



# W and Z Physics from HERA

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on behalf of the H1 and ZEUS Collaborations

The Physics of W and Z Bosons, June 24 - 25 2010,



## Outline:

Introduction to HERA, H1 and ZEUS

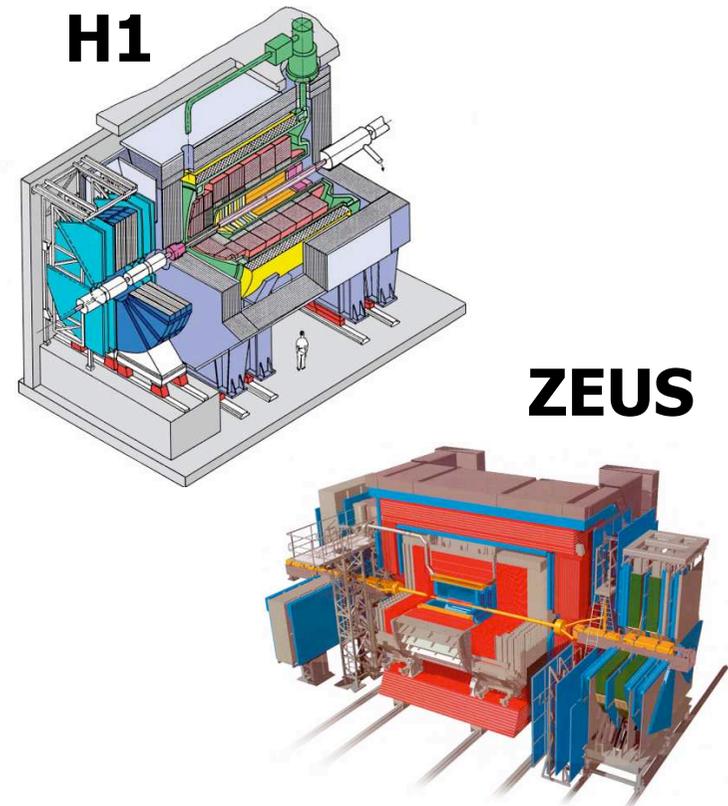
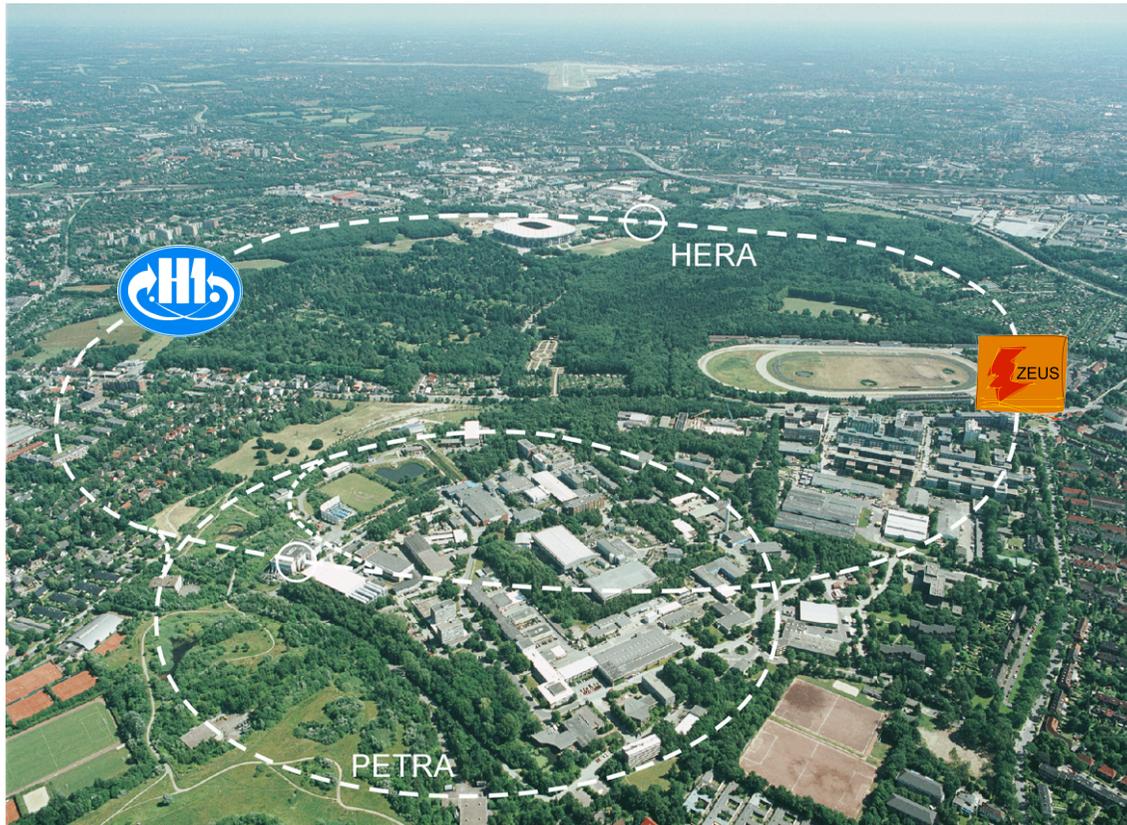
High  $Q^2$  Measurements of Neutral and Charge Current

Combined H1 and ZEUS measurements and QCD/EW fits

Rare processes at HERA involving W and Z Bosons

Summary

# The H1 and ZEUS Experiments at HERA



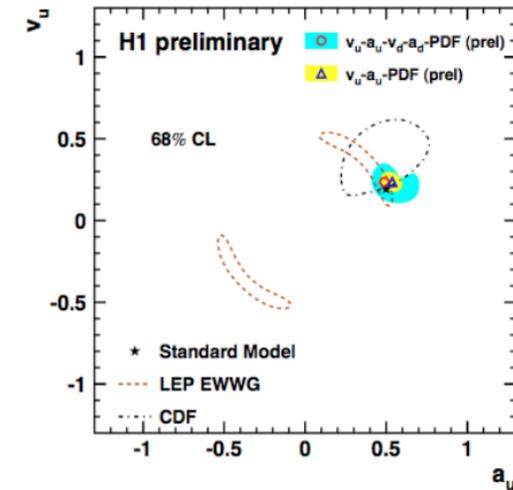
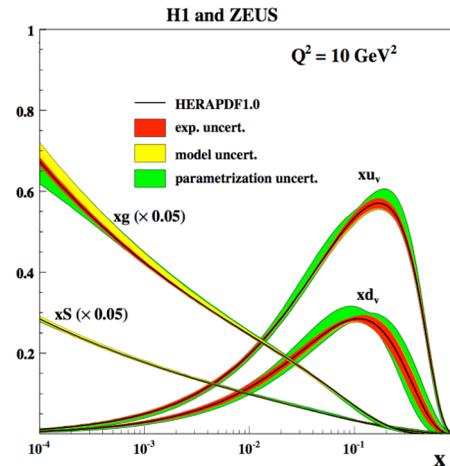
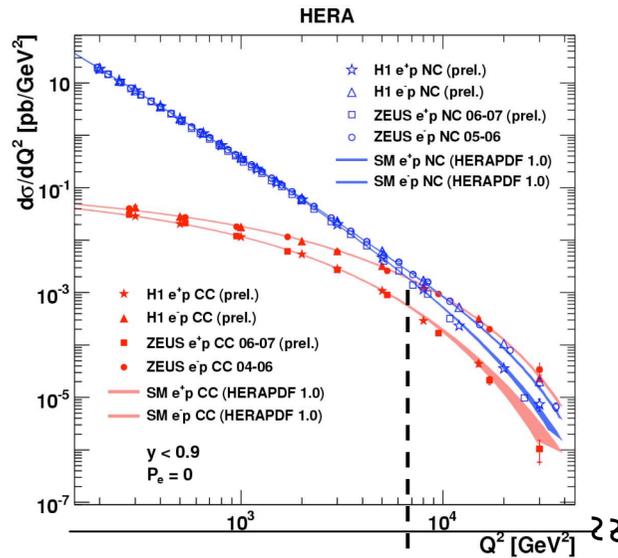
- Two multi-purpose experiments located at the ep interaction points
- The world's most powerful electron microscope, counter-rotating 6.3 km long accelerators
- Particle energies allow us to probe proton structure down to  $\Delta x \approx 10^{-18}\text{m}$



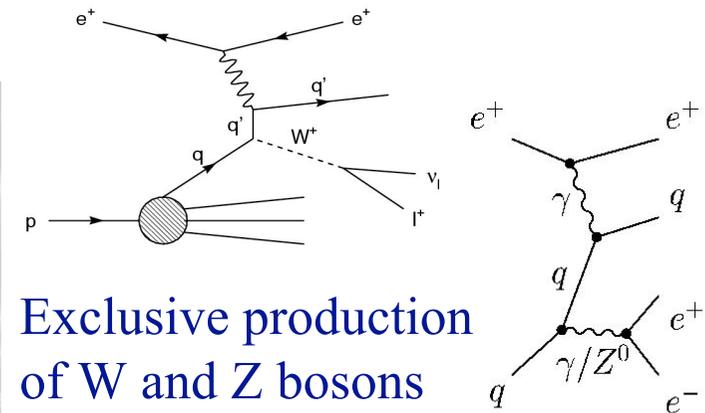
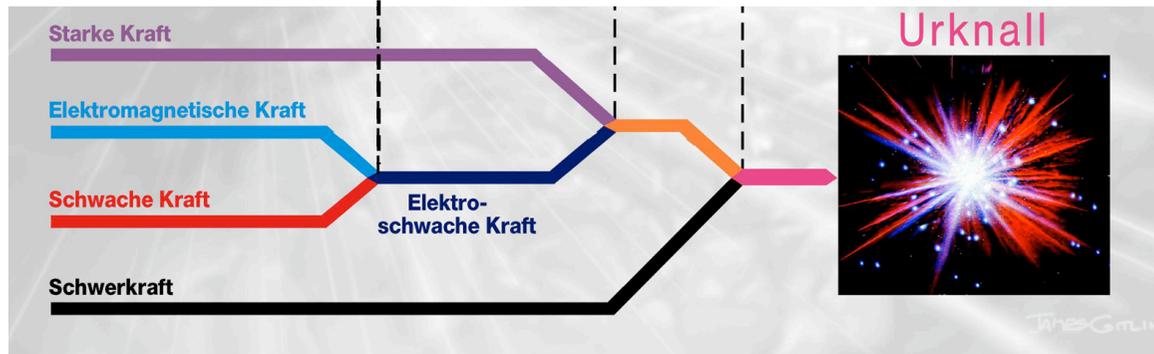
Collisions every 96ns,  $\sqrt{s} = 319 \text{ GeV}$

# Electroweak Physics at HERA

## Inclusive measurements electroweak effects at $Q^2 \sim M_{W,Z}$



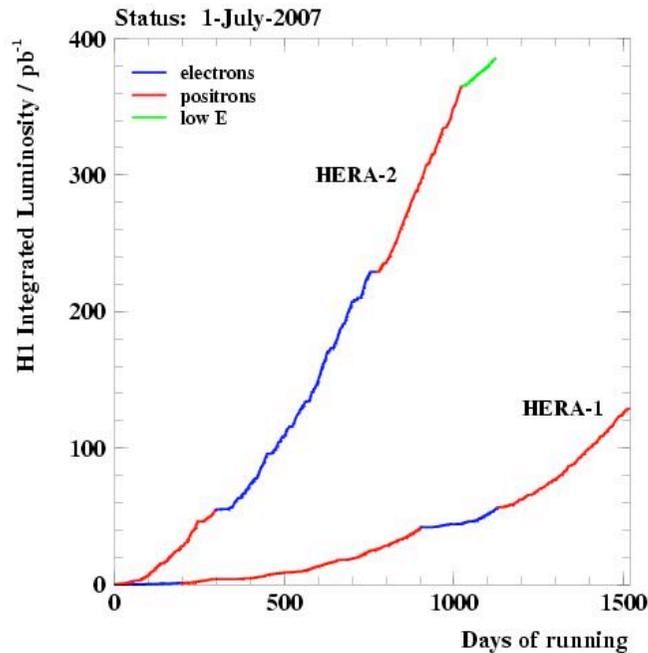
## QCD and electroweak fits to the HERA data



Exclusive production  
of W and Z bosons

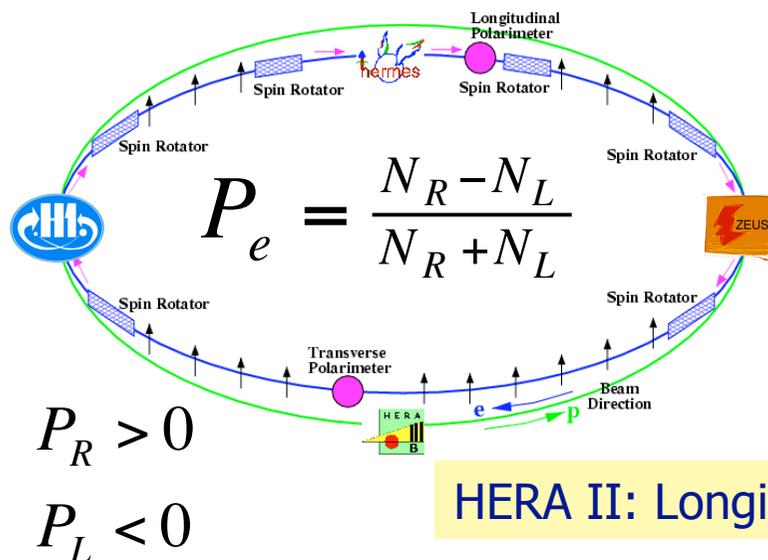
Measurements with W and Z bosons at HERA are within reach!

# Data Taking at HERA 1994-2007

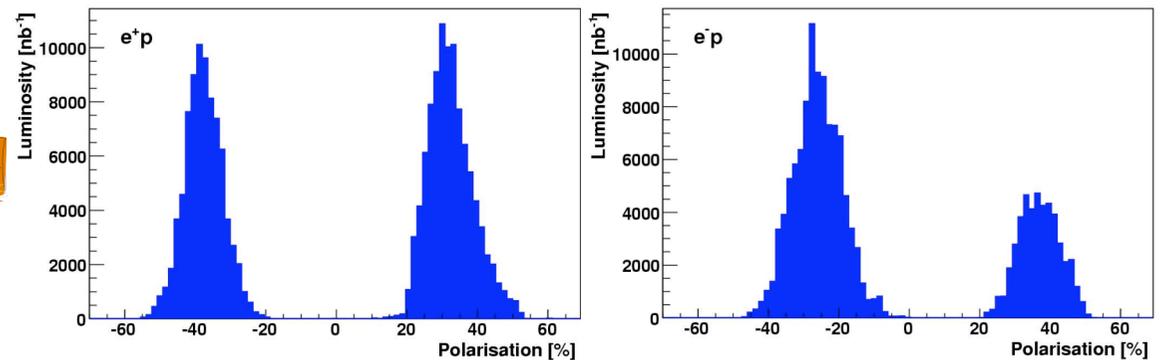


- Large increase in data per experiment after the luminosity upgrade for HERA II (x3)
- Large increase (x12) in data taken from e-p collisions: HERA I mostly e<sup>+</sup>p data

Final HERA I+II dataset ~ 0.5 fb<sup>-1</sup> / experiment

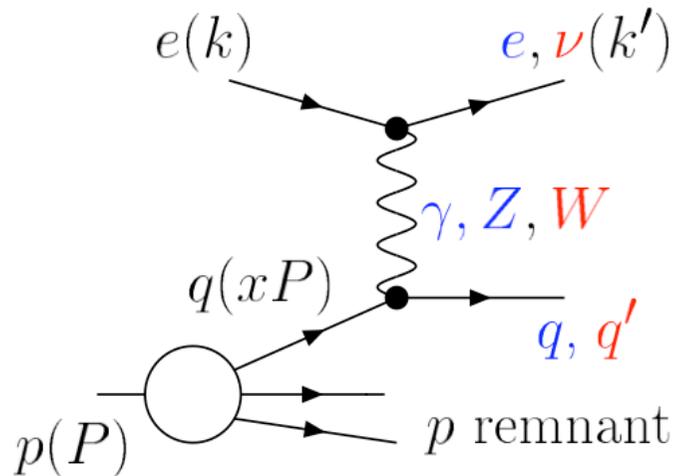


e<sup>+</sup>p, -P      e<sup>+</sup>p, +P      e<sup>-</sup>p, -P      e<sup>-</sup>p, +P



HERA II: Longitudinally Polarised Lepton Beam: 4 modes of running

# Deep Inelastic Scattering at HERA



$$Q^2 = -(k - k')^2$$

Virtuality of the exchanged boson

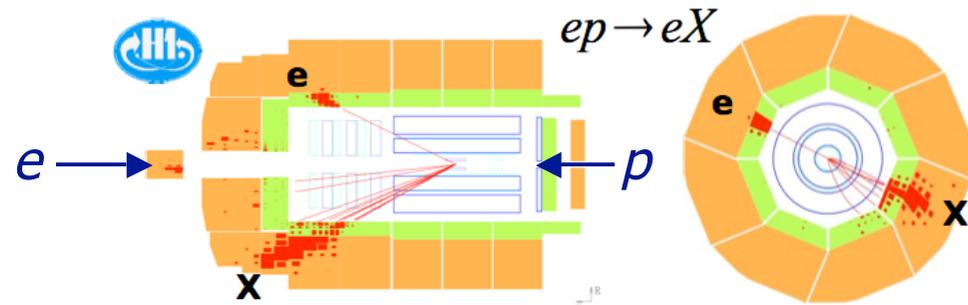
$$x = \frac{Q^2}{2P \cdot (k - k')}$$

Fraction of proton momenta carried by the struck quark

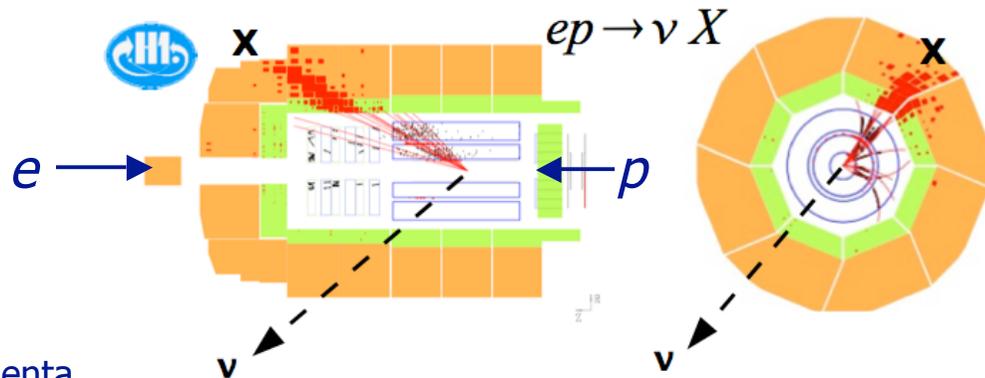
$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

Inelasticity: fraction of lepton energy transferred in the proton rest frame

$$Q^2 = sxy, Q^2_{\max} \sim 10^5$$



Neutral Current interaction



Charged Current interaction

NC and CC cross section measurements done using up to the full HERA I+II data in the range  $200 < Q^2 < 30,000 \text{ GeV}^2$

# Neutral Current Cross Sections

$$\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} Y_\pm \left[ F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right] \quad \tilde{\sigma}_{NC}(x, Q^2) \text{ Reduced cross section}$$

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

The **dominant** contribution



Sizeable only at **high y**  
- Measure with special  
low energy runs

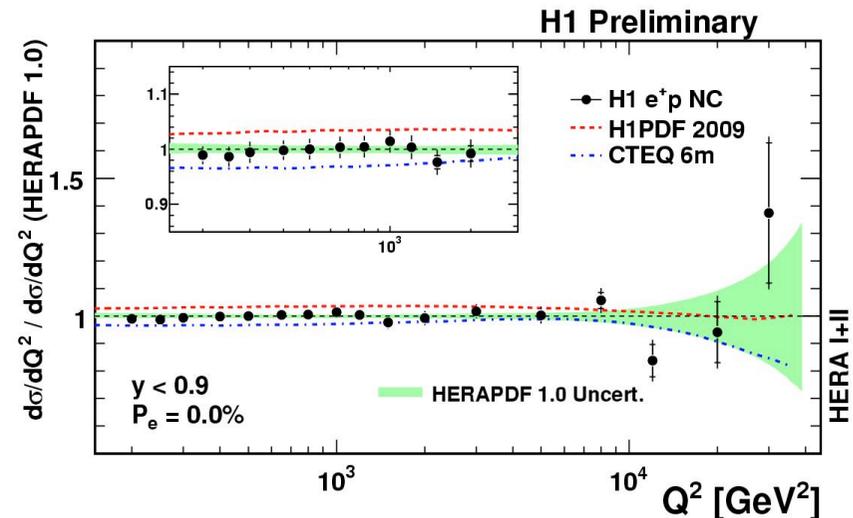
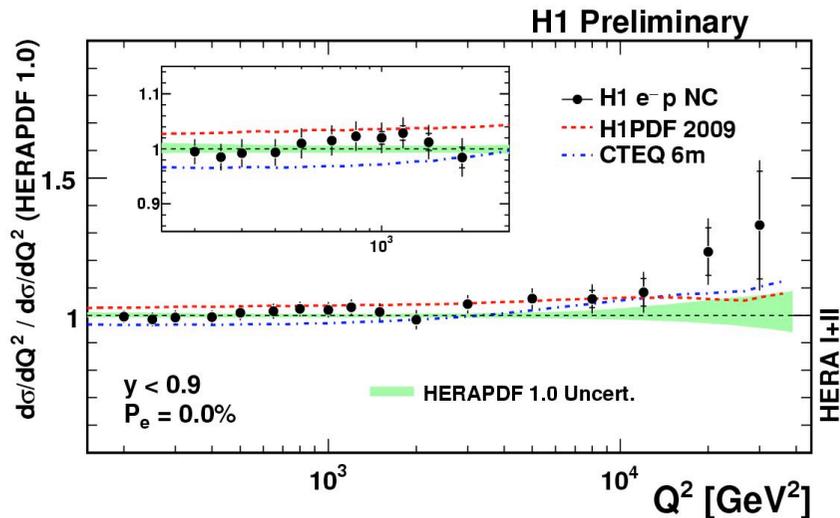
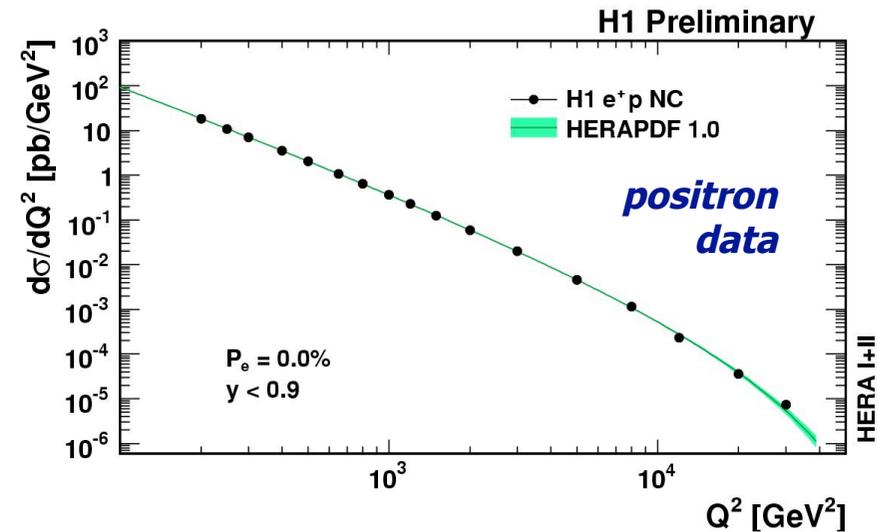
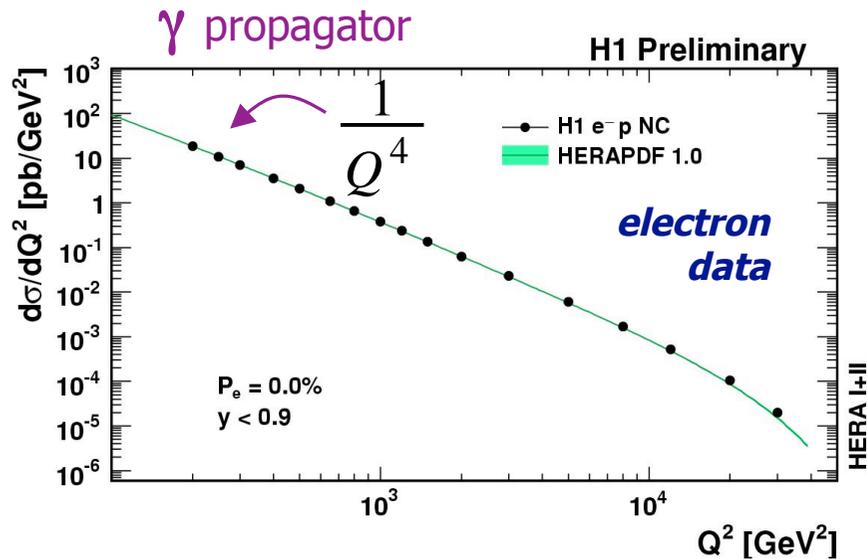
Only important at **high Q<sup>2</sup>**  
- Measure using difference  
of e<sup>+</sup>p and e<sup>-</sup>p cross sections

$$F_2 = F_2^{em} + \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z \propto \sum_{q=u\dots b} (q + \bar{q}) \quad \text{Sum of quark densities: PDFs}$$

$$xF_3 = \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 xF_3^Z \propto \sum_{q=u\dots b} (q - \bar{q}) \quad \text{Difference between quark and anti-quark densities}$$

In addition, the NC cross section is also sensitive to the *lepton polarisation*, but only via the Z and  $\gamma Z$  interference terms: small effect only visible at high  $Q^2$

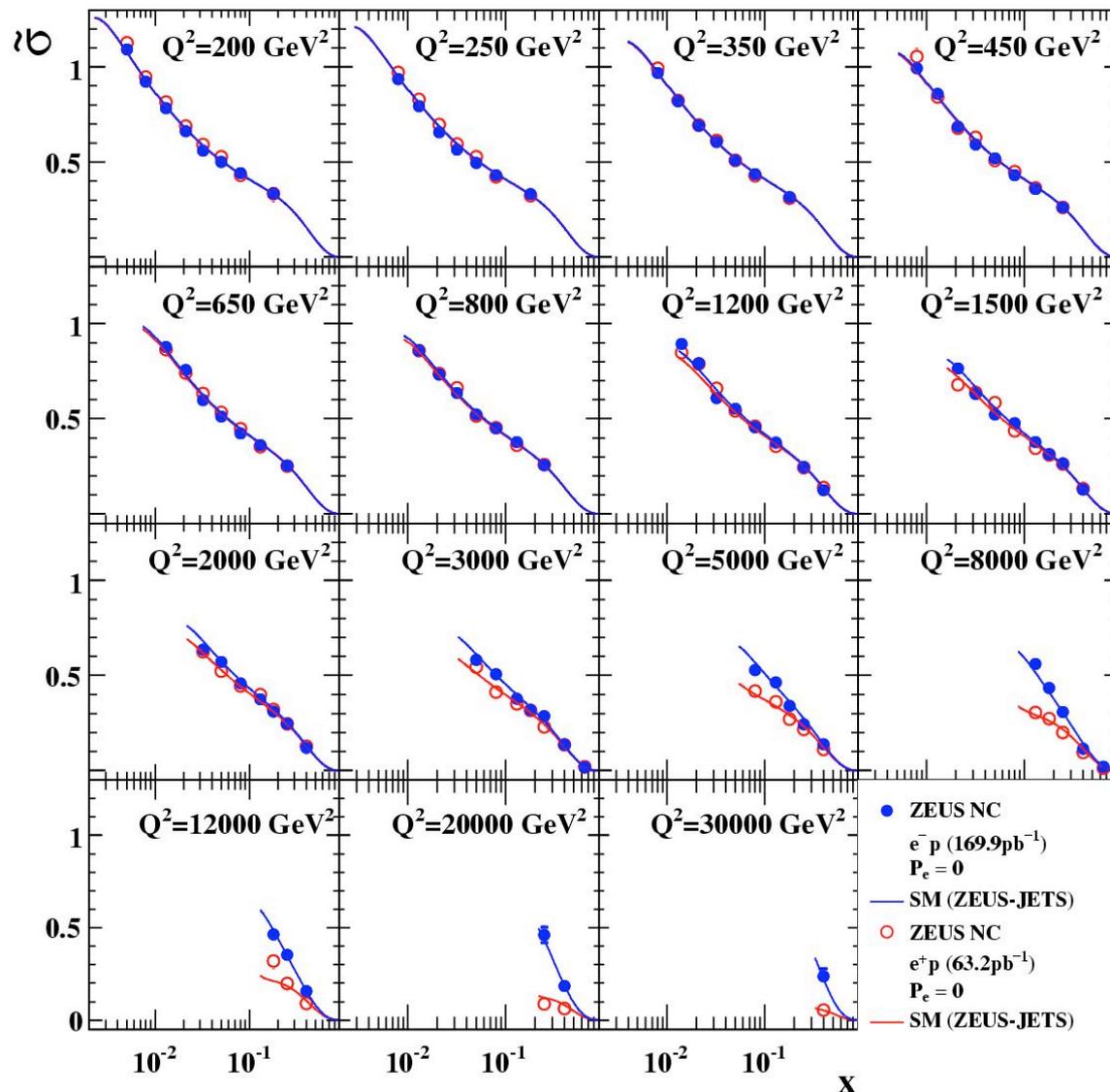
# Unpolarised Cross Sections: HERA I+II



High precision of full HERA I+II data set and comparison to various PDF fits

# Unpolarised Reduced NC Cross Section: e<sup>-</sup>p vs. e<sup>+</sup>p

## ZEUS



$$\tilde{\sigma}_{NC}^{\pm} = \tilde{F}_2 - \frac{y^2}{Y_+} \tilde{F}_L \mp \frac{Y_-}{Y_+} x \tilde{F}_3$$

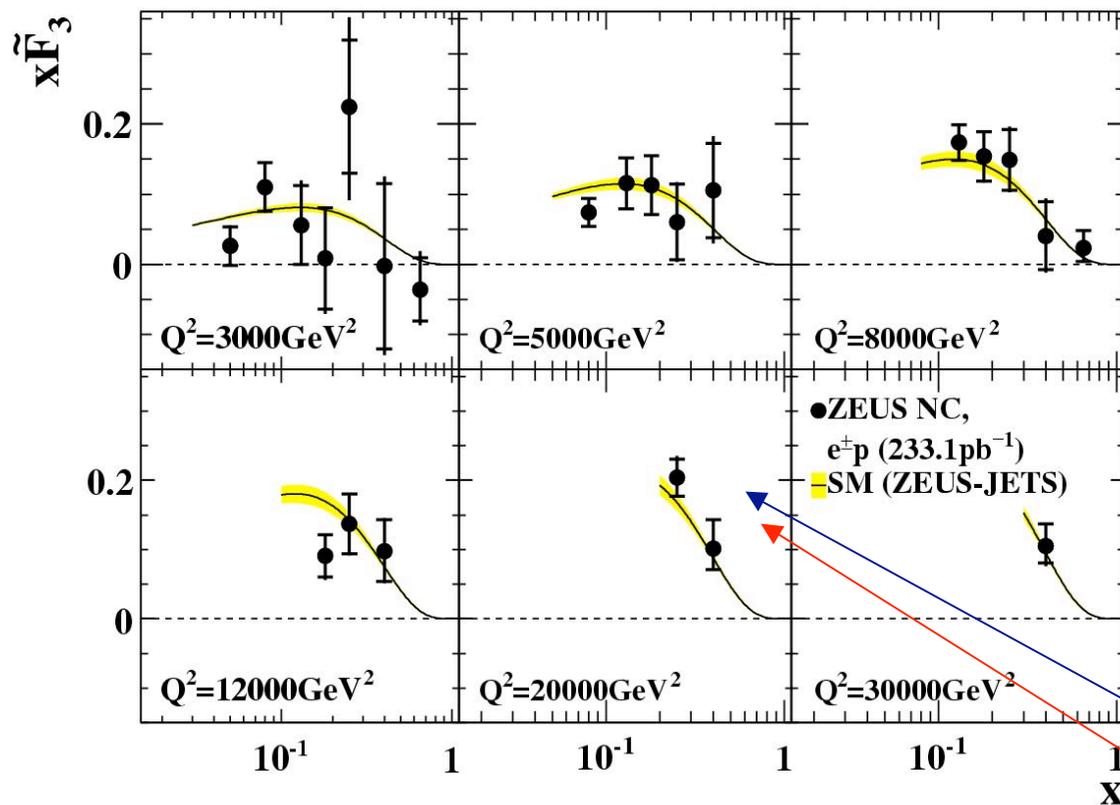
Separation of e<sup>+</sup>p and e<sup>-</sup>p cross sections at high Q<sup>2</sup>

Influence of  $\gamma Z$  interference term

Visible difference in the e<sup>+</sup>p and e<sup>-</sup>p cross sections is described well by the SM predictions

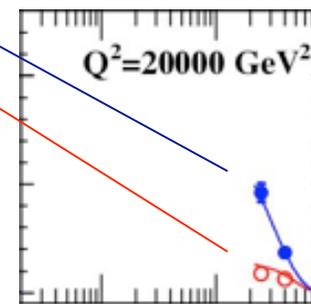
# Evaluation of $x\tilde{F}_3$

## ZEUS

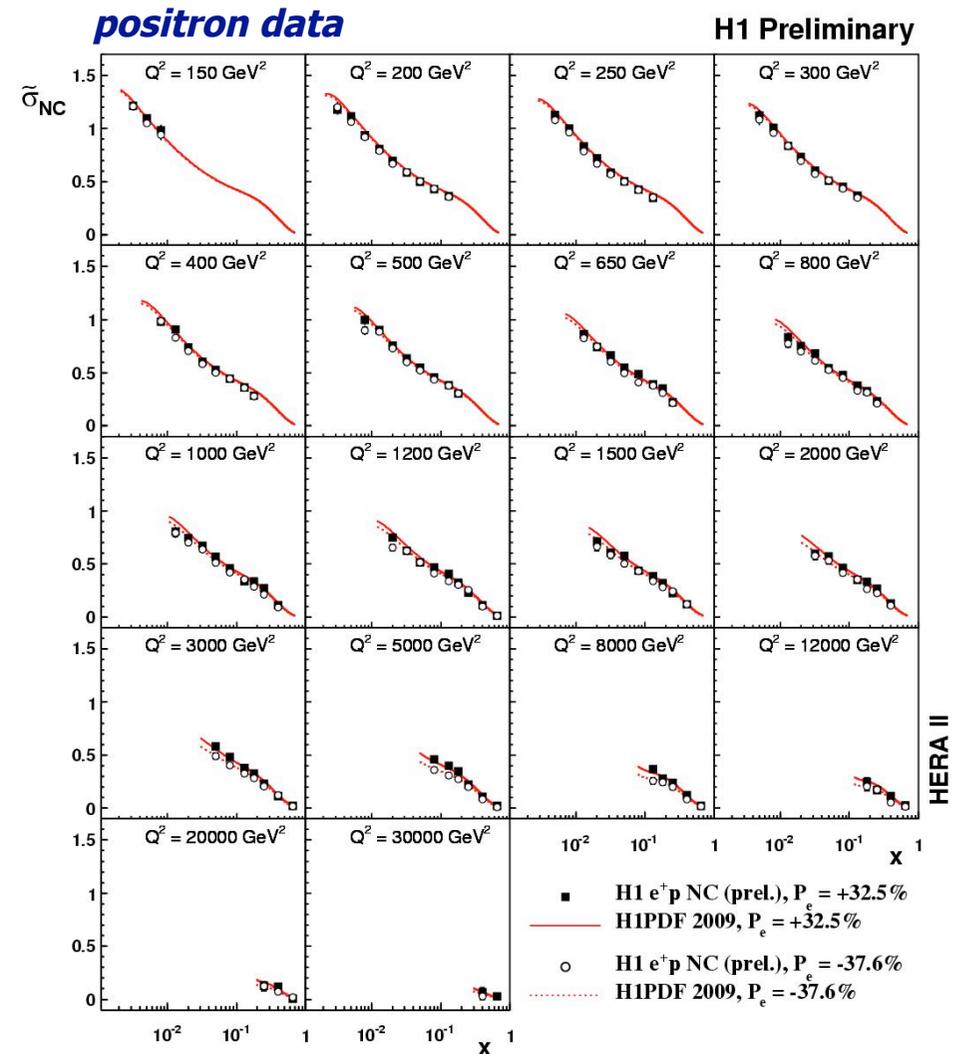
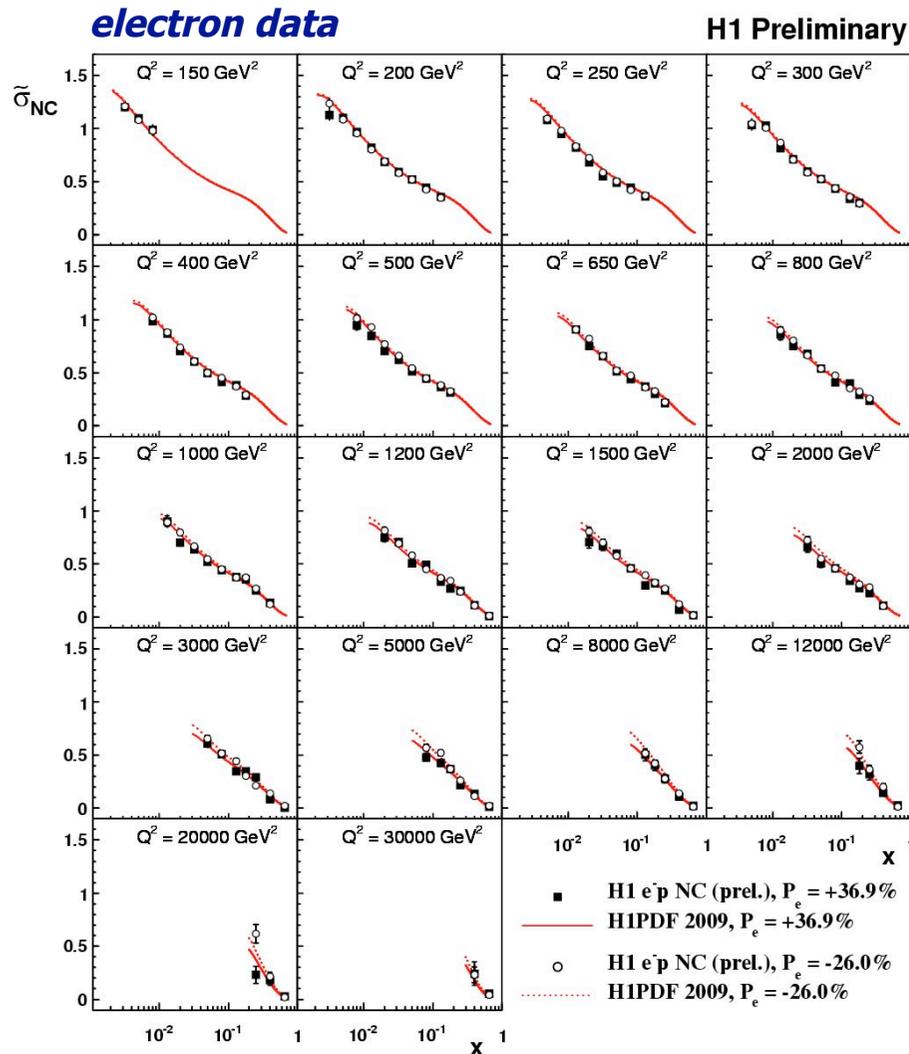


