Contact Interactions and

Future Prospects for High Energy Physics

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Outline

- Introduction
  Contact Interaction model
- Results from global analysis
  Mass scale limits for different models
- Predictions for future data taking
  Correlations between experiments

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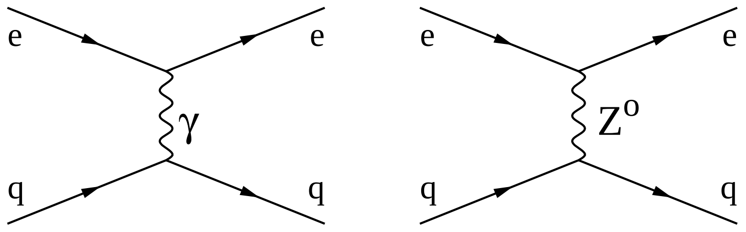
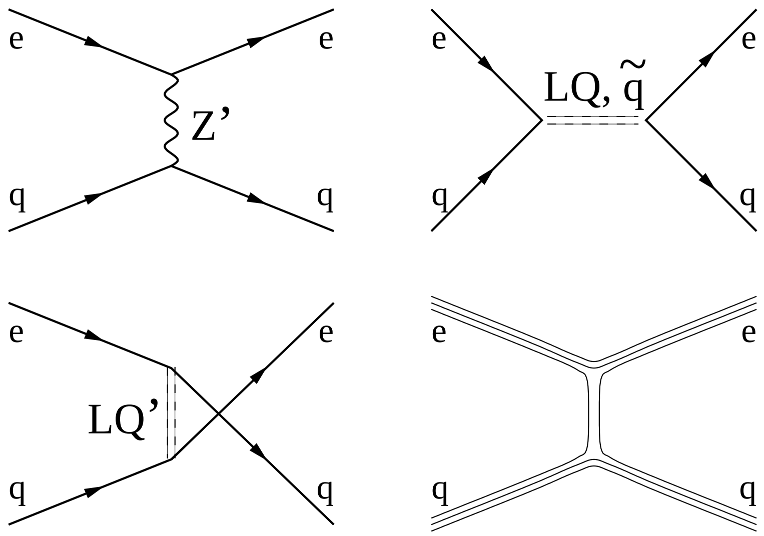
Introduction

Neutral Current eq Scattering

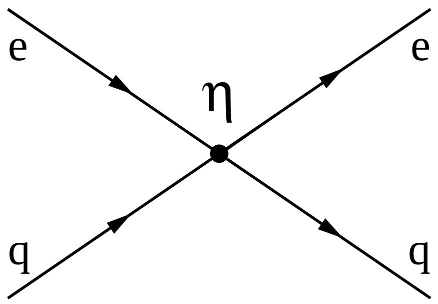
Two processes contribute in the Standard Model :



Possible "new physics" processes:



For energies much smaller than their characteristic energy scale Λ these processes can be parametrised as:



$eeqq$ contact interactions (CI)

Introduction

Contact Interactions

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 our sensitivity.

Contact Interactions modify $eq \rightarrow eq$ 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 flavour 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 $g^2_{CI} = 4\pi$.

Introduction

Data

Take all relevant experimental data:

- HERA high-Q^2 e^+p and e^-p NC DIS results
- Tevatron data on high-mass Drell-Yan lepton pair production
- LEP2 results on quark-pair production cross-section $\sigma(e^+e^- \rightarrow q\bar{q})$, heavy quark production ratios R_b, R_c and forward-backward asymmetries A^b_{FB}, A^c_{FB}, A^{uds}_{FB}
- Data from eN and μN scattering, and Atomic Parity Violation (APV) measurements
- Assuming $SU(2)_L \times U(1)_Y$ universality: HERA e^+p CC DIS results, νN scattering ...

Use data to extract:

Mass scale limits

- "combined" limits for one-parameter scenarios
- general limits from multi-parameter models

Predictions

- limits on possible deviations at HERA, LEP, Tevatron
- correlations between effects possible at different experiments

Results

One-parameter models

Assuming quark flavour symmetry (u=c, d=s=b), there are 8 independent vector contact interaction couplings. 30 one-parameter scenarios are explored, assuming different relations between these couplings:

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							$+\eta$	$-\eta$

Each row represents two models: $\eta > 0$ ($\varepsilon = +1$) and $\eta < 0$ ($\varepsilon = -1$).
All models conserve parity:

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

Results

Mass scale limits

Model	Mass scale limits [TeV]			
	No SU(2)		With SU(2)	
	Λ^-	Λ^+	Λ^-	Λ^+
VV	9.8	10.7	9.6	11.4
AA	10.5	10.1	9.9	11.1
VA	6.6	6.2	6.3	8.0
X1	8.7	8.1	8.1	9.5
X2	8.2	8.4	7.8	9.6
X3	9.9	10.2	9.5	11.1
X4	5.7	5.2	6.0	5.4
X5	5.9	6.4	6.2	6.4
X6	6.2	5.8	6.2	5.8
U1	6.4	7.7	7.9	17.0
U2	6.9	9.1		
U3	8.5	11.7	8.6	18.2
U4	5.1	5.5		
U5	6.4	8.8	7.1	8.8
U6	7.0	5.6		

U2, U4 and U6 models violate $SU(2) \times U(1)$ invariance.

