

Multi-lepton and general searches at HERA

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on behalf of **H1** and **ZEUS** collaborations



- DIS 2008 -

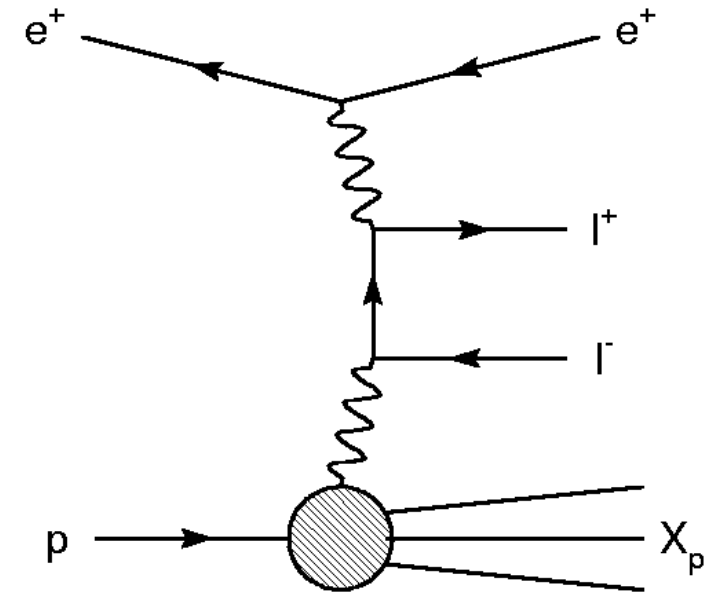
Outline:

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

Multi-electrons (H1+ZEUS)

Motivation

- Main production process is Bethe-Heitler: $\gamma\gamma \rightarrow l^+l^-$ ($l=e, \mu, \tau$)
- 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 ($\mu\mu$ & $e\mu\mu$ 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 $20^\circ < \theta < 150^\circ$ with $P_T > 10, 5$ GeV
 - Additional electrons searched for in $5^\circ < \theta < 175^\circ$
 - Events are classified as “2e” or “3e” according to the number of electrons found.

Data/SM comparison

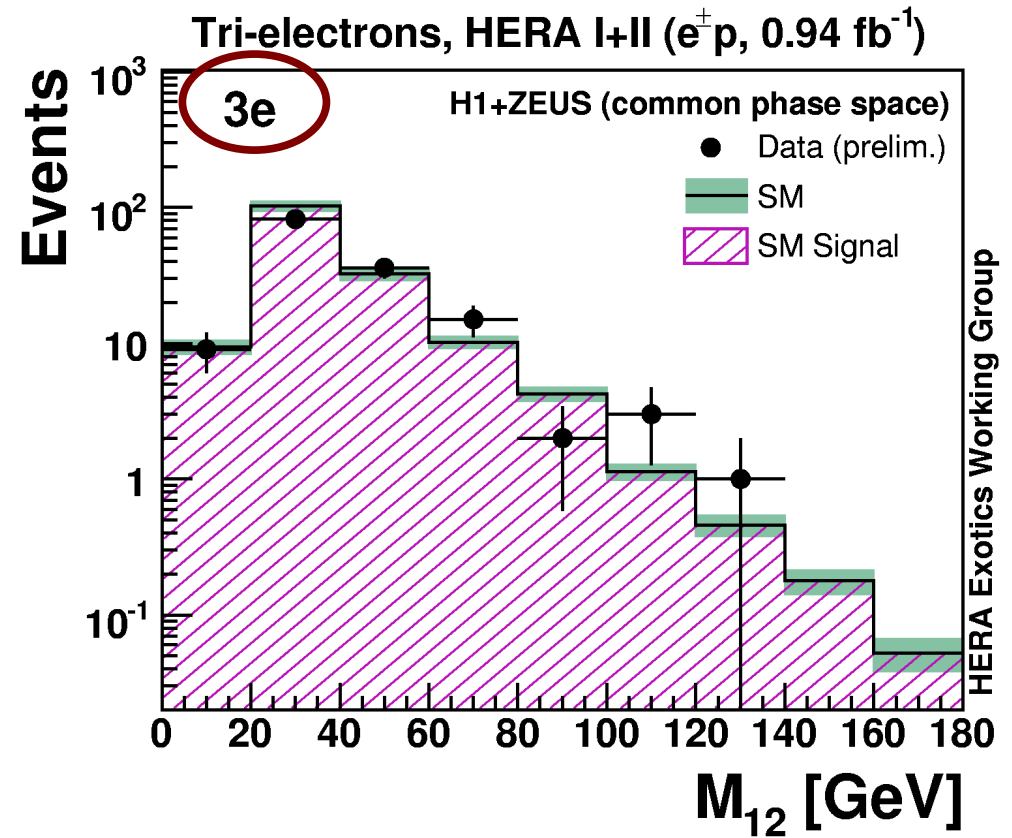
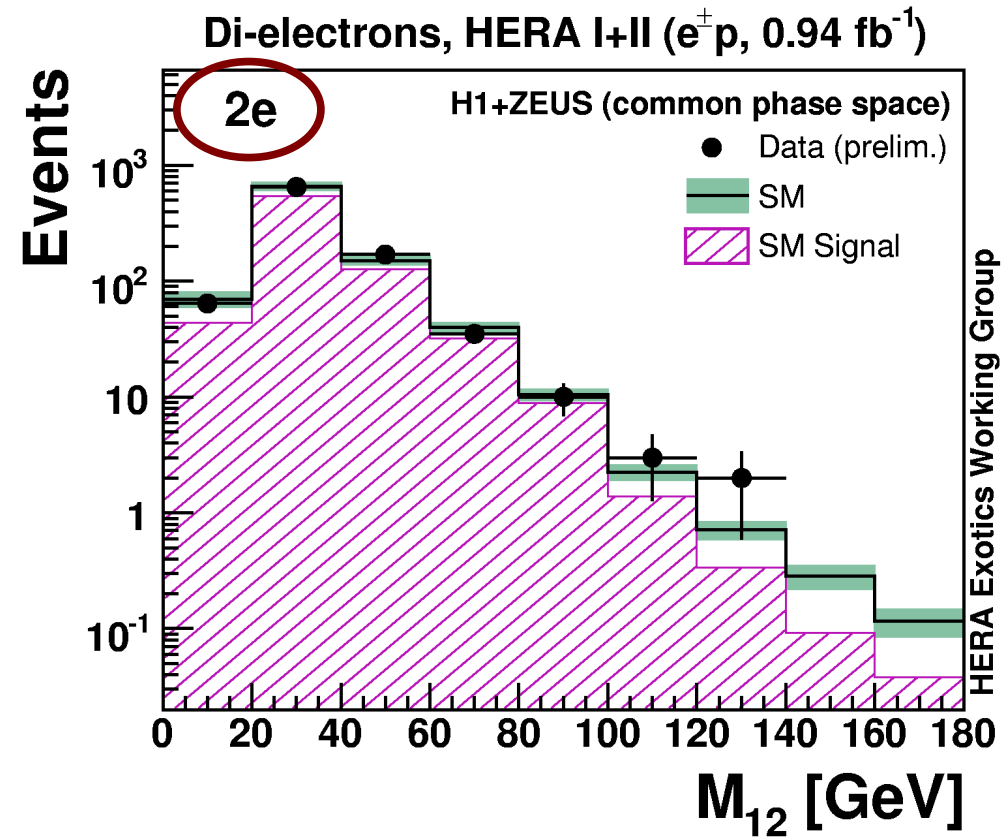
- Overall agreement between data and SM:

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

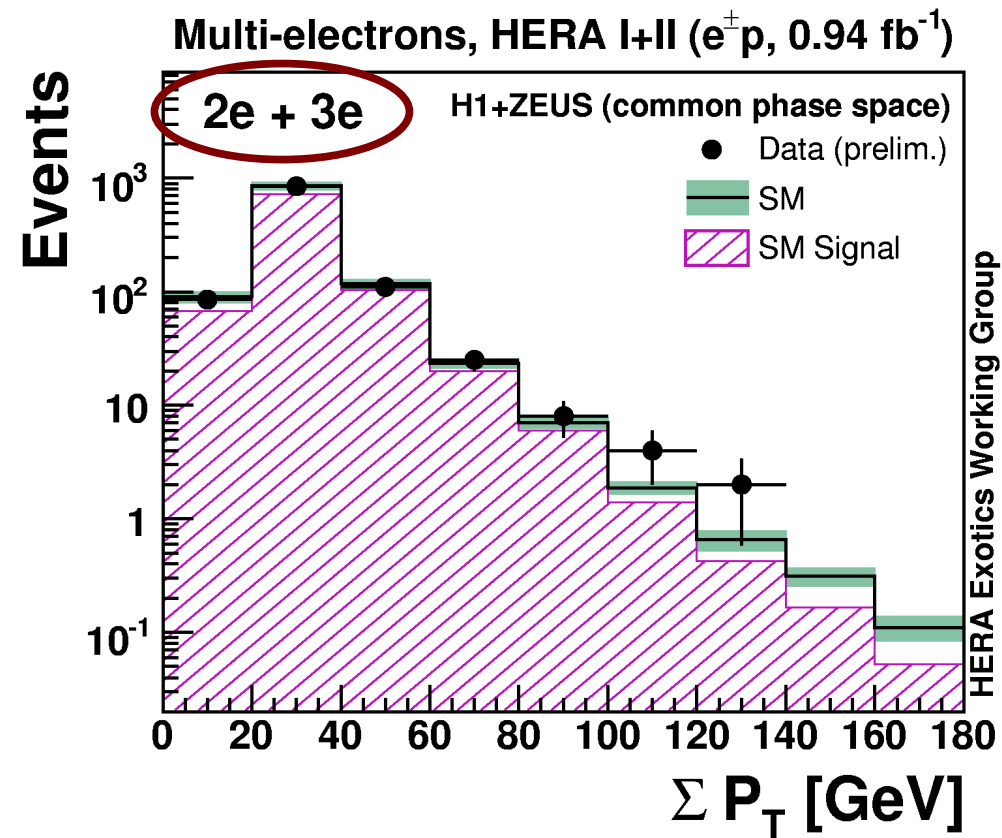
- Let's see the differential distributions...

