Contact Interactions:

Results from ZEUS and a Global Analysis

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Outline

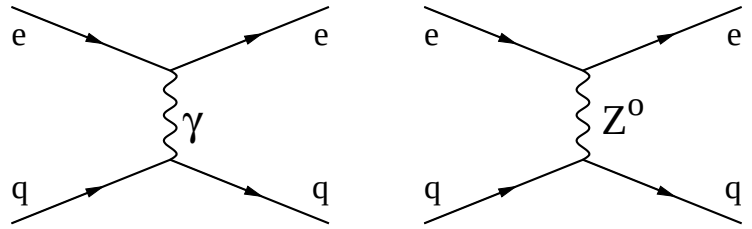
- Introduction
  - Contact Interaction model
  - One-parameter scenarios
- Results from ZEUS — ZEUS Collaboration
  - e^+p NC DIS data (1994-97)
  - Unbinned Log-likelihood method
  - Mass scale limits
- Results from global analysis — A.F.Żarnecki
  - Limits from combined data
  - Limits for most general model
  - Predictions for future data taking
  - Correlations between experiments

7th International Workshop on Deep Inelastic Scattering and QCD
DESY Zeuthen, April 20, 1999

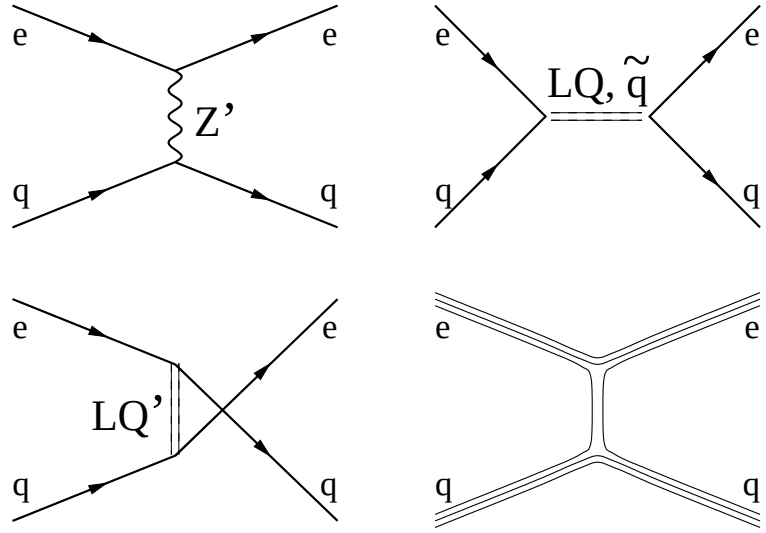
Introduction

Neutral Current eq Scattering

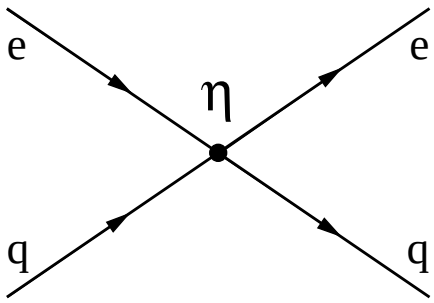
Two processes contribute in the Standard Model :



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 HERA sensitivity.

Contact Interactions modify $eq \to eq$ 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

Contact interaction models

Assuming quark flavour symmetry (u=c, d=s=b), there are 8 independent vector contact interaction couplings. ZEUS explores 30 one-parameter scenarios, 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:

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

ZEUS analysis

Data sample

47.7 pb^{-1} of e^+p data collected in 1994-97
energies: E_e=27.5 GeV, E_p=820 GeV, $\sqrt{s} \approx 300$ GeV.

NC DIS selection

- reconstructed interaction vertex position w.r.t. nominal IP
$$|z| < 50 \text{ cm}$$
- isolated scattered positron reconstructed with energy
$$E'_e > 10 \text{ GeV}$$
- energy-momentum balance in the positron direction:
$$38 \text{ GeV} < E - p_z < 65 \text{ GeV}$$
- y reconstructed from the scattered positron
$$y_e < 0.95$$

Event reconstruction

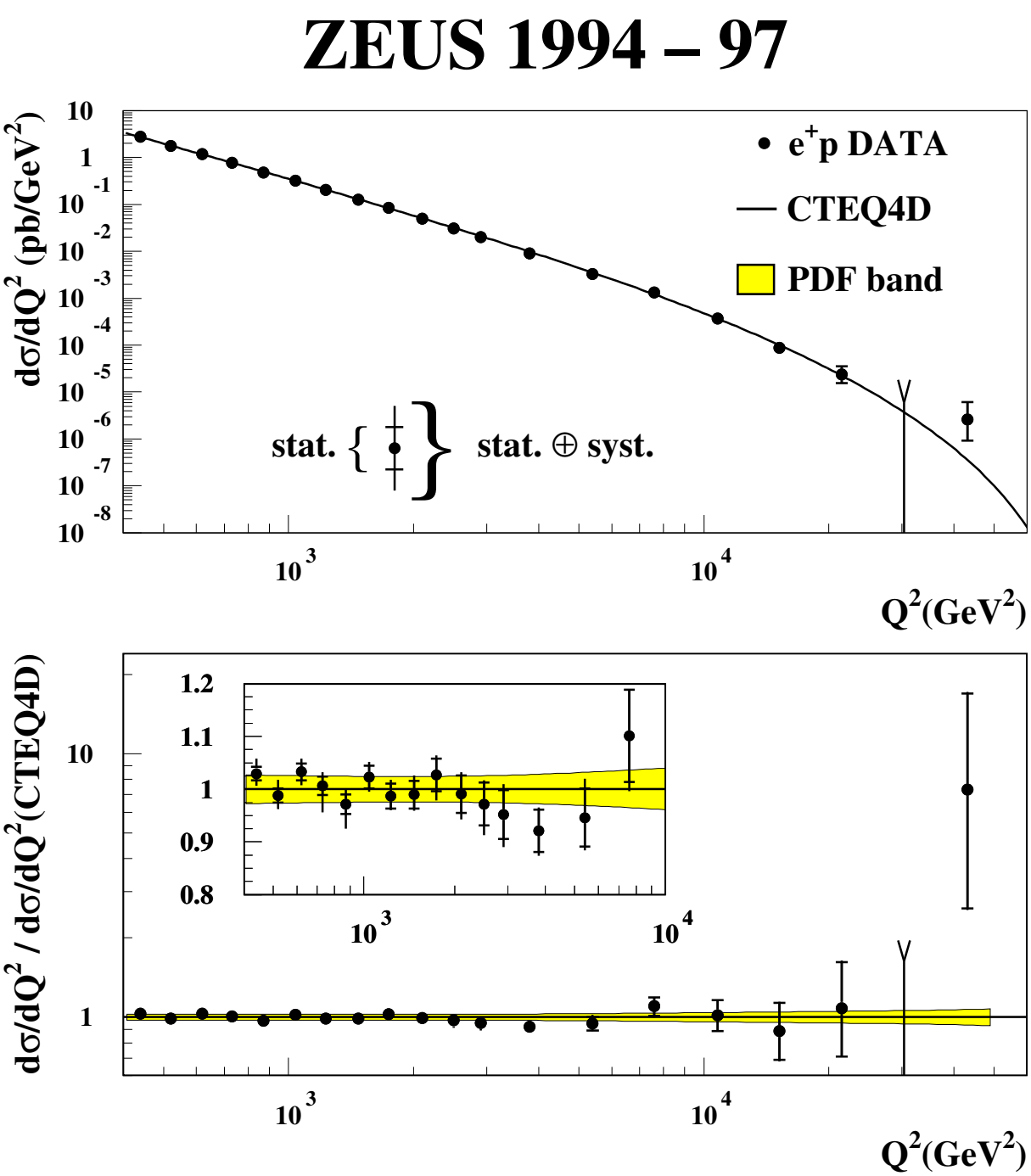
Kinematic variables calculated using double angle (DA) method, based on the measurement of:

- the positron scattering angle
- the effective quark scattering angle
from the transverse momentum and the $E - p_z$ of the hadronic final state.

Details have been described in the talk given by R.Pawlak.

ZEUS analysis

High-Q^2 NC DIS cross-section

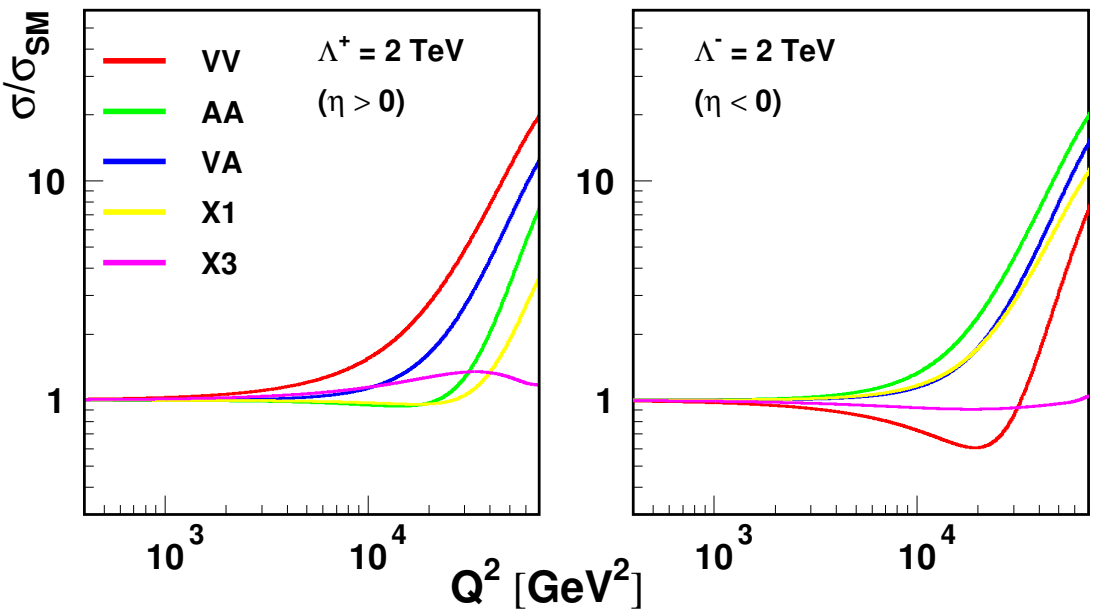


Good agreement between data and the Standard Model predictions except for the two events at $Q^2 > 35\,000$ GeV^2.

ZEUS analysis

Contact Interaction cross-section

CI modify the Q^2 dependence of the scattering amplitude $M^{eq}_{\alpha\beta}(Q^2)$. This has "direct" influence on the cross-section $\frac{d\sigma}{dQ^2}$:



Sensitivity to X3 and U3 scenarios is limited by the kinematic factor $(1-y)^2$ modifying η_{LL} and η_{RR} terms.

$\Rightarrow$ Can be improved by considering 2-dim. event distribution.

Unbinned Log-Likelihood Method

Measured event distribution in (x_{DA}, y_{DA}) is compared to the density of MC events for given CI model.

