A General Search for New Phenomena at HERA

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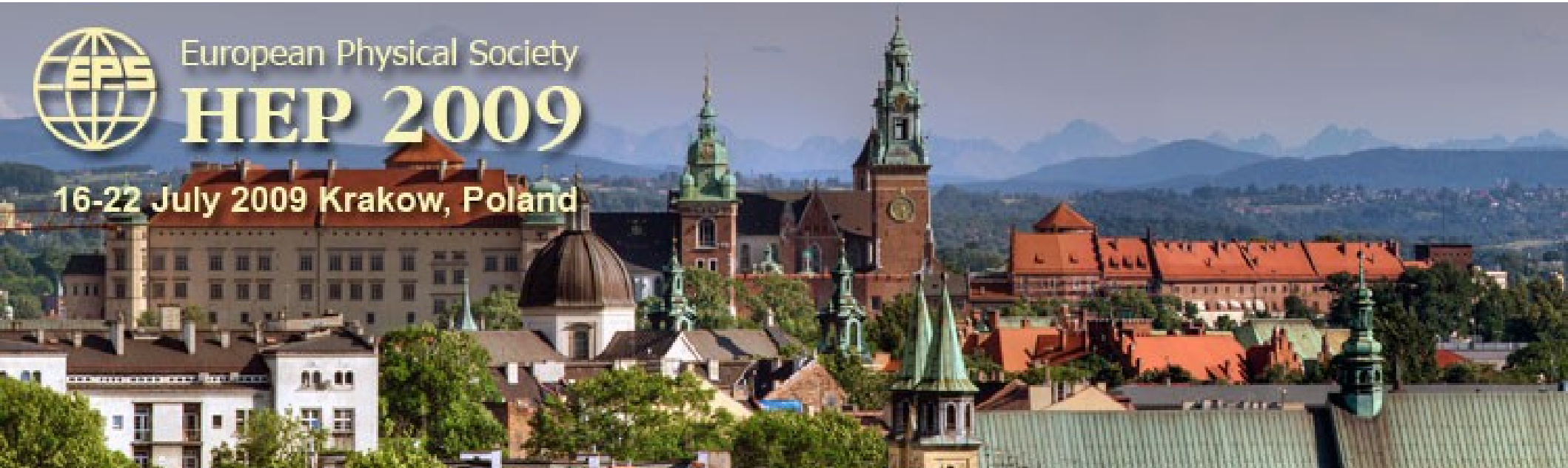
On behalf of the H1 Collaboration

Outline

Event Selection
Event Yields
Discriminating Observables
Statistical Analysis

Presented Paper:
*Phys. Lett. B **674** (2009), 257*
[arxiv:0901.0507]



Collider and Experiments

HERA

HERA: $\sqrt{s}$ = 318 GeV

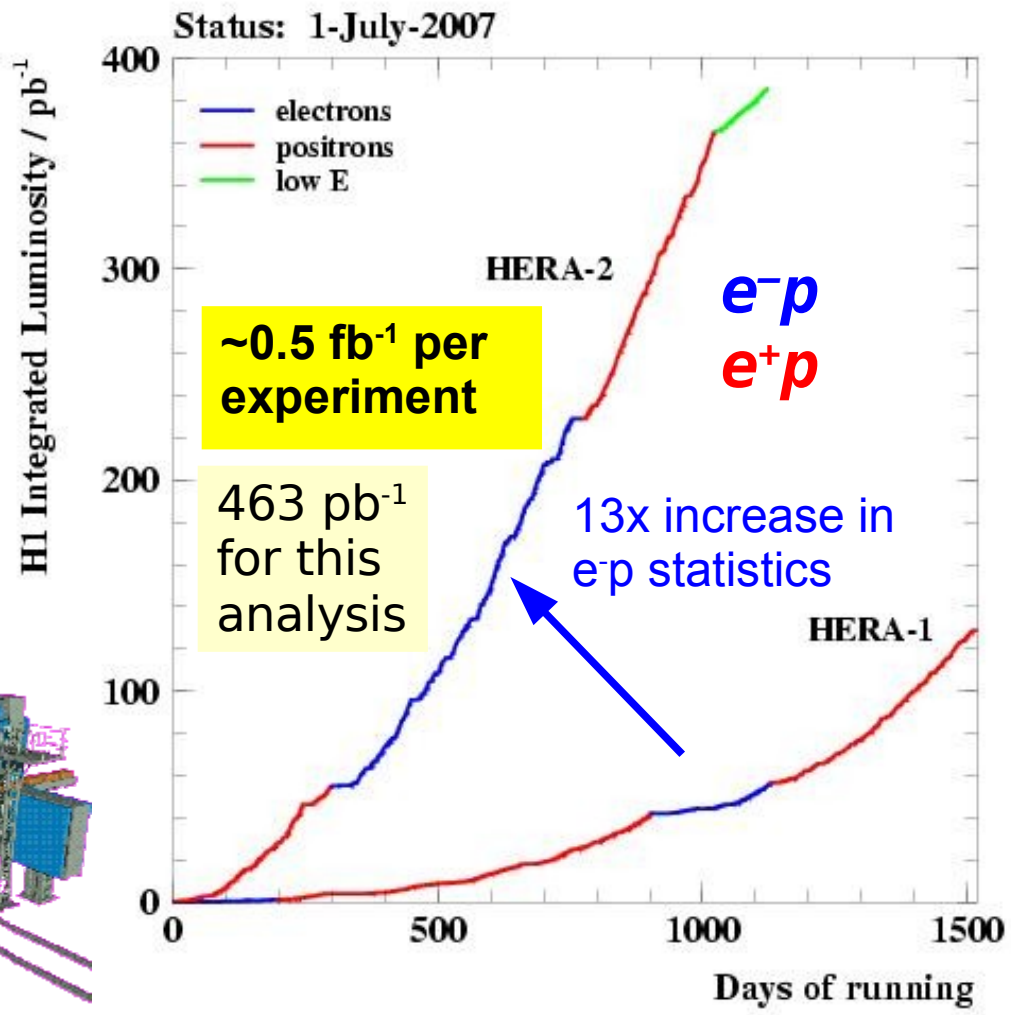
p (920 GeV) e (27.6 GeV)

World's only *ep* Collider at DESY,Hamburg
Active 1991-2007
H1 and ZEUS Experiments

Asymmetric Design
4π Coverage
Excellent Lepton ID + HFS Reconstruction

HERA-I (1994-00)
~130 pb^{-1} per exp., (90% e^+p)

HERA-II (2003-07)
Luminosity upgrade
Long. *e* polarisation (avg. 40%)



The H1 General Search

General Search for Physics beyond the Standard Model (BSM)

- Purely signature based
  Look for events with high inv. masses and missing particles

- Do not depend on particular BSM models
- Search for deviations from the Standard Model
- Minimise probability of missing anything
- Quantify significance of any observation

In contrast: **Specific Searches**

- Need a BSM model
- Look only in particular corner of phase space
- Possibly larger sensitivity
- Can be cross checked by the general search

Strategy

- Select events with **all** possible high-P_T signatures
  Requires good understanding of detector and SM processes

- Use a statistical algorithm to look for deviations from the SM prediction in kinematic distributions
  Also include topological variables

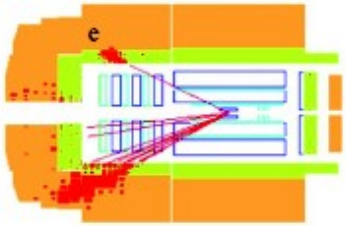
Standard Model Processes

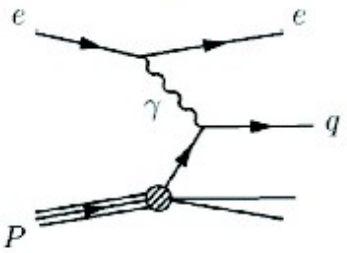
All HERA high-P_T processes taken into account

