HERA Physics Inclusive measurements

Hans-Ulrich Martyn *RWTH Aachen & DESY*

- DIS ep kinematics
- Polarised cross section measurements
- Structure functions & parton densities
  - QCD & electroweak fits
  - quark couplings & strong coupling
  - heavy flavour structure functions
  - diffractive parton densities
- Searches – isolated lepton events, multi-leptons
- Future measurement of F_L

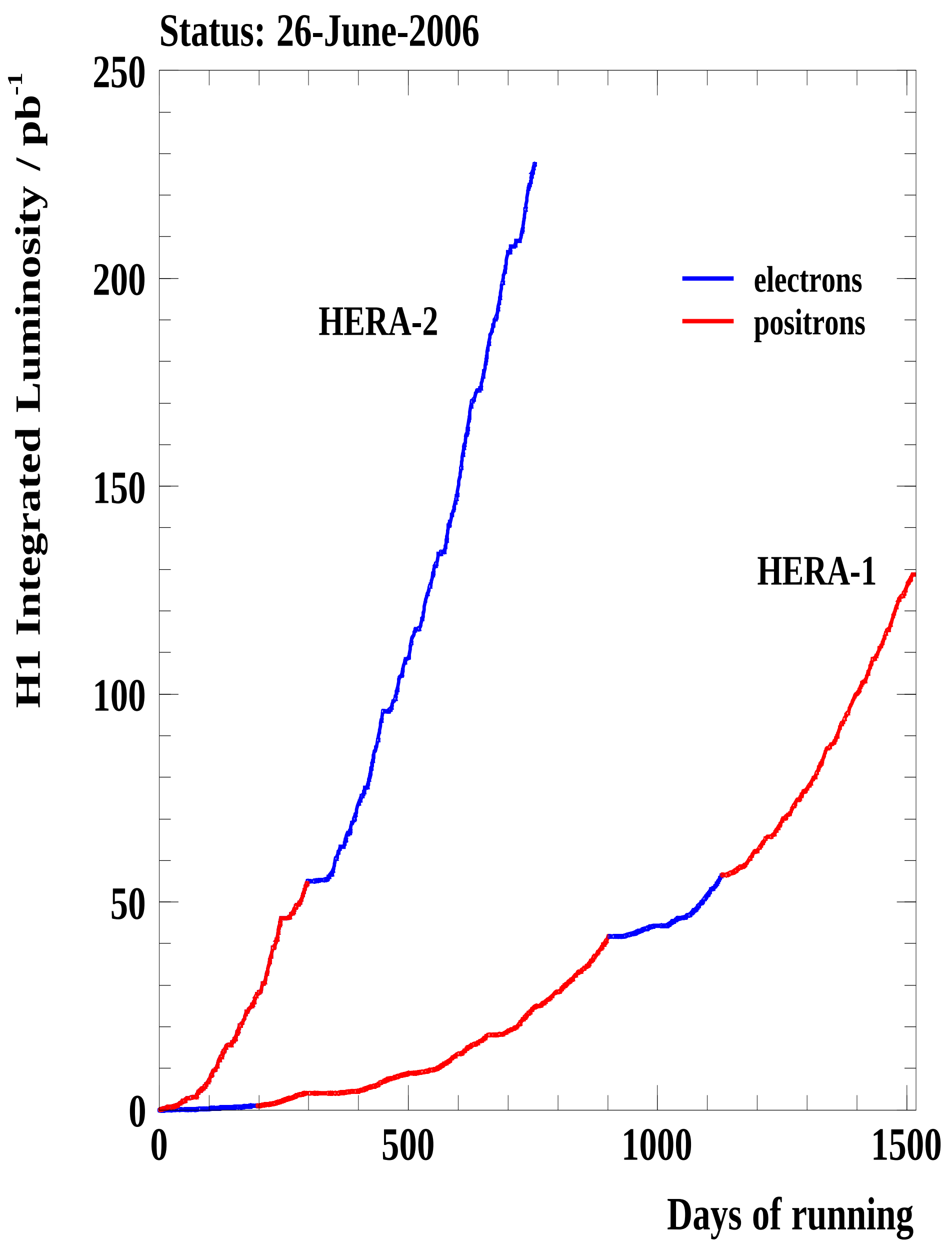
HERA performance

HERA II

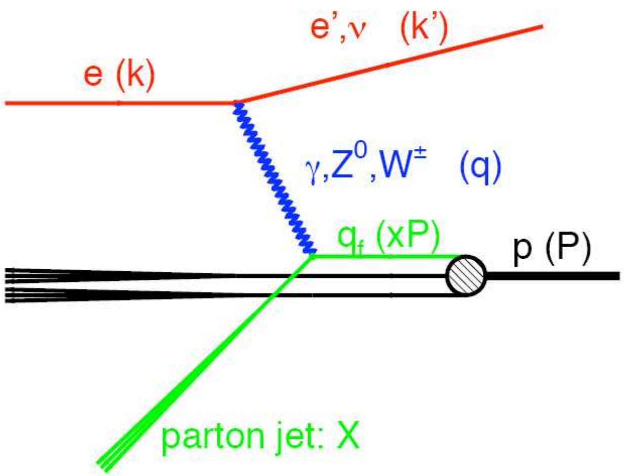
- $E_e = 27.6\,GeV,\, E_p = 920\,GeV,\, \sqrt{s} = 320\,\text{GeV}$
- **Detectors & luminosity upgrade**

$\mathcal{L}$ per expt		e^+p	e^-p
HERA I	93-00	$\sim 120\,\text{pb}^{-1}$	$\sim 20\,\text{pb}^{-1}$
HERA II	03-now	$\sim 50\,\text{pb}^{-1}$	$\sim 210\,\text{pb}^{-1}$
HERA II	total?	$\sim 200\,\text{pb}^{-1}$	$\sim 210\,\text{pb}^{-1}$

- **Longitudinally polarised lepton beams**
  typically $\mathcal{P}_e \simeq 30 - 40\%$, $t_{\mathcal{P}} \sim 30$ min
  helicity flip every 2-3 months
- **Schedule**
  - **switch to positrons July**
    collect $\mathcal{L} \sim 100\,\text{pb}^{-1}$
  - **measure F_L at lower $E_p = 460\,\text{GeV}$**
    run 3 months for $\mathcal{L} = 10\,\text{pb}^{-1}$
  - **end of HERA data taking June 2007**



Kinematics of ep interactions

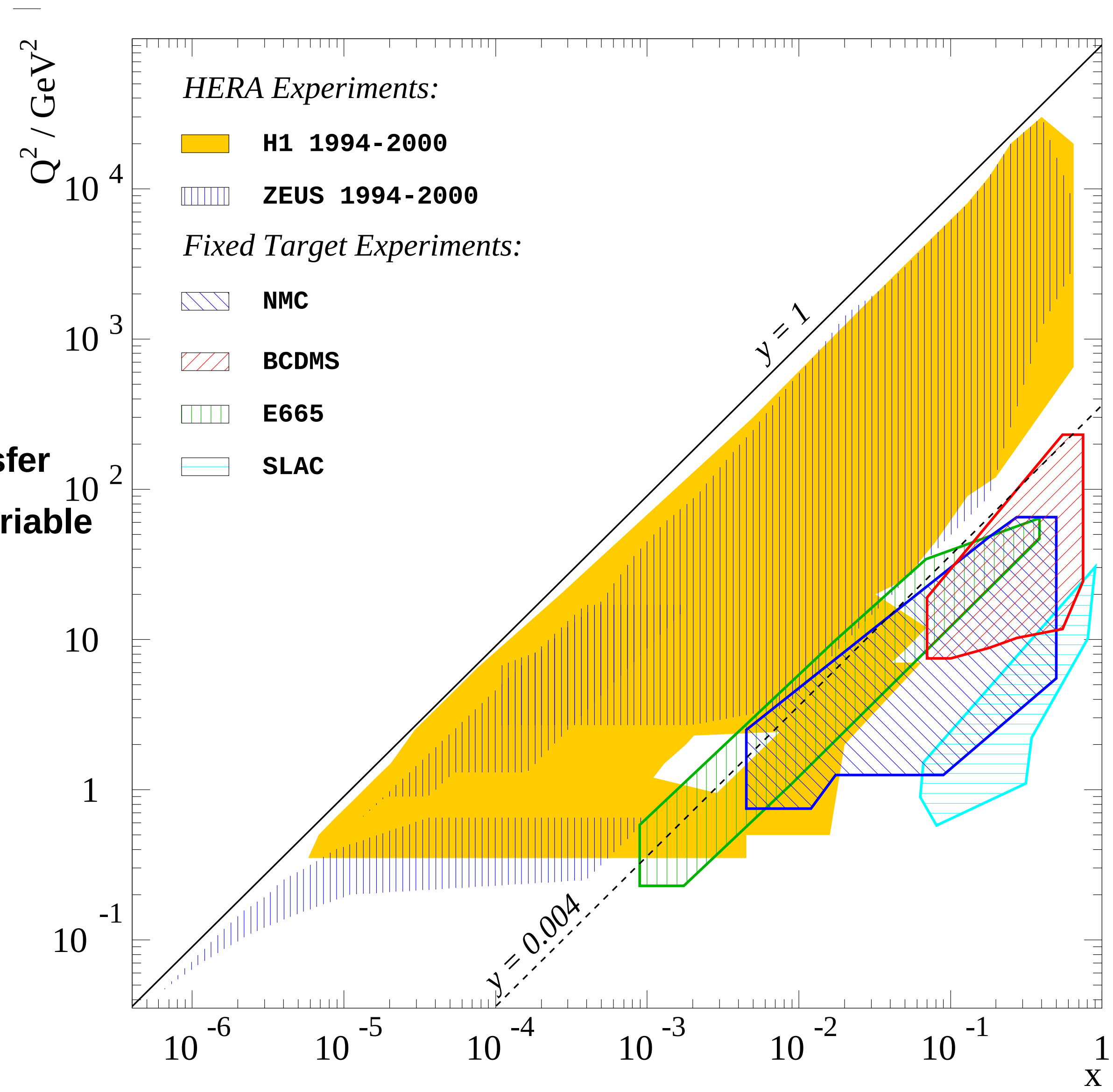


$Q^2 = -q^2$ **4-momentum transfer**

$x = Q^2/2(P \cdot q)$ **Bjorken scaling variable**

$y = (P \cdot q)/(P \cdot k)$ **inelasticity**

$Q^2 = x\, y\, s$



Inclusive DIS ep interactions

- **NC** $e^{\pm}p \longrightarrow e^{\pm}X$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_-x\tilde{F}_3 - y^2\tilde{F}_L\right] \equiv \frac{2\pi\alpha^2}{xQ^4}Y_+\tilde{\sigma}^{\pm}_{NC}$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

$\tilde{F}_2$	dominant contribution in LO QCD	$\{F_2, F_2^{\gamma Z}, f_2^Z\} = x\sum_q\{e_q^2, 2e_qv_q, v_q^2 + a_q^2\}(q+\bar{q})$
$x\tilde{F}_3$	γZ interference at $Q^2 \sim m_Z^2$	$\{xF_3^{\gamma Z}, xF_3^Z\} = 2x\sum_q\{e_qa_q, v_qa_q\}(q-\bar{q})$
$\tilde{F}_L$	sensitivity at low Q^2, high y	$\sim \alpha_s xg(x, Q^2)$

- **CC** $e^{\pm}p \longrightarrow \nu X$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{Q^2+m_W^2}\right]^2\left[Y_+\tilde{W}_2 \mp Y_-x\tilde{W}_3 - y^2\tilde{W}_L\right]$$

