Leptoquarks and Contact Interactions at LeHC

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Outline:

- Introduction
- LQ model
- CI approach
- Results

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Introduction

Analysis

Presented analysis was developed in 2000/2001 as a contribution to TESLA TDR (February 2001) and the THERA Book (December 2001).

Results were also published in :
A.F.Zarnecki, Acta Phys.Polon.B33 (2002) 619-640 [e-Print: hep-ph/0104107]

LeHC

Same approach (with only minor modifications) has been used since 2005 to demonstrate physics capabilities of ep upgrade option of LHC.

Current update was prepared assuming following scenarios:

- electron/positron energy of 70 GeV, luminosities of 2×10 or 2×100 fb^{-1}
- electron/positron energy of 140 GeV, luminosities of 2×1 or 2×10 fb^{-1}

Leptoquarks

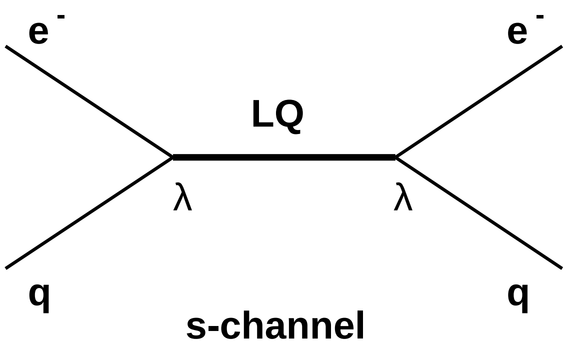
BRW model

Buchmüller-Rückl-Wyler

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance
- lepton and baryon number conservation
- strong bounds from rare decays
  $\Rightarrow$ either left- or right-handed couplings
- family diagonal

$\Rightarrow$ 7 scalar and 7 vector leptoquarks

First generation LQ can be produced as an s-channel resonance in the $e^{\pm}p$ collisions.



Fermion number - F

- F=0 resonances in $e^{+}q$
- F=2 resonances in $e^{-}q$

Leptoquarks

Narrow width approximation

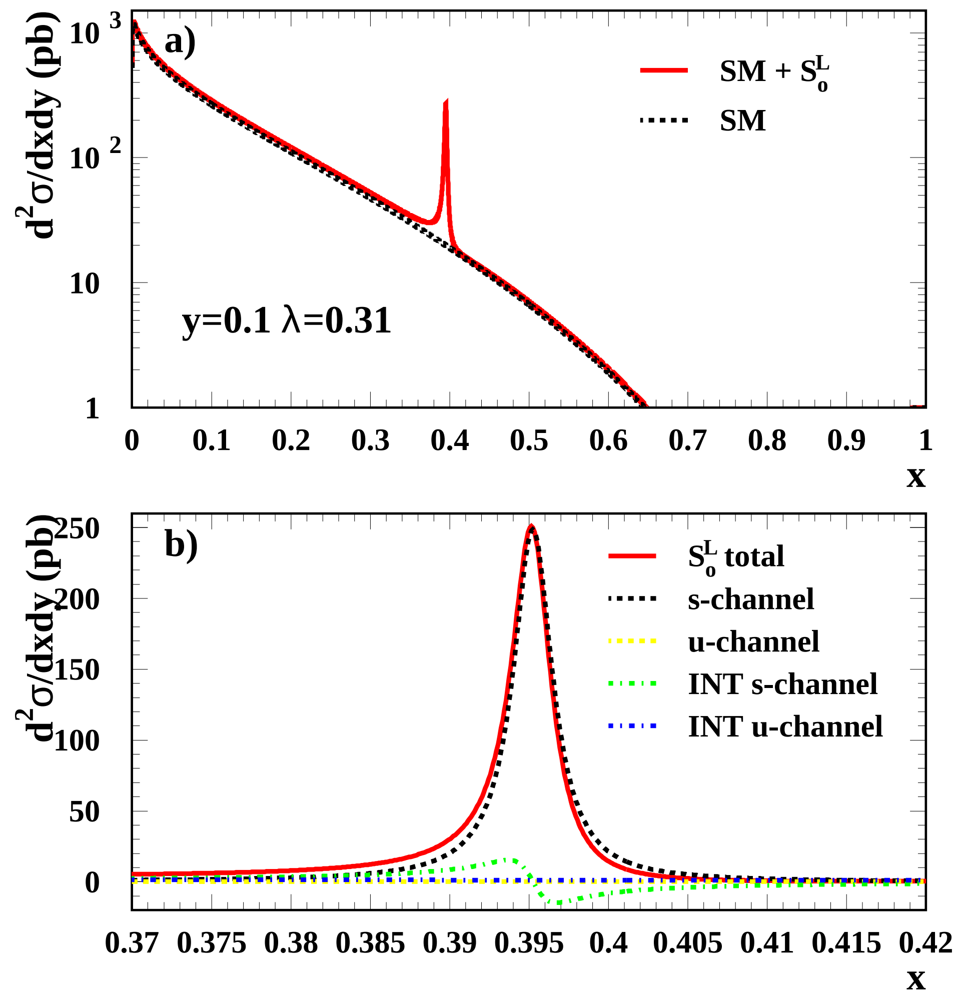
Leptoquark width

$$\Gamma_{LQ} = \frac{\lambda_{LQ}^2 M_{LQ}}{8\pi(J+2)}$$

M_{LQ} - leptoquark mass

$J = 0, 1$ - leptoquark spin

λ_{LQ} - Yukawa coupling
leptoquark-electron-quark



If the width is small and $M_{LQ} \ll \sqrt{s_{ep}}$
production cross section:

$$\sigma^{NWA} = (J+1)\frac{\pi}{4s}\lambda_{LQ}^2 q(x_0, \mu^2)$$

Interference effects can be neglected.

Leptoquarks

Limit setting

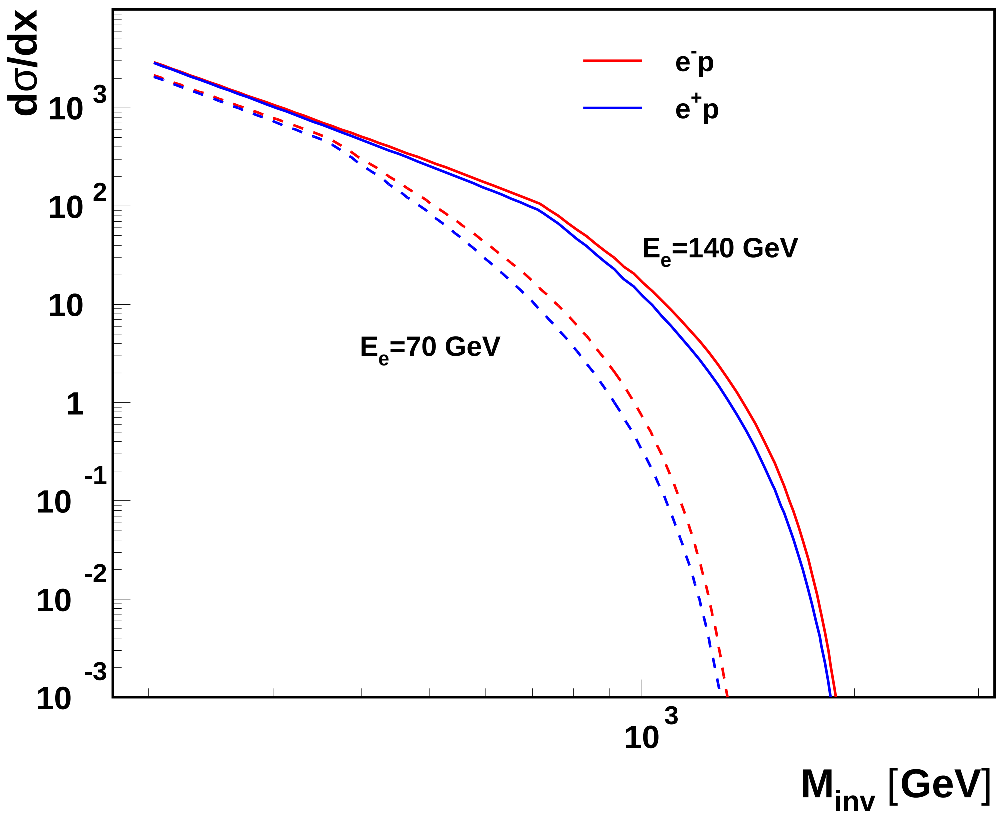
For $M_{LQ} \ll \sqrt{s_{ep}}$ and small λ_{LQ} we expect narrow resonance in $\frac{d\sigma}{dM_{eq}}$.

