# Proton Structure Functions at low $x$

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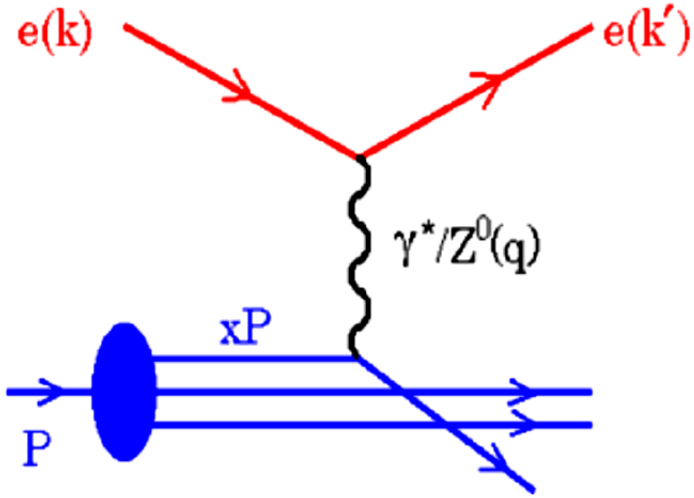
# Deep Inelastic Scattering




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 provide

- A unique tool to study validity of the QCD evolution for a wide range in $x$ and $Q^2$.
- Within the standard QCD evolution, measurement of the proton parton densities.

Knowledge of the proton structure is vital for a number of "practical" applications including $pp$ colliders (LHC).

# PDF determination

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

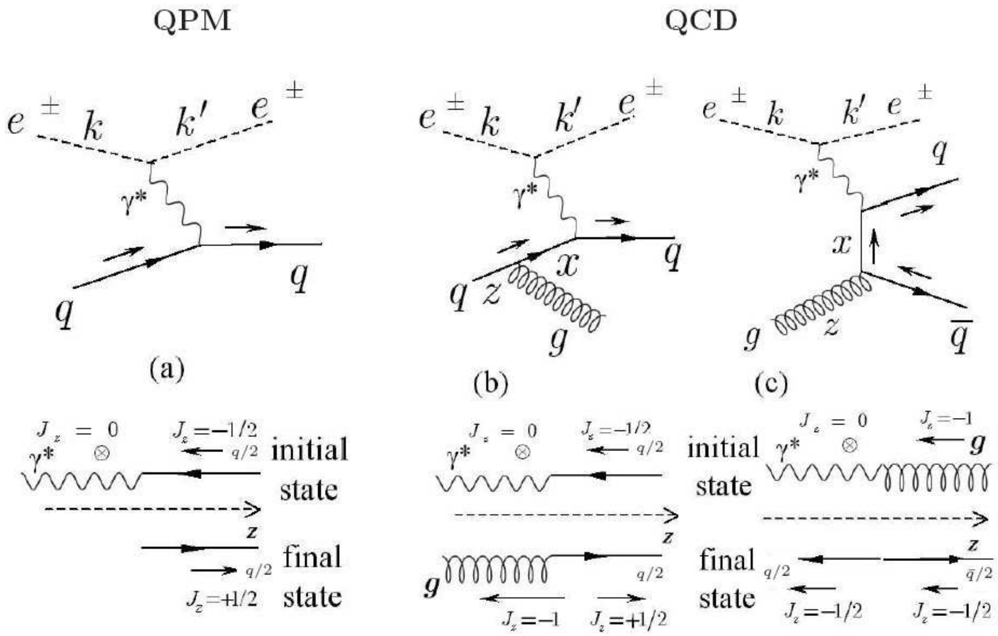
Leading order relations:

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

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.

# The Proton Structure Functions at low $Q^2$



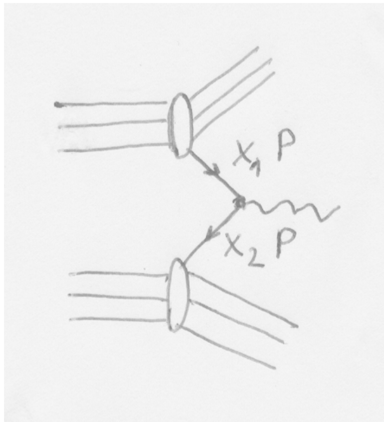

For low $Q^2$:

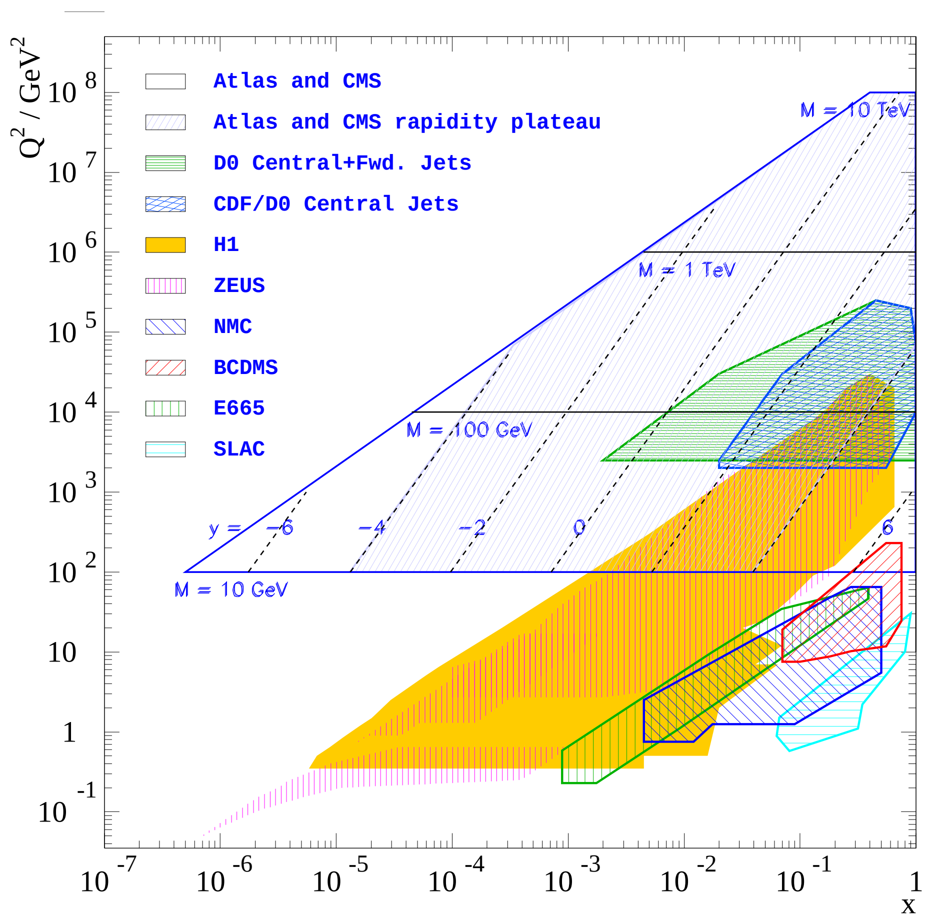
$$F_2 \sim \sigma_L + \sigma_T \qquad F_L \sim \sigma_L$$

which implies $0 \leq F_L \leq F_2$.

- In Quark-Parton Model $F_L = 0$ for spin $1/2$ quarks.
- In QCD, $F_L > 0$ due to gluon radiation.
- At low $x$, sea quark and gluon density are measured using $F_2$ and its scaling violation, $\mathrm{d}F_2/\mathrm{d}\log Q^2$.
  $F_L$ measures gluon via cross section polarization decomposition.

# HERA and LHC kinematics



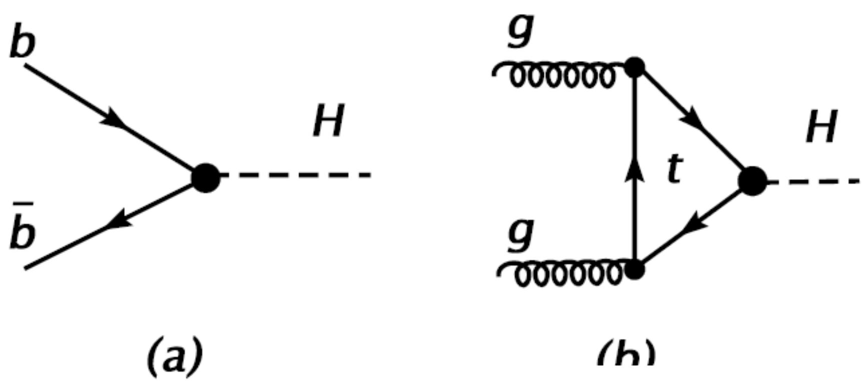




$x_1$, $x_2$ are momentum fractions. Factorization theorem states that cross section can be calculated using universal partons $\times$ short distance calculable partonic reaction.

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

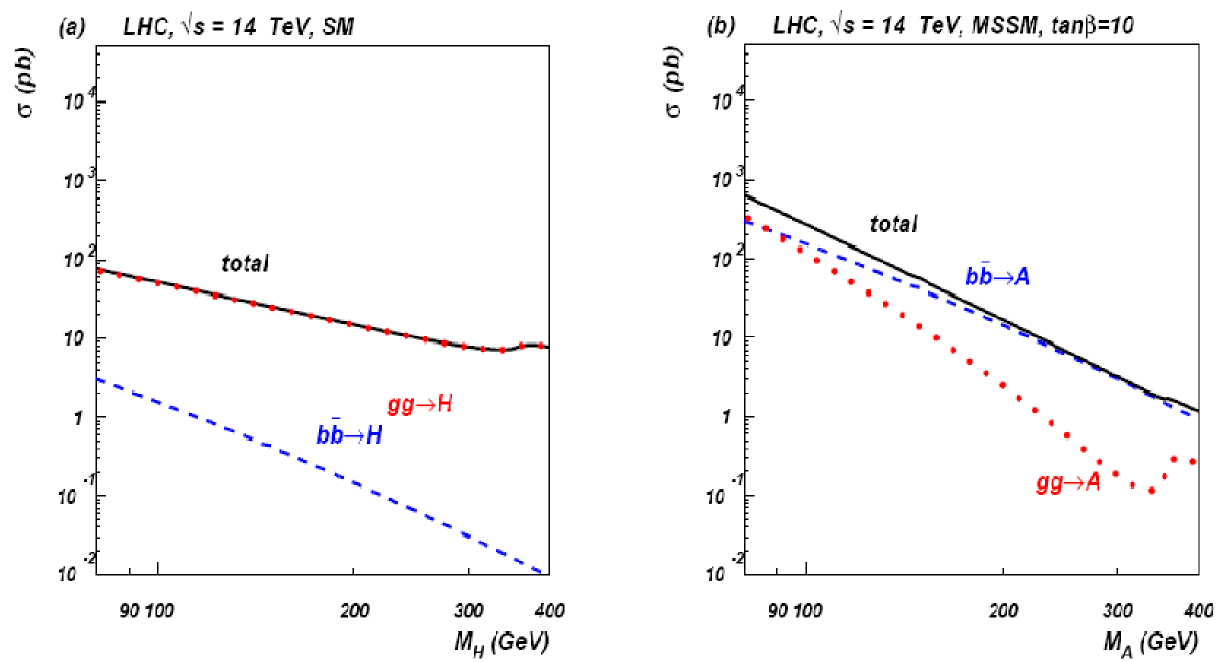
Notation clash: $y$ – rapidity (LHC) vs $y$ – inelasticity (HERA, $Q^2 = Sxy$).

