Isolated Leptons at H1/ZEUS

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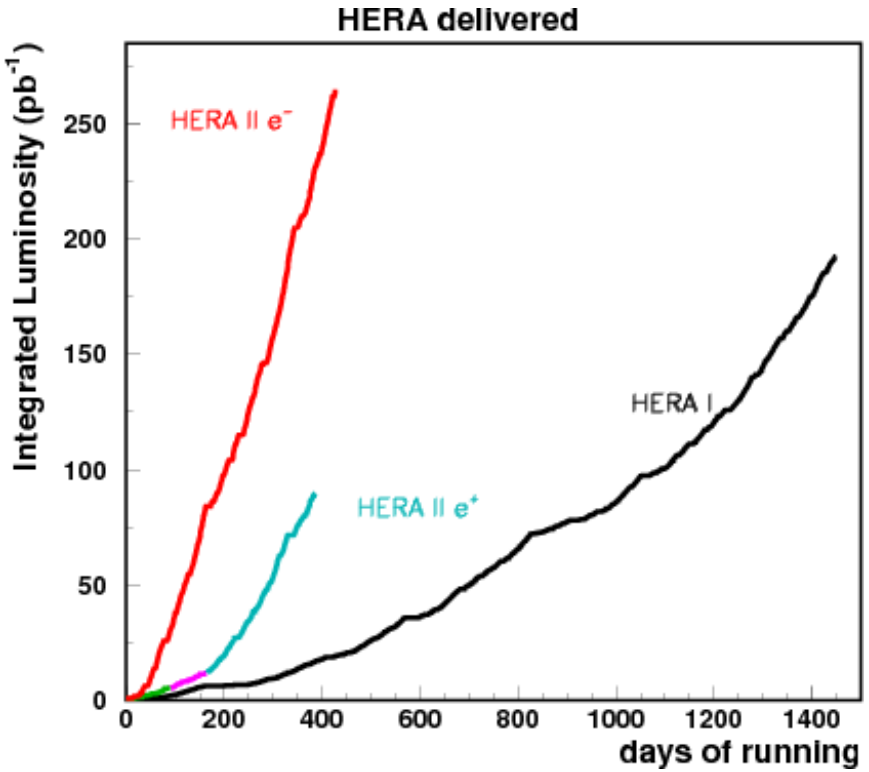
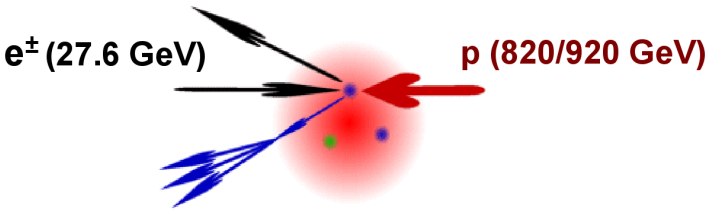
Outline

HERA

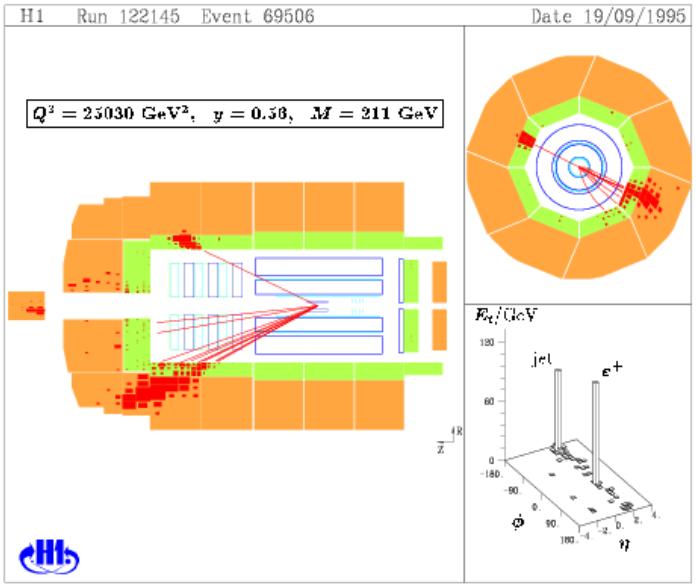


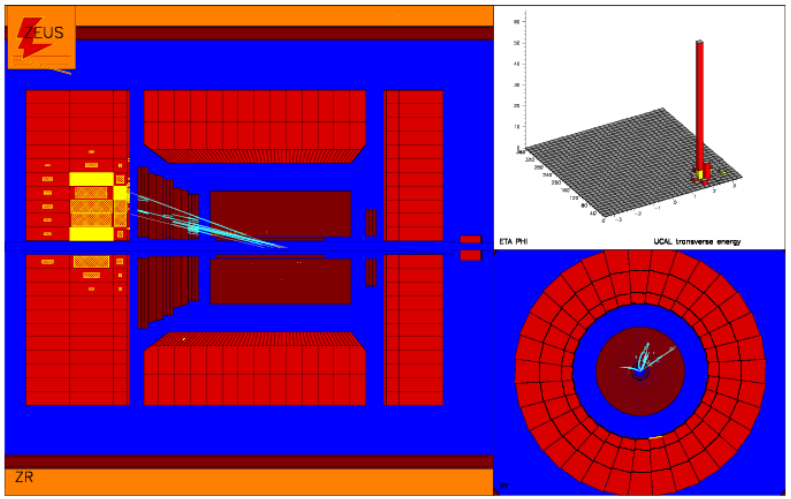
At HERA $e^{\pm}$ are collided with protons at the interaction points of H1 and ZEUS with $\sqrt{s} \approx 320$ GeV



HERA I: ZEUS $\mathcal{L} \sim 130\ \mathrm{pb}^{-1}$
HERA II: ZEUS $\mathcal{L} \sim 310\ \mathrm{pb}^{-1}$
In HERA II the lepton beam is longitudinally polarised

ZEUS & H1





H1

- Liquid Argon Calorimeter
- Optimised for precision measurement of the scattered lepton

ZEUS

- Depleted Uranium Calorimeter
- Optimised for precision measurement of the hadronic final state

HERA Physics

A rich variety of physics topics is available for Study at HERA:

High Q^2

- Structure of Proton
- EW physics: $\sigma_{\mathrm{NC,CC}}$ DIS
- Rare Standard Model processes
- Physics beyond the SM

QCD/Hadronic Final State

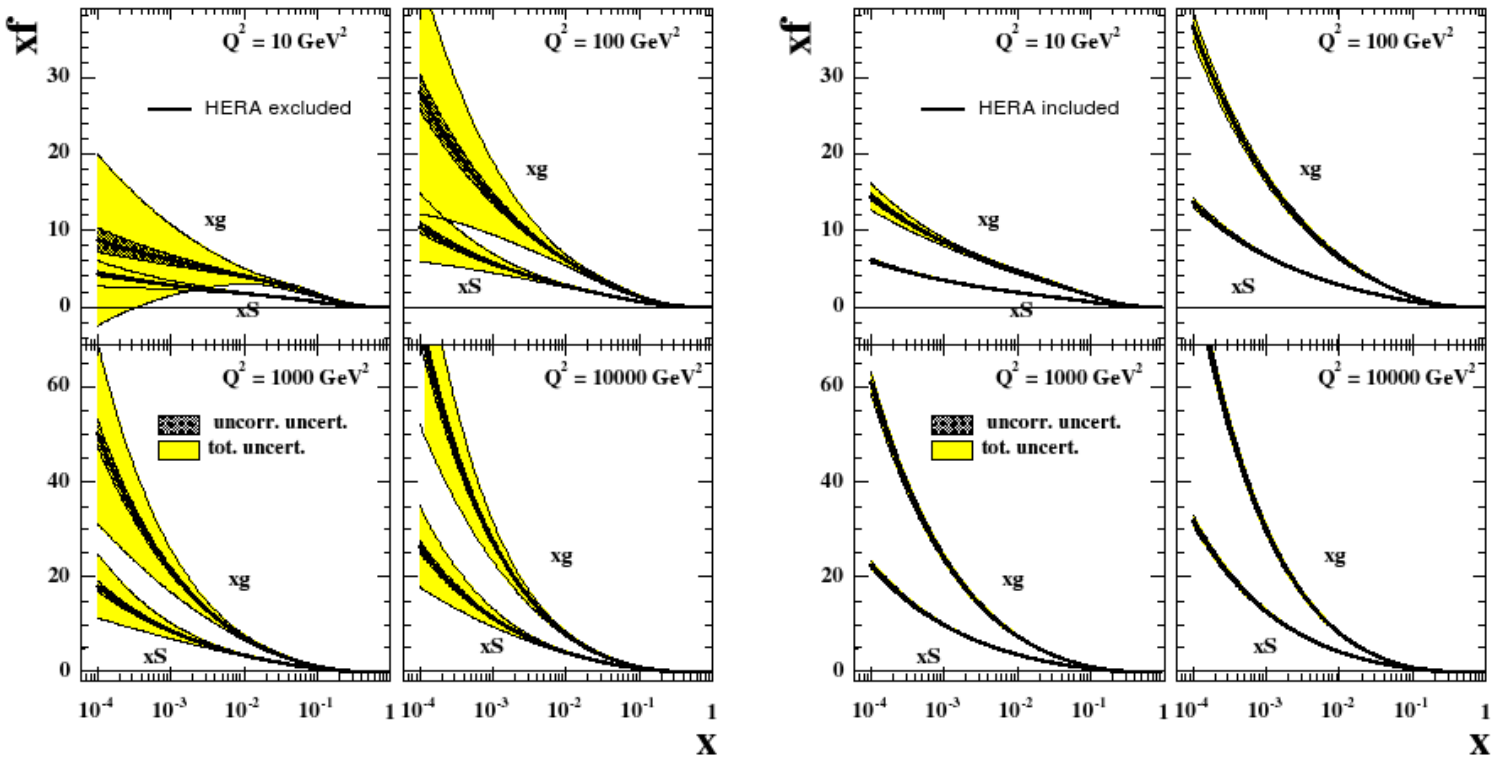
- Photon structure.
- Jet production.
- Particle production.
- Measurements of α_S.

Heavy Flavour

- Production of c, b quarks
- Hadronisation of heavy quarks
- $F_2^{c\bar{c}}$,$F_2^{b\bar{b}}$

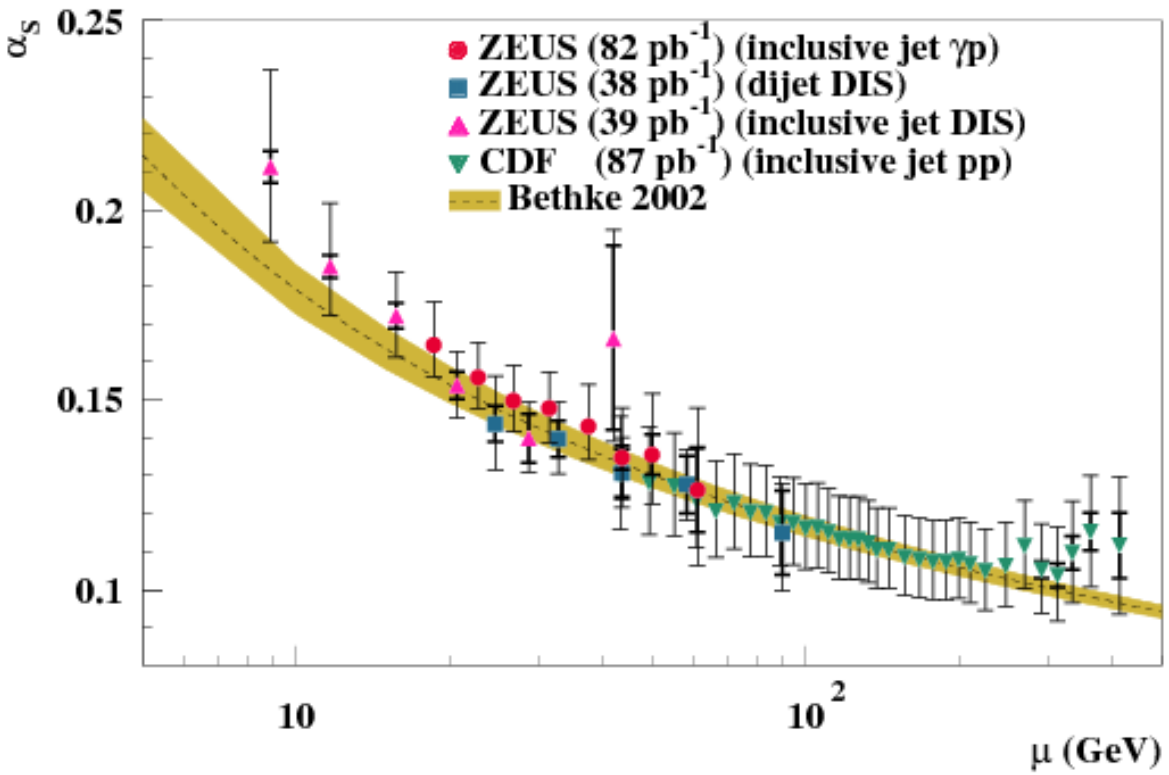
Diffractive/Low x

- Study of events with a large rapidity gap.
- Vector Meson production.



