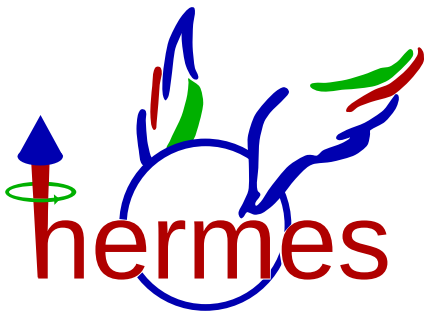
HERA Physics: Status and Prospects

Andrew Mehta

University of Liverpool

on behalf of the

H1, ZEUS and Hermes Collaborations



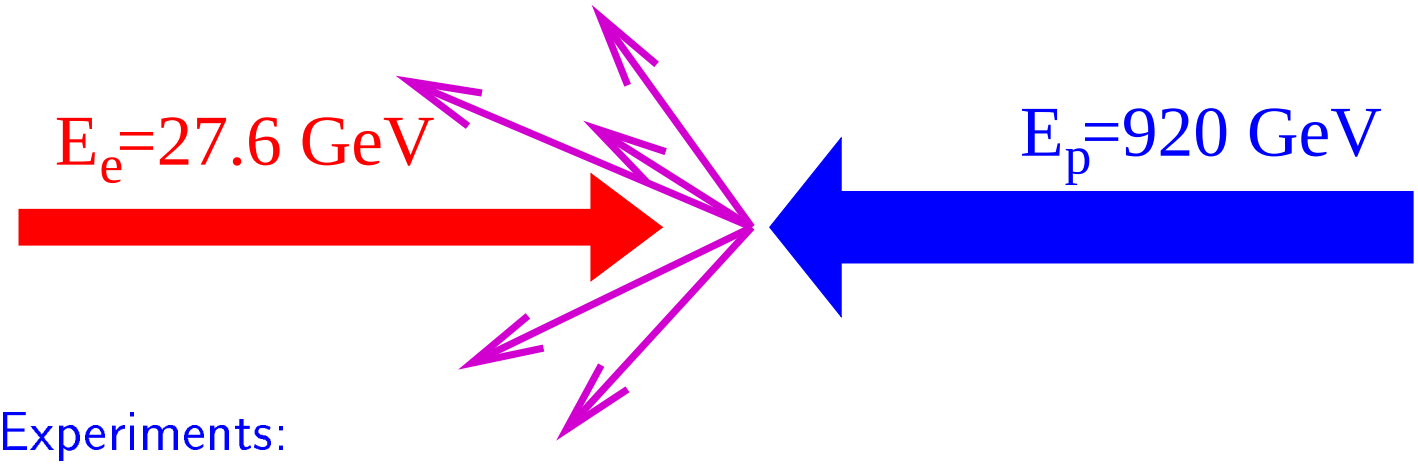
68th Plenary ECFA Meeting, 1.12.2000

Contents

- **HERA and Deep Inelastic Scattering**
- **Proton structure**
  - F_2 and F_L
  - Gluon density
  - Transition to nonperturbative regime
- **Spin structure of nucleon**
- **Exclusive Measurements**
  - α_s from Jets
  - Beauty production
  - Diffraction
- **CC and NC reactions at high Q^2**
- **Searches**
  - W events
  - Leptoquarks
  - Excited fermions
- **Future perspectives**

Only a tiny selection of available results!

HERA



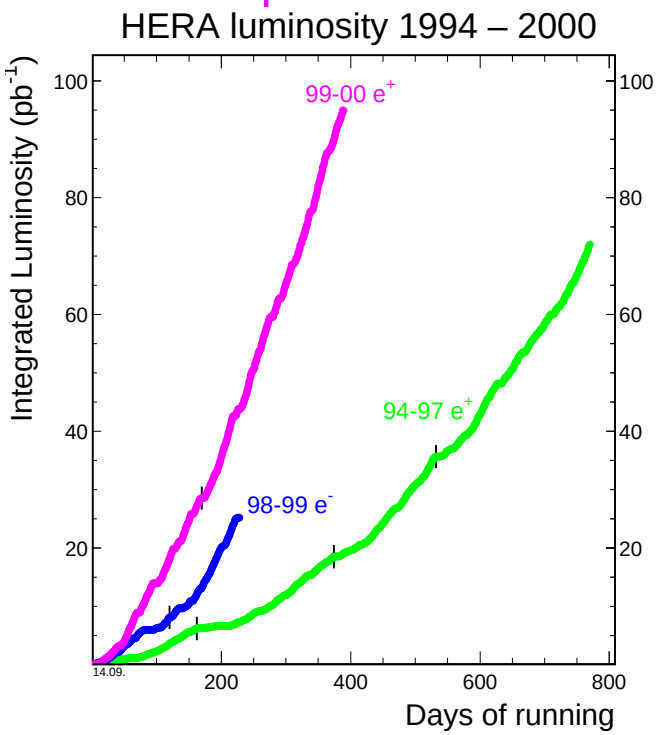
Experiments:

– H1 and ZEUS: e and p beam: CMS-energy $\sqrt{s} \approx 320$ GeV

$\Rightarrow$ probe proton structure ($\lambda \approx 10^{-18}$ m)

– HERMES: polarised e beam on polarised targets

$\Rightarrow$ measure spin structure of the nucleon



1994-97: e^+p

– $E_p = 820$ GeV

$\Rightarrow \sqrt{s} = 300$ GeV

– $\mathcal{L} \approx 40$ pb^{-1} per Exp.

1998-2000

– $E_p = 920$ GeV

$\Rightarrow \sqrt{s} = 320$ GeV

e^-p $\mathcal{L} \approx 15$ pb^{-1} per Exp.

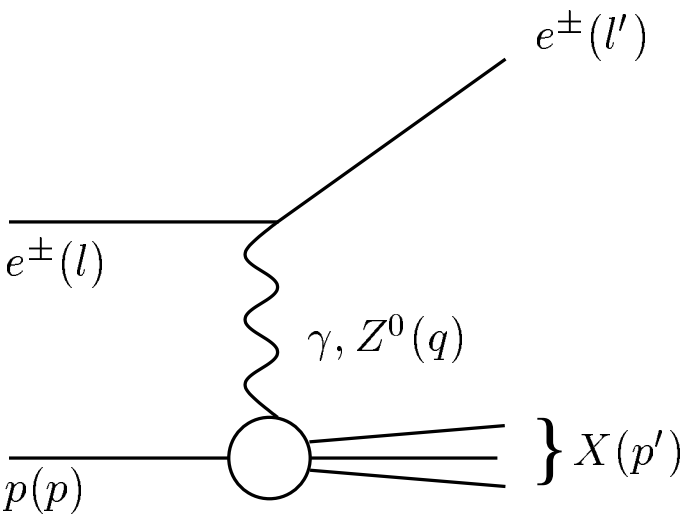
e^+p $\mathcal{L} \approx 65$ pb^{-1} per Exp.

HERA performance improving every year

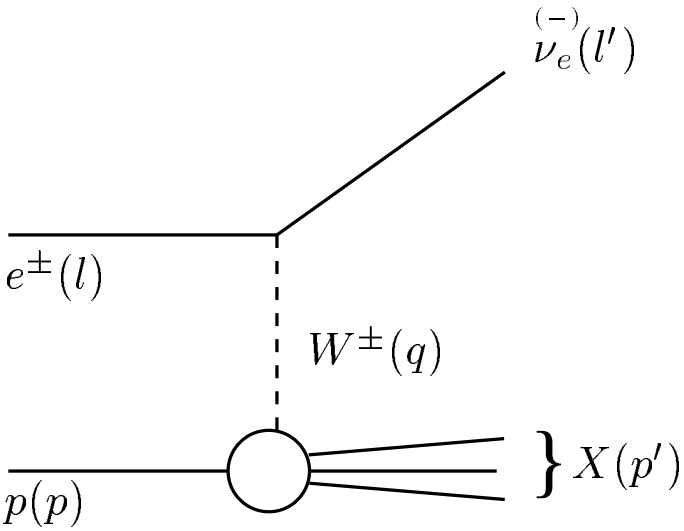
In 2000 design goals exceeded!

Deep Inelastic Scattering

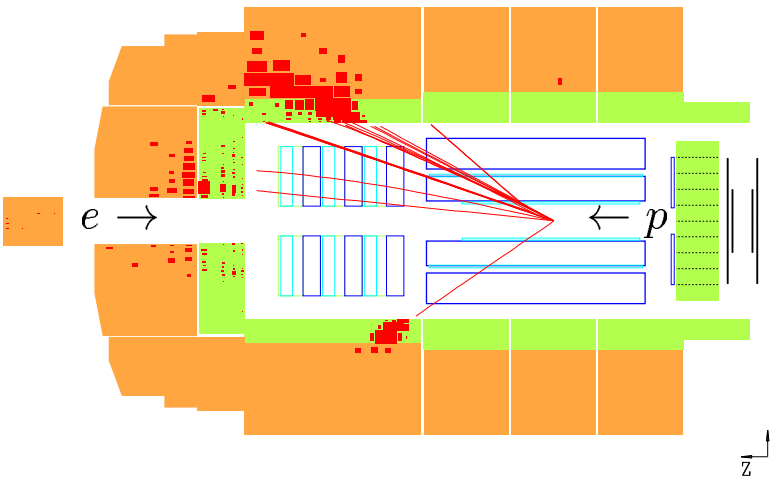
NC: $e^{\pm}p \to e^{\pm}X$



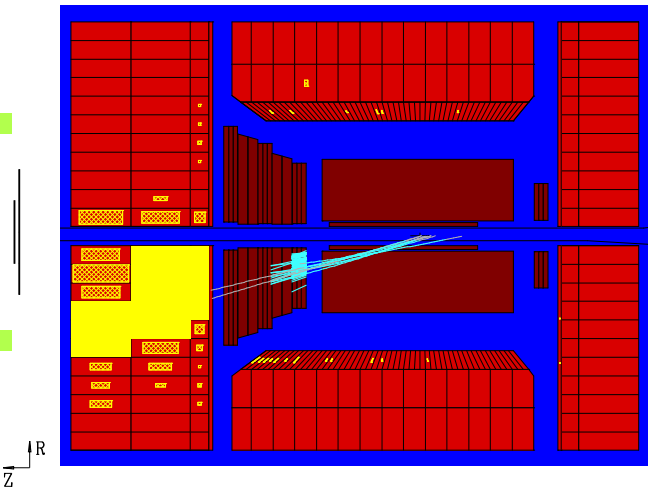
CC: $e^{\pm}p \to \nu X$



H1



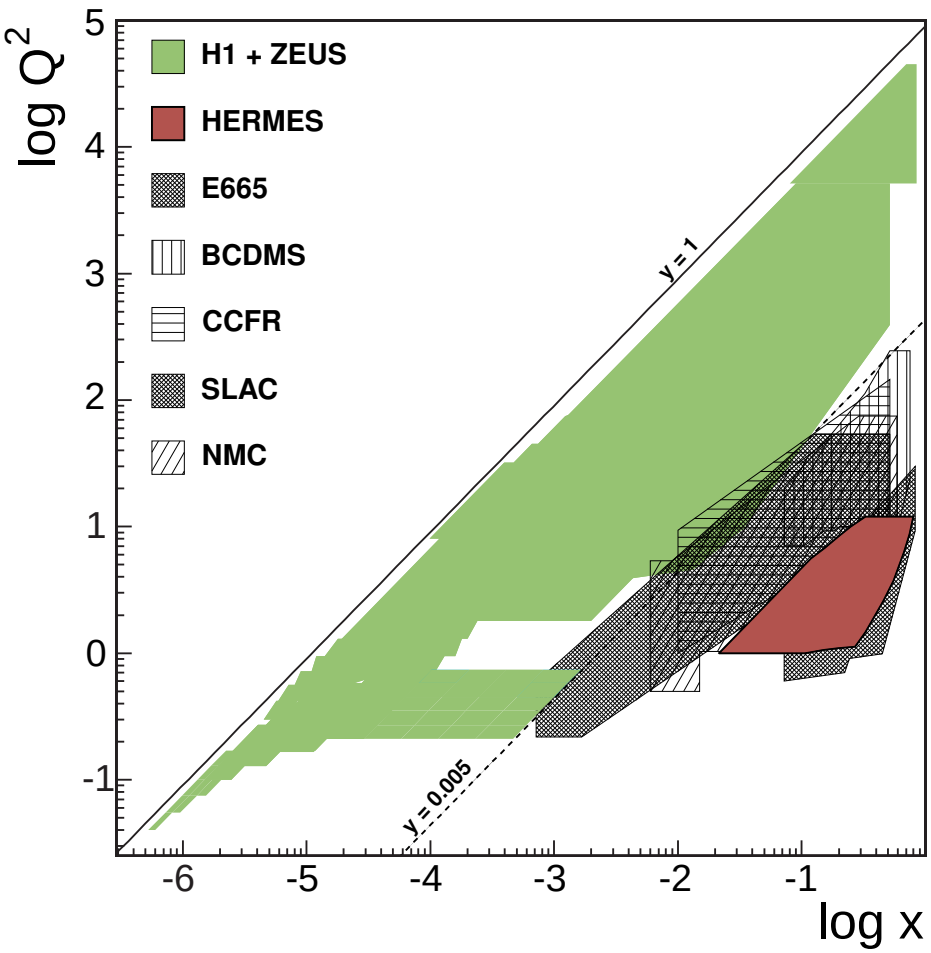
ZEUS



Kinematic Variables

$Q^2 = -q^2 = -(l - l')^2$	squared 4-momentum transfer
$x = Q^2/(2p \cdot q)$	Bjorken-x
$y = p \cdot q/(p \cdot l)$	Inelasticity

Kinematic Range



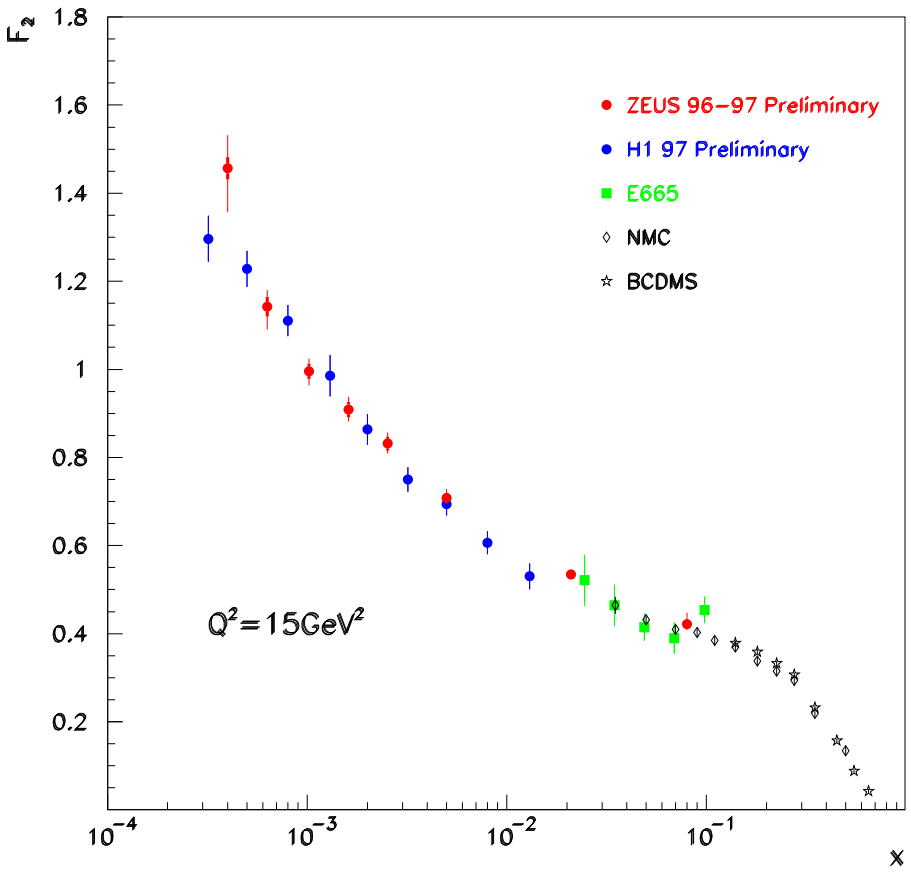
x	$\rightarrow 10^{-6}$	$\Rightarrow$ low x limit of pQCD
y_{HERA}	$\rightarrow 0.005$	$\Rightarrow$ overlap with fixed target experiments
Q^2	$\rightarrow 0.045$ GeV^2	$\Rightarrow$ transition from $\gamma^* p$ to γp ($Q^2 \approx 0$)
Q^2	$\rightarrow 50000$ GeV^2	$\Rightarrow$ EW sector, (new physics?)