QCD
• Large Cross Sections

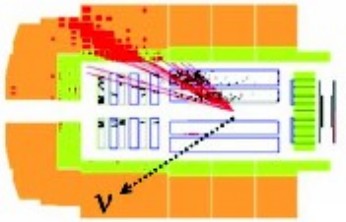
QED/weak
• Striking Signatures

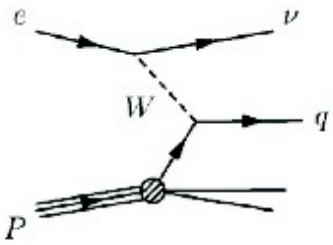
- Neutral Current DIS $ep \to eX$



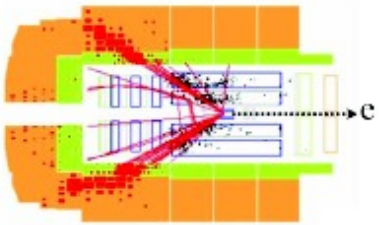


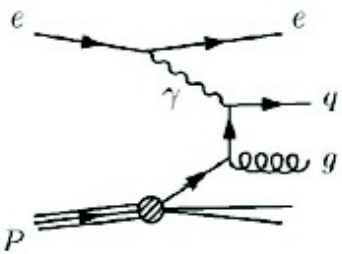
- Charged Current DIS $ep \to \nu X$



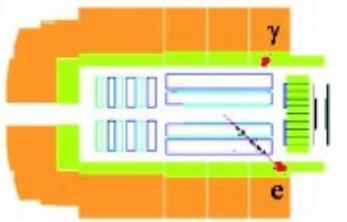


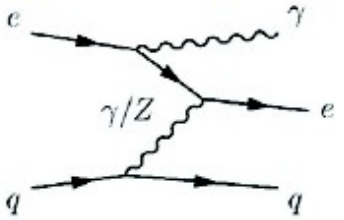
- Photoproduction $\gamma p \to X$



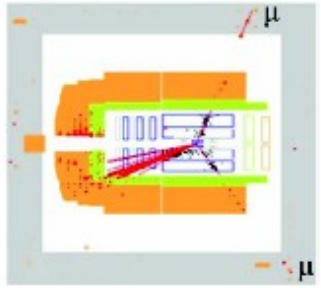


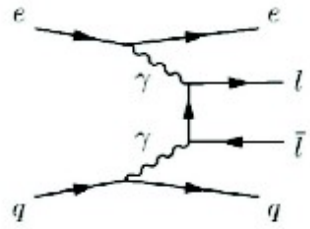
- QED Compton $ep \to e\gamma X$



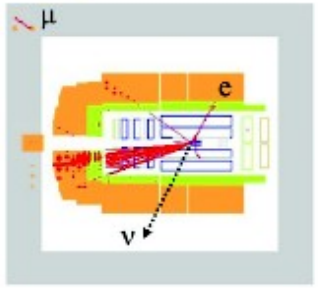


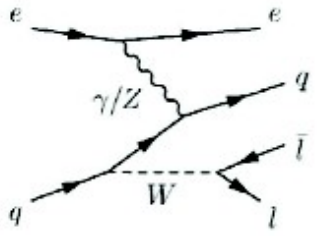
- Lepton pair production $ep \to ellX$





- W production $ep \to eWX$





Event Selection

- Identify particles ("bodies") based on detector performance
  electrons, photons, muons, jets and neutrino
  e γ μ **j** ν

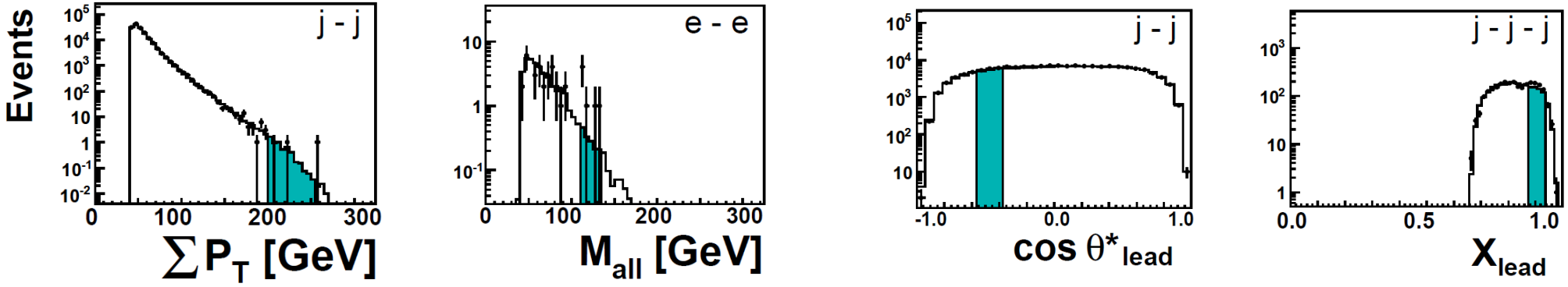
- Select them in the phase space

$P_T > 20$ GeV High P_T – suppress SM contributions
$10° < \theta < 140°$ Well contained in detector acceptance
$D(\eta\phi) > 1$ Isolation

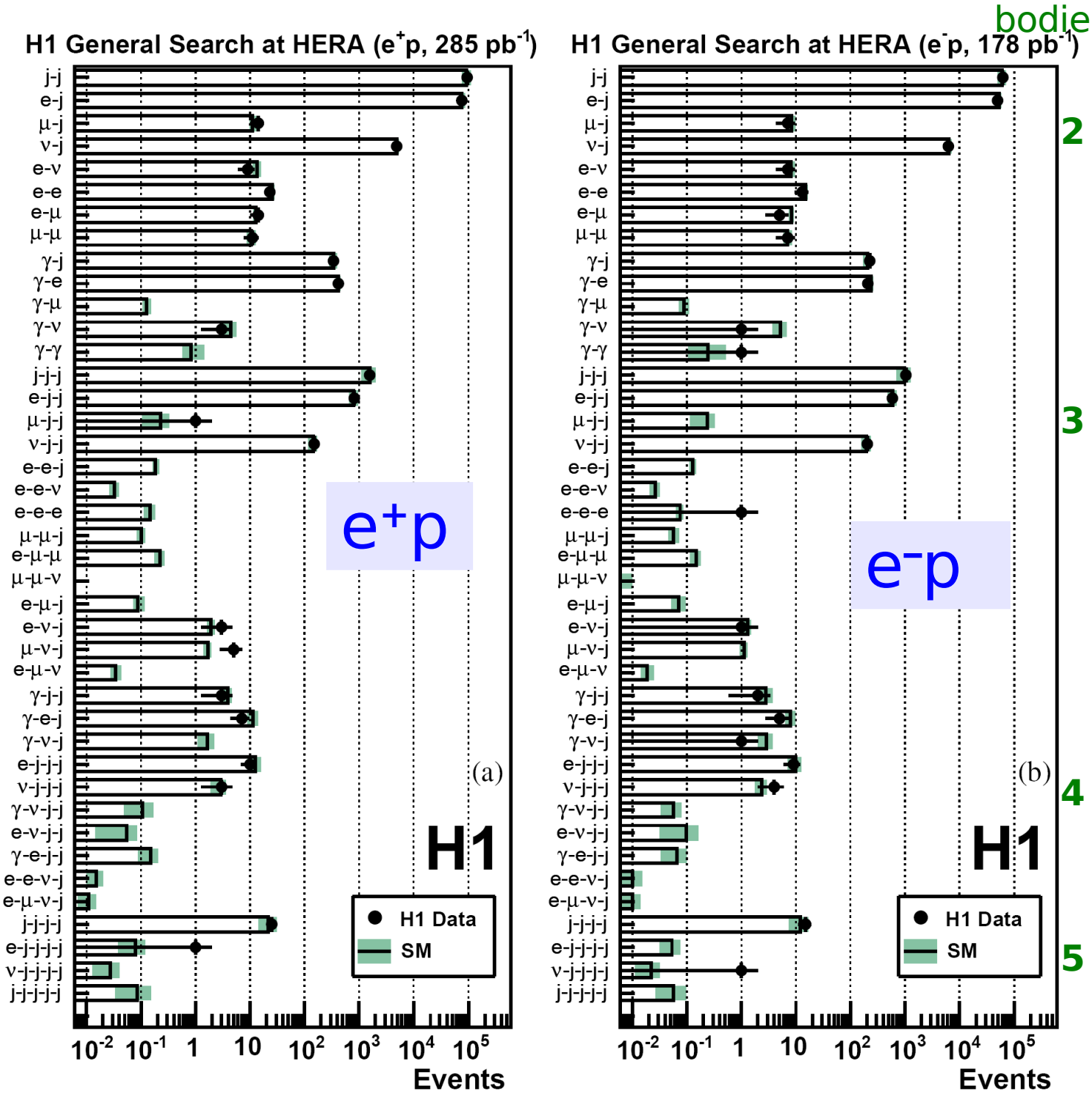
- Classify into channels by counting bodies (at least 2) (***e-e***, ***e-j***, ***j-j***, ...)

