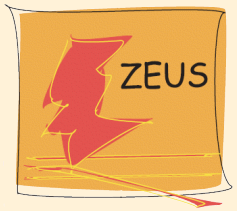


Multi-lepton and isolated-lepton searches at HERA

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

- Introduction: HERA, H1 and ZEUS
- H1 + ZEUS **combined** searches
  - **multi-leptons**
  - **isolated leptons and missing transverse momentum**
- Summary

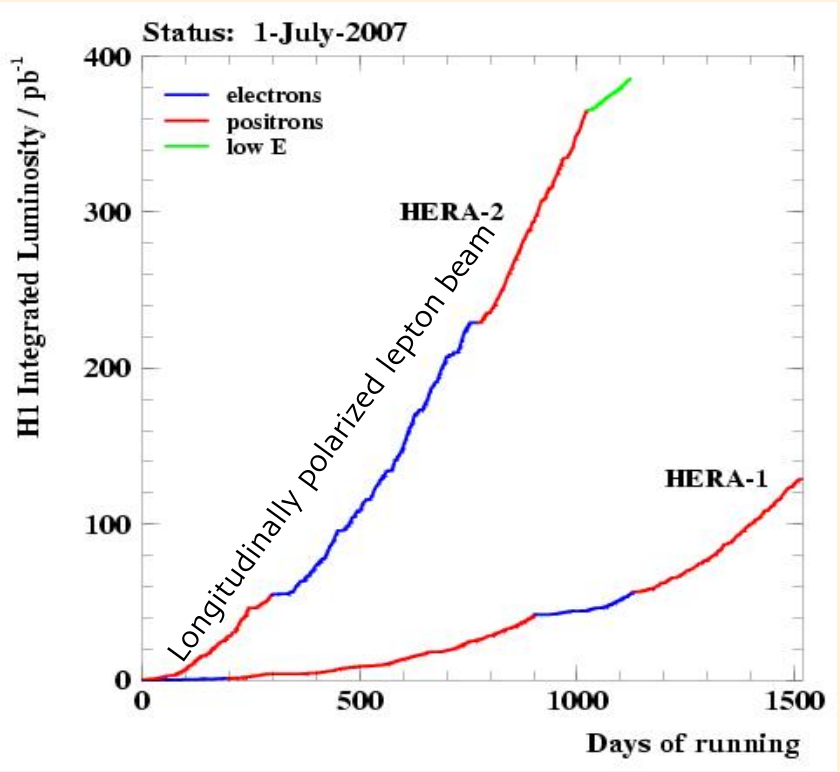
HERA operation

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

Analyses presented utilize the final combined 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 data set 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

Isolated-lepton searches at HERA

- We distinguish two classes of these events:

  High-P_T multi-lepton events, where there is NO accompanying hadronic activity in the detector

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

- The topologies
  - provide clean, striking signals
  - require good lepton ID and HFS reconstruction

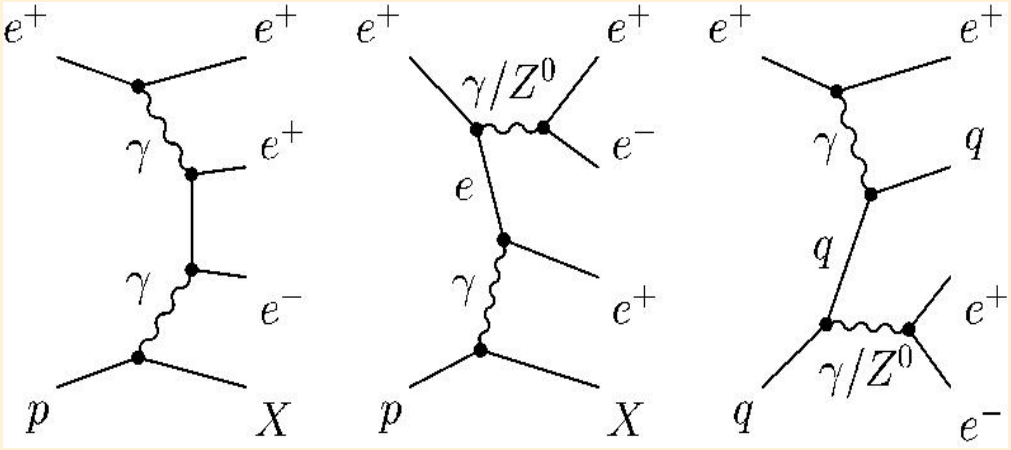
  Since the SM expectation for these events at HERA (high mass, high P_T) is low, the analyses benefit from the combination of the H1 and ZEUS data

Multi-lepton events

(NO accompanying hadronic activity in the detector)

Multi-leptons events

The main SM process in ep collisions with multi-leptons in the final state is that of photon-photon interactions: $\gamma\gamma \longrightarrow l^+l^-$



As this process is entirely described by EW physics, it is very well known… so this QED process has a precise SM prediction (modeled by GRAPE MC)

Main SM backgrounds:

- ee: NC-DIS (ep $\longrightarrow$ eX), QEDC process (ep $\longrightarrow$ eγX)
- eμ: NC-DIS
- e$\mu\mu$, $\mu\mu$: negligible (from cosmic rays, non-ep)

Multi-lepton event selection

Step 1: identify e and μ candidates using wider angular range and lower energy thresholds

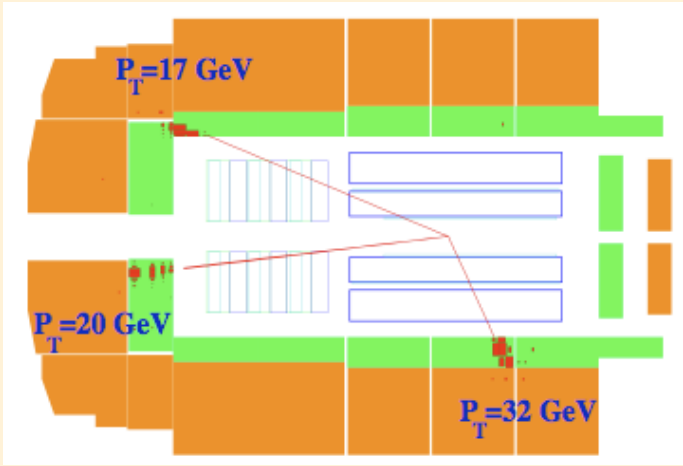
- **Electrons** identified in the polar angle region $5^O<\theta<175^O$ with E >10 GeV, with E >5 GeV in the backward region ($\theta>150^O$)

- **Muons** identified in the polar angle region $20^O<\theta<160^O$ with P_T > 2 GeV

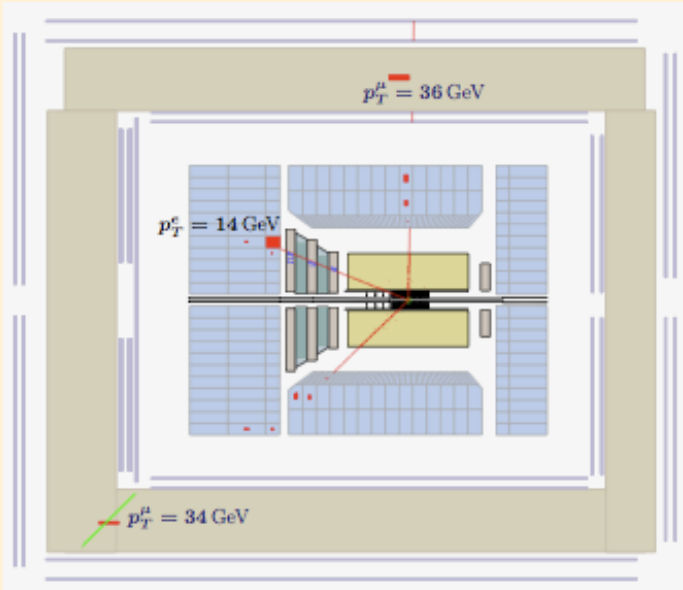
Step 2: classify events into independent, exclusive samples

- ee, eee, μμ, eμ, eμμ and so on..

Step 3: require at least two of the leptons to be in the central region ($20^O < \theta < 150^O$) and to have high P_T (P_T > 5, 10 GeV)



eee event in H1



eμμ event in ZEUS

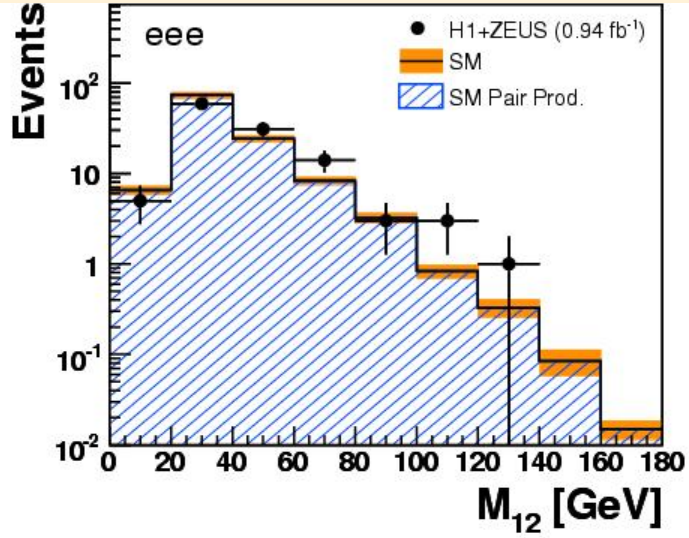
Results of different multi-lepton topologies

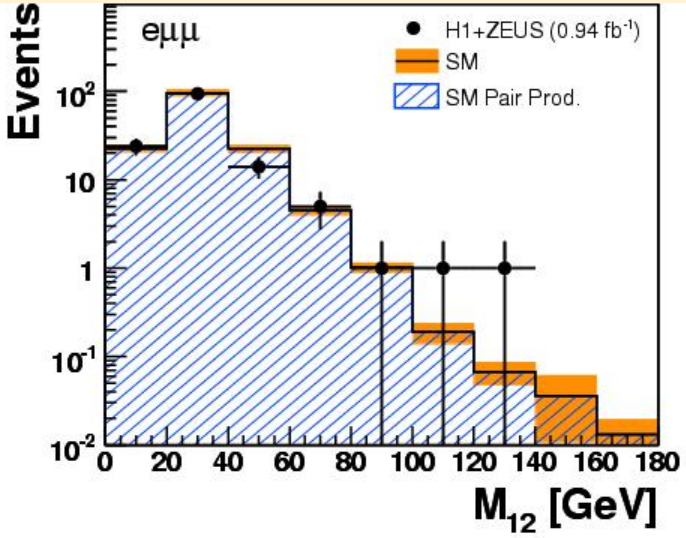
Multi-Leptons at HERA (0.94 fb^{-1})

