HERA Anomalies

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Representing ZEUS and H1

- Non-Anomalies
  - Leptoquarks
  - Contact Interactions
  - Excited Fermions

- Anomalies
  - Multi-Electron Production
  - Isolated Leptons
  - Search for $\mathbf{ep} \to \mathbf{tX}$
  - Isolated τ search

Beam Energies

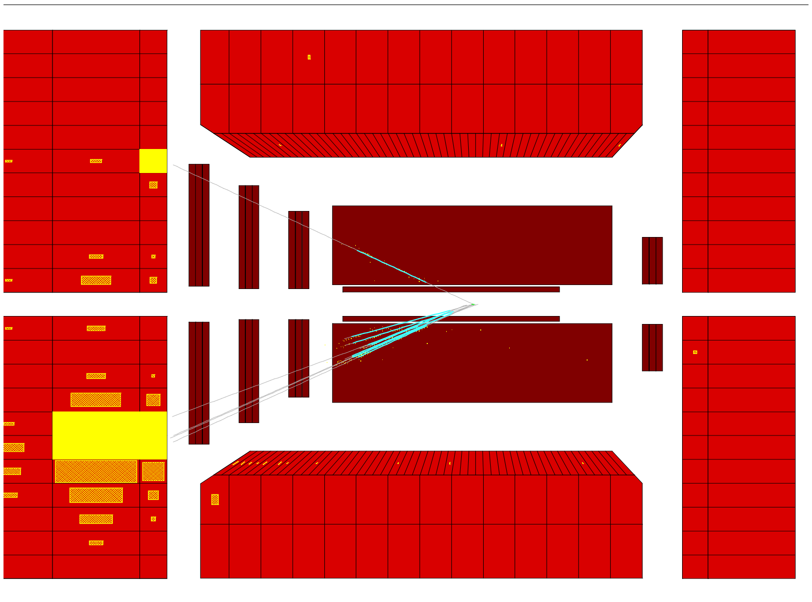
$$E_e = 27.5\,\mathrm{GeV}$$

$$E_p = \begin{cases} 820\,\mathrm{GeV} & \text{until 1997} \\ 920\,\mathrm{GeV} & \text{from 1998} \end{cases}$$

Data Sets

run period	e charge	$\sqrt{s}$ (GeV)	$\int dt\mathcal{L}$ (pb^{-1}) H1	ZEUS
1994-1997	e^+	300	37	48
1998-1999	e^-	318	14	17
1999-2000	e^+	318	65	66

ZEUS Detector



Uranium-Scintillator Calorimeter

6000 Cells,

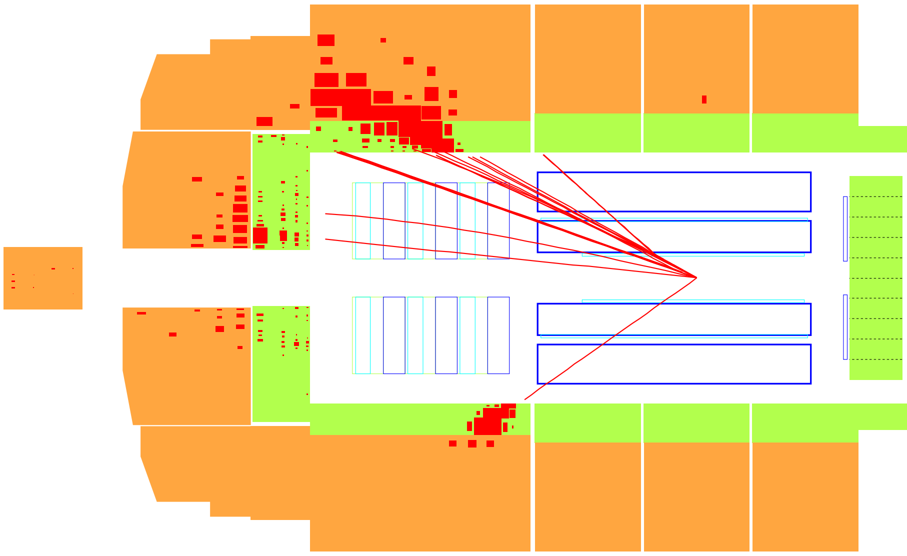
each read out by 2 PMTs

σ_{θ_e} = 5 mrad

$\sigma/\sqrt{E}$ (e) = 18 %

$\sigma/\sqrt{E}$ (had) = 35 %

H1 Detector



Liquid Argon Calorimeter

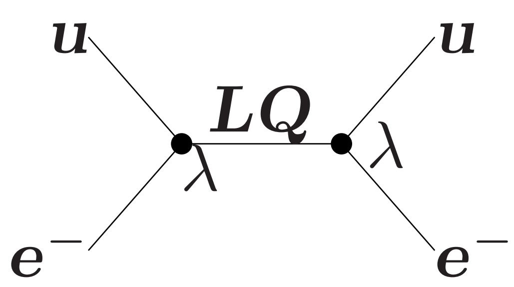
44000 Cells

σ_{θ_e} = 2-5 mrad

$\sigma/\sqrt{E}$ (e) = 12 %

$\sigma/\sqrt{E}$ (had) = 50 %

Leptoquarks



Color triplet bosons with spin zero or one. Dimensionless chiral coupling(s) λ_L or λ_R are $SU(3)\times SU(2)\times U(1)$ invariant.

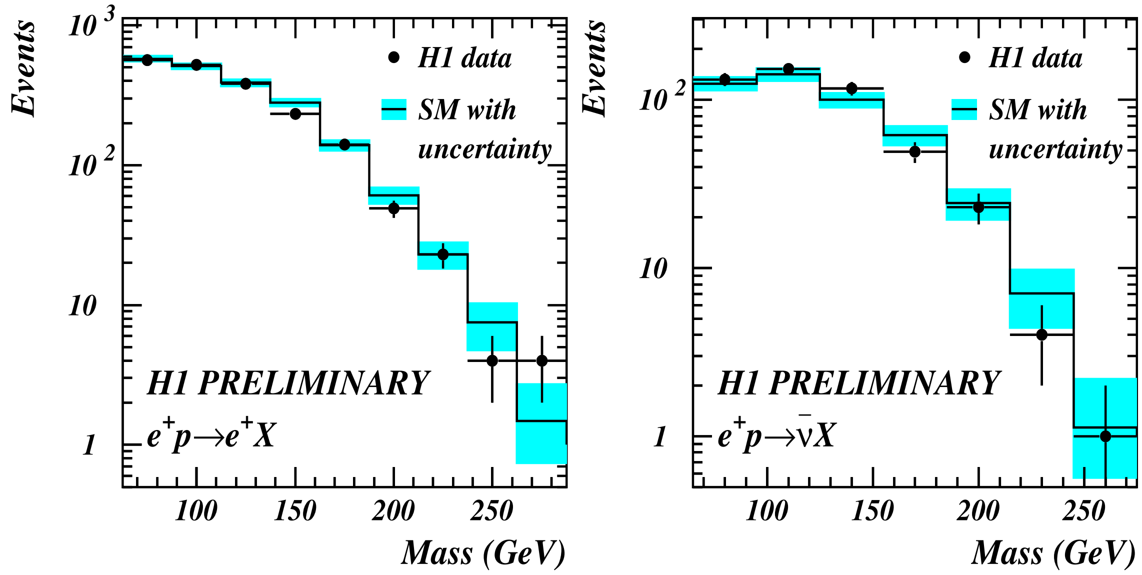
$F = 2$ LQs couple to e^-q or $e^+\bar{q}$, $F = 0$ to e^+q or $e^-\bar{q}$

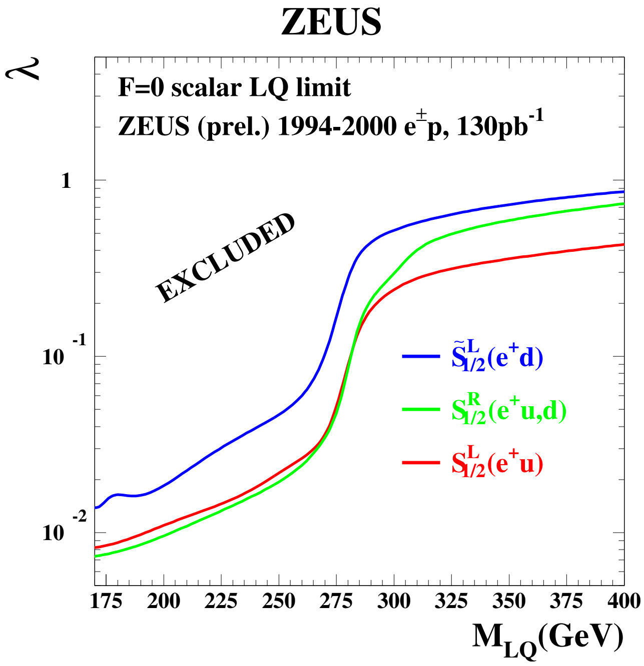
Scalar LQs decay uniformly in $\cos\theta^*$, y
Vector LQs decay $\sim (1+\cos\theta^*)^2 \sim (1-y)^2$
$\theta^* = e$ angle in LQ rest frame
$y = (1-\cos\theta^*)/2 =$ fraction of $E - P_z$ transferred from beam e to hadronic f.s.

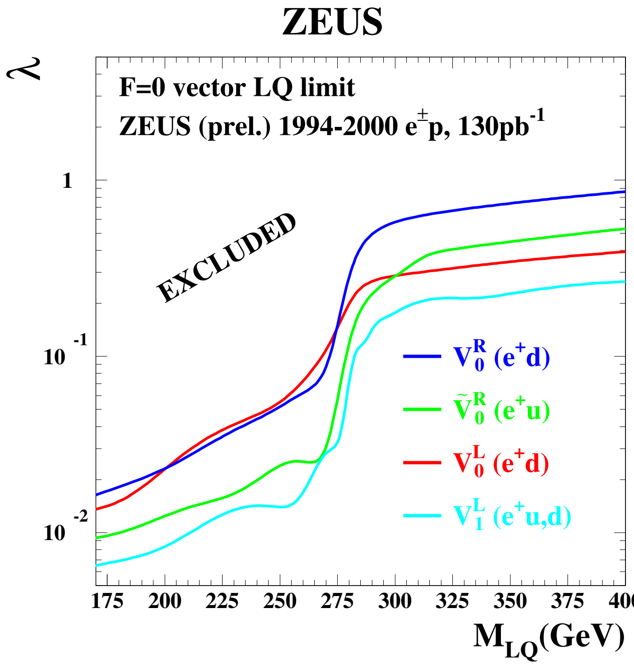
$M_{\rm LQ} < \sqrt{s}$, $\rightarrow$ s-channel resonance at $x = {M_{\rm LQ}}^2/s$.

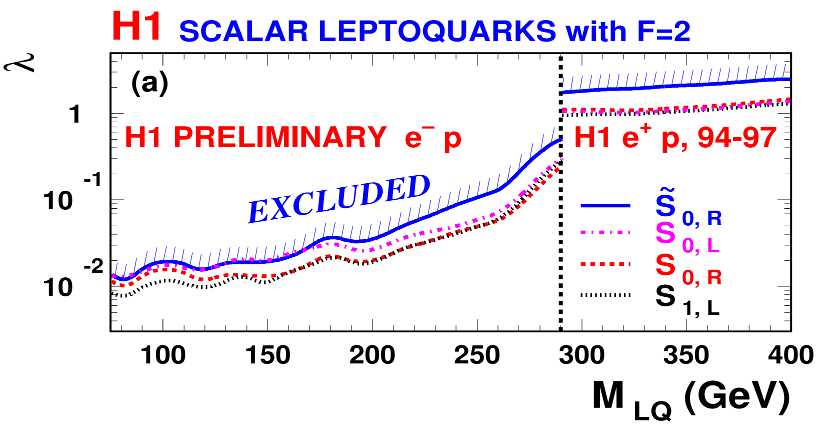
$$\sigma(ep \rightarrow LQ) = (\pi/4s)\lambda^2 q({M_{\tilde{q}}}^2/s) \times \begin{cases} 1 \text{ spin zero} \\ 2 \text{ spin one} \end{cases}$$

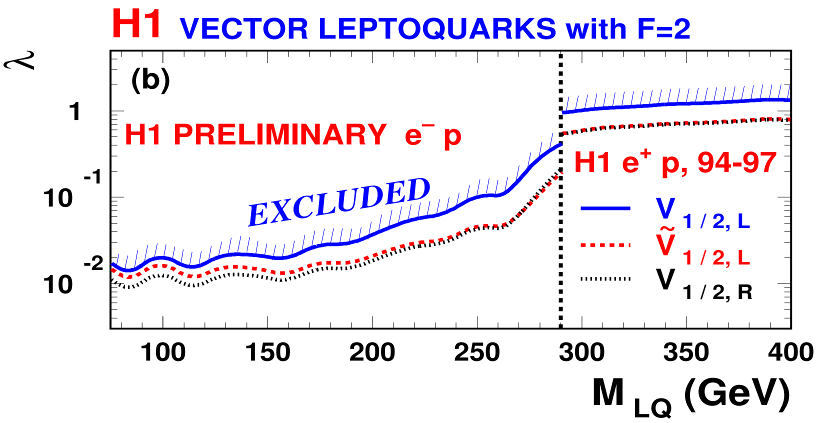
(Narrow-width approximation)



