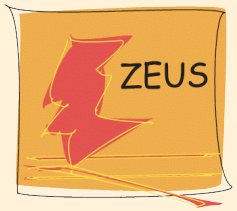


W production at HERA

Amita Raval
for the **H1** and **ZEUS** collaborations

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

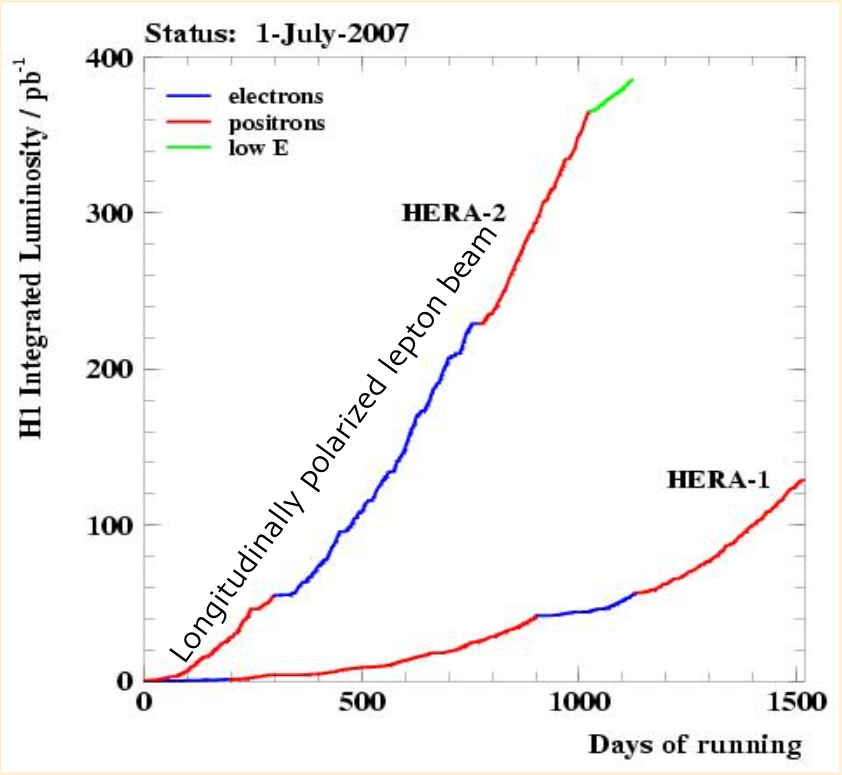
HERA operation

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 GeV



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

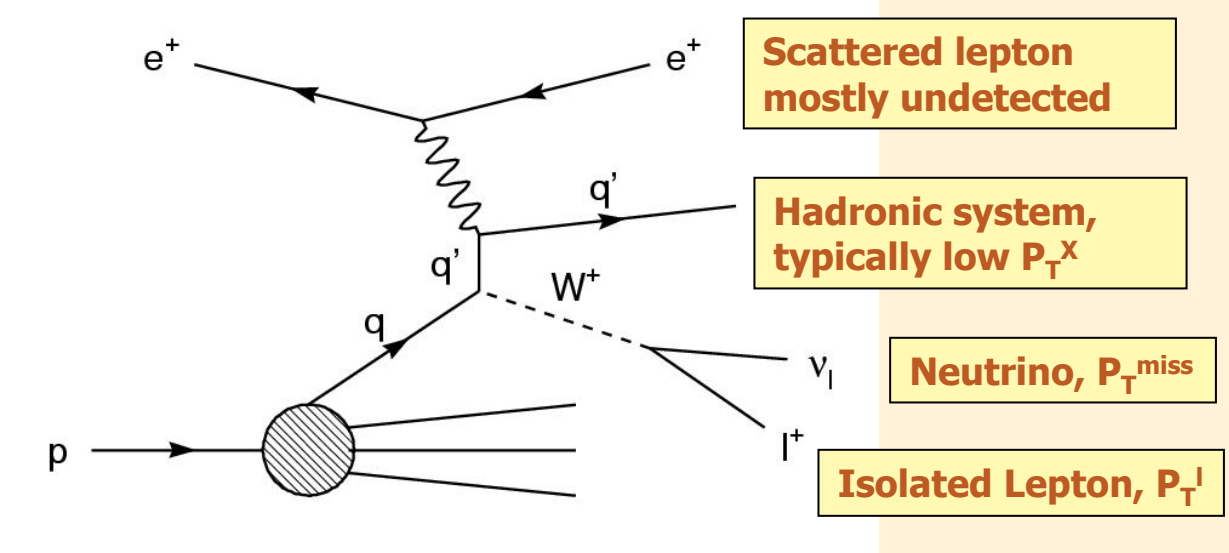
Combination analysis presented utilizes the final dataset ~ 1 fb^{-1}

Isolated-lepton searches at HERA: why?

- 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^{miss}

- The main SM process in ep interactions with a single, high-P_T isolated lepton in coincidence with P_T^{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^O production with decay to neutrinos

- Total cross section ~ 1.3 pb, with 10% of W decays to each lepton flavour
- Modelled at HERA using EPVEC (ep->eWX) w/ NLO corr, uncertainty 15%
- Main SM backgrounds: NC-DIS, CC-DIS and lepton-pair production

Events with isolated leptons and P_T^{miss}

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

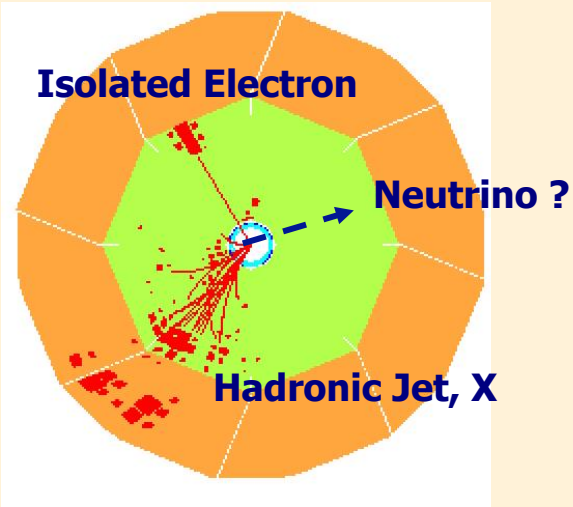
- provides increased sensitivity to possible new phenomena
- allows cross section measurement with better precision

Combined H1+ZEUS event selection

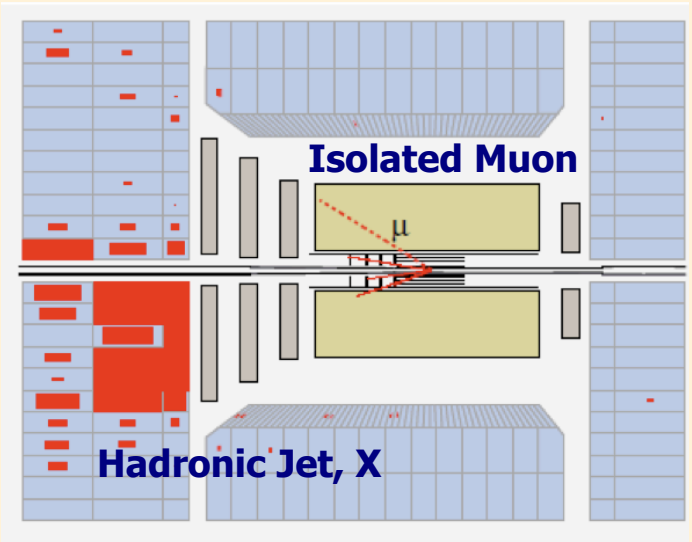
In events with large missing P_T, require high-P_T lepton (e or μ) in main body of the detector.
Common H1+ZEUS phase space:

- events with an e or μ satisfying P_T>10 GeV, $15^O<\theta<120^O$ and P_T^{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

