

# W production at HERA

**Amita Raval**

for the **H1** and **ZEUS** collaborations

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- Introduction: HERA, H1 and ZEUS
- Searches for isolated Leptons and missing  $P_T$ 
  - W cross section measurement
  - Limits on  $WW\gamma$  couplings
  - W polarization measurement
- Summary

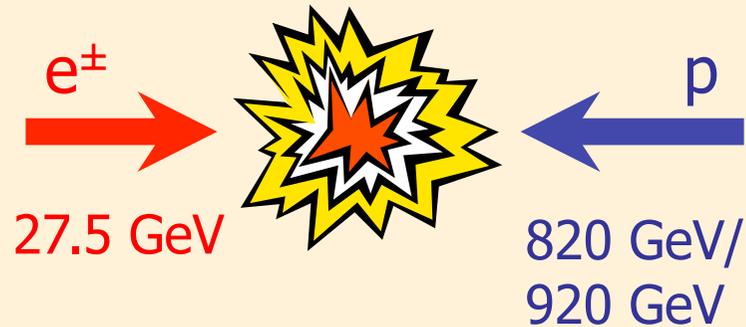
# HERA operation



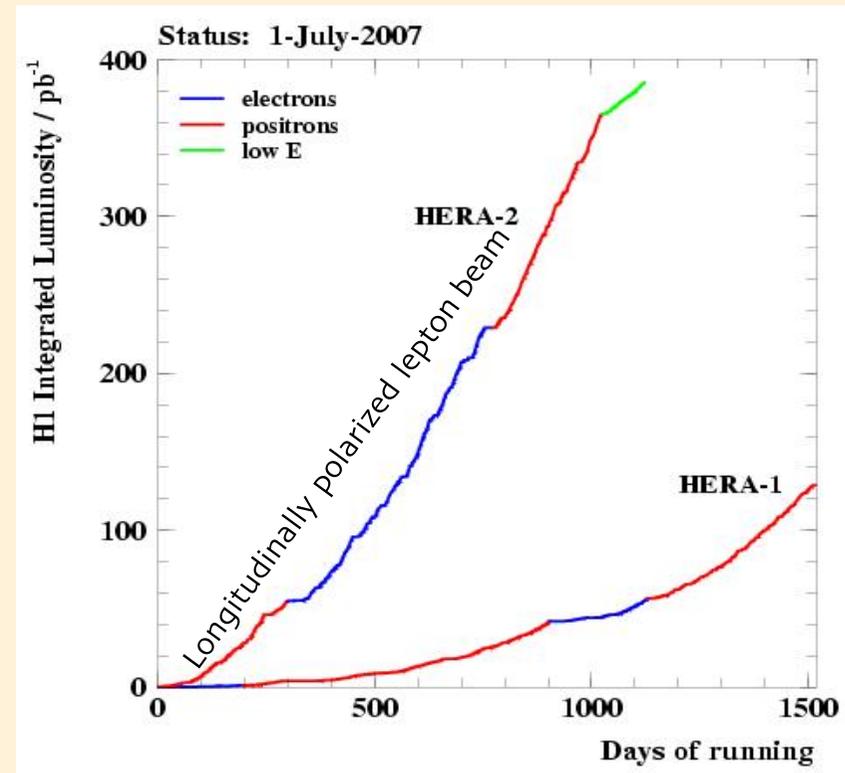
**HERA:** electron(positron)-proton collider at DESY, Hamburg  
delivered luminosity between 1992 and 2007

**H1, ZEUS:** two general-purpose detectors  
located at the ep interaction points

# HERA operation



$$\sqrt{s} = 300/318 \text{ GeV}$$



- Large increase in data per experiment from HERA II (x3)
- $\sim 20 \text{ pb}^{-1}$  from low & medium energy running ( $F_L$ )
- About  $0.5 \text{ fb}^{-1}$  of data collected by each experiment
- Balanced samples of  $e^+p$ ,  $e^-p$  data

Combination analysis presented utilizes the final dataset  $\sim 1 \text{ fb}^{-1}$

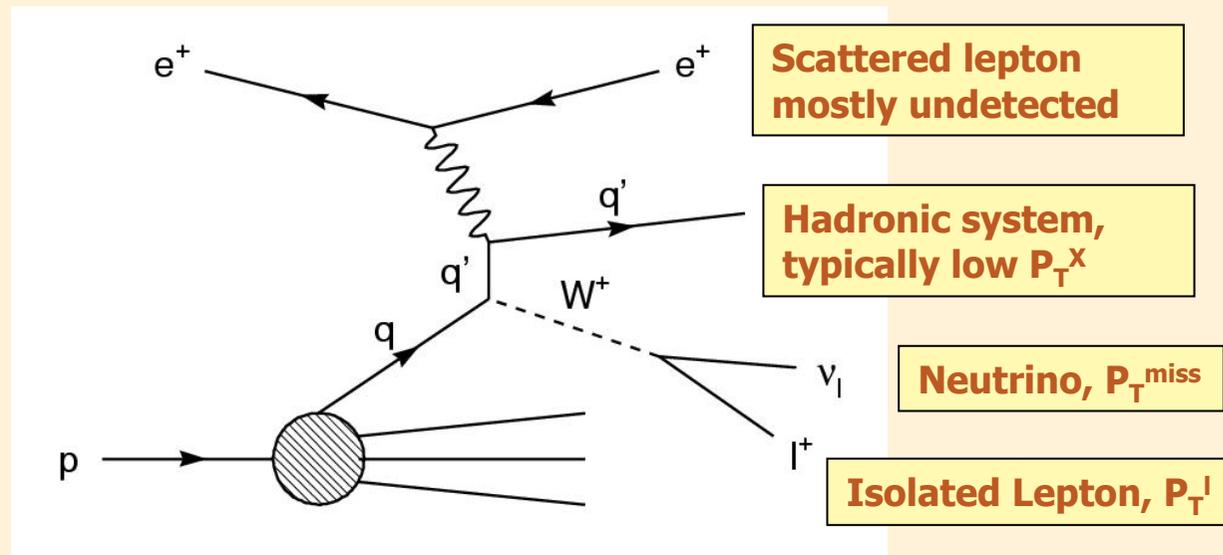
# Isolated-lepton searches at HERA: why?

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- HERA is an excellent testing ground for SM physics
  - QCD and also EW physics
- However in those corners of phase space where the SM expectation is small, it is also an excellent testing ground for physics beyond the SM
- Perhaps the most prominent example of this is the production of isolated leptons, both with and without accompanying jets
- The SM expectation for these processes (high mass, high  $P_T$ ) is extremely small - the entire HERA dataset contains only a handful of these events
- Any enhancement of these events would be a clear sign of new physics; else measure cross sections of rare processes

# SM processes with isolated leptons and $P_T^{\text{miss}}$

- The main SM process in ep interactions with a single, high- $P_T$  isolated lepton in coincidence with  $P_T^{\text{miss}}$  in the final state is single W production:



- Smaller additional contributions occur to the signal via the equivalent diagram in CC-DIS, as well as from  $Z^0$  production with decay to neutrinos
- Total cross section  $\sim 1.3$  pb, with 10% of W decays to each lepton flavour
- Modelled at HERA using EPVEC ( $ep \rightarrow eWX$ ) w/ NLO corr, uncertainty 15%
- Main SM backgrounds: NC-DIS, CC-DIS and lepton-pair production

# Events with isolated leptons and $P_T^{\text{miss}}$

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## Event topologies:

High- $P_T$  isolated-lepton events which have, in coincidence, large missing transverse momentum AND are accompanied by hadronic activity in the detector

- Provide clean, striking signals
- Excellent lepton ID and HFS reconstruction required

Since the SM expectation for these events at HERA (high mass, high  $P_T$ ) is low, **the analyses benefit from the combination of H1 and ZEUS data**

- provides increased sensitivity to possible new phenomena
- allows cross section measurement with better precision

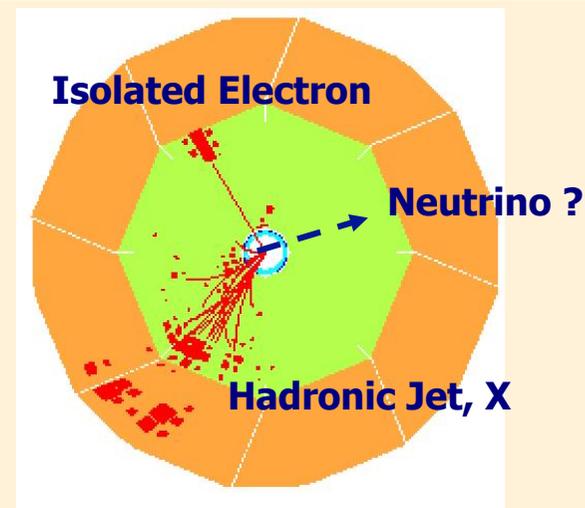
# Combined H1+ZEUS event selection

In events with **large missing  $P_T$** , require **high- $P_T$  lepton** (e or  $\mu$ ) in main body of the detector.