If no such resonance is observed, we can set λ_{LQ} limits based on numbers of events measured in bins of electron-quark invariant mass:

$$M_{inv} \;=\; \sqrt{x \cdot s_{ep}}$$

Leptoquarks with masses up to about 1 TeV can be searched for.

NC DIS cross section at LeHC



Leptoquarks

Limit setting

NS DIS background suppressed by additional cut on:

$$y \;=\; 0.5 \cdot (1 - cos\theta^{\star})$$

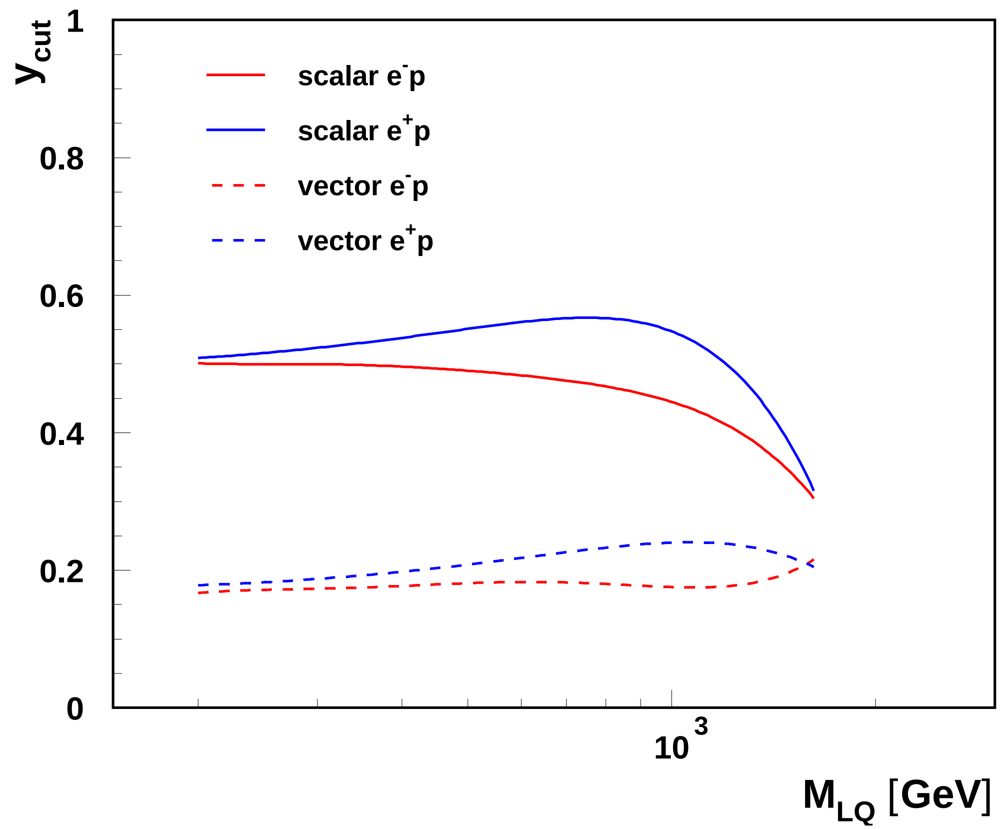
$\theta^{\star}$ - e scattering angle in eq rest frame

NC DIS background cross section largest at low y: $\frac{d\sigma^{e^{\pm}p}}{dy} \sim \frac{1}{y^2}$

Scalar Leptoquarks: $\left.\frac{d\sigma}{dy}\right|_S \sim$ const

Vector Leptoquarks: $\left.\frac{d\sigma}{dy}\right|_V \sim (1-y)^2$

Optimized cut on y for E_e =140 GeV



CI approach

CI limit

In the limit $M_{LQ} \gg \sqrt{s_{ep}}$ both virtual LQ production (s-channel) and exchange (u-channel) important. Cross section can be described by an effective $eeqq$ coupling:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta} \cdot \left(\frac{\lambda_{LQ}}{M_{LQ}} \right)^2$$

Effective Lagrangian for vector $eeqq$ contact interactions:

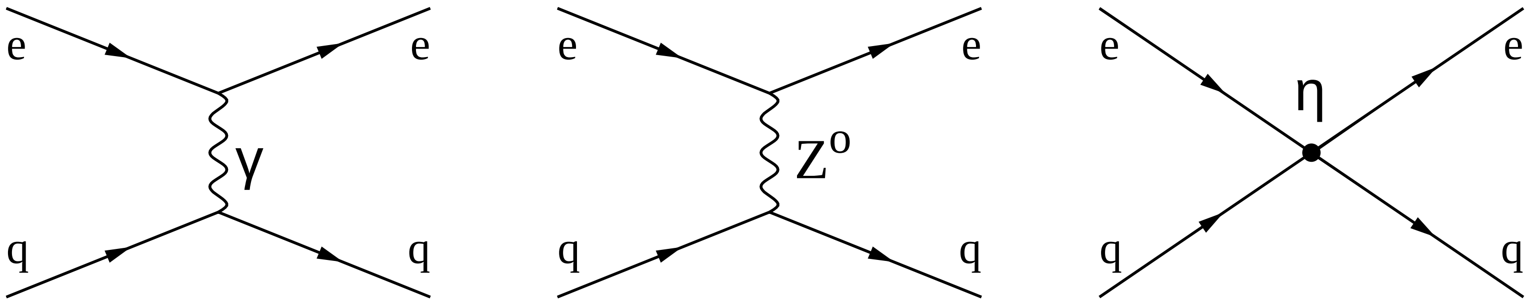
$$\mathcal{L}_{CI} = \sum_{\substack{\alpha,\beta=L,R \\ q}} \eta^{eq}_{\alpha\beta} \cdot (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

Model	a^{ed}_{LL}	a^{ed}_{LR}	a^{ed}_{RL}	a^{ed}_{RR}	a^{eu}_{LL}	a^{eu}_{LR}	a^{eu}_{RL}	a^{eu}_{RR}
$S^L_\circ$					$+\frac{1}{2}$			
$S^R_\circ$								$+\frac{1}{2}$
$\tilde{S}_\circ$				$+\frac{1}{2}$				
$S^L_{1/2}$						$-\frac{1}{2}$		
$S^R_{1/2}$			$-\frac{1}{2}$				$-\frac{1}{2}$	
$\tilde{S}_{1/2}$		$-\frac{1}{2}$						
S_1	$+1$				$+\frac{1}{2}$			
$V^L_\circ$	-1							
$V^R_\circ$				-1				
$\tilde{V}_\circ$								-1
$V^L_{1/2}$		$+1$						
$V^R_{1/2}$			$+1$				$+1$	
$\tilde{V}_{1/2}$						$+1$		
V_1	-1				-2			

CI approach

Contact Interactions

Contact Interactions modify tree level $eq \rightarrow eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$:



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

γ Z° LQ

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

$e^- p$ NC DIS sensitive mostly to η^{eq}_{LL} and η^{eq}_{RR}

$e^+ p$ NC DIS sensitive mostly to η^{eq}_{LR} and η^{eq}_{RL} (q=u,d)