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 is seen with the SM prediction

$\gamma\gamma$ selections are used to measure the cross sections in the photo-production regime





In the high mass region, a few events survive…

Multi-lepton events at high mass (H1+ZEUS)

High-mass events

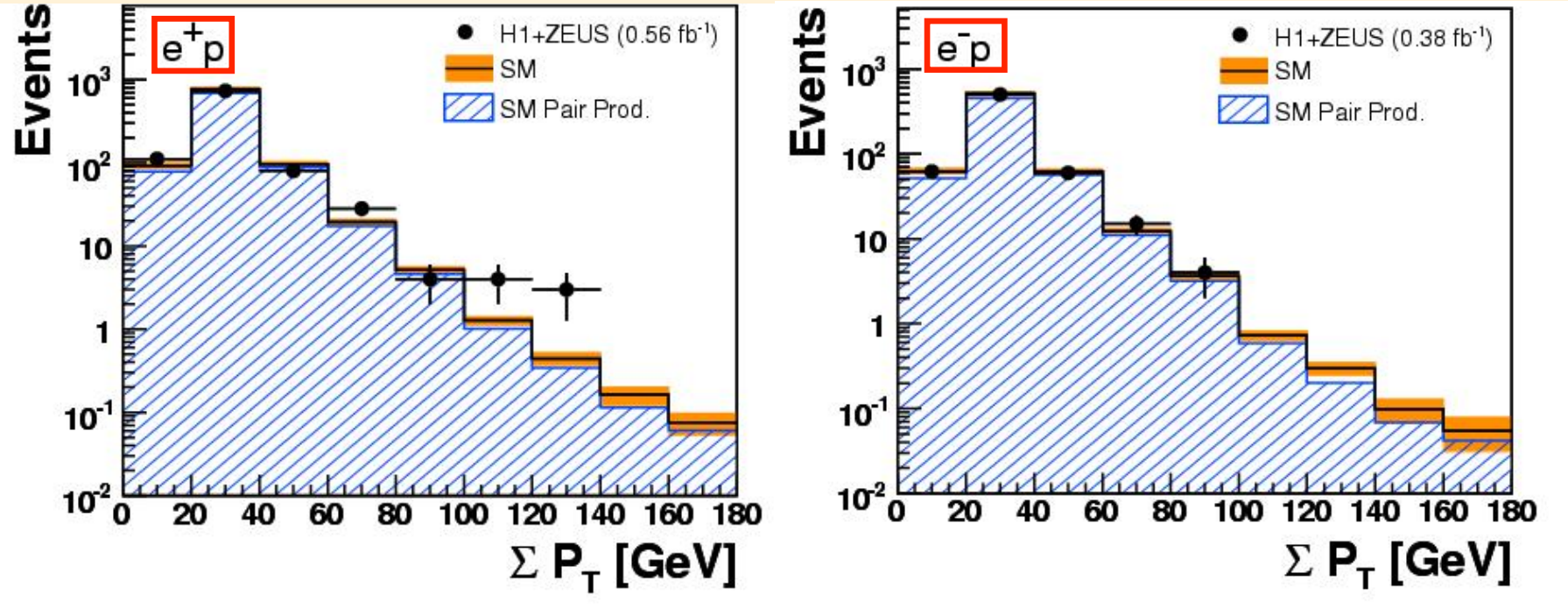
9 events from H1
3 events from ZEUS

SM expectation
~ 6 events

All high-mass events are seen in e^+p data...

Multi-Leptons at HERA (0.94 fb^{-1})				
M_{12} >100 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

Multi-lepton events at high ΣP_T (H1+ZEUS)

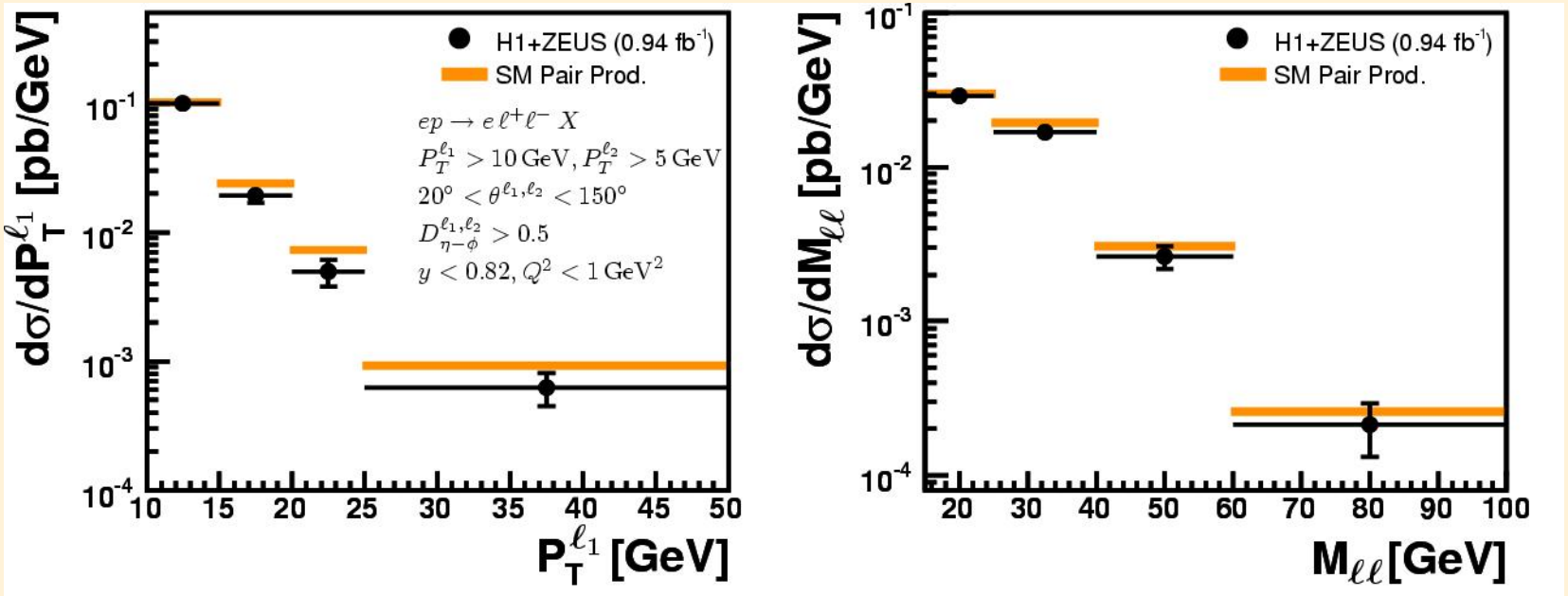


Multi-Leptons at HERA (0.94 fb^{-1})				
$\sum P_T$ >100 GeV				
Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p (0.56 fb^{-1})	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e^-p (0.38 fb^{-1})	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb^{-1})	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10

7 events observed in the e^+p data with ΣP_T > 100 GeV; SM Exp: ~2 events

Measurement of the $\gamma\gamma \to \ell^+\ell^-$ cross section

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



Differential cross sections measured as a function of the P_T of the leading lepton and the invariant mass of the lepton pair

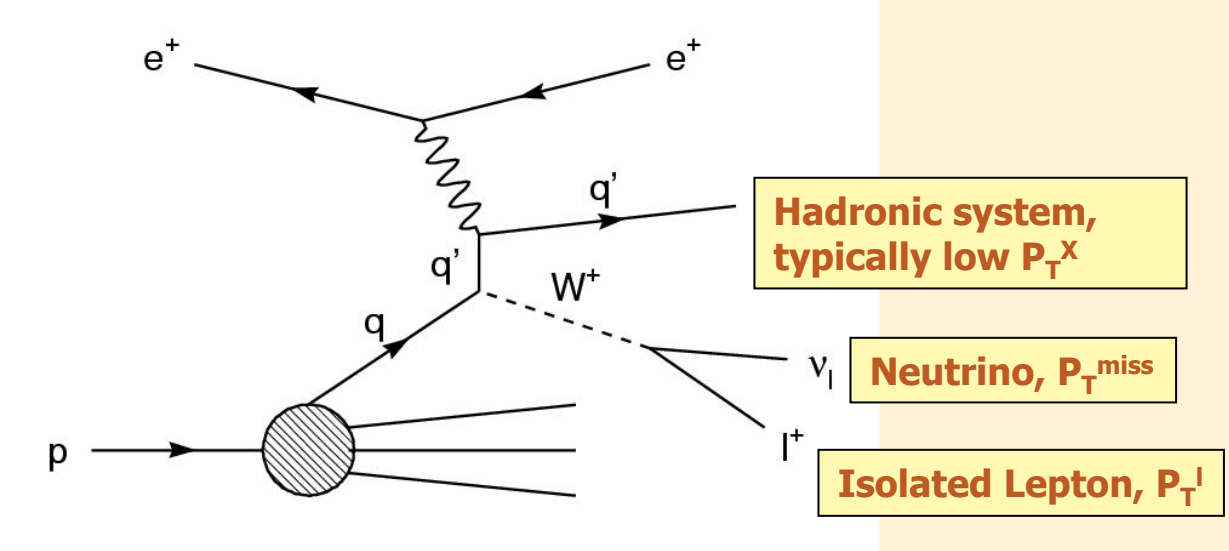
Total visible cross section measured **0.66 ± 0.03 (stat.) ± 0.03 (sys.) pb** and in **good agreement with the SM prediction of 0.69 ± 0.02 pb**

Isolated-leptons events and missing P_T

(and accompanying hadronic activity in the detector)

