



W and Z Physics from HERA

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on behalf of the H1 and ZEUS Collaborations

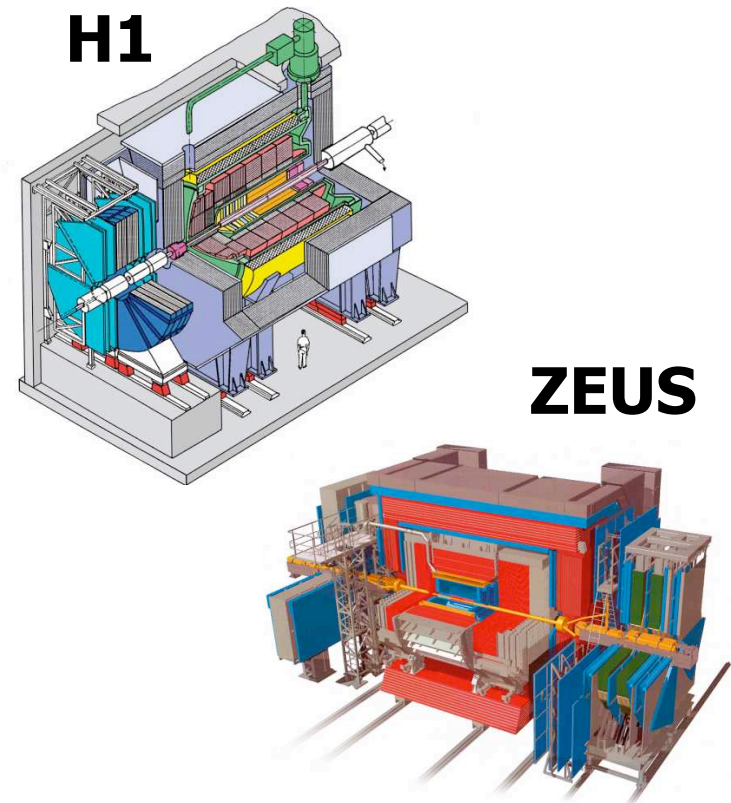
The Physics of W and Z Bosons, June 24 - 25 2010,



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



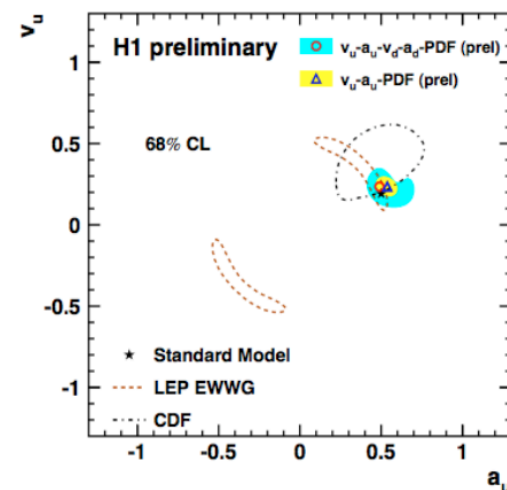
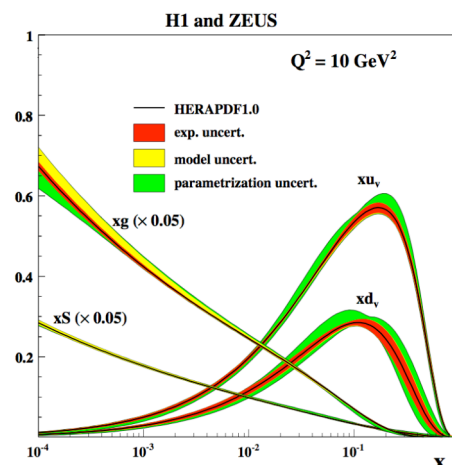
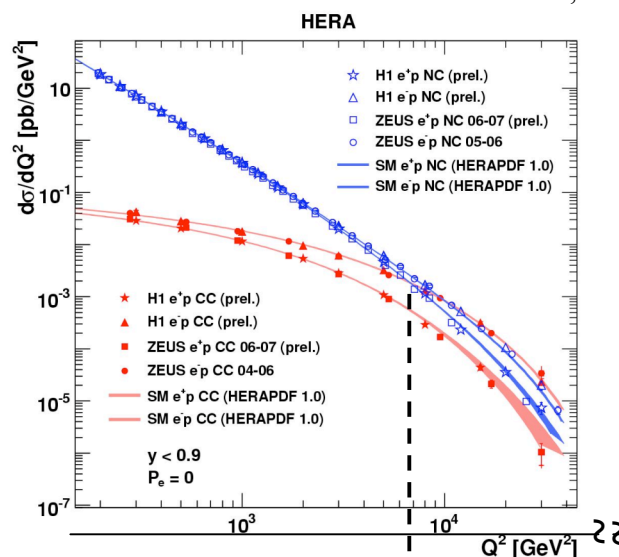
- Two multi-purpose experiments located at the ep interaction points
- The world's most powerful electron microscope, counter-rotating 6.3 km long accelerators
- Particle energies allow us to probe proton structure down to $\Delta x \approx 10^{-18}\text{m}$



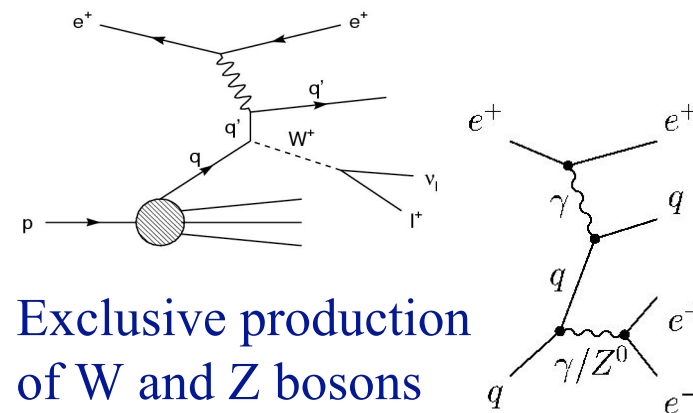
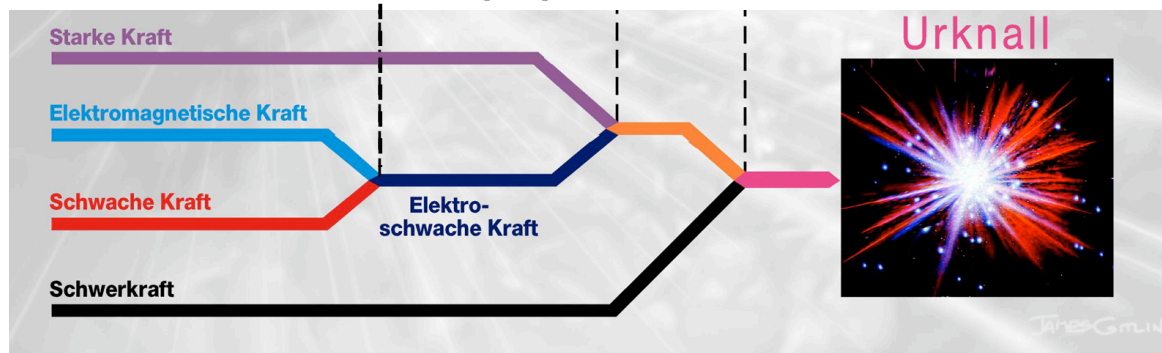
Collisions every 96ns, $\sqrt{s} = 319 \text{ GeV}$

Electroweak Physics at HERA

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

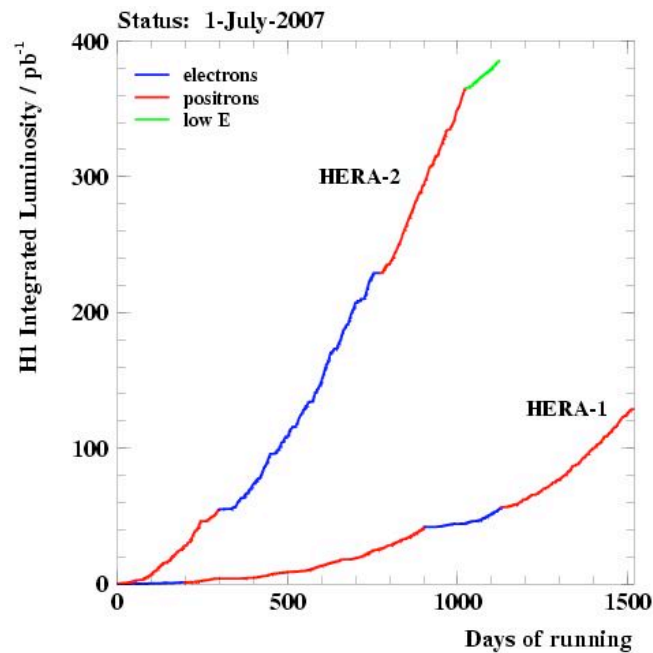


QCD and electroweak fits to the HERA data



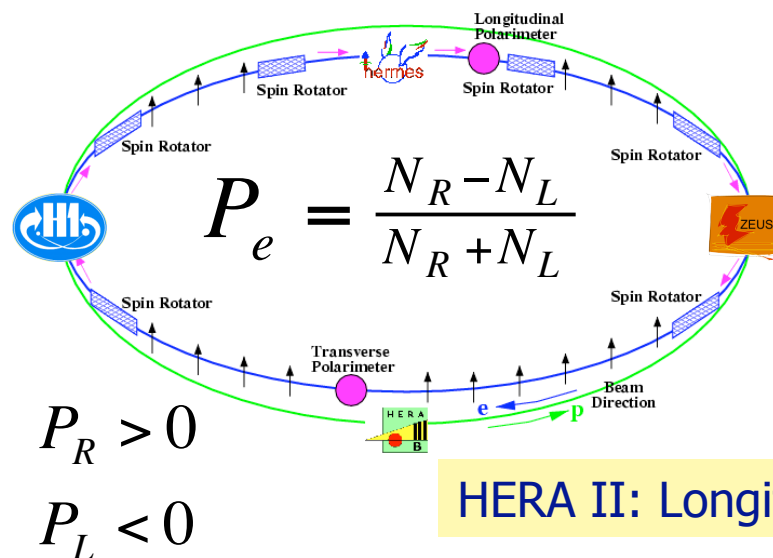
Measurements with W and Z bosons at HERA are within reach!

Data Taking at HERA 1994-2007

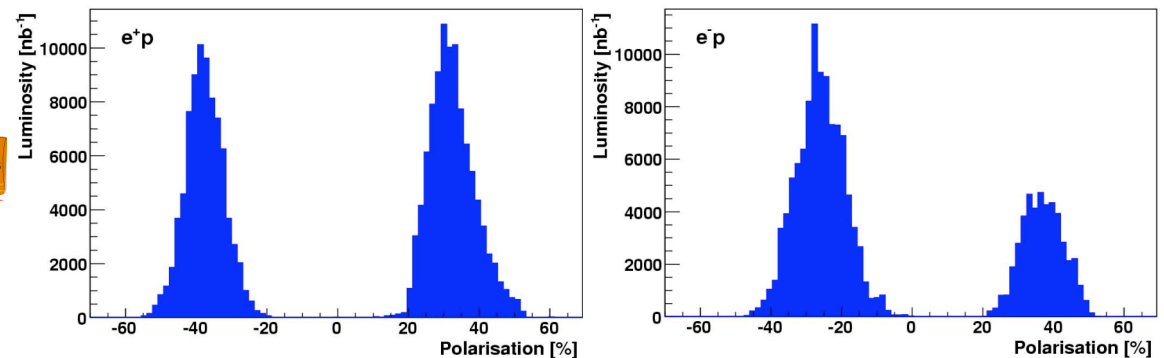


- Large increase in data per experiment after the luminosity upgrade for HERA II (x3)
- Large increase (x12) in data taken from e-p collisions: HERA I mostly e⁺p data

Final HERA I+II dataset $\sim 0.5 \text{ fb}^{-1}$ / experiment

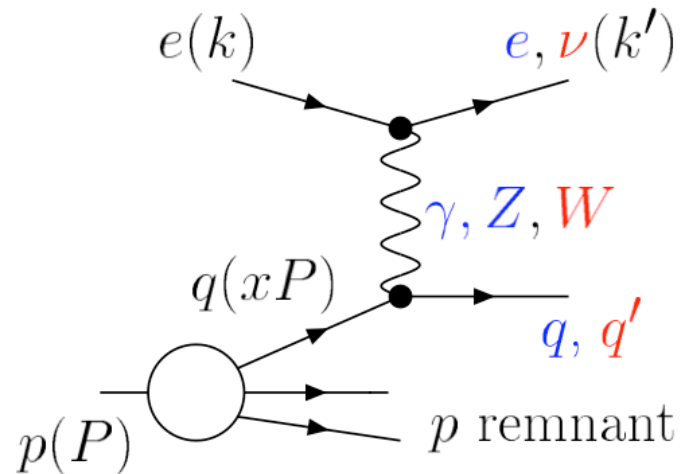


e⁺p, -P e⁺p, +P e⁻p, -P e⁻p, +P



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

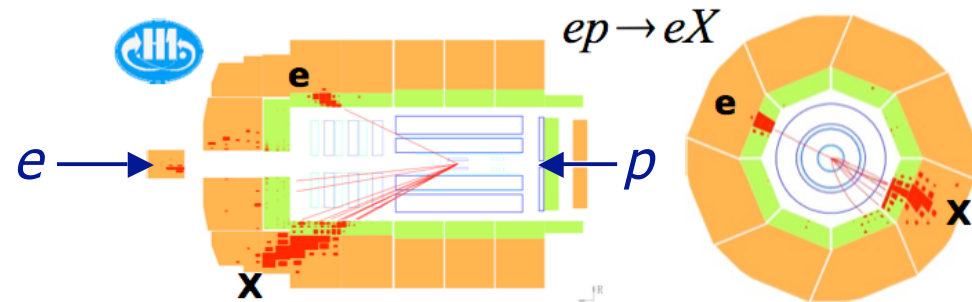
$$x = \frac{Q^2}{2P \cdot (k - k')}$$

Fraction of proton momenta carried by the struck quark

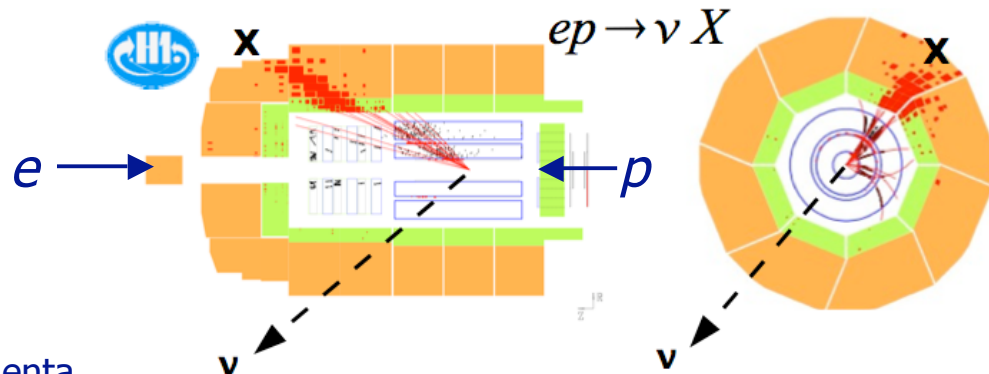
$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

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

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



Neutral Current interaction



Charged Current interaction

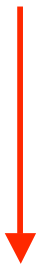
NC and CC cross section measurements done using up to the full HERA I+II data in the range $200 < Q^2 < 30,000 \text{ GeV}^2$

Neutral Current Cross Sections

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

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

The **dominant** contribution



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

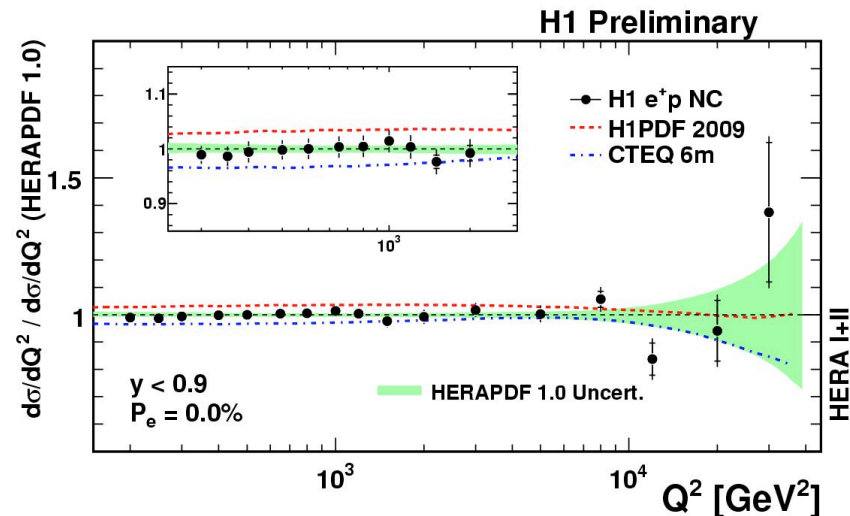
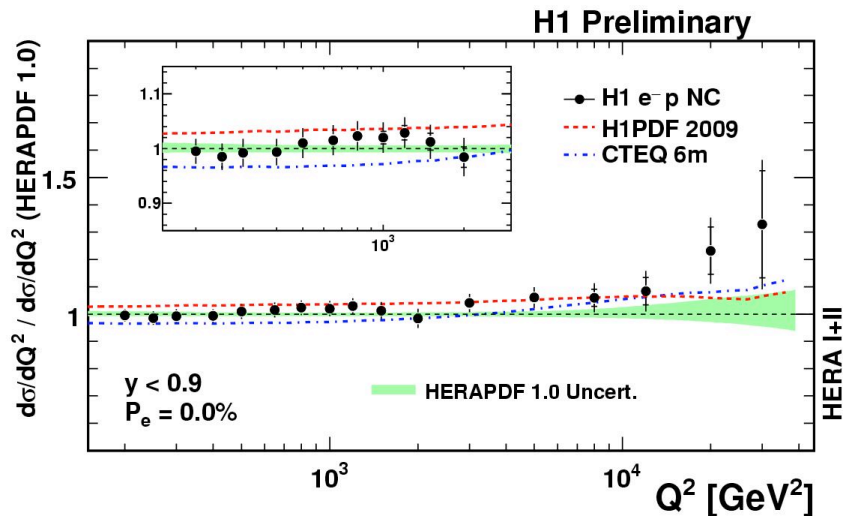
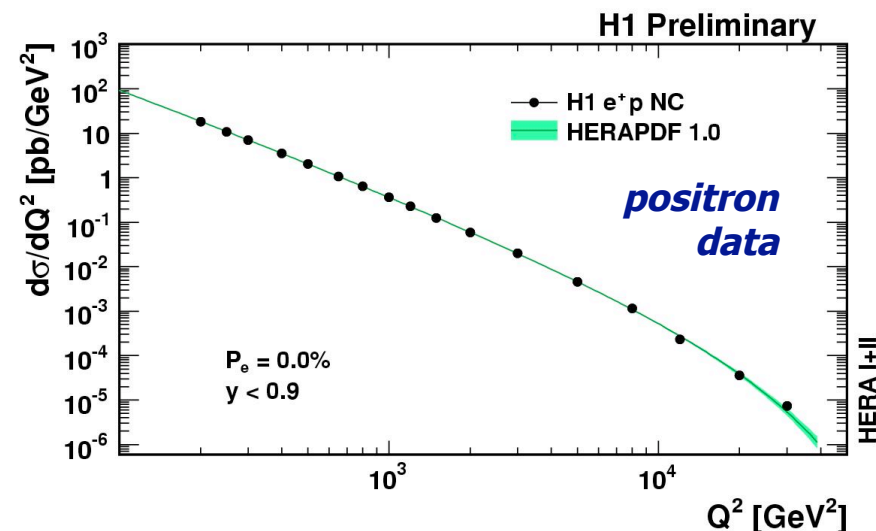
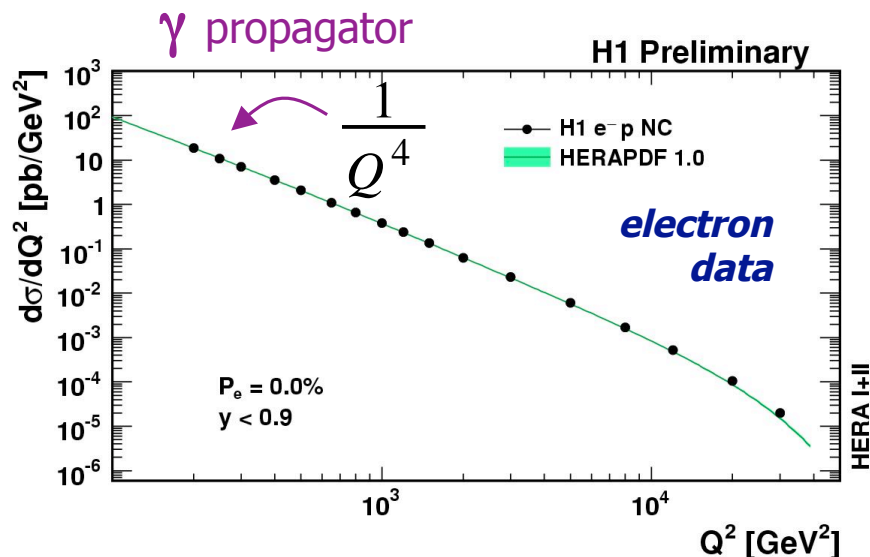
Only important at **high Q²**
- Measure using difference
of e⁺p and e⁻p cross sections

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

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

In addition, the NC cross section is also sensitive to the *lepton polarisation*, but only via the Z and γZ interference terms: small effect only visible at high Q²

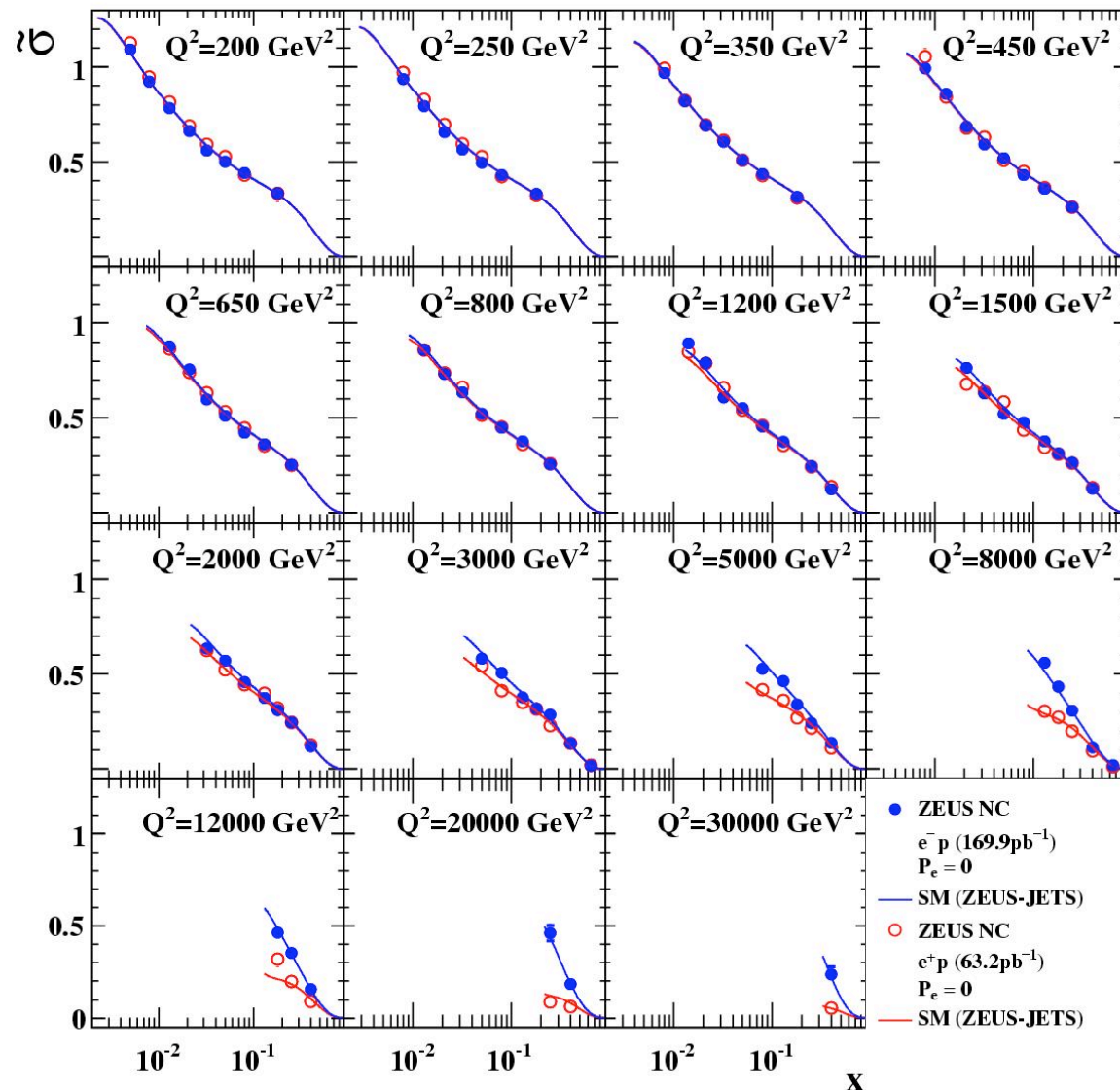
Unpolarised Cross Sections: HERA I+II



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

Unpolarised Reduced NC Cross Section: e^-p vs. e^+p

ZEUS



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

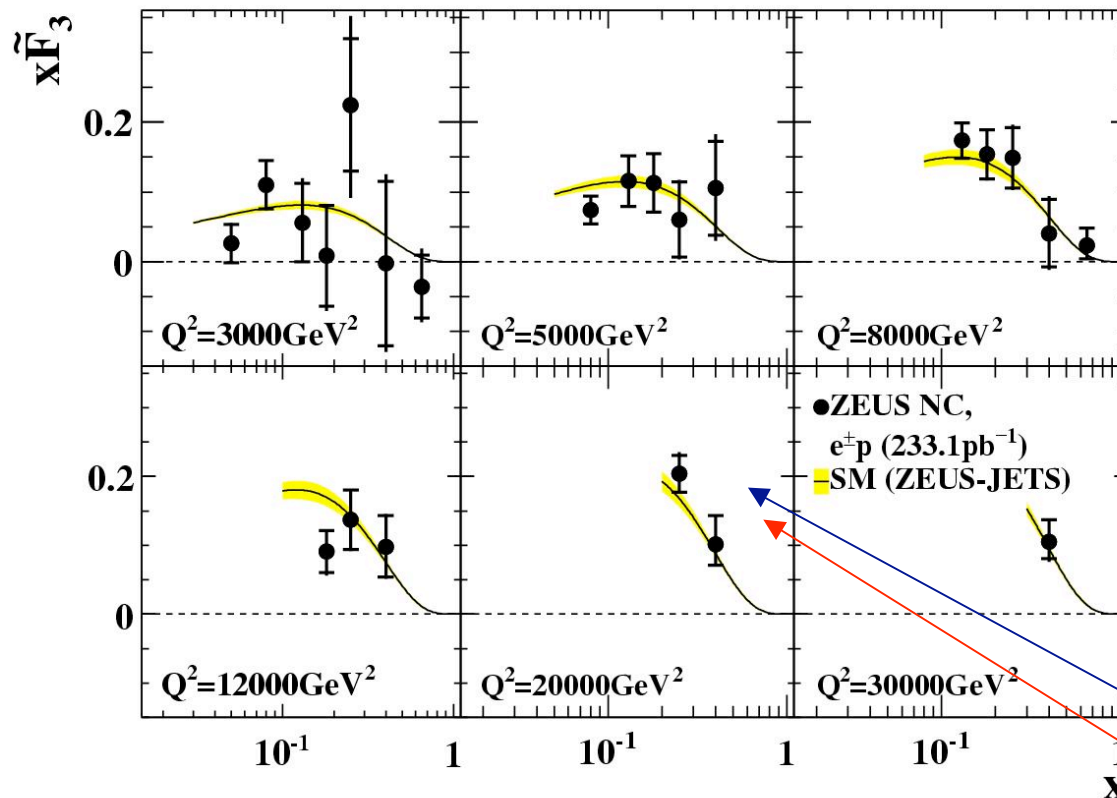
Separation of e^+p and e^-p cross sections at high Q^2

Influence of γZ interference term

Visible difference in the e^+p and e^-p cross sections is described well by the SM predictions

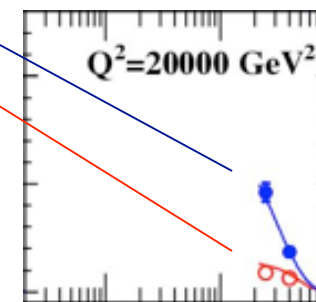
Evaluation of $x\tilde{F}_3$

ZEUS

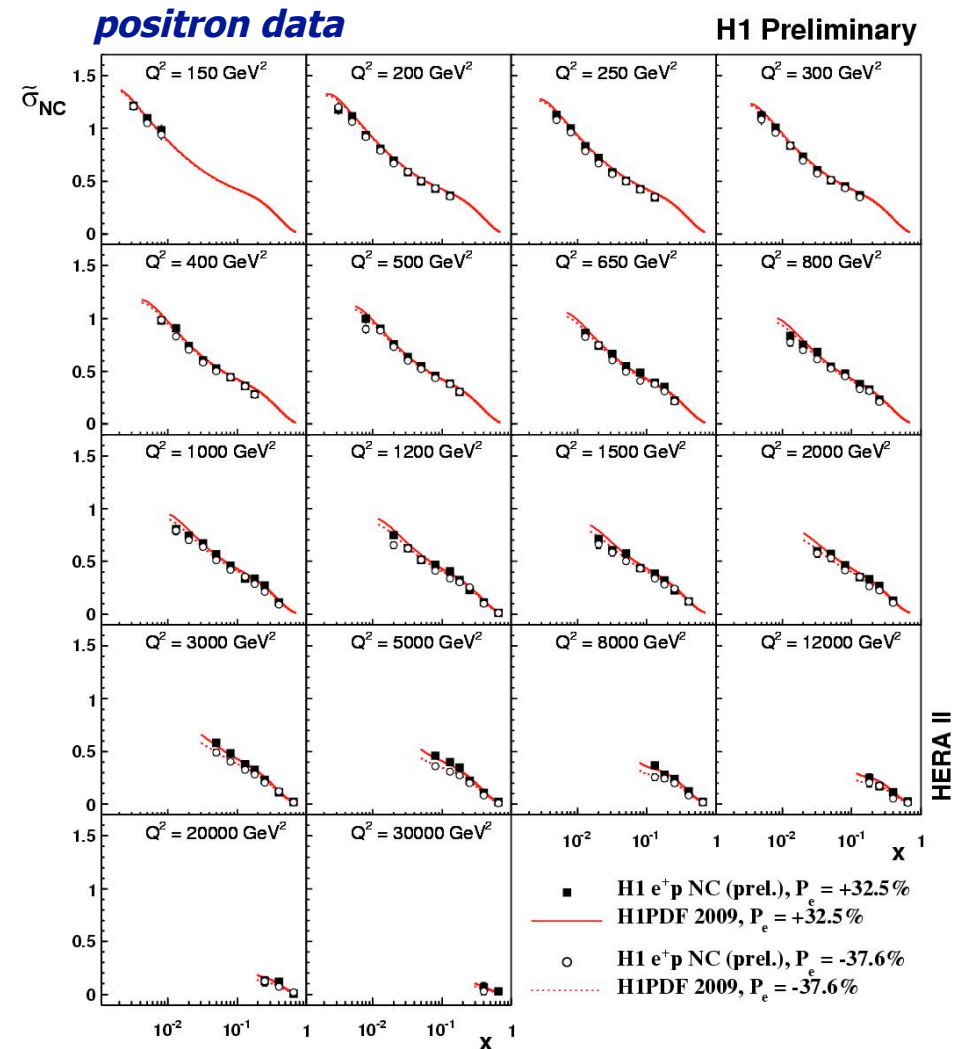
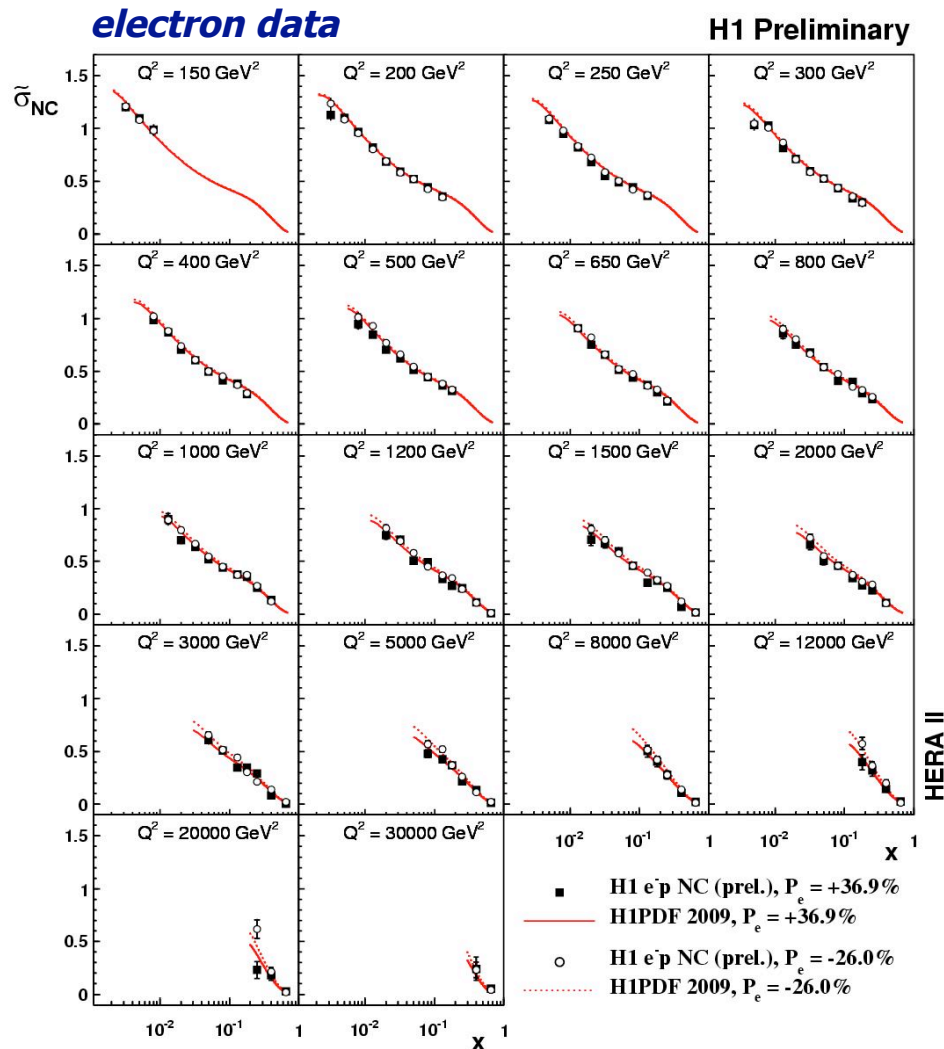