Mass scale limits range from 5.1 to 18.2 TeV.

Significant improvement as compared to single experiments.

One-parameter models test only specific combinations of couplings !

Can we consider all possible combinations ?!...

Results

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

Three multi-parameter models are considered

General (First-generation) Model

- 8 u-e and d-e couplings can vary independently,
- all other couplings (for s, c, b, t, μ, τ) assumed to vanish.

Model with Family Universality

Assume lepton universality:

$$\eta_{ij}^{eq} = \eta_{ij}^{\mu q} = \eta_{ij}^{\tau q}$$

and quark family universality:

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

Model with $SU(2)_L \times U(1)_Y$ Universality

Impose $SU(2)_L \times U(1)_Y$ gauge invariance of the Standard Model.
Reduces number of free model parameters from 8 to 7:

$$\eta_{RL}^{eu} = \eta_{RL}^{ed}$$

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

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

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

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

Results

Mass scale limits

Mass scale limits for single couplings
assuming no constraints on other couplings.

Coupling	Mass scale limits [TeV]					
	General model (1st. generation)		Model with family universality		SU(2) model with family univ.	
	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
η^{ed}_{LL}	3.1	3.6	4.3	5.4	7.5	6.1
η^{ed}_{LR}	2.4	2.2	2.8	3.2	3.6	3.7
η^{ed}_{RL}	2.6	2.1	3.9	2.8	4.5	3.9
η^{ed}_{RR}	2.8	2.8	3.3	3.5	3.5	5.1
η^{eu}_{LL}	5.1	3.9	5.3	4.1	6.5	7.8
η^{eu}_{LR}	4.1	3.3	3.7	3.5	4.9	4.7
η^{eu}_{RL}	3.1	3.5	3.1	3.5	4.5	3.9
η^{eu}_{RR}	3.7	3.7	3.8	4.2	4.8	4.4

Least constrained coupling combination:

η_1	2.1	2.7	3.1

For general model:

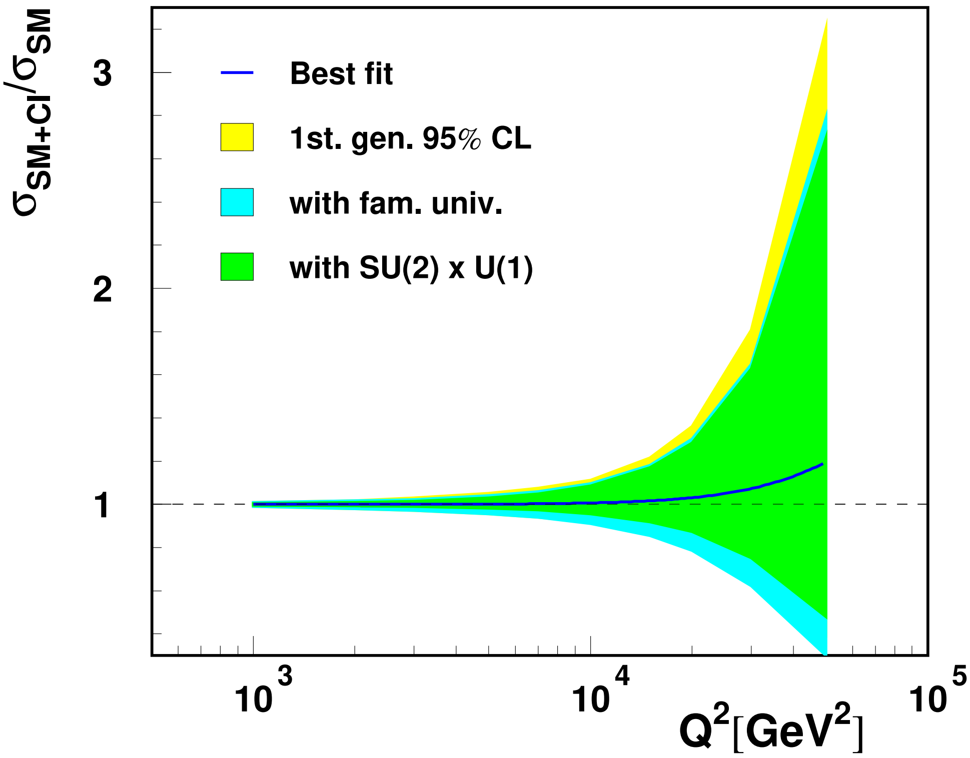
$$\eta_1 \equiv -0.26\eta^{ed}_{LL} + 0.84\eta^{ed}_{LR} + 0.15\eta^{ed}_{RL} + 0.33\eta^{ed}_{RR} - 0.06\eta^{eu}_{LL} + 0.11\eta^{eu}_{LR} - 0.10\eta^{eu}_{RL} + 0.27\eta^{eu}_{RR}$$