Events with isolated leptons events and missing P_T

- The main SM process in ep interactions with a single, high-P_T isolated lepton in coincidence with missing transverse momentum the final state is single W production:

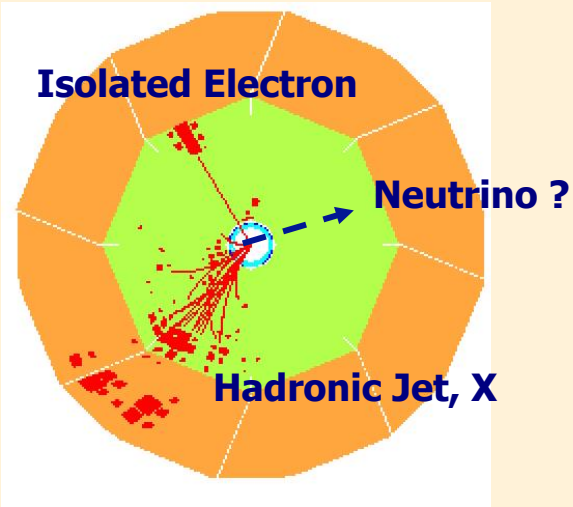


- Smaller additional contributions occur to the signal via the equivalent diagram in CC-DIS, as well as from Z^O production with decay to neutrinos

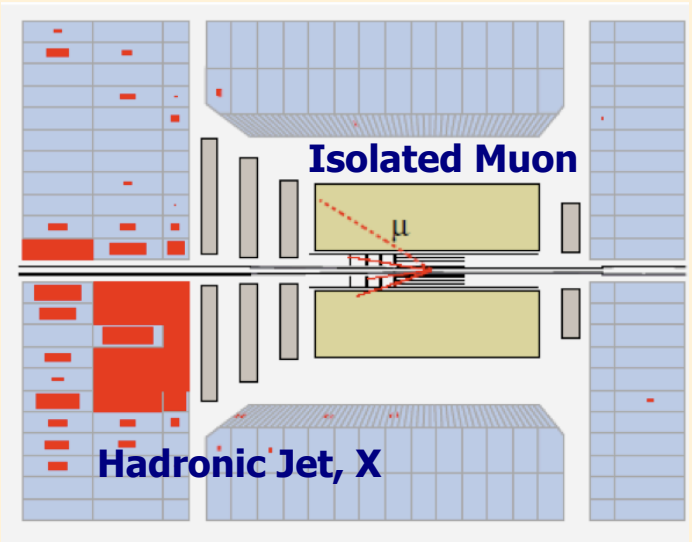
- Total cross section ~ 1.3 pb, with 10% of W decays to each lepton flavour
- Modelled at HERA using EPVEC with a NLO correction, uncertainty 15%
- Main SM backgrounds: NC-DIS, CC-DIS and lepton pair production

Isolated lepton and missing-P_T event selection

- In events with large missing transverse momentum, require a high-P_T lepton (electron or muon), in the main body of the detector
- Common H1+ZEUS analysis phase space: events with an electron or muon satisfying P_T>10 GeV, $15^O<\theta<120^O$ and P_T^{Miss} >12 GeV
- The lepton is also required to be well isolated from the nearest jet and track in the event (rejects mainly CC events with a lepton in the jet)
- Further cuts applied to reduce SM background such as rejecting back-to-back topologies (NC, lepton-pairs)
- Electron and muon channels are exclusive, and are combined, also in the cross section measurement

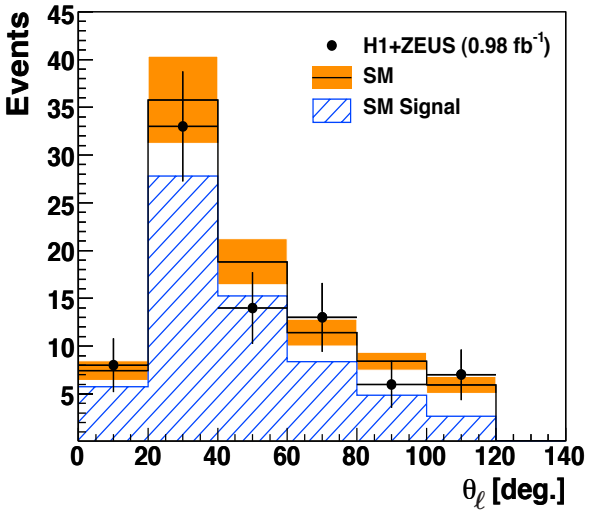


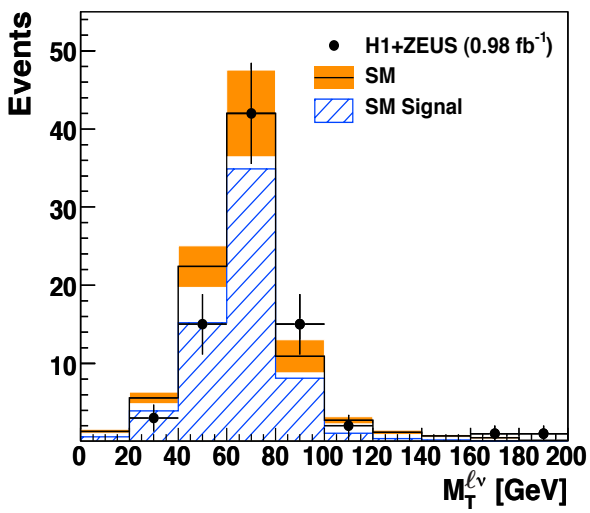
e + P_T^{Miss} event in H1

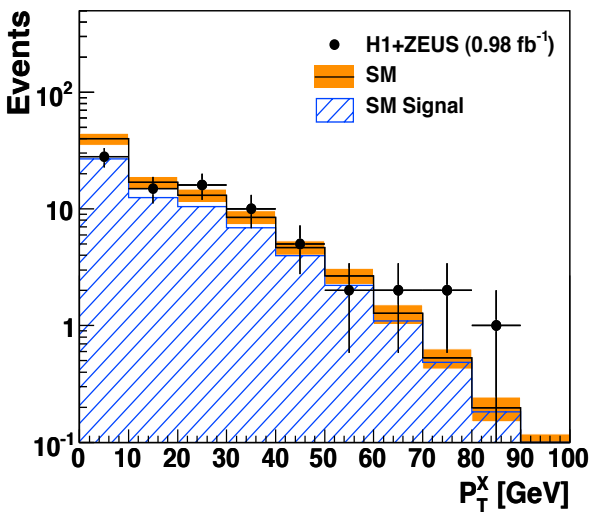


μ + P_T^{Miss} event in ZEUS

Isolated leptons (H1+ZEUS): results



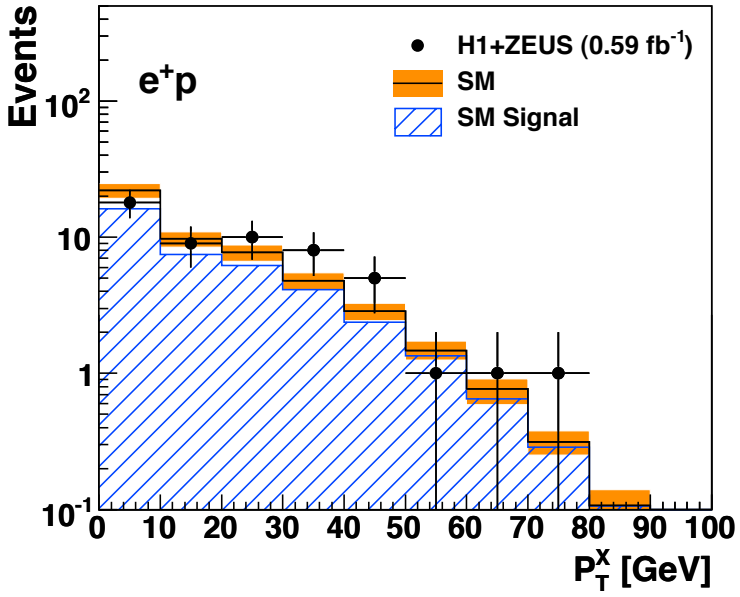




H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined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

Isolated Leptons (H1+ZEUS): positron data

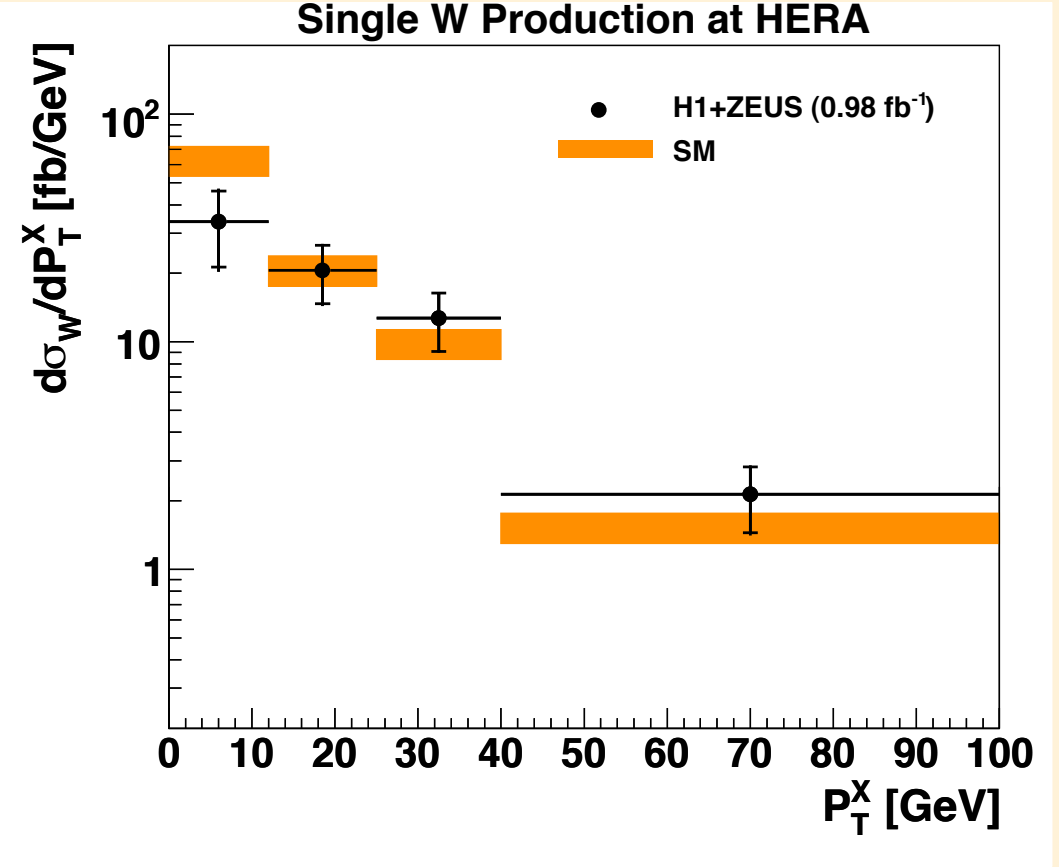


- Excess of data events seen in the published H1 analysis at large P_T^X, an area of phase space where the SM expectation is small
  - Not confirmed in the ZEUS analysis
- Small excess remains in the common phase space of the combination analysis
  - Still driven by the H1 data