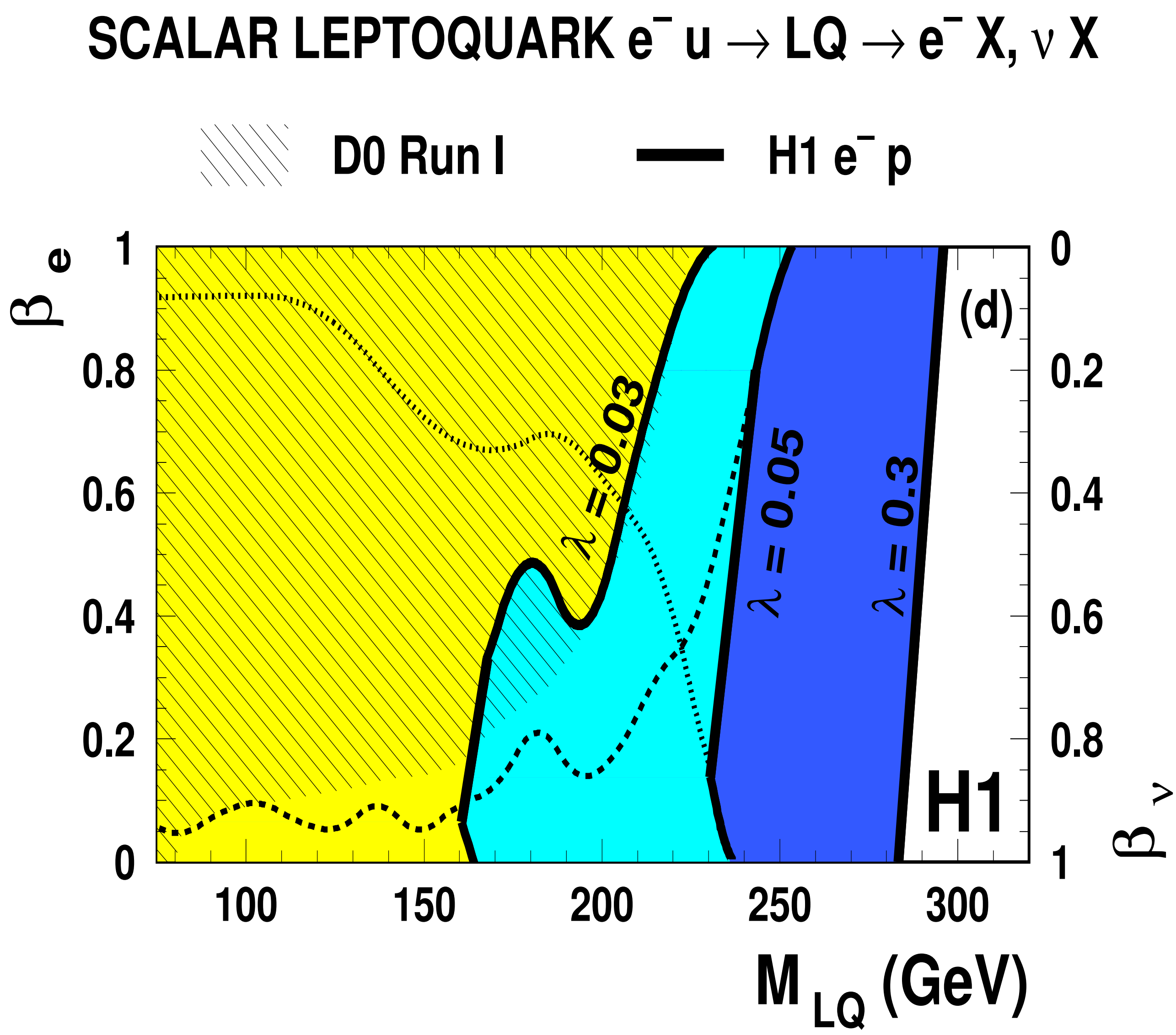




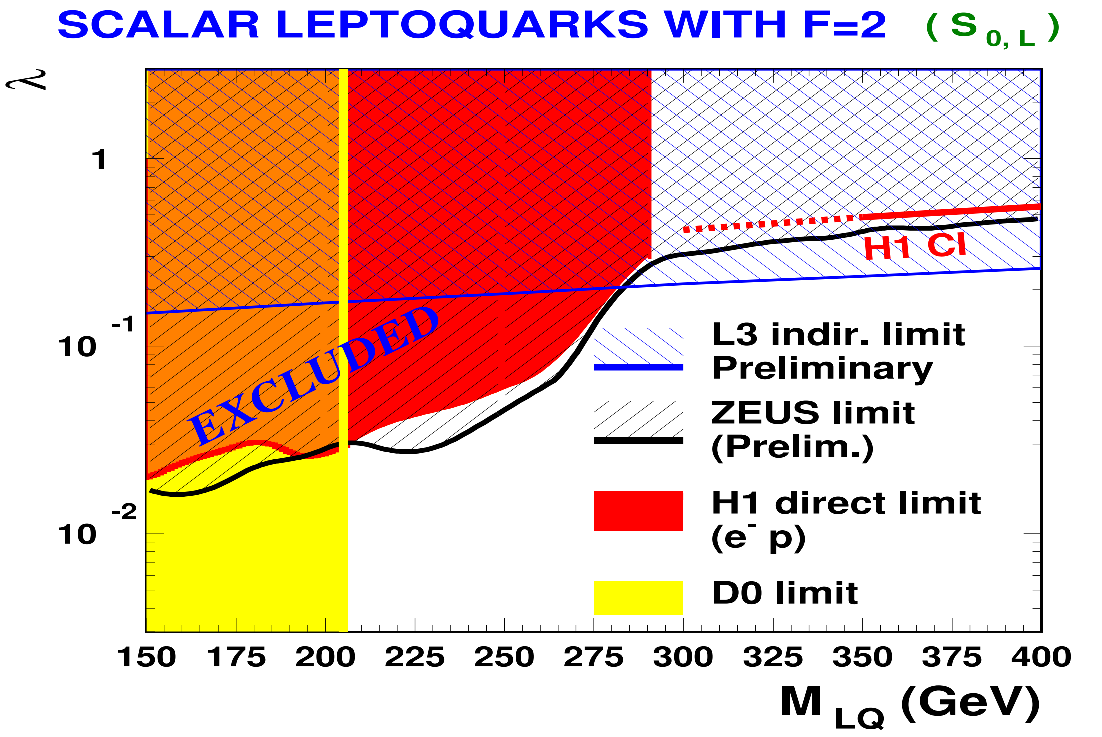


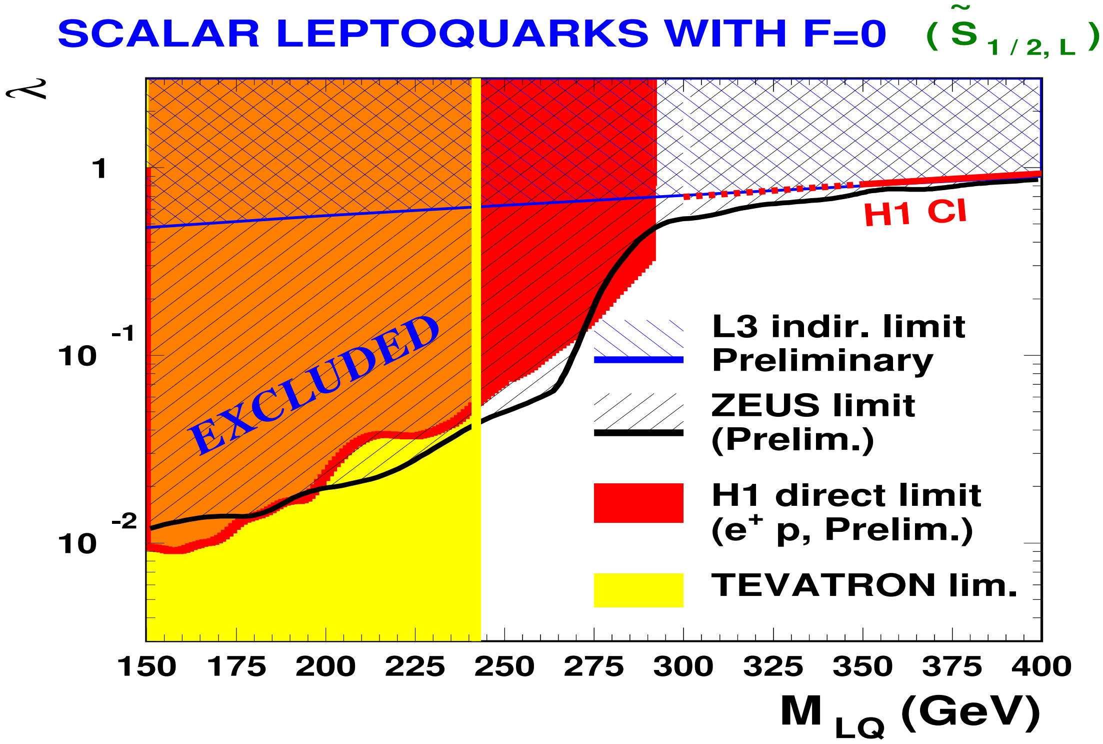


Limits derived from λ-dependent likelihood of $(M_{LQ}, \cos\theta^*)$ distribution. LQ cross section includes s– and u–channel (important for $M_{\rm LQ} > \sqrt{s}$) and LQ-NC interference.



Tevatron sensitivity for eq decays is $>>$ than for νq
HERA eq and νq sensitivities are roughly equal


SCALAR LEPTOQUARKS WITH F=2 ($S_{0,L}$)
λ
1
10^{-1}
10^{-2}
EXCLUDED
H1 CI
L3 indir. limit
Preliminary
ZEUS limit
(Prelim.)
H1 direct limit
(e^- p)
D0 limit
150 175 200 225 250 275 300 325 350 375 400
M_{LQ} (GeV)

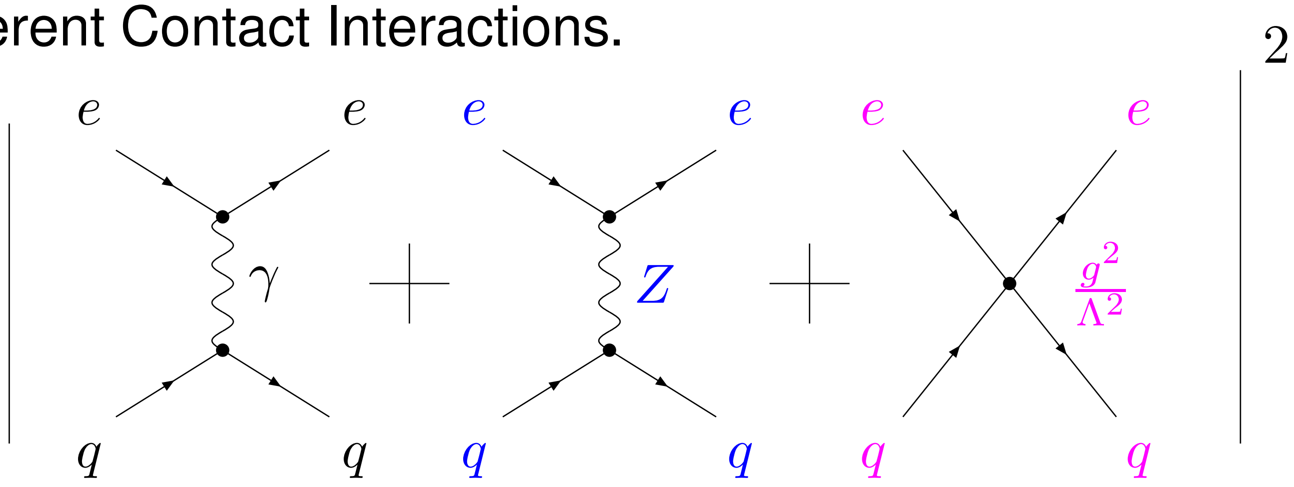

SCALAR LEPTOQUARKS WITH F=0 ($\tilde{S}_{1/2,L}$)
λ
1
10^{-1}
10^{-2}
EXCLUDED
H1 CI
L3 indir. limit
Preliminary
ZEUS limit
(Prelim.)
H1 direct limit
(e^+ p, Prelim.)
TEVATRON lim.
150 175 200 225 250 275 300 325 350 375 400
M_{LQ} (GeV)