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)

$M_{12} > 100 \text{ GeV}$				
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)

$\Sigma P_T > 100 \text{ GeV}$				
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

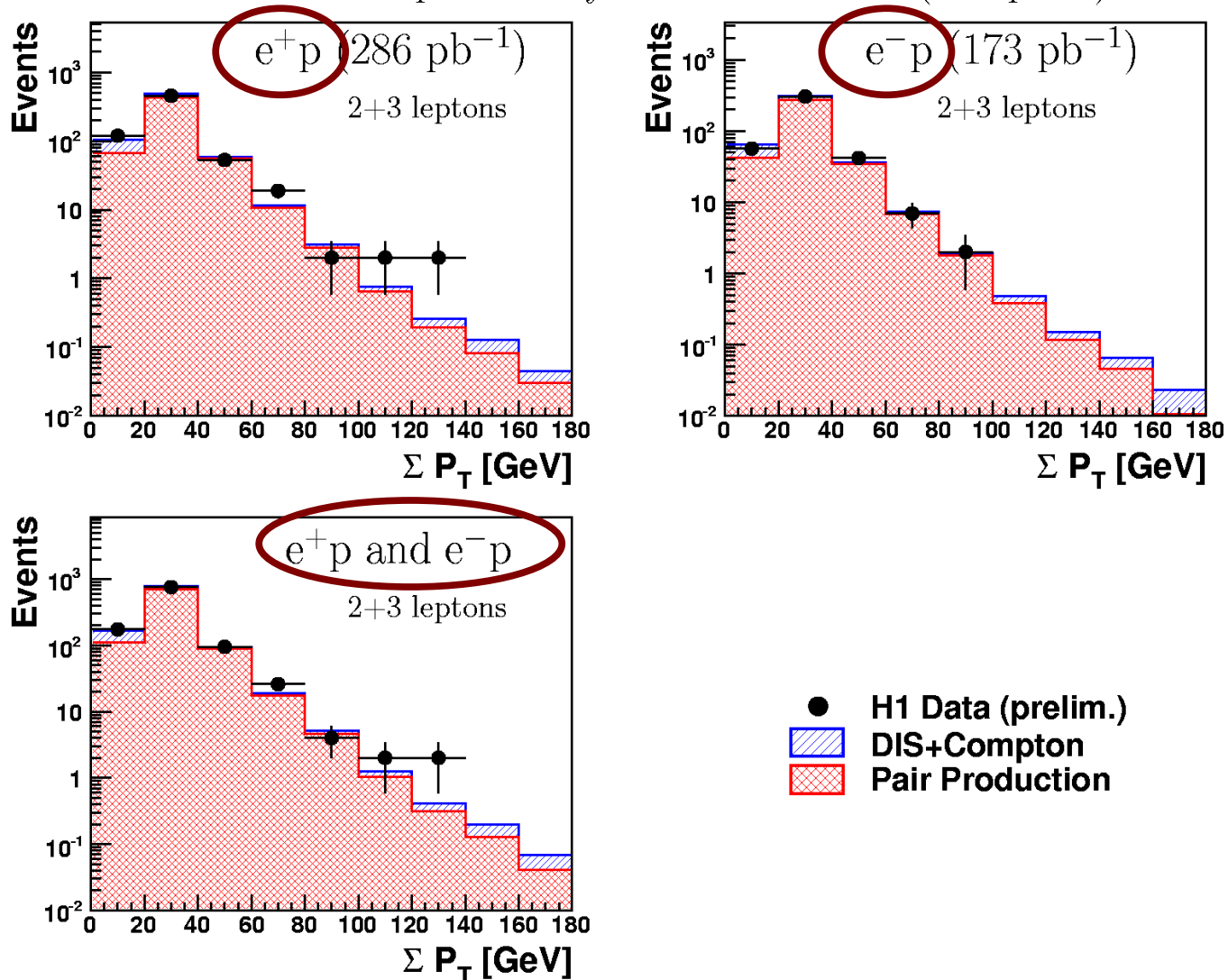
Multi-leptons (H1)

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 $20^\circ < \theta < 150^\circ$ with $P_T > 10,5$ GeV
 - Additional electrons searched for in $5^\circ < \theta < 175^\circ$
 - Additional muons searched for in $20^\circ < \theta < 160^\circ$

ΣP_T distribution

H1 Multi-lepton analysis HERA I+II (459 pb⁻¹)



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
μμ	185	194 ± 38	194 ± 38	—
eμ	201	194 ± 26	136 ± 13	58 ± 17
eee	81	90 ± 10	90 ± 10	—
eμμ	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

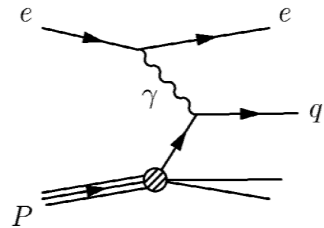
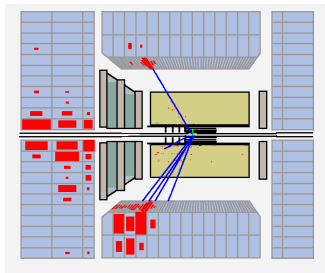
Data sample and selection

- 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:
 - $P_T > 20 \text{ GeV}$ and $10^\circ < \theta < 140^\circ$

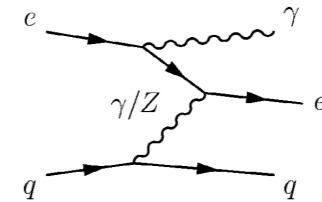
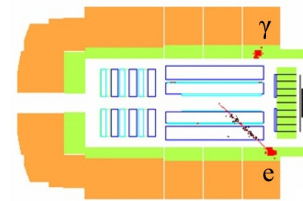
Standard Model processes

- All SM ep processes need to be simulated
- High statistics needed

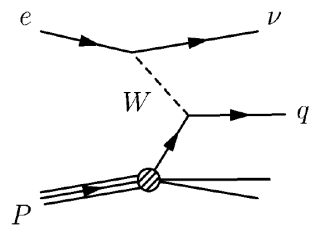
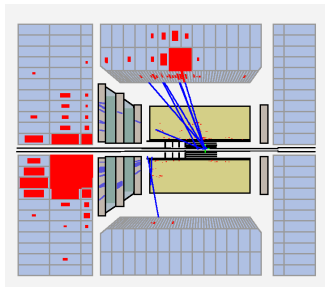
- Neutral Current DIS: $ep \rightarrow eX$



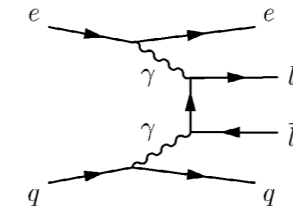
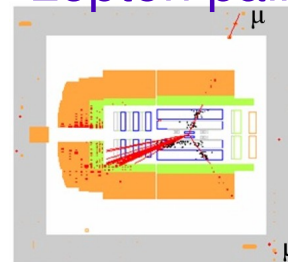
- QED Compton: $ep \rightarrow e\gamma X$



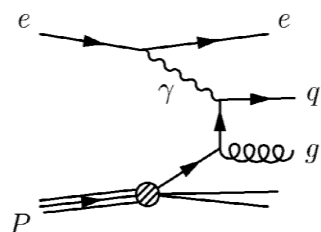
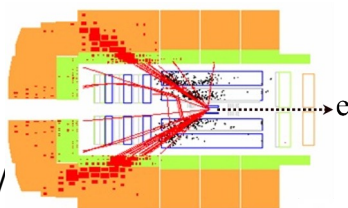
- Charged Current DIS: $ep \rightarrow \nu X$



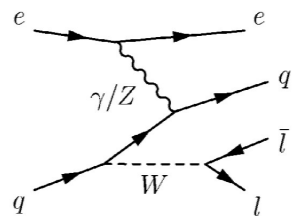
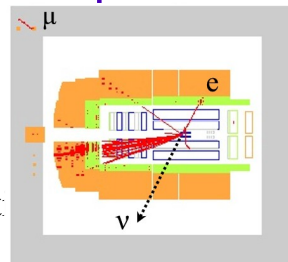
- Lepton pair production: $ep \rightarrow e l \bar{l} X$



