QCD and EW analysis of the ZEUS NC/CC inclusive and jet cross sections

Shima Shimizu
(Univ. of Tokyo)
on behalf of ZEUS collaboration

Extraction of PDFs

- x-dependence of PDFs can be extracted from fits to measured cross sections.

PDFs@ Q_0^2 ⟵ Input

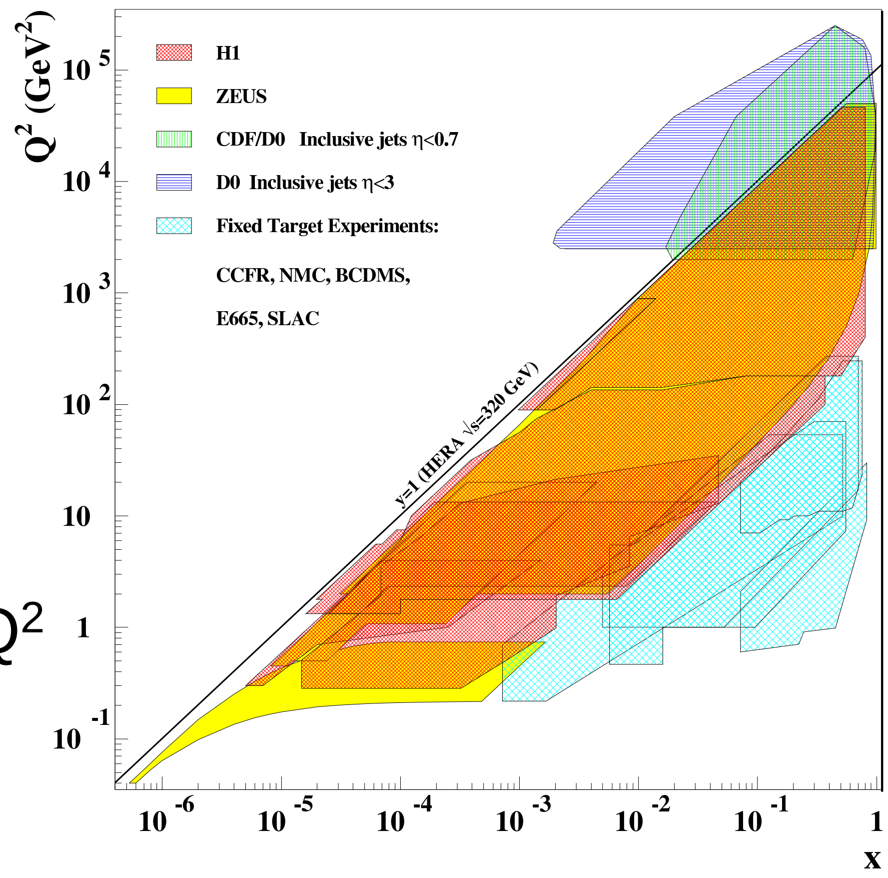
↓ Evolution in Q^2

PDFs@ Q^2

↓

Fit to measured cross sections @ Q^2

More details are in the next slide.



- Wide kinematic region at HERA
  → suitable for extraction of PDFs
    – Sea & Gluon (from $dF_2/d\ln Q^2$) @ low x
  → EW sensitivity @ high Q^2

Extraction of PDFs at ZEUS

- PDFs: parameterization @ $Q_0^2 = 7\text{GeV}^2$

  $$\boxed{x\,f(x) = A\,x^b(1-x)^c(1+dx)} \quad \text{for} \quad xu_v,\ xd_v,\ xS,\ xg,\ x\Delta(=x\bar{d}-x\bar{u})$$

  A: Normalization, *b*: Low x, *c*: High x, *d*: smoothing for middle x

  Constraints

  – Momentum and number sum rule → A_{uv}, A_{dv}, A_g

  – Equal behaviour of u_v and d_v at low x → $b_{uv}=b_{dv}$

  – Δ: consistent with Gottfried sum rule and Drell Yan (CCFR)

  11 free parameters

- DGLAP evolution at NLO (MSbar)
- Heavy quarks are treated in variable flavour-number scheme of Thorne and Roberts.
- Corr. syst. uncertainties are evaluated using OFFSET method.

ZEUS-JETS fit

Eur. Phys. J. C 42, 1-16 (2005)

First fit using HERA jets data.

→ Making use of full potential of ZEUS data (and alone) in HERA I.

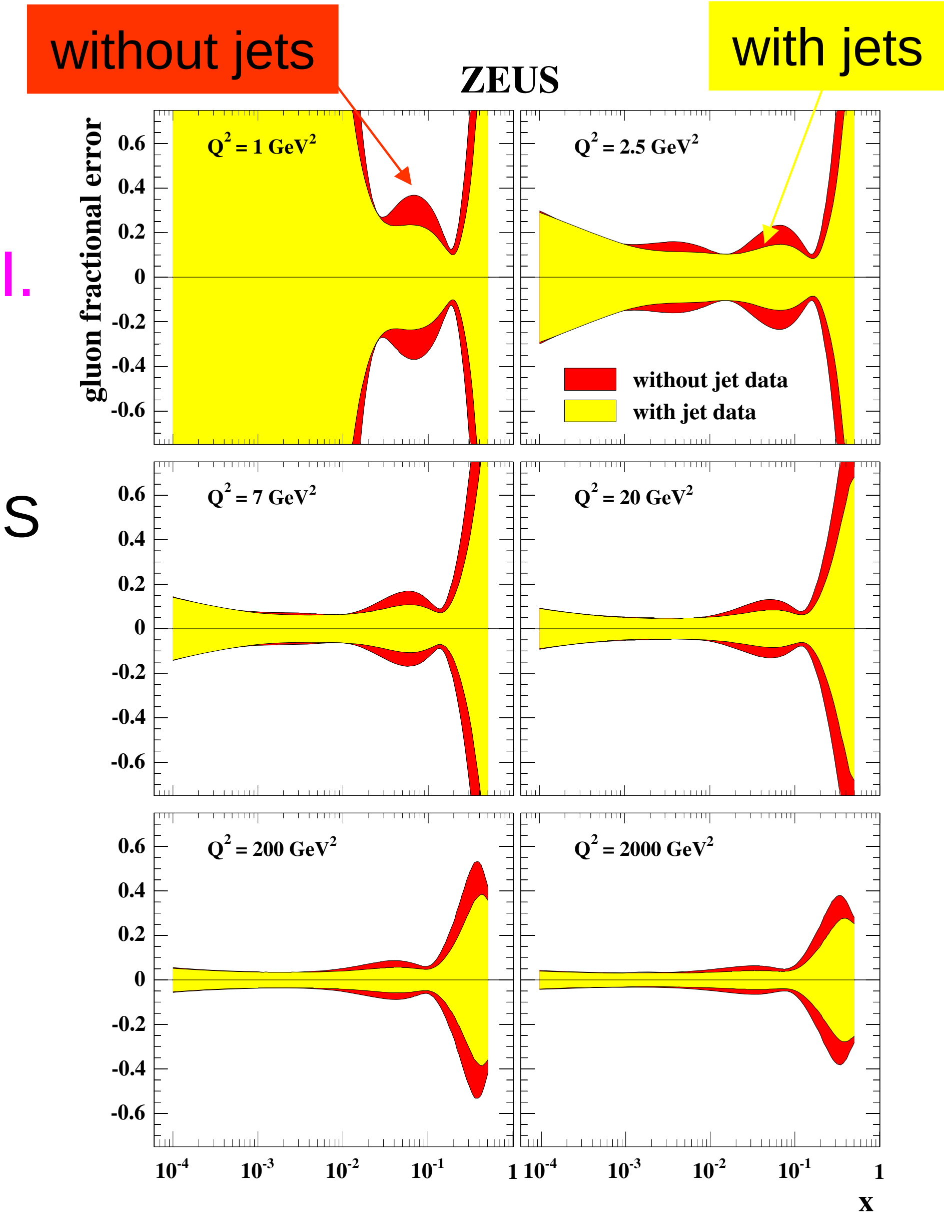
- HERA I inclusive NC/CC cross sections (94-00)
- Inclusive jets cross sections in DIS (96-97)
- Dijets in photoproduction (96-97)