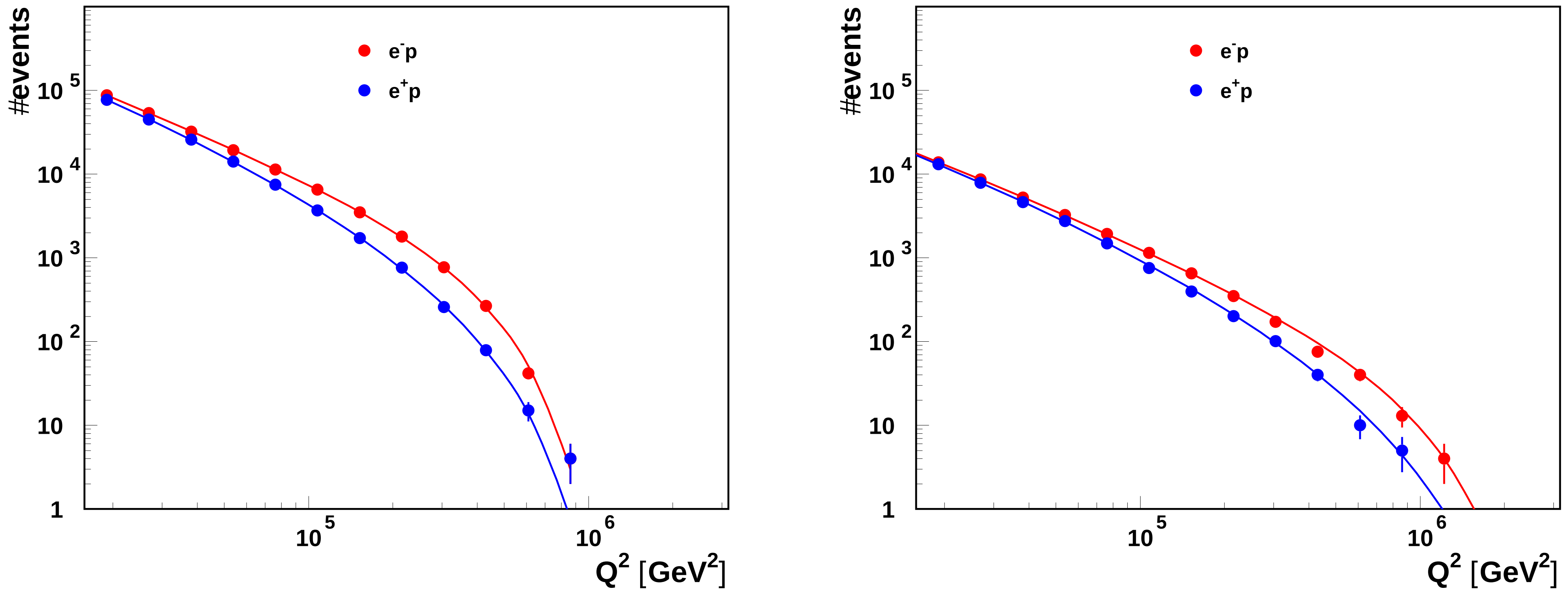
Different LQ models correspond to different helicity structure of new interactions

CI approach

Limit setting

In the CI approximation $\frac{\lambda_{LQ}}{M_{LQ}}$ limits can be derived from measured high-Q^2 NC DIS

$E_e = 70$ GeV $\quad 2 \times 10 fb^{-1}$ $\qquad$ $E_e = 140$ GeV $\quad 2 \times 1 fb^{-1}$



SM expectations systematic uncertainty of 5% assumed for $Q^2 \sim 10^5 GeV^2$

CI approach

Intermediate masses

For $M_{LQ} \sim \sqrt{s}$ neither NWA nor CI limit can be used.

Limits are derived from high-Q^2 NC DIS using "modified CI" approach.

LQ contribution to scattering amplitudes:

- s-channel LQ production:

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

where

$$\hat{s} = x s_{ep} > 0$$

- u-channel LQ exchange:

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

where

$$\hat{u} = -\hat{s} - \hat{t} = -x(1-y)s_{ep} < 0$$

Full LO cross section, including interference effects.

CI approach

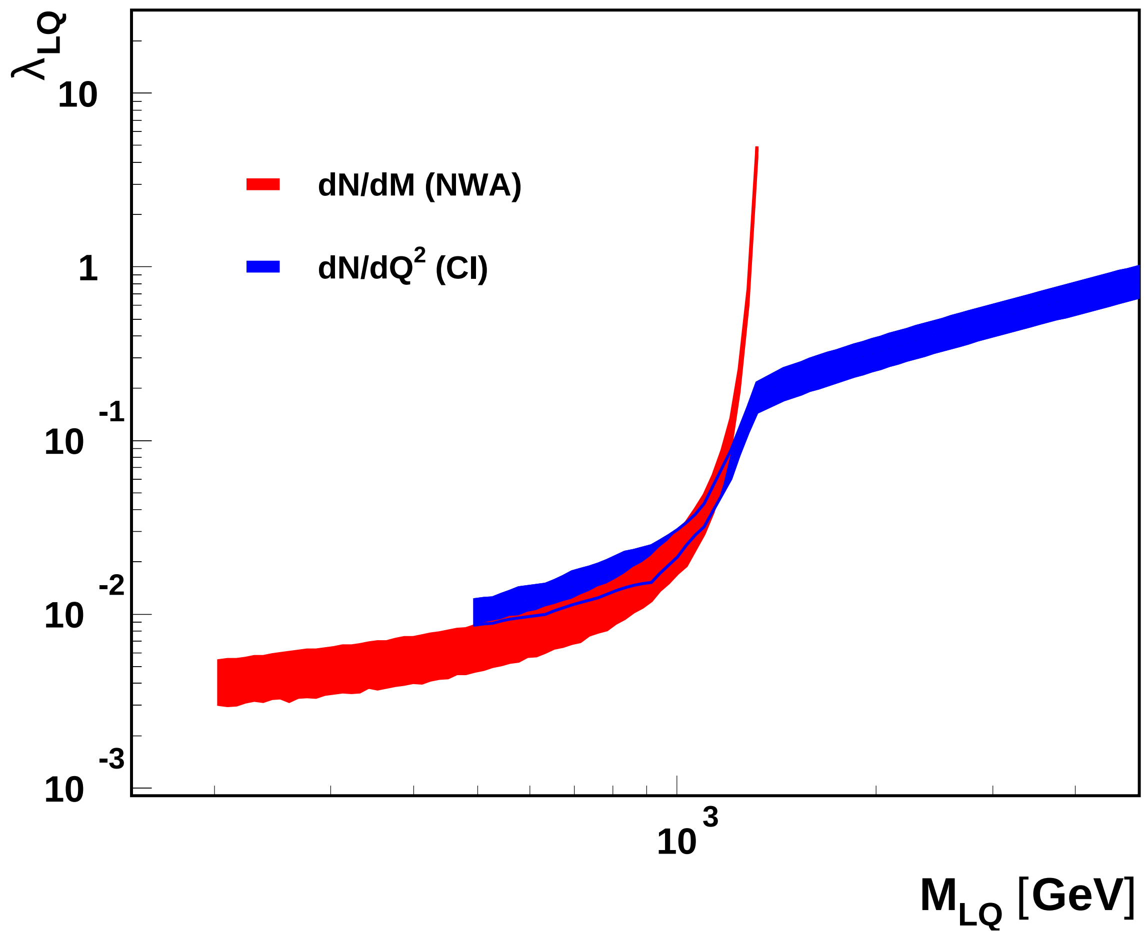
Comparison of limits

Modified CI approach can be used also for $M_{LQ} < \sqrt{s}$.

However, for low masses NWA gives better limits.