Contact Interactions

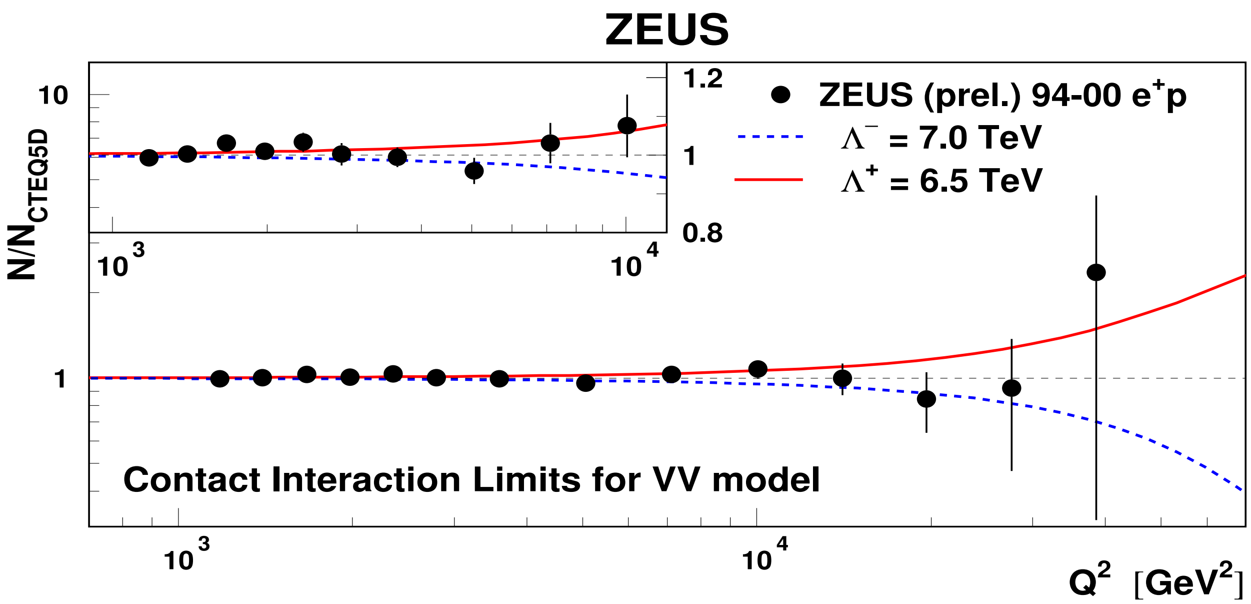
$$\mathcal{L} = \frac{g^2}{\Lambda^2} \sum_{q=u,d} \sum_{\alpha=L,R} \sum_{\beta=L,R} \eta^{eq}_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

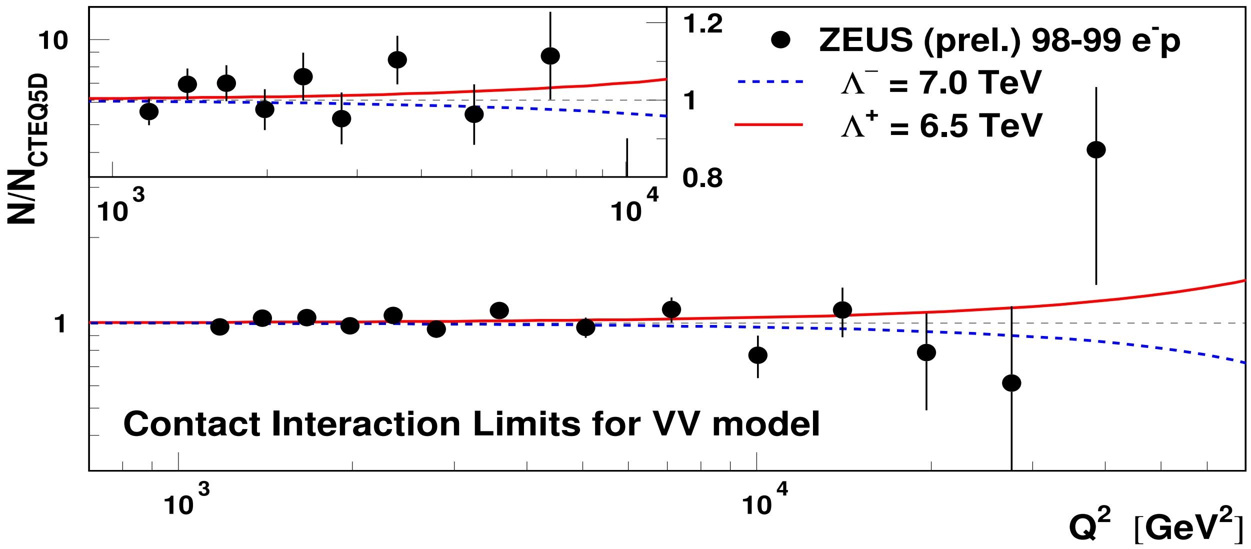
$g^2 = 4\pi$ $\qquad\qquad$ $|\eta^{eq}_{\alpha\beta}| = 0$ or 1

Different combinations of $\eta_{LL}, \eta_{LR}, \eta_{RL}, \eta_{RR}$ yield different Contact Interactions.



Q^2 dependence:	$\frac{1}{Q^4}$	$\frac{1}{(Q^2+M_Z^2)^2}$	flat





Curves show excluded models (95% CL).
ZEUS, H1 both use entire data set (e^- and e^+).

Limits on $\Lambda^{\pm}$ (TeV) for various models.

Model	Coupling structure η_{LL}^{eq}	η_{LR}^{eq}	η_{RL}^{eq}	η_{RR}^{eq}	ZEUS Λ^-	ZEUS Λ^+	H1 Λ^-	H1 Λ^+
VV	+1	+1	+1	+1	7.0	6.5	5.4	5.1
AA	+1	-1	-1	+1	5.3	4.6	3.9	2.5
VA	+1	-1	+1	-1	3.4	3.3	2.9	2.9
LL	+1				-	-	2.3	2.8
LR		+1			-	-	1.8	3.2
RL			+1		-	-	1.9	3.2
RR				+1	-	-	2.3	2.8
X1	+1	-1			4.0	2.7	-	-
X2	+1		+1		4.7	4.7	-	-
X3	+1			+1	4.3	4.2	-	-
X4		+1	+1		5.6	5.6	-	-
X5		+1		+1	4.8	4.8	-	-
X6			+1	-1	2.6	3.9	-	-

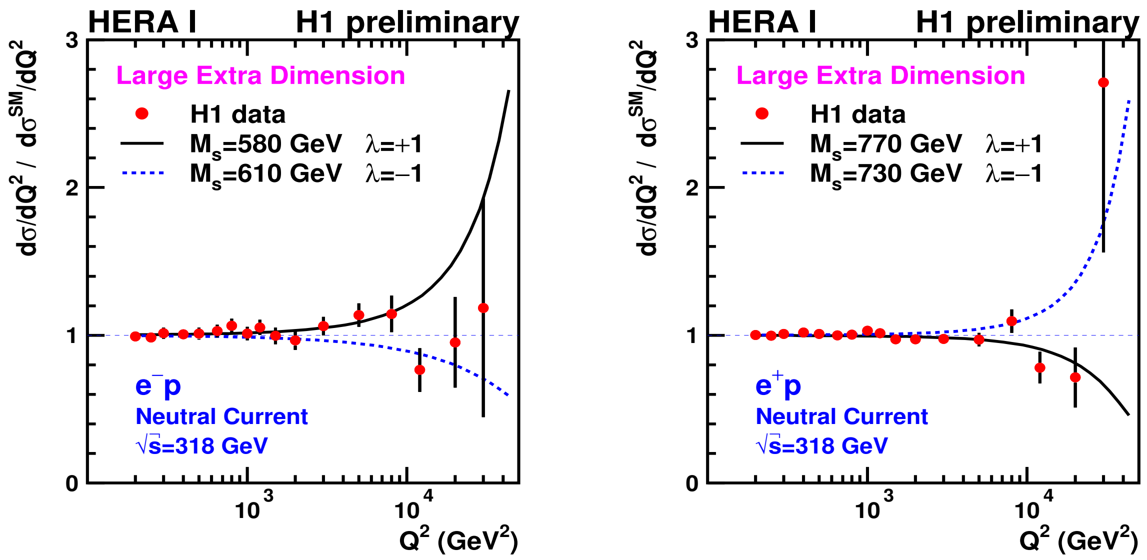
Heavy leptoquarks look like contact interactions
e.g. S_0^L corresponds to $\eta_{LL}^{eu} = +\frac{1}{2}$

95% C.L. limits on S_0^L: $M_{\rm LQ}/\lambda > \begin{cases} 0.72\,\mathrm{TeV} & \mathrm{H1} \\ 0.75\,\mathrm{TeV} & \mathrm{ZEUS} \end{cases}$

For different LQ species, lower limits on $M_{\rm LQ}/\lambda$ range from 0.3 TeV to 1.7 TeV

Large Extra Dimensions

Examine Q^2 spectra for characteristic distorsions.



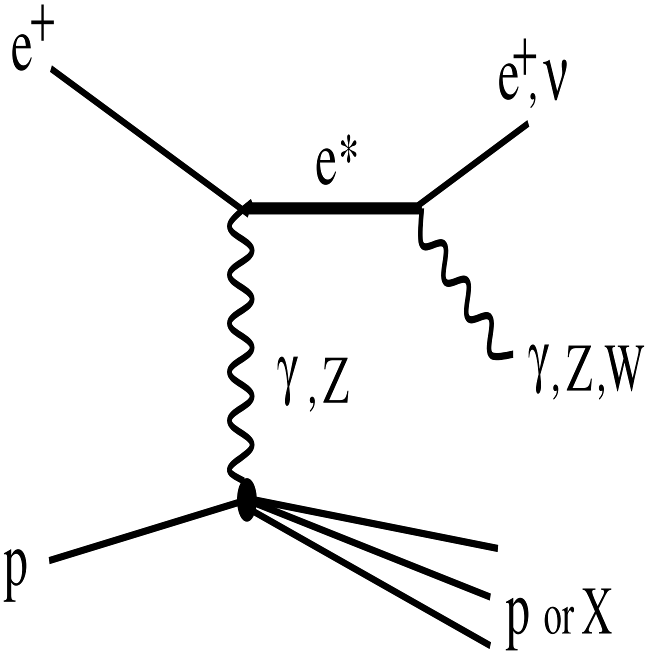
If δ compact dimensions $(R \sim 1\mathrm{mm} = 5 \times 10^{12}\mathrm{GeV}^{-1})$,
$\Rightarrow$ Gravitational interactions with scale M_S
$M_S^{1+\delta/2} \sim R^{-\delta/2} M_P$, where $(M_P = 1.2 \times 10^{19}\mathrm{GeV})$
$\Rightarrow M_S \sim 1\,\mathrm{TeV}$

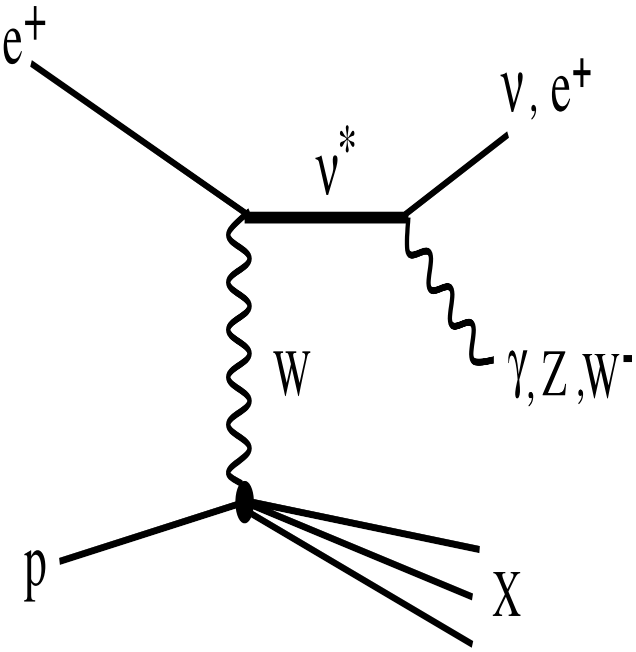
Excited Fermions

If fermions are composite, then excited states are expected

$$\mathcal{L} = \frac{1}{2\Lambda}\bar{F}^*_R\sigma^{\mu\nu}\left[g f\frac{\tau^a}{2}W^a_{\mu\nu} + g' f'\frac{Y}{2}B_{\mu\nu} + g_s f_s\frac{\lambda^a}{2}G^a_{\mu\nu}\right]F_L + h.c.$$

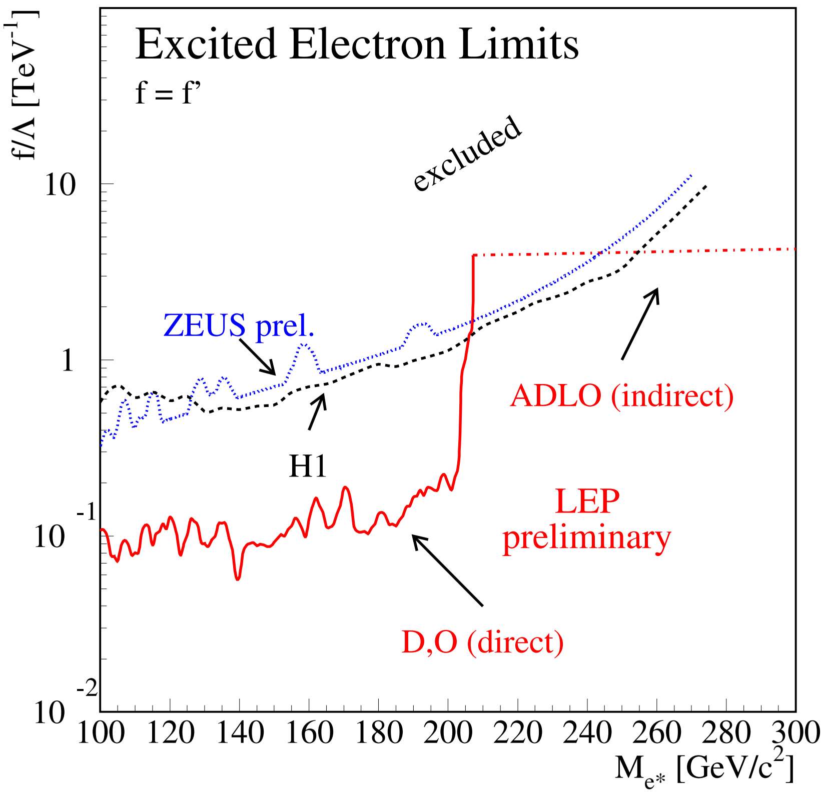
- Magnetic coupling between fermion weak-isodoublet F_L and excited fermions F^*_R
- f, f', f_s are weight factors for Standard Model gauge fields.
- $\Lambda =$ the compositeness scale