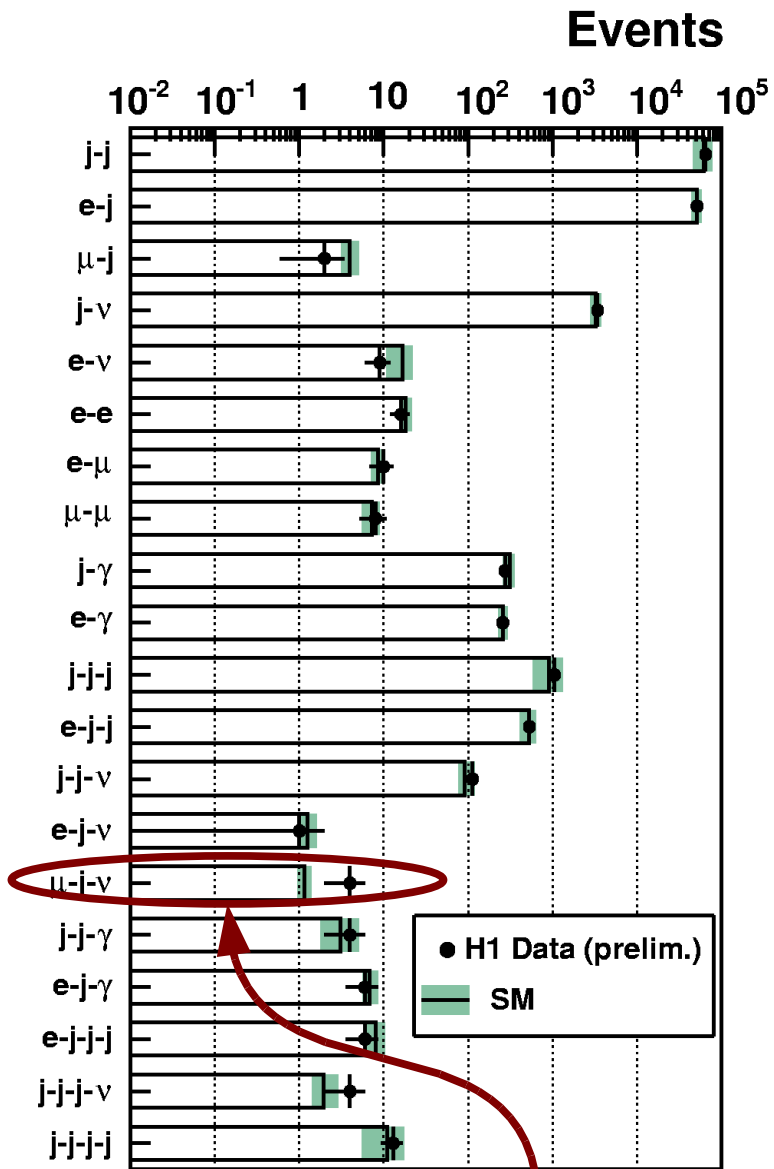
- Photoproduction: $\gamma p \rightarrow X$



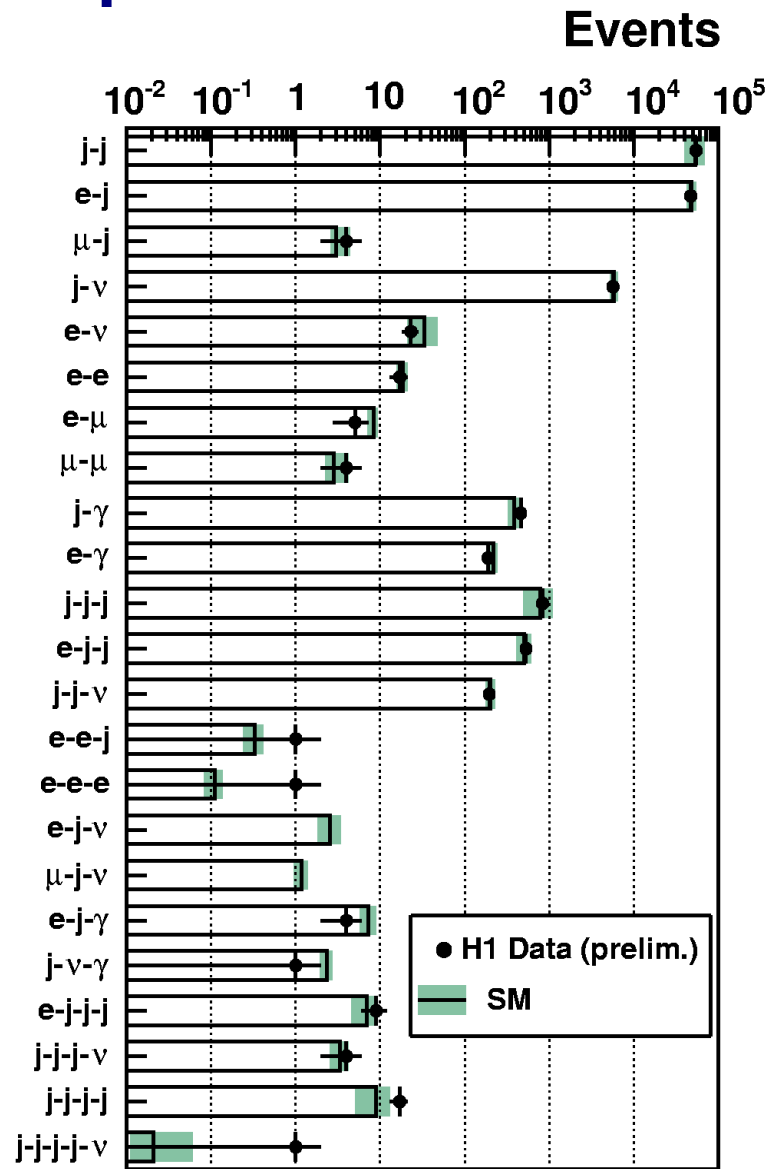
- W production: $ep \rightarrow e W X$



Check of SM predictions



H1 General Search, HERA II e^+p (178 pb⁻¹)



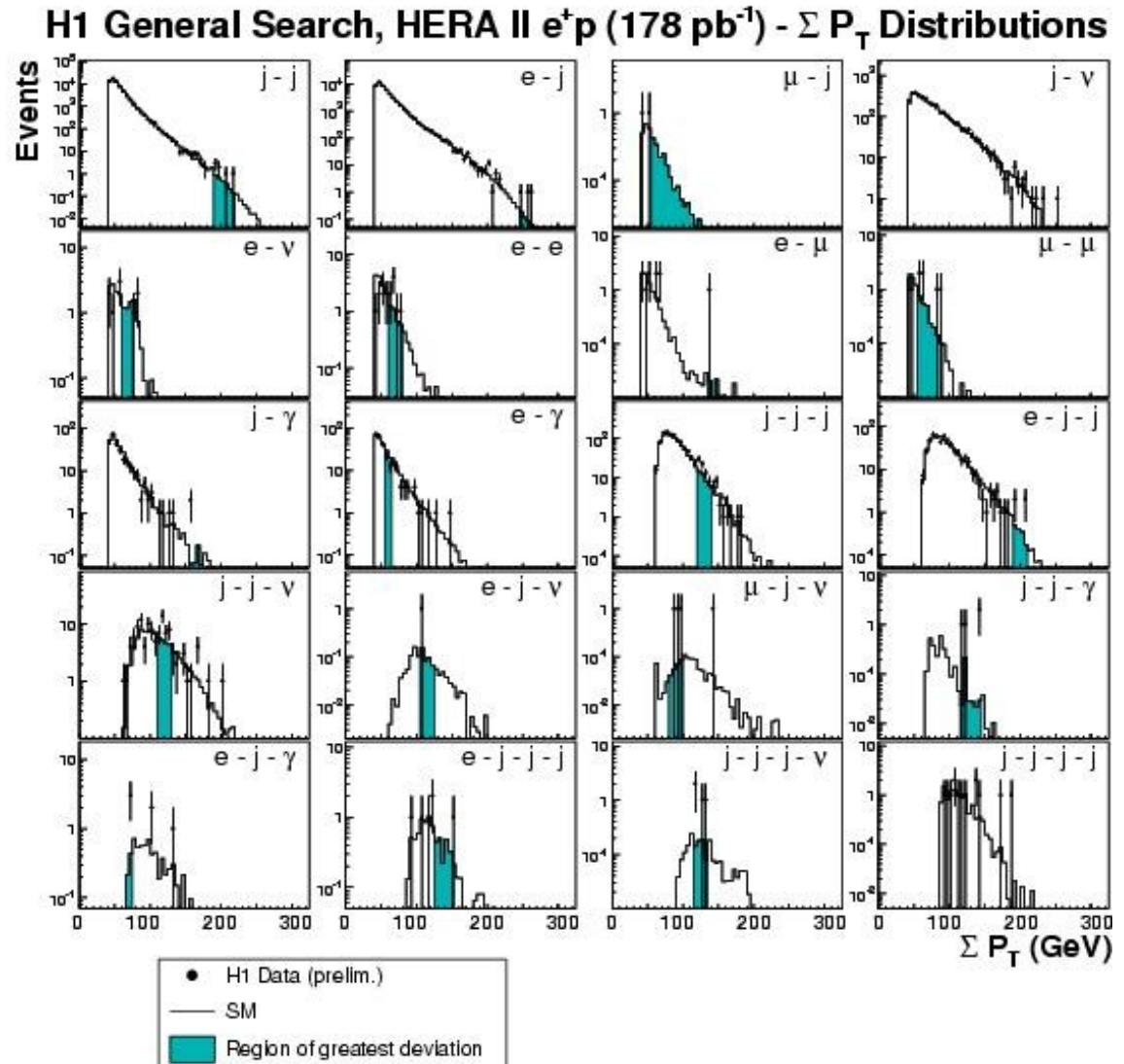
H1 General Search, HERA II e^-p (159 pb⁻¹)

