Search for new Physics at HERA

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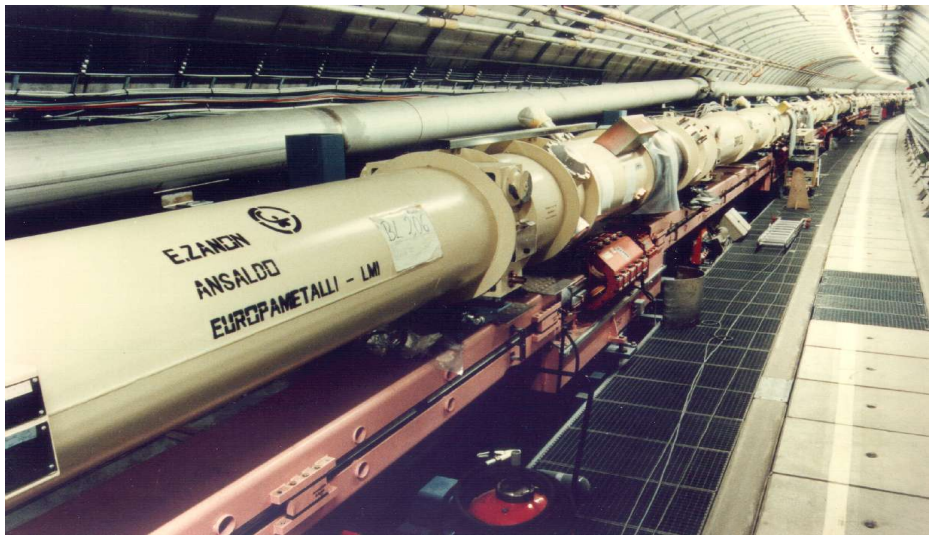
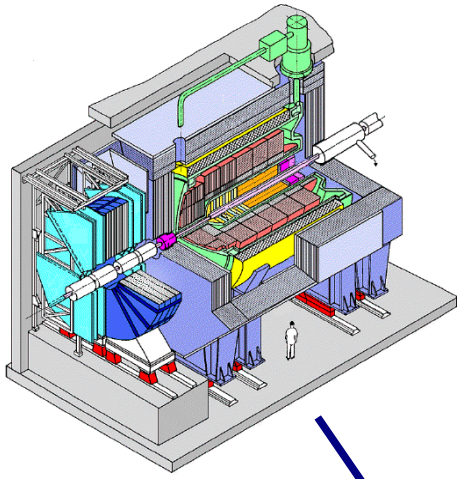
on behalf of the
H1 and ZEUS collaborations



27.5 GeV electron – 920 GeV proton

HERA



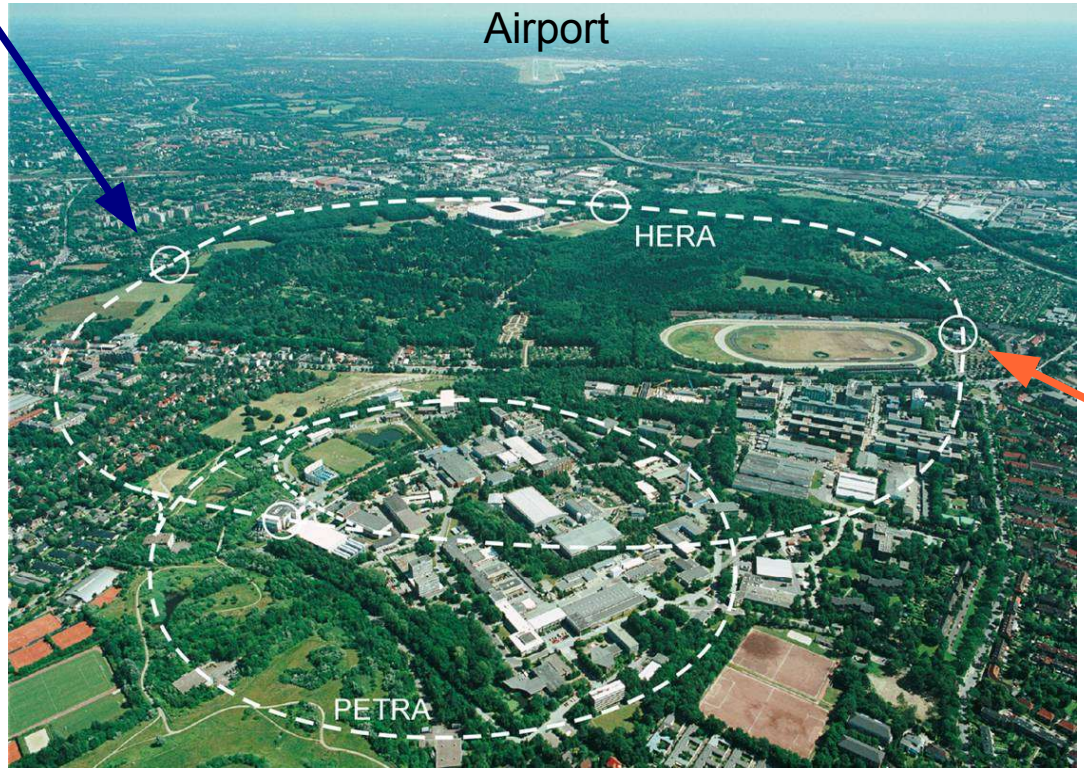
H1

"Hadron-Electron Ring Anlage"

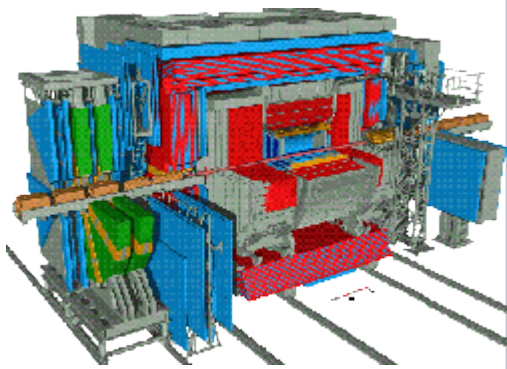
protons: 920 (820) GeV
electrons/positrons: 27.5 GeV

→ cms = 318 (300) GeV

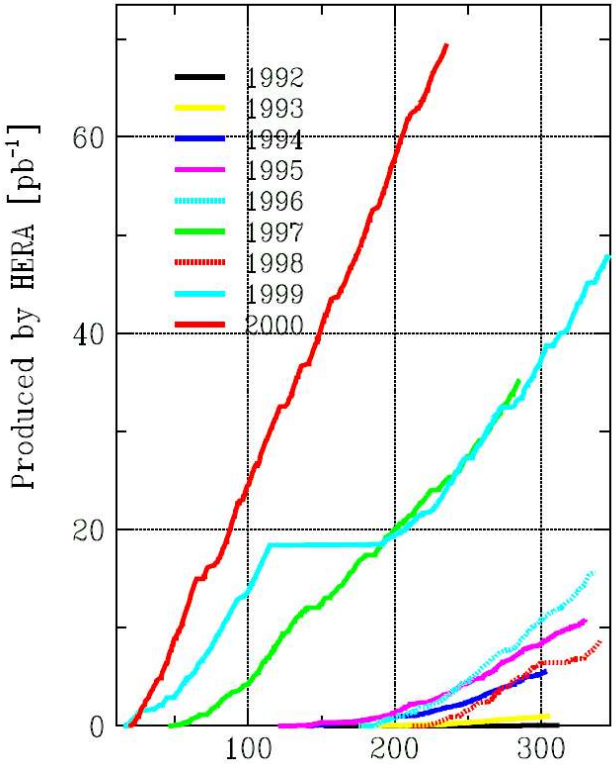
City of Hamburg



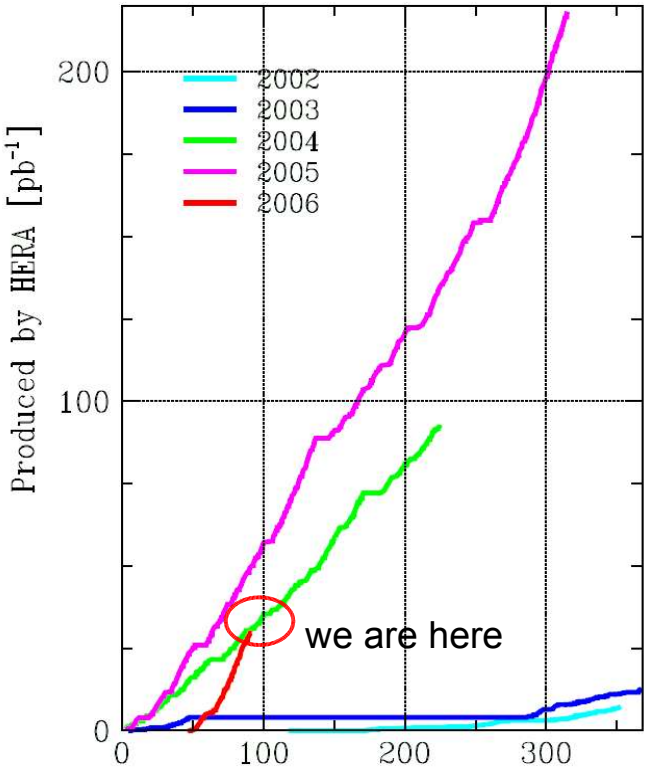
ZEUS



HERA Running Periods



HERA I: 1994-2000



HERA II: 2003-2006

- new optics higher → luminosity
- longitudinally polarised beams

1994-2000: e^+p data ~ 100 pb^{-1} (per experiment)

1998-1999: e^-p data ~ 15 pb^{-1} (per experiment)

2003-2004: e^+p data ~ 60 pb^{-1} (per experiment)

2005: e^-p data ~ 100 pb^{-1} (per experiment)

until HERA end (mid 2007)

expect ~ 600 pb^{-1} (per experiment)

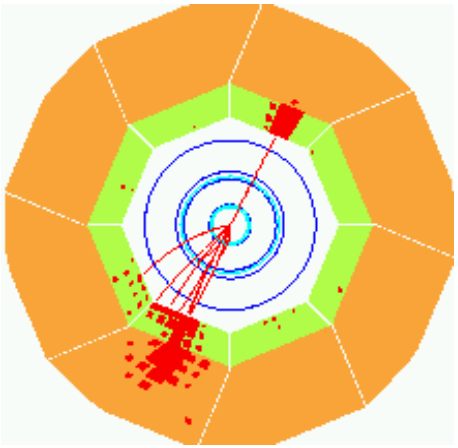
Overview

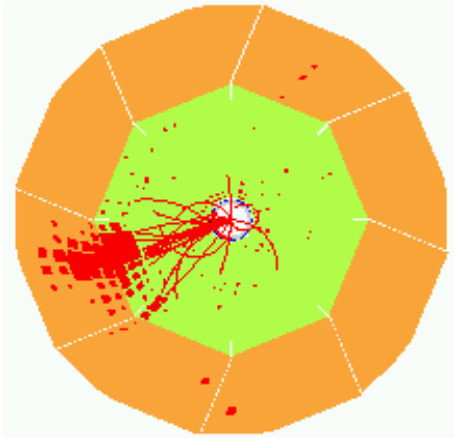
- SM processes at HERA
- Look Beyond the SM:
  - inclusive final states
  - phenomenological searches
  - selected specific models
- Summary

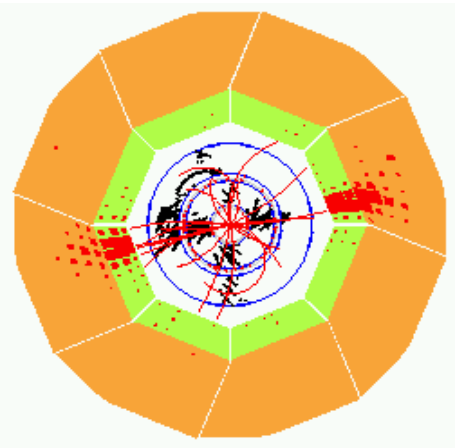
HERA Kinematics + SM Processes

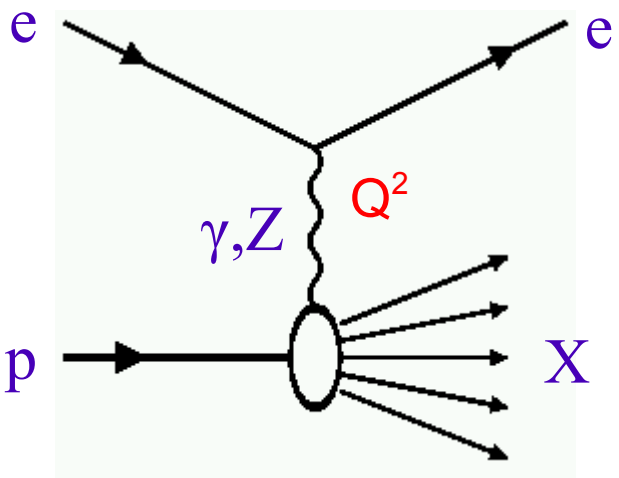
- Dominant processes at high p_T:

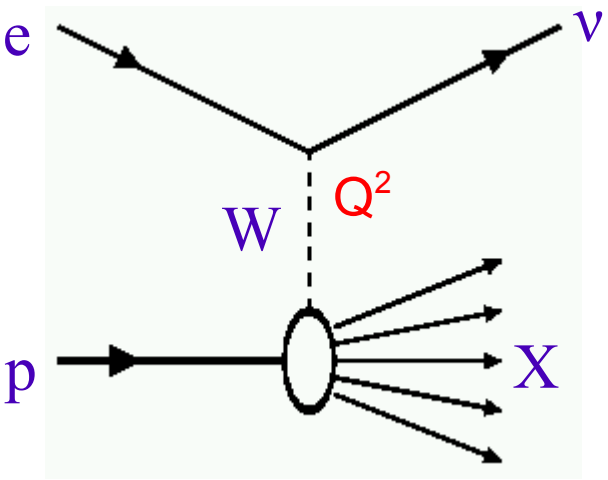
NC DIS: $ep \rightarrow eX$ CC DIS: $ep \rightarrow \nu X$ photoproduction: $\gamma p \rightarrow jj$

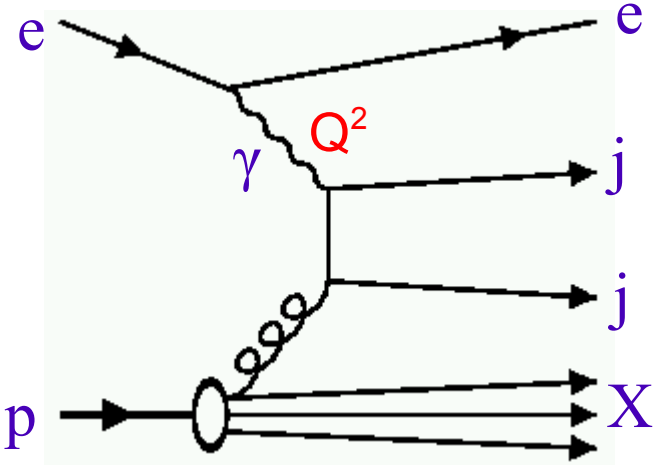










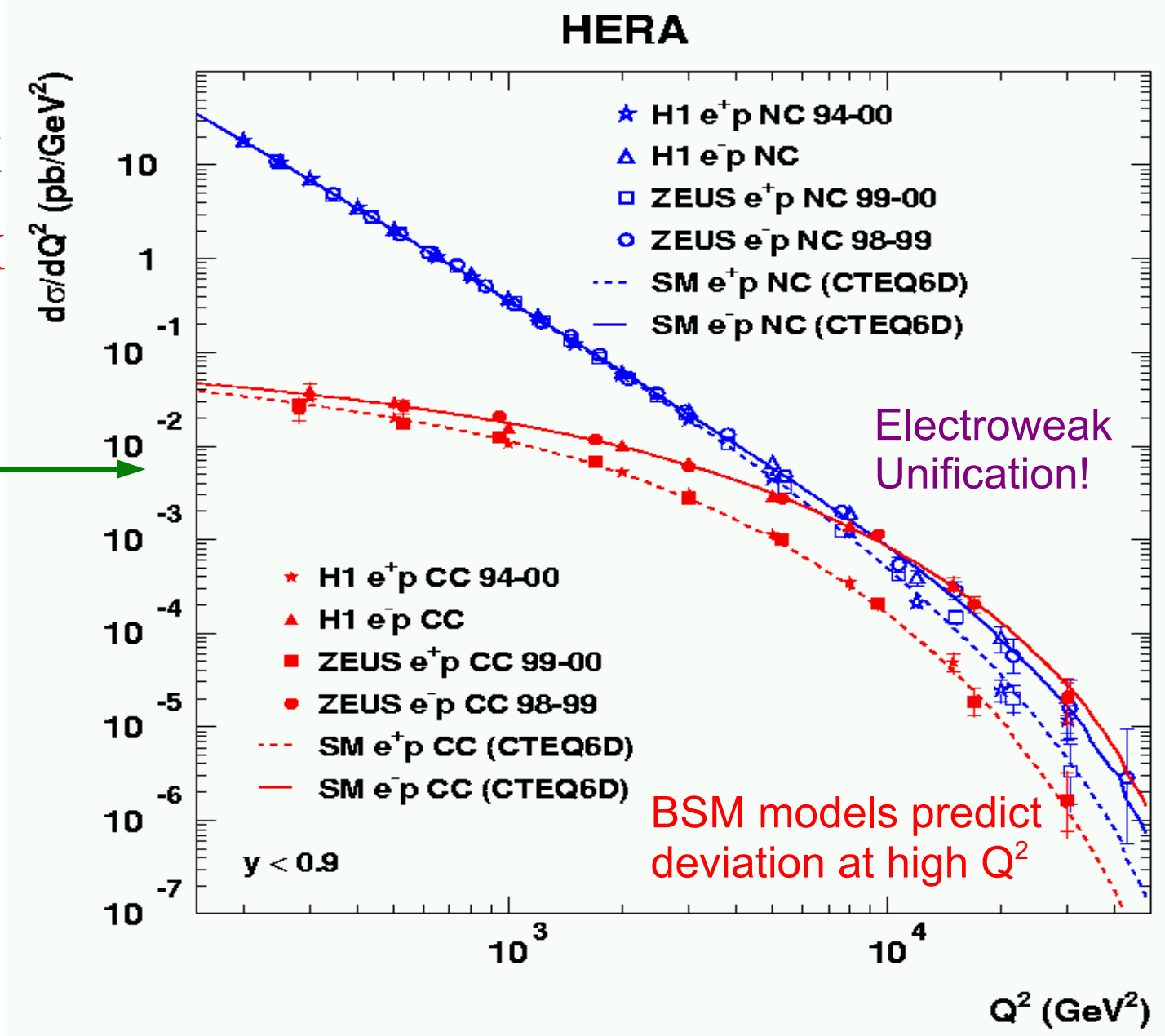


SM Differential Cross Sections

NC DIS: $ep \rightarrow eX$

CC DIS: $ep \rightarrow \nu X$

at high Q^2 →



The Chiral SM

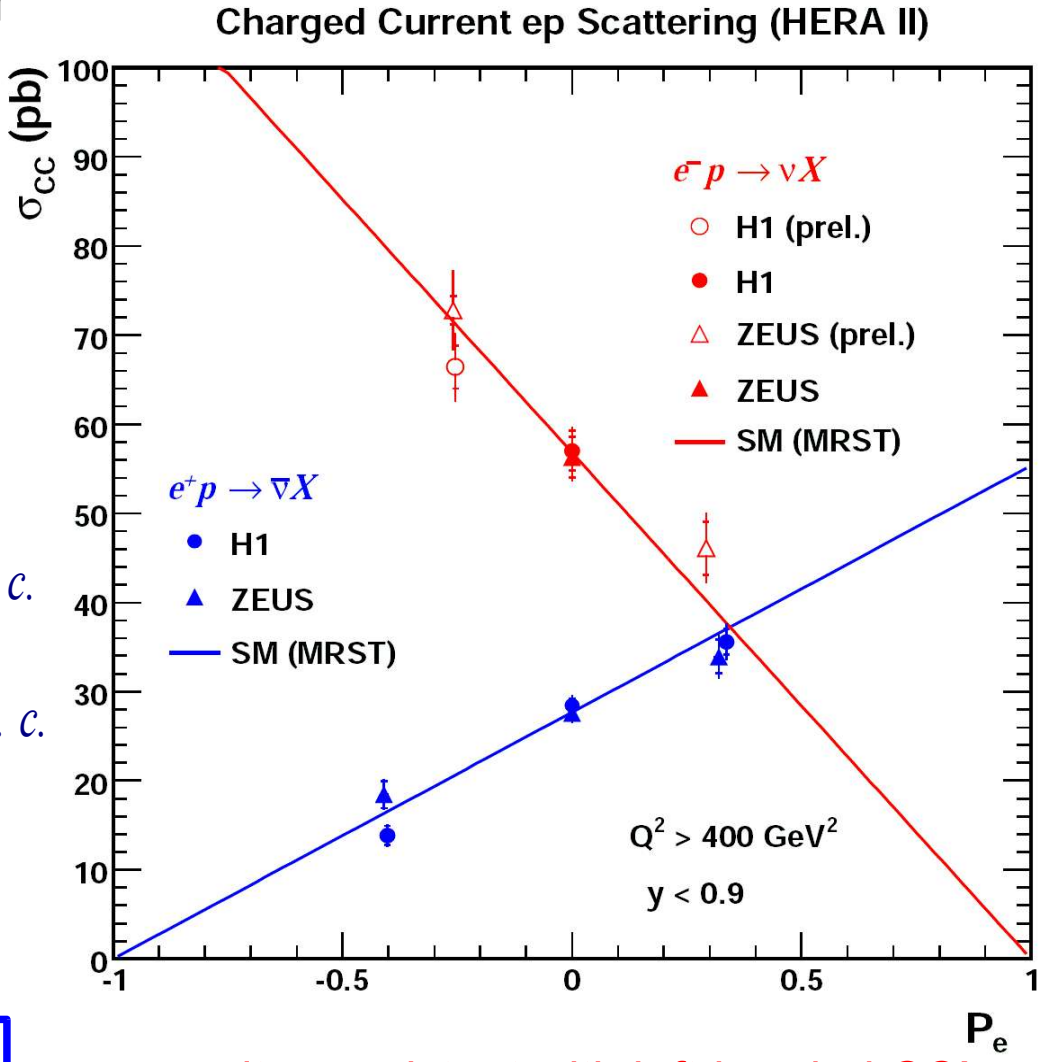
- CC polarised cross section for e^+p and and e^-p scattering:

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

P_e = longitudinal $e^{\pm}$ polarisation

$$L_{CC,L} = -\frac{e}{2\sqrt{2}\sin\Theta_W}\,[W_{L_\mu}\,\bar{e}\gamma^\mu(1-\gamma^5)\nu] \quad + \; h.\,c.$$

$$L_{CC,R} = -\frac{e}{2\sqrt{2}\sin\Theta_W}\,[W_{R_\mu}\,\bar{e}\gamma^\mu(1+\gamma^5)\nu] \quad + \; h.\,c.$$



results consistent with left-handed CC!

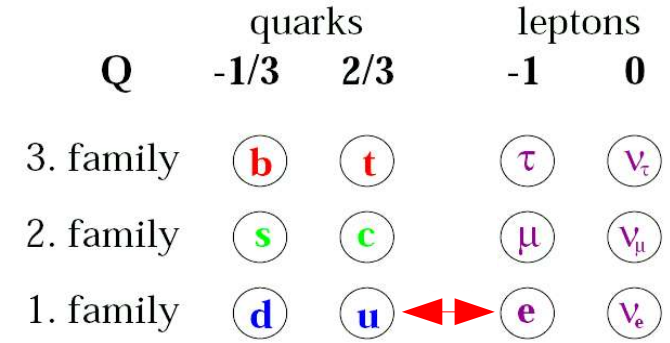
- extract limit on right-handed $m(W_R)$:

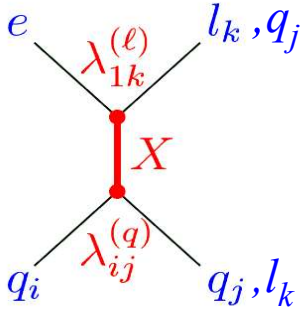
$$m(W_R) > 208 \text{ GeV} \quad (95\%\ CL)$$

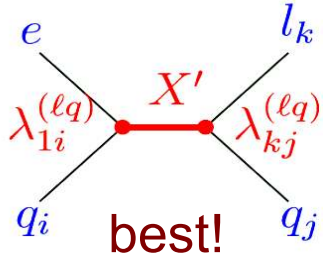
(H1 e^+p only) (Phys. Lett. B 634 (2006) 173)

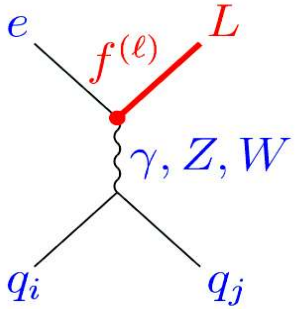
The Search Machine HERA

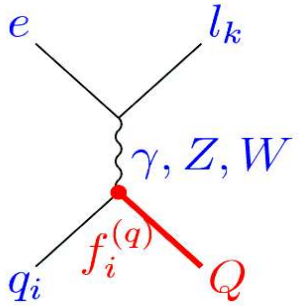
- Directly Probing new physics in lepton quark interactions:











HERA is probes small cross sections:
limits on → masses ⊗ couplings

HERA: unique sensitivity to

<u>new bosonic states</u>

- Leptoquarks
  → Lepton Flavor Violation
- R-parity violating Scalar Quarks
- Gravitons
  → space time structure (LED)

<u>new fermionionic states:</u>

- quark subtructure
- excited fermions
- anomalous top production

BSM Topics

- Searches in Inclusive Final States
  - Leptoquarks (Deep Inelastic Scattering)
  - Lepton Flavor Violation
  - Contact Interactions, Extra Dimensions, Substructure
- Phenomenological Searches
  - General Search
  - Isolated Lepton Events with missing P_T
    → W production
    → Single Top Production
  - Multi Lepton Final States → Doubly Charged Higgs
- Other Models
  - Excited Fermions
  - SUSY

Leptoquarks at HERA

Properties:

- multiple charges of 1/3
- carry lepton & baryon number, $SU(3)_C$ color

Motivation: light Leptoquarks $M_{LQ} < M_{GUT}$ predicted

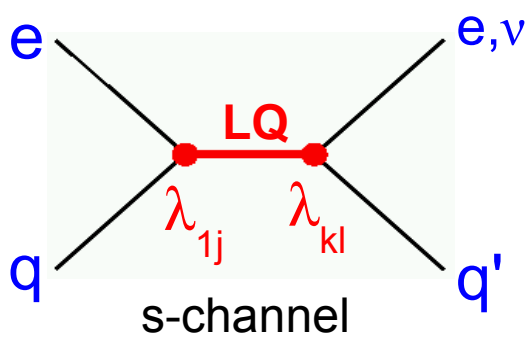
- GUTs: E_6, SO(10)
- SUSY, Technicolor, Superstrings

Production at HERA:

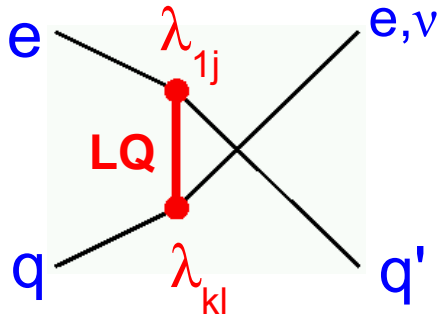
Yukawa coupling λ_{ij}

(i,j = family indices)

$\longrightarrow$ single production



s-channel



u-channel

Leptoquark Model:

- $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ symmetry
- 7 scalar / 7 vector (Buchmüller, Wyler, Rückl)
- F = B+L = 0, 2

Leptoquark Types

BRW model:

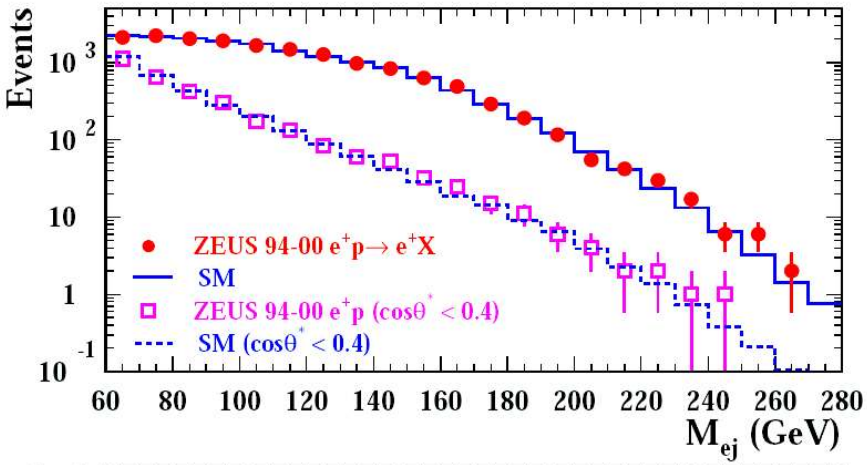
fixed LQ decay branching ratios

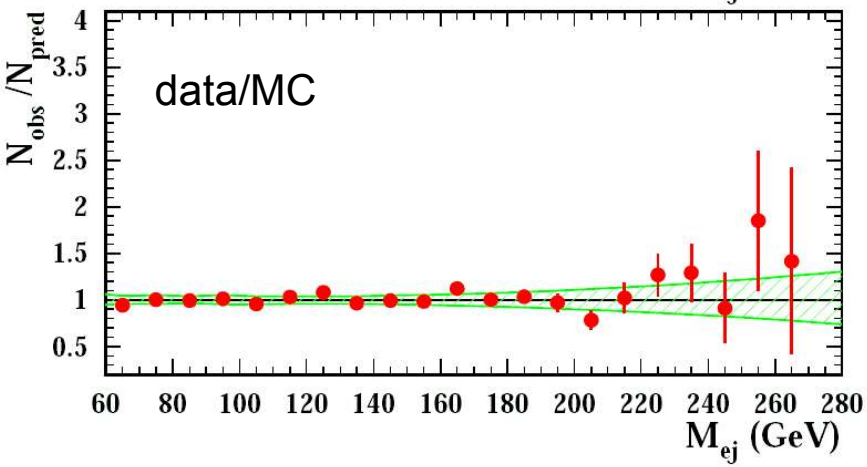
$F=2$	Prod./Decay	β_e	$F=0$	Prod./Decay	β_e
Scalar Leptoquarks					
$S_{0,L}$	$e_L^- u_L \to e^- u$	1/2	$S_{1/2,L}$	$e_R^+ u_R \to e^+ u$	1
	$\to \nu d$	1/2			
$S_{0,R}$	$e_R^- u_R \to e^- u$	1	$S_{1/2,R}$	$e_L^+ u_L \to e^+ u$	1
$\tilde{S}_{0,R}$	$e_R^- d_R \to e^- d$	1		$e_L^+ d_L \to e^+ d$	1
$S_{1,L}$	$e_L^- d_L \to e^- d$	1	$\tilde{S}_{1/2,L}$	$e_R^+ d_R \to e^+ d$	1
	$e_L^- u_L \to e^- u$	1/2			
	$\to \nu d$	1/2			
Vector Leptoquarks					
$V_{1/2,R}$	$e_R^- d_L \to e^- d$	1	$V_{0,R}$	$e_L^+ d_R \to e^+ d$	1
	$e_R^- u_L \to e^- u$	1	$V_{0,L}$	$e_R^+ d_L \to e^+ d$	1/2
				$\to \overline{\nu} u$	1/2
$V_{1/2,L}$	$e_L^- d_R \to e^- d$	1	$\tilde{V}_{0,R}$	$e_L^+ u_R \to e^+ u$	1
$\tilde{V}_{1/2,L}$	$e_L^- u_R \to e^- u$	1	$V_{1,L}$	$e_R^+ u_L \to e^+ u$	1
				$e_R^+ d_L \to e^+ d$	1/2
				$\to \overline{\nu} u$	1/2