Structure of the Proton

For $Q^2 \ll M_Z^2$:

$$\frac{\mathrm{d}\sigma^{NC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+F_2 - y^2F_L) \qquad Y_\pm = 1 \pm (1-y)^2$$

F_2 dominant at HERA for $y \lesssim 0.7$

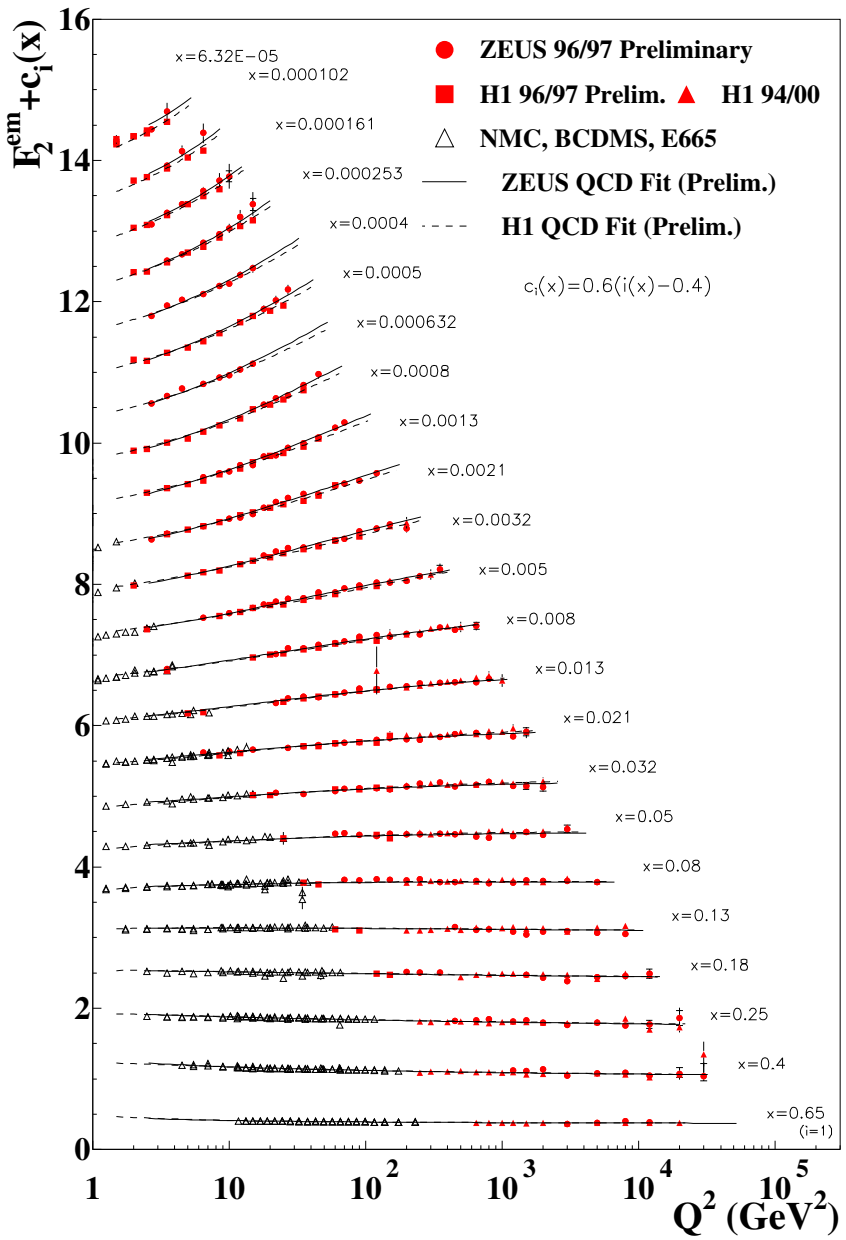


- $F_2 = x\Sigma_q e_q^2(q + \bar{q})$, measures quark density
- $\mathrm{d}F_2/\mathrm{d}\log Q^2$ measures gluon density
- Strong rise of F_2 towards low x

$\Rightarrow$ increasing parton density at low x

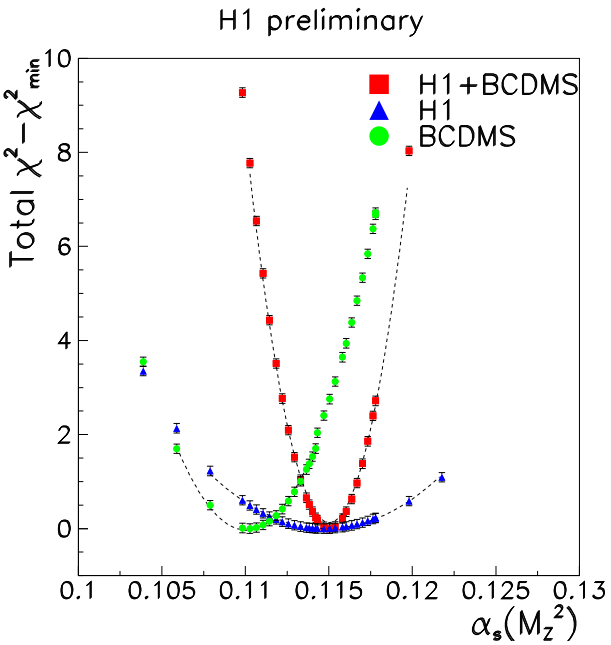
- High Precision: 1% (stat) $\oplus$ $3-4\%$ (syst)
- Good Agreement between H1 and Zeus
- Overlap with Fixed-Target Experiments

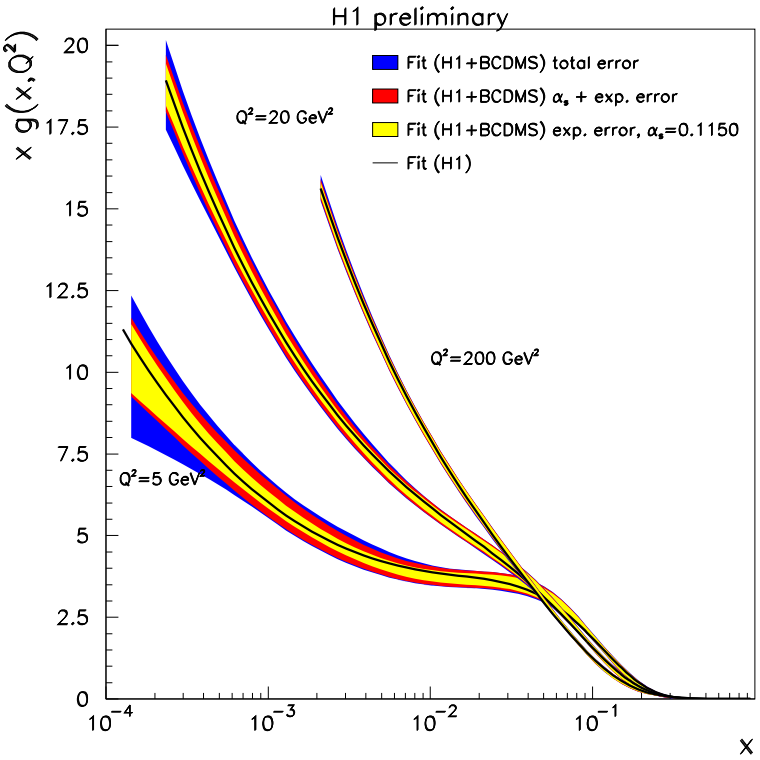
F_2 Measurements



- Kinematic range extended by orders of magnitude in Q^2 and x
- Scaling violations: positive at low x, negative at high x
- Data described by QCD down to $Q^2 \approx 1$ GeV^2
- Use fit to determine α_s and gluon

Fit Result on α_s and Gluon





preliminary result:

$$\alpha_s = 0.1150 \pm 0.0017(\text{exp})^{+0.0011}_{-0.0012}(\text{model})$$

± 0.005 due to renormalisation scale uncertainty

H1+BCDMS α_s larger than BCDMS alone
Value in good agreement with world average

Gluon density at low x known to 2–10% accuracy
Gets steeper as Q^2 increases

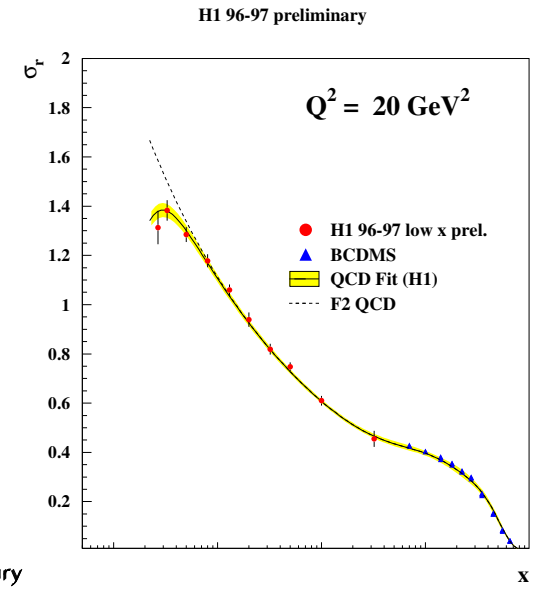
Longitudinal Structure Function

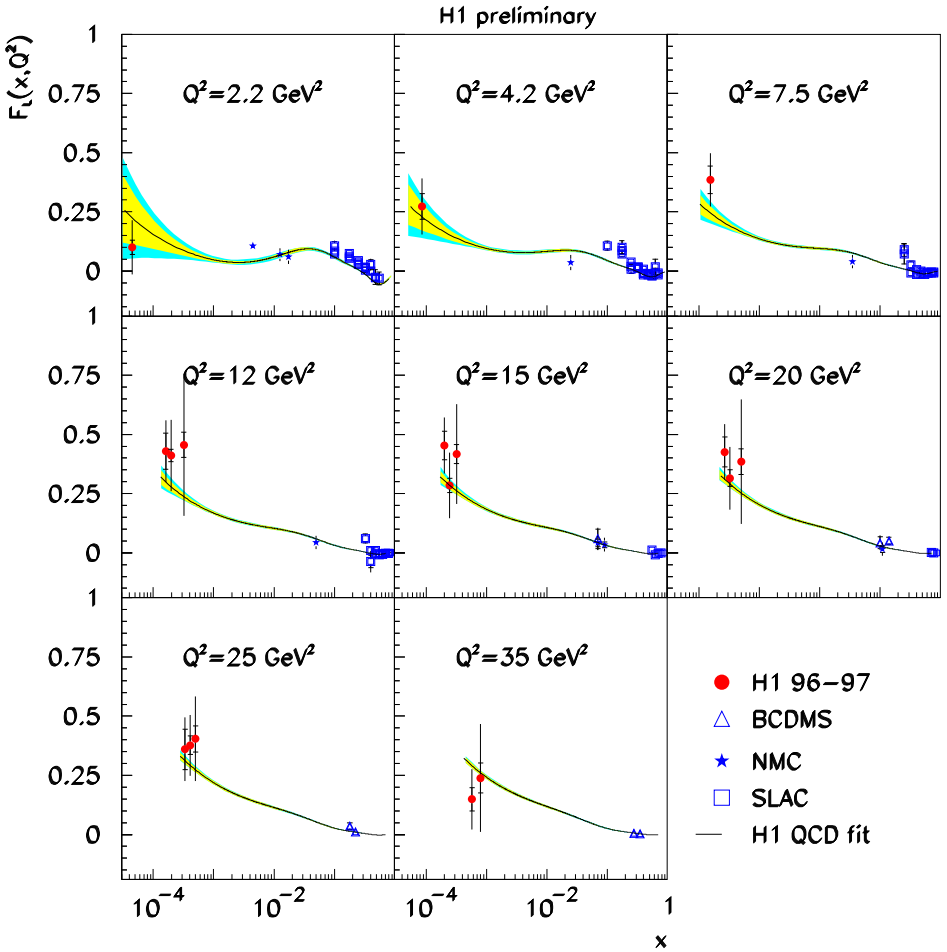
$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

Assume Q^2 evolution of F_2

(QCD Fit to data with $y < 0.4$)

$\Rightarrow$ Indirect measurement of F_L

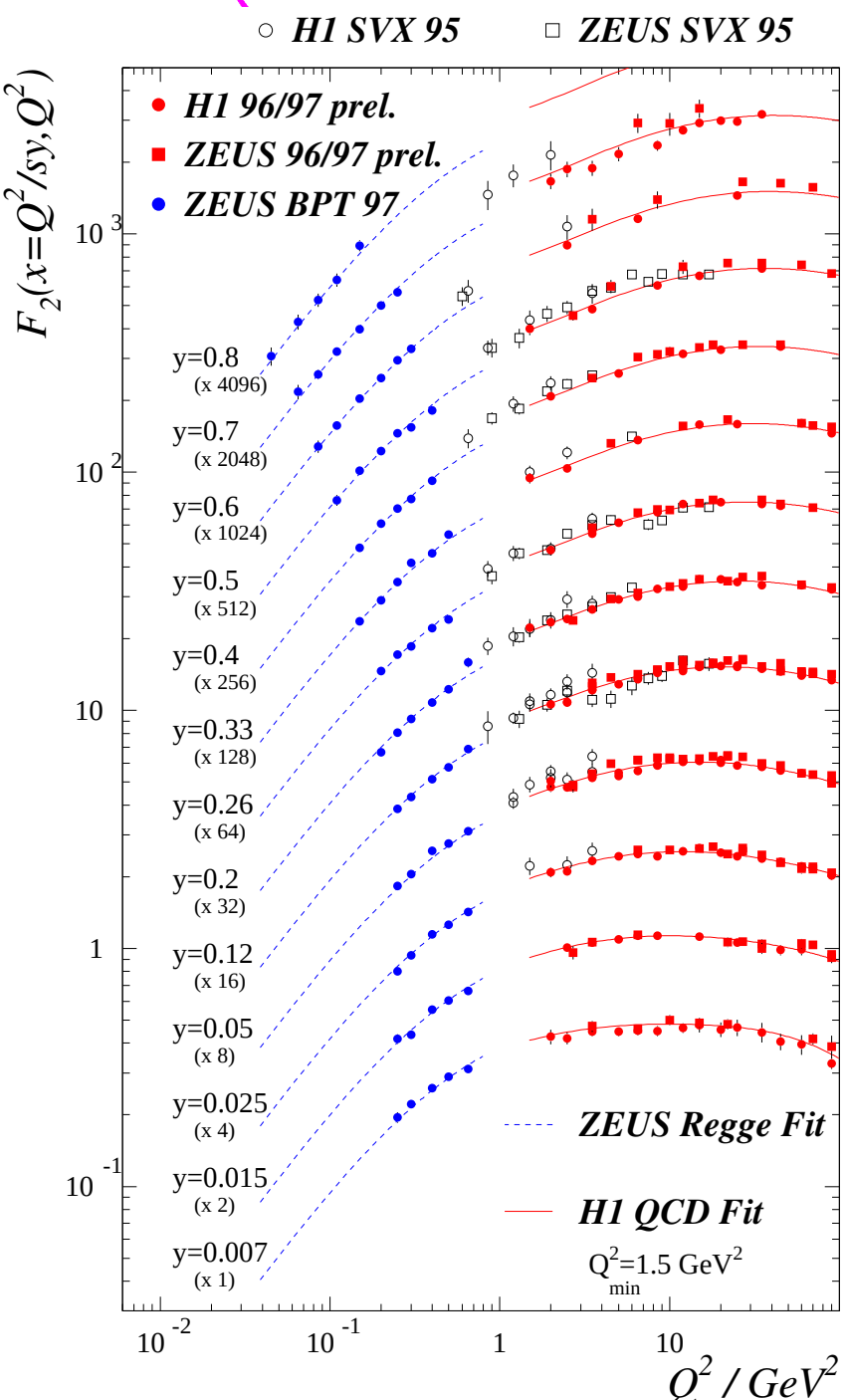




- F_L in agreement with NLO QCD fit
- x values 1000 times smaller than previous measurements
- Direct measurement in future by varying beam energies

