Production of Z^0 bosons in elastic and quasi-elastic ep collisions at HERA

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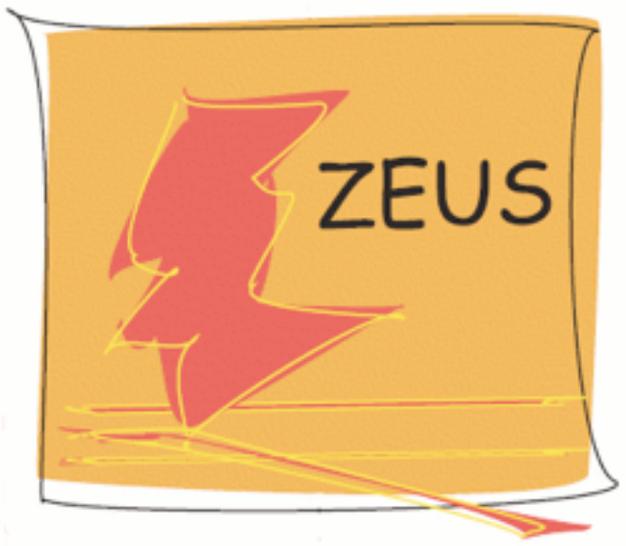
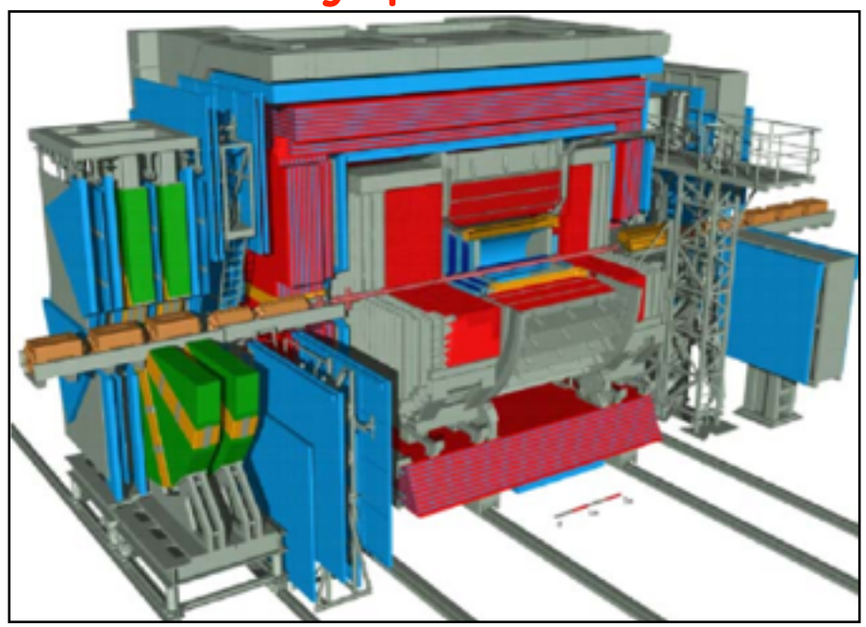


130th Anniversary in 2011

HERA and ZEUS

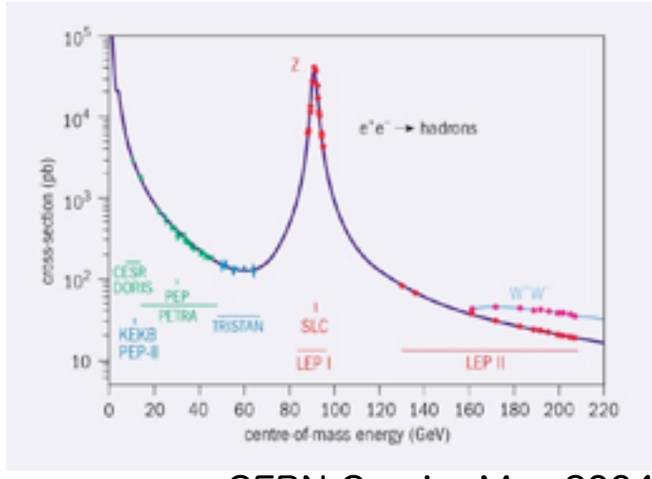
- HERA at DESY: the only $e^{\pm}p$ collider (1992-2007)
  - E_p = 920GeV, E_e = 27.6GeV ($\sqrt{s}$ = 318GeV)
  - Collected ~0.5 fb^{-1} per exp. (H1 and ZEUS)
- ZEUS: a general-purpose 4π detector
  - features high-resolution Uranium-Scint. CAL
    - $\sigma_E/E = 18\%/\sqrt{E(GeV)}$ for electrons
    - $\sigma_E/E = 35\%/\sqrt{E(GeV)}$ for hadrons ←key point in this analysis



