Search for Anomalous Single Top Production at HERA

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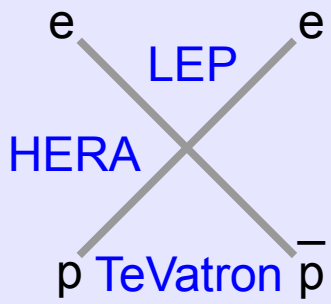
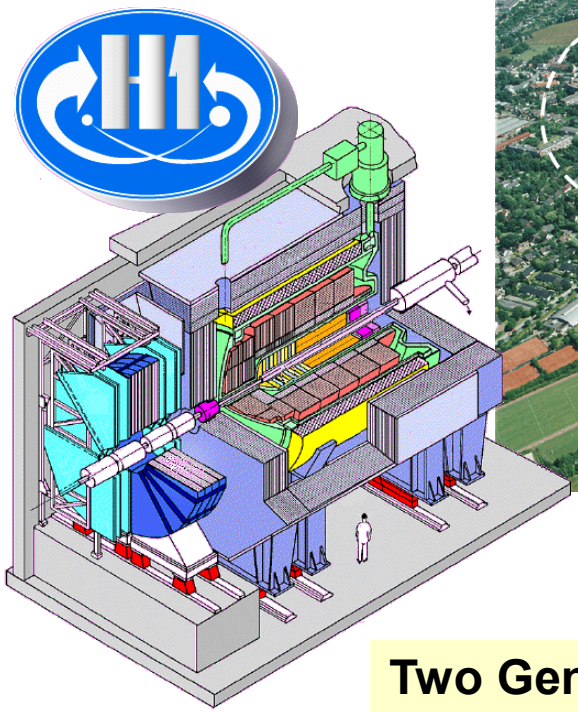
HERA and Experiments

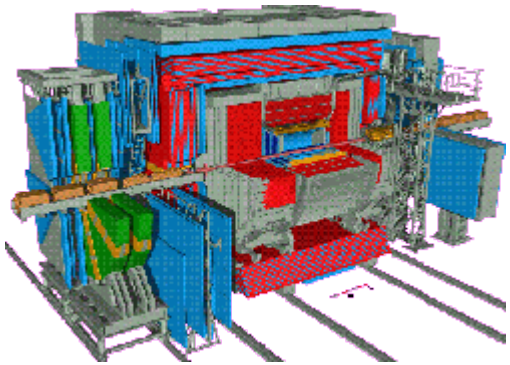
The energy frontier before LHC



HERA at DESY, Hamburg
- Was the world's only *ep* collider
- Up to $\sqrt{s} = 320\mathrm{GeV}$



ZEUS



Two General Purpose *ep* Experiments H1 and ZEUS
- Full 4π coverage to measure missing energy
- Excellent lepton id

HERA Data

Two running periods:

HERA-I (1994-00)

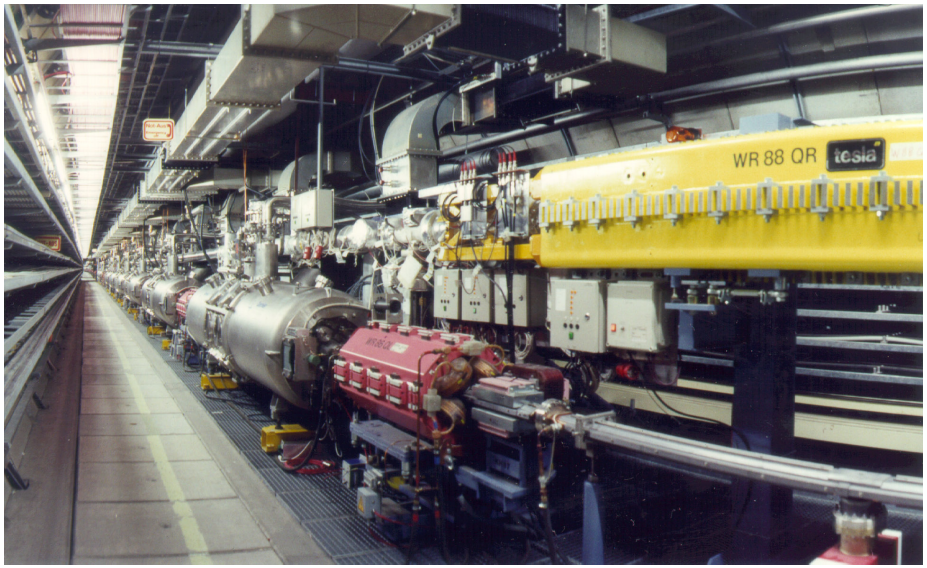
~130 pb^{-1} per exp., (90% e^+p)

HERA-II (2003-07)

- Luminosity upgrade
- Long. *e* polarisation (up to 50%)

~0.5 fb^{-1} per experiment

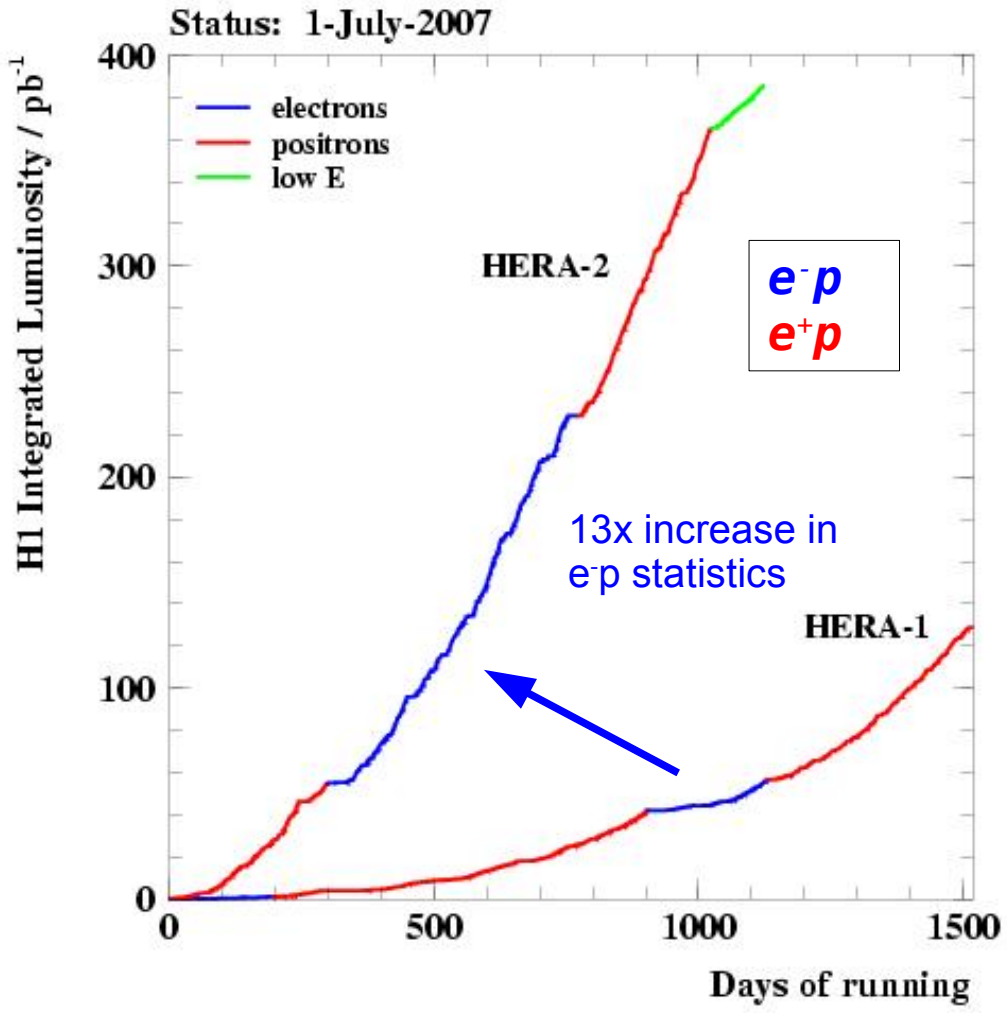
Processes with small cross section σ (~1pb) and/or σ(q$_e$), σ(P) in reach of available data



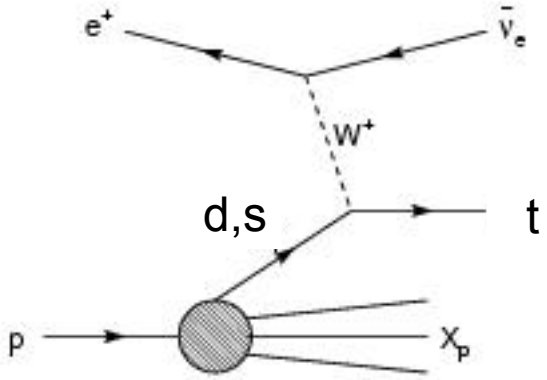
p

e

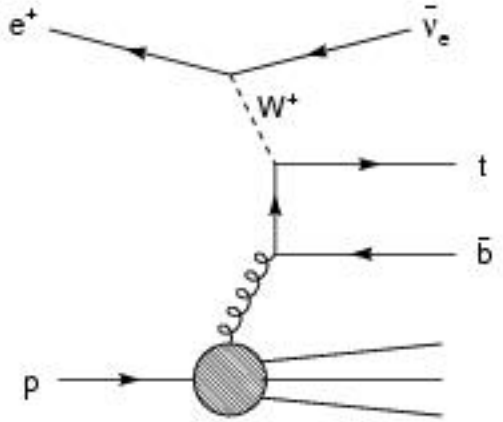
(e^+ and e^-)



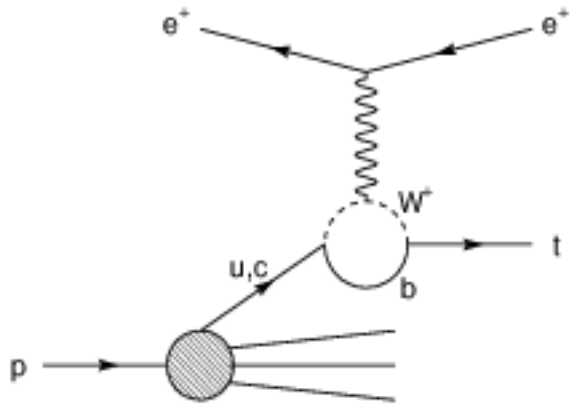
Single Top Production at HERA in the SM



Charged Current
W coupling to light down-type quark



Charged Current
involving *b*-quark



Neutral Current
FCNC at loop level
("penguin")

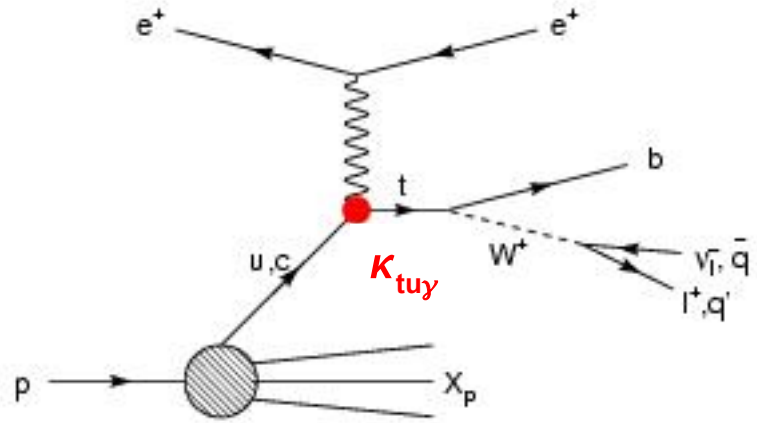
- $\sqrt{s}$ at HERA sufficient for single *top* production
- Production in SM possible but strongly suppressed
- Cross section ~1 fb
  (About 1 *top* event was produced at HERA in the SM)

Not observable

Anomalous Single Top Production at HERA

- If single top production is observed at HERA, it is a signal for **new physics**
- Template process: Anomalous single *top* production via **FCNC**
- **Effective Lagrangian** used:

$$\mathcal{L}_{eff}^{FCNC} = \sum_{U=u,c} \frac{e e_U}{2\Lambda} \kappa_{tU\gamma} \bar{t} \sigma_{\mu\nu} A^{\mu\nu} U$$
$$+ \frac{g}{2\cos\theta_W} \bar{t} \left[\gamma_\mu (v_{tUZ} - a_{tUZ}\gamma^5) U Z^\mu + \frac{1}{2\Lambda} \kappa_{tUZ} \sigma_{\mu\nu} Z^{\mu\nu} U \right] + \text{h.c.},$$



Could be

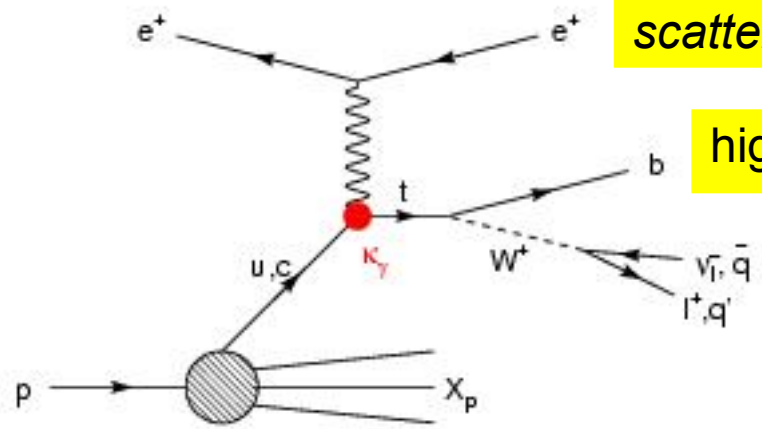
- Dynamical Symmetry Breaking
- Multi-Higgs Doublets
- RPV SUSY
- Exotic quarks...

