Multi-lepton and general searches at HERA

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on behalf of H1 and ZEUS collaborations

- DIS 2008 -

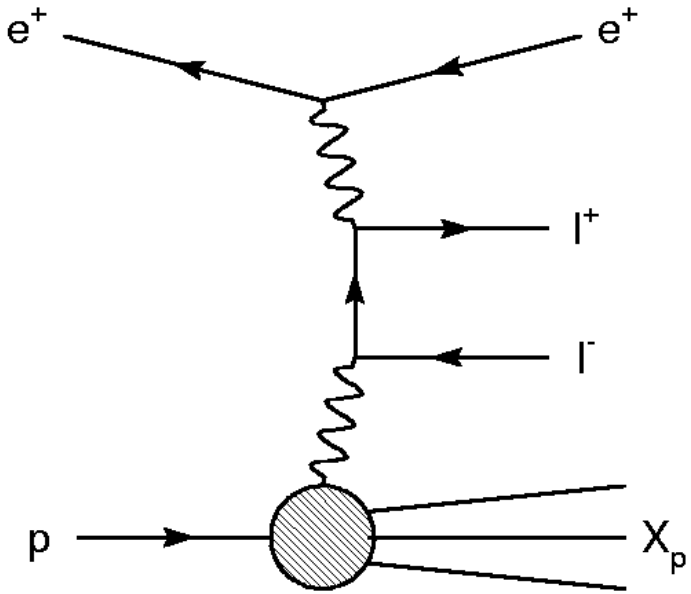
Outline:

- Multi-electron search
- Multi-lepton search
- General search
- Conclusions

Multi-electrons (H1+ZEUS)

Motivation

- Main production process is Bethe-Heitler: $\gamma\gamma \rightarrow l^+l^-$ (l=e, μ, τ)
- This is a QED process, precisely calculable by theory.
- SM expectation falls steeply with P_T: deviations from SM would be hint of new physics.



History of the electron search

- H1 found some excess in HERA-I data, at high di-electron mass:

Selection	Data	SM	Pair Production (GRAPE)	DIS + Compton
"2e" $M_{12} > 100$ GeV	3	0.30 ± 0.04	0.21 ± 0.03	0.09 ± 0.02
"3e" $M_{12} > 100$ GeV	3	0.23 ± 0.04	0.23 ± 0.03	< 0.02 (95% C.L.)

- But:
  - no excess found in di-muon search (μμ & *e*μμ channels) by H1 (HERA-I data)
  - no excess found by ZEUS, both in di-*e* and di-μ.
- More investigation was needed!

Data sample and selection

- Full HERA data (1994-2007):
  - 0.94 fb^{-1} (H1+ZEUS)
- Selection cuts:
  - Two electrons in $20° < \theta < 150°$ with $P_T > 10, 5$ GeV
  - Additional electrons searched for in $5° < \theta < 175°$
  - Events are classified as "2*e*" or "3*e*" according to the number of electrons found.

Data/SM comparison

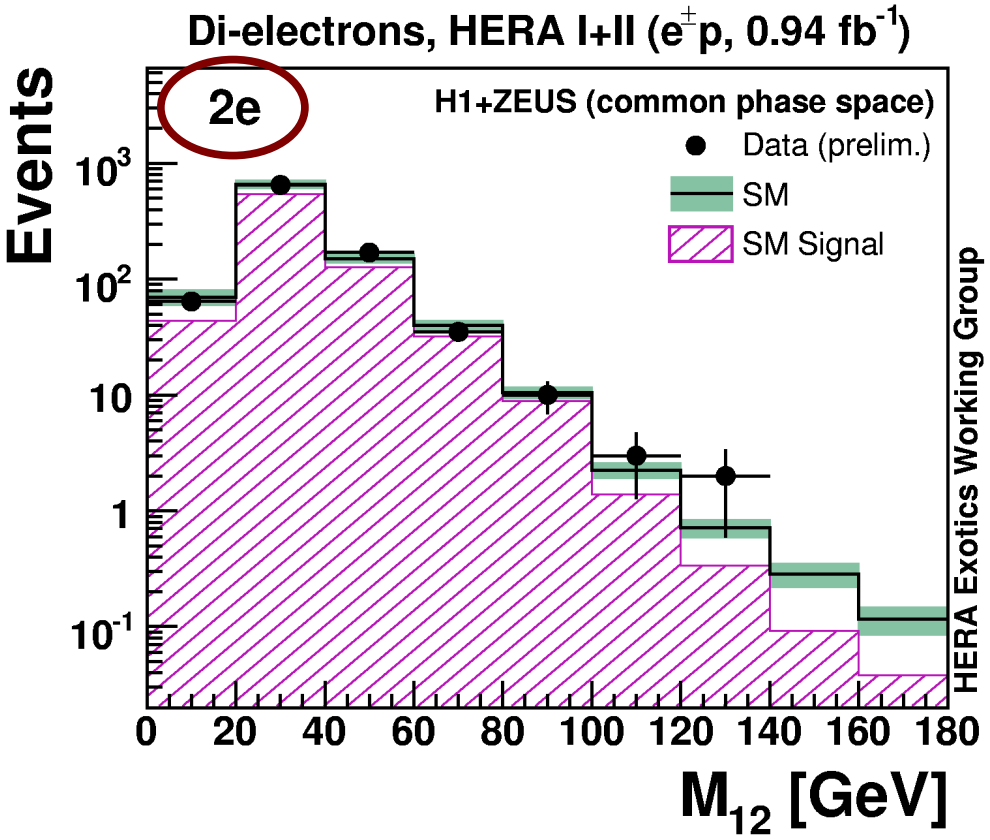
- Overall agreement between data and SM:

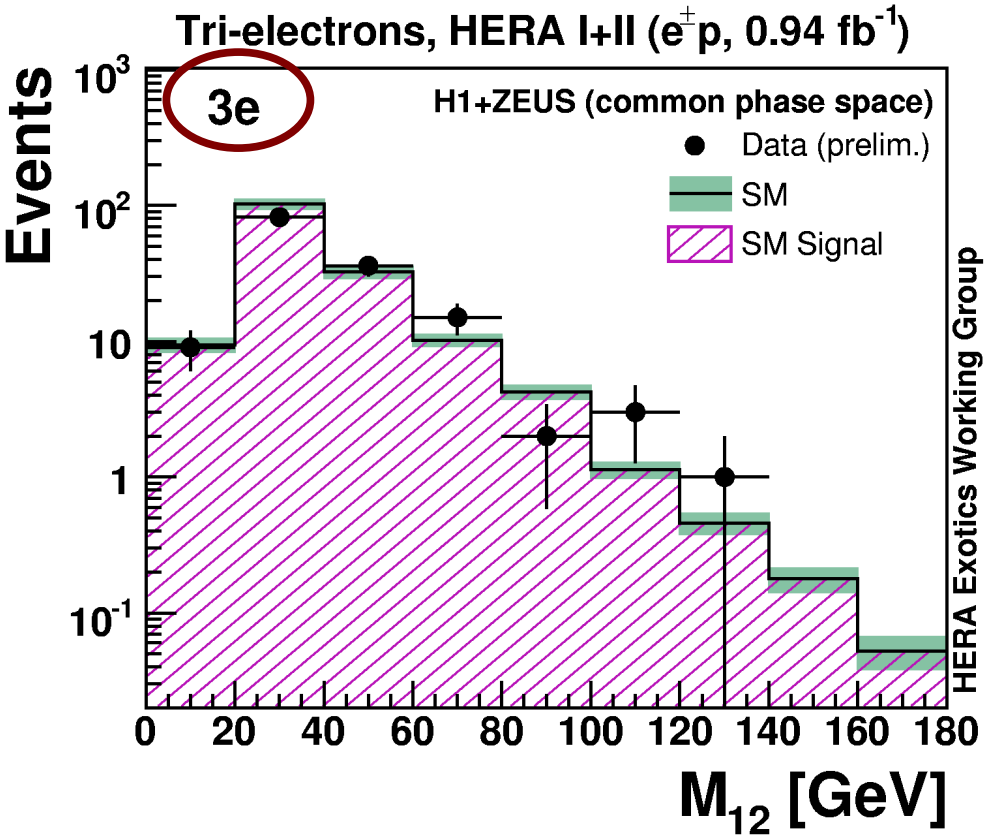
H1+ZEUS Multi-electron analysis HERA I+II (0.94 fb^{-1}, preliminary)

Selection	Data	SM	Pair Production	NC-DIS + Compton
2e	937	937 ± 67	756 ± 48	181 ± 39
3e	148	161 ± 10	160 ± 10	0.4 ± 0.01
All	1085	1098 ± 75	916 ± 58	182 ± 39

- Let's see the differential distributions...

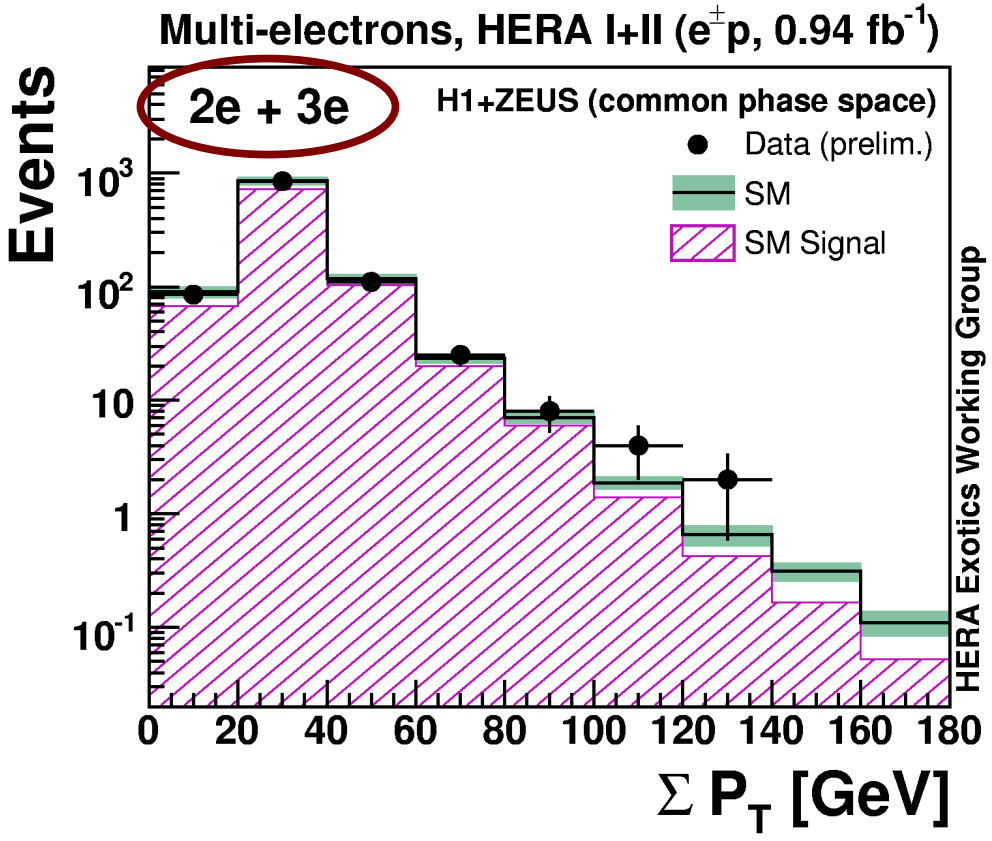
Invariant-mass distribution





- M_{12} is the invariant mass of the two highest-P_T electrons.