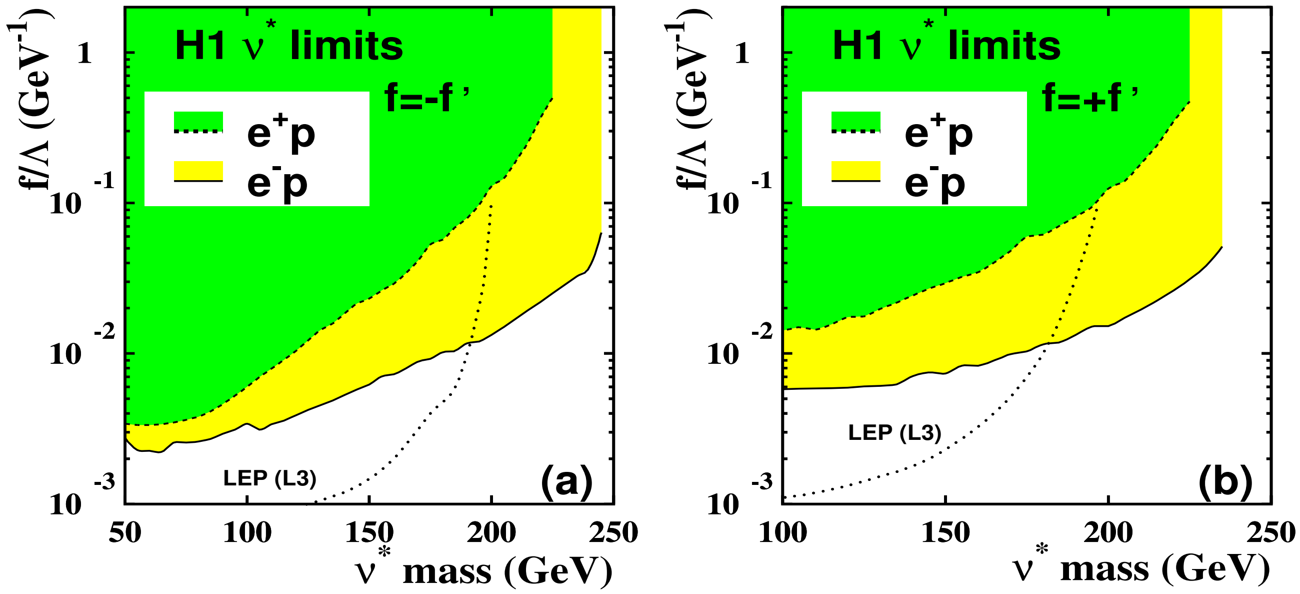




$\sim 50\%$ of e^* production is elastic.

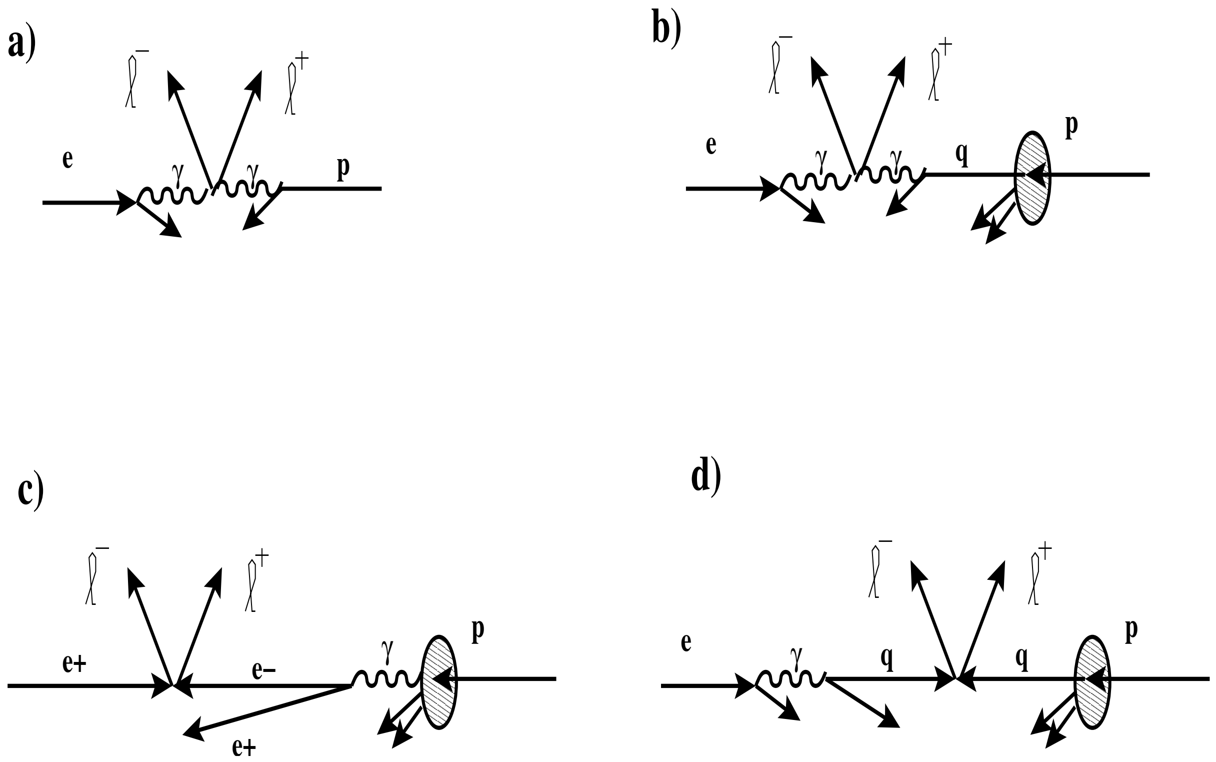
Excited Fermion Limits





For $f = f'$, no ν^* decay to $\nu\gamma$

Multi-Electron Events



Simulated using GRAPE generator

Event Selection

- require at least 2 central, isolated electrons with $E_e > 10\,\text{GeV}$,
- Central $= \begin{cases} 20^\circ < \theta < 150^\circ & \text{H1} \\ 17^\circ < \theta < 163^\circ & \text{ZEUS} \end{cases}$
- one of the above electrons has $P_{t,e} > 10\,\text{GeV}$.

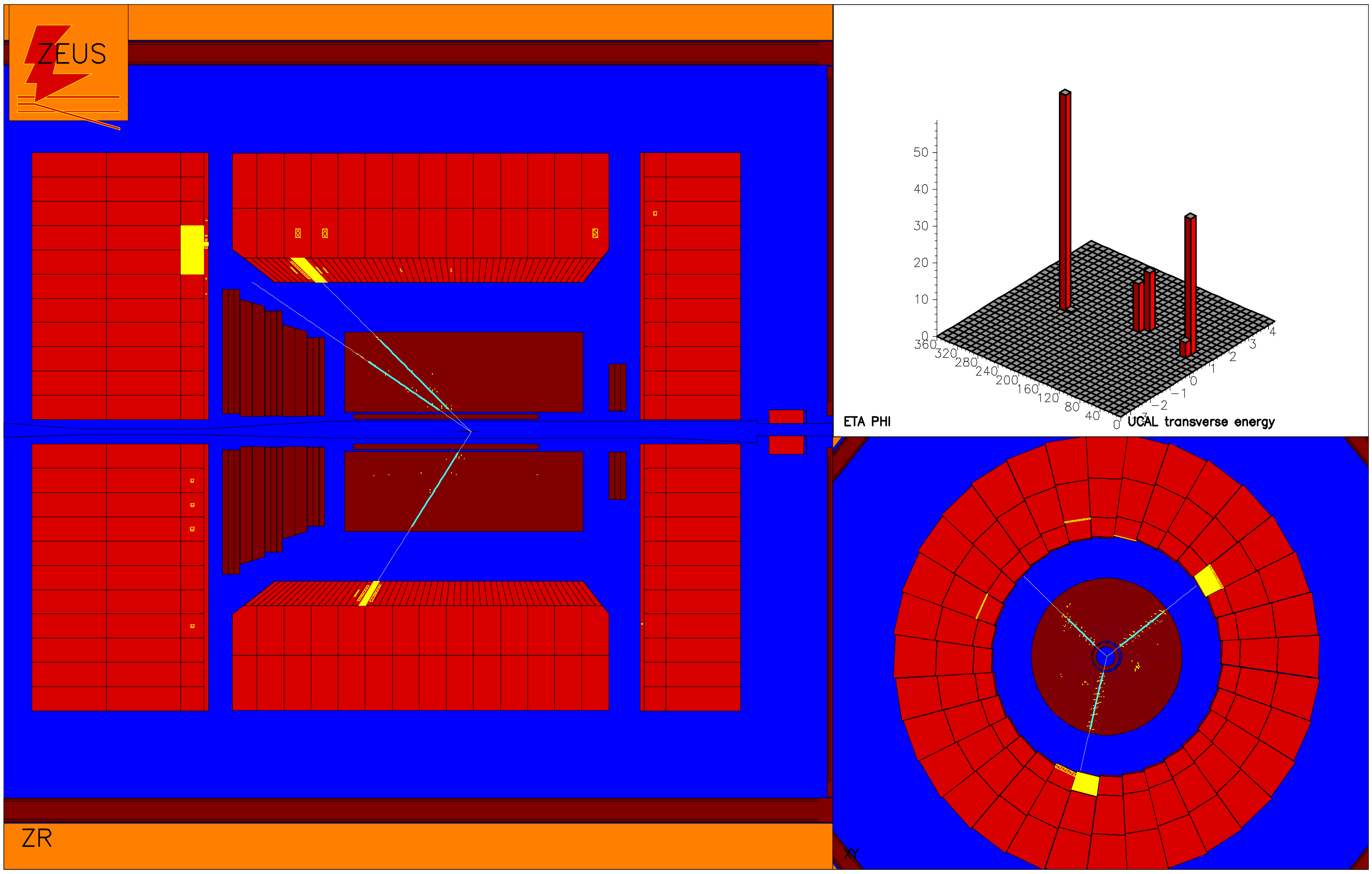
Define M_{12} = the invariant mass of the two highest P_t electrons (including non-central electrons).

ee Events

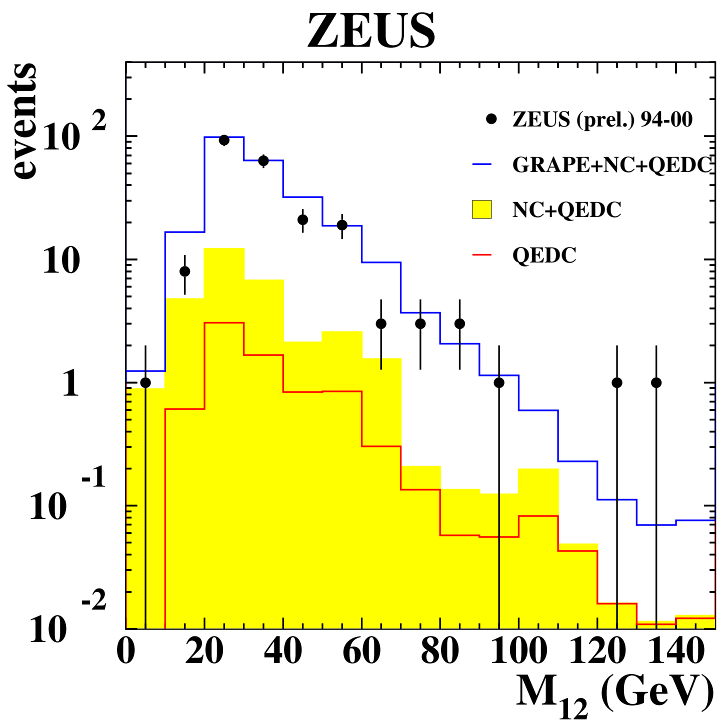
Sample	Exp	Data	Expected	Grape	NC+Compton
ALL	ZEUS	191	214 ± 4	182 ± 1	31.7 ± 3.7
ALL	H1	105	118 ± 13	93 ± 12	25.0 ± 5.5
$M_{12} > 100$ GeV	ZEUS	2	0.77 ± 0.08	0.47 ± 0.05	0.30 ± 0.07
$M_{12} > 100$ GeV	H1	3	0.25 ± 0.05	0.21 ± 0.04	0.04 ± 0.03

