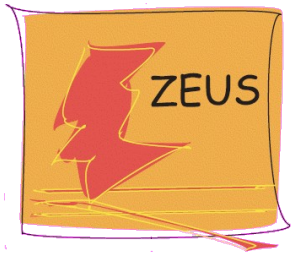
Electroweak Physics at HERA

Gerhard Brandt

On behalf of the H1 and ZEUS Collaborations



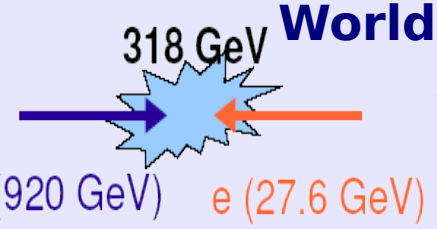
CIPANP 2009: Tenth Conference on the Intersections of Particle and Nuclear Physics

Torrey Pines Hilton—San Diego, California—26 May to 31 May, 2009

Collider and Experiments

HERA

HERA: $\sqrt{s}$



World's only *ep* Collider at DESY,Hamburg
Active 1991-2007
H1 and ZEUS Experiments

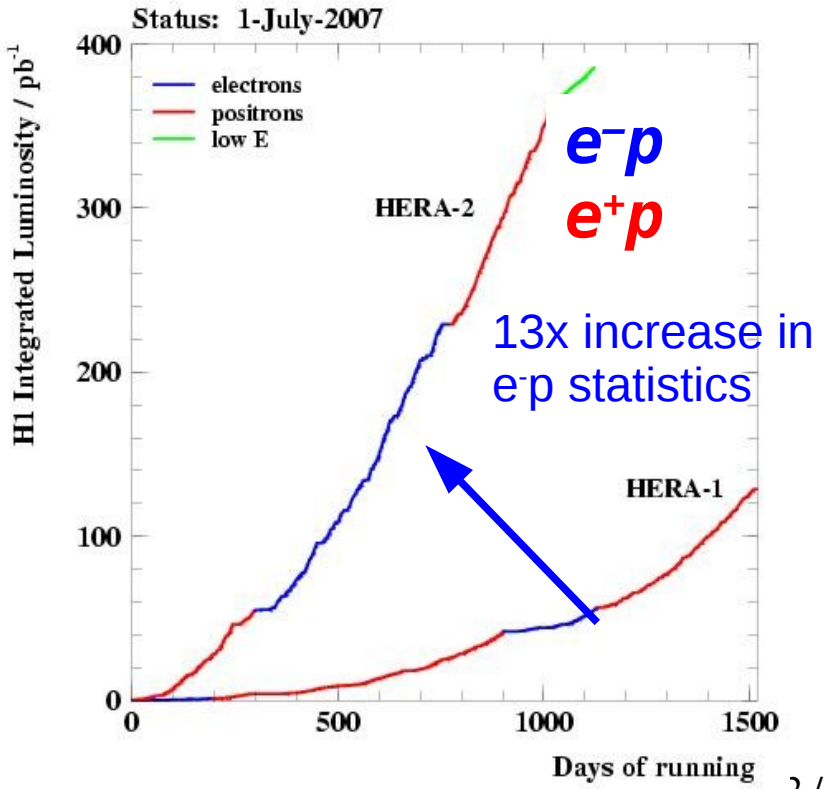
Asymmetric Desgin
4π Coverage
Excellent Lepton ID + HFS Reconstruction

HERA-I (1994-00)
~130 pb^{-1} per exp., (90% e^+p)

HERA-II (2003-07)
Luminosity upgrade
Longitudinal e polarisation (avg. 30%-40%)

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

~0.5 fb^{-1} per experiment



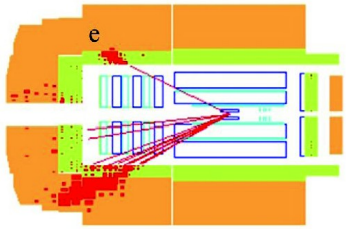
Overview of EW Physics Processes at HERA

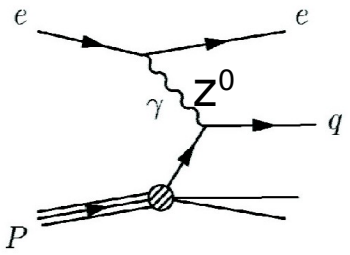
- Physics processes covered in this talk

Large cross section O(α)

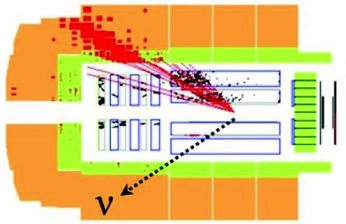
Small cross section O(α^2)

