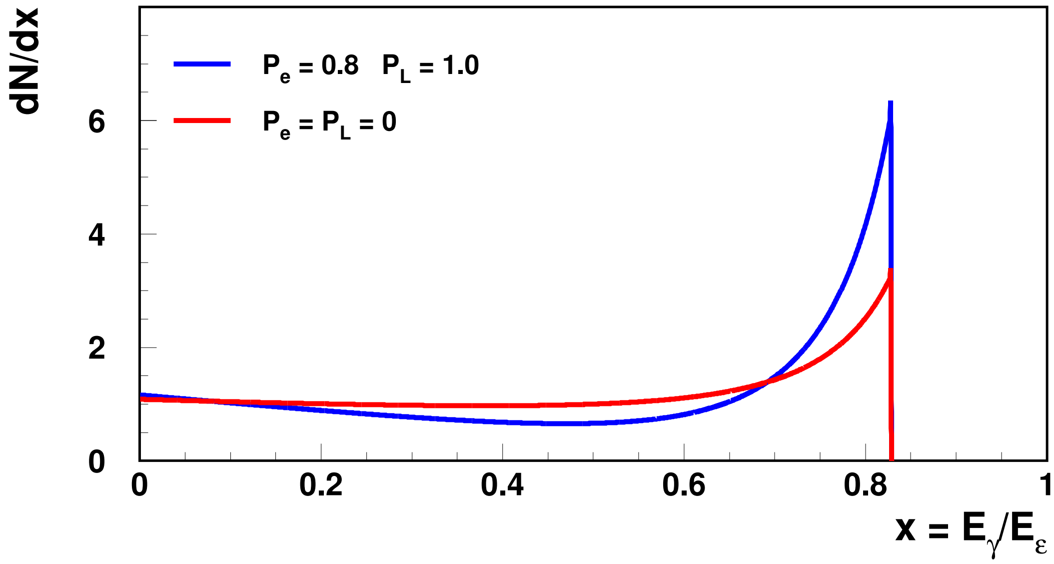


cross-section formula: F.Cuypers, Nucl.Phys.B474(1996)57
hep-ph/9508397

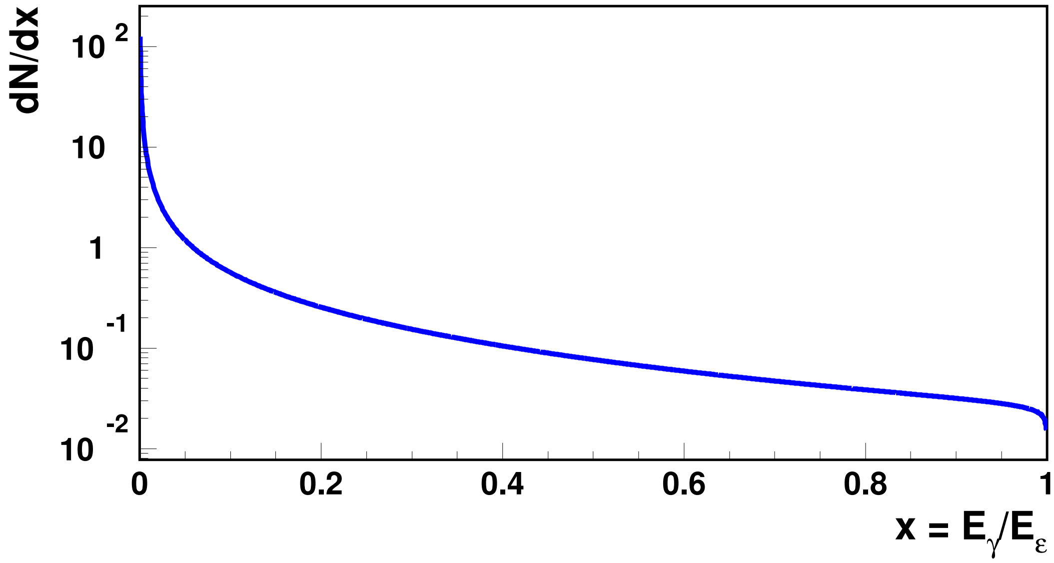
Leptoquark search methods

γ sources

- $e\gamma$ - Compton backscattering

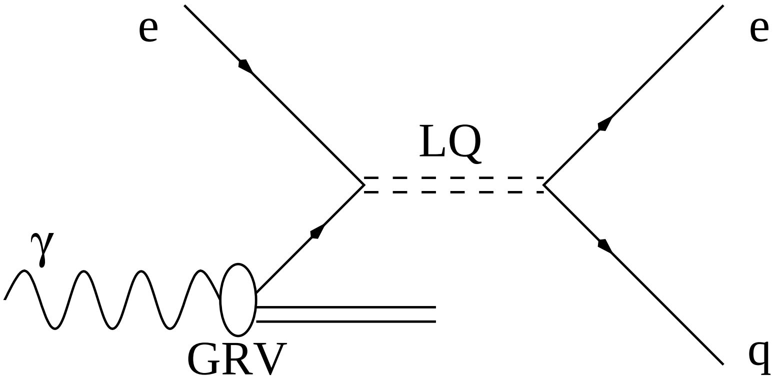


- e^+e^- - Waizsäcker-Williams Approximation



Leptoquark search methods

Resolved photon contribution



- $e^{\pm}\gamma \to LQ + X$

$$\sigma(M_{LQ}, \lambda_{LQ}) = (J+1) \cdot \frac{\pi \lambda_{LQ}^2}{4 M_{LQ}^2} \cdot x q_\gamma(x_{LQ}, M_{LQ}^2)$$

$$x_{LQ} = \frac{M_{LQ}^2}{s}$$

- $e^+e^- \to LQ + X$

$$\sigma(M_{LQ}, \lambda_{LQ}) = 2 \cdot (J+1) \cdot \frac{\pi \lambda_{LQ}^2}{4 M_{LQ}^2} \cdot (x q_\gamma \otimes f_{\gamma/e})$$

Expected number of leptoquark events is compared to the Standard Model background coming from NC DIS:

