# Proton Structure Functions at HERA

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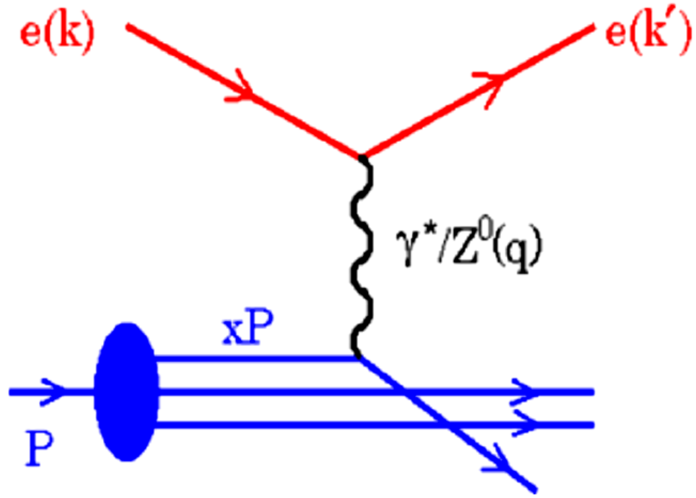
# Outline

- 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).

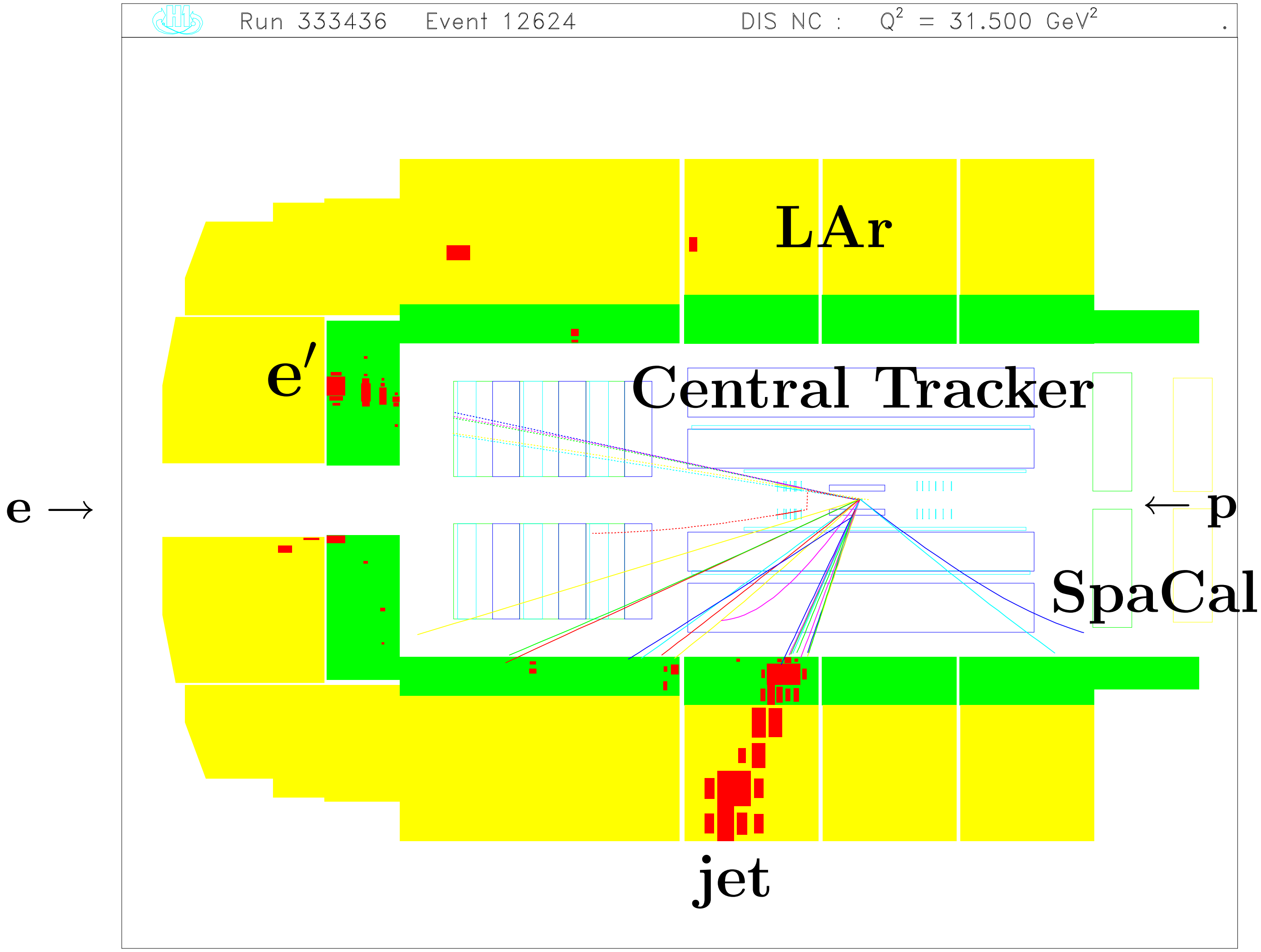
DIS scattering experiments at HERA with $\sqrt{S} = 318$ GeV are (at least) dual purpose:

- 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 $\nu$), heavy ion physics, $pp$ colliders (LHC).

# HERA, H1 and ZEUS

# DIS Event Reconstruction




Virtuality:

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

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:

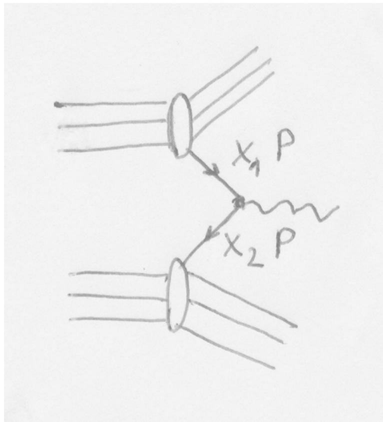
| | |
|---|---|
| $F_2$ | $= x\sum e_q^2(q(x)+\bar{q}(x))$ |
| $xF_3$ | $= x\sum 2e_q a_q(q(x)-\bar{q}(x))$ |
| $\sigma^{CC}_{e^+p}$ | $\sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s)$ |
| $\sigma^{CC}_{e^-p}$ | $\sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s})$ |
| $pp \to (\ell\bar{\ell})X$ | $\sim \sum x_1 x_2 q(x_1)\bar{q}(x_2)$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

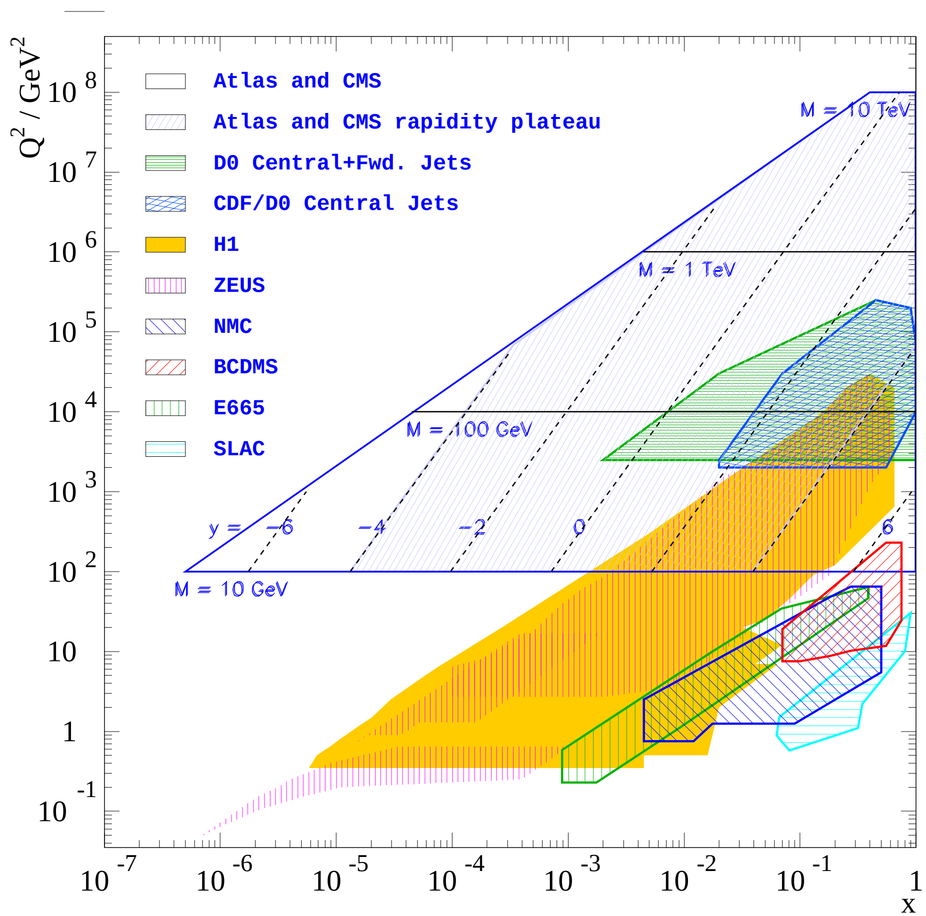
DIS *ep* and *ed* data allows to unfold individual quark flavors.

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



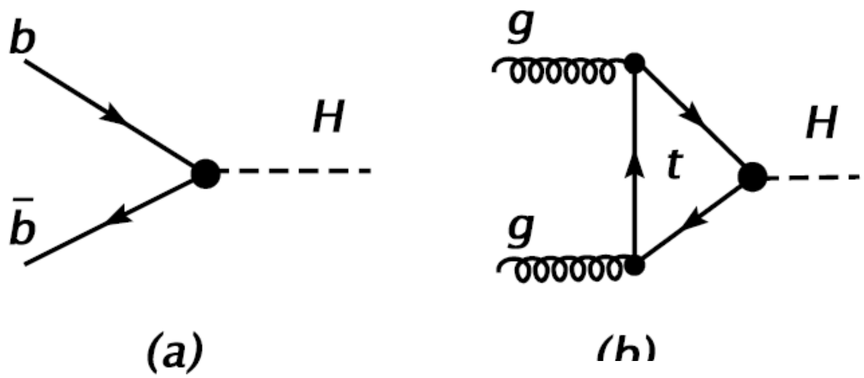




$x_1$, $x_2$ are momentum fractions. Factorization theorem states that cross section can be calculated using universal partons $\times$ short distance calculable partonic reaction.