Look into distributions of typical variables sensitive to BSM signals

kinematic ***topological***



Event Yields In All Selected Channels



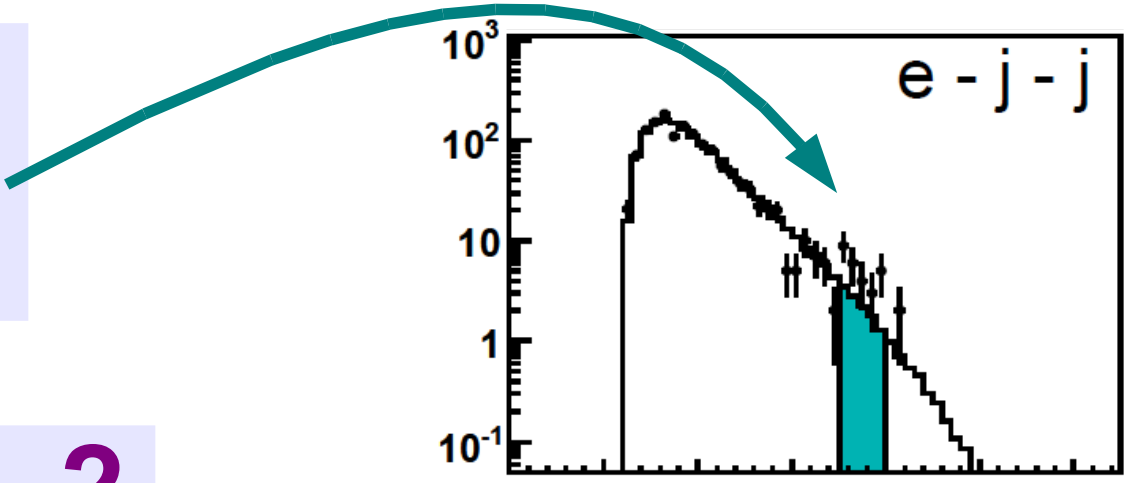
- Good overall agreement of yields between data and MC
- Shown are the **41** channels with at least one data event
  $N_{obs} > 0$
  or SM prediction
  $N_{SM} > 0.01$
- Many channels appear in specific analyses:

[*See eg.*
Excited Fermions
talk by Z. Zhang]
e-γ, ν-j-j, e-j-j, e-e-e,
e-μ-μ, e-ν, ν-γ, e-ν-μ, e-ν

Search Algorithm and Statistical Interpretation

Find Interesting Regions **1**

• In each distribution of each channel look for region of greatest deviation from SM prediction

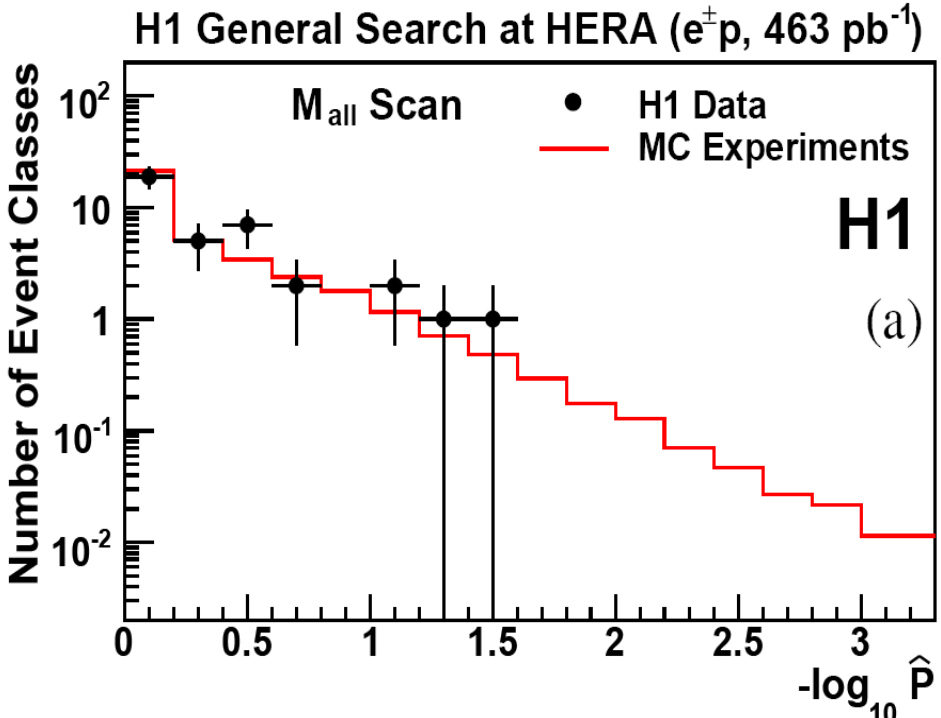


$\hat{P}$ Quantify Significance of deviation **2**

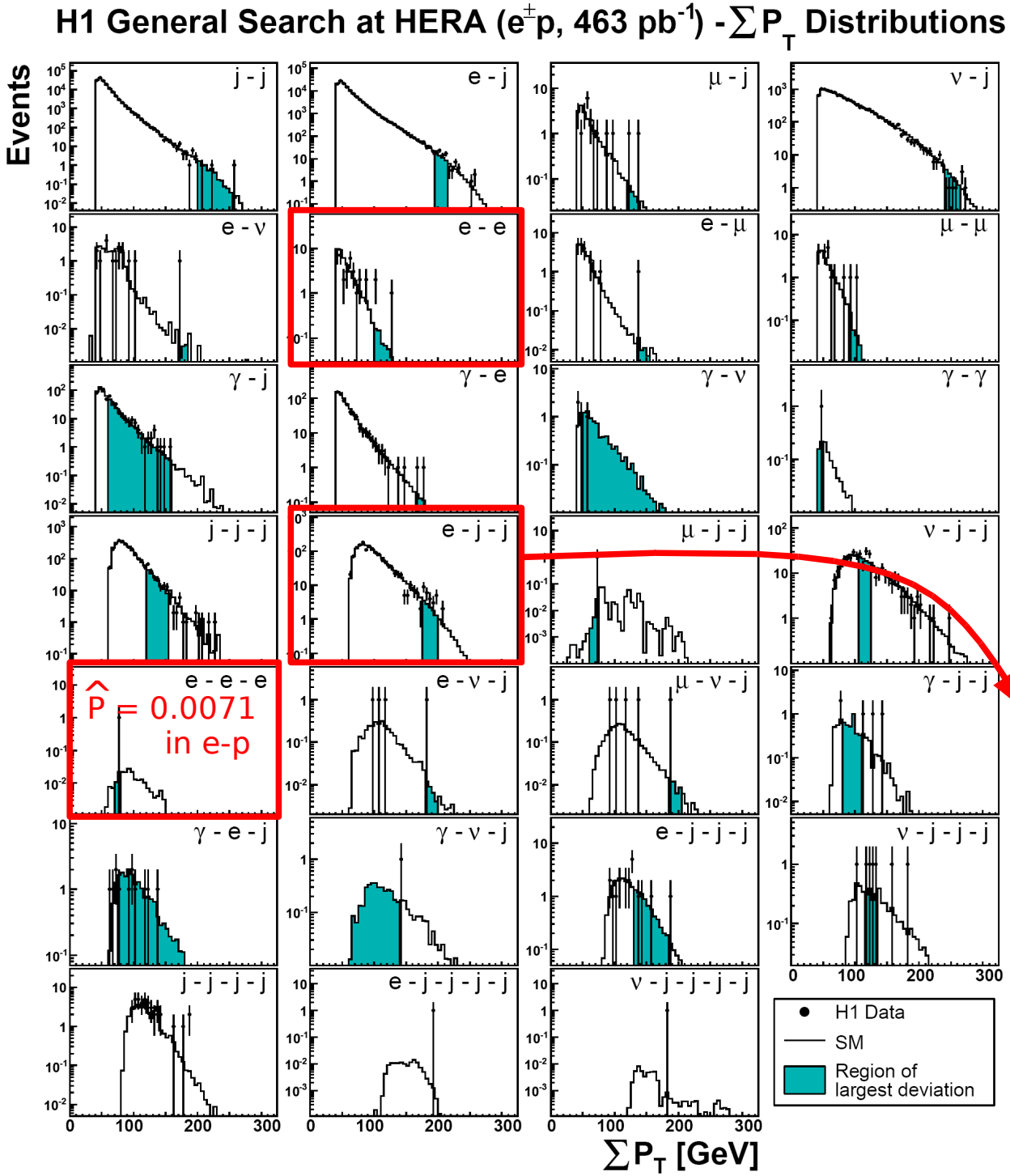
• Test by finding interesting regions in many MC experiments