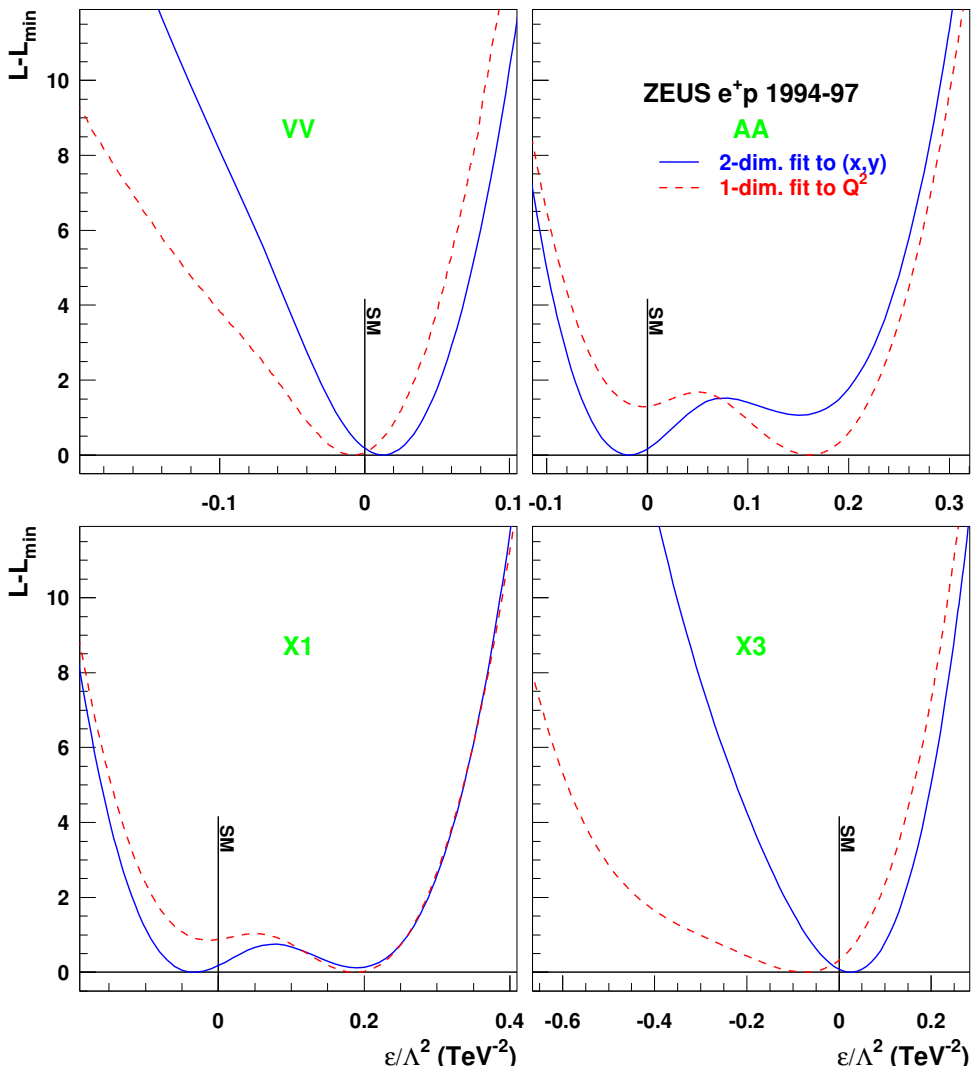
Log-Likelihood function:

$$L(\eta) \;=\; -\sum_i \log p(x_i, y_i; \eta)$$

where $p(x_i, y_i; \eta)$ is the probability that an event i observed at (x_i, y_i) results from the model described by coupling η.

ZEUS analysis

Log-Likelihood Functions

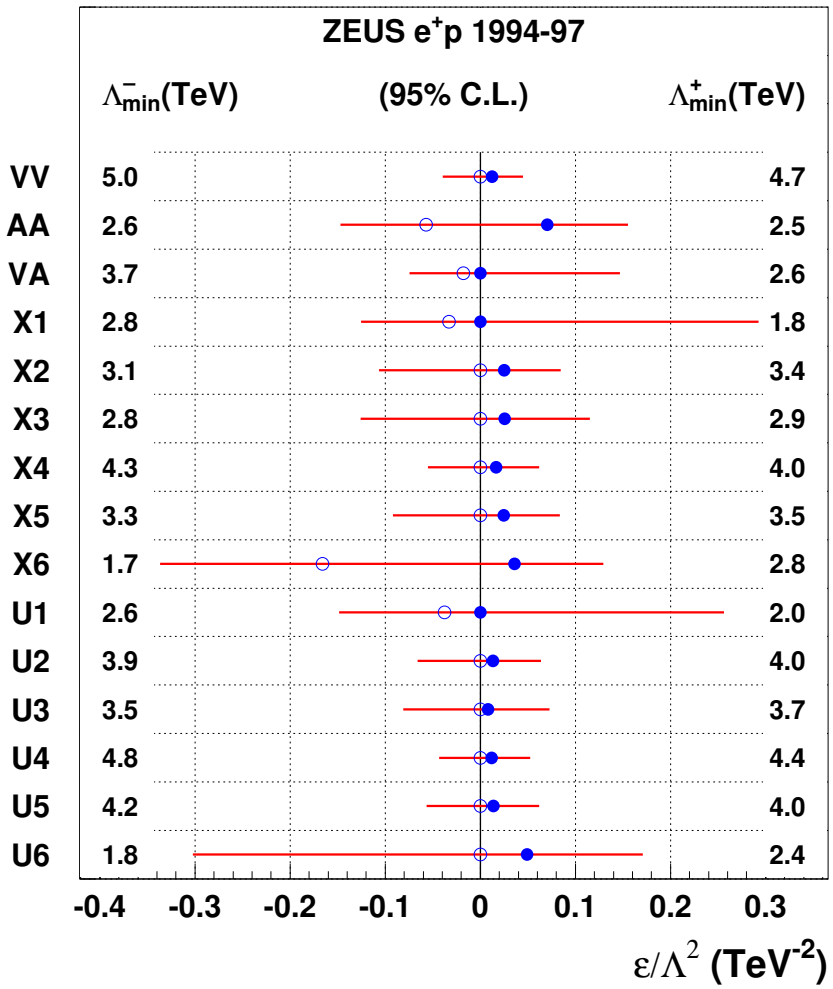


Limit setting:

- Mass scales $\Lambda^{\pm}_{\circ}$ resulting in the best description of the data are calculated separately for $\varepsilon = \pm 1$.
- 95% CL limits $\Lambda^{\pm}_{min}$ are defined as the mass scales for which MC experiments have a 5% chance to result in $\Lambda^{\pm}_{\circ}$ values larger than that observed in data.

ZEUS analysis

Limits on CI mass scale parameter



Filled points • :

best values for positive η ($\varepsilon = +1$)

Open points ∘ :

best values for negative η ($\varepsilon = -1$)

Horizontal bars :

95% CL allowed range for CI amplitude

All CI fits compatible with Standard Model.

