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DIS03 Conference

Multi–Lepton events at HERA

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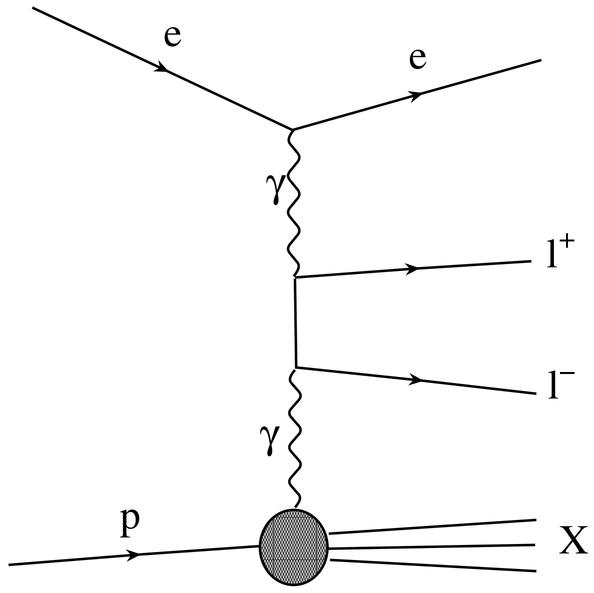
Outline

- Introduction
- Di–muon events at H1 and ZEUS
- Multi–electron events at H1 and ZEUS
- Search for Doubly–Charged Higgs at H1
- Conclusions

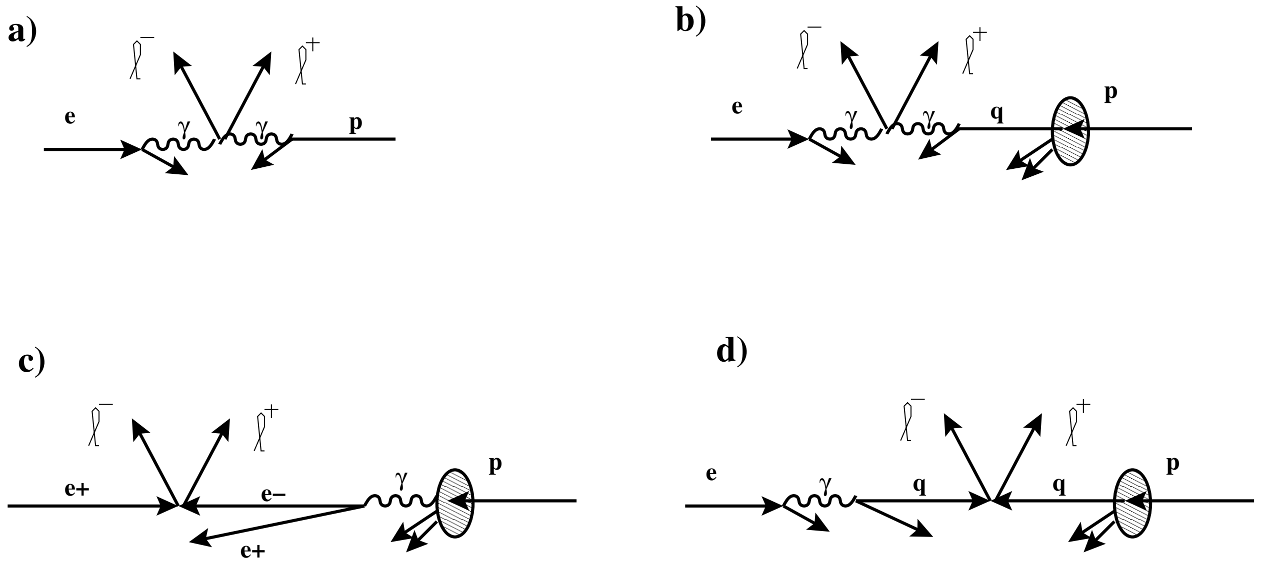
Introduction

- Multi–lepton production at high P_T proceeds mainly through 2 photon process: $ep \to e(\gamma\gamma)X \to el^+l^-X$
- BKG to Multi–e search:
  - NC–DIS (DIS e + fake electron)
  - Elastic Compton (γ misidentified as e)



→ SM expectation (QED) is well known; DATA–MC comparison is a good test for new physics

Multi–lepton production at HERA



- a) and b) $\gamma\gamma$ processes: dominate the cross–section
- c) Cabibbo–Parisi process (elastic or inelastic):

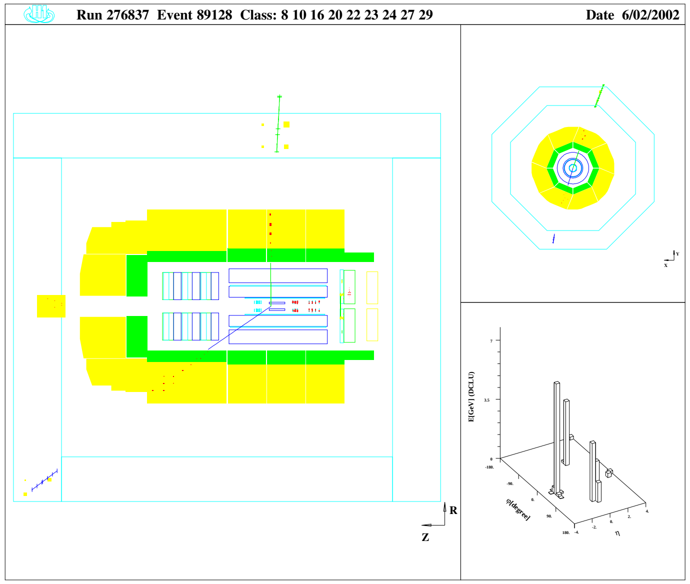
1 order of magnitude below (except at high–P_T)

- d) Drell–Yan process: negligible
- GRAPE Monte Carlo simulates a) b) and c)

Di–Muons at H1

Data taking: 1999–00

Lumi used: 70.9 pb^{-1}



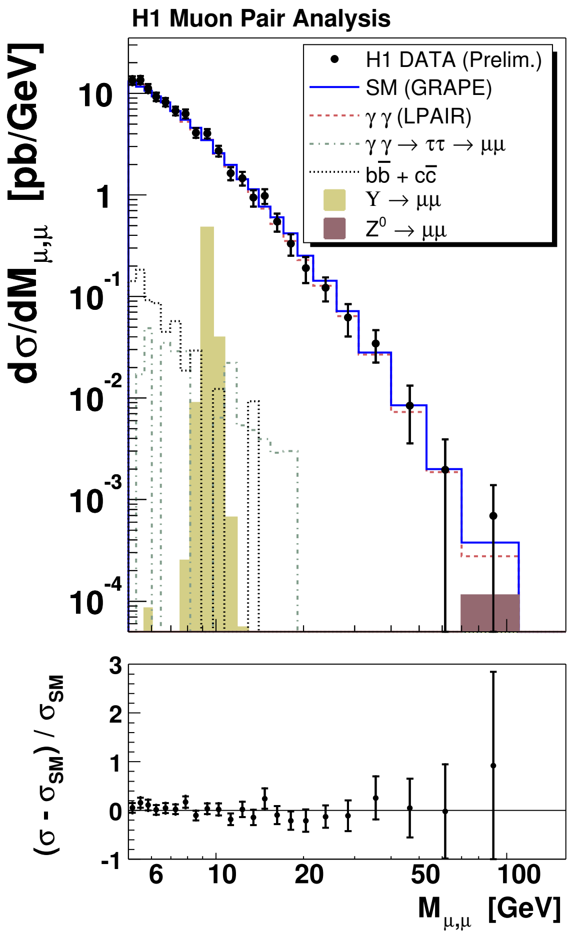
Muon Selection

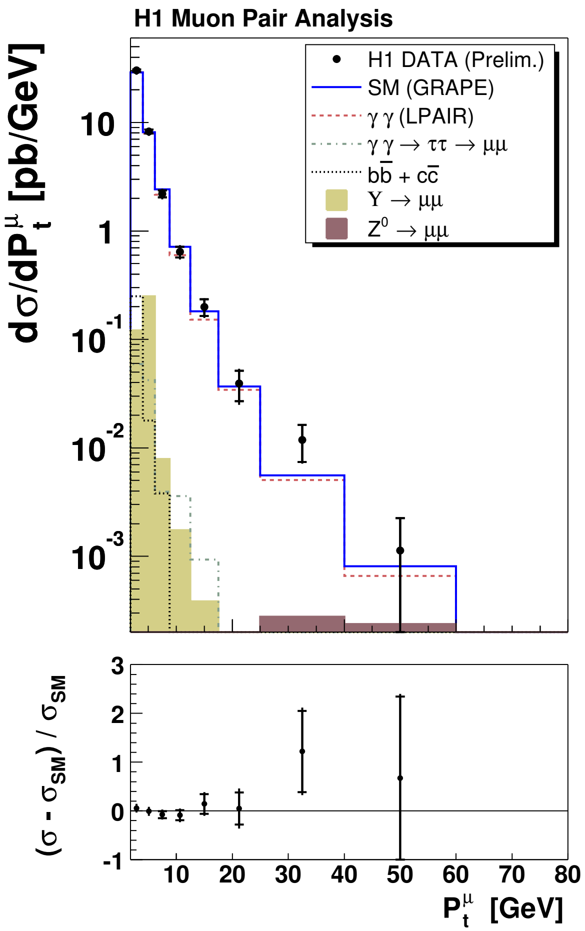
- Track in both CTD and Muon Detector
- Angular region: $20^o < \theta < 160^o$
- For low momentum μ's: Track + MIP

Event Selection

- Two muons: $P_T^{\mu 1} > 2.00$ GeV, $P_T^{\mu 2} > 1.75$ GeV
- Invariant mass cut: $M_{\mu\mu} > 5$ GeV
- Muon Isolation: $D^{\mu}_{\mathrm{Trk,jet}} > 1.0$ in η–ϕ (or $D^{\mu}_{\mathrm{Trk,jet}} > 0.5$ if $P^{\mu}_T > 10$ GeV)