Global Significance of Channel **3**

- Calculate **MC prediction** from toy experiments of HERA data
- Can compare all channels in one plot
- More interesting channels to the right of -log10$\hat{P}$ Distribution



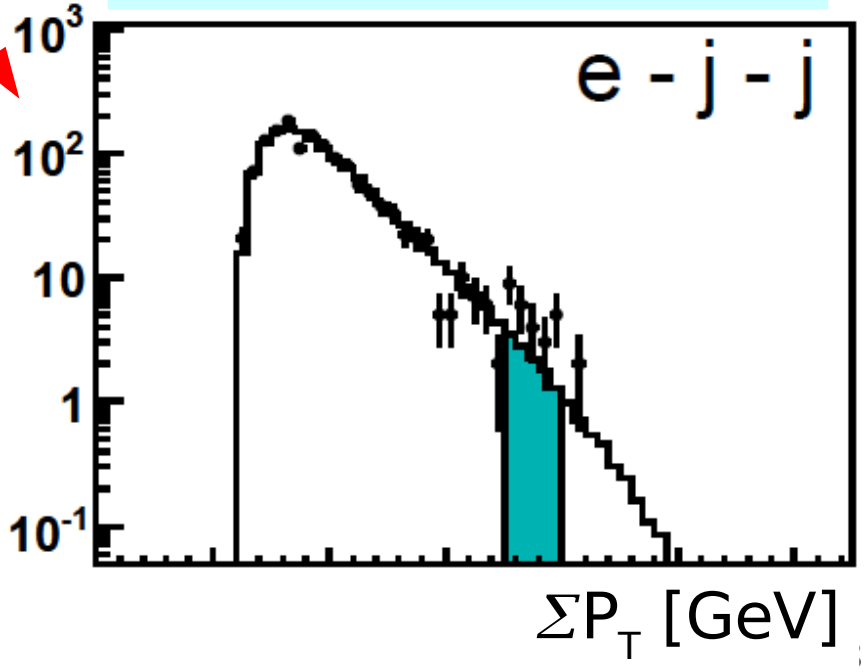
Kinematic Distributions ΣP_T



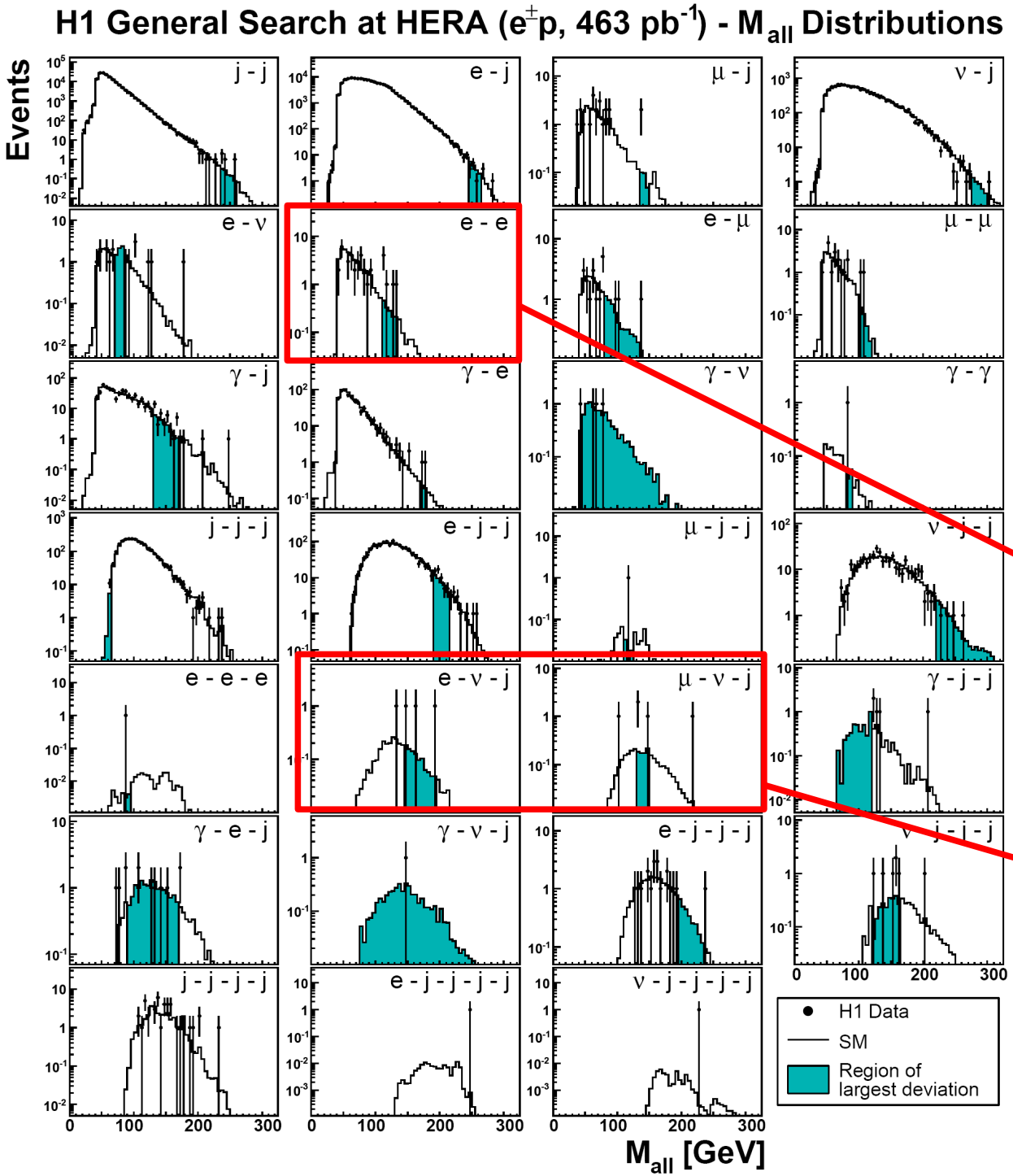
- Scalar sum of P_Ts of all bodies
- All channels scanned and interesting regions defined
- Channels with 4 jets or more not considered

$\hat{P}$ = 0.0044 in e±p data

27 obs. / 11.6±1.2



Kinematic Distributions M_{all}



- Invariant mass of all bodies
- All channels scanned and interesting regions defined
- Channels with 4 jets or more not considered

