Real W and Z boson production at HERA

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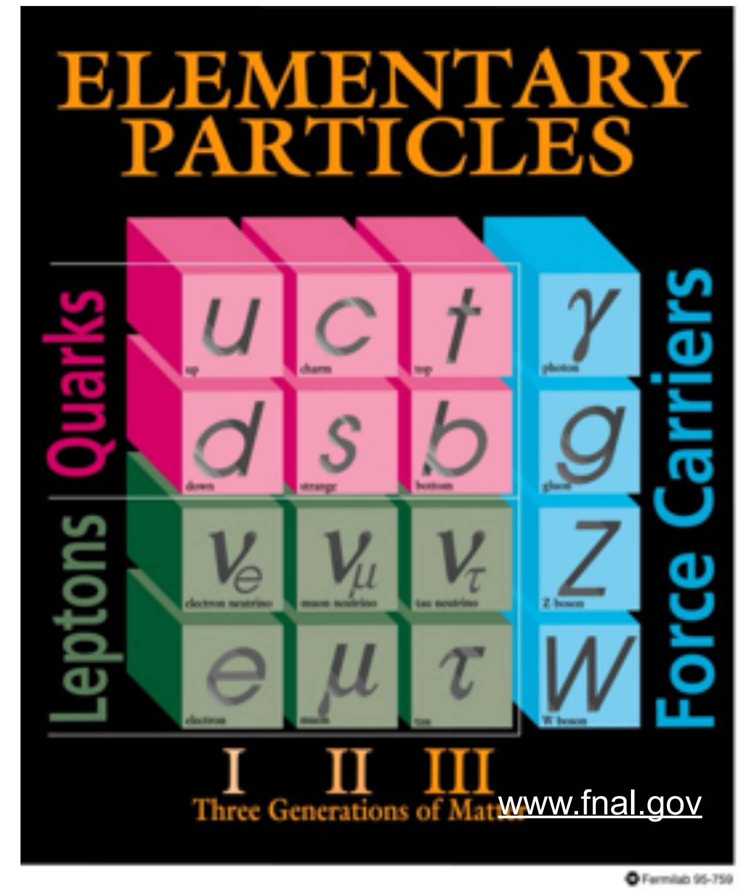
Introduction

- The **Standard Model** (SM):
  excellent description of fundamental **particles** and **interactions** among them by Gauge theory
  1. electro magnetic (EM) interaction
  2. weak interaction

     ※ unification of EM and weak interactions;
     electro-weak interaction.
  3. strong interaction (QCD)

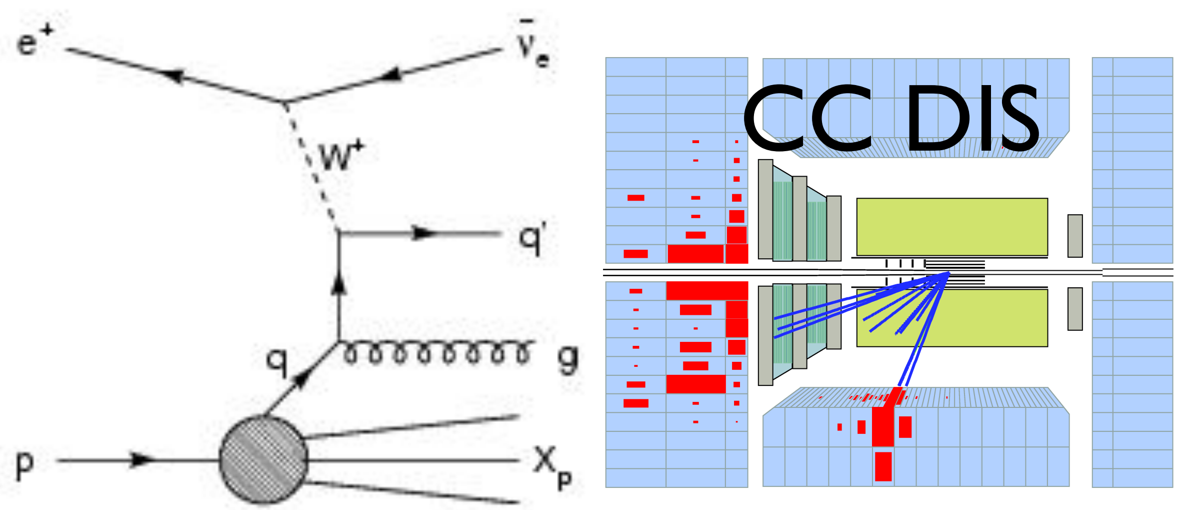


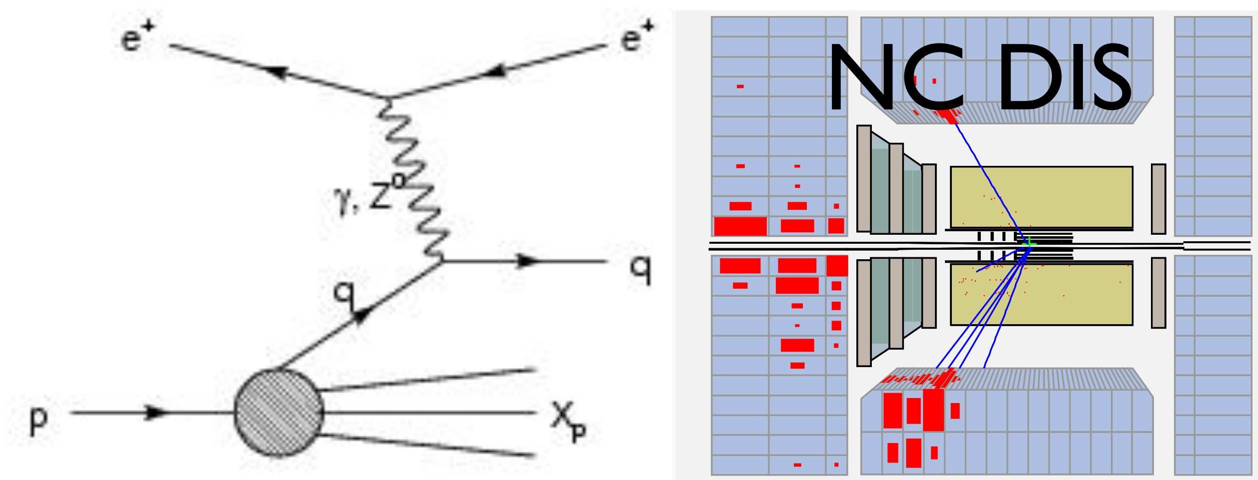
- Tested for long time by many experiments and **good agreement** between data/theory

- **W and Z boson**: mediate weak interaction. Spin=1
  - $W^{\pm}$: m~80GeV, charged current (CC)
  - Z^{0} : m~90GeV, neutral current (NC)

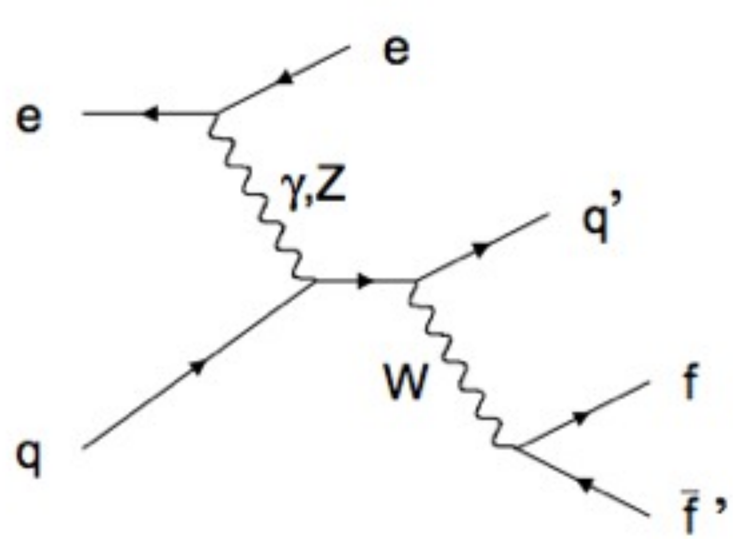
Weak bosons at HERA ep collider

- Important to prove the electro-weak sector in the SM
- Virtual W and Z: studied precisely in high-Q^2 CC and NC Deep Inelastic Scattering (DIS)

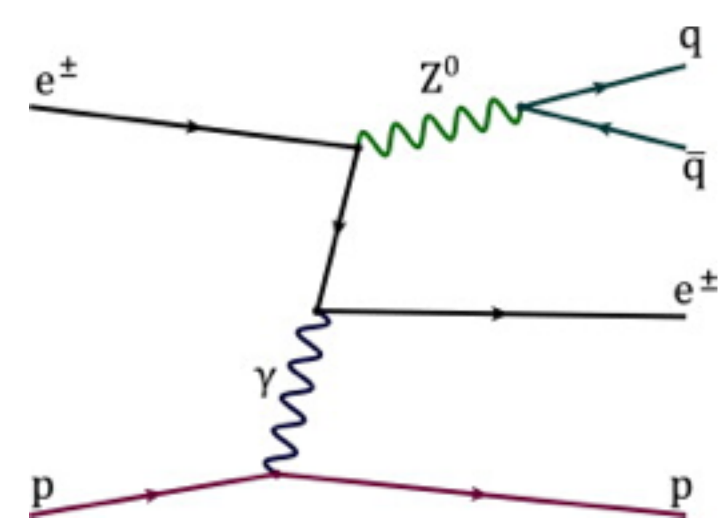




- Real W and Z : cross section is very small ($\lesssim$1pb);



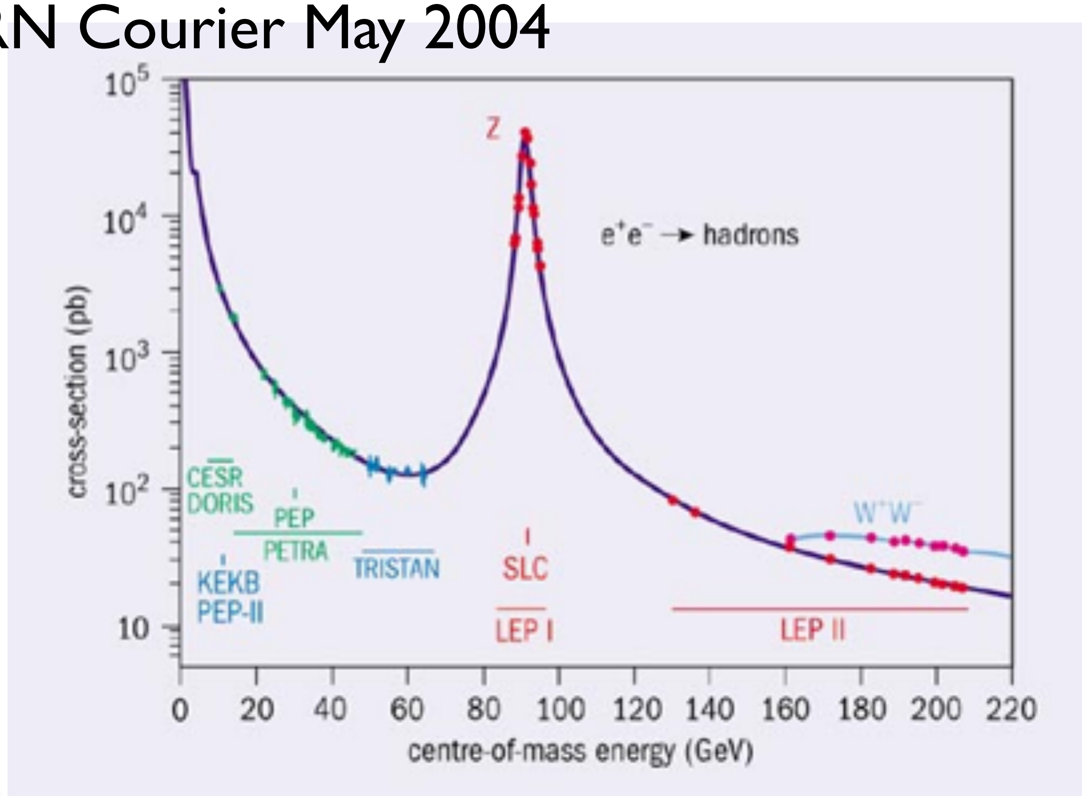
Challenging topic!

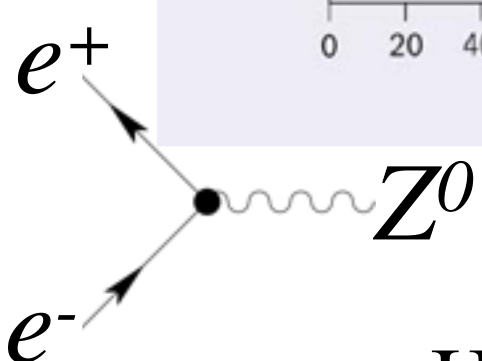


W/Z production at e^+e^-/hadron colliders

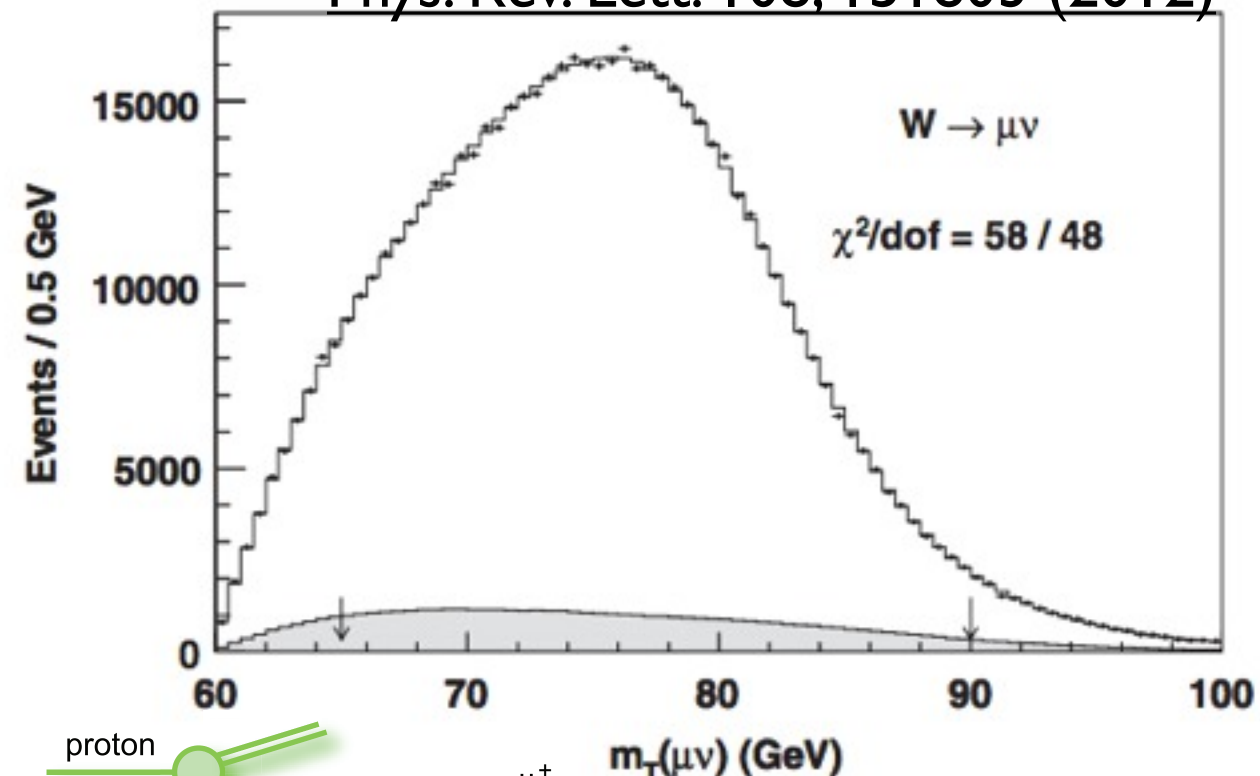
- s-channel annihilation provides rich W/Z bosons

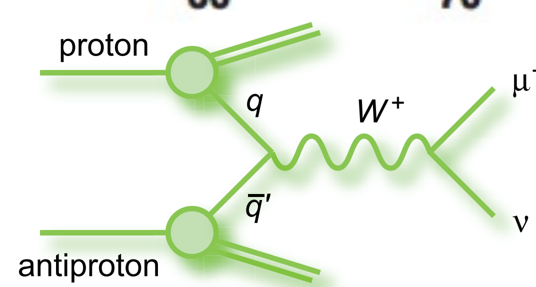
CERN Courier May 2004





CDF Collaboration,
Phys. Rev. Lett. 108, 151803 (2012)



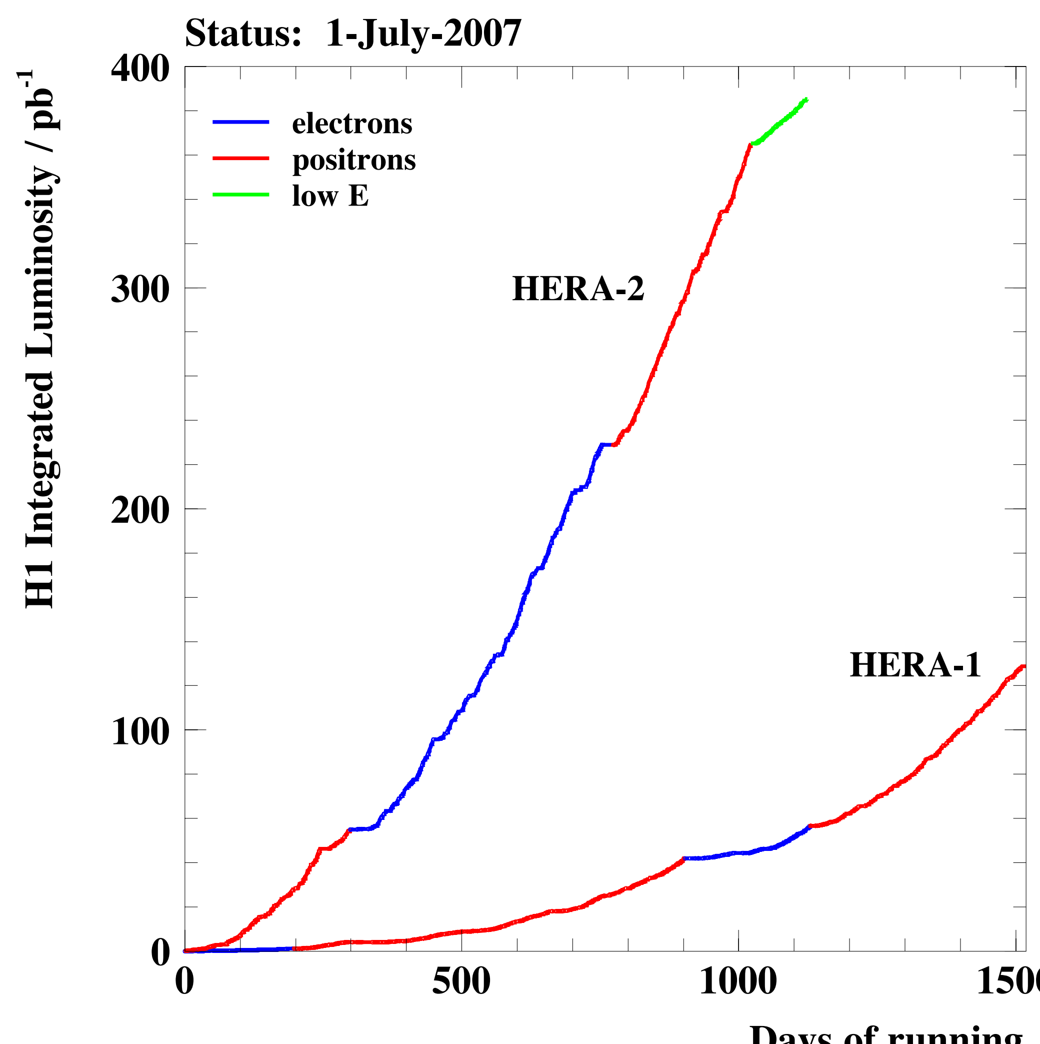


- ⇔ HERA *ep* collision: only from lepton/quark line (conservation of L and B numbers)
  → small cross section

- Background for physics beyond the SM

HERA

- World only electron-proton collider at DESY
- Operated: 1992-2007
- Center-of-mass energy: 318GeV
  - proton:920GeV
  - electron(positron):27.5GeV
- Recorded integrated luminosity: ~0.5fb^{-1} per experiment



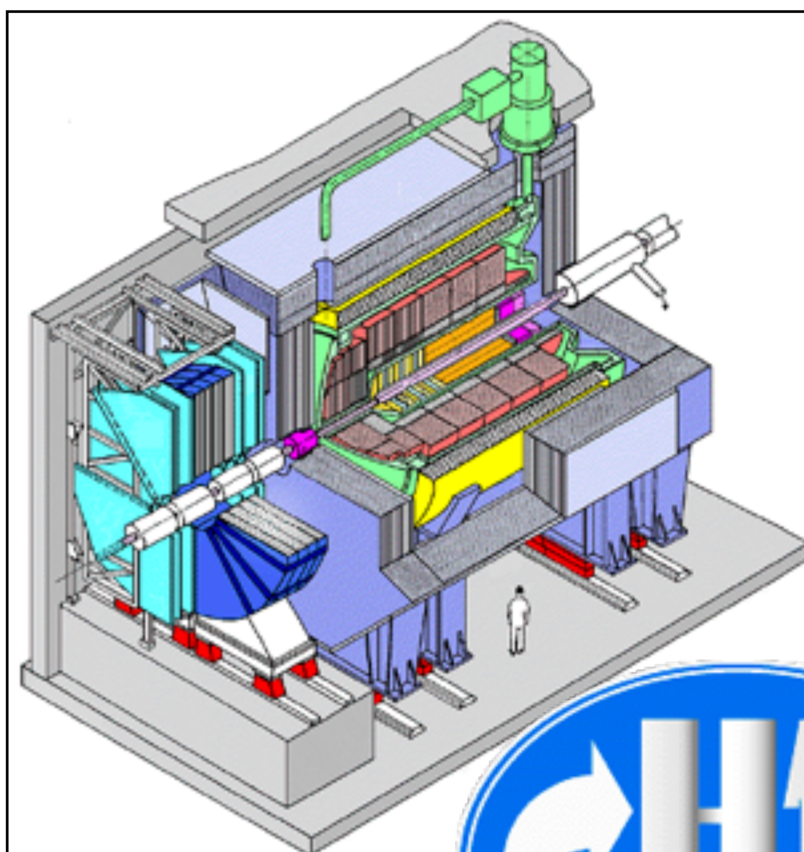
H1 and ZEUS detectors

- Two general purpose detectors, H1 and ZEUS are constructed at HERA

H1 detector

High resolution EM calorimeter using LAr

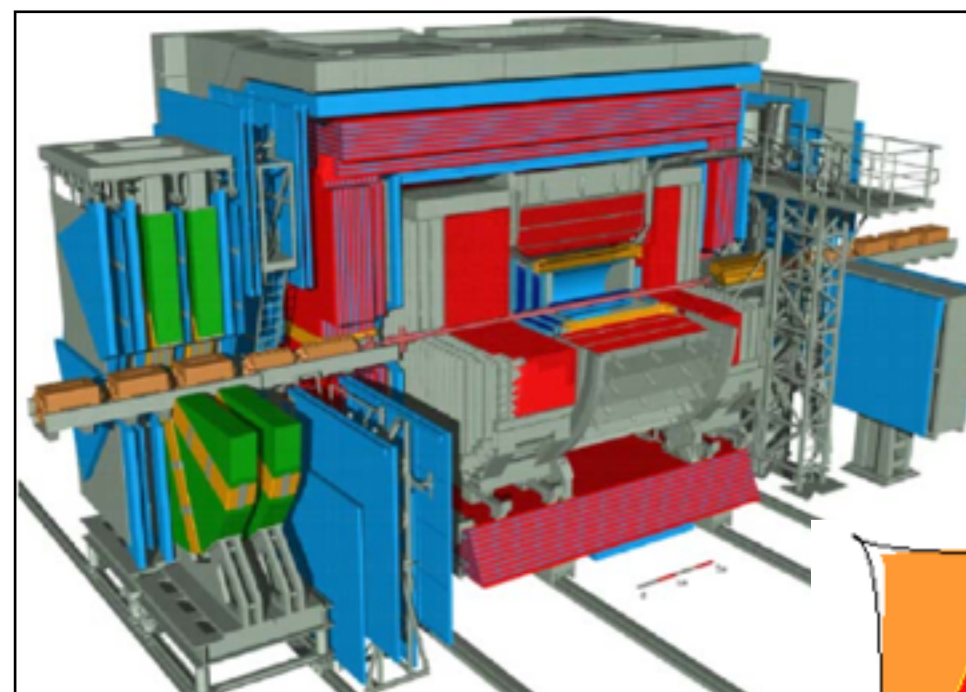
- electron $\sigma(E)/E = 0.11/\sqrt{E}$
- hadrons $\sigma(E)/E \sim 0.50/\sqrt{E}$



ZEUS detector

High resolution hadron calorimeter using Uranium absorber

- electron $\sigma(E)/E = 0.18/\sqrt{E}$
- hadrons $\sigma(E)/E = 0.35/\sqrt{E}$



W production at HERA

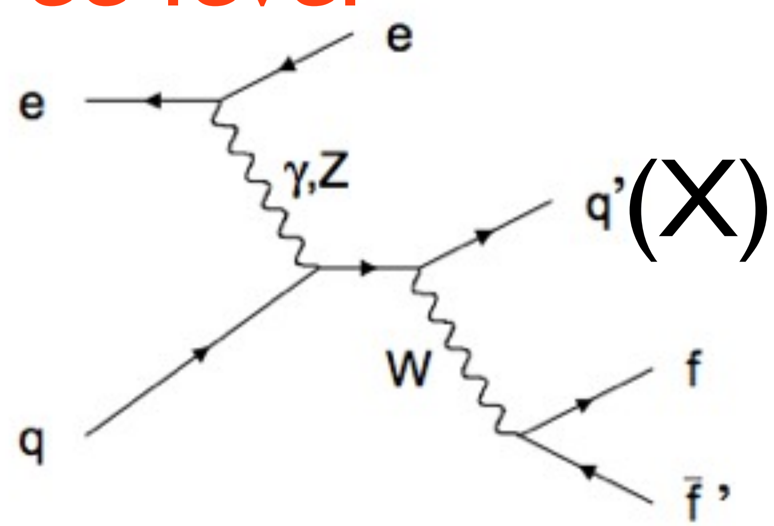
JHEP 1003 (2010) 035

Starategy

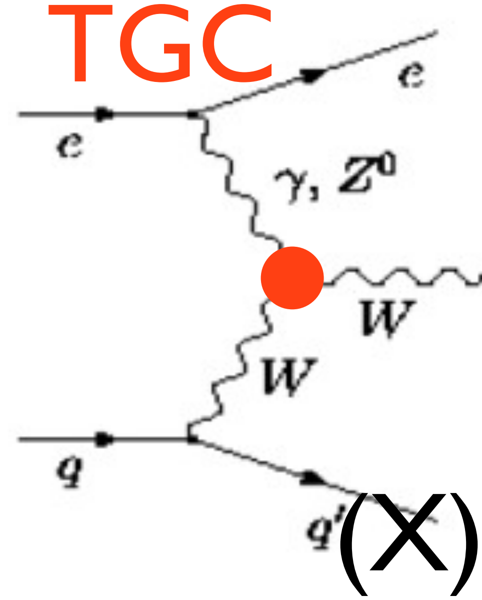
- SM cross section: **1.26 pb**
- **~1fb^{-1}** data collected with H1 and ZEUS
- High p_T **isolated lepton** (decay branch of W→lν is ~20%)
  - lepton p_T>10GeV, 15°<θ_l<120°, isolation: D(l; jet)>1.0 & D(l; track)>0.5
- High **missing transverse momentum, p_T**
  - ensure high missing p_T, p_T measured in calorimeter, $p_{T,calo}$>12GeV
- Contributions of **new physics**:
  - rare TGC (triple gauge coupling);
  - FCNC (flavor changing neutral current) process of single top;

  can enhance this mode at higher p_T^X (p_T of additional hadron, X)

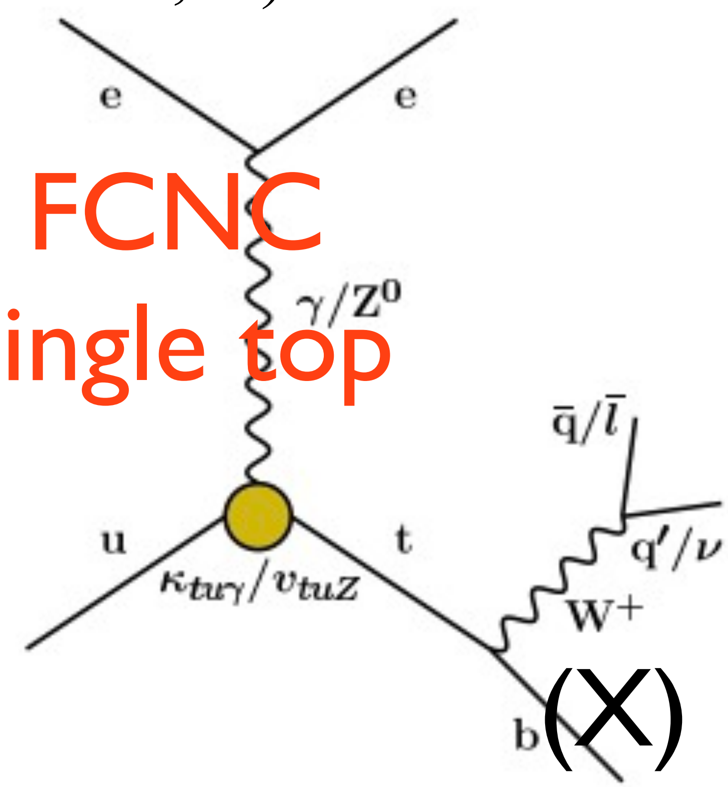
tree level



anormalous TGC



FCNC single top

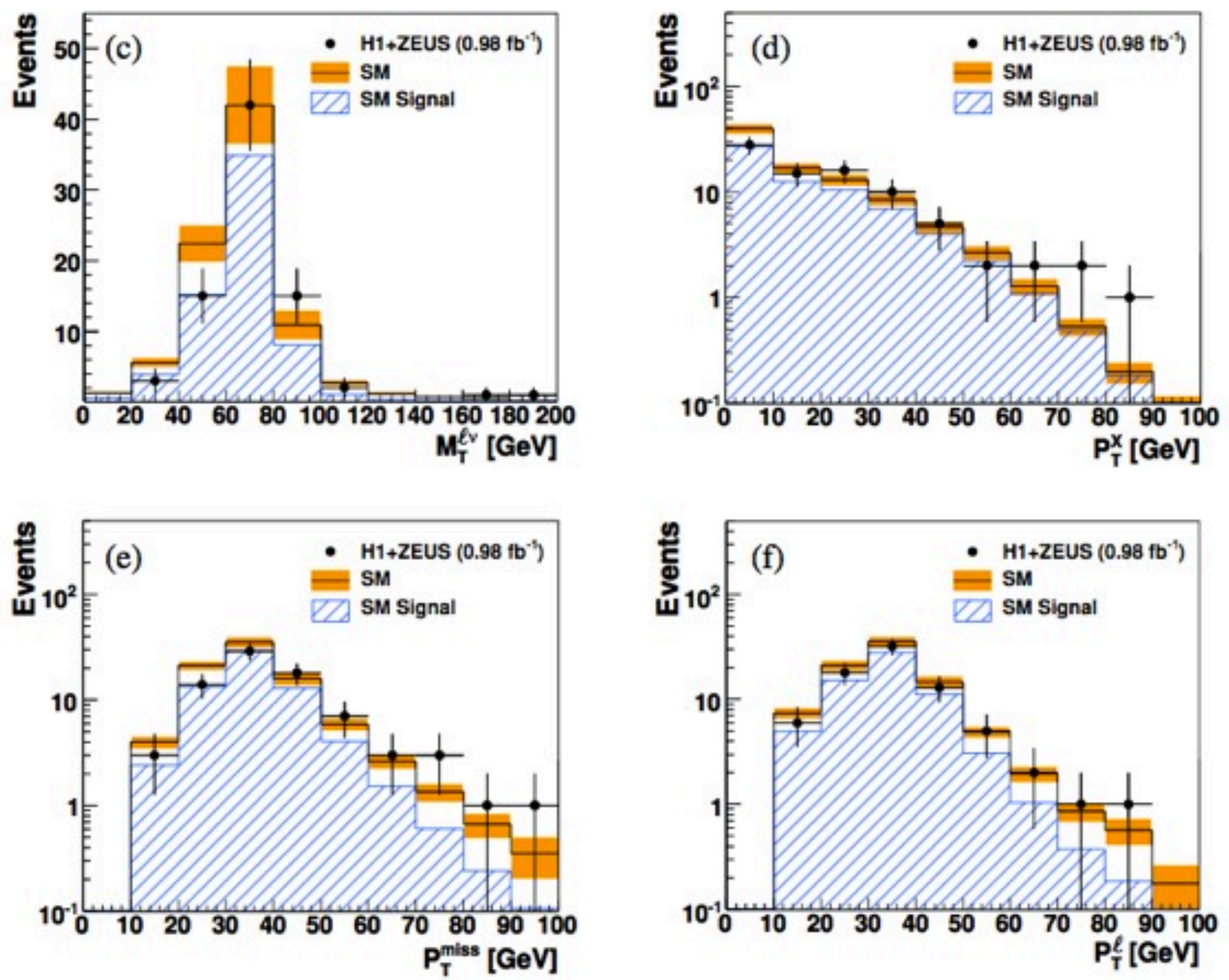


Results

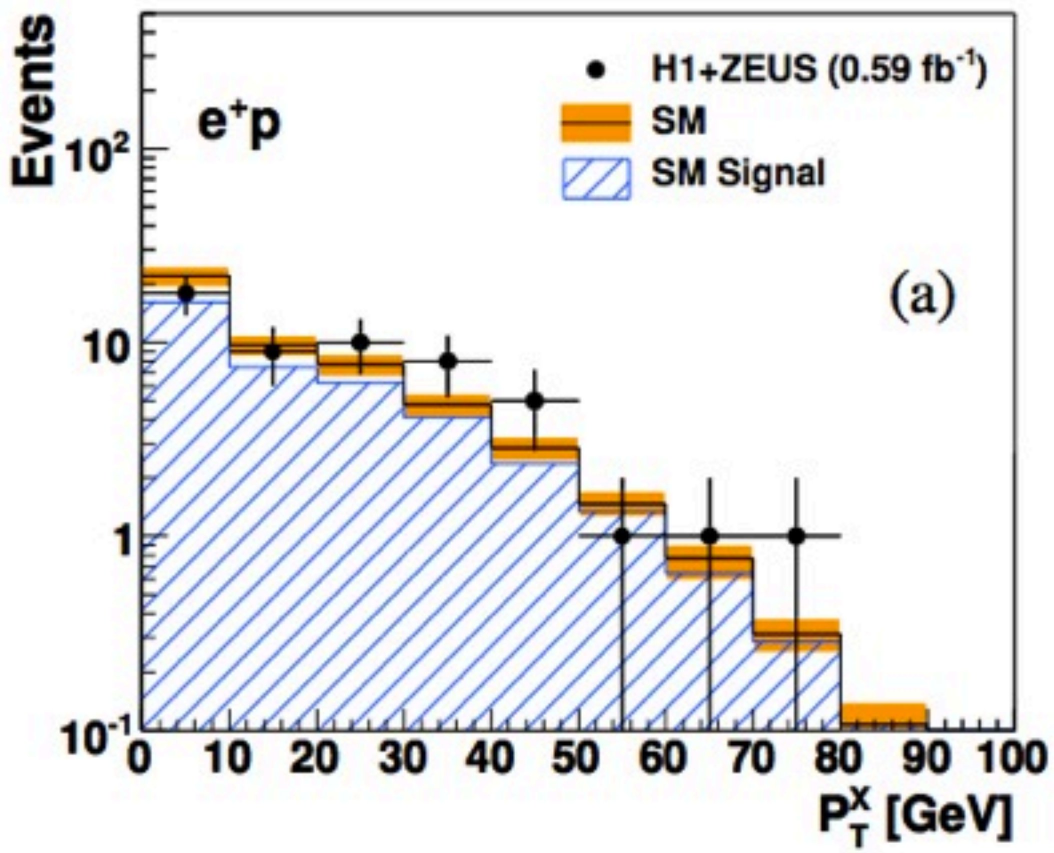
- 81 events are observed while 87.8±11.0 expected
-

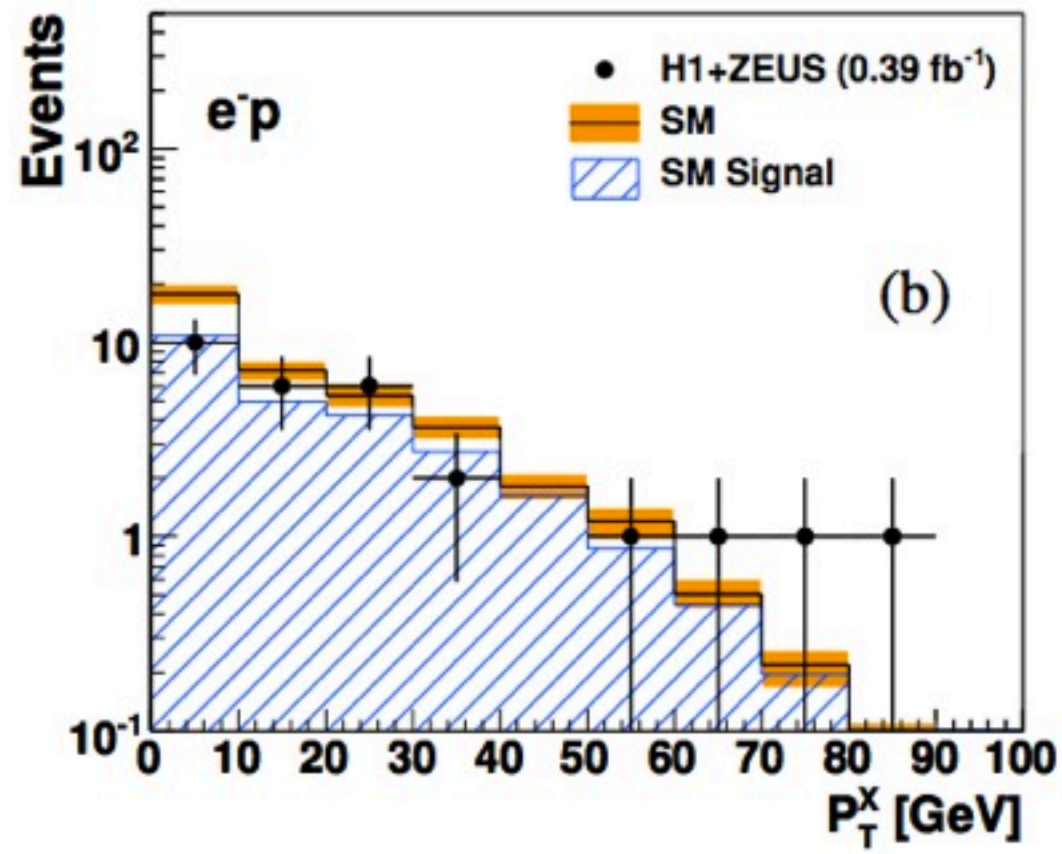
	$W \to e\nu$	$W \to \mu\nu$
Selection acceptance by MC	~30%	~10%
Purity of $W \to l\nu$	~70%	~90%

- Observed cross section: $\sigma\left(ep \to eW^{\pm}X\right) = 1.06 \pm 0.16\,(\text{stat.}) \pm 0.07\,(\text{syst.})\,\text{pb.}$ in good agreement with the SM prediction of 1.26 ± 0.19pb



H1+ZEUS combination: p_T^X disctribution

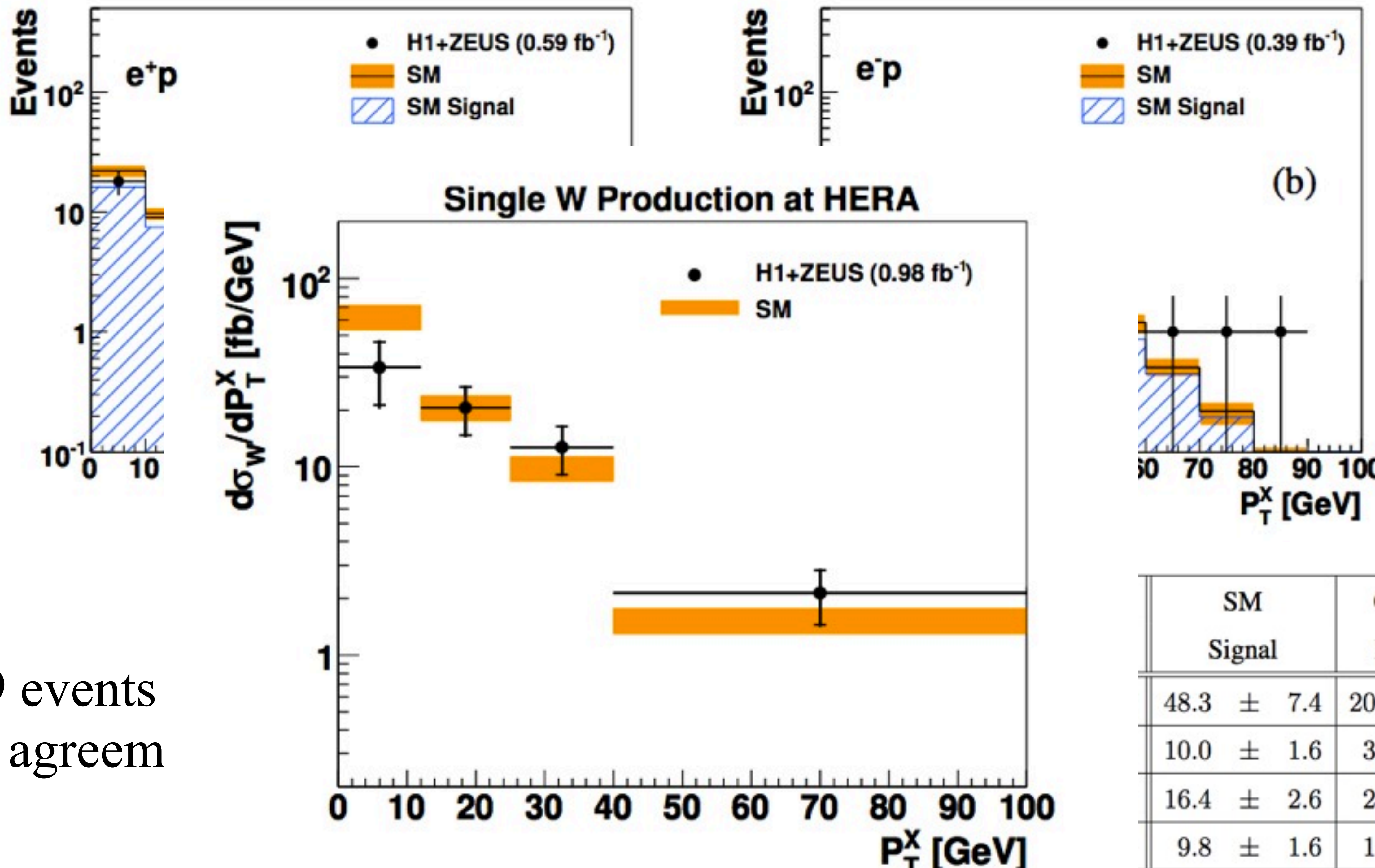




- 29 events in p_T^X>25GeV in agreement with the SM

H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	Total	81	87.8 ± 11.0	64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

H1+ZEUS combination: p_T^X disctribution



- 29 events
  in agreem

				SM Signal	Other SM Processes
				48.3 ± 7.4	20.9 ± 3.2
				10.0 ± 1.6	3.1 ± 0.7
				16.4 ± 2.6	2.2 ± 0.5
				9.8 ± 1.6	1.2 ± 0.3
				64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

Z production at HERA

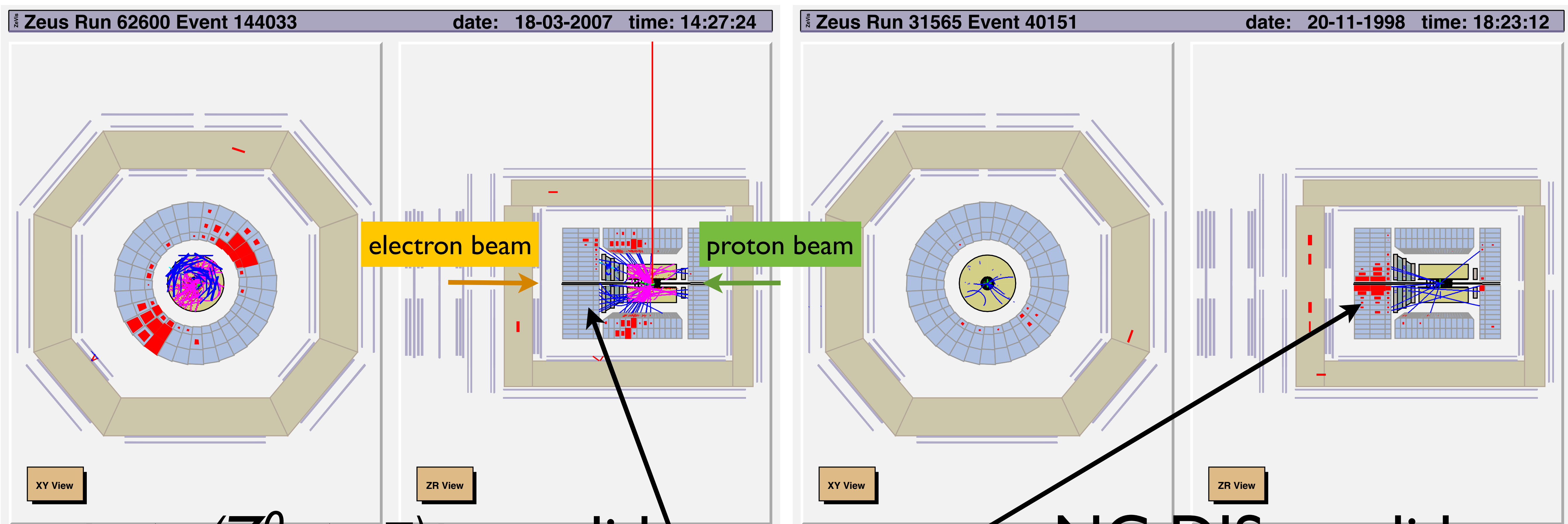
Phys. Lett. B 718 (2013) 915-921

Strategy

- SM cross section **0.4pb**
- ~$0.5fb^{-1}$ data collected with ZEUS
- Branching ratio of leptonic decay is too small : **~3%** for each
- **Hadronic decay** $Z \to q\bar{q}$(70% branching fraction)
  - require at least 2 jets with p_T>25GeV and $|\eta|<2.5$
  - two leading jets are back-to-back in x-y plane ($\Delta\varphi$>2.0)
  - invariant mass, m_{jets} is reconstructed by all jets with p_T>4GeV and $|\eta|<2.5$
- To suppress QCD multi-jet background, **(quasi-)elastic production**, $ep \to ep^{(*)}Z^0$, is selected (σ = **0.16pb**)
- Cross section is obtained by a **shape fit** on m_{jets} with signal(MC) + b.g.(Data-Driven) template

(Quasi-) elastic-interaction selection

- Require $\eta_{max} < 3.0$
  ※ η_{max} : maximum pseudo rapidity of energy deposit at calorimeter
  ※ Systematic uncertainty according to this cut is estimated by $\eta_{max}<(3.0\pm0.2)$
- Almost all inelastic events are removed by this



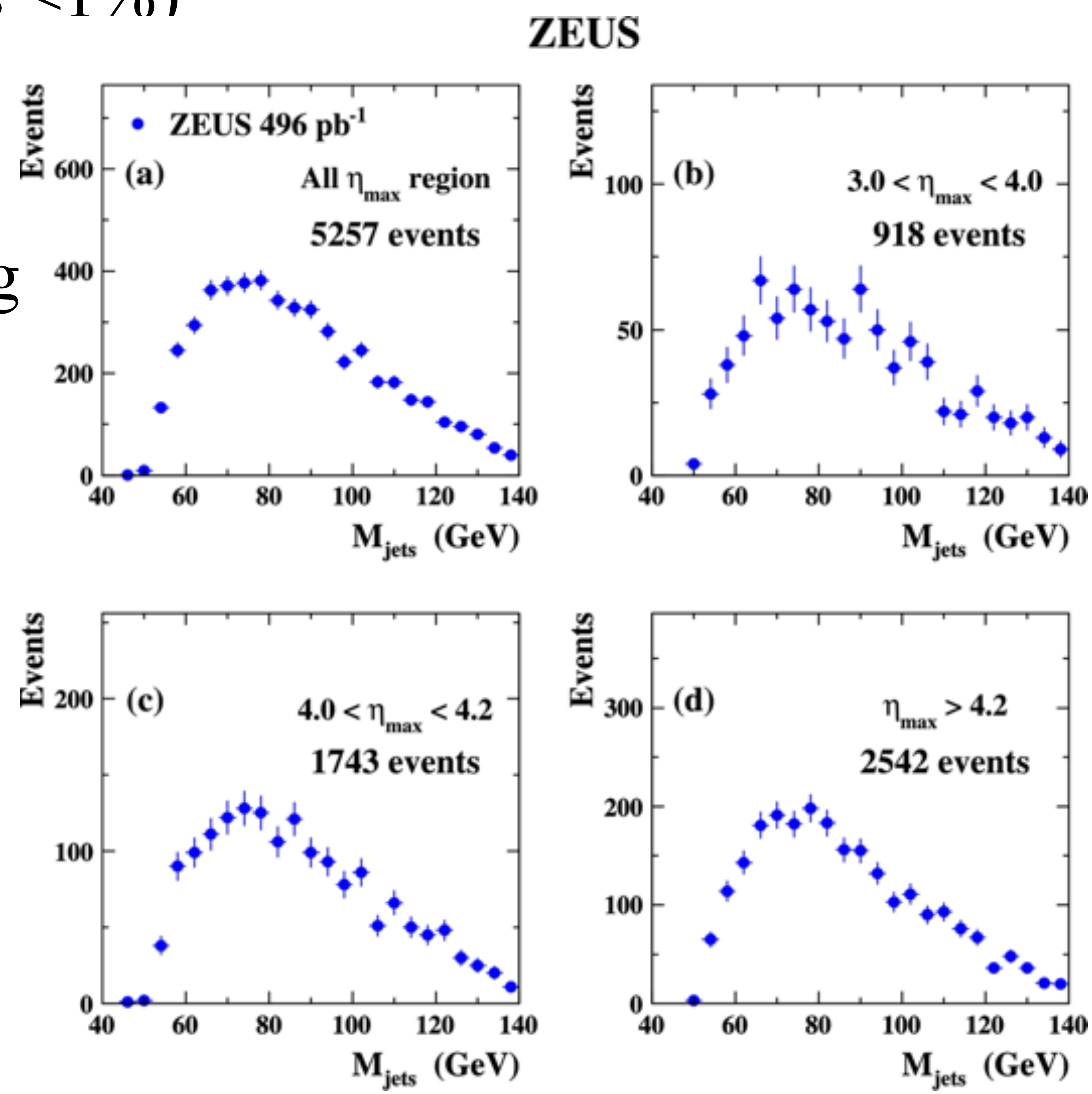
$ep \rightarrow e(Z^0 \rightarrow q\bar{q})p$ candidate
$\eta_{max}=1.24$

NC DIS candidate
$\eta_{max}=4.03$

Small η_{max} implies beam proton is not broken up after the collision

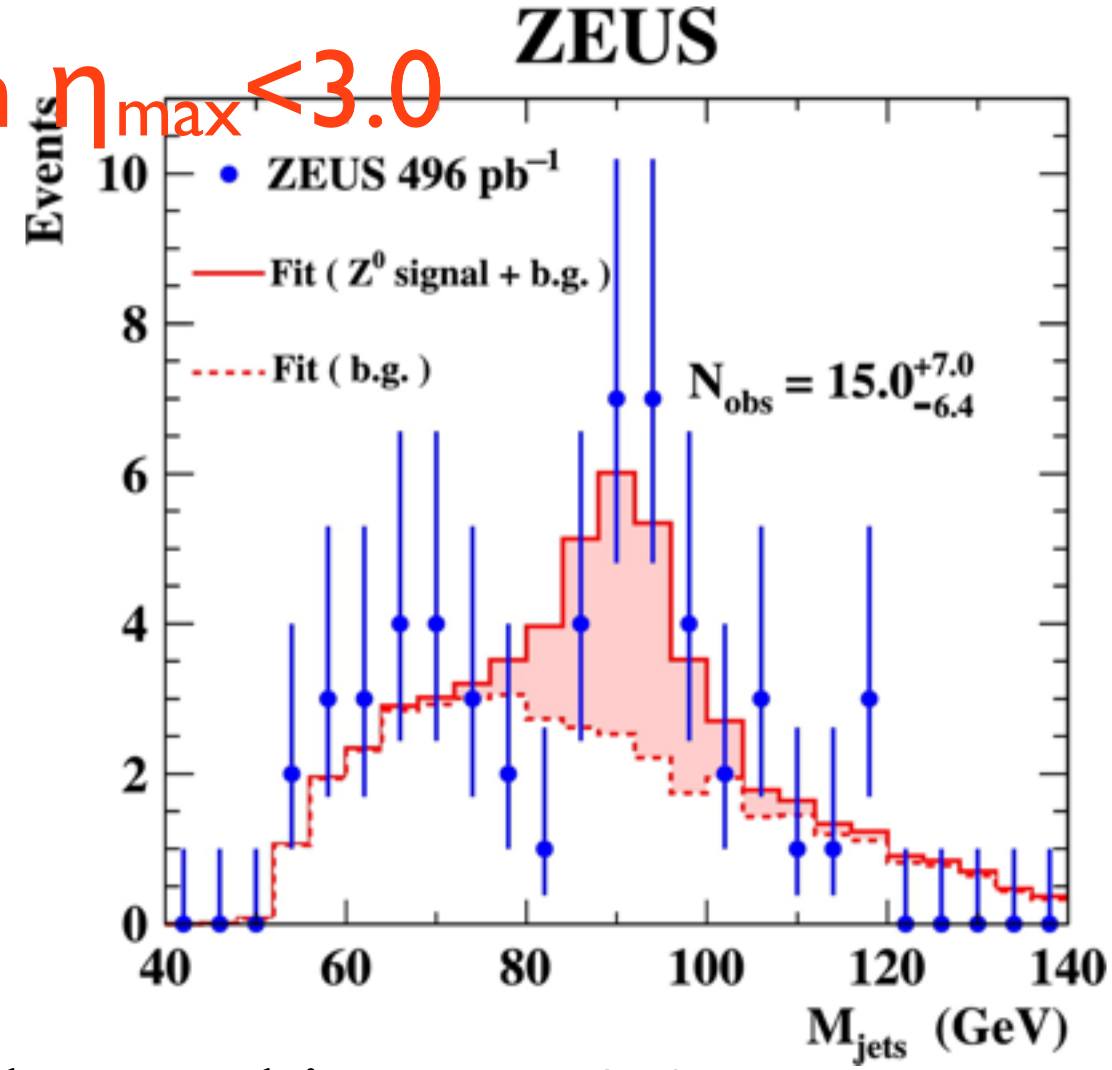
Background shape template

- No η_{max} dependency is found on m_{jets} distributions
- Use $\eta_{max} > 3.0$ region as a background template (signal contamination is <1%)
- Systematic error on b.g. shape template is estimated by performing the fit with several η_{max} slices as a b.g. template



Fitting result

m_{jets} in η_{max}<3.0



- 55events are observed in η_{max}<3.0
- Maximum likelihood fit is performed and $15.0^{+7.0}_{-6.4}$ signals are observed
- Extracted cross section: $\sigma\left(ep \rightarrow eZ^0 p^{(*)}\right) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})\,\text{pb}$ in agreement with the SM (0.16pb).
  First measurement of real Z cross section in ep collisions!

Summary

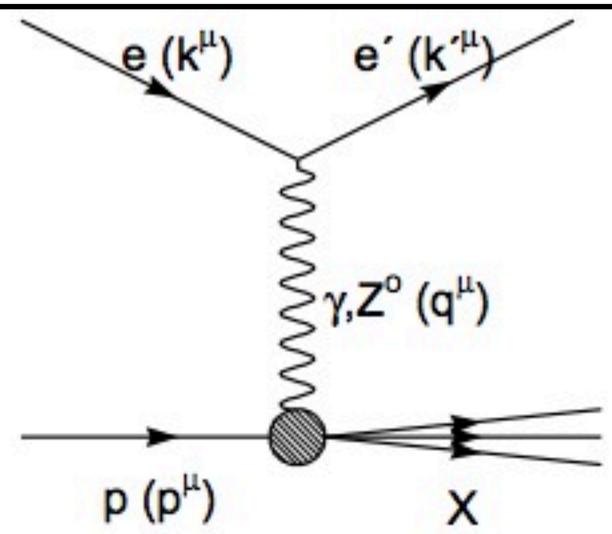
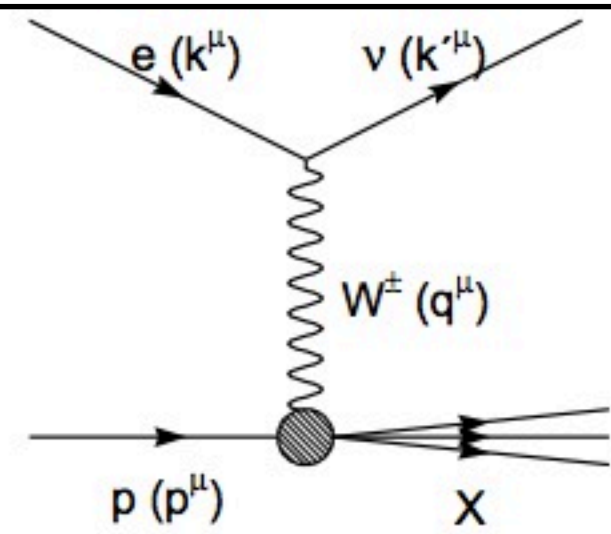
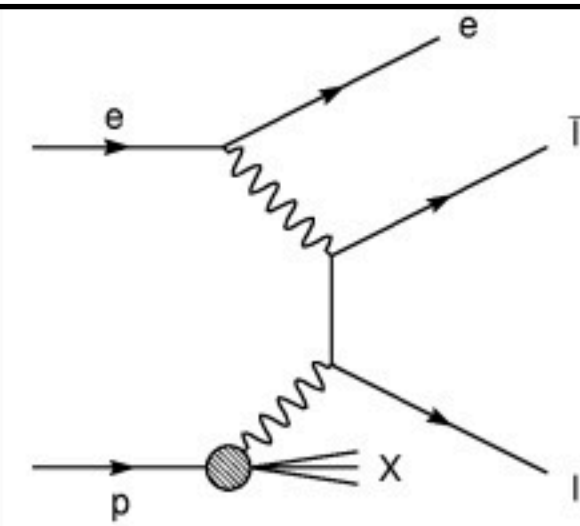
- Measurements of cross sections of W and Z boson in *ep* collisions have been performed
- Important to test the Standard Model (SM) and as background processes for physics beyond the SM
- Cross sections are expected to be very small : challenging topic
- Total W boson cross section :
  $\sigma\left(ep \to eW^{\pm}X\right) = 1.06 \pm 0.16\,(\text{stat.}) \pm 0.07\,(\text{syst.})\,\text{pb.}$
  in agreement with the SM : 1.26 pb.
  - H1-ZEUS combined ~1fb^{-1}
  - Searched in events with isolated lepton and missing transverse momentum
- Z boson cross section in (quasi-)elastic scattering, $ep \to eZ^0 p^{(*)}$:
  $\sigma\left(ep \to eZ^0 p^{(*)}\right) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})\,\text{pb.}$
  in agreement with the SM : 0.16 pb.
  - ZEUS data ~0.5fb^{-1}
  - Searched in $Z^0 \to$hadrons events
  - This is the first measurement of Z^0 cross section in *ep* collisions!

[redacted]

SM prediction of the real W and Z production

- U. Baur, J. A. Vermaseren and D. Zeppenfeld, Nucl. Phys. B375 (1992) 3.
- EPVEC: Monte-Carlo simulated events
  - to **correct the instrumental effects**
  - to know **selection acceptance**
- Three categories to calculate cross section:
  - **(Quasi-)elastic process** : calculated by form factors and structure functions fitted directly to experimental data
  - **DIS**: calculated in the quark-parton model using a full set of leading-order Feynman diagrams.
  - **Resolved photoproduction** : parameterized using a photon structure function and is carefully matched to the DIS region
- Total cross section@NLO at HERA centre-of-mass energy: **1.26 pb** for W and **0.40 pb** for Z
- ~15% uncertainty mainly PDF uncertainty

W production: Background components

NC DIS	CC DIS	Dilepton production
		
Real lepton + fake missing p_T	Real missing pT + mis-identified lepton	Real lepton + fake missing p_T
σ=8000pb	σ=40pb	σ=30pb

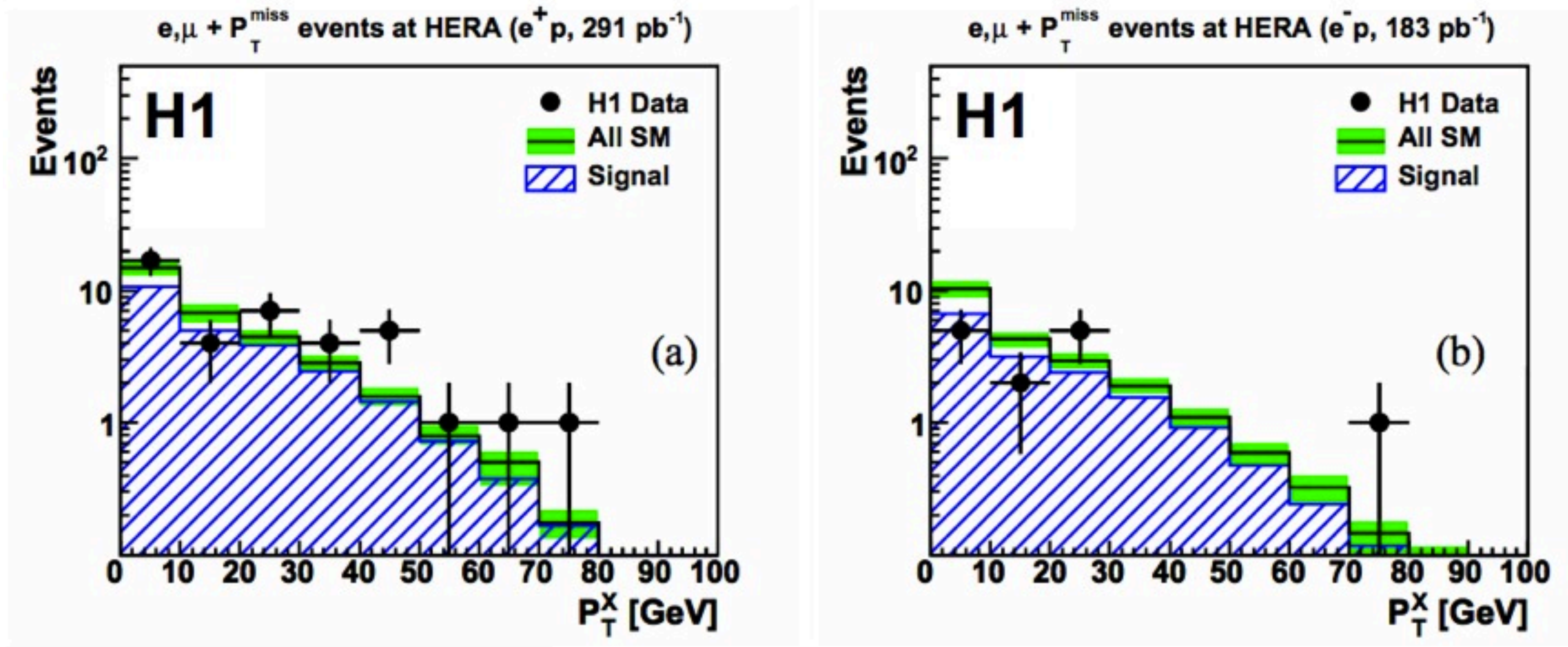
- These processes are simulated by MC
- To remove them, series of cuts are applied for example:
  - lepton and missing p_T should be back-to-back
  - measured longitudinal balance: $\delta_{miss}=2E_e^0 - \Sigma_i(E_i-p_{Z,i}) \in [5,\ 50]$ GeV
  (if only proton beam direction particles are un-detected, $\delta_{miss}=0$)

  etc.

W production: Event selection

H1+ZEUS Isolated Lepton $+P_T^{\text{miss}}$ Event Selection		
Channel	Electron	Muon
Basic Event Selection	$15^\circ < \theta_\ell < 120^\circ$	
	$P_T^\ell > 10$ GeV	
	$P_T^{\text{miss}} > 12$ GeV	
	$P_T^{\text{calo}} > 12$ GeV	
Lepton Isolation	$D(\ell;\text{jet}) > 1.0$	
	$D(e;\text{track}) > 0.5$ for $\theta_e > 45^\circ$	$D(\mu;\text{track}) > 0.5$
Background Rejection	$V_{\text{ap}}/V_{\text{p}} < 0.5$	
	$V_{\text{ap}}/V_{\text{p}} < 0.15$ for $P_T^e < 25$ GeV	$V_{\text{ap}}/V_{\text{p}} < 0.15$ for $P_T^{\text{calo}} < 25$ GeV
	$\Delta\phi_{e-X} < 160^\circ$	$\Delta\phi_{\mu-X} < 170^\circ$
	$5 < \delta_{\text{miss}} < 50$ GeV	–
	$\zeta_e^2 > 5000$ GeV^2 for $P_T^{\text{calo}} < 25$ GeV	–
	$M_T^{\ell\nu} > 10$ GeV	
	–	$P_T^X > 12$ GeV
	# electrons < 3	–

Excess in H1 only result



- 18events in p_T^X>25GeV
- 17/18events are observed in e^+p channel (~8 predicted)
- 2.4σ excess in e^+p

H1	1994-2007 $e^{\pm}p$ 474 pb^{-1}	Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	39	43.1 ± 6.0	30.3 ± 4.8	12.8 ± 3.4
	$P_T^X > 25$ GeV	10	7.5 ± 1.3	5.79 ± 0.99	1.71 ± 0.72
Muon	Total	14	11.0 ± 1.8	10.1 ± 1.7	0.88 ± 0.28
	$P_T^X > 25$ GeV	8	6.1 ± 1.0	5.64 ± 0.99	0.47 ± 0.15
Combined	Total	53	54.1 ± 7.4	40.4 ± 6.3	13.7 ± 3.5
	$P_T^X > 25$ GeV	18	13.6 ± 2.2	11.4 ± 1.9	2.18 ± 0.80

Eur.Phys.J.**C64** (2009) 251-271

W production: H1 only result

H1	1994-2007 e^+p 291 pb^{-1}	Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	28	25.6 ± 3.5	18.6 ± 2.9	6.9 ± 1.7
	$P_T^X > 25$ GeV	9	4.32 ± 0.71	3.56 ± 0.61	0.76 ± 0.32
Muon	Total	12	6.7 ± 1.1	6.1 ± 1.0	0.55 ± 0.18
	$P_T^X > 25$ GeV	8	3.70 ± 0.63	3.43 ± 0.60	0.28 ± 0.09
Combined	Total	40	32.3 ± 4.4	24.8 ± 3.9	7.5 ± 1.8
	$P_T^X > 25$ GeV	17	8.0 ± 1.3	7.0 ± 1.2	1.04 ± 0.37

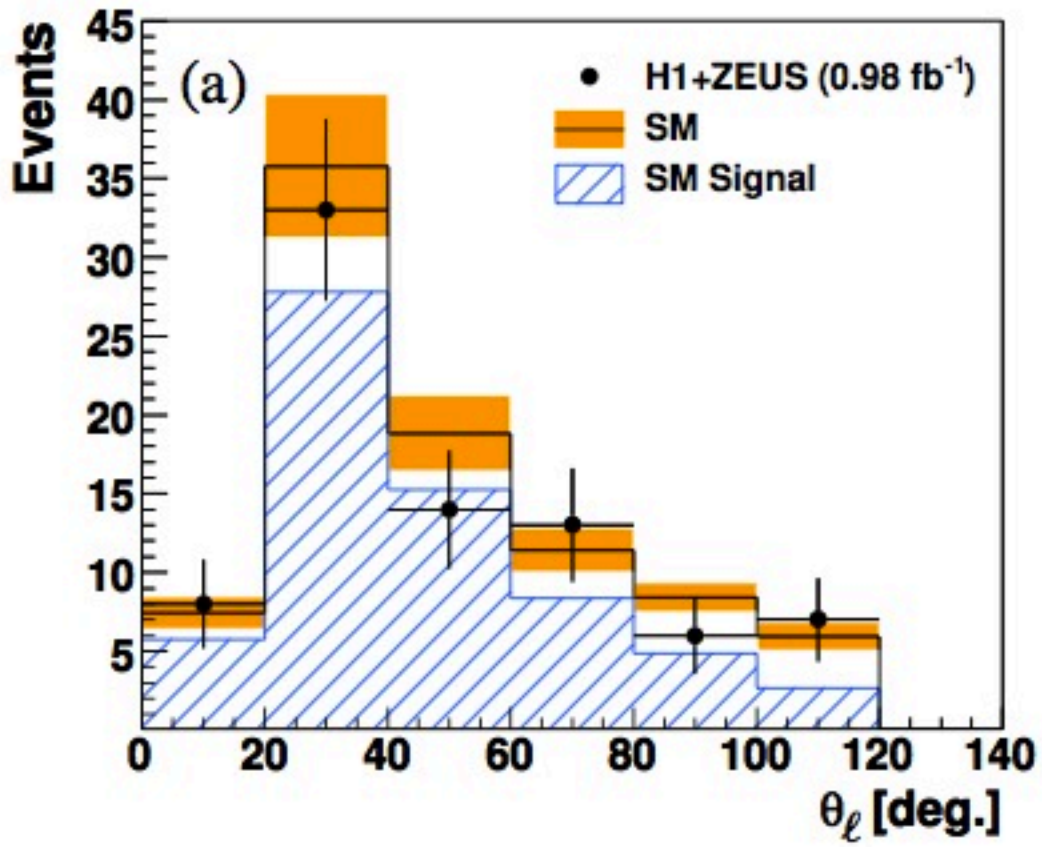
H1	1998-2006 e^-p 183 pb^{-1}	Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	11	17.5 ± 2.7	11.6 ± 1.8	5.9 ± 1.9
	$P_T^X > 25$ GeV	1	3.18 ± 0.59	2.23 ± 0.38	0.95 ± 0.41
Muon	Total	2	4.29 ± 0.69	3.96 ± 0.66	0.33 ± 0.11
	$P_T^X > 25$ GeV	0	2.40 ± 0.41	2.22 ± 0.39	0.19 ± 0.06
Combined	Total	13	21.8 ± 3.1	15.6 ± 2.4	6.2 ± 1.9
	$P_T^X > 25$ GeV	1	5.58 ± 0.91	4.45 ± 0.75	1.14 ± 0.44

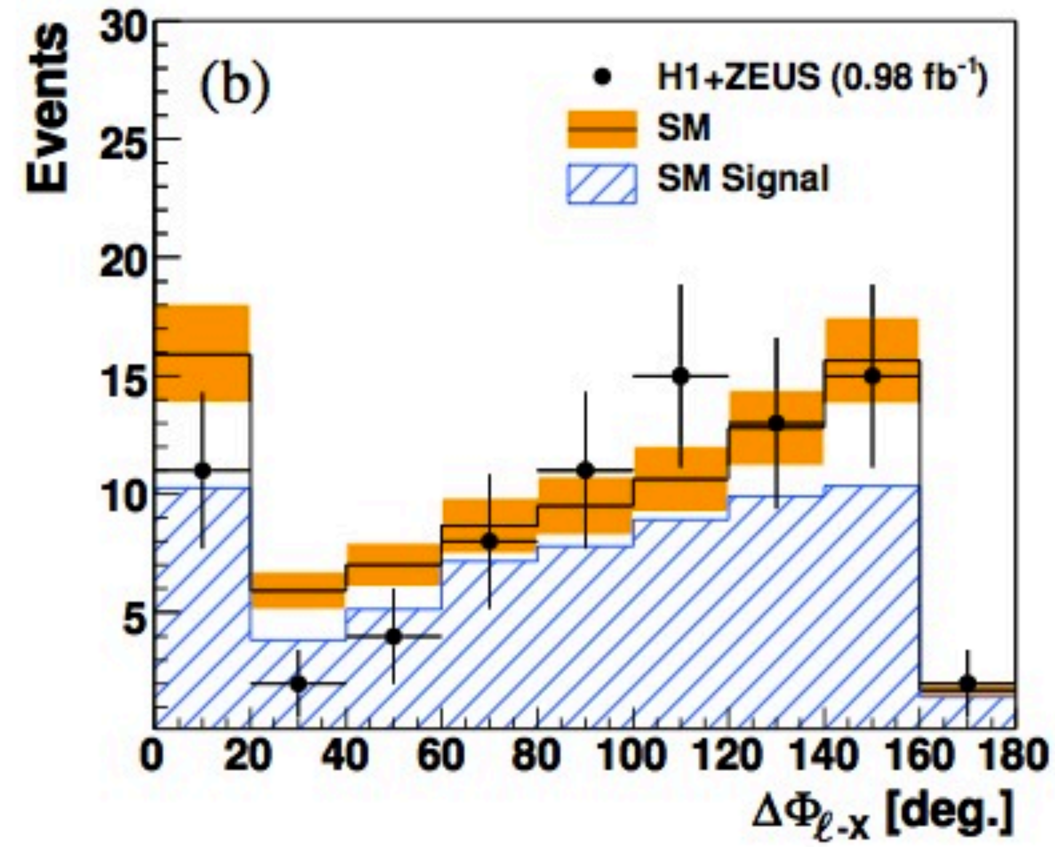
W production: H1 + ZEUS

H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	37	38.6 ± 4.7	28.9 ± 4.4	9.7 ± 1.4
	$P_T^X > 25$ GeV	12	7.4 ± 1.0	6.0 ± 0.9	1.5 ± 0.3
Muon	Total	16	11.2 ± 1.6	9.9 ± 1.6	1.3 ± 0.3
	$P_T^X > 25$ GeV	11	6.6 ± 1.0	5.9 ± 0.9	0.8 ± 0.2
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4

H1+ZEUS 1998–2006 e^-p 0.39 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	24	30.6 ± 3.6	19.4 ± 3.0	11.2 ± 1.9
	$P_T^X > 25$ GeV	4	5.6 ± 0.8	4.0 ± 0.6	1.6 ± 0.4
Muon	Total	4	7.4 ± 1.1	6.6 ± 1.0	0.9 ± 0.3
	$P_T^X > 25$ GeV	2	4.3 ± 0.7	3.9 ± 0.6	0.4 ± 0.2
Combined	Total	28	38.0 ± 3.4	26.0 ± 3.4	12.0 ± 2.0
	$P_T^X > 25$ GeV	6	10.0 ± 1.3	7.9 ± 1.2	2.1 ± 0.5

W production: other plots





W production: systematic uncertainties

- Systematic uncertainties are considered individual for H1 and ZEUS, respectively.
  - CAL energy scale (EM and hadronic)
  - Muon momentum scale
  - Track reconstruction
  - Trigger
  - Luminosity
  - MC (theory) uncertainties

  etc.
- All systematics are treated as correlated
- Totally: 11% (ZEUS) and 12% (H1)

Z production: detailed event selection

- CAL ET trigger
- Cleaning cuts for cosmic and beam-gas background
- Jes defined by kt algorithm
  - At least 2jets with ET>25GeV, $|\eta|<2.0$. $\Delta\varphi j1j2>2$rad
  - Use all jets with ET>4GeV and $|\eta|<2.0$ for invariant mass calculation
  - Remove fit if it overlaps with e/γ within R<1.0
- At most 1 electron in detector
  - Ee>5GeV, isolation, track match if in tracking coverage
  - θe<80deg required
- No particles in rear directrion
  - ERCAL<2GeV
  - 50<E-pZ<64GeV

Z production: fitting procesure

Fit procedure

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

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

- **Poisson likelihood and nuisance parameter**

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

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

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

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

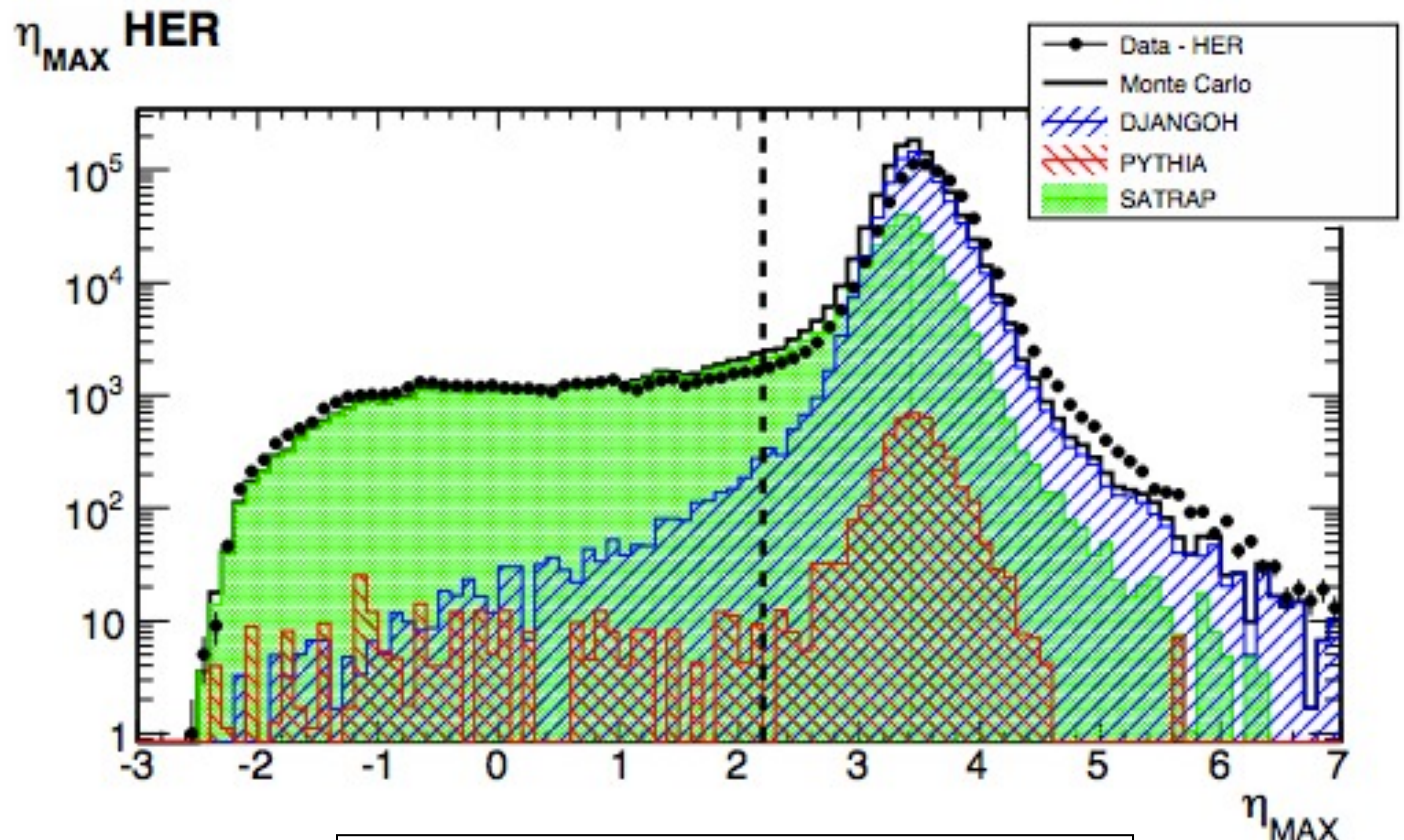
- **Minimize χ^2 to find best set of (a, b, ϵ)**

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

Z production: systematic uncertainties

- **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%

ηmax uncertainty



Data/MC on η_{max} agree within ±0.2 in study of diffractive cross section of DIS (DESY-THESIS-2012-008)