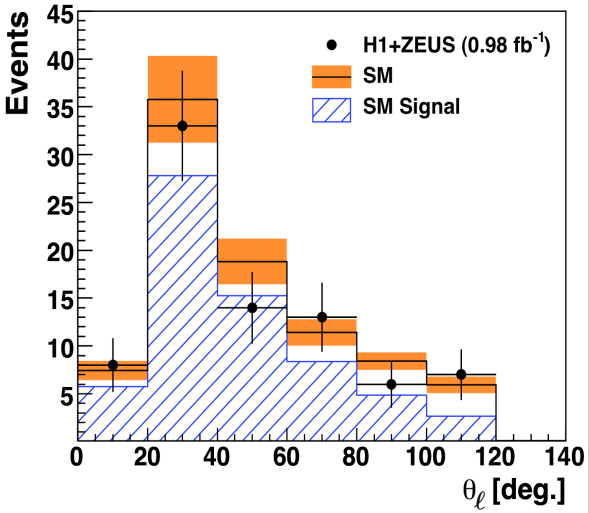


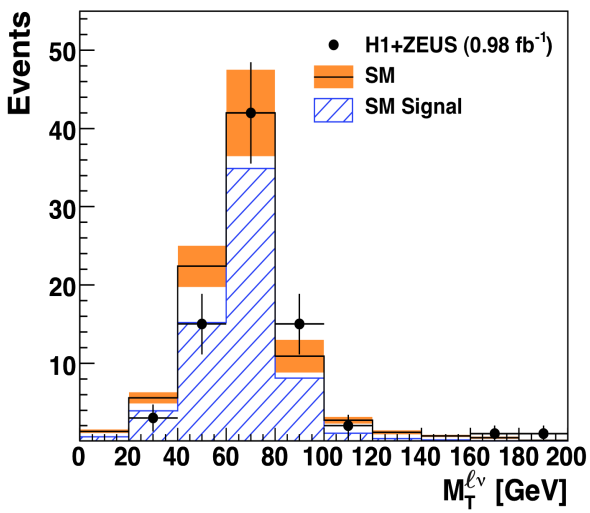
e + P_T^{Miss} event in H1

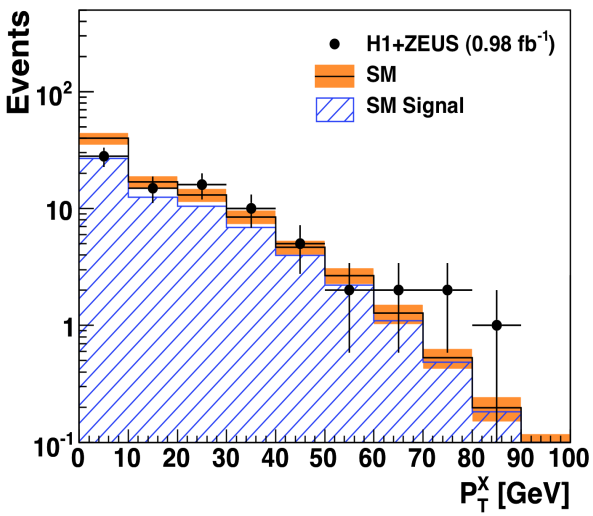


μ + P_T^{Miss} event in ZEUS

H1+ZEUS Isolated Leptons: results





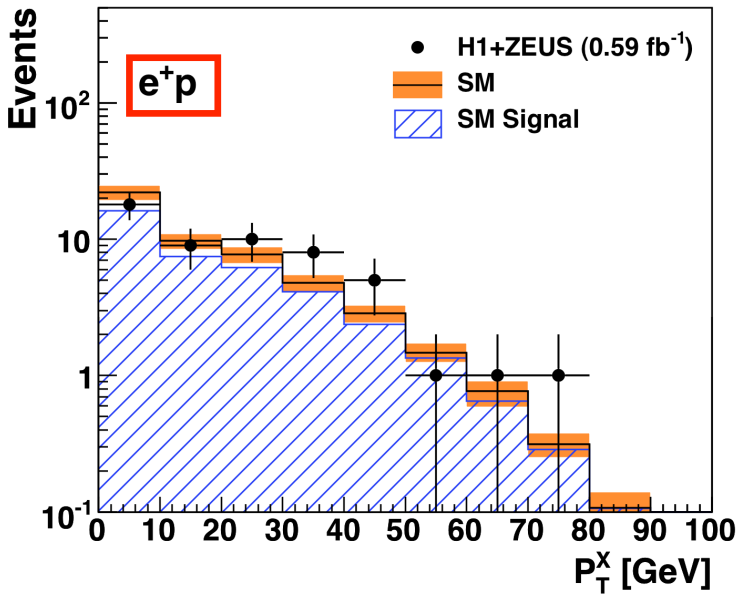


H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	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

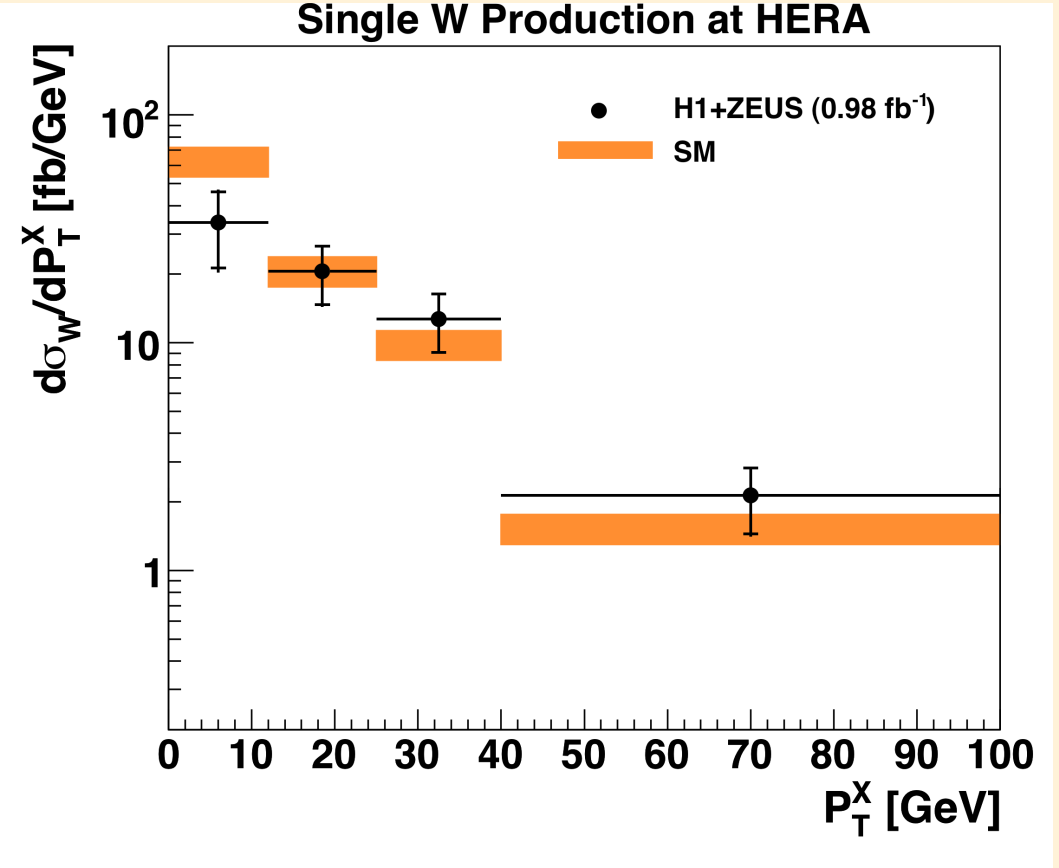


- Excess of data events seen in published H1 analysis at large P_T^X, an area of phase space where the SM expectation is small
  - this is not confirmed in the ZEUS analysis
- Small excess remains in the common phase space of the combination analysis
  - but still driven by the H1 data (17 events)

H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		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 ±0.16 (stat.) ± 0.07 (sys.) pb** in good agreement with the SM prediction of 1.26 ± 0.19 pb from EPVEC at NLO

Intermezzo

Recap: I have shown the combined H1 + ZEUS search for isolated leptons with missing P_T in **e, μ channels using ~ 1 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 fb^{-1} (previously performed by both H1 and ZEUS)

