Search for Exotic Physics at HERA

Gerhard Brandt
Physical Institute, Heidelberg

On behalf of the H1 and ZEUS collaborations

The 13th International Conference on Supersymmetry and Unificationof Fundamental Interactions

SUSY 2005

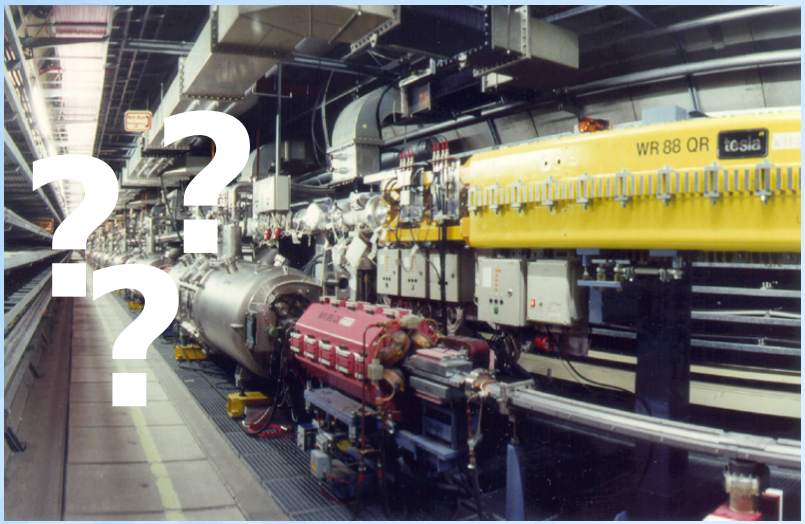
July 18-23, 2005, IPPP Durham

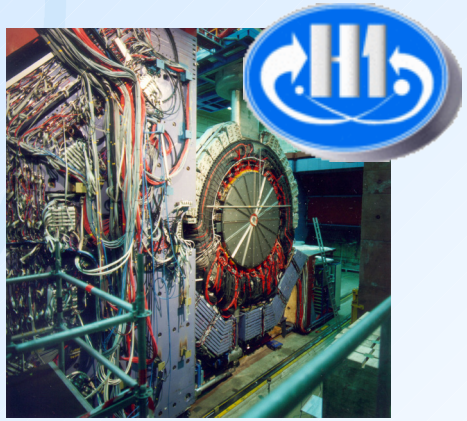
Search for Exotic Physics at HERA

Contents

- HERA Running and Data
- Search for Magnetic Monopoles
- Searches for Leptoquarks and Lepton Flavor Violation
- Observation of High-P_T Leptons and Search for Doubly-Charged Higgs

Focus on recent results and updates since last SUSY





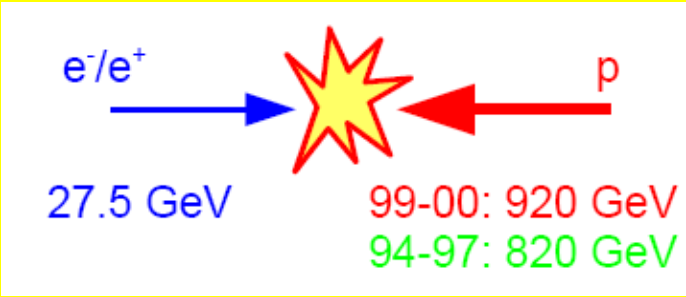
Sorry, not covered:

- Pentaquarks
- Excited Fermions, Leptons
- Contact Interactions, Large Extra Dimensions, Quark Radius
- ***All SUSY-related Searches at HERA***
  (→ Talk by N. Brummer)

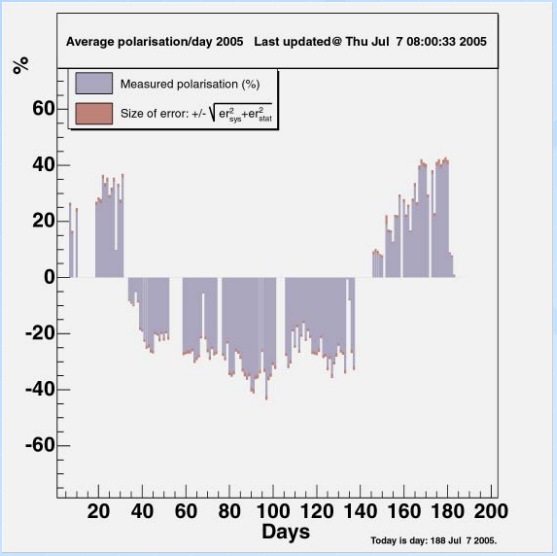
HERA Running and Data

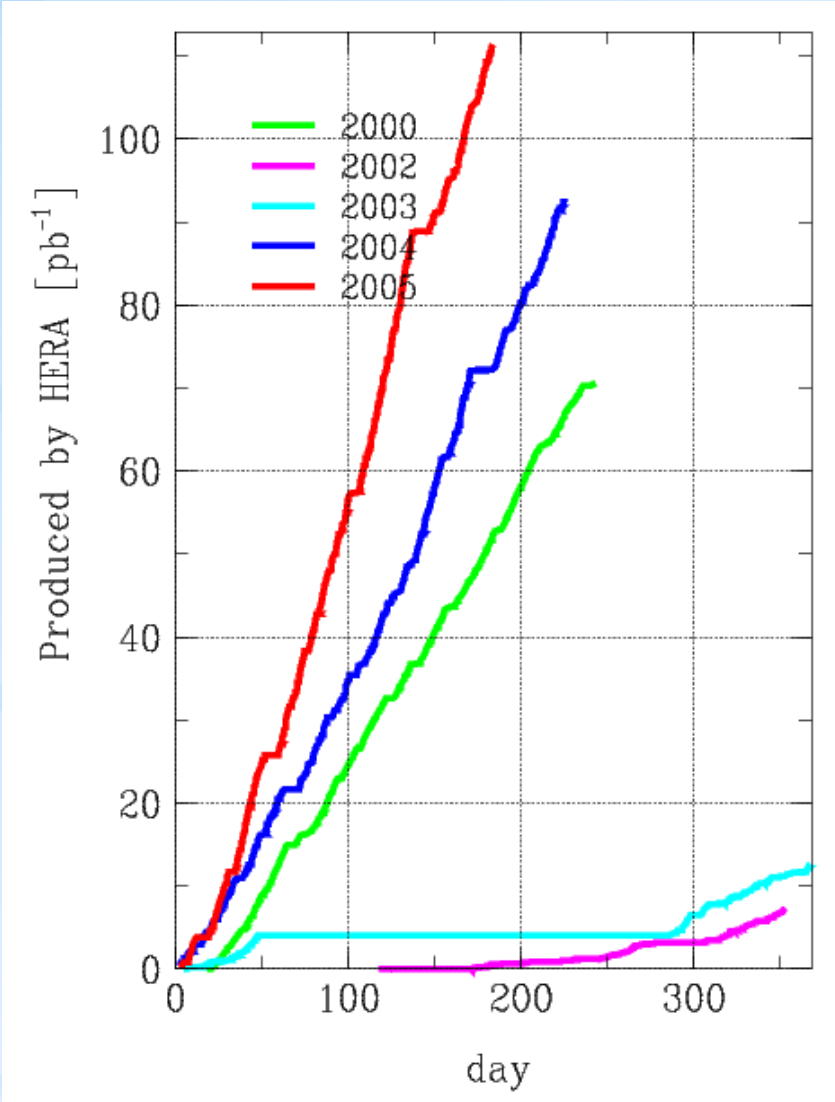
HERA

- HERA running well 1994 - 2000, 2003 - now
- $e^{\pm}p$ Collisions at $\sqrt{s} = 320$ GeV



- Experiments busy collecting lumi
- Harvest up to now: H1 219 pb^{-1}, ZEUS 254 pb^{-1}
- At HERA II: Longitudinal *e* Polarisation up to 40%



