Imperial College
London

ZEUS

Latest results from ZEUS

Alex Tapper

Definitions

- “Latest” means since ICHEP ‘04 in Beijing
- “results” means a personal and highly subjective selection of what interests me
- “from ZEUS” allows me to show a few things I like from the H1 Collaboration too…

Results since ICHEP ‘04

QCD and Hadronic Final states

1. Multijet production in deep inelastic scattering at HERA
2. Search for pentaquark baryons in the Xi-pi- and Xi-pi+ channels at HERA
3. Measurement of azimuthal asymmetries in neutral current deep inelastic scattering
4. Forward jet production in deep inelastic ep scattering and low x parton dynamics at HERA
5. Event shapes in deep inelastic scattering at HERA
6. Study of interjet energy flow at HERA
7. Inclusive jet production in extended pseudo-rapidity range in deep inelastic ep scattering at HERA
8. Cross section measurements of a narrow baryonic state decaying to K0s-p and K0s-\bar{p} in deep inelastic scattering at HERA
9. Multiplicity distributions in deep inelastic scattering at HERA
10. Study of color dynamics in photoproduction at HERA
11. The dependence of dijet production on photon virtuality in ep collisions at HERA
12. Substructure dependence of jet cross sections at HERA and determination of alphas
13. Evidence for a narrow baryonic state decaying to K0sp and K0spbar in deep inelastic scattering at HERA
14. Observation of isolated high-E_T photons in deep inelastic scattering
15. Search for QCD-instanton induced events in deep inelastic ep scattering at HERA
16. Bose-Einstein correlations in one and two dimensions in deep inelastic scattering
17. Observation of K0sK0sresonances in deep inelastic scattering at HERA

Results since ICHEP '04

Diffraction/low x

1. Exclusive electroproduction of J/psi mesons at HERA
2. Deep inelastic total and diffractive scattering measured with the ZEUS forward plug calorimeter
3. Dissociation of virtual photons in events with a leading proton at HERA
4. Exclusive electroproduction of phi mesons at HERA
5. Diffractive photoproduction of dijets at HERA
6. Studies of the hadronic component of the photon light-cone wave function using exclusive di-pion events at HERA
7. Measurement of proton-dissociative diffractive photoproduction of J/psi mesons at HERA

Results since ICHEP '04

Heavy flavours

1. Measurement of D* production in deep inelastic e+/-p scattering at HERA
2. Photoproduction of D* mesons associated with a leading neutron
3. Beauty photoproduction measured using decays into muons in dijet events in ep collisions at \sqrt(s)=318 GeV
4. Measurement of beauty production in deep inelastic scattering at HERA
5. Search for a charm baryonic state decaying to D*p in ep collisions at HERA
6. Inclusive charm jet cross sections in photoproduction
7. Measurement of inelastic J/\psi production in deep inelastic scattering at HERA
8. Measurement of open beauty production in deep inelastic scattering at HERA using a D* plus muon tag
9. Measurements of charm production in DIS
10. Charm production in DIS using HERA II data
11. First results on beauty production using HERA II data

Results since ICHEP ‘04

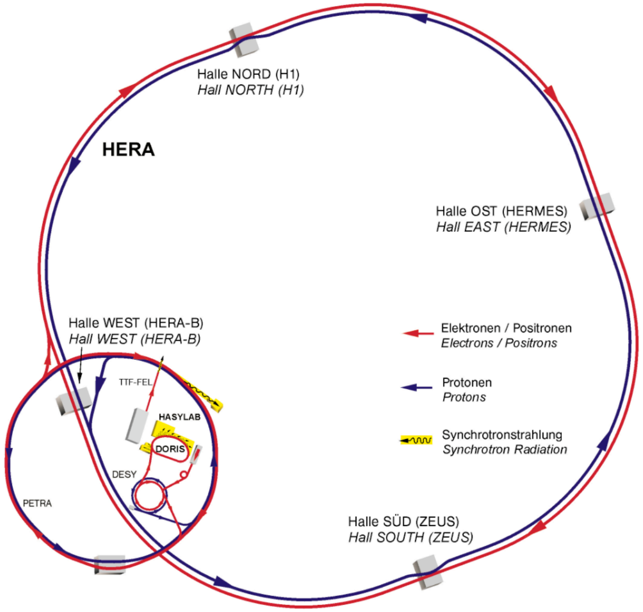
High Q^2 and beyond the Standard Model

1. A next-to-leading-order QCD analysis of ZEUS data from HERA-I
2. Search for W production using the leptonic decay channels in ep collisions at HERA I and HERA II
3. Charged current deep inelastic scattering with longitudinally polarised positron beams
4. Search for lepton flavor violation in ep collisions at HERA
5. Search for Stop Production in R-Parity Violating Supersymmetry at HERA
6. Search for gaugino production in R-parity violating supersymmetry at HERA
7. Study of dimuon production with the ZEUS detector at HERA
8. Observation of Large Rapidity Gap Events in Charged and Neutral Current High Q^2 DIS at HERA
9. Search for contact interactions, large extra dimensions and finite quark radius in ep collisions at HERA
10. Isolated tau leptons in events with large missing transverse momentum at HERA
11. High-Q^2 neutral current cross sections in e^+p deep inelastic scattering at sqrt{s}=318 GeV
12. Neutral current deep inelastic scattering measurements at high x

Contents

- **The HERA collider and the ZEUS detector**
  - Usual pictures and numbers
- **Proton structure**
  - Where the information comes from
  - A new high-x measurement
  - What we do with the information: QCD fits
- **Electroweak**
  - Fitting for Z^0 couplings to quarks
  - Using polarised lepton beams
- **Searches for new physics**
  - A couple of SUSY searches
  - Single top?
- **Conclusions & future prospects**

The HERA collider



Two 6.3 km long accelerators:

Proton accelerator energy 920 GeV

Electron/positron accelerator energy 27.5 GeV

Collisions every 96ns

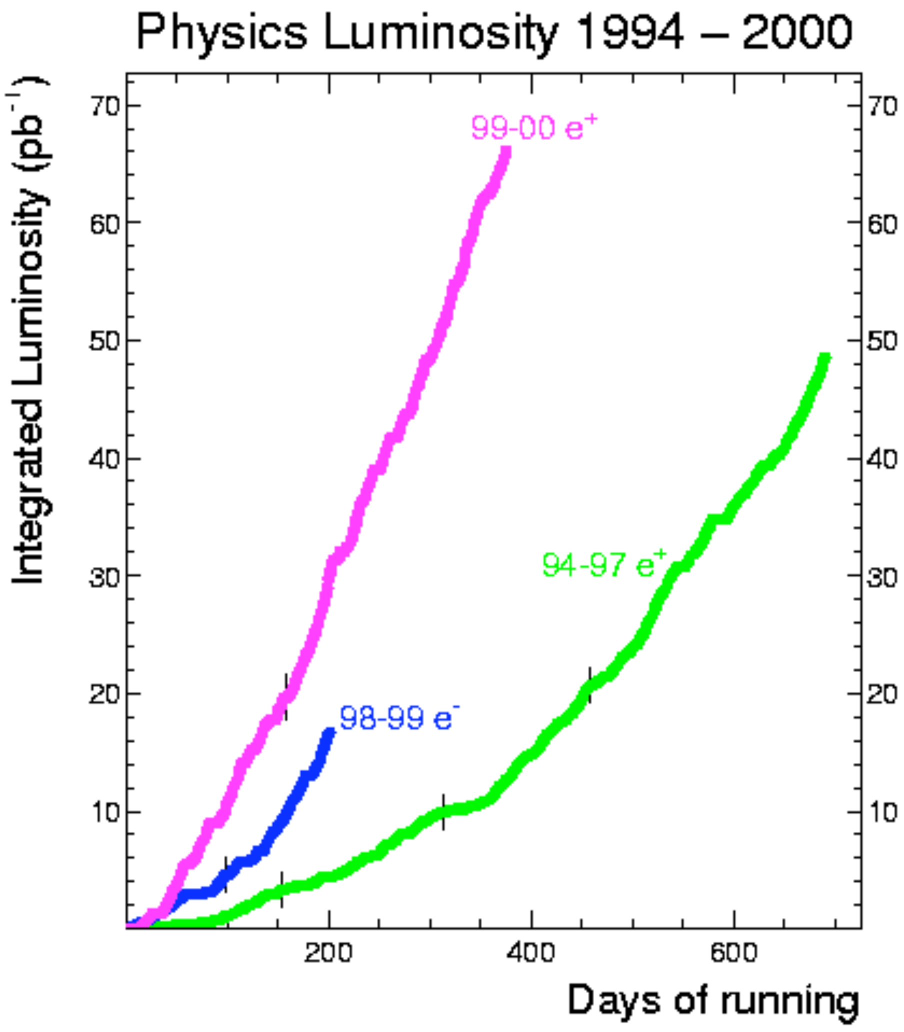
The HERA story so far…

HERA I: 1994 - 2000

Successful first phase but upgrade could improve the physics programme

Lepton	E_e (GeV)	E_p (GeV)	CM (GeV)	L (pb^{-1})
e^+	27.5	820	300	50
e^+	27.5	920	320	65
e^-	27.5	920	320	16

Most of the results from this data

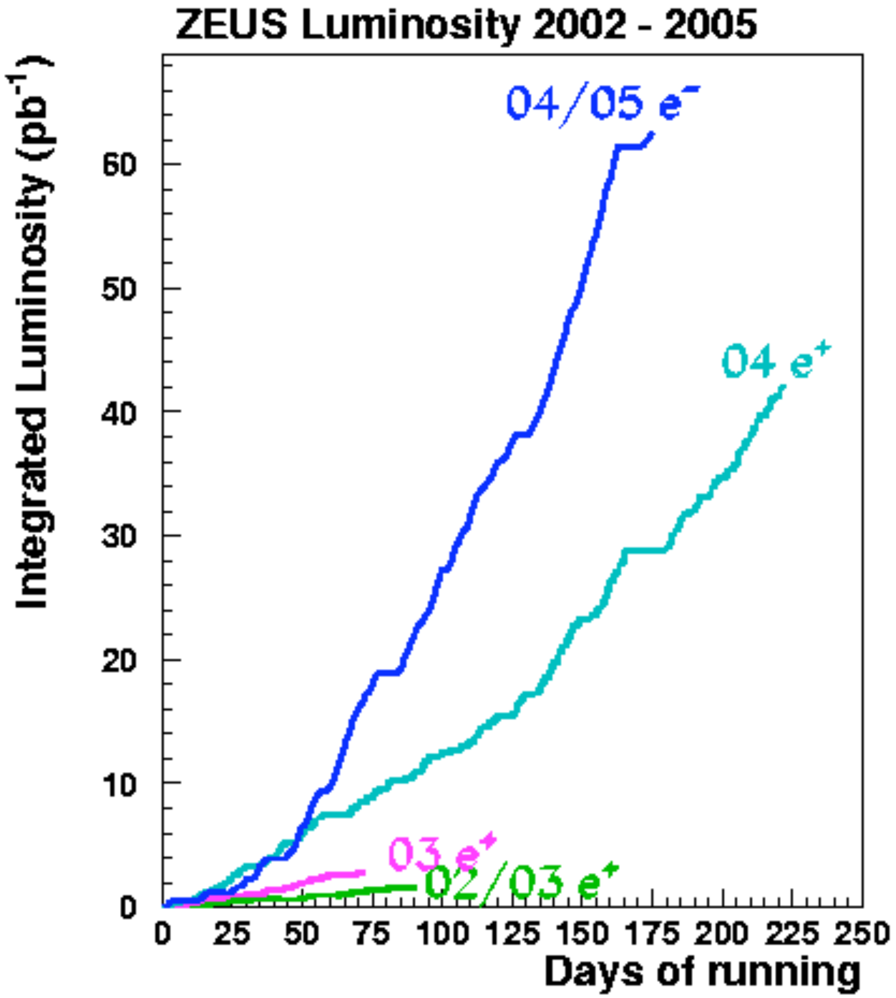


The HERA story continues…

HERA II: 2002 - 2007

Upgraded to deliver 5xLumi and long. polarised lepton beams

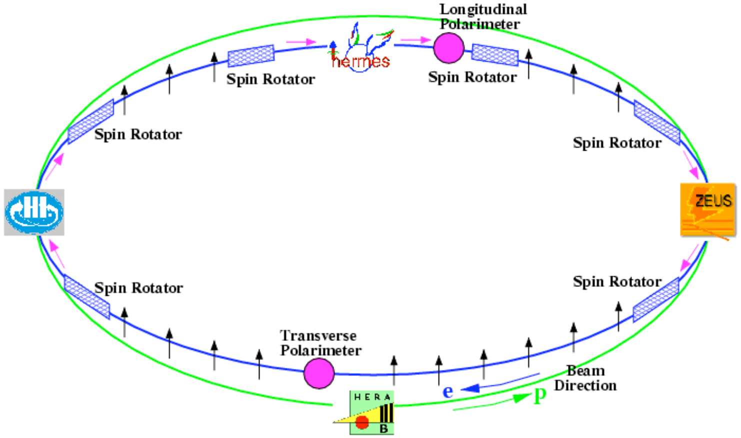
Lepton	E_e (GeV)	E_p (GeV)	CM (GeV)	L (pb^{-1})
e^+	27.6	920	320	40
e^-	27.6	920	320	60