ΣP_T distribution



- Scalar sum of electron P_T.

Data/SM comparison

- Some striking events found at high mass...

H1+ZEUS Multi-electron analysis HERA I+II (preliminary)

M_{12} >100 GeV				
Selection	Data	SM	Pair Production	NC-DIS + Compton
$e^{\pm}$ collisions (0.94 fb^{-1})				
2e	5	3.41 ± 0.37	1.87 ± 0.25	1.54 ± 0.29
3e	4	1.85 ± 0.24	1.85 ± 0.24	—

- ... and high ΣP_T

H1+ZEUS Multi-electron analysis HERA I+II (0.94 fb^{-1}, preliminary)

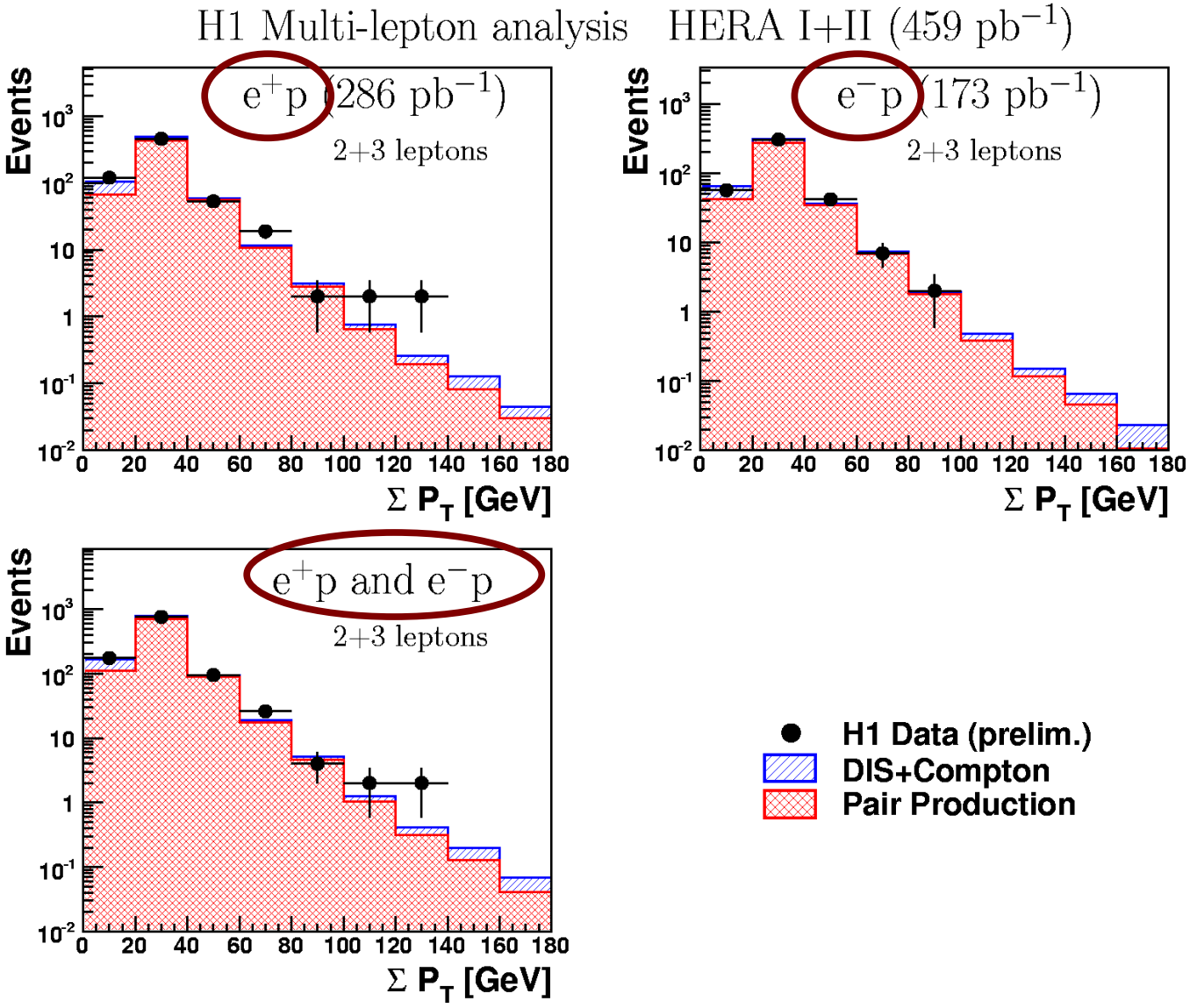
ΣP_T >100 GeV				
Data sample	Data	SM	Pair Production	NC-DIS + Compton
e^+p (0.56 fb^{-1})	5	1.82 ± 0.21	1.28 ± 0.16	0.54 ± 0.10
e^-p (0.38 fb^{-1})	1	1.19 ± 0.14	0.79 ± 0.09	0.40 ± 0.08
$e^{\pm}p$ (0.94 fb^{-1})	6	3.00 ± 0.34	2.07 ± 0.24	0.94 ± 0.16

Multi-leptons (H1)

Data sample and selection

- This is an extension of multi-electron search: look for events with electrons or muons.
- Full HERA data (1994-2007):
  - 459 pb^{-1} (H1)
- Selection cuts:
  - 2 leptons (e, μ) in $20° < \theta < 150°$ with $P_T > 10{,}5$ GeV
  - Additional electrons searched for in $5° < \theta < 175°$
  - Additional muons searched for in $20° < \theta < 160°$

ΣP_T distribution



Data/SM comparison

- Overall nice agreement between data and SM:

H1 Multi-lepton analysis HERA I+II (459 pb^{-1}, preliminary)

Selection	Data	SM	Pair Production	NC-DIS + Compton
ee	446	450 ± 68	375 ± 42	75 ± 39
$\mu\mu$	185	194 ± 38	194 ± 38	—
eμ	201	194 ± 26	136 ± 13	58 ± 17
eee	81	90 ± 10	90 ± 10	—
e$\mu\mu$	102	112 ± 19	112 ± 19	—

- Few events found at high ΣP_T:

H1 Multi-lepton analysis HERA I+II (459 pb^{-1}, preliminary)

$\Sigma E_T > 100$ GeV				
Data sample	Data	SM	Pair Production	NC-DIS + Compton
e^+p (286 pb^{-1})	4	1.2 ± 0.2	1.0 ± 0.2	0.2 ± 0.1
e^-p (173 pb^{-1})	0	0.8 ± 0.2	0.6 ± 0.2	0.2 ± 0.1
All (459 pb^{-1})	4	1.9 ± 0.4	1.5 ± 0.3	0.4 ± 0.1

General search for new phenomena (H1)

Introduction

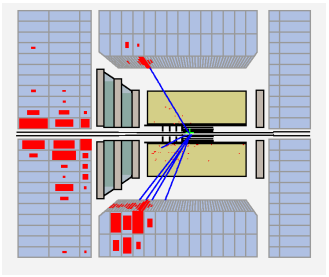
- Model independent search: look for all high-P_T topologies, where SM expectation is small.
- Unify all searches in a coherent statistical treatment:
  - few channels may fluctuate, we want to evaluate the global significance of these fluctuations.
- Though the selection (and sensitivity) is different, this search allows to inspect same topologies as multi-leptons and isolated-leptons and evaluate their global significance

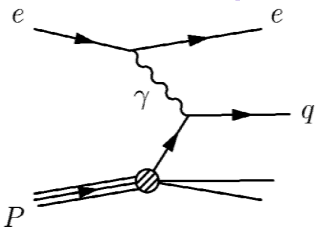
Data sample and selection

- Full HERA-II data (H1)
  - e^+p collisions (178 pb^{-1})
  - e^-p collisions (159 pb^{-1})
  - HERA-I data published [PLB602(2004)14]
- All final states involving isolated, high-P_T, and well reconstructed electrons (e), muons (μ), jets (j), photons (γ), neutrinos (ν) are investigated.
- ≥ 2 of these "objects" are required, having:
  - $P_T > 20$ GeV and $10° < \theta < 140°$

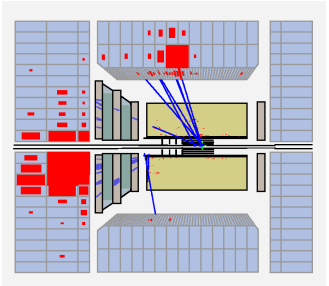
Standard Model processes

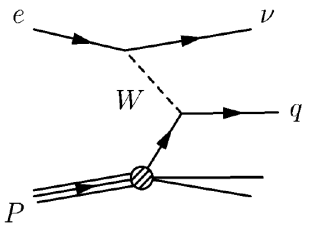
- All SM *ep* processes need to be simulated
- High statistics needed
  - Neutral Current DIS: $ep \rightarrow eX$



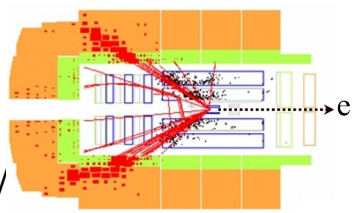


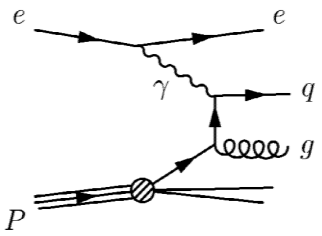
  - Charged Current DIS: $ep \rightarrow \nu X$



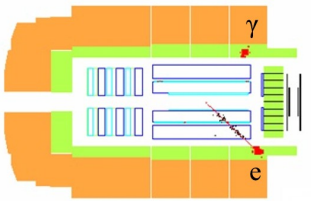


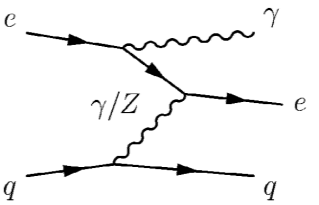
  - Photoproduction: $\gamma p \rightarrow X$



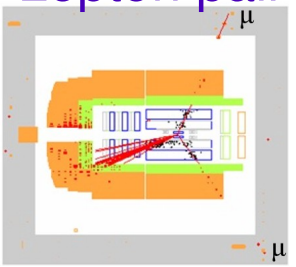


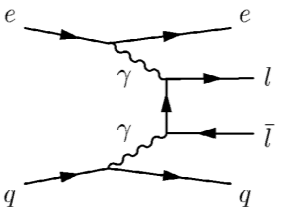
  - QED Compton: $ep \rightarrow e\gamma X$



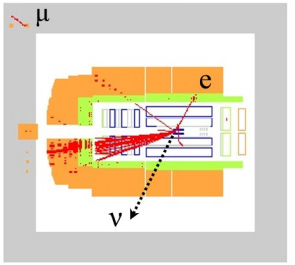


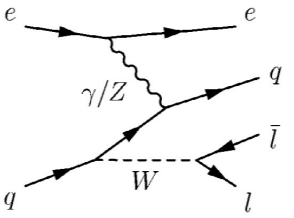
  - Lepton pair production: $ep \rightarrow ellX$