Eur. Phys. J. C48 (2006) 699

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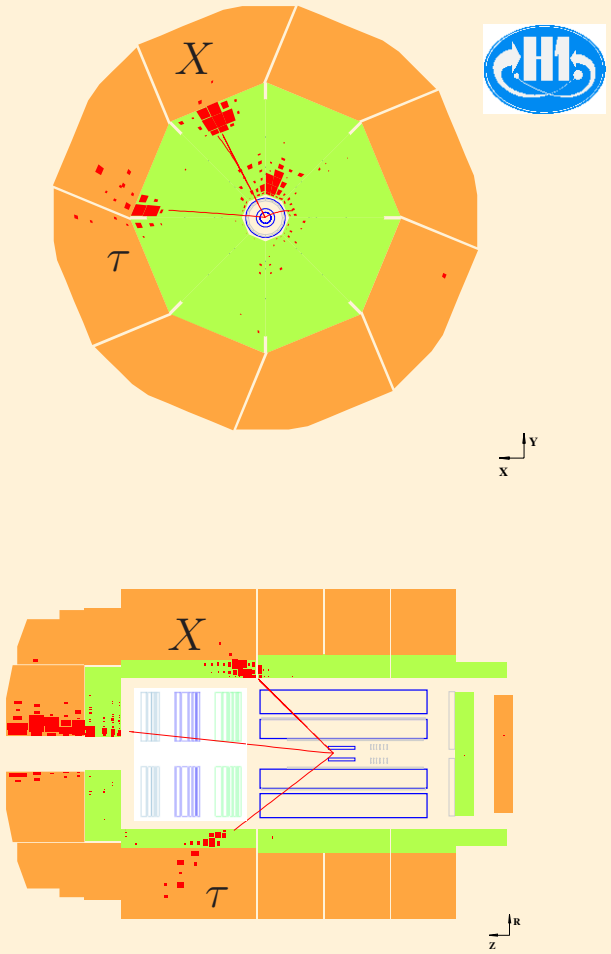
H1 analysis of Isolated Tau-Leptons

- Look for events with P_T^{miss} and narrow jets from hadronic decay

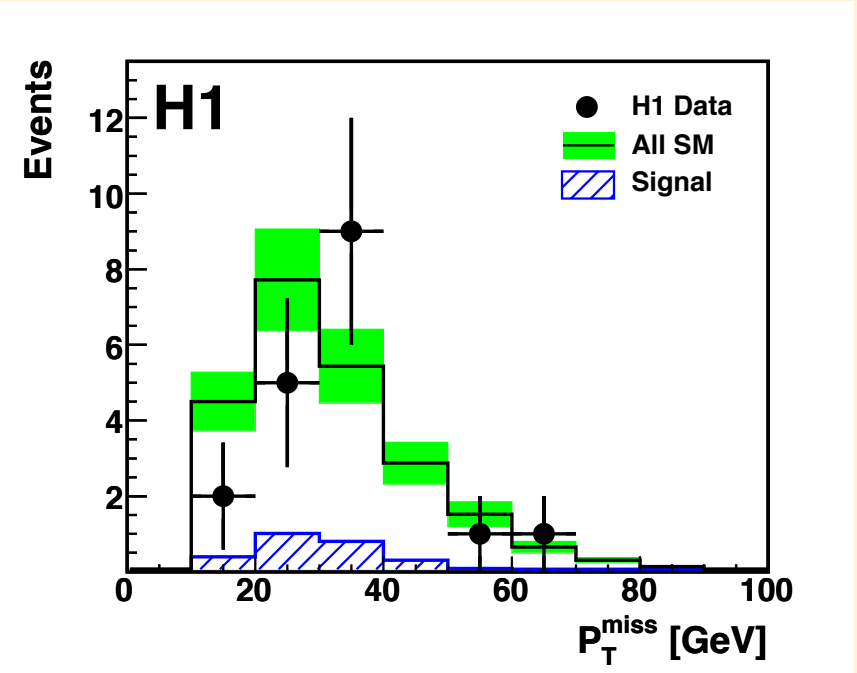
- Signature: 1-prong tau decay (decays with one-charged hadron 45% branching ratio)
  - 1 charged track (the “prong”) narrow, pencil-like jet

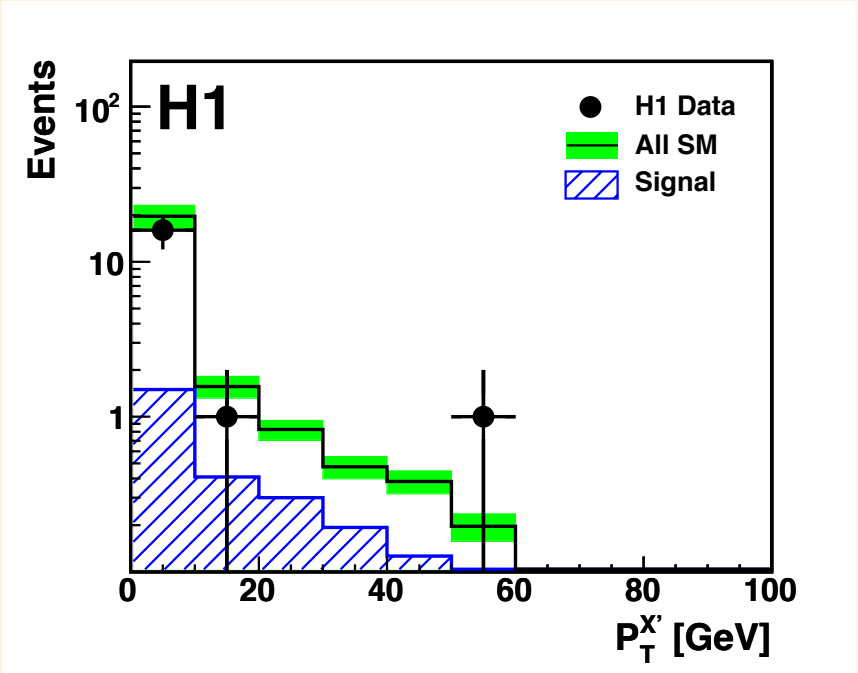
- Events with tau-like jet satisfying $P_T>7$ GeV, $20^O<\theta<120^O$ and $P_T^{Miss}>12$ GeV



Run 417955 Event 105857

H1 analysis of Isolated Tau-Leptons



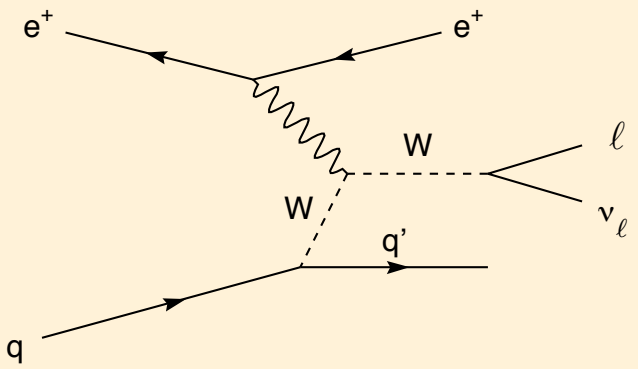


H1	Tau Channel	Data	SM Expectation	SM Signal	Other SM Processes
1994-2007 e^+p	Total	9	12.3 ± 2.0	1.66 ± 0.25	10.6 ± 1.8
291 pb^{-1}	$P_T^X > 25$ GeV	0	0.82 ± 0.12	0.38 ± 0.06	0.44 ± 0.06
1999-2006 e^-p	Total	9	11.0 ± 1.9	1.00 ± 0.15	10.0 ± 1.8
183 pb^{-1}	$P_T^X > 25$ GeV	1	0.68 ± 0.11	0.21 ± 0.03	0.47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

- Production of W bosons at HERA is sensitive to anomalous triple gauge couplings