- Highest sensitivity to $\kappa_{tu\gamma}$
- Coupling to v_{tuZ} suppressed due to high m_Z
- Production at high x_{Bj} because of large m_{top}

  → coupling $\kappa_{tc\gamma}$ suppressed (set ≡ 0) due to low *c*-density

ANOTOP
MC generator based on
LO matrix element
of complete process
$e+q \rightarrow e+t \rightarrow e+b+W \rightarrow e+b+f+\bar{f}$
(E. Perez)

Final States of Single Top Production



scattered e (visible in ~30% of events: inelastic scattering)

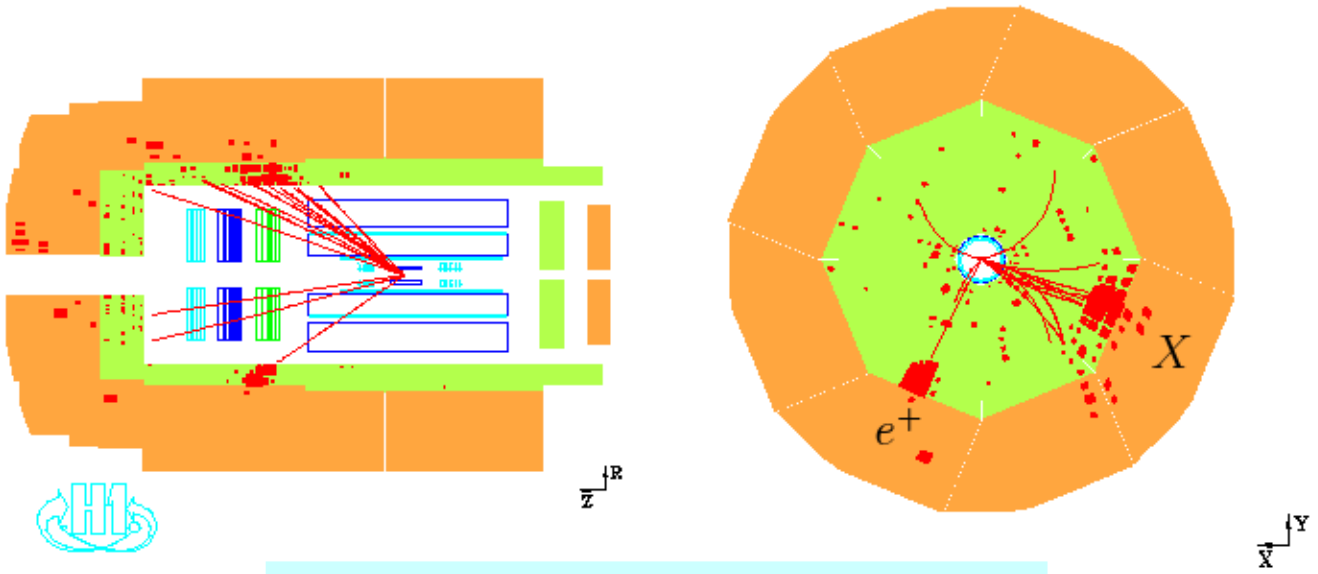
high P_T *b*-jet

l + E^{miss}
or
2 jets with M = m_W

Channels
- **Electron**
- **Muon**
- Tau (hadronic decay)
- Jets

Event with $e + P_T^{miss}$ in HERA II e^+p data

$\mathbf{P}_T^e = 37$ **GeV**, $\mathbf{P}_T^{miss} = 44$ **GeV**, $\mathbf{P}_T^X = 29$ **GeV**

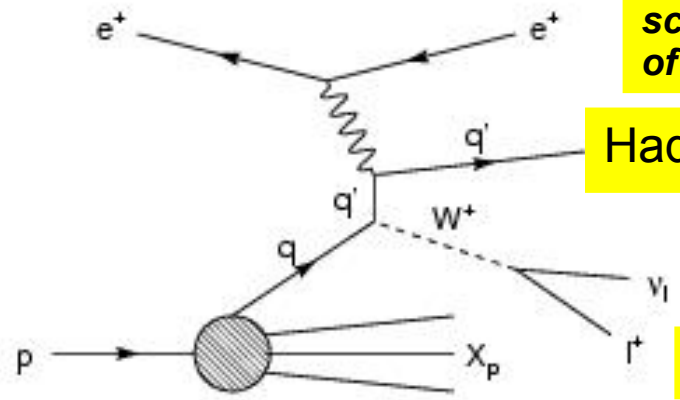


Anomalous single *top* production?

Background: *W* Production in the SM

Typical Signature expected by Standard Model **W-Production**
(σ ~ 1 pb, with ~40% efficiency expect
~ 400 events in 1 fb^{-1})

MC: EPVEC framework
(15% theo. error after reweighting to NLO)



scattered e (visible in ~25% of events – DIS)

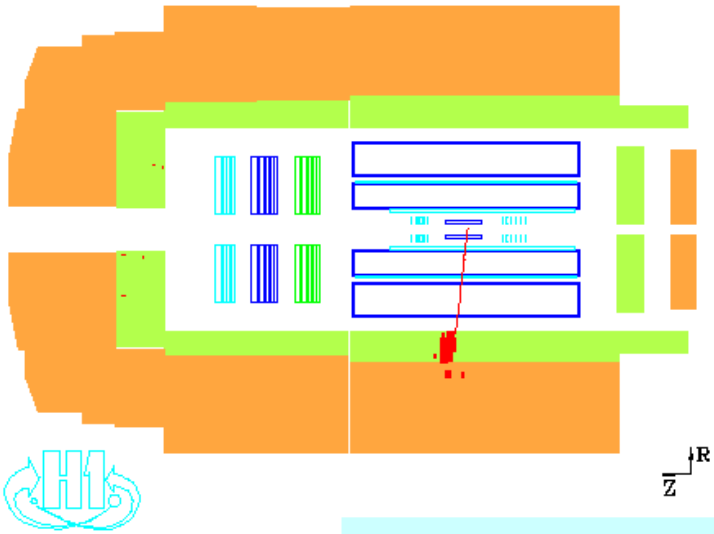
Hadr. System **X**, low P_T^X

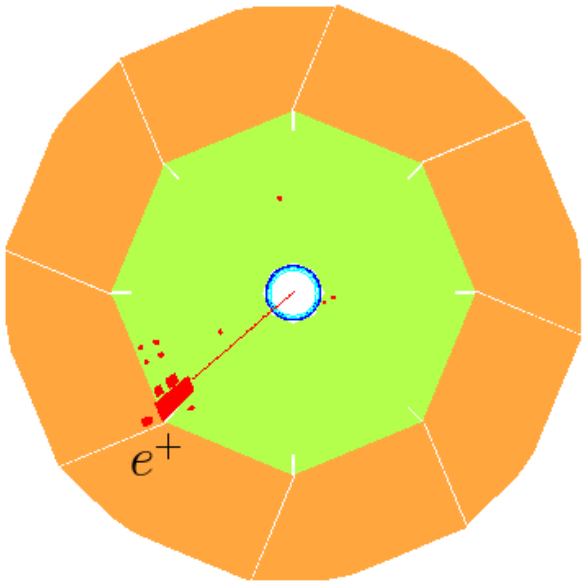
Missing Energy

Isolated Lepton

Event with $e + P_T^{miss}$ in HERA II e^+p data

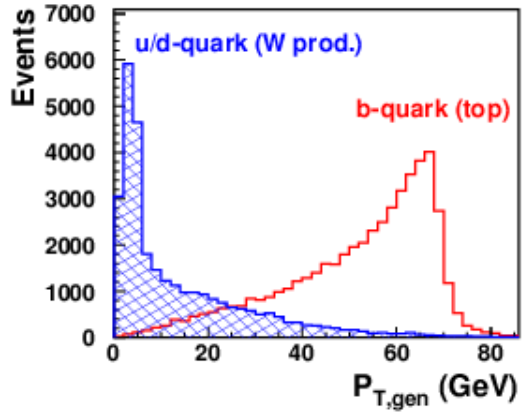
$\mathbf{P_T^e = 47\ GeV, P_T^{miss} = 47\ GeV}$





Elastic *W*-Production?

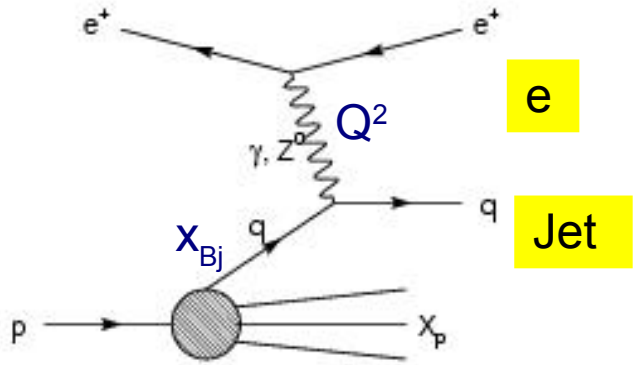
- P_T^X is main difference between *W*- and *top*-production

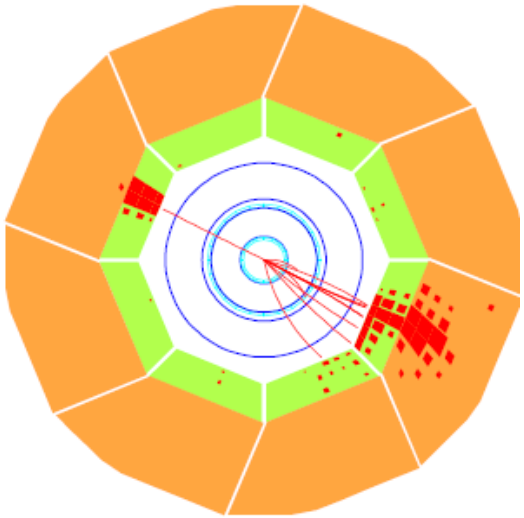


Backgrounds: Deep Inelastic Scattering

- Mostly suppressed by selecting high lepton P_T and missing P_T

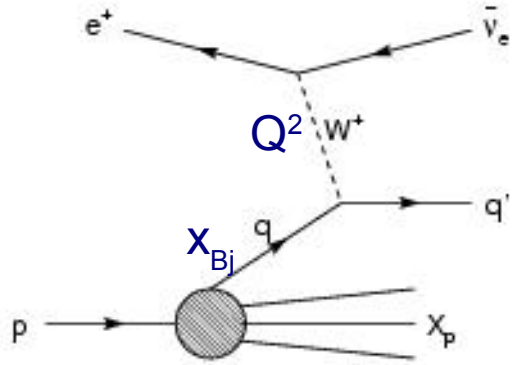
Neutral Current

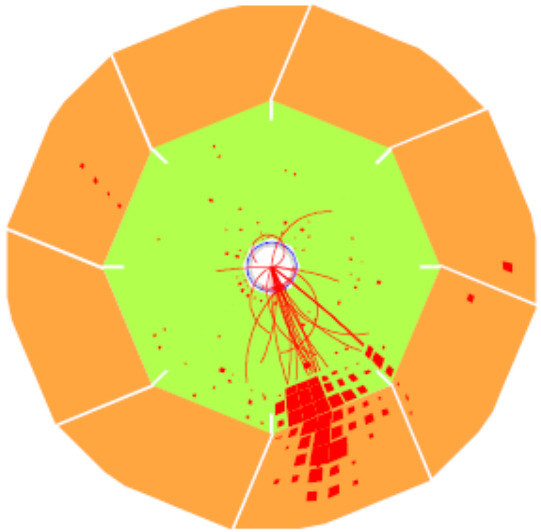




- Back-to-back topology
- Missing energy due to mismeasurement only

Charged Current





- No isolated leptons (unless from misid'ed hadrons or non-*ep*)