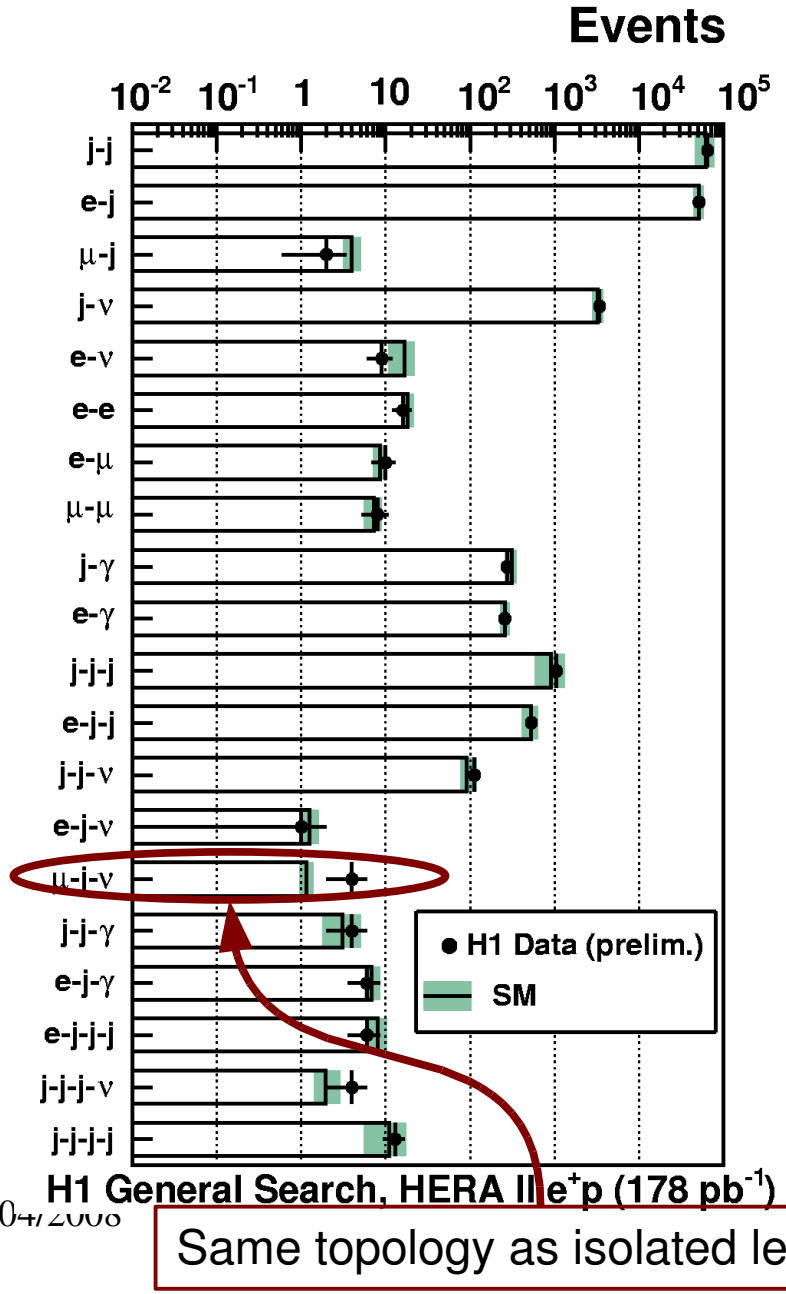


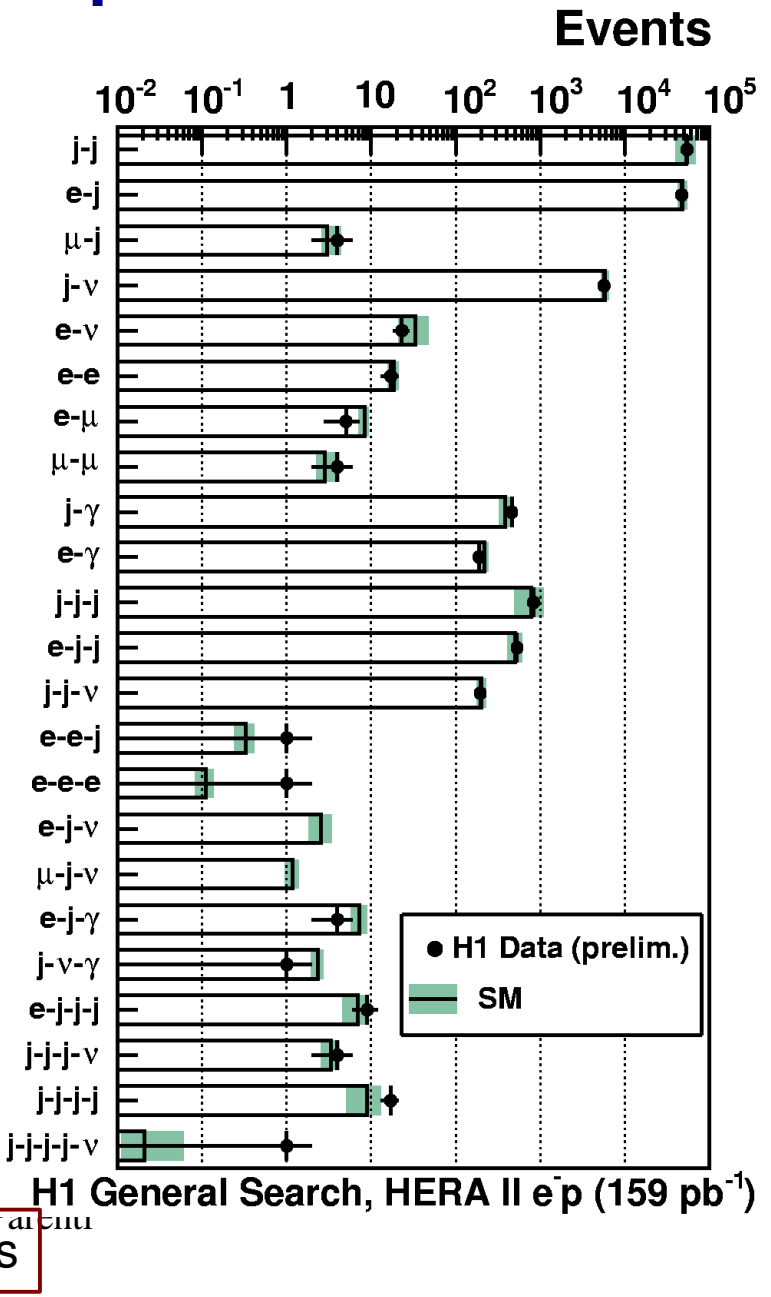
  - W production: $ep \rightarrow eWX$





Check of SM predictions



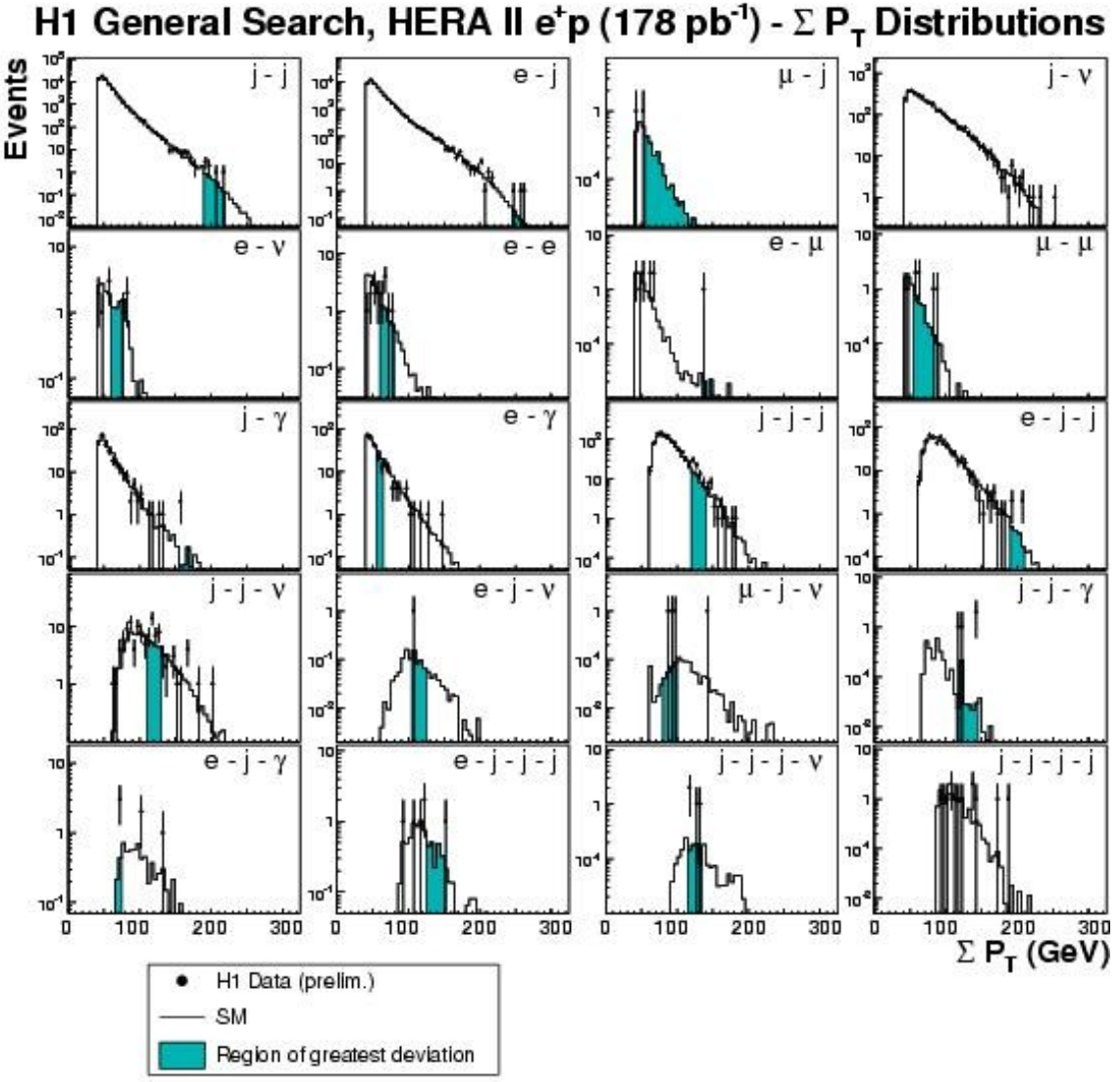


Only channels with ≥1event (Data or SM) are shown

Same topology as isolated leptons

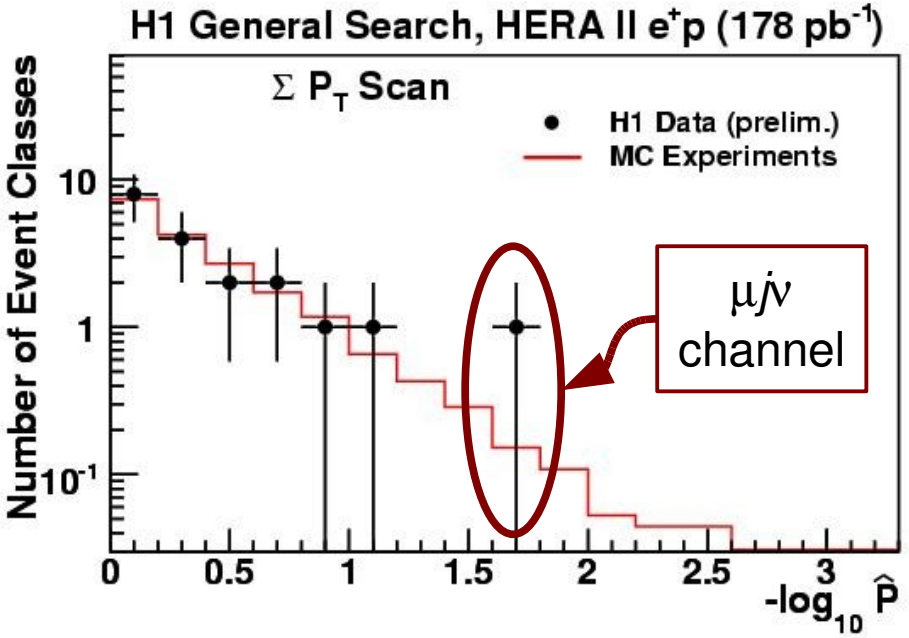
Data/MC comparison

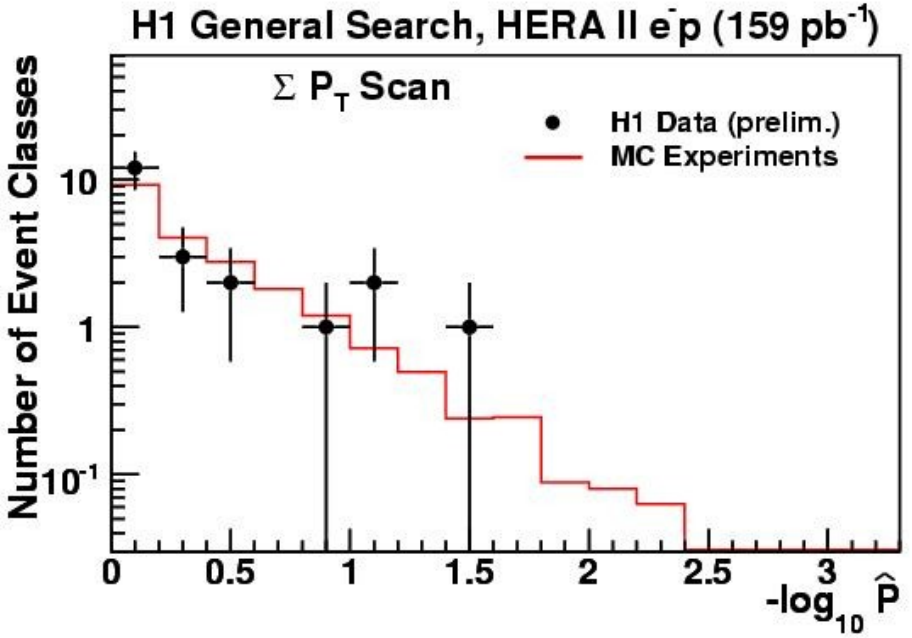
- Regions of largest deviation from SM (shaded) are identified
- Significance of largest fluctuation ($\hat{P}$) is evaluated with use of toy experiments
  - Not done on *jjjj* and *jjjν* classes (large uncertainty on SM prediction)



Data/SM comparison (cont.)

- $\hat{P}$ evaluated also on SM:
  - Data are completely replaced by Toy MC: we re-do a large number of "H1" experiments with ~300pb^{-1} of lumi
- SM reproduces data:





Conclusions