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

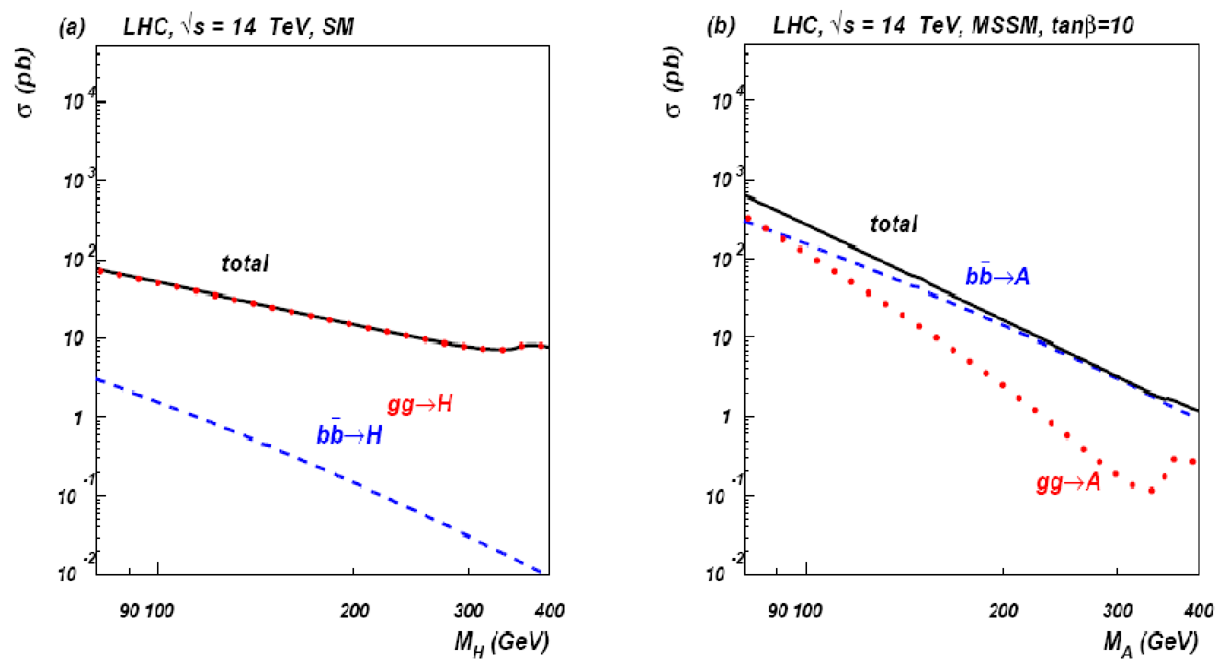
Notation clash: $y$ – rapidity (LHC) vs $y$ – inelasticity (HERA, $Q^2 = Sxy$).

# Case study: Higgs production at LHC, SM vs MSSM



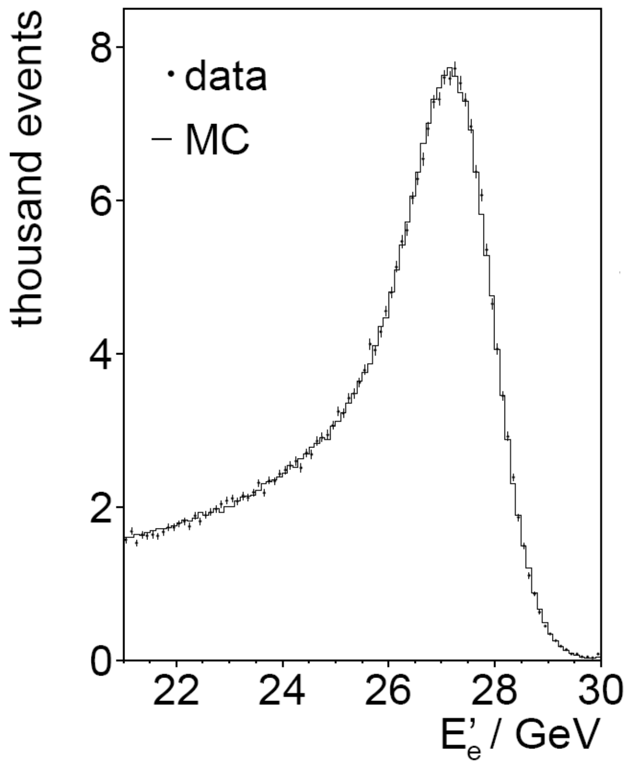

In SM, $b\bar{b} \to H$ is small vs $gg \to H$.
In MSSM, $b\bar{b} \to H$ can be enhanced by $\times \tan^2 \beta$

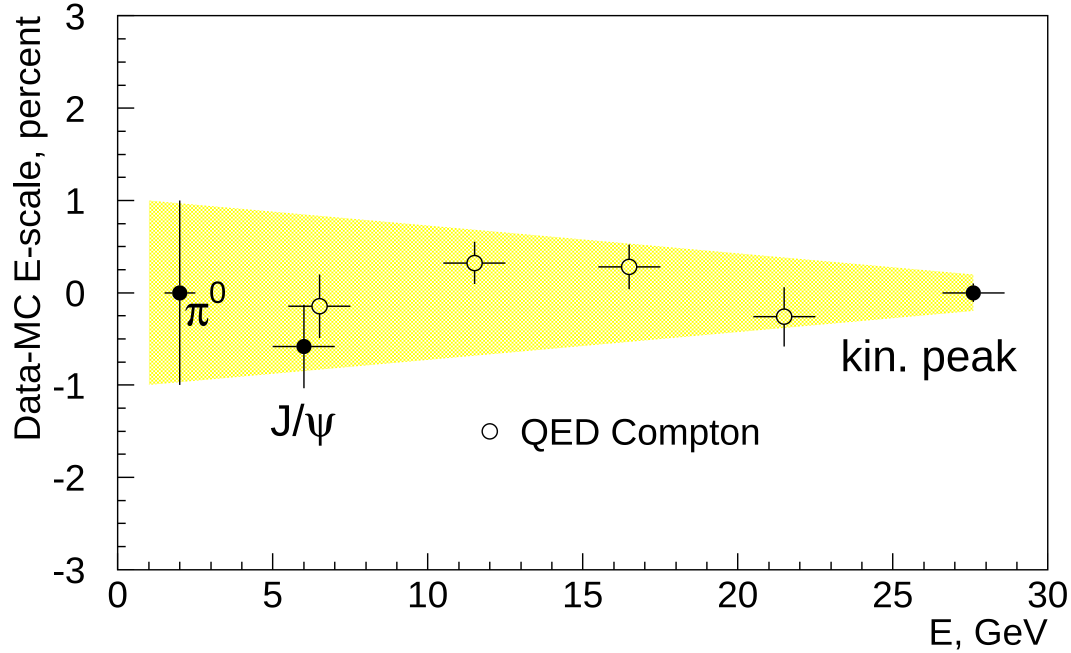
Even for MSSM with $\tan\beta = 10$, $b\bar{b} \to H$ dominates over $gg$ production.




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

# The Cross Section Measurement

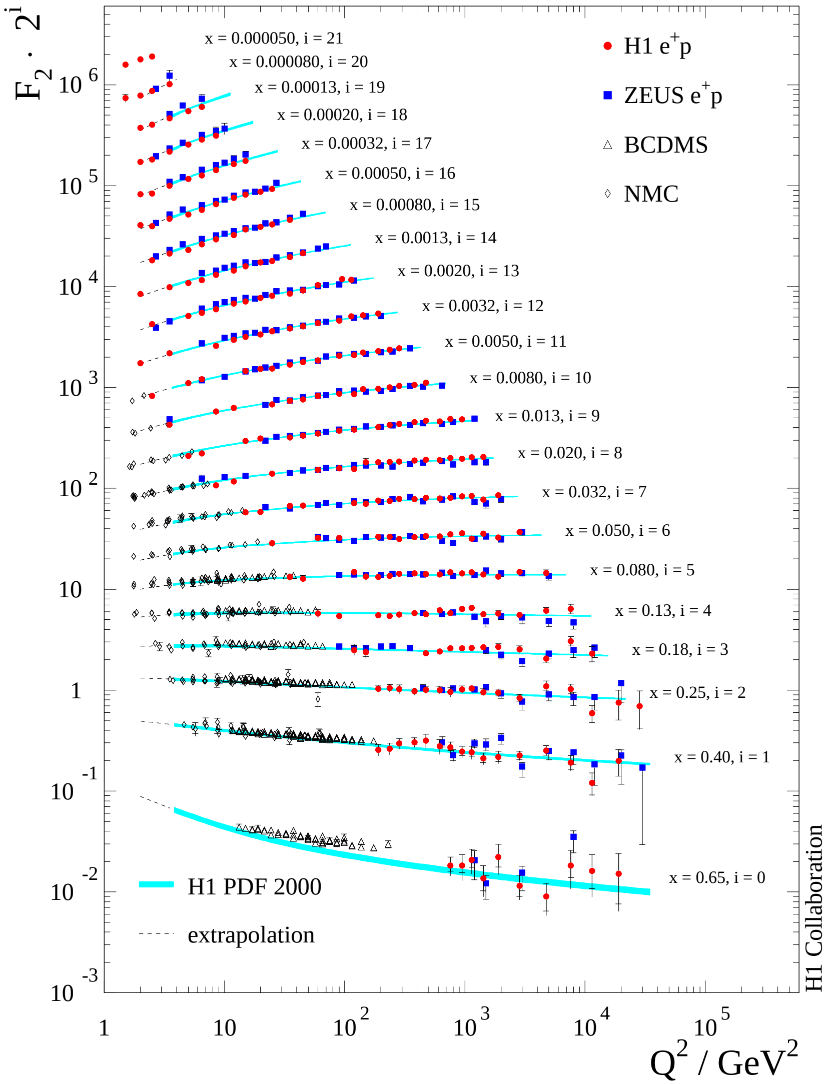


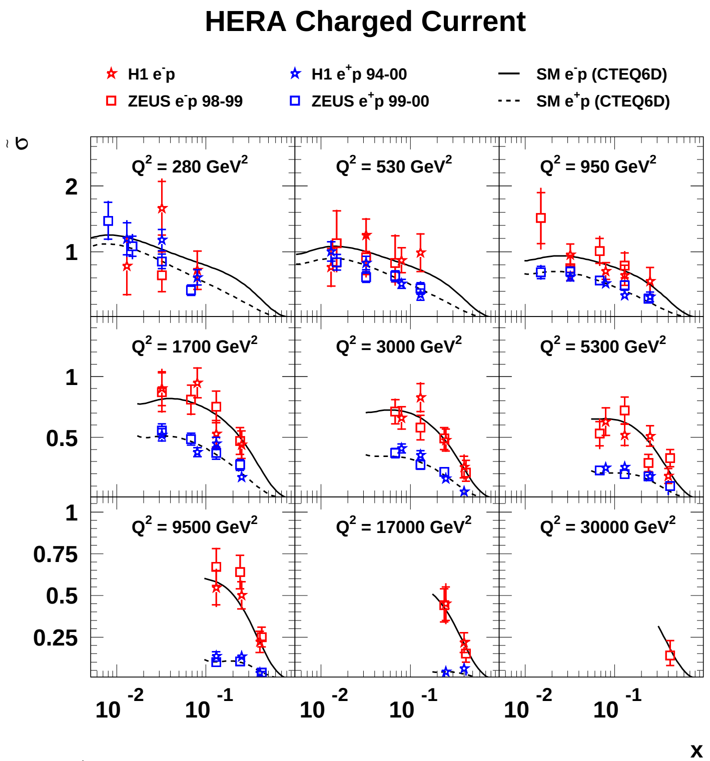




Total cross section measurement with low background.