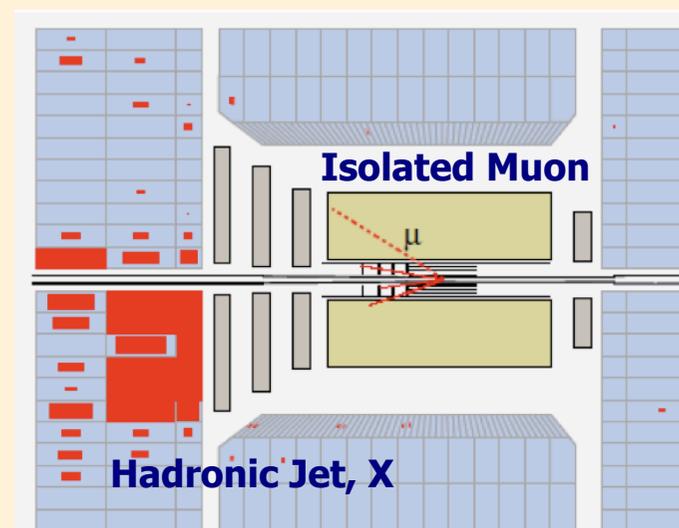
Common H1+ZEUS phase space:

- events with an e or  $\mu$  satisfying  $P_T > 10$  GeV,  $15^\circ < \theta < 120^\circ$  and  $P_T^{\text{Miss}} > 12$  GeV
- lepton to well isolated from nearest jet and track in event (mainly rejects CC events with a lepton in the jet)
- further cuts to reduce SM background (eg. rejecting back-to-back topologies removes NC, lepton-pairs)

Electron and muon channels are exclusive, and are combined, also in the cross section measurement

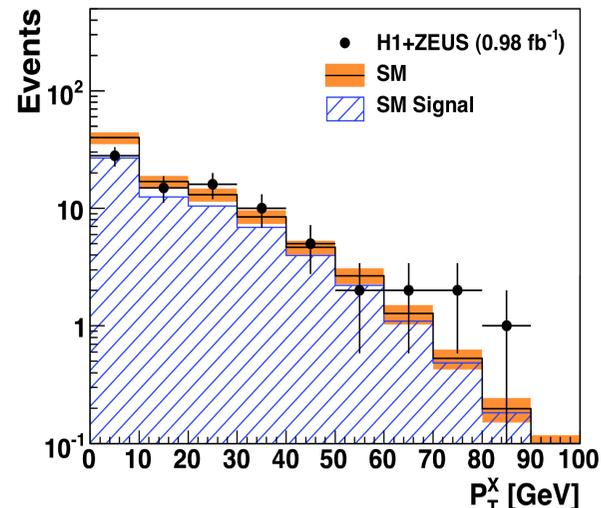
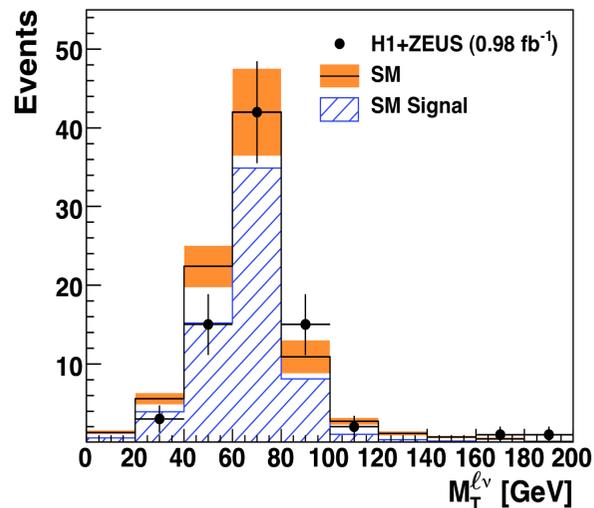
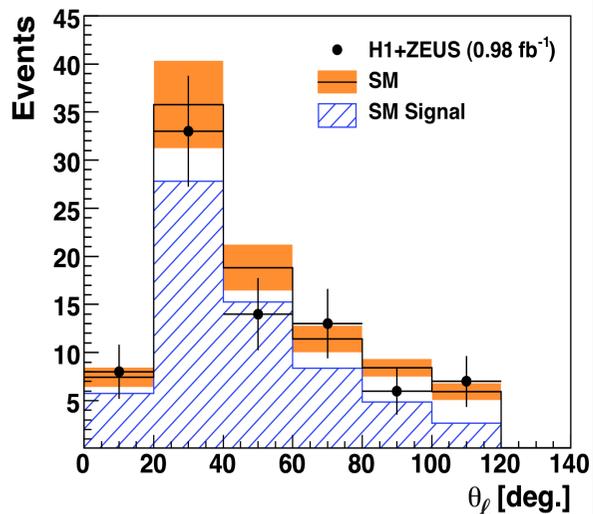


$e + P_T^{\text{Miss}}$  event in H1



$\mu + P_T^{\text{Miss}}$  event in ZEUS

# H1+ZEUS Isolated Leptons: results

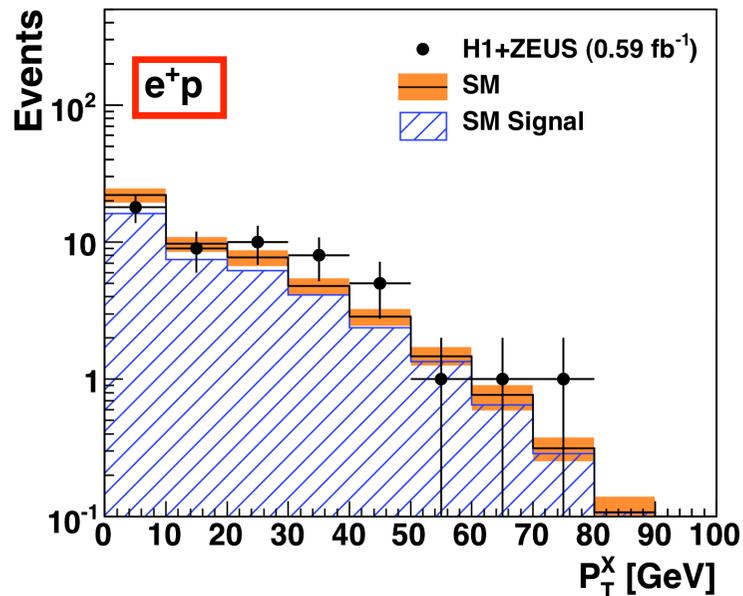


H1+ZEUS 1994–2007 $e^\pm p$ 0.98 fb <sup>-1</sup>		Data	SM Expectation		SM Signal		Other SM Processes	
Electron	Total	61	69.2	± 8.2	48.3	± 7.4	20.9	± 3.2
	$P_T^X > 25$ GeV	16	13.0	± 1.7	10.0	± 1.6	3.1	± 0.7
Muon	Total	20	18.6	± 2.7	16.4	± 2.6	2.2	± 0.5
	$P_T^X > 25$ GeV	13	11.0	± 1.6	9.8	± 1.6	1.2	±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