- WWγ vertex can be parametrized using 2 free parameters, Δκ, λ

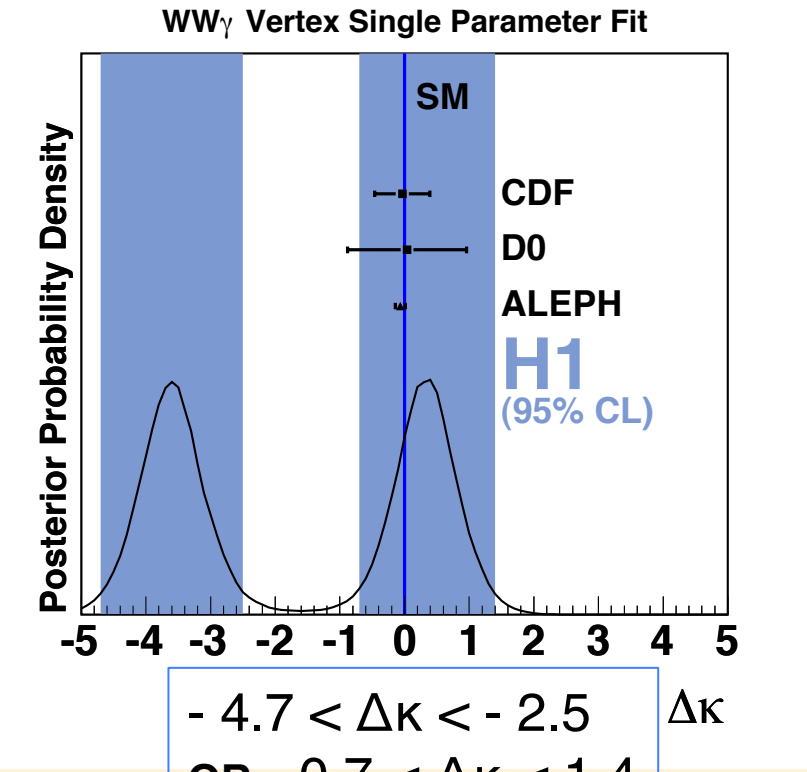
Magnetic dipole moment:
$\mu_W = e/2M_W (1 + \kappa + \lambda)$

Electric quadrupole moment:
$Q_W = -e/M_W^2 (\kappa - \lambda)$

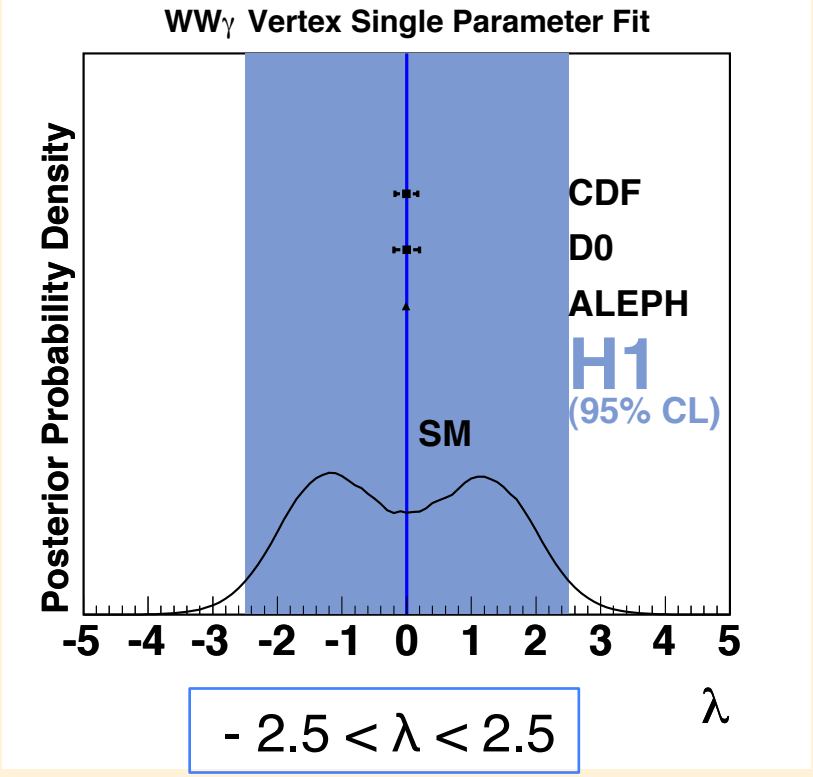
In the SM, κ=1 and λ=0 at tree level

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

Limits on WWγ coupling parameters: II



- 4.7 < Δκ < - 2.5
OR - 0.7 < Δκ < 1.4



- 2.5 < λ < 2.5

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

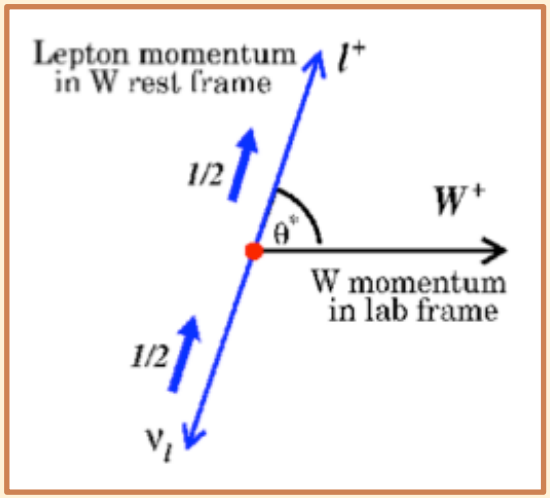
Δκ = -1 excluded with 95% confidence level →
demonstration of presence of a magnetic coupling of γ along w/ coupling to electric charge of the W boson