Huge improvement in sea-q and g uncertainties from HERA data

Running of α_S

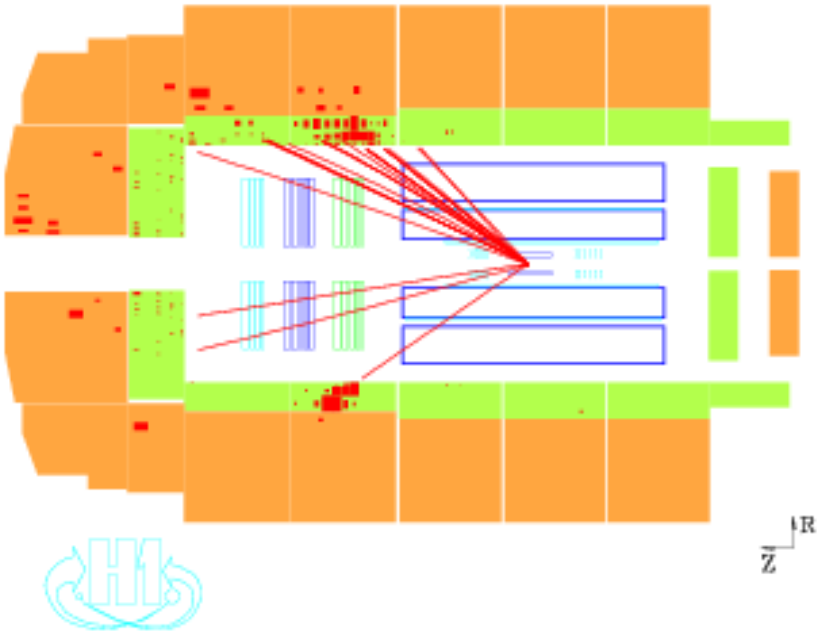


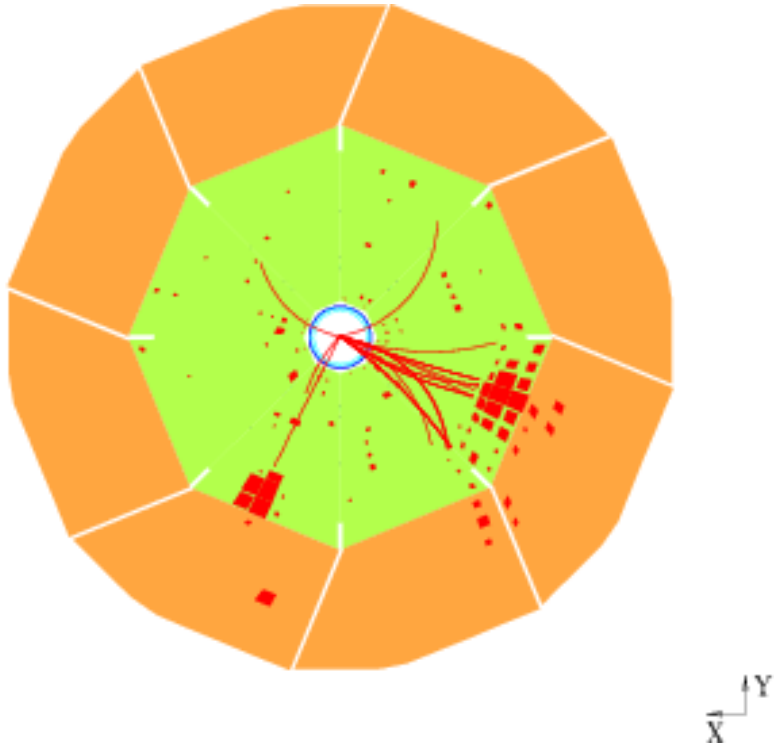
All the measurements are consistent with the running of α_S as predicted by QCD

Several ways to search for BSM physics at HERA:

- Searches for new currents affecting DIS processes:
  - Charged Current DIS
  - Neutral Current DIS
- Model dependent searches for new particles:
  - HERA is not an annihilation machine $\longrightarrow$ the cross section for pair producing heavy new particles is small
  - Single particle production is usually investigated
  - Limits depend on coupling of new particle to SM ones $\longrightarrow$ no absolute mass limits
- Model Independent Searches for new physics:
  - Study SM processes with a low cross-section
  - investigate all possible final states, compare data to SM expectation

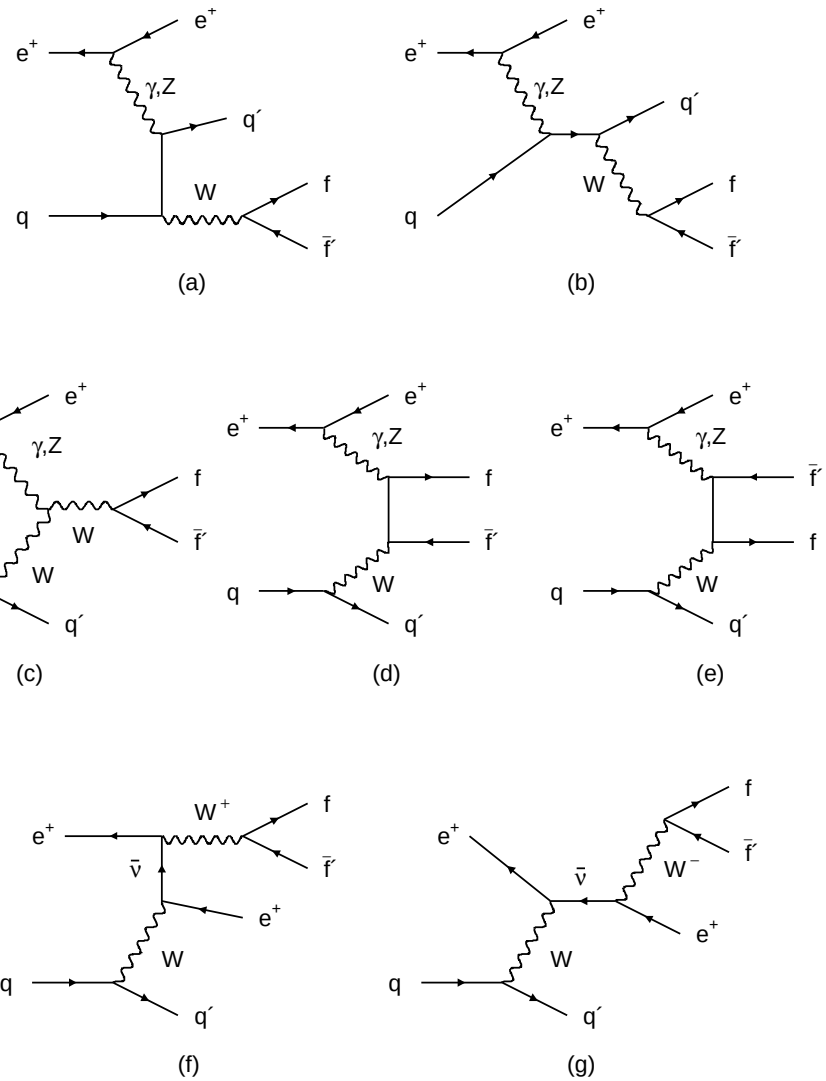
Event Topology





High P_T Isolated leptons in events with large missing P_T are the signature of many BSM processes at HERA
SM source at HERA is Single W production.

Single W Production @ LO



Cross section calculated in:
Nucl. Phys. B375 (1992) 3
Total cross section is ≈ 1.1 pb at $\sqrt{s} = 320$ pb^{-1}. 8 LO Diagrams in LO MC (EPVEC):

- (a) and (b) dominant diagrams
- (c) involves TGC
- (d) and (e) EM gauge invariance
- (f) and (g) suppressed (2^{nd} W)

CC diagrams are similar but σ order of magnitude lower

Uncertainties

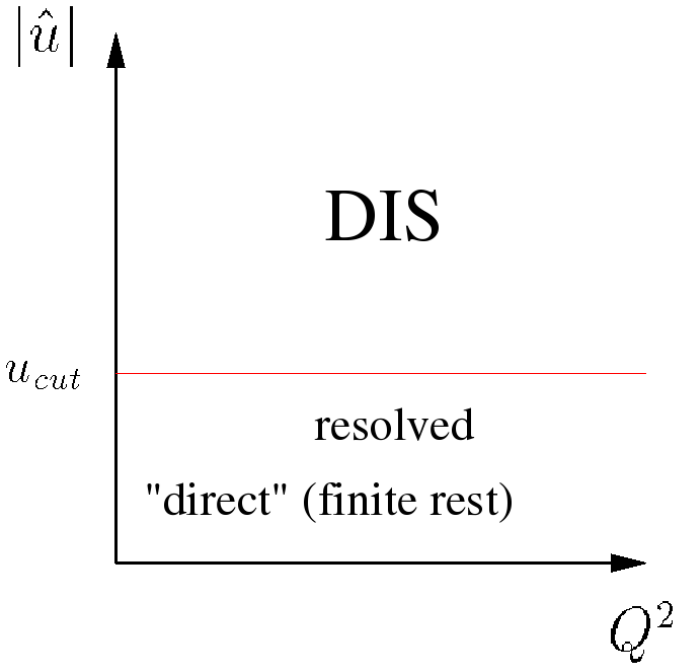
EPVEC splits phase space into:

- DIS part
- RES part

Separated by $u_{\mathrm{cut}} = 25\ \mathrm{GeV}^2$

$$u = (p_q - p_W)^2$$

W^+ and W^- generated separately



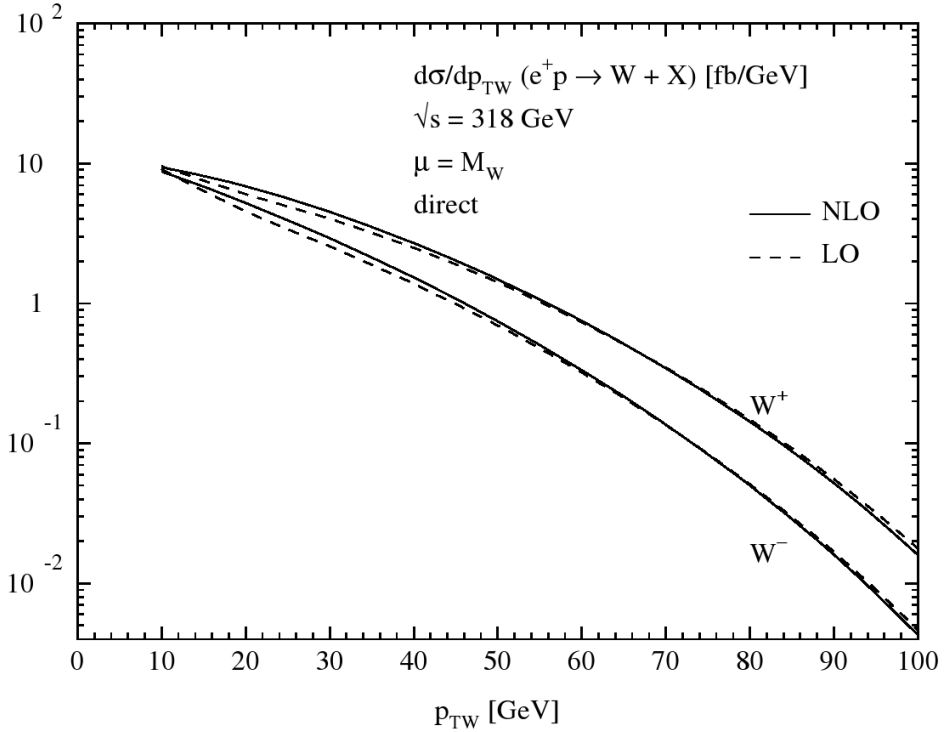
The following uncertainties exist on the EPVEC calculation

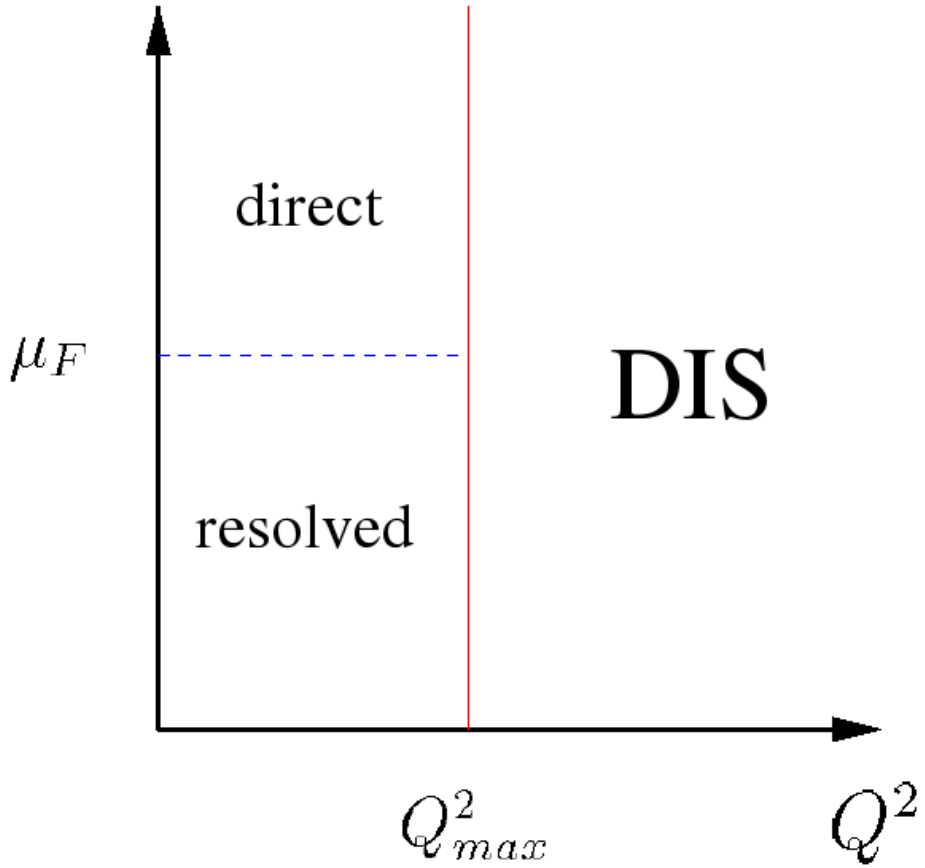
- 5% from u_{cut}
- 10% from Q^2 scale
- 10 % PDFs

adding QCD NLO term uncertainty gives total $\sim 30\%$

NLO calculation

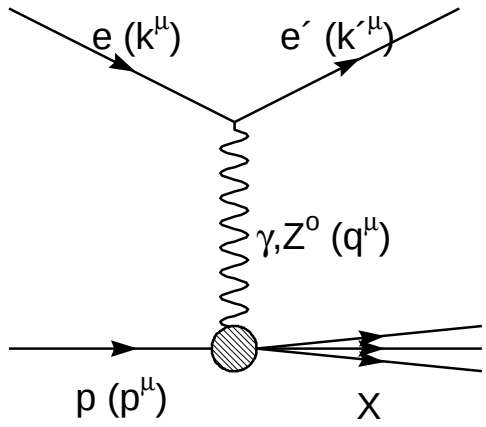
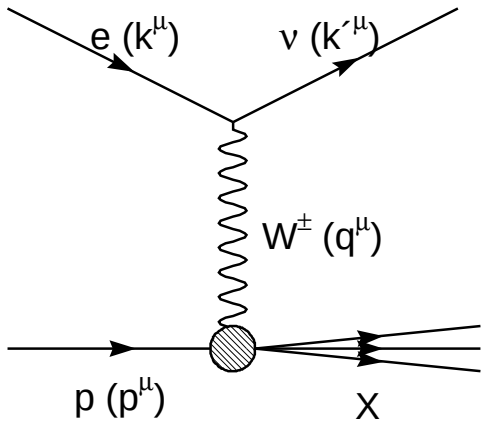
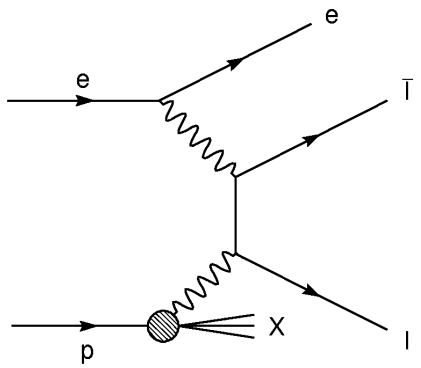
A calculation including NLO QCD corrections exist: Diener, Schwanenberger & Spira
hep-ph/0203269
Uncertainty 10%