$\Rightarrow$ $\pm 5\%$ mass window

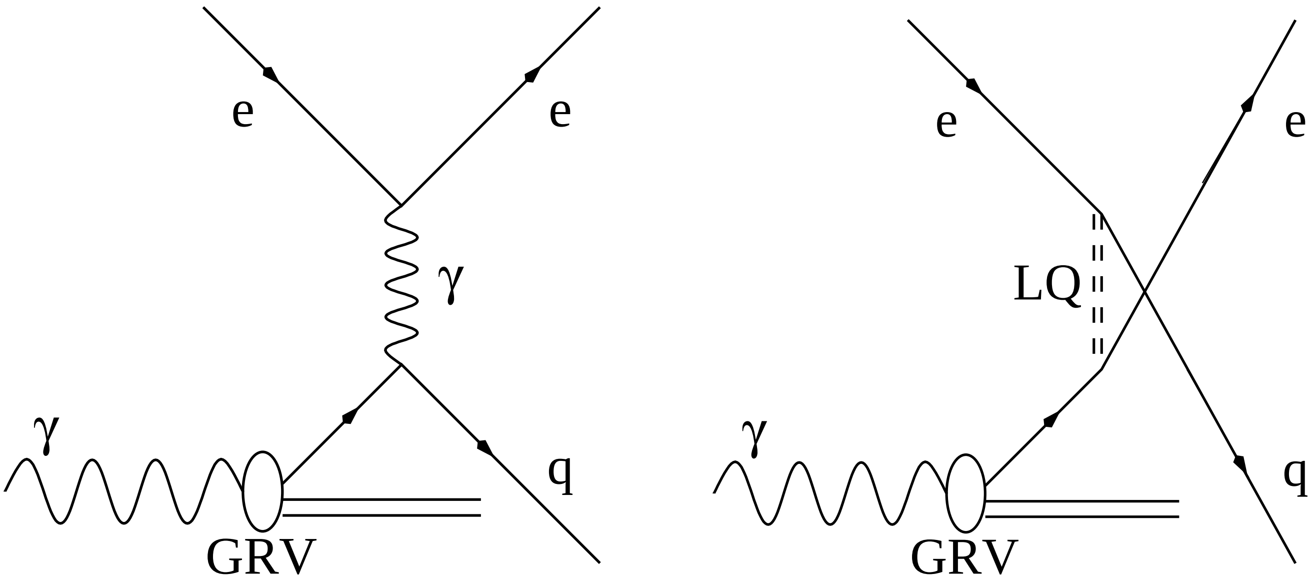
$\Rightarrow$ y cut is tuned (to optimize S/B) for every M_{LQ}

Direct search possible only for $M_{LQ} < \sqrt{s}$

Leptoquark search methods

NC DIS $\frac{d\sigma}{dQ^2}$ measurement

Deep-inelastic scattering $e^{\pm}\gamma \rightarrow e^{\pm}q + X$



$+$ s-channel LQ production diagram

Production and/or exchange of leptoquarks results in deviations in the measured high-Q^2 NC DIS cross-section.

Advantage: sensitive to both $M_{LQ} \gg \sqrt{s}$ and $M_{LQ} \sim \sqrt{s}$

Leptoquark search methods

Indirect limits can also be obtained from

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

Hadronic cross-section is sensitive to the virtual leptoquark exchange. In the limits $M_{LQ} \gg \sqrt{s}$ contact interaction approach can be used.

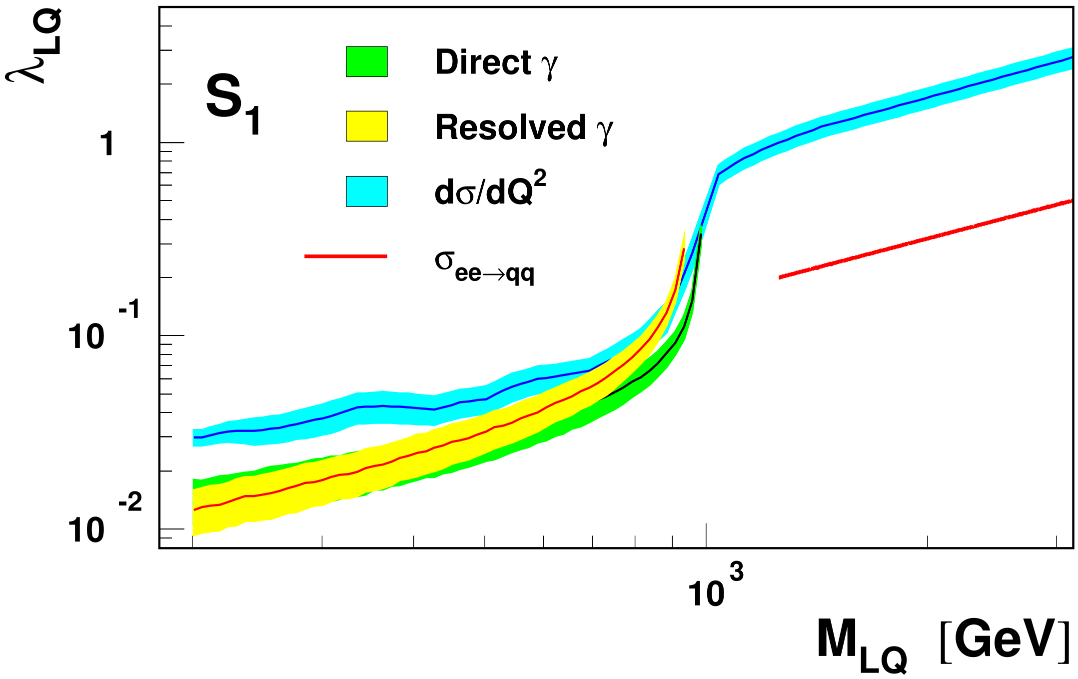
Expected 95% CL exclusion limits on M_{LQ}/λ_{LQ} assuming 1% accuracy in σ_{had} measurements at TESLA:

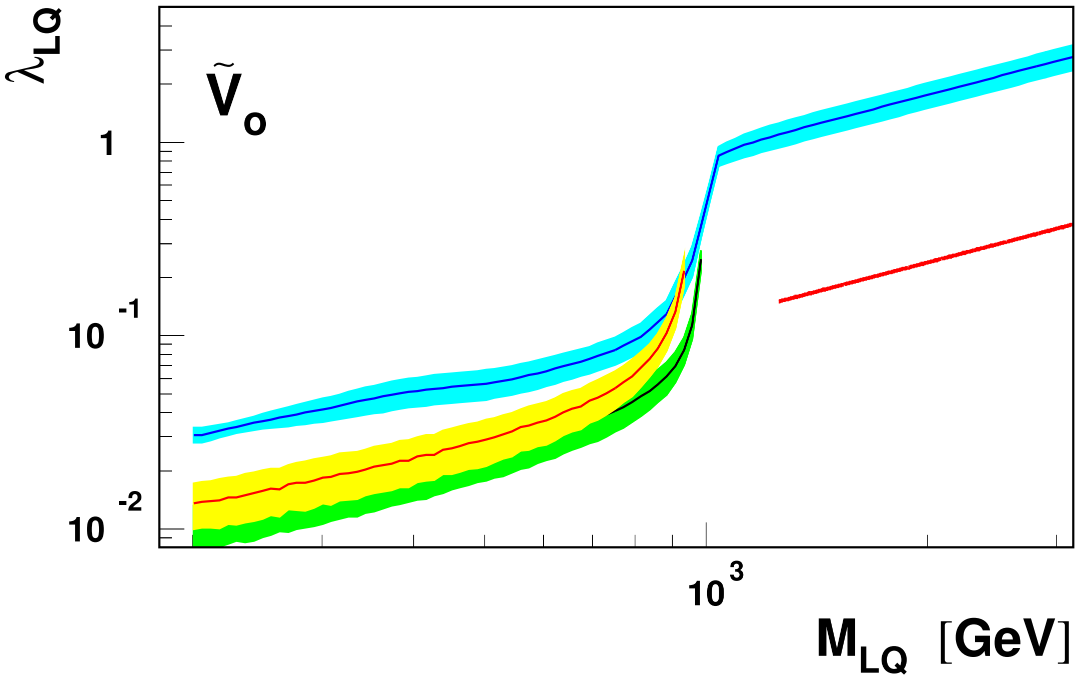
Model	LEP2 limits [TeV]	Expected TESLA limits [TeV]	
		$\sqrt{s}$=0.5 TeV	$\sqrt{s}$=1 TeV
$S^L_\circ$	2.0	3.5	6.7
$S^R_\circ$	1.7	3.0	5.6
$\tilde{S}_\circ$	0.7	2.2	4.5
$S^L_{1/2}$	0.6	2.2	4.5
$S^R_{1/2}$	0.7	2.4	4.9
$\tilde{S}_{1/2}$	0.4	1.3	2.6
S_1	1.0	3.1	6.3
$V^L_\circ$	2.6	4.5	8.5
$V^R_\circ$	0.5	1.6	3.1
$\tilde{V}_\circ$	1.2	4.0	8.4
$V^L_{1/2}$	0.8	2.6	5.4
$V^R_{1/2}$	0.7	2.0	4.0
$\tilde{V}_{1/2}$	0.6	1.6	3.1
V_1	1.6	5.2	11.0