ZEUS analysis

Summary

- 47.7 pb^{-1} of ZEUS e^+p data have been used to search for $eeqq$ contact interactions
- High-Q^2 NC DIS event distributions have been compared to 30 different CI scenarios
- No evidence for contact interactions has been found
- 95% CL limits for the effective mass scale Λ range from 1.7 to 5 TeV.

Outlook

- Complementary results expected from e^-p data collected in 1998-99 ($E_p = 920$ GeV)
- After 2000:
  higher luminosities with longitudinal polarisation

Presented results are covered in the paper:
"Search for Contact Interactions in Deep-Inelastic $e^+p \to e^+X$ Scattering at HERA", to be submitted soon.

ZEUS analysis

Comparison with other experiments

CI	$\Lambda^{\pm}_{min}$ [TeV] (95% C.L.)					
	ZEUS	ALEPH	L3	OPAL	CDF	D0
VV+	4.7	9.6	3.8	4.1	3.5	4.9
VV−	5.0	9.2	5.0	5.7	5.2	6.1
AA+	2.6	10.5	5.6	6.3	3.8	4.7
AA−	3.7	10.4	3.5	3.8	4.8	5.5
X1+	1.8					3.9
X1−	2.8					4.5
X3+	2.9	10.0	4.0	4.4		4.2
X3−	2.8	9.7	3.4	3.8		5.1
X4+	4.0	3.3	2.9	3.1		3.9
X4−	4.3	5.6	4.8	5.5		4.4
X6+	2.8					4.0
X6−	1.7					4.3
U3+	3.7		6.1	4.1		
U3−	3.5		4.9	5.8		
U4+	4.4		2.1	2.3		
U4−	4.8		2.9	3.2		

CDF Collaboration, F. Abe et al., Phys.Rev.Lett. 79(1997)2198.
DO Collaboration, D. Abbott et al., FERMILAB–PUB–98–391–E
ALEPH Collaboration, ALEPH 99–018 (1999)
L3 Collaboration, M.Acciarri et al., L3–2229 (1998), ICHEP98 #513
D.Bourilkov, ETHZ-PPP PR-98-02, hep-ex/9806027
OPAL Collaboration, G. Abbiendi et al., Eur.Phys.J. C6(1999)1

HERA sensitivity is similar to that reported by other experiments.

Some of the limits are the strictest published so far.

Several scenarios have been studied for the first time :

X2, X5, U1, U2, U5, U6

Global analysis

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

Global analysis

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 ?!...

Global analysis

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 $e\nu qq'$:

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

Global analysis

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:

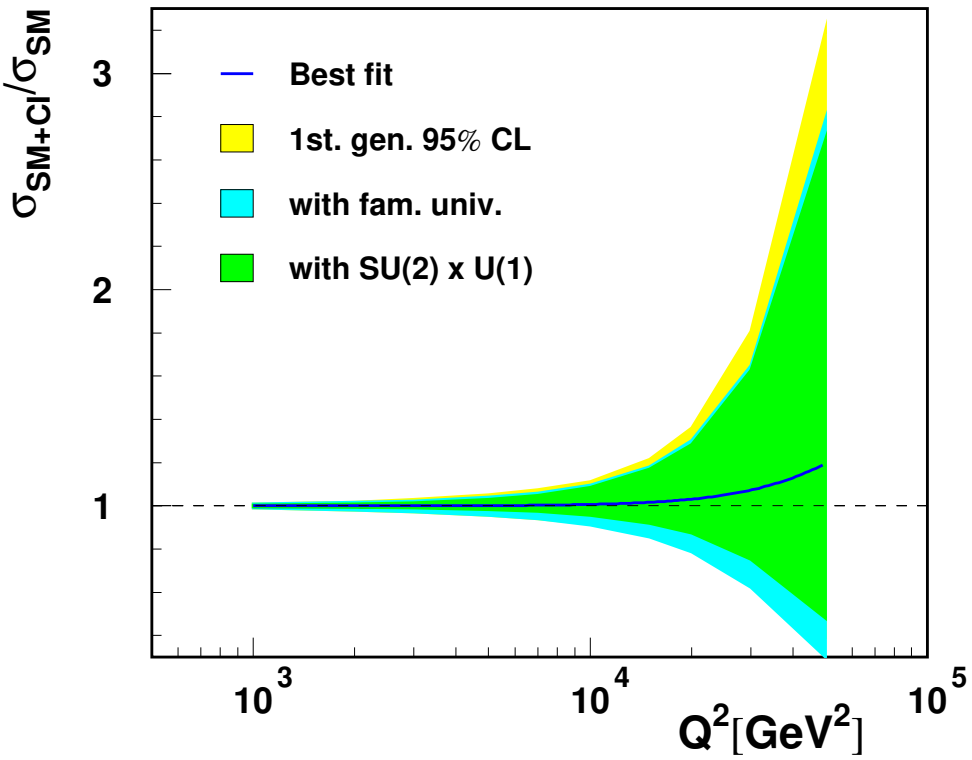
$$\eta_1 \equiv -0.26\eta^{ed}_{LL} + 0.84\eta^{ed}_{LR} + 0.15\eta^{ed}_{RL} + 0.33\eta^{ed}_{RR} - 0.06\eta^{eu}_{LL} + 0.11\eta^{eu}_{LR} - 0.10\eta^{eu}_{RL} + 0.27\eta^{eu}_{RR}$$

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

on 95% CL

Global analysis

Limits for e^+p NC DIS



95% CL limits on integrated cross-section:

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

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

Possible effect can be measured only with

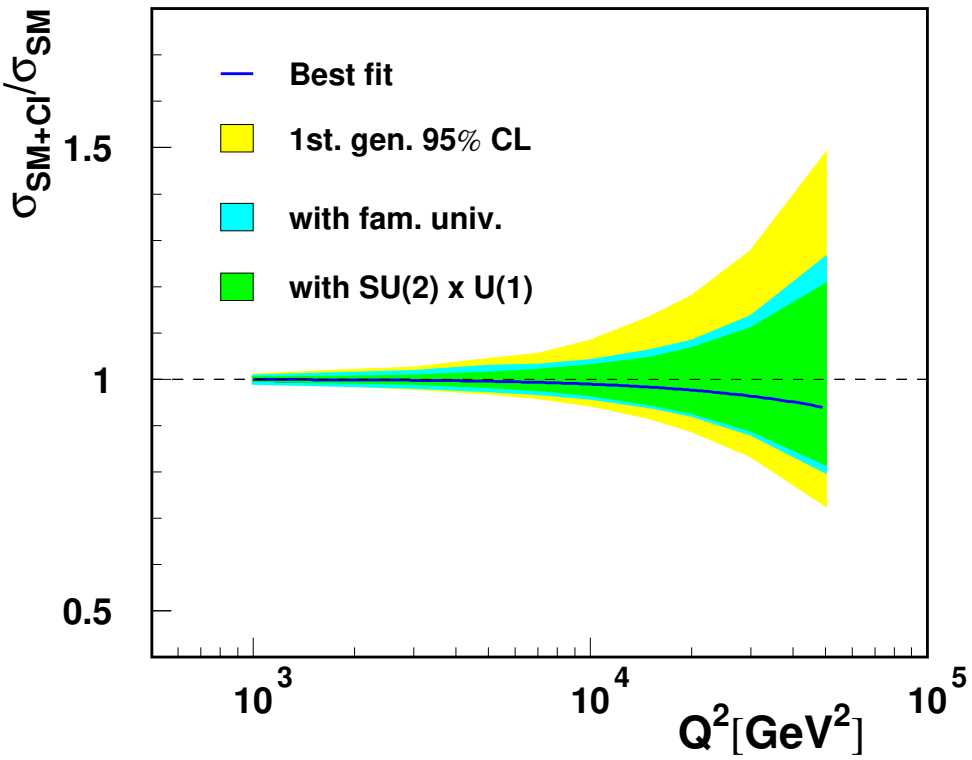
$$\mathcal{L} \ \sim \ 100 - 200\ \text{pb}^{-1}$$

depending on the model

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

Global analysis

Limits for $e^- p$ NC DIS



95% CL limits on integrated cross-section:

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

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

Possible effect can be measured only with

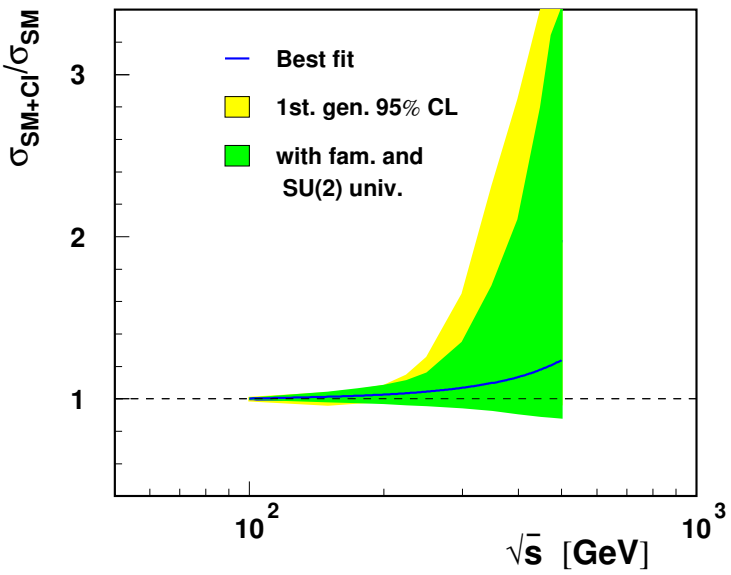
$$\mathcal{L} \ \geq \ 400\ \text{pb}^{-1}$$

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

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

Global analysis

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



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

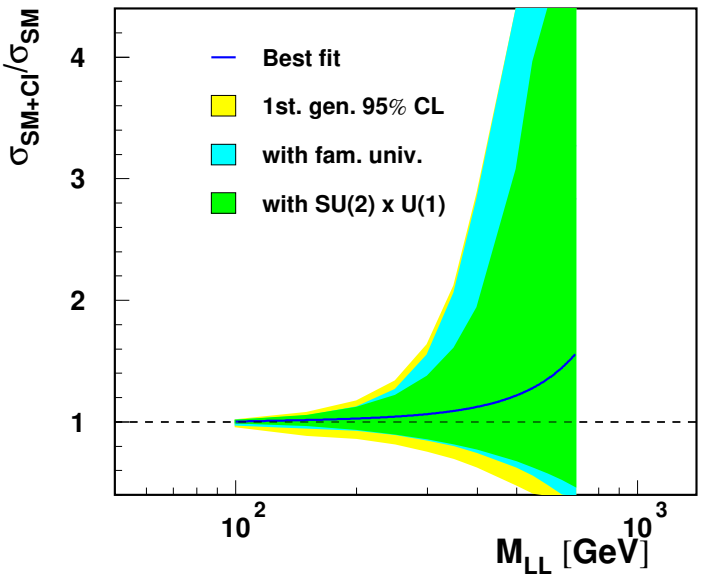
$$\frac{\Delta\sigma}{\sigma_{\rm SM}} < 8\%$$

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

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

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 $M_{ll} > 500GeV$:

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

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

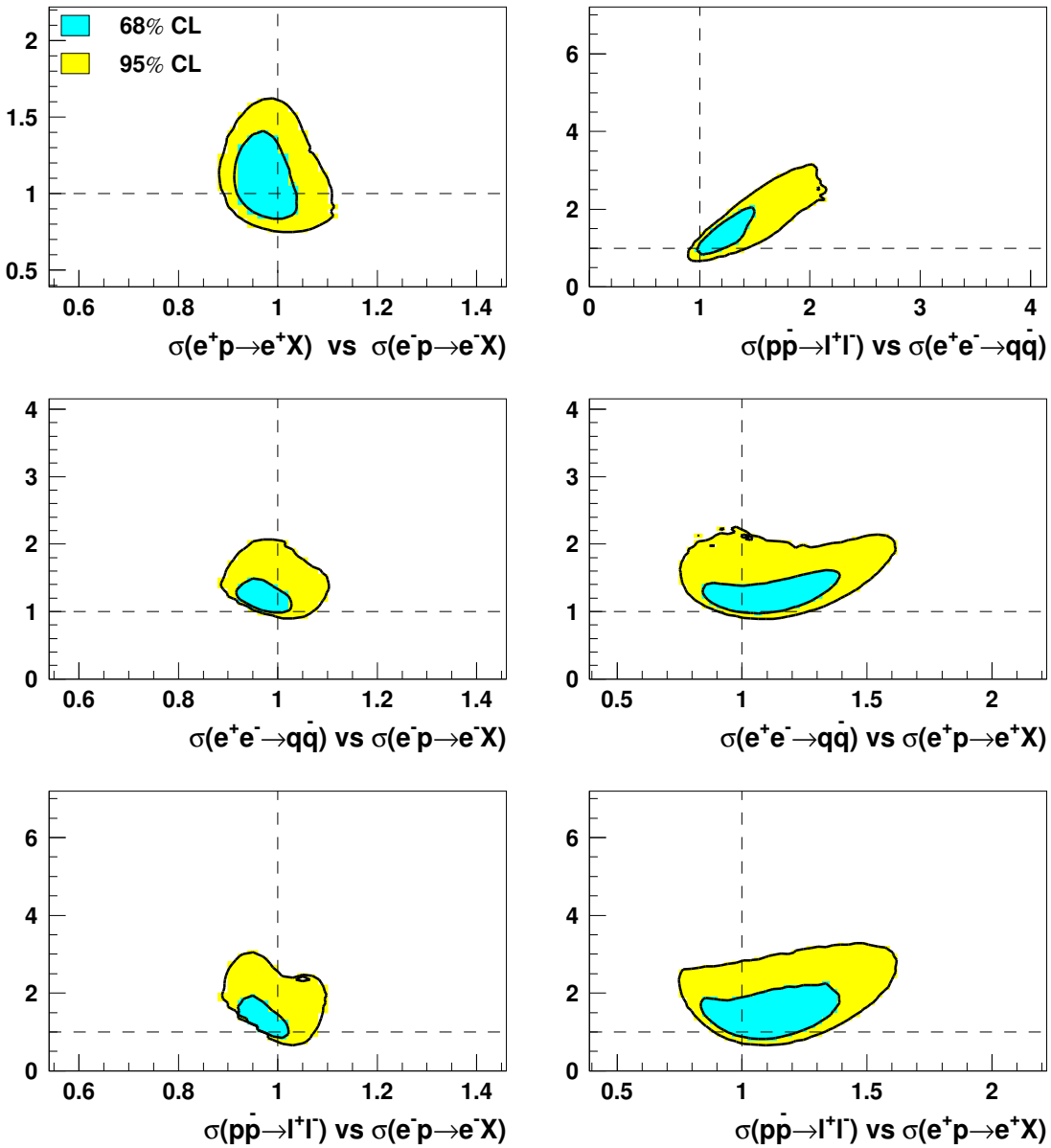
Large effects still possible !

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

Global analysis

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).

Global analysis

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.

More details of the analysis can be found in hep-ph/9904334

Global analysis

Summary of limits

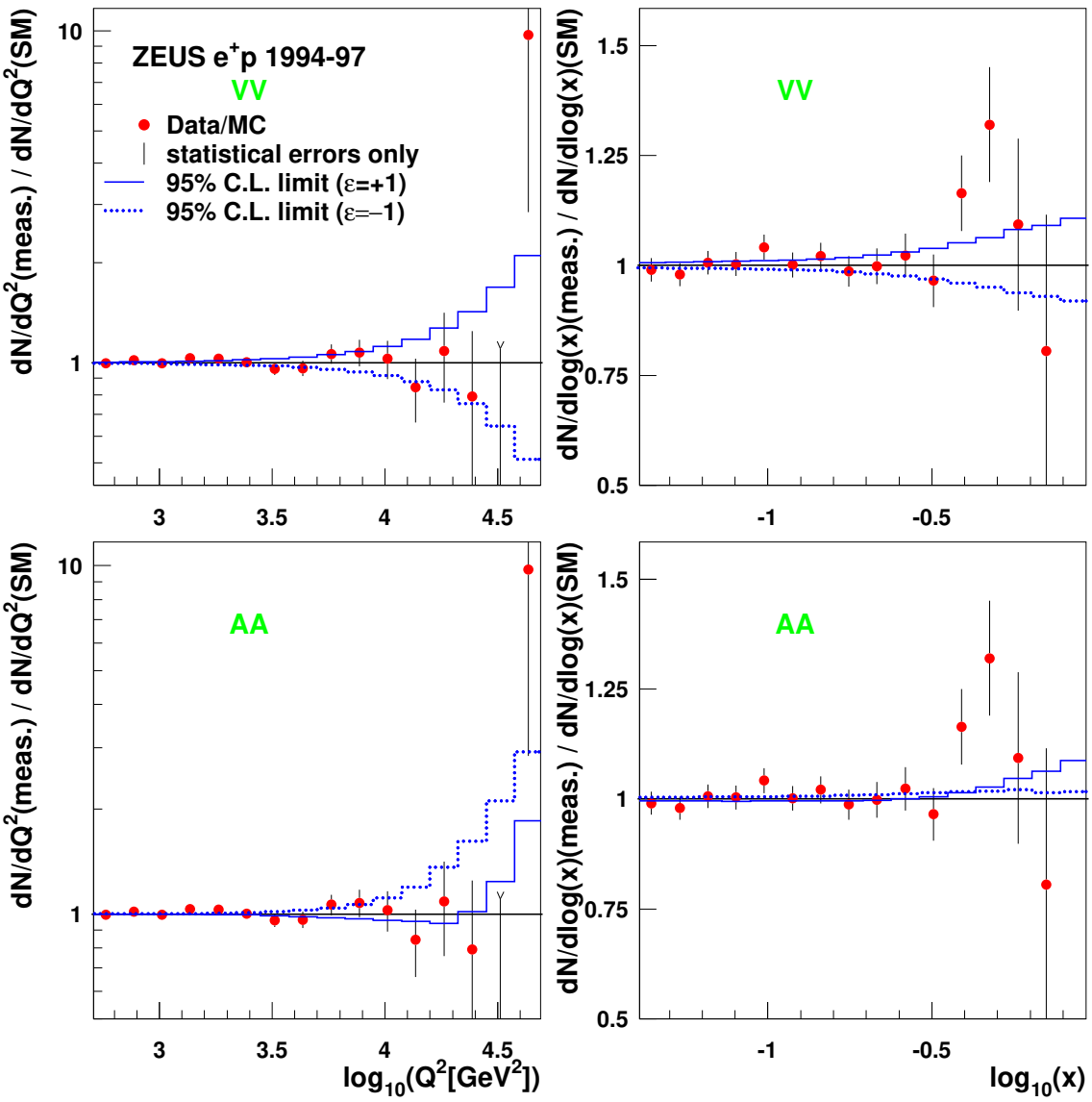
95% CL limits, resulting from existing data, on possible cross-section deviations in future experiments