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



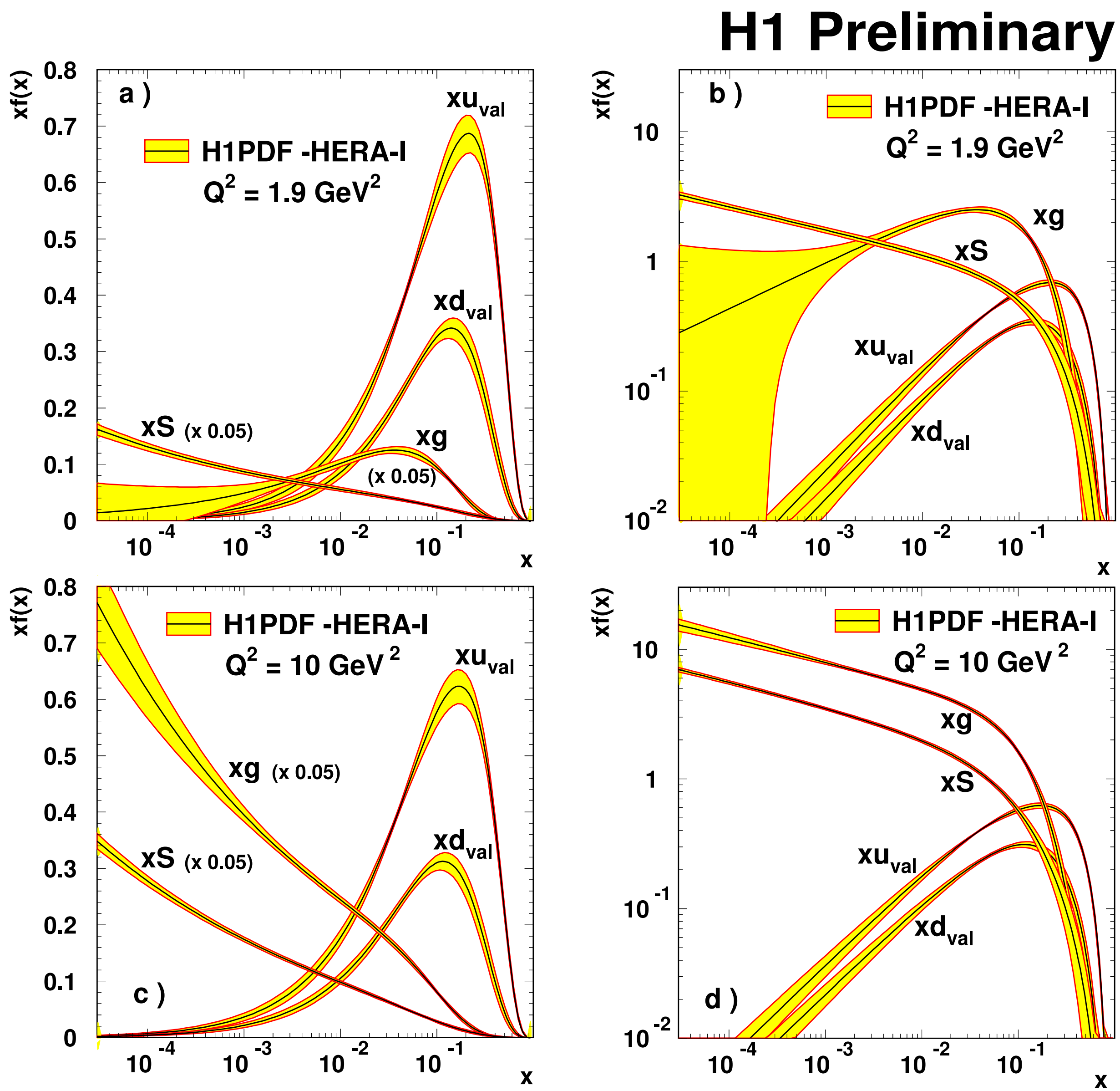

In SM, $b\bar{b} \to H$ is small vs $gg \to H$.
In MSSM, $b\bar{b} \to H$ can be enhanced by $\times \tan^2 \beta$

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.

# Partons at low $x$

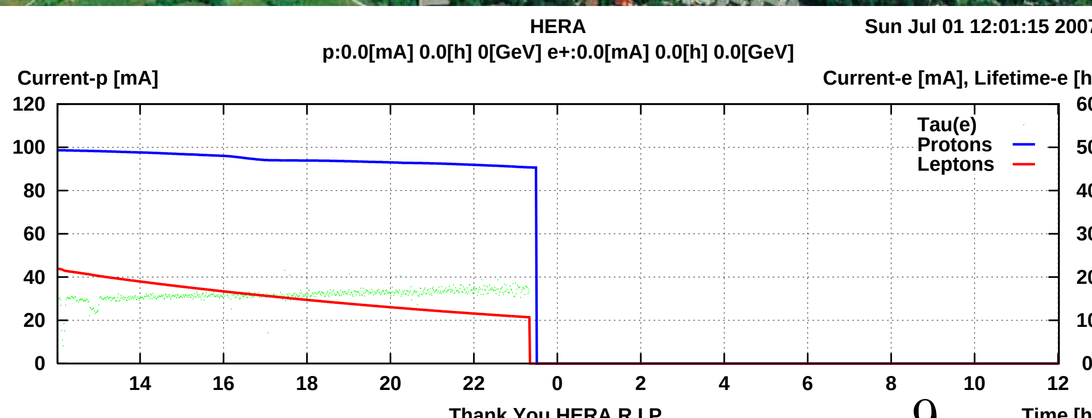



- For $x < 0.01$ $xS$ and $xG$ dominate.
- Very rapid evolution for $xS$ and $xG$.
- Analysis based on very new H1 data.

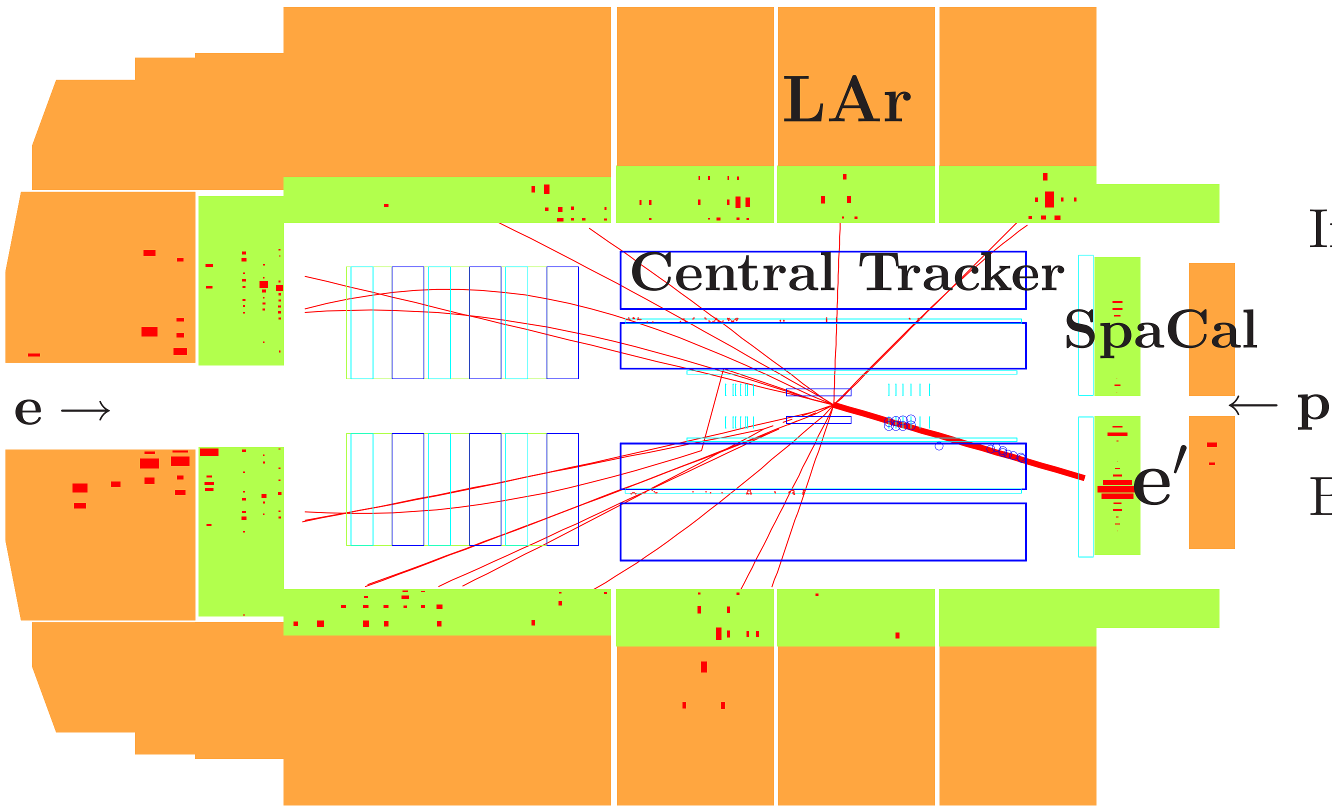
# Intermediate Summary

- Production of $M \sim 100$ GeV particles in the central detector region at LHC corresponds to Bjorken $0.002 < x < 0.02$.
- For this $x$ range gluon and sea quarks dominate.
- Gluon and sea are determined from the $F_2$ structure function data, which for this $x$ range come from HERA for $5 \leq Q^2 \leq 500$ GeV$^2$ and evolved to higher $Q^2$ using QCD evolution.

# HERA, H1 and ZEUS. 1992-2007.

# DIS Event Reconstruction




$$Q^2 = 4E_eE'_e\cos^2\frac{\theta_e}{2}$$

Inelasticity:

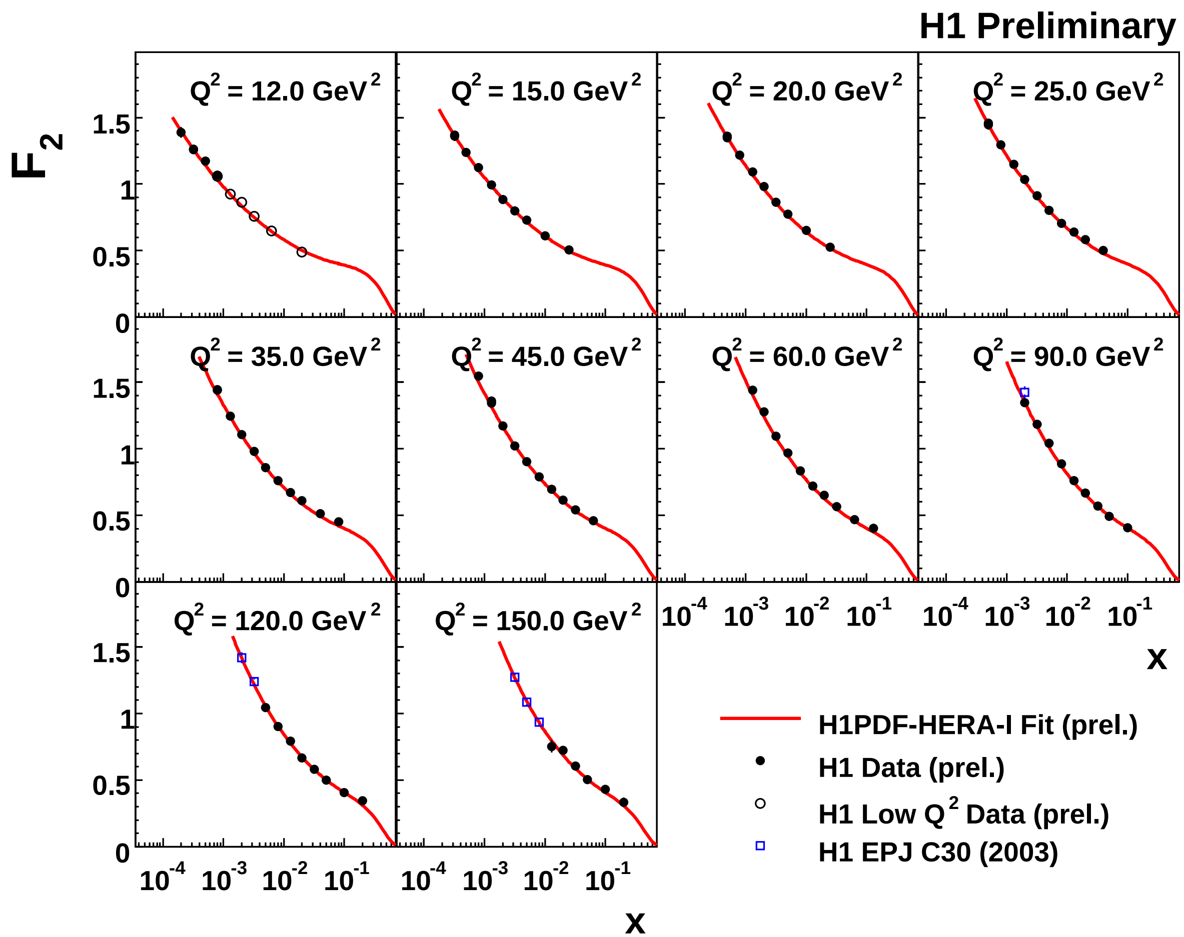
$$y = 1 - \frac{E'_e}{E_e}\sin^2\frac{\theta_e}{2}$$

Bjorken $x$:

$$x = \frac{Q^2}{Sy}$$

Both the scattered electron and hadronic final state can be used to reconstruct event kinematics.

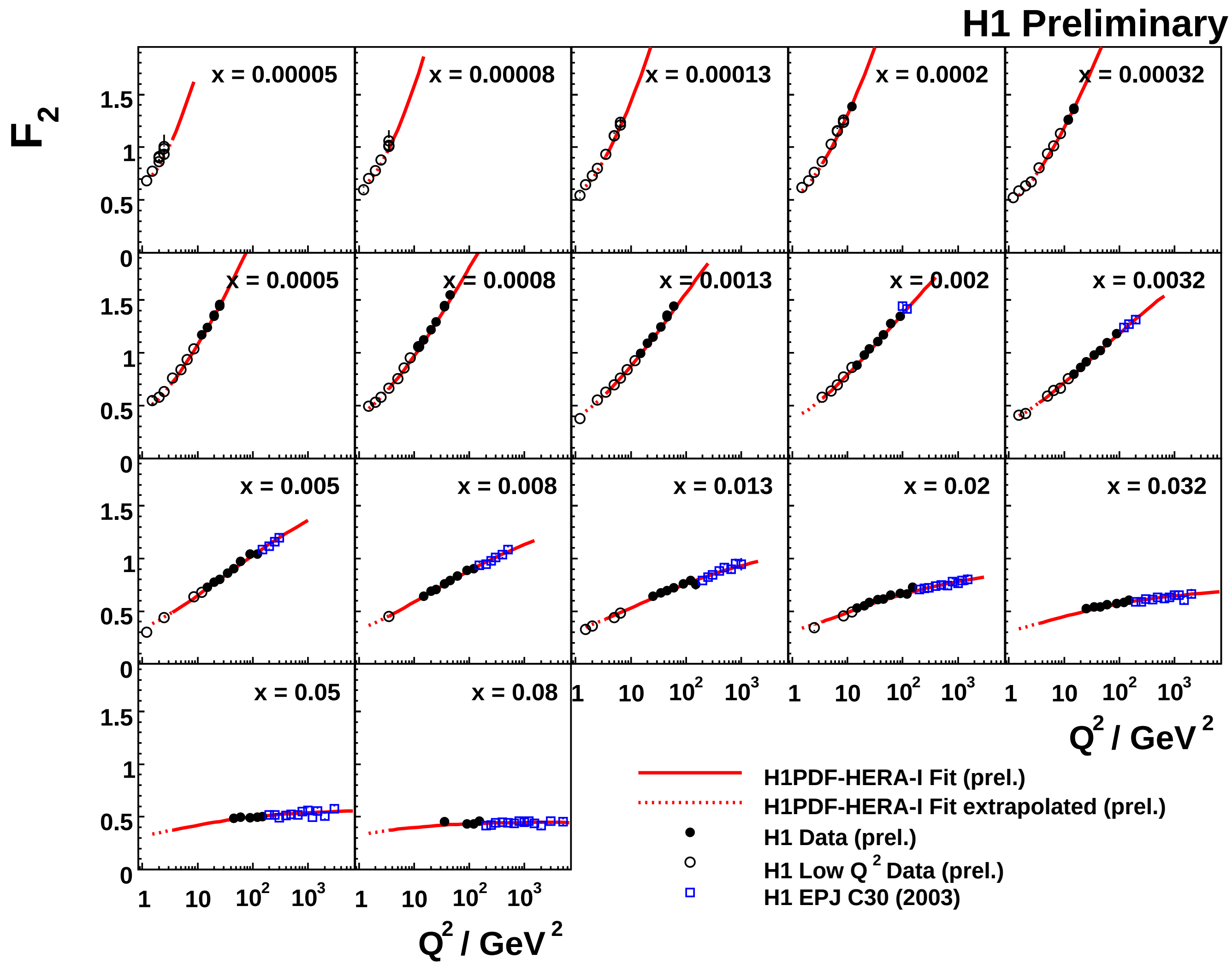
# Structure Function $F_2$ at low $x$




Recent measurement peformed by the H1 collaboration.
Final result base on HERA-I data. Precision reaches $\sim$ 1.5%.

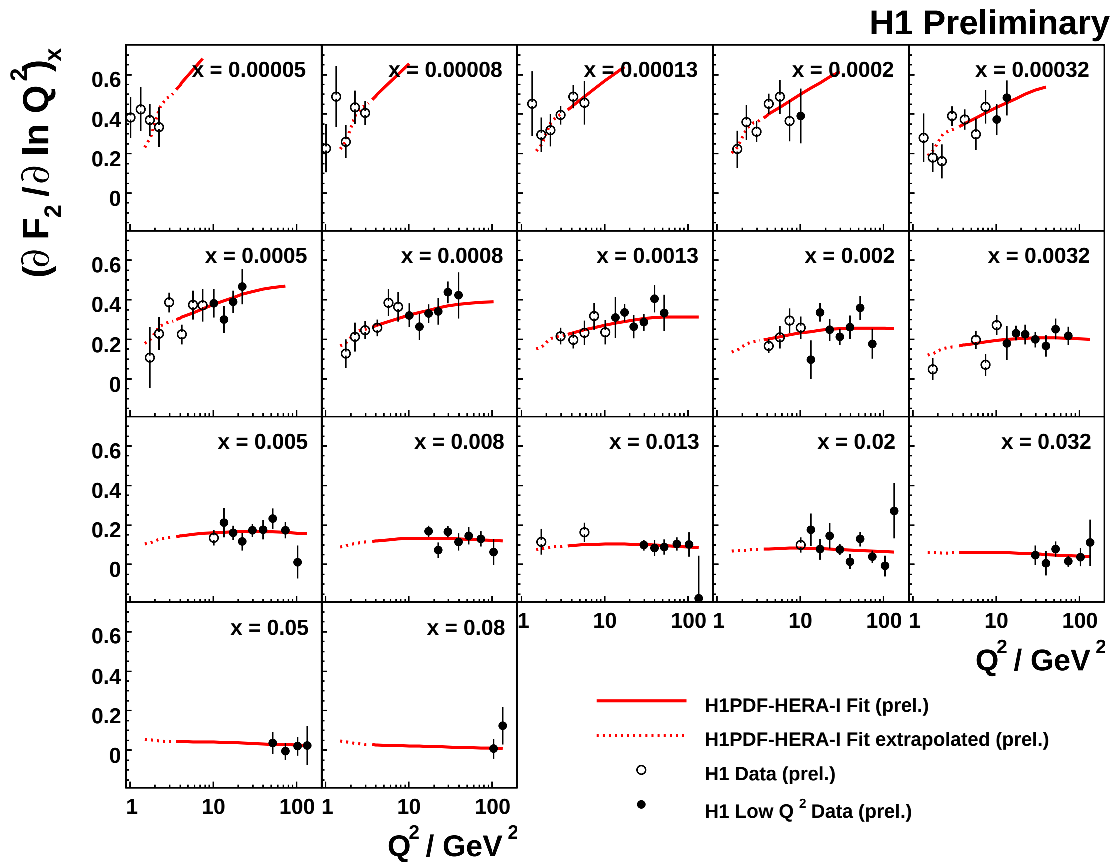
$F_2(x, Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing $Q^2$.

# $F_2$ Scaling violation at low $x$




Large scaling violation at low $x$ — large gluon density. Good agreement between the data and theory.

# $\partial F_2/\partial \ln Q^2$ at low $x$




Data precision allows for local determination of $\partial F_2/\partial \ln Q^2 \sim \alpha_S G$. Note that there is a strong anti-correlation between the data points. Good consistency between data and QCD fit (even for extrapolation to low $Q^2$).

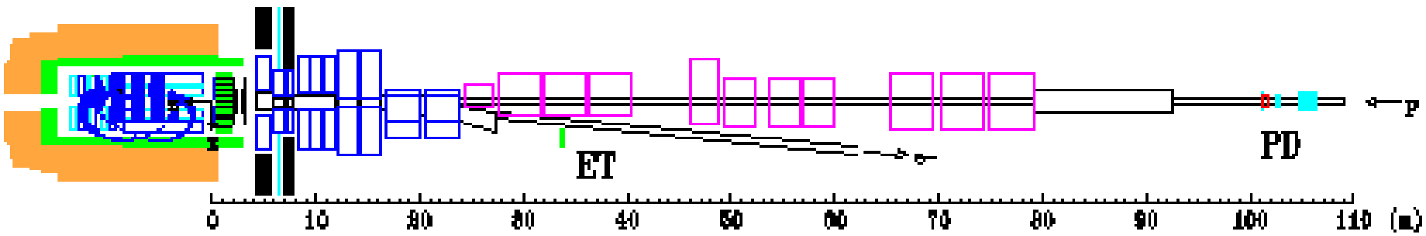
# Sources of Experimental Uncertainty

For a double differential cross section measurement, sources of uncertainties are luminosity, kinematic determination and identification efficiency.

$$\delta\mathcal{L} \quad \delta\sigma_r^{stat}, \quad \delta\sigma_r^{corr\ syst} \quad \delta\sigma_r^{uncorr\ syst}$$

- Global normalizations – arise from luminosity uncertainty $\delta\mathcal{L}$, global inefficiencies. Affect data sets uniformly. Typical value $\sim 1.5 - 2\%$. Most serious for PDFs: $3\sigma$ shift generates $4.5 - 6\%$ bias with only 9 units of $\chi^2$.
- Correlated systematic uncertainties, $\sigma_r^{corr\ syst}$ – arise from misreconstruction of event kinematics, background. Affect groups of experimental points, typically $y$ dependent $\rightarrow$ can change $x$-shape globally, affect $xG(x)$.
- Uncorrelated systematic uncertainties, $\sigma_r^{uncorr\ syst}$ – arise from local efficiencies, miscalibrations. Often the largest source of uncertainty but impact on PDFs is $\sim 1/sqrt(N_{meas})$.
- Statistical uncertainties, $\sigma_r^{stat}$ – at HERA are small for $x \sim 0.005$ range, become important for high $Q^2, x$.