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 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

Summary

- Analyses of events with multi-leptons and isolated leptons with P_T^{Miss} have recently been published by H1 and ZEUS, individually

- Combined H1+ZEUS analyses have also been performed to take advantage of the full HERA statistics:

  Multi-leptons: JHEP 0910 (2009) 013

  Isolated Leptons + P_T^{Miss}: accepted by JHEP, arXiv:0911.0858 [hep-ex]

- Cross sections of rare processes measured with greater statistical precision

  In general, a good agreement with the SM is observed

- A few interesting events remain at high P_T and high mass in the e^+p HERA data, from both H1 and ZEUS, where the SM expectation is low

Final word on these subjects from HERA! More combinations to come…

More fun stuff…

Multi-leptons: doubly charged Higgs?

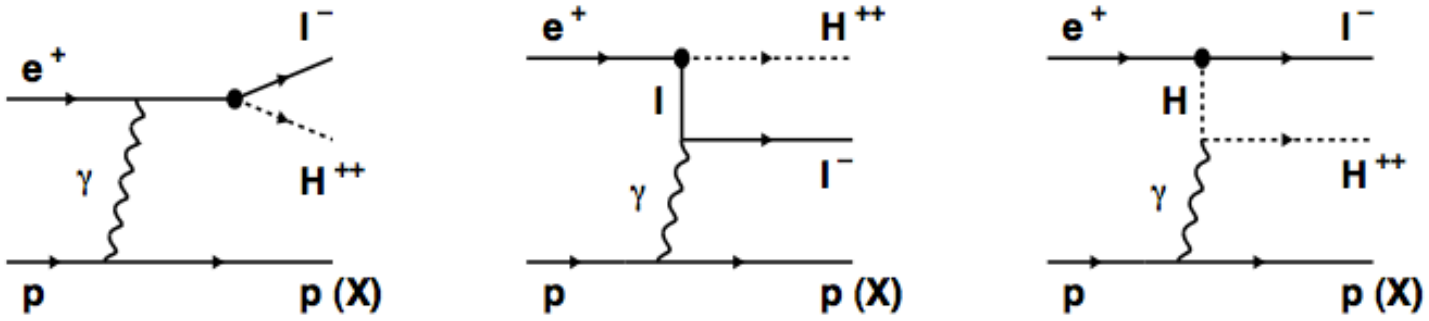


Figure 1: Diagrams for the single production of a doubly-charged Higgs boson in e^+p collisions at HERA via the h_{el} coupling. The hadronic final state is denoted by p (X) in the elastic (inelastic) case, where the initial proton remains intact (dissociates). The contribution of Z exchange can be safely neglected.

Within the mass range considered in this analysis, it is assumed that decays of the $H^{\pm\pm}$ into gauge bosons and other Higgs particles are not allowed kinematically such that the doubly-charged Higgs only decays via its Yukawa couplings into a lepton pair.

A search for the single production of doubly-charged Higgs bosons coupling to ee, eμ or eτ was investigated by H1

No significant excess over the SM expectation was observed

Isolated leptons: RPV SUSY?

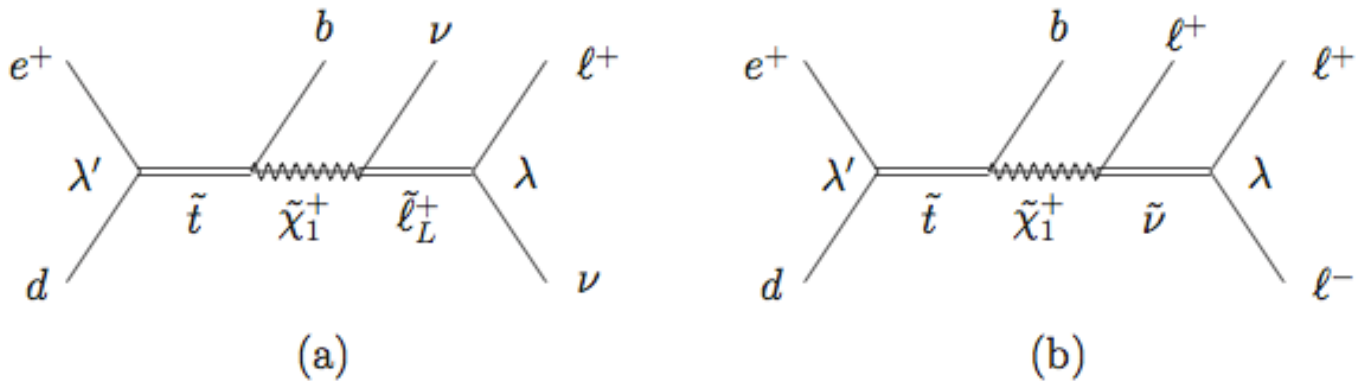
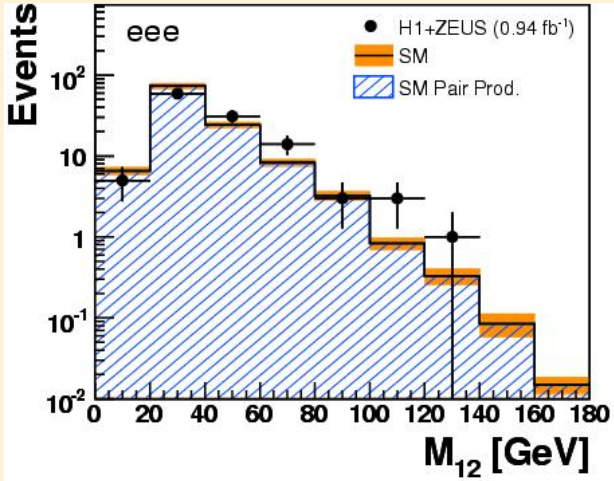
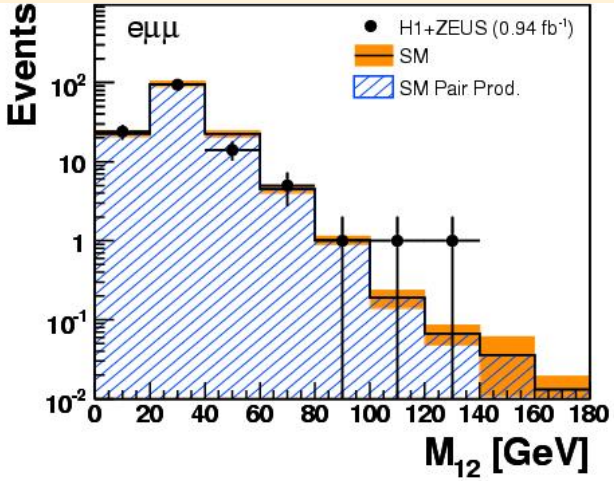


Figure 1: *Supersymmetric R-parity violating interactions generating isolated lepton events*

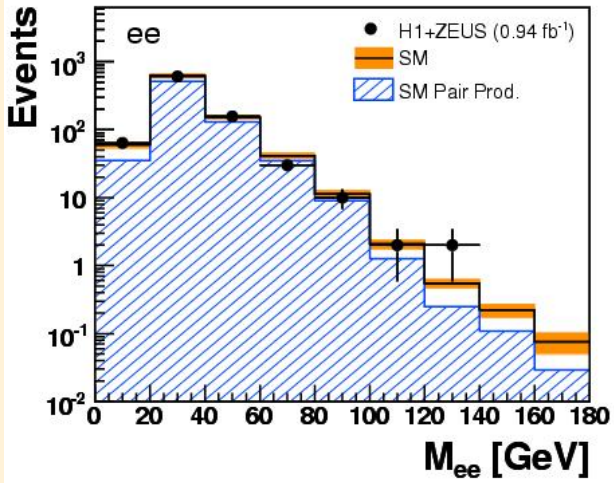
DESY 06-238
IFT-06/027
MZ-TH/06-28
hep-ph/0612302

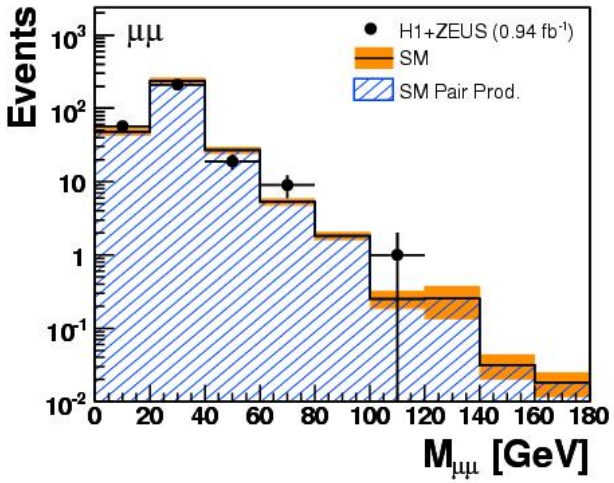
Multi-lepton channels: mass distributions