LO MC can be reweighted to this calculation

Backgrounds

NC DIS	CC DIS	Dilepton production
		
Genuine electron and fake P_T^{miss} due to mismeasurement	misidentified lepton and genuine P_T^{miss}	Genuine μ and fake P_T^{miss} due to mismeasurement
$\sigma \approx 8000$ pb	$\sigma \approx 40$ pb	$\sigma \approx 30$ pb

Selection

Examples of cuts used in most recent analyses:

	H1	ZEUS
Lepton within detector acceptance	$5^\circ < \theta < 140^\circ$	$\theta_e < 86^\circ$ $\theta_\mu < 115^\circ$
High Transverse Momentum of Lepton	$p_T^l > 10\,\text{GeV}$	$p_T^l > 10\,\text{GeV}$
Lepton Isolation	$D_{\text{track}} > 0.5$ $D_{\text{jet}} > 1.0$	$D_{\text{track}} > 0.5$ implicit
Large Missing Transverse Momentum	$P_T^{\text{miss}} > 12\,\text{GeV}$	$P_T^{\text{miss}} > 12\,\text{GeV}$
Acoplanarity	$e : \phi_{\text{acop}} > 20^\circ$ $\mu : \phi_{\text{acop}} > 10^\circ$	$e : \phi_{\text{acop}} > 17^\circ$ $\mu : \phi_{\text{acop}} > 11^\circ$

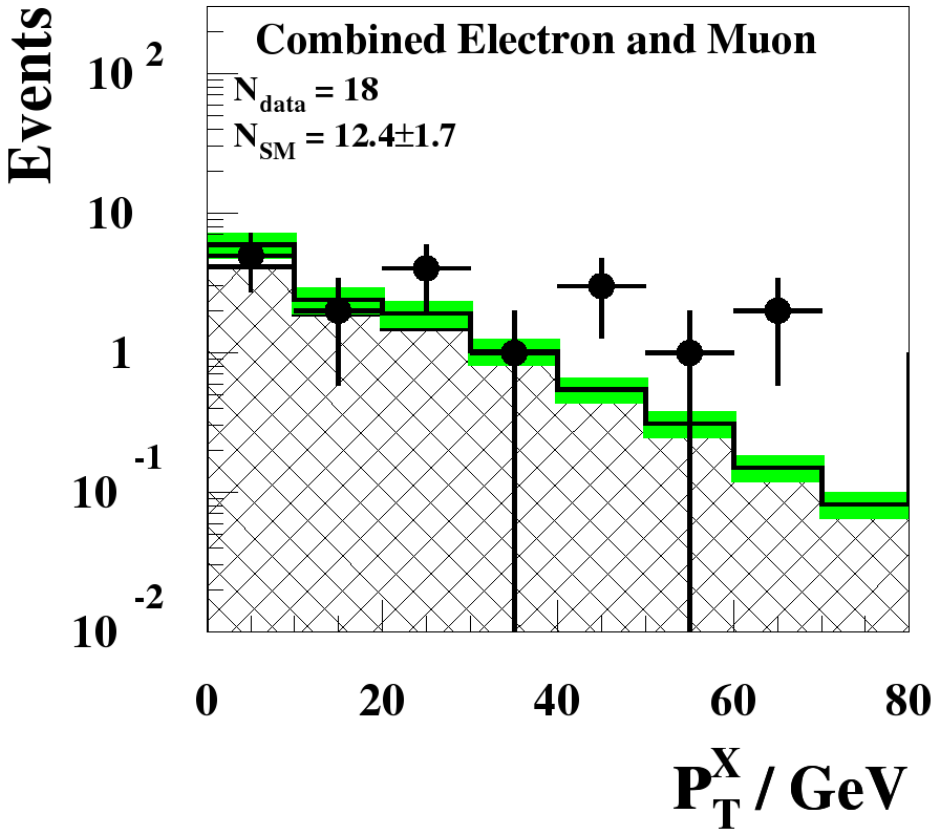
H1 Searches
e & μ

Early searches by the H1 collaboration for isolated e and μ showed an excess over SM predictions:

H1 Collab., C. Adloff et al., Eur. Phys. J. C5 (1998) 575

H1 Collab., V. Andreev et al., Phys. Lett. B561 (2003) 241

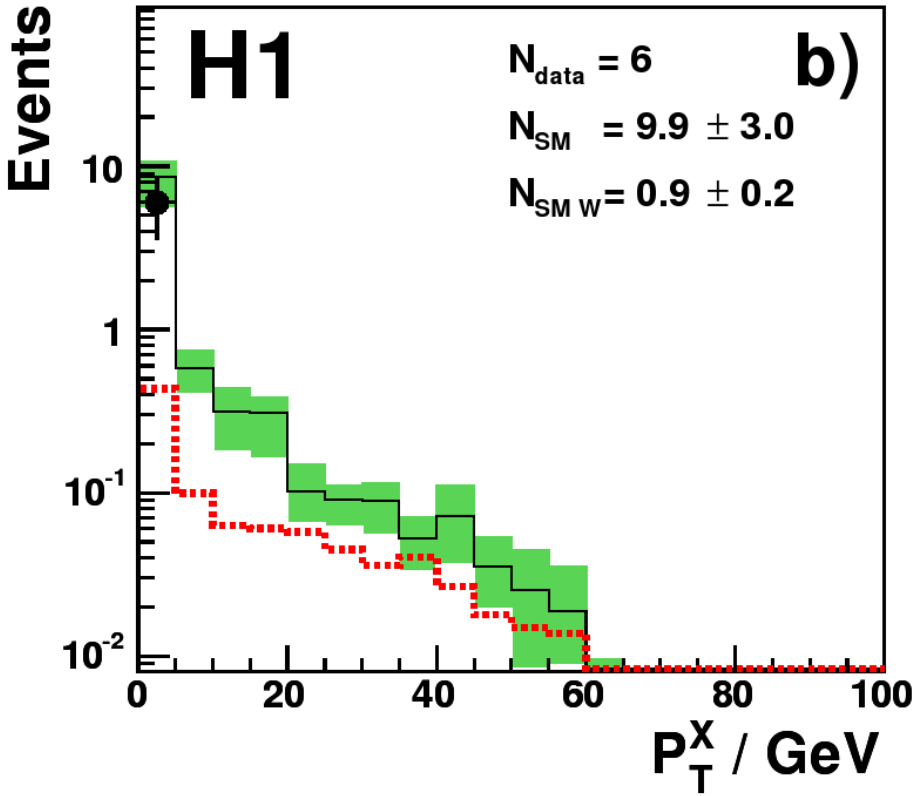
Excess occurs at large hadronic transverse momentum (P_T^X)



H1 118.4 pb^{-1} 94-00 $e^{\pm}p$	e obs./exp.($W^{\pm}$)	μ obs./exp. ($W^{\pm}$)
all P_T^X	11 / 11.5 $\pm$ 1.5(71%)	8 / 2.9 $\pm$ 0.5(86%)
$p_T^X > 25$ GeV	5 / 1.8 $\pm$ 0.3(82%)	6 / 1.7 $\pm$ 0.3(88%)

H1 Searches

τ



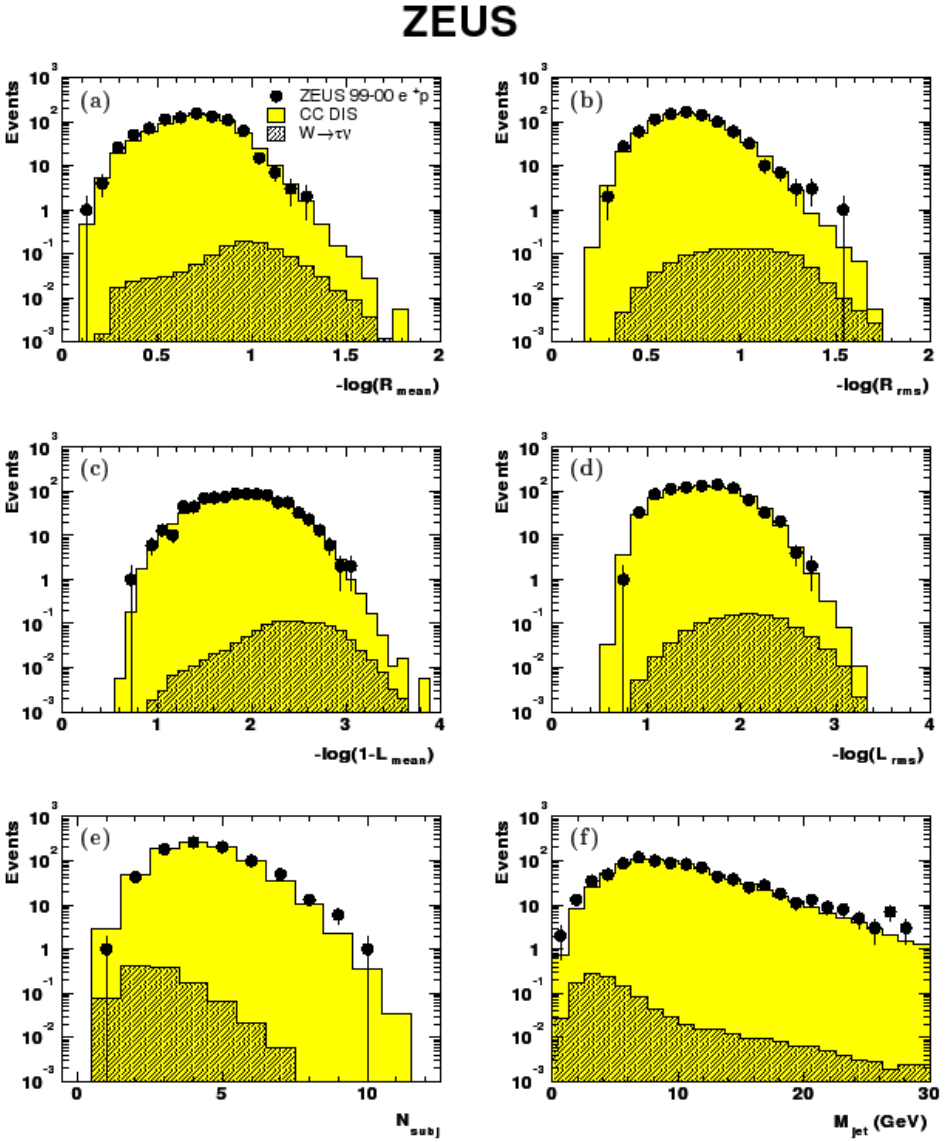
τ finding is very challenging at HERA, approach used by both H1 and ZEUS is to use 1-prong hadronic decays and dicriminate from QCD background via jet shape variables

H1 118.4 pb^{-1} 94-00 $e^{\pm}p$	τ obs./exp.($W^{\pm}$)
all P_T^X	6 / $9.9^{+2.5}_{-3.6}$(9%)
$p_T^X > 25$ GeV	0 / $0.39^{+0.09}_{-0.11}$(51%)

No τ channel excess observed by H1

H1 Collab., A. Aktas et al., Accepted by Eur. Phys. J. C

ZEUS τ Search



Physics Letters B 583 (2004) 41

- Main background to τ jets is QCD jets
- Individual jet shape variables do not offer clear separation

ZEUS τ Search Method

- Multivariate Discriminant $\mathcal{D}$ used to separate τ jets from QCD jets:

$$\mathcal{D}(\mathbf{x}) = \frac{\rho_{\mathrm{sig}}(\mathbf{x})}{\rho_{\mathrm{sig}}(\mathbf{x}) + \rho_{\mathrm{bkg}}(\mathbf{x})}$$

- x is a state vector formed using six jet shape variables
- Full 6 dimensional phase space is populated using signal and background MC and stored in memory
- The trees are weighted so that the total number of weighted jets in signal and background trees are equal
- The number of signal (n_{sig}) and background (n_{bkg}) jets in a 6-dimensional box around data jets is counted
- $\mathcal{D}$ can then be evaluated as:

$$\mathcal{D}(\mathbf{x}) = \frac{n_{\mathrm{sig}}(\mathbf{x})}{n_{\mathrm{sig}}(\mathbf{x}) + n_{\mathrm{bkg}}(\mathbf{x})}$$

- The size of the boxes used, and minimum $n_{\mathrm{sig}} + n_{\mathrm{bkg}}$ are parameters tuned to optimise performance

Virtues of this method

- Intuitive, we are just counting signal and background jets to evaluate our discriminating function
- Simple to implement
- No extrapolation outside of well populated MC phase space (minimum number of events cut off)

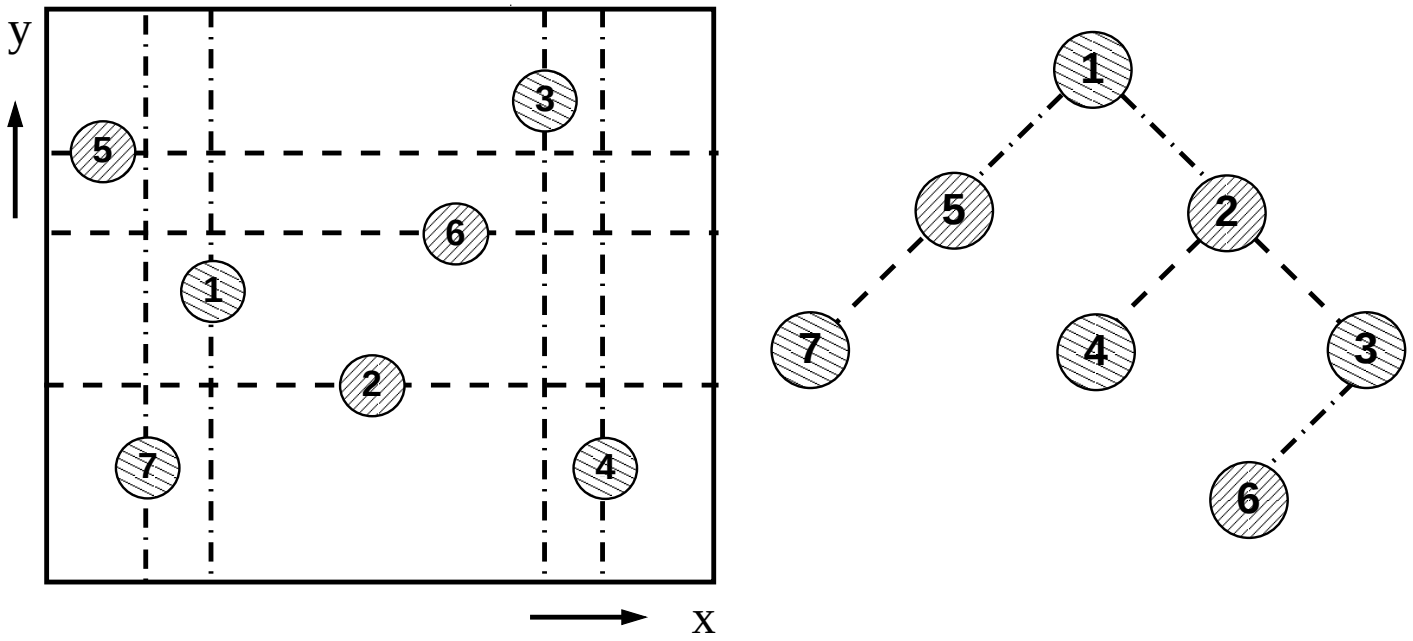
Disadvantage:

- For very large training samples and large numbers of dimensions requires a large amount of memory.
- CPU needed for simplistic implementation of counting scales as $\propto n_{\mathrm{tot}}$ where n_{tot} is the total number of jets in the training sample

Use of the Range Search Algorithm makes CPU time needed $\propto \ln n$

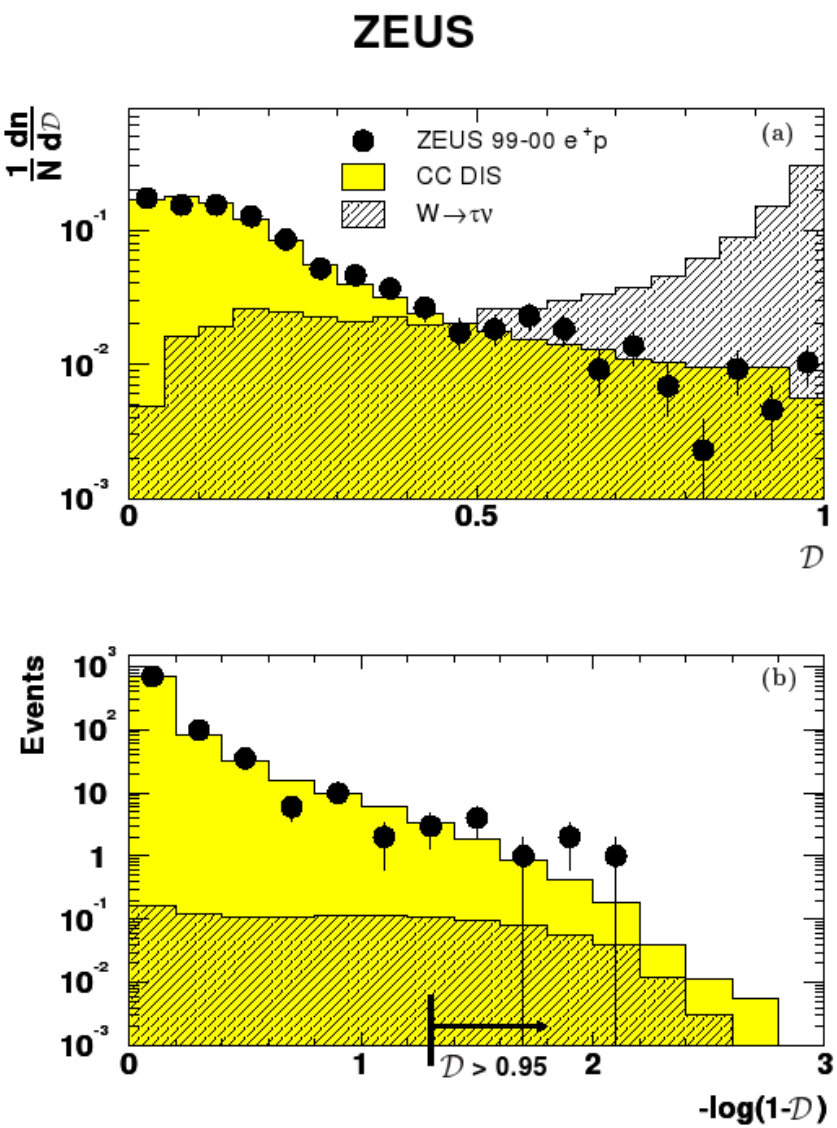
Range Search Algorithm

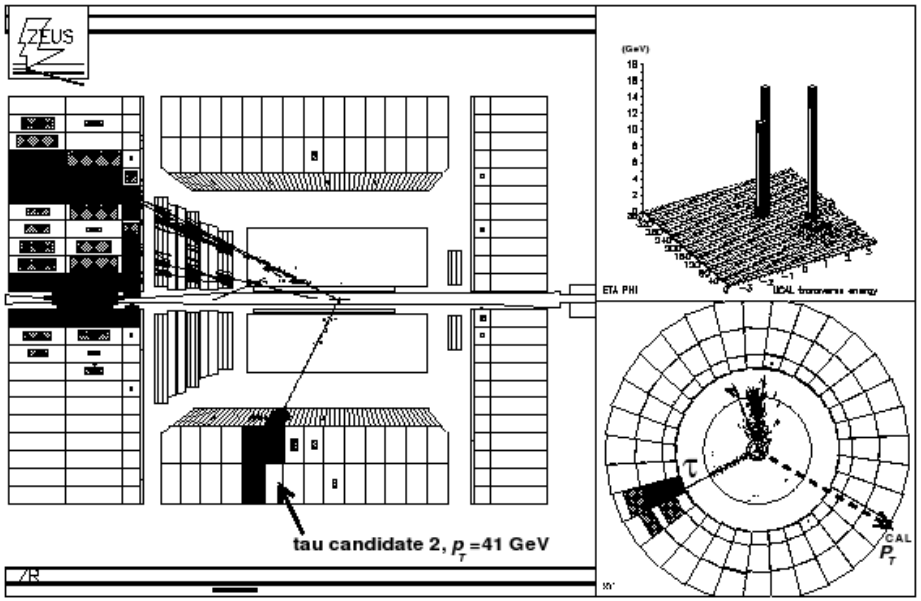
2 dimensional example of storing events as binary trees:



- At each level i, $x_{i\%2}$ of events compared (call events a and b)
- if $x_i^b > x_i^a$ go right, if $x_i^b < x_i^a$ go left
- number of events to search halves at each level

ZEUS τ Search





- Discriminant used simply to classify jets as τ jets

ZEUS also searched for isolated e,μ:

Physics Letters B 471, (2000) 4, 411

Physics Letters B 559 (2003) 153

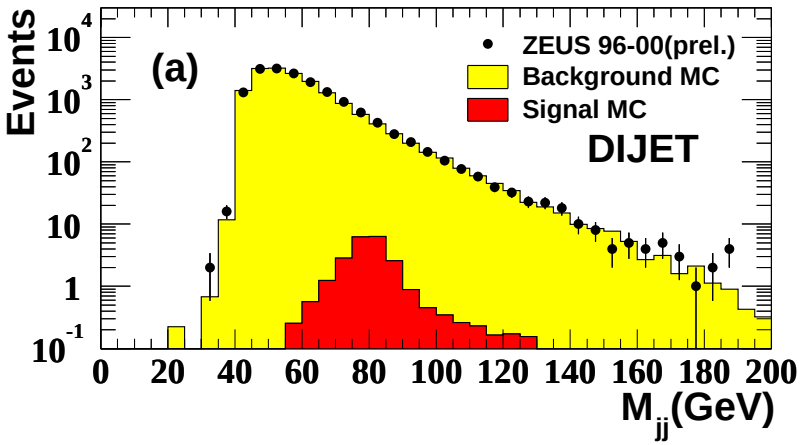
The following numbers were obtained in the context of a search for single top production:

ZEUS 130.1 pb^{-1}	e	μ	τ
$P_T^X > 25$ GeV	$2/2.90^{+0.59}_{-0.32}(45\%)$	$5/2.75^{+0.21}_{-0.21}(50\%)$	$2/0.20^{+0.05}_{-0.05}$

The excess observed by H1 in the electron and muon channels was not confirmed

A small excess was observed in the τ channel

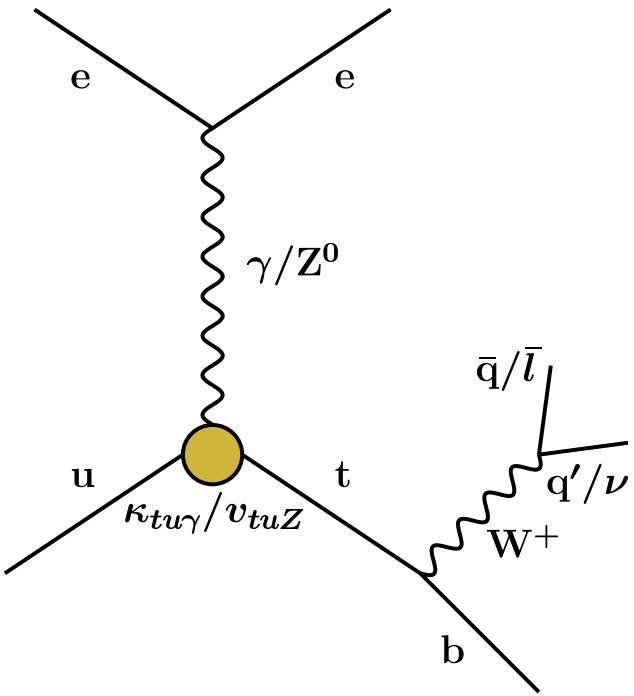
If the excess comes from anomalous couplings that enhance single W production then it might also be visible in the hadronic channel



- Events containing to high E_T jets were selected
- Invariant mass spectra fitted
- W cross section extracted:

$$\sigma_{ep\rightarrow eWX} = 2.97 \pm 2.51(\mathrm{st.})^{+1.75}_{-0.53}(\mathrm{sy.})\ \mathrm{pb}$$

- Limit of $\sigma_{ep\rightarrow eWX} < 8.3$ pb extracted
- Hadronic channel is not so sensitive as leptonic channel

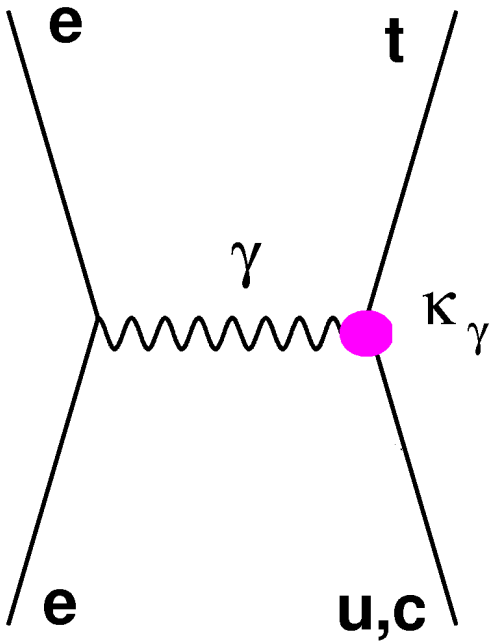


- Single Top Production (STP) via FCNC as a Standard Model Process:
  - Not a tree level SM process
  - Small σ (GIM mechanism): $\sigma < 1$ fb
- Events at HERA attributable to STP would unambiguously signal new physics
- Final State: Isolated High P_T isolated lepton in event with large total missing transverse momentum and large hadronic P_T

Single Top Production via Anomalous FCNC

$$\Delta\mathcal{L}_{\text{eff}} = ee_t\bar{t}\frac{i\sigma_{\mu\nu}}{\Lambda}\kappa_{tu\gamma}A^{\mu\nu} + \frac{g}{2\cos\theta_W}\bar{t}\gamma_\mu v_{tuZ}Z^{\mu\nu} + \text{h.c.}; \quad (1)$$

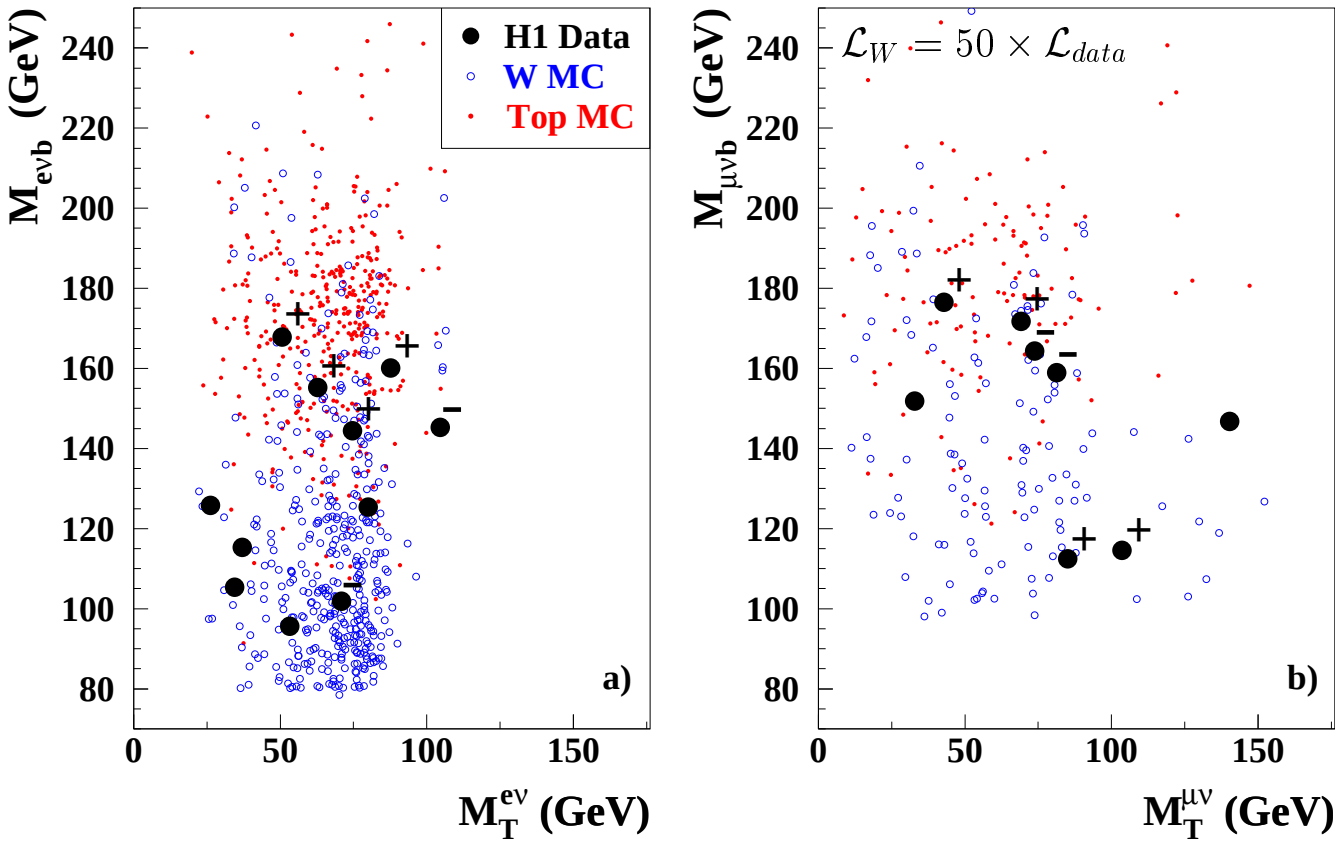
Experiments at both LEP and TeVatron are also sensitive to these FCNC couplings.