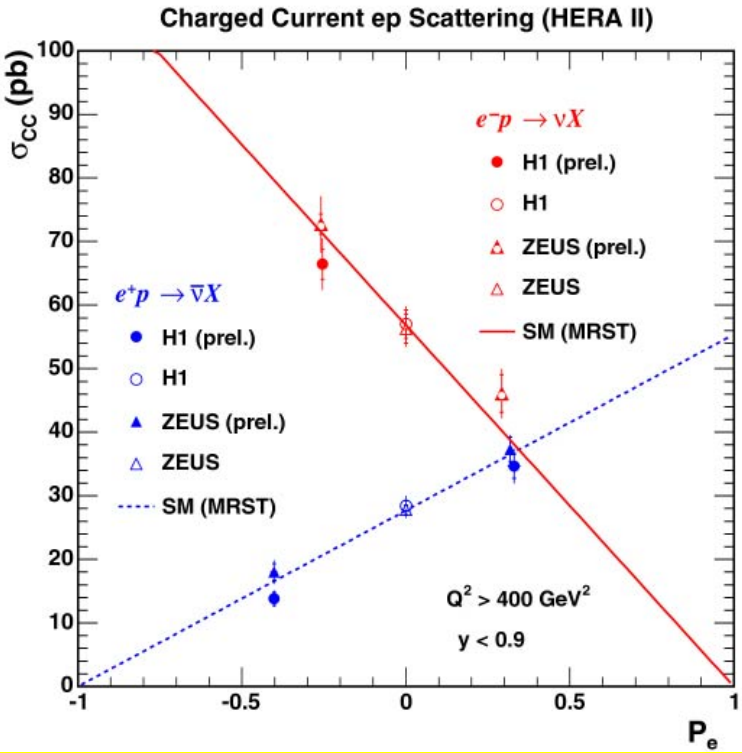


Inclusive NC/CC Crosssection Measurements

- HERA Data well described by SM over 7 orders of magnitude in Q^2

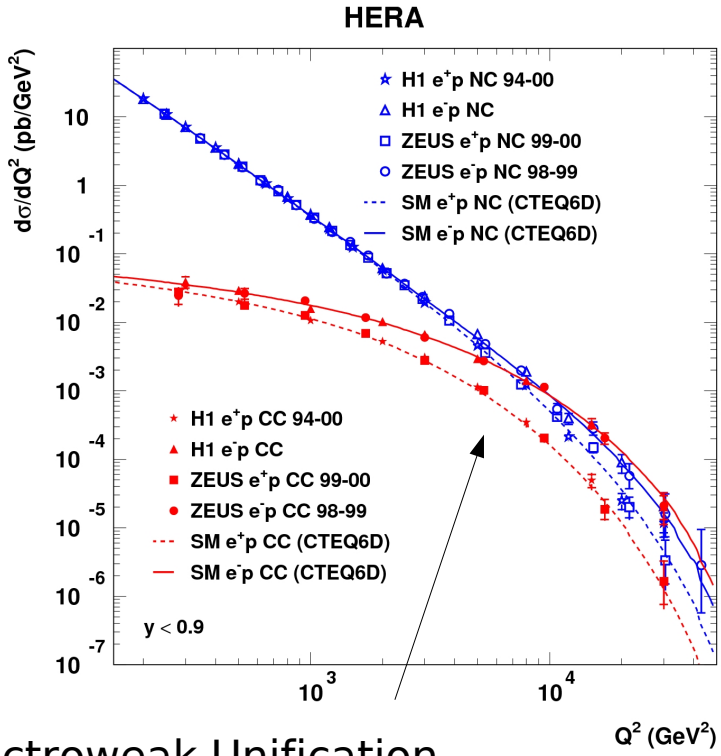
HERA II Polarised CC Crosssections

$$\sigma^{\pm}_{CC} = (1 \pm P_e)\,\sigma^{\pm}_{CC,\,unpol}$$

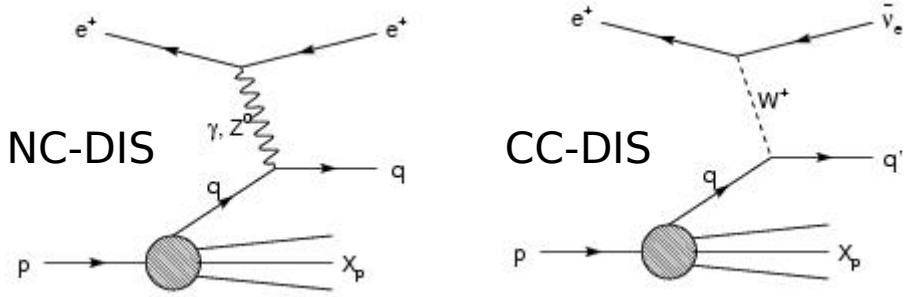


no evidence for righthanded currents

HERA I Inclusive CC Crosssections



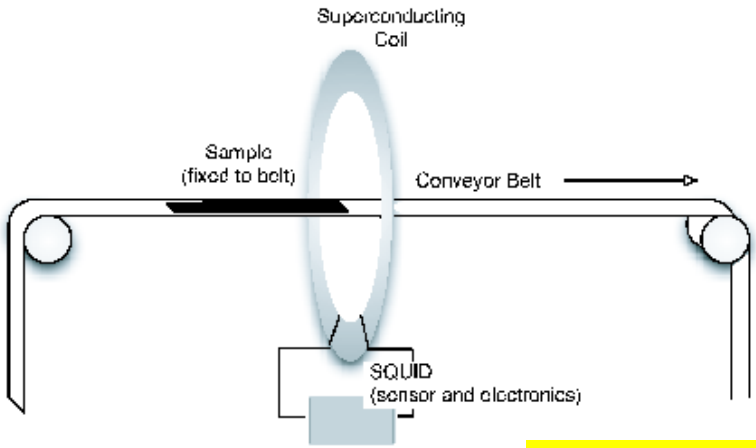
Electroweak Unification

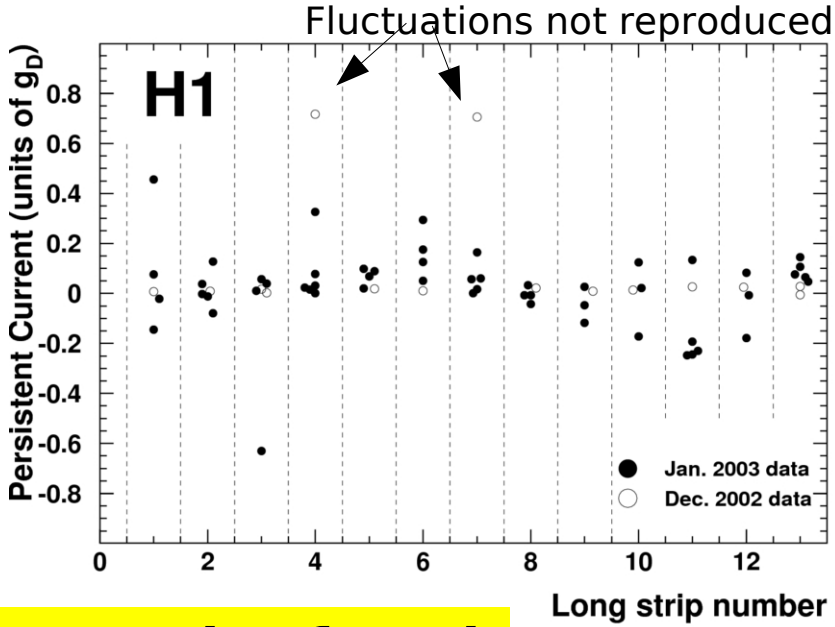


Search for Magnetic Monopoles

- Predicted by *Dirac* Proc.Roy.Soc. Lond. A 133, 60 (1931)
- Charge quantisation condition: $eg = n\hbar c/2$
- Minimum magnetic charge (n=1): Dirac magnetic charge g_D

- H1 Beampipe 1995-1997 (exposed to $\mathscr{L}$ = 62 pb^{-1})
- Made from Al: good stopping and binding power for HIPs
- Cut into strips, passed through SQUID Sensitive down to $0.1\,g_D$
- Induced currents from dipoles cancel
- Monopole: persistent current





No magnetic monopoles found

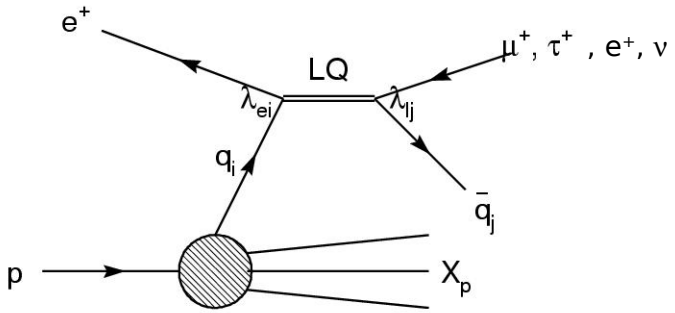
Search for Leptoquarks / Lepton Flavor Violation

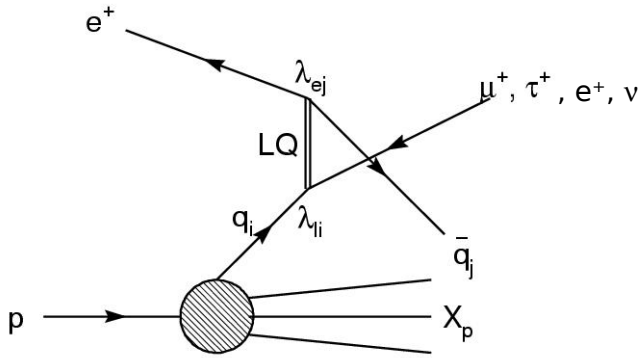
- *ep*-Collisions at HERA:
  Unique hunting ground for Leptoquarks
  Single production in s-channel (resonant) or u- channel

- Predicted by GUTs, SUSY, Technicolor, ...

- *BRW* Classification:
  7 scalar LQs, 7 vector LQs
  Fermion Number F = 3B + L (= 0 or 2 at HERA)
  Parameters: M_{LQ}, Yukawa couplings λ_{ij}

- Lepton Flavor Violation if $eq \rightarrow LQ \rightarrow \mu q, \tau q$





Analyses at HERA

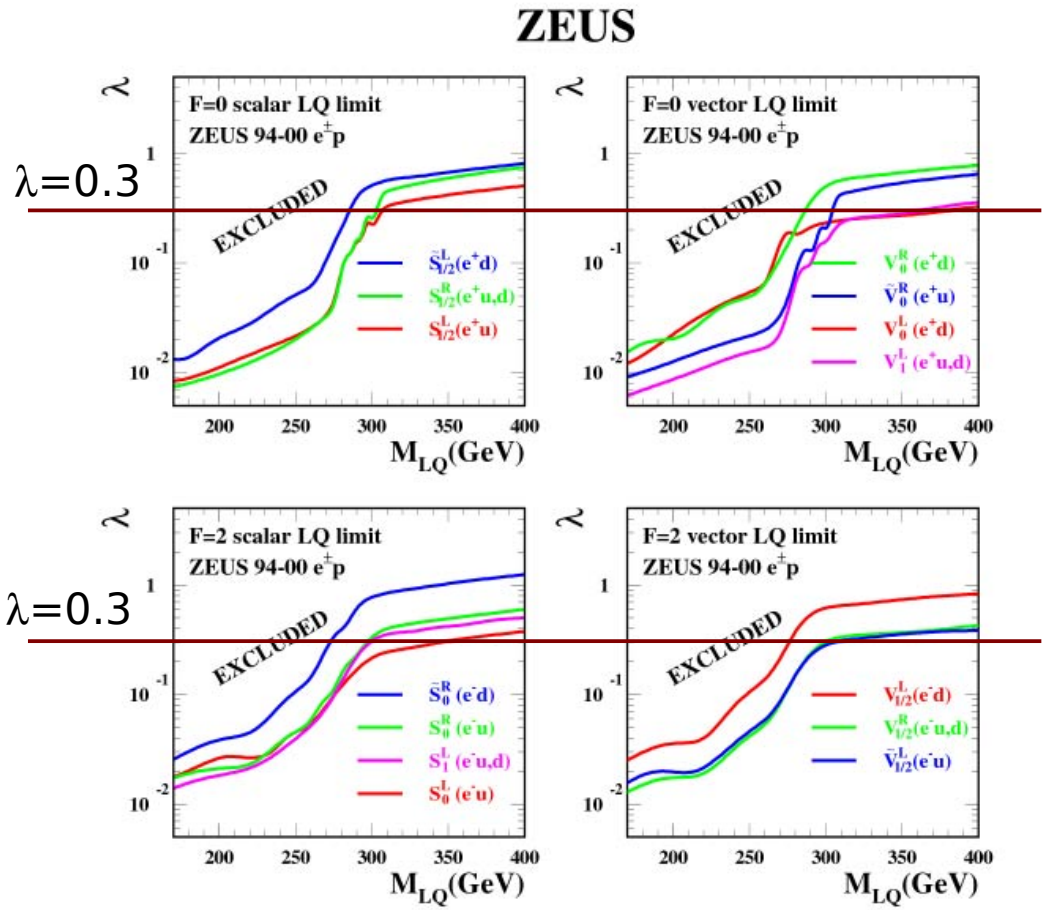
Channel	***Signature***	***Lumi***	***Lumi***
eq, νq	*NC, CC*	*117 pb^{-1}*	*130 pb^{-1}*
μq, τq	*Isolated Lepton, b2b w. Jet*	*65 pb^{-1}*	*130 pb^{-1}*

