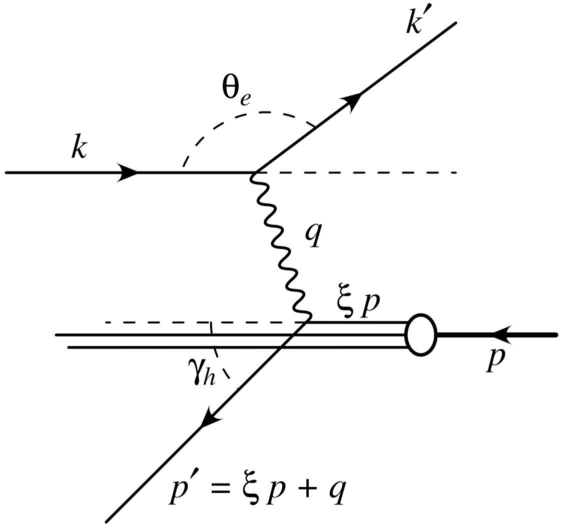
QCD Physics and HERA - Lecture II

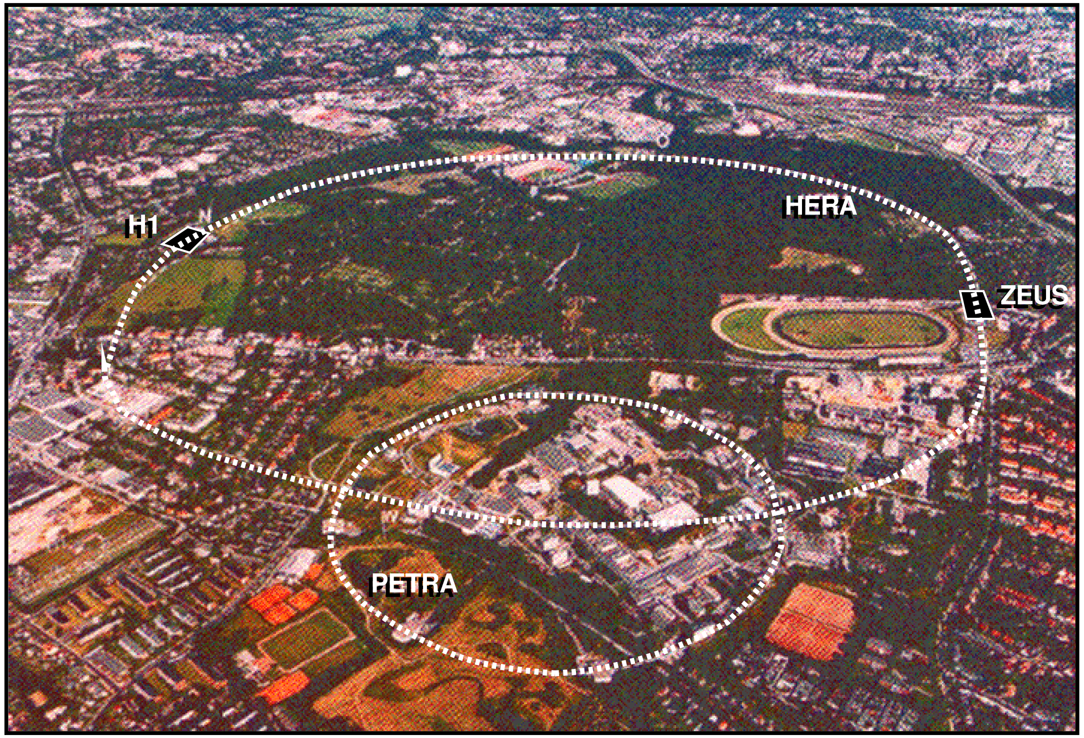
James Ferrando - ZEUS Collaboration.

8/2/2005.

- *QCD Introduction.*
- *HERA Accelerator.*
- *Experiments.*
- *Deep Inelastic Scattering.*
- *Proton Structure.*
- *Photon Structure.*
- α_S *measurements.*
- *Beyond the SM.*



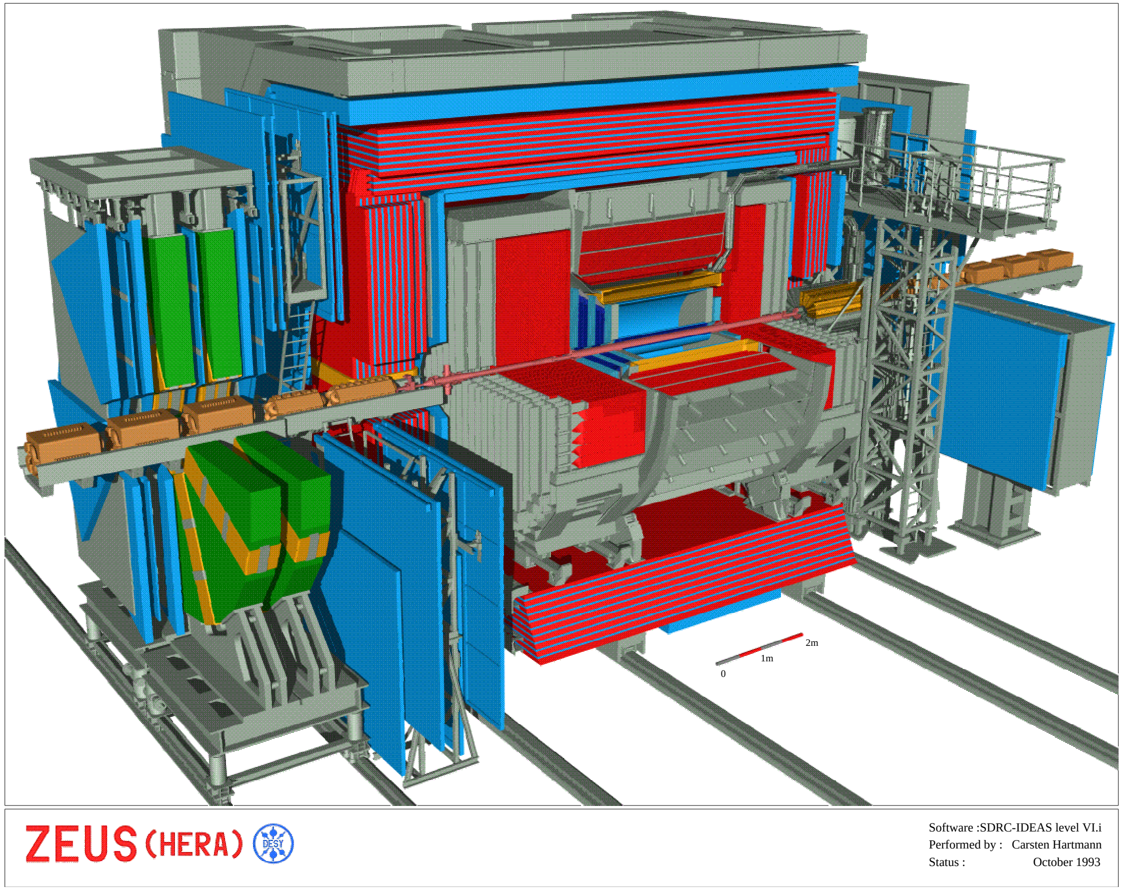
The HERA Accelerator



- *HERA is the only* ep *collider in existence.*
- *Collides 920 GeV protons and 27.52 GeV protons at the IRs of H1 and ZEUS.*
- *Offers an order of magnitude more COM energy than previous (fixed target) DIS experiments.*
- *Allows probing of very high* Q^2 *and low* x *regions of DIS.*
- *Also HERMES - A fixed target experiment studying nucleon spin structure.*

The HERA Experiments

- *ZEUS/H1 started taking data in 1992.*
- *ZEUS optimised for precision measurements of the hadronic final state.*
- *H1 optimised for precision measurements of the scattered lepton. (fixed target) DIS experiments.*
- *HERA experiments have published on a wide variety of topics.*
- *2003-2007 is HERA II running with luminosity upgrade + polarised leptons.*



Software :SDRC-IDEAS level VI.i
Performed by : Carsten Hartmann
Status : October 1993

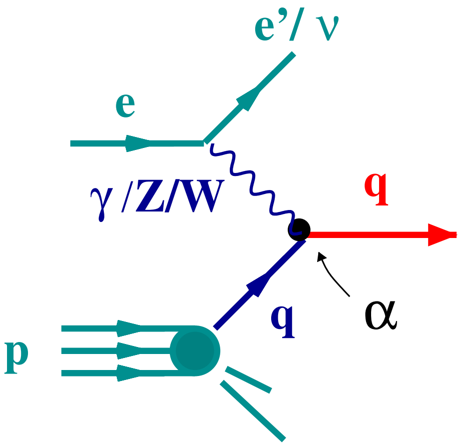
HERA Physics

A rich variety of physics topics is available for Study at HERA, Zeus Physics Working Groups:

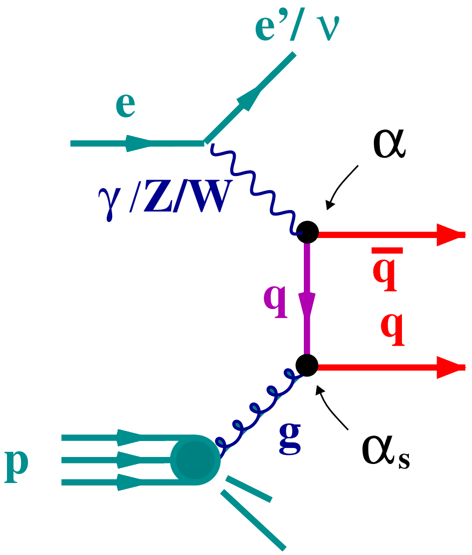
- High Q^2:
  - Structure of Proton.
  - Electroweak physics: NC/CC DIS cross section.
  - Rare Standard Model processes.
  - Searches for Physics beyond the standard model.
- Heavy Flavour:
  - Production of Charm, Beauty quarks.
  - Hadronisation of heavy quarks.
  - charm,beauty structure functions.
- QCD/Hadronic Final State:
  - Photon structure.
  - Jet production.
  - Particle production.
  - Measurements of α_{S}.
- Diffractive/Low x:
  - Study of events with a large rapidity gap.
  - Vector Meson production.

Deep Inelastic Scattering

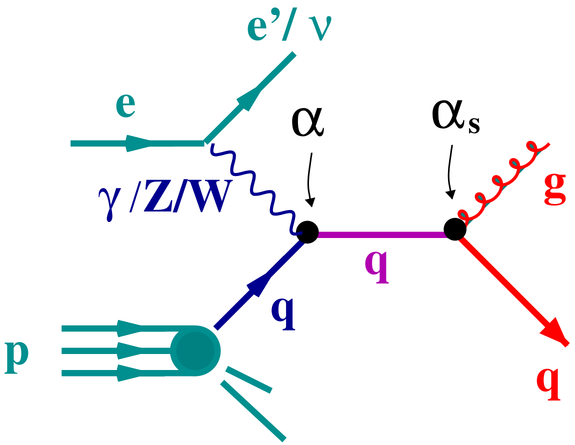
- *DIS of leptons on nucleons has been an important tool for understanding nucleon structure and many elements of the SM.*
- *At HERA DIS processes are studied at* $\sqrt{s} \approx 320$ *GeV and* $Q^2 > M_W, M_Z$*.*
- *Unique tests of the SM and it's extensions are possible in this regime.*
- *Neutral and charged current interactions up to* $\alpha\alpha_S$ *:*