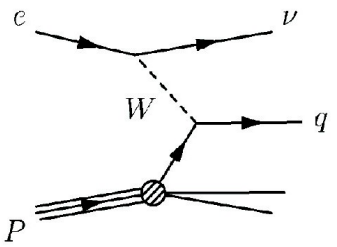
- Neutral Current DIS $ep \to eX$



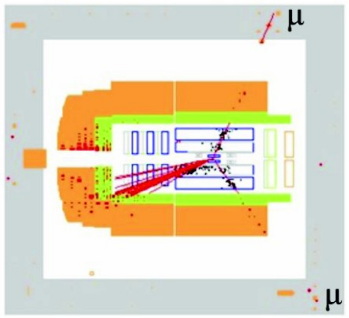


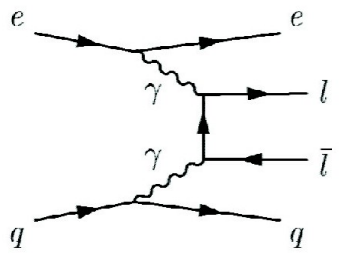
- Charged Current DIS $ep \to \nu X$



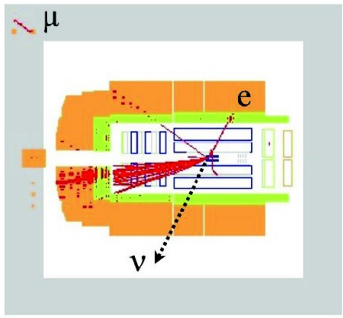


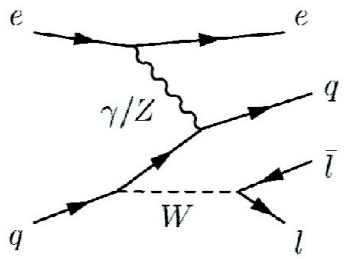
- Lepton pair production $ep \to ellX$





- W production $ep \to eWX$



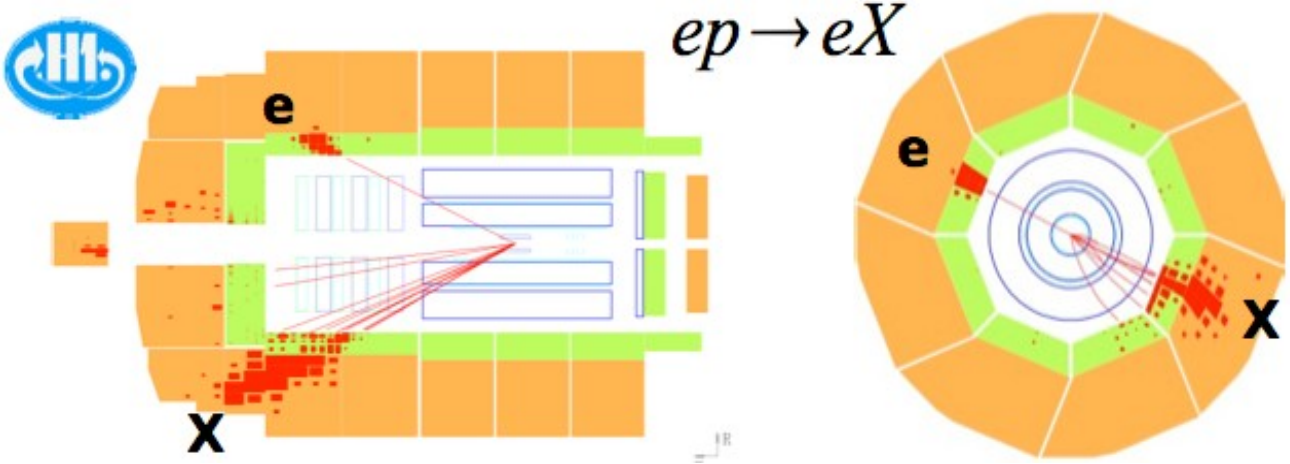


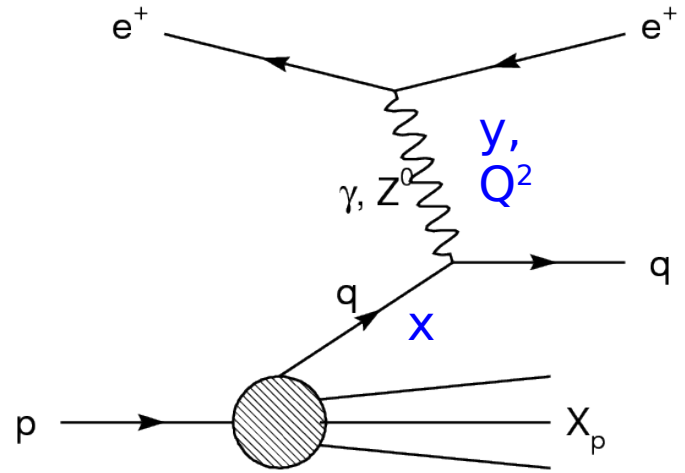
Deep Inelastic Scattering

Main Standard Model Process at HERA: Deep Inelastic Scattering

Neutral Current

$ep \to eX$

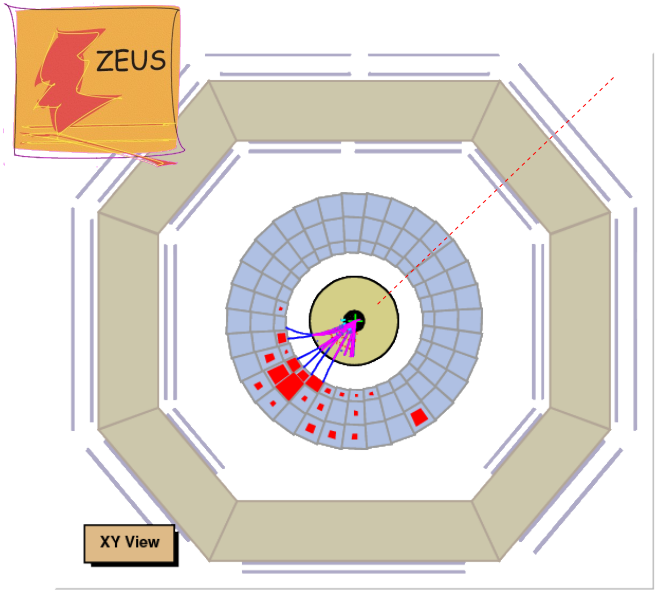


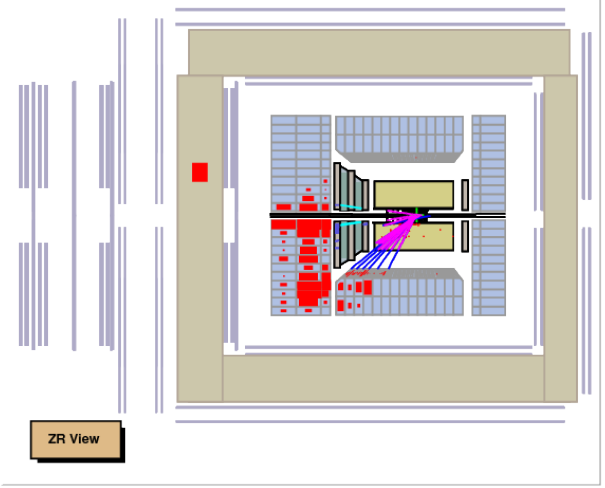


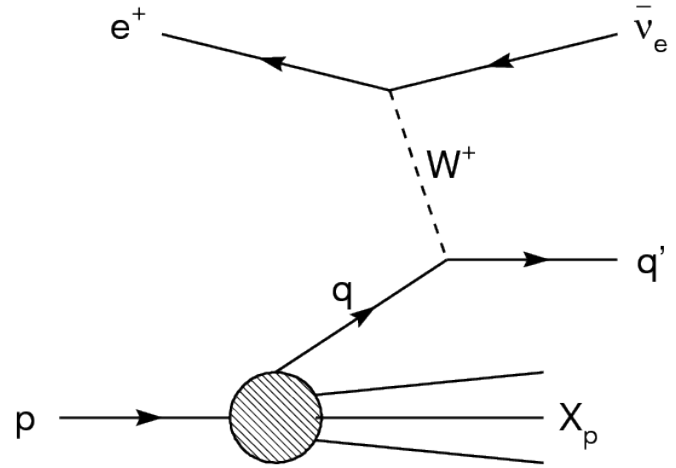
Q^2 – virtuality of exchange boson
x – Bjorken scaling variable
y – Inleasticity

Charged Current

$ep \to \nu X$







Unpolarised DIS Cross Sections

Unpolarised DIS cross sections measured using full HERA data

H1prelim06-041
ZEUS-prel-09-001

Neutral Current

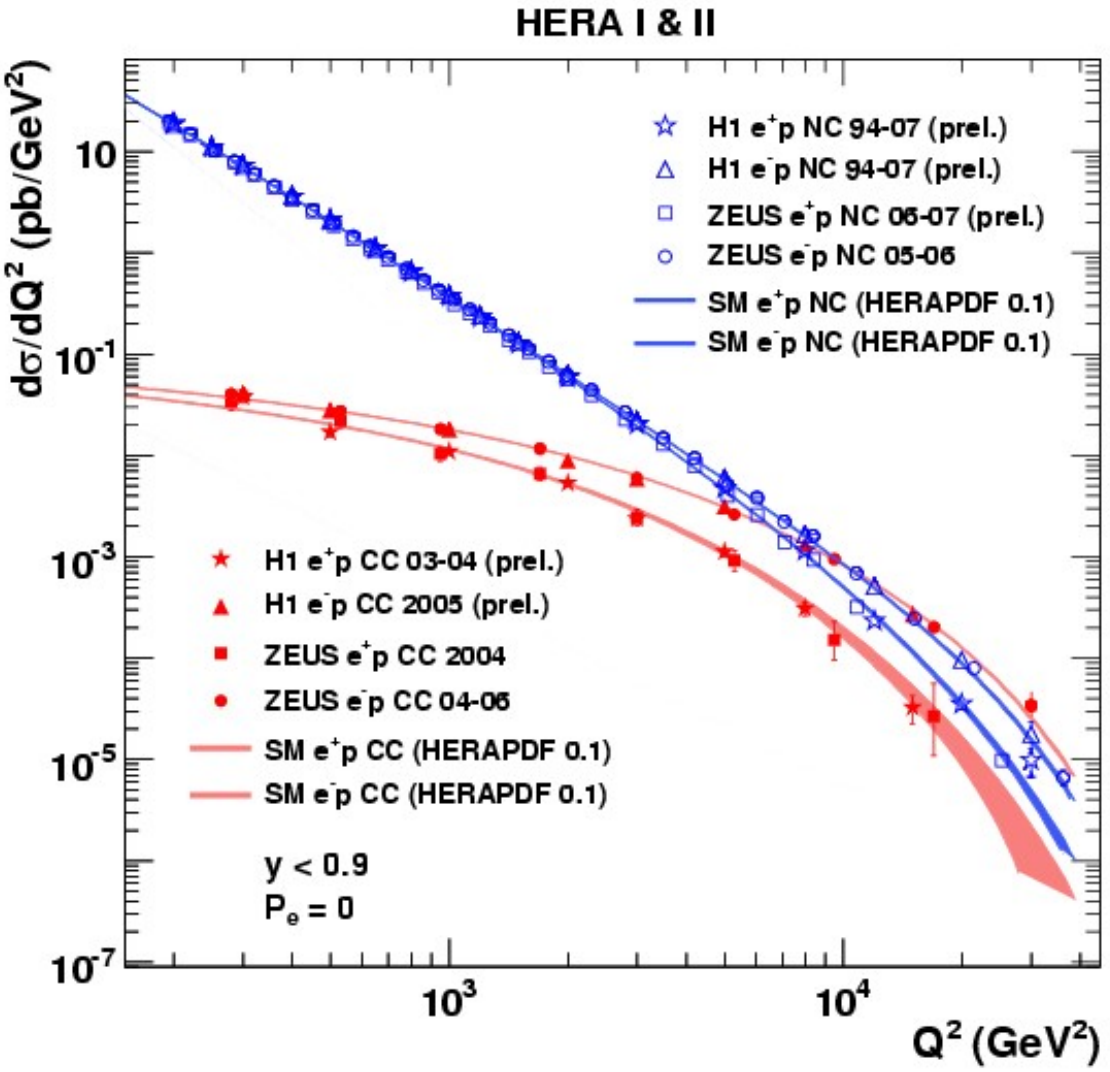
$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

Charged Current

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

~0

~ $1/Q^4$ at $Q^2 > M_W^2$



- Good agreement with SM (shown here: HERAPDF0.1) over large kinematic range
- Electroweak unification at M_W^2
- Differences between e^+p/e^-p data at high Q^2

Neutral Current Cross Section

A closer look at the neutral current cross section in (x, Q^2)

$$Y_\pm = 1 \pm (1-y)^2$$

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ \tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - F_L\right]$$

- cross section parametrised using generalised structure functions related to quark/gluon density distributions in proton

F_2 γ exchange dominant contribution, γZ interference
depends on polarisation (axial-vector coupling to Z a_e large)

$$\tilde{F}_2^\pm = F_2 - (v_e \pm P_e a_e)\kappa\frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2 v_e a_e)\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z$$

xF_3 γZ interference / Z exchange dominate,
depends on beam lepton charge (vector coupling to Z v_e small)

$$x\tilde{F}_3^\pm = -(a_e \pm P_e v_e)\kappa\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + (2 a_e v_e \pm P_e[v_e^2 + a_e^2])\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z$$

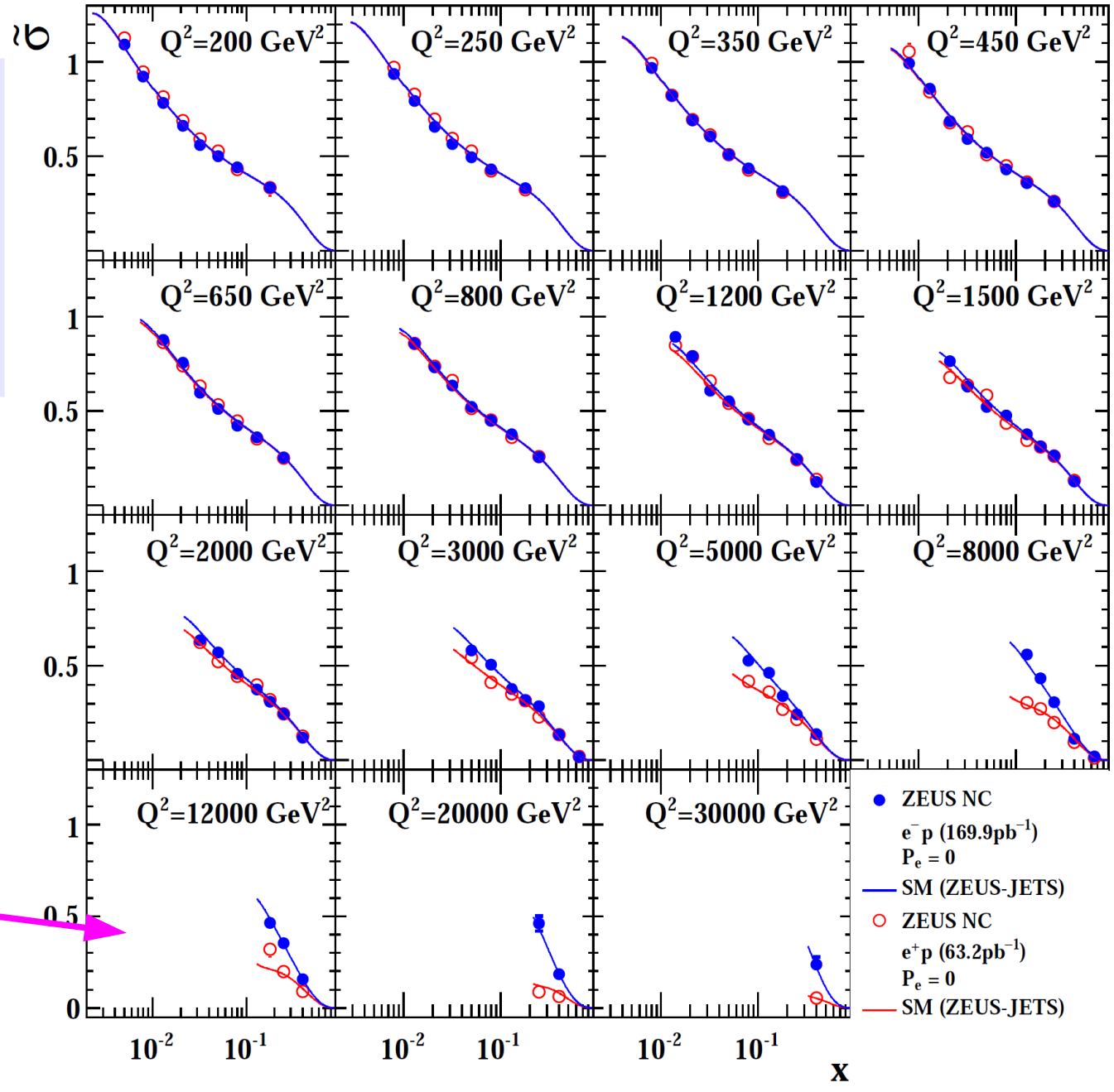
Unpolarised NC Cross Sections

ZEUS DESY-08-202

- Measured using 170 pb^{-1} of HERA-2 data
- Good agreement with SM (ZEUS-JETS) over large kinematic range