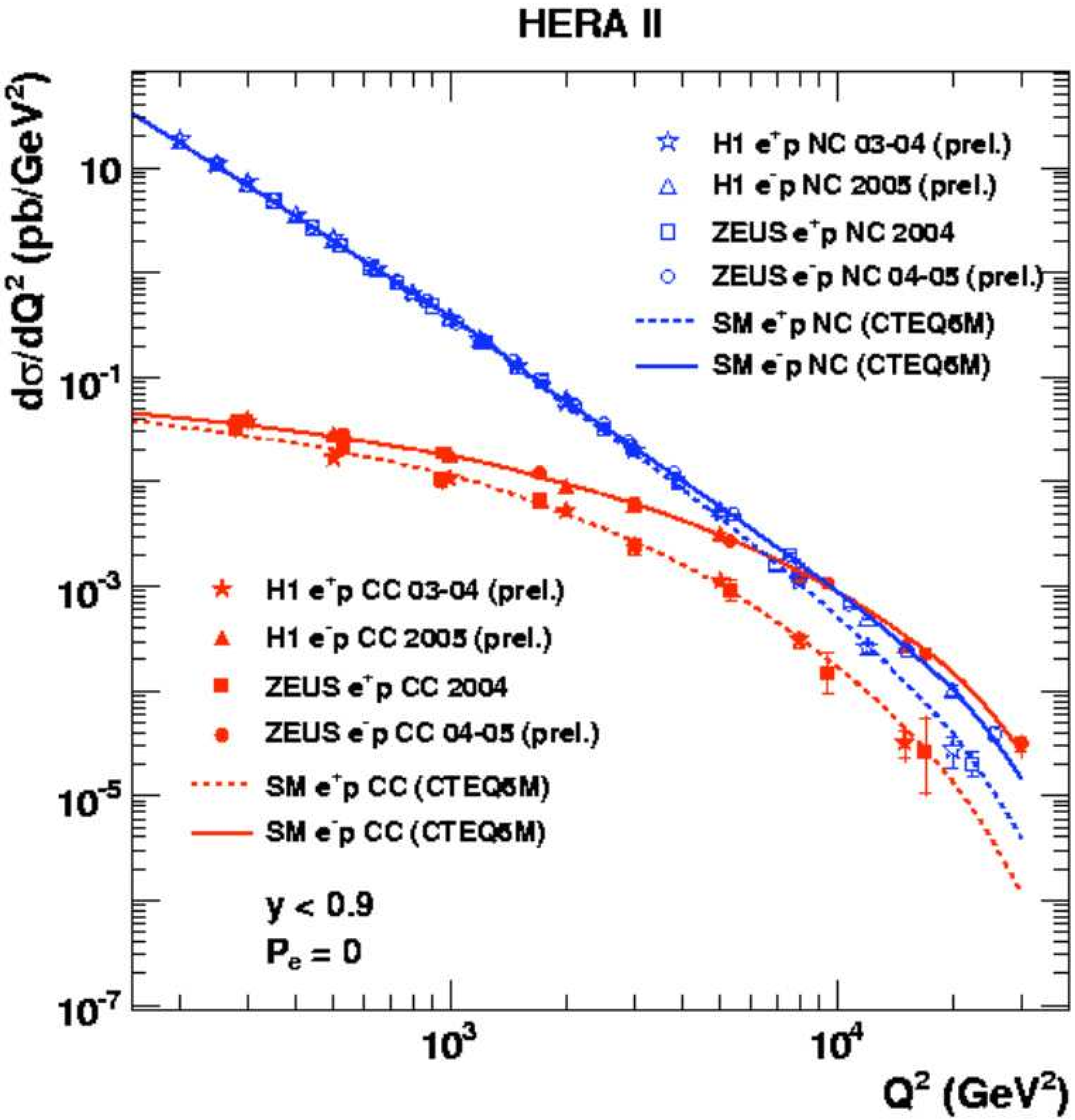
$\tilde{\sigma}^{+}_{CC} = x[(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$	sensitive to d quark at high x
$\tilde{\sigma}^{-}_{CC} = x[(u+c) + (1-y)^2(\bar{d}+\bar{s})]$	sensitive to u quark at high x

NC & CC cross sections

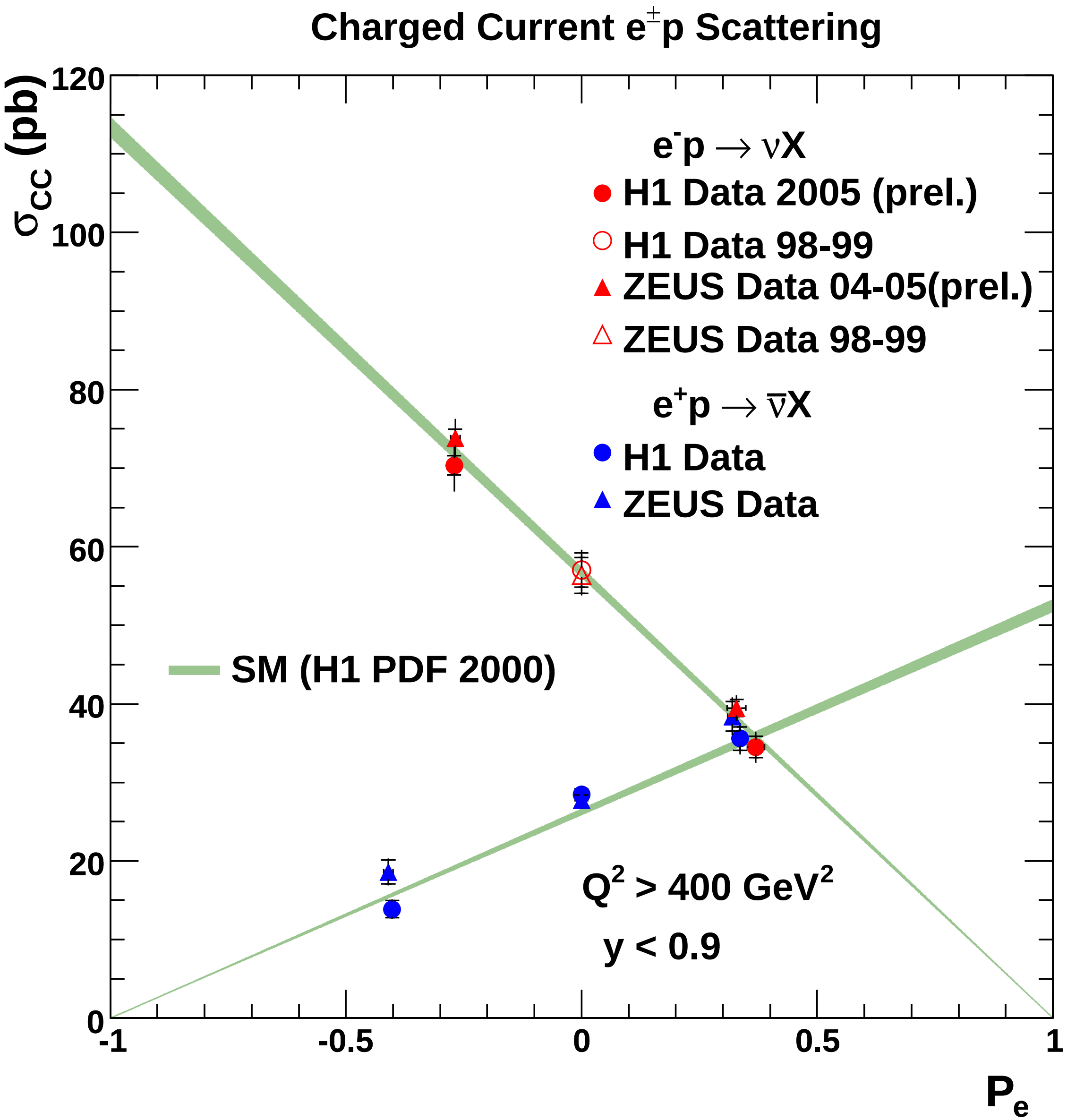
- **Excellent agreement with SM prediction over many orders of magnitude**
- **CC cross section suppressed at low Q^2 by W propagator**
- **NC and CC comparable cross sections at high $Q^2 \sim M_W^2$**
- **$\sigma^{e^-p} > \sigma^{e^+p}$ at high Q^2 electroweak effects**

$\Rightarrow$ **Stringent limits on eq compositeness**

quark radius $R_q < 1 \cdot 10^{-18}$ **m**
LQ's $M_{LQ}/\lambda \gtrsim 1\,\mathrm{TeV}$
LED $M_S > 0.8\,\mathrm{TeV}$



Polarised CC cross section



- Test V-A structure of CC interaction
- No right-handed current in SM
- Linear polarisation dependence

$$\sigma^{\pm}_{CC} = (1 \pm \mathcal{P}_e)\sigma^{\pm}_{CC,unpol}$$

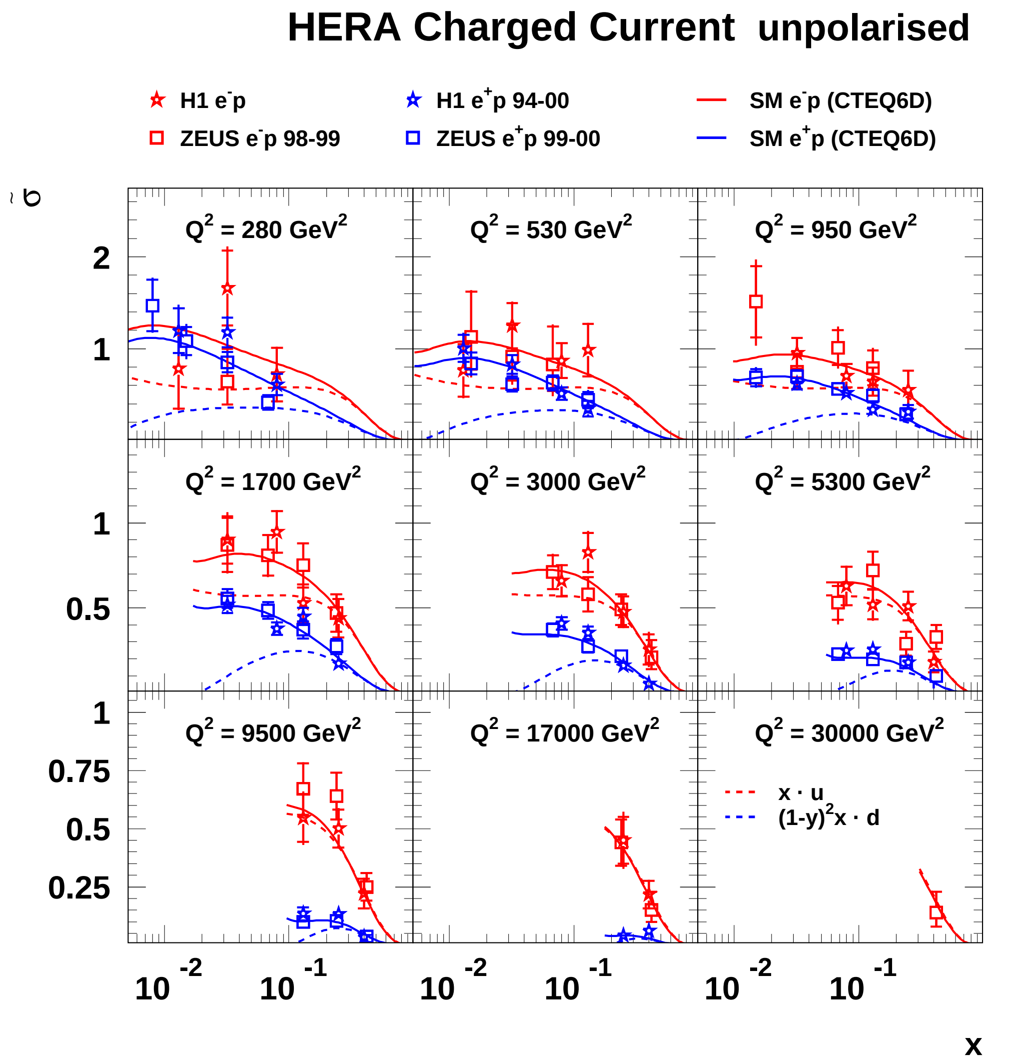
- Extrapolation to
  $\mathcal{P}_{e^-} = +1$ resp $\mathcal{P}_{e^+} = -1$

