An NLO QCD and EW analysis of the ZEUS inclusive DIS and jet cross sections

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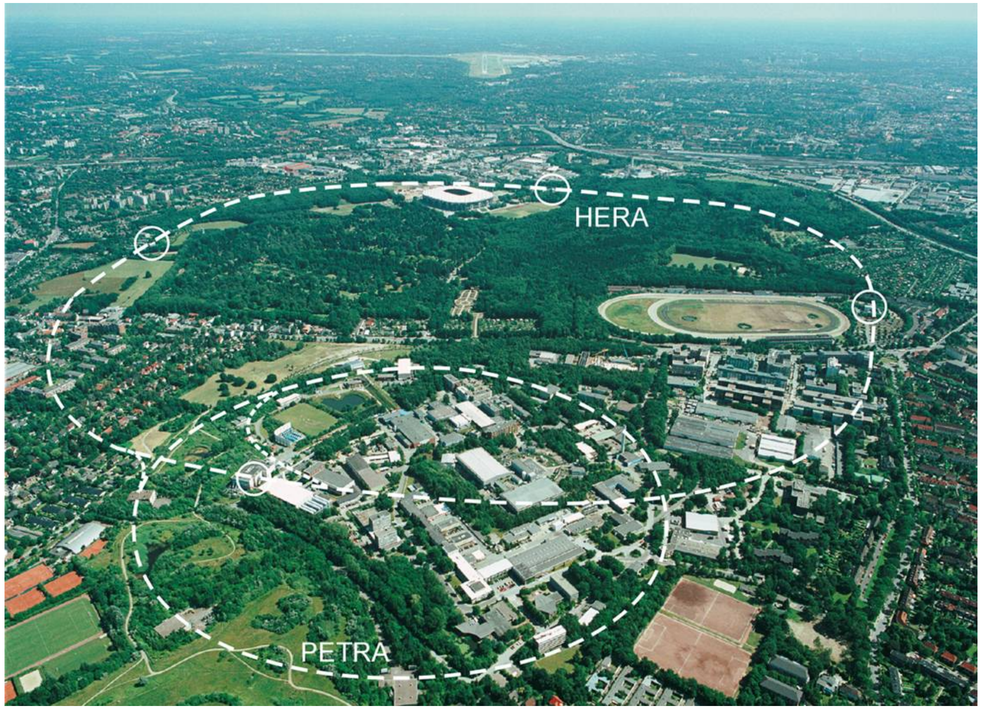
Contents

- Introduction
- Proton structure
- QCD only analysis
- Combined QCD and EW analysis
- Summary

The world's only *e-p* collider: HERA

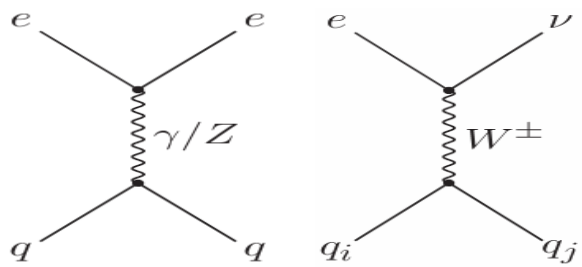
p 920 GeV
e^+/e^- 27.5 GeV

→ $\sqrt{s} = 318\,\mathrm{GeV}$



- Electrons can probe the inside of a proton.
  i.e. Electrons interact with quarks in a proton.
  = Deep inelastic scattering (DIS)

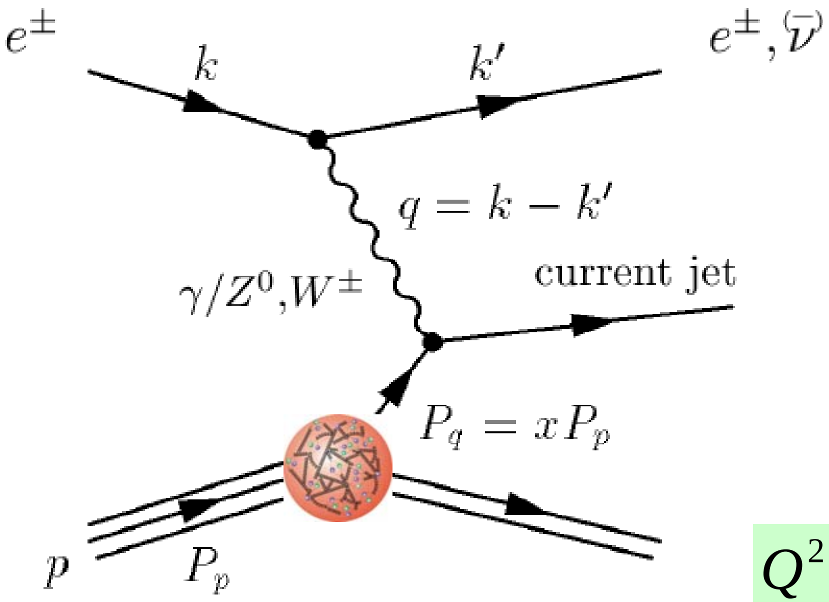
- *eq* collision @ EW energy scale.
  Z^0, $W^\pm$ are exchanged in a space-like process.



High energy *e-p* collision at HERA ➔

- proton structure
- EW physics

Deep Inelastic Scattering



- DIS cross section can be described by
  Q^2: Virtuality
  → probing power $\lambda \sim \frac{1}{Q^2}$
  x : Bjorken scaling variable
  → momentum fraction of struck quark
  y : Inelasticity

$$Q^2 = -q^2 = -(k - k')^2 \qquad x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k} = \frac{Q^2}{sx}$$

- Proton has a structure.
  DIS cross section can be written with Structure functions (SFs).

e.g.) γ -exchange only; $\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}(1+(1-y)^2)\, F_2(x, Q^2)$

F_2=1, if proton is point-like with charge=1

SFs parameterize how the proton differs from point-like.

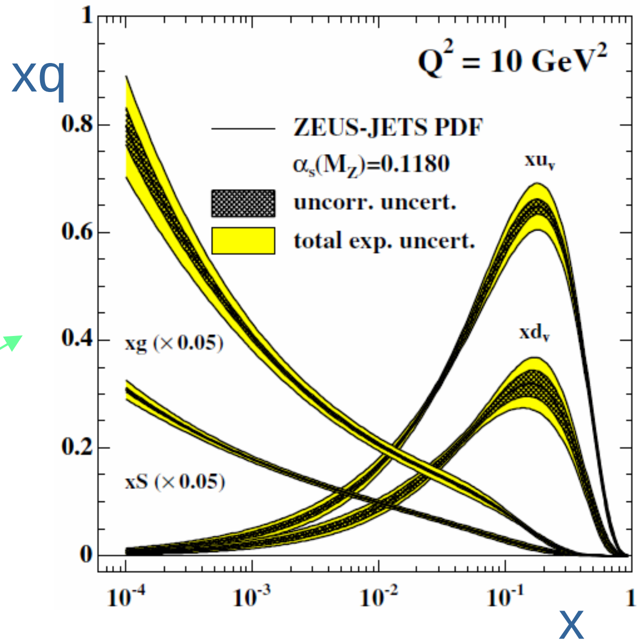
Proton structure

- In QCD, proton structure is described by Parton Density Functions (PDFs).

$q(x,Q^2)$ = number density of parton q with momentum x at Q^2.

→ Essential to understand any physics process involving proton.

ZEUS published PDFs
(ZEUS-JETS, Eur. Phys. J. C42, 1-16 (2005))
xu_V, xd_v, xSea, xg



- Structure functions can be written with PDFs.