Dependence on beam charge apparent: e^+p cross section larger at high Q^2

Interference $xF_3^{\gamma Z}$



Interference Structure Function $xF_3^{\gamma Z}$

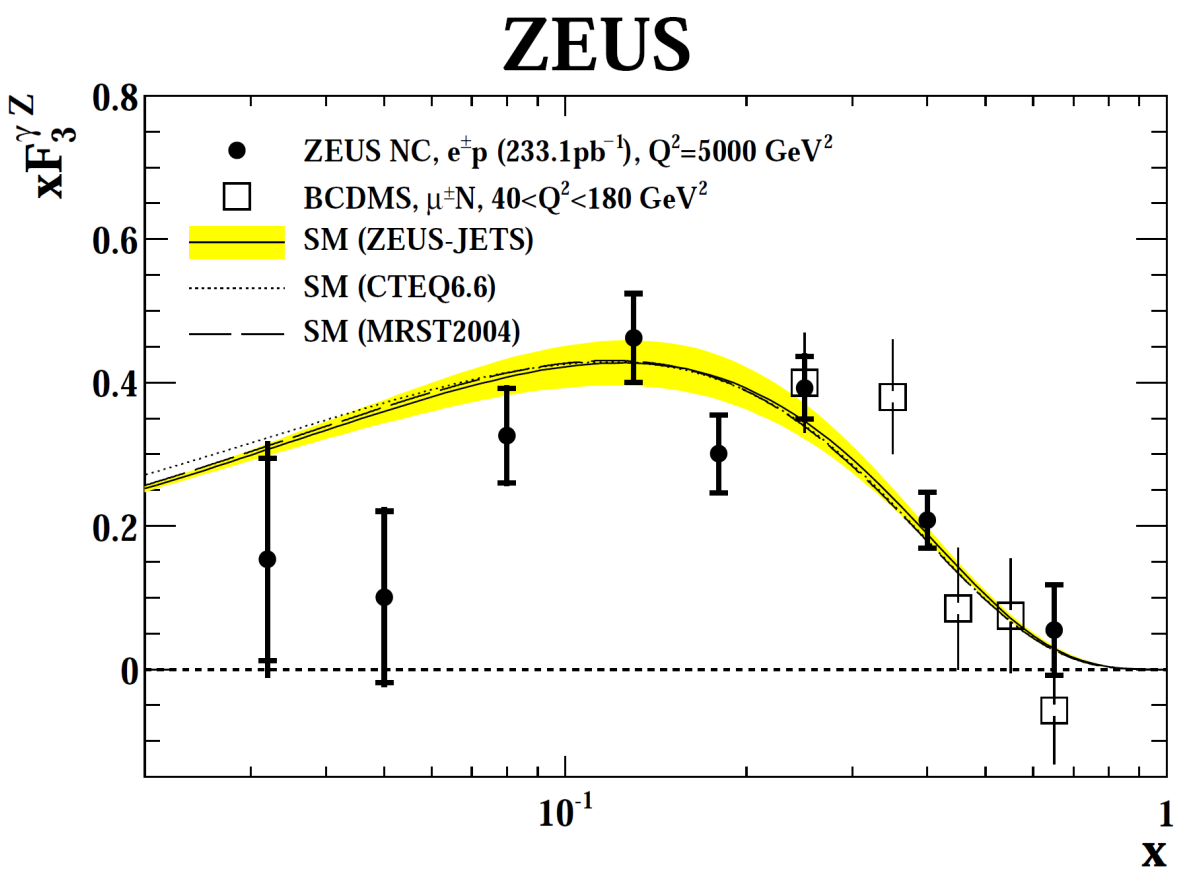
Charge Asymmetry observed:
Exploit difference in e^+p/e^-p cross sections to measure xF_3

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

In HERA kinematic range
γ-Z interference dominates:
Measure "interference structure function"

$$xF_3^{\gamma Z} \simeq x\tilde{F}_3 \frac{(Q^2 + M_Z^2)}{a_e \kappa Q^2}$$

- Adjust all measurements to Q^2=1500 GeV
- Measure as function of x



DESY-08-202

Polarised NC Cross Sections: Parity Violation

Polarisation asymmetries:
Measurement of
γZ intereference term in F_2

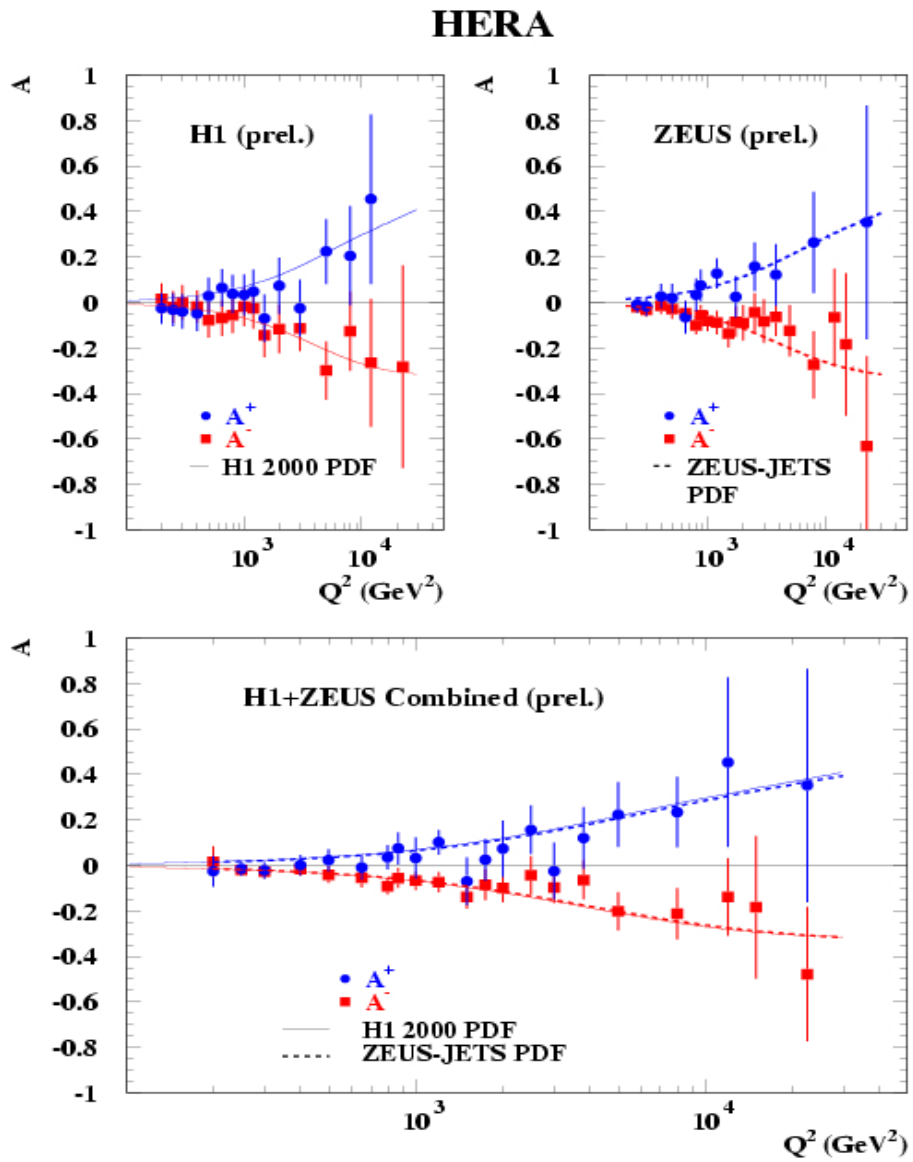
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \quad \sim a_e v_q$$

- Observation of parity violation in NC $e^{\pm}p$ scattering down to 10^{-18}m
- Direct measurement of electroweak SM effects

Combined measurement increases statistics (prelim.)

H1prelim-06-142
ZEUS-prel-06-022



Unpolarised Charged Current Cross Section

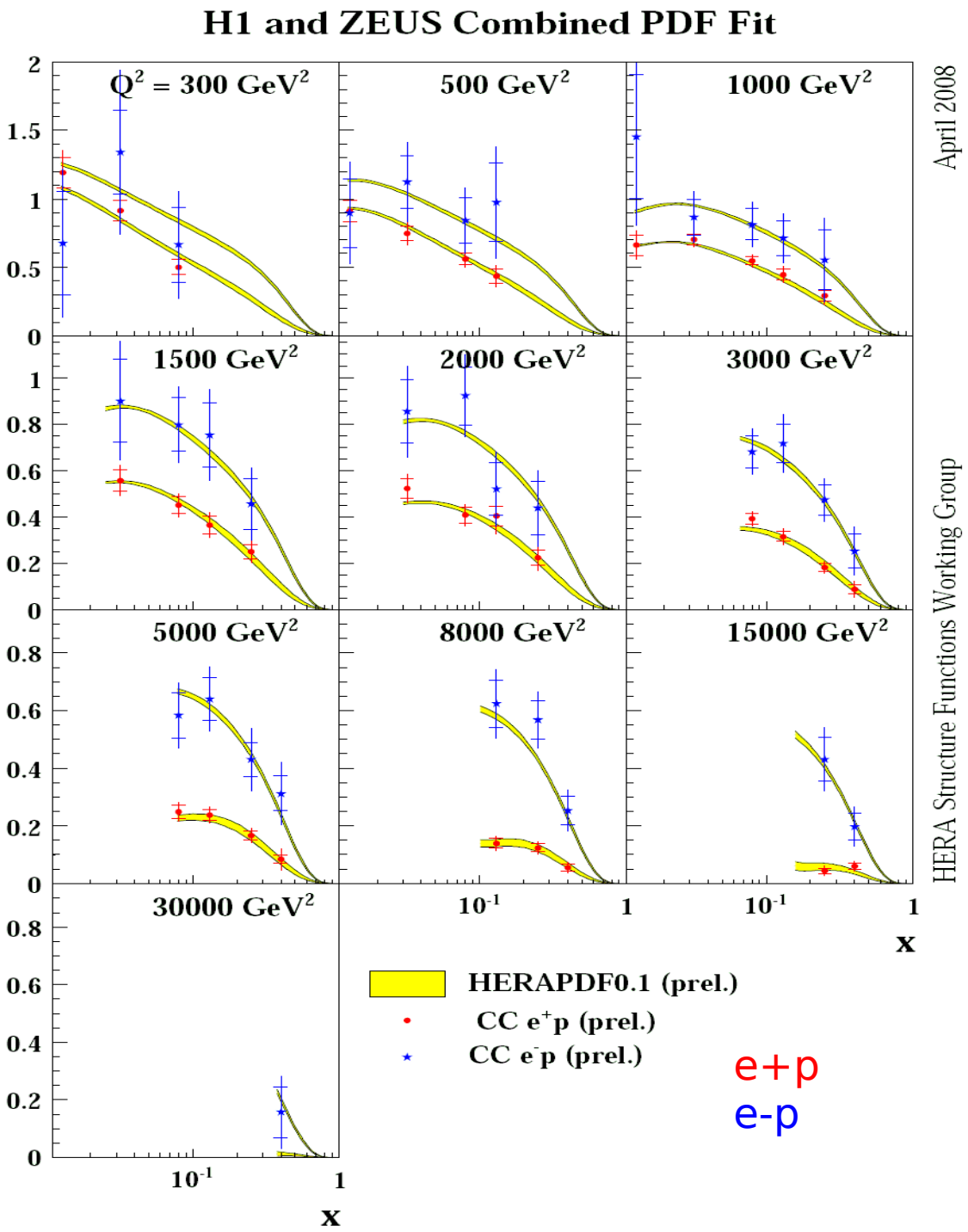
- Measured charged current cross sections for e^+p/e^-p data (HERA-1, unpolarised)

- Good agreement with SM over large kinematic range (shown here: HERAPDF0.1)

