

QCD and electroweak working group

First look at potential of LHeC data in a combined PDF and electroweak fit

LHeC pre-meeting, 25 April 2009

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Outline

- Introduction
- LHeC simulated data
- Combined PDF+EW fit
- Results



Introduction

Goal: to investigate the potential impact of **LHeC data** on **proton PDFs** and **electroweak parameters**

presented today:

first results from a combined **PDF + electroweak fit** to existing HERA data plus simulated LHeC data (for various LHeC running scenarios)

so far, some initial results on:

- » **proton PDFs** (quick look at impact on uncertainties)
- » **electroweak parameters** (NC axial and vector quark couplings to Z^0 ; M_W)

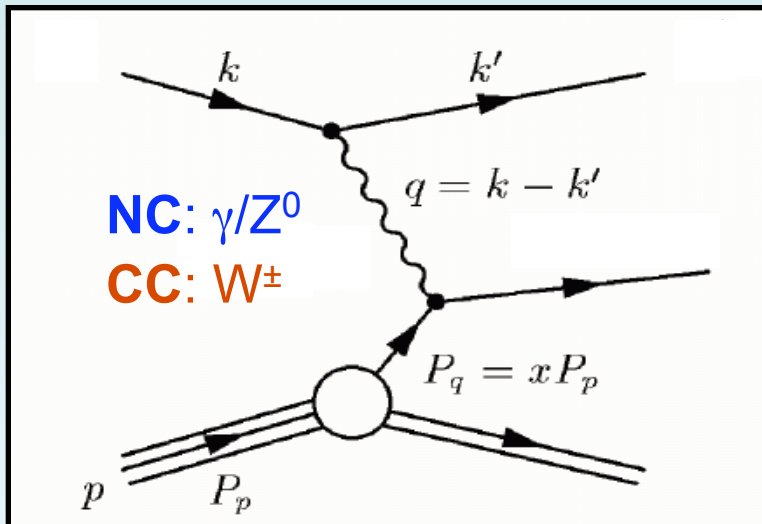
* in this talk, slightly more emphasis on electroweak, since this has not been looked at before

→ very much a work in progress ...

(needless to say, comments or suggestions welcome!)

Deep inelastic scattering (DIS)

processes: **Neutral Current (NC)**: $ep \rightarrow eX$; **Charged Current (CC)**: $ep \rightarrow \nu X$



Kinematic Variables:

- 4-momentum transfer ('resolution'):
 $Q^2 = -q^2 = -(k - k')^2$
- Bjorken scaling variable: $x = Q^2/2p \cdot q$
- inelasticity: $y = p \cdot q/p \cdot k$

related via: $Q^2 = sxy$

[where \sqrt{s} = CoM energy: $s = (k + p)^2$]

NC: "reduced" cross section:

$$\tilde{\sigma}^\pm = \frac{d^2\sigma^\pm}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^\pm \mp \frac{Y_-}{Y_+} x \tilde{F}_3^\pm - \frac{y^2}{Y_+} \tilde{F}_L^\pm$$

valence and sea quarks
[gluon via scaling violations]

valence quarks

gluon

CC: similar decomposition, but **different quark combinations** accessed in e^+p or $e^-p \rightarrow$ **flavour sensitive**

Polarisation dependence

CC – cross sections scale linearly:

$$\sigma_{CC}^{e\pm p}(P_e) = (1 \pm P_e) \cdot \sigma_{CC}^{e\pm p}(P_e=0)$$

NC – polarisation effects more subtle:

reduced cross section:

$$\sigma_{NC}^{e\pm p} \sim Y_+ F_2 \mp Y_- xF_3$$

$\kappa_Z \equiv Z$ boson propagator

$$\begin{aligned} F_2(\pm P_e) &= F_2^\gamma - (v_e \pm P_e a_e) \kappa_Z F_2^{\gamma Z} + ((v_e^2 + a_e^2) \pm P_e 2v_e a_e) \kappa_Z^2 F_2^Z \\ xF_3(\pm P_e) &= -(a_e \pm P_e v_e) \kappa_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e (v_e^2 + a_e^2)) \kappa_Z^2 xF_3^Z \end{aligned}$$

» weak parity violating effect though γZ interference and pure $Z \rightarrow$ high Q^2 only

» γZ dominates (pure Z suppressed by additional propagator i.e. $\kappa_Z \gg \kappa_Z^2$; also $v_e \approx 0.04$)

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γZ structure functions in the QPM:

$$\begin{aligned} F_2^{\gamma Z} &= 2e_q v_q \sum x(q+\bar{q}) \\ xF_3^{\gamma Z} &= 2e_q a_q \sum x(q-\bar{q}) \end{aligned}$$

unpolarised $xF_3 \rightarrow a_i$
polarised $F_2 \rightarrow v_i$

LHeC scenarios studied

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	Pol	L/10 ³²	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ ²
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	0.5	0.5	0.4	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb

Scenario D:

$E(e^\pm) = 100$ GeV

$E(p) = 7$ TeV

($\sqrt{s} = 1.673$ TeV)

$P_e = \pm 0.9$

... simulated LHeC data (M. Klein); mainly looked at **scenario D** (since it was produced first!)
[available at: <http://hep.ph.liv.ac.uk/~mklein/simdis09>]

LHeC scenarios studied

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	Pol	L/ 10^{32}	P/MW	years	type
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C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	0.5	0.5	0.4	0.5	30	1	eD
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... but also looked briefly at A, B, C, E as well as D
[available at: <http://hep.ph.liv.ac.uk/~mklein/simdis09>]

LHeC scenarios studied

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F	50	3.5	D	0.5	0.5	0.4	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb

all scenarios studied:

» before fitting, the cross section values were **re-calculated** using the ZEUS PDFs (since provided values are from LO PDFs)

% uncertainties then taken from the provided simulations

... but also looked briefly at A, B, C, E as well as D
[available at: <http://hep.ph.liv.ac.uk/~mklein/simdis09>]

LHeC simulated data

numbers based on **scenario D**:

pseudo-data spans kinematic region:

$$2 < Q^2 < 10^6 \text{ GeV}^2; 2 \times 10^{-6} < x < 0.8$$

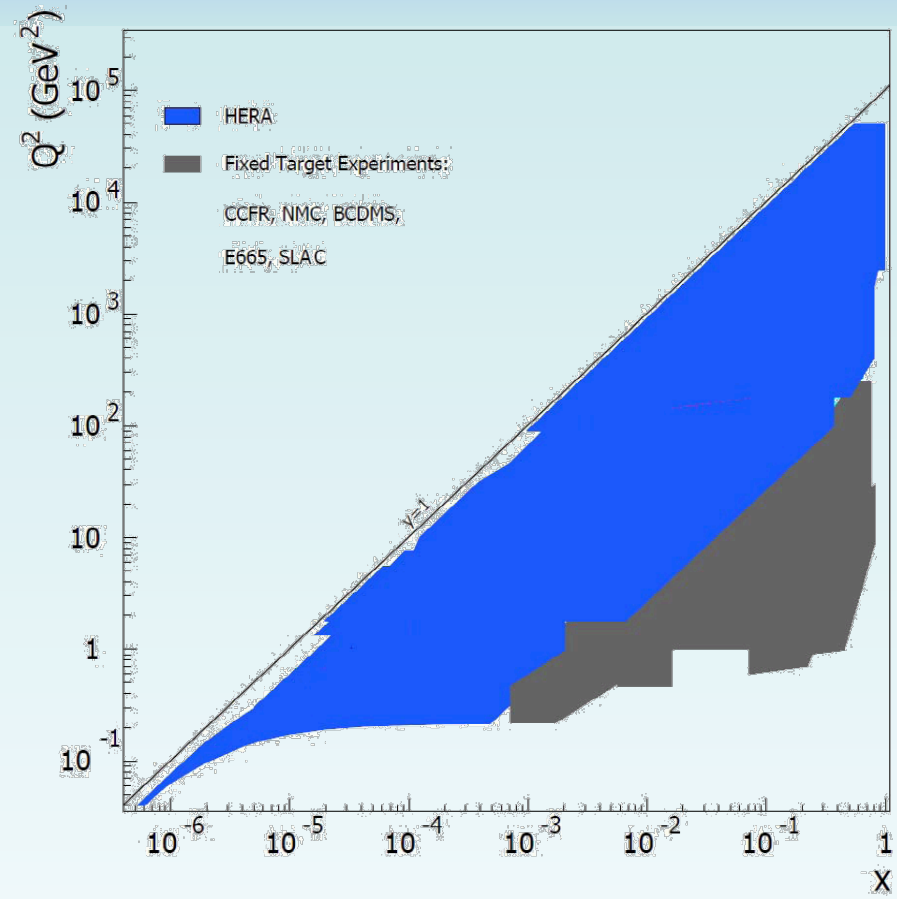
typical uncertainties:

- » statistical: typically < 1%
(but ranges from 0.1% at lowest Q^2 to as large as ~10–50% at highest Q^2 , x)
- » uncorrelated systematic: 0.7%
- » correlated systematic: typically 1–3%



also included in fit:

1% luminosity and polarisation uncertainties (as additional correlated systematics)



NLO QCD and electroweak fit

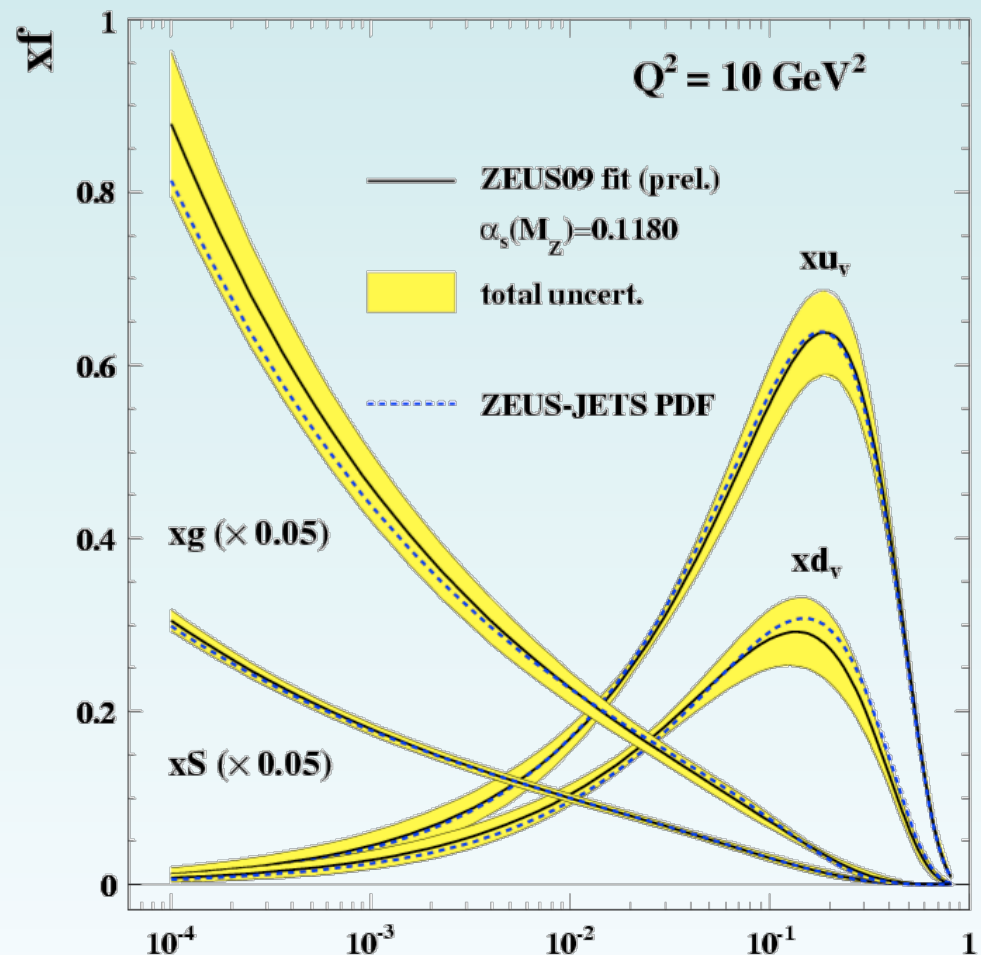
Study presented here is based on new
ZEUS NLO QCD fit to **HERA-I** and
HERA-II data

Data included in ZEUS fit:

- **HERA-I:**
 - CC and NC inclusive $e^\pm p$
 - DIS inclusive jet and dijet γp
- **HERA-II**
 - CC $e^\pm p$ (polarised)
 - NC $e^\pm p$ (polarised)

correlated uncertainties:
treated using the Offset method

ZEUS09 fit (c.f. central values of HERA-I fit)



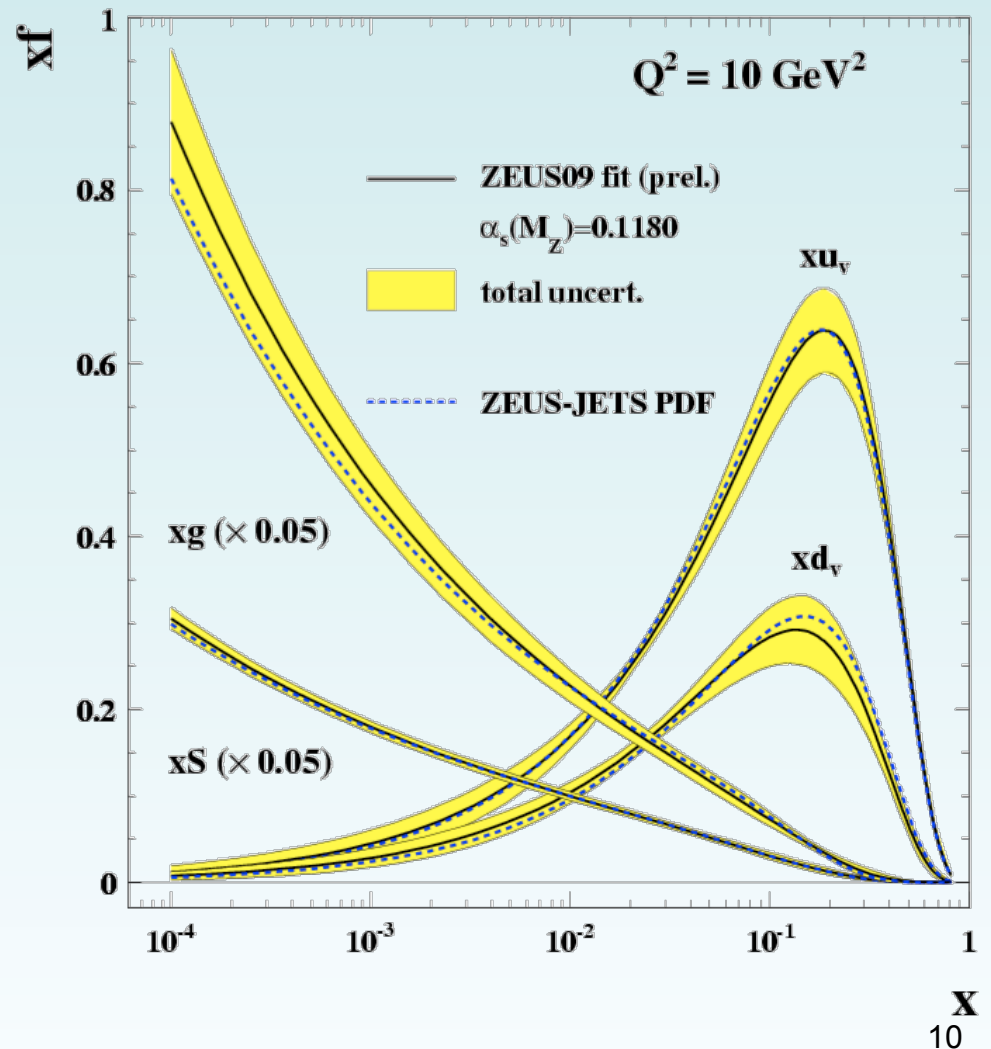
↑ full details of fit will be shown at DIS09 (some further details also given in backups)