Di–Muons at H1: Cross section



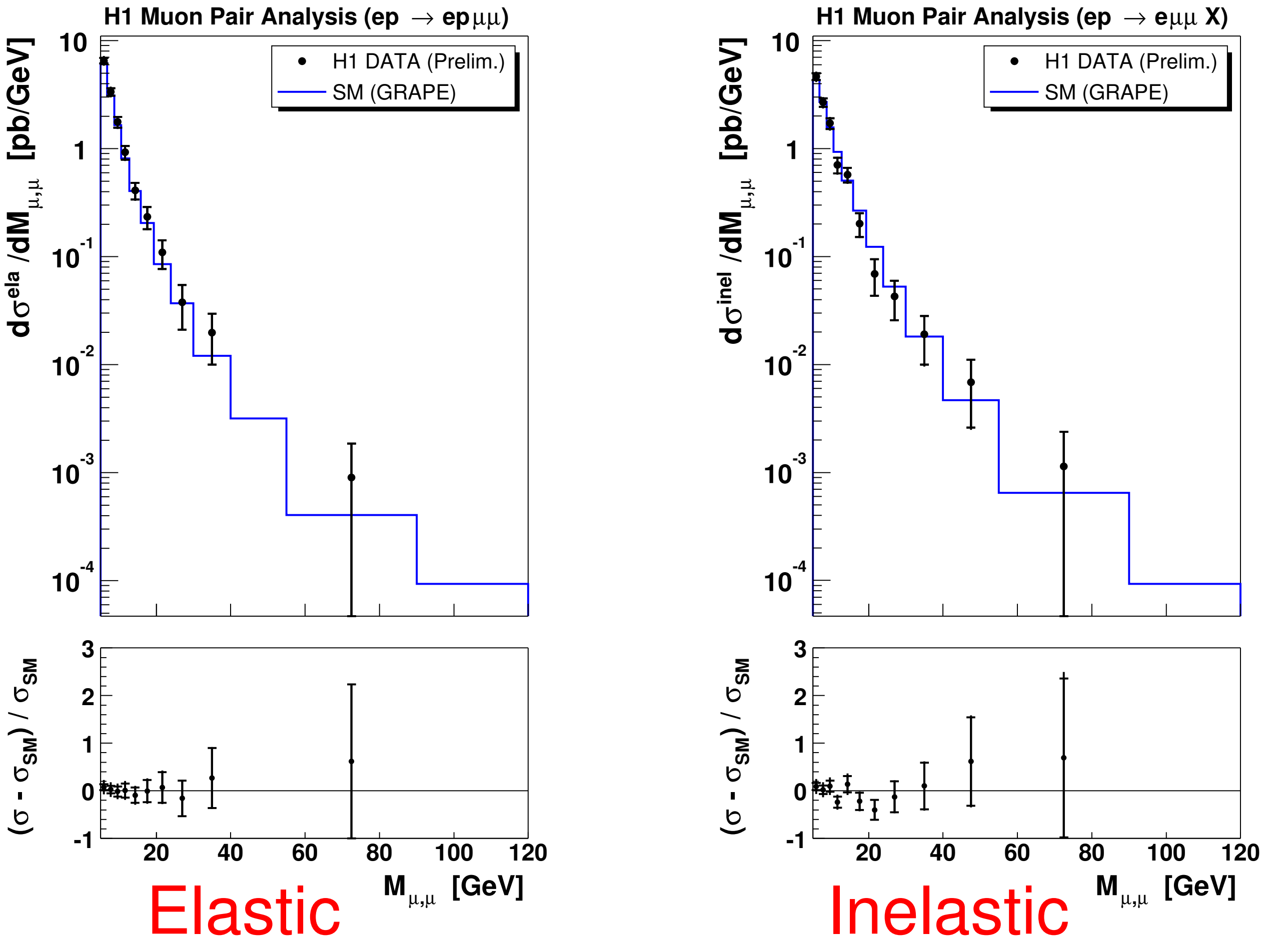


- Main contribution: $\gamma\gamma$ interaction
- Small contribution to $\mu^+\mu^-$ from: Υ, and Z^0 and $q\bar{q}$ decays

➡ Total Cross–Section: $\sigma = 46.5 \pm 1.3 \pm 4.7$ pb

➡ Good Agreement w/ SM: $\sigma(\mathrm{GRAPE}) = 46.2$ pb

Di–Muons at H1: Cross section

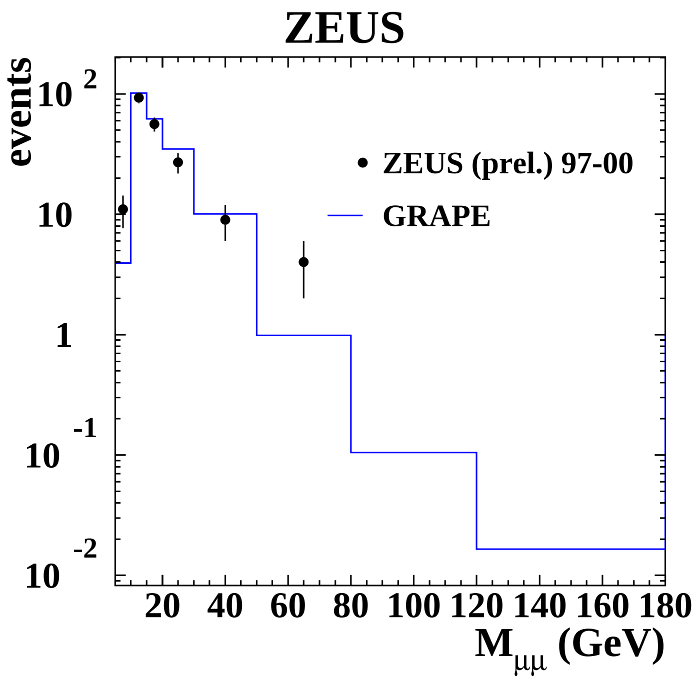


- Elastic and Inelastic separated by tagging proton remnant

➔ Inelastic Cross–Section: $\sigma^{\rm inel} = 20.8 \pm 0.9 \pm 3.3$ pb

➔ Good Agreement w/ SM: $\sigma^{\rm inel}(\rm GRAPE) = 21.5$ pb

Di–Muons at ZEUS



Data taking: 1997–00

Lumi used: 105.2 pb^{-1}

Muon Selection

- Track in CTD ($P_T >$ 5 GeV)+ MIP in CAL
- Angular region: $20^o < \theta < 160^o$

Event Selection

- Two muons: 1μ matched to muon chambers
- Muon Isolation: $N_{\rm trks}(R_{\eta\phi} < 1)$ = 0
- Good Vertex: $|Z_{\rm vtx}| <$ 40 cm, $\sqrt{X^2_{\rm vtx} + Y^2_{\rm vtx}} <$ 0.5 cm
- Acollinearity: $\cos(\Omega) >$ -0.995

Multi–electrons at H1

Data taking: 1994–00 Lumi used: 115.2 pb^{-1}

Event Selection

- Two "central" ($20^o < \theta < 150^o$),"isolated", electrons
- P_T cut: $P_T^{e1} > 10$ GeV, $P_T^{e2} > 5$ GeV

Event Classification

- "2e": Only 2 central electrons
- "3e/4e": Additional "isolated" electrons (also Forward and Rear)

"$\gamma\gamma$" subsample

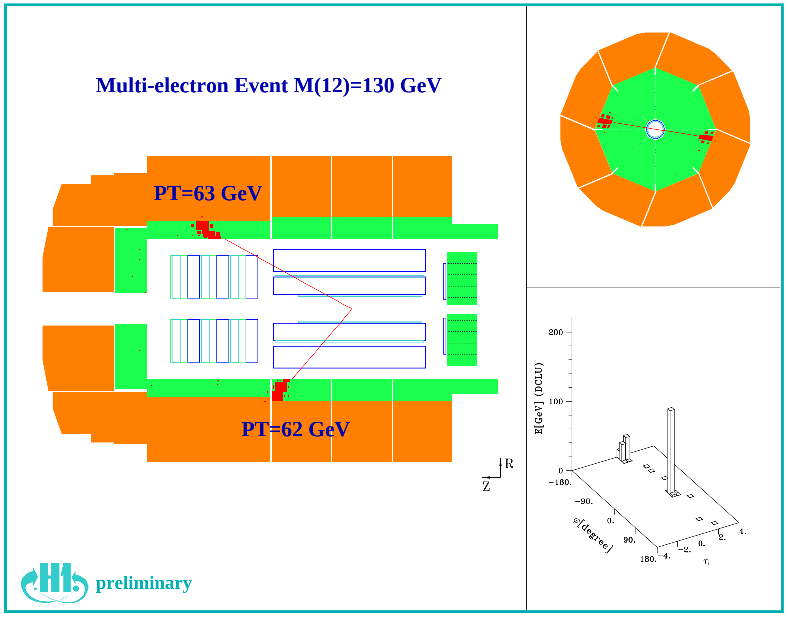
- Just 2 opposite charge electrons: $ep \rightarrow e^+e^-X$
- $E - P_z <$ 45 GeV (ie $y < 0.82$, $Q^2 < 1$ GeV^2)

→ "Cleaner" sample; scattered electron is lost in beam–pipe; both detected electrons come from interaction

Multi–electron events at H1

Different topology for “2e” and “3e” events:

A “2e” event:

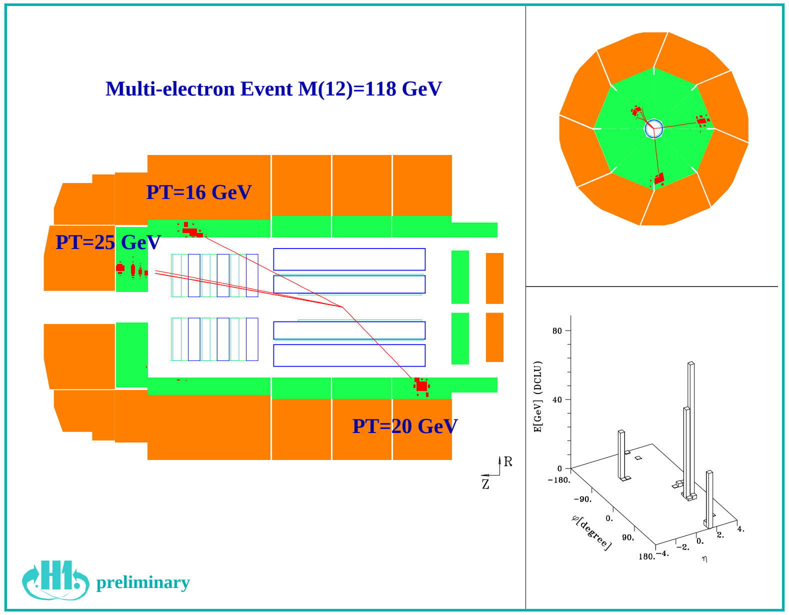


P_T^{e1} = 63 GeV, P_T^{e2} = 62 GeV

M_{12} = 130 GeV

Harder P_T in “2e”

A “3e” event:

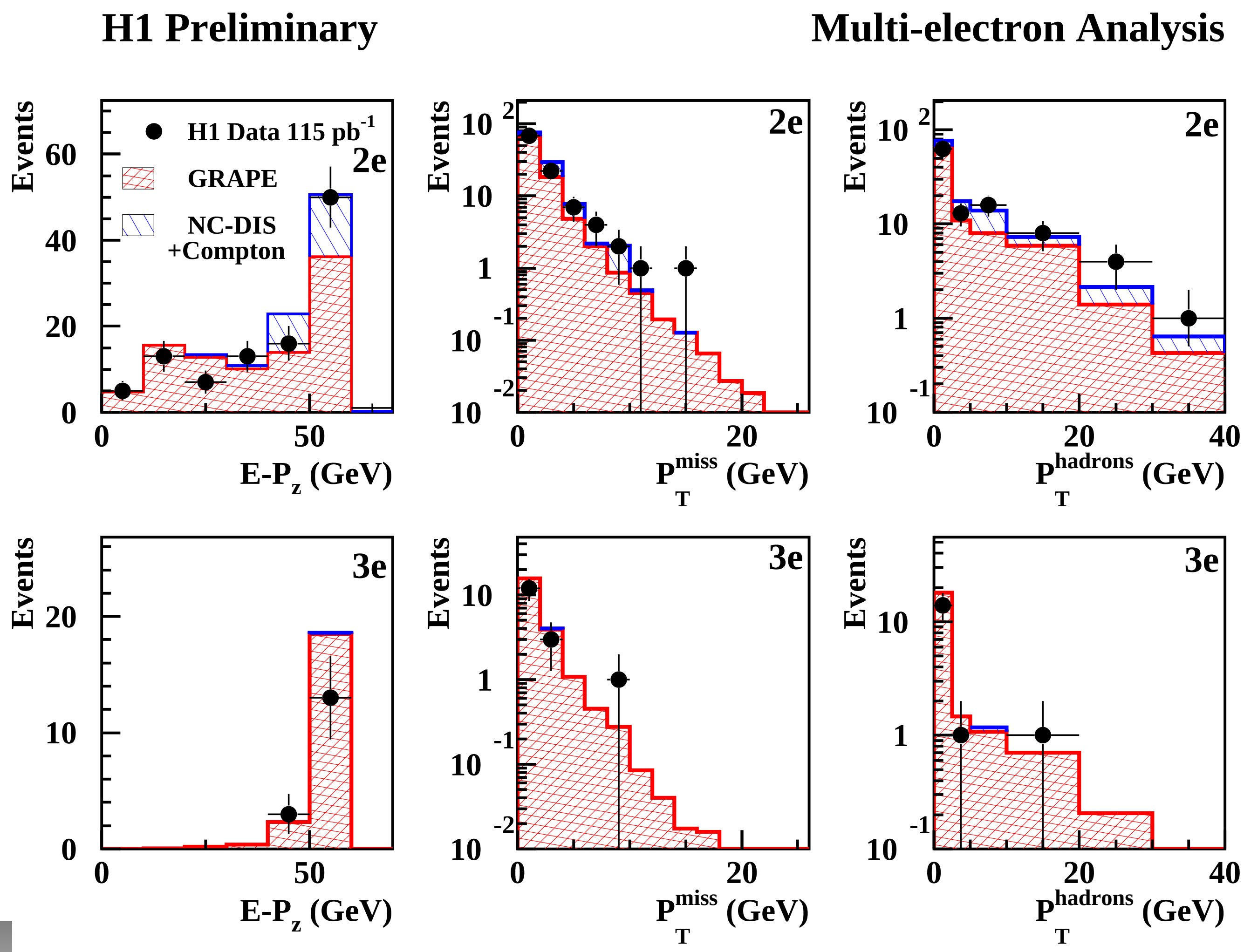


P_T^{e1} = 25 GeV, P_T^{e2} = 20 GeV

M_{12} = 118 GeV

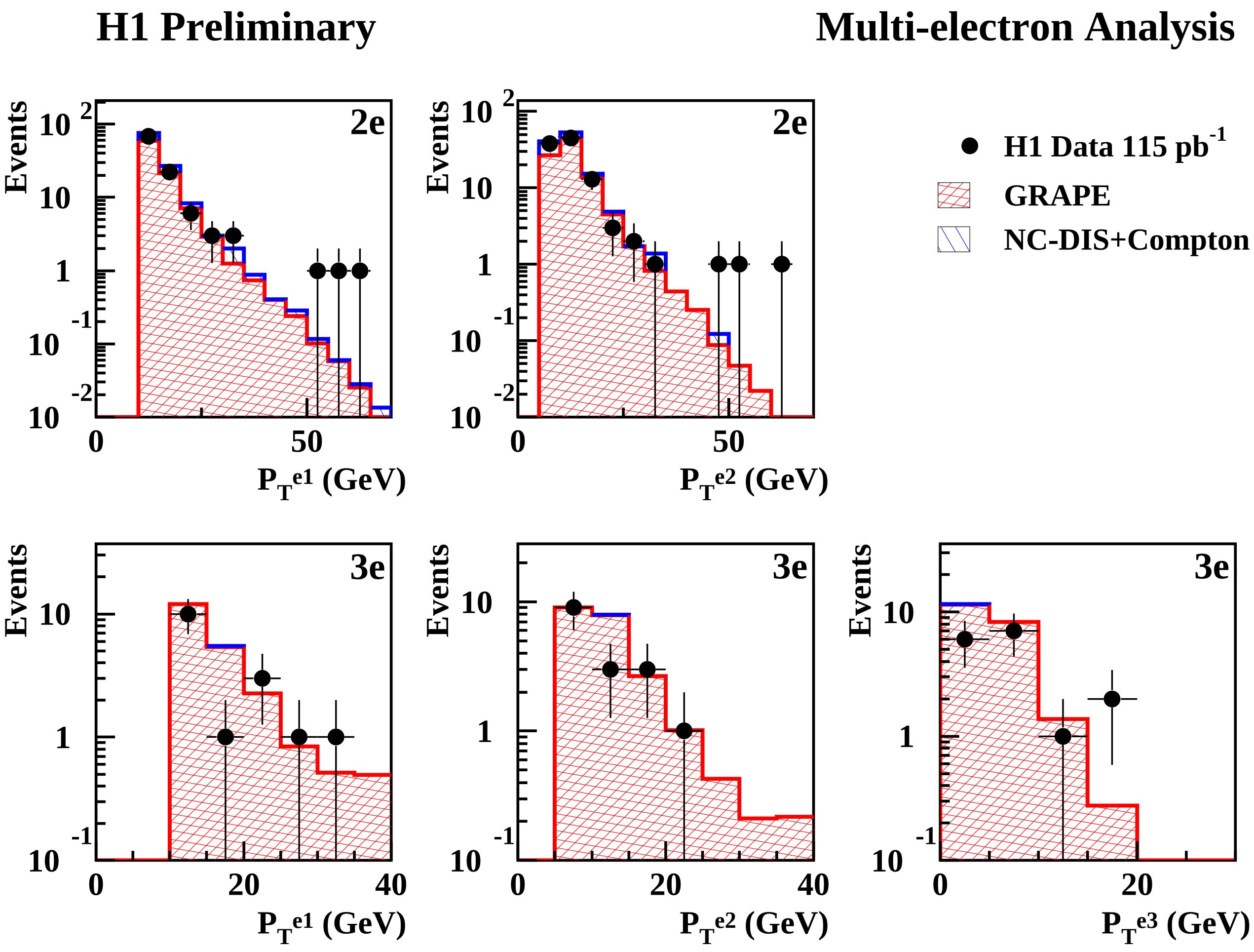
More forward e’s in “3e”

Multi–electrons at H1: global variables



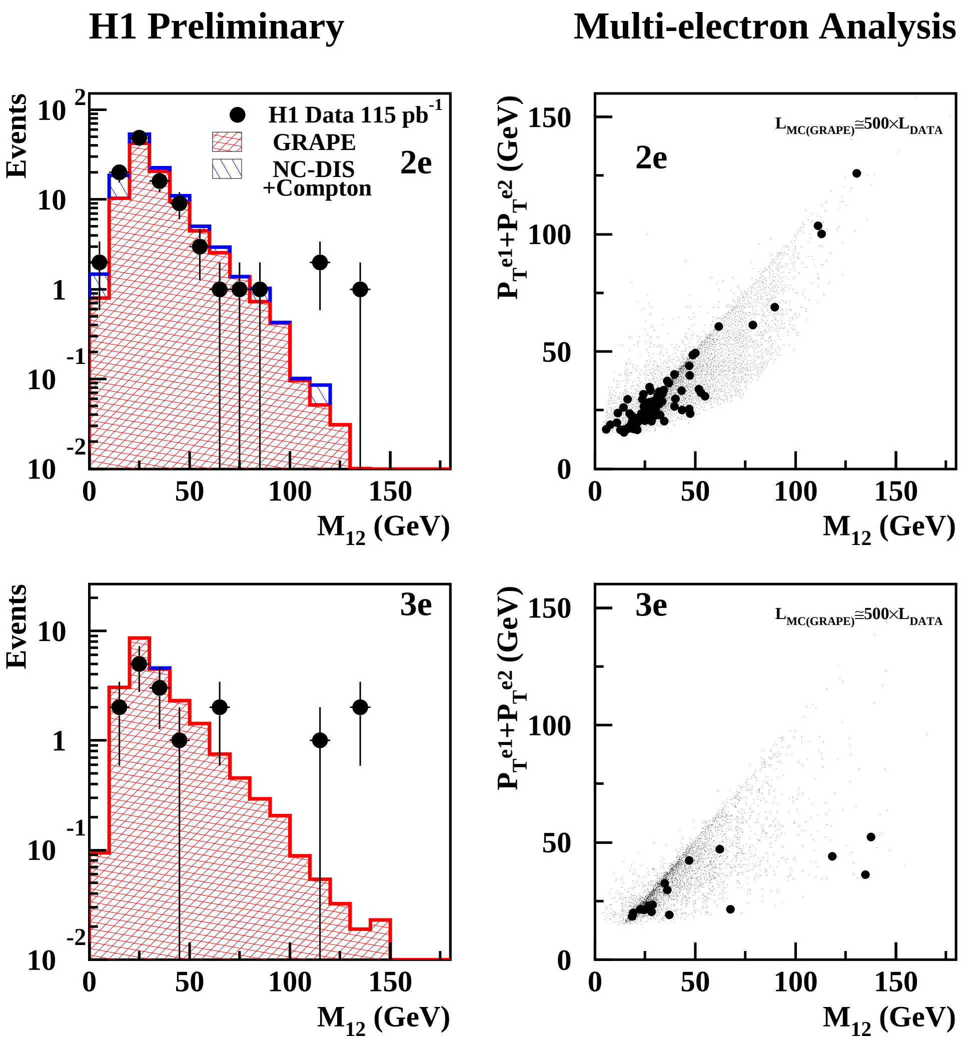
- GRAPE: $\gamma\gamma$ interaction + γ & Z^0 conversion
- NC–DIS + Compton: fake “2e”–”3e” events

Multi–electrons at H1: electron variables



➔ Three “2e” events with $P_T^{e1} > 50$ GeV (but low SM expectation)

Multi–electrons at H1: Mass distributions



- M_{12} = Mass of two highest P_T electrons
- Harder P_T for "2e"

At $M_{12} > 100$ GeV

- "2e" events:

3 found

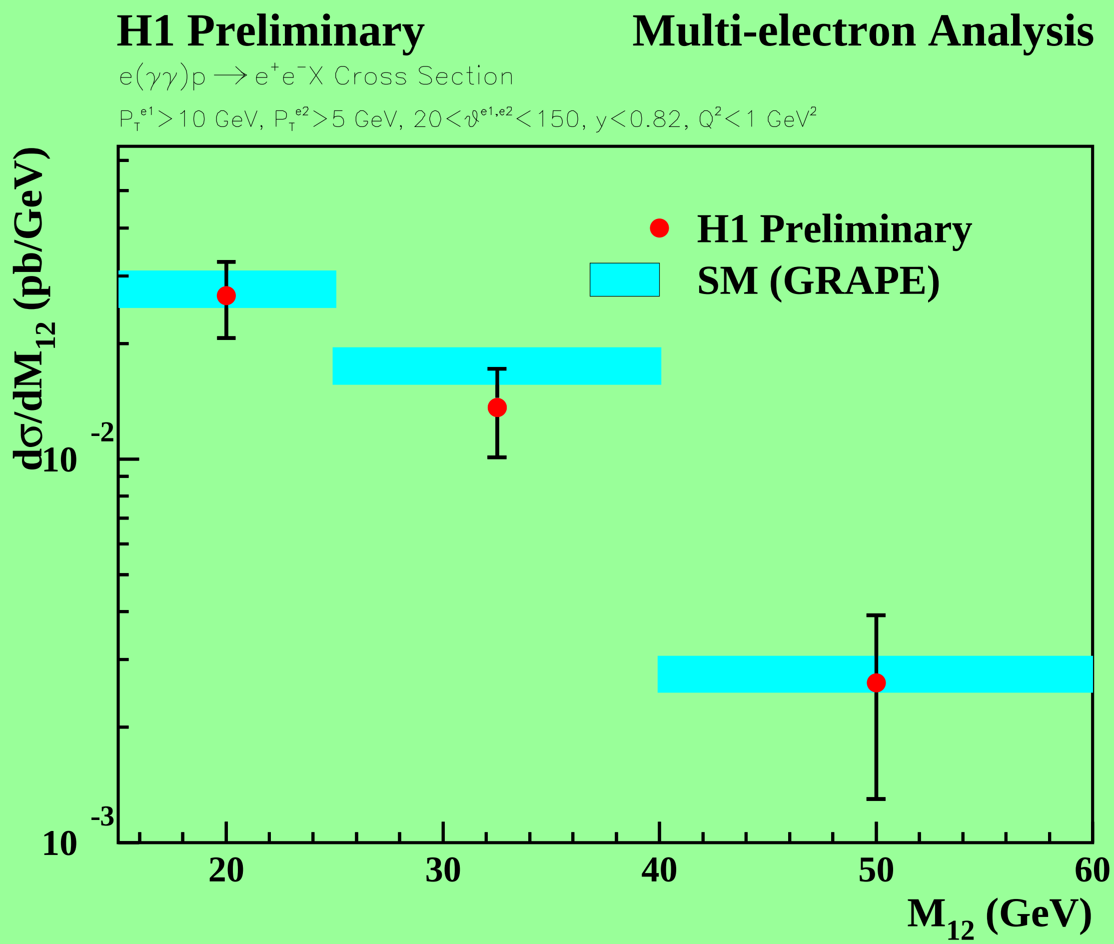
0.25±0.05 expected

- "3e" events:

3 found

0.23±0.04 expected

Multi–electrons at H1: $\gamma\gamma$ Cross Section



- Extracted from “γ–γ” sample
- Good Agreement w/ SM
- Good agreement also for $\frac{\mathrm{d}\sigma}{\mathrm{d}P_T^{\mathrm{had}}}$ and $\frac{\mathrm{d}\sigma}{\mathrm{d}P_T^{e1}}$

Multi–electrons at H1: Overview

Selection	DATA	SM	GRAPE	NC-DIS + Compton
Visible 2e	105	118.2±12.8 *	93.3±11.5	25.0±5.5
Visible 3e	16	21.6±3.0	21.5±3.0	0.1±0.1
Visible 4e or more	0	0.1±0.0	0.1±0.0	0.0±0.0
$\gamma\gamma \to e^+e^-$ subsample	41	48.3±6.1	46.4±6.1	1.9±0.9
Visible 2e $M(12) >$100	3	0.25±0.05	0.21±0.04	0.04±0.03
Visible 3e $M(12) >$100	3	0.23±0.04	0.23±0.04	0.00±0.00

* Statistical $\oplus$ Systematic Uncertainty

- DATA agree with SM at low M_{12}
- Excess in DATA at high M_{12}
- Possible explanation: doubly charged Higgs?

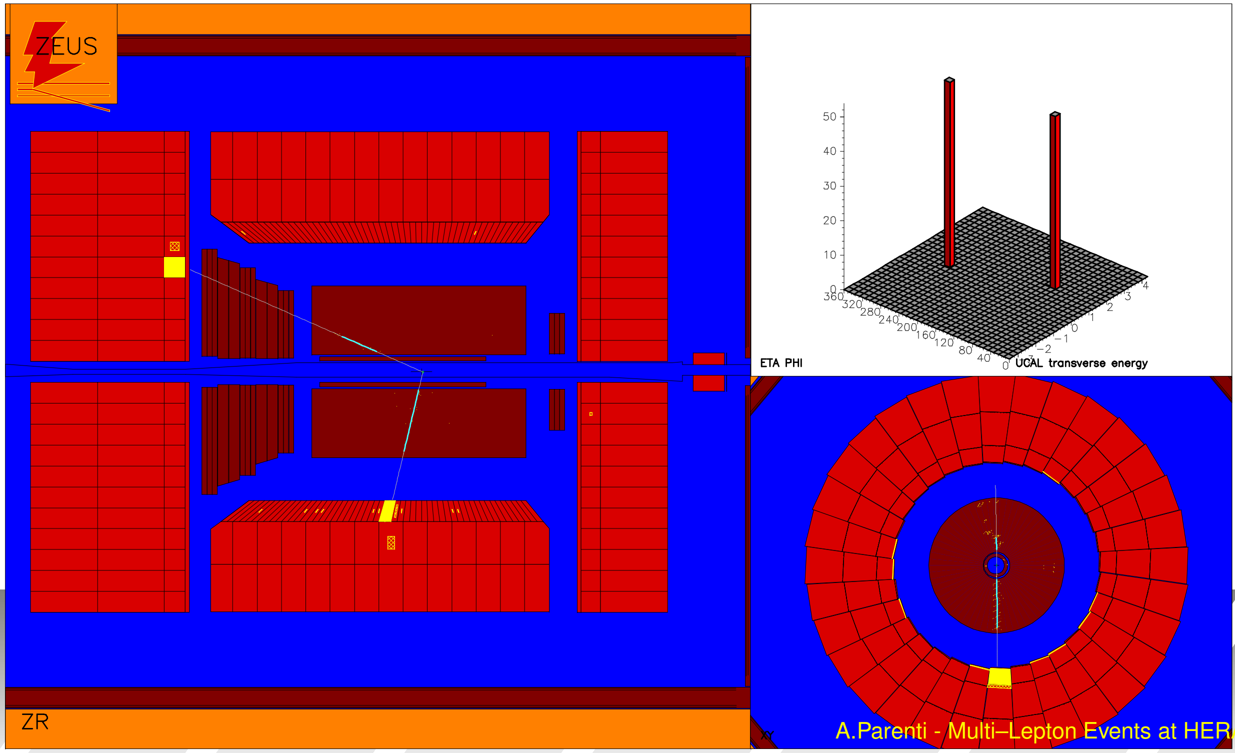
Multi–electrons at ZEUS

Data taking: 1994–00 **Lumi used:** 130.5 pb^{-1}

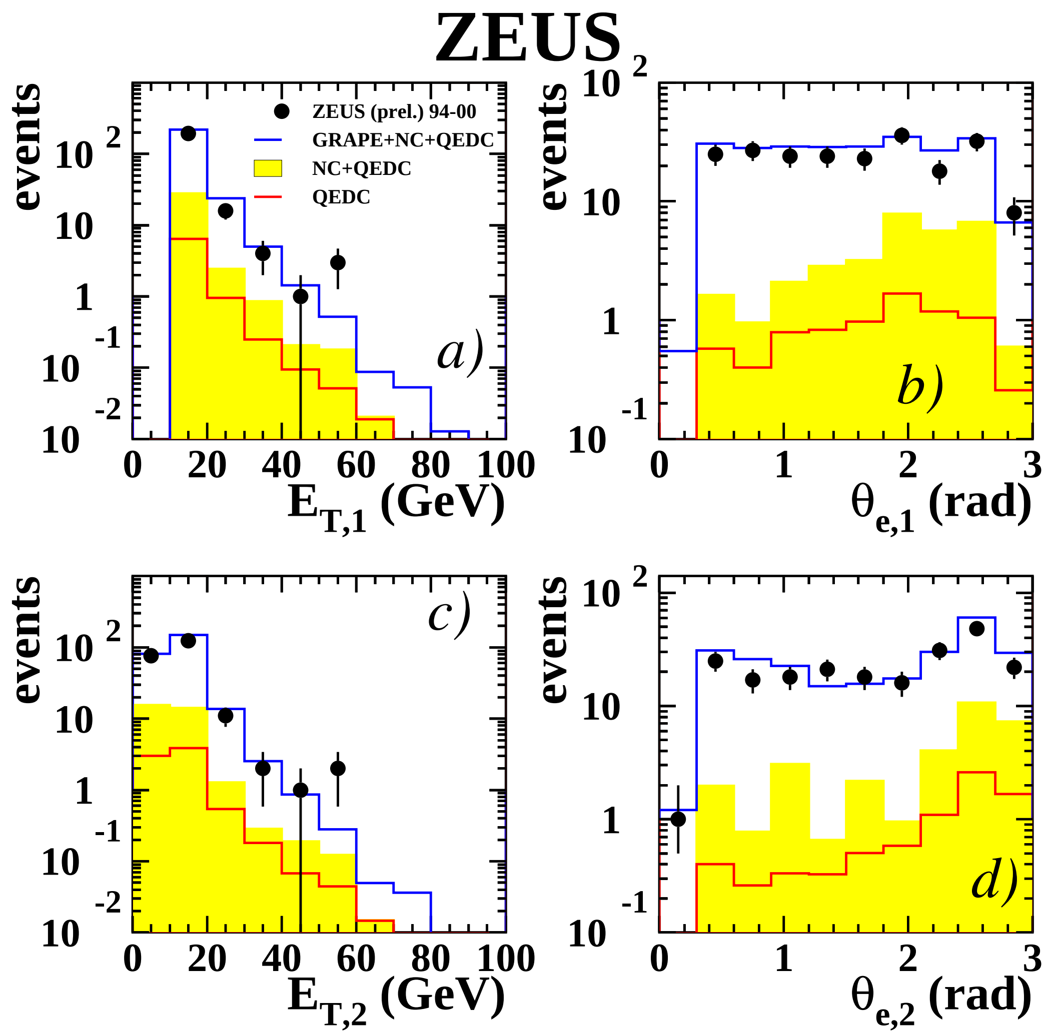
Event Selection

- “Good Vertex”: $|Z_{\rm vtx}| < 50$ cm
- Two “central” ($17^o < \theta < 164^o$) electrons: $E_T^{e1} > 10$ GeV, $E^{e2} > 10$ GeV