- A search for multi-lepton production has been done by H1 and ZEUS in HERA data (~1fb^{-1}):
  - The event yield of multi-lepton events in HERA data is in good agreement with SM predictions.
  - few striking events are found at high-P_T
- A general search for high-P_T topologies has been done by H1 in HERA-II data (~0.3 fb^{-1}; HERA-I already published)

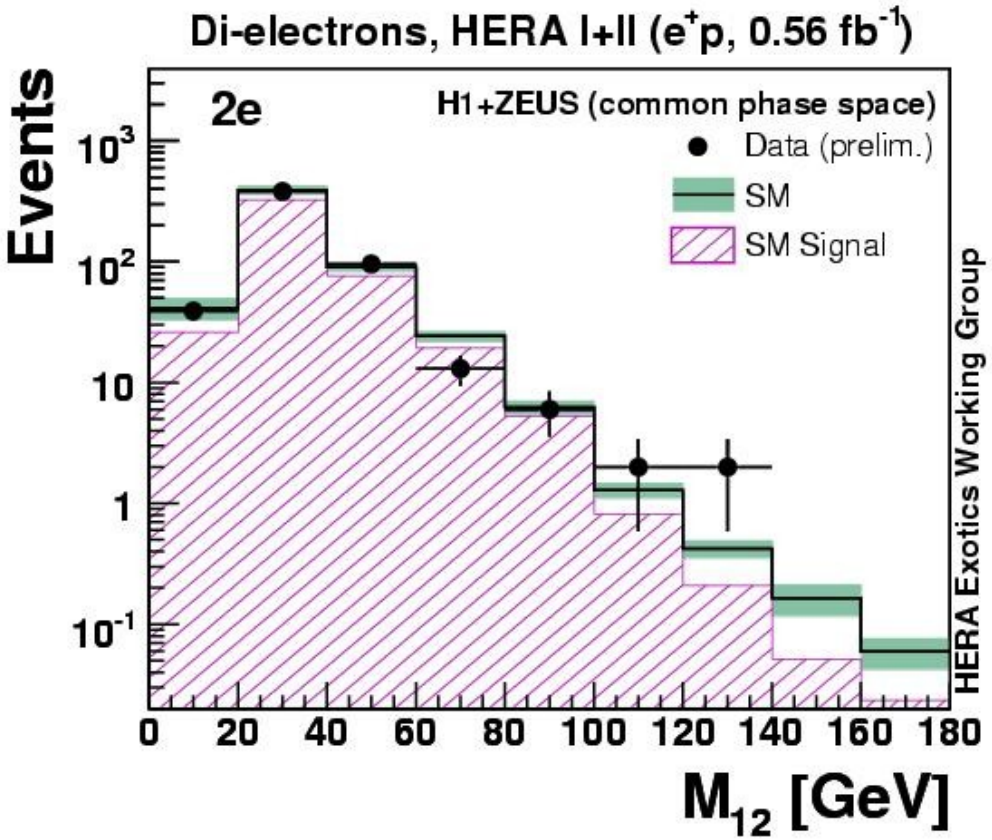
Conclusions (cont.)

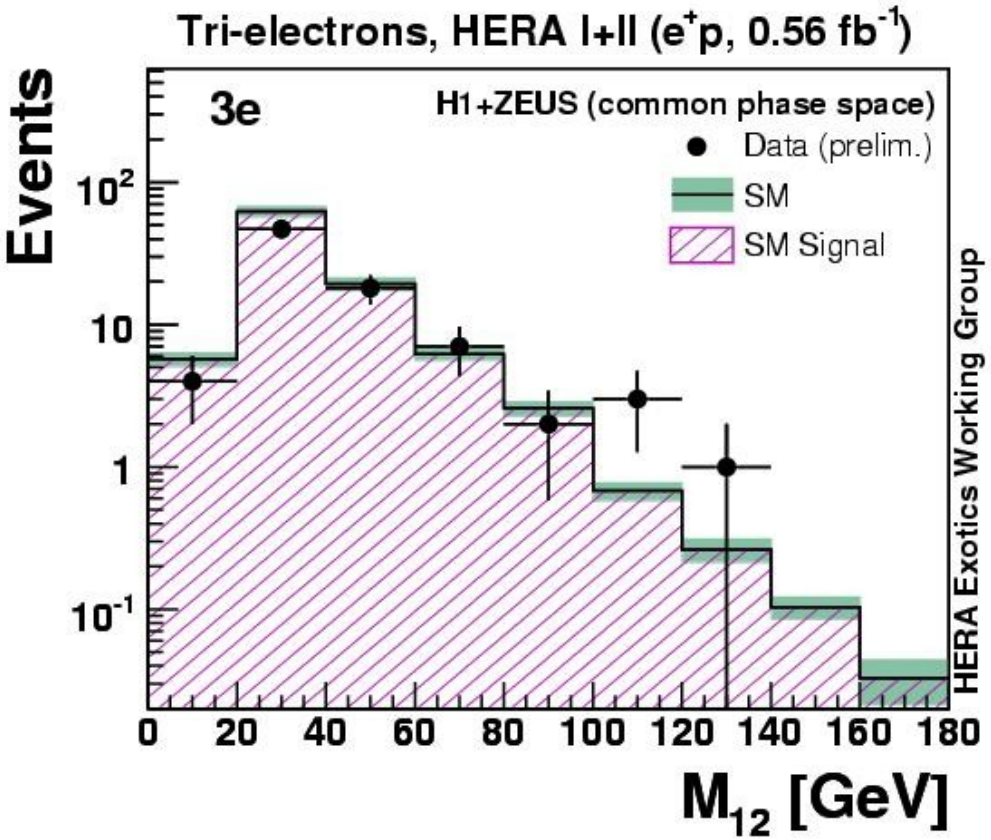
- The largest deviation in HERA-II is observed in $\mu j \nu$ class in e^+p collisions. The significance of this observation is $-\log_{10}\hat{P}=1.7$.
  - In HERA-I also the largest deviation was in $\mu j \nu$, having $-\log_{10}\hat{P}=3$.
- The significance distribution of data is well reproduced. No significant deviation from the Standard Model was found.

Additional Slides

Multi-electrons (H1+ZEUS)