Excluded are all models with $\Lambda < 2.1$ TeV .

on 95% CL

Predictions

Limits for e^+p NC DIS



95% CL limits on integrated cross-section:

$$\frac{\sigma(Q^2 > 15,000\ GeV^2)}{\sigma_{\rm SM}} \quad < \ 1.40 \qquad \text{1st. gen. model}$$

$$< \ 1.30 \qquad \text{SU(2) model}$$

Possible effect can be measured only with

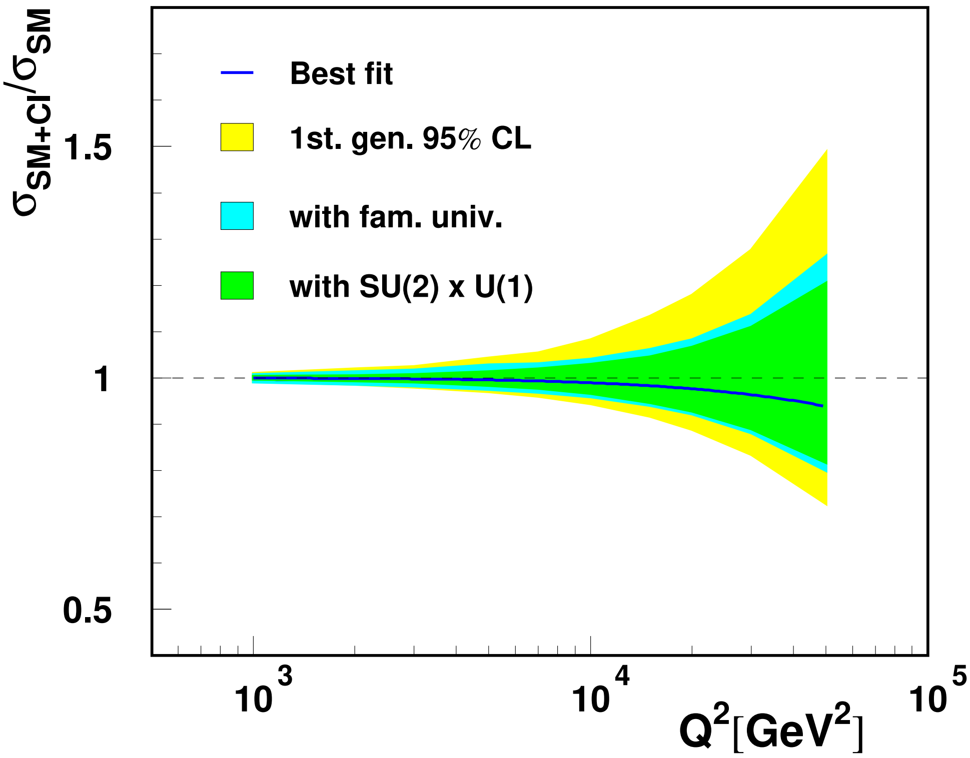
$$\boxed{\mathcal{L} \ \sim \ 100 - 200 \text{ pb}^{-1}}$$

depending on the model

required to observe "3 σ" effect for $Q^2 > 15,000\ GeV^2$

Predictions

Limits for $e^- p$ NC DIS



95% CL limits on integrated cross-section:

$$\frac{\sigma(Q^2 > 15,000\ GeV^2)}{\sigma_{\rm SM}} \ < \ 1.19 \quad \text{1st. gen. model}$$