A “2e” event →

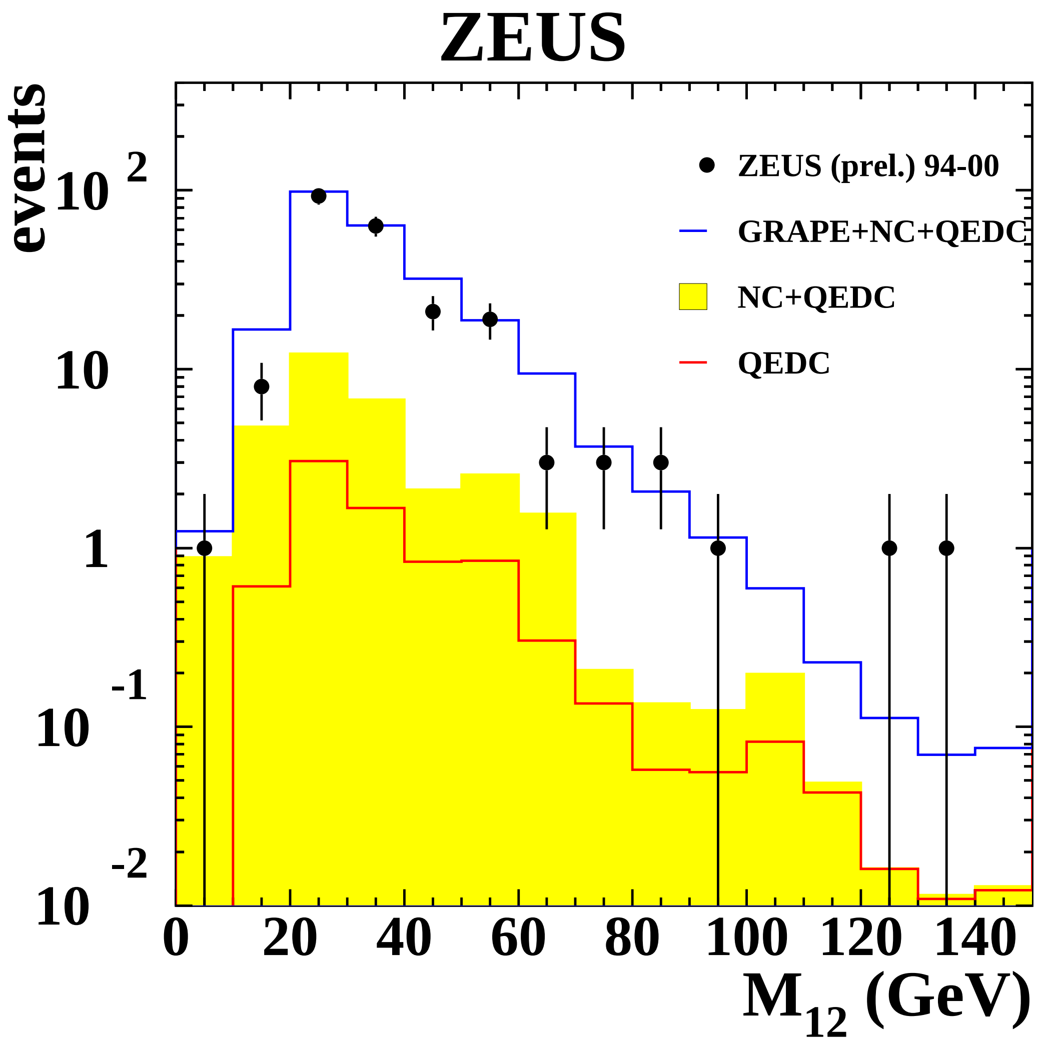


Multi–electrons at ZEUS: electron variables



➡ Good Agreement

Multi–electrons at ZEUS: Mass distribution



- Two events w/ $M_{12} > 100$ GeV; expected 1.2±0.1

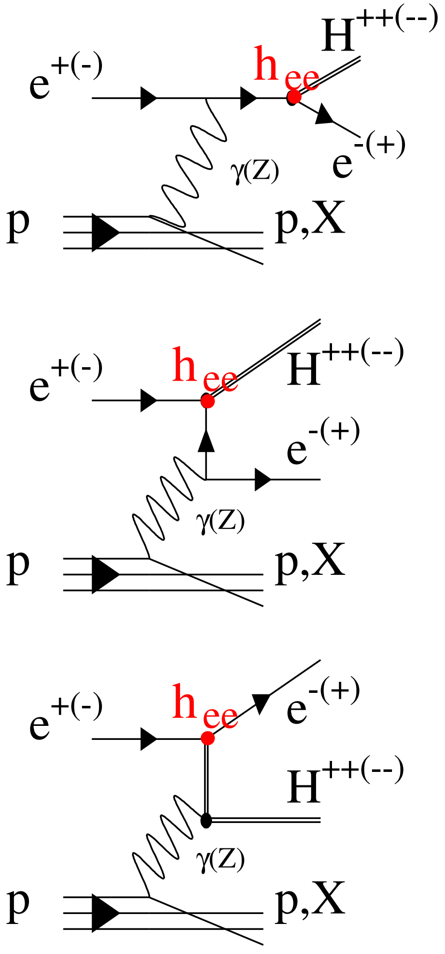
Multi–electrons at ZEUS: Overview

Type	Data	SM	GRAPE	NC–DIS	Compton
2e sample					
2e	191	213.9±3.9 *	182.2±1.2	23.9±3.7	7.8±0.5
$E_T^{e1} > 30$ GeV	6	5.7±0.3	4.4±0.2	0.9±0.2	0.4±0.1
$M_{12} > 100$ GeV	2	0.77±0.08	0.47±0.05	0.12±0.06	0.18±0.03
3e sample					
3e	26	34.7±0.5	34.7±0.5	-	-
$E_T^{e1} > 30$ GeV	2	1.43±0.08	1.43±0.08	-	-
$M_{12} > 100$ GeV	0	0.37±0.04	0.37±0.04	-	-

* Only Statistical Error

Search for $H^{\pm\pm}$ at H1

- $H^{\pm\pm}$ appears in various extensions to SM
- $H^{\pm\pm}$ couples to $l^{\pm}$ pairs at tree level
- $H^{\pm\pm}$ is a possible explanation of H1 excess in multi–e search
- H1 looked for $H^{\pm\pm}$ coupled only to $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$ and $\tau^{\pm}\tau^{\pm}$ (ie $h_{e\mu} = h_{e\tau} = h_{\mu\tau}$ = 0)



Search for $H^{\pm\pm}$ at H1

➡ Uses samples and cuts from Multi–electron and Di–muon analyses

➡ Additional Cuts for electron (muon) analysis:

- Mass window:
  $|M_H - M_{ee}| <$ 10 GeV ($|M_H - M_{\mu\mu}| < 2\sigma_{\mu\mu}$)
- Transverse momentum cut:
  $P_T^{e1} + P_T^{e2} > P_T^{cut}(M_H)$ (electron only)
  where $P_T^{cut}(M_H)$ = 45–120 GeV (keeps 95% of signal)
- "Wrong Charge" cut: $\boxed{\begin{array}{l} e^{\pm}p \to e^{\mp}H^{\pm\pm}X \\ \qquad\qquad \hookrightarrow \; l^{\pm}l^{\pm} \end{array}}$

  If e^+p (e^-p), events with l^- (l^+) are rejected

$H^{\pm\pm}$ at H1: Overview

M_H (GeV)	electron analysis ("2e"+"3e")				muon analysis			
	N_{obs}	N_{bkg}*	ϵ	N_{signal} **	N_{obs}	N_{bkg} *	ϵ	N_{signal} **
100	0	0.23	0.46	4.72	0	0.01	0.31	2.25
120	1	0.09	0.43	1.77	0	0.01	0.26	0.80
150	0	0.02	0.32	0.37	0	0.01	0.20	0.15

* From γ–γ processes, γ and Z^0 conversions

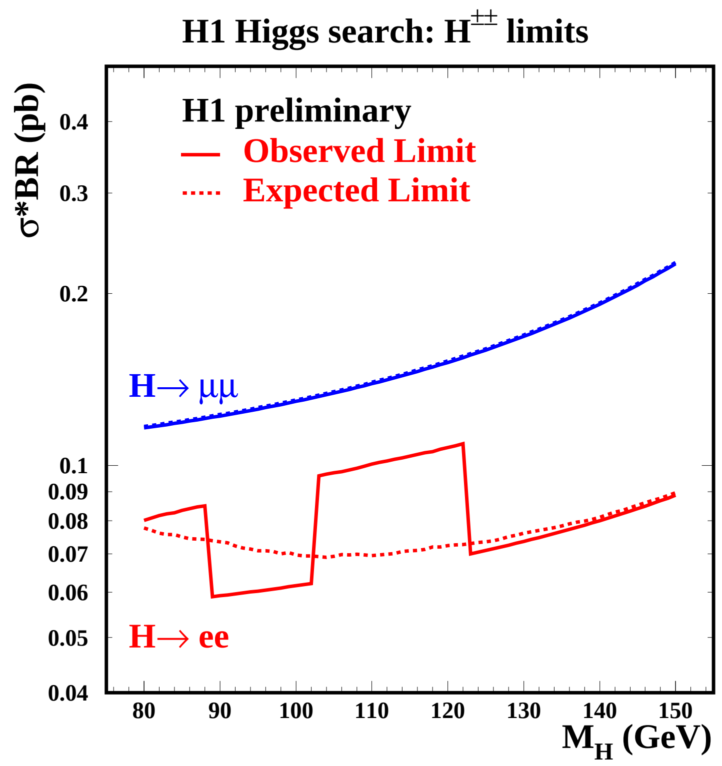
** Expected signal if h_{ee} = 0.3

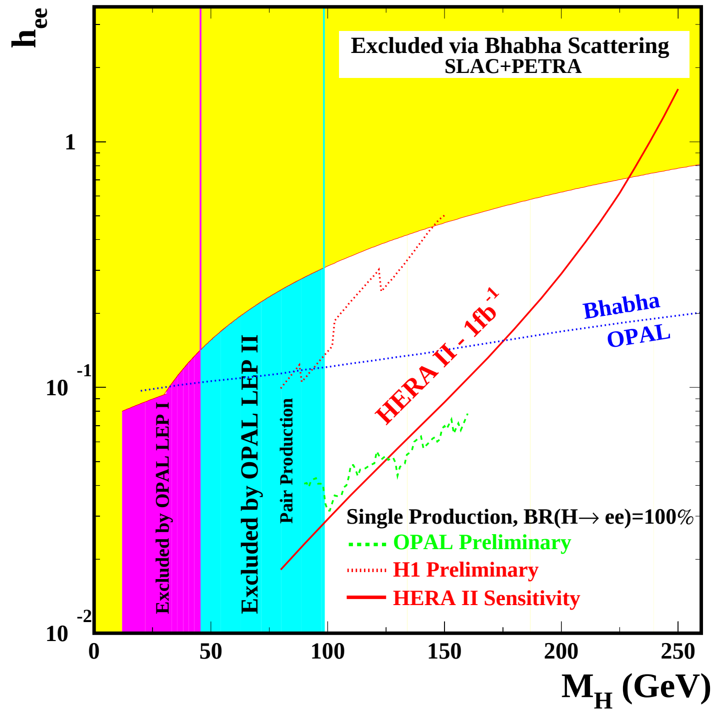
- The efficiency on signal is high
- Only 1 of "2e" events survives the cuts (none of "3e")