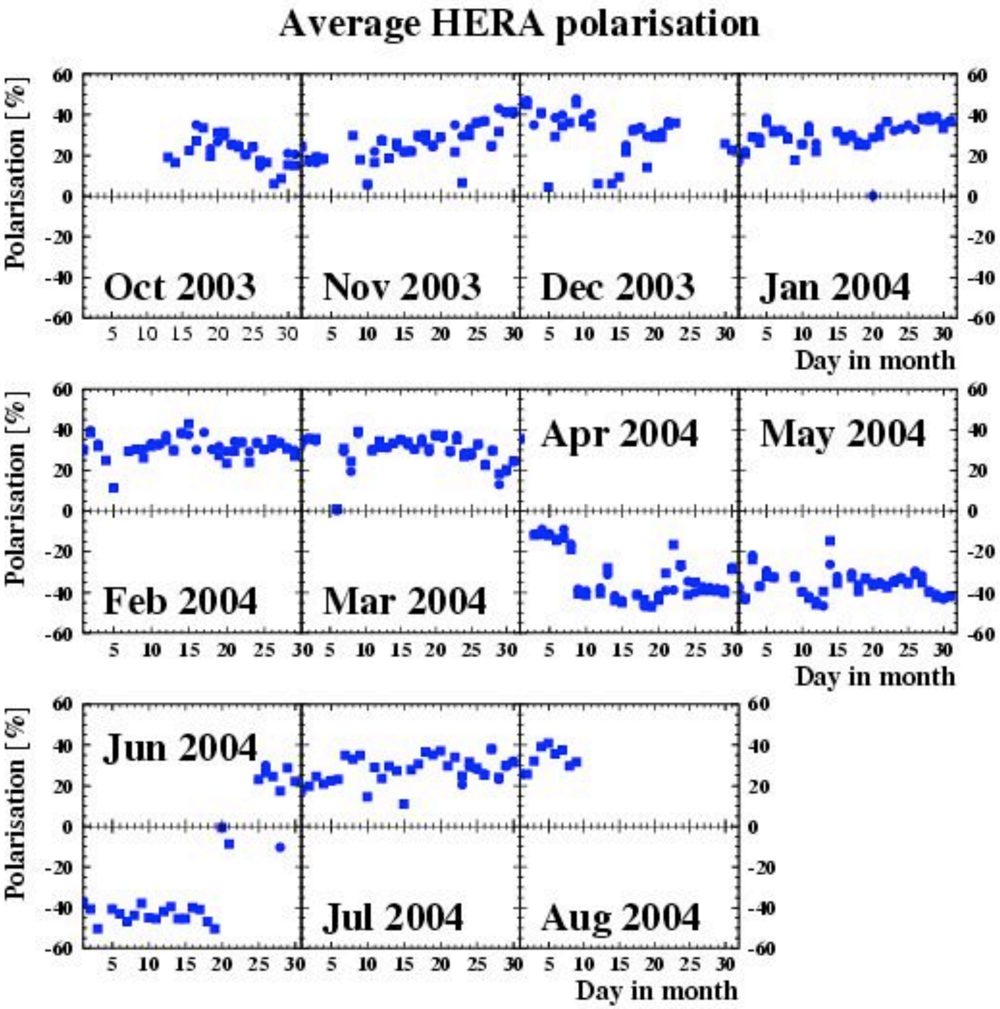


A few of the results from this data

Many new results to come this summer

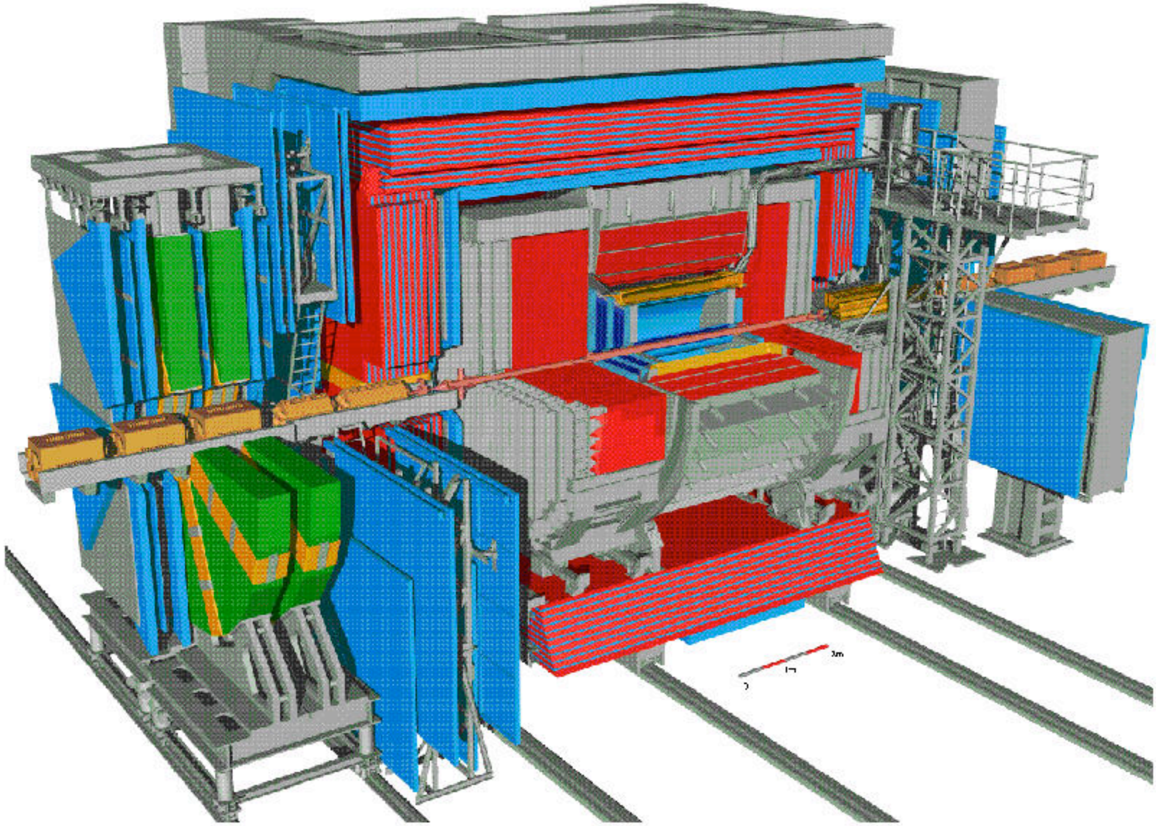
Lepton beam polarisation





- Transverse polarisation of leptons builds up naturally
- Measured by two independent Compton polarimeters
- Spin rotators convert to longitudinal polarisation
- Tuning polarisation a tortuous process….

The ZEUS detector



Calorimeter

EM:

$$\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E}} \oplus 1\%$$

Systematic 1-2%

HAD:

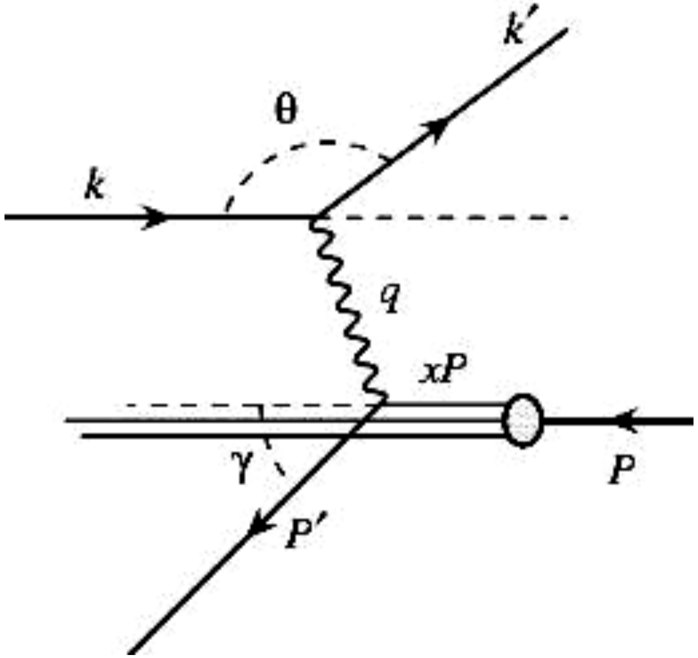
S $$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}} \oplus 1\%$$

Tracking

Central: 15° < θ < 164°

Silicon: 7° < θ < 158°

Deep inelastic scattering at HERA



Neutral current: exchange of γ or Z^0

Charged current: exchange of $W^{\pm}$

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

$$s = (p + k)^2 \qquad Q^2 = x \cdot y \cdot s$$

- Q^2 is the probing power
- x is the Bjorken scaling variable
- y is the inelasticity

Kinematics over-constrained.
Can reconstruct event from any two of θ, γ, E_e and E_q

Neutral current DIS cross section

NC Reduced cross section: $\tilde{\sigma}_{NC}(x,Q^2)$

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}Y_+\overbrace{\left[F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right]} \qquad Y_\pm = 1 \pm (1-y)^2$$

Dominant contribution

Sizeable only at high y

Contribution only important at high Q^2

$$F_2 = F_2^{em} + \frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z \propto \sum_{q=u\ldots b}(q+\bar{q})$$

$$xF_3 = \frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z \propto \sum_{q=u\ldots b}(q-\bar{q})$$

Charged current DIS cross section

CC e^+p cross section:

$$\frac{d^2\sigma^{CC}(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\overline{u}+\overline{c}+(1-y)^2(d+s)\right]$$

CC e^-p cross section:

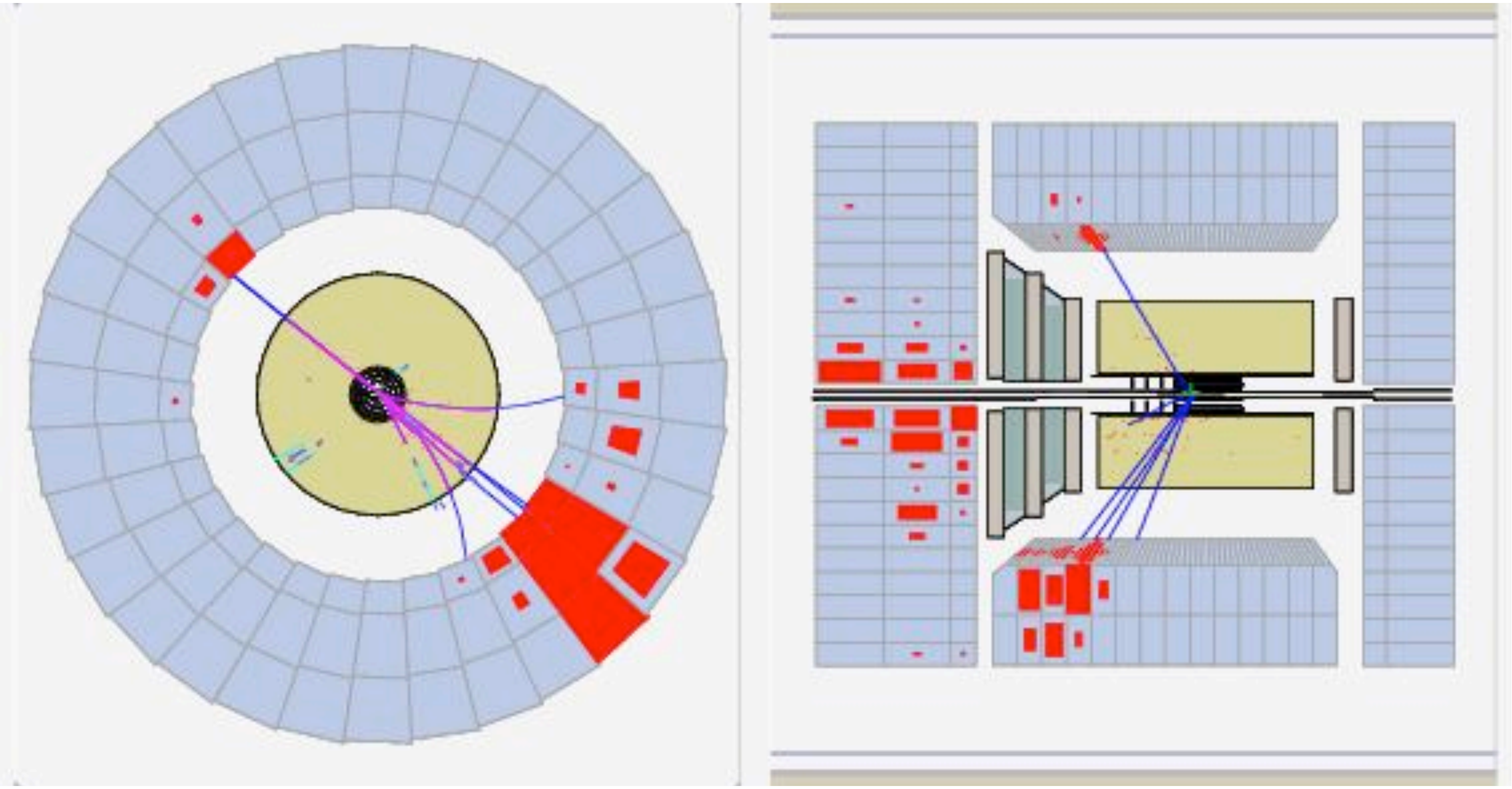
$$\frac{d^2\sigma^{CC}(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u+c+(1-y)^2(\overline{d}+\overline{s})\right]$$