Further background processes:

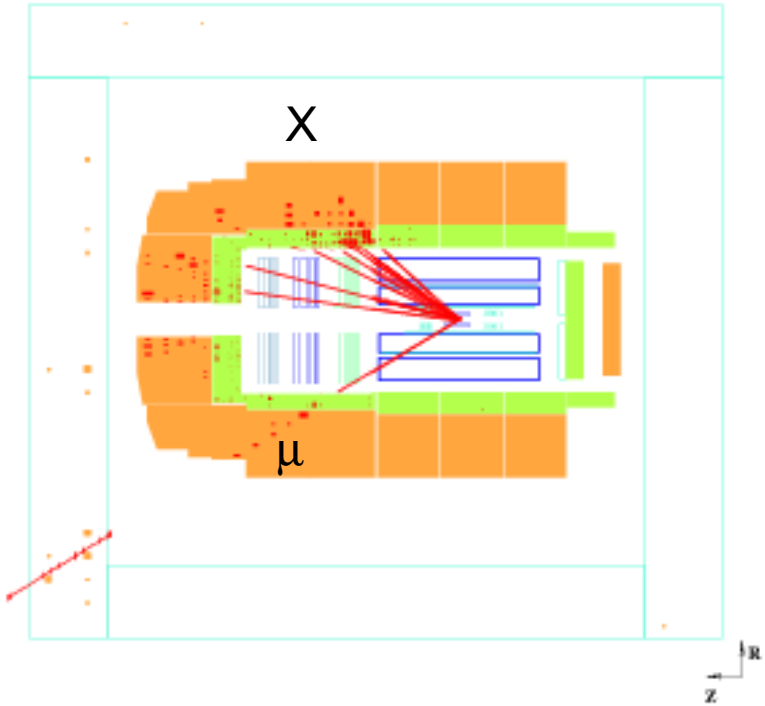
- Lepton Pair Production
- Photoproduction

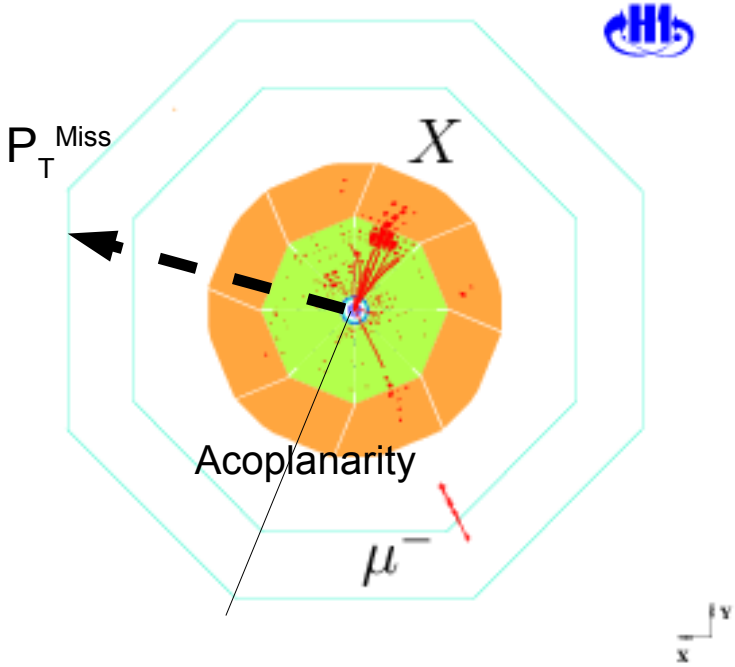
Events with Isolated Leptons and Missing P_T

To search for *top* and *W* production and possible other processes:

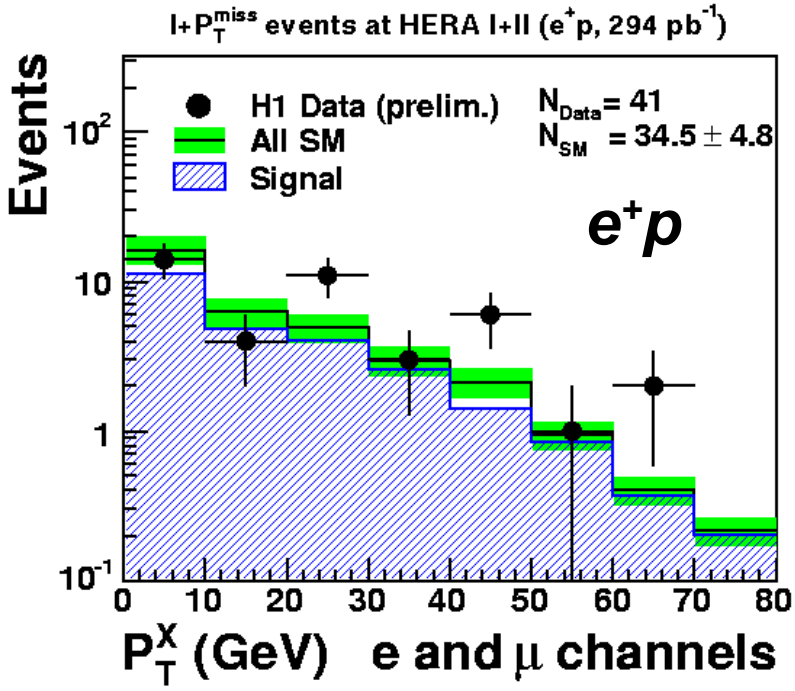
Signature Search for
Events with Isolated Leptons and Missing Transverse Momentum
done by H1 and ZEUS

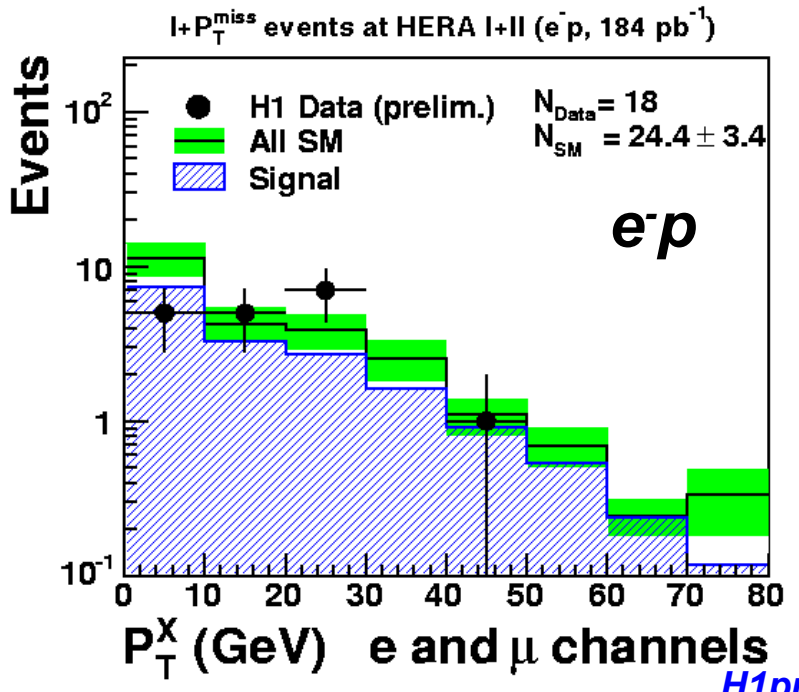
- Lepton ID phase space:
  $P_T > 10$ GeV
  $5° < \theta < 140°$
- $P_T^{Miss} > 12$ GeV
- Lepton isolation
- Event balance and other topological variables





Isolated Leptons Results from H1





H1prelim-07-063

- Excess at high P_T^X > 25 GeV in e^+p data (~ 3 sigma) – single *top*?
- e^+p / e^-p Asymmetry – not expected from single *top* production
- Overall good agreement with SM:

59 obs. / 58.9±8.2 exp.

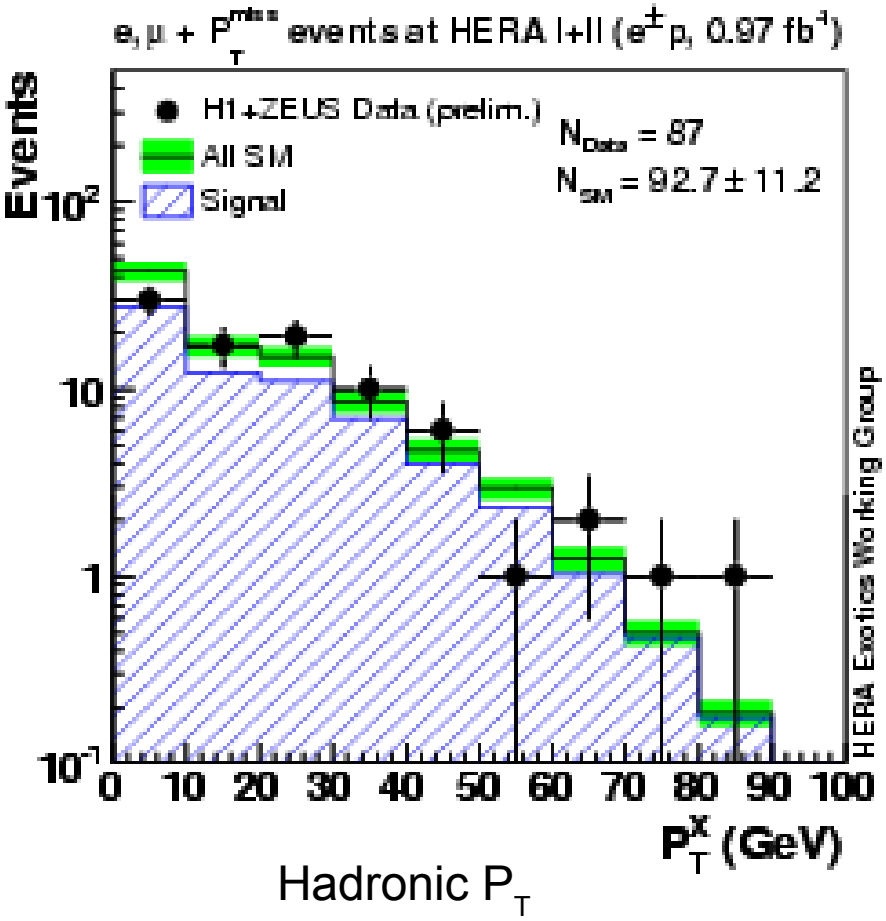
- ~70% contribution from SM *W* production

H1 Preliminary $l+P_T^{miss}$ events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
e^+p	Full Sample	26 / 27.3 ± 3.8 (71%)	15 / 7.2 ± 1.1 (85%)	41 / 34.5 ± 4.8 (74%)
294 pb^{-1}	$P_T^X > 25$ GeV	11 / 4.7 ± 0.9 (75%)	10 / 4.2 ± 0.7 (85%)	21 / 8.9 ± 1.5 (80%)
e^-p	Full Sample	16 / 19.4 ± 2.7 (65%)	2 / 5.1 ± 0.7 (78%)	18 / 24.4 ± 3.4 (68%)
184 pb^{-1}	$P_T^X > 25$ GeV	3 / 3.8 ± 0.6 (61%)	0 / 3.1 ± 0.5 (74%)	3 / 6.9 ± 1.0 (67%)
$e^\pm p$	Full Sample	42 / 46.7 ± 6.5 (69%)	17 / 12.2 ± 1.8 (82%)	59 / 58.9 ± 8.2 (72%)
478 pb^{-1}	$P_T^X > 25$ GeV	14 / 8.5 ± 1.5 (68%)	10 / 7.3 ± 1.2 (79%)	24 / 15.8 ± 2.5 (73%)