Limits on LQ → eq, νq

- Signature:
  SM-like NC-DIS and CC-DIS,
  No cuts to differentiate signal / background
- Derive limits on couplings using MC experiments using full x-sections
- Limit on M_{LQ} for coupling with em. strength $\lambda = 0.3$:

$$M_{LQ} > 275 \ldots 325 \text{ GeV}$$

Exclusion Limits on 14 BRW LQs (fixed *Br*)

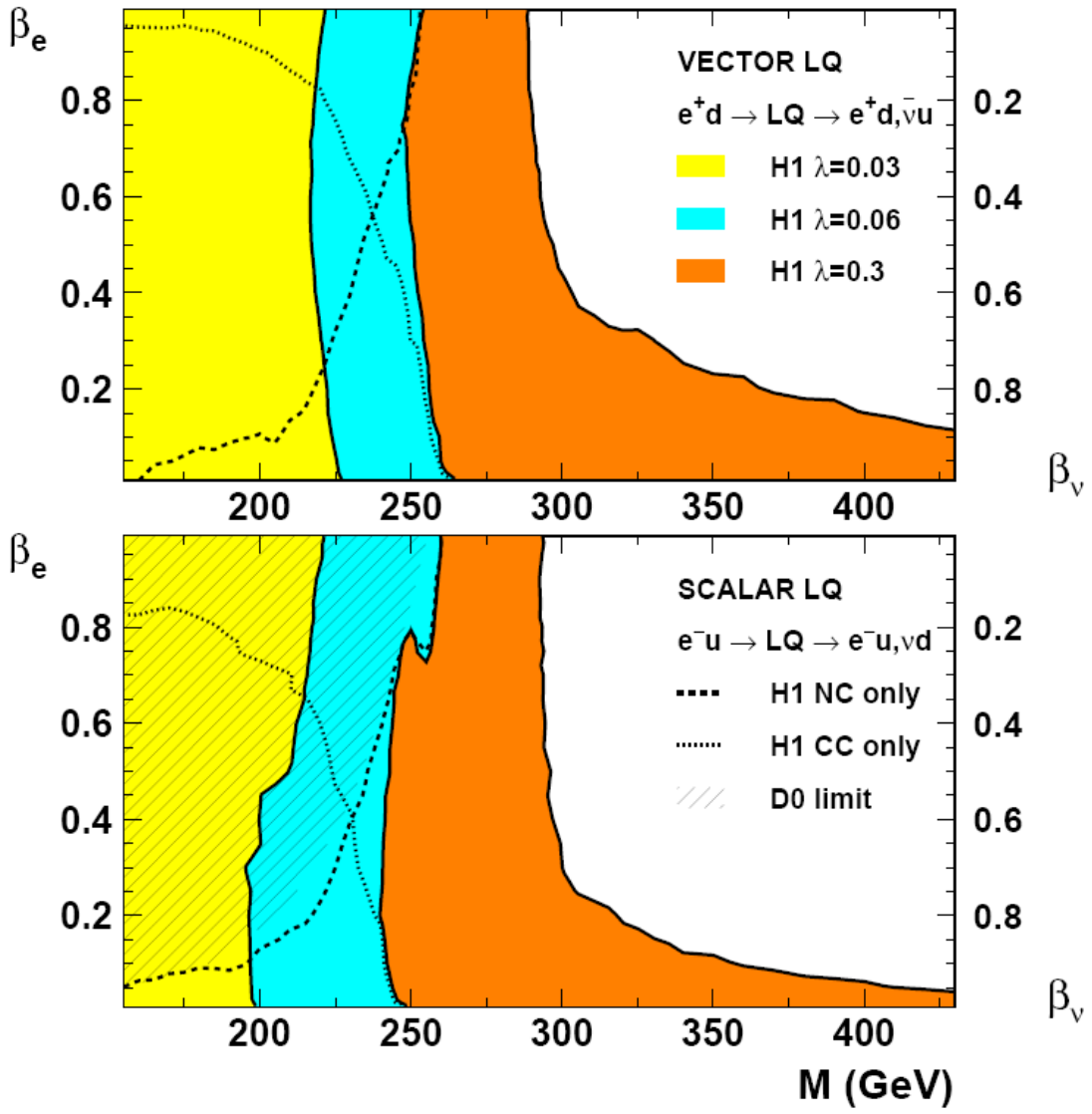


Generalized Limits on LQ → eq, νq

- Beyond BRW: More generic LQ models (eg. R-parity viol. SUSY) with free decay branching ratios
- HERA limits extend D0 limits considerably for LQ with $\beta_e > 0$ for $\lambda > 0.06$ (M_{LQ} > 250 GeV)
- Limit on M_{LQ} for coupling with em. strength $\lambda = 0.3$ extends beyond resonant region:

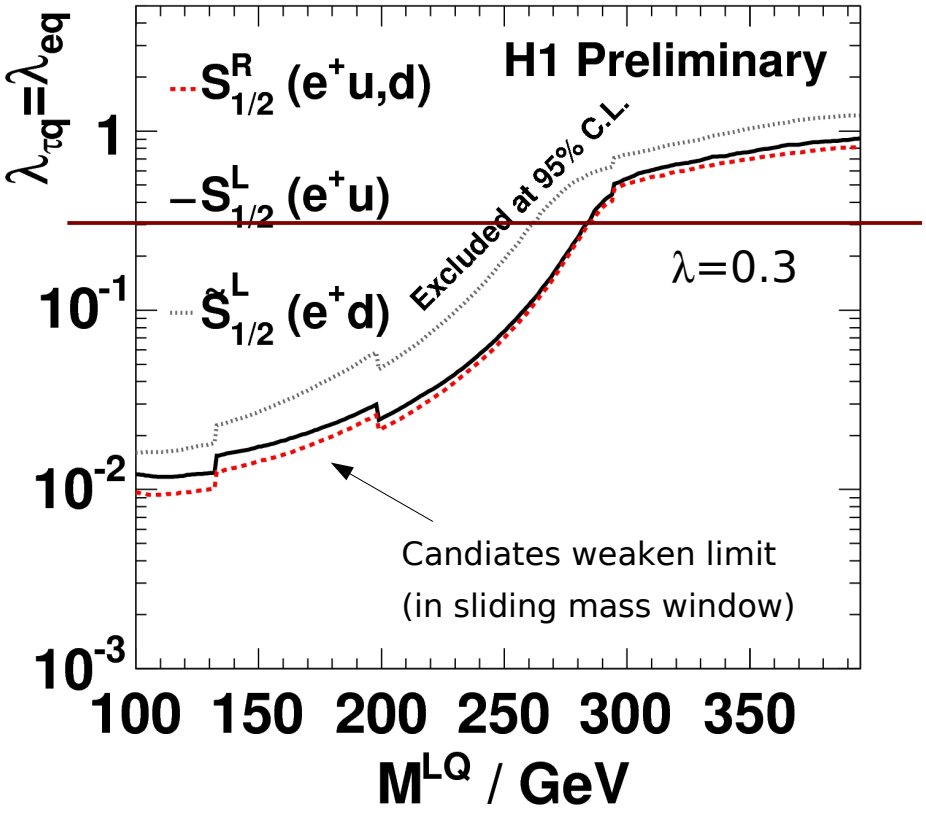
$$M_{LQ} > 400 \text{ GeV}$$

Limits on generic LQs (β_e, β_ν free)

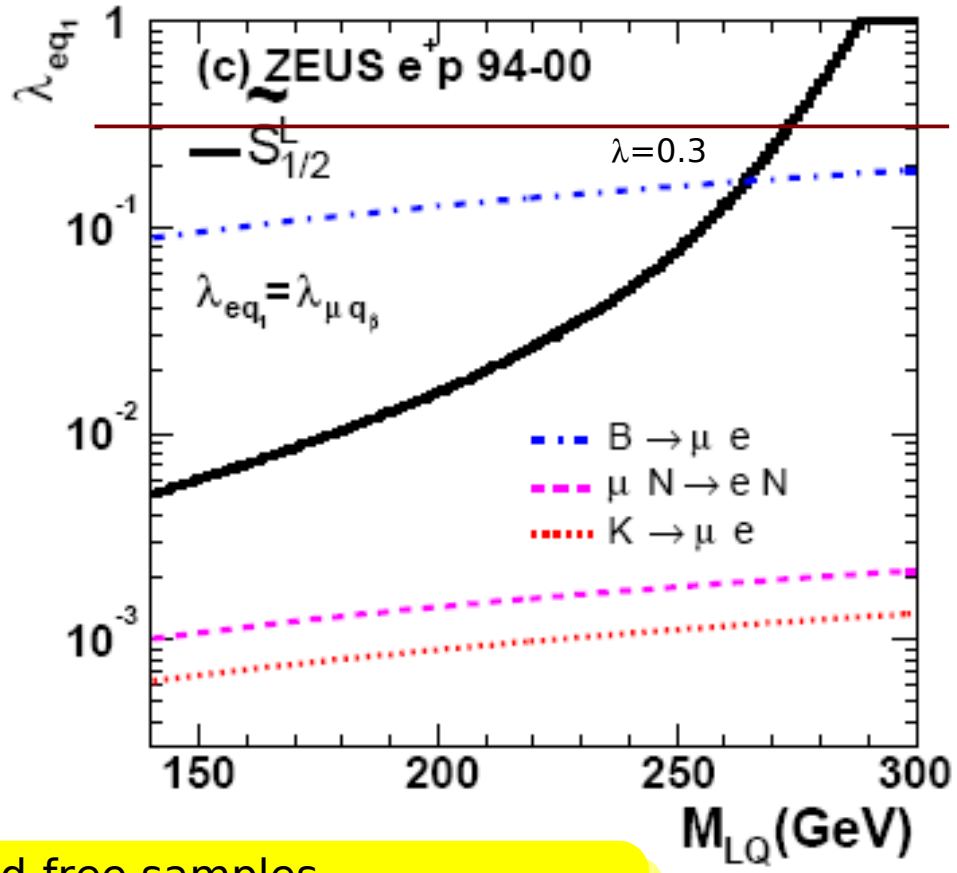


Limits on Lepton Flavor Violating LQs

μq



τq



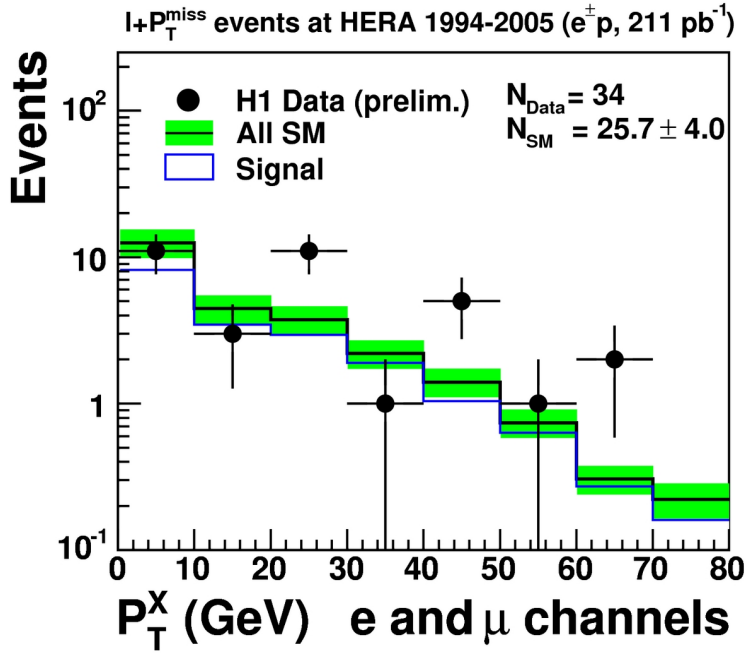
- Good Limits because of almost background-free samples
- For coupling of em. strength $\lambda = 0.3$ can set $M_{LQ} < 270$ GeV
- Stringent Limits on LFV from low E and rare decays, but competitive in some cases, eg. c, τ sector (see DESY-05-016)

Events with High-P_T Isolated Leptons

• *H1:*
Steady flux (~ 1 / 10pb^{-1}) of isolated Leptons coming in, in excess of the SM expectation!