F_2 at very low Q^2

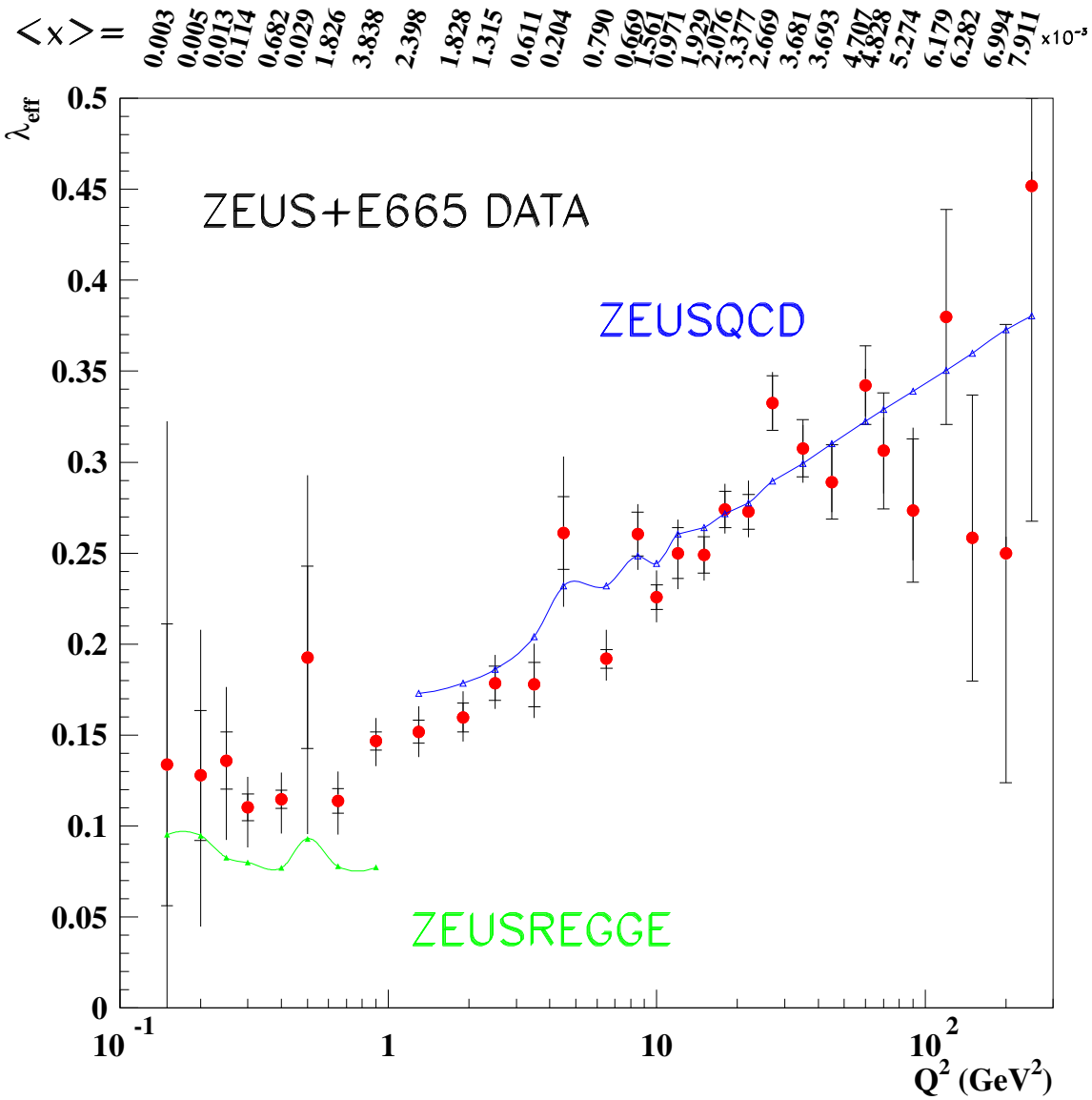
Transition between perturbative and non-perturbative QCD



- F_2 is small ($F_2 \propto Q^2$ for $Q^2 \to 0$)
- Regge models describe the data well

Very Low Q^2

Fit the form $F_2 \propto x^{-\lambda_{eff}}$

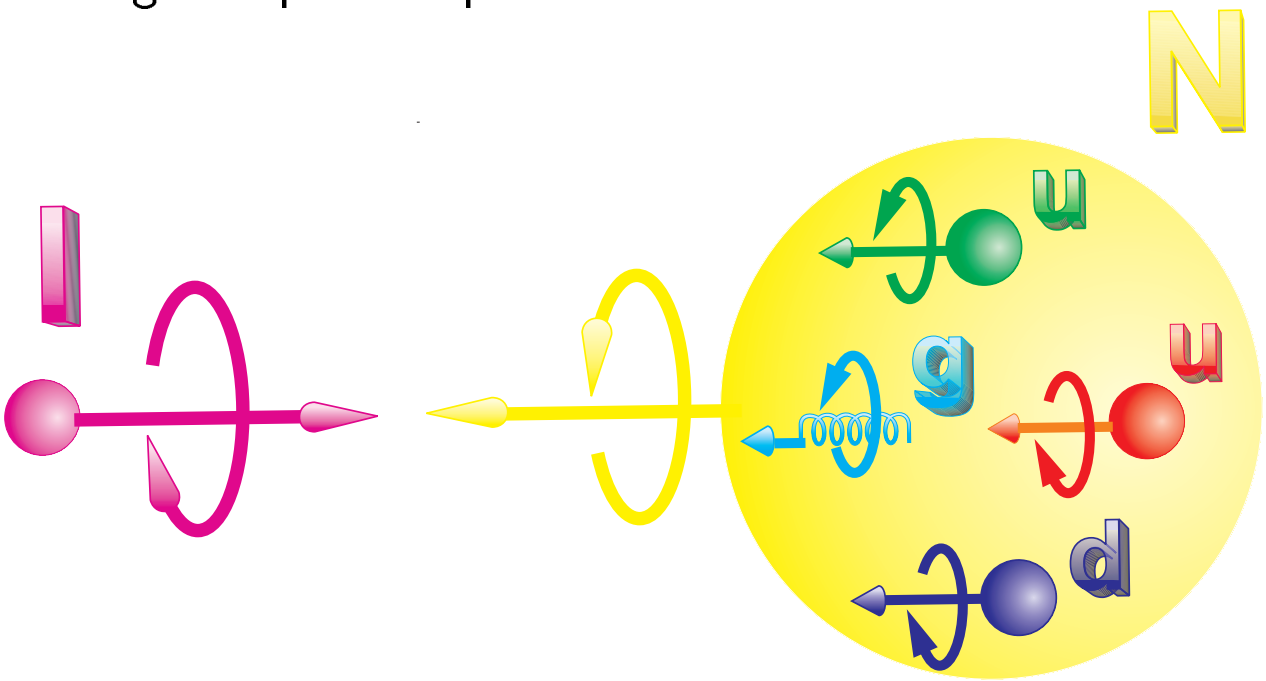


- F_2 rises more steeply towards low x as Q^2 increases
- QCD describes behaviour for $Q^2 > 1$ GeV^2
- At low Q^2 the data approach the soft pomeron limit ($\lambda_{eff} \approx 0.085$)

Spin Structure of the Nucleon

Scatter polarised e off polarised nucleon

$\Rightarrow$ origin of proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

From Deep Inelasitc Scattering:

– quark spins $\Delta\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$

– gluon spins $\Delta G = ?$

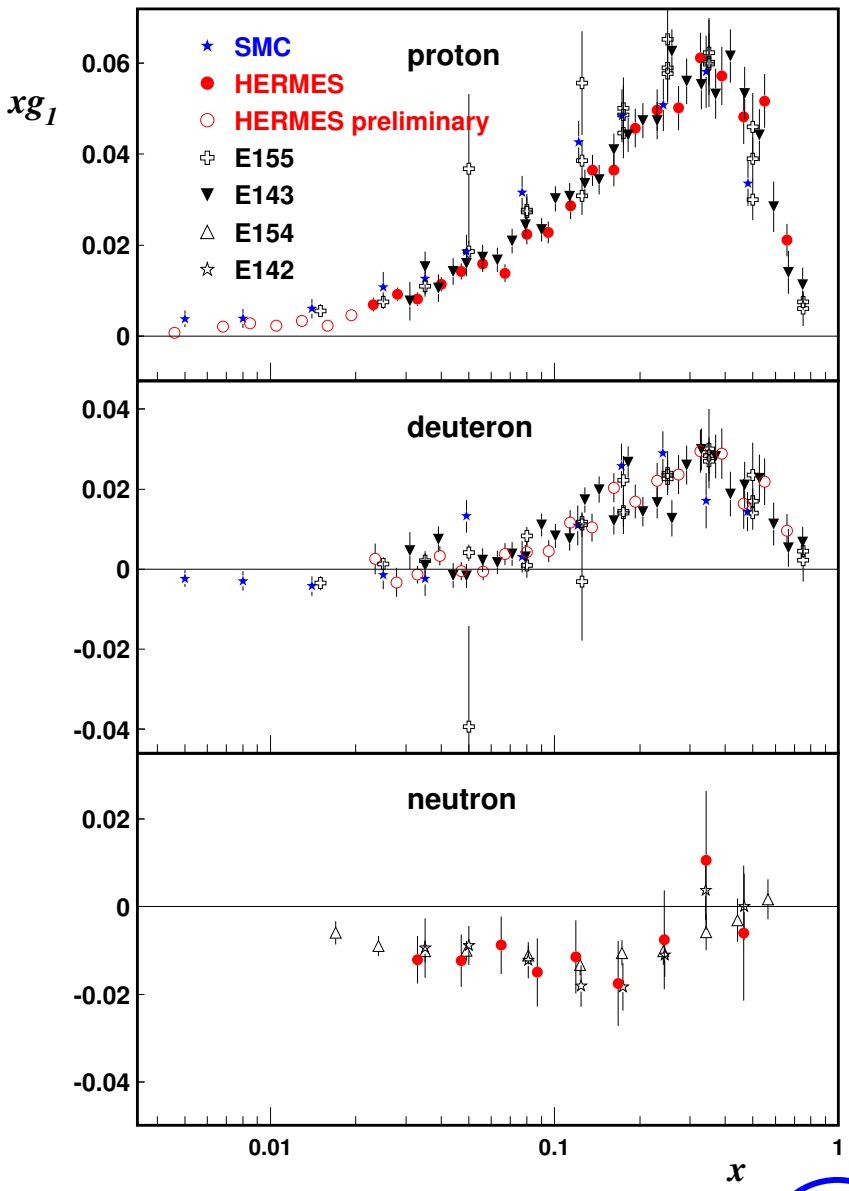
– orbital angular momenta $L_q, L_G = ?$

with $\Delta q(x) = q^+(x) - q^-(x)$

HERMES: measure Δu, Δd, Δq_s and ΔG

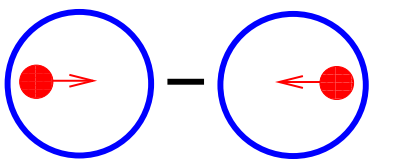
Targets: ^3He (1995), H (1996-97), D 1998-2000

Measurement of xg_1



g_1 measures quark helicty

$g_1 = \frac{1}{2}\Sigma_q e_q^2(\Delta q + \Delta\bar{q})$

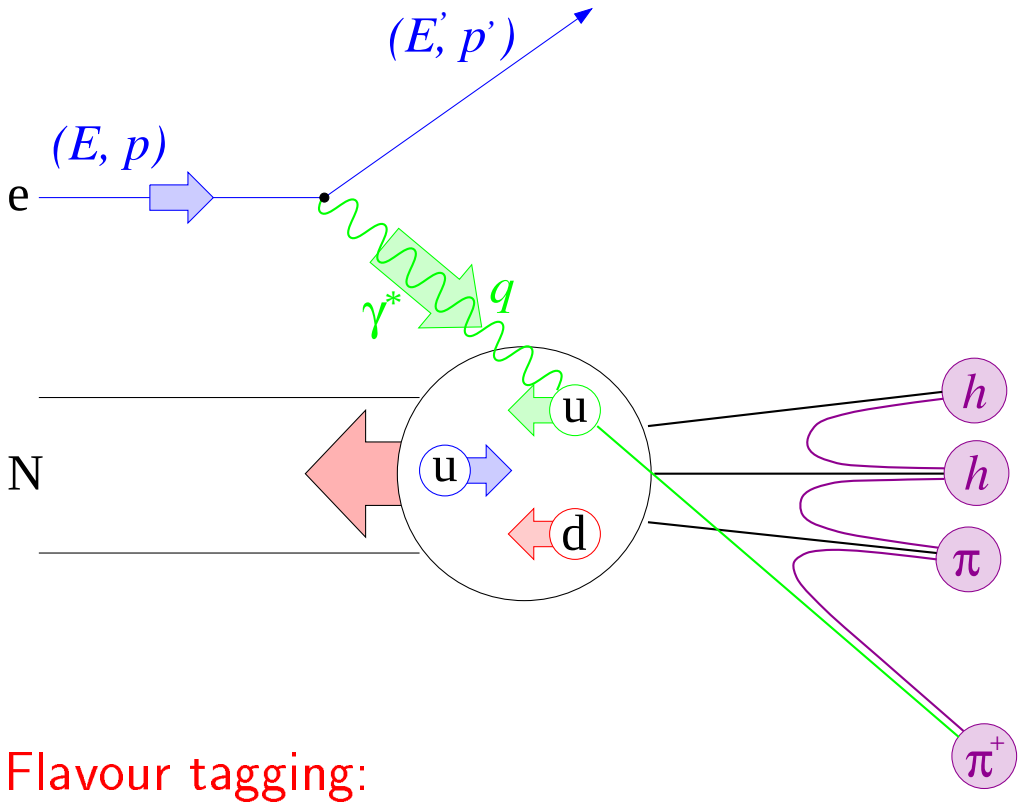


$\Delta q = q^+ - q^-$

Precison measurements of quark spin structure

Semi-inclusive Measurements

In semi-inclusive DIS a hadron is detected
in coincidence with the scattered lepton



Flavour tagging:

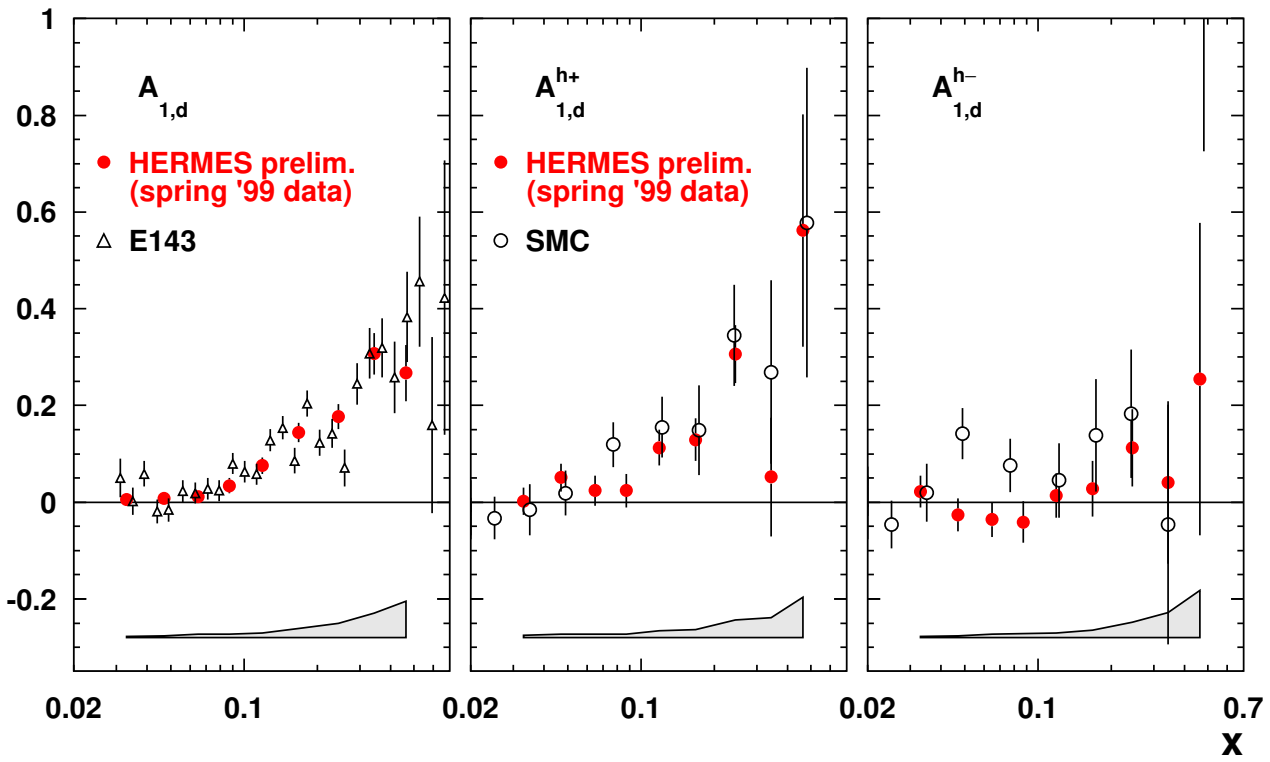
- Select hadrons from current hemisphere by cuts on $z = E_h/\nu$ and $x_F = 2p_{||}/W$
- Measure spin asymmetries for production of h^+ and h^-

$$A_{||}^h = \frac{1}{\langle P_T P_B \rangle} = \frac{(N_h/\mathcal{L})^{\uparrow\Uparrow} - (N_h/\mathcal{L})^{\downarrow\Uparrow}}{(N_h/\mathcal{L})^{\uparrow\Uparrow} + (N_h/\mathcal{L})^{\downarrow\Uparrow}}$$

- Inclusive Asymmetry: $A_1^h = \left(\frac{g_1}{F_1}\right)^h = \frac{A_{||}^h}{D(1+\gamma\eta)}$

γ, η kinematic factors, D depolarization

Semi-Inclusive Asymmetries



- Related to Δq:

$$A_1^h(x) \simeq \sum_q P_q^h(x) \cdot \frac{\Delta q(x)}{q(x)}$$

with purity $P_q^h(x)$ being probability that a quark $q(x)$ was struck when a hadron h is detected

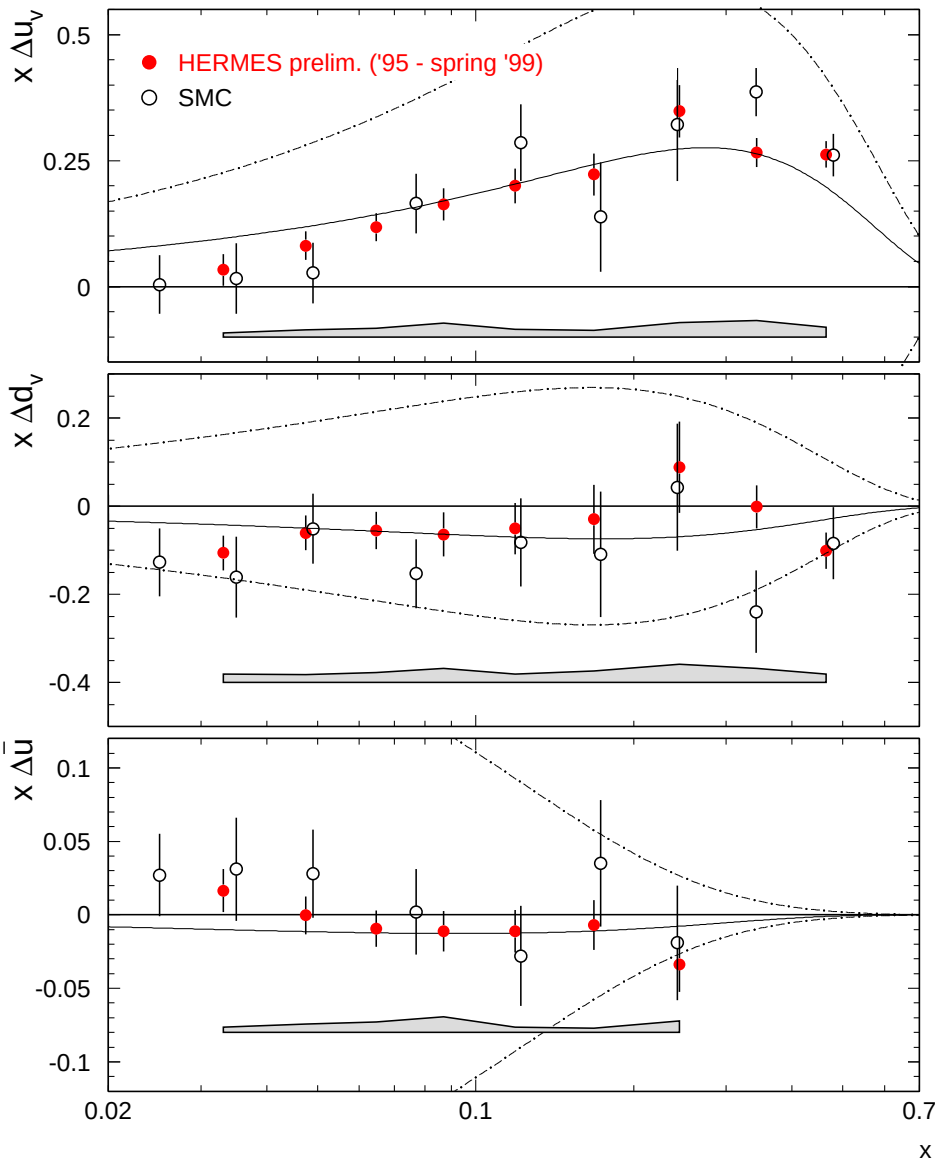
Only $\simeq 20\%$ of data yet analysed!

Spin Contribution of the Quarks

Assume symmetric behaviour of sea quarks

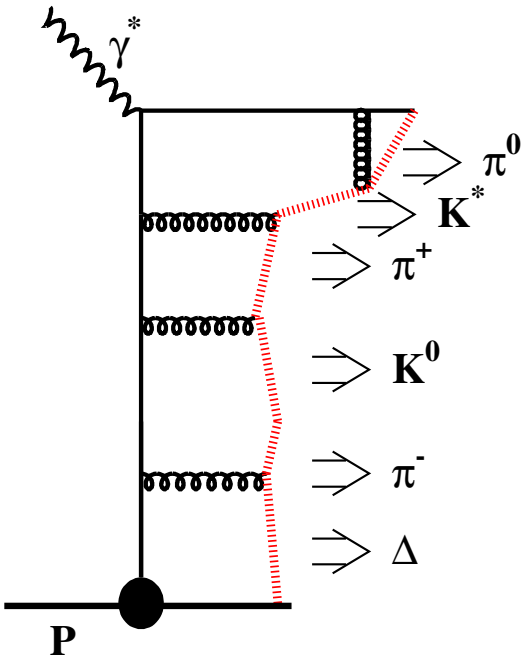
HERMES: $\Delta u_s/u_s = \Delta d_s/d_s = \Delta s/s$

SMC: $\Delta u_s = \Delta d_s = \Delta s$



- Good agreement between SMC and HERMES results
- Good agreement with QCD: T. Gehrmann et al. (1996)
- $\boldsymbol{\Delta u_v > 0,\ \Delta d_v < 0,\ \Delta q_s \approx 0}$

Final States



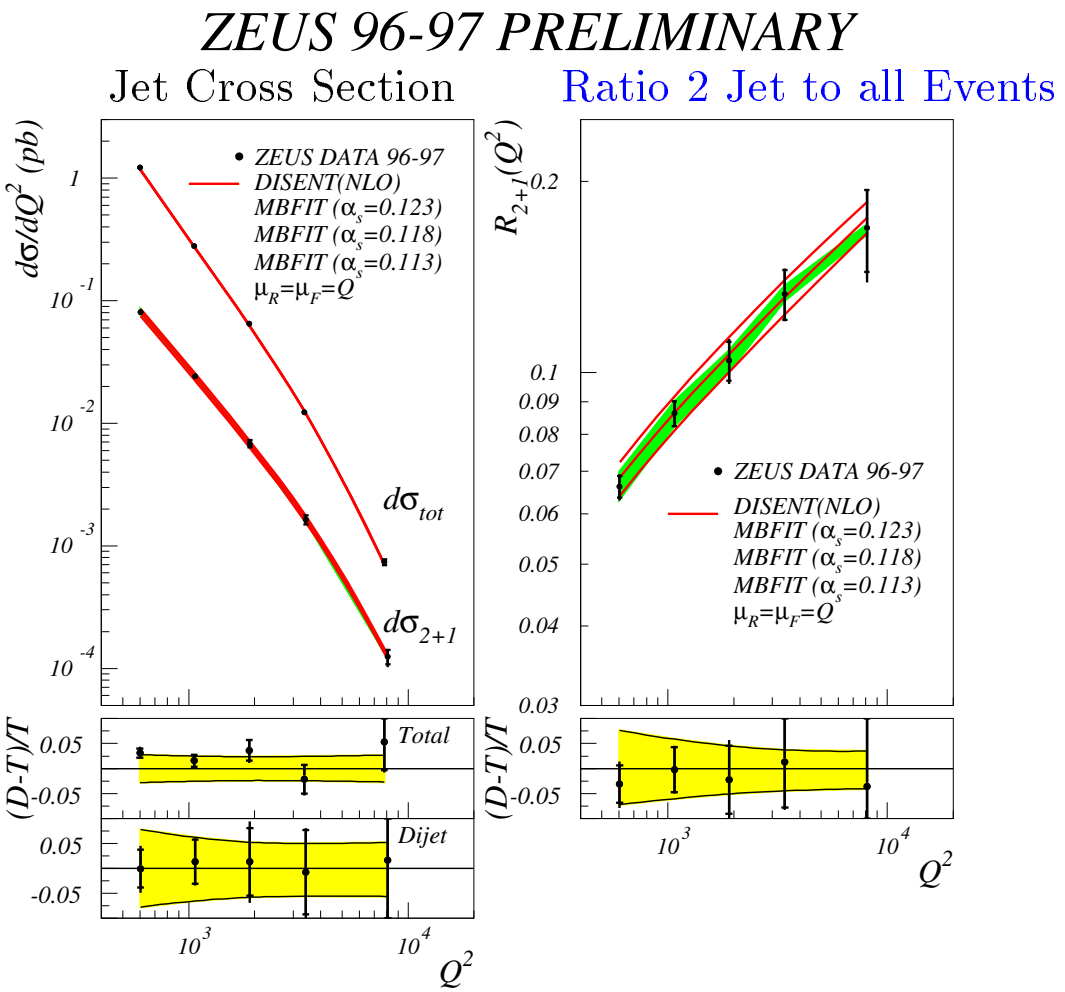
Final State Measurements

- Jets at high Q^2
- Event shapes
- Photon structure
- Jet photoproduction
- Heavy flavour production
- Pion structure
- Forward particle production
- Forward jets
- Diffraction
- High t Jet production
- Vector meson production
- Fragmentation functions
- Instantons

Jet Cross Sections at High Q^2

- Jet cross sections sensitive to higher order processes
- Jets provide additional hard scale

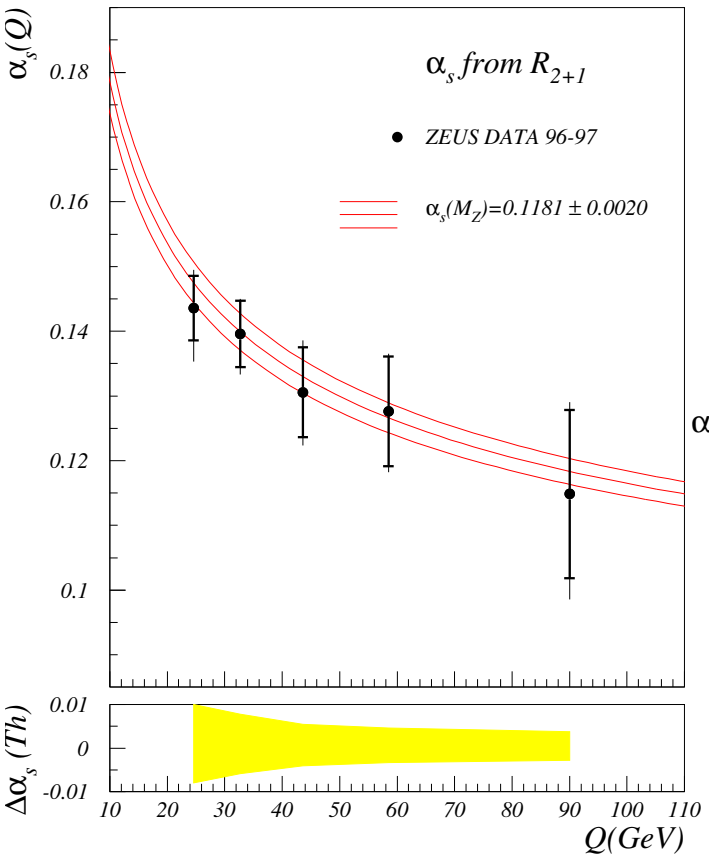
$\Rightarrow$ Important test of perturbative QCD

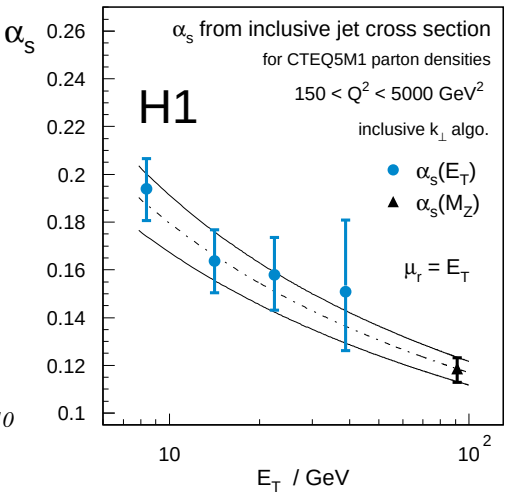


- Very precise Measurements
- Cross sections described by NLO QCD
- Use to measure gluon in the proton and α_s $\Rightarrow$

α_s from jets

ZEUS 96-97 PRELIMINARY





$\alpha_s(M_Z) = 0.1166^{+0.0039}_{-0.0047}(exp.)^{+0.0057}_{-0.0044}(th.)$ (ZEUS Jets Prel.)

$\alpha_s(M_Z) = 0.1186 \pm 0.0019(exp.)^{+0.0039}_{-0.0045}(th.)$ (H1 Jets)

$\alpha_s(M_Z) = 0.1150 \pm 0.0017(exp.) \pm 0.0051(th.)$ (H1 F_2Prel.)