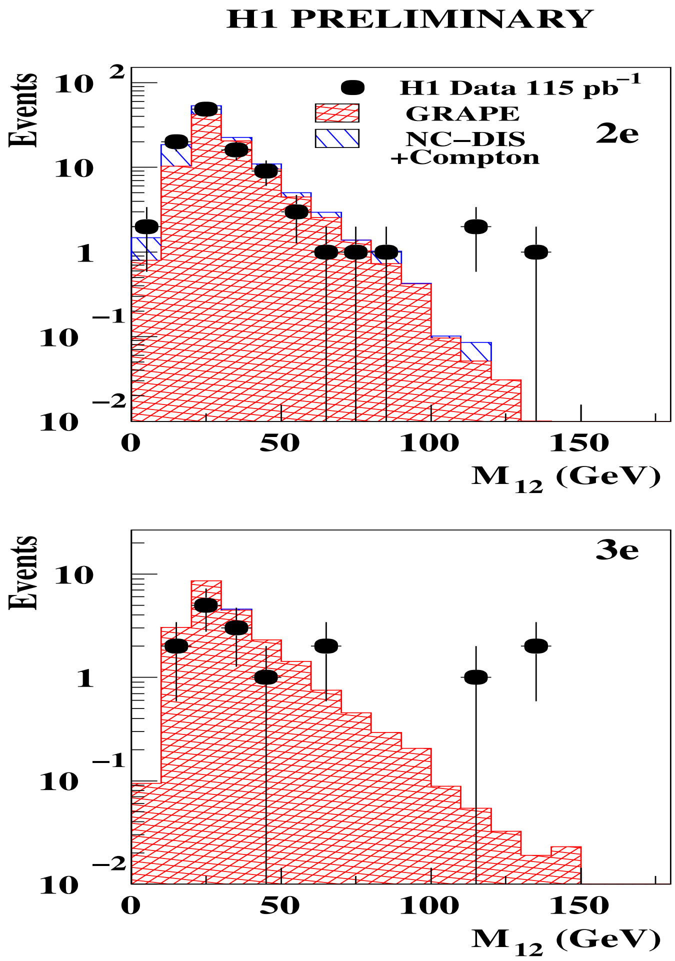
eee Events

Sample	Exp	Data	Expected	Grape	NC + Compton
ALL	ZEUS	26	34.7 ± 0.5	34.7 ± 0.5	-
ALL	H1	16	21.6 ± 3.0	21.5 ± 3.0	0.1 ± 0.1
$M_{12} > 100$ GeV	ZEUS	0	0.37 ± 0.04	0.37 ± 0.04	-
$M_{12} > 100$ GeV	H1	3	0.23 ± 0.04	0.23 ± 0.04	-



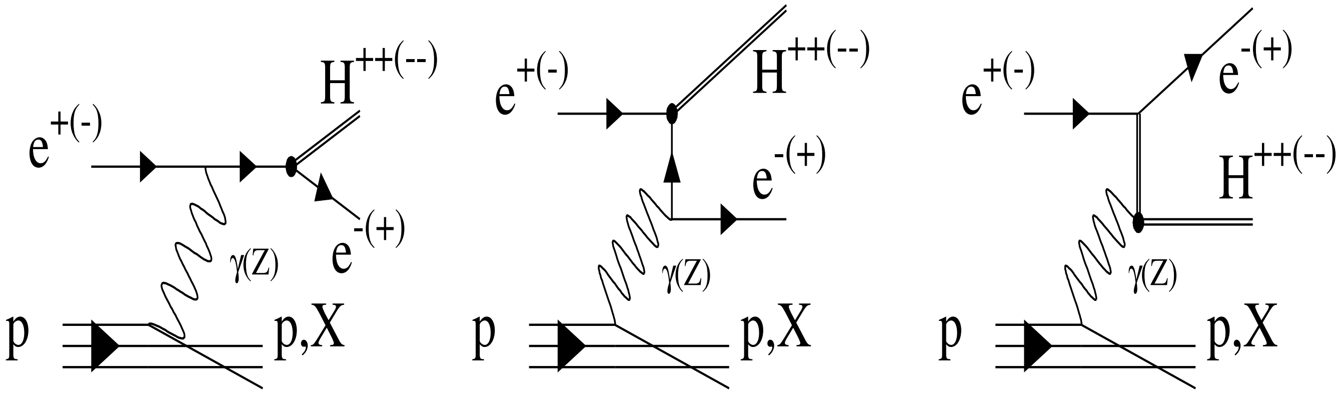
M_{12} =94 GeV	Electron energies	61 GeV	68 GeV	65 GeV
	polar angles	57°	44°	33°
	transverse momenta	52 GeV	47 GeV	36 GeV


ZEUS
events
ZEUS (prel.) 94-00
GRAPE+NC+QEDC
NC+QEDC
QEDC
M12 (GeV)

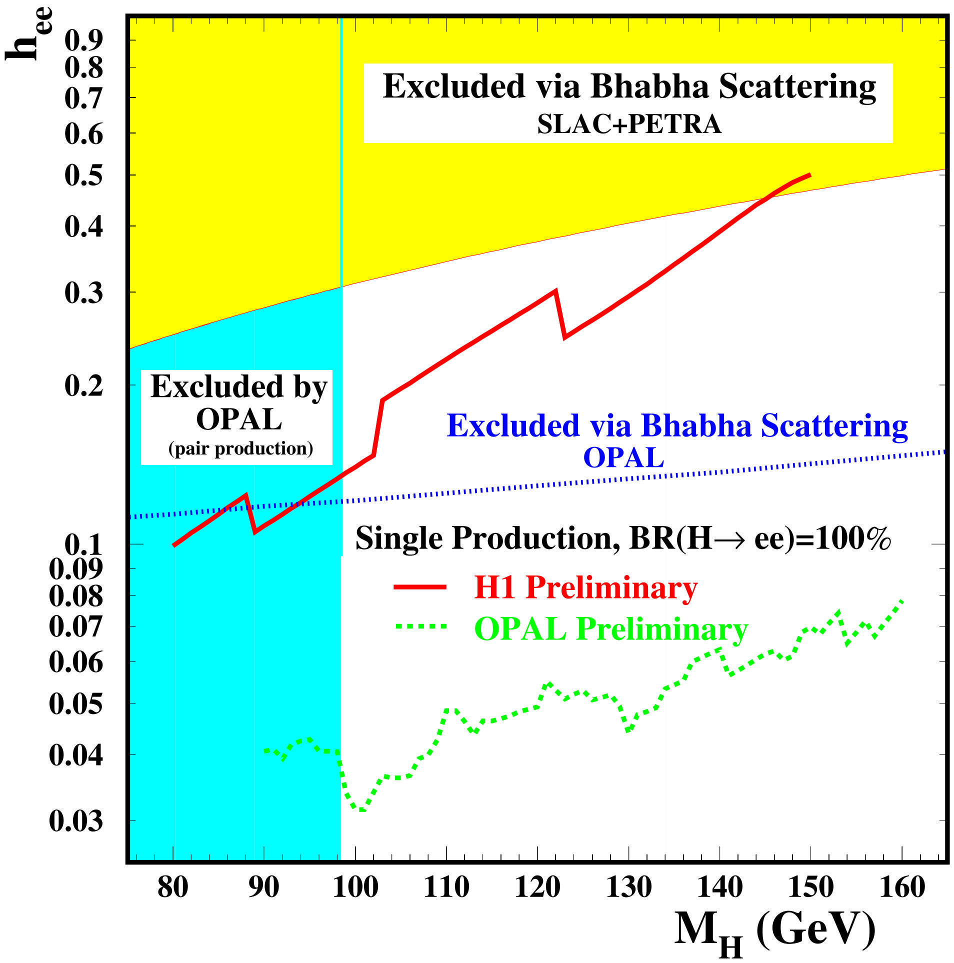

H1 PRELIMINARY
Events
H1 Data 115 pb−1
GRAPE
NC−DIS
+Compton
2e
M12 (GeV)
3e
M12 (GeV)

Doubly-Charged Higgs?

H1 has searched for H^{++} (e^+ beam) or H^{--} (e^- beam)

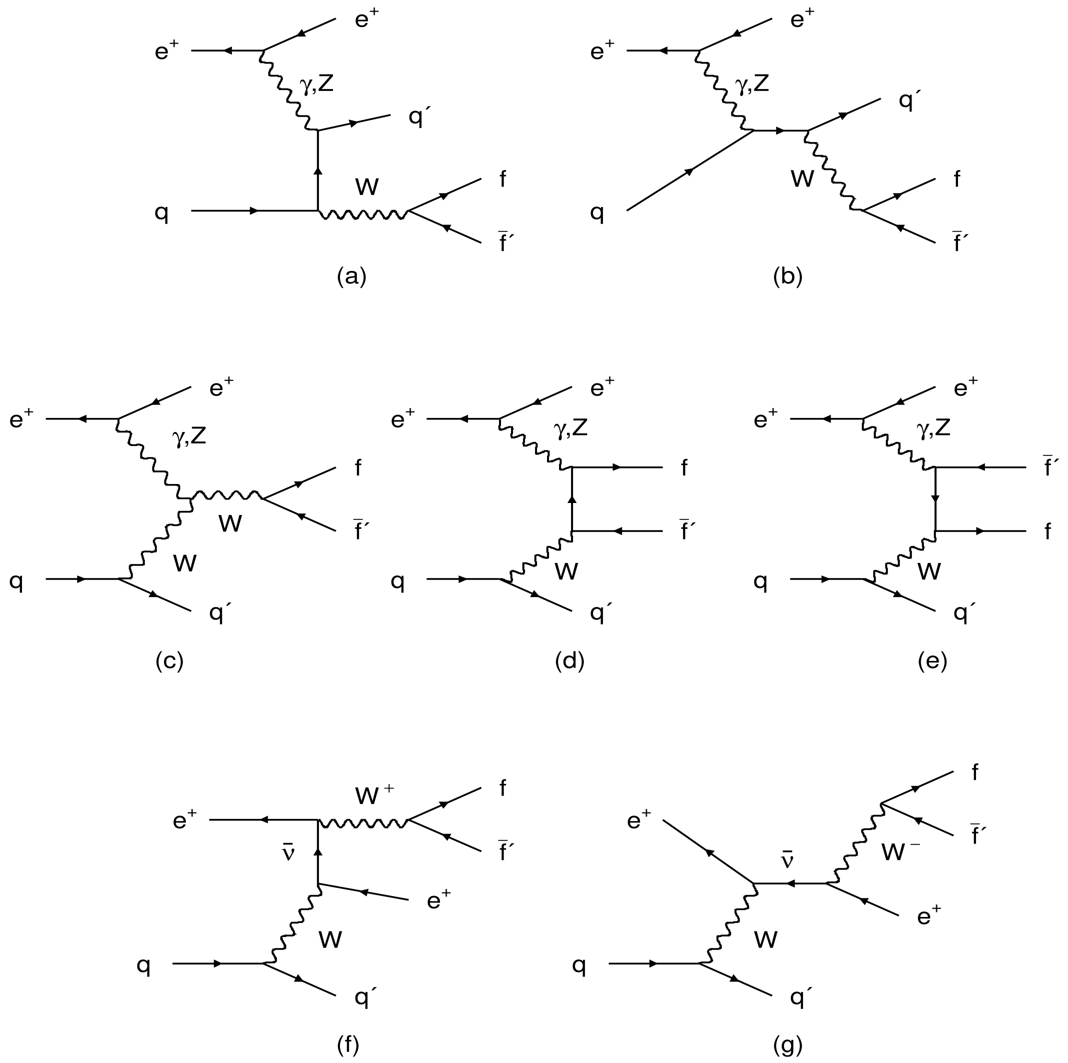


Perform sliding mass window search on ee events



Events with an Isolated Lepton and $\not{P}_t$

Standard Model source is $ep \to WX \to \ell\nu X$



Processes which contribute due to $\not{P}_t$ from mismeasurement:

- NC DIS ($ep \to eX$)
- $ep \to \ell^+\ell^- X$ (via inelastic $\gamma\gamma \to \ell^+\ell^-$)

(X denotes the hadronic final state)

Isolated Lepton Event Selection

- H1 selection optimized for W production
- ZEUS selection more generic

cut	H1	ZEUS
$P_t^{\mathrm{cal}} >$	12 GeV	20 GeV
$P_t^{\mathrm{lepton}} >$	10 GeV	5 GeV
Lepton polar angle	$5^\circ < \theta_\ell < 145^\circ$	$17^\circ < \theta_\ell < 115^\circ$
Lepton $\eta\phi$ isolation	$D_{\mathrm{jet}} > 1$ $D_{\mathrm{track}} > 0.5$	$D_{\mathrm{jet}} > 1$ $D_{\mathrm{track}} > 0.5$
$P_t^X >$	12 GeV (muon only)	5 GeV (jet P_t cut)
Acoplanarity $\ell X >$	$20^\circ(e)$, $10^\circ(\mu)$	8° (e only)