- Sensitive to flavors of partons in proton p ~ (uud) at high x

$$\tilde{\sigma}^{e^+p}_{CC} = x[\overline{u} + \overline{c}] + (1-y)^2 x[d + s]$$

$$\tilde{\sigma}^{e^-p}_{CC} = x[u + c] + (1-y)^2 x[\overline{d} + \overline{s}]$$

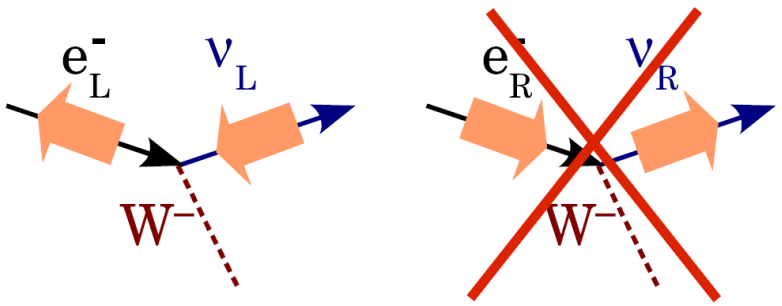


Polarised Charged Current Cross Section

- Different HERA-2 data sets allow measuring CC cross section as function of polarisation
- P_e positive, negative and zero

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

- Fundamental feature of SM directly visible:
- Only L(R)-handed (anti)particles interact weakly



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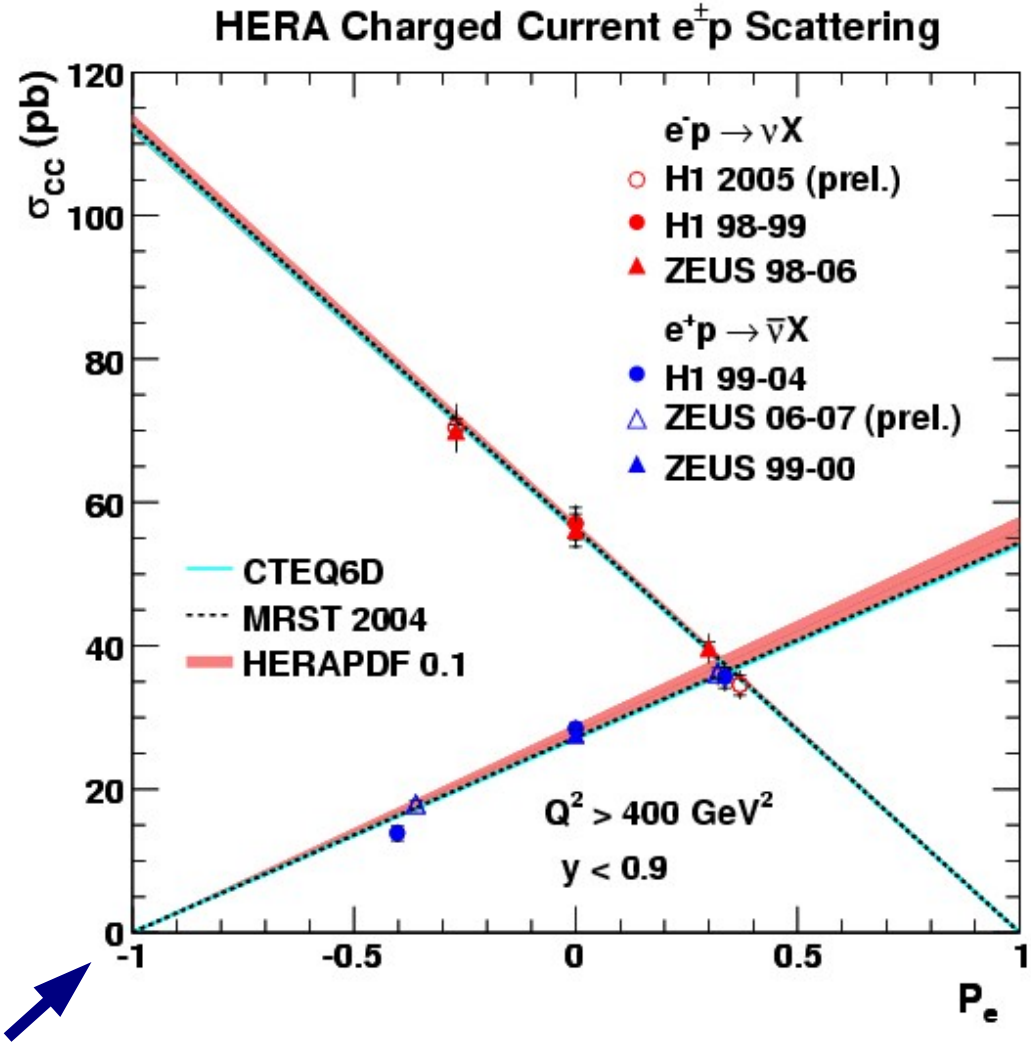
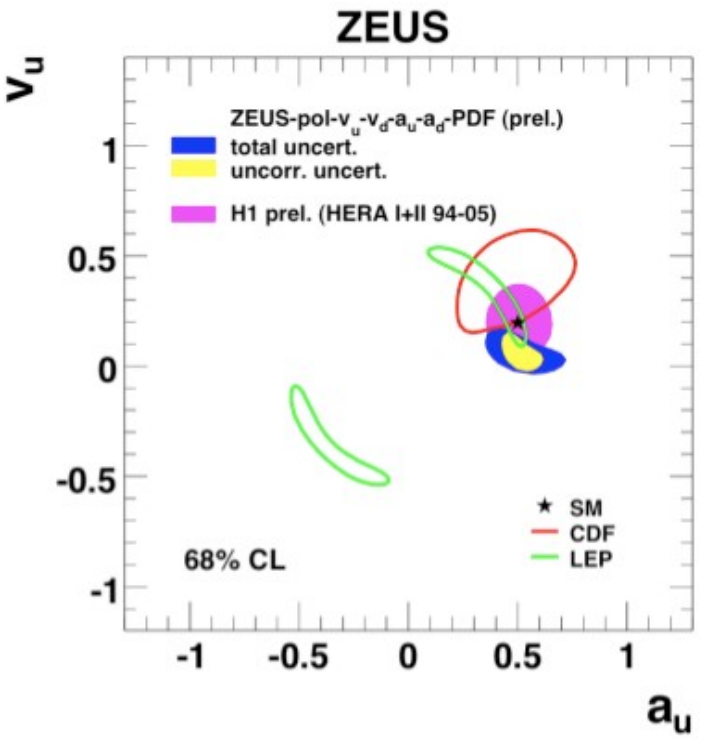
ZEUS-prel-09-001

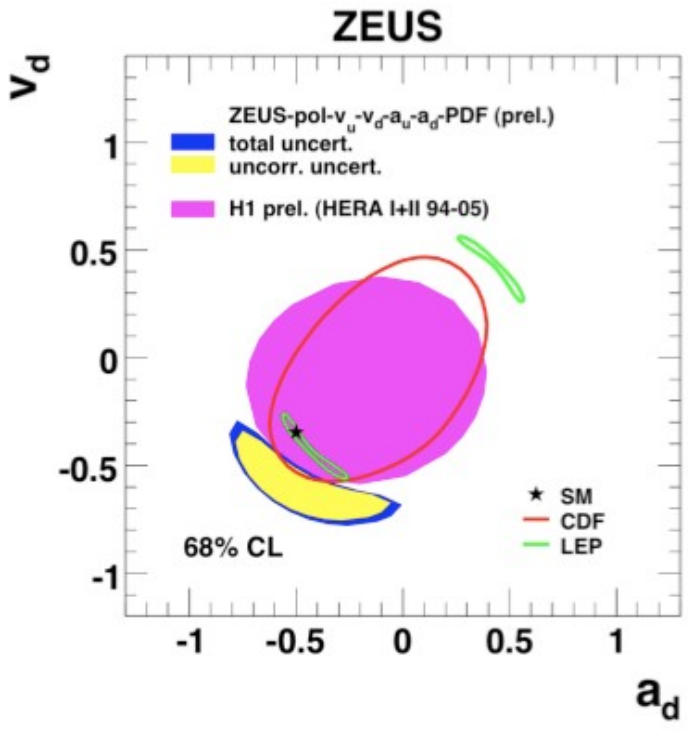


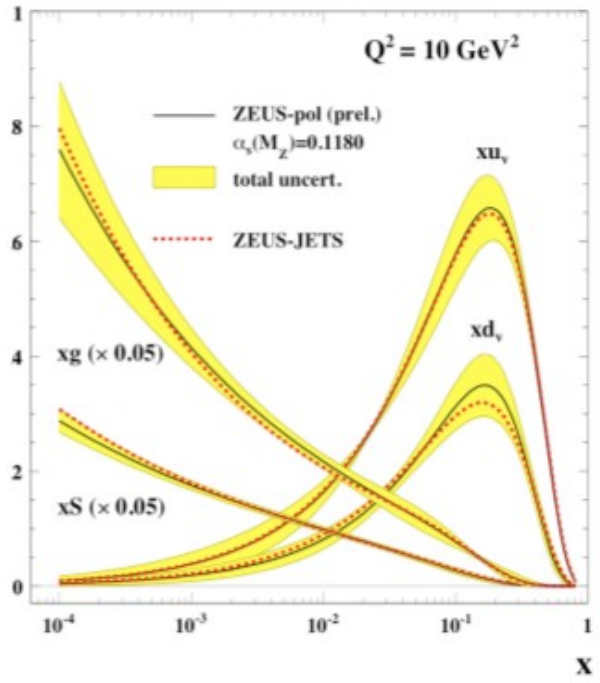
Right-handed currents forbidden in SM.
At P =-1 (extrapolated): $M_W^R > 208$ GeV

Phys.Lett. B643 173, 2006

Combined EW-QCD Fits

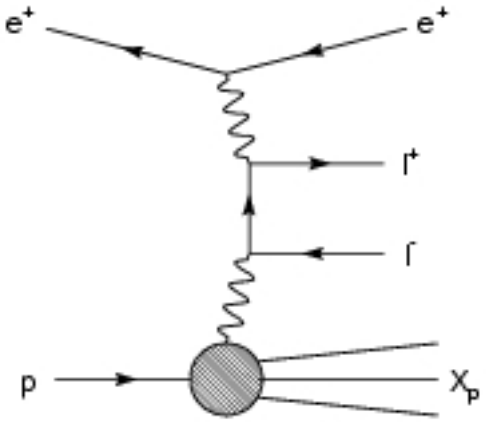






- All these measurements are used to extract
  Extract 5 PDFs (g,u,$\bar{u}$,d,$\bar{d}$) and weak couplings to Z^0 (a_u,a_d,v_u,v_d) simultaneously
  - NC: γZ interference / Z exchange sensitive to a_u,a_d
    and can resolve signs of couplings
  - CC: flavor sensitivity helps to disentangle u, d-quarks
- Precision competitive with LEP and Tevatron results
- Most precise value for u-coupling to Z comes from HERA