$$< \ 1.07 \quad \text{SU(2) model}$$

Possible effect can be measured only with

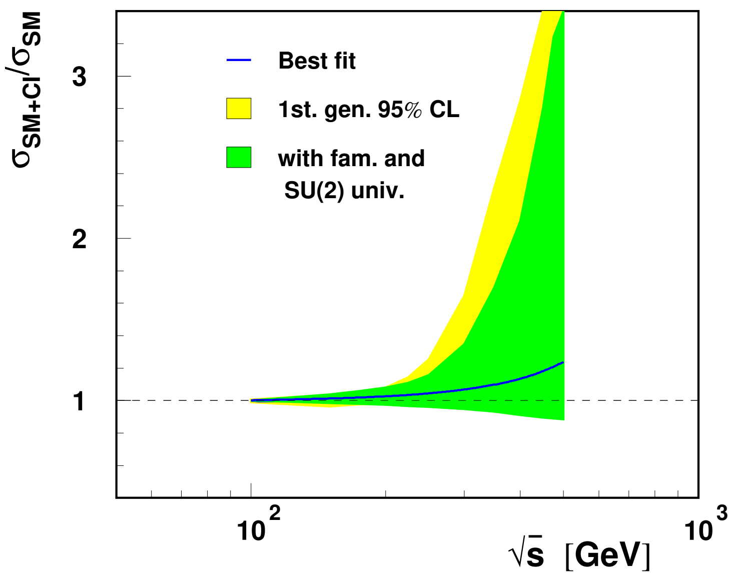
$$\boxed{\mathcal{L} \ \geq \ 400 \ \mathrm{pb}^{-1}}$$

However, when running with 60% e^-_R polarisation:

$$\mathcal{L} \ \geq \ 120 \ \mathrm{pb}^{-1}$$

Predictions

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



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

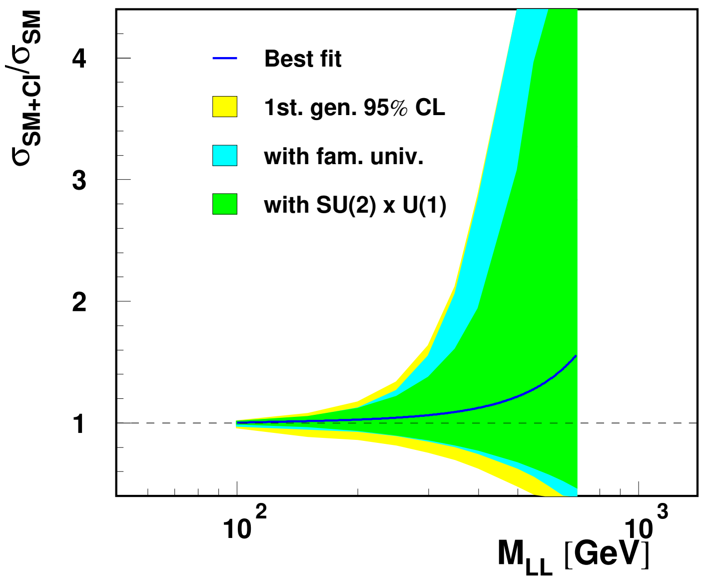
$$\frac{\Delta\sigma}{\sigma_{\rm SM}} < 8\%$$

$$\left|\frac{\Delta R_b}{R_b}\right| < 13\%$$

$$\left|\frac{\Delta A^b_{FB}}{A^b_{FB}}\right| < 40\%$$

Significant effects possible in the Next-Linear-Collider...

Limits on $\sigma(q\bar{q} \to l^+l^-)$ at Tevatron



95% CL limits for cross-section $M_{ll} > 500 GeV$:

$$\frac{\sigma}{\sigma_{\rm SM}} < 10. \quad \text{1st. gen. model}$$

$$< 5. \quad \text{SU(2) model}$$

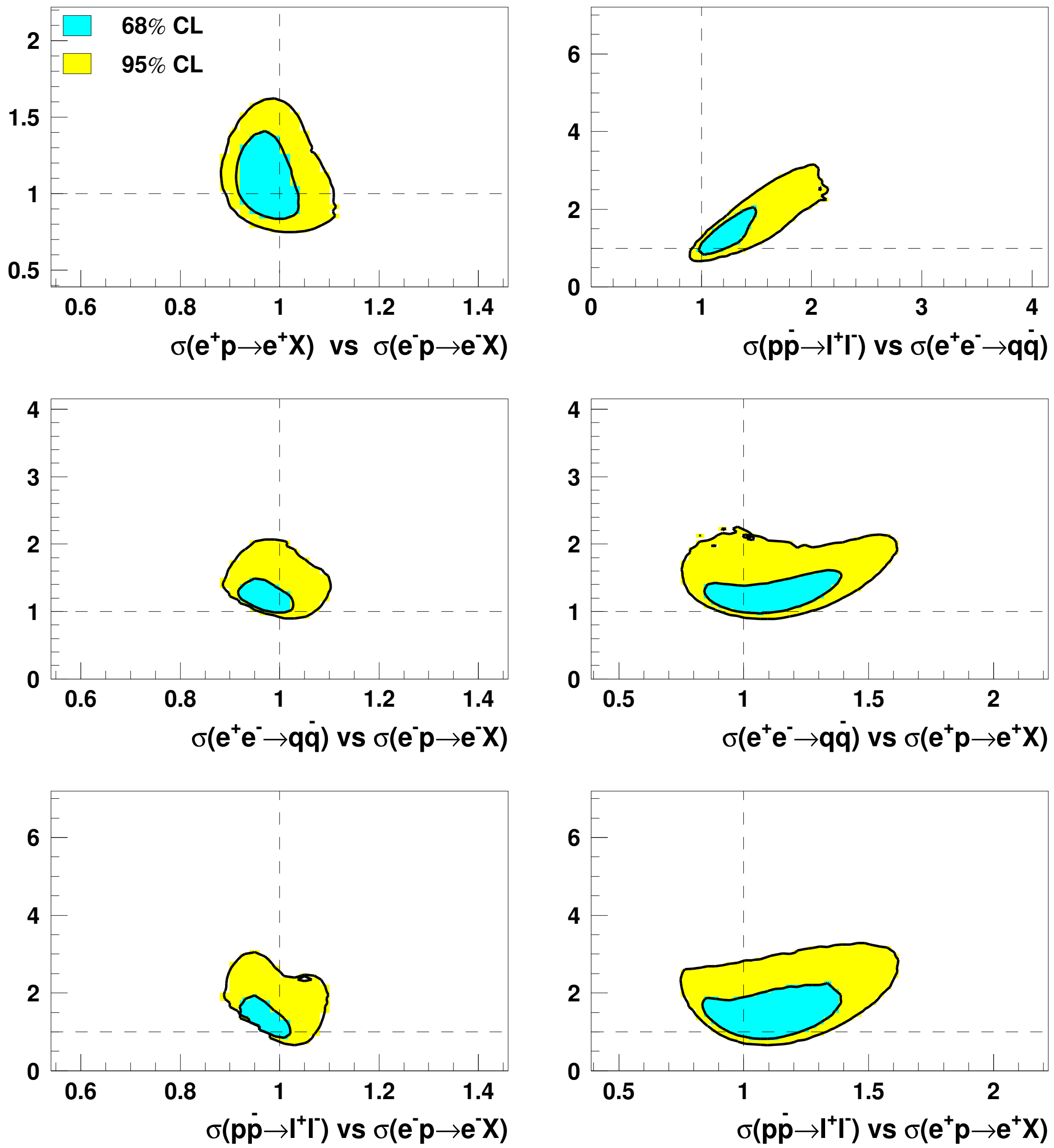
Large effects still possible !

Require $\mathcal{L} \sim 0.3 - 1$ fb^{-1}

Predictions

Comparison of experiments

Model with $SU(2) \times U(1)$ universality



$Q^2 = 30\,000\ GeV^2$ $\sqrt{s} = 400\ GeV$ $M_{ll} = 500\ GeV$

Different experiments are, to large extent, complementary.

Significant correlation between LEP (σ_{had}) and Tevatron (Drell-Yan).

Summary

- Data from HERA, LEP, Tevatron and low energy experiments were combined to constrain electron-quark contact interactions.
- 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 .
- Excluded are all models with $\Lambda <$ 2.1 TeV (3.1 TeV for SU(2) model).

- Limits on possible effects to be observed in future HERA, LEP and Tevatron running are estimated.
- Current data exclude any sizable cross-section deviations from the Standard-Model for e^-p scattering at HERA.
- Possible cross-section deviations for LEP and e^+p scattering at HERA are also strongly limited by existing data.
- However, experimental sensitivity can be improved :
  $\Rightarrow$ additional observables at LEP,
  $\Rightarrow$ polarised beams at HERA.
- The best "discovery potential" seems to come from future Tevatron running.

$\boxed{\text{More details of the analysis can be found in hep-ph/9904334}}$

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Predictions

Summary of limits

95% CL limits, resulting from existing data, on possible cross-section deviations in future experiments

Reaction	Energy scale	Limits on $\Delta\sigma/\sigma_{SM}$ [%] General m. (1st. gen.)	Model with family univ.	SU(2) model w. fam. univ.
e^+p NC DIS	Q^2=10000 GeV^2	11	10	9
$\sqrt{s}$ =318 GeV	Q^2=20000 GeV^2	36	30	28
	Q^2=30000 GeV^2	81	65	63
	Q^2=50000 GeV^2	220	180	170
e^-p NC DIS	Q^2=10000 GeV^2	8	4	3
$\sqrt{s}$ =318 GeV	Q^2=20000 GeV^2	18	8	7
	Q^2=30000 GeV^2	28	13	11
	Q^2=50000 GeV^2	49	26	21
$e^-e^+ \rightarrow q\bar{q}$	$\sqrt{s}$=175 GeV	5	5	6
	$\sqrt{s}$=200 GeV	8	8	8
	$\sqrt{s}$=225 GeV	14	13	11
	$\sqrt{s}$=250 GeV	26	24	16
	$\sqrt{s}$=300 GeV	65	61	35
	$\sqrt{s}$=400 GeV	185	185	110
$p\bar{p} \rightarrow l^+l^-X$	M_{ll}=200 GeV	17	12	12
$\sqrt{s}$ = 1800 GeV	M_{ll}=300 GeV	64	55	38
	M_{ll}=400 GeV	190	185	95
	M_{ll}=500 GeV	440	450	210