- For low $Q^2 < 1000$ 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.

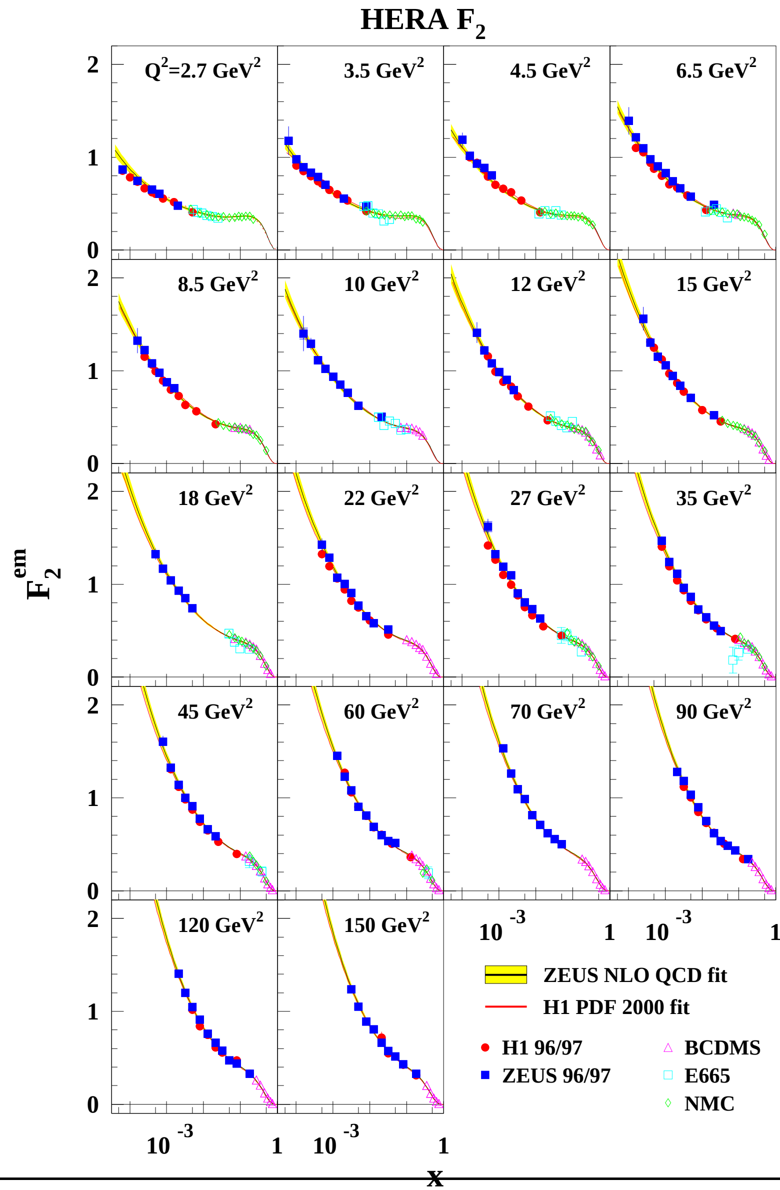
# The Measured Cross Sections

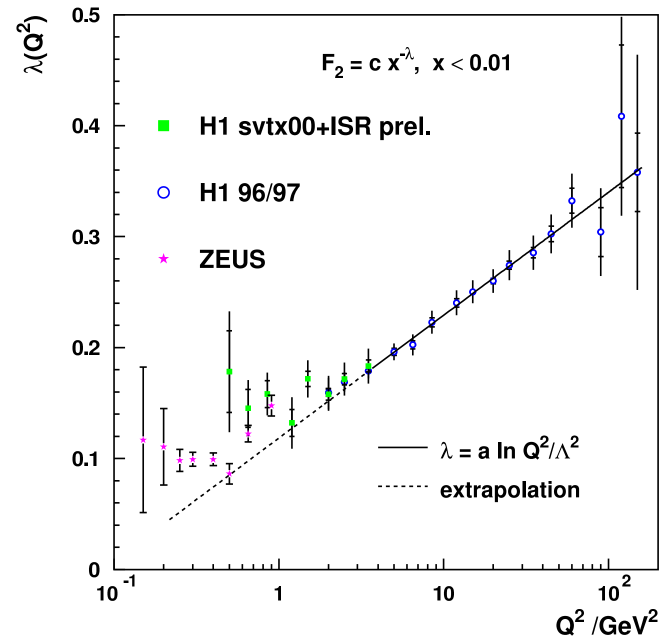



HERA data allows to measure $xU = x(u+c)$, $xD = x(d+s)$, $x\bar{U} = x(\bar{u}+\bar{c})$, $x\bar{D} = x(\bar{d}+\bar{s})$, and $xg$ in a single experiment.

# Measurement at low $x$

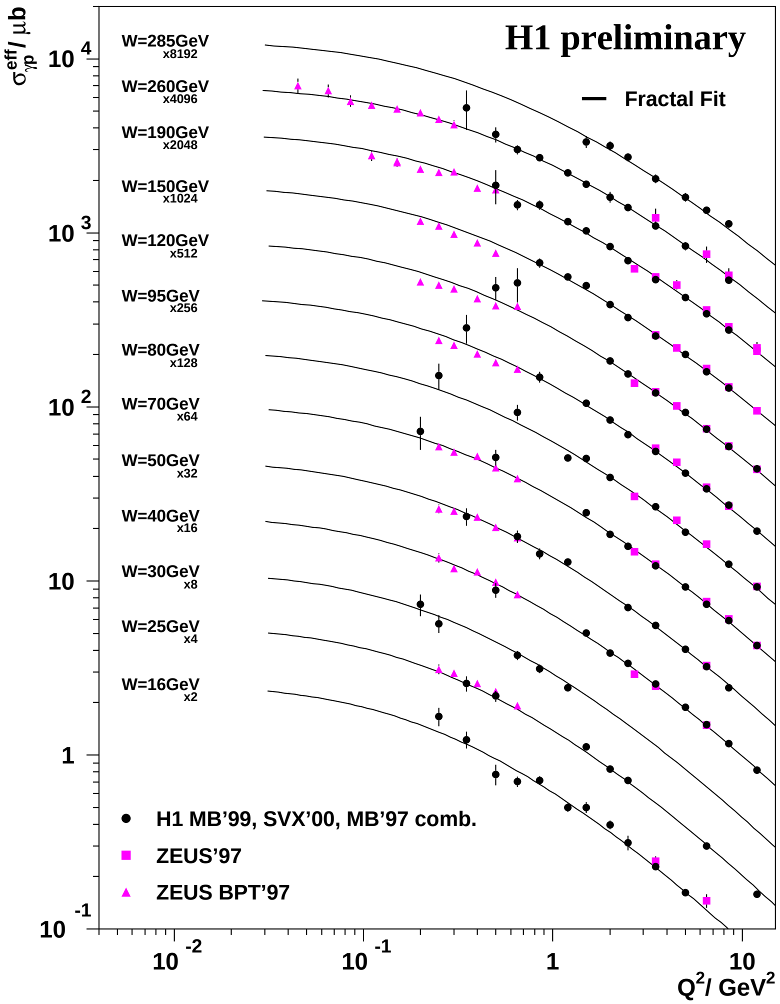



$F_2(x, Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing $Q^2$. To quantify the rise, $F = cx^{-\lambda}$ fit is performed for each $Q^2$ bin.

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

# Measurement at low $Q^2$



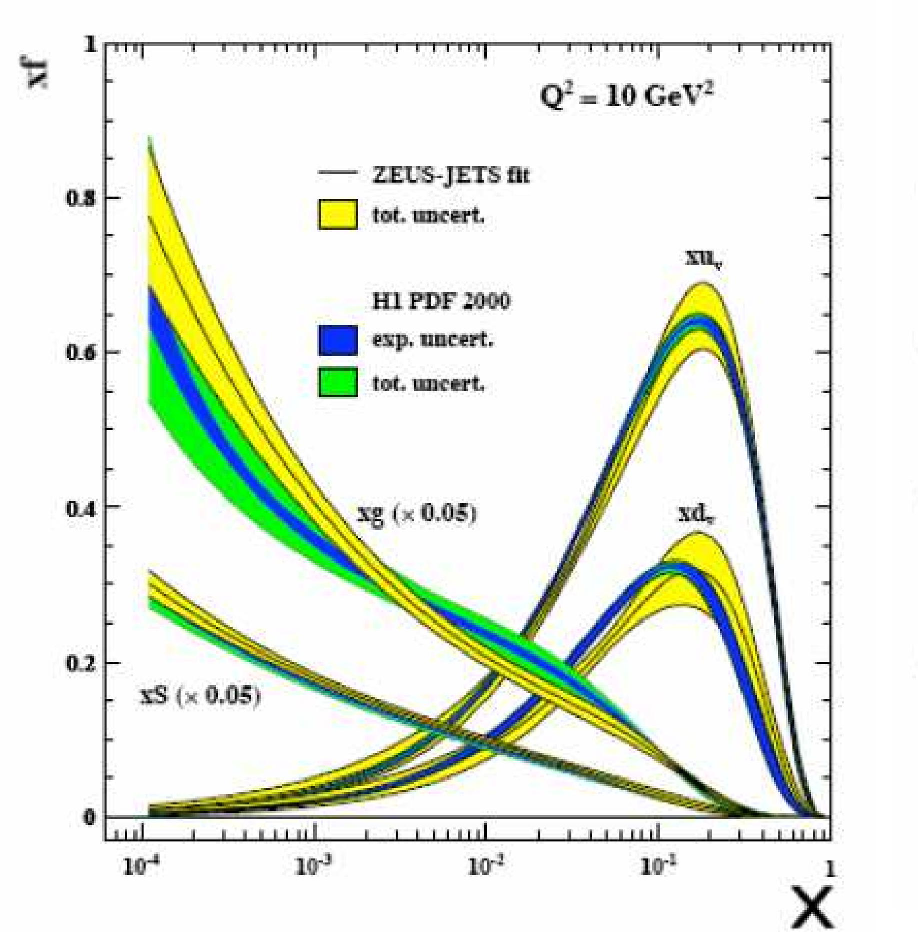

At low $Q^2$, $F_2 \sim \sigma_T + \sigma_L$ and $F_L \sim \sigma_L$ — scattering cross sections of transversely and longitudinally polarized photons.
New preliminary measurement of

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

by H1 compared to published ZEUS data.
Data agree well, new results fill the gap at $Q^2 \sim 1$ GeV$^2$.

Precision for $Q^2 > 3$ GeV$^2$ reaches 1.5%.