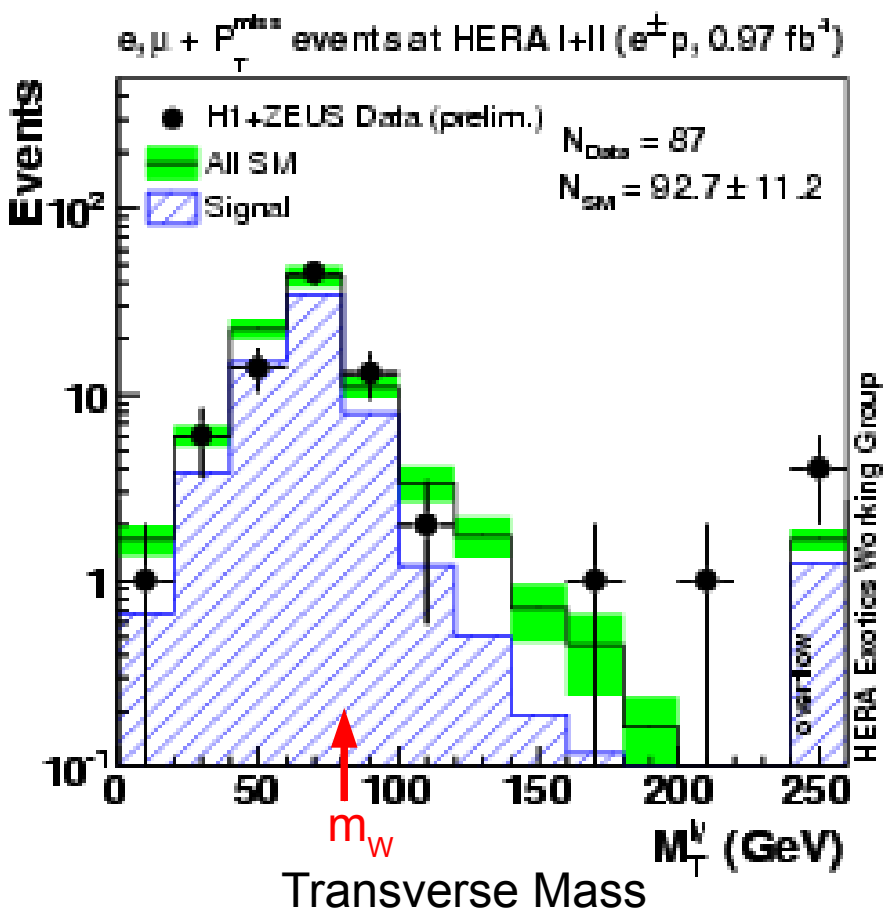
Isolated Leptons Results: H1+ZEUS Combination

- Both experiments reanalysed and combined isolated leptons in common phasespace
  $P_T > 10$ GeV
  $15° < \theta < 120°$
  $P_T^{Miss} > 12$ GeV
- Good agreement with SM

H1prelim-07-162
ZEUS-prel- 07-029



Hadronic P_T



Transverse Mass

Search for Anomalous top Production

Strategy:

In Isolated Leptons Sample ...

- Reconstruct neutrino and *top*
- Preselect *top*-like events
- Form *top*/*W*-Discriminator using MVA
- Extract number of top events using a max. likelihood fit
- Convert to cross section limit at 95% confidence level
- Convert to limit on coupling $\kappa_{tu\gamma}$

Neutrino Reconstruction

Exploit missing energy measurement and kinematic constraints

- **Scattered electron in detector**
  Complete kinematics can be reconstructed

$$\vec{P}_T^{\,\nu} = \vec{P}_T^{\,miss}$$

$$(E - P_z)^{\nu} = 2E_e - (E - P_z)^{leptons} - (E - P_z)^{X}$$

From MC:
~25% of all W events,
~30% of all anomalous *top* events

- **Scattered electron escapes in beam pipe**
  Solve quadratic equation after constraining kinematics using m_W

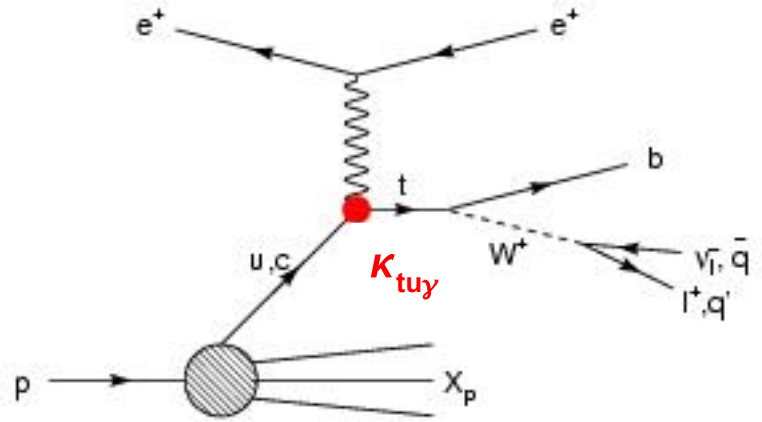
$$M_{\ell\nu} = \sqrt{P_\ell^2 + P_\nu^2 + 2P_\ell P_\nu} \approx \sqrt{2P_\ell P_\nu} = M_W = 80.42\ \mathrm{GeV}$$

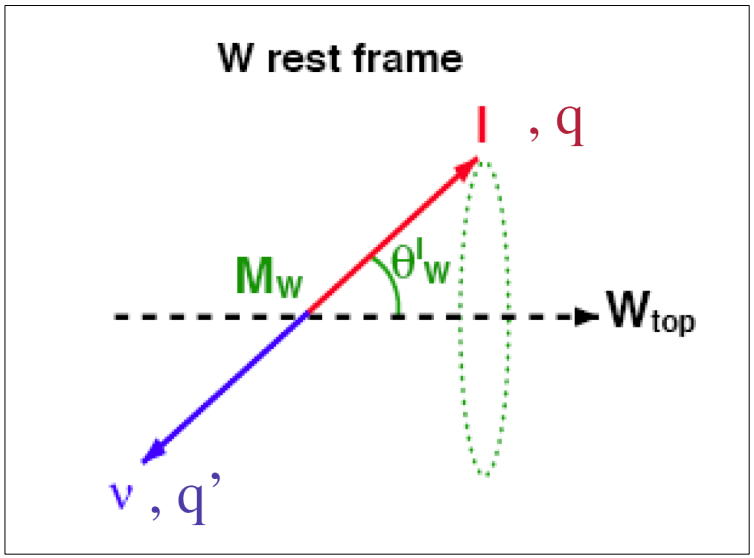
  - Possible cases:
    - Two Solutions – choose by lepton polar angle (MC)
    - Single Solution
    - Complex Solution
    - No Solution

Top Reconstruction and Preselection

Define Variables to discriminate *top* and *W* production

- Reconstructed *top*-Mass — $M_{top}^{rec} = M_{lvb}$
- *b*-Jet Candidate Transverse Momentum — *b*-Jet = sum of all hadronic jets
- *W*-decay angle — $\cos\theta^{l}_{W}$



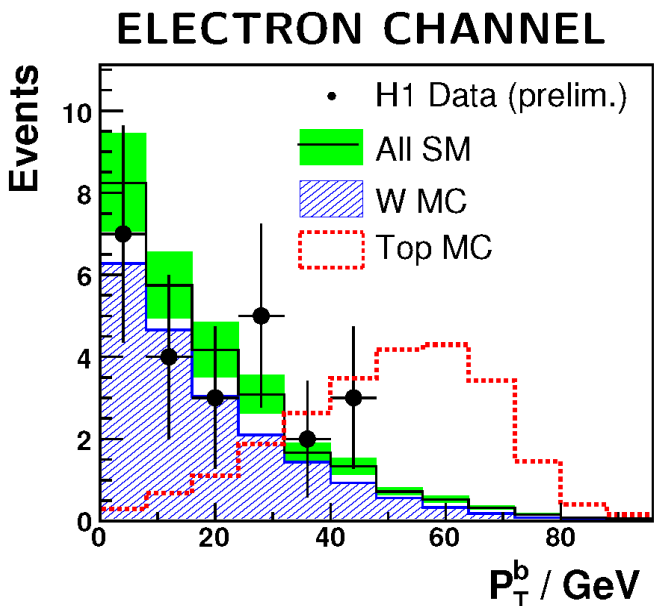


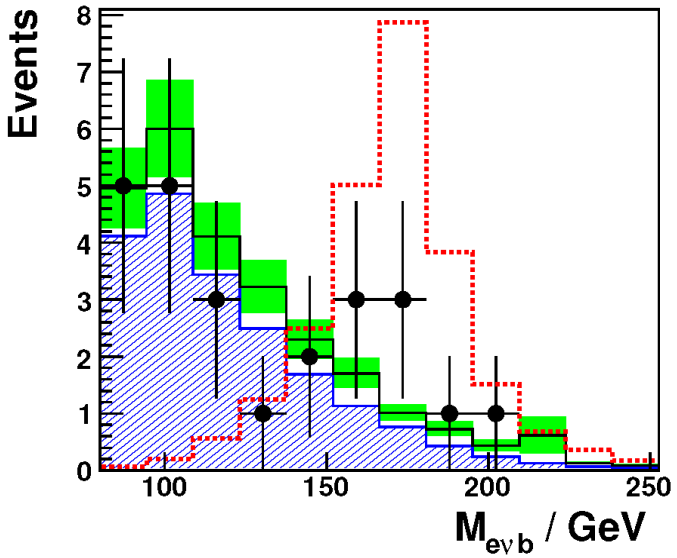
Require good reconstruction of top quark

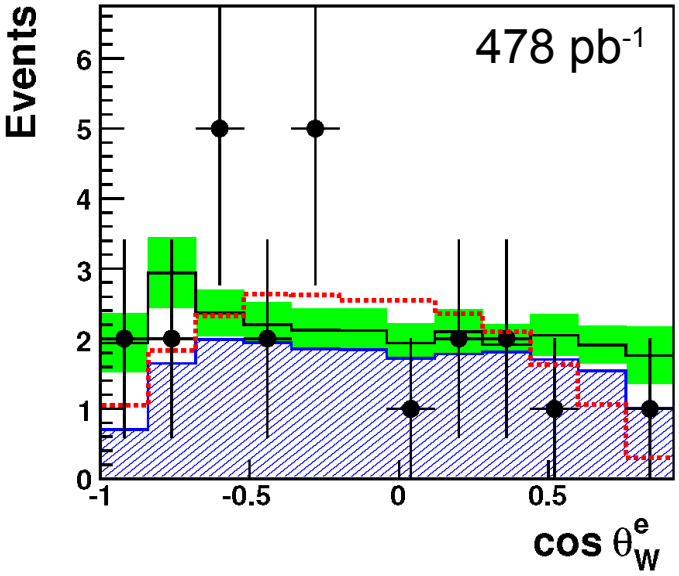
- $\sigma(q_\ell) > -2.0$ in θ = 20 ... 160 deg. Charge Requirement
- $0 < P_T^b < 100\mathrm{GeV},\ 80 < M_{\mathrm{top}} < 260\mathrm{GeV},\ \cos\theta_W^* \leq 1.$