$x\tilde{F}_3$  is calculated from the difference in the unpolarised reduced cross sections at high  $Q^2$

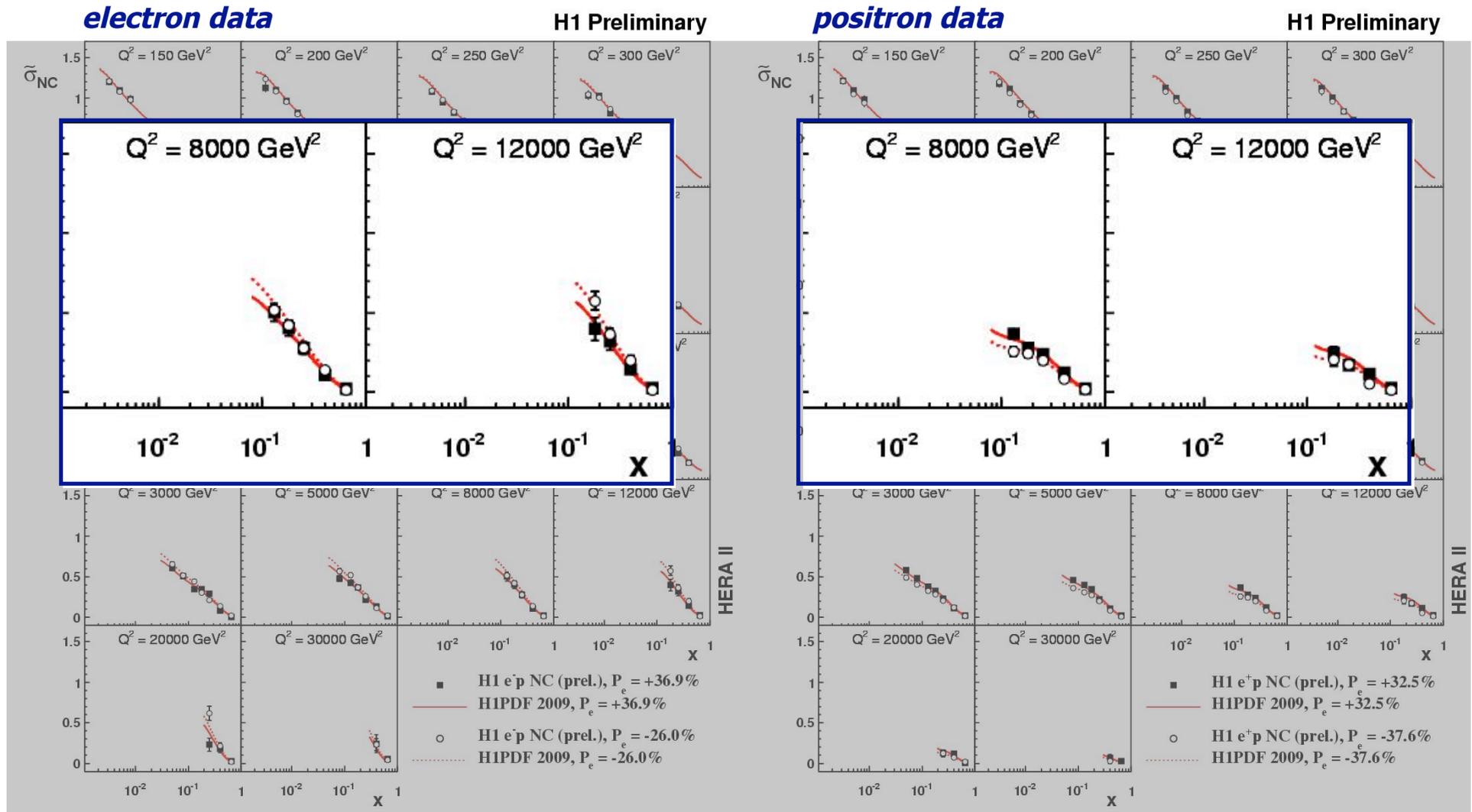
$$x\tilde{F}_3 = \frac{Y_+}{2Y_-} [\tilde{\sigma}^-(x, Q^2) - \tilde{\sigma}^+(x, Q^2)]$$



# Polarised Reduced NC Cross Section: -P vs. +P



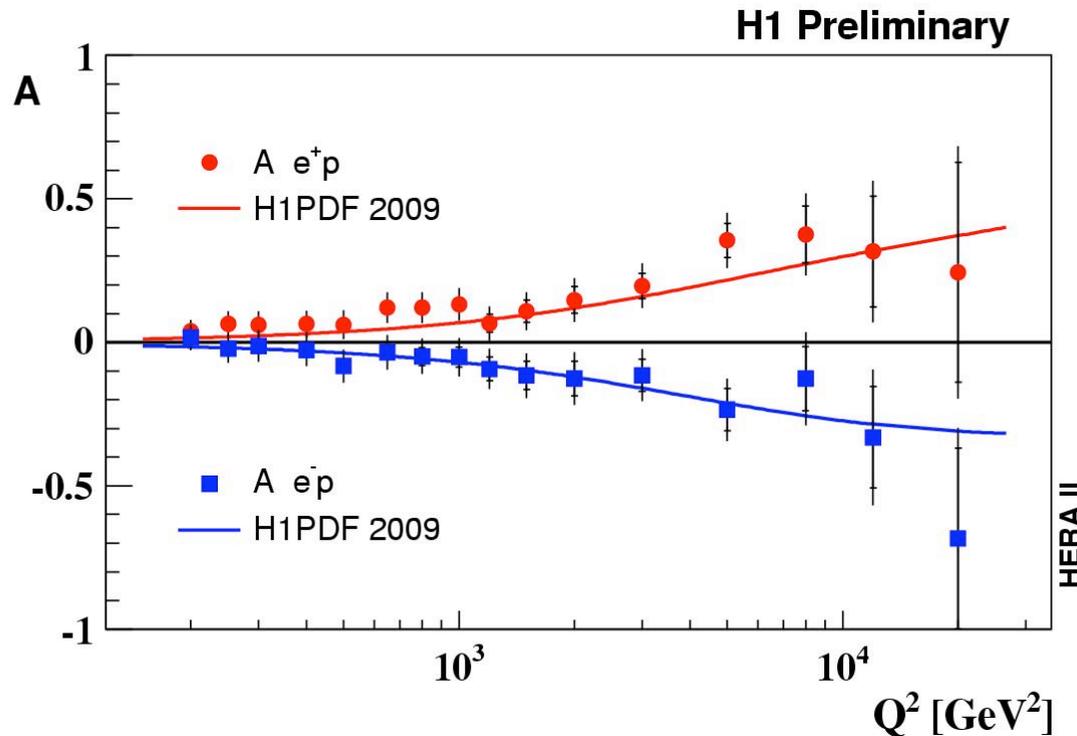
# Polarised Reduced NC Cross Section: -P vs. +P



Influence of lepton beam polarisation visible at high  $Q^2$ : separation of measurements

# HERA II Polarisation Asymmetry in NC

$\gamma$   $\longrightarrow$  influence of  $Z^0$



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

$$P_e = \frac{N_R - N_L}{N_R + N_L} \quad \begin{array}{l} P_R > 0 \\ P_L < 0 \end{array}$$

Form polarisation asymmetry from HERA II Neutral Current measurements

- clear observation of parity violation of NC electroweak exchange

Nicely illustrates the properties of the different polarisation and lepton charge data

Well described by the SM prediction

# Charged Current Cross Sections

**$e^+p$  cross section:**

Sensitive to the density of the d quark

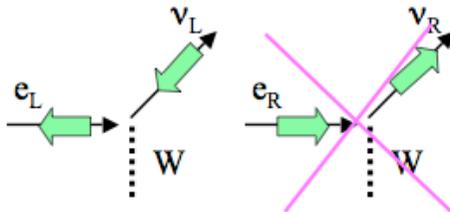
$$\frac{d^2\sigma^{CC}(e^+p)}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ \bar{u} + \bar{c} + (1-y)^2(d+s) \right]$$

**$e^-p$  cross section:**

$\tilde{\sigma}(x, Q^2)/x$

$$\frac{d^2\sigma^{CC}(e^-p)}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ u + c + (1-y)^2(\bar{d} + \bar{s}) \right]$$

Sensitive to the density of the u quark



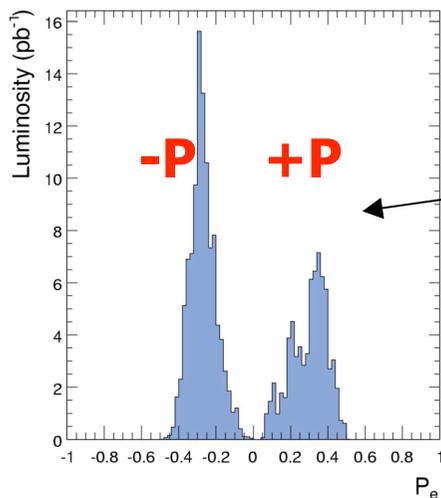
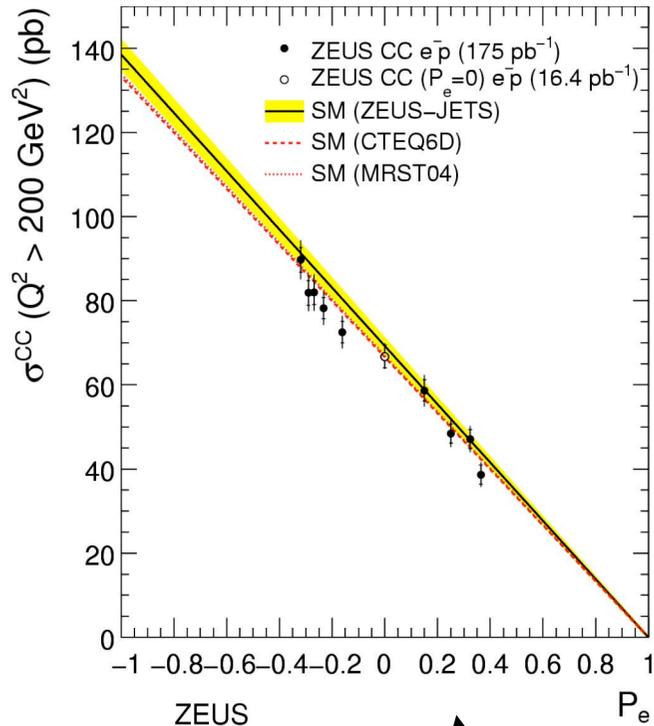
Standard Model weak interaction left-handed:  
only LH Particles (RH anti-particles) interact

**CC cross section modified by polarisation  $P_e$ :**

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

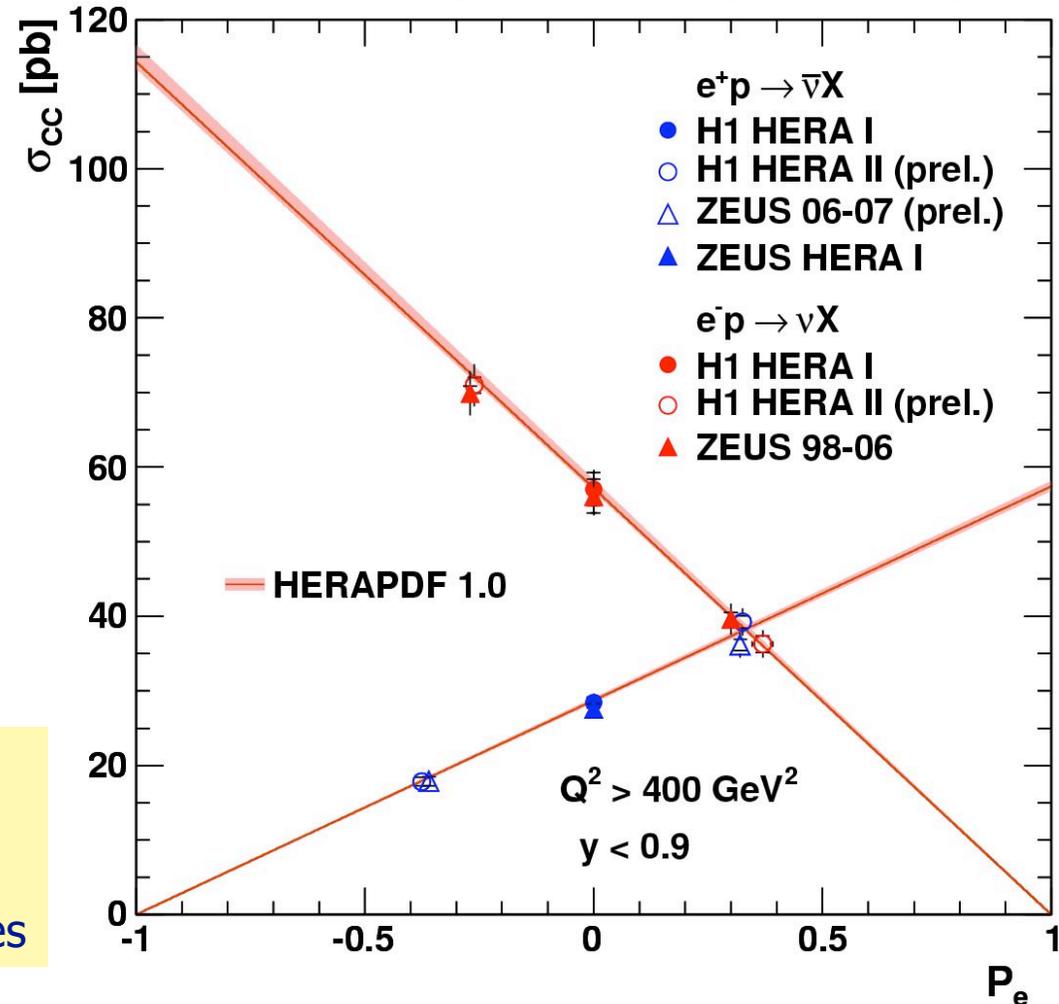
Polarisation scales the  $P_e=0$  cross section  
linearly: *clear and large effect at HERA*  
**SM predicts zero cross section for  $P_e=+1(-1)$  in  $e^{-(+)p}$  scattering**

# Charged Current Cross Section vs. Polarisation



Measurements made by ZEUS using various polarisation values

## HERA Charged Current $e^\pm p$ Scattering

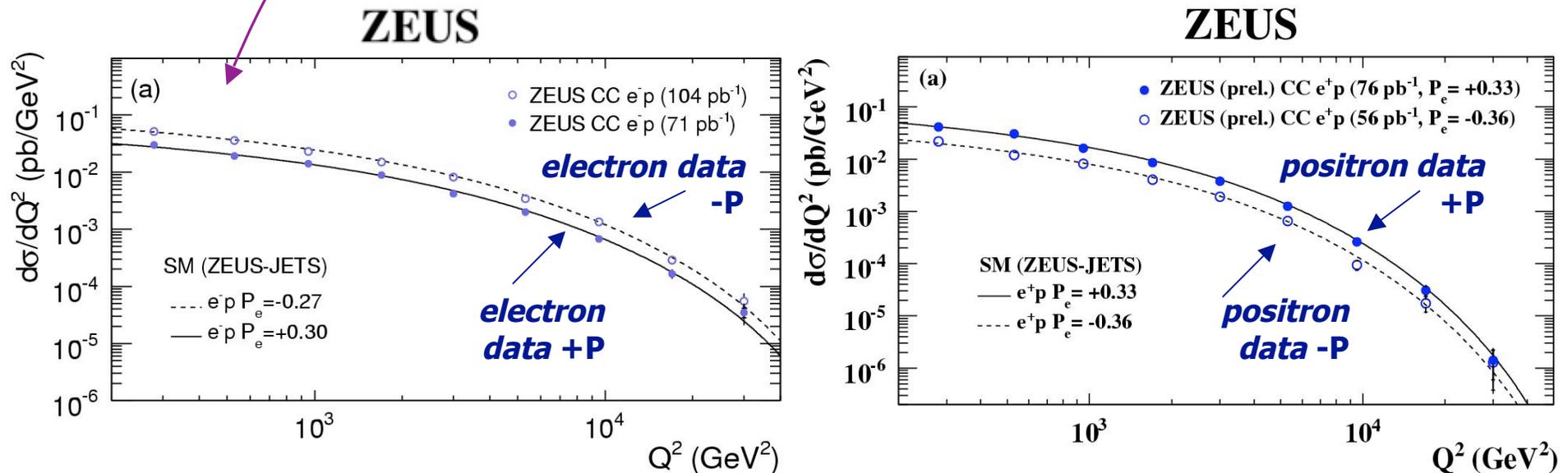


Data exhibit linear dependence of average polarisation and HERA I and II measurements agree with the SM prediction

# Single Differential CC Cross Sections $d\sigma/dQ^2$

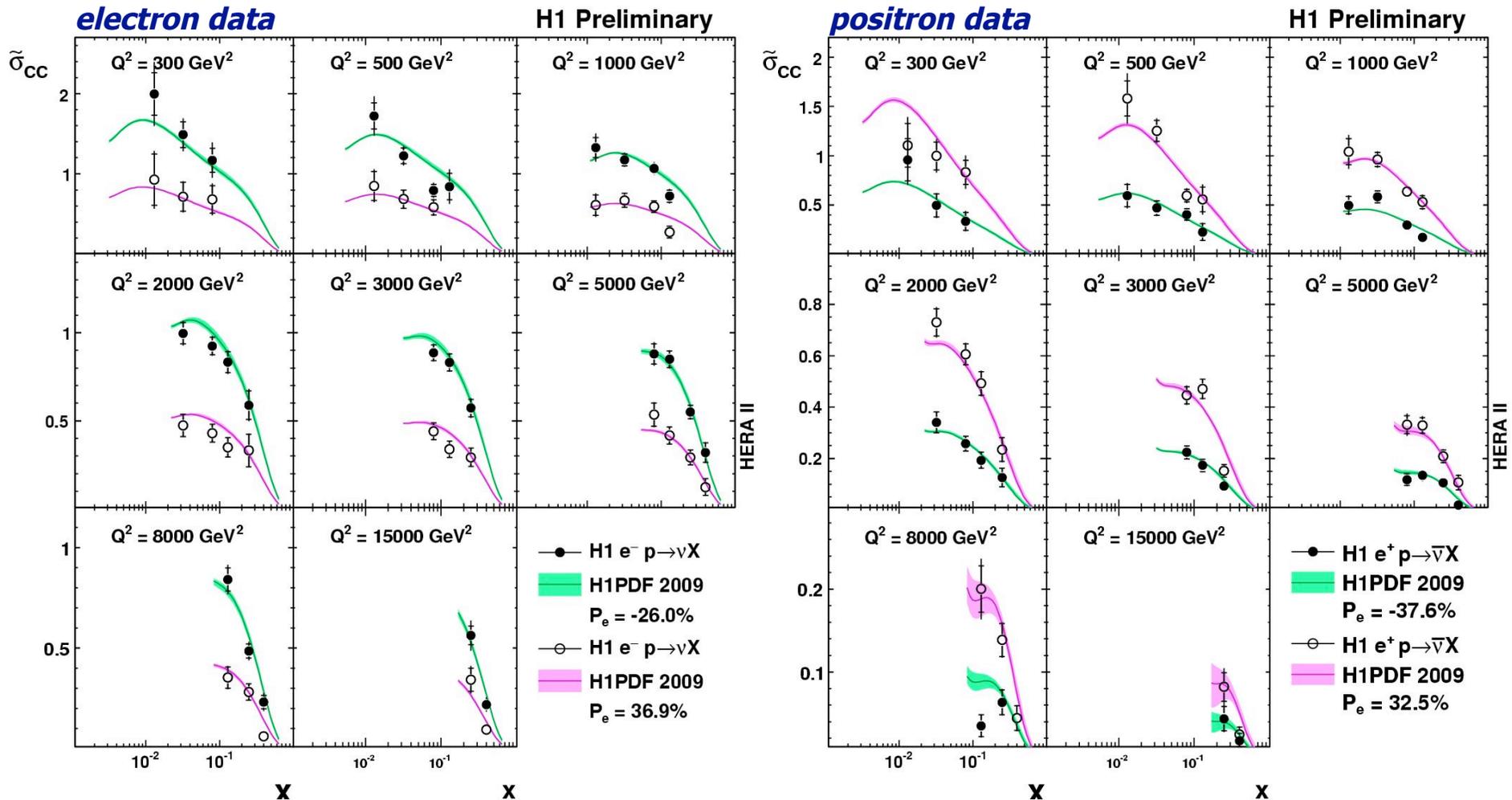
W propagator: cross section much lower than NC

$$\left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2$$



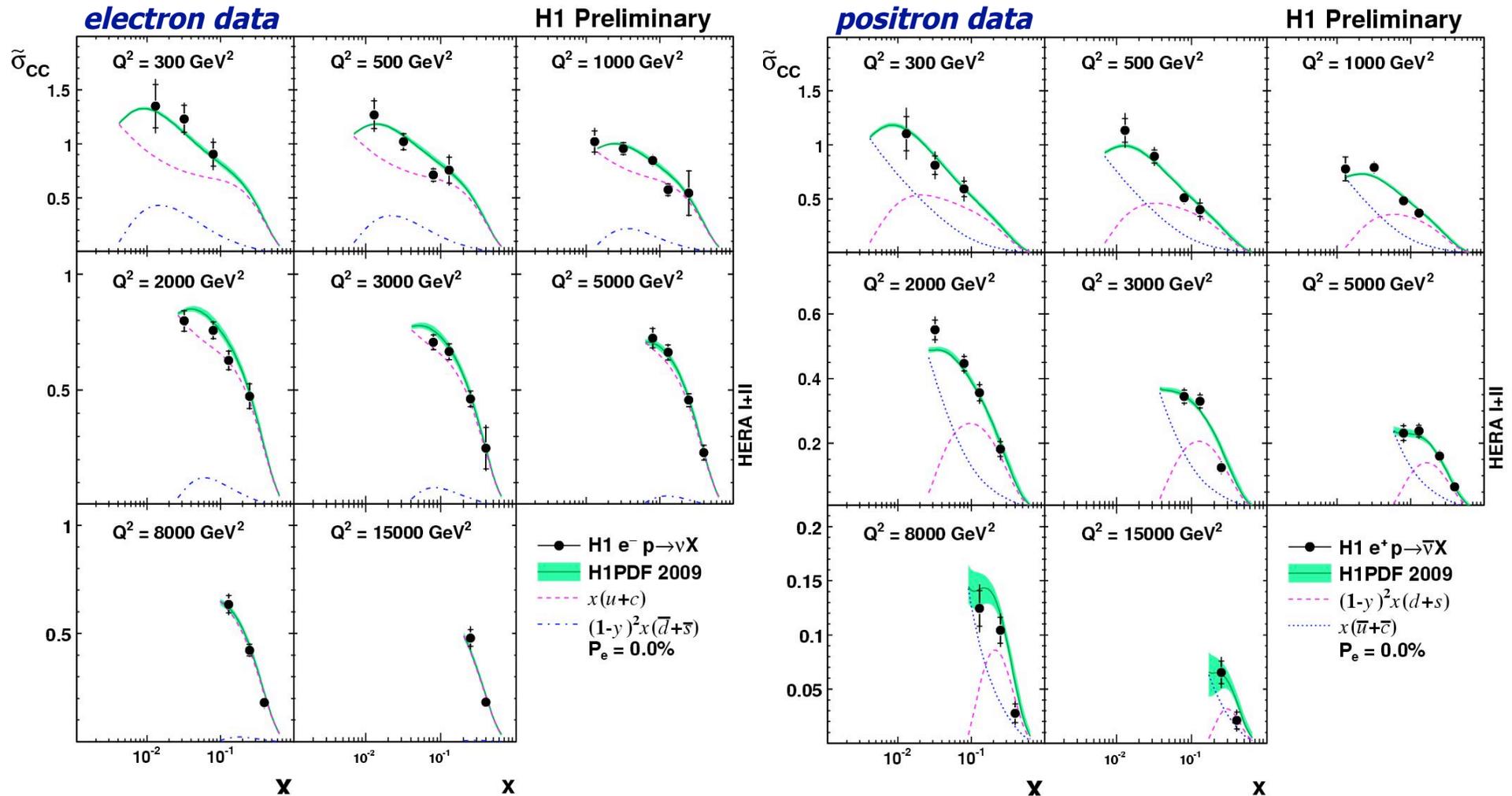
Higher cross section of  $e^-p$  data visible, difference due to quark content  
 Opposite polarisation dependence of data sets visible  
 Good agreement with SM model prediction based on ZEUS-JETS QCD fit

# Reduced CC Cross Section: -P vs. +P



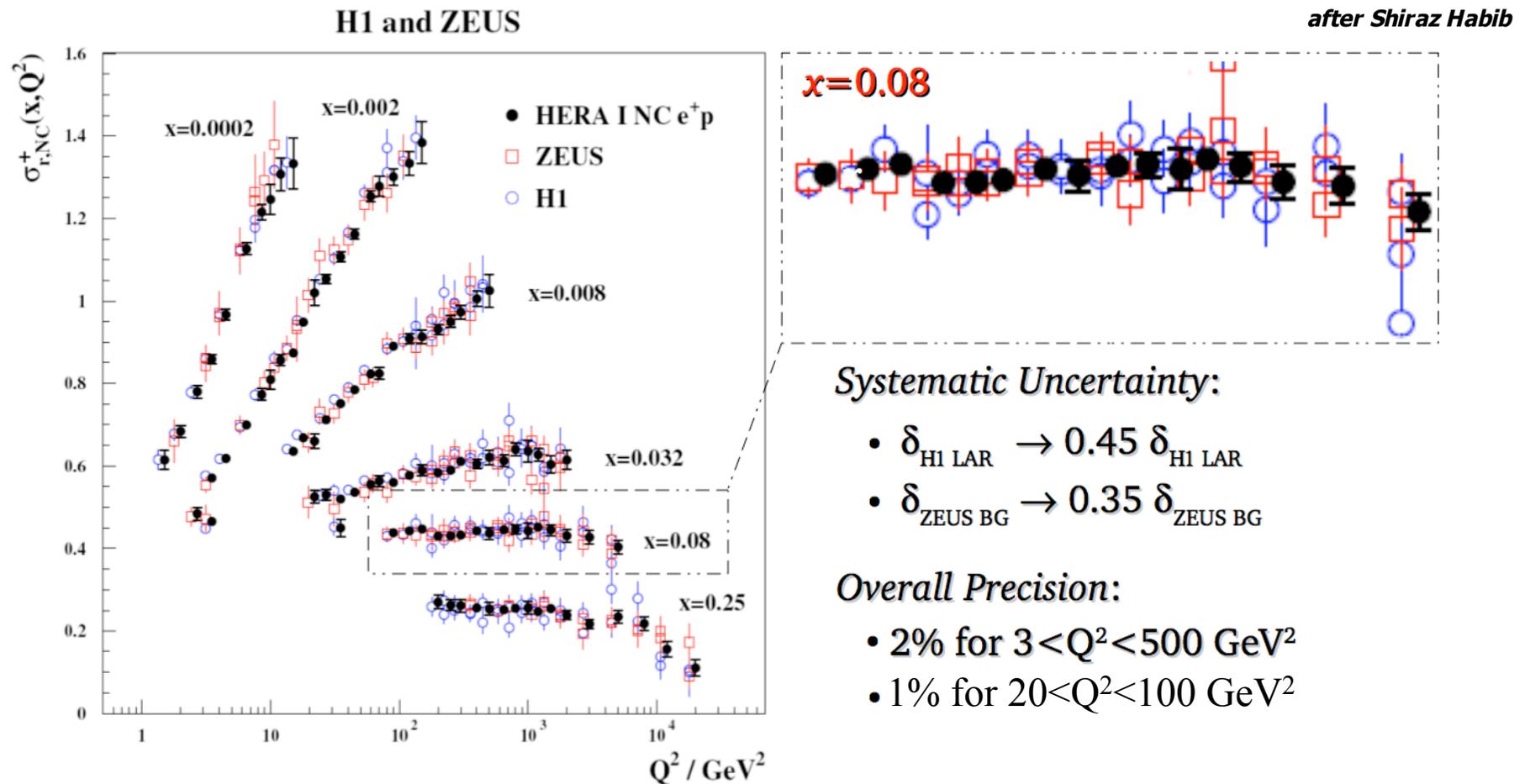
Similarly from H1, double differential cross sections show clear polarisation asymmetry

# Unpolarised Reduced CC Cross Section: $e^-p$ vs. $e^+p$



CC interaction allows for a clean flavour decomposition:  
 $e^-p$ : u-type quarks dominate;  $e^+p$ : d-type dominates at high  $x$ , sea dominates at low  $x$

# Combined H1 and ZEUS High $Q^2$ Measurements



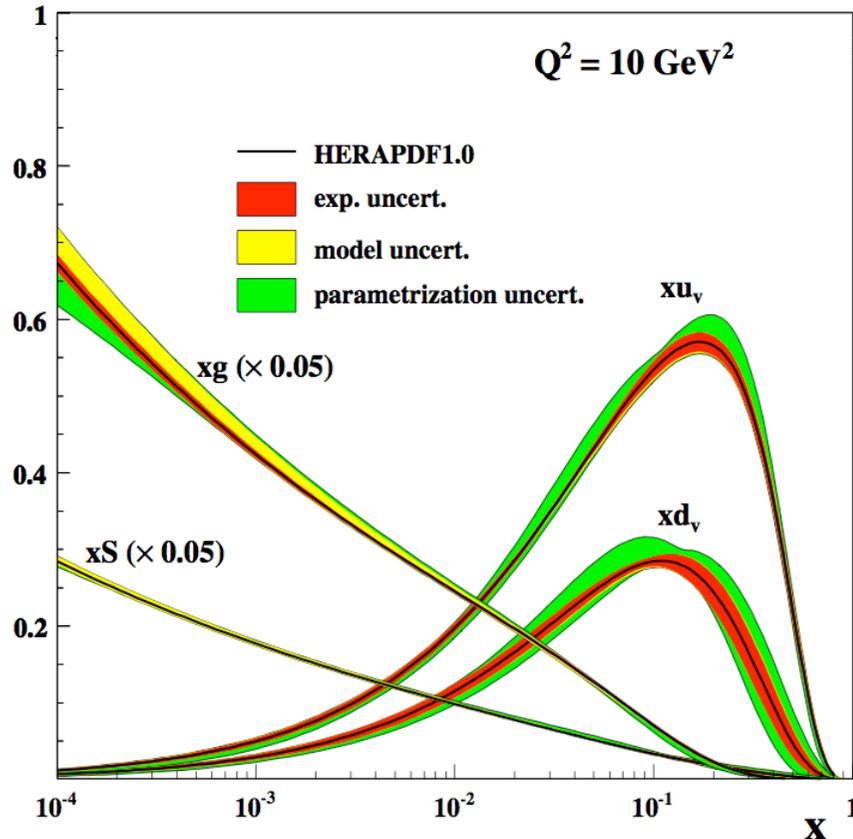
Improved measurements by combining the H1 and ZEUS high  $Q^2$  data

– So far only HERA I, *but HERA II will follow soon*

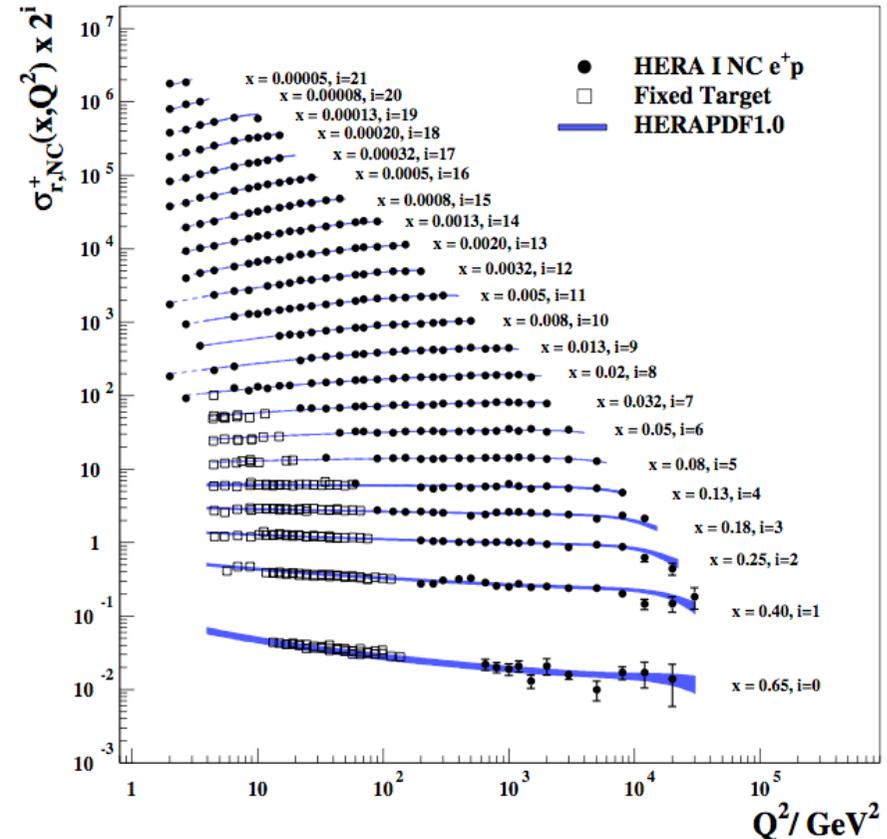
The HERA inclusive combined cross sections (NC and CC,  $e^\pm p$ ) form a consistent data set, allowing the extraction of valence quark, sea quark and gluon PDFs

# HERAPDF 1.0

H1 and ZEUS



H1 and ZEUS

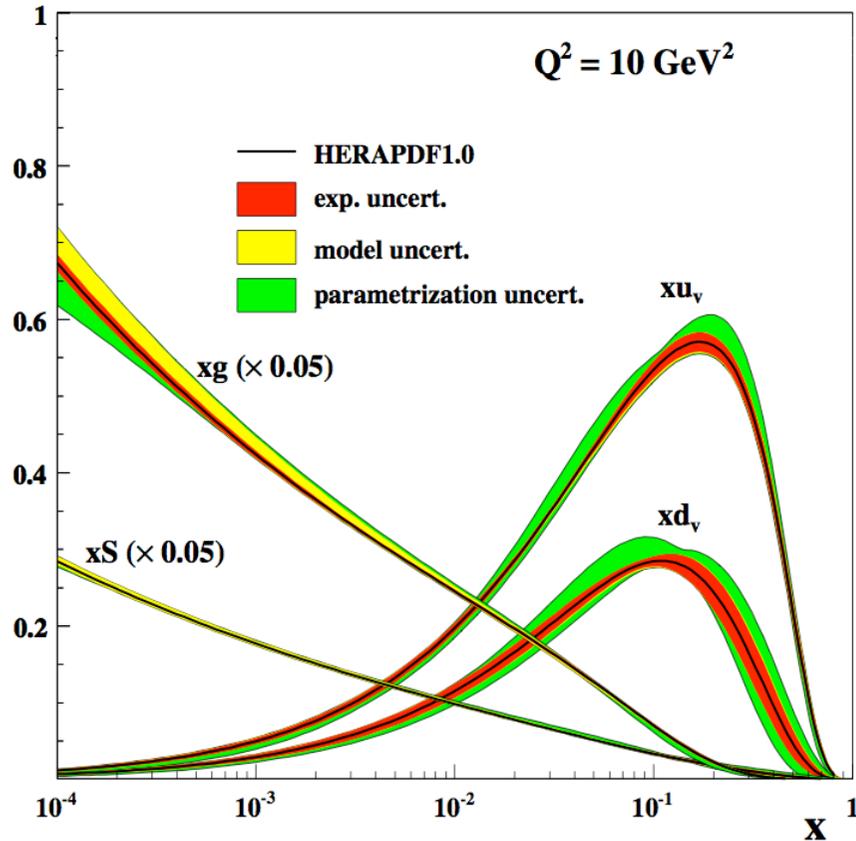


An NLO QCD fit to the combined measurement results in the **HERAPDF 1.0** PDFs with a precision at the level of a few % in the low  $x$  region