Leptoquark search methods

Comparison of methods

10 fb^{-1} 500 GeV $e^+ \rightarrow\leftarrow e^-$ 500 GeV

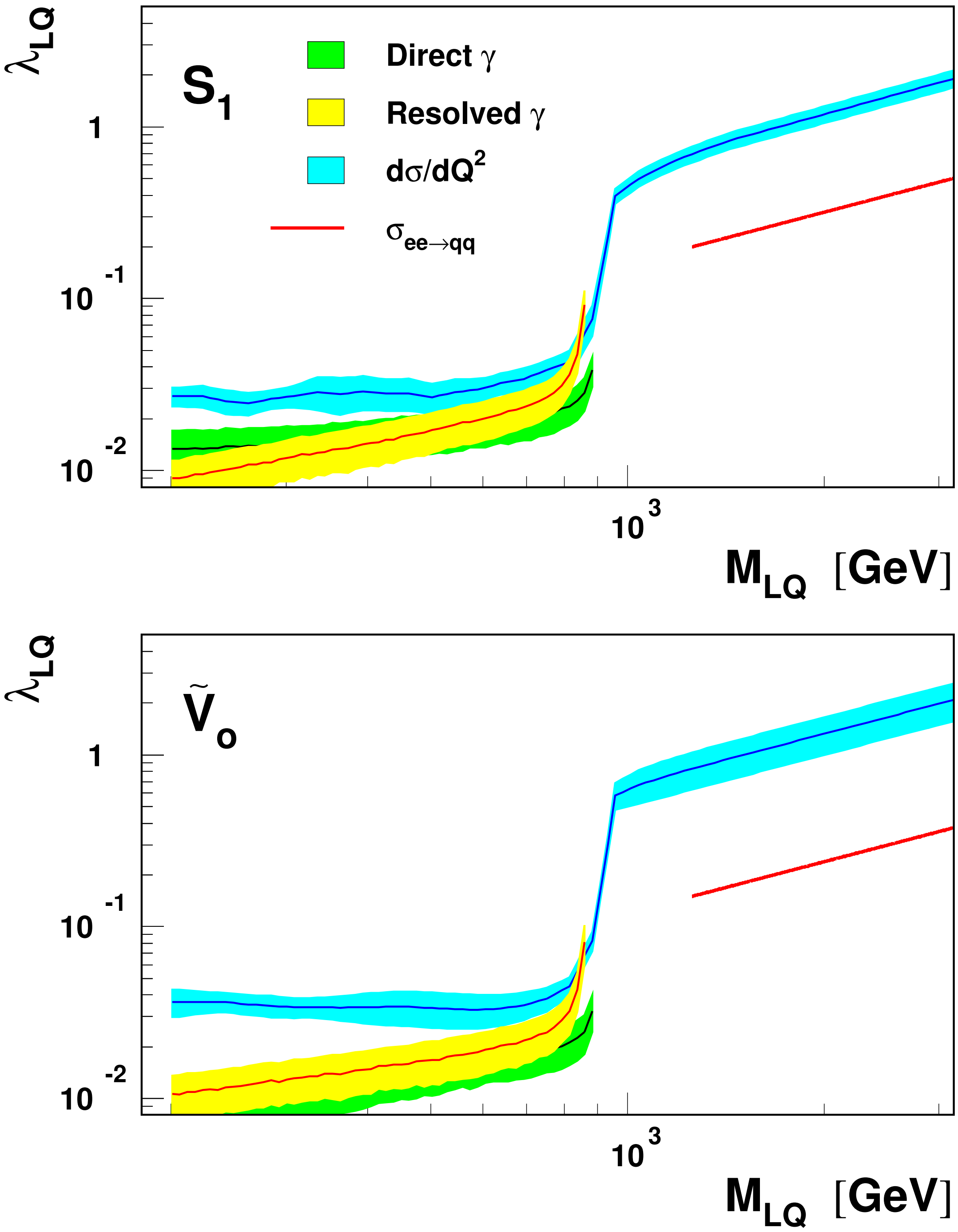




Leptoquark search methods

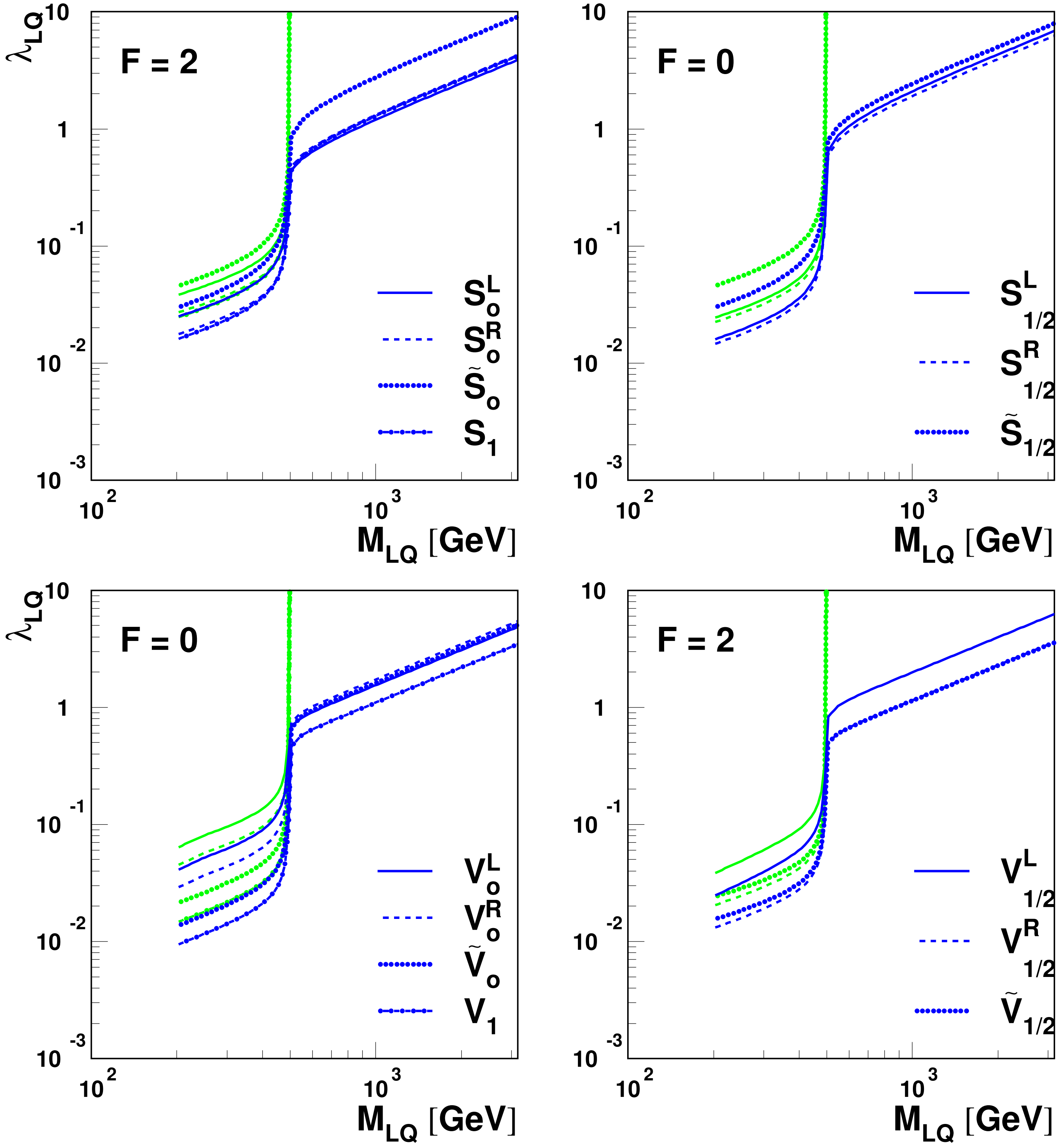
Comparison of methods