Additional H1 cuts:

reject μ events with an additional μ

reject NC DIS (electron only) $\quad Q_e^2 > \begin{cases} 500\ \mathrm{GeV}^2 & \text{if } P_t^{\mathrm{cal}} < 25\ \mathrm{GeV} \\ 5000\ \mathrm{GeV}^2 & \text{if } P_t^{\mathrm{cal}} > 25\ \mathrm{GeV} \end{cases}$

reject NC DIS (electron only) $\quad$ Missing $E - P_z > 5$ GeV

hadronic final state is collimated $\quad \dfrac{V_{\mathrm{ap}}}{V_{\mathrm{p}}} < \begin{cases} 0.5 & \text{electrons with } P_t^e > 25\ \mathrm{GeV} \\ 0.15 & \text{electrons with } P_t^e < 25\ \mathrm{GeV} \\ 0.4 & \text{muons with } P_t^{\mathrm{cal}} > 25\ \mathrm{GeV} \\ 0.15 & \text{muons with } P_t^{\mathrm{cal}} < 25\ \mathrm{GeV} \end{cases}$

Define:

$\vec{P}_{t,i}$ = transverse momentum of i^{th} hadronic particle

$\hat{n}_h$ = unit vector in direction of $\sum_i P_{t,i}$

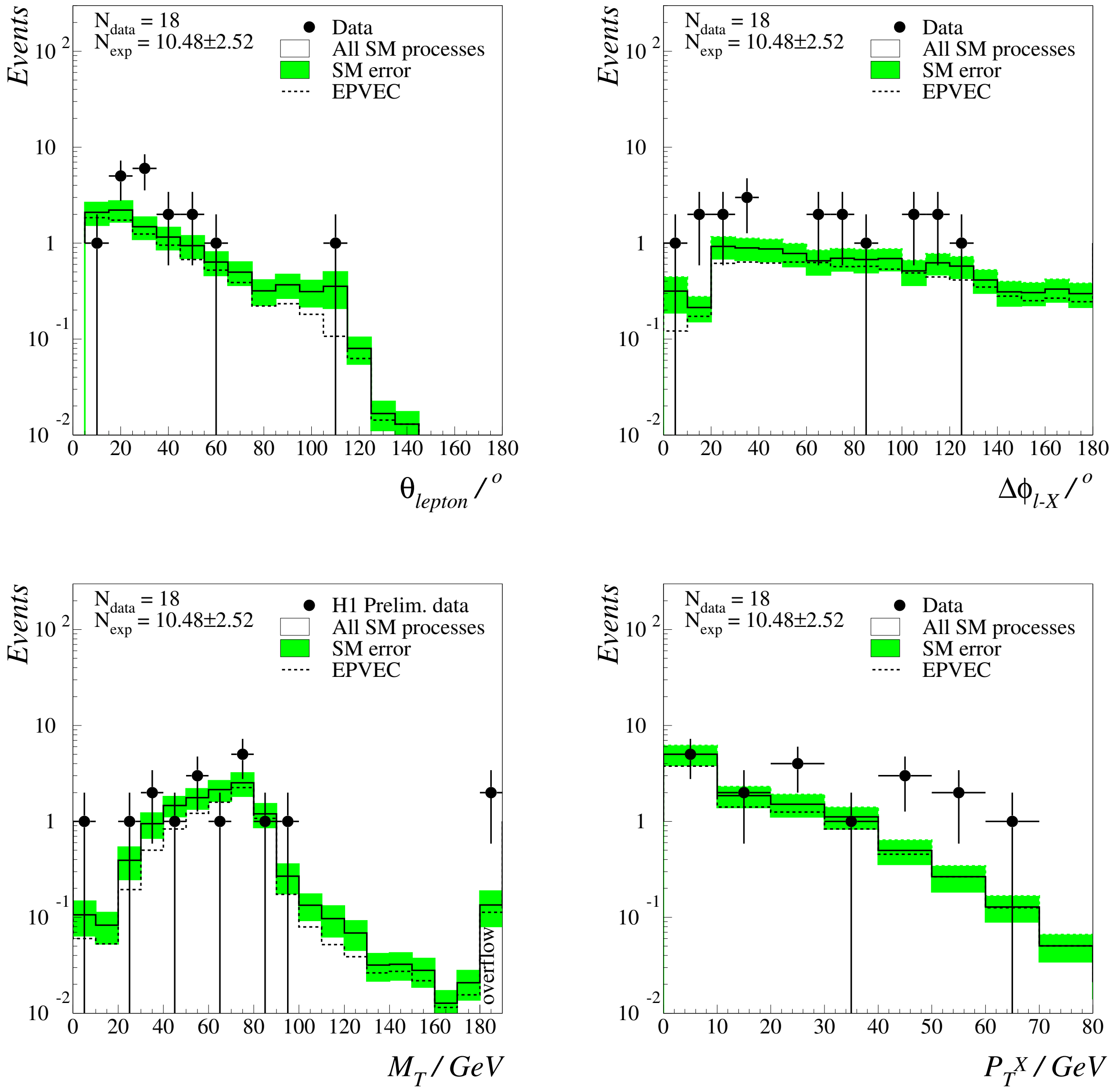
$V_{\mathrm{p}} = \sum_i \hat{n}_h \cdot \vec{P}_{t,i}$ for particles i with $\hat{n}_h \cdot \vec{P}_{t,i} > 0$

$V_{\mathrm{ap}} = -\sum_i \hat{n}_h \cdot \vec{P}_{t,i}$ for particles i with $\hat{n}_h \cdot \vec{P}_{t,i} < 0$

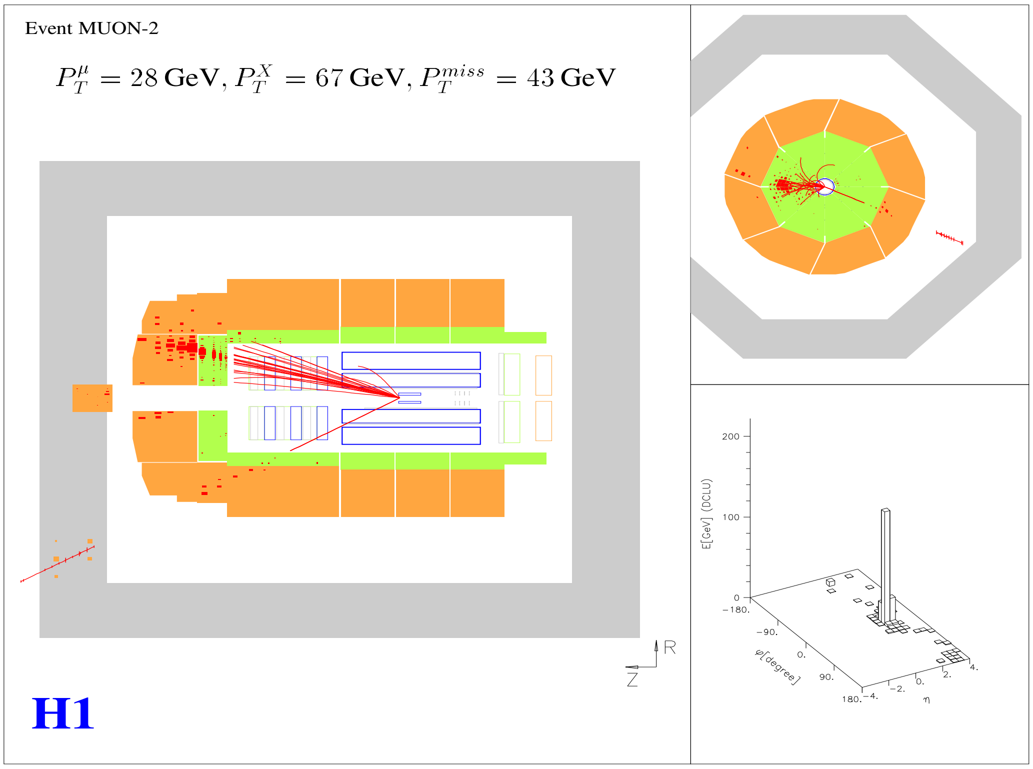
Number of events $(e + \mu)$ passing cuts

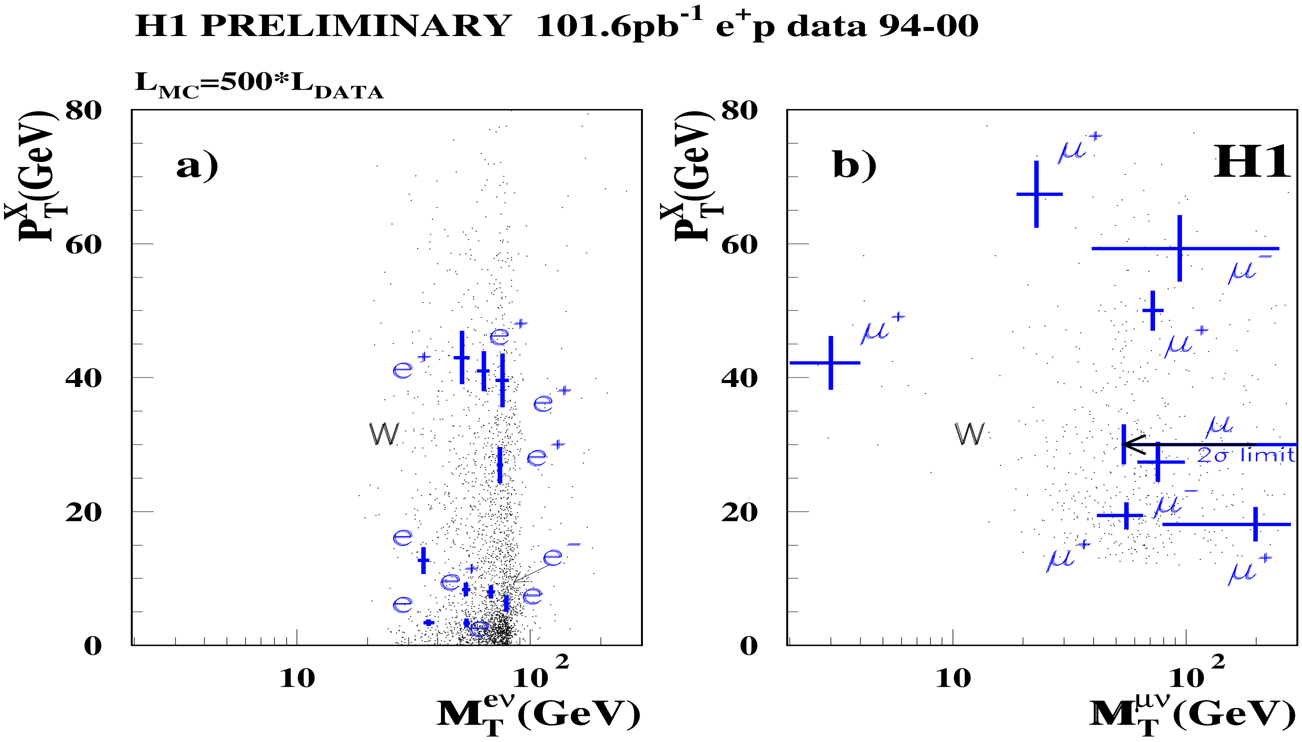
	H1 (115 pb^{-1}) Observed	H1 Expected	H1 W	ZEUS (130 pb^{-1}) Observed	ZEUS Expected	ZEUS W
No P_t^X cut	10 (e only)	7.9 ± 1.9	6.1	$24 + 12 = 36$	32.5 ± 4.7	5.4
$P_t^X > 12$ GeV	$5 + 8 = 13$	5.1 ± 1.3	4.2	-	-	-
$P_t^X > 25$ GeV	$4 + 6 = 10$	2.8 ± 0.7	2.3	$2 + 5 = 7$	5.8 ± 0.6	2.8
$P_t^X > 40$ GeV	$2 + 4 = 6$	1.0 ± 0.3	0.9	0	2.0 ± 0.2	1.3