EW bosons at colliders

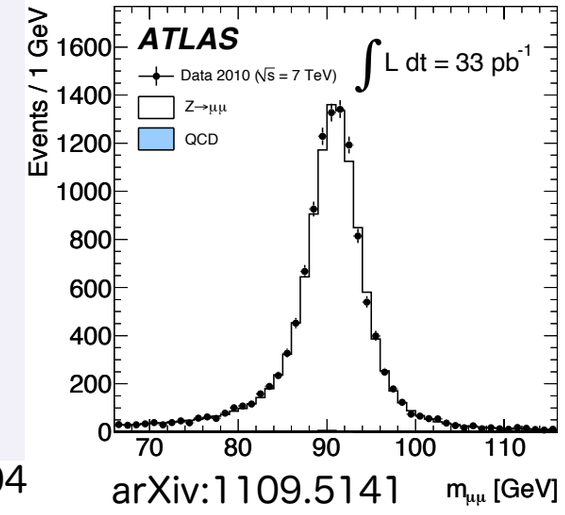
- e^+e^- and hadron colliders
  - abundant Z/W productions via e^+e^- or $q\bar{q}$ annihilation
- In ep collisions at HERA
  - not the case due to L,B conservation
  - small xsec via radiation from quark/lepton lines
    - W xsec measured using high-p_T-lepton + ETmiss events (~1 pb)
    - Z production even smaller (~0.4 pb), not yet measured.
  - Z/W bosons play important roles in t-channel (off-shell) exchange
    - NC/CC DIS processes at high-Q^2

$\sigma(e^+e^-\rightarrow hadrons)$

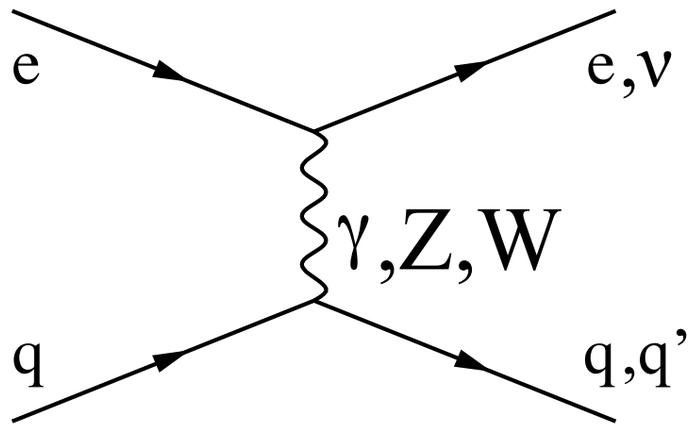


CERN Courier May 2004

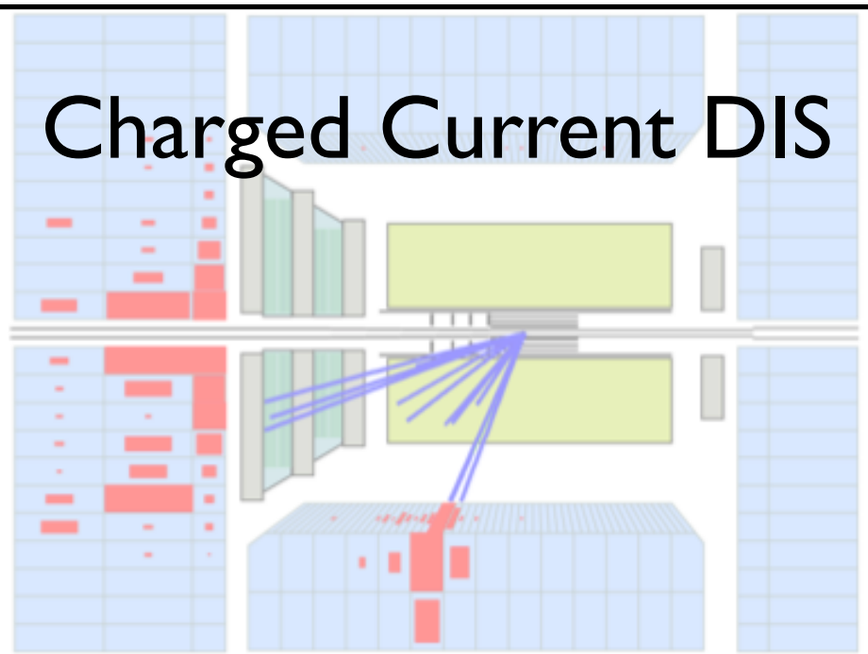
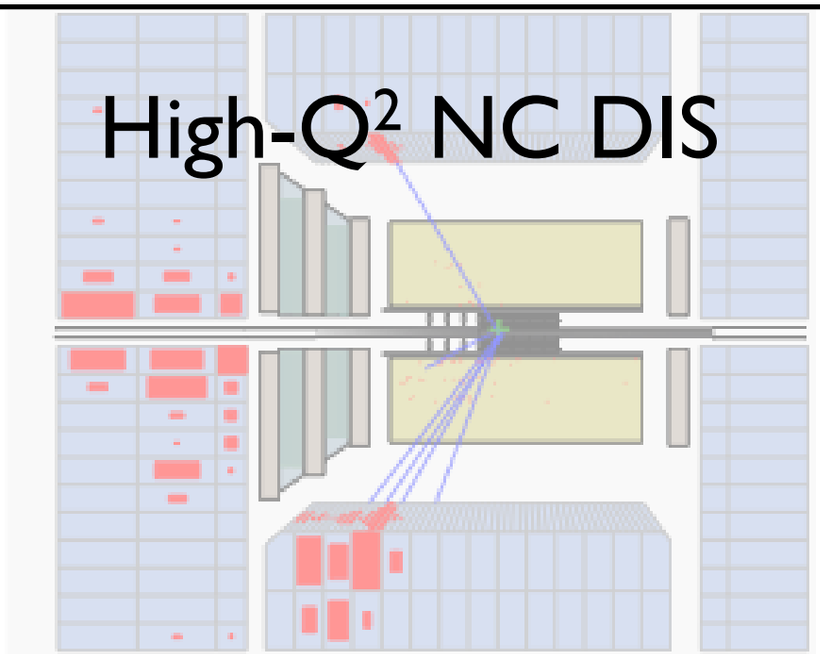
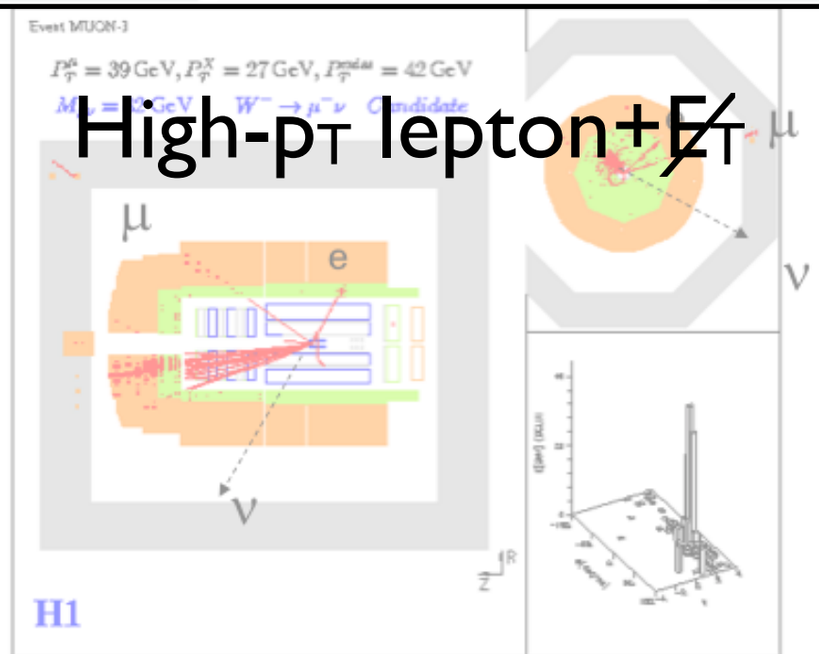
$Z\rightarrow\mu\mu$