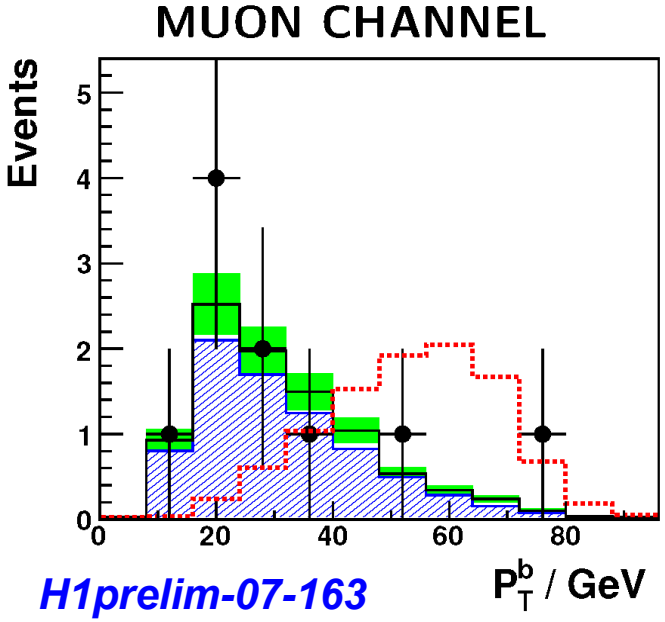
Single Top Preselection Results

Good agreement with SM – no evidence for single top production









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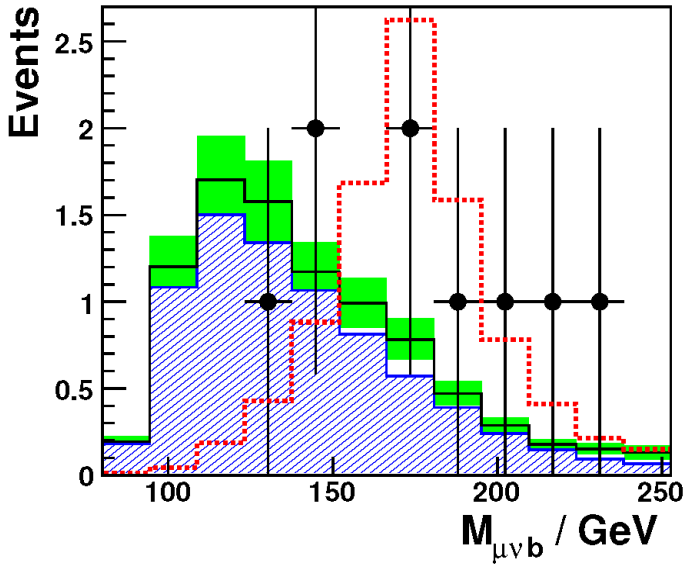
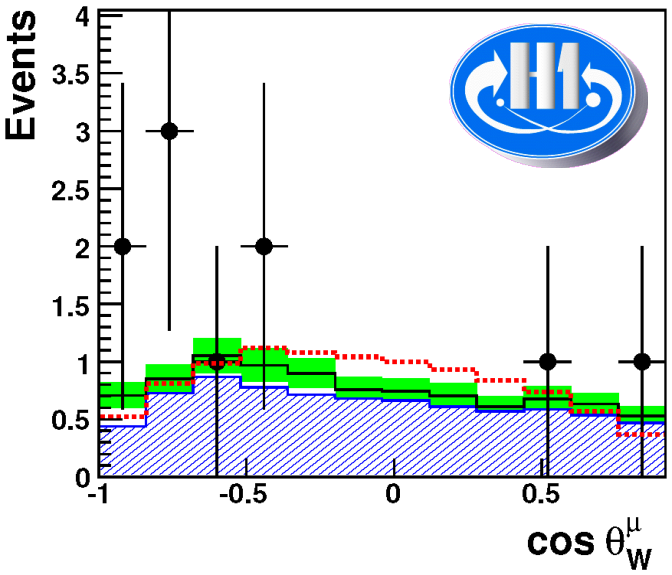
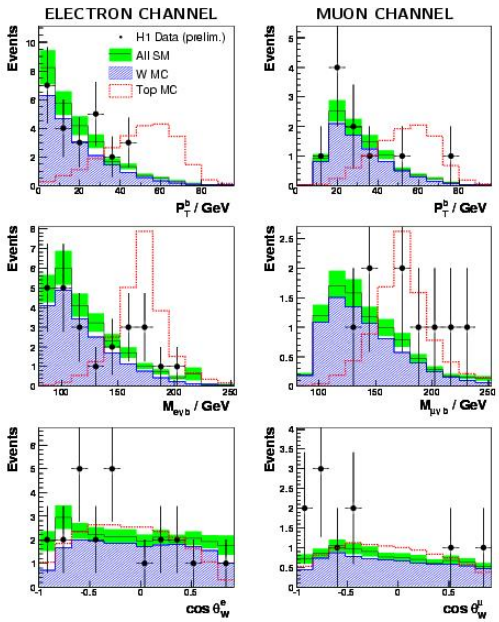
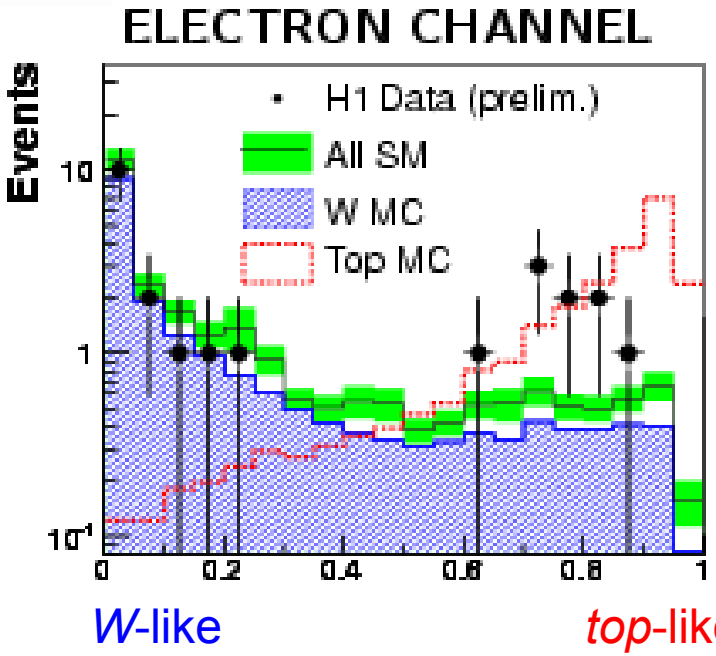


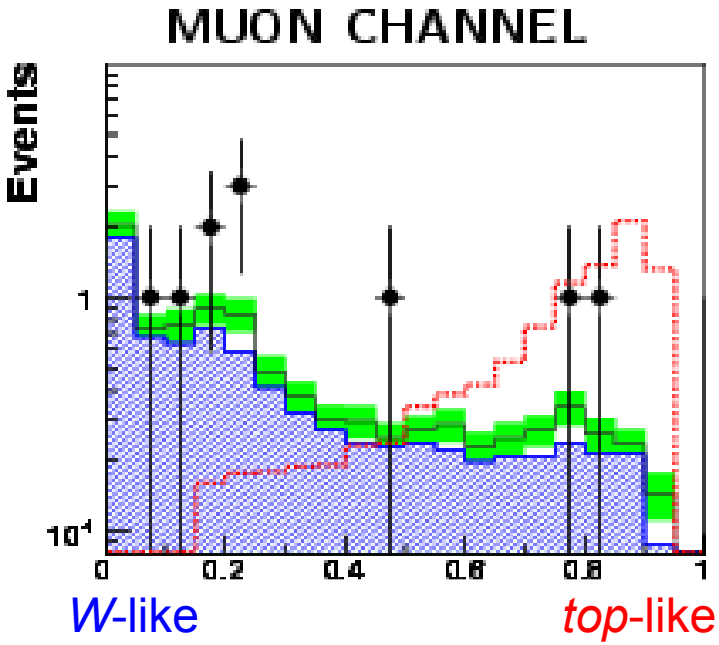


MVA Discriminator Distributions

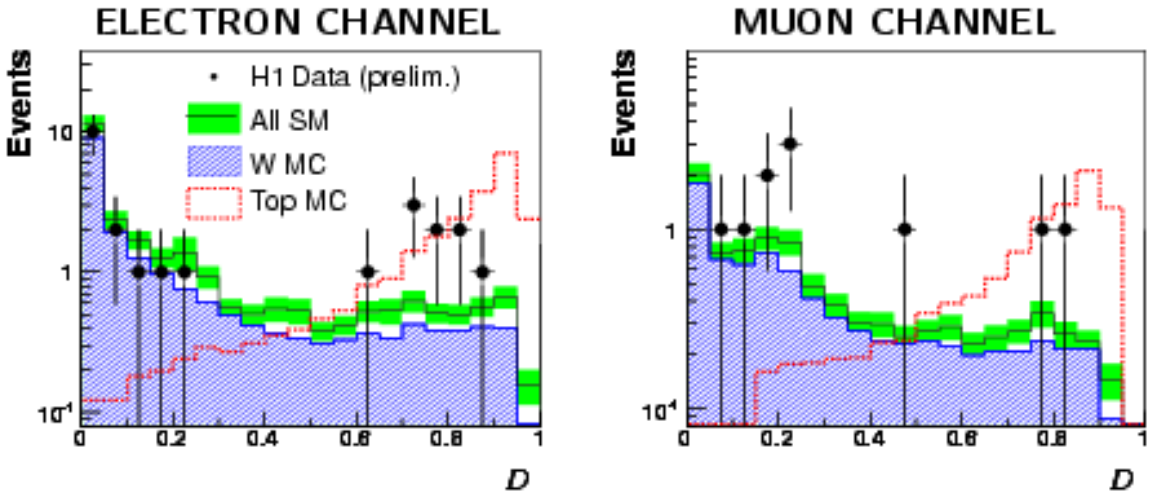
- Combine these *W/top* Variables into single discriminator ***D***
- Use TMVA to choose MVA methods with most favorable properties (monotony of discriminators, competitive performance)
- Chosen: Range-Search based Phase Space Density Estimator







Cross Section from Maximum Likelihood Fit



$$L = \prod_{k=1}^{n_{bin}} e^{-\mu_k} \frac{\mu_k^{n_k}}{n_k!}$$

$$\mu_k = B_k + S \cdot \hat{s}_k$$

shape of Top MC

- Fit number of signal events ***S*** using a Bayesian maximum likelihood estimator assuming Poisson-distributed background
- Convert to signal cross section

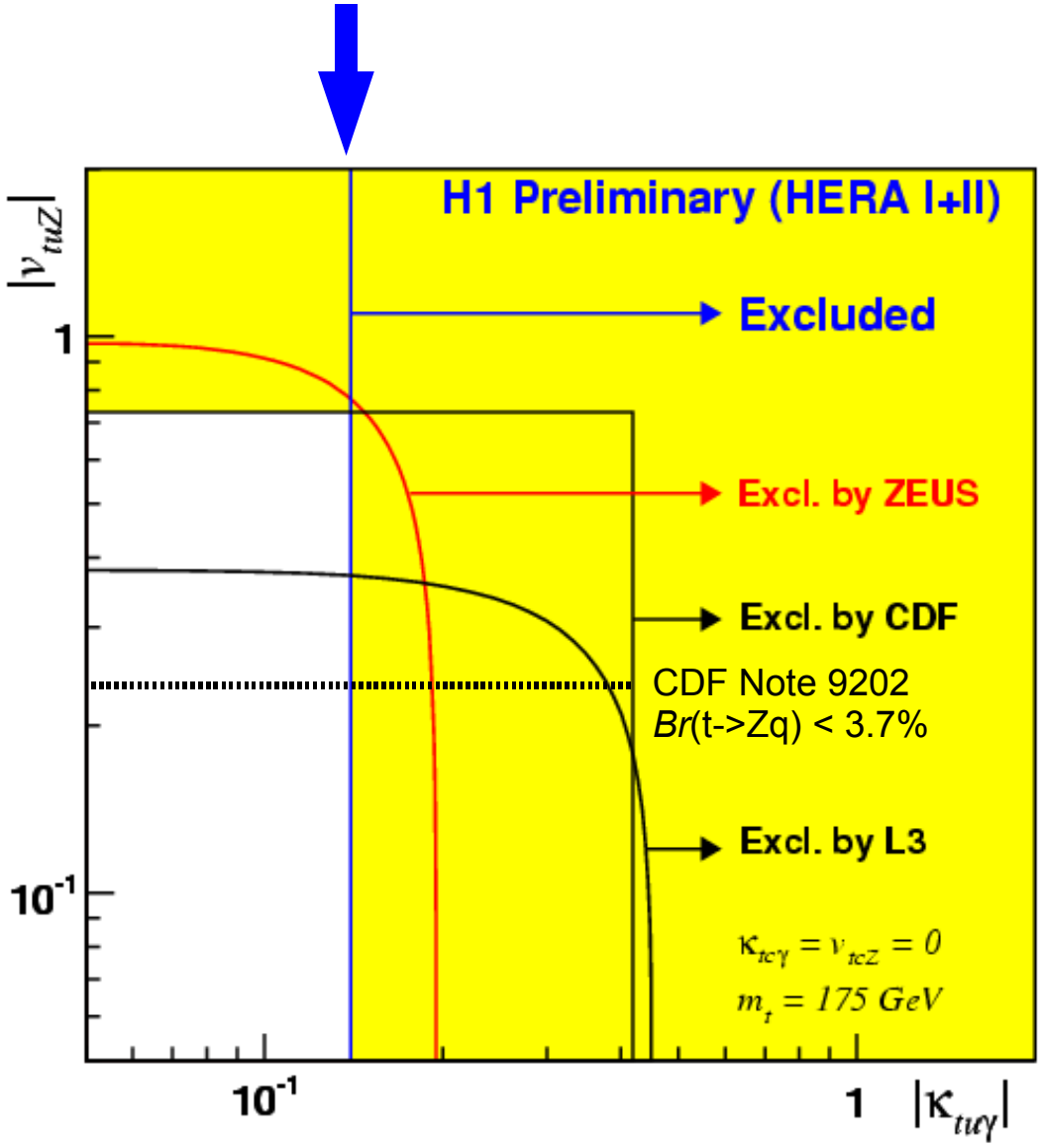
$$\sigma = \frac{S}{\epsilon_{top} \cdot BR \cdot \mathcal{L}_{tot}}$$