10 fb^{-1} 500 GeV e^- $\rightarrow\leftarrow$ γ from 500 GeV e^-



Results

$10\ \mathrm{fb}^{-1}$ 250 GeV $e^+ \rightarrow\leftarrow e^-$ 250 GeV

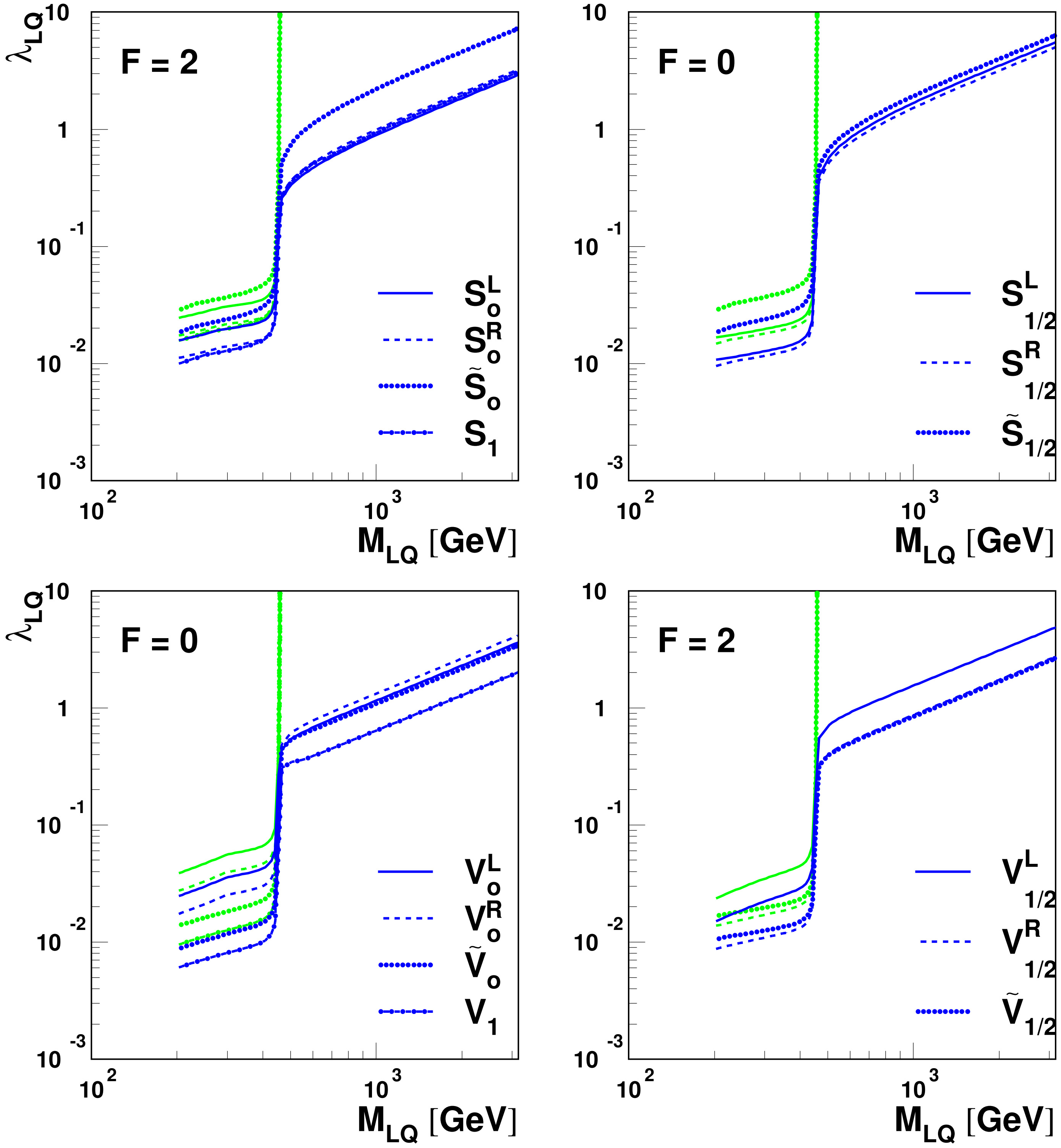


95% CL exclusion limits

5 σ discovery limits

Results