arXiv:1109.5141

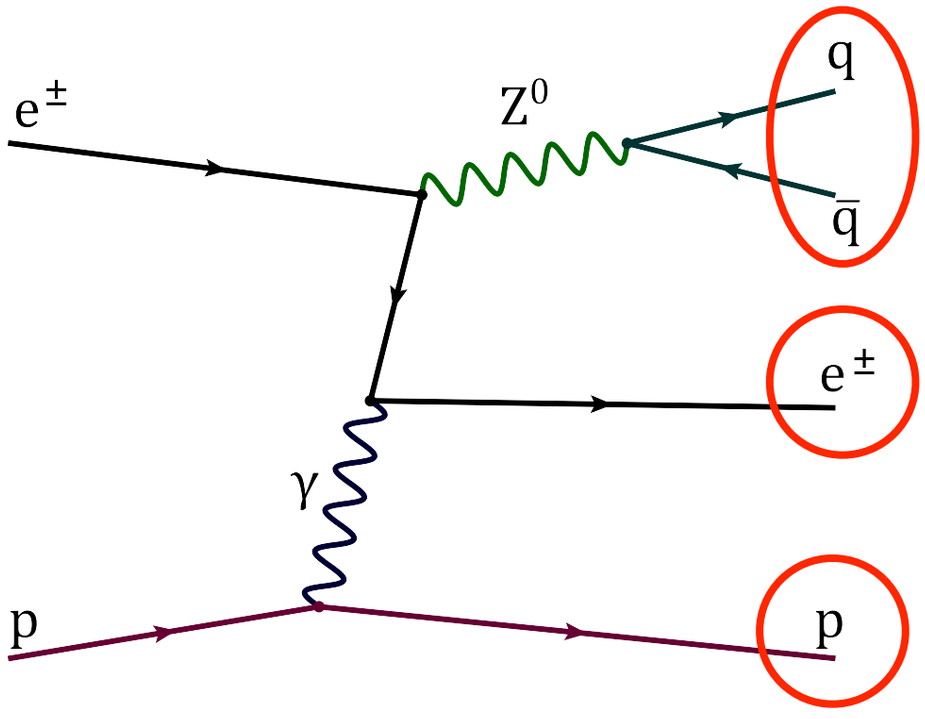


Completing EW programs at HERA

	W	Z
Virtual	Charged Current DIS 	High-Q^2 NC DIS 
Real	High-p_T lepton+$\not{E}_T$ 	**Missing piece in HERA EW program?** Also important background for BSM search (e.g. $e^* \rightarrow eZ$) Smallest cross section measured at HERA!

