Proton Structure Functions at HERA

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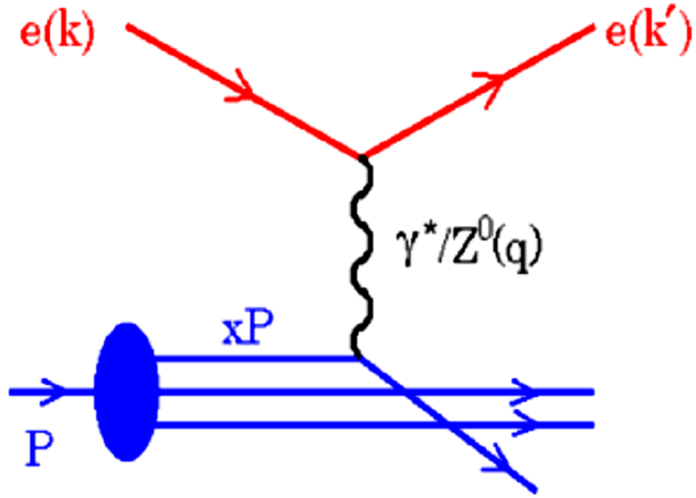
Outline

- Deep Inelastic Scattering
- HERA, H1 and ZEUS
- Cross sections, Structure Functions and PDFs
- From HERA to LHC
- Summary of HERA-I results
- New Results from HERA-II
- Low Energy Run for Determination of F_L
- Conclusions

Deep Inelastic Scattering



Kinematics of inclusive scattering is determined by Q^2 and Bjorken x.
In x "scale parameter" 1/3 - equal sharing among quarks Proton structure for

- $x \geq 0.05$ — valence quarks
- $x \leq 0.05$ — coupled quark-gluon QCD evolution. Large gluon density.

At small x complex dynamics which must obey simple asymptotic solutions (unitarity).

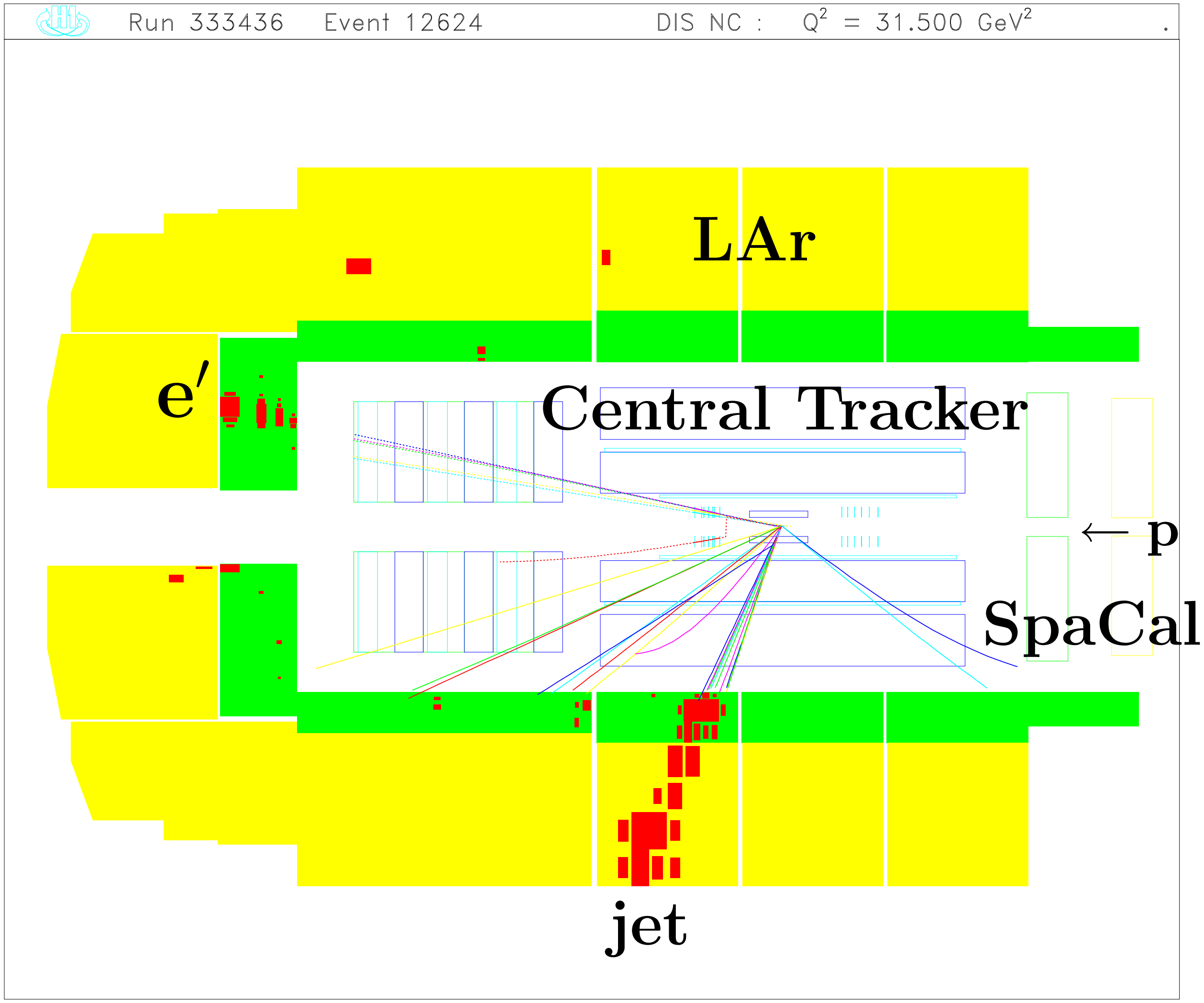
DIS scattering experiments at HERA with $\sqrt{S} = 318$ GeV are (at least) dual purpose:

- High energy frontier of particle physics (exclusive processes)
- "Super microscope" to study proton structure (inclusive cross sections).

Knowledge of the proton structure is vital for a number of "practical" applications: cosmic rays (p and ν), heavy ion physics, pp colliders (LHC).

HERA, H1 and ZEUS

DIS Event Reconstruction



Virtuality:

$$Q^2 = 2E_eE'_e(1+\cos\theta_e)$$

Inelasticity:

$$y = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e}$$

Bjorken x:

$$x = Q^2/(Sy)$$

$p-\gamma$ invariant mass:

$$W = \sqrt{Q^2(1-x)/x}$$

Kinematics can be reconstructed using e' or hadronic final state.

PDF determination

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

Leading order relations:

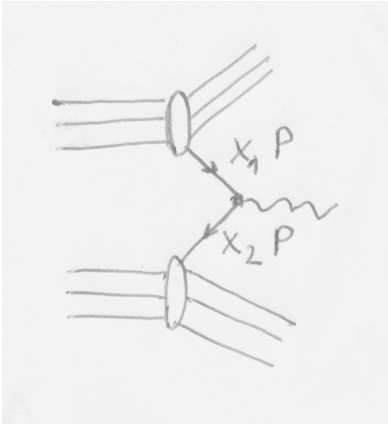
$$\boxed{\begin{array}{cc} F_2 & = x\sum e_q^2(q(x)+\bar{q}(x)) \\ xF_3 & = x\sum 2e_q a_q(q(x)-\bar{q}(x)) \\ \sigma^{CC}_{e^+p} & \sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s) \\ \sigma^{CC}_{e^-p} & \sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s}) \\ pp \to (\ell\bar{\ell})X & \sim \sum x_1 x_2 q(x_1)\bar{q}(x_2) \end{array}}$$

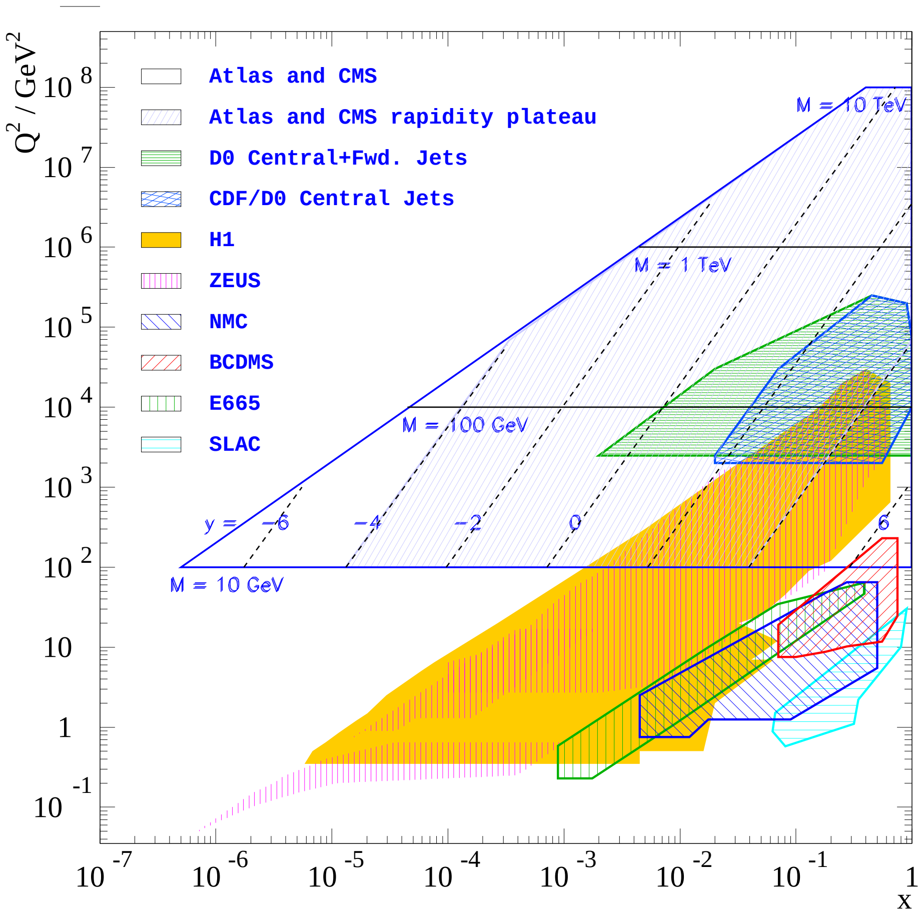
DIS *ep* and *ed* data allows to unfold individual quark flavors.

Gluon is determined from F_2 scaling violation and from jet cross section.

$F_L = 0$ at leading order; proportional to Gluon at higher orders.

HERA and LHC kinematics



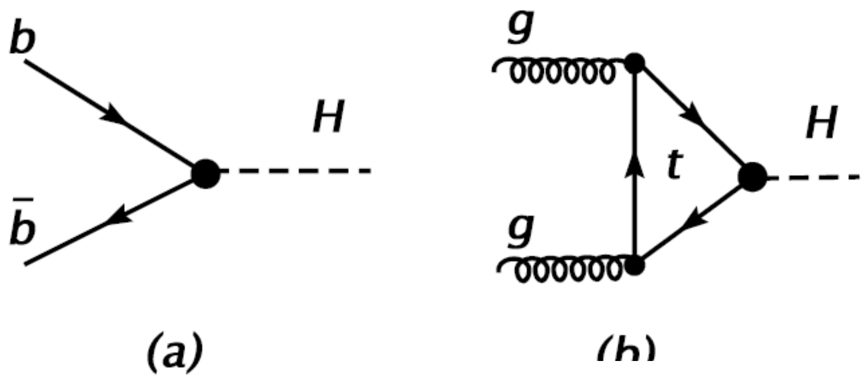


x_1, x_2 are momentum fractions. Factorization theorem states that cross section can be calculated using universal partons $\times$ short distance calculable partonic reaction.