Quark-Parton Model

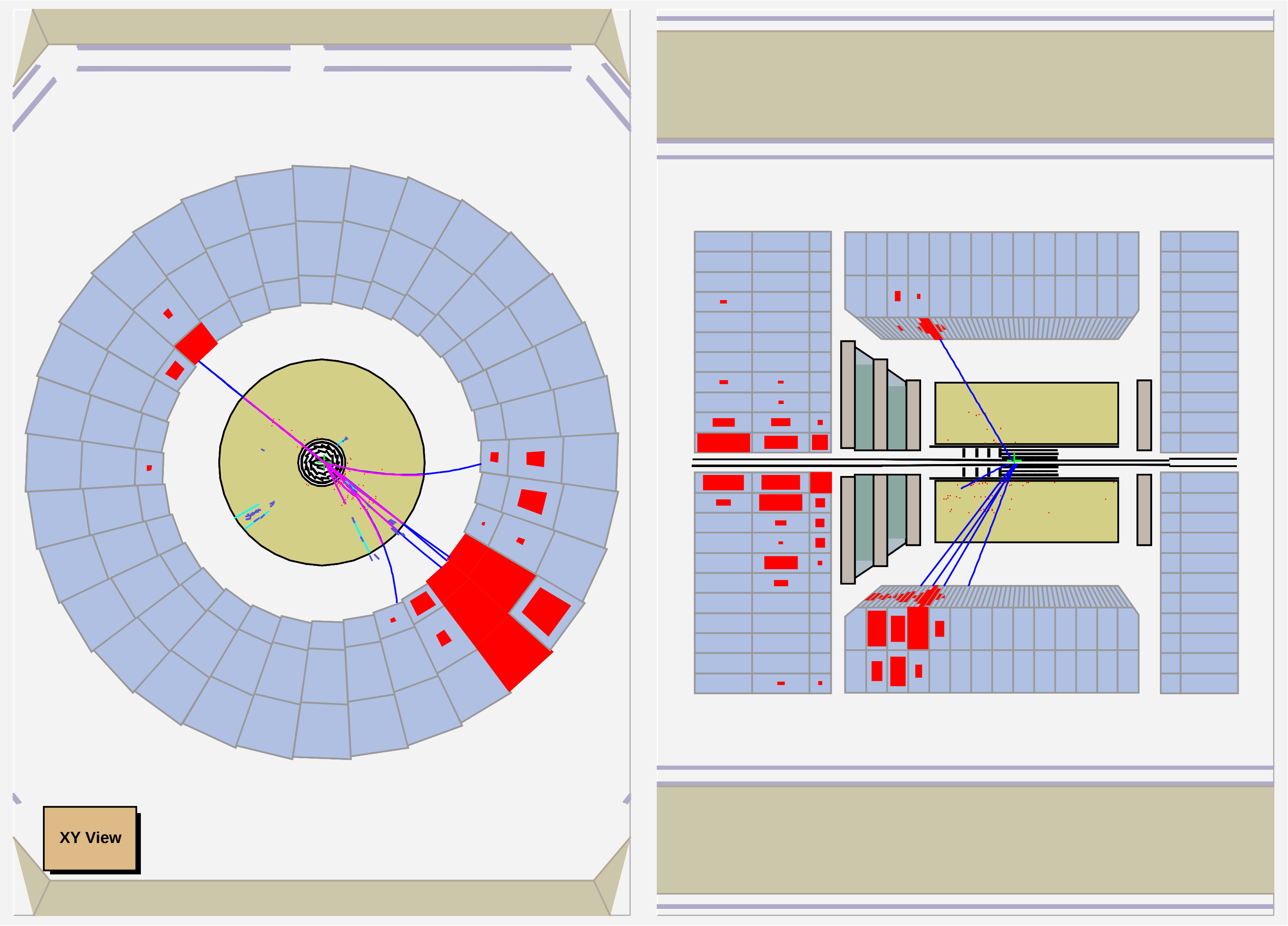


Boson-Gluon Fusion



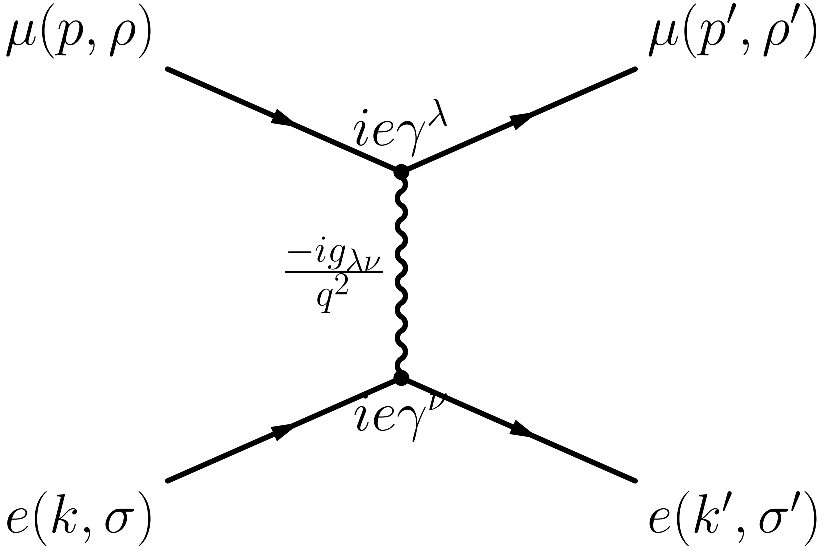
QCD Compton

Neutral Current Deep Inelastic Scattering Event



Calculating The Cross Section For NC DIS I

First consider elastic electron-muon scattering (neglect masses)



lepton currents:

$$j_e^\nu = ie\bar{u}(k',\sigma')\gamma^\nu u(k,\sigma) \tag{1}$$

$$j_\mu^\lambda = ie\bar{u}(p',\rho')\gamma^\lambda u(p',\rho') \tag{2}$$

propagator:

$$\frac{-ig_{\lambda\nu}}{q^2} \tag{3}$$

$$\mathcal{M} = i\frac{ee'}{q^2}[\bar{u}(k',\sigma')\gamma_\lambda u(k,\sigma)][\bar{u}(p',\rho')\lambda^\mu u(p,\rho)]$$

For the unpolarised cross section, the initial spin states must be averaged over.

$$\frac{1}{4}\sum_{\text{spins}}|\mathcal{M}|^2 = \frac{e^2 e'^2}{q^4}L_e^{\lambda\nu}L^\mu_{\lambda\nu}$$

Where: $L_e^{\lambda\nu} = 2(k'^\lambda k^\nu + k'^\nu k^\lambda - (k'.k)g^{\lambda\nu})$

Calculating The Cross Section For NC DIS II

Contraction of the leptonic tensors:

$$L_e^{\lambda\nu} = 2(k'^{\lambda}k^{\nu} + k'^{\nu}k^{\lambda} - (k'.k)g^{\lambda\nu}) \,,\, L^{\mu}_{\lambda\nu} = 2(p'_{\lambda}p_{\nu} + p'^{\nu}p_{\lambda} - (p'.p)g_{\lambda\nu})$$

$$L_e.L^{\mu} = 8[(k'.p')(k.p) + (k'.p)(k'.k)]$$

Can be rewritten in terms of the Mandelstam variables:

$$s = (k+p)^2 = (k'+p')^2,\ t = (k-k')^2 = (p'-p)^2,\ u = (k-p')^2 = (k'-p)^2$$

as $L_e.L^{\mu} = 2(s^2+u^2)$. *and substitute* $y = \frac{(p.q)}{(p.k)} = \frac{u}{s} + 1$

$$\frac{1}{4}\sum_{\text{spins}}|\mathcal{M}|^2 = \frac{e^2e'^2}{Q^4}2s^2[1+(1-y)^2]$$

Finally, putting in phase space and flux factor gives:

$$\frac{\mathrm{d}\sigma}{\mathrm{dy}} = \frac{e^2e'^2}{8\pi Q^4}[1+(1-y)^2]s$$

of course in this case $e = e'$ *so that:*

$$\frac{\mathrm{d}\sigma}{\mathrm{dy}} = \frac{2\pi\alpha^2}{Q^4}[1+(1-y)^2]s$$

One isotropic contribution from same handed spin directions.

(1-y) contribution from opposite spin directions.

Calculating The Cross Section For NC DIS III

Calculation for Electron - Muon scattering applies to electron quark scattering.However we change the variables, the quark contains a fraction x' of momentum of the proton. meaning that $p \longrightarrow x'p$ gives $s \longrightarrow x's$ so that the scattering cross section is:

$$\frac{\mathrm{d}\sigma}{\mathrm{dy}} = \frac{2\pi\alpha^2}{Q^4}[1 + (1 - y)^2]x'se_i^2$$

where e_i is the charge of the quark.

Now in the quark-parton model we can interpret lepton hadron scattering as the incoherent sum of lepton-parton scattering. so we can write the scattering cross section as:

$$\frac{\mathrm{d}\sigma}{\mathrm{dxdy}} = \frac{2\pi\alpha^2}{Q^4}[1 + (1 - y)^2]s\sum_i x'e_i^2 q_i(x)$$

where $q(x_i)$ is the probability that the struck quark i carries a fraction x of the hadron's momentum. The momentum distribution $xq_i(x)$ is called a parton distribution function. We can rewrite the double differential cross section, using $Q^2 = sxy$, as:

$$\frac{\mathrm{d}\sigma}{\mathrm{dxdQ^2}} = \frac{2\pi\alpha^2}{xQ^4}[1 + (1 - y)^2]\sum_i x'e_i^2 q_i(x)$$

Calculating The Cross Section For NC DIS IV

Compare quark-parton Model result to general formulae for lepton-hadron scattering.

$$\mathrm{d}\sigma \sim \mathrm{L}^{\mathrm{e}}_{\mu\nu} W^{\mu\nu}$$

where $W^{\mu\nu}$ *is the hadronic tensor analogous to the lepton tensor. It must have the general form:*

$$W^{\mu\nu} = -W_1 g^{\mu\nu} + \frac{W_2}{m^2} p^\mu p^\nu - i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta \frac{W_3}{2m^2} + \frac{W_4}{m^2} q^\mu q^\nu + \frac{W_5}{m^2}(p^\mu q^\nu + p^\nu q^\mu) + i(p^\mu q^\nu - p^\nu q^\mu)\frac{W_6}{2m^2}$$

$\epsilon^{\mu\nu\alpha\beta}$ *is the totally antisymmetric rank 2 tensor which is +1(-1) when* $\mu\nu\alpha\beta$ *is an even (odd) permutation of 0123 and 0 otherwise.*

The W_6 *term disappears for unpolarised scattering since* $L^{\mu\nu}$ *is antissymetric. For* γ *scattering the parity violating* W_3 *term can also be discarded.*

Calculating The Cross Section For NC DIS V

$$W^{\mu\nu} = -W_1 g^{\mu\nu} + \frac{W_2}{m^2} p^\mu p^\nu + \frac{W_4}{m^2} q^\mu q^\nu + \frac{W_5}{m^2}(p^\mu q^\nu + p^\nu q^\mu)$$

We can further simplify the hadronic tensor using conservation of current at the hadronic vertex:

$$q_\mu W^{\mu\nu} = q_\nu W^{\mu\nu} = 0$$

giving:

$$W_5 = -\frac{p.q}{q^2} W_2$$

and:

$$W_4 = \left(\frac{p.q}{q^2}\right)^2 W_2 + \frac{M^2}{q^2} W_1$$

So that:

$$W^{\mu\nu} = W_1 \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + W_2 \frac{1}{M^2} \left(p^\mu - \frac{p.q}{q^2} q^\mu\right) \left(p^\nu - \frac{p.q}{q^2} q^\nu\right)$$

Calculating The Cross Section For NC DIS VI

Following the calculation with this hadronic tensor (see e;g; Halzen and Martin) gives:

$$\frac{\mathrm{d}^2\sigma^{e^\pm p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{xQ^4}\left[y^2 xF_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

where

$F_1(x,Q^2) = MW_1(\nu,Q^2), \nu = (p.q)$

and

$F_2(x,Q^2) = \nu W_2(\nu,Q^2) = \frac{p.q}{M}W_2(x,Q^2).$

define:

$F_L = F_2 - 2xF_1$

then:

$$\frac{\mathrm{d}^2\sigma^{e^\pm p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[[1+(1-y)^2]F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

Predictions of QPM

Compare our general result to the quark parton model result:

$$\frac{\mathrm{d}^2\sigma^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[[1+(1-y)^2]F_2(x,Q^2) - y^2F_L(x,Q^2)\right]$$

$$\frac{\mathrm{d}\sigma}{\mathrm{dxdQ^2}} = \frac{2\pi\alpha^2}{xQ^4}[1+(1-y)^2]\sum_i x' e_i^2 q_i(x)$$

This implies that $F_2(x,Q^2) = \sum_i x' e_i^2 q_i(x)$ ***SCALING!***

Another prediction is the Callan-Gross relationship $F_L = 0$*:*

$$2xF_1(x) = F_2(x)$$

This is a consequence of the partons having spin 1/2.

Full cross section includes Parity Violating term,neglected in this calculation.