Structure functions (SFs) = Σ_{quark} [coupling] x [PDF]

$$F_2 = \sum A_q x(q + \bar{q})$$ ← parity conservative term

$$xF_3 = \sum B_q x(q - \bar{q})$$ ← parity violating term

Extraction of PDFs

- Q^2 evolution of PDFs can be predicted by perturbative QCD, i.e. by DGLAP equation.
- x-dependence of PDFs can be extracted from fits to measured cross sections.

PDFs@ Q_0^2 ← Input

↓ Evolution in Q^2 : DGLAP@NLO

PDFs@ Q^2

↓

Fit to measured cross sections @ Q^2

ZEUS

PDFs are parameterized @ $Q_0^2 = 7\text{GeV}^2$

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

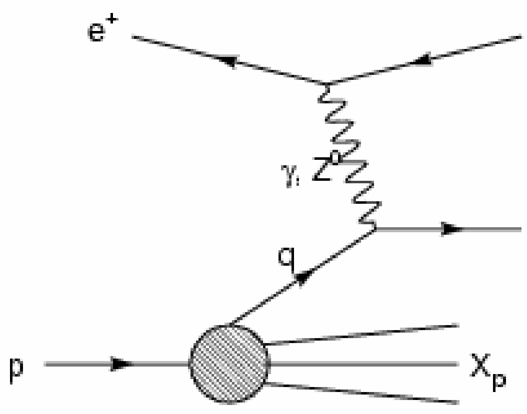
A: Normalization, *b*: Low x, *c*: High x, *d*: smoothing for middle x

Constraints from momentum and number sum rule, etc.

→ 11 free parameters

Cross sec. sensitive to PDF at HERA

- Neutral current DIS (NC)



γ , Z0 exchange

γ , Z0 → $F_2 \propto \sum x(q+\overline{q})$

Sea + valence quark

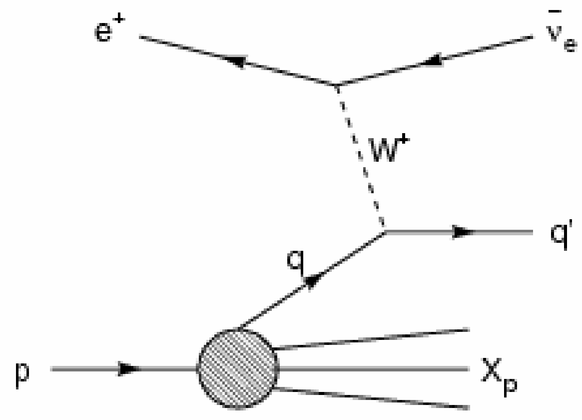
$$\frac{\partial F_2}{\partial \ln Q^2} \propto xg$$ gluon

Z0 introduces parity violation.

→ $xF_3 \propto \sum x(q-\overline{q})$

valence quark

- Charged current DIS (CC)



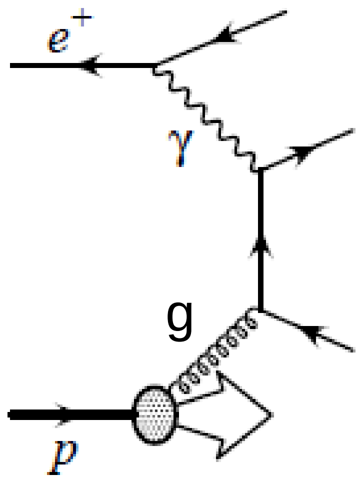
W± exchange

Charge selective interaction

e- : u quark e+: d quark

- Jet process

Directly sensitive to gluon density

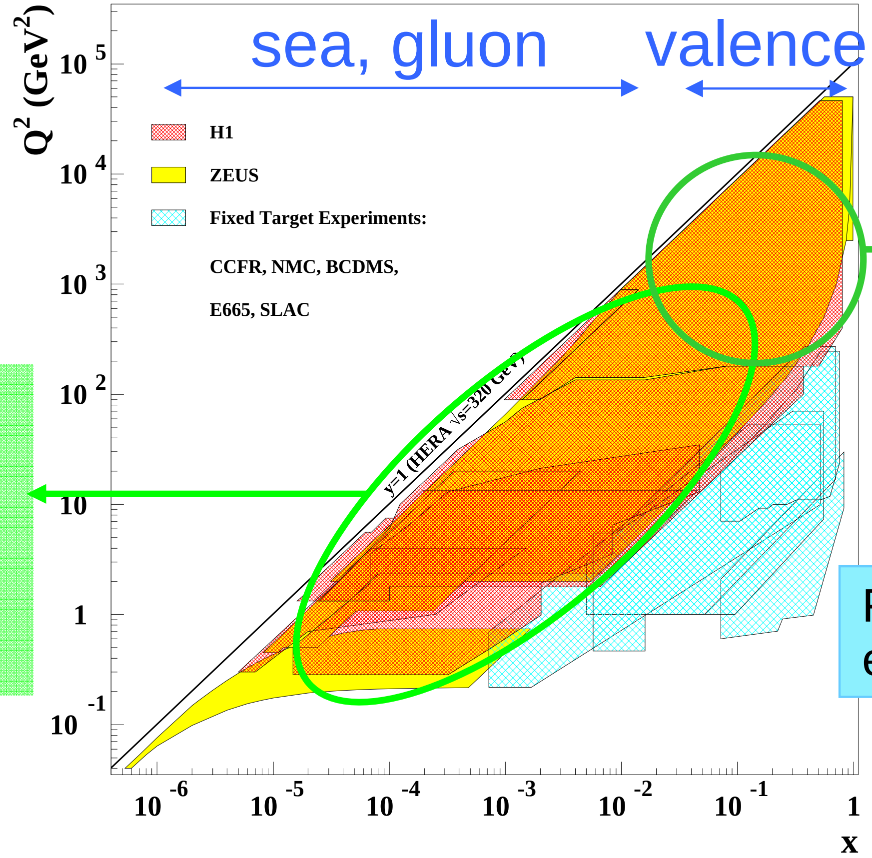


PDF extraction at ZEUS

A **single experiment** can determine PDFs!

Jets cross sections
→ gluon

γ exchange
→ sea
scaling violation
→ gluon



QCD + EW physics

Z^0 exchange
→ • sea + valence
• valence only
$W^{\pm}$ exchange
→ u or d quark

Fixed target experiments

- Pure proton target→ Free from target correction, nuclear effect.
- Single experiment→ systematic uncertainties are well understood.

Furthermore, based on own knowledge of PDFs, EW physics can be studied.

ZEUS fits

DIS is a convoluted phenomenon of electron-quark scattering and proton structure.

$$\sigma(ep) \propto \sum \sigma(eq) \otimes (\mathrm{PDF})$$

$\sigma(eq)$ → EW   (PDF) → QCD

A fit on $\sigma(ep)$ is a combined analysis of QCD and EW.

- Data (In total, ~800 data points)
  - 94-00 inclusive e^-p/e^+p NC/CC cross sections
  - 96-97 Jet cross sections in DIS and PHP

  → Published PDFs

  - 04-05 polarized e^-p NC/CC inclusive cross sections (prel.)

  → New data (See next slide)

- QCD only analysis : ZEUS-pol fit

  Only PDFs are free to see the impact of the new data.

- Combined QCD and EW analysis

  EW parameters and PDFs are determined simultaneously to exploit HERA sensitivity fully.

QCD only analysis: ZEUS-pol fit

HERA is now running as **HERA II** since 2003 with upgrades;
- Large luminosity
- Polarized $e^{\pm}$ beam

ZEUS has measured $e^{-}p$ NC/CC inclusive cross sections in HERA II.