NLO QCD and electroweak fit

Study presented here is based on new
ZEUS NLO QCD fit to **HERA-I** and
HERA-II data

LHeC NC/CC simulated data added
to this in a **combined fit** for the
PDFs and **electroweak parameters**

ZEUS09 fit (c.f. central values of HERA-I fit)



NLO QCD and electroweak fit

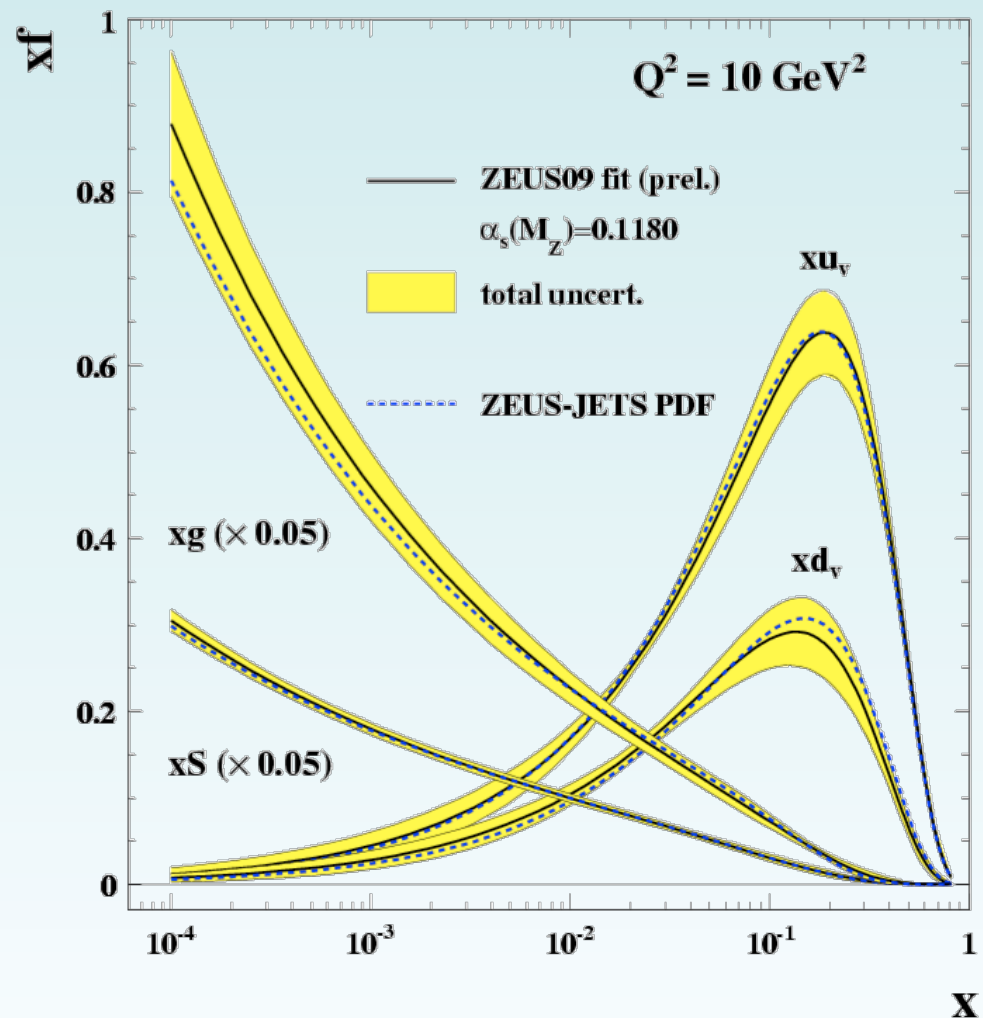
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PDFs and **electroweak parameters**

caveats to comparisons:

- **not all** HERA-II data yet included
in ZEUS fit (NC e^+p still to come)
- best HERA PDF+EW constraints
will come from a **future HERA-II
combination** of H1+ZEUS data
- » still some **improvement to come
from HERA** (but difficult to quantify)

ZEUS09 fit (c.f. central values of HERA-I fit)



Proton PDFs

Proton PDFs

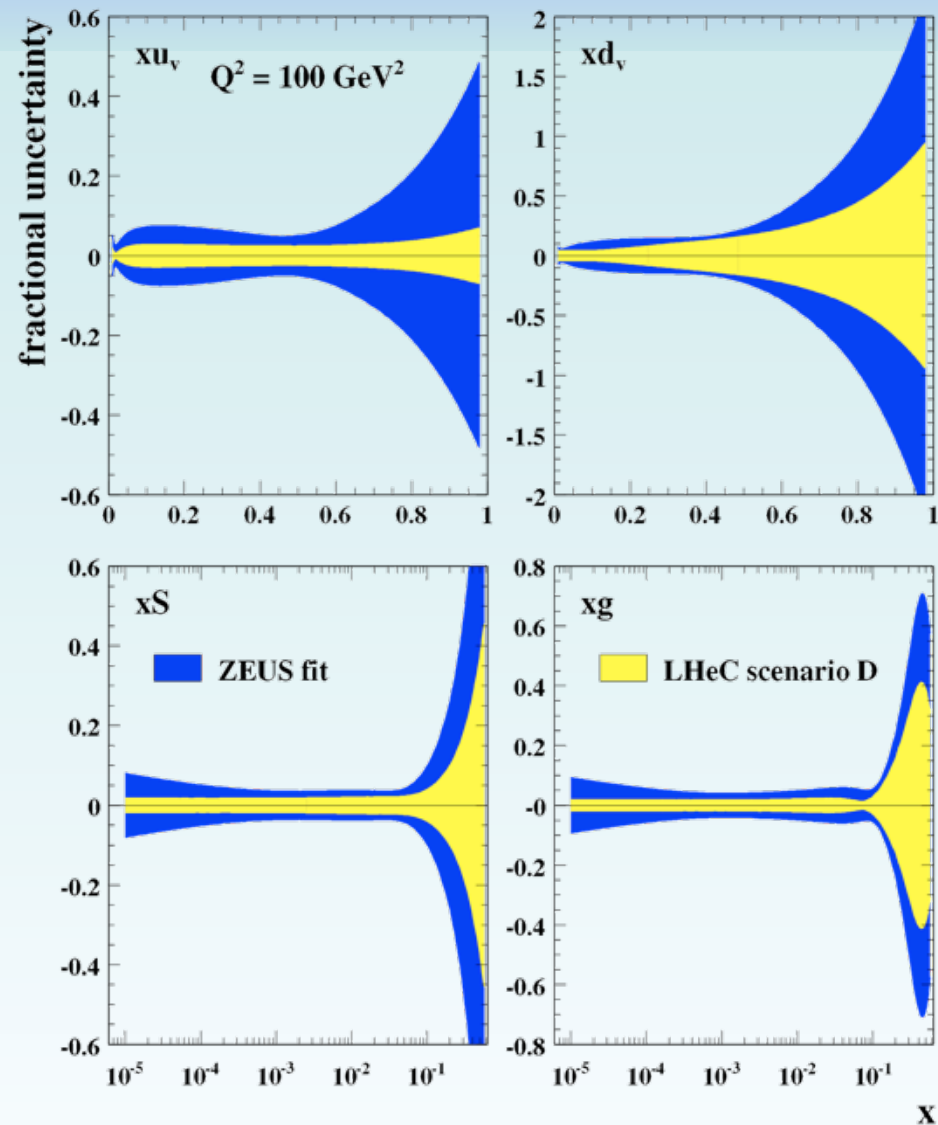
- » only PDF parameters free
(LHeC **NC** $e^\pm p$ included)

PDF uncertainties:

- **NC $e^\pm p$** : direct constraints on **quark densities**; indirect on **gluon** via scaling violations

$$Q^2 = 100 \text{ GeV}^2$$

scenario D



Proton PDFs

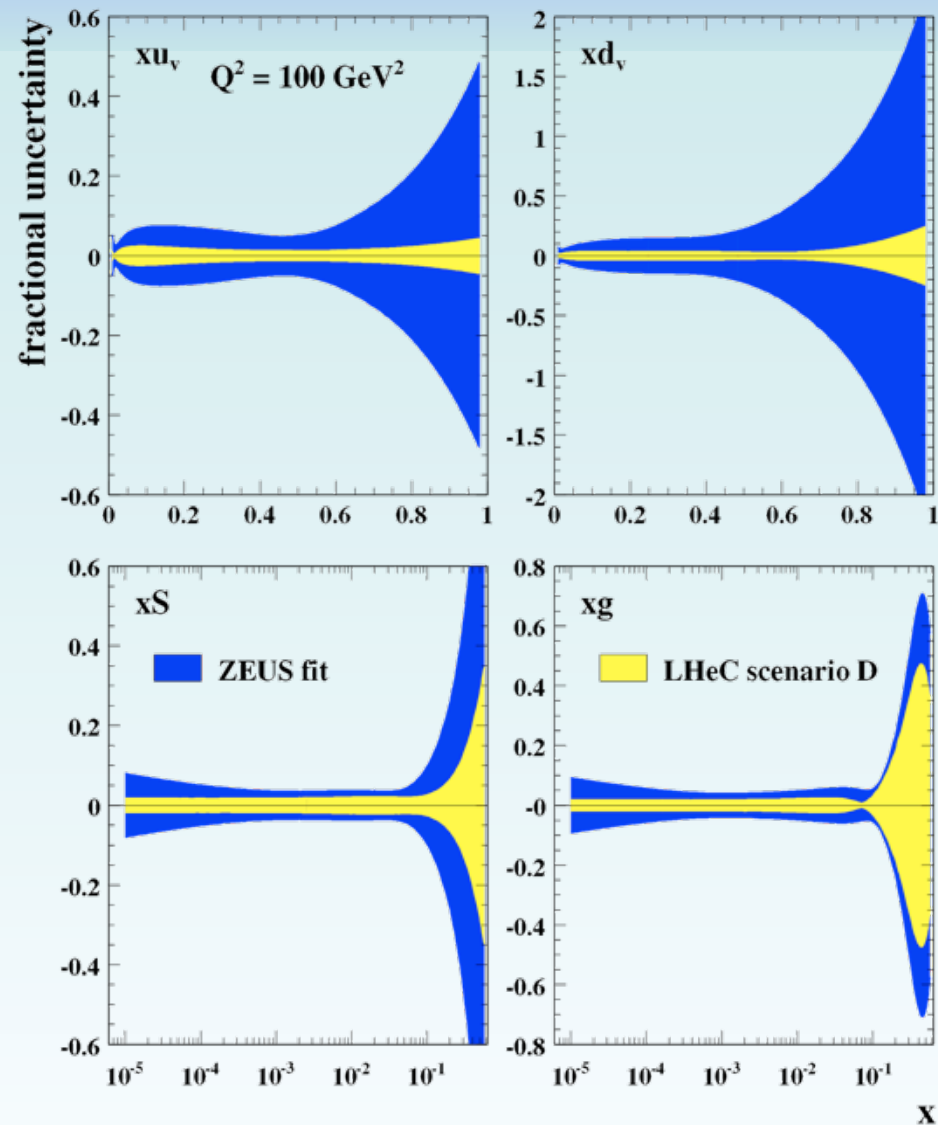
- » only PDF parameters free
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PDF uncertainties:

- **NC $e^\pm p$** : direct constraints on **quark densities**; indirect on **gluon** via scaling violations
- **CC $e^\pm p$** : constraints on quarks
→ **flavour decomposition**
(e^- : mostly u; e^+ : mostly d)

$$Q^2 = 100 \text{ GeV}^2$$

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Proton PDFs

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(LHeC NC and CC $e^\pm p$ included)

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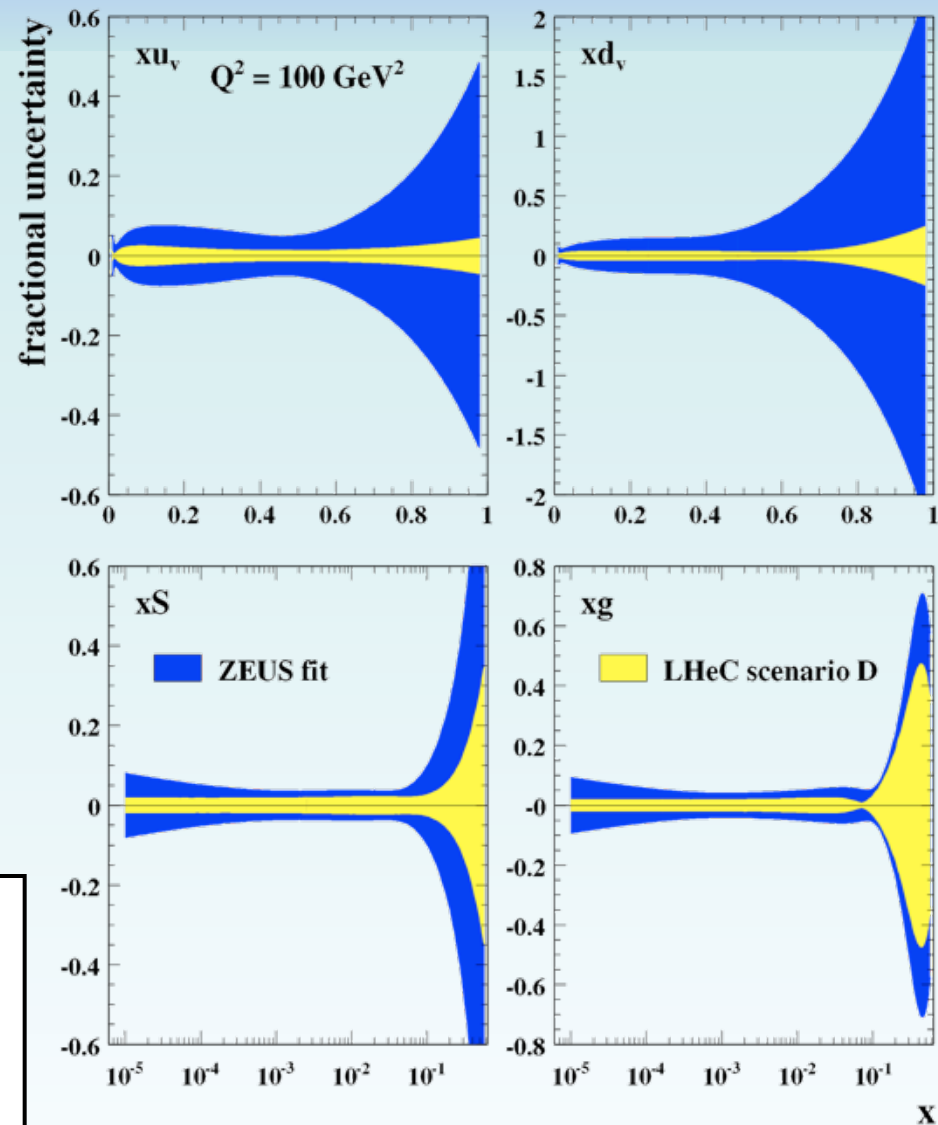
→ results encouraging!