Proton structure Functions

- *Full expression for the double differential cross section for inclusive ep scattering:*

$$\frac{\mathrm{d}^2\sigma^{e^\pm p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2) - y^2F_L(x,Q^2)\right]\right](1+\delta_r(x,Q^2))$$

$Y_\pm = 1 \pm (1-y)^2$
F_L *is the Longitudinal Structure Function.*
xF_3 *is the parity violating term.*
δ_r *is the electroweak radiative correction.*

- *The structure function F_2 contains contributions from virtual photon and Z_0 exchange:*

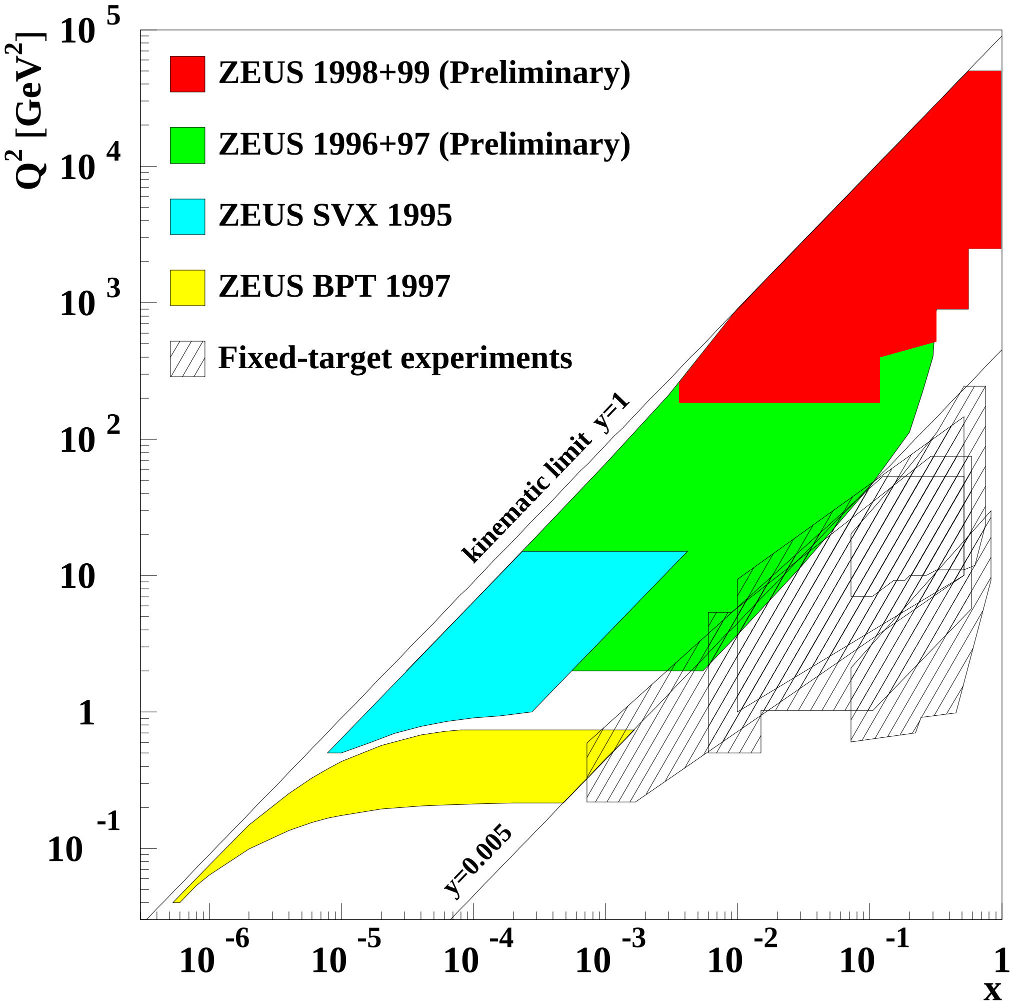
$$F_2 = F_2^{\mathrm{em}} + \frac{Q^2}{(Q^2+M_Z^2)}F_2^{\mathrm{int}} + \frac{Q^4}{(Q^2+M_Z^2)}F_2^{\mathrm{wk}} = F_2^{\mathrm{em}}(1+\Delta F_2)$$

F_2^{em} *is the contribution from the photon.*
F_2^{wk} *is the contribution from the Z_0.*
F_2^{int} *is the interference term.*

Kinematic Regions of Structure Function Measurements

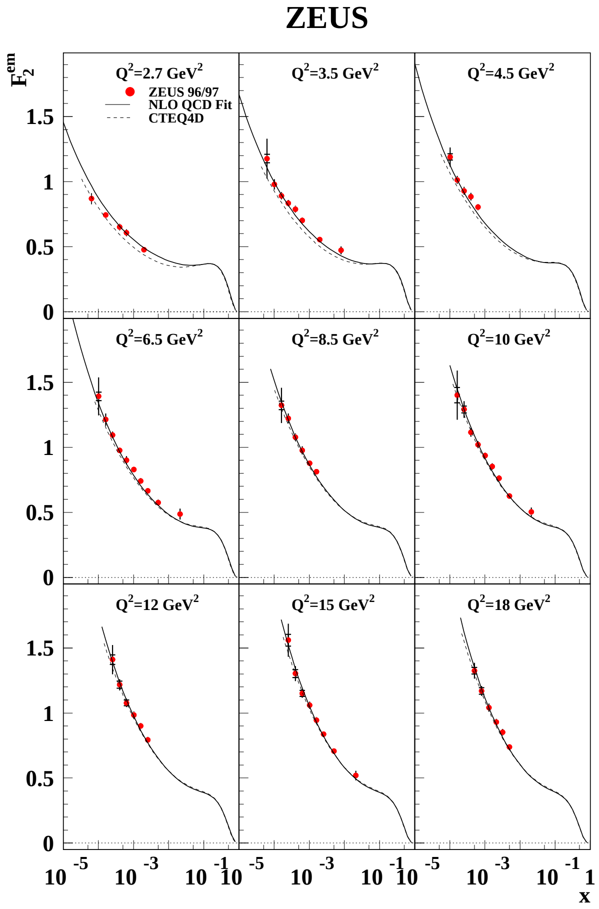
- *HERA: ZEUS, NC cross sections:* $x > 10^{-6}$ *and* $0.05 < Q^2 < 10^5$ GeV^2
- *Fixed Target*
  - *μ-induced F_2 from BCDMS, NMC, E665.*
  - *Deuterium-target data from NMC and E665.*
  - *NMC data on F_2^D/F_2^p*
  - *CCFR xF_3 data.*

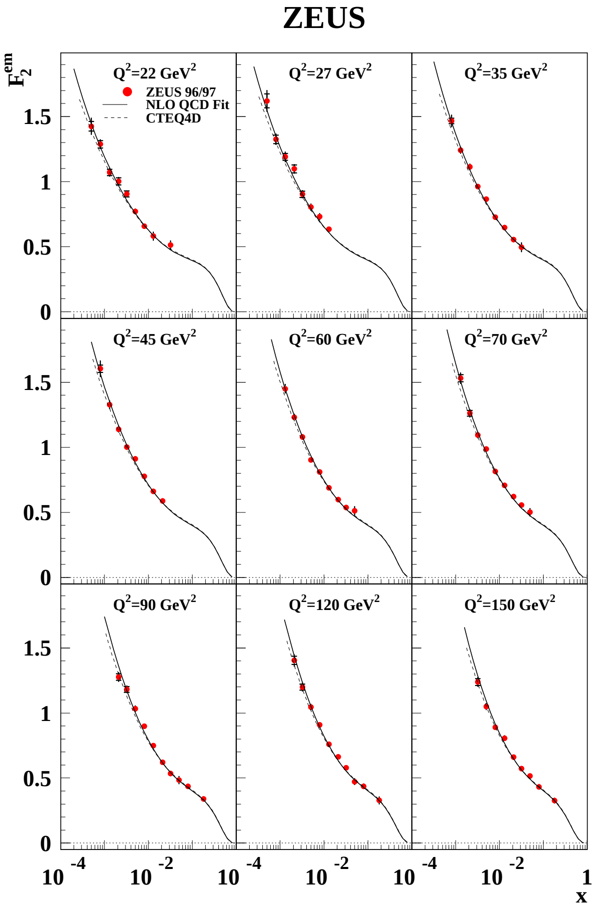
$x > 6.10^{-4}$ *and* $0.2 < Q^2 < 200$ GeV^2

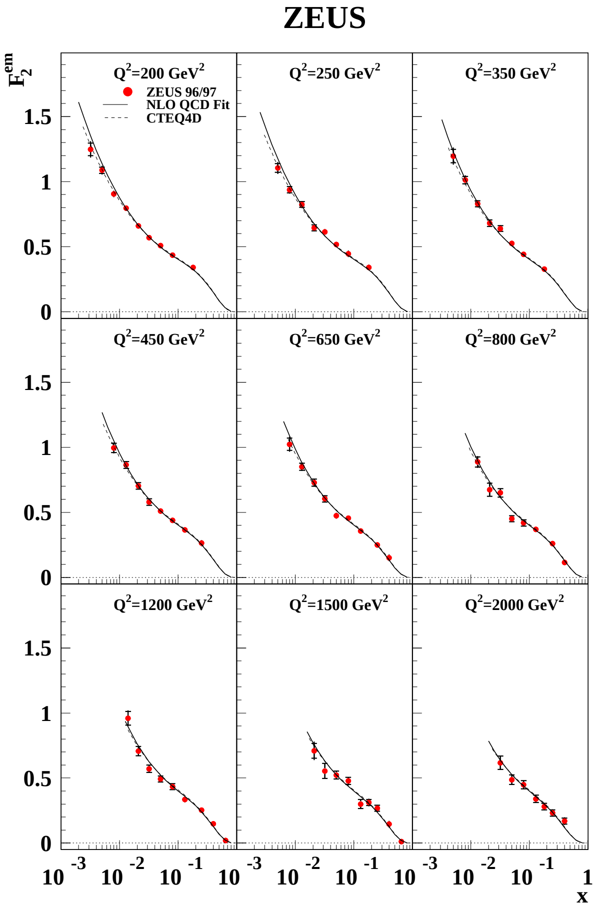


The Proton Structure Functions: F_2

Measurement of F_2 *for* $2.7 < Q^2 < 30000\mathrm{GeV}^2$ *and* 6×10^5 *with statistical and systematic uncertainties below 2% in most of the* (x, Q^2) *region covered.*



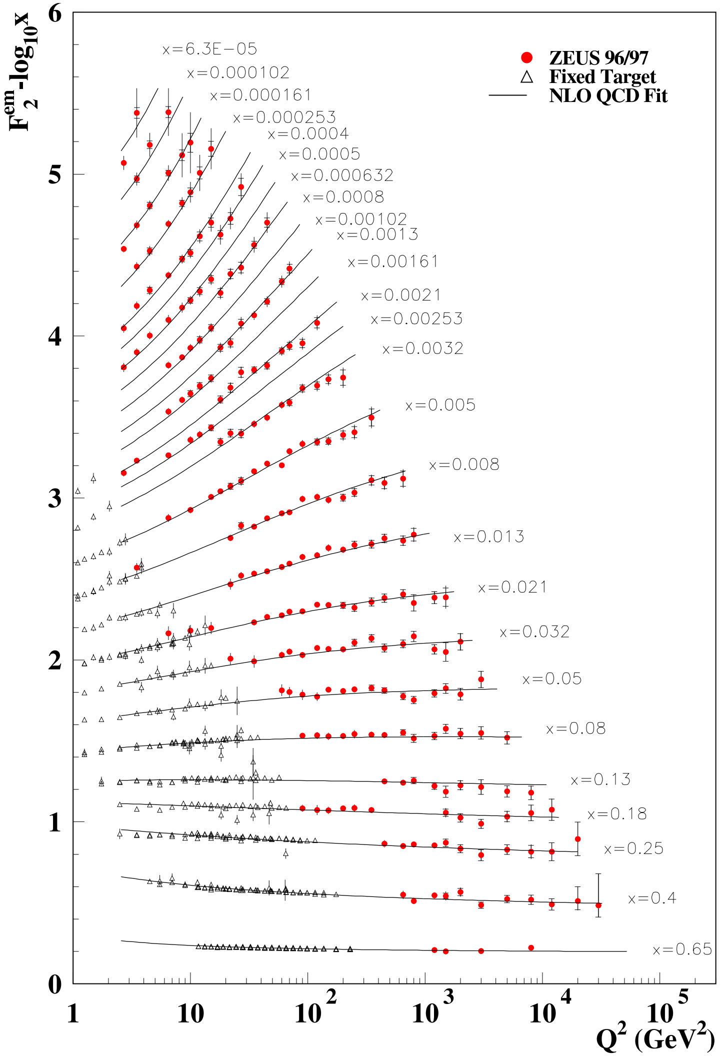


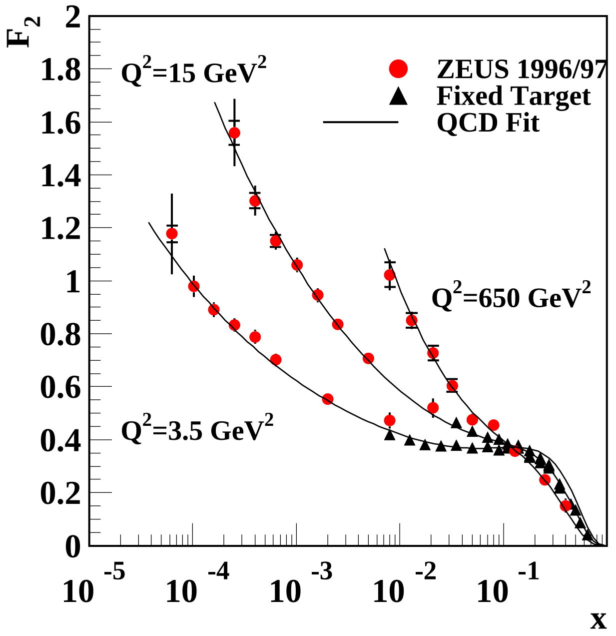


Good agreement with fixed target experiments at large x *values and* $Q^2 < 70\mathrm{GeV}^2$

