Search for excited leptons in the H1 experiment at HERA

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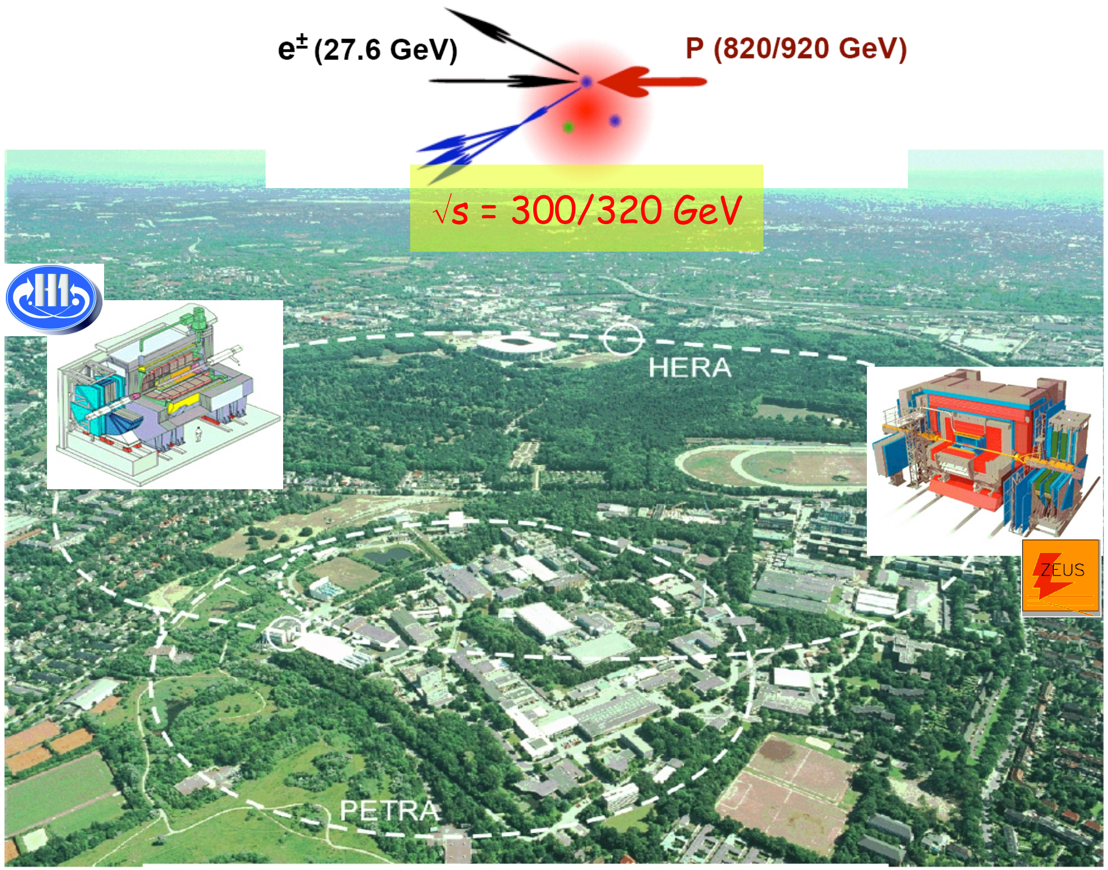
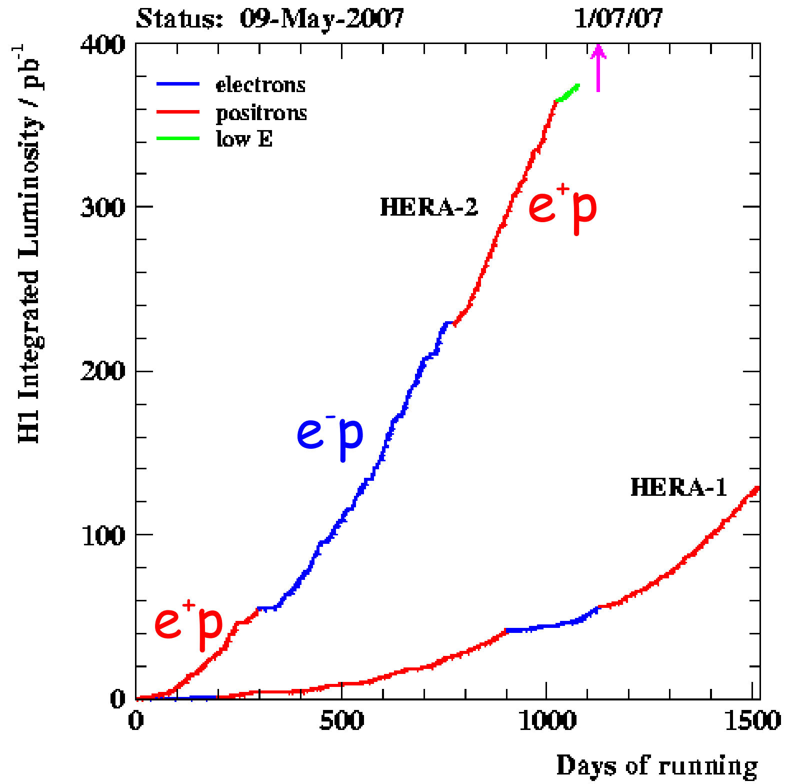
Contents

- The HERA e-p collider: a history !
- Compositeness and Excited leptons in H1
  - Motivation: Phenomenology of excited leptons
  - New preliminary results:
    - Search for excited neutrinos
    - Search for excited electrons
- Conclusion & Perspective

The HERA collider: the game is over



All high energy taking data

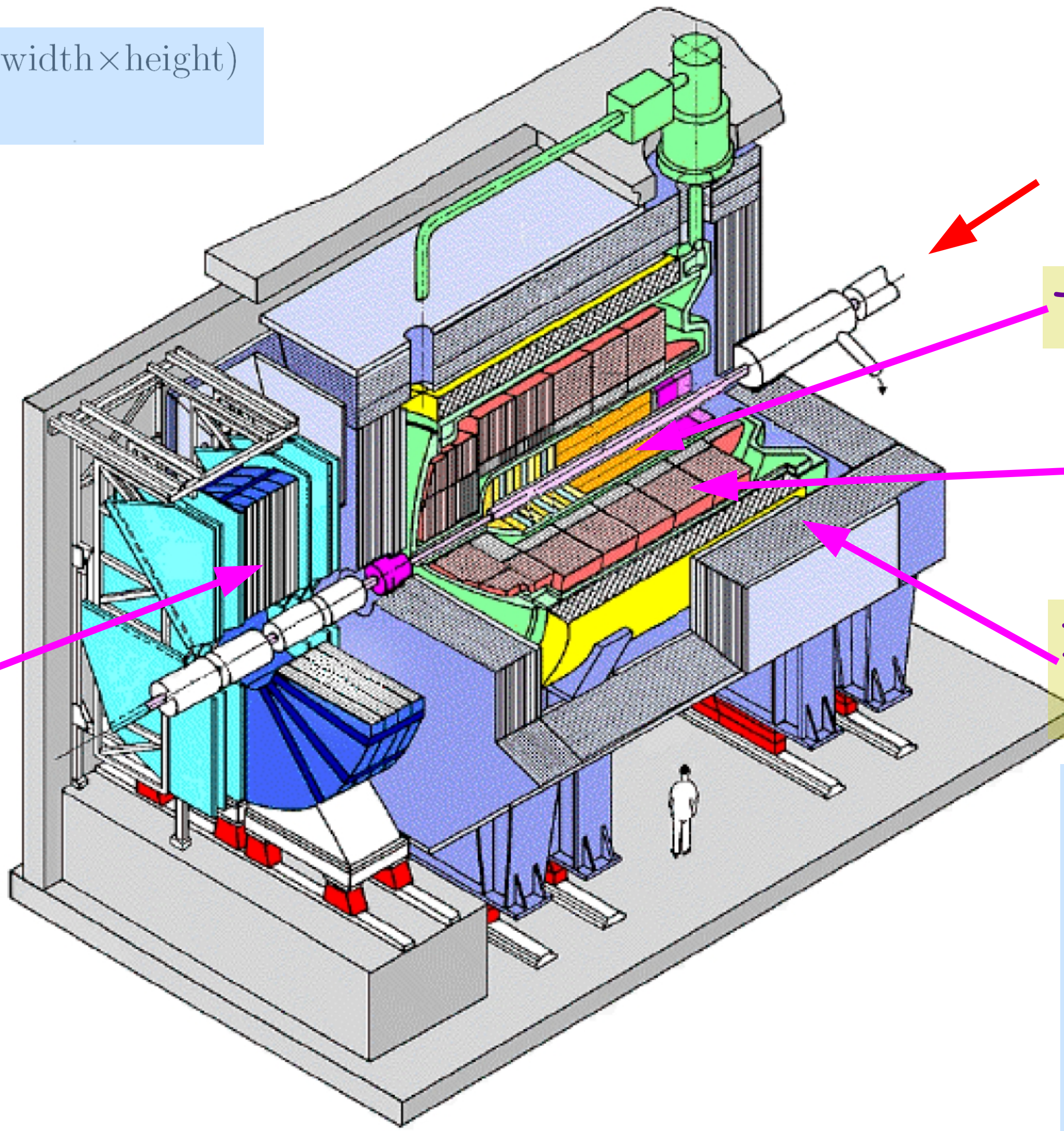


- ➔ HERA I: 1992-2000, ~ 120 pb^{-1}
- ➔ HERA II: luminosity upgrade and polarised lepton beams
  - ➘ High energy run ended on March 2007
    - ☞ H1 at HERA I+II: ~ 0.5 fb^{-1}

The H1 detector at the ep storage ring HERA

$12 \times 10 \times 15\ \mathrm{m}^3$ (length×width×height)