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

Same topology as isolated leptons

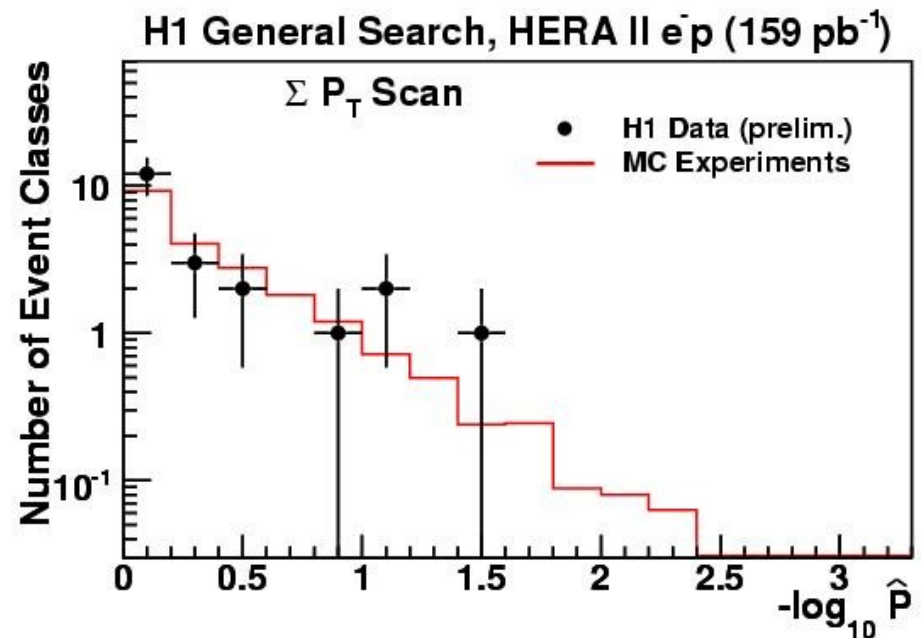
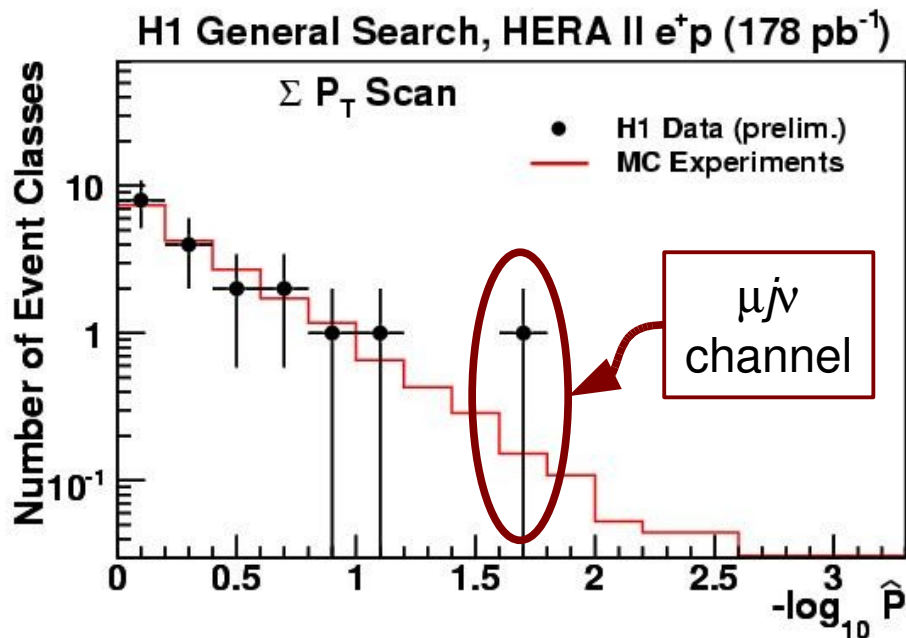
Data/MC comparison

- 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 $jjjj\nu$ 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 $\sim 300\text{pb}^{-1}$ of lumi
- SM reproduces data:



Conclusions

- A search for multi-lepton production has been done by H1 and ZEUS in HERA data ($\sim 1 \text{ fb}^{-1}$):
 - 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 ($\sim 0.3 \text{ fb}^{-1}$; HERA-I already published)

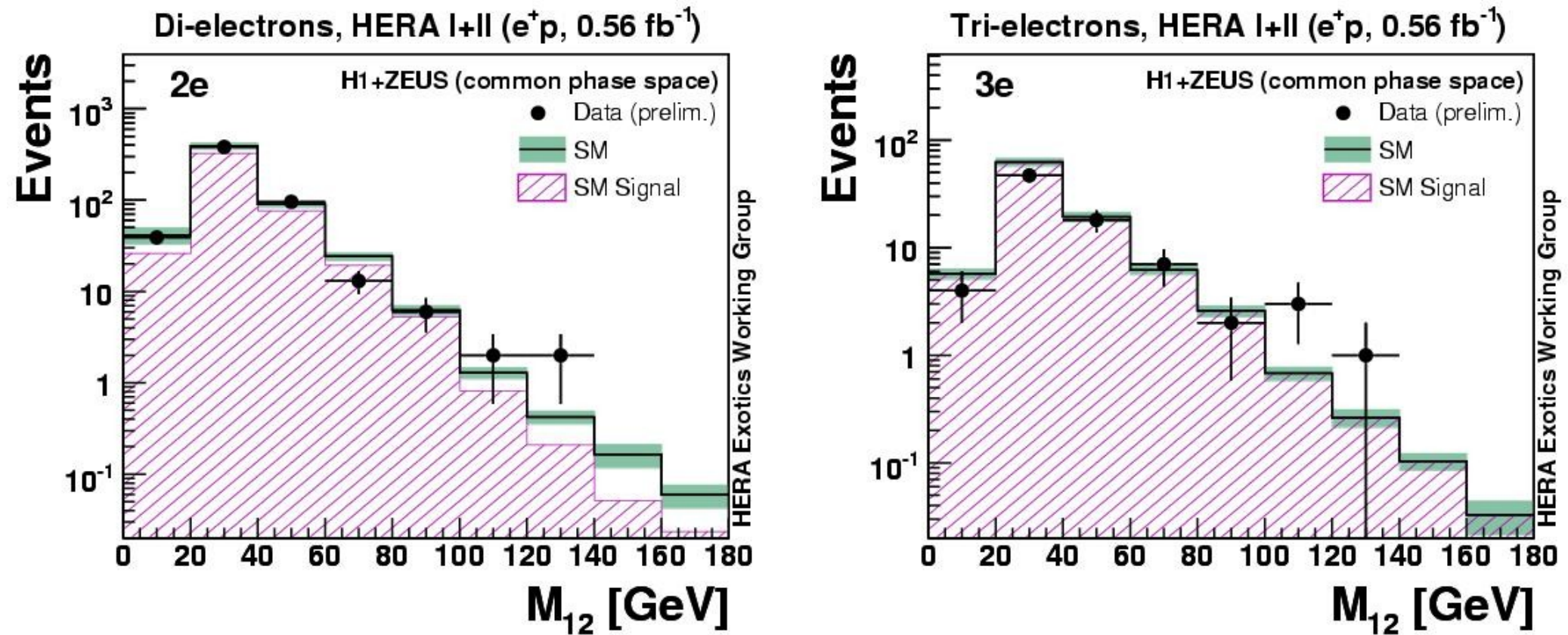
Conclusions (cont.)

- The largest deviation in HERA-II is observed in $\mu\nu$ 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 $\mu\nu$, 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