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
$e^-e^+ \to q\bar{q}$	$\sqrt{s}$=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
$p\bar{p} \to l^+l^-X$	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

ZEUS analysis

Example limits

Cross-section deviations corresponding to 95% CL mass scale limits.



Global analysis

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).

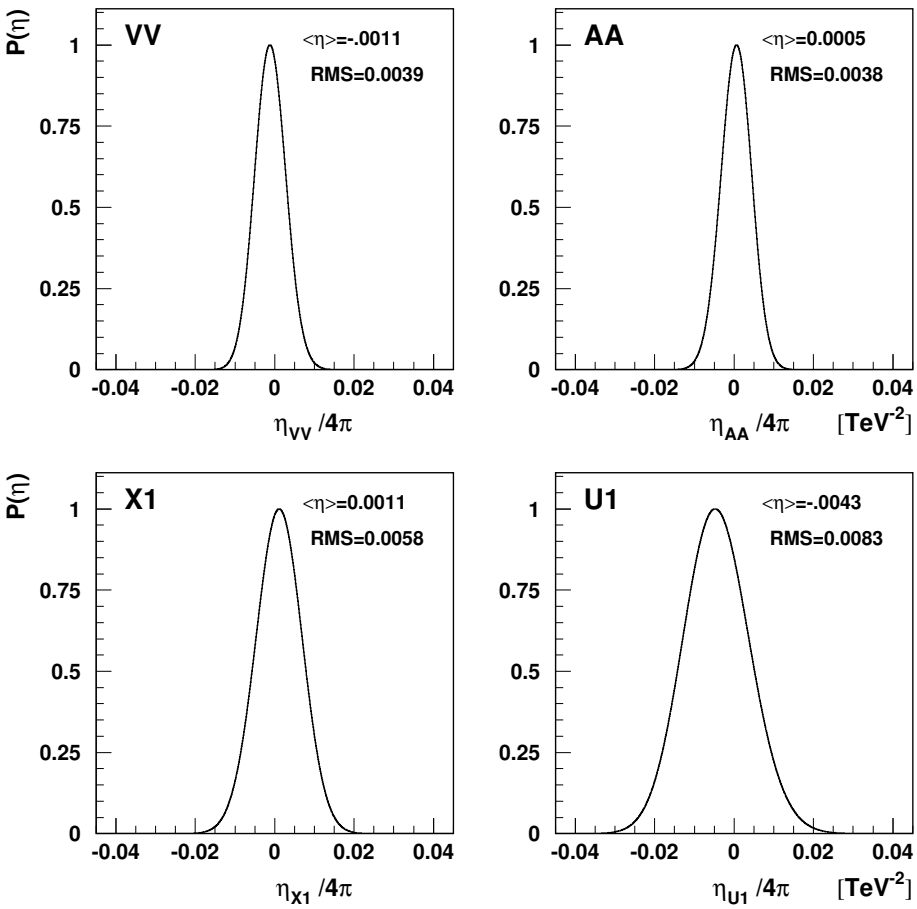
  Parameter δ can been treated as an additional free parameter when maximising the overall model probability $\mathcal{P}(\vec{\eta})$.

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

Global analysis

Probability functions

Probability functions for chosen models:



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

95% CL limit definition:

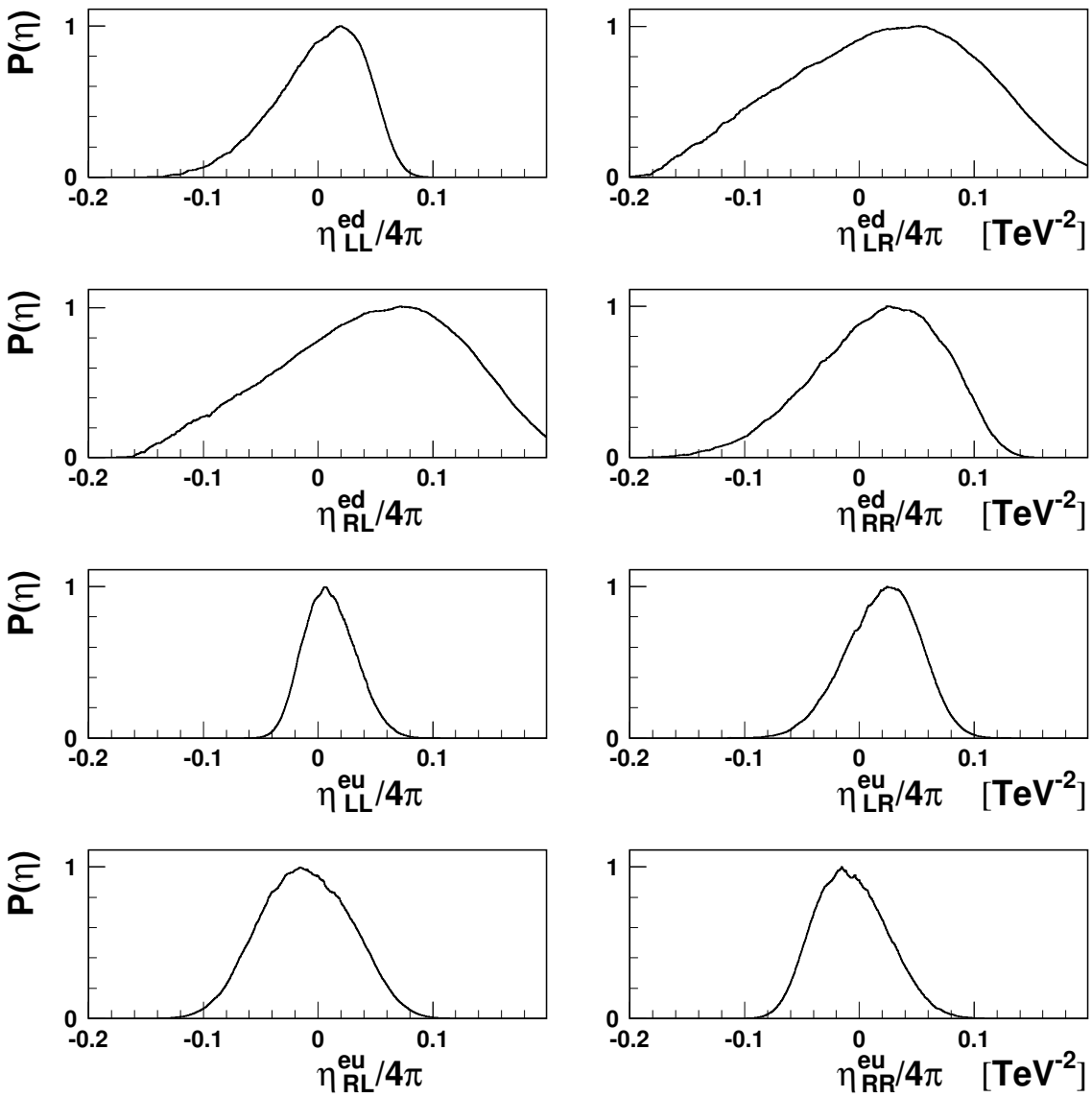
$$\mathcal{P}(\eta^-) = 0.05 \cdot \max_{\eta<0} \mathcal{P}(\eta)$$
$$\mathcal{P}(\eta^+) = 0.05 \cdot \max_{\eta>0} \mathcal{P}(\eta)$$

Global analysis

General model

Probability functions for single couplings

All coupling allowed to vary simultaneously.



All couplings consistent with the Standard Model.

Global analysis

Predictions

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.

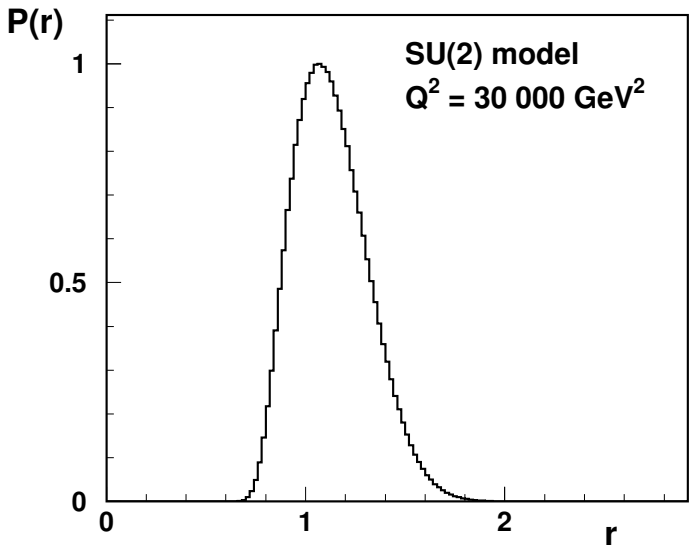
Consider cross-section ratio:

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

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

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

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

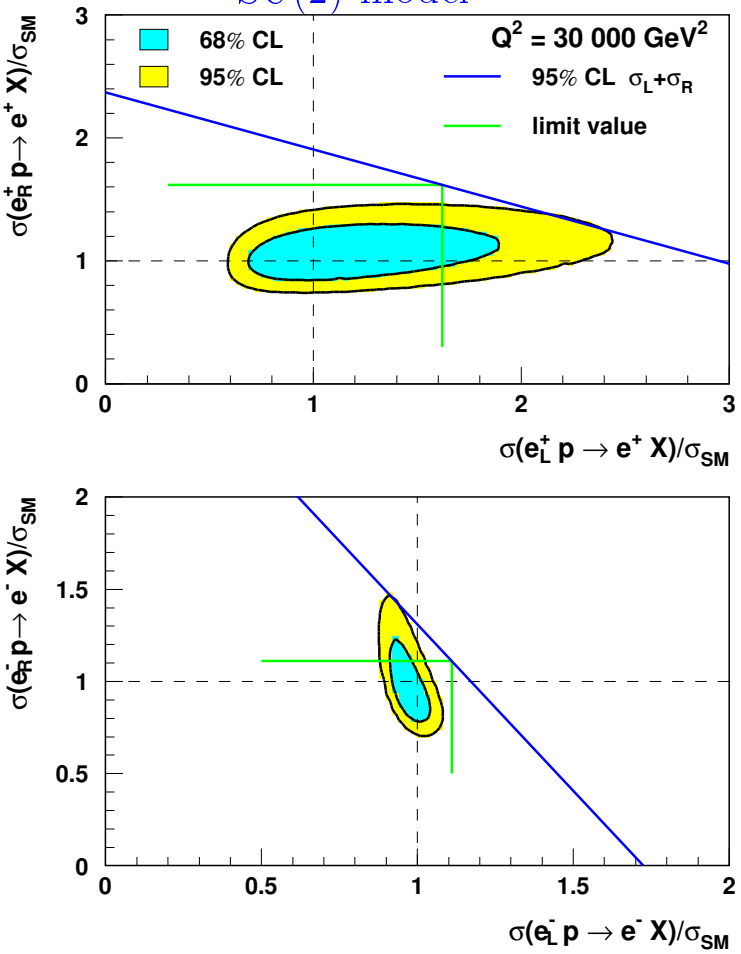


Global analysis

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 :

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

$$< \ 1.19 \quad \text{SU(2) model}$$

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

depending on the model