→ $H^{\pm\pm}$ cannot explain H1 excess in multi–e search

→ H1 set limits on $H^{\pm\pm}$ production

Search for $H^{\pm\pm}$ at H1: Limits





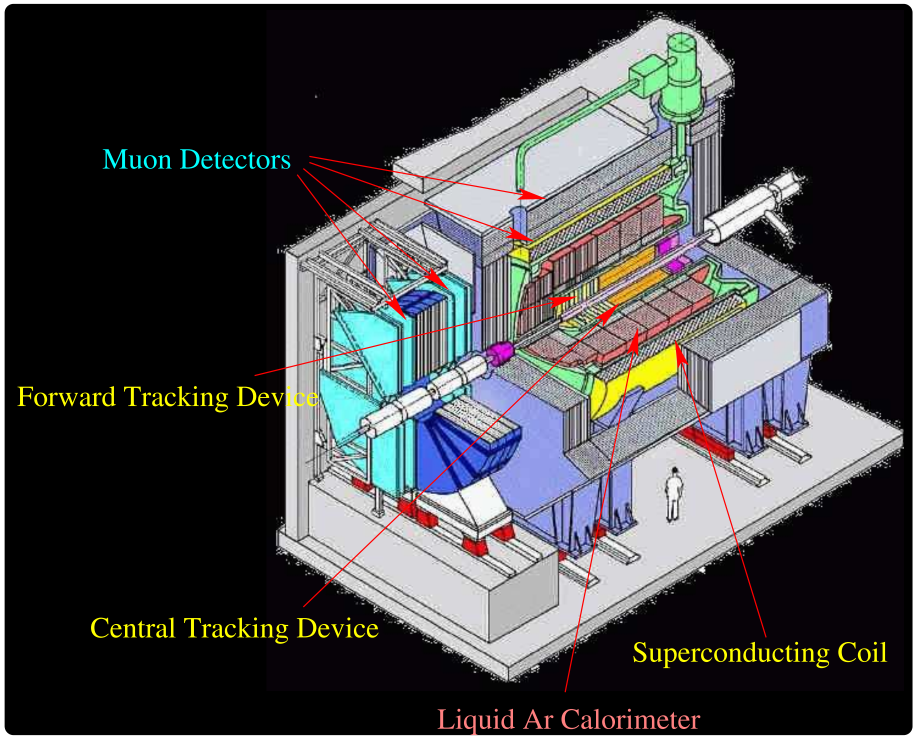
- Left Plot: Limit of $\sigma(e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X) \times BR(H^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$
- Right Plot: Exclusion limits on h_{ee}, $BR(H^{\pm\pm} \rightarrow e^{+}e^{-})$ = 100%. Best results from LEP, but HERA will tell something new with higher luminosity

Conclusions

- HERA collisions were analysed by H1 and ZEUS, in the search for di–lepton events
- The major contribution to the process comes from QED: $\gamma\gamma \rightarrow l^+l^-$
- Monte Carlo simulations agree well with data, except “2e” and “3e” at high mass in H1 (3+3 events found, 0.25+0.23 expected)
- $H^{\pm\pm}$ production was analysed (and excluded) by H1 as explanation for the excess

Additional Slides

The H1 Detector



Muon Detectors

- LSTs ($6^o < \theta < 172^o$): $\sigma(p)/p \simeq 35\%$
- Forward Spectrometer ($3^o < \theta < 17^o$): $24\% < \sigma(p)/p < 36\%$

Liquid Argon CAL

- Angular coverage: $4^o < \theta < 153^o$
- Thickness: 20–30 X_0 (EM), 5–8 λ_I (HAD)
- Energy Resolution (EM, HAD):
  $\sigma(E)/E = 12\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$
  $\sigma(E)/E = 50\%/\sqrt{E(\mathrm{GeV})} \oplus 2\%$

Tracking Devices

- Forward Tracking Device
  - Coverage: $7^o < \theta < 25^o$
- Central Tracking Device
  - Coverage: $25^o < \theta < 155^o$
  - $\sigma(p)/p^2 < 0.01\ \mathrm{GeV}^{-1}$
- Back–Ward Proport. Chamber
  - Coverage: $155^o < \theta < 175^o$

Monte Carlo samples: H1

Multi–electrons analysis

- GRAPE: $\gamma\gamma$ interaction + Cabibbo–Parisi, γ and Z^0 conversion (no Drell–Yan)
- LPAIR: only $\gamma\gamma$ in Weizsäcker–Williams approximation
- DJANGO: NC–DIS
- WABGEN: Elastic Compton

Di–muons analysis

- GRAPE: as above
- DIFFVM: Υ resonance
- LPAIR: $\gamma\gamma \to \tau\tau \to \mu\mu$
- AROMA: $c\bar{c}$ and $b\bar{b}$ decays

Signal simulation in $H^{\pm\pm}$ search

- CompHEP computes cross–section
- CTEQ4L for PDF's
- DGLAP eqt.s for parton shower
- PYTHIA for hadronization

Systematic Uncertainties at H1

Multi–electron analysis

- PDF's of proton
- Cuts used in the generator
- Tracking Efficiency: 3–15%
- Energy Scales in CAL: 0.7–3% (EM), 2% (HAD)
- Trigger Efficiency: 3%
- Lumi measurement: 1.5%

Di–muon analysis

- Trigger Efficiency: 5.5%
- Muon ID: 5.8%
- Lumi measurement

Electron ID at H1

Three types of electrons:

- “Central” electrons ($20^o < \theta < 150^o$): CAL deposit ($E >$ 5 GeV) + CTD matched track
- “Forward” electrons ($5^o < \theta < 20^o$): CAL deposit ($E >$ 10 GeV)
- “Backward” electrons ($150^o < \theta < 175^o$): CAL deposit ($E >$ 5 GeV)

Isolation cut:

- Isolation cut: $N_{\mathrm{trks}}(R_{\eta\phi} < 0.5)$ = 0

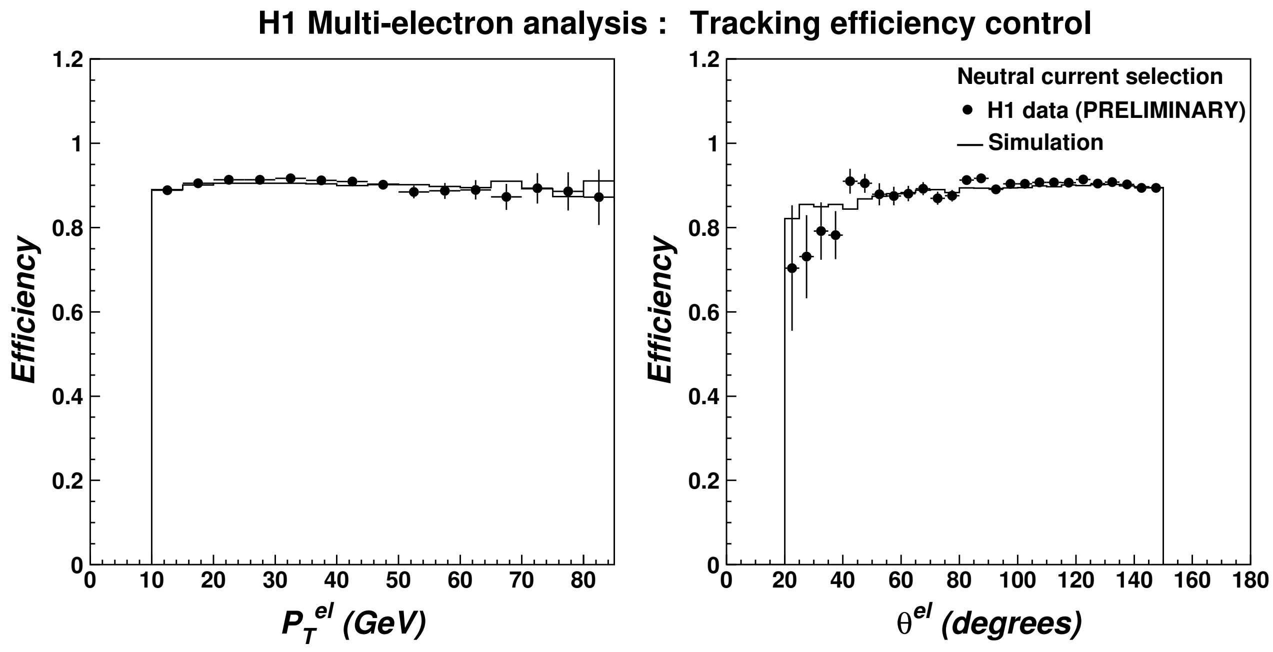
The ID procedure was tested for:

- Tracking Efficiency
- Electron Misidentification
- Photon Conversions

Electron ID at H1: Test of Tracking Efficiency

NC–DIS Selection:

- (Just) 1 E.M. cluster in CAL, $P_T > 10$ GeV
- Central Region $(20^o < \theta < 150^o)$
- No tracking requirements

