

# Recent ZEUS results

## and selected combined H1+ZEUS results

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DESY Symposium, Hamburg  
07/07/2009

# New results since ICHEP08

## Inclusive, SFs and Exotics:

FL measurement

High-Q<sup>2</sup> e+p/e-p NC/CC cross sections

ZEUS09 NLO QCD fits

Inclusive Cross sections -   comb.

HERAPDF0.2 NLO QCD fits -   comb.

## Contact Interactions

Single-top production

Isolated leptons -   comb.

Multi-leptons -   comb.

## Diffraction:

NLO QCD analysis of diffr. DIS data

Di-jet PhP with Leading Barions

DVCS

High-t J/Psi Photoproduction

Exclusive Upsilon Photoproduction

## QCD/HFS:

Jet cross sections in NC DIS

$\alpha_s$  measurement in NC DIS and PhP

Multi-jet cross sections in CC DIS

Jet substructure

Angular correlations in 3-jet

Prompt-photon production in DIS

Scaled momentum distributions in PhP

Energy dependence of charged

multiplicity in DIS

K<sub>0</sub>sK<sub>0</sub>s

## HFL:

Charm fragmentation f. with D\* PhP

D<sup>+</sup>-, D<sup>0</sup> DIS with life time meas.

Beauty PhP with muons

Beauty PhP with inclusive di-jets

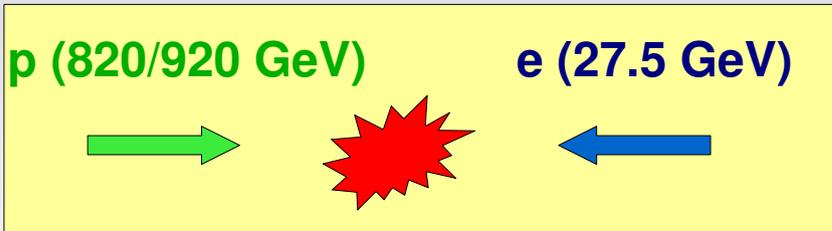
Charm and Beauty DIS with muons

J/Psi helicity distributions PhP

<http://www-zeus.desy.de/physics/phch/conf/eps09/>

# HERA Reminder

It ended 2 years ago...



$$\sqrt{s} = 318 \text{ GeV}$$

HERA II

High luminosity

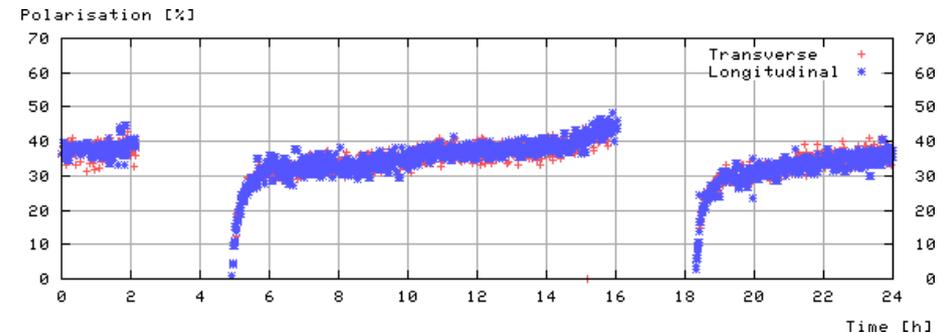
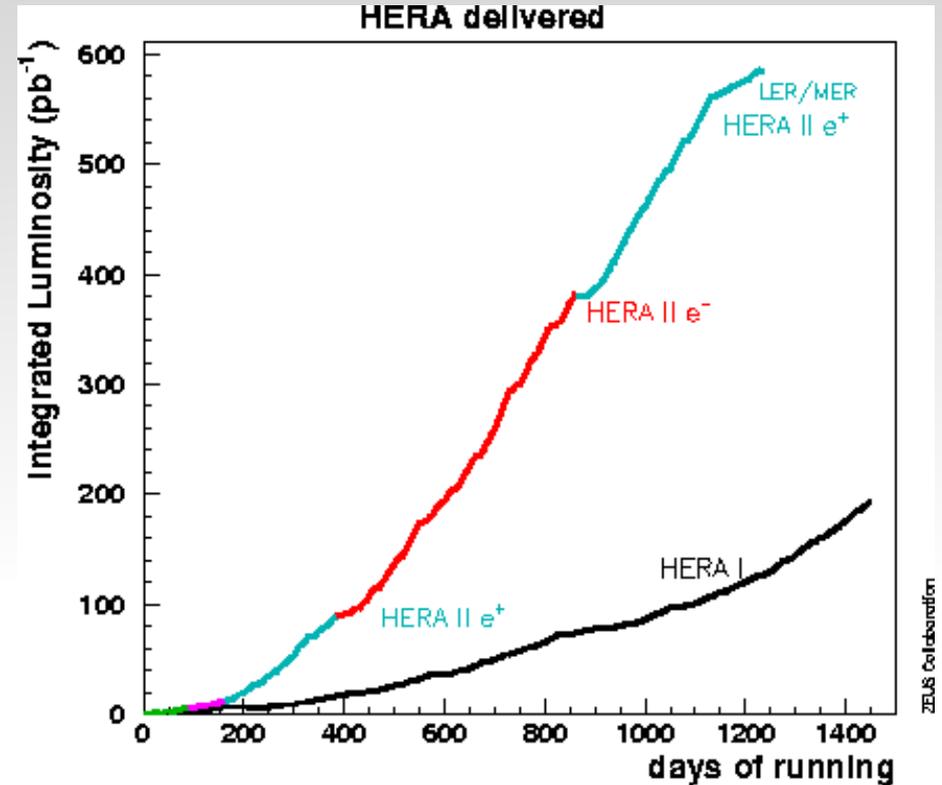
Equal sharing between  $e^+p$  and  $e^-p$  ( $\sim 200 \text{ pb}^{-1}$ )  
 Significant increase of statistics for  $e^-p$  wrt. HERA I

$\sim 0.5 \text{ fb}^{-1}$  per experiment (HERA I + HERAII)

Longitudinal polarisation of the lepton beam

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

typically 30-40%

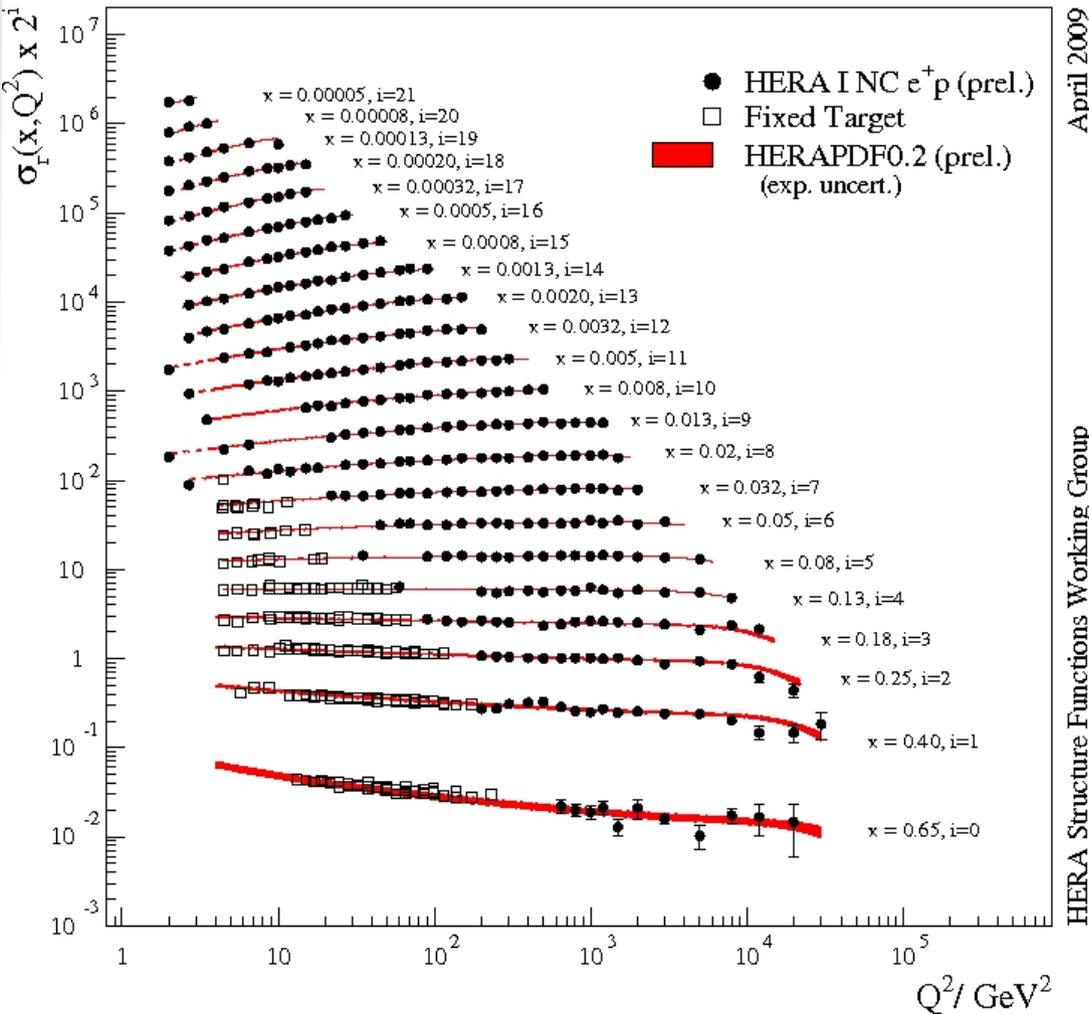


# H1+ZEUS combined HERA I cross sections



Greatly reduced experimental uncertainties compared to the separate analyses of the ZEUS and H1 experiments (“cross calibration”).

H1 and ZEUS Combined PDF Fit



April 2009

HERA Structure Functions Working Group

New data included since DIS08:

ZEUS BPC/BPT, SVX95	$0.045 \leq Q^2 \leq 17 \text{ GeV}^2$
H1 95-00 “low $Q^2$ ”	$0.5 \leq Q^2 \leq 12 \text{ GeV}^2$
H1 96-00 “medium $Q^2$ ”	$12 \leq Q^2 \leq 150 \text{ GeV}^2$

Complete set of published inclusive NC/CC  
HERA I DIS data (1994-2000,  $L=240 \text{ pb}^{-1}$ )

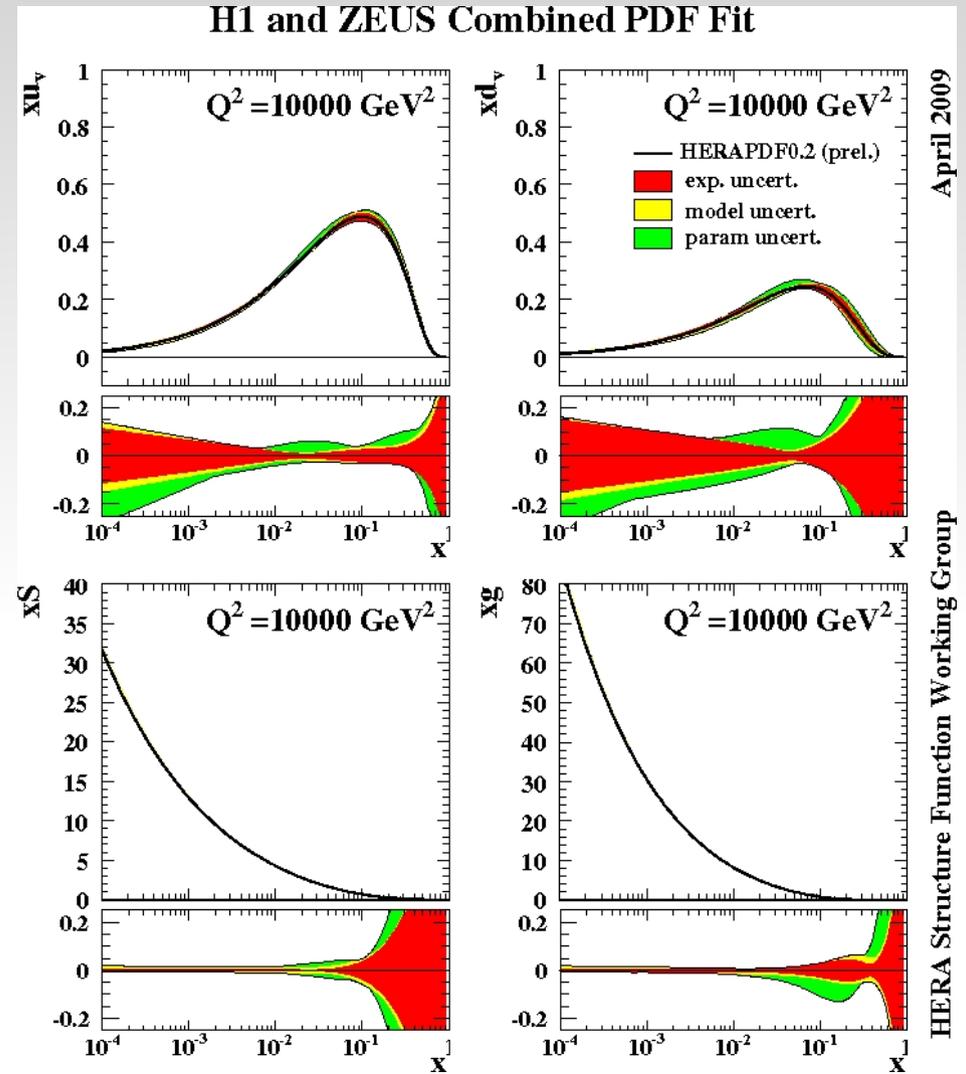
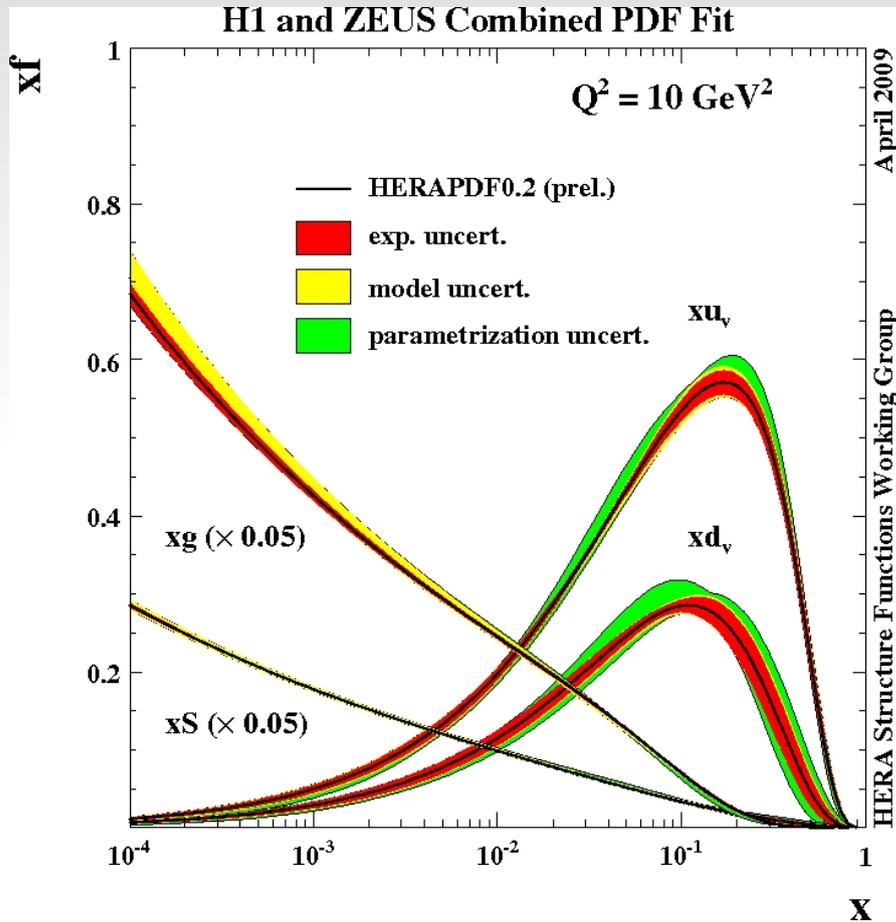
O(1%) precision for  $10 < Q^2 < 100 \text{ GeV}^2$

Combined data serve as an input to the NLO  
QCD fits, **HERAPDF0.2**.