10 fb^{-1} 250 GeV e^- $\rightarrow\leftarrow$ γ from 250 GeV e^-

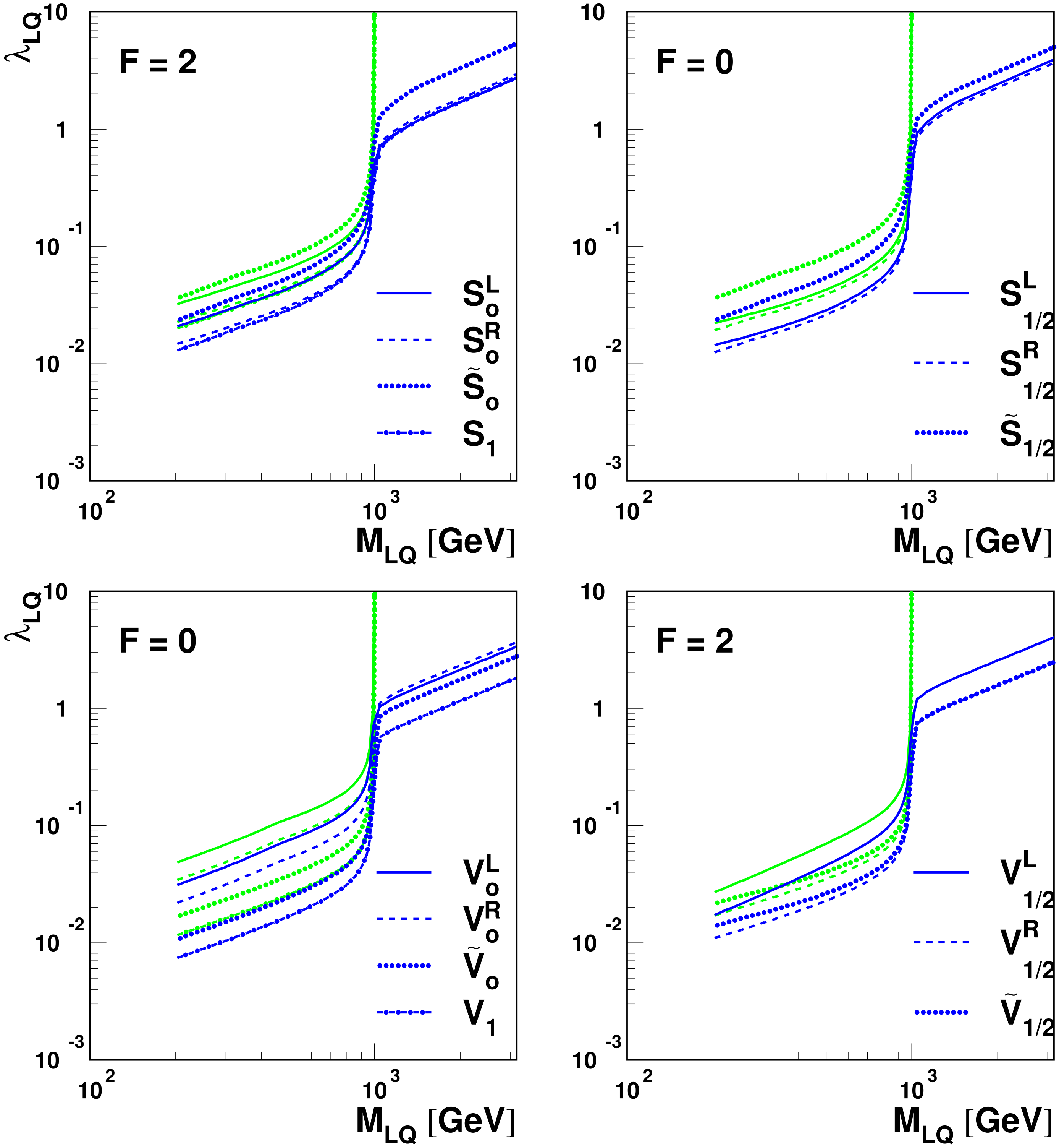


95% CL exclusion limits

5 σ discovery limits

Results

10 fb^{-1} 500 GeV e^+ $\rightarrow\leftarrow$ e^- 500 GeV

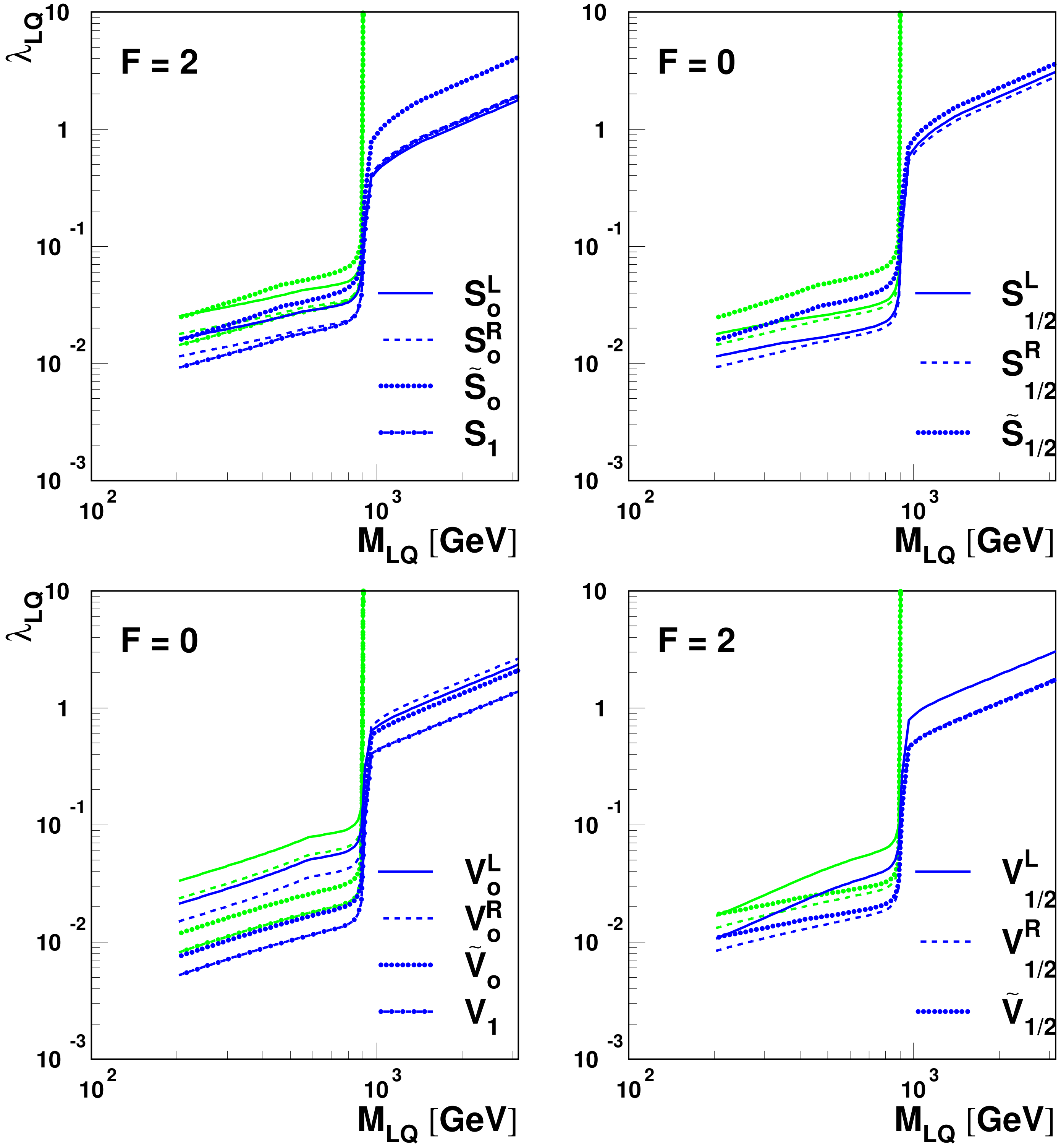


95% CL exclusion limits