2800 tons

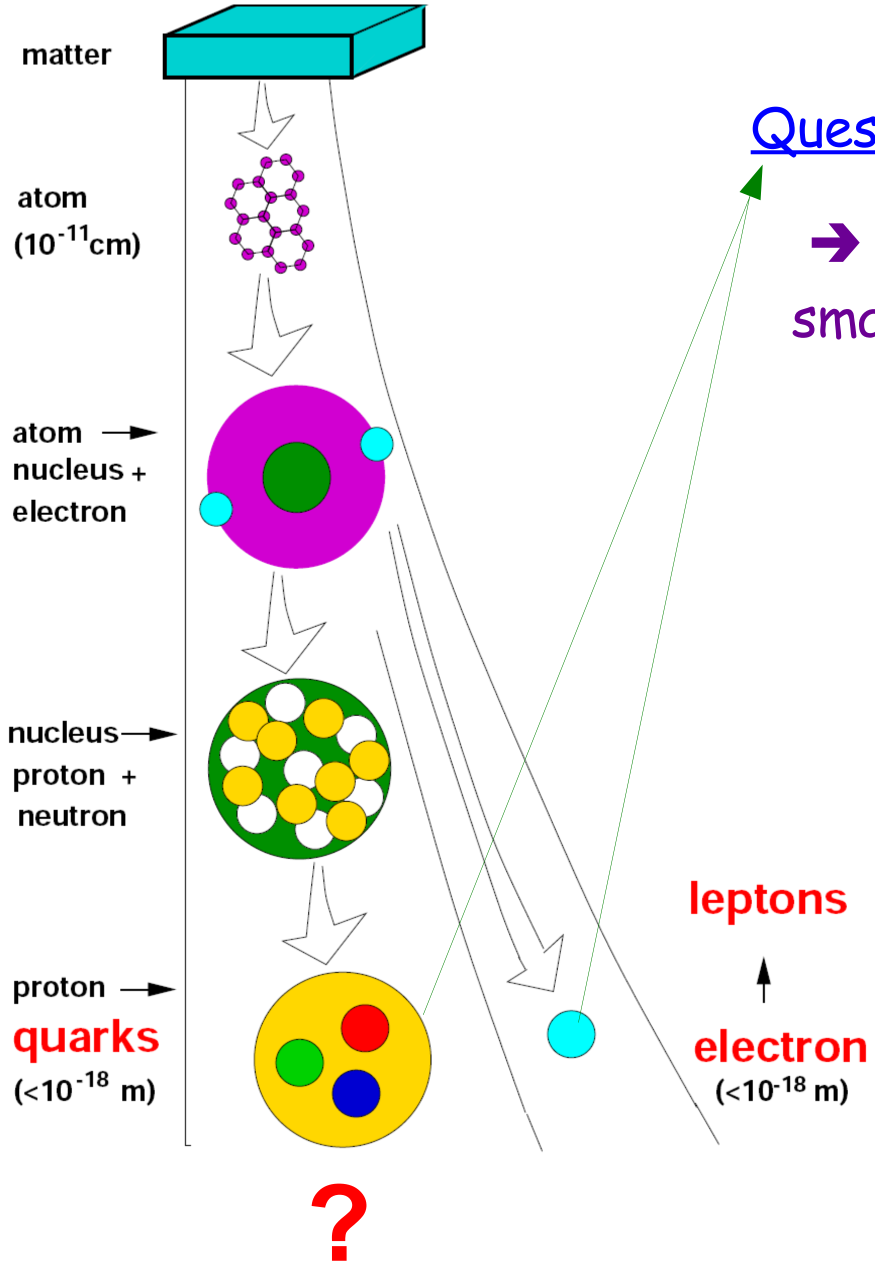


$$\frac{\sigma_E^{em}}{E} = \frac{0.12}{\sqrt{E\ [\mathrm{GeV}]}},$$

$$\frac{\sigma_E^{had}}{E} = \frac{0.50}{\sqrt{E\ [\mathrm{GeV}]}},$$

$$\frac{\sigma(p_T)}{p_T} = 0.01 \cdot p_T[\mathrm{GeV}]$$

Sub-scales of matter



Questions:

➔ Should quark and lepton be made of smaller constituents, like excited states ?

☞ Composite fermion is predicted in various models beyond SM.

☞ They could be produced in high energy collisions.

Excited leptons: Phenomenology

If energy scale: $\Lambda \geq 1$ TeV

↓

Leptons could be made of smaller constituents (ex: excited leptons)

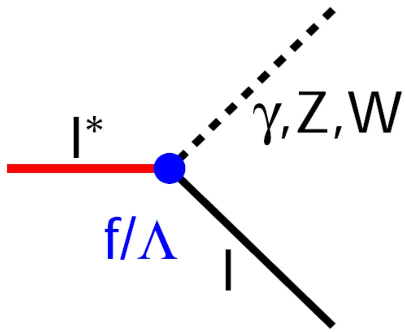
↓

Compositeness Model could explain it

- Basics of the phenomenological model
  - Excited leptons (l*) are considered as spin=1/2 & isospin=1/2 particles
  - Generally assume $\begin{pmatrix} \nu_\ell^* \\ \ell^* \end{pmatrix}_{\mathrm{L}} \begin{pmatrix} \nu_\ell^* \\ \ell^* \end{pmatrix}_{\mathrm{R}}$
  - Excited leptons couple to gauge bosons (ll*V) (Gauge Mediated Interaction)

$$\mathcal{L}_{\ell\ell^* V} = \underbrace{\frac{1}{2\Lambda}}_{\text{compositeness scale}} \bar{\ell}^* \sigma^{\mu\nu} \left[g f \frac{\tau}{2} \mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] \ell_{\mathrm{L}}$$

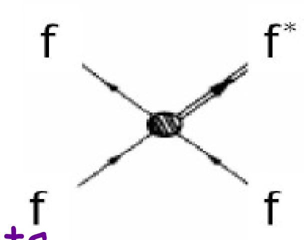
weight factors



- Another approach: couplings of excited leptons to quark and leptons via Contact Interactions

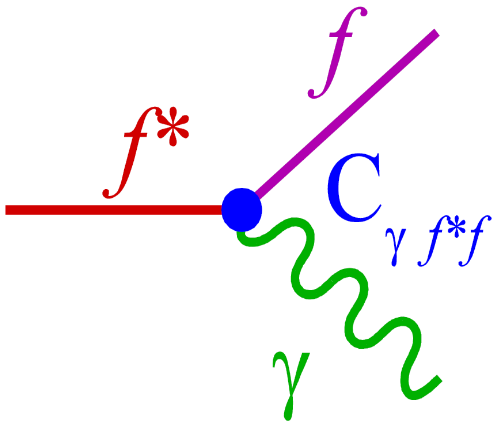
$$\mathcal{L} \,\alpha\, \frac{4\pi}{\Lambda^2} (\bar{e}^* \gamma^\mu e)(\bar{q} \gamma_\mu q)$$

- similar phenomena
- mainly differs from GM by a normalisation factor
- ✓ not considered in following results



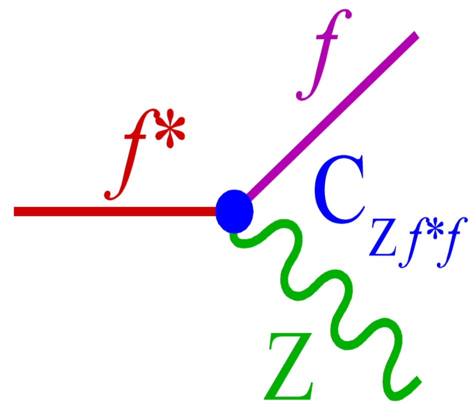
Gauge group weights: *f* & *f'*

- f*fγ vertex



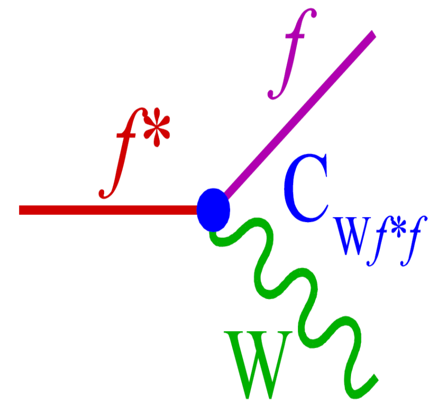
$$C_{\gamma f^* f} = \frac{1}{2}\left(f\, I_3 + f'\frac{Y}{2}\right)$$

- f*fZ vertex



$$C_{Z f^* f} = \frac{1}{2}\left(f\, I_3 \cot\theta_W - f'\frac{Y}{2}\tan\theta_W\right)$$

- f*fW vertex



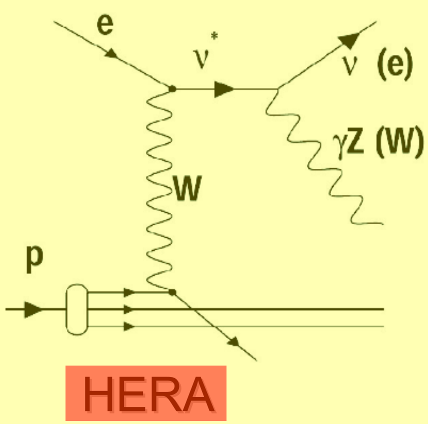
$$C_{W^- f^* f} = \frac{f}{2\sqrt{2}\sin\theta_W}$$

- I_3 : third component of isospin
- Y: hypercharge (Y=±1 for l*)
- θ_W: Weinberg angle

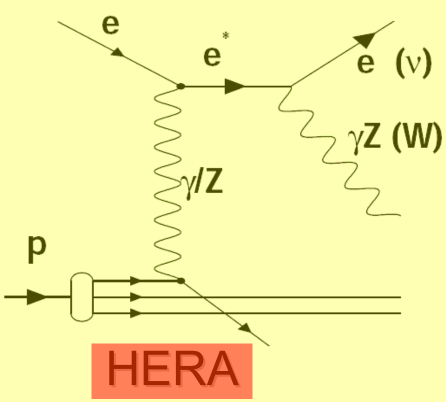
$$C_{\gamma\nu\nu*} = \frac{1}{4}(f - f') = 0|_{f=f'}$$
$$C_{\gamma ee*} = -\frac{1}{4}(f + f') = 0|_{f=-f'}$$