$x\tilde{F}_3$ is calculated from the difference in the unpolarised reduced cross sections at high Q^2

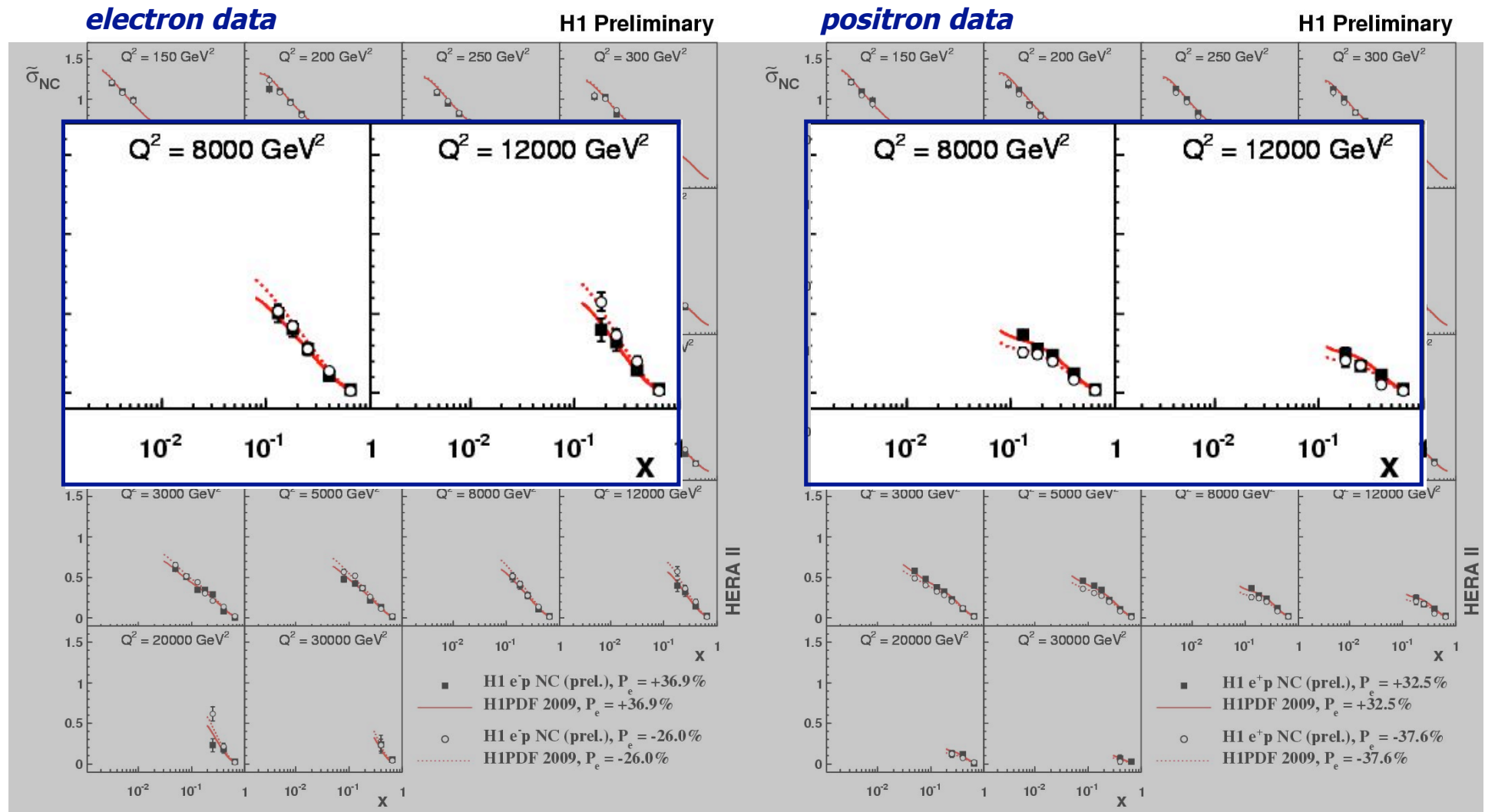
$$x\tilde{F}_3 = \frac{Y_+}{2Y_-} [\tilde{\sigma}^-(x, Q^2) - \tilde{\sigma}^+(x, Q^2)]$$



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

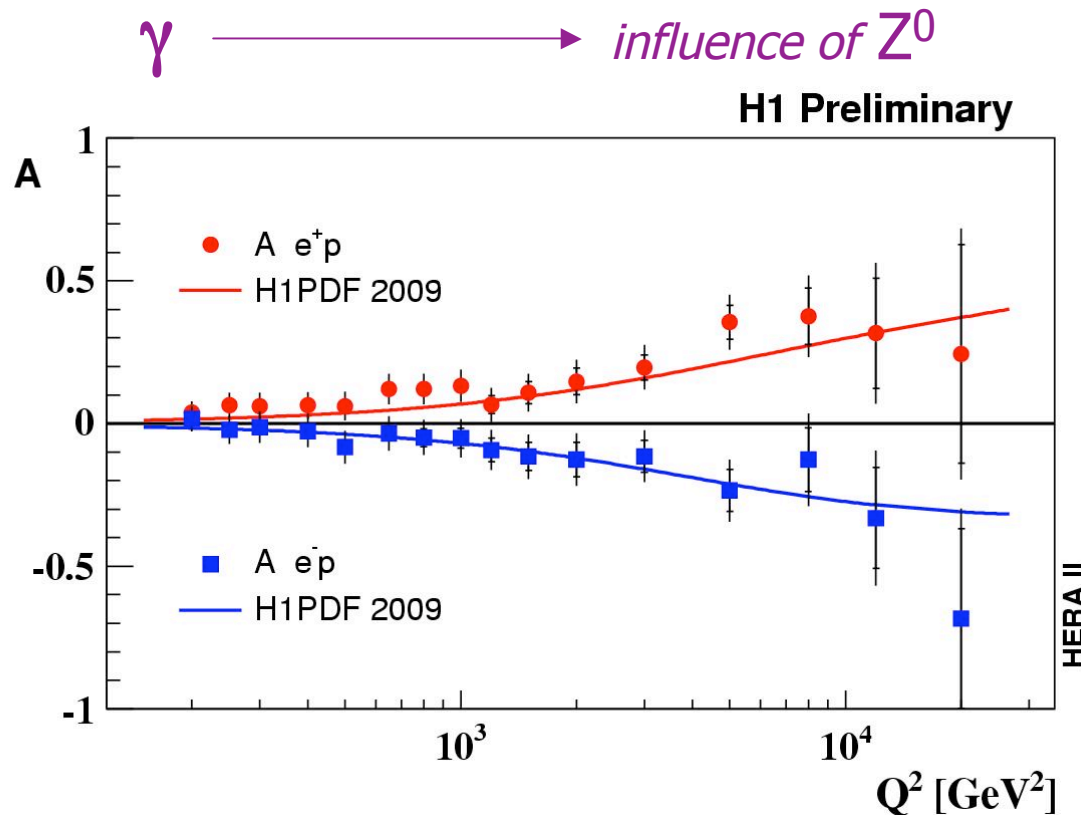


Polarised Reduced NC Cross Section: -P vs. +P



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

HERA II Polarisation Asymmetry in NC



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

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

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:

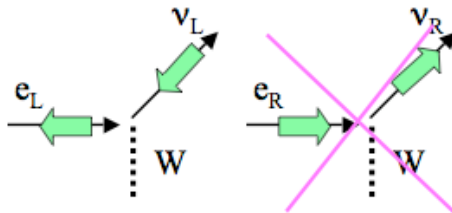
Sensitive to the density of the d quark

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

e^-p cross section:

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

Sensitive to the density of the u quark



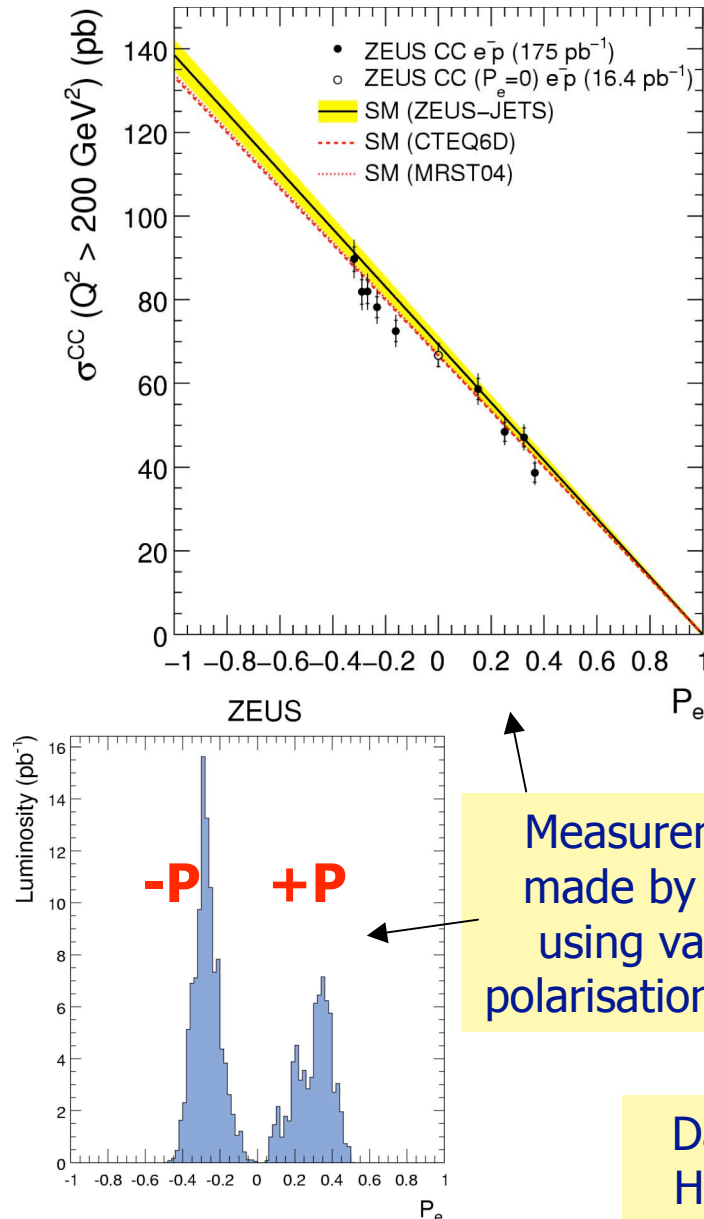
Standard Model weak interaction left-handed:
only LH Particles (RH anti-particles) interact

CC cross section modified by polarisation P_e :

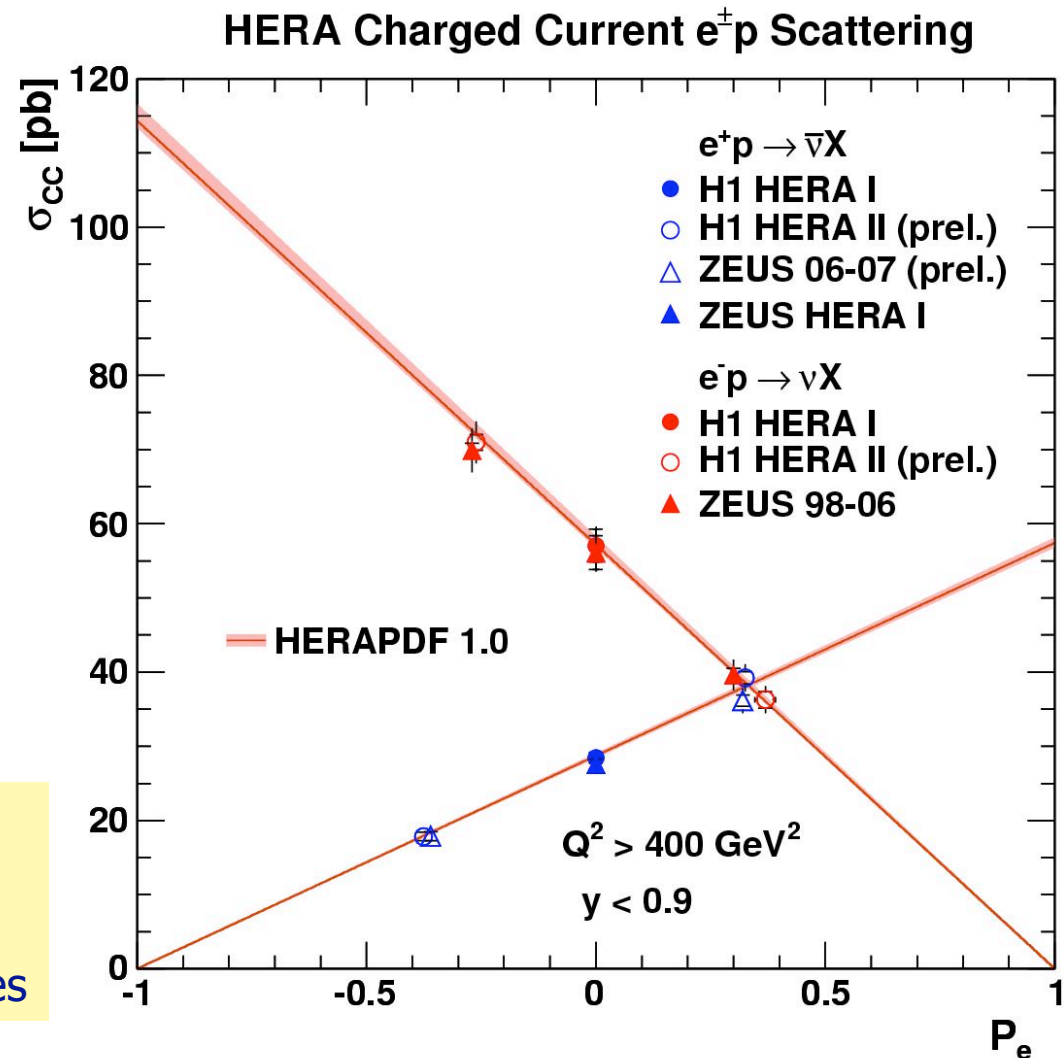
$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e) \cdot \sigma_{CC}^{e^\pm p}(P_e = 0)$$

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



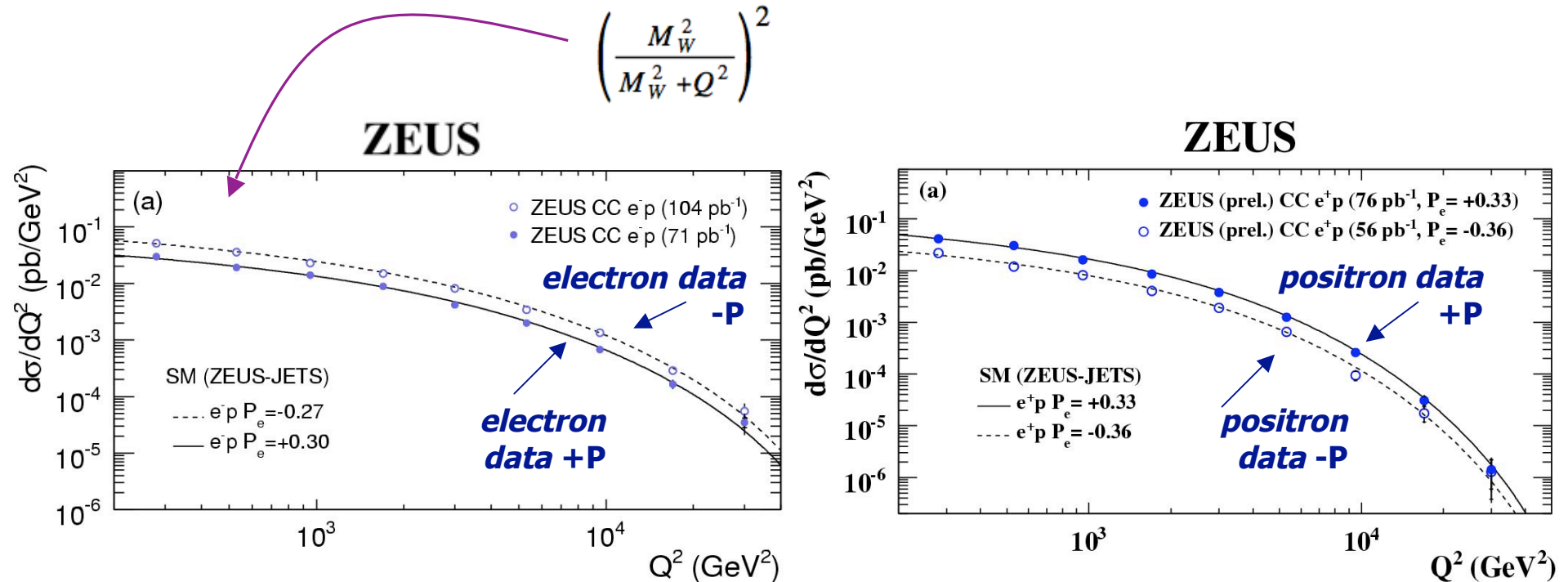
Measurements made by ZEUS using various polarisation values



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

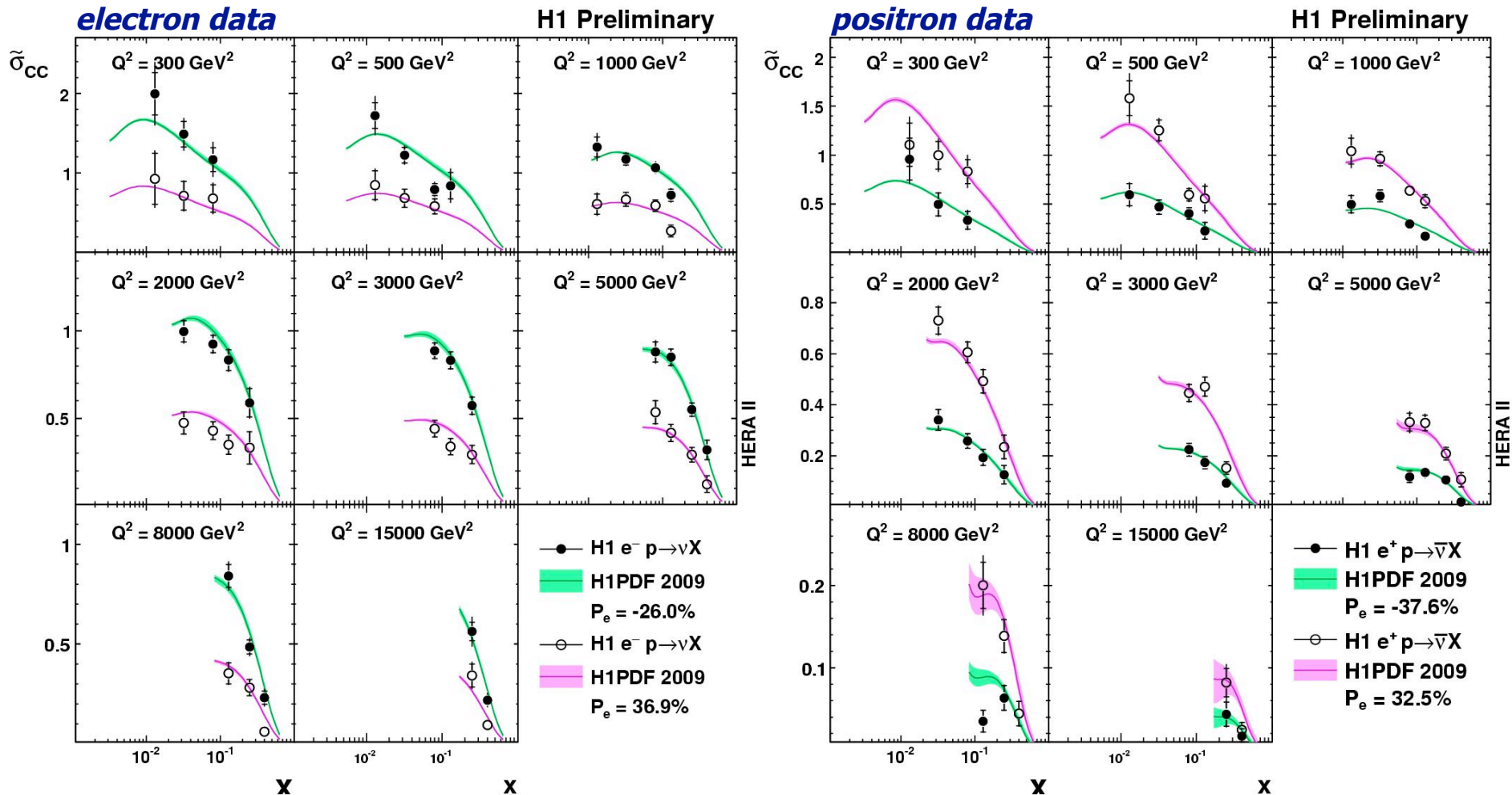
Single Differential CC Cross Sections $d\sigma/dQ^2$

W propagator: cross section much lower than NC



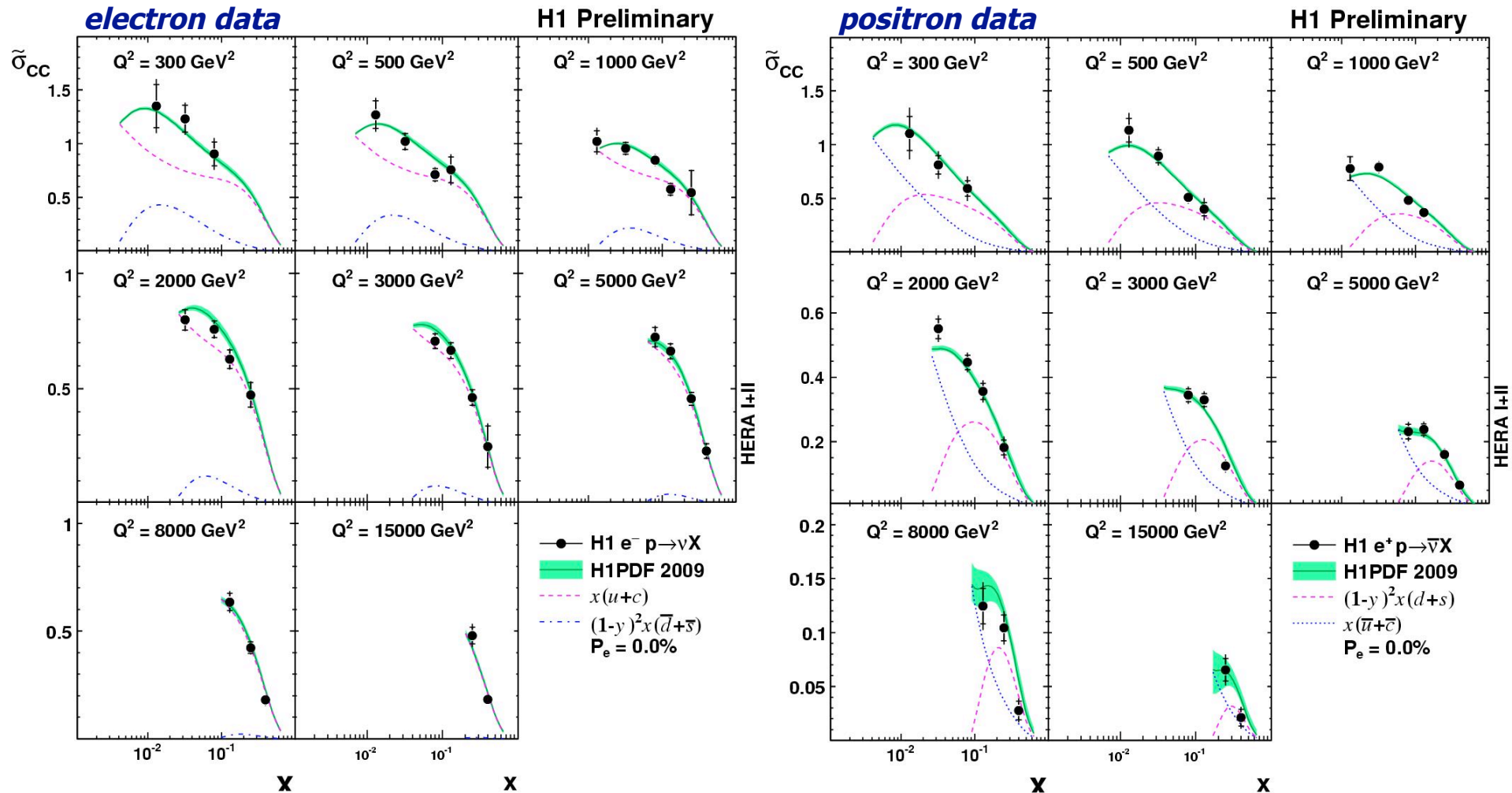
Higher cross section of e^-p data visible, difference due to quark content
 Opposite polarisation dependence of data sets visible
 Good agreement with SM model prediction based on ZEUS-JETS QCD fit

Reduced CC Cross Section: -P vs. +P



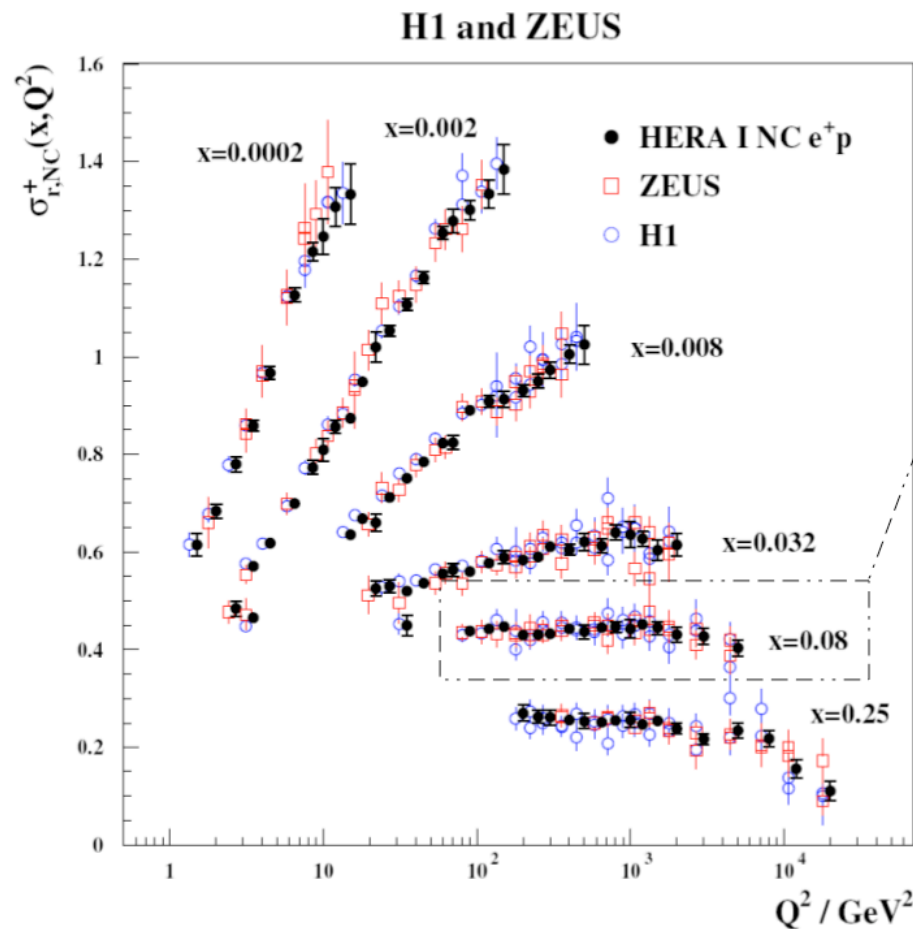
Similarly from H1, double differential cross sections show clear polarisation asymmetry

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



after Shiraz Habib

$x=0.08$

Systematic Uncertainty:

- $\delta_{\text{H1 LAR}} \rightarrow 0.45 \delta_{\text{H1 LAR}}$
- $\delta_{\text{ZEUS BG}} \rightarrow 0.35 \delta_{\text{ZEUS BG}}$

Overall Precision:

- 2% for $3 < Q^2 < 500 \text{ GeV}^2$
- 1% for $20 < Q^2 < 100 \text{ GeV}^2$

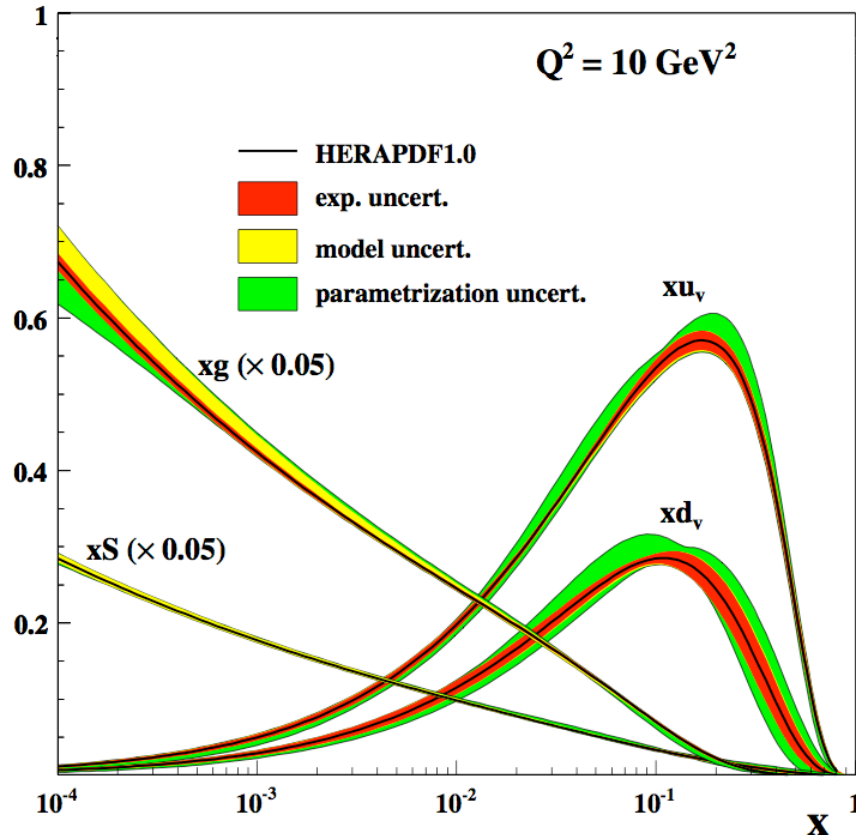
Improved measurements by combining the H1 and ZEUS high Q^2 data