# PDFs extraction



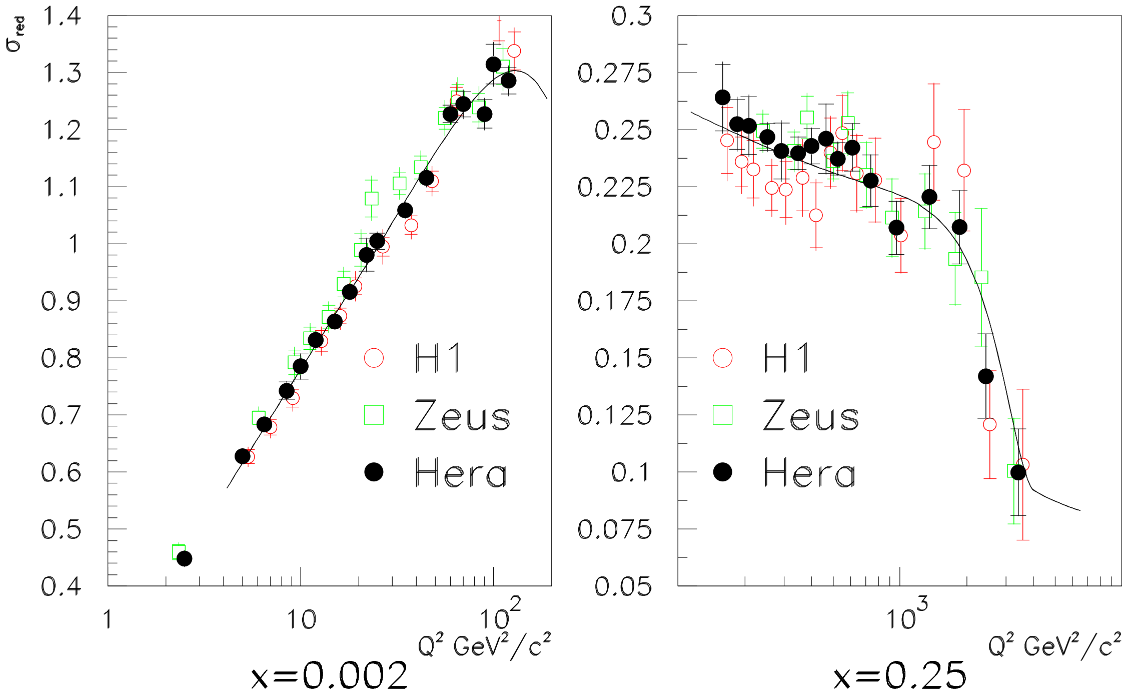

Valence quarks $u_v, d_v$ determine proton structure at high $x$.
Sea $S$ and gluon $g$ are far more important at low $x$.
Mind the $\times 0.05$ scale factor for them.

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 $\chi^2$ vs $\sigma_{red}$.

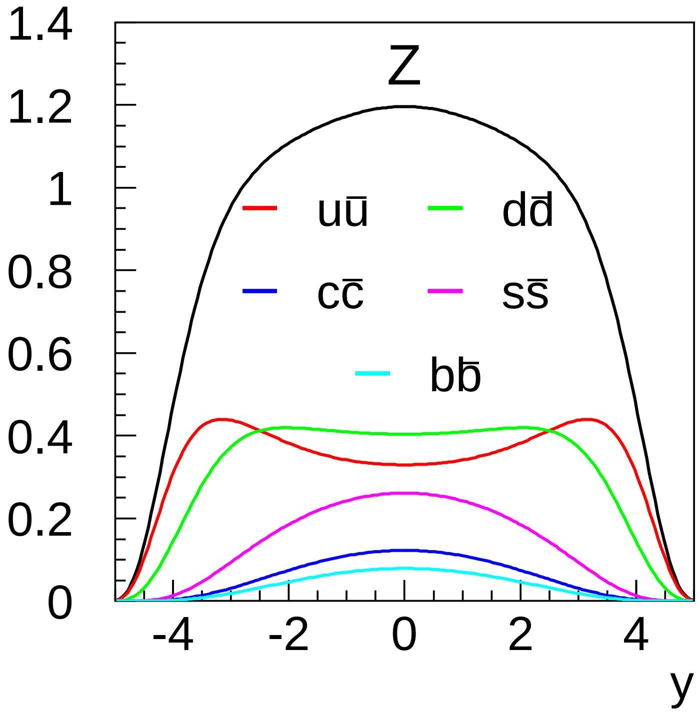
$$\sigma_{red}(e^+p) = F_2 - \frac{y^2}{Y_+}F_L - \frac{Y_-}{Y_+}xF_3$$

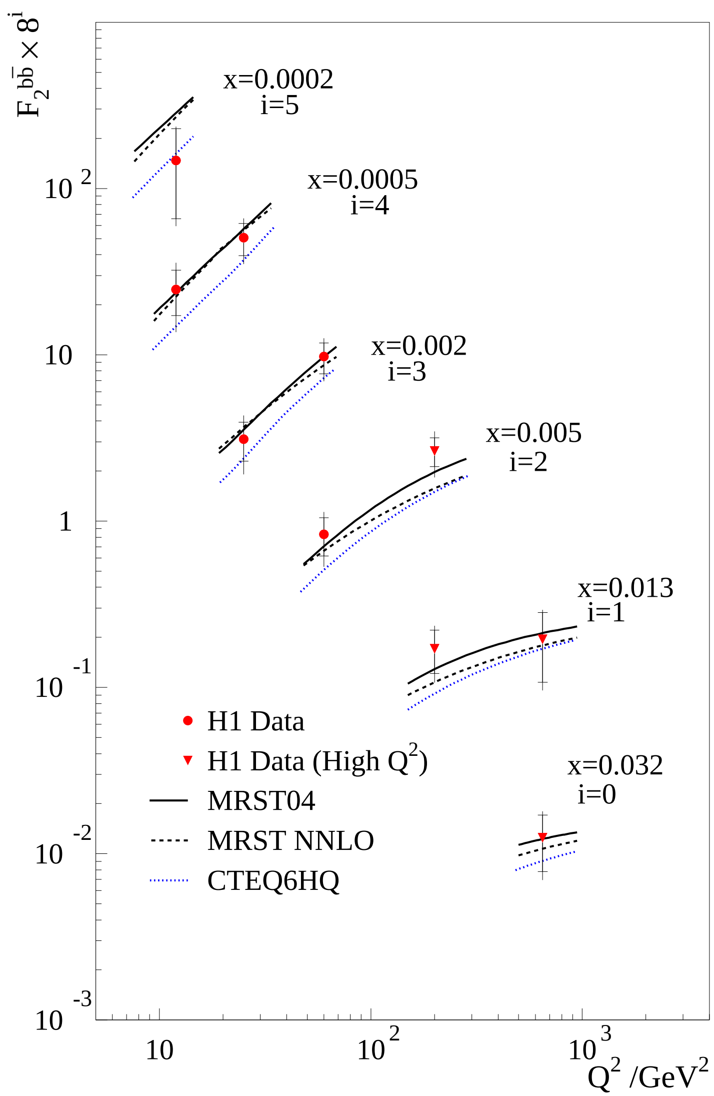



Average of H1 and Zeus data: model independent check of the consistency, $\chi^2/ndf = 534/601$. Experiments cross-calibrate each other → systematic errors reduced.

H1 and ZEUS initiated work on HERA average DIS cross section

# $Z$ production flavor decomposition

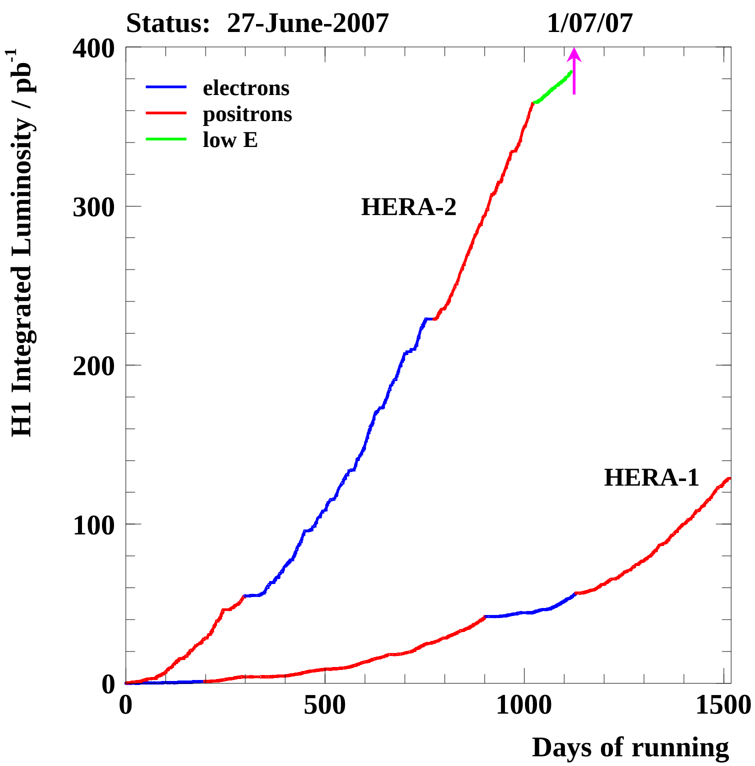


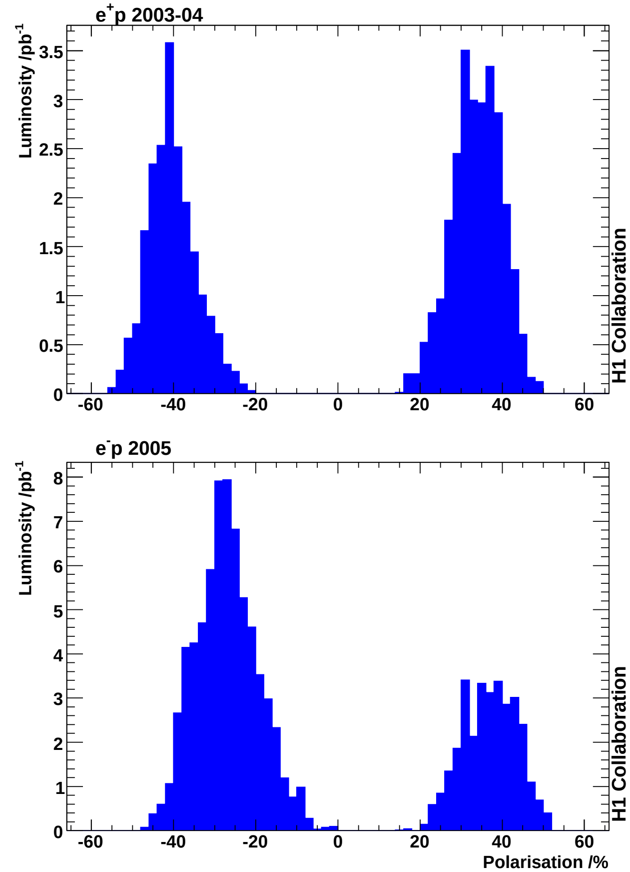




Larger coupling to $Z$ vs $\gamma$ makes $b\bar{b}$ contribution more important for $Z$ production vs inclusive $F_2$.