Introduction

Procedure

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 results and Drell-Yan lepton pairs at Tevatron :

Poisson distribution for the observed number of events.

"Best" coupling values are found using MINUIT, by minimising $\mathcal{P}(\vec{\eta})$.

For multi-parameter models, Monte Carlo technique is used to determine probability functions for couplings and resulting limits.

Corrections

Experimental conditions are taken into account:

- detector resolution

  Event migration due to finite Q^2 resolution (for high-Q^2 HERA data) or M_{ll} resolution (for lepton pair production data from Tevatron).

  Flavour mixing and charge "confusion" factors at LEP.

- systematic errors

  For every data set common systematic shift parameter δ is introduced (assume 100% correlation of systematic errors).

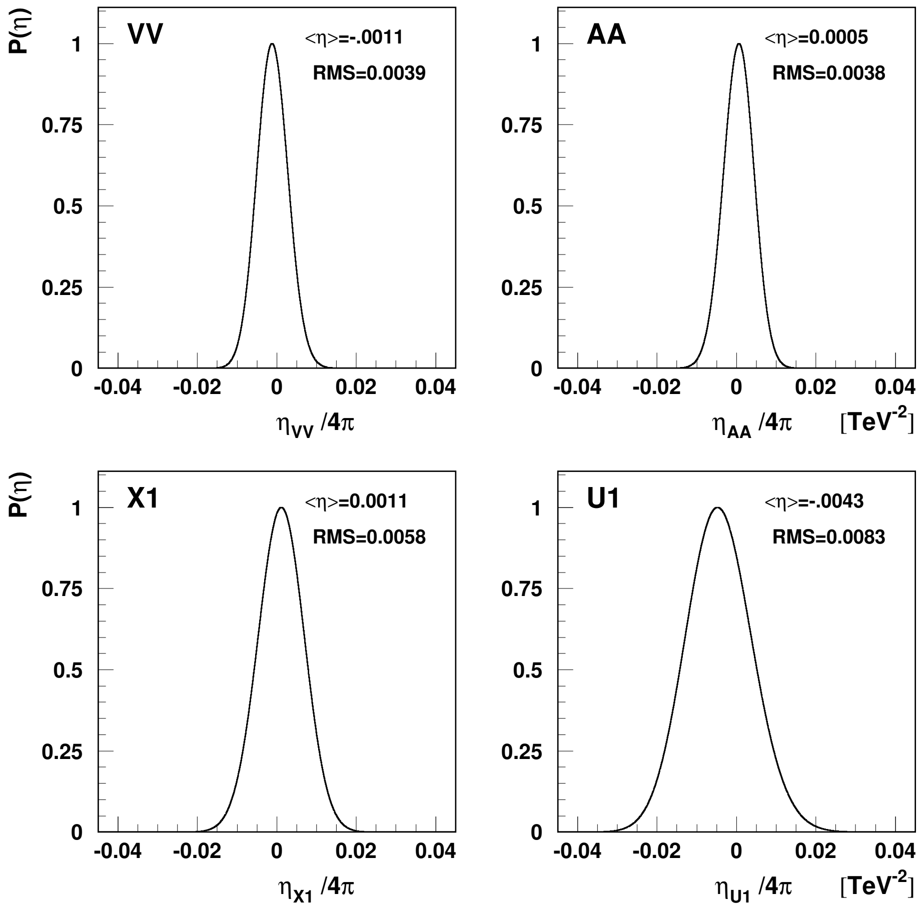
  Parameter δ can been treated as an additional free parameter when maximising the overall model probability $\mathcal{P}(\vec{\eta})$.

  Normal probability distribution for parameter δ is included in $\mathcal{P}(\vec{\eta})$.

Results

One-parameter models

Probability functions for chosen models:



Results for all one-parameter contact interaction models are consistent with the Standard Model.