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

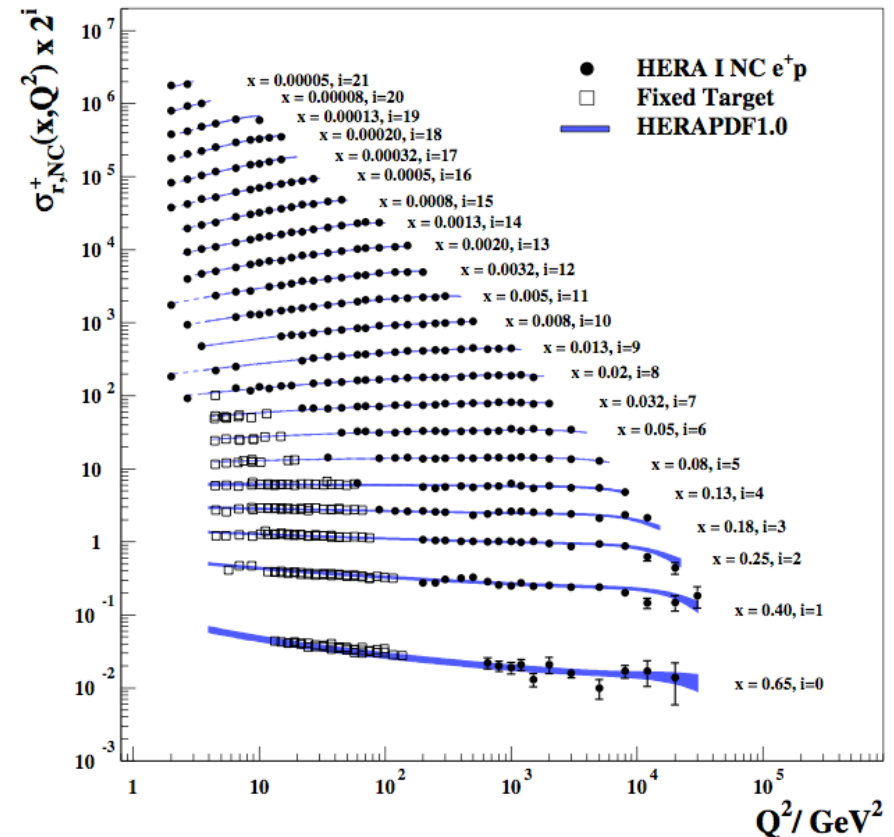
The HERA inclusive combined cross sections (NC and CC, $e^\pm p$) form a consistent data set, allowing the extraction of valence quark, sea quark and gluon PDFs

HERAPDF 1.0

H1 and ZEUS



H1 and ZEUS

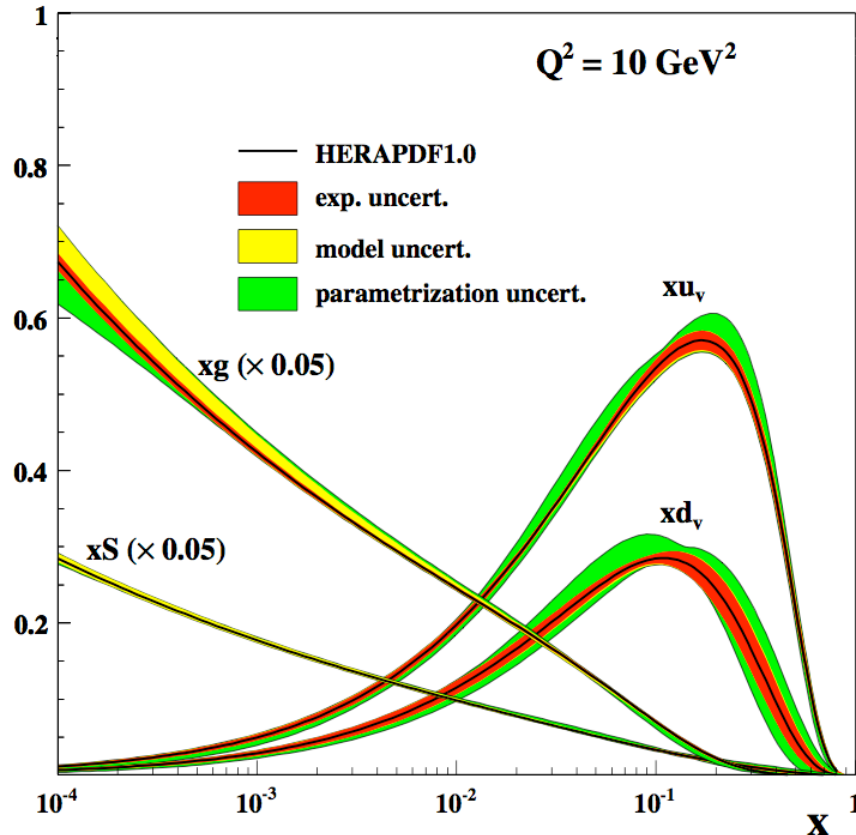


An NLO QCD fit to the combined measurement results in the **HERAPDF 1.0** PDFs with a precision at the level of a few % in the low x region

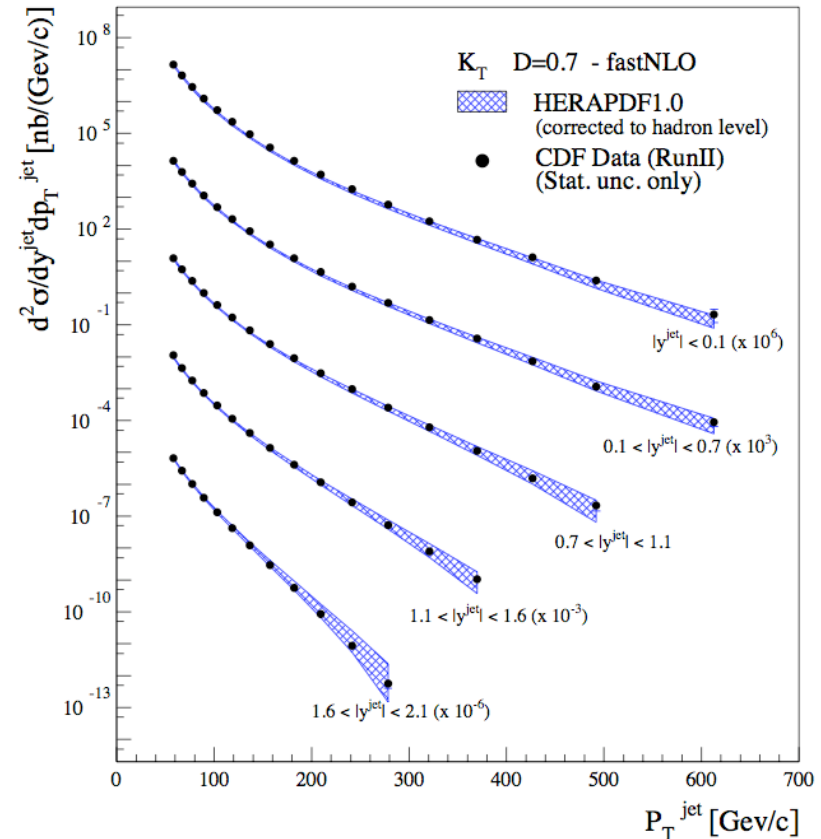
HERA (and fixed target) data well described by the fit, scaling violation observed

HERAPDF 1.0

H1 and ZEUS



Tevatron Jet Cross Sections



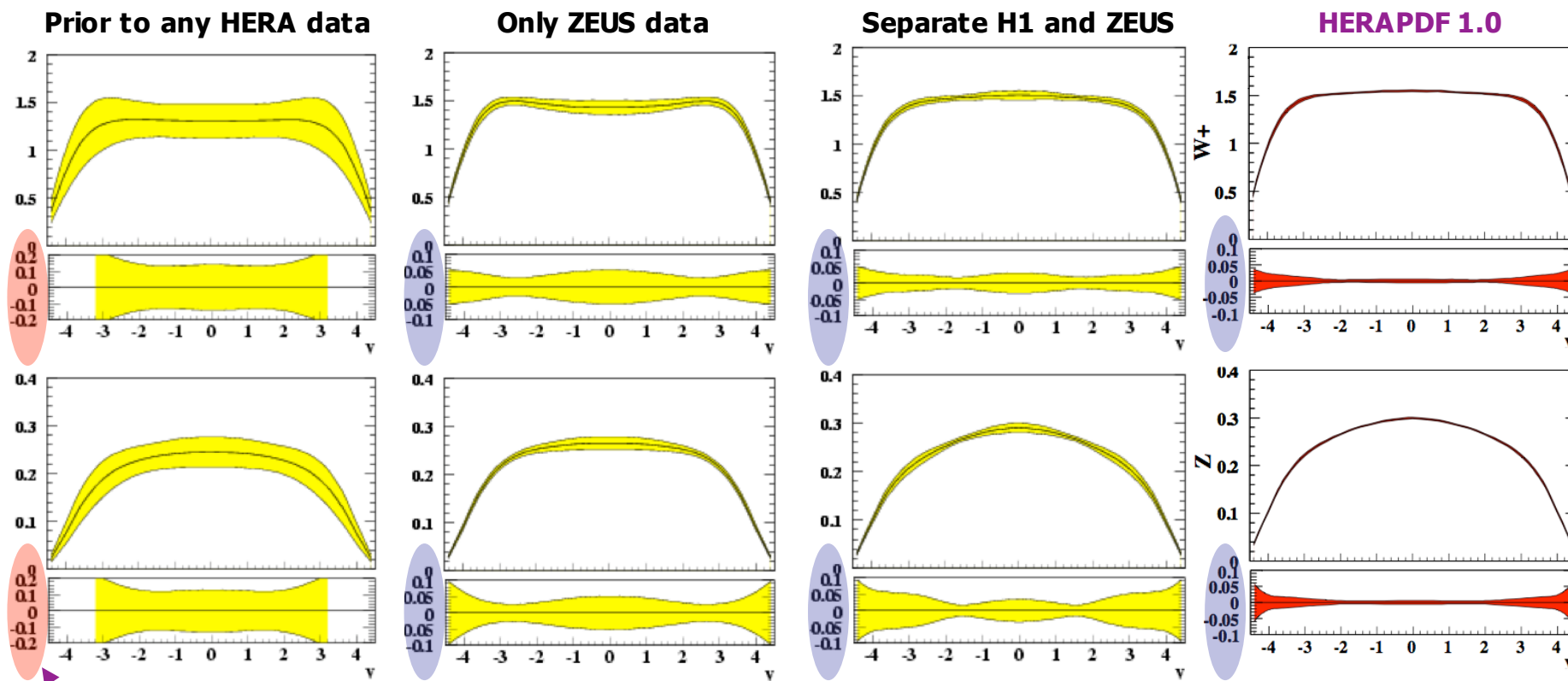
An NLO QCD fit to the combined measurement results in the **HERAPDF 1.0** PDFs with a precision at the level of a few % in the low x region

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

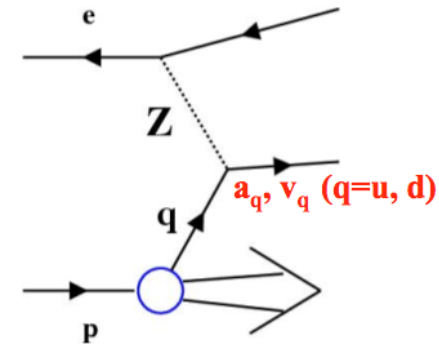
Impressive precision on the low x sea and gluon of the HERAPDF 1.0 is relevant for W, Z production at the LHC

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

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



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

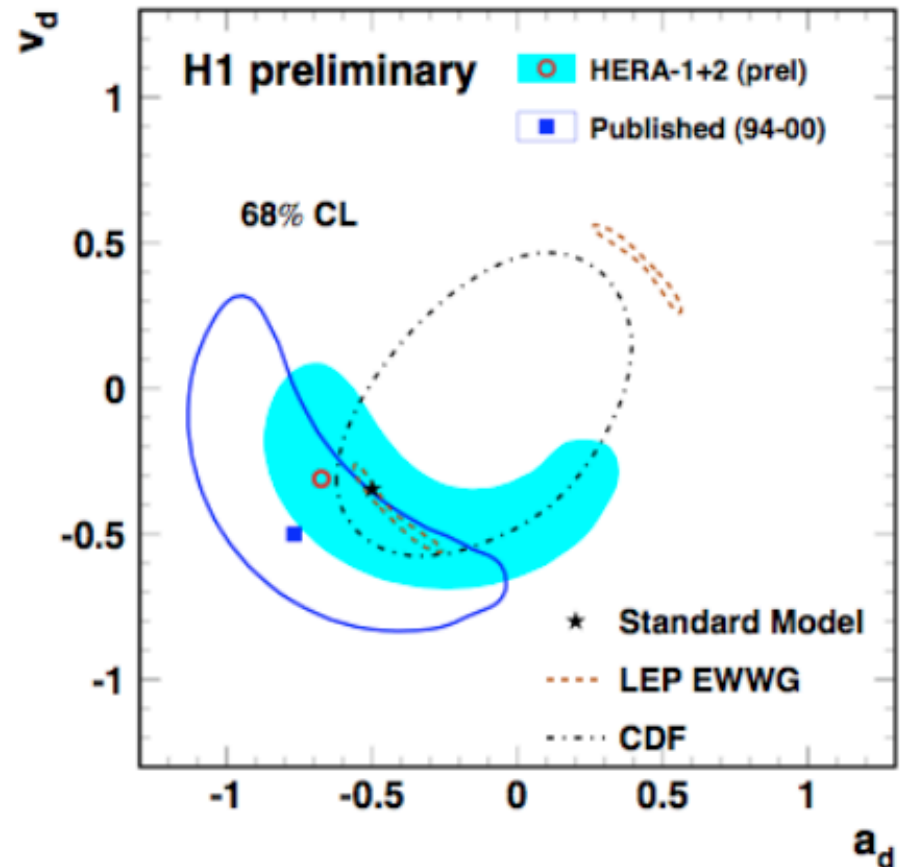
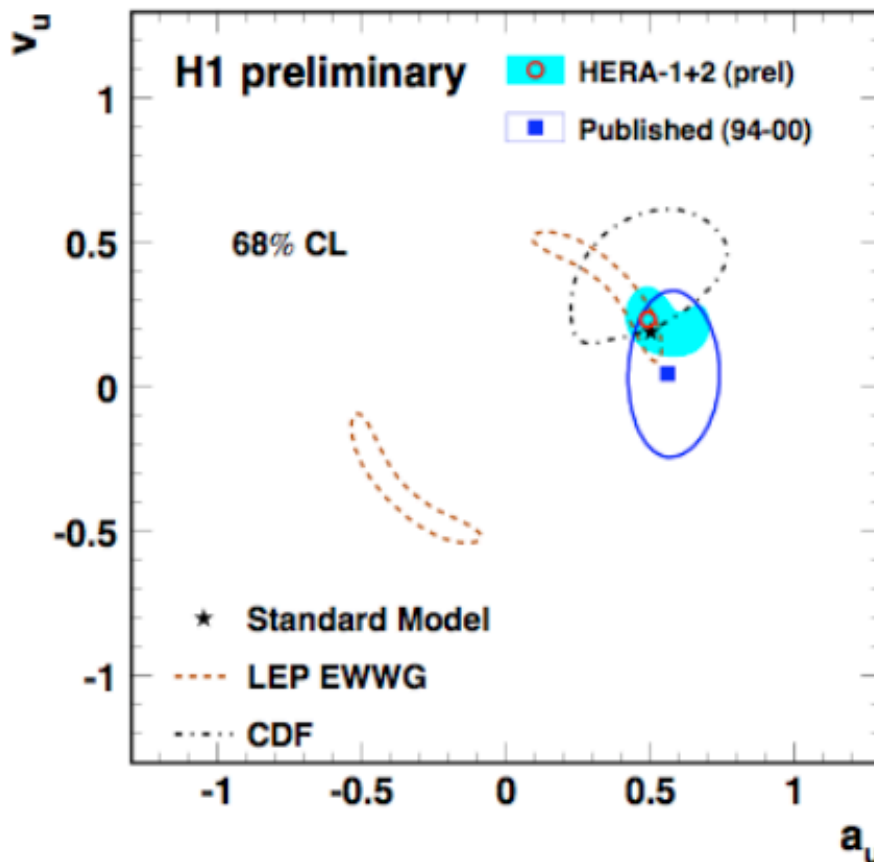
$$\left[xF_3^{\gamma Z}, xF_3^Z \right] = 2x \sum_q \left[e_q a_q, v_q a_q \right] \{q - \bar{q}\}$$

- 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}

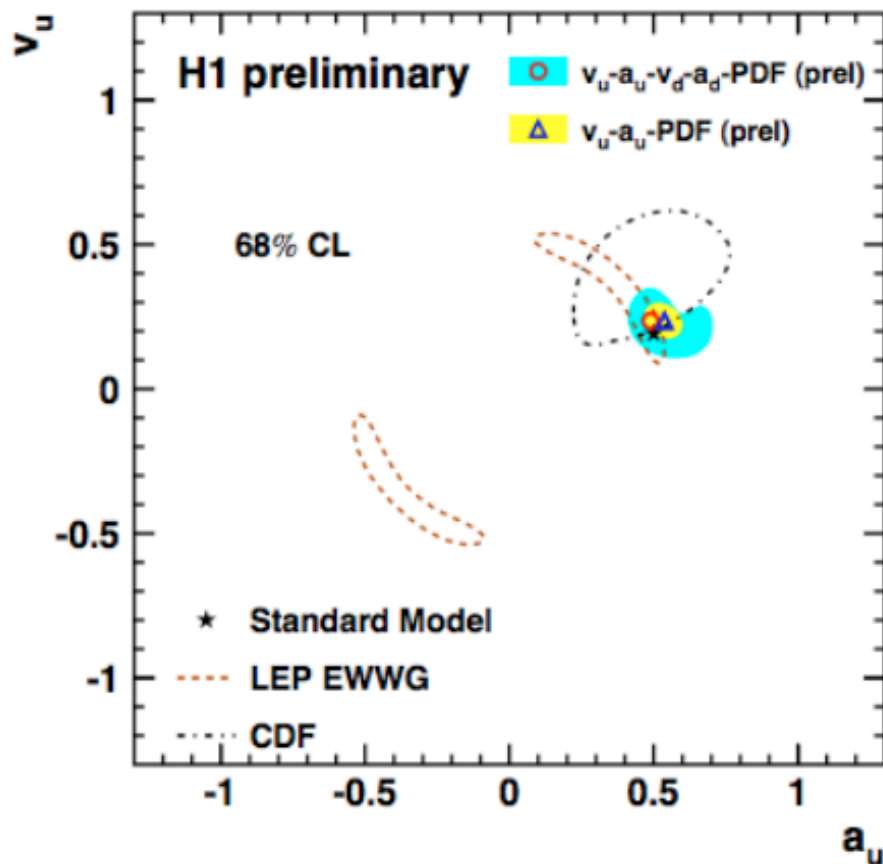
LEP: $e^+e^- \rightarrow qq(\gamma)$, $a_q^2 + v_q^2$



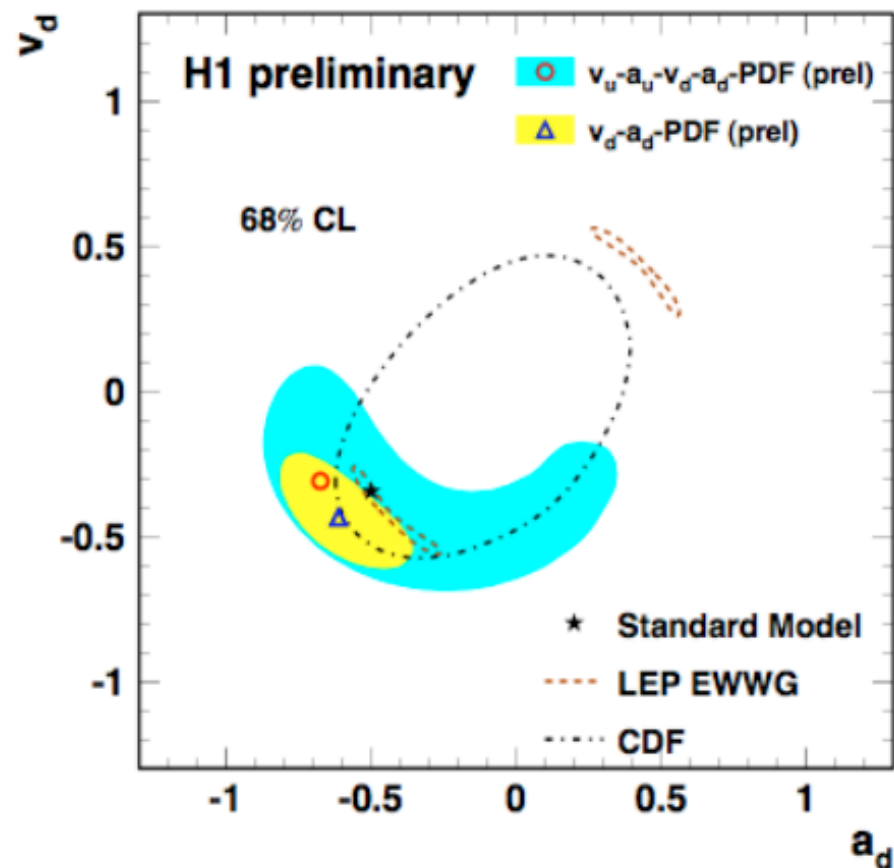
Good agreement with the SM, most improvement in vector coupling from HERA II data as expected

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



1930

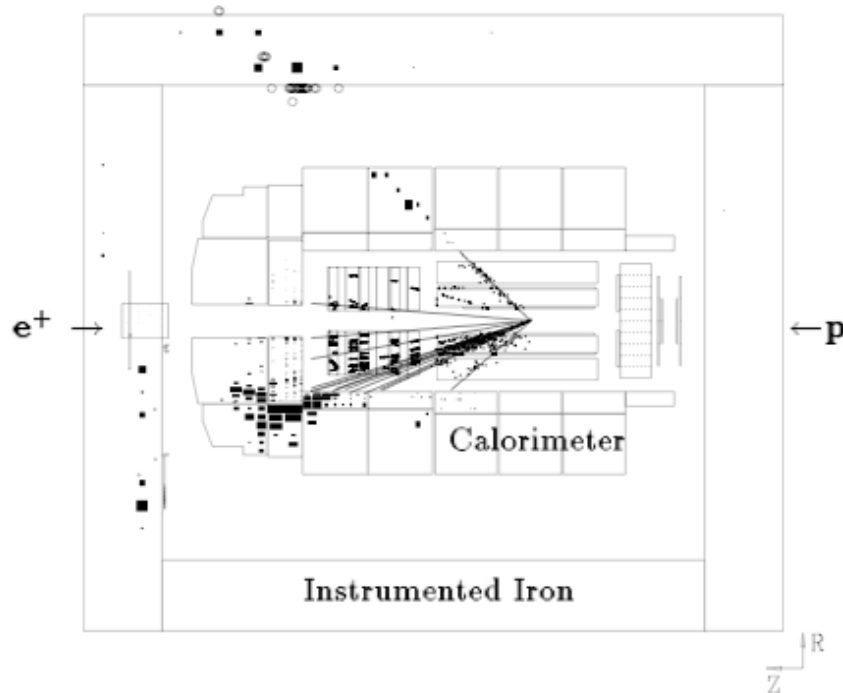
Team	Pld	W	D	L	GF	GA	GD	Pts
United States	2	2	0	0	6	0	+6	4
Paraguay	2	1	0	1	1	3	-2	2
Belgium	2	0	0	2	0	4	-4	0



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



DESY 94-248
December 1994

ISSN 0418-9833

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 pb^{-1} .

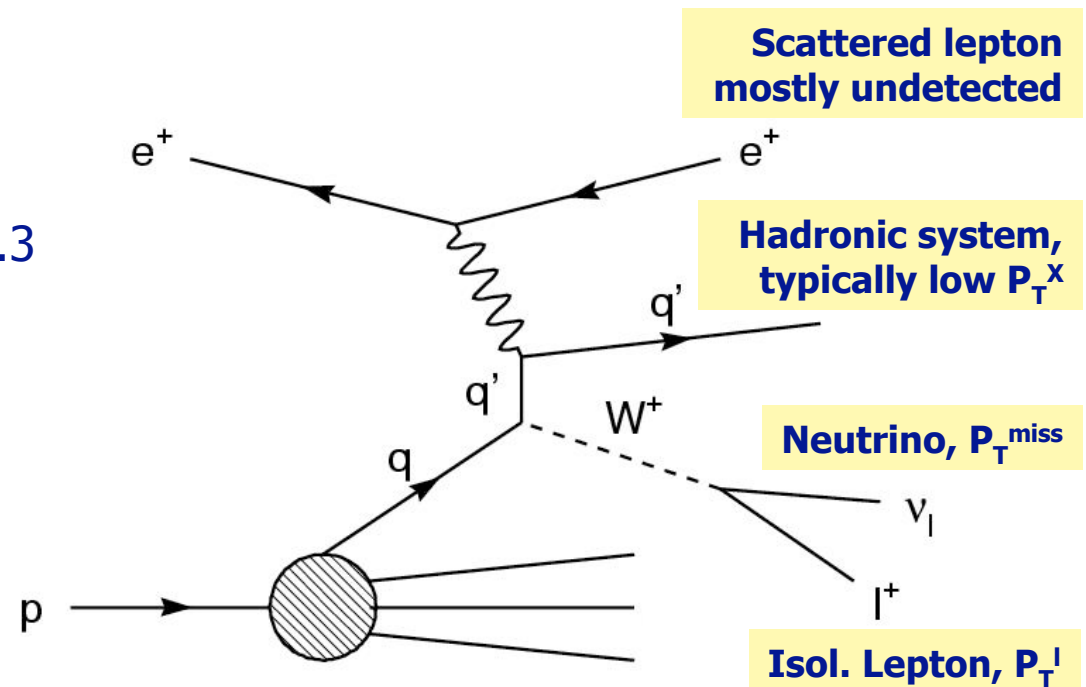
1994: Interesting H1 event observed during manual scanning of candidate CC events

Several interpretations postulated:

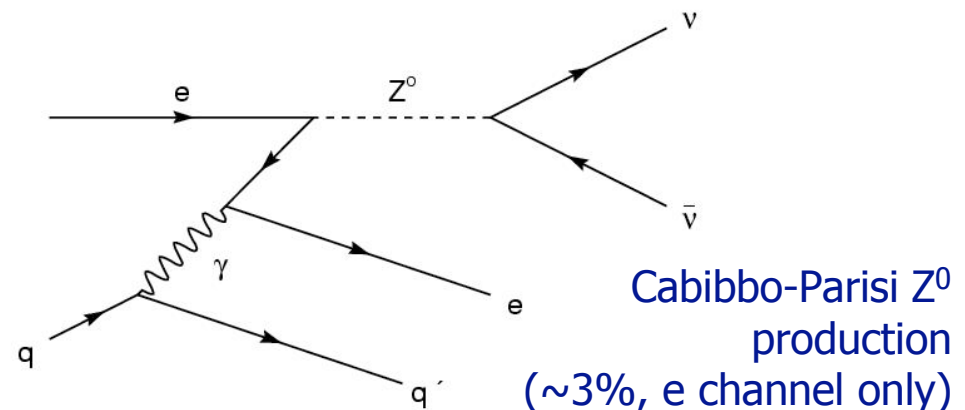
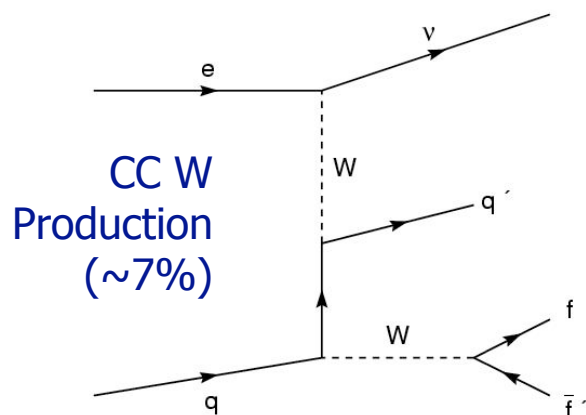
- ✗ High P_T di-jet event, where 1 jet contains a single particle (pion) faking the muon signature
- ✗ A flavour changing NC process $e^+ + p \rightarrow \mu^+ + X$, leptoquark production?
- ✗ A background event due to (e.g.) a halo muon
- ✓ Production of W bosons with leptonic decay

SM Processes with Isolated Leptons and P_T^{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



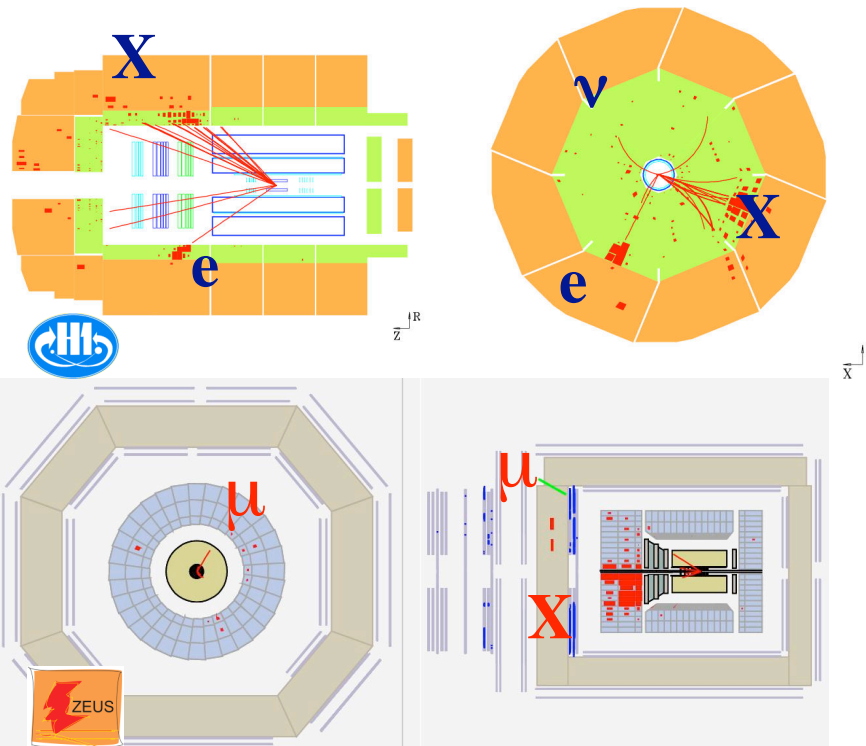
- Two additional processes included that contribute to the signal topology:



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 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