Z^0 search strategy

- Use hadronic decay (large B.R.)
- Use elastic (+quasi-elastic) events ($\sigma \sim$ 0.16 pb)
  - $ep \rightarrow ep(p^*)Z$ (p^*: nucleon resonances)
  - require $\eta_{max} < 3$ (maximum η of CAL energy deposits)
  - suppress QCD background



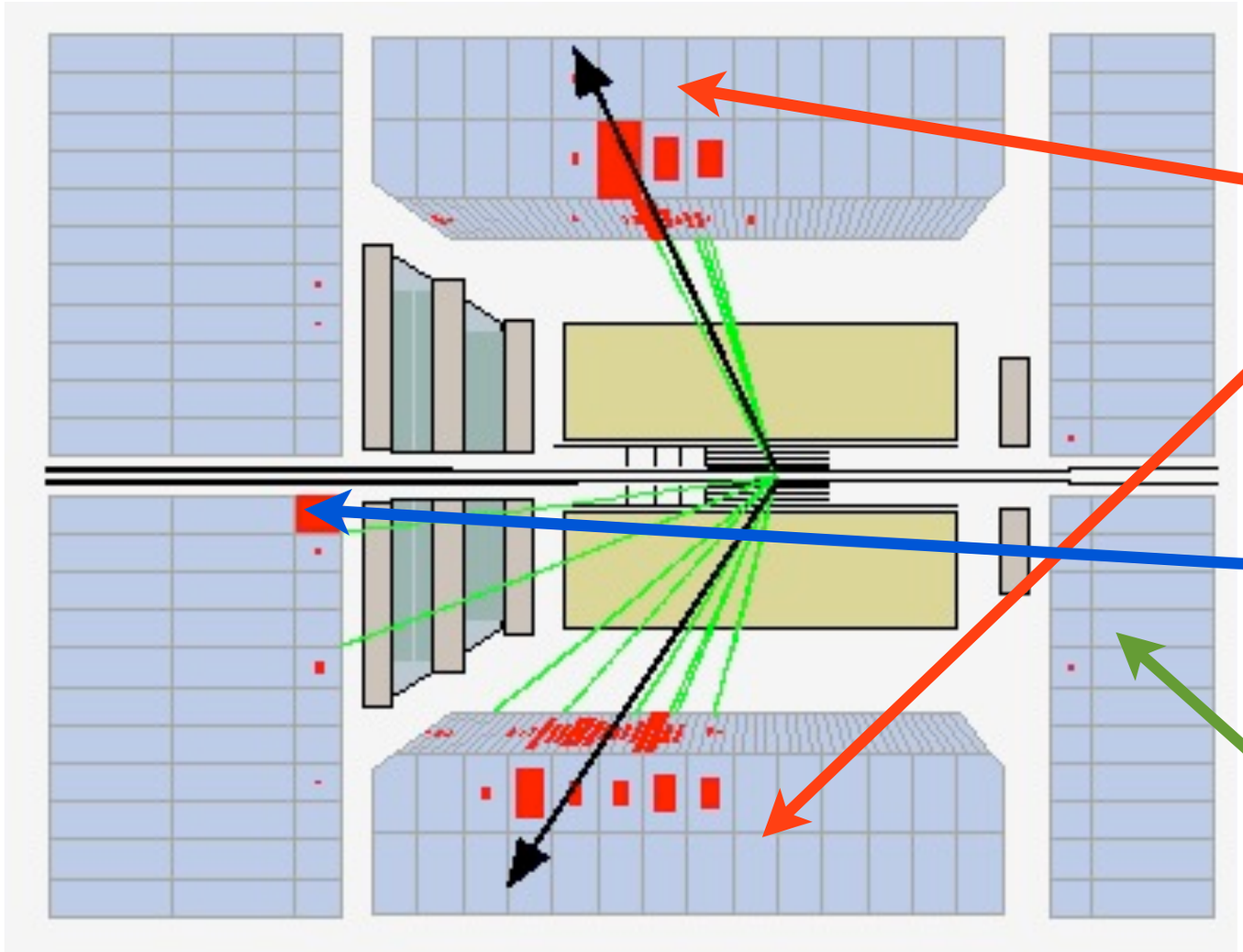
← 2 (or more) high-E_T jets

beam electron back-scattered to
← forward (proton) direction
(in Forward CAL or beam-pipe)

← p or p*: no proton remnant in detector

Event selection overview

electron →← proton



θ=0

η>0 η<0

≧2 high E_T jets
(E_T>25GeV)

$\eta_{max} < 3$
to select elastic events
(this event will be rejected)

Rear CAL veto
E-Pz peaks at $2E_e$=55GeV
to suppress low-Q^2 NC and photo-production

Event selection (496 pb^{-1})