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

NC/CC electron data

HERA I	$16 pb^{-1}$
HERA II	$121.5 pb^{-1}$

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

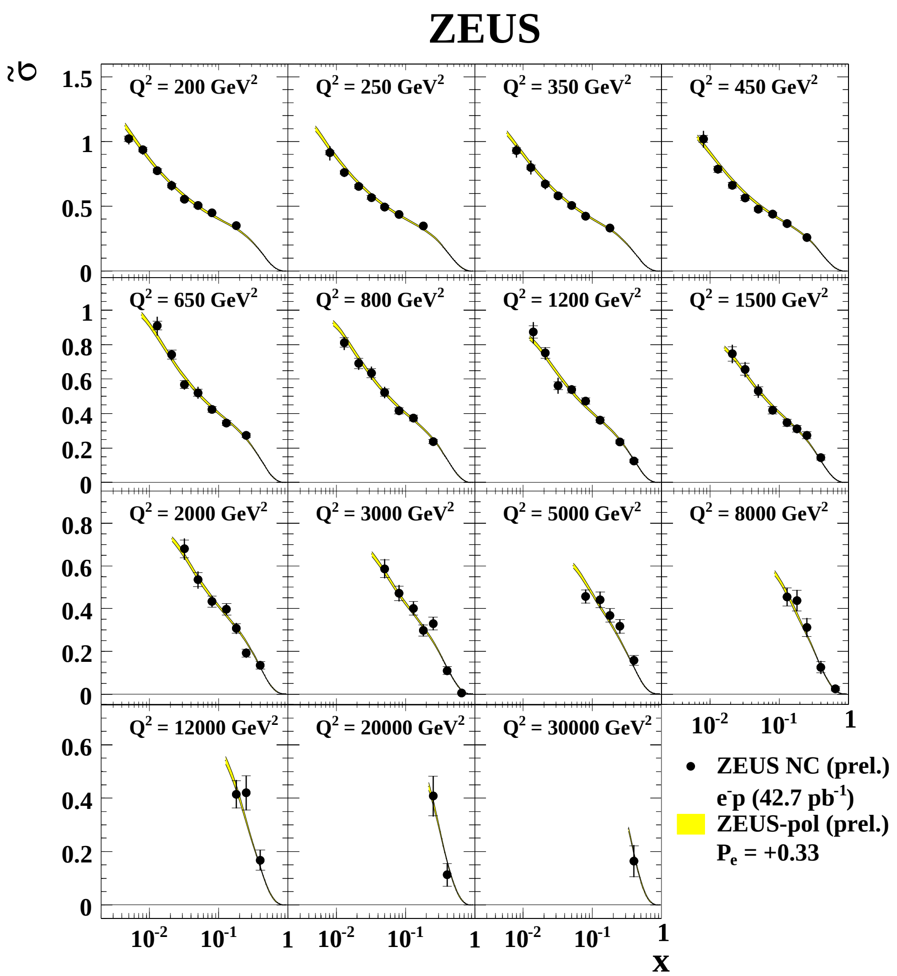
→ better sensitivity to EW

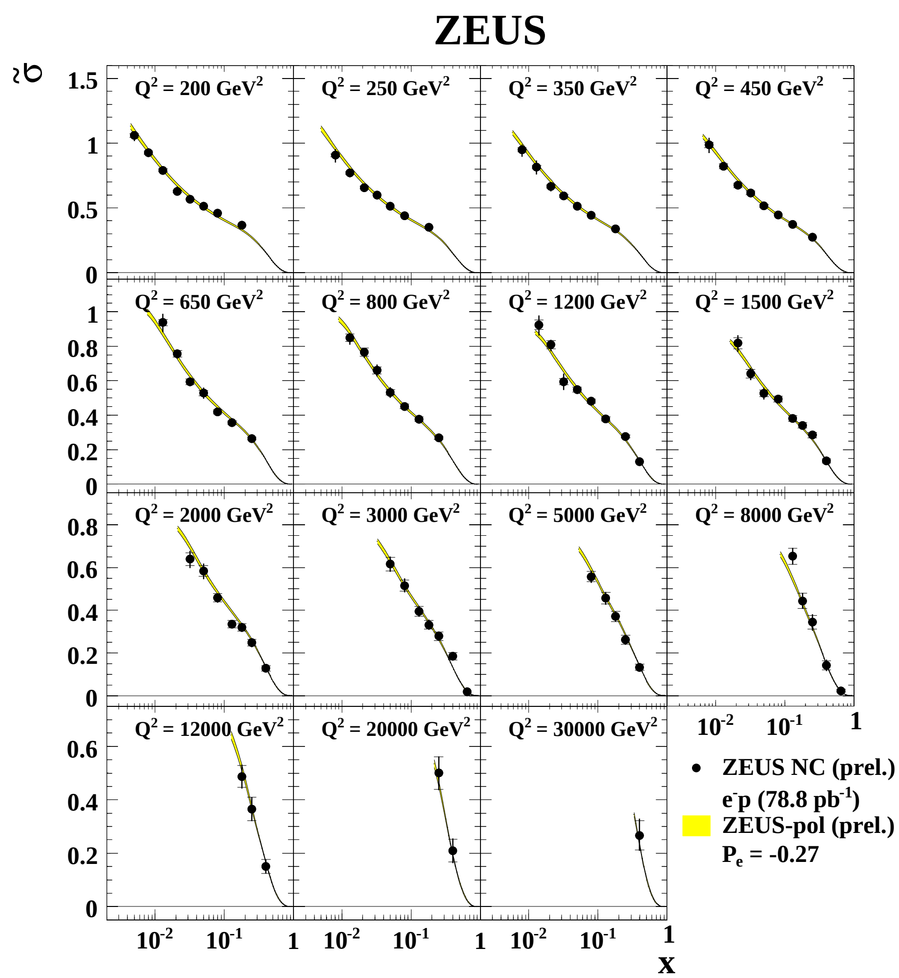
ZEUS performed the first fit including the HERA II cross sections.

ZEUS-pol fit (prel.)

- The first fit including polarized electron DIS cross sections.
- The fit to see any effect on PDFs by including these new data.
- All EW parameters are fixed to SM values.