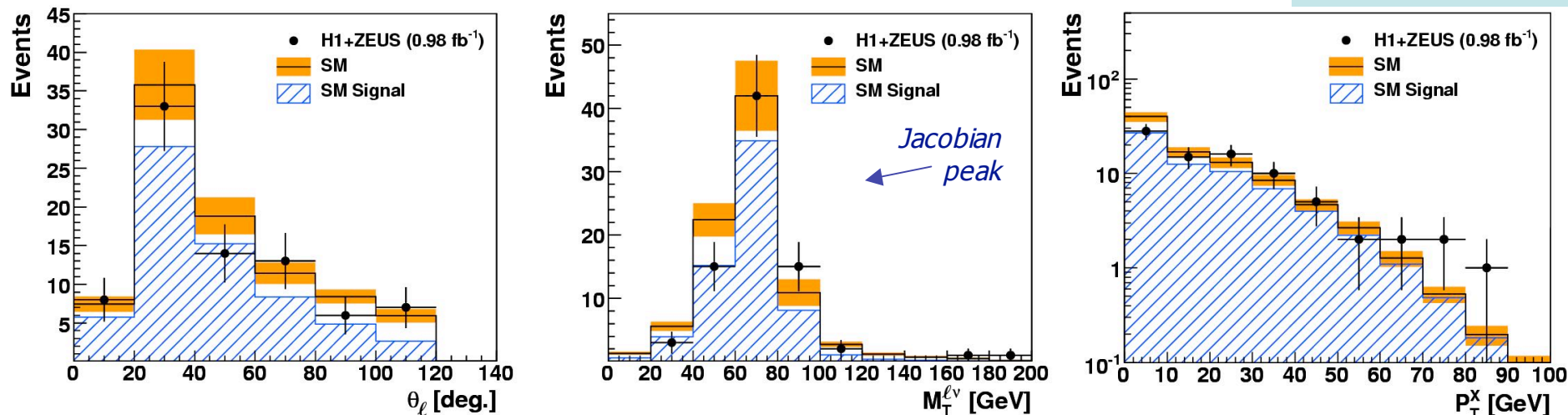
$$\theta^\mu = 32^\circ$$

$$M_{T^{\mu\nu}} = 79 \text{ GeV}$$

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

H1+ZEUS Isolated Leptons: Results

JHEP 1003 (2010) 35

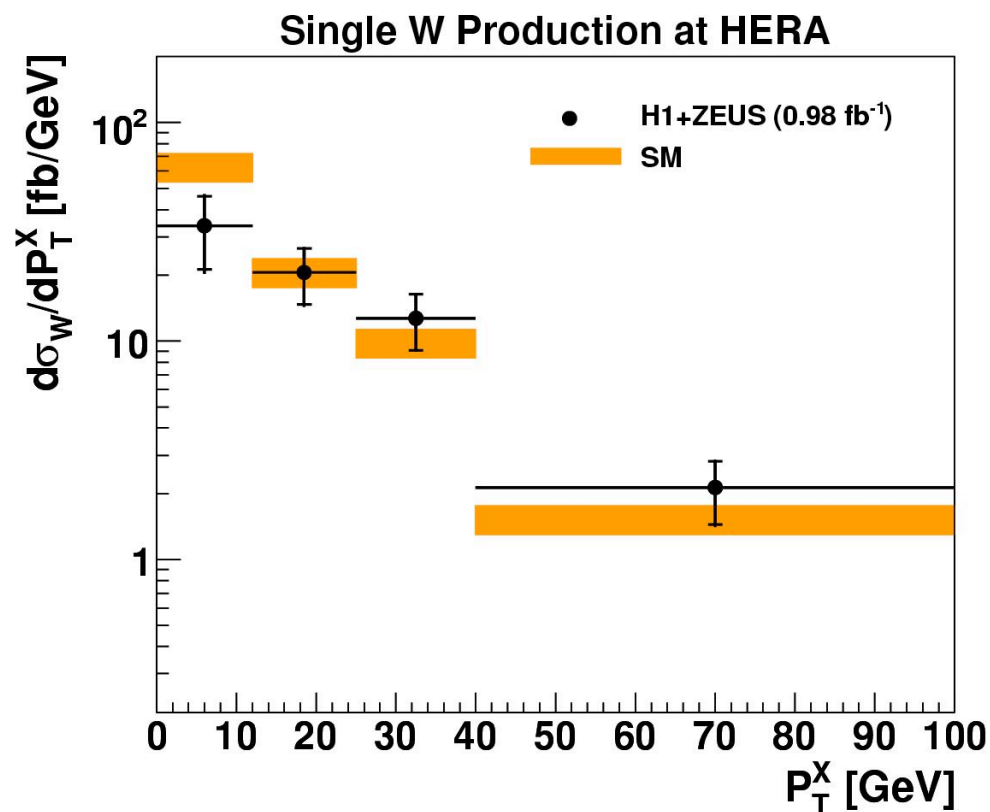


H1+ZEUS 1994–2007 $e^\pm p$ 0.98 fb $^{-1}$		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 \pm 8.2	48.3 \pm 7.4	20.9 \pm 3.2
	$P_T^X > 25$ GeV	16	13.0 \pm 1.7	10.0 \pm 1.6	3.1 \pm 0.7
Muon	Total	20	18.6 \pm 2.7	16.4 \pm 2.6	2.2 \pm 0.5
	$P_T^X > 25$ GeV	13	11.0 \pm 1.6	9.8 \pm 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 ± 0.16 (stat.) ± 0.07 (sys.) pb, good agreement with the SM prediction of 1.26 ± 0.19 pb from EPVEC, reweighted to NLO

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



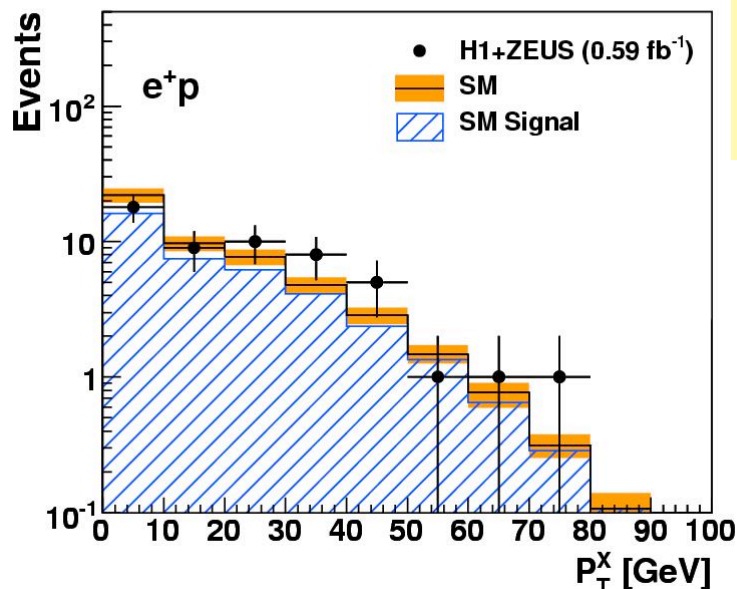
1.14 ± 0.25 (stat.) ± 0.14 (sys.) pb



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

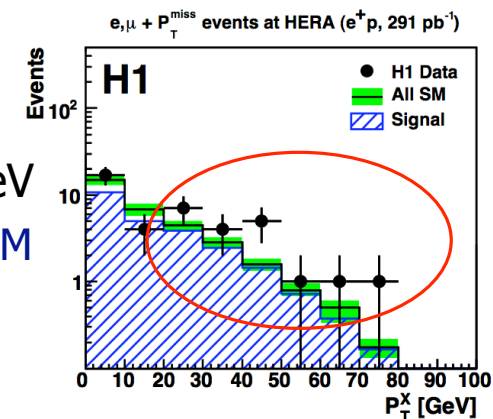
H1+ZEUS Isolated Leptons: Positron Data

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

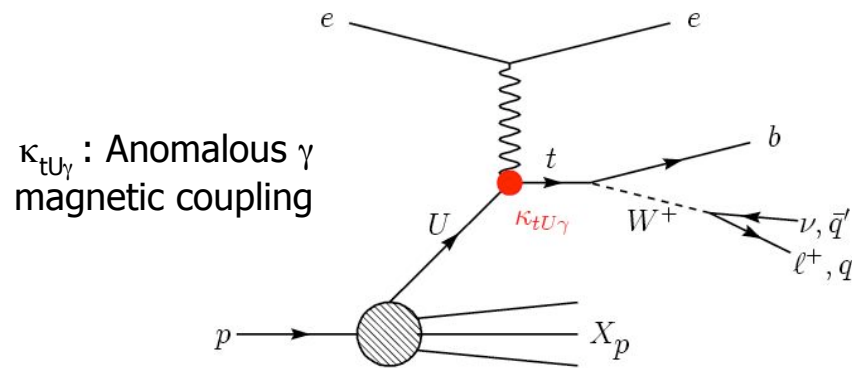


Excess seen in the H1 e^+p data at large P_T^X still in the common phase space of the combined analysis but is less significant, around 1.9σ

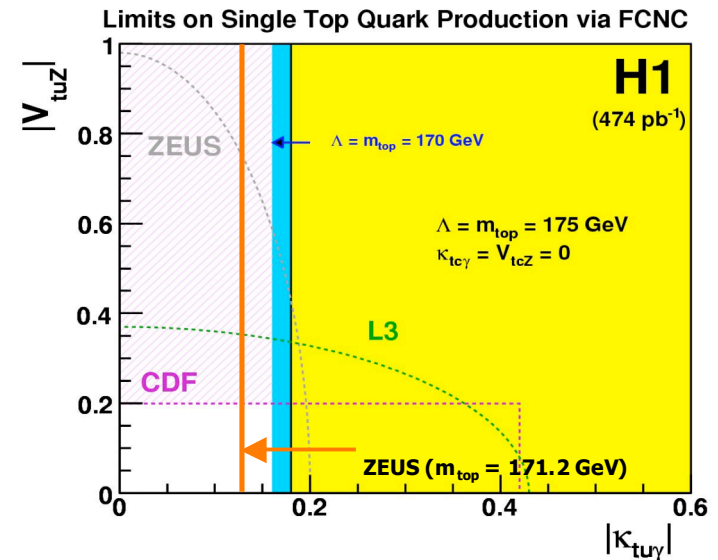
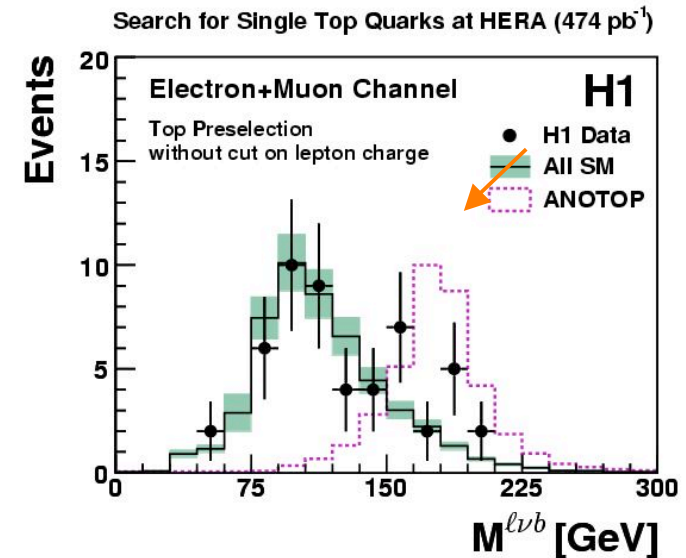
H1 e^+p $P_T^X > 25$ GeV
17 data / 8.0 ± 1.3 SM



Search for Anomalous Single Top Production



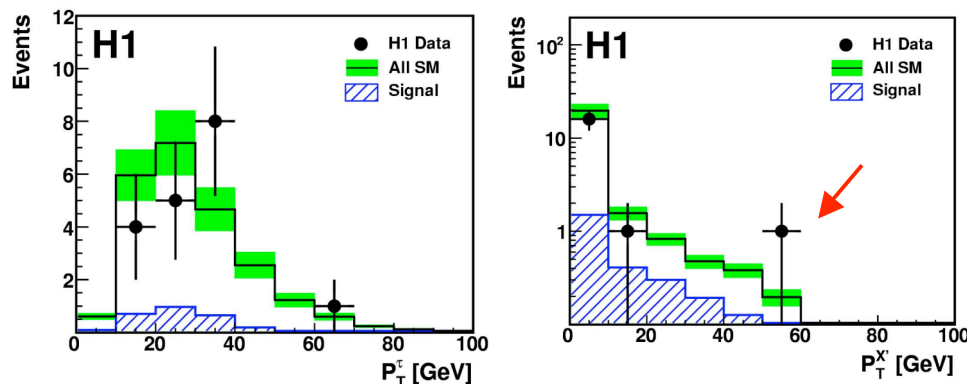
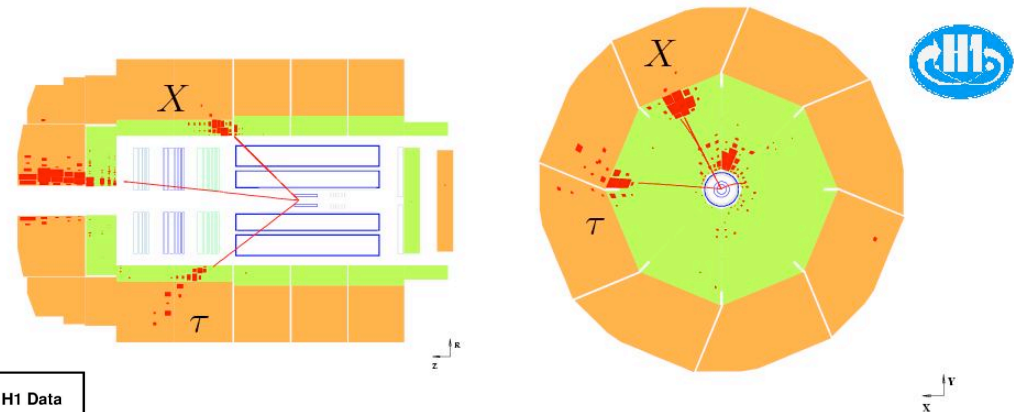
- Leptonic W decay channels:
 - Top pre-selection is like a subset of the isolated lepton selection
- Hadronic W decay channel (H1 only)
 - 3 jet selection $P_{T,jet1,2,3} > 40, 30, 15$ GeV
 - Pair of jets with $65 < M_{ij} < 95$ GeV
- No significant signal observed, derive upper bounds on cross section 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

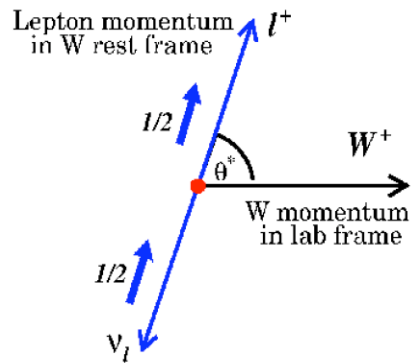
- Look for events with P_T^{miss} and narrow jets from hadronic decay
- Complementary results to those in the electron and muon channels
- Signature of 1-prong tau decay (45% branching ratio)
 - 1 charged track (the "prong"): narrow, pencil like jet
- Good overall agreement with the SM prediction
- Expectation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

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



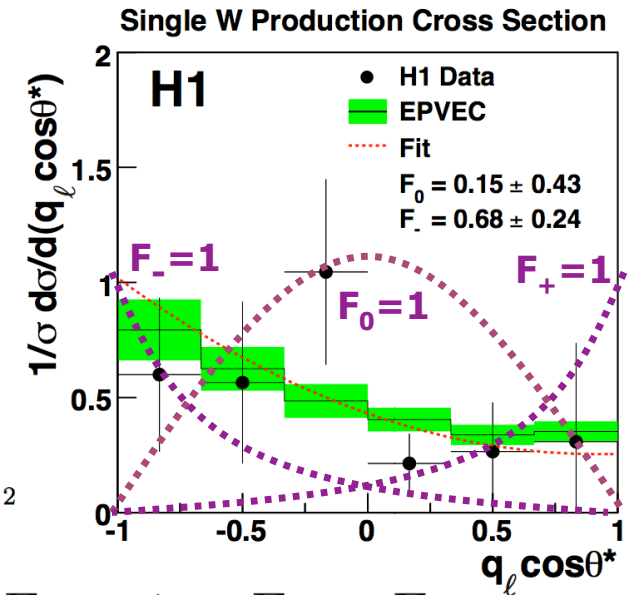
HERA-I:
Isolated Tau Leptons
2 / 0.2 \pm 0.05 at $P_T^X > 25$ GeV

H1 Measurement of W Polarisation Fractions

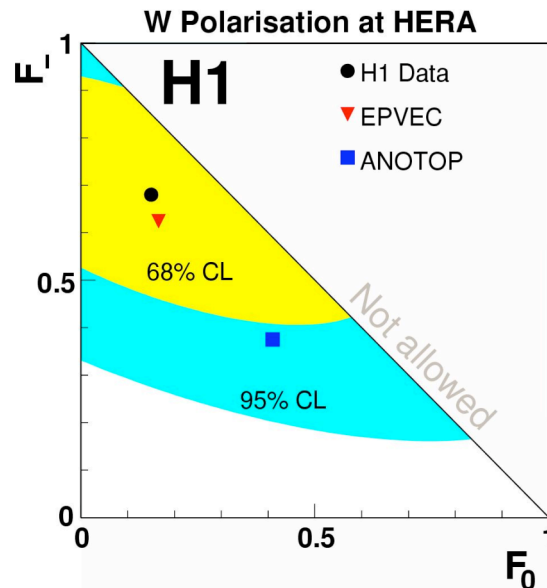


- Cross section can be expressed in terms of W polarisation fractions: *sensitive to angular properties of the decay*
- Measure cross section as a function of $\cos \theta^*$

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



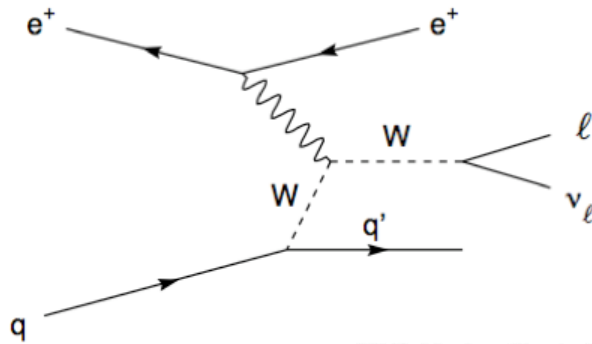
$$F_+ \equiv 1 - F_- - F_0$$



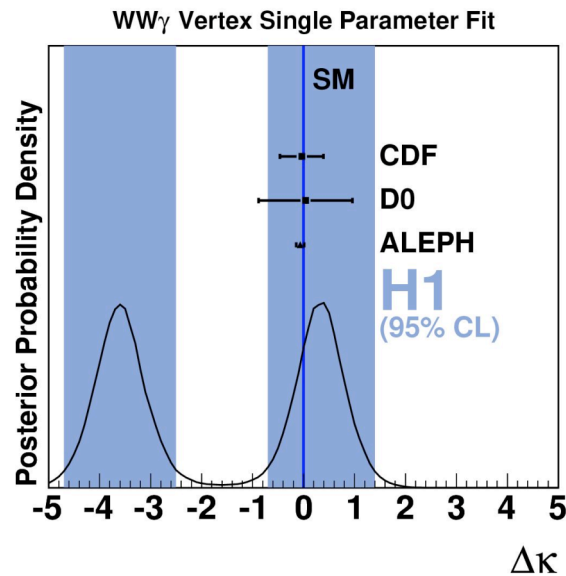
- F_0 and F_- simultaneously extracted in a fit
- Measure for single W Production, and test with anomalous top production model
 - May be different for SM and BSM contributions

Difference demonstrated, but sensitivity only at the 1 sigma level

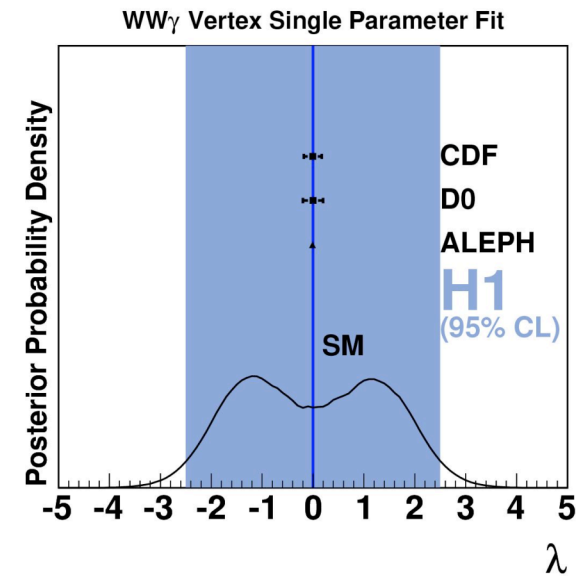
H1 Limits on $WW\gamma$ Coupling Parameters



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



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

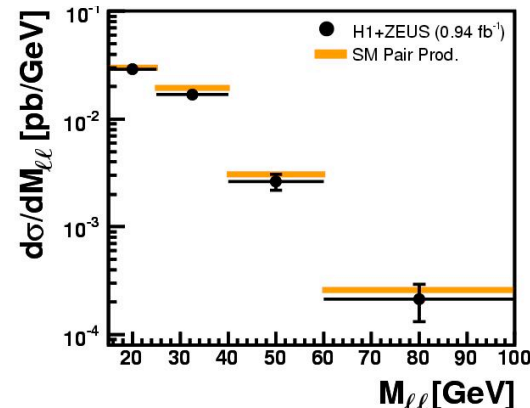
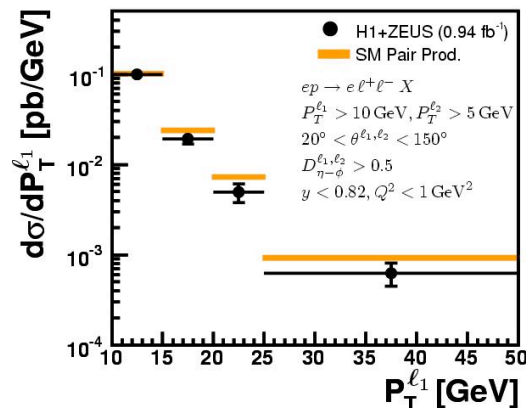
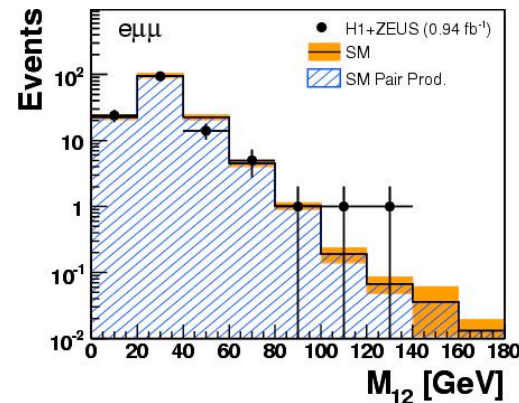
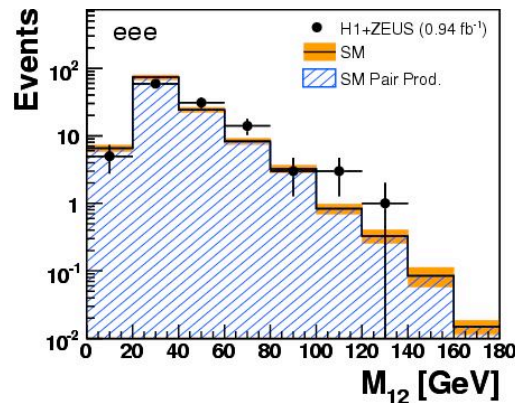
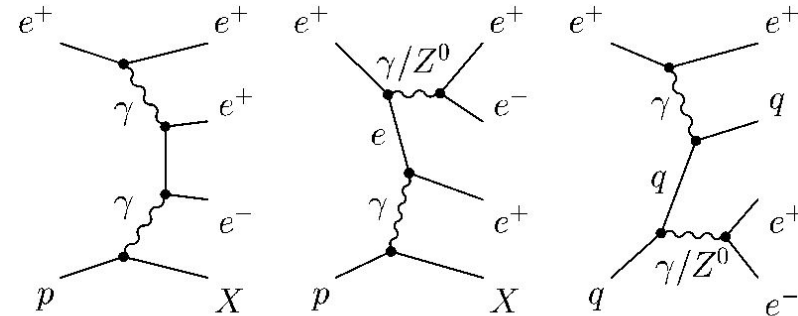


$$-2.5 < \lambda < 2.5$$

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

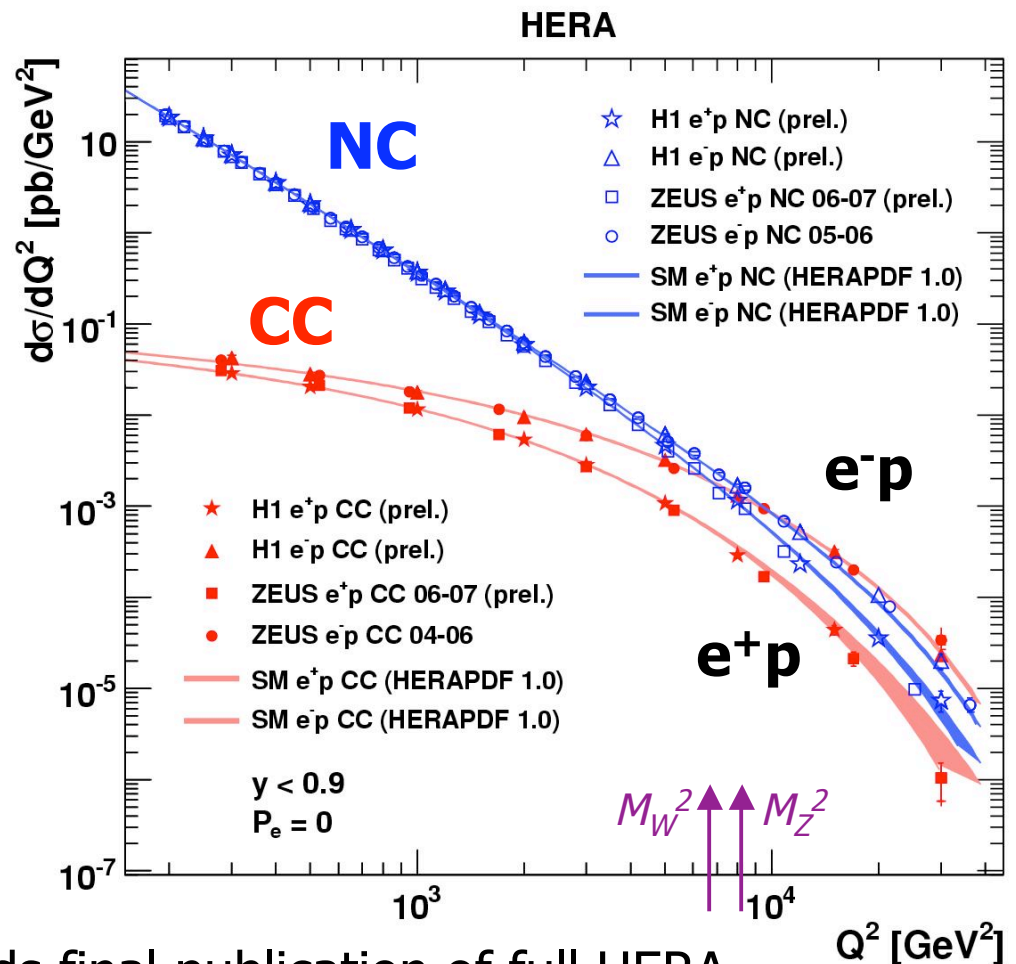


- Events are selected by requiring at least two, isolated high P_T electrons or muons in the final state
- Events are then classified into independent, exclusive samples:
 - $ee, eee, \mu\mu, e\mu, e\mu\mu$ and so on..
- Overall good agreement seen with the SM prediction

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

Summary

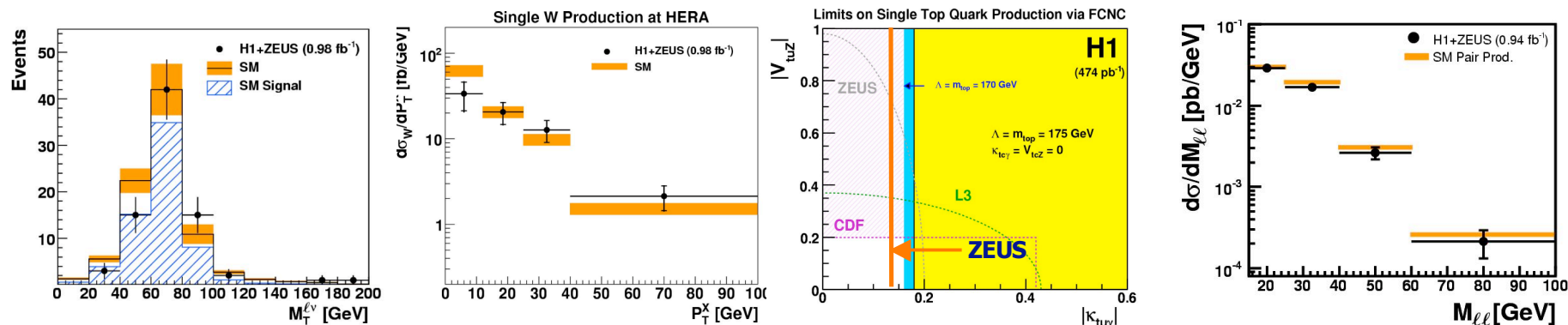
- Measurements of polarised and unpolarised neutral and charged current cross sections at HERA
 - Observed polarisation asymmetry in NC agrees with the SM prediction
 - Polarisation dependence of the CC cross section established in both e^+p and e^-p data: no right handed charged currents
 - The HERA 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

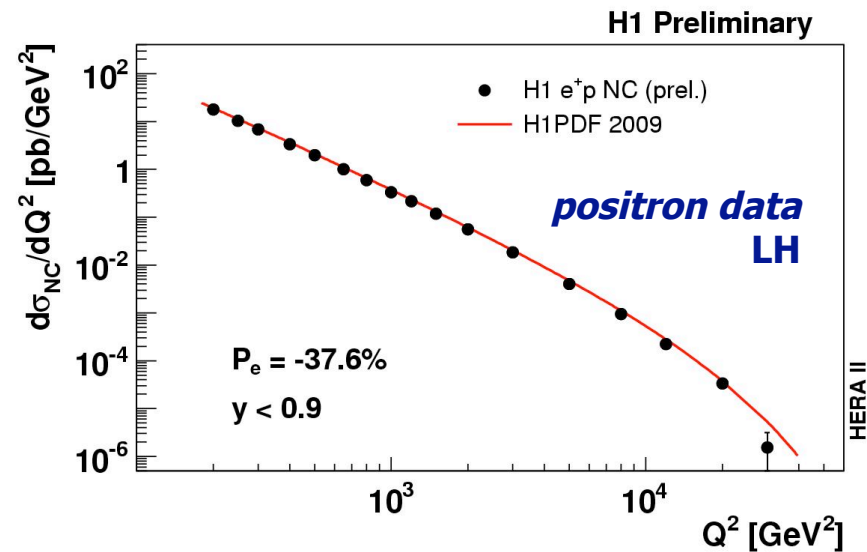
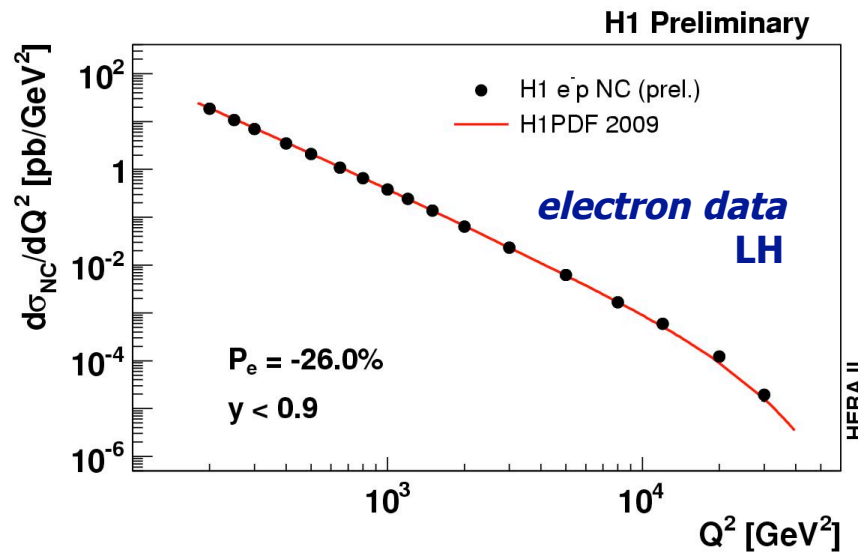
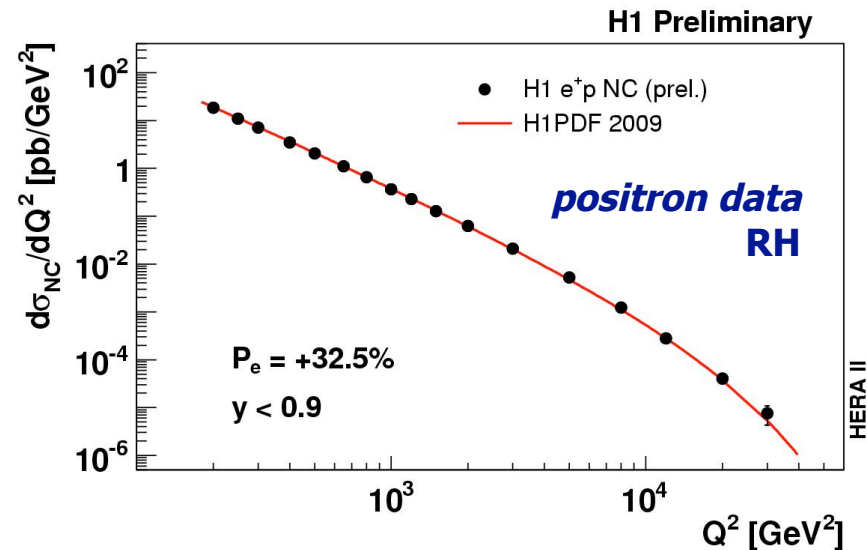
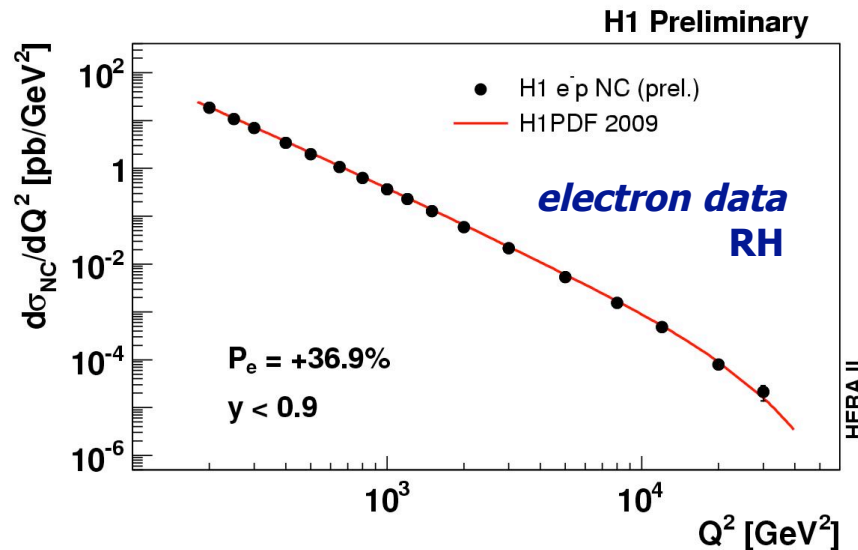
Summary