Trigger mainly based on CAL E_T
Cleaning cuts in backup

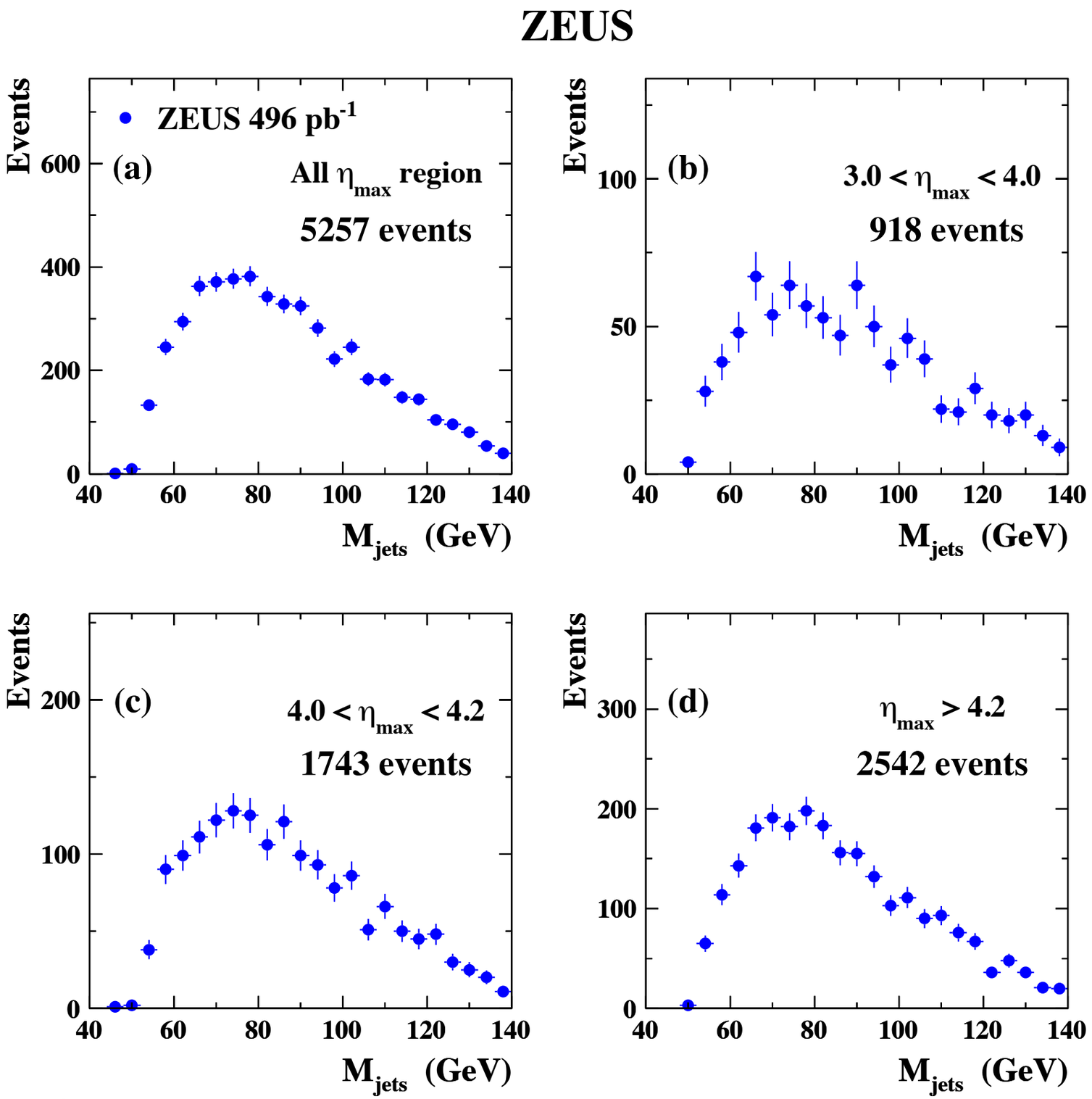
- Jets defined by k_T algorithm
  - At least 2 jets with $E_T > 25GeV$, $|\eta| < 2$. $\Delta\Phi_{12} > 2rad$
  - Use all jets ($E_T > 4GeV$, $|\eta| < 2$) for invariant mass
  - Remove jet if it overlaps with e/γ within R < 1
- At most 1 electron in detector
  - $E_e > 5GeV$, isolation, track match if in tracking coverage
  - $\theta_e < 80deg$ required (reject low-Q^2 NC b.g.)
- No particles in rear (electron beam) direction
  - $E_{RCAL} < 2GeV$
  - $50 < \Sigma(E-p_Z) < 64GeV$ (sum over all CAL deposits)

MC simulation

- EPVEC used for signal
  - Baur, Vermaseren and Zeppenfeld (1992)
  - Interfaced to PYTHIA+JETSET
- Elastic and quasi-elastic $ep \to ep(p^*)Z$: 0.16 pb
  - Selection acceptance ~22%, expect 17.9 events
- Inelastic processes: 0.24 pb
  - DIS ($\gamma^* p \to Z^0 X$) and resolved php ($\gamma p \to (q\bar{q} \to Z^0)X$)
  - Selection acceptance <1%, expect 0.4 events
- Do not use background MC
  - Tail of high-E_T diffractive DIS, hard to model
  - Use data-driven estimation (next slide)