Leptoquark Mass Spectra

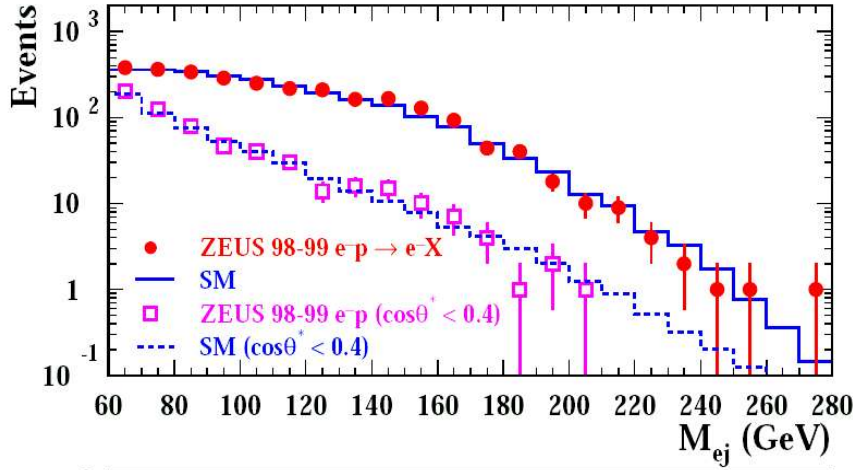
(ZEUS: Physical Review D 68 (2003))

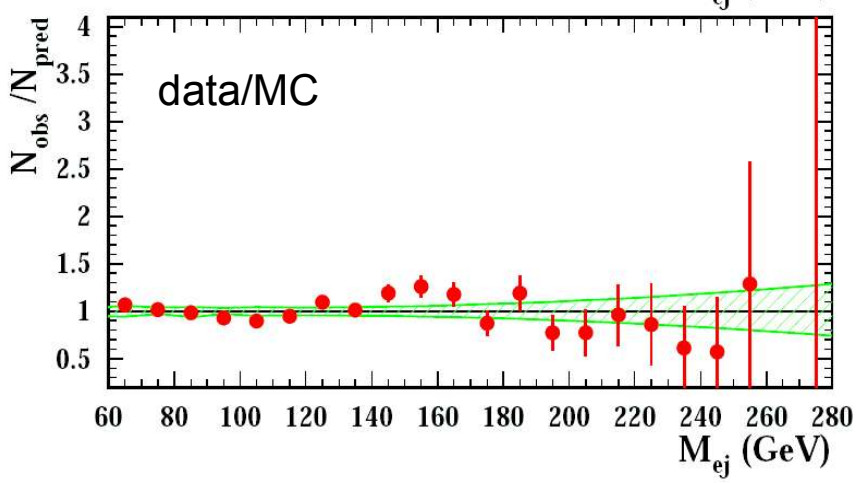
e^+p ZEUS





e^-p ZEUS





search for narrow resonant state: $\Gamma_{S(V)} = \frac{1}{16(24)\pi^2}\,\lambda^2_{L,R} M \ll 1\,\mathrm{GeV}$

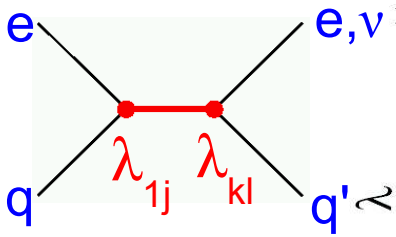
Leptoquark Limits

(ZEUS: Physical Review D 68 (2003))

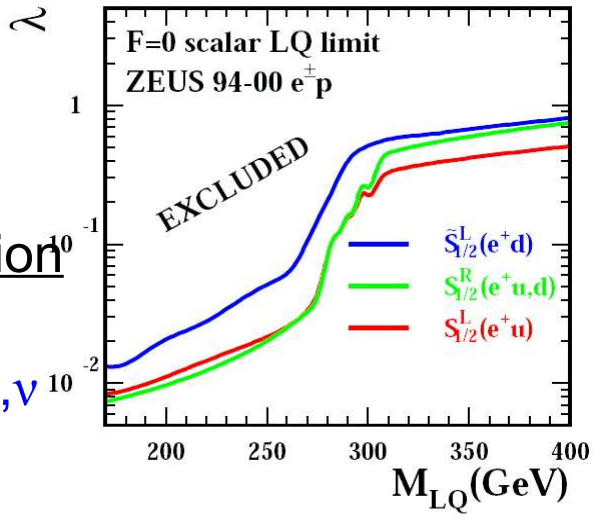
in total 14 limits:

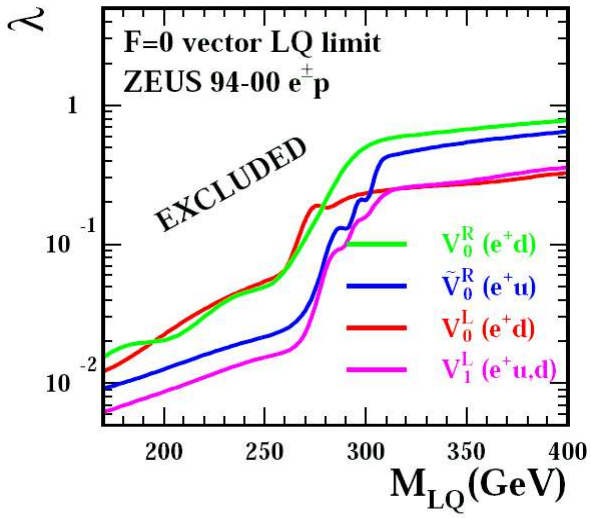
ZEUS

low mass region

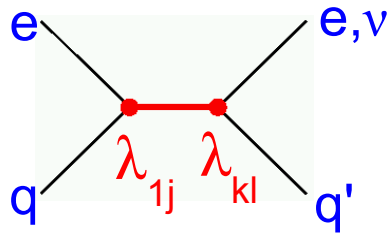


s-channel only

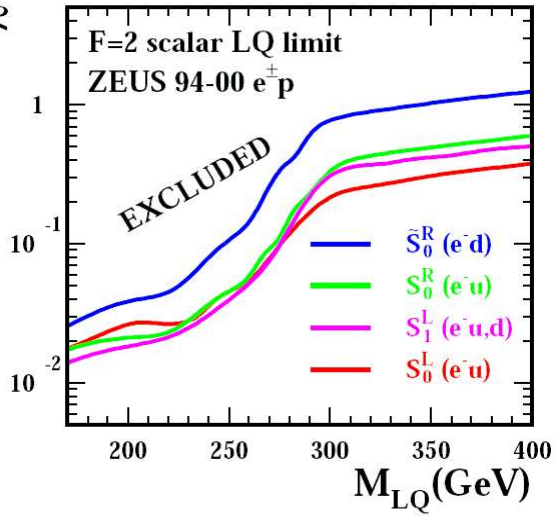


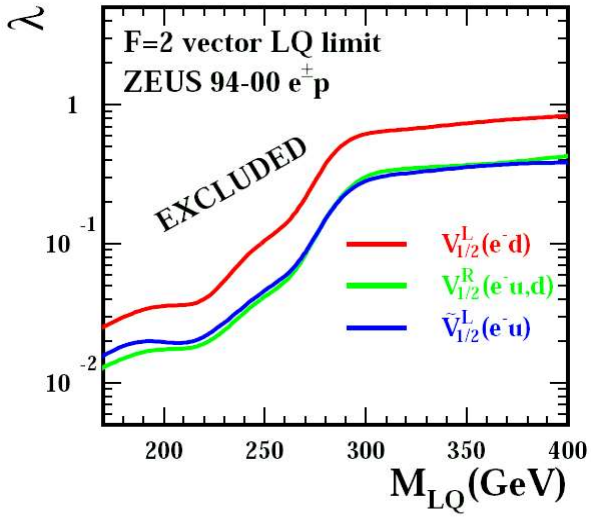


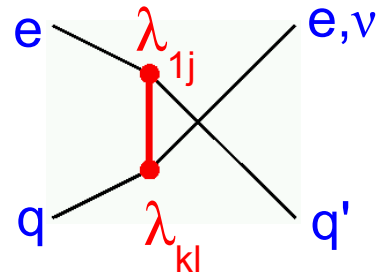
high mass region



s-channel +







u-channel

side remark:

LQ limits hold also for direct RPV Squark (SUSY) decays: $\tilde{S}^L_{1/2} \to \tilde{u}_L \quad S^L_0 \to \tilde{d}_L$

General LQ Framework

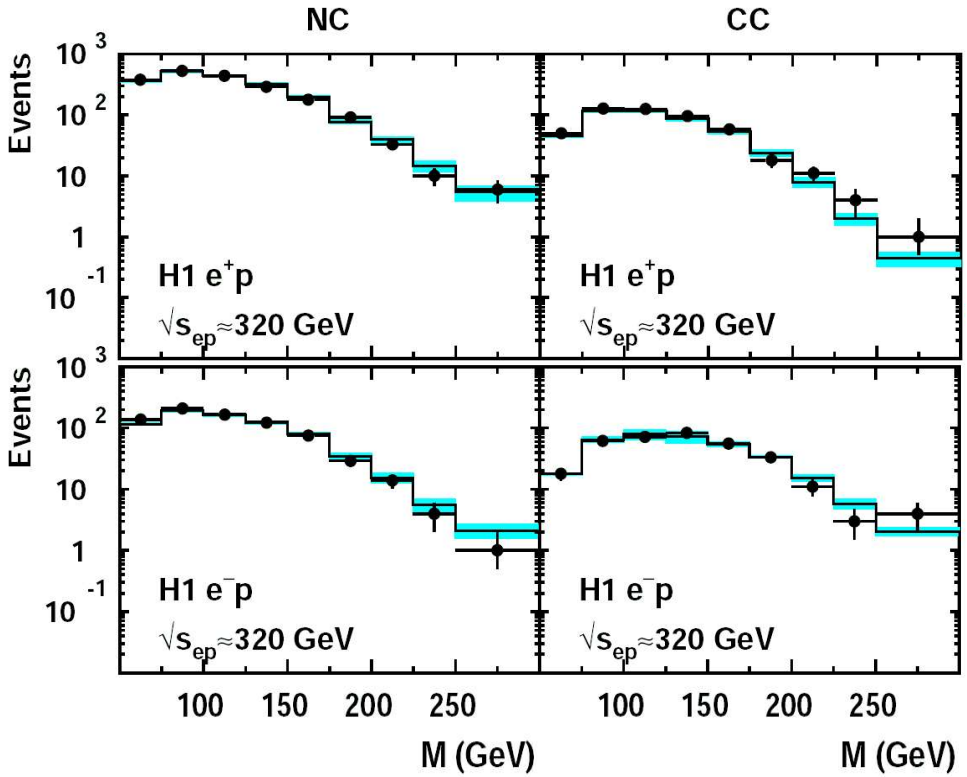
(H1: Phys. Lett. B629 (2005) 9-19)

BRW: fixed branching ratios:

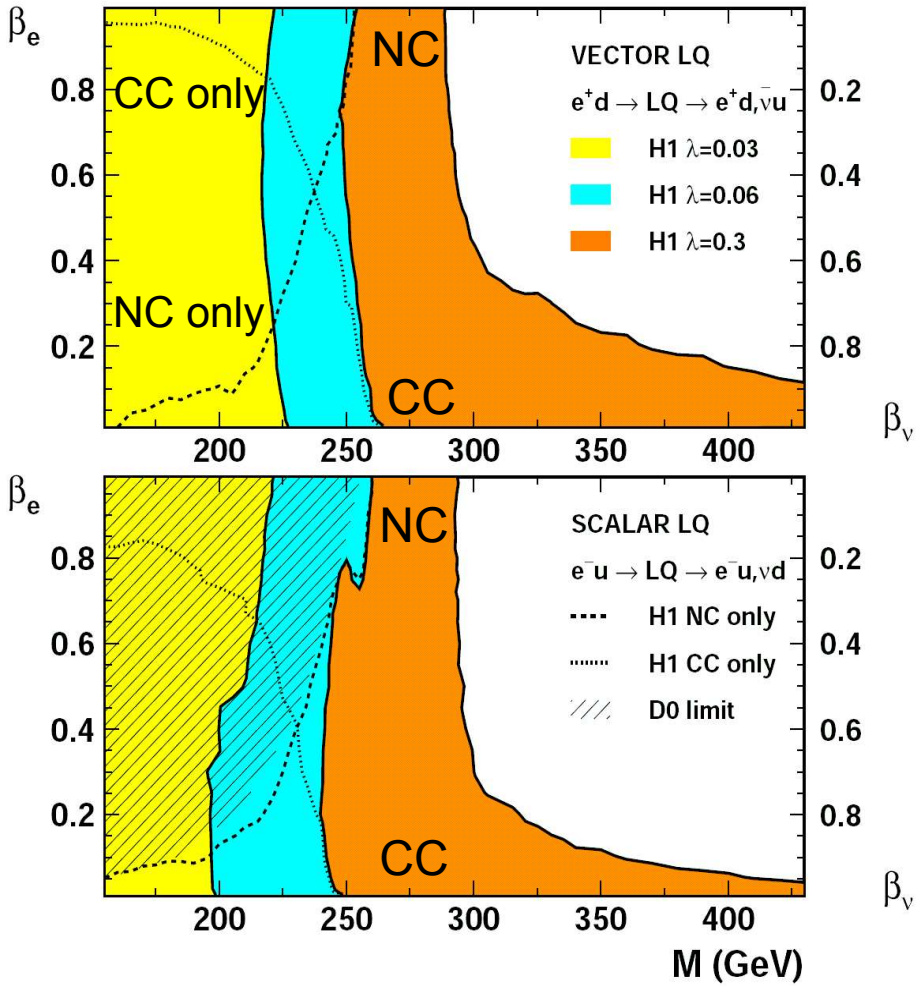
$LQ \rightarrow eq$, $LQ \rightarrow \nu q$

General:

β_e = BR($LQ \rightarrow eq$)/BR($LQ \rightarrow \nu q$) arbitrary

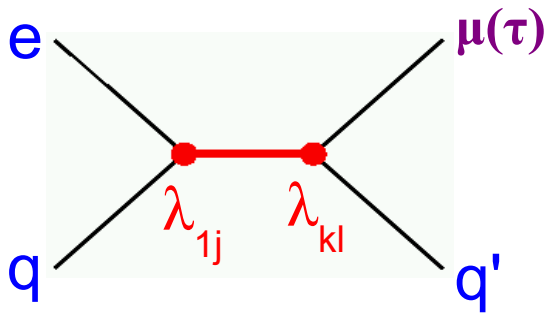


HERA Limits (H1 publ.):

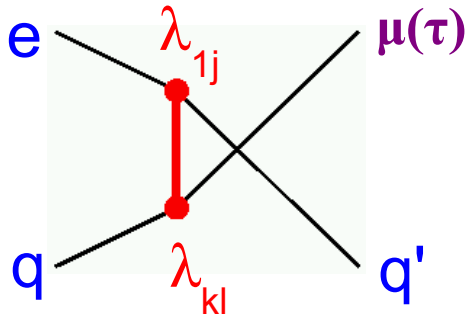


Lepton Flavor Violation Leptoquarks

Leptoquark model with LFV coulings:

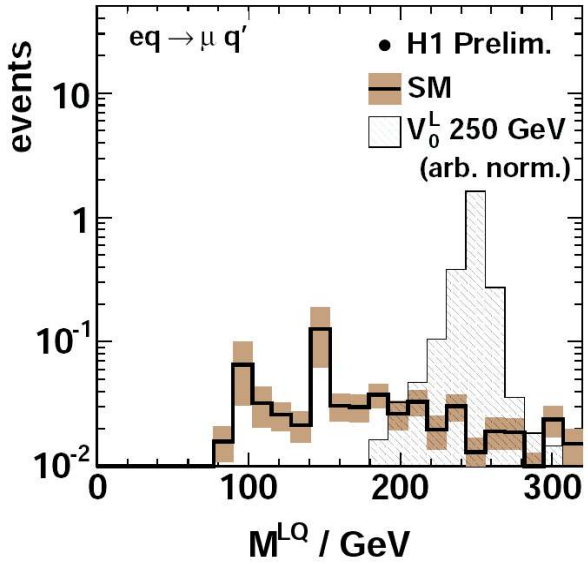


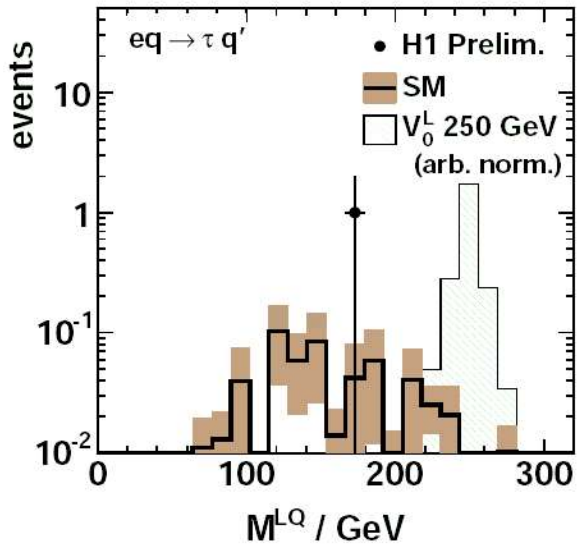
s-channel



u-channel

similar analysis as for LQ (~DIS signature) but with almost no background here!





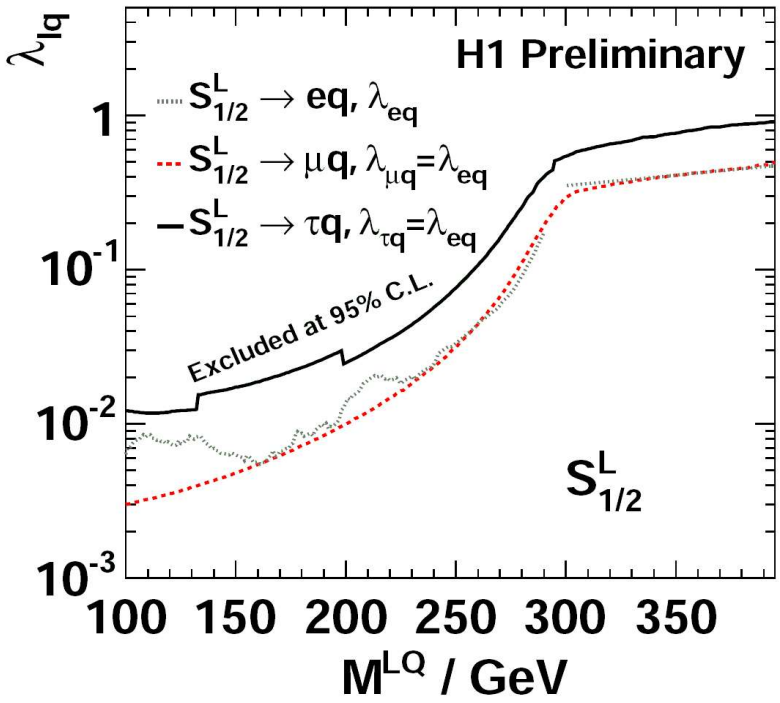
LFV Limits

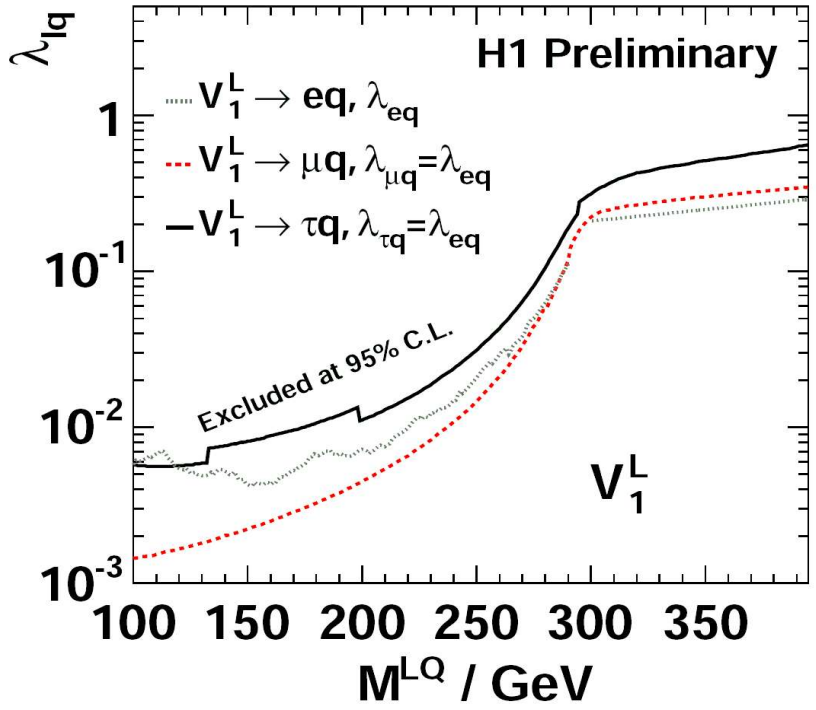
limits for different scenarios:

$eq \rightarrow LQ \rightarrow eq$

$eq \rightarrow LQ \rightarrow eq\,,\ \mu q$ (50%)

$eq \rightarrow LQ \rightarrow eq\,,\ \tau q$ (50%)





Contact Interaction

Contraction of a time-like/space-like interaction to a four fermion point-like Contact Interaction

- Effective Lagrangian

  (considering only vector-type terms)

$$L_V = \sum \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a) (\bar{q}_b \gamma_\mu q_b)$$
$$a, b = L, R$$

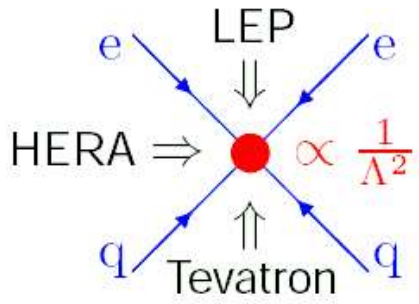
model: $\eta^q_{ab} = \epsilon (\frac{g}{\Lambda^q_{ab}})^2$

$\epsilon = \pm 1$ interference with SM:

Λ effective mass scale

g coupling strength

often set: $g = \sqrt{4\pi} \approx 3.5 \approx 11e$



⇒ testing new physics above the collider energy at high scales, for example Q^2

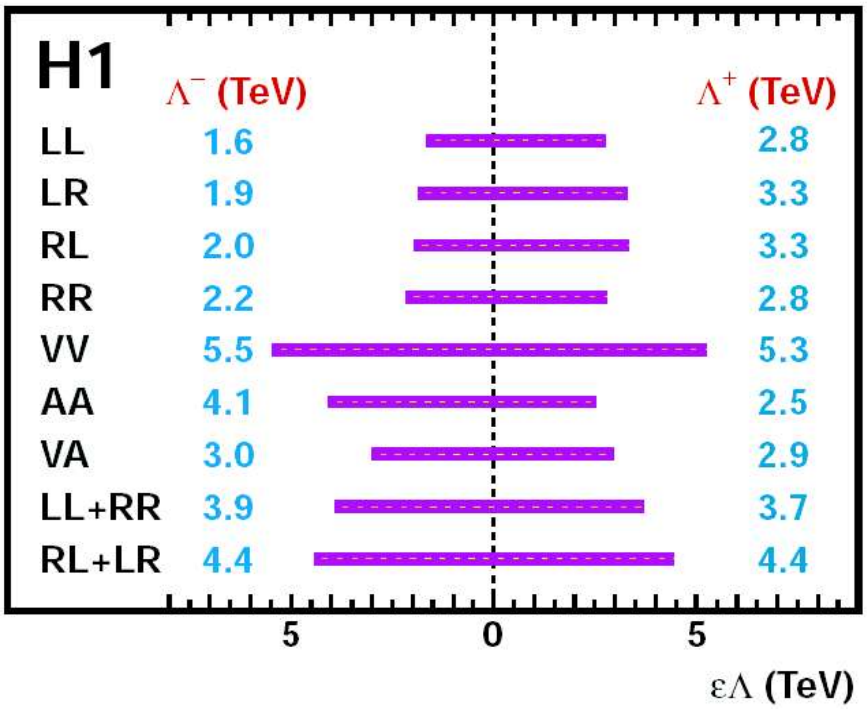
- considering proper LQ couplings

  ⇒ access to Leptoquarks

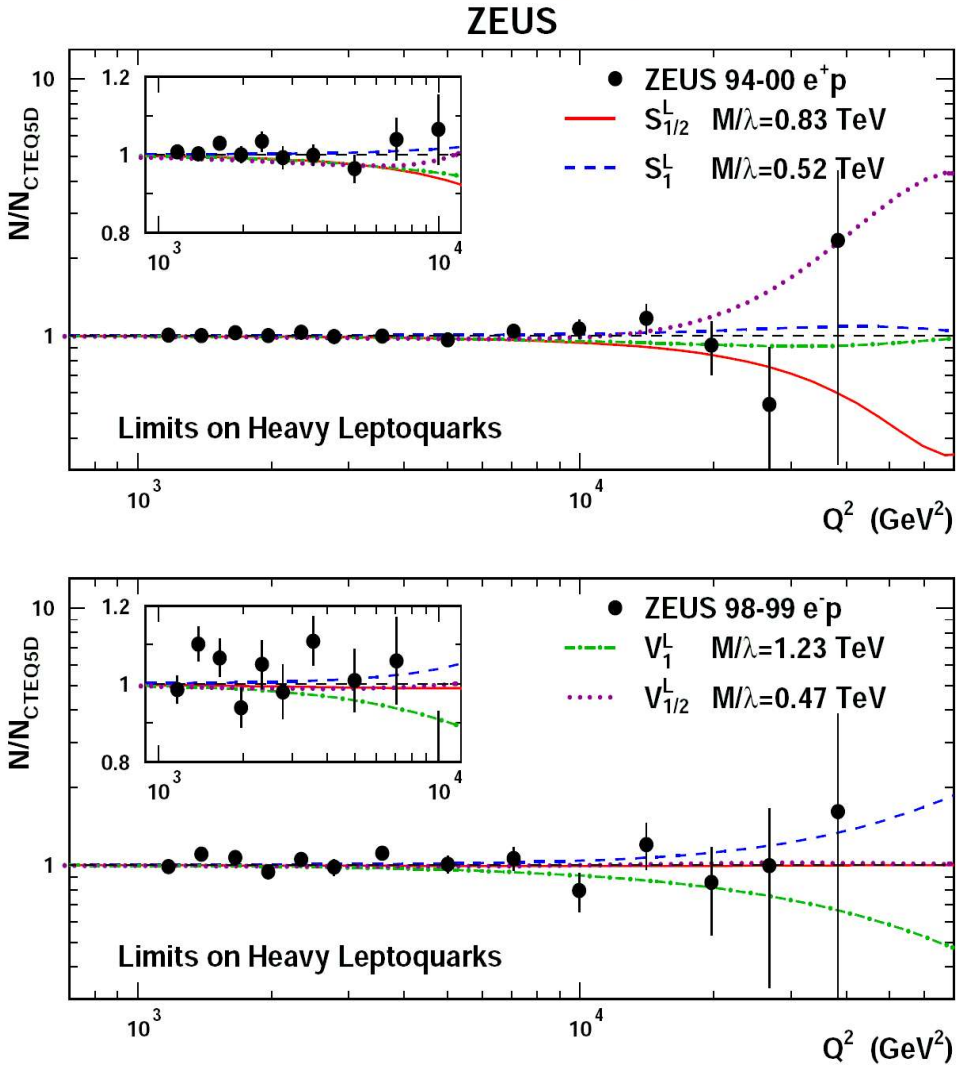
Contact Interaction Limits

(H1: Phys Lett B568 (2003) 35-47; ZEUS: Physics Letters B 591 (2004) 23-41)

Limits on Effective Mass Scale Λ



LQ interpretation: $M/\lambda \quad (= \Lambda/g)$

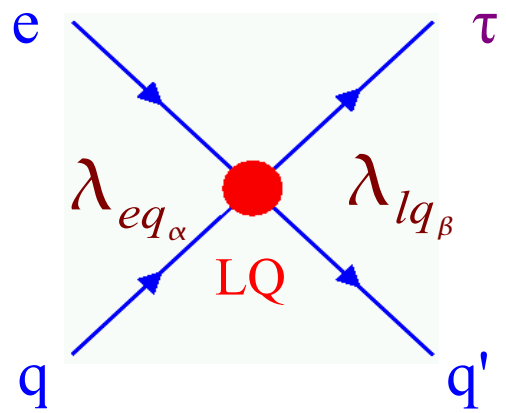


(fits include CI/SM interference)

Lepton Flavor Violation

ZEUS Collab., DESY-05-016 (1/2005), submitted to EPJ

- high mass limit M > s:



four fermion contact IA

- α,β generation indices
- limits set on $(1/\mathrm{TeV}^2)$:

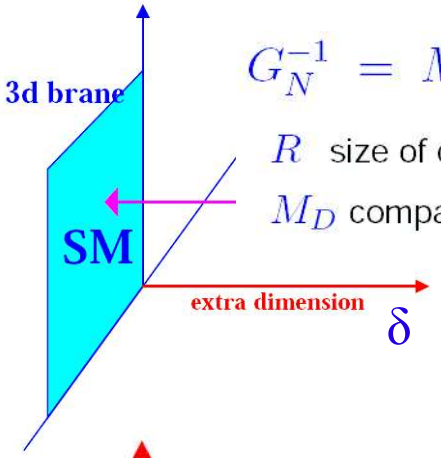
$$\frac{\lambda_{eq_\alpha}\lambda_{lq_\beta}}{M^2_{LQ}}$$