- 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 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
 - $\sigma_W = 1.06 \pm 0.16 \text{ (stat.)} \pm 0.07 \text{ (sys.) pb}$, cf $1.26 \pm 0.19 \text{ pb}$ from SM
- Exclusion limit on anomalous top cross section extended to $\sigma < 0.13 \text{ pb}$
 - 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
 - $\sigma_{\gamma\gamma} = 0.66 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (sys.) pb}$, cf $0.69 \pm 0.02 \text{ pb}$ from SM



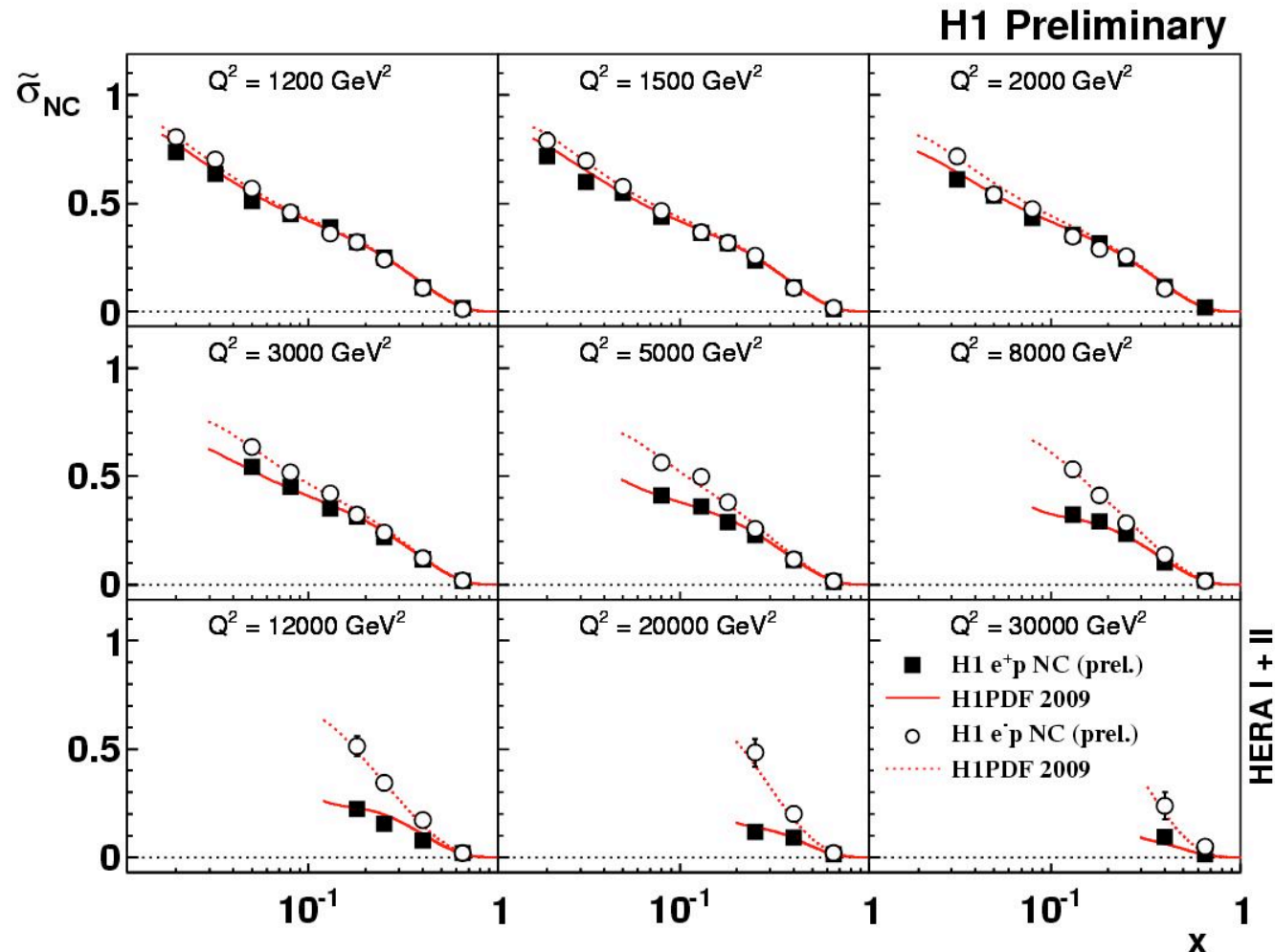
EXTRA SLIDES

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

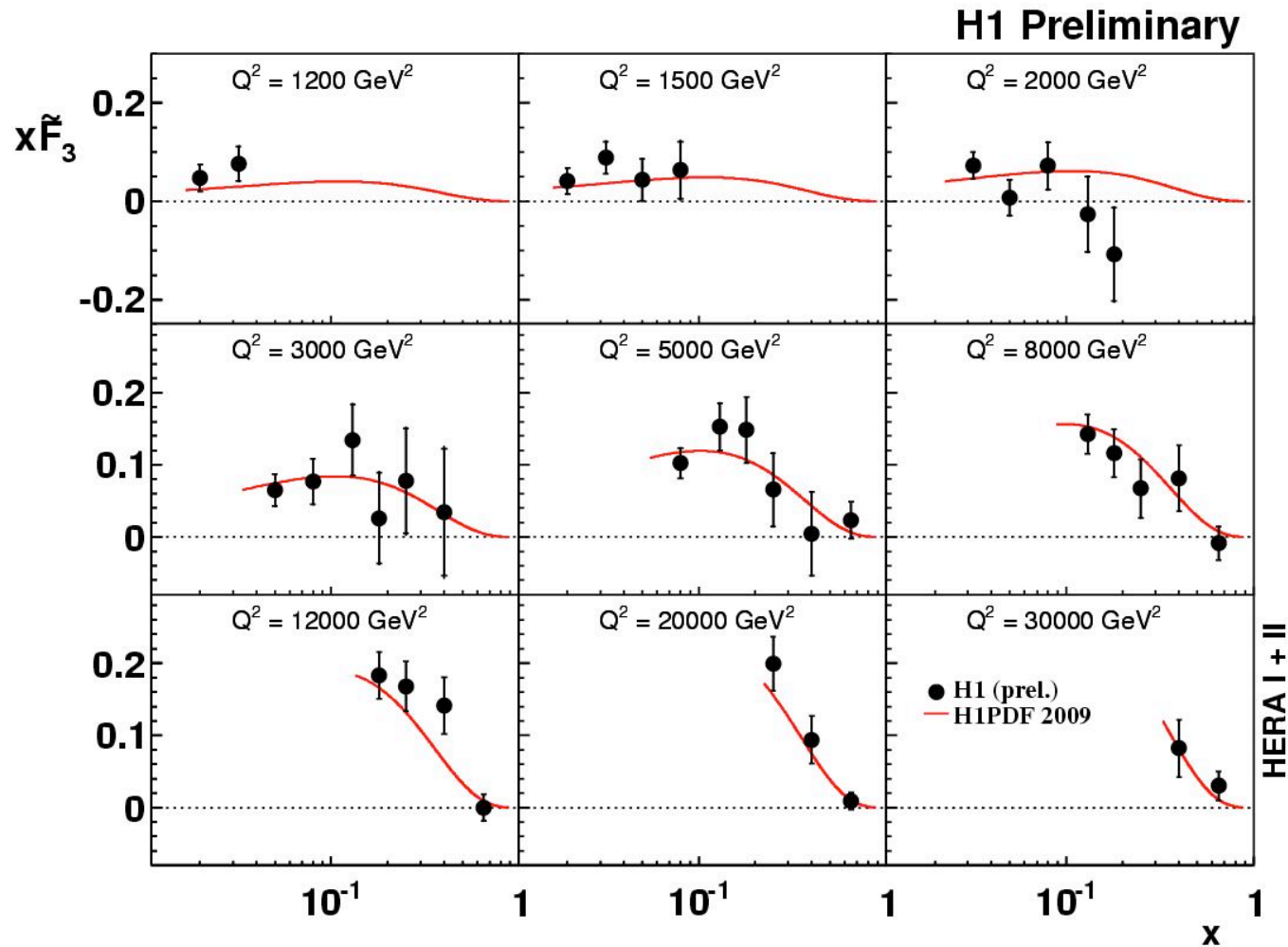


Excellent description of the Q^2 dependence of the data by the SM (from a QCD fit)

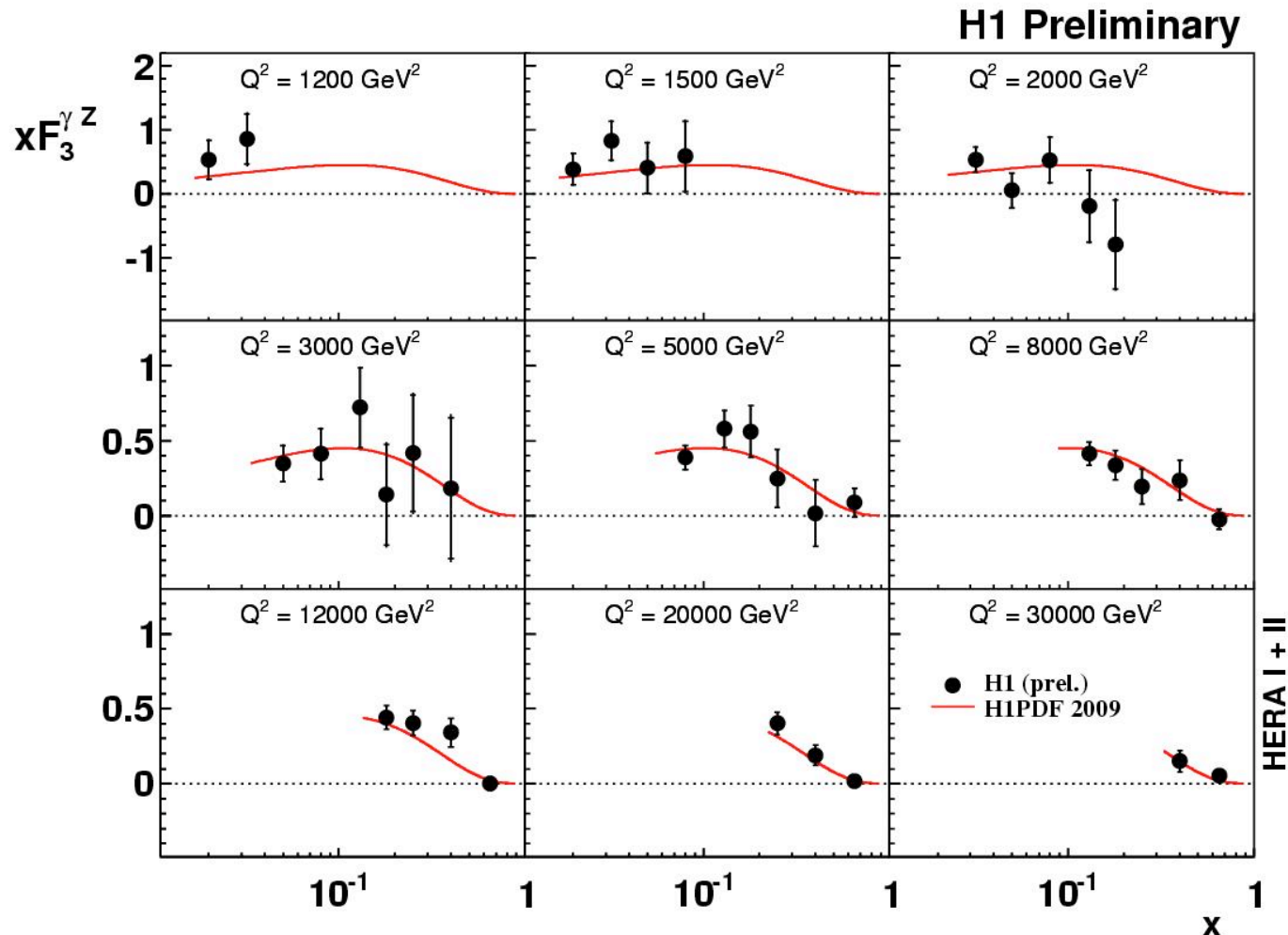
Unpolarised Reduced NC Cross Section: Full HERA I+II



Extraction of $x\tilde{F}_3$



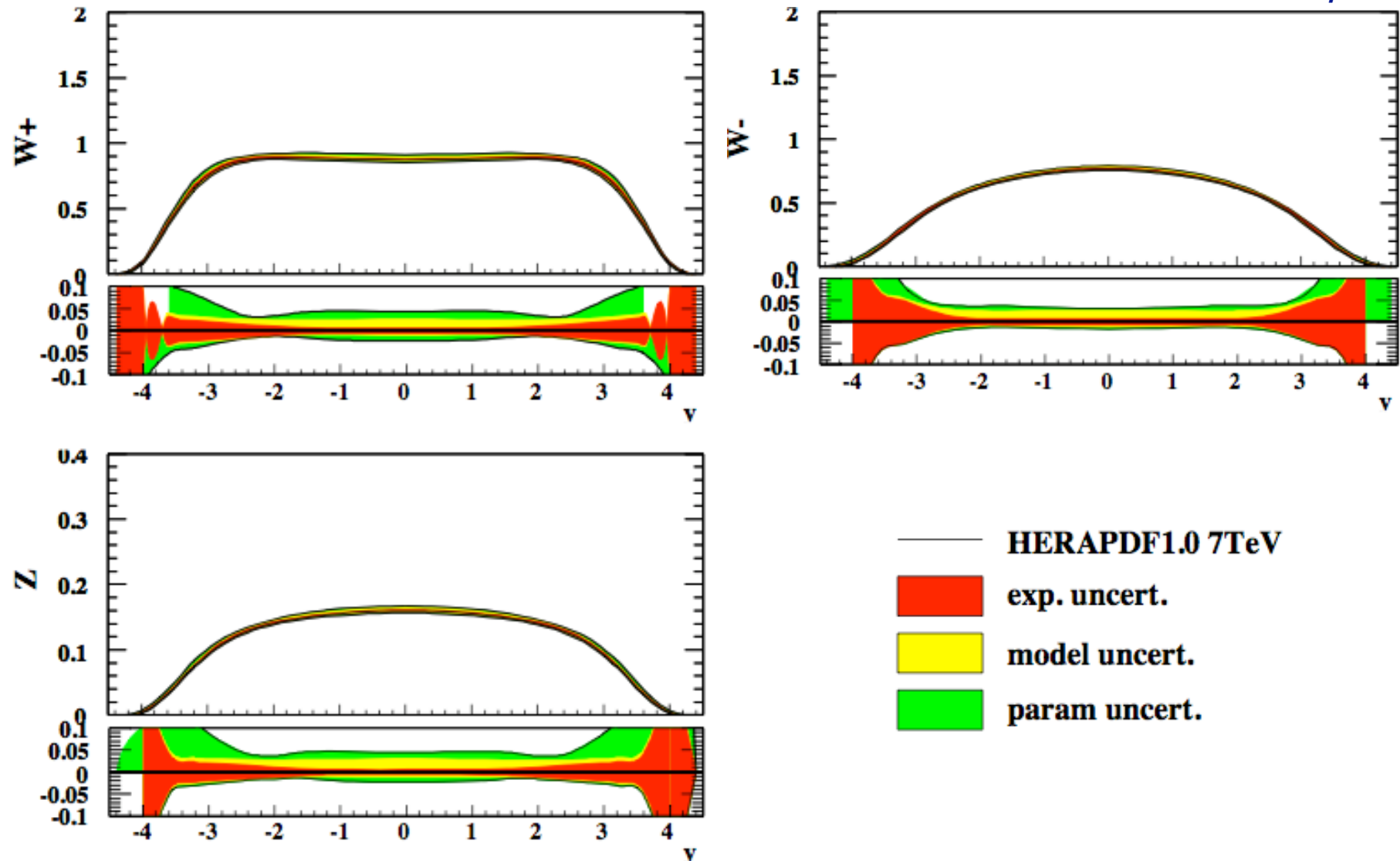
Extraction of $xF_3^{\gamma Z}$



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

Boson Rapidity Distributions at the LHC (7 GeV)

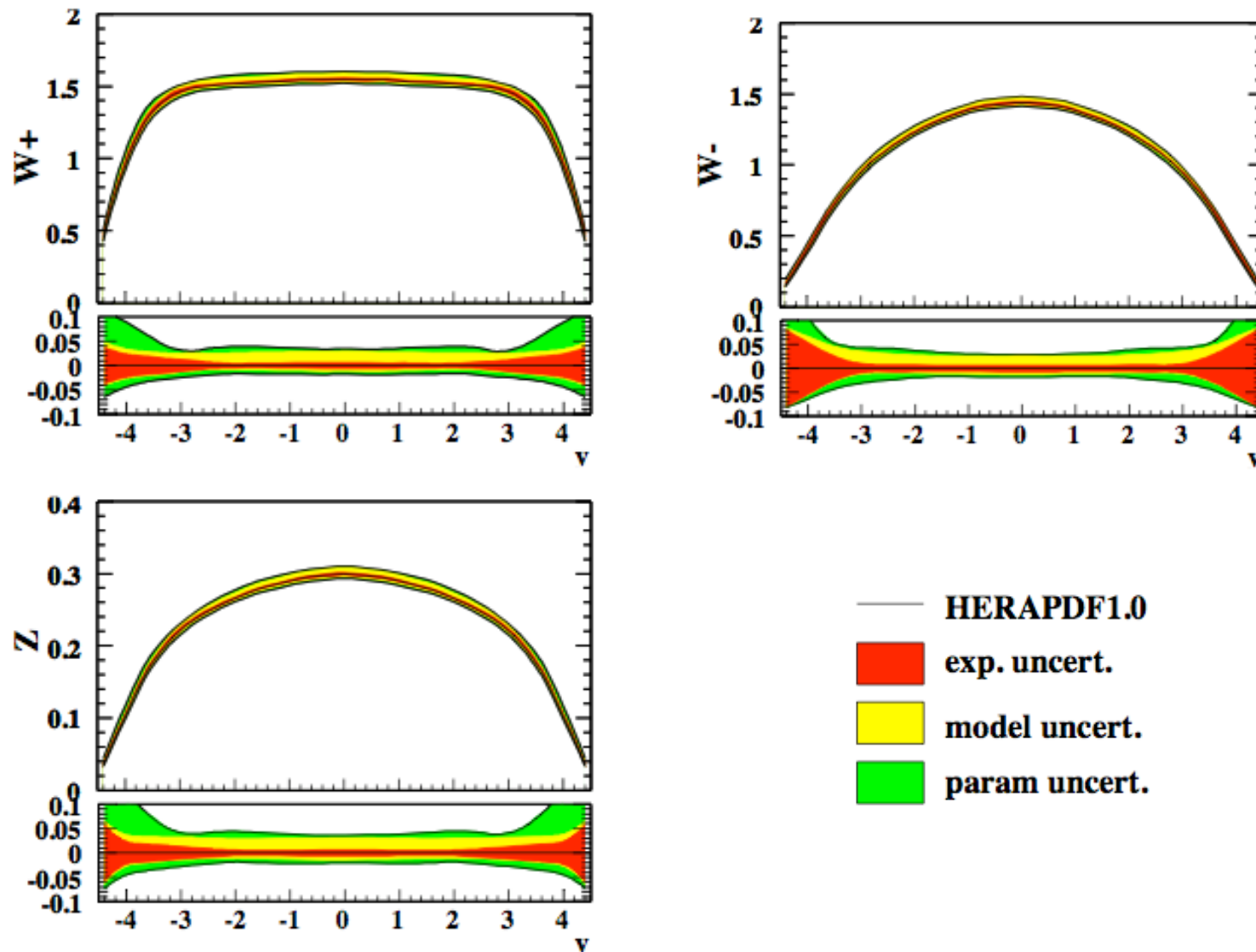
Amanda Cooper-Sarkar



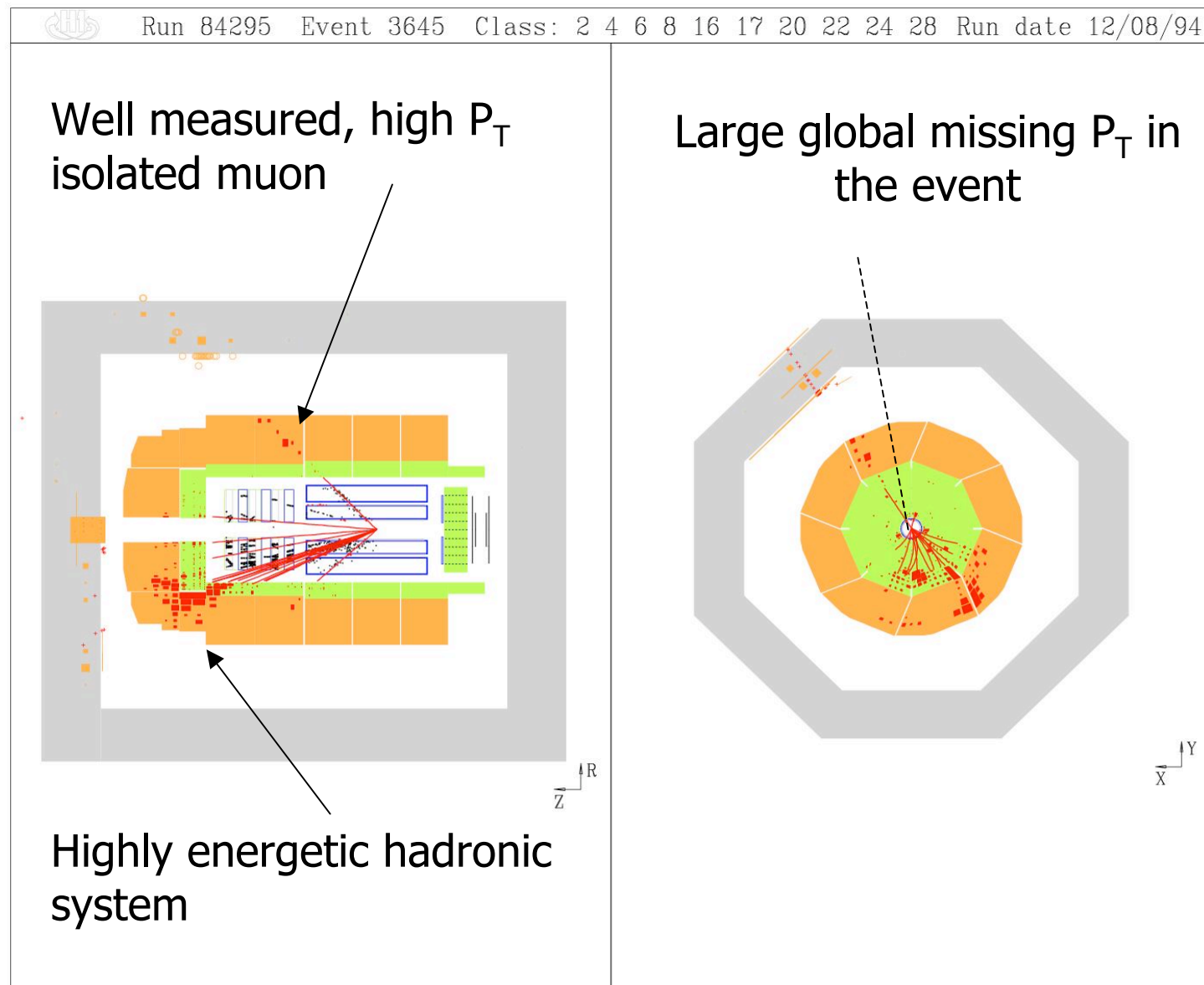
http://www.desy.de/h1zeus/combined_results/benchmark/herapdf1.0.html

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

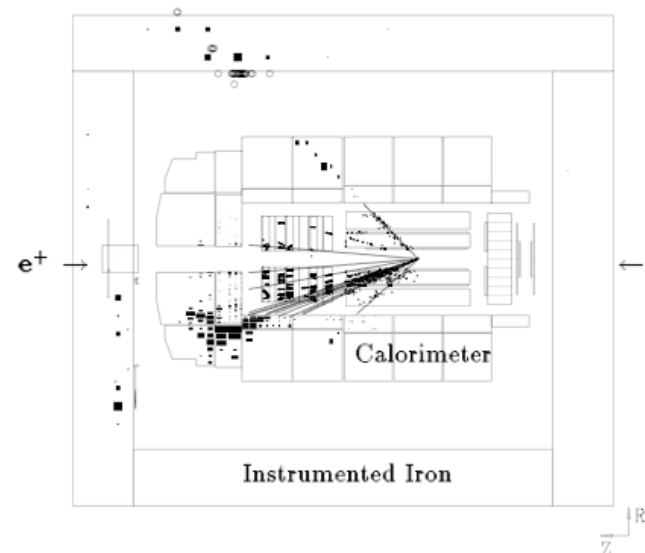
December 1994

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

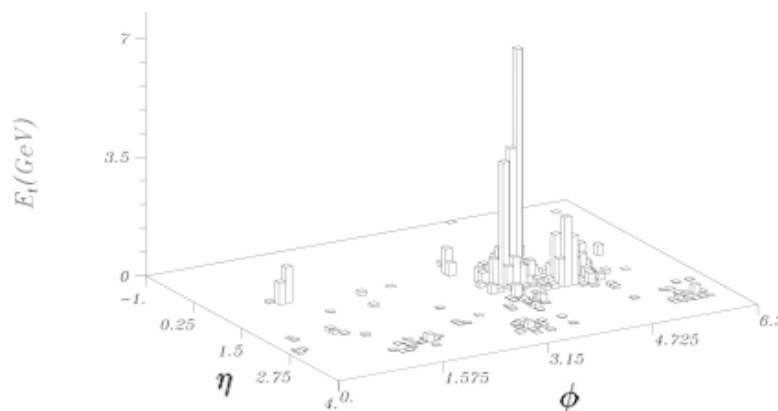
H1 Collaboration

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 pb^{-1} .



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

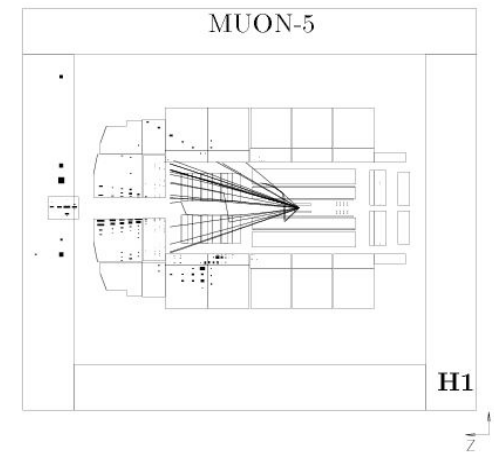
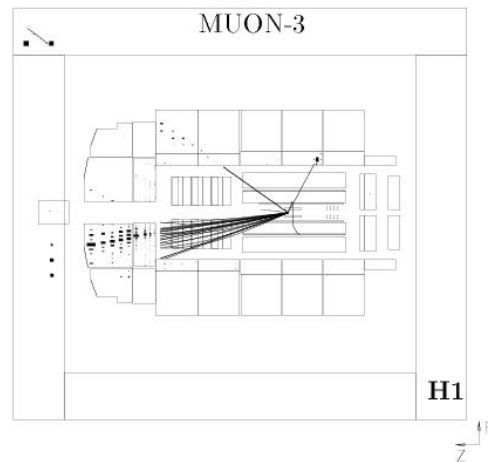
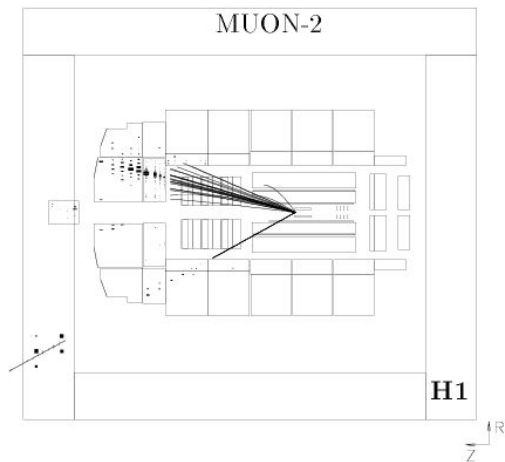
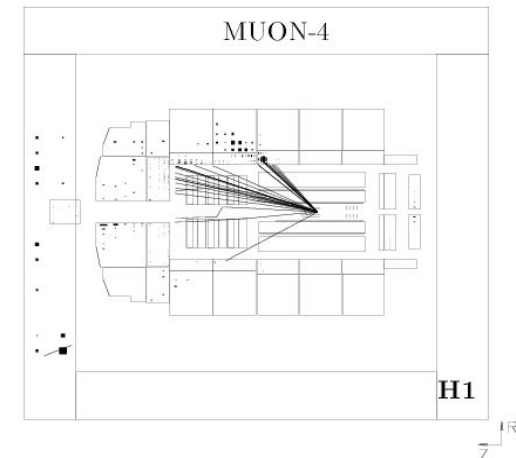
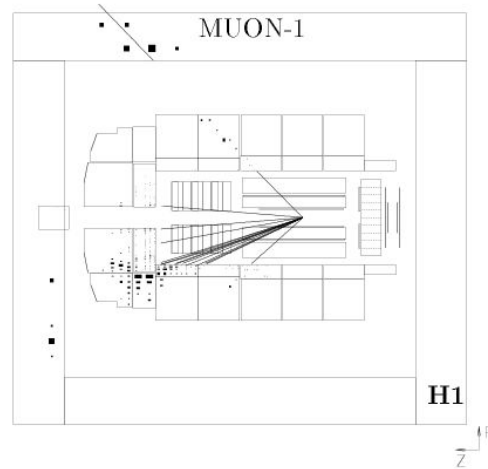
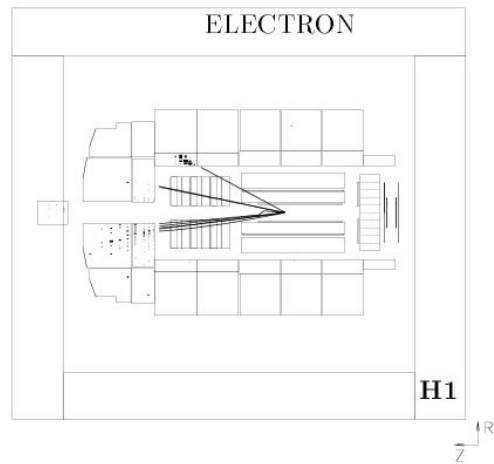


The isolated track :	
Charge	Positive
Transverse momentum	$23.4 \pm 2.4^{+7}_{-5} \text{ GeV}$
Polar angle	$46.2 \pm 1.3^\circ$
Azimuthal angle	$57.4 \pm 0.1^\circ$
The total hadronic system :	
Transverse momentum	$42.1 \pm 4.2 \text{ GeV}$
Average azimuthal angle	$240 \pm 1^\circ$
Hadronic cluster 1:	
Transverse momentum	$25.3 \pm 3.0 \text{ GeV}$
Polar angle	$22.3 \pm 0.5^\circ$
Azimuthal angle	$227 \pm 1^\circ$
Hadronic cluster 2 :	
Transverse momentum	$15.2 \pm 1.9 \text{ GeV}$
Polar angle	$16.5 \pm 0.5^\circ$
Azimuthal angle	$270 \pm 1^\circ$
Global event properties :	
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