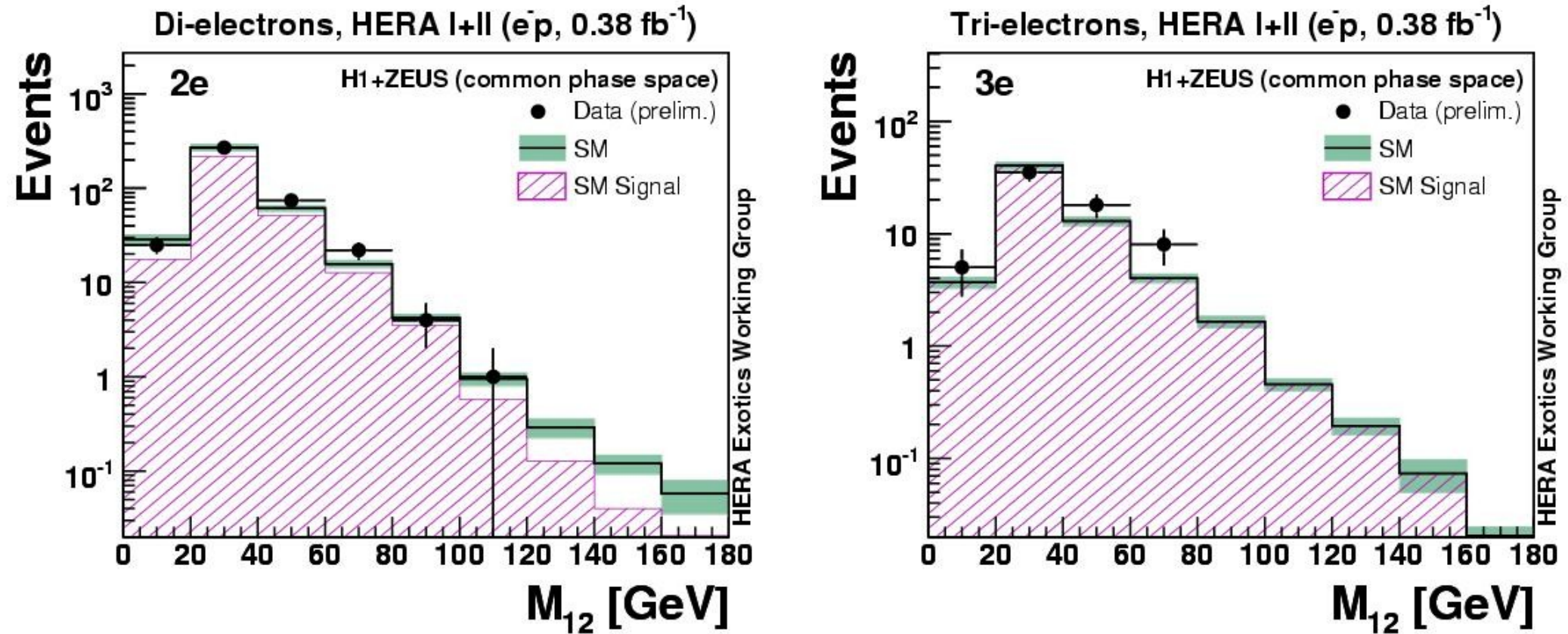
Multi-electrons (H1+ZEUS)

Invariant mass distribution



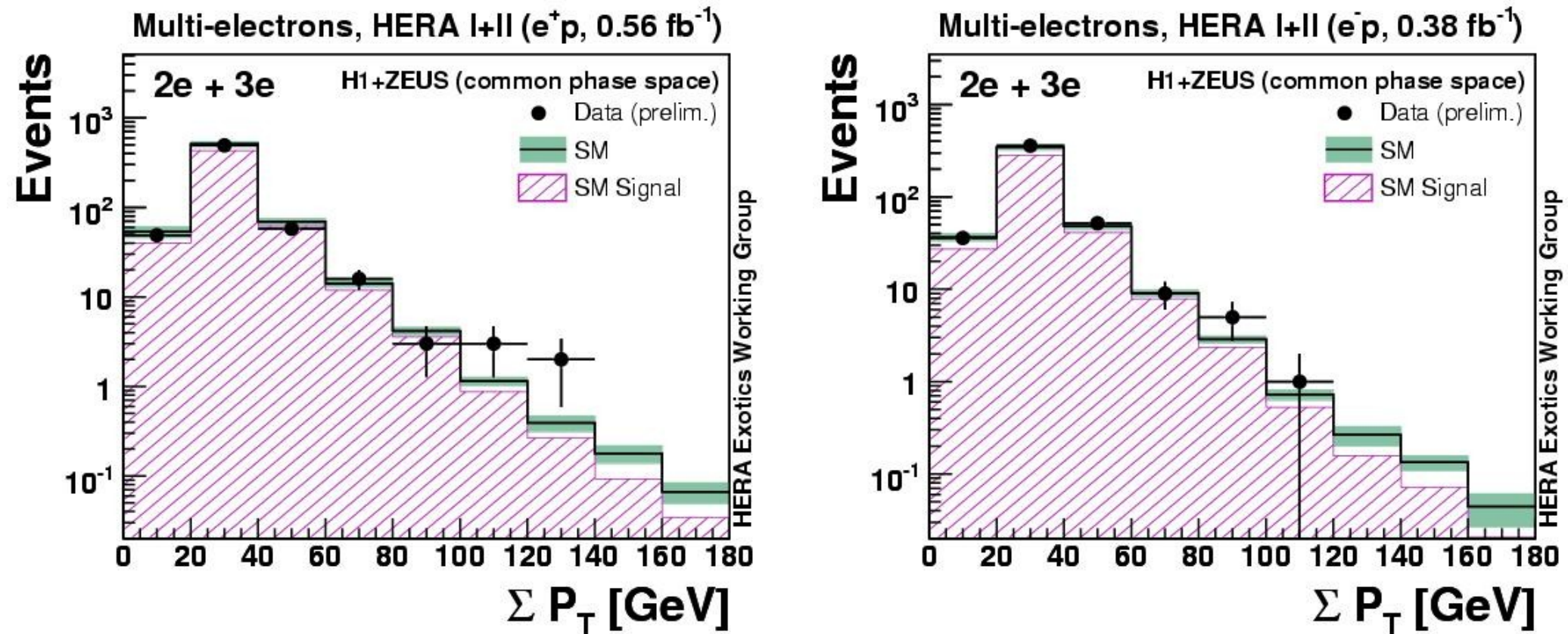
- Invariant mass M_{12} for $2e$ and $3e$ samples, e^+p collisions only.

Invariant mass distribution



- Invariant mass M_{12} for 2e and 3e 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)

$M_{12} > 100 \text{ GeV}$				
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)