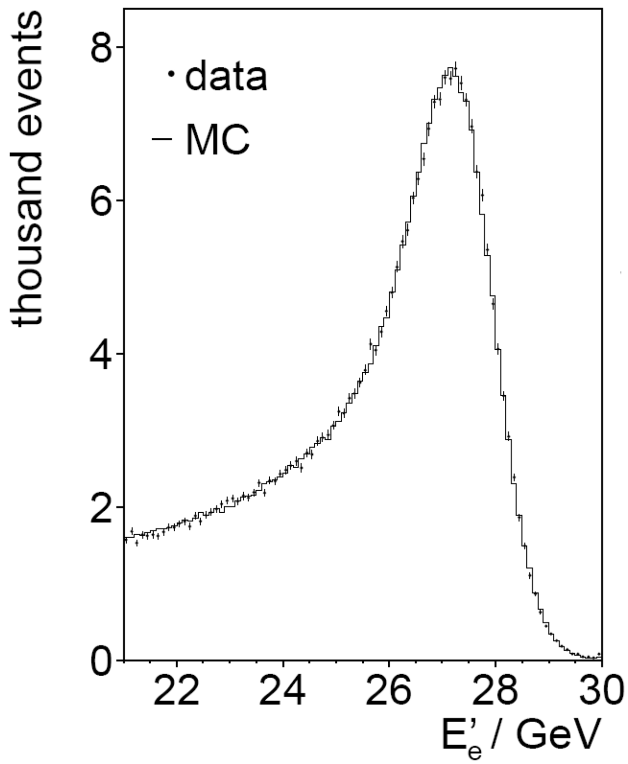
# Luminosity measurement at HERA

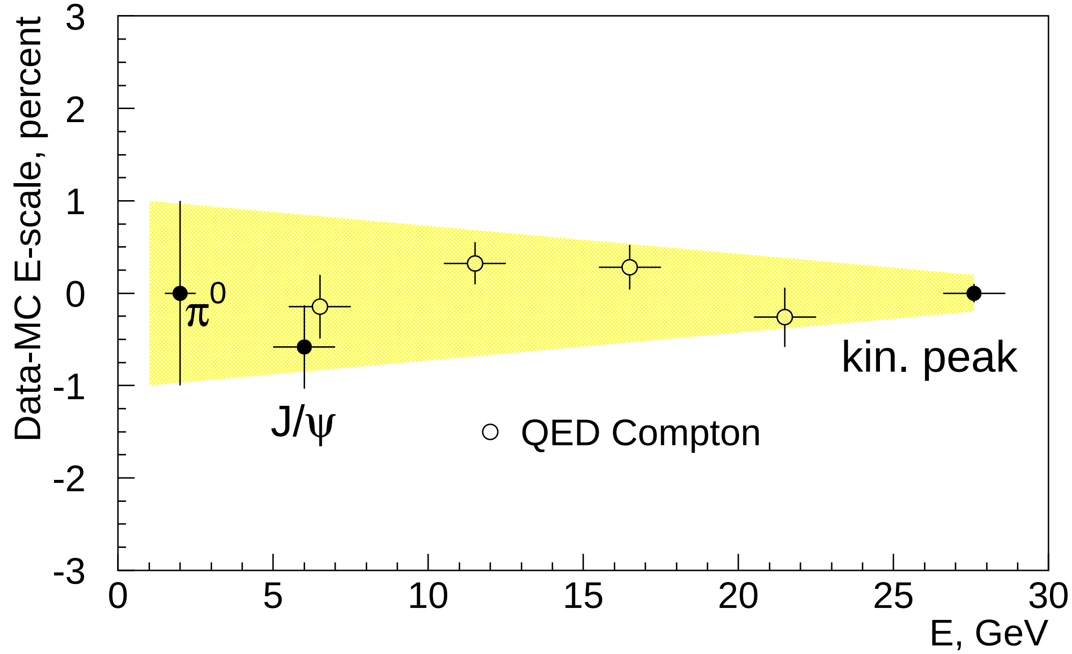



- Use $ep \rightarrow ep\gamma$ Bethe-Heitler process, detect the scattered photon in a photon tagger $\sim 100$ m away from the IP.
- QED prediction with 0.5% precision (effect of higher orders).
- Experimental uncertainty dominated by detector acceptance knowledge ($\sim 90 \pm 1\%$), energy calibration, and beam longitudinal profile.

$\rightarrow$ complicated measurement. Ultimate experimental uncertainty: 1%, uncorrelated H1 vs ZEUS.

# Correlated Systematic Uncertainties

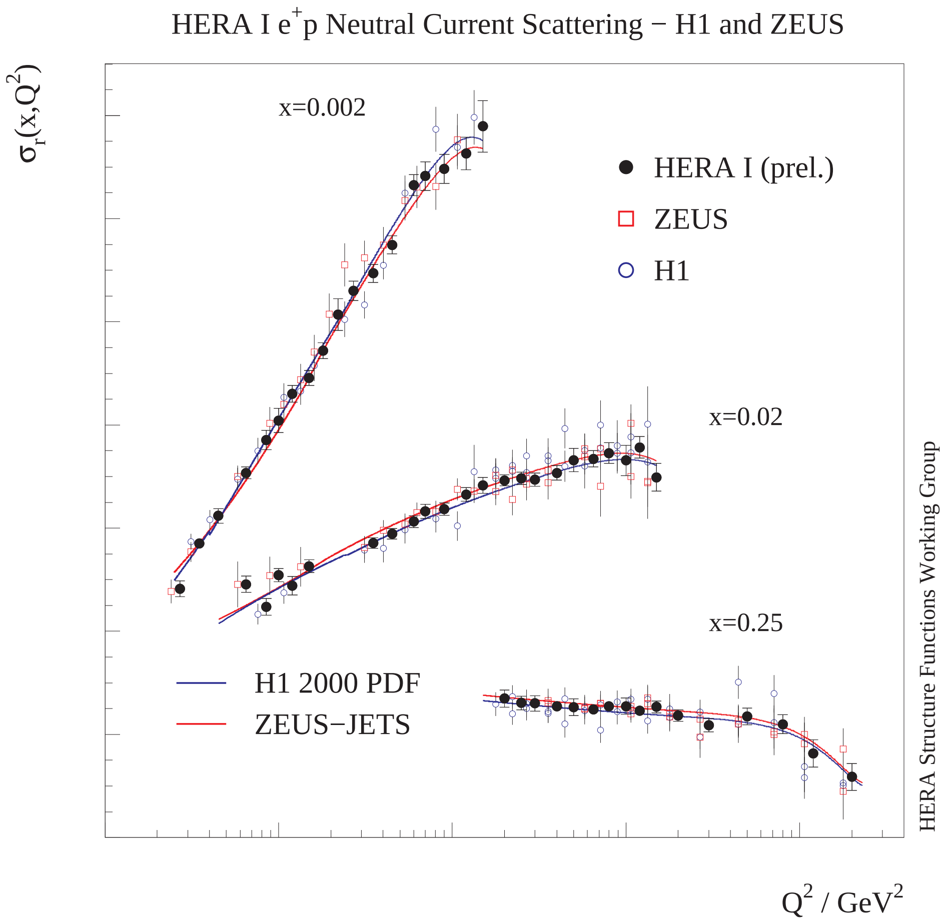



Example: scattered electron energy $E'_e$. Affects $y, Q^2$.

- Calibrated to the electron beam energy using the scattered electron angle and the angle of hadronic final state.
- 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.

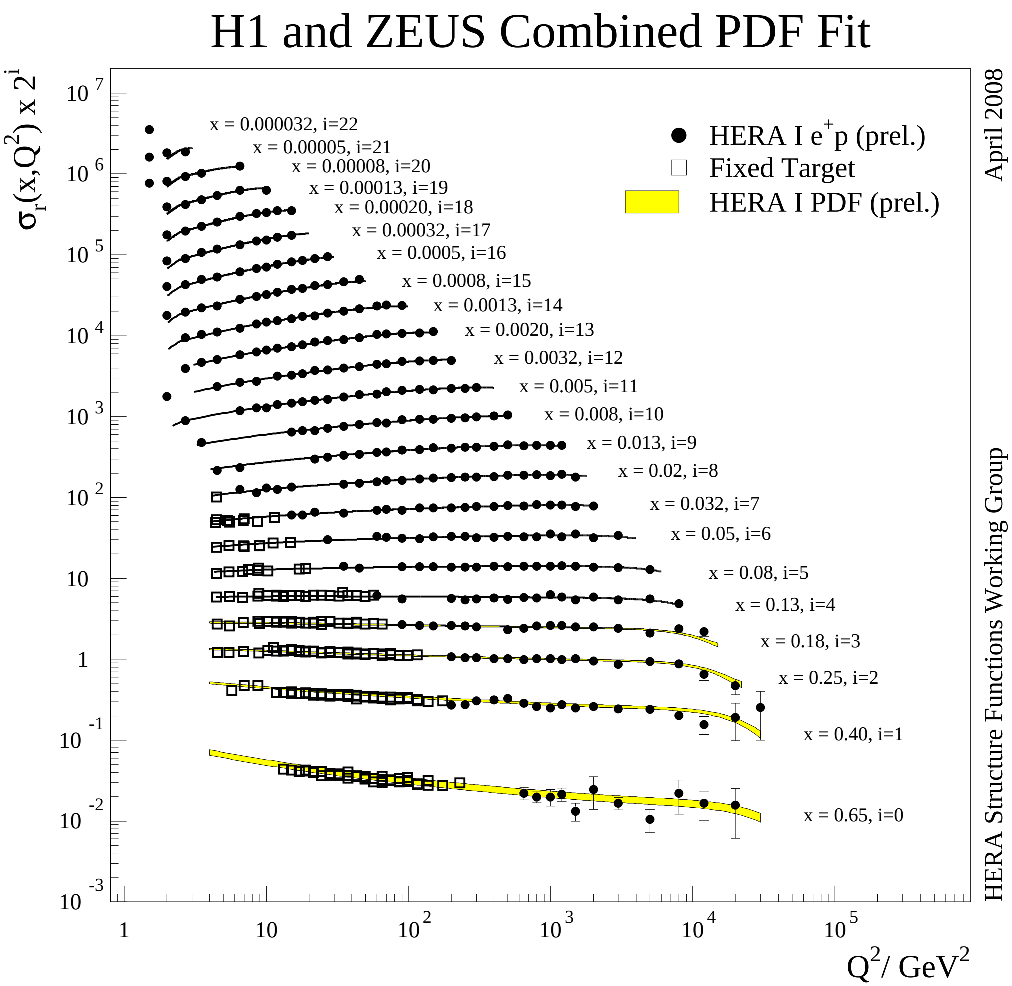
# Combination of HERA data




*Average* H1 and ZEUS data before applying QCD analysis.
Achieved by fitting $\sigma_r$ values, global normalizations and the correlated systematic uncertainties.