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

# HERA-II Results



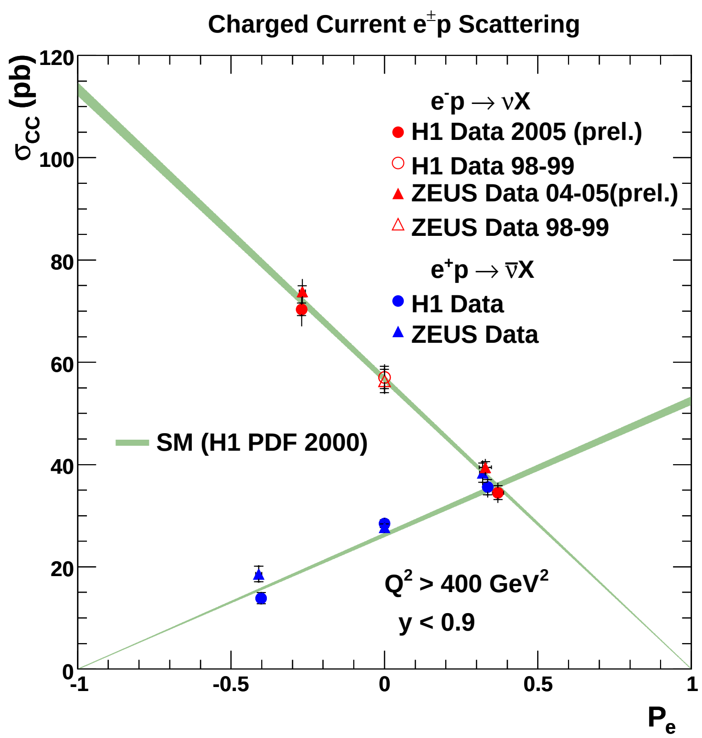




HERA-II upgrade provides better instantaneous luminosity and longitudinal beam polarization.

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

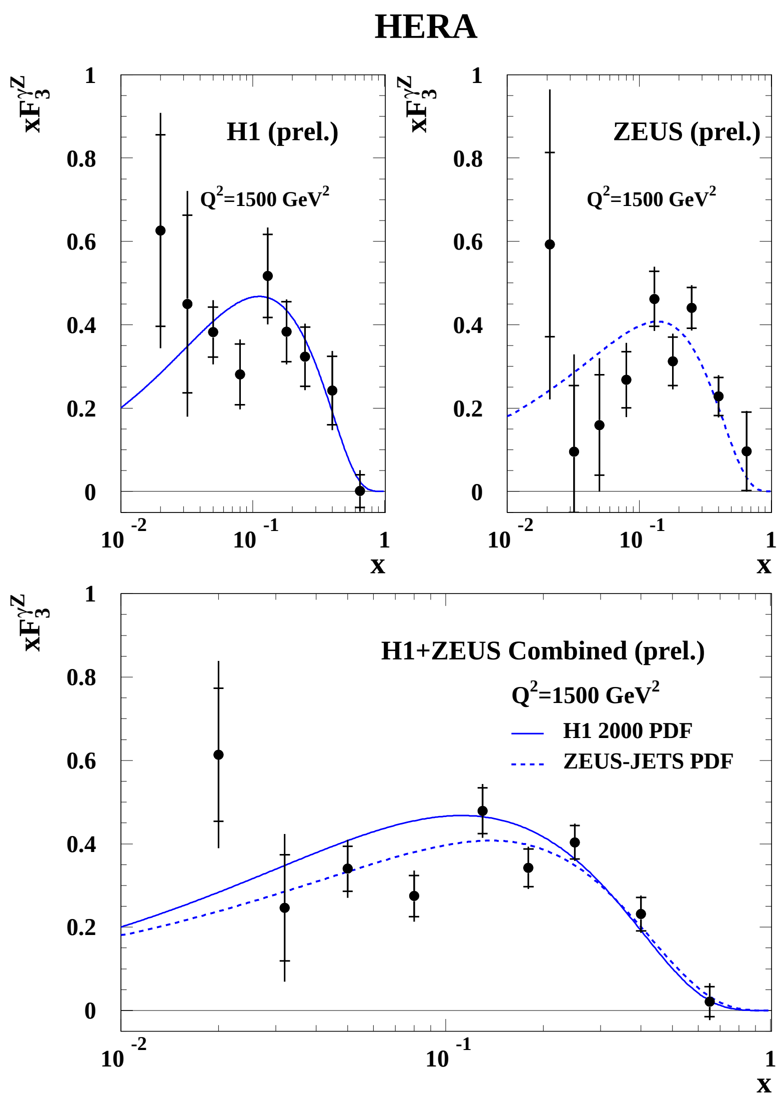



CC cross section is linearly proportional to the degree of the longitudinal beam polarization:

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

Consistent with no right-handed weak currents

# Neutral Current Cross Section and $xF_3$

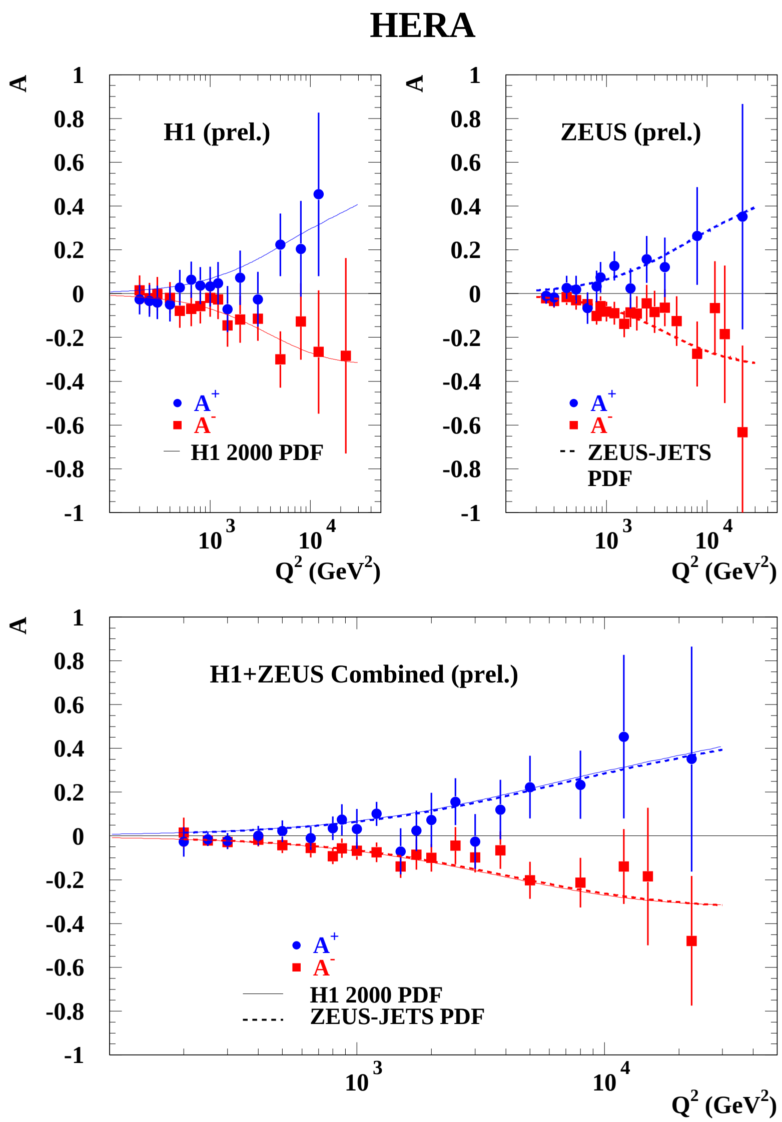



$$xF_3 = x \sum 2 e_q a_q (q(x) - \bar{q}(x))$$

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

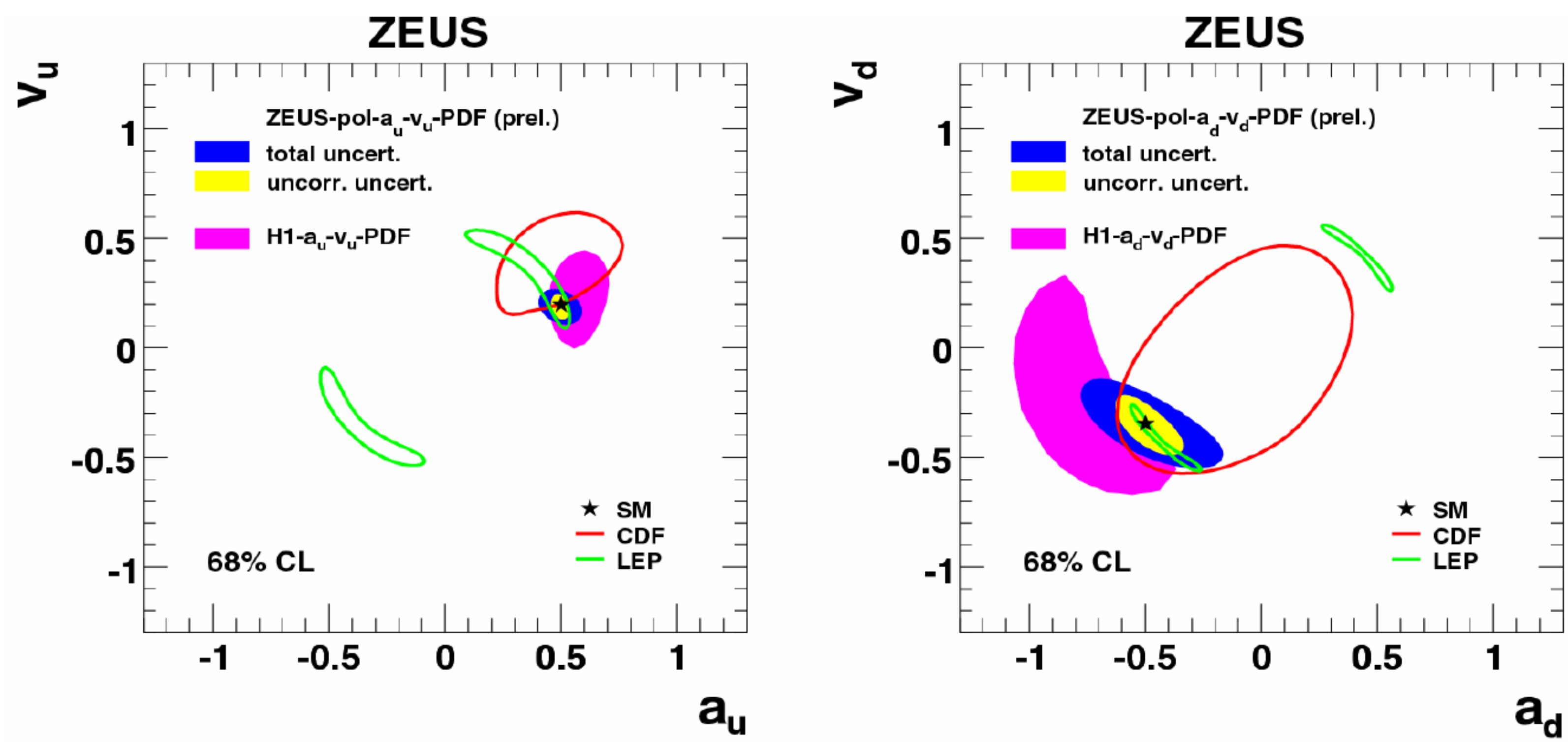
$$F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q})$$

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.