e-e:
Region 110 < M_{all} < 120 GeV
5 obs. / 0.43±0.04

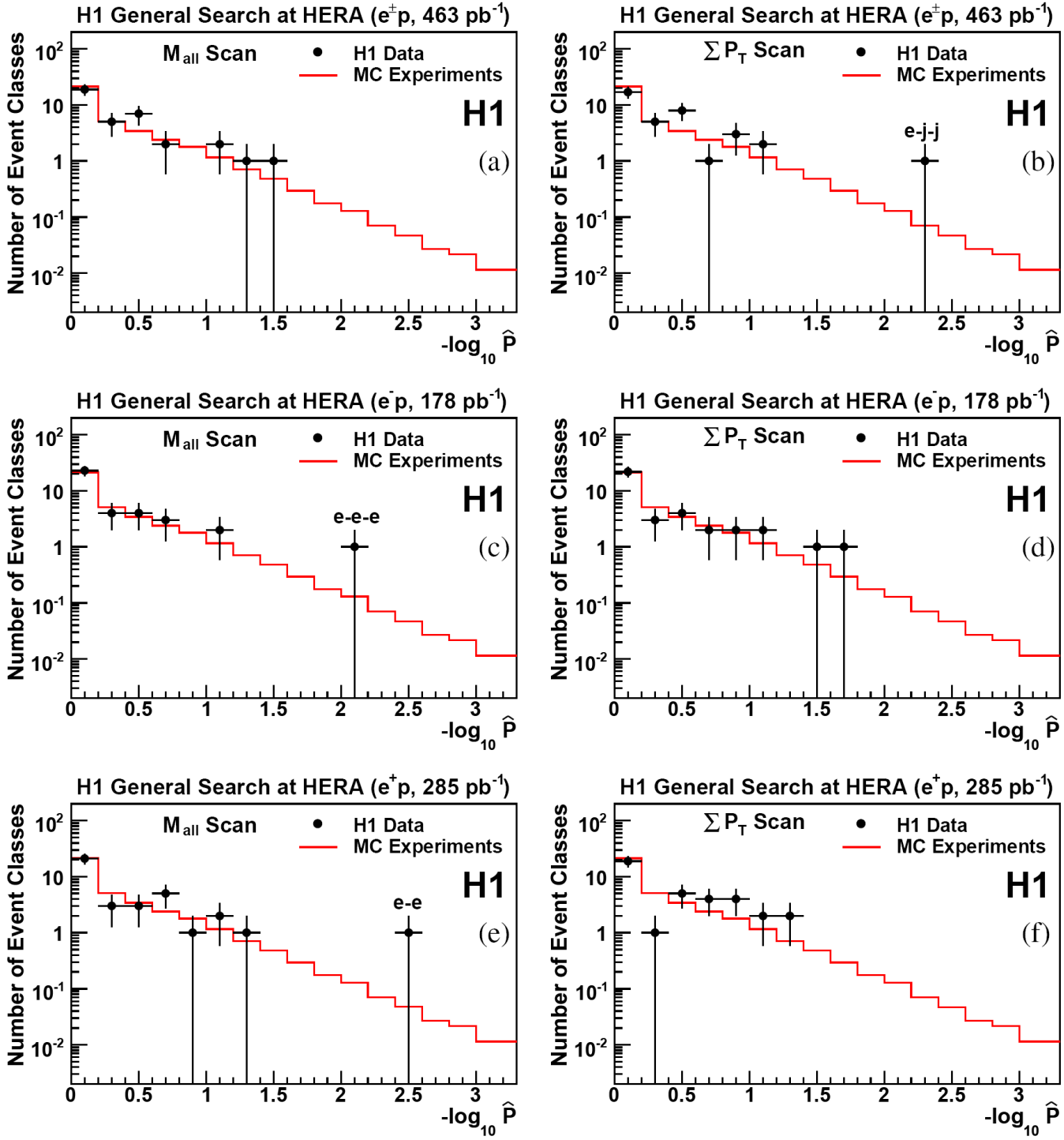
[see Multi-Leptons, talk by D. South]

Most interesting channels in HERA-I

now $\hat{P}$~0.3

[see Single top, talk by L. Bellagamba]

Global Significances



- Significance Distributions investigated for $e^{\pm}p$, $e^{+}p$ and $e^{-}p$ samples in the

  ΣP_T and M_{all}

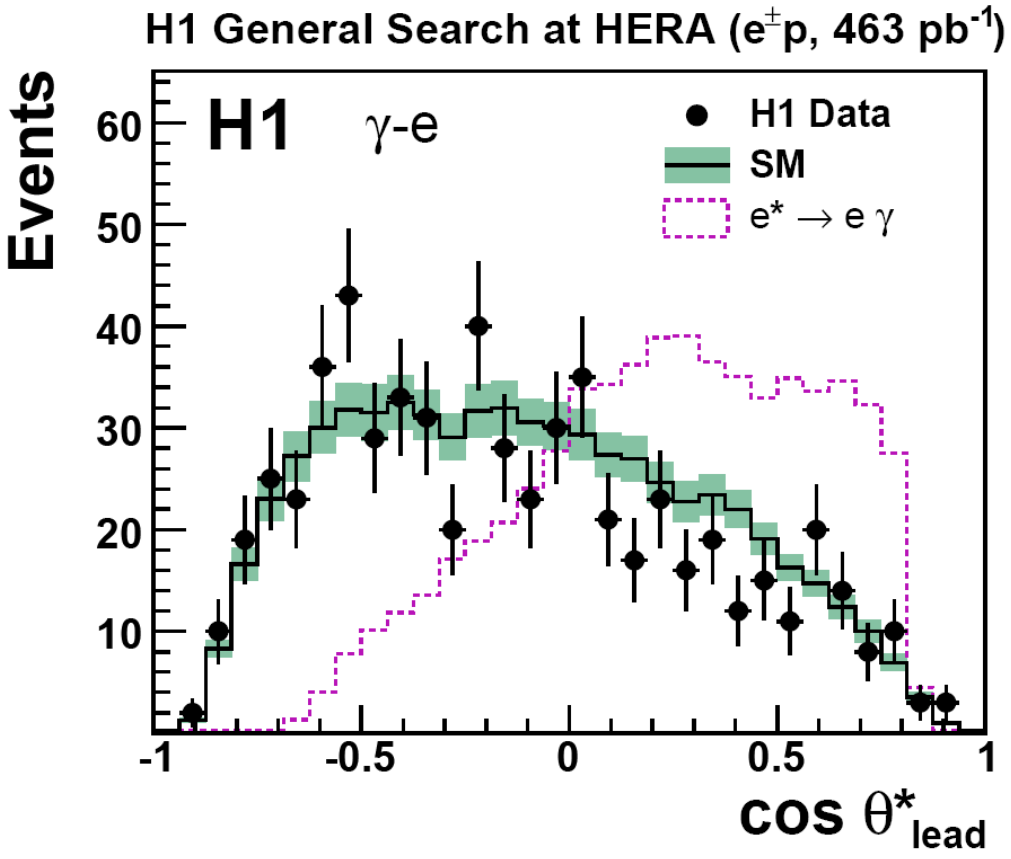
  distributions separately

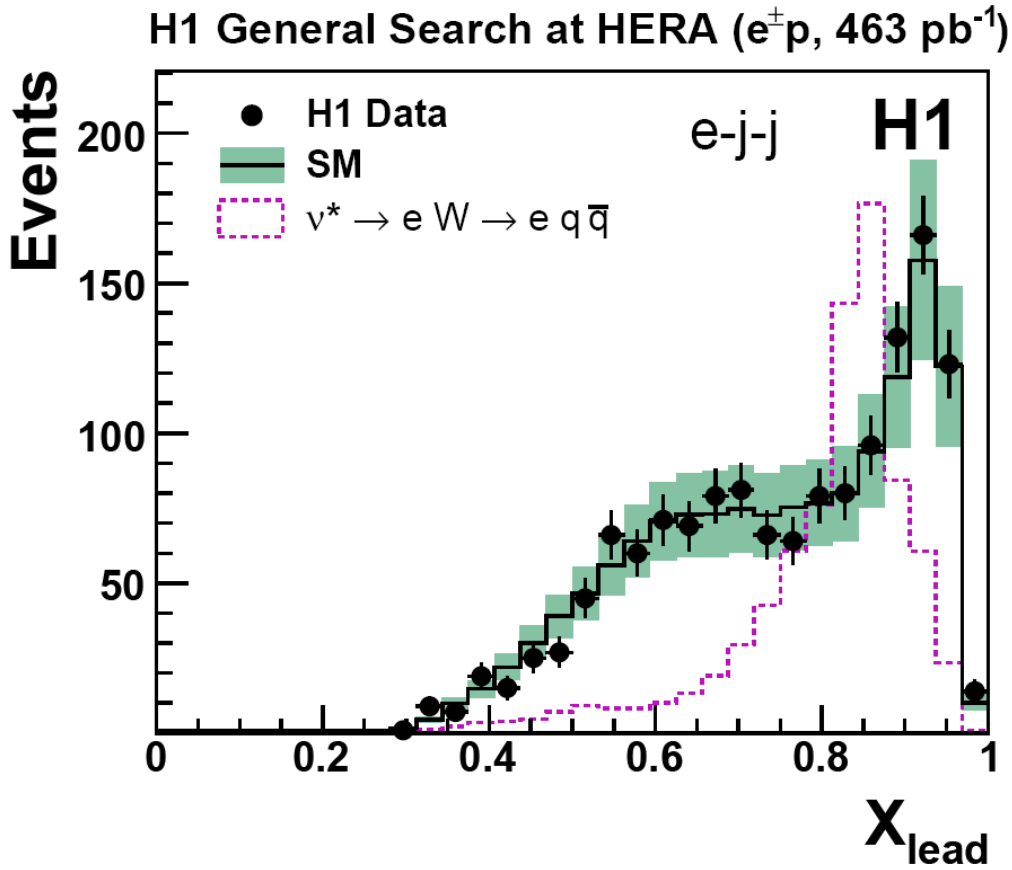
- Channels with large deviations identified

Sensitivity of Topological Variables to BSM Signals

- Differences in the angular distributions of otherwise similar event signatures for SM and BSM processes are possible
- Tested with many BSM signatures (LQ, single top, ...)