Lepton-Pair Production Cross Section

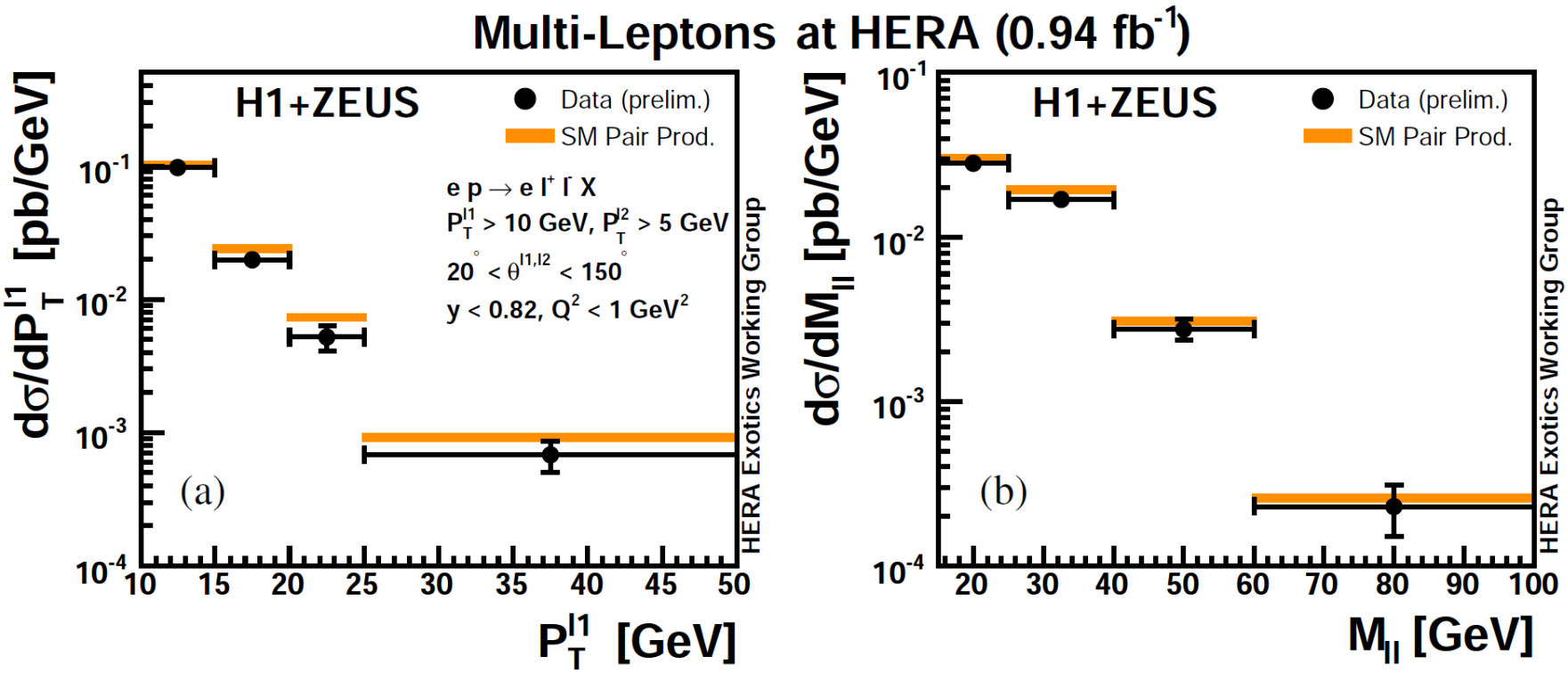


- Lepton-Pair Production via $\gamma\gamma$-collisions

- Main signal in analysis of multi-lepton events at HERA
- Powerful tool for lepton id + test of SM *(talk by A. Parenti)*

- Individual papers published by H1, ZEUS
- Preliminary H1-ZEUS combination
- Good agreement with SM prediction (GRAPE)

H1prelim-09-064
ZEUS-prel-09-008



Single *W* Production

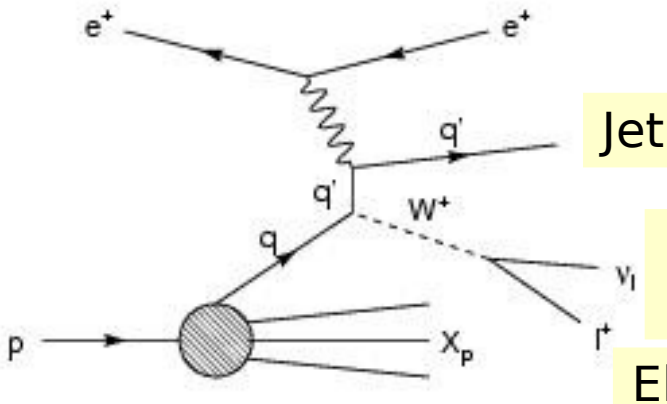
Signature:
Isolated Lepton (Electron or Muon, $P_T > 10$ GeV) and Missing Energy ($P_T > 12$ GeV)

ZEUS [arXiv:0807.0589 Phys.Lett.B672:106-115,2009]

H1 [arXiv:0901.0488 Subm. to Eur.Phys.J **C**]

Signature is also sensitive to physics beyond the Standard Model (BSM)

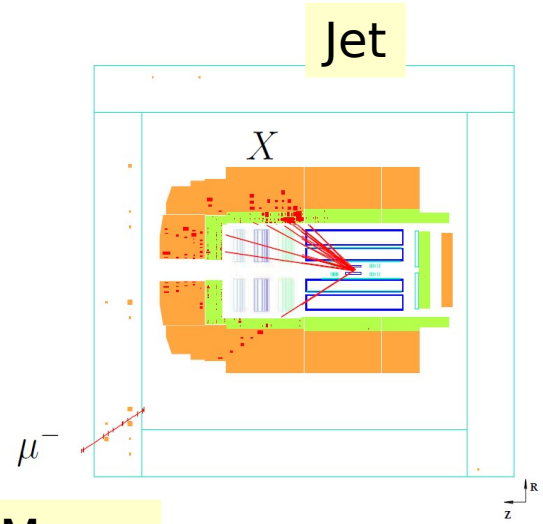
-> see talk by A. Parenti



Jet / HFS

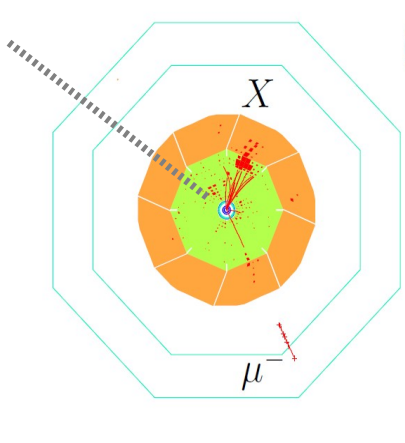
Missing Energy

Electron/ Muon



Jet

Muon

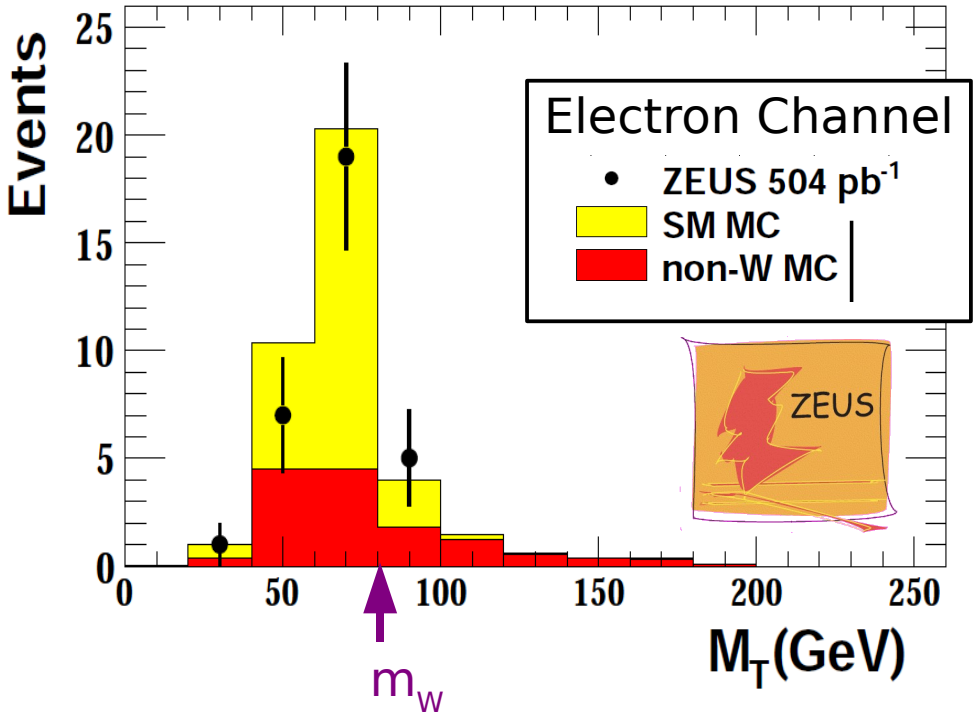


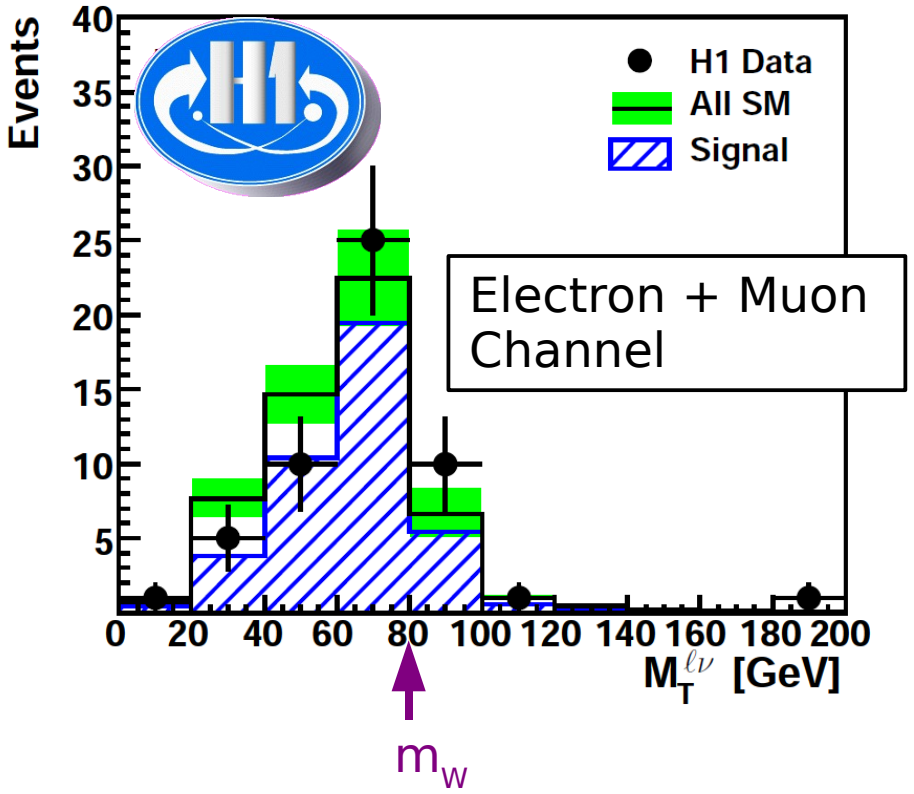
Neutrino

Example Event

- Single *W* Production σ~1.3 pb

W Production Cross Section Measurement





- High Purity of ~75% of *W* Prediction (EPVEC)
- Clear Jacobian Peak
- Strong evidence for *W* Production at HERA