Overall,  
good  
agreement  
with SM  
prediction

... except  
for at high  
 $P_T^X$

# H1+ZEUS Isolated Leptons: positron data

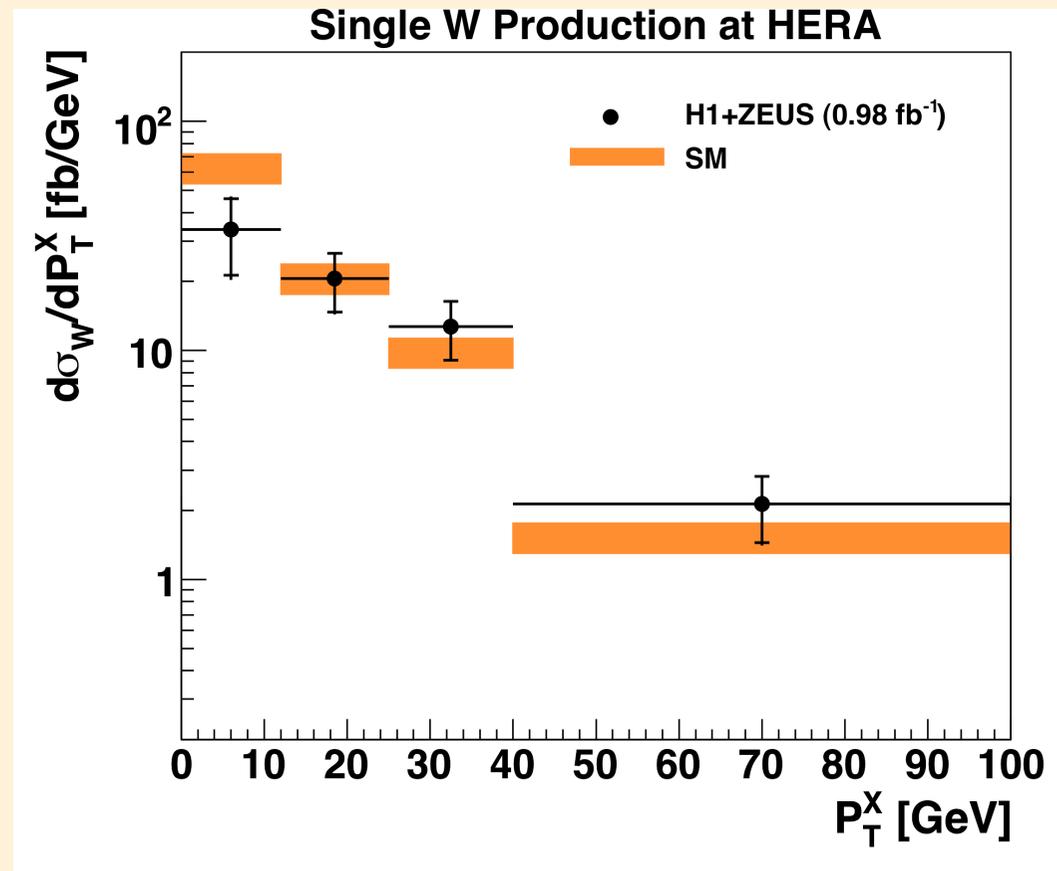


- Excess of data events seen in published H1 analysis at large  $P_T^X$ , an area of phase space where the SM expectation is small  
**- this is not confirmed in the ZEUS analysis**
- Small excess remains in the common phase space of the combination analysis  
**- but still driven by the H1 data (17 events)**

H1+ZEUS 1994–2007 $e^+p$ 0.59 fb <sup>-1</sup>		Data	SM Expectation	SM Signal	Other SM 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

# Single W-production cross section

- Measurement of the Single W cross section performed in the common phase space
- Branching ratio of W decays to leptons used to calculate the full W production cross section
- Measurement done differentially as a function of hadronic transverse momentum,  $P_T^X$ 
  - 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



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

# Intermezzo

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Recap: I have shown the combined H1 + ZEUS search for isolated leptons with missing  $P_T$  in **e,  $\mu$  channels** using  $\sim 1 \text{ fb}^{-1}$

## What about tau leptons?

If lepton universality holds, the same rate of tau leptons is expected from SM processes. (In many new physics scenarios, an enhanced rate of tau leptons is expected).

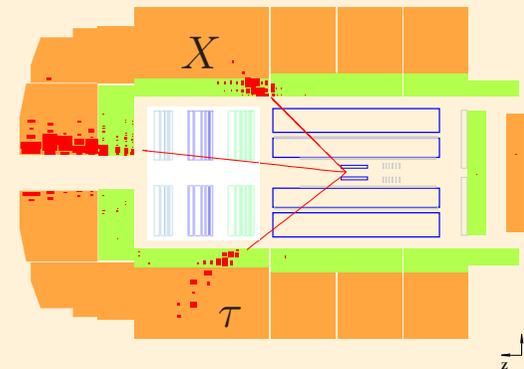
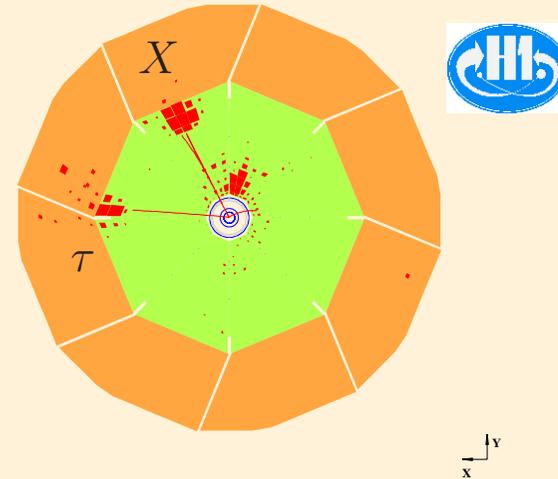
**H1 have conducted a search for isolated tau leptons** using  $1 \text{ fb}^{-1}$  (previously performed by both H1 and ZEUS)

Eur. Phys. J. C48 (2006) 699

Phys. Lett. B 583 (2004) 41

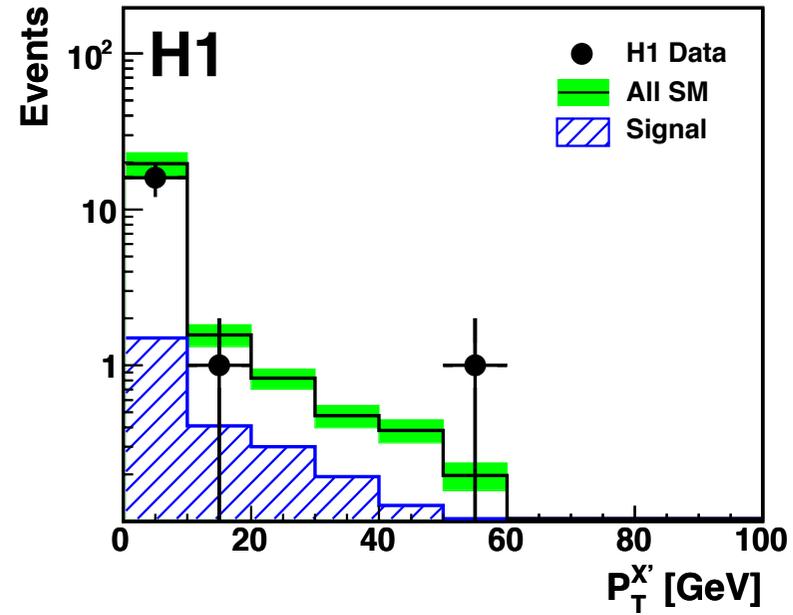
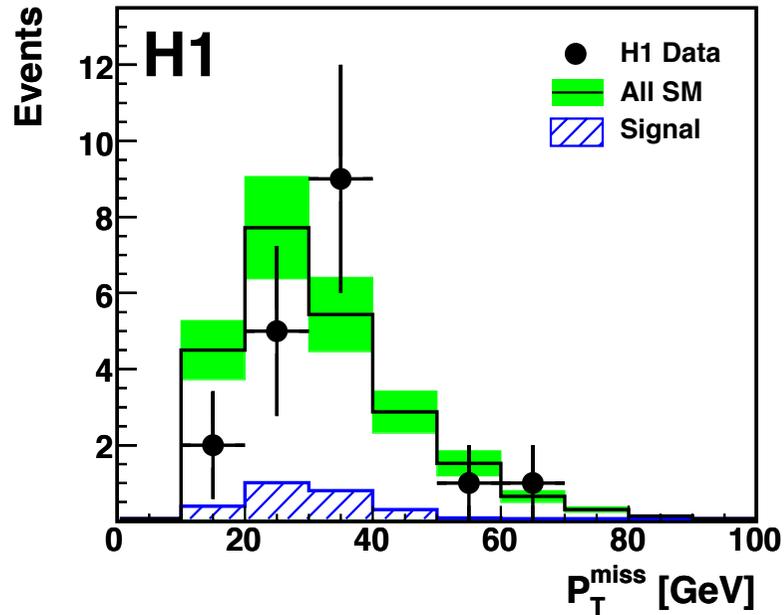
# H1 analysis of Isolated Tau-Leptons

- Look for events with  $P_T^{\text{miss}}$  and narrow jets from hadronic decay
- Signature: 1-prong tau decay (decays with one-charged hadron 45% branching ratio)
  - 1 charged track (the “prong”)
  - narrow, pencil-like jet
- Events with tau-like jet satisfying  $P_T > 7 \text{ GeV}$ ,  $20^\circ < \theta < 120^\circ$  and  $P_T^{\text{Miss}} > 12 \text{ GeV}$