- LEP diagram similar to HERA diagram
- At TeVatron $t \rightarrow q\gamma/Z$ decays give sensitivity to the same couplings
- LHC will also be sensitive via $t \rightarrow q\gamma/Z$

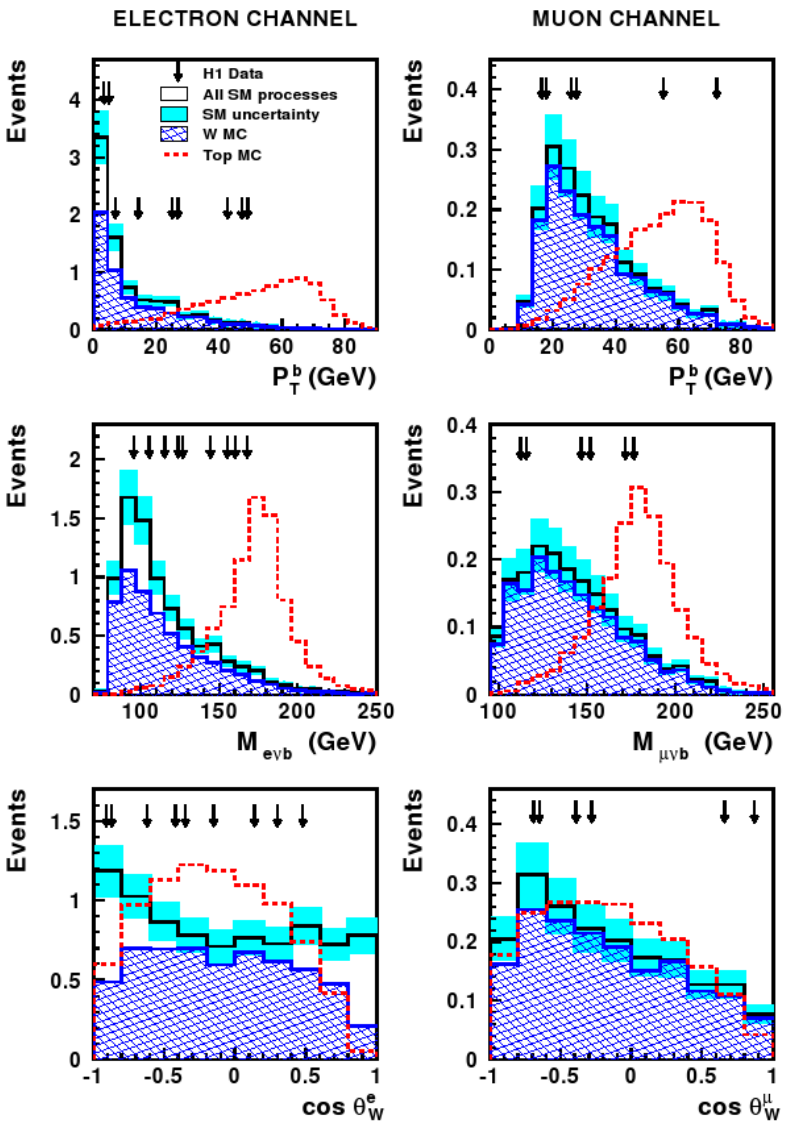
Lagrangians are slightly different, but limits can be compared.

H1 Single Top



- b reconstructed from sum of all jets in event
- W mass constraint applied $M_{l\nu} \approx= \sqrt{2 P_l p_\nu} \approx= M_W$

H1 Single Top



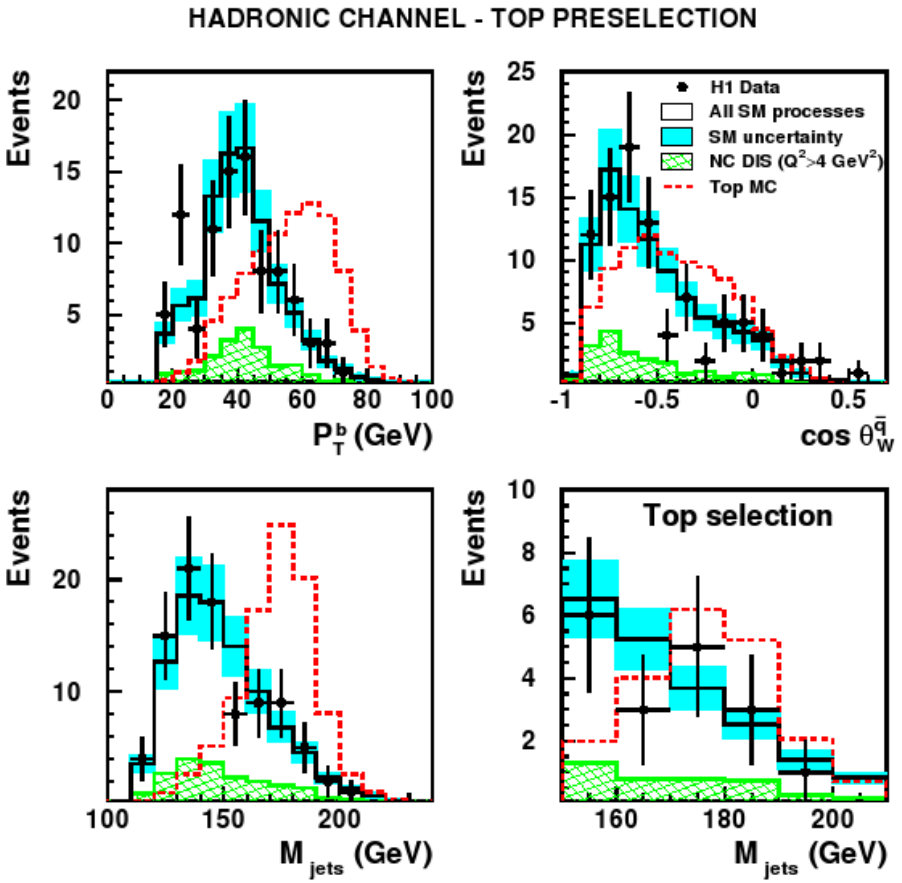
- Multivariate likelihood analysis is used, based on the discriminator function:

$$D(V) = \frac{\mathcal{P}^{\mathrm{sig}}}{\mathcal{P}^{\mathrm{sig}} + \mathcal{P}^{\mathrm{bkg}}},$$
$$\mathcal{P} = C(V)\Pi_i p_i$$

  Method described in D.Karlen **Computers in Physics 12 (1998) 380**

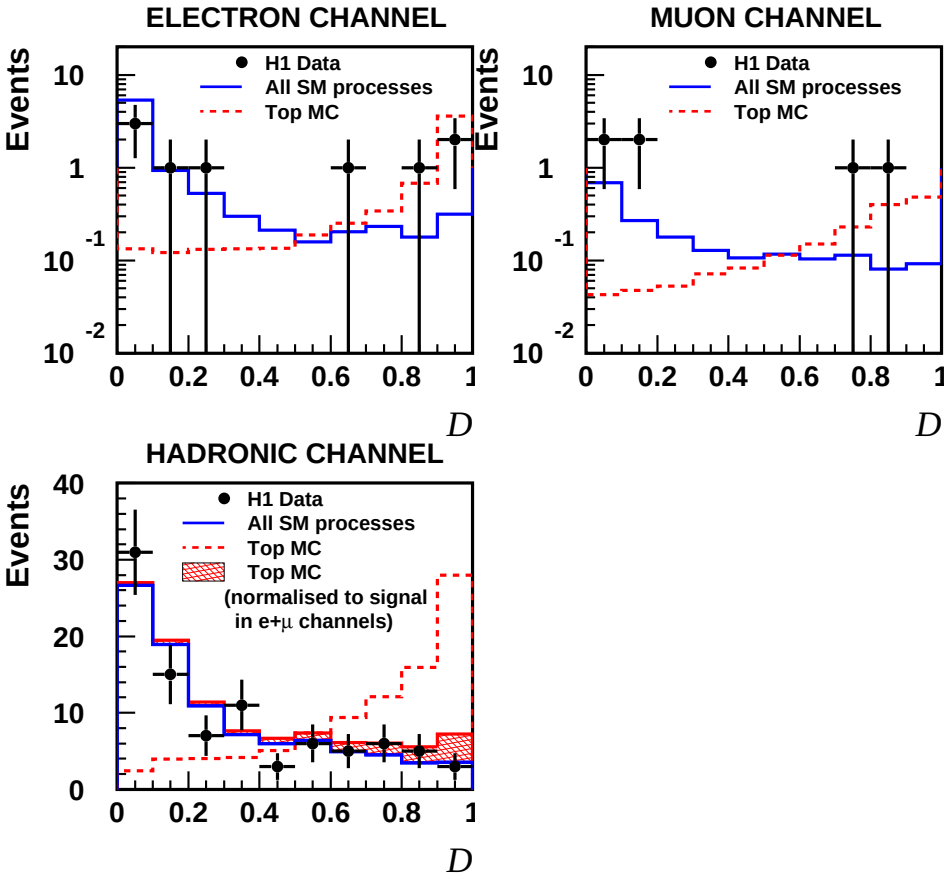
- In the leptonic channels Discriminator is constructed from P_T^b, $M_{l\nu b}$ and the decay angle of the W relative to its momentum ($\cos\theta_W$)

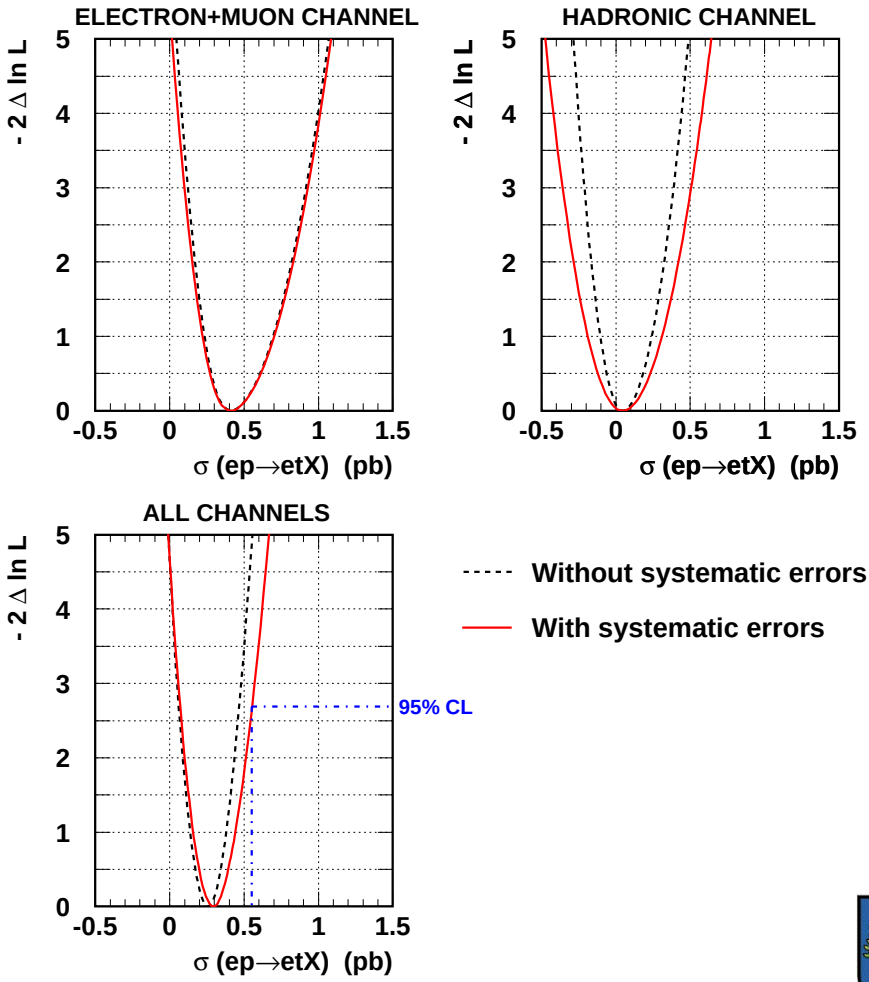
H1 Single Top



- Preselection $E_T^{\text{jet1}} > 40$ GeV, $E_T^{\text{jet2}} > 30$ GeV, $E_T^{\text{jet3}} > 15$ GeV, $E_{\text{tot}} > 110$ GeV. $65 < M_{jj} < 95$ GeV for any two jets
- Discriminator constructed from P_T^b, M_{jets} and $\cos\theta_W$

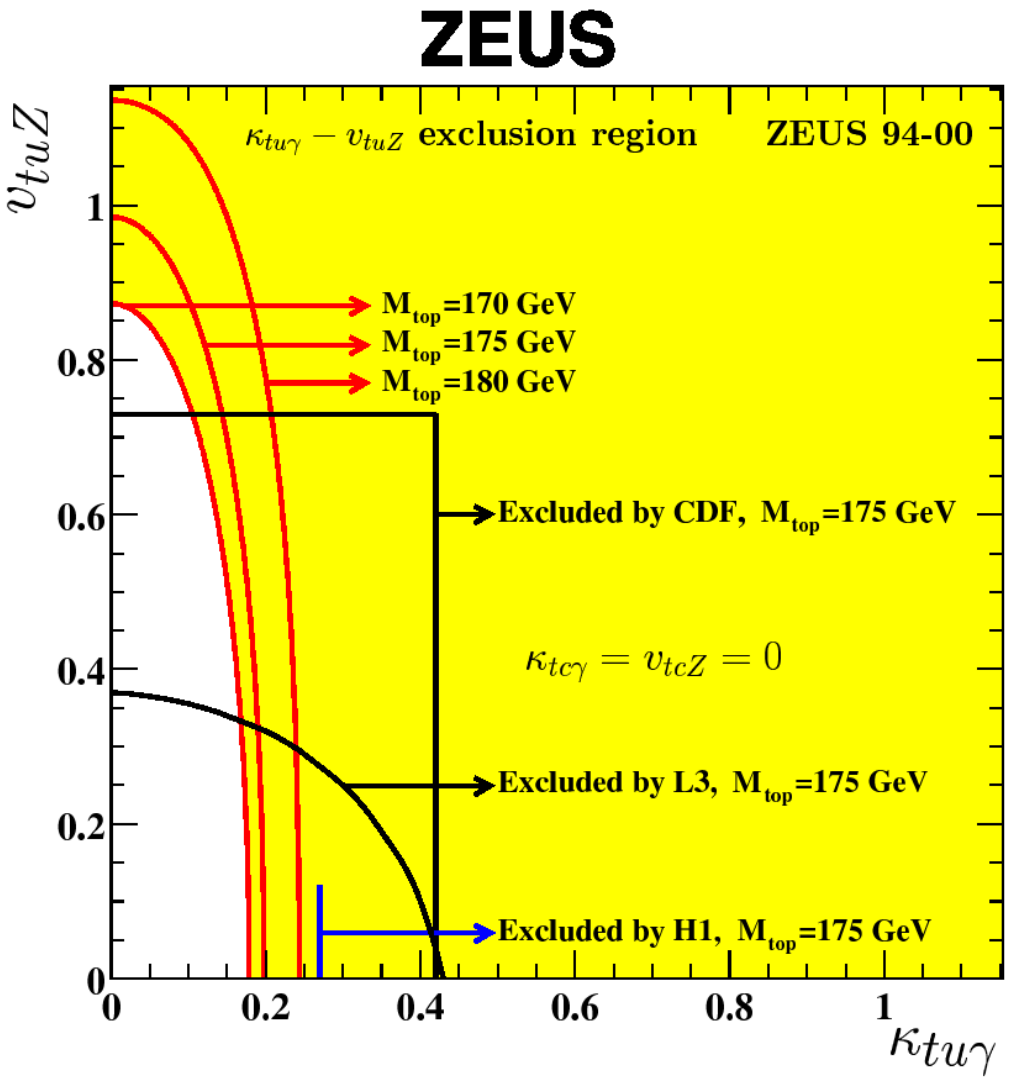
H1 Single Top





Signal is extracted from simultaneous fits to discriminant

Limits



- H1 excess compatible with FCNC limits from L3 & CDF
- Run II results from CDF/D0 could help clarify the situation
- Single Top Production results from TeVatron are also sensitive to these couplings
- LHC will also have something to say

Significance of Excess

- Excess observed by H1 in e, μ channels
- Excess observed by ZEUS in μ, τ channels
- We need to assess how significant the excess is, otherwise numbers are meaningless
- Common framework is to quote the probability of a fluctuation from the SM giving the same or larger excess (p-value)
- This p-value can be translated into 'σ' by analogy with a simple normal probability distribution

Significance Example

Consider H1 e, μ : H1 Collab., V. Andreev et al., Phys. Lett. B561 (2003) 241

According to this publication the probability an excess of $(11/3.5 \pm 0.6)$ is observed.