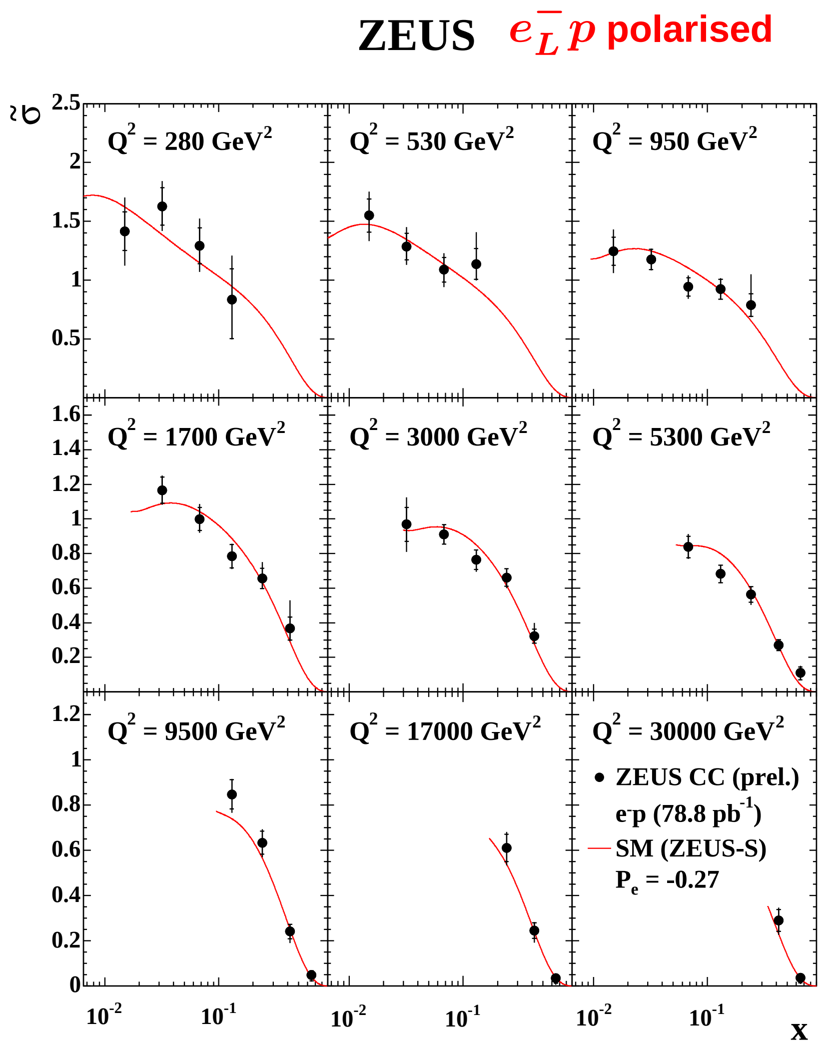
  sets limit on W_R

  $$M_{W_R} \gtrsim 200\,\mathrm{GeV}$$

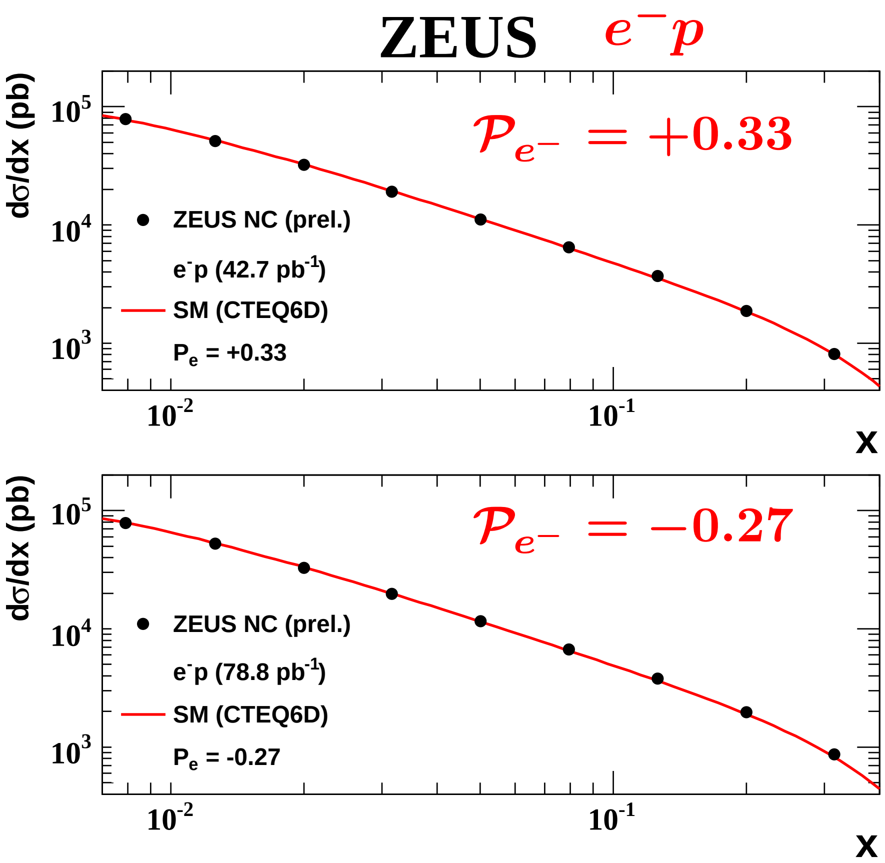
CC cross section

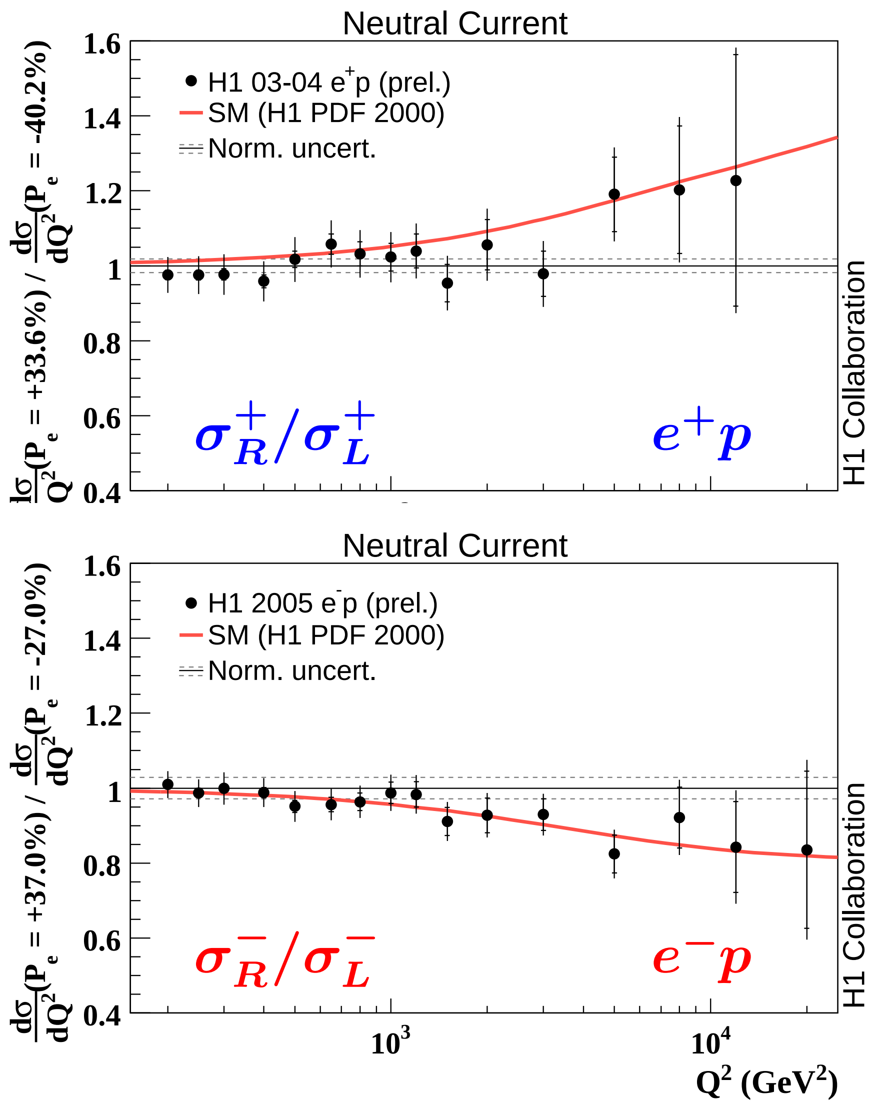
- u, d quark separation at high x dominating for $x > 0.2$, consistency check wit $xF_3 \sim 2u_v + d_v$
- e^+p sensitive to d quark, particularly valuable (free of nuclear effects of eD scattering)
- e^-p sensitive to u quark, new HERA II meas. improve u_v





NC polarised cross sections





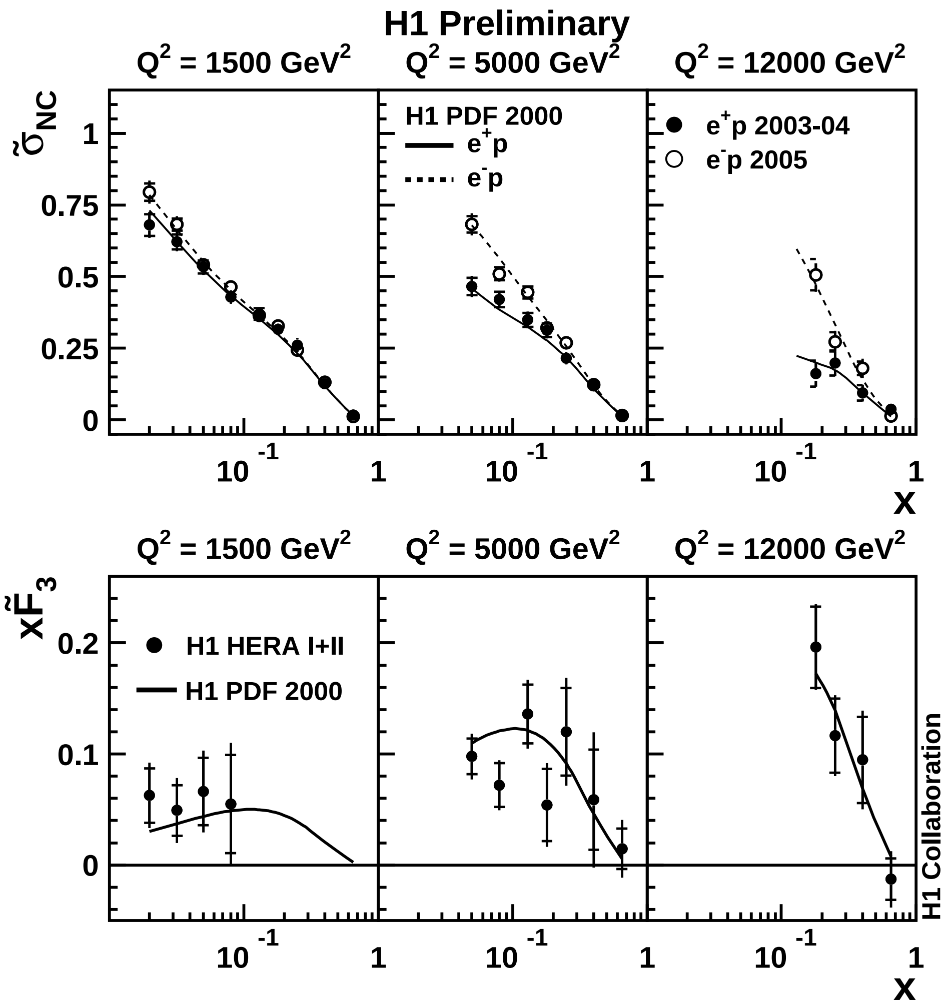
$$\sigma_{NC}^{\pm} \sim F_2 \mp \mathcal{P}_e a_e \chi_Z F_2^{\gamma Z} \mp a_e \chi_Z x F_3^{\gamma Z}$$

Polarisation effects at high Q^2 clearly established in NC

Measurement of xF_3

$$x\tilde{F}_3 = (\tilde{\sigma}^{-}_{NC} - \tilde{\sigma}^{+}_{NC})(Y_+/2Y_-)$$

$$\boxed{xF_3^{\gamma Z} = x\tilde{F}_3/[-a_e\kappa_W/(Q^2 + M_Z^2)] \sim 2u_v + d_v}$$



HERA I $15\,\mathrm{pb}^{-1}\ e^-,\ 100\,\mathrm{pb}^{-1}\ e^+$

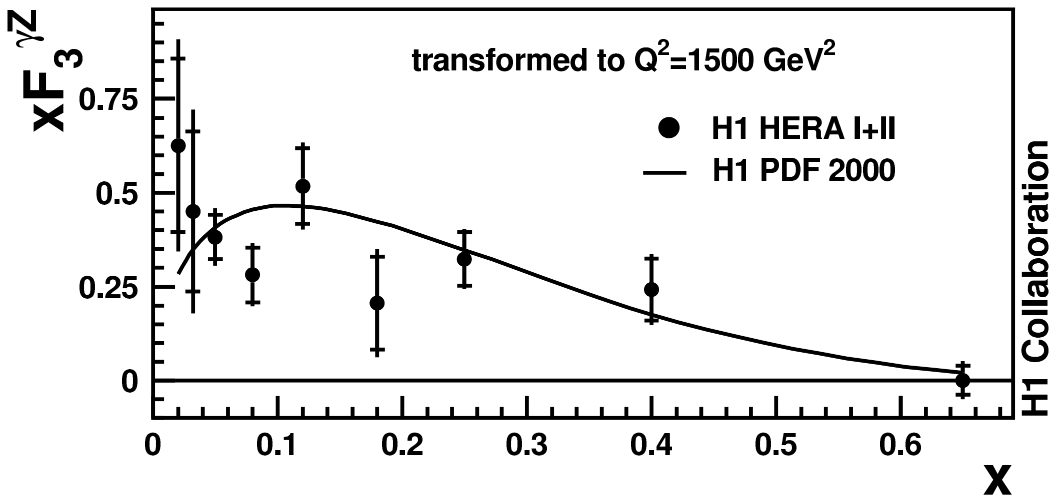
HERA II $120\,\mathrm{pb}^{-1}\ e^-,\ 50\,\mathrm{pb}^{-1}\ e^+$

corrected for polarisation effects

precision increased by 20%

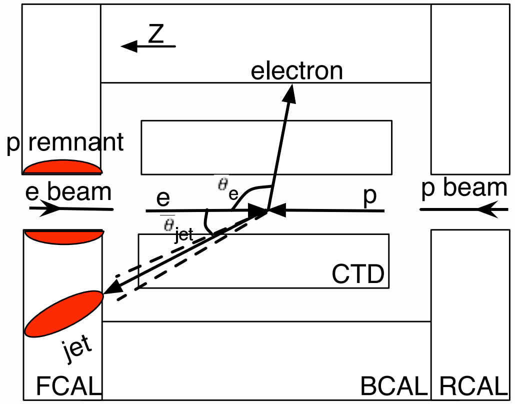
neglect pure Z contribution (small) & correct for propagator (Q^2) terms

$\rightarrow$ Test x dependence of valence quarks



NC cross section at very high x

ZEUS technique to access high x region



Q^2 well measured by electron

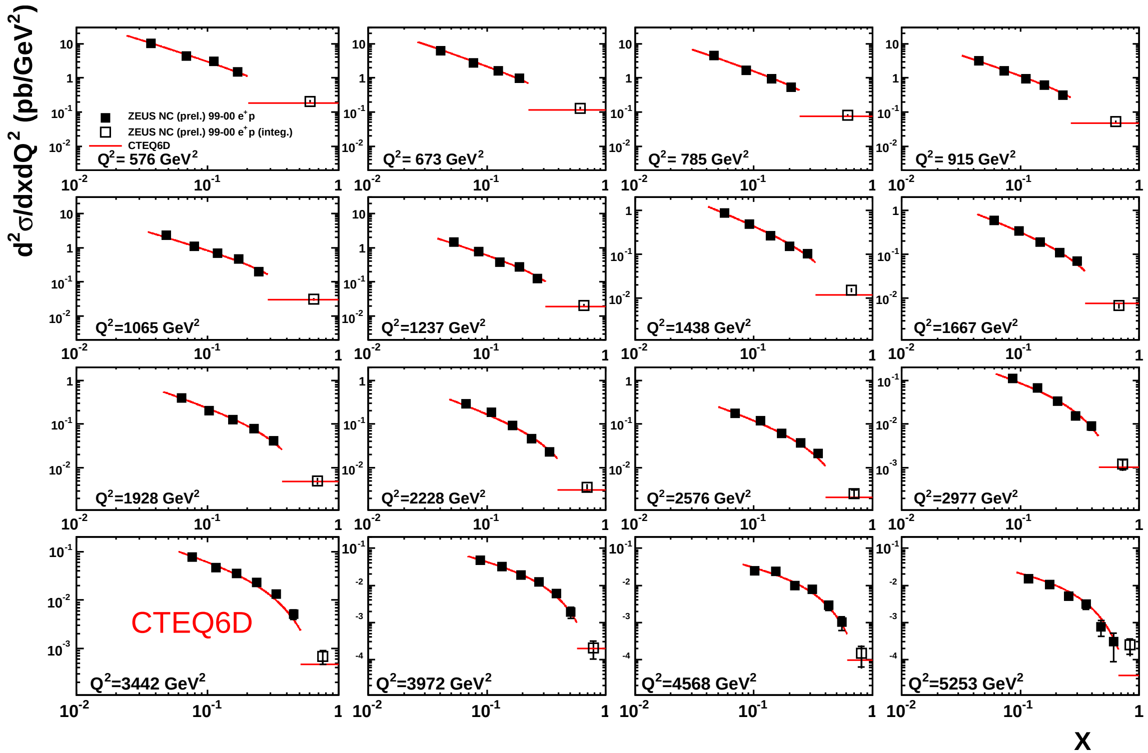
jet in detector — x from jet $E_T > 10\,\mathrm{GeV}, \theta > 0.12$