Run 417955 Event 105857

# H1 analysis of Isolated Tau-Leptons

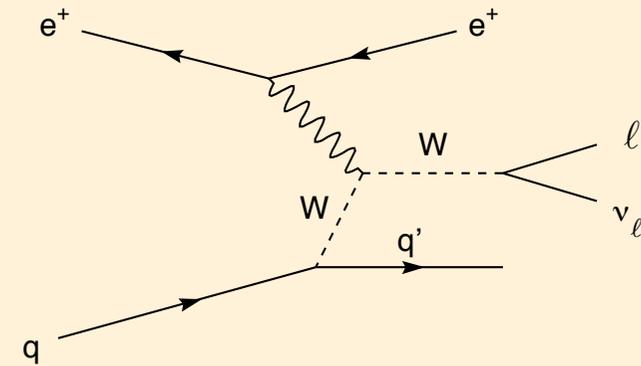


<b>H1</b>	Tau Channel	Data	SM Expectation	SM Signal	Other SM Processes
1994-2007 $e^+p$	Total	9	12.3 ± 2.0	1.66 ± 0.25	10.6 ± 1.8
291 pb <sup>-1</sup>	$P_T^X > 25$ GeV	0	0.82 ± 0.12	0.38 ± 0.06	0.44 ± 0.06
1999-2006 $e^-p$	Total	9	11.0 ± 1.9	1.00 ± 0.15	10.0 ± 1.8
183 pb <sup>-1</sup>	$P_T^X > 25$ GeV	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 <sup>-1</sup>	$P_T^X > 25$ GeV	1	1.50 ± 0.21	0.59 ± 0.09	0.91 ± 0.12

- Good overall agreement with the SM prediction
- Expectation dominated by CC background (challenging hadronic environment; signal contribution 11%)

# Limits on $WW\gamma$ coupling parameters: I

- Production of W bosons at HERA is sensitive to anomalous triple gauge couplings
- $WW\gamma$  vertex can be parametrized using 2 free parameters,  $\Delta\kappa$ ,  $\lambda$



## Magnetic dipole moment:

$$\mu_W = e/2M_W (1 + \kappa + \lambda)$$

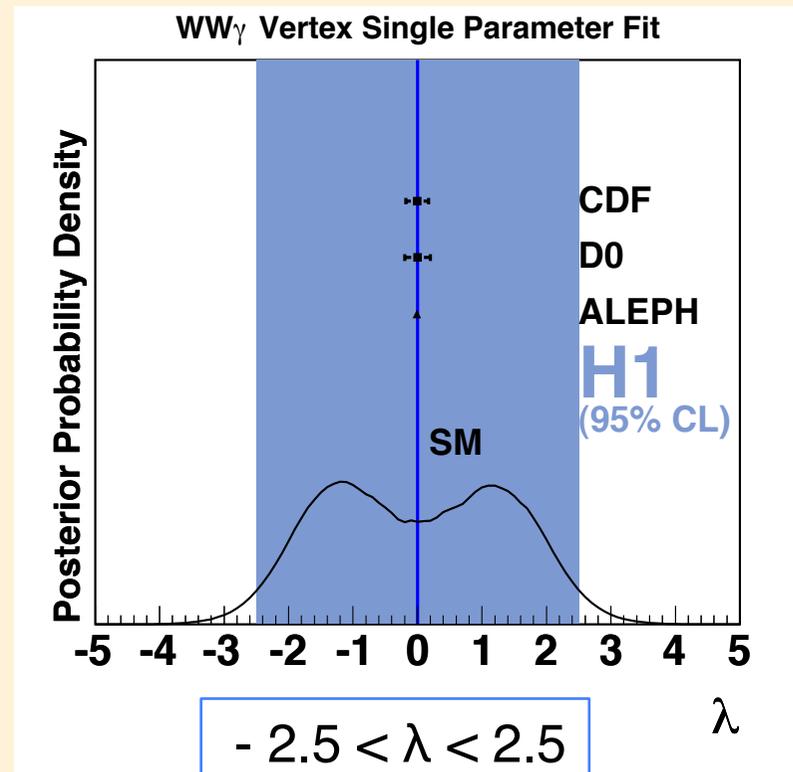
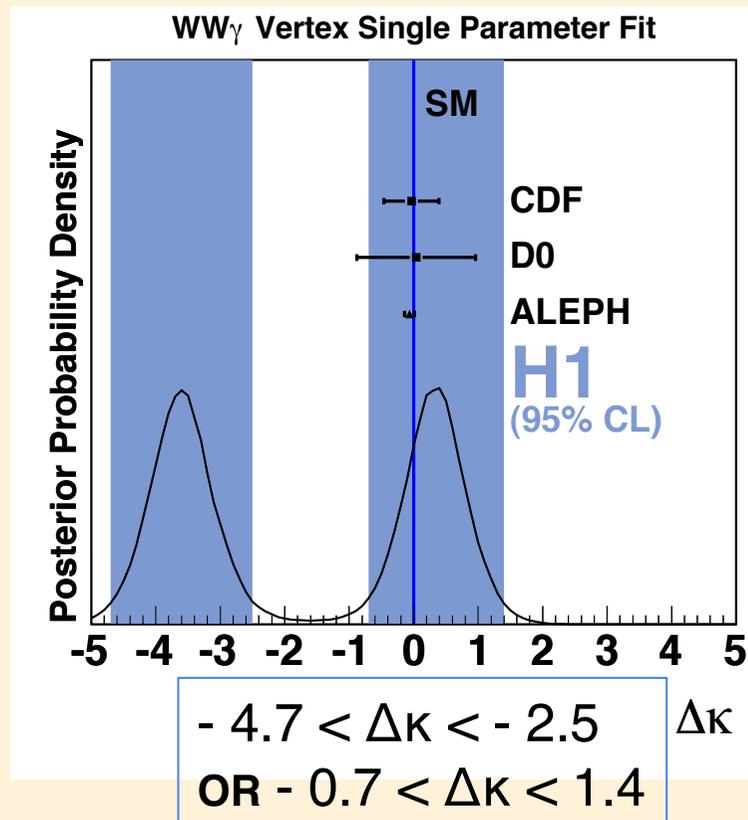
## Electric quadrupole moment:

$$Q_W = -e/M_W^2 (\kappa - \lambda)$$

## In the SM, $\kappa=1$ and $\lambda=0$ at tree level

- Upper limits are set on  $\kappa$ ,  $\lambda$ :
  - using method of maximum likelihood
  - in a Bayesian approach
  - employing Poisson statistics
  - instead of  $\kappa$ ,  $\Delta\kappa=\kappa-1$  is used such that **any non-zero value for  $\Delta\kappa$  or  $\lambda$  represents a deviation from the SM**

# Limits on $WW\gamma$ coupling parameters: II



NB: the double peak structure in the probability densities arise from the quadratic dependence of the cross section to the coupling parameters

$\Delta\kappa = -1$  excluded with 95% confidence level →  
demonstration of presence of a magnetic coupling of  $\gamma$  along w/ coupling to electric charge of the W boson

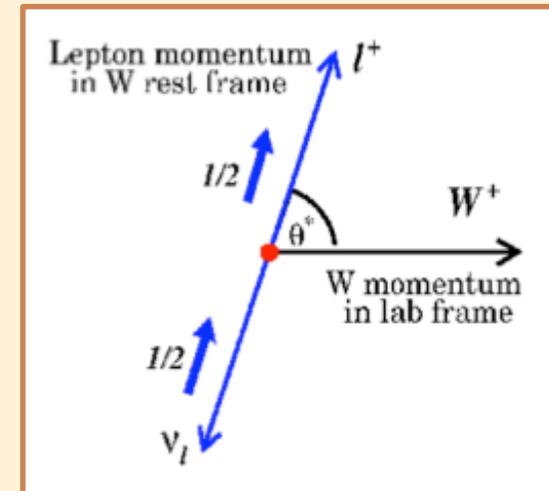
H1 measurements compatible to W production at other colliders

# Measurement of W polarization fractions: I

Measure for single W production and test with anomalous top production model

- May be different for SM and BSM contributions

W cross section can be expressed in terms of W polarization fractions: **sensitive to angular properties of the decay** → measure cross section as function of  $\cos\theta^*$