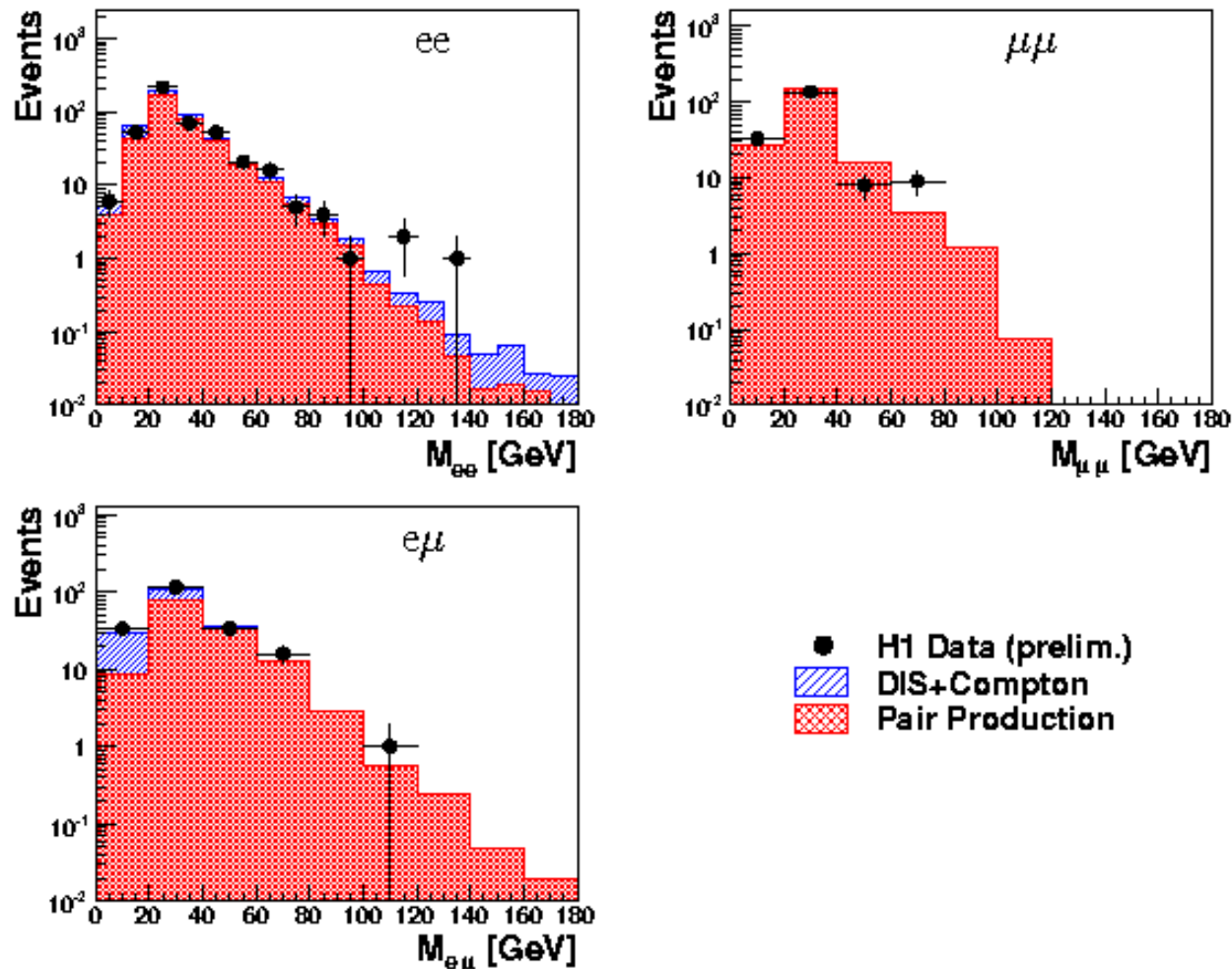
Data/MC comparison

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

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

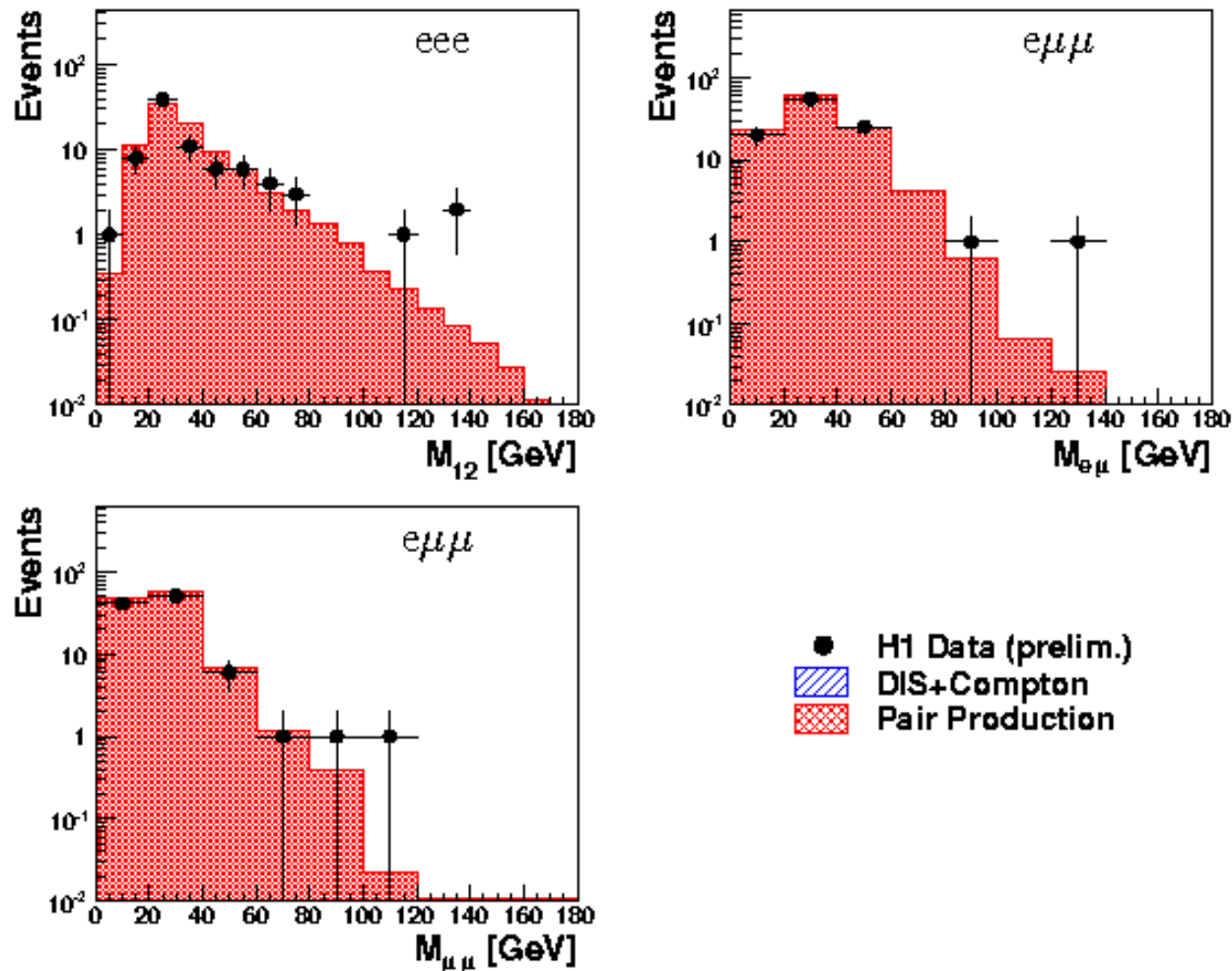
Two-lepton sample

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

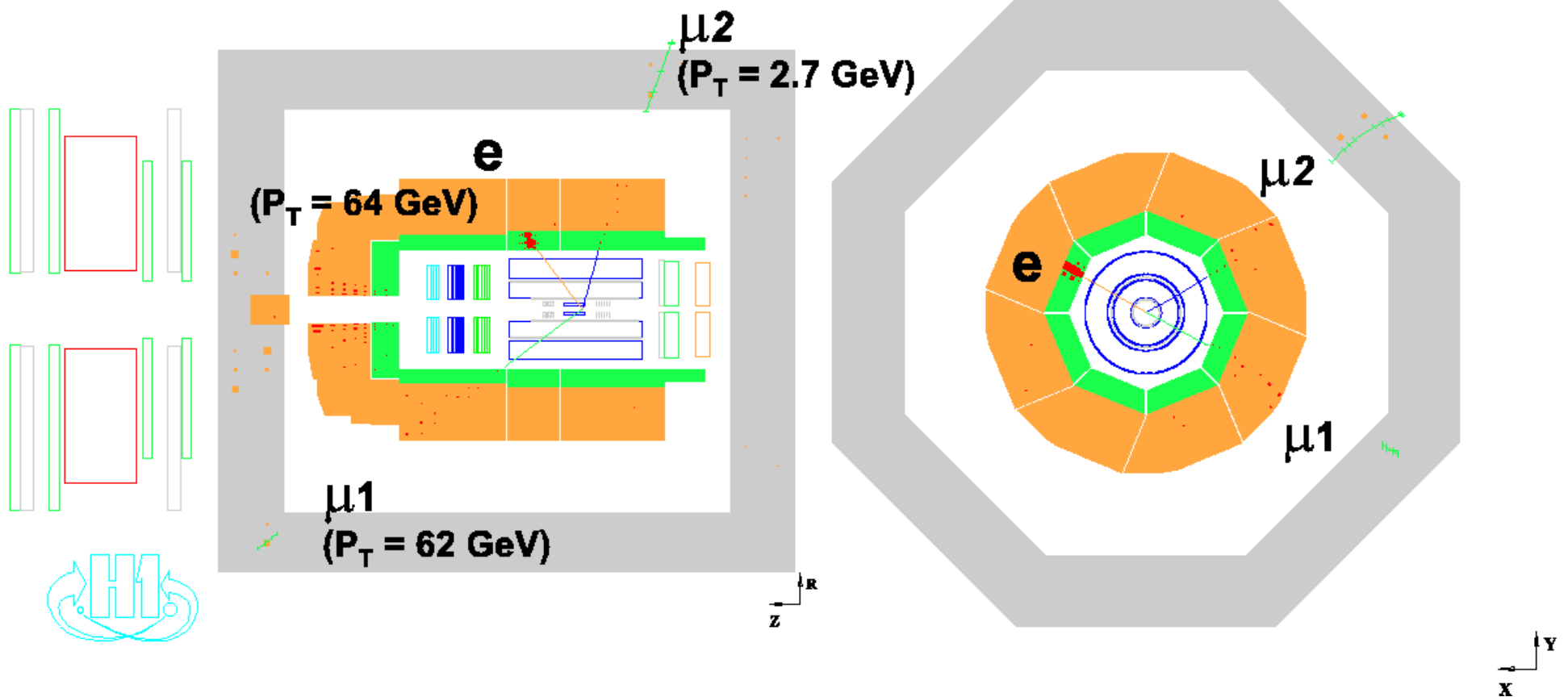


Three-lepton sample

H1 Multi-lepton analysis HERA I+II (459 pb⁻¹)



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
$jjX, \gamma jX$	NC DIS (low P_T elec.)	RAPGAP+HERACLES
$\nu jX, \nu jjX$	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 $< 165^\circ$ (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 on 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 one lepton is found, $\Delta\phi(l-X_{tot}) < 170^{\circ}$

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:

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

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

- p_{\min} is the smallest value in a distribution
- p_{\min}^{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 $p_{\min}^{\text{SM}} < p_{\min}$ is the probability \hat{P} .
 - A p_{\min} -value of $5.7\text{E-}7$ (“ 5σ ”) corresponds to a probability $1\text{E-}6$ to $1\text{E-}5$, 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.)