5 σ discovery limits

Results

10 fb^{-1} 500 GeV e^- $\rightarrow\leftarrow$ γ from 500 GeV e^-



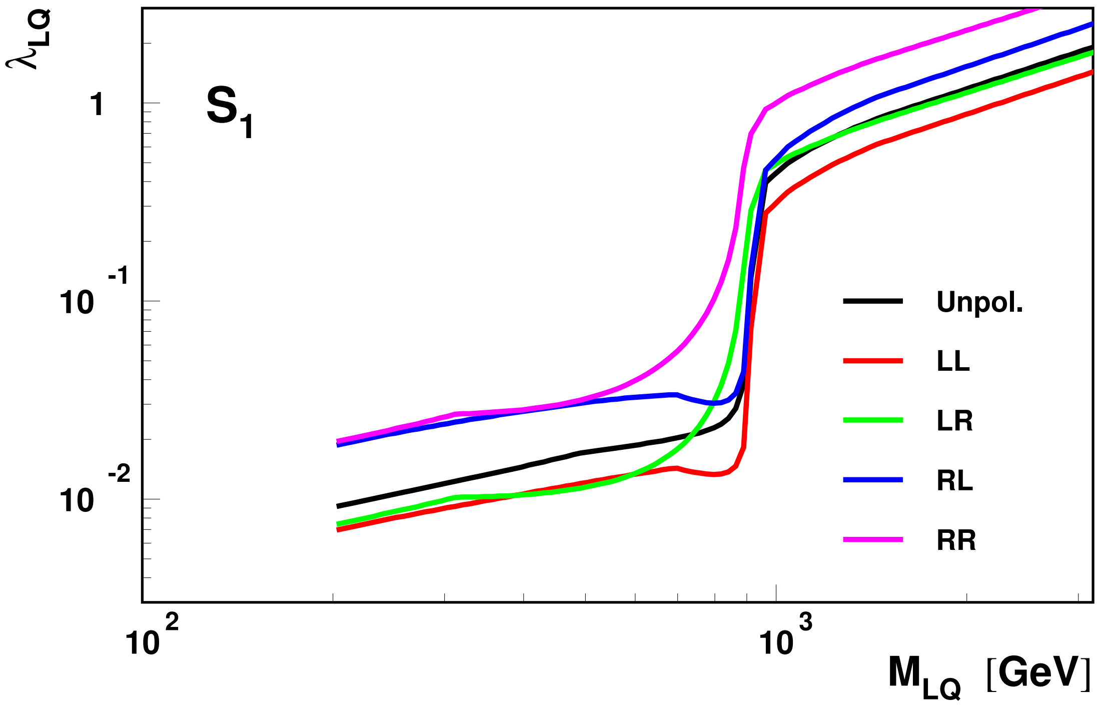
95% CL exclusion limits

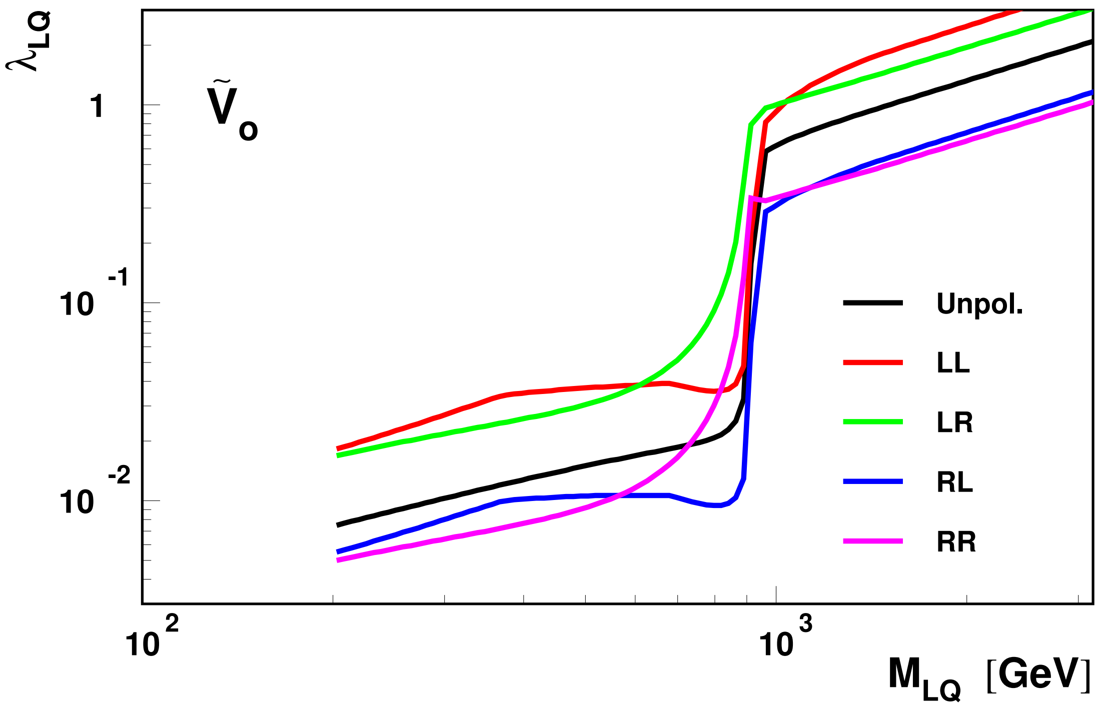
5 σ discovery limits

Results

Polarization