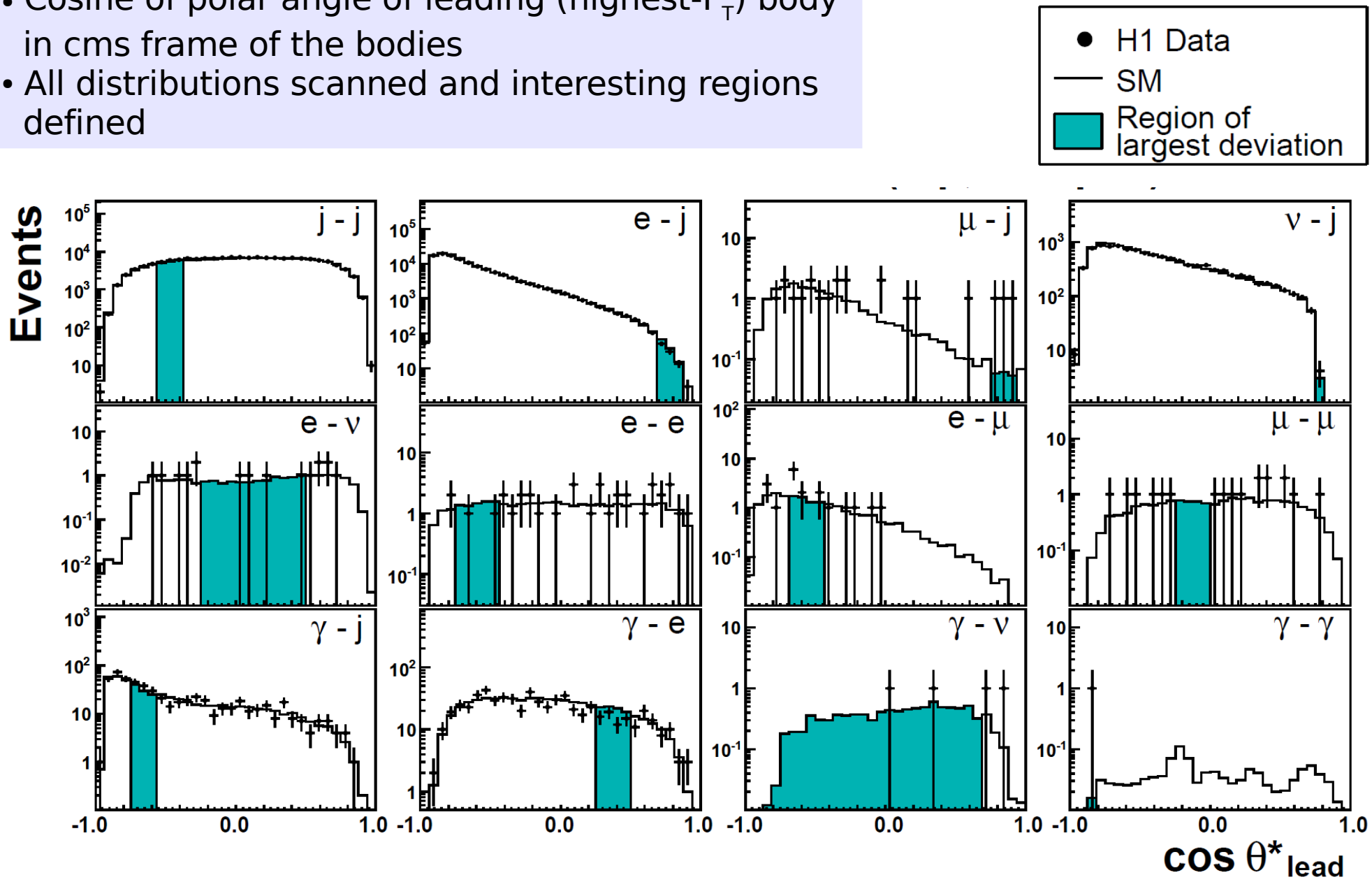
Example:
Production and Decay of Excited Fermions (Electrons and Neutrinos)





Topolgical Distributions cosθ^*_{lead}

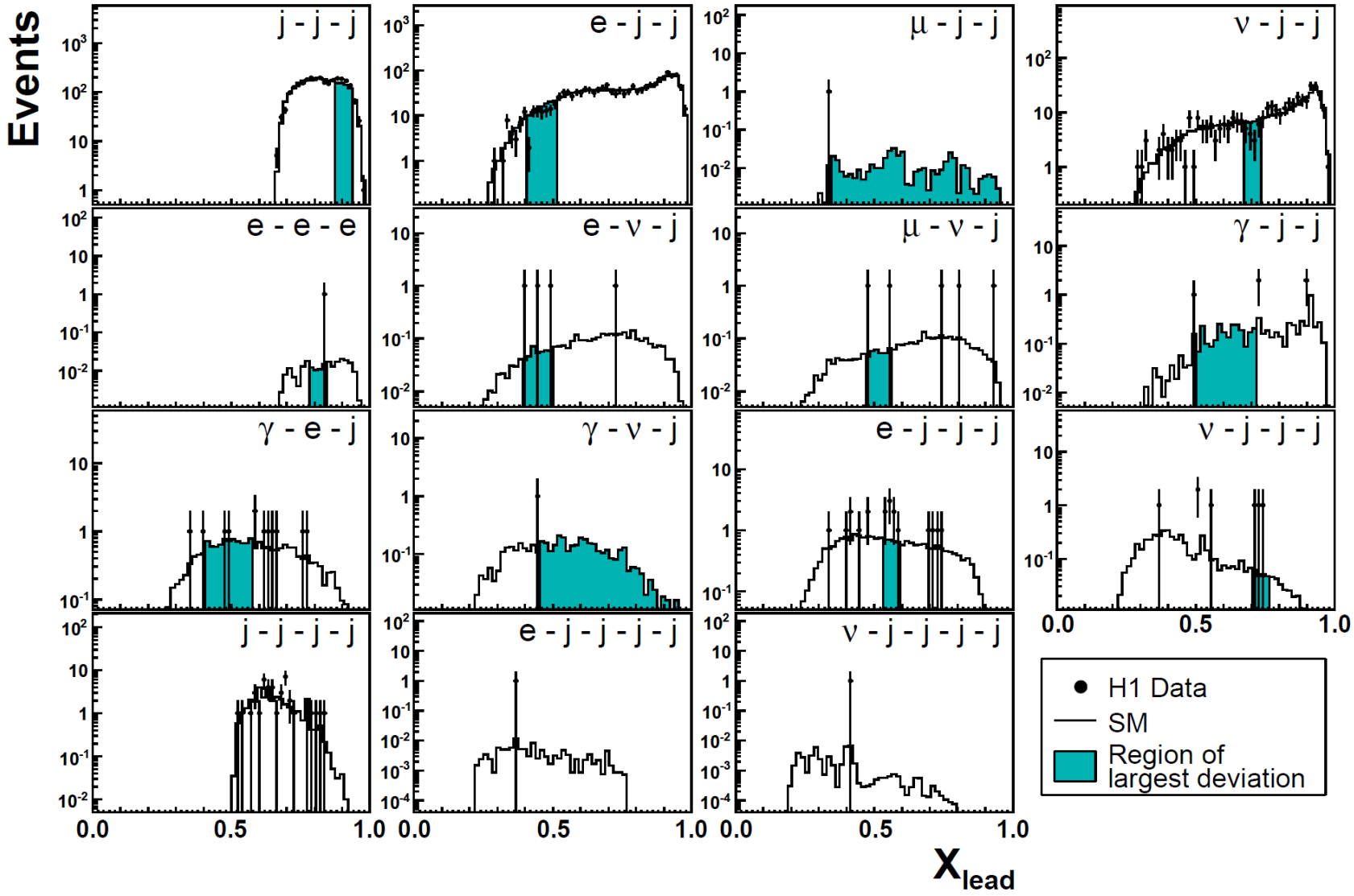
- Defined for two-body channels
- Cosine of polar angle of leading (highest-P_T) body in cms frame of the bodies
- All distributions scanned and interesting regions defined



Distributions of Topological Variable X_{lead}

- Defined for channels with at least three bodies
- Energy fraction of leading body in cms frame of all bodies
- Sensitive to multi-body decay of new particles (eg. cascade decays)

$$X_{\text{lead}} = \frac{2E^*_{\text{lead}}}{\sum_i E^*_i}$$



Summary

- A model independent search for new physics has been performed by H1 on the full HERA data (484 pb^{-1})
- All high-P_T signatures were investigated
- Good overall agreement with the SM is observed in all channels
- Good understanding of detector and physics at HERA for all high-P_T phenomena demonstrated
- One of the broadest range signature searches done at a collider