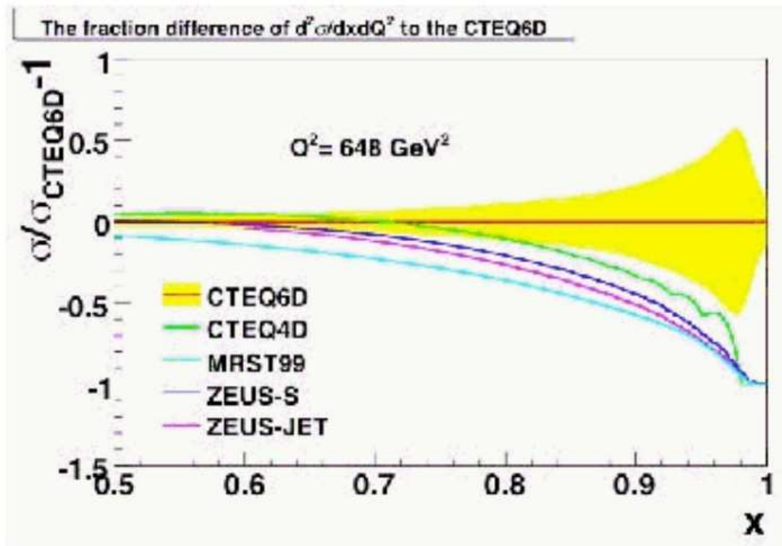
jet in beampipe — integrate σ over $x_{edge}(Q^2) < x < 1$

discard ≥ 2 jet events

Still large uncertainties at high x

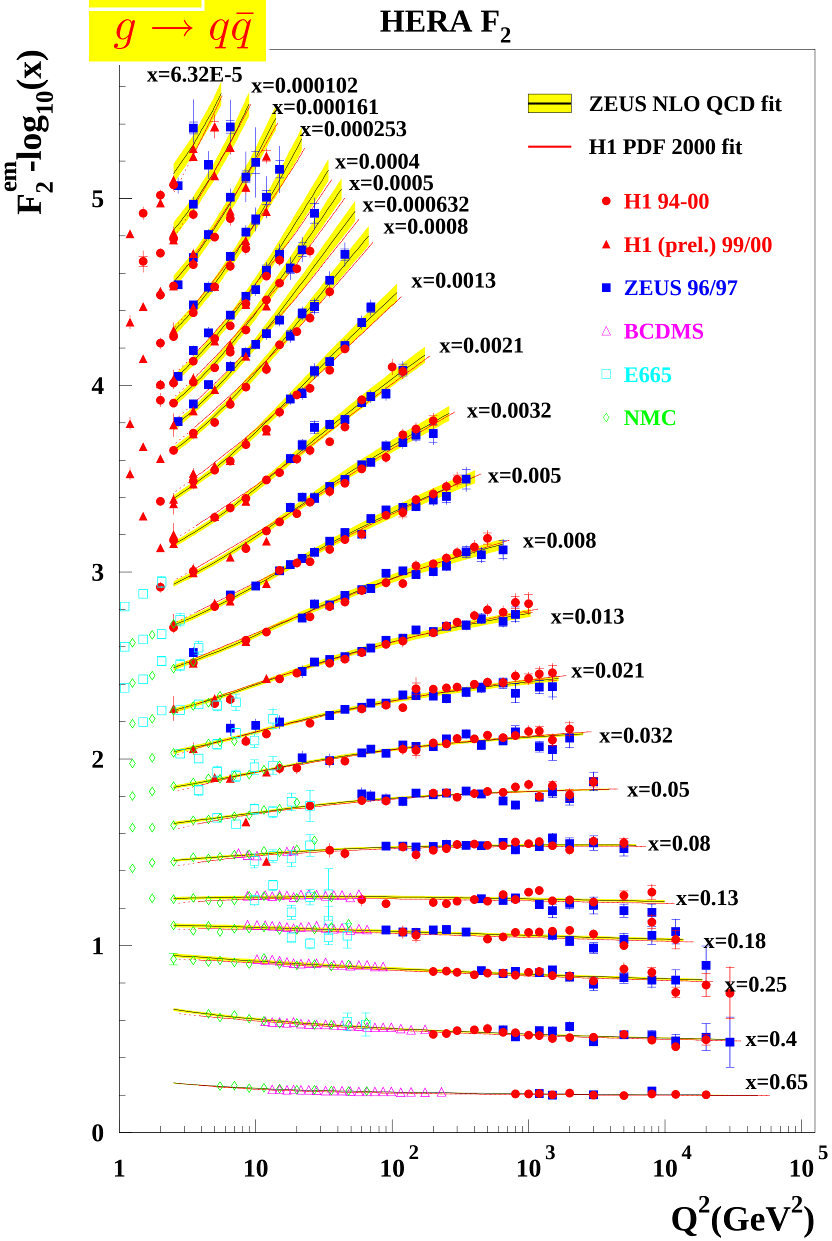
Input to PDF fits, integrated points tend to lie above CTEQ6D





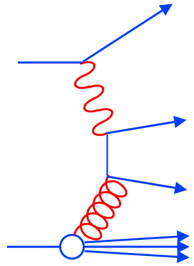
Structure functions & parton densities

low x
$g \longrightarrow q\bar{q}$



high x
$q \longrightarrow q\,g$

- HERA data well described by NLO QCD
- parton densisties parametrised at some Q_0^2
  e.g. $xf(x) = ax^b(1-x)^c(1+dx)$
  Q^2 evolution using DGLAP in NLO
- low x sea, gluon constrained by F_2 @ low Q^2
- high x u, d valence constrained by high Q^2 NC & CC cross sections
- medium x gluon constrained by jet data (DIS jets and γp di-jets)

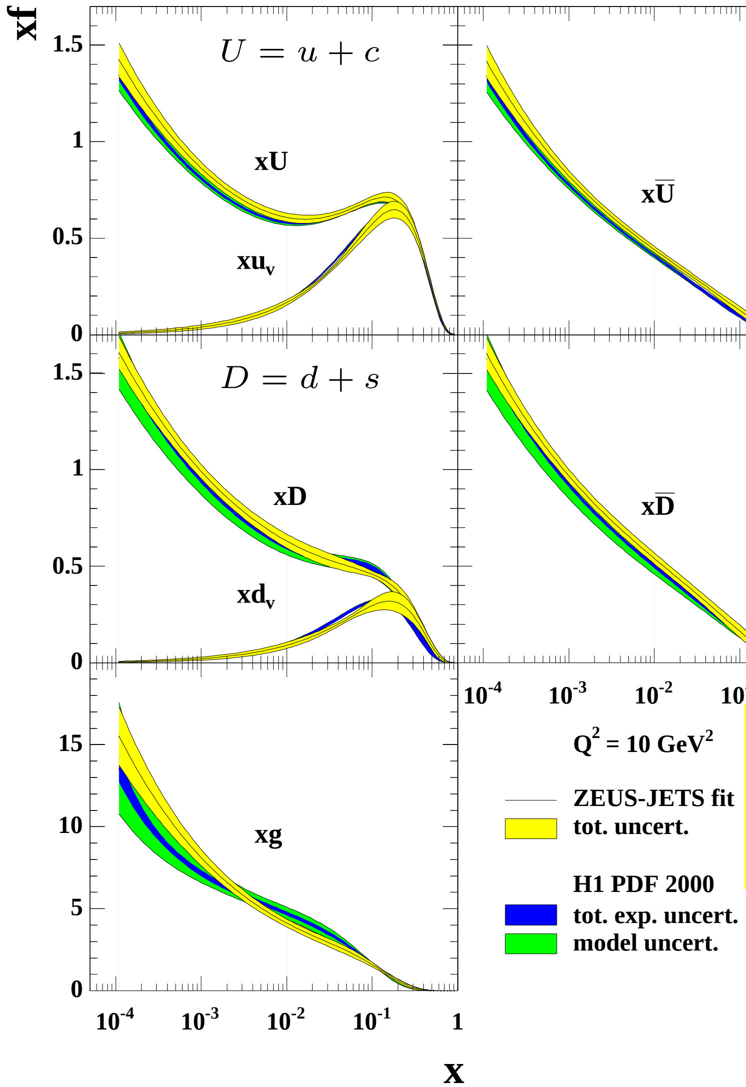


boson gluon fusion, QCD Compton

- correlations between $\alpha_s(Q^2)$ and $g(x, Q^2)$ resolved by using wide range of x and Q^2
- consistent analysis within a single experiment, advantage for treatment of error correlations

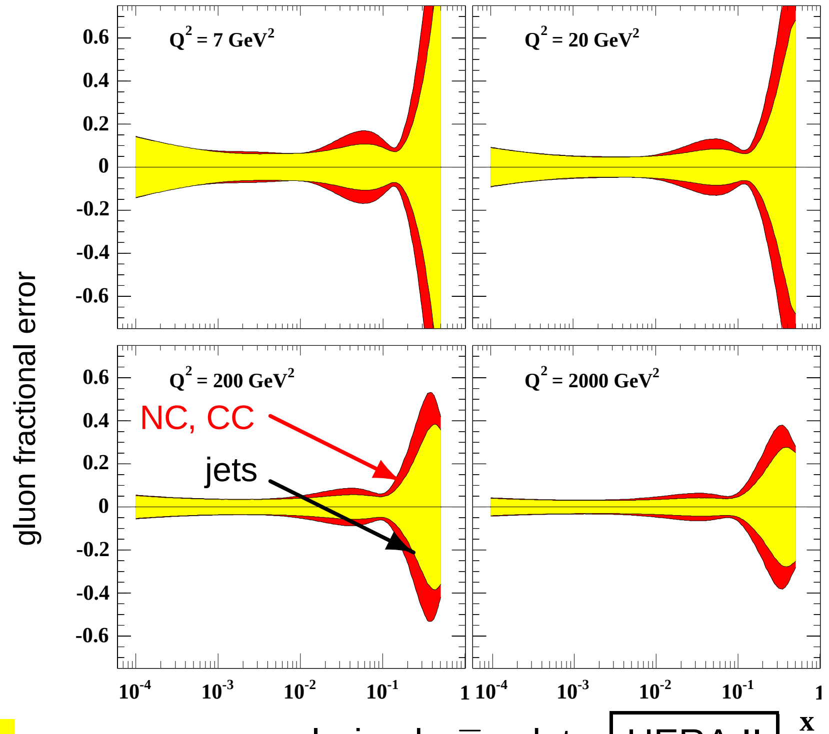
Combined QCD & EW fits

ZEUS-Jets fit vs H1 pdf 2000

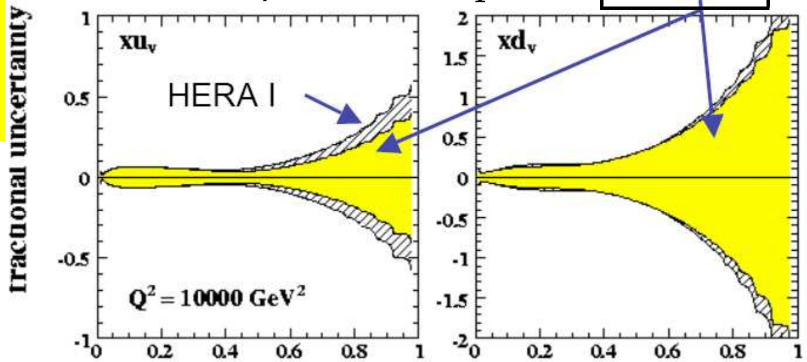


x	0.01	0.4	0.65
xU	1%	3%	7%
xD	2%	10%	30%

impact of jets on gluon



polarised e^-p data HERA II



ZEUS and H1 PDFs consistent (and MRST, CTEQ)
slight differences in $g(x)$ at $x \sim 0.01$
combined H1/ZEUS analysis in progress