Electron/positron-proton collisions probe different quark content of proton

Big difference in cross section magnitude

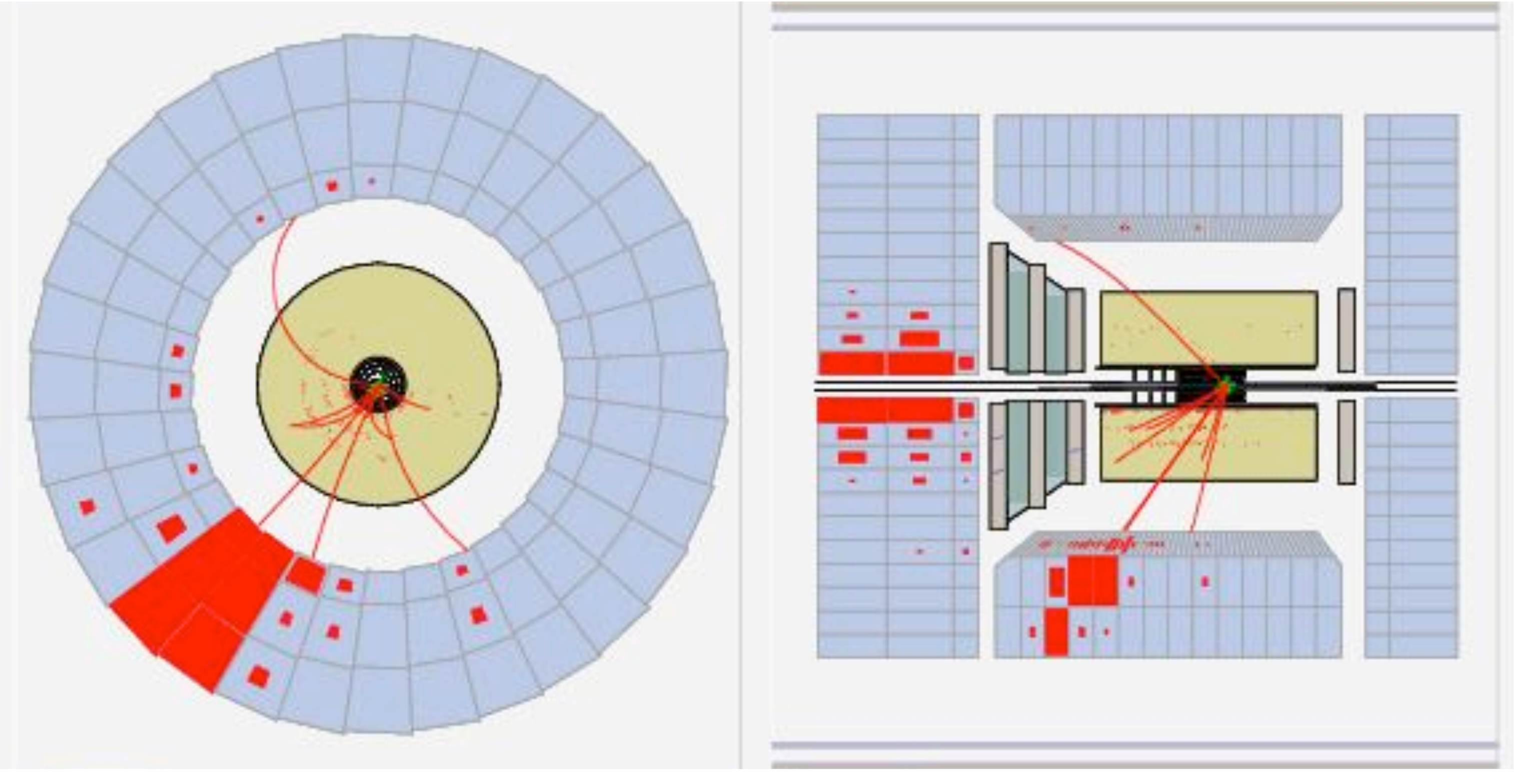
Cross sections suppressed due to large mass of W boson compared to NC DIS

NC events in the ZEUS detector



Isolated high P_T positron with hadronic jet balanced in ϕ

CC events in the ZEUS detector

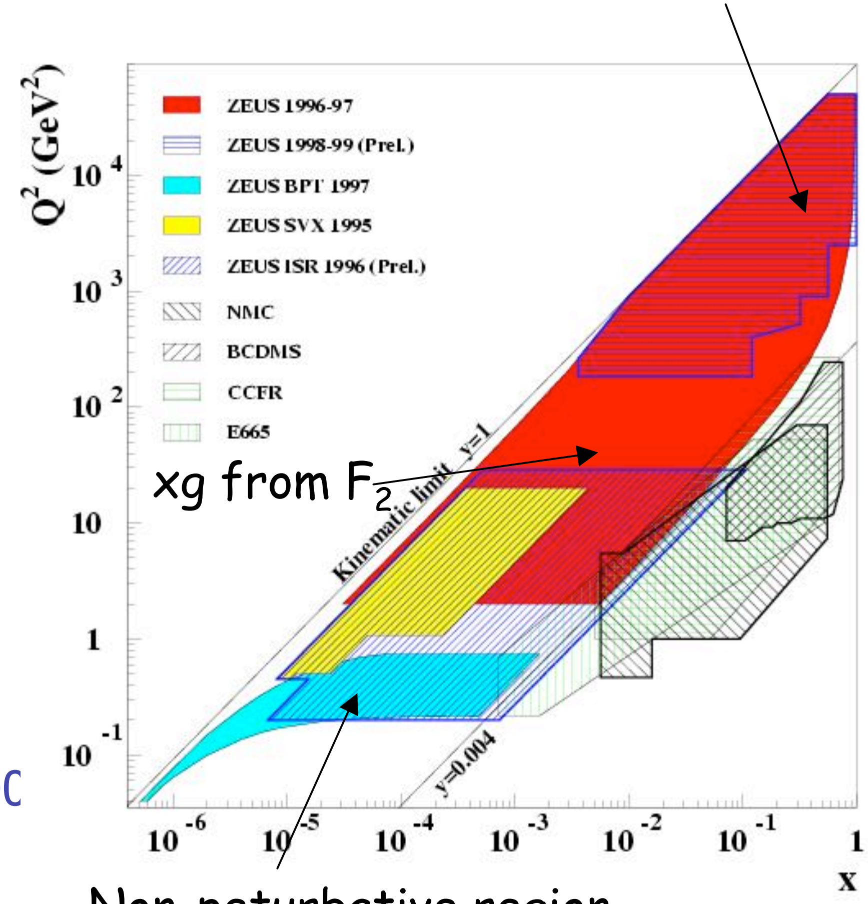


Missing transverse momentum from the undetected neutrino

Kinematic range of ZEUS data

- Overlap with fixed target data at low Q^2 and high x
- Gluon distn at low x
- Valence quarks at high x
- Access to non-peturbative region
- Measurements extend fixed target data to higher Q^2 and higher y
- Probe distances down to 1/1000 proton

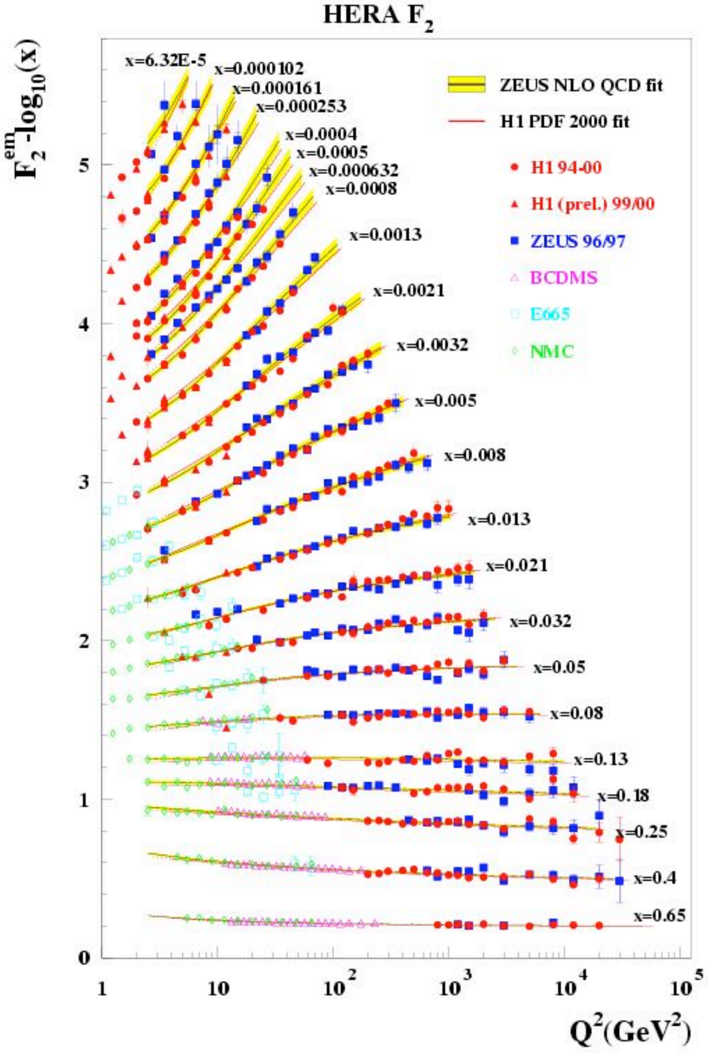
xF$_3$ & valence quarks



xg from F$_2$

Non-peturbative region

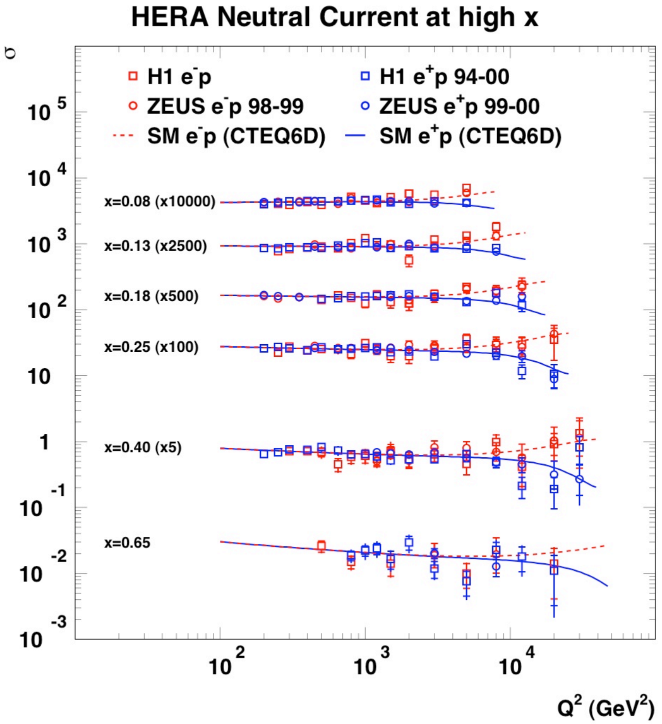
Structure function measurements

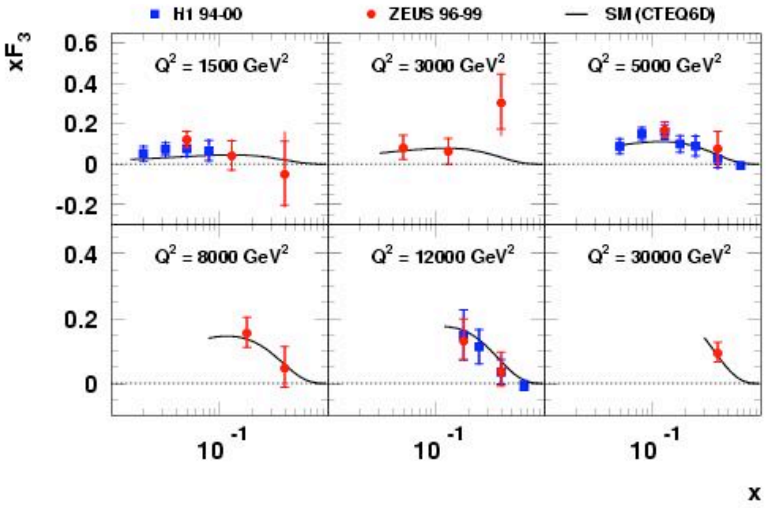


$$F_2 \propto \sum_q e_q^2 x(q+\overline{q})$$

- F_2 dominates cross section
- Measured with precision of ~2-3%
- Systematics limited at low Q^2 (< 1000 GeV^2)
- Directly sensitive to sum of quarks and antiquarks
- F_2 sensitive to gluon density via QCD radiation
- Scaling violations
  - Largest at low x
  - Driven by gluon density

High Q^2 cross sections & xF_3



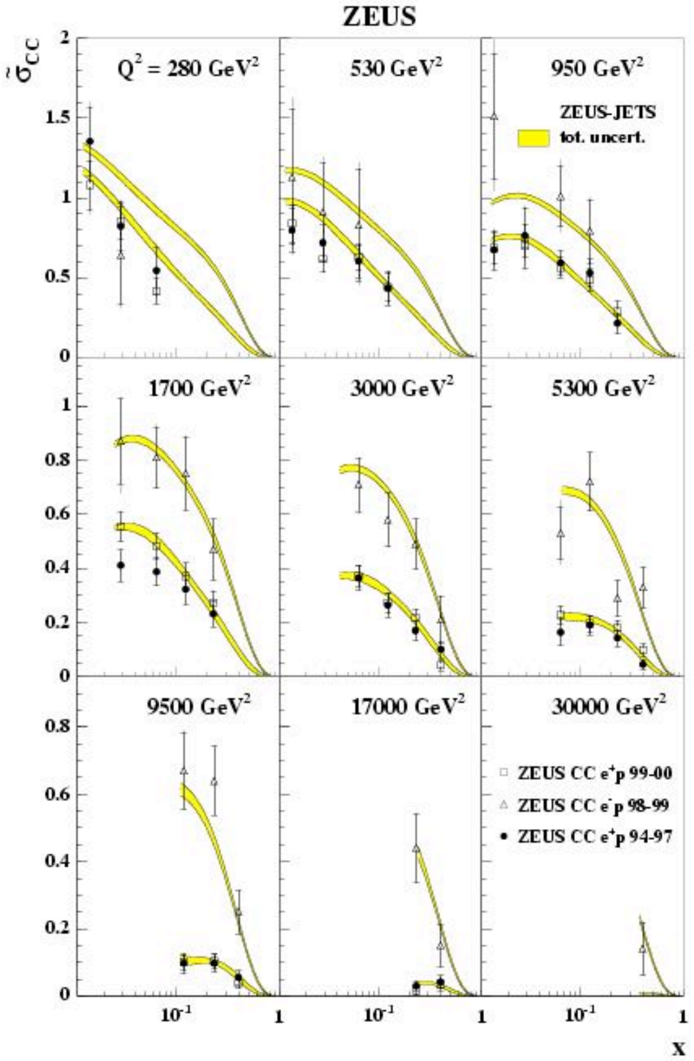


$$xF_3 \propto \sum_q x(q-\overline{q})$$

- Difference between e^+p and e^-p cross sections gives xF_3
- xF_3 comes from interference between gamma and Z^0 exchange processes

- Uncertainties dominated by statistical uncertainty of e^-p data sample
  - Already have 4x data in HERA II. Better measurement soon