10 fb^{-1} 500 GeV e^- $\rightarrow\leftarrow$ γ from 500 GeV e^-

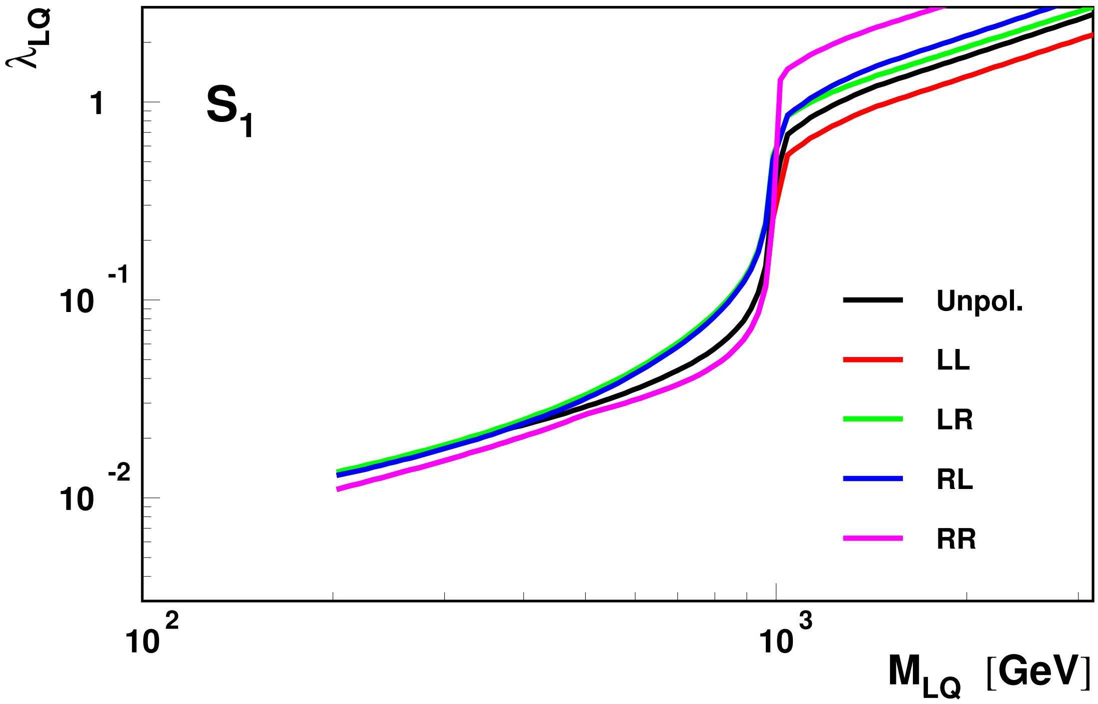


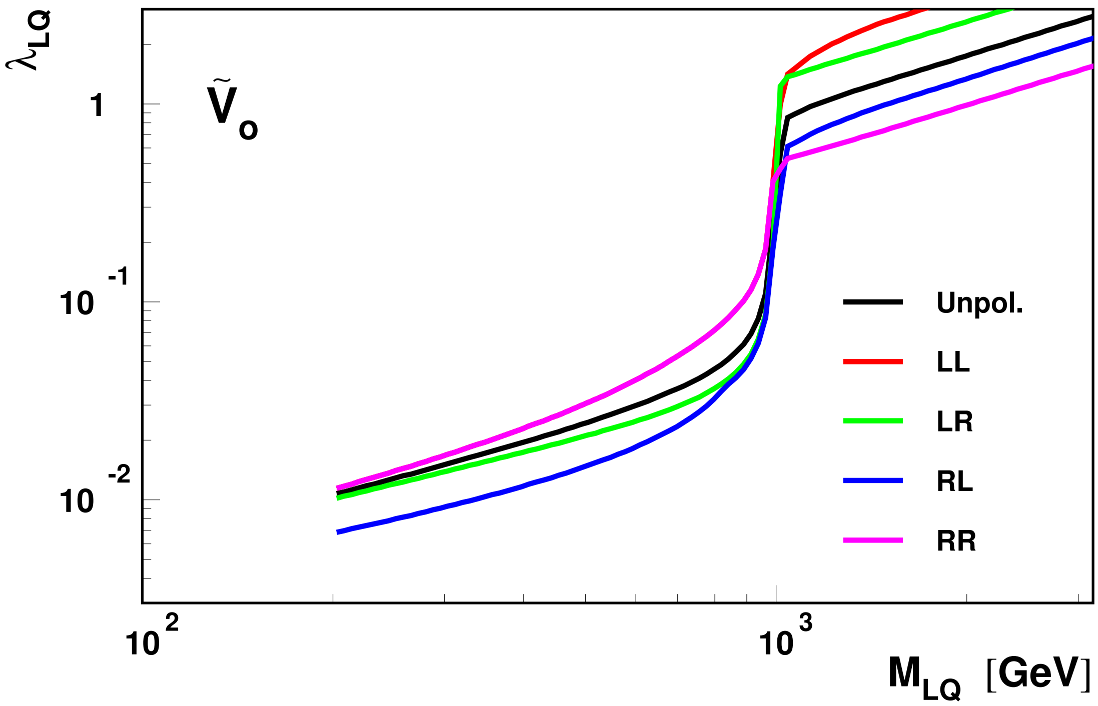


Results

Polarization

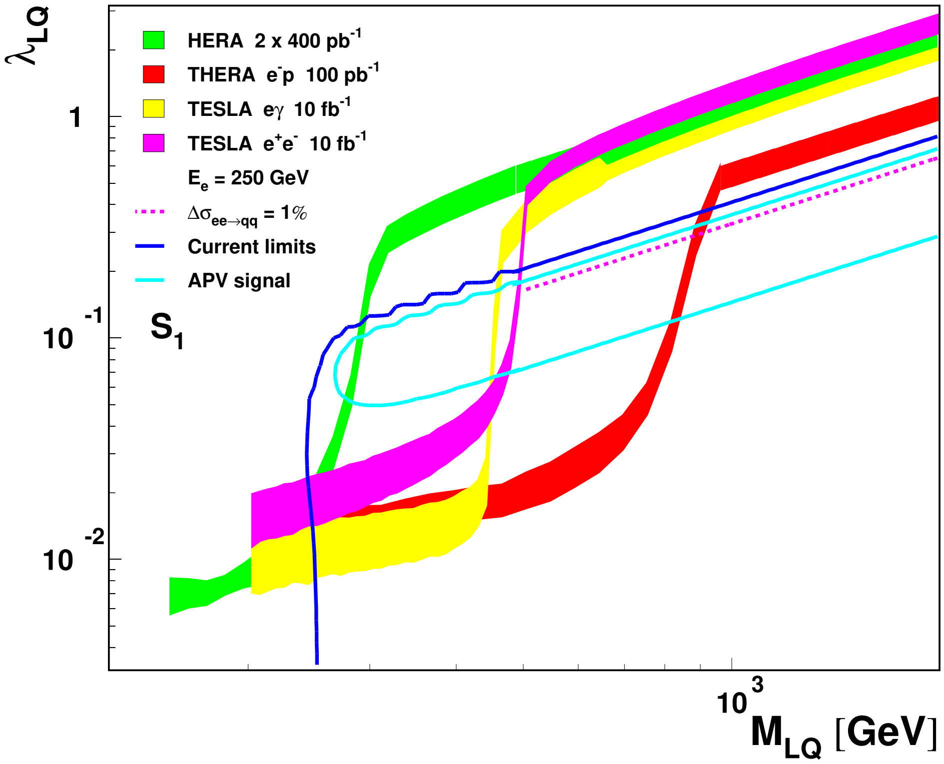
10 fb^{-1} 500 GeV e^- $\rightarrow\leftarrow$ e^+ 500 GeV