jet data improve error on gluons
polarised e^-p reduce $u_v(d_v)$ uncertainty

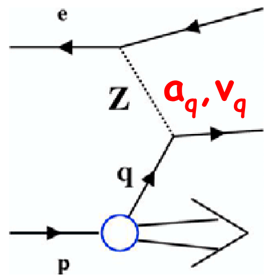
Light quark couplings

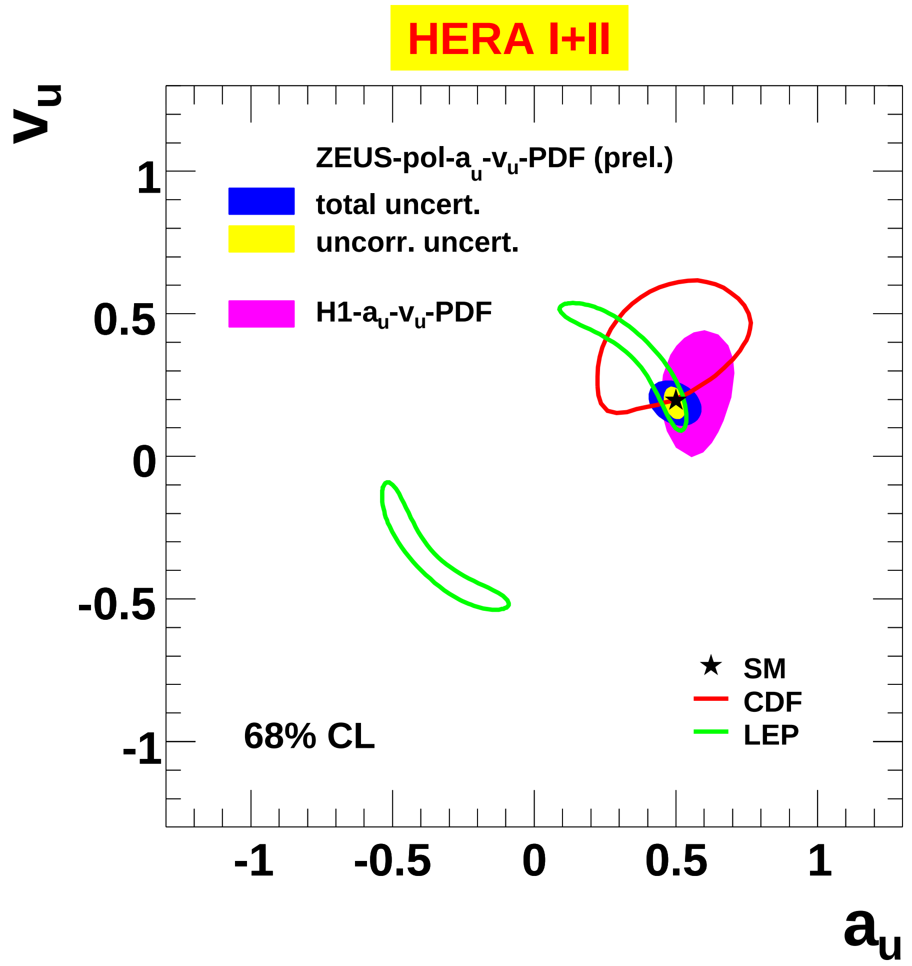
Combined QCD & EW fit in space-like region: $a_q \leftrightarrow xF_3$ and $v_q \leftrightarrow F_2^{pol}$

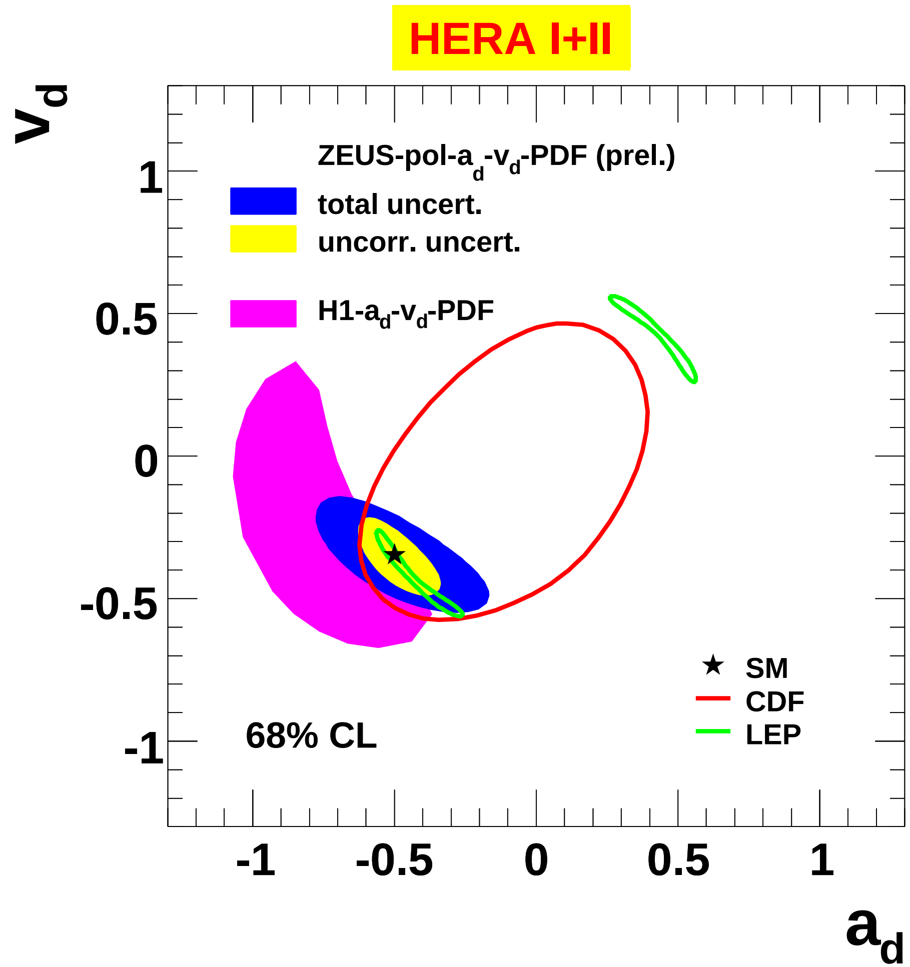
H1 HERA I unpolarised data, ZEUS HERA II polarised data