$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y)$$

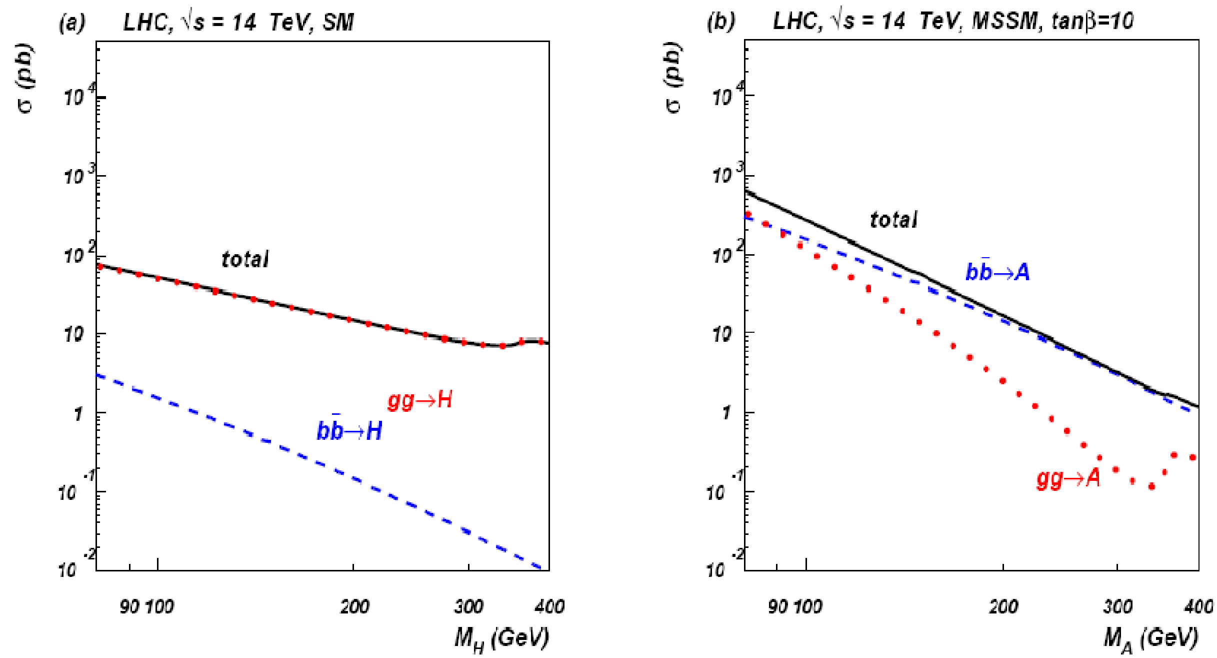
Notation clash: y – rapidity (LHC) vs y – inelasticity (HERA, $Q^2 = Sxy$).

Case study: Higgs production at LHC, SM vs MSSM



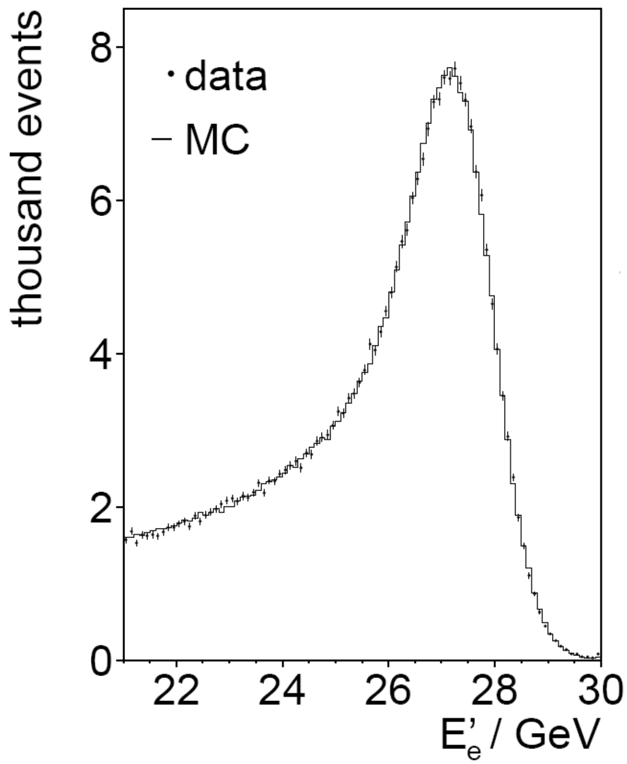
In SM, $b\bar{b} \to H$ is small vs $gg \to H$.
In MSSM, $b\bar{b} \to H$ can be enhanced by $\times \tan^2\beta$

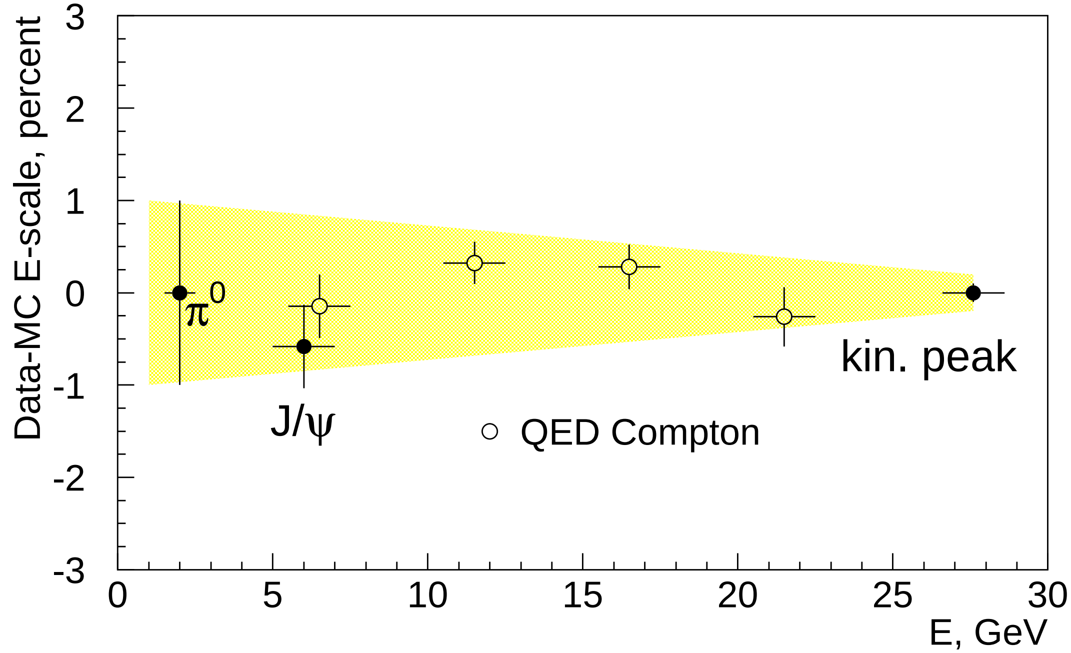
Even for MSSM with $\tan\beta = 10$, $b\bar{b} \to H$ dominates over gg production.



$\to$ production cross section measurement of Higgs is a key ingredient to disentangle new physics scenarios.

The Cross Section Measurement

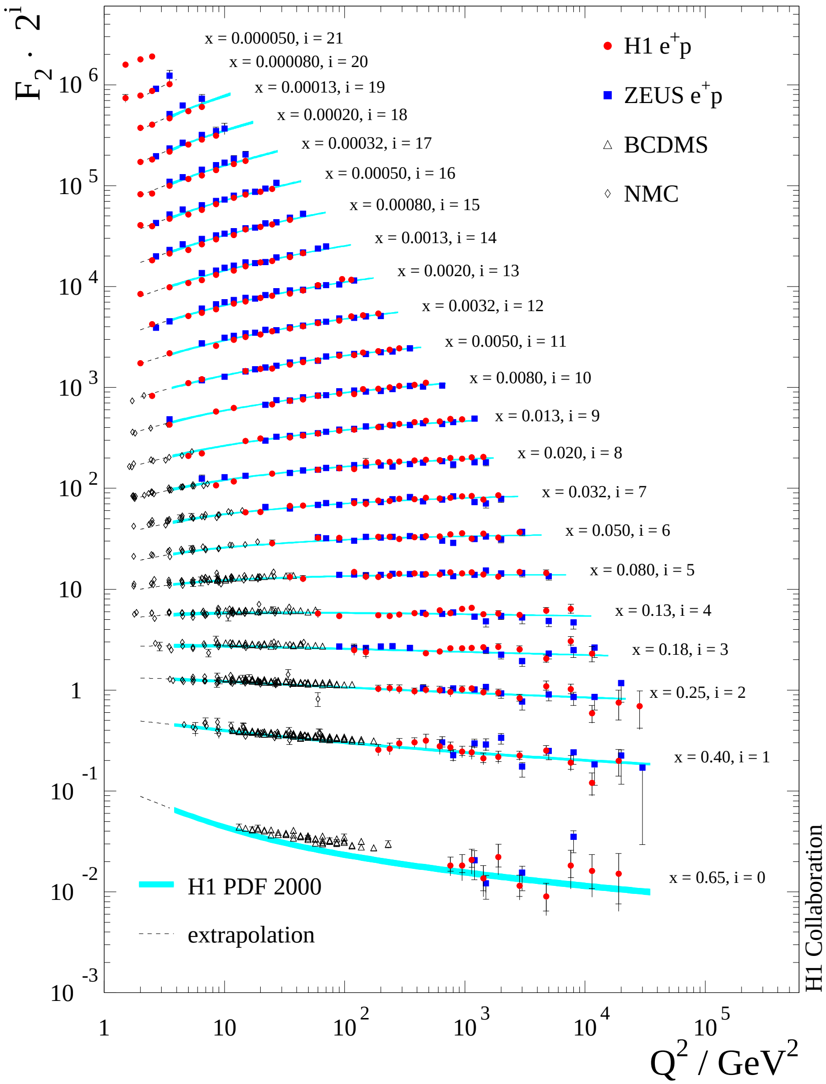


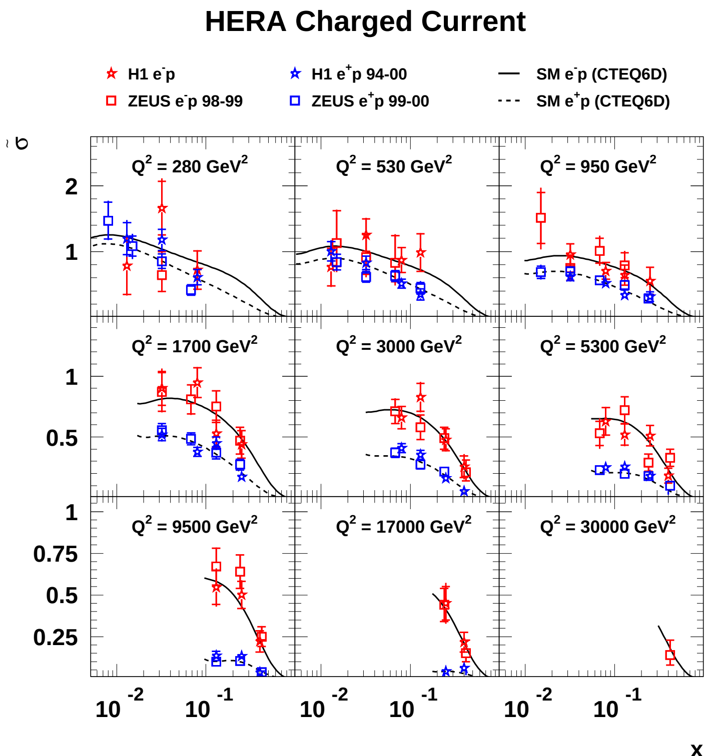


Total cross section measurement with low background.