- Running of α_s tested in a single experiment
- α_s from DIS jets in good agreement with α_s from F_2 and world average

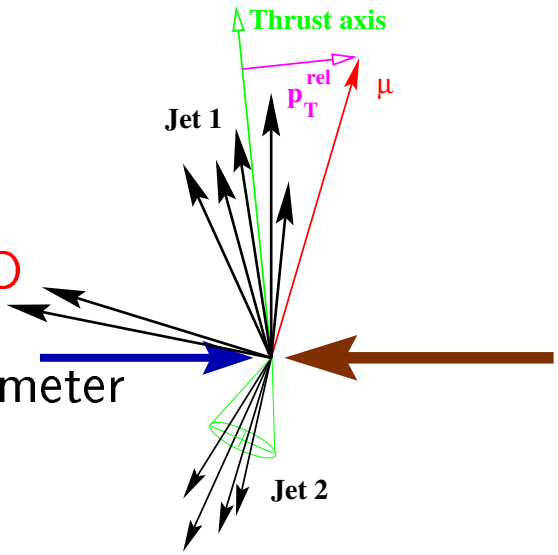
Successful test of QCD!

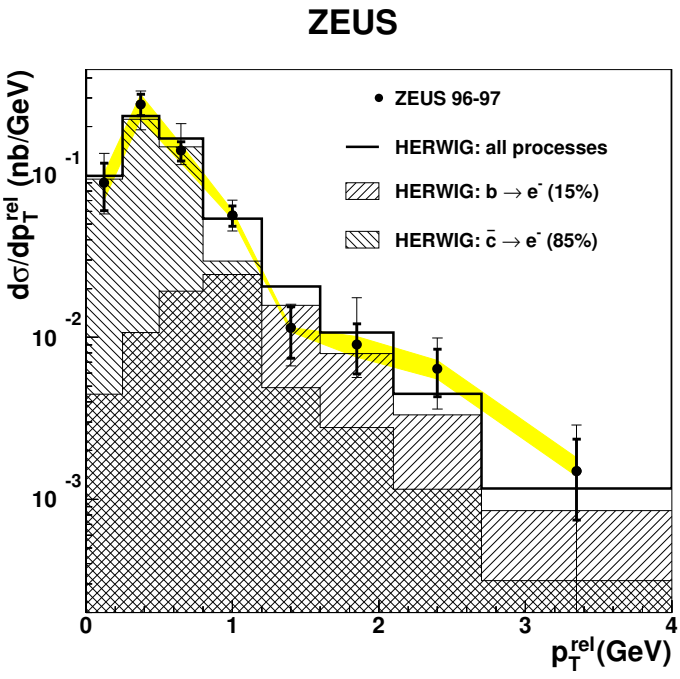
Open Beauty Production

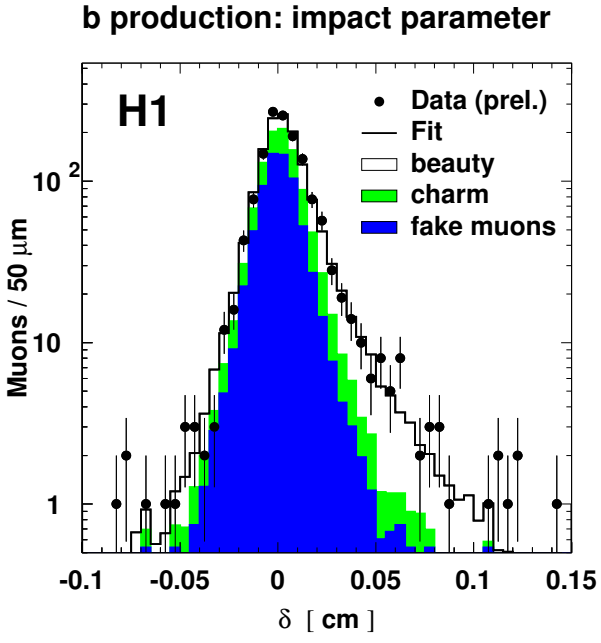
- Tag lepton (e or μ) from semi-leptonic b-decay:

$$b \to c l \nu_l$$

- Photoproduction: $Q^2 < 1$ GeV^2
- $m_b \approx 5$ GeV $\Rightarrow$ hard scale for pQCD
- Require high $p^l_{T,rel}$ or impact parameter



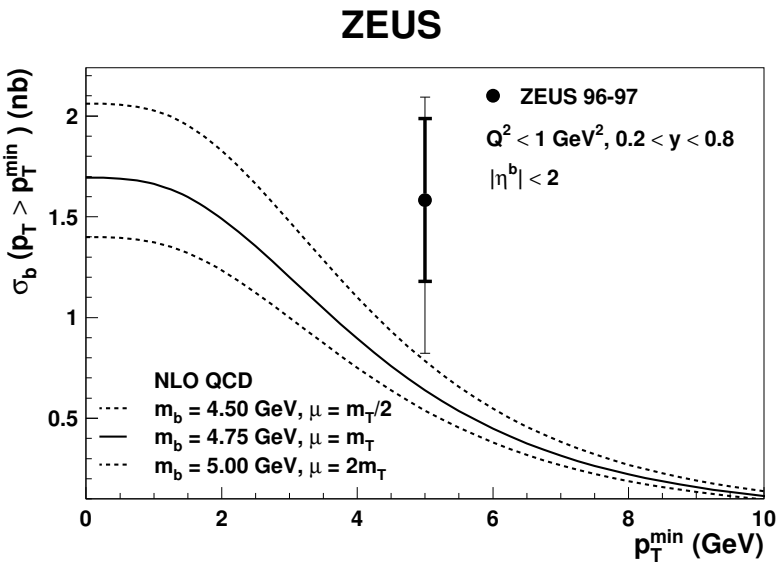




b contribution from shape of $p^l_{T,rel}$ and/or impact parameter

Beauty Cross Section

- Visible Cross section larger than NLO QCD in e and μ channels for H1 and ZEUS



H1

$ep \to eb\bar{b}X \to e\mu X$

$Q^2 < 1\text{GeV}^2, 0.1 < y < 0.8$

$p_t(\mu) > 2$ GeV

$35° < \theta(\mu) < 130°$

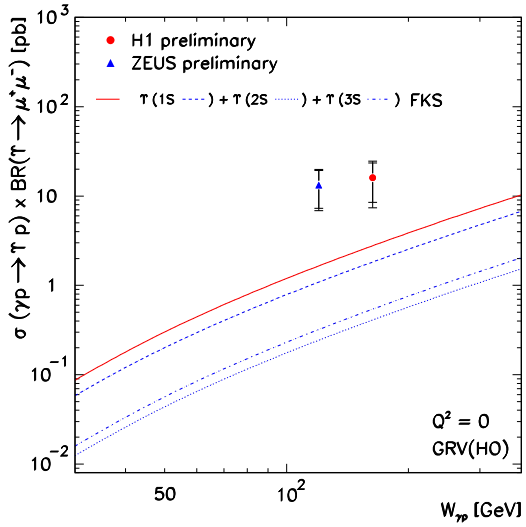
$\sigma_{vis} = (170 \pm 25)$ pb

$\sigma_{vis}^{QCD} = (104 \pm 17)$ pb

Hard scale! $\Rightarrow$ NLO QCD seems not to work.

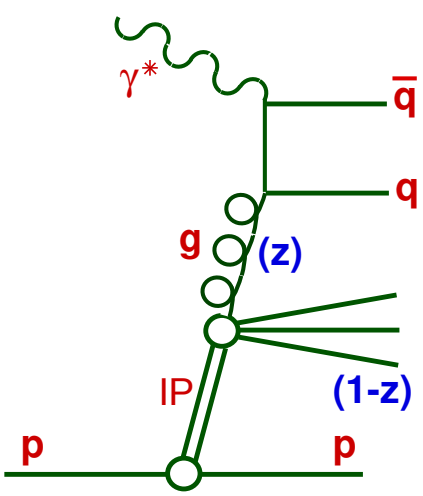
Why?

- missing higher orders?
- theo. uncertainty underestimated?
- resolved component of photon?

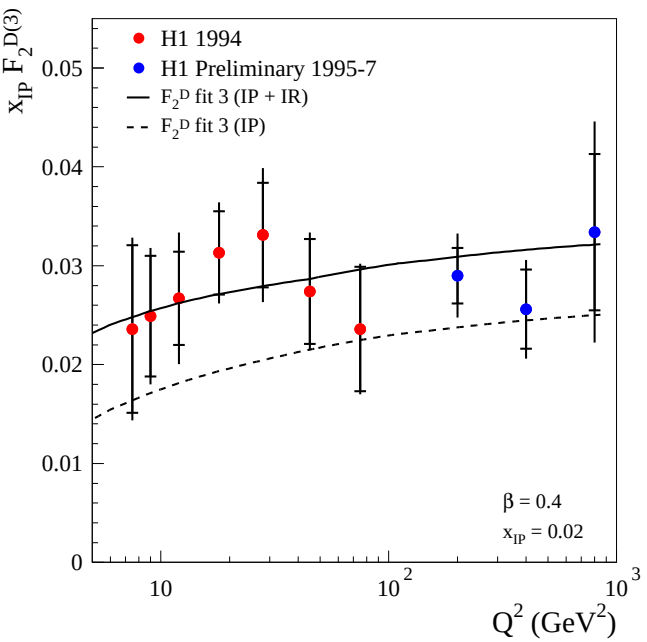


Similar disagreement observed for Υ (closed b) production and also at Tevatron

Pomeron Structure

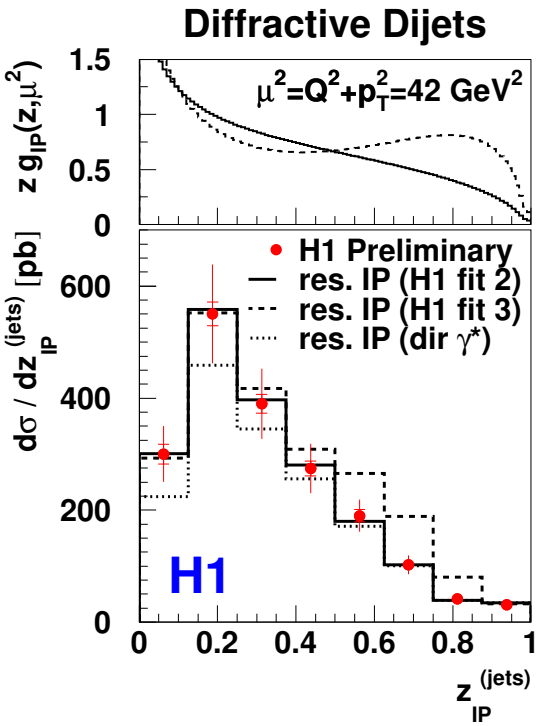


Diffractive Structure function $F_2^{D(3)}$



+ve scaling violations of $F_2^{D(3)}$ at high fractional momenta β

$\rightarrow$ gives large gluon density



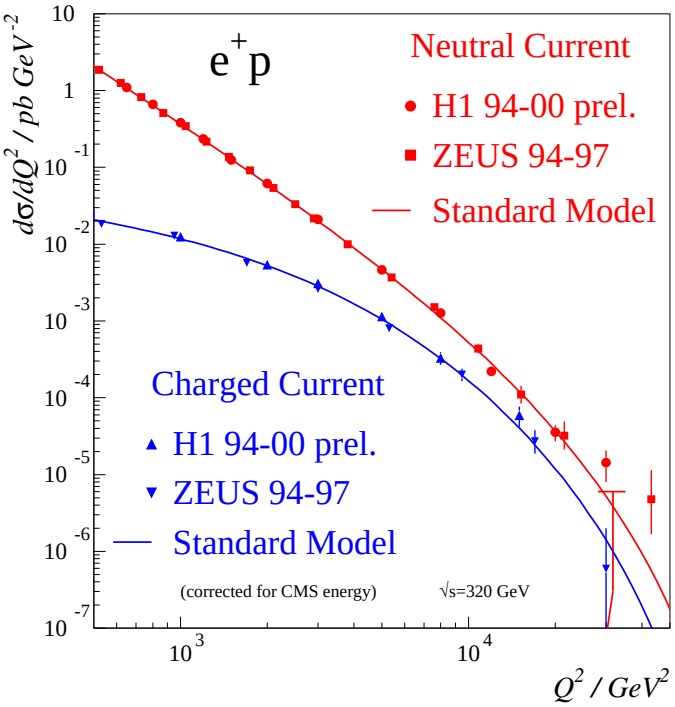
Dijets give best estimate of gluon

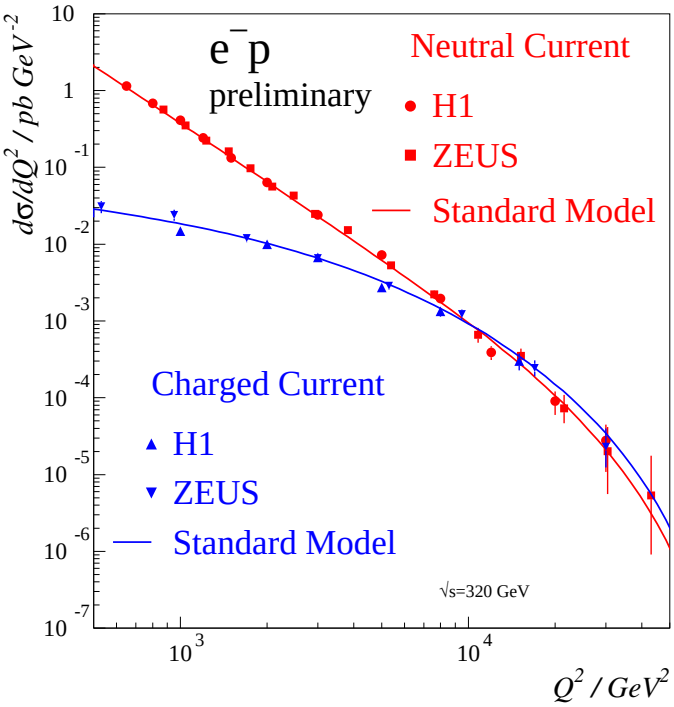
Overall agreement with gluon from $F_2^{D(3)}$

Testing the Electroweak Sector

$$\frac{\mathrm{d}\sigma_{NC}(e^{\pm}p)}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3]$$

$$\frac{\mathrm{d}^2\sigma_{CC}(e^{\pm}p)}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{g^4}{64\pi x}\left[\frac{1}{Q^2+M_W^2}\right]^2 (Y_+W_2^{\pm} \mp Y_- xW_3^{\pm})$$





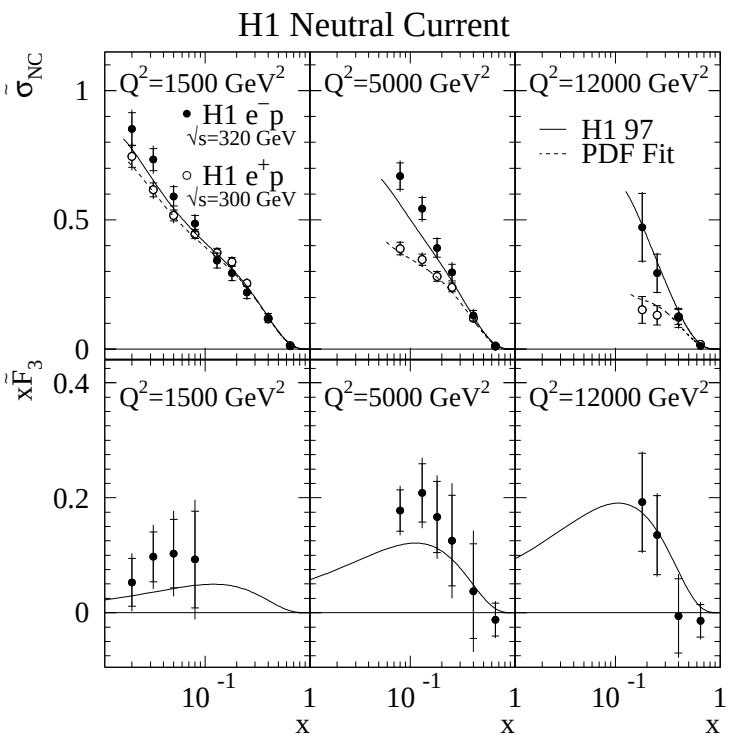
- NC cross section falls as $1/Q^4$
- W propagator suppresses CC cross section at low Q^2