Single experiment

→ systematic uncertainties are well understood.

Jets cross sections

→ sensitive to gluon density.



Fractional errors of gluon density

NEW! Fit including HERA II

Now we measure polarized e^-p NC/CC inclusive cross sections in **HERA II** *!* → *See talks from U.Noor & H.Kaji.*

Much statistics at High Q^2 with **Polarized electrons**

NC/CC electron data

HERA I	HERA II
$16pb^{-1}$	$121.5pb^{-1}$
92/26 data points	180/70 data points

polarization: P=-0.27: 78.8pb-1, P=+0.33: 42.7pb-1

→ better determination of PDFs at high x (← high Q^2).

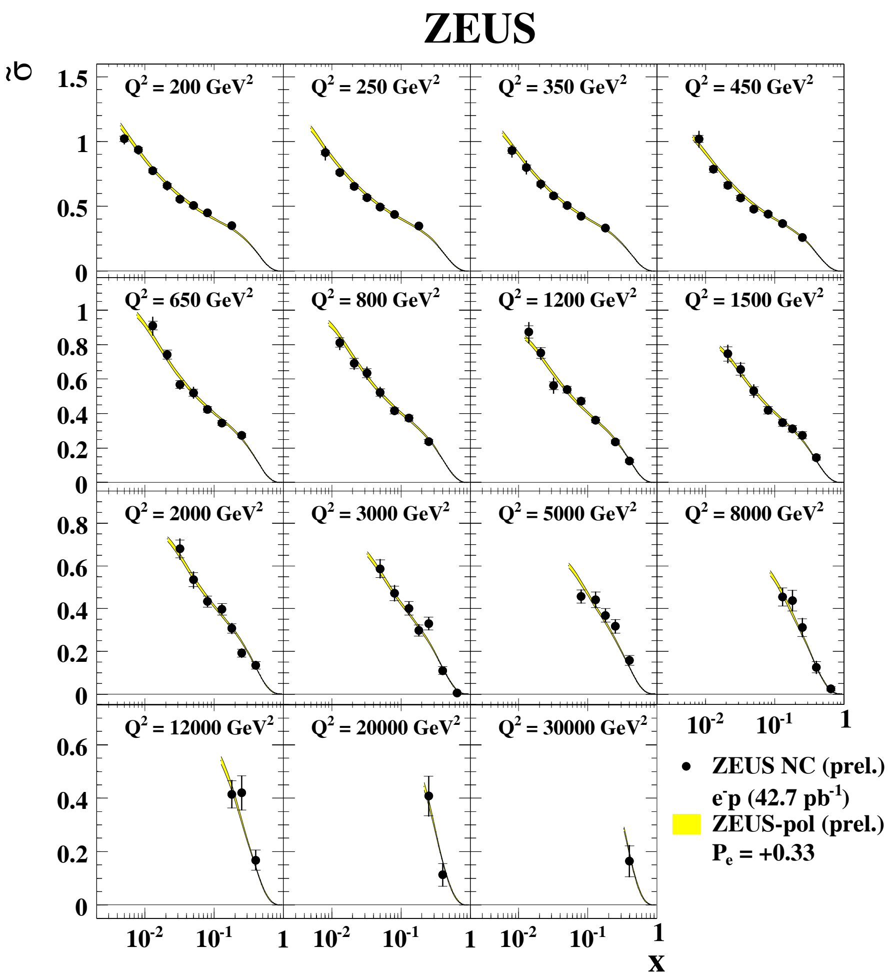
→ better sensitivity to EW

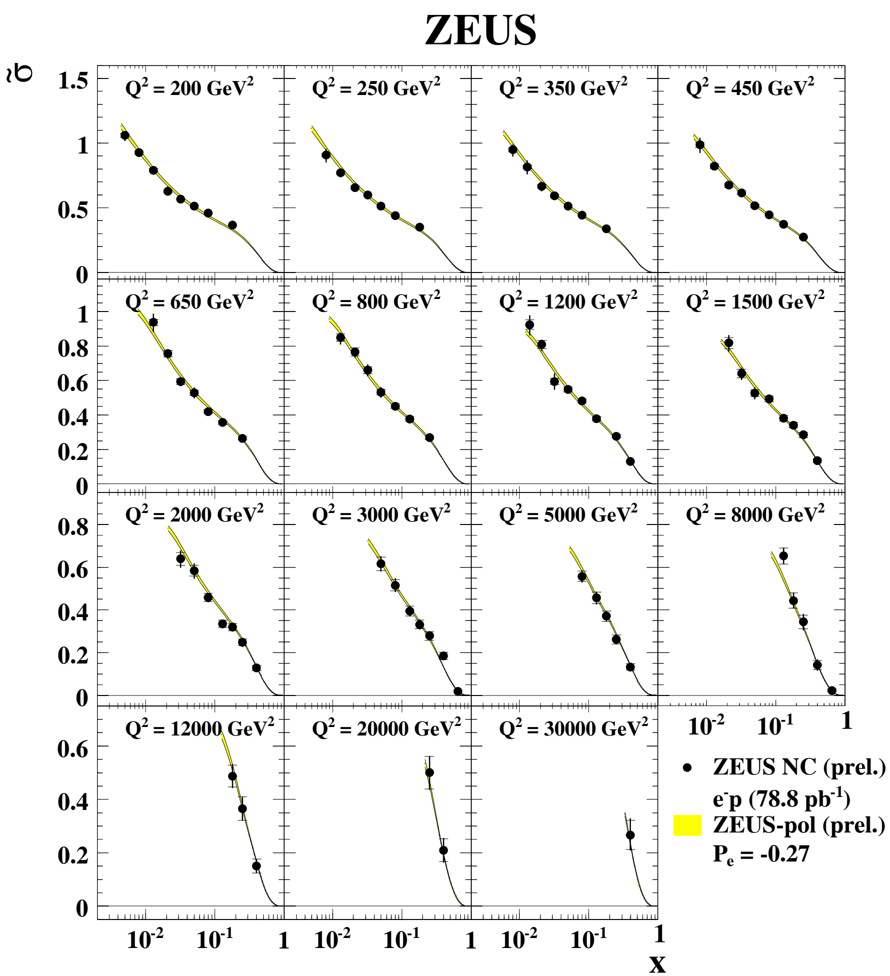
New fit: ZEUS-pol fit (preliminary)

First fit including polarized cross sections!