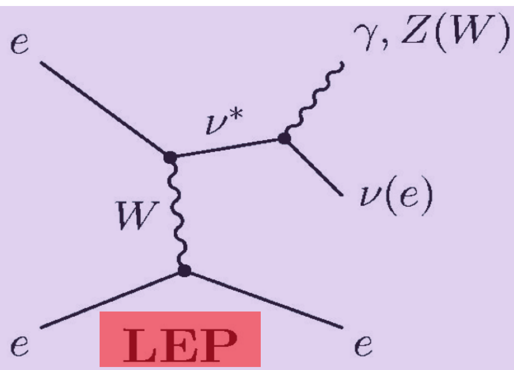
➥ Search for leptons de-excitations could give informations on compositeness coupling

Excited leptons at colliders

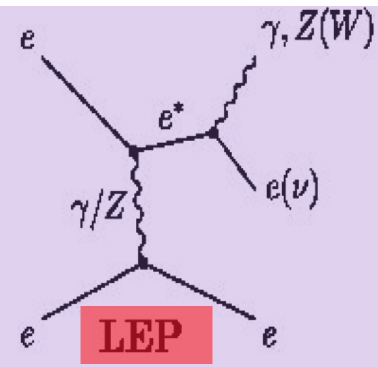


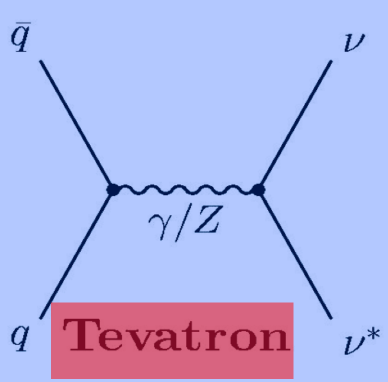
- Production of excited leptons (e^*, ν^*) via t-channel γ(Z) or W exchange
- Lepton de-excitation by emission of γ, $Z^0/W^{\pm}$
- ν^* search: σ much more in e-p collision mode





- Similar production mechanism
- Larger cross section & smaller background
- But lower centre-of-mass energy



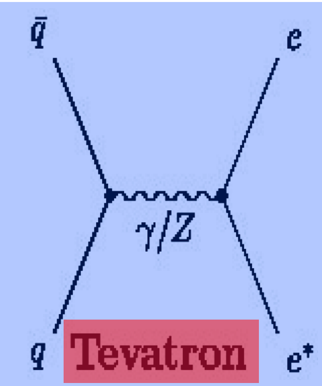


<u>ν^* search:</u>

- signature: (ν or jets + PTmissing)
- Not analysis yet

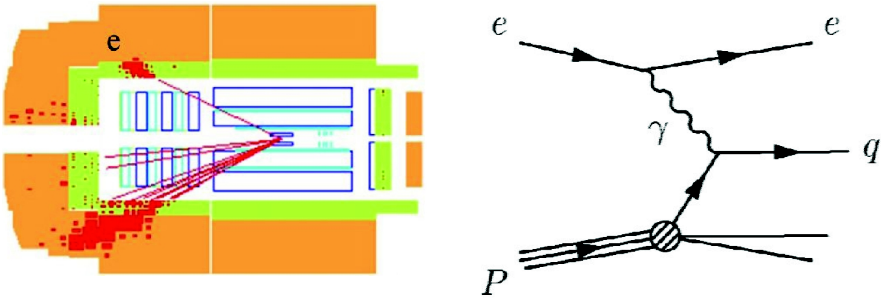
<u>e^* search:</u>

- Signature: (2e + γ) or (2e + jets)
- Look for (2e+γ) e^* in both CI & GM model

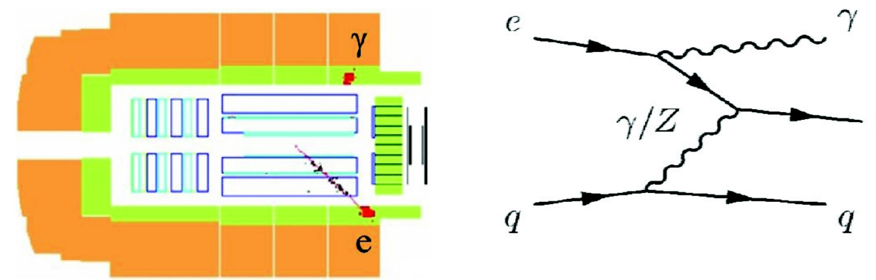


Main SM processes at HERA

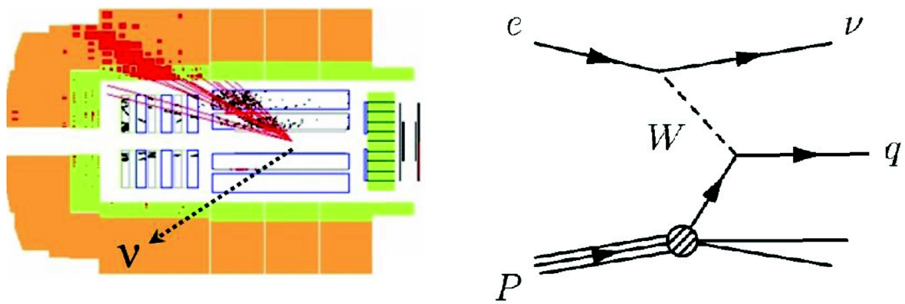
- Neutral Current DIS: $ep \rightarrow e X$



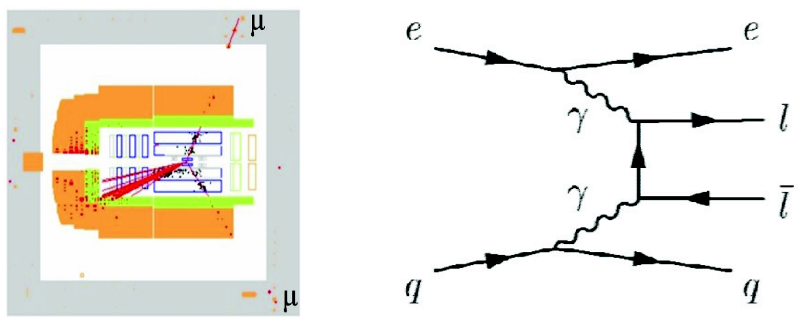
- QED Compton: $ep \rightarrow e\gamma X$



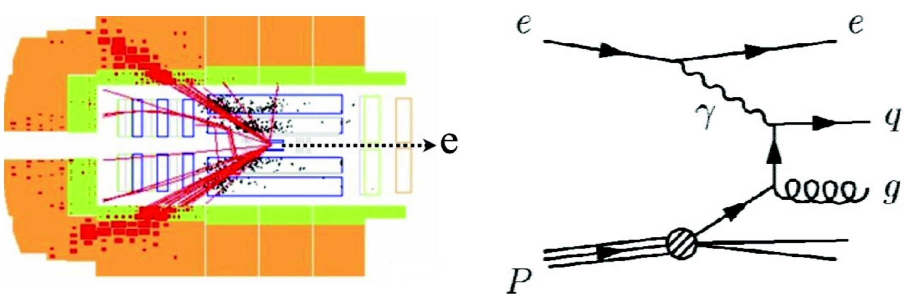
- Charged Current DIS: $ep \rightarrow \nu X$



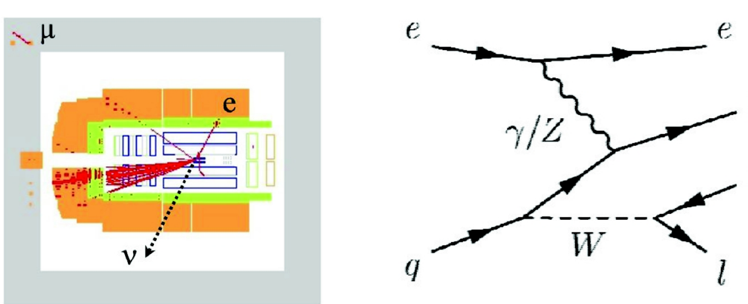
- Lepton pair production: $ep \rightarrow ell X$



- Photoproduction: $\gamma p \rightarrow X$



- W production: $ep \rightarrow eW X$



Taking data for analysis

- Data samples taken by the H1 experiment used in this search for excited leptons

HERA periods/Collisions	$\mathscr{L}(pb^{-1})$
HERA-I (e^-p)	14.2
HERA-I (e^+p)	103
HERA-II (e^-p)	170.1
HERA-II (e^+p)	184
Total	184.3 (e^-p)
	287 (e^+p)
	471.3 $(e^{\pm}p)$

published (HERA-I)

(N. Delerue PhD thesis, CPPM)

new data sets (HERA-II)