Precision on axial and vector couplings of u and d quarks

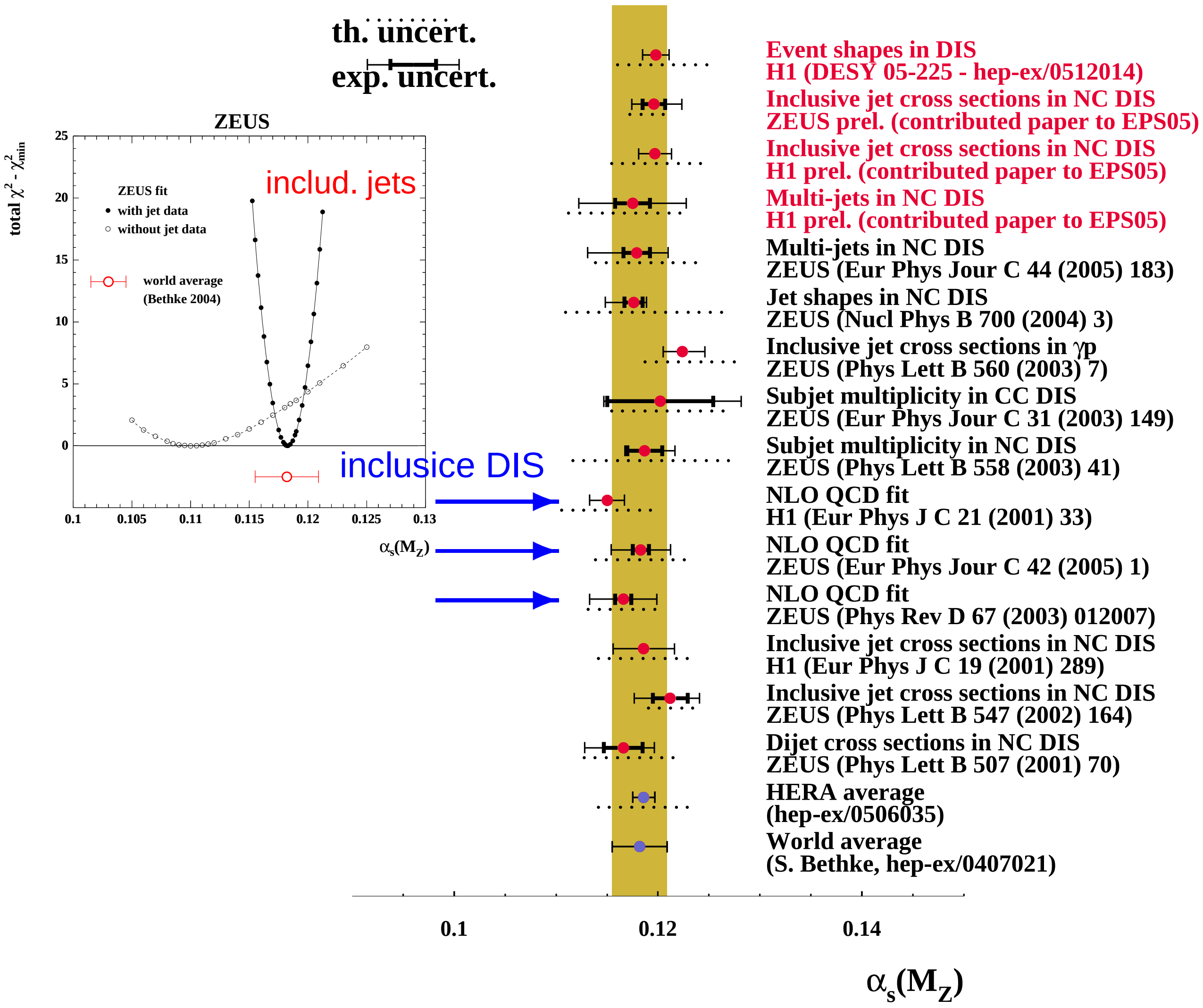
comparable with LEP, ambiguity resolved

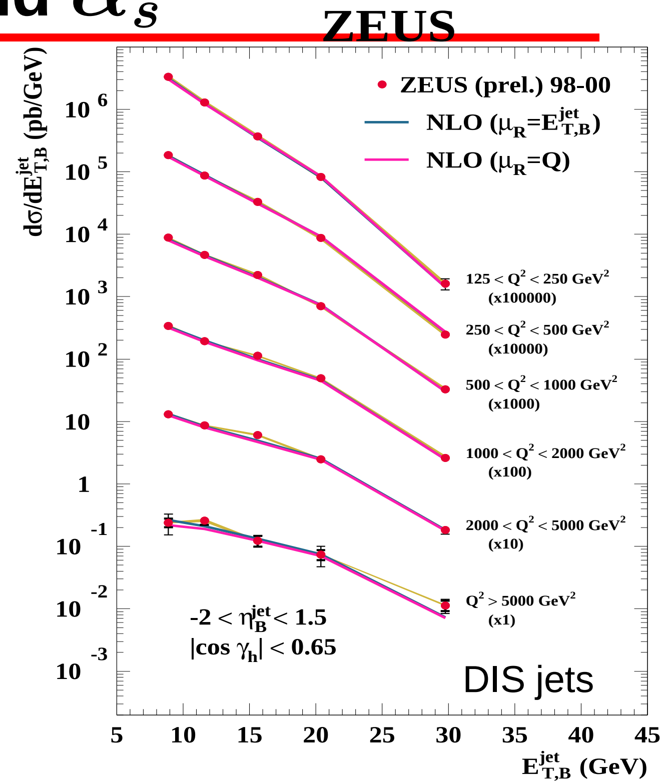


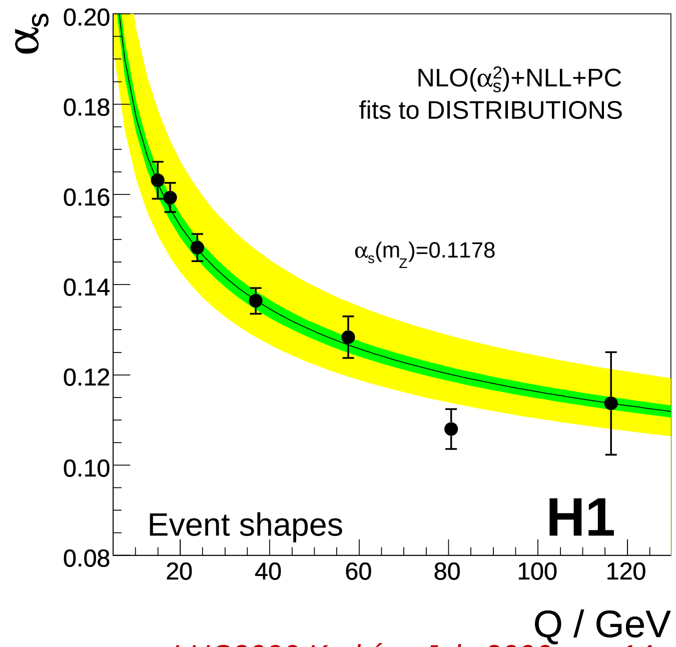




QCD fits, DIS inclusive, jets and α_s







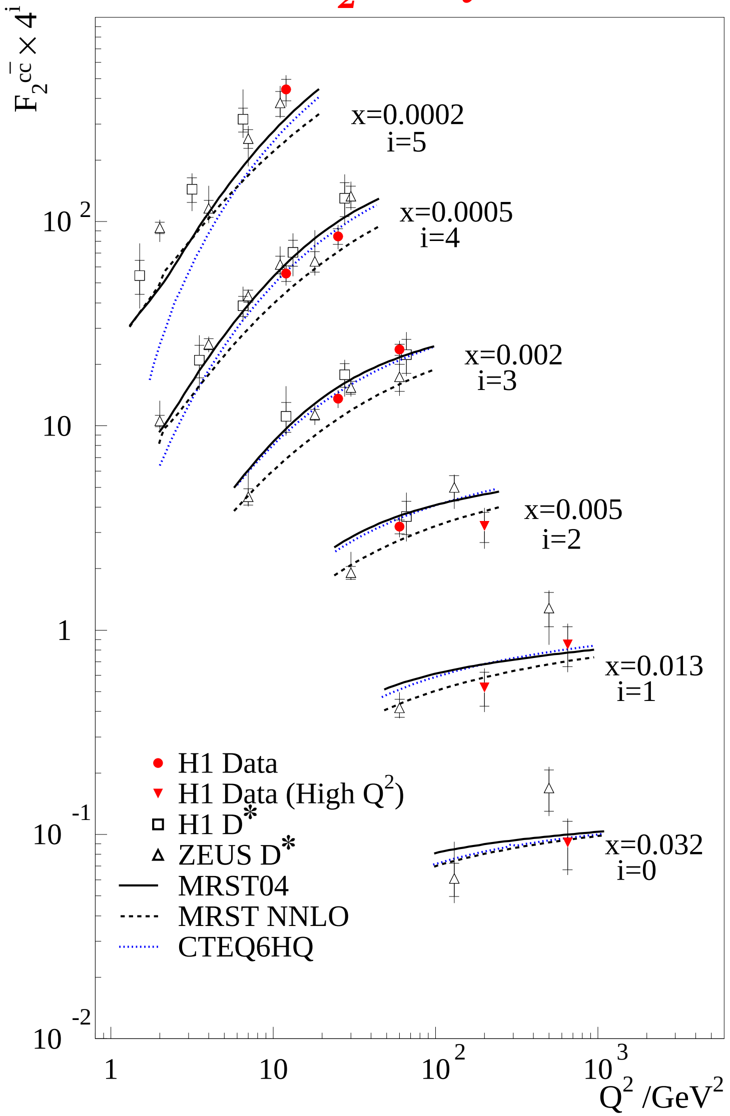
Precise α_s measurements at HERA

uncertainty dominated by theory, NNLO required

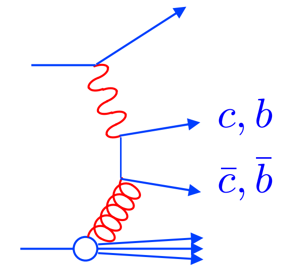
Evolution $\alpha_s(Q^2)$ from jets, event shapes in a single experiment

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

$F_2^{c\bar{c}}$ vs Q^2



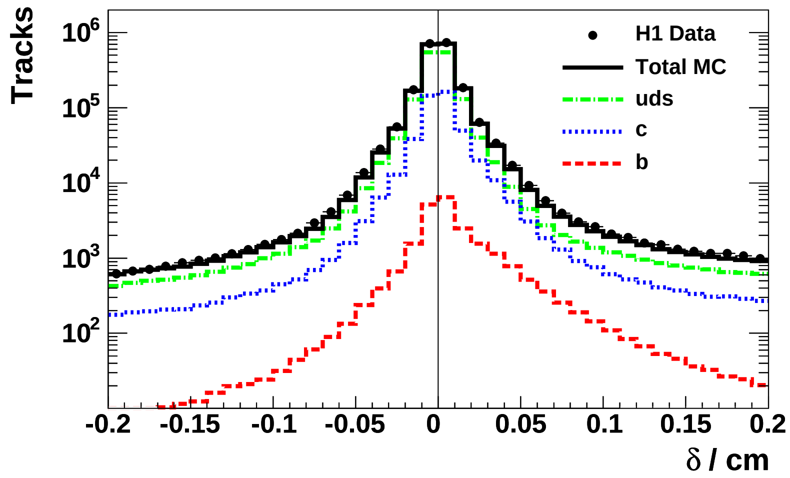
Heavy quark production via boson gluon fusion



Flavour ID:

D^* reconstruction (charm)

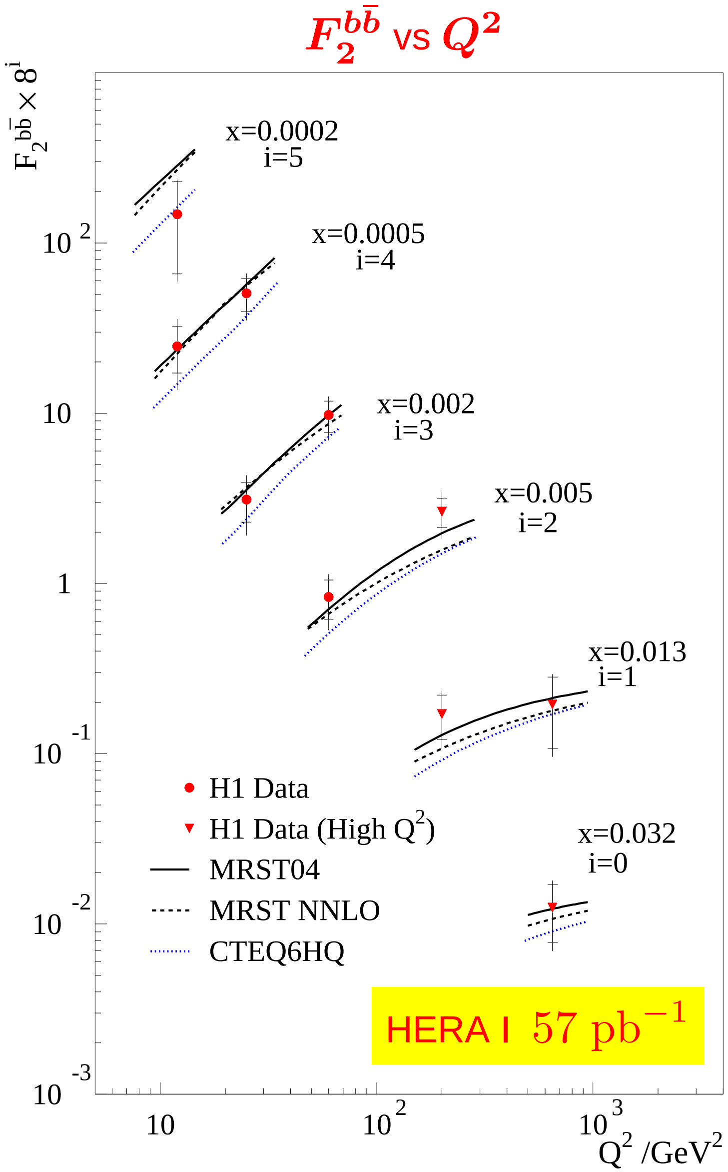
Impact parameter of track to vertex (charm & bottom) using Si tracker, minimal extrapolation needed to extract $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$



$F_2^{c\bar{c}}$ both methods agree

good agreement with SM

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$



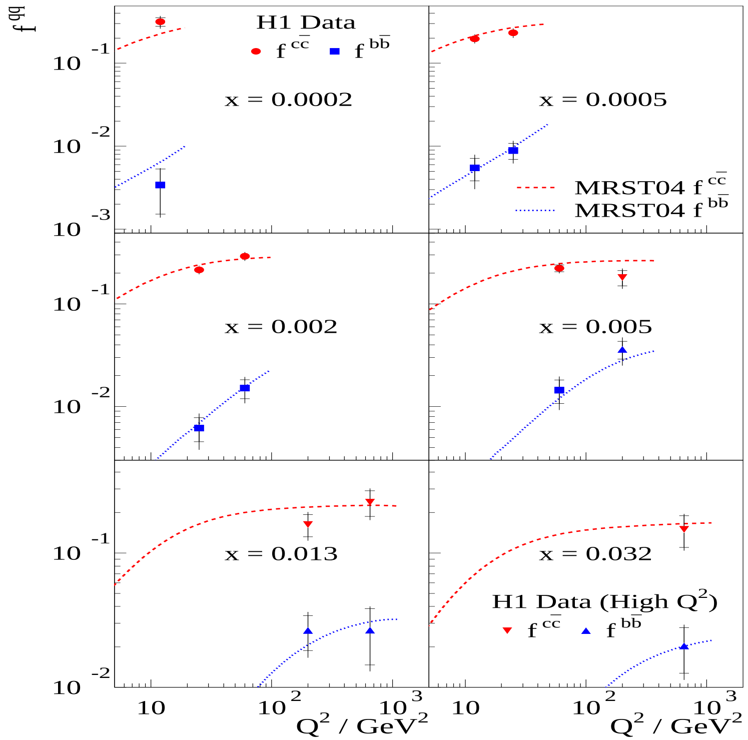
$F_2^{b\bar{b}}$ first measurement

good agreement with SM, no excess

CTEQ + MRST differences at low Q^2

HERA II expect $\sim 450\,\mathrm{pb}^{-1}$ per expt

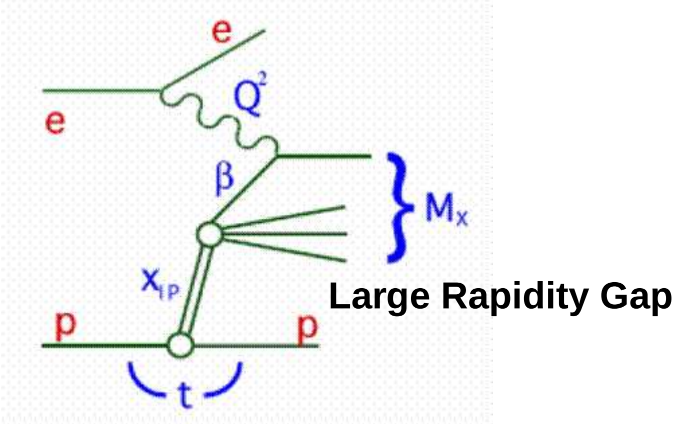
charm and bottomm fractions

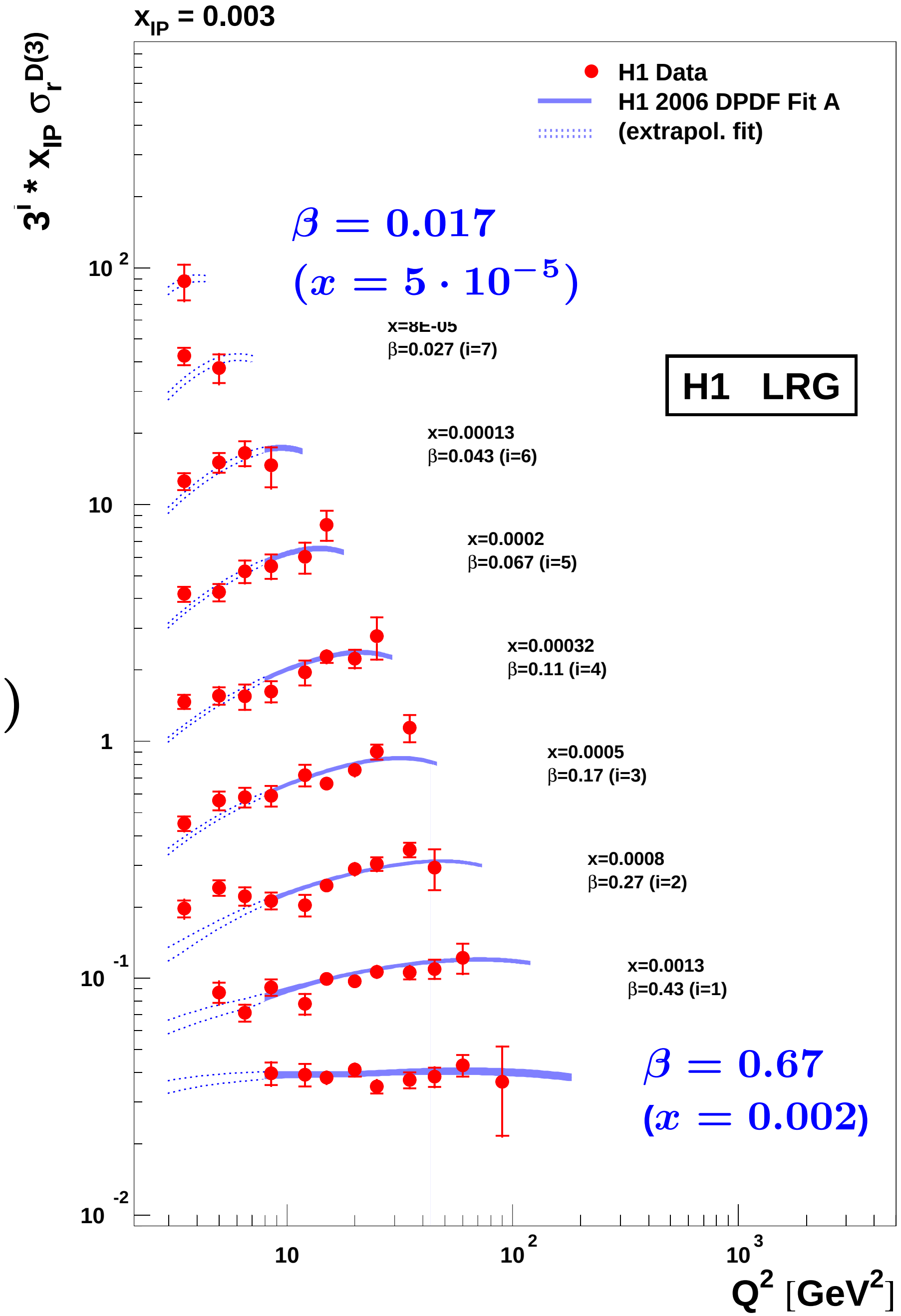


$f^{c\bar{c}} \sim 20 - 30\%$

$f^{b\bar{b}} \sim 0.3 - 1.5\%$

Diffractive DIS





Diffractive inclusive cross section

$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\,d\beta\,dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P},\beta,Q^2)$$