# NLO QCD fit to combined HERA I data

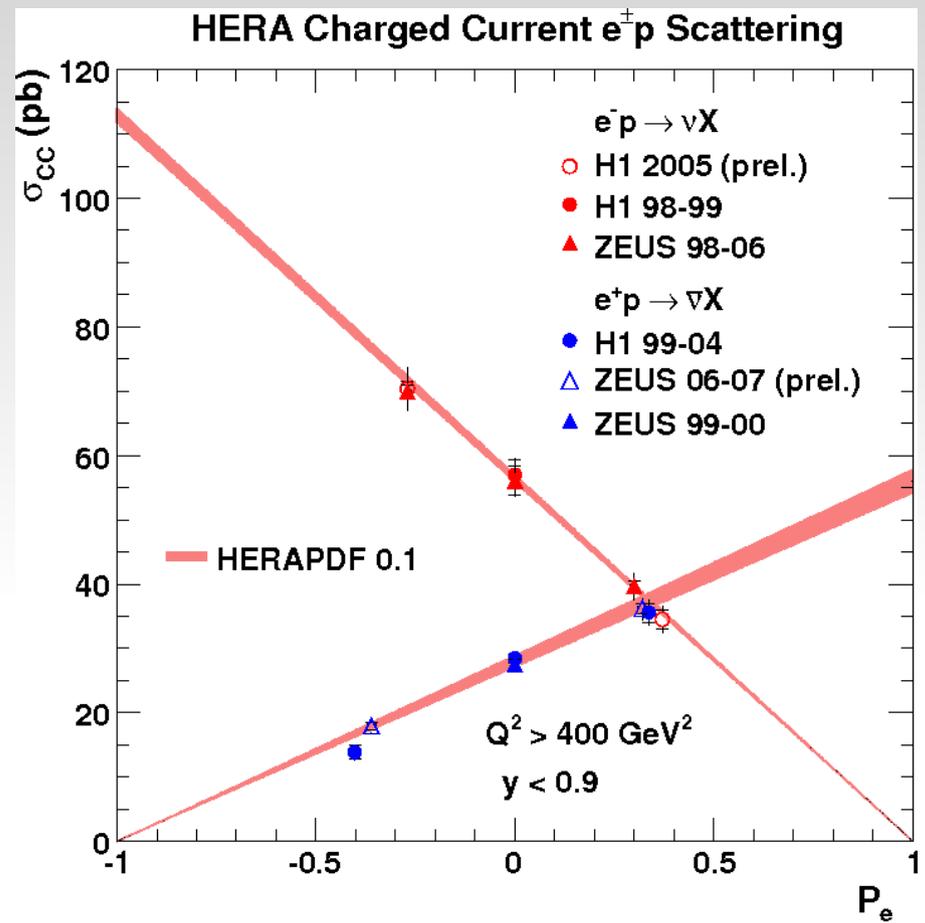
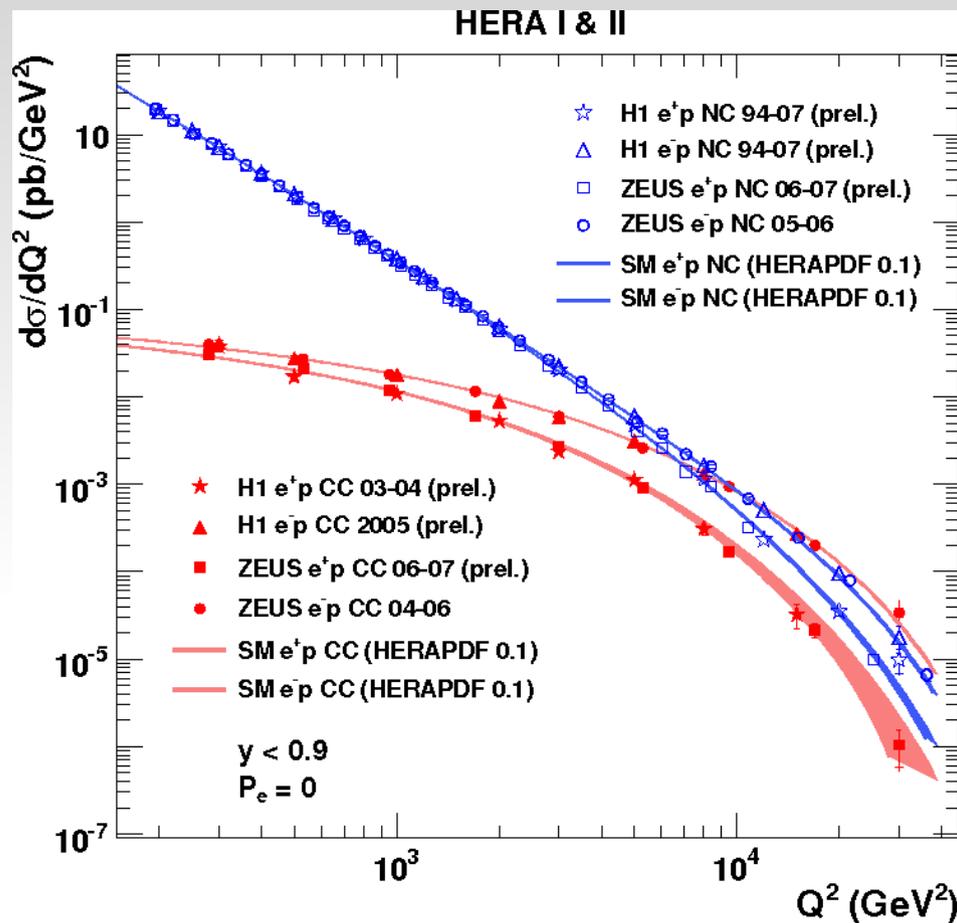


HERAPDF0.2



High precision, new treatment for heavy flavours (TR-VFNS), detailed study of PDFs unc.  
 Very close to completion.

# HERA II high- $Q^2$ NC and CC cross sections



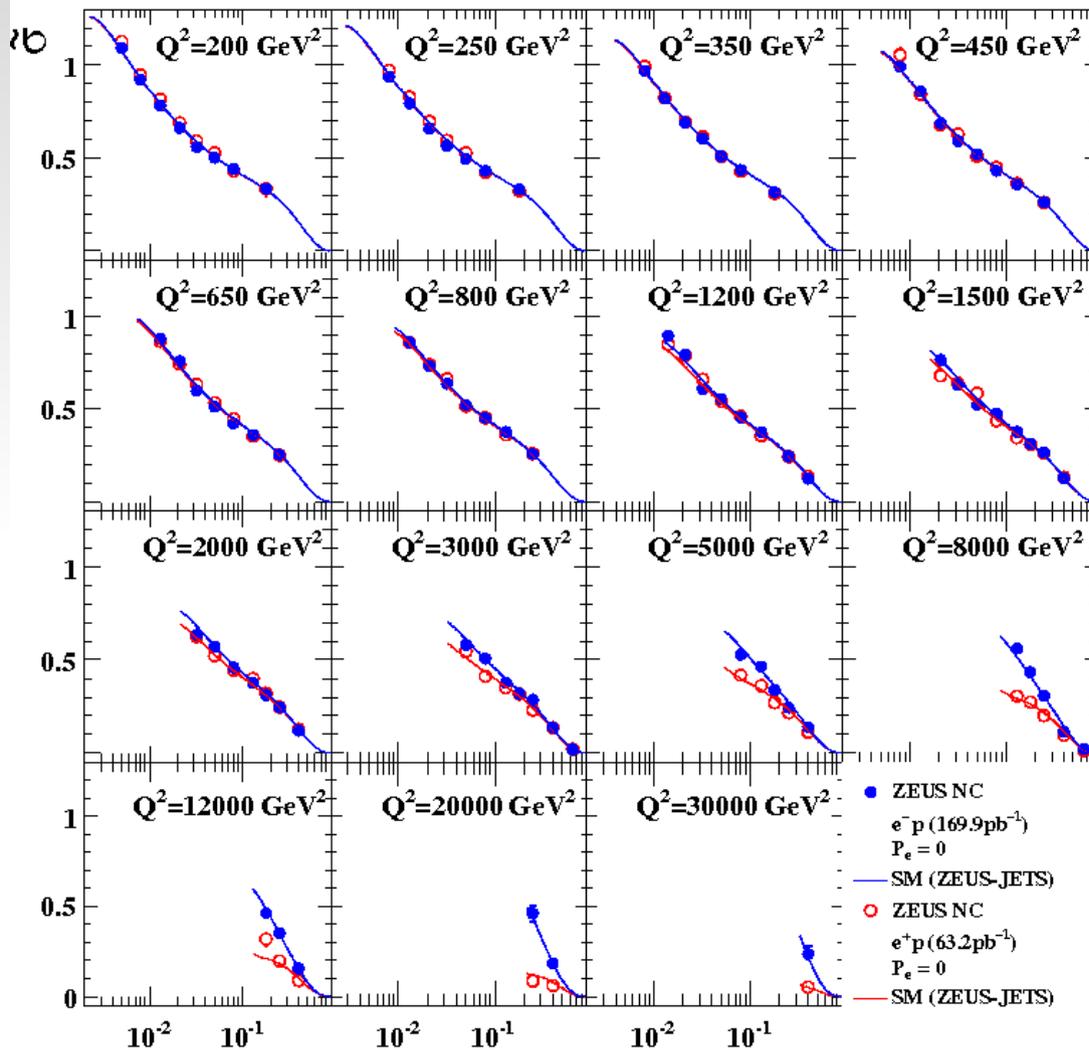
Electroweak: EW unification, parity violation and xF3, chiral structure of weak int.  
 QCD: tests of QCD in a wide kinematic range, measurement of proton SF and PDFs.  
 Searches for new physics.

These plots include full datasets of ZEUS NC e<sup>-</sup>p, e<sup>+</sup>p and CC e<sup>-</sup>p, e<sup>+</sup>p.

# High- $Q^2$ NC $e^-p$ cross sections

DESY-08-202

ZEUS



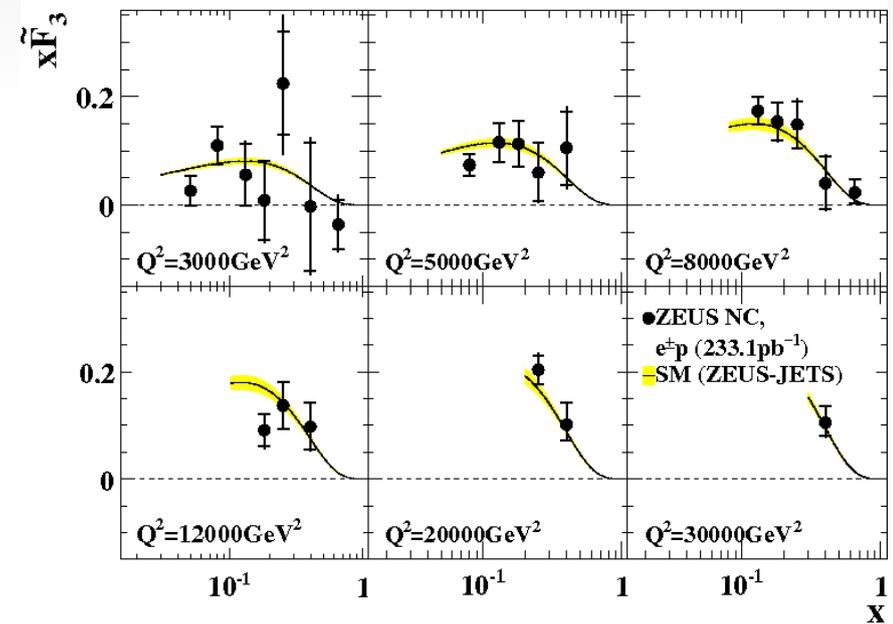
$$\tilde{\sigma}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_\pm} \frac{d^2\sigma(e^\pm p)}{dx dQ^2} = \tilde{F}_2(x, Q^2) \mp \frac{Y_-}{Y_+} x\tilde{F}_3(x, Q^2)$$

HERA II  $e^-p$  ( $L=170 \text{ pb}^{-1}$ )

HERA I  $e^+p$  ( $L=63 \text{ pb}^{-1}$ )

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-} (\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p})$$

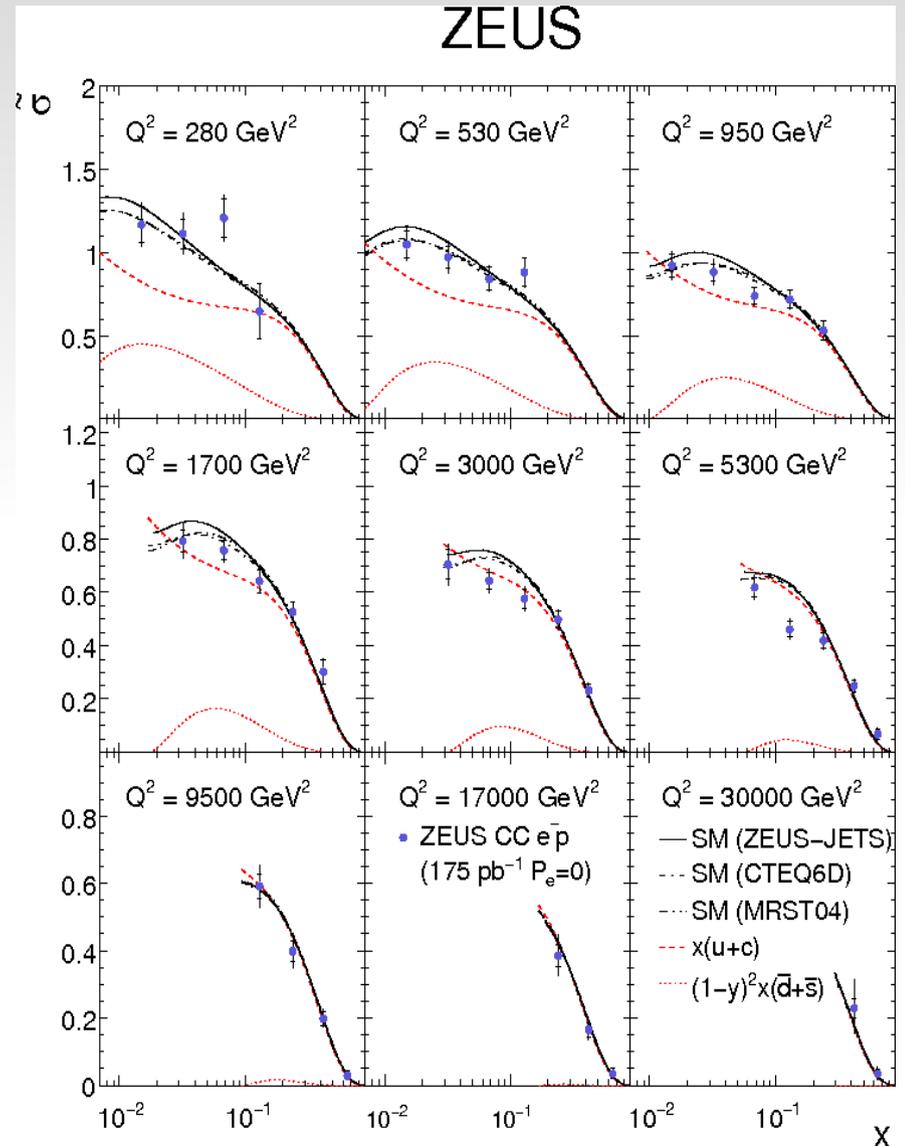
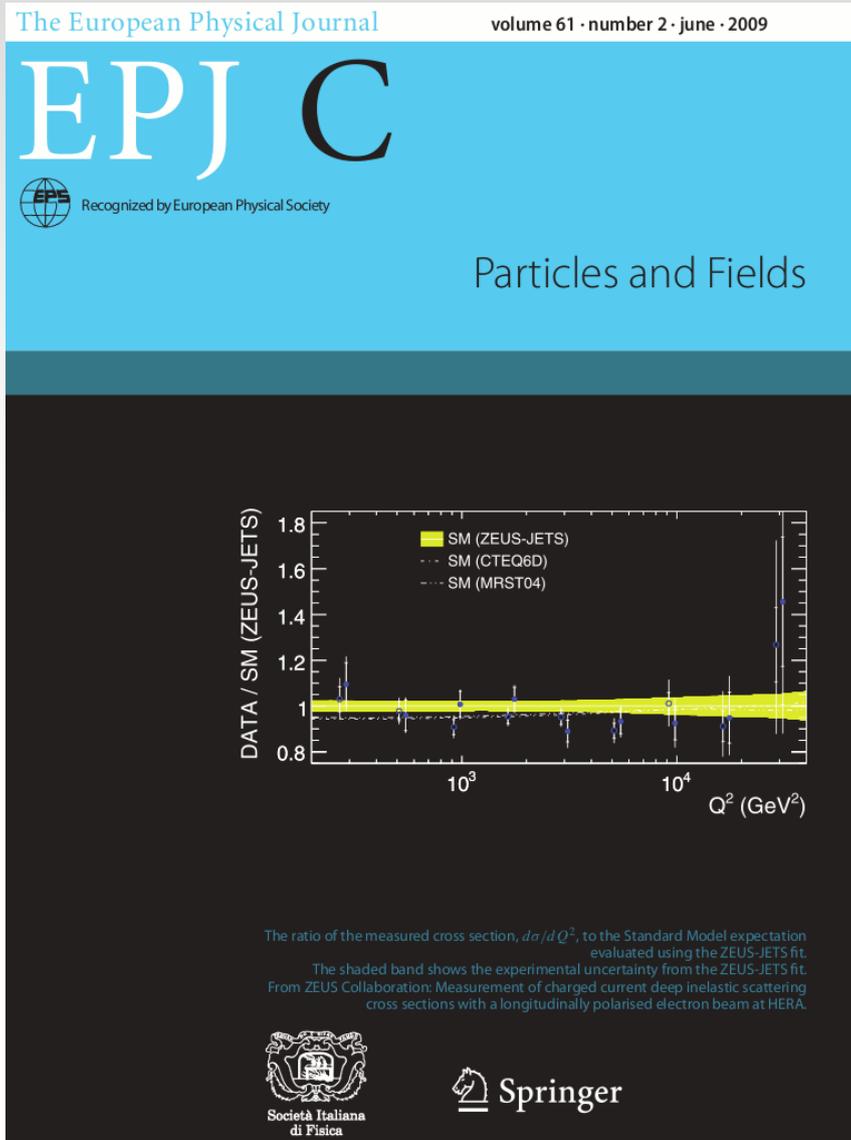
ZEUS