- For low $Q^2 < 1000\ \text{GeV}^2$ systematic errors dominate.
- Main uncertainties are from energy scale(s), selection efficiency.
- Check E'_e using "kinematic peak" distribution — 0.2% precision.
- Measure non-linearity with $\pi^0 \to \gamma\gamma$, $J/\psi \to e^+e^-$, QED-compton $ep \to ep\gamma$ events.

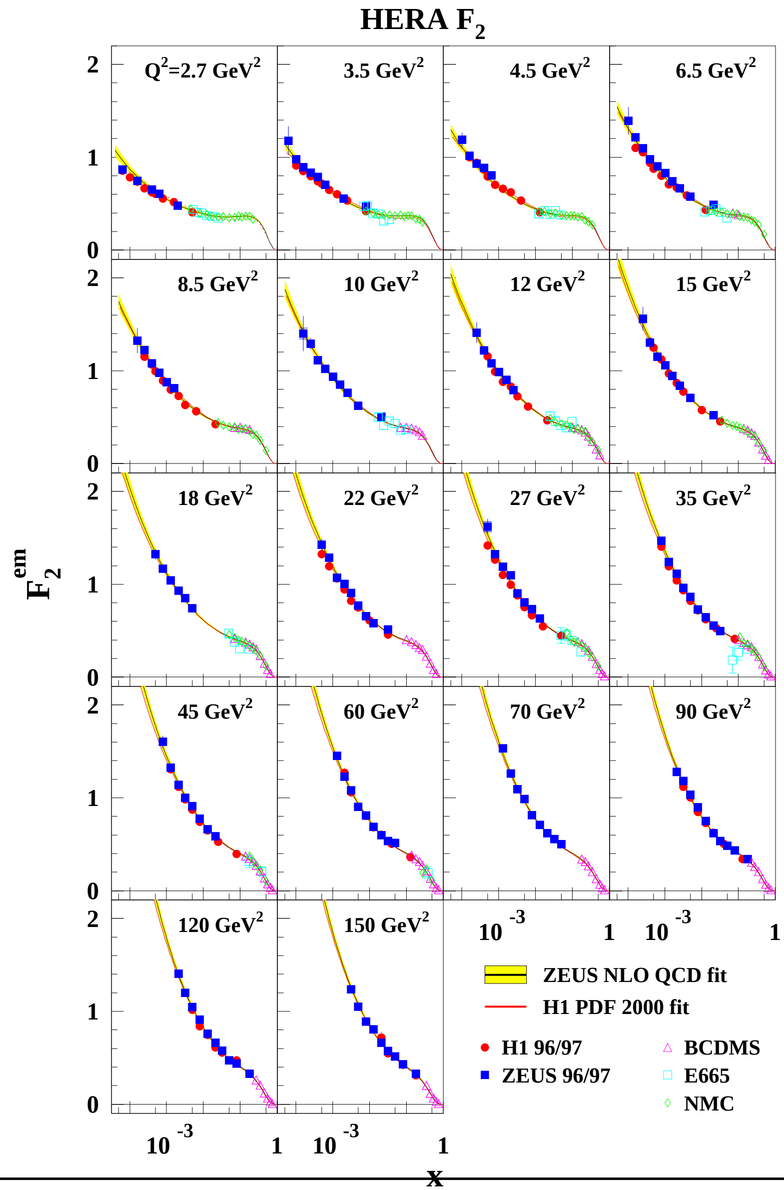
The Measured Cross Sections

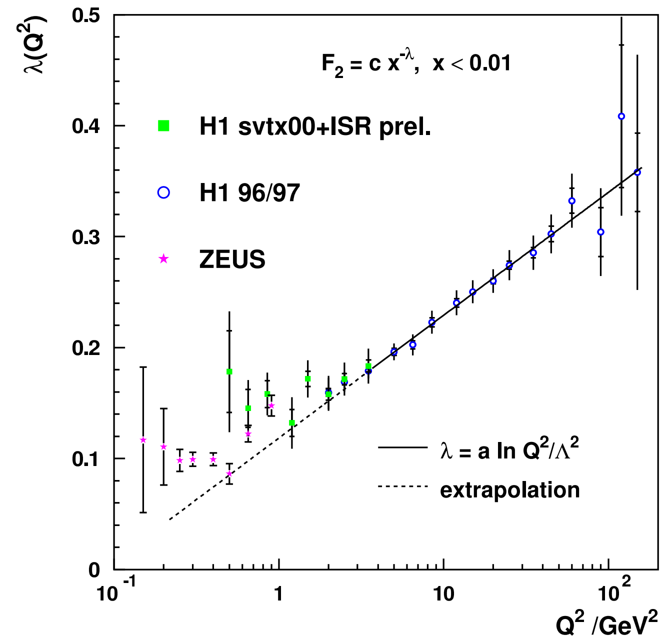




HERA data allows to measure $xU = x(u + c)$, $xD = x(d + s)$, $x\bar{U} = x(\bar{u} + \bar{c})$, $x\bar{D} = x(\bar{d} + \bar{s})$, and xg in a single experiment.

Measurement at low x

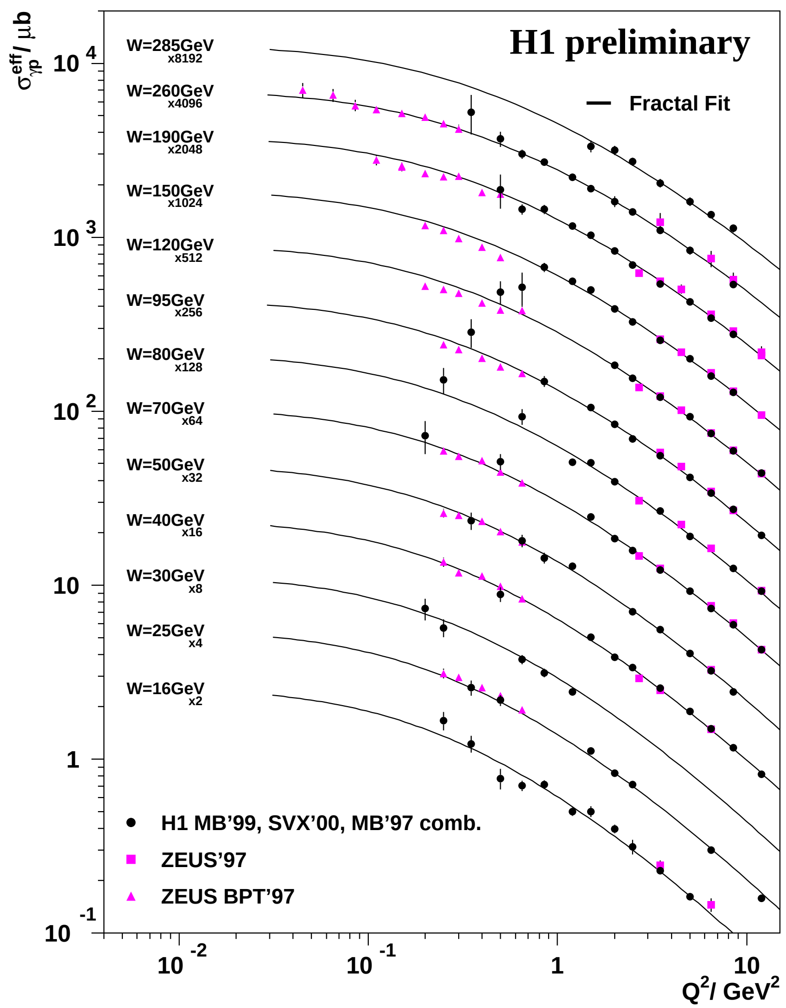




$F_2(x, Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing Q^2. To quantify the rise, $F = cx^{-\lambda}$ fit is performed for each Q^2 bin.

Currently $2-3\%$ precision ($\to 5\%$ for LHC X-sections), goal to reach 1%

Measurement at low Q^2



At low Q^2, $F_2 \sim \sigma_T + \sigma_L$ and $F_L \sim \sigma_L$ — scattering cross sections of transversely and longitudinally polarized photons.

New preliminary measurement of

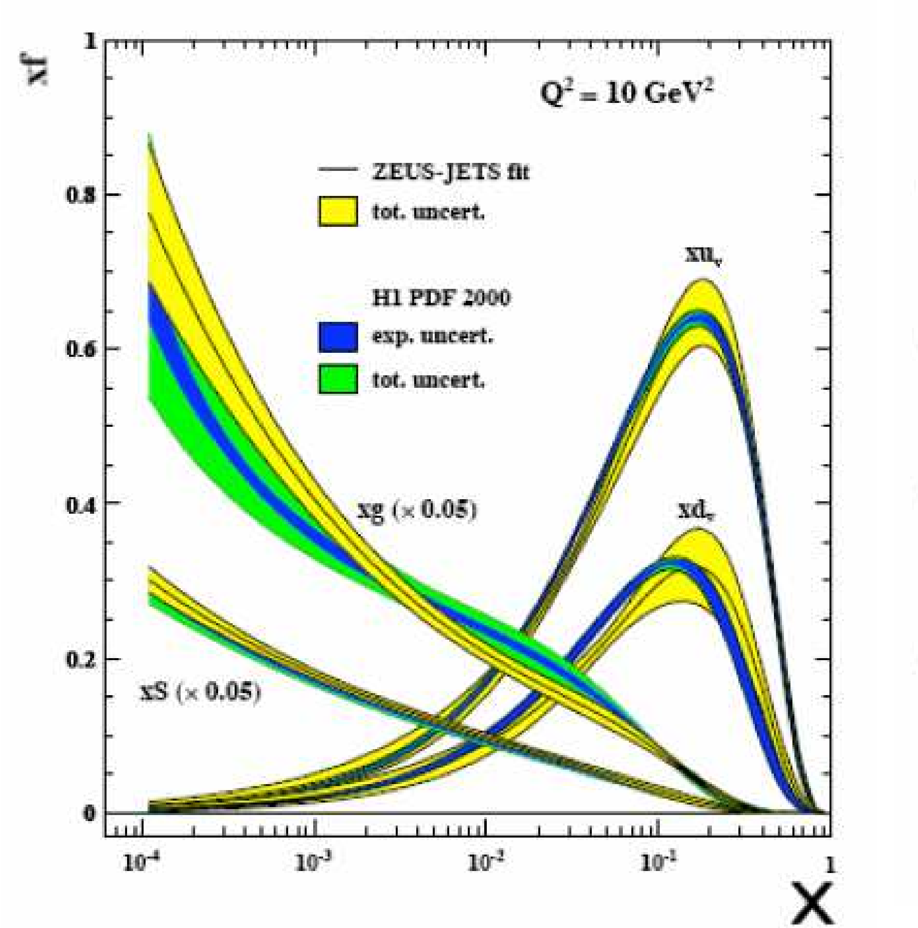
$$\sigma_{\gamma p}^{eff} = \sigma_T + [1 - y^2/(1 + (1-y)^2)]\sigma_L$$

by H1 compared to published ZEUS data.

Data agree well, new results fill the gap at $Q^2 \sim 1\ \mathrm{GeV}^2$.

Precision for $Q^2 > 3\ \mathrm{GeV}^2$ reaches 1.5%.