- Determine Upper Limit at 95% Confidence Level
- Convert to limit on coupling $\kappa_{tu\gamma}$

Results: Limits on Coupling and Cross Section

- New H1 upper bound on cross section at 95% CL:
  $\sigma(ep \rightarrow etX) < 0.16$ pb
- Upper bound on the anomalous coupling
  $\kappa_{tu\gamma} < 0.14$

- Most stringent limit on $\kappa_{tu\gamma}$ coupling comes from HERA



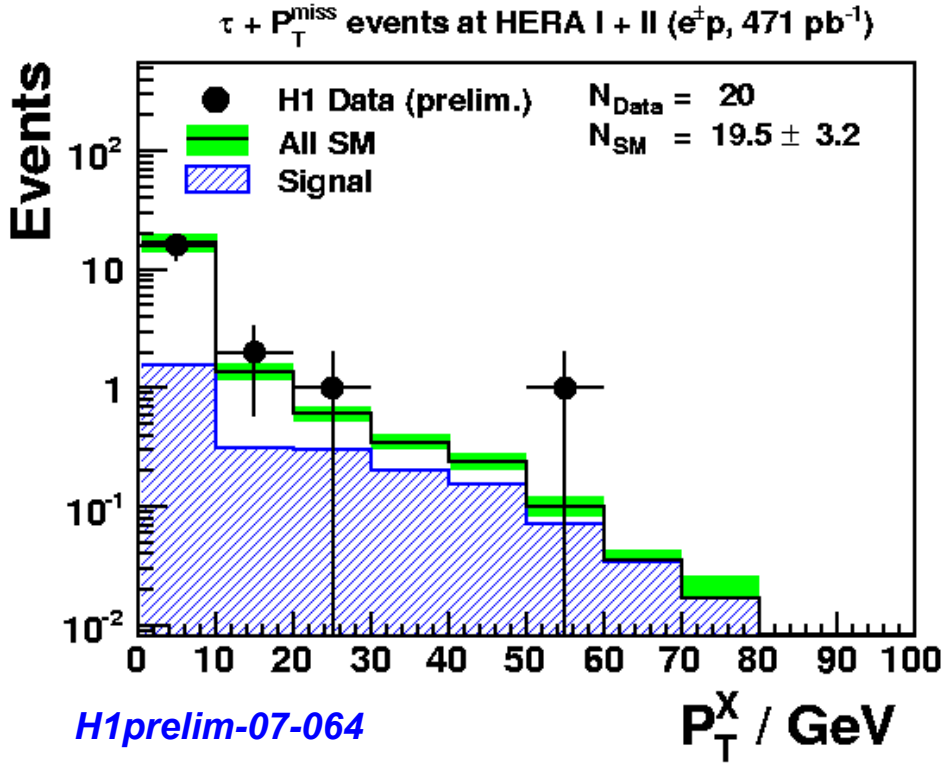
A look at the Tau Channel

- Lepton-Universality in SM:
  Tau appears like e/μ
- Tau Channel favoured in many BSM models
  (heaviest lepton assumed to couple strongest)
- Experience from HERA:
  - Efficiency about ~10% of that of e/μ channels
  - Difficult to suppress CC background overall
  - At high $P_T X > 25$ GeV:
    1 obs. / 1 $\pm$ 0.13 exp.
    (~60% *W* contribution to expectation)
- Tau channel has little impact on search for anomalous single *top* production

Search for isolated tau leptons at HERA

Look for Tau-Leptons decaying hadronically (1-prong) in events with missing transverse momentum

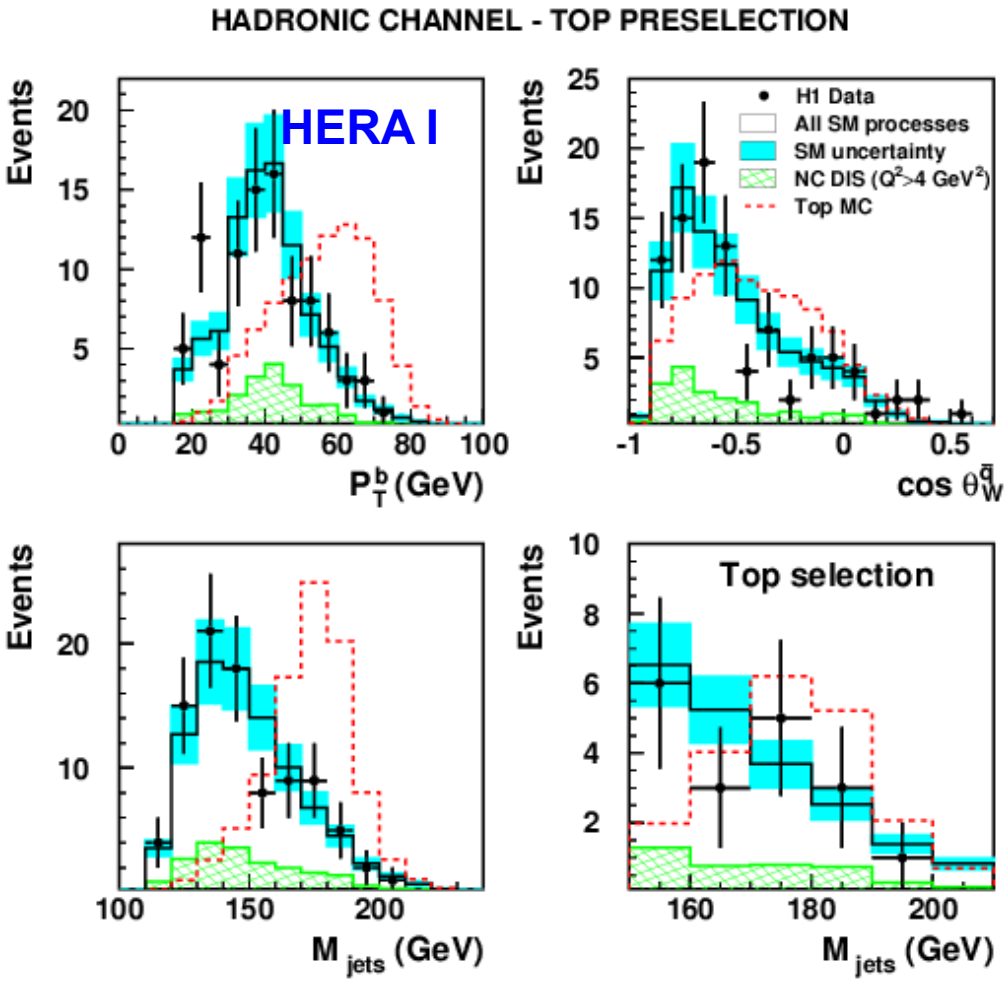
- $P_T > 7$ GeV
- $R < 0.12$
- Exactly one track

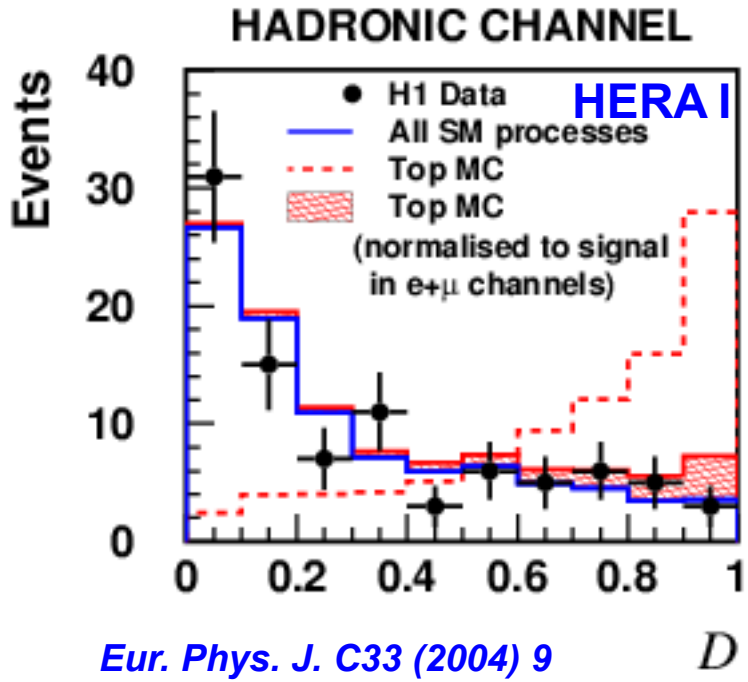


A look at the Hadronic Channel

- HERA-1: Select 3 Jets ($P_T^{1,2,3}$ > 40, 30, 15 GeV), E_{tot} > 110 GeV
- Reconstruction: (P_T^b, M_{jets}, cos θ^q_W) → MVA
- Lower Efficiency than e/μ channels expected (HERA-I: 37% e/μ, 30% hadrons)

- Adds sensitivity to search for single top production





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Summary & Outlook

- Events with isolated leptons and missing energy analysed by H1 and ZEUS using full HERA data: ~1 fb^{-1}
  - Overall excellent agreement with SM
    (H1: excess in e^+p at high P_T^X at 3σ level)
- H1 searched for anomalous single *top* production in ~0.5 fb^{-1}

$$\sigma(ep \to etX) < 0.16 \text{ pb}$$

$$\kappa_{tu\gamma} < 0.14$$

Limit extends the reach of previous analyses.

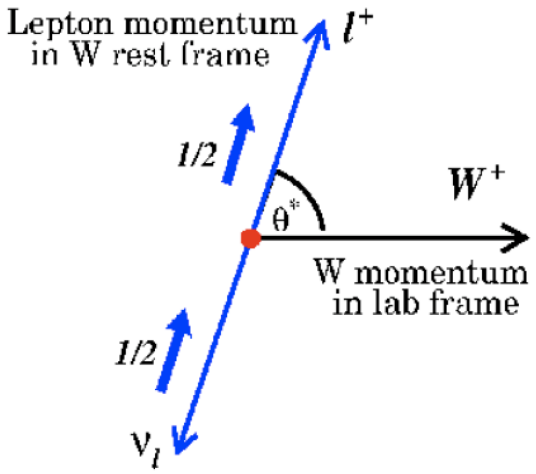
Outlook

- Finalise electron + muon channels based on final isolated leptons analysis
- Include hadronic channel
- Set limit on v_{tuZ}
- Combine results from both HERA experiments

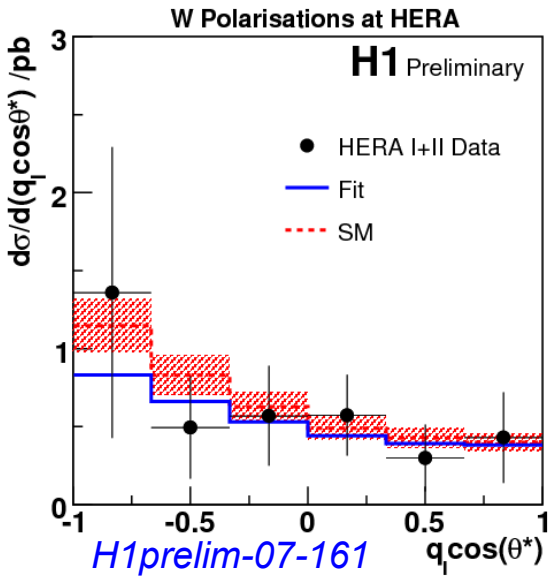
b a c k u p

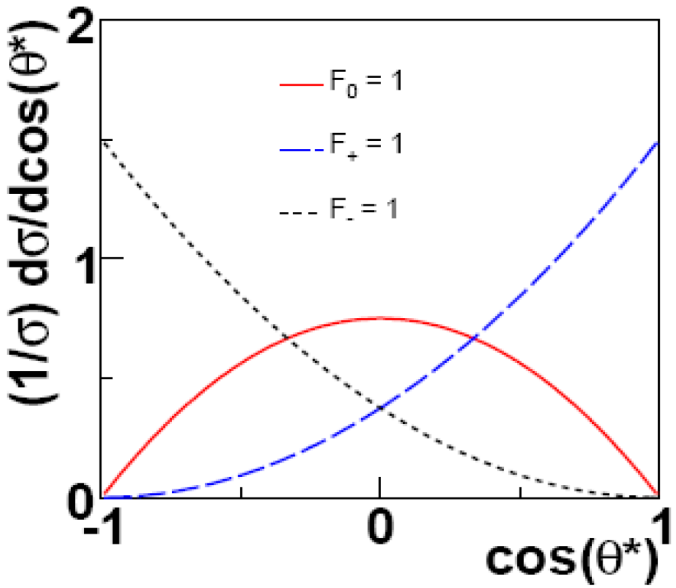
Another Handle? *W*-Polarisation Fractions