Backup

Summary of Results in Search Channels

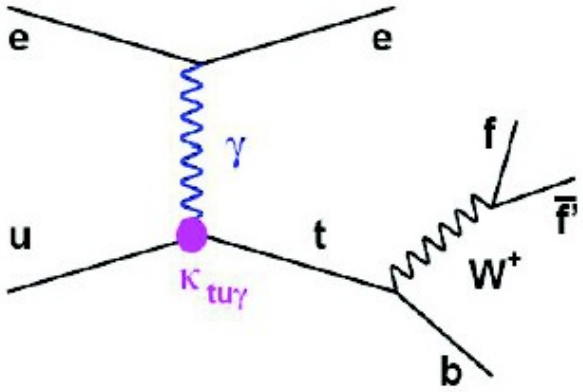
H1 General Search at HERA ($e^{\pm}p$, 463 pb^{-1})

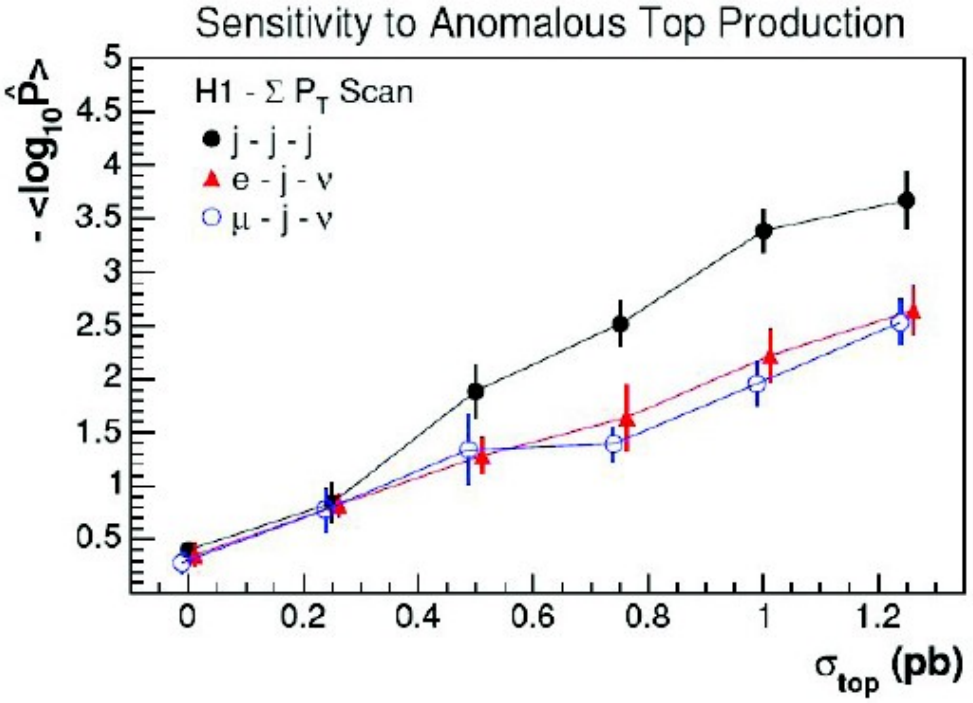
Event class	Data	SM	$\hat{P}_{\sum P_T}$	$\hat{P}_{M_{\rm all}}$	$\hat{P}_{\cos\theta^*_{\rm lead}}$	$\hat{P}_{X_{\rm lead}}$
j-j	156724	153278 ± 27400	0.57	0.33	0.98	
e-j	125900	127917 ± 15490	0.090	0.99	0.40	
μ-j	21	19.5 ± 3.0	0.30	0.46	0.024	
ν-j	11081	11182 ± 1165	0.33	0.31	0.25	
e-ν	16	21.5 ± 3.5	0.13	0.084	0.62	
e-e	36	40.0 ± 3.7	0.35	0.041	0.52	
e-μ	19	21.0 ± 2.1	0.46	0.83	0.81	
μ-μ	18	17.5 ± 3.0	0.31	0.50	0.88	
γ-j	563	538 ± 86	0.31	0.21	0.77	
γ-e	619	648 ± 62	0.93	0.99	0.10	
γ-μ	0	0.22 ± 0.04	1	1	1	
γ-ν	4	9.6 ± 2.8	0.076	0.33	0.22	
γ-γ	1	1.1 ± 0.6	0.66	0.35	0.11	
j-j-j	2581	2520 ± 725	0.54	0.65		0.18
e-j-j	1394	1387 ± 270	0.0044	0.70		0.28
μ-j-j	1	0.46 ± 0.18	0.12	0.072		0.99
ν-j-j	355	338 ± 62	0.80	0.48		0.62
e-e-j	0	0.31 ± 0.04	1	1		1
e-e-ν	0	0.06 ± 0.01	1	1		1
e-e-e	1	0.22 ± 0.04	0.15	0.031		0.14
μ-μ-j	0	0.16 ± 0.03	1	1		1
e-μ-μ	0	0.37 ± 0.07	1	1		1
μ-μ-ν	0	0.010 ± 0.005	1	1		1
e-μ-j	0	0.16 ± 0.04	1	1		1
e-ν-j	4	3.2 ± 0.5	0.24	0.57		0.095
μ-ν-j	5	2.8 ± 0.5	0.27	0.30		0.35
e-μ-ν	0	0.05 ± 0.01	1	1		1
γ-j-j	5	6.7 ± 1.3	0.41	0.25		0.91
γ-e-j	12	19.4 ± 4.0	0.31	0.28		0.53
γ-ν-j	1	4.5 ± 1.5	0.35	0.62		0.47
e-j-j-j	19	22 ± 6.5	0.84	0.80		0.14
ν-j-j-j	7	5.2 ± 1.4	0.47	0.39		0.017
γ-ν-j-j	0	0.16 ± 0.07	1	1		1
e-ν-j-j	0	0.15 ± 0.09	1	1		1
γ-e-j-j	0	0.22 ± 0.07	1	1		1
e-e-ν-j	0	0.10 ± 0.06	1	1		1
e-μ-ν-j	0	0.08 ± 0.05	1	1		1
j-j-j-j	40	33 ± 13				
e-j-j-j-j	1	0.13 ± 0.06				
ν-j-j-j-j	1	0.05 ± 0.02				
j-j-j-j-j	0	0.14 ± 0.09				

Sensitivity Compared to Dedicated Searches

↘ Test the sensitivity of the method to new physics

- Anomalous top production via FCNC
  - → A decay t → bW would appear mostly in j-j-j, e-j-ν and μ-j-ν
  - → Evolution of $-\log_{10} \hat{P}$ as a function of σ_{top}





- In j-j-j: $-\log_{10} \hat{P}$ ~2 for σ_{top} = 0.5 pb
  - → From H1 dedicated analysis in hadronic channel: σ_{top} < 0.48 pb at 95% C.L.
- $-\log_{10} \hat{P} \geq 3$ for σ_{top} ~ 1.5 pb

↘ Sensitivity equivalent or slightly lower than dedicated searches

Yields and P^-Values of Interesting Channels

P^<0.01: significant deviation

e-j-j in $e^{\pm}p$ data

Region: $175 < \Sigma P_T < 200$ GeV P^ = 0.0044
27 obs. / 11.6±1.2

e-e-e in $e^{-}p$ data

1 obs. / low SM expectation P^ = 0.0071

e-e in $e^{+}p$ data P^ = 0.0035

Region: $110 < M_{all} < 120$ GeV
5 obs. / 0.43±0.04

Other topologies studied elsewhere:

Excited Fermions Analysis
e-γ, ν-j-j, e-j-j, e-e-e,
e-μ-μ, e-ν, ν-γ, e-ν-μ, e-ν

Multi-Leptons Analysis
e-e, e-e-e, e-μ, μ-μ, e-μ-μ

see Multi-Leptons Analysis

Regions showing deviations in HERA-1 now checked in the full data:

μ-j-ν	now P^~ 0.3	5 obs. / 2.8±0.5 exp.
e-j-ν	now P^~ 0.3	4 obs. / 3.2±0.5 exp.
e-e	still interesting	
e-j	now P^=0.09 in ΣP_T	

see Isolated Leptons and Single Top Quark Analyses

visible in inclusive LQ/CI/q~ Analyses

Search Algorithm for Deviations from SM

Define regions (sliding expandable windows in histograms)

Look at all regions with a width > resolution

Assume Poisson-distributed background b_i with a Gaussian error G

Form pdf from the histogram by normalising (constant A) the distribution

Define **probability** $\boldsymbol{p}$ to observe N_{obs} events in regions fluctuating up or down from N_b predicted background events

$$p = \begin{cases} A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!} & \text{if } N_{obs} \geq N_b \\ A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=0}^{N_{obs}} \frac{e^{-b} b^i}{i!} & \text{if } N_{obs} < N_b \end{cases}$$

Most interesting region is the one with the minimum $\boldsymbol{p_{min}}$
(= largest deviation)

p_{min} < 0.01 → significant deviation

Developed by H1 for HERA-I data ***[PLB 602, 14 (2004)]***

Significance of Deviations $\hat{P}$

Search algorithm looks for region with greatest deviation from SM

Bias towards fluctuations?