- Data: ZEUS-JETS data + **HERA II**
  - 94-00 inclusive NC/CC cross sections
  - 96-97 Jet cross sections in DIS and photoproduction
  - 04-05 polarized e^-p NC/CC inclusive cross sections
- All EW parameters are fixed to SM values.

Polarized NC cross sections



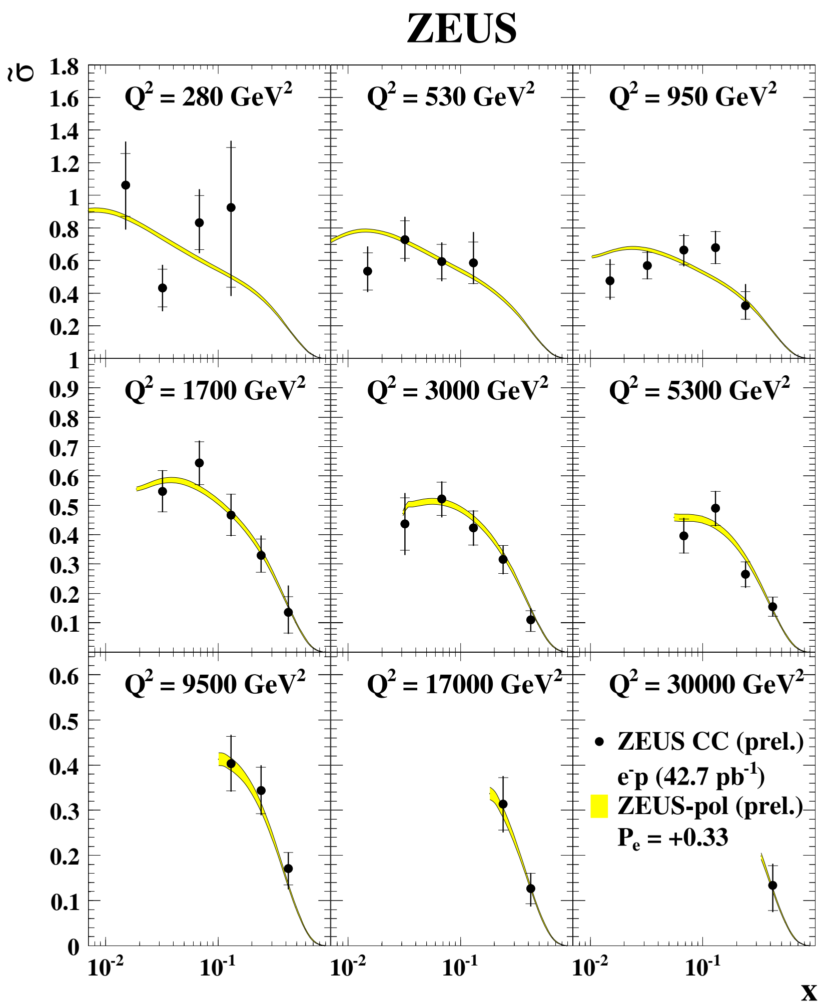


positive pol. P=+0.33

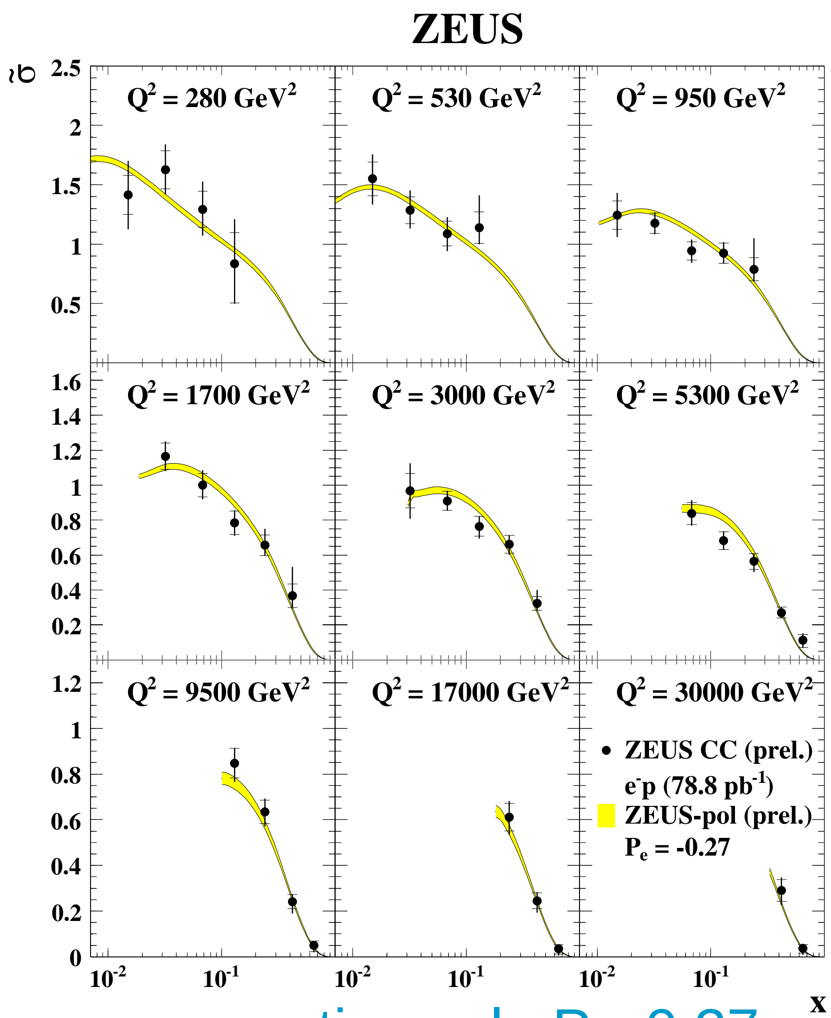
negative pol. P=-0.27

Data is well described by ZEUS-pol Fit.
The polarized cross sections from HERA-II were successfully fitted for the first time.