$e \rightarrow \tau$ — ZEUS $e^{\pm}p$ 94-00 — F=0

αβ	$S^L_{1/2}$ $e^-\bar{u}$ e^+u	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ $e^-\bar{d}$ e^+d	V^L_0 $e^-\bar{d}$ e^+d	V^R_0 $e^-\bar{d}$ e^+d	$\tilde{V}^R_0$ $e^-\bar{u}$ e^+u	V^L_1 $e^-(\sqrt{2}\bar{u}+\bar{d})$ $e^+(\sqrt{2}u+d)$
1 1	$\tau \rightarrow \pi e$ 0.4 **1.8**	$\tau \rightarrow \pi e$ 0.2 **1.5**	$\tau \rightarrow \pi e$ 0.4 **2.7**	$\tau \rightarrow \pi e$ 0.2 **1.7**	$\tau \rightarrow \pi e$ 0.2 **1.7**	$\tau \rightarrow \pi e$ 0.2 **1.3**	$\tau \rightarrow \pi e$ 0.06 **0.6**
1 2	**1.9**	$\tau \rightarrow Ke$ 6.3 **1.6**	$K \rightarrow \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.9**	$\tau \rightarrow Ke$ 3.2 **2.1**	$\tau \rightarrow Ke$ 3.2 **2.1**	**1.6**	$K \rightarrow \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.8**
1 3	*	$B \rightarrow \tau\bar{e}$ 0.3 **3.2**	$B \rightarrow \tau\bar{e}$ 0.3 **3.3**	$B \rightarrow \tau\bar{e}$ 0.13 **2.6**	$B \rightarrow \tau\bar{e}$ 0.13 **2.6**	*	$B \rightarrow \tau\bar{e}$ 0.13 **2.6**
2 1	**6.0**	$\tau \rightarrow Ke$ 6.3 **4.1**	$K \rightarrow \pi\nu\bar{\nu}$ 5.8×10^{-4} **5.2**	$\tau \rightarrow Ke$ 3.2 **2.3**	$\tau \rightarrow Ke$ 3.2 **2.3**	**2.1**	$K \rightarrow \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.9**
2 2	$\tau \rightarrow 3e$ 5 **10**	$\tau \rightarrow 3e$ 8 **5.6**	$\tau \rightarrow 3e$ 17 **6.5**	$\tau \rightarrow 3e$ 9 **3.4**	$\tau \rightarrow 3e$ 9 **3.4**	$\tau \rightarrow 3e$ 3 **5.5**	$\tau \rightarrow 3e$ 1.6 **2.1**
2 3	*	$B \rightarrow \tau\bar{e}X$ 14 **8.1**	$B \rightarrow \tau\bar{e}X$ 14 **7.8**	$B \rightarrow \tau\bar{e}X$ 7.2 **5.5**	$B \rightarrow \tau\bar{e}X$ 7.2 **5.5**	*	$B \rightarrow \tau\bar{e}X$ 7.2 **5.5**
3 1	*	$B \rightarrow \tau\bar{e}$ 0.3 **7.8**	$B \rightarrow \tau\bar{e}$ 0.3 **7.2**	V_{ub} 0.12 **2.5**	$B \rightarrow \tau\bar{e}$ 0.13 **2.5**	*	V_{ub} 0.12 **2.5**
3 2	*	$B \rightarrow \tau\bar{e}X$ 14 **11**	$B \rightarrow \tau\bar{e}X$ 14 **10**	$B \rightarrow \tau\bar{e}X$ 7.2 **4.2**	$B \rightarrow \tau\bar{e}X$ 7.2 **4.2**	*	$B \rightarrow \tau\bar{e}X$ 7.2 **4.2**
3 3	*	$\tau \rightarrow 3e$ 8 **15**	$\tau \rightarrow 3e$ 17 **14**	$\tau \rightarrow 3e$ 9 **8.1**	$\tau \rightarrow 3e$ 9 **8.1**	*	$\tau \rightarrow 3e$ 1.6 **8.1**

Extra Dimensions + Substructure

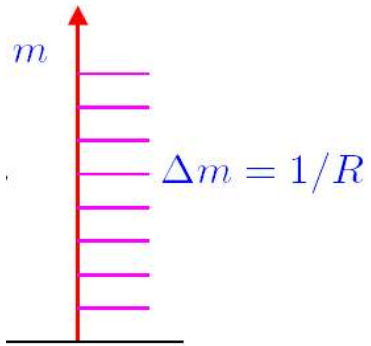
- Large Extra Dimensions:



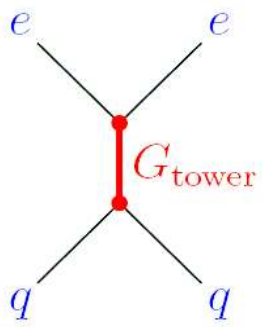
$$G_N^{-1} = M_{Pl}^2 = M_D^{2+\delta} R^\delta$$

R size of compactified extra dimension

M_D compactification mass scale

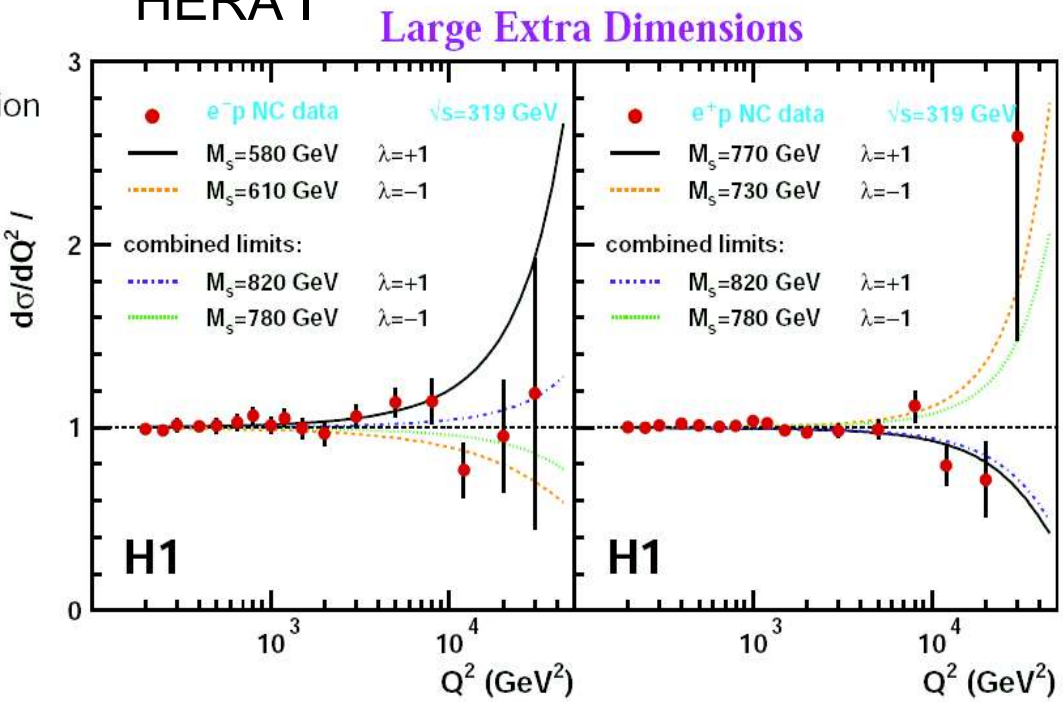


Kaluzza-Klein tower



deviation from SM

HERA I



$M_D > 0.8$ TeV

similar limit by ZEUS

- Quark Radius:

fit form factor to data $f(Q^2) = 1 - \frac{1}{6}\langle R^2 \rangle Q^2$

HERA I:

$R_q < 10^{-16}$ cm

BSM Topics

- Searches in Inclusive Final States
  - Leptoquarks (Deep Inelastic Scattering)
  - Lepton Flavor Violation
  - Contact Interactions, Extra Dimensions, Substructure
- Phenomenological Searches
  - General Search
  - Isolated Lepton Events with missing P_T
    → W production
    → Single Top Production
  - Multi Lepton Final States → Doubly Charged Higgs
- Other Models
  - Excited Fermions
  - SUSY

General Search HERA I

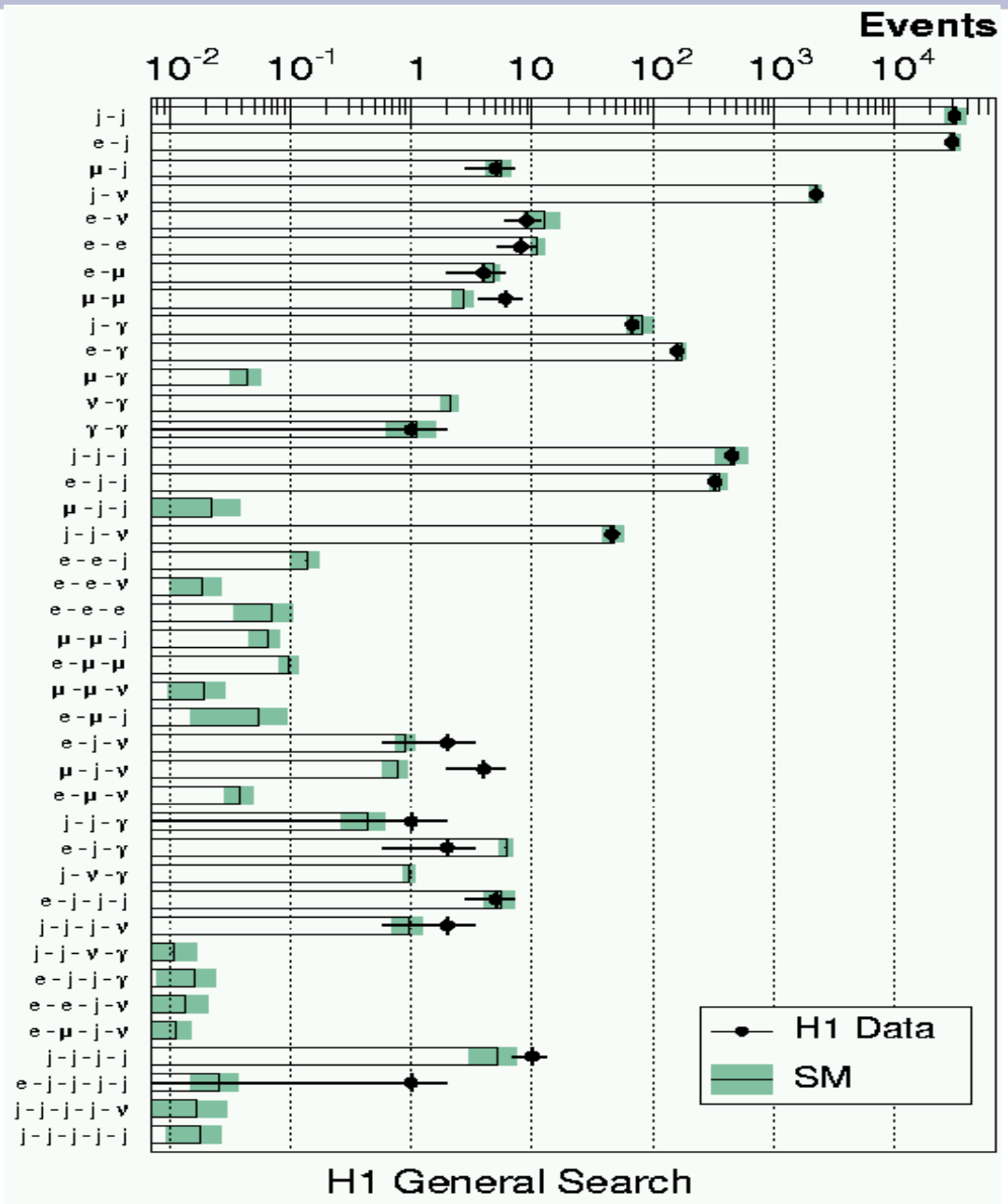
H1 Collab., Phys Lett B602 (2004)14

- study of ALL high p_T final states
  in a single coherent analysis
- model independent:
  → search for deviations

objects: e, μ, γ, jet ,ν

p_T > 20 GeV → define classes

- investigate differential distributions
- peform a global statistical inter-
  pretation → check SM consistency

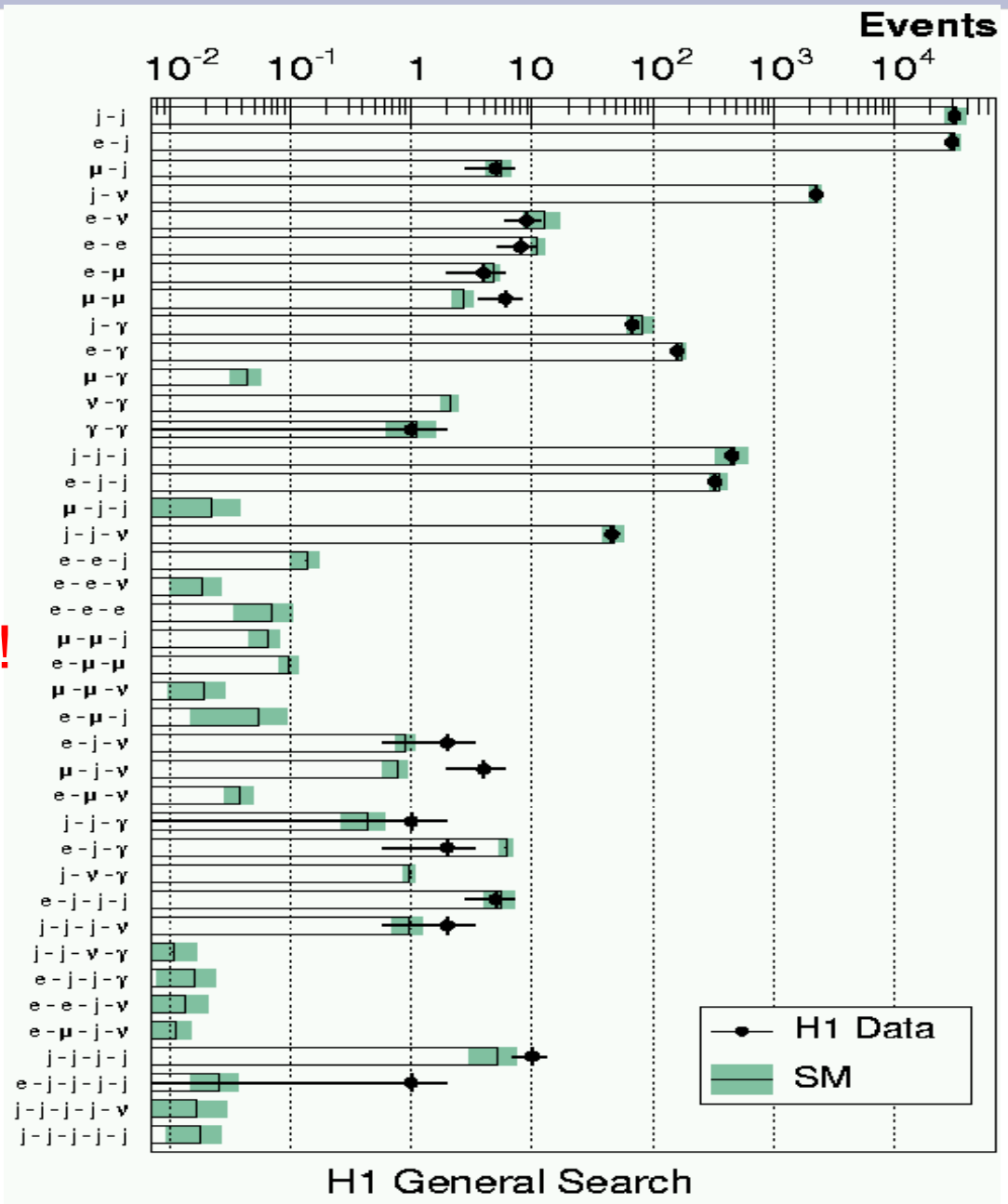


General Search HERA I

H1 Collab., Phys Lett B602 (2004)14

in general:

good agreement with the SM!



General Search HERA I

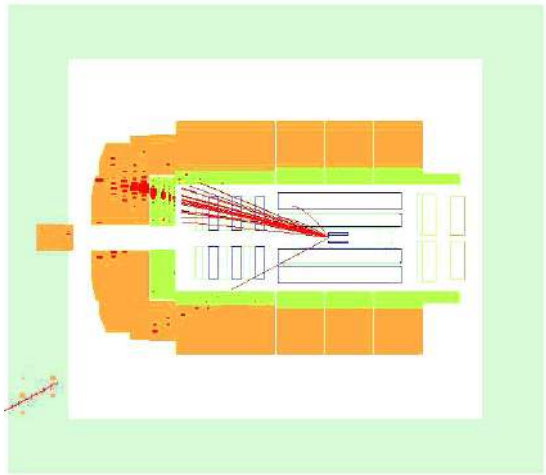
H1 Collab., Phys Lett B602 (2004)14

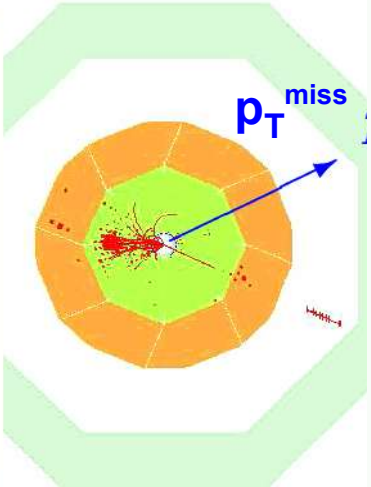
Isolated Lepton + Missing p_T classes:

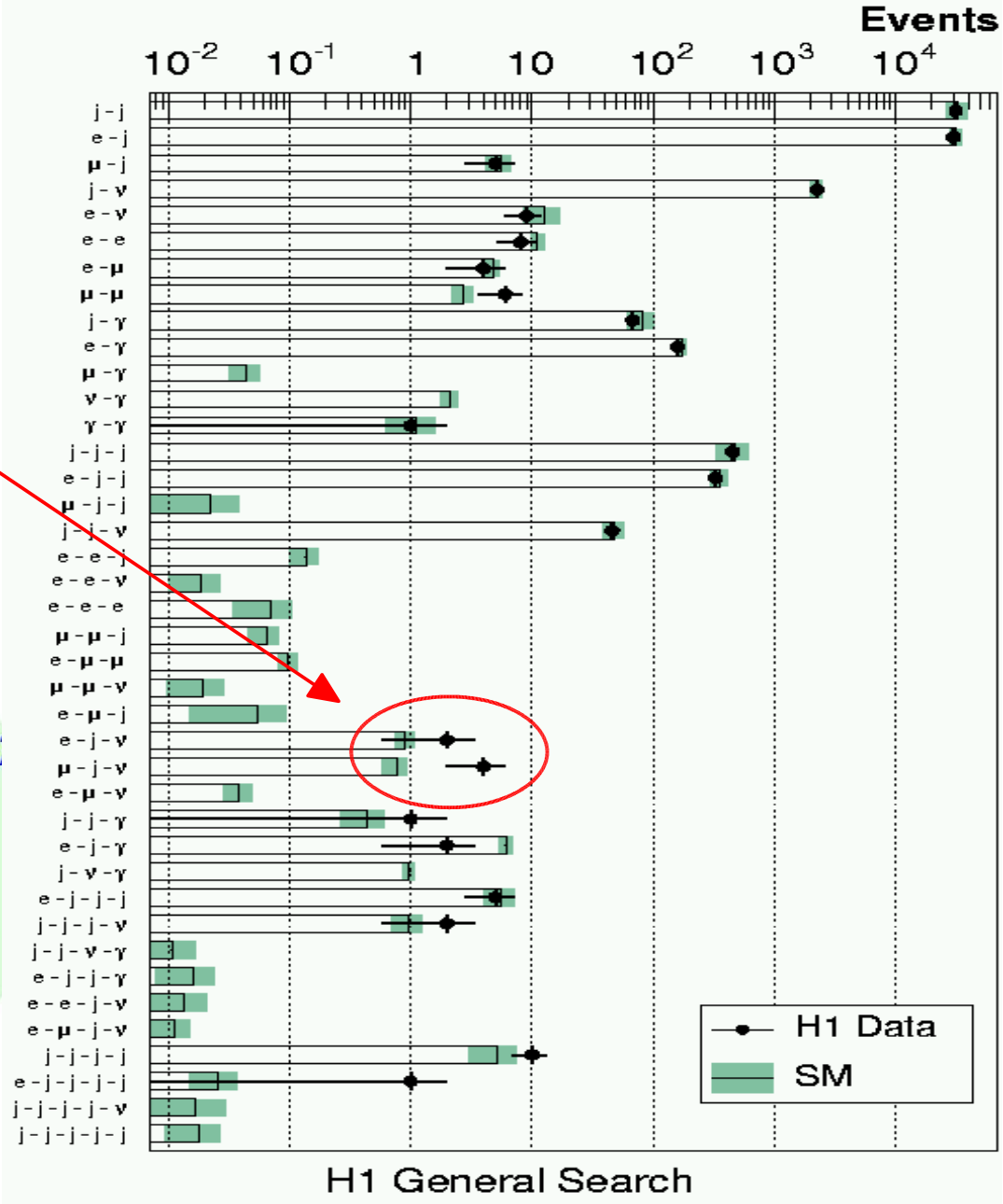
- $ejν$
- $μjν$

SM process W production:

- $ep \to (e)WX \to (e)\ell\nu j$
- SM cross section $\approx 1\ pb$



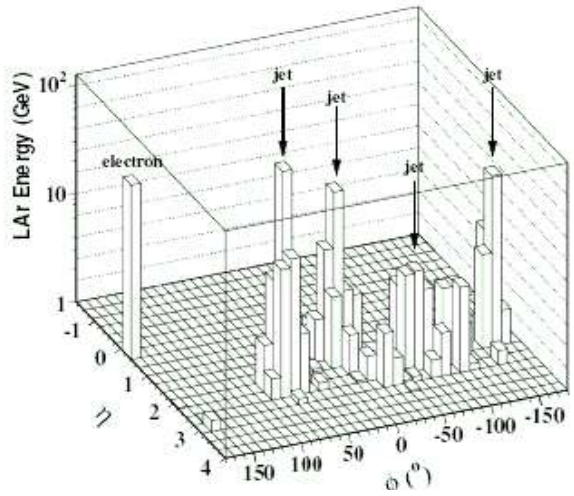




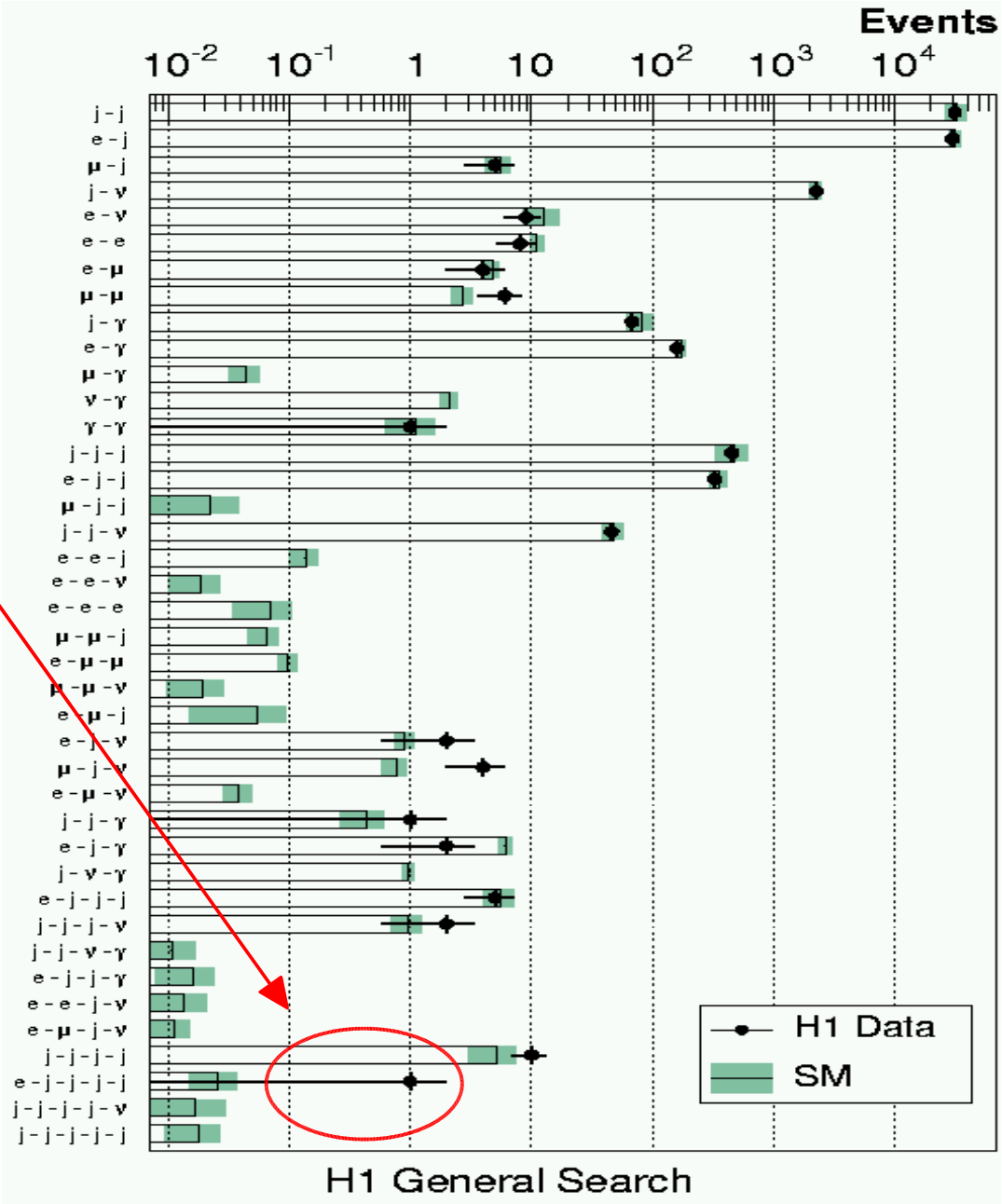
General Search HERA I

H1 Collab., Phys Lett B602 (2004)14

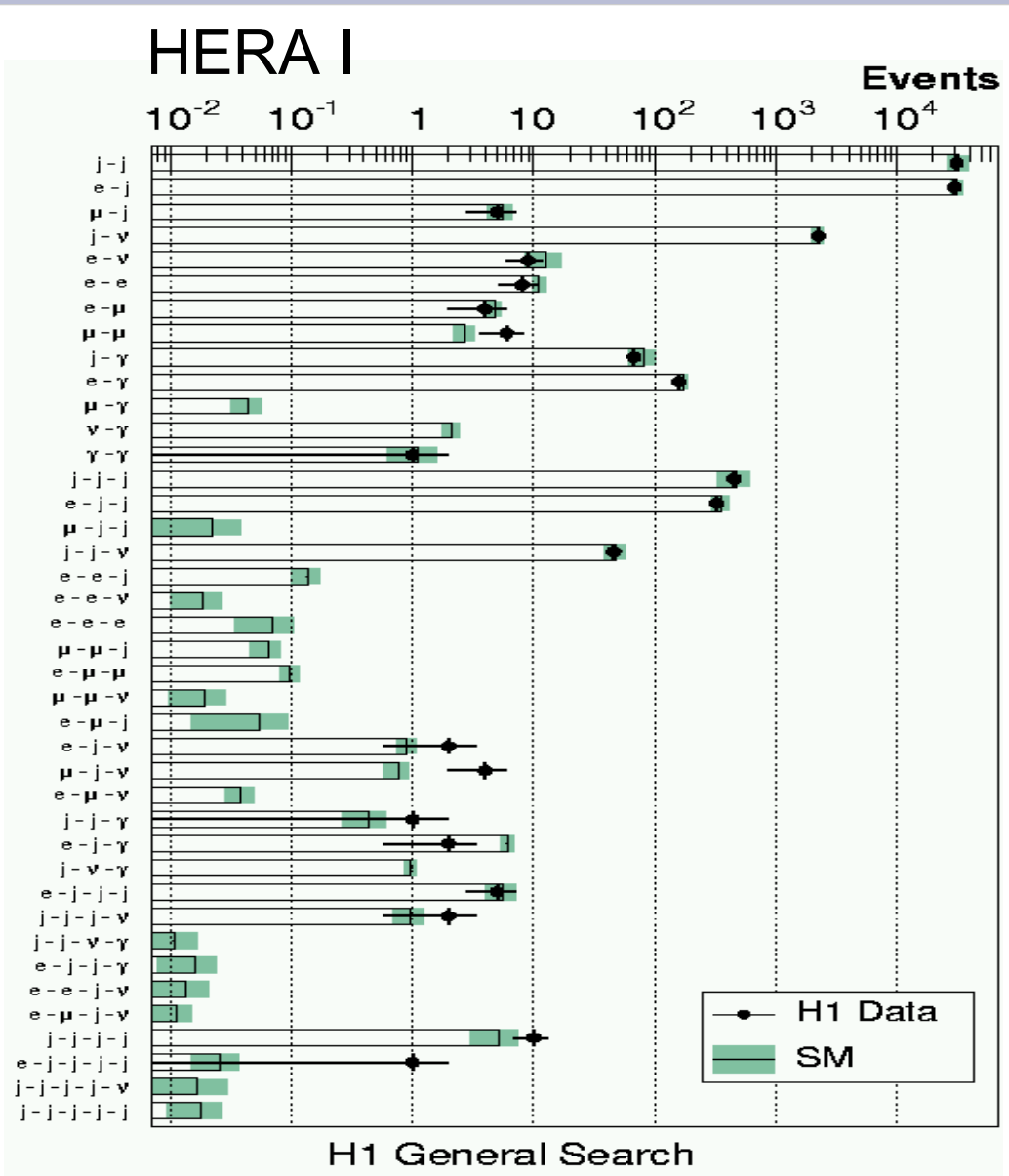
Interesting $ejjjj$ event observed

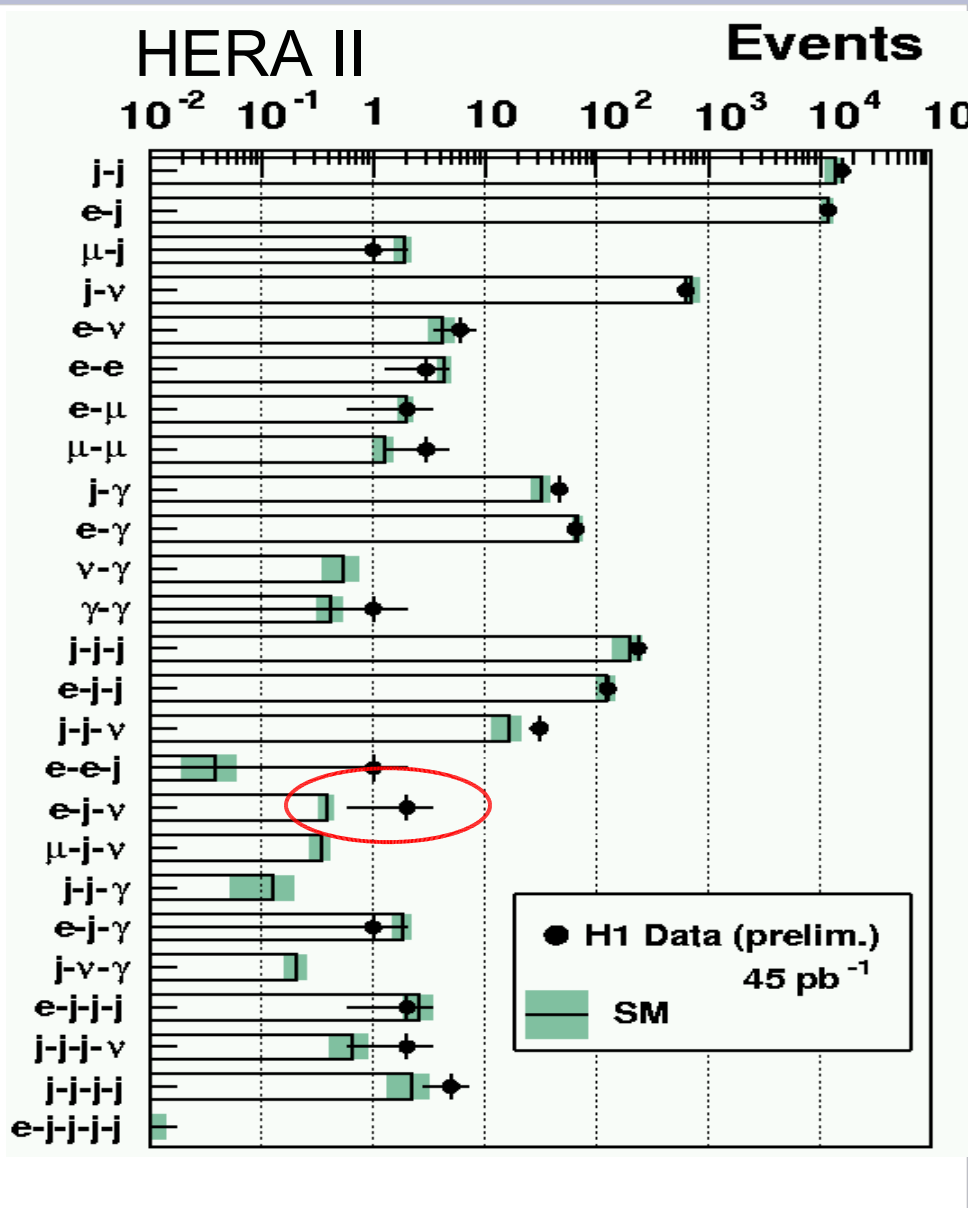


- total invariant mass M_{all} = 262 GeV
- SM exp. from higher order QCD is ~ 0.02 events
- Other (rare SM/BSM) explanations:
  - (anomalous) top quark production
  - WW production, Higgs ?