PDFs extraction



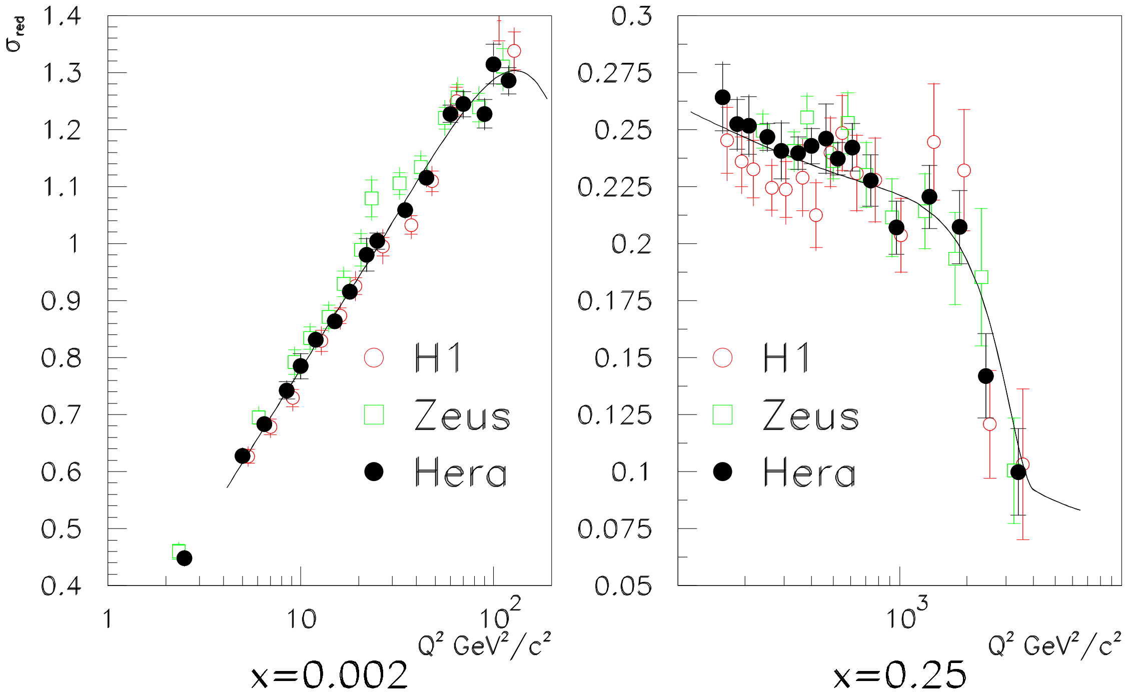
Valence quarks u_v, d_v determine proton structure at high x.
Sea S and gluon g are far more important at low x.
Mind the $\times 0.05$ scale factor for them.

ZEUS and H1 PDFs are extracted using their own data. Agree within the uncertainties, but shapes seems to be different.

Combination of Experimental Data

Before fitting to theory one can combine data in a generalized averaging procedure. Achieved by fitting χ^2 vs σ_{red}.

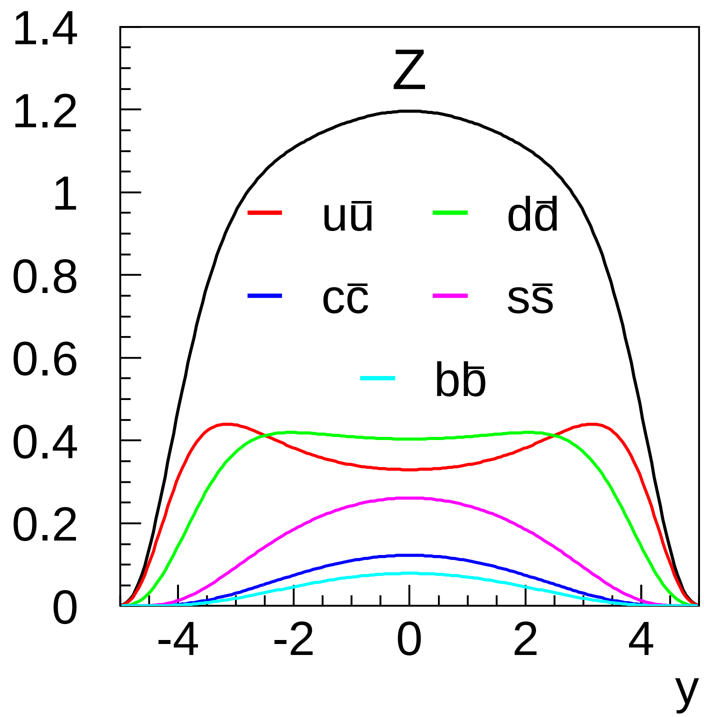
$$\sigma_{red}(e^+p) = F_2 - \frac{y^2}{Y_+}F_L - \frac{Y_-}{Y_+}xF_3$$

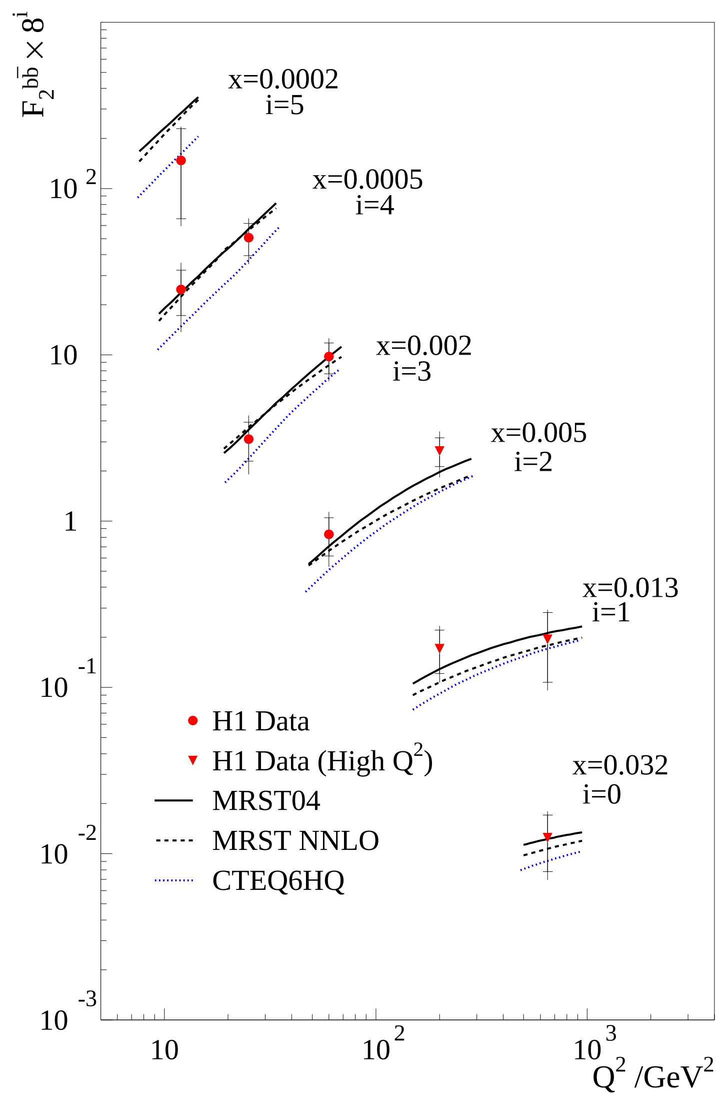


Average of H1 and Zeus data: model independent check of the consistency, $\chi^2/ndf = 534/601$.
Experiments cross-calibrate each other $\rightarrow$ systematic errors reduced.

H1 and ZEUS initiated work on HERA average DIS cross section

Z production flavor decomposition

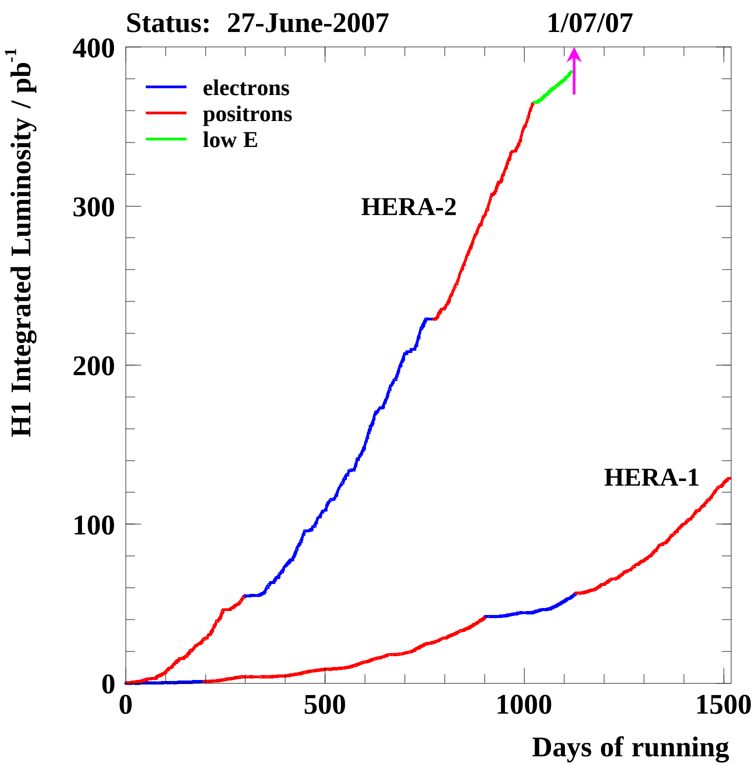


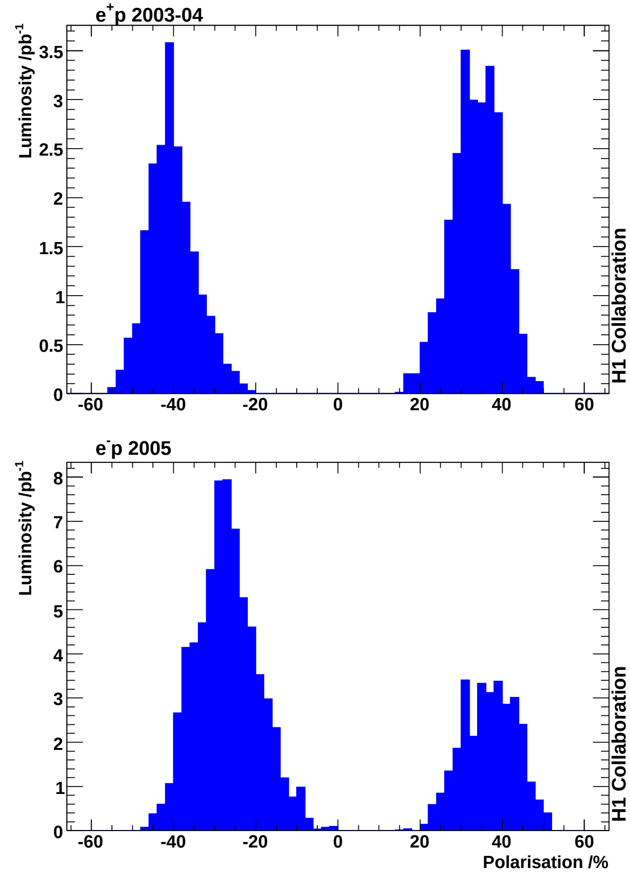


Larger coupling to Z vs γ makes $b\bar{b}$ contribution more important for Z production vs inclusive F_2.

F_2^{bb} is measured by H1, in relevant for LHC x range.