Experiments cross calibrate each other: total uncertainties reduced, sometimes better than $\sqrt{2}$.

# Combined HERA data



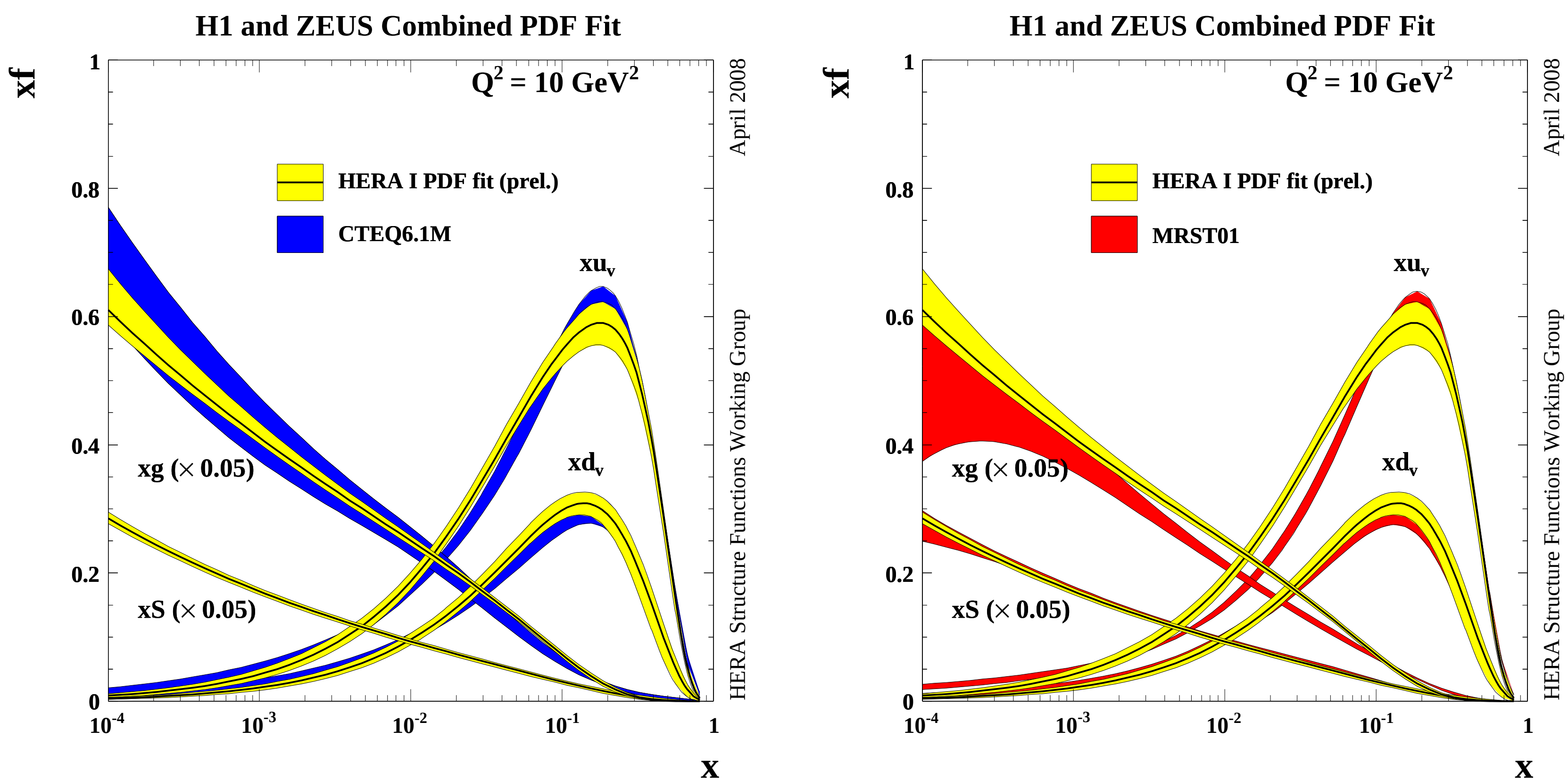

Combination of published H1/ZEUS data for CC,NC, $e^{\pm}p$ data.

$$\chi^2/dof = 510/599$$

(over-consistency, conservative $\delta\sigma_{red}^{uncorr\ syst}$)

HERA data approaches precision of fixed target experiments.
Combined data vs theory: stringent test of DGLAP evolution.

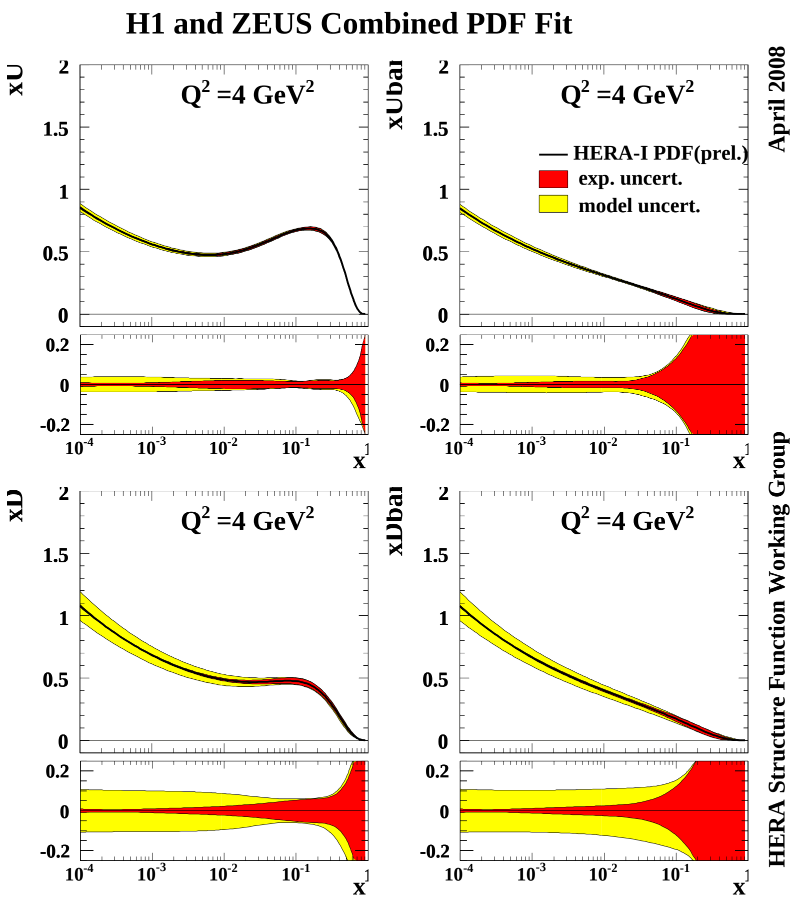
# PDFs extraction




Sea $S$ and gluon $g$ are far more important at low $x$. Mind the $\times 0.05$ scale factor for them.

Fit to combined H1/ZEUS data returns much more precise $xG(x)$ compared to global fits of CTEQ and MRST: improved data precision and also different data errors treatment.

# Model Uncertainties




Experimental errors at low $x$ are often smaller compared to model uncertainties:

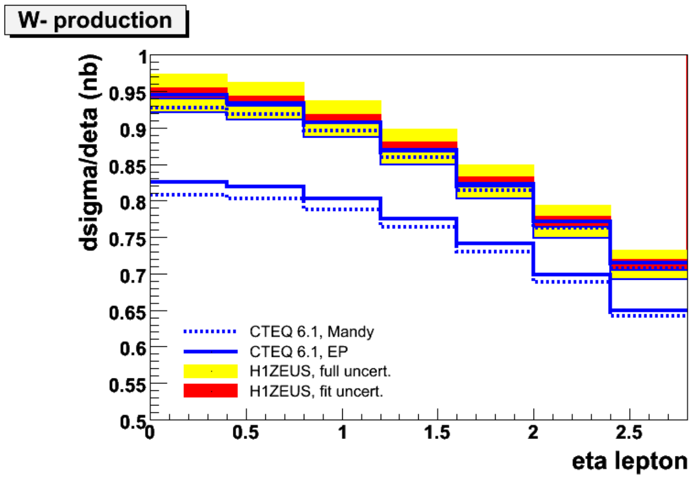
- Evolution starting scale, lowest $Q^2$ in data.
- Flavour separation at low $x$, strangeness fraction.
- Masses of heavy **c**, **b** quarks
- $\alpha_S$ value (not in the bands).

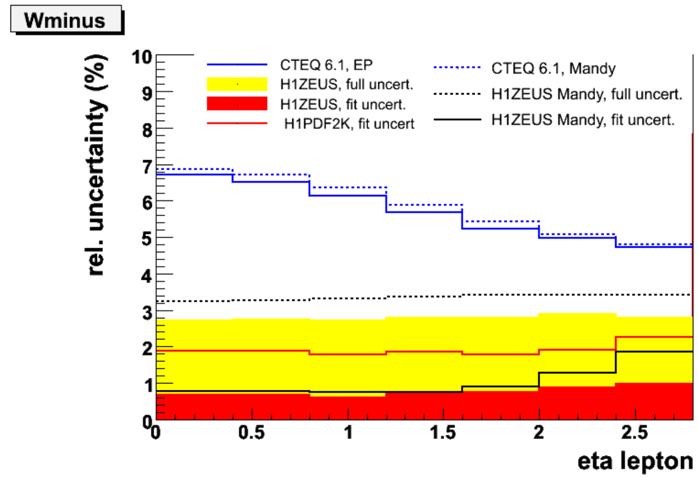
Typical functional forms at a starting scale are

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+...),$$

additional uncertainty from the choice of the parameterization.