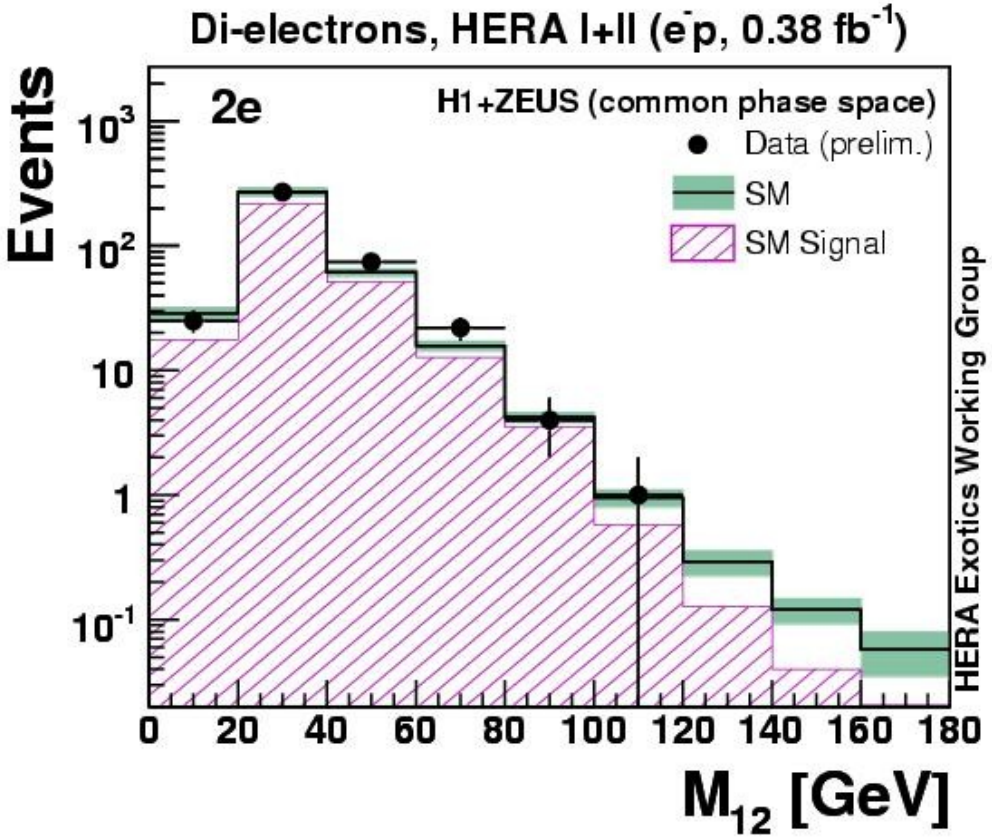
Invariant mass distribution

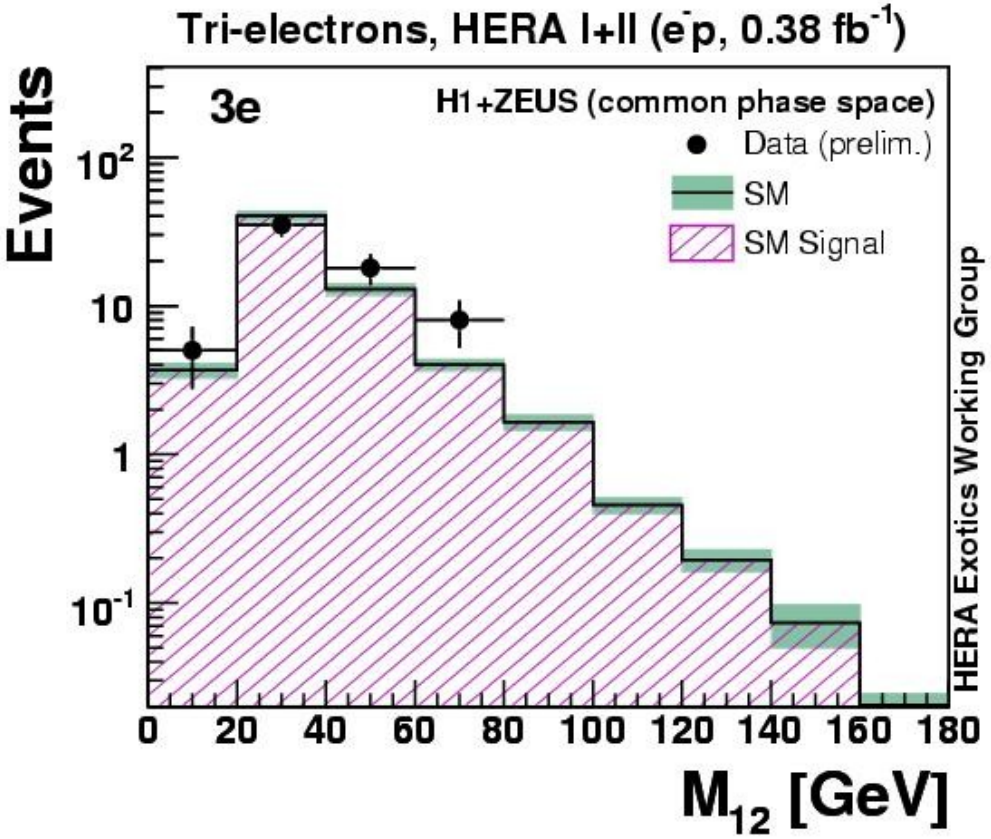




- Invariant mass M_{12} for 2*e* and 3*e* samples, e^+p collisions only.

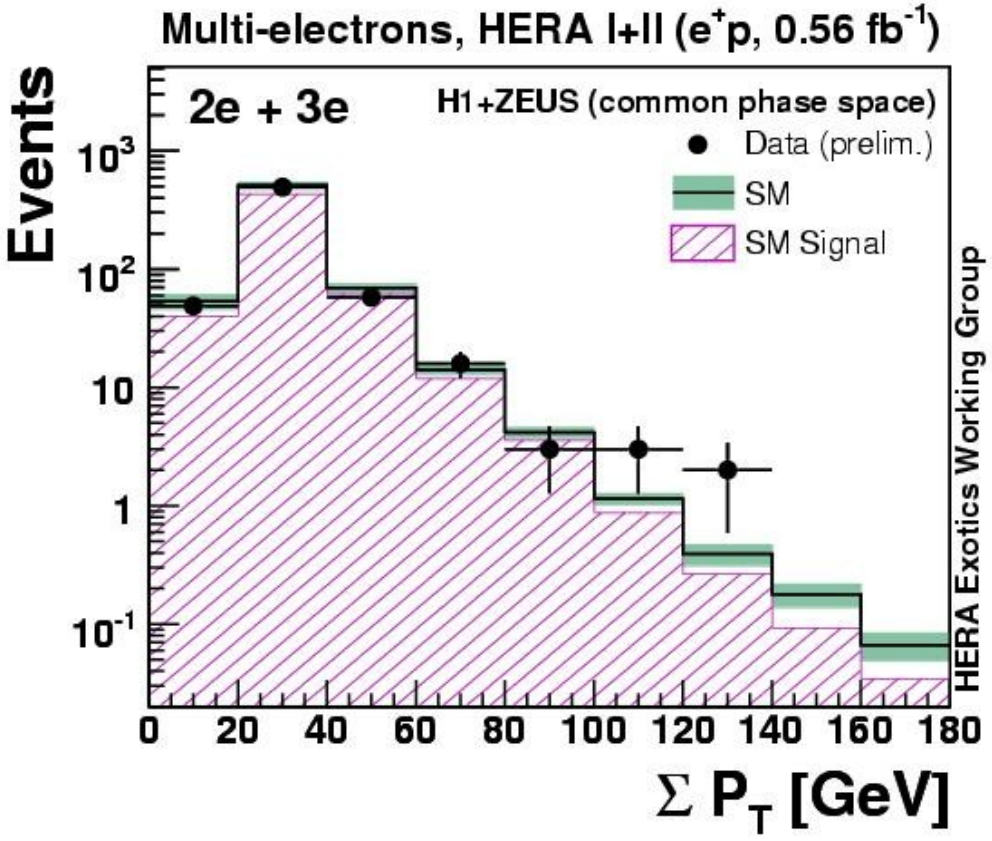
Invariant mass distribution

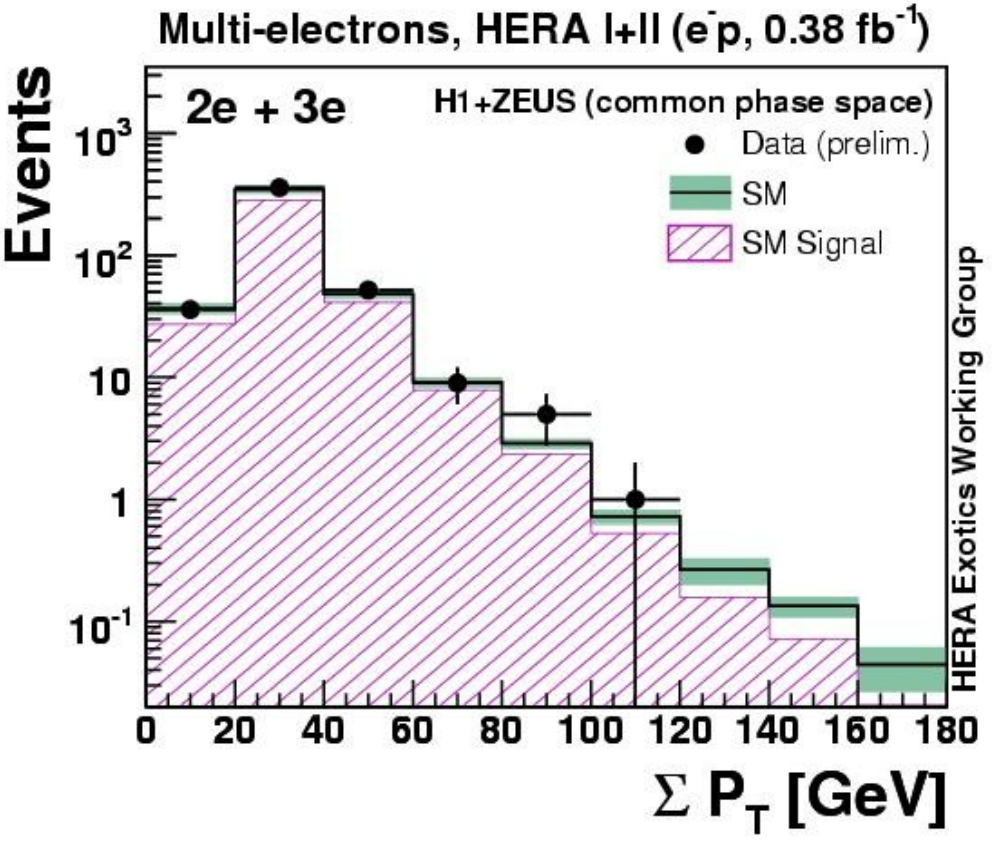




- Invariant mass M_{12} for 2*e* and 3*e* samples, e^-p collisions only.

ΣP_T distribution





- Scalar sum of electron's P_T, $2e+3e$ sample, e^+p and e^-p collisions separately.

Data/MC comparison

- Few events found at high mass:

H1+ZEUS Multi-electron analysis HERA I+II (preliminary)

$M_{12} > 100$ GeV				
Selection	Data	SM	Pair Production	NC-DIS + Compton
e^+p collisions (0.56 fb^{-1})				
2e	4	1.97 ± 0.22	1.10 ± 0.21	0.87 ± 0.18
3e	4	1.10 ± 0.12	1.10 ± 0.12	—
e^-p collisions (0.38 fb^{-1})				
2e	1	1.44 ± 0.15	0.77 ± 0.10	0.67 ± 0.12
3e	0	0.75 ± 0.08	0.75 ± 0.08	—
$e^\pm$ collisions (0.94 fb^{-1})				
2e	5	3.41 ± 0.37	1.87 ± 0.25	1.54 ± 0.29
3e	4	1.85 ± 0.24	1.85 ± 0.24	—

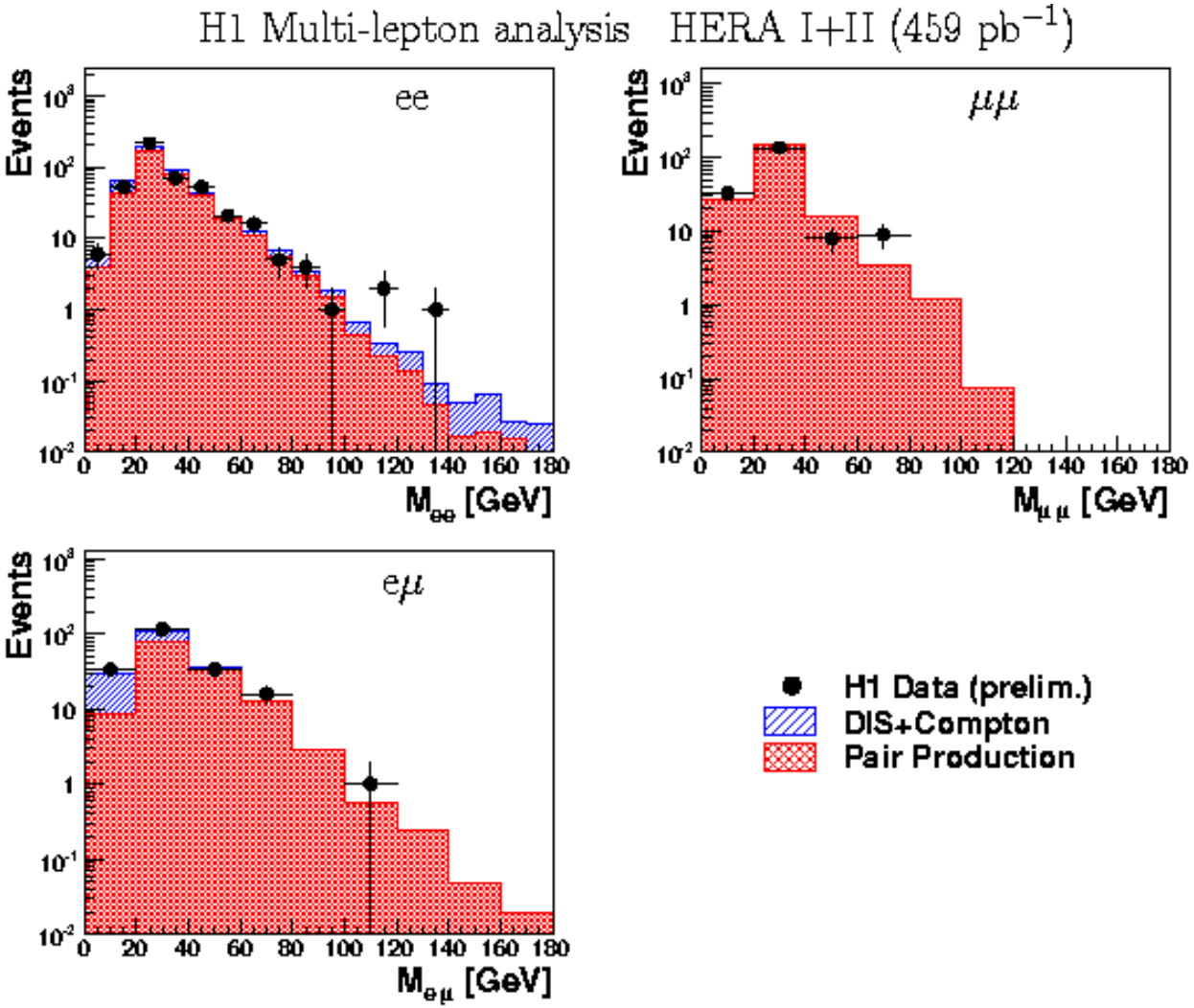
Multi-leptons (H1)