# High- $Q^2$ CC $e^-p$ cross sections

DESY-08-177  $L=175 \text{ pb}^{-1}$

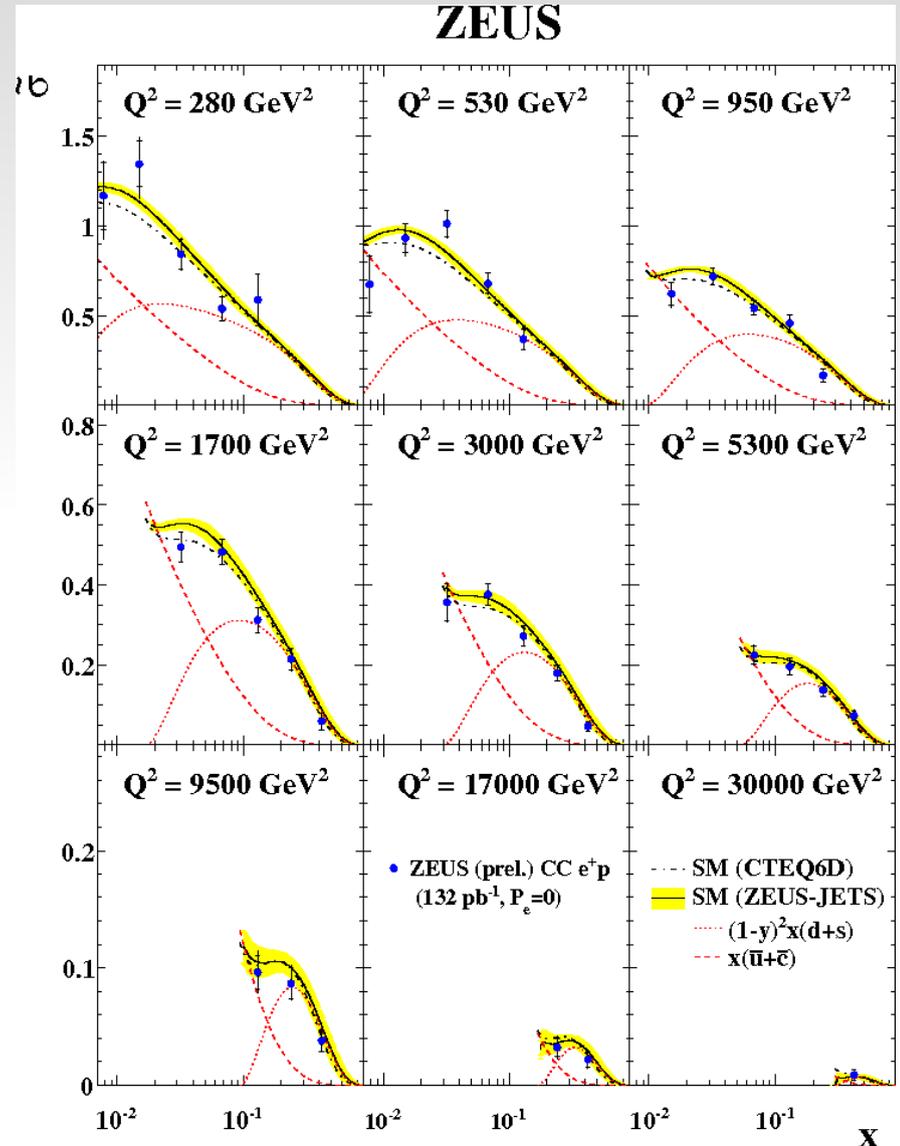
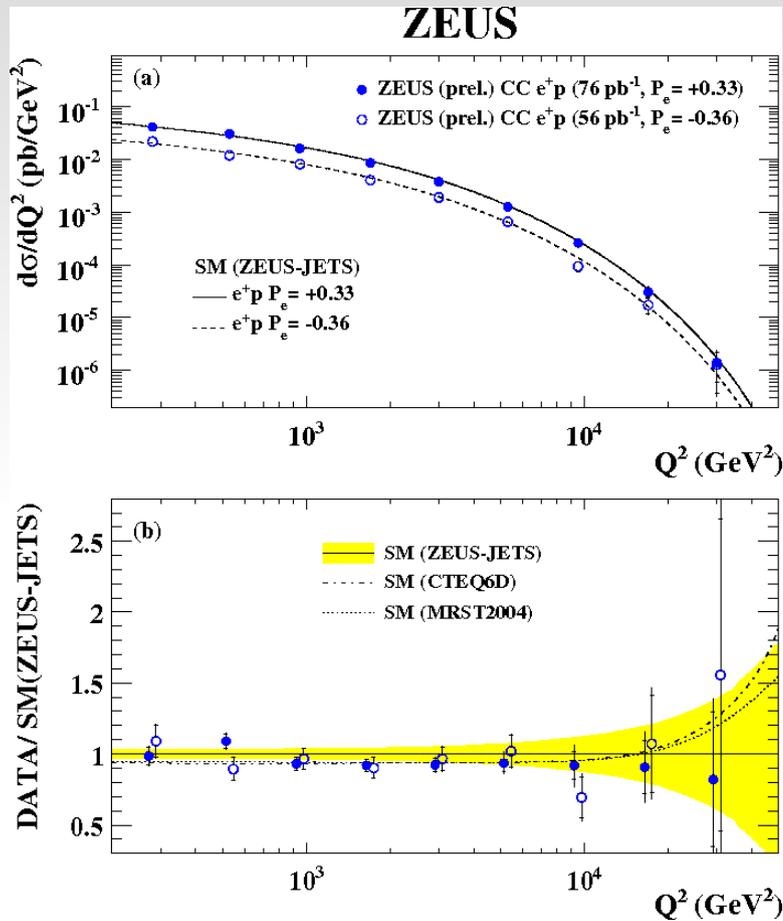
$$\tilde{\sigma}(e^- p \rightarrow \nu X) = [(u+c) + (1-y)^2(\bar{d} + \bar{s})]$$



# High- $Q^2$ CC $e^+p$ cross sections

$L=132 \text{ pb}^{-1}$

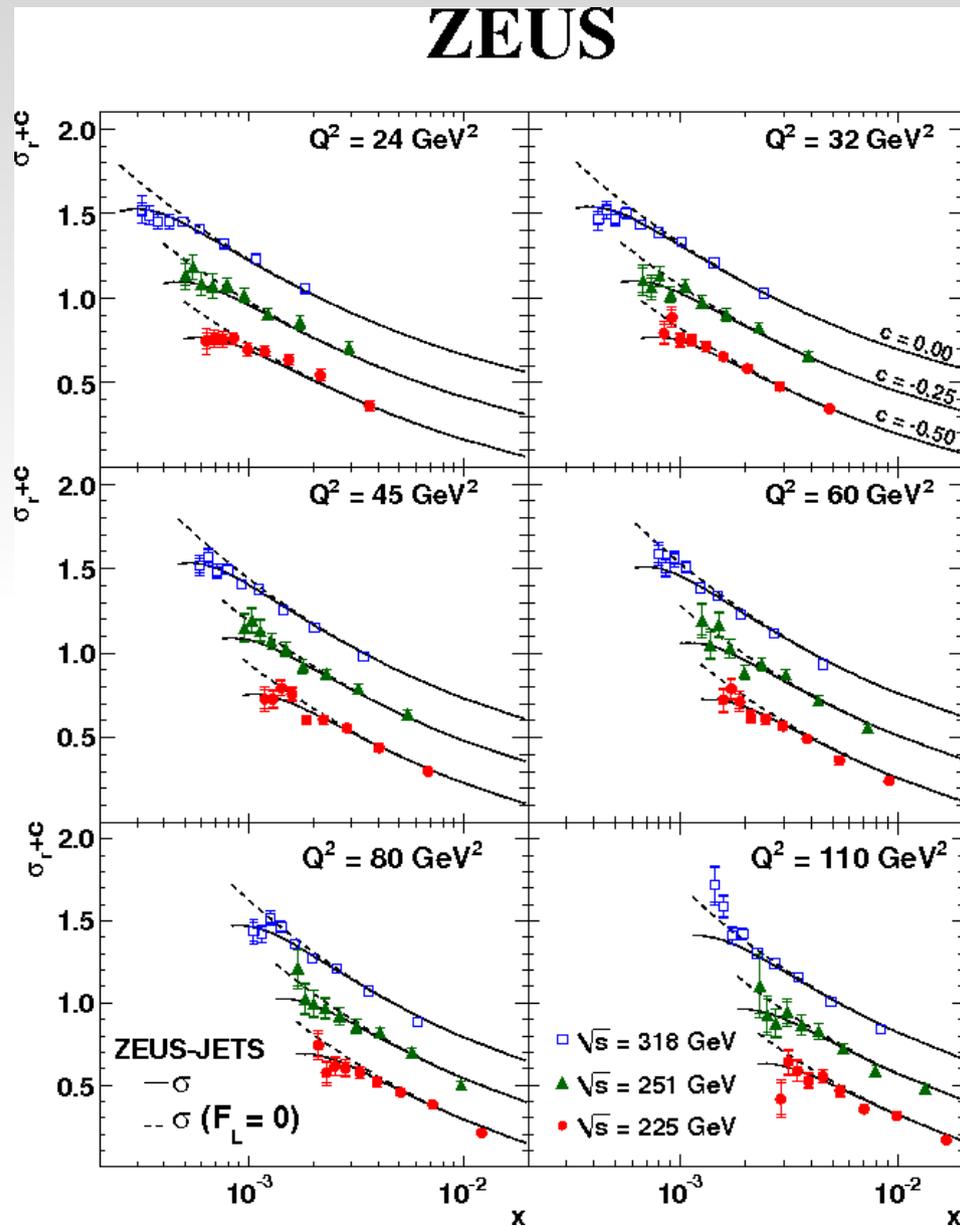
$$\tilde{\sigma}(e^+ p \rightarrow \bar{\nu} X) = [(\bar{u} + \bar{c}) + (1-y)^2(d+s)]$$



Measurement very close to completion.

# Low- and Mid- $Q^2$ NC cross sections

DESY-09-046



NC e+p data from dedicated running periods:

HER:  $E_p = 920 \text{ GeV}$   $\sqrt{s} = 318 \text{ GeV}$   $L = 44.5 \text{ pb}^{-1}$

MER:  $E_p = 575 \text{ GeV}$   $\sqrt{s} = 251 \text{ GeV}$   $L = 7.1 \text{ pb}^{-1}$

LER:  $E_p = 460 \text{ GeV}$   $\sqrt{s} = 225 \text{ GeV}$   $L = 13.9 \text{ pb}^{-1}$

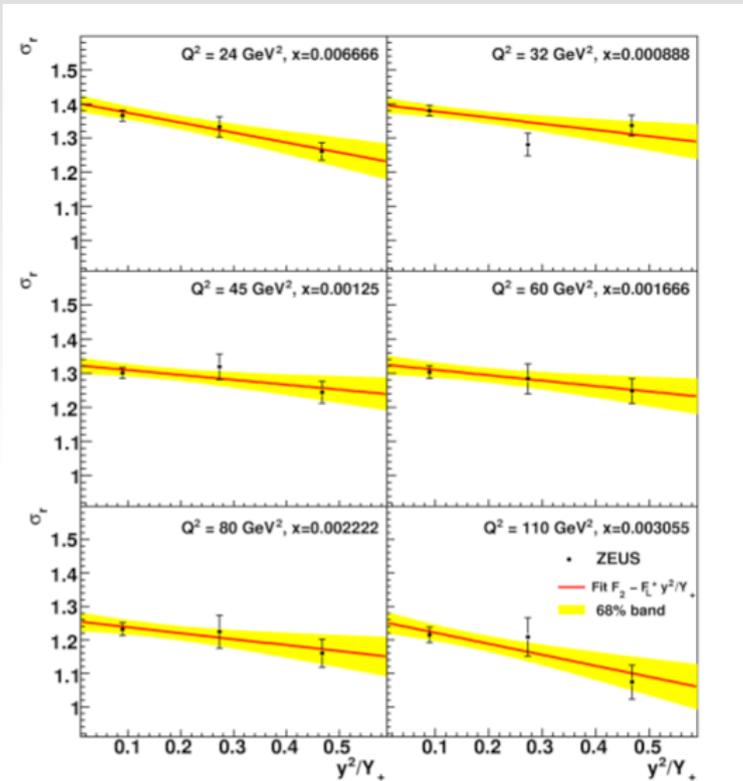
Reduced cross sections measured for  
 $20 < Q^2 < 130 \text{ GeV}^2$  and  $5 \times 10^{-4} < x < 0.007$

Different  $\sqrt{s}$  to measure at a given  $(x, Q^2)$  but  
 different  $y$

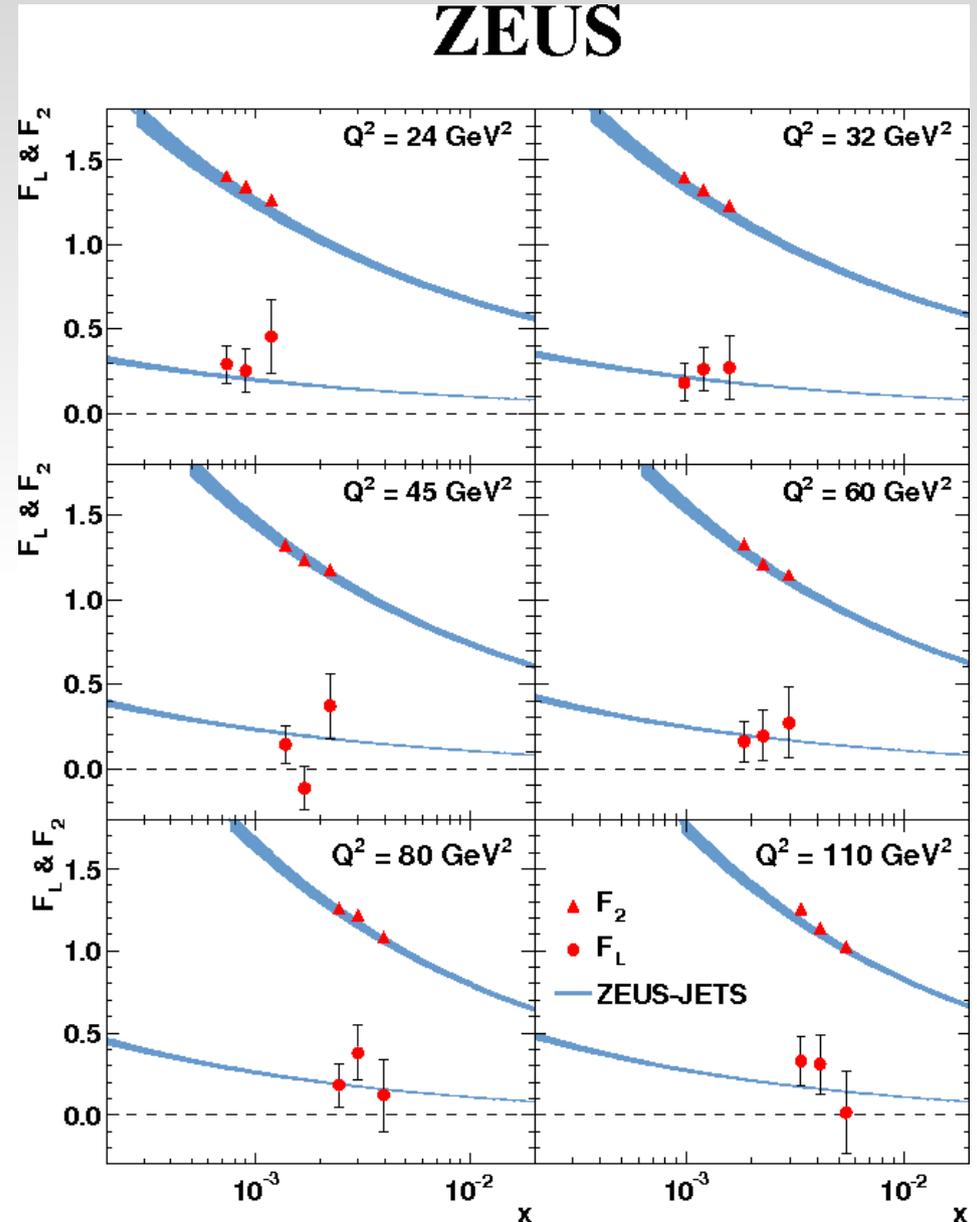
$$Q^2 = sxy$$

# Measurement of $F_L$ and $F_2$ DESY-09-046

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$

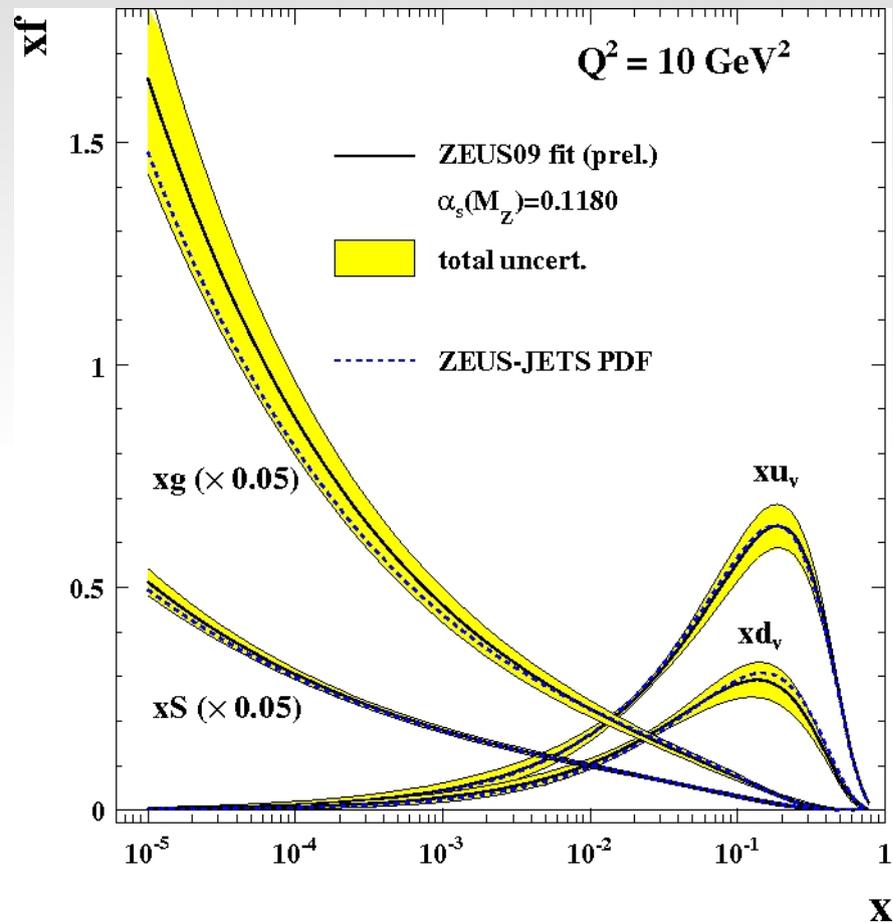


Non zero  $F_L$ .  
 Most precise ZEUS measurement of  $F_2$   
 in this kinematic region.