Polarized CC cross sections



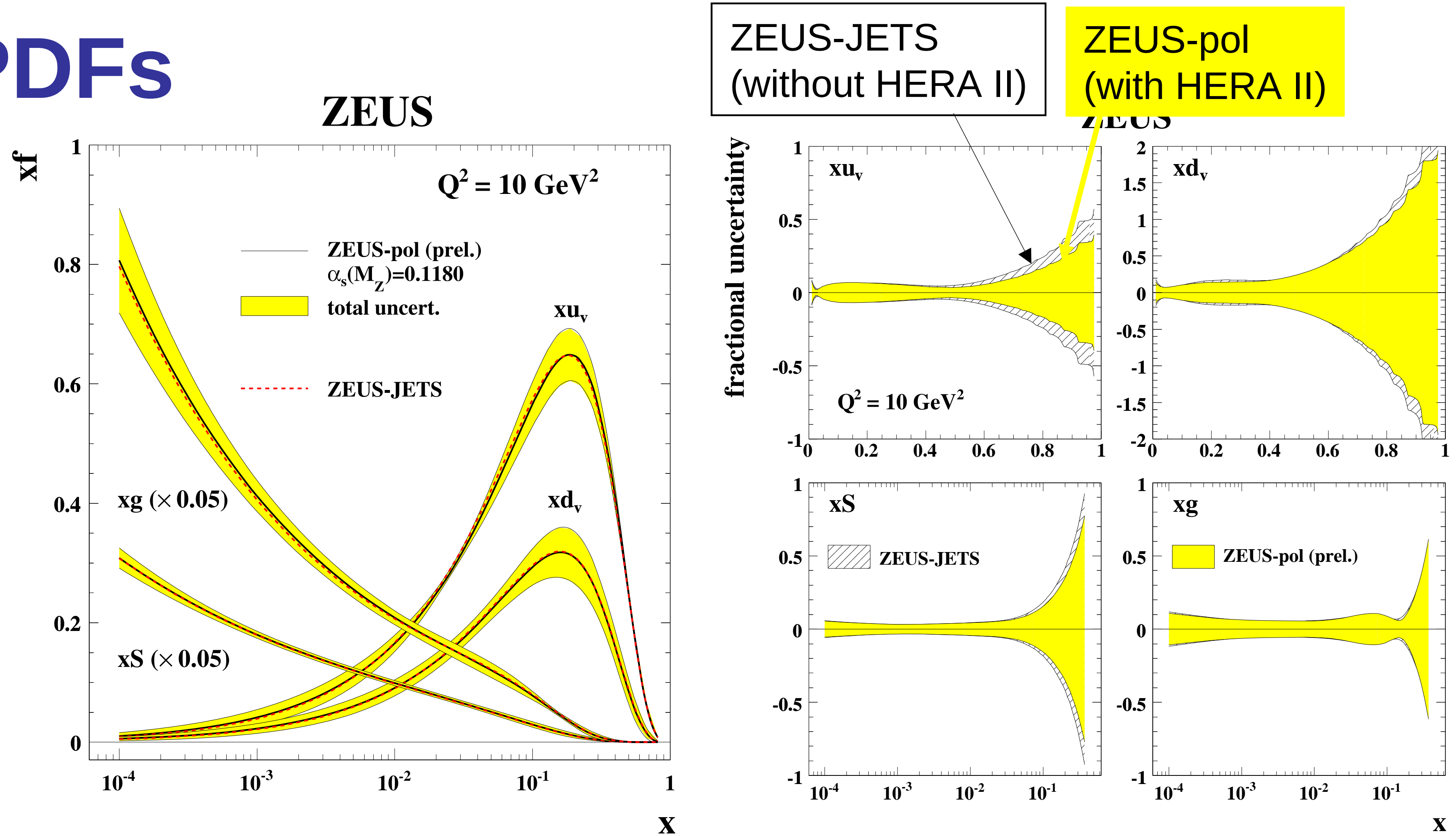
positive pol. P=+0.33



negative pol. P=-0.27

Data is well described by ZEUS-pol Fit.
The polarized cross sections from HERA-II were successfully fitted for the first time.

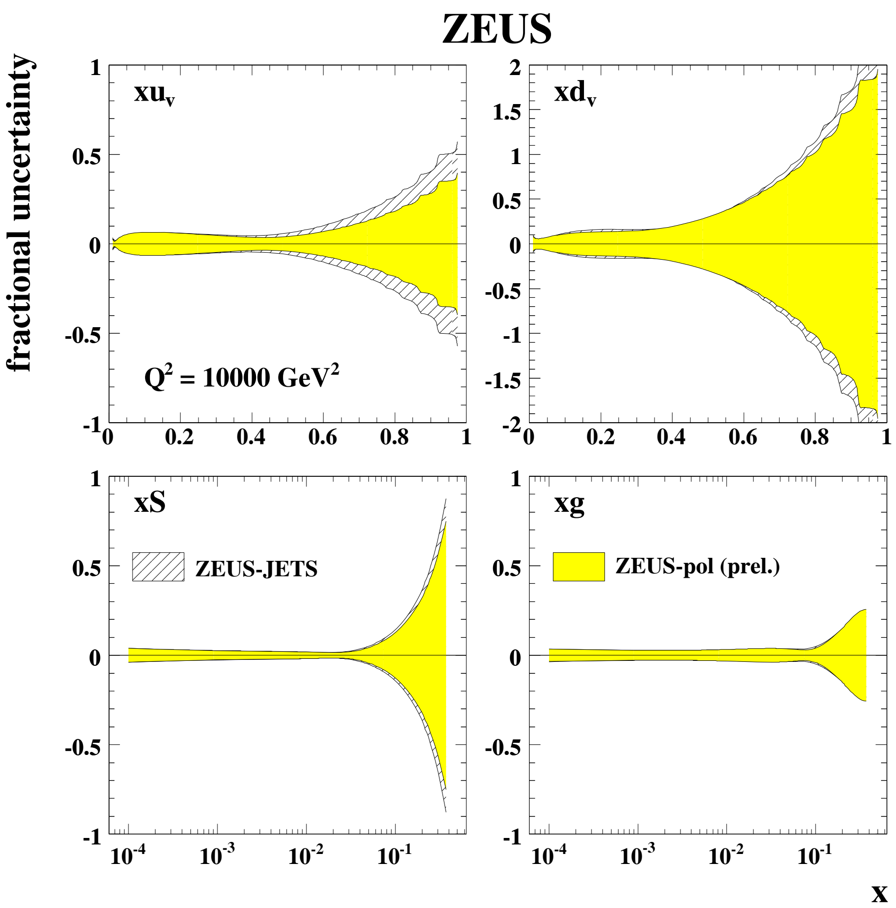
PDFs



- Central values of PDFs are almost unchanged by addition of HERA II electron data.
- Uncertainties are reduced. – high-x and particulary on xu_v

e⁻p: $e_u = \frac{2}{3}e,\ e_d = -\frac{1}{3}e \rightarrow \sigma_{NC} \propto (4u+d),\ \sigma_{CC} \propto u$

PDF uncertainties at very High Q^2



Q^2=10000 GeV^2

- Improvement of PDF uncertainties is also seen at Q^2=10000GeV^2.
  Good news for LHC physics.

Combined QCD and EW analysis

HERA II data:

In addition to much statistics, polarization gives direct sensitivity to EW.

→ Let's exploit the sensitivity to determine EW parameters!

A combined QCD + EW analysis

EW parameters and PDFs are determined simultaneously.
← The correlation between them is taken into account automatically in the fit.