Data/MC comparison

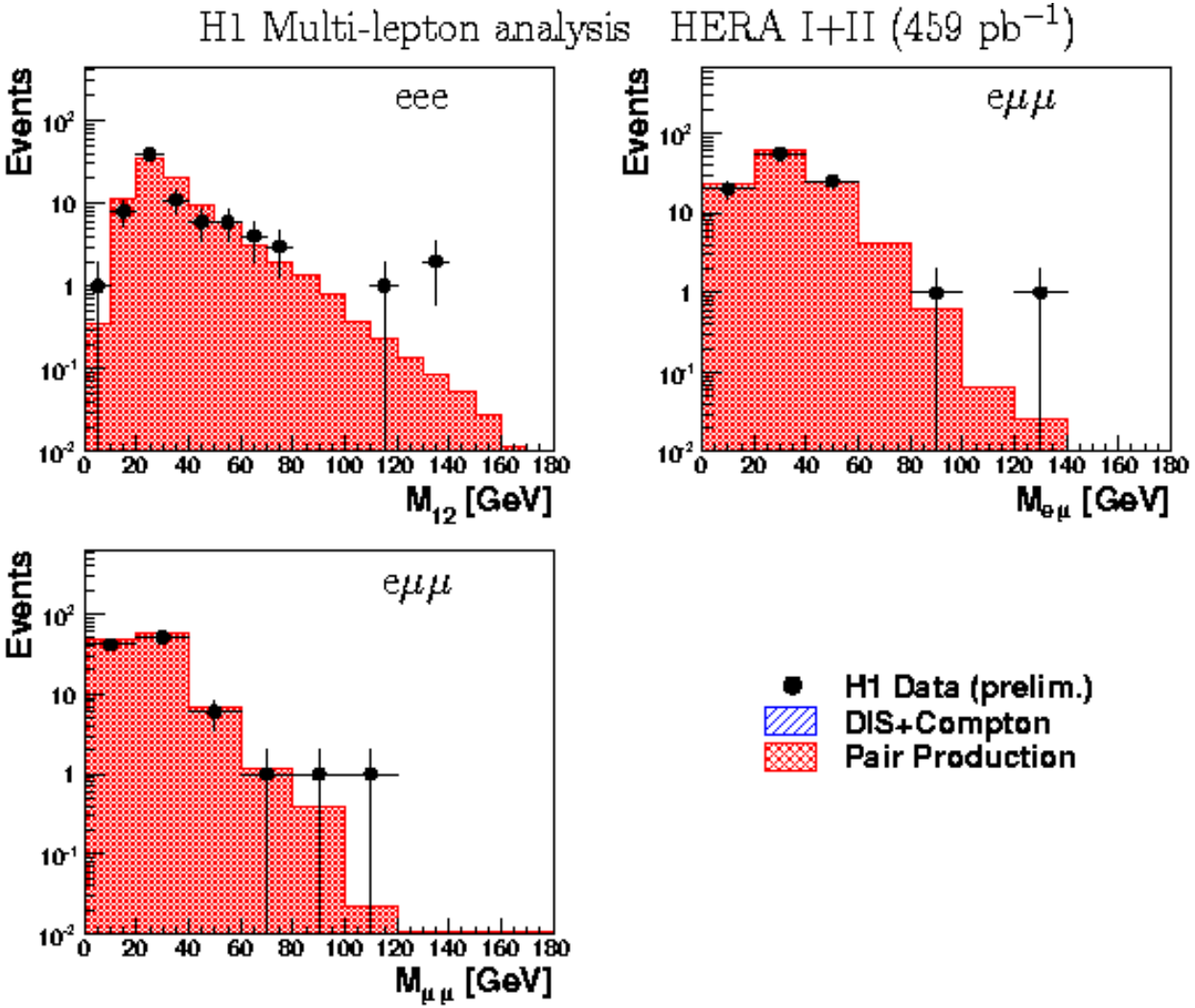
H1 Multi-lepton analysis HERA I+II (preliminary)

Selection	Data	SM	Pair Production	NC-DIS + Compton
e^+p collisions (286 pb^{-1})				
ee M_{12} >100 GeV	3	1.0 ± 0.2	0.6 ± 0.2	0.4 ± 0.1
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.06 ± 0.03	0.06 ± 0.03	—
eμ $M_{e\mu}$ >100 GeV	1	0.53 ± 0.05	0.53 ± 0.05	—
eee M_{12} >100 GeV	3	0.6 ± 0.1	0.6 ± 0.1	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	1	0.04 ± 0.02	0.04 ± 0.02	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	1	0.007 ± 0.005	0.007 ± 0.005	—
e^-p collisions (173 pb^{-1})				
ee M_{12} >100 GeV	0	0.55 ± 0.1	0.3 ± 0.1	0.25 ± 0.07
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.03 ± 0.02	0.03 ± 0.02	—
eμ $M_{e\mu}$ >100 GeV	0	0.3 ± 0.05	0.3 ± 0.05	—
eee M_{12} >100 GeV	0	0.32 ± 0.06	0.32 ± 0.06	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	0	0.04 ± 0.01	0.04 ± 0.01	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.006 ± 0.004	0.006 ± 0.004	—
All data (459 pb^{-1})				
ee M_{12} >100 GeV	3	1.5 ± 0.3	0.9 ± 0.2	0.6 ± 0.2
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.09 ± 0.05	0.09 ± 0.05	—
eμ $M_{e\mu}$ >100 GeV	1	0.9 ± 0.1	0.9 ± 0.1	—
eee M_{12} >100 GeV	3	0.9 ± 0.2	0.9 ± 0.2	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	1	0.1 ± 0.04	0.1 ± 0.04	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	1	0.03 ± 0.02	0.03 ± 0.02	—

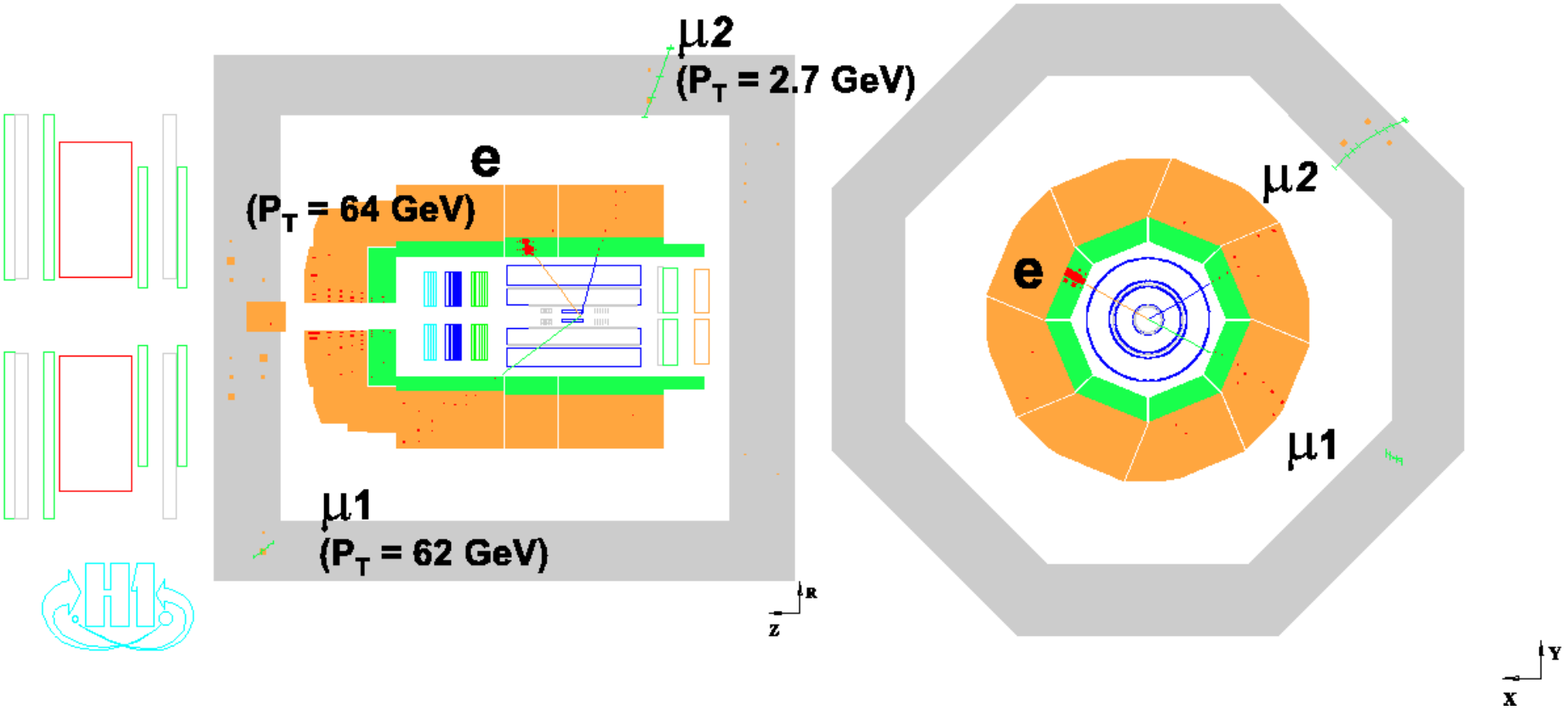
Two-lepton sample



Three-lepton sample



The $e\mu\mu$ event at high ΣP_T



General search for new phenomenon (H1)

Standard Model processes

Final State	Process	Generator
jjX	Jet photoproduction	PYTHIA 6.1
γjX	Prompt photon	PYTHIA 6.1
$\gamma\gamma X$	Photon pair photopr.	PYTHIA 6.1
ejX, $ejjX$, $e\gamma jX$	NC DIS	RAPGAP+HERACLES
jjX, γjX	NC DIS (low P_T elec.)	RAPGAP+HERACLES
νjX, νjjX	CC DIS	RAPGAP
$e\gamma X$	QED compton (ela+qela)	WABGEN
$\mu\mu X, eeX, e\mu\mu X, eeeX$	EW dilepton production	GRAPE+PYHTIA (SOPHIA)
WX, WjX	W production	EPVEC

“Object” identification

- Electrons:
  - e.m. deposit in calorimeter, compact and isolated
  - High quality track matched in position and momentum, isolated
  - Finding efficiency: 90% (70% in the forward region)
- Photons:
  - Same calorimeter requirements as for electrons
  - No track, isolation from high-P_T jets
  - Finding efficiency: ~85%

“Object” identification (cont.)