We now examine the significance of this excess:

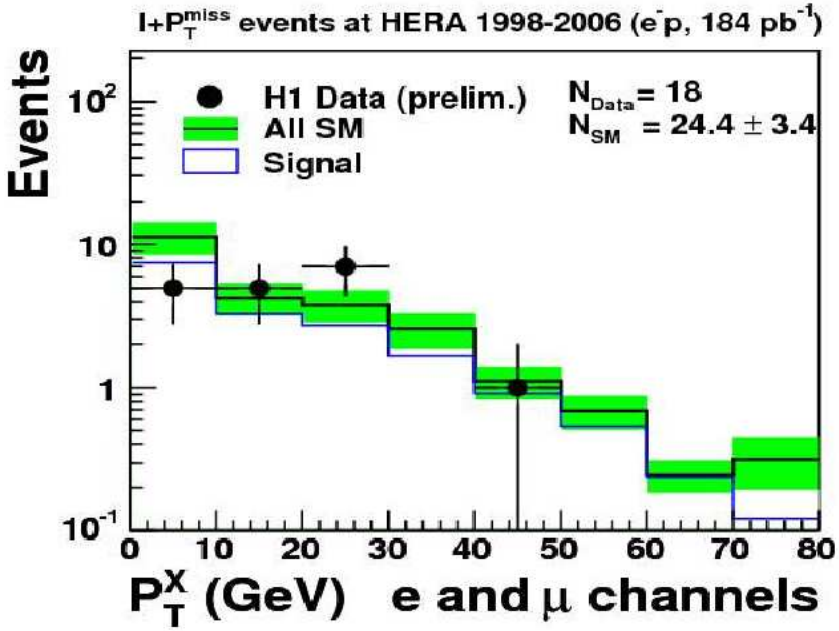
- Consider a perfectly precise SM prediction of exactly p events
- The probability of observing n events is described by a Poissonian $\mathcal{P}(n; p) = \frac{e^{-p} p^n}{n!}$
- In fact we have an error on the prediction, we treat this as gaussian, and convolute a gaussian of width 0.6 and mean 3.5 with the Poissonian distribution
- Numerically integrate from $n \to \infty$ to obtain the probability of observing this excess or larger (0.002)

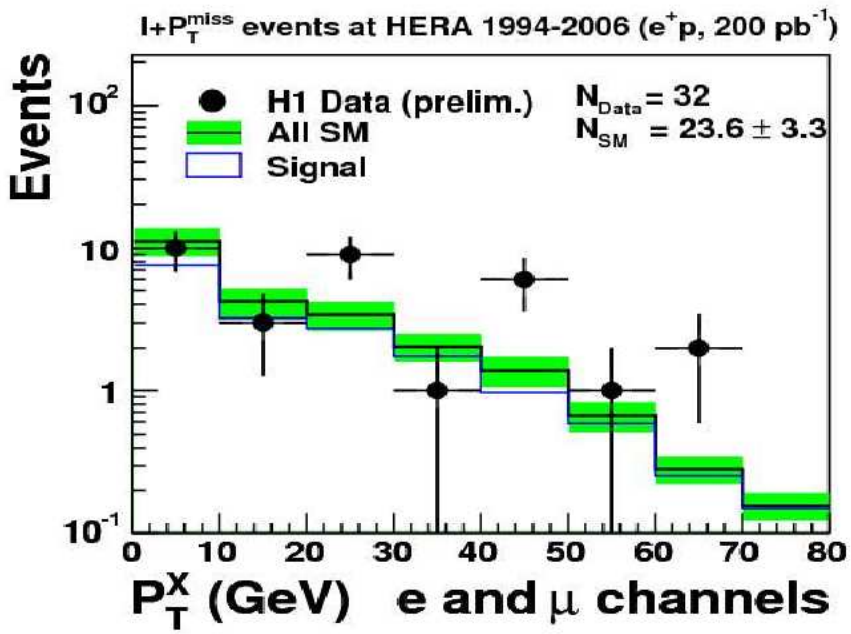
Significance Example

Having obtained our probability it is straightforward to convert it to a sigma value.
One way is to simply look it up in a table, but a fast numerical approach runs as follows:

- Create a gaussian function of x of width 1.0 units centered on 0 ('Standard Gaussian')
- Find the value of x (x_p) for which the integral of the gaussian from $x \longrightarrow \infty$ equals the probability
- x_p is the significance of the excess in sigmas, in this case it would be 2.9 σ

A similar approach gives the p-value(significance) of the ZEUS $2/0.20^{+0.05}_{-0.05}$ τ excess as $0.02(2.0\sigma)$

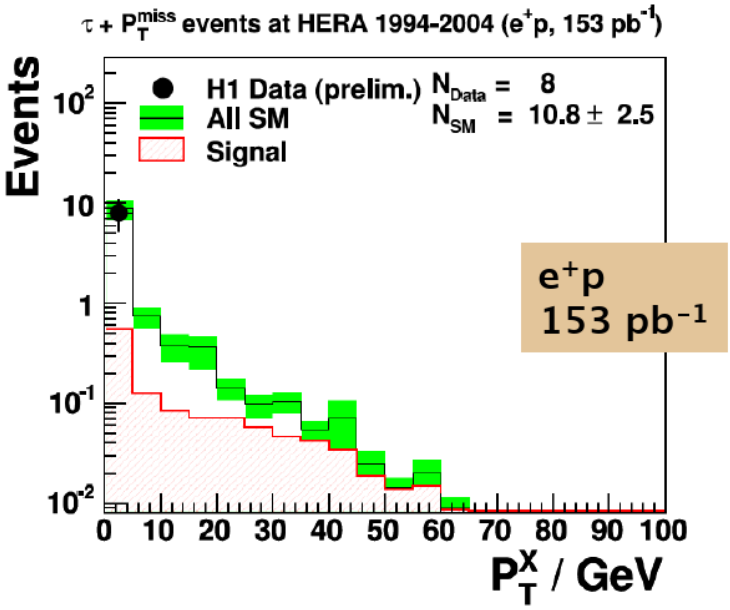


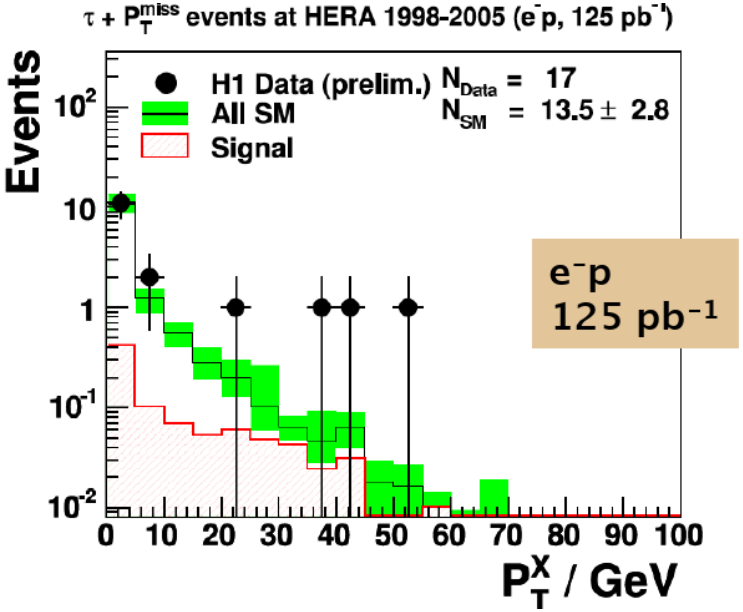


- No evidence for excess in $e^- p$ data
- Excess in $e^+ p$ data at the 3.3 σ level

H1 Searches

τ





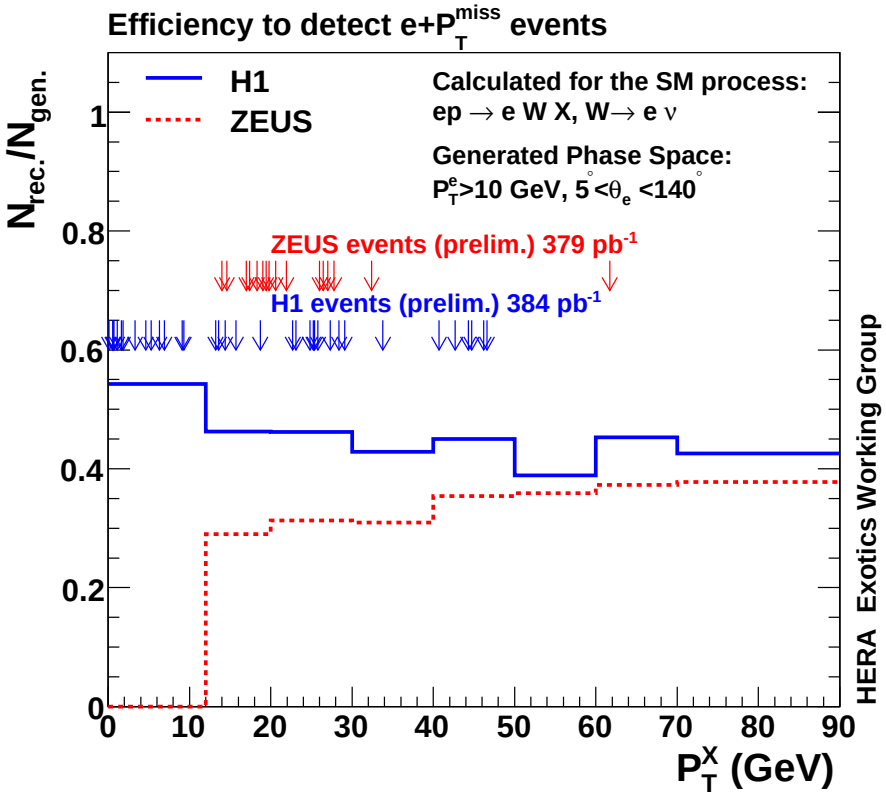
H1 Preliminary		H1 Data	Total SM expectation	SM signal (W)	Other SM Processes
94-04 e^+p 153 pb^{-1}	Total	8	10.6 ± 2.9	1.1 ± 0.23	9.5 ± 2.9
	P_T^X>25 GeV	0	0.40 ± 0.10	0.24 ± 0.05	0.15 ± 0.09
98-05 e^-p 125 pb^{-1}	Total	17	13.5 ± 2.6	0.9 ± 0.15	12.6 ± 2.6
	P_T^X>25 GeV	3	0.35 ± 0.09	0.19 ± 0.03	0.16 ± 0.09

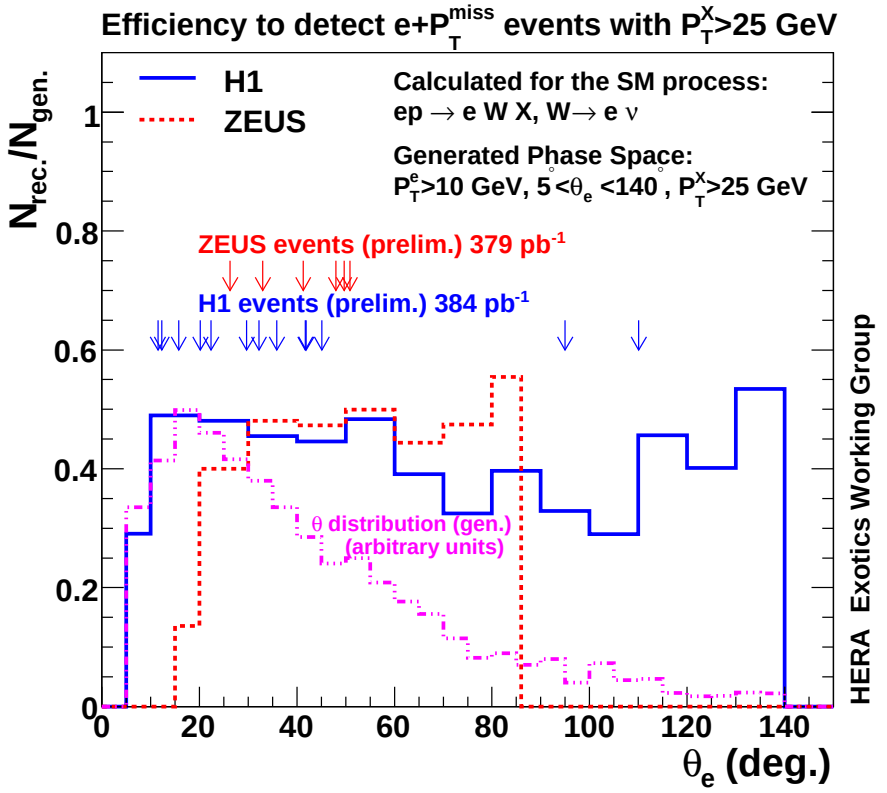
A different search was made compared to published results, less focused on single top production like topologies:

Isolated e	$12 < p_T^X < 25$ **GeV**	$p_T^X > 25$ **GeV**
ZEUS (prel.) 96-06 e^+p (175 pb^{-1})	**4**/2.1 ± 0.3 (63%)	**1**/2.2 ± 0.3 (75%)
ZEUS (prel.) 98-06 e^-p (204 pb^{-1})	**6**/2.9 ± 0.5 (56%)	**5**/3.8 ± 0.6 (55%)
ZEUS (prel.) 96-06 $e^\pm p$ (379 pb^{-1})	**10**/5.0 ± 0.6 (59%)	**6**/6.0 ± 0.7 (63%)