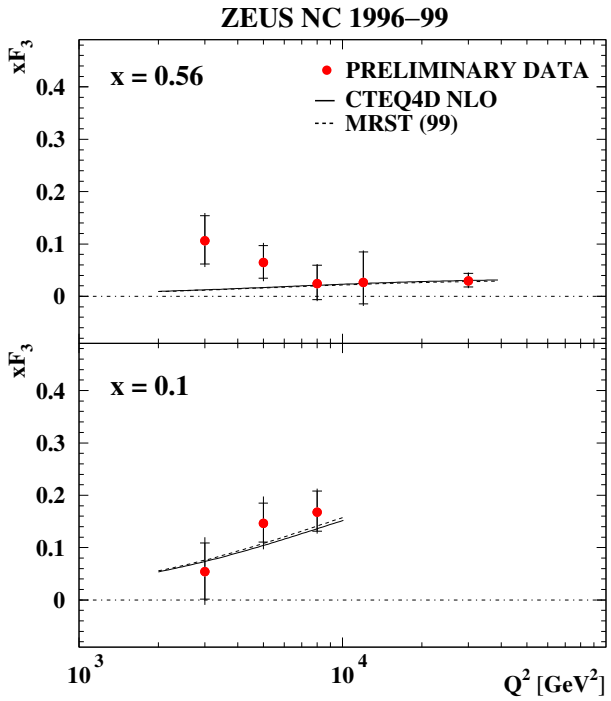
Electroweak unification at $Q^2 \approx M_W^2 \approx M_Z^2$

γZ - Interference

$$\frac{\mathrm{d}\sigma_{NC}(e^{\pm}p)}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3]$$

$\Rightarrow$ difference between $e^{\pm}$ due to γZ interference





- Difference between e^- and e^+ clearly observed
- First determination of xF_3 at HERA

Better precision $\Rightarrow$ HERA upgrade

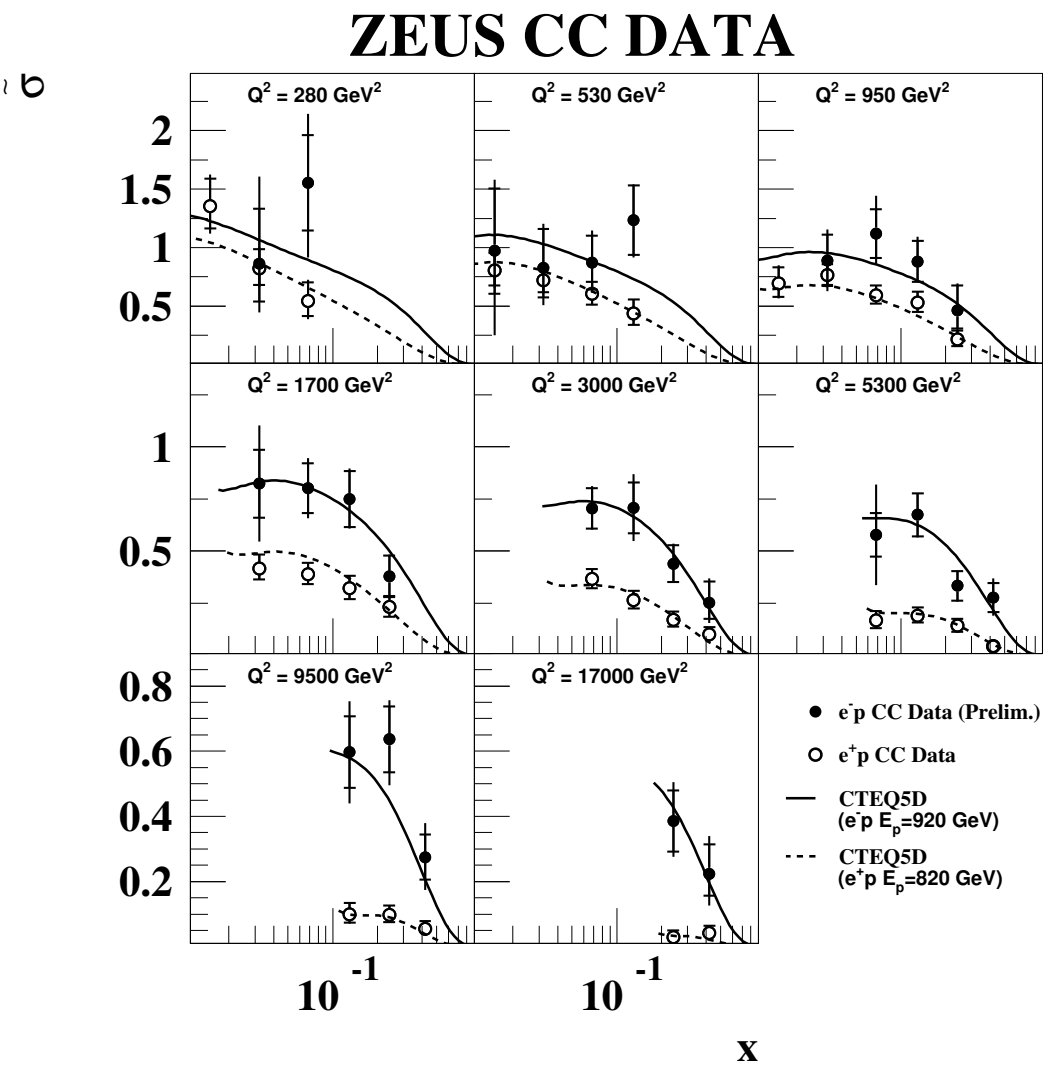
CC Cross Section

At leading order:

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

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

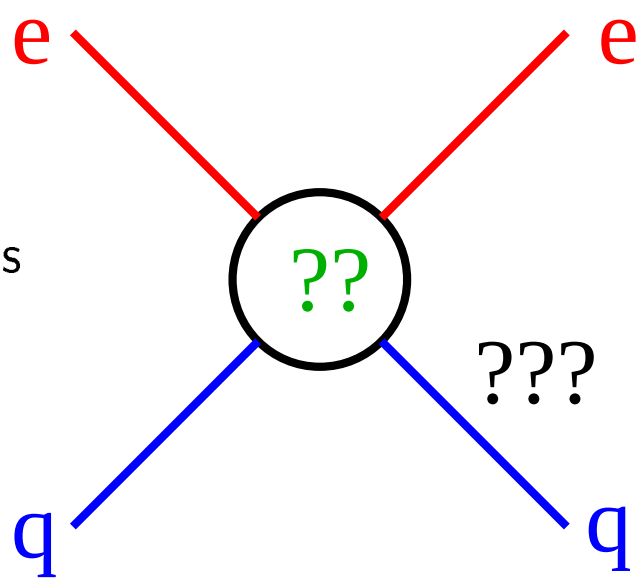
- e^+p: test d-density at high x / $\bar{u}$-density at low x
- e^-p: test u-density



- Low x: sea quarks dominate $\Rightarrow e^-p \approx e^+p$
- High x: valence quarks dominate $\Rightarrow e^-p \gg e^+p$
- Data well described by QCD fit

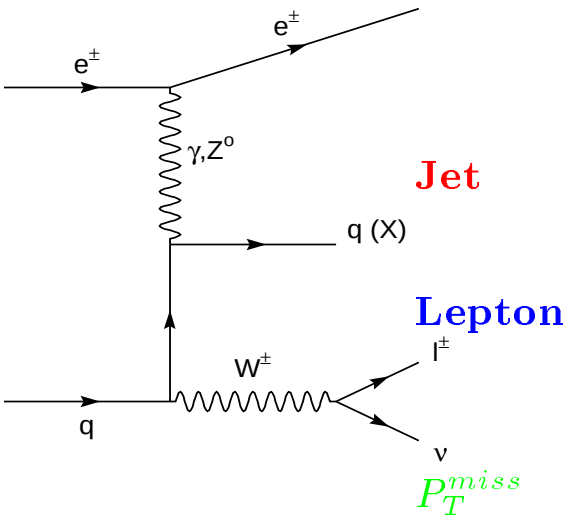
Rare Processes and Searches

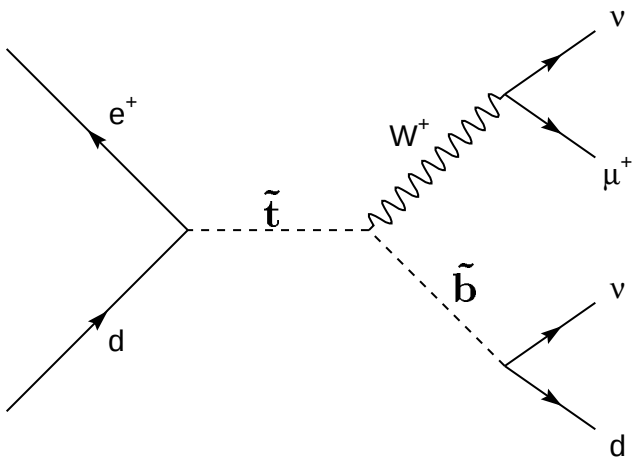
- W and Z production
- Contact interactions
- 1st generation leptoquarks
- Flavour-changing NC: $eq \to \mu q$, $eq \to \tau q$
- R_p-violating supersymmetry
- MSSM: $\tilde{e}$ and $\tilde{q}$
- Quark substructure
- Top production
- Excited fermions
- Large Extra Dimensions
- ...



W Production

Look for high P_T lepton + P_T^{miss}

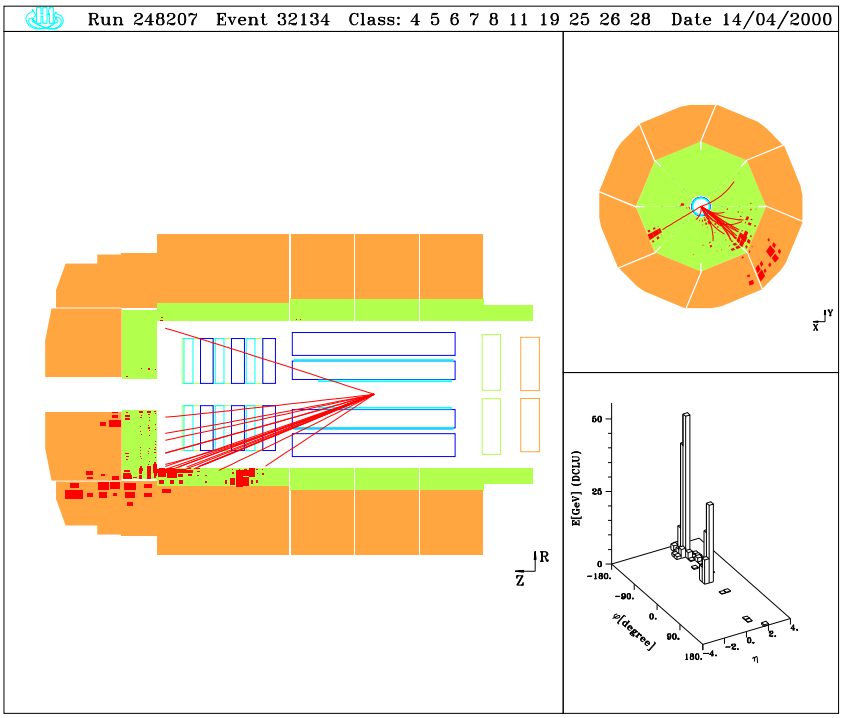




SM production

SUSY with decay W

W channel sensitive to new physics!



Recent Event in $W \to e\nu$ Channel

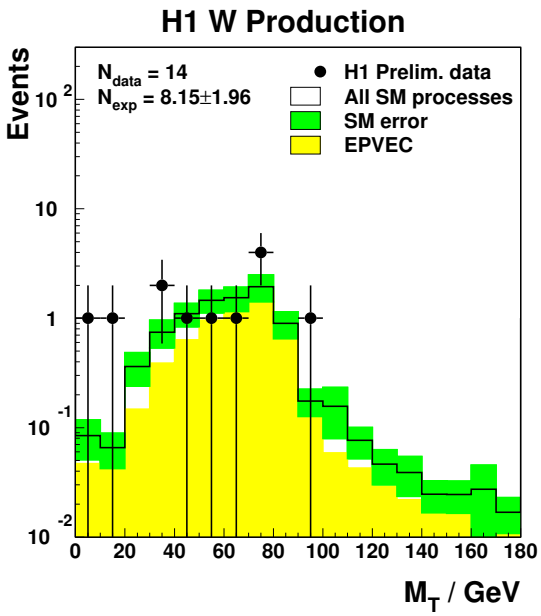
W Production

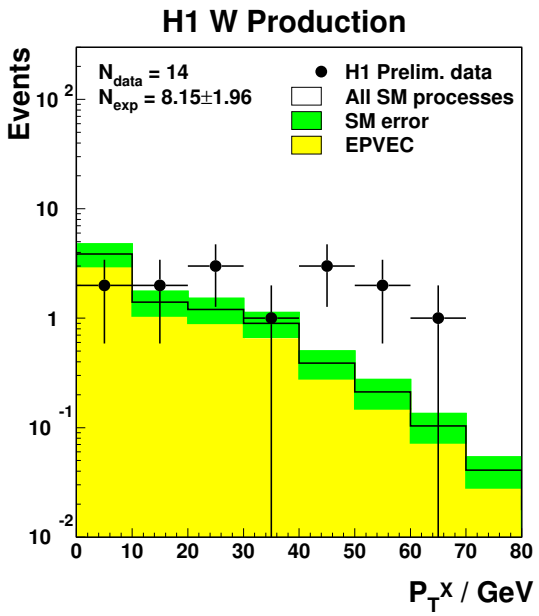
Tables show:
observed events /expectation from all SM processes

ZEUS 94-99 $e^{\pm}p$ 82 pb^{-1} Preliminary	Electrons	Muons	combined $e + \mu$
$P_T^X > 25$ GeV	1 /0.8	0 / 0.8	1/1.6 (only W 1.4)
$P_T^X > 40$ GeV	0 / 0.3	0 / 0.3	0/0.6 (only W 0.5)

H1 94-00 $e^{+}p$ 82 pb^{-1} Preliminary	Electrons	Muons	combined $e + \mu$
$P_T^X > 25$ GeV	3 /1.1	6 / 1.2	9/2.3 (only W 1.8)
$P_T^X > 40$ GeV	2 / 0.3	4 / 0.5	6/0.8 (only W 0.7)

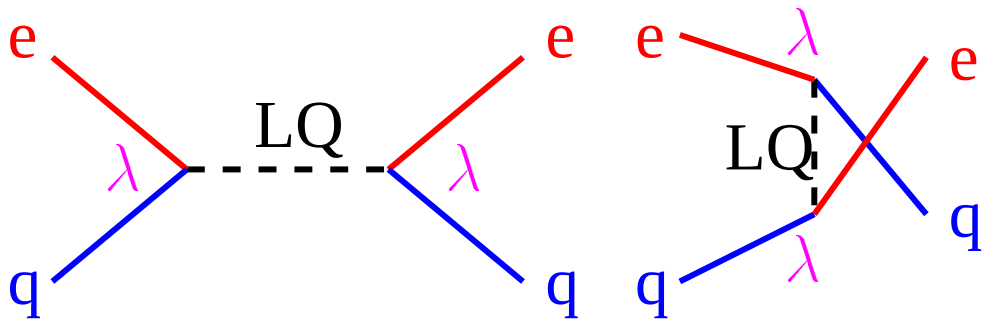
- ZEUS see good agreement with SM expectation
- H1 see an excess for $P_T^X > 25$ GeV
  4 new events in 99-00 data (5 events in 94-97)