- Muons:
  - track in the forward muon system or inner tracker
  - track segment or energy deposit in the central muon detector
  - Di-muons: separated by < 165° (cosmic rejection)
  - Muons must come from vertex (halo-μ rejection)
  - Isolation from high-P_T jets (suppresses mis-identified hadrons)
  - Efficiency: >90%

"Object" identification (cont.)

- Jets:
  - Identified by inclusive $k\perp$ algorithm in lab frame
  - It is run an all tracks not associated to objects
  - Cuts against fake jets
  - Efficiency: 97%
- Neutrinos:
  - Identified by missing momentum
  - "neutrino" must be isolated from other objects
  - If <u>one</u> lepton is found, $\Delta\phi(l\text{-}X_{tot})<170°$

Search strategy

- "Regions": are sets of connected bins (ΣP_T or M_{all}) wide at least twice the resolution
- Probability of fluctuation of data in a region:

$$A \int_0^\infty db\, G(b; N_{SM}, \delta N_{SM}) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!} \qquad \text{if } N_{obs} \geq N_{SM}$$

$$A \int_0^\infty db\, G(b; N_{SM}, \delta N_{SM}) \sum_{i=0}^{N_{obs}} \frac{e^{-b} b^i}{i!} \qquad \text{if } N_{obs} < N_{SM}$$

- p_{min} is the smallest value in a distribution
- $p_{\text{min}}^{\text{SM}}$ is also evaluated for the MC by varying N_{SM} accordingly to δN_{SM}.

Search strategy

- Significance per event class: the fraction of MC histograms having $p_{min}^{SM} < p_{min}$ is the probability $\hat{P}$.
  - A p_{min}-value of 5.7E-7 ("5σ") corresponds to a probability 1E-6 to 1E-5, depending on the final state
- Global significance: Many MC experiments are performed in order to evaluate $\hat{P}$ for the SM.

Systematic uncertainties

- Luminosity measurement: 2.5%
- Electron/photon measurement:
  - Electromagnetic energy scale: 1-3%
  - Polar angle measurement: 3 mrad
  - Tracking efficiency (for e/γ separation): 3-5%
- Jets:
  - Hadronic energy scale: 2%
  - Polar angle measurement: 5-10 mrad

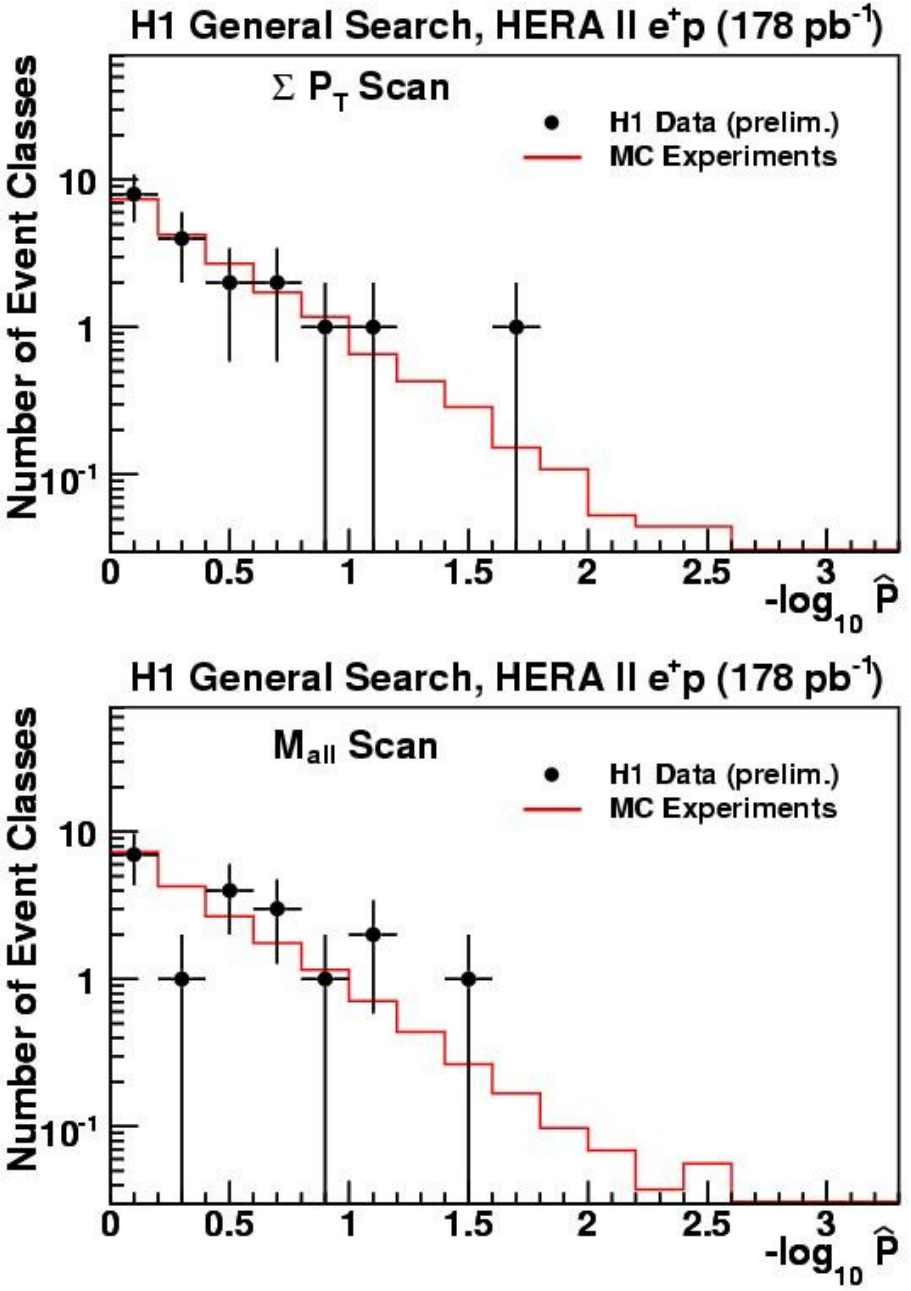
Systematic uncertainties (cont.)

- Muon measurement:
  - P_T measurement: 5%
  - Polar angle measurement: 3 mrad
  - Muon identification: 5%
- Trigger efficiencies:
  - Jet or missing P_T triggered events: 3%
  - Muon triggered events: 10%
  - Electron/photon triggered events: negligible

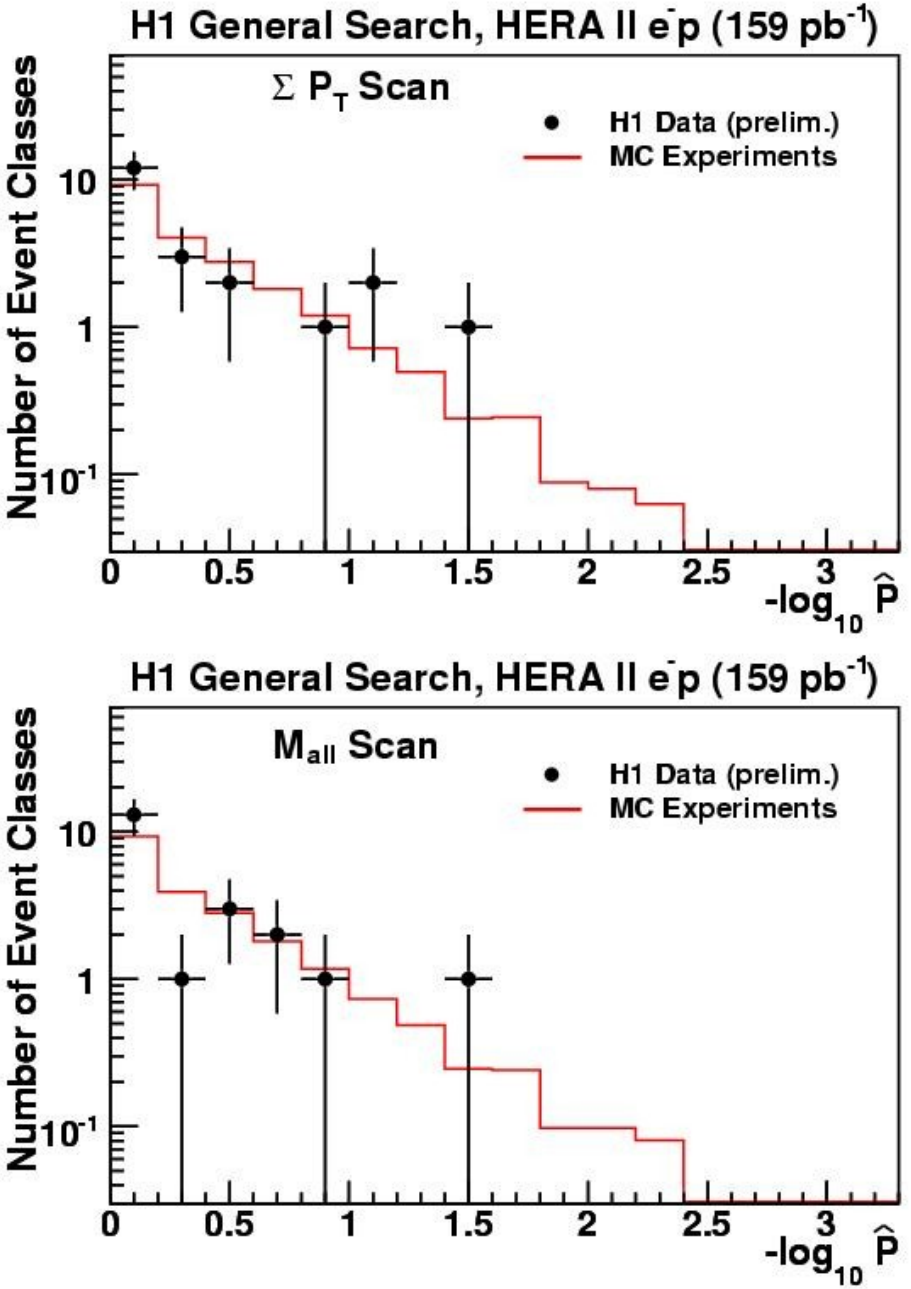
Theoretical uncertainties

Final state	Uncertainty
jjX, $j\gamma X$	15%
$j\nu$X, jeX	10%
$jj\nu$X, jjeX	15%
$\mu\mu X$, eeX	3%
WX, WjX	15%
$e\gamma X$, $e\gamma j$	10%
$e\gamma$p	5%