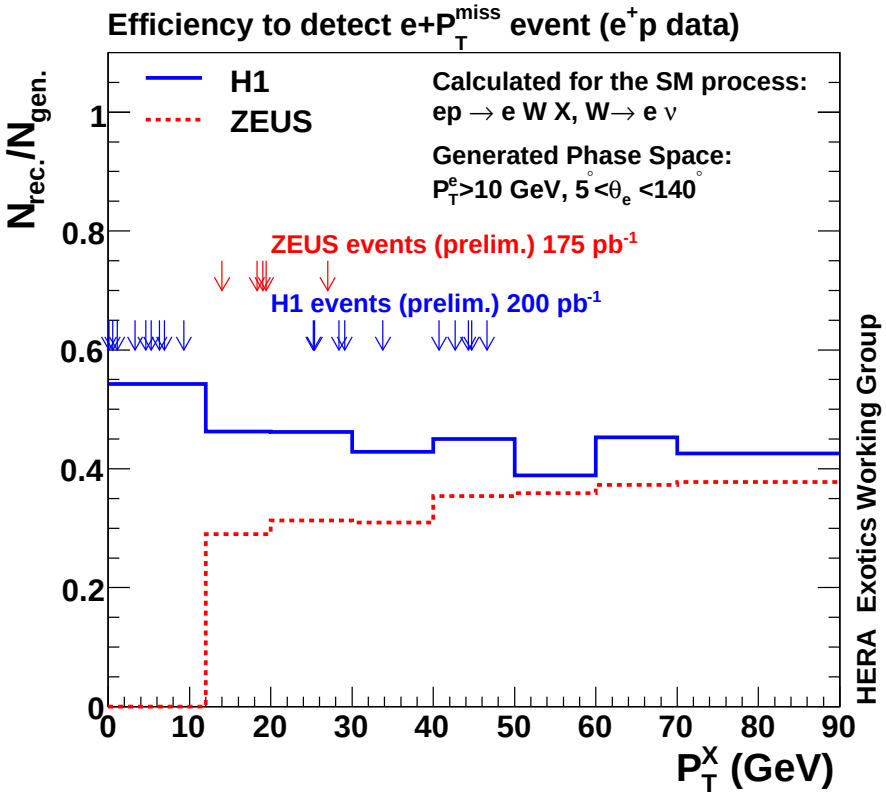
Isolated μ	$12 < p_T^X < 25$ **GeV**	$p_T^X > 25$ **GeV**
ZEUS (prel.) 96-06 e^+p (175 pb^{-1})	**3**/1.9 ± 0.4 (71%)	**1**/2.3 ± 0.4 (78%)
ZEUS (prel.) 98-06 e^-p (204 pb^{-1})	**2**/2.2 ± 0.3 (68%)	**2**/2.2 ± 0.3 (86%)
ZEUS (prel.) 96-06 $e^\pm p$ (379 pb^{-1})	**5**/4.1 ± 0.5 (75%)	**3**/4.5 ± 0.5 (82%)

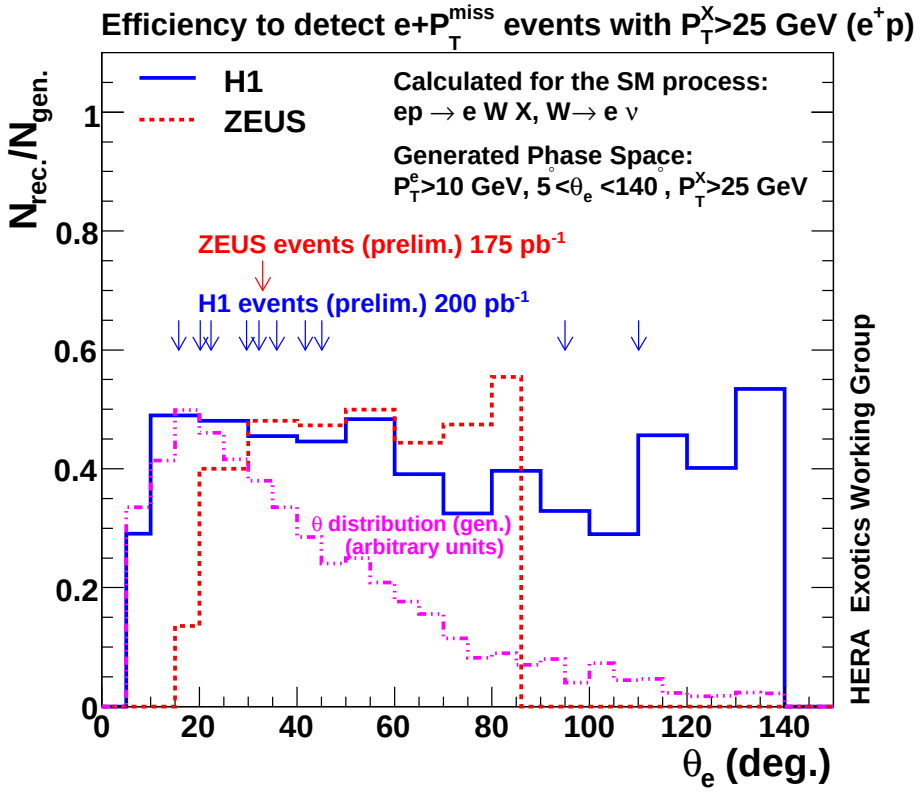
Still no confirmation of the H1 excess


Efficiency to detect e+P$_T^{miss}$ events
H1
ZEUS
Calculated for the SM process:
ep → e W X, W→ e ν
Generated Phase Space:
P$_T^e$>10 GeV, 5°<θ$_e$ <140°
ZEUS events (prelim.) 379 pb^{-1}
H1 events (prelim.) 384 pb^{-1}
N$_{rec.}$/N$_{gen.}$
P$_T^X$ (GeV)
HERA Exotics Working Group

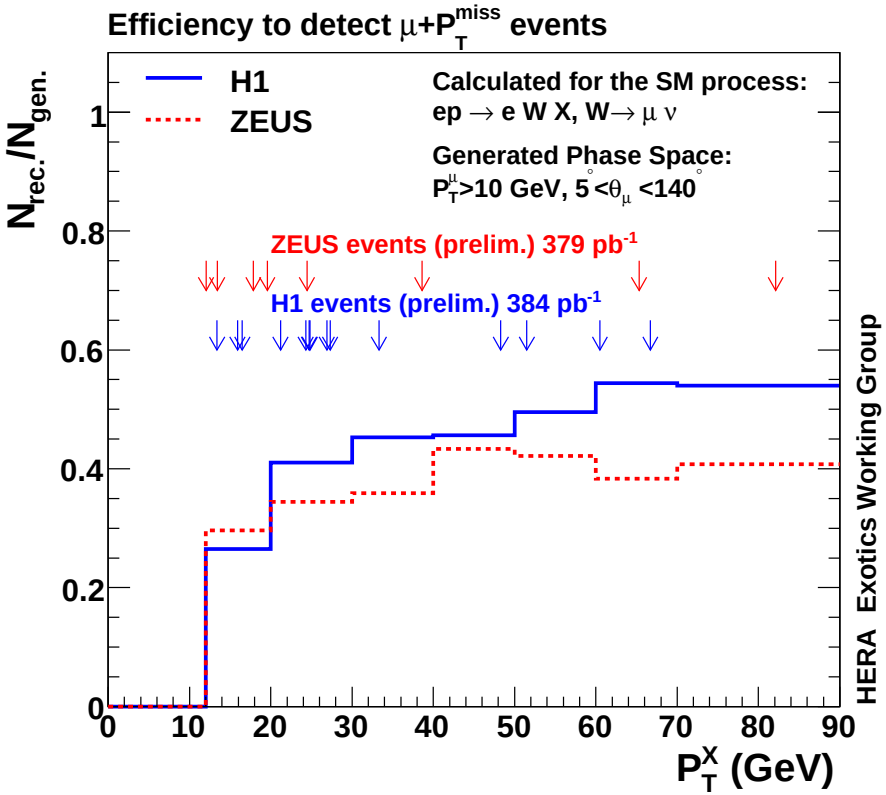

Efficiency to detect e+P$_T^{miss}$ events with P$_T^X$>25 GeV
H1
ZEUS
Calculated for the SM process:
ep → e W X, W→ e ν
Generated Phase Space:
P$_T^e$>10 GeV, 5°<θ$_e$ <140°, P$_T^X$>25 GeV
ZEUS events (prelim.) 379 pb^{-1}
H1 events (prelim.) 384 pb^{-1}
θ distribution (gen.)
(arbitrary units)
N$_{rec.}$/N$_{gen.}$
θ$_e$ (deg.)
HERA Exotics Working Group

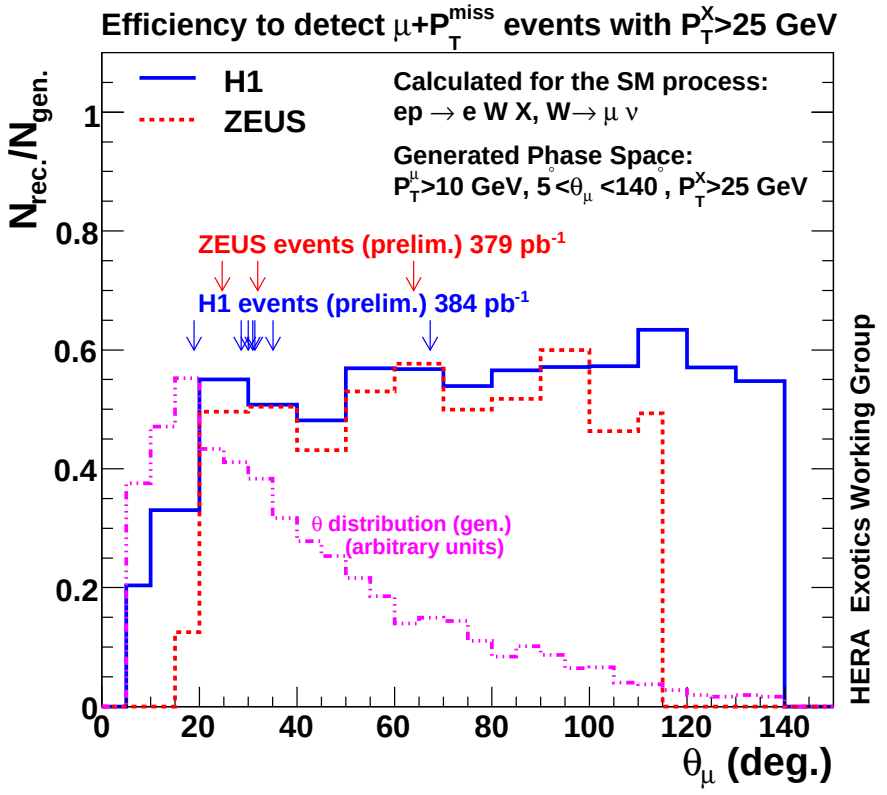
ZEUS/H1 comparison



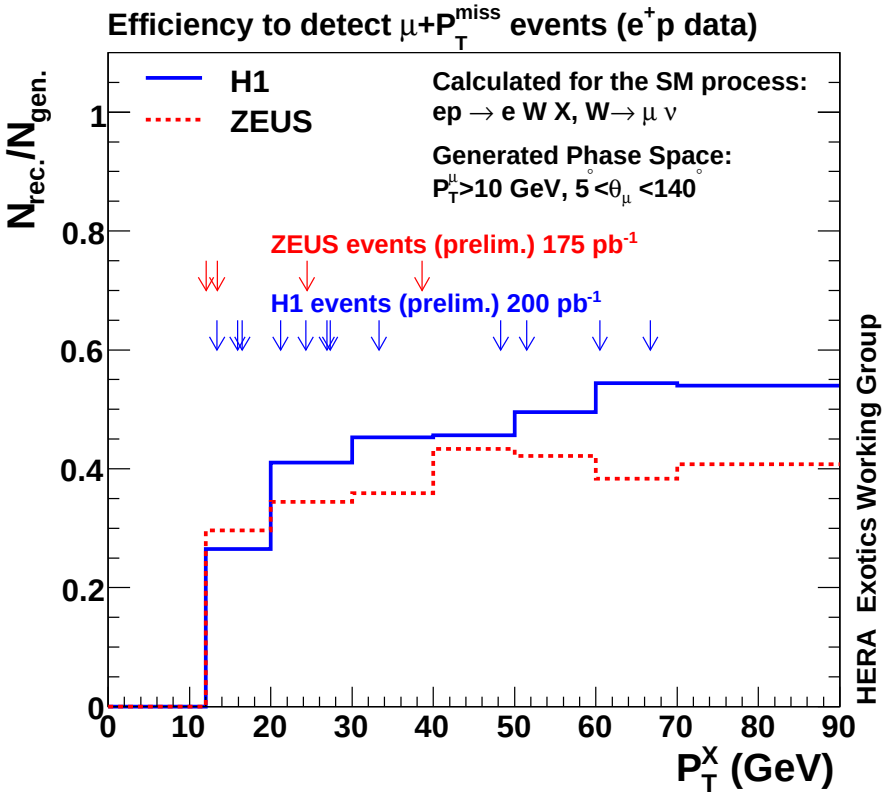


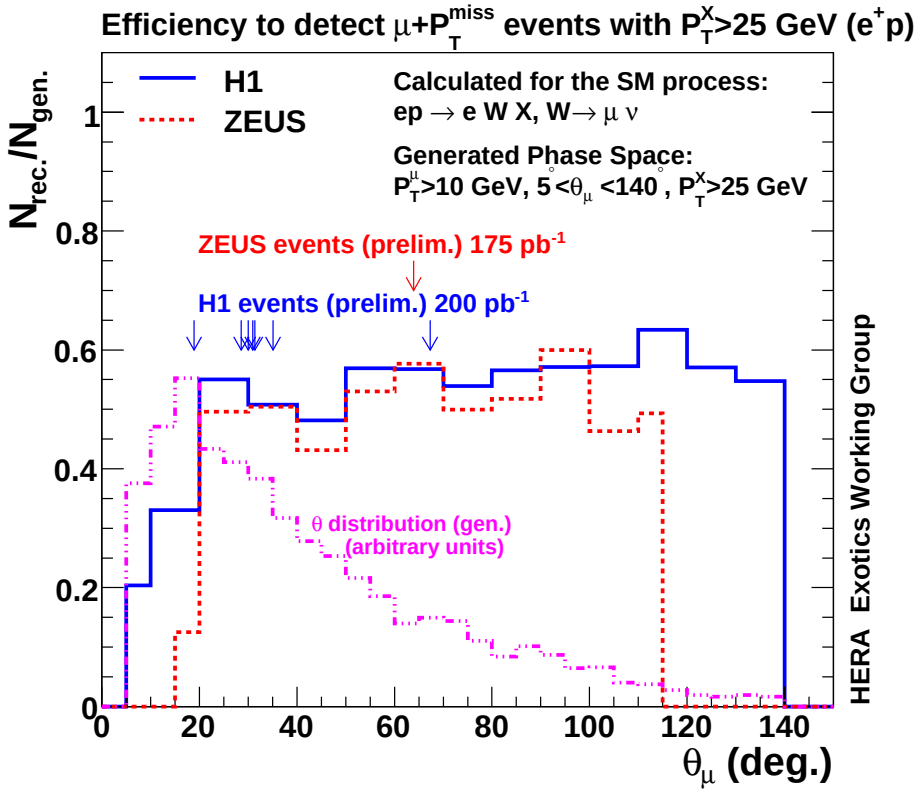
ZEUS/H1 comparison





ZEUS/H1 comparison





$e^{\pm}p$ Data Preliminary $P_T^X > 25$ GeV			Electron obs./exp.	Muon obs./exp.	Combined obs./exp.
e^+p	H1	200 pb^{-1}	10 / 3.1 $\pm$ 0.6	7 / 2.9 $\pm$ 0.5	17 / 6.0 $\pm$ 1.0
	ZEUS	175 pb^{-1}	1 / 2.2 $\pm$ 0.3	1 / 2.3 $\pm$ 0.4	2 / 4.5 $\pm$ 0.7
	H1+ZEUS	375 pb^{-1}	11 / 5.3 $\pm$ 0.9	8 / 5.2 $\pm$ 0.9	**19 / 10.5 $\pm$ 1.7**
e^-p	H1	184 pb^{-1}	3 / 3.8 $\pm$ 0.6	0 / 3.1 $\pm$ 0.5	3 / 6.9 $\pm$ 1.1
	ZEUS	204 pb^{-1}	5 / 3.8 $\pm$ 0.6	2 / 2.2 $\pm$ 0.3	7 / 6.0 $\pm$ 0.9
	H1+ZEUS	388 pb^{-1}	8 / 7.6 $\pm$ 1.2	2 / 5.3 $\pm$ 0.8	**10 / 12.9 $\pm$ 2.0**