Charged current cross sections



- Different for e^+p and e^-p

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

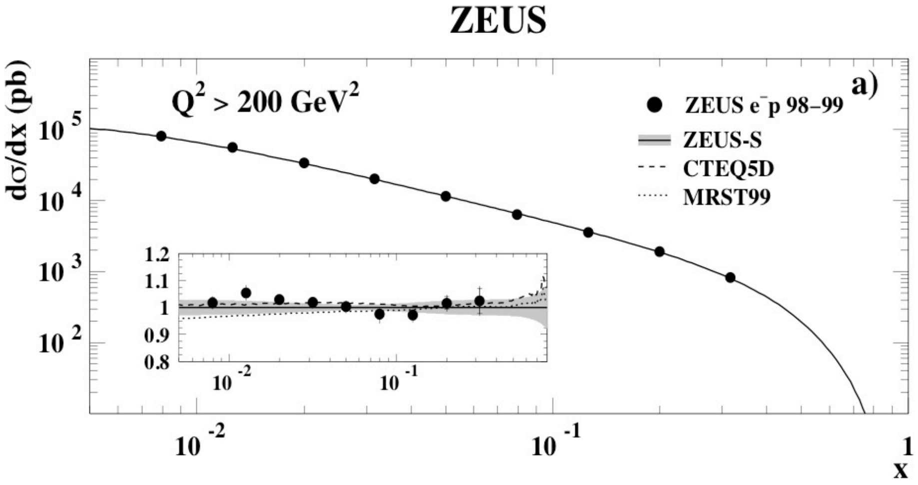
  - e^-p sensitive to $u(x,Q^2)$

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

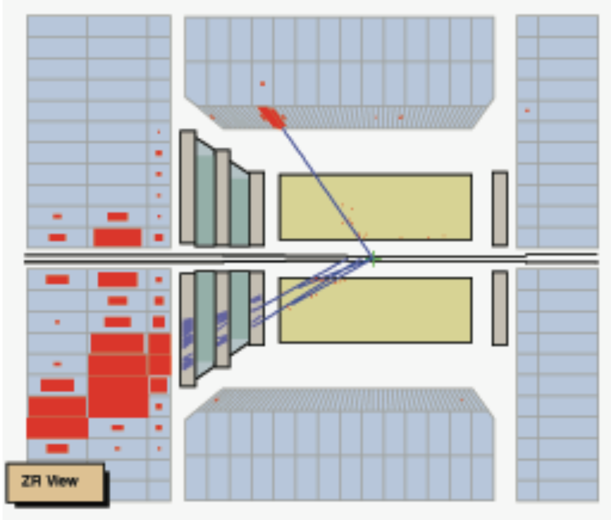
  - e^+p sensitive to $d(x,Q^2)$
  - e^+p suppressed by $(1-y)^2$ helicity factor
- Flavour specific probe of the proton
- e^+p data particularly valuable since $d(x,Q^2)$ poorly known

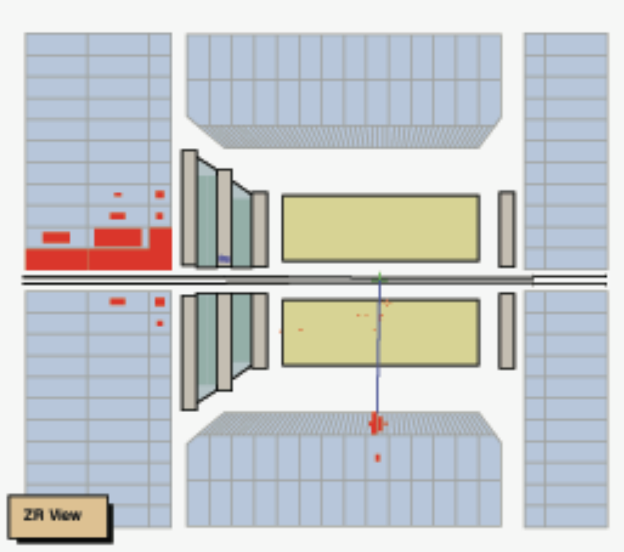
New measurement at high x: Motivation

- PDFs decrease very quickly at high x, hard to measure because of low statistics and large migrations
- Highest measured point x=0.75, BCDMS, data is available at highe x but at low W, needs huge correction.
- ZEUS published x=0.65
- The uncertainties on PDF grow with x, might be infinite at x=1
- New reconstruction methods are needed to reach the highest x



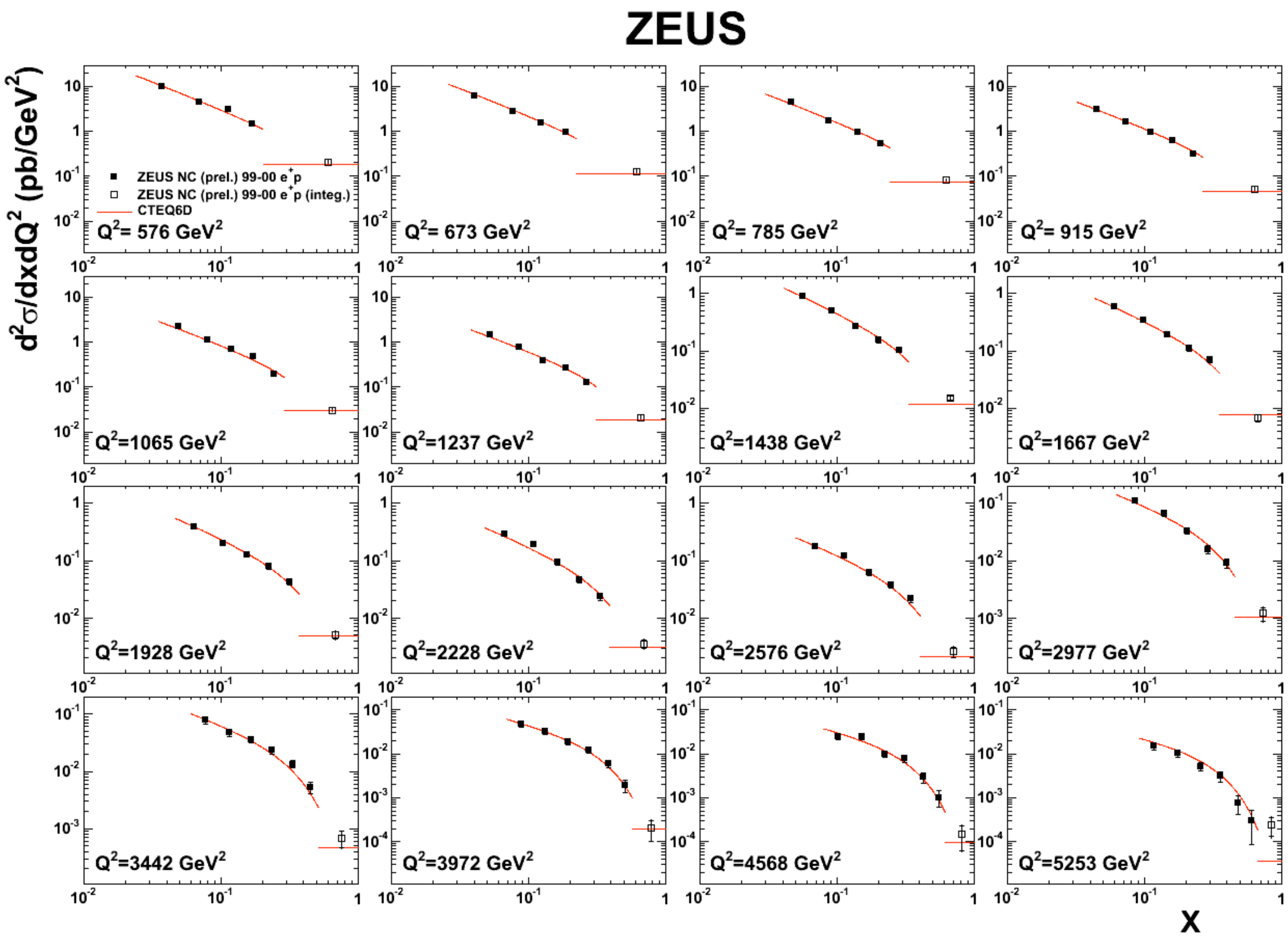
High x: Method





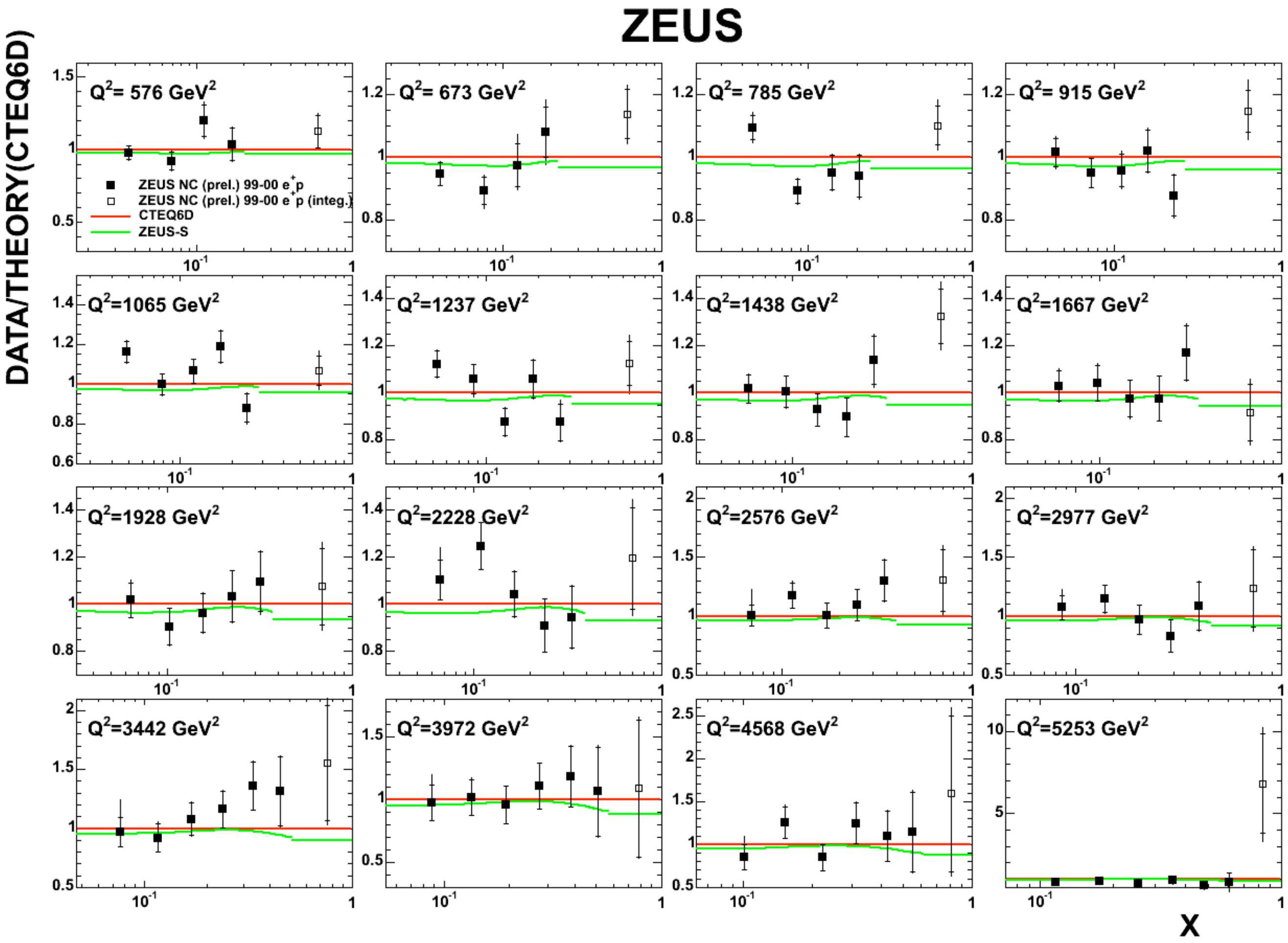
- As x increases the jet in NC DIS events becomes further forward in the detector
- At some point unable to measure jet any longer. In previous publications x~0.65
- New method uses electron to measure Q2 and jet to measure x
- When jet measurement becomes impossible just count number of events i.e. measure integrated cross section
- In this way extend sensitivity to x=1

High x: Cross sections



$$\frac{\int_{x_{\max}}^{1} dx \frac{d^2\sigma}{dxdQ^2}}{1 - x_{\max}}$$

High x: Ratio to theory



General tendency for high-x data to be above theory

How we get the PDFs: QCD fits

General method

PDFs cannot be calculated by pQCD. Need to fit from data.
Remember x dependence is not known from theory but Q^2 is!