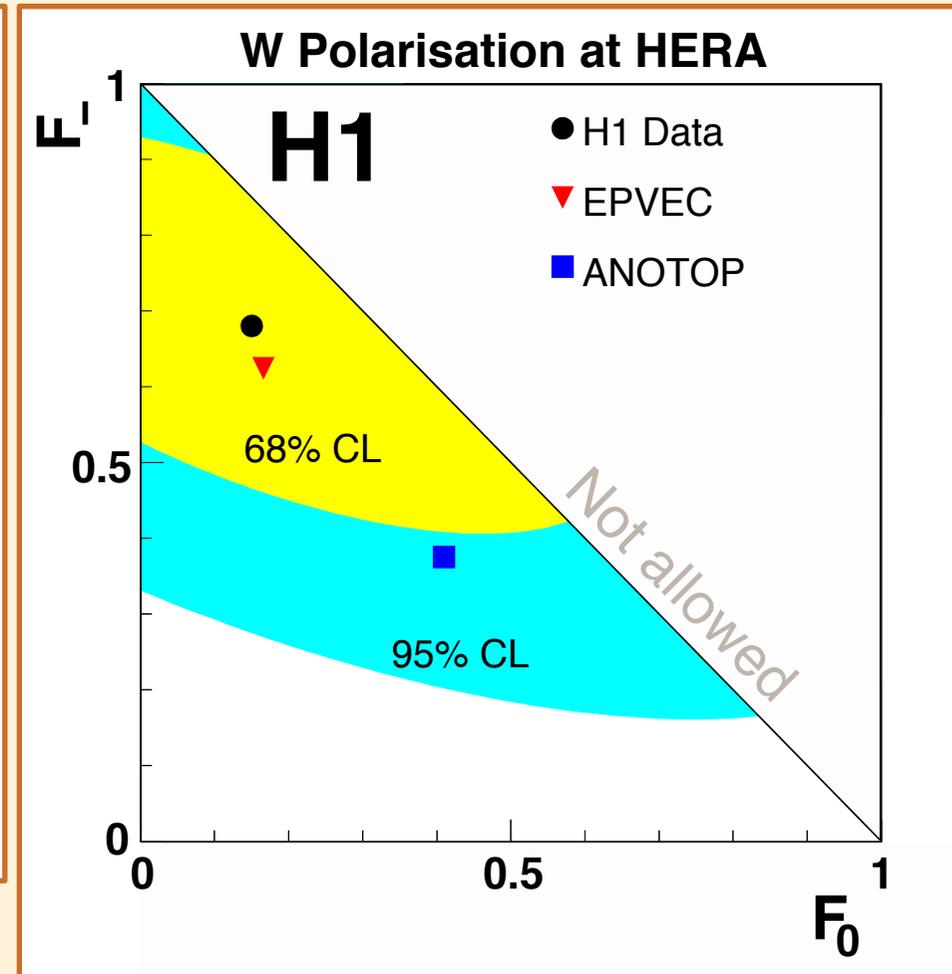
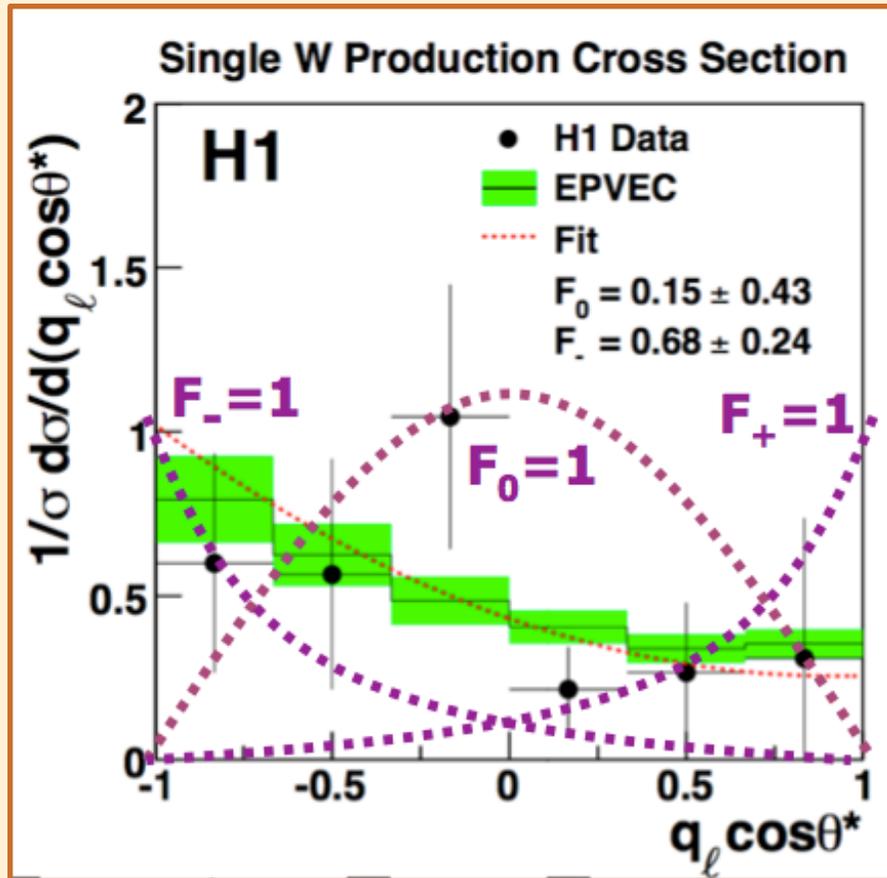


$$\frac{1}{\sigma_{W \rightarrow \ell + \nu}} \frac{d\sigma_{W \rightarrow \ell + \nu}}{d\cos\theta^*} = \frac{3}{4}F_0 (1 - \cos^2\theta^*) + \frac{3}{8}F_- (1 - \cos\theta^*)^2 + \frac{3}{8}F_+ (1 + \cos\theta^*)^2$$

$F_+$ : Right-handed  
 $F_-$ : Left-handed  
 $F_0$ : Longitudinal polarization fractions

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

# Measurement of W polarization fractions: II



$F_0$  and  $F_-$  are simultaneously extracted in fit  
**Sensitivity only at the 1  $\sigma$  level**

# Summary

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- A search for events with isolated leptons and missing  $P_T$  has been performed by H1 and ZEUS using the full HERA I + II dataset, luminosity  $\sim 1 \text{ fb}^{-1}$
- In general, the SM prediction describes data well;
  - a few interesting events remain at high  $P_T$  and high mass in the  $e^+p$  HERA data in the combination analysis where the SM expectation is low
- Single W cross section has been measured  
 $\sigma_W = 1.06 \pm 0.16 \text{ (stat.)} \pm 0.07 \text{ (sys.) pb}$ , cf  $1.26 \pm 0.19 \text{ pb}$  from SM
- The H1 limits on  $WW\gamma$  coupling parameters  $\Delta\kappa$ ,  $\lambda$  are compatible with W production at other colliders

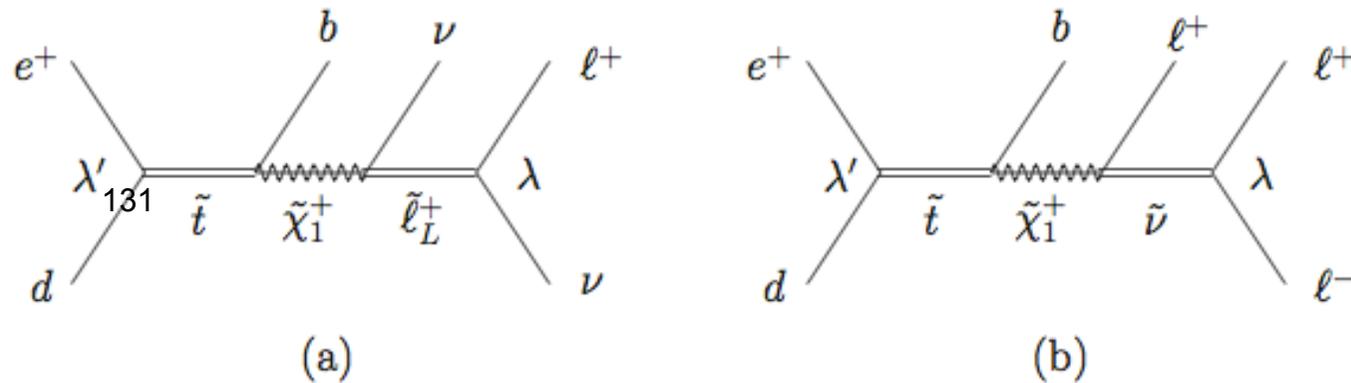
**Final word on these subjects from HERA!**

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More fun stuff...

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# Why $e^+p$ : Squarks in RPV SUSY?