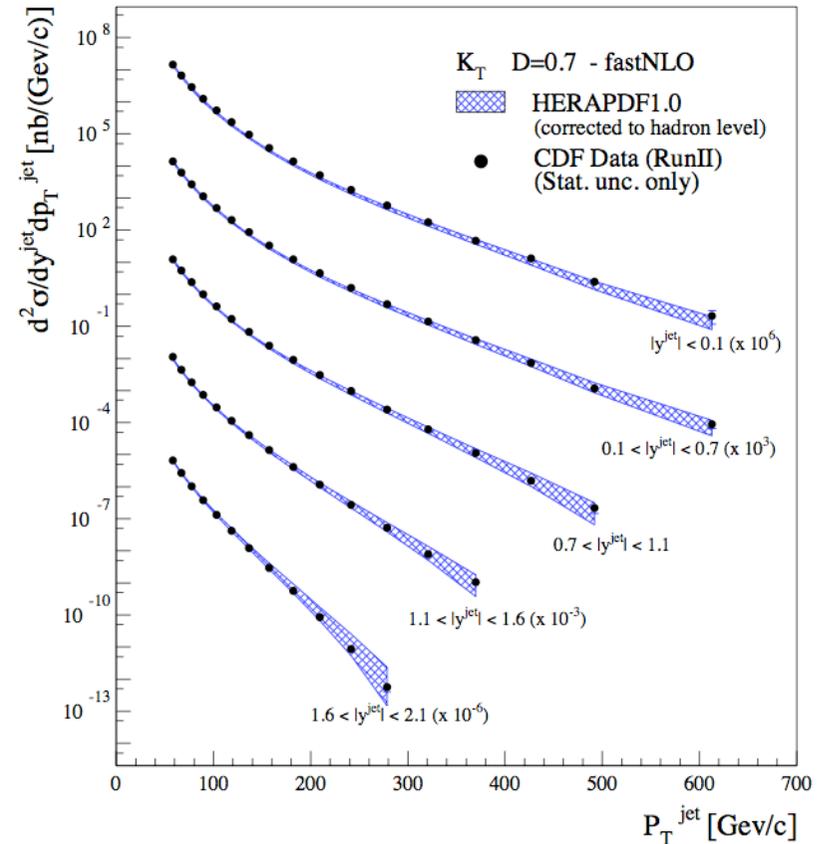
HERA (and fixed target) data well described by the fit, scaling violation observed

# HERAPDF 1.0

H1 and ZEUS



Tevatron Jet Cross Sections



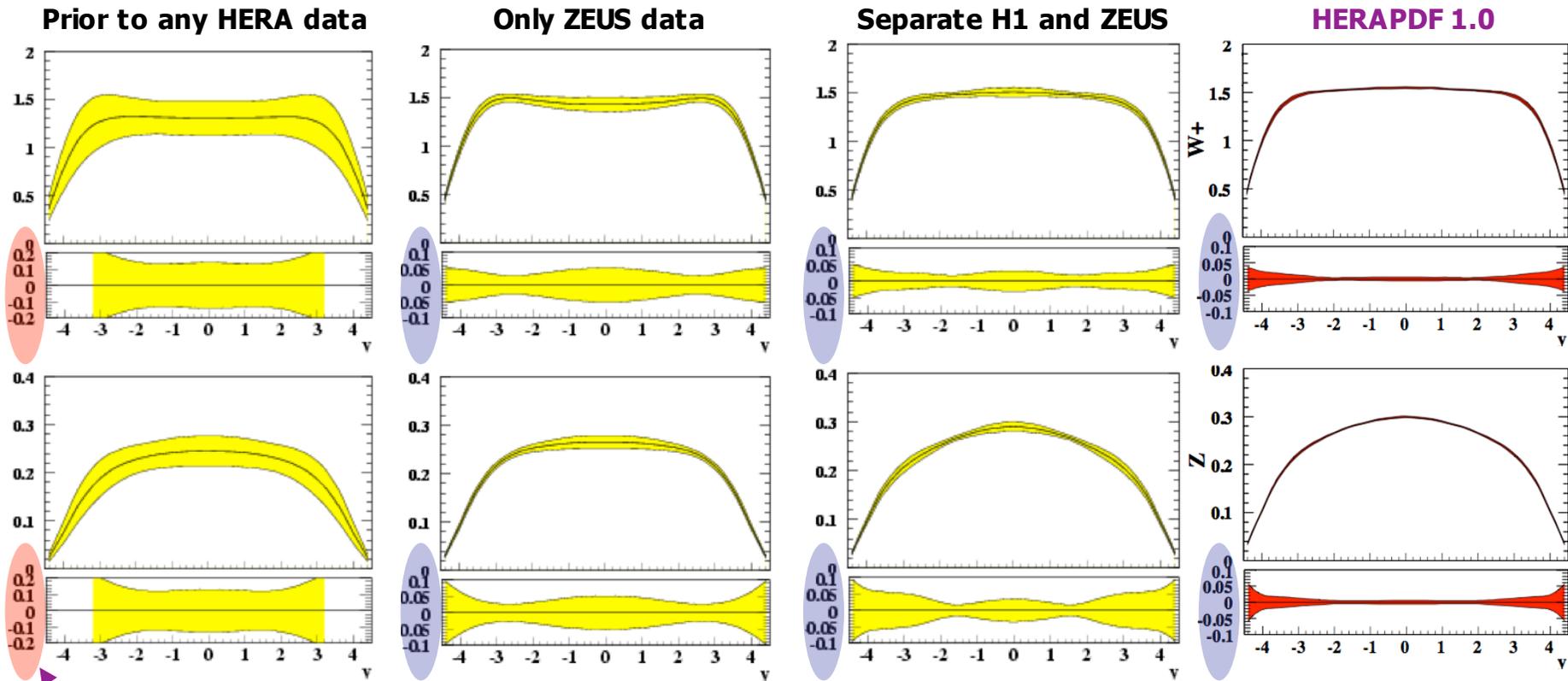
An NLO QCD fit to the combined measurement results in the **HERAPDF 1.0** PDFs with a precision at the level of a few % in the low x region

And Tevatron data are described too!

# Impact of HERA Data at the LHC

$W^+$ , Z rapidities (at 14 TeV!)

after Voica Radescu, and Amanda Cooper-Sarkar



Note scale!

Experimental uncertainty at central rapidities using combined HERA data ~1%!  
[http://www.desy.de/h1zeus/combined\\_results/benchmark/herapdf1.0.html](http://www.desy.de/h1zeus/combined_results/benchmark/herapdf1.0.html)

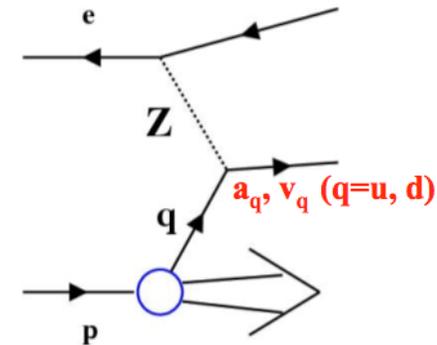
Impressive precision on the low  $x$  sea and gluon of the HERAPDF 1.0 is relevant for  $W, Z$  production at the LHC

Inclusion of HERA data shows the tremendous improvement on the predictions for  $W$  and  $Z$  production at the central rapidity

# Electroweak Fits

NC cross section at HERA also sensitive to the light quark couplings of the Z boson

$$\frac{d^2\sigma_{\text{NC}}^{\pm}}{dx dQ^2} \sim Y_+ \tilde{F}_2 \mp Y_- x \tilde{F}_3 \quad Y_{\pm} = 1 \pm (1-y)^2$$



$$\left[ F_2^{\gamma Z}, F_2^Z \right] = x \sum_q \left[ 2e_q v_q, v_q^2 + a_q^2 \right] \{q + \bar{q}\}$$

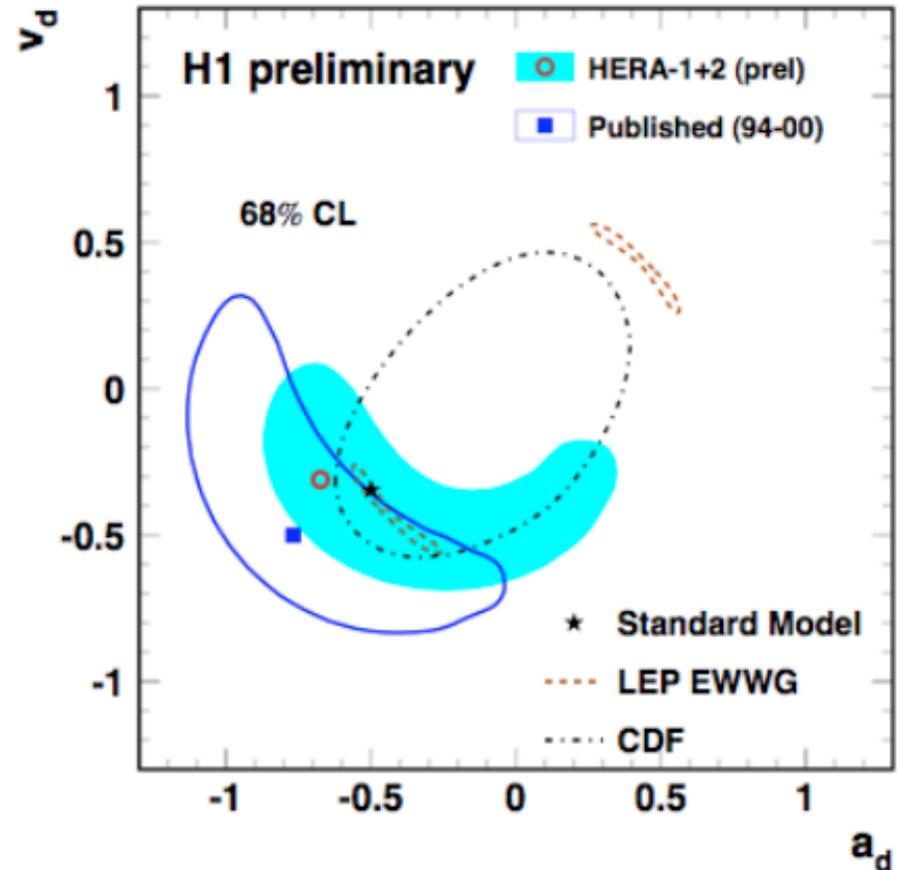
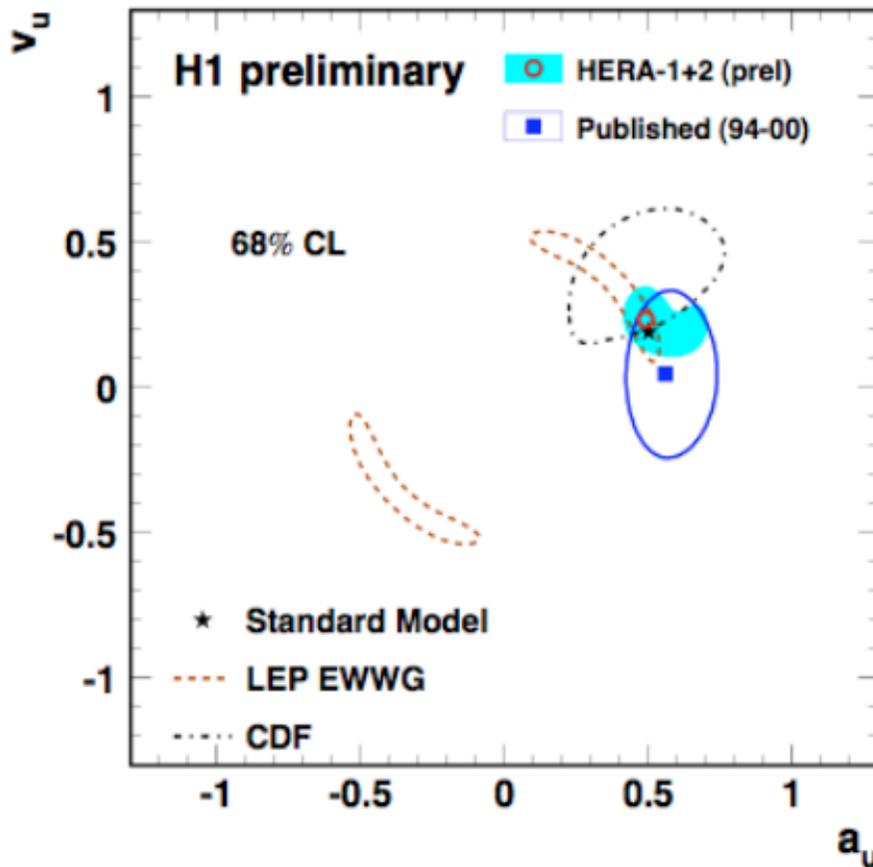
$$\left[ xF_3^{\gamma Z}, xF_3^Z \right] = 2x \sum_q \left[ e_q a_q, v_q a_q \right] \{q - \bar{q}\}$$

- Explored in a combined electroweak and QCD fit of total of 19 data sets
  - New high  $Q^2$  NC and CC as well as precision low  $Q^2$  data
- $a_q$  is mainly constrained by  $xF_3^{\gamma Z}$
- $v_q$  constrained by  $F_2^Z$
- Additional constraint from  $F_2^{\gamma Z}$  using the polarised HERA II data

# Electroweak Fits: Comparison to HERA I Result

CDF:  $qq \rightarrow e^+e^-$  (Drell Yan),  $A_{FB}$

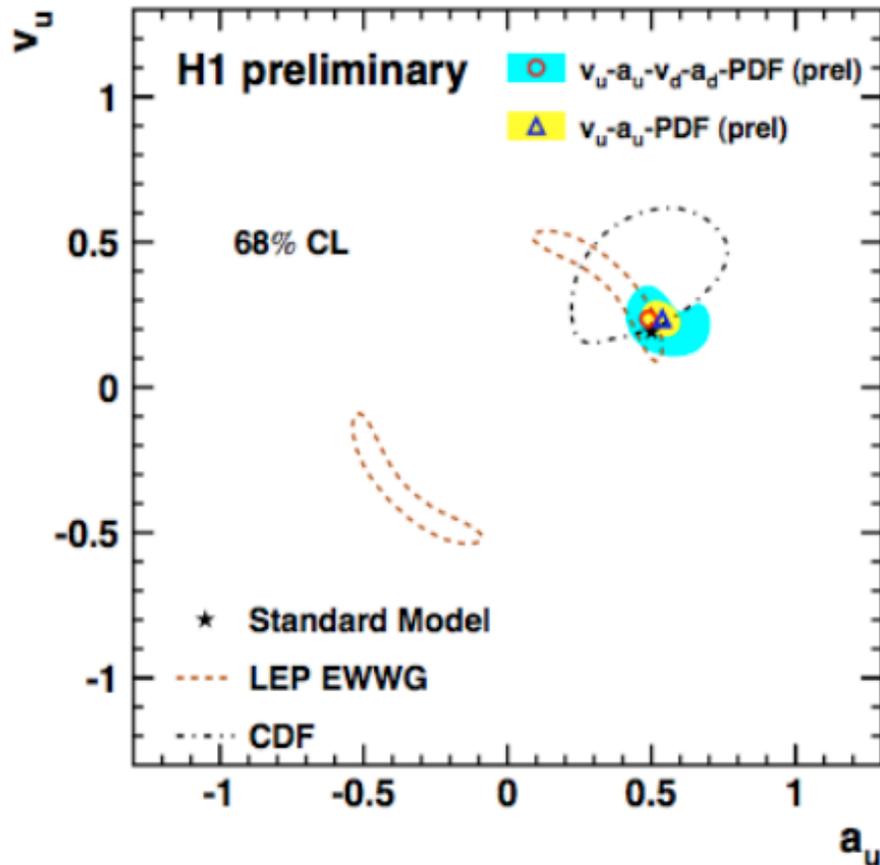
LEP:  $e^+e^- \rightarrow qq(\gamma)$ ,  $a_q^2 + v_q^2$



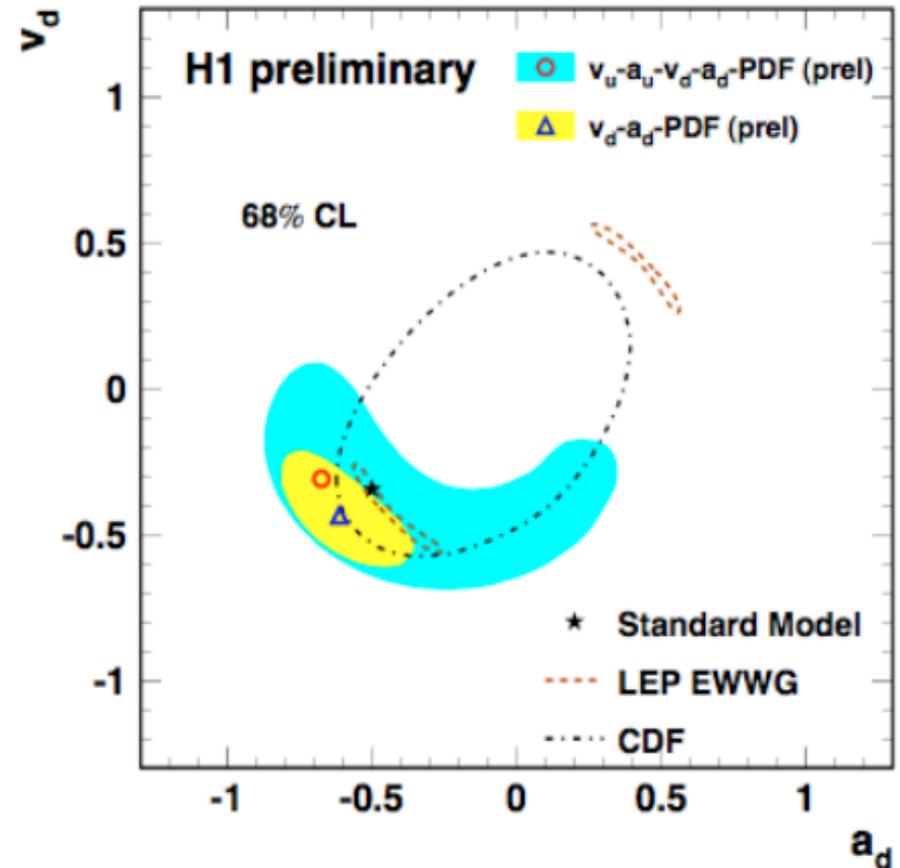
Good agreement with the SM, most improvement in vector coupling from HERA II data as expected

# Electroweak Fits: Additional Constraint

Fix d quark couplings & fit  $v_u$ - $a_u$ -PDF



Fix u quark couplings & fit  $v_d$ - $a_d$ -PDF



Reduced correlation and thus much improved precision  
Further improvement expected from combined H1+ZEUS data

# Moving on to Rare Events and Processes



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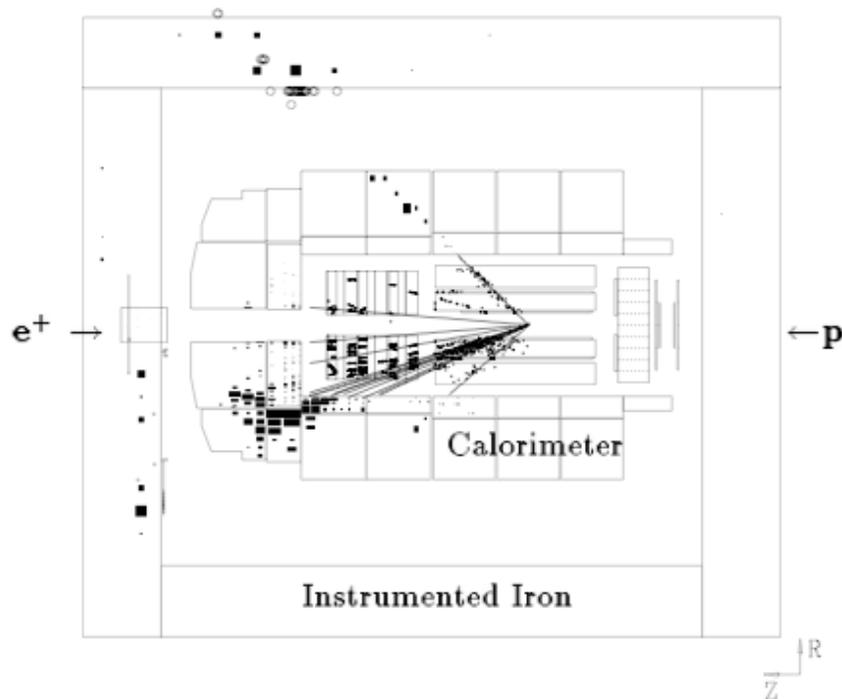
Team	Pld	W	D	L	GF	GA	GD	Pts
United States	2	2	0	0	6	0	+6	4
Paraguay	2	1	0	1	1	3	-2	2
Belgium	2	0	0	2	0	4	-4	0



2010

Team	v · d · e	Pld	W	D	L	GF	GA	GD	Pts
United States		3	1	2	0	4	3	+1	5
England		3	1	2	0	2	1	+1	5
Slovenia		3	1	1	1	3	3	0	4
Algeria		3	0	1	2	0	2	-2	1

# Moving on to Rare Events and Processes



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December 1994

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Observation of an  $e^+p \rightarrow \mu^+X$  Event with High Transverse Momenta at HERA

H1 Collaboration

Abstract

At the HERA electron-proton collider an event has been observed in the H1 detector which shows an isolated muon recoiling against a hadronic system, both of high transverse momentum. The event was registered in a total integrated luminosity of  $4 \text{ pb}^{-1}$ .

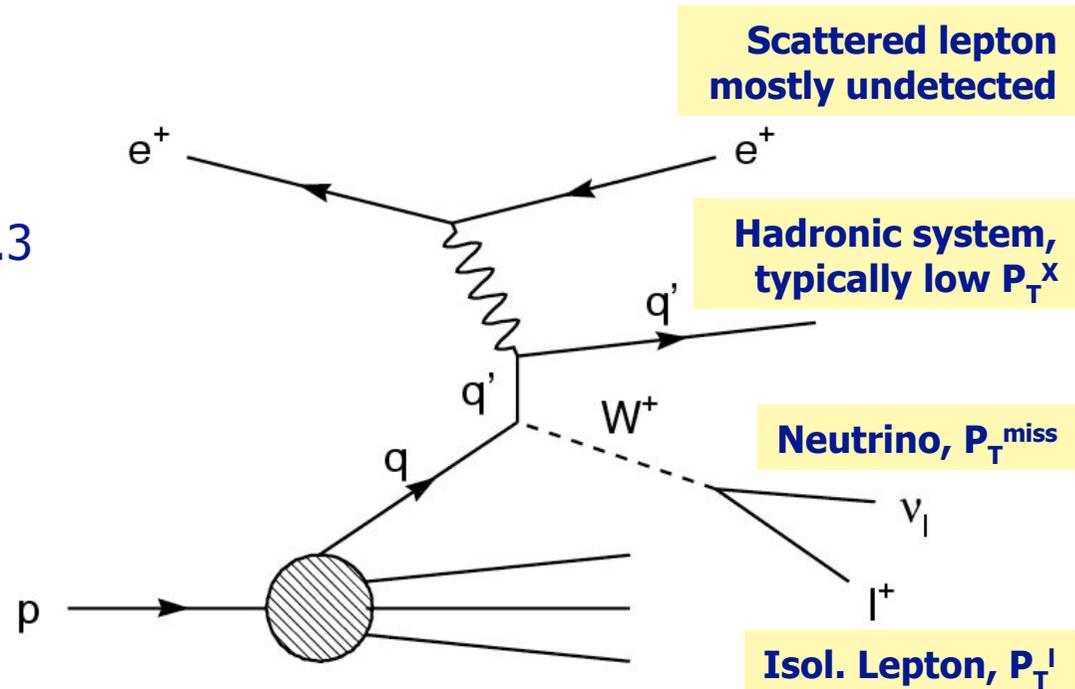
1994: Interesting H1 event observed during manual scanning of candidate CC events

Several interpretations postulated:

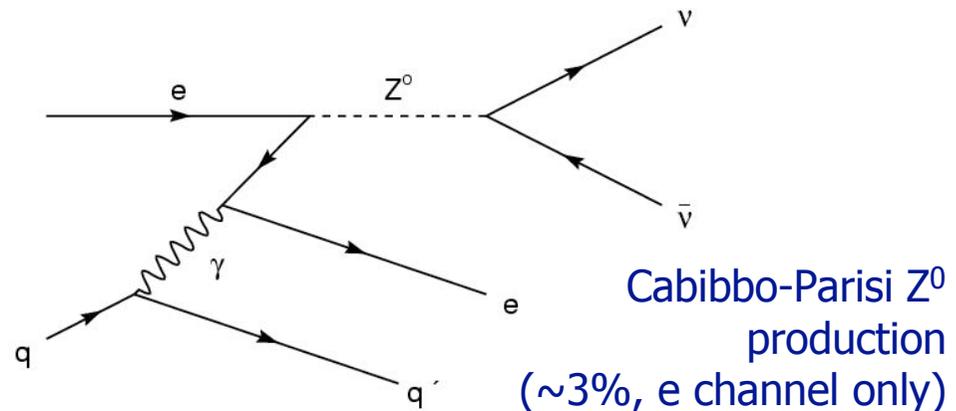
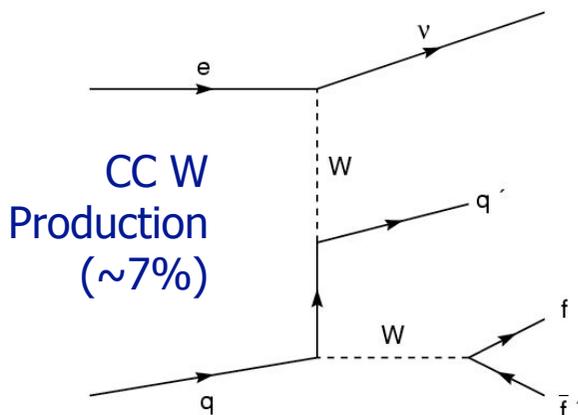
- ✗ High  $P_T$  di-jet event, where 1 jet contains a single particle (pion) faking the muon signature
- ✗ A flavour changing NC process  $e^+ + p \rightarrow \mu^+ + X$ , leptoquark production?
- ✗ A background event due to (e.g.) a halo muon
- ✓ Production of W bosons with leptonic decay

# SM Processes with Isolated Leptons and $P_T^{\text{miss}}$

- Main SM contribution to signal from *real W production* with subsequent decay to leptons
  - Total cross section of about 1.3 pb, with 10% of W decays to each lepton flavour: very few events expected at HERA
  - Hadronic system typically has **low** transverse momentum
  - Modelled using EPVEC, re-weighted to a NLO calculation



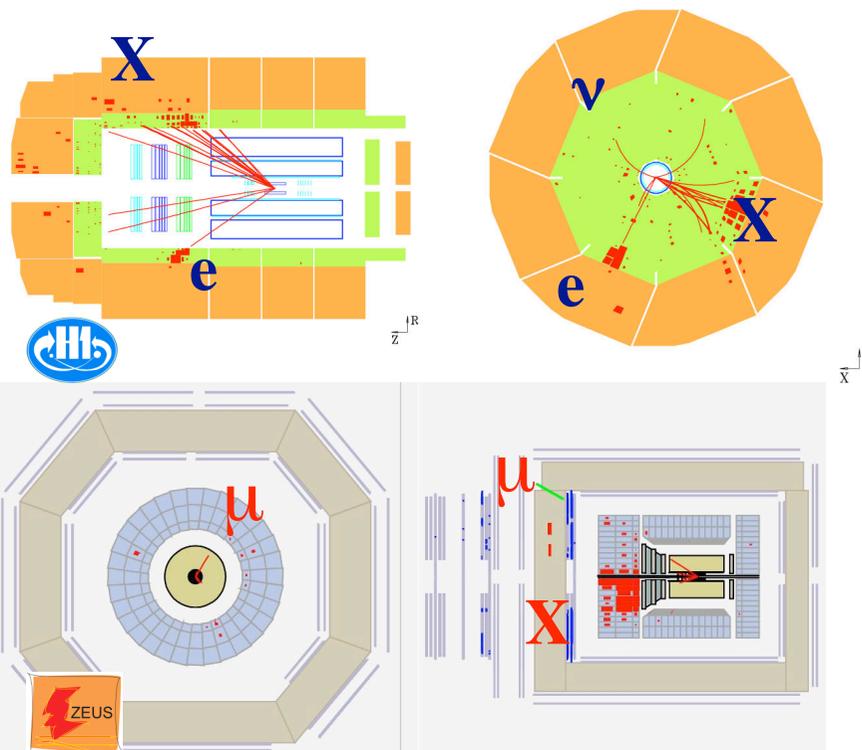
- Two additional processes included that contribute to the signal topology:



# Combined H1 and ZEUS Event Selection

- The SM expectation for signal events at HERA is low, so the analysis benefits from the combination of the full  $1 \text{ fb}^{-1}$  of H1 and ZEUS data in a common phase space
  - Cross sections measured with better statistical precision
  - Increase sensitivity to possible new phenomena
- Electron or muon with high transverse momentum and isolated from other parts of the event, with missing transverse momentum :

$$15^\circ < \theta_{\text{lep}} < 120^\circ, P_T^{\text{lep}} > 10 \text{ GeV}, P_T^{\text{miss}} > 12 \text{ GeV}, D_{\text{lep-jet}} > 1.0, D_{\text{lep-track}} > 0.5$$



*$e + P_T^{\text{miss}}$  event in H1  $e^+p$  data*

$$P_T^e = 37 \text{ GeV}$$

$$P_T^{\text{Miss}} = 44 \text{ GeV}$$

$$P_T^X = 29 \text{ GeV}$$

*$\mu + P_T^{\text{miss}}$  event in ZEUS  $e p$  data*

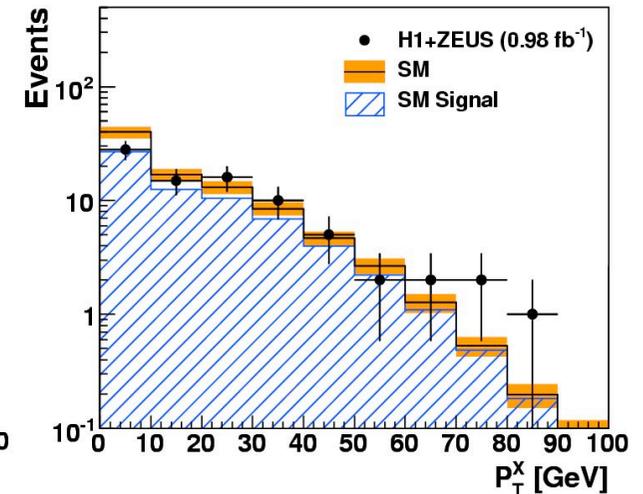
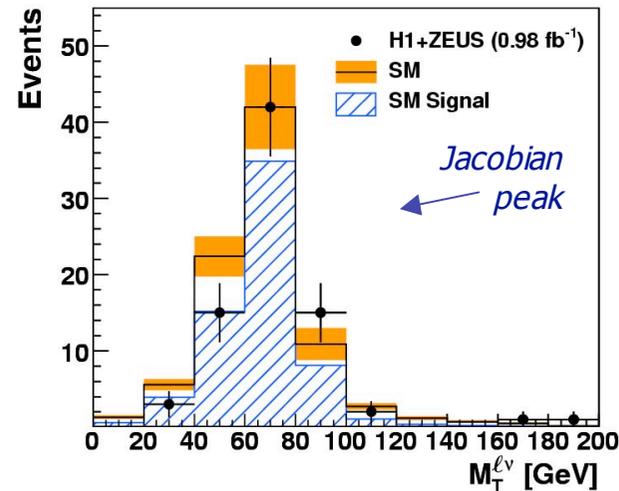
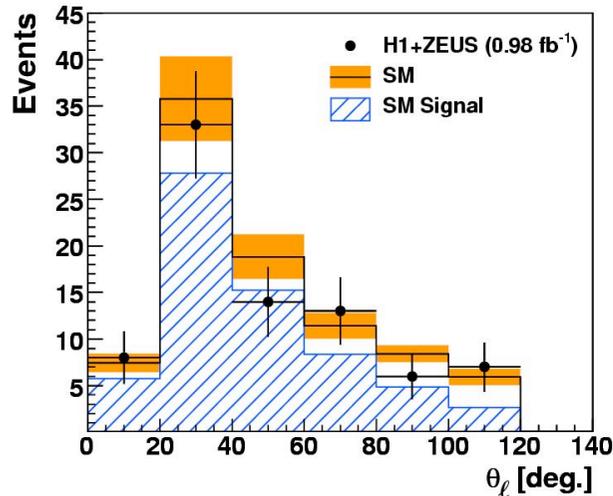
$$\theta^\mu = 32^\circ$$

$$M_T^{\mu\nu} = 79 \text{ GeV}$$

$$P_T^X = 82 \text{ GeV}$$

# H1+ZEUS Isolated Leptons: Results

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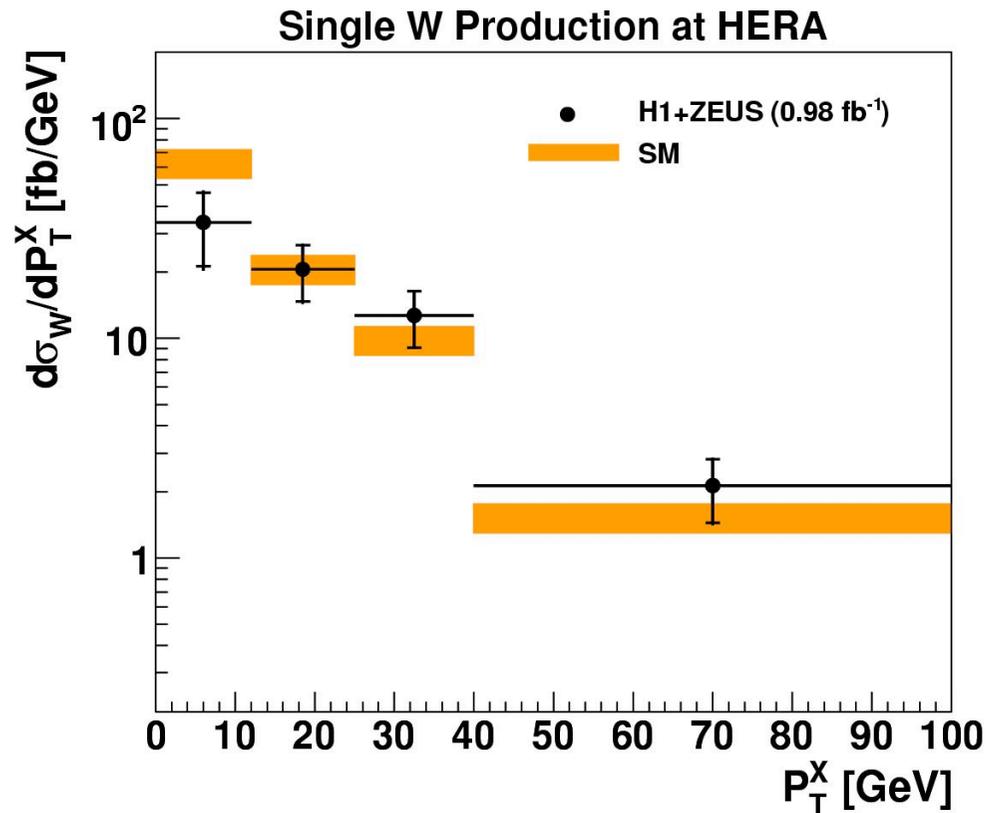


<b>H1+ZEUS</b>		Data	SM	SM	Other SM
1994–2007 $e^\pm p$ 0.98 fb $^{-1}$			Expectation	Signal	Processes
Electron	Total	61	69.2 $\pm$ 8.2	48.3 $\pm$ 7.4	20.9 $\pm$ 3.2
	$P_T^X > 25$ GeV	16	13.0 $\pm$ 1.7	10.0 $\pm$ 1.6	3.1 $\pm$ 0.7
Muon	Total	20	18.6 $\pm$ 2.7	16.4 $\pm$ 2.6	2.2 $\pm$ 0.5
	$P_T^X > 25$ GeV	13	11.0 $\pm$ 1.6	9.8 $\pm$ 1.6	1.2 $\pm$ 0.3
Combined	Total	81	87.8 $\pm$ 11.0	64.7 $\pm$ 9.9	23.1 $\pm$ 3.3
	$P_T^X > 25$ GeV	29	24.0 $\pm$ 3.2	19.7 $\pm$ 3.1	4.3 $\pm$ 0.8

Good overall agreement with the Standard Model

SM expectation dominated W production  
→ *Cross section*

# Single W Production Cross Section



Inclusive single W cross section measured  $1.06 \pm 0.16$  (stat.)  $\pm 0.07$  (sys.) pb, good agreement with the SM prediction of  $1.26 \pm 0.19$  pb from EPVEC, reweighted to NLO