However, should also consider:

- **flexibility of parameterisation?**
- **model uncertainties?**

$$Q^2 = 100 \text{ GeV}^2$$

scenario D



Proton PDFs

- » only PDF parameters free
(LHeC **NC** and **CC** $e^\pm p$ included)

scenarios: **A**, **B**, **C**, **D** and **E**

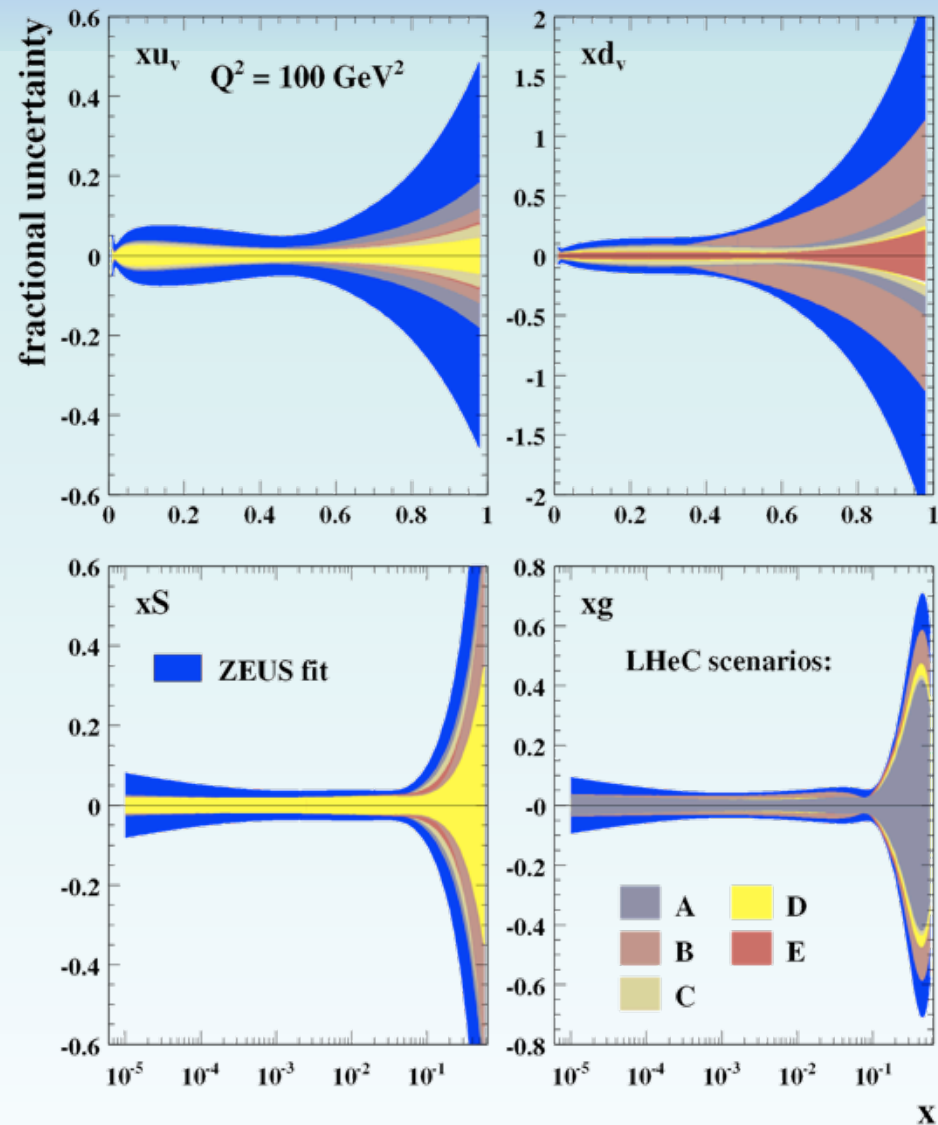
	E_e (GeV)	P	L ($e^-:e^+$)
A	20	0	2 (1:1)
B	50	0.4	200 (1:1)
C	50	0.4	4 (1:1)
D	100	0.9	30 (2:1)
E	150	0.9	18 (2:1)

(examples with several different Q^2 values are shown in backups)

* acceptance for scenario B has been taken to be: $10 < \theta < 170^\circ$

$$Q^2 = 100 \text{ GeV}^2$$

scenario D



electroweak parameters

- » fit with PDF and electroweak parameters simultaneously free
 - neutral current axial and vector quark couplings (a_u, v_u, a_d, v_d)
 - mass of the W boson

* the following results currently have only the LHeC NC (CC will not change things by much)

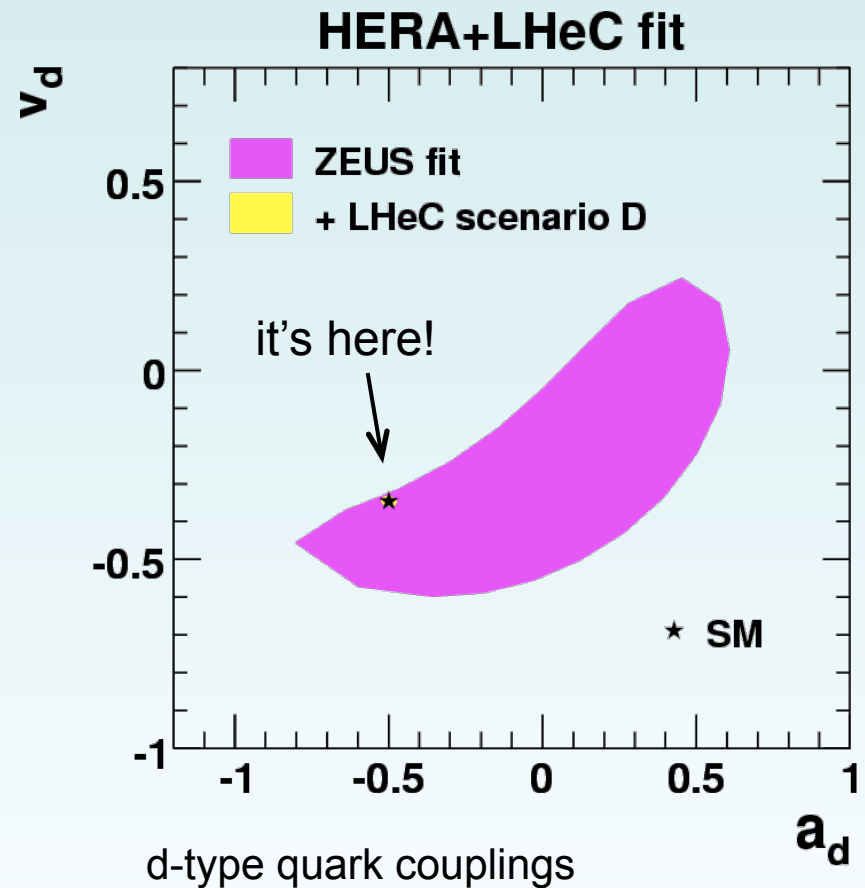
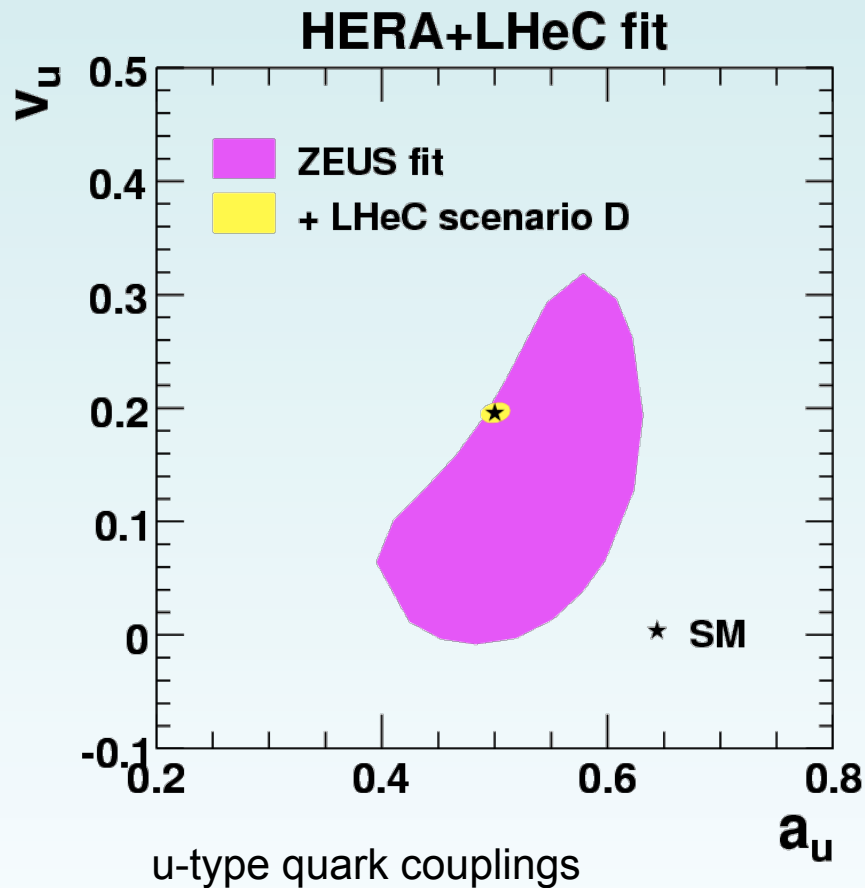
neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

comparison with **ZEUS fit** (base to which LHeC pseudo-data added)

» still to come: HERA-II NC e^+p data in ZEUS fit; **H1+ZEUS combined HERA-II results**



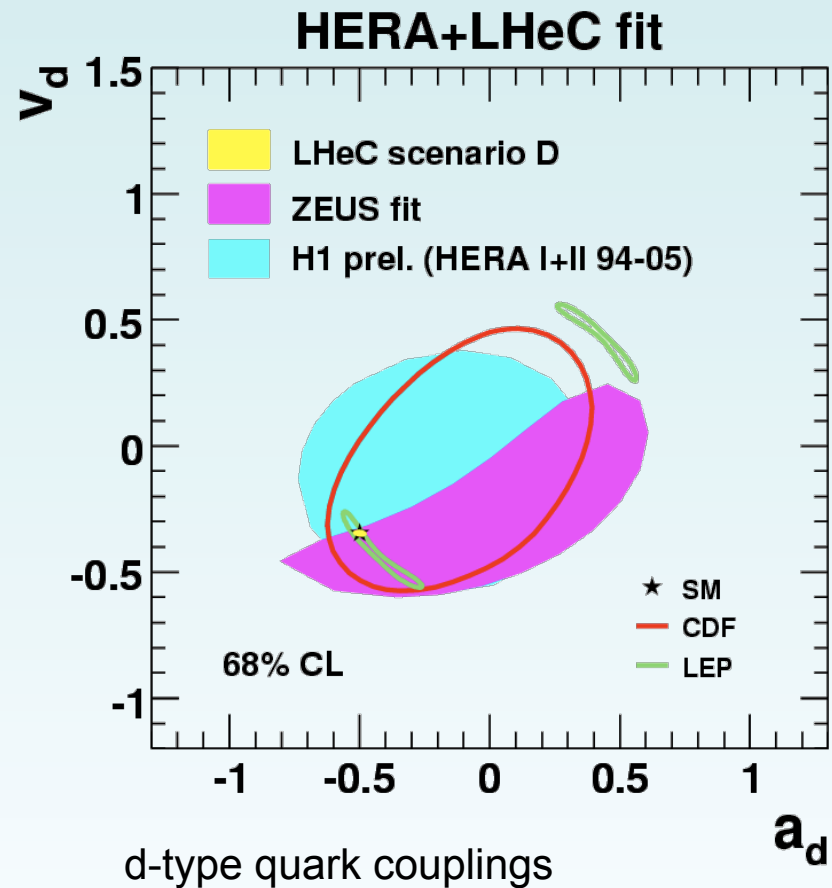
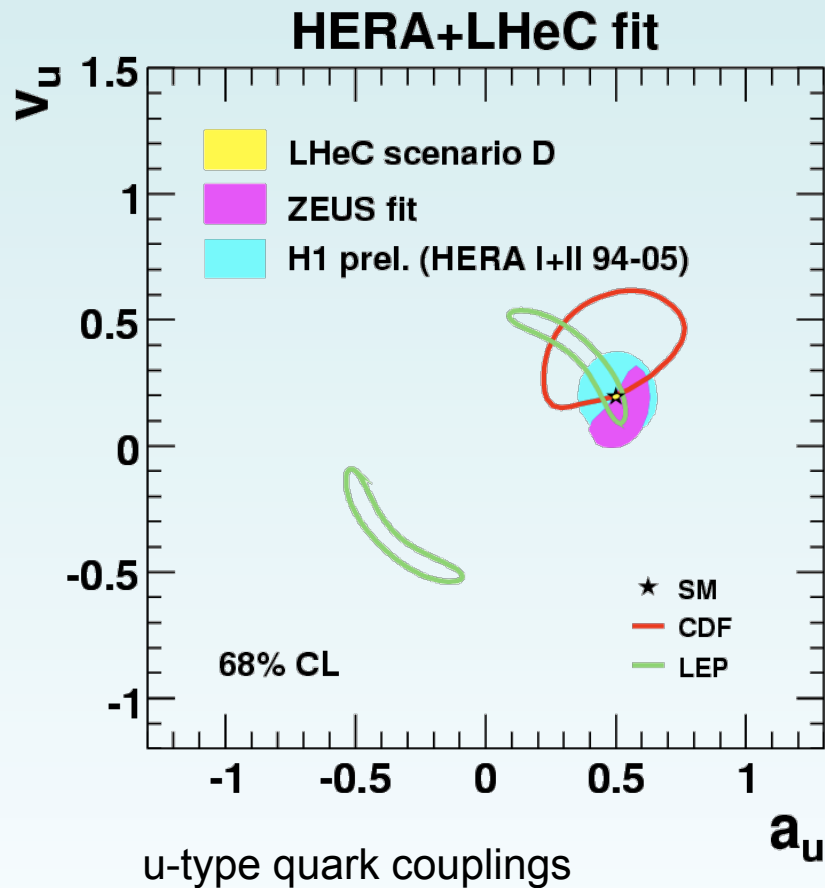
neutral current quark couplings

scenario D:

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comparison with **other experiments**

» still to come: HERA-II NC e^+p data in **ZEUS fit**; **H1+ZEUS combined HERA-II results**

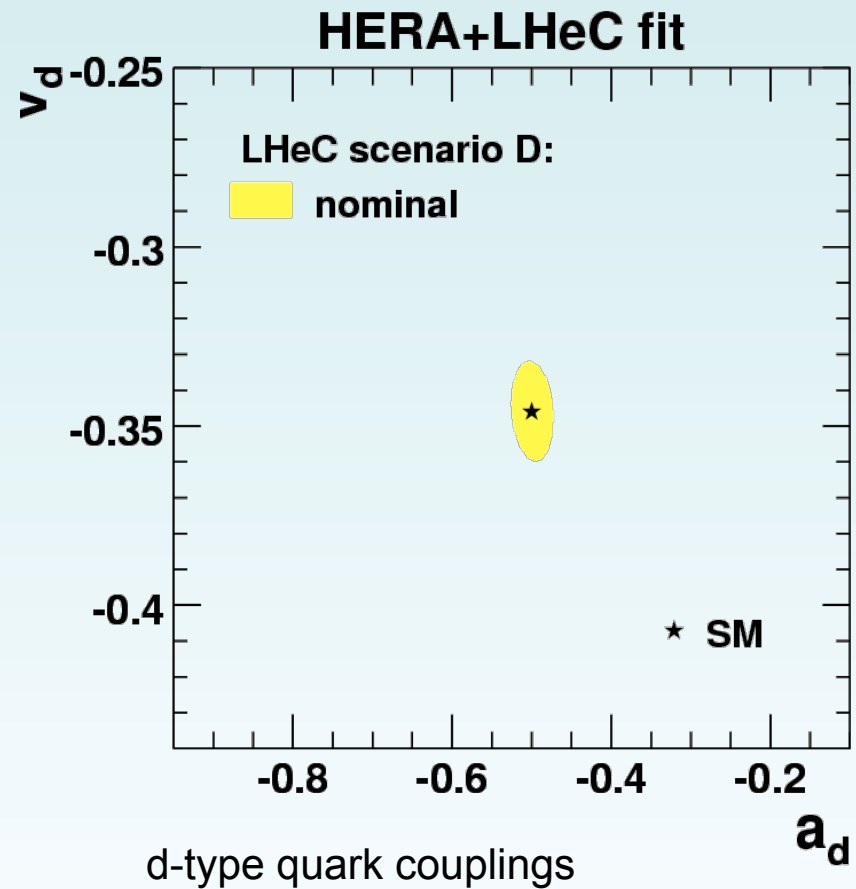
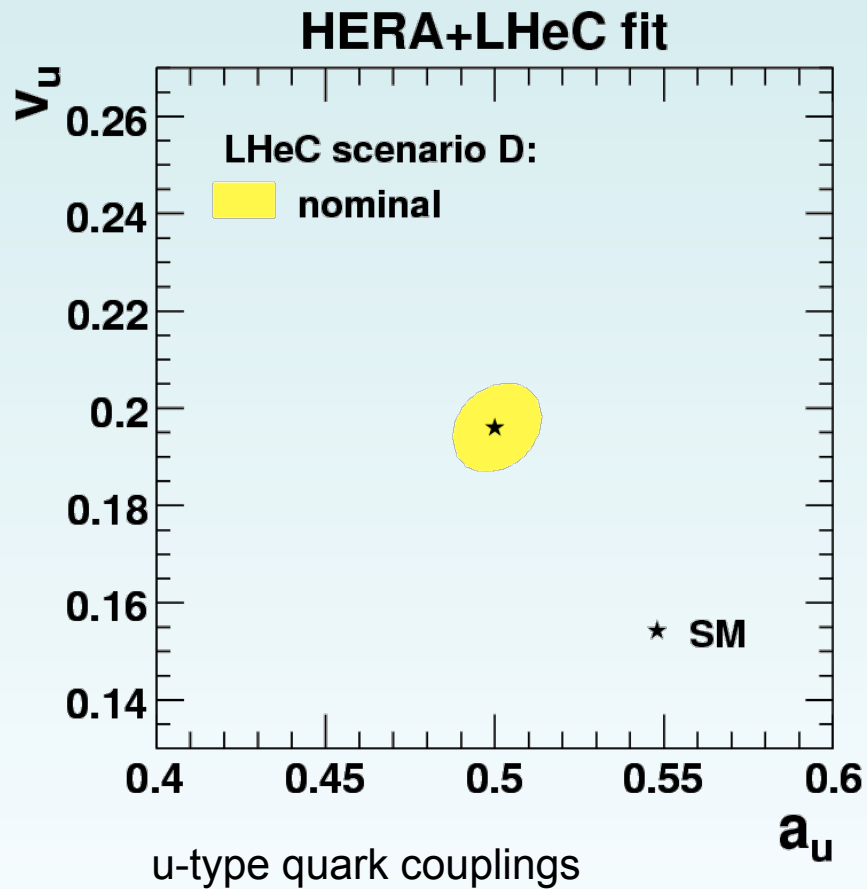


neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

What if assumed level of statistical and systematic precision **not achieved**?