# Model Uncertainties for LHC predictions



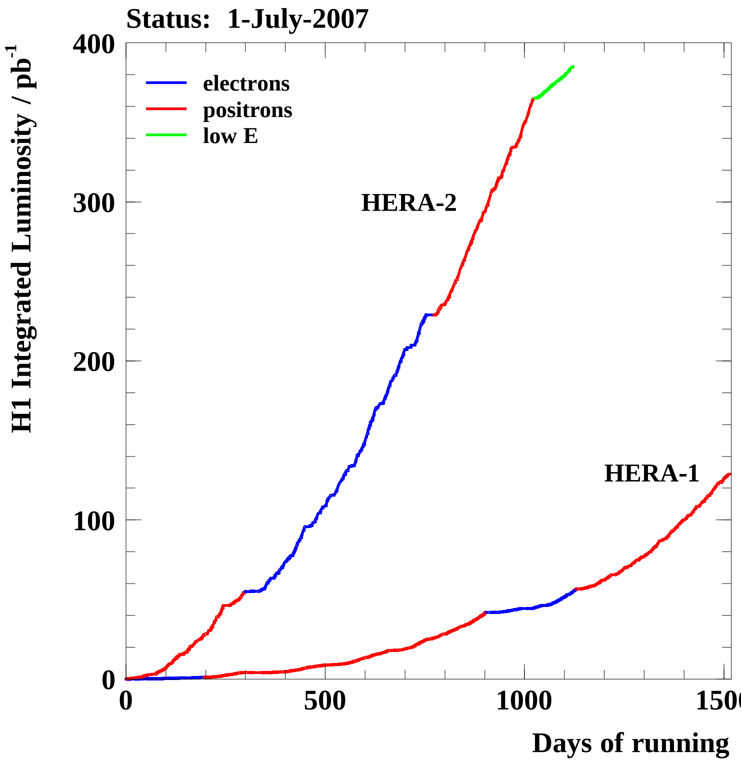

A study performed by E. Perez and A. Cooper-Sarkar based on HERAPDF 0.1:

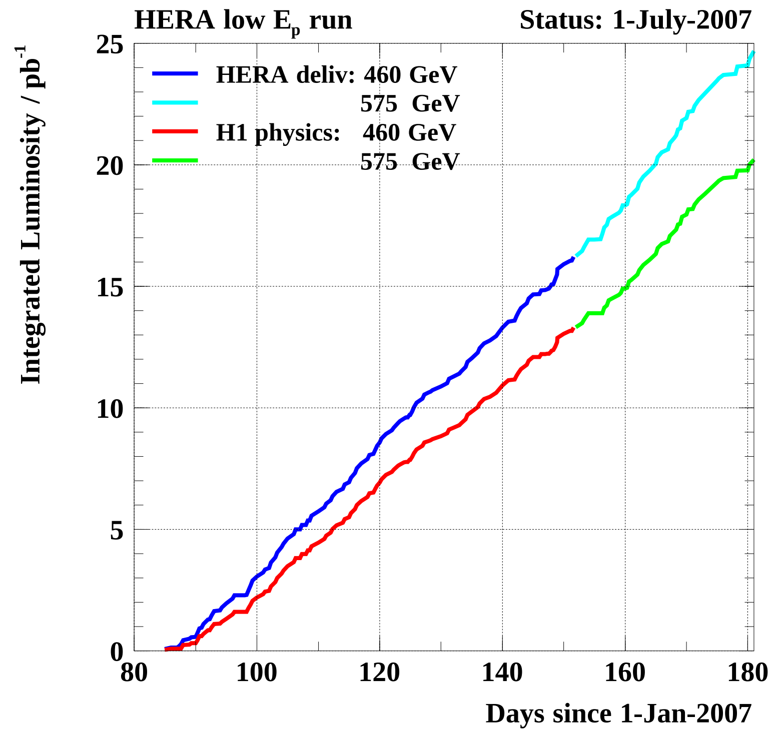
- Different treatment of experimental errors ("Hessian" for EP vs "Offset" for ACS) of the H1-ZEUS averaged dataset does not affect uncertainty for $W^-$ production
- Significantly smaller errors vs CTEQ 6.1 estimation.
- Model uncertainties seem to have larger impact vs experimental precision.

## HERA and other alternative PDF sets

- HERAPDF 0.1 is included in the latest release of LHAPDF, version 5.6.0.
- This release is already inlcuded in ATLAS software.
- HERA PDF set is based on HERA data only, returns smaller experimental uncertainty and allows to estimate model uncertainties, which are typically relativelly large.
- In addition, release 5.6.0 includes NNPDF set, which is base on very open Neural Net parameterization, can be used for concervative estimate of the parameterization bias.

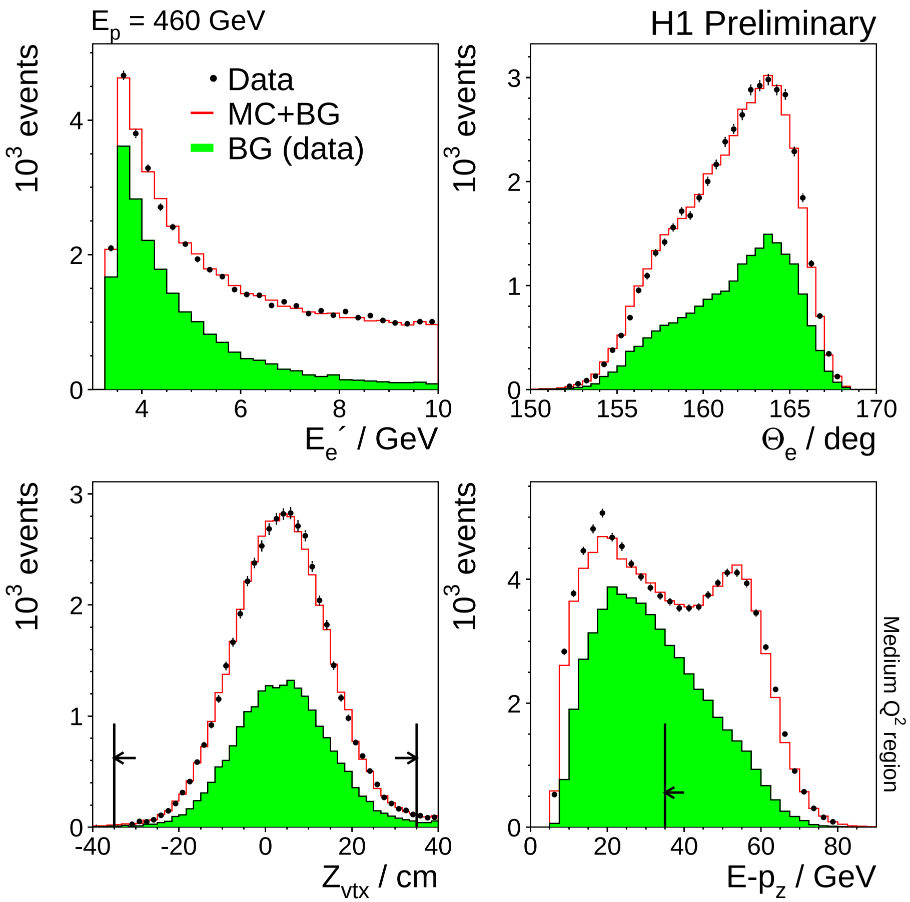
# HERA runs at reduced $E_p$ to measure $F_L$




- 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.

# $F_L$ measurement challenges




Determination of $F_L$ requires measurement at high $y \approx 1 - \frac{E_e'}{E_e}$

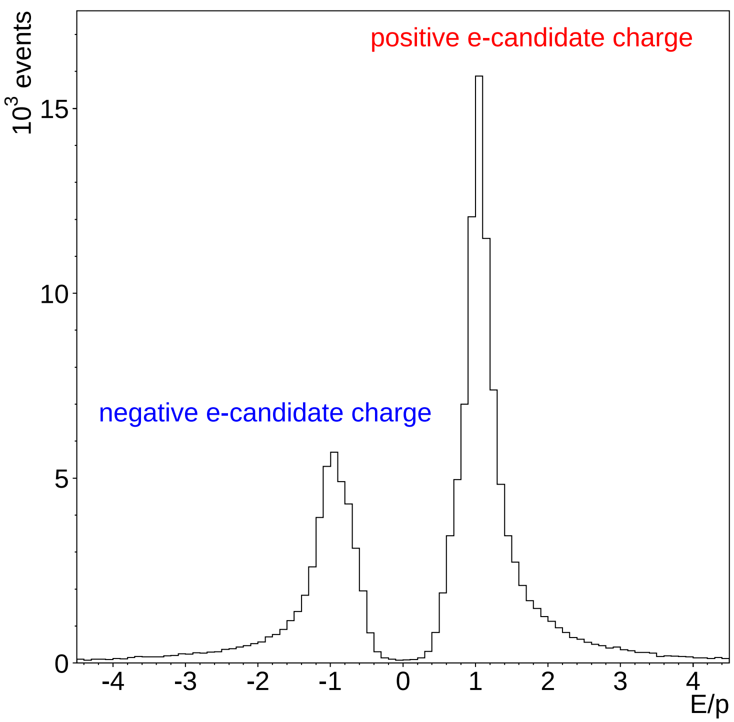
H1 estimates background directly from data using the measured charge of the electron candidate.

# Background Estimation

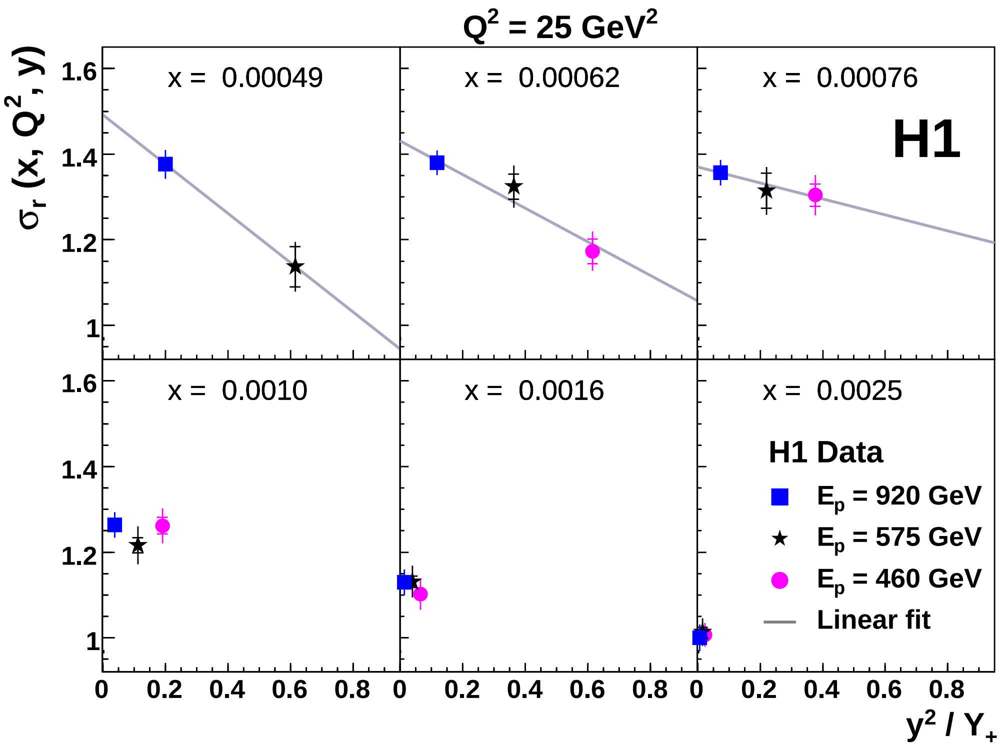
$e^+p$ scattering:

- $+$ Scattered lepton has the beam charge (positive).
- $-$ Background from hadronic particles, $\gamma$ conversions is almost charge symmetric: $N_{bg}^+ \approx N_{bg}^-$

$\rightarrow$ require positive charge for the signal sample. Estimate remaining background using negative sample.