→ Good agreement also with the individual cross section measurements by H1 and ZEUS



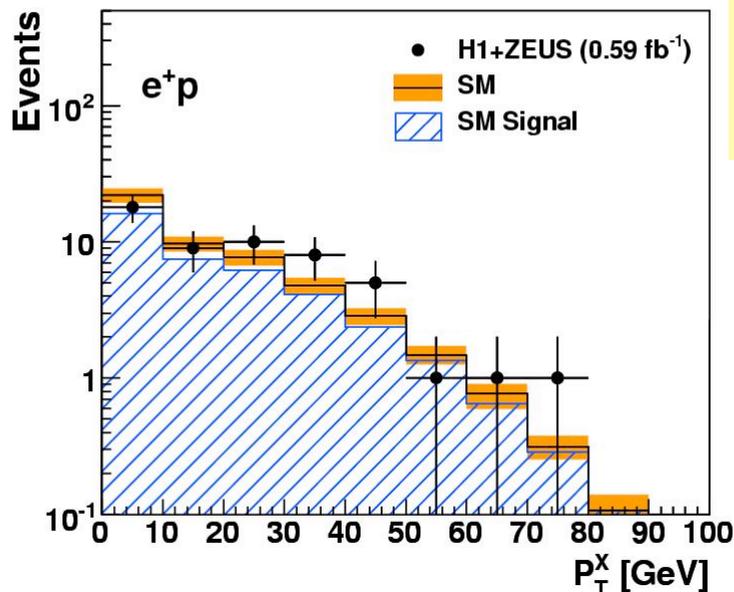
$1.14 \pm 0.25$  (stat.)  $\pm 0.14$  (sys.) pb



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

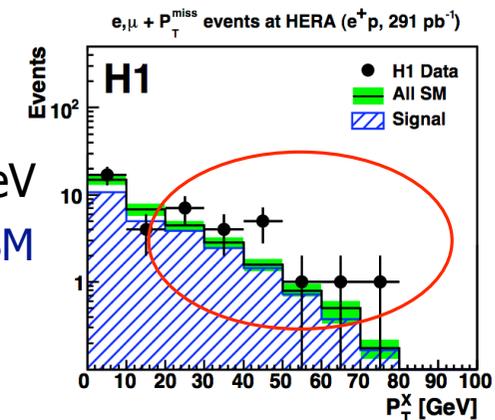
# H1+ZEUS Isolated Leptons: Positron Data

H1+ZEUS		Data	SM	SM	Other SM
1994–2007 $e^+p$ 0.59 fb <sup>-1</sup>			Expectation	Signal	Processes
Electron	Total	37	38.6 ± 4.7	28.9 ± 4.4	9.7 ± 1.4
	$P_T^X > 25$ GeV	12	7.4 ± 1.0	6.0 ± 0.9	1.5 ± 0.3
Muon	Total	16	11.2 ± 1.6	9.9 ± 1.6	1.3 ± 0.3
	$P_T^X > 25$ GeV	11	6.6 ± 1.0	5.9 ± 0.9	0.8 ± 0.2
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4

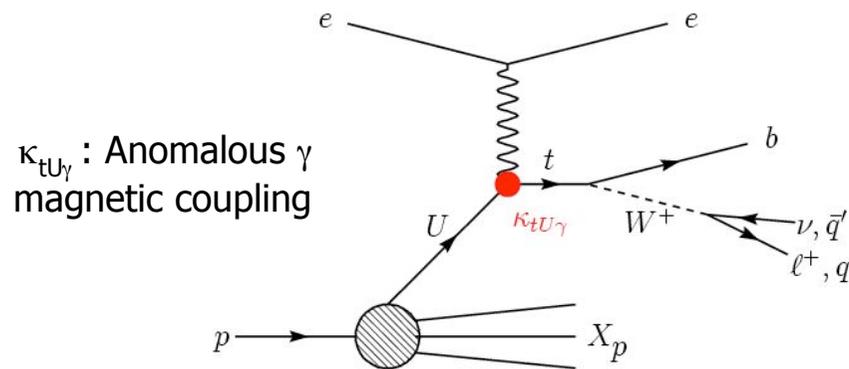


Excess seen in the H1  $e^+p$  data at large  $P_T^X$  still in the common phase space of the combined analysis but is less significant, around  $1.9\sigma$

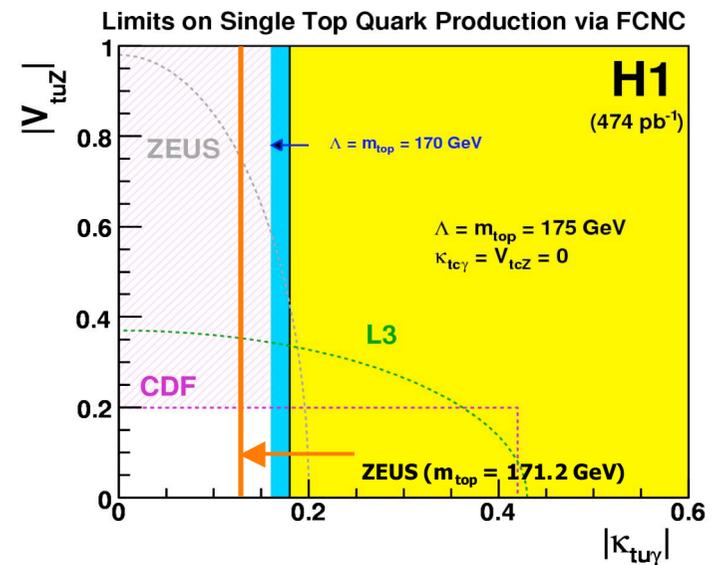
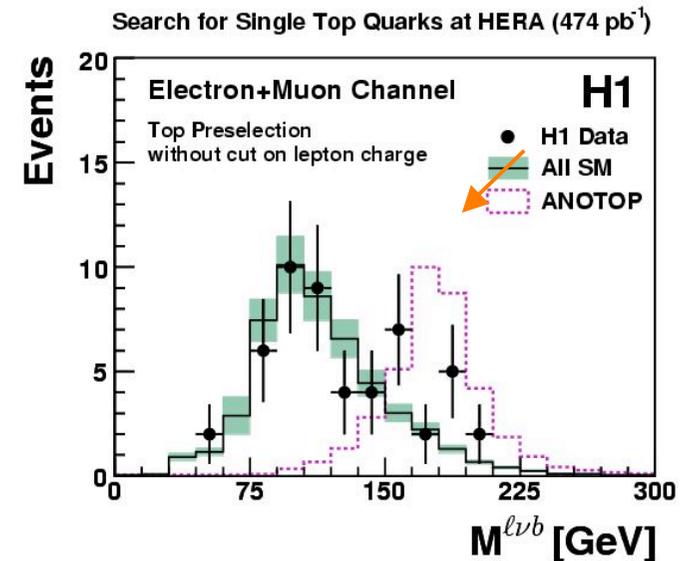
H1  $e^+p$   $P_T^X > 25$  GeV  
17 data /  $8.0 \pm 1.3$  SM



# Search for Anomalous Single Top Production



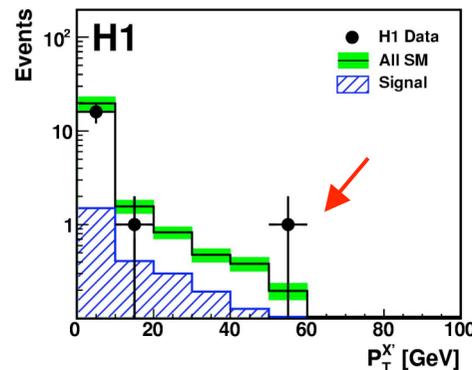
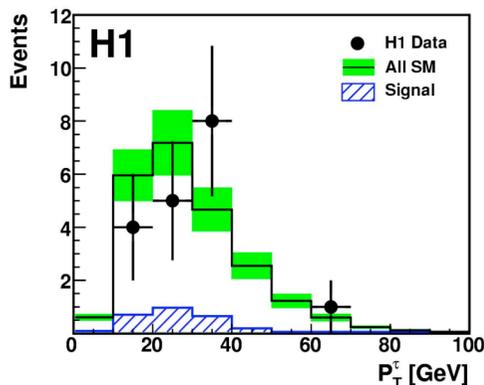
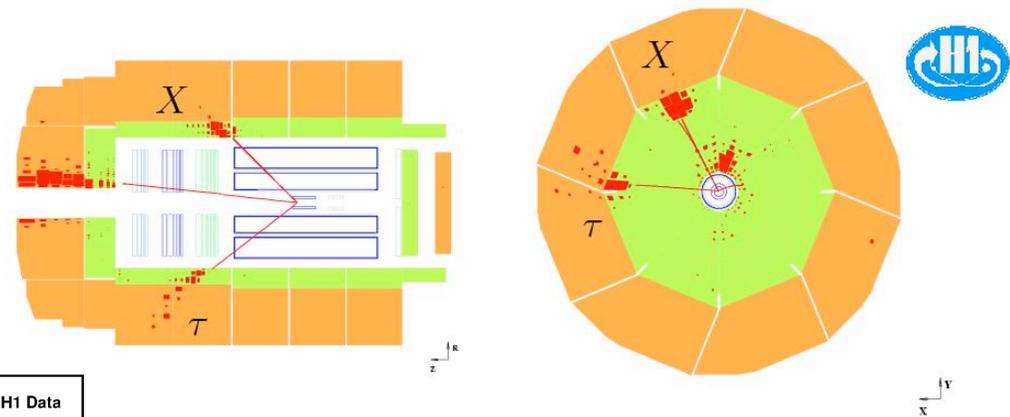
- Leptonic W decay channels:
  - Top pre-selection is like a subset of the isolated lepton selection
- Hadronic W decay channel (H1 only)
  - 3 jet selection  $P_{T,jet1,2,3} > 40, 30, 15$  GeV
  - Pair of jets with  $65 < M_{i,j} < 95$  GeV
- No significant signal observed, derive upper bounds on cross section at 95% CL:
  - H1:  $\sigma(ep \rightarrow etX) < 0.25$  pb
  - ZEUS:  $\sigma(ep \rightarrow etX) < 0.13$  pb



# Analysis of Events with Isolated Tau-Leptons

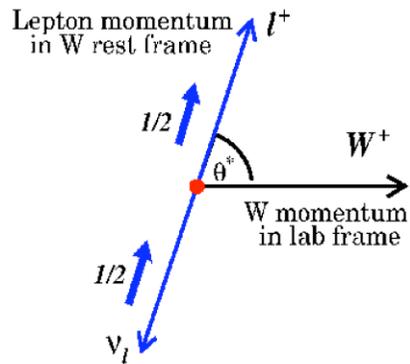
- Look for events with  $P_T^{\text{miss}}$  and narrow jets from hadronic decay
- Complementary results to those in the electron and muon channels
- Signature of 1-prong tau decay (45% branching ratio)
  - 1 charged track (the "prong"): narrow, pencil like jet
- Good overall agreement with the SM prediction
- Expectation dominated by CC background (challenging hadronic environment)

H1	Tau Channel	Data	SM	SM	Other SM Processes
			Expectation	Signal	
1994-2007 $e^+p$ 291 pb <sup>-1</sup>	Total	9	12.3 ± 2.0	1.66 ± 0.25	10.6 ± 1.8
	$P_T^X > 25$ GeV	0	0.82 ± 0.12	0.38 ± 0.06	0.44 ± 0.06
1999-2006 $e^-p$ 183 pb <sup>-1</sup>	Total	9	11.0 ± 1.9	1.00 ± 0.15	10.0 ± 1.8
	$P_T^X > 25$ GeV	1	0.68 ± 0.11	0.21 ± 0.03	0.47 ± 0.07
1994-2007 $e^\pm p$ 474 pb <sup>-1</sup>	Total	18	23.2 ± 3.8	2.66 ± 0.40	20.6 ± 3.4
	$P_T^X > 25$ GeV	1	1.50 ± 0.21	0.59 ± 0.09	0.91 ± 0.12



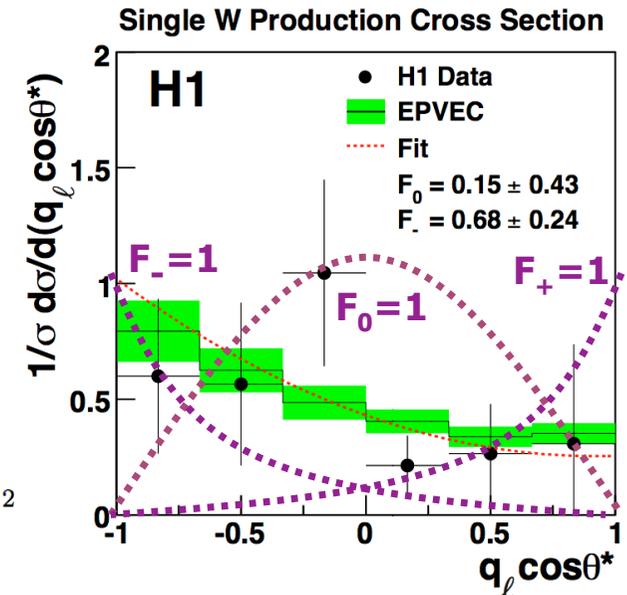
HERA-I:  
Isolated Tau Leptons  
2 / 0.2 ± 0.05 at  $P_T^X > 25$  GeV

# H1 Measurement of W Polarisation Fractions

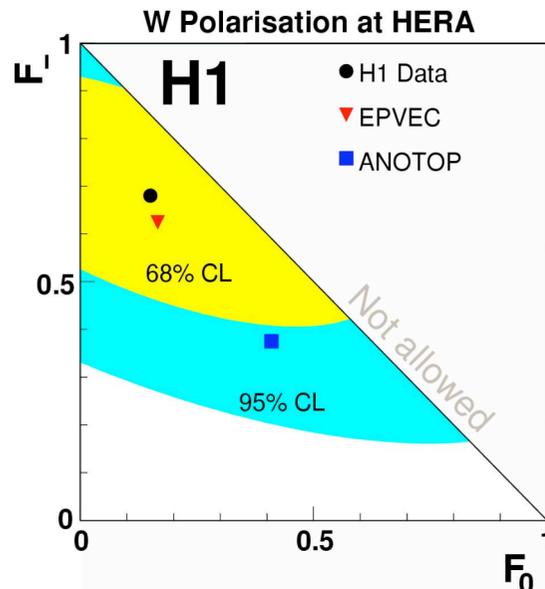


- Cross section can be expressed in terms of W polarisation fractions: *sensitive to angular properties of the decay*
- Measure cross section as a function of  $\cos \theta^*$

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



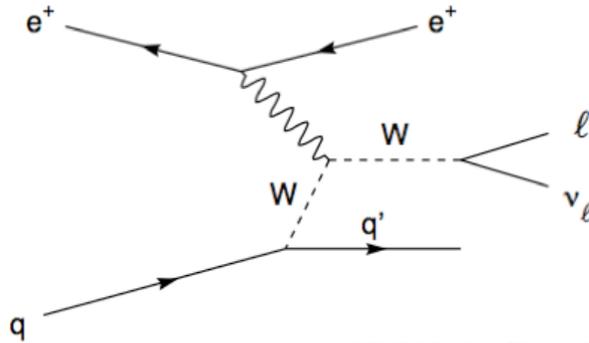
$$F_+ \equiv 1 - F_- - F_0$$



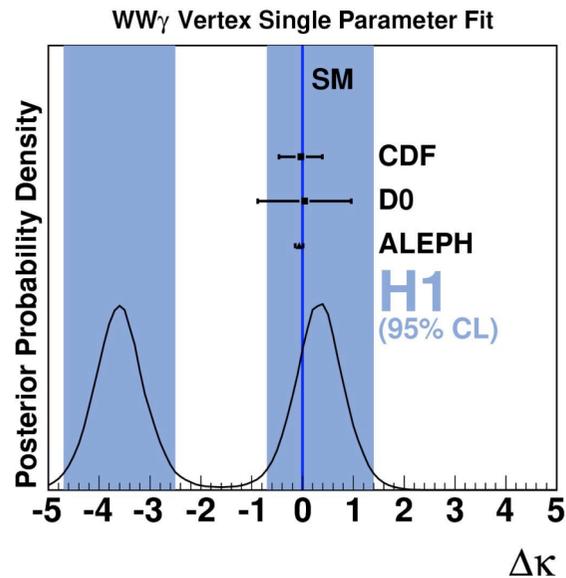
- $F_0$  and  $F_-$  simultaneously extracted in a fit
- Measure for single W Production, and test with anomalous top production model
  - May be different for SM and BSM contributions

Difference demonstrated, but sensitivity only at the 1 sigma level

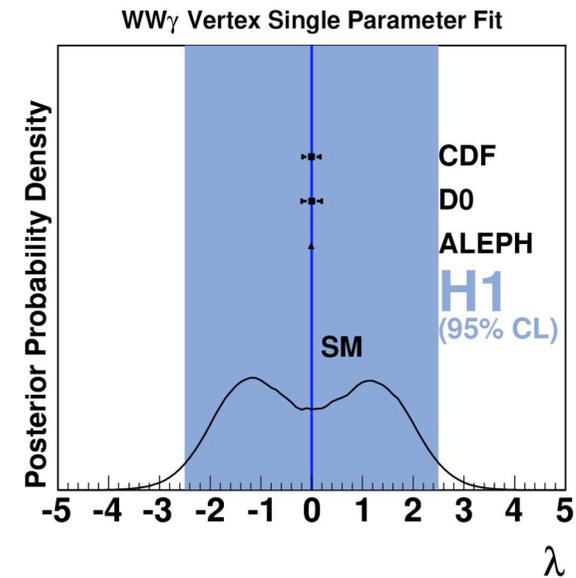
# H1 Limits on $WW\gamma$ Coupling Parameters



- 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  $\Delta\kappa$ ,  $\lambda$  using maximum likelihood analysis



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

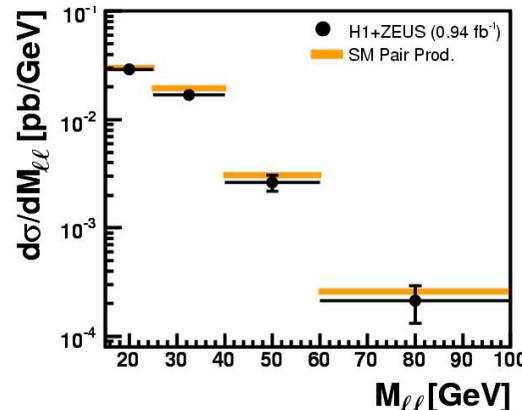
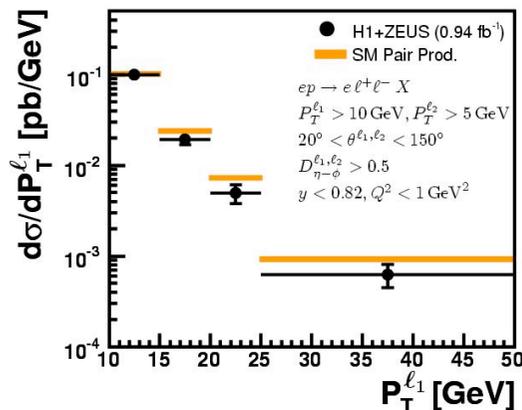
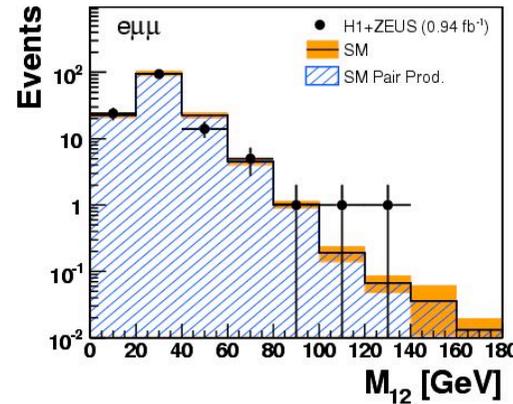
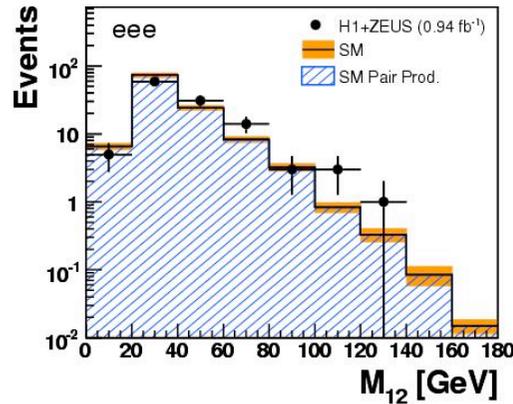
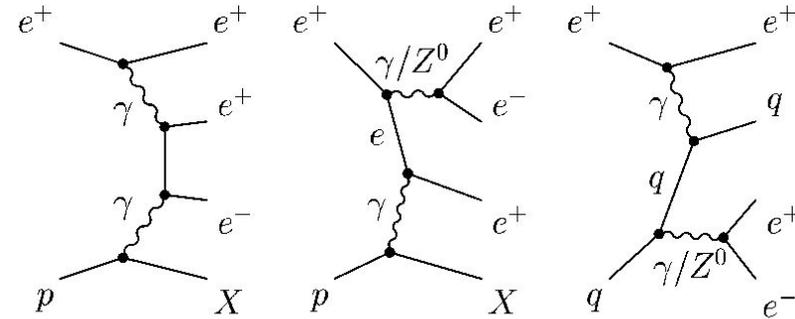


$$-2.5 < \lambda < 2.5$$

H1 measurements compatible to W production at other colliders

# Events with Multiple High $P_T$ Leptons

This QED process has a precise SM prediction, modelled using GRAPE  
Two photon process dominates, but  $Z^0$  production contributes at high masses

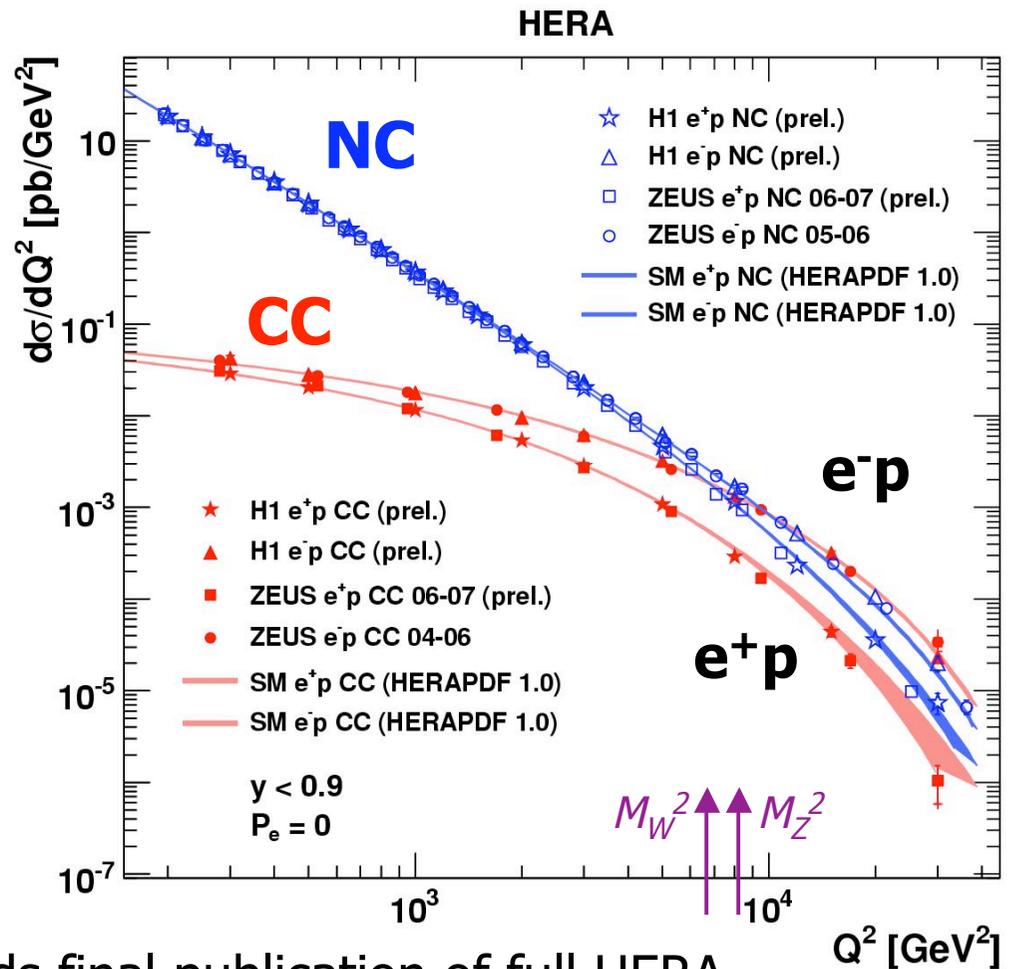


- Events are selected by requiring at least two, isolated high  $P_T$  electrons or muons in the final state
- Events are then classified into independent, exclusive samples:
  - $ee$ ,  $eee$ ,  $\mu\mu$ ,  $e\mu$ ,  $e\mu\mu$  and so on..
- Overall good agreement seen with the SM prediction

Total visible cross section measured  $0.66 \pm 0.03$  (stat.)  $\pm 0.03$  (sys.) pb compared to a SM prediction of  $0.69 \pm 0.02$  pb from GRAPE

# Summary

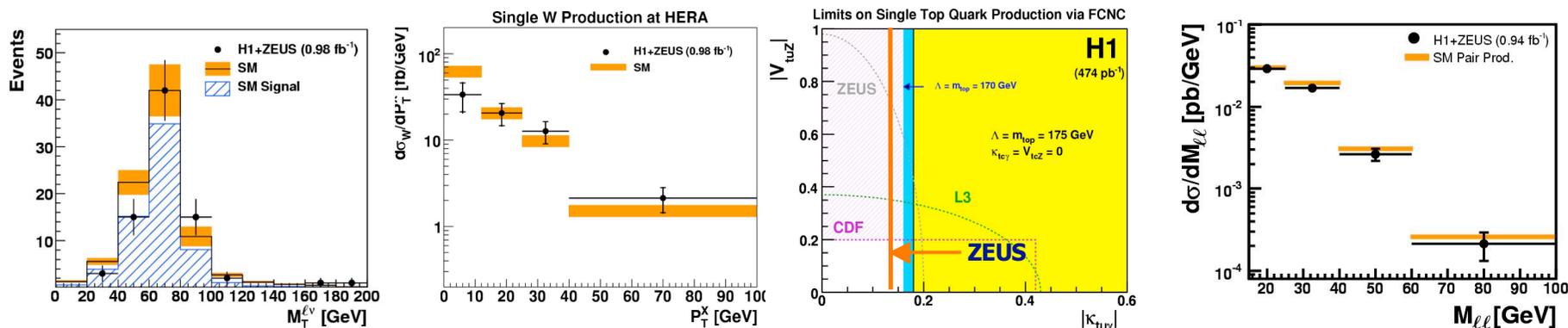
- Measurements of polarised and unpolarised neutral and charged current cross sections at HERA
  - Observed polarisation asymmetry in NC agrees with the SM prediction
  - Polarisation dependence of the CC cross section established in both  $e^+p$  and  $e^-p$  data: no right handed charged currents
  - The HERA I and II data have been combined to form unpolarised measurements and  $xF_3$  is extracted



- Both H1 and ZEUS heading towards final publication of full HERA data, with more combined measurements to follow
  - Providing more constraints on the proton structure and input into new QCD fits such as HERA PDF as well as EW fits on the light quark couplings to the Z

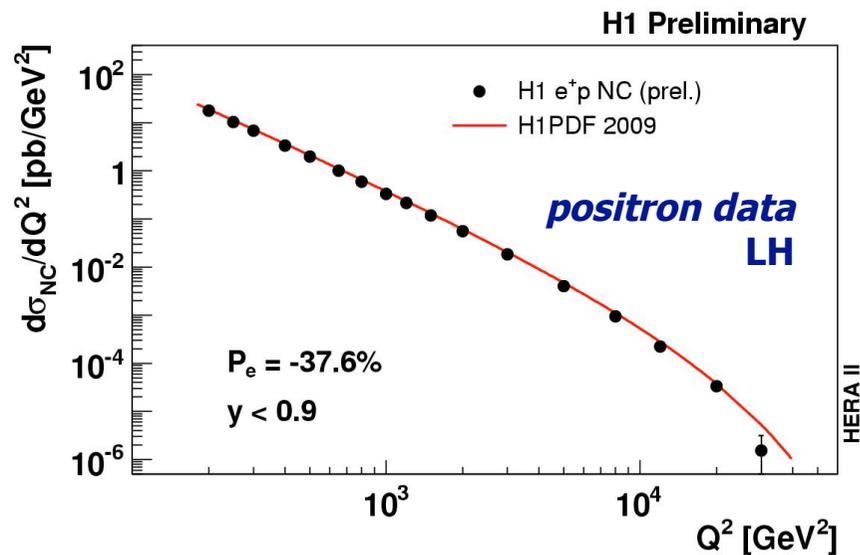
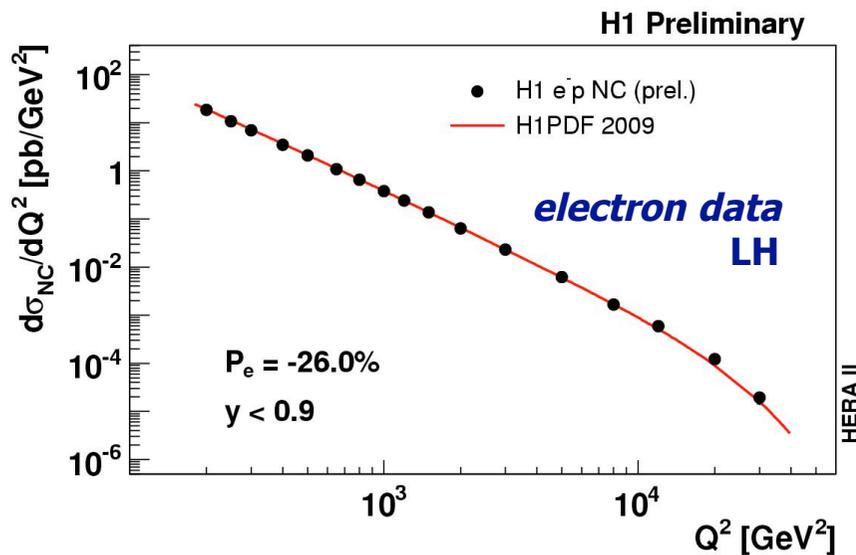
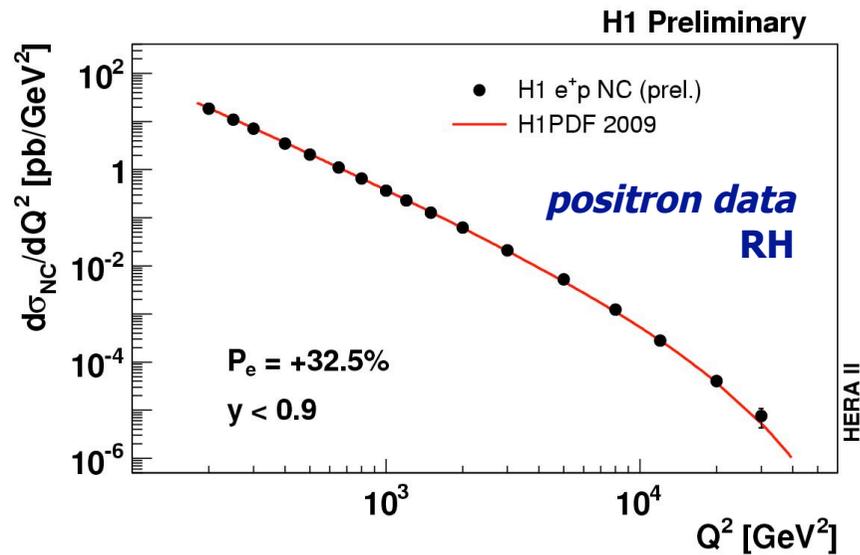
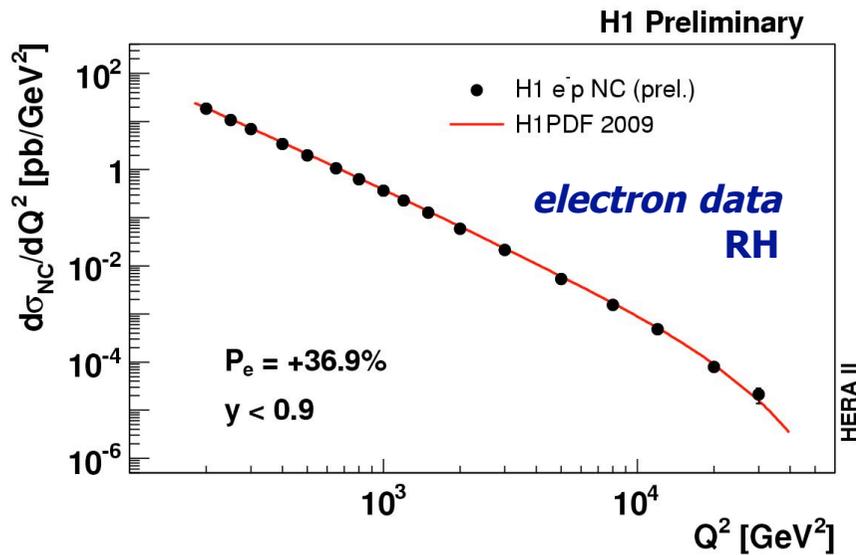
# Summary

- A search for events with isolated leptons and missing  $P_T$  performed by H1 and ZEUS using the full HERA I+II dataset, luminosity  $1 \text{ fb}^{-1}$ 
  - H1 excess at large  $P_T^X$  in  $e^+p$  data persists in full HERA I+II data set
- Single W cross section measured with greater statistical precision
  - $\sigma_W = 1.06 \pm 0.16$  (stat.)  $\pm 0.07$  (sys.) pb, cf  $1.26 \pm 0.19$  pb from SM
- Exclusion limit on anomalous top cross section extended to  $\sigma < 0.13$  pb
  - Best limit on the anomalous magnetic coupling:  $\kappa_{t\gamma} < 0.13$  (for  $M_{\text{top}}=171.2 \text{ GeV}$ )
- Multi-lepton production also measured in a combined H1+ZEUS analysis
  - $\sigma_{\gamma\gamma} = 0.66 \pm 0.03$  (stat.)  $\pm 0.03$  (sys.) pb, cf  $0.69 \pm 0.02$  pb from SM