Polarized NC cross sections



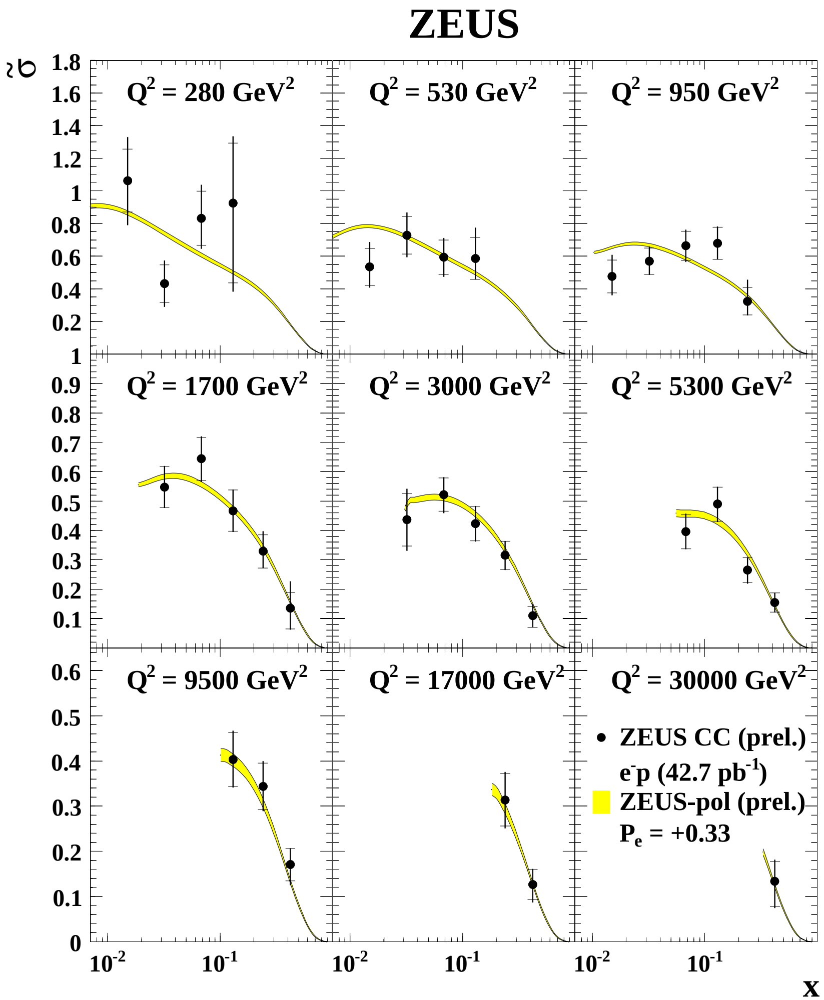


positive pol. P=+0.33

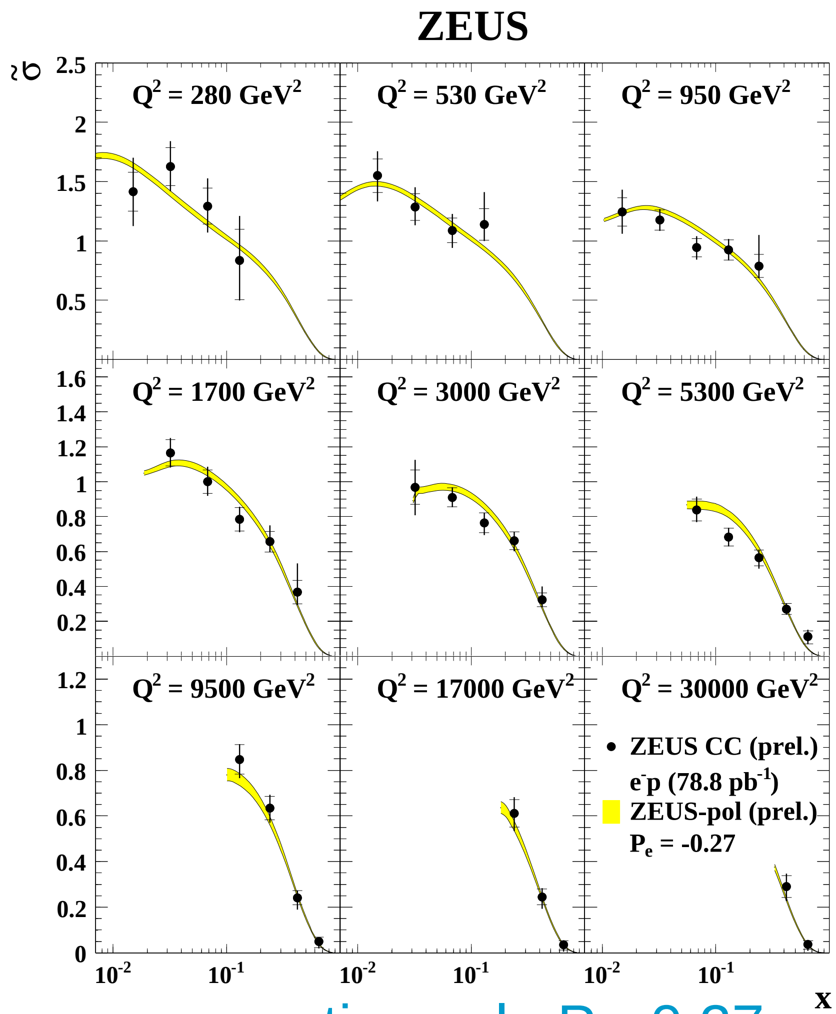
negative pol. P=-0.27

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.
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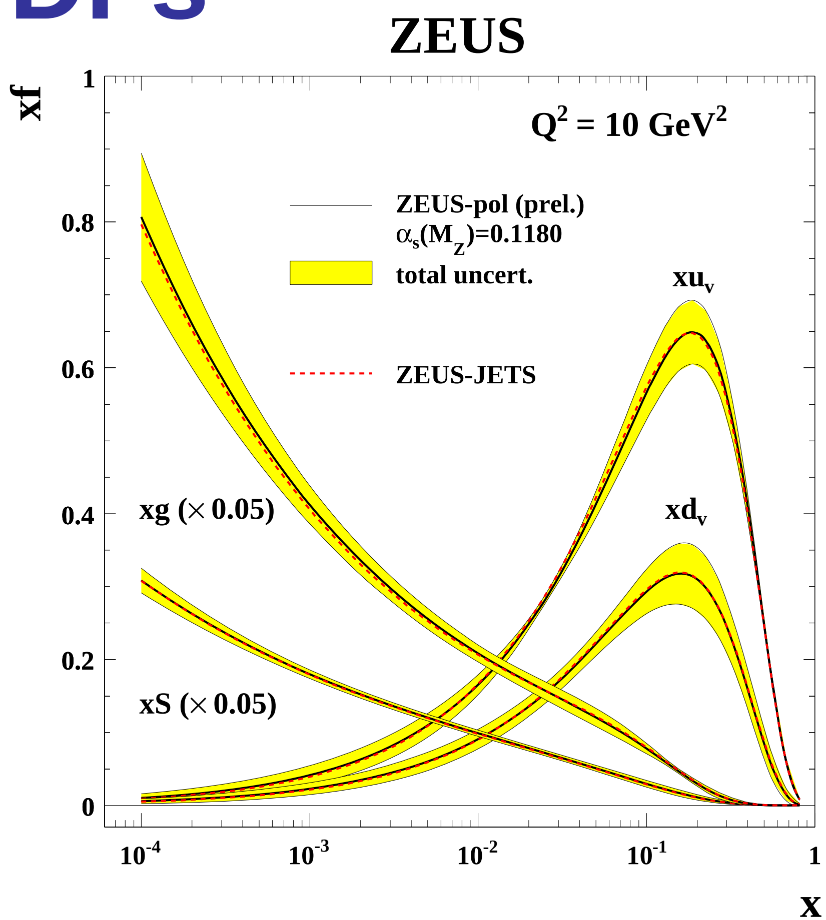
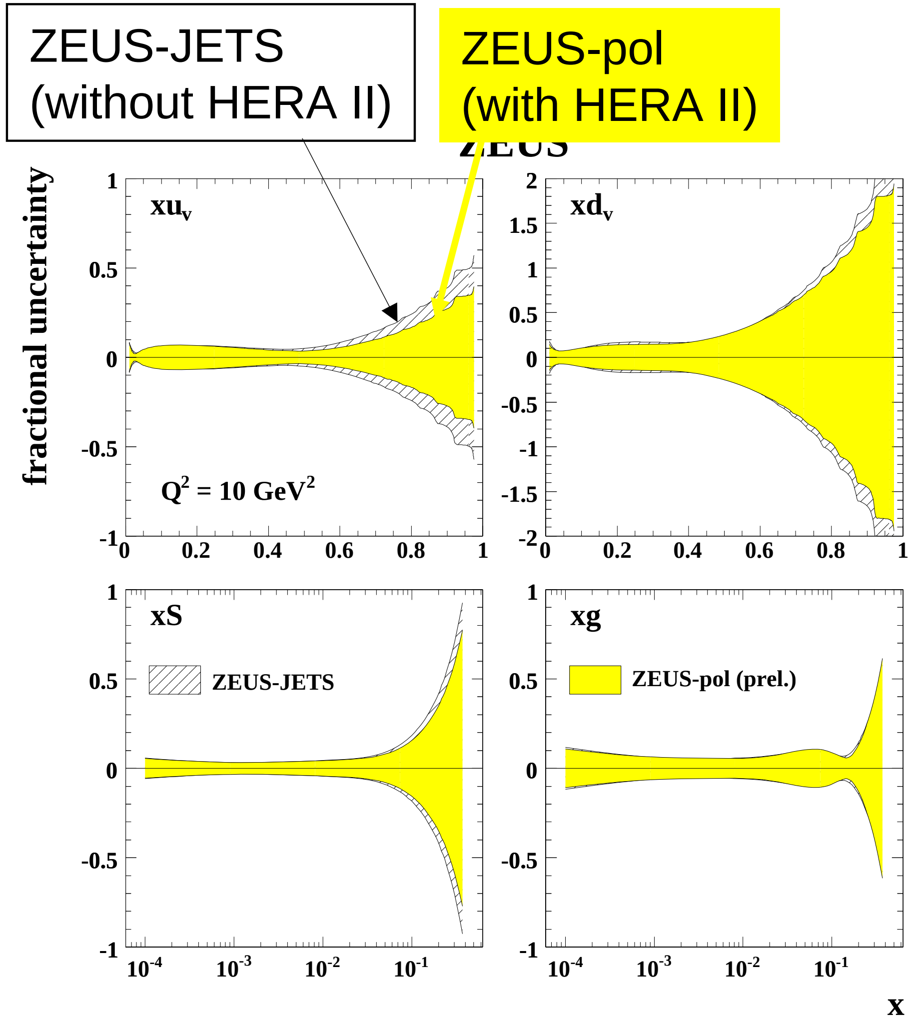
PDFs