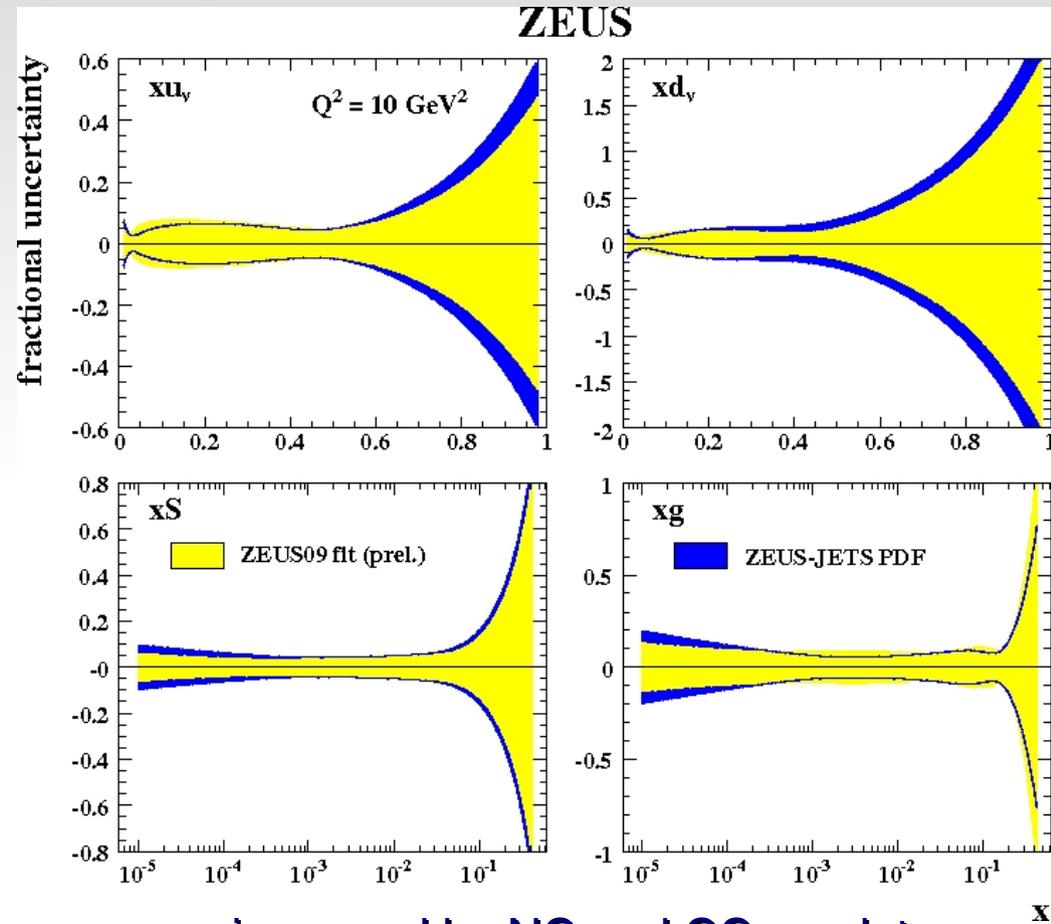


# ZEUS09 NLO QCD fit

With the approach described in the ZEUS-JETS publication study the impact of new HERA II CC  $e^\pm p$ , NC  $e^- p$  and NC  $e^+ p$  HER/MER/LER data on PDFs

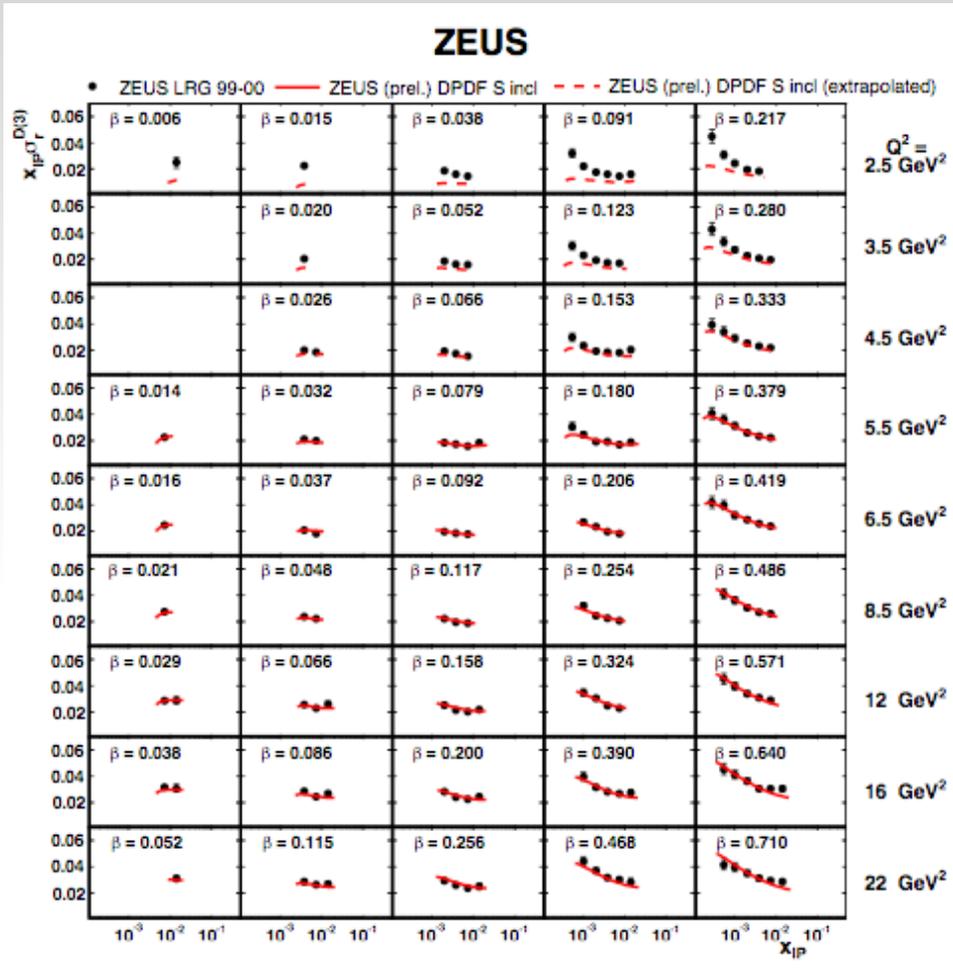


Consistent with ZEUS-JETS.  
 Slightly steeper gluons at low  $x$ .

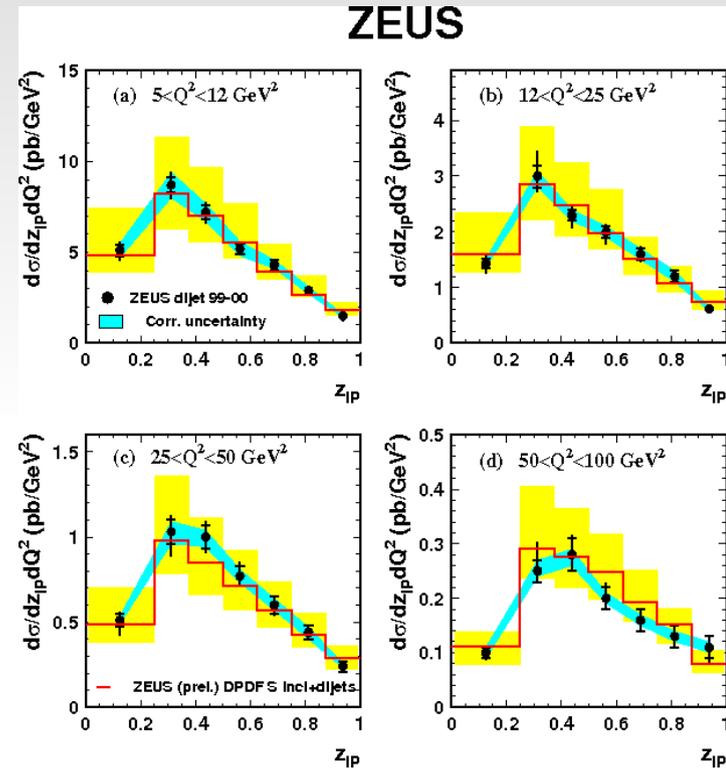


$xu_v$  – improved by NC and CC  $e^- p$  data  
 $xd_v$  – improved by CC  $e^+ p$  data  
 $xg$  – improved by NC  $e^+ p$  data ( $F_L$  meas.)

# Diffraction NLO QCD fit and dPDFs



NLO QCD fits to inclusive DIS data and diffractive di-jets in DIS.

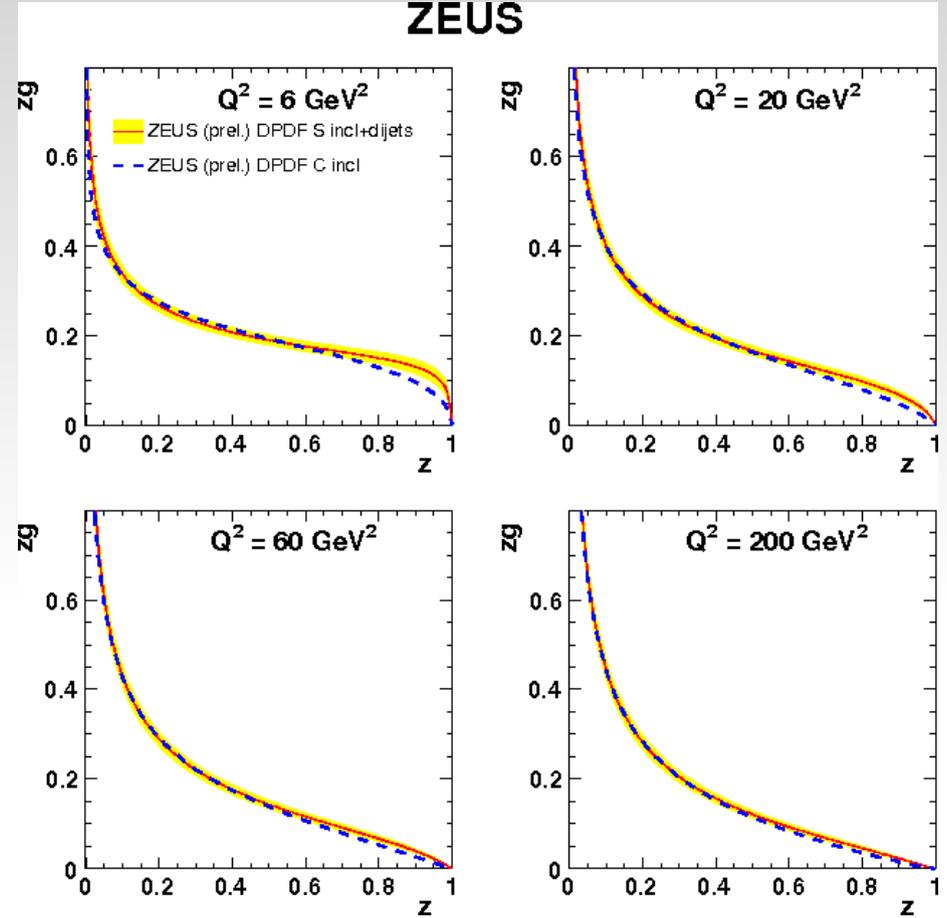
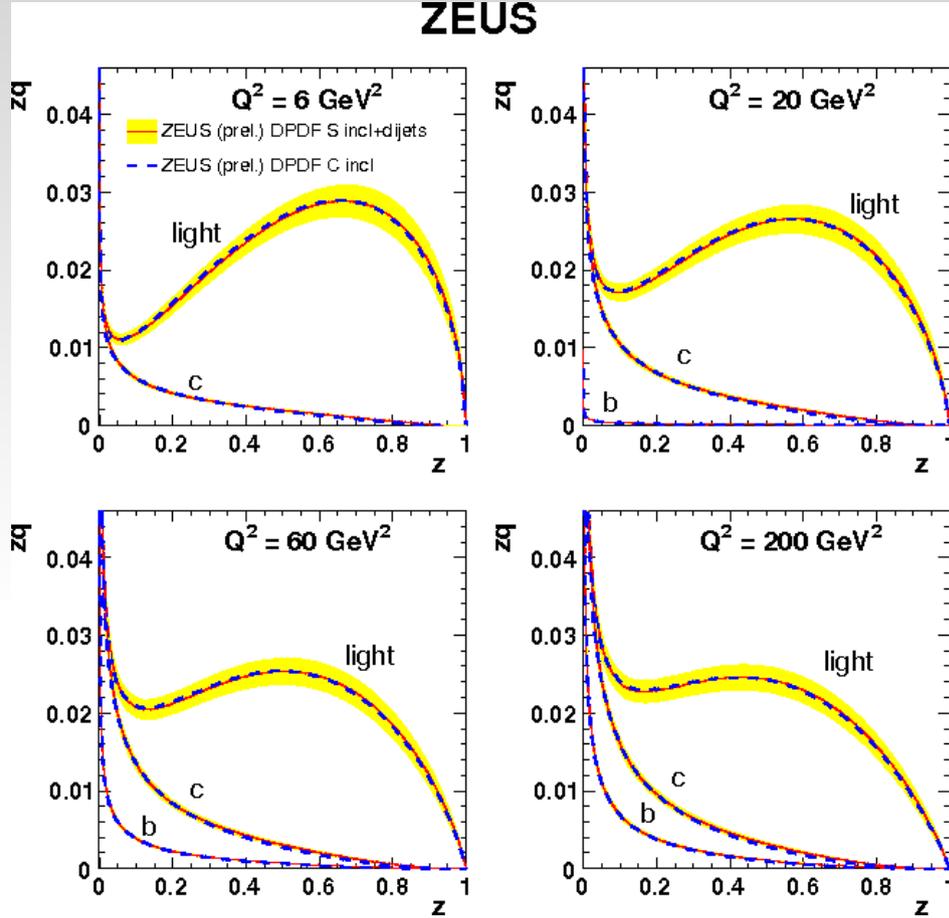


Data with  $Q^2 > 5 \text{ GeV}^2$  fitted within the combined framework of DGLAP evolution and proton-vertex factorisation. TR-VFNS treatment of heavy quarks.

Inclusive data constrain the quark PDFs,

Diffractive di-jet data (BGF) constrain the gluon PDFs and the diffractive exchange

# Diffractive NLO QCD fit and dPDFs



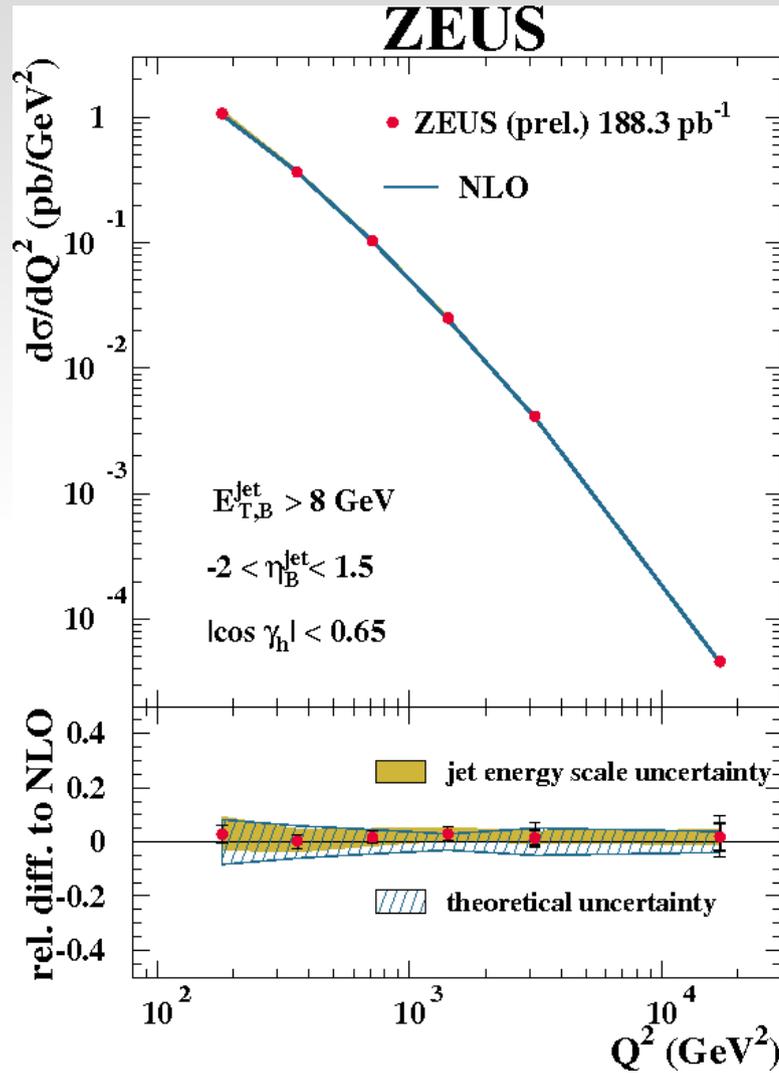
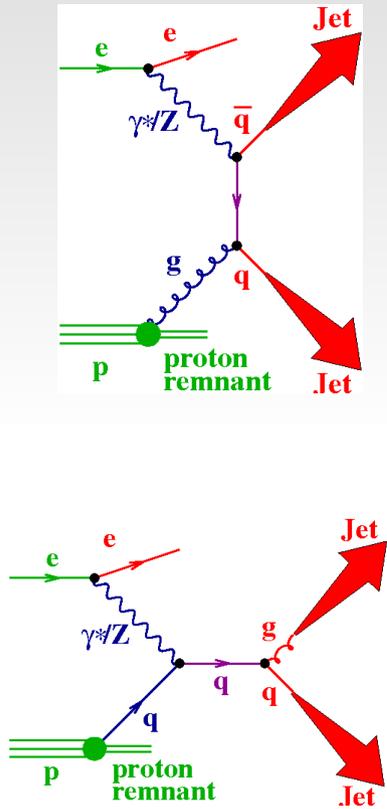
Predictions based on extracted dPDFs satisfactory describe:

- diffractive charm production
- diffractive di-jet photoproduction cross sections

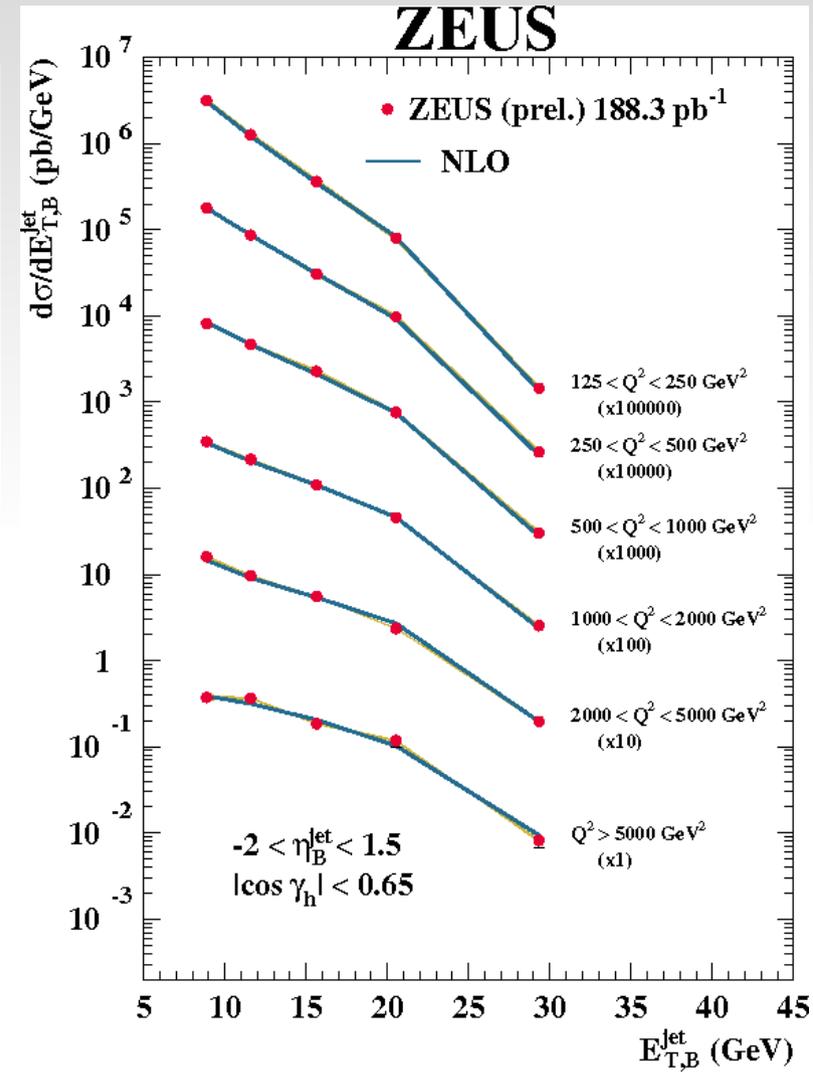
# Jet production in NC DIS

HERA II  $e^-p$  data ( $L=188 \text{ pb}^{-1}$ )

Breit frame

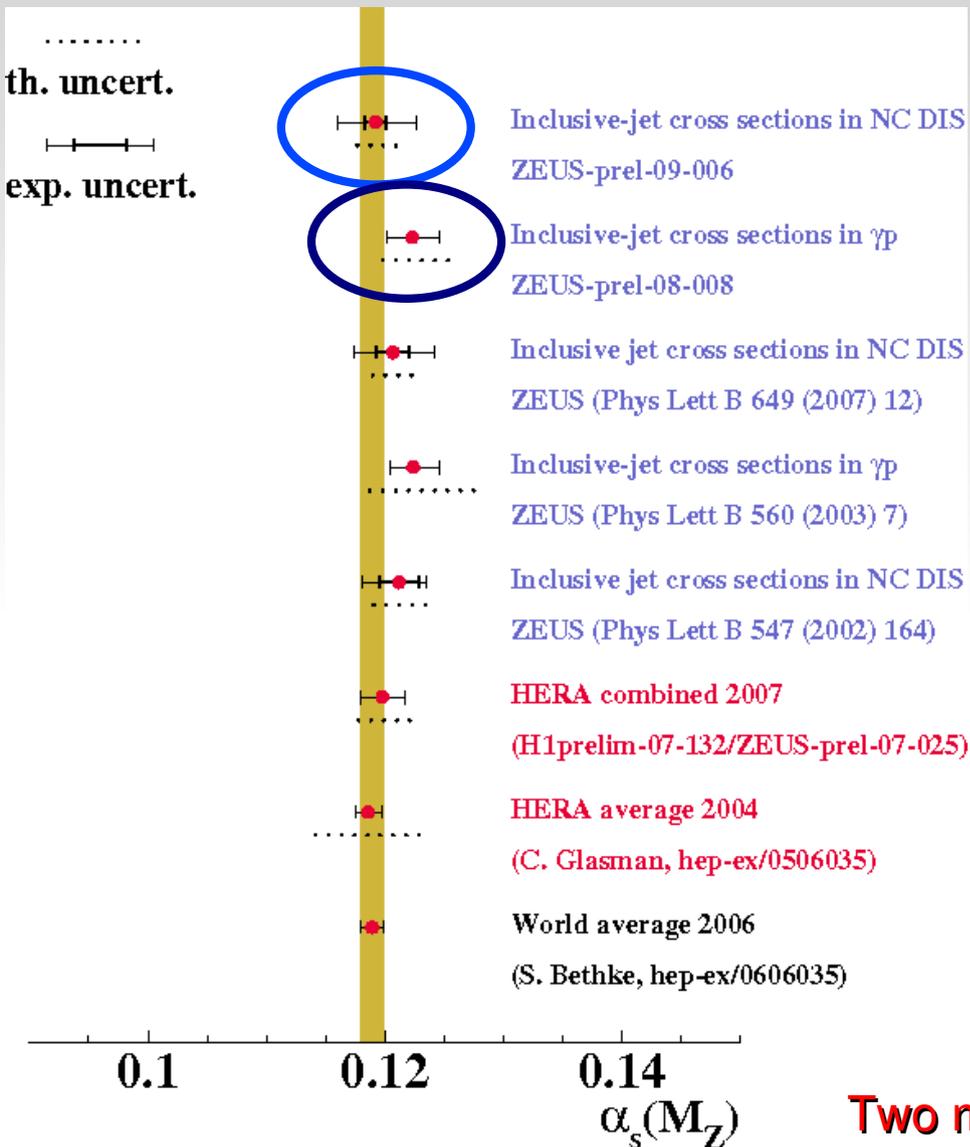


Measurement of  $\alpha_s(M_z)$



Input to PDFs

# New measurements of $\alpha_s(M_Z)$



HERA II NC DIS inclusive jets:

$$\alpha_s(M_Z) = 0.1192 \pm 0.0009 \text{ (stat.)}_{-0.0032}^{+0.0035} \text{ (exp.)}_{-0.0021}^{+0.0020} \text{ (th.)}$$

3.5% (total)

First measurement from ZEUS HERAII data

Re-analysis of HERA I inclusive jets PhP  
(reduced theoretical unc., the same data):

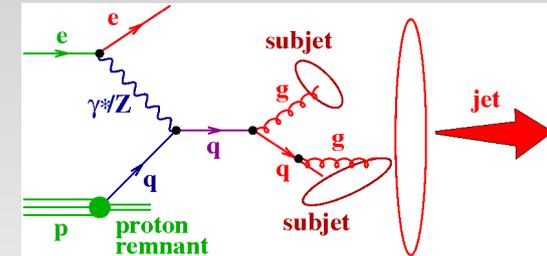
$$\alpha_s(M_Z) = 0.1223 \pm 0.0001 \text{ (stat.)}_{-0.0021}^{+0.0023} \text{ (exp.)}_{-0.0030}^{+0.0029} \text{ (th.)}$$

3.1% (total)

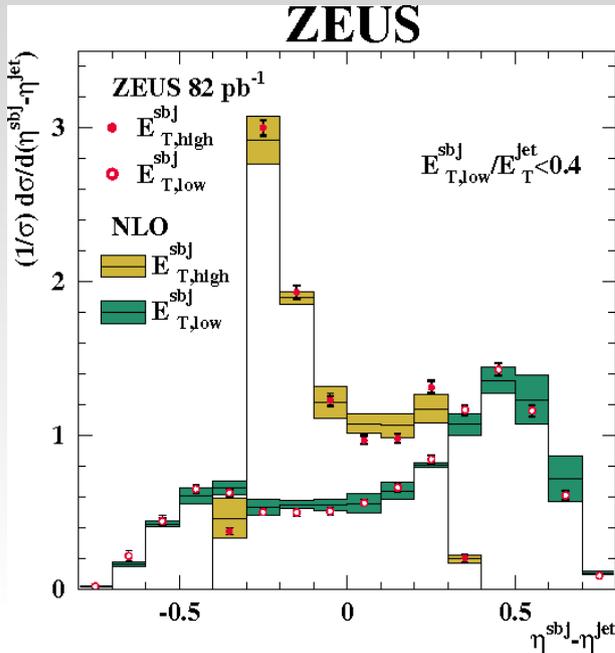
Two most precise single ZEUS measurements of  $\alpha_s(M_Z)$ .

NNLO calculations needed.

# Subjets in NC DIS



Subjets: - pattern of parton radiation  
- colour coherence



Two resolved subjets ( $y_{cut}=0.05$ )  $L= 82 \text{ pb}^{-1}$

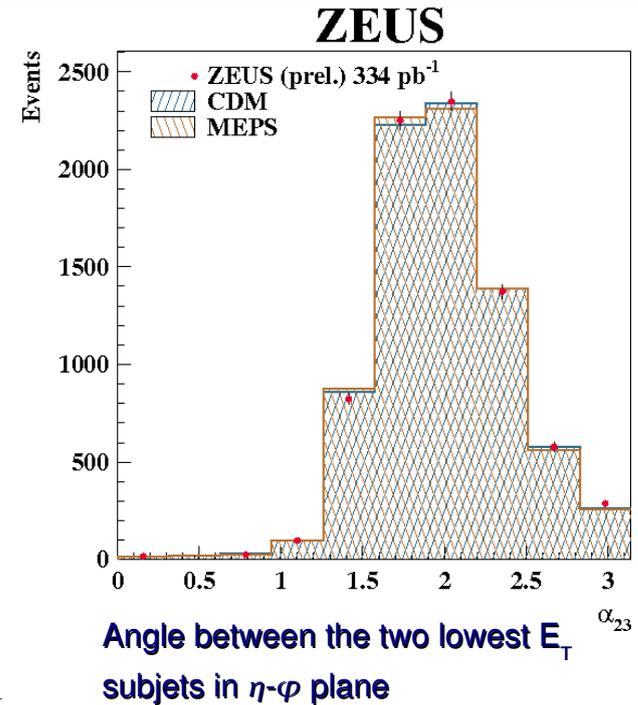
Predictions:

- soft gluon radiation to be emitted towards proton direction
- subjet with lower  $E_T$  emitted predominantly towards proton direction

Three resolved subjets ( $y_{cut}=0.03$ )  $L= 344 \text{ pb}^{-1}$

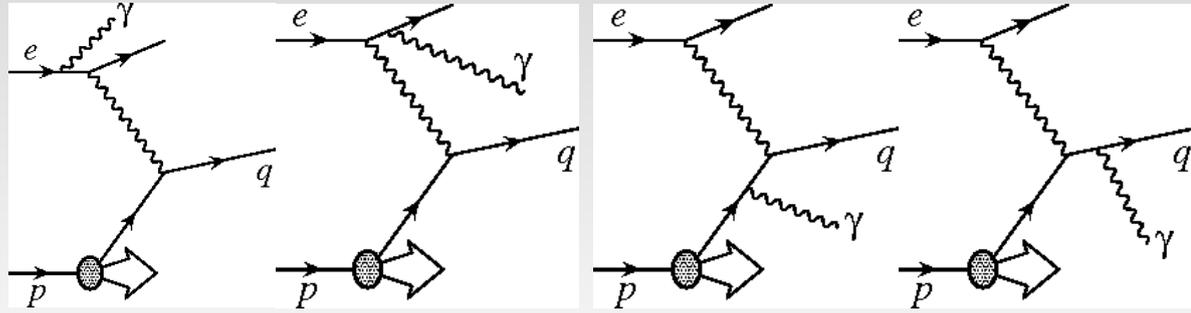
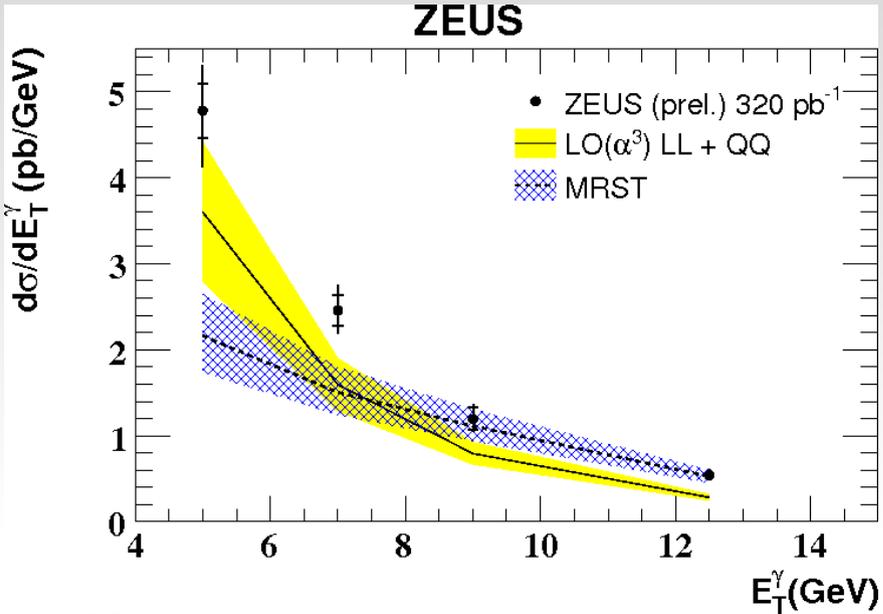
- gives a handle on underlying colour dynamics
- angular correlations are sensitive to different colour configurations.

NLO QCD describes the data adequately.



# Isolated and Prompt Photons in DIS

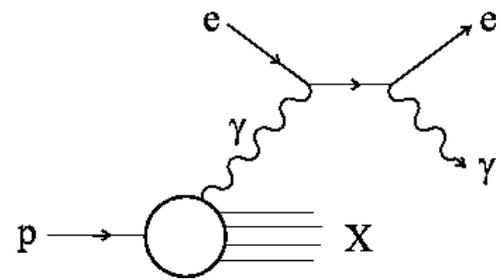
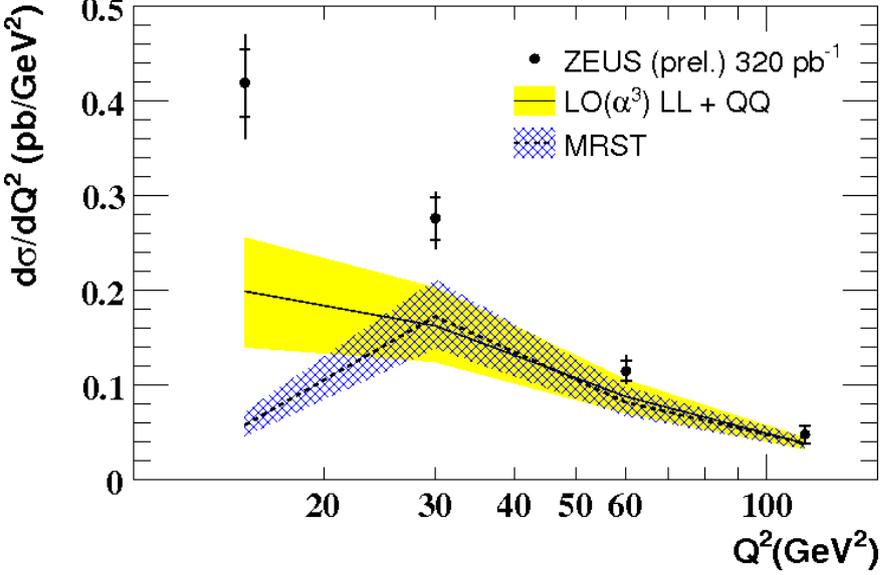
HERA II data ( $L=320 \text{ pb}^{-1}$ ),  $10 < Q^2 < 350 \text{ GeV}^2$ ,  $4 < E_T < 15 \text{ GeV}$ ,  $-0.7 < \eta < 0.9$



LL

QQ

+ photons from quark hadronisation

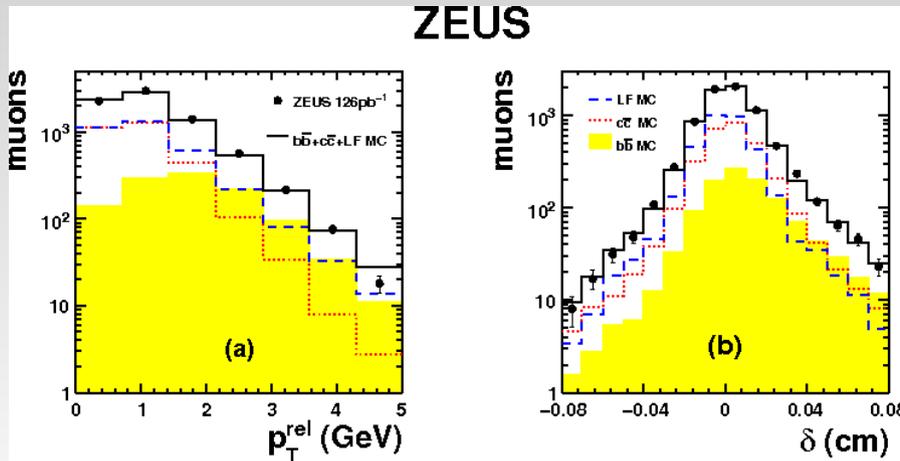
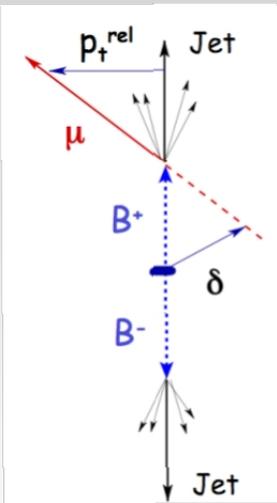