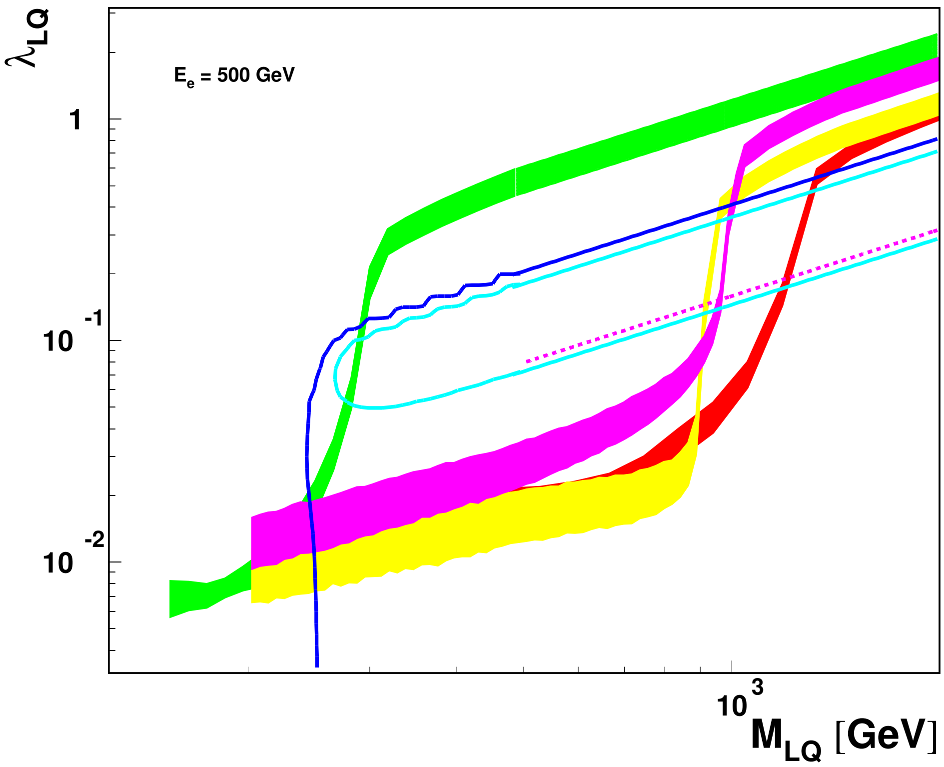




Results

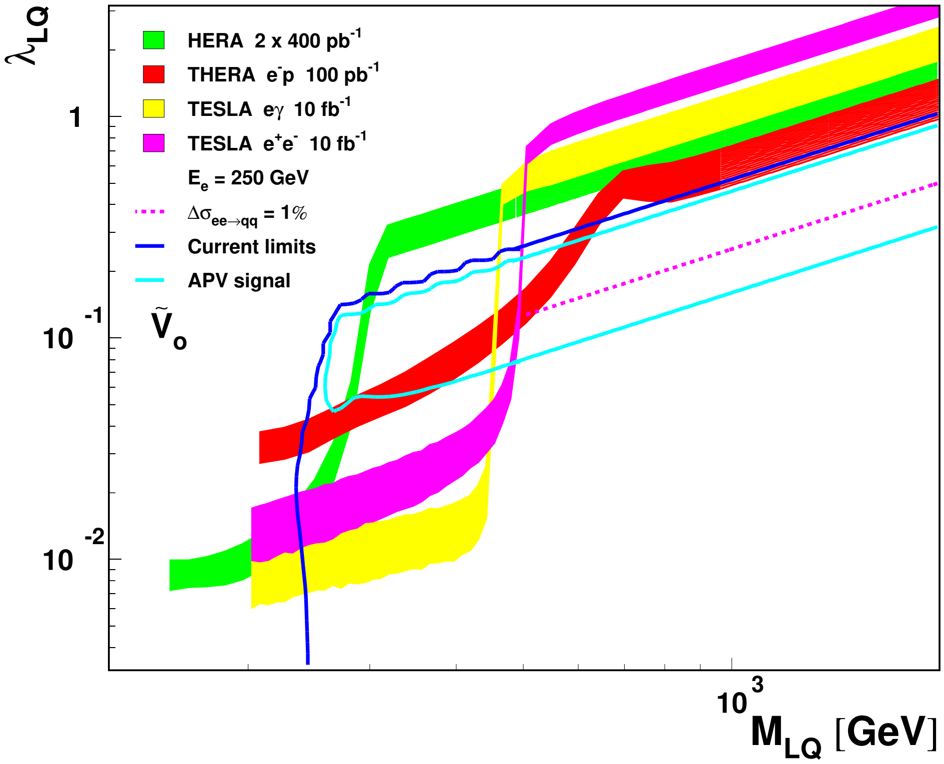
Comparison of experiments

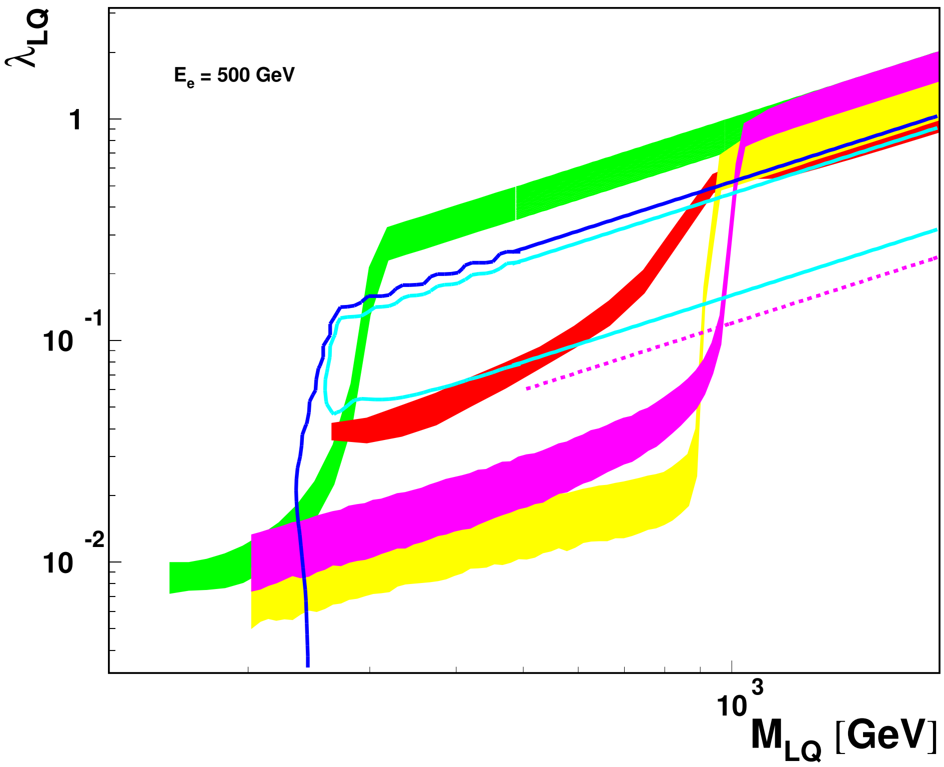




Results

Comparison of experiments





Summary

- Some recent data indicate possible deviations from the Standard Model predictions...
- Possible signal for "new physics" observed for:

$\Rightarrow$ d_{LL} contact interaction model

$$\Lambda \sim 13.2 \text{ TeV}$$

$\Rightarrow$ S_1 leptoquark model

$$\lambda/M \sim 0.28 \text{ TeV}^{-1}$$

$\Rightarrow$ $\tilde{V}_\circ$ leptoquark model

$$M = 276 \pm 7 \text{ GeV}$$
$$\lambda = 0.095 \pm 0.015$$

- $e^{\pm}\gamma$ scattering sensitive to leptoquark couplings down to

$$\lambda_{LQ} \sim 0.01 \qquad \text{for } \mathcal{L} = 10 fb^{-1}$$
$$\lambda_{LQ} \sim 0.003 \qquad \text{for } \mathcal{L} = 500 fb^{-1}$$

and for masses M_{LQ} up to the very kinematic limit

- limits from e^+e^- scattering weaker than those from $e^{\pm}\gamma$, especially close to the kinematic limits

- limits from very precise measurement of $\sigma(e^+e^- \rightarrow q\bar{q})$ competitive to those from direct search and NC DIS