1. Parameterise x dependence of PDFs at some starting scale
   Use some (almost) arbitrary polynominal
2. Evolve to arbitrary Q^2 using NLO QCD DGLAP equations

$$\frac{dq(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_0^1 \frac{dy}{y}\left[\sum_q P_{qq}(z)q(y,Q^2) + P_{qg}(z)g(y,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_0^1 \frac{dy}{y}\left[\sum_q P_{gq}(z)q(y,Q^2) + P_{gg}(z)g(y,Q^2)\right]$$

3. Calculate cross sections and compare to data
4. Iteratively change the starting parameters until best fit is found

ZEUS QCD fits: A brief history

Traditional

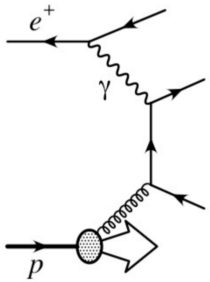
- Valence quarks constrained by heavy target data (νFe and μD).
  - Data very precise but subject to theoretical uncertainties (Nuclear binding effects, Non-peturbative effects at low Q^2)
- World F_2 data used
  - Many different experiments, not just ZEUS or even HERA
- Inclusive cross sections indirectly sensitive to gluon (scaling violations) α_S and gluon strongly correlated via DGLAP evolution
  - poor α_S and gluon extraction

New developments

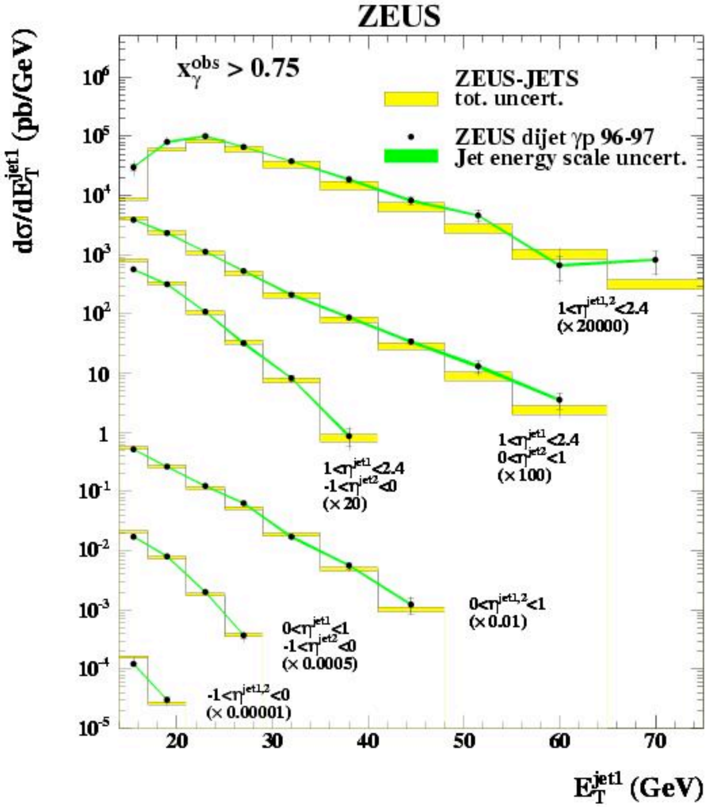
- High Q^2 NC and CC data constrain valence quarks
  - No fixed target data problems but low statistics since high x and Q^2
- Jet cross sections tie down the gluon, accurate determination of α_S.
- Fits done entirely with HERA data, no external experiments

NEW! Jet cross sections

HERA jet data very precise and sensitive to the gluon e.g. BGF



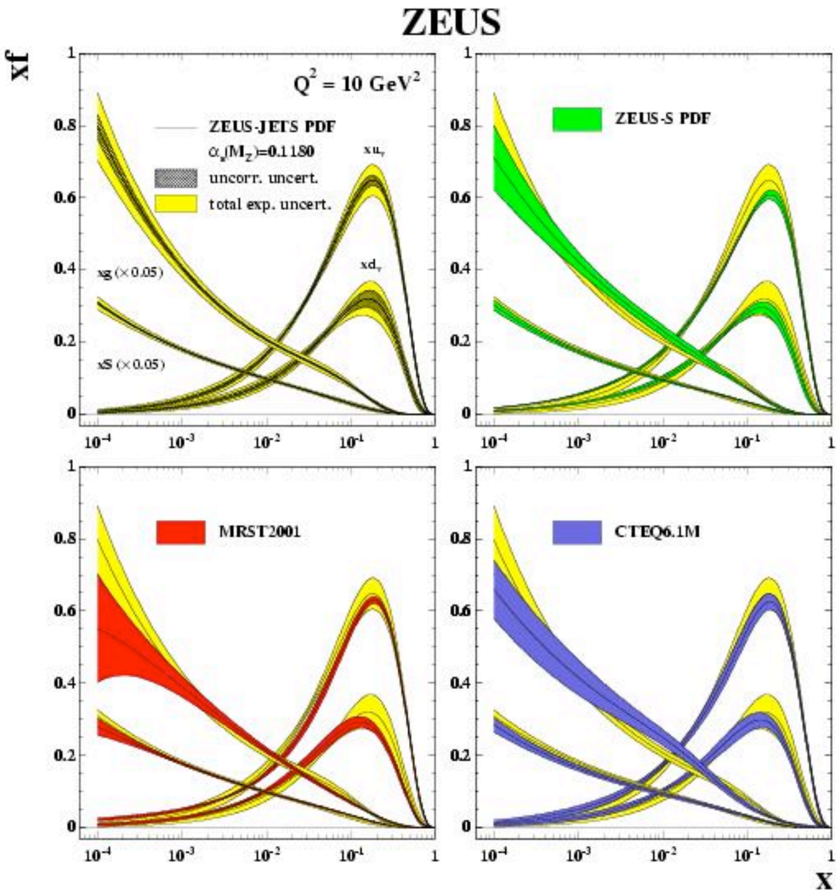
(charm production is the same diagram!)

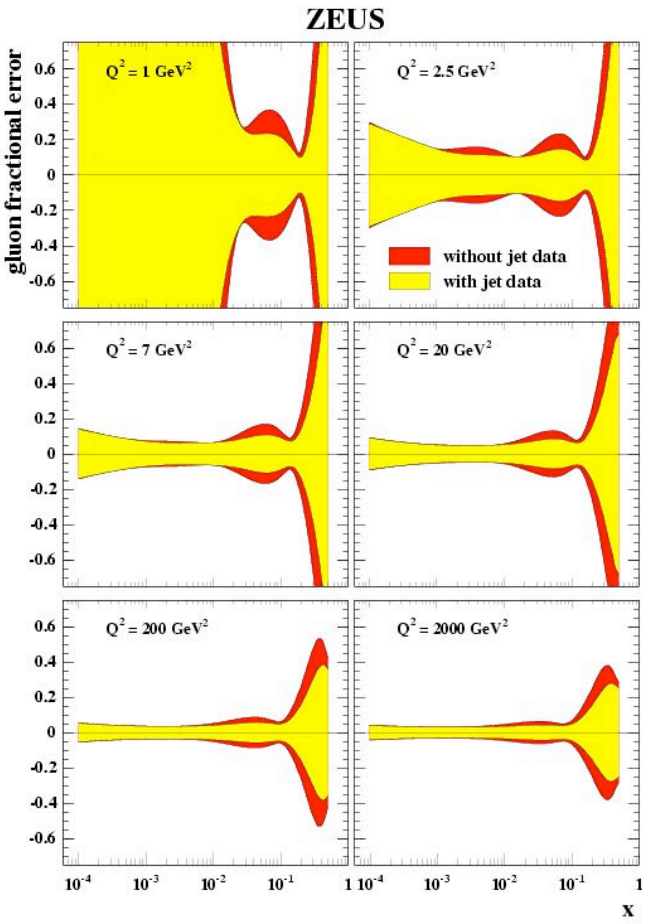


- Small uncertainties on jet energy scale
- Well understood correlations between points

- Never included before rigorously at NLO
  - Not even by CTEQ or MRST
- Computationally impossible
- Use theory program to calculate a grid of weights from the pQCD predictions and then interpolate

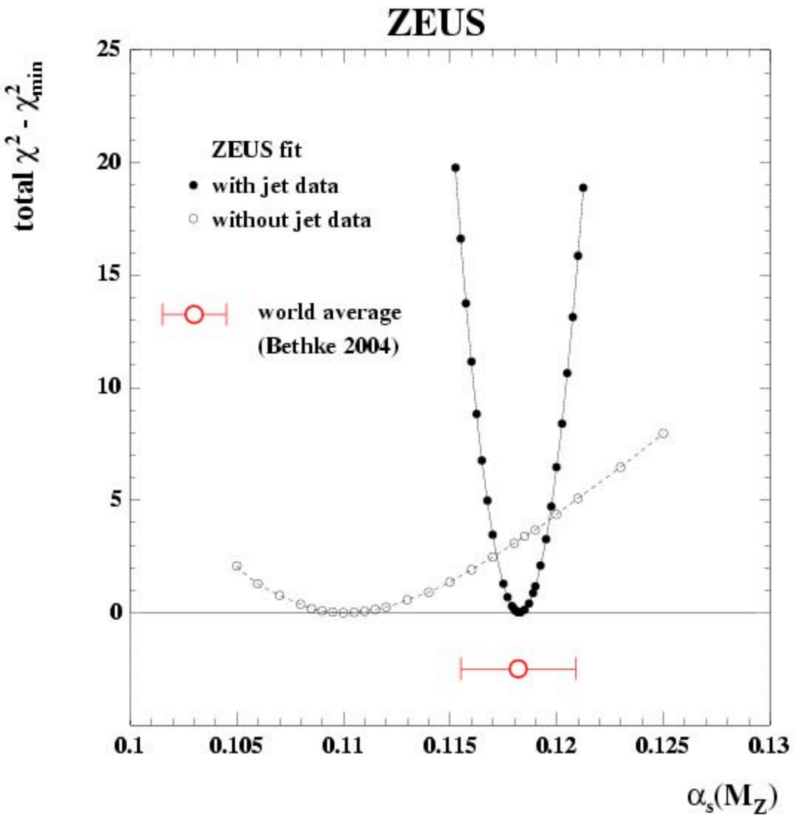
Fit results

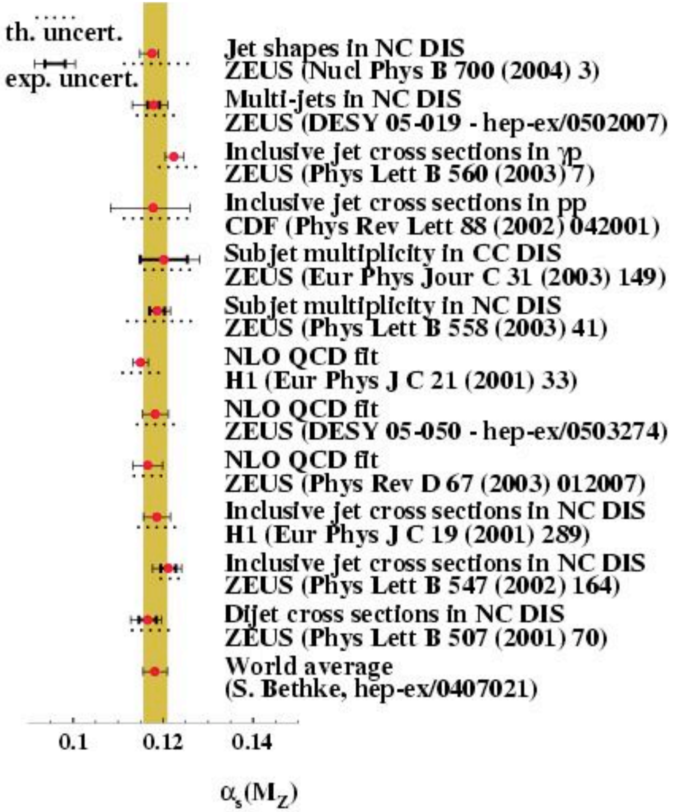




First time exclusive processes from HERA included
Improvement in gluon uncertainty at mid-high x

α_S determination



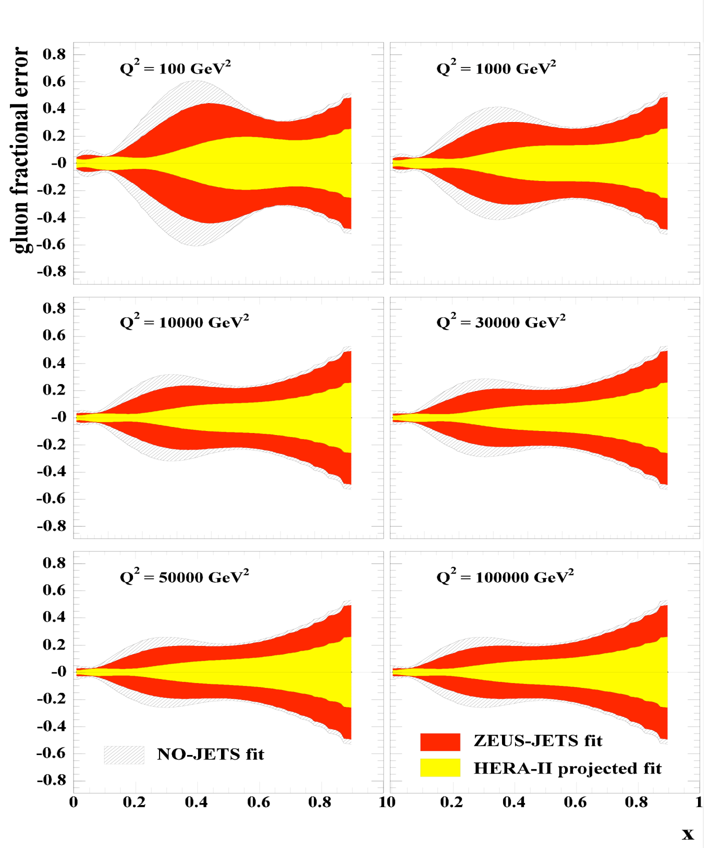


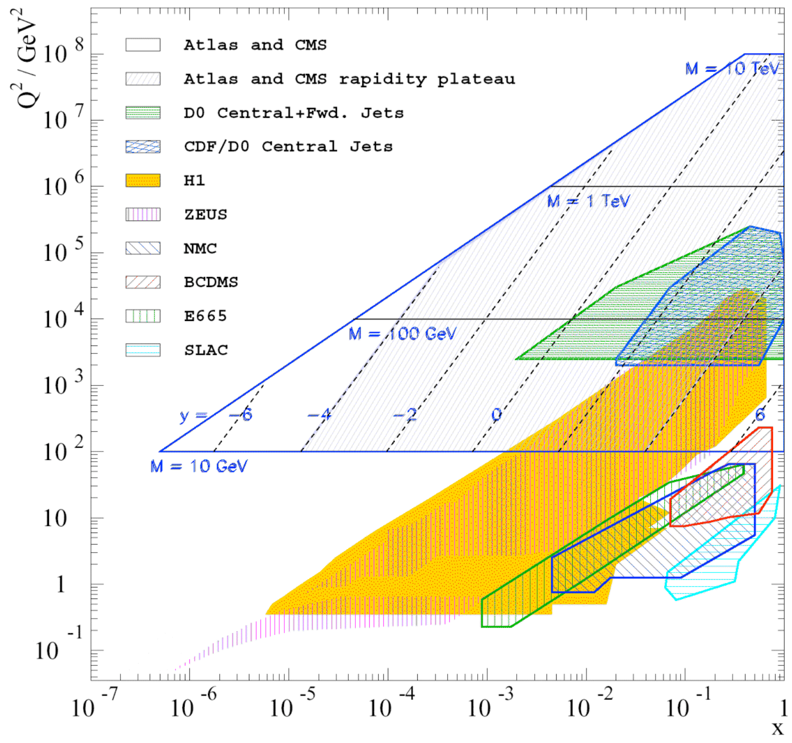
Jet data constrains α_S:

$\alpha_S(M_Z)$ = 0.1183 ±0.0028 (exp) ±0.0008 (model)

Theoretically limited! Need NNLO QCD

Future measurements



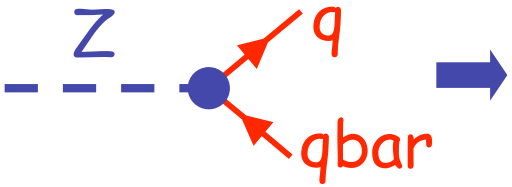


Expect large improvement in gluon precision at high x

- relevant for LHC

What about other parameters: Electroweak fits

Z^0 couplings to quarks:



$$\frac{ig}{\cos\theta_W}\gamma^\mu \frac{v_q - a_q\gamma^5}{2}$$

$a_q = I_3^L$ Axial coupling, I^3=+1/2 for u, -1/2 for d

$v_q = I_3^L - 2e_q \sin^2\theta_W$ Vector coupling

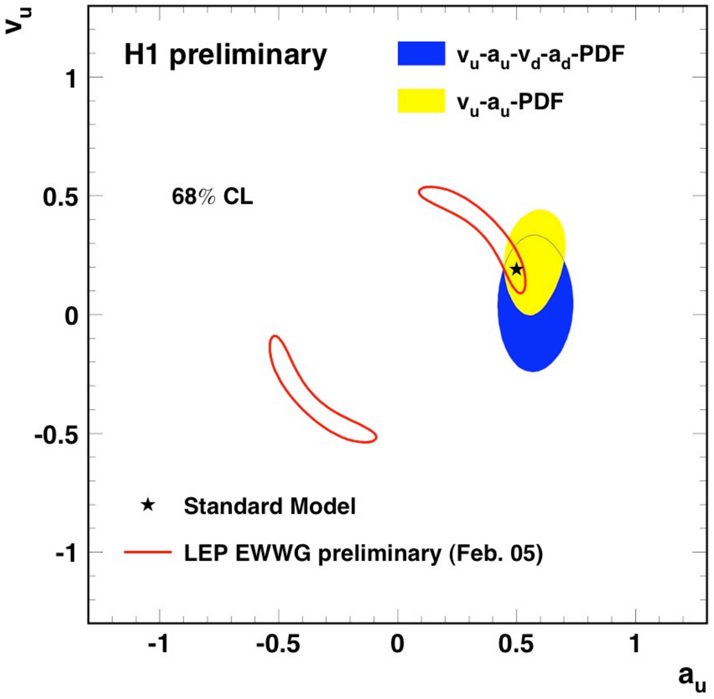
These terms found in NC DIS at high Q^2

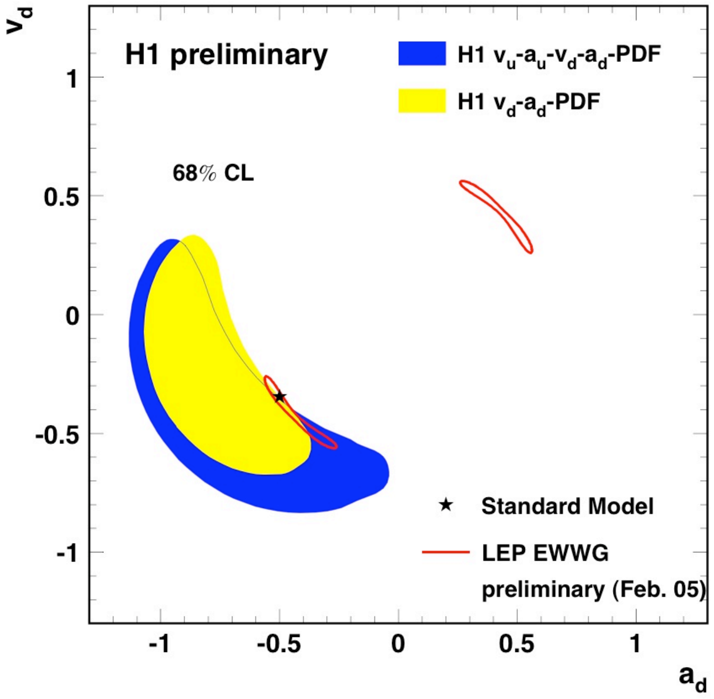
$$F_2 = \sum_q \left[e_q^2 - 2e_q v_q v_e \chi_Z + \left(v_q^2 + a_q^2\right)\left(v_e^2 + a_e^2\right)\chi_Z^2\right] x(q+\bar{q})$$

$$xF_3 = \sum_q \left[-2e_q a_q a_e \chi_Z + 4v_q a_q v_e a_e \chi_Z^2\right] x(q-\bar{q})$$

Fit simultaneously for the PDFs and also the couplings

Electroweak fit





First measurement of Z^0 couplings at HERA

More sensitivity to u than d, just from quark content of the proton

Should both improve with more luminosity and $v_{u,d}$ with polarised data

Polarised DIS cross sections

NC cross section modified by P:

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[H_0^{\pm} + PH_P^{\pm}\right] \qquad P = \frac{N_R - N_L}{N_R + N_L}$$

Unpolarised contribution

Polarised contribution - only includes Z and γZ terms

Polarised contribution only significant at high Q^2 - subtle effect at HERA

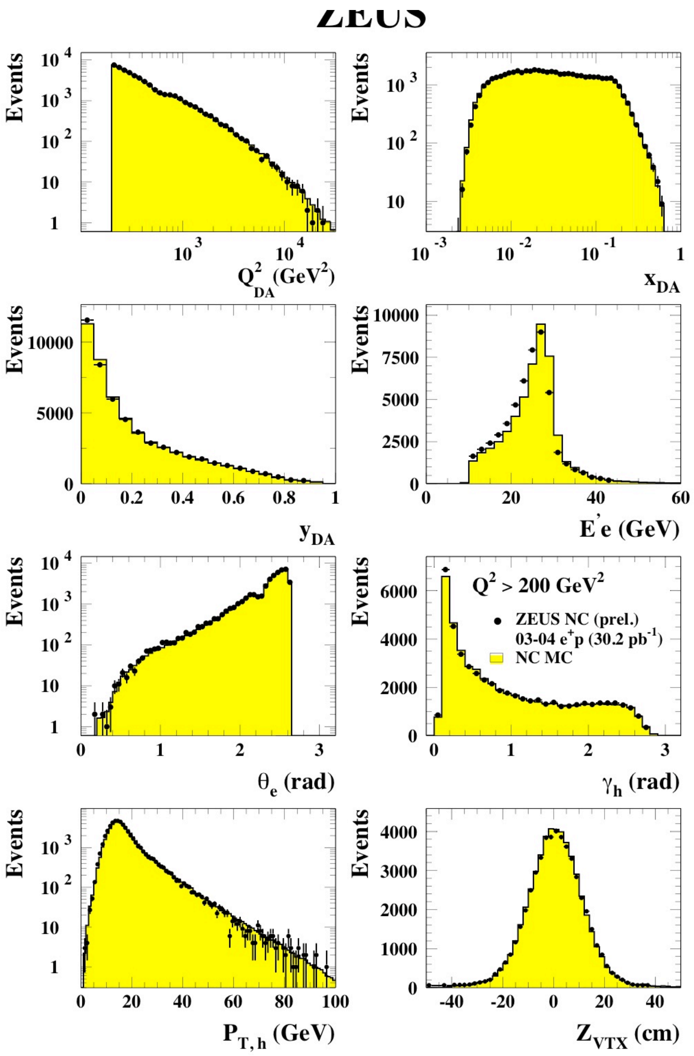
CC cross section modified by P:

$$\sigma_{CC}^{e^{\pm}p}(P) = (1 \pm P)\cdot\sigma_{CC}^{e^{\pm}p}(0)$$

Polarisation scales P=0 cross section linearly - clear and large effect at HERA

Pure V-A structure of the SM - no right-handed charged currents

Detector calibration



- Use NC DIS events to make precise in-situ calibration of the detector
- Use kinematic redundancy to measure energy scale from angles
- Also use E/p and presampler detectors to calibrate EM energy scale
- Balance electron P_T with hadronic P_T to determine HAD energy scale
- Detector response well understood
- Proceed to measuring CC DIS cross sections

Charged current cross sections

$Q^2 > 200$ GeV^2

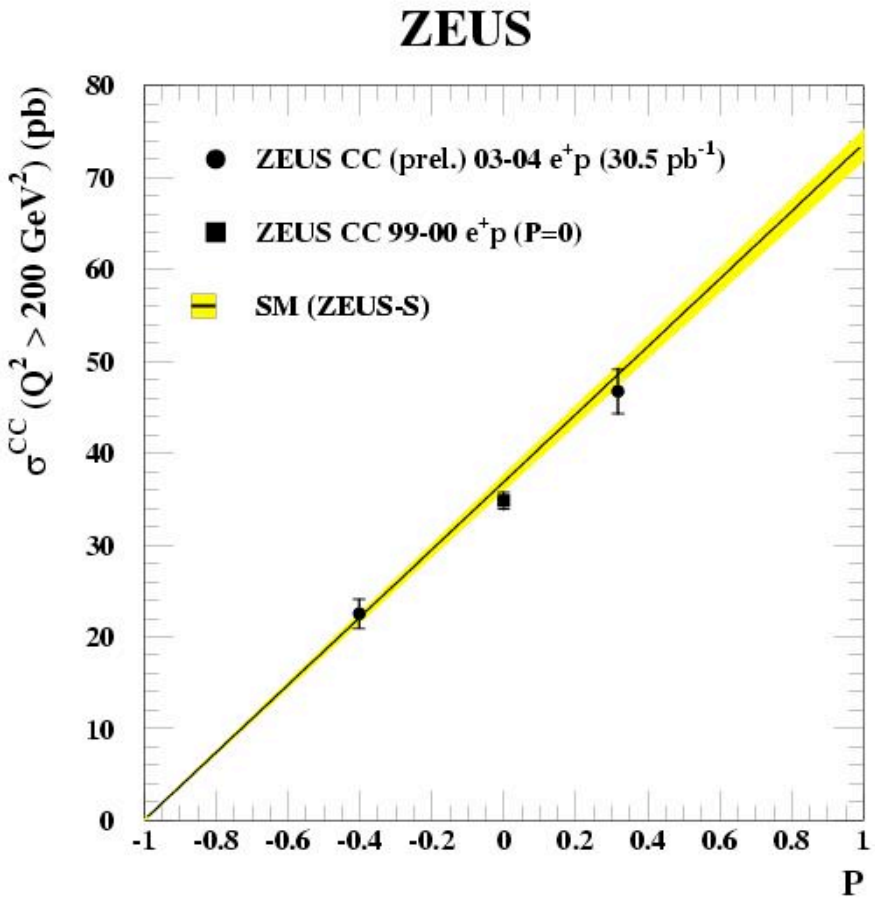
$P = +31.8 \pm 0.9\%$
$L = 14.1$ pb^{-1}

$\sigma = 46.7 \pm 2.4$ (stat.) ± 1.0 (syst.)
± 2.3 (lumi) pb

$P = -40.2 \pm 1.1\%$
$L = 16.4$ pb^{-1}

$\sigma = 22.5 \pm 1.6$ (stat.) ± 0.5 (syst.)
± 1.1 (lumi) pb

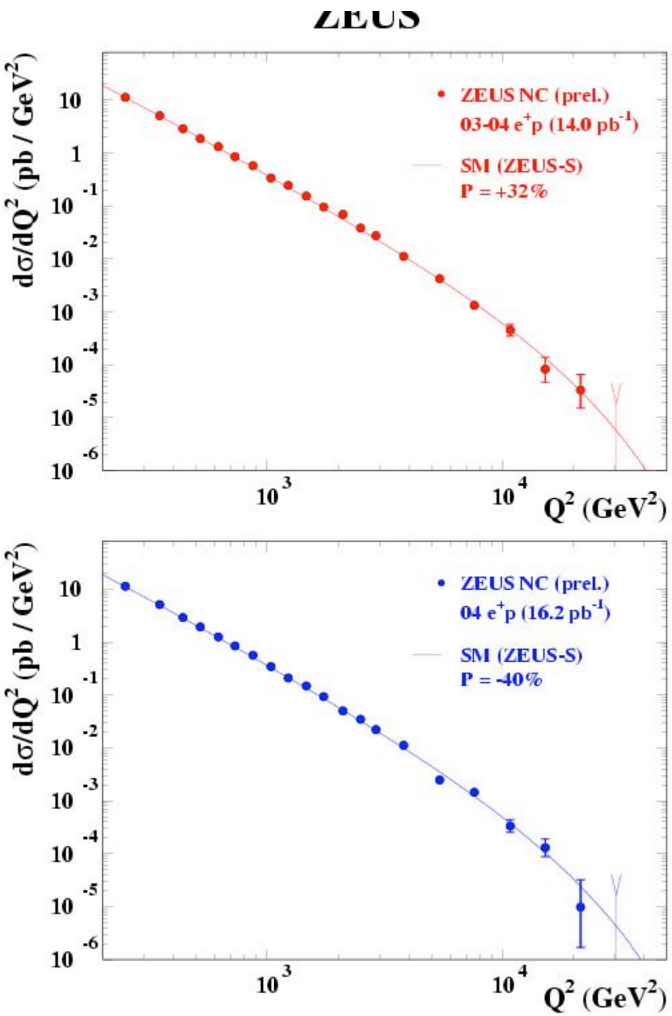
No hint of right-handed charged current $\sigma(P=-1)=0$