1. Extraction of M_W
   ←CC cross sections

2. Extraction of quark couplings to Z
   ←NC cross sections

Extraction of M_W (1)

- CC cross sections

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}[Y_+W_2(x,Q^2)\mp Y_-W_3(x,Q^2)]$$ (F_L neglected)

- M_W and PDF parameters are free:

  (Note: G_F is fixed. M_w contributes also to normalization.)

$$M_W = 79.1 \pm 0.77(stat+uncorr) \pm 0.99(corr.sys.)\,[\mathrm{GeV}]$$ (prel.)

HERA I results:

M_W=78.9 ±2.0 (stat) ±1.8 (sys)$^{+2.2}_{-1.8}$ (PDF) [GeV]

(ZEUS *Euro. Phys. J. C32 (2003) 1-16*)

M_W=82.87 ±1.82 (exp) $^{+0.32}_{-0.18}$ (model) [GeV]

(H1 *Phys. Lett. B632 (2006) 35-42*)

- The combined QCD and EW analysis on HERA I + II CC data gives us improved determination of M_W.
- Note: M_W is space-like. → more general 'propagator' fit can be done.

Extraction of M_W (2)

- Determination of BOTH G_F and M_W
  (ZEUS-pol-G_F-M_w fit)

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

$G_F=1.127 \pm 0.013 \pm 0.014 \times 10^{-5}$ [GeV^{-2}]

$M_W=82.8 \pm 1.5 \pm 1.3$ [GeV]

preliminary

- Determination of M_W as more general 'propagator mass' with general coupling g
  (ZEUS-pol-g-M_w fit)

$$\frac{1}{4\pi x}\frac{g^2}{(Q^2+M_W^2)^2}$$

$g= 0.0772 \pm 0.0021 \pm 0.0019$

$M_W=82.8 \pm 1.5 \pm 1.3$ [GeV]

preliminary

- They are in good agreement with the world average values!

$G_F=1.16639 \times 10^{-5}$ GeV^{-2}

$M_W=80.4$ GeV

$g = G_F M_W^2 = 0.07542$

Polarized NC cross sections

NC cross section: $\sigma(e^{\pm}p) = (Y_+F_2^0 \mp Y_- xF_3^0) \mp P(Y_+F_2^P \mp Y_- xF_3^P)$

Structure functions:
$$F_2^{0,P} = \sum_i A_i^{0,P}(Q^2)[xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$$
$$xF_3^{0,p} = \sum_i B_i^{0,P}(Q^2)[xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$$

unpolarized coefficients

$$A_i^0(Q^2) = e_i^2 - 2e_i v_i v_e P_Z + (v_e^2 + a_e^2)(v_i^2 + a_i^2)P_Z^2$$
$$B_i^0(Q^2) = \underline{-2e_i a_i a_e P_Z} + 4a_i a_e v_i v_e P_Z^2$$

polarized coefficients

$$A_i^P(Q^2) = \underline{2e_i v_i a_e P_Z} - 2v_e a_e(v_i^2 + a_i^2)P_Z^2$$
$$B_i^P(Q^2) = 2e_i a_i v_e P_Z - 2v_i a_i(v_e^2 + a_e^2)P_Z^2$$

$$P_Z = \frac{1}{\sin^2 2\theta}\frac{Q^2}{(M_Z^2 + Q^2)}$$

a : axial coupling
v : vector coupling
: quarks

In SM formalism,
$$a_q = T_q^3$$
$$v_q = T_q^3 - 2e_q \sin^2\theta_W$$

v_e is very small (~0.04).
$P_Z >> P_Z^2$ (~middle Q^2)

→

$\boxed{\text{unpolarized } xF_3 \rightarrow a_i, \quad \text{polarized } F_2 \rightarrow v_i}$

Extraction of quark couplings to Z

Axial/vector couplings of u/d-type quark: 4 couplings

→2 of them are free and fitted together with PDFs: 4 fits in total

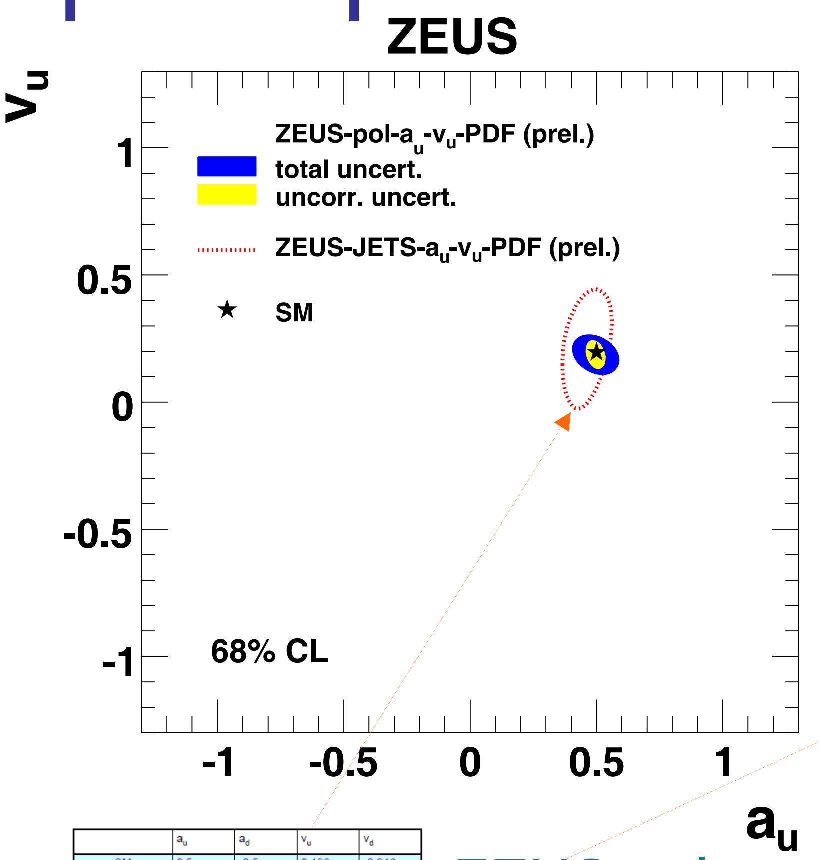
Results (preliminary)

	a_u	a_d	v_u	v_d
SM	0.5	-0.5	0.196	-0.346
ZEUS-pol-a_u-v_u fit	0.50 $\pm0.04\pm0.09$	fixed	0.19 $\pm0.06\pm0.06$	fixed
ZEUS-pol-a_d-v_d fit	fixed	-0.49 $\pm0.14\pm0.28$	fixed	-0.37 $\pm0.14\pm0.16$
ZEUS-pol-a_u-a_d fit	0.48 $\pm0.06\pm0.10$	-0.55 $\pm0.10\pm0.21$	fixed	fixed
ZEUS-pol-v_u-v_d fit	fixed	fixed	0.12 $\pm0.10\pm0.05$	-0.47 $\pm0.15\pm0.19$

- Note: These fits parameterize the couplings in most general way.
- They are in good agreement with SM predictions.