Analyses at HERA (Covered here*)

Channel	***H1***	***ZEUS***
e	*211 pb^{-1}*	*106 pb^{-1} (Re-Ana.)*
μ	*211 pb^{-1}*	*130 pb^{-1}*



* *Not further covered here (no news since SUSY 2004)*

Tau Channel

• ZEUS: 2 events for 0.2 expected at $P_T^X > 25$ GeV

• H1: Observes nothing in this region

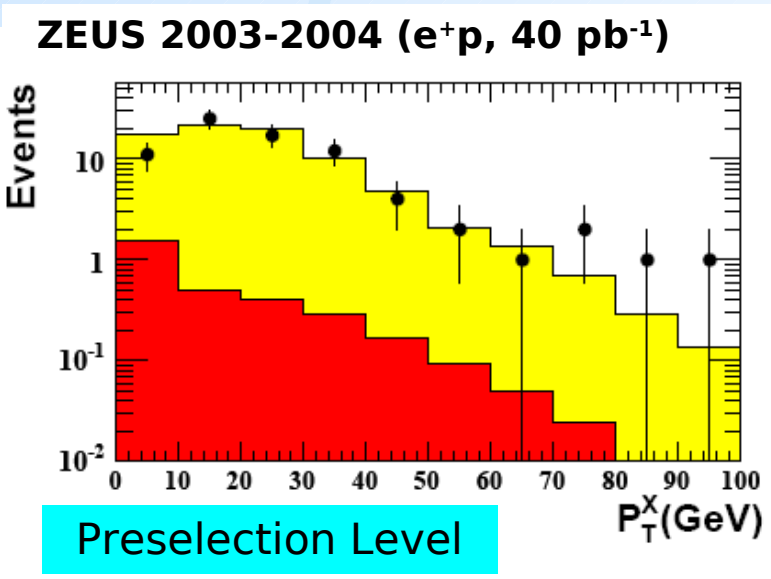
Single top Production

• Excess observed by H1 could be explained by single top production

• Competitive HERA exclusion limits set by H1, ZEUS

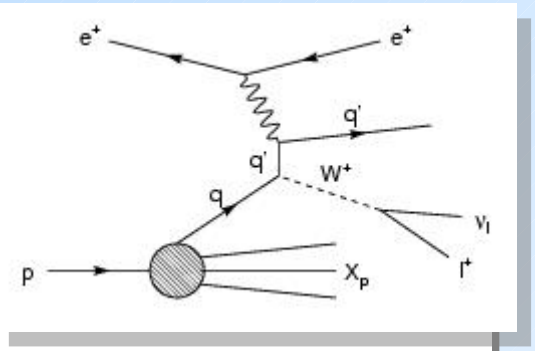
H1 Generic Search

• Observations repeated in general search for high-P_T objects



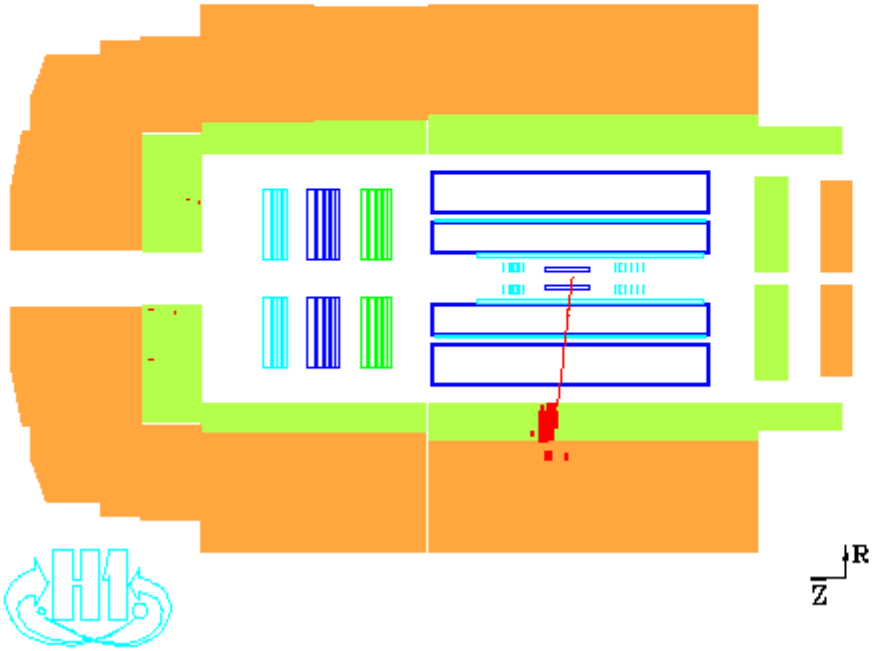
Typical Event with high P_T Lepton: Low P_T^X

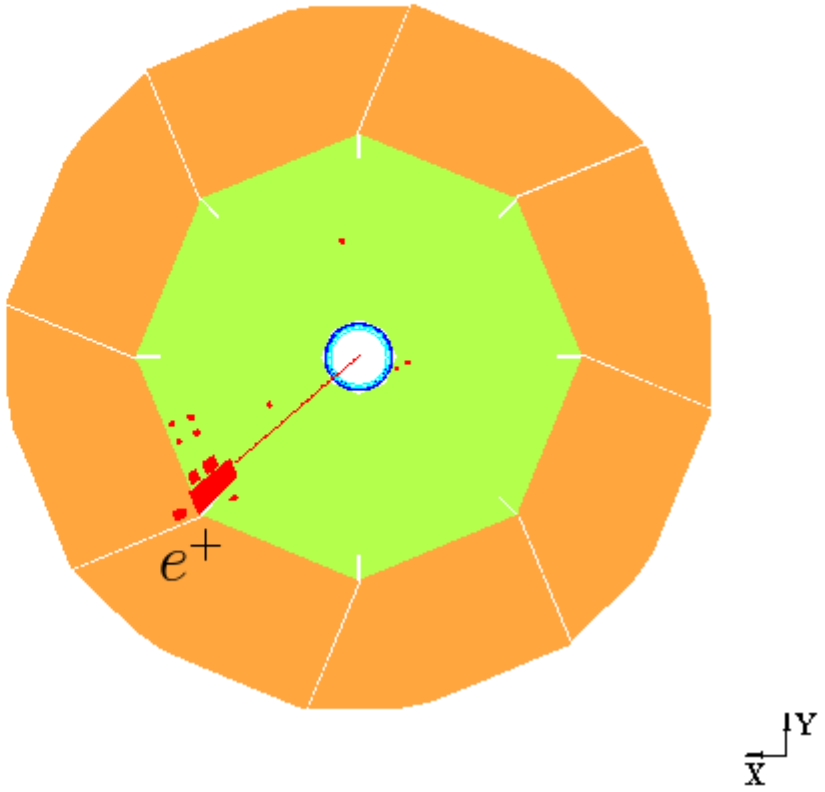
Example of a SM like Event: Elastic W Production?



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

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



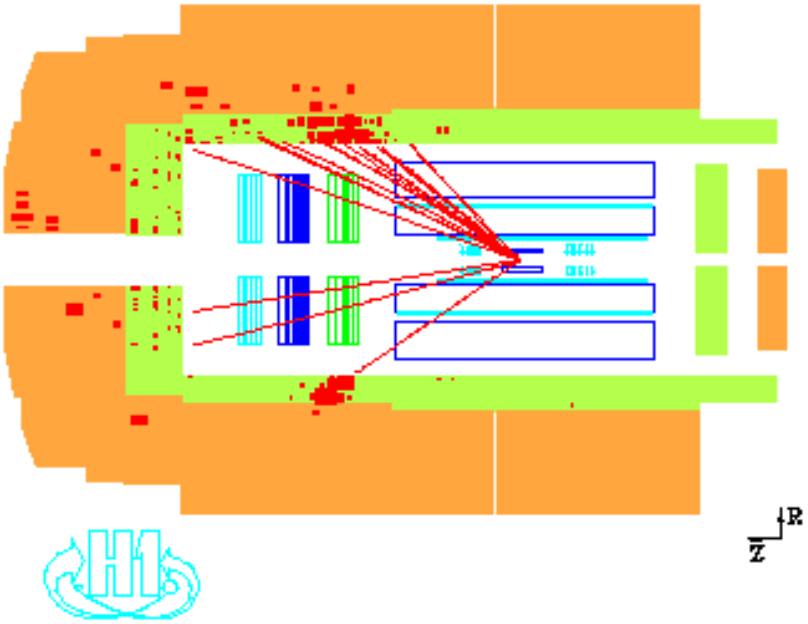


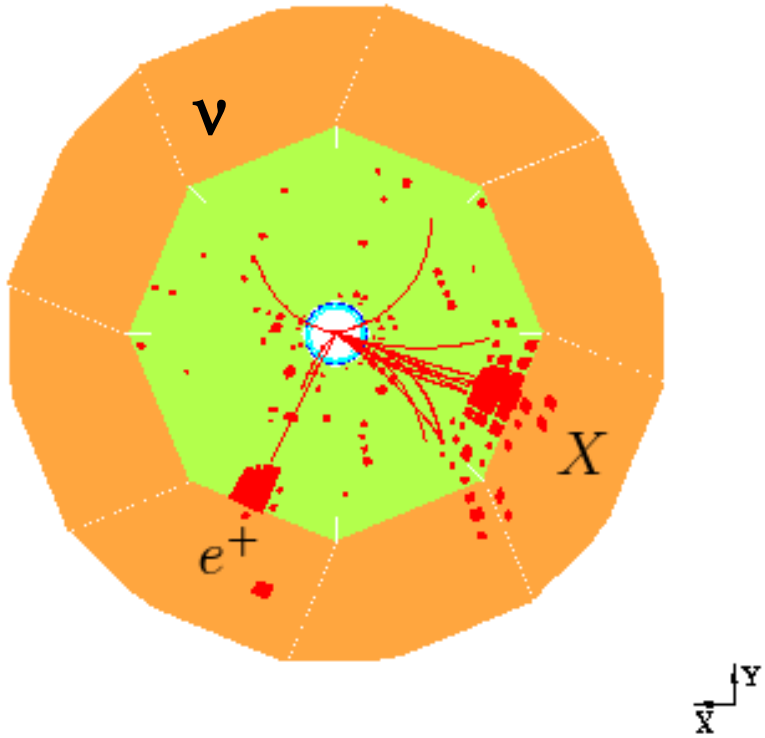
Atypical Event with high P_T Lepton: High P_T^X