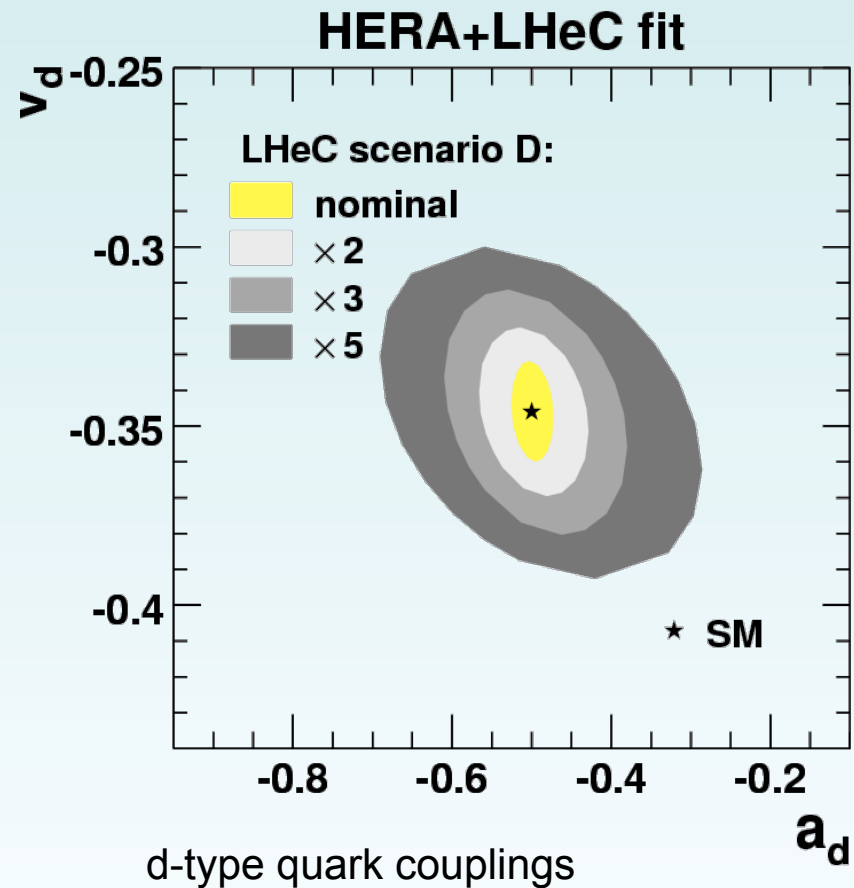
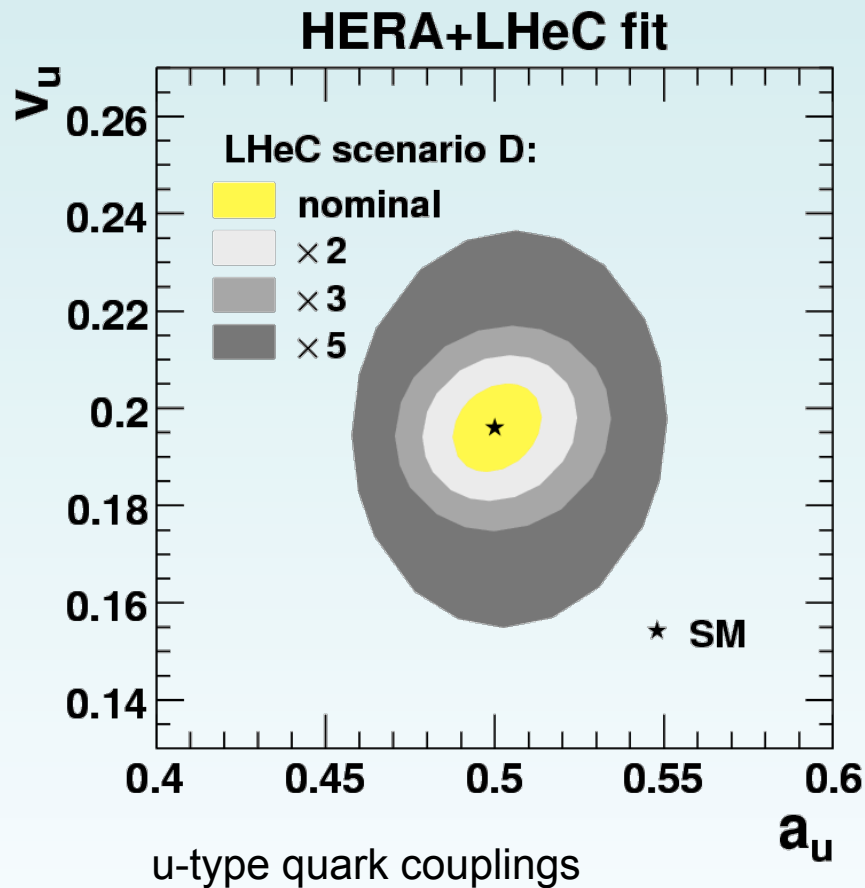
neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

What if assumed level of statistical and systematic precision **not achieved**?

» reducing **luminosity** and increasing all **systematic uncertainties** by factors of $\times 2, 3, 5$



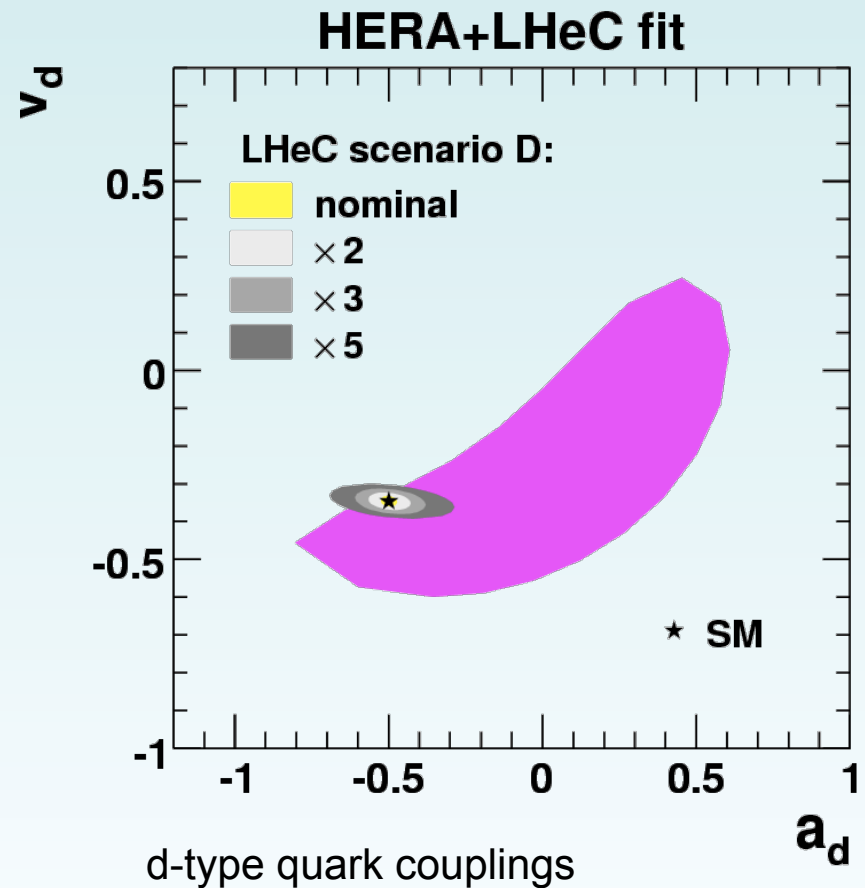
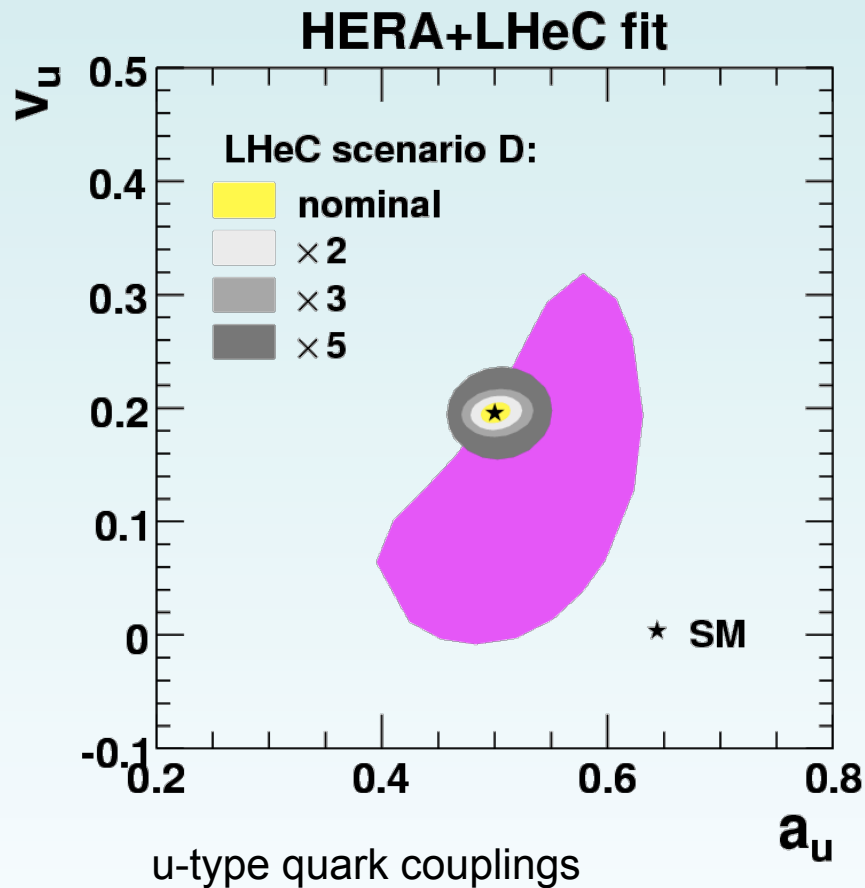
neutral current quark couplings

scenario D:

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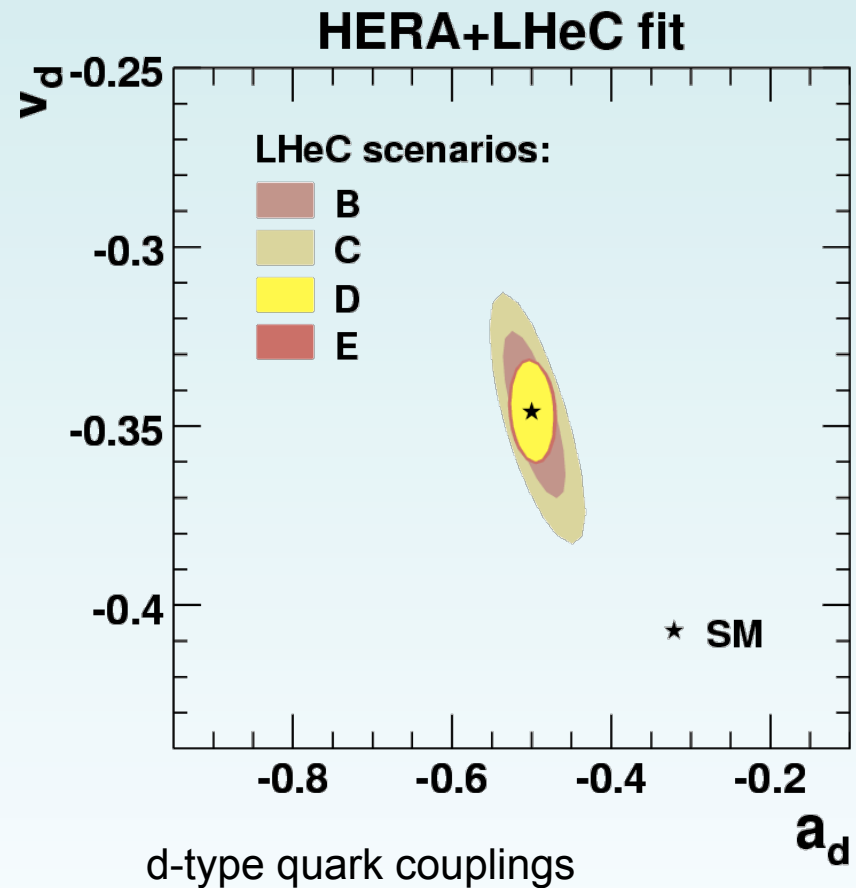
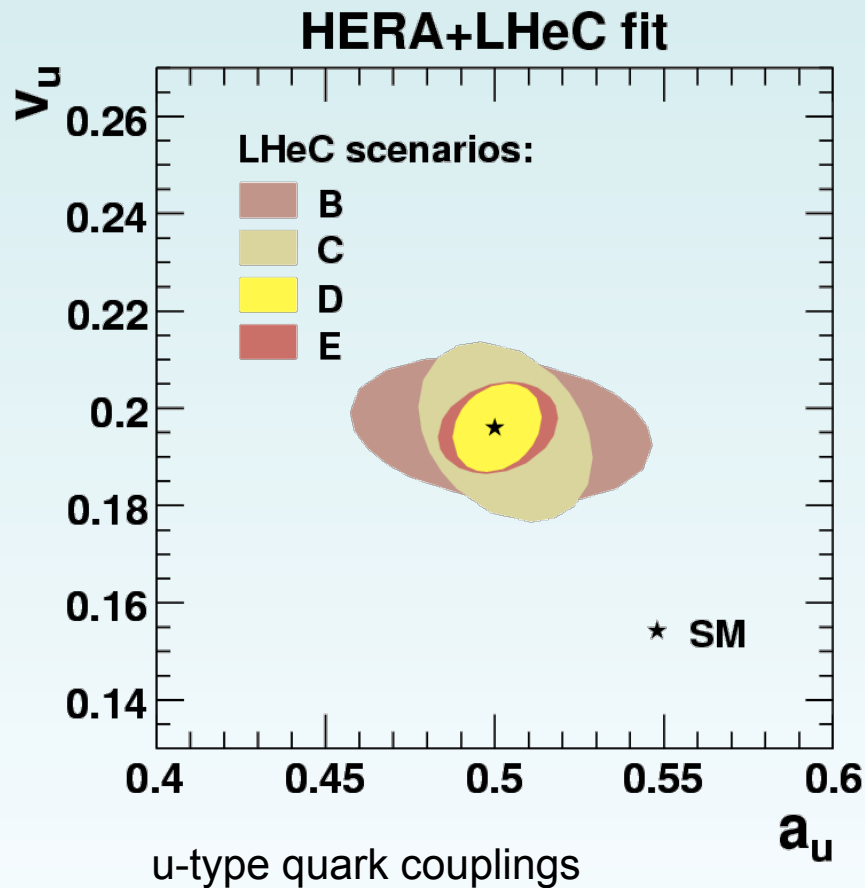
neutral current quark couplings

polarisations:

$P_e = \pm 0.4$ (B,C)

$P_e = \pm 0.9$ (D,E)

other scenarios: B, C, (D) and E



neutral current quark couplings

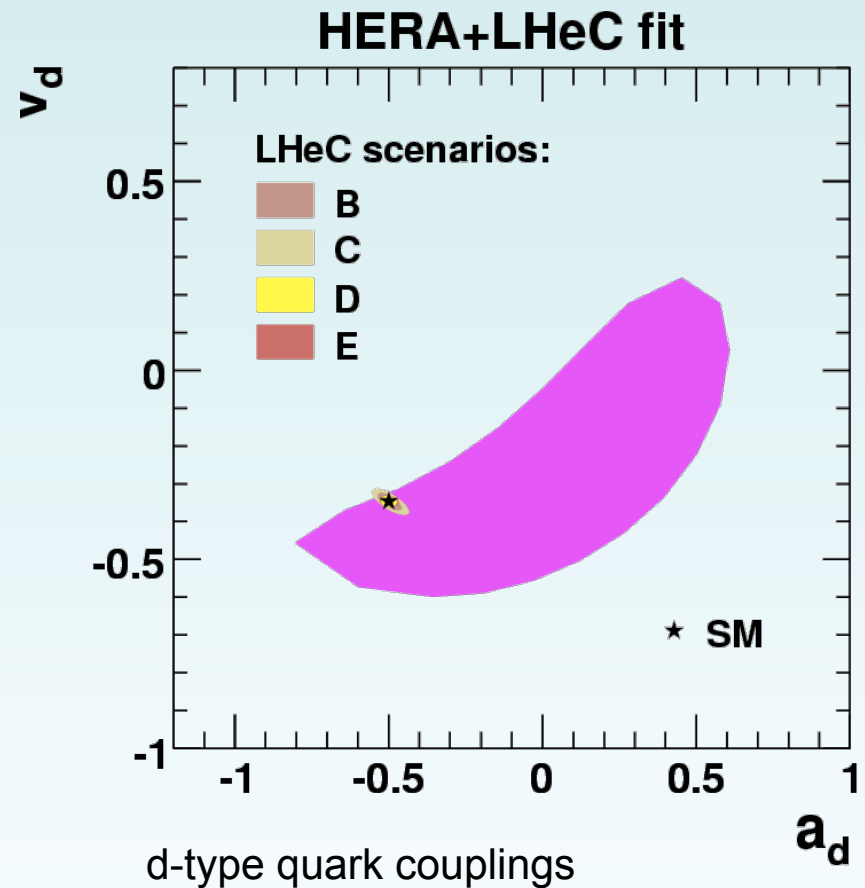
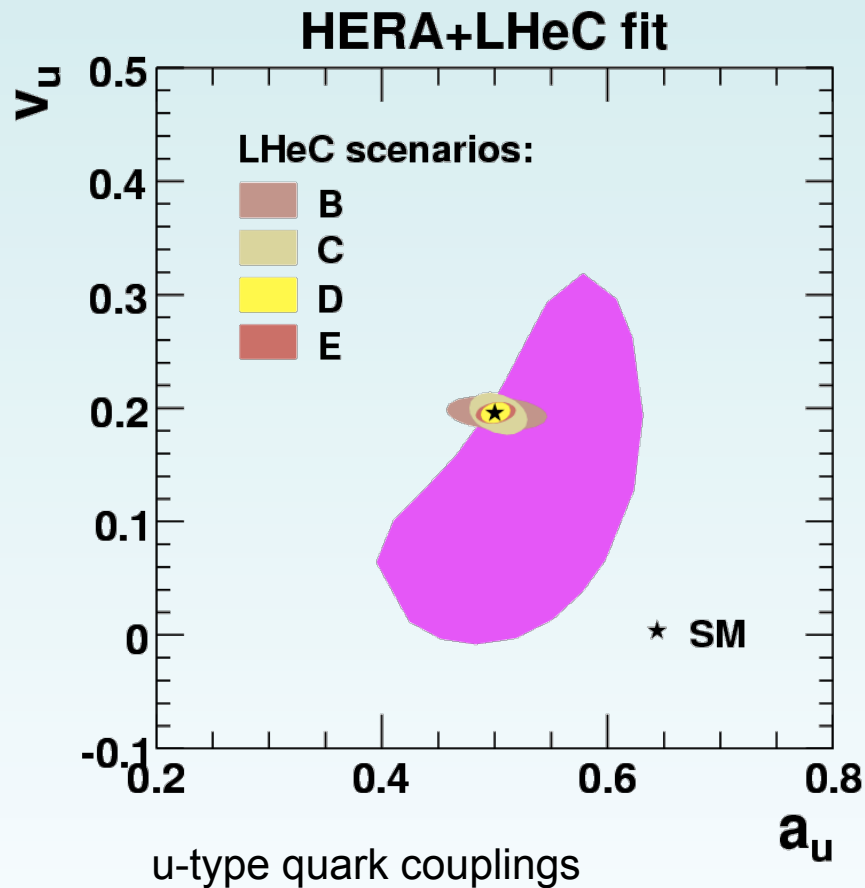
polarisations:

$P_e = \pm 0.4$ (B,C)

$P_e = \pm 0.9$ (D,E)

other scenarios: **B**, **C**, (**D**) and **E** (versus ZEUS base fit)

→ factors of **×10–40 improvement** (depending on exact coupling and scenario)



neutral current quark couplings

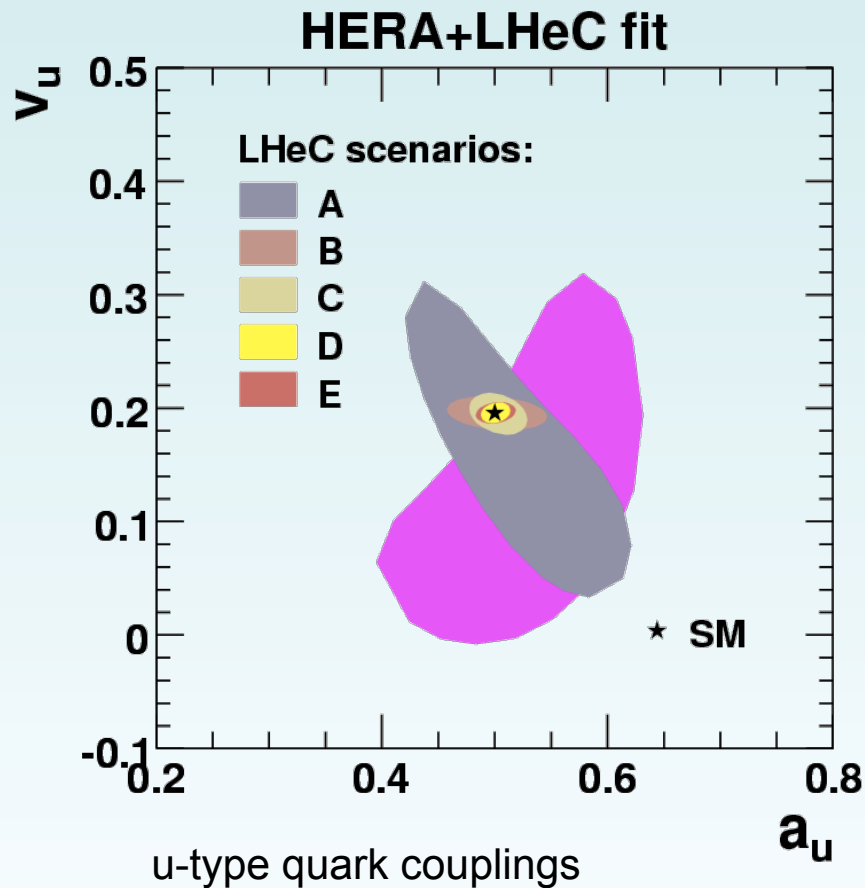
polarisations:

$$P_e = 0 \quad (\text{A})$$

$$P_e = \pm 0.4 \quad (\text{B,C})$$

$$P_e = \pm 0.9 \quad (\text{D,E})$$

also, an example with scenario A (no polarisation):



↪ less tight constraint from scenario A
(especially for vector couplings, as expected)

W boson mass

$$\frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2}$$

M_W enters the fit through the **propagator** in the CC cross sections:

→ also performed fit including LHeC CC, **with M_W free**, together with the PDFs (NC quark couplings fixed to SM)

$$M_W (= 80.4 \text{ SM})$$

Scenario D

$$M_W = 80.40 \pm 0.04 \text{ (uncorr.)} \pm 0.15 \text{ (corr.) GeV (total exp. 0.2\%)}$$

c.f. same method using **only HERA data** currently giving uncertainties of order **1 GeV** (total experimental; no accounting for model uncertainties in the fit)

improved but not competitive ↓ (although still interesting as a cross-check; space-like regime)

current world average (PDG 2008): $M_W = 80.398 \pm 0.025 \text{ GeV (0.03\% total)}$

Summary

» **combined PDF and electroweak fit to HERA+LHeC simulated data** [scenarios A, B, C, D and E considered]

- study based on new ZEUS NLO QCD fit to HERA-I and HERA-II data
(caution for comparisons since this is not yet the final word from HERA)

results of this initial study:

» **proton PDFs:**

- » potential for **significant reduction** in **quark** and **gluon** uncertainties
BUT, want to investigate model uncertainties and different PDF parameterisations
(e.g. try MSTW-type for low-x gluon)

» **electroweak parameters:**

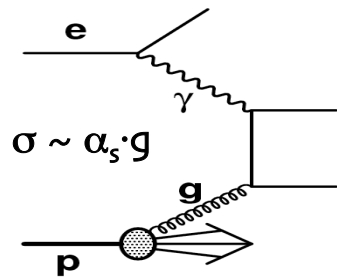
- » looked at NC **axial** and **vector quark couplings** to Z^0 (also, briefly, M_W)
- » results show **tight constraints** on **couplings** (for all scenarios with polarised leptons)
(further investigations:– **couplings for individual quark flavours?** **other suggestions?**)

extras

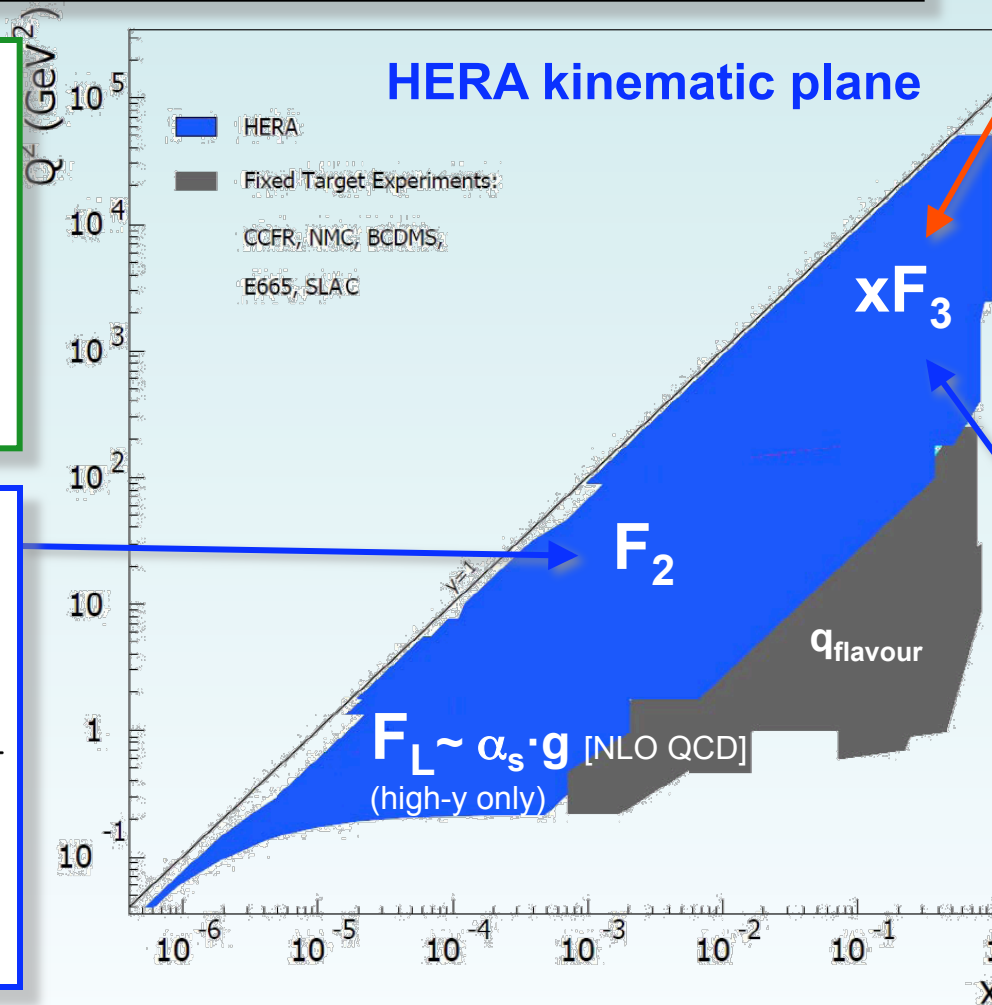
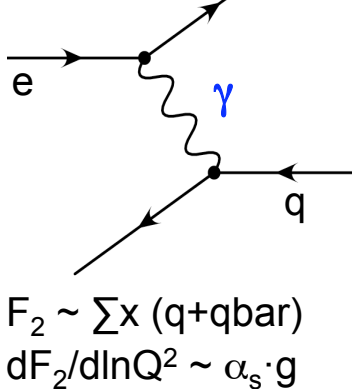
HERA and PDFs: a rough guide

$$\text{NC DIS: } \tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+} x \tilde{F}_3^{\pm} - \frac{y^2}{Y_+} \tilde{F}_L^{\pm}$$

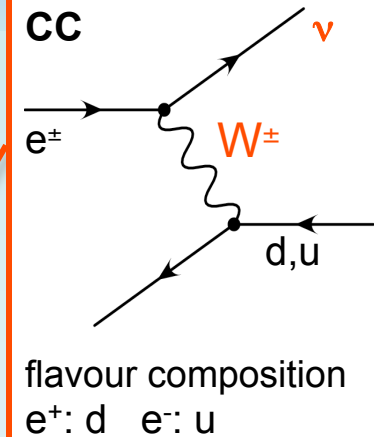
Final States:
(Jets, Charm, ...)