  → Contours will be shown in the next slides.

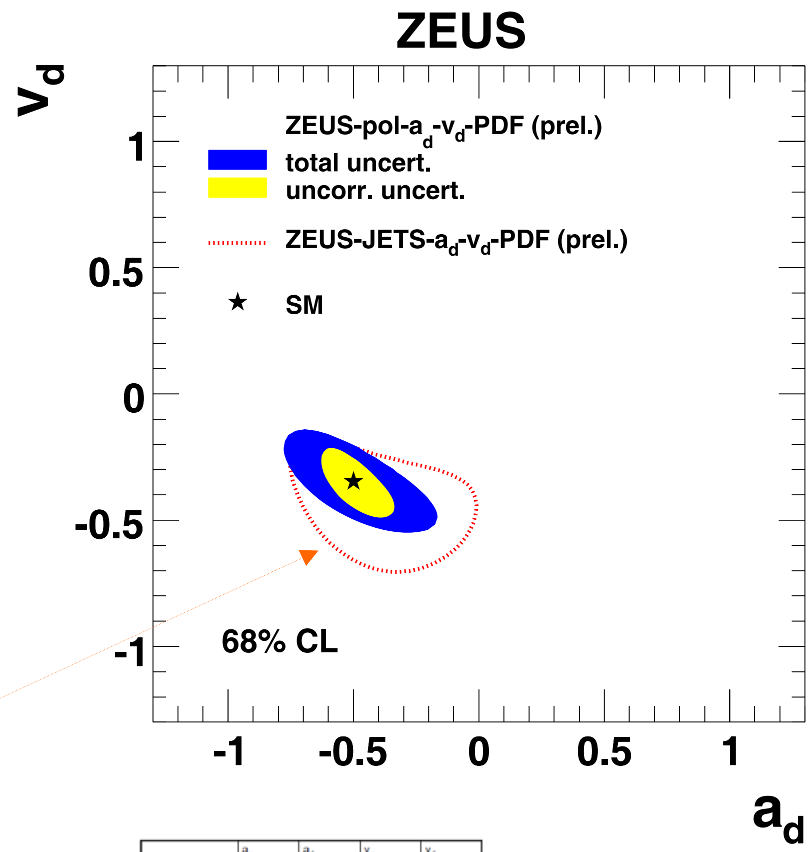
a_i vs. v_i



	a_u	a_d	v_u	v_d
SM	0.5	-0.5	0.196	-0.346
ZEUS-pol-a_u-v_u fit	0.50 $\pm0.04\pm0.09$	fixed	0.19 $\pm0.06\pm0.06$	fixed
ZEUS-pol-a_d-v_d fit	fixed	-0.49 $\pm0.14\pm0.28$	fixed	-0.37 $\pm0.14\pm0.16$
ZEUS-pol-a_u-a_d fit	0.48 $\pm0.06\pm0.10$	-0.55 $\pm0.10\pm0.21$	fixed	fixed
ZEUS-pol-v_u-v_d fit	fixed	fixed	0.12 $\pm0.10\pm0.05$	-0.47 $\pm0.15\pm0.19$

ZEUS-pol-a_u-v_u

a_d, v_d: fixed



	a_u	a_d	v_u	v_d
SM	0.5	-0.5	0.196	-0.346
ZEUS-pol-a_u-v_u fit	0.50 $\pm0.04\pm0.09$	fixed	0.19 $\pm0.06\pm0.06$	fixed
ZEUS-pol-a_d-v_d fit	fixed	-0.49 $\pm0.14\pm0.28$	fixed	-0.37 $\pm0.14\pm0.16$
ZEUS-pol-a_u-a_d fit	0.48 $\pm0.06\pm0.10$	-0.55 $\pm0.10\pm0.21$	fixed	fixed
ZEUS-pol-v_u-v_d fit	fixed	fixed	0.12 $\pm0.10\pm0.05$	-0.47 $\pm0.15\pm0.19$