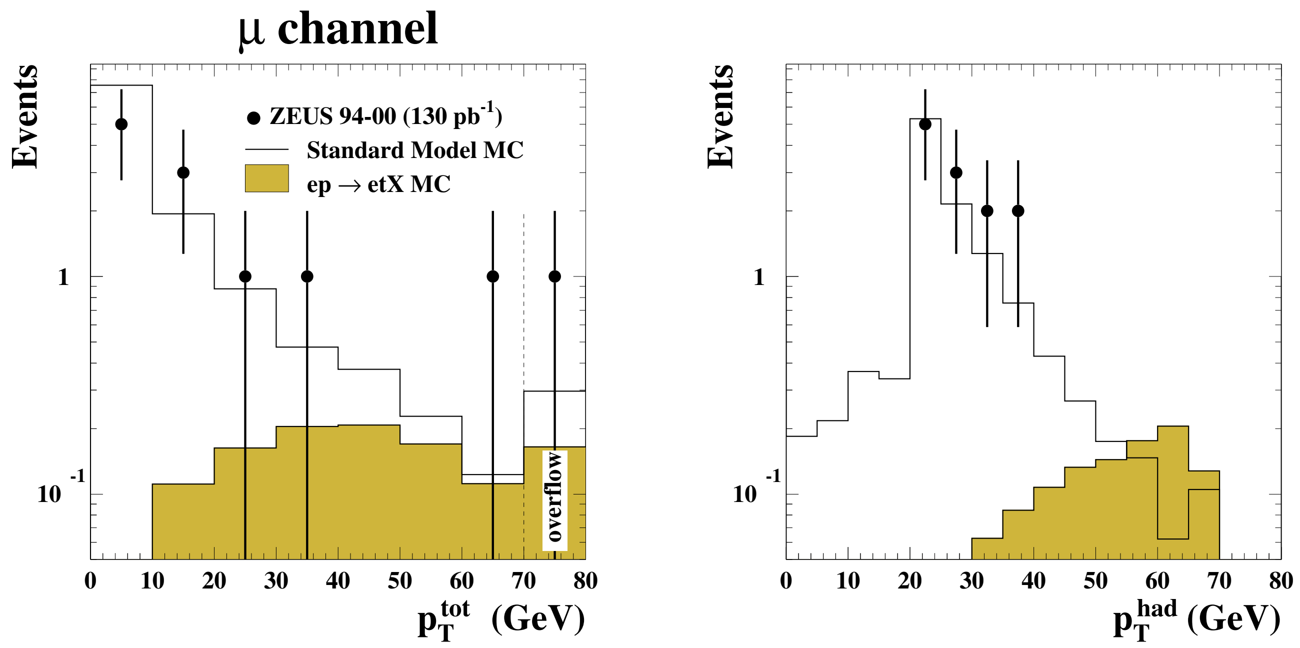
H1 sees an excess at high P_t^X



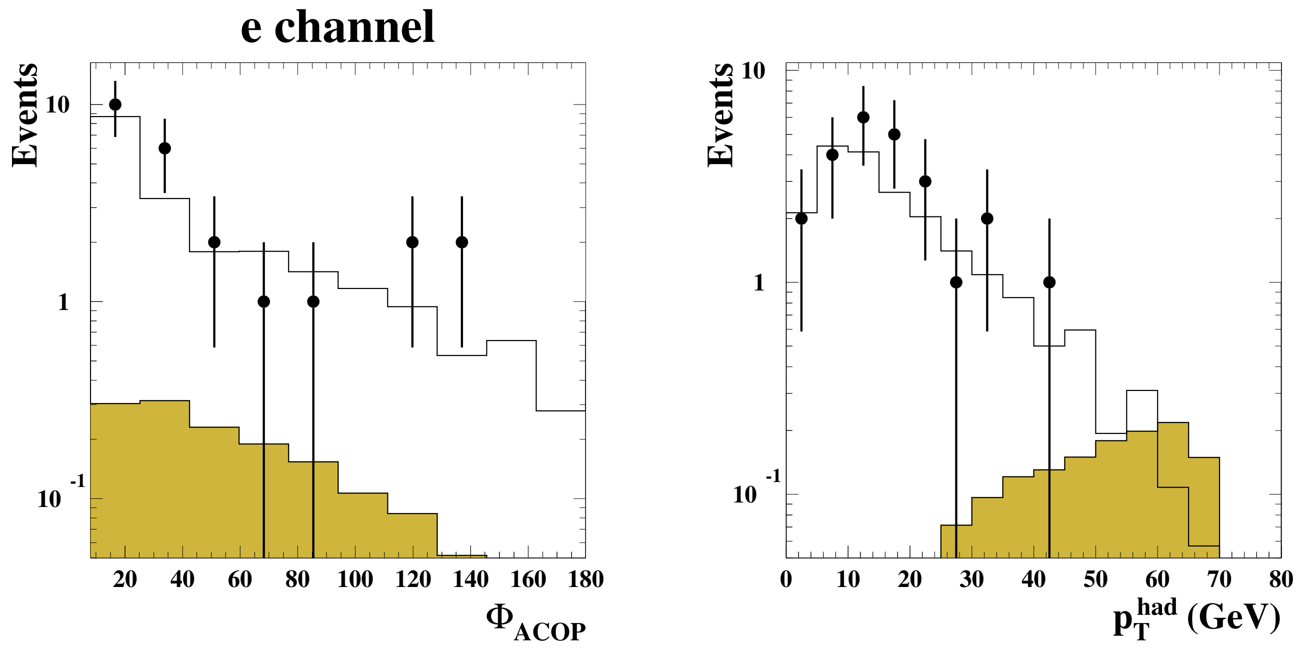
$$e^+p \to \mu^+ X$$


Event MUON-2
$P_T^\mu = 28\,\mathrm{GeV}, P_T^X = 67\,\mathrm{GeV}, P_T^{miss} = 43\,\mathrm{GeV}$
H1
R
Z
E[GeV] (DCLU)
φ[degree]
η


H1 PRELIMINARY 101.6pb^{-1} e$^+$p data 94-00
$L_{MC}=500*L_{DATA}$
a)
b)
H1
W
P_T^X(GeV)
$M_T^{e\nu}$(GeV)
$M_T^{\mu\nu}$(GeV)
2σ limit



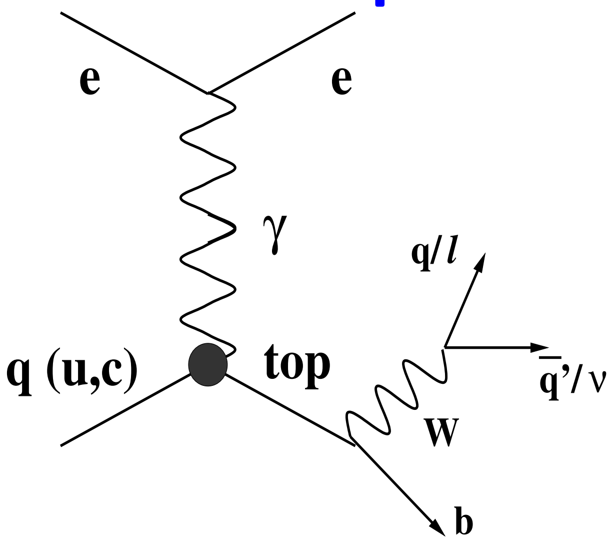
ZEUS μ data



ZEUS e data

ZEUS data is consistent with expected background.

Search for ep $\rightarrow$ tX



Leptonic selections are applied to isolated lepton sample.

ZEUS

- $P_t^X > 40\,\mathrm{GeV}$
- $E - P_Z < 47\,\mathrm{GeV}$ (e only)
- $\not{P}_t(\mu + \mathrm{had}) > 10\,\mathrm{GeV}$ (μ only)

no events pass, 2.04 expected, efficiency$(e+\mu) = 7.1\%$

H1

- $P_t^X > 25\,\mathrm{GeV}$
- a jet with $P_t^{\mathrm{jet}} > \begin{cases} 25\,\mathrm{GeV} & \text{if } \theta_{\mathrm{jet}} > 35^\circ \\ 35\,\mathrm{GeV} & \text{if } \theta_{\mathrm{jet}} < 35^\circ \end{cases}$
- $M_T^{\ell\nu} > 10\,\mathrm{GeV}$
- lepton has positive charge (if measureable)

3 e events pass, 0.8 expected, efficiency$= 4.0\%$
2 μ events pass, 0.8 expected, efficiency=4.8%

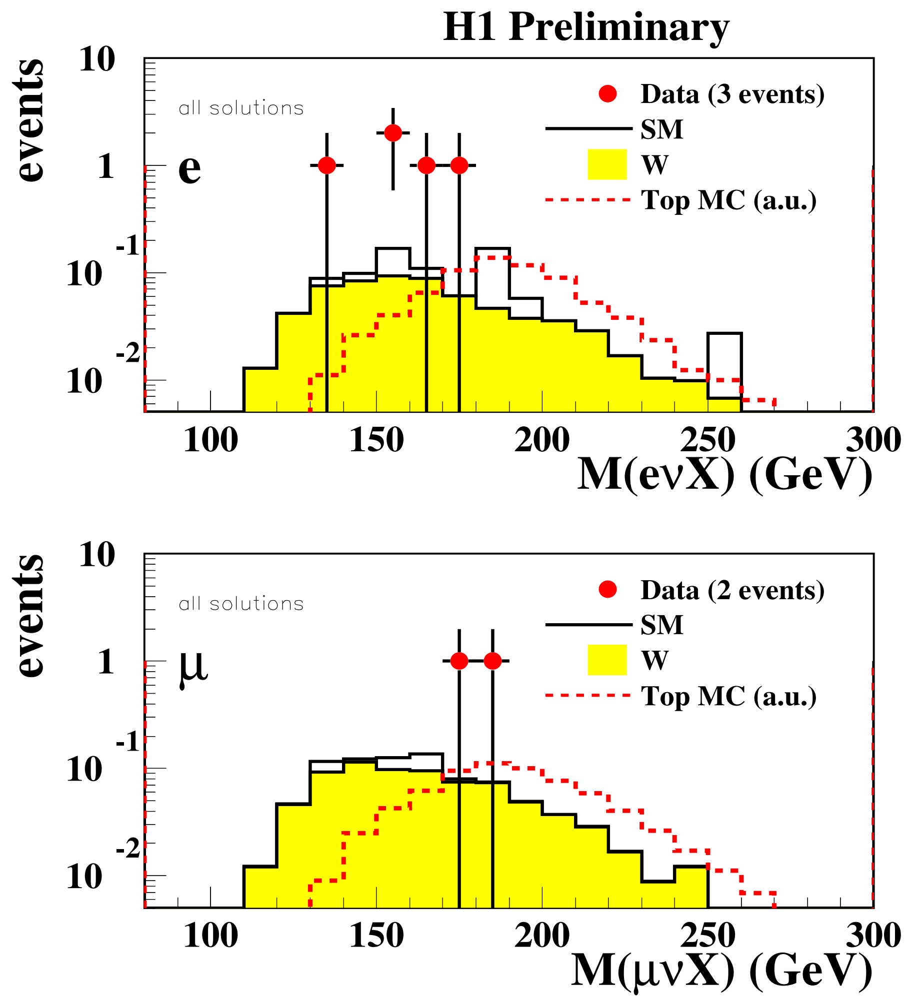
efficiencies include $BR(W \rightarrow \ell\bar{\nu}_\ell)$

Top mass reconstruction

Determine ν momentum using constraints:

1. Net $P_x = 0$
2. Net $P_y = 0$
3. $\ell\nu$ invariant mass = M_W

Two solutions, some are unphysical.

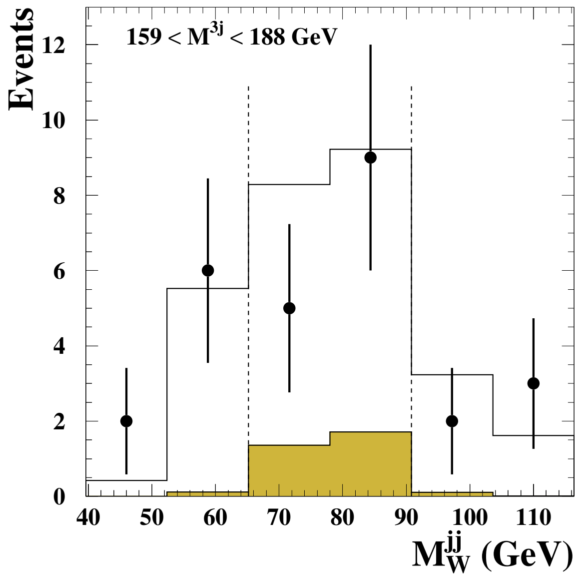


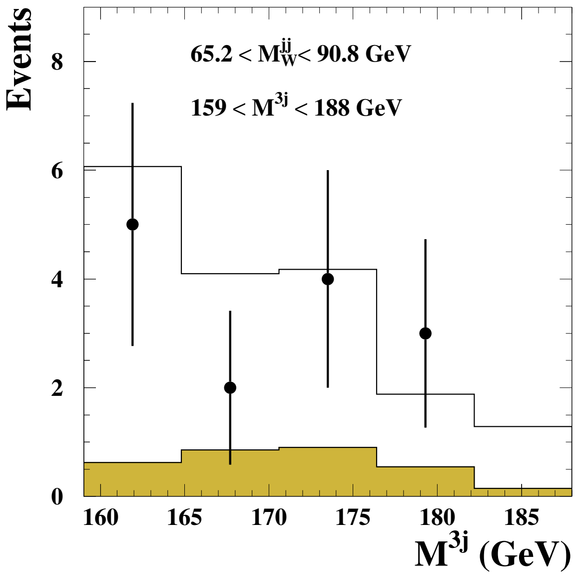
Most solutions are compatible with top decay

ZEUS Hadronic selection

- 3 jets with $-1 < \eta^{\text{jet}} < 2.5$
- $E_T^{\text{jet}} > 40, 25, 14\,\text{GeV}$
- $65.2\,\text{GeV} < M^{JJ} < 90.8\,\text{GeV}$ (for M^{JJ} closest to M_W)
- $159\,\text{GeV} < M^{3J} < 188\,\text{GeV}$
- $0.16 < y_{JB} < 0.95$
- Veto NC DIS