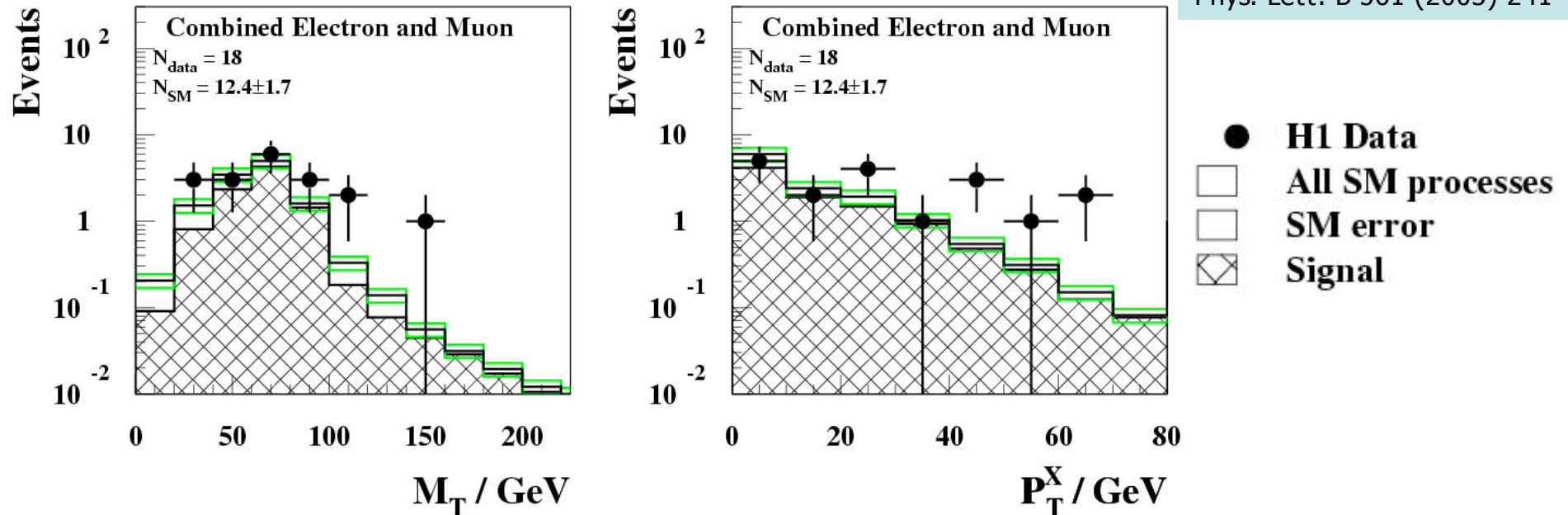
- Production of two high P_T jets, where one jet contains a single particle (a pion) which fakes the muon signature
 - Interpretation unlikely, probability calculated to be less than 0.001
- A flavour changing NC process $e^+ + p \rightarrow \mu^+ + X$, topologically identical to the production of a 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⁻¹ of H1 e⁺p data



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

Phys. Lett. B 561 (2003) 241



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

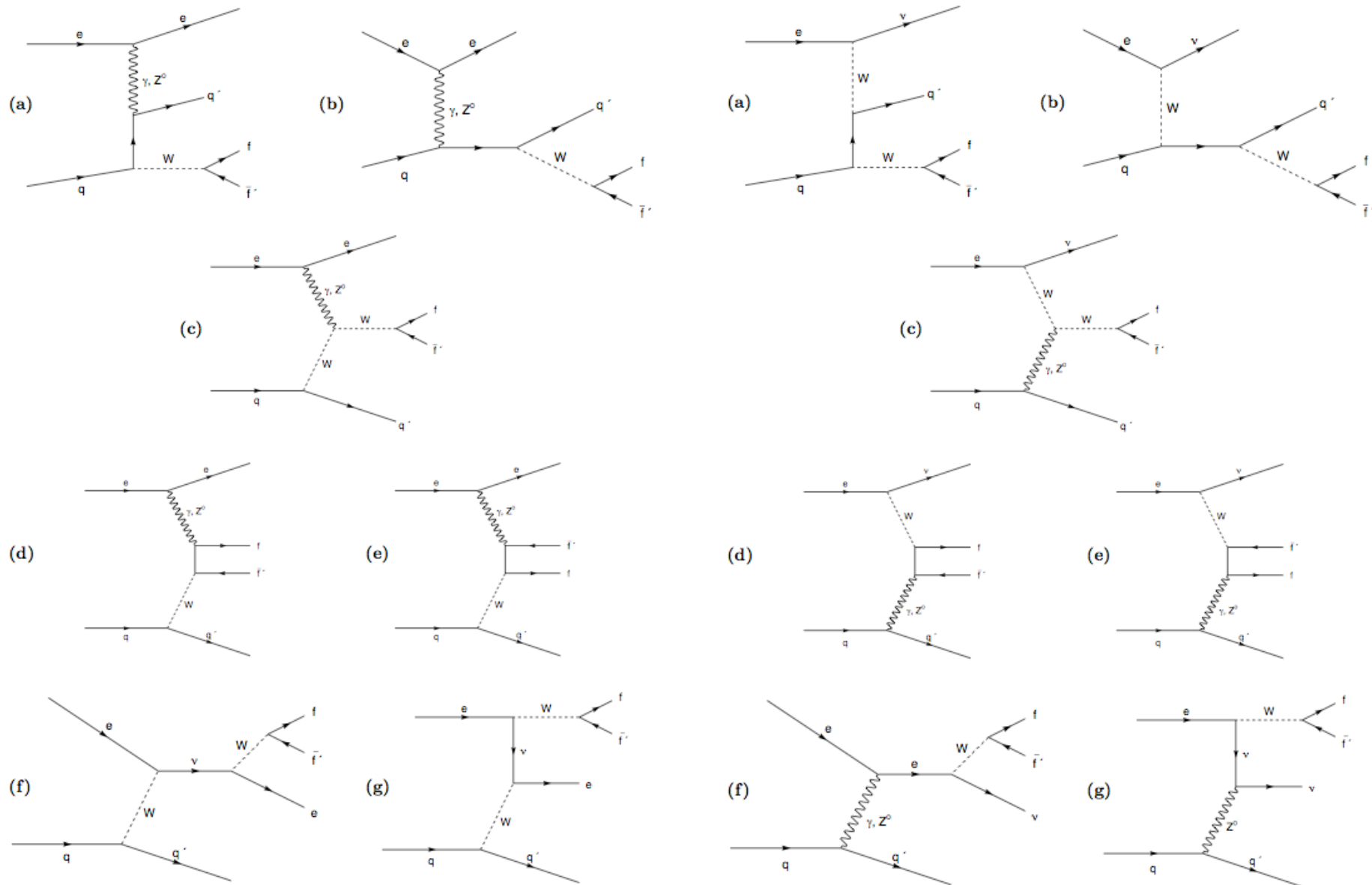
H1 e^+p data HERA I (106 pb^{-1})	e channel obs. / exp.	μ channel obs. / exp.	e and μ channels obs. / exp.
Full sample	10 / 9.9 ± 1.3	8 / 2.6 ± 0.4	18 / 12.4 ± 1.7
$P_T^X > 25 \text{ GeV}$	4 / 1.5 ± 0.3	6 / 1.4 ± 0.3	10 / 2.9 ± 0.5

3.0 σ 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
θ_l	$15^\circ < \theta_l < 120^\circ$	
P_T^l	$> 10 \text{ GeV}$	
P_T^{calo}	$> 12 \text{ GeV}$	
* M_T	$> 10 \text{ GeV}$	
P_T^{miss}	$> 12 \text{ GeV}$	
P_T^X	-	$> 12 \text{ GeV}$
D_{jet}	> 1.0	
D_{track}	$> 0.5 \text{ for } \theta_e \geq 45^\circ$	> 0.5
ξ_l^2	$> 5000 \text{ GeV}^2 \text{ for } P_T^{\text{calo}} < 25 \text{ GeV}$	-
* V_{ap}/V_p	$< 0.5 \text{ (} < 0.15 \text{ for } P_T^e < 25 \text{ GeV)}$	$< 0.5 \text{ (} < 0.15 \text{ for } P_T^{\text{calo}} < 25 \text{ GeV)}$
$\Delta\phi_{l-X}$	$< 160^\circ$	$< 170^\circ$
* δ_{miss}	$5 \text{ GeV} < \delta_{\text{miss}} < 50 \text{ GeV}$	
* # isolated μ	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

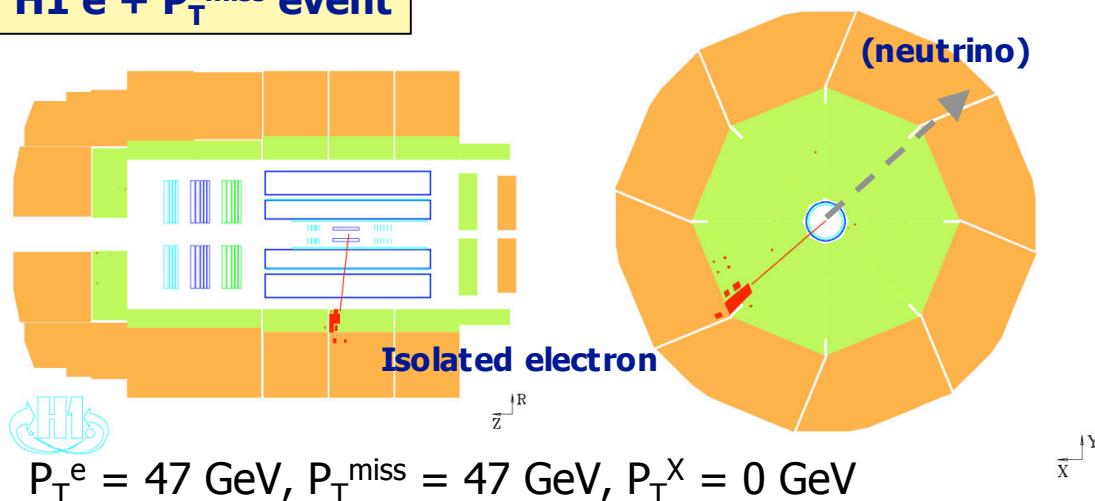
Cuts designed to reduce SM background, whilst preserving large signal purity

* 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

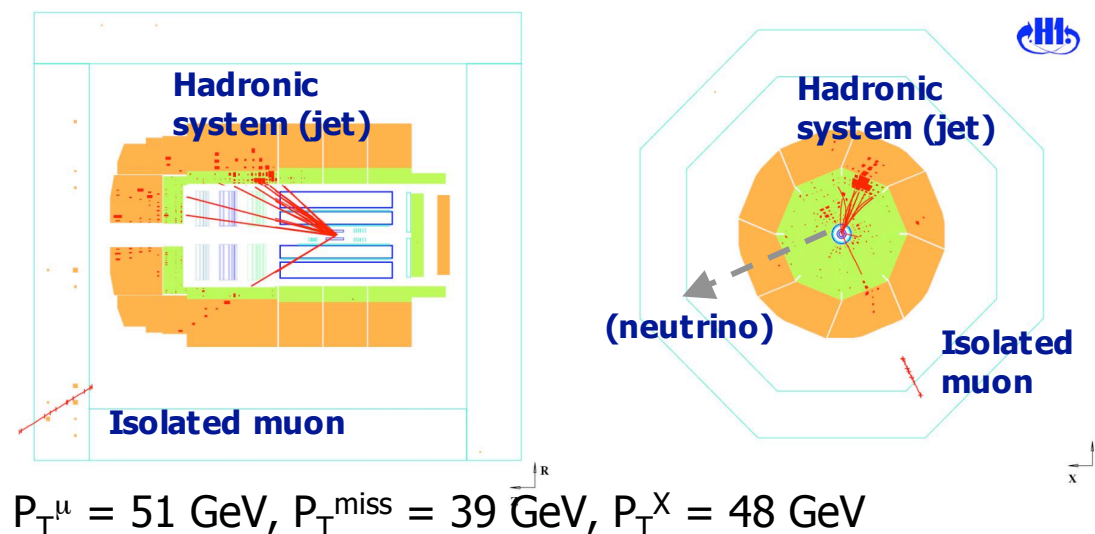
H1: $5^\circ < \theta_l < 140^\circ$

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



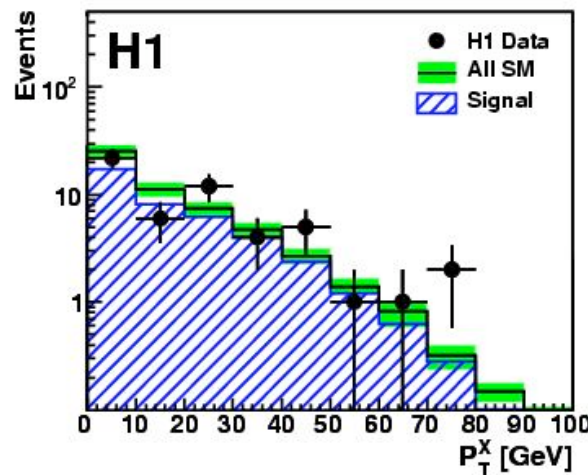
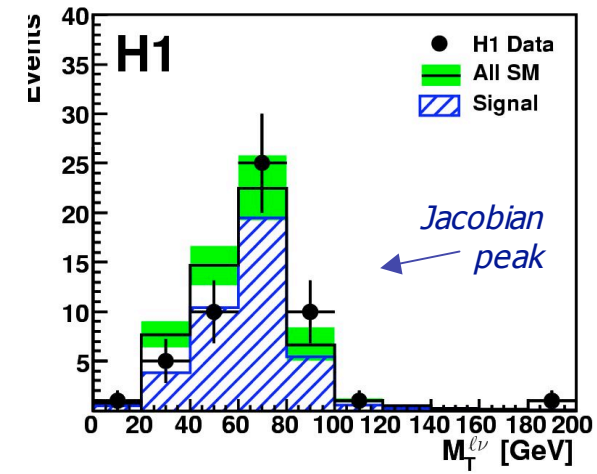
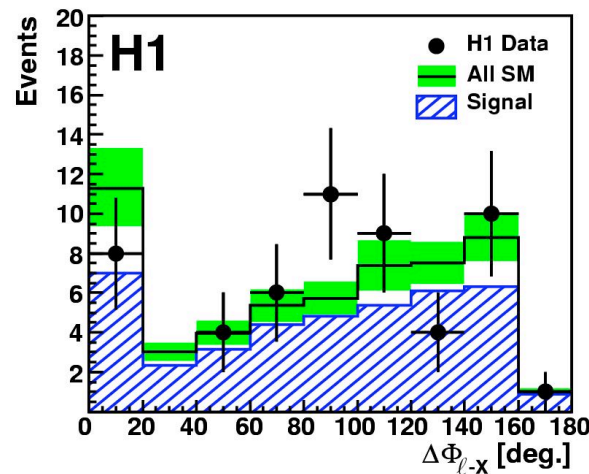
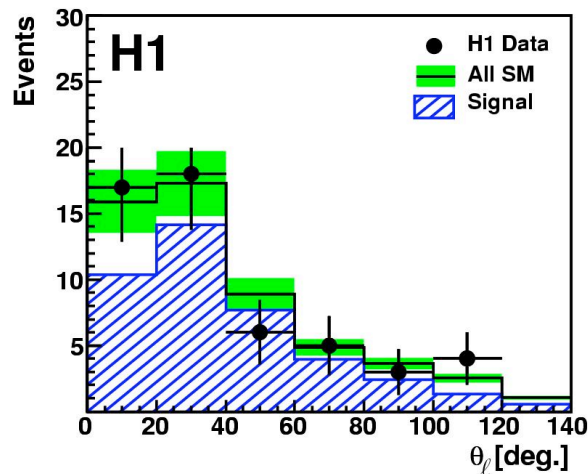
- Large missing global transverse momentum

$P_T^{\text{miss}} > 12 \text{ GeV}$

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

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

Eur. Phys. J. C64 (2009) 251



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

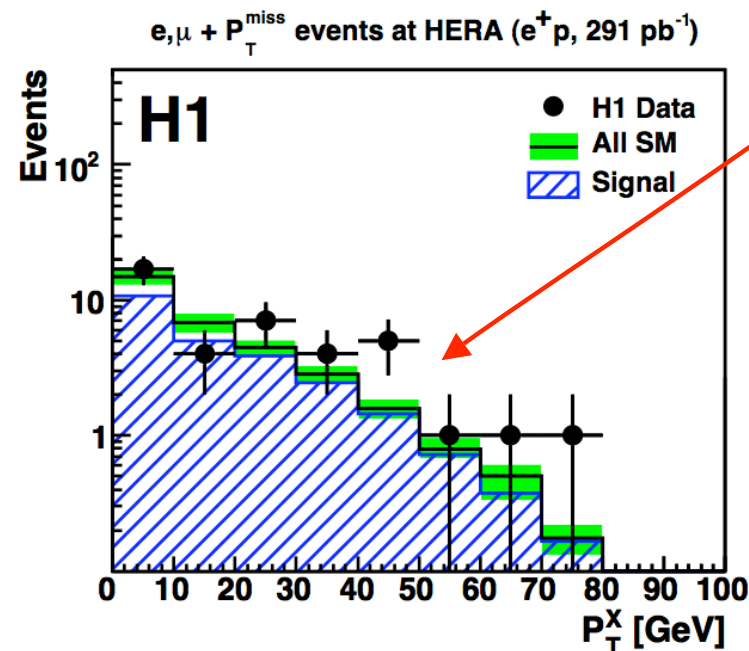
Good overall agreement with the Standard Model: W Production

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

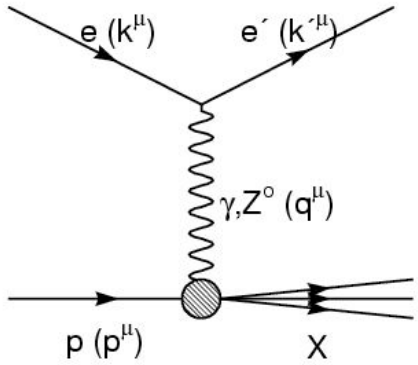
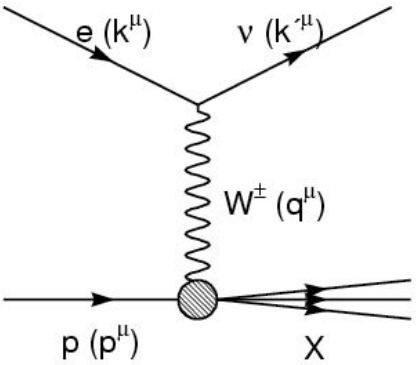
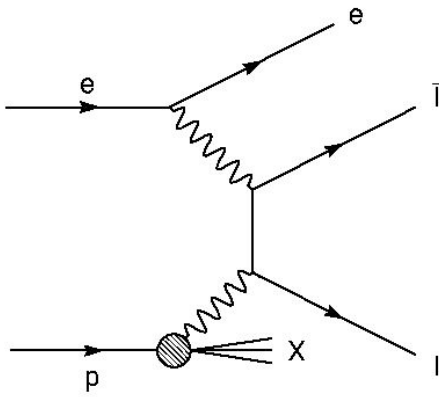
Eur. Phys. J. C64 (2009) 251

H1	1994-2007 e^+p 291 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
	$P_T^X > 25$ 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
	$P_T^X > 25$ 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
	$P_T^X > 25$ 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

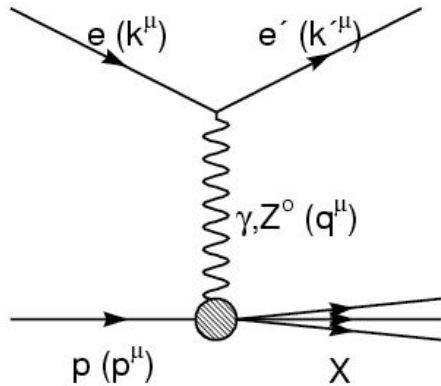


Standard Model Background

e: Neutral Current	e, μ : Charged Current	μ : 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

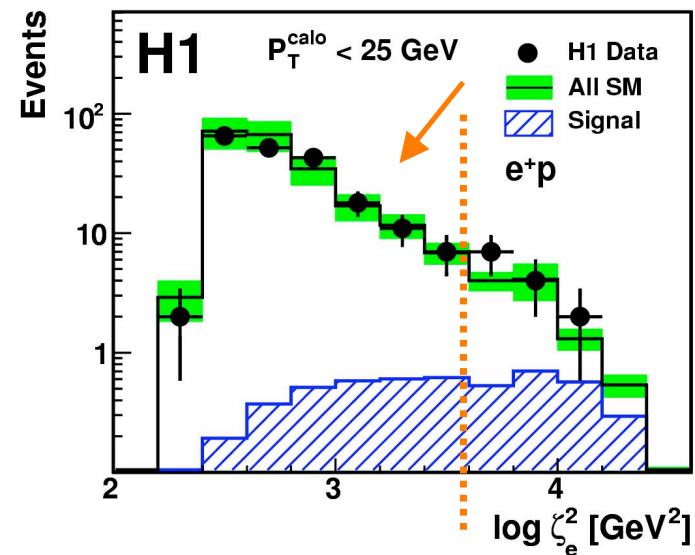
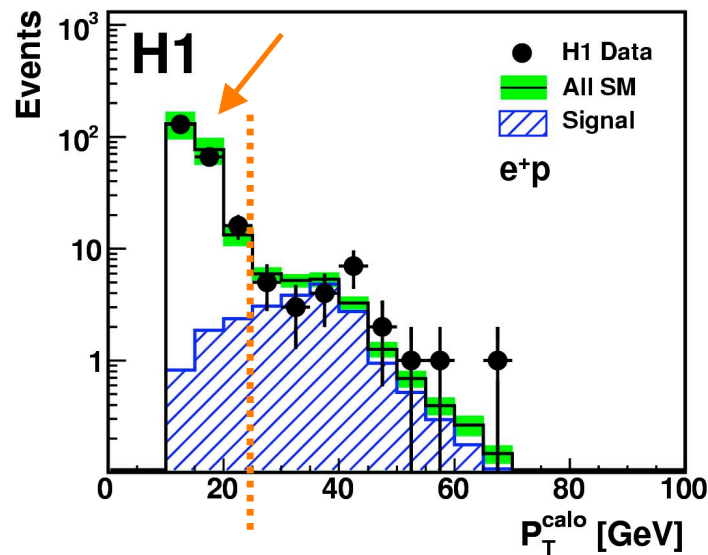
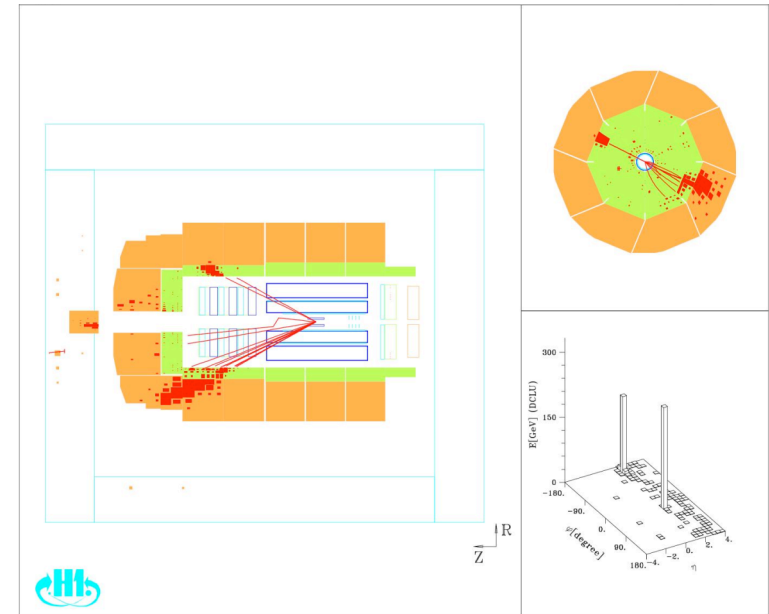
- Further topological cuts are applied to reduce SM background
 - Acoplanarity, longitudinal and transverse balance of the event
- Dedicated control samples used in both the H1 and ZEUS analyses to estimate the uncertainties on these processes in the analysis phase space
 - Control samples formed by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

SM Background: Neutral Current

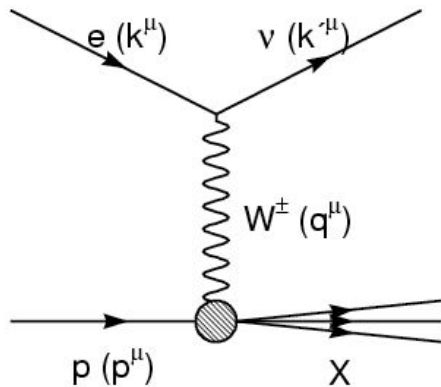


Real electron and
fake missing P_T from
mismeasurement

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

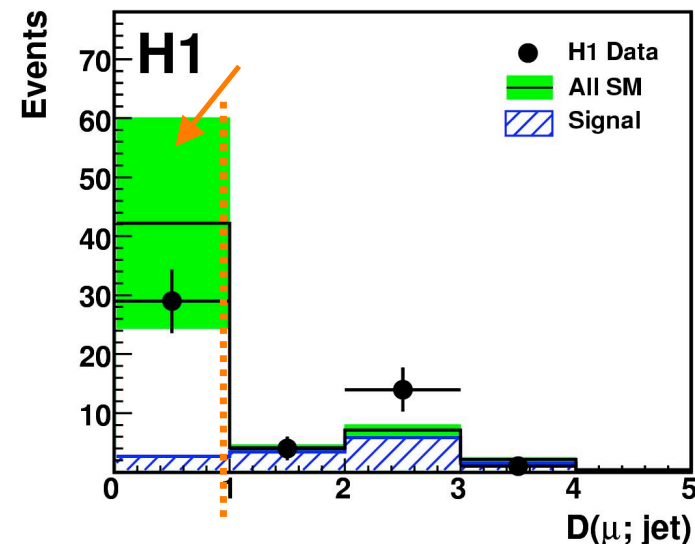
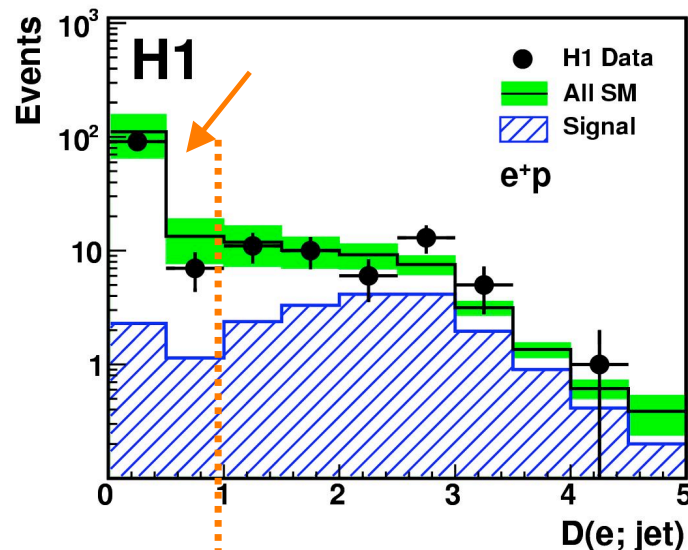
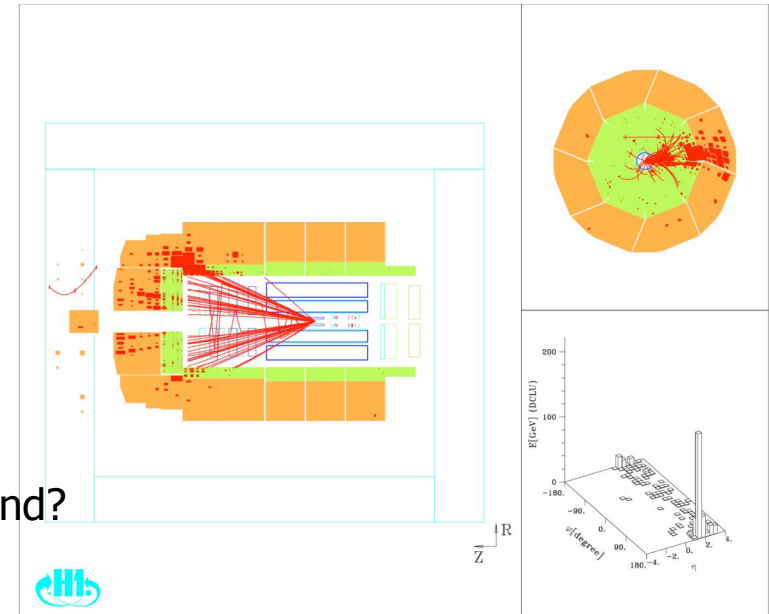


SM Background: Charged Current

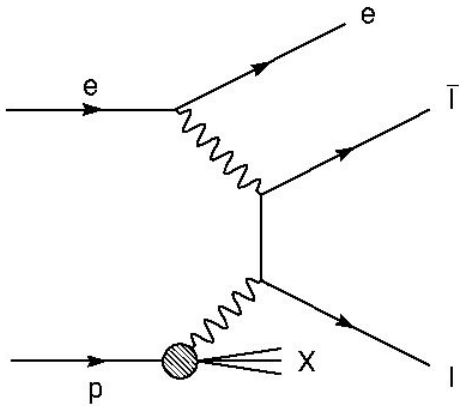


Misidentified
electron or muon
and real missing P_T

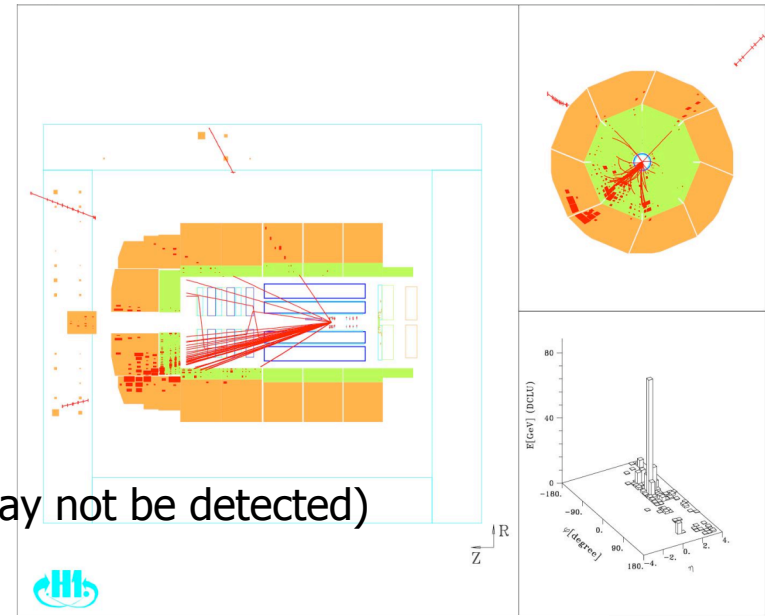
- Origin of electron or isolated muon events: CC background?
- Remove Anti-CC cuts (D jet)
- Electrons and muons in CC jets described within 50%



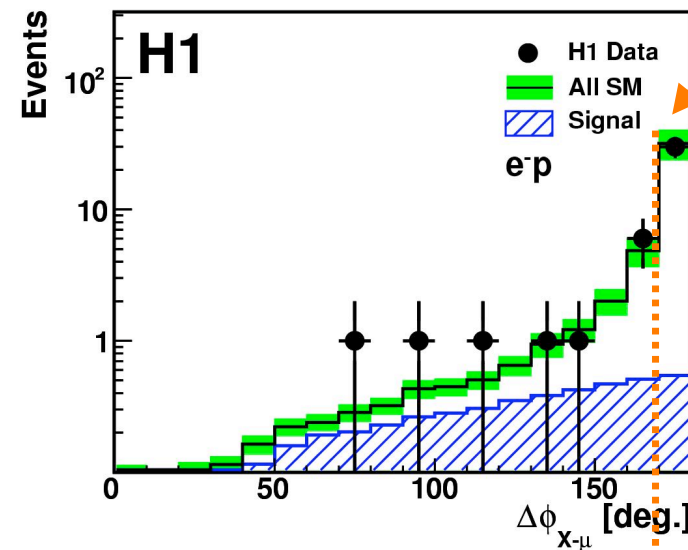
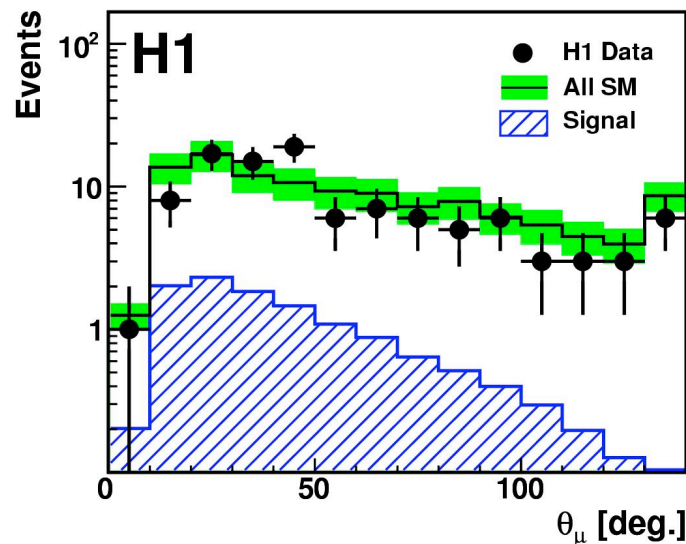
SM Background: Pair Production