Global significance – e^+p data

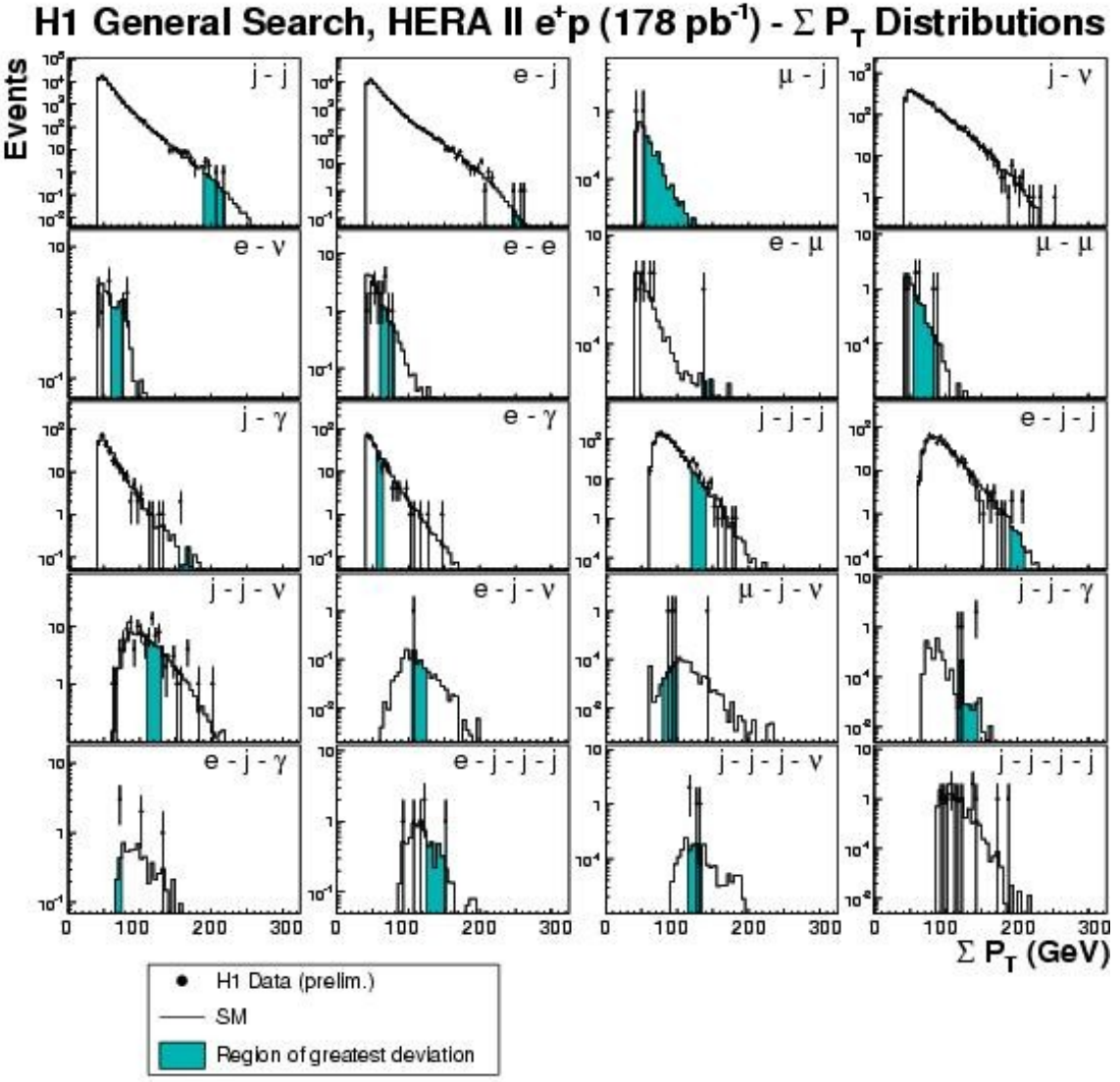


Global significance – $e^- p$ data

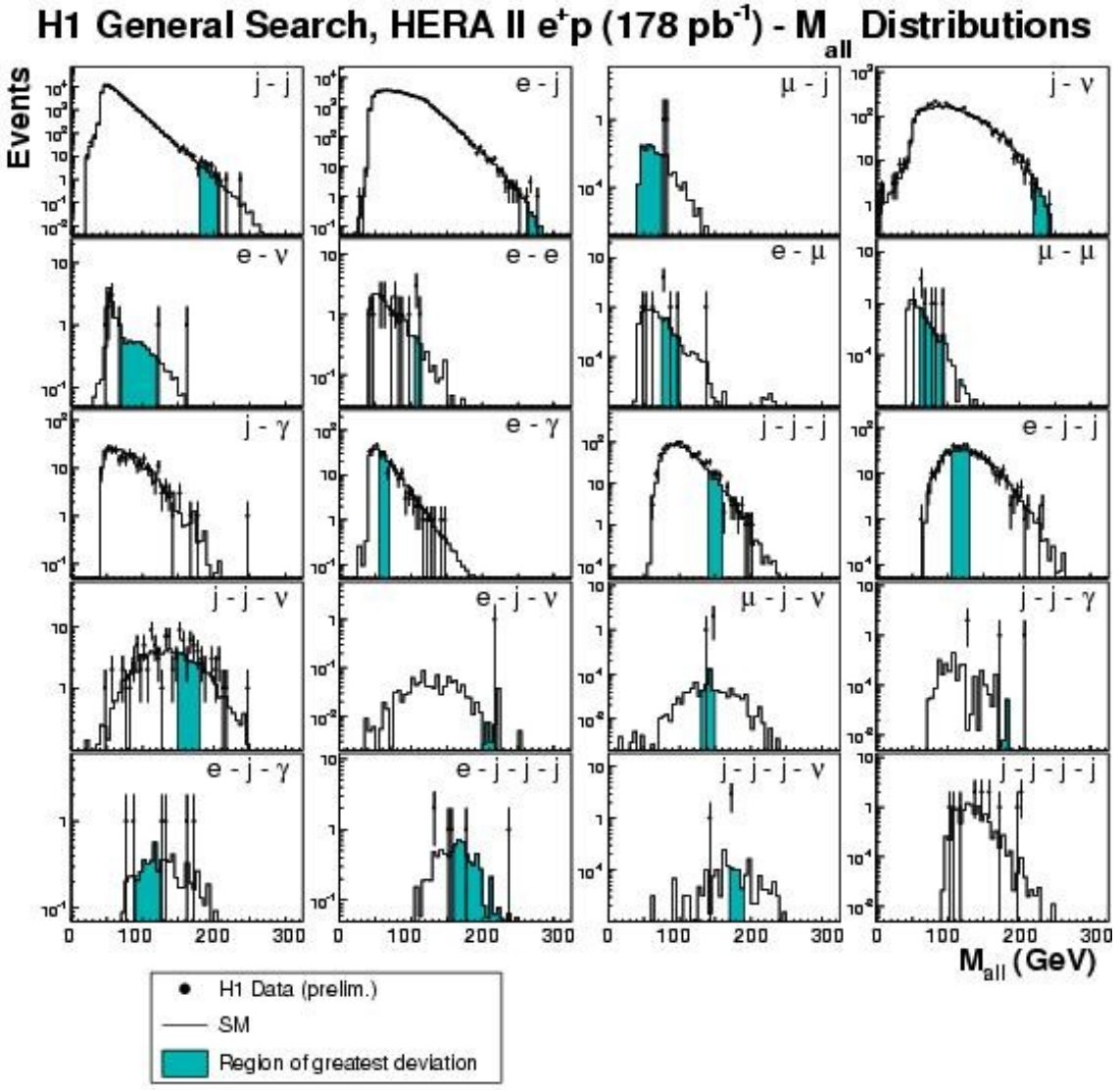


Region of interest - e^+p data

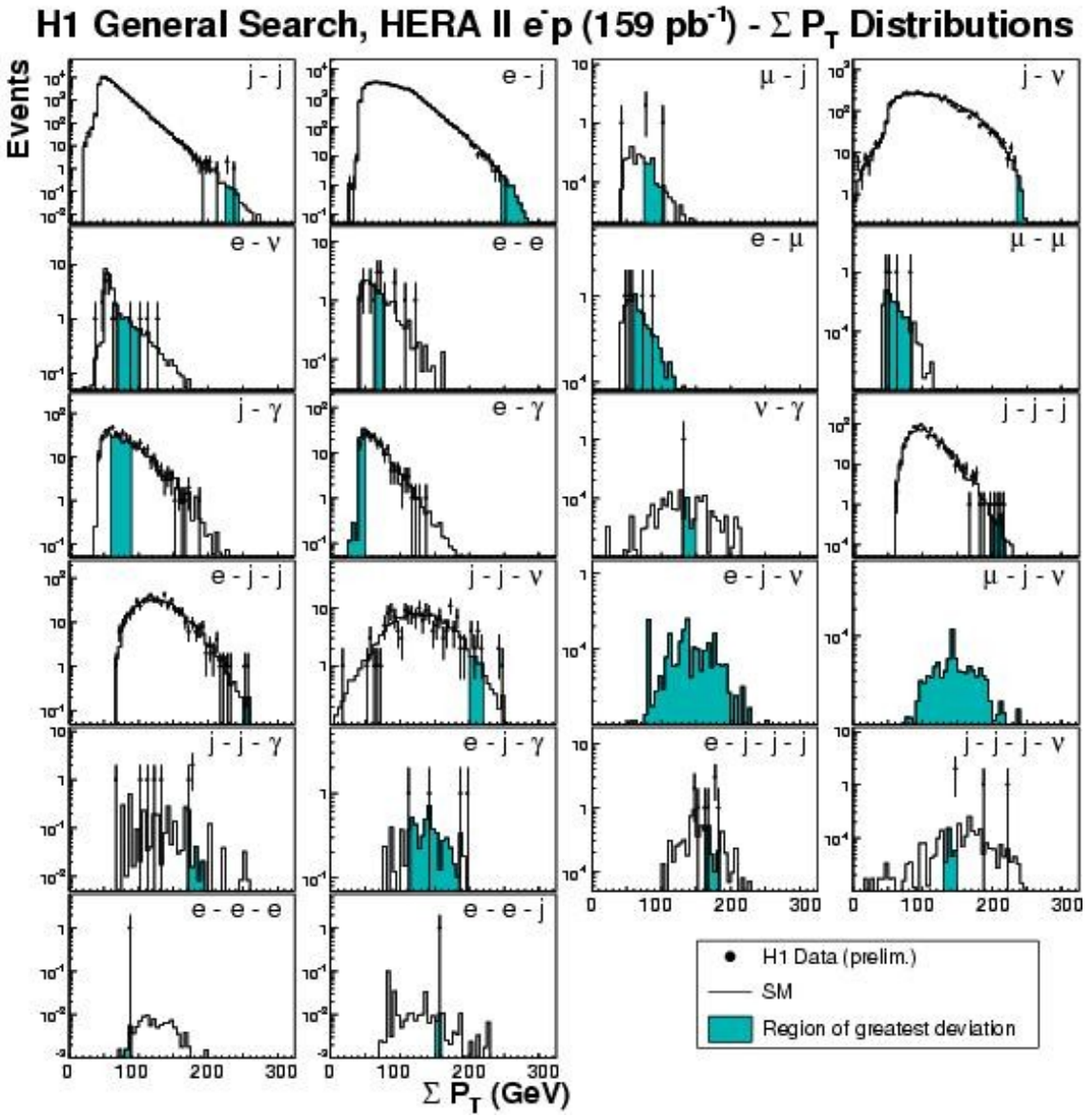
- Shaded areas are regions of greatest deviation from SM
- No search performed for *jjjj* and *jjjν* classes (large uncertainty on SM prediction)



Region of interest - e^+p data



Region of interest - $e^{-}p$ data



Region of interest - $e^- p$ data