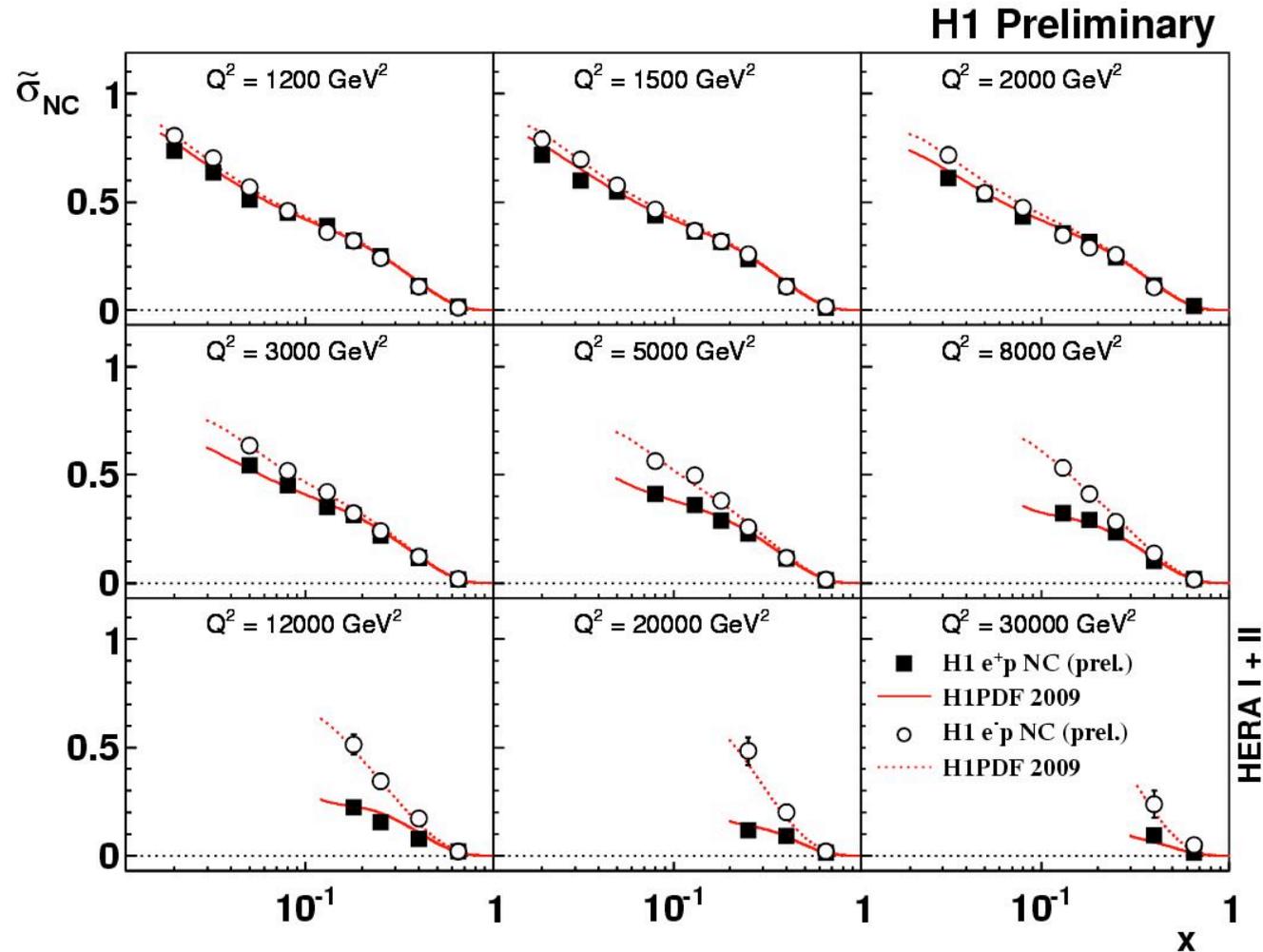
# EXTRA SLIDES

# Single Differential NC Cross Sections $d\sigma/dQ^2$

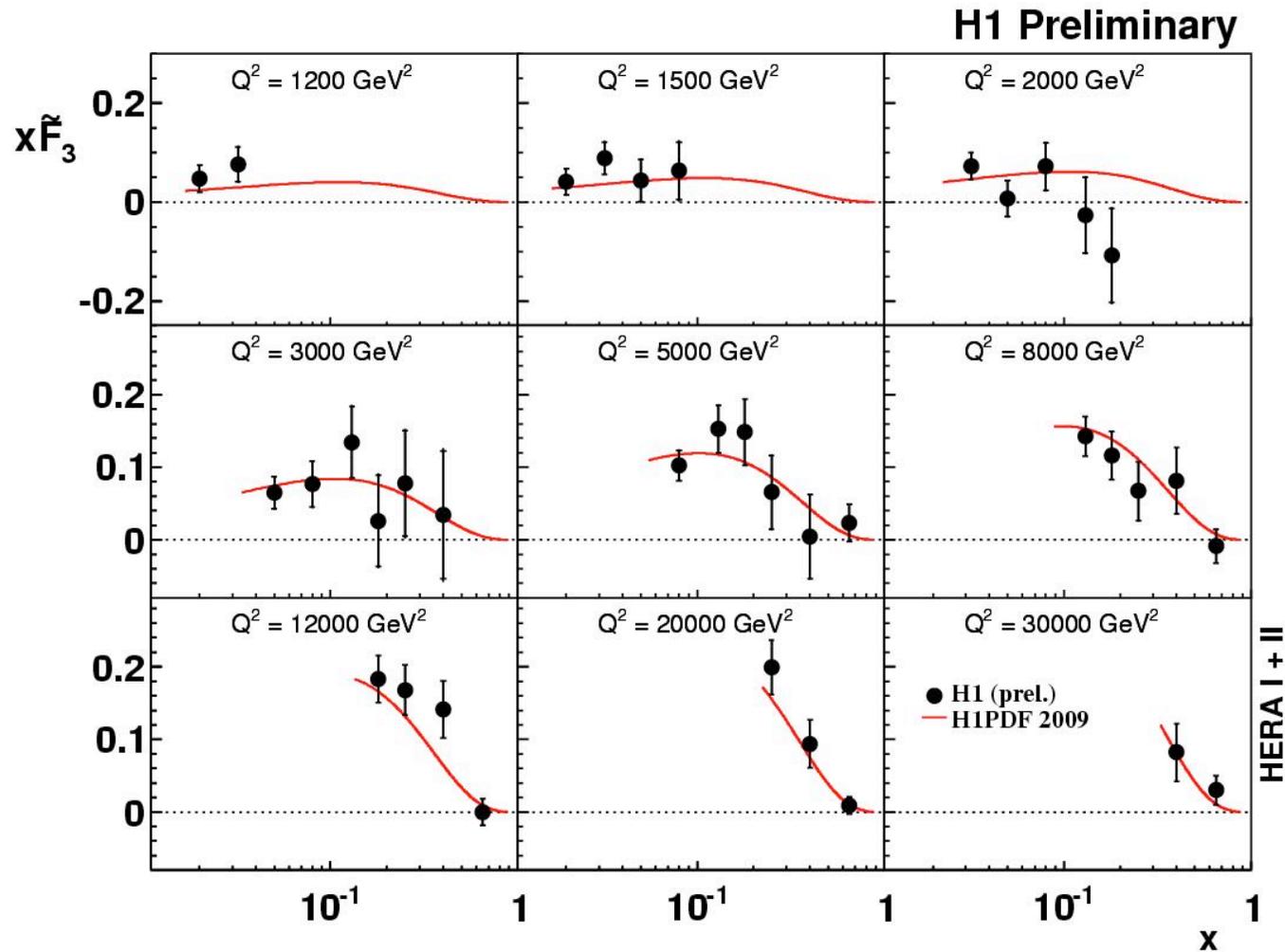


Excellent description of the  $Q^2$  dependence of the data by the SM (from a QCD fit)

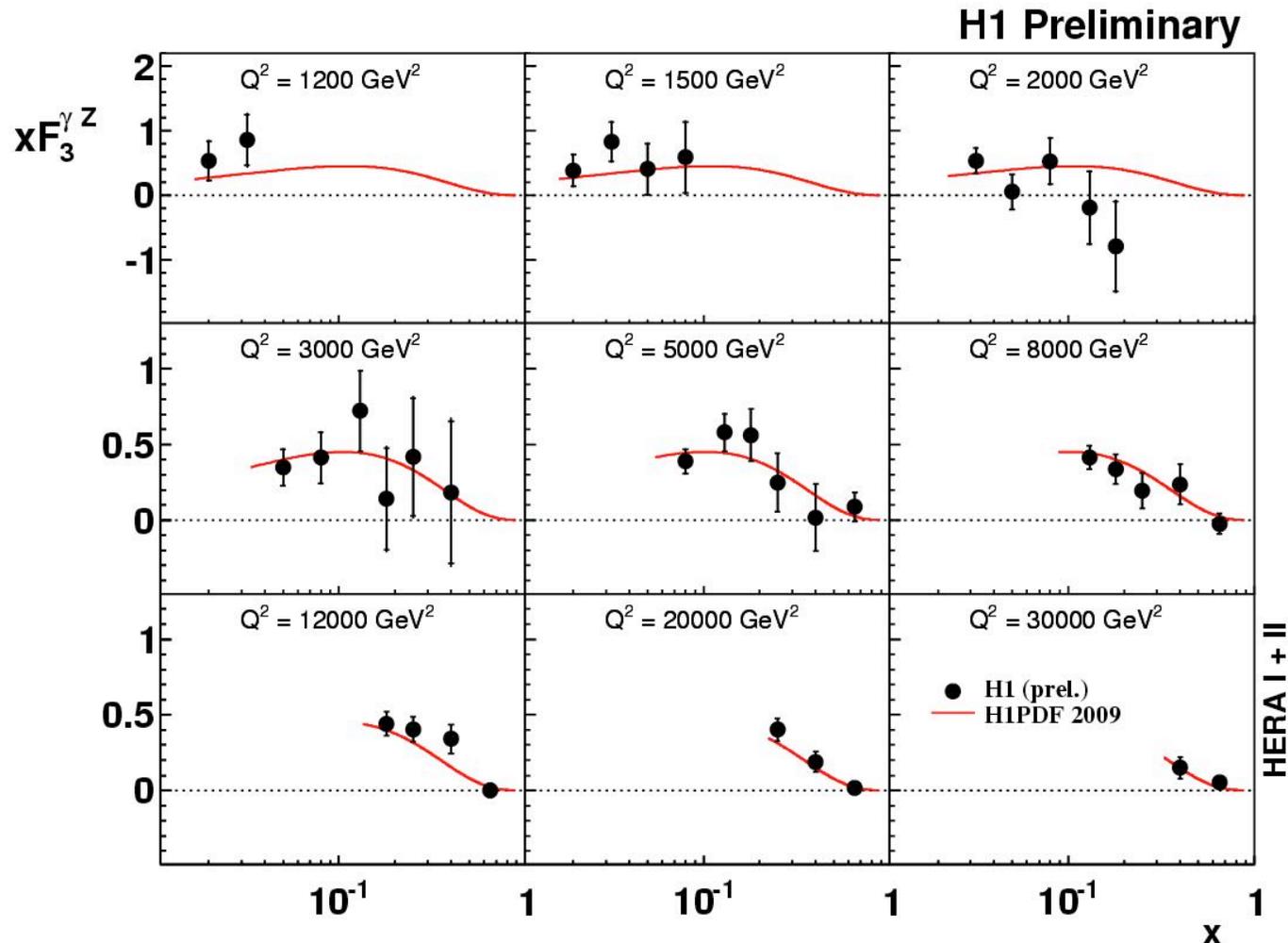
# Unpolarised Reduced NC Cross Section: Full HERA I+II



# Extraction of $x\tilde{F}_3$



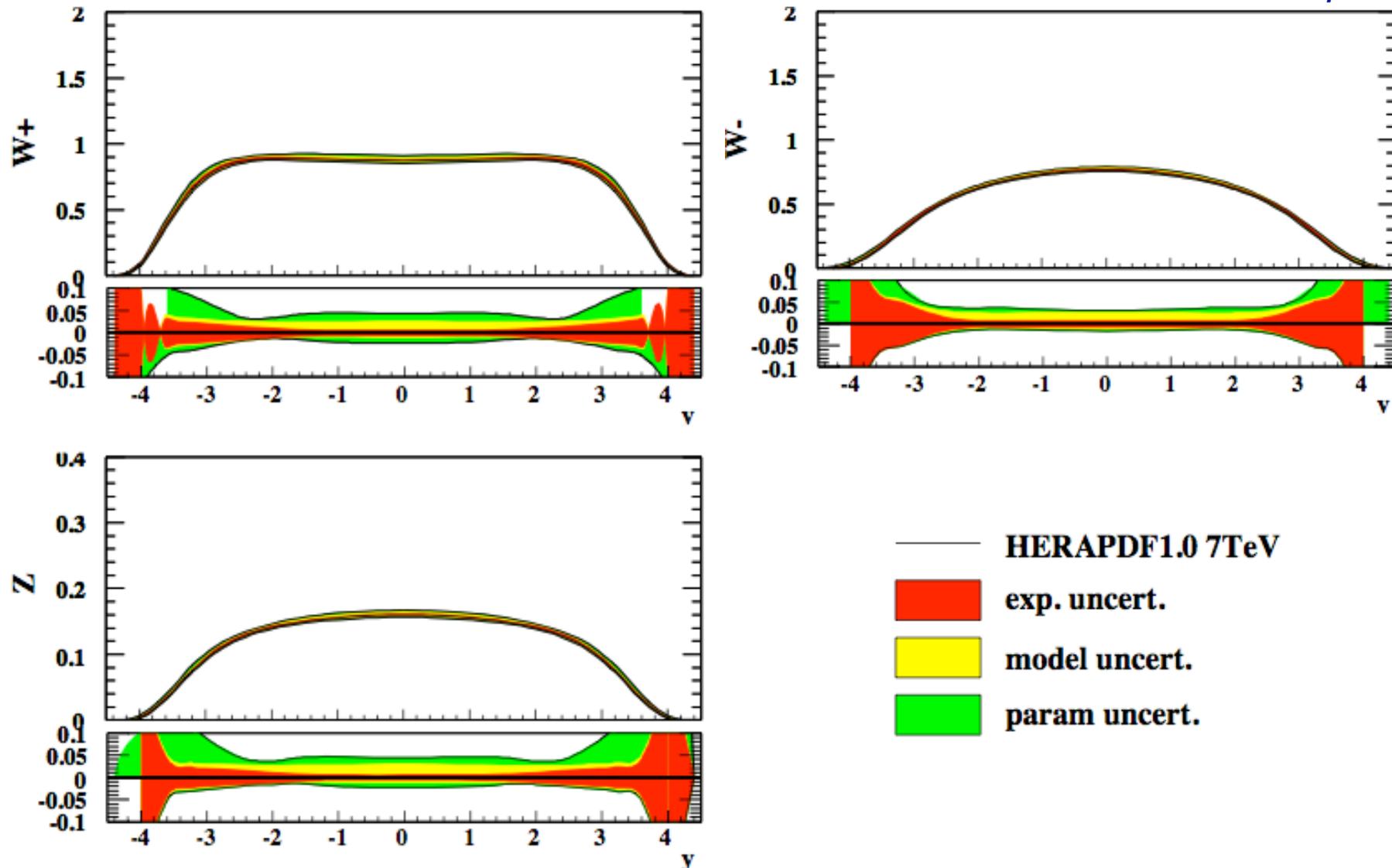
# Extraction of $xF_3^{\gamma Z}$



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

# Boson Rapidity Distributions at the LHC (7 GeV)

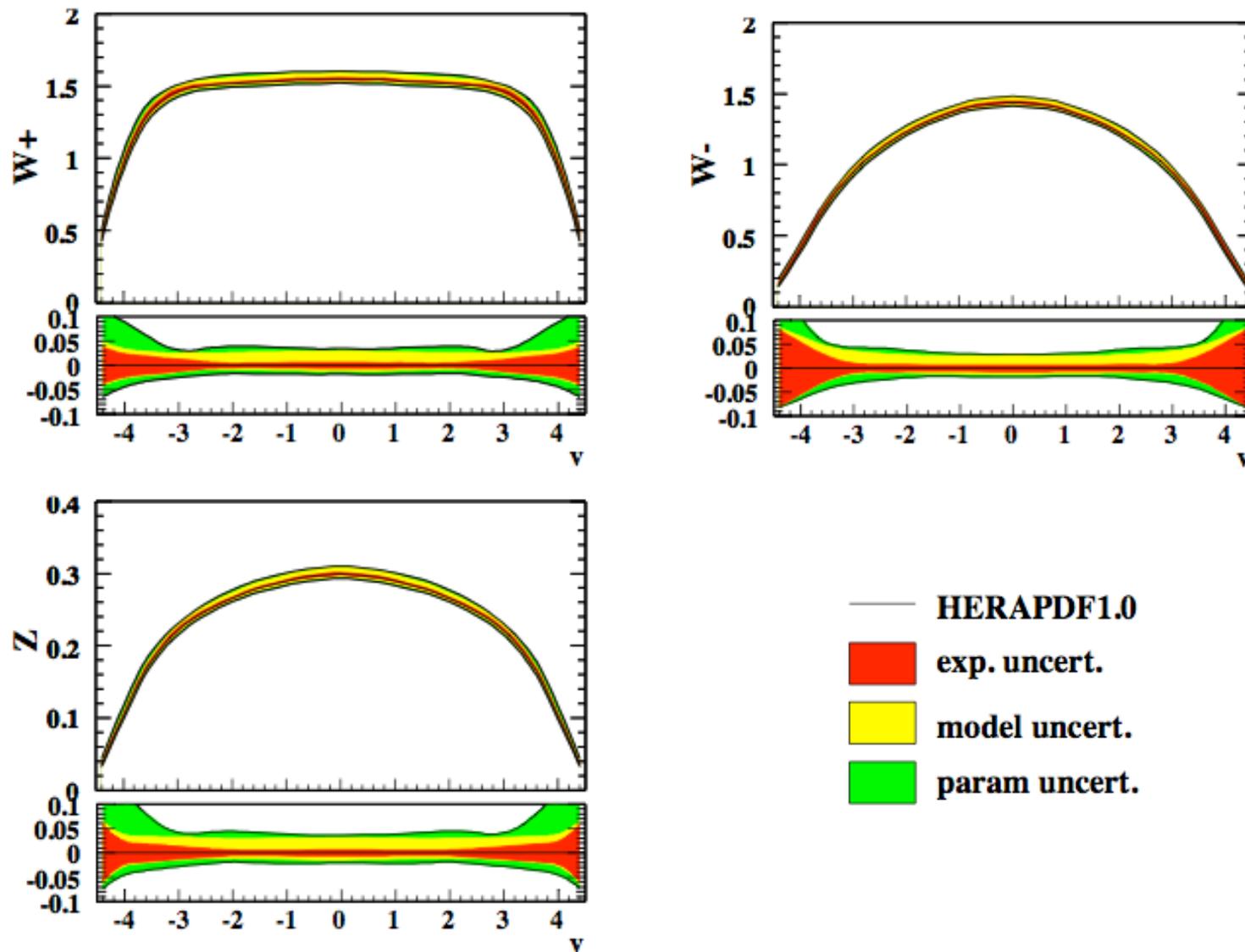
Amanda Cooper-Sarkar



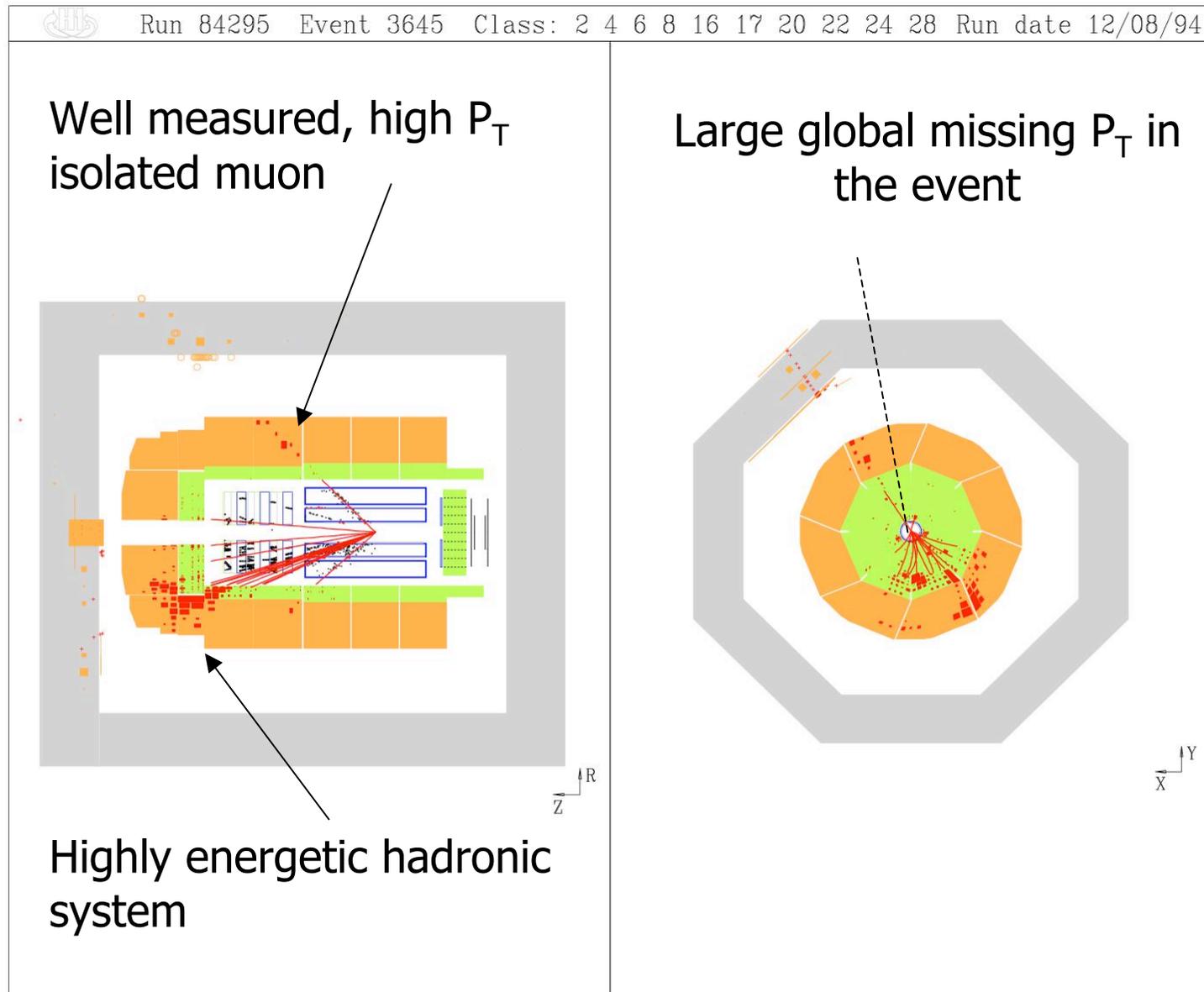
[http://www.desy.de/h1zeus/combined\\_results/benchmark/herapdf1.0.html](http://www.desy.de/h1zeus/combined_results/benchmark/herapdf1.0.html)

# Boson Rapidity Distributions at the LHC (14 GeV)

Amanda Cooper-Sarkar



# An Event Observed by H1 in 1994



# Described in a Dedicated Paper

DESY 94-248

ISSN 0418-9833

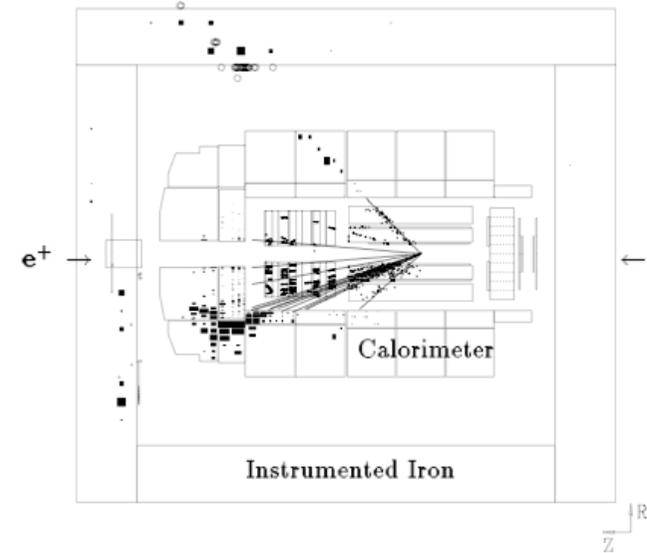
December 1994

## Observation of an $e^+p \rightarrow \mu^+X$ Event with High Transverse Momenta at HERA

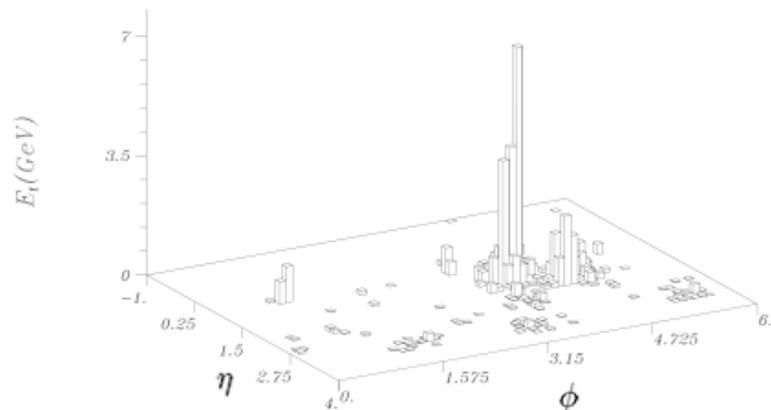
H1 Collaboration

### Abstract

At the HERA electron-proton collider an event has been observed in the H1 detector which shows an isolated muon recoiling against a hadronic system, both of high transverse momentum. The event was registered in a total integrated luminosity of  $4 \text{ pb}^{-1}$ .



Analysis used  
the first  $4 \text{ pb}^{-1}$   
of H1 data

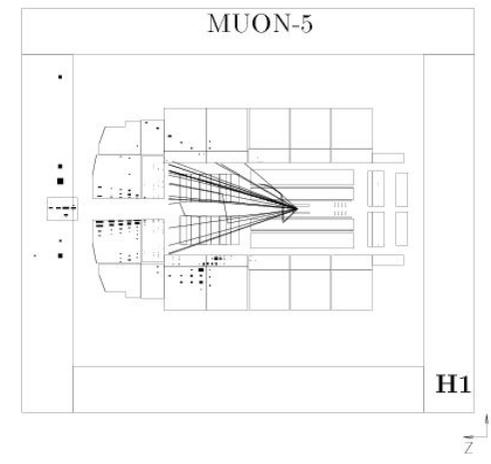
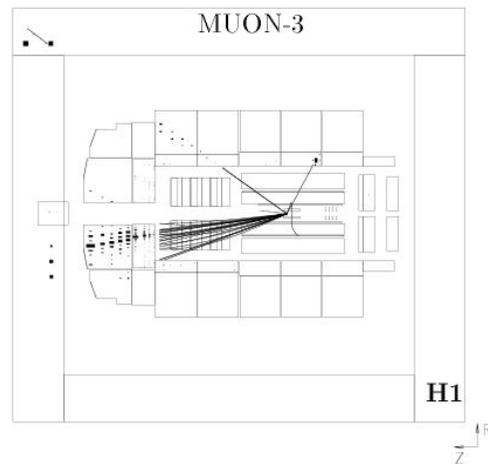
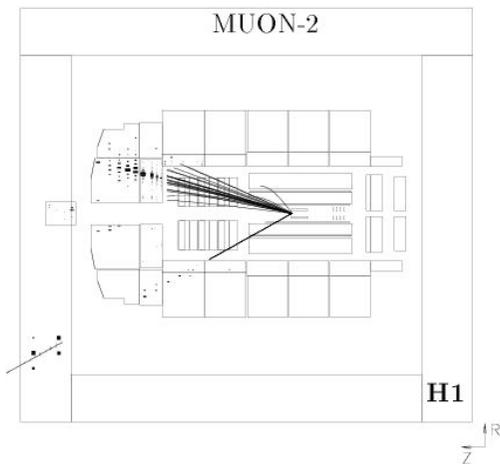
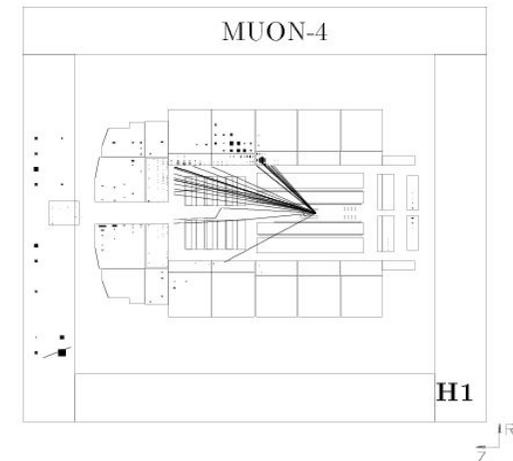
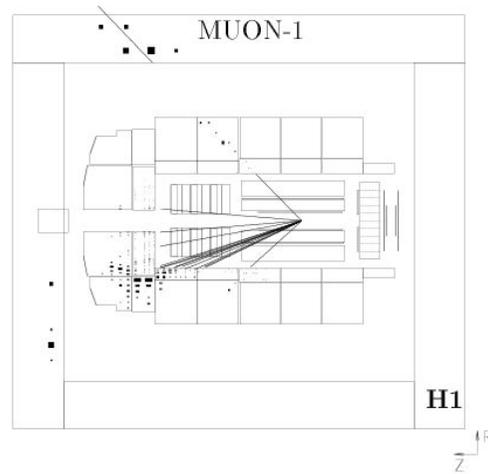
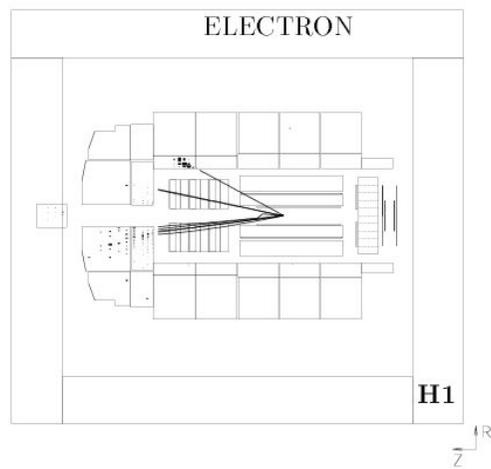


<b>The isolated track :</b>	
Charge	Positive
Transverse momentum	$23.4 \pm 2.4^{+7}_{-5} \text{ GeV}$
Polar angle	$46.2 \pm 1.3^\circ$
Azimuthal angle	$57.4 \pm 0.1^\circ$
<b>The total hadronic system :</b>	
Transverse momentum	$42.1 \pm 4.2 \text{ GeV}$
Average azimuthal angle	$240 \pm 1^\circ$
<b>Hadronic cluster 1:</b>	
Transverse momentum	$25.3 \pm 3.0 \text{ GeV}$
Polar angle	$22.3 \pm 0.5^\circ$
Azimuthal angle	$227 \pm 1^\circ$
<b>Hadronic cluster 2 :</b>	
Transverse momentum	$15.2 \pm 1.9 \text{ GeV}$
Polar angle	$16.5 \pm 0.5^\circ$
Azimuthal angle	$270 \pm 1^\circ$
<b>Global event properties :</b>	
Missing transverse momentum	$18.7 \pm 4.8^{+5}_{-7} \text{ GeV}$
$\delta = \sum E(1 - \cos \theta)$	$19.2 \pm 1.6^{+3.0}_{-2.1} \text{ GeV}$
$\Delta\phi$ muon-hadronic system	$183 \pm 1^\circ$

# Including some possible Interpretations

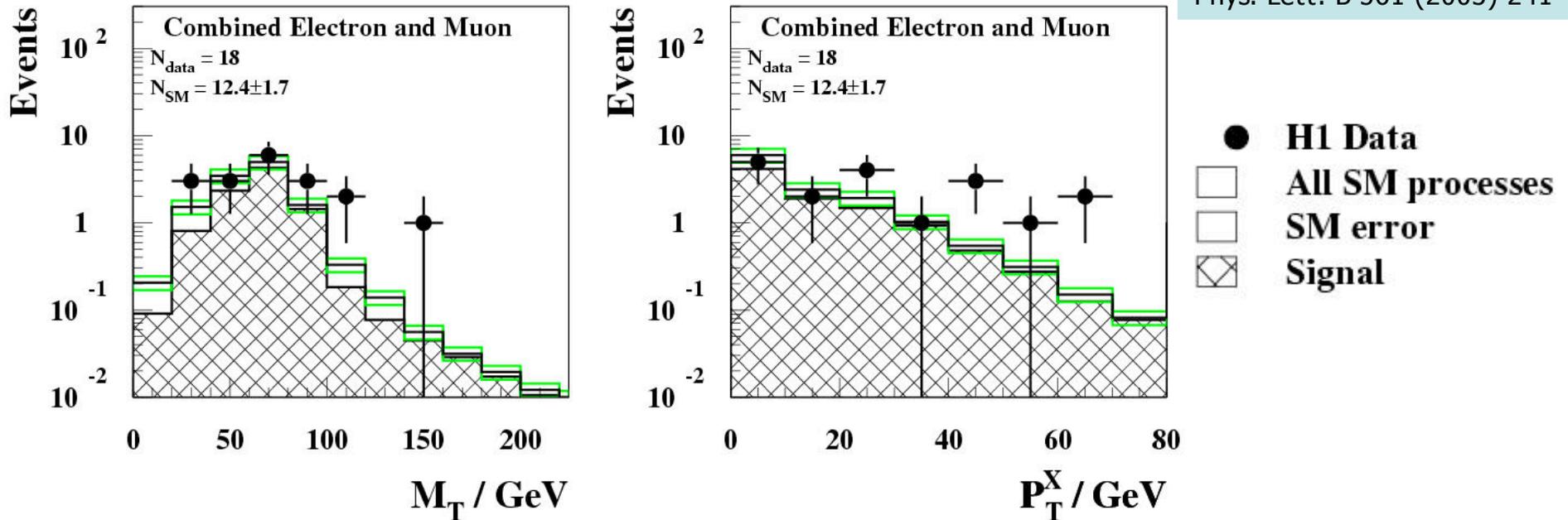
- Production of two high  $P_T$  jets, where one jet contains a single particle (a pion) which fakes the muon signature
  - Interpretation unlikely, probability calculated to be less than 0.001
- A flavour changing NC process  $e^+ + p \rightarrow \mu^+ + X$ , topologically identical to the production of a leptoquark
  - Large missing momentum makes this unlikely
- A background event due to (e.g.) a halo muon
  - The  $E_T$  in the event is too large, also ruled out (the muon also points to the vertex..)
- *Production of W bosons with leptonic decay*
  - OK, maybe, but the hadronic jet should have low  $P_T$ ..

# 1998: Now 37 pb<sup>-1</sup> of H1 e<sup>+</sup>p data



# Results from H1 HERA I $e^+p$ Data: $106 \text{ pb}^{-1}$

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- Significant excess observed by H1 at large hadronic momentum  $P_T^X > 25 \text{ GeV}$

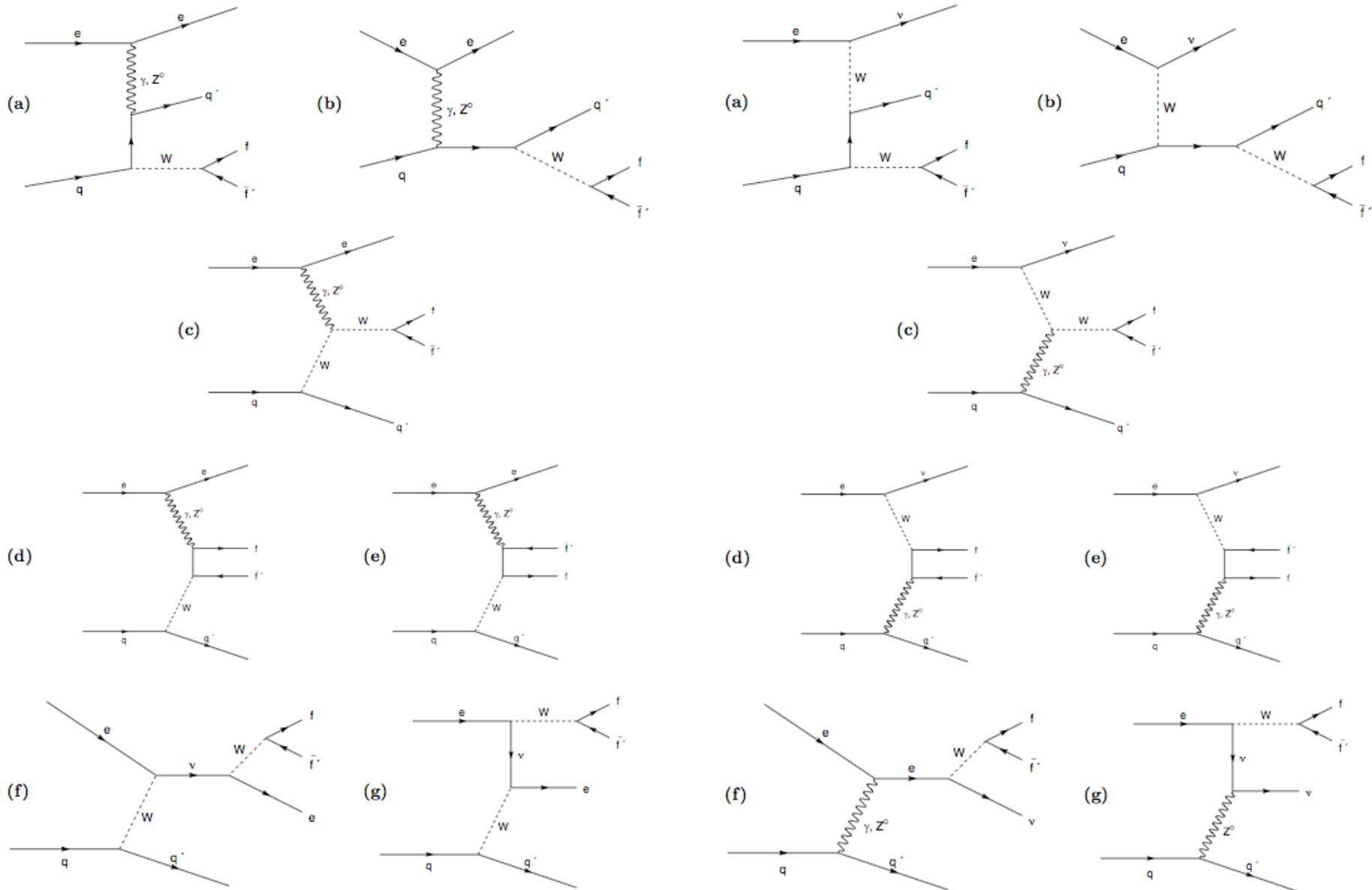
H1 $e^+p$ data HERA I ( $106 \text{ pb}^{-1}$ )	e channel obs. / exp.	$\mu$ channel obs. / exp.	e and $\mu$ channels obs. / exp.
Full sample	10 / $9.9 \pm 1.3$	8 / $2.6 \pm 0.4$	18 / $12.4 \pm 1.7$
$P_T^X > 25 \text{ GeV}$	4 / $1.5 \pm 0.3$	6 / $1.4 \pm 0.3$	10 / $2.9 \pm 0.5$

$3.0\sigma$  excess

- *Result not confirmed by ZEUS HERA I analysis (in a more limited phase space)*

Phys. Lett. B 559 (2003) 153

# Full Set of W Production Diagrams in EPVEC



# H1+ZEUS Isolated Lepton Event Selection

Variable	Electron	Muon
$\theta_l$	$15^\circ < \theta_l < 120^\circ$	
$P_T^l$	$> 10 \text{ GeV}$	
$P_T^{\text{calo}}$	$> 12 \text{ GeV}$	
* $M_T$	$> 10 \text{ GeV}$	
$P_T^{\text{miss}}$	$> 12 \text{ GeV}$	
$P_T^X$	-	$> 12 \text{ GeV}$
$D_{\text{jet}}$	$> 1.0$	
$D_{\text{track}}$	$> 0.5$ for $\theta_e \geq 45^\circ$	$> 0.5$
$\zeta_l^2$	$> 5000 \text{ GeV}^2$ for $P_T^{\text{calo}} < 25 \text{ GeV}$	-
* $V_{\text{ap}}/V_p$	$< 0.5$ ( $< 0.15$ for $P_T^e < 25 \text{ GeV}$ )	$< 0.5$ ( $< 0.15$ for $P_T^{\text{calo}} < 25 \text{ GeV}$ )
$\Delta\phi_{l-X}$	$< 160^\circ$	$< 170^\circ$
* $\delta_{\text{miss}}$	$5 \text{ GeV} < \delta_{\text{miss}} < 50 \text{ GeV}$	
# isolated $\mu$	0	1
* # electrons	$< 3$	-