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 cosθ*

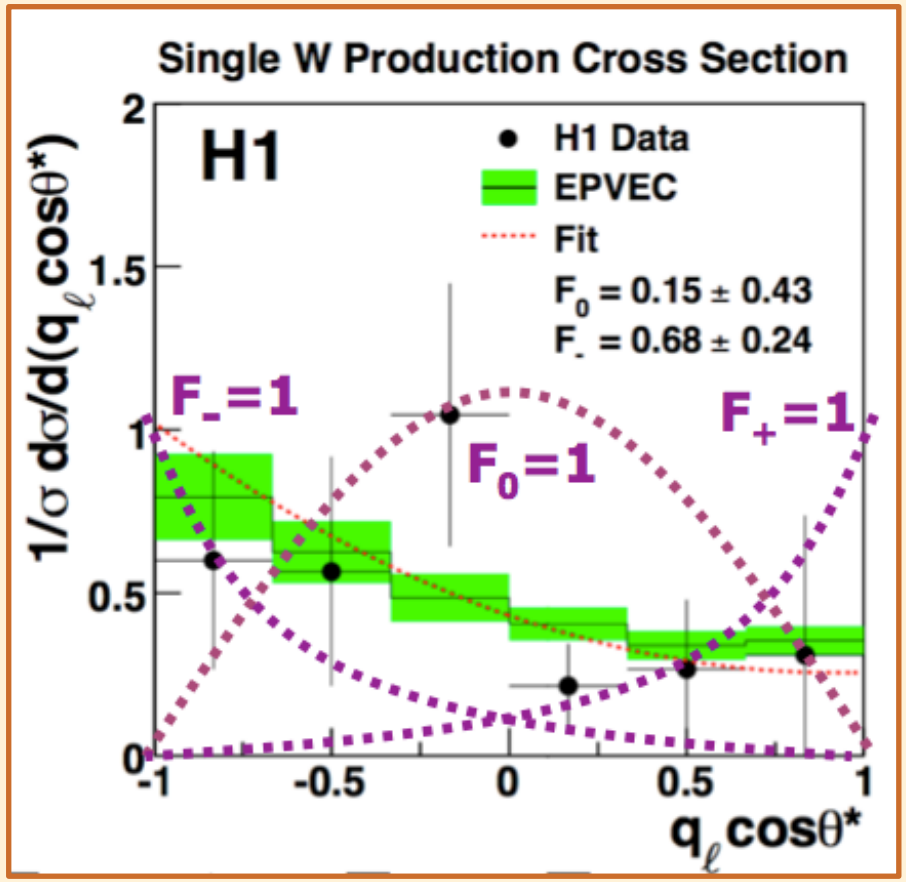


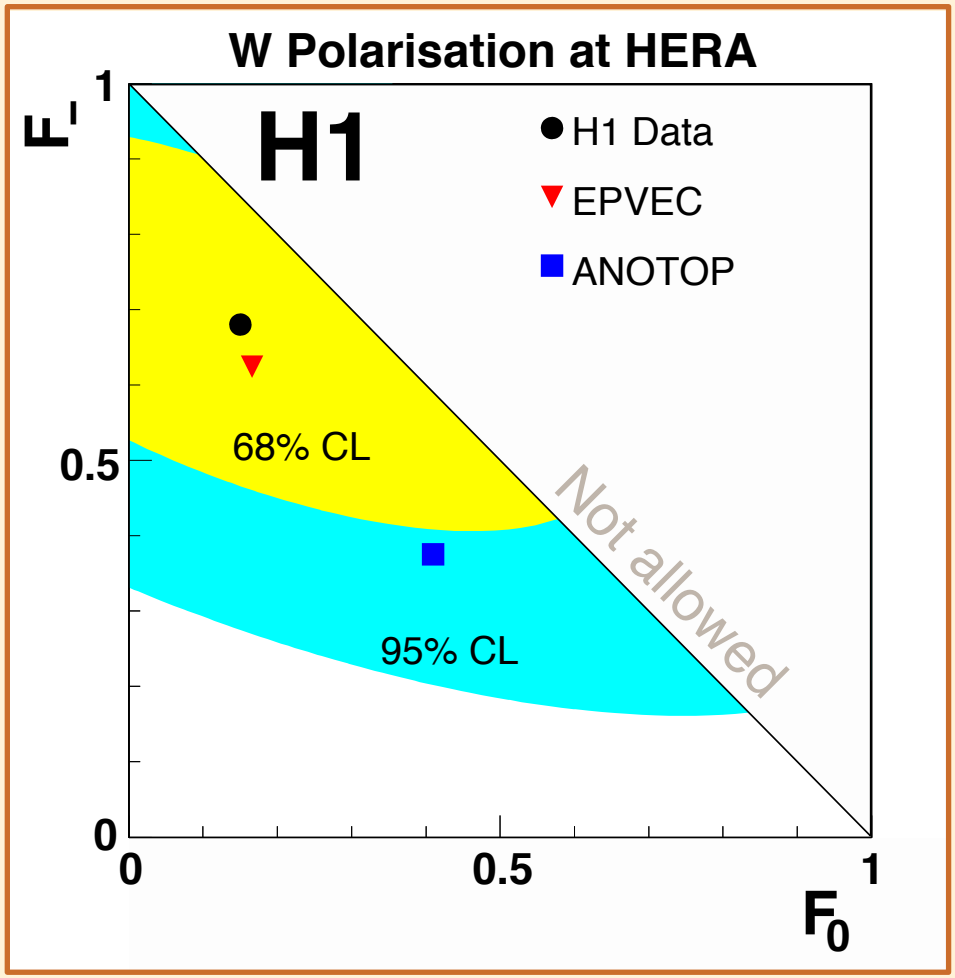
$$\frac{1}{\sigma_{W\to\ell+\nu}}\frac{d\sigma_{W\to\ell+\nu}}{d\cos\theta^*} = \frac{3}{4}F_0\left(1-\cos^2\theta^*\right) + \frac{3}{8}F_-\left(1-\cos\theta^*\right)^2 + \frac{3}{8}F_+\left(1+\cos\theta^*\right)^2$$

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 σ level

Summary

- 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 ~1 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
  σ_W = 1.06 ±0.16 (stat.) ± 0.07 (sys.) pb, cf 1.26 ± 0.19 pb from SM

- The H1 limits on WWγ coupling parameters Δκ, λ are compatible with W production at other colliders

Final word on these subjects from HERA!

More fun stuff…

Why e^+p: Squarks in RPV SUSY?

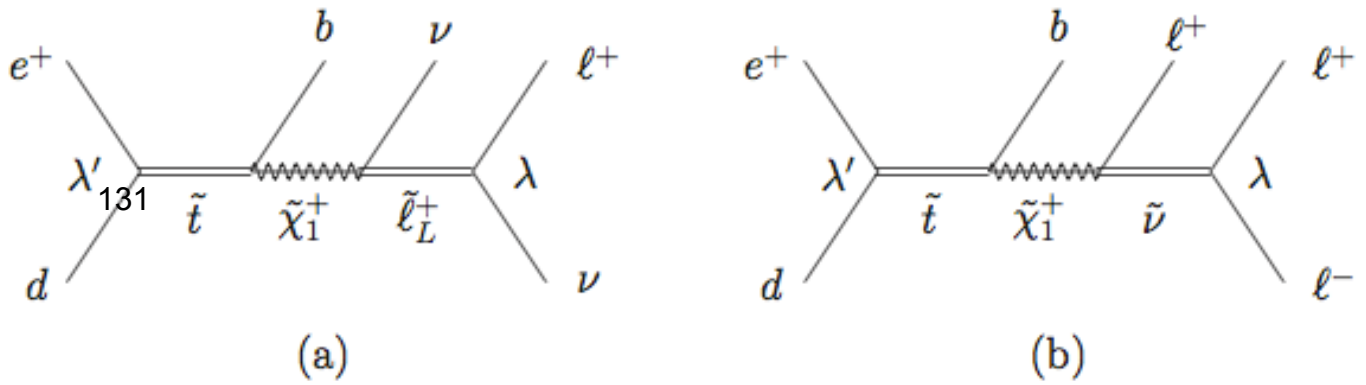
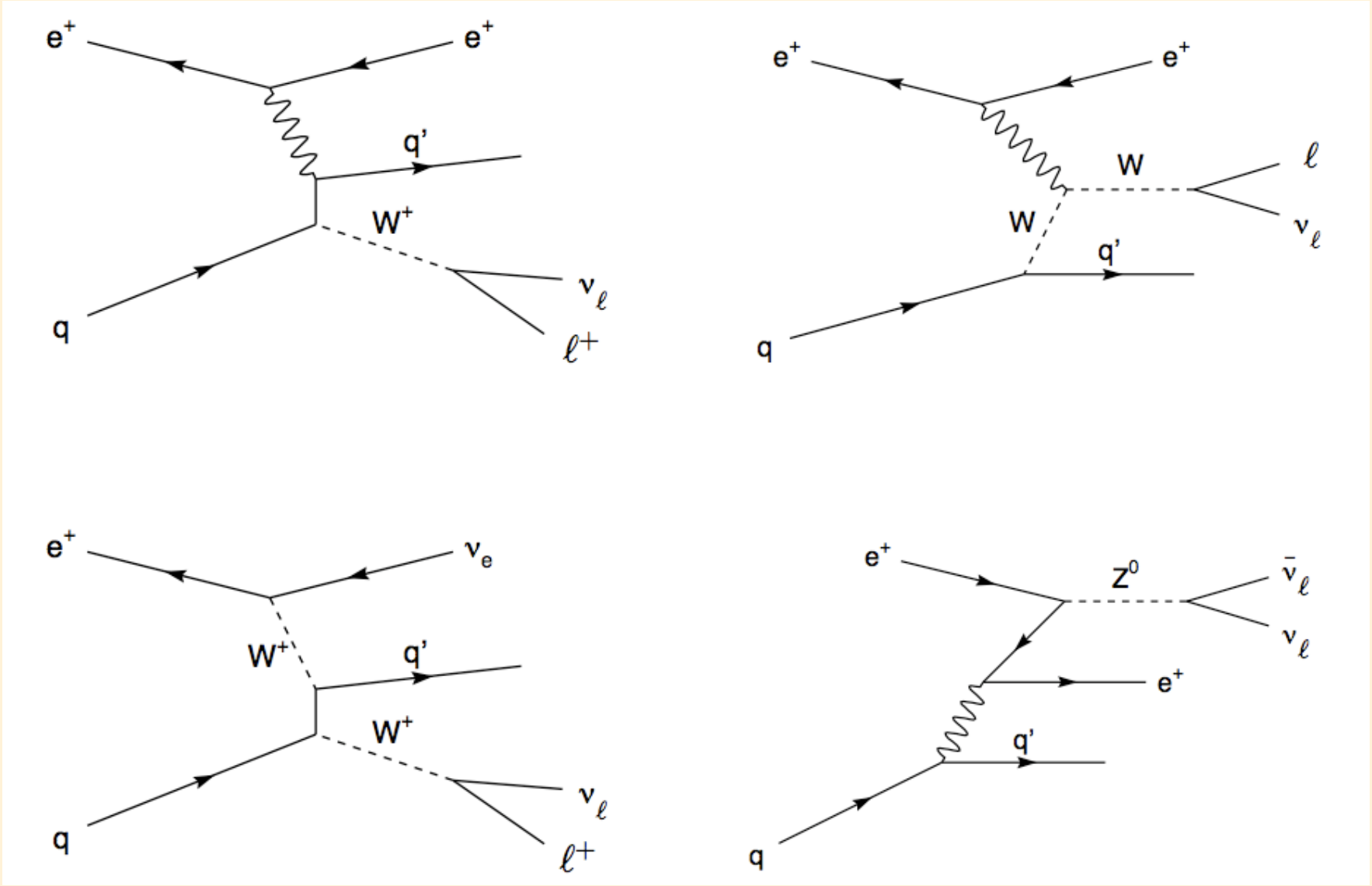