General Search: Comparision HERA I + II





results consistent but again excess in ejν channel even more pronounced

Statistical Interpretation of General Search

Look in differential distributions with high sensitivity to BSM processes:

- M_{all}: invariant mass of all objects
- $\sum p_T$: scalar sum of tranverse momenta

Quantify possible deviations (deficit or excess)

- new algorithm to find region of largest deviation in distribution:

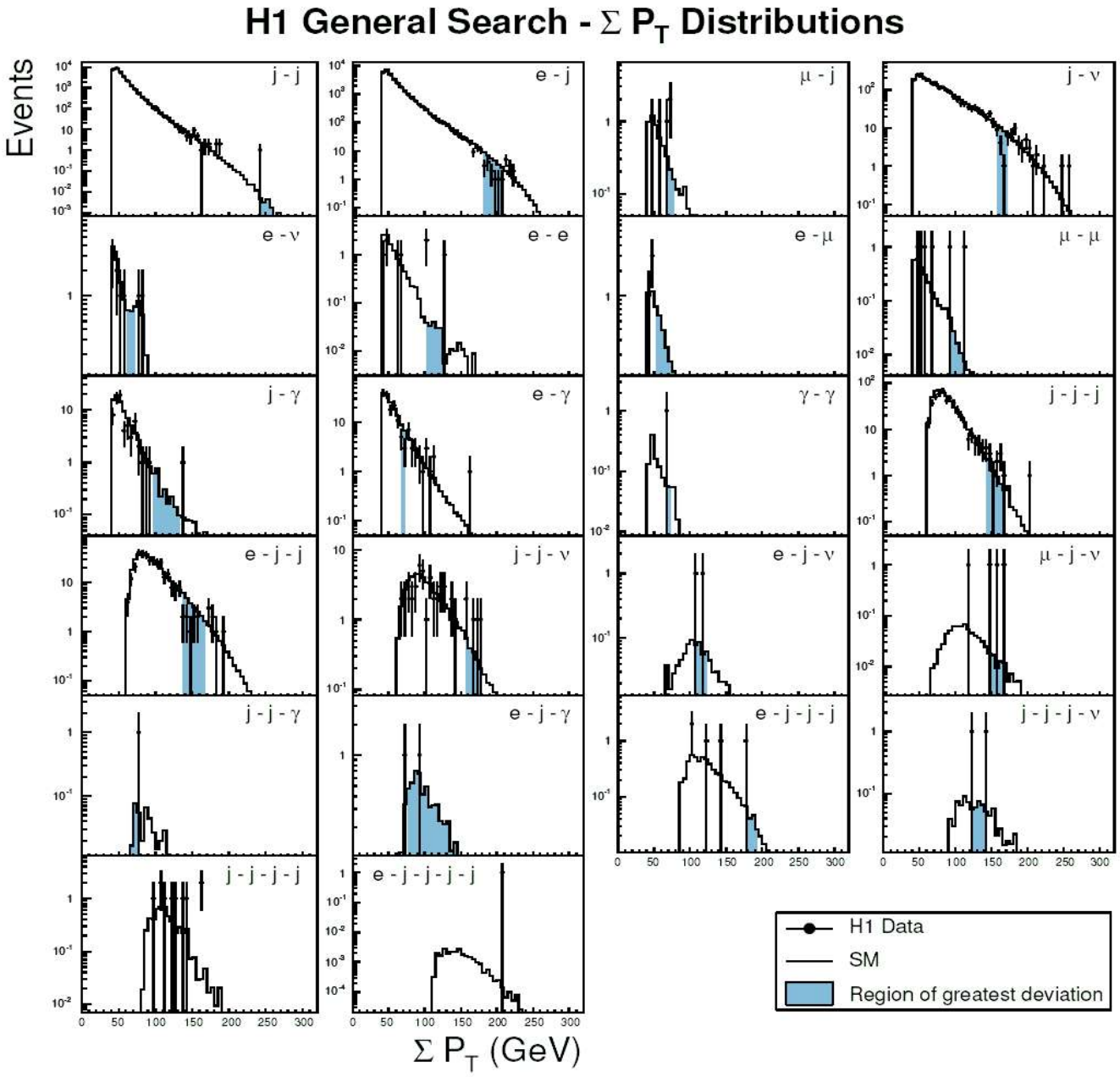
$$p_{\mathrm{region}} = G_{\mathrm{syst}}(\mathrm{BG}) \otimes P_{\mathrm{Poisson}}(N_{obs} \geq N_{SM}, N_{obs} < N_{SM})$$

N_{SM} = number of **expected** events in region

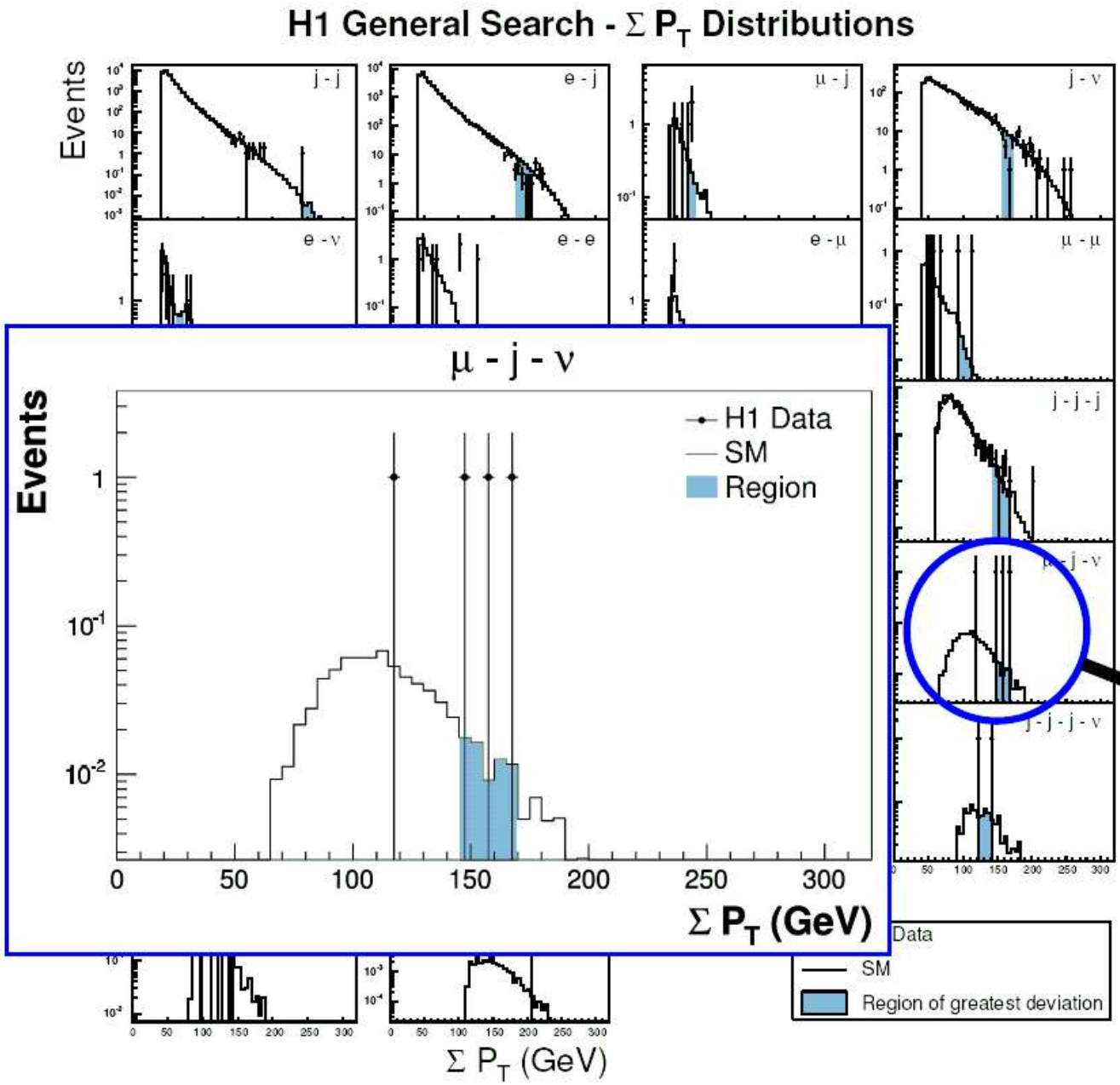
N_{obs} = number of **observed** events in region

- significant deviation: $p_{\mathrm{region}} \ll 1$

Statistical Interpretation of General Search



Statistical Interpretation of General Search



Region of bf largest deviation:

→ excess: 3/0.068±0.029

$\Rightarrow p_{\text{region}} = 7.5 \cdot 10^{-5}$

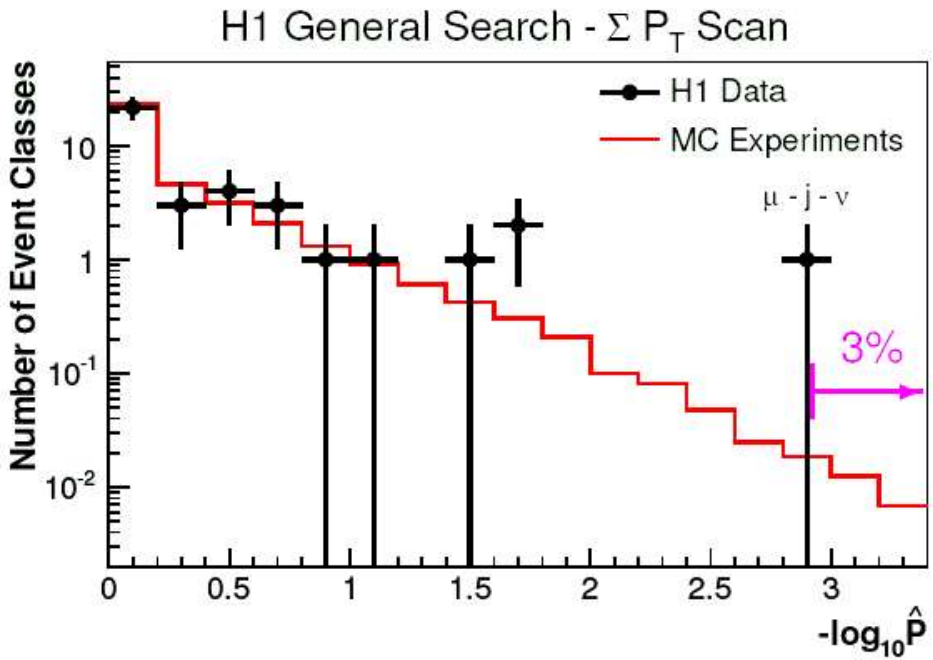
Event Class Probability

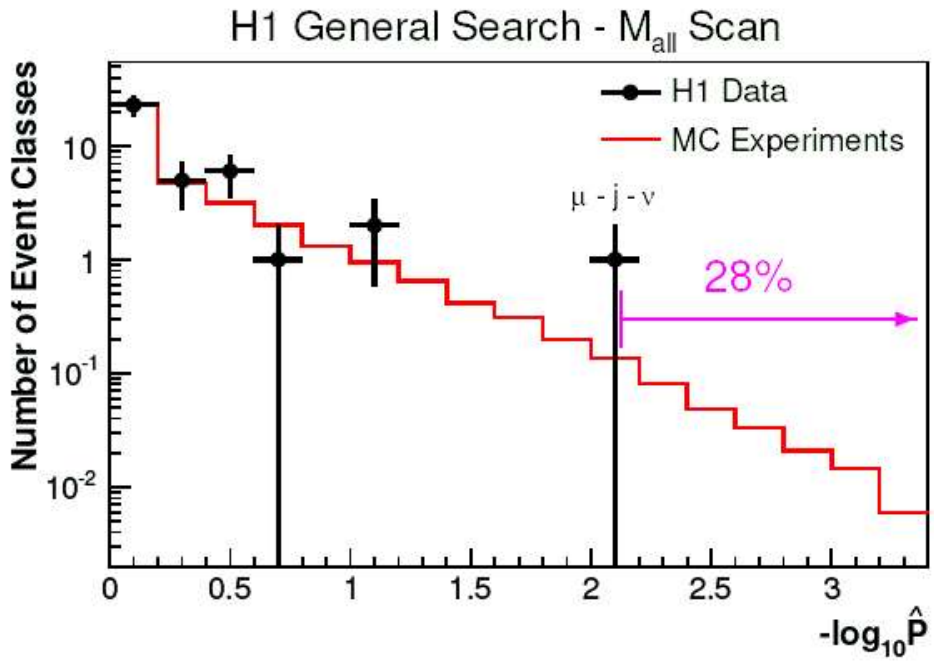
- What is the probability $\hat{P}$ to observe such a deviation $p < p_{\text{region}}$ per class?
- $\hat{P}$ derived from MC experiments

$\Rightarrow$ for this class: $\hat{P} = 0.001$

Event Class Probabilities (HERA I)

Event Class Probabilities $\hat{P}$ derived for all event classes:





$\Rightarrow$ largest deviation from the SM found in the $\mu j \nu$ class

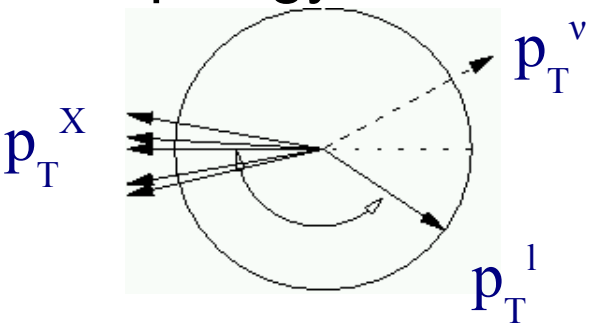
$\hookrightarrow$ "isolated lepton events" + missing p_T

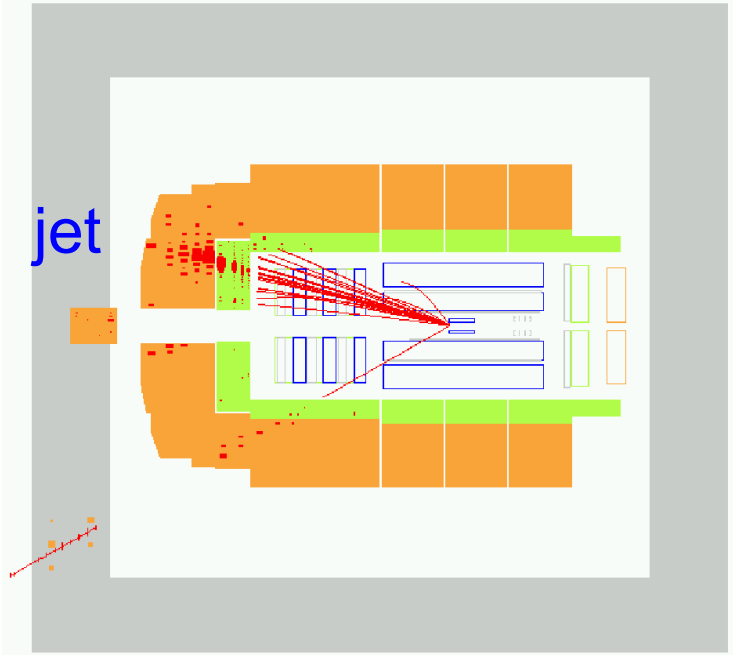
- excess previously reported by H1 (*Phys.Lett.***B** 561 (2003))

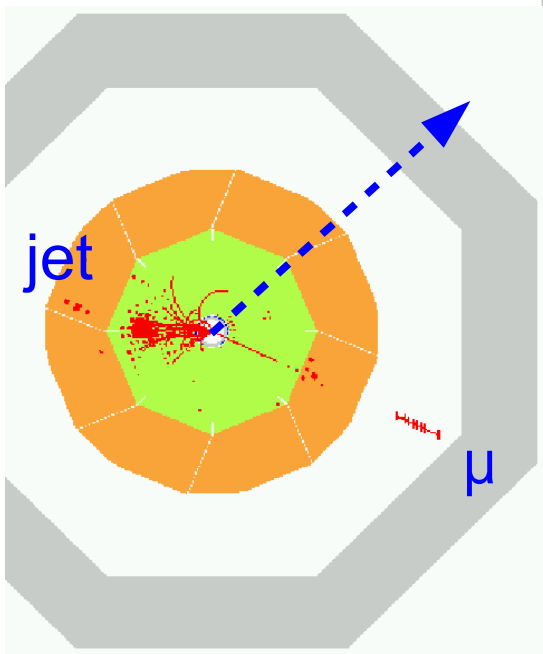
Isolated Lepton Events

H1 Collab., Phys. Lett. B561 (2003) 241; ZEUS Collab. Phys. Lett. B559 (2003) 153

- Topology:







- SM Process:

  W-production (p_T^X small)

  $ep \rightarrow eX\,W \hookrightarrow l\,\nu$

- BSM Process:

  ➔ anomalous single top production

  ➔ RPV SUSY: stop

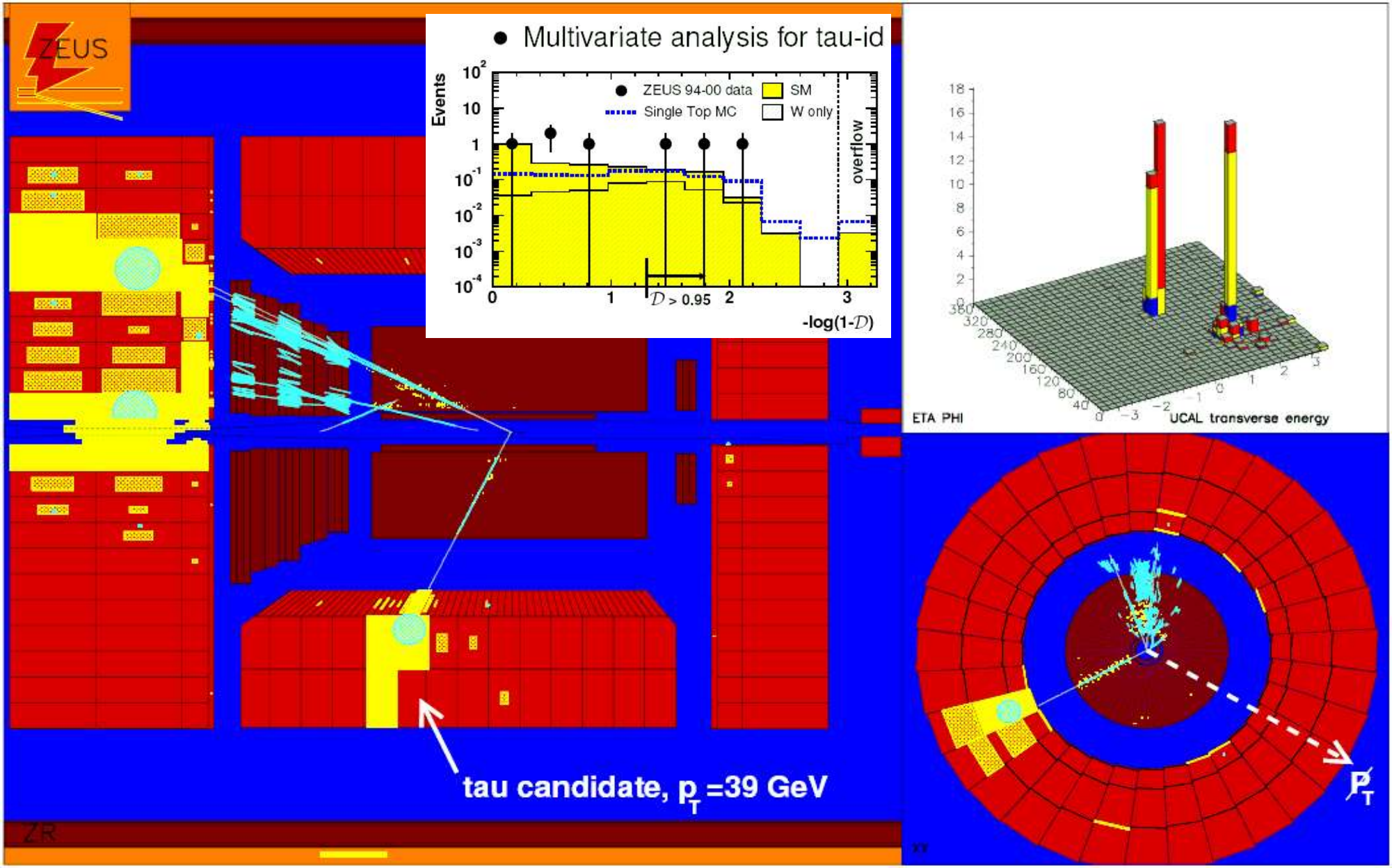
  predict high p_T^X !

HERA I publ. results by H1/ZEUS

H1 1994-2000 $L(e^{\pm}p)=118\ pb^{-1}$	electron obs./exp.	muon obs./exp.	tau (subm. publ.) obs./exp.	W eff. e,mu(tau)
Full Sample	11 / 11.5 ± 1.5	8 / 2.94 ± 0.51	6 / 9.9 $\pm^{2.5}_{3.6}$	~75% (~9%)
p_T^X > 25 GeV	5 / 1.76 ± 0.29	6 / 1.68 ± 0.30	0 / 0.39 ± 0.10	~85% (~50%)

ZEUS 1994-2000 $L(e^{\pm}p)=130\ pb^{-1}$	electron obs./exp.	muon obs./exp.	tau obs./exp.	W eff. e,mu(tau)
Full Sample	24 / 20.6 ± 3.2	12 / 11.9 ± 0.6	3 / 0.40 ± 0.12	~17% (~48%)
p_T^X > 25 GeV	2 / 2.90 ± 0.46	5 / 2.75 ± 0.21	2 / 0.20 ± 0.05	~50% (~50%)

Isolated Tau Events

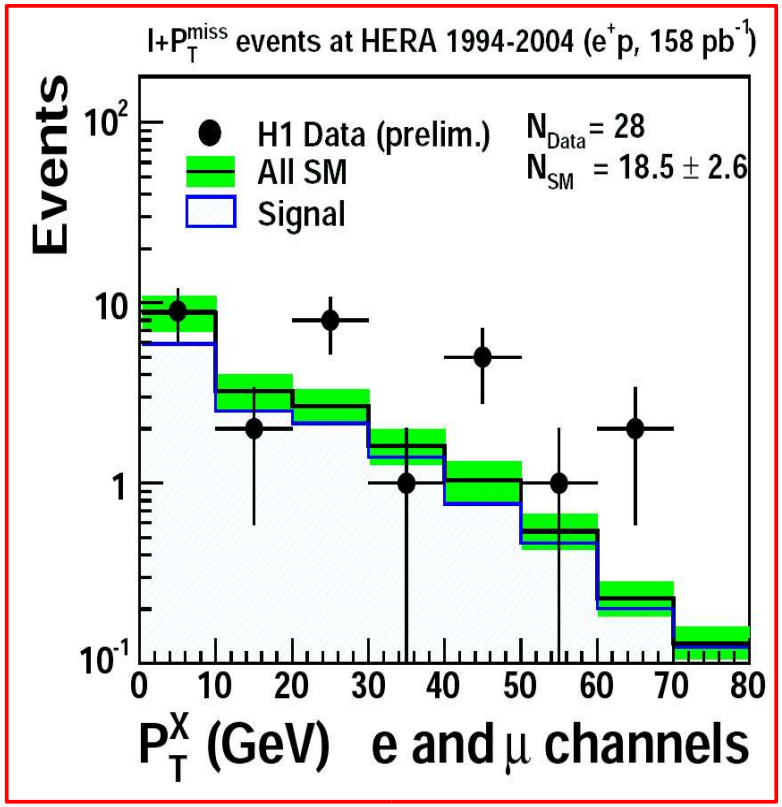


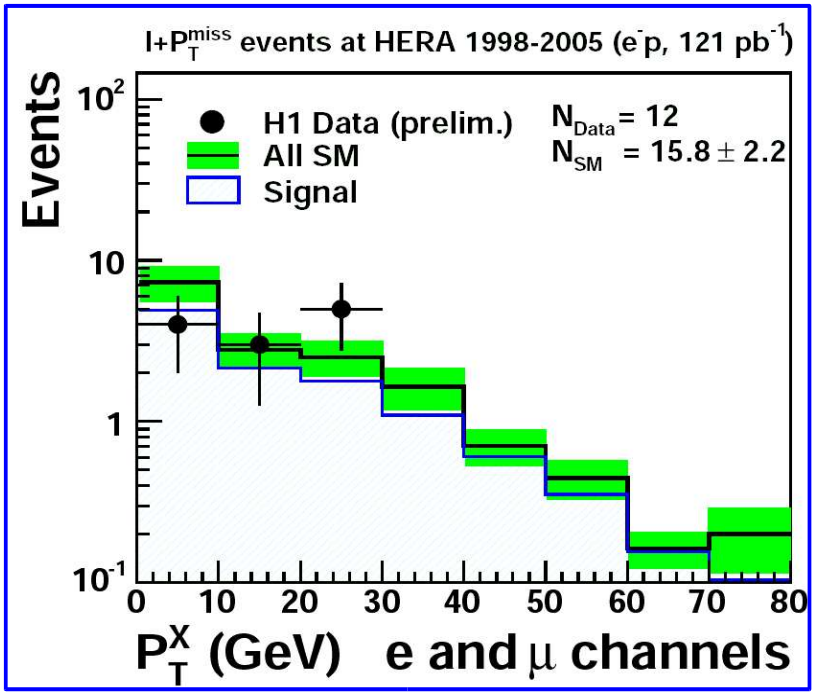
Isolated Lepton Events HERA II

e^+p scattering (H1: 2003-2004)

H1 2003-2004 $L(e^+p)=53\ pb^{-1}$	electron obs./exp.	muon obs./exp.	total obs./exp.
Full Sample	9 / 4.75 ± 0.76	1 / 1.33 ± 0.19	10 / 6.08 ± 0.92
$p_T^X > 25$ GeV	5 / 0.84 ± 0.19	0 / 0.85 ± 0.13	5 / 1.69 ± 0.28

excess for $p_T^X > 25$ GeV again in positron channel !





e^-p scattering (H1: 2005 + (1998/99))

H1 1998-2005 $L(e^-p)=121\ pb^{-1}$	electron obs./exp.	muon obs./exp.	total obs./exp.
Full Sample	11 / 12.6 ± 1.8	1 / 3.3 ± 0.5	12 / 15.8 ± 2.2
$p_T^X > 25$ GeV	2 / 2.4 ± 0.5	0 / 2.0 ± 0.3	2 / 4.4 ± 0.7