184.3 (e^-p): Used to look for ν^*

471.3 $(e^{\pm}p)$: Used to look for e*

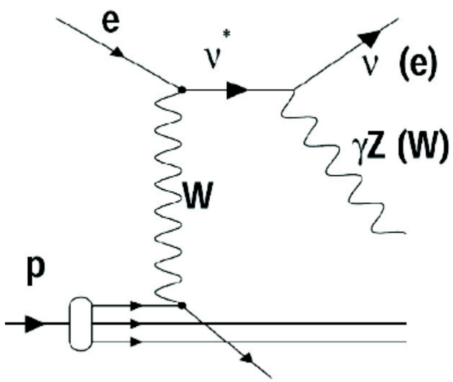
Note: for ν^*, $\sigma(e^-p)/\sigma(e^+p) \sim 100$

due to favourable valence u-quarks and helicity enhancement

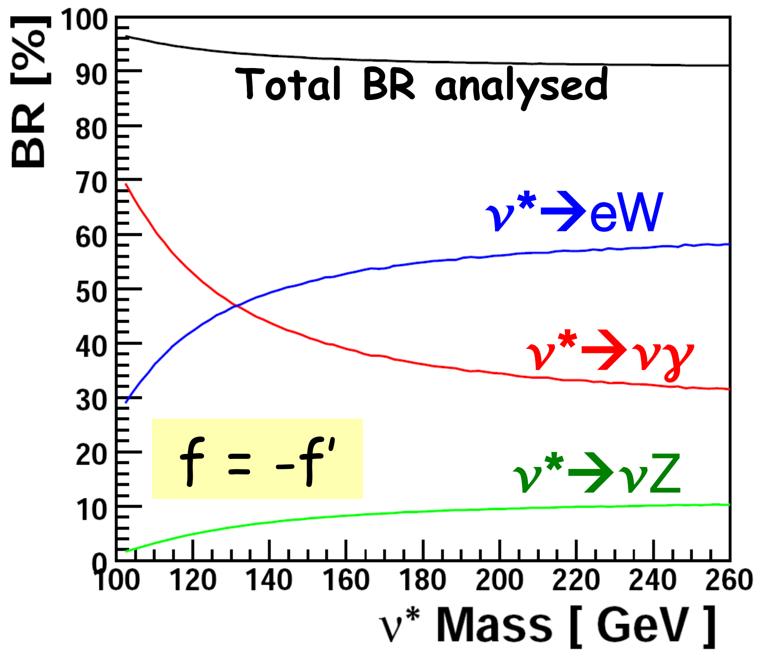
↳ Using full HERA I+II data set

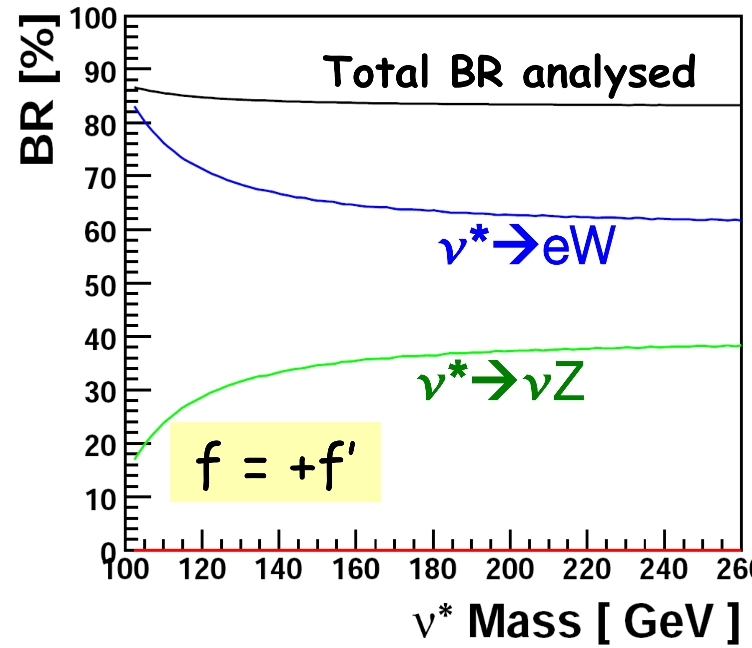
Excited neutrinos search

- Almost all ν^* decay topologies are investigated



Decay	Signature	Main SM Background
$\nu^* \to \nu\gamma$	$\gamma + P_T^{miss}$	Radiative CC-DIS
$\nu^* \to eW_{\hookrightarrow qq}$	e + 2jets	NC-DIS+ 2jets
$\nu^* \to \nu Z_{\hookrightarrow qq}$	P_T^{miss} + 2jets	CC-DIS+ 2jets
$\nu^* \to \nu Z_{\hookrightarrow ee}$	2e + P_T^{miss}	NC-DIS
$\nu^* \to eW_{\hookrightarrow e\nu}$	2e + P_T^{miss}	W production
$\nu^* \to eW_{\hookrightarrow \mu\nu}$	e + μ + P_T^{miss}	μ-pairs

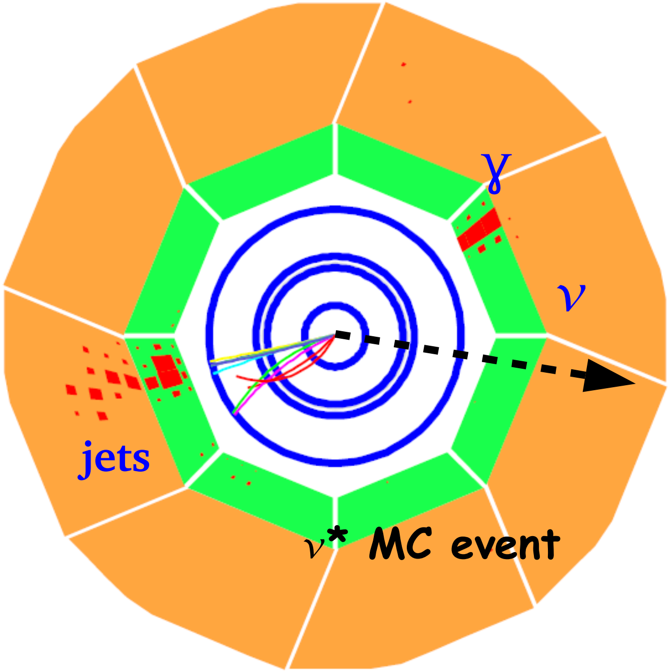




Search for ν^*: radiative decay

$\nu^* \rightarrow \nu\gamma$

- Radiative CC-DIS
  - Isolated electromagentic deposit
  - No track associated
  - $P^{miss}_T > 15$ GeV
  - Reduce main background (CC-DIS) :
    - $P^{\gamma}_T > 20$ GeV
    - $E-P_z > 45$ GeV or $P^{\gamma}_T > 40$ GeV



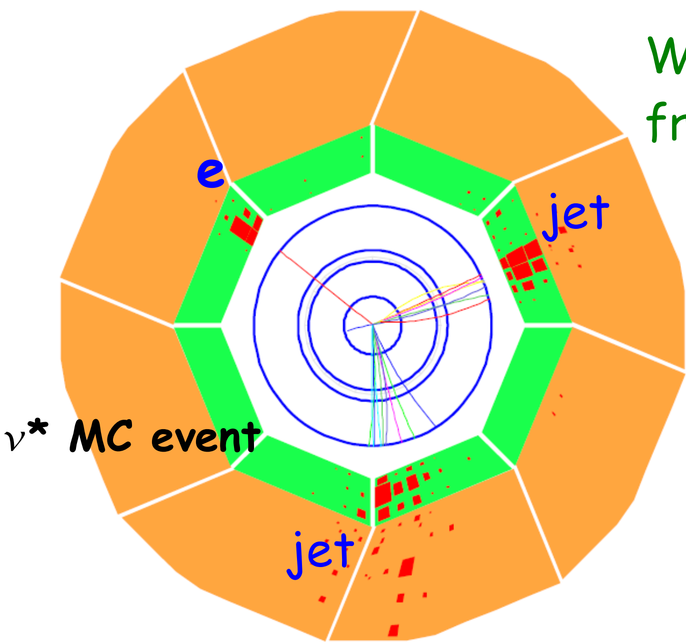
Search for ν^*: multi-jets decay

$\nu^* \rightarrow eW$

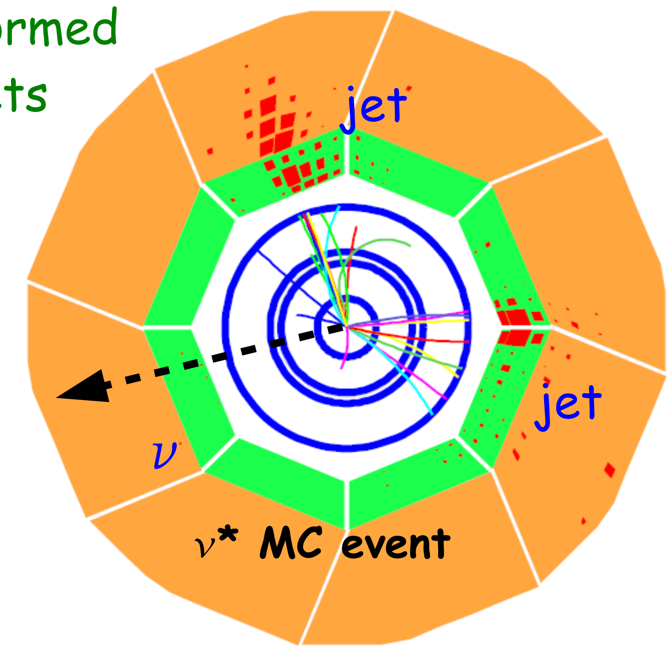
- NC-DIS + 2jets
- P^e_T > 10 GeV
- $P_T^{jet1,2}$ > 20,15 GeV
- Reduce NC-DIS:
  - $Q^2_e > 2500$ GeV^2 if P_t^e < 25 GeV

$\nu^* \rightarrow \nu Z$

- CC-DIS + 2jets
- $P_T^{jet1,2}$ > 20,15 GeV
- P_T^{miss} > 15 GeV
- Reduce CC-DIS, γP:
  - E-Pz> 25 GeV or P_T^{miss} > 50 GeV
  - Vap/Vp > 0.1