Width of the limit distributions: expected statistical fluctuations from simulation of multiple MC experiments

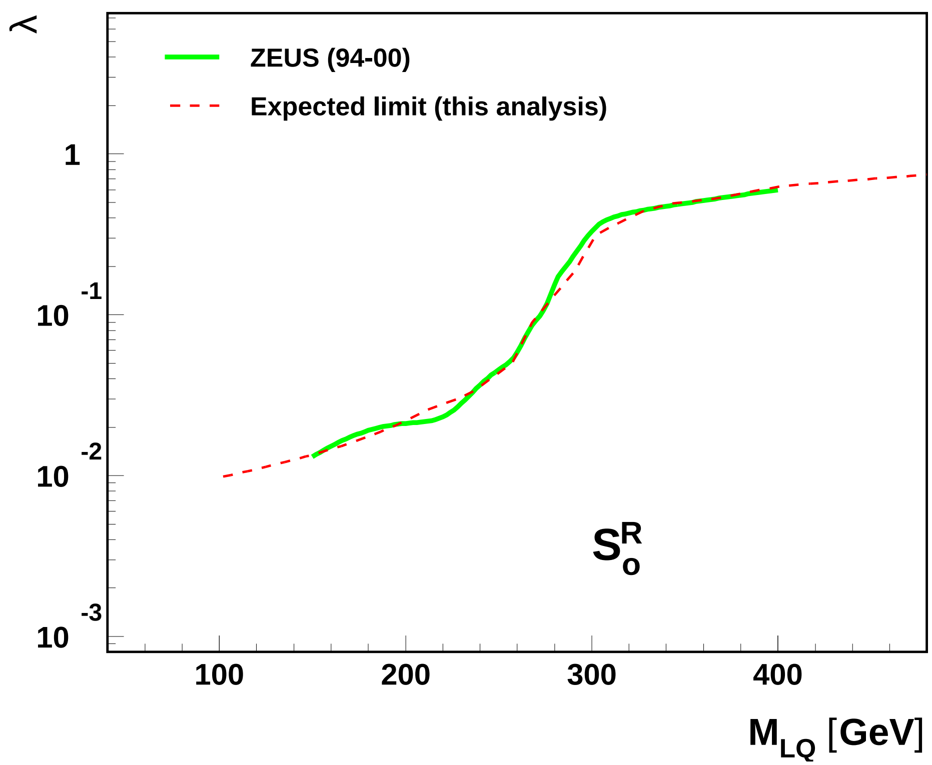
Expected S_0^L limits for $E_e = 70$ GeV, $2 \times 10 fb^{-1}$

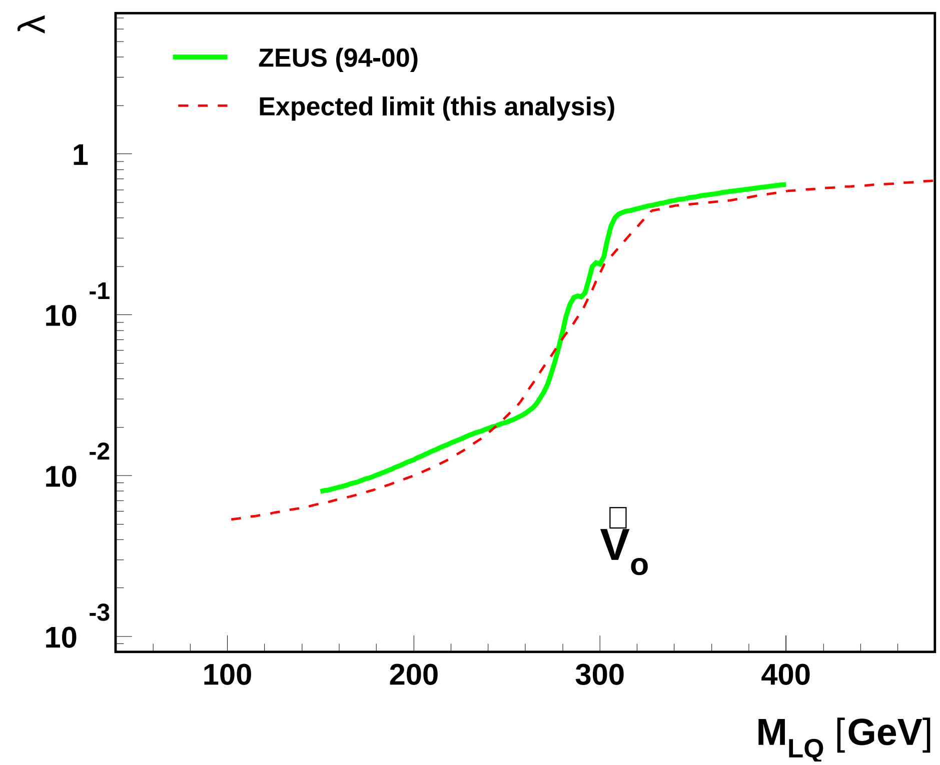


Results

Comparison of limits

Expected limits from NWA $\oplus$ CI method, compared with ZEUS 94-00 results





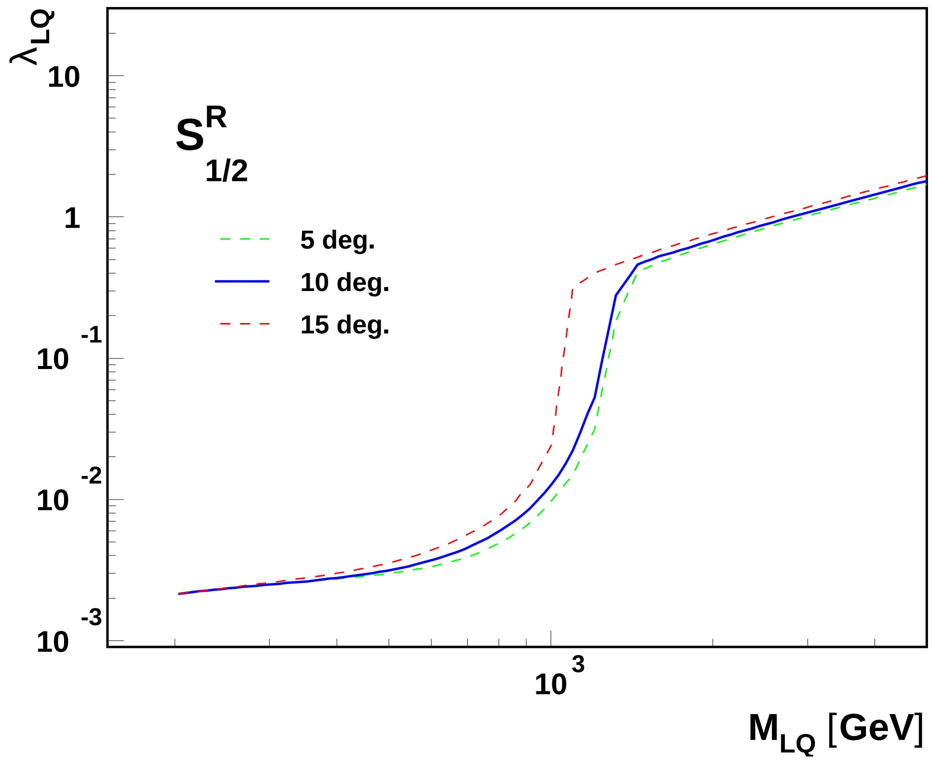
Very good agreement with detailed experimental study.