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

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

Combined QCD and EW analysis

- Precise understanding of PDFs at HERA allows to see physics in *eq* scattering at EW scale ($Q^2 \sim M_W^2$, M_Z^2).
- HERA II data:

  In addition to the large statistics at EW energy scale, 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
   (ZEUS-pol-M_W, ZEUS-pol-g-M_W) ←CC cross sections
2. Extraction of quark couplings to Z
   (ZEUS-pol-a_u-v_u, ZEUS-pol-a_d-v_d etc.) ←NC cross sections

Extraction of M_W

- CC cross section

M_W is space-like.

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}[Y_+F_2^{CC}(x,Q^2) - y^2F_L^{CC} \mp Y_- xF_3^{CC}(x,Q^2)]$$

- M_W and PDF parameters are free:
  (M_w contributes also to normalization due to fixed G_F.)

  M_W=79.1 ± 0.77 (stat+uncorr) ± 0.9 (corr.sys) [GeV] *prel.*

  HERA I result:

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

- Determination of M_W as general 'propagator mass' with general coupling g (=$G_F M_W^2$)

  g = 0.0772 ± 0.0021 ± 0.0019

  M_W= 82.8 ± 1.5 ± 1.3 [GeV]

  prel.

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

The combined QCD+EW analysis on HERA I + II improves M_W.
Complementary and consistent with time-like M_W at LEP/Tevatron.

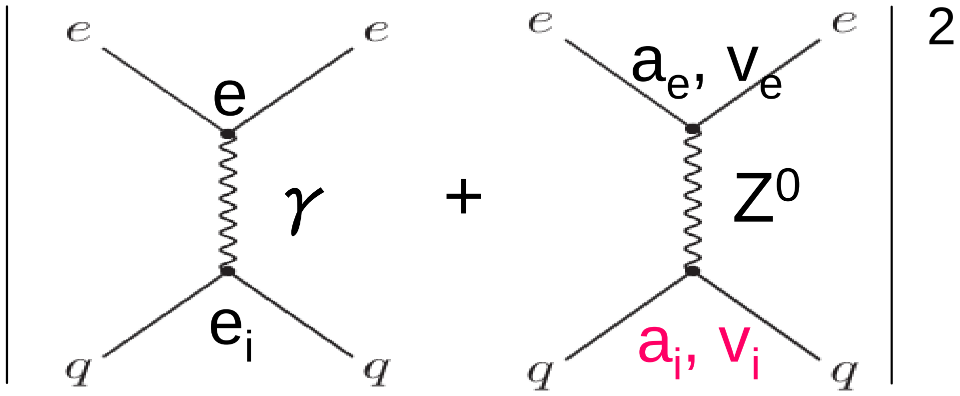
NC cross sections

At HERA, NC interaction occurs by γ and Z^0 exchange.

→ electron-quark cross sections are sum of three terms;

γ-term, γ**Z** interference-term, **Z**-term

σ(eq)=



a : axial coupling
v : vector coupling

In SM formalism,

$$a_i = T_i^3$$

$$v_i = T_i^3 - 2e_i \sin^2\theta_W$$

- DIS cross sections are sensitive to quark couplings to Z (a_i, v_i).
- They can be determined together with PDFs.

Note: a, v are parameterizations of the couplings in the most general way. i.e. less SM formalism.

Polarized NC cross sections

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}\left[\underbrace{(Y_+F_2^0 \mp Y_- xF_3^0)}_{\text{unpol.}} \mp P\underbrace{(Y_+F_2^P \mp Y_- xF_3^P)}_{\text{pol.}}\right]$$ with polarization 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

$$A_i^0(Q^2) = e_i^2 \quad - 2e_i v_i v_e P_Z \quad + (v_e^2 + a_e^2)(v_i^2 + a_i^2)P_Z^2$$