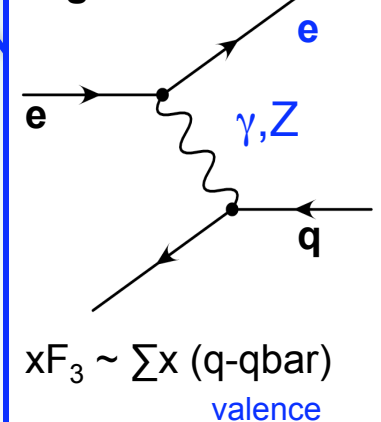
Low Q^2 NC
(γ exchange)



CC



High Q^2 NC



ZEUS fit parameterisation

choose form of PDF parameterisation at $Q_0^2 = 4 \text{ GeV}^2$

$$xf(x) = Ax^B(1-x)^C(1+Dx)$$

normalisation

low-x behaviour

high-x behaviour

polynomial term
(controls middling-x shape)

partons parameterised: gluon, u_v , d_v , sea = $u_{\text{sea}} + u + d_{\text{sea}} + d + s + \bar{s} + c + \bar{c}$
[sea flavour break-up at Q_0 : $s = (u+d)/4$, charm dynamically generated, d-u fixed to E866 data]

	A	B	C	D
gluon	sum rule			
u_v	sum rule			
d_v	sum rule	$=B(u_v)$		
sea (S)				0.
u-d	parameters from ZEUS-S global fit (2002)			0.

$$\begin{aligned} xg(x) &= Ax^B(1-x)^C(1+Dx) \\ xu_v(x) &= Ax^B(1-x)^C(1+Dx) \\ xd_v(x) &= Ax^B(1-x)^C(1+Dx) \\ xS(x) &= Ax^B(1-x)^C \end{aligned}$$

→ 11 free parameters

more details

extra info on the fit:

- **NLO DGLAP framework** used to evolve PDFs in Q^2
- **heavy flavour scheme: Zero-Mass Variable-Flavour-Number**
[due to time restrictions → variable flavour number scheme takes ~ 1 week to produce EW contours!]
- renormalisation and factorisation scales: Q^2
- fit **898 HERA-I and -II** data points **plus** **LHeC** pseudo-data points
- total of **11 free parameters** in the PDF fit (details on previous slide)

further fixed parameters:

- $Q_0^2 = 4 \text{ GeV}^2$ (**starting scale**)
- $Q_{\min}^2 = 2.5 \text{ GeV}^2$ (**minimum Q^2 cut on fitted data**)
- $m_c = 1.4 \text{ GeV}$ (**charm mass**); $m_b = 4.75 \text{ GeV}$ (**beauty mass**)
- $\alpha_s(M_Z) = 0.118$ (**strong coupling**)

Offset method

correlated uncertainties have been treated with the **Offset method**

Offset Method (in a nutshell)

1. perform fit without correlated uncertainties for central fit
2. shift measurements to upper limit of one of its systematic uncertainties
3. redo fit, record differences of parameters from those of step 1
4. go back to 2, shift measurement to lower limit
5. go back to 2, repeat 2-4 for next source of systematic (and so on ...)
6. add all deviations from central fit in quadrature (positive and negative deviations separately)

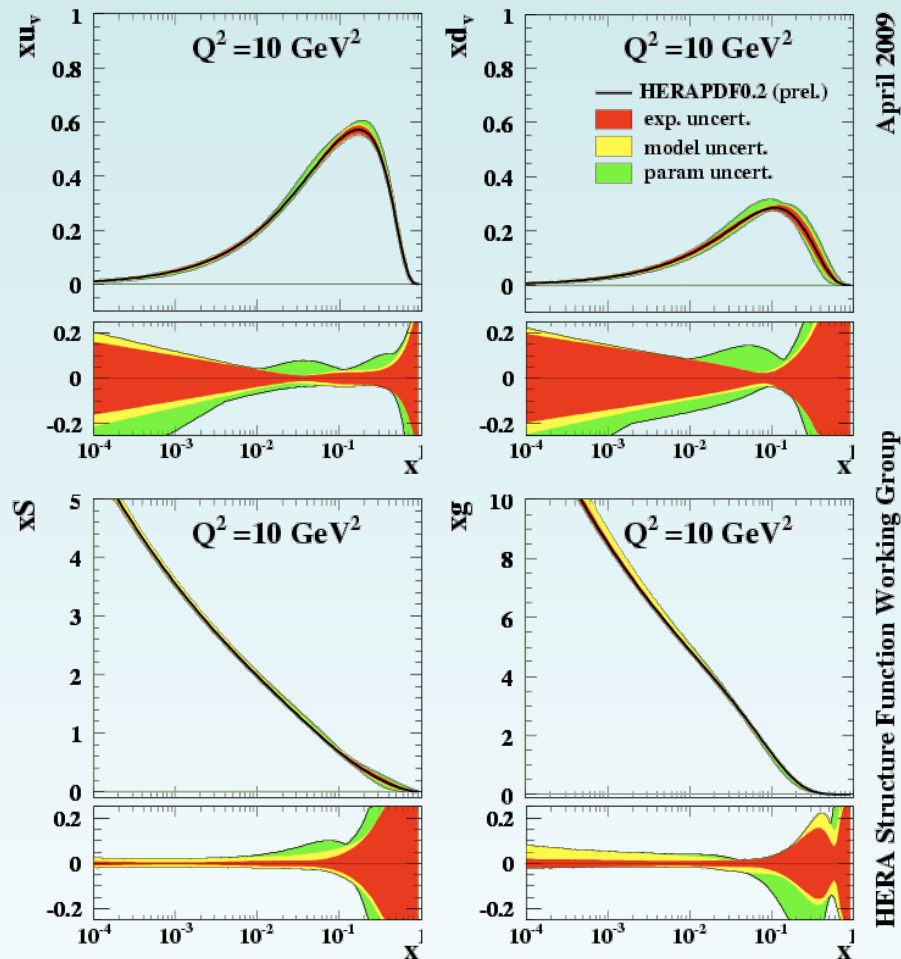
» does **not** assume uncertainties are **Gaussian distributed**.

» also tends to give **more conservative uncertainty estimates** than other methods

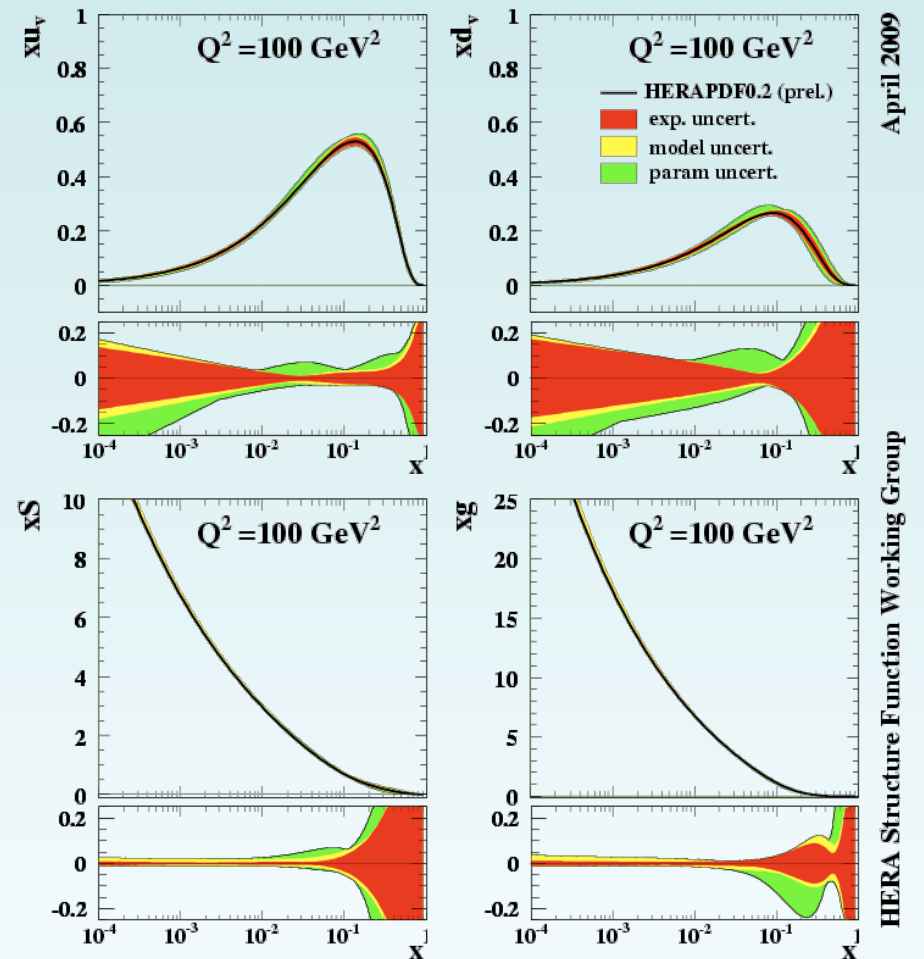
note: clever ways to do this in practice [Pascaud and Zomer LAL-95-05, Botje hep-ph-0110123]

HERA PDFs (best current from HERA)

H1 and ZEUS Combined PDF Fit

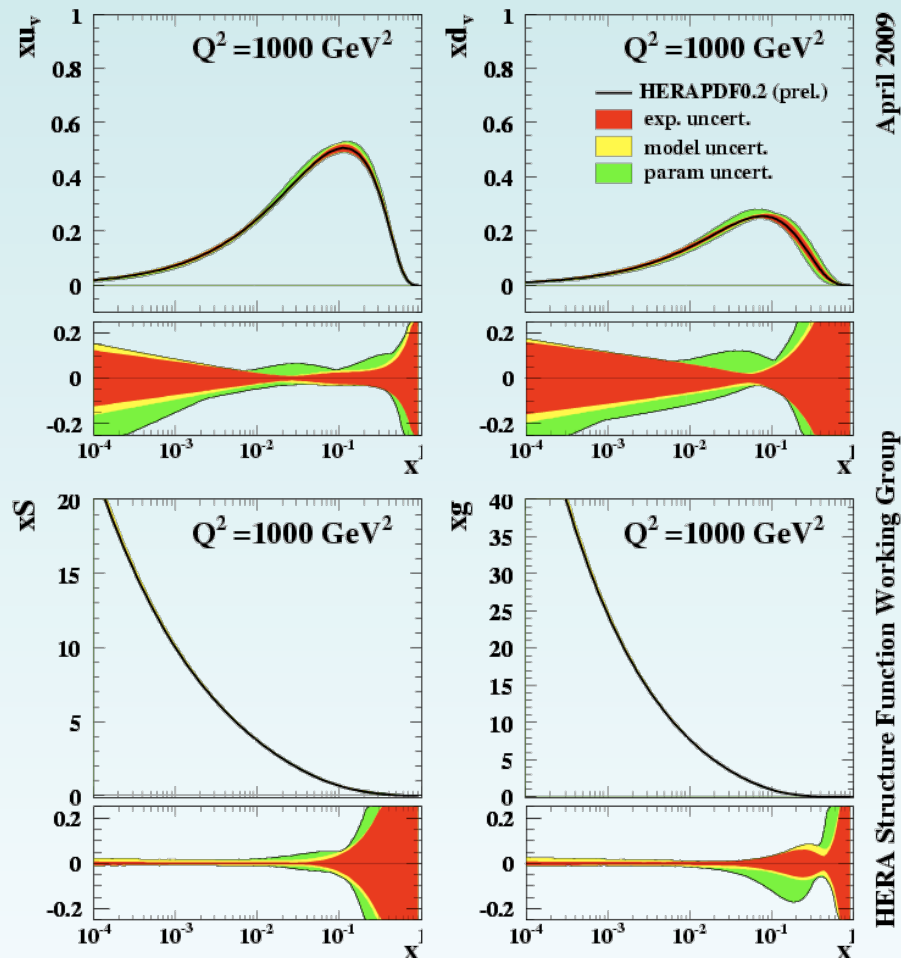


H1 and ZEUS Combined PDF Fit

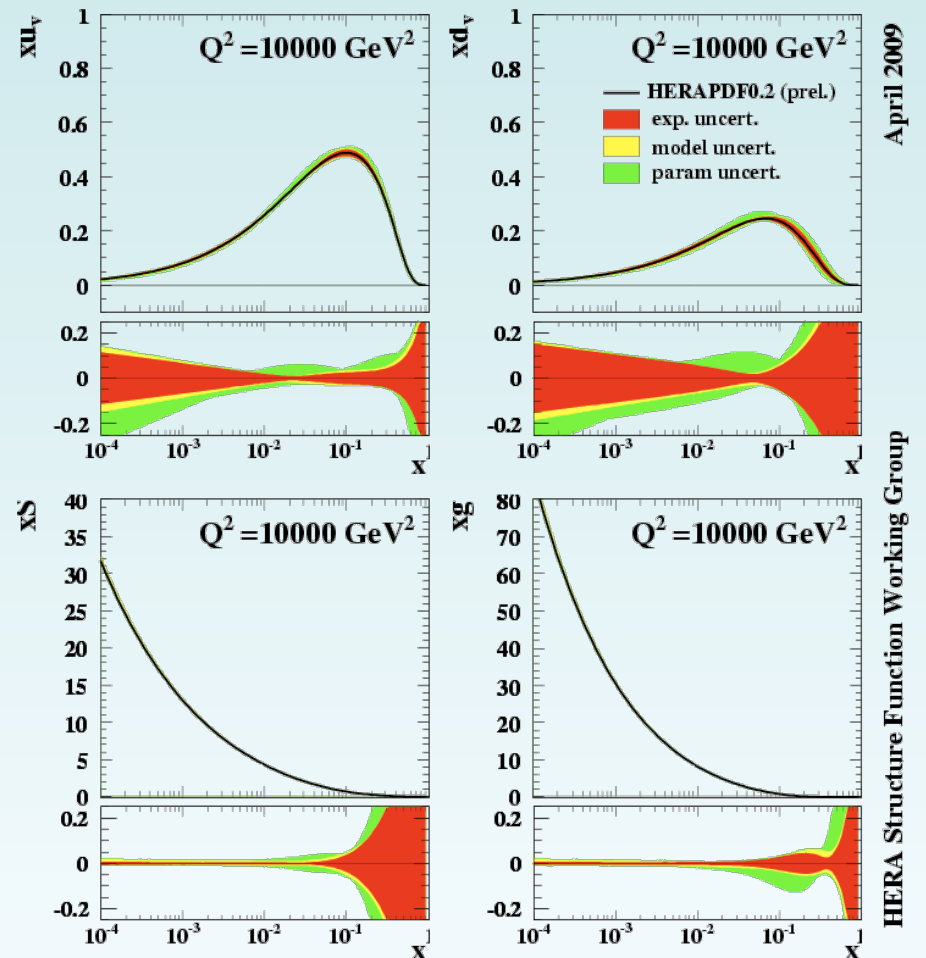


HERA PDFs (best current from HERA)