Results

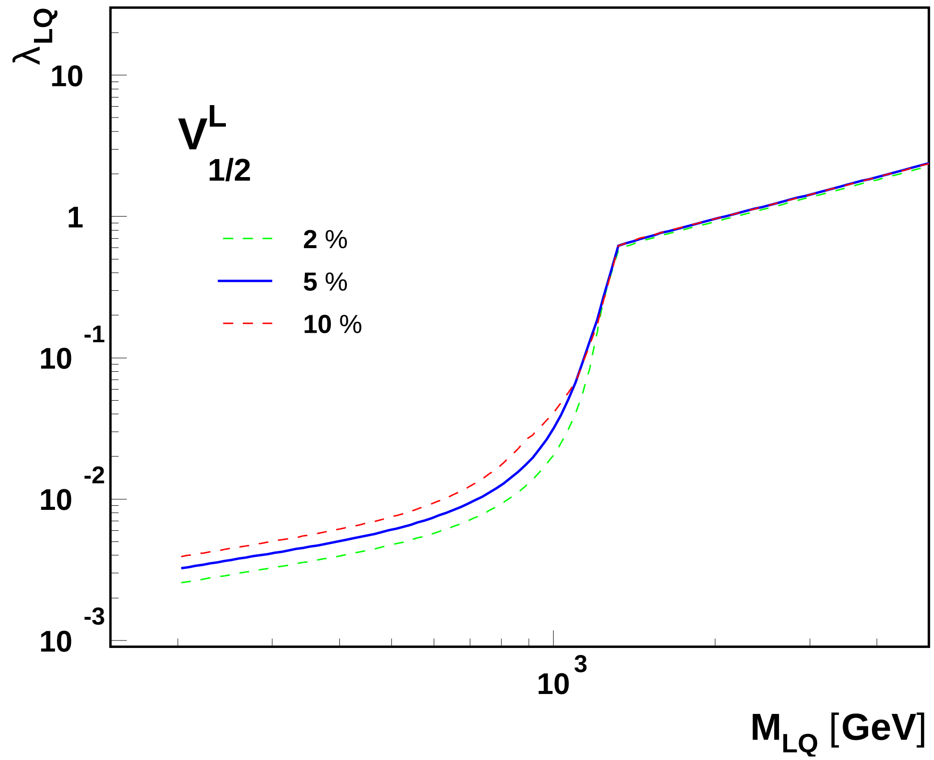
Experiment at LeHC

Expected limits depend also on the assumed detector parameters

Angular coverage: (default: 10°)



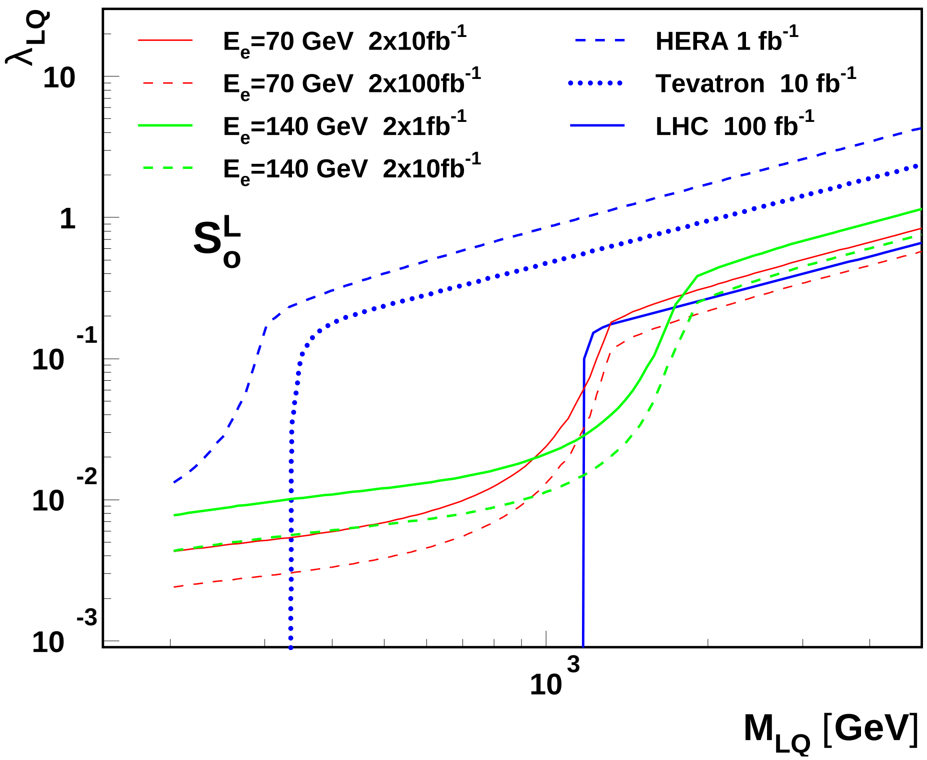
Mass resolution: (default: 5%)

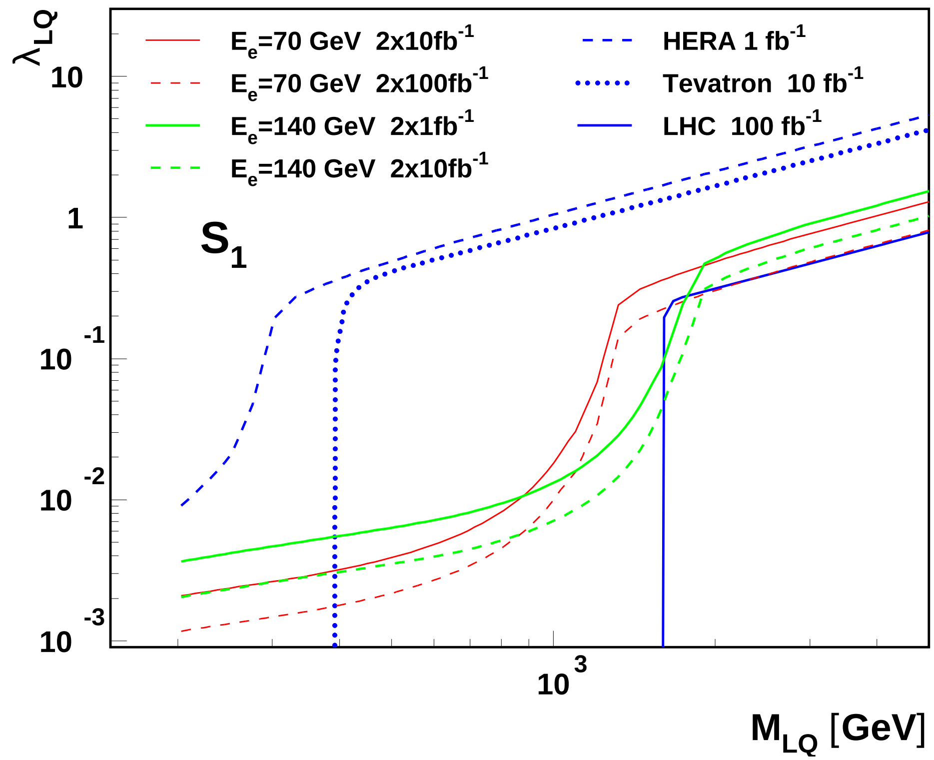


Results

Expected scalar LQ limits

Comparison of expected LQ limits from LeHC,
with expected limits from HERA (new), as well as from Tevatron and LHC (2001).