Expect e^-p measurements very soon

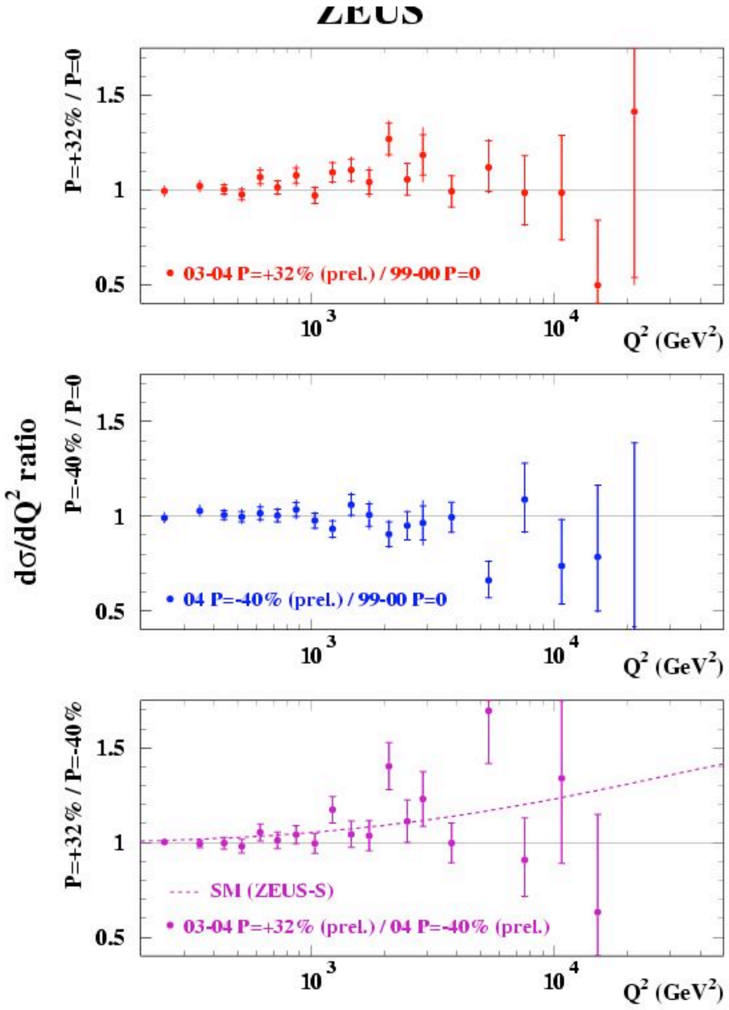
Neutral current cross sections

- Polarisation effect more subtle in NC
- Only in Z^0 exchange, therefore at high Q^2
- Look to see if we observe it yet
- $d\sigma/dQ^2$ cross sections for polarised e^+p samples
- Well described by Standard Model predictions



Neutral current cross sections

- Ratio of polarised cross sections
- Unpolarised cross sections from Phys. Rev. D 70 (2004) 052001
- Precision statistically limited
- Not yet conclusive observation of effect of longitudinal polarisation on cross sections
- Consistent with Standard Model prediction

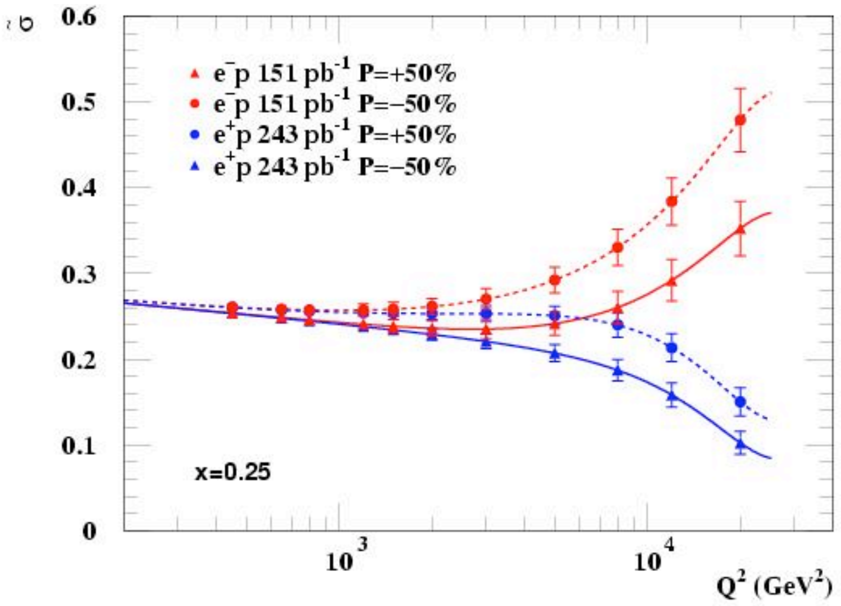


Future prospects for polarised measurements

Measure left and right handed cross sections for e^+p and e^-p Scattering in NC and CC

Search for evidence of right-handed charged currents

Extract couplings of Z^0 to the light quarks with high precision



Challenging!

Need highest possible luminosity and polarisation

SUSY searches at ZEUS

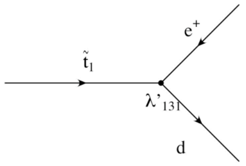
- Usually search for R-parity violating SUSY at HERA
- R_P is $(-1)^{3B+L+2S}$
  - +1 for SM particles
  - -1 for sparticles
- Gives terms in superpotential:

$$W_{\not{R}_P} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i D_j \overline{D}_k + \ldots$$

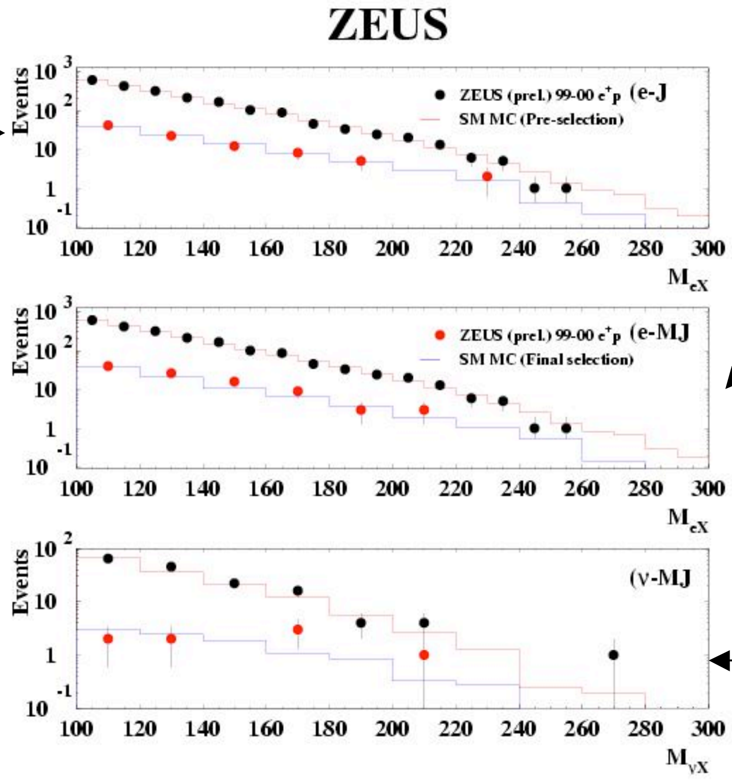
- Sparticles can be singly produced (good for HERA)
- LSP unstable (bad for cosmology)
- General searches for example resonant squark production in eq fusion already made
- Only MSSM here but others (e.g. GMSB and mSUGRA)

Search for stop production

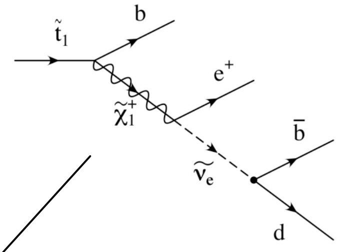
Assume stop the lightest sfermion (large mixing between t_L and t_R states)



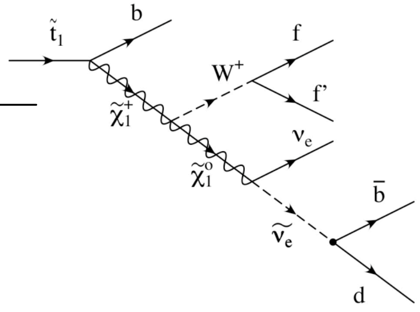
NC like single jet



NC like multi jet



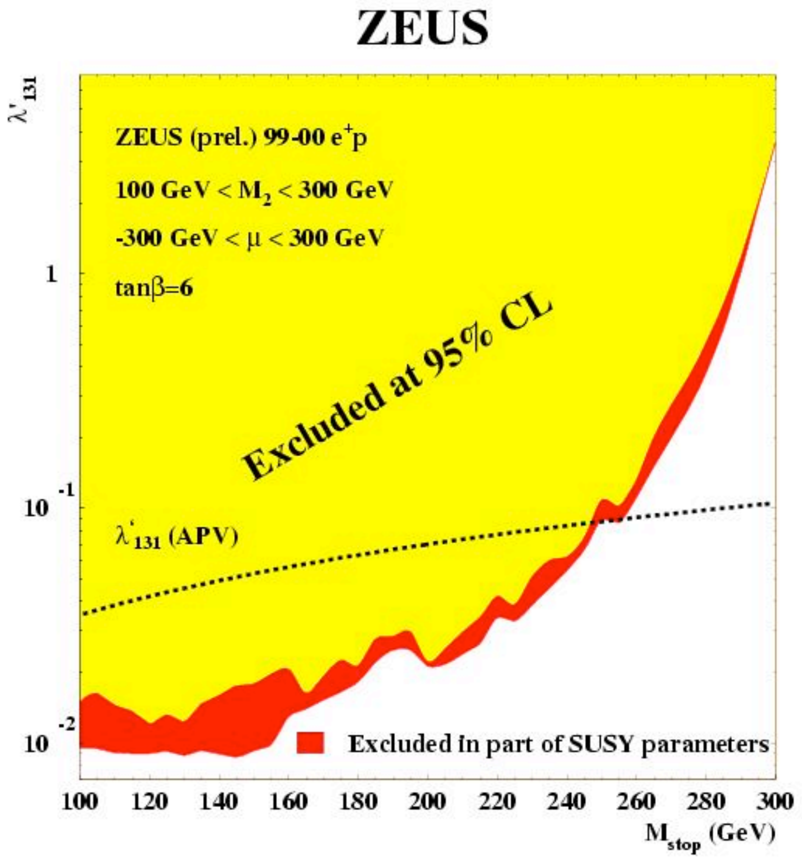
CC like



Cover almost full BR with three topologies

Search for stop production

- Limits @ 95% CL combining all three channels
- Use sliding mass window and Bayesian approach
- Limits not very sensitive to M_2 and μ at high M_{STOP}
- Stop masses up to 270 GeV can be excluded for em strength coupling
- Improves APV limits for M_{stop} > 275 GeV

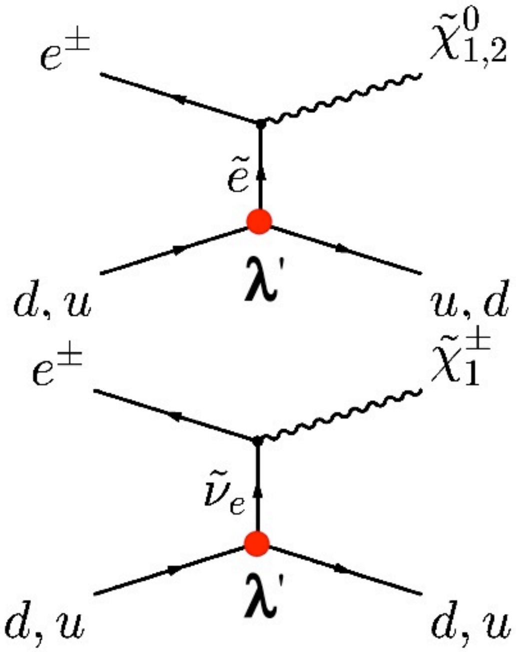


Search for gaugino production

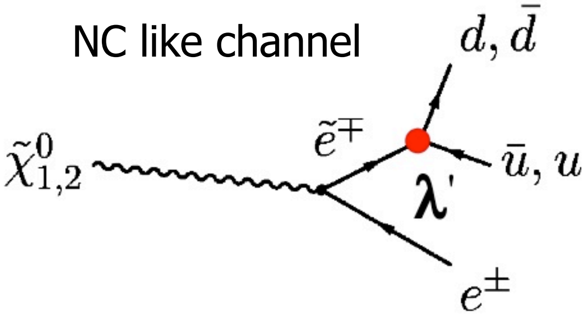
Consider

$M_{SQUARKS} >> M_{SLEPTONS}$
s-channel suppressed
t-channel slepton exchange

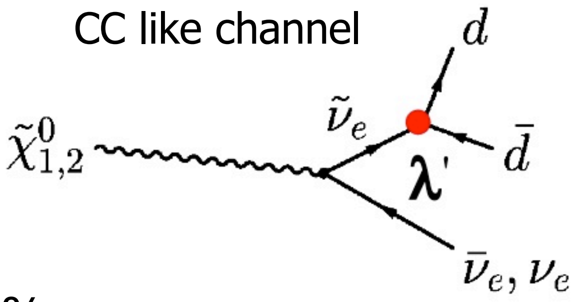
Assume neutralino is LSP
Assume $\lambda'_{111}=1$