HERA-II Results



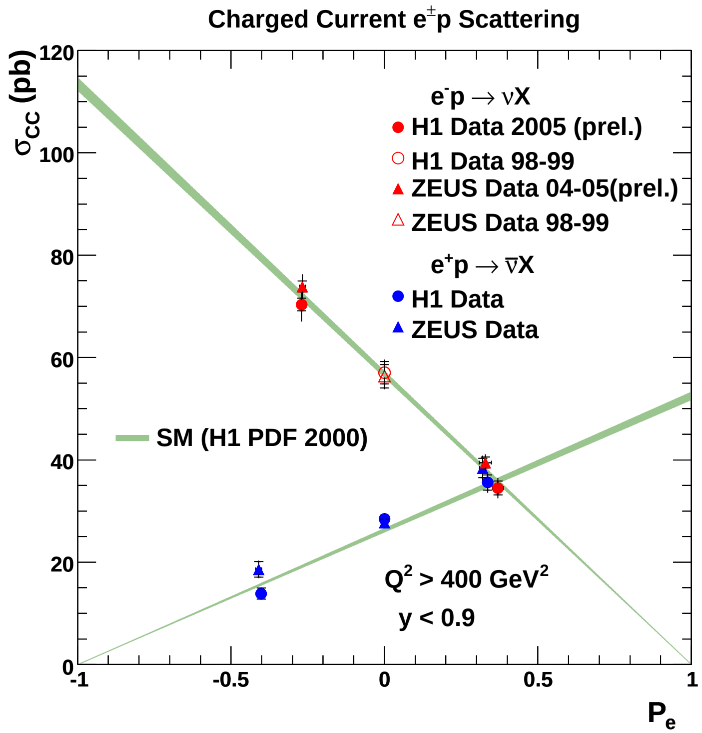


HERA-II upgrade provides better instantaneous luminosity and longitudinal beam polarization.

Special low proton beam energy runs $E_p = 460, 575$ GeV to measure F_L

Shutdown 30 June 2007 at 12:00am.

Charged Current Cross Section

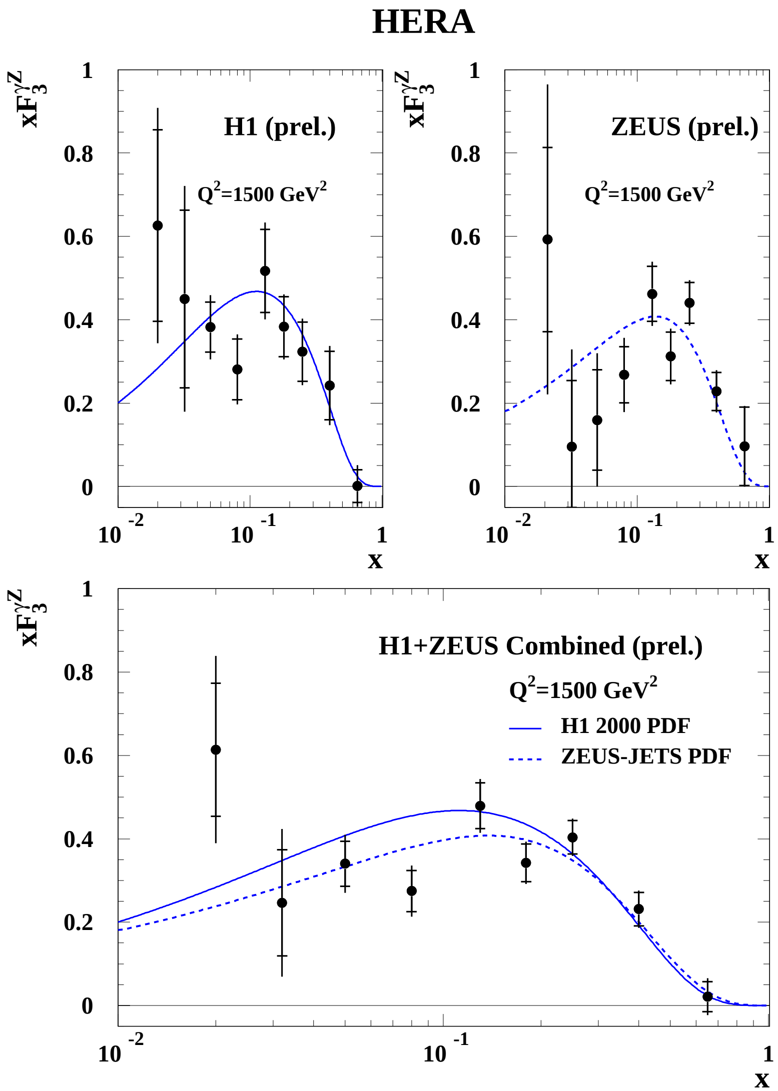


CC cross section is linearly proportional to the degree of the longitudinal beam polarization:

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = [1 \pm P_e]\,\frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2 + M_W^2}\right]^2 \phi_{CC}^{\pm}$$

Consistent with no right-handed weak currents

Neutral Current Cross Section and xF_3

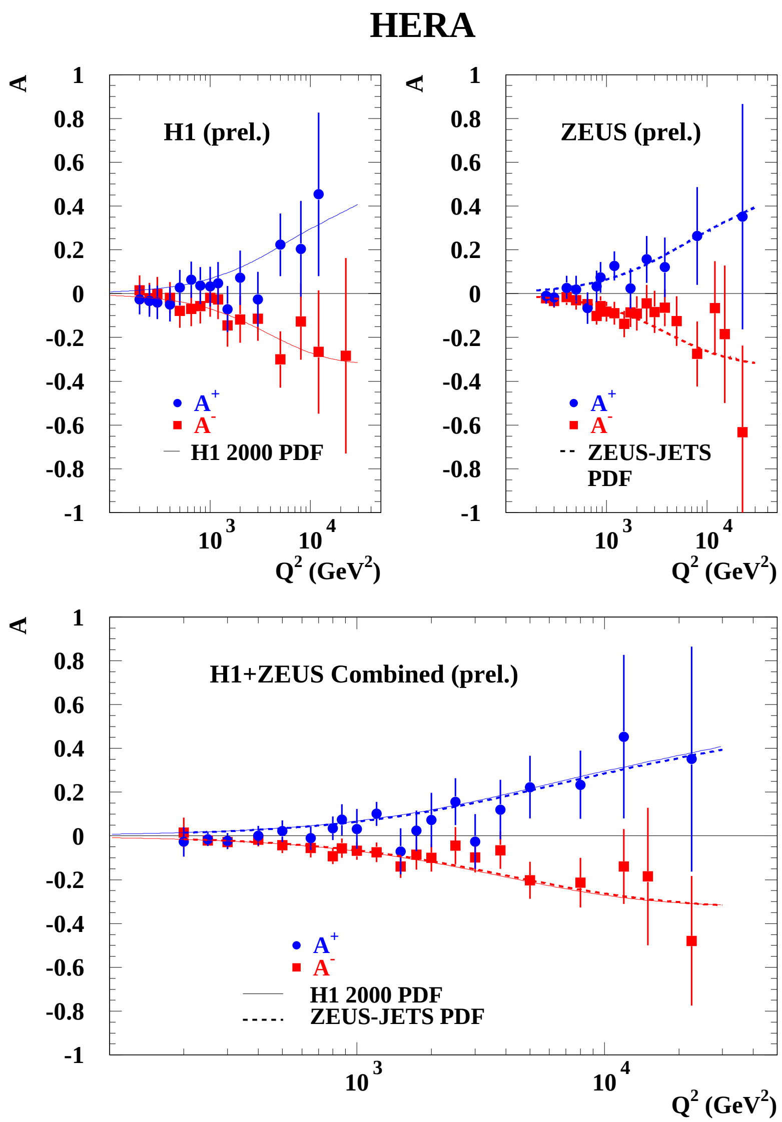


$$xF_3 = x \sum 2e_q a_q (q(x) - \bar{q}(x))$$

Large increase compared to HERA-I of e^- sample allows to improve precision of the interference structure function $xF_3^{\gamma Z}$

- First combined H1-ZEUS SF result
- $xF_3^{\gamma Z}$ is consistent with no-enhancement for low x, supports q-$\bar{q}$ symmetric low x sea.

NC Cross Section Polarization Dependence



Neglecting pure Z exchange term, generalized F_2:

$$\overline{F_2^{\pm}} \approx F_2 + k(-v_e \mp P a_e) F_2^{\gamma Z}$$

where $k = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}$

At leading order

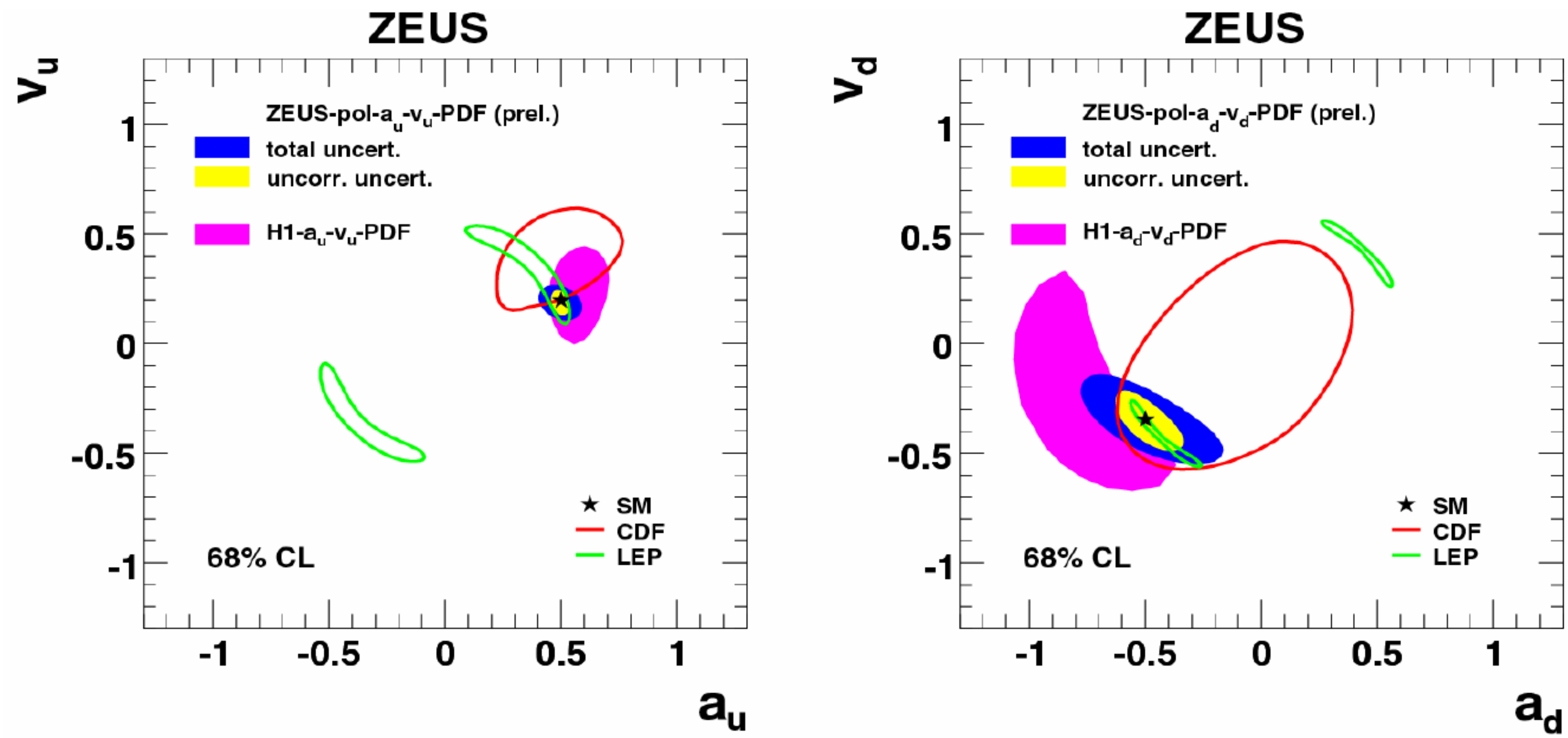
$$F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q})$$

Defined as

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

directly measures NC parity violation.