The Proton Structure Functions: F_2

Measurement of F_2 *for* $2.7 < Q^2 < 30000\mathrm{GeV}^2$ *and* 6×10^5 *with statistical and systematic uncertainties below 2% in most of the* (x, Q^2) *region covered.*

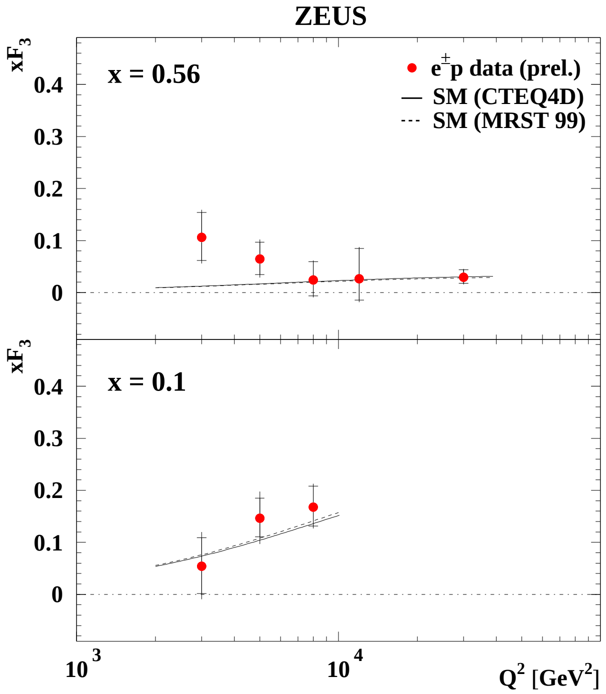


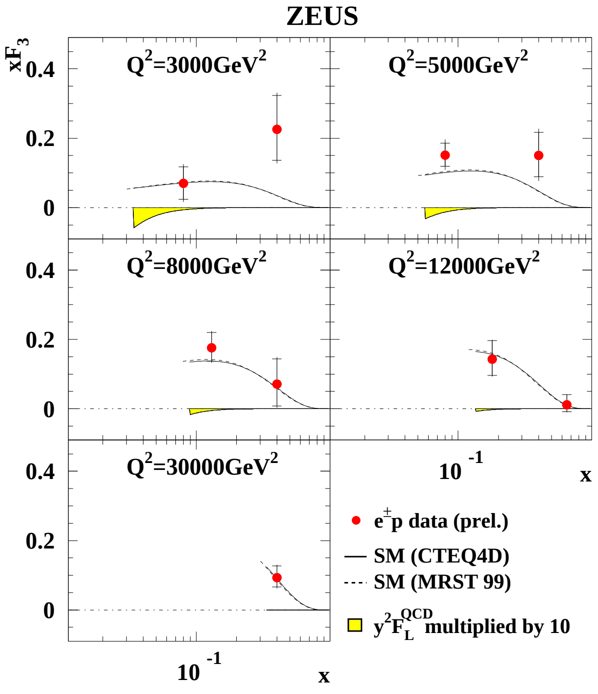


- *Strong scaling violations for* $x < 0.02$
- *Measured* $x - Q^2$ *behaviour can be described by the DGLAP equations over the whole kinematic range.*

The Proton Structure Functions: xF_3

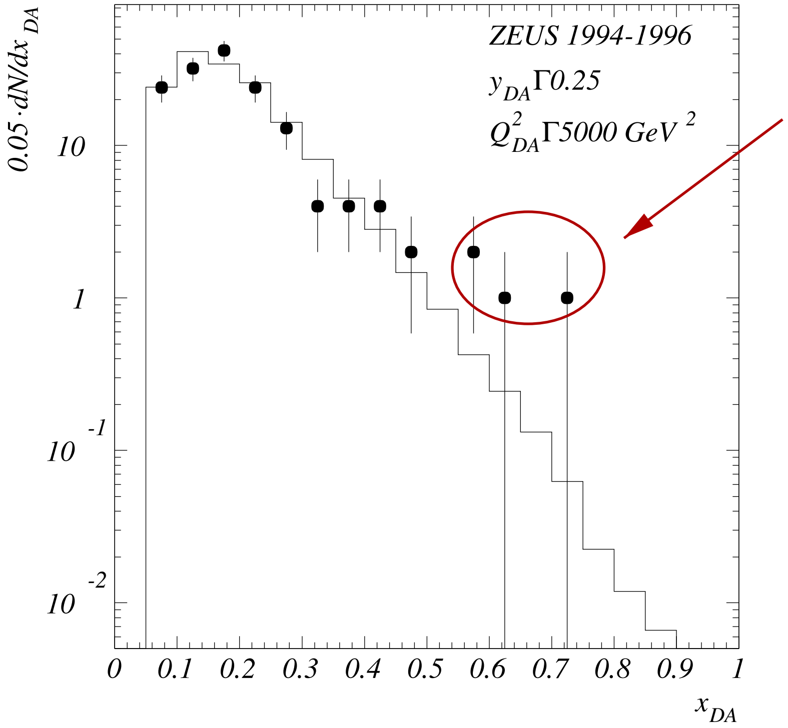
- *The parity violating part of Z-exchange (xF_3) in NC DIS makes a negative contribution to the e^+p and a positive contribution to the e^-p cross section.*
- *Can be measured by subtracting e^+p from e^-p cross section.*
- *Both cross sections available at HERA.*
- *SM expectation describes data well.*

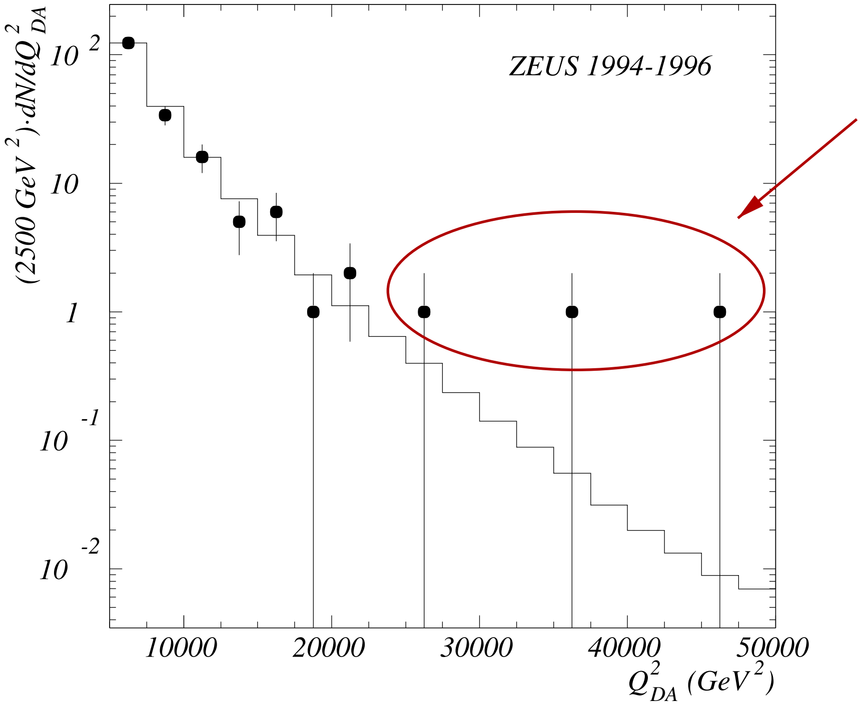




Comparison of Data and SM Predictions for NC DIS

x and Q^2 distributions show good agreement with the SM expectations at low values of x and Q^2, but a small excess of events is seen at the high ends of both distributions.





Comparison of Data and SM Predictions for DIS

- *Experimental and theoretical uncertainties:*
  - *Luminosity measurement: precision and calibration of the detector, effects from beam satellite bunches* → 2.3%.
  - *Detector simulation: uncertainties in the overall calorimeter energy scale and in the simulation of the CAL and CTD response to positrons* → 4.4%.
  - *Electroweak parameters: Relevant EW parameters have been measured to high accuracy and contribute a small uncertainty in the predicted cross section over the HERA kinematic range* → 0.25%.
  - *Radiative corrections: corrections due to initial state radiation convoluted with the experimental resolution produce uncertainties* $\rightarrow< 2\%$
  - *Structure functions: uncertainties in the fits to obtain the pSTF parametrisation"*
    - *experimental uncertainties* → $\pm 6.2\%$
    - *Uncertainty of the quark-gluon coupling* α_S *used in the evolution to higher* Q^2 → 1.9%
    - *total* $\pm 6.5\%$
- *Total systematic uncertainty* → $\pm 8.4\%$

Charged Current DIS

- *The lowest order EW cross section for the reaction* $e^+p \longrightarrow \bar{\nu}_e X$ *can be written as:*

$$\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}(e^+p)}{\mathrm{d}x\mathrm{d}Q^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \{Y_+F_2^{\mathrm{CC}}(x,Q^2) - Y_-xF_3^{\mathrm{CC}}(x,Q^2) - y^2F_L^{\mathrm{CC}}(x,Q^2)\}$$

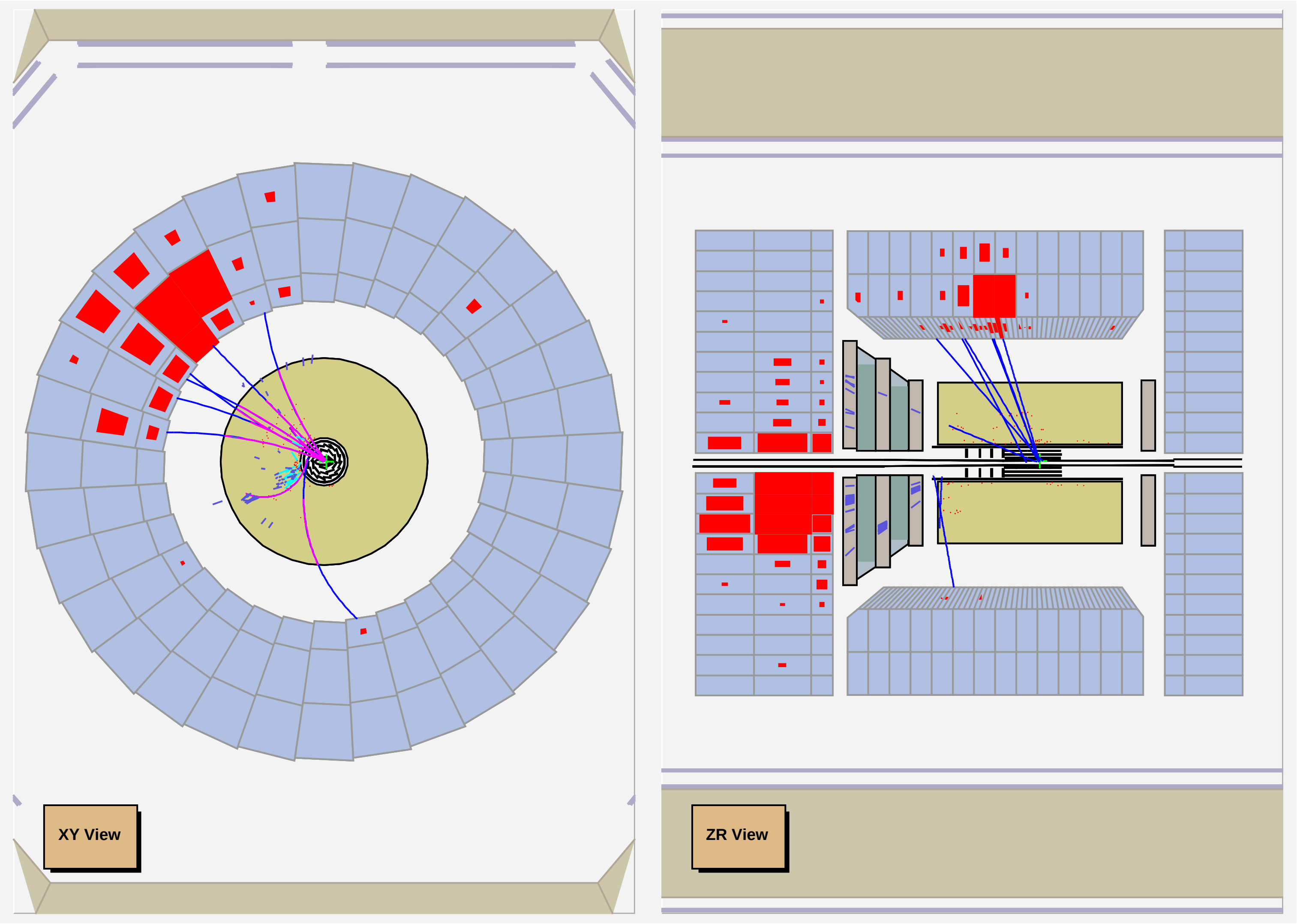
with G_F *the fermi constant and* M_W *the* W *mass.*