ZEUS

$$0.89^{+0.25}_{-0.22}\,(\text{stat.}) \pm 0.10(\text{syst.})\,\text{pb},$$

H1

$$\sigma_W = 1.14 \pm 0.25\ (\text{stat.}) \pm 0.14\ (\text{sys.})\ \text{pb}$$

EPVEC

$$1.27 \pm 0.19\ \text{pb}$$

Summary

- Full HERA data from 1994-2007 being analysed
  ~1 fb^{-1} for H1 and ZEUS combined

- Measurements of deep inelastic scattering processes

  - NC/CC cross sections
  - Precision tests of Standard Model
  - Observation of electroweak effects
  - Combined QCD+EW fits performed

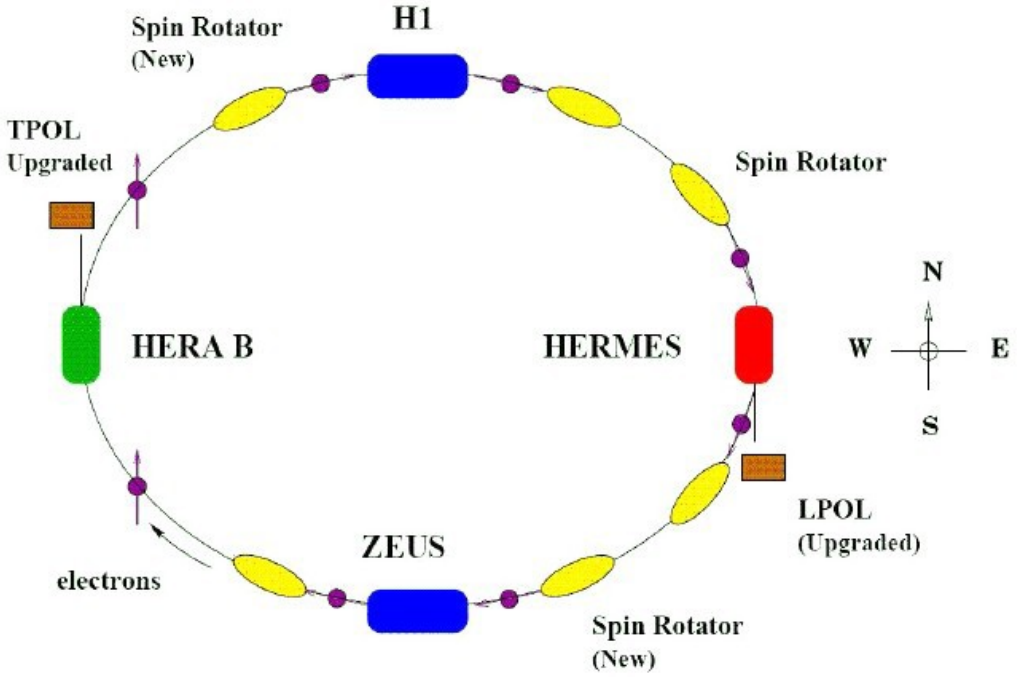
- Rare electroweak processes investigated

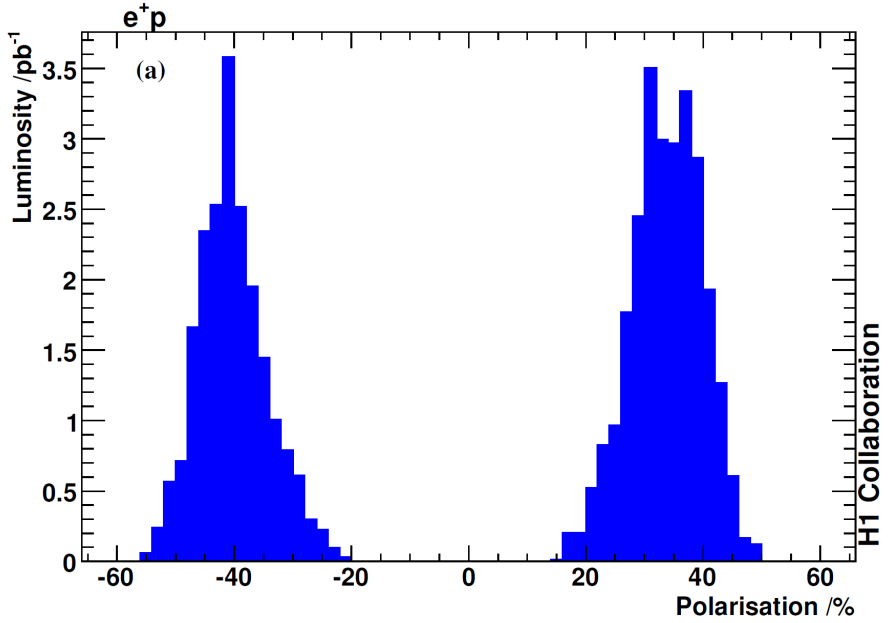
  - Single *W* Production Cross Section measured
  - Lepton-Pair production cross section measured

Analysis of electroweak processes at HERA still a very active field

Polarisation at HERA-2

- Spin rotators allow polarisation of electron/positron beam



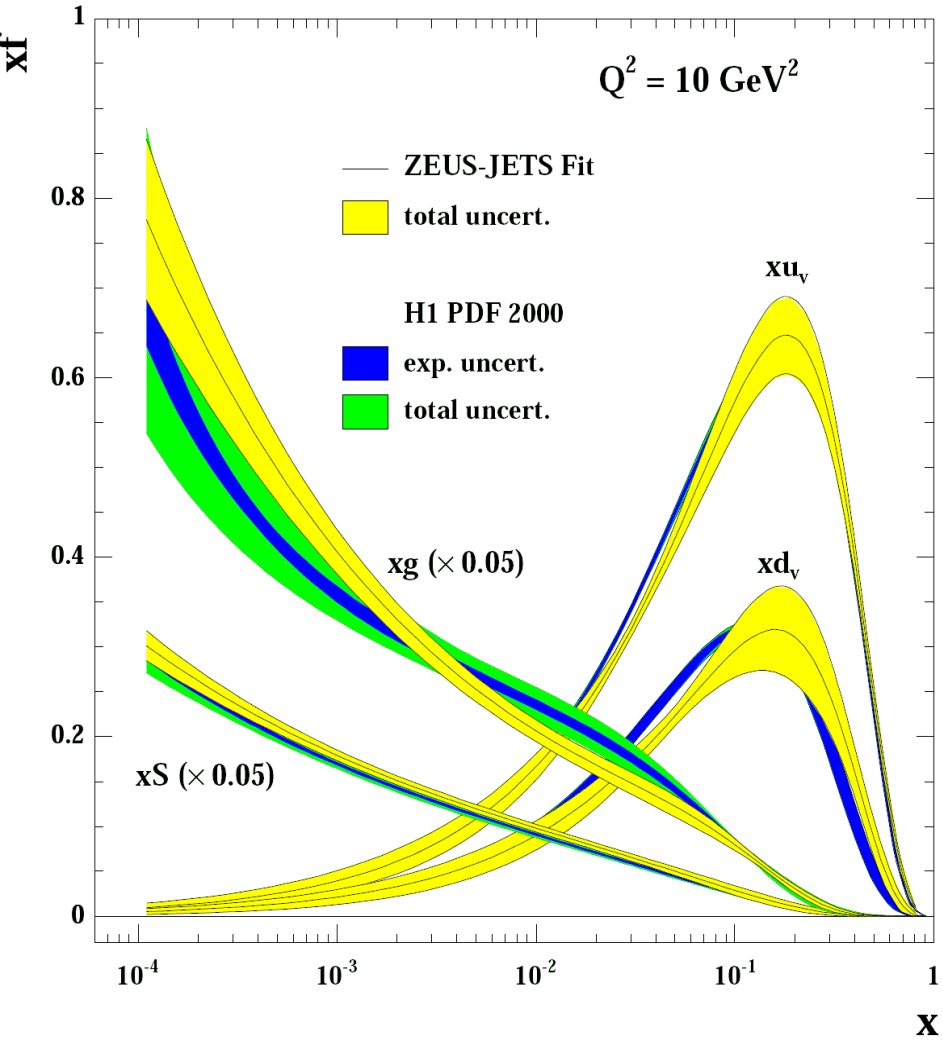


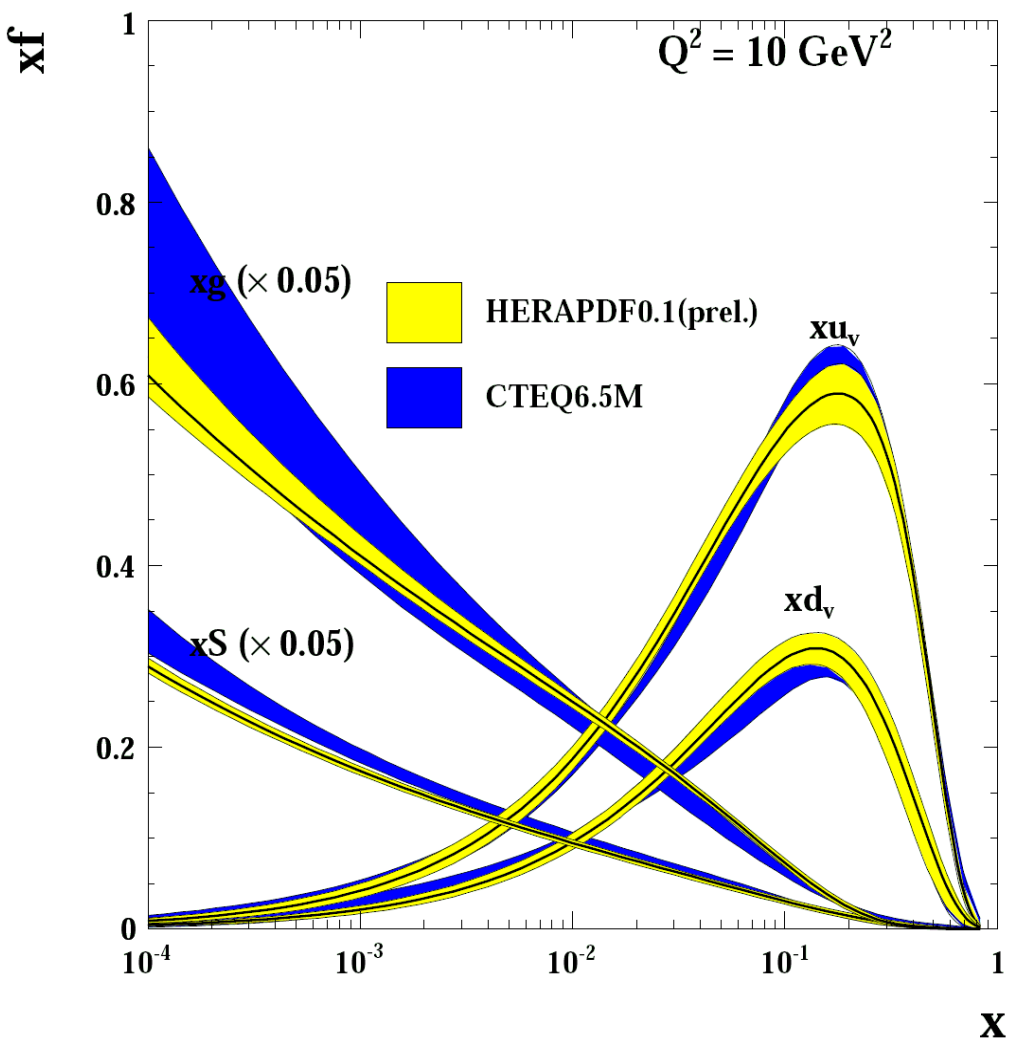
- On average ~ 30-40% polarisation
- Overall polarisation close to ~0