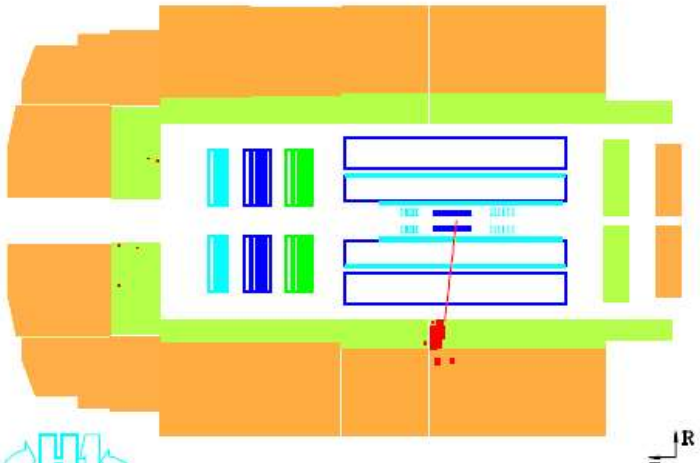
no excess at high p_T^X in e^-p

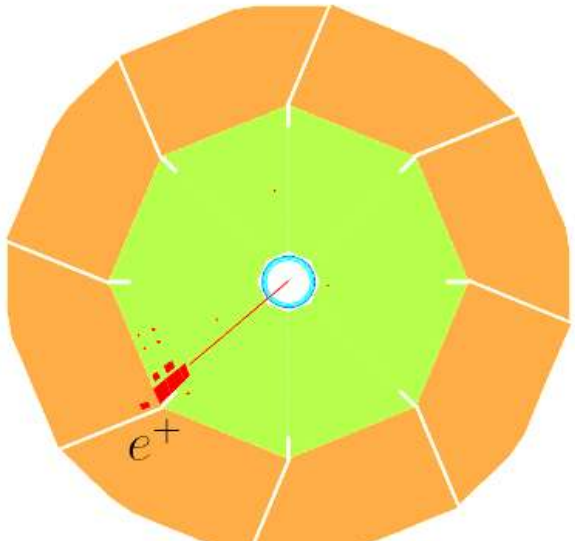
HERA II Isolated Electrons Events

$P_T^e = 47$ **GeV**, $P_T^{miss} = 47$ **GeV**

"quasi" elastic:

ep → (eN*) W
W → eν

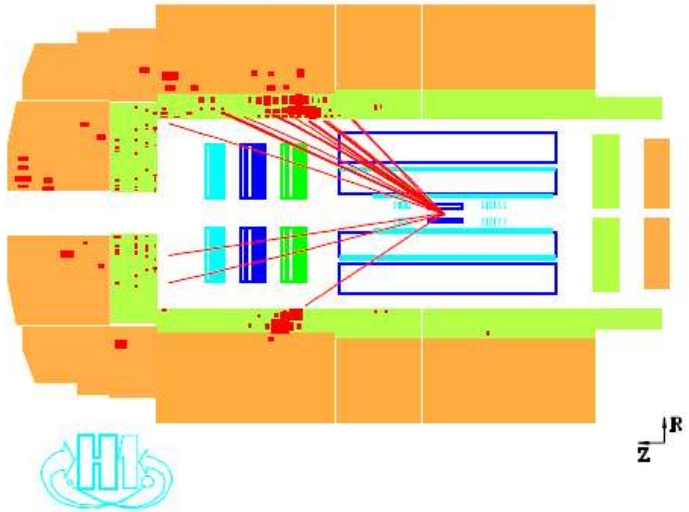


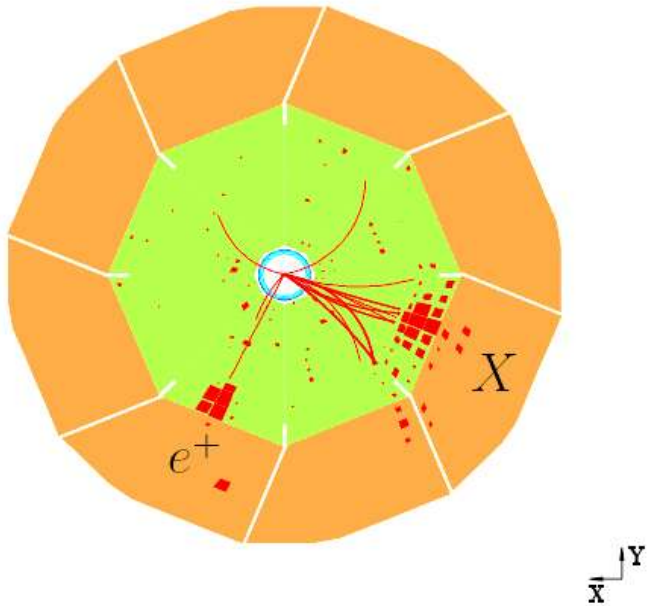


$P_T^e = 37$ **GeV**, $P_T^{miss} = 44$ **GeV**, $P_T^X = 29$ **GeV**

inelastic:

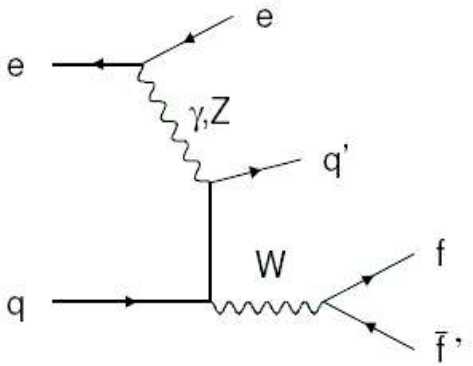
ep → (e) X W
W → eν

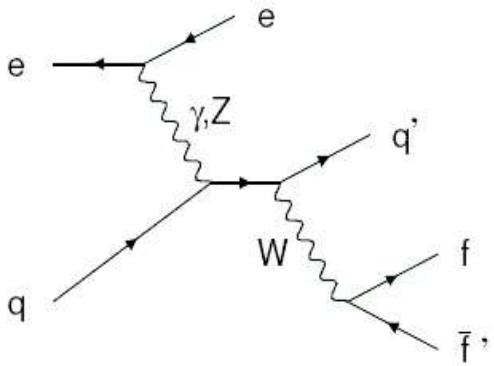




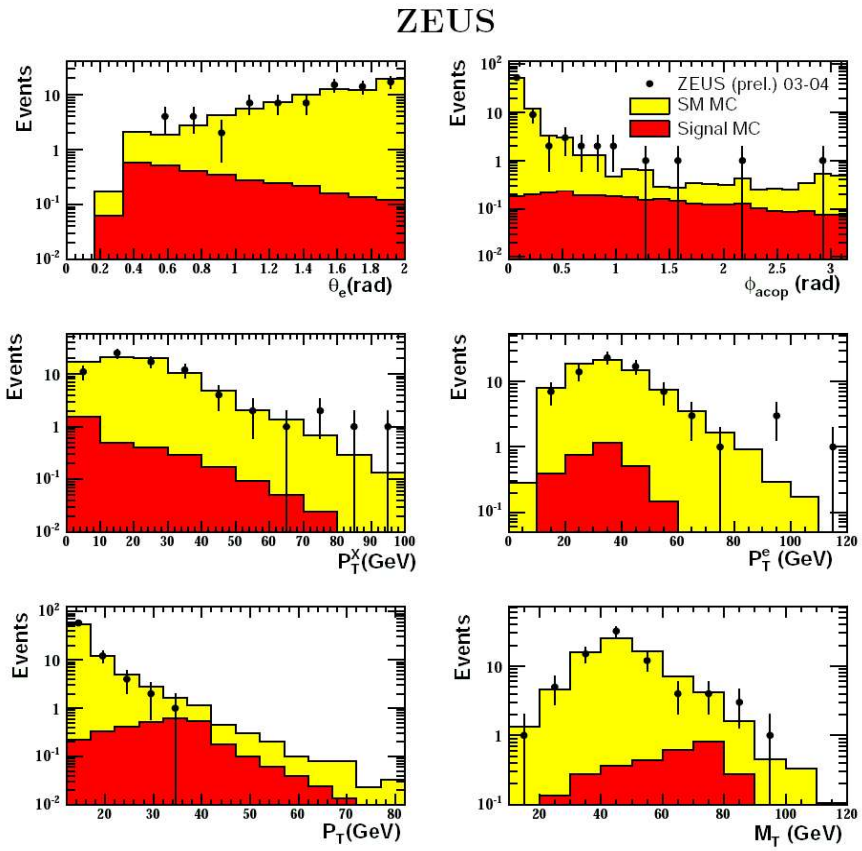
Study of W-production (ZEUS)

- analysis of early 2003/04 data
- re-analysis of 1999/00 data
- aim for high W purity + efficiency
- total luminosity 106 pb^{-1}





electron channel:



only W electron decay channel:

Isolated e candidates	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
ZEUS (prel.) 99-00 e^+p (66 pb^{-1})	$1/1.04 \pm 0.11(57\%)$	$1/0.92 \pm 0.09(79\%)$
ZEUS (prel.) 03-04 e^+p (40 pb^{-1})	$0/0.46 \pm 0.10(64\%)$	$0/0.58^{+0.08}_{-0.09}(76\%)$

results are consistent with SM expectation

Isolated Leptons High p_T^X Summary

H1 1994-2005	electron obs./exp.	muon obs./exp.	tau obs./exp.
L(e^+p)=158 pb^{-1}	9 / 2.3 ± 0.4	6 / 2.3 ± 0.4	0 / 0.39 ± 0.10 *
L(e^-p)=121 pb^{-1}	2 / 2.4 ± 0.5	0 / 2.0 ± 0.3	* = 118pb^{-1}

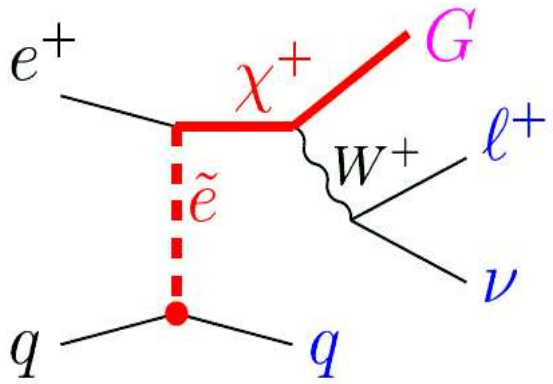
H1: excess in e^+p data only

ZEUS 1994-2004	electron obs./exp.	muon obs./exp.	tau obs./exp.
L(e^+p)=106 pb^{-1}	1 / 1.5 ± ~0.3		
L($e^\pm p$)=130 pb^{-1}		5 / 2.75 ± 0.2	2 / 0.2 ± 0.05

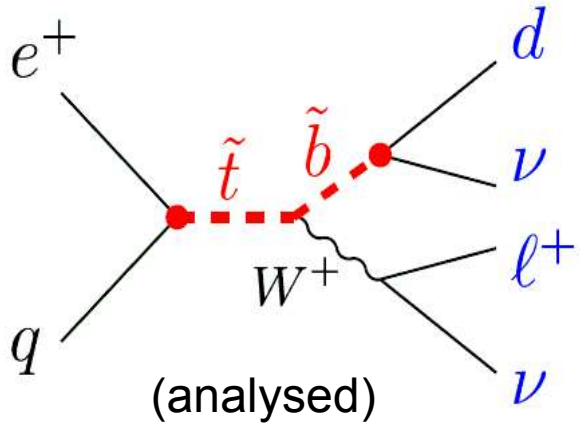
ZEUS: for W hypothesis excess in tau channel (10x expectation) inconsistent with electron and muon rates

Interpretation of Isolated Leptons

RPV SUSY (GMSB): chargino decay

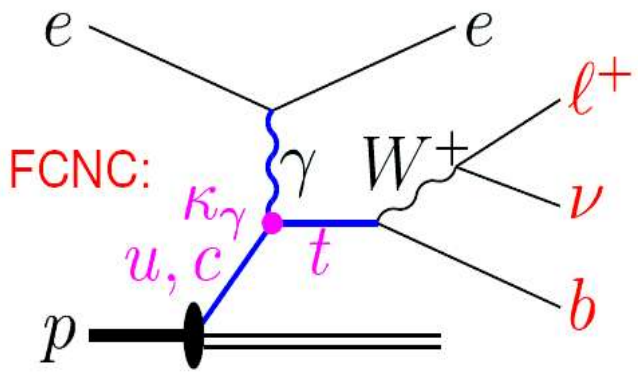


RPV SUSY: light sbottom scenario



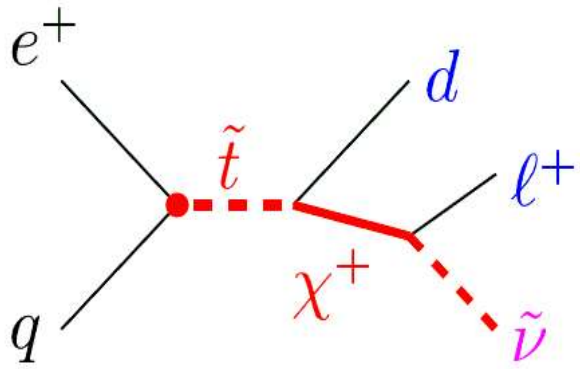
(analysed)

Anomalous single top production:



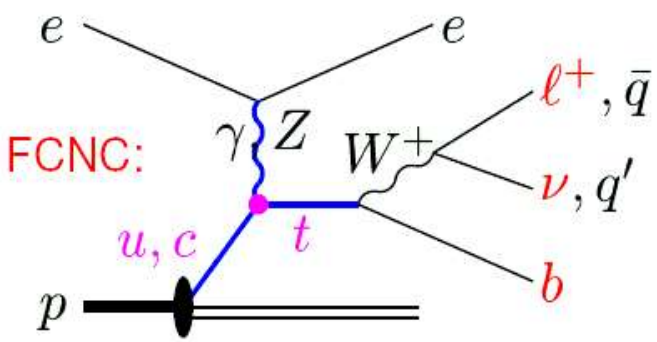
(analysed)

RPV SUSY: light long-lived neutrino

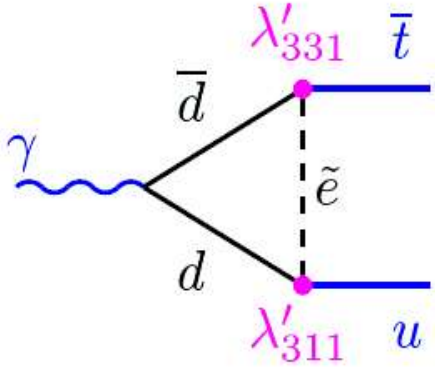


Anomalous Single Top Production

- Production of single top quarks at HERA via anomalous magnetic coupling κ_γ
  - Search for: $eq \to eXt^+$



sensitive to new physics: e.g. SUSY



$\to$ isolated lepton topology (excess at high p_T^X !) / high E_T 3-jet events

- Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \sum_{U=u,c} i\frac{ee_U}{\Lambda}\bar{t}\,\sigma_{\mu\nu}q^\nu\,\kappa_{\gamma,U}\,U\,A^\mu \quad + \quad \frac{g}{2\cos\Theta_W}\bar{t}\,\gamma_\mu v_{Z,U}\,U\,Z^\mu \quad + \quad \ldots$$

  - $\kappa_{\gamma,U}$ is the anomalous magnetic coupling
  - $v_{Z,U}$ is the anomalous Z boson vector coupling

T.Han and J.L.Hewett PR D60 (1999)

Theoretical Model	BR($t \to cV$)
Standard Model	$10^{-13} - 10^{-12}$
Two Higgs Doublet Models	$10^{-9} - 10^{-8}$
Supersymmetry	$10^{-9} - 10^{-8}$
Multi Higgs Doublet Models	$10^{-6} - 10^{-5}$
Singlet Quarks	10^{-2}
Dynamical EWSB	10^{-2}

Top Quark Selections

(H1 *Eur.Phys.J.C33* (2004), ZEUS *Phys.Lett.***B** 559 (2003))

H1 Selection

Analysis Methods

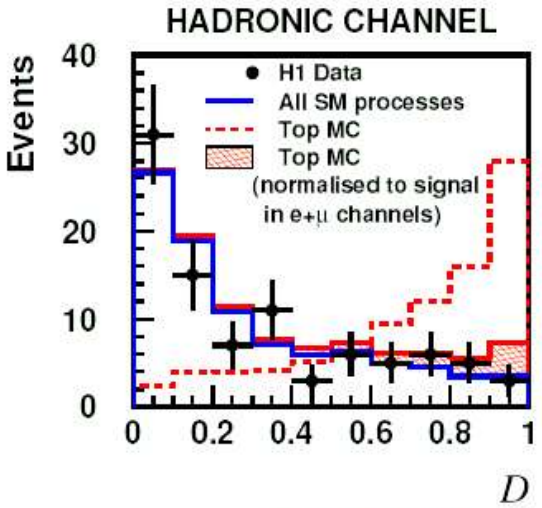
- cut based / multivariate

Variables:

- e, μ decay: p_T^{b}, $M_{\ell\nu b}$, $\cos\Theta_W^{\ell}$

  $\rightarrow$ 5 events / 1.31$\pm$0.22 expected

- hadronic decay: p_T^{b}, M_{jets}, $\cos\Theta_W^{\bar{q}}$



QCD background!

hadr. channel consistent with SM exp.

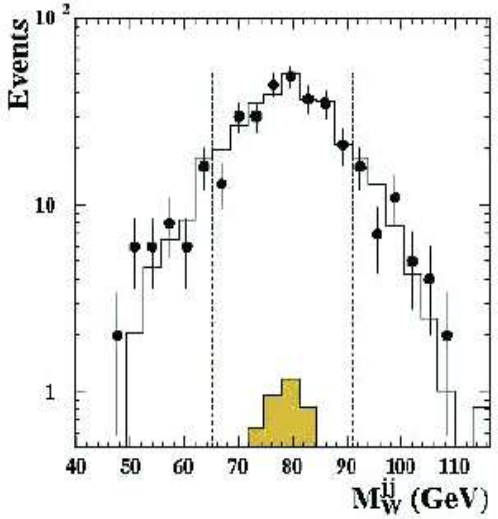
ZEUS Selection

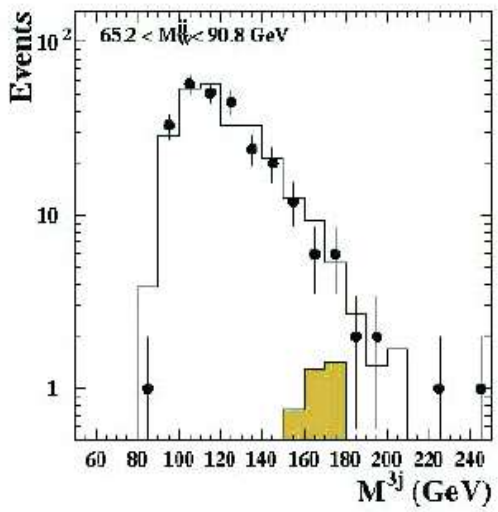
e, μ decay

- isolated leptons $p_T^X > 40$ GeV

hadronic decay

- $p_T^{\mathrm{jet}(1,2,3)} > 40, 25, 24$
- W-, t mass cuts





$14/17.6^{+2.5}_{-1.5}$ consistent with SM expextation

Anomalous Single Top Production

H1 Collab., Eur. Phys. J. C33 (2004) 9; ZEUS Collab. Physics Letters B 559 (2003) 153

Top Cross Section Limits

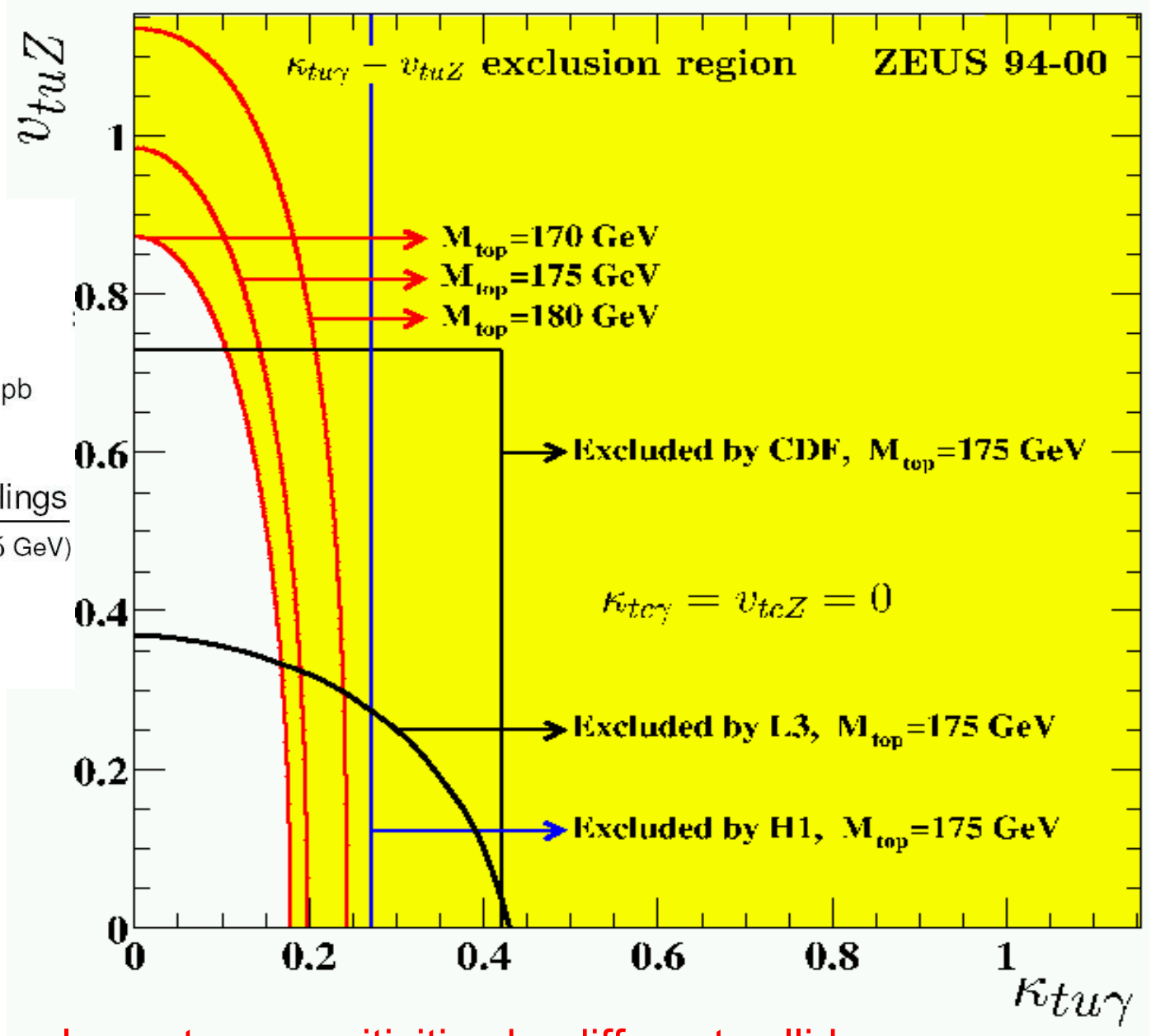
($\sqrt{s} = 318$ GeV, CL 95%):

- H1: $\sigma(ep \to etX) < 0.55$ pb
- ZEUS: $\sigma(ep \to etX) < 0.225$ pb

Conversion to anomalous couplings

(NLO: Belyaev and Kidonakis, $m_t = 175$ GeV)

- H1: $\kappa_{tu\gamma} < 0.27$
- ZEUS: $\kappa_{tu\gamma} < 0.174$



→ complementary sensitivities by different colliders

Anomalous Single Top Production

H1 Collab., Eur. Phys. J. C33 (2004) 9; ZEUS Collab. Physics Letters B 559 (2003) 153

Top Cross Section Limits

($\sqrt{s} = 318$ GeV, CL 95%):

- H1: $\sigma(ep \to etX) < 0.55$ pb
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Conversion to anomalous couplings

(NLO: Belyaev and Kidonakis, $m_t = 175$ GeV)

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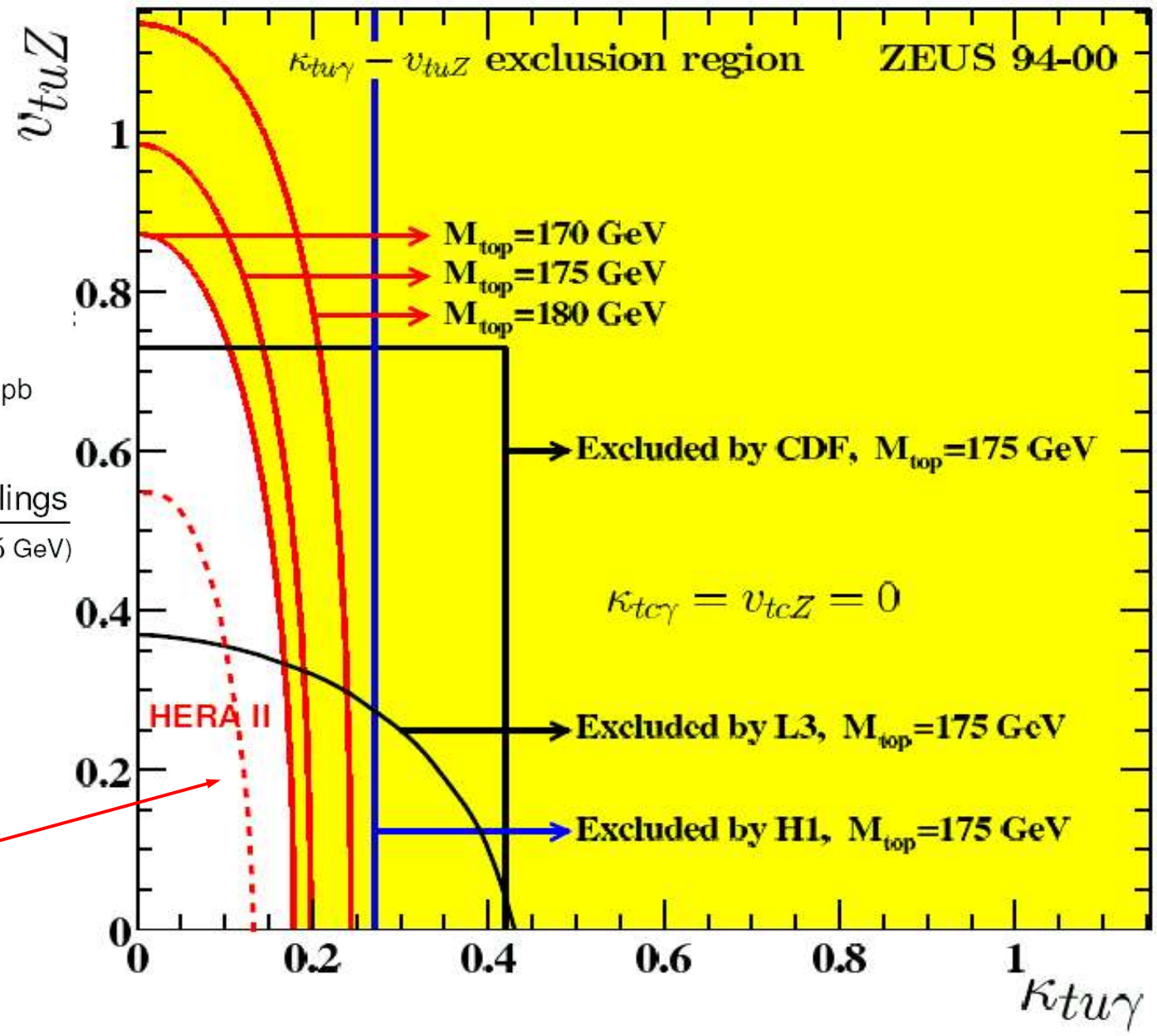
- ZEUS: $\kappa_{tu\gamma} < 0.174$

HERA II perspective

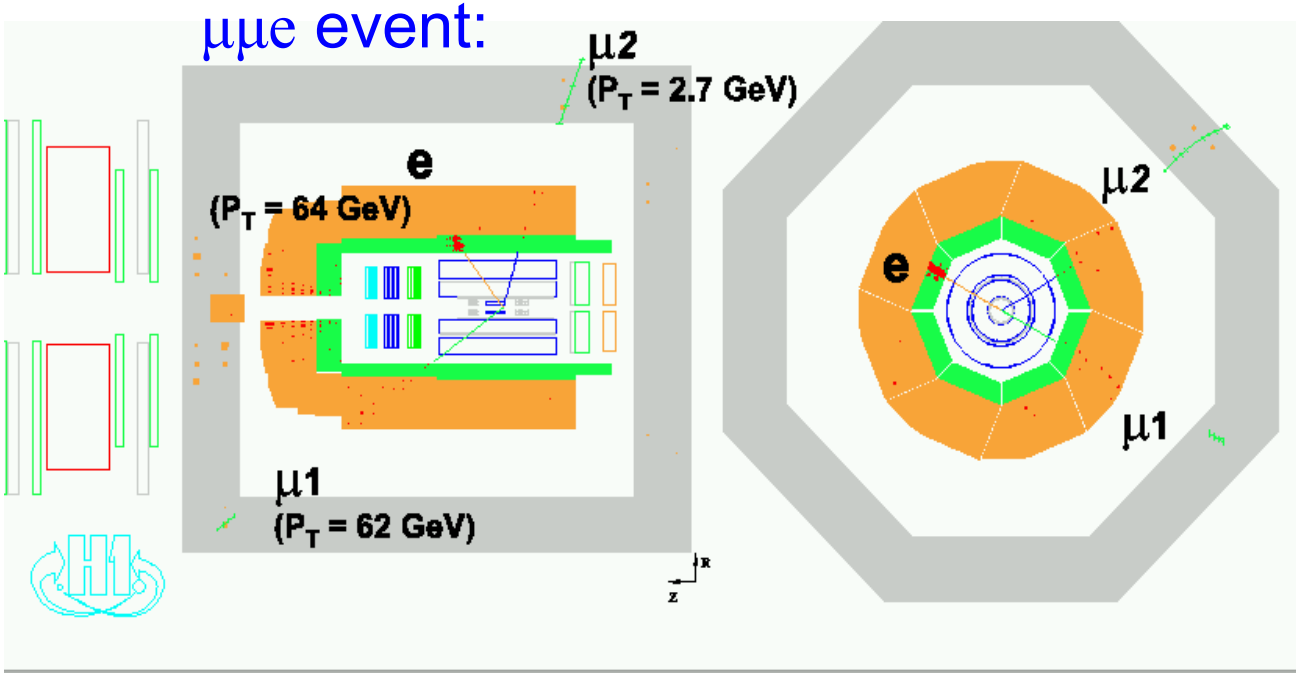


Multi-Lepton Events

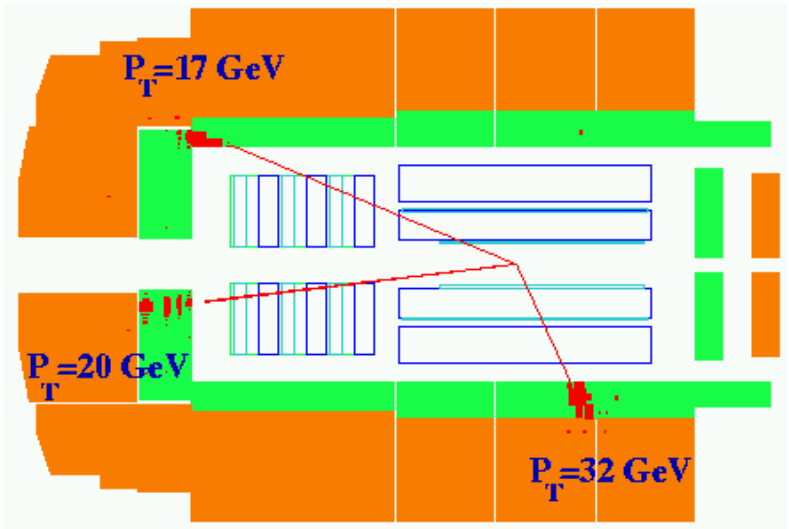
Study events with 2 or 3 isolated leptons

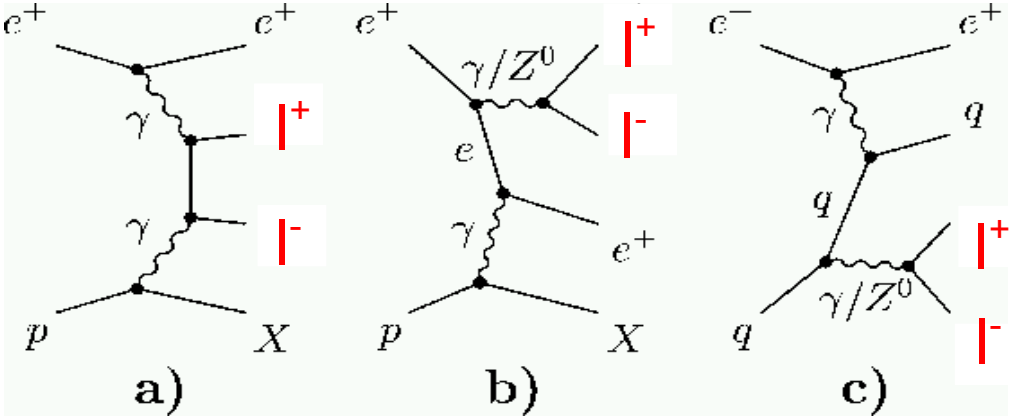
(electron, muon, tau)