Example of an exotic Event with high P_T^X

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

$\mathbf{P_T^e = 37\ GeV, P_T^{miss} = 44\ GeV, P_T^X = 29\ GeV}$





e, μ Summary Tables

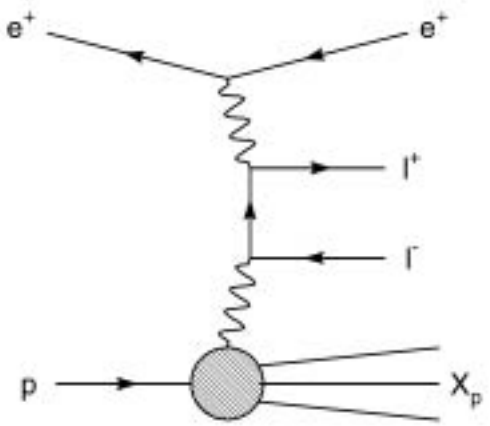
H1 Preliminary		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2004 e^+p 158 pb^{-1}	Full Sample	19 / 14.6 ± 2.0 (70%)	9 / 3.9 ± 0.6 (84%)	28 / 18.5 ± 2.7 (73%)
	$P_T^X > 25$ GeV	9 / 2.3 ± 0.4 (80%)	6 / 2.3 ± 0.4 (84%)	15 / 4.6 ± 0.8 (82%)
1998-2005 e^-p 53 pb^{-1}	Full Sample	6 / 5.8 ± 0.9 (62%)	0 / 1.5 ± 0.5 (76%)	6 / 7.3.± 1.4 (65%)
	$P_T^X > 25$ GeV	2 / 0.9 ± 0.2 (71%)	0 / 0.9 ± 0.2 (73%)	2 / 1.8 ± 0.3 (72%)
1994-2005 $e^\pm p$ 211 pb^{-1}	Full Sample	25 / 20.4 ± 2.9 (68%)	9 / 5.4 ± 1.1 (82%)	34 / 25.7 ± 4.0 (71%)
	$P_T^X > 25$ GeV	11 / 3.2 ± 0.6 (77%)	6 / 3.2 ± 0.5 (81%)	17 / 6.4 ± 1.1 (79%)

ZEUS Preliminary		
1999-2000 e^+p 66 pb^{-1}	$12 < P_T^X < 25$ GeV	1 / 1.04 ± 0.11 (57%)
	$P_T^X > 25$ GeV	1 / 0.92 ± 0.09 (79%)
2003-2004 e^+p 40 pb^{-1}	$12 < P_T^X < 25$ GeV	0 / 0.46 ± 0.10 (64%)
	$P_T^X > 25$ GeV	0 / 0.58 ± 0.09 (76%)

ZEUS (Previous Analysis)			
1994-2000 $e^\pm p$ 130.1 pb^{-1}	$P_T^X > 25$ GeV	2 / 2.9 ± 0.45 (45%)	5 / 2.75 ± 0.21 (50%)

- HERA II: No high-PTX μ event
- Excess most prominent in e^+p
- ZEUS Reanalysis with H1 like cuts still cannot confirm H1 excess (But starts at $P_T^X > 12$ GeV and full lumi not yet exploited)

Analysis of Events with 2 or 3 Leptons: e, μ, τ



SM Signal Processes

- Dominant SM Process: $\gamma\gamma \rightarrow l^+ l^-$
- Minor SM contributions:
  „Cabbibo-Parisi“, „Drell-Yan“, $Y \rightarrow \mu\mu$

SM Background Processes

- NC-DIS, Compton (misidentified hadrons, photons)

- **Possible BSM Interpretation: Doubly Charged Higgs** → *next topic ...*

Analyses at HERA

Channel	***Lumi***	***Lumi***
ee, eee	*209 pb^{-1}*	*130 pb^{-1}*
$\mu\mu$	*209 pb^{-1}*	*101 pb^{-1}*
eμ, eeμ	*209 pb^{-1}*	—

Multi-Lepton Production

H1 preliminary 94-05 ($e^{\pm}p$ 209 pb^{-1})

Selection	Data	SM	Pair Production (GRAPE)	NC-DIS + Compton
ee	190	196 ± 29	163 ± 17	33 ± 20
$\mu\mu$	82	85 ± 16	85 ± 16	—
$e\mu$	106	99 ± 13	61 ± 5	38 ± 10
eee	37	39 ± 4	39 ± 4	0.1 ± 0.1
$e\mu\mu$	50	51 ± 8	51 ± 8	—

ZEUS preliminary 94-00 ($e^{\pm}p$ 130 pb^{-1})

ee	**191**	**213.9 ± 3.9**	**182.2 ± 1.2**	**31.2 ± 3.7**
eee	**26**	**34.7 ± 0.5**	**34.7 ± 0.5**	**—**

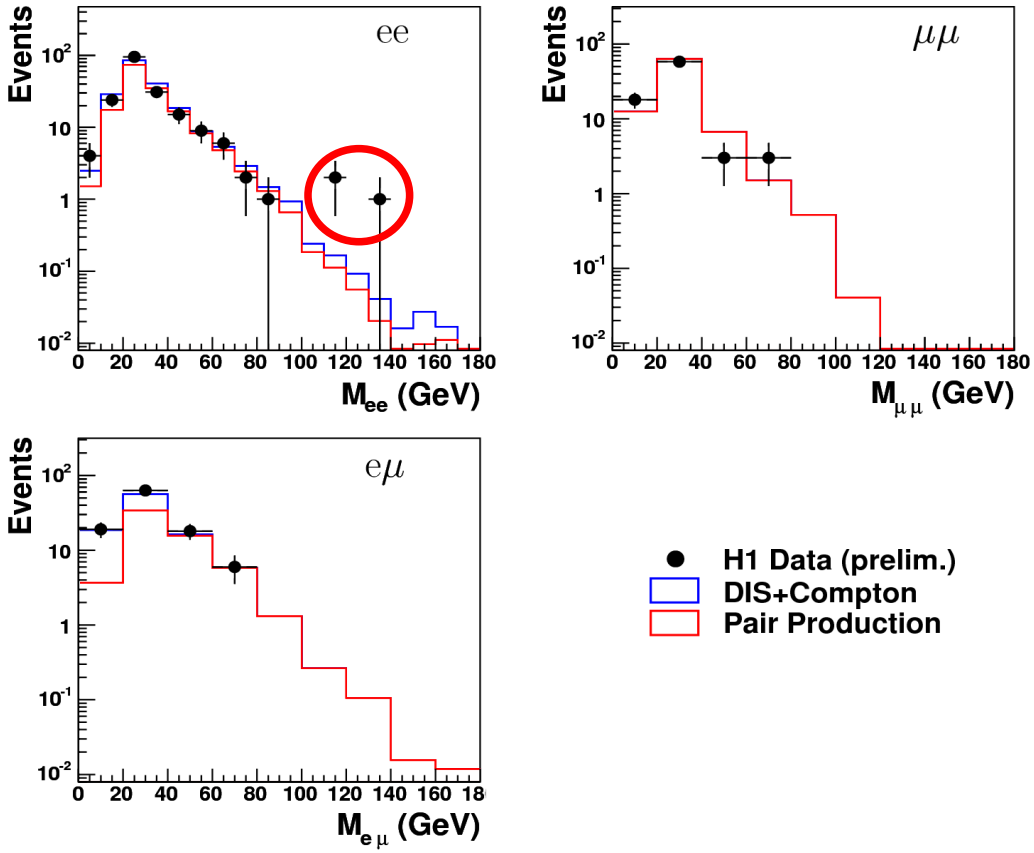
ZEUS preliminary 96-00 ($e^{\pm}p$ 101 pb^{-1})

$\mu\mu$	**255**	**294.9**	**294.7 ± 2.7**	**—**

- Full Analysis yields good agreement with the SM for both experiments
- Dedicated measurements of Pair Production x-Sections done – well understood
- *But let's have a closer look at the mass spectra...*

Multi-Lepton Events
Di-Lepton Topologies

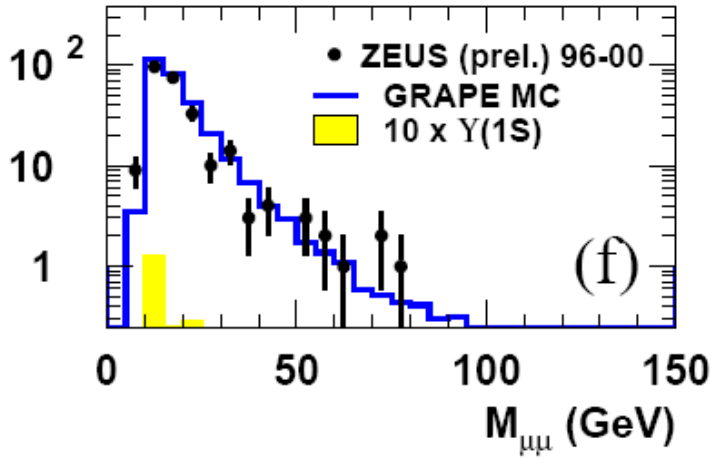
H1 Preliminary Multi-lepton analysis (209 pb^{-1})



- Slight excess at high invariant mass in *ee* channel (appear in HERA-I Data)

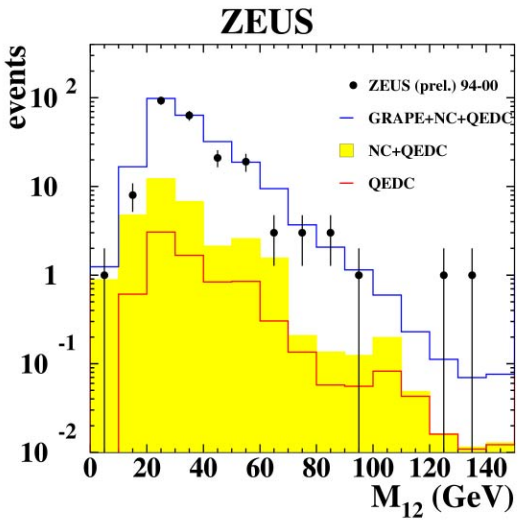
ZEUS

$\mu\mu$ 96-00 (101 pb^{-1})