Background estimation

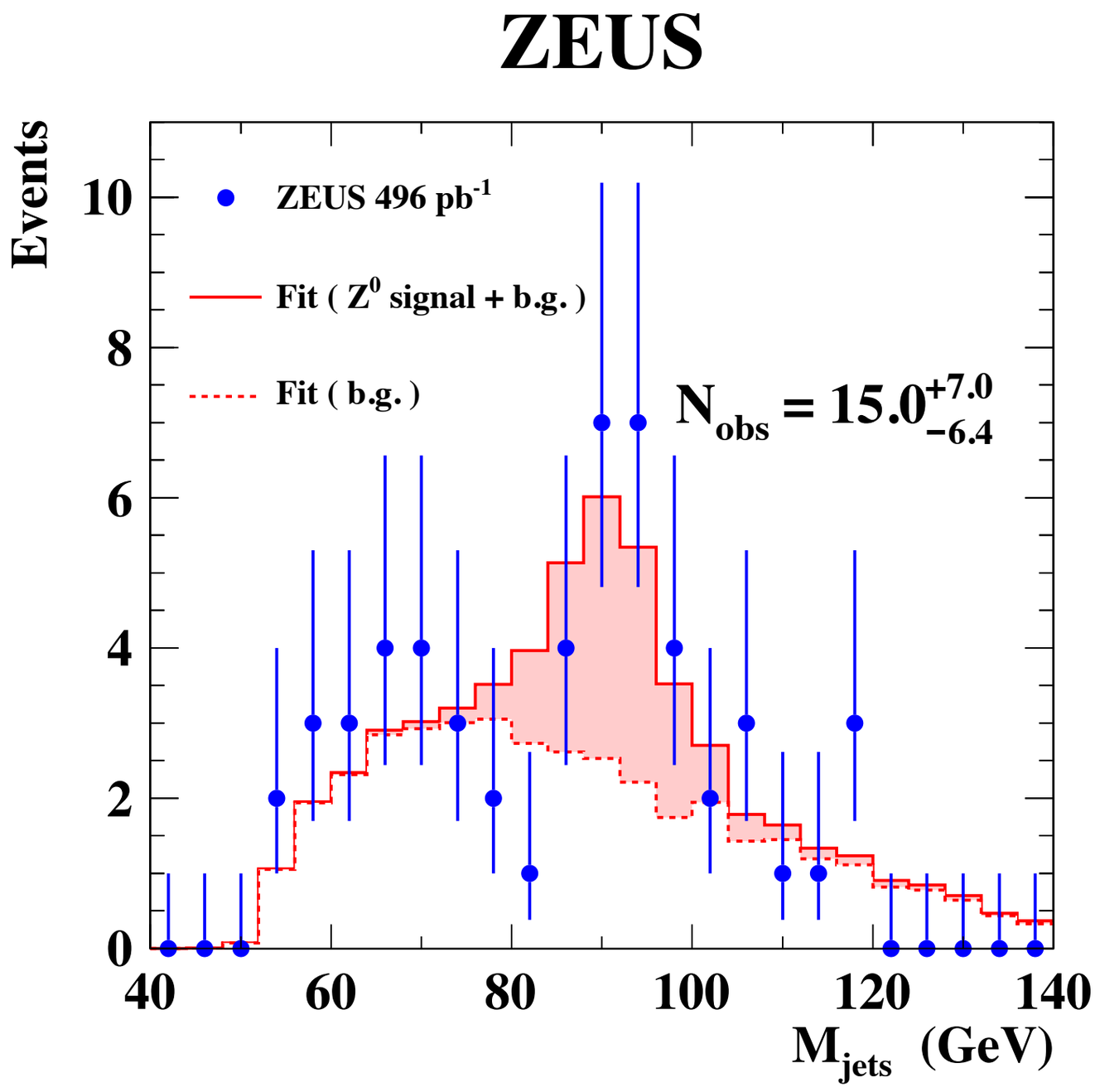
- Invariant-mass shape has little η_{max} dependence
- Use invariant-mass distribution for data in $\eta_{max} > 3$ region as b.g. template + Use EPVEC MC as signal template
- Fit signal region ($\eta_{max} < 3$) w/ templates



Result after all selections

- invariant mass after $\eta_{max} < 3$ cut
- maximum likelihood fit (details in backup) with b.g. and signal templates
- mass peak shift due to energy scale fitted as a nuisance parameter ($\sigma_\varepsilon = 3\%$, the fit gave $\varepsilon = 3 \pm 2\%$)

$\tilde{\chi}^2/ndf = 17.6/22$



- signal obtained with 2.3σ significance

Cross-section extraction

- Systematic uncertainties: total (+7.2, -6.2)%
  - acceptance change by ±3% e-scale: (+2.1, -1.7)%
  - η_{max} cut varied by ±0.2: (+6.4, -5.4)%
  - using different η_{max} slices for b.g. template: ±1.5%
  - signal template peak width (6GeV) smeared: negligible
  - luminosity: ±2%
- Resulting cross section
  - $\sigma(ep \to eZ^0 p^{(*)}) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})\,\text{pb}$
  - consistent with SM prediction 0.16 pb
  - first measurement of on-shell Z^0 cross section in ep!