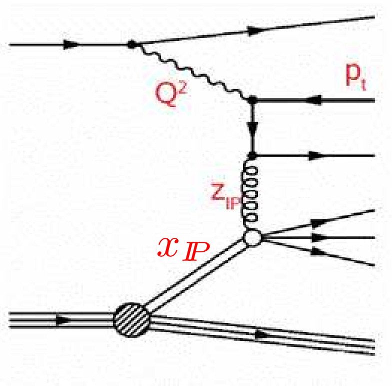
$$F_2^D(x_{I\!P},\beta,Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta,Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\,\mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*

Diffractive parton densities



diffractive di-jet production

Combined fit of F_2^D and di-jet data constrain quark and in particular gluon densities in the range
$$0.05 < z_{I\!P} < 0.9$$

gluon carries $\sim 70\%$ *of the momentum of the colourless exchange*

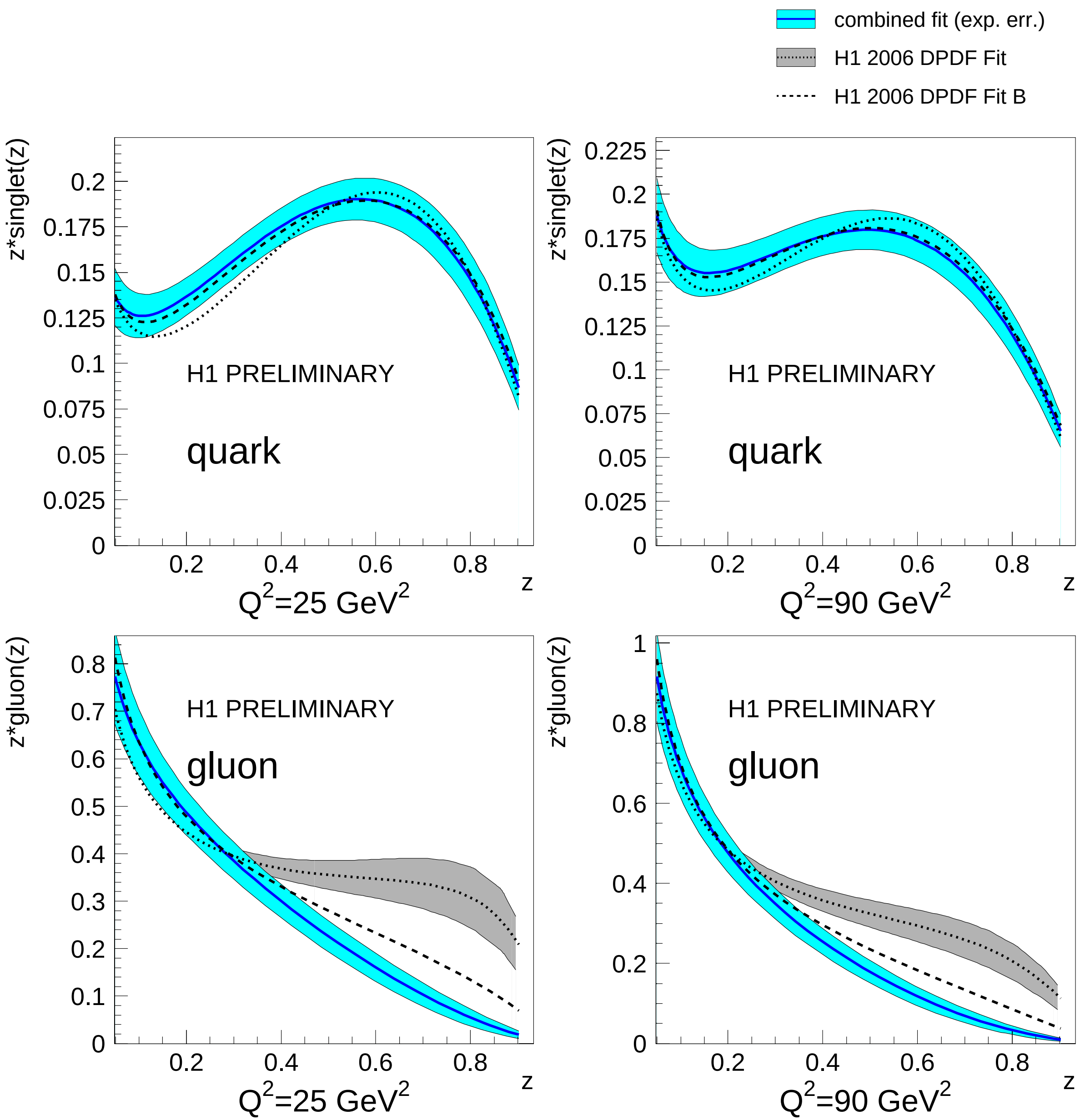
Sensitivity to gluon at scale Q_0

$$z f_g(z) = A_g z^{B_g} (1 - z)^{C_g}$$

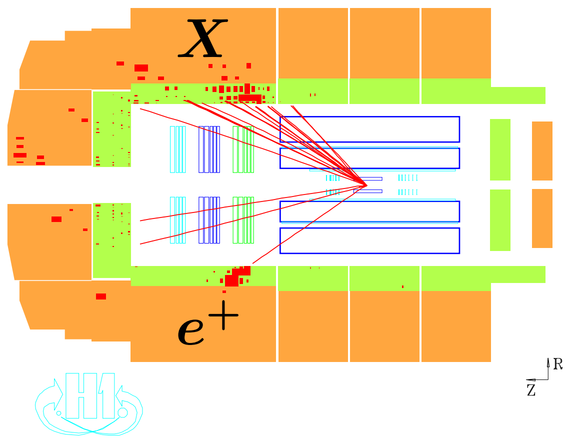
F_2^D not sensitive to B_g

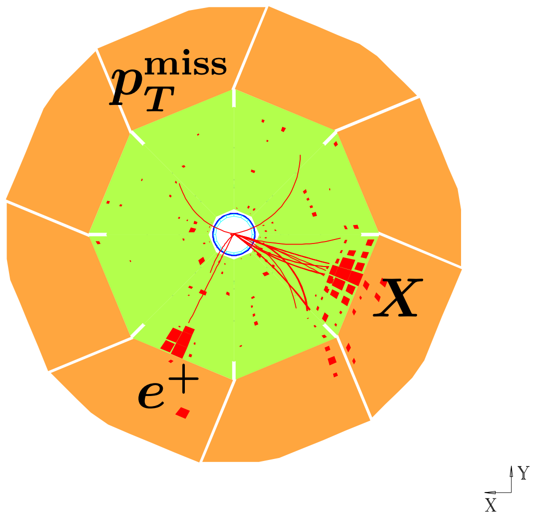
DPDF Fit $\quad z f_g(z) = A_g (1 - z)^{C_g}$

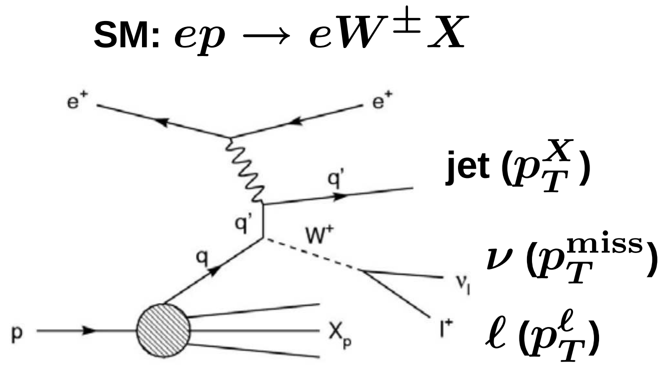
DPDF Fit B $\quad z f_g(z) = A_g$



Events with isolated lepton and missing p_T



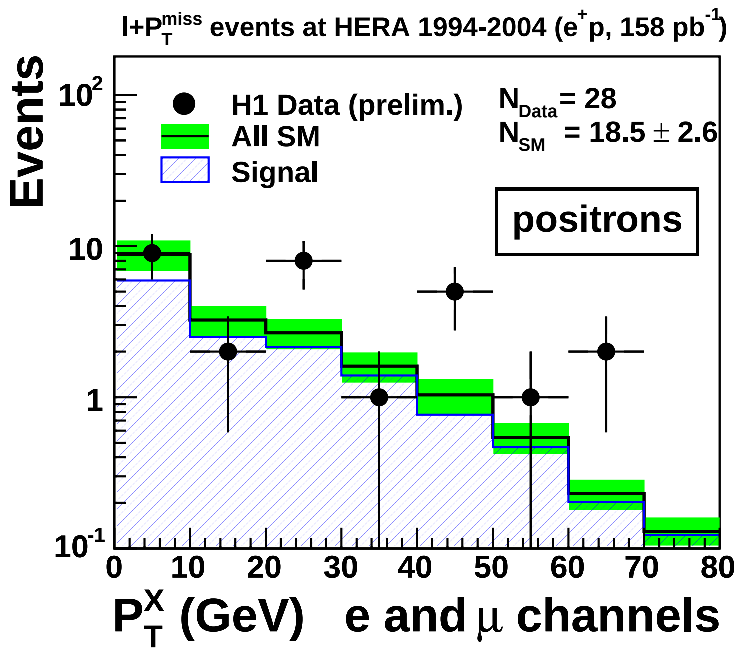


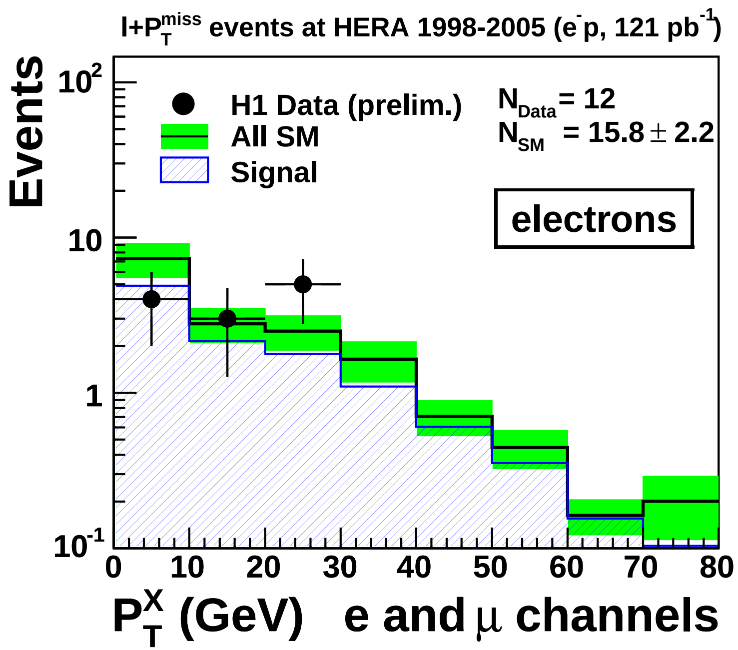


HERA I: H1 observes excess of e, μ in high p_T^X in e^+p collision

HERA II: excess persists in e^+p data only

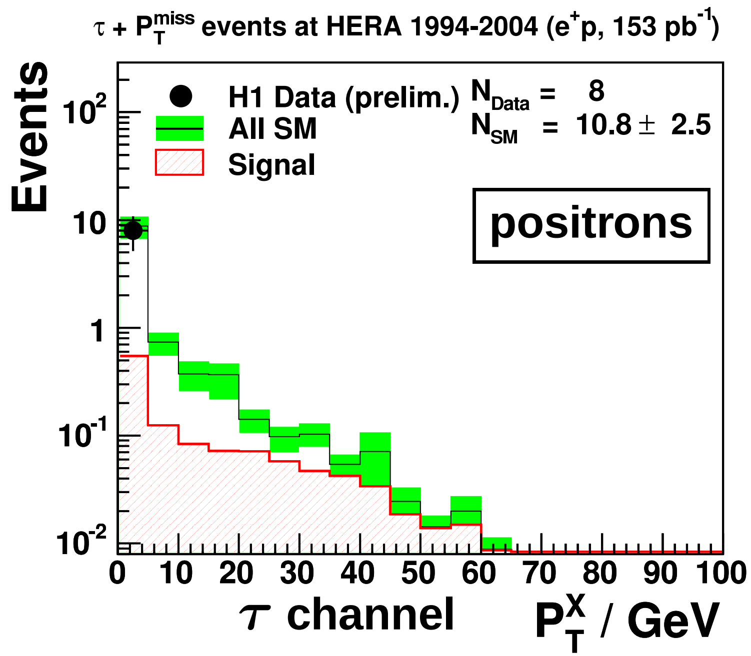
Isolated e and μ

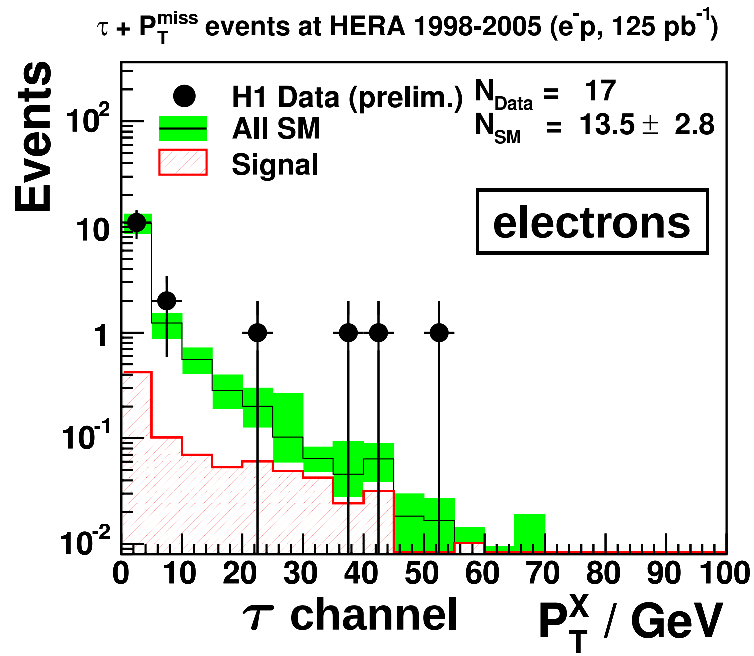




Events with isolated leptons and missing p_T

Isolated τ





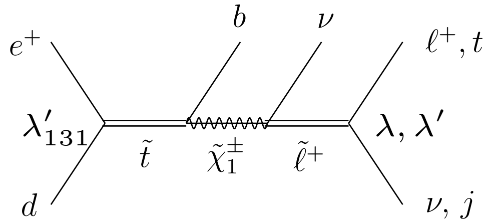
$p_T^X > 25\,\mathrm{GeV}$			e channel	μ channel	τ channel
H1	e^+p	$158\,\mathrm{pb}^{-1}$	$9/2.3$	$6/2.3$	$0/0.4$
H1	e^-p	$175\,\mathrm{pb}^{-1}$	$3/3.6$	$0/2.9$	$3/0.4$
ZEUS	e^+p	$106\,\mathrm{pb}^{-1}$	$1/1.5$		$2/0.2$
ZEUS	e^-p	$143\,\mathrm{pb}^{-1}$	$3/2.9$	$2/1.4$	