Figure 1: *Supersymmetric R-parity violating interactions generating isolated lepton events*

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

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

Isolated leptons + P_T^{Miss}: signal diagrams



Isolated leptons: event selection (H1+ZEUS)

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

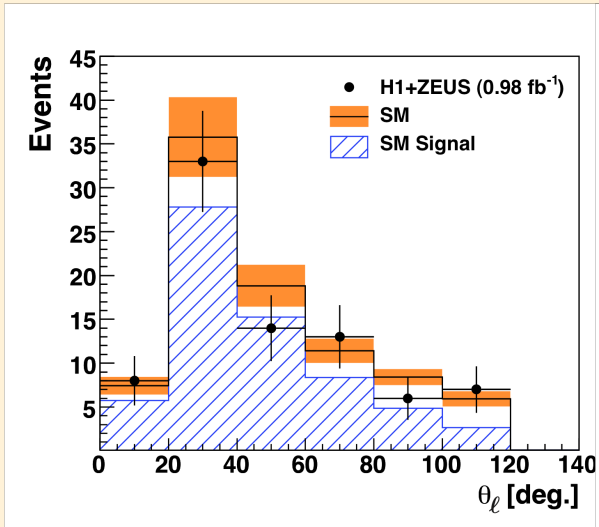
Major difference to H1 nominal analysis

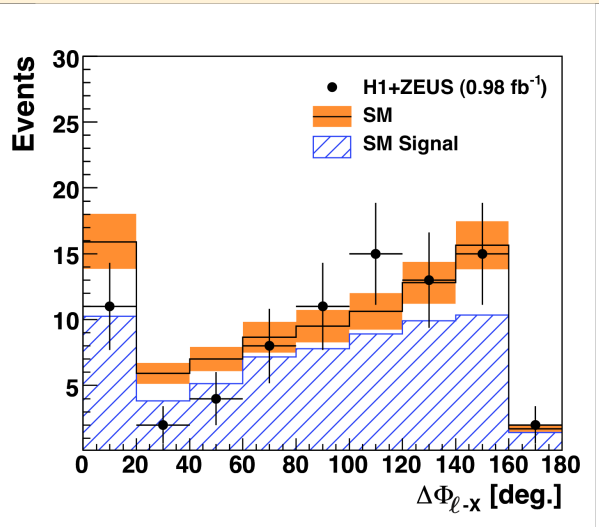
Analysis phase space selection

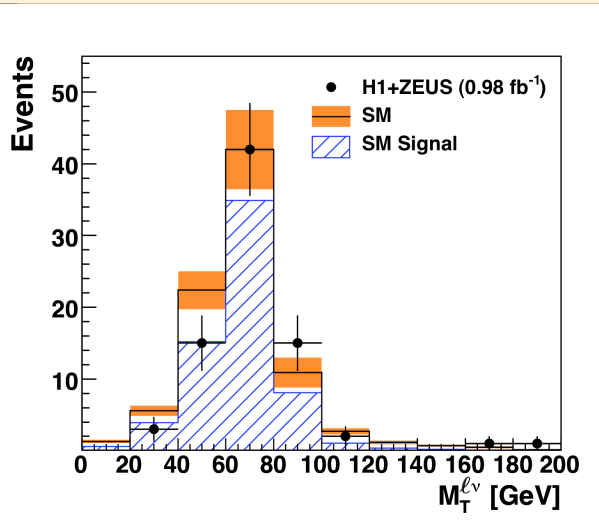
Isolation of lepton

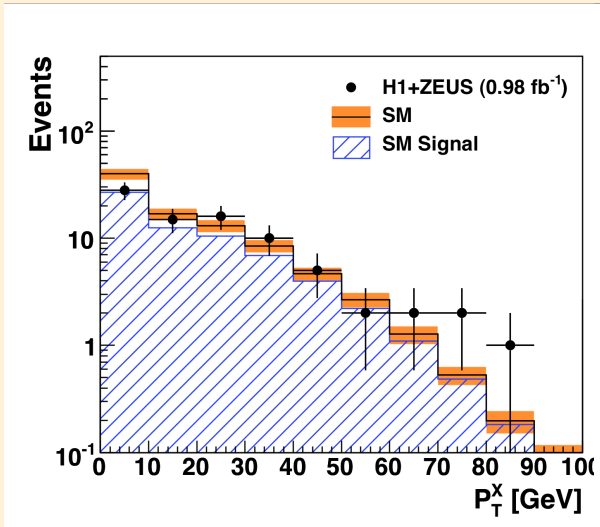
Cuts designed to reduce SM background, whilst preserving large signal purity

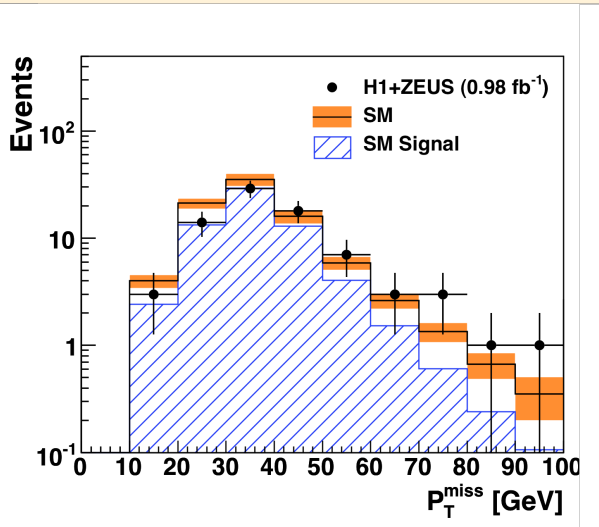
Isolated leptons: all distributions (H1+ZEUS)