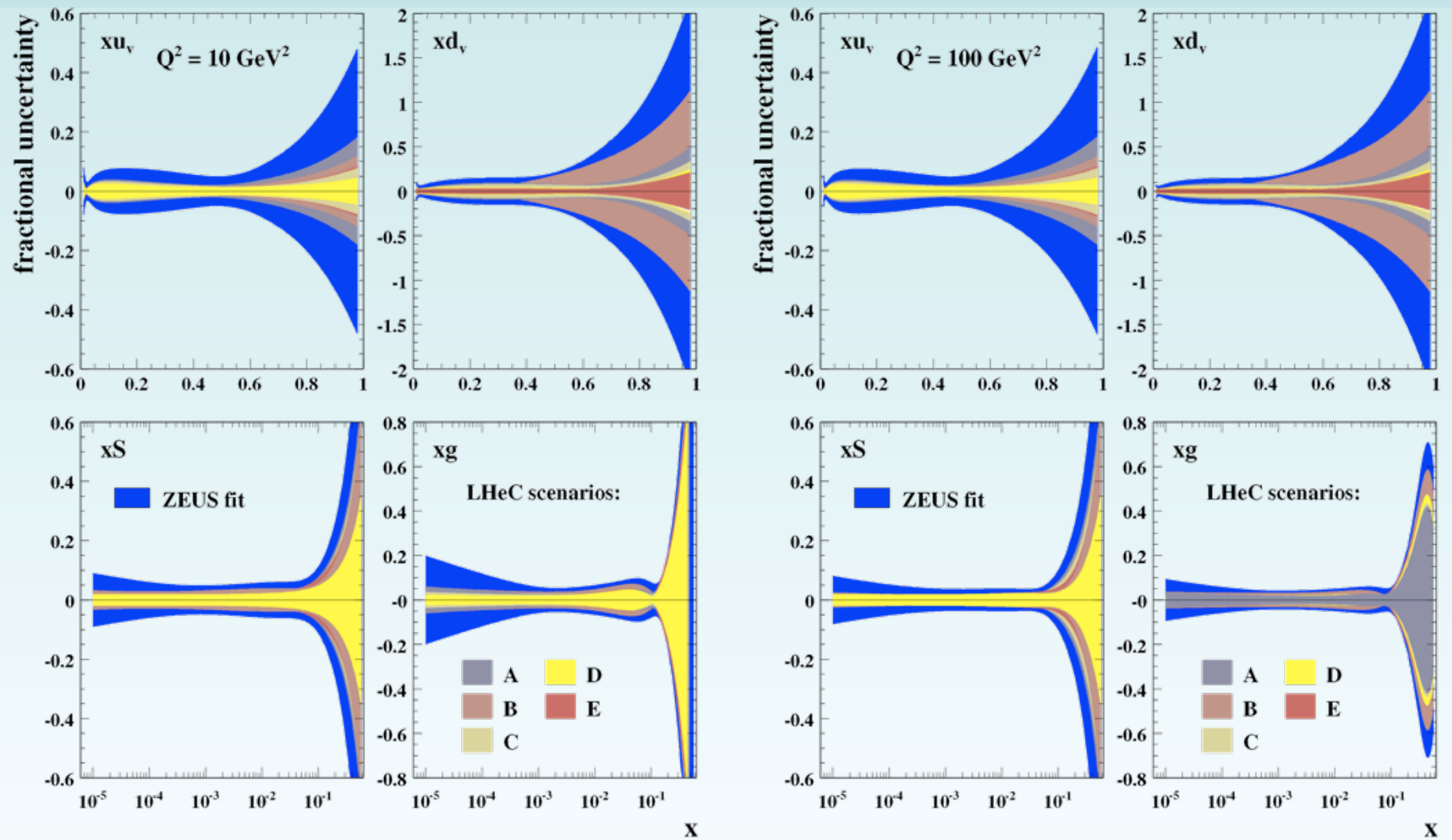
H1 and ZEUS Combined PDF Fit



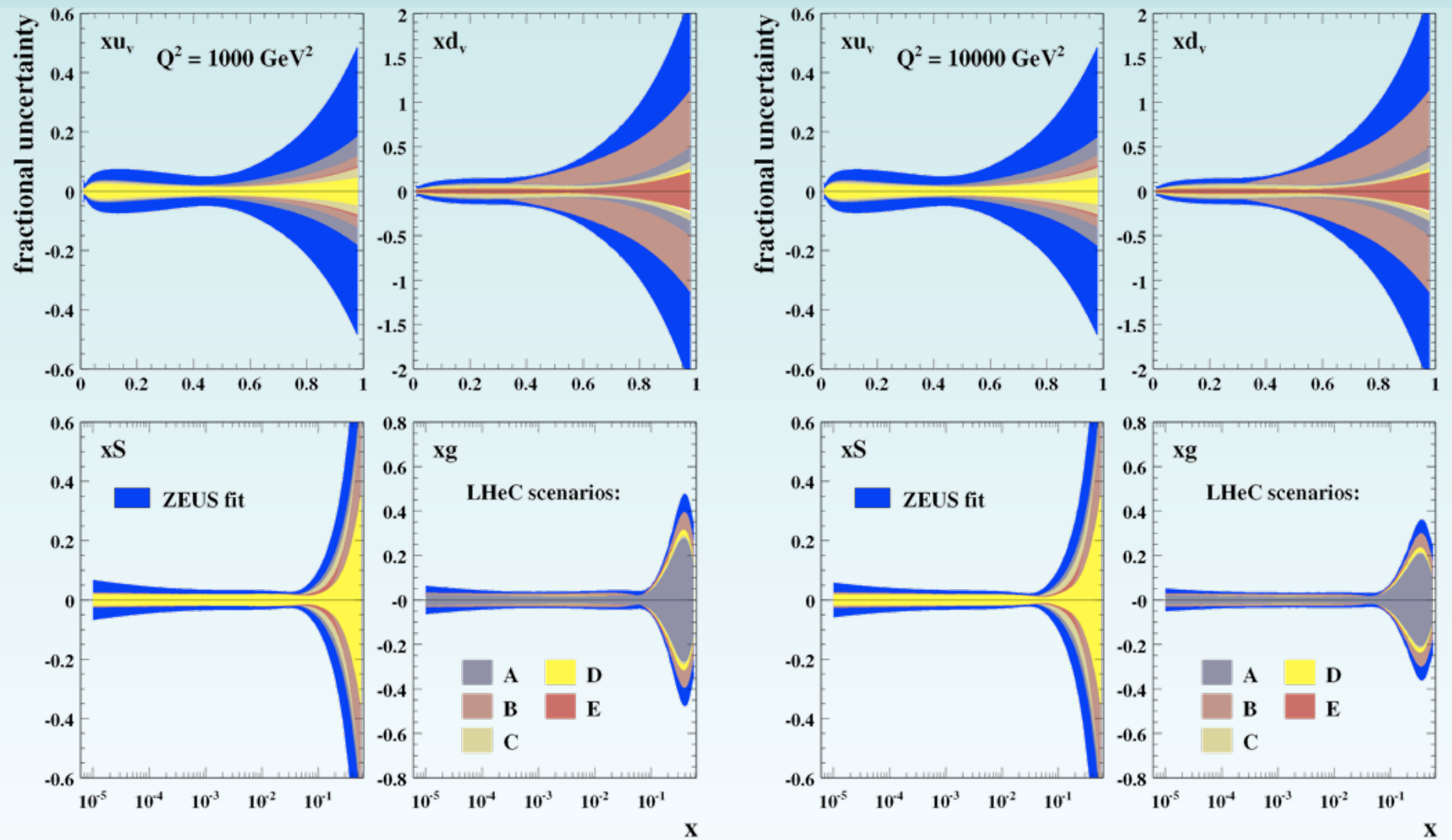
H1 and ZEUS Combined PDF Fit



Proton PDFs (other scales)



Proton PDFs (other scales)



Proton PDFs

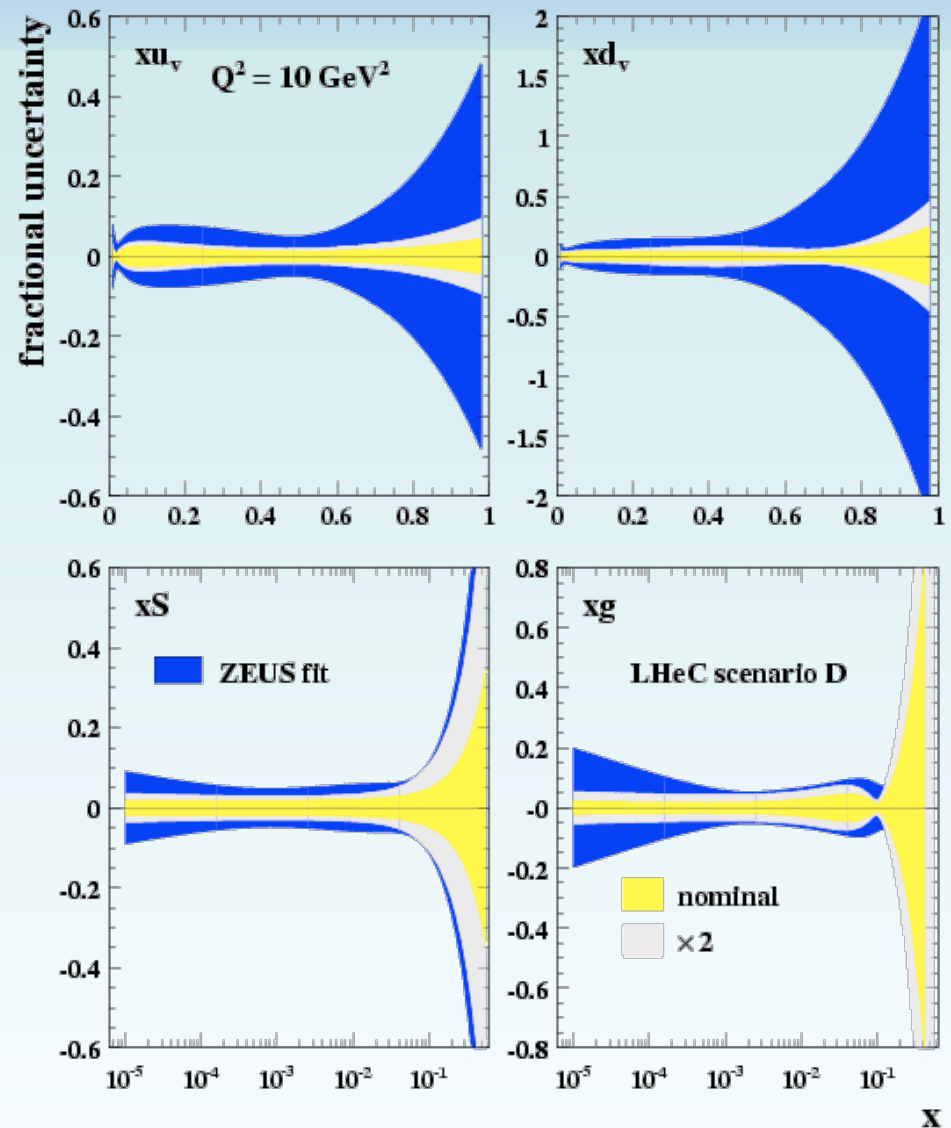
- » only PDF parameters free
(LHeC **NC** and **CC** $e^\pm p$ included)

What if this level of statistical and systematic precision **not achieved**?

- » reducing luminosity, and increasing all **systematic uncertainties** by a factor of $\times 2$

$$Q^2 = 10 \text{ GeV}^2$$

scenario D



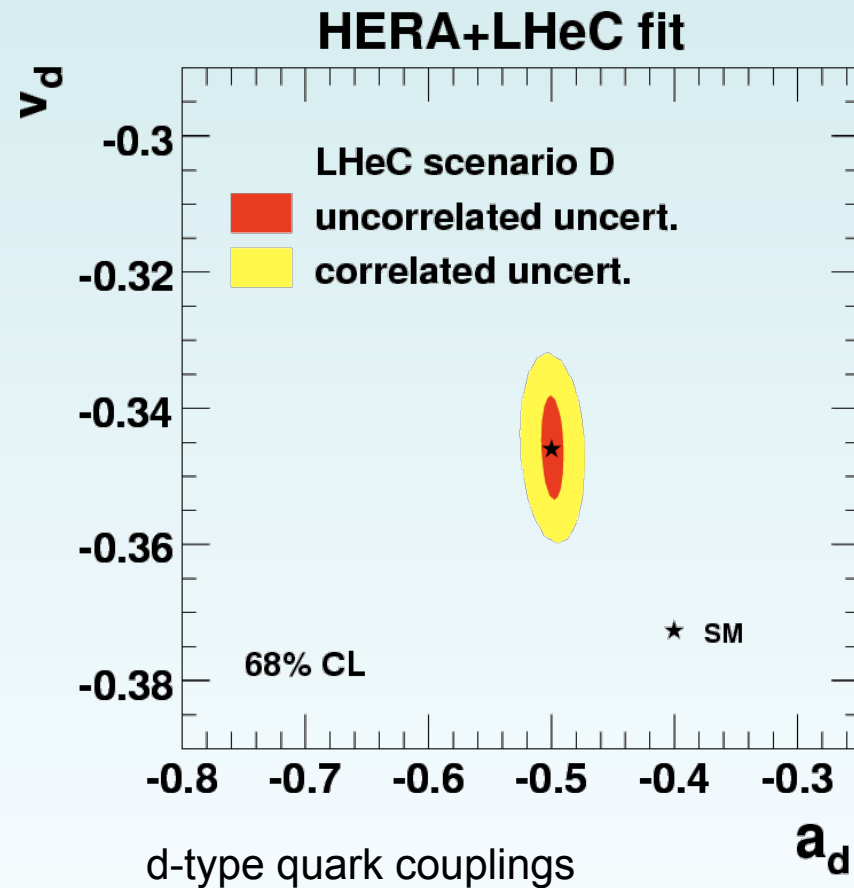
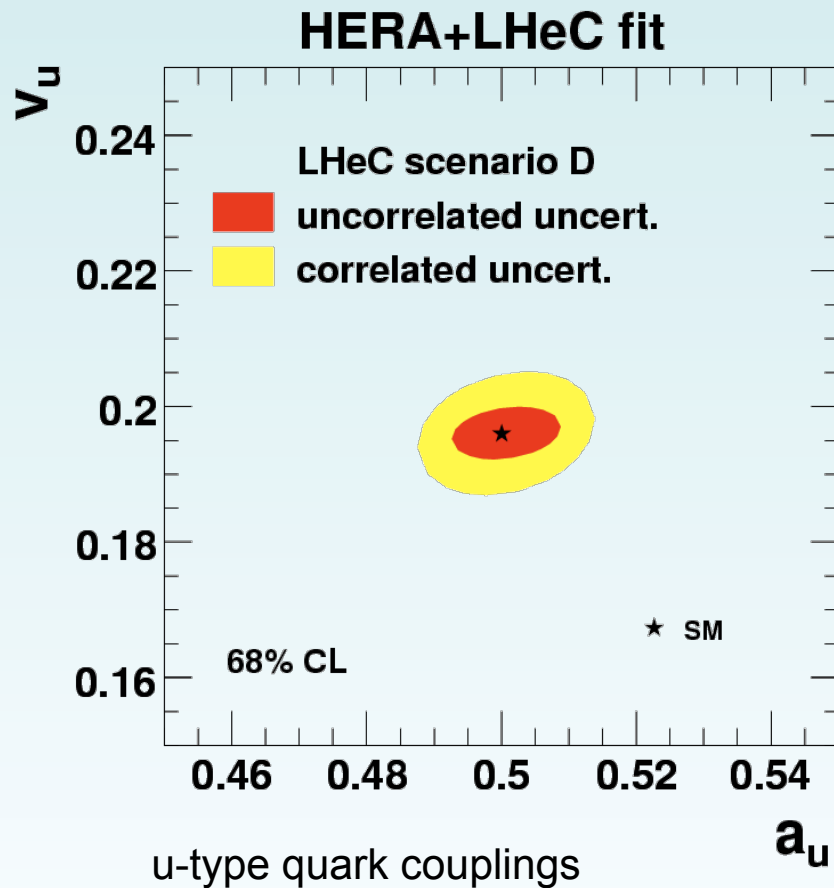
neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

electroweak couplings of quarks to Z^0

(uncorrelated and correlated uncertainties shown separately)