$$B_i^0(Q^2) = \quad - 2e_i a_i a_e P_Z \quad + 4a_i a_e v_i v_e P_Z^2$$

γ γZ^0 Z^0

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

: quarks

polarized coefficients

$$A_i^P(Q^2) = 2e_i v_i a_e P_Z \quad - 2v_e a_e (v_i^2 + a_i^2)P_Z^2$$

$$B_i^P(Q^2) = 2e_i a_i v_e P_Z \quad - 2v_i a_i (v_e^2 + a_e^2)P_Z^2$$

γZ^0 Z^0

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

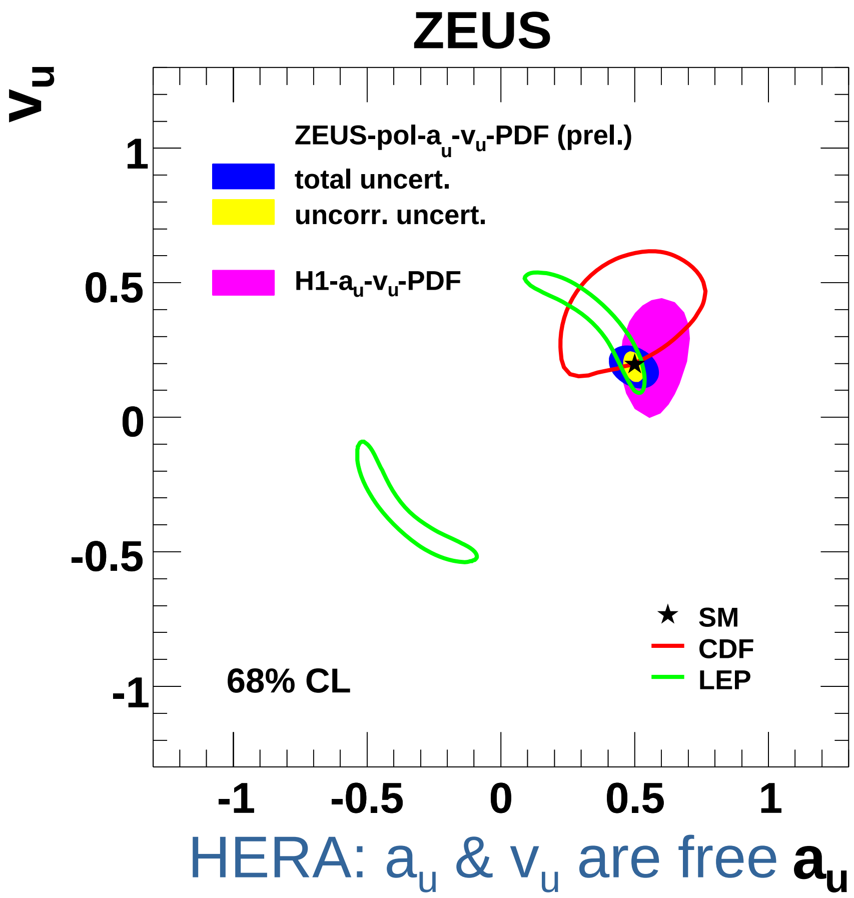
↓

unpolarized xF_3 → a_i,
polarized F_2 → v_i

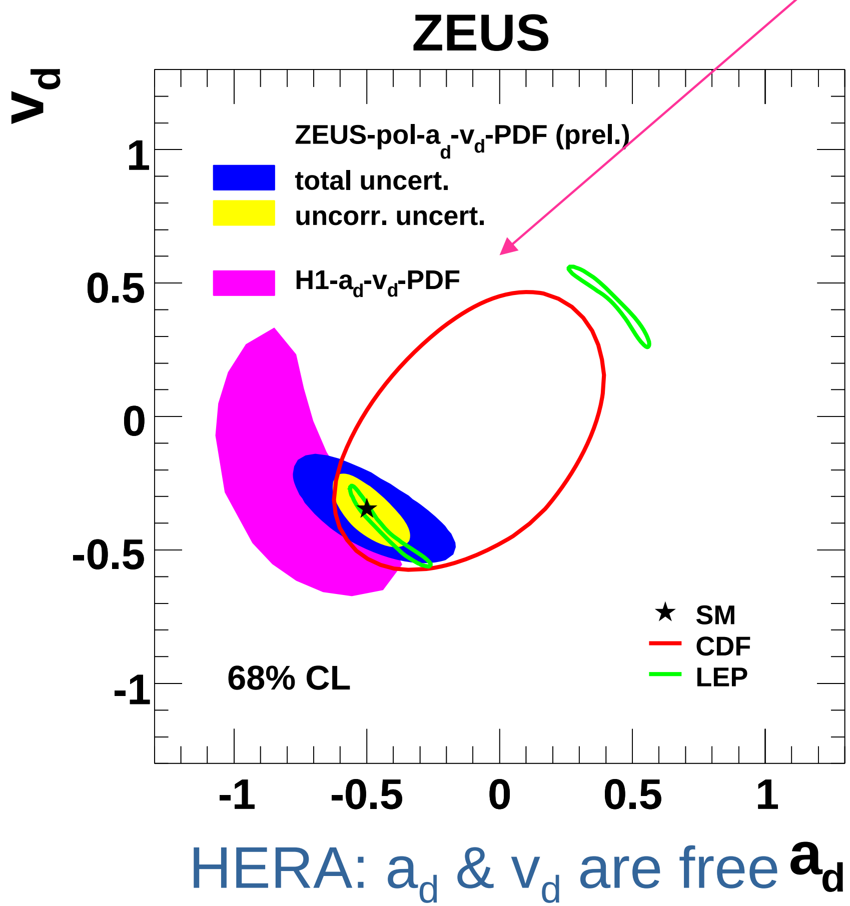
Quark couplings to Z

a_i, v_i and PDFs are determined simultaneously.

H1 performed similar fit but without HERA II data.



HERA: a_u & v_u are free



HERA: a_d & v_d are free

- Comparing to H1 fit, HERA II polarized data improves the sensitivity, especially to vector couplings.
- ZEUS-pol-a_i-v_i fit shows excellent constraint on quark couplings.

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±0.05±0.13

T_d^3 = -0.55±0.18±0.35

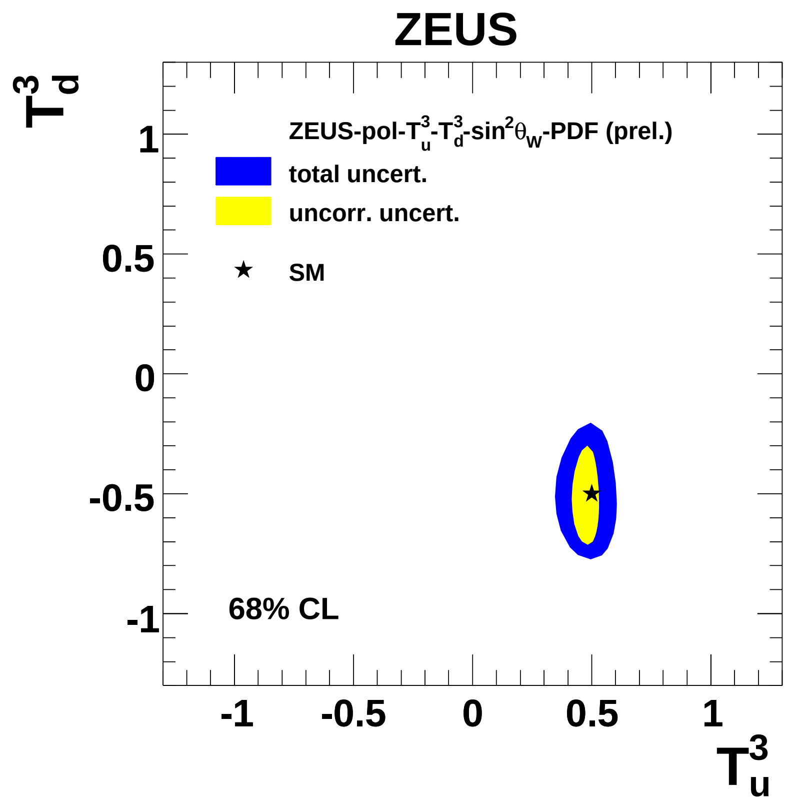
$\sin^2\theta_W$ = 0.231±0.024±0.070

Good agreement with SM values.

T_u^3 = 0.5

T_d^3 = -0.5

$\sin^2\theta_W$ = 0.2315



Summary

- **HERA has sensitivities to both EW and QCD physics.**
- **We have HERA II data.**
  - Large luminosity at high-Q^2 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

Extraction of PDFs at ZEUS

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

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

  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.

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

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

F_i^{QCD} : prediction from QCD

F_i^{meas} : measured data point

s_λ : fit parameter of systematic uncertainty

σ_i^{stat} : statistical uncertainty

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

$\Delta_{i\lambda}^{\mathrm{sys}}$: 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.

HERA I : ZEUS-JETS fit

First fit using HERA jets data.