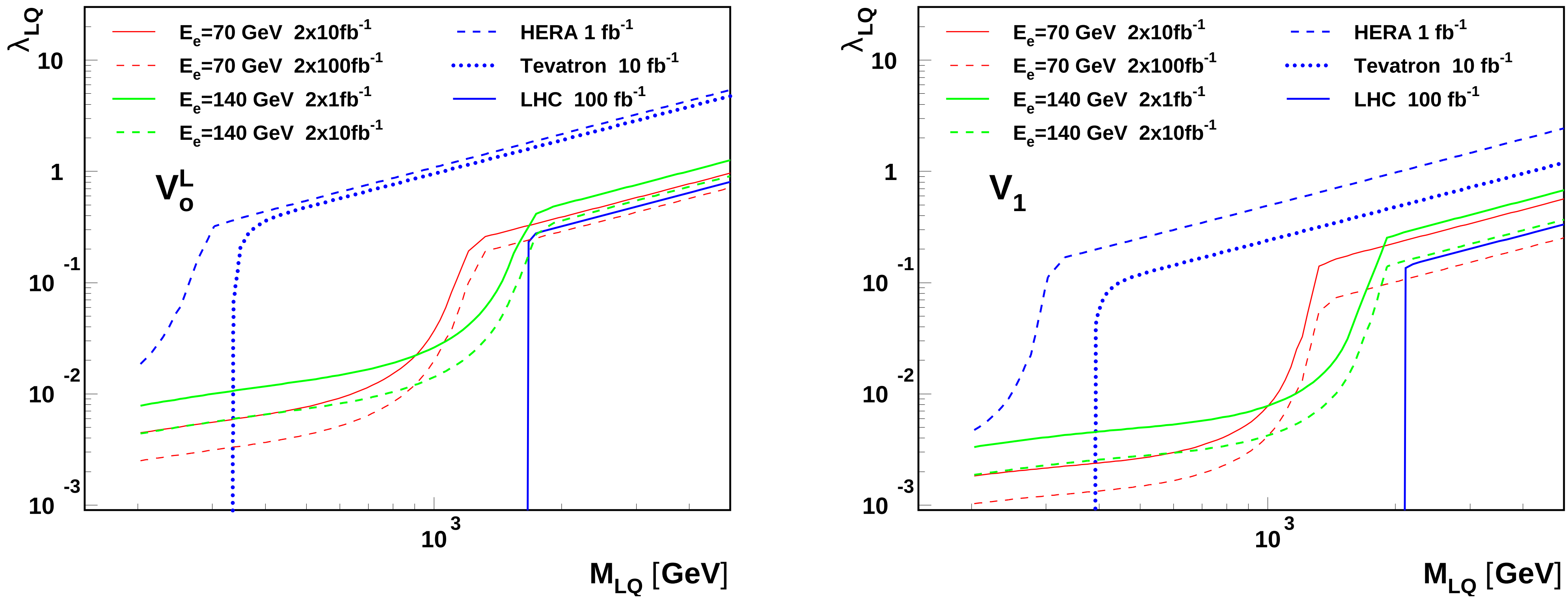




Results

Expected vector LQ limits

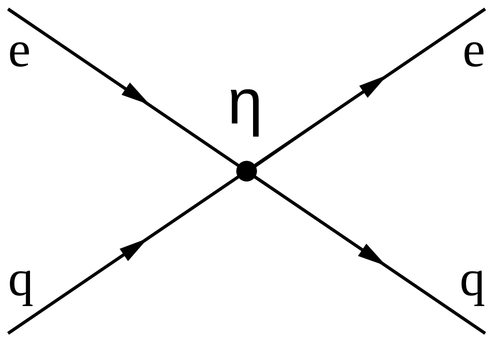
Comparison of expected LQ limits from LeHC,
with expected limits from HERA (new), as well as from Tevatron and LHC (2001).



CI Models

New physics in eq scattering

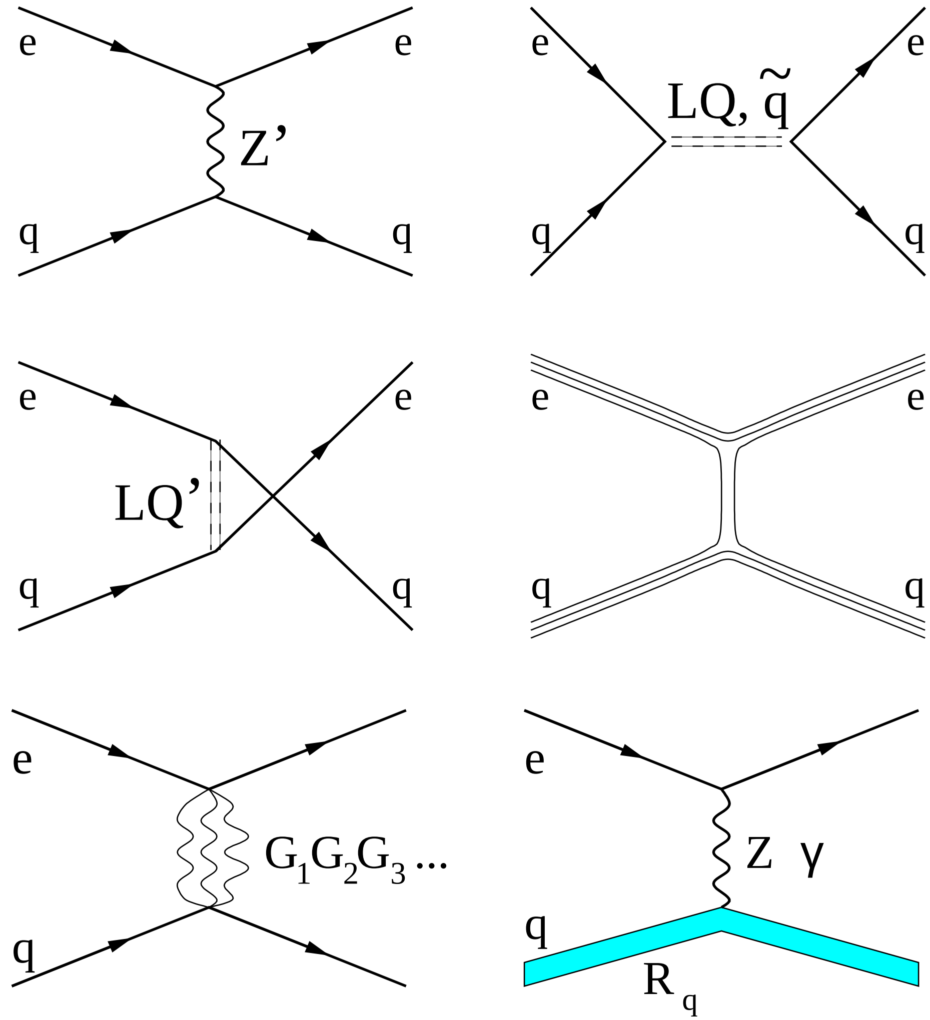
Contact interactions can be used to describe many "new physics" phenomena at energy scales $\sqrt{s_{ep}}$ much smaller than "new" scale



Considered in this analysis:

- general CI models
- large extra dimensions
- quark form factor

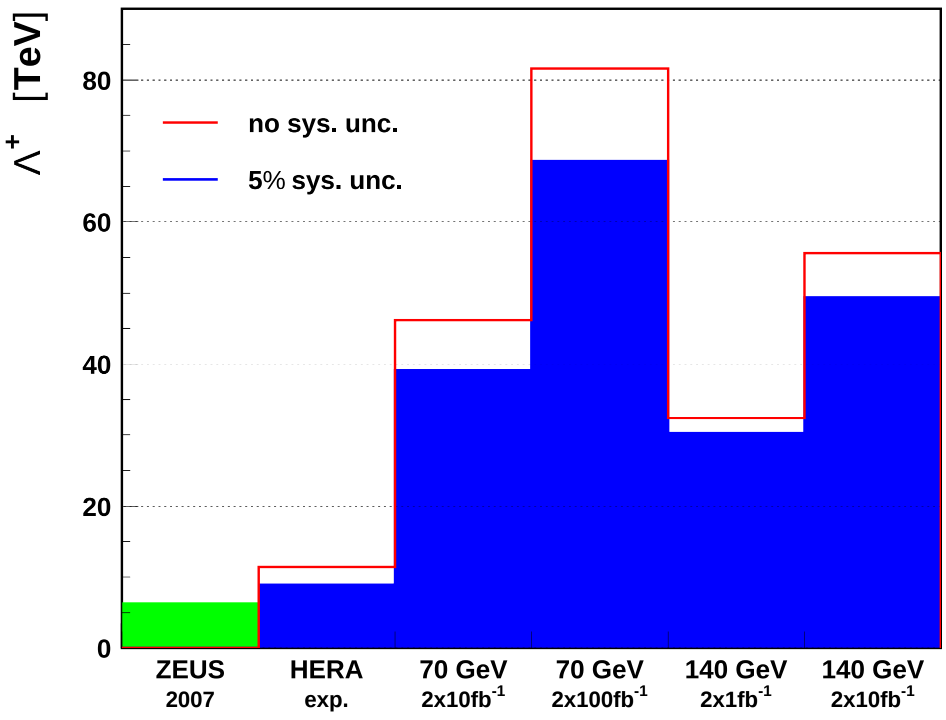
Possible "new physics" processes:



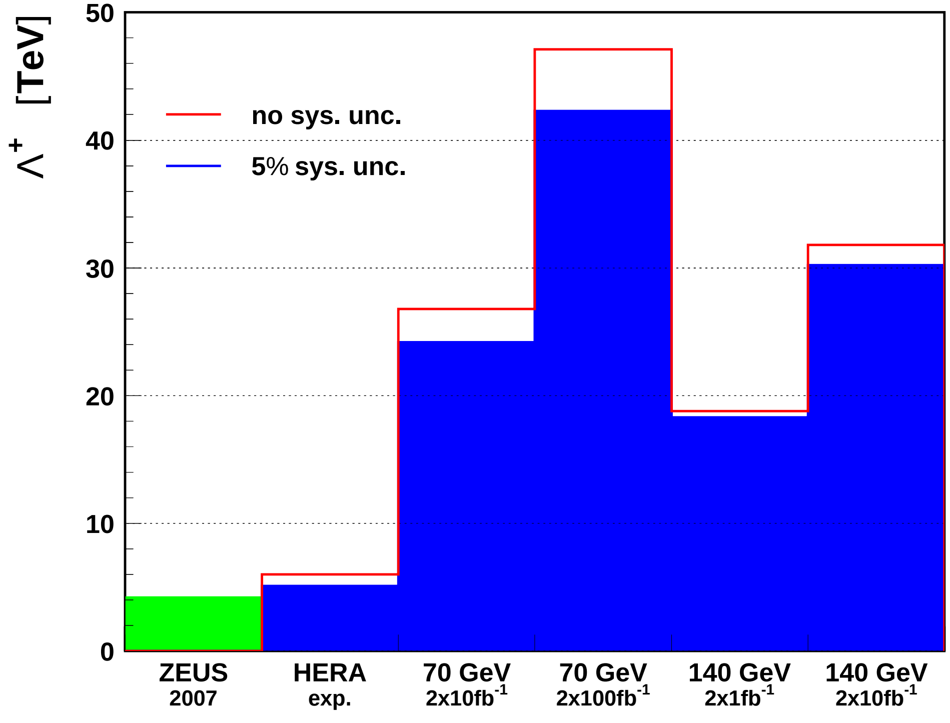
Results

Expected limits for general CI models

VV model (conserving parity)



LL model (violating parity)



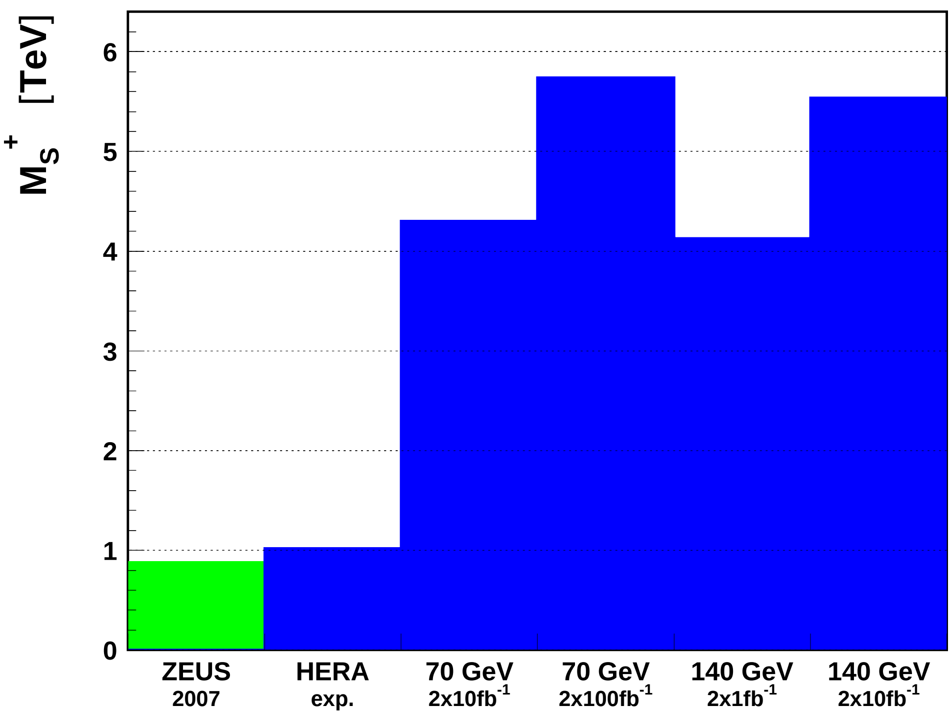
Understanding of systematics important !

Similar limits for Λ^-

Results

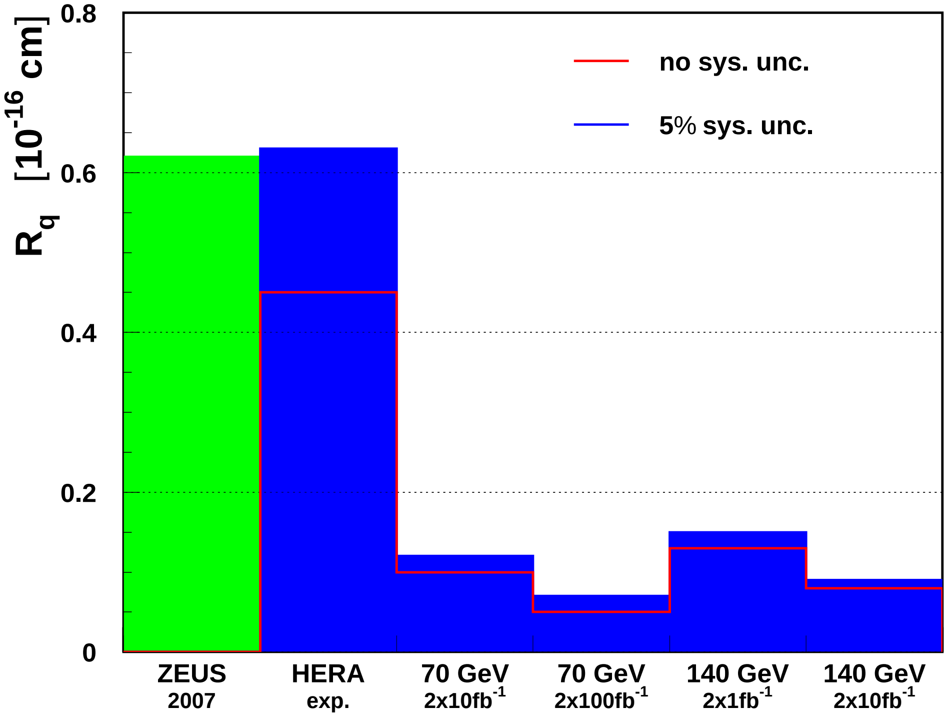
Expected limits for other CI models

AAD model (Large Extra Dimensions)