Combination is for interest, since kinematic region not yet identical, statements that can be made are limited

- Significance of combined excess for $P_T^X > 25$ GeV in e^+p is 2.0σ

- HERA will stop operating at the end of June 2007
- Two possible scenarios remain (e^+p collisions only)
  - High energy running - continue with running as before (HER)
  - Low energy running - halve proton energy (LER) would have to start in March 2007
- LER would enable measurement of the F_L structure function, an important measurement to make
- LER would also reduce the luminosity available for studying the isolated lepton events

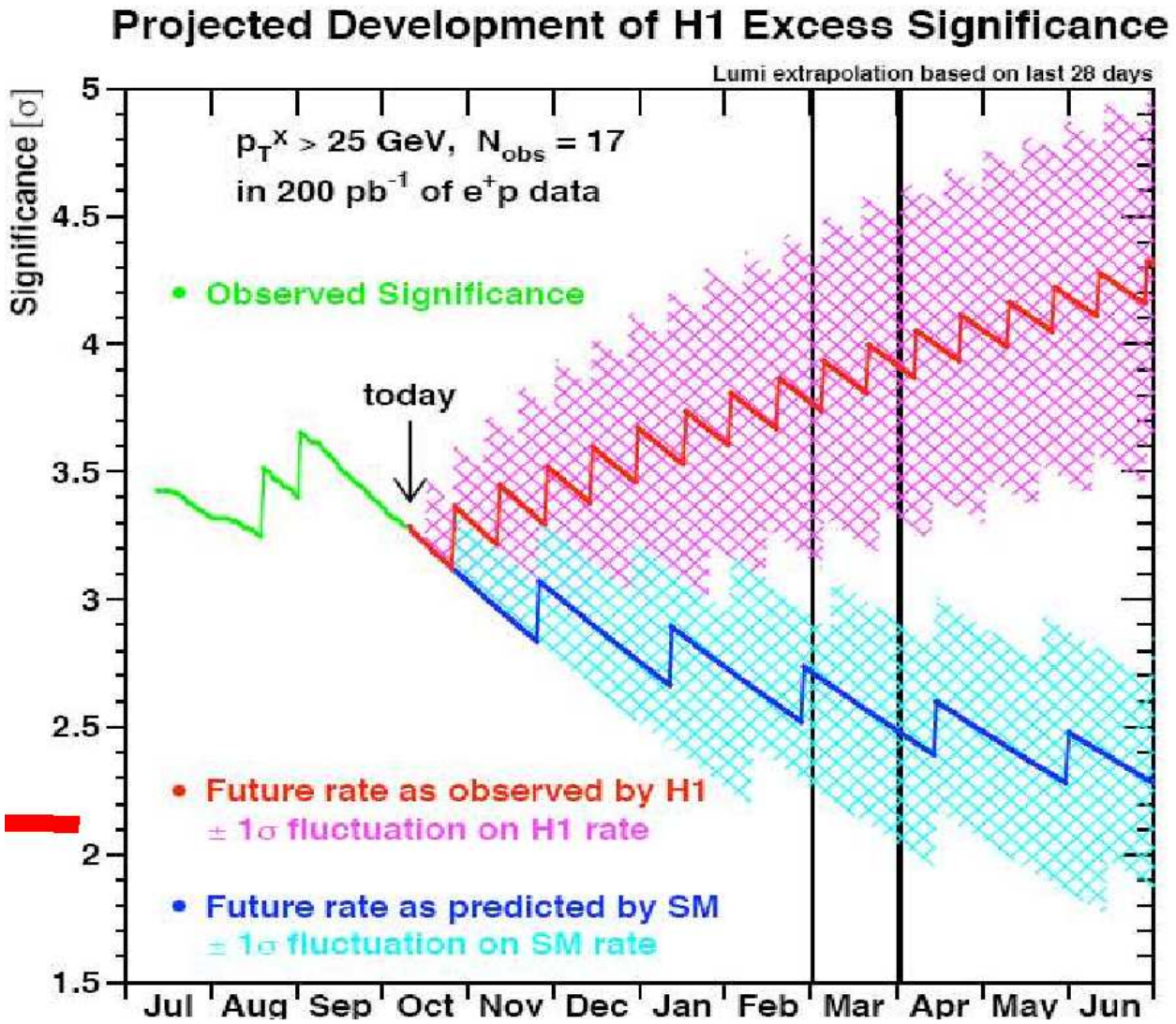
The current state of results indicated that H1 see evidence for an excess ($> 3\sigma$)
In order to make the correct decision, the discovery prospects must be correctly assessed

A simple model can be used to predict the evolution of the significance with luminosity:

- Simply Scale MC and Data predictions + errors by luminosity
- Use calculation outlined previously to calculate significance

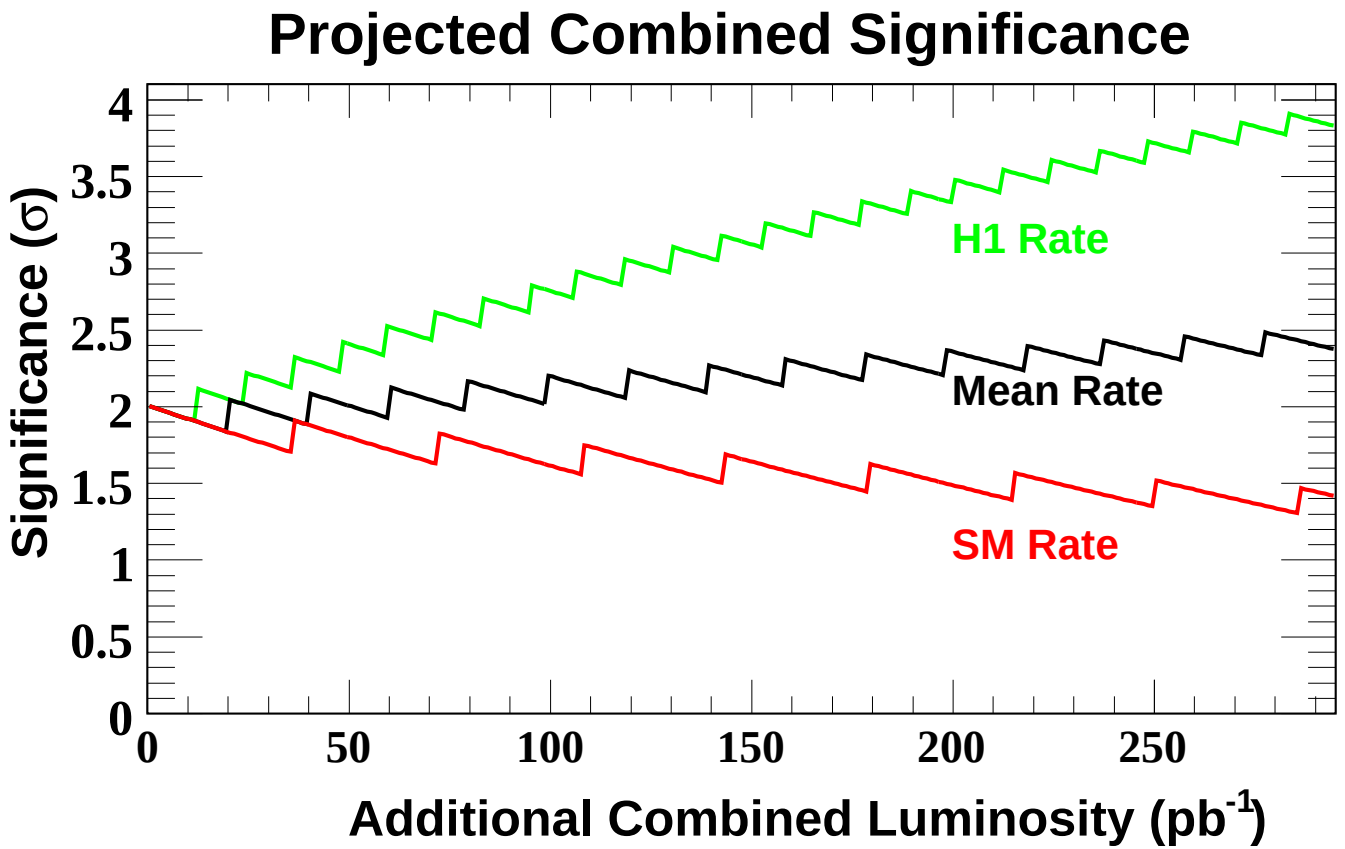
For running schedule issues, it is also important to know realistic deliverable luminosity from HERA ($\approx 5\ \mathrm{pb}^{-1}$ per week, per experiment)
Begin by looking at a plot of this from H1 based on H1 data. This was shown on 27/10/2006

H1 projected Significance



- If H1 continue to observe events at rate as seen up to Oct 2006, could be an excess of $> 4\sigma$ by the end of June
- Excess will still not reach 4σ by March
- We should also consider ZEUS data

Projected Significance

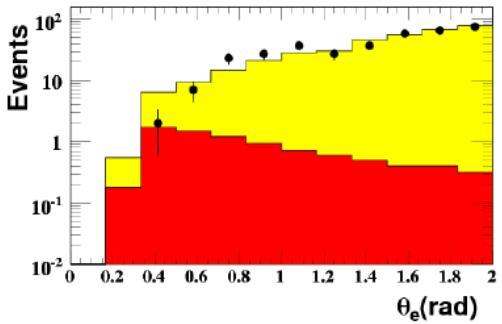


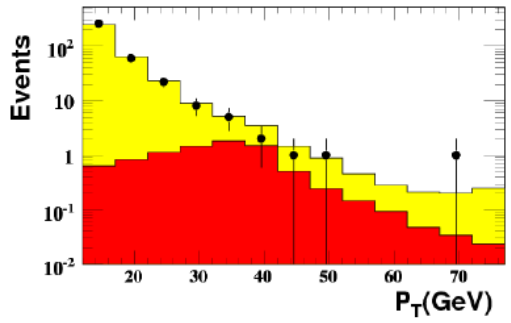
- Realistically can expect extra 210 pb^{-1} by mid March
- Experiments will update numbers before final decision is made

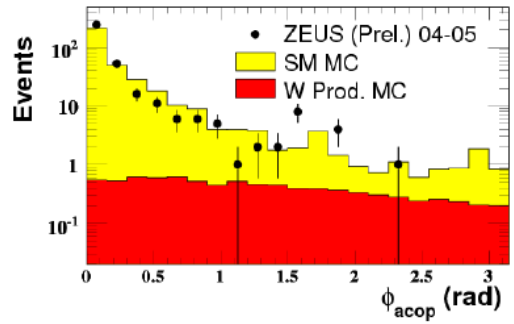
Summary

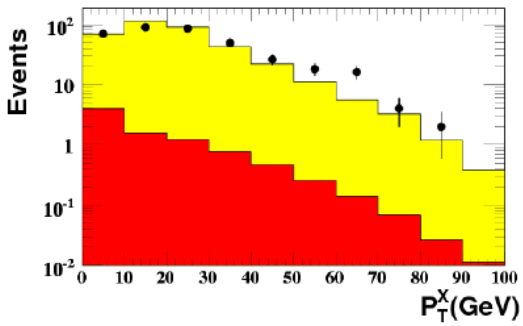
- H1 observe an excess of high P_T isolated leptons in events with large missing P_T at high values of hadronic transverse momentum
  - Significance of the excess is 3.3 σ in e^+p data
- ZEUS have not confirmed this excess in the e, μ channel
- The two experiments have similar efficiency for this topology of event
- Combining ZEUS and H1 results (naively) gives a significance of deviation from the SM of 2.0 σ
- HERA experiments are competitive in terms of sensitivity to some type of new physics with TeVatron and LEP experiments
- Expect new and final results from both collaborations soon

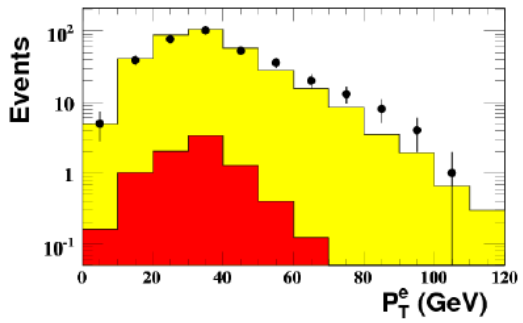
ZEUS Control Plots I

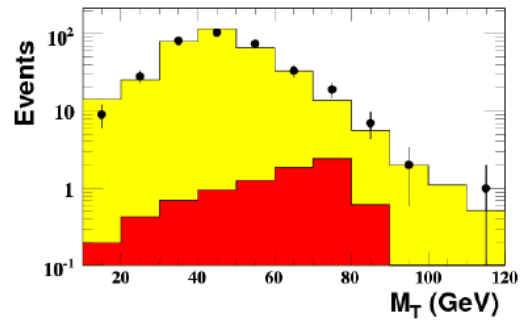












ZEUS Control Plots II