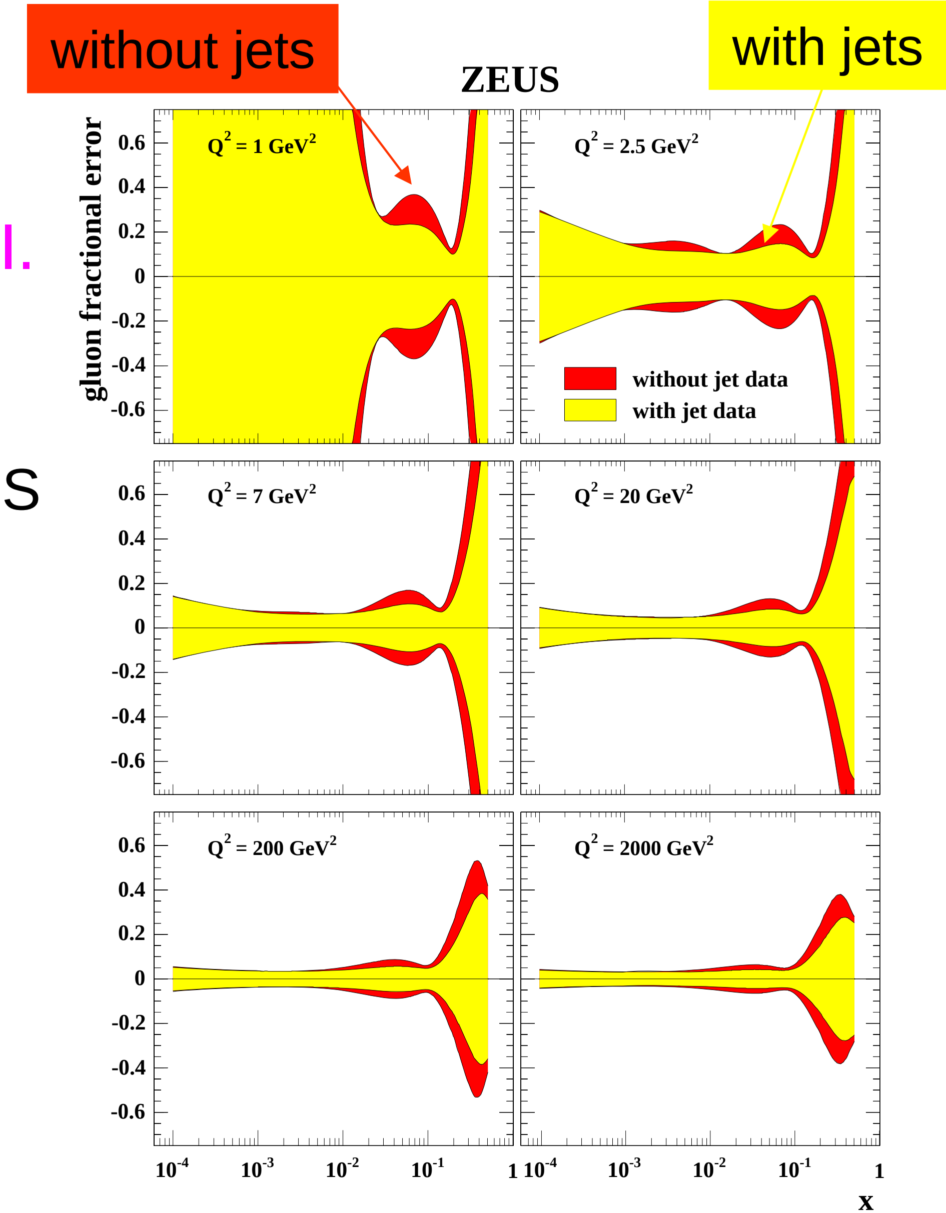
→ Making use of full potential of ZEUS data (and alone) in HERA I.

- 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.

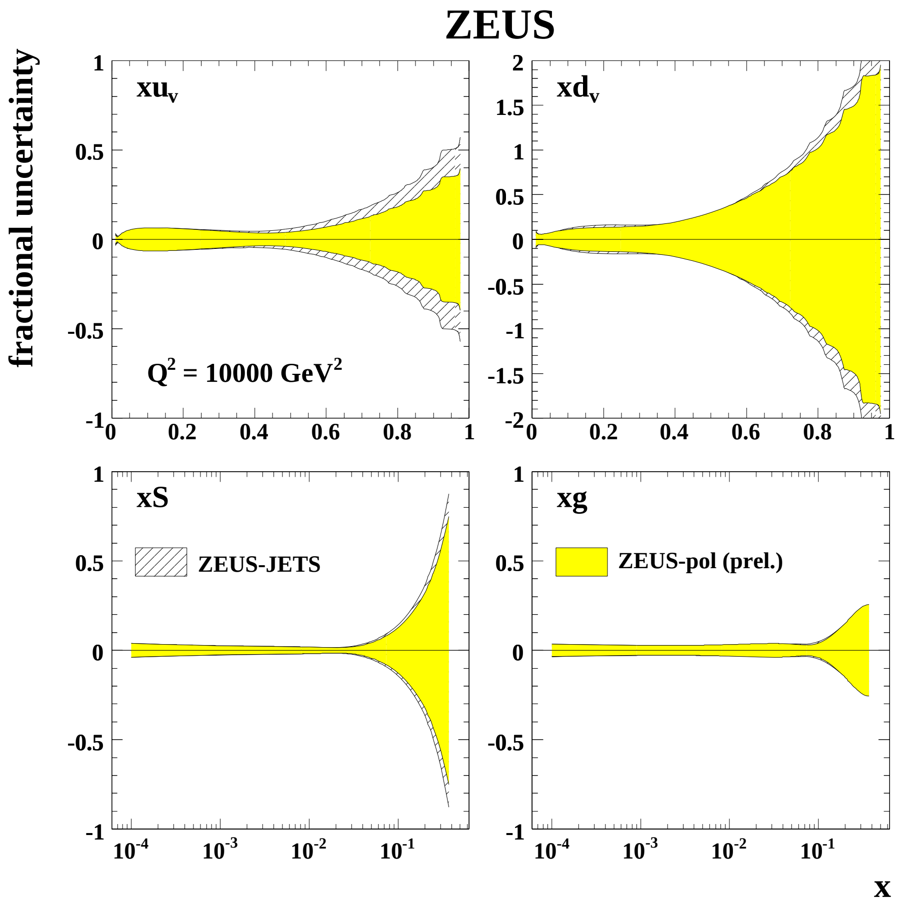
Jets cross sections
→ sensitive to gluon density.

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



Fractional errors of gluon density

PDF uncertainties at very High Q^2



Q^2=10000 GeV^2

- Improvement of PDF uncertainties is also seen at $Q^2=10^4$ GeV^2. Good news for LHC physics.
- HERA is now running with positron beam.
  → Further improvement can be expected in future.

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.

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)

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

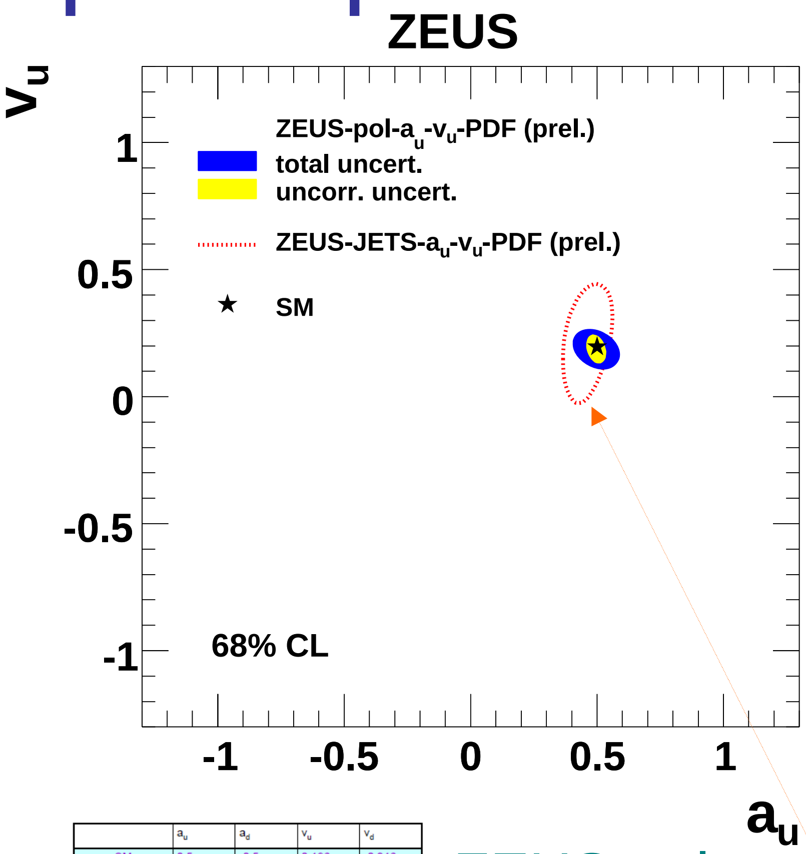
$g= 0.0772 \pm 0.0021 \pm 0.0019$

$M_W=82.8 \pm 1.5 \pm 1.3$ [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
  $g = G_F M_W^2 = 0.07542$