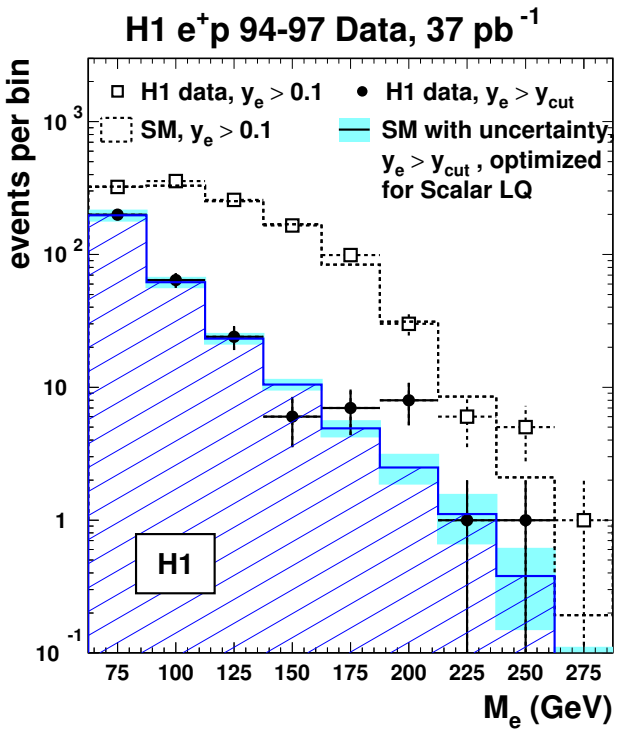


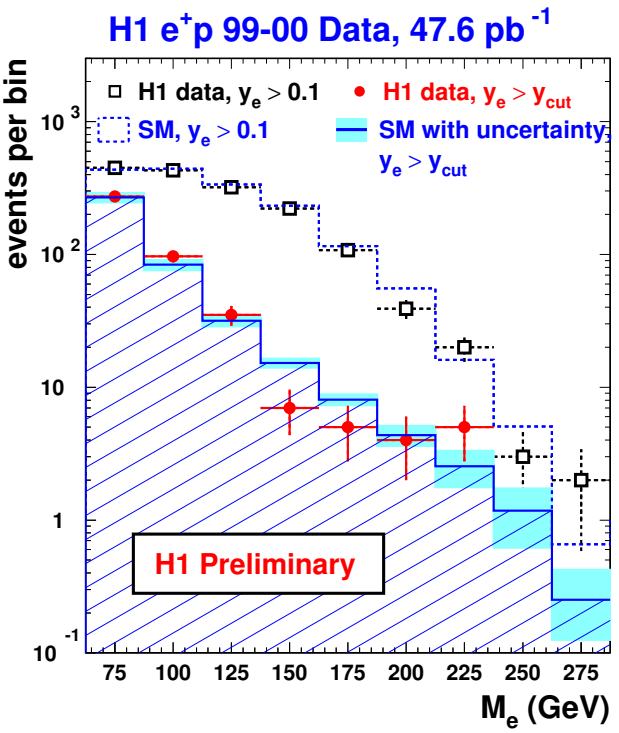


Leptoquarks?

1st generation: $eq \rightarrow$ leptoquark(LQ) $\rightarrow eq$





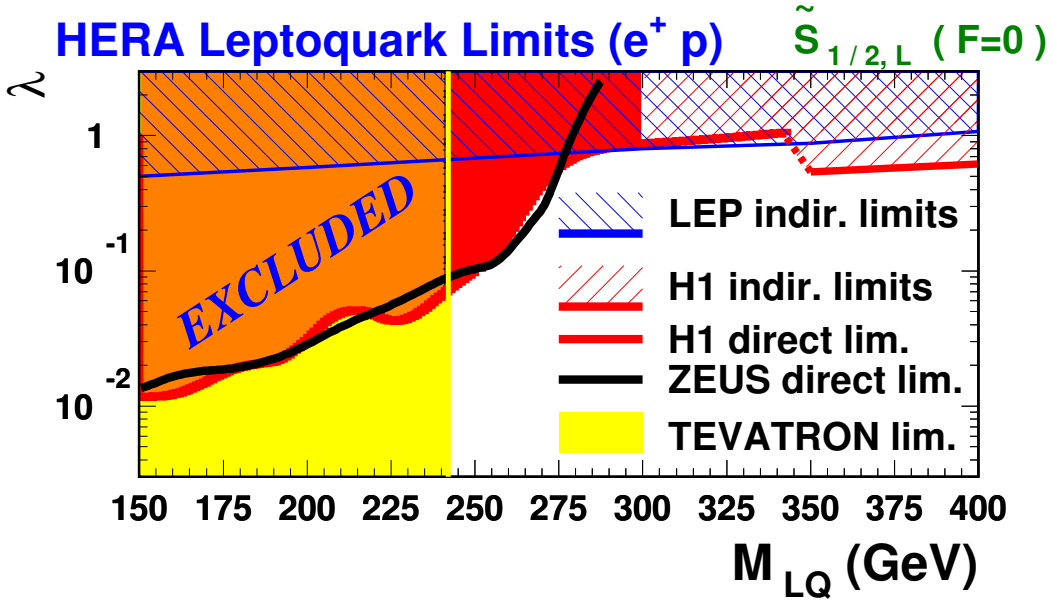


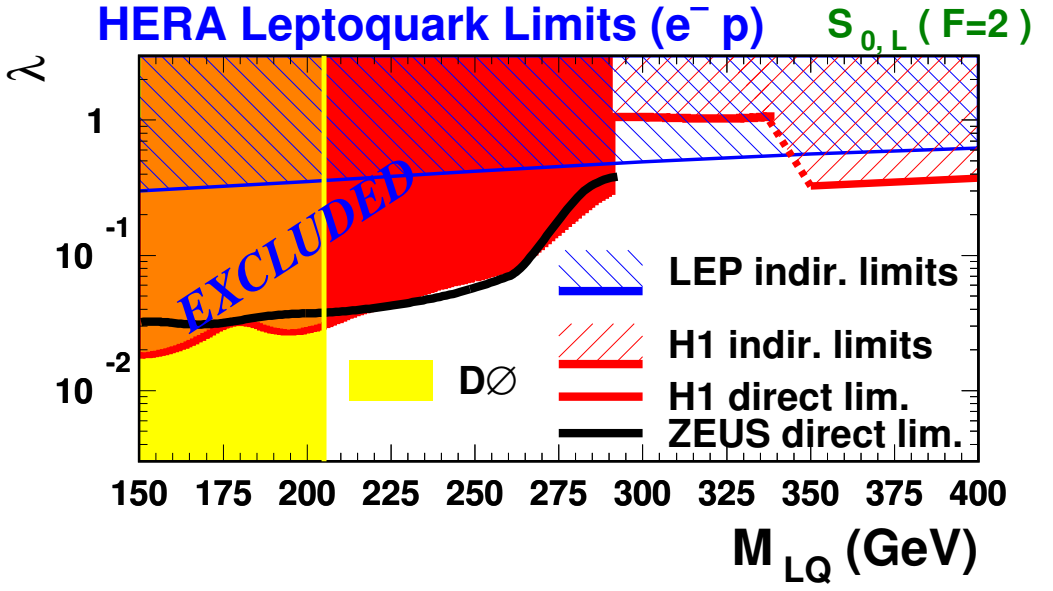
- Suggestions of resonance in 94-97 not confirmed by new data

  $\Longrightarrow$ was statistical fluctuation...
- No significant excess seen by H1 or ZEUS

  $\Longrightarrow$ **derive limits!**

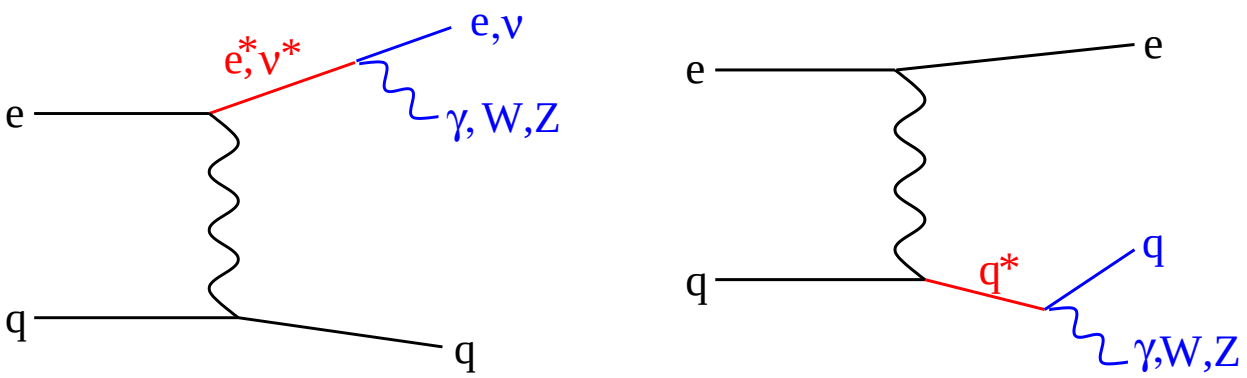
Limits for Leptoquarks



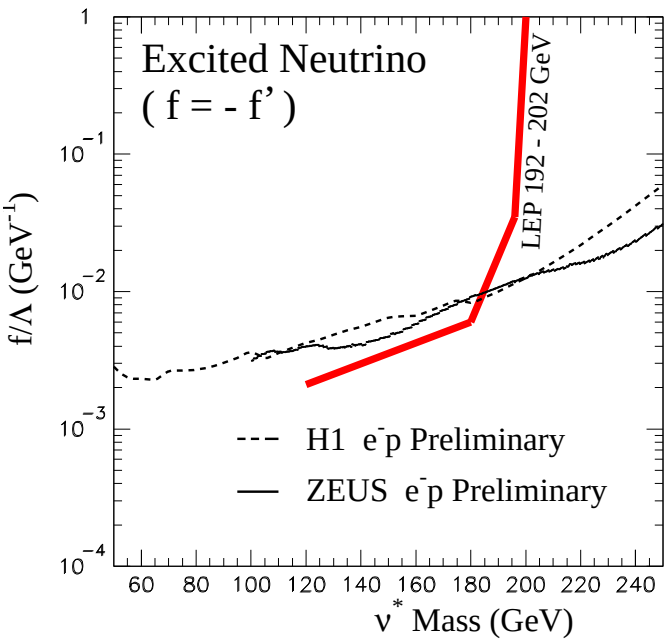


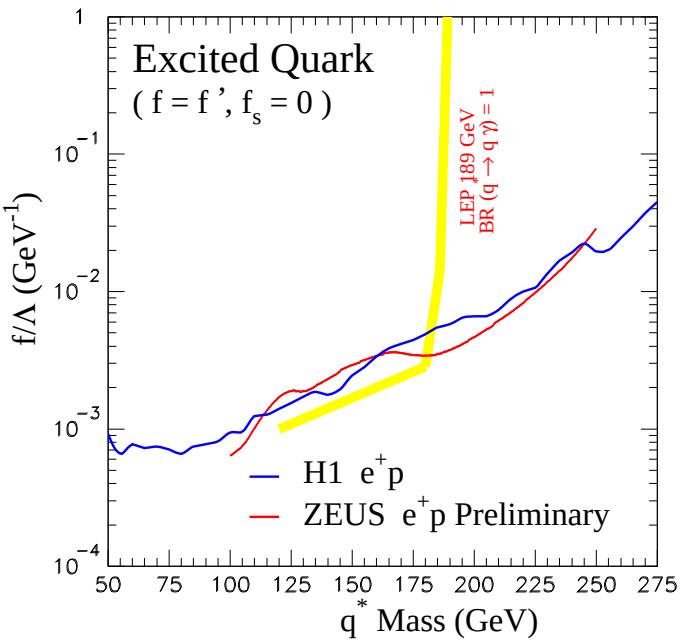
- Healthy competition between Tevatron, LEP and HERA
- For $\lambda = 0.3$ ($\equiv \alpha_{em}$) leptoquarks with $M \lesssim 290$ GeV are excluded

Search for Excited Fermions



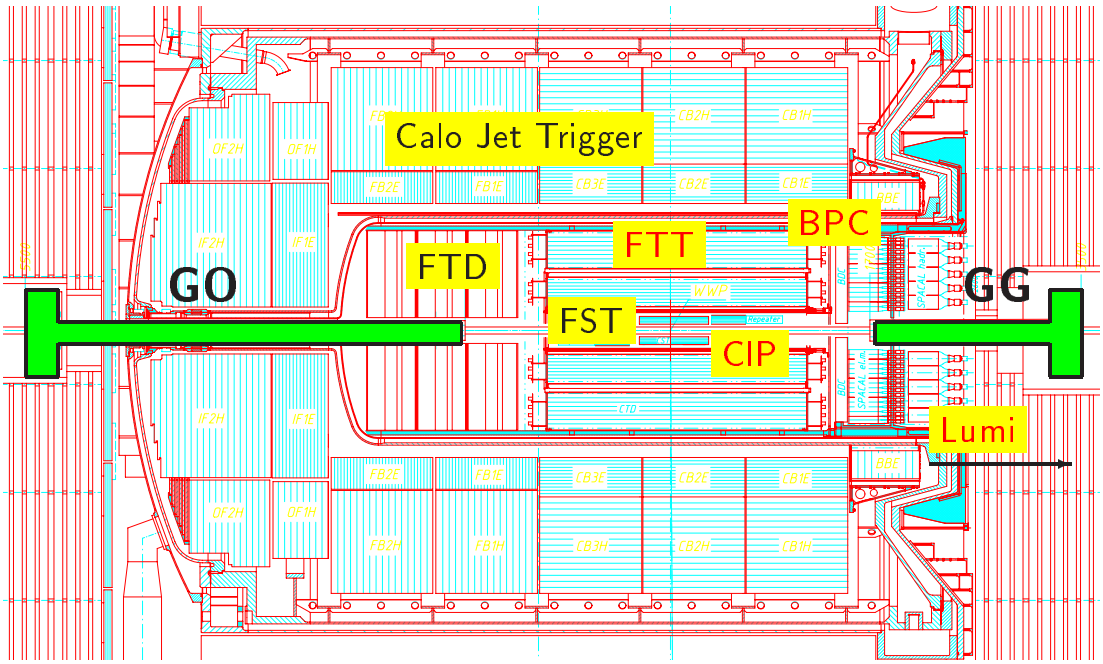
- high mass excited fermion states f^*
- couple to ground-state fermions and gauge bosons
- Model: $\mathcal{L}_{ff^*} = \frac{1}{\Lambda} f_R^* [f(gV)_{SU(2)} + f'(gV)_{U(1)} + f_s(gV)_{SU(3)}]$
  by Hagiwara, Komamiya, Zeppenfeld





HERA discovery potential at high masses

Upgrade of HERA and Detectors



- Magnets placed around beam line including inside detector volume
- β functions reduced by factor of 4-5
- Increased electron and proton Currents

$\Rightarrow$ Factor of 5 increase in luminosity

- Longitudinal polarisation of lepton beam
- Major upgrades of detectors:
  - Micro vertex detector (H1+ZEUS+HERMES)
  - Forward Tracking (H1+ZEUS)
  - New Lumi Systems (H1+ZEUS)
  - Improved Track Triggering (H1)

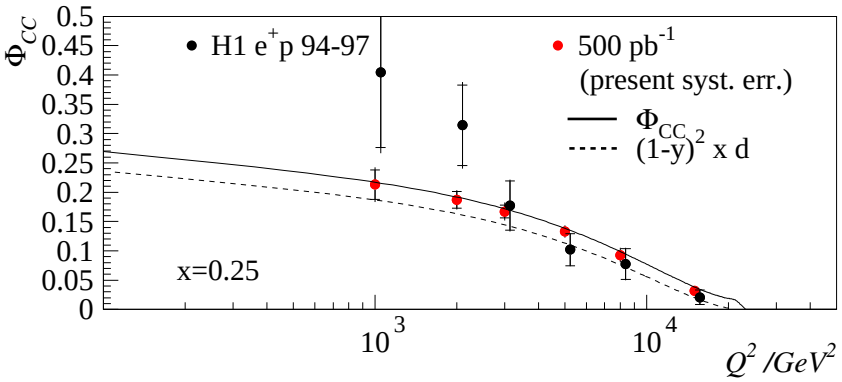
  ...and more...