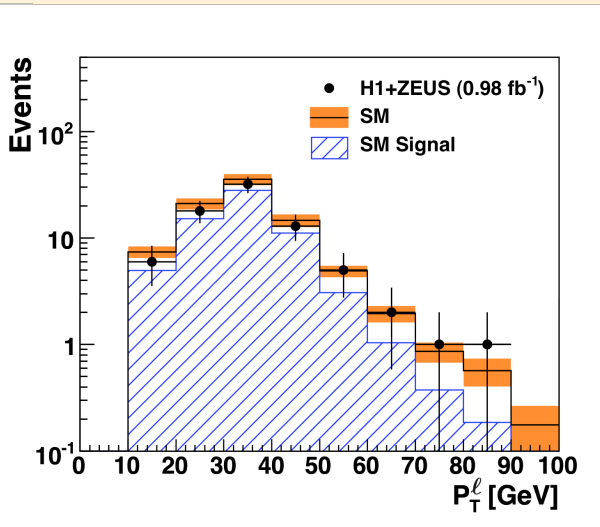




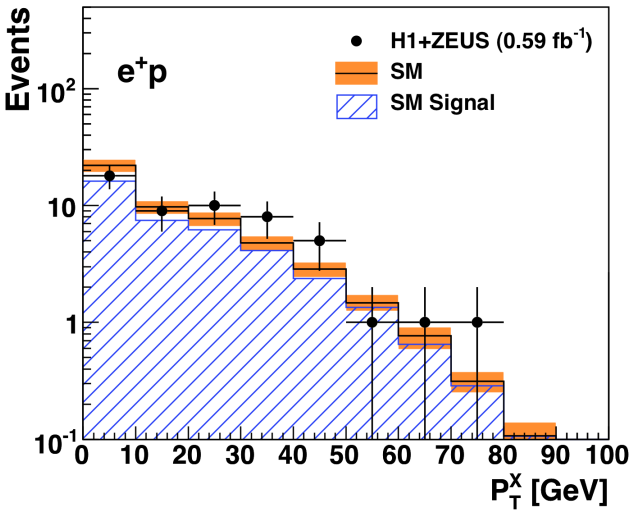




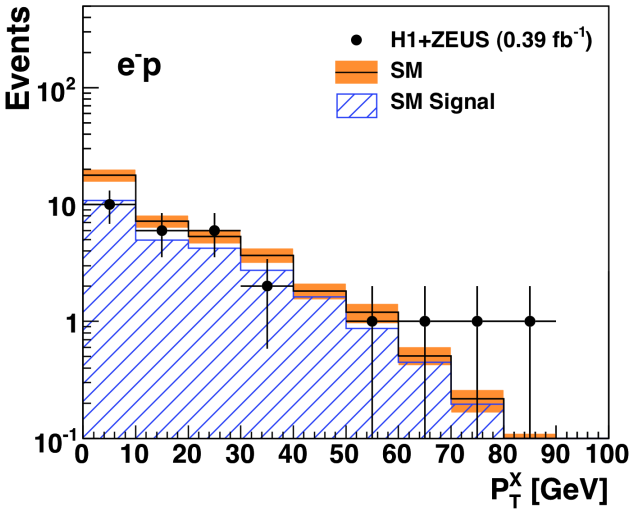




Isolated leptons: e^+p and e^-p (H1+ZEUS)



H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		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



H1+ZEUS 1998–2006 e^-p 0.39 fb^{-1}		Data	SM Expectation	SM Signal	Other SM 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

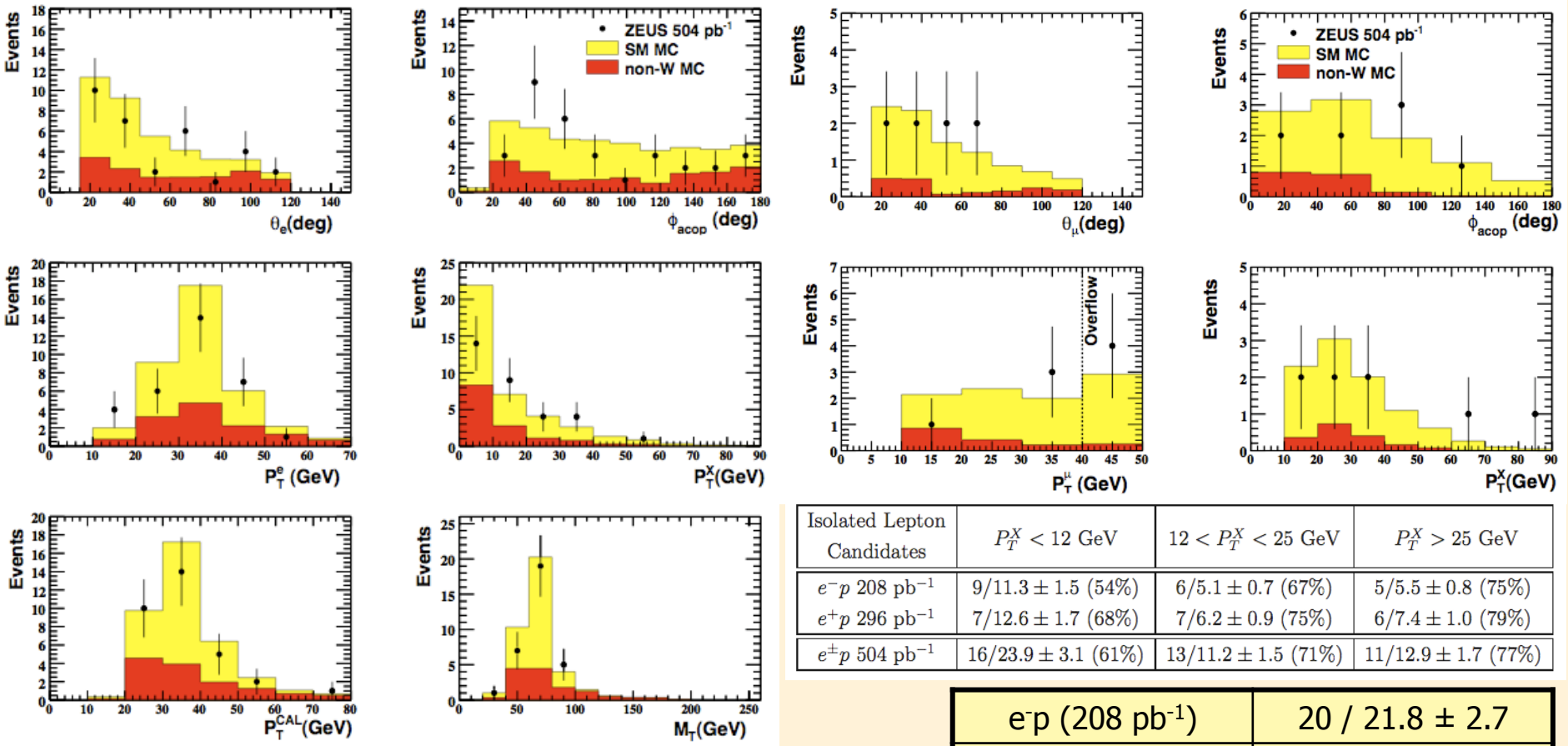
Isolated leptons: W cross sections (H1+ZEUS)

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

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%)

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

SM cross section: 1.2 pb

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

Isolated leptons: published results (H1)

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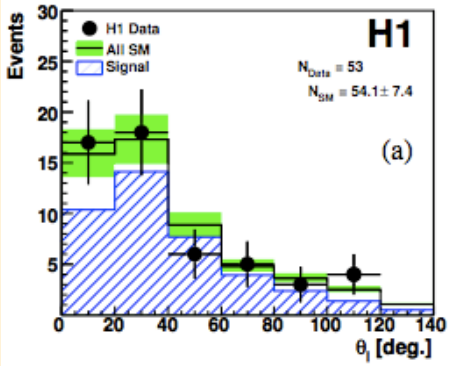

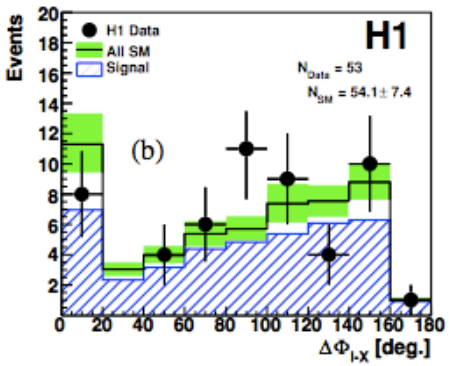

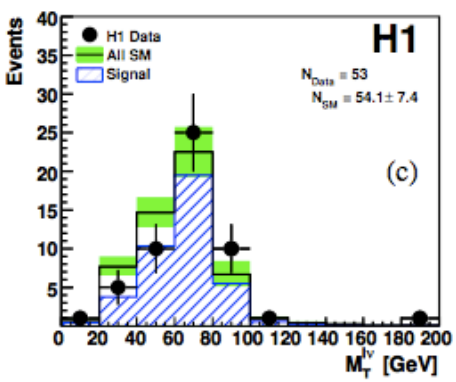

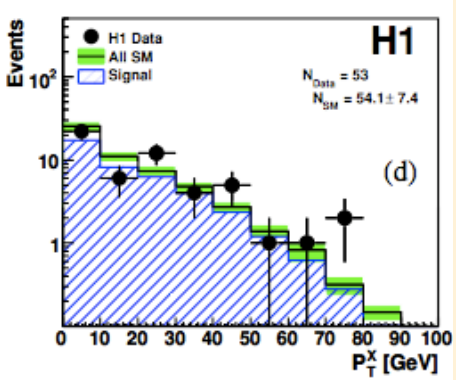

Main difference to combined H1+ZEUS analysis: extended polar angle range down to 5°

H1	1994-2007 $e^{\pm}p$ 474 pb^{-1}	Data	SM Expectation	SM Signal	Other SM 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