W/Z candidate is formed from 2 highest P_T jets



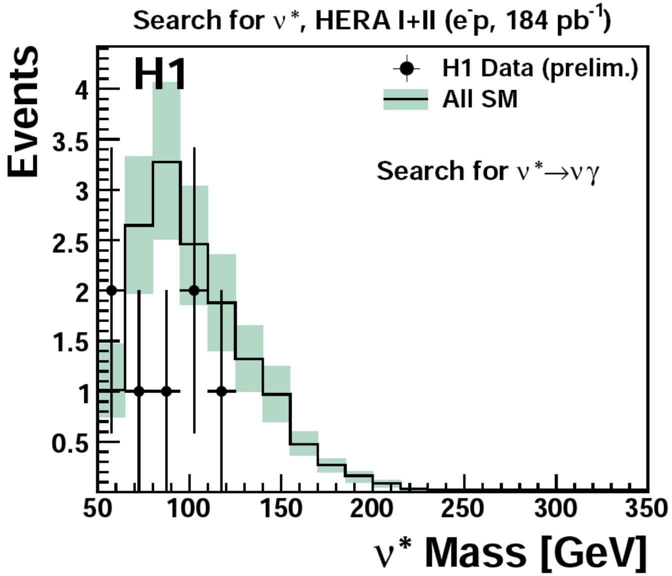
Results for ν^*

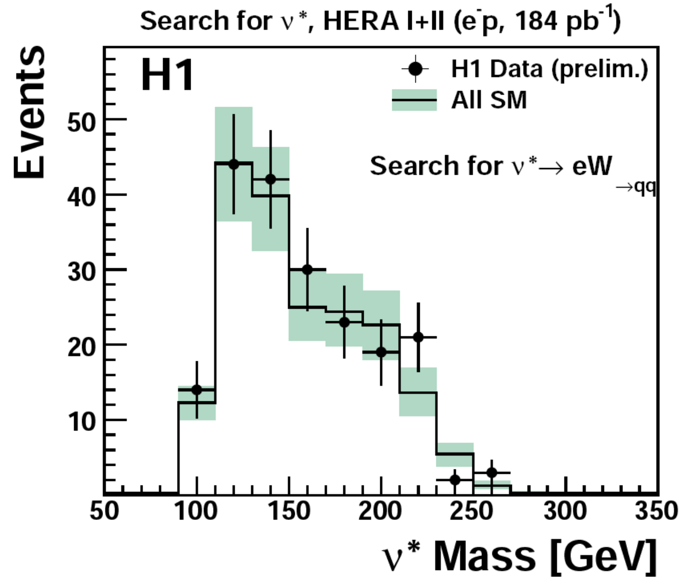
- Total event yields in each decay channel:

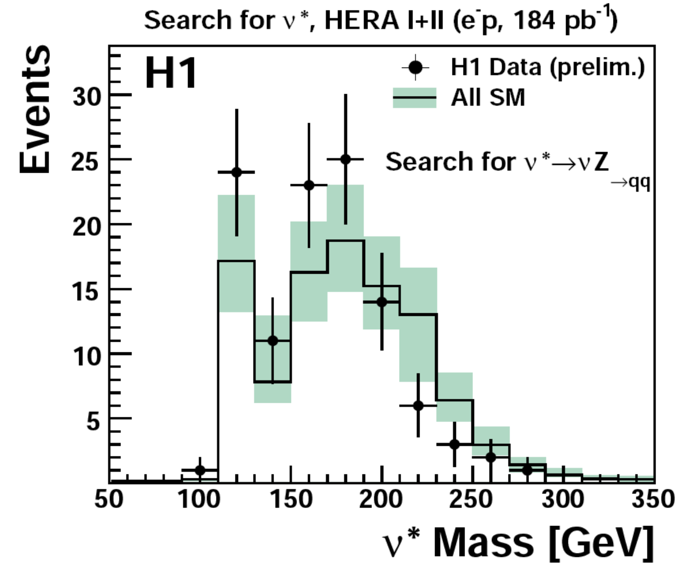
Search for ν^*, HERA I+II (e^-p, 184 pb^{-1}, preliminary)

Selection	Data	SM	Efficiency $\times$ BR
$\nu^* \to \nu\gamma$	9	15 ± 4	50 %
$\nu^* \to eW_{\hookrightarrow qq}$	198	189 ± 33	30–40 %
$\nu^* \to \nu Z_{\hookrightarrow qq}$	111	102 ± 24	40 %
$\nu^* \to eW_{\hookrightarrow \nu\mu}$	0	0.54 ± 0.04	3–4.5 %
$\nu^* \to eW_{\hookrightarrow \nu e}$	0	0.6 ± 0.3	4–6 %
$\nu^* \to \nu Z_{\hookrightarrow ee}$	0	0.12 ± 0.04	2 %

- Invariant mass distributions for 3 main channels:







↳ In all channels: good agreement between data and SM prediction

↳ No significant deviation from the SM prediction => exclusion regions (f/Λ, M_{ν^*})

Limit calculation

- Use the Modified frequentist approach (T. Junk)

[Nucl.Instrum.Method.A434, 435, 1999]

  - Define a **test statistic** X:

For each i^th channel: (s_i, b_i, d_i : expected signal, background, observed candidates)

$$X_i = \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!} \Big/ \frac{e^{-b_i} b_i^{d_i}}{d_i!} \quad \text{and} \quad X = \Pi_{i=1}^{n} X_i$$

  - Define a **confidence level** CL:

$$\left.\begin{aligned} CL_{s+b} &= P_{s+b}\left(X \le X_{obs}\right) \\ CL_b &= P_b\left(X \le X_{obs}\right) \end{aligned}\right\} CL_s = \frac{CL_{s+b}}{CL_b}$$

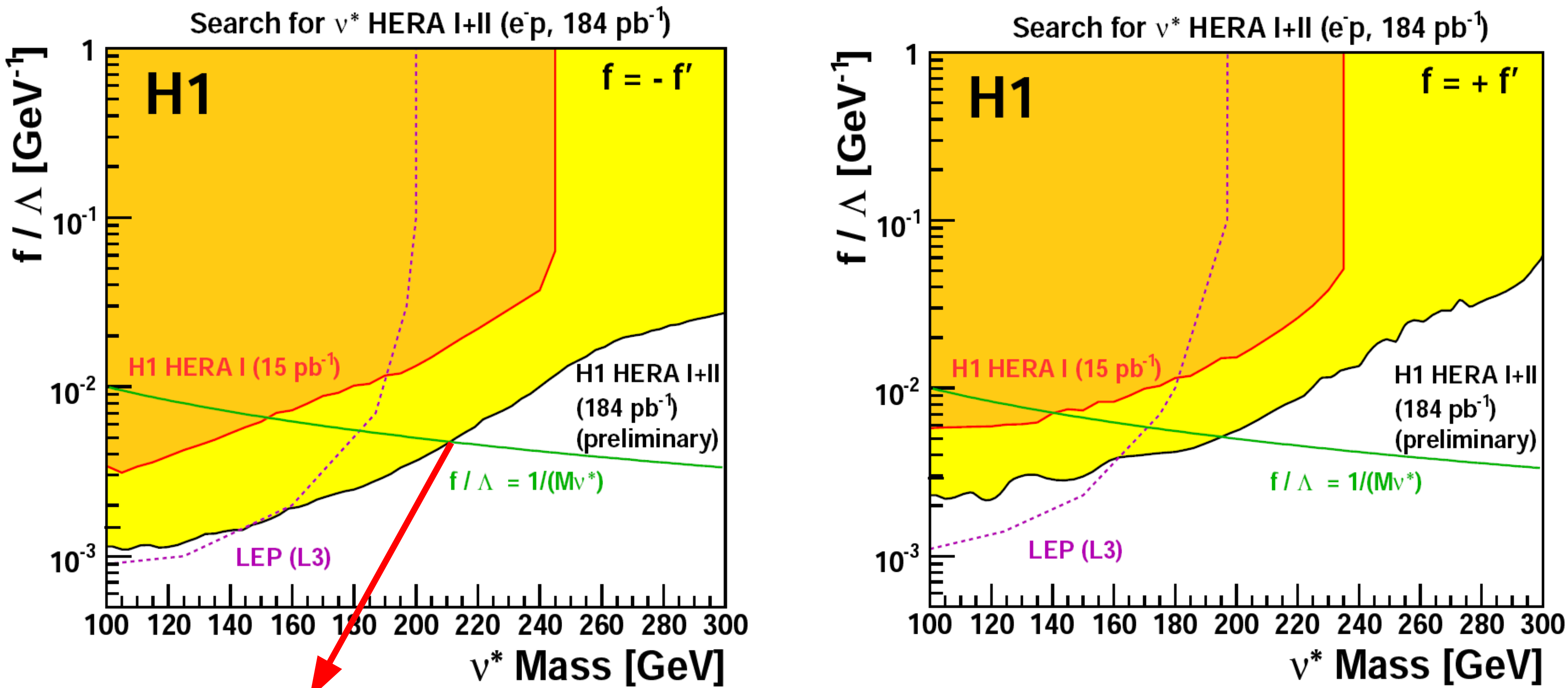
(Modified Frequentist CL)

  - 95% CL upper limit (N_{lim}) on the signal such that: $CL_s \le 0.05$

- Systematics taken into account

Preliminary Result: new domain limit

- 95% C.L. exclusion limits:

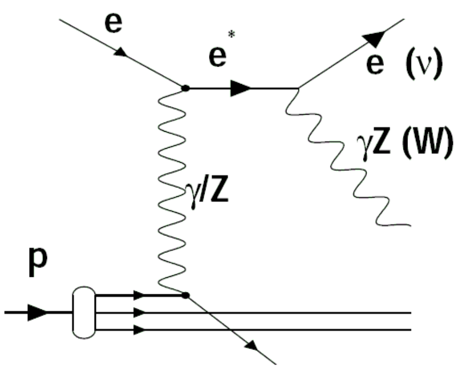


- For $f = -f'$ and $f/\Lambda = 1/M_{\nu^*}$: $M_{\nu^*} < 211$ GeV are excluded

- the new H1 limits greatly extend the previous searched domains at HERA
- better sensitivity at HERA for ν^* with masses beyond the LEP reach