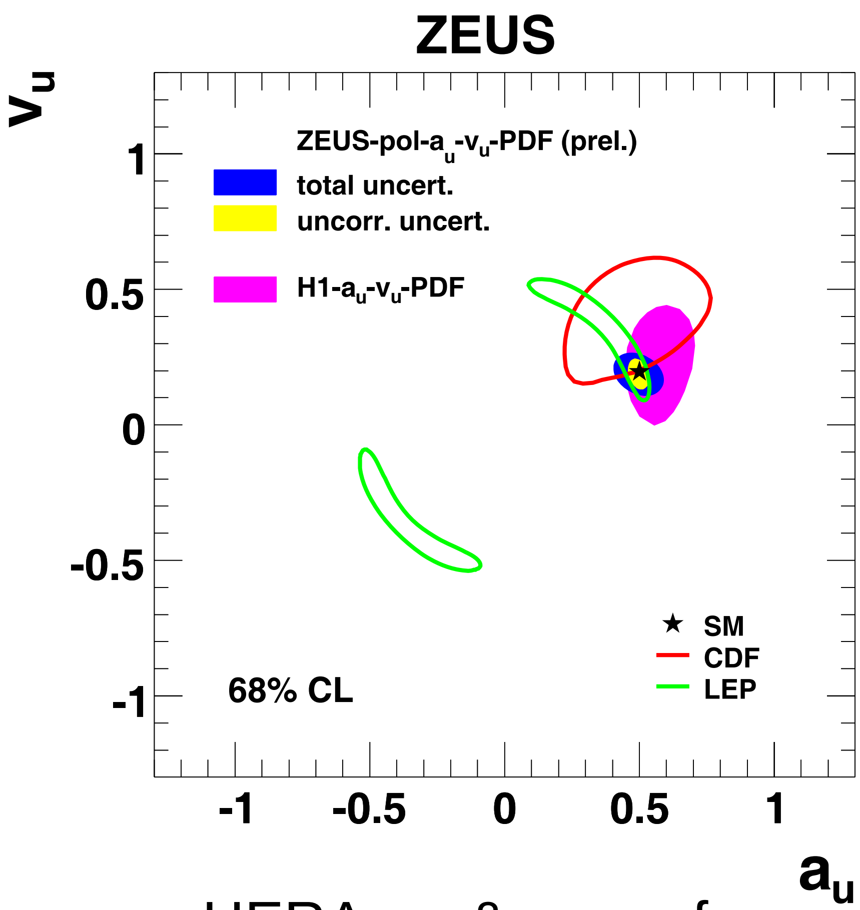
ZEUS-pol-a_d-v_d

a_u, v_u: fixed

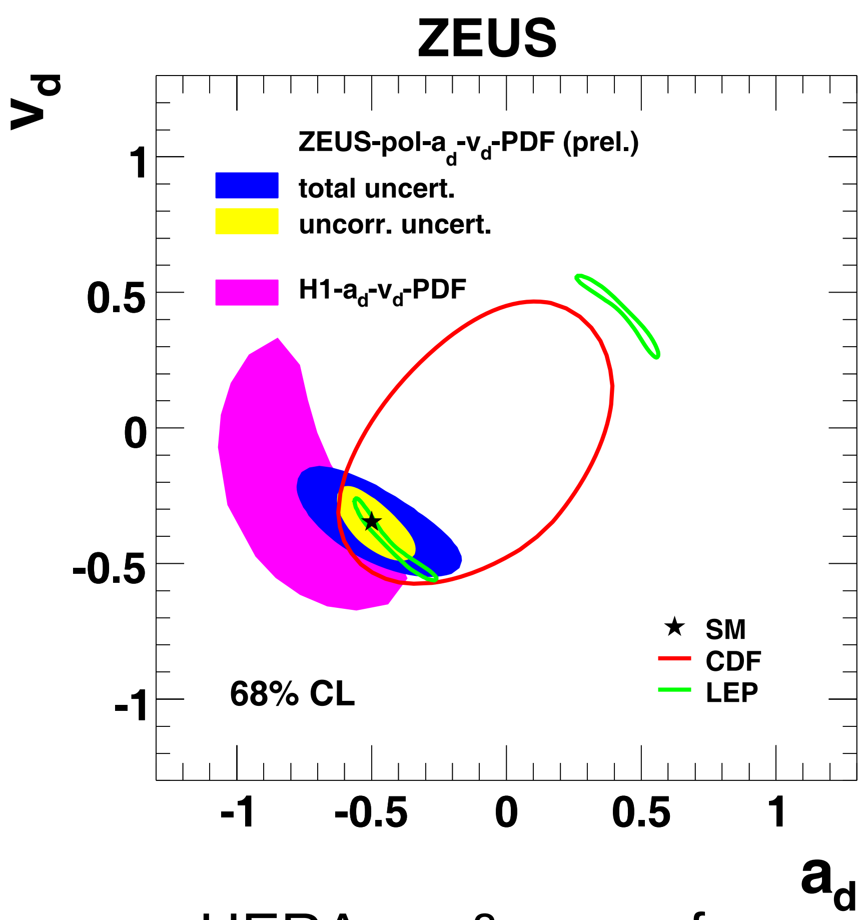
We also extract couplings without HERA II data with same parameter settings (----- ZEUS-JETS-a_i-v_i fit)

HERA II data constrains the quark couplings well.
They agree well with SM prediction.

a_i vs. v_i : Comparison with other experiments



HERA: a_u & v_u are free



HERA: a_d & v_d are free

ZEUS-pol-a_i-v_i fit shows excellent constraint on quark couplings.
(Better or comparable constraint with respect to others!)

v_u vs. v_d

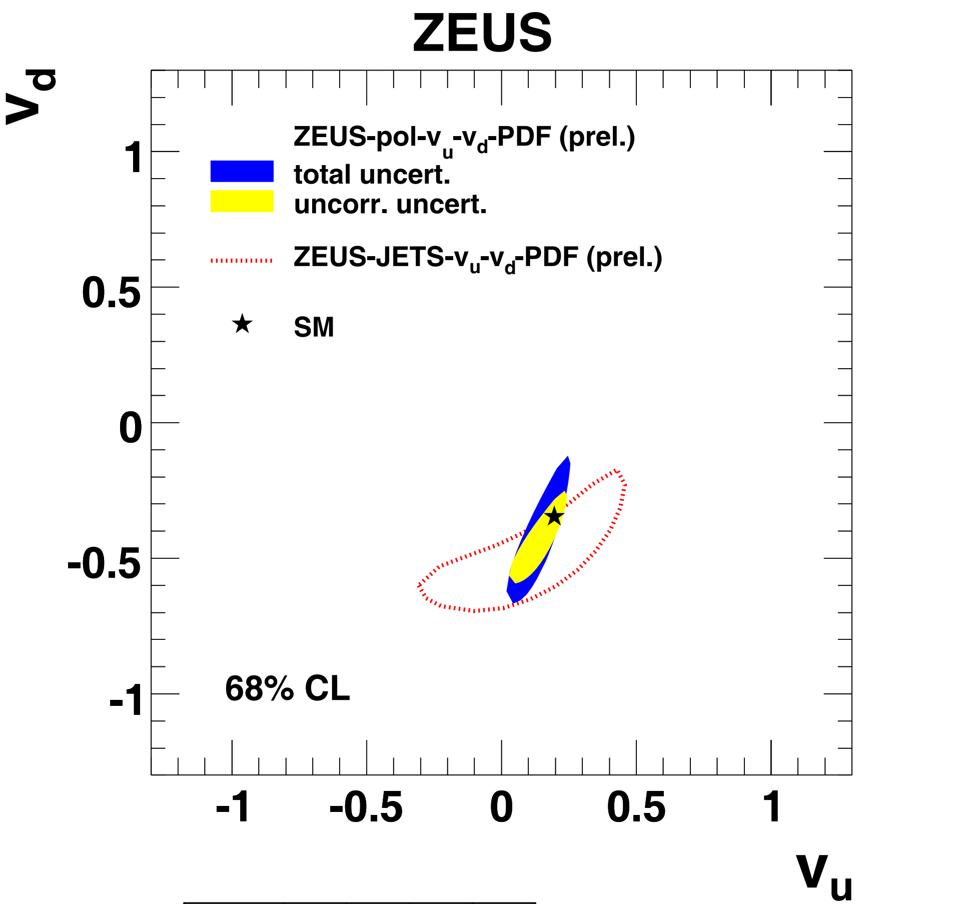
Now we have polarized data!

→ Vector couplings should be determined from polarized F_2.

Reminder:

unpolarized xF_3 → a_i,
polarized F_2 → v_i

- v_u and v_d are determined well by the fit with HERA II. – especially on v_u.



	a_u	a_d	v_u	v_d
SM	0.5	-0.5	0.196	-0.346
ZEUS-pol-a_u-v_u fit	0.50 $\pm0.04\pm0.09$	fixed	0.19 $\pm0.06\pm0.06$	fixed
ZEUS-pol-a_d-v_d fit	fixed	-0.49 $\pm0.14\pm0.28$	fixed	-0.37 $\pm0.14\pm0.16$
ZEUS-pol-a_u-a_d fit	0.48 $\pm0.06\pm0.10$	-0.55 $\pm0.10\pm0.21$	fixed	fixed
ZEUS-pol-v_u-v_d fit	fixed	fixed	0.12 $\pm0.10\pm0.05$	-0.47 $\pm0.15\pm0.19$

ZEUS-pol-v_u-v_d
a_u, a_d: fixed

QCD+EW fit: Using SM relation

- In SM formalism,
$$a_q = T_q^3$$
$$v_q = T_q^3 - 2e_q \sin^2\theta_W$$

→ Determine T_u^3, T_d^3, $\sin^2\theta_W$: 3 EW parameters

Note: $\sin^2\theta_W$ is also in Z exchange term (P_Z)