- *At LO QCD the structure functions* F_2^{CC} *and* xF_3^{CC} *measure sums and differences of quark and antiquark parton momentum distributions.*
- *For longitudinally unpolarised beams:*

$$F_2^{\mathrm{CC}} = x[d(x,Q^2) + s(x,Q^2) + \bar{u}(x,Q^2) + \bar{c}(x,Q^2)]$$
$$xF_3^{\mathrm{CC}} = x[d(x,Q^2) + s(x,Q^2) - \bar{u}(x,Q^2) - \bar{c}(x,Q^2)]$$

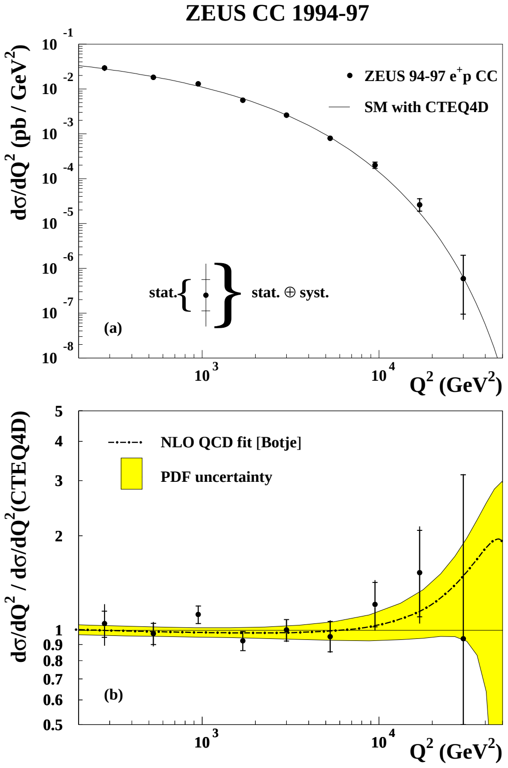
- F_L^{CC} *is zero at LO but finite at NLO and has a negligible contribution to the cross section except at high values y (close to 1), where it can be as large as* 10%.

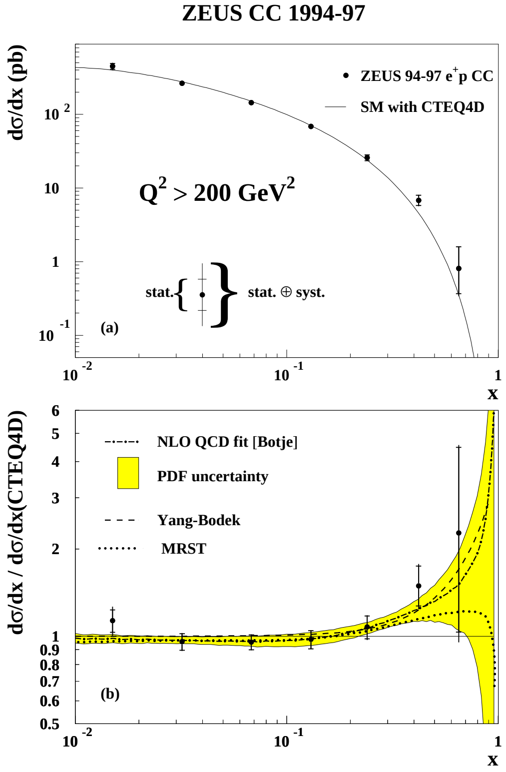
Charged Current Deep Inelastic Scattering Event



Single-Differential Cross Sections in Inclusive CC

- *SM prediction using CTEQ4D describes data well except for small excess over SM for* $\mathrm{d}\sigma/\mathrm{d}x$ *at* $x \geq 0.3$.
- *The prediction using a NLO QCD fit performed to fixed target and low-*Q^2 *NC DIS data, describes the data well over the whole range measured.*
- *The* e^+p *CC DIS cross section is dominated by the* d*-quark contribution at high* x *(a larger* d/u *than previously assumed).*
- *Modification of the PDFs with an additional term yields a predicted* $\mathrm{d}\sigma/\mathrm{d}x$ *close to the NLO QCD fit.*





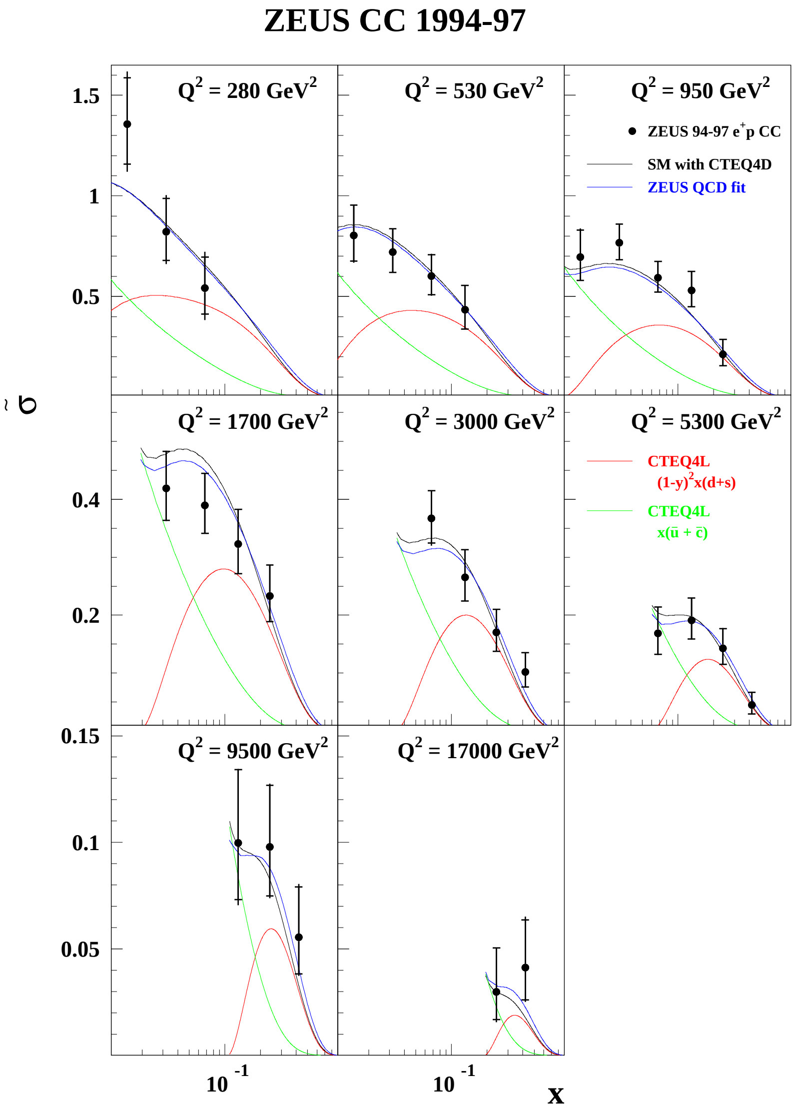
Double-Differential Cross Sections in Inclusive CC

$$\tilde{\sigma} = \left[\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\right]^{-1}\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}(e^+p)}{\mathrm{d}x\mathrm{d}Q^2}$$

- *CTEQ4D describes the data well, though there is a slight excess at the highest x value.*
- *The predictions from the NLO QCD fit at high x are higher than those from CTEQ4D.*
- *At LO QCD, $\tilde{\sigma}$ depends on the quark momentum distributions as:*

$$\tilde{\sigma} = x[\bar{u} + \bar{c} + (1-y^2)(d+s)]$$

- *For fixed Q^2, $\tilde{\sigma}$ at low x is mainly sensitive to the antiquark combination $(\bar{u}+\bar{c})$, while at high x it is dominated by the quark combination $(d+s)$*
- *Both q and $\bar{q}$ combinations are required to obtain a good description of the data.*

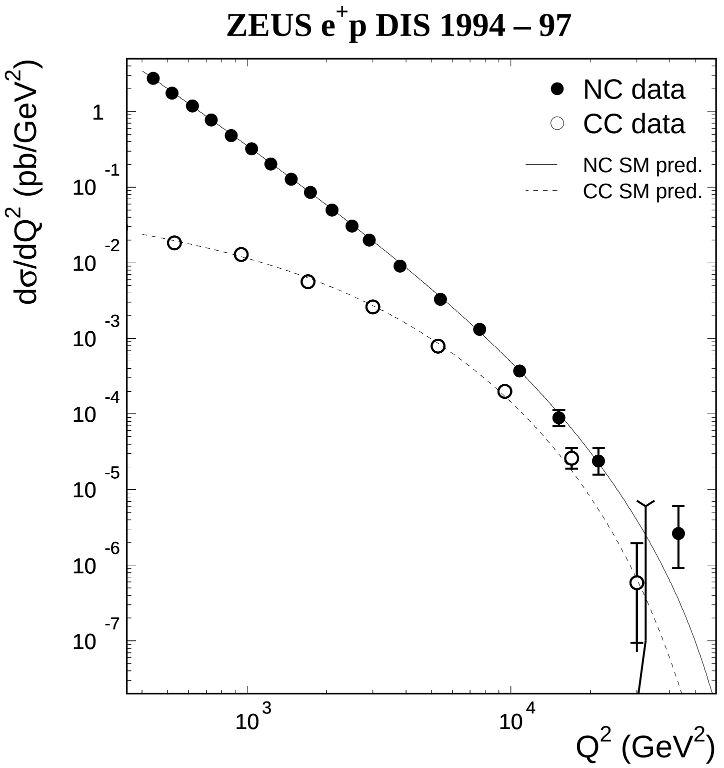


Comparison of NC and CC Cross Sections

- *At low Q^2 the CC cross section is much smaller than the NC cross section due to the relative strength of the weak force compared to the electromagnetic force:*

$$\sigma^{\mathrm{NC}} \propto \frac{1}{Q^4} \quad , \quad \sigma^{\mathrm{CC}} \propto \frac{1}{(Q^2+M_W^2)^2}$$

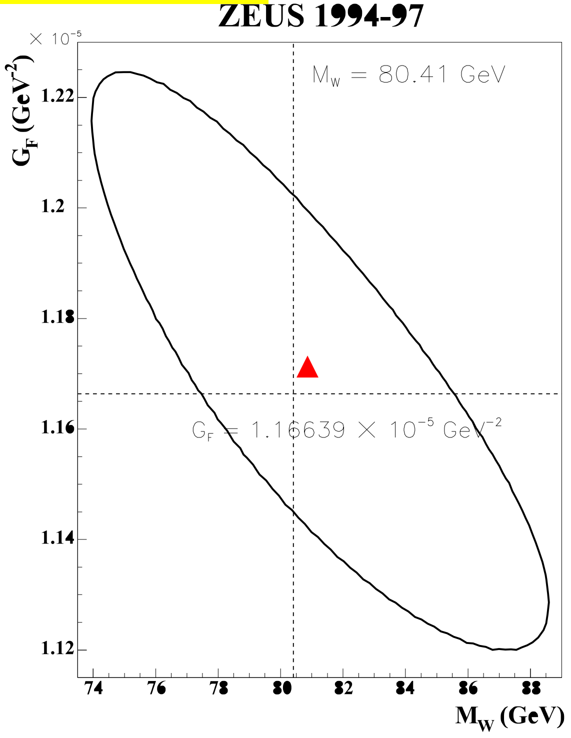
- *The CC cross section decreases with Q^2 less rapidly than that for NC scattering, reflecting the behaviour of the W propagator as contrasted to the photon propagator which dominates NC scattering.*
- *At $Q^2 \sim M_W^2, M_Z^2$, the CC and NC cross sections become comparable (approaching electroweak unification!).*
- *At very high Q^2, the rapid fall of both CC and NC cross sections with Q^2 is due to the effects of the W and Z propagators, the decrease of the parton densitities with increasing x and for CC, the $(1-y)^2$ term in the cross sections.*