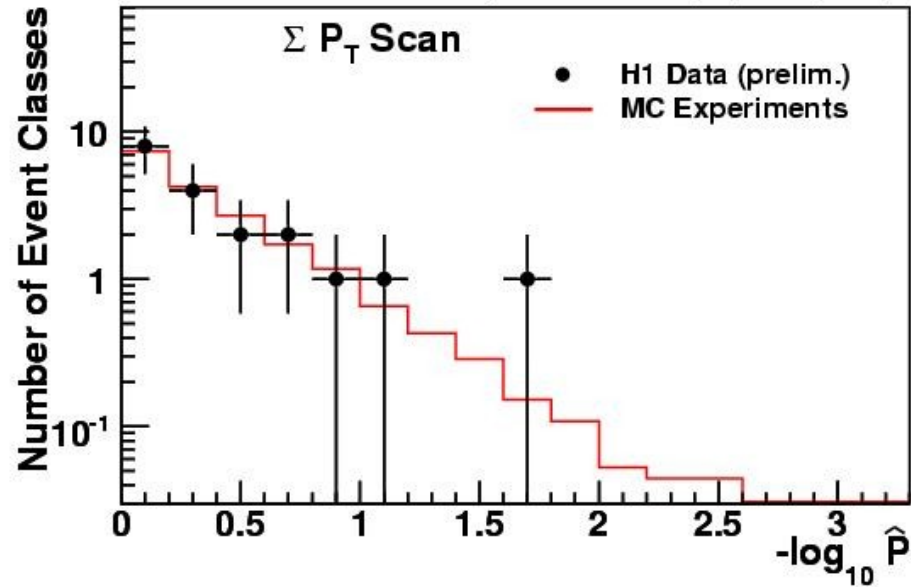
- Muon measurement:
 - P_T measurement: 5%
 - Polar angle measurement: 3 mrad
 - Muon identification: 5%
- Trigger efficiencies:
 - Jet or missing P_T triggered events: 3%
 - Muon triggered events: 10%
 - Electron/photon triggered events: negligible

Theoretical uncertainties

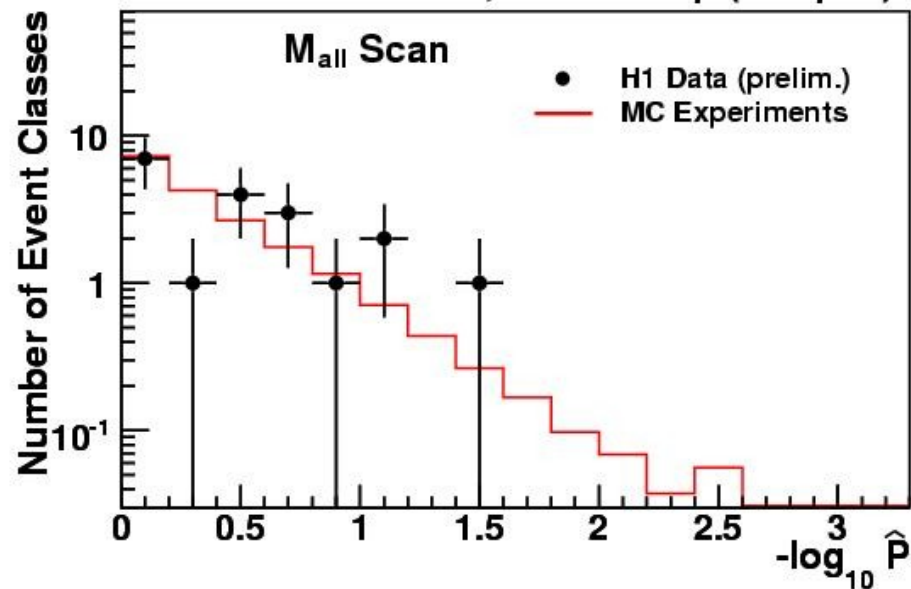
Final state	Uncertainty
$j\bar{j}X, j\bar{\nu}X$	15%
$j\nu X, jeX$	10%
$j\bar{j}\nu X, j\bar{j}eX$	15%
$\mu\mu X, eeX$	3%
WX, WjX	15%
$e\gamma X, e\gamma j$	10%
$e\gamma p$	5%

Global significance – e^+p data

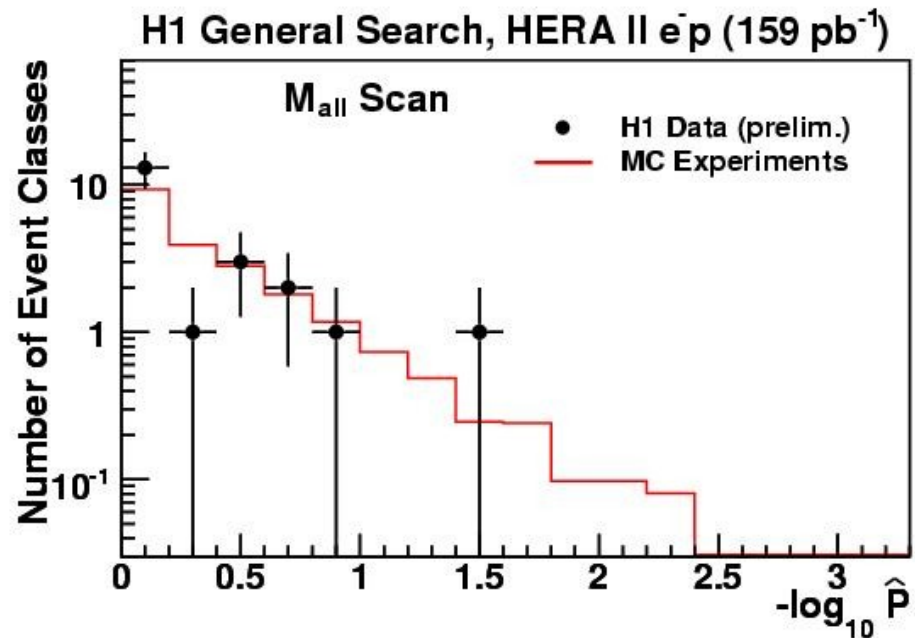
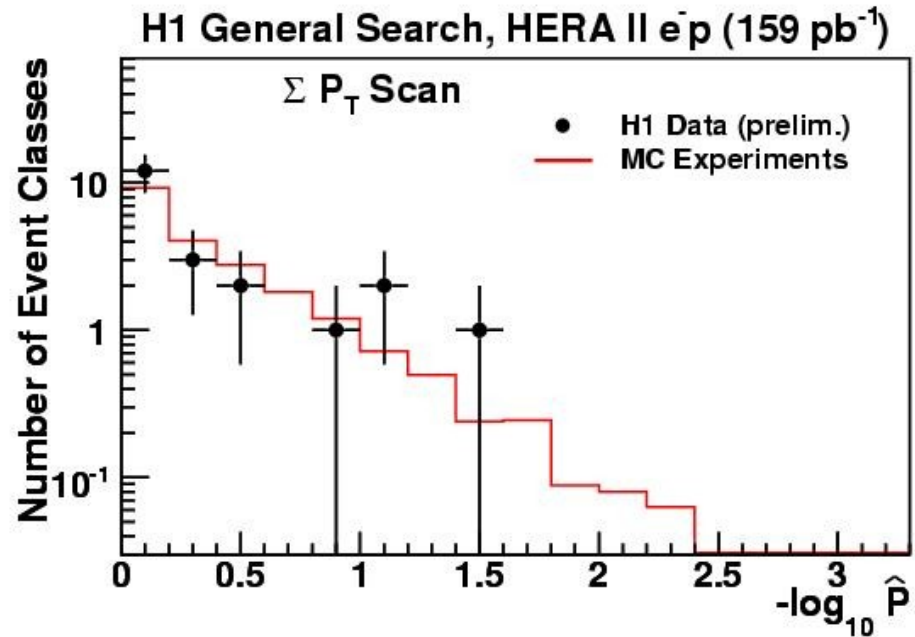
H1 General Search, HERA II e^+p (178 pb^{-1})



H1 General Search, HERA II e^+p (178 pb^{-1})