μμe event:



eee event:





"two photon" (dominant)

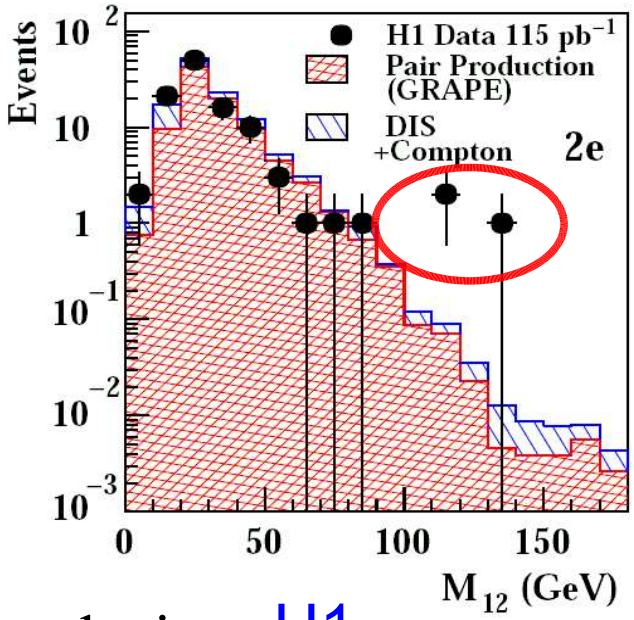
"Cabibo-Parisi"

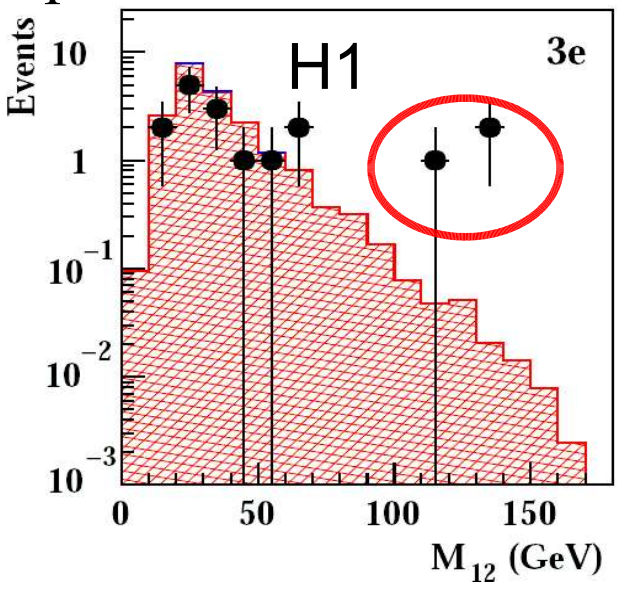
"Drell-Yan"

Multi-Electrons HERA I

H1 Collab., Eur Phys J C31 (2003) 17

1996-2000 $e^{\pm}p$





Full Analysis H1

H1(L=115pb^{-1})	data	SM
ee	108	117.1 ± 8.6
eee	17	20.3 ± 2.1

good agreement with SM

M_{12}>100 GeV:

H1 (L=163pb^{-1})	data	SM
ee	3	0.30 ± 0.04
eee	3	0.23 ± 0.04

⇒ excess at high invariant mass

ZEUS

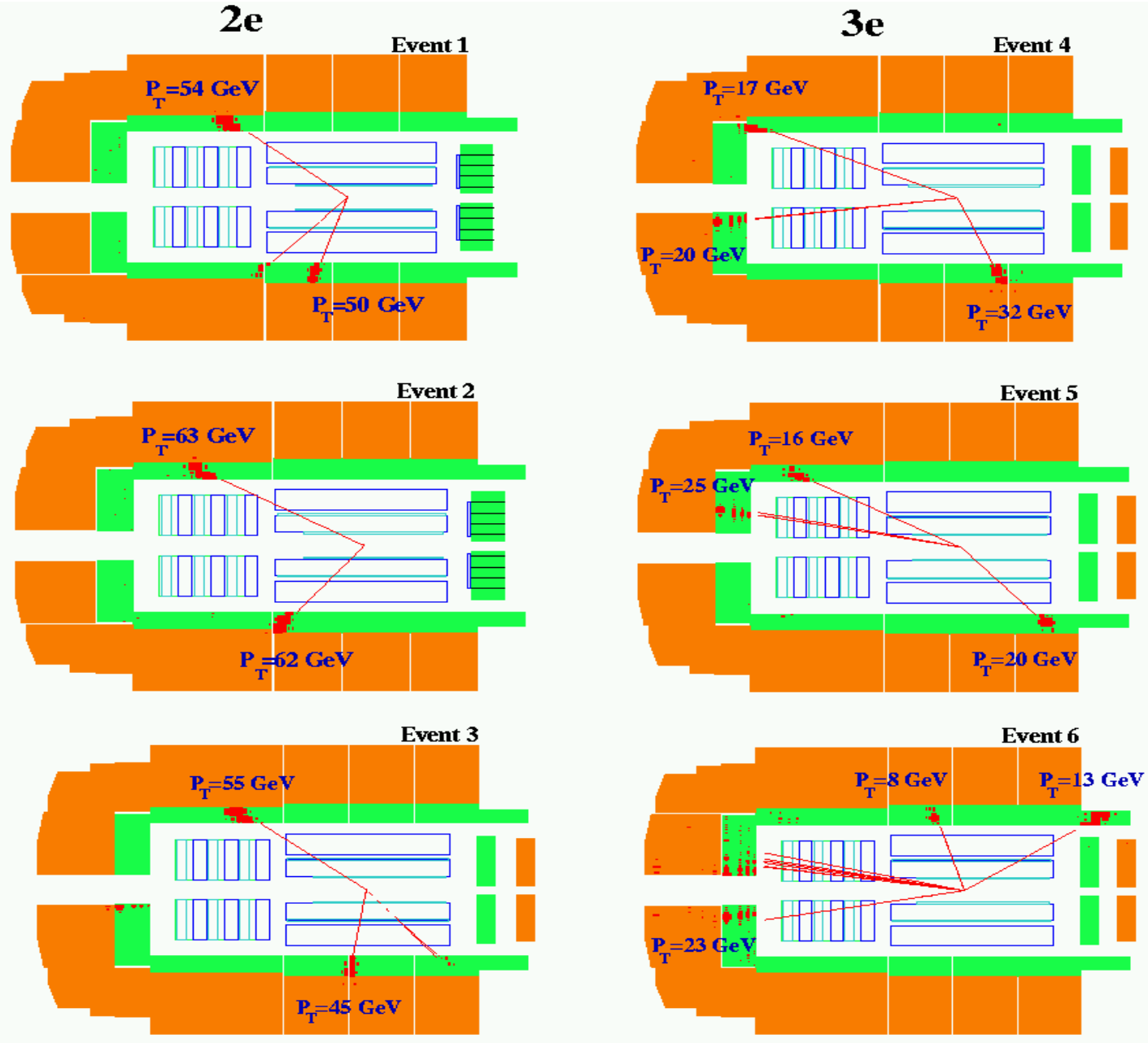
ZEUS(L=130pb^{-1})	data	SM
ee	191	213.9 ± 3.9
eee	26	34.7 ± 0.5

good agreement with SM

ZEUS(L=130pb^{-1})	data	SM
ee	2	0.8 ± 0.1
eee	0	0.4 ± 0.04

⇒ consistent with SM

Multi-Electrons Events



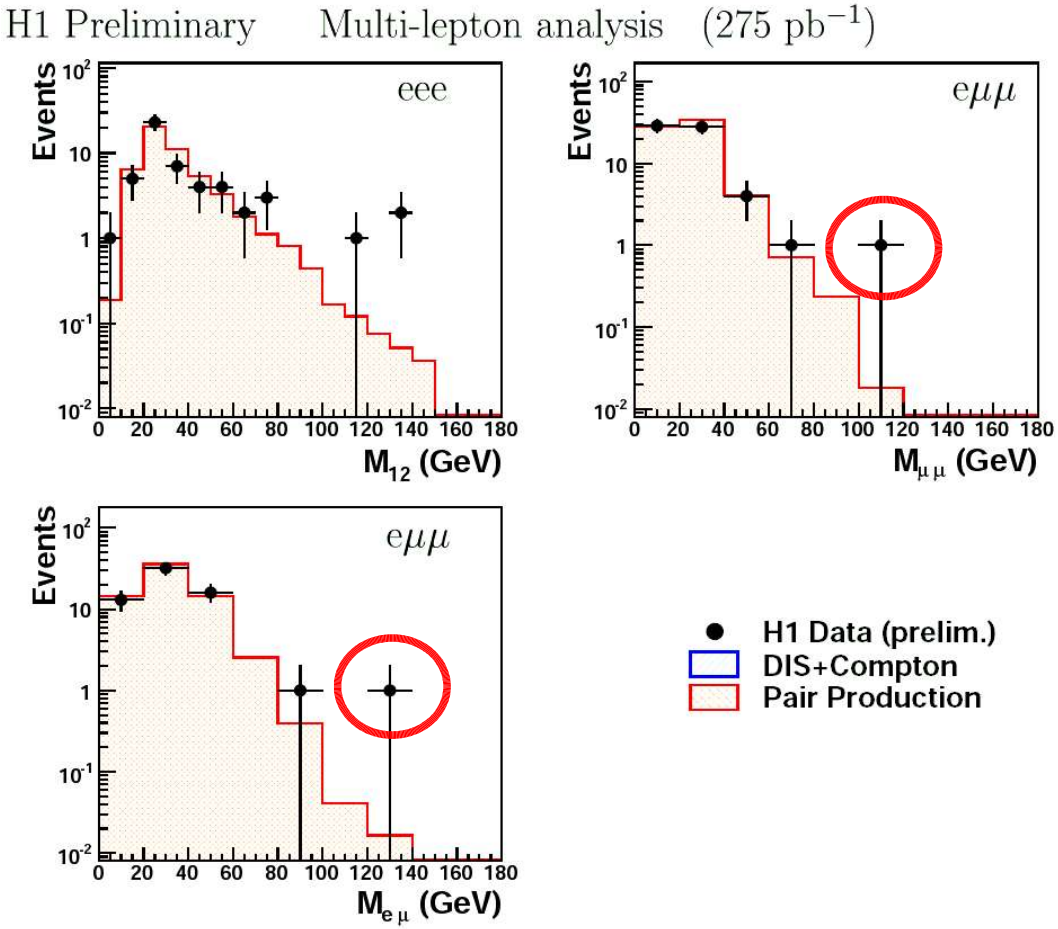
HERA Multi-Leptons HERA I + II

H1 Preliminary 275 pb^{-1} (1994–2005)

Selection	Data	SM	Pair Production	NC-DIS + Compton
ee	266	261 ± 37	217 ± 23	44 ± 22
$\mu\mu$	113	112 ± 21	112 ± 21	—
eμ	137	136 ± 21	83 ± 6.5	53 ± 16
eee	52	52 ± 6	52 ± 6	—
e$\mu\mu$	63	67 ± 10.5	67 ± 10.5	—

H1 Preliminary 275 pb^{-1} (1994–2005)

	Selection	Data	SM	Pair Production
	e^+p collisions (156 pb^{-1})			
e^+p	ee M_{12} >100 GeV	3	0.44 ± 0.10	0.29 ± 0.09
	$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.03 ± 0.02	0.03 ± 0.02
	eμ $M_{e\mu}$ >100 GeV	0	0.29 ± 0.03	0.29 ± 0.03
	eee M_{12} >100 GeV	3	0.29 ± 0.06	0.29 ± 0.06
	e$\mu\mu$ $M_{e\mu}$ >100 GeV	1	0.04 ± 0.01	0.04 ± 0.01
	e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	1	0.015 ± 0.007	0.015 ± 0.007
	e^-p collisions (119 pb^{-1})			
e^-p	ee M_{12} >100 GeV	0	0.42 ± 0.11	0.23 ± 0.06
	$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.02 ± 0.02	0.02 ± 0.02
	eμ $M_{e\mu}$ >100 GeV	0	0.24 ± 0.04	0.24 ± 0.04
	eee M_{12} >100 GeV	0	0.18 ± 0.05	0.18 ± 0.05
	e$\mu\mu$ $M_{e\mu}$ >100 GeV	0	0.03 ± 0.01	0.03 ± 0.01
	e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.004 ± 0.003	0.004 ± 0.003



⇒ two more interesting events at high mass in HERA II

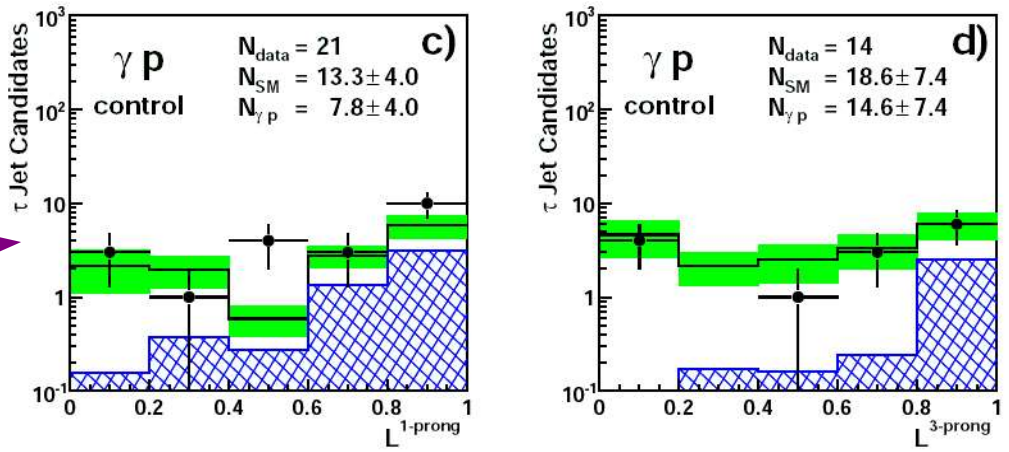
- excess observed only in e^+p data
- events not peaked in mass (resolution 2-5 GeV)

Tau Pair Production

H1: submitted to Eur. Phys. J. C

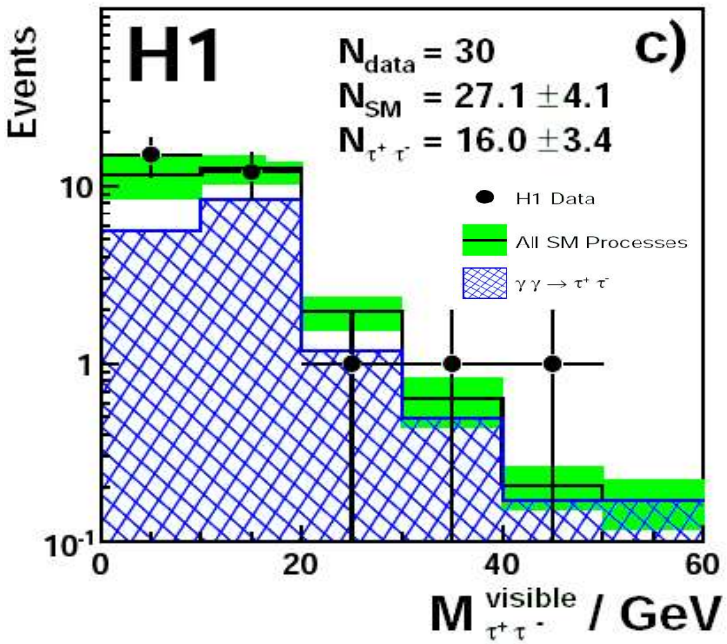
First measurement of tau pair production at a hadron machine:

multivariate ID methods (NN) for hadronic tau decays →

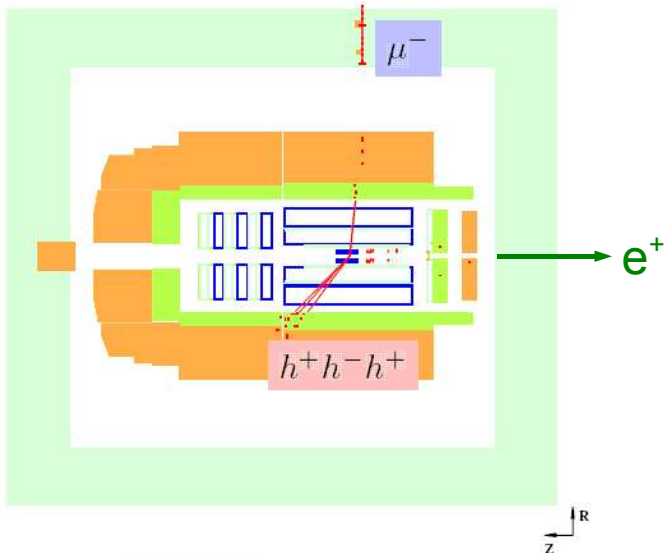


Selection of $\tau \to e$, $\tau \to \mu$, $\tau \to$ hadrons:

HERA I: $e^{\pm}p$ data L=108 pb^{-1}



good agreement with SM!



$e^+p \longrightarrow e^+ \quad \tau^- \quad \tau^+p$

$\mu^- \quad \bar{\nu}_\mu\nu_\tau \qquad h^+h^+h^- \quad \bar{\nu}_\tau$

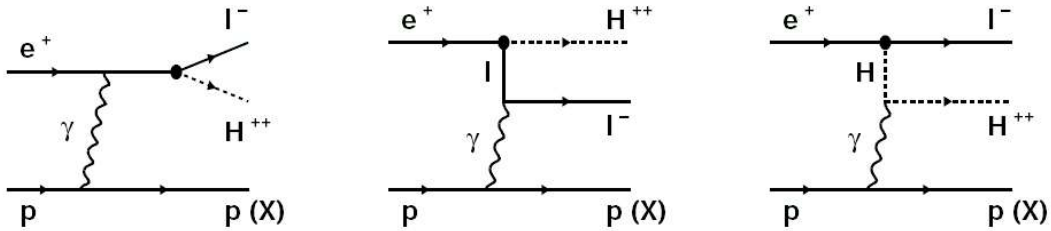
Doubly Charged Higgs at HERA

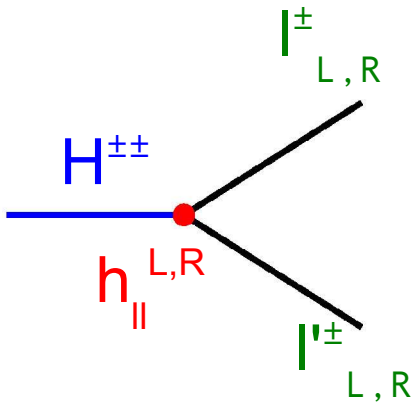
H1: submitting to Phys. Lett. B

Motivation:

- H^{++} appear in Higgs triplet(s) of non-zero hypercharge
- occur in extension of the SM
- e.g. Left-Right symmetries:
  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- vev might give mass to Majorana neutrinos
- chiral couplings to standard leptons unknown:

HERA: single production of $H^{\pm\pm}$





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

expectation:

- 2 equally charged high p_T leptons
- lepton charge = beam charge

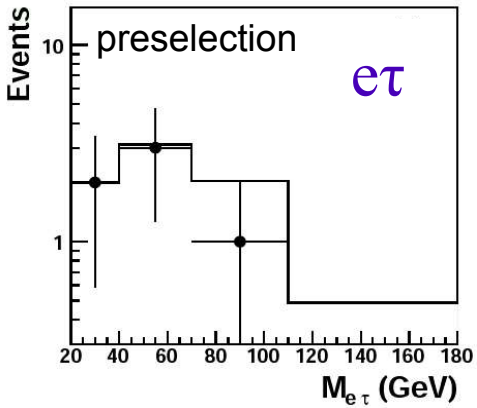
e.g. - democratic scenario: $h_{ee} = h_{\mu\mu} = h_{\tau\tau}$

- one dominant coupling: $h_{ee} >> 0$ or $h_{e\mu} >> 0$ or $h_{e\tau} >> 0$, others ~ 0

Doubly Charged Higgs Results

Invariant Masses:

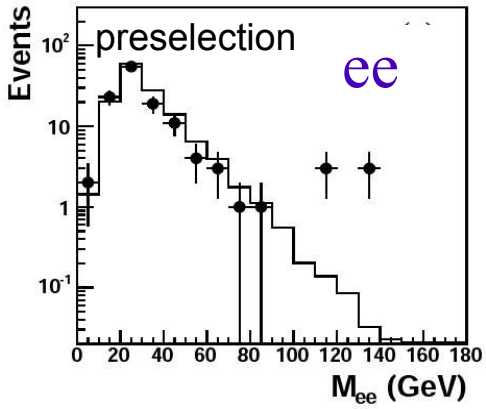
(preselection before charge cuts)



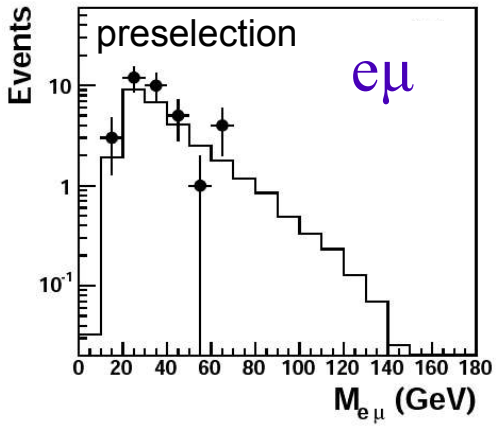
results for tau decay classes:

Event class	$H^{++} \to e^+\tau^+$ final selection		
	N_{obs}	N_{bckg}	Signal fraction
$e\mu$	0	0.27 ± 0.02	6 %
eh	1	1.66 ± 0.48	12 %
ee	0	0.14 ± 0.04	7 %
total	1	2.07 ± 0.54	25 %

eτ: one candidate

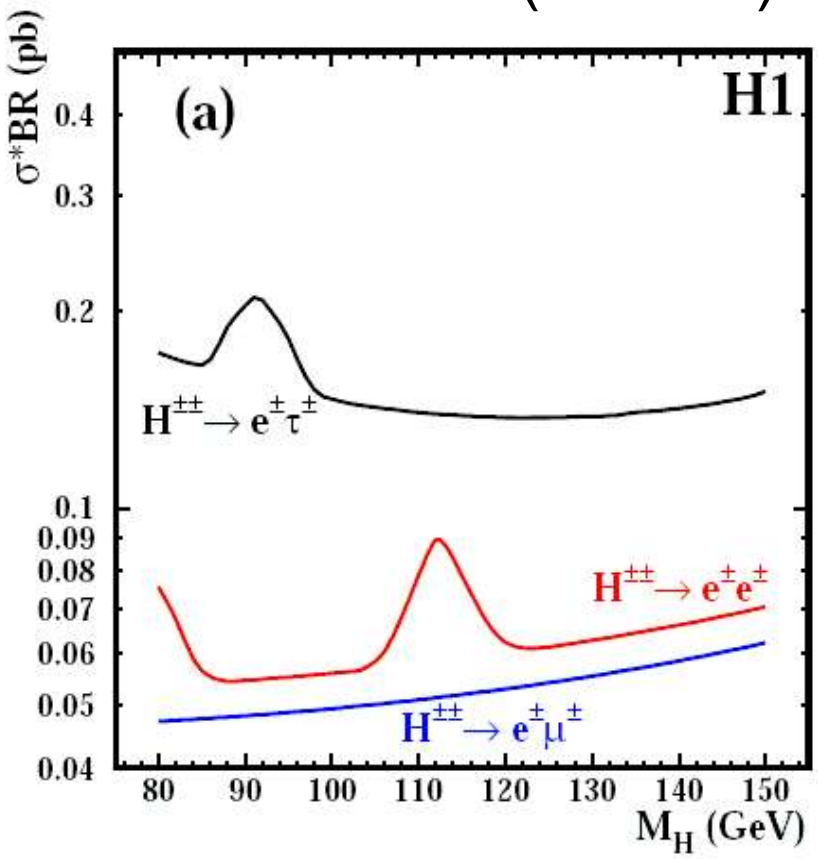


ee channel final selection:
2 events/ 2.5 expected
(for M>65 GeV)



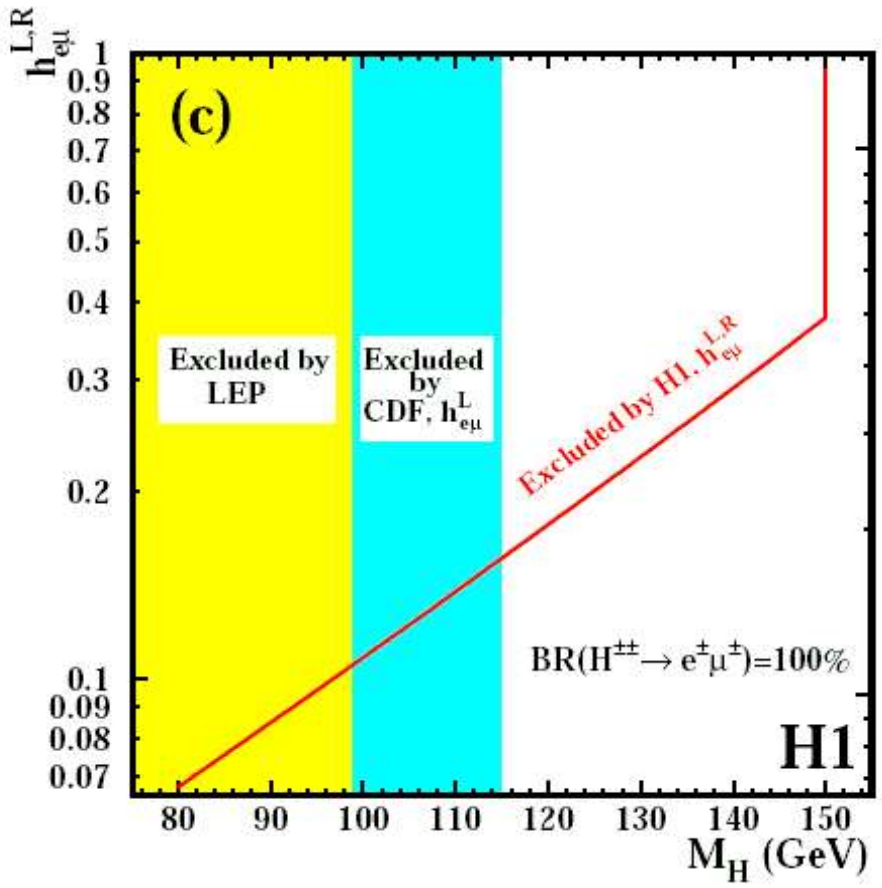
eμ channel: no candidate

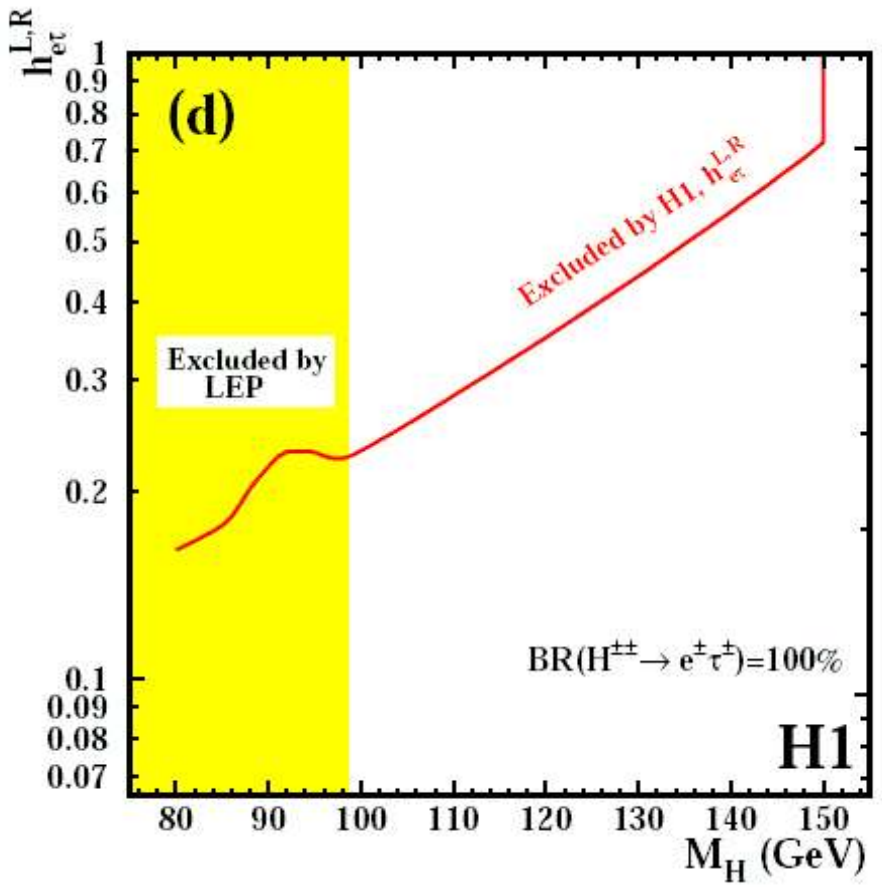
Final Results (HERA I):



Doubly Charged Higgs Results

Limits on off-diagonal couplings $h_{e\mu}$ and $h_{e\tau}$:



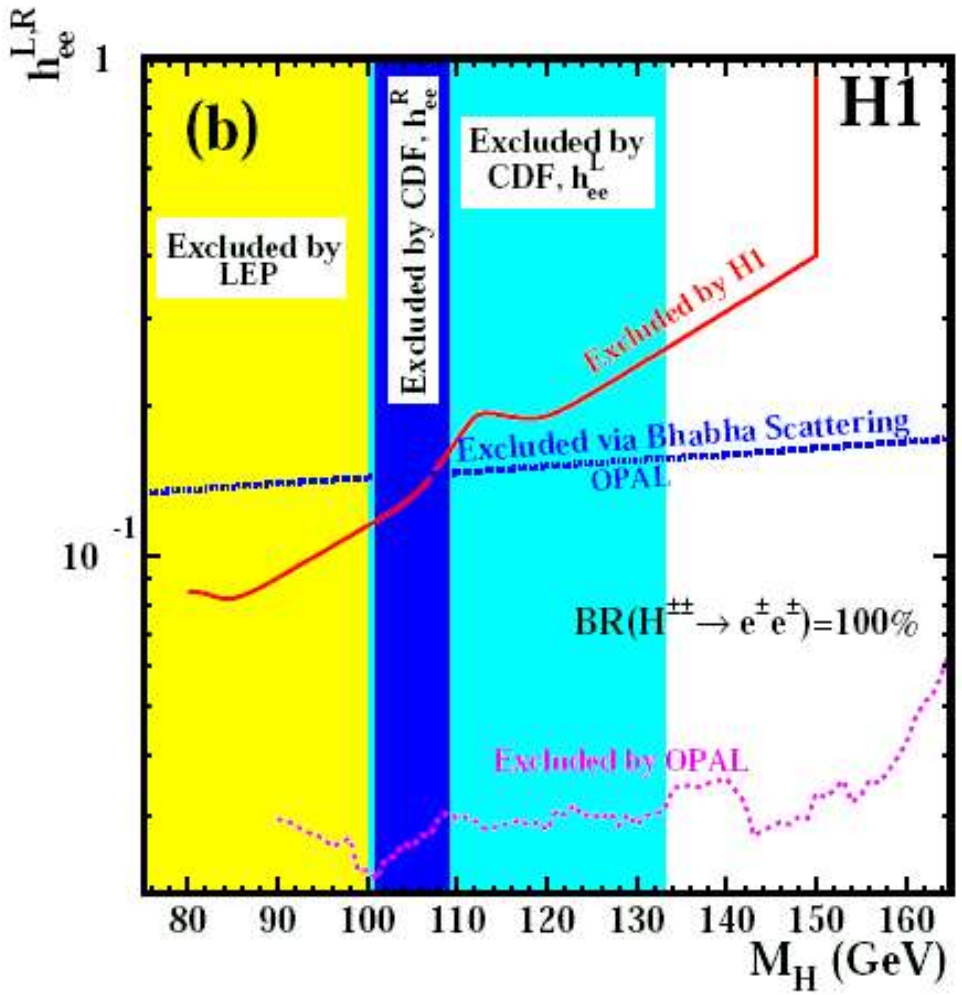


$h_{e\mu}$=0.3 : $M_H > 141$ GeV

$h_{e\tau}$=0.3 : $M_H > 112$ GeV

Doubly Charged Higgs Results

Comparison of h_{ee} limits:



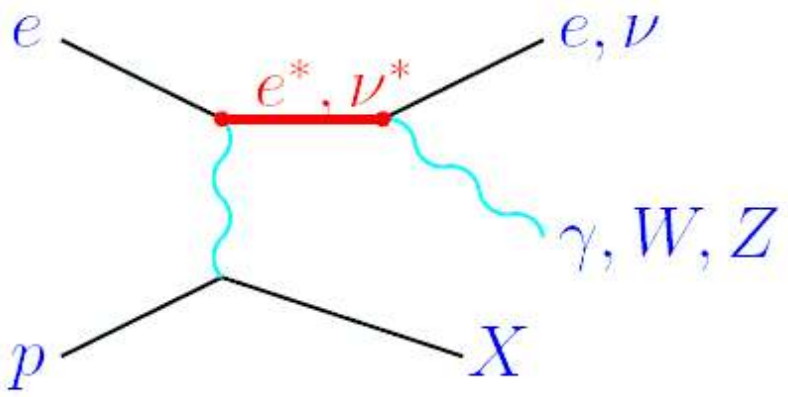
$H^{\pm\pm}$ interpretation of H1 di-electron excess excluded by OPAL

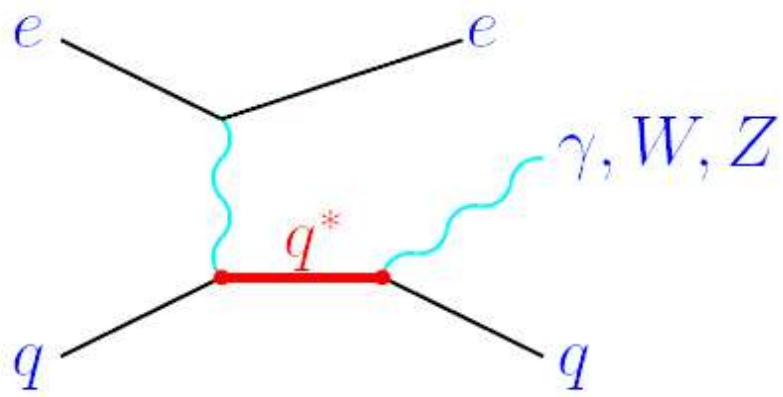
BSM Topics

- Searches in Inclusive Final States
  - Leptoquarks (Deep Inelastic Scattering)
  - Lepton Flavor Violation
  - Contact Interactions, Extra Dimensions, Substructure
- Phenomenological Searches
  - General Search
  - Isolated Lepton Events with missing P_T
    → W production
    → Single Top Production
  - Multi Lepton Final States → Doubly Charged Higgs
- Other Models
  - Excited Fermions
  - SUSY

Excited Fermions at HERA

- Compositeness of fermions would manifest in excited states f^*
- Only single production of e^*, ν^*, q^* considered at HERA





- (De-)excitation described by effective Lagrangian (Hagiwara et al.):

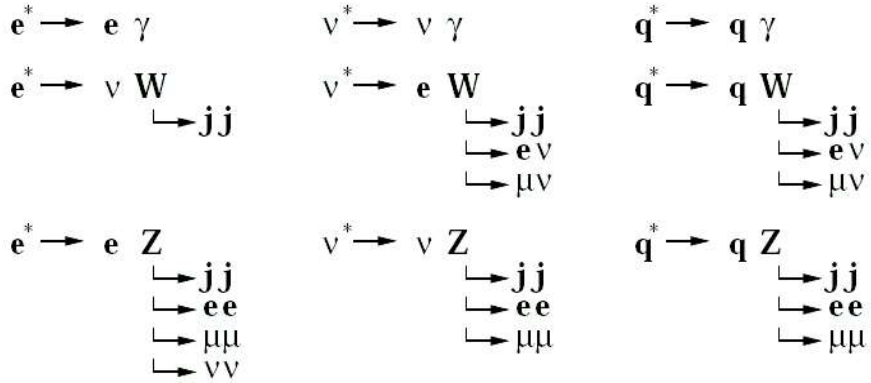
$$\mathcal{L} = \frac{1}{\Lambda} \cdot F_R^* \left[f SU(2)_W + f' U(1)_Y + f_s SU(3)_C \right] F_L$$

Λ: Compositeness scale

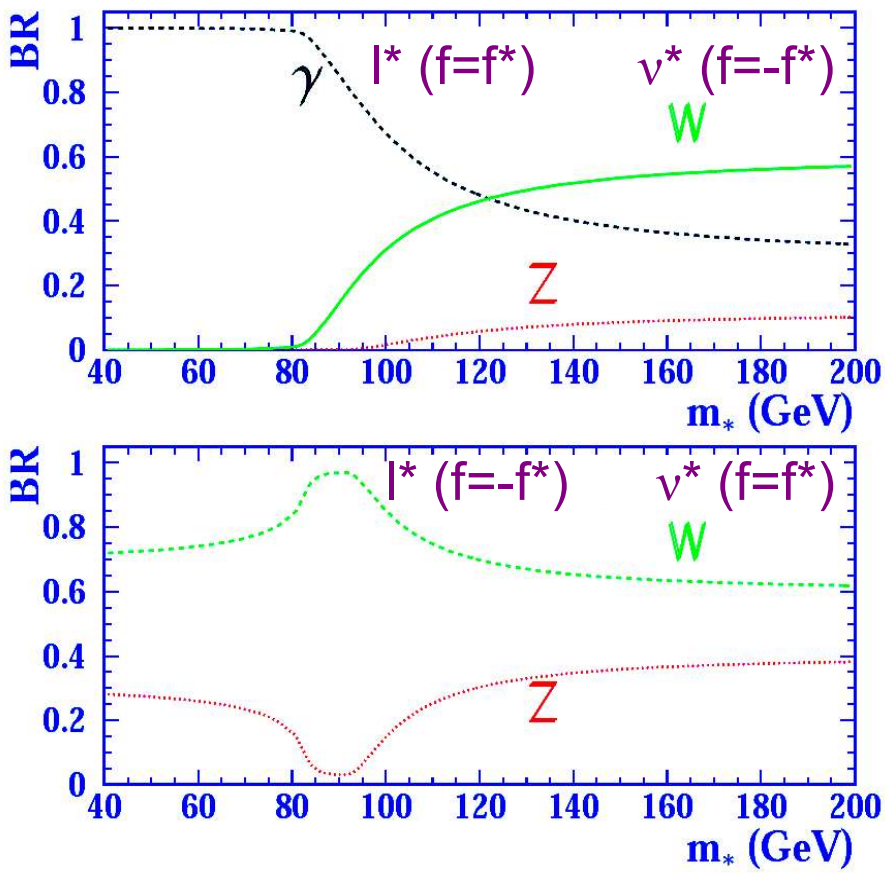
f, f', f_s: gauge group weights

Excited Fermions at HERA

Complex final states investigated:



Branching ratios for example couplings



production cross section:

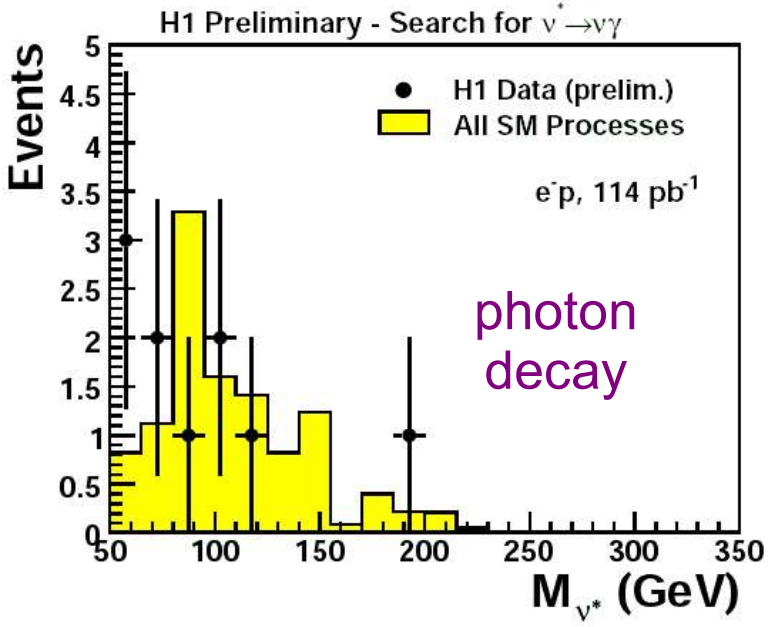
$$\sigma \propto \frac{f^2}{\Lambda^2}$$

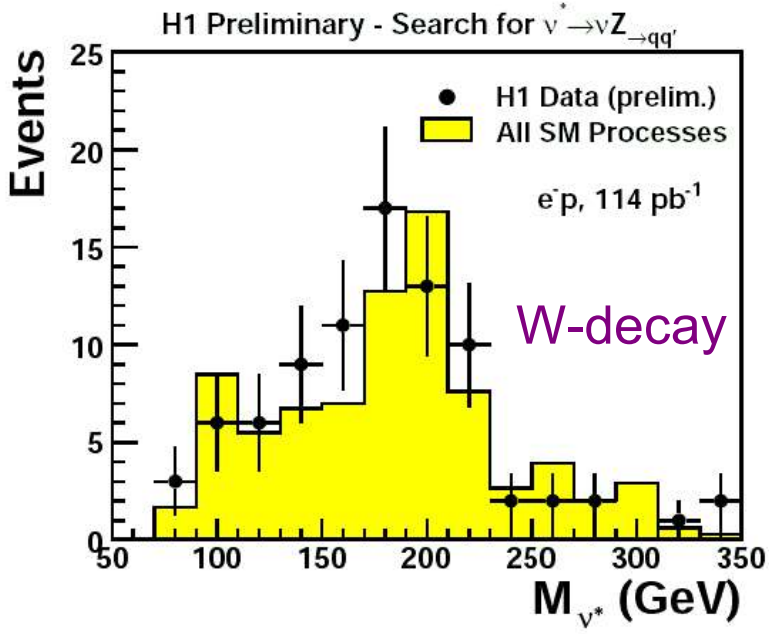
decay:

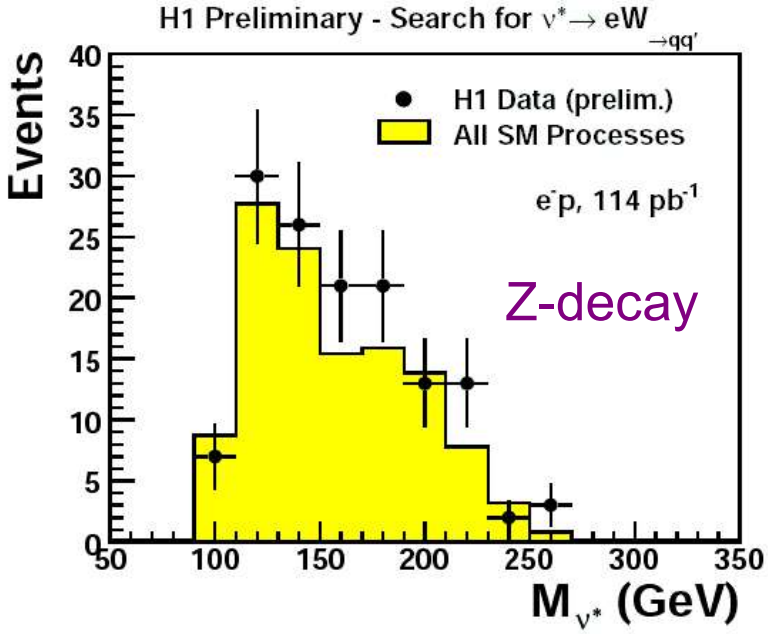
$$\Gamma \propto \frac{f^2}{\Lambda^2} m_{f^*}^3$$

→ can became large!

Example: Excited Neutrinos





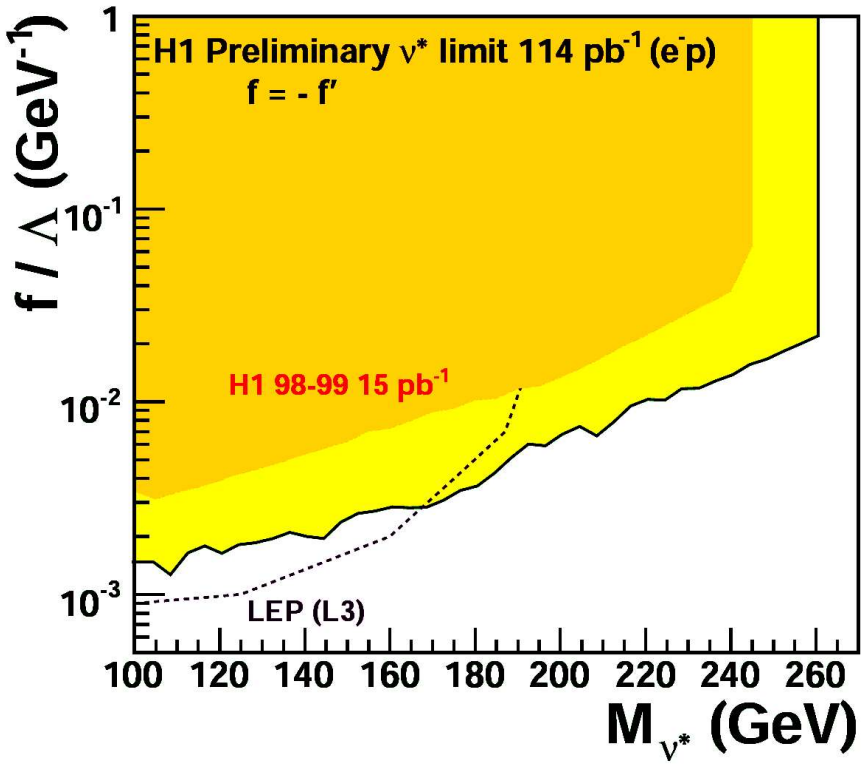


no peaks!

→ combination of channels

Selected Excited Fermions Results

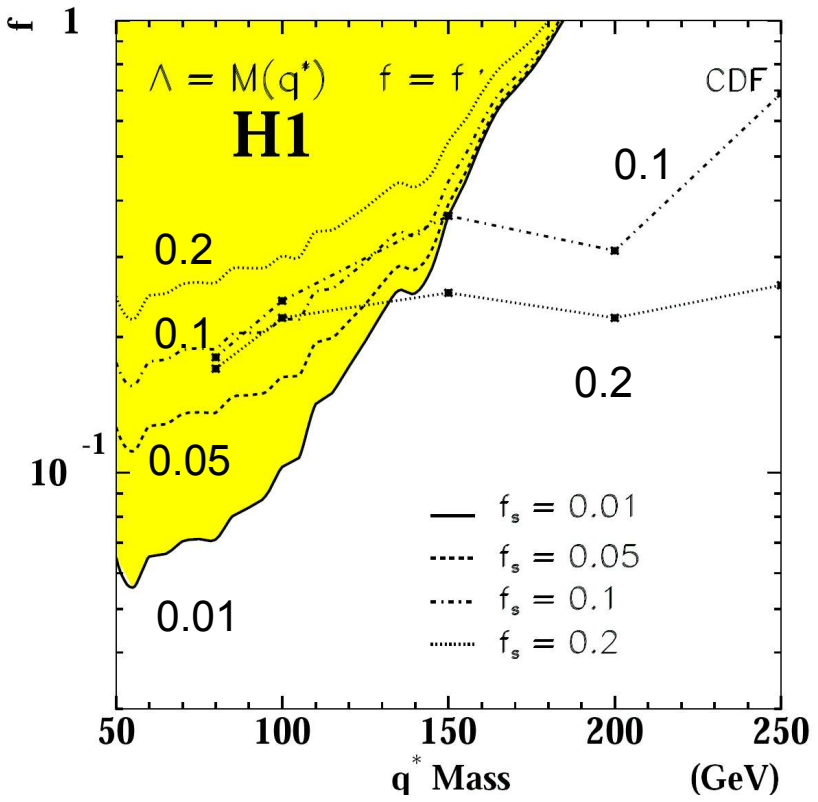
Excited neutrinos (HERA I+II)



HERA extends beyond LEP
for M>170 GeV

(Eur. Phys. J. C17 (2000) 567
[ZEUS: Physics Letters B 549 (2002)])

Excited quarks (HERA I)

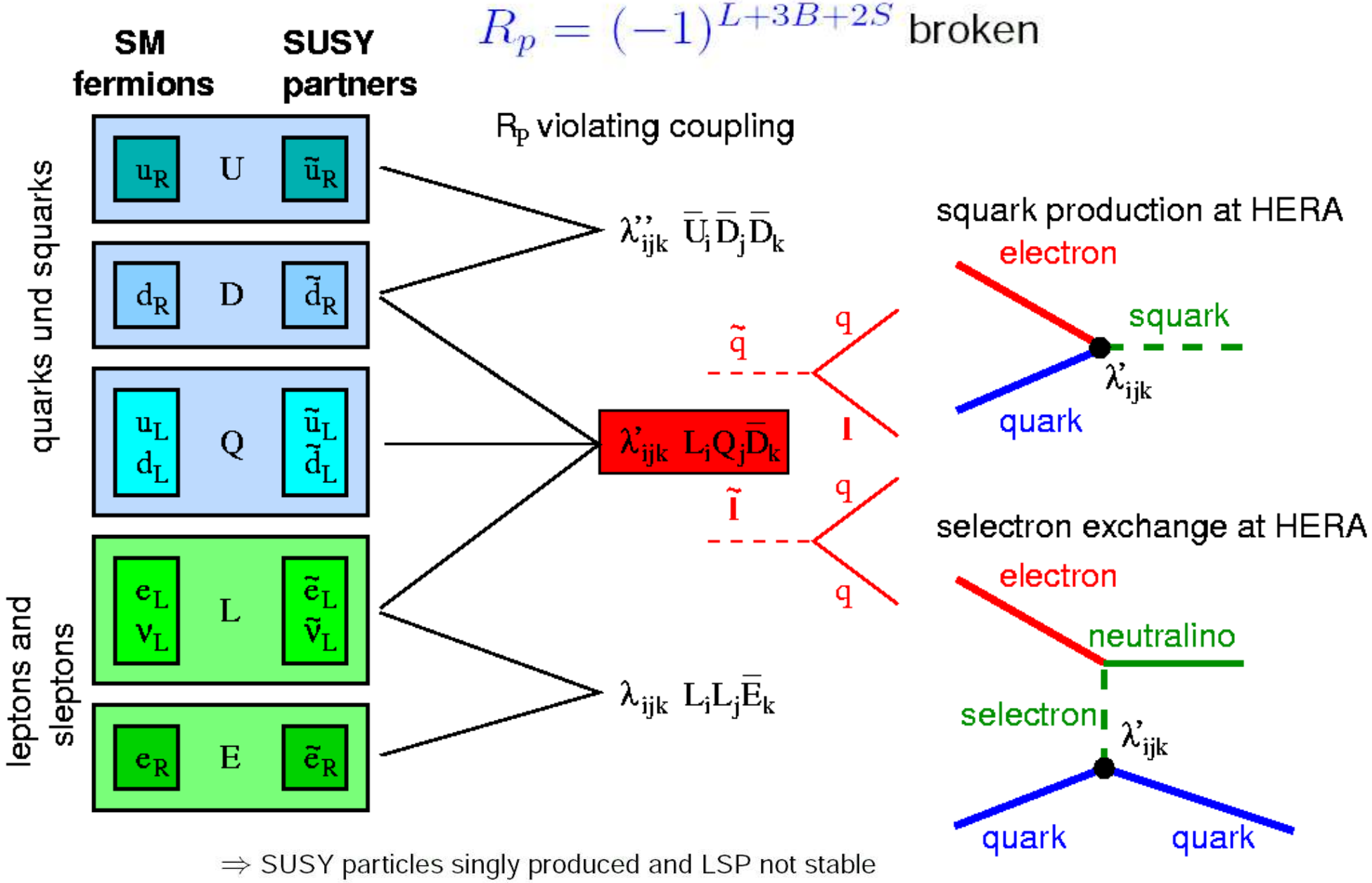


Limit on f for $\Lambda = M(q^*)$

$\Rightarrow$ HERA more sensitive for small f_s

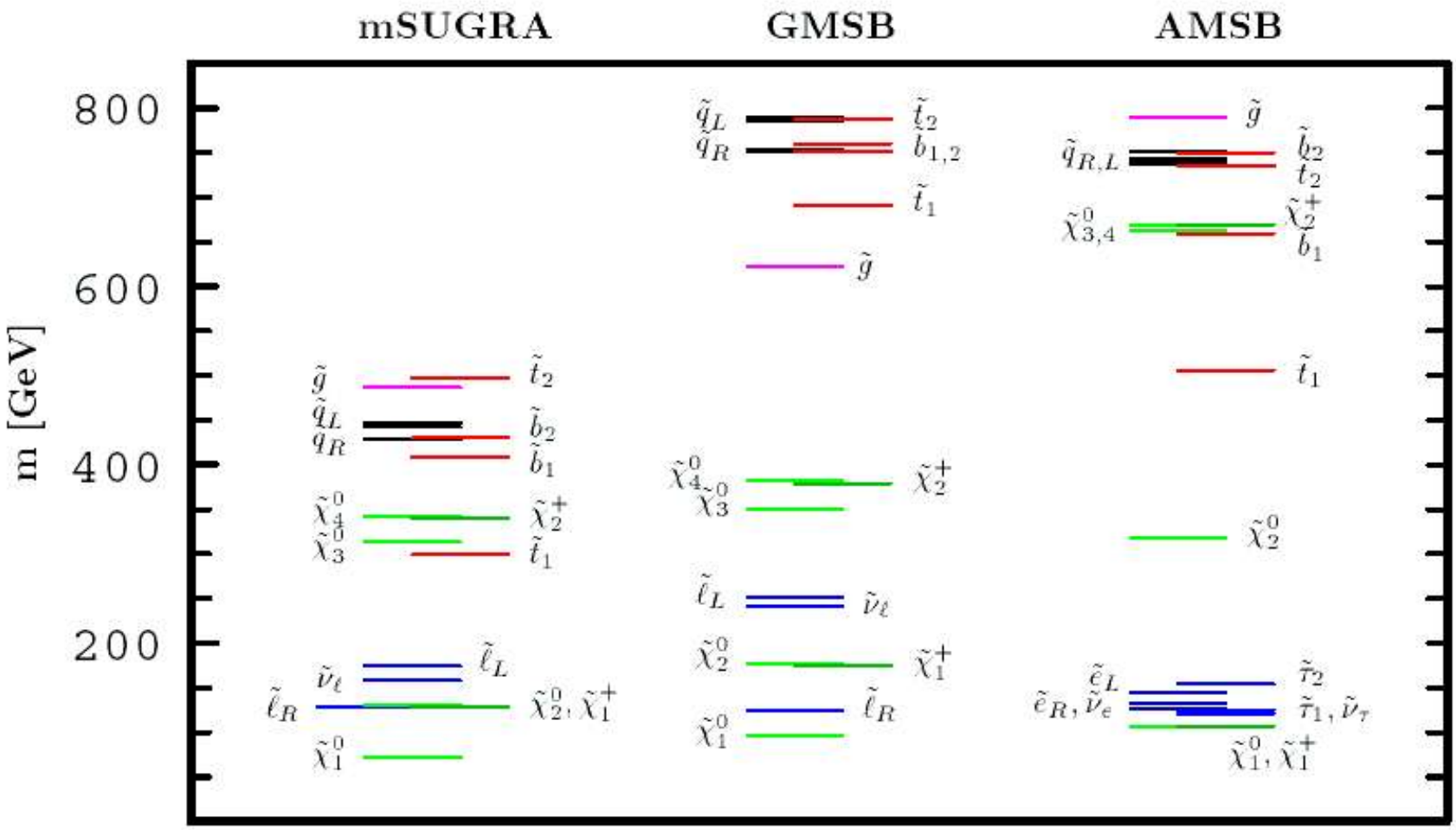
RPV SUSY at HERA

$R_p = (-1)^{L+3B+2S}$ broken



$\Rightarrow$ SUSY particles singly produced and LSP not stable

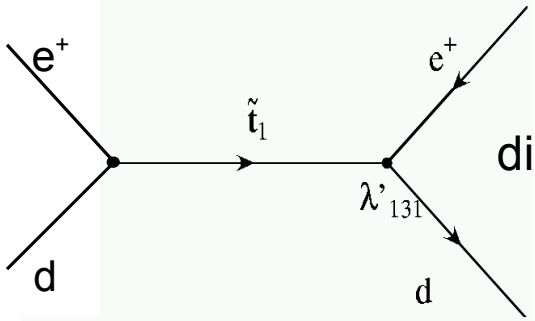
RPV SUSY



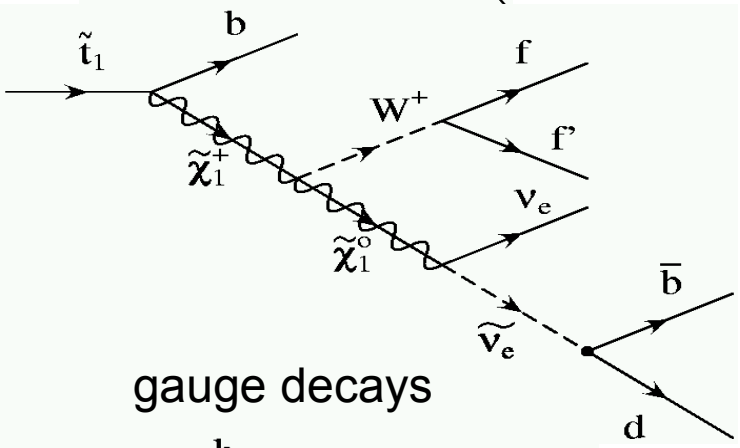
Scenarios with not too heavy scalar quarks

R_P Violating SUSY : light stop

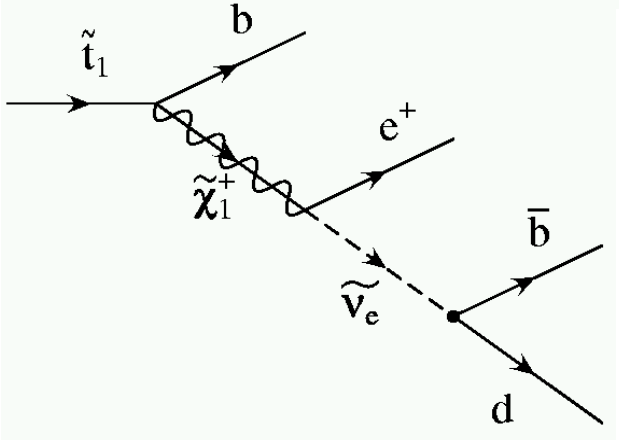
production: $e^+ d \to \tilde{t}$

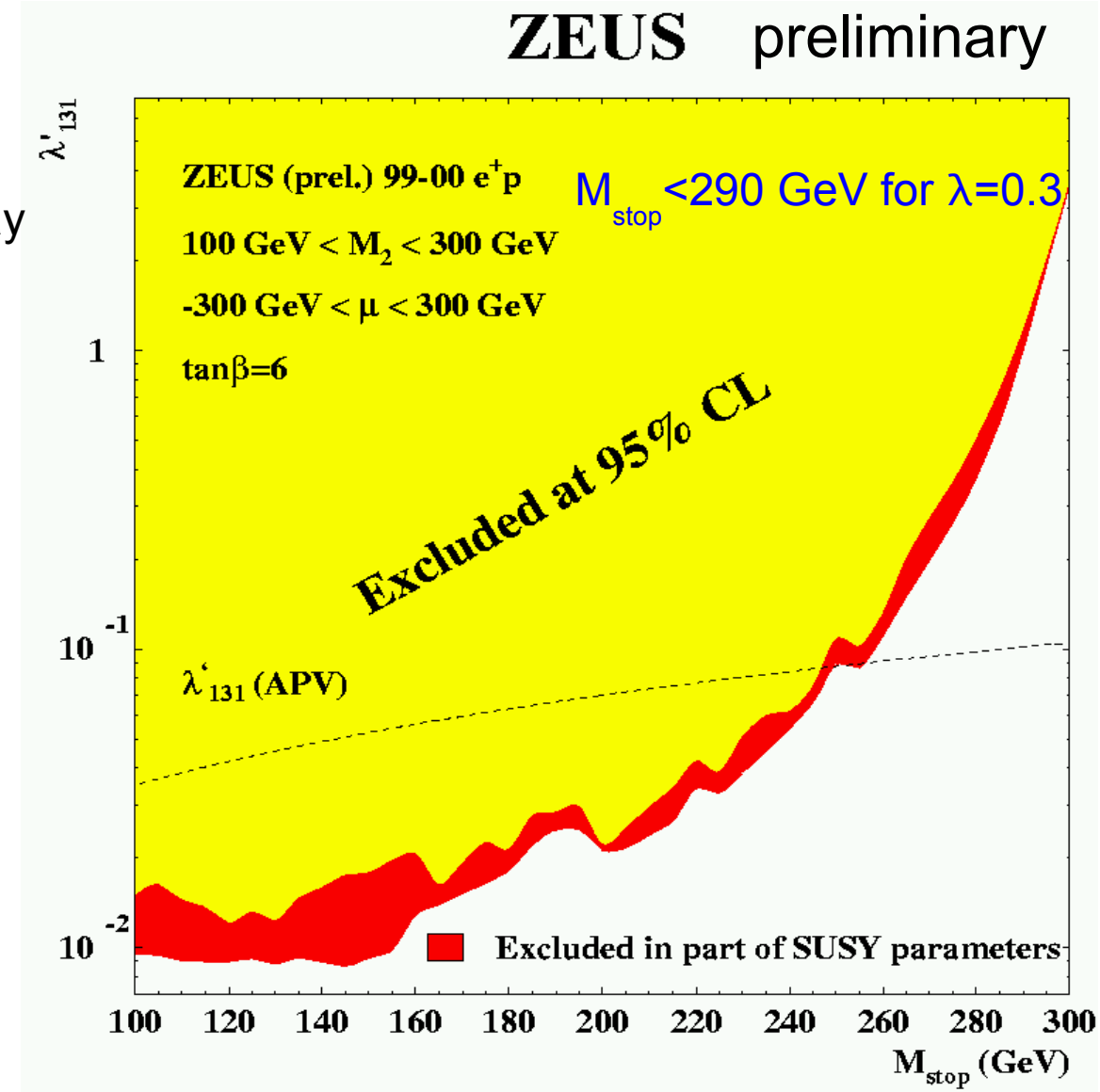


direct RPV decay



gauge decays





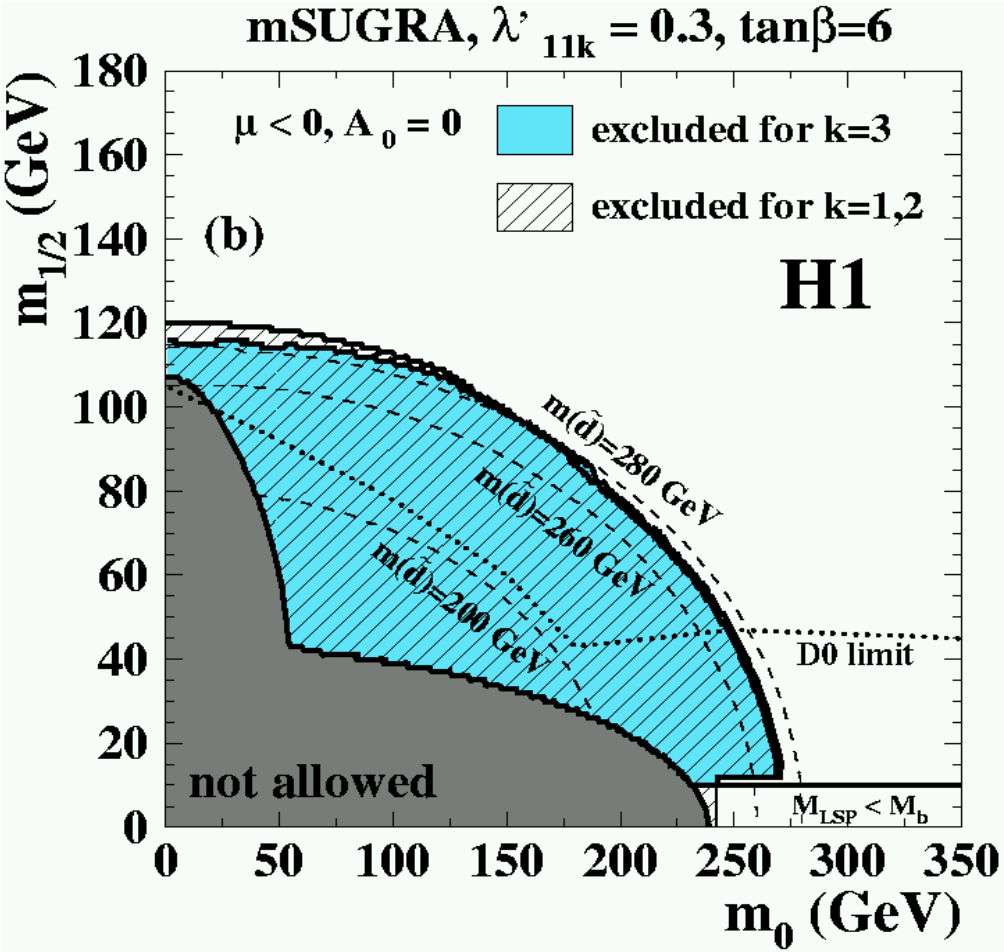
many different final states!