# $F_L$ extraction

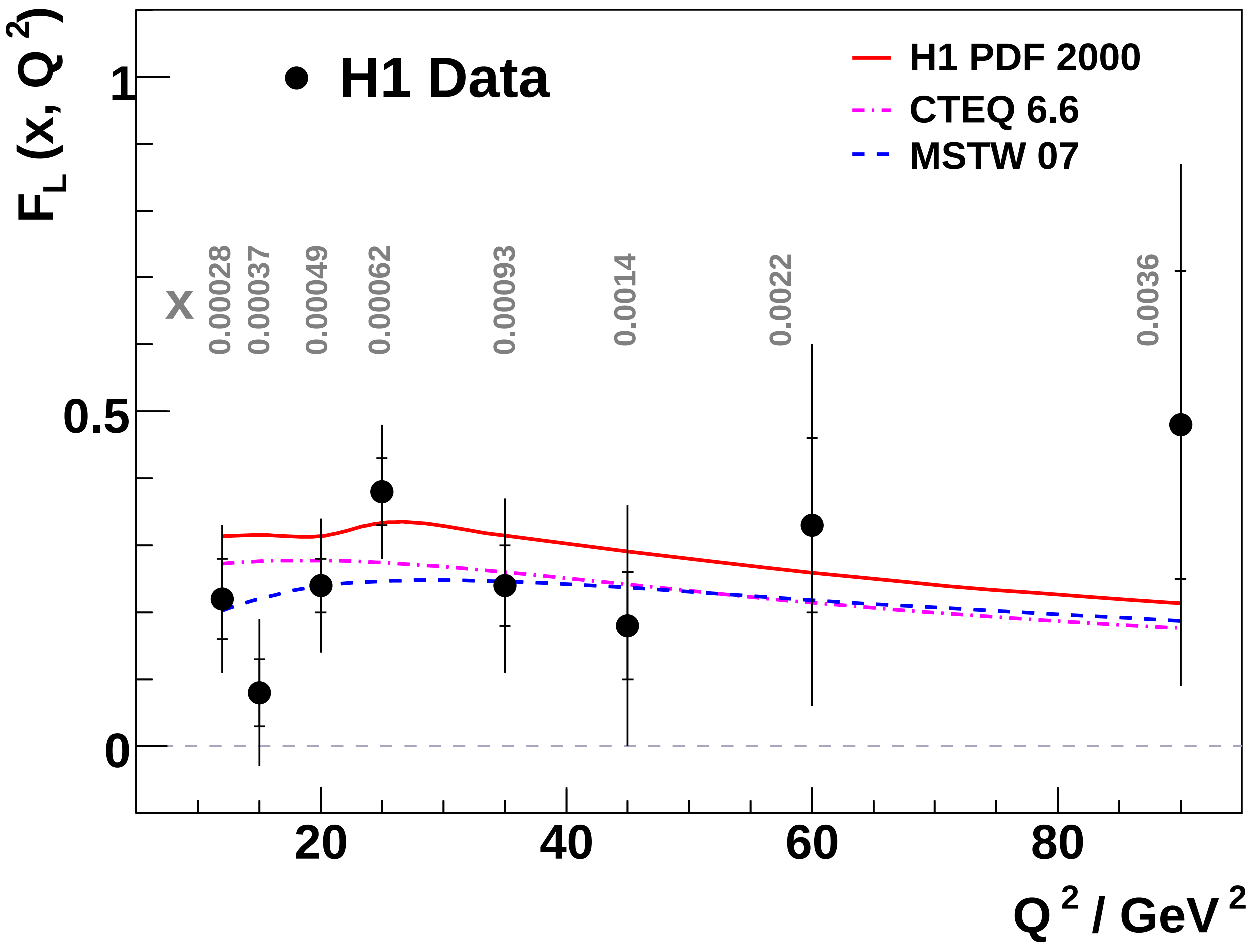



$$\sigma_r(y) = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

- Linear fit to get $F_2$ and $F_L$
- Relative normalization from low $y$ data

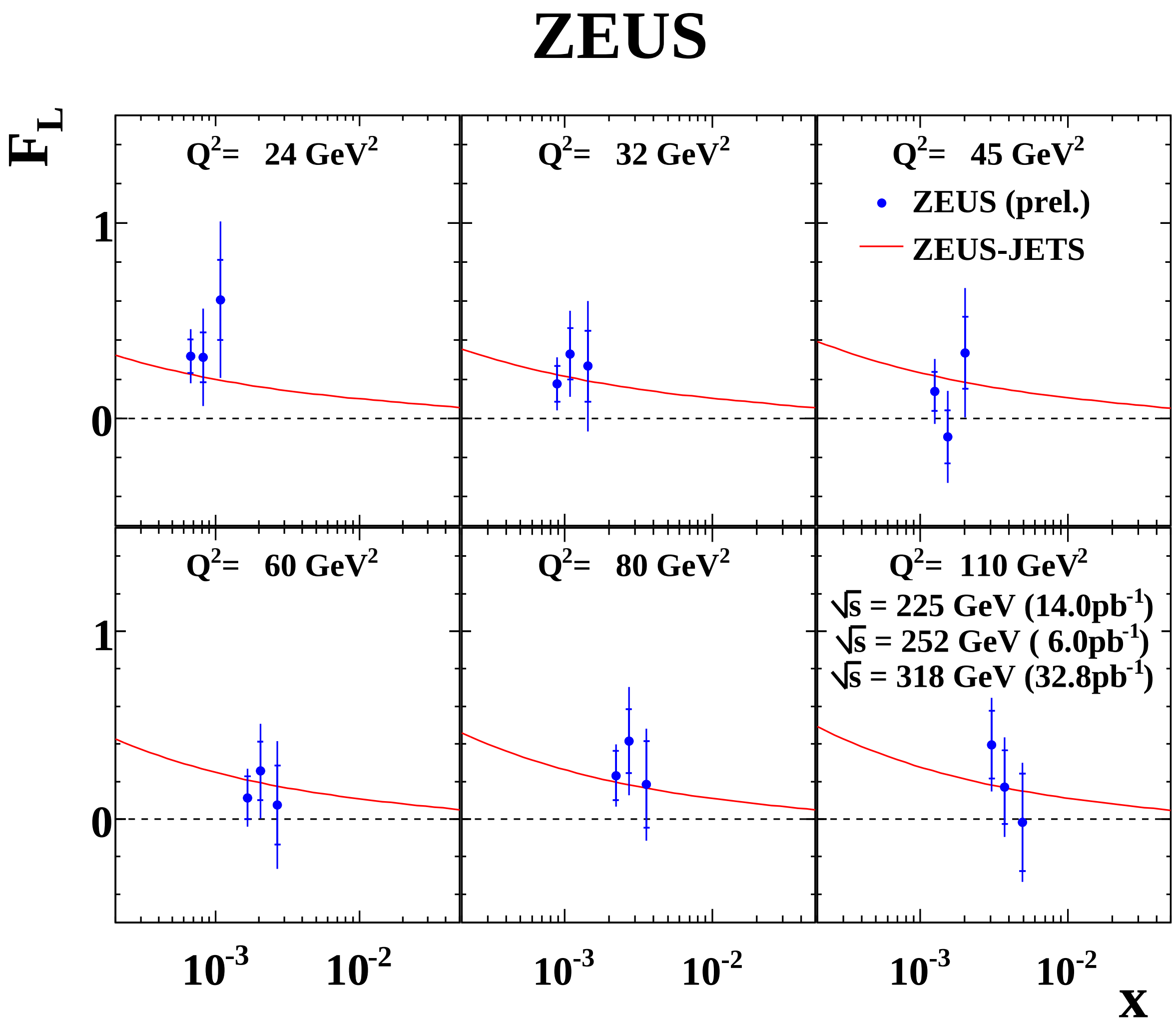
Data at $\mathbf{E_p = 575}$ provides cross check and extends measurement to low $x$.

# Average $F_L$ by H1 at medium $Q^2$



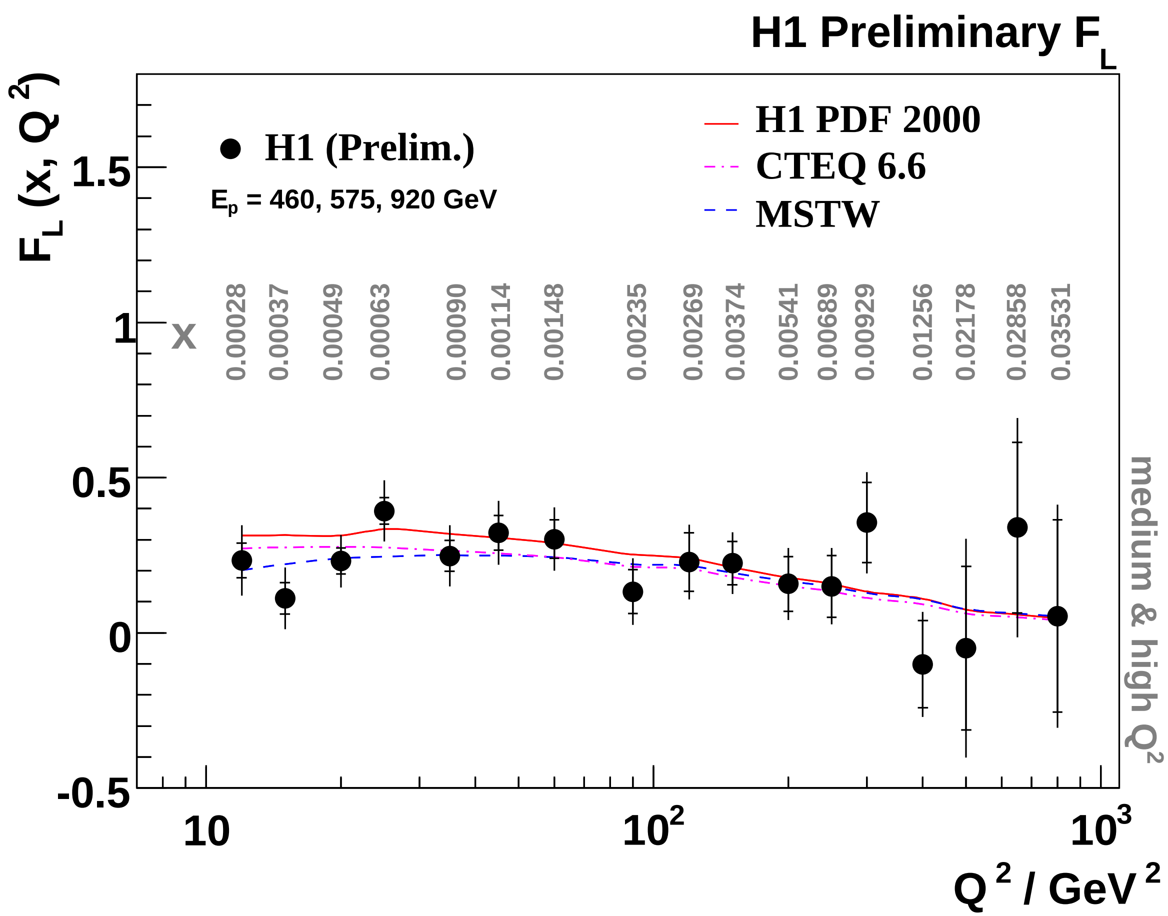

$F_L$ compared to prediction based on H1 QCD fit to published by H1 DIS cross section data and global MSTW, CTEQ fits.

# Measurement of $F_L$ by ZEUS




- Updated for ICHEP to include $E_p = 575$ GeV data.
- Consistent with NLO prediction and H1.