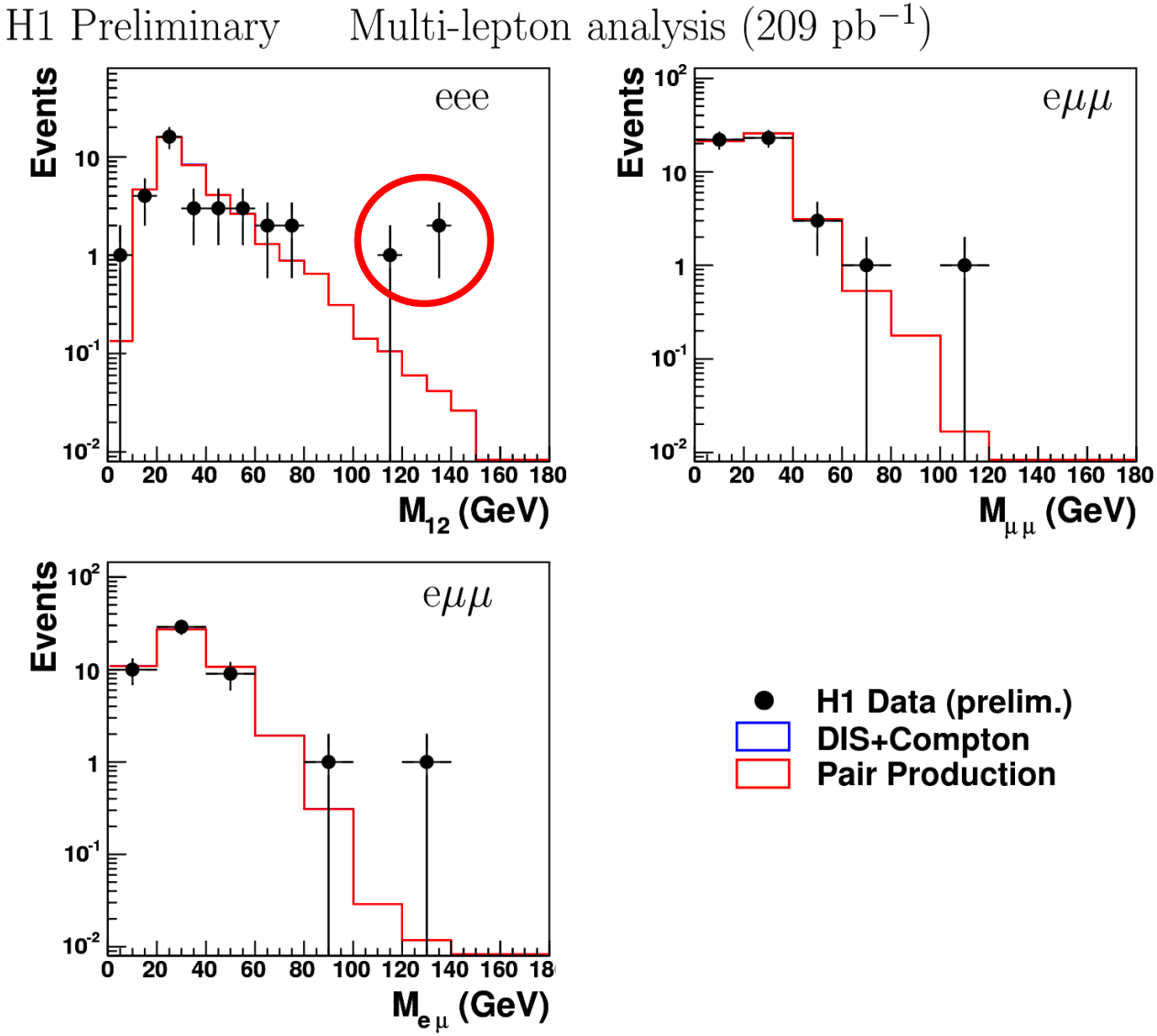


ZEUS *ee* 94-00 (130 pb^{-1})

- No excess



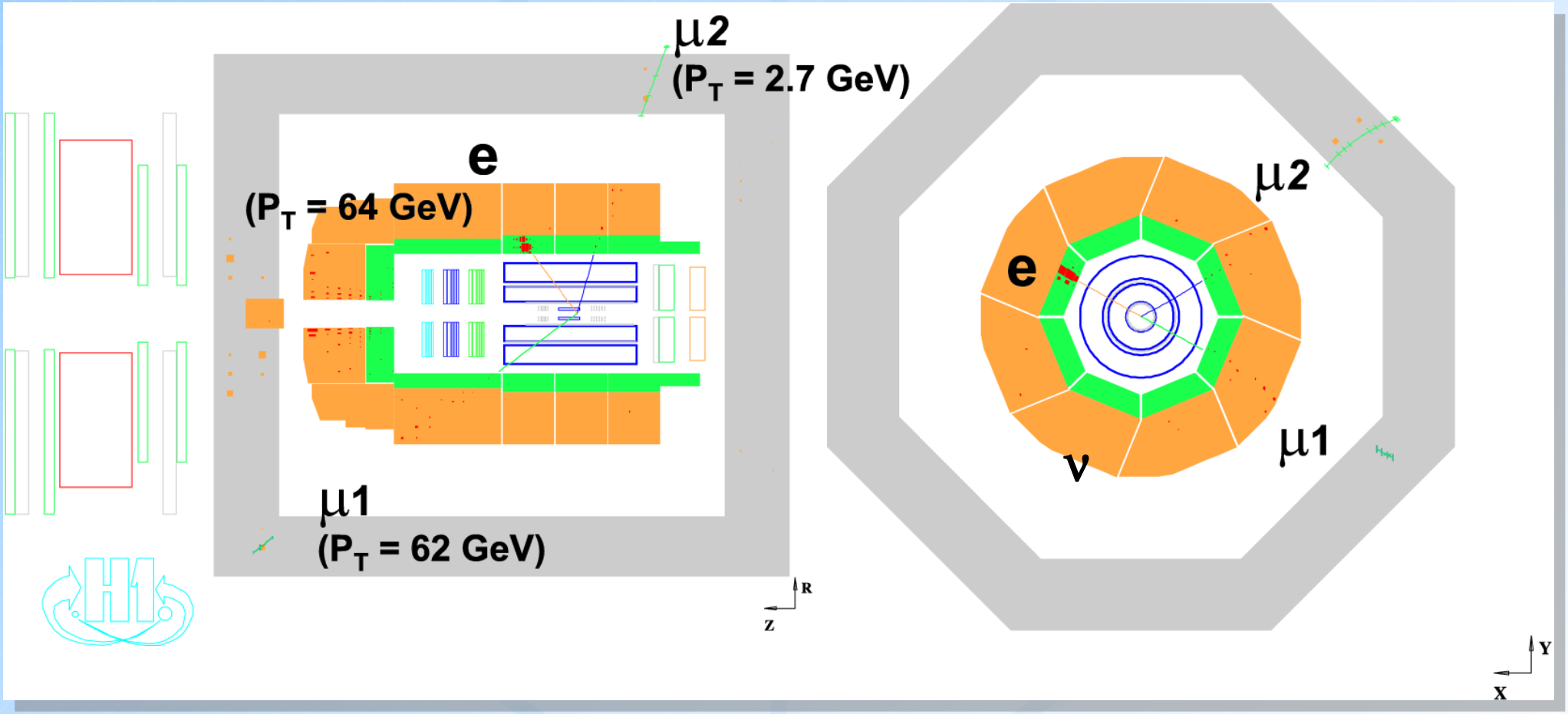
Multi-Lepton Events
Tri-Lepton Topologies



- Another slight excess at high invariant mass in *eee* channel (in HERA I sample)
- Two *eμμ* events at high mass with low background (in HERA II sample)

Event Display: $e\mu\mu$ Event in HERA 2 Data

$M_{e\mu} > 100$ GeV



Yield of Events at High Invariant Mass / High $\sum P_T$

- H1: At $\sum P_T > 100$ GeV, 4 obs. / 0.81 ± 0.14 exp.
- ZEUS: Excess not confirmed with current lumi & selection

preliminary 94-05 (209 pb^{-1})

Selection	Data	SM	Pair Production (GRAPE)	NC-DIS + Compton
ee M_{12} >100 GeV	3	0.61 ± 0.14	0.39 ± 0.12	0.22 ± 0.06
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.047 ± 0.03	0.047 ± 0.03	—
eμ $M_{e\mu}$ >100 GeV	0	0.40 ± 0.04	0.40 ± 0.04	—
eee M_{12} >100 GeV	3	0.39 ± 0.07	0.39 ± 0.07	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	1	0.05 ± 0.015	0.05 ± 0.015	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	1	0.02 ± 0.01	0.02 ± 0.01	—

ZEUS preliminary 96-00 (101 pb^{-1})

$\mu\mu$	$M\mu\mu$ >100 GeV	2	2.16	2.16 ± 0.54	—

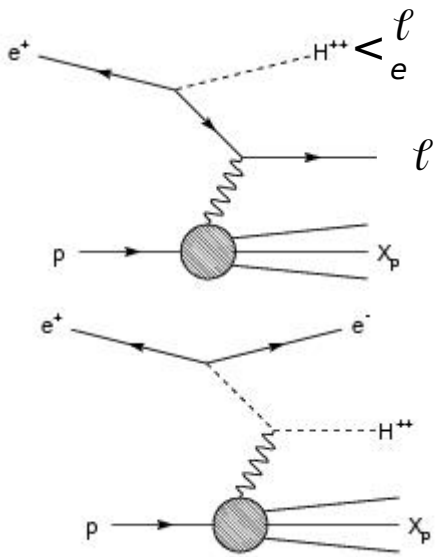
ZEUS preliminary 94-00 ($e^{\pm}p$ 130 pb^{-1})

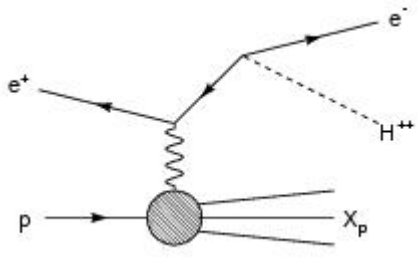
ee	M_{12} >100 GeV	2	0.77 ± 0.08	0.47 ± 0.05	0.3 ± 0.09
eee	M_{12} >100 GeV	0	0.37 ± 0.04	0.37 ± 0.04	—