95% CL limit definition:

$$\mathcal{P}(\eta^-) = 0.05 \cdot \max_{\eta<0} \mathcal{P}(\eta)$$

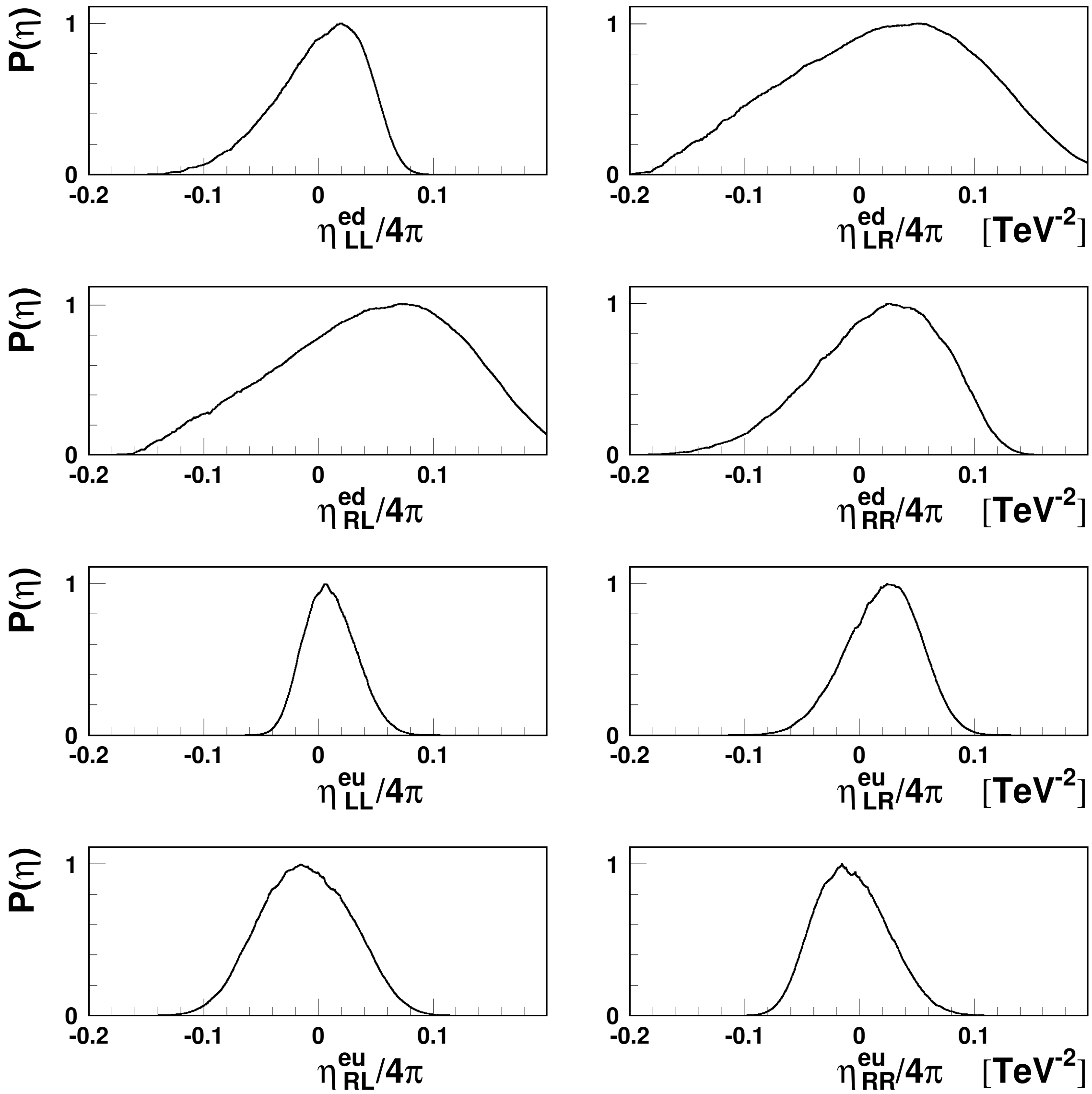
$$\mathcal{P}(\eta^+) = 0.05 \cdot \max_{\eta>0} \mathcal{P}(\eta)$$

Results

General model

Probability functions for single couplings

All coupling allowed to vary simultaneously.



All couplings consistent with the Standard Model.

Predictions

Probability function

Having defined $\mathcal{P}(\vec{\eta})$ we should be able to calculate the probability distribution for any other variable, which can be expressed in terms of $\vec{\eta}$.

For example, we can try to find out what is the probability of observing deviations from Standard Model predictions for e^+p NC DIS at high Q^2.