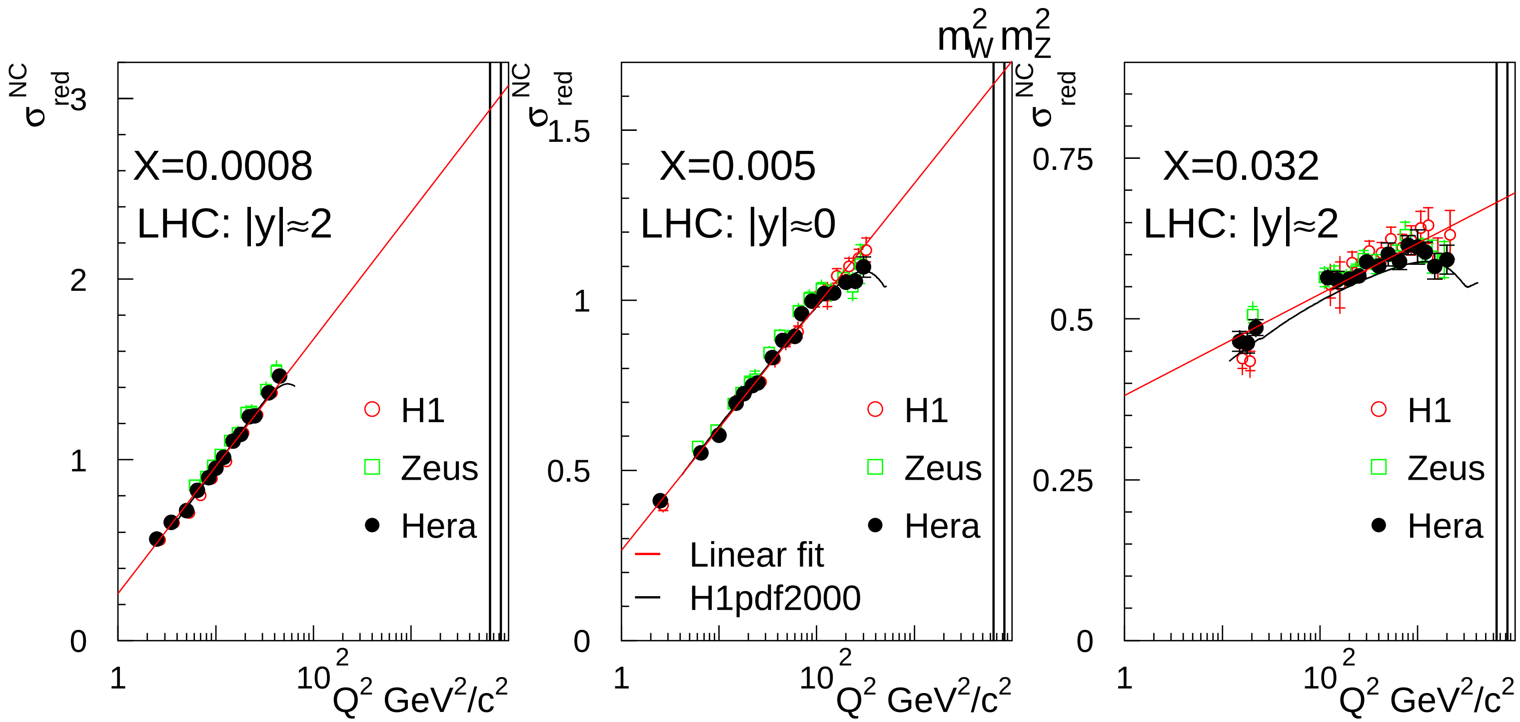
Combined EW-QCD fit



Sensitivity to a, v couplings of the light quarks to Z allows combined QCD-EW fit. H1 performs fit using unpolarized HERA-I data. ZEUS and H1 provide preliminary results including HERA-II data.

Polarization brings better sensitivity to v_q

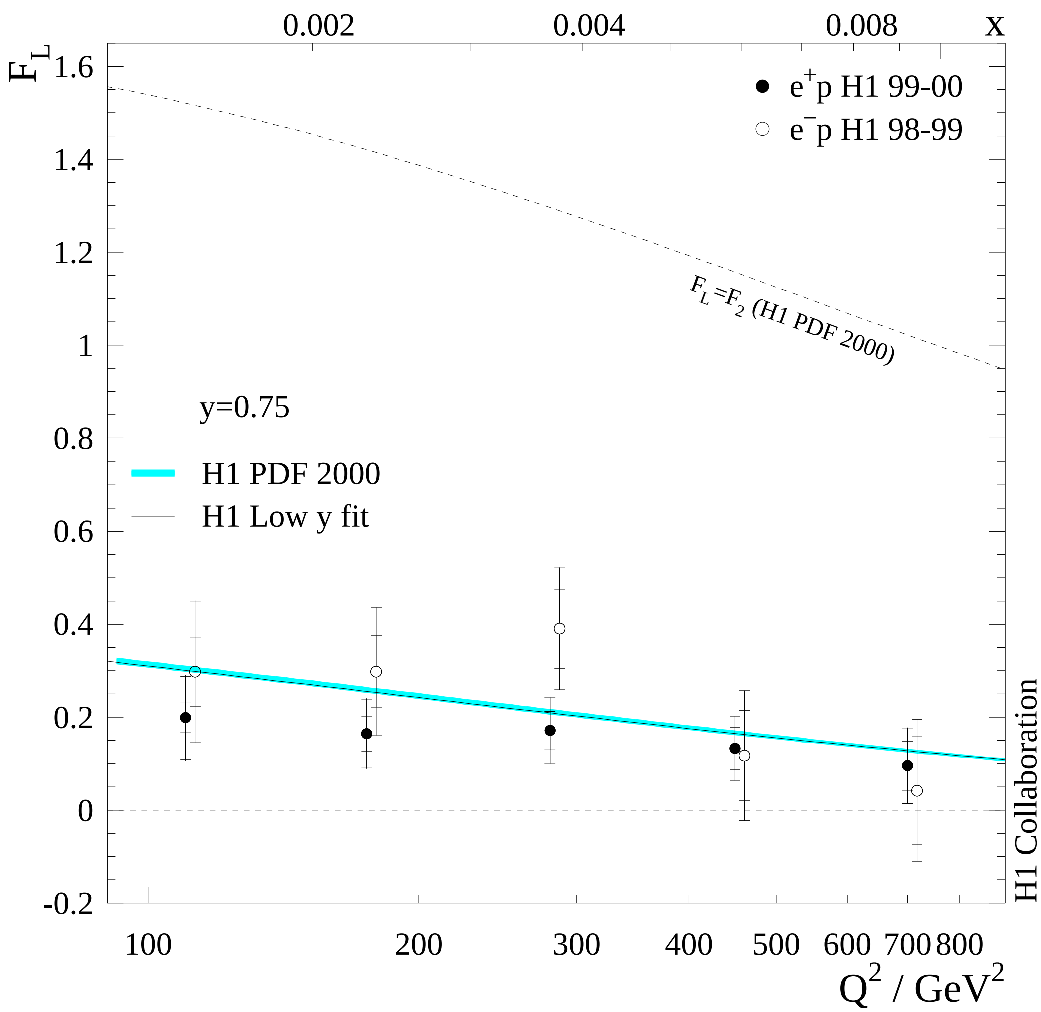
Extrapolation to LHC energies



HERA data covers complete central rapidity range of LHC for W, Z production. "Leading order" predictions can be read directly from HERA data + linear extrapolation.

Experimental part of PDF uncertainties comes from absolute F_2 normalization and the slope, $dF_2/d\log Q^2$ (gluon). Turn down of σ_{red}^{NC} for highest Q^2 ($\rightarrow$ highest y) is due to F_L.

Consistency check: H1 F_L determination at high Q^2



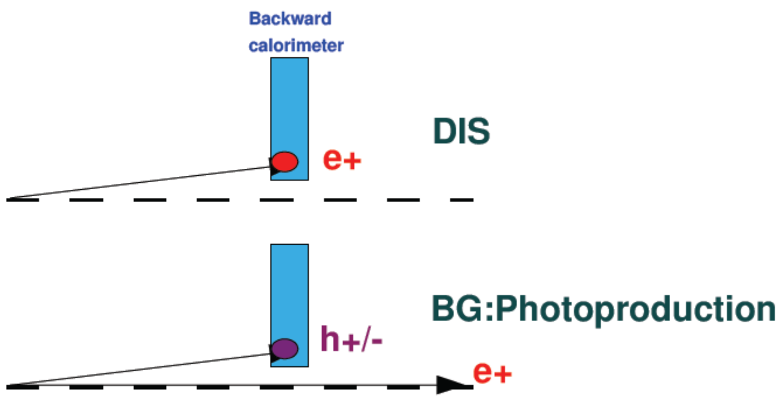
Determination of F_L as

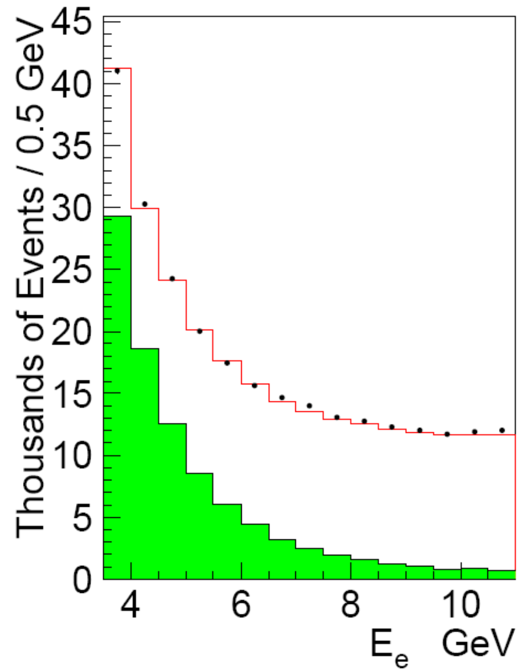
$$F_L = \frac{Y_+}{y^2}\left(F_2^{fit} - \sigma_r\right)$$

Important consistency check of gluon determined from F_2 scaling violation vs X-section decrease at high y.

Still large statistical uncertainties, to be improved with HERA-II

Experimental Challenges for F_L determination



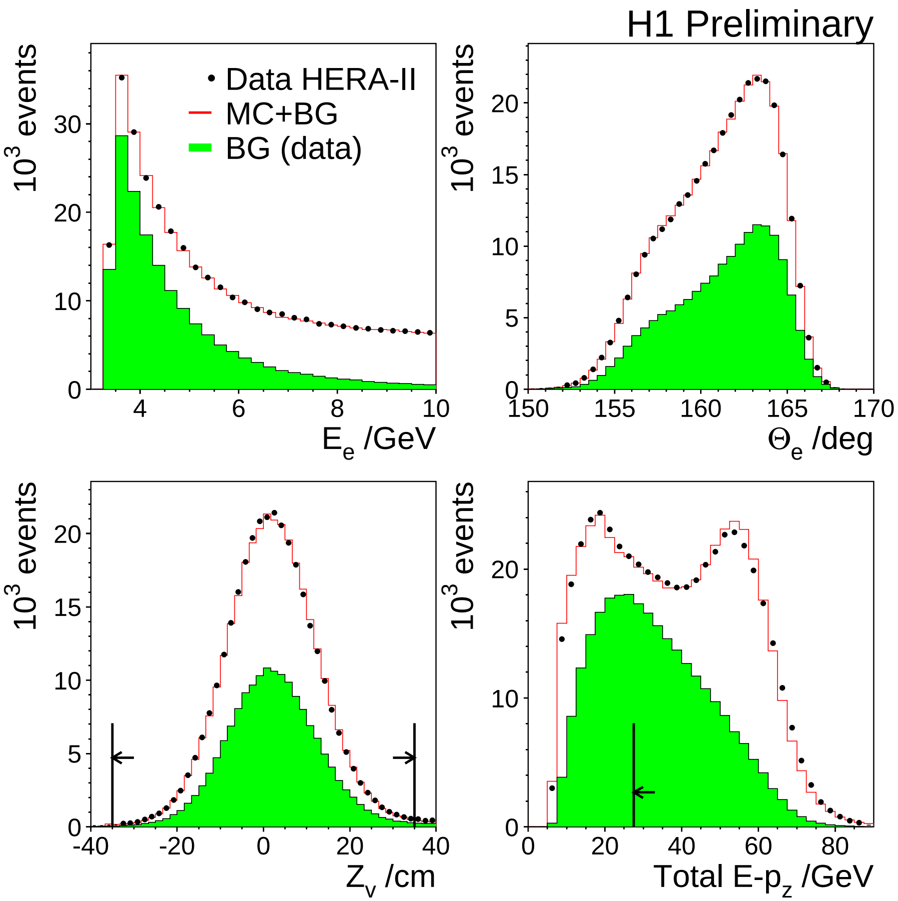


Measurement at high y (low scattered electron energy E_e) is challenging. The signature of the scattered electron can be faked by hadronic final state in a γp event.