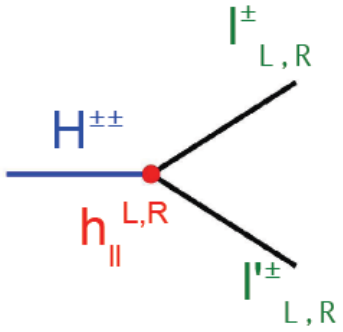
Search for Doubly Charged Higgs

Motivation

- Signature similar to observed Multi-Lepton Events
  Explanation for events at high mass?
- Occur in extensions of the SM, e.g. Left-Right Symmetric Models







$$h_{ll'}^{L,R} = \begin{vmatrix} h_{ee} & h_{e\mu} & h_{e\tau} \\ h_{e\mu} & h_{\mu\mu} & h_{\mu\tau} \\ h_{e\tau} & h_{\mu\tau} & h_{\tau\tau} \end{vmatrix}$$

Yukawa couplings

Expected Signature

- 2 High-P_T Leptons with charge of beam lepton
- Invariant Mass M_{ll} compatible to decay of heavy Higgs boson

Strategy

- Use Multi-Lepton Sample for *ee*, *eμ*, *μμ* and **add τ in dedicated Analysis**
- Add kinematic and same charge constraints

Search for H^{++}
Selection Results

- $ee(e)$, $\mu\mu(e)$

M_H (GeV)	electron analysis ("2e" + "3e")				muon analysis			
	N_{obs}	N_{bckg}	ε	N_{signal}	N_{obs}	N_{bckg}	ε	N_{signal}
100	0	0.29	0.48	6.78	0	0.05	0.36	4.96
120	1	0.12	0.44	2.58	0	0.03	0.29	1.67
150	0	0.02	0.36	0.56	0	0.02	0.17	0.25

(@ λ=0.3)

- $e\mu$

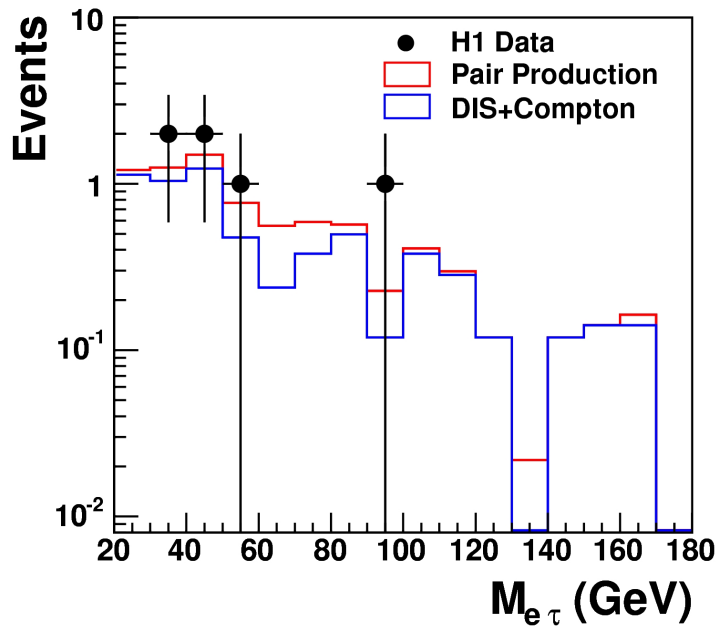
M_H (GeV)	electron-muon analysis			
	N_{obs}	N_{bckg}	ε	N_{signal}
100	0	1.01	0.49	7.12
120	0	0.65	0.47	2.82
150	0	0.33	0.42	0.67

H1 Preliminary

- τ: $e\mu$, ej, μj, jj

Decay Topology	$\tau\tau$ preselection			$H^{\pm\pm}$ final selection			Eff.×BR	
	obs.	SM bg	($\tau\tau$)	obs.	SM bg	($\tau\tau$)	elastic	quasi-elastic
$e\mu$	0	0.29± 0.03	(0.11)	0	0.09± 0.01	(0.00)	2.9%	2.6%
ej	0	1.20± 0.24	(0.31)	0	0.78± 0.16	(0.03)	6.9%	2.8%
μj	0	0.25± 0.05	(0.16)	0	0.03± 0.01	(0.03)	6.4%	5.5%
jj	1	0.38± 0.10	(0.16)	0	0.13± 0.08	(0.00)	8.0%	2.9%
total	1	2.12± 0.32	(0.74)	0	1.03± 0.19	(0.06)	24.2%	13.8%

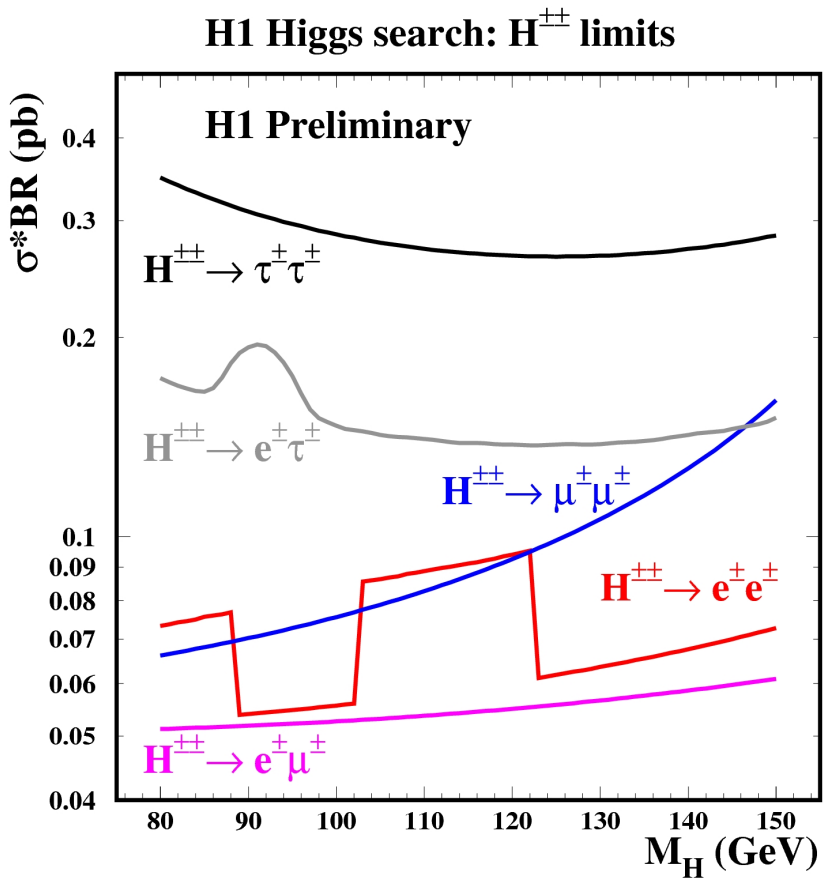
- $e\tau$



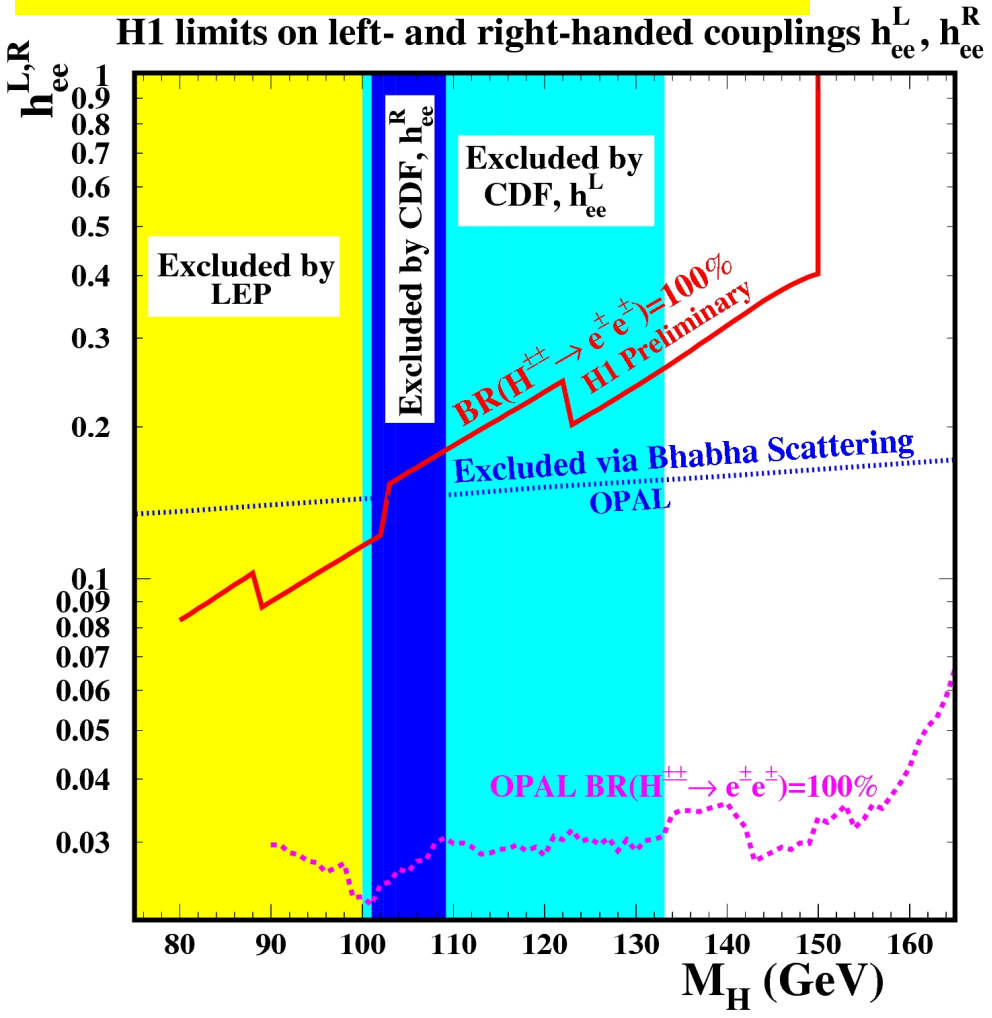
- One ee event at M_{ee} = 112 GeV , one τjj and one $e\tau$ event pass Higgs selection
- High-Mass Multi-Electron-Events observed by H1 not compatible with H^{++} Interpretation
- Set Limits on Crosssections and couplings h_{ee} , $h_{e\mu}$, $h_{e\tau}$

Limits on σx*Br* and dominant h_{ee}

Limits on σ ($e^{\pm}p \to eH^{\pm\pm}X$) x Br($H^{\pm\pm} \to l^{\pm}l^{\pm}$)