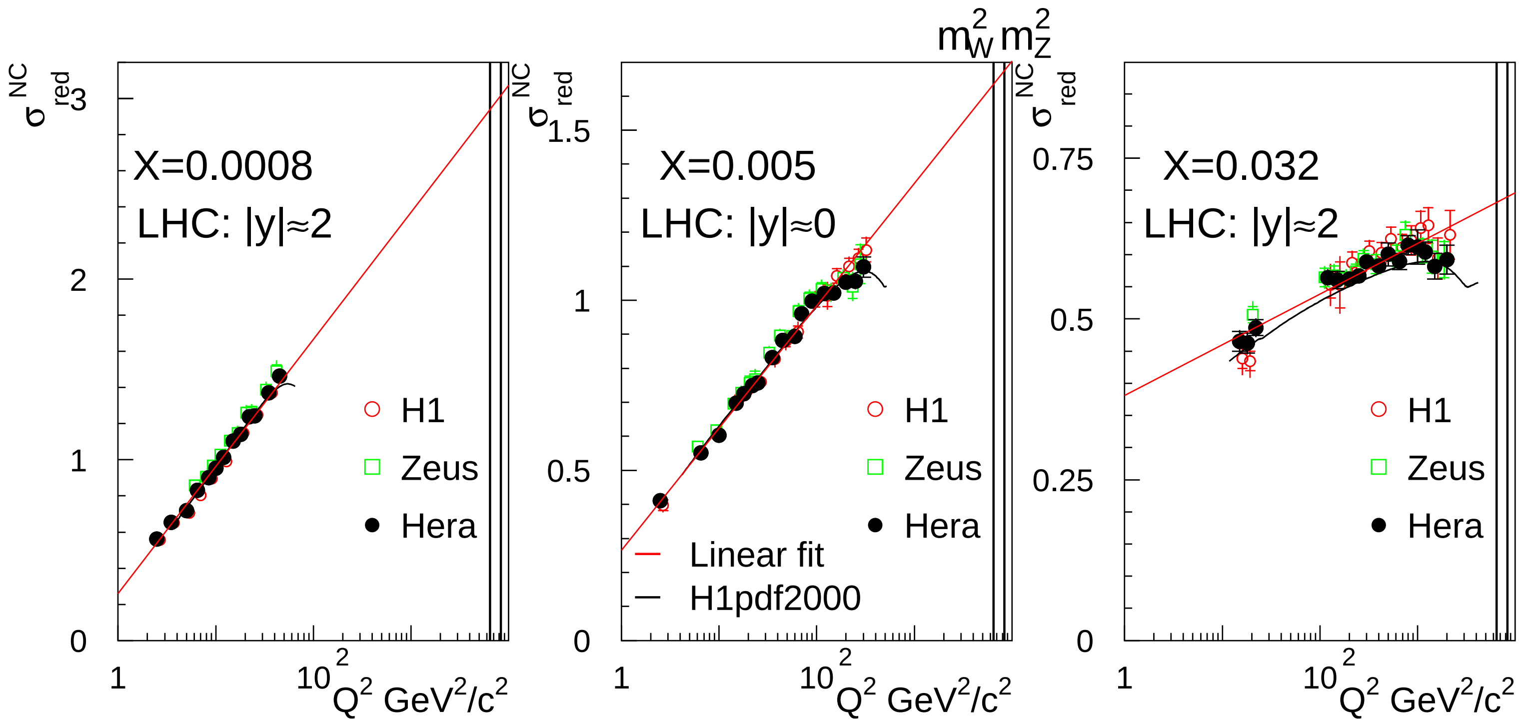
# Combined EW-QCD fit




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 $v_q$

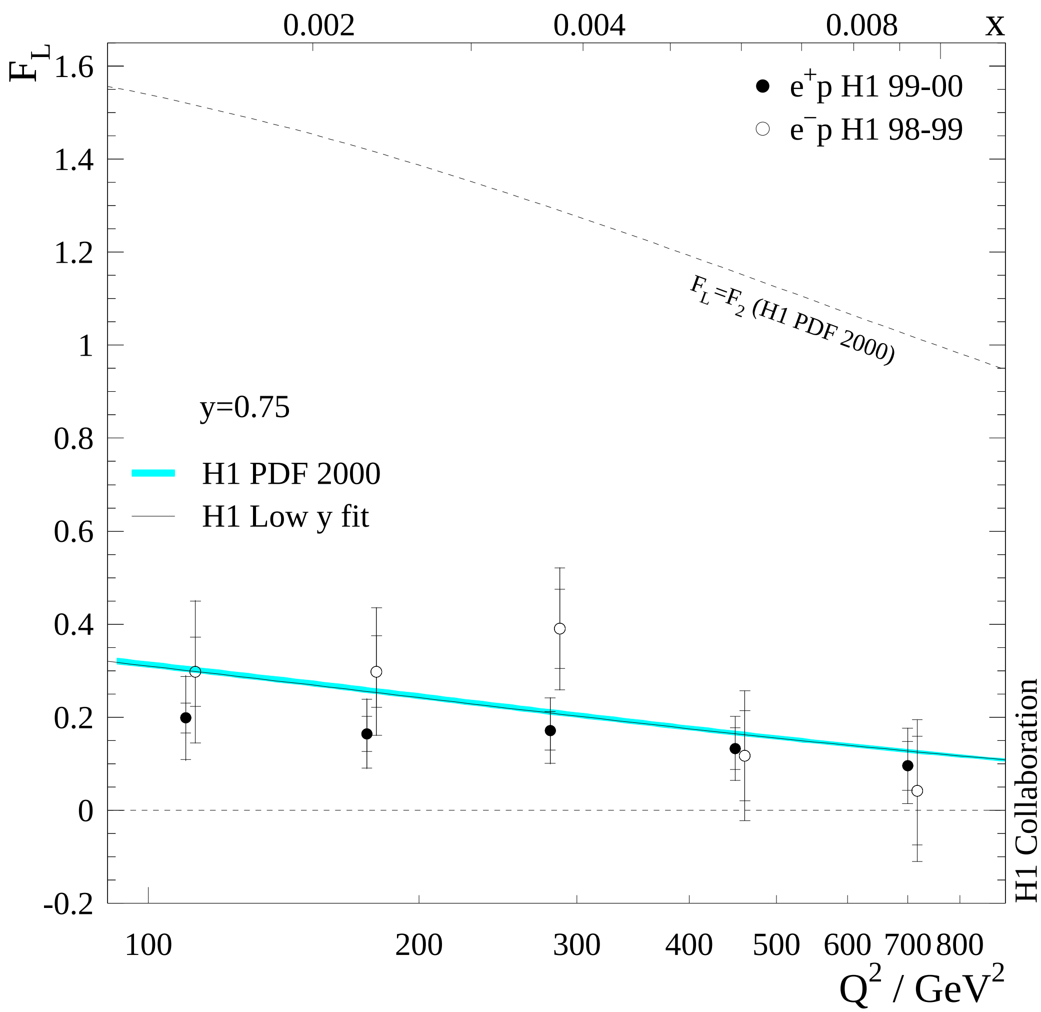
# Extrapolation to LHC energies




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 $\sigma^{NC}_{red}$ for highest $Q^2$ ($\rightarrow$ highest $y$) is due to $F_L$.

# Consistency check: H1 $F_L$ determination at high $Q^2$



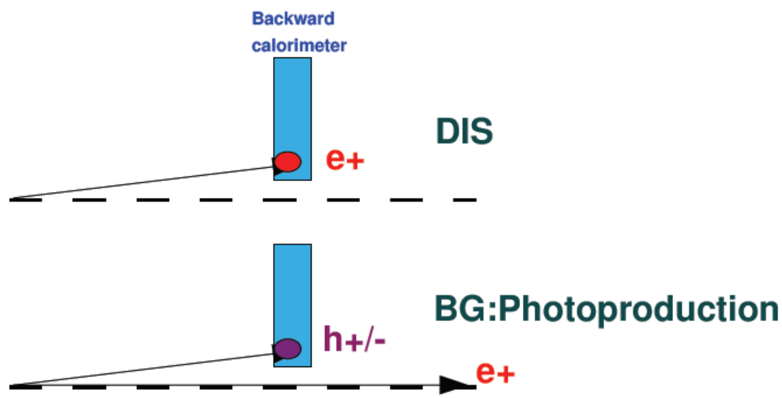

Determination of $F_L$ as

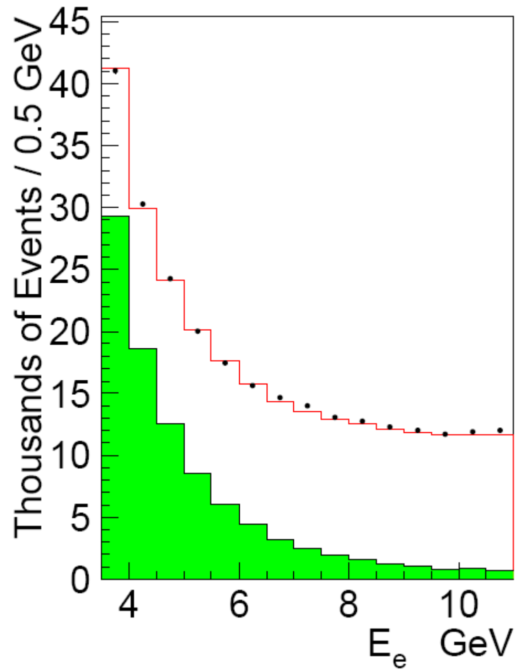
$$F_L = \frac{Y_+}{y^2}\left(F_2^{fit} - \sigma_r\right)$$

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

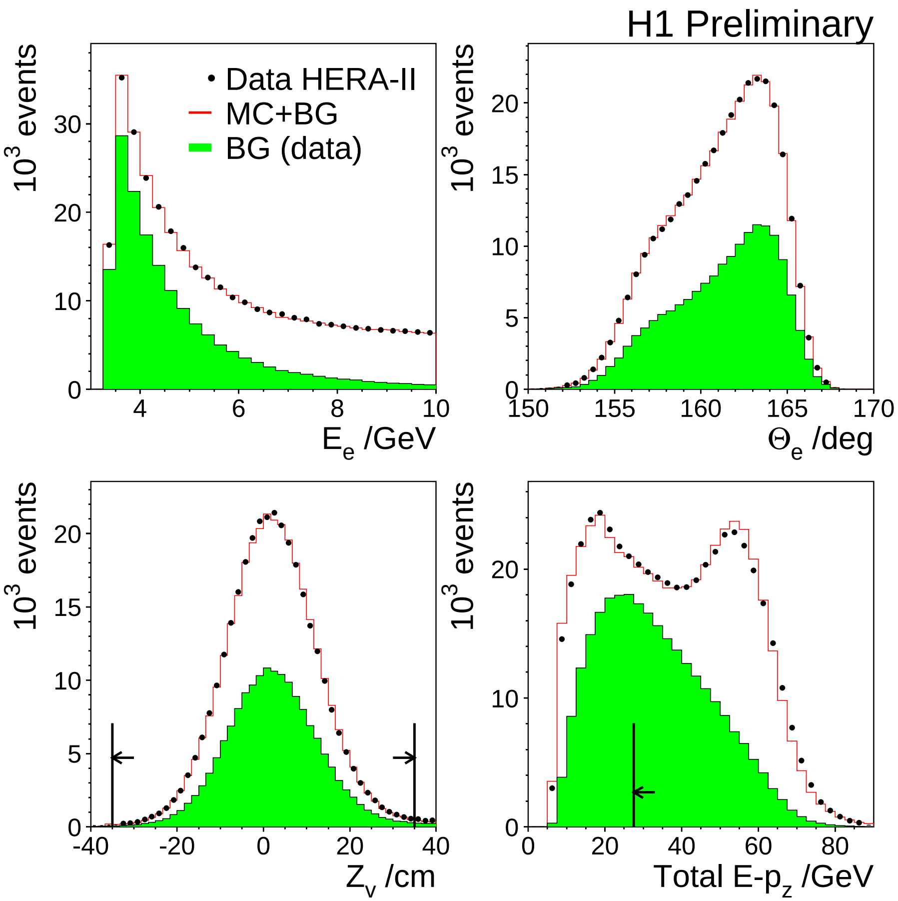



Measurement at high $y$ (low scattered electron energy $E_e$) is challenging. The signature of the scattered electron can be faked by hadronic final state in a $\gamma p$ event.