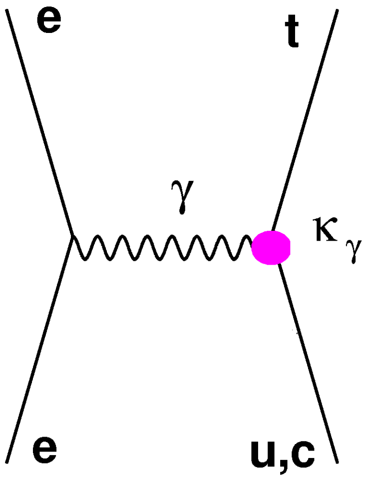
Electroweak Analysis

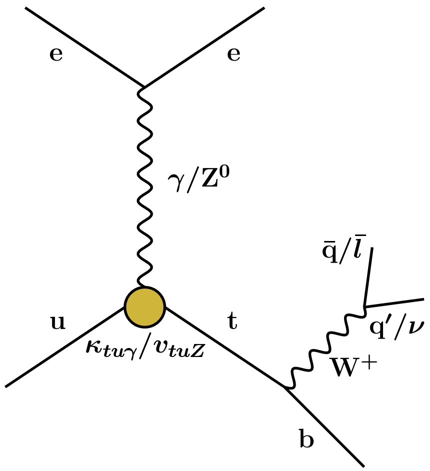
- *The absolute magnitude of the CC cross section is determined by* G_F *and the PDFs*
- *The* Q^2 *dependence of the CC cross section includes the propagator* $[M_W^2/(M_W^2+Q^2)^2]$
- *a* χ^2 *fit to the measured differential cross section* $\mathrm{d}\sigma/\mathrm{d}Q^2$ *has been performed with* G_F *and* M_W *as free parameters.*

- *The results of the fit are:*
  $$G_F = 1.171 \pm 0.034(\mathrm{Sta.})^{+0.026}_{-0.032}(\mathrm{Sys.})^{+0.016}_{-0.015}(\mathrm{PDF}) \times 10^{-5}\ \mathrm{GeV}^{-2}$$
  and $M_W = 80.8^{+4.9}_{-4.5}(\mathrm{Sta.})^{+5.0}_{-4.3}(\mathrm{Sys.})^{+1.4}_{-1.3}(\mathrm{PDF})\ \mathrm{GeV}$
- *Value of* G_F *obtained is in good agreement with the value of* $G_F = (1.16639 \pm 0.00001) \times 10^{-5}\mathrm{GeV}^{-2}$ *obtained from muon decay* $\longrightarrow$ *universality of the CC interaction.*
- *The value of* M_W *obtained agrees with the value of* $M_W = 80.419 \pm 0.056\mathrm{GeV}$ *from fits to measurements of* W *production at TeVatron (*$p\bar{p}$*) and LEP (*e^+e^-*)* $\longrightarrow$ *important experimental consistency check of the SM.*



Example of a Search for New Physics at HERA: Single Top Production via FCNC



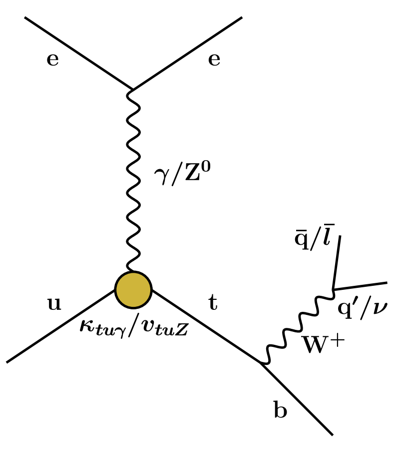
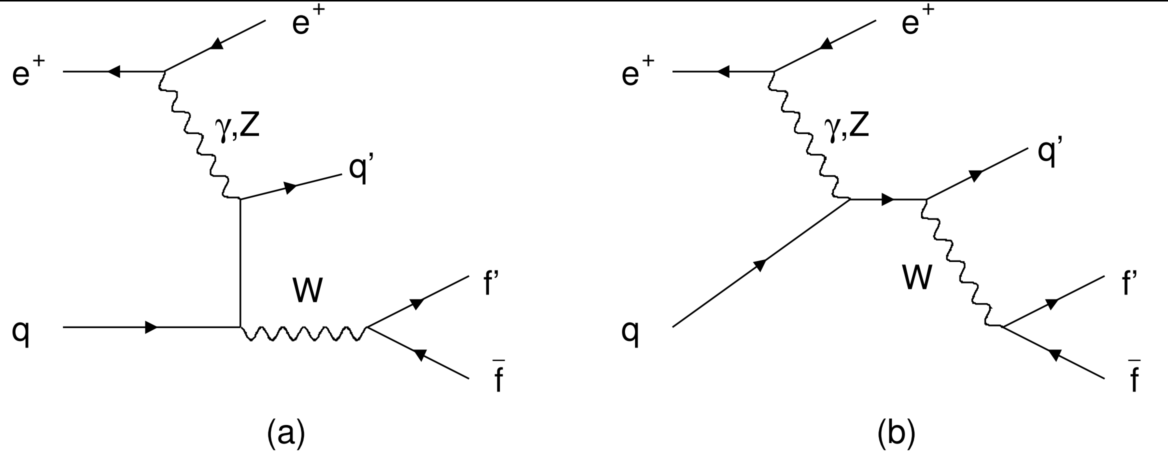


- *Single Top Production (STP) via FCNC as a Standard Model Process:*
  - *Not a tree level SM process.*
  - *Small σ (GIM mechanism): ($\sigma < 1$ fb HERA,$\sigma \approx 10^{-9}$ fb LEP)*
- *Single Top Production via Anomalous FCNC:*
  - $\Delta\mathcal{L}_{\text{eff}} = e\, e_t\, \bar{t}\, \frac{i\sigma_{\mu\nu}q^{\nu}}{\Lambda}\, \kappa_{tq\gamma}\, q\, A^{\mu} + \frac{g}{2\cos\theta_{\mathrm{W}}}\, \bar{t}\, \gamma_{\mu}\, v_{tqZ}\, q\, Z^{\mu} + \text{h.c.}$
  - *Events at LEP or HERA attributed to STP must be from anomalous couplings.*
  - *Would unambiguously signal new physics.*

FCNC Search at the Tevatron

- *CDF searched for* $t \longrightarrow q\gamma$ *and* $t \longrightarrow qZ$ *with* $\mathcal{L} = 110$ *pb*$^{-1}$.
- *From SM expect* 10^{-10} *branching fraction.*
- *use* $t\bar{t}$ *events, one* $t \longrightarrow bW$.
- $tq\gamma$
  - *Look for* γj *combination with* $140 < M < 210$ *GeV +*$t \longrightarrow bW$ *topologies.*
  - *no* b *tagged jet in* γj *combination.*
  - *main background* $W + \gamma + 2$ *or more jet events, Estimated using* $W + \gamma$ *event rate.*
  - *Branching fraction limit:* $3.2\% \longrightarrow k_{\gamma}^{2} < 0.176$
- tqZ
  - *One* t *quark goes to 3 jets other* $t \longrightarrow Zq \longrightarrow l^{+}l^{-}q$
  - *Require opposite charge leptons* $75 < M_{ll} < 105$
  - *Branching fraction limit:* $33\% \longrightarrow k_{Z}^{2} < 0.533$

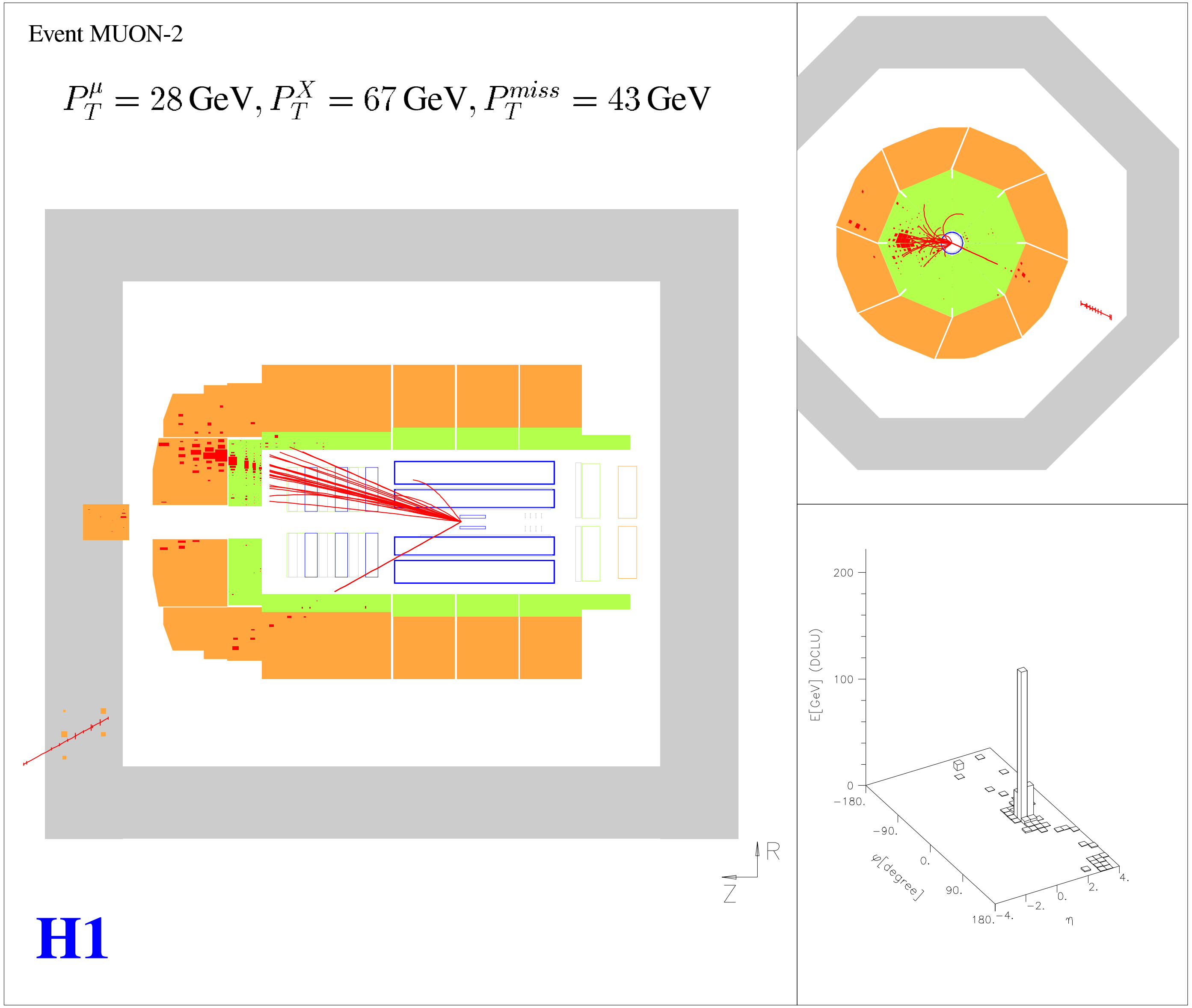
Searches at HERA I - I

Signal	*Background (W production)*
	

- *Signature of Single Top Production:*
  - *Isolated high p_T lepton in events with large missing transverse momentum)*
  - *Or 3 jets with $M_{jj} \approx M_W$, $M_{3j} \approx M_{\text{top}}$*
- *In leptonic channels main backgrounds are 2γ processes (μ), NC DIS and Single W Production.*
- *In hadronic channel, main background is QCD.*
- *Searches have been performed in both hadronic and leptonic channels, $\mathcal{L} \approx 120\ pb^{-1}$.*