14 observed, 17.6 expected, efficiency $= 16.5\%$ of all top



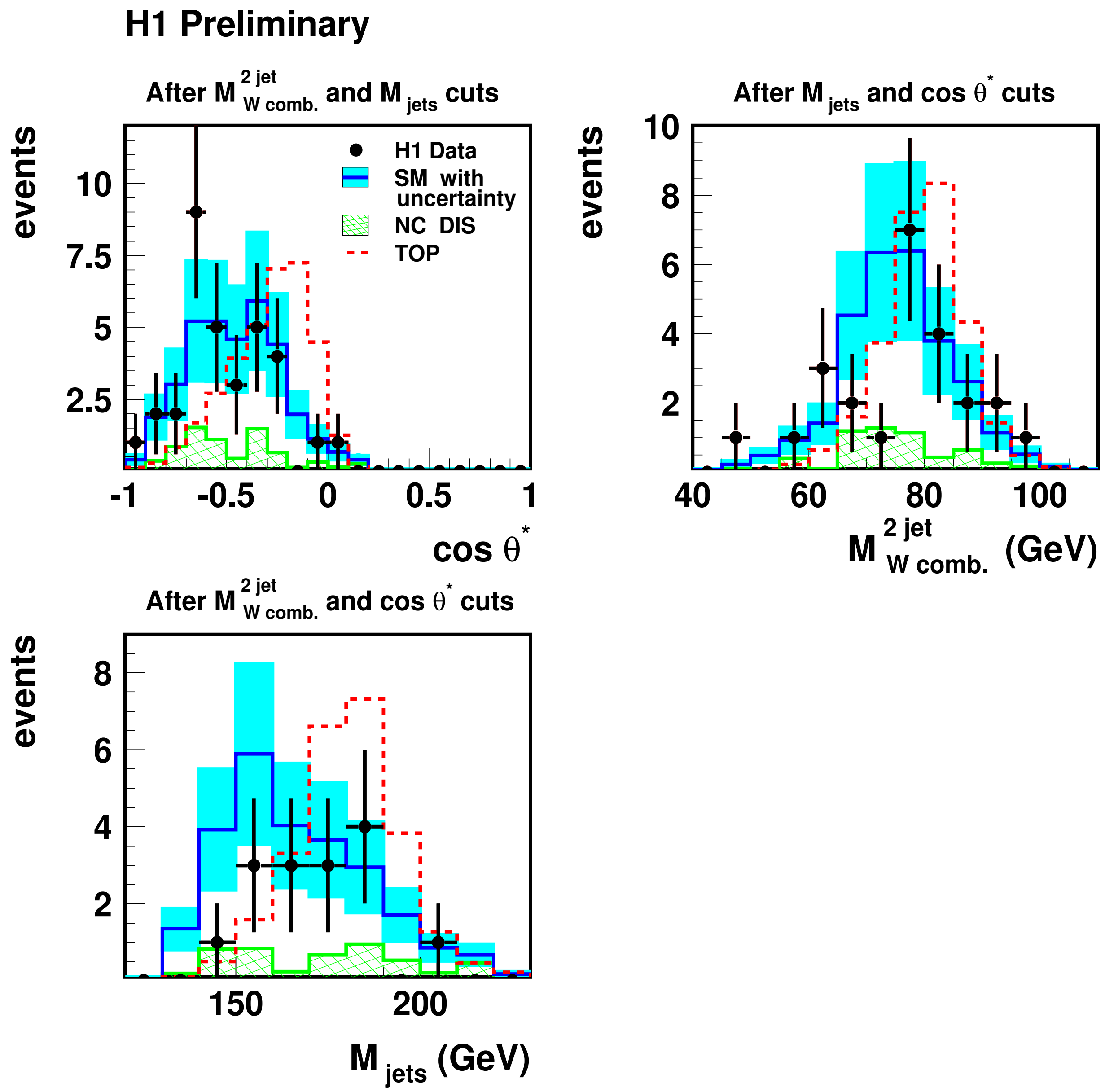


γp background normalized to data with $M^{3J} < 159$ GeV

H1 Hadronic selection

- 3 jets with $E_T^{\text{jet}} > 40, 25, 20\,\text{GeV}$
- $E_t > 110\,\text{GeV}$
- $70\,\text{GeV} < M^{JJ} < 90\,\text{GeV}$ (for M^{JJ} closest to M_W)
- $150\,\text{GeV} < M^{3J} < 210\,\text{GeV}$
- θ^* =angle between 2 jets from W in top rest frame: $\cos\theta^* > -0.5$

14 observed, 19.6 ± 7.8 expected, efficiency $= 27\%$ of all top



ZEUS Lepton + hadron channels $\longrightarrow$ 95% CL limit

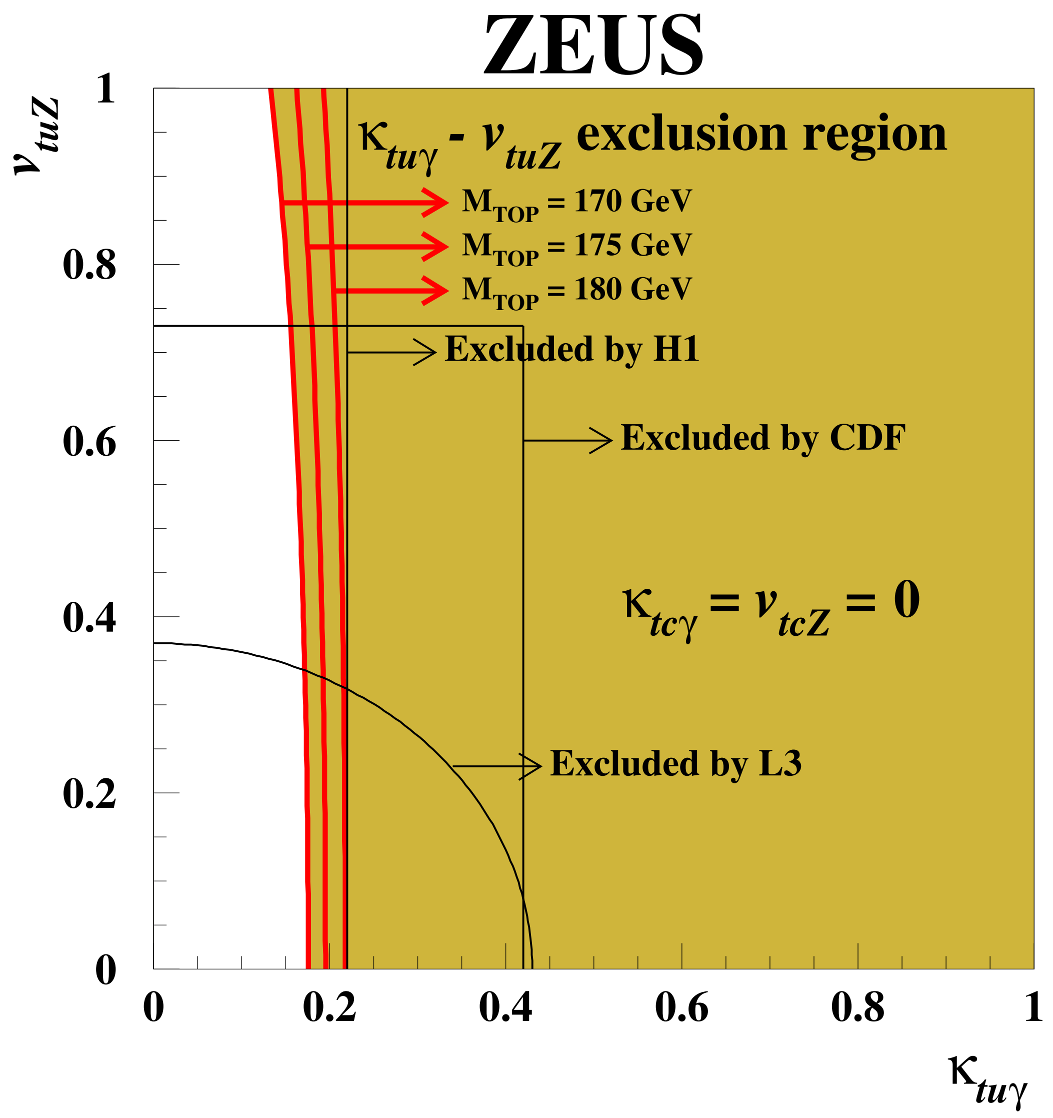
$\sigma(ep \rightarrow etX) < 0.224\,\mathrm{pb}(\sqrt{s} = 318\,\mathrm{GeV})$

Limit on anomalous FCNC coupling: $\kappa_{tu\gamma} < 0.179$

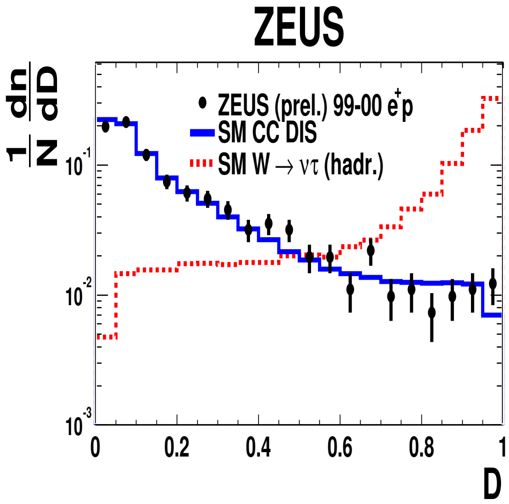
H1 Lepton + hadron channels $\longrightarrow$ 95% CL limit

$\sigma(ep \rightarrow etX) < 0.43\,\mathrm{pb}(\sqrt{s} = 318\,\mathrm{GeV})$

Limit on anomalous FCNC coupling: $\kappa_{tu\gamma} < 0.22$



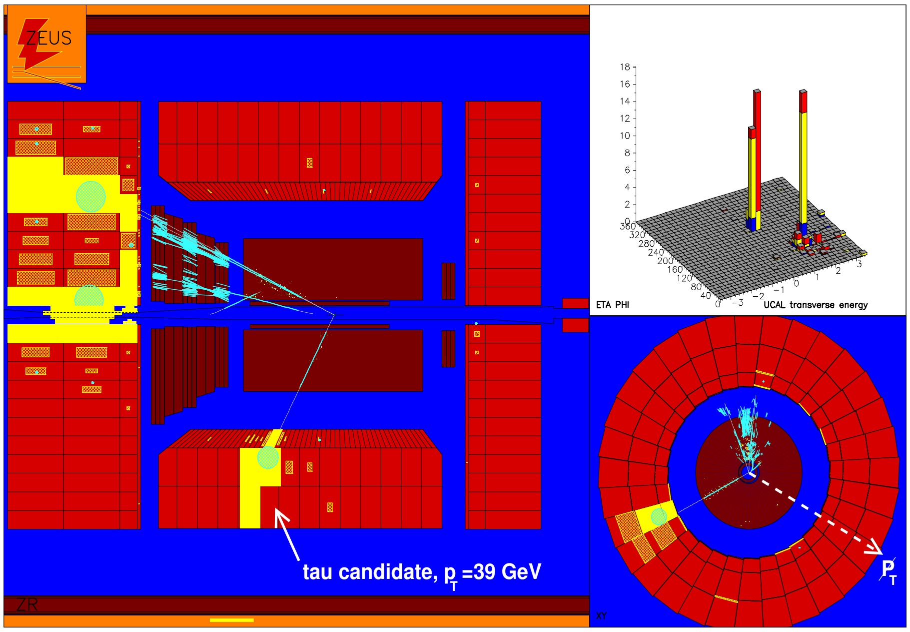
ZEUS search for isolated τ leptons

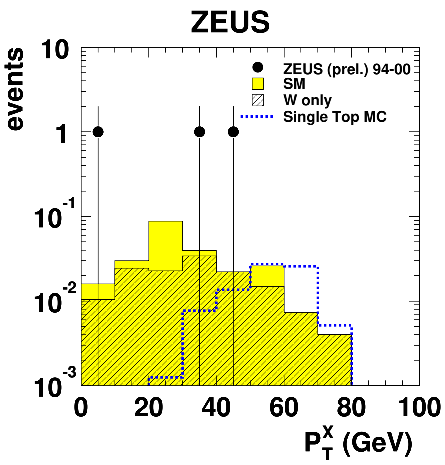


Separate τ →hadrons from QCD jets using multi-dimensional discriminator based on 6 jet shape variables.

1. $P_t^{\rm cal} > 20$ GeV
2. e found $\Rightarrow$ acoplanarity between e and hadrons $> 8°$
3. An isolated track with $P_t > 5$ GeV and $17° < \theta < 115°$
4. track is matched to a jet with tau discriminant> 0.95

P_t^X cut	observed	expected
none	3	0.23 ± 0.06
25 GeV	2	0.12 ± 0.02
40 GeV	1	0.06 ± 0.01





Conclusions

- Searches use $> 100\,\text{pb}^{-1}$data sets.
- HERA is sensitive to LQ, $\tilde{q}$, f^* production with masses $< 300\,\text{GeV}$ if coupling is high enough.
- More massive states detectable via virtual effects.

Outlook

- More luminosity will clarify isolated lepton excess.
- HERA has been upgraded to increase $\mathcal{L}$ and have polarized electron beams.
- Upgraded detectors for H1 and ZEUS (Si μ-vertex detectors, improved forward tracking, trigger upgrades...).
- New data taking delayed by > 1 year due to high backgrounds in ZEUS and H1. Improvements to the interaction regions planned for spring.
- Expect 1 fb^{-1} by 2006.