Real muon and fake
missing P_T from
mismeasurement

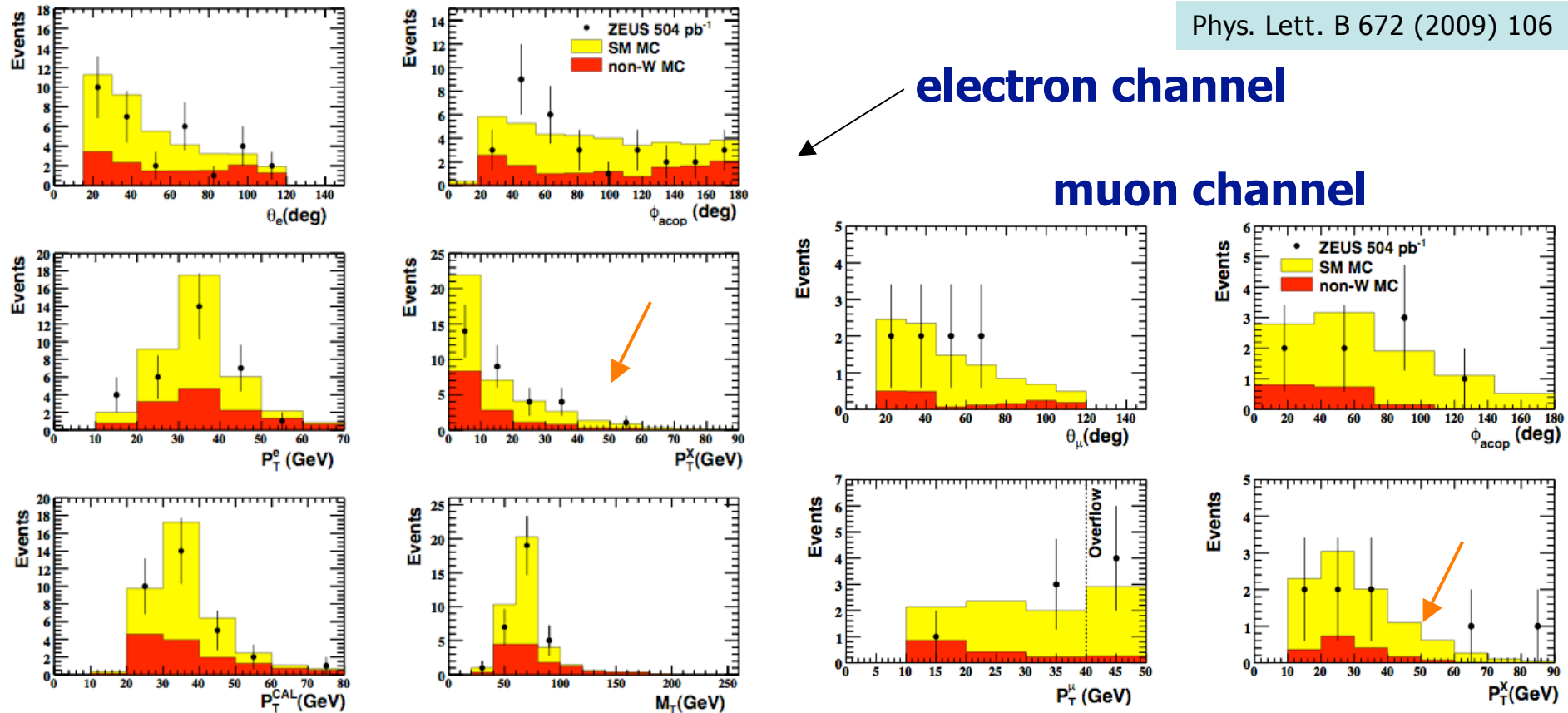


- Muon events from lepton-pair production? (One muon may not be detected)
- Remove Anti-lepton-pair cuts (P_T^{miss} , acoplanarity)
- Lepton-pair Production described in enriched region



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

Phys. Lett. B 672 (2009) 106



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 ± 1.5 (54%)	6/ 5.1 ± 0.7 (67%)	5/ 5.5 ± 0.8 (75%)
$e^+p \ 296 \text{ pb}^{-1}$	7/ 12.6 ± 1.7 (68%)	7/ 6.2 ± 0.9 (75%)	6/ 7.4 ± 1.0 (79%)
$e^\pm p \ 504 \text{ pb}^{-1}$	16/ 23.9 ± 3.1 (61%)	13/ 11.2 ± 1.5 (71%)	11/ 12.9 ± 1.7 (77%)

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

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

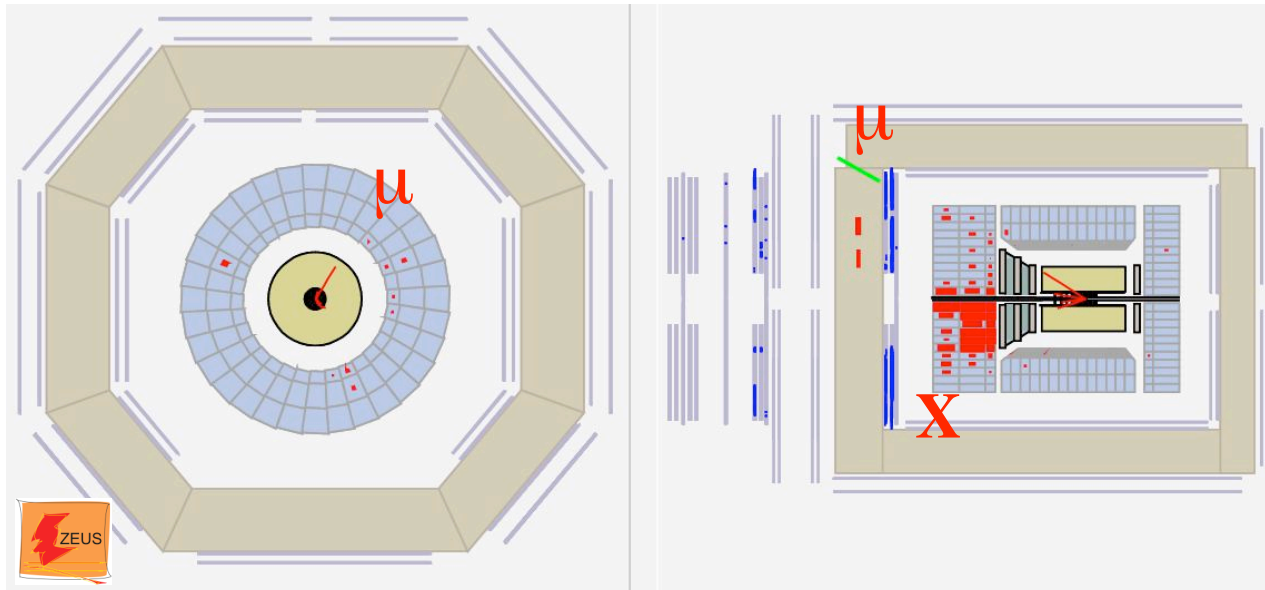
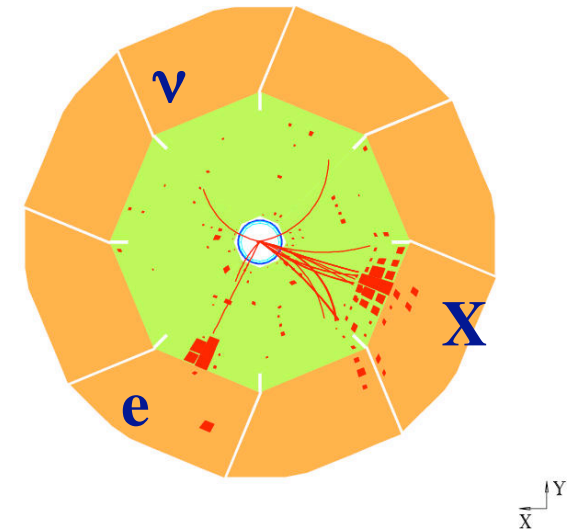
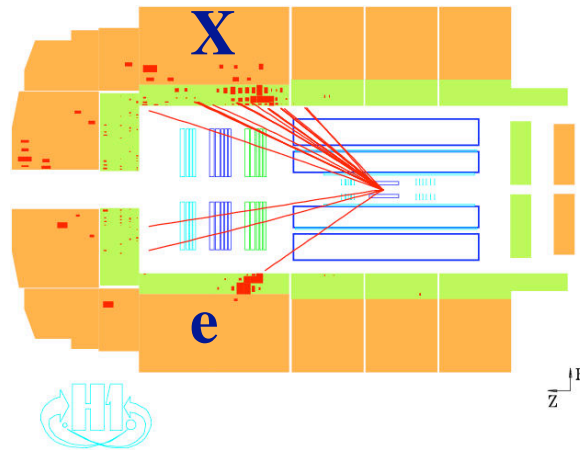
A Combined H1 and ZEUS Analysis

- The SM expectation for signal events at HERA is low, so the analysis benefits from the combination of the full 1 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⁻¹
 - 474 pb⁻¹ H1 and 504 pb⁻¹ ZEUS data
 - 587 pb⁻¹ of e⁺p data, 391 pb⁻¹ of e⁻p data
 - 84 pb⁻¹ of data at 301 GeV, 894 pb⁻¹ 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 : $100 \text{ cm} < z$ 2.0%
	Spacal: 0.5%
θ_e	LAr : 3 mrad Spacal: 1 mrad
ϕ_e	1 mrad
P_T^μ	2.5%
θ_μ	3 mrad
ϕ_μ	1 mrad
E_{had}	2% (5% if $P_T^X < 8$ GeV)
θ_{had}	10 mrad
ϕ_{had}	10 mrad
$\frac{V_{ap}}{V_p}$	± 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

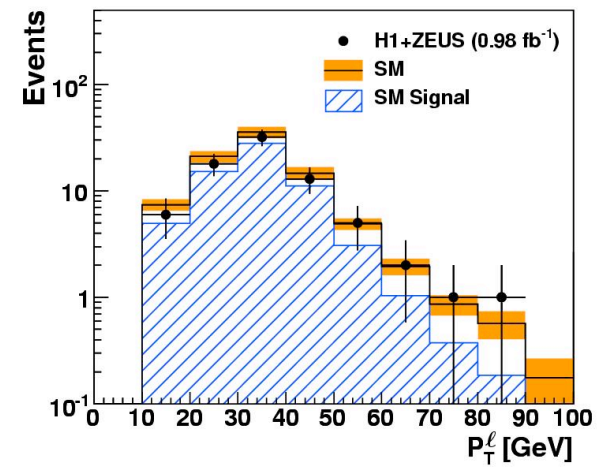
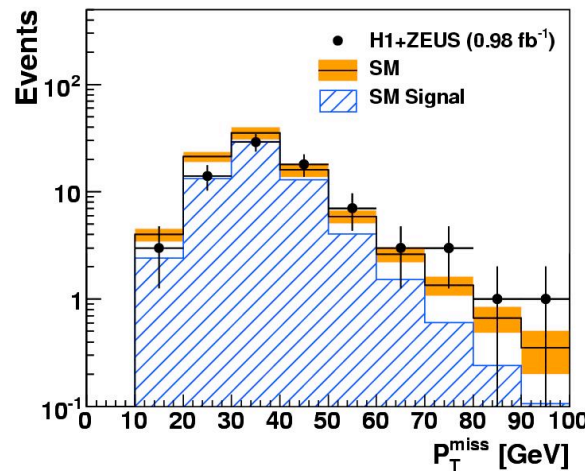
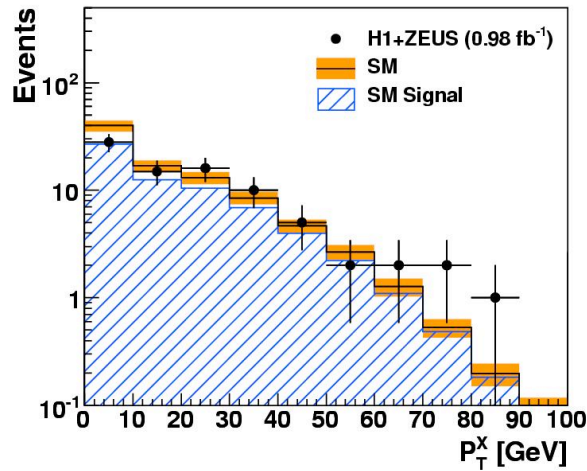
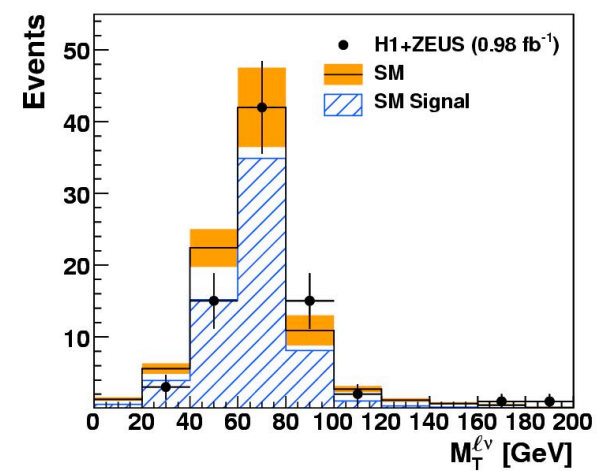
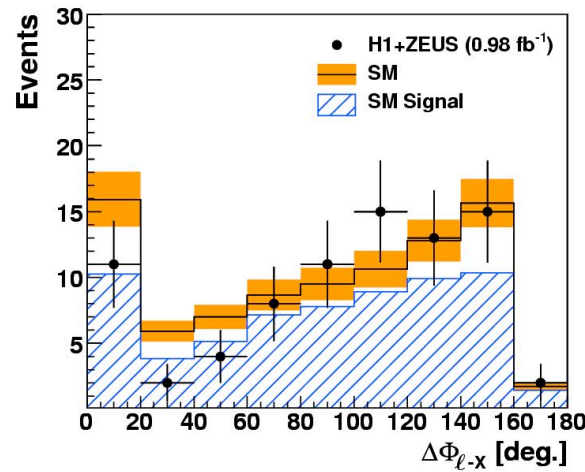
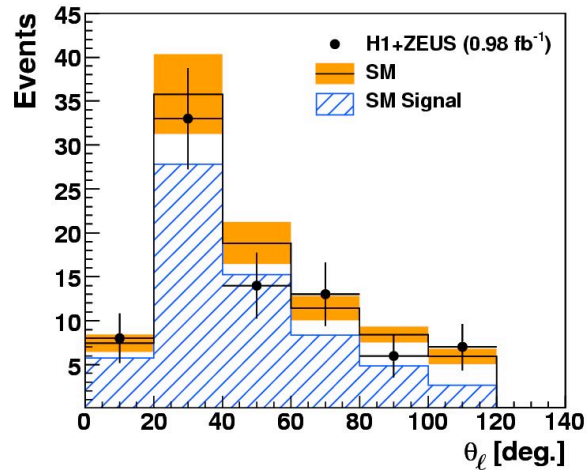
- EPVEC: 15% (NLO model error)

SM Background uncertainties from agreement in control samples

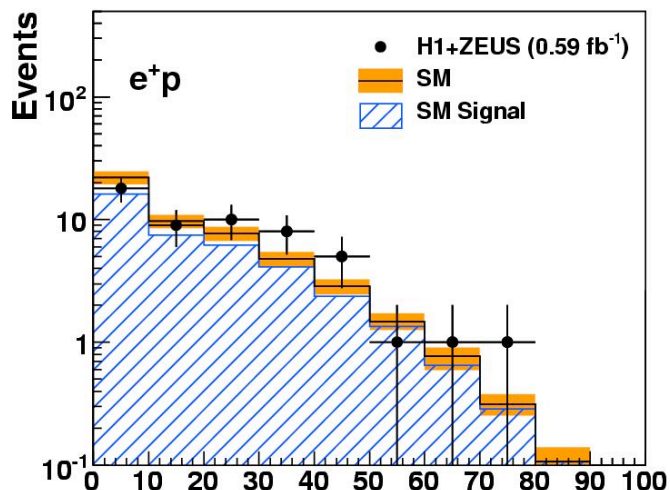
- NC: 30% (15%) H1 (ZEUS)
- LPAIR: 30% (25%) H1 (ZEUS)
- CC: 50% (25%) H1 (ZEUS)
- COMPTON, GAMMAP: 30% (H1)

All errors treated uncorrelated between H1 and ZEUS except EPVEC

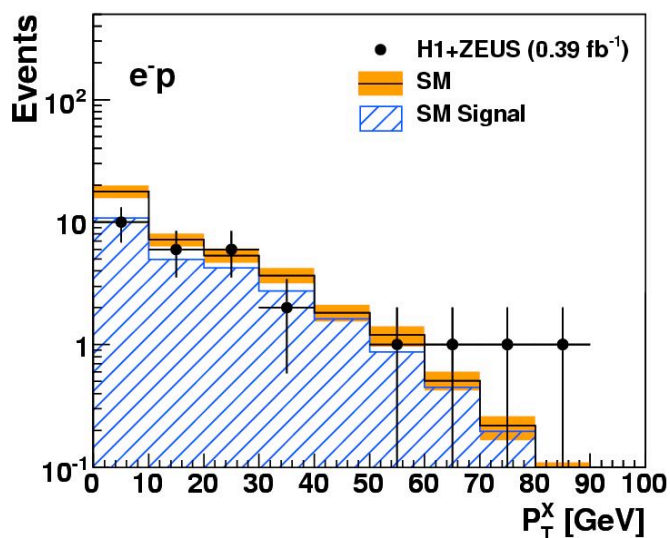
H1+ZEUS Isolated Leptons: All Distributions



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



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



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

H1+ZEUS Isolated Leptons: Cross Section

H1+ZEUS Differential Single W Production Cross Section		
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 ± 9.4
12 – 25	$20.6 \pm 6.0 \pm 1.9$	20.7 ± 3.1
25 – 40	$12.7 \pm 3.6 \pm 1.0$	9.8 ± 1.5
40 – 100	$2.1 \pm 0.7 \pm 0.2$	1.5 ± 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^ℓ [GeV]	θ_ℓ [°]	P_T^X [GeV]	$M_T^{\ell\nu}$ [GeV]	P_T^{miss} [GeV]
186729	702	μ	> 42.5	30.0 ± 0.4	75.3 ± 5.5	> 33.7	> 40.0
188108	5066	$\mu^- (8.3\sigma)$	$40.9^{+5.6}_{-4.4}$	35.1 ± 0.4	29.4 ± 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 ± 0.3	63.9 ± 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 ± 0.4	30.1 ± 2.6	$88.7^{+23.5}_{-37.0}$	$33.5^{+10.6}_{-15.8}$
248207	32134	$e^+ (15\sigma)$	32.1 ± 1.3	32.2 ± 0.3	42.0 ± 3.9	62.7 ± 2.3	43.4 ± 2.8
252020	30485	$e^+ (40\sigma)$	25.6 ± 1.2	110.2 ± 0.3	39.1 ± 3.3	48.6 ± 2.1	35.5 ± 2.5
266336	4126	$\mu^+ (26\sigma)$	$19.7^{+0.8}_{-0.7}$	67.3 ± 0.4	50.0 ± 3.8	$69.8^{+2.4}_{-2.5}$	66.6 ± 3.7
268338	70014	$e^+ (1.6\sigma)$	33.8 ± 1.3	29.7 ± 0.2	45.2 ± 3.2	90.3 ± 3.1	67.2 ± 3.0
275991	29613	$e^+ (37\sigma)$	37.8 ± 1.5	41.7 ± 0.3	27.1 ± 1.8	73.3 ± 2.8	40.3 ± 1.4
369241	6588	e	29.2 ± 1.1	20.3 ± 0.2	40.5 ± 4.8	74.3 ± 3.0	55.5 ± 4.2
385422	76666	$e^+ (22\sigma)$	28.1 ± 1.3	96.1 ± 0.3	25.9 ± 2.8	63.1 ± 2.8	40.0 ± 2.3
389826	2783	$e^- (10\sigma)$	62.0 ± 2.2	45.6 ± 0.3	45.3 ± 4.5	79.7 ± 6.0	30.3 ± 2.1
391884	49715	e	38.2 ± 1.4	22.7 ± 0.2	32.4 ± 2.6	48.5 ± 3.0	20.1 ± 0.8
473929	107593	$\mu^- (9.6\sigma)$	$53.5^{+6.2}_{-5.1}$	31.4 ± 0.4	49.1 ± 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 ± 0.4	37.0 ± 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 ± 0.4	29.6 ± 2.8	$63.1^{+1.7}_{-1.8}$	$40.3^{+2.0}_{-2.0}$
498117	316609	$e^+ (9.8\sigma)$	27.4 ± 1.1	30.7 ± 0.3	26.7 ± 1.8	72.5 ± 2.5	49.9 ± 2.0
433051	64528	$e^- (24\sigma)$	26.2 ± 1.3	69.9 ± 0.3	72.9 ± 5.6	71.3 ± 2.9	75.8 ± 5.2

Different Isolated Lepton Event Selections

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

- 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 δ_{miss} cuts adopted by H1

- The more limited polar angle range is needed

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

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

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

Lepton from W
(TRUTH)

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

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: $\mathcal{A} = \frac{N_{rec}}{N_{gen}}$

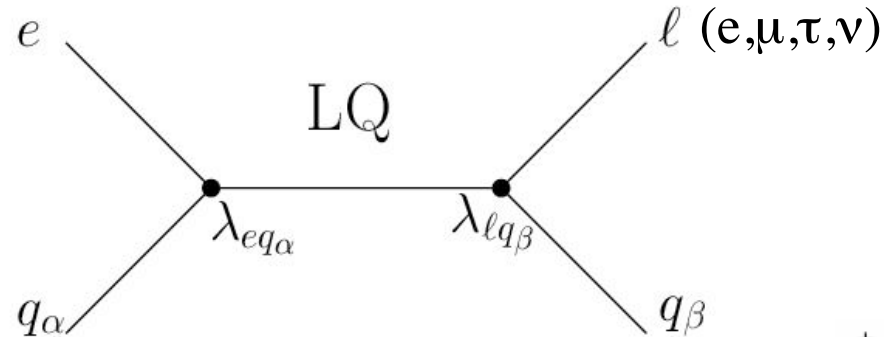
- N_{gen} : Number of generated W events decaying to the electron and muon channel
- Leptonic tau decays included in N_{gen} and therefore also in the branching ratio, Br

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

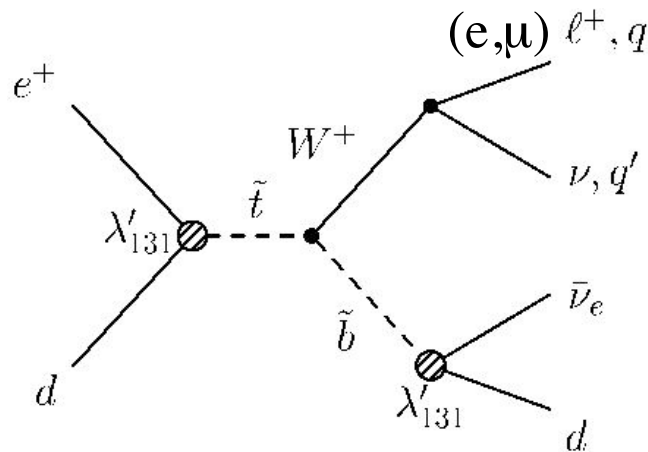
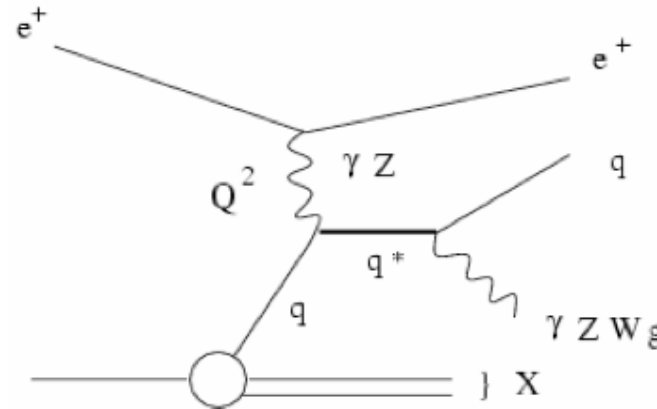
$$\frac{\sigma_\mu^{SM}}{\sigma_e^{SM}} \Big|_{P_T^X < 12} = 1.0092$$

What could the high P_T^X events be?



Leptoquarks ?

Excited Fermions ?

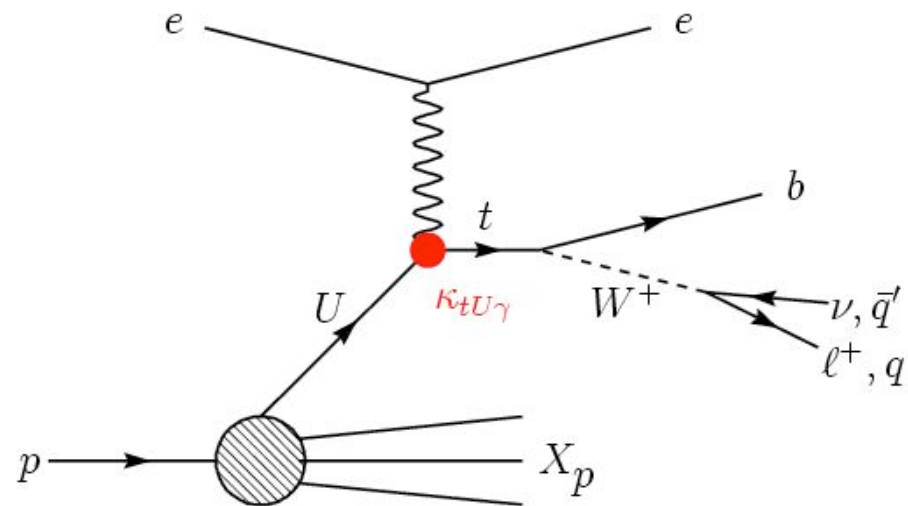


Bosonic Stop Production ?

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..

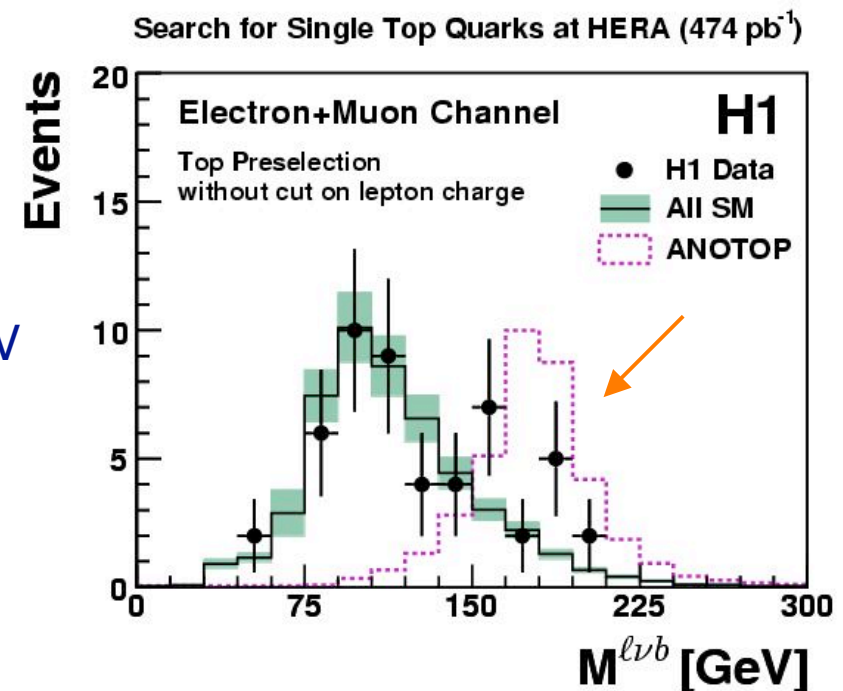


$\kappa_{tU\gamma}$: Anomalous γ magnetic coupling

H1 Single Top Analysis

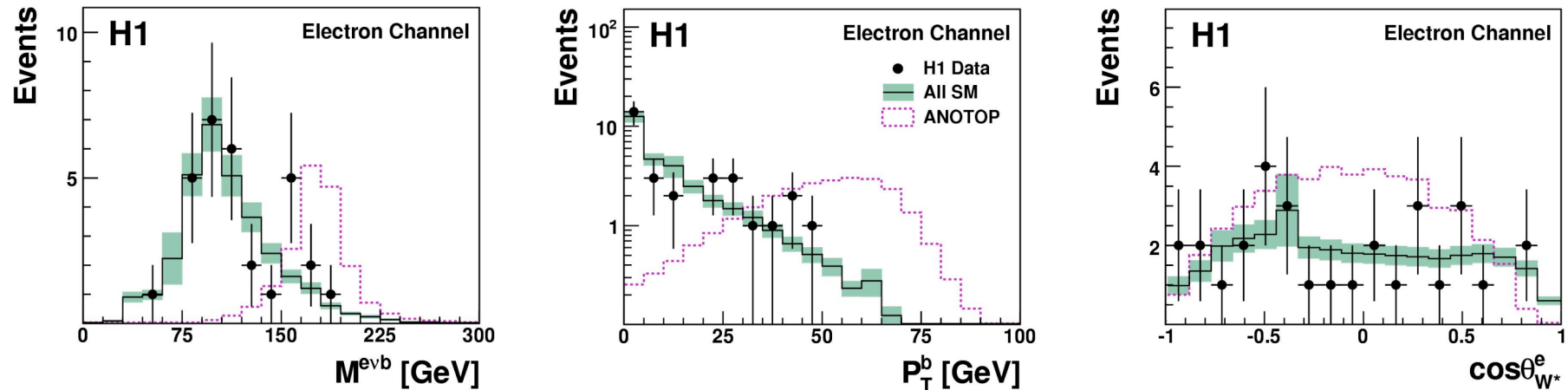
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- Leptonic channels:
 - Top pre-selection is subset of the isolated lepton selection
 - Add good neutrino reconstruction
 - Require positively charged lepton
- Hadronic channel:
 - 3 jet selection $P_{T}^{\text{jet}1,2,3} > 40, 30, 15 \text{ GeV}$
 - 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 , $M^{\ell\nu b}(\text{jets})$ and $\theta_W^l(q)$
 - Cut-based analysis used as cross check

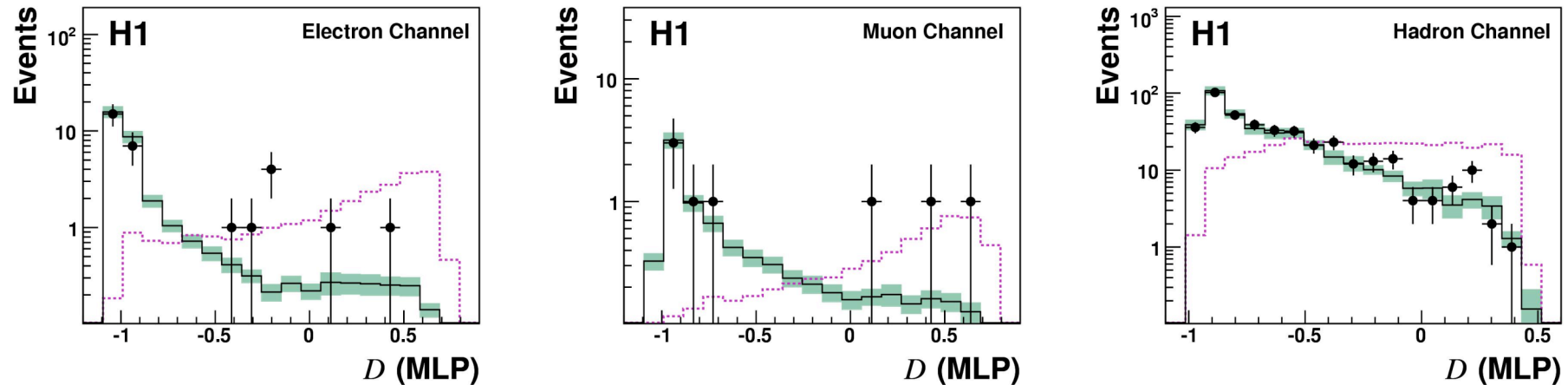


H1 Single Top Analysis: Discriminator Output

Discriminator input variables (electron channel):