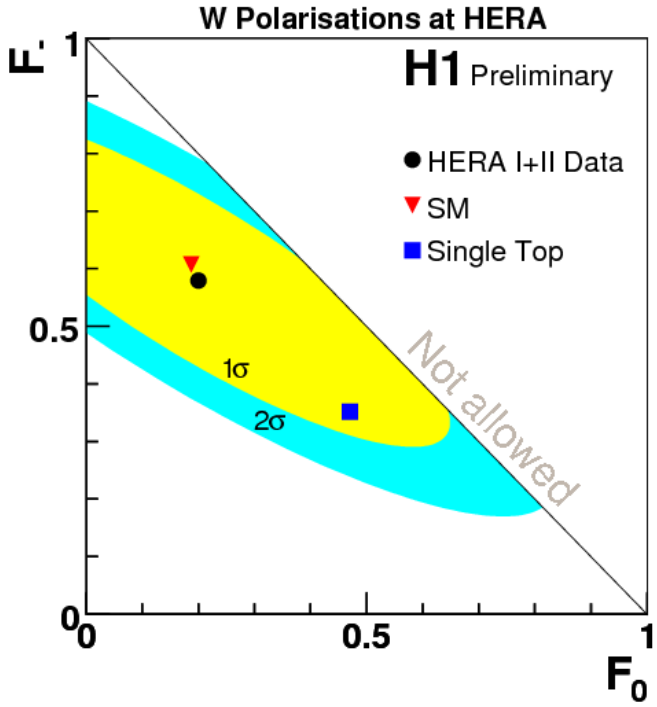
- Reconstruct *W* – Measure *W* Cross Section – good agreement with SM
- Determine *W* Polarisation Fractions from Fit – Parametrise angular distribution
- W Polarisation Fractions from SM W Prod. and anomalous single *top* Production differ – compatible within 1σ



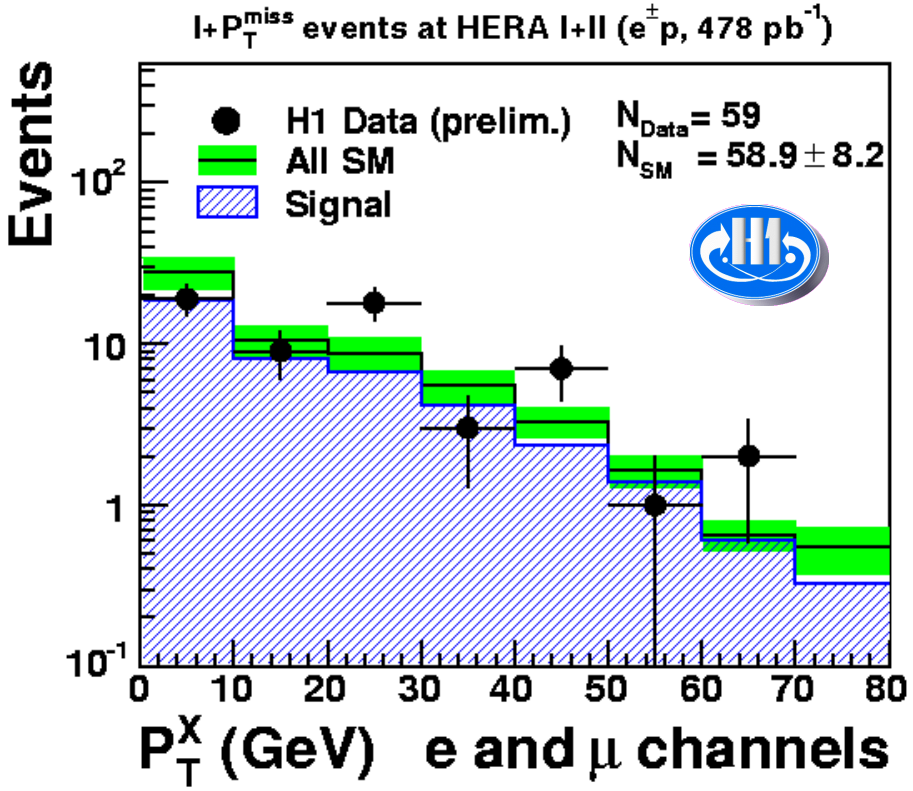
H1	HERA I+II Data	SM
$\sigma_{\sigma_{\ell+\not{P}_T}}$	$0.24 \pm 0.05\,(\text{stat}) \pm 0.05\,(\text{sys})$	$0.26 \pm 0.04\,(\text{th.sys})$
σ_W	$1.23 \pm 0.25\,(\text{stat}) \pm 0.22\,(\text{sys})$	$1.31 \pm 0.20\,(\text{th.sys})$







More Isolated Leptons Results



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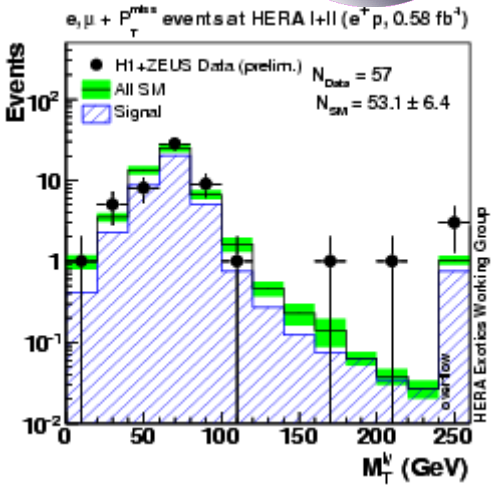
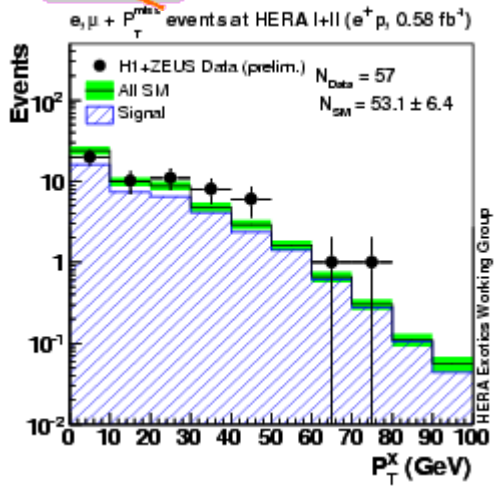
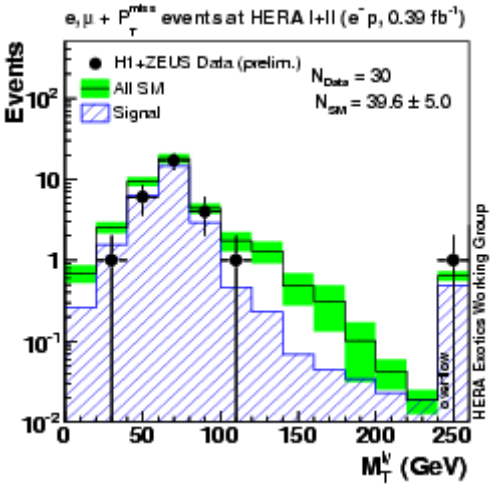
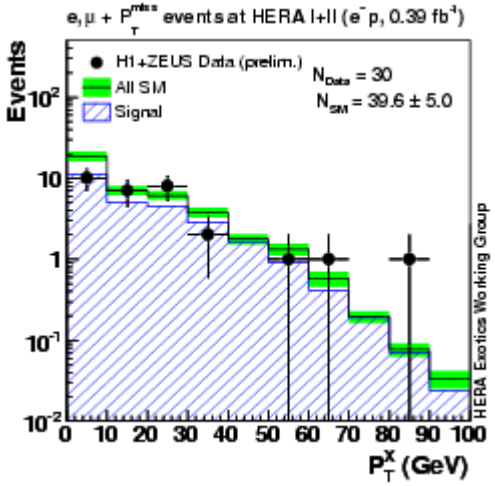


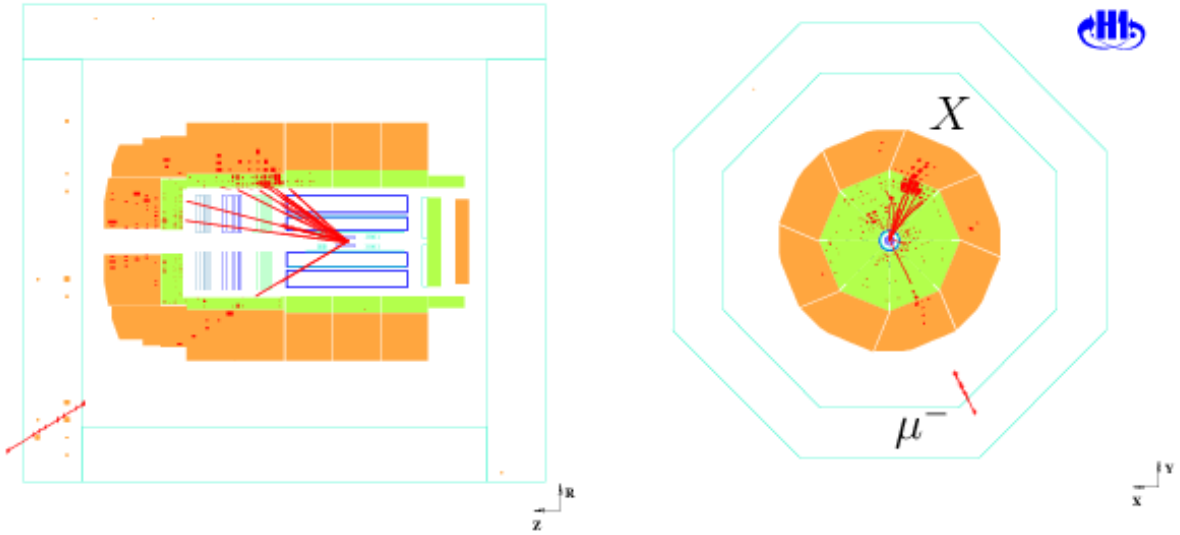




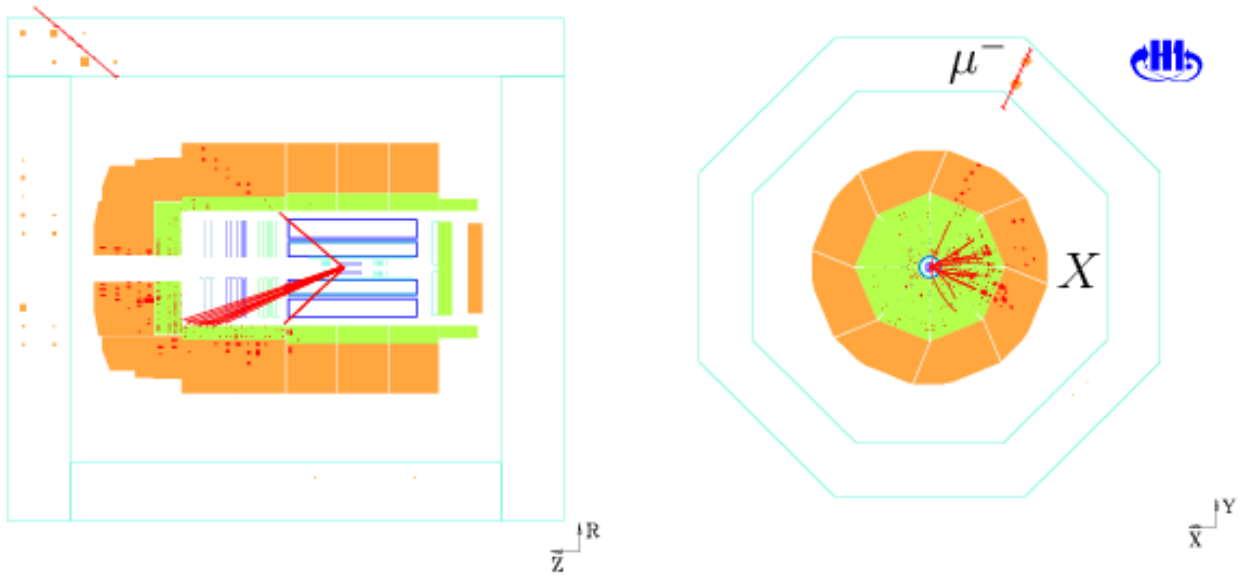


More Isolated Lepton Events (H1)