Summary

- A search for on-shell Z^0 production in ~0.5 fb^{-1} ep collisions at HERA using ZEUS detector
- Hadronic decay was used: (quasi-)elastic process was aimed to suppress inelastic b.g.
- $\eta_{max} < 3$ was used for elastic condition
- Background template made from $\eta_{max} > 3$ events
- Fit invariant mass from all jets with signal (MC) and background (data) templates
- First measurement of Z^0 production in ep

SM: 0.16pb

$$\sigma(ep \to eZ^0 p^{(*)}) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})\,\text{pb}$$

Cuts against cosmic+beamgas

- Reject if any of following conditions are met.

- $|Z_{vtx}| > 50cm$
- $175 < \theta_1+\theta_2 < 185deg$ and $\Delta\Phi_{12} > 175deg$
- $|t_u-t_d| > 6ns$ (up-down timing difference in BCAL)
- ETmiss > 25GeV
- $N^{trk}_{vtx} < 0.25*(N^{vtx}_{all}-20)$ (vertex tracks and all tracks)

Fit procedure

- For each bin i of invariant mass M_{jets}

$$N_{\mathrm{ref},i} = aN_{\mathrm{sg},i}^{\mathrm{MC}}(\epsilon) + bN_{\mathrm{bg},i}^{\mathrm{data}} \qquad M_{\mathrm{jets}} = (1+\epsilon)\, M_{\mathrm{jets}}^{\mathrm{MC}}$$

- Poisson likelihood and nuisance parameter

$$\mathcal{L} = \mathcal{L}_1(N_{\mathrm{obs}}, N_{\mathrm{ref}}) \times \mathcal{L}_2(\epsilon, \sigma_\epsilon) \qquad \mathcal{L}_1 = \prod_i \frac{\exp(-N_{\mathrm{ref},i})\,(N_{\mathrm{ref},i})^{N_{\mathrm{obs},i}}}{N_{\mathrm{obs},i}!} \quad \text{and} \quad \mathcal{L}_2 = \exp\left(-\frac{\epsilon^2}{2\sigma_\epsilon^2}\right)$$

- χ^2-like log-likelihood function

$$\tilde{\chi}^2 = -2\ln\frac{\mathcal{L}_1(N_{\mathrm{obs}}, N_{\mathrm{ref}})}{\mathcal{L}_1(N_{\mathrm{obs}}, N_{\mathrm{obs}})} - 2\ln\mathcal{L}_2 = 2\sum f_i + \left(\frac{\epsilon}{\sigma_\epsilon}\right)^2,$$

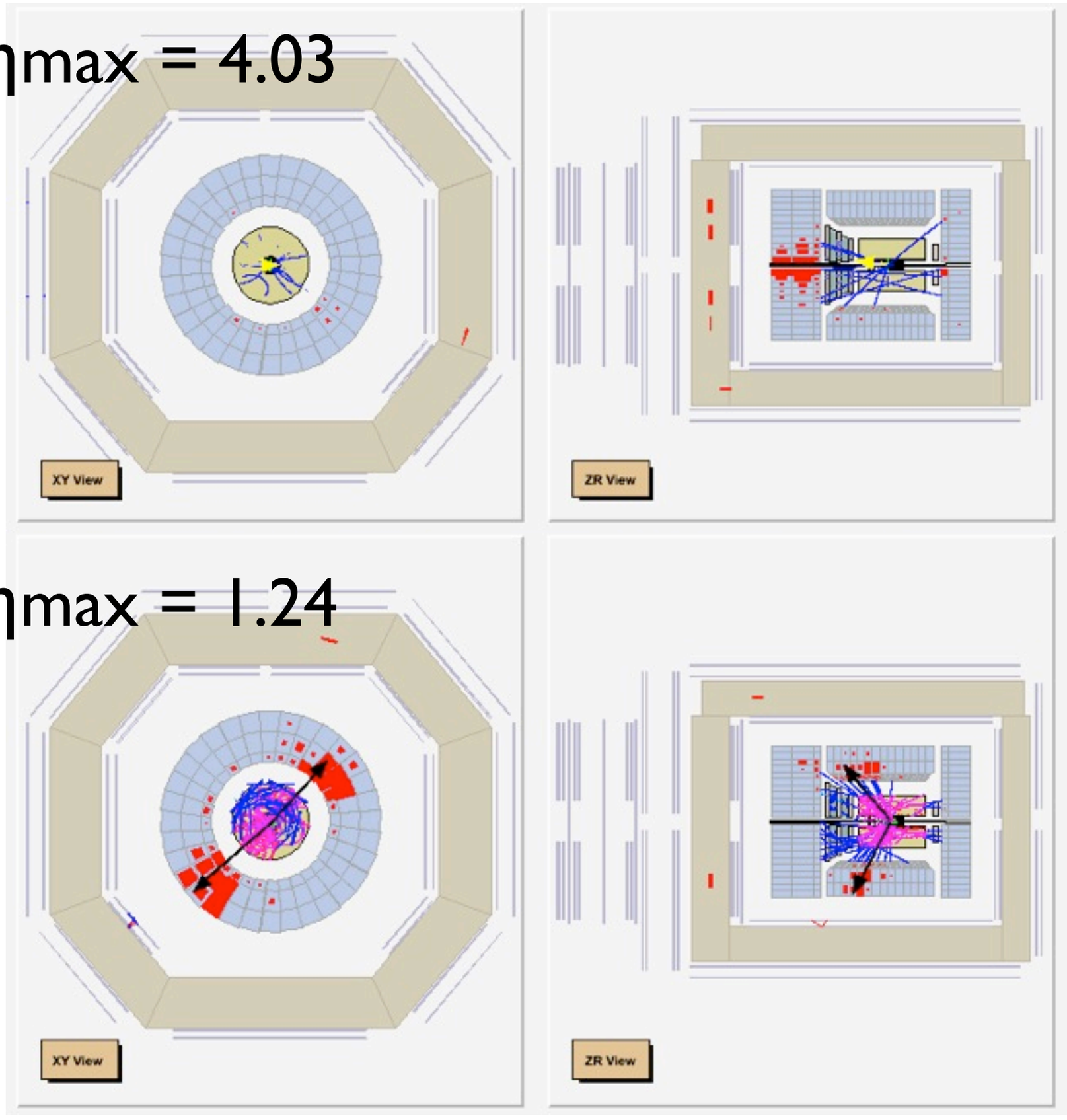
$$f_i = \begin{cases} N_{\mathrm{ref},i} - N_{\mathrm{obs},i} + N_{\mathrm{obs},i}\ln(N_{\mathrm{obs},i}/N_{\mathrm{ref},i}) & (\text{if } N_{\mathrm{obs},i} > 0) \\ N_{\mathrm{ref},i} & (\text{if } N_{\mathrm{obs},i} = 0) \end{cases}$$