Discriminator output (separation) of all three channels:

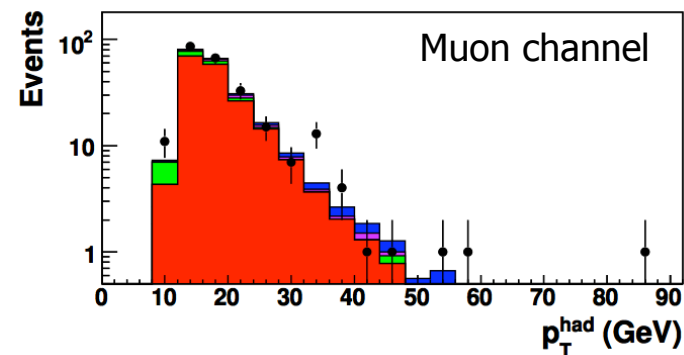
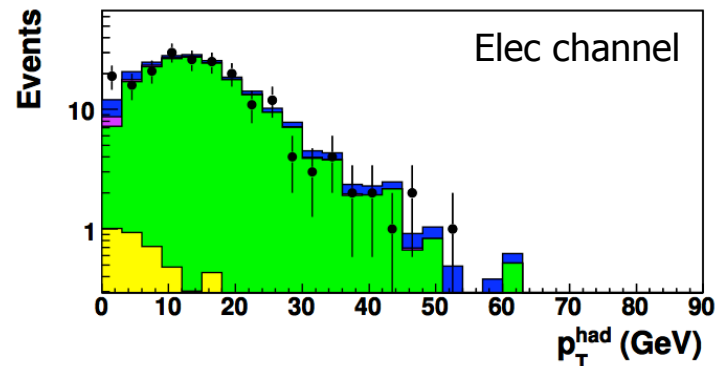


No significant deviation from the SM \rightarrow *Derive limit..*

ZEUS Single Top Analysis

ZEUS-prel-09-009

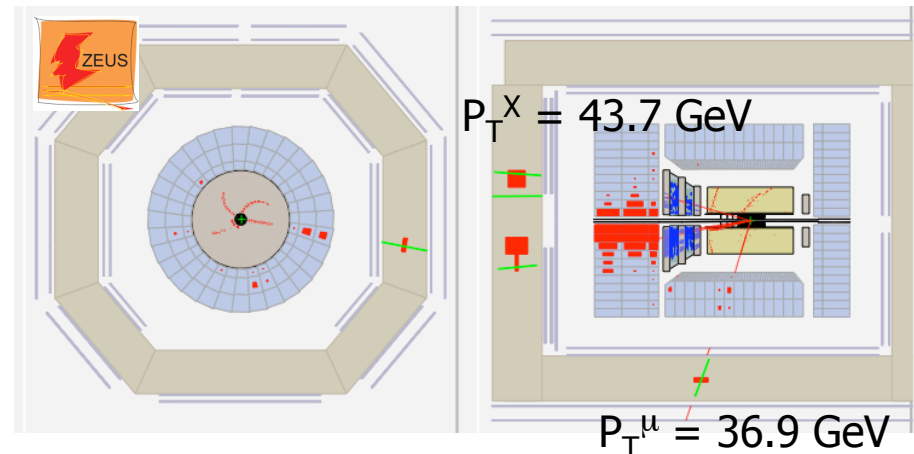
- Investigate leptonic channels in a dedicated analysis
 - Similar to ZEUS isolated lepton selection, but optimised for single top



- 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*

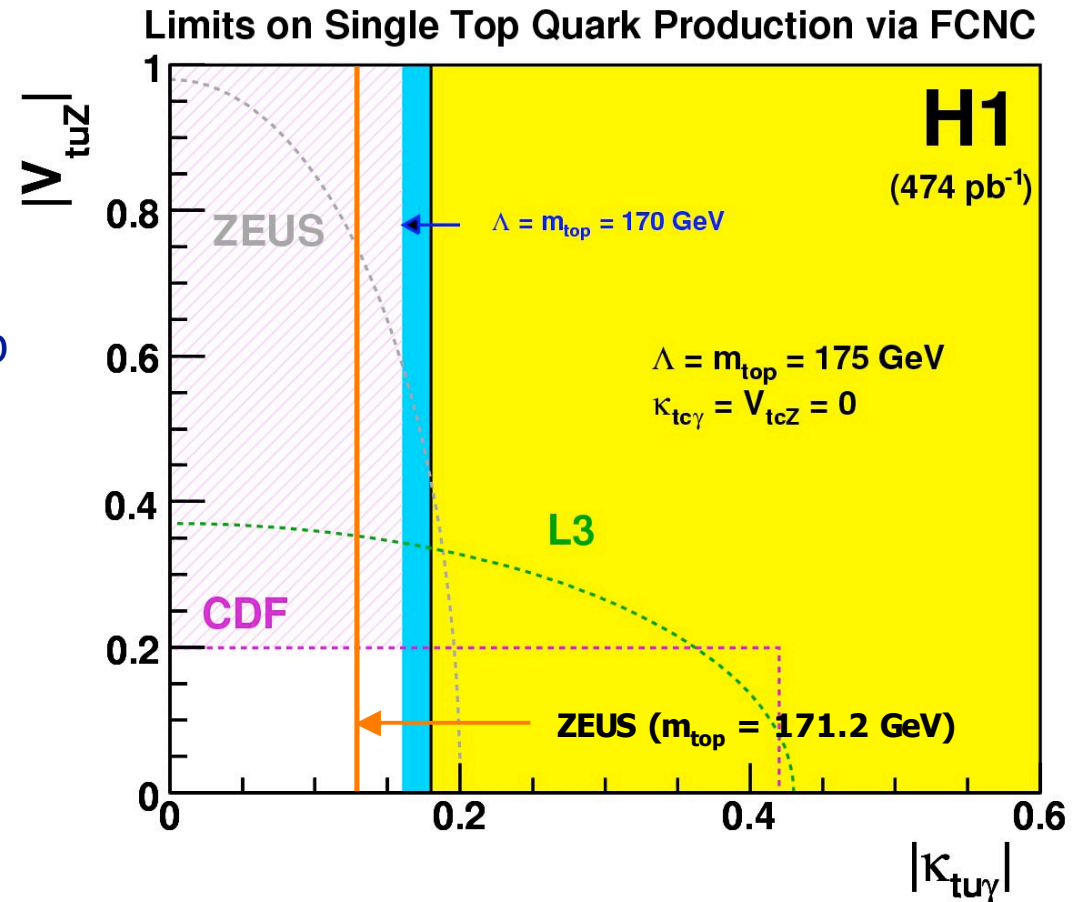
Single Top Selection

	N_{obs}	N_{pred}	$W\%$	Efficiency
Electron Channel 04-05 e-p	0	2.1 ± 0.6	38	0.033
Muon Channel 04-05 e-p	1	1.5 ± 0.4	47	0.026
Electron Channel 06-07 e+p	0	0.9 ± 0.3	78	0.033
Muon Channel 06-07 e+p	1	1.4 ± 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: $\kappa_{t\gamma} < 0.18$
 - ZEUS: $\kappa_{t\gamma} < 0.13$



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^{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 pb^{-1}
 - Good overall agreement with the SM prediction
 - Expectation dominated by CC background
 - Challenging hadronic environment



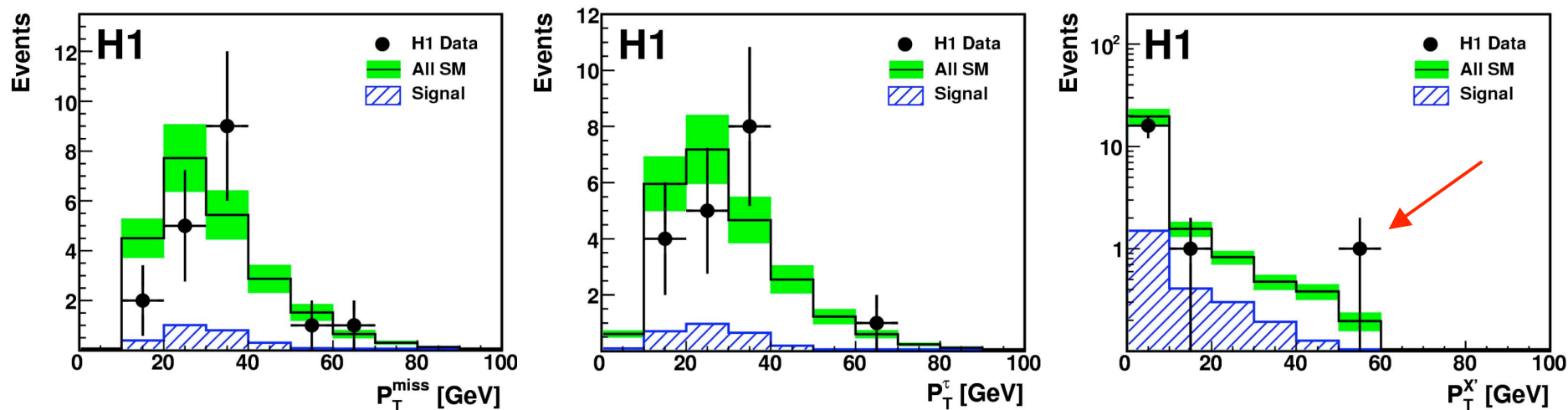
HERA-I:

Isolated Tau Leptons

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

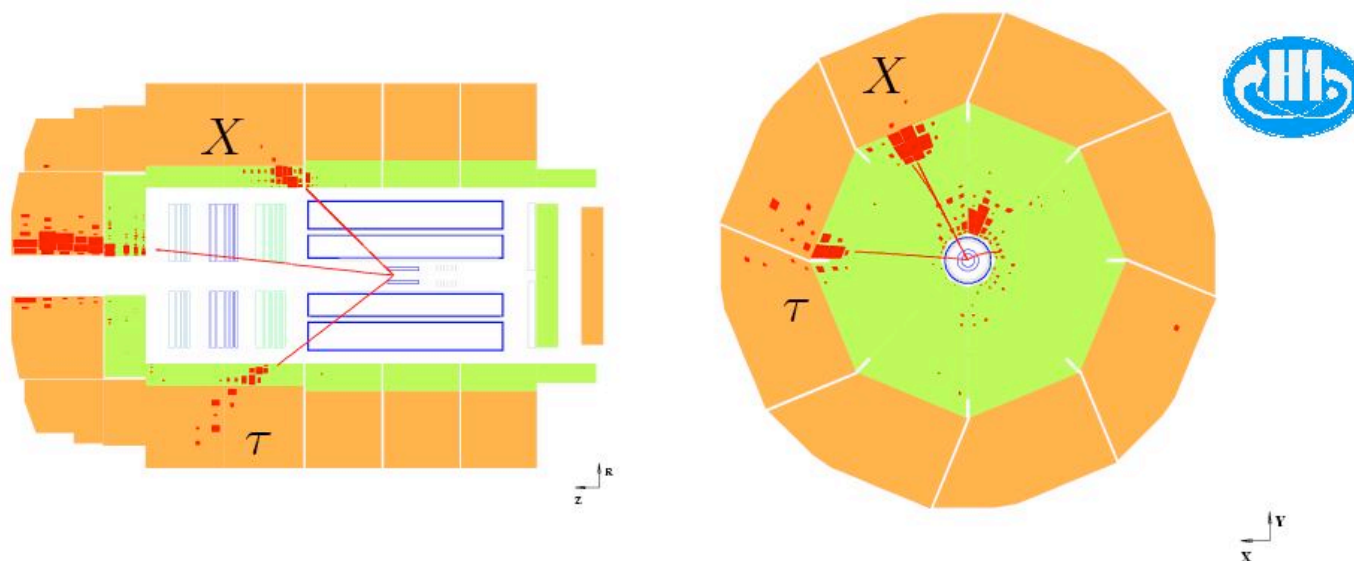
H1	Tau Channel	Data	SM Expectation	SM Signal	Other SM Processes
1994-2007 e^+p	Total	9	12.3 ± 2.0	1.66 ± 0.25	10.6 ± 1.8
291 pb^{-1}	$P_T^X > 25 \text{ GeV}$	0	0.82 ± 0.12	0.38 ± 0.06	0.44 ± 0.06
1999-2006 e^-p	Total	9	11.0 ± 1.9	1.00 ± 0.15	10.0 ± 1.8
183 pb^{-1}	$P_T^X > 25 \text{ GeV}$	1	0.68 ± 0.11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

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

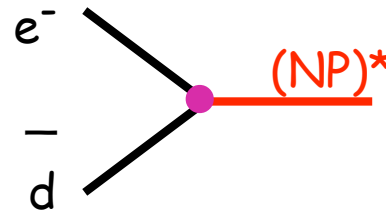
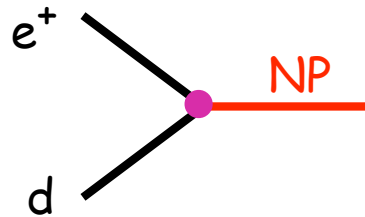
Missing Energy

Narrow, high P_T jet

Exactly one track in the jet

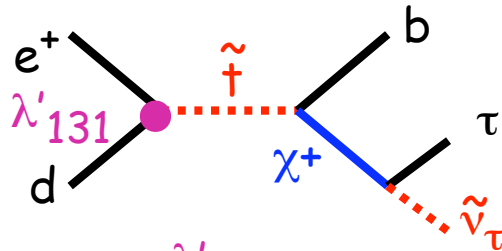
A BSM Model favouring e^+p over e^-p

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

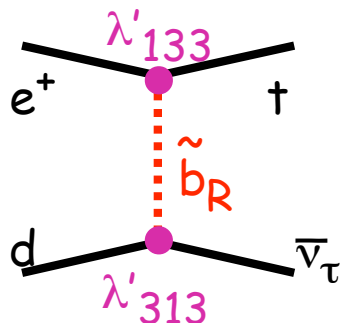


Large mass i.e. large x_{Bj}
 $d \gg \bar{d}$, hence $\sigma(e^+) \gg \sigma(e^-)$

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



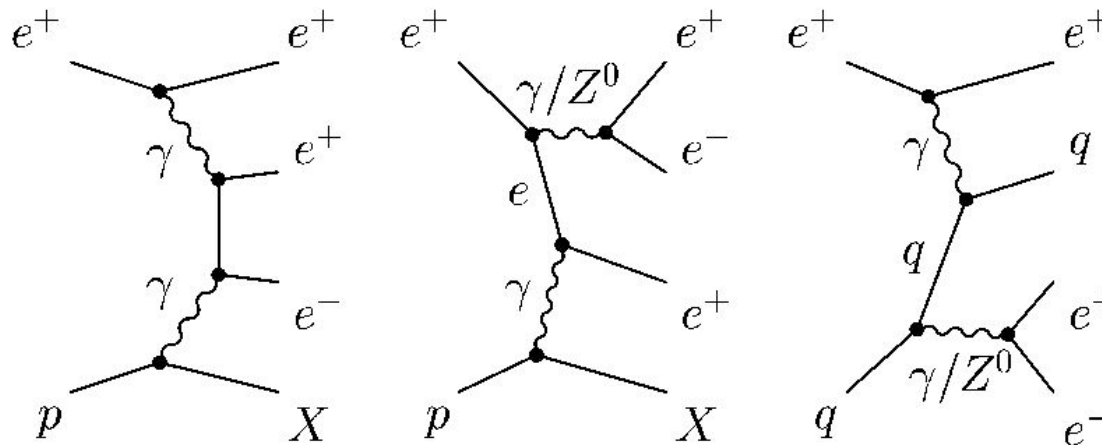
If LSP is $\tilde{\nu}_\tau$ and no large RpV coupling involving the τ : $\tilde{\nu}_\tau$ could be long-lived



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

Multi-Lepton Events

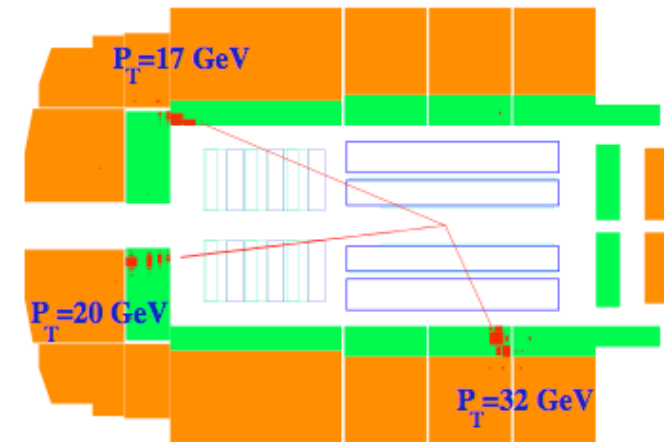
- The main SM process in ep interactions with multi-leptons in the final state is the $\gamma\gamma$ process:



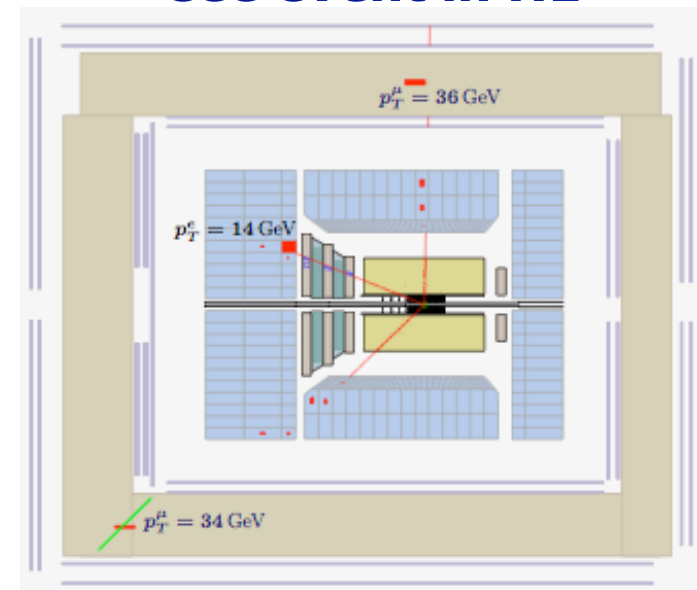
- This QED process has a precise SM prediction, modelled using GRAPE
- Cross section is low at high mass, high P_T : look for deviations from the SM prediction: indications of new phenomena
- Main SM backgrounds: NC-DIS, QED Compton for multi-electron events; multi-muon events have very low background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



$e\mu\mu$ event in ZEUS

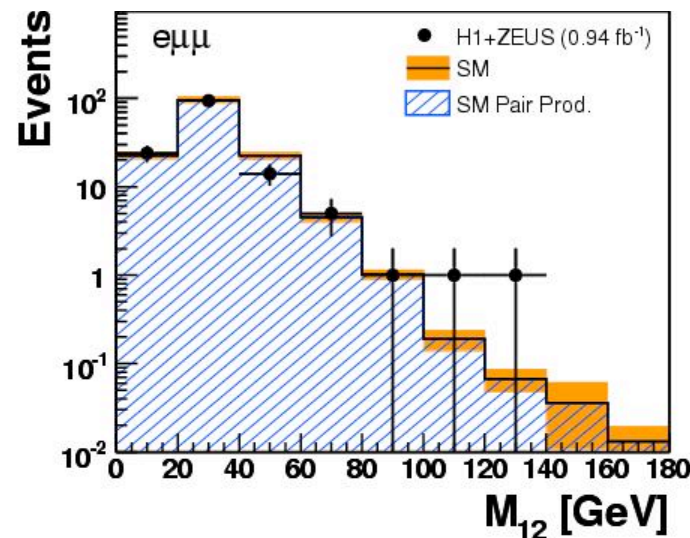
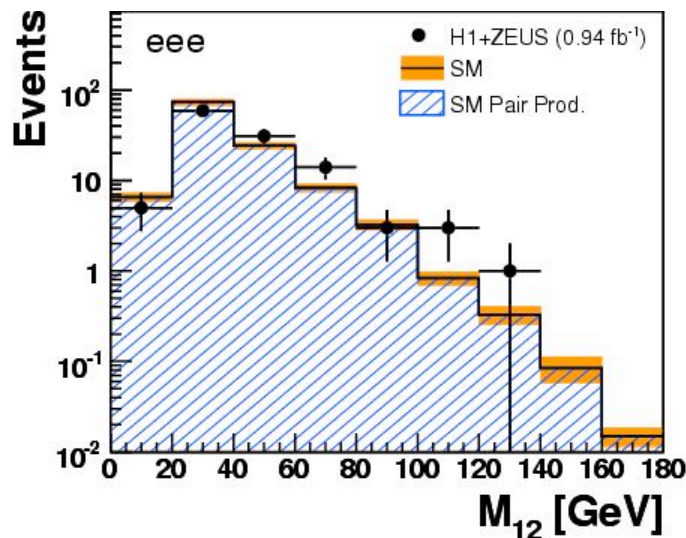
Results of Different Multi-lepton Topologies

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

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

Overall good agreement seen with the SM prediction

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



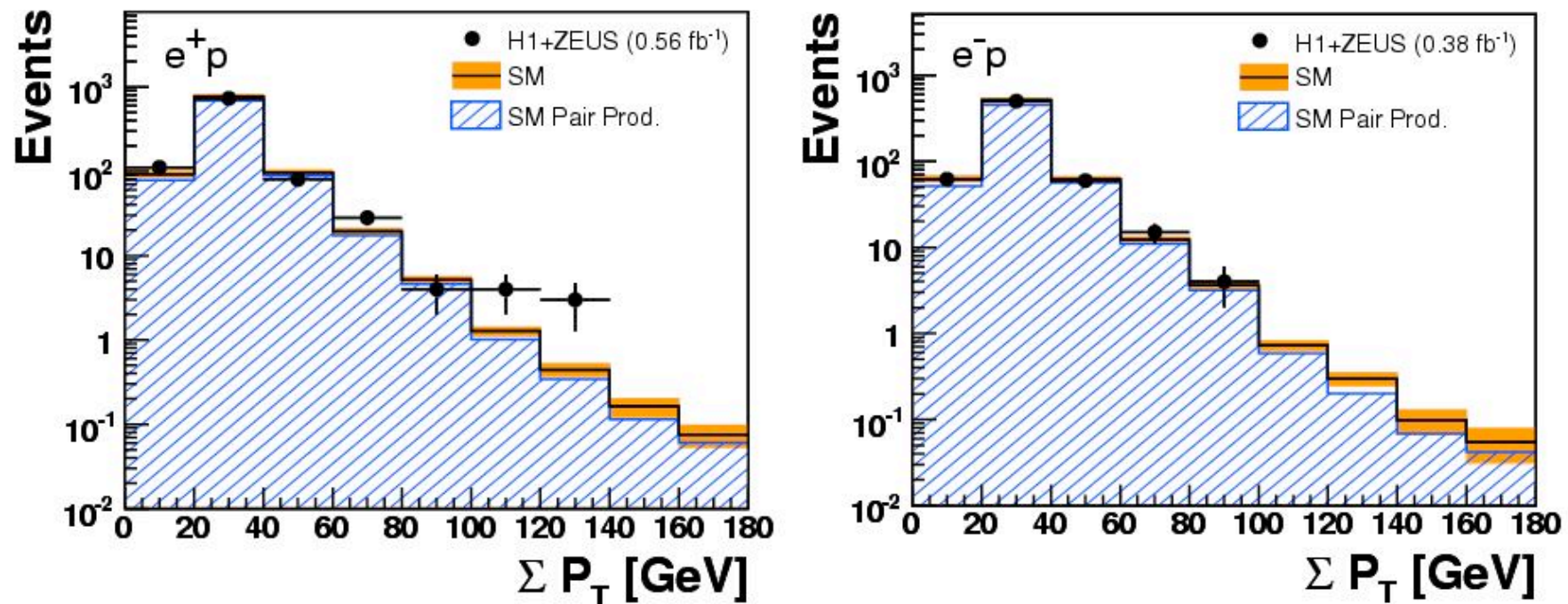
Looking at the high mass region, a few interesting events show up in the data

H1+ZEUS Multi-lepton Events at High Mass

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

Multi-Leptons at HERA (0.94 fb^{-1})				
$M_{12} > 100 \text{ GeV}$				
Sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p collisions (0.56 fb^{-1})				
ee	4	1.68 ± 0.18	0.94 ± 0.11	0.74 ± 0.12
$\mu\mu$	1	0.32 ± 0.08	0.32 ± 0.08	< 0.01
$e\mu$	1	0.40 ± 0.05	0.39 ± 0.05	< 0.02
eee	4	0.79 ± 0.09	0.79 ± 0.09	< 0.03
$e\mu\mu$	2	0.16 ± 0.04	0.16 ± 0.04	< 0.01
e^-p collisions (0.38 fb^{-1})				
ee	0	1.25 ± 0.13	0.71 ± 0.11	0.54 ± 0.08
$\mu\mu$	0	0.23 ± 0.10	0.23 ± 0.10	< 0.01
$e\mu$	0	0.26 ± 0.03	0.25 ± 0.03	< 0.02
eee	0	0.49 ± 0.07	0.49 ± 0.07	< 0.03
$e\mu\mu$	0	0.14 ± 0.05	0.14 ± 0.05	< 0.01
All data (0.94 fb^{-1})				
ee	4	2.93 ± 0.28	1.65 ± 0.16	1.28 ± 0.18
$\mu\mu$	1	0.55 ± 0.12	0.55 ± 0.12	< 0.01
$e\mu$	1	0.65 ± 0.07	0.64 ± 0.06	< 0.02
eee	4	1.27 ± 0.12	1.27 ± 0.12	< 0.03
$e\mu\mu$	2	0.31 ± 0.06	0.31 ± 0.06	< 0.01

H1+ZEUS Multi-lepton Events at High ΣP_T



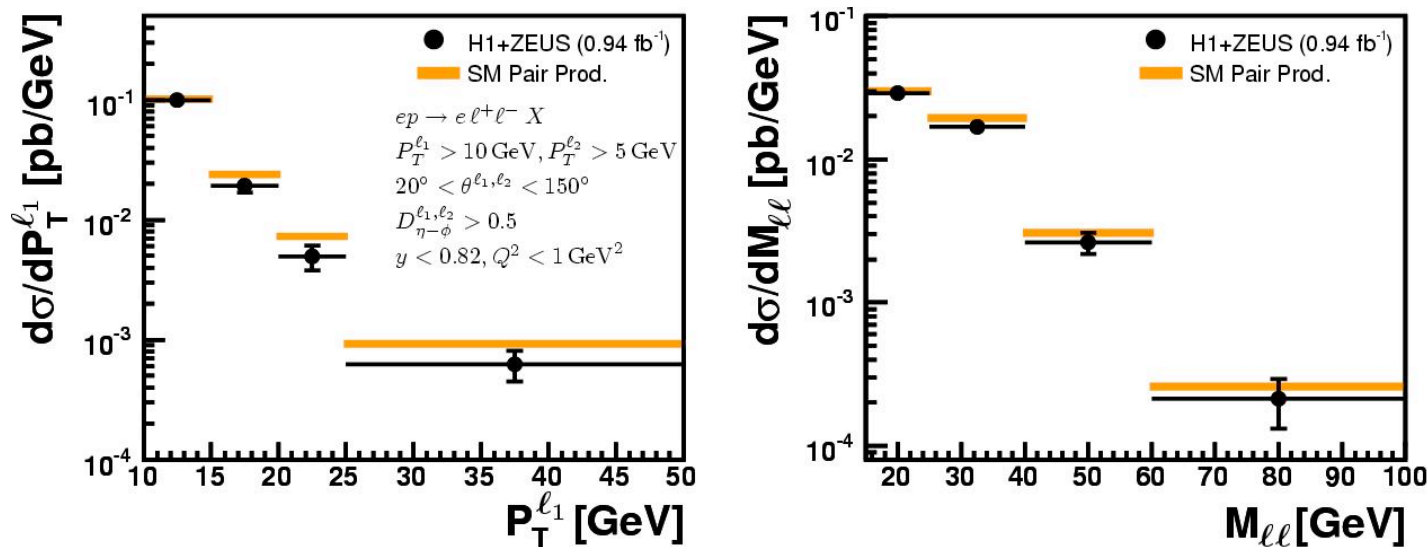
Multi-Leptons at HERA (0.94 fb⁻¹)

$\Sigma P_T > 100$ GeV				
Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p (0.56 fb ⁻¹)	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e^-p (0.38 fb ⁻¹)	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb ⁻¹)	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10

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

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 $0.66 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (sys.) pb}$ in good agreement with the SM prediction of $0.69 \pm 0.02 \text{ pb}$ from GRAPE

Full Set of Pair Production Diagrams in GRAPE

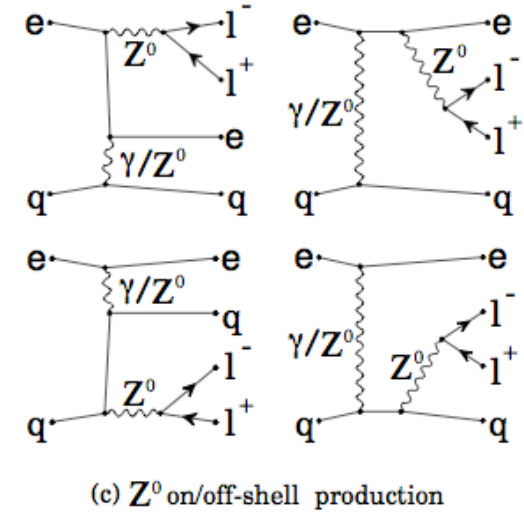
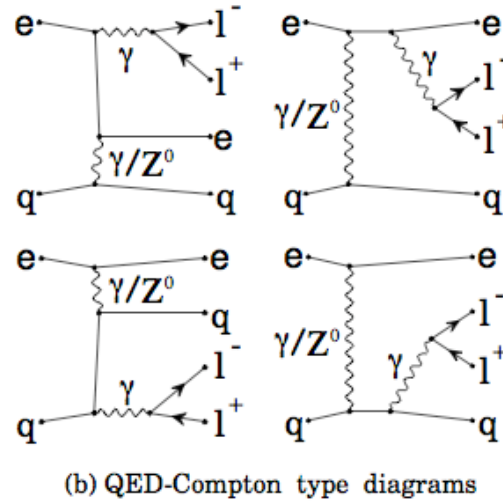
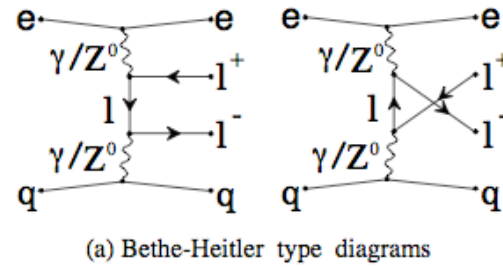
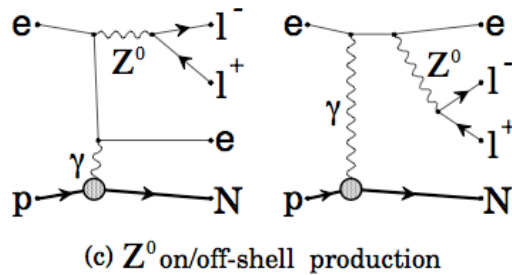
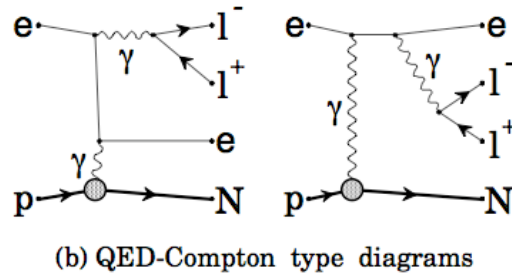
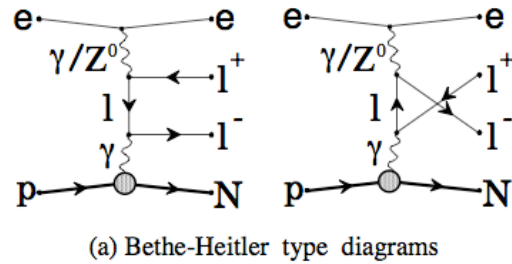


Fig. 2: Feynman diagrams included in the DIS process. $e=\{e^+, e^-\}$, $l^\pm=\{e^\pm, \mu^\pm, \tau^\pm\}$

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.