MRST  $\gamma^p \times \sigma(e\gamma \rightarrow e\gamma)$   
 LL enhanced

NLO calculations needed

# Beauty in photoproduction

DESY-08-210



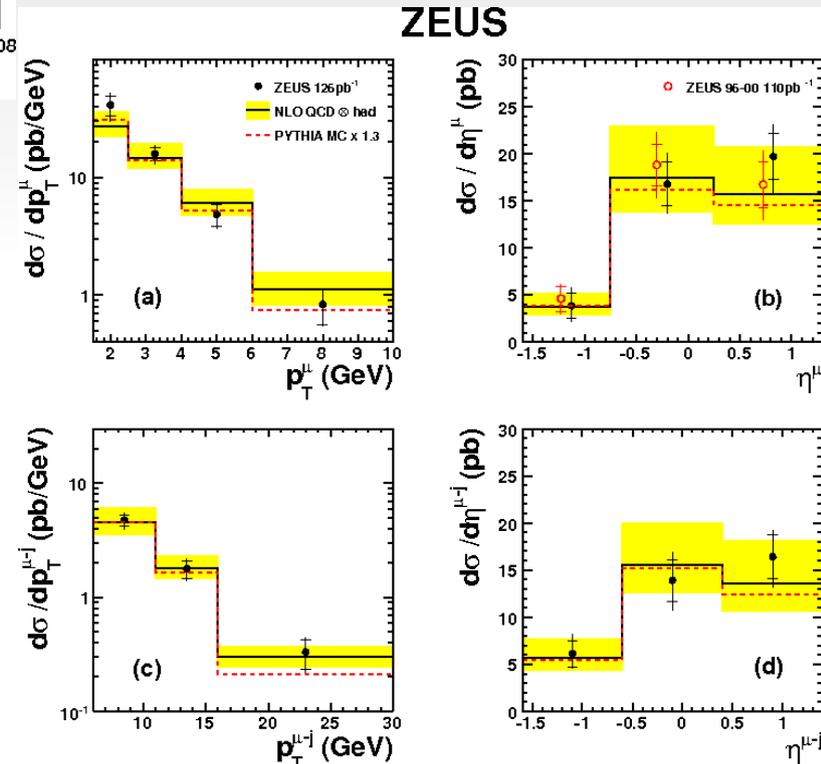
HERA II data, 2005  $e^+p$  ( $L=125 \text{ pb}^{-1}$ )

Look for  $b$  in events with two jets (Kt clust.):

$N_{\text{jet}} \geq 2$ ,  $P_{\text{t}} > 7(6) \text{ GeV}$ ,  $|\eta| < 2.5$

with high- $p_{\text{T}}$  muon

Simultaneous fits to  $p_{\text{T}}^{\text{rel}}$  and impact parameter  $\delta$

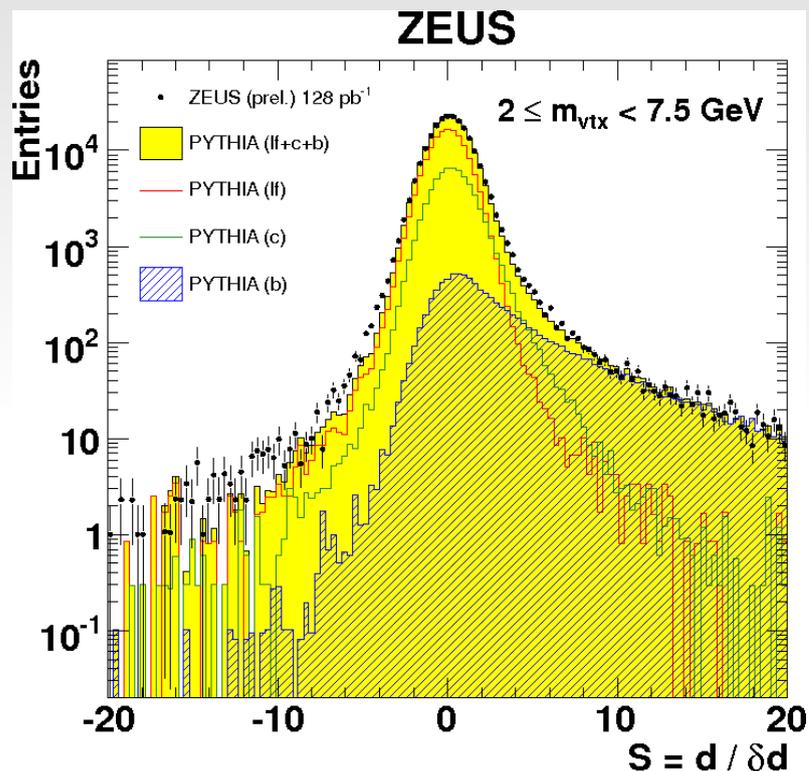


In agreement with previous ZEUS meas. (HERA I with  $p_{\text{T}}^{\text{rel}}$  method and  $c$  fraction from external ZEUS measurement). Good agreement with NLO QCD (FMNR)

# Beauty in photoproduction

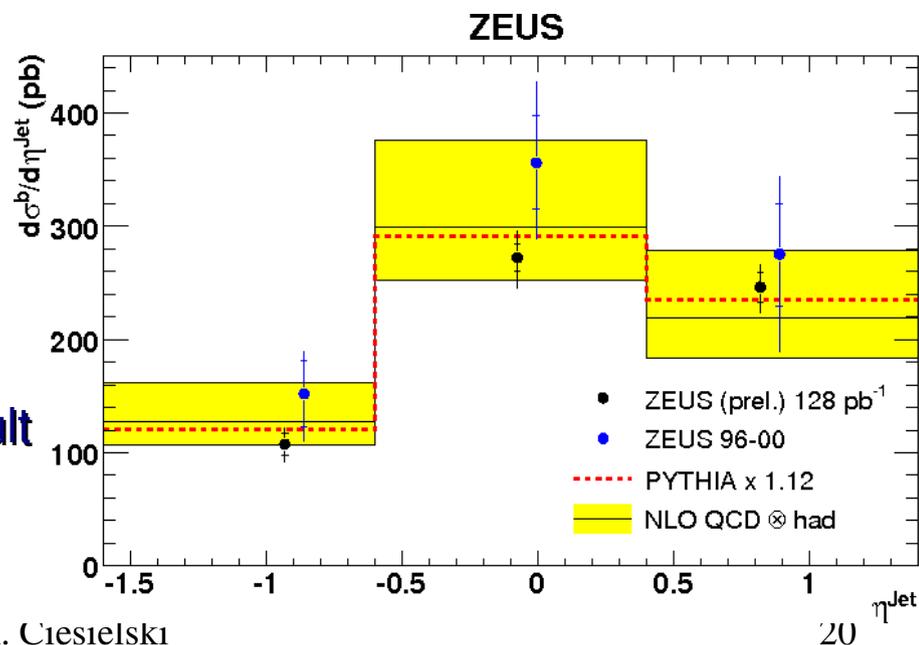
HERA II data, 2006/07  $e^+p$  ( $L=128 \text{ pb}^{-1}$ )

First ZEUS inclusive di-jet measurement with secondary vertexing.



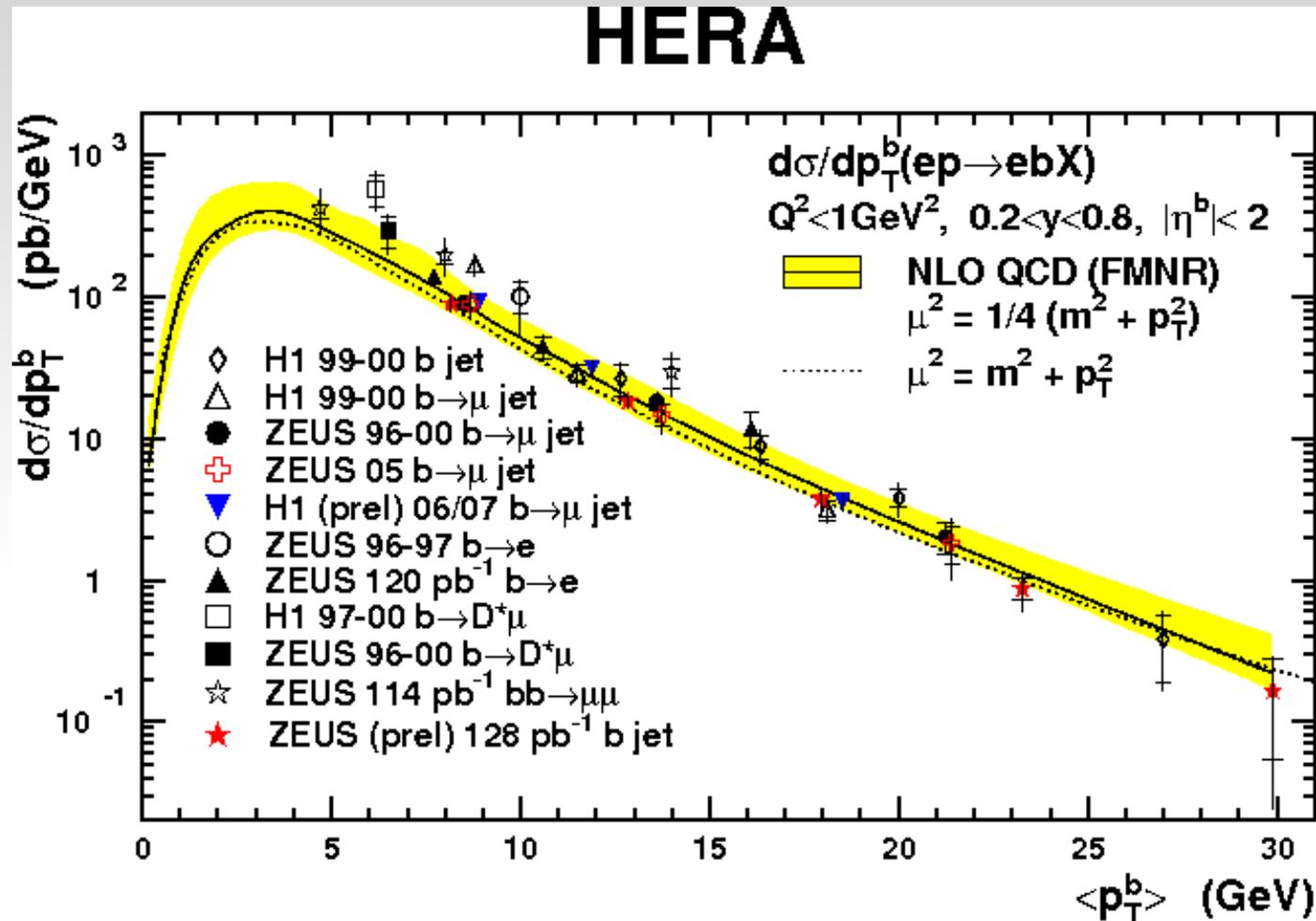
Fraction of b extracted from decay length significance, after reconstructing the decay vertices of B hadrons

Invariant mass at the reconstructed vertices (m<sub>vtx</sub>) used to distinguish beauty-enriched regions



Greatly improved precision compared to HERA I result  
In agreement with NLO QCD (FMNR)

# Beauty in photoproduction



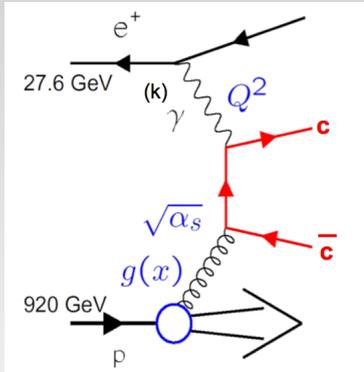
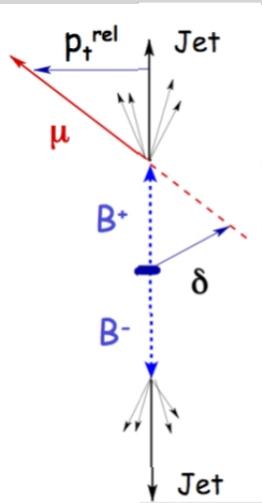
Newest ZEUS results in red.

Good overall agreement of ZEUS and H1 data with NLO QCD (FMNR).

More precise theory would be useful.

# Semileptonic charm and beauty in DIS

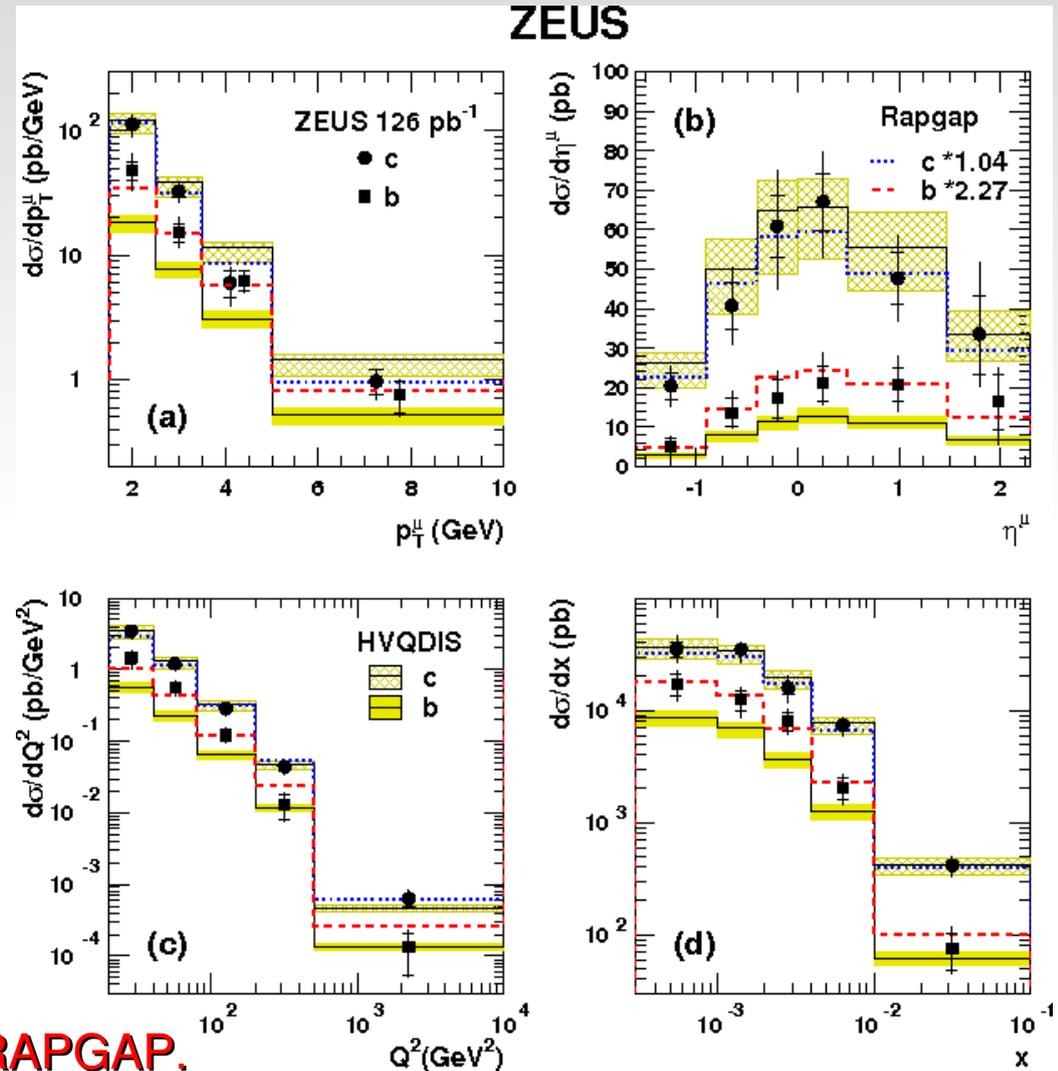
DESY-09-056



HERA II data, 2005 e-p ( $L=126 \text{ pb}^{-1}$ )  
 Di-jets with muons  
 $Q^2 > 20 \text{ GeV}^2$ ,  $0.01 < y < 0.7$   
 $p_T^\mu > 1.5 \text{ GeV}$ ,  $-1.6 < \eta^\mu < 2.3$