Similar limits for M_S^-

Quark form factor model

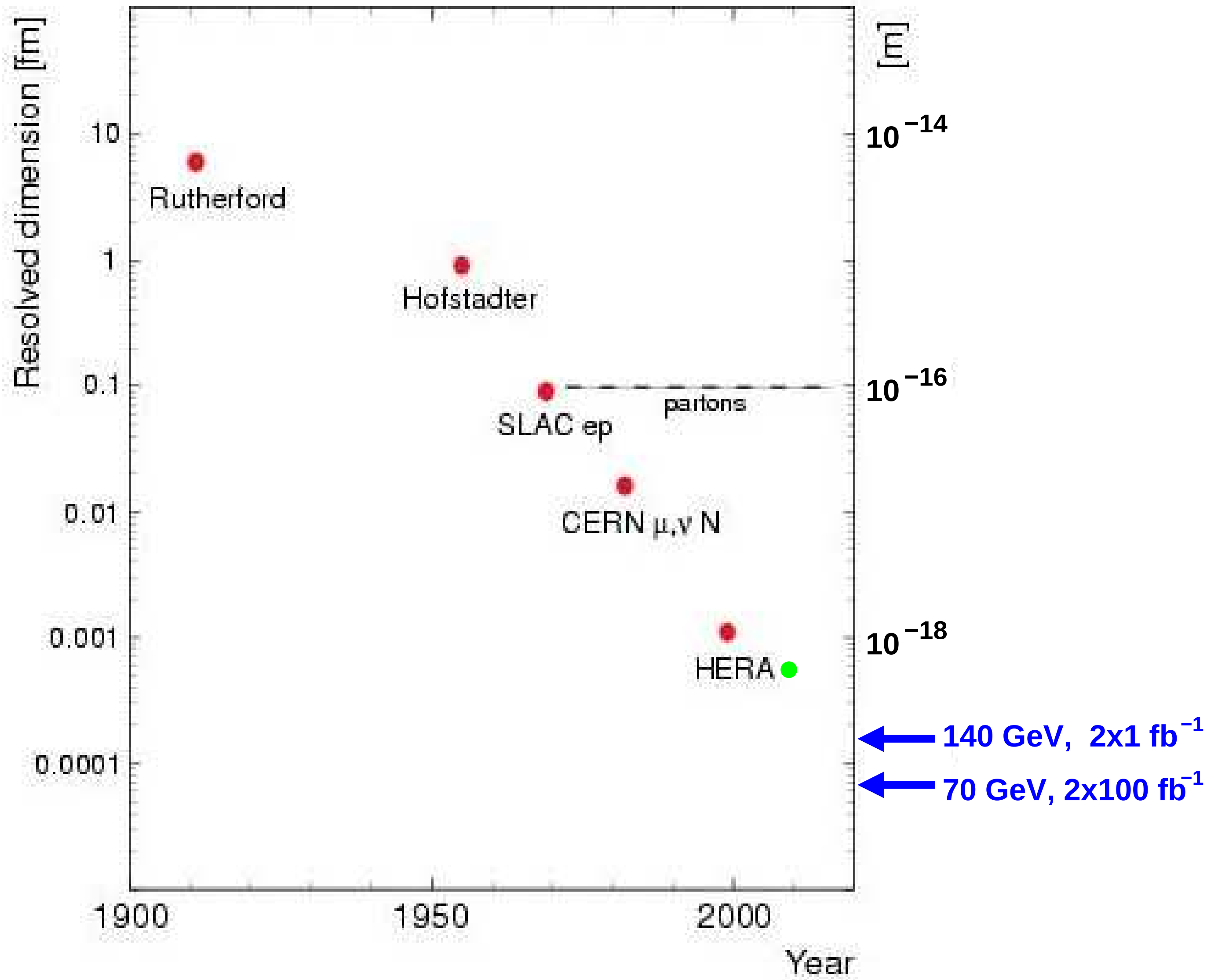


Resolution below $10^{-19}m$ can be obtained !

Results

Quark size limits

LeHC would improve our resolving power by about an order of magnitude, compared to HERA.



Conclusions

LeHC would extend the energy domain of ep studies by about an order of magnitude.

With high luminosity precise SM tests possible.

Direct LQ production can be studied for masses up to about 1-2 TeV.

For higher mass scales stringent limits can be set for LQ couplings, comparable to those expected from LHC.

Mass scale limits about order of magnitude better than at HERA are expected for considered models.

Backup slides

Leptoquarks

Aachen notation

Model	Fermion number F	Charge Q	$BR(LQ \rightarrow e^{\pm}q)$ 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		νu	
$V_\circ^L$	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		$\nu \bar{d}$	

CI Models

General models

Also referred to as compositeness models

Couplings $\eta^{eq}_{\alpha\beta}$ are related to the "new physics" mass scale 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 conserving parity:

$$\eta^{eq}_{LL} + \eta^{eq}_{LR} - \eta^{eq}_{RL} - \eta^{eq}_{RR} = 0$$

Family universality assumed !

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				$+\eta$				$+\eta$

CI Models

Large Extra Dimensions

Arkani-Hamed–Dimopoulos–Dvali Model

If gravity propagates in the $4+\delta$ dimensions, the effective mass scale M_S can be as low as 1 TeV.

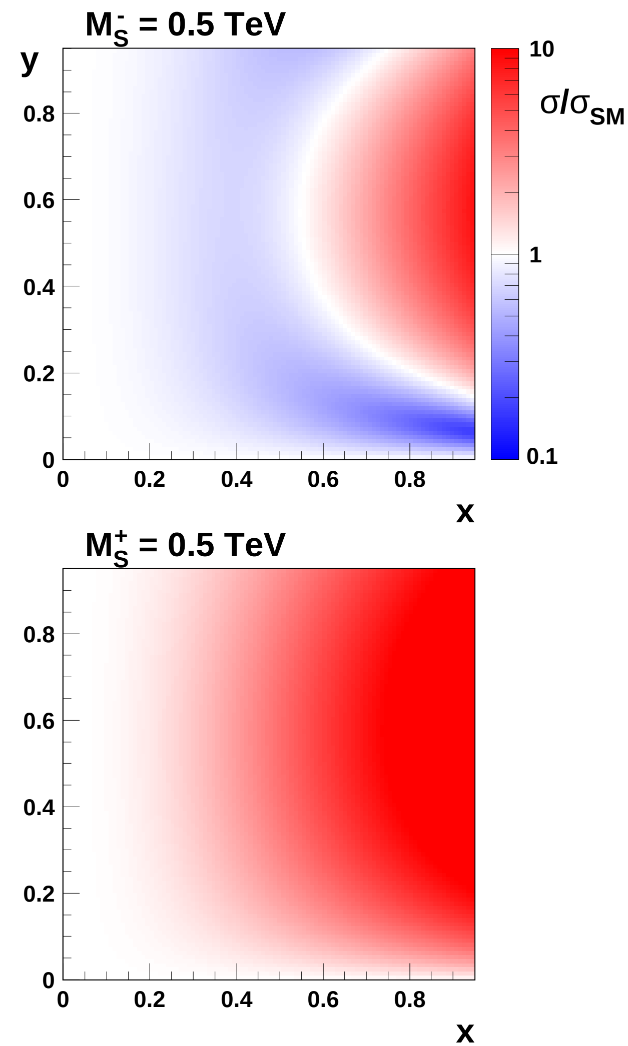
$\Rightarrow$ Gravitational interactions become comparable in strength to electroweak interactions.

The contribution of graviton (Kaluza-Klein tower) exchange to the $e^{\pm}p$ NC DIS cross section can be described by an effective contact interaction type coupling:

$$\eta_G = \pm\lambda \cdot \frac{\mathcal{E}^2}{M_S^4}$$

where λ is the coupling strength and $\mathcal{E}$ is related to the energy scales of hard interaction. $(\sqrt{s}, Q^2)$

Cross-section deviations for e^-p:



CI Models

Quark form factor

"classical" method to look for possible fermion (sub)structure.

If a quark has finite size, the standard model cross-section is expected to decrease at high momentum transfer:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2\right]^2 \cdot \left[1 - \frac{R_e^2}{6} Q^2\right]^2$$

where R_q is the root mean-square radius of the electroweak charge distribution in the quark.

We do not consider the possibility of finite electron size...

same dependence expected for e^+p and e^-p !