PDF fit to combined HERA data

HERA data used for PDF fit
low x → sea and gluon PDF
high Q^2 → valence PDF

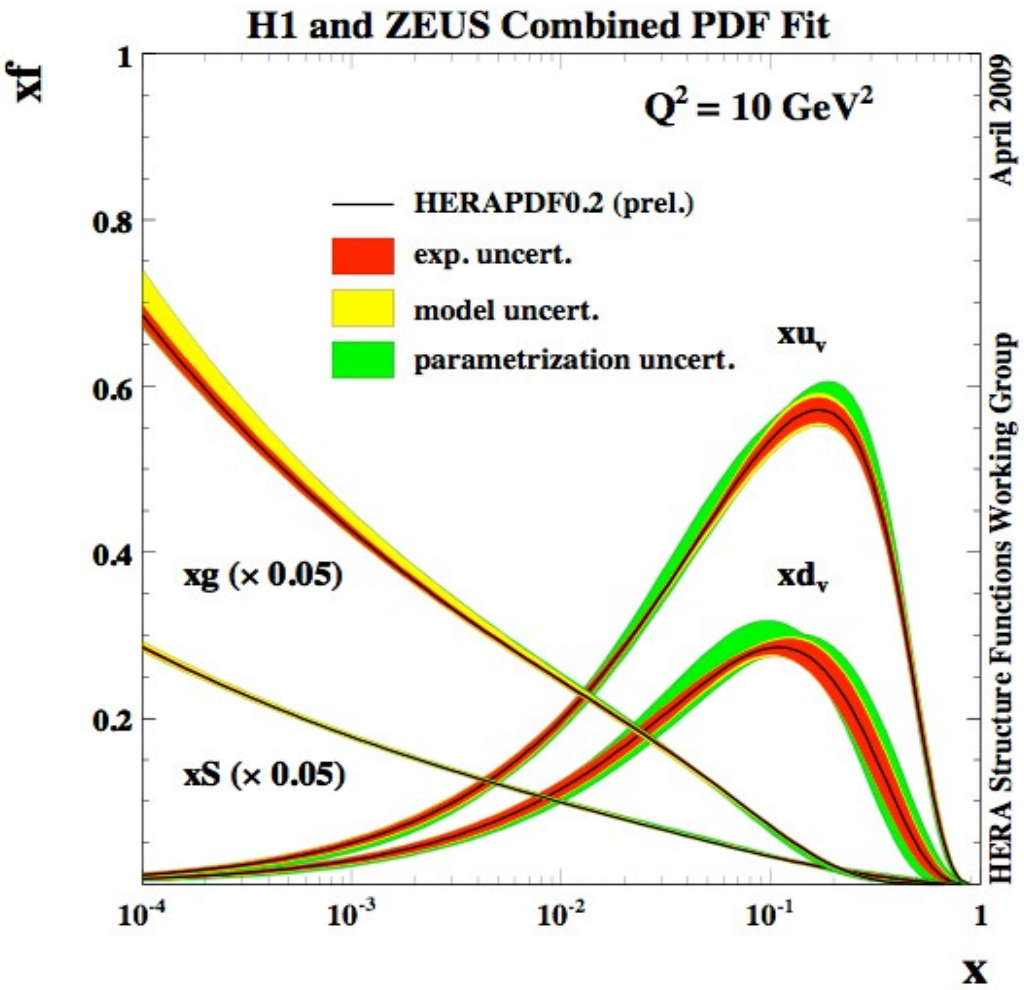
H1 prelim-08-045
ZEUS prelim-08-003





impressive precision achieved
important input for LHC

New HERAPDF0.2 Fit

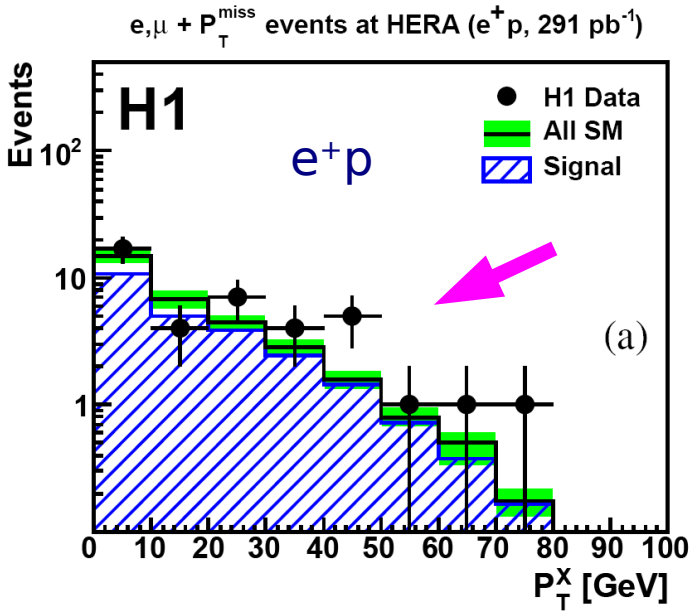


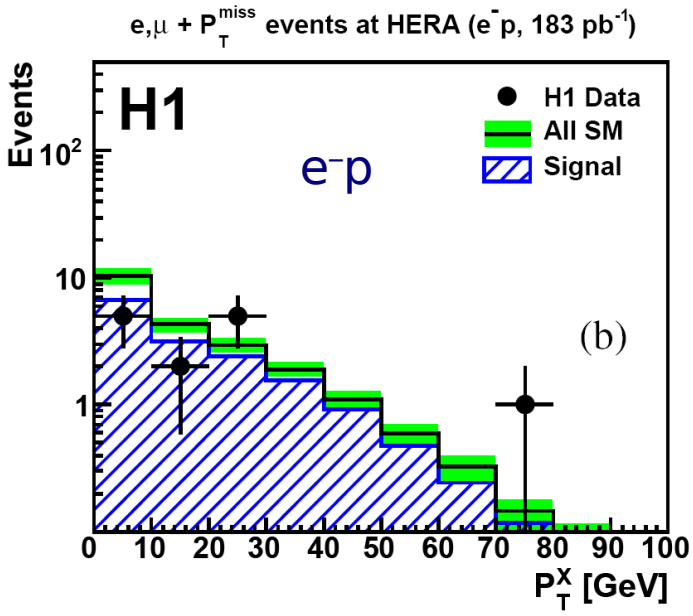
- Improved treatment of exp. and model uncertainties
- Include uncertainties due to parametrisation
- Massive HF scheme

(see talk by V. Radescu, DIS'09)

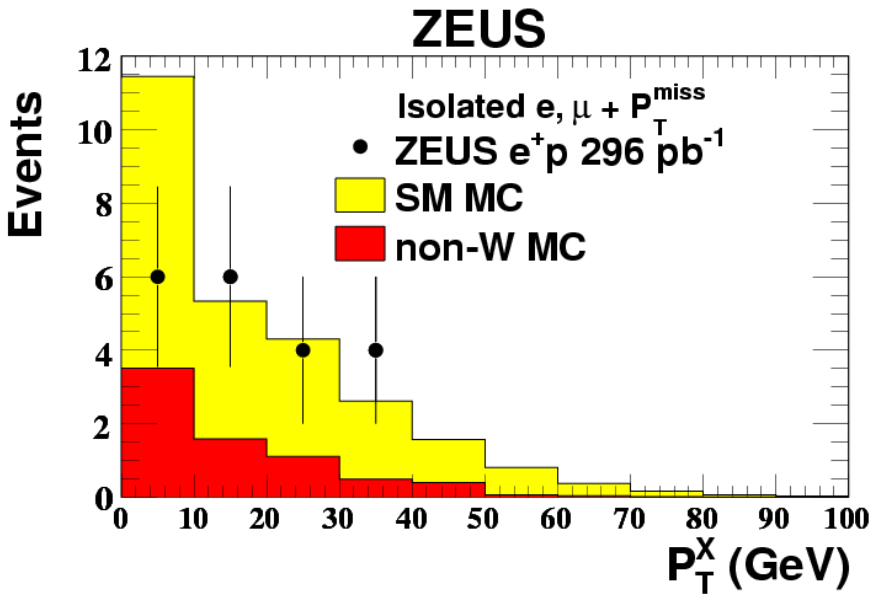
For cosmetic reasons
In this talk comparison to previous HERAPDF0.1 fit shown

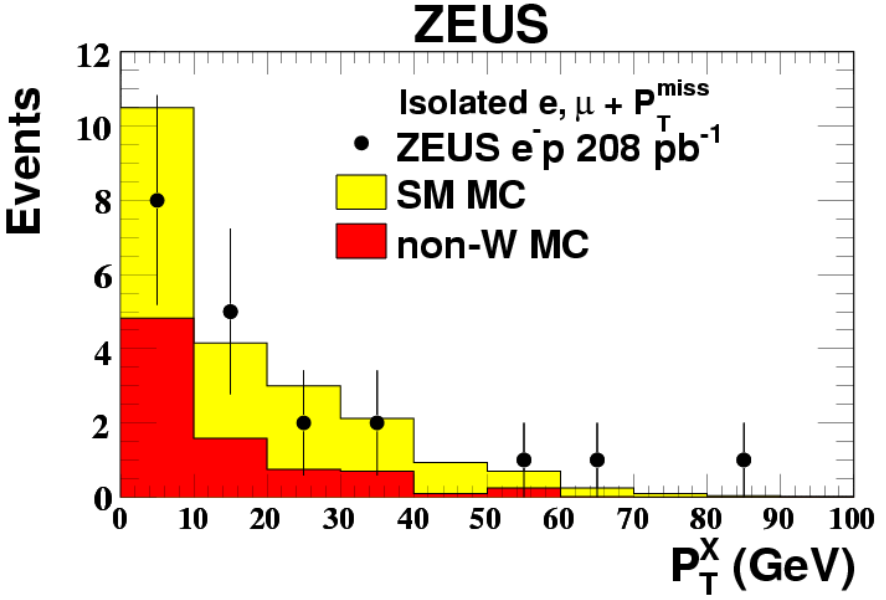
Isolated Leptons P_T^X Distributions





Good overall agreement with Standard Model
Interesting events at high hadronic P_T^X > 25 GeV observed in e^+p by H1