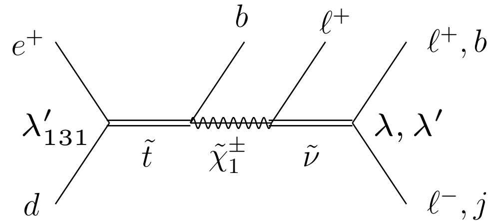
Inconclusive situation

Expect final e^-p analysis and future e^+p running

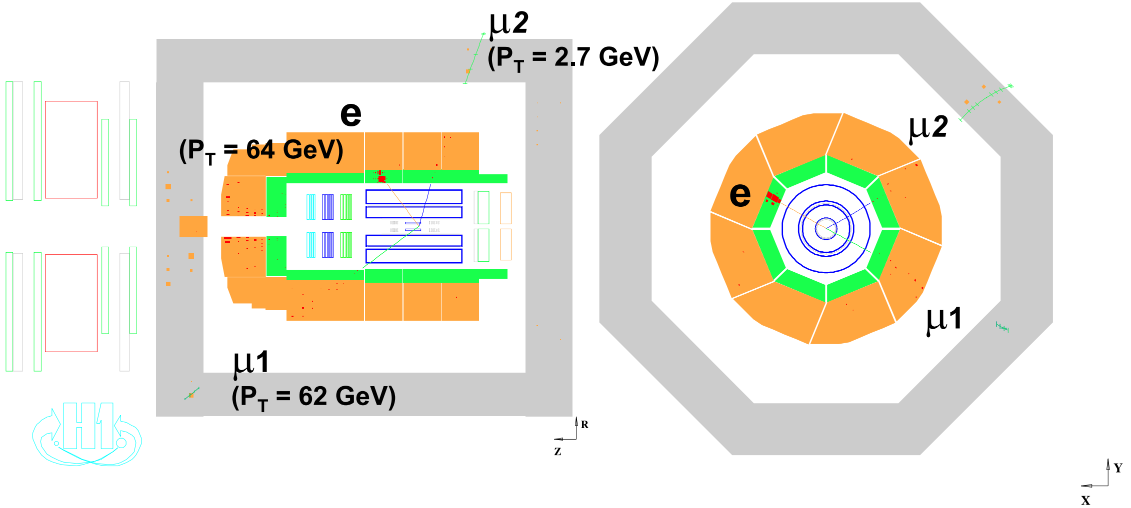
Possible explanation of H1 excess

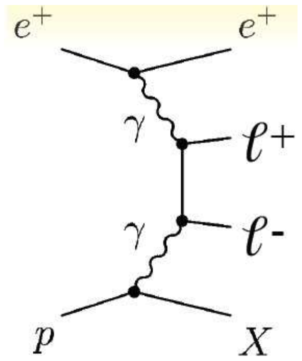
R parity violating SUSY couplings: λ'_{LQD} and λ_{LLE}





Multi-lepton events



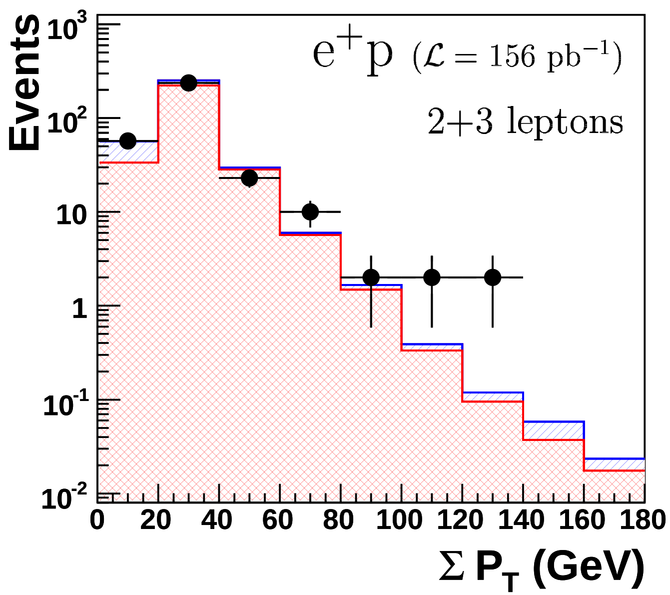


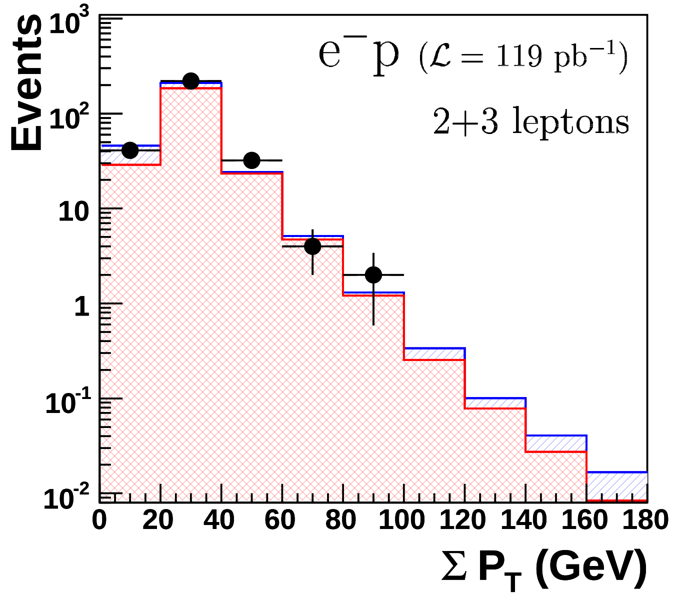
H1 investigates high p_T lepton topologies $ee, \mu\mu, e\mu, eee, e\mu\mu$

HERA I+II data $\mathcal{L} = 275\,\mathrm{pb}^{-1}$

striking events observed at large $\sum p_T > 100\,\mathrm{GeV}$ only in e^+p scattering

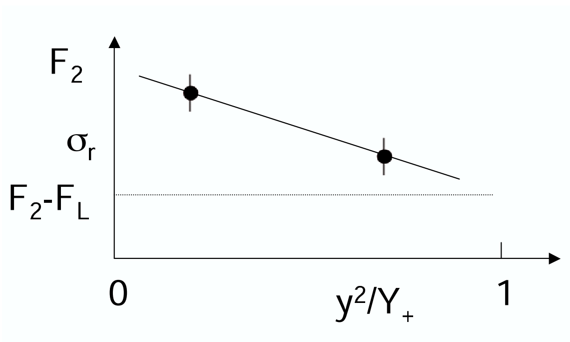
$\sum p_T > 100\,\mathrm{GeV}$	Data/SM
e^+p ($156\,\mathrm{pb}^{-1}$)	$4/0.6$
e^-p ($119\,\mathrm{pb}^{-1}$)	$0/0.5$
$e^\pm p$ ($275\,\mathrm{pb}^{-1}$)	$4/1.1$





Prospect: Measurement of F_L

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$



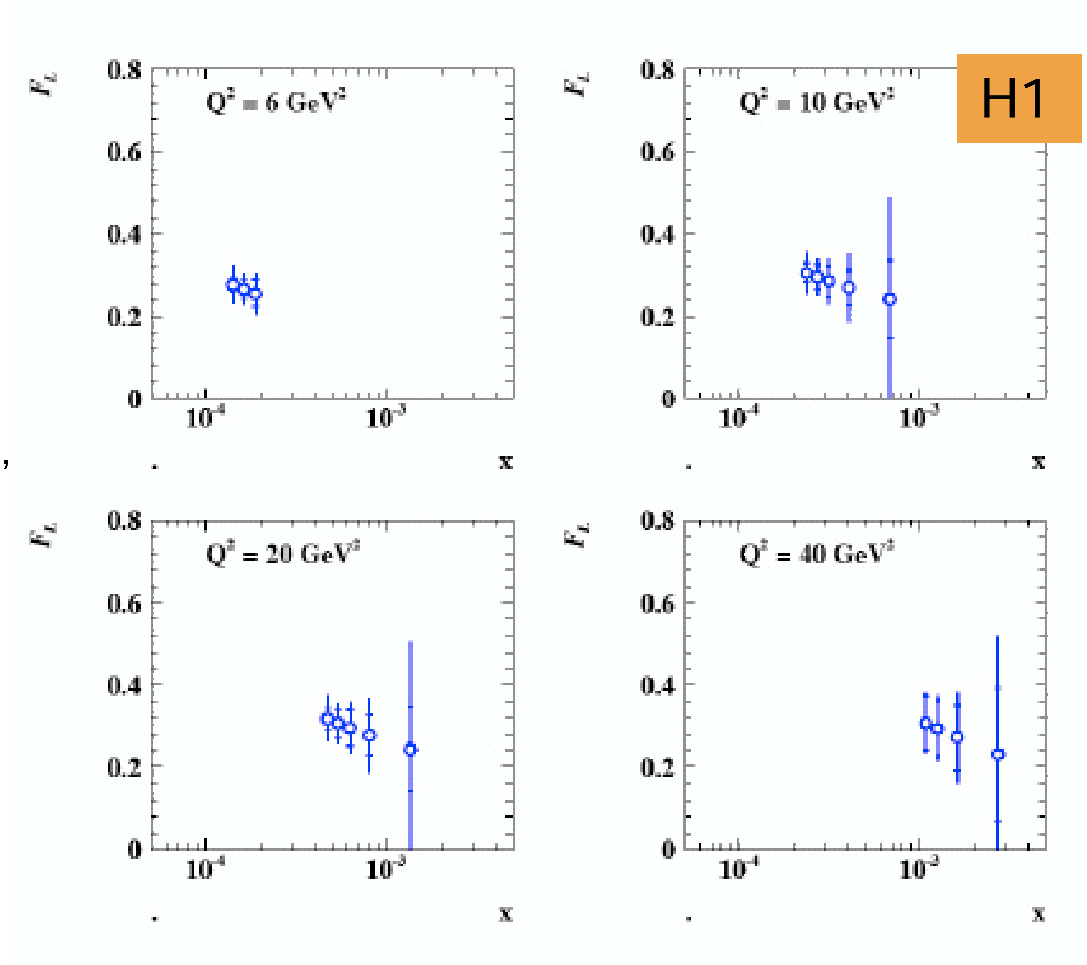
Longitudinal structure function gives direct access to poorly known gluon density at low x, theoretically very uncertain, important to understanding of pQCD

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) zg \right]$$

sizeable at large $y > 0.6$

Measure cross section at same x, Q^2 and different y, change $y = Q^2/xs$ by lowering s with $E_p = 460\,\mathrm{GeV}$

Challenge to machine   lower E_p, reduced lumi $\sim 1/4$
Challenge to experiment   low scattered e^+ $E'_e \gtrsim 3\,\mathrm{GeV}$, huge γp bkg at high y



H1 + ZEUS: F_L is a must for HERA

agreed to collect $\mathcal{L} = 10\,\mathrm{pb}^{-1}$
3 months data taking
$Q^2 = 5 - 40\,\mathrm{GeV}^2$, $x = (0.1 - 4)\cdot 10^{-3}$
expect moderate precision $\delta F_L \sim 0.05$
corresponding to 5 st. dev depending on F_L

Summary & outlook

- Beautiful inclusive HERA data available over 4 orders of magnitude in x and Q^2
- Rich physics output centered around QCD, but electroweak physics become interesting
- Expect considerable progress
  - e^-p data to be analysed, e^+p data to be collected
  - more involved and sophisticated QCD analyses
    combine DIS inclusive & exclusive processes, H1 & ZEUS data, ...
- Searches for a discovery ongoing
  - isolated lepton and multi-lepton events, leptoquarks, RPV Susy, ...
- Low E_p run and measurement of F_L towards end of HERA

$\Rightarrow$ Precision measurements of proton structure functions & parton distributions provide solid basis for LHC physics