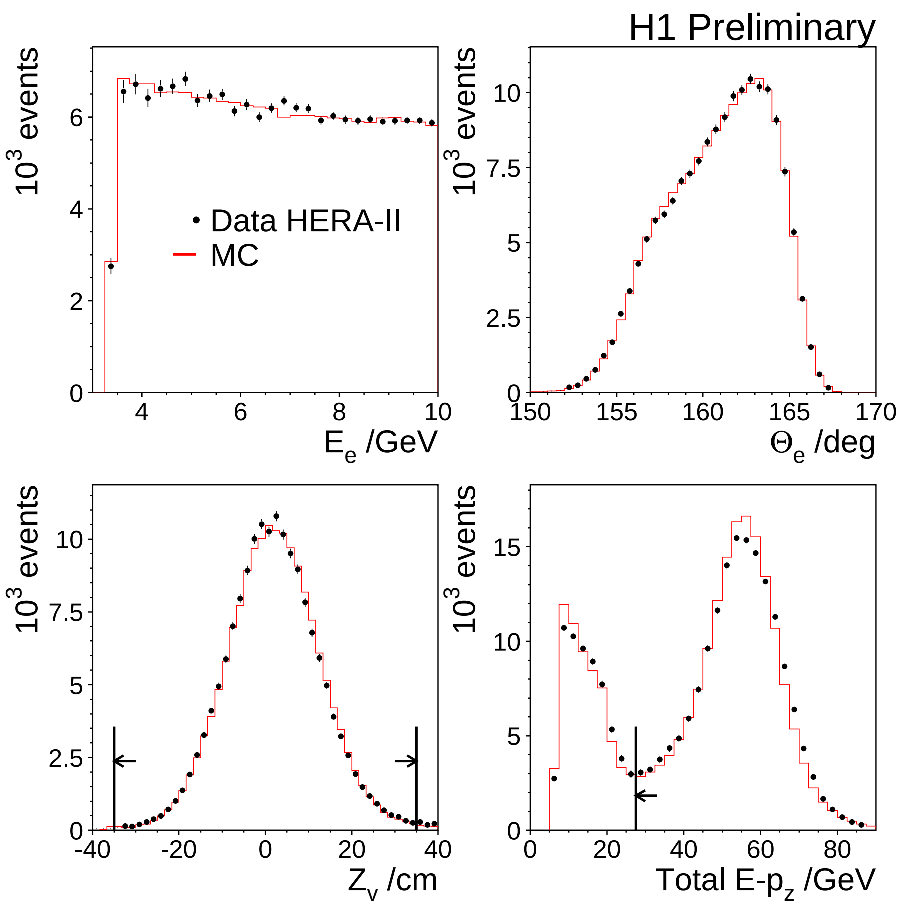
Solution (H1): estimate photoproduction background using electron candidates associated with wrong charge tracks. Charge symmetric lepton beam sample eliminates calorimeter response induced background charge asymmetry ($p$ vs $\bar{p}$)

# H1 high $y$ analysis with HERA-II data




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

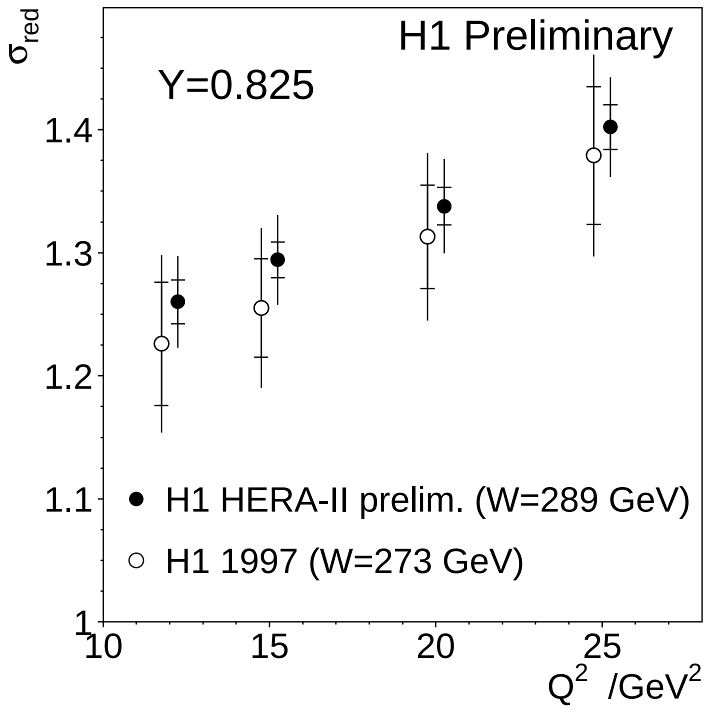
# H1 high $y$ analysis with HERA-II data

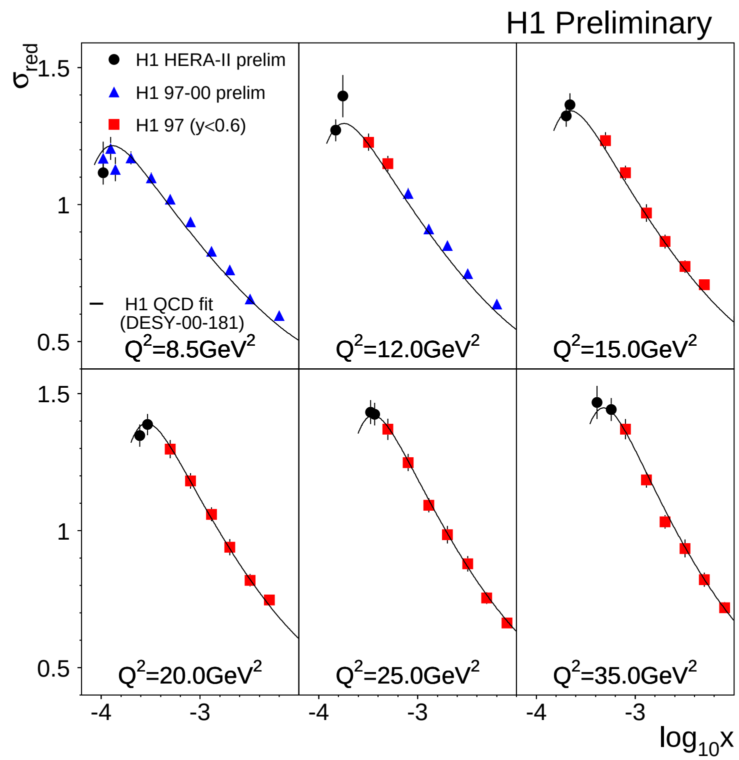



Radiative corrections are controlled using the measured beam energy:

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

# High $y$ cross section at low $x$

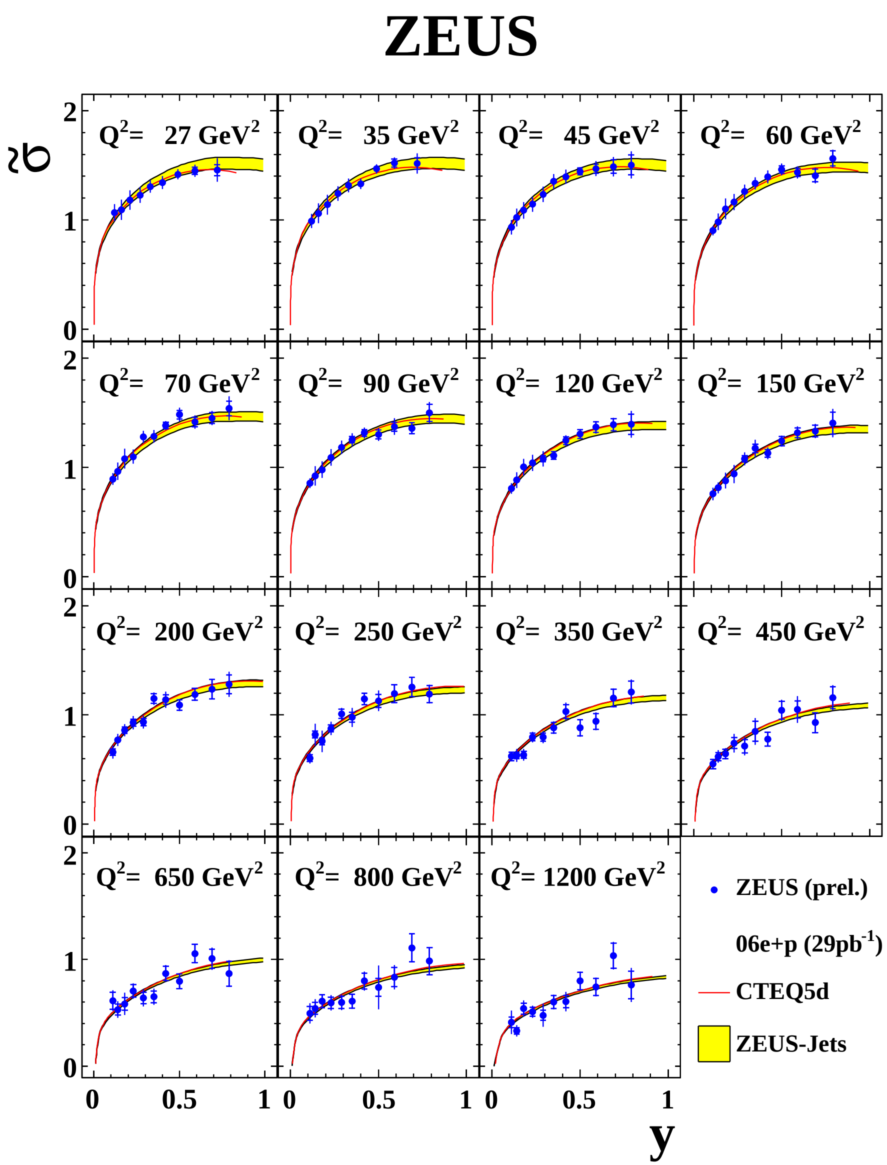



For $y = 0.825$, about factor of 2 improvement in total uncertainty and factor of 3 in stat. uncertainty vs published.