- Minimize χ^2 to find best set of (a,b,ε)

→ $\sigma_{obs} = a \cdot \sigma_{MC}$, error of a given by $\Delta\chi^2 < 1$

η_{max}

$\eta max = 4.03$



$\eta max = 1.24$

Systematics on $\eta_{max} < 3$

- From PhD thesis

  V. Sola

  Inclusive Diffractive Cross Sections in Deep Inelastic ep Scattering at HERA

  DESY-THESIS-2012-008

- MC/data agreement of η_{max} within ±0.2 for NC DIS events

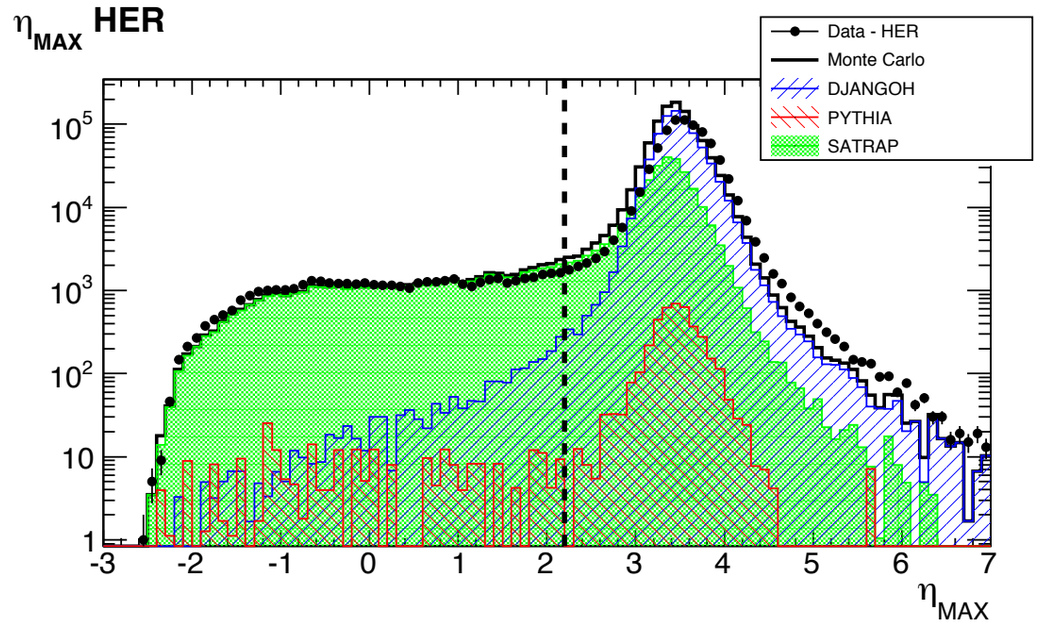


Figure 5.10: *The η_{MAX} distributions for the DIS HER (up) and LER (down) inclusive data samples. The histograms represent the sum of the Monte Carlo contribution: non-diffractive DIS (*Djangoh*) is the blue histogram, photoproduction (*Pythia*) is the red one and diffractive events (*Satrap*) are shown in green.*