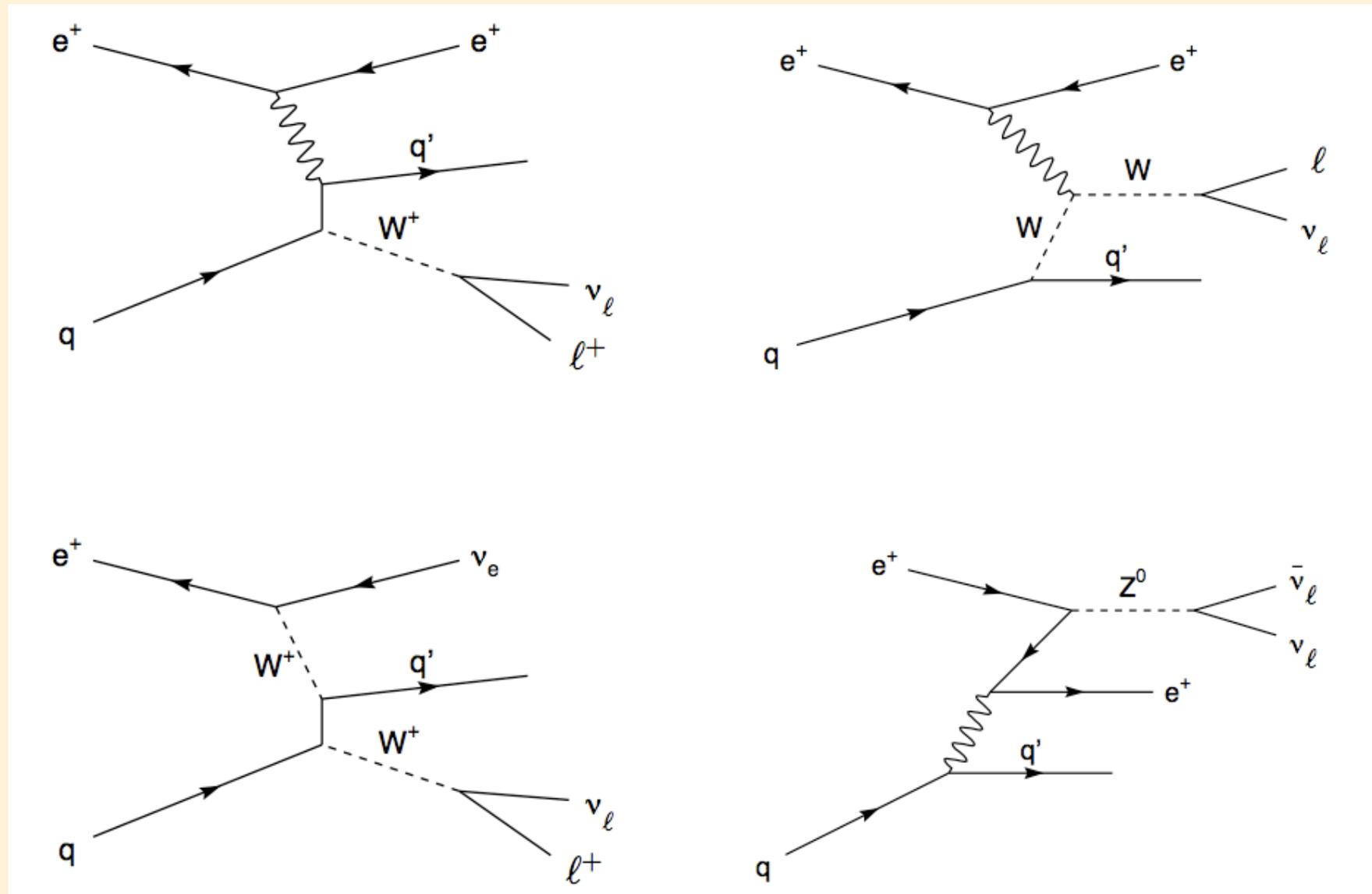


**Figure 1:** *Supersymmetric R-parity violating interactions generating isolated lepton events*

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

DESY 06-238  
IFT-06/027  
MZ-TH/06-28  
hep-ph/0612302

# Isolated leptons + $P_T^{\text{Miss}}$ : signal diagrams



# Isolated leptons: event selection (H1+ZEUS)

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	$< 3$	-

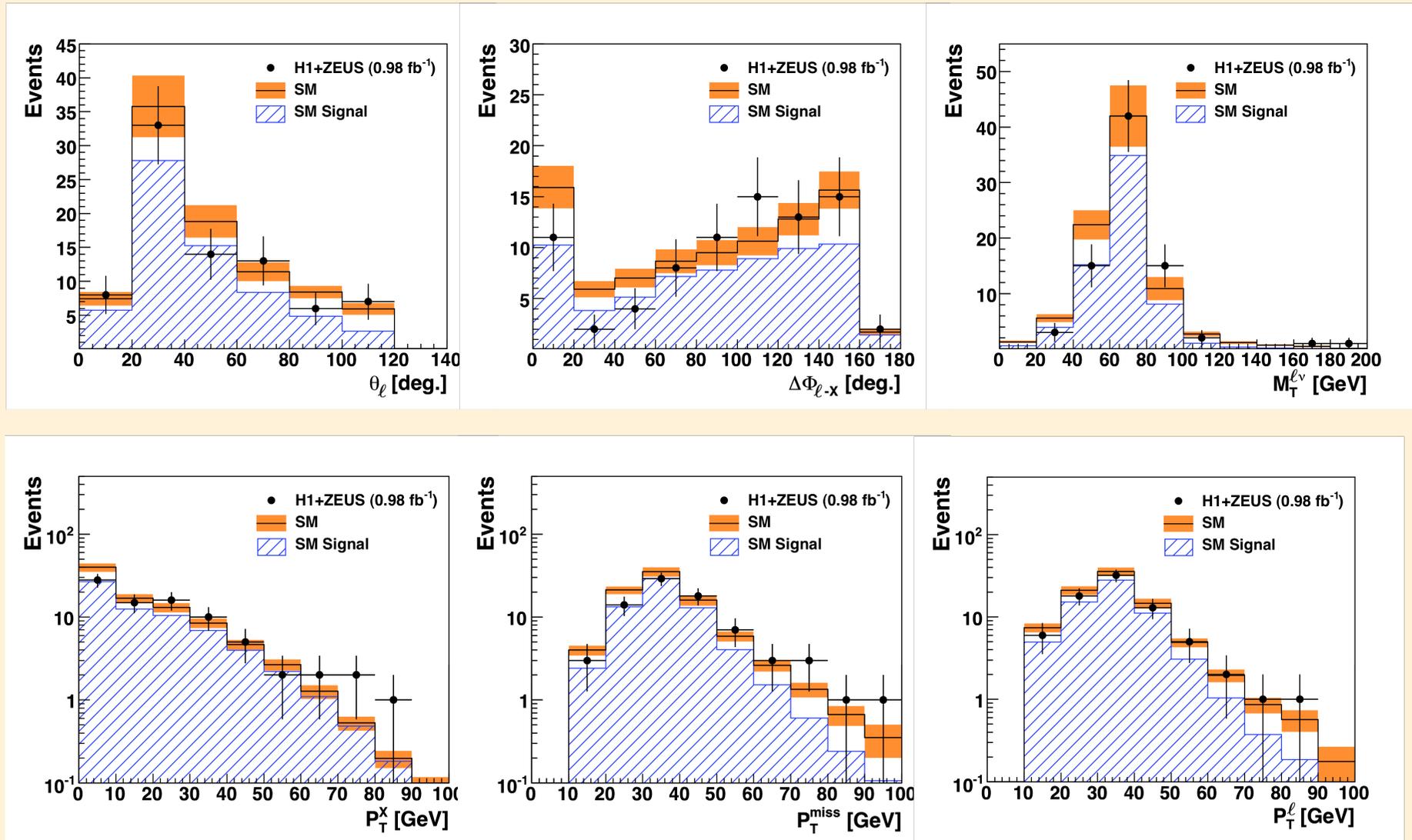
Major difference to H1 nominal analysis

Analysis phase space selection

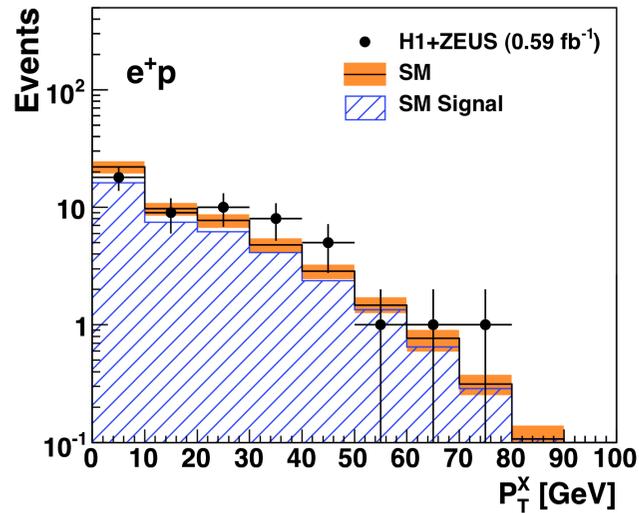
Isolation of lepton

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

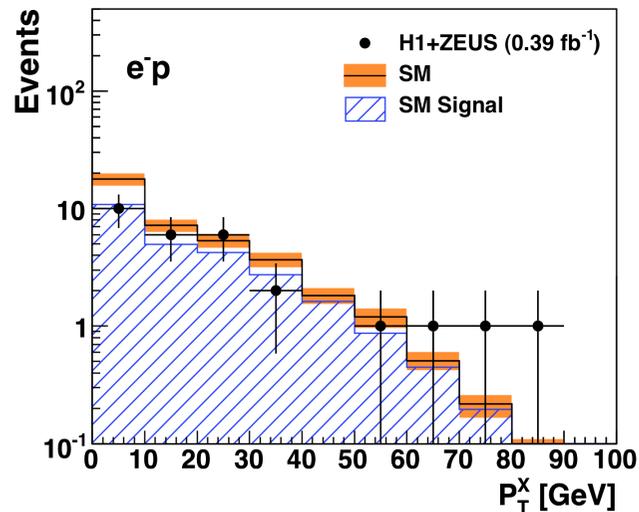
# Isolated leptons: all distributions (H1+ZEUS)