**Major difference between H1 and ZEUS:**  
**H1 nominal analysis:**  
 $5^\circ < \theta_l < 140^\circ$

Analysis phase space selection

Isolation of lepton

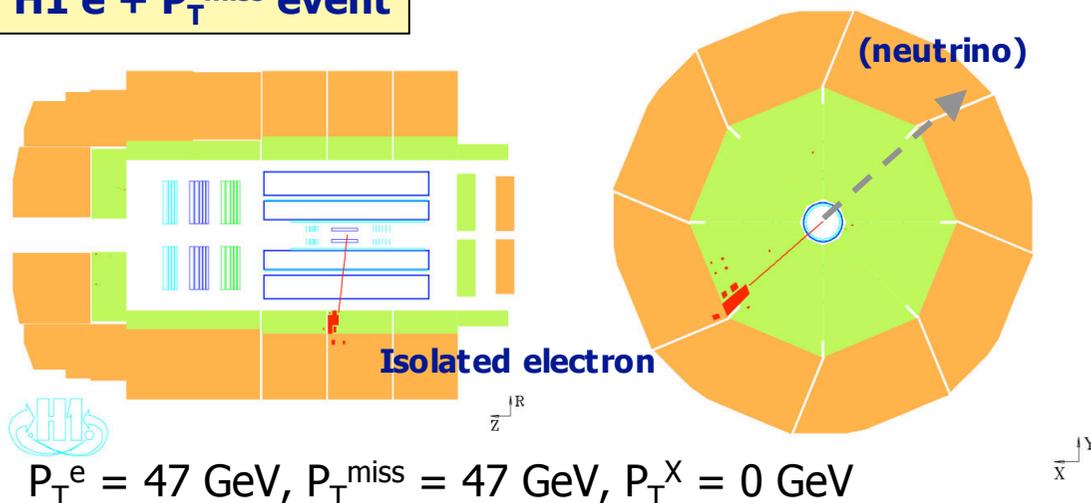
Cuts designed to reduce SM background, whilst preserving large signal purity

\* Other small differences between H1 and ZEUS analyses

Electron and muon channels are exclusive and can therefore be combined

# Signal Event Characteristics

## H1 e + $P_T^{\text{miss}}$ event



- Electron or muon with high transverse momentum, isolated from other parts of the event

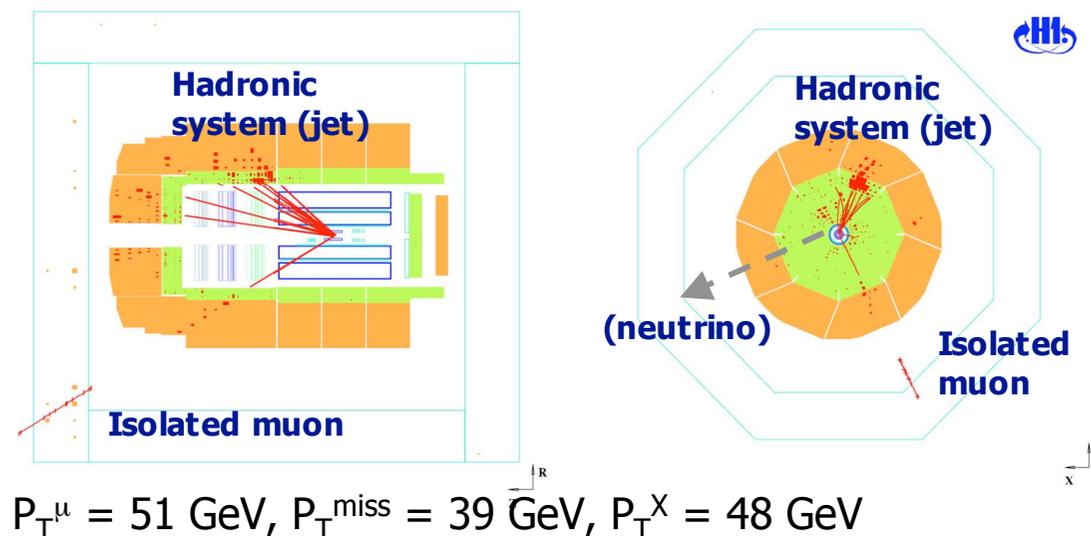
$$\text{H1: } 5^\circ < \theta_l < 140^\circ$$

$$\text{ZEUS: } 15^\circ < \theta_l < 120^\circ$$

$$P_T^l > 10 \text{ GeV}$$

$$D_{l\text{-jet}} > 1.0, D_{l\text{-track}} > 0.5$$

## H1 $\mu$ + $P_T^{\text{miss}}$ event

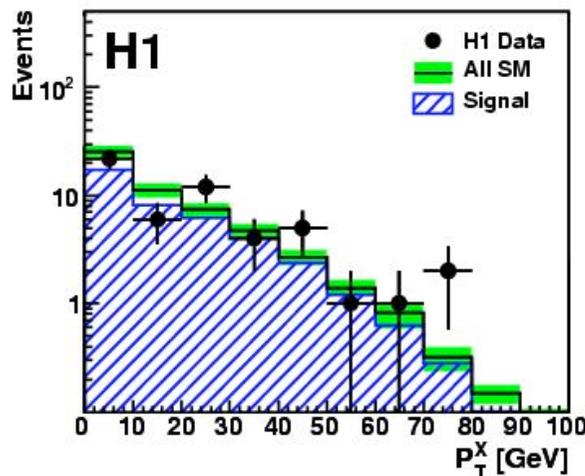
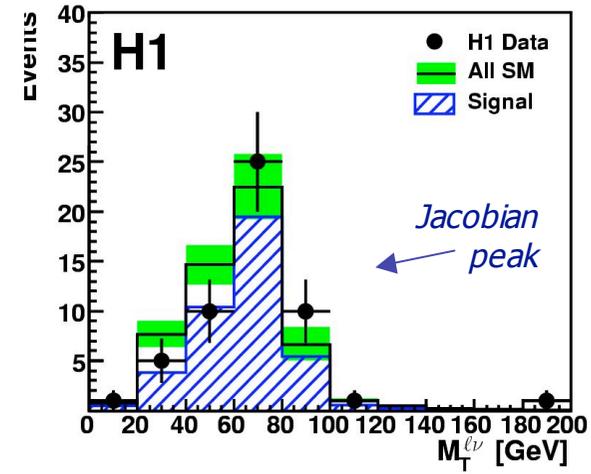
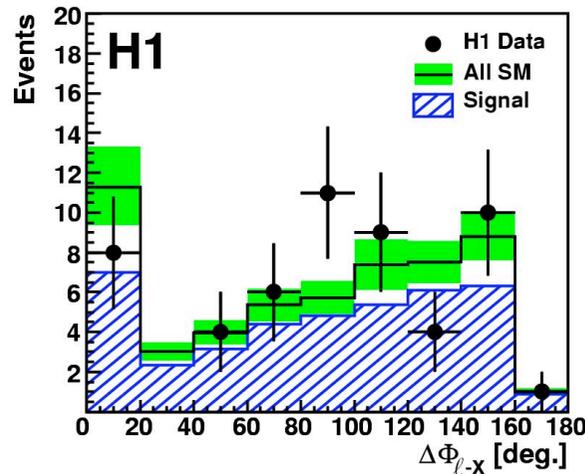
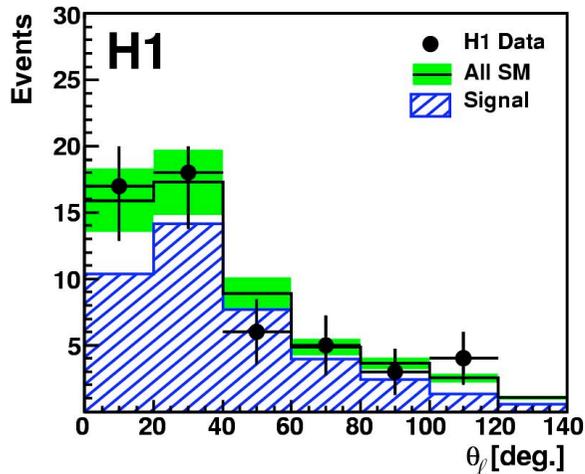


- Large missing global transverse momentum
- $$P_T^{\text{miss}} > 12 \text{ GeV}$$

- Sometimes with a hadronic system, sometimes at large transverse momentum

# H1 Analysis with full $e^\pm p$ Data, 474 $\text{pb}^{-1}$

Eur. Phys. J. C64 (2009) 251



H1	1994-2007 $e^\pm p$ 474 $\text{pb}^{-1}$	Data	SM	SM	Other SM
			Expectation	Signal	Processes
Electron	Total	39	$43.1 \pm 6.0$	$30.3 \pm 4.8$	$12.9 \pm 3.4$
	$P_T^X > 25 \text{ GeV}$	10	$7.5 \pm 1.3$	$5.79 \pm 0.99$	$1.71 \pm 0.71$
Muon	Total	14	$11.0 \pm 1.8$	$10.1 \pm 1.7$	$0.88 \pm 0.29$
	$P_T^X > 25 \text{ GeV}$	8	$6.1 \pm 1.0$	$5.64 \pm 0.99$	$0.47 \pm 0.15$
Combined	Total	53	$54.1 \pm 7.4$	$40.4 \pm 6.3$	$13.7 \pm 3.5$
	$P_T^X > 25 \text{ GeV}$	18	$13.6 \pm 2.2$	$11.4 \pm 1.9$	$2.18 \pm 0.80$

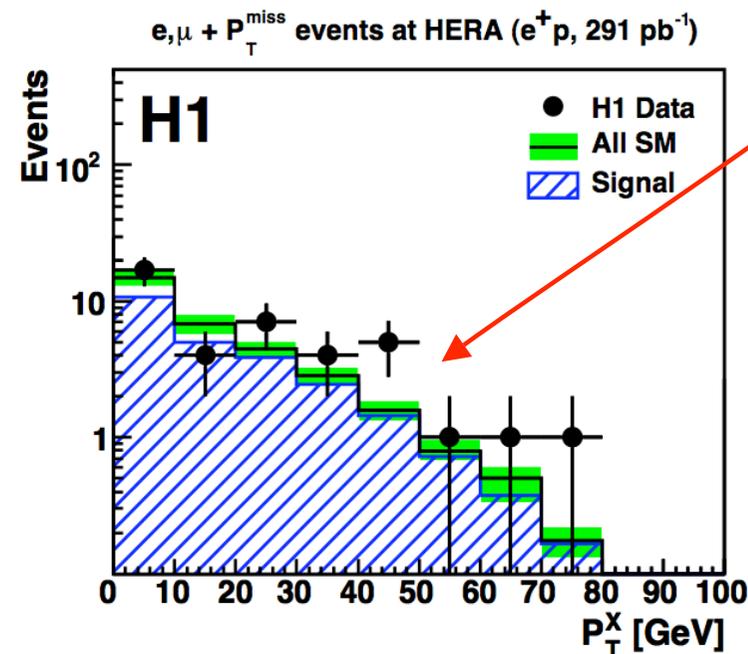
Good overall agreement with the Standard Model: W Production

# H1 Analysis with full $e^+p$ Data 291 $\text{pb}^{-1}$

Eur. Phys. J. C64 (2009) 251

<b>H1</b>	1994-2007 $e^+p$ 291 $\text{pb}^{-1}$	Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	28	25.6 $\pm$ 3.5	18.6 $\pm$ 2.9	6.9 $\pm$ 1.7
	$P_T^X > 25 \text{ GeV}$	9	4.32 $\pm$ 0.71	3.56 $\pm$ 0.61	0.76 $\pm$ 0.32
Muon	Total	12	6.7 $\pm$ 1.1	6.2 $\pm$ 1.0	0.55 $\pm$ 0.18
	$P_T^X > 25 \text{ GeV}$	8	3.70 $\pm$ 0.63	3.42 $\pm$ 0.60	0.28 $\pm$ 0.09
Combined	Total	40	32.3 $\pm$ 4.4	24.8 $\pm$ 3.9	7.5 $\pm$ 1.8
	$P_T^X > 25 \text{ GeV}$	17	8.0 $\pm$ 1.3	7.0 $\pm$ 1.2	1.04 $\pm$ 0.37

- Excess of data events H1 analysis at large  $P_T^X$  persists
  - Significance less than in HERA I data alone
  - Also still not confirmed in the ZEUS analysis

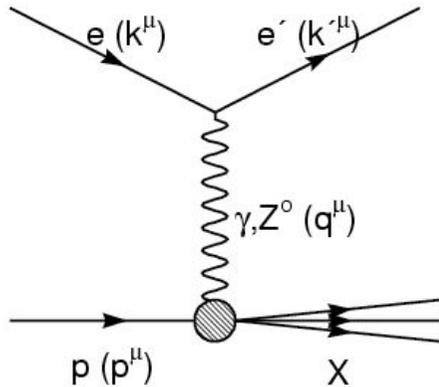


# Standard Model Background

e: Neutral Current	$e, \mu$ : Charged Current	$\mu$ : Lepton Pair Production
Real electron and fake missing $P_T$ from mismeasurement	Misidentified electron or muon and real missing $P_T$	Real muon and fake missing $P_T$ from mismeasurement

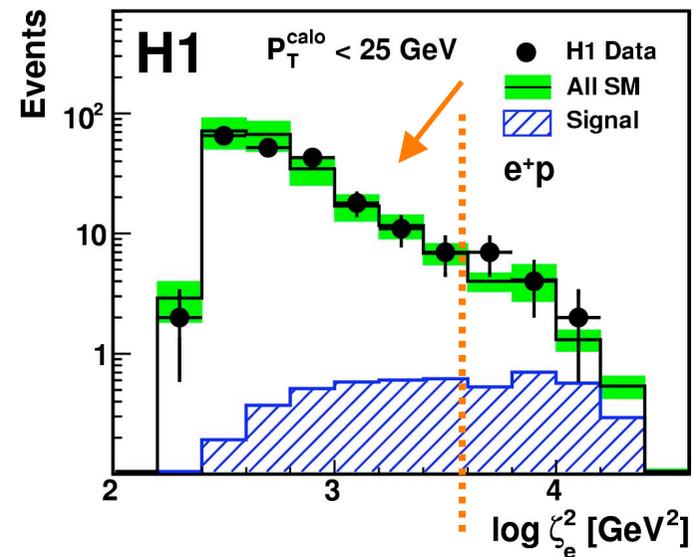
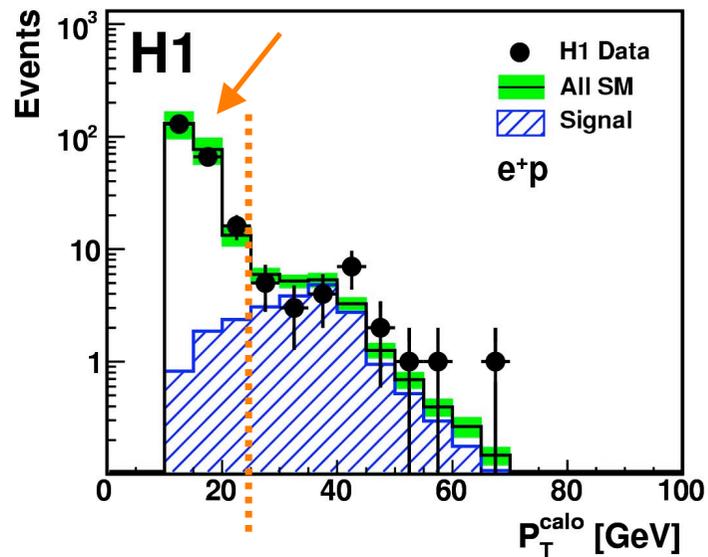
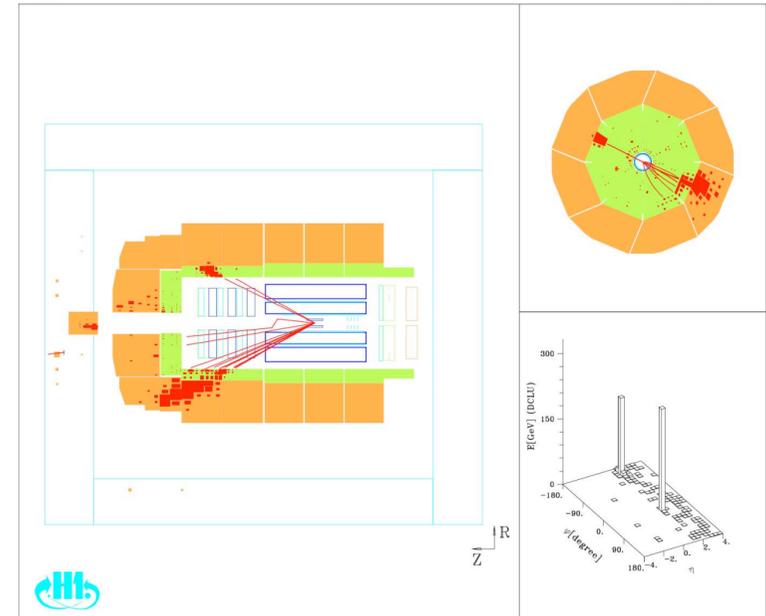
- Further topological cuts are applied to reduce SM background
  - Acoplanarity, longitudinal and transverse balance of the event
- Dedicated control samples used in both the H1 and ZEUS analyses to estimate the uncertainties on these processes in the analysis phase space
  - Control samples formed by removing cuts from final sample

# SM Background: Neutral Current

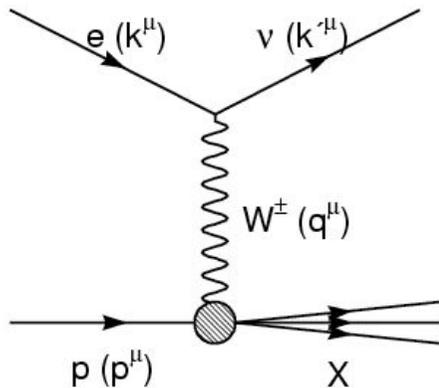


Real electron and fake missing  $P_T$  from mismeasurement

- Origin of isolated electron events NC background?
- Remove Anti-NC Cuts on  $P_T^{\text{miss}}$ ,  $Q^2$
- NC background well described in enriched region

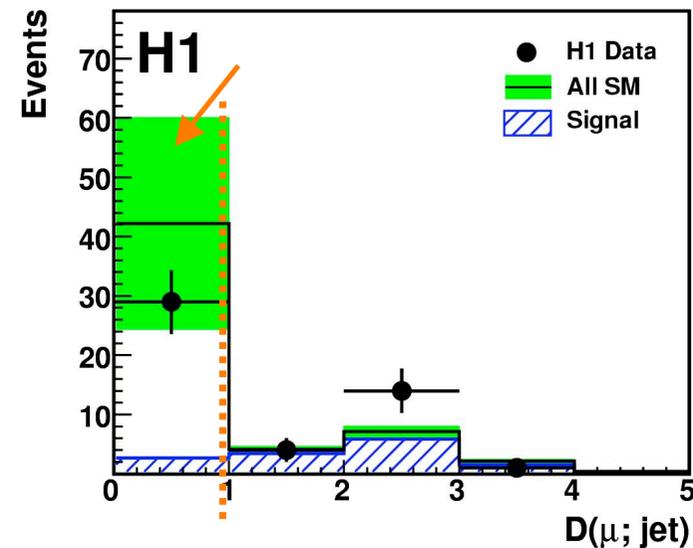
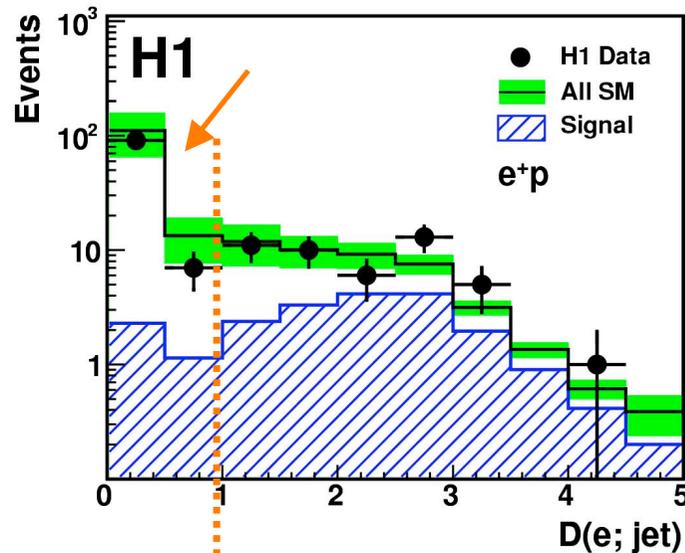
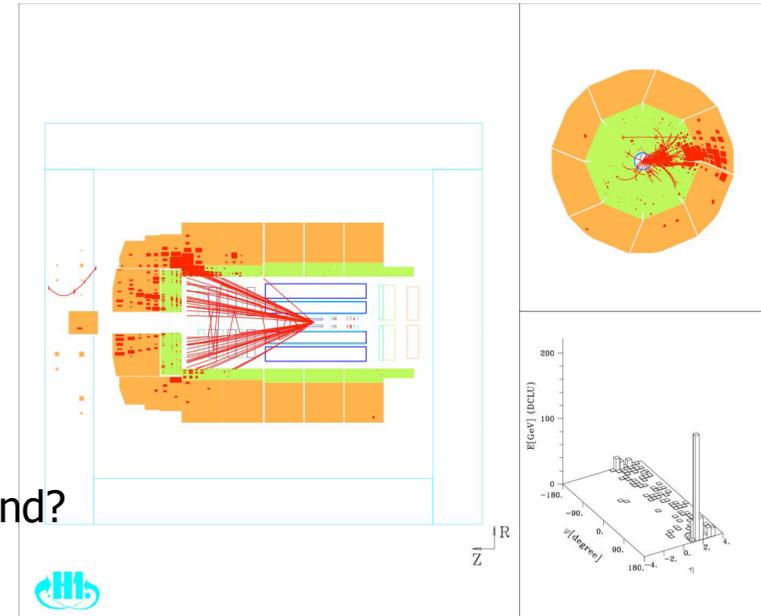


# SM Background: Charged Current

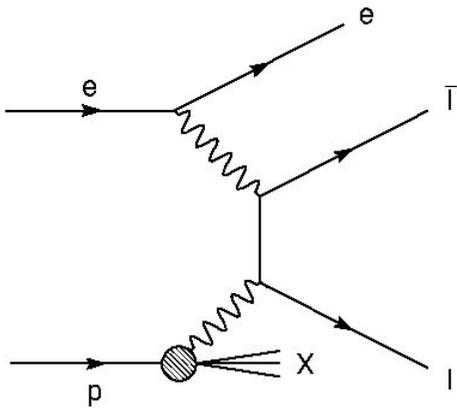


Misidentified  
electron or muon  
and real missing  $P_T$

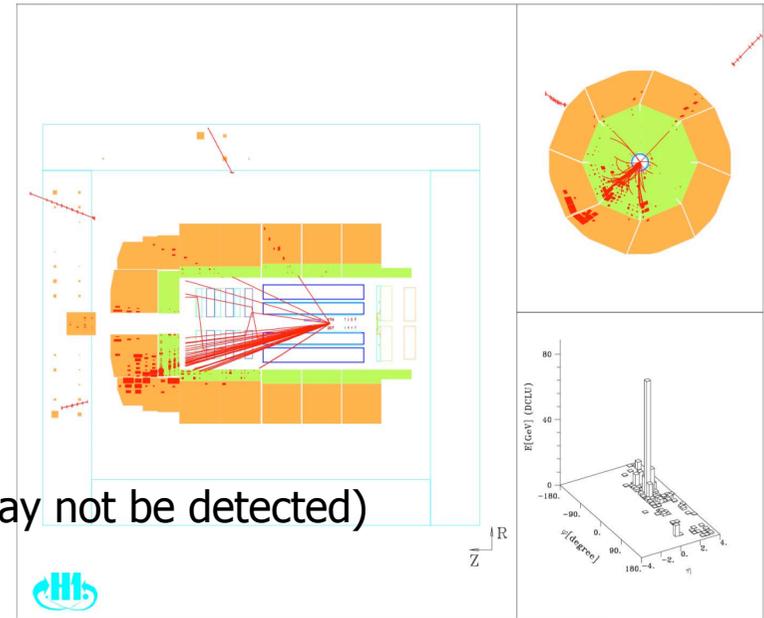
- Origin of electron or isolated muon events: CC background?
- Remove Anti-CC cuts (D jet)
- Electrons and muons in CC jets described within 50%



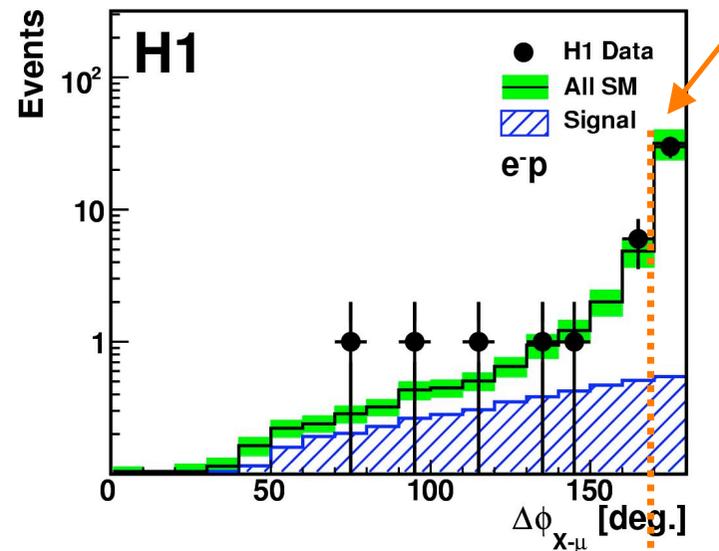
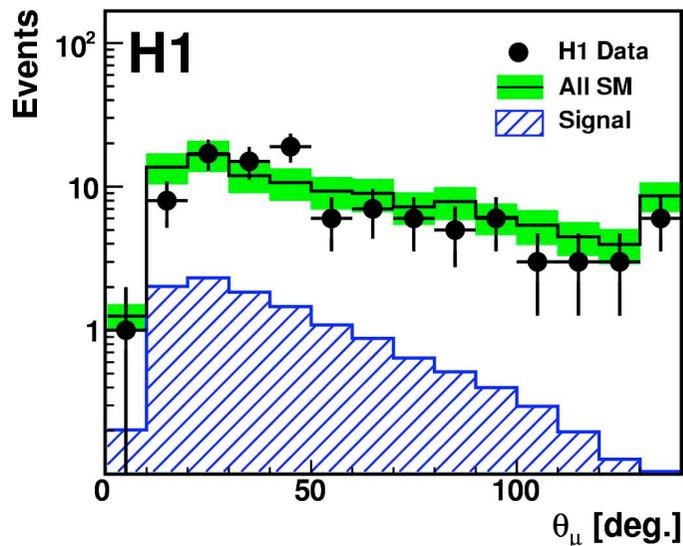
# SM Background: Pair Production



Real muon and fake missing  $P_T$  from mismeasurement

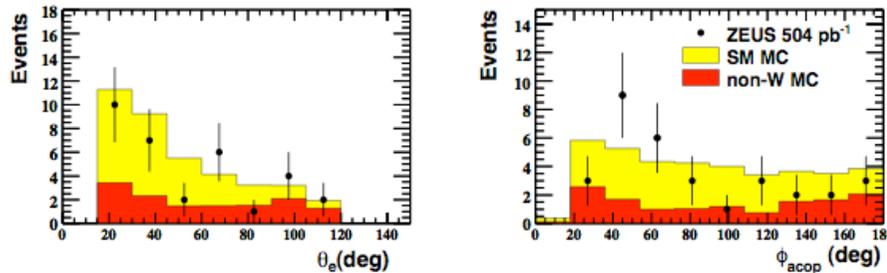


- Muon events from lepton-pair production? (One muon may not be detected)
- Remove Anti-lepton-pair cuts ( $P_{T}^{\text{miss}}$ , acoplanarity)
- Lepton-pair Production described in enriched region



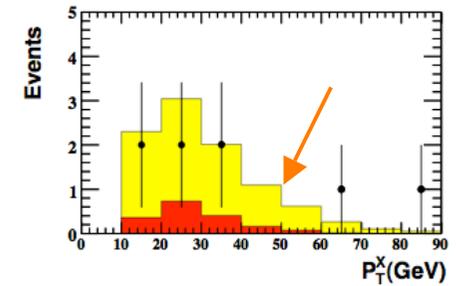
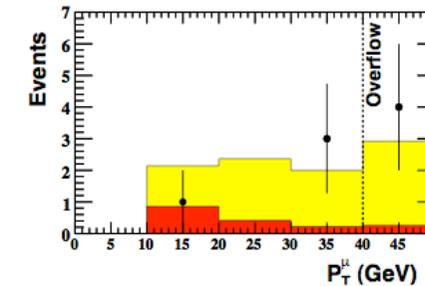
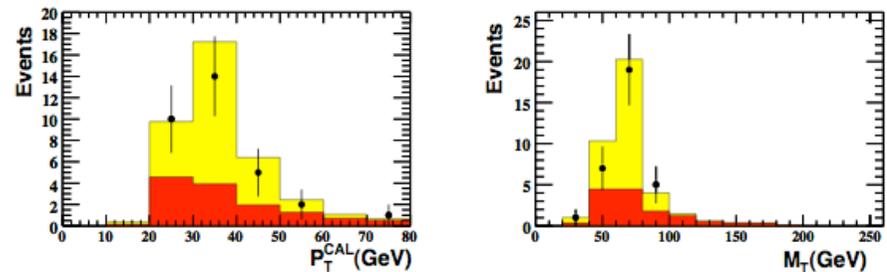
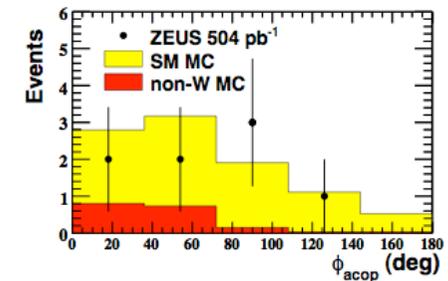
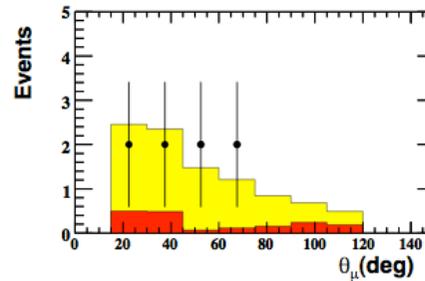
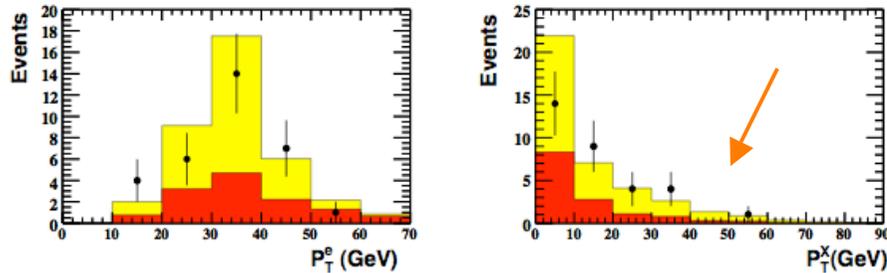
# ZEUS Analysis with full $e^\pm p$ Data, 504 $\text{pb}^{-1}$

Phys. Lett. B 672 (2009) 106



electron channel

muon channel



Isolated Lepton Candidates	$P_T^X < 12 \text{ GeV}$	$12 < P_T^X < 25 \text{ GeV}$	$P_T^X > 25 \text{ GeV}$
$e^- p$ 208 $\text{pb}^{-1}$	9/11.3 $\pm$ 1.5 (54%)	6/5.1 $\pm$ 0.7 (67%)	5/5.5 $\pm$ 0.8 (75%)
$e^+ p$ 296 $\text{pb}^{-1}$	7/12.6 $\pm$ 1.7 (68%)	7/6.2 $\pm$ 0.9 (75%)	6/7.4 $\pm$ 1.0 (79%)
$e^\pm p$ 504 $\text{pb}^{-1}$	16/23.9 $\pm$ 3.1 (61%)	13/11.2 $\pm$ 1.5 (71%)	11/12.9 $\pm$ 1.7 (77%)

Total ZEUS rates	
$e^- p$ (208 $\text{pb}^{-1}$ )	20 / 21.8 $\pm$ 2.7
$e^+ p$ (296 $\text{pb}^{-1}$ )	20 / 26.2 $\pm$ 3.2
$e^\pm p$ (504 $\text{pb}^{-1}$ )	40 / 48.0 $\pm$ 5.9

Good agreement with the Standard Model, no excess at high  $P_T^X$

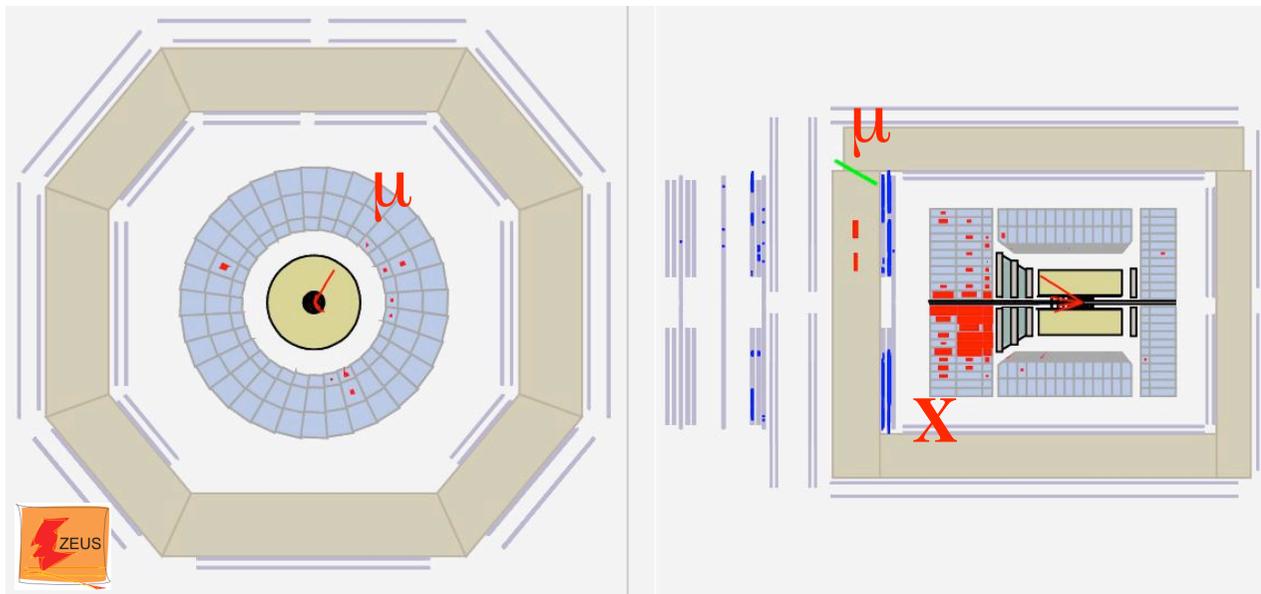
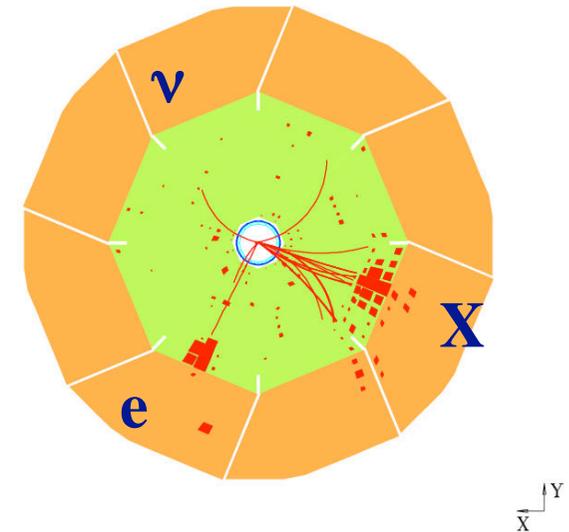
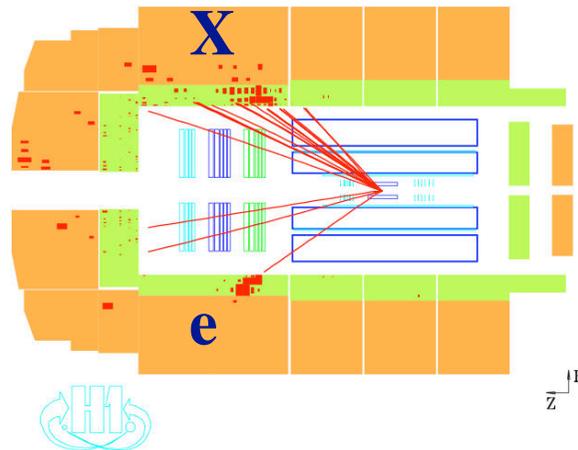
# A Combined H1 and ZEUS Analysis