Solution (H1): estimate photoproduction background using electron candidates associated with wrong charge tracks.

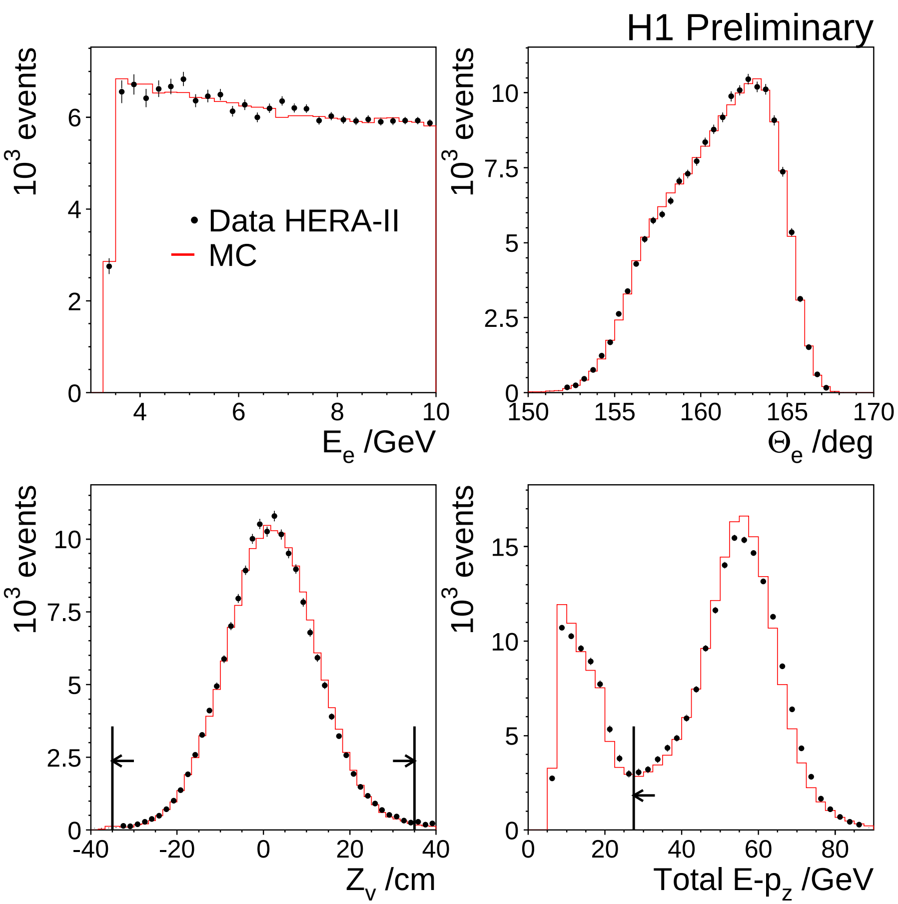
Charge symmetric lepton beam sample eliminates calorimeter response induced background charge asymmetry (p vs $\bar{p}$)

H1 high y analysis with HERA-II data



Analysis based on 96pb^{-1} collected in $2003-2006$, nearly symmetric for e^+ and e^- beam luminosity.

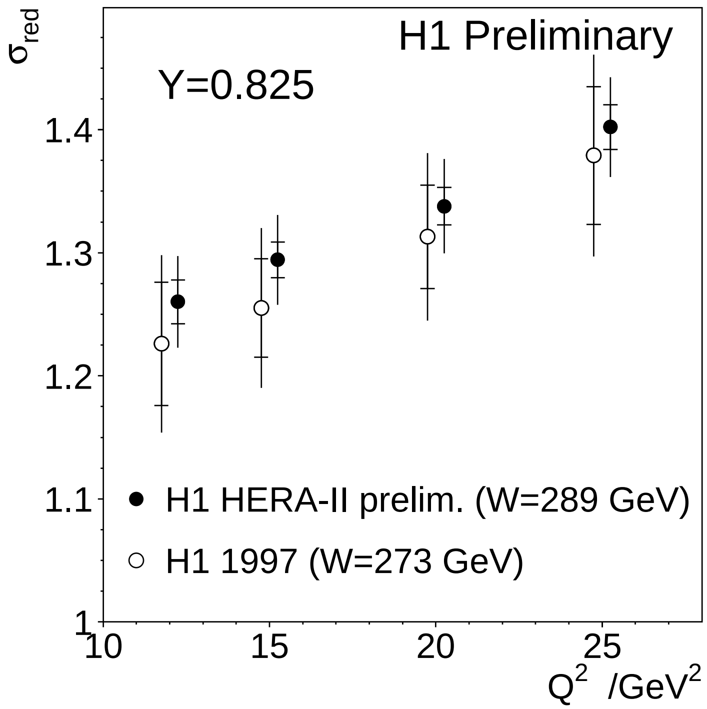
H1 high y analysis with HERA-II data

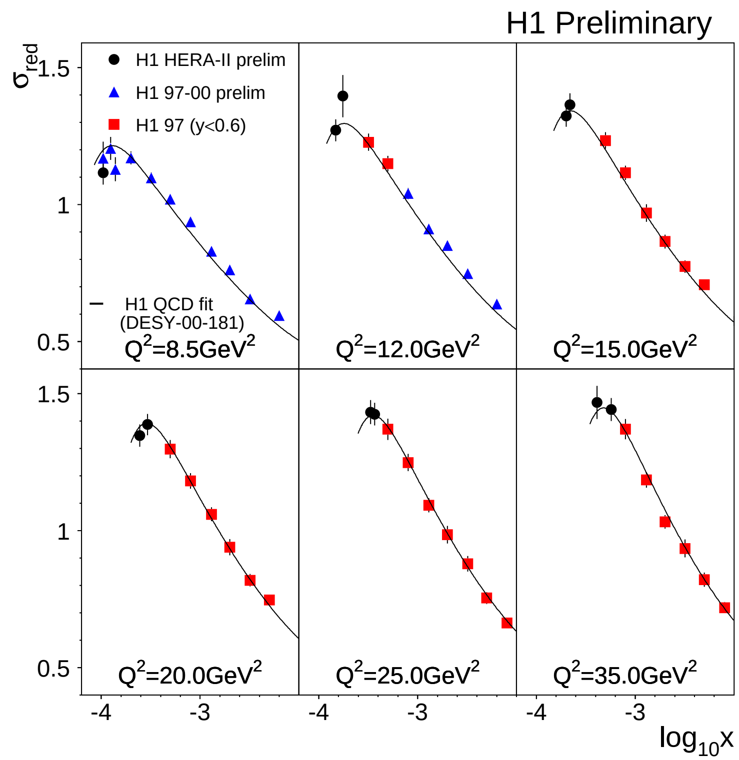


Radiative corrections are controlled using the measured beam energy:

$$2E_e = E - p_Z = \sum_h \left(E^h - p_Z^h\right) + \left(E^{e'} - P_Z^{e'}\right)$$

High y cross section at low x

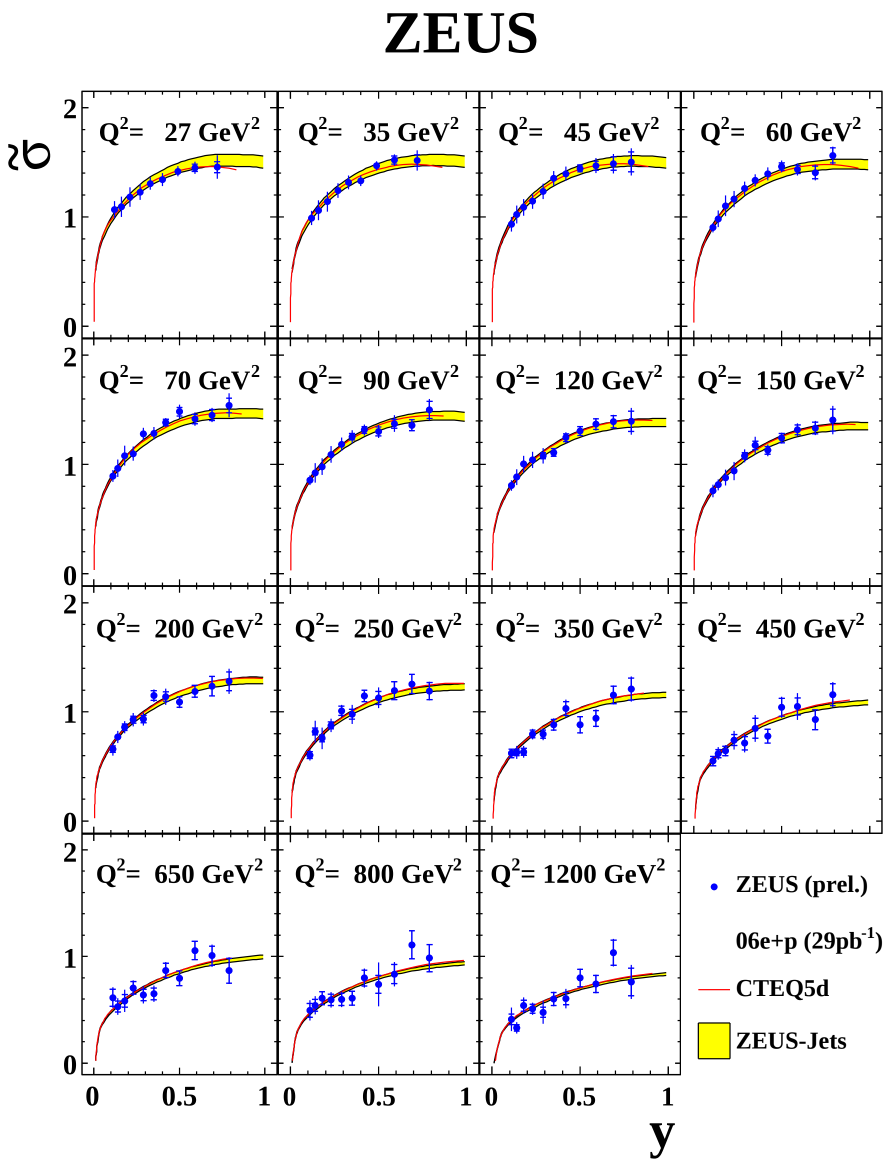




For $y = 0.825$, about factor of 2 improvement in total uncertainty and factor of 3 in stat. uncertainty vs published.