# Isolated leptons: $e^+p$ and $e^-p$ (H1+ZEUS)



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

# Isolated leptons: $W$ cross sections (H1+ZEUS)

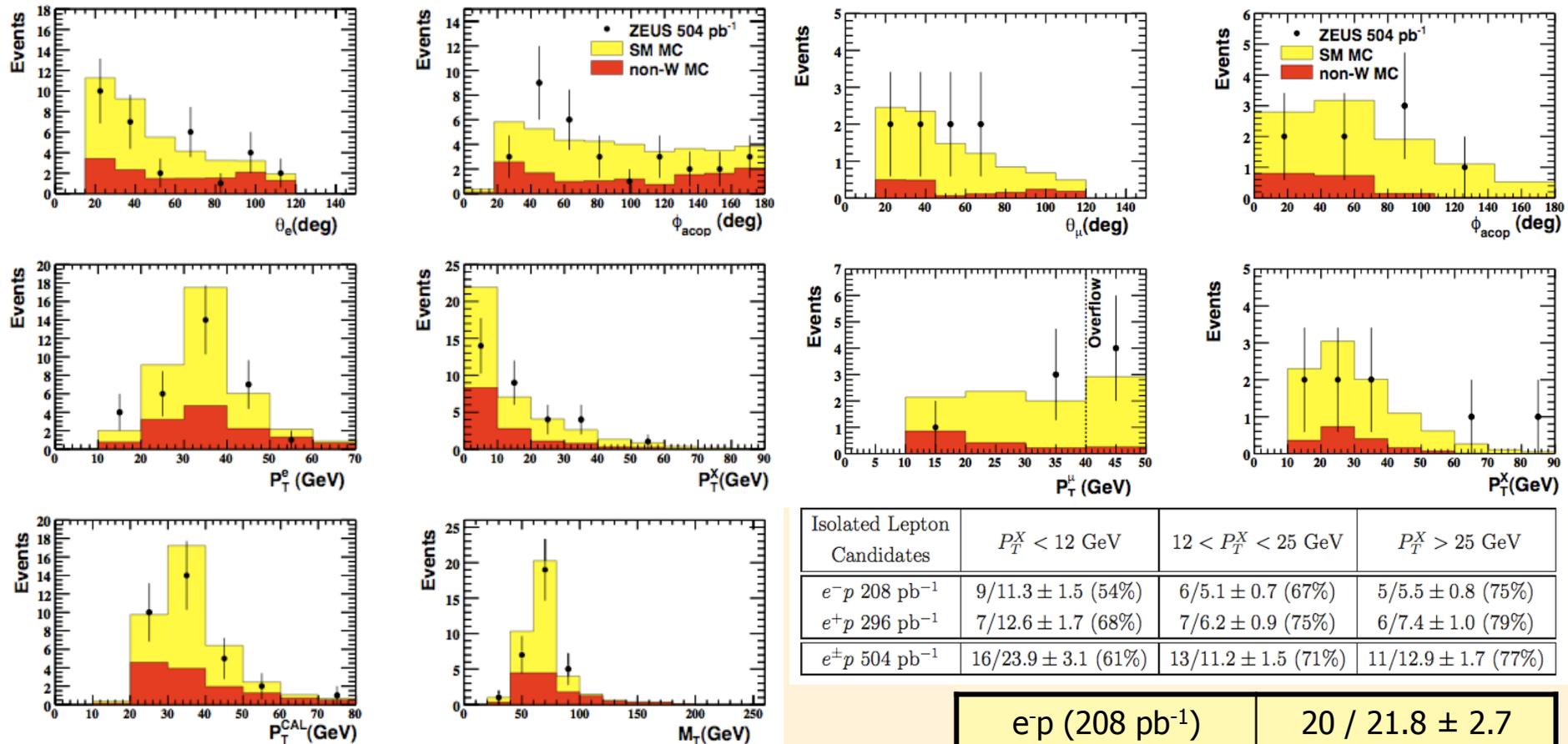
<b>H1+ZEUS Differential Single <math>W</math> Production Cross Section</b>		
$P_T^X$ [GeV]	Measured $\pm$ stat. $\pm$ sys. [fb / GeV]	SM NLO [fb / GeV]
0 – 12	$33.6 \pm 12.3 \pm 5.0$	$62.7 \pm 9.4$
12 – 25	$20.6 \pm 6.0 \pm 1.9$	$20.7 \pm 3.1$
25 – 40	$12.7 \pm 3.6 \pm 1.0$	$9.8 \pm 1.5$
40 – 100	$2.1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

# Isolated leptons: published results (ZEUS)

Phys. Lett. B 672 (2009) 106

electron channel

muon channel



Isolated Lepton Candidates	$P_T^X < 12$ GeV	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
$e^-p$ 208 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 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 pb $^{-1}$	16/23.9 $\pm$ 3.1 (61%)	13/11.2 $\pm$ 1.5 (71%)	11/12.9 $\pm$ 1.7 (77%)

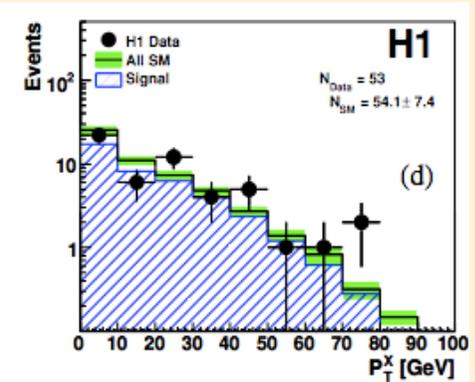
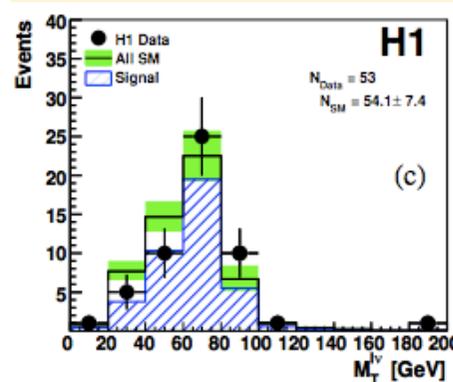
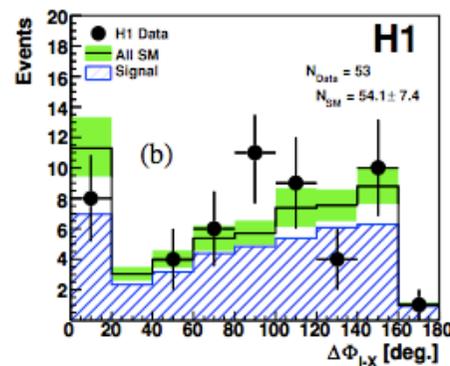
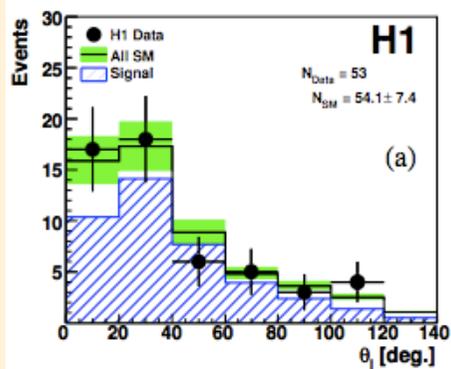
$e^-p$ (208 pb $^{-1}$ )	20 / 21.8 $\pm$ 2.7
$e^+p$ (296 pb $^{-1}$ )	20 / 26.2 $\pm$ 3.2
$e^\pm p$ (504 pb $^{-1}$ )	40 / 48.0 $\pm$ 5.9

$$\sigma_{ep \rightarrow lWX} = 0.89_{-0.22}^{+0.25} \text{ (stat.)} \pm 0.10 \text{ (syst.) pb}$$

SM cross section: 1.2 pb

# Isolated leptons: published results (H1)

Eur. Phys. J. C64 (2009) 251



Main difference to combined H1+ZEUS analysis: **extended polar angle range down to 5°**

<b>H1</b>	1994-2007 $e^\pm p$	Data	SM	SM	Other SM
	474 pb <sup>-1</sup>		Expectation	Signal	Processes
Electron	Total	39	43.1 ± 6.0	30.3 ± 4.8	12.9 ± 3.4
	$P_T^X > 25$ 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
	$P_T^X > 25$ 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
	$P_T^X > 25$ GeV	18	13.6 ± 2.2	11.4 ± 1.9	2.18 ± 0.80