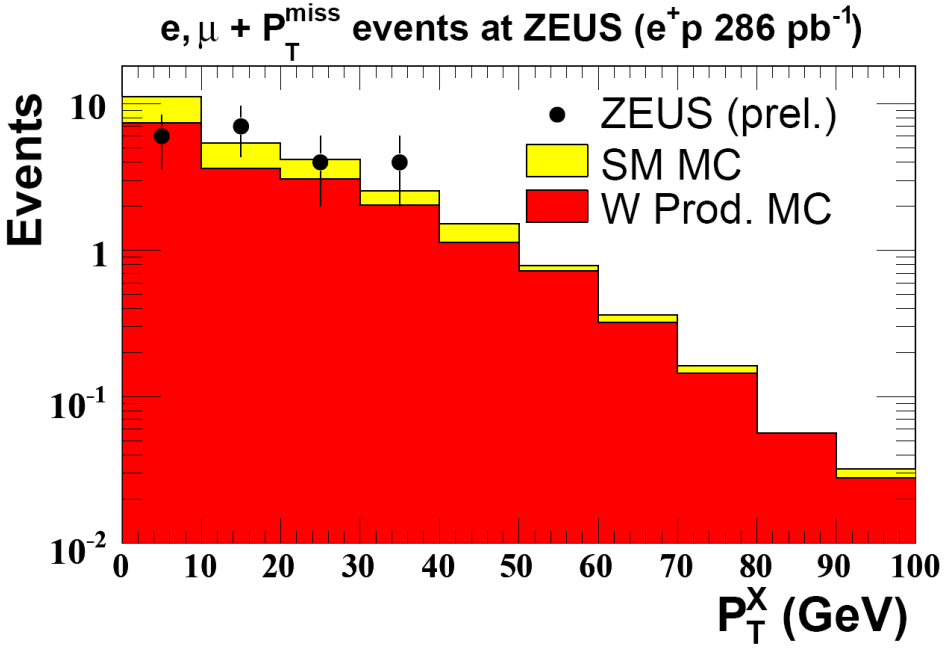
$\mathbf{P}_T^{\mu} = 51\,\mathbf{GeV}, \mathbf{P}_T^{\mathrm{miss}} = 39\,\mathbf{GeV}, \mathbf{P}_T^{X} = 48\,\mathbf{GeV}$

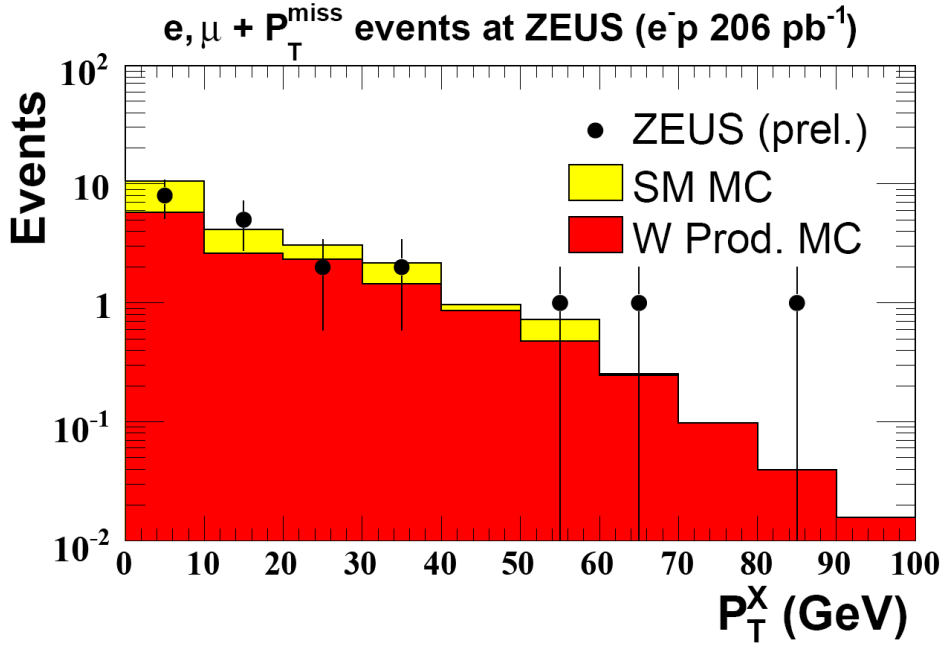


$\mathbf{P}_T^{\mu} = 38\,\mathbf{GeV}, \mathbf{P}_T^{\mathrm{miss}} = 51\,\mathbf{GeV}, \mathbf{P}_T^{X} = 24.7\,\mathbf{GeV}$



Isolated Leptons: ZEUS Results





Isolated e Candidates	$P_T^X < 12$ GeV	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
ZEUS (prel.) e^-p 206 pb^{-1}	$9/11.3 \pm 2.0$ (55%)	$5/3.4 \pm 0.8$ (62%)	$3/3.2 \pm 0.6$ (69%)
ZEUS (prel.) e^+p 286 pb^{-1}	$7/12.3 \pm 1.9$ (66%)	$5/4.1 \pm 0.7$ (67%)	$3/3.9 \pm 0.6$ (76%)
ZEUS (prel.) $e^\pm p$ 492 pb^{-1}	$16/23.6 \pm 3.8$ (60%)	$10/7.5 \pm 1.4$ (65%)	$6/7.1 \pm 1.1$ (73%)

EPS'07
ZEUS-79

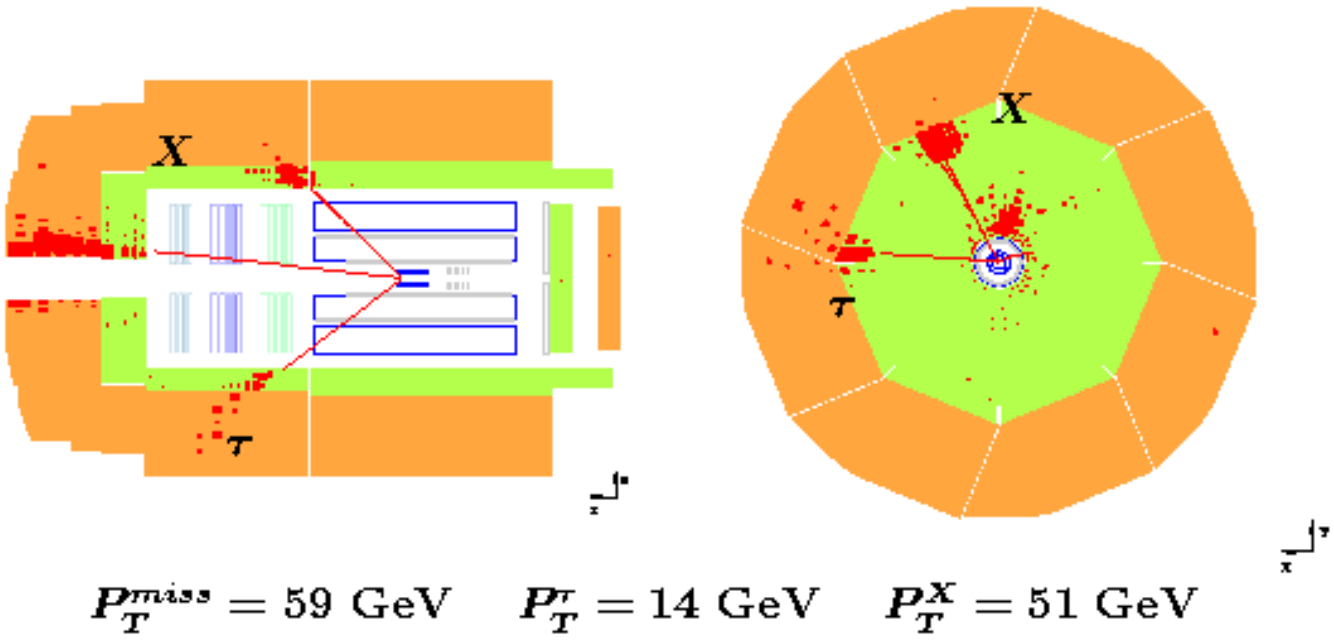
- $P_T > 10$ GeV
- $15° < \theta < 120°$
- $P_T^{Miss} > 12$ GeV

Isolated μ Candidates	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
ZEUS (prel.) e^-p 206 pb^{-1}	$1/1.7 \pm 0.3$ (77%)	$2/2.4 \pm 0.4$ (85%)
ZEUS (prel.) e^+p 286 pb^{-1}	$3/2.3 \pm 0.3$ (82%)	$3/3.6 \pm 0.5$ (81%)
ZEUS (prel.) $e^\pm p$ 492 pb^{-1}	$4/4.1 \pm 0.6$ (80%)	$5/6.0 \pm 0.8$ (82%)

Tau Channel: Cuts and Event Display

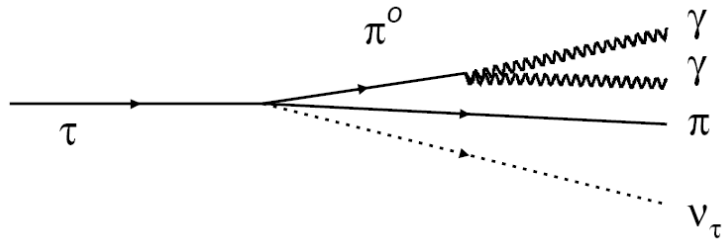
Inclusive CC	$P_T^{\text{calo}} > 12$ GeV
	$P_T^{\text{had}} > 12$ GeV
	$P_T^{\text{miss}} > 12$ GeV
	$\delta^{\text{miss}} > 5$ GeV
	$V_{ap}/V_p < 0.5$
	(< 0.15 if $P_T^{\text{miss}} < 25$ GeV)
Narrow Jets	$P_T^{jet} > 7$ GeV
	$20 < \theta^{jet} < 120$
	$R^{jet} < 0.12$
	$N_{tracks}^{jet} \geq 1$, $\max(P_T^{track}) > 5$ GeV
Isolation	$D_{em,\mu,jet} > 1.0$
Acoplanarity	$\Delta\varphi(\tau, X) < 170$ if $P_T^X > 5$ GeV
1-Prong Jets	$N_{tracks}^{Djet<1.0} = 1$
Final Selection	$N_{\text{DTNV}}^{D_{track}<0.3} = 1$

H1 $\tau + P_T^{miss}$ candidate with large P_T^X



$P_T^{miss} = 59$ GeV $P_T^{\tau} = 14$ GeV $P_T^X = 51$ GeV

H1 Preliminary τ+P_T^{miss} events at HERA I+II		H1 Data	SM Expectation	SM Signal	Other SM Processes
e^+p	Full Sample	10	10.8 ± 1.8	1.6 ± 0.3	9.2 ± 1.6
287 pb^{-1}	$P_T^X > 25$ GeV	0	0.53 ± 0.07	0.38 ± 0.06	0.15 ± 0.01
e^-p	Full Sample	10	8.6 ± 1.5	1.0 ± 0.2	7.6 ± 1.4
184 pb^{-1}	$P_T^X > 25$ GeV	1	0.47 ± 0.07	0.25 ± 0.04	0.22 ± 0.03
$e^{\pm}p$	Full Sample	20	19.5 ± 3.2	2.7 ± 0.4	16.8 ± 2.8
471 pb^{-1}	$P_T^X > 25$ GeV	1	0.99 ± 0.13	0.62 ± 0.10	0.37 ± 0.03



ZEUS HERA I
2 events observed and 0.2 ± 0.05 expected from SM processes.

HERA I Anomalous Single Top Results

DESY-03-188