An ideal sample to study experimental conditions for the structure function F_L measurement.

ZEUS high y cross section measurement

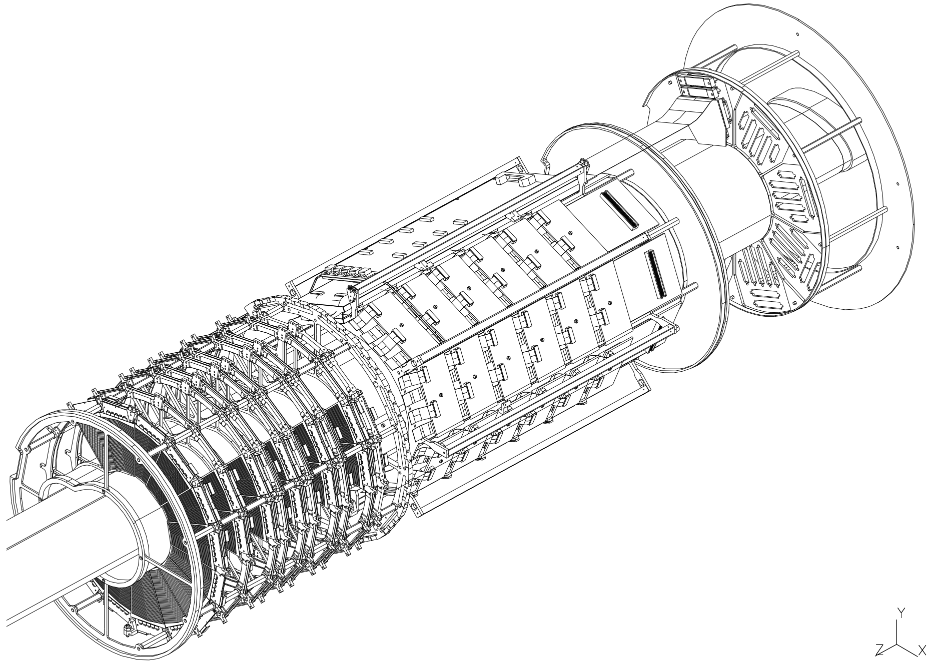


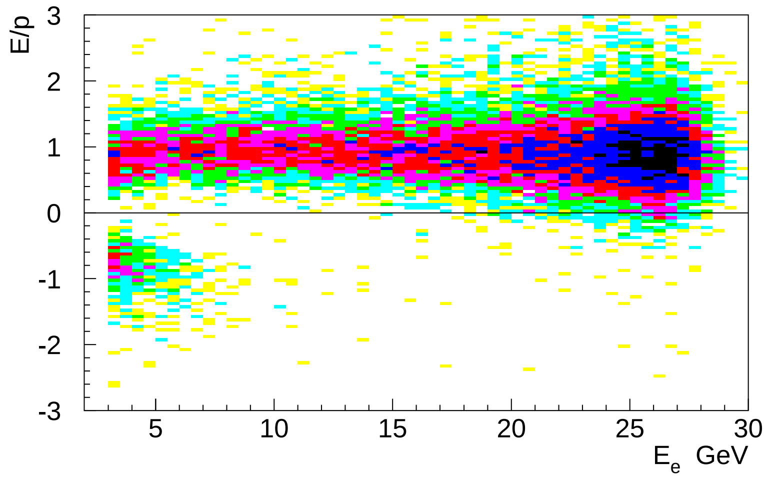
ZEUS performes new measurement focused on high y with HERA-II data.

Photoproduction background is modeled by MC which is controlled for a special sample with a tagged scattered electron.

H1 Backward Silicon Tracker in 2006-2007

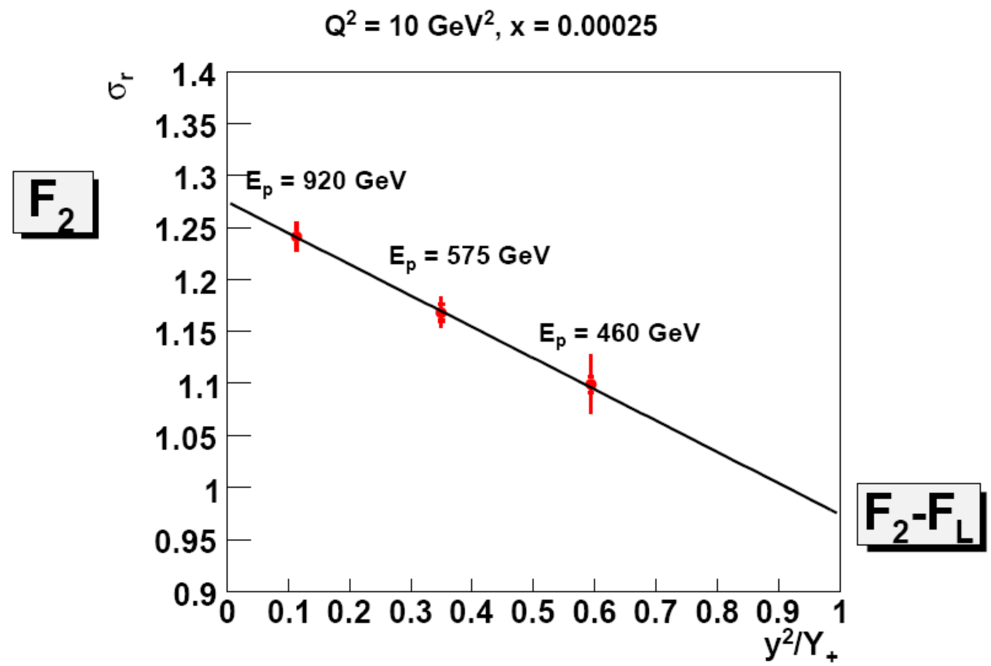
2006 data – re-install Backward Silicon Tracker back in H1 detector. Covers $3 < Q^2 < 10$ GeV^2 range for $y > 0.6$.





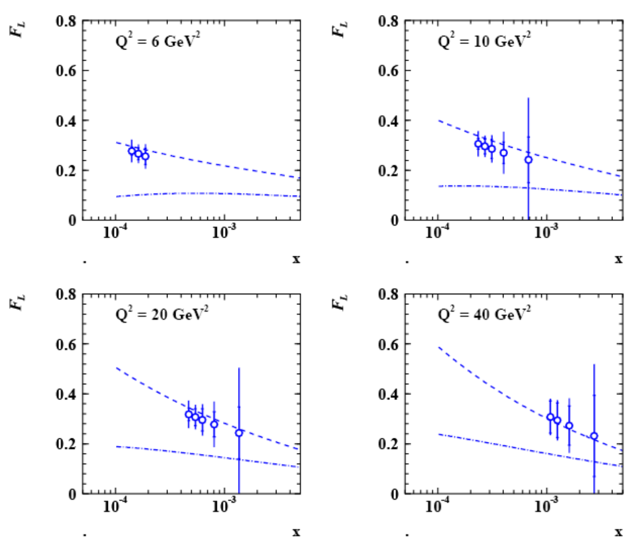
Allows scattered angle reconstruction/charge determination for the electron candidate.

Measurement of F_L (simulation!)



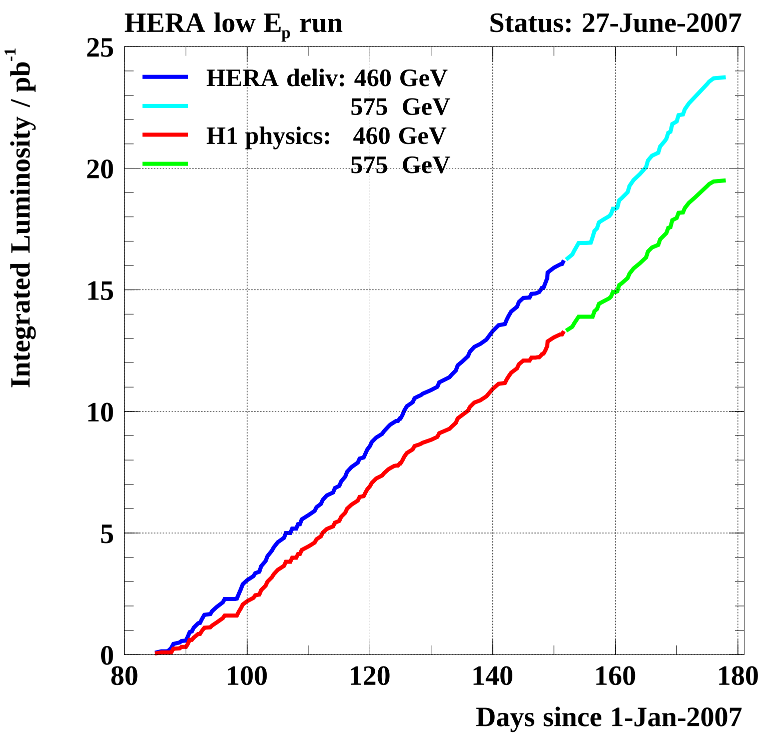
$$\sigma_r(x, Q^2) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

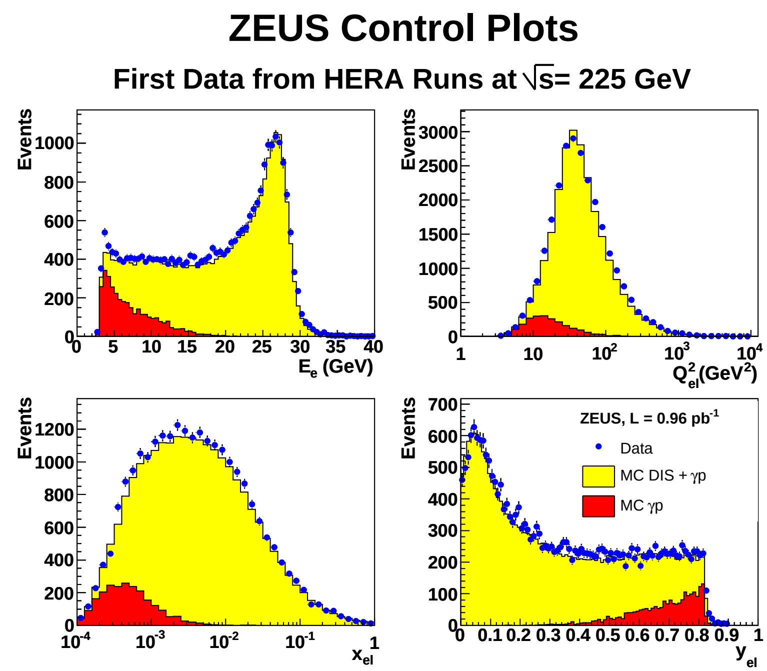
Measure σ_r at the same Q^2, x for different beam energies



F_L measurement should allow to distinguish between different PDF fits (MRST vs CTEQ).

Special 460 GeV and 575 GeV runs





- Last 3 months of HERA operation are dedicated for F_L measurement.
- Luminosity is proportional to E_p^2, from the beam focusing, thus reduced vs nominal 920 GeV run.
- Successful HERA operation, 13.6 pb^{-1} and 6.5 pb^{-1} collected for 460 and 575 GeV run.

Conclusions and Outlook

- HERA experiments provide unique information on proton structure at low x which is not only interesting by itself but also provides an important input for physics at LHC.
- Precision of HERA measurements has already reached $2-3\%$ level, next step is $1-1.5\%$ which will be of importance for W, Z, H cross section predictions at LHC.
- Direct measurement of the longitudinal structure function F_L will provide an important check of the theory and a new handle on the gluon density.