Quantify this ...

$\hat{P}$: Probability to observe a region with $p < p_{min}$ in a given channel

Calculated with toy experiments based on SM prediction for one channel

$\hat{P}$ = Ratio of toy experiments with $p_{min}^{toy} < p_{min}^{data}$
and number of toy experiments

The smaller $\hat{P}$ the more interesting the channel

Can be used to compare results of different channels

Global Significance: $-\log_{10}\hat{P}$ Distribution

The statistical significance of the data can be small, leading to small values of $\hat{P}$

Quantify the expectation for $\hat{P}$

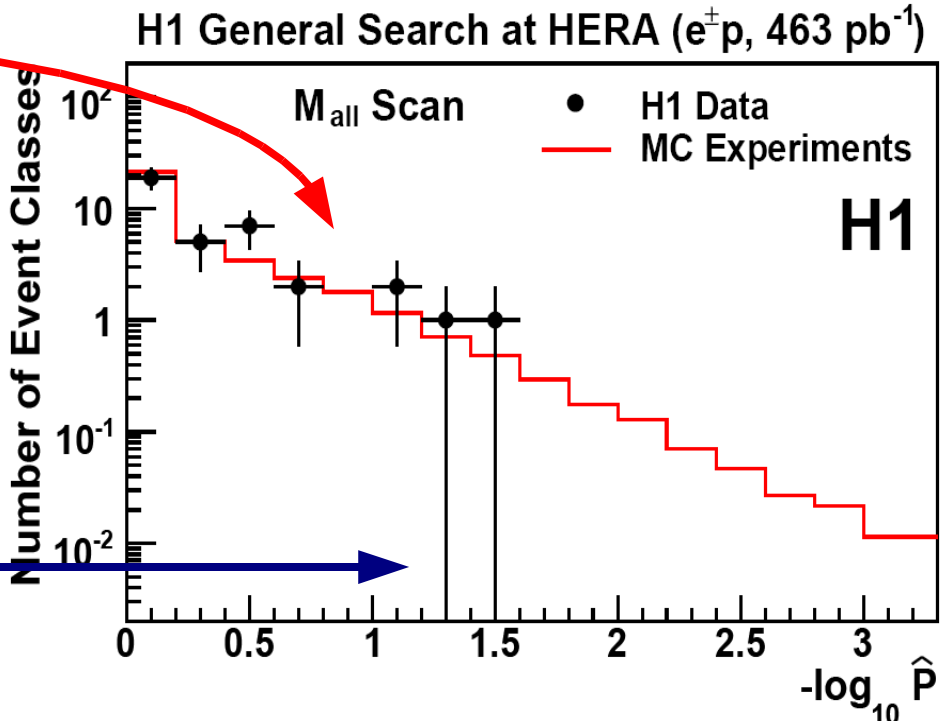
Do many toy experiments based on SM background simulating the whole HERA data

Apply the search algorithm

Get a MC prediction for $\hat{P}$

Now we can look at all channels simultaneously, comparing them to each other and the MC prediciton

Most interesting channels are on the right of the distribution $-log_{10}\hat{P}$



Refined Topological Analysis

Good overall agreement in distributions of topological variables
Most interesting region still not so interesting (p=0.017 in ν-j-j-j)

Further reduce samples to select events with
Leading body emitted in forward direction
or with
Topologies expected for bodies from sequential resonance decay

$\cos\theta^*_{\text{lead}} > 0$

$0.75 < X_{\text{lead}} < 0.9$

H1 General Search at HERA ($e^{\pm}p$, 463 pb^{-1})

Event class	Selection	Data	SM	$\hat{P}_{\sum P_T}$	$\hat{P}_{M_{\text{all}}}$
j-j	$\cos\theta^*_{\text{lead}} > 0$	83155	82800 ± 15610	0.46	0.44
e-j	$\cos\theta^*_{\text{lead}} > 0$	6532	6603 ± 783	0.23	0.033
ν-j	$\cos\theta^*_{\text{lead}} > 0$	2177	2076 ± 240	0.61	0.75
γ-j	$\cos\theta^*_{\text{lead}} > 0$	123	118 ± 20	0.15	0.016
γ-e	$\cos\theta^*_{\text{lead}} > 0$	227	260 ± 25	0.12	0.19
j-j-j	$\cos\theta^*_{\text{lead}} > 0$	1359	1218 ± 340	0.36	0.63
e-j-j	$\cos\theta^*_{\text{lead}} > 0$	65	74 ± 13	0.75	0.37
ν-j-j	$\cos\theta^*_{\text{lead}} > 0$	58	53 ± 12	0.62	0.26
j-j-j	$0.75 < X_{\text{lead}} < 0.9$	1672	1658 ± 482	0.096	0.40
e-j-j	$0.75 < X_{\text{lead}} < 0.9$	419	419 ± 81	0.018	0.07
ν-j-j	$0.75 < X_{\text{lead}} < 0.9$	133	109 ± 22	0.26	0.19

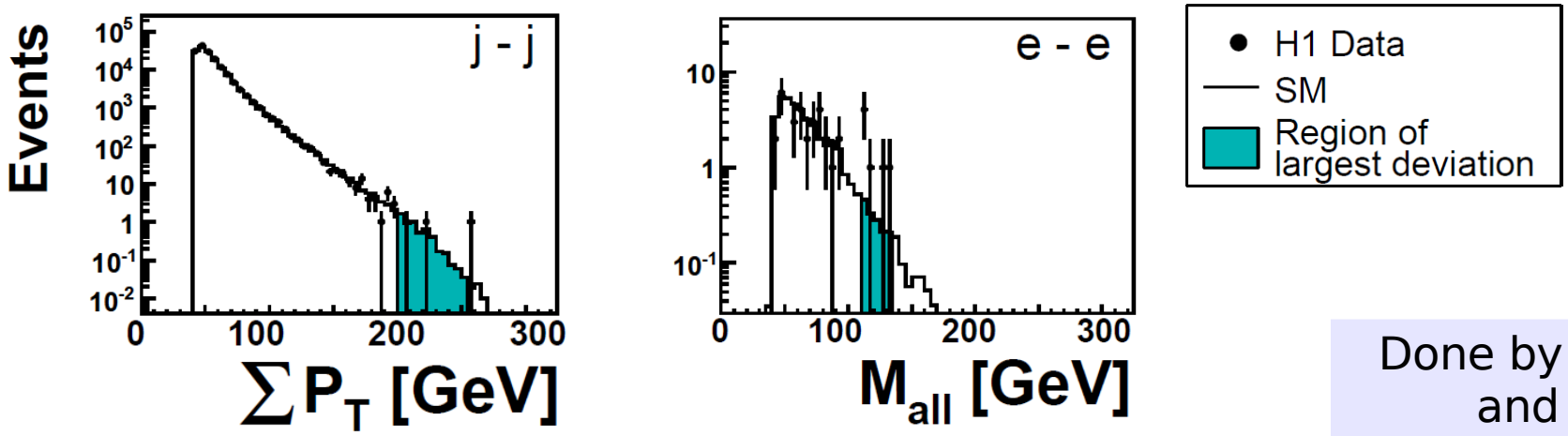
j-j-j also in single top analysis
e-j-j also in kinematic scan

Still good agreement of data and SM in all channels
Still no region with significant deviation p < 0.01 identified

Distributions to differentiate SM and BSM

Look into distributions of typical variables sensitive to BSM signals

Investigate both **kinematic** ...



Scalar sum of P_Ts of all bodies

Invariant mass of all bodies

Done by eye and **automatically**

... and **topological** properties of signatures

Cosine of polar angle (2 bodies) or **energy fraction** (> 3 bodies) of leading (highest P_T) body in cms frame of all bodies