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

# ZEUS high $y$ cross section measurement

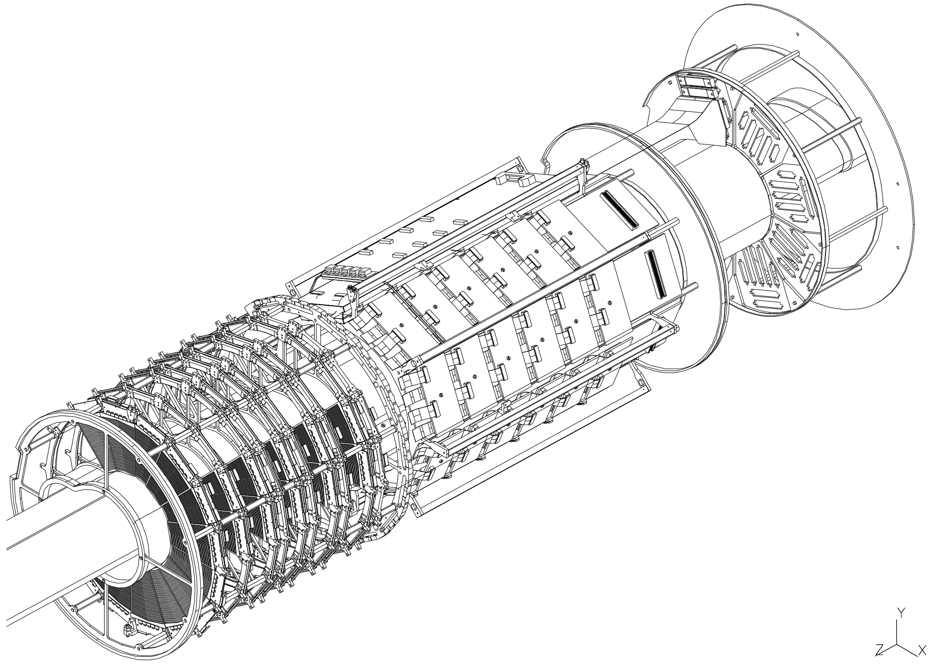


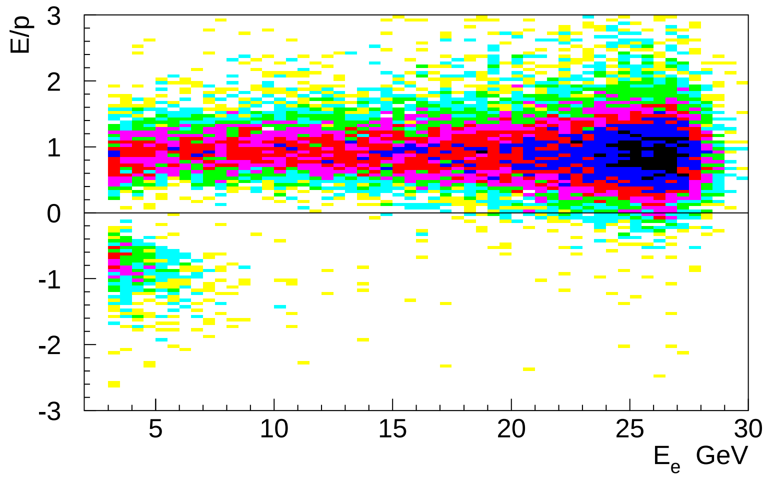

ZEUS performes new measurement focused on high $y$ with HERA-II data.

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

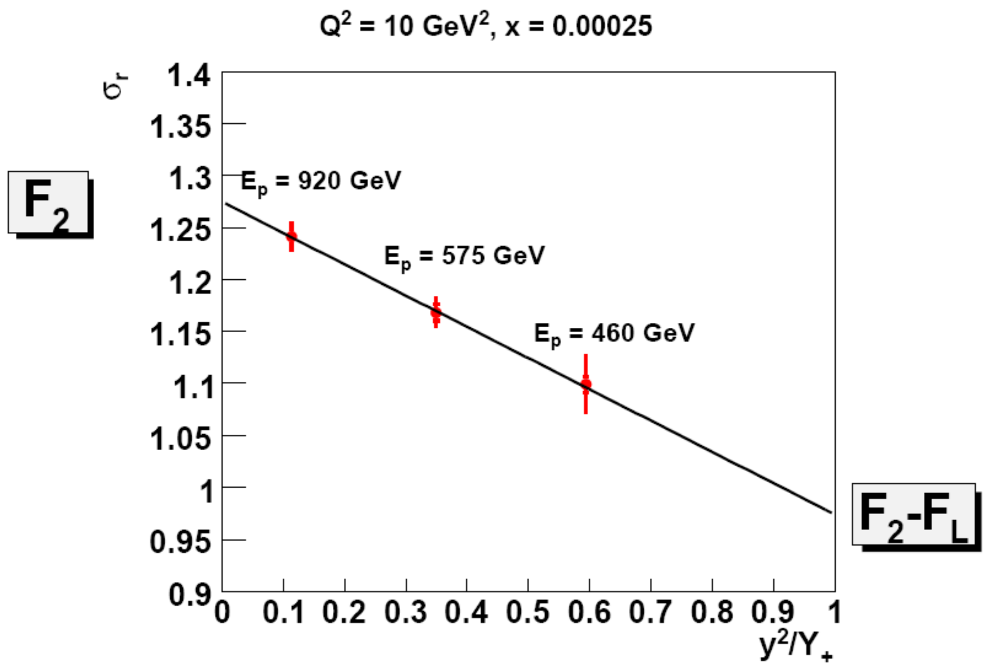
2006 data – re-install Backward Silicon Tracker back in H1 detector. Covers $3 < Q^2 < 10\ \mathrm{GeV}^2$ range for $y > 0.6$.



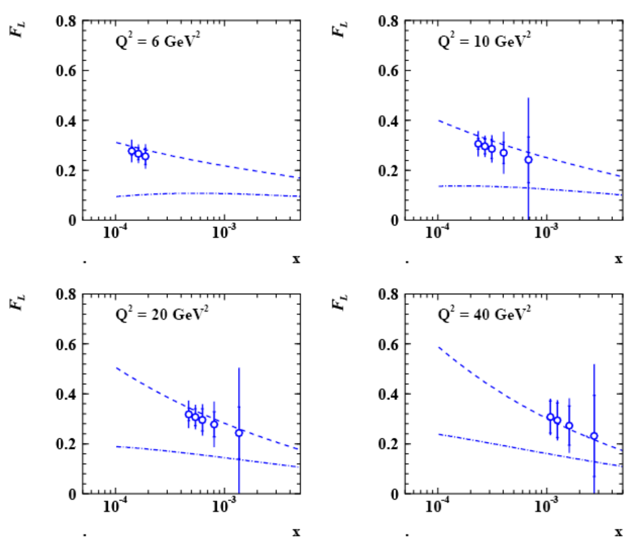

Allows scattered angle reconstruction/charge determination for the electron candidate.

# Measurement of $F_L$ (simulation!)



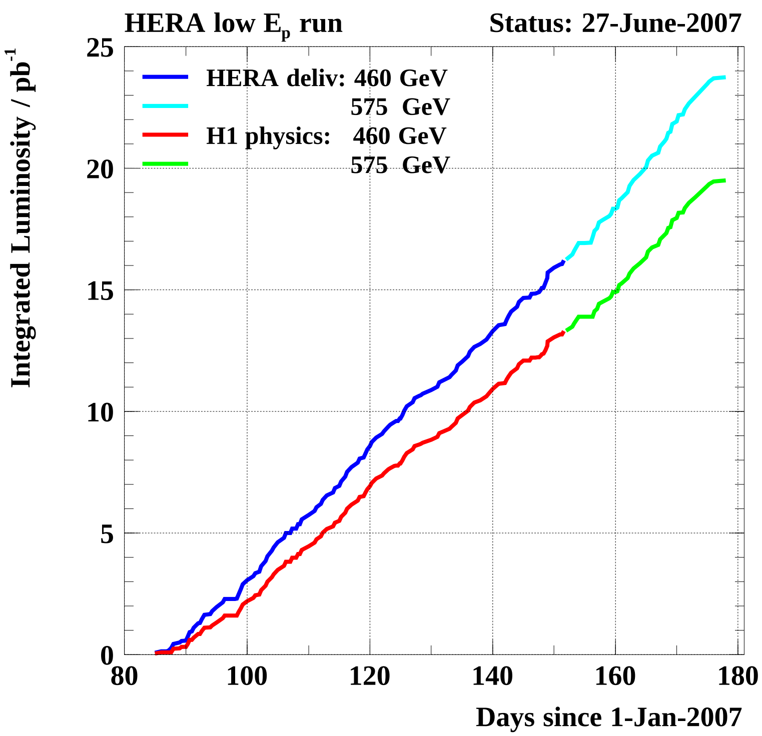

$$\sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

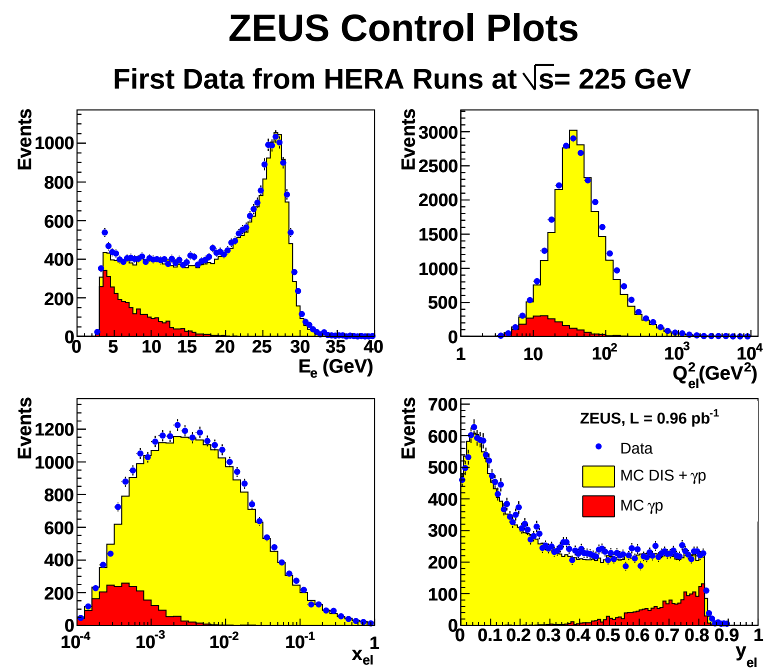
Measure $\sigma_r$ at the same $Q^2, x$ for different beam energies




$F_L$ 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.