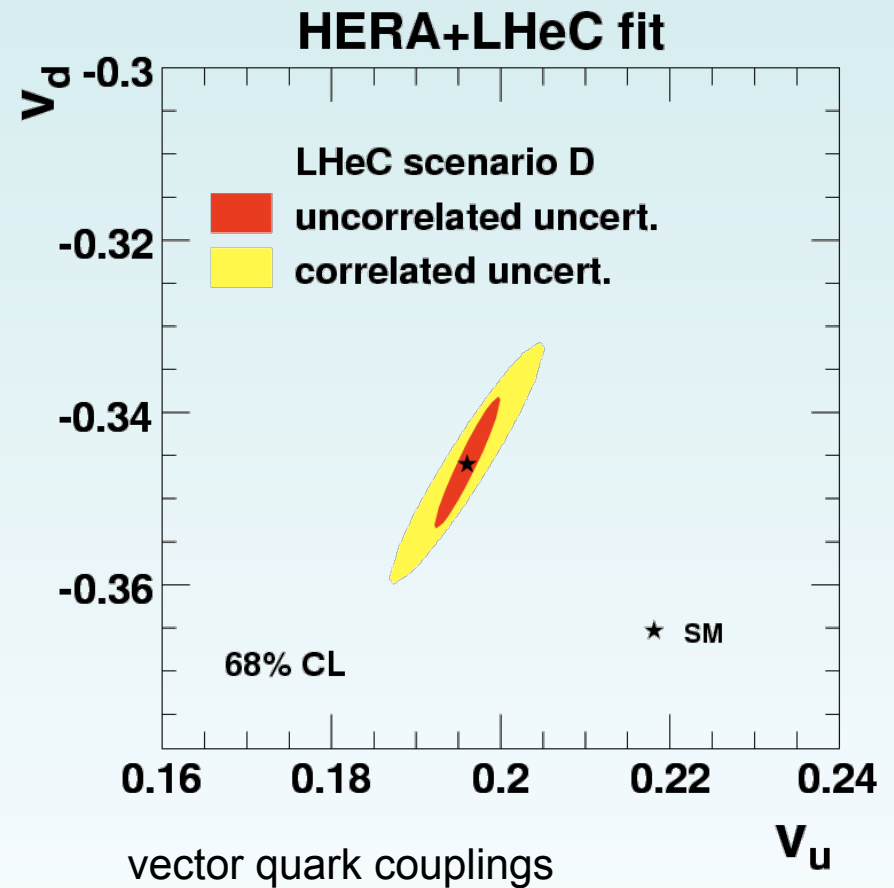
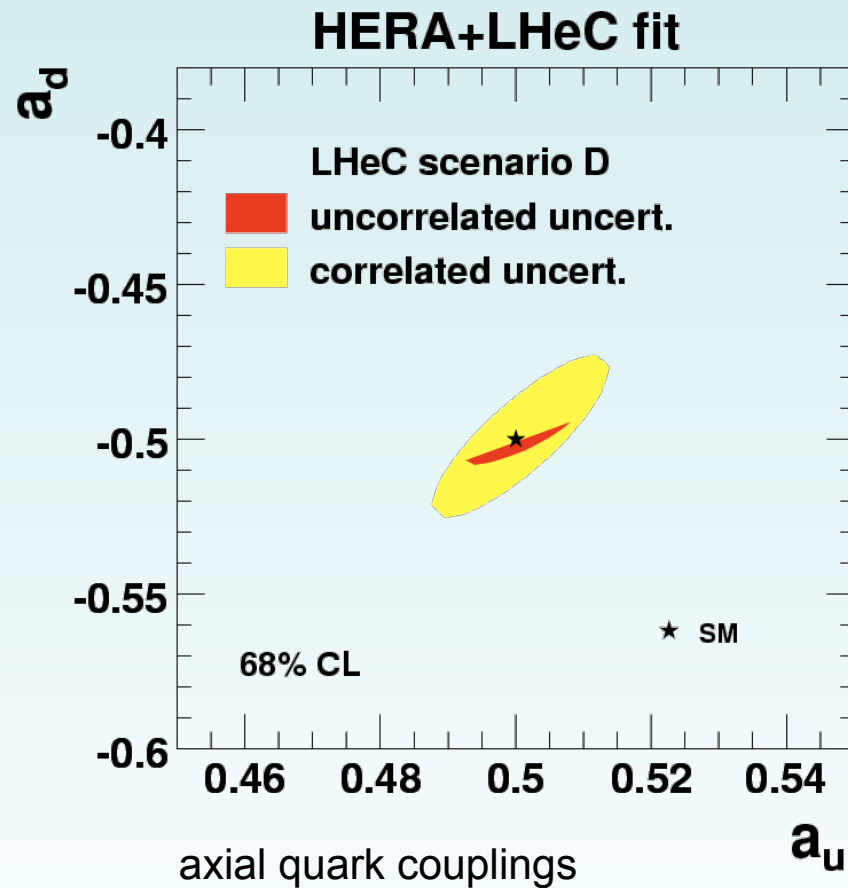
neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

electroweak couplings of quarks to Z^0

(uncorrelated and correlated uncertainties shown separately)



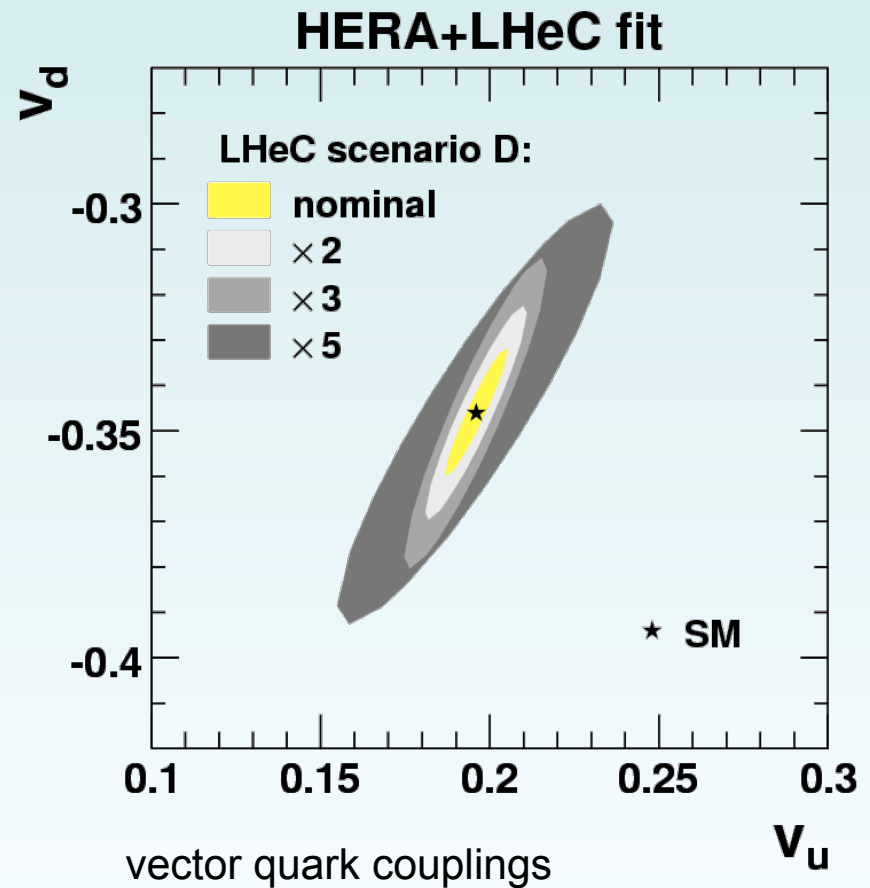
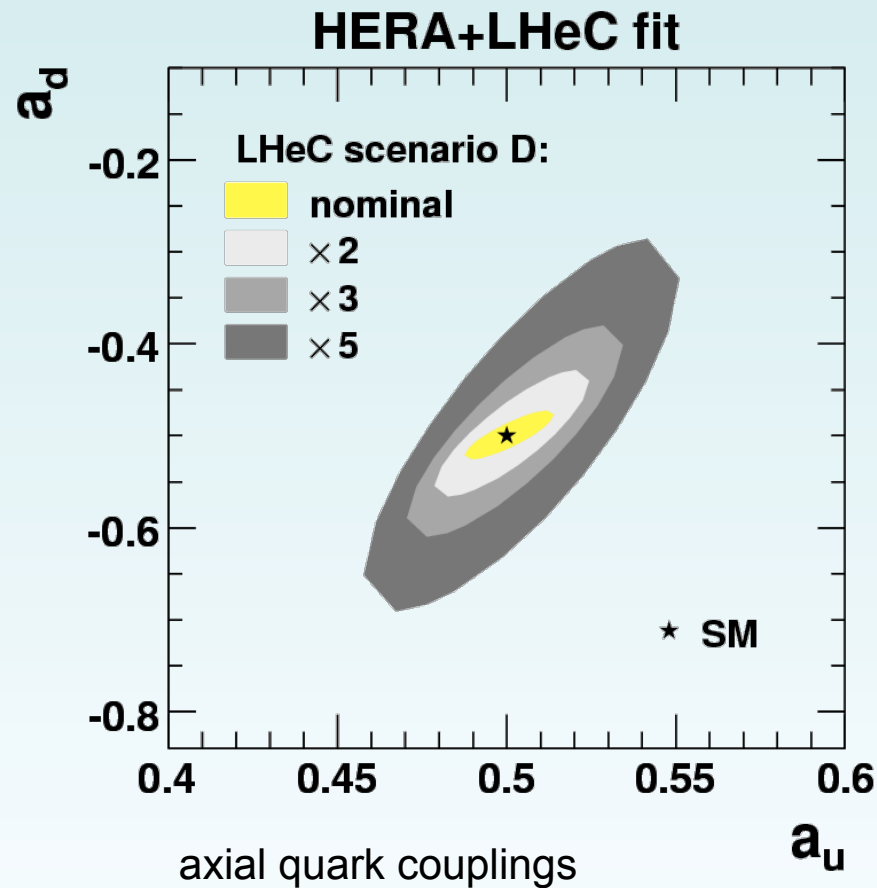
neutral current quark couplings

scenario D:

$$P_e = \pm 0.9$$

What if assumed level of statistical and systematic precision **not achieved**?

» reducing **luminosity** and increasing all **systematic uncertainties** by factors of $\times 2, 3, 5$



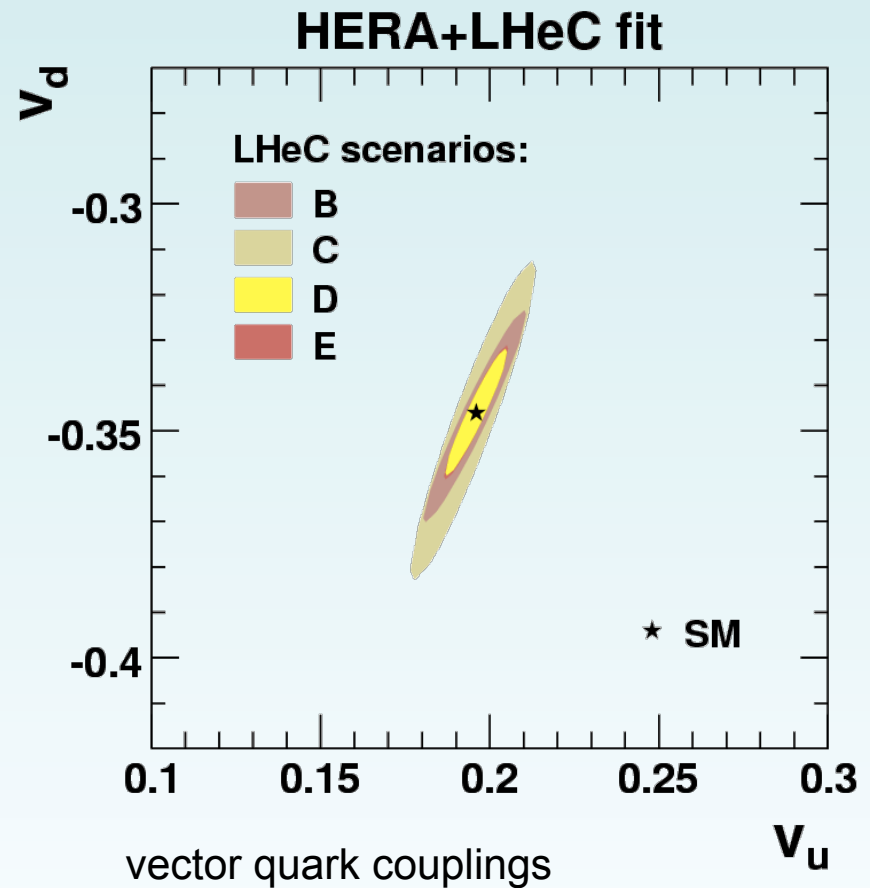
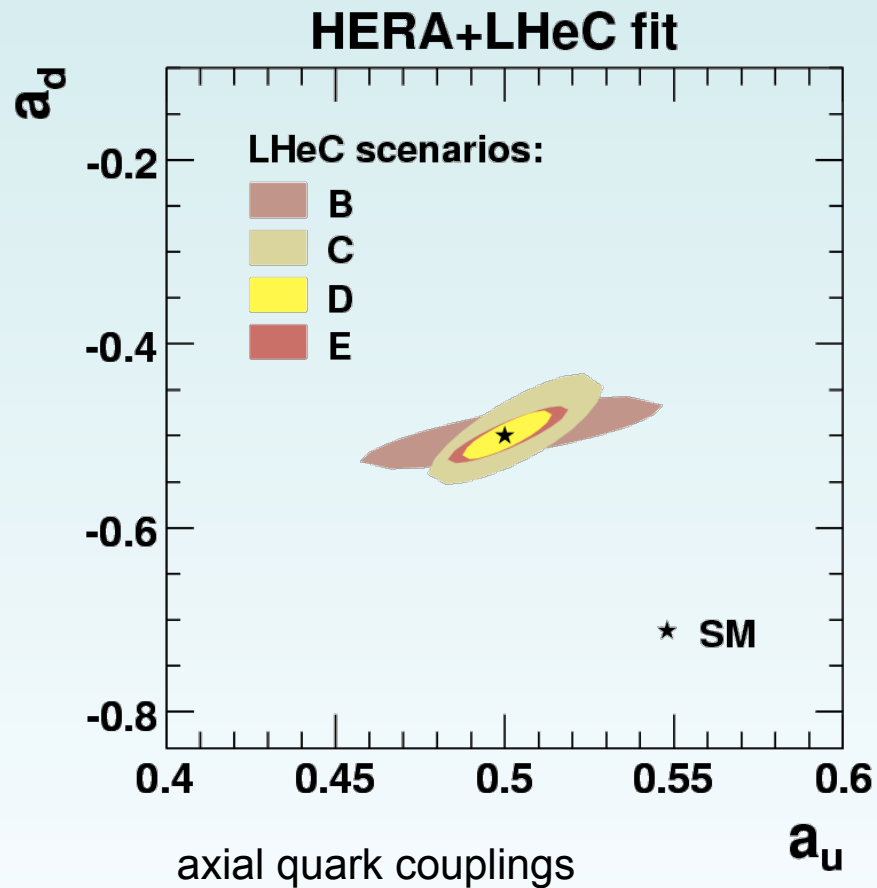
neutral current quark couplings

other scenarios: **B**, **C**, **D** and **E**

polarisations:

$P_e = \pm 0.4$ (B,C)

$P_e = \pm 0.9$ (D,E)



neutral current quark couplings

uncertainties on the **neutral current quark couplings**: $\Delta_{\text{uncorr}} \pm \Delta_{\text{corr}}$

	$a_u (0.5)$	$v_u (0.196)$	$a_d (-0.5)$	$v_d (-0.346)$
A	0.05 ± 0.10	0.075 ± 0.116	0.22 ± 0.51	0.120 ± 0.252
B	0.01 ± 0.04	0.010 ± 0.011	0.02 ± 0.04	0.020 ± 0.012
C	0.02 ± 0.02	0.015 ± 0.011	0.03 ± 0.05	0.030 ± 0.017
D	0.01 ± 0.01	0.004 ± 0.008	0.01 ± 0.02	0.008 ± 0.012
E	0.01 ± 0.01	0.004 ± 0.008	0.01 ± 0.03	0.008 ± 0.012

neutral current quark couplings

uncertainties on the **neutral current quark couplings**: $\Delta_{\text{uncorr}} \pm \Delta_{\text{corr}}$

	$a_u (0.5)$	$v_u (0.196)$	$a_d (-0.5)$	$v_d (-0.346)$
A	0.05 ± 0.09	0.073 ± 0.120	0.21 ± 0.44	0.112 ± 0.225
B	0.01 ± 0.01	0.010 ± 0.067	0.01 ± 0.02	0.020 ± 0.010
C	0.02 ± 0.02	0.014 ± 0.007	0.03 ± 0.05	0.030 ± 0.012
D	0.01 ± 0.01	0.003 ± 0.007	0.01 ± 0.02	0.006 ± 0.009
E	0.01 ± 0.01	0.004 ± 0.007	0.01 ± 0.02	0.007 ± 0.009

(note: with LHeC NC **and** CC included)