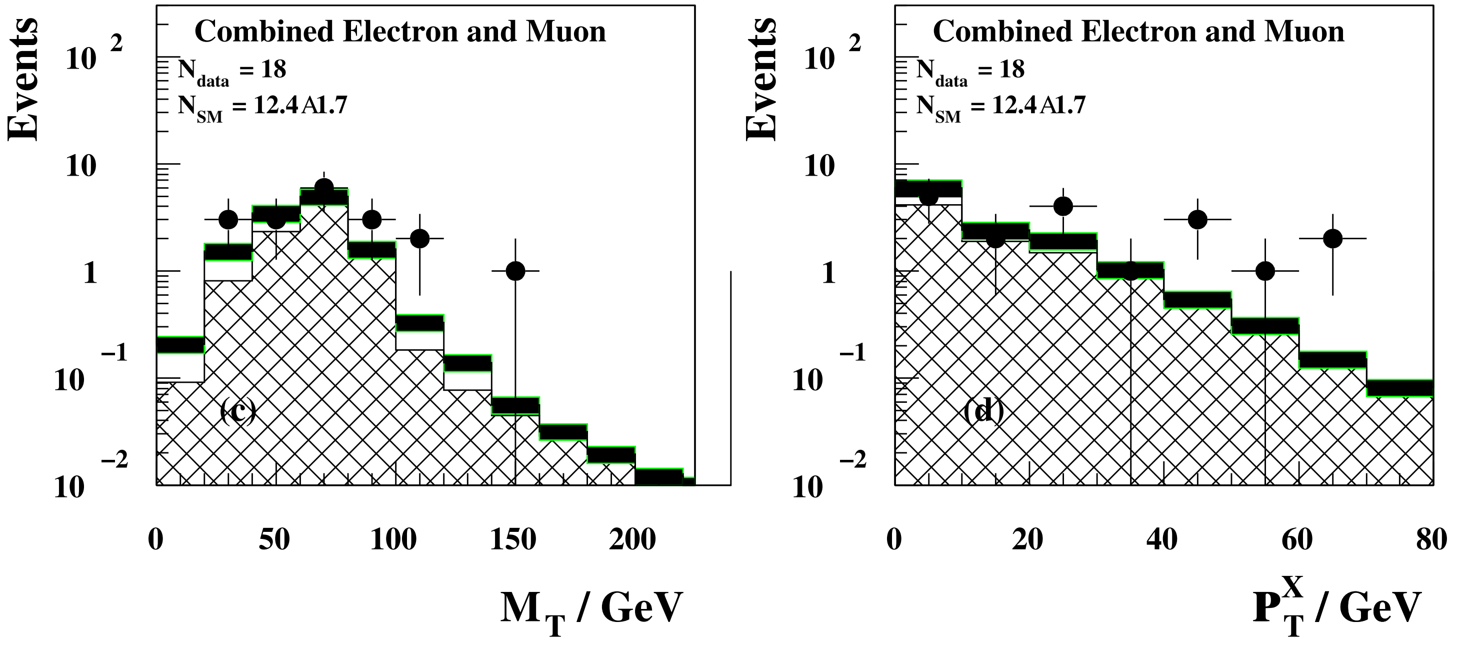
Isolated High P_T lepton event from H1

$$e^+p \rightarrow \mu^+X$$


Event MUON-2

$$P_T^\mu = 28\,\mathrm{GeV},\, P_T^X = 67\,\mathrm{GeV},\, P_T^{miss} = 43\,\mathrm{GeV}$$

Searches at HERA I - II: H1 Isolated Leptons



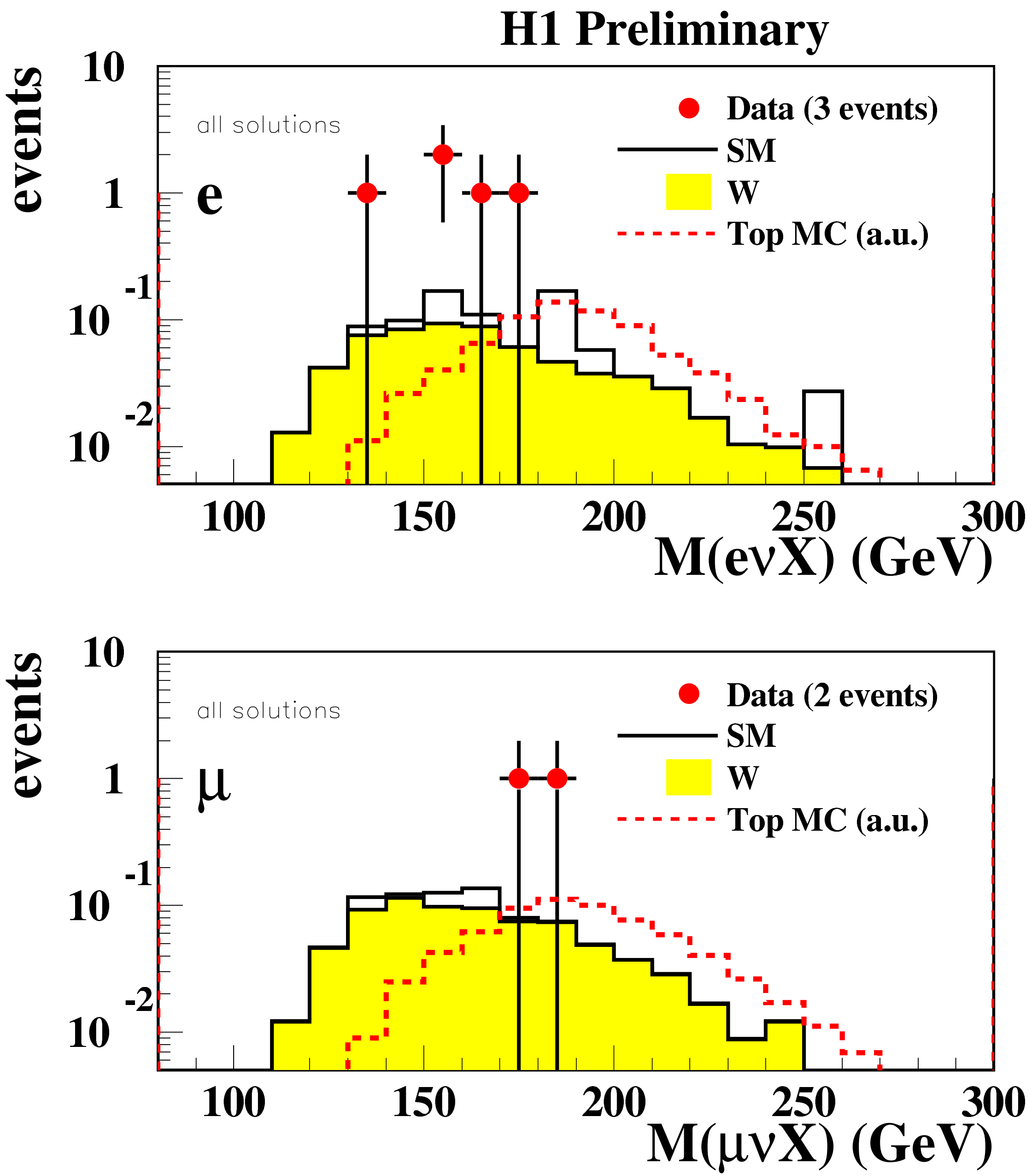
- *Main excess is at high hadronic p_T - from a Heavy particle decay?.*

Leptonic channel	*Electron*	*Muon*
p_T^X range (GeV)	*channel* *obs./expected (W)*	*channel* *obs./expected (W)*
$p_T^X < 12$	$5/6.40 \pm 0.79$(70%)	—
$12 < p_T^X < 25$	$1/1.96 \pm 0.27$(74%)	$2/1.11 \pm 0.19$(85%)
$25 < p_T^X < 40$	$1/0.95 \pm 0.14$(86%)	$3/0.89 \pm 0.14$(87%)
$p_T^X > 40$	$3/0.54 \pm 0.11$(83%)	$3/0.55 \pm 0.12$(93%)

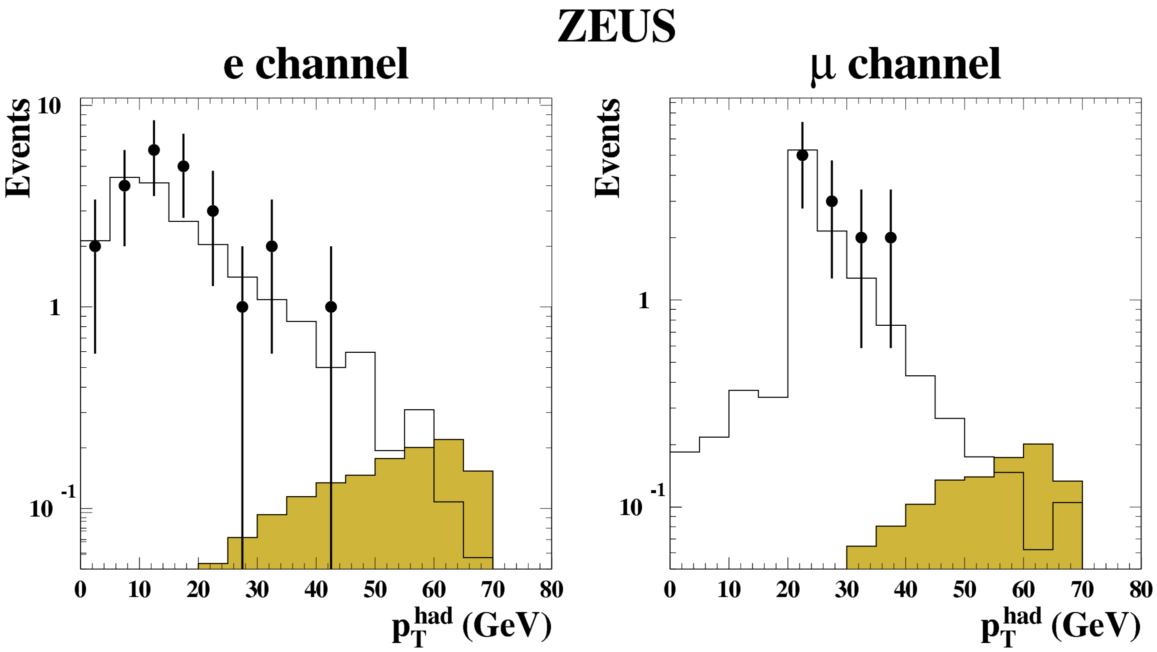
Searches at HERA I - III: H1 Single Top

Top mass is reconstructed from invariant mass of $l\nu j$ combinations.

- *Final Selection*
  - *Isolated l^+.*
  - $p_T^X > 25(35)$ *GeV.*
  - $M_T^{l\nu} > 10$ *GeV*
- *Results*
  - *3 e, 2 μ events compatible with STP.*
  - *expect* 1.77 ± 0.46 *from W production.*



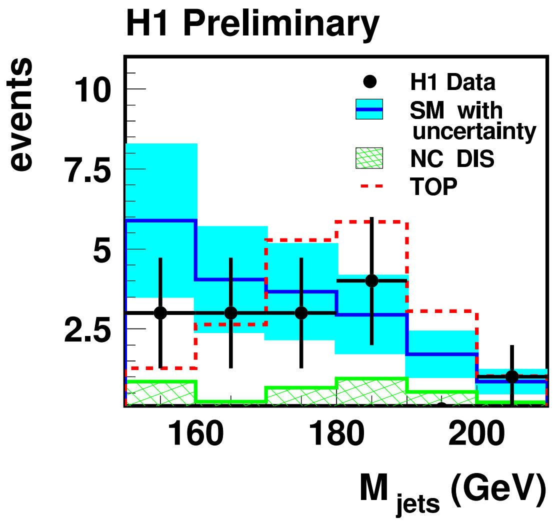
Searches at HERA I - IV: ZEUS Isolated Leptons + Single Top



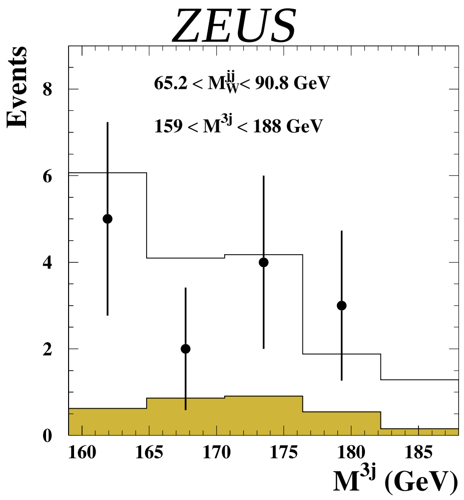
- *Kinematic distributions compatible with SM ,no excess over SM observed*

	e Channel *Obs./Exp.*	*μ Channel* *Obs./Exp.*
preselection	$24/20.6^{+1.7}_{-4.6}$	$12/11.9^{+0.6}_{-0.7}$
$p_T^{had} > 25$ *GeV*	$2/2.90^{+0.59}_{-0.32}$	$5/2.75^{+0.21}_{-0.21}$
$p_T^{had} > 40$ *GeV*	$0/0.94^{+0.11}_{-0.10}$	$0/0.95^{+0.14}_{-0.10}$

Searches at HERA I - V: Hadronic Channel



After all top cuts

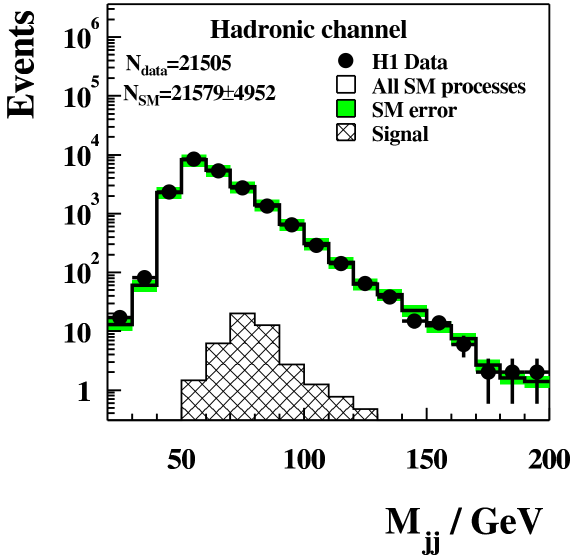


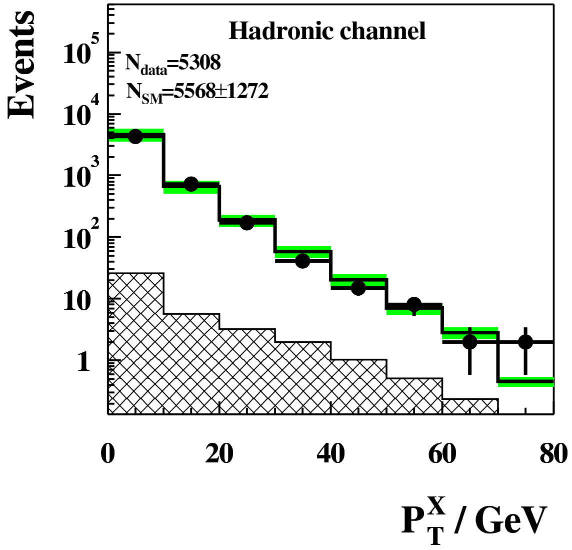
- *Search for* $eu \to et \to ebW \to ebqq$.
- *look for* $M_{jj} \approx M_W$, *make 3j Mass spectrum.*
- *After final cuts:*

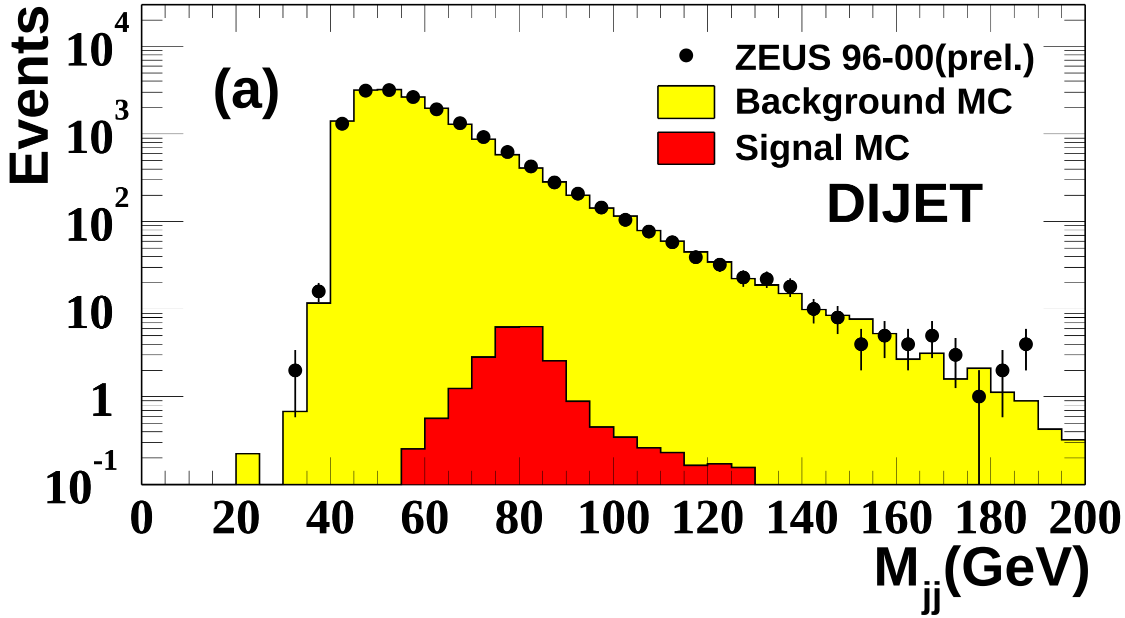
	H1(94-00)
Data	*14*
SM	19.6 ± 7.8
	ZEUS(95-00)
Data	*14*
SM	$17.6^{+1.8}_{-1.2}$

- *No excess in either experiment.*

Searches at HERA I - VI: $W \rightarrow$ Jets

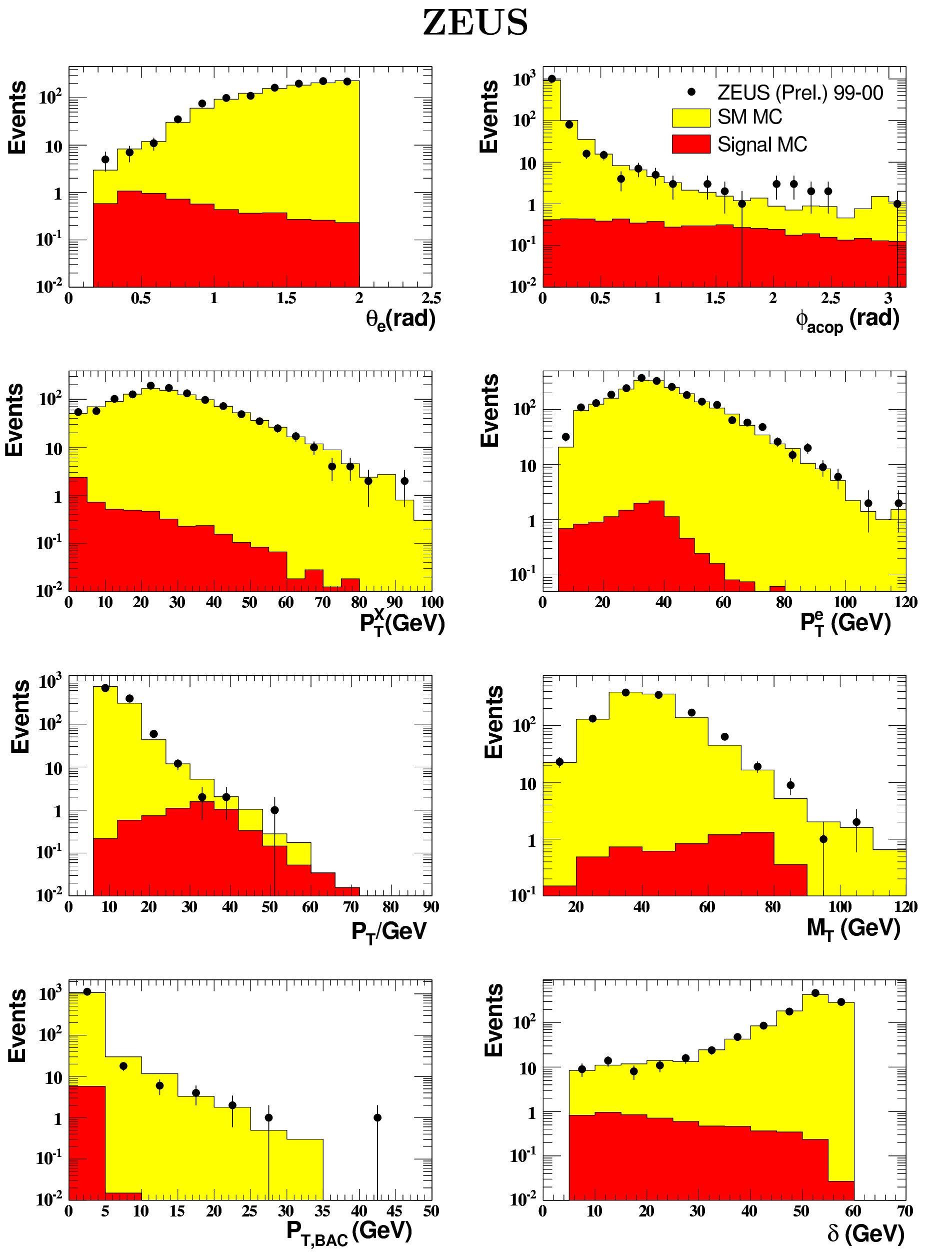






- *Leptonic excess from anomalous W production? ($\sigma_{SM} = 1\text{pb}$)*
- *Check in hadronic channel.*
- *Select Events with 2+ High E_T jets.*
- *Reconstruct invariant mass spectrum.*
- *No excess over SM seen.*
- *Limit (ZEUS): $\sigma < 8.3$ pb, does not eliminate possibility of anomalous W production.*

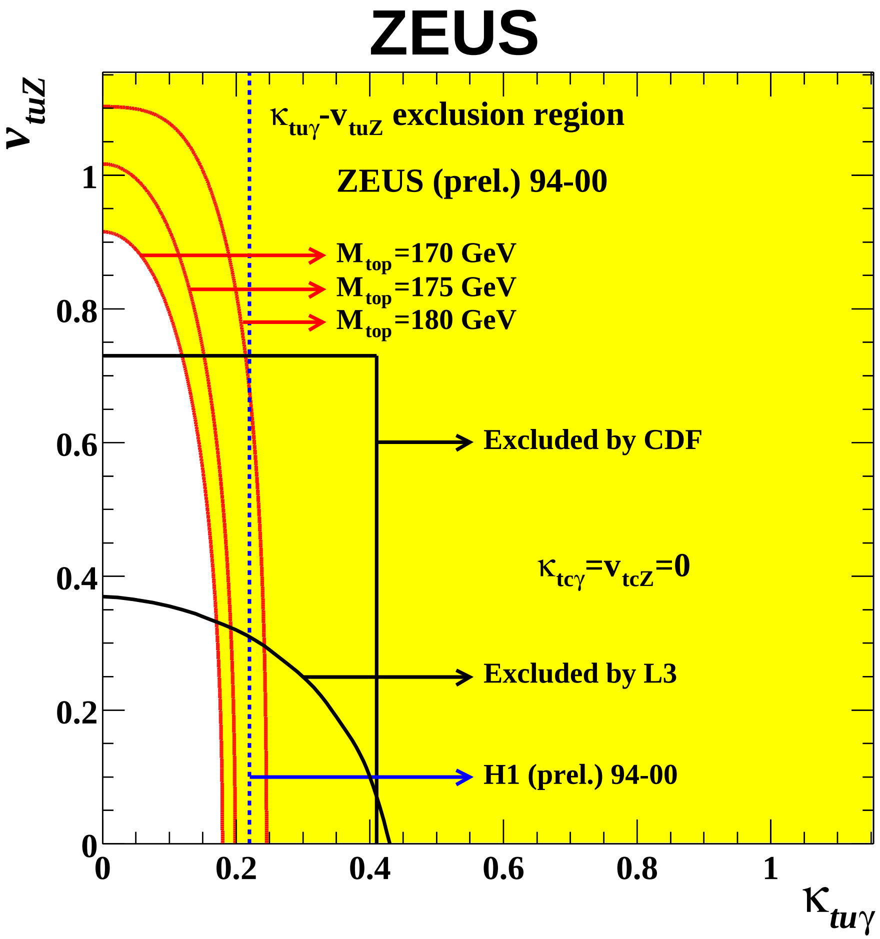
Searches at HERA I - VII: $W \rightarrow e\nu_e$



- *Isolated high P_T leptons in events with large missing P_T.*
- *5 events observed in Data*
- *3.5 events expected from SM backgrounds.*
- *3.2 events expected from*
- *ZEUS 99-00 (Prel) limit:* $\sigma(e^+p \rightarrow e^+WX < 2.8\text{pb})$*.*
- *Still cannot eliminate possibility of anomolous W production.*

Searches at HERA I: Summary

- *Searches for Single Top Production performed by H1 , ZEUS.*
- *In Leptonic channel H1 sees an excess of isolated lepton events compatible with STP:*
  - *H1 : 5 seen , expect 1.8.*
  - *ZEUS: 0 seen, expect 1.0.*
- *No excess in hadronic channel.*
- *ZEUS sets strongest limit on photon coupling (0.2).*
- *ZEUS latest results add sensitivity to* v_{tuZ}
- *No sensitivity at HERA to* tcZ/γ *couplings.*
- *Waiting for HERA II:*
  - *10x more luminosity.*
  - *Improved detectors.*



Lecture II : Summary

- *HERA offers the chance to study DIS in kinematic regions previously unattainable.*
- *A rich variety of physics is available for study.*
- *The structure of the proton is understandable in terms of the independent structure functions* F_2, F_3, F_L.
- *Electroweak physics can also be studied with high precision.*
- *HERA also offers the chance to search for physics beyond the standard model, in a manner competitive with LEP, and TeVatron.*
- *One example of new physics in which HERA is particulary capable of excluding or confirming are FCNC by searching for single top Production.*