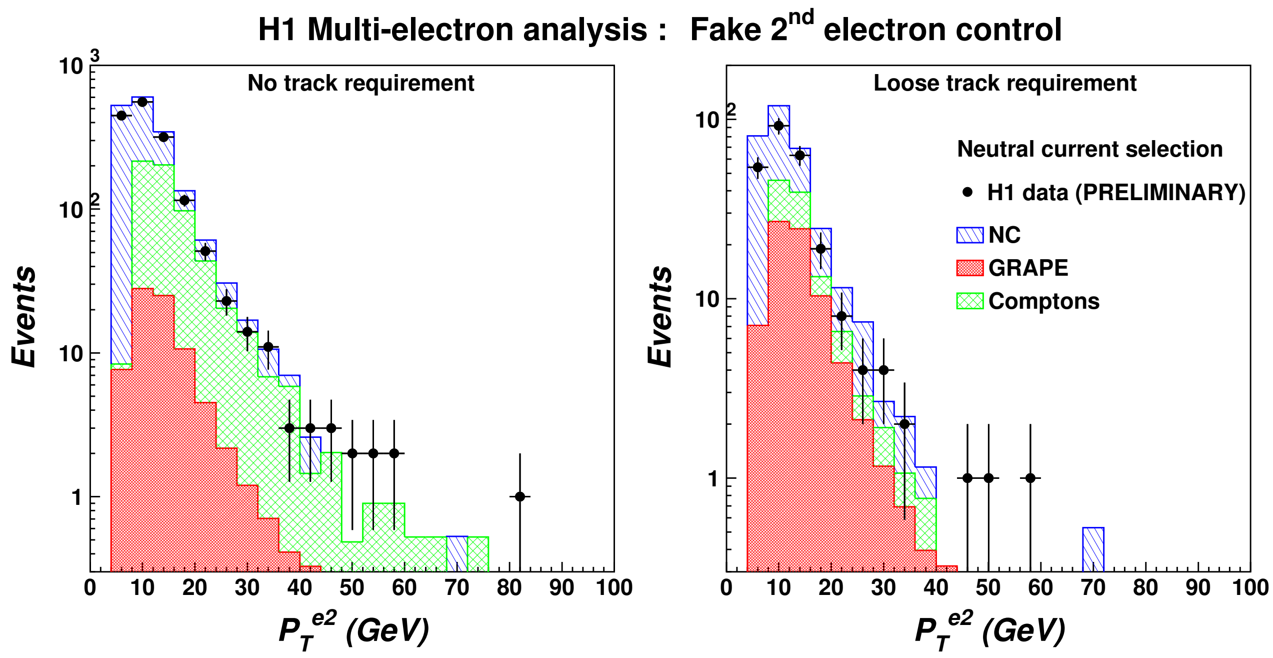


➡ Quite flat, high efficiency; well described by MC

Electron ID at H1: Electron Misidentification

NC–DIS Selection, plus second E.M. Cluster in CAL:

- Left: No tracking requirements → Dominated by Compton
- Right: Loose tracking requirements → Compton is suppressed

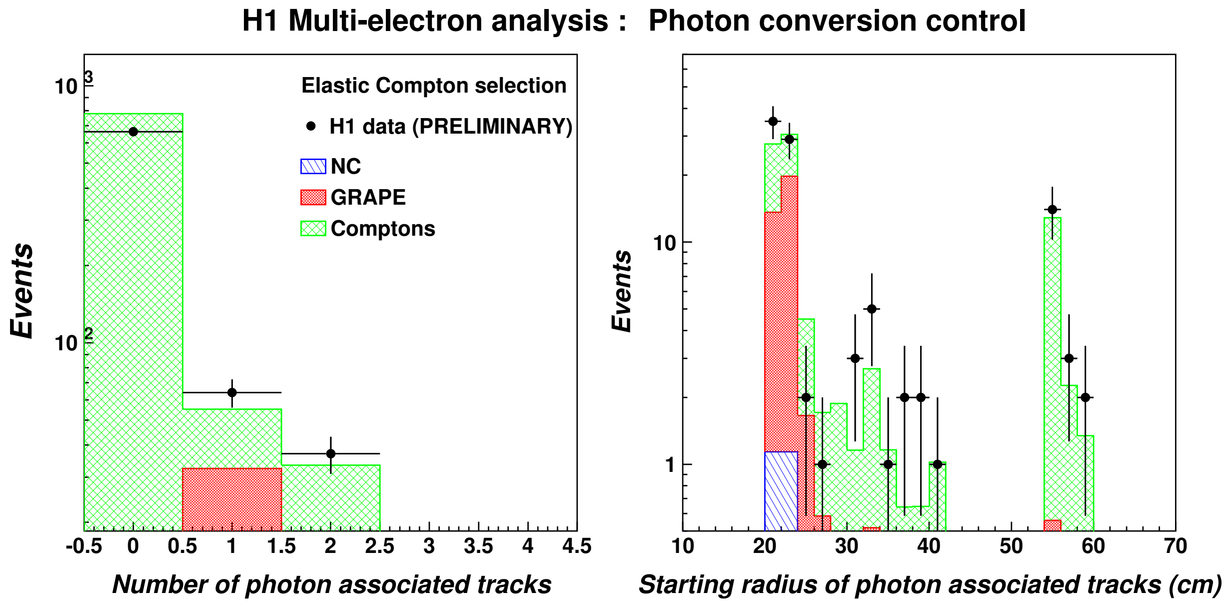


→ In both cases, BKG described by MC

Electron ID at H1: Photon Conversions

Compton Enriched Sample:

- 1 central electron
- 1 E.M. cluster (photon candidate)
- No (significant) extra energy in CAL

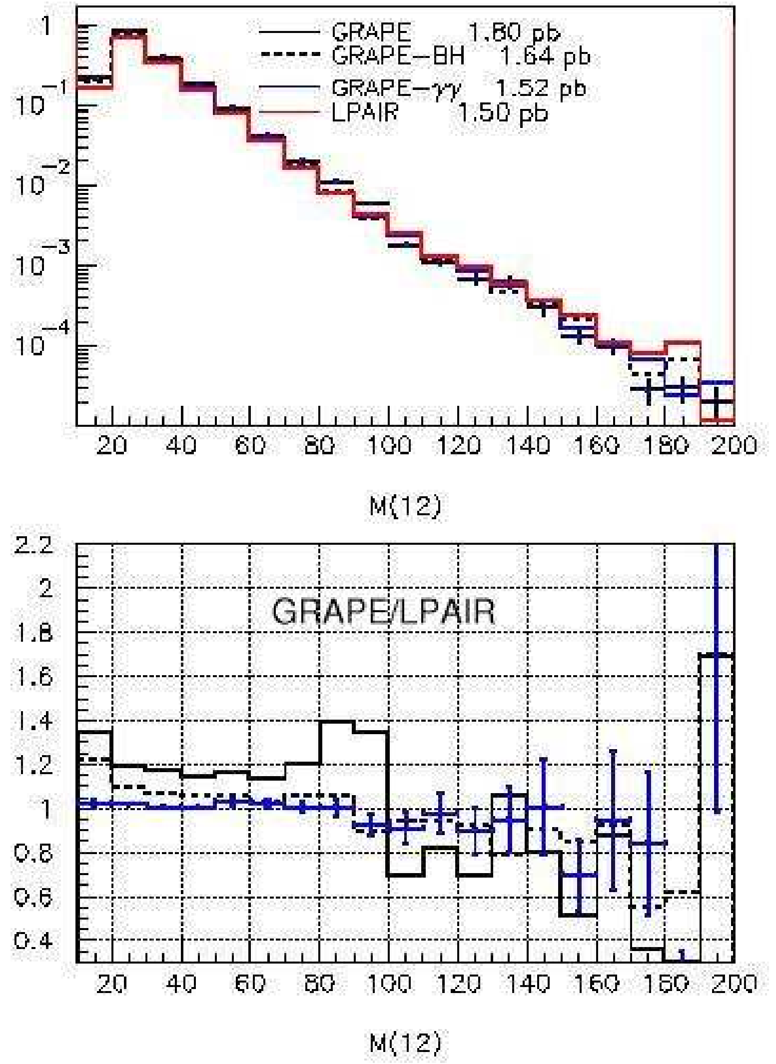


➡ DATA well described by MC

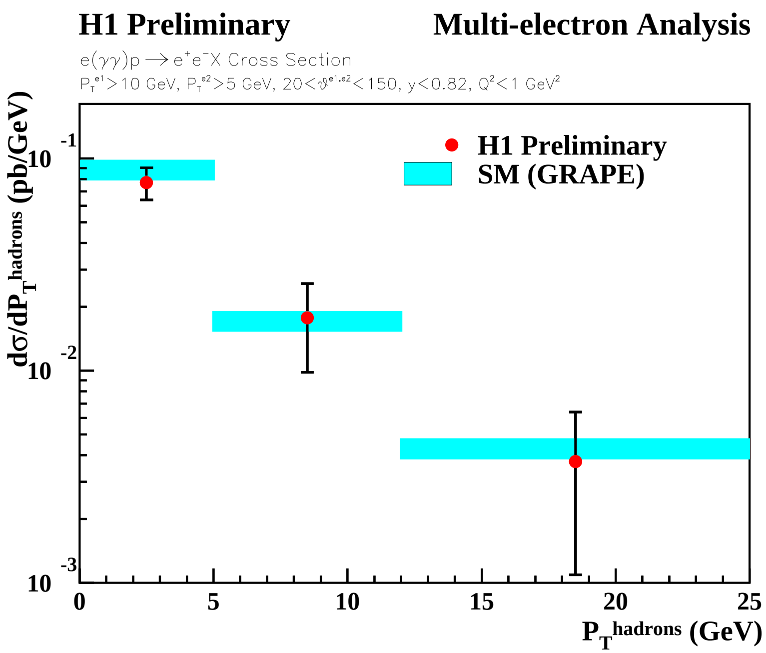
➡ Conversions in tracker walls (peaks in right plot) well described, too

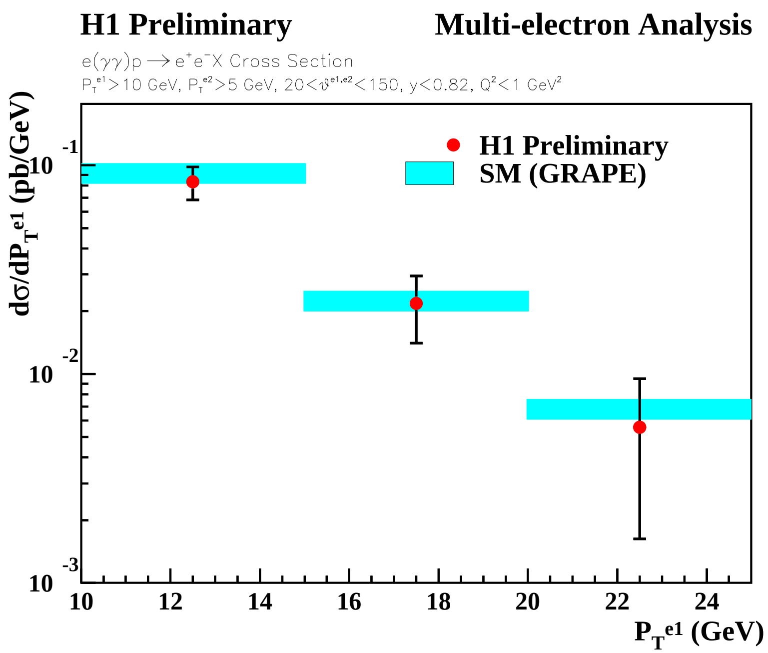
Di–electrons at H1: GRAPE Vs. LPAIR

- LPAIR simulates only $\gamma\gamma$ process
- Good Agreement (within %) of LPAIR and ($\gamma\gamma$ only) GRAPE
- Effect of GRAPE additional diagrams:
  - 20% total cross–section increase
  - 40% cross–section increase at low mass (γ conversions) and at Z^0 mass

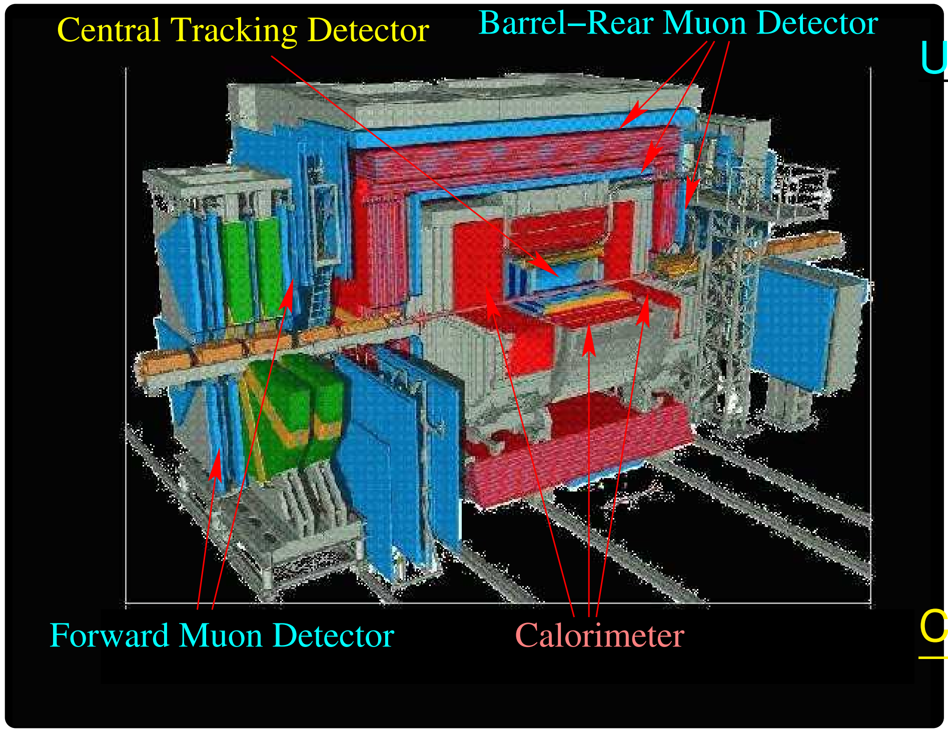


Multi–electrons at H1: $\gamma\gamma$ Cross Section





The ZEUS Detector



Uranium Calorimeter

- Angular coverage: $2.5^o < \theta < 178.4^o$
- Thickness: 20–25 X_0 (EM), 4–7 λ_I (HAD)
- Energy Resolution (EM, HAD): $\sigma(E)/E = 18\%/\sqrt{E(\mathrm{GeV})} \oplus 2\%$ $\sigma(E)/E = 35\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

Central Tracking Device

- Angular Coverage: $15^o < \theta < 164^o$
- $\sigma(P_T)/P_T = 0.58\% PT(GeV) \oplus 0.65\% \oplus 0.14\%/P_T$

Muon Detectors

- Forward MUON detector: $6^o < \theta < 32^o$, $\sigma(p)/p <$ 25% up to $p = 100$ GeV
- Barrel–Rear MUON: $35^o < \theta < 160^o$, $\sigma(p)/p$ = 30–50% for $p <$ 50 GeV

Monte Carlo samples: ZEUS

Multi–electrons analysis

- GRAPE: $\gamma\gamma$ interaction + Cabibbo–Parisi, γ and Z^0 conversion (no Drell–Yan)
- DJANGO: NC–DIS + Inelastic Compton
- COMPTON2.0: Elastic Compton

Di–muons analysis

- GRAPE: as above

Electron ID at ZEUS

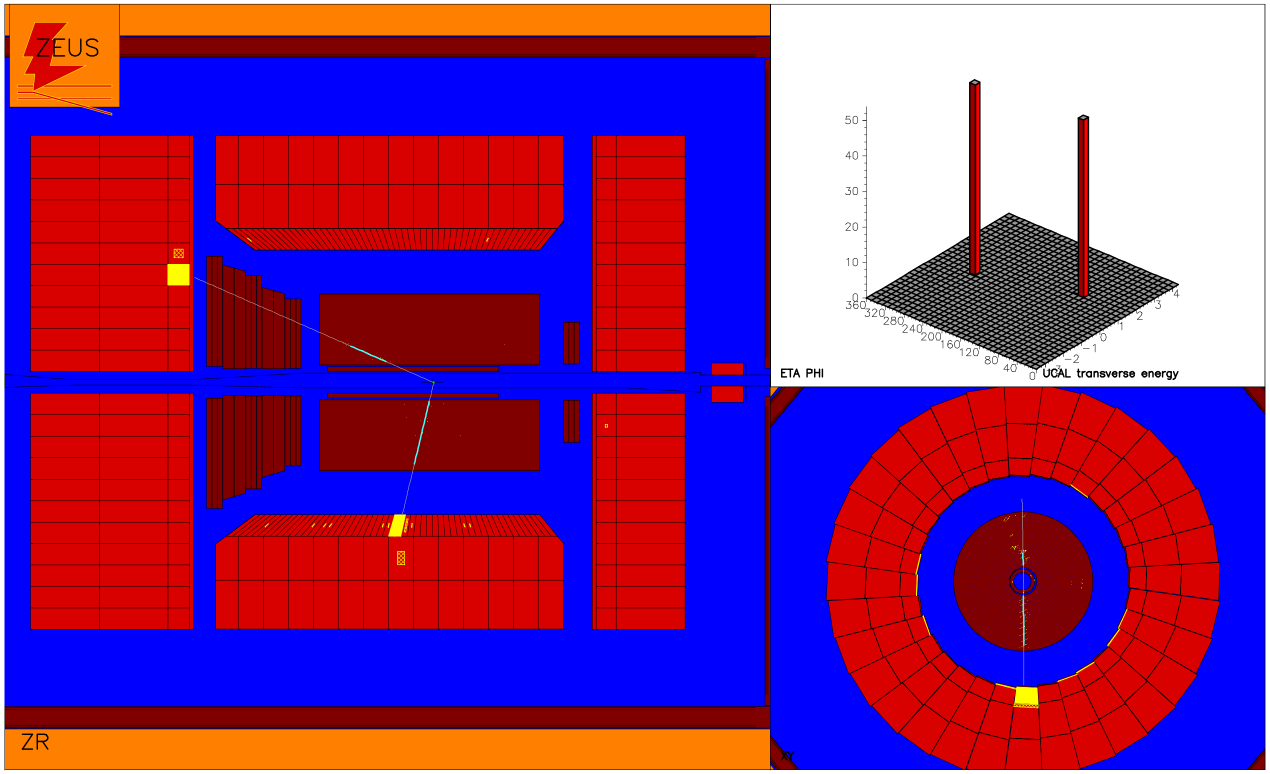
Three types of electrons:

- “Central” electrons ($17^o < \theta < 164^o$): CAL deposit ($E >$ 10 GeV) + CTD track ($P >$ 5 GeV) + DCA < 8 cm
- “Forward” electrons ($6^o < \theta < 17^o$): CAL deposit ($E > 10$ GeV)
- “Backward” electrons ($164^o < \theta < 175^o$): CAL deposit ($E > 5$ GeV)

Isolation cut:

- Isolation cut: $N_{\mathrm{trks}}(R_{\eta\phi} < 0.4)$ = 0, $E_{\mathrm{CAL}}(R_{\eta\phi} < 0.8) <$ 0.3 GeV

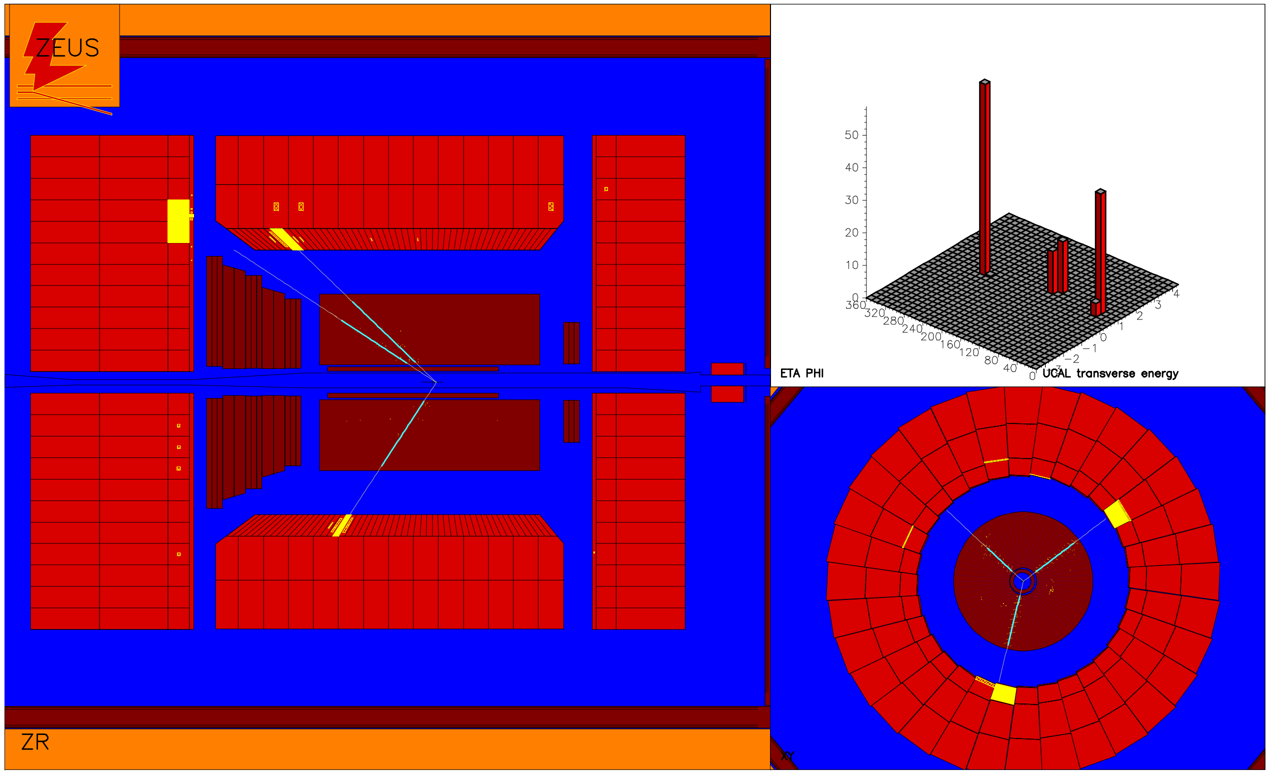
A “2e” event at ZEUS



$\boxed{M_{12} = 134 \text{ GeV}}$

$E_T^{e1} = 56$ GeV, $\theta^{e1} = 1.34$ rad, $E_T^{e2} = 53$ GeV, $\theta^{e2} = 0.41$ rad

A “3e” event at ZEUS



$\boxed{M_{12} = 94 \text{ GeV}}$, $E_T^{e1} = 52$ GeV, $\theta^{e1} = 1.00$ rad, $E_T^{e2} = 47$ GeV, $\theta^{e2} = 0.76$ rad, $E_T^{e3} = 36$ GeV, $\theta^{e2} = 0.58$ rad