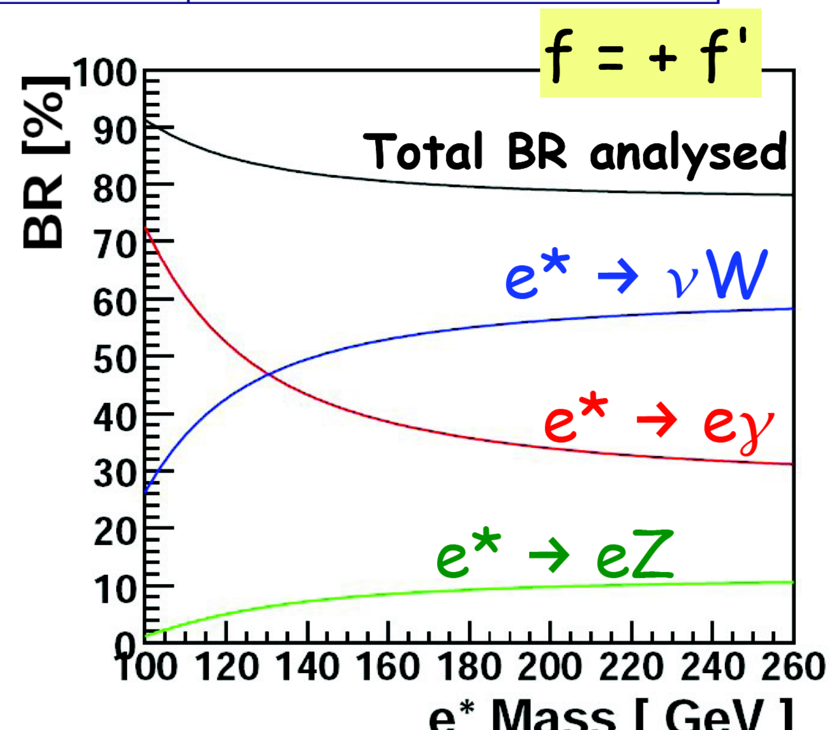
Excited electrons search

- Almost all e* decay topologies are investigated



Decay	Signature	Main SM Background
$e^* \to e\gamma$	2 e.m clusters	QED-Compton, NC-DIS, $\gamma\gamma$
$e^* \to eZ_{\hookrightarrow qq}$	electron + 2jets	NC-DIS, γP
$e^* \to \nu W_{\hookrightarrow qq}$	P_T^{miss} + 2jets	NC/CC-DIS, γP
$e^* \to eZ_{\hookrightarrow ee}$	3 electrons	NC-DIS, $\gamma\gamma$
$e^* \to eZ_{\hookrightarrow \nu\nu}$	electron + P_T^{miss}	W production,$\gamma\gamma$
$e^* \to eZ_{\hookrightarrow \mu\mu}$	electron + 2 μ	$\gamma\gamma$
$e^* \to \nu W_{\hookrightarrow e\nu}$	electron + P_T^{miss}	W production, $\gamma\gamma$

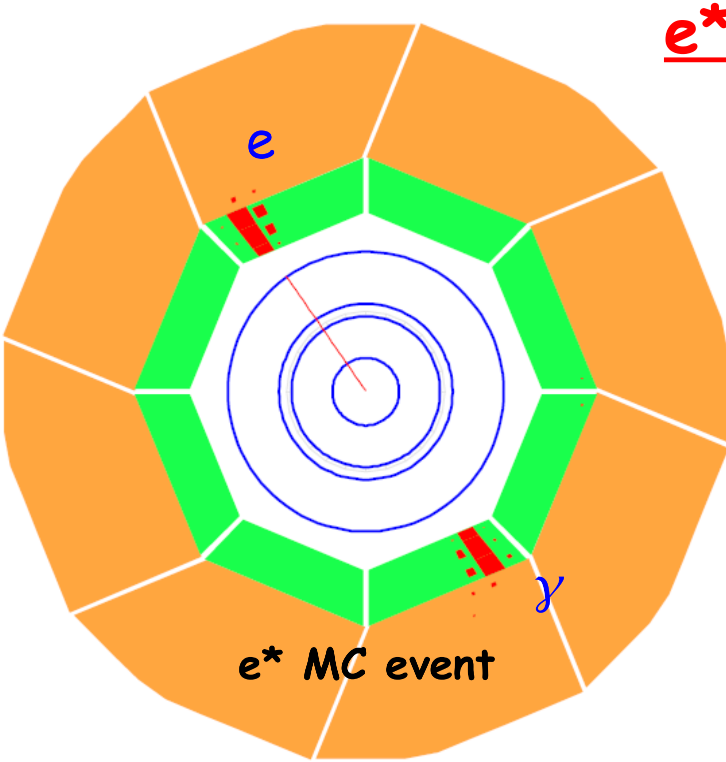
☞Signatures similar to ν^*



- If f = -f' ☞ $C_{\gamma e^* e}$ = 0 : the cross section in this case is very small

↳Study only the case f = +f'

How to look for excited electrons



$e^* \rightarrow e\,\gamma$

- At least two isolated em. deposits
  - $P^{e,\gamma}_T$ > 20,15 GeV
  - No track associated to 2nd em. cluster
- Reduce QED-Comptons background :
  - $P^e_T + P^\gamma_T > 75$ GeV
  - $E^e + E^\gamma > 100$ GeV

$e^* \rightarrow \nu\, W$ → P_T^{miss} + at least 2 jets , similar to $\nu^* \rightarrow \nu Z$

$e^* \rightarrow e\, Z$ → e + at least 2 jets , similar to $\nu^* \rightarrow eW$

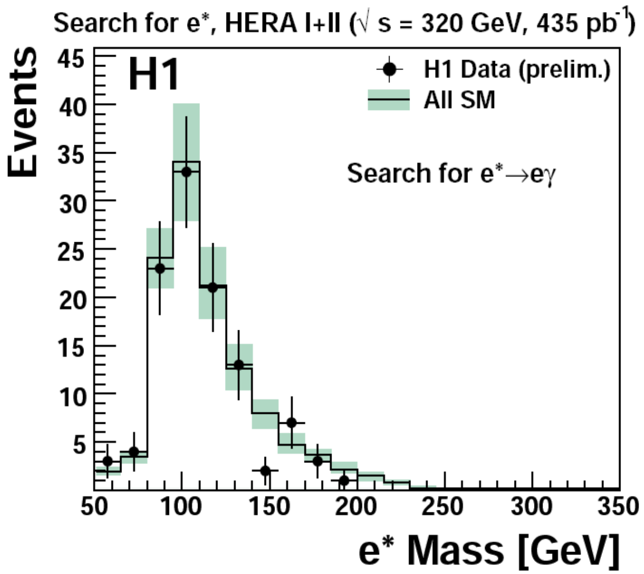
Preliminary Result for e*

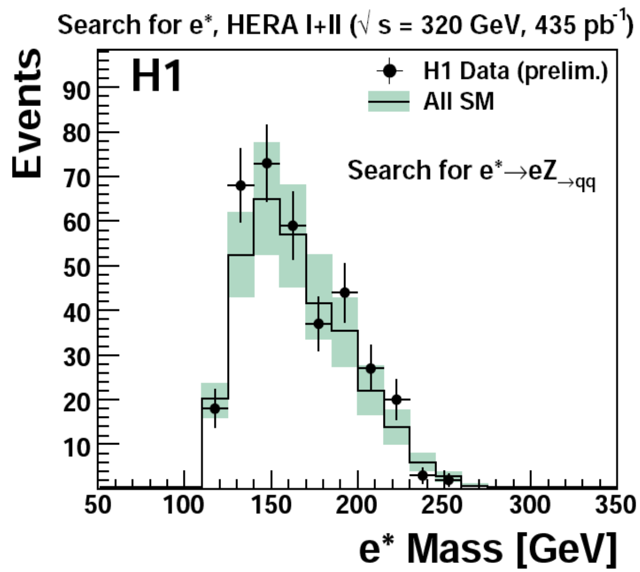
- Total event yields in each decay channel:

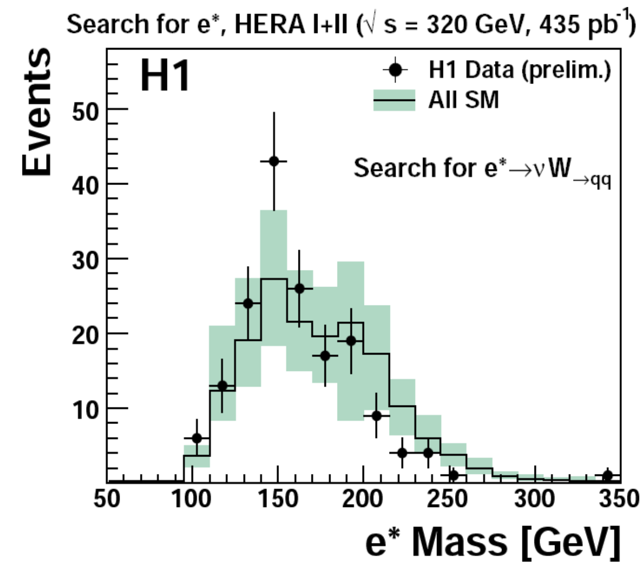
Search for e* HERA I+II ($\sqrt{s} = 320$ GeV, 435 pb^{-1}, preliminary)

Selection	Data	SM	Efficiency × BR
$e^* \to \nu W_{\hookrightarrow qq}$	172	175 ± 39	~ 40 %
$e^* \to e Z_{\hookrightarrow qq}$	351	318 ± 64	~ 45 %
$e^* \to e\gamma$	112	125 ± 19	60–70 %

- Invariant mass distributions for 3 main channels:





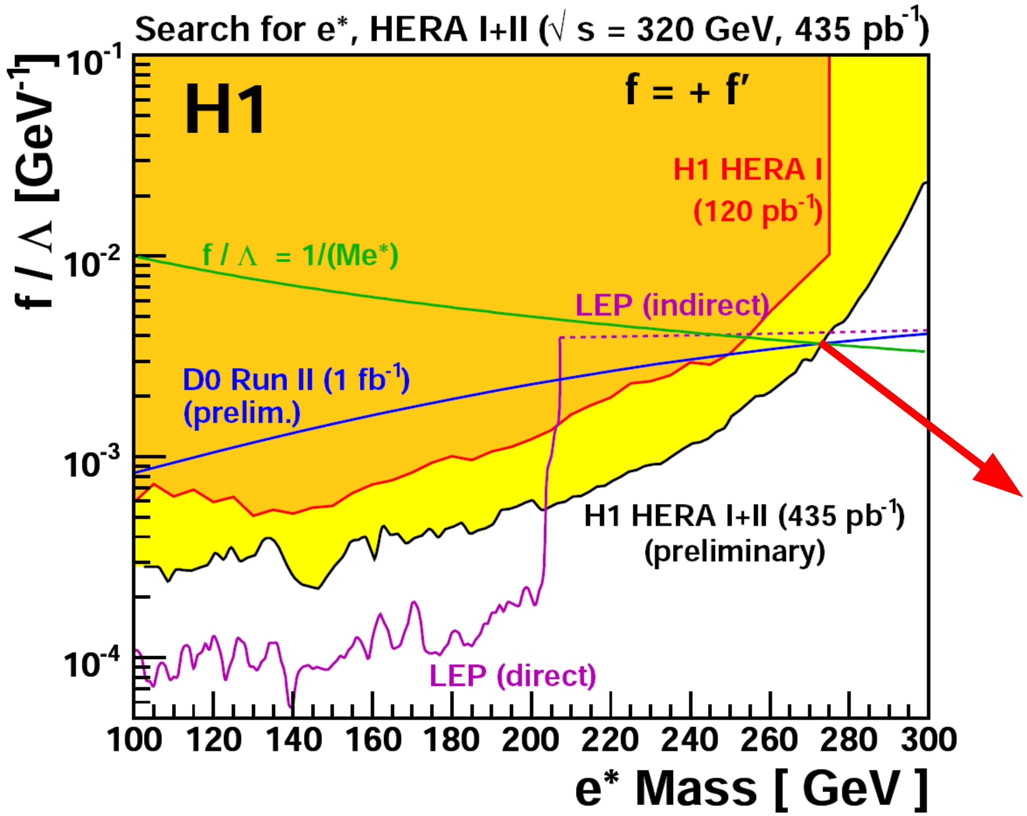


↳ In all channels: good agreement between data and SM prediction

↳ No significant deviation from the SM prediction => exclusion regions (f/Λ, M_{e^*})

Preliminary Result: new domain limit

- 95% C.L. exclusion limits:
  - analysis of all $\sqrt{s}$ =320 GeV data made preliminary for DIS 2007 conference
  - only 3 main decay channels included, leptonic decay of Z/W not included



New domain explored. The combined limit is dominated by the limit of the decay $e^* \to e\gamma$

if $f/\Lambda = 1/M_{e^*}$: $M_{e^*} < 273$ GeV are excluded

At high mass: new H1 limit are more stringent than present LEP or Tevatron results

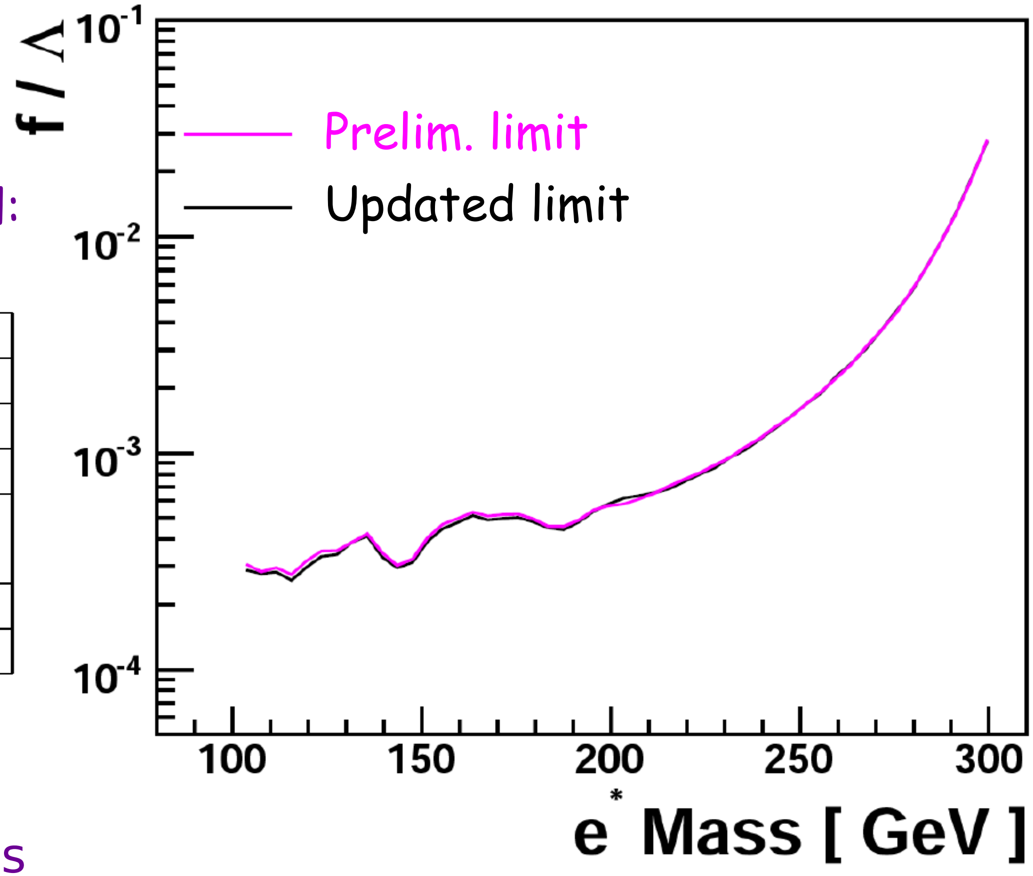
Update of e* analysis

- 2 improvements since prelim. result:
  - ➔ adding the leptonic decay of Z/W boson
  - ➔ adding $\sqrt{s}$=300 GeV data: ➔ all HERA data has been analysed: 472 pb^{-1}

- Total event yields in each decay channel:

Search for e*, all HERA I+II ($e^{\pm}p$, 472 pb^{-1})

Selection	Data	MC	Efficiency$\times BR$
$e^* \to e\gamma$	116	134 $\pm$ 20	60 – 75%
$e^* \to eZ_{\hookrightarrow qq}$	328	294 $\pm$ 64	~45%
$e^* \to \nu W_{\hookrightarrow qq}$	176	180 $\pm$ 49	~40%
$e^* \to \nu W_{\hookrightarrow e\nu}$ $e^* \to eZ_{\hookrightarrow \nu\nu}$	27	17$\pm$6.5	~15%
$e^* \to eZ_{\hookrightarrow ee}$	2	2.25$\pm$0.8	~2%
$e^* \to eZ_{\hookrightarrow \mu\mu}$	0	0.46$\pm$0.14	~1.5%



➘ no excess found in additional channels

➘ small effect on derived limit, but channels and extra data included for completeness

Conclusion

- The search for excited leptons (e^*, ν^*) in the full $e^{\pm}p$ HERA I+II data collected by the H1 at $\sqrt{s}$ = 300 GeV and $\sqrt{s}$ = 320 GeV has been presented

  - Almost all decay channels investigated
  - In all channels: Data and SM predictions in good agreement

- No evidence of excited leptons has been found

Upper limits at 95% C.L. are derived

  - For ν^*: M_{ν^*} < 211 GeV are excluded ($f=-f'$ & $f/\Lambda=1/M_{\nu^*}$)
  - For e^*: M_{e^*} < 273 GeV are excluded ($f=+f'$ & $f/\Lambda=1/M_{e^*}$)

- Presently the most stringent world limits on high masses e^* and ν^*

- **Perspectives:**

☺ Plan: Publish as soon as possible

To extract limit on ($\sigma\times$BR) and f/Λ

- Limits on ($\sigma\times$BR):

  ☞ The data used having the different centre-of-mass energy ($\sqrt{s}$ = 300, 320 GeV)

  ➘ Limits on ($\sigma\times$BR) at $\sqrt{s}$ = 320 GeV is defined as:

$$(\sigma^{\sqrt{s}=320}\times BR)_{lim} = \frac{N_{obs}}{\frac{\sigma^{\sqrt{s}=300}}{\sigma^{\sqrt{s}=320}}L_{\sqrt{s}=300} + L_{\sqrt{s}=320}}$$

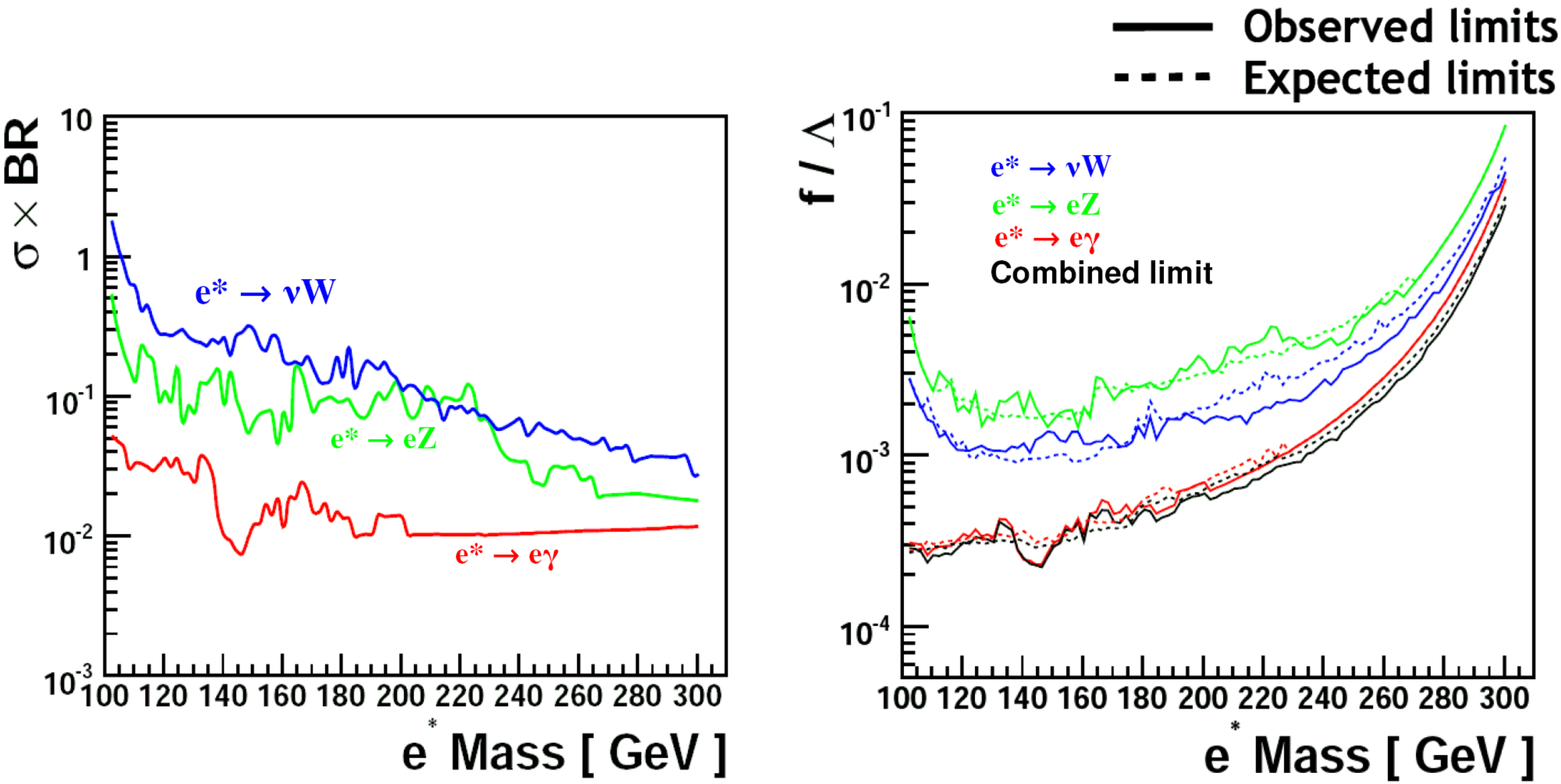
- Limits on f/Λ:

  ➘ Combined all HERA data with different $\sqrt{s}$ = (300, 320 GeV)

$$(\frac{f}{\Lambda})_{lim} = \frac{\frac{N_{obs}}{L_{\sqrt{s}=300}+L_{\sqrt{s}=320}}}{\sigma^{\sqrt{s}=320}\frac{L_{\sqrt{s}=320}}{L_{\sqrt{s}=300}+L_{\sqrt{s}=320}} + \sigma^{\sqrt{s}=300}\frac{L_{\sqrt{s}=300}}{L_{\sqrt{s}=300}+L_{\sqrt{s}=320}}}$$

New domain explored limit : e* search

- 95% C.L. exclusion limit for each decay channel:



New domain explored. The combined limit is dominated by the limit of the decay $e^* \to e\gamma$

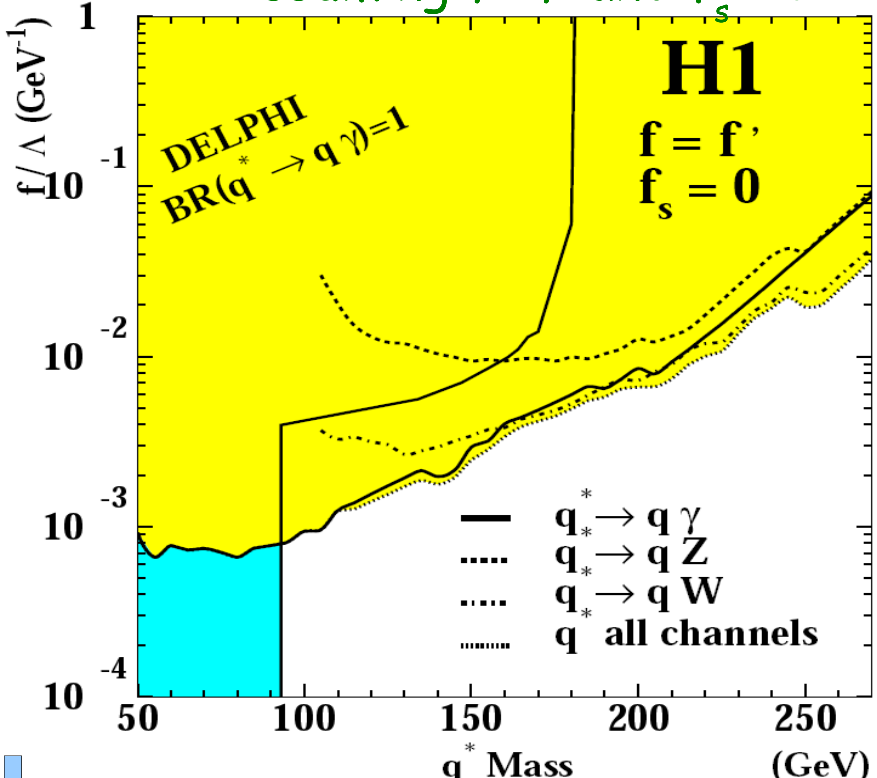
Systematic errors

- Electron energy scale: 1% -> 3% depending on z_e
- Hadrons energy scale: 2%
- θ electron: 3 mrad
- θ jets: 10 mrad central, 5 mrad forward
- Photon identification: 5%
- V_{ap}/V_p cut: 10%
- Processes: gP: 15%, NC and CC >= 2jets: 15% and 20%, W: 15%
- Triggers: 3%
- Lumi: 2%

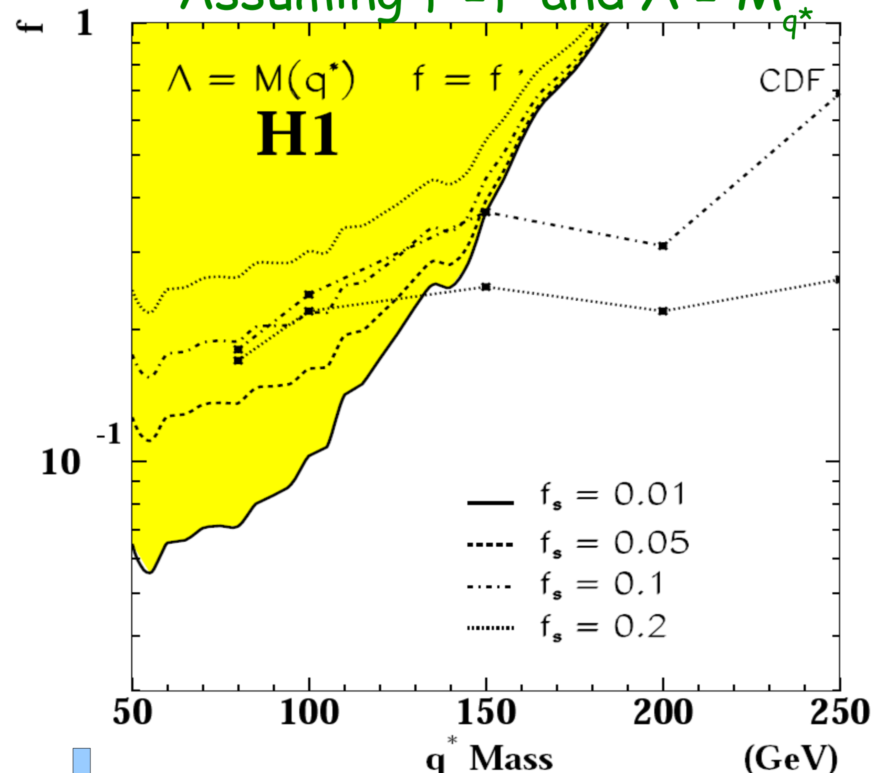
Search for q* (status)

- Search for q* using the data obtained during 94-97 period

Assuming f =f' and f_s = 0



Assuming f =f' and Λ = M_{q*}



- H1 limits extend the excluded region to higher masses than reached in DELPHI

- H1 more sensitive than CDF at small f_s

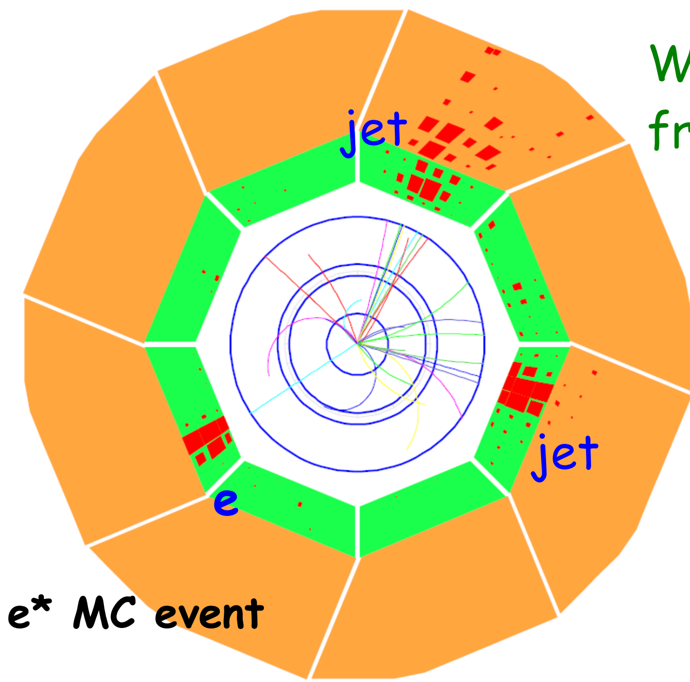
Search for e*: multi-jets decay

$e^* \rightarrow e\,Z$

- NC DIS + 2jets
  - $P^e_T > 20$ GeV
  - $P_T^{jet1,2} > 20{,}15$ GeV
  - Reduce NC:
    - $M_{jj} > M_Z$ - 15 GeV if $P^e_T < 65$ GeV
    - $\theta^{jet1} < 80$ degrees

$e^* \rightarrow \nu\,W$

- CC DIS + 2jets
  - $P_T^{jet1,2} > 20{,}15$ GeV
  - $P_T^{miss} > 15$ GeV
  - Reduce CC, γP:
    - Vap/Vp < 0.3
    - $M_{jj} > M_W$ - 15 GeV if $E^{miss} < 65$ GeV



W/Z candidate is formed from 2 highest P_T jets