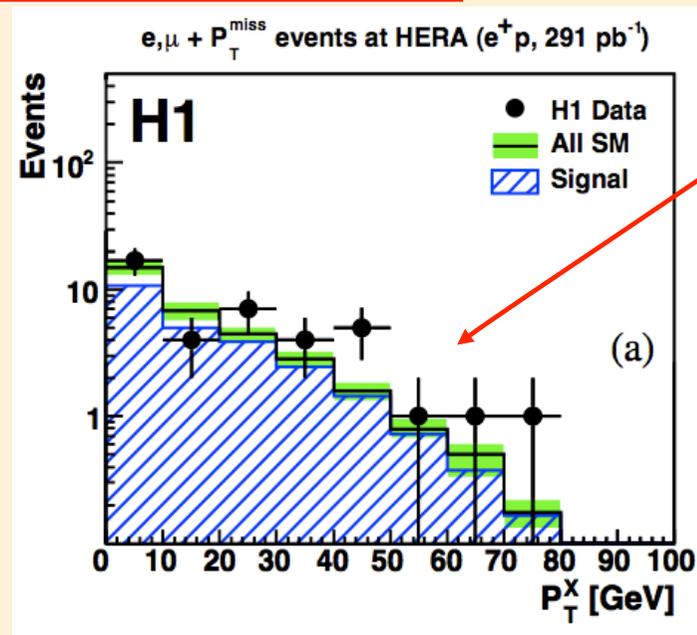
$$\sigma_W = 1.14 \pm 0.25 \text{ (stat.)} \pm 0.14 \text{ (sys.) pb}$$

$$\text{SM cross section: } 1.27 \pm 0.19 \text{ pb}$$

# Isolated leptons: published results, $e^+p$ data (H1)

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

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# Isolated leptons: Tau channel (H1)

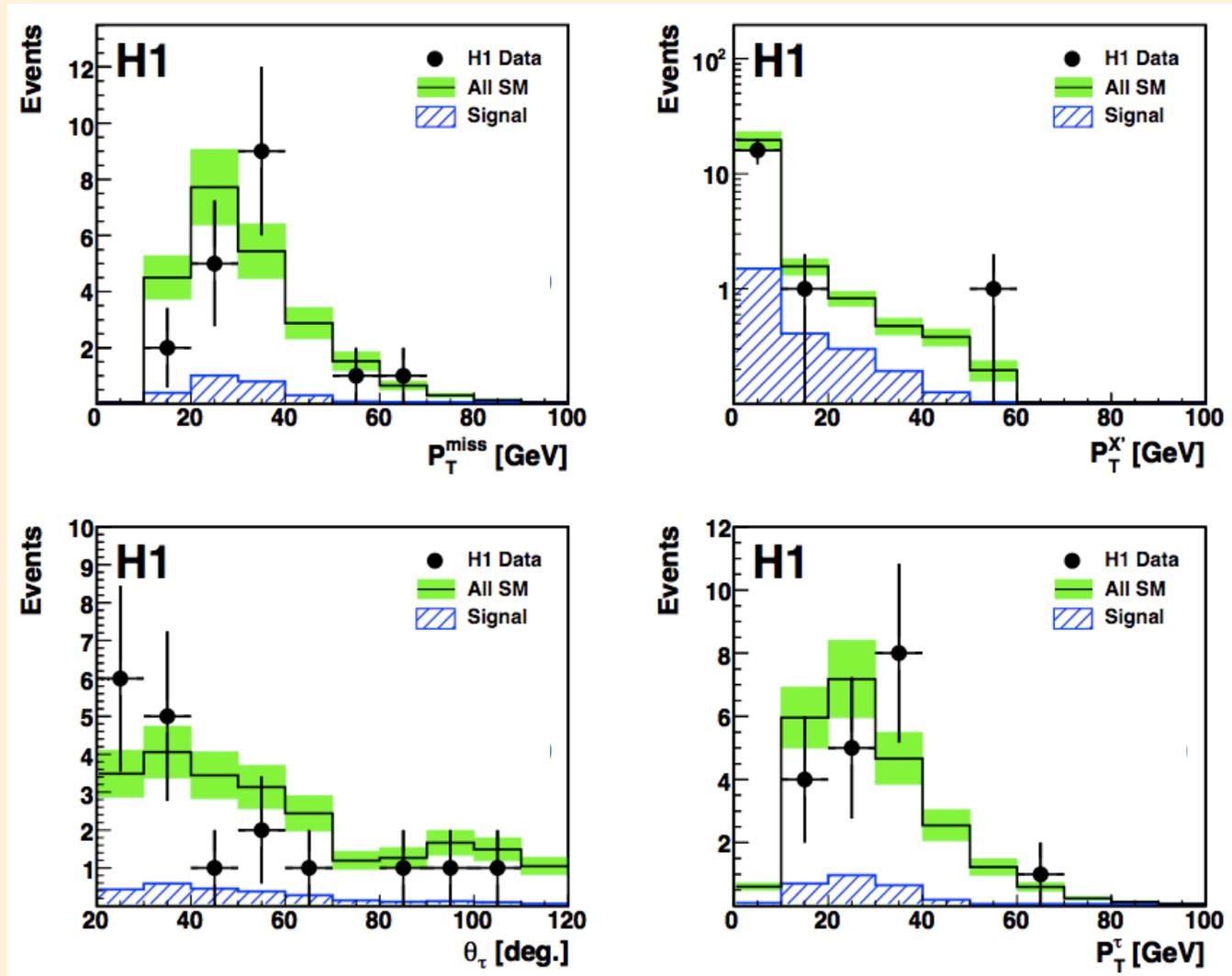
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- Look for hadronic 1-prong tau decays in events with  $P_T^{\text{Miss}}$
- Topology is challenging, unlike electron and muon channels the SM expectation is dominated by background (mainly CC)

<b>H1</b>	Tau Channel	Data	SM Expectation	SM Signal	Other SM Processes
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

# Isolated leptons: Tau channel (H1)

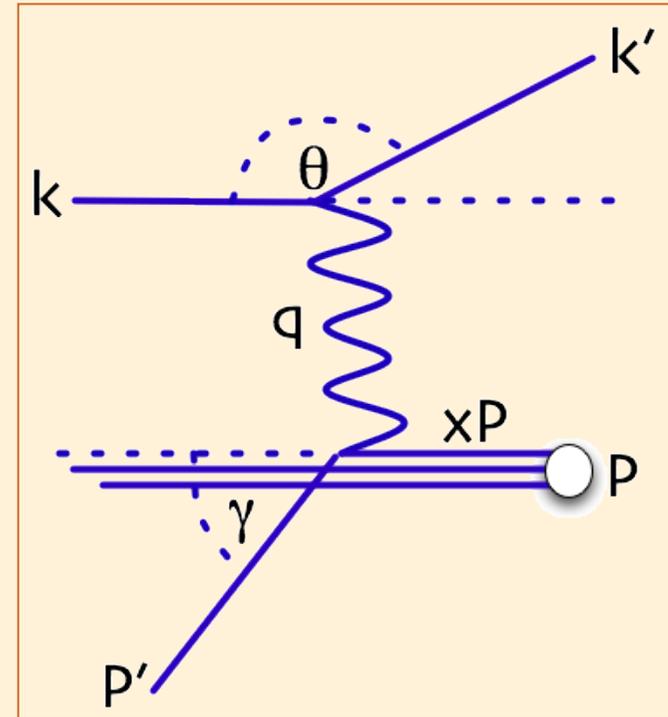
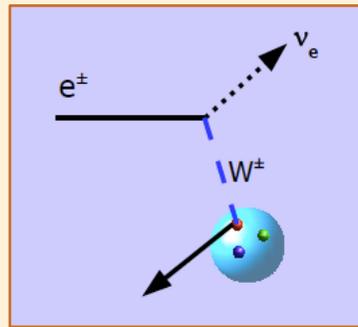
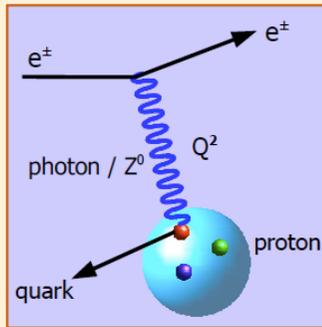
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# Deep inelastic e±p scattering: basics

Two deep inelastic scattering processes:

- Neutral current: exchange of  $\gamma$  or  $Z^0$
- Charged current: exchange of  $W^\pm$



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

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$s = (p + k)^2$$

$$Q^2 = x \cdot y \cdot s$$

- $Q^2$  is probing power
- $x$  is Bjorken scaling var.
- $y$  is inelasticity of  $e$
- $s$  is CME