a_i vs. v_i



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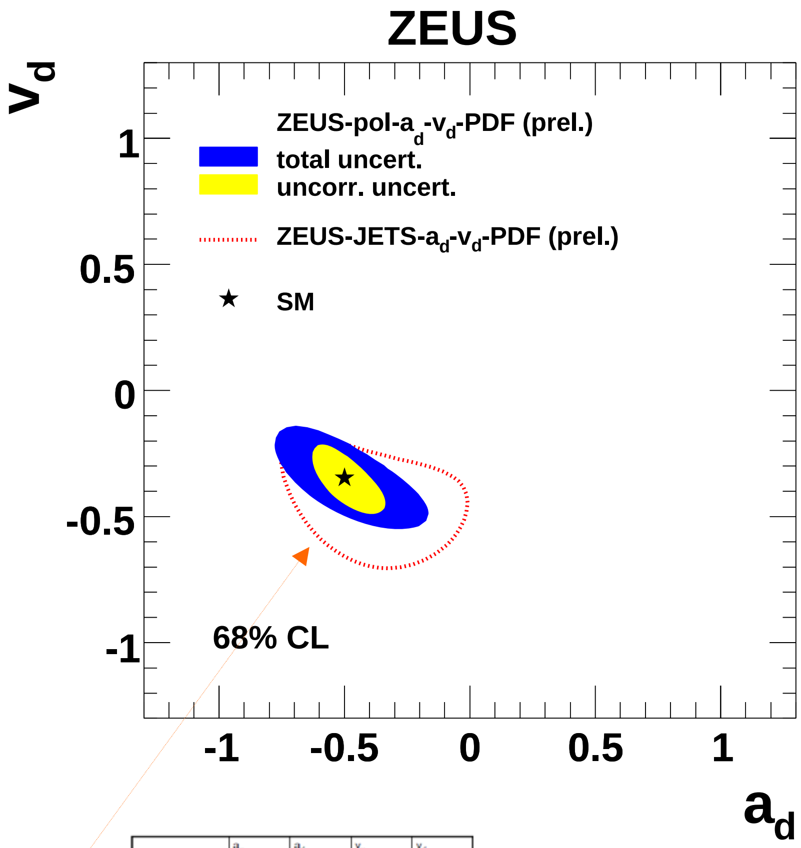
ZEUS-pol-a_u-v_u

a_d, v_d: fixed



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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.

v_u vs. v_d

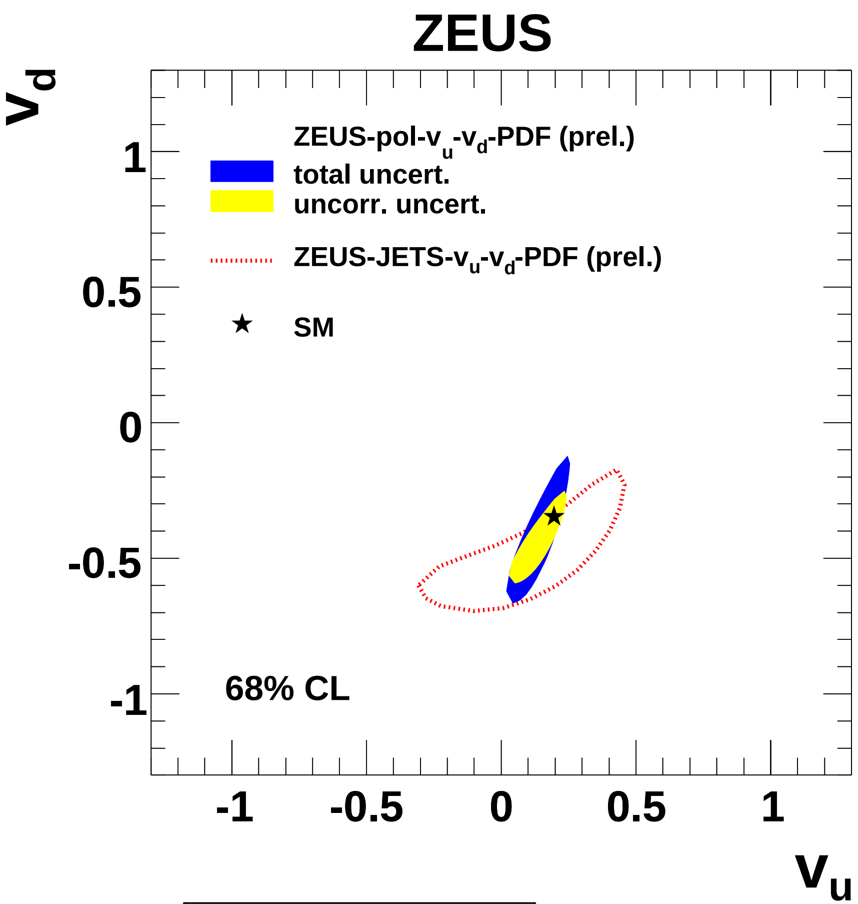
Now we have polarized data!

→ Vector couplings benefit from extra sensitivity 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

Right handed Isospin

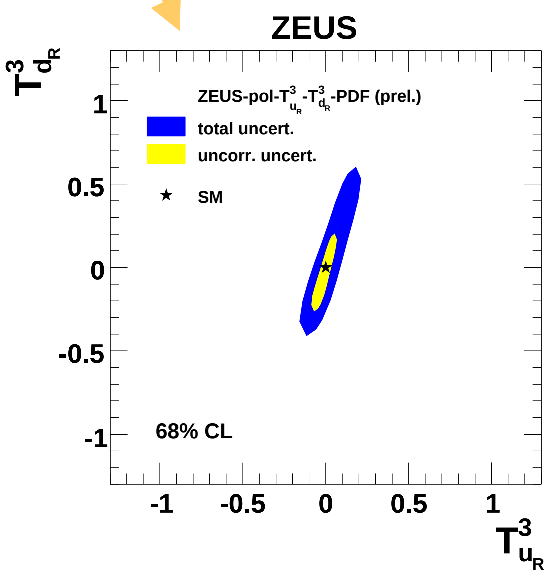
- Introduce right handed isospin, $T^3_{q,R}$, which should be 0 in SM,

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

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

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

Results (preliminary)	T^3u_R	T^3d_R	$\sin^2\theta_W$
ZEUS-pol-$T^3_{u,R}$-$T^3_{d,R}$ fit	-0.04 $\pm0.06\pm0.13$	-0.14 $\pm0.18\pm0.33$	0.2315 fixed
ZEUS-pol-$T^3_{u,R}$-$T^3_{d,R}$-$\sin^2\theta_W$ fit	-0.07 $\pm0.07\pm0.07$	-0.26 $\pm0.19\pm0.19$	0.238 $\pm0.011\pm0.023$



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