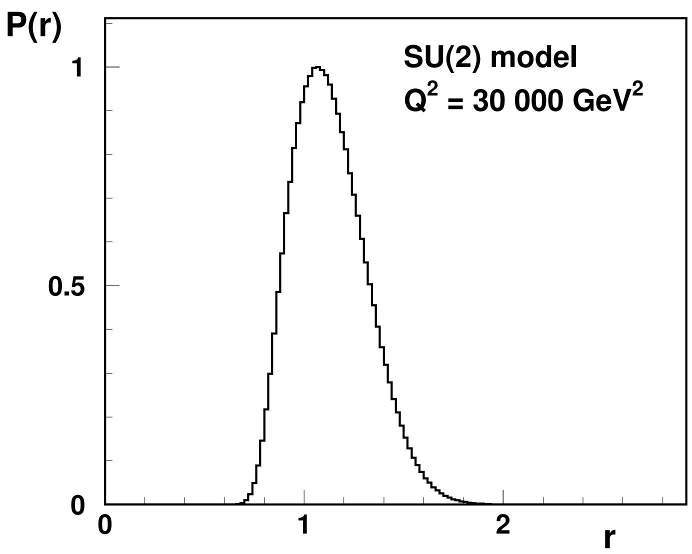
Consider cross-section ratio:

$$r \;=\; R(\vec{\eta}) \;=\; \frac{\frac{d\sigma}{dQ^2}(\vec{\eta})}{\frac{d\sigma^{SM}}{dQ^2}}$$

Probability function $P_r(r)$:
probability that our data come from the model with $R(\vec{\eta}) \;=\; r$.

$$\boxed{P_r(r) = \langle \mathcal{P}(\vec{\eta}) \rangle_{R(\vec{\eta})=r}}$$

Averaging is based on the assumption that $\vec{\eta}$ has flat underlying (prior) distribution (all $\vec{\eta}$ values are equally probably).

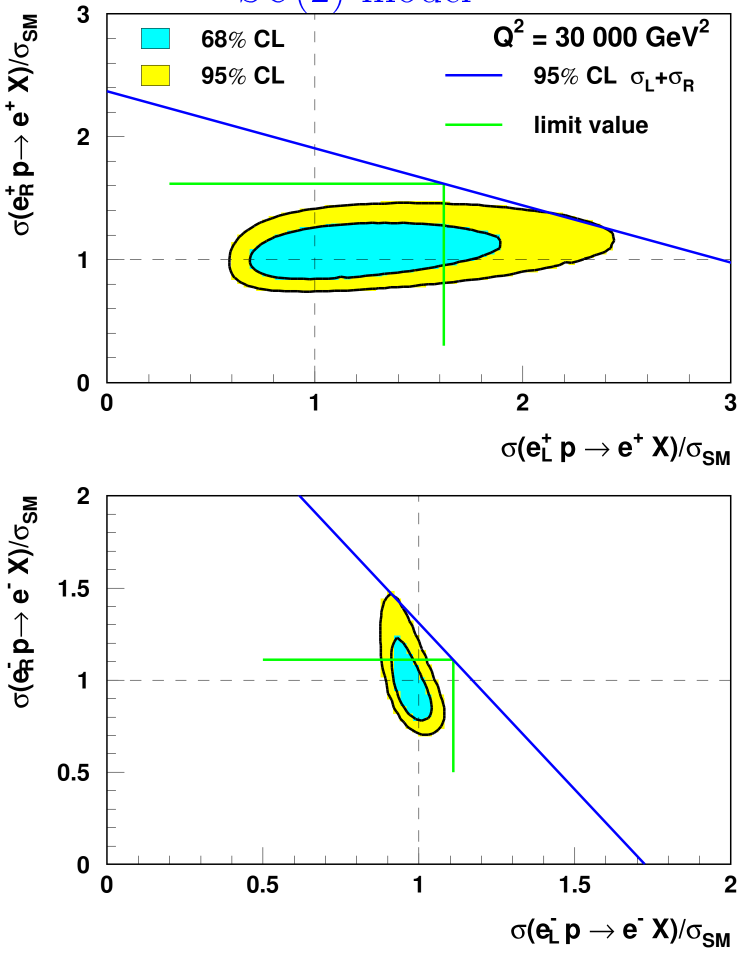


Predictions

HERA "discovery window" can be enlarged for

Scattering of polarised $e^{\pm}$

SU(2) model



Limits from existing data significantly weaker for e^+_L and e^-_R .
Running with 60% e^-_R polarisation :

$$\frac{\sigma(Q^2 > 15{,}000\ GeV^2)}{\sigma_{\rm SM}} \quad \begin{array}{ll} < \ 1.28 & \text{1st. gen. model} \\ < \ 1.19 & \text{SU(2) model} \end{array}$$

$$\boxed{\mathcal{L} \ \sim \ 120 - 500\ \mathrm{pb}^{-1}}$$

depending on the model