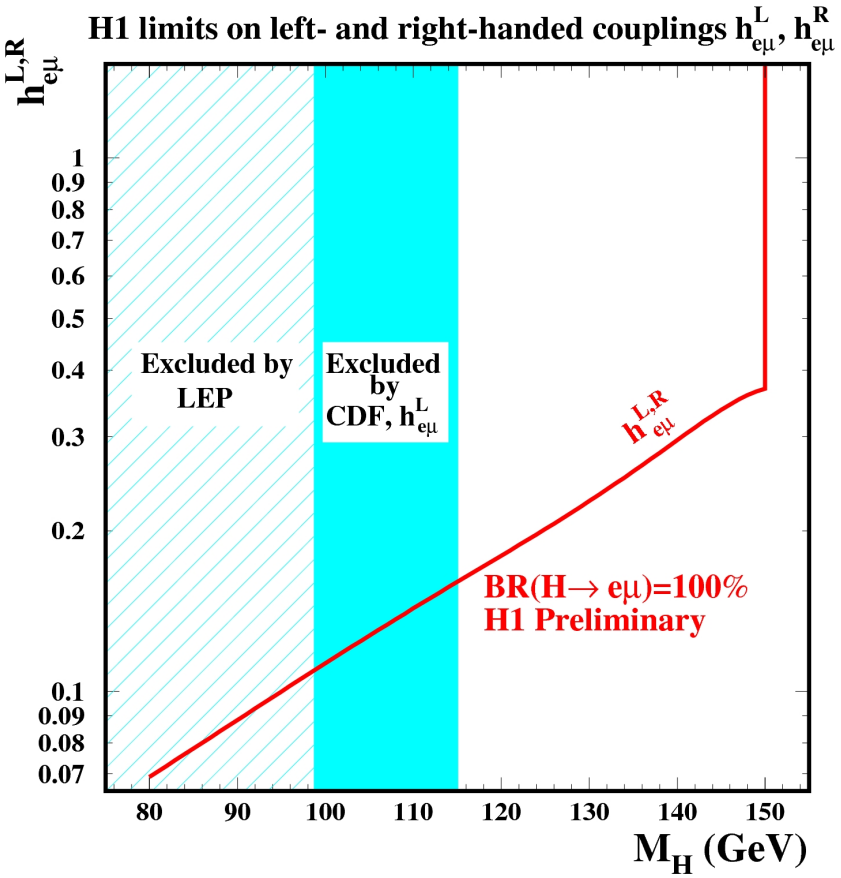


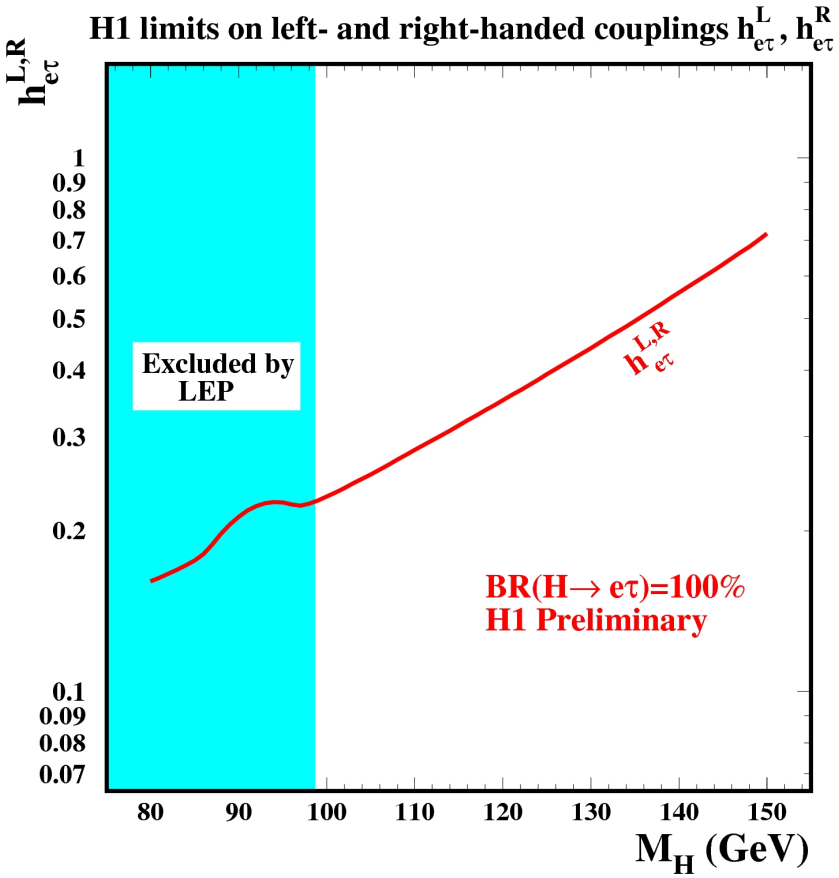
Dominant coupling h_{ee}



- H1 Limits competitive with CDF and LEP Pair Production Limits for large h_{ee}
- OPAL confirms: Multi-Electron-Events observed by H1 not compatible with H++ Interpretation

Limits on Couplings $h_{e\mu}$, $h_{e\tau}$





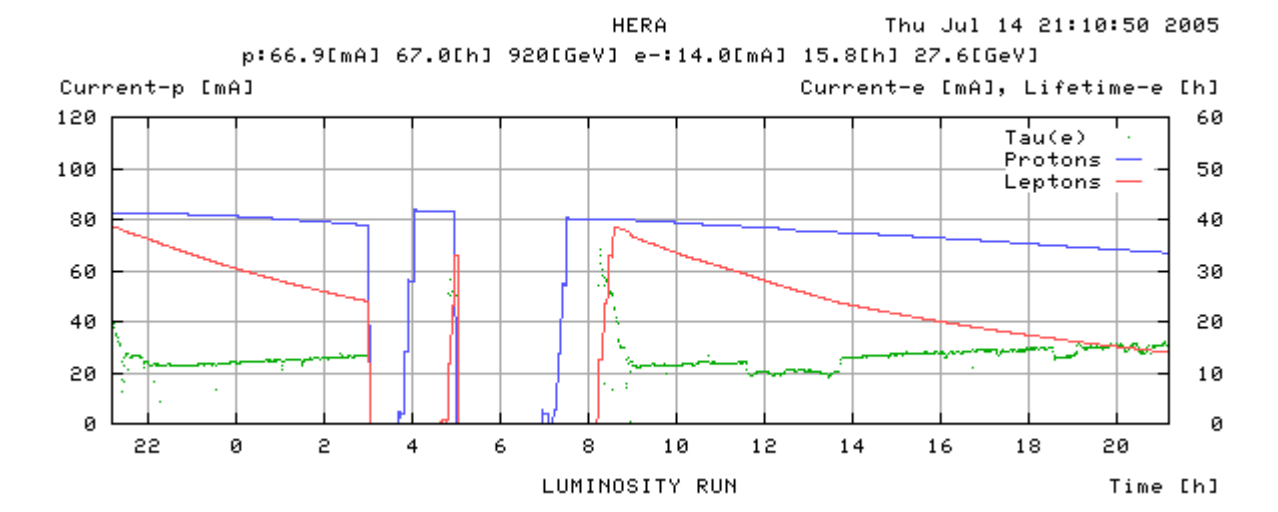
- H1 Limits also competitive to LEP, CDF Pair Production Limits in $H^{++} \rightarrow e\mu$, $e\tau$ channel for M_H > ~100 GeV

Summary & Outlook

- Competitive and complementary limits set at HERA on Monopoles, (LFV) Leptoquarks, Doubly Charged Higgs
- Puzzling events with isolated leptons observed in H1
- They keep coming to H1 at HERA II
- Need as much statistics as possible to solve this mystery
- End of HERA forseen in 2007 - Expected do deliver 700 pb^{-1}

Bulk of data still to come ...

... "Searching" at HERA is still exciting!

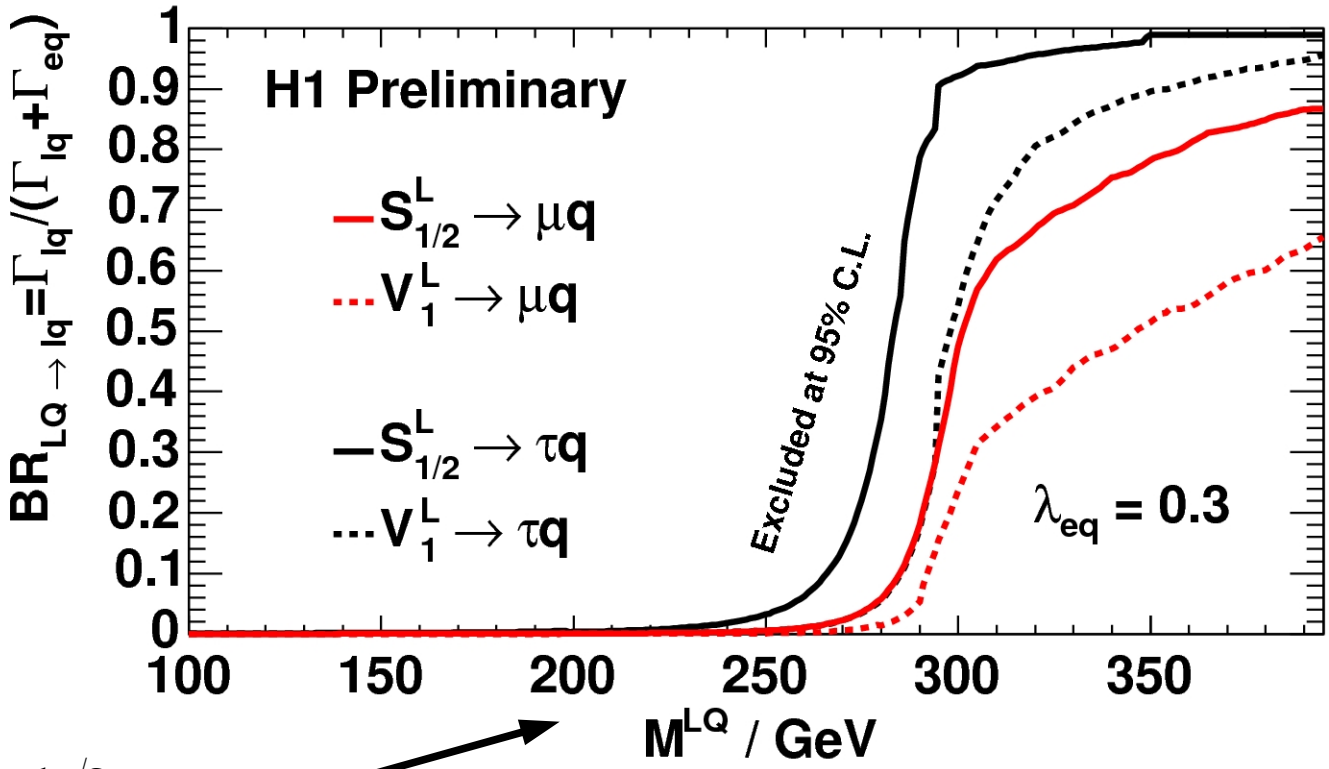


Backup

LQ Mass Limits from Lepton Flavor Violation

$M_{LQ} > \sqrt{s}$

u-channel Regime (Contact Interaction)



$M_{LQ} < \sqrt{s}$

s-channel Regime

(Resonant Production)