- The SM expectation for signal events at HERA is low, so the analysis benefits from the combination of the full  $1 \text{ fb}^{-1}$  of H1 and ZEUS data in a common phase space
  - Cross sections measured with better statistical precision
  - Increase sensitivity to possible new phenomena
- The individual analyses are similar in their selections due to initial comparison work
  - Combined selection very close to the nominal ZEUS analysis selection
  - Limited polar angle range of ZEUS analysis is main change to H1
- Common phase space was studied individually in H1 and ZEUS
  - Excellent agreement found between signal rates and acceptances
  - Some background still higher in ZEUS analysis, within reasonable level of agreement
- H1, ZEUS SM signal contributions added together with 15% correlated systematic
- All others errors treated uncorrelated and use individual (level of agreement) errors
- Effect of common phase space on data events:
  - 11/53 H1 events not in common phase space (mainly due to polar angle)
  - 1/40 ZEUS events not in common phase space (low transverse mass)

# More Selected Events

High  $P_T^X e + P_T^{\text{miss}}$   
event in H1  $e+p$  data

$P_T^e = 37 \text{ GeV}$   
 $P_T^{\text{Miss}} = 44 \text{ GeV}$   
 $P_T^X = 29 \text{ GeV}$



High  $P_T^X \mu + P_T^{\text{miss}}$   
event in ZEUS  $e p$  data

$\theta^\mu = 32^\circ$

$M_T^{\mu\nu} = 79 \text{ GeV}$

$P_T^X = 82 \text{ GeV}$

# H1 and ZEUS Analysis Details

- Analysis uses full HERA data set: 978 pb<sup>-1</sup>
  - 474 pb<sup>-1</sup> H1 and 504 pb<sup>-1</sup> ZEUS data
  - 587 pb<sup>-1</sup> of e<sup>+</sup>p data, 391 pb<sup>-1</sup> of e<sup>-</sup>p data
  - 84 pb<sup>-1</sup> of data at 301 GeV, 894 pb<sup>-1</sup> of data at 319 GeV
- Large MC samples used in each analysis, simulated for the different running conditions

Process	H1	ZEUS
Signal (W, Z0*)	EPVEC NLO	EPVEC NLO
NC	RAPGAP	DJANGO
Lepton Pair	GRAPE	GRAPE
Photoproduction	PYTHIA	-
Compton	WABGEN	(included in NC)
Charged Current	DJANGO	DJANGO

\*not ZEUS

- Average HERA II beam polarisation taken into account in CC

# Full Treatment of Systematic Errors

## Systematics taken from H1 and ZEUS nominal analyses

### H1 Experimental Systematics

Source	Systematic
$E_e$	LAr : $z < 20$ cm 0.7%
	LAr : $20 < z < 100$ cm 1.5%
	LAr : $100$ cm $< z$ 2.0%
	Spacal: 0.5%
$\theta_e$	LAr : 3 mrad
	Spacal: 1 mrad
$\phi_e$	1 mrad
$P_T^\mu$	2.5%
$\theta_\mu$	3 mrad
$\phi_\mu$	1 mrad
$E_{had}$	2% (5% if $P_T^X < 8$ GeV)
$\theta_{had}$	10 mrad
$\phi_{had}$	10 mrad
$\frac{V_{ap}}{V_p}$	$\pm 0.02$
Muon ID	5% if $\theta_\mu > 12.5^\circ$ else 15%
Electron ID	2%
Electron track-clus linking	3%
CC trigger	$2\% \oplus 30\%(1 - \epsilon_{CC})$
$\mathcal{L}$	1994-2000 $e^\pm p$ : 1.5%
	2003-2006 $e^\pm p$ : 2.5%
	2006-2007 $e^+ p$ : 5.0%

### ZEUS experimental systematics

- Muon ID: 5%
- EM calo: 2%
- HAD calo: 3%
- Lumi ( $e^+p$ ): 2.9%
- Lumi ( $e^-p$ ): 3.4%

### SM Signal model uncertainty

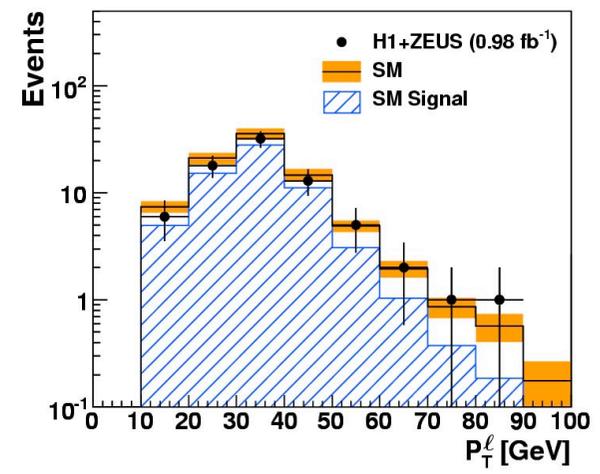
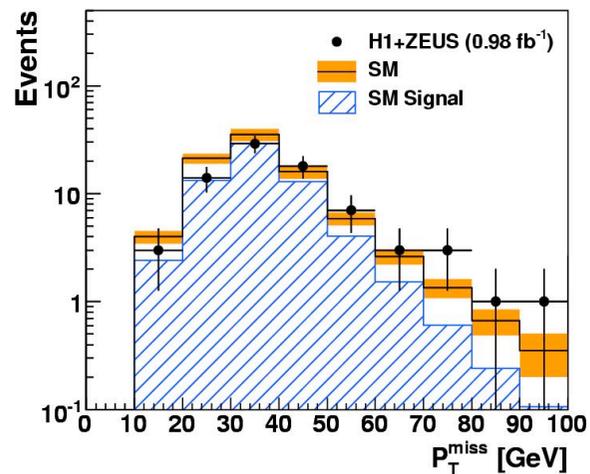
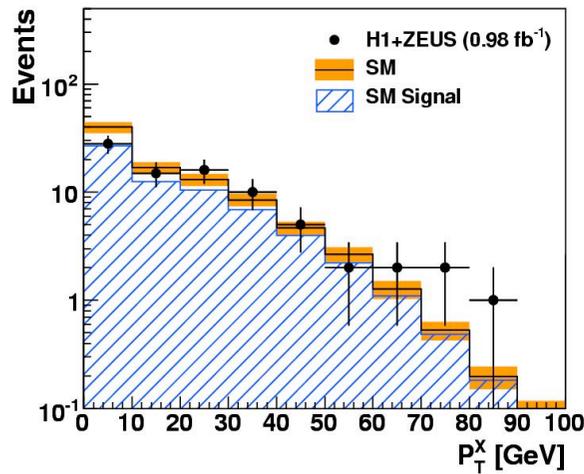
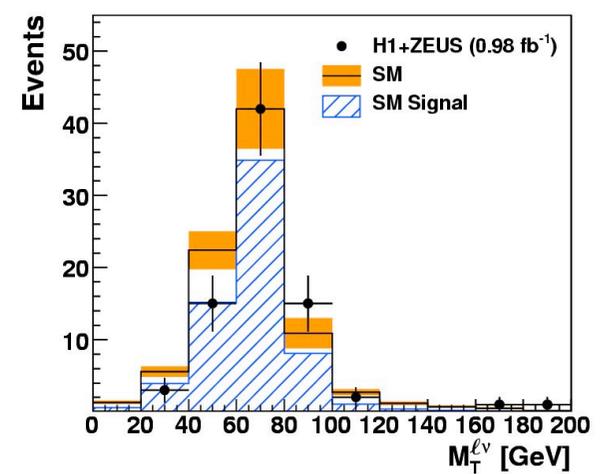
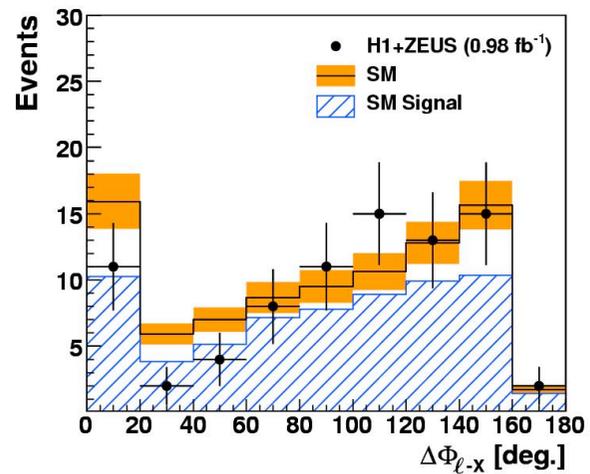
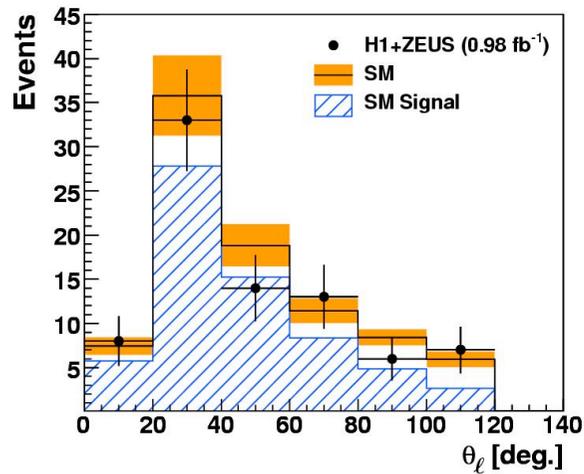
- EPVEC: 15% (NLO model error)

### SM Background uncertainties from agreement in control samples

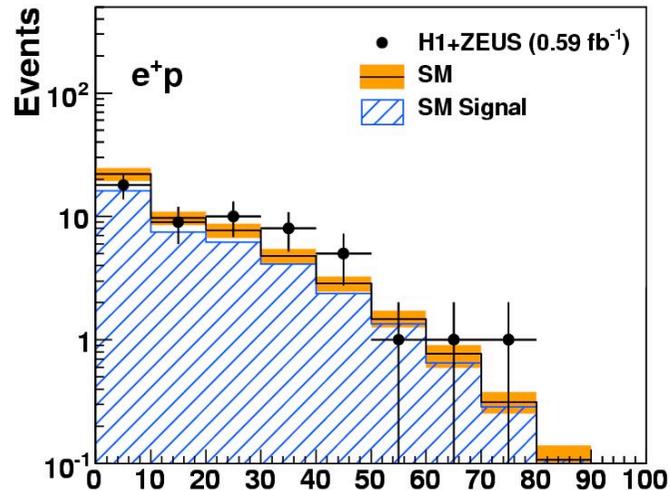
- NC: 30% (15%) H1 (ZEUS)
- LPAIR: 30% (25%) H1 (ZEUS)
- CC: 50% (25%) H1 (ZEUS)
- COMPTON, GAMMAP: 30% (H1)

**All errors treated uncorrelated between H1 and ZEUS except EPVEC**

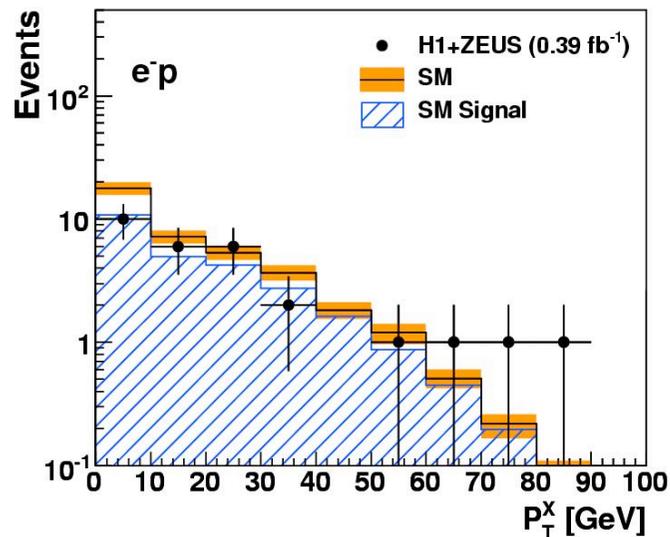
# H1+ZEUS Isolated Leptons: All Distributions



# H1+ZEUS Isolated Leptons: $e^+p$ and $e^-p$



H1+ZEUS		Data	SM	SM	Other SM
1994–2007 $e^+p$		0.59 fb <sup>-1</sup>	Expectation	Signal	Processes
Electron	Total	37	38.6 ± 4.7	28.9 ± 4.4	9.7 ± 1.4
	$P_T^X > 25$ GeV	12	7.4 ± 1.0	6.0 ± 0.9	1.5 ± 0.3
Muon	Total	16	11.2 ± 1.6	9.9 ± 1.6	1.3 ± 0.3
	$P_T^X > 25$ GeV	11	6.6 ± 1.0	5.9 ± 0.9	0.8 ± 0.2
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4



H1+ZEUS		Data	SM	SM	Other SM
1998–2006 $e^-p$		0.39 fb <sup>-1</sup>	Expectation	Signal	Processes
Electron	Total	24	30.6 ± 3.6	19.4 ± 3.0	11.2 ± 1.9
	$P_T^X > 25$ GeV	4	5.6 ± 0.8	4.0 ± 0.6	1.6 ± 0.4
Muon	Total	4	7.4 ± 1.1	6.6 ± 1.0	0.9 ± 0.3
	$P_T^X > 25$ GeV	2	4.3 ± 0.7	3.9 ± 0.6	0.4 ± 0.2
Combined	Total	28	38.0 ± 3.4	26.0 ± 3.4	12.0 ± 2.0
	$P_T^X > 25$ GeV	6	10.0 ± 1.3	7.9 ± 1.2	2.1 ± 0.5

# H1+ZEUS Isolated Leptons: Cross Section

<b>H1+ZEUS Differential Single <math>W</math> Production Cross Section</b>		
$P_T^X$ [GeV]	Measured $\pm$ stat. $\pm$ sys. [fb / GeV]	SM NLO [fb / GeV]
0 – 12	$33.6 \pm 12.3 \pm 5.0$	$62.7 \pm 9.4$
12 – 25	$20.6 \pm 6.0 \pm 1.9$	$20.7 \pm 3.1$
25 – 40	$12.7 \pm 3.6 \pm 1.0$	$9.8 \pm 1.5$
40 – 100	$2.1 \pm 0.7 \pm 0.2$	$1.5 \pm 0.2$

# List of Relevant Publications

- H1 Collaboration, *T. Ahmed et al.*, Observation of an  $e^+p \rightarrow \mu^+X$  Event with High Transverse Momenta at HERA, *unpublished, DESY-94-248*
- H1 Collaboration, *C. Adloff et al.*, Observation of Events with an Isolated High Energy Lepton and Missing Transverse Momentum at HERA, *Eur. Phys. J. C5 (1998) 575*
- ZEUS Collaboration, *J. Breitweg et al.*, W Production and the Search for Events with an Isolated High-Energy Lepton and Missing Transverse Momentum at HERA, *Phys. Lett. B471 (1999) 411*
- ZEUS Collaboration, *S. Chekanov et al.*, Search for Single-top Production in ep Collisions at HERA, *Phys. Lett. B559 (2003) 153*
- H1 Collaboration, *V. Andreev et al.*, Isolated Electrons and Muons in Events with Missing Transverse Momentum at HERA, *Phys. Lett. B561 (2003) 241*
- H1 Collaboration, *A. Aktas et al.*, Search for Single Top Quark Production in ep Collisions at HERA, *Eur. Phys. J. C 33 (2004) 9*
- ZEUS Collaboration, *S. Chekanov et al.*, Search for events with an Isolated Lepton and Missing Transverse Momentum and a Measurement of W production at HERA, *Phys. Lett. B672 (2009) 106*
- H1 Collaboration, *F. D. Aaron et al.*, Events with Isolated Leptons and Missing Transverse Momentum and Measurement of W Production at HERA, *Eur. Phys. J. C64 (2009) 251*
- H1 Collaboration, *F. D. Aaron et al.*, Search for Single Top Quark Production at HERA, *Phys. Lett. B678 (2009) 450*
- H1 Collaboration and ZEUS Collaboration, *F. D. Aaron et al.*, Events with an Isolated Lepton and Missing Transverse Momentum and Measurement of W Production at HERA, *JHEP 1003 (2010) 35*

# Kinematics of H1 High $P_T^X$ Events

H1 Isolated Lepton Events at High $P_T^X$							
Run	Event	Lepton $q(\sigma_q)$	$P_T^\ell$ [ GeV ]	$\theta_\ell$ [ $^\circ$ ]	$P_T^X$ [ GeV ]	$M_T^{\ell\nu}$ [ GeV ]	$P_T^{\text{miss}}$ [ GeV ]
186729	702	$\mu$	$> 42.5$	$30.0 \pm 0.4$	$75.3 \pm 5.5$	$> 33.7$	$> 40.0$
188108	5066	$\mu^- (8.3\sigma)$	$40.9^{+5.6}_{-4.4}$	$35.1 \pm 0.4$	$29.4 \pm 2.4$	$79.2^{+8.0}_{-10.1}$	$43.7^{+3.3}_{-4.2}$
192227	6208	$\mu^- (7.0\sigma)$	$73.3^{+12.2}_{-9.2}$	$28.6 \pm 0.3$	$63.9 \pm 5.9$	$67.8^{+19.8}_{-24.9}$	$19.8^{+5.4}_{-6.8}$
195308	16793	$\mu^+ (4.2\sigma)$	$60.1^{+18.6}_{-11.5}$	$30.9 \pm 0.4$	$30.1 \pm 2.6$	$88.7^{+23.5}_{-37.0}$	$33.5^{+10.6}_{-15.8}$
248207	32134	$e^+ (15\sigma)$	$32.1 \pm 1.3$	$32.2 \pm 0.3$	$42.0 \pm 3.9$	$62.7 \pm 2.3$	$43.4 \pm 2.8$
252020	30485	$e^+ (40\sigma)$	$25.6 \pm 1.2$	$110.2 \pm 0.3$	$39.1 \pm 3.3$	$48.6 \pm 2.1$	$35.5 \pm 2.5$
266336	4126	$\mu^+ (26\sigma)$	$19.7^{+0.8}_{-0.7}$	$67.3 \pm 0.4$	$50.0 \pm 3.8$	$69.8^{+2.4}_{-2.5}$	$66.6 \pm 3.7$
268338	70014	$e^+ (1.6\sigma)$	$33.8 \pm 1.3$	$29.7 \pm 0.2$	$45.2 \pm 3.2$	$90.3 \pm 3.1$	$67.2 \pm 3.0$
275991	29613	$e^+ (37\sigma)$	$37.8 \pm 1.5$	$41.7 \pm 0.3$	$27.1 \pm 1.8$	$73.3 \pm 2.8$	$40.3 \pm 1.4$
369241	6588	$e$	$29.2 \pm 1.1$	$20.3 \pm 0.2$	$40.5 \pm 4.8$	$74.3 \pm 3.0$	$55.5 \pm 4.2$
385422	76666	$e^+ (22\sigma)$	$28.1 \pm 1.3$	$96.1 \pm 0.3$	$25.9 \pm 2.8$	$63.1 \pm 2.8$	$40.0 \pm 2.3$
389826	2783	$e^- (10\sigma)$	$62.0 \pm 2.2$	$45.6 \pm 0.3$	$45.3 \pm 4.5$	$79.7 \pm 6.0$	$30.3 \pm 2.1$
391884	49715	$e$	$38.2 \pm 1.4$	$22.7 \pm 0.2$	$32.4 \pm 2.6$	$48.5 \pm 3.0$	$20.1 \pm 0.8$
473929	107593	$\mu^- (9.6\sigma)$	$53.5^{+6.2}_{-5.1}$	$31.4 \pm 0.4$	$49.1 \pm 4.5$	$80.6^{+8.7}_{-10.7}$	$40.9^{+2.8}_{-3.4}$
494115	121996	$\mu^+ (22\sigma)$	$22.6^{+1.0}_{-1.0}$	$61.5 \pm 0.4$	$37.0 \pm 3.7$	$45.2^{+1.8}_{-1.9}$	$35.8^{+3.0}_{-3.0}$
495399	85500	$\mu^- (32\sigma)$	$29.4^{+0.9}_{-0.8}$	$62.4 \pm 0.4$	$29.6 \pm 2.8$	$63.1^{+1.7}_{-1.8}$	$40.3^{+2.0}_{-2.0}$
498117	316609	$e^+ (9.8\sigma)$	$27.4 \pm 1.1$	$30.7 \pm 0.3$	$26.7 \pm 1.8$	$72.5 \pm 2.5$	$49.9 \pm 2.0$
433051	64528	$e^- (24\sigma)$	$26.2 \pm 1.3$	$69.9 \pm 0.3$	$72.9 \pm 5.6$	$71.3 \pm 2.9$	$75.8 \pm 5.2$

# Different Isolated Lepton Event Selections

Variable	Electron	Muon
1. $\theta_l$	$15^\circ < \theta_l < 120^\circ$	
$P_T^l$	$> 10 \text{ GeV}$	
$P_T^{\text{calo}}$	$> 12 \text{ GeV}$	
2. $M_T$	$> 10 \text{ GeV}$	
$P_T^{\text{miss}}$	$> 12 \text{ GeV}$	
$P_T^X$	-	$> 12 \text{ GeV}$
$D_{\text{jet}}$	$> 1.0$	
$D_{\text{track}}$	$> 0.5$ for $\theta_e \geq 45^\circ$	$> 0.5$
$\zeta_l^2$	$> 5000 \text{ GeV}^2$ for $P_T^{\text{calo}} < 25 \text{ GeV}$	-
3. $V_{\text{ap}}/V_p$	$< 0.5$ ( $< 0.15(0.20)$ for $P_T^e < 25 \text{ GeV}$ )	$< 0.5$ ( $< 0.15(0.20)$ for $P_T^{\text{calo}} < 25 \text{ GeV}$ )
$\Delta\phi_{l-X}$	$< 160^\circ$	$< 170^\circ$
4. $\delta_{\text{miss}}$	$5 \text{ GeV}^{\text{apple}} < \delta_{\text{miss}} (< 50 \text{ GeV})$	
# isolated $\mu$	0	1
5. # electrons	$< 3$	-

 only if one e candidate is detected, with the same charge as the beam lepton

- Five cut differences between the nominal H1 and ZEUS selections

- The preliminary CPS selection is still based on the ZEUS nominal selection

**$M_T$  and # electrons cuts adopted by ZEUS**

**V (the 2D part) and  $\delta_{\text{miss}}$  cuts adopted by H1**

- The more limited polar angle range is needed

# H1 Cross Section Measurements

- H1 selection results in the electron and muon channels are used to calculate production cross sections (excess only at high  $P_T^X$ )
- Two cross section definitions: i) topology based and ii) for W production

$$\sigma_{IsoLep} = \frac{N_d - N_{bg}^{MC}}{\mathcal{L}\epsilon}$$

$$\epsilon = \frac{N_{rec}^{MC}}{N_{gen}^{MC}}$$

$$\sigma_W = \frac{N_d - N_{bg}^{MC}}{\mathcal{L}\Gamma\epsilon}$$

Isolep

W

$P_{T,\ell} > 10 \text{ GeV}$   
 $5^\circ < \theta_\ell < 140^\circ$   
 $D_{jet} > 1 \text{ (in } \eta - \phi)$

Here just look in this phase space (include all signal processes)

Lepton from W (TRUTH)

Here specifically leptons produced in W decays

H1	HERA I+II Data	SM
$\sigma_{\ell+P_T^{\text{miss}}} = 0.23 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (sys.) pb}$		$0.25 \pm 0.04 \text{ pb}$
$\sigma_W = 1.14 \pm 0.25 \text{ (stat.)} \pm 0.14 \text{ (sys.) pb}$		$1.27 \pm 0.19 \text{ pb}$

Both measured H1 cross sections in good agreement with the SM predictions

# Single W Production Cross Section

$$\sigma = \frac{N_{data} - N_{bg}^{MC}}{\mathcal{L} \cdot Br \cdot \mathcal{A}}$$

$N_{bg}^{MC}$  : Number of background events from MC

$\mathcal{L}$  : Luminosity of full HERA data

$Br$  : Branching ratio of decay channels included

$\mathcal{A}$  : Acceptance calculated in full phase space

- Acceptance defined as:  $\mathcal{A} = \frac{N_{rec}}{N_{gen}}$

- $N_{gen}$  : Number of generated W events decaying to the electron and muon channel
- Leptonic tau decays included in  $N_{gen}$  and therefore also in the branching ratio, Br

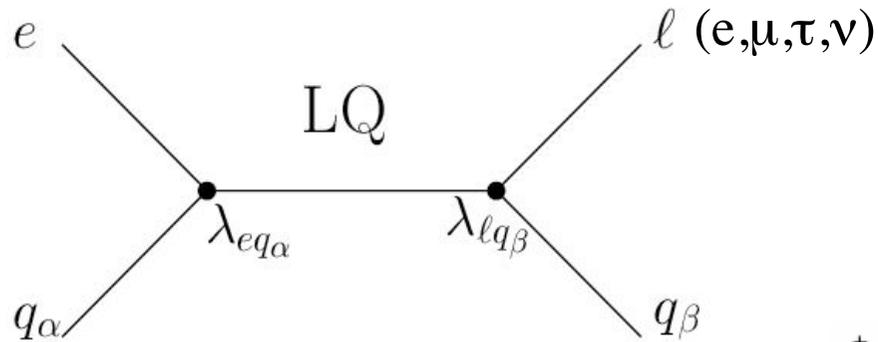
- Measure inclusive cross section and also in 4 bins in  $P_T^X$

- There is no measurement in the  $P_T^X < 12$  GeV bin in the muon channel, so the electron channel is used under the assumption of lepton universality:

- This is valid if  $\sigma_\ell^{All P_T^X} = \sigma_e^{P_T^X > 12} + \sigma_\mu^{P_T^X > 12} + 2\sigma_e^{P_T^X < 12}$

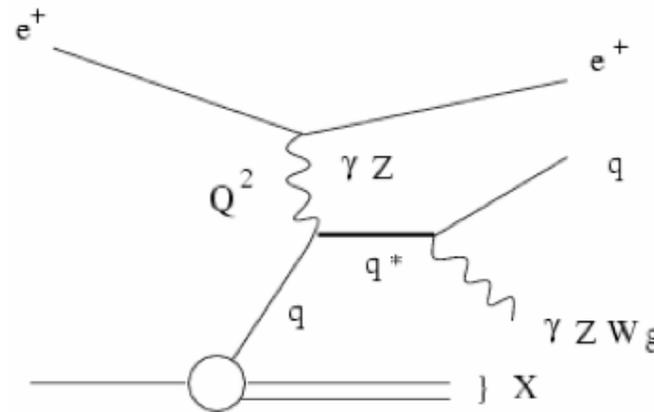
$$\frac{\sigma_\mu^{SM}}{\sigma_e^{SM}} \Big|_{P_T^X < 12} = 1.0092$$

# What could the high $P_T^X$ events be?

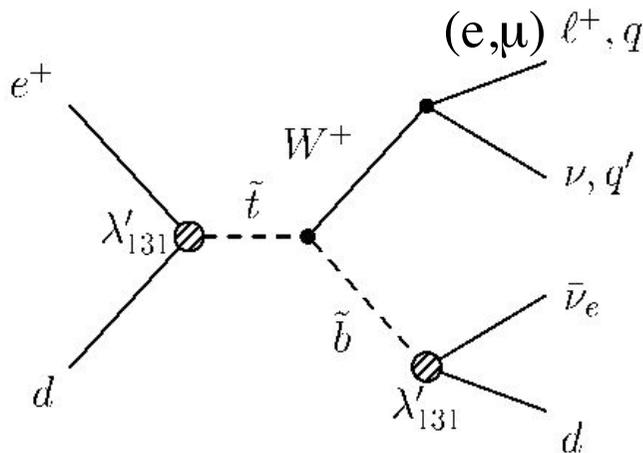


Leptoquarks ?

Excited Fermions ?



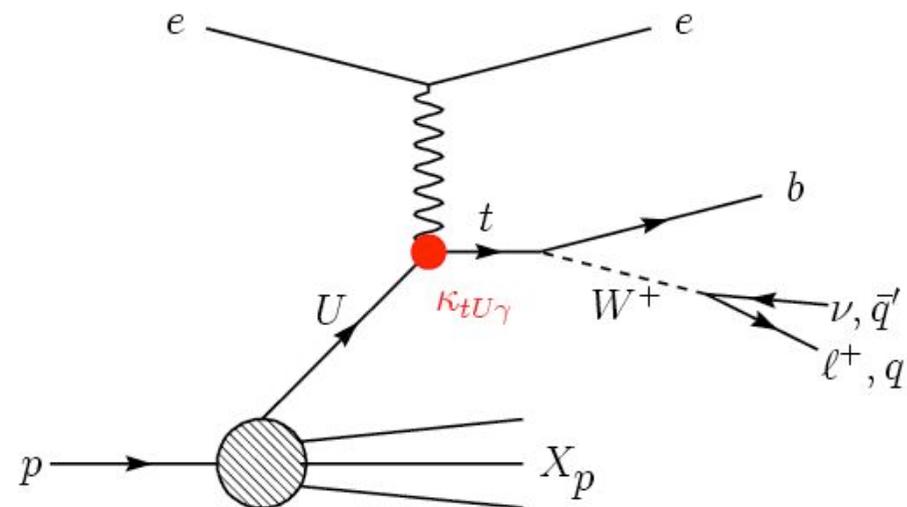
Bosonic Stop Production ?



Ruled out in the H1 data in dedicated analyses...

# What about Single Top Production?

- Excess of observed events at high  $P_T^X$  unlikely to be due to  $W$  production (typically low  $P_T^X$ )
  - Observed topology is typical signature of top decay  $t \rightarrow bW$
  - Tiny SM top production cross section  $< 1$  fb
  - Anomalous top production via Flavour Changing Neutral Current ?
  - However: This process cannot explain asymmetry between the  $e^+p$  and  $e^-p$  datasets..

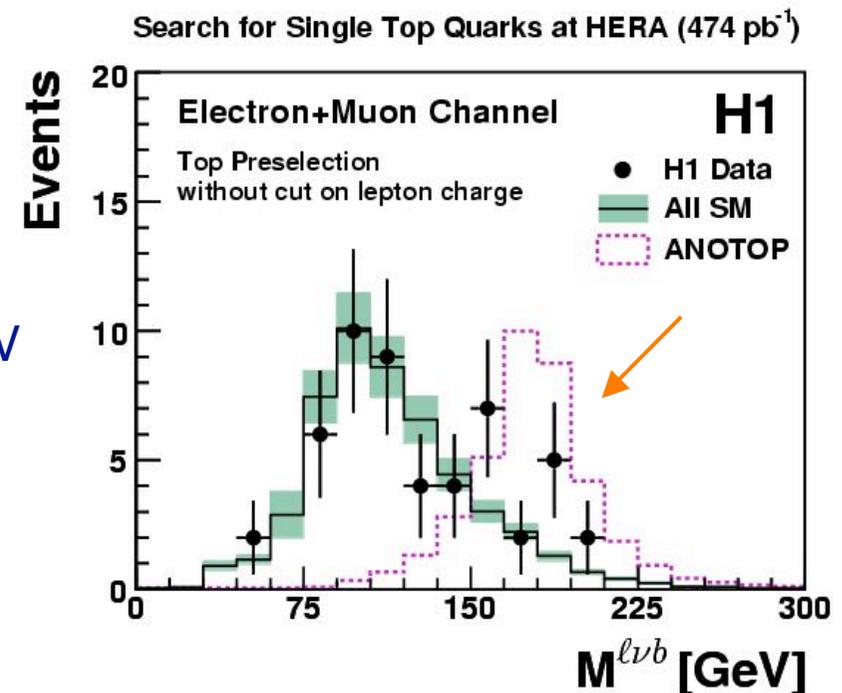


$\kappa_{tU\gamma}$  : Anomalous  $\gamma$  magnetic coupling

# H1 Single Top Analysis

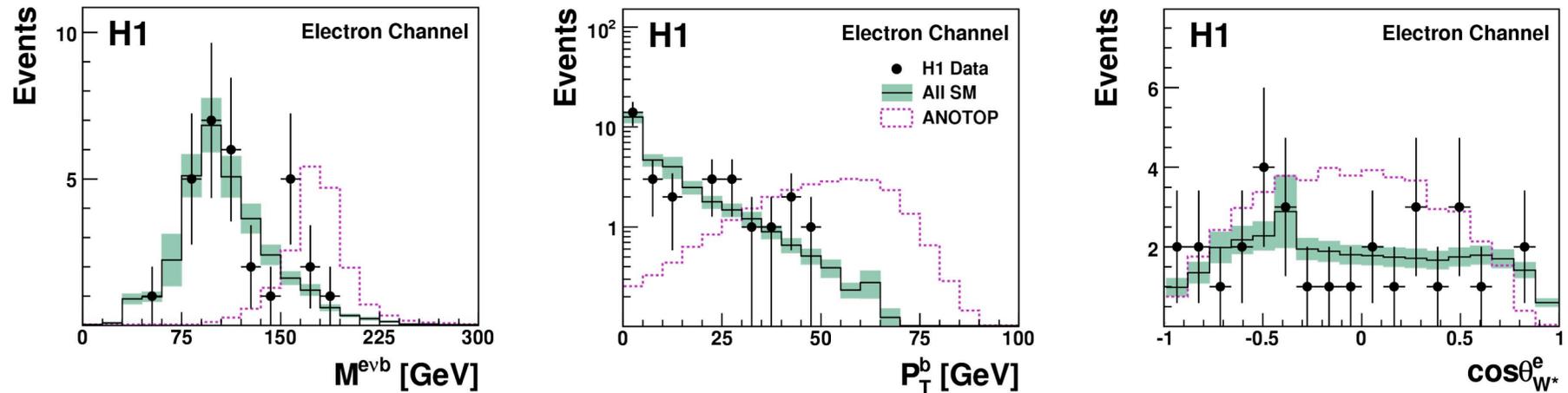
Phys. Lett. B678 (2009) 450

- Leptonic channels:
  - Top pre-selection is subset of the isolated lepton selection
  - Add good neutrino reconstruction
  - Require positively charged lepton
- Hadronic channel:
  - 3 jet selection  $P_{T}^{\text{jet}1,2,3} > 40, 30, 15 \text{ GeV}$
  - Pair of jets with  $65 < M^{i,j} < 95 \text{ GeV}$
- Multivariate discriminator then used to separate signal (Single Top) and background (W production)
  - Used as input:  $P_{T}^b$ ,  $M^{\ell\nu b}$  (jets) and  $\theta_W^l(q)$
  - Cut-based analysis used as cross check

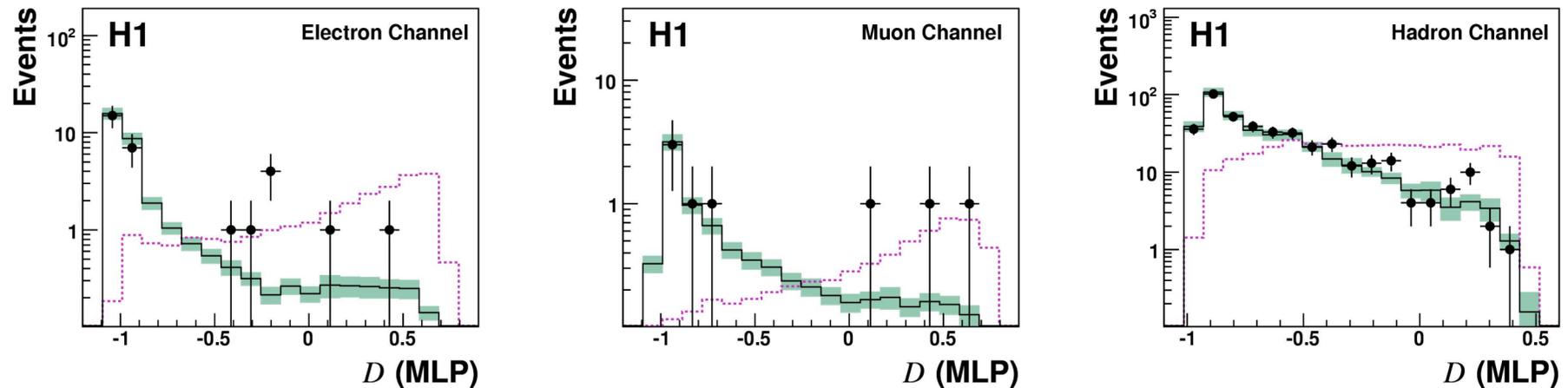


# H1 Single Top Analysis: Discriminator Output

Discriminator input variables (electron channel):



Discriminator output (separation) of all three channels:

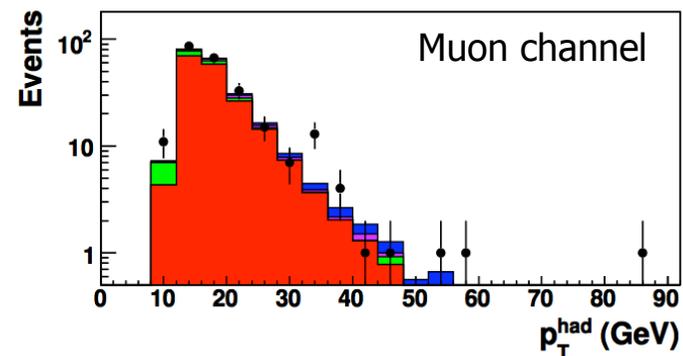
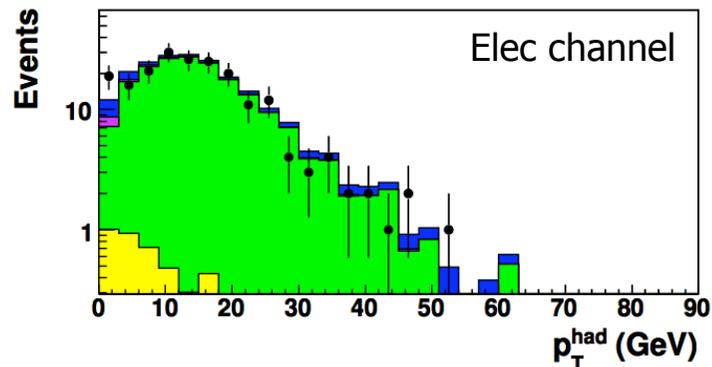