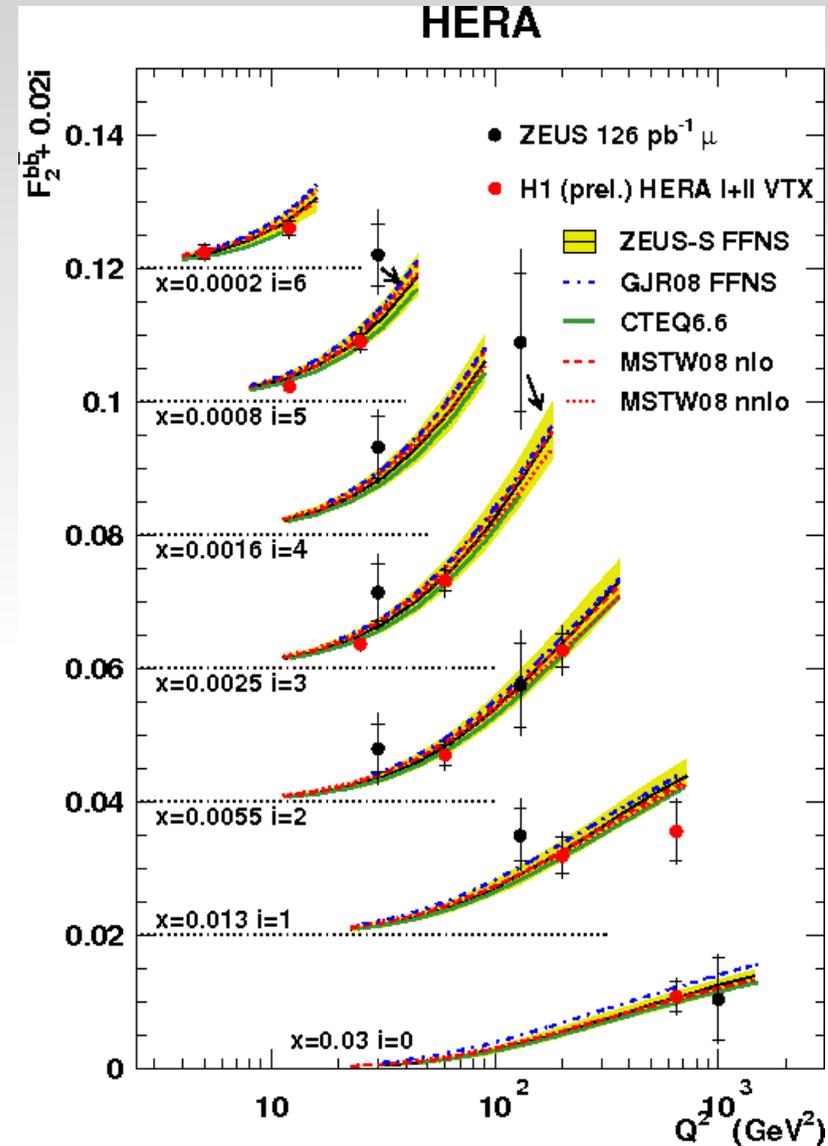
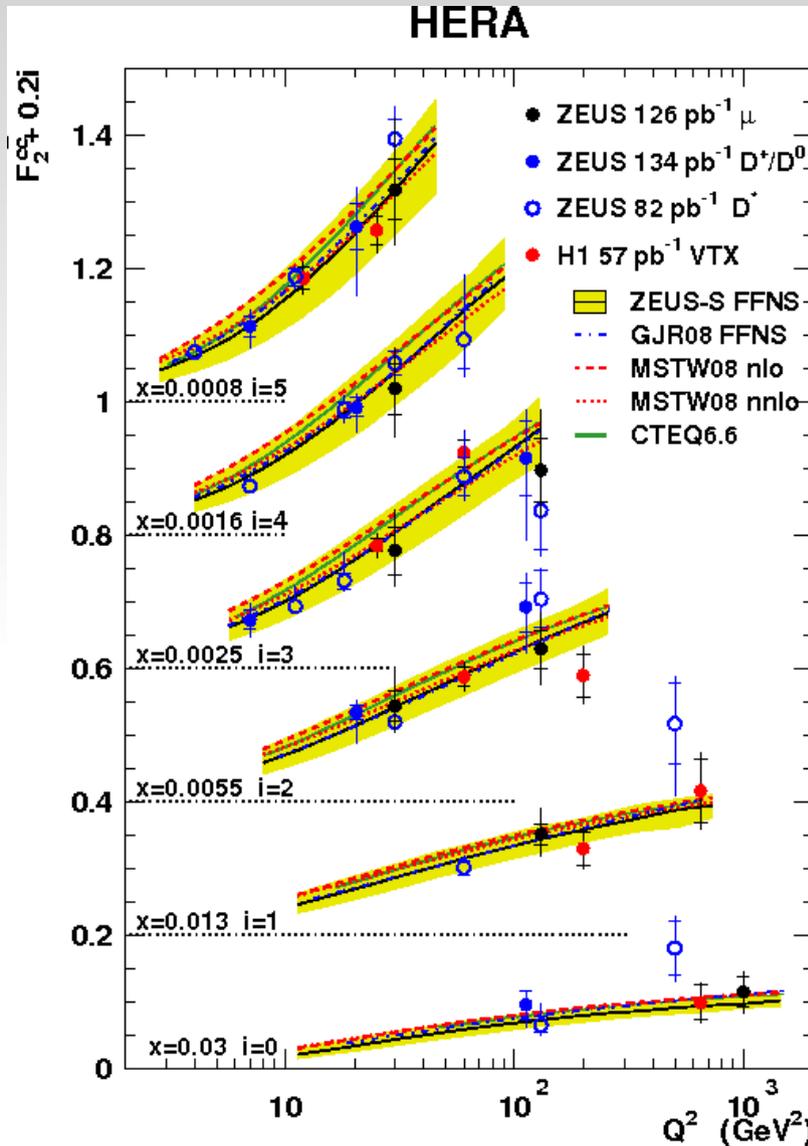
The c and b fractions extracted simultaneously using  $p_T^{\text{rel}}$ , impact parameter  $\delta$  and  $p_T^{\text{miss}||\mu}$  ( $p_T$  balance from neutrinos)

Charm: good agreement with HVQDIS and RAPGAP.  
 Beauty: good agreement in shape, HVQDIS predictions scaled by a factor of 2.



# F2cc and F2bb

DESY-09-056



Good agreement between ZEUS and H1 measurements.  
Results well described by theory.

# Limits on Quark Radius

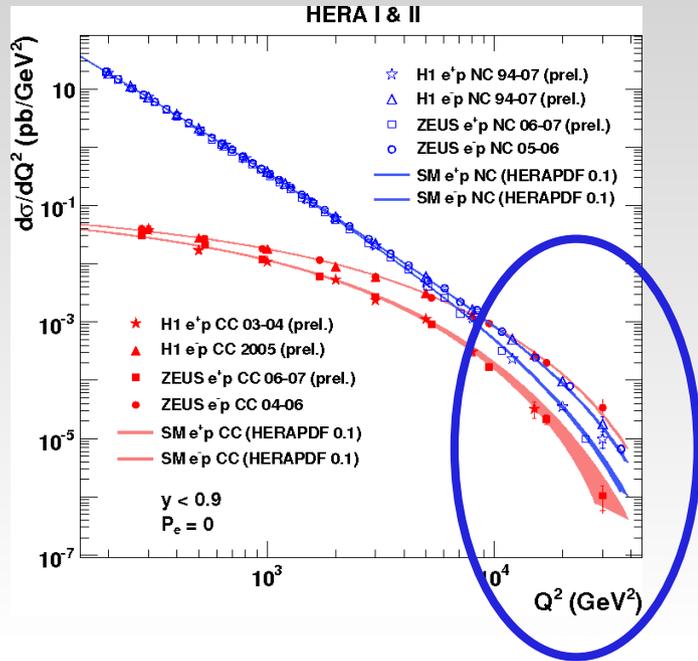
Search for new physics by looking for deviations from SM NC cross sections at highest  $Q^2$ .

Recently added data:

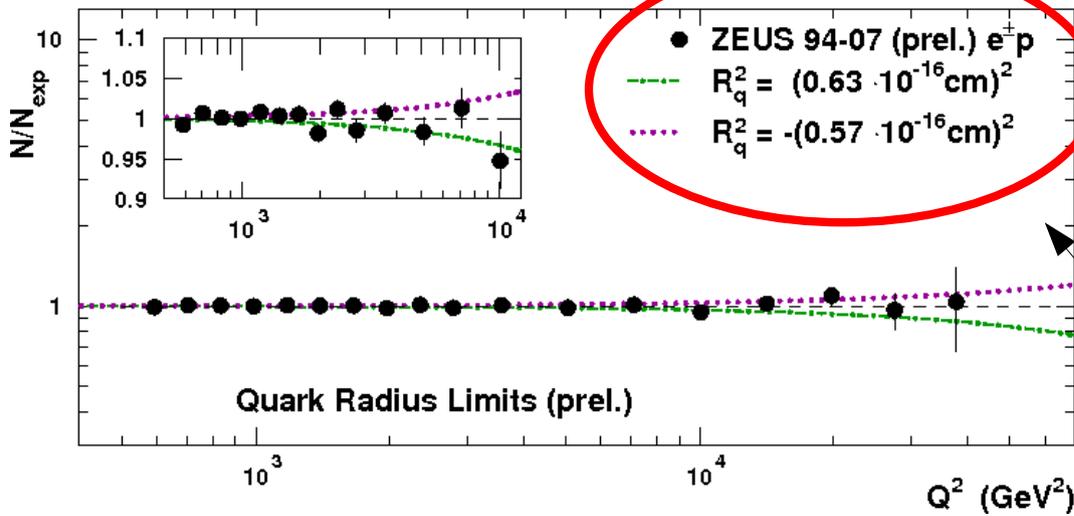
2004/06  $e^-p$  prelim.  $\rightarrow$  pub.

2006/07  $e^+p$  prelim.

Full HERA I + HERA II dataset ( $L=0.44 \text{ fb}^{-1}$ )



ZEUS



Quark form factor:

If a quark has a finite size, the SM cross section is expected to decrease at high  $Q^2$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left[ 1 - \frac{R_q^2}{6} Q^2 \right]^2$$

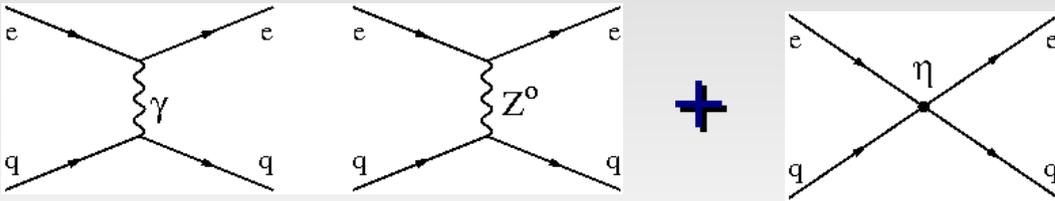
No deviations, limits set:

$$R_q^2 < 0.63 \times 10^{-3} \text{ fm} \quad (95\% \text{ C.L.})$$

We are probing down to 1/1000 proton radius.

# Limits on Contact Interactions

New physics at higher scale described at lower energy as 4-fermion Contact Interaction (CI).



$$M_{\alpha\beta}^{eq}(Q^2) = \frac{e^2 e_q^2}{Q^2} - \frac{e^2}{\sin^2 \theta_W \cos^2 \theta_W} \frac{g_\alpha^e g_\beta^q}{Q^2 + M_Z^2} + \eta_{\alpha\beta}^{eq}$$

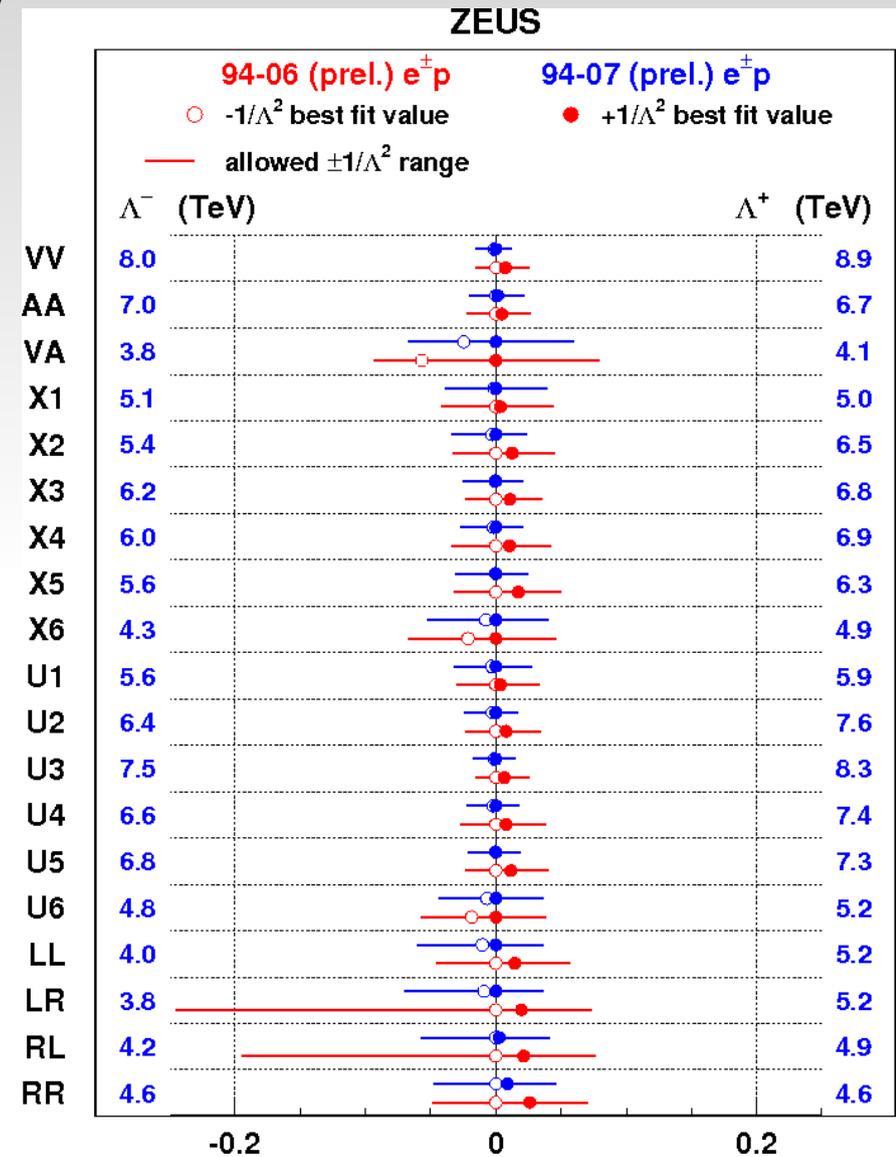
where  $\alpha$  and  $\beta$  are electron and quark helicities. Coupling  $\eta_{\alpha\beta}^{eq}$  are related to the “new physics” mass scale  $\Lambda$  by:

$$\eta_{\alpha\beta}^{eq} = \frac{\epsilon g_{CI}^2}{\Lambda^2} \quad \epsilon = \pm 1, g_{CI}^2 = 4\pi$$

Models with different chiral structure considered,

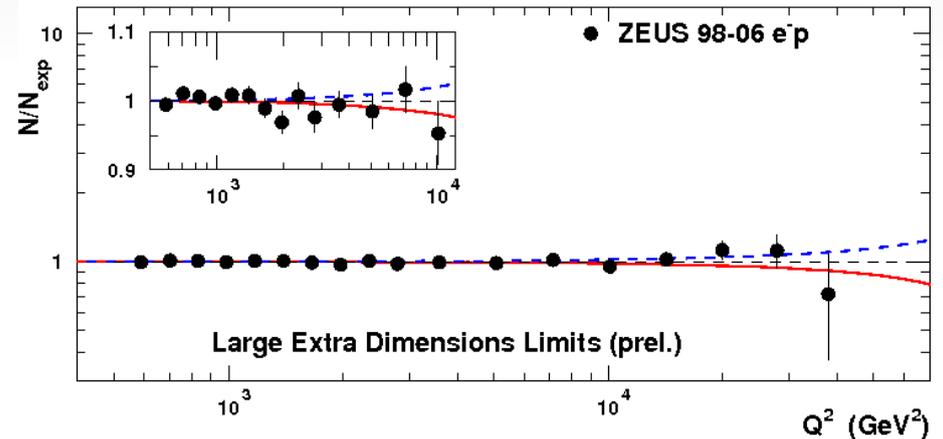
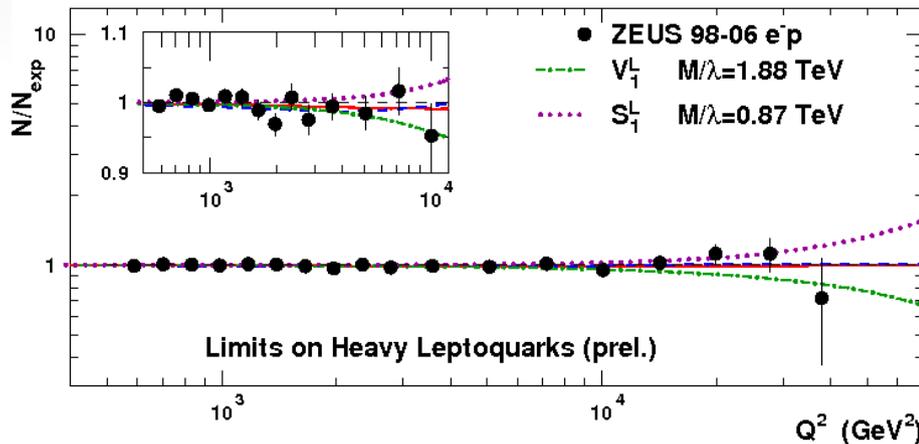
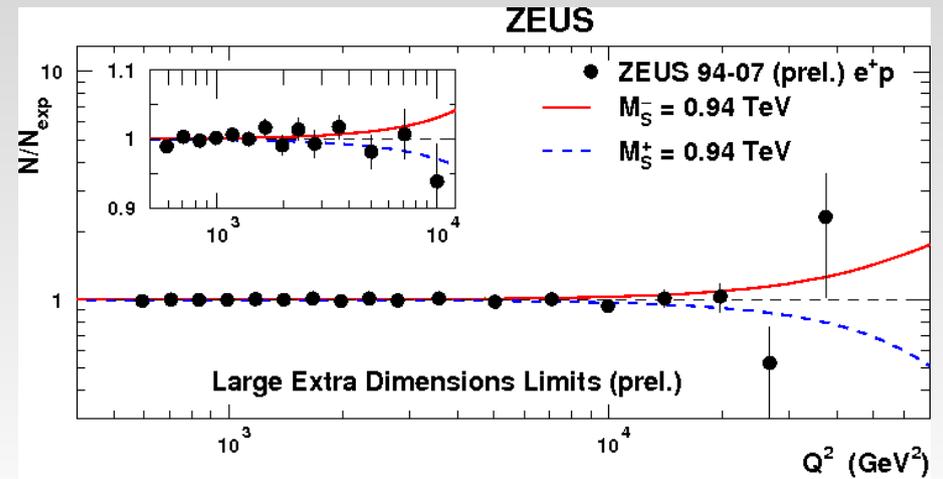
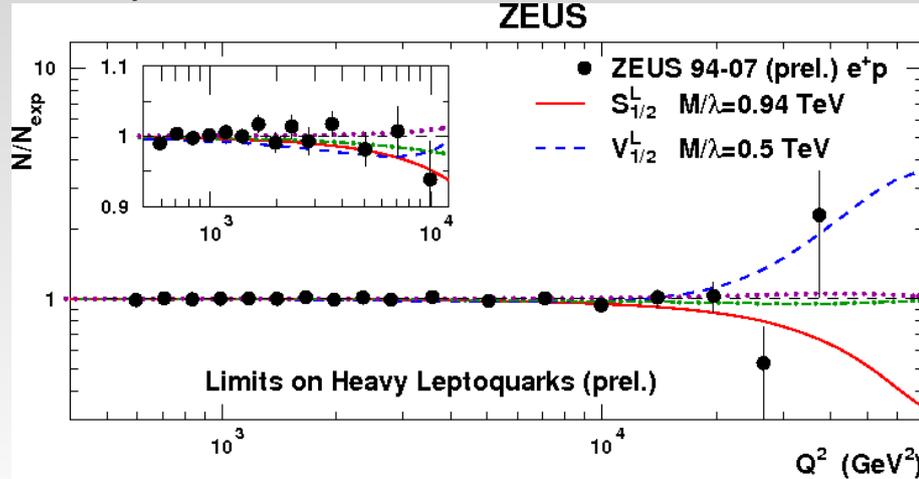
eg.  $VV = \eta_{LL}^{eq} + \eta_{LR}^{eq} + \eta_{RL}^{eq} + \eta_{RR}^{eq}$

Limits on CI:  $\Lambda > 3.8 \text{ to } 8.9 \text{ TeV}$  (95% C.L.)