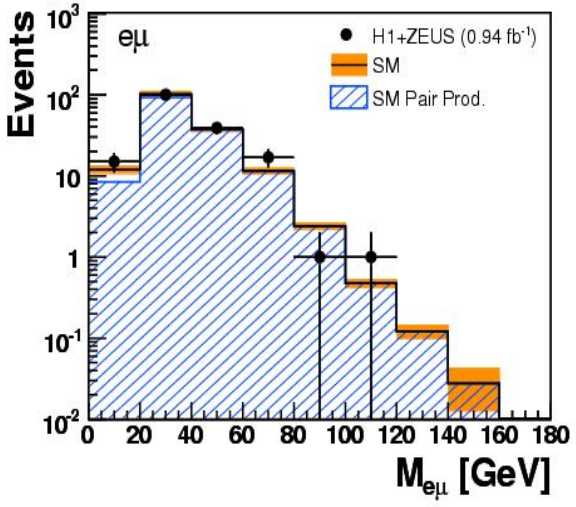




H1+ZEUS





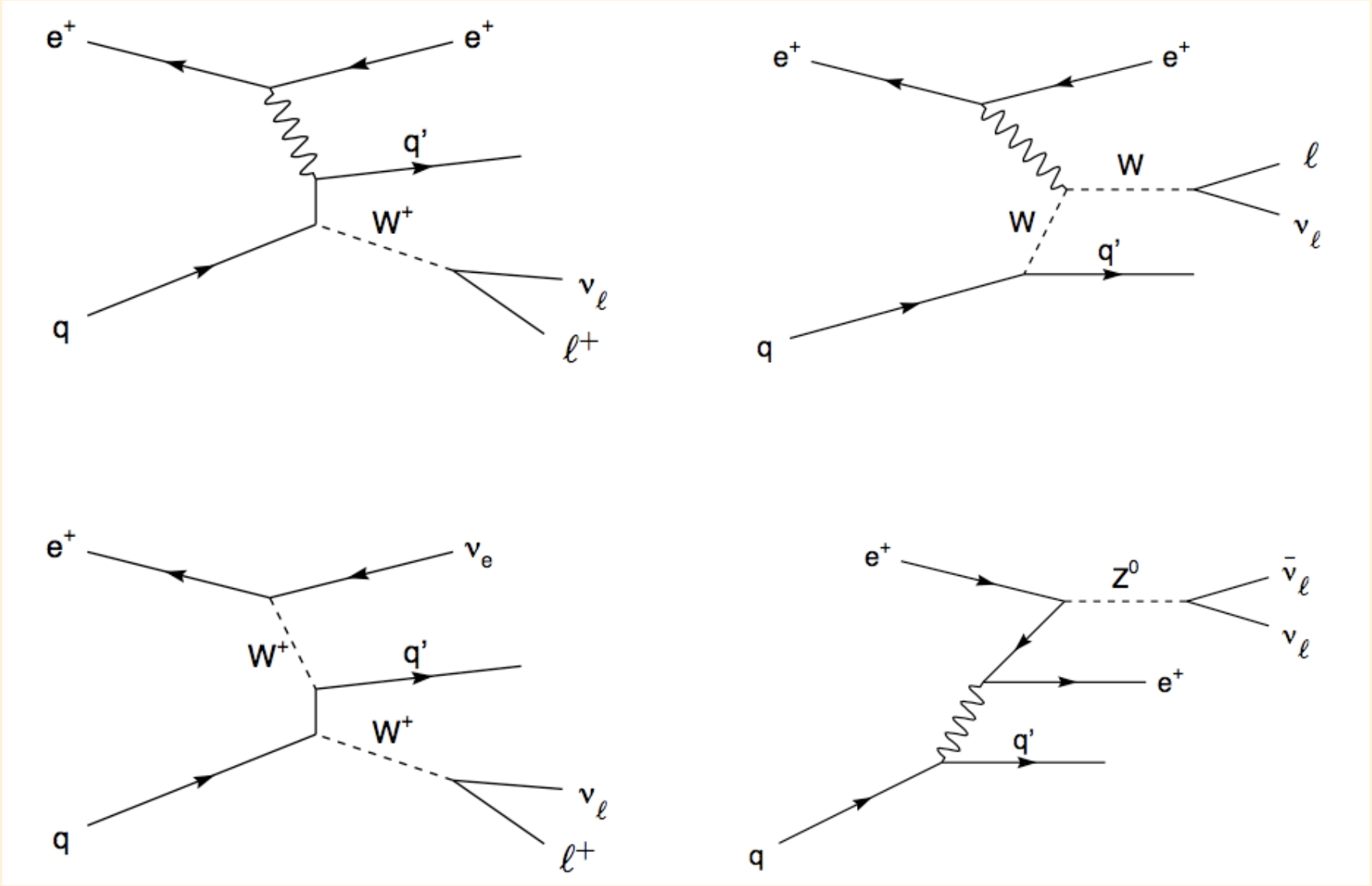


Multi-leptons (H1+ZEUS): cross sections

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

Variable range [GeV]	Measured (e^+e^-) [fb/GeV]	Measured $(\mu^+\mu^-)$ [fb/GeV]	Measured (average) [fb/GeV]	Pair Production (GRAPE) [fb/GeV]
$P_T^{\ell_1}$		$d\sigma/dP_T^{\ell_1}$		
$[10, 15]$	$101.1 \pm 7.1 \pm 5.5$	$97.7 \pm 7.7 \pm 9.2$	$99.9 \pm 5.3 \pm 4.9$	101.3 ± 3.1
$[15, 20]$	$22.4 \pm 3.1 \pm 1.3$	$15.9 \pm 3.2 \pm 1.7$	$19.4 \pm 2.3 \pm 1.0$	23.9 ± 0.7
$[20, 25]$	$5.0 \pm 1.5 \pm 0.6$	$4.9 \pm 1.6 \pm 0.6$	$5.0 \pm 1.1 \pm 0.4$	7.3 ± 0.2
$[25, 50]$	$0.56 \pm 0.22 \pm 0.05$	$0.75 \pm 0.29 \pm 0.09$	$0.63 \pm 0.18 \pm 0.04$	0.93 ± 0.03
$M_{\ell\ell}$		$d\sigma/dM_{\ell\ell}$		
$[15, 25]$	$27.3 \pm 2.8 \pm 1.5$	$31.9 \pm 2.9 \pm 3.0$	$29.0 \pm 2.1 \pm 1.5$	30.0 ± 0.9
$[25, 40]$	$18.4 \pm 1.6 \pm 1.1$	$14.9 \pm 1.8 \pm 1.4$	$16.9 \pm 1.2 \pm 0.9$	19.5 ± 0.6
$[40, 60]$	$3.4 \pm 0.6 \pm 0.2$	$2.0 \pm 0.5 \pm 0.2$	$2.6 \pm 0.4 \pm 0.2$	3.1 ± 0.1
$[60, 100]$	$0.17 \pm 0.09 \pm 0.03$	$0.32 \pm 0.15 \pm 0.04$	$0.21 \pm 0.08 \pm 0.02$	0.26 ± 0.01

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	-

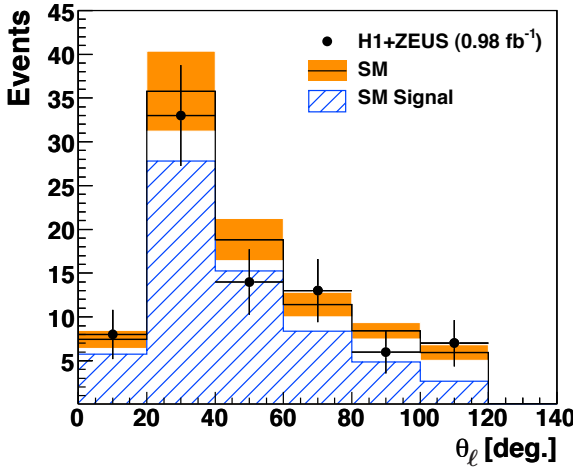
Major difference to H1 nominal analysis

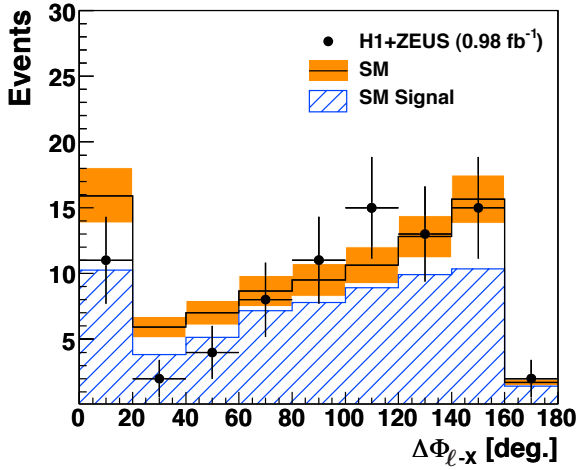
Analysis phase space selection

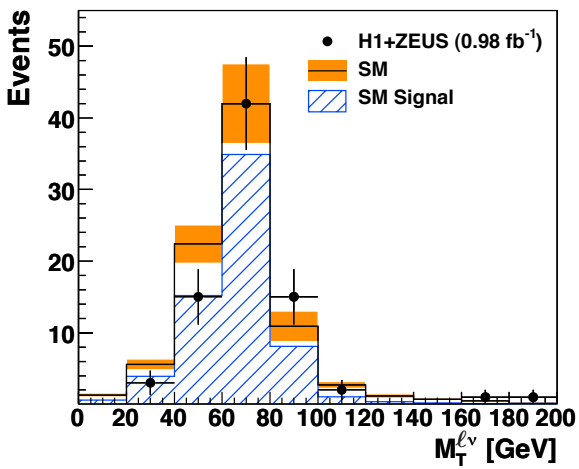
Isolation of lepton

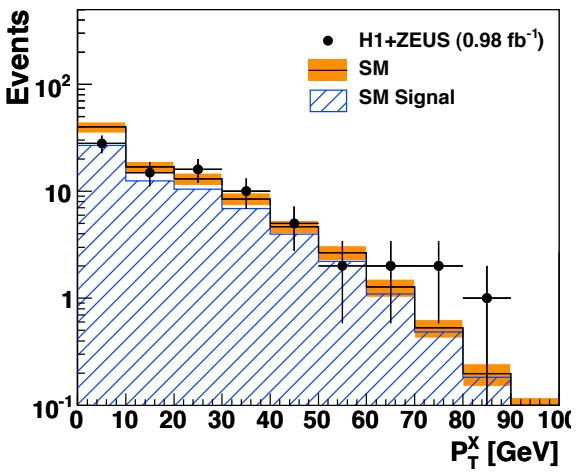
Cuts designed to reduce SM background, whilst preserving large signal purity