No significant deviation from the SM  $\rightarrow$  *Derive limit..*

# ZEUS Single Top Analysis

ZEUS-prel-09-009

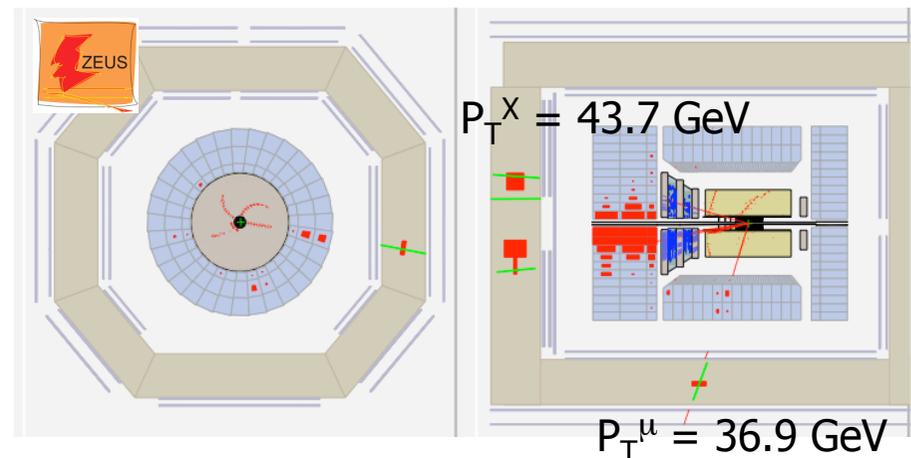
- Investigate leptonic channels in a dedicated analysis
  - Similar to ZEUS isolated lepton selection, but optimised for single top



- No large deviation at high  $P_T^X$ , further topological cuts added to remove SM background (acoplanarity, missing transverse momentum)
- No significant deviation from the SM observed, two high  $P_T$  data events in the muon channel  $\rightarrow$  *Limit*

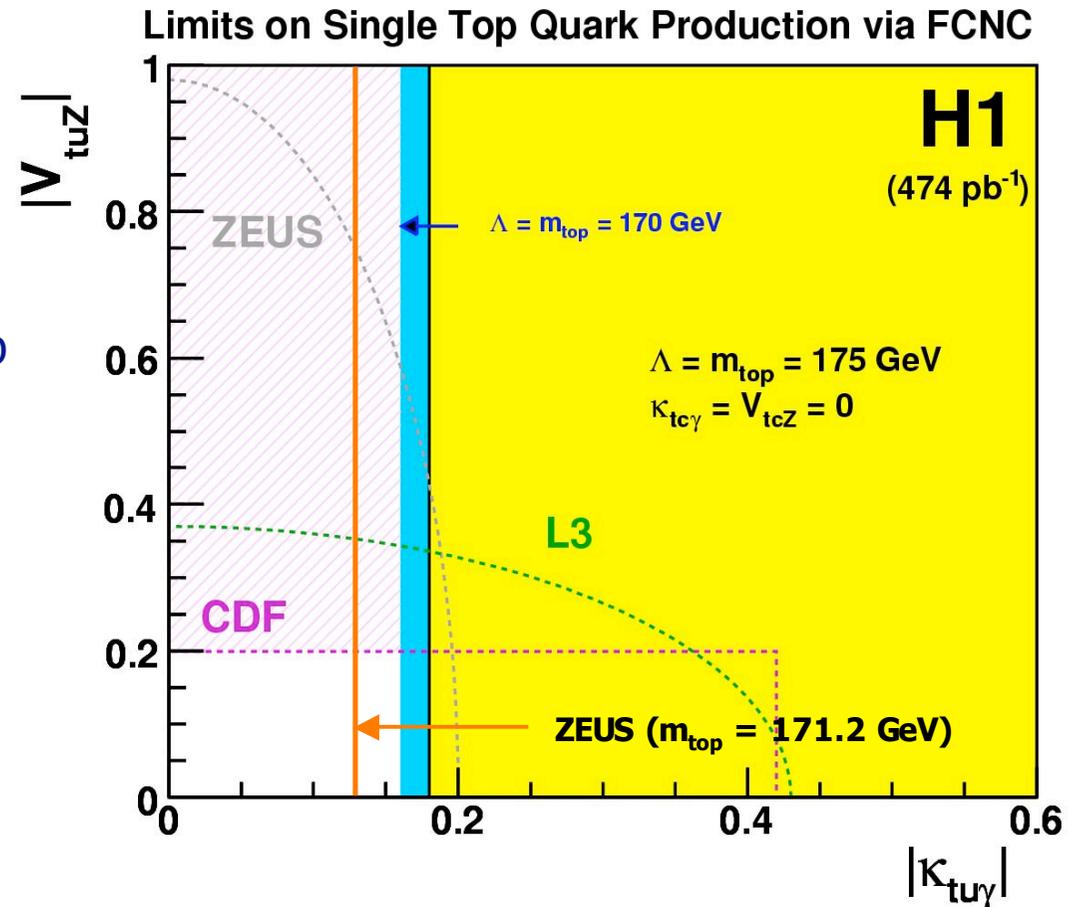
Single Top Selection

	$N_{obs}$	$N_{pred}$	$W\%$	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



# Limits on FCNC Single Top Cross Section

- Upper bounds at 95% CL:
  - H1:  $\sigma(ep \rightarrow etX) < 0.25 \text{ pb}$
  - ZEUS:  $\sigma(ep \rightarrow etX) < 0.13 \text{ pb}$
- Upper bounds on the anomalous coupling
  - H1:  $\kappa_{tu\gamma} < 0.18$
  - ZEUS:  $\kappa_{tu\gamma} < 0.13$



New limit extends into region of phase space uncovered by other colliders

# What about the Tau Channel?

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- Look for events with  $P_T^{\text{miss}}$  and narrow jets from hadronic decay
- Complementary results to those in the electron and muon channels
- Signature of 1-prong tau decay (45% branching ratio)
  - One charged track (the “prong”): narrow, pencil like jet
- H1 analysis using full HERA statistics:  $474 \text{ pb}^{-1}$ 
  - Good overall agreement with the SM prediction
  - Expectation dominated by CC background
  - Challenging hadronic environment



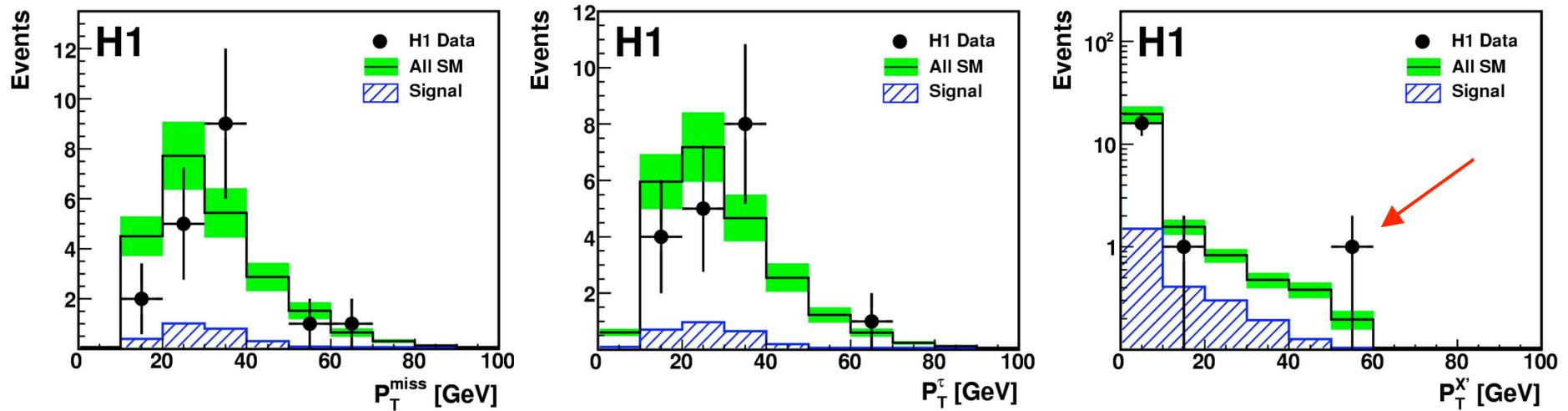
HERA-I:

Isolated Tau Leptons

$2 / 0.2 \pm 0.05$  at  $P_T^X > 25 \text{ GeV}$

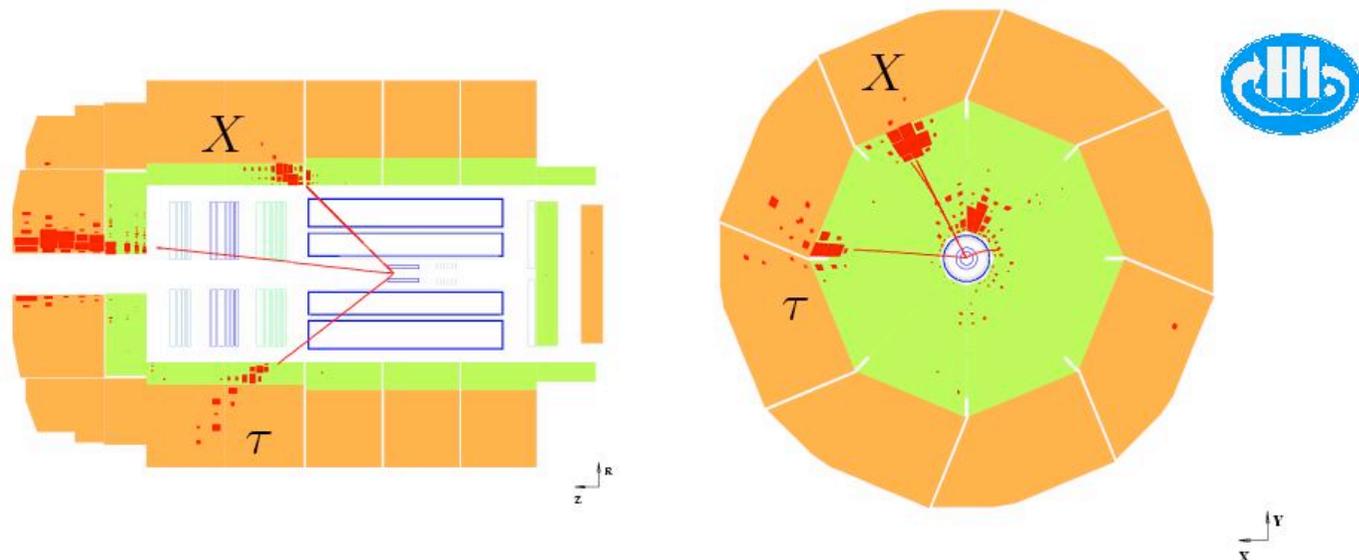
<b>H1</b>	Tau Channel	Data	SM Expectation	SM Signal	Other SM Processes
1994-2007 $e^+p$ $291 \text{ pb}^{-1}$	Total	9	$12.3 \pm 2.0$	$1.66 \pm 0.25$	$10.6 \pm 1.8$
	$P_T^X > 25 \text{ GeV}$	0	$0.82 \pm 0.12$	$0.38 \pm 0.06$	$0.44 \pm 0.06$
1999-2006 $e^-p$ $183 \text{ pb}^{-1}$	Total	9	$11.0 \pm 1.9$	$1.00 \pm 0.15$	$10.0 \pm 1.8$
	$P_T^X > 25 \text{ GeV}$	1	$0.68 \pm 0.11$	$0.21 \pm 0.03$	$0.47 \pm 0.07$
1994-2007 $e^\pm p$ $474 \text{ pb}^{-1}$	Total	18	$23.2 \pm 3.8$	$2.66 \pm 0.40$	$20.6 \pm 3.4$
	$P_T^X > 25 \text{ GeV}$	1	$1.50 \pm 0.21$	$0.59 \pm 0.09$	$0.91 \pm 0.12$

# Tau Channel Distributions



Good overall agreement with the SM prediction

One interesting event observed at high  $P_T^X$  (compared to  $1.5 \pm 0.2$  SM)



$$P_T^{\tau} = 14 \text{ GeV}, P_T^{\text{miss}} = 60 \text{ GeV}, P_T^X = 56 \text{ GeV}$$

# H1 Isolated Tau Selection

<b>H1 Isolated Tau Lepton + <math>P_T^{\text{miss}}</math> Event Selection</b>	
<b>CC-like Sample</b>	$P_T^{\text{miss}} > 12 \text{ GeV}$ $P_T^{\text{calo}} > 12 \text{ GeV}$ $P_T^X > 12 \text{ GeV}$ $\delta_{\text{miss}} > 5 \text{ GeV}$ $V_{\text{ap}}/V_{\text{p}} < 0.5$ $V_{\text{ap}}/V_{\text{p}} < 0.15$ for $P_T^{\text{miss}} < 25 \text{ GeV}$
<b>Tau-like Jets</b>	$P_T^{\text{jet}} > 7 \text{ GeV}$ $20^\circ < \theta_{\text{jet}} < 120^\circ$ $R_{\text{jet}} < 0.12$ $N_{\text{tracks}}^{\text{jet}} \geq 1$ for $P_T^{\text{track}} > 5 \text{ GeV}$
<b>Isolation</b>	$D(\tau; e, \mu, \text{jet}) > 1.0$
<b>Acoplanarity</b>	$\Delta\phi_{\tau-X'} < 170^\circ$ for $P_T^{X'} > 5 \text{ GeV}$
<b>One-prong</b>	$N_{\text{tracks}}^{D_{\text{jet}} < 1.0} = 1$ $N_{\text{NVtracks}}^{D_{\text{track}} < 0.3} = 1$

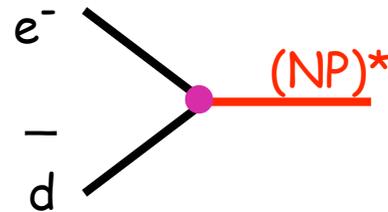
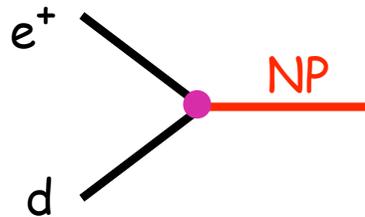
*Missing Energy*

*Narrow, high  $P_T$  jet*

*Exactly one track in the jet*

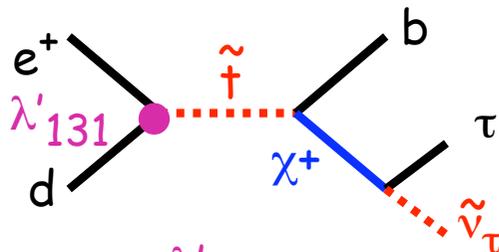
# A BSM Model favouring $e^+p$ over $e^-p$

- Particle coupling to  $e$ - $q$  with fermion number  $F=0$  ?

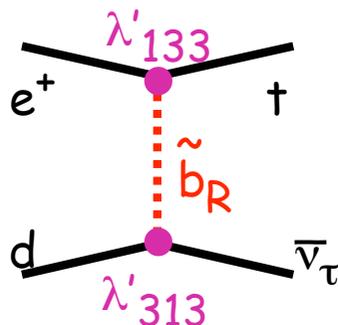


Large mass i.e. large  $x_{Bj}$   
 $d \gg \bar{d}$ , hence  $\sigma(e^+) \gg \sigma(e^-)$

- Another example : Squarks in R-parity violating SUSY ?



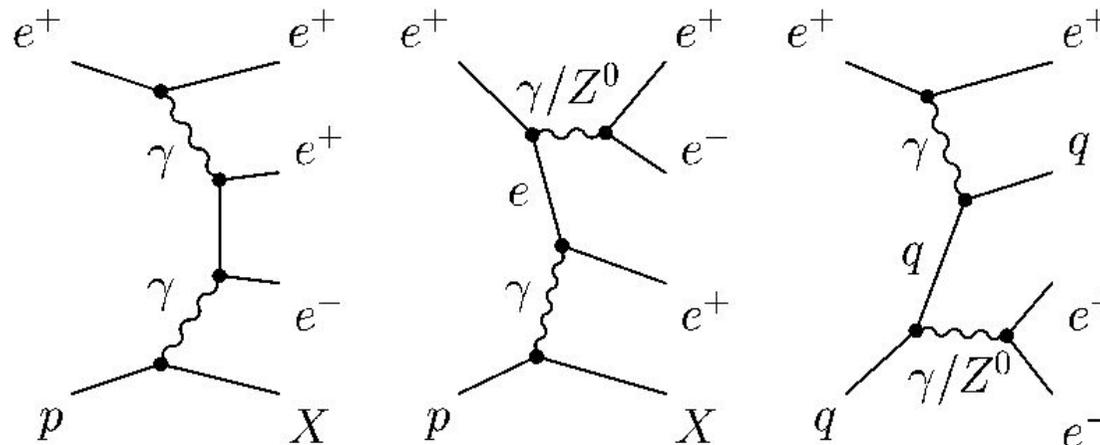
If LSP is  $\tilde{\nu}_\tau$  and no large RpV coupling involving the  $\tau$  :  $\tilde{\nu}_\tau$  could be long-lived



RpV via couplings involving two 3<sup>rd</sup> generation fields, light sbottom. Large  $M_{top} \rightarrow$  large  $x_{Bj}$

# Multi-Lepton Events

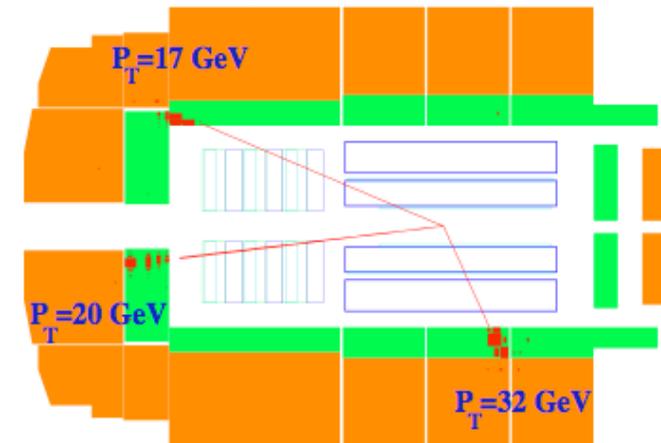
- The main SM process in ep interactions with multi-leptons in the final state is the  $\gamma\gamma$  process:



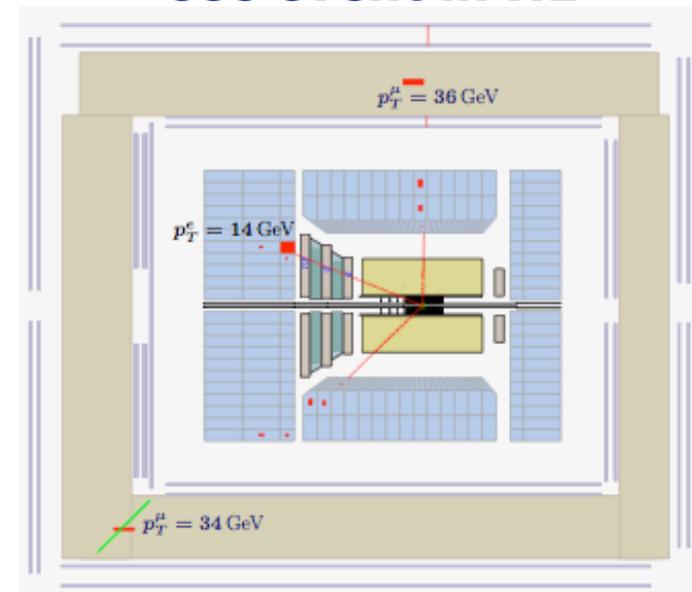
- This QED process has a precise SM prediction, modelled using GRAPE
- Cross section is low at high mass, high  $P_T$ : look for deviations from the SM prediction: indications of new phenomena
- Main SM backgrounds: NC-DIS, QED Compton for multi-electron events; multi-muon events have very low background (non-ep from cosmic rays)

# Multi-Lepton Event Selection

- Events are selected by requiring at least two, isolated high  $P_T$  electrons or muons in the final state
- Electrons identified in the polar angle region  $5^\circ < \theta < 175^\circ$  with  $E > 10$  GeV, with  $E > 5$  GeV in the backward region ( $\theta > 150^\circ$ )
- Muons identified in the polar angle region  $20^\circ < \theta < 160^\circ$  with  $P_T > 2$  GeV
- Events are then classified into independent, exclusive samples:
  - $ee$ ,  $eee$ ,  $\mu\mu$ ,  $e\mu$ ,  $e\mu\mu$  and so on..
- At least two of the leptons must be in the region  $20^\circ < \theta < 150^\circ$  and have  $P_T > 5, 10$  GeV



**eee event in H1**



**eμμ event in ZEUS**

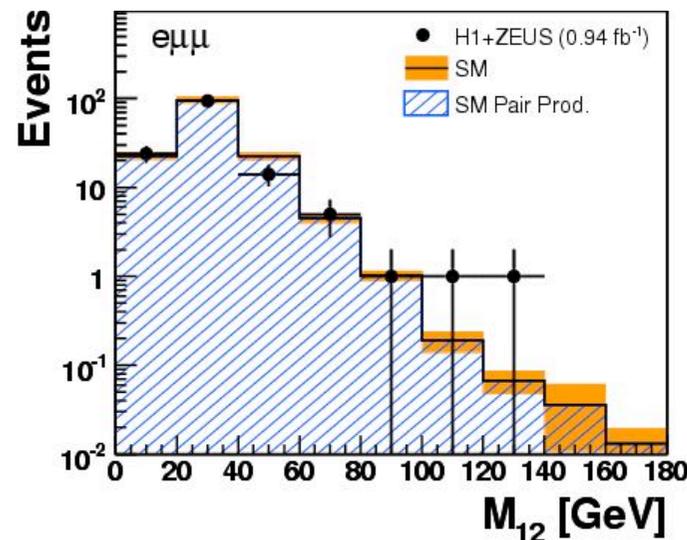
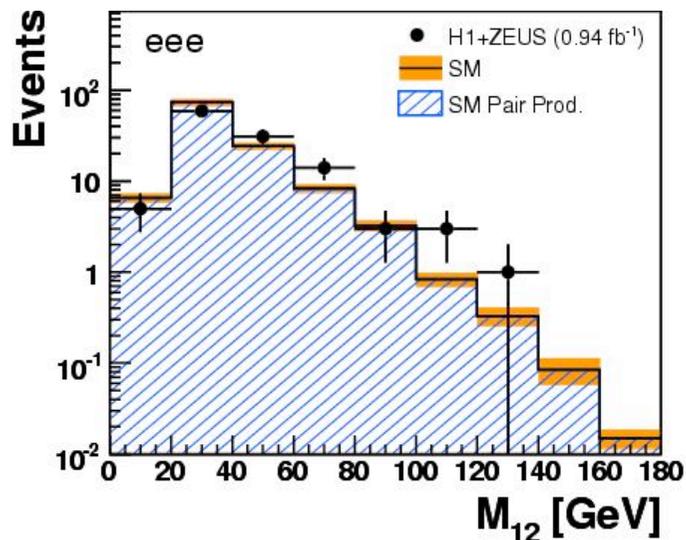
# Results of Different Multi-lepton Topologies

Multi-Leptons at HERA ( $0.94 \text{ fb}^{-1}$ )

Sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
$ee$	873	$895 \pm 57$	$724 \pm 41$	$171 \pm 28$
$\mu\mu$	298	$320 \pm 36$	$320 \pm 36$	$< 0.5$
$e\mu$	173	$167 \pm 10$	$152 \pm 9$	$15 \pm 3$
$eee$	116	$119 \pm 7$	$117 \pm 6$	$< 4$
$e\mu\mu$	140	$147 \pm 15$	$147 \pm 15$	$< 0.5$
$(\gamma\gamma)_e$	284	$293 \pm 18$	$289 \pm 18$	$4 \pm 1$
$(\gamma\gamma)_\mu$	235	$247 \pm 26$	$247 \pm 26$	$< 0.5$

Overall good agreement seen with the SM prediction

$\gamma\gamma$  selections used to measure the cross sections in the photoproduction regime



Looking at the high mass region, a few interesting events show up in the data

# H1+ZEUS Multi-lepton Events at High Mass

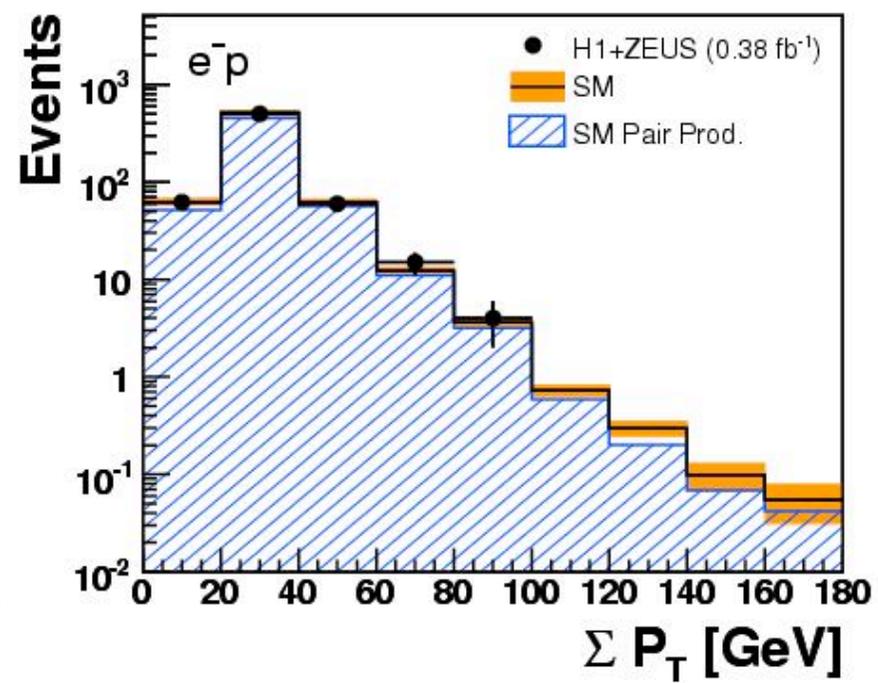
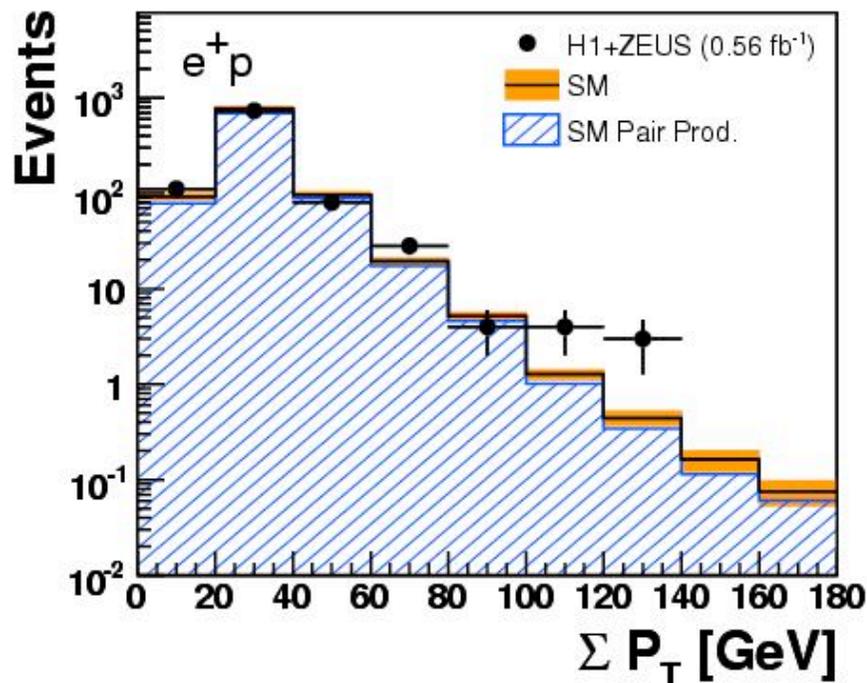
Multi-Leptons at HERA ( $0.94 \text{ fb}^{-1}$ )

$M_{12} > 100 \text{ GeV}$

Sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
$e^+p$ collisions ( $0.56 \text{ fb}^{-1}$ )				
$ee$	4	$1.68 \pm 0.18$	$0.94 \pm 0.11$	$0.74 \pm 0.12$
$\mu\mu$	1	$0.32 \pm 0.08$	$0.32 \pm 0.08$	$< 0.01$
$e\mu$	1	$0.40 \pm 0.05$	$0.39 \pm 0.05$	$< 0.02$
$eee$	4	$0.79 \pm 0.09$	$0.79 \pm 0.09$	$< 0.03$
$e\mu\mu$	2	$0.16 \pm 0.04$	$0.16 \pm 0.04$	$< 0.01$
$e^-p$ collisions ( $0.38 \text{ fb}^{-1}$ )				
$ee$	0	$1.25 \pm 0.13$	$0.71 \pm 0.11$	$0.54 \pm 0.08$
$\mu\mu$	0	$0.23 \pm 0.10$	$0.23 \pm 0.10$	$< 0.01$
$e\mu$	0	$0.26 \pm 0.03$	$0.25 \pm 0.03$	$< 0.02$
$eee$	0	$0.49 \pm 0.07$	$0.49 \pm 0.07$	$< 0.03$
$e\mu\mu$	0	$0.14 \pm 0.05$	$0.14 \pm 0.05$	$< 0.01$
All data ( $0.94 \text{ fb}^{-1}$ )				
$ee$	4	$2.93 \pm 0.28$	$1.65 \pm 0.16$	$1.28 \pm 0.18$
$\mu\mu$	1	$0.55 \pm 0.12$	$0.55 \pm 0.12$	$< 0.01$
$e\mu$	1	$0.65 \pm 0.07$	$0.64 \pm 0.06$	$< 0.02$
$eee$	4	$1.27 \pm 0.12$	$1.27 \pm 0.12$	$< 0.03$
$e\mu\mu$	2	$0.31 \pm 0.06$	$0.31 \pm 0.06$	$< 0.01$

All high mass events seen in the  $e^+p$  data:  
 9 from H1  
 3 from ZEUS

# H1+ZEUS Multi-lepton Events at High $\Sigma P_T$



Multi-Leptons at HERA (0.94 fb<sup>-1</sup>)

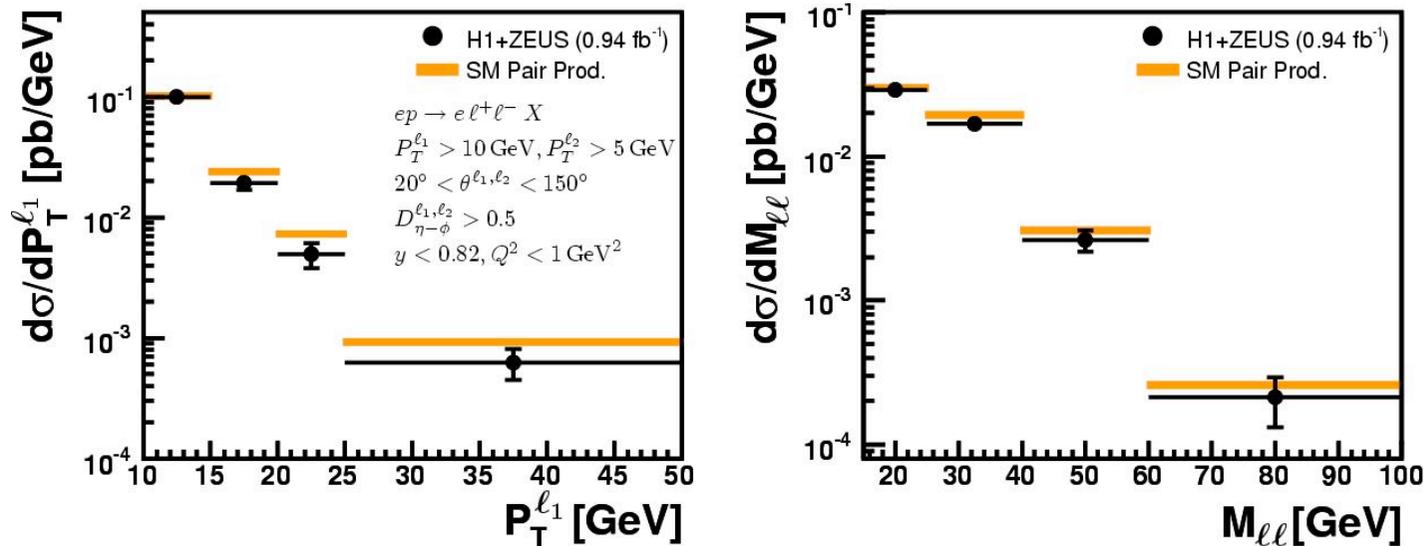
$\Sigma P_T > 100$  GeV

Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
<b>e<sup>+</sup>p (0.56 fb<sup>-1</sup>)</b>	<b>7</b>	<b>1.94 ± 0.17</b>	<b>1.52 ± 0.14</b>	<b>0.42 ± 0.07</b>
e <sup>-</sup> p (0.38 fb <sup>-1</sup> )	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb <sup>-1</sup> )	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10

- 7 events observed in the e<sup>+</sup>p data with  $\Sigma P_T > 100$  GeV, where the significance of excess of SM expectation is  $2.6\sigma$

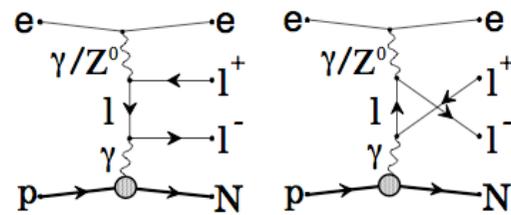
# Measurement of the $\gamma\gamma \rightarrow l^+l^-$ Cross Section

- Two-photon channels used to measure the H1+ZEUS weighted average cross section for electron and muon pair production in the kinematic region indicated

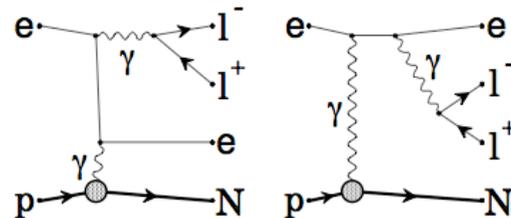


- Differential cross sections measured as a function of the  $P_T$  of the leading lepton and the invariant mass of the lepton pair
- Total visible cross section measured  $0.66 \pm 0.03$  (stat.)  $\pm 0.03$  (sys.) pb in good agreement with the SM prediction of  $0.69 \pm 0.02$  pb from GRAPE

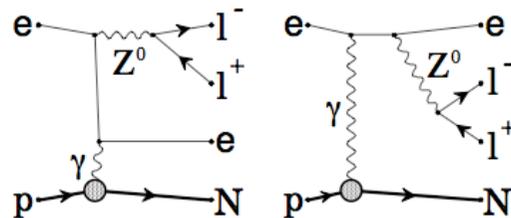
# Full Set of Pair Production Diagrams in GRAPE



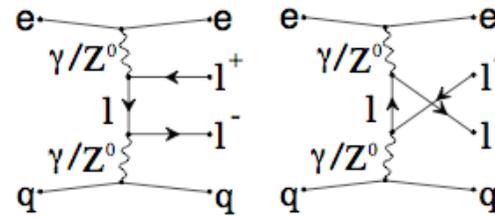
(a) Bethe-Heitler type diagrams



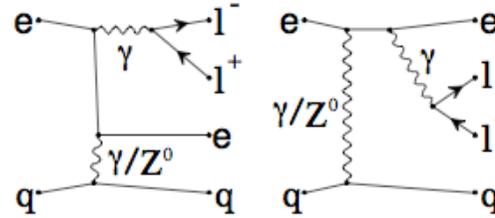
(b) QED-Compton type diagrams



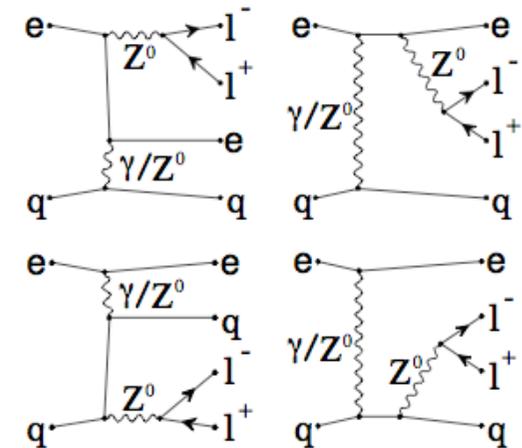
(c)  $Z^0$  on/off-shell production



(a) Bethe-Heitler type diagrams



(b) QED-Compton type diagrams



(c)  $Z^0$  on/off-shell production

Fig. 2: Feynman diagrams included in the DIS process.  $e=\{e^+, e^-\}$ ,  $l^\pm=\{e^\pm, \mu^\pm, \tau^\pm\}$

Fig. 1: Feynman diagrams included in the (quasi-)elastic process.  $e=\{e^+, e^-\}$ , and  $q=\{\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, \bar{t}\}$ .  $l^\pm=\{e^\pm, \mu^\pm, \tau^\pm\}$ . N means a (dissociated) proton or a nucleon resonance.