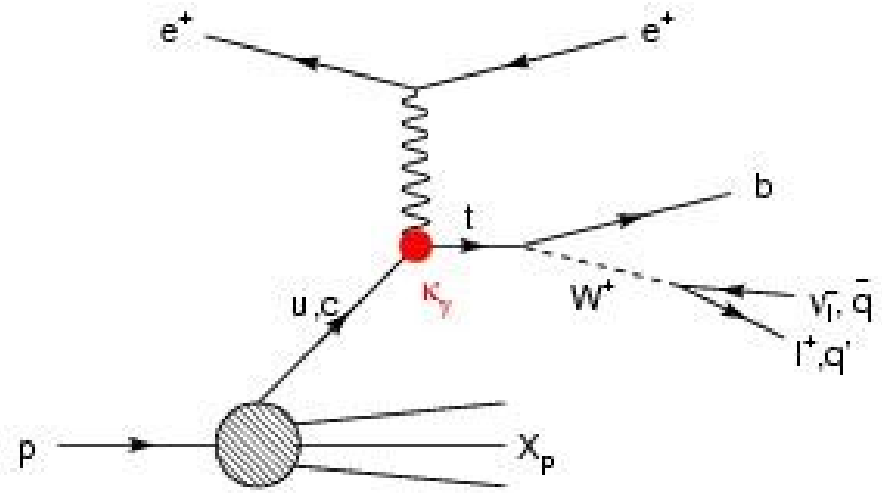


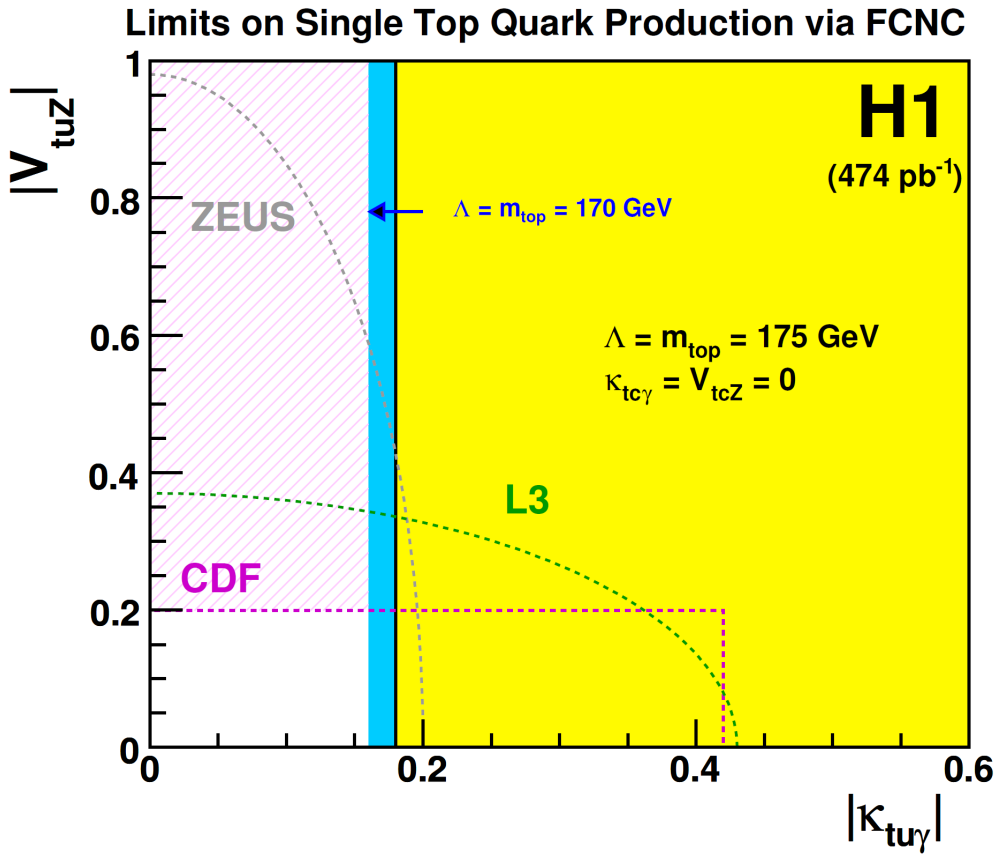
Search for Anomalous Single *top* Production

At high P_T^X isolated leptons signature compatible to anomalous single top production via FCNC
Study using effective couplings $\kappa_{tu\gamma}$, v_{tuZ}

Reconstruct *top* in isolated leptons samples
No significant excess observed
Set limits

DESY09-050

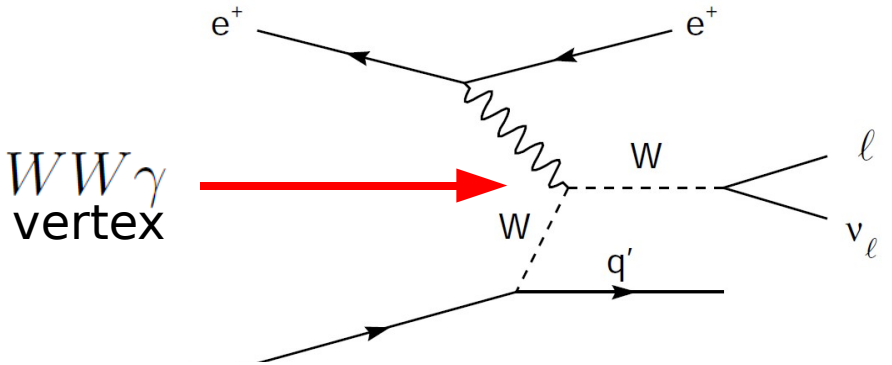


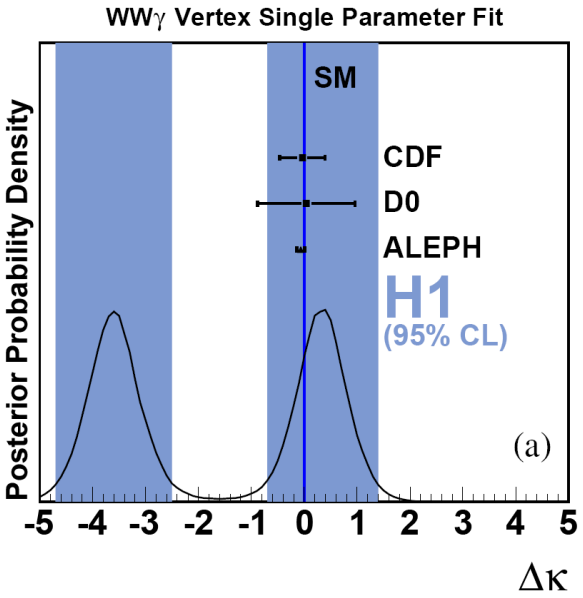


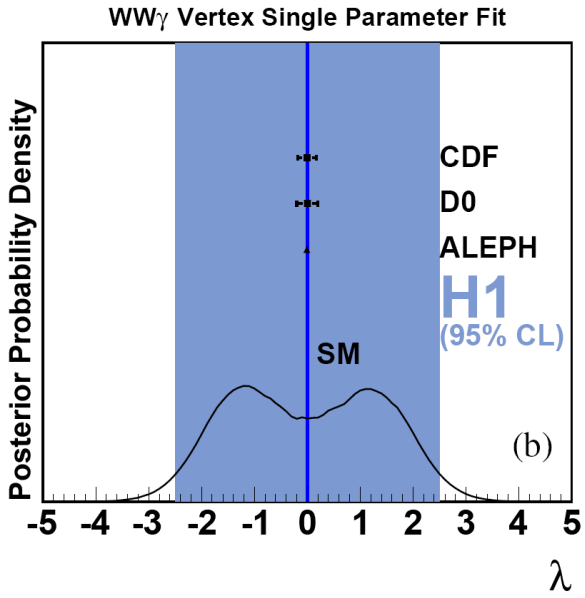
HERA Limits on $\kappa_{tu\gamma}$ explore domain not covered by other colliders

Measurement of $WW\gamma$ Vertex Parameters

Production of W Bosons is sensitive to triple gauge couplings
Attempt to provide complementary information to LEP, Tevatron on the $WW\gamma$ Vertex coupling parameters $\Delta\kappa$, λ
H1 Measurements compatible to W production at other colliders







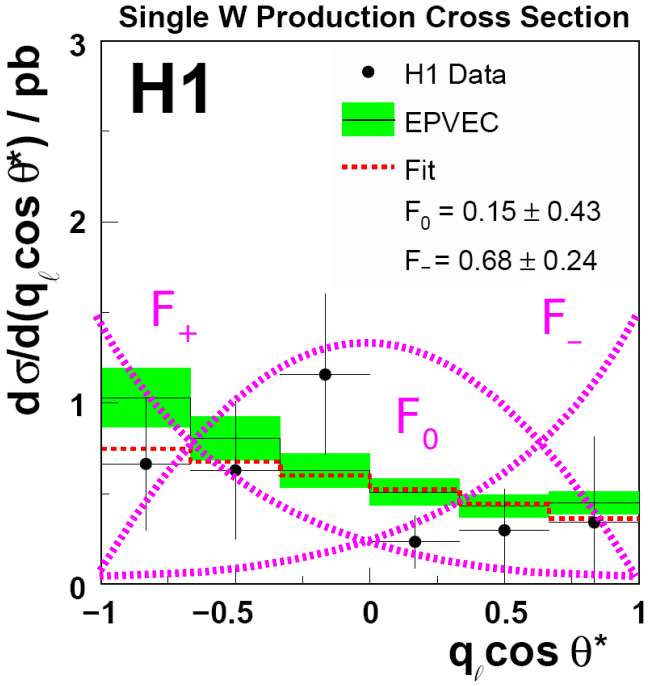
$$-4.7 < \Delta\kappa < -2.5 \quad \text{or} \quad -0.7 < \Delta\kappa < 1.4,$$

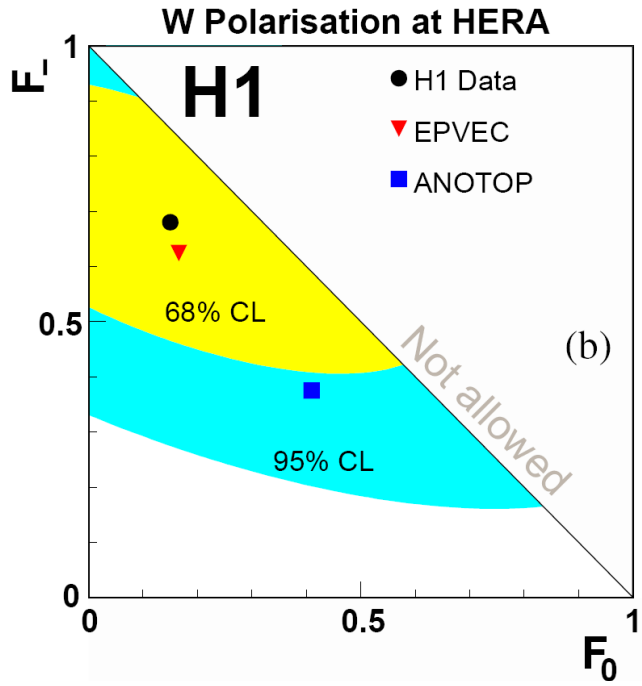
$$-2.5 < \lambda < 2.5.$$

H1 W Polarisation Fractions

W polarisation fractions sensitive to angular properties of the decay
May be different for SM and BSM contributions
Measure for single *W* Production, and test with anomalous top production model
Difference demonstrated, but sensitivity at 1σ level

Method:
Measure differential *W* cross section in $q_l^*(\cos\theta^*)$
Fit F- (LH), F+ (RH), F0 (longitudinal) *W* polarisation Fractions





$$\frac{1}{\sigma_{W\to\ell+\nu}}\frac{\mathrm{d}\sigma_{W\to\ell+\nu}}{\mathrm{d}\cos\theta^*} = \frac{3}{4}F_0\left(1-\cos^2\theta^*\right) + \frac{3}{8}F_-\left(1-\cos\theta^*\right)^2 + \frac{3}{8}F_+\left(1+\cos\theta^*\right)^2$$