NC like channel



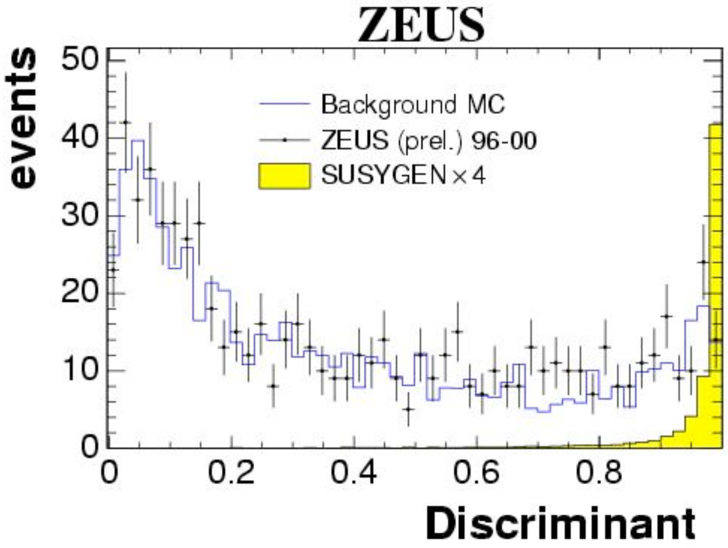
CC like channel

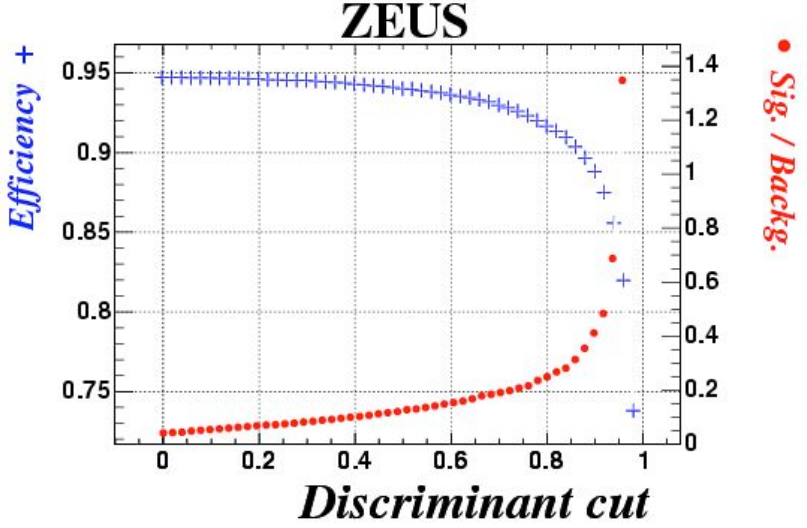


Only NC like channel so far… BR 30-60%

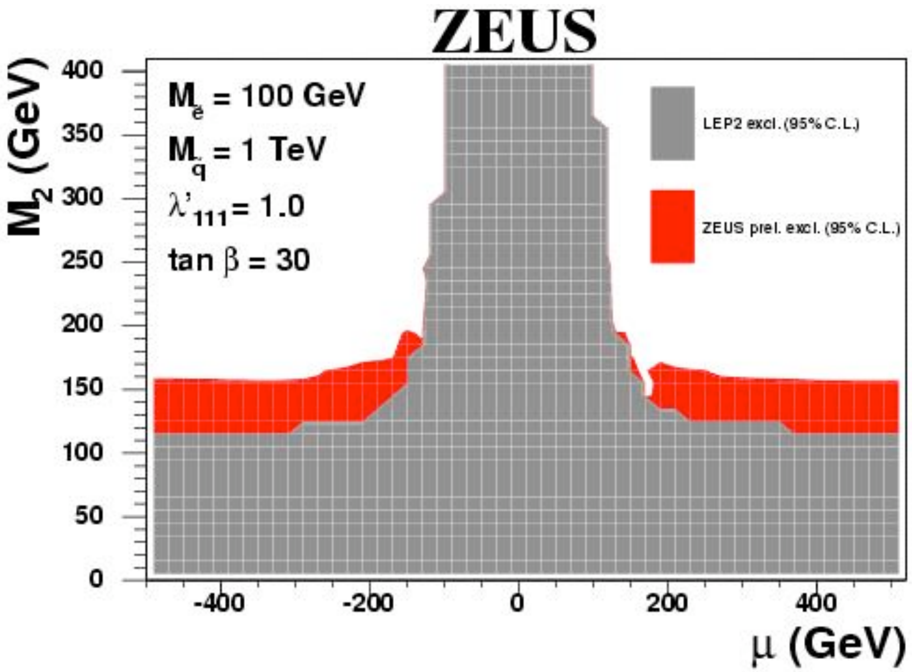
Search for gaugino production

- Select multi jet, high-E_T events with electron
- Use likelihood from multivariate discriminant to improve signal to background ratio
- No signal observed
- Set limits using D>0.7





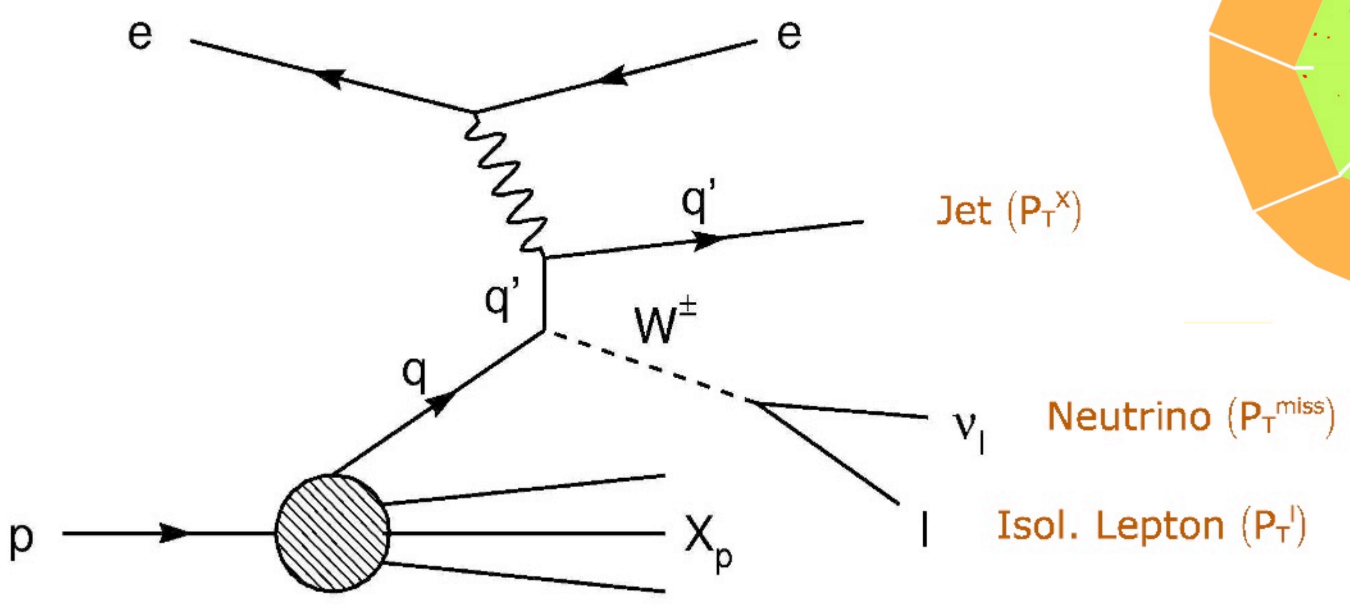
Search for gaugino production

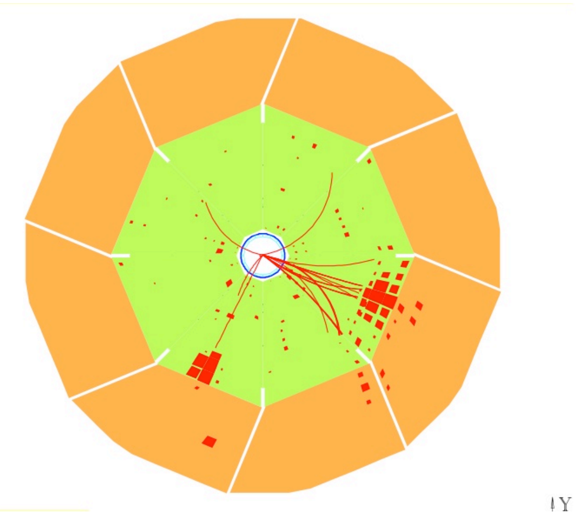


Extends LEP2 limits from ALEPH and DELPHI
(Eur. Phys. J. C37 (2004), hep-ex/0406009)
For high |μ| to M_2~160 GeV

Events with isolated high P_T leptons

SM Signal: Production of real W Bosons





- Cross-Section $\sigma(ep \rightarrow eWX) \approx 1pb$ (at NLO)
- Branching Fraction $W \rightarrow l\nu \approx 10\%$ each for e,μ,τ

Events with isolated high P_T leptons

$e^{\pm}p$ data (1994-2005) 192 pb^{-1}

	Electron obs./exp. (W)	Muon obs./exp. (W)	Tau① obs./exp. (W)
All P_T^X	25/18.3 ± 2.5 (70%)	9/4.8 ± 0.8 (85%)	5/5.8 ± 1.4 (15%)
P_T^X > 25 GeV	11/3.0 ± 0.6 (81%)	6/3.0 ± 0.6 (86%)	0/0.5 ± 0.1 (49%)

① **$e^{\pm}p$ (1996-2000) 108 pb^{-1}**

$e^{\pm}p$ data (1994-2000) 130 pb^{-1}

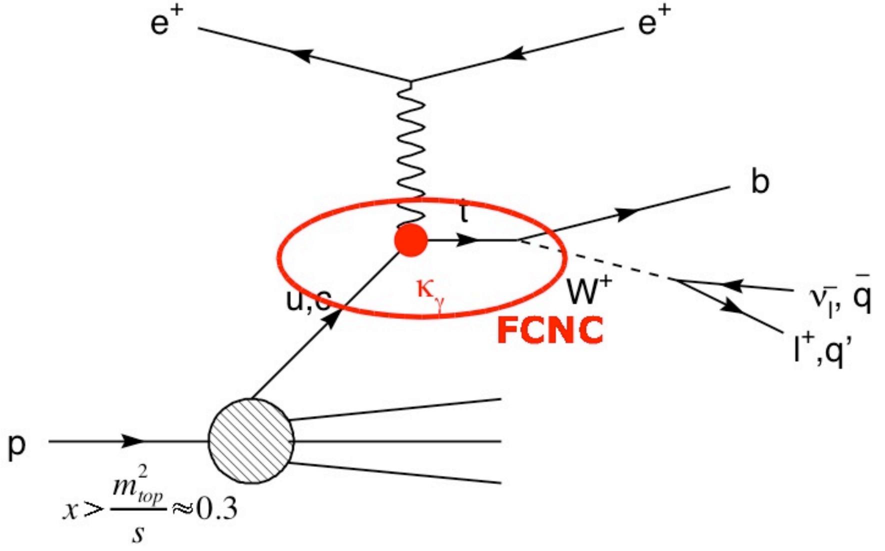
	Electron obs./exp. (W)	Muon obs./exp. (W)	Tau obs./exp. (W)
All P_T^X	$24/20.6^{+1.7}_{-4.6}$ (17%)②	$12/11.9^{+0.6}_{-0.7}$ (16%)②	3/0.40 ± 0.12 (43%)
P_T^X > 25 GeV	2/2.90 ± 0.6 (45%)	5/2.75 ± 0.21 (50%)	2/0.20 ± 0.05 (49%)

② **Preselection**

Excess reported by H1 is not confirmed by ZEUS

Single top production?

Motivation: explains the large hadronic Transverse Momenta observed in the “Isolated Lepton” Events as P_T of b-Jets resulting from t → bW Decays



- SM single top Production highly suppressed ($\sigma < 1$fb)
- Flavour-Changing Neutral Current (FCNC) Interactions may yield observable Cross-Sections

Single top production

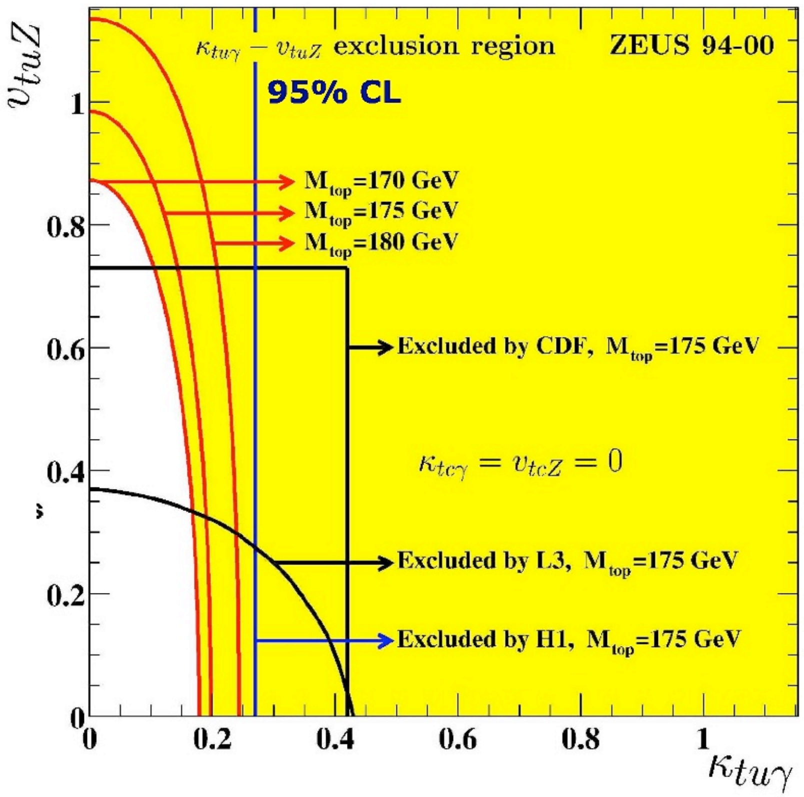
Multivariate likelihood analysis to determine cross section

$$\sigma(ep \rightarrow etX) = 0.29^{+0.27}_{-0.14}\,\text{pb}$$

giving

$$\kappa_{tu\gamma} = 0.20^{+0.05}_{-0.06}$$

Not ruled out by limits from other experiments



Statistical fluctuation?

More data needed

Prospects for HERA II

- Proton structure
  - Measurements at high Q^2 and xF_3
  - Jet and heavy flavour measurements also constrain the gluon at high x

- Electroweak
  - Measurements of polarised cross sections test the chiral nature of the SM and extract parameters

- Searches
  - Tantilising excess from H1 to be investigated
  - Still space for SUSY, leptoquarks, LFV, LED etc.

The future of HERA

- HERA II scheduled to finish mid 2007
- Expected to accumulate around 600 pb^{-1} per experiment by then
- Currently discussion about lower/higher energy running in the last few months
- PETRA injector ring then to be a synchrotron radiation source so really the end.