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

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- HERA and ZEUS
- EW bosons@HERA
- Z^0 Search strategy
- Background estimation
- Results

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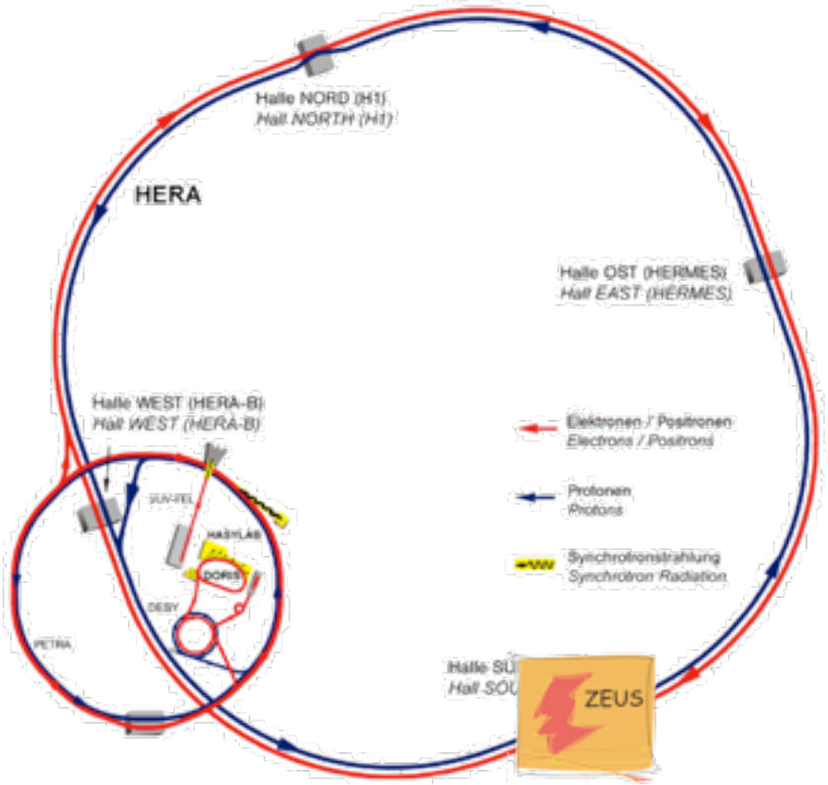
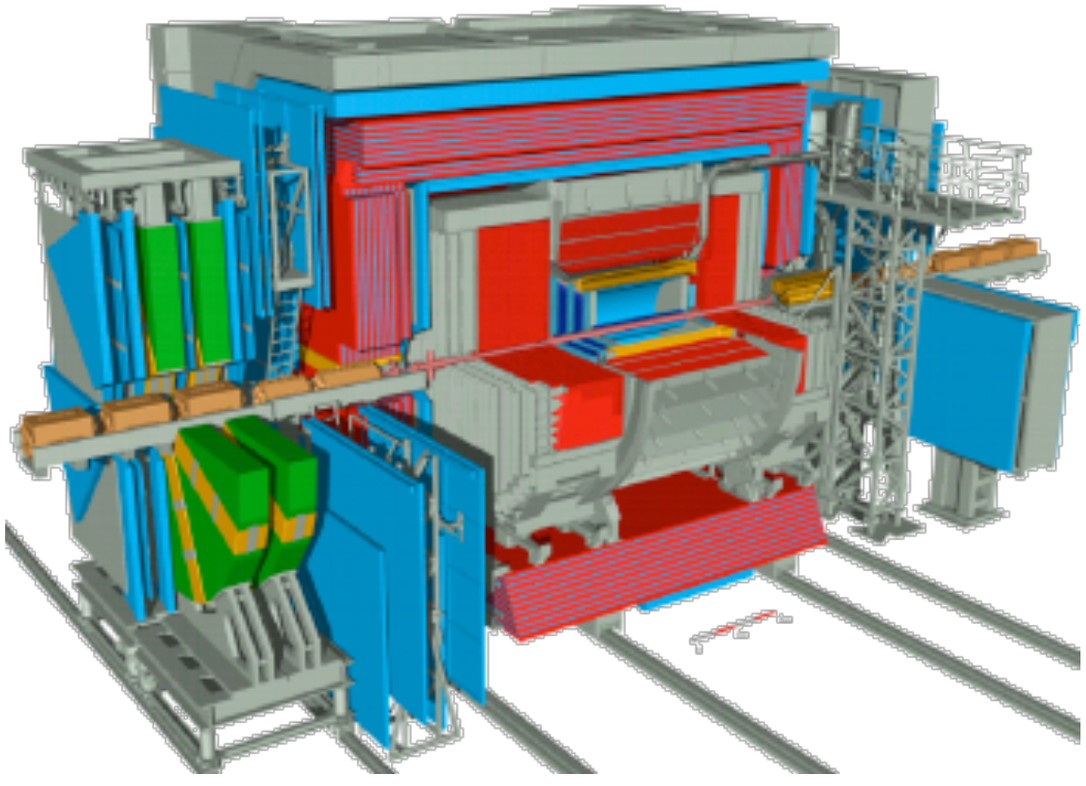
HERA and ZEUS

- **HERA: World's only *ep* collider at DESY**
- **Operated during 1992-2007.**
- **Collected ~0.5 fb^{-1} per experiment**
- **Center-of-mass energy: 318 GeV**
  - proton: 920 GeV
  - electron (positron): 27.5 GeV



- **ZEUS: General-purpose 4π detector**
- **High resolution calorimeter using Uranium absorber**
  - electron: $\sigma_E/E = 18\% / \sqrt{E\,(\mathrm{GeV})}$
  - hadron: $\sigma_E/E = 35\% / \sqrt{E\,(\mathrm{GeV})}$

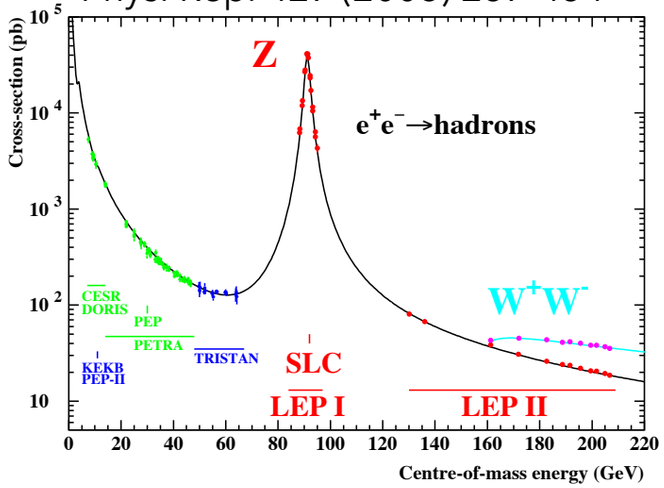
key point in this analysis



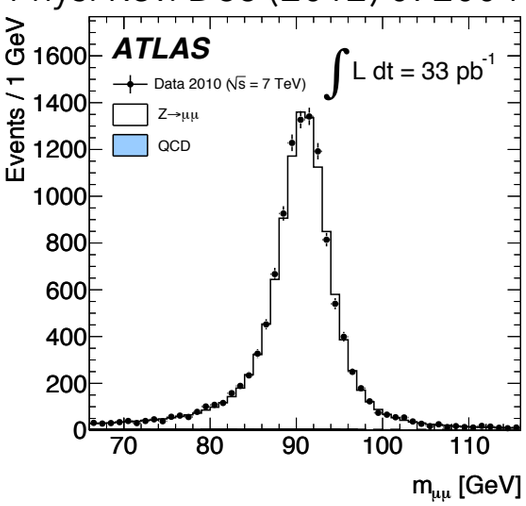
Electroweak Bosons at HERA

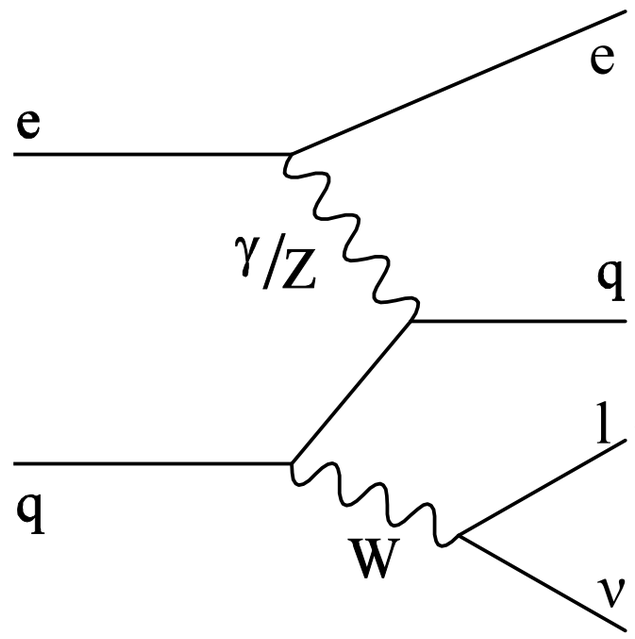
- **e^+e^- and hadron colliders**
  - abundant Z/W productions via e^+e^- or $q\bar{q}$ annihilation
- **In *ep* collisions at HERA**
  - not the case due to L,B conservation
  - small cross section via radiation from quark/lepton lines
    - W cross section measured using lepton+E_T^{miss} events (~1 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-Q2

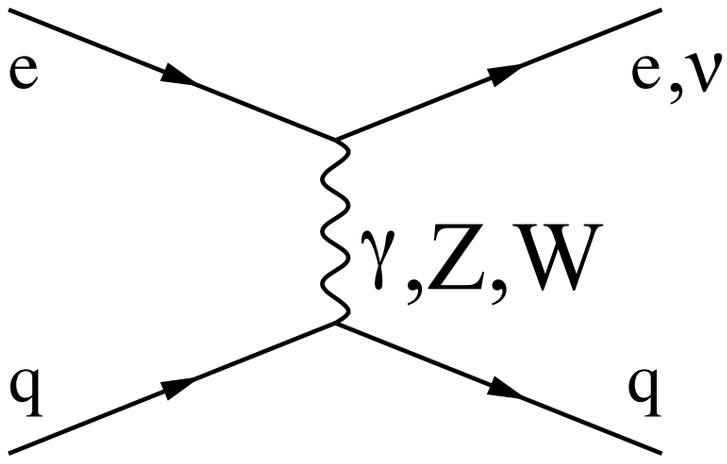
Phys. Rep. 427 (2006) 257-454



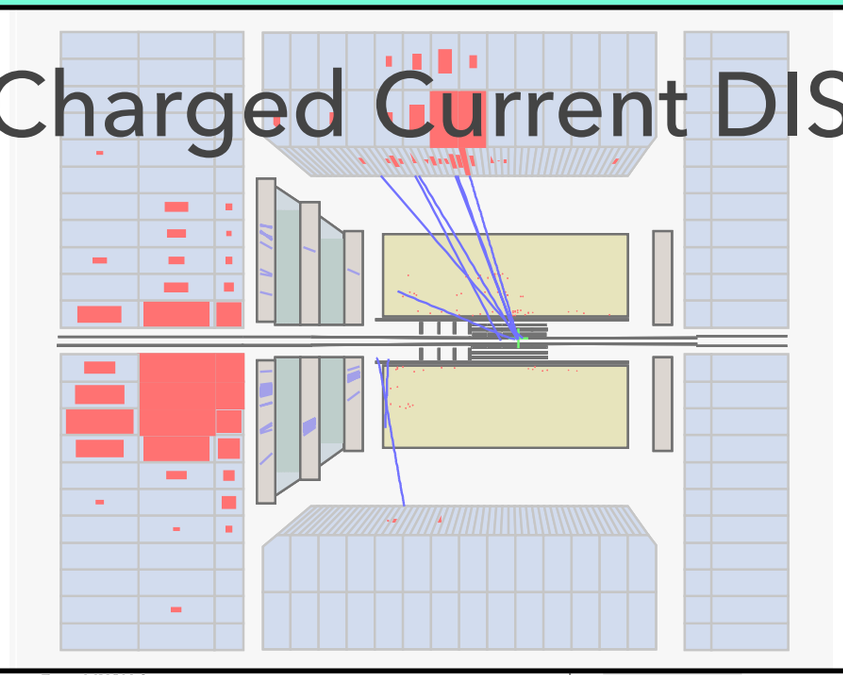
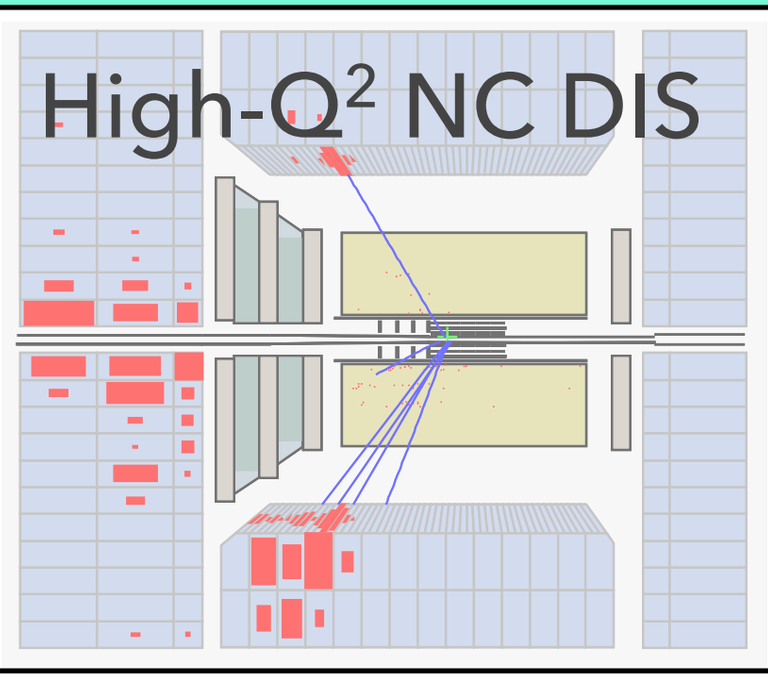
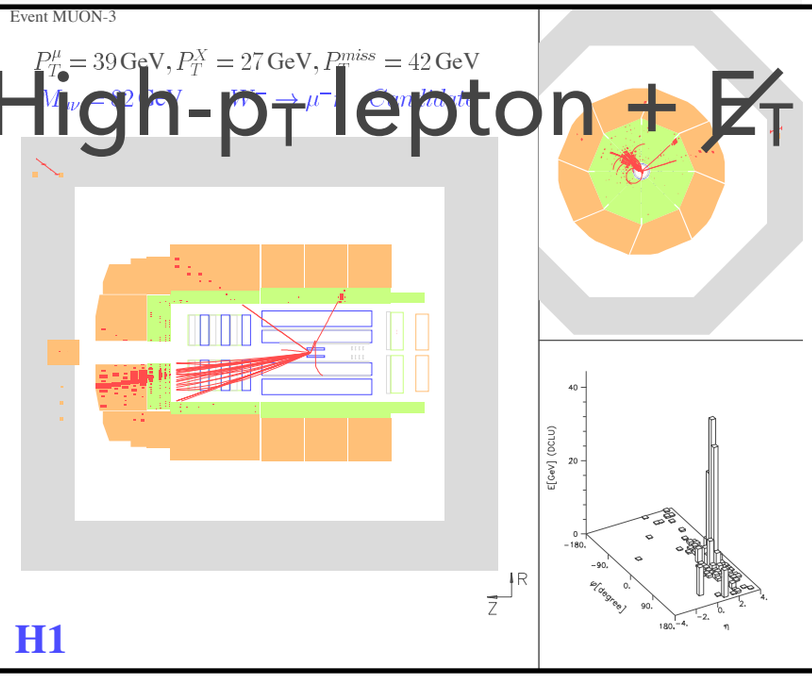
Phys. Rev. D85 (2012) 072004





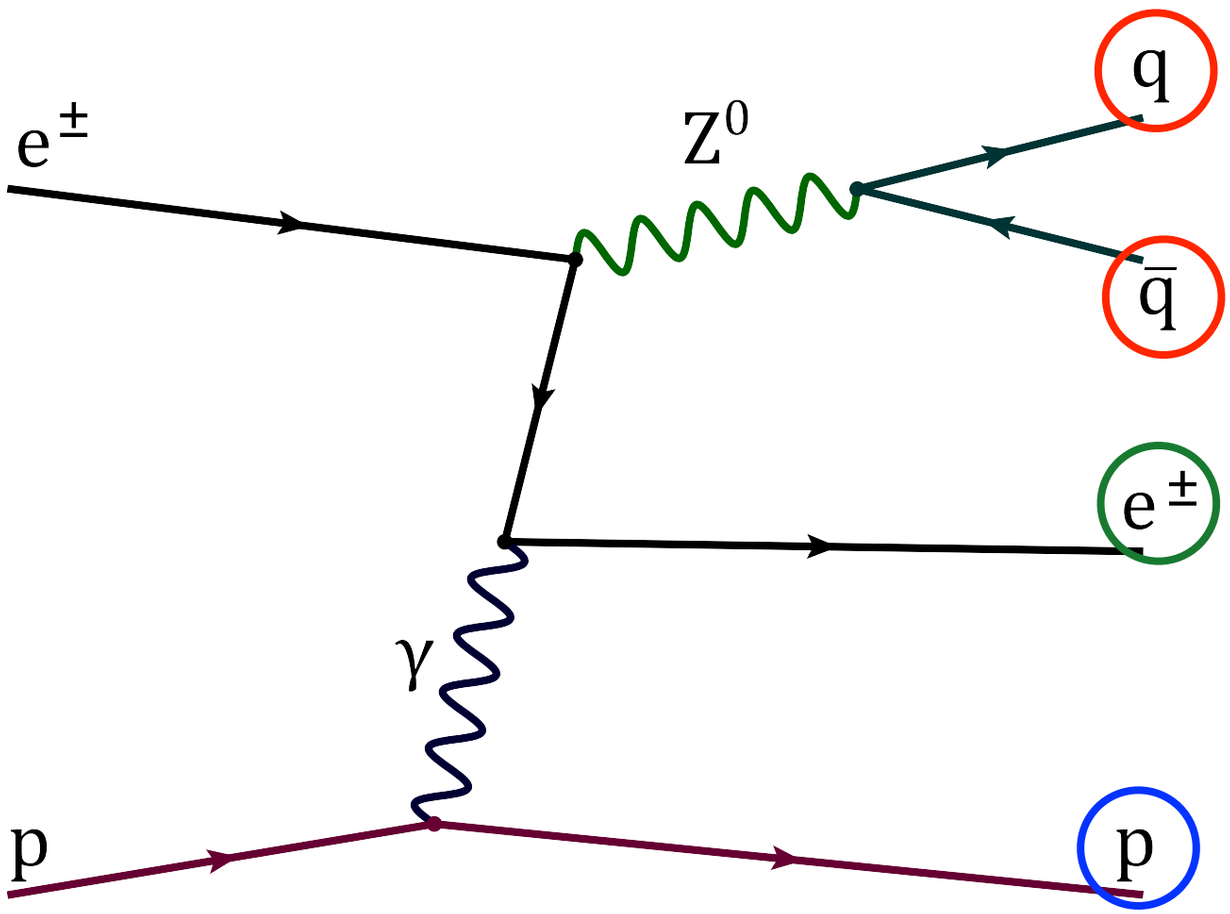


Electroweak Bosons at HERA

	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?** Smallest cross section measured at HERA!

Z^0 Search strategy

- **Use hadronic decay (large branching ratio of ~70%)**
- **Use elastic (+quasi-elastic) events (σ~0.16 pb)**
  - $ep \rightarrow ep(p^*)Z^0$ (p^*: nucleon resonances)
  - require $\eta_{max} < 3$ (maximum pseudo-rapidity 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)

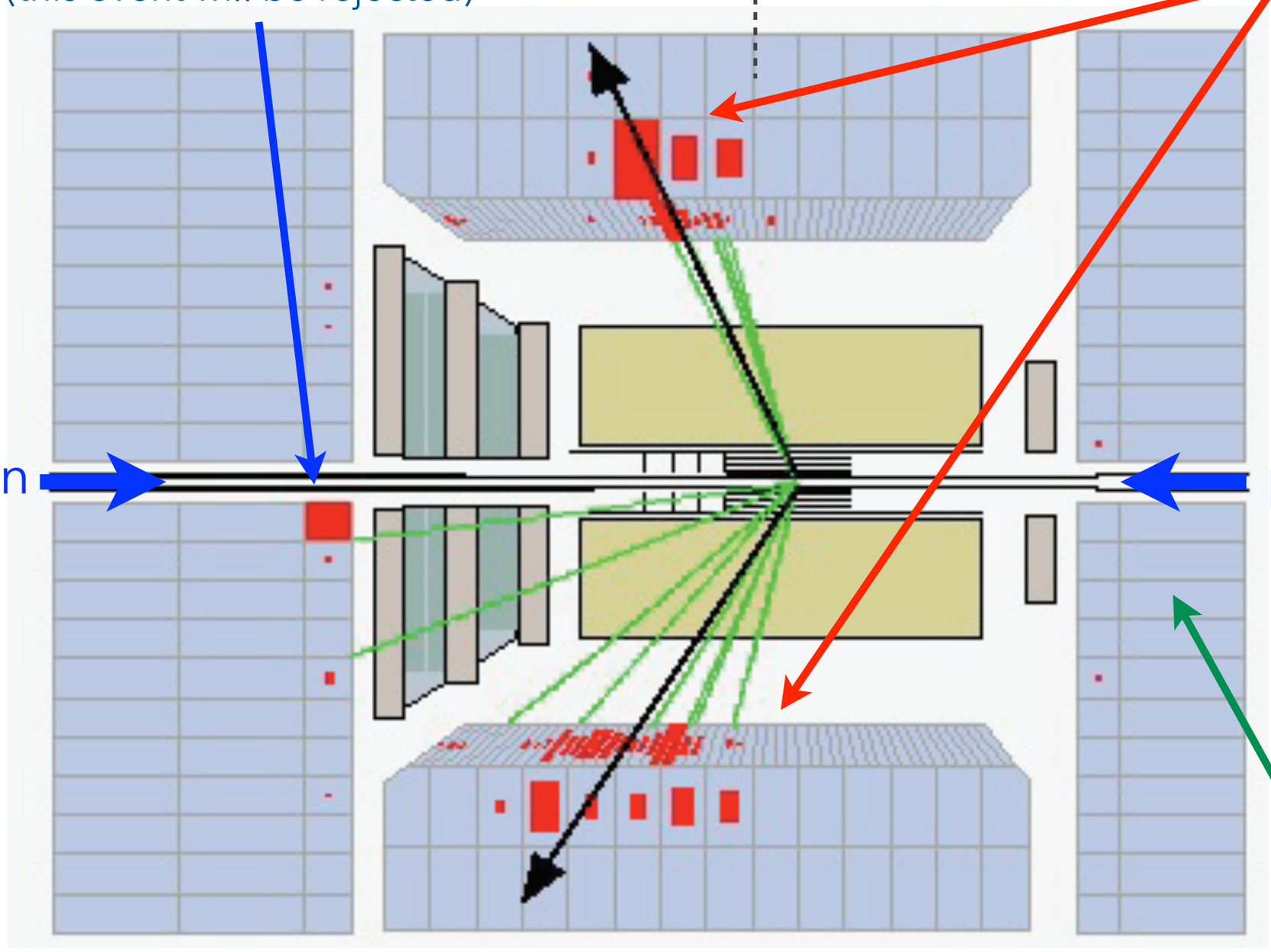
p or p*: no proton remnant in detector

2° Search strategy - event selection

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

η>0 | η<0

≧2 high E_T jets
(E_T > 25 GeV, |η| < 2)



Rear CAL veto
$E\text{-}P_Z$ peaks at $2E_e$=55 GeV
to suppress low-Q2 NC and photo-production

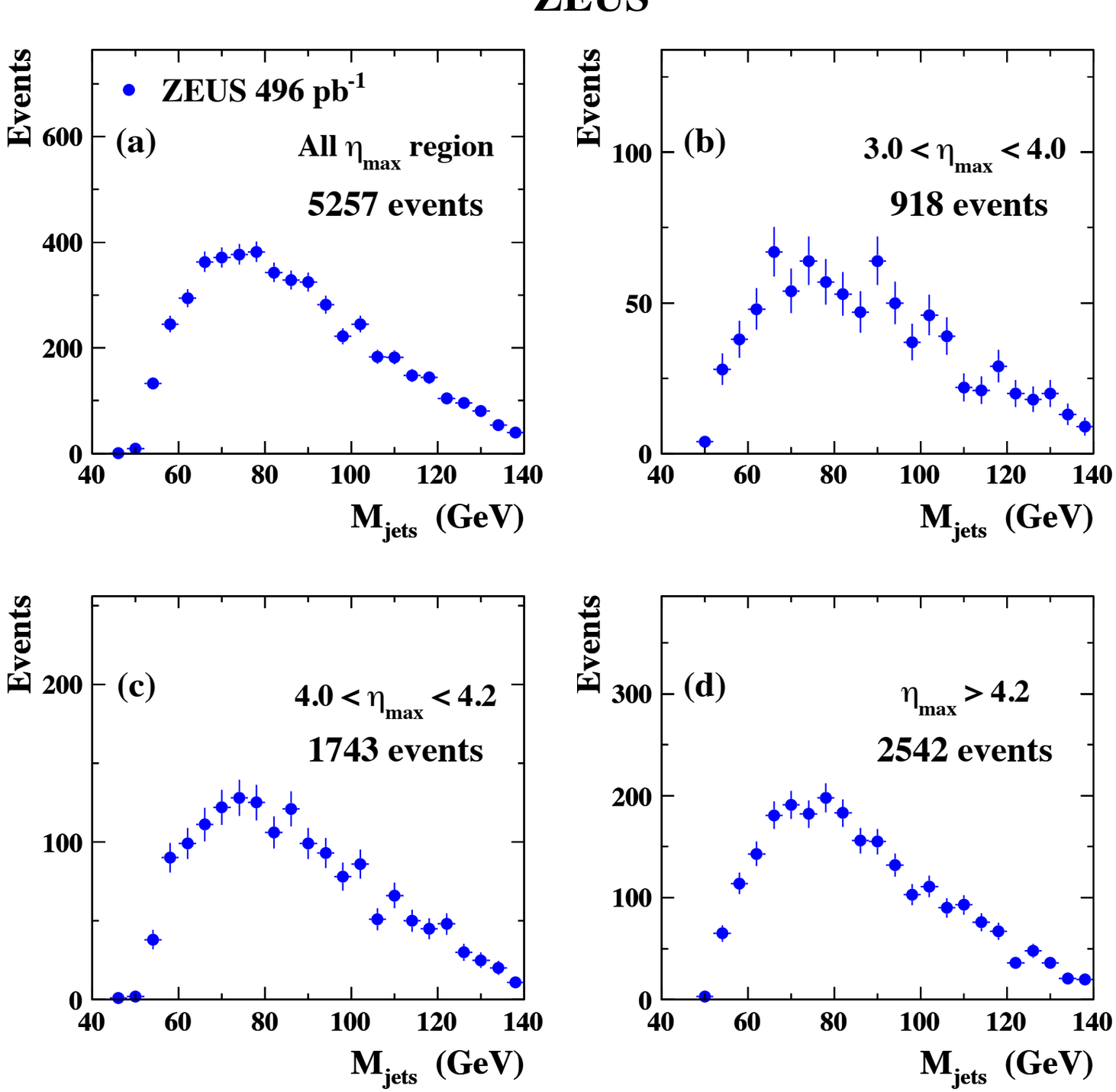
At most 1 electron in θ_e<80 deg
(proton direction)

MC simulation

- **EPVEC used for signal**
  - Baur, Vermaseren, and Zeppenfeld (1992)
  - Interfaced to PYTHIA+JETSET
- **Elastic and quasi-elastic $ep \to ep(p^*)Z^0$: 0.16 pb**
  - Selection acceptance ~22%, expect 17.9 events
- **Inelastic processes: 0.24 pb**
  - DIS ($\gamma^* p \to Z^0 X$) and resolved photoproduction ($\gamma p \to (q\bar{q} \to Z^0)X$)
  - 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 for background shape (next page)

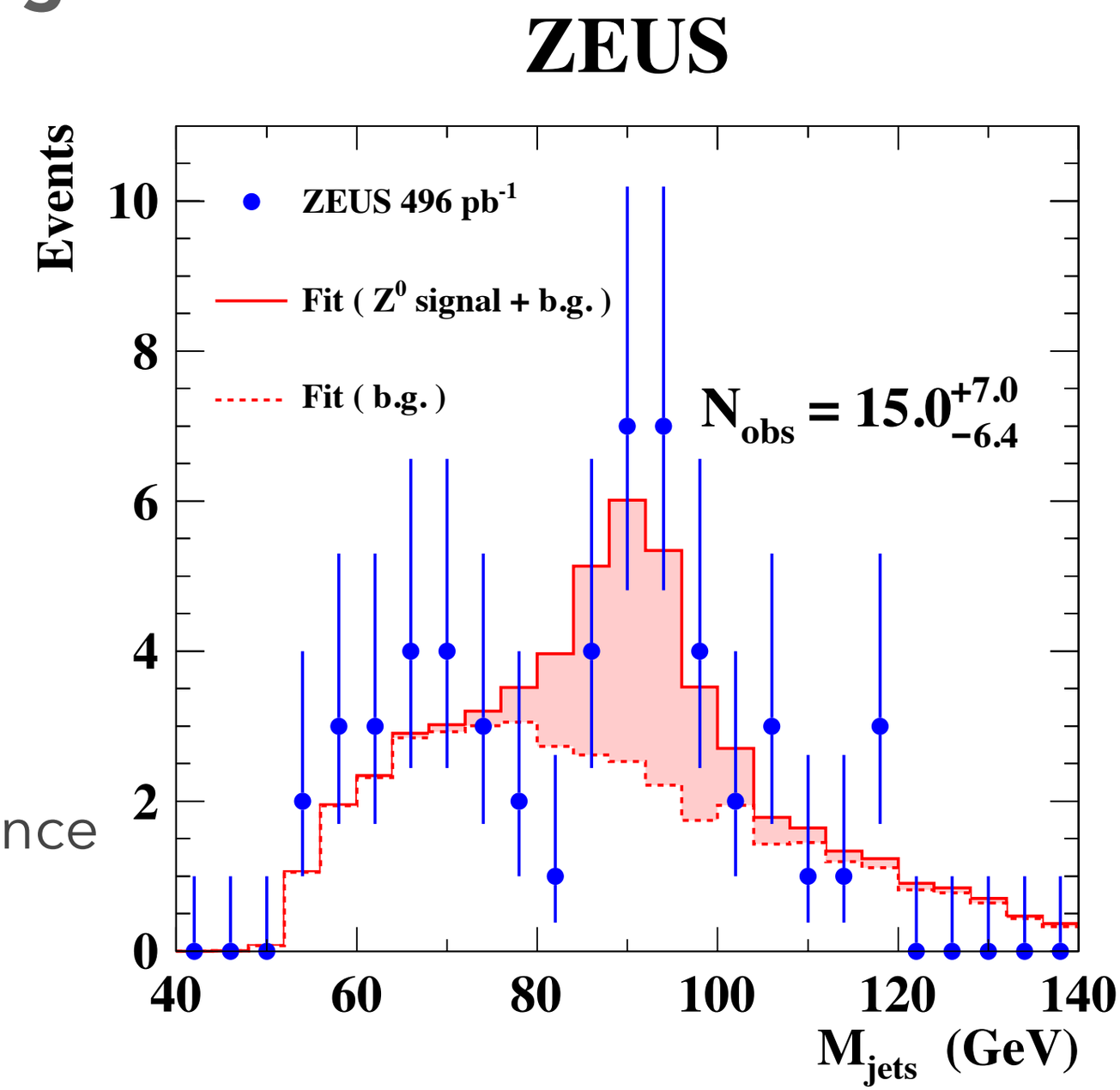
Data driven background shape estimation

- **invariant mass shape has little η_{max} dependence**
- **Use invariant mass distribution:**
  - background template from data in $\eta_{max} > 3$ region
  - signal template from EPVEC MC
- **Fit signal region ($\eta_{max} < 3$) with templates**



Result after all selections

- invariant mass after $\eta_{max} < 3$ cut
- **maximum likelihood fit** with signal and background templates
- mass peak shift due to **energy scale** fitted as a nuisance parameter (σ_ε=3%, the fit gave ε=3±2%)
- **$15.0^{+7.0}_{-6.4}$ events observed**
  - signal obtained with 2.3σ significance



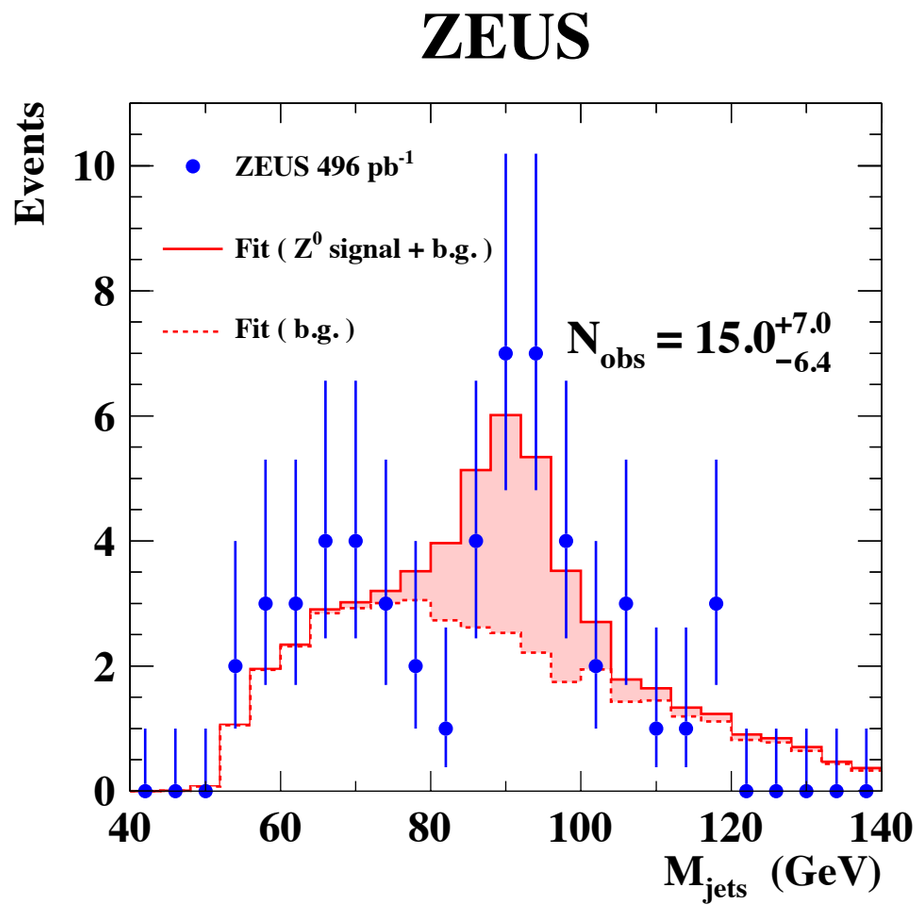
Cross section extraction

- **Systematic uncertainties: total (+7.2, −6.2)%**
  - acceptance change by ±3% energy scale: (+2.1, −1.7)%
  - η_{max} cut varied by ±0.2: (+6.4, −5.4)%
  - using different η_{max} slices for background template: ±1.5%
  - signal template peak width (6 GeV) 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* collisions!

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 backgrounds.**
  - Demonstrates excellent resolution of ZEUS uranium calorimeter
- **First measurement of Z^0 production in *ep* collisions**



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

- In agreement with SM elastic cross section of 0.16 pb
- Electroweak bosons at HERA fully exploited

backup slides

Used data period and luminosity

- **Data collected between 1996 and 2007**
- **Total integrated luminosity : 496 pb^{-1}**

	proton beam energy (GeV)	luminosity (pb^{-1})	
96/97 e^+	820	38.6	HERA-I total 121
98/99 e^-	920	16.7	
99/00 e^+		65.9	
03/04 e^+		41.0	HERA-II total 375
04/05 e^-		135.1	
06 e^-		55.2	
06/07 e^+		143.8	

- **Average polarisation is less than 1%**
  - the effect is neglected in this analysis

Event selection

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

Cuts for cosmic-rays & beamgas rejection

- **Reject if any of following conditions are met:**
  - $|Z_{vtx}| > 50$ cm
  - $175 < \theta_1+\theta_2 < 185$ deg and $\Delta\Phi_{12} > 175$ deg for jets
  - $|t_u - t_d| > 6$ ns (up-down timing difference in BCAL)
  - $E_T^{miss} > 25$ GeV
  - $N_{trk}^{vtx} < 0.25(N_{trk}^{all}-20)$ (vertex tracks and all tracks)

Fit procedure

- **For each bin i on invariant mass M_{jets}**

$$N_{\mathrm{ref}} = a\, N^{\mathrm{MC}}_{\mathrm{sg},i}(\epsilon) + b\, N^{\mathrm{data}}_{\mathrm{bg},i} \qquad M_{\mathrm{jets}} = (1+\epsilon) M^{\mathrm{MC}}_{\mathrm{jets}}$$

- **Poisson likelihood and nuisance parameter**

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

- **χ^2-like log-likelihood function**

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

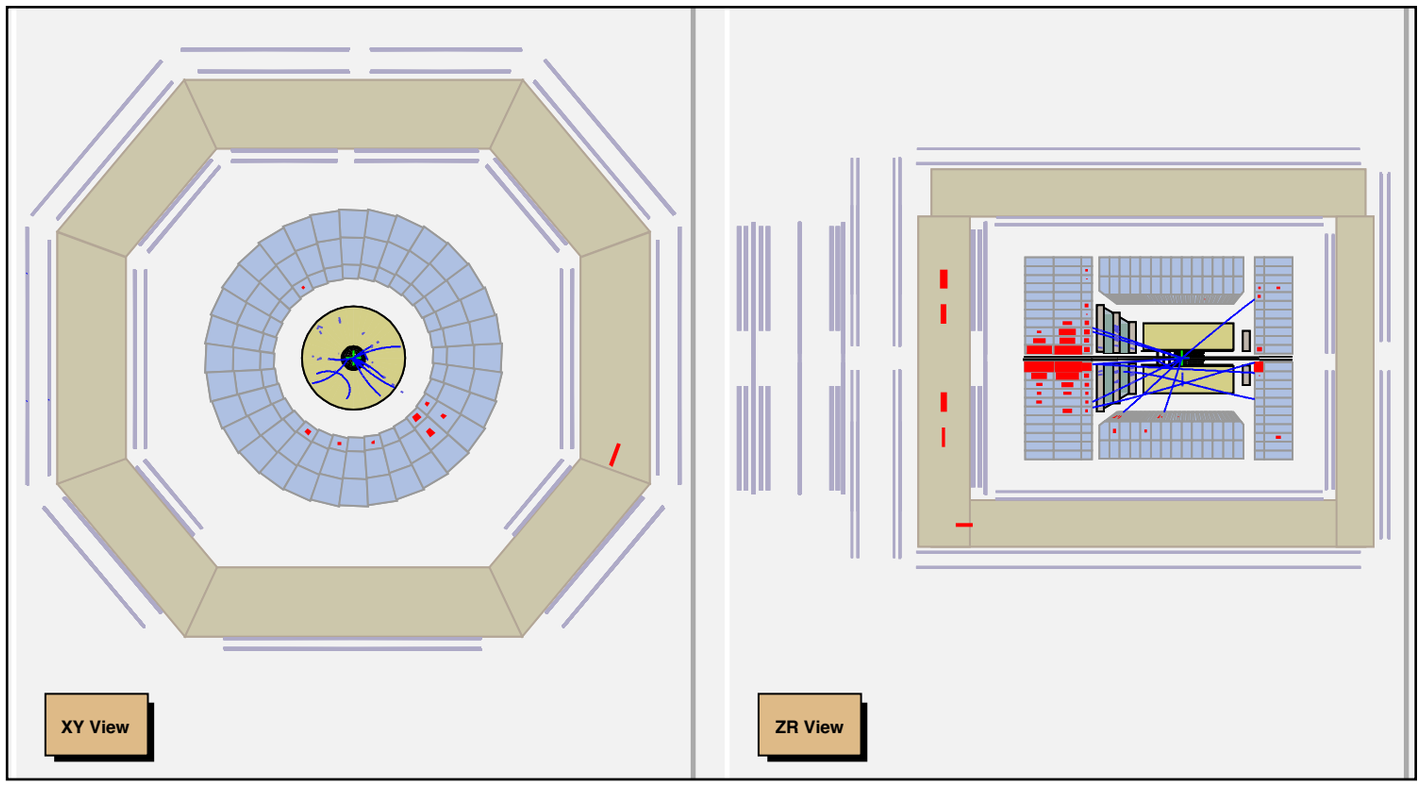
$$f_i = \begin{cases} N_{\mathrm{ref},i} - N_{\mathrm{obs},i} + N_{\mathrm{obs},i}\ln(N_{\mathrm{obs},i}/N_{\mathrm{ref},i}) & (\text{if } N_{\mathrm{obs},i} > 0) \\ N_{\mathrm{ref},i} & (\text{if } N_{\mathrm{obs},i} = 0) \end{cases}$$

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

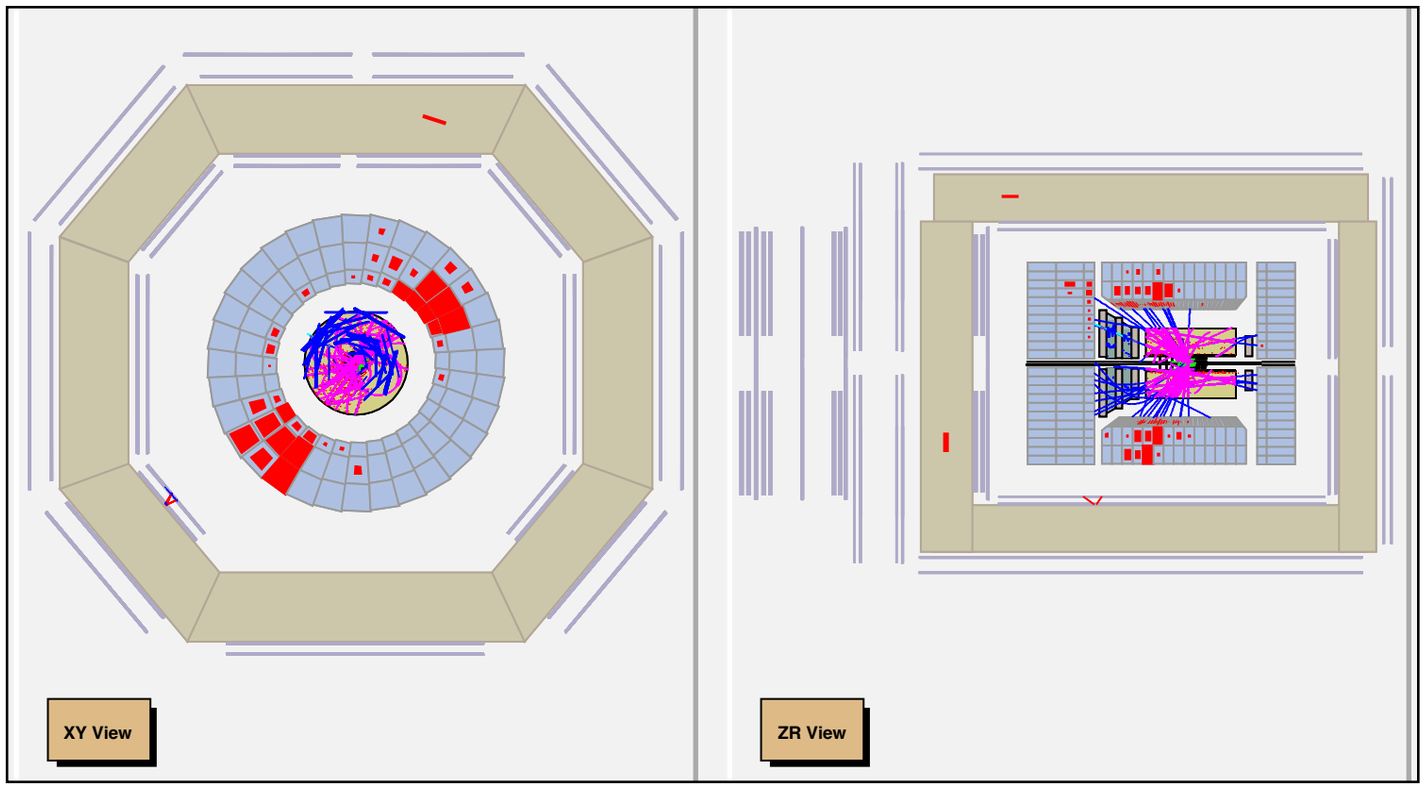
→ $\sigma_{\mathrm{obs}} = a \cdot \sigma_{\mathrm{MC}}$, error of a given by $\Delta\chi^2 < 1$

η_{max}

$\eta_{max}=4.03$



$\eta_{max}=1.24$



Systematics on $\eta_{max} < 3$

- **From PhD thesis by 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**

- **The uncertainty on the cross section measurement was:**

$$\begin{cases} +6.4\% \\ -5.4\% \end{cases}$$

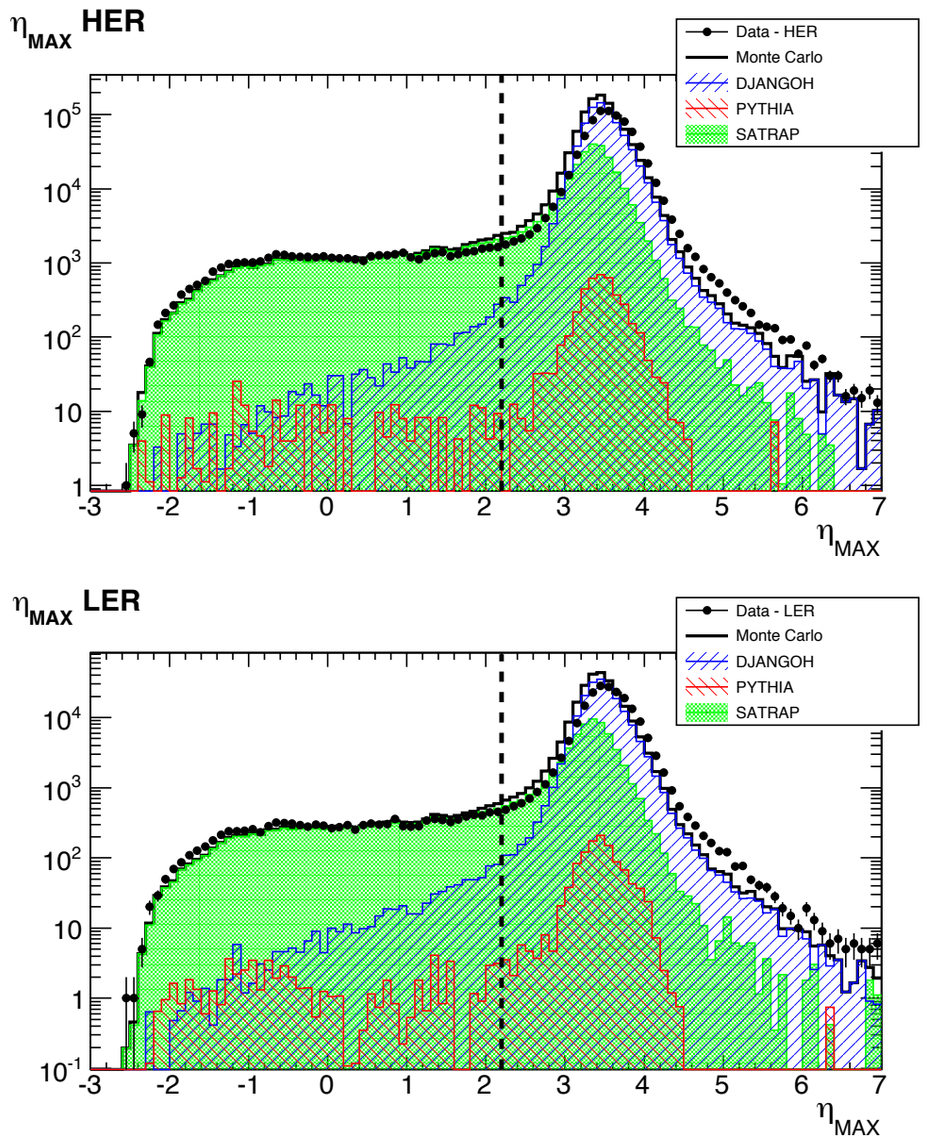


Figure 5.10: *The η_{MAX} distributions for the DIS HER (up) and LER (down) inclusive data samples. The histograms represent the sum of the Monte Carlo contribution: non-diffractive DIS (*Djangoh*) is the blue histogram, photoproduction (*Pythia*) is the red one and diffractive events (*Satrap*) are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