# Limits on Contact Interactions

## Interpretation of CI in other models



### Limits on Heavy Leptoquarks:

$$M_{LQ}/\lambda > 0.41 \text{ to } 1.88 \text{ TeV}$$

$M_{LQ}$  - LQ mass,  $\lambda$  - Yukawa LQ-e-q coupling

### Limits on Large Extra Dimensions (LED)

$$M_S > 0.9 \text{ TeV}$$

$M_S$  - effective mass scale of graviton exchange

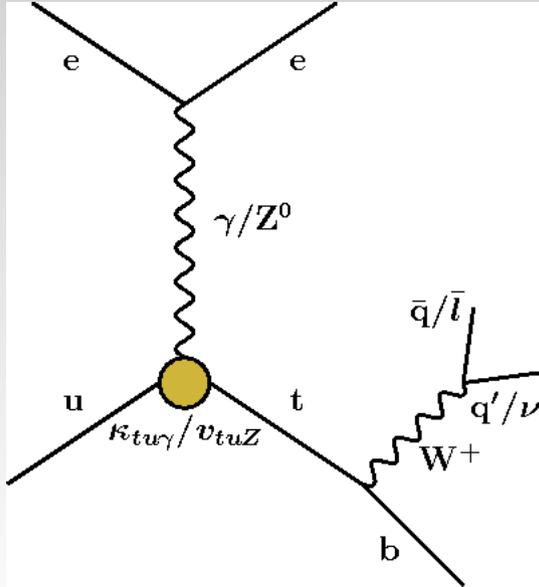
# Summary

- **Inclusive measurements and Proton Structure**
  - Progress in the combination of H1+ZEUS results
  - First FL measurement at ZEUS completed
  - Huge effort to complete the high- $Q^2$  measurements
- **Exclusive processes and QCD**
  - New precise results on jets and heavy quarks
  - Need better theory here
- **Productive year for ZEUS**
  - 18 papers in 2008
  - In 2009: 6 published, 3 in reading, ~5 in advanced stage
- **More results to come**



paper in reading, ~2 in advanced stage

# Limit on FCNC single-top production



SM single-top production negligible at HERA.

FCNC single-top production topology similar to SM W production:  
isolated lepton ( $p^\mu > 8 \text{ GeV}$ ,  $p^e > 10 \text{ GeV}$ ) +  
missing  $p_T$  ( $> 10 \text{ GeV}$ ,  $> 15 \text{ GeV}$ ) +

$p_T^{\text{had}} > 40 \text{ GeV}$

HERAII ( $L=276 \text{ pb}^{-1}$ )

Single Top Selection

	$N_{\text{obs}}$	$N_{\text{pred}}$	$W\%$	Efficiency
Electron Channel 04-05 e-p	0	$2.1 \pm 0.6$	38	0.033
Muon Channel 04-05 e-p	1	$1.5 \pm 0.4$	47	0.026
Electron Channel 06-07 e+p	0	$0.9 \pm 0.3$	78	0.033
Muon Channel 06-07 e+p	1	$1.4 \pm 0.4$	50	0.026

$(V_{\text{tuZ}} = 0)$

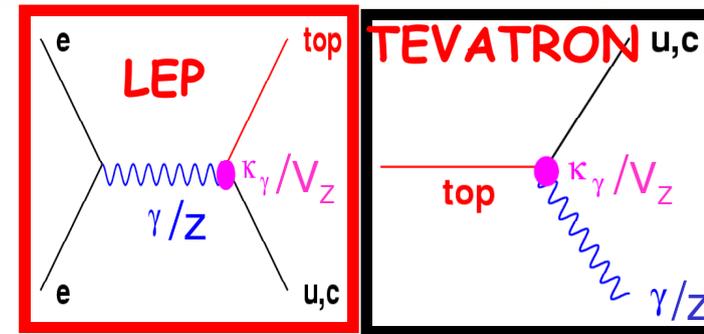
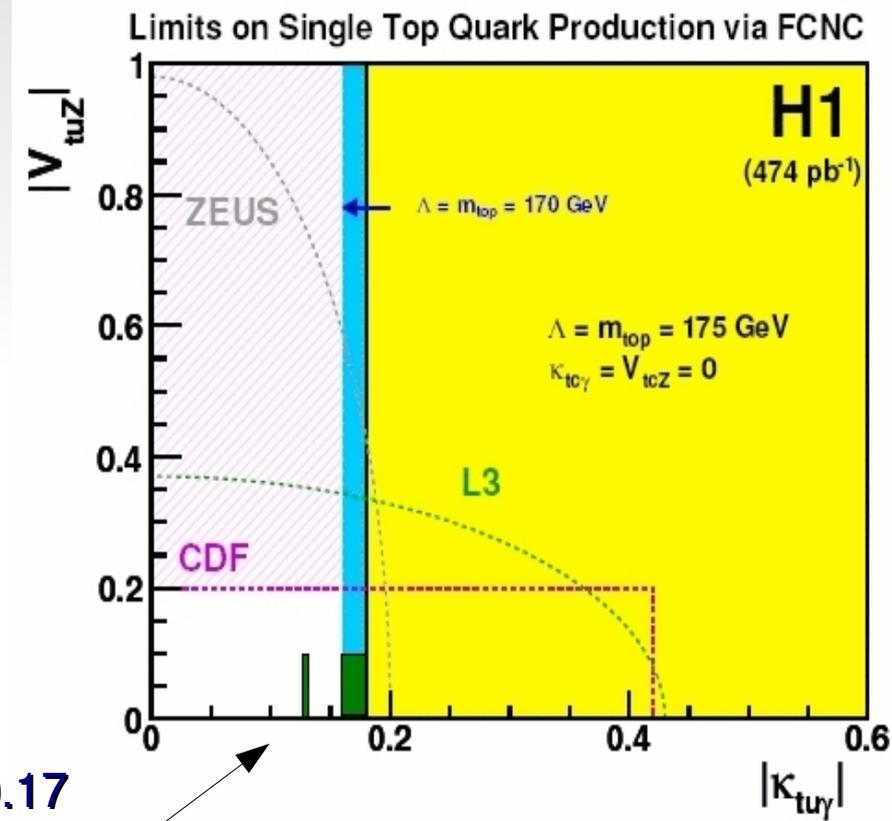
ZEUS HERAII (prel.) :  $\sigma < 0.23 \text{ pb}$  (95% C.L.),  $k_{\text{tug}} < 0.17$

ZEUS HERAI+HERAII:  $\sigma < 0.13 \text{ pb}$  (95% C.L.),  $k_{\text{tug}} < 0.13$

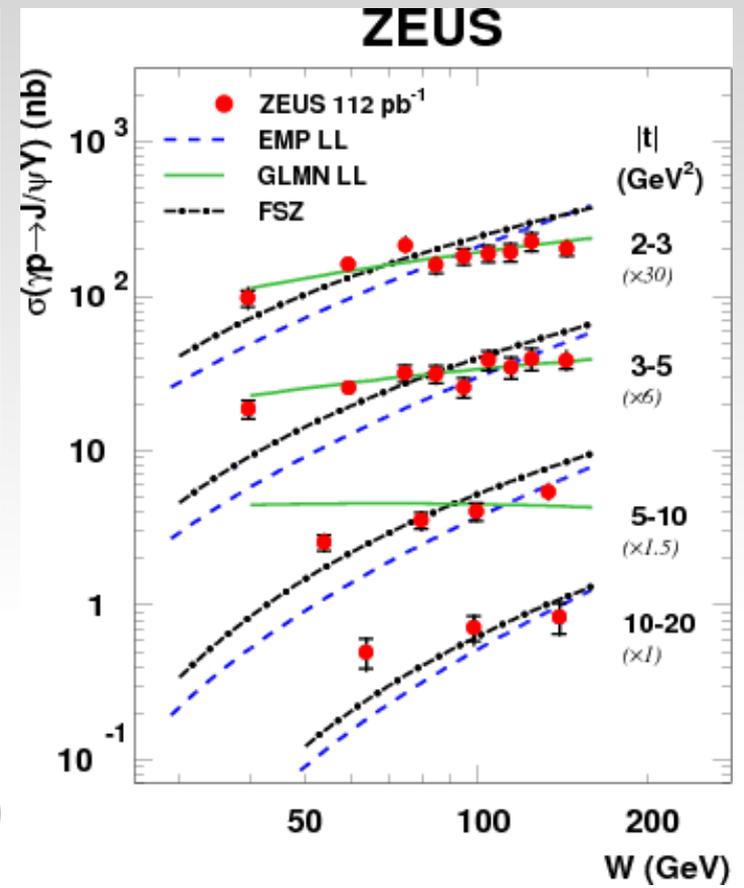
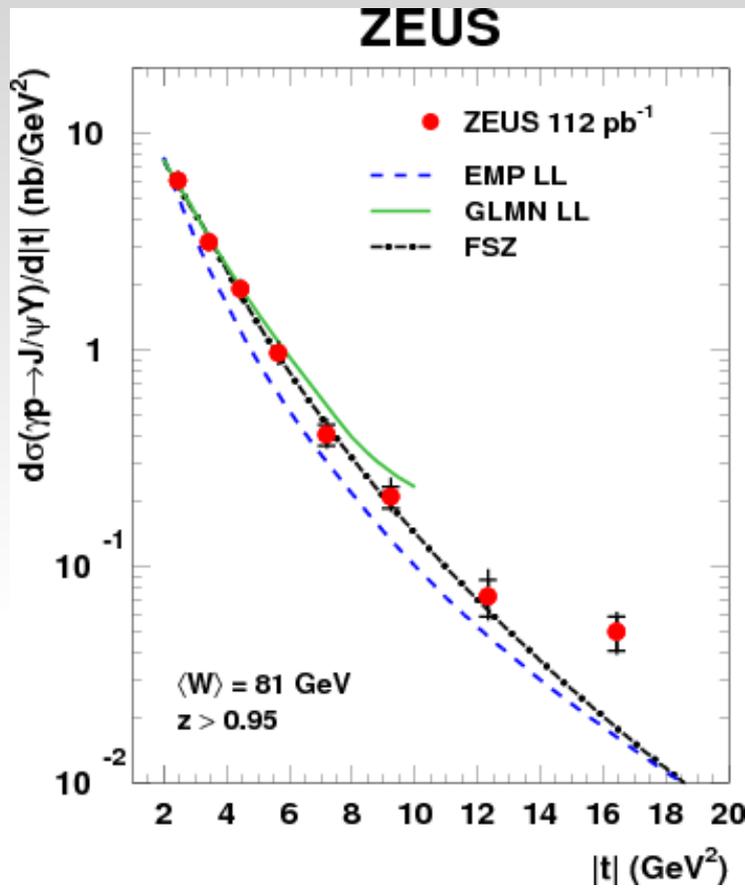
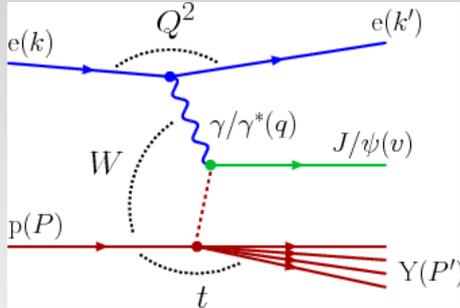
HERA limits on  $k_{\text{tug}}$  more stringent than Tevatron and LEP

07/07/2009

Recent ZEUS results R. Ciesielski



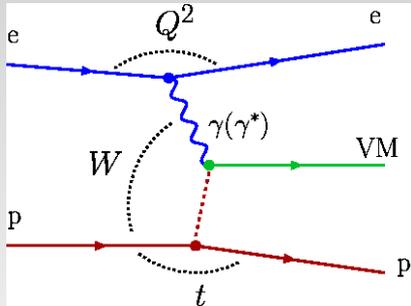
# High- $t$ $J/\Psi$ photoproduction



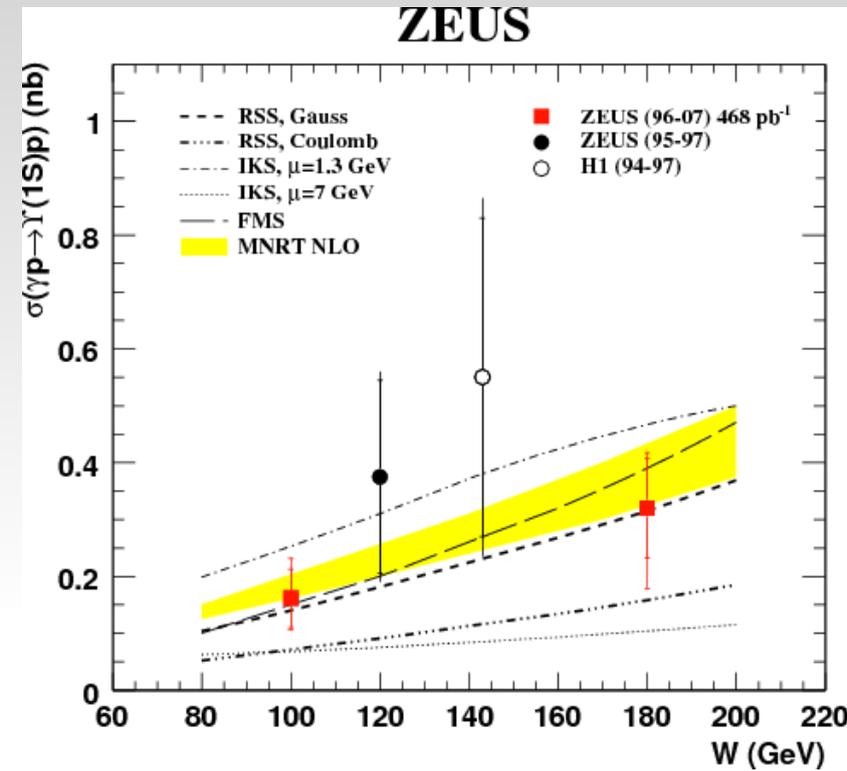
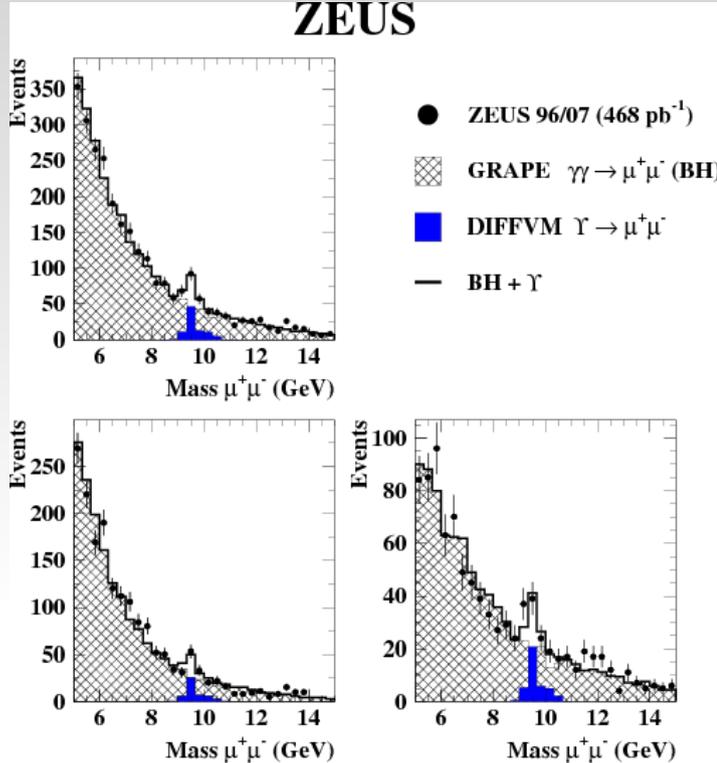
Measurement up to  $|t| < 20 \text{ GeV}^2$

Compared to pQCD models based on DGLAP (GLMN) and BFKL (EMP) dynamics.  
 Non of the models fully describe the  $|t|$  and  $W$  dependence of the cross section.

# Upsilon photoproduction



DESY-09-036



Measurement based on full HERAII statistics.  
 Signal observed and cross section measured in two bins of  $W$ .  
 Satisfactory agreement with pQCD based theoretical models.

# NLO QCD fit to combined HERA I data



HERAPDF0.2