Results: *(preliminary)*

$T_u^3 = 0.47 \pm 0.05 \pm 0.13$

$T_d^3 = -0.55 \pm 0.18 \pm 0.35$

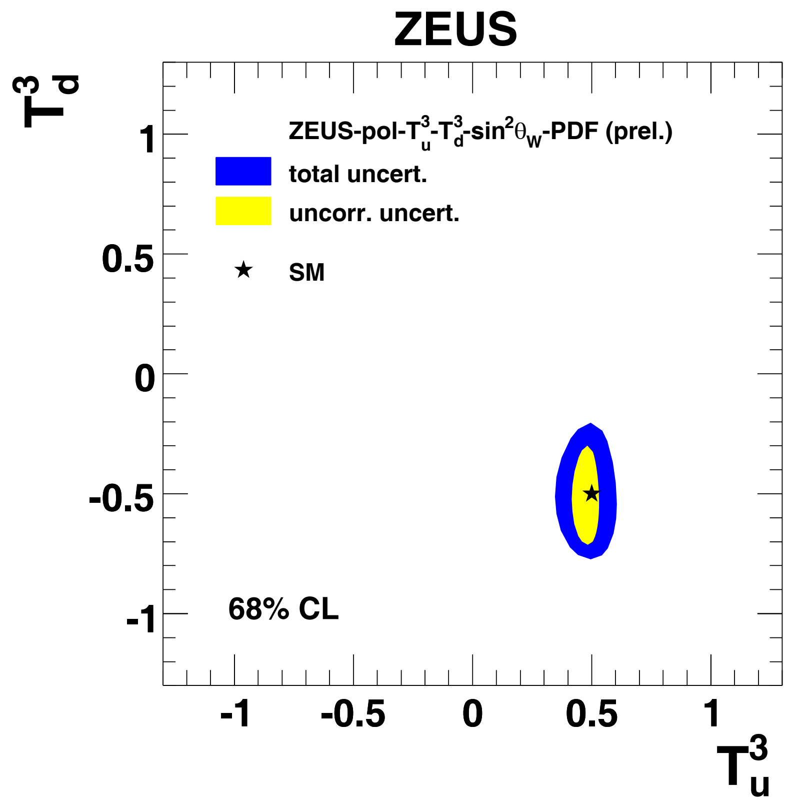
$\sin^2\theta_W = 0.231 \pm 0.024 \pm 0.070$

Good agreement with SM values!

$T_u^3 = 0.5$

$T_d^3 = -0.5$

$\sin^2\theta_W = 0.2315$



Right handed Isospin

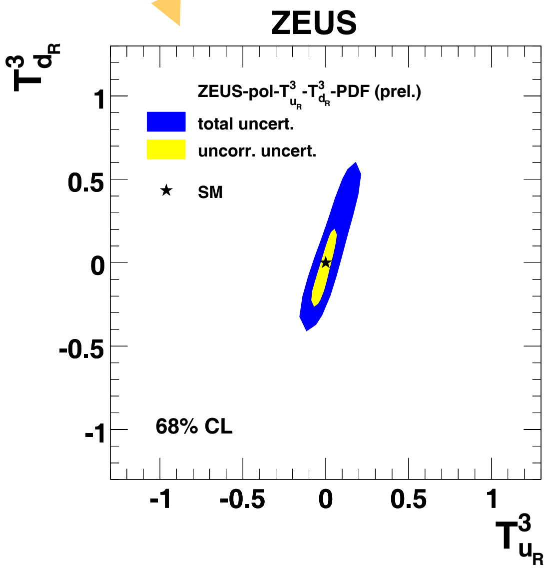
- Introduce right handed isospin, $T^3_{q,R}$, which should be 0 in SM,

$$a_q = T^3_{q,L} + T^3_{q,R}$$

$$v_q = T^3_{q,L} - T^3_{q,R} - 2e_q \sin^2\theta_W$$

$T^3_{q,L}$ are fixed:
$T^3_{u,L}$=1/2, $T^3_{d,L}$=-1/2

Results (preliminary)	$T^3 u_R$	$T^3 d_R$	$\sin^2\theta_W$
ZEUS-pol-$T^3_{u,R}$-$T^3_{d,R}$ fit	-0.04 $\pm$0.06$\pm$0.13	-0.14 $\pm$0.18$\pm$0.33	0.2315 fixed
ZEUS-pol-$T^3_{u,R}$-$T^3_{d,R}$-$\sin^2\theta_W$ fit	-0.07 $\pm$0.07$\pm$0.07	-0.26 $\pm$0.19$\pm$0.19	0.238 $\pm$0.011$\pm$0.023



No deviation from SM is seen.
They are well constrained by the fits.

Summary

- **We have HERA II data.**
  - Large luminosity with polarized electrons.
- **New fit including HERA II data: ZEUS-pol fit**
  - HERA II data is well described and fitted.
  - Uncertainties of PDFs are reduced.
- **EW parameters are extracted from combined analysis of EW and PDFs** (ZEUS-pol-Mw fit, etc).
  - Extracted M_W is consistent with the world average value.
  - Quark couplings are determined with excellent precision.
    They are well consistent with SM.

Back up slides

PDF Parameterization

u-valence (xu_v)	$A_{uv}\, x^{b_{uv}}\, (1-x)^{c_{uv}}\, (1+d_{uv}x)$
d-valence (xd_v)	$A_{dv}\, x^{b_{dv}}\, (1-x)^{c_{dv}}\, (1+d_{dv}x)$
Sea (xS)	$A_S\, x^{b_S}\, (1-x)^{c_S}$
gluon (xg)	$A_g\, x^{b_g}\, (1-x)^{c_g}\, (1+d_g x)$
dbar-ubar ($x\Delta$)	$0.27\, x^{0.5}\, (1-x)^{c_\Delta}$

Constraints
- Momentum and number sum rule
- Equal behaviour of u_v and d_v at low x
- Δ: consistent with Gottfried sum rule and Drell Yan

11 free parameters

OFFSET method

χ^2 is defined as

$$\chi^2 = \sum_i \frac{[F_i^{\text{QCD}}(p) + \sum_\lambda s_\lambda \Delta_{i\lambda}^{\text{sys}} - F_i^{\text{meas}}]^2}{(\sigma_i^{\text{stat}\,2} + \sigma_i^{\text{unc.sys}\,2})} + \sum_\lambda s_\lambda^2$$

F_i^{QCD} : prediction from QCD

F_i^{meas} : measured data point

s_λ : fit parameter of systematic uncertainty

σ_i^{stat} : statistical uncertainty

$\sigma_i^{\text{unc.sys}}$: uncorrelated systematic uncertainty

$\Delta_{i\lambda}^{\text{sys}}$: correlated systematic uncertainty

1. Central values are extracted without any correlated systematic uncertainties ($s_\lambda=0$).
2. For each source of correlated systematic uncertainty (i.e. for each λ);
   - Data points are shifted to the limit of the uncertainty ($s_\lambda=\pm 1$).
   - Deviation from the central value is extracted by re-doing the fit.
3. Add all deviations in quadrature

No assumption of gaussian shape for correlated systematic uncertainties.

Conservative method.