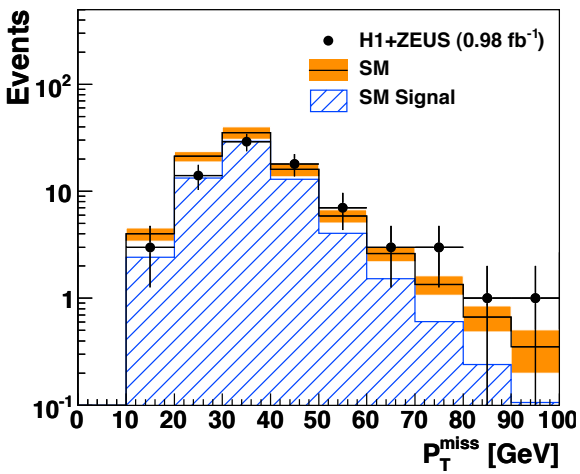
Isolated leptons: all distributions (H1+ZEUS)

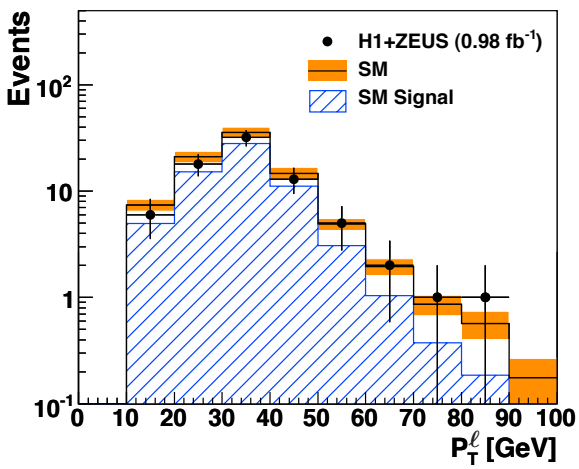




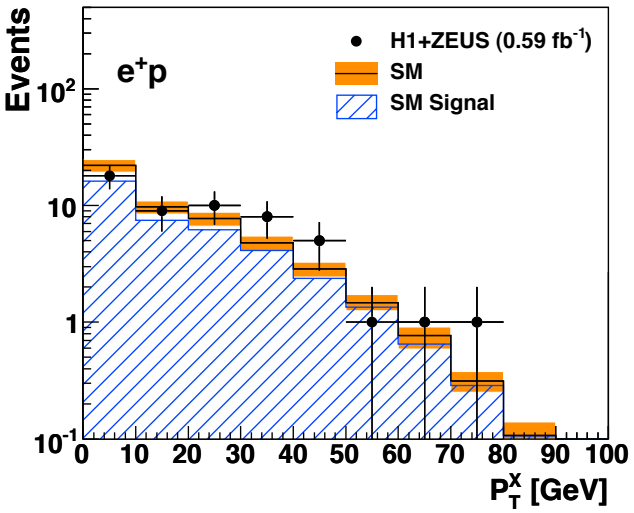




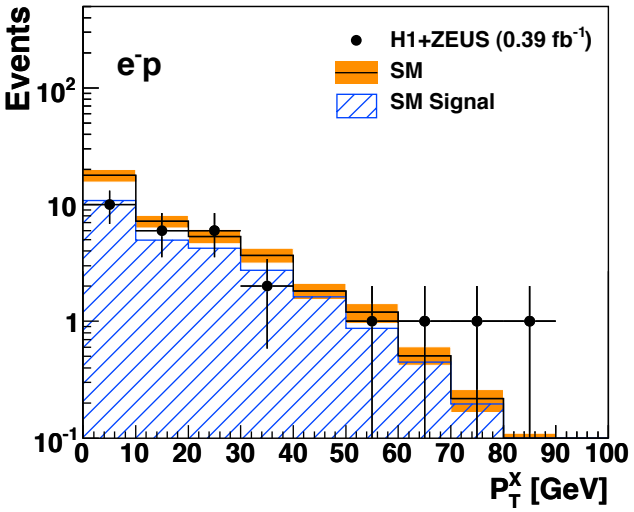




Isolated leptons: e^+p and e^-p (H1+ZEUS)



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

Multi-leptons: H1 published results

Multi-Leptons at HERA (463 pb^{-1})

Selection	Data	SM	Pair Production (GRAPE)	NC DIS + Compton
ee	368	390 ± 46	332 ± 26	58 ± 30
$\mu\mu$	201	211 ± 32	211 ± 32	< 0.005
$e\mu$	132	128 ± 9	118 ± 8	10.0 ± 2.5
eee	73	70 ± 7	69.8 ± 7.0	0.2 ± 0.1
$e\mu\mu$	97	102 ± 14	102 ± 14	< 0.005
$ee\mu$	4	1.43 ± 0.26	1.18 ± 0.20	0.25 ± 0.14
$eeee$	1	0.33 ± 0.07	0.33 ± 0.07	< 0.005
$(\gamma\gamma)_e$	146	138 ± 12	135 ± 11	3.0 ± 1.0
$(\gamma\gamma)_\mu$	163	162 ± 24	162 ± 24	< 0.005

M_{12} >100 GeV

Selection	Data	SM	Pair Production (GRAPE)	NC DIS + Compton
All data (463 pb^{-1})				
ee	3	1.34 ± 0.20	0.83 ± 0.11	0.51 ± 0.13
$\mu\mu$	1	0.17 ± 0.07	0.17 ± 0.07	< 0.005
$e\mu$	1	0.59 ± 0.06	0.59 ± 0.06	< 0.005
eee	3	0.66 ± 0.09	0.66 ± 0.09	< 0.005
$e\mu\mu$	2	0.16 ± 0.05	0.16 ± 0.05	< 0.005
e^+p collisions (285 pb^{-1})				
ee	3	0.76 ± 0.11	0.49 ± 0.07	0.27 ± 0.07
$\mu\mu$	1	0.10 ± 0.04	0.10 ± 0.04	< 0.005
$e\mu$	1	0.35 ± 0.04	0.35 ± 0.04	< 0.005
eee	3	0.39 ± 0.05	0.39 ± 0.05	< 0.005
$e\mu\mu$	2	0.09 ± 0.03	0.09 ± 0.03	< 0.005
e^-p collisions (178 pb^{-1})				
ee	0	0.58 ± 0.09	0.34 ± 0.04	0.24 ± 0.07
$\mu\mu$	0	0.07 ± 0.03	0.07 ± 0.03	< 0.005
$e\mu$	0	0.24 ± 0.03	0.24 ± 0.03	< 0.005
eee	0	0.27 ± 0.04	0.27 ± 0.04	< 0.005
$e\mu\mu$	0	0.07 ± 0.03	0.07 ± 0.03	< 0.005

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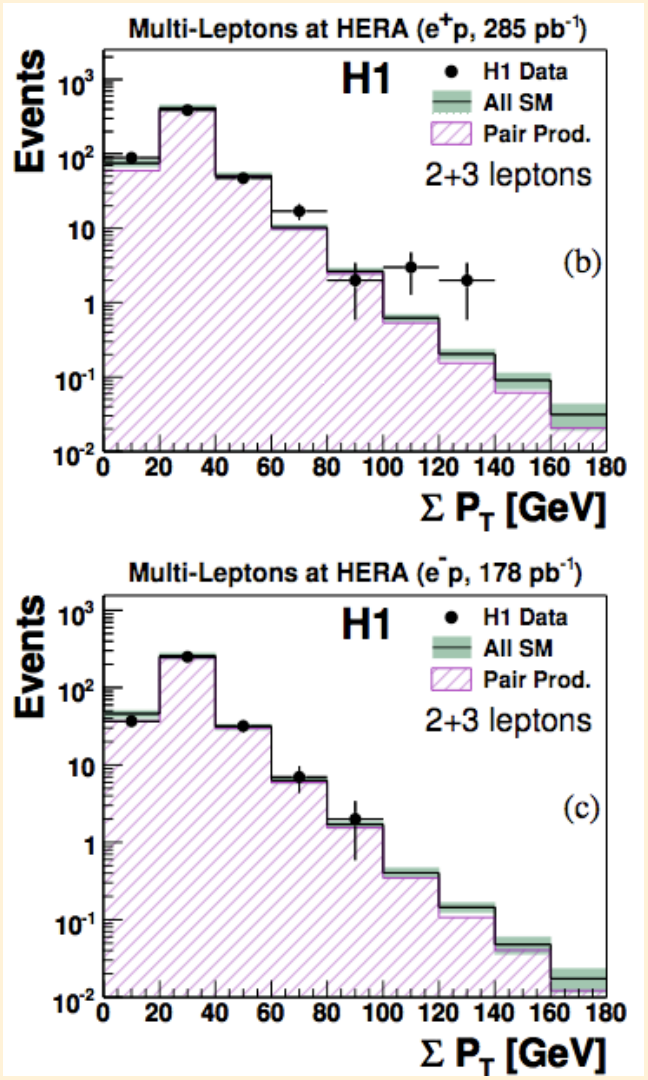
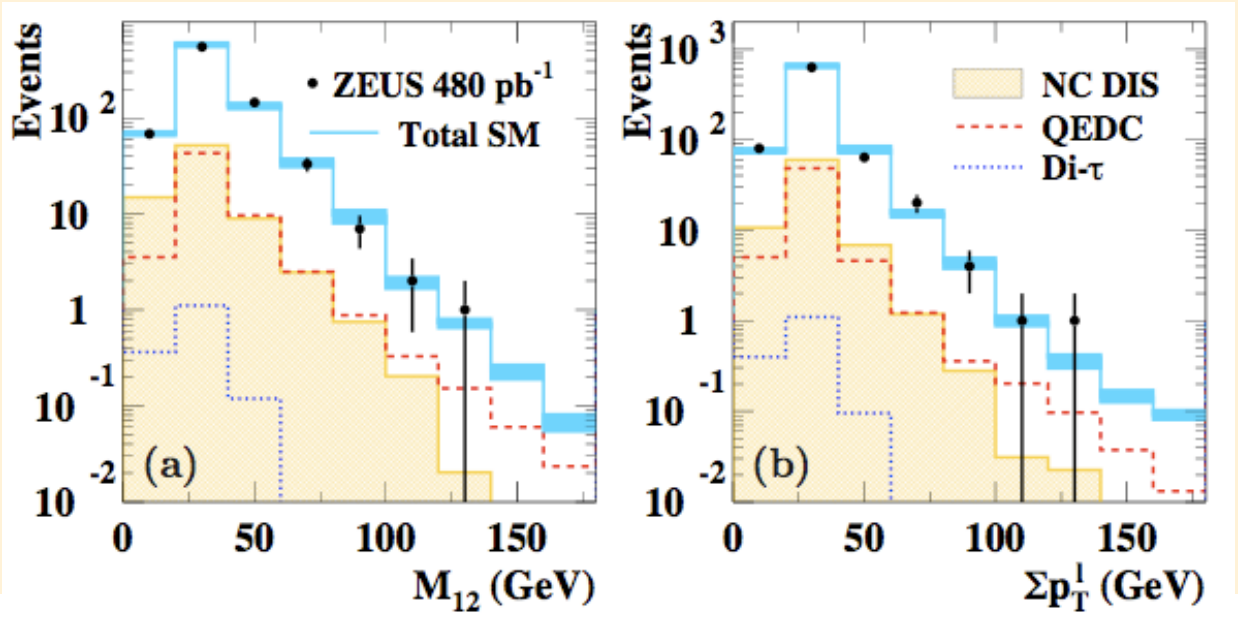