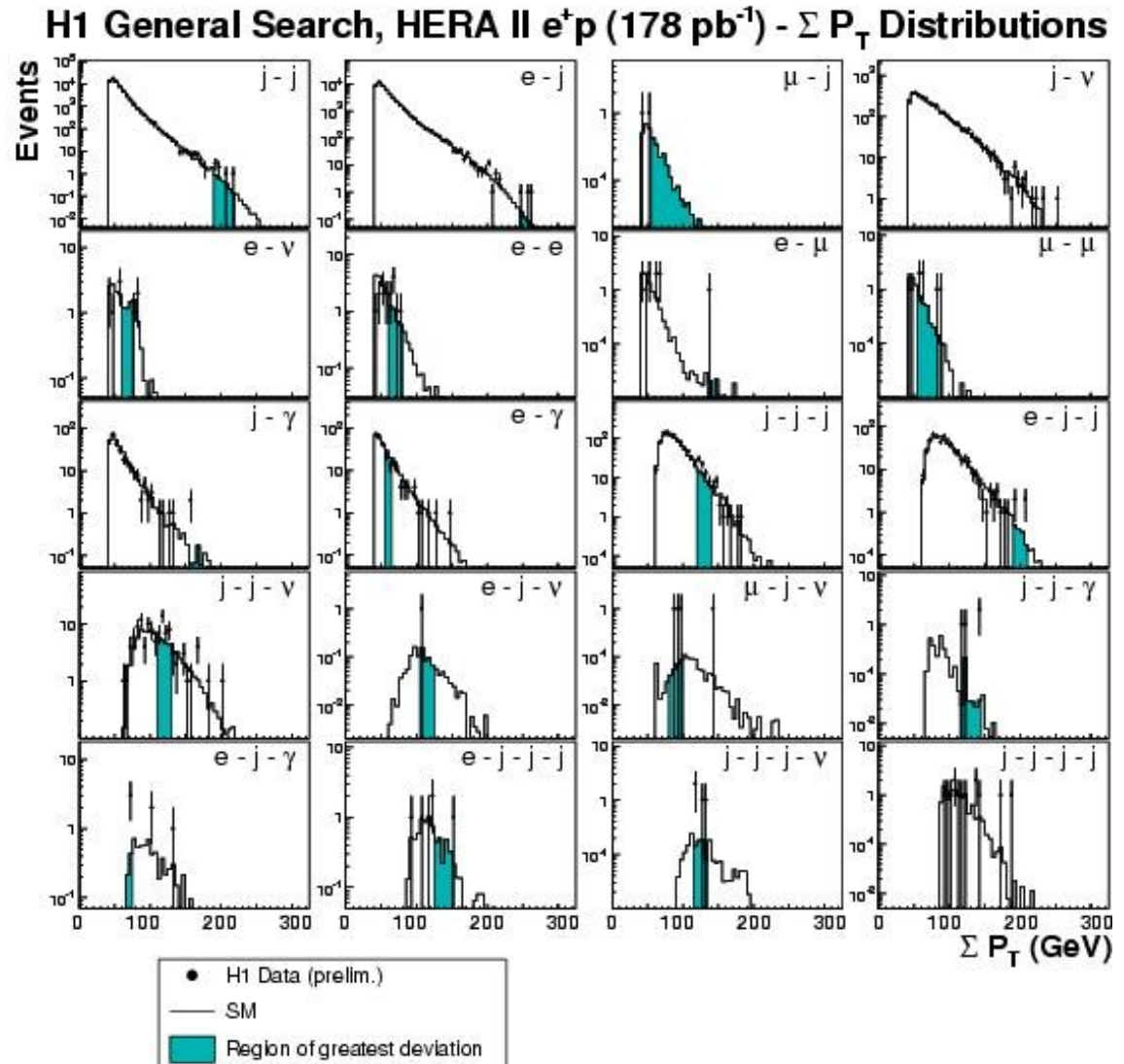


Global significance – e^-p data

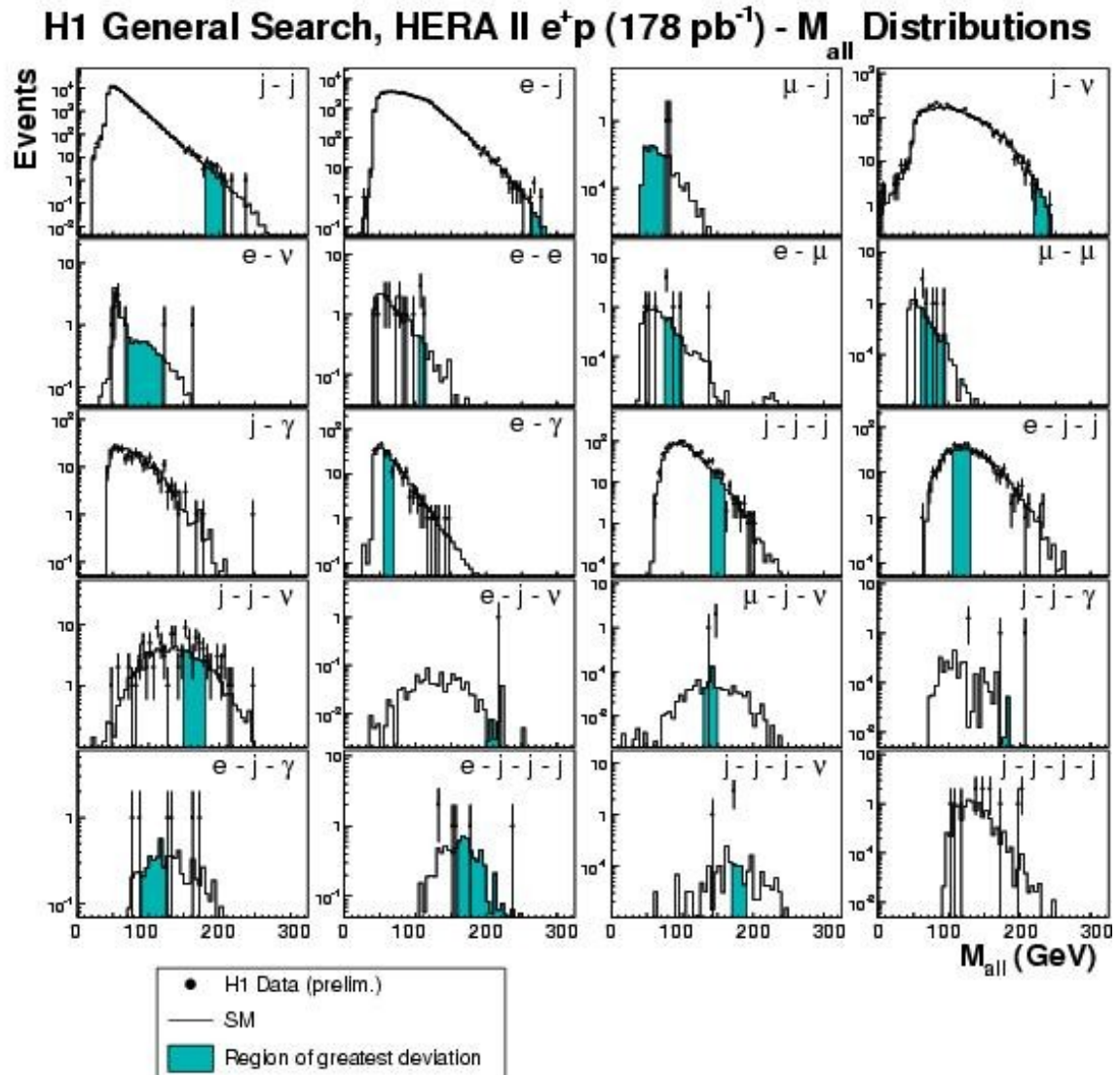


Region of interest - e^+p data

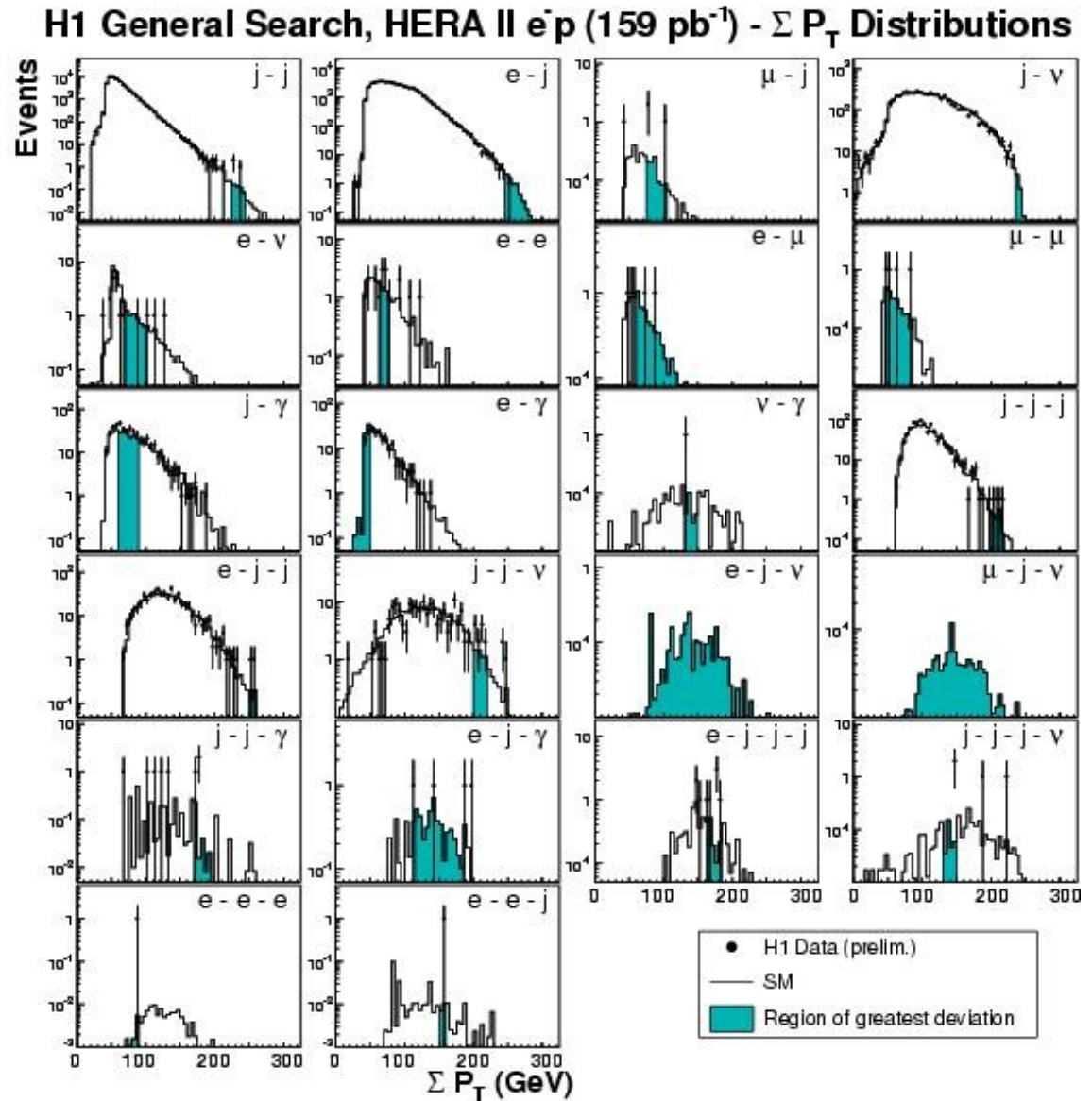
- Shaded areas are regions of greatest deviation from SM
- No search performed for $jjjj$ and $jjjj\nu$ classes (large uncertainty on SM prediction)



Region of interest - e^+p data



Region of interest - e^-p data



Region of interest - e^-p data

