# Measurement of $F_2$ at Medium $Q^2$ and the PDF determination using H1 HERA I data

**Jan Kretzschmar, University of Liverpool**

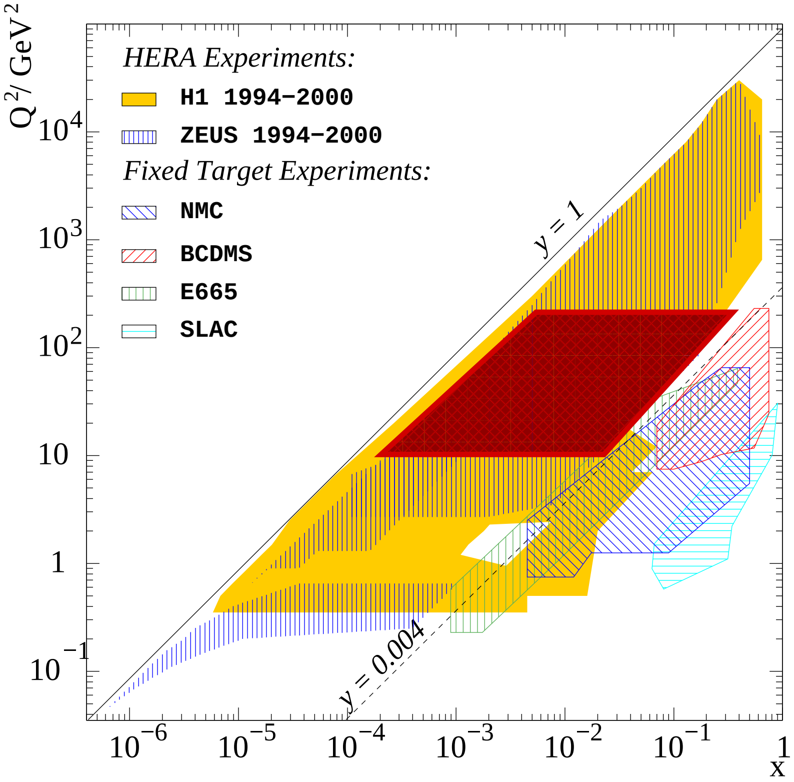
**On behalf of the H1 Collaboration**

**DIS 2009, $26^{th}$ – $30^{th}$ April, Madrid**

# Overview

- A new measurement of the inclusive DIS cross section $ep \to e'X$ using H1 data from the year 2000 ($\mathcal{L} \sim 22\,\mathrm{pb}^{-1}$), combined with published results using 1996/97 data
- Covering the region of *medium* $12\,\mathrm{GeV}^2 \leq Q^2 \leq 150\,\mathrm{GeV}^2$ at HERA with unprecedented accuracy

- **Introduction**
- **Cross Section Measurement and Combination**
- **Structure Function $F_2$ and its Derivatives**
- **QCD Analysis H1PDF 2009**




Available as *arXiv:0904.3513*

# Inclusive DIS Cross Section

- Two structure functions $F_2(x,Q^2)$, $F_L(x,Q^2)$ parameterise the inclusive NC cross section for $ep \to e'X$ at low $Q^2$:

$$\frac{\mathrm{d}^2\sigma^{NC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4} \underbrace{\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)}_{\text{Reduced cross section } \sigma_r}, \quad Y_+ = 1 + (1-y)^2$$

- New analysis restricted to medium and low inelasticities $y < 0.6$ $\Rightarrow$ Contribution of $F_2$ to the cross section is dominant, Effect of $F_L$ very small *separate high $y$ analyses $\to$ A. Glazov*

- In the Quark-Parton Model simple relation to quark distribution functions $q_i(x)$:

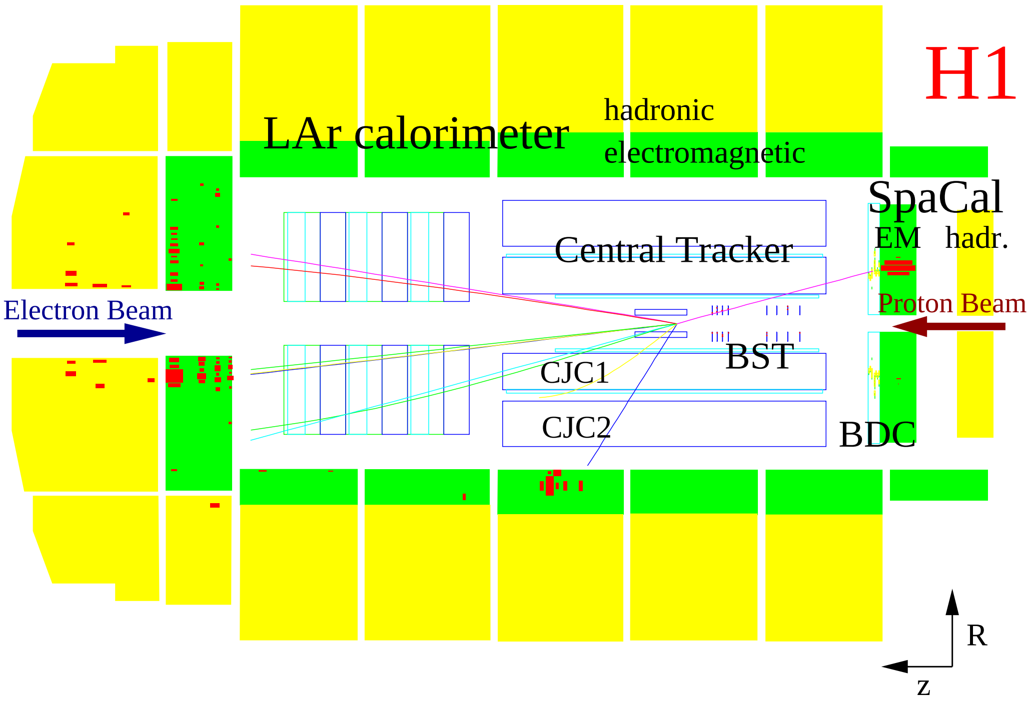
$$F_2(x) = x\sum_i e_i^2(q_i(x) + \bar{q}_i(x)) = \sigma_r\,, \quad F_L = 0$$

- Scaling violations sensitive to the gluon $xg(x,Q^2)$ and $\alpha_s$

$$\partial F_2(x,Q^2)/\partial \ln Q^2 \propto \alpha_s \cdot xg(x,Q^2)$$

# Event Selection and Reconstruction

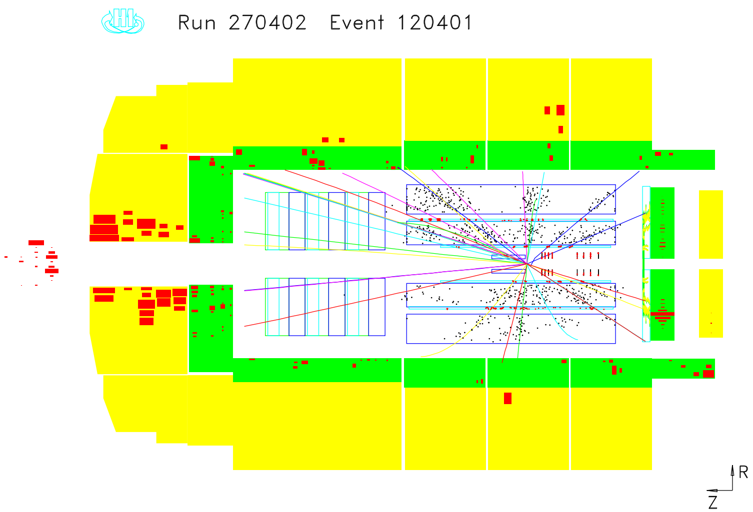
- Analysis similar to lower $Q^2 \leq 12\,\mathrm{GeV}^2$ domain
  → *A. Petrukhin arXiv:0904.0929*
- At $Q^2 \lesssim 150\,\mathrm{GeV}^2$, the scattered electron is detected in the “backward” region: SpaCal and BDC track segment




- At higher $Q^2$ the Central Tracker is used to reconstruct the event vertex, BST for cross checks only
- Hadronic Final State *(HFS)* combined from tracks and calorimeters (LAr + SpaCal)

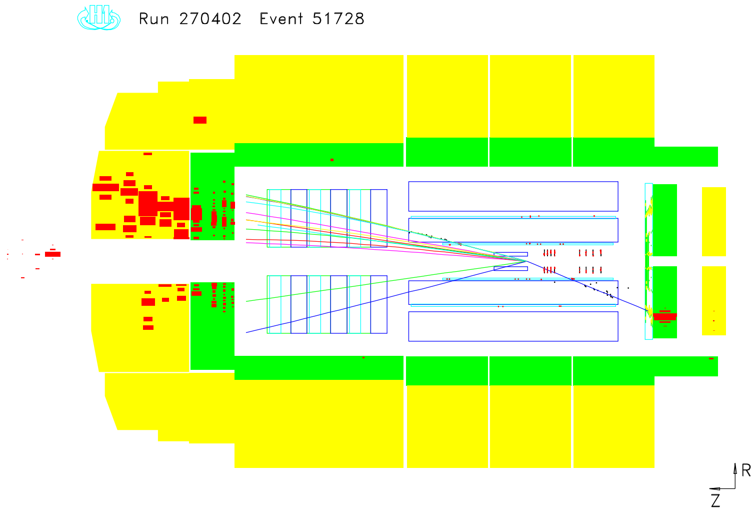
# Kinematics

- High Inelasticity $y \gtrsim 0.1$




$$y_e = 0.52,\ Q^2_e = 51\,\mathrm{GeV}^2,\ x_e = 0.00097$$

- Low Inelasticity $y \lesssim 0.1$




$$y_\Sigma = 0.019,\ Q^2_\Sigma = 123\,\mathrm{GeV}^2,\ x_\Sigma = 0.063$$

- **Electron Method**:

$$y_e = 1 - \frac{E'_e}{2E_e}\left(1 - \cos\theta_e\right),$$

$$Q^2_e = \frac{E'^2_e \sin^2\theta_e}{1 - y_e},\quad x_e = \frac{Q^2_e}{s y_e}$$