R_P Violating SUSY : light squarks

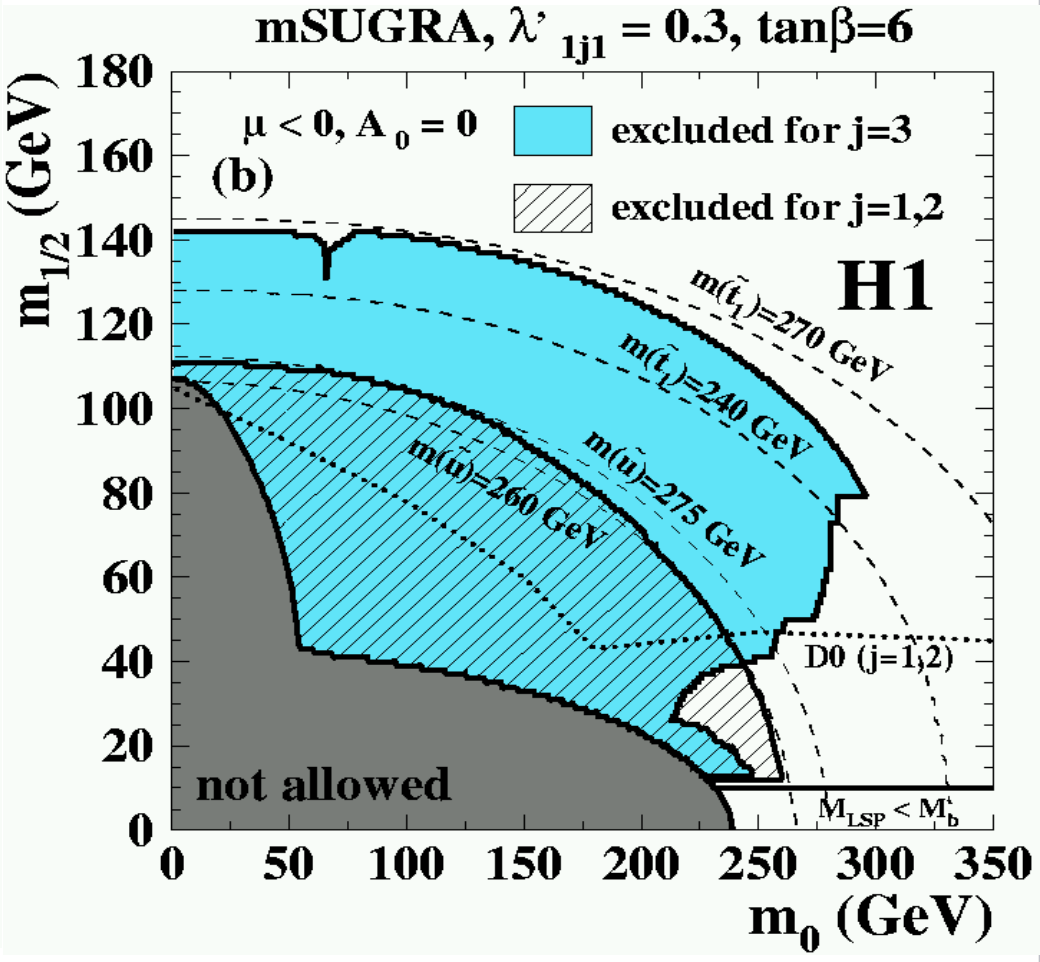
→ limits for all quark flavors interpreted in mSUGRA

(H1 Collab., Eur. Phys. J. C36 (2004) 425)

scalar down,strange,bottom

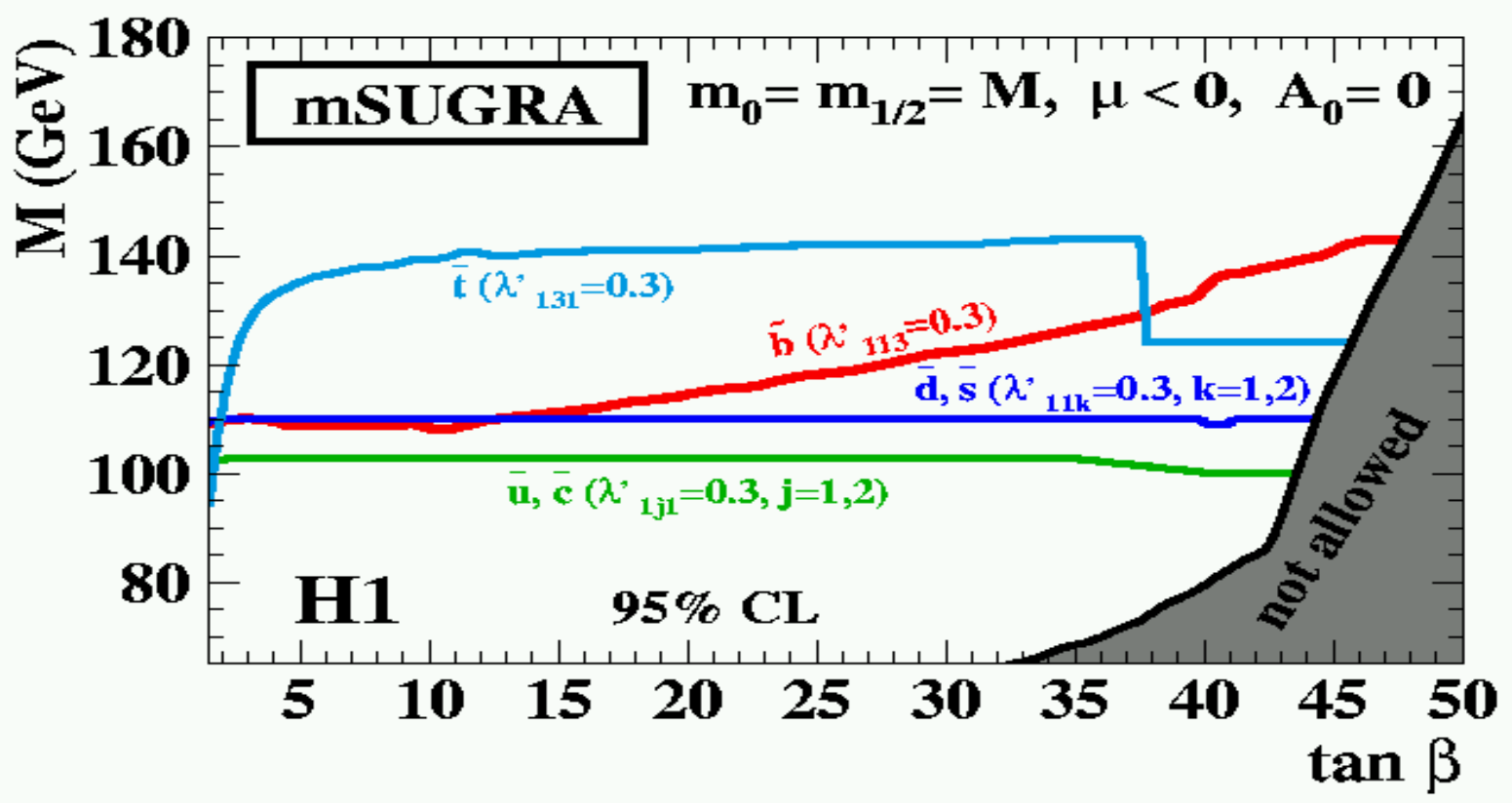


scalar up,charm,top



R_P Violating SUSY : all quark flavors

limits on all squark masses:

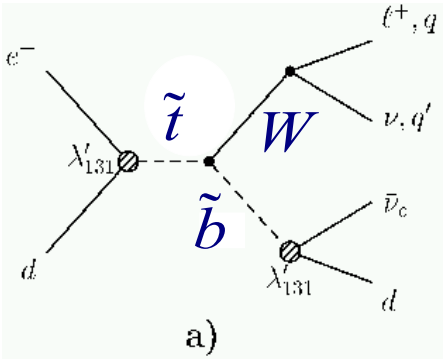


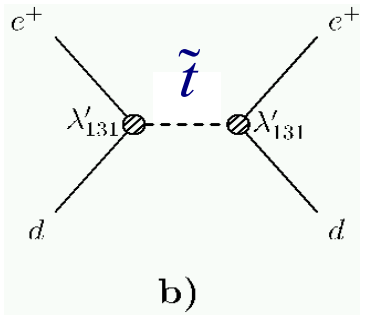
for λ'=0.3 (coupling of em. strength) values of $M=m_0=m_{1/2}$ below 100-140 GeV are excluded for a large tan β range

Stop with Bosonic Decay

H1 Collab., A. Aktas et al., Phys Lett B599 (2004) 159-172

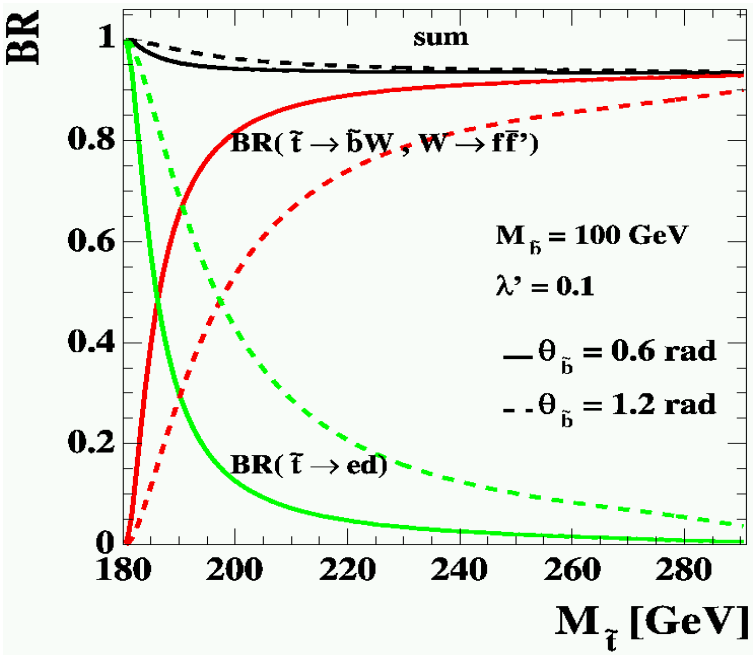
- Sbottom is LSP: $M_{stop} > M_{sbottom} + 80$ GeV

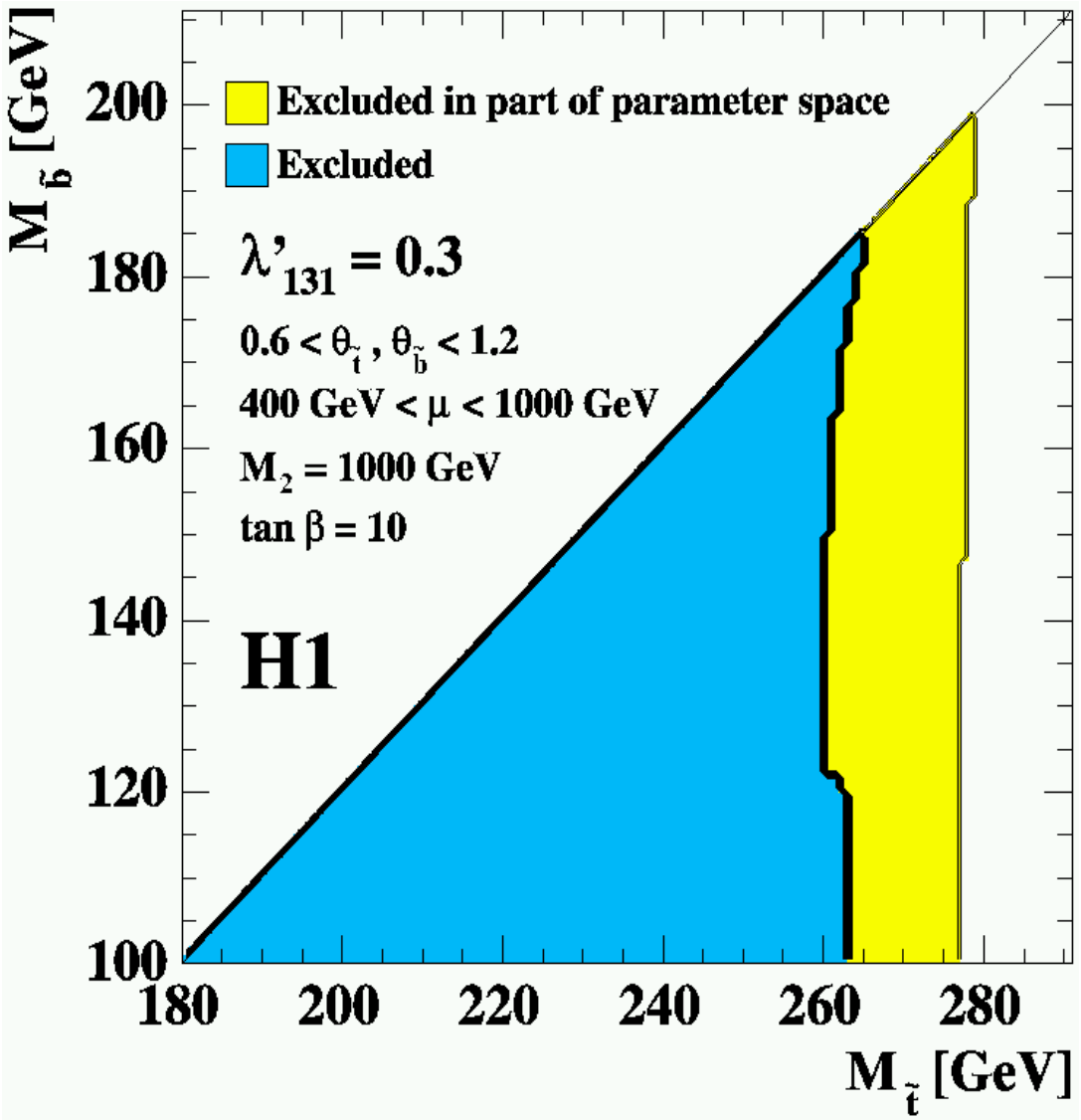




sbottom decay

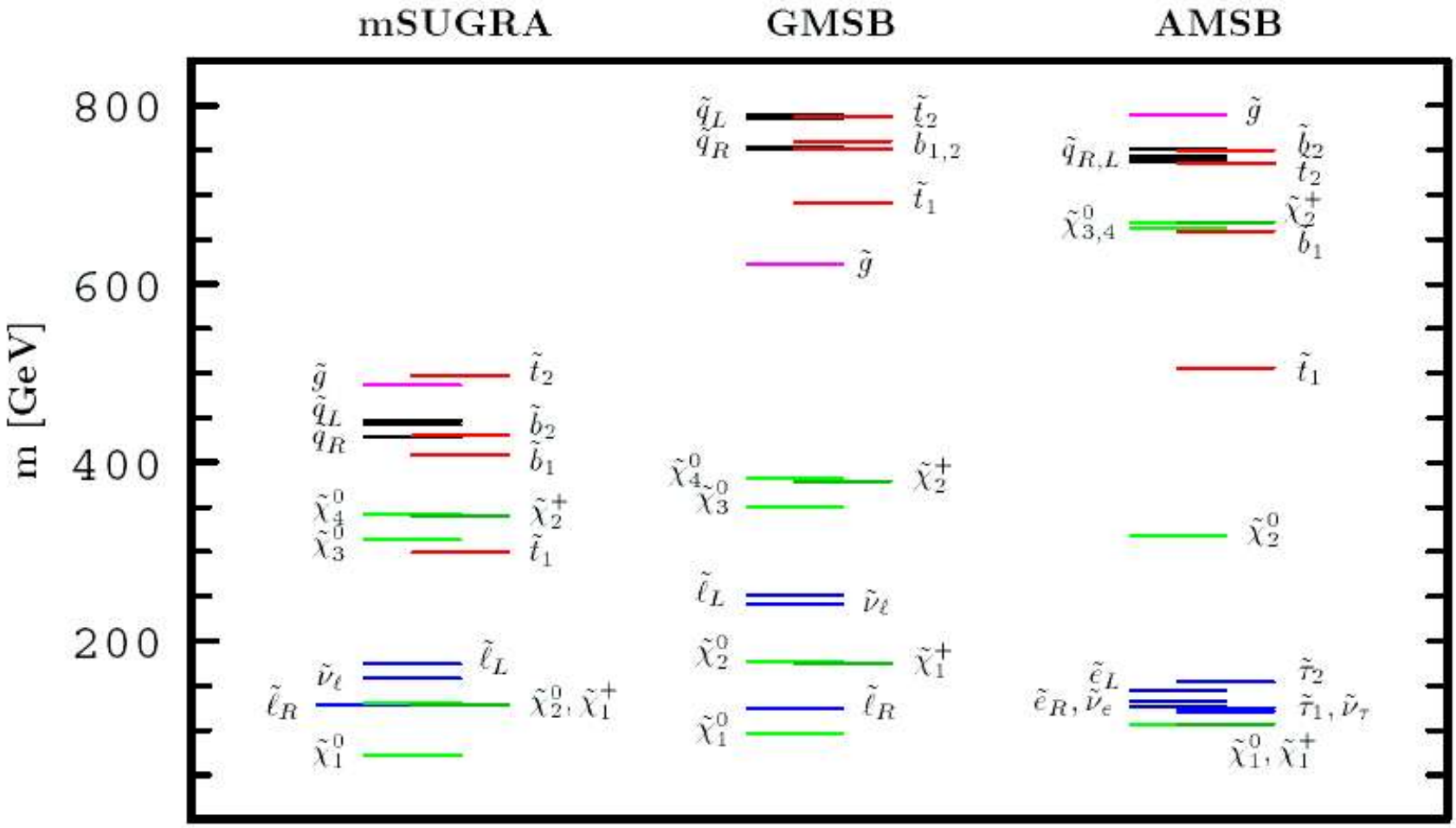
direct RPV decay





→ stop mass exclusion limits
up to 260-280 GeV (λ'_{131}=0.3)

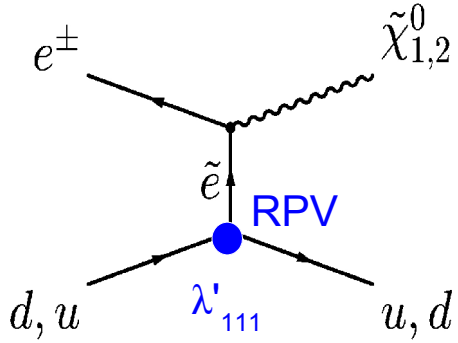
RPV SUSY



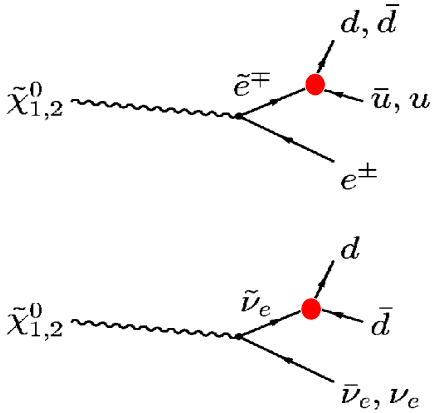
Scenarios with
light gauginos and scalar leptons

RPV Gaugino Production at HERA

- mSUGRA: scenario: $M_{squark} >> M_{sleptons}$

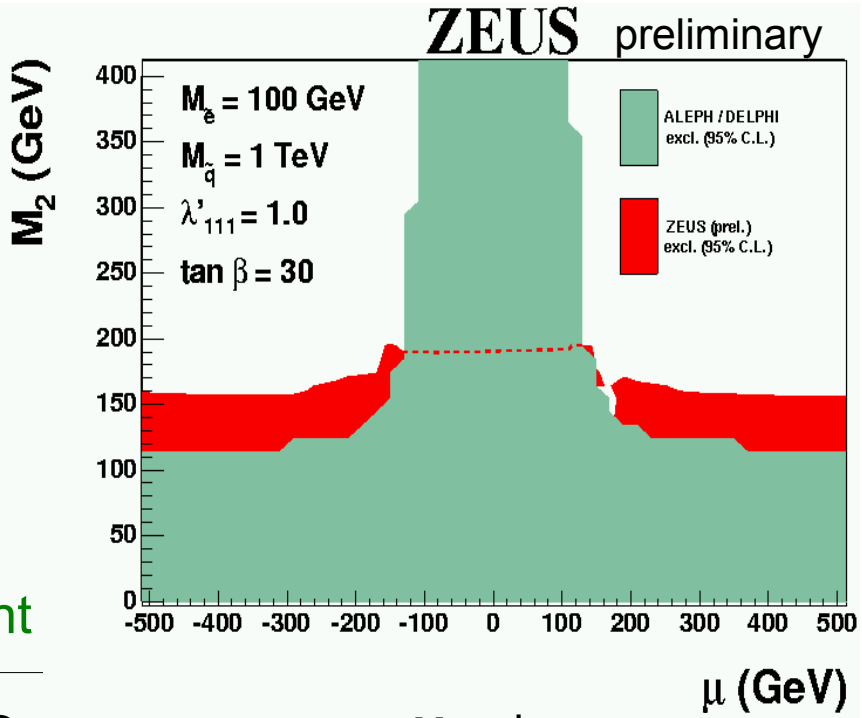


production

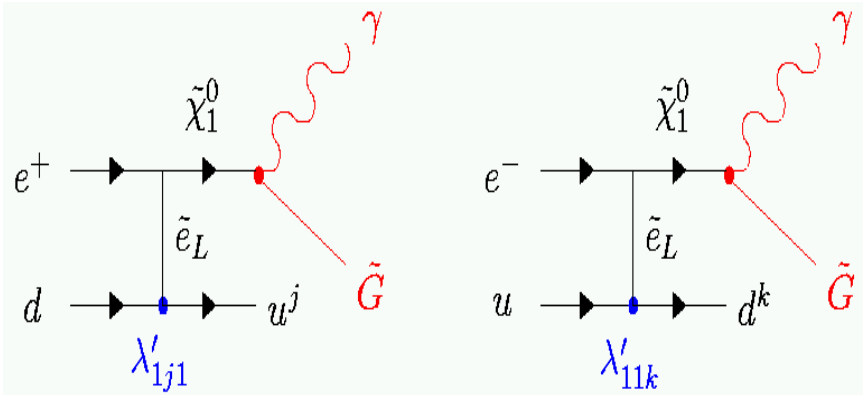


RPV neutralino decay

large BG - uses discrimant

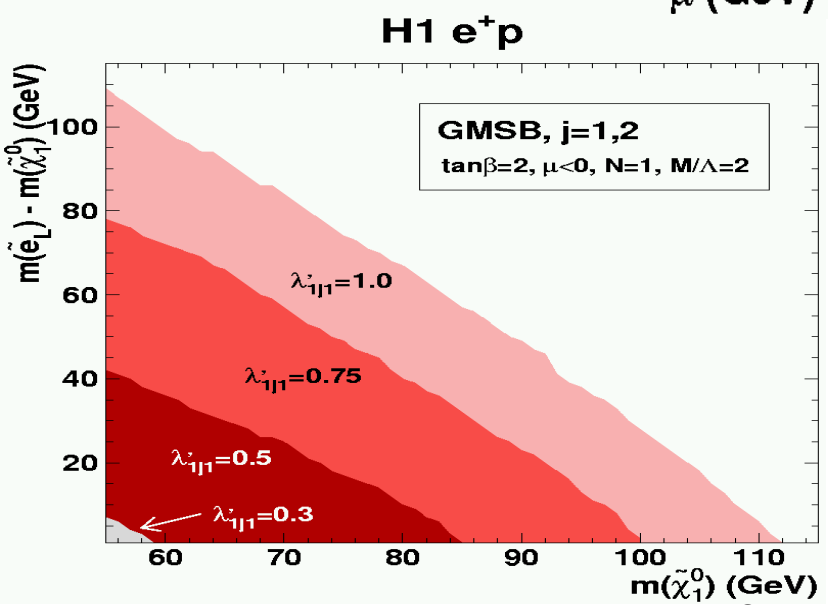


- GMSB: $M_{squark} >> M_{sleptons}$ + light gravitino



(H1: Phys. Lett. B616 (2005) 31-42)

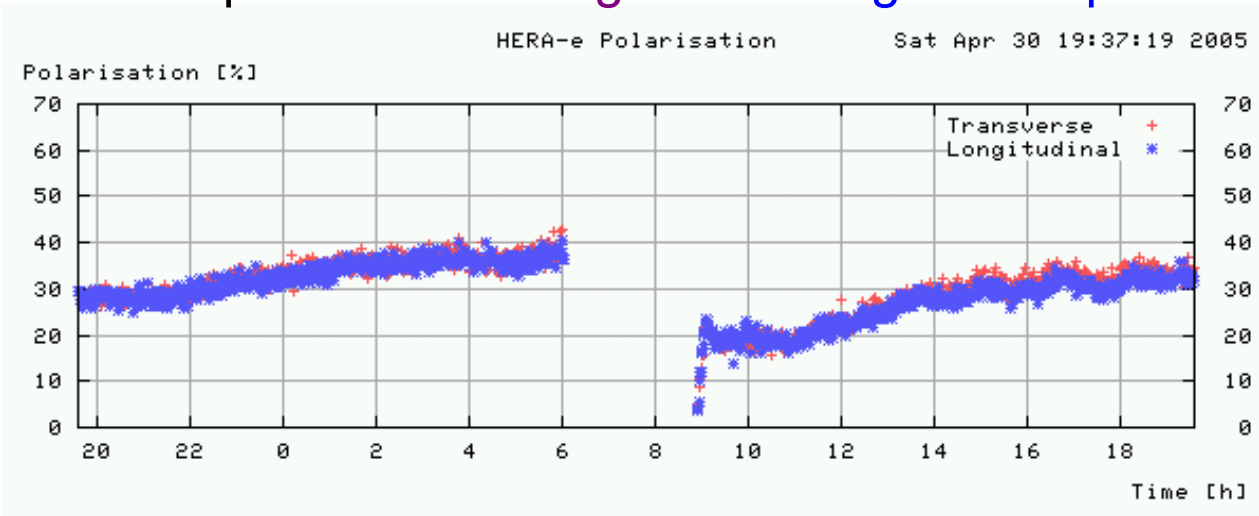
clean signature



HERA Search Summary

- Many interesting new results and puzzling excesses
- Results often competitive and complementary to LEP/Tevatron
- HERA II has become a high luminosity machine
- More interesting HERA results expected in near future
  >~250pb^{-1} still to come (until mid 2007 when HERA ends)

- Further detailed studies expected exploiting:
  - ➔ different lepton beam charges and longitudinal polarisation



It is the unexpected which makes greatest surprises

Keep your eyes open!