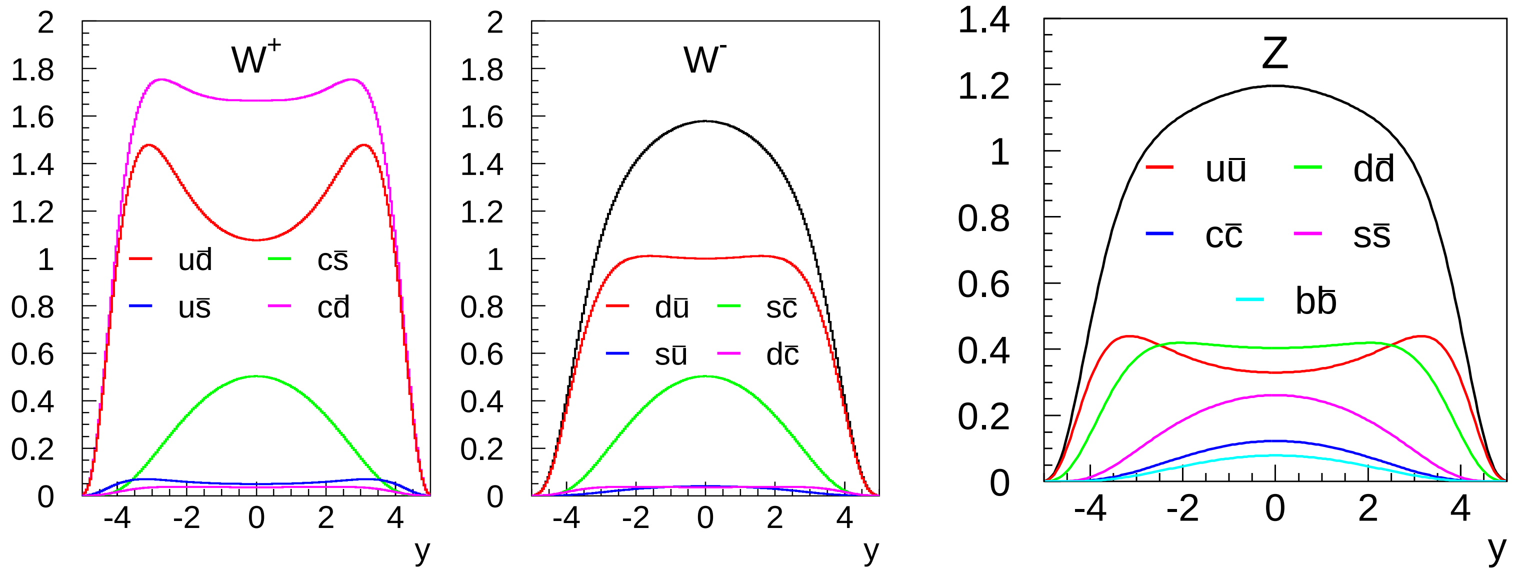
# Average $F_L$ by H1, extended range, preliminary



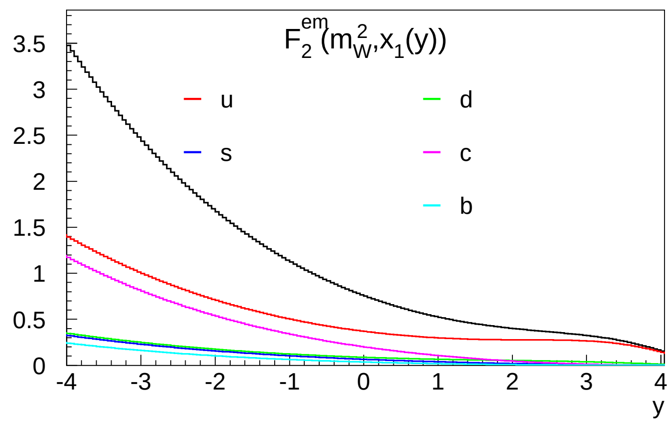

- Extend to higher $Q^2$ using $e$ scattered in LAr calorimeter.
- Future: extend to lower $Q^2$ using Backward Silicon Tracker.

Good agreement with theory expectations.

# Flavor Decomposition

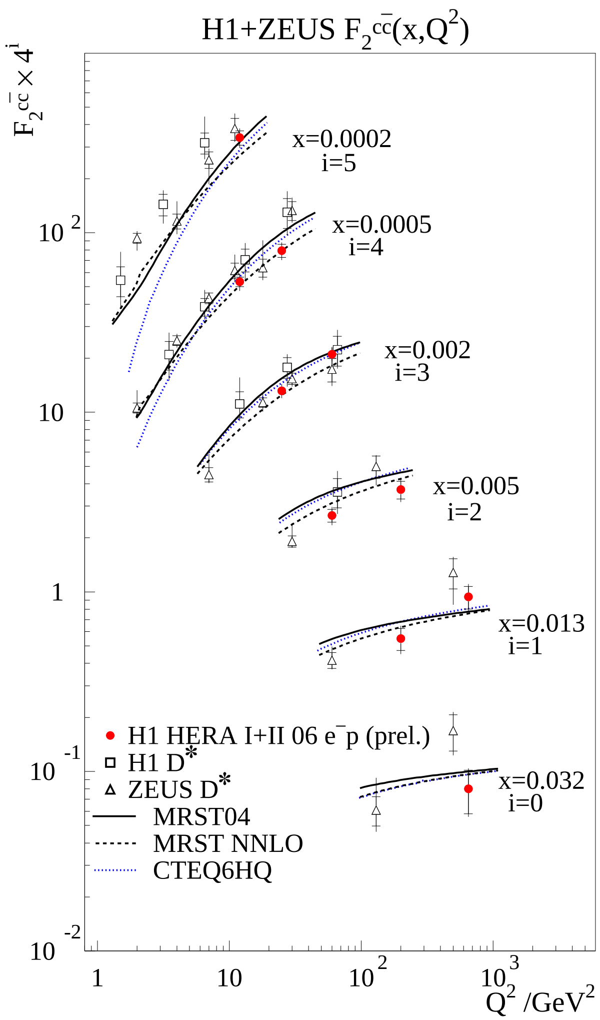


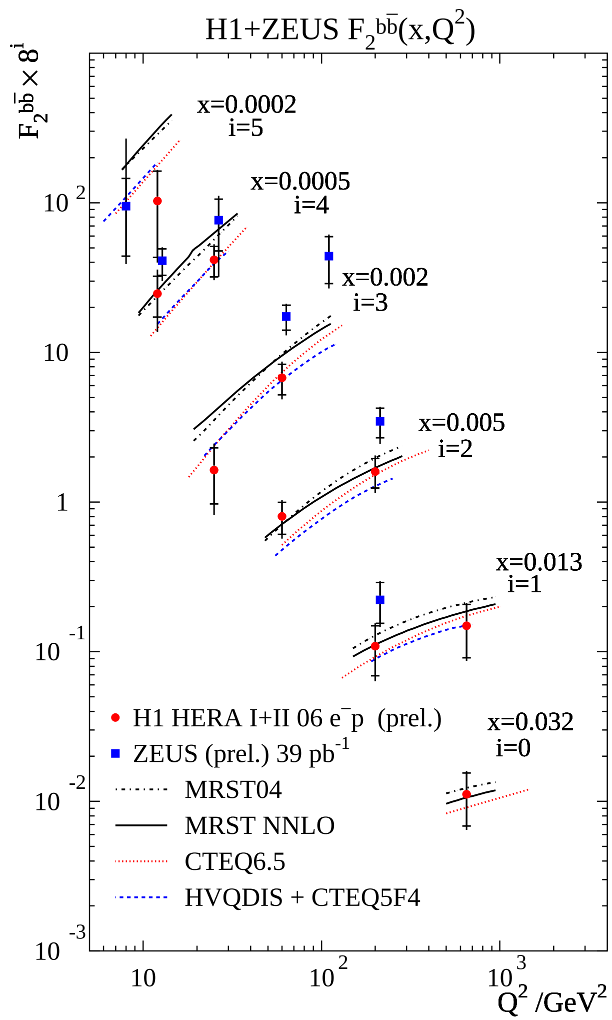

We want to have predictions for $W^+$, $W^-$, $Z$ with the main experimental input from $F_2^{em}$:




- More important $d, s$ quarks
- For $Z$, significant contribution from $b$.

# Measurements of heavy flavors

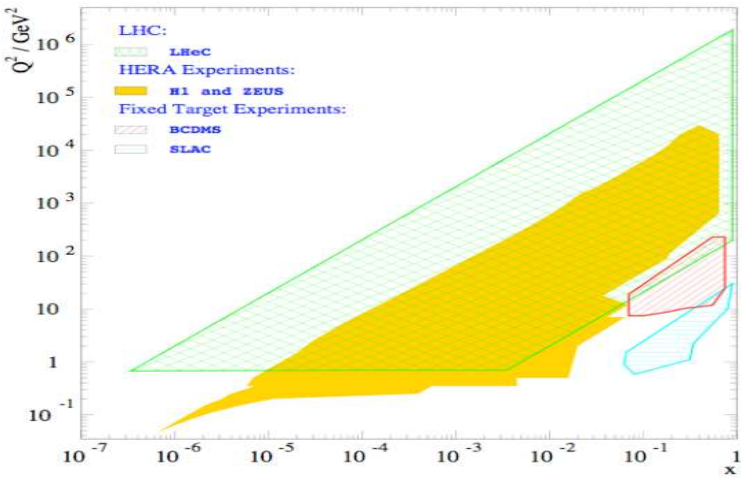


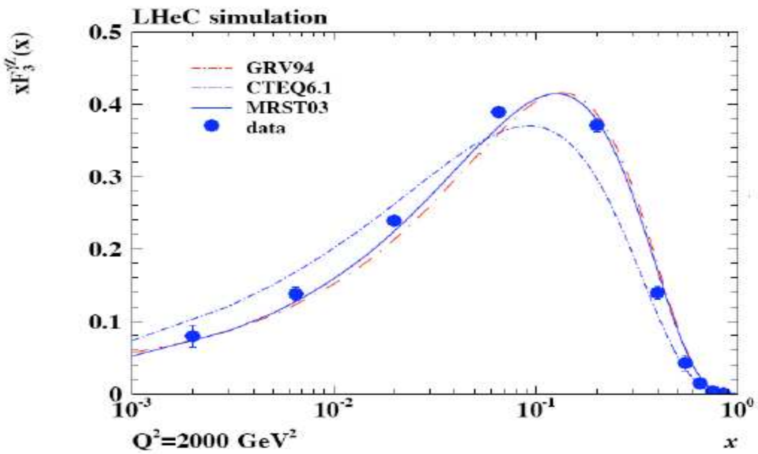




Measure $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ structure functions by tagging the $c$ quarks via $D^*$ decay or $c/b$ quark using secondary vertex.

# PDFs for LHC energy scale: LHeC

Consider LHC result: $\sigma(H)/\sigma(Z)$ about $3\sigma$ away from SM prediction. New physics or new QCD evolution ?




Measurement of PDFs close to LHC energy could be performed by 70 GeV $\times$7000 GeV $ep$ machine at CERN: **LHeC**.

- High luminosity (10 $\text{fb}^{-1}$): yield of $\sim 10^5$ events at 10000 $\text{GeV}^2$.
- $e^+$ and $e^-$ beams to measure $xF_3$.
- Lepton beam polarization (?) for $F_2^{\gamma Z}$.

An attractive machine at its cost.

# Experimental data still to come

- Final analysis of $F_2$ structure function at low $Q^2 < 100$ GeV$^2$ and low $x$ (H1).
- Analysis of $\sigma_r$ at high $Q^2$ and high $x$ using HERA-II data.
- Measurement of $F_L$ structure function in complete kinematic domain.
- HERA-II analysis of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$.
- Combination of all HERA data.
- PDF extraction based on the combined HERA data.

# Conclusions

- HERA enables precise determination of PDFs for the LHC kinematic range.
- DGLAP evolution works very well so far.
- Experimental input for PDFs could be vastly expanded with LHeC.
- More information will come with finalization of HERA analyzes, combination of H1/ZEUS data, measurement of heavy flavors and of $F_L$.