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

SM cross section: 1.27 ± 0.19 pb

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

H1	1994-2007 e^+p 291 pb^{-1}	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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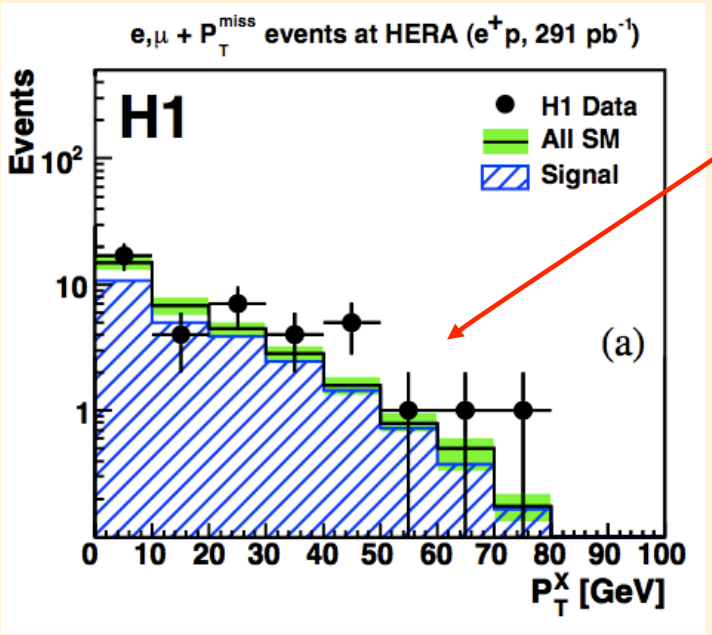

Isolated leptons: Tau channel (H1)

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

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}	$P_T^X > 25$ 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}	$P_T^X > 25$ 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}	$P_T^X > 25$ GeV	1	1.50 ± 0.21	0.59 ± 0.09	0.91 ± 0.12

Isolated leptons: Tau channel (H1)

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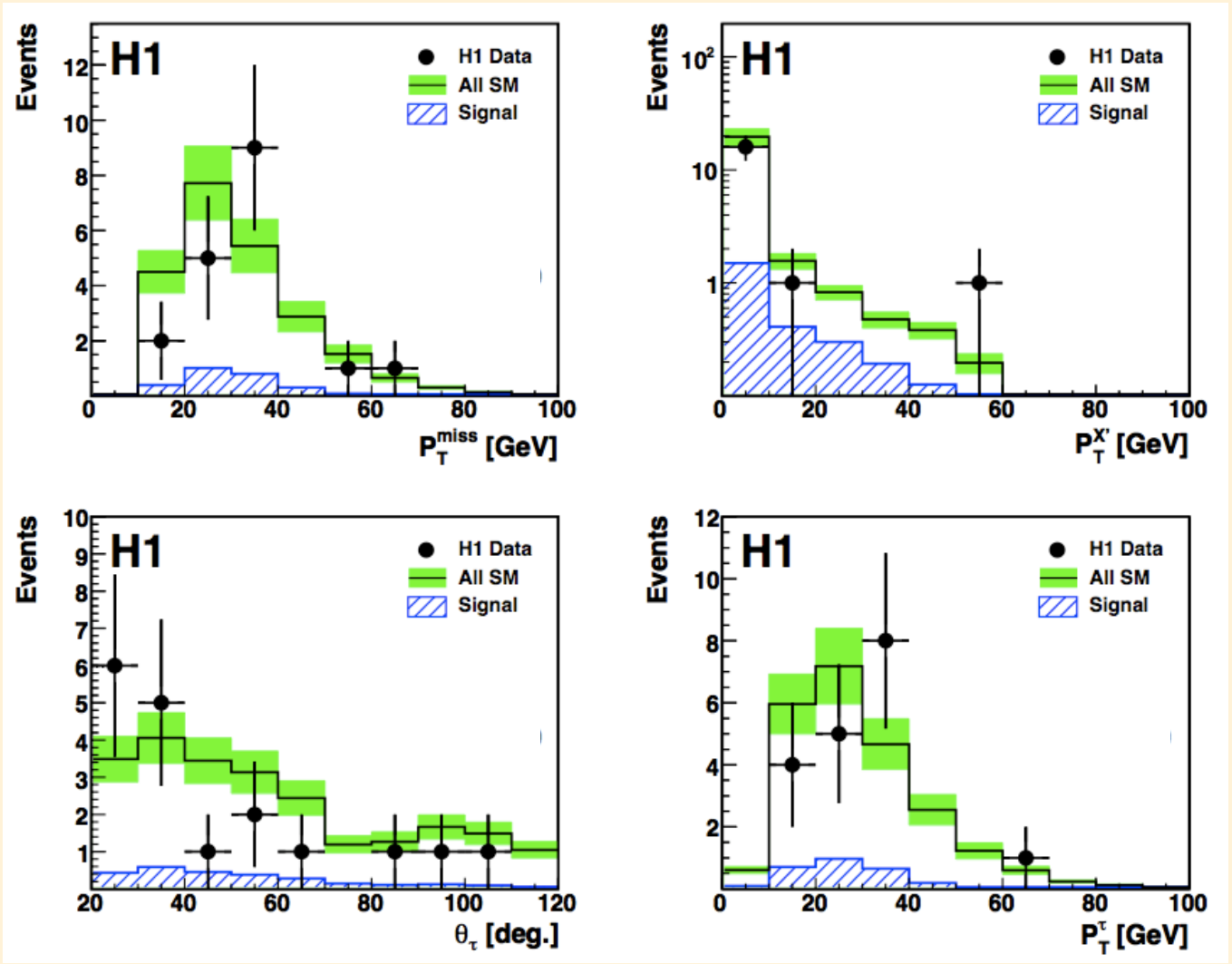
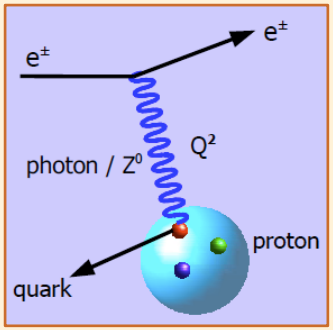
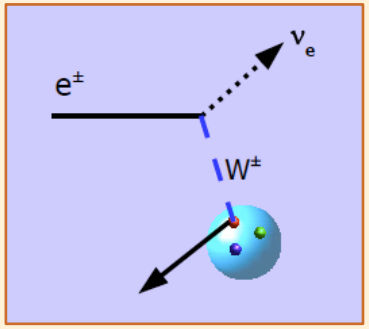


Deep inelastic e±p scattering: basics

Two deep inelastic scattering processes:

— Neutral current: exchange of γ or Z^0
— Charged current: exchange of $W^{\pm}$

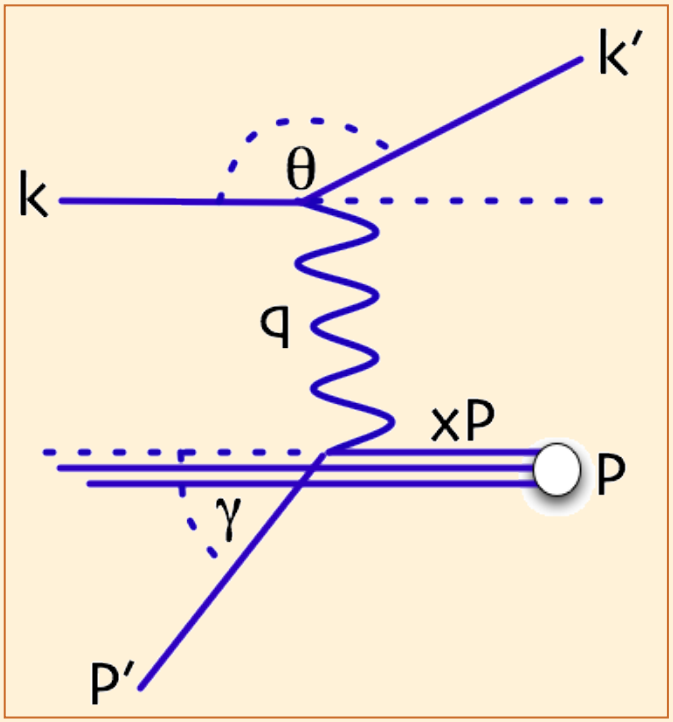




$$Q^2 = -q^2 = -(k - k')^2$$

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

$$s = (p + k)^2 \qquad Q^2 = x \cdot y \cdot s$$



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