HERA Upgrade

2000 $\rightarrow$ HERA runs with $L = 300$ pb^{-1} per year (luminosities for H1+ZEUS together)

$\Rightarrow$ **estimated total integrated luminosity of 2 fb^{-1}**

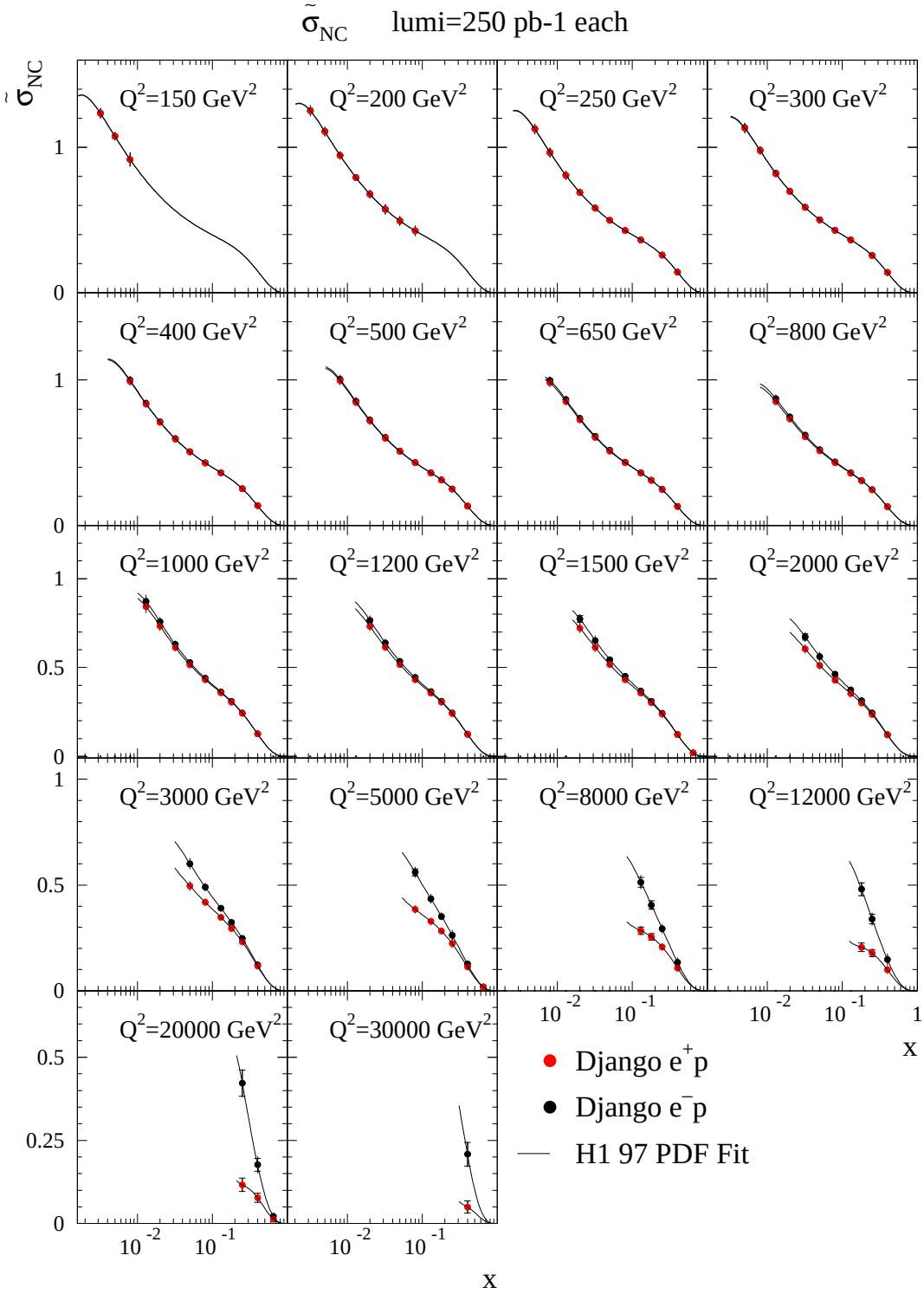
- eg. 5% Error on CC cross section at high x



- eg. NC cross section measured better than 10% up to $Q^2 = 20000$ GeV^2 $\Rightarrow$ plot.
- Polaristion. Opens up new possibilities $\Rightarrow$ plot.
- eg. Measurement of F_2 charm to 5% and F_2 bottom to 10% utilising new detectors and increased statistics $\Rightarrow$ plot.
- eg. 160 to 300 W events $\Rightarrow$ plot.
- eg. Hermes transversity measurements.

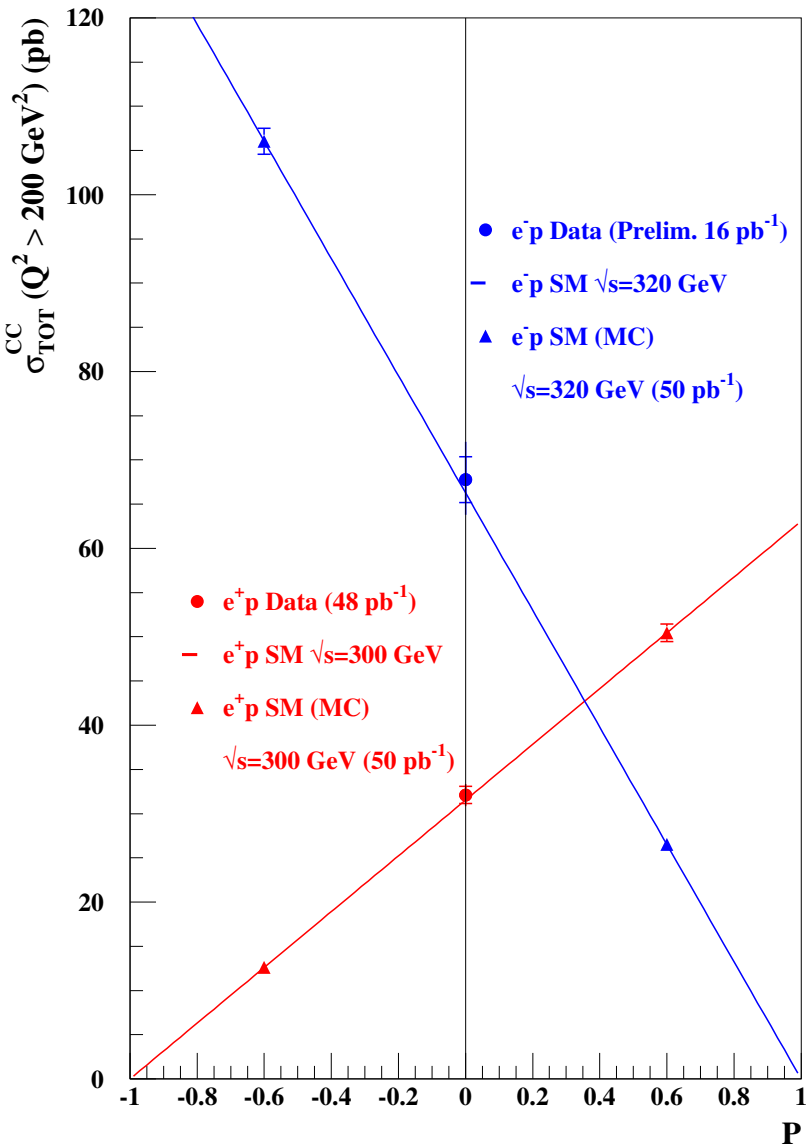
HERA Has a Bright Future!

Simulated NC Cross section



- Low Q^2 precision will be reached at high Q^2
- Precision measurement of xF_3

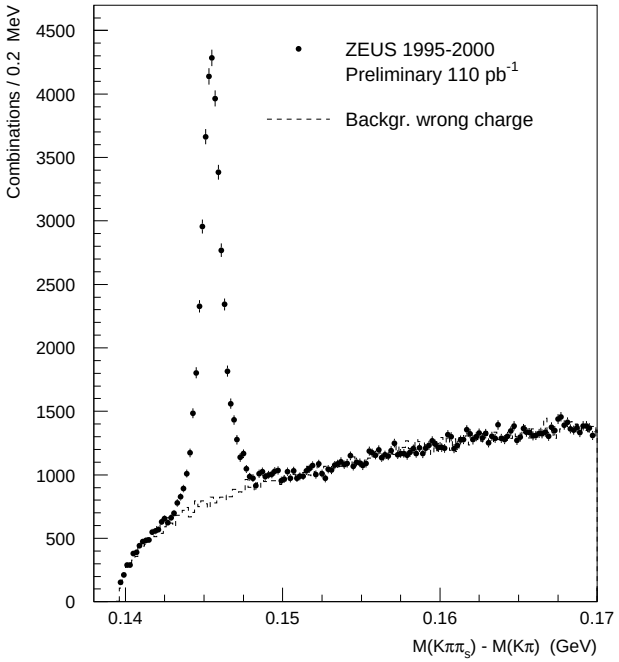
Polarised $e^{\pm}p$ CC Cross sections



- Look for right handed charge currents
- Helps identify new physics

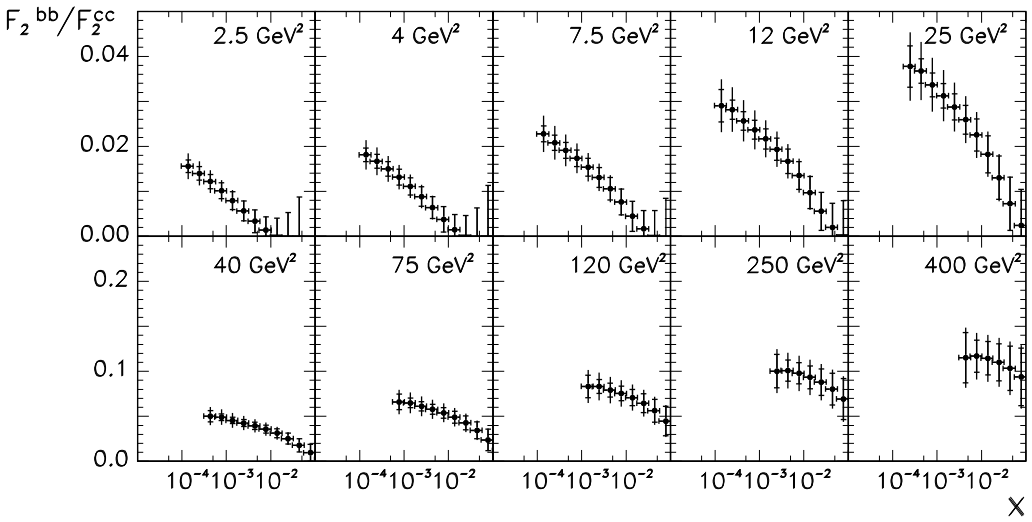
Heavy Flavour Future

Numbers of D^*s now!



HERA is already a charm factory.

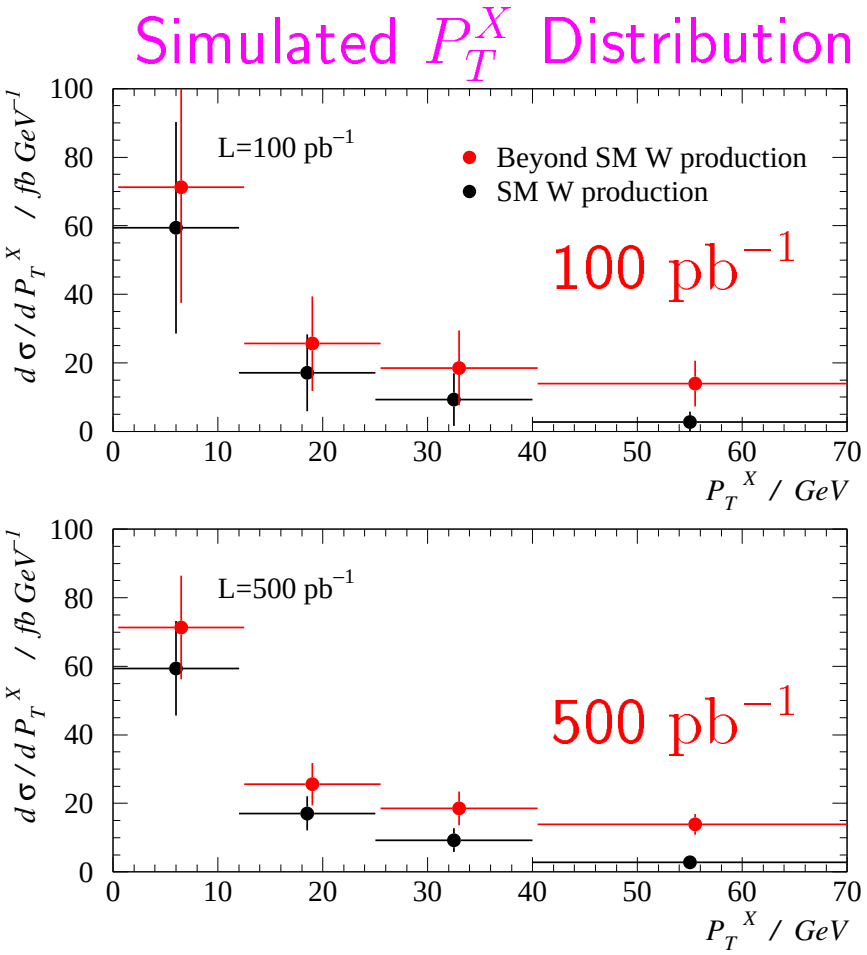
Expect 250,000 D^*s after upgrade!



Simulated $F_2^{b\bar{b}}/F_2^{c\bar{c}}$

Future W Production

$500\ \mathrm{pb}^{-1}$ enough to make discovery if H1 effect persists

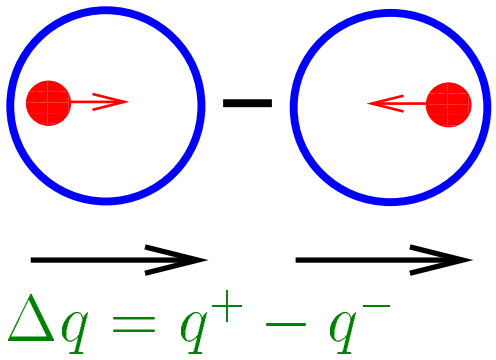


- Can make total cross section measurement with 15% error
- 5σ effect for $P_T^X > 40$ GeV
- Different cross section with e^+/e^- or polarisation gives new physics evidence independent of SM calculations

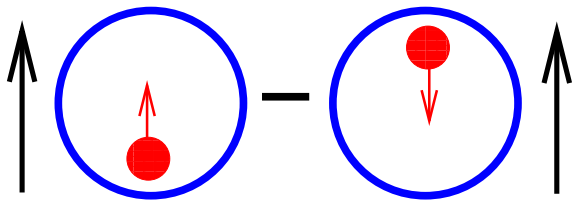
HERMES after Upgrade

- Continue unpolarised end of fill running
- Measure quark transversity:

$g_1 \rightarrow$ quark helicity Δq
$g_1 = \frac{1}{2}\Sigma_q e_q^2(\Delta q + \Delta\bar{q})$



$h_1 \rightarrow$ quark transversity δq
$h_1 = \frac{1}{2}\Sigma_q e_q^2(\delta q + \delta\bar{q})$



- $\Delta q \neq \delta q$ due to relativistic and spin orbital effects

HERMES will make first ever measurements of transversity

Summary

★ HERA is a leading facility for studies of the QCD sector and the search for new physics

★ Important input from HERMES for understanding the origin of nucleon spin

★ Precision increased
$\Rightarrow$ higher sensitivity to new physics and better accuracy for QCD tests

★ The upgrade of HERA and the experiments will allow us to optimally exploit the discovery potential at HERA