Multi-leptons: ZEUS published results

Phys. Lett. B680 (2009) 13



ZEUS ($\mathcal{L} = 480\,\mathrm{pb}^{-1}$)

Topology, $M_{12} > 100$ GeV	Data	Total SM	Multi-lepton Production	NC DIS	Compton
ee	1	1.7 ± 0.2	0.9 ± 0.1	0.2 ± 0.1	0.6 ± 0.1
$\mu\mu$	0	0.4 ± 0.1	0.4 ± 0.1	< 0.01	–
$e\mu$	0	$0.06^{+0.03}_{-0.01}$	0.05 ± 0.02	< 0.02	–
eee	2	0.7 ± 0.1	0.7 ± 0.1	< 0.01	< 0.02
$e\mu\mu$	0	0.18 ± 0.05	0.18 ± 0.05	< 0.01	–

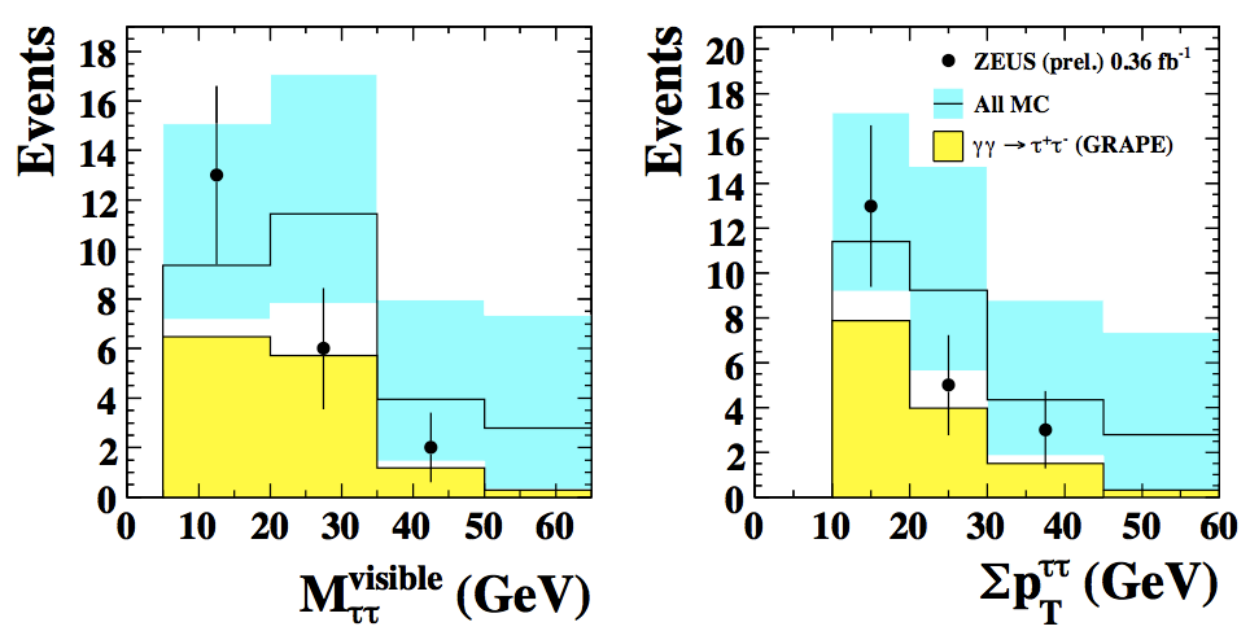
Multi-leptons: multi-Tau analysis (ZEUS)

ZEUS-prel-08-009

ZEUS ditau events HERA II data (L=0.36 fb^{-1})

Topology	All	jet-jet	e-jet-jet	e-jet	e-e-jet
D cut		0.80	0.50	0.90	0.90
Data	21	14	3	4	0
Total SM	$27.2^{+7.1}_{-6.3}$	$20.2^{+6.8}_{-5.7}$	$1.4^{+3.3}_{-0.2}$	$4.9^{+3.1}_{-1.3}$	$0.7^{+4.4}_{-0.1}$
ditau MC	$13.2^{+0.6}_{-1.0}$	$9.1^{+0.4}_{-0.8}$	1.4 ± 0.1	2.2 ± 0.1	0.5 ± 0.1
(purity)	(49%)	(45%)	(97%)	(46%)	(74%)

- Analysis uses HERA II data
- Topologies with jets and electrons investigated



Isolated leptons: published results (ZEUS)

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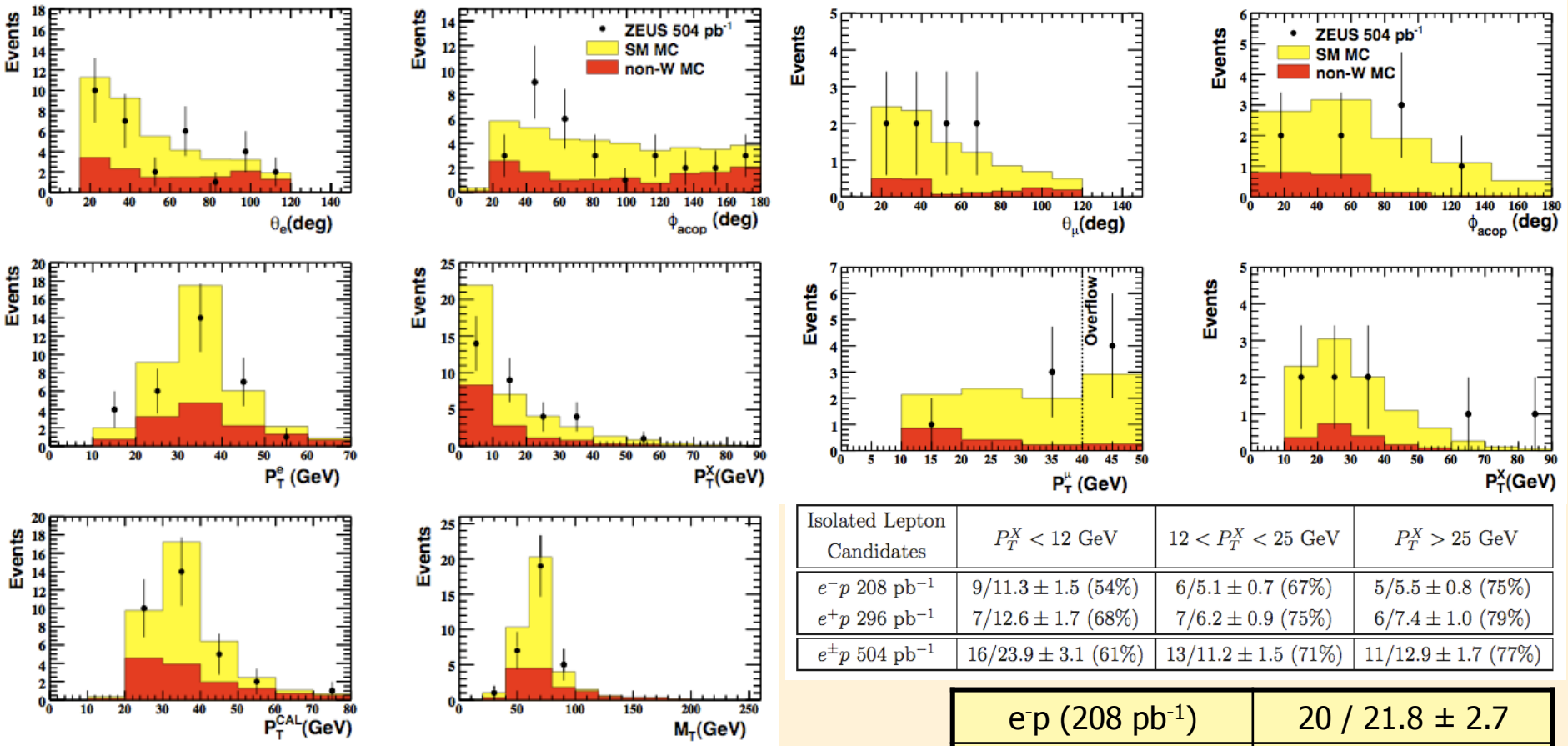
electron channel | **muon channel**



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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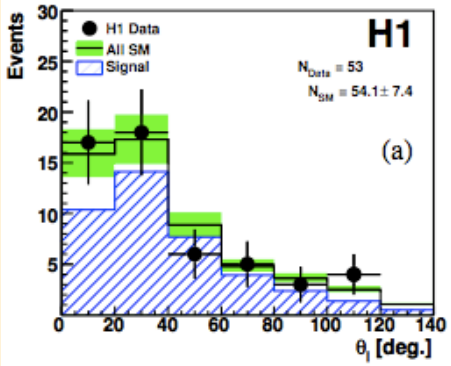

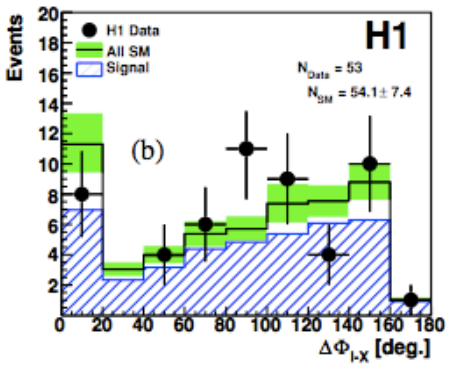

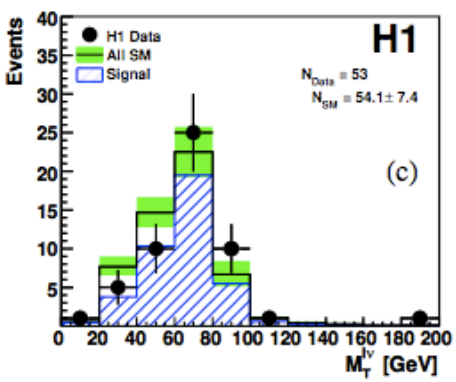

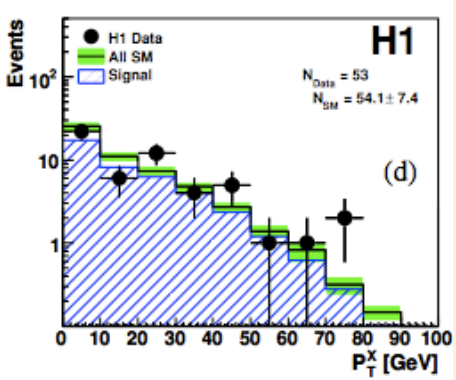

Main difference to combined H1+ZEUS analysis: extended polar angle range down to 5°

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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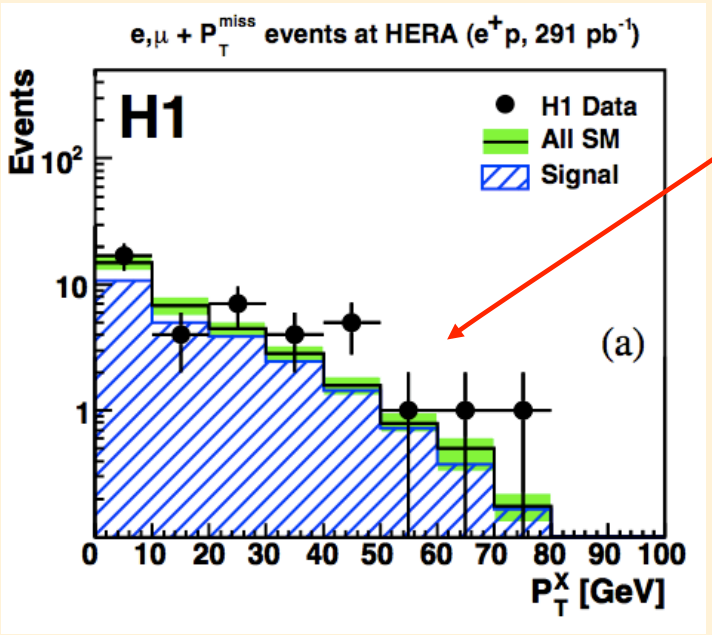

Isolated leptons: Tau channel (H1)

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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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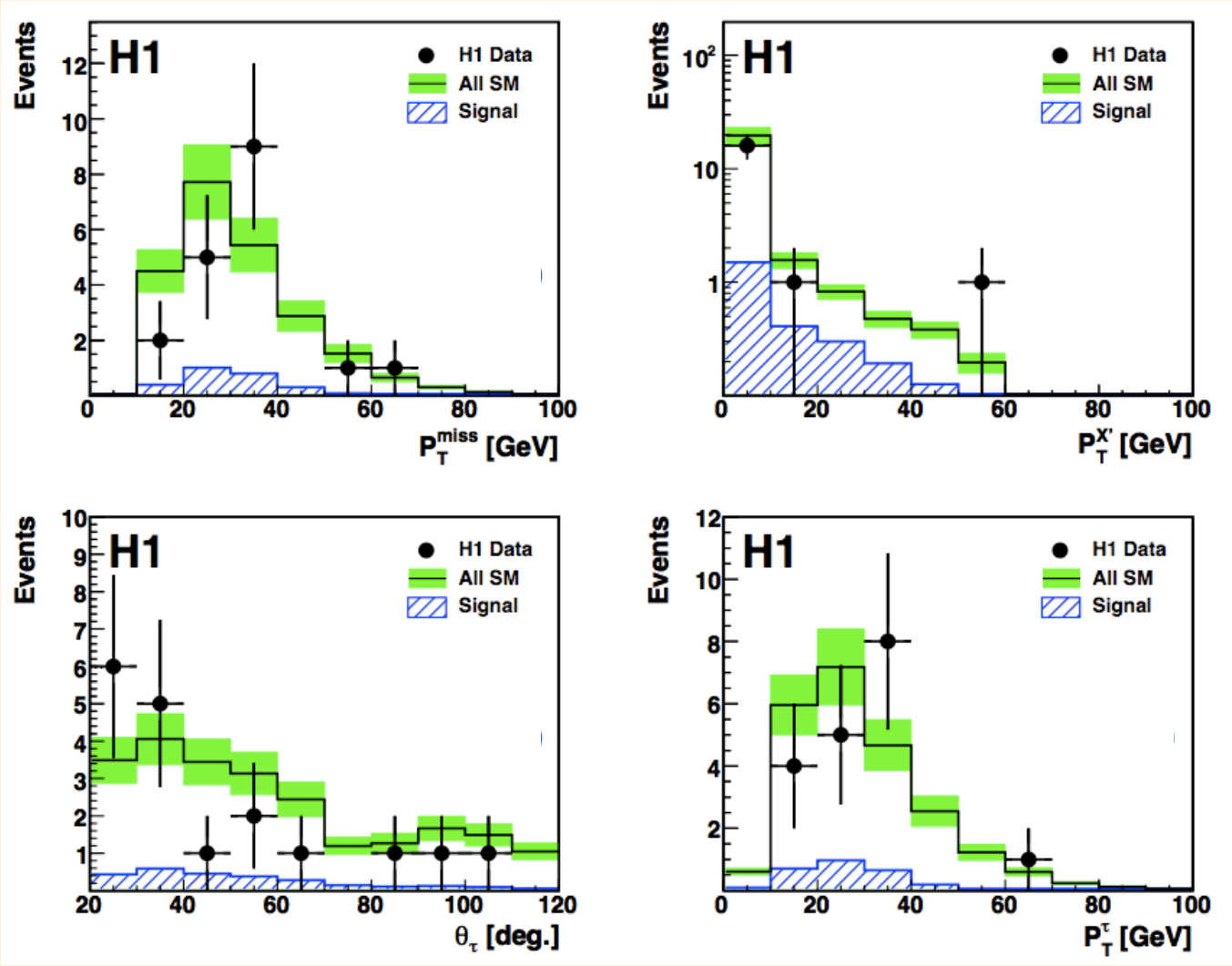
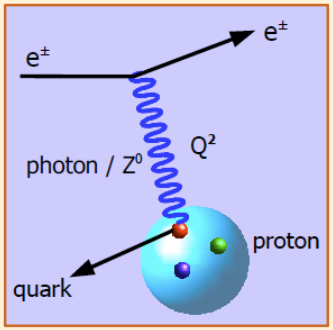
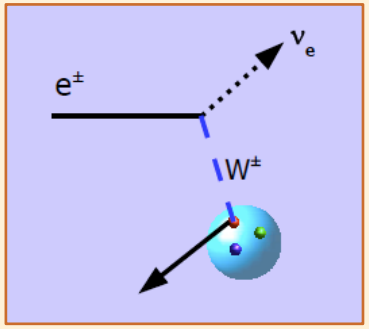


Deep inelastic e±p scattering: basics

Two deep inelastic scattering processes:

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

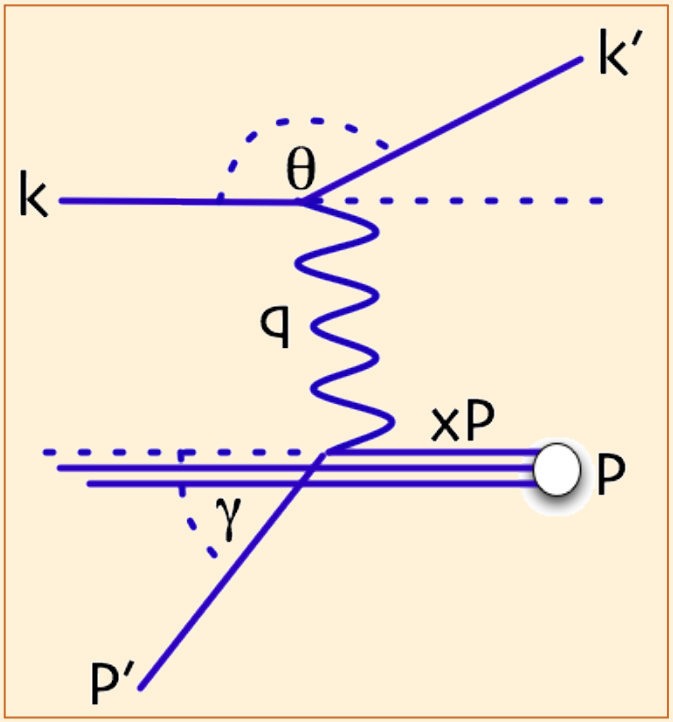




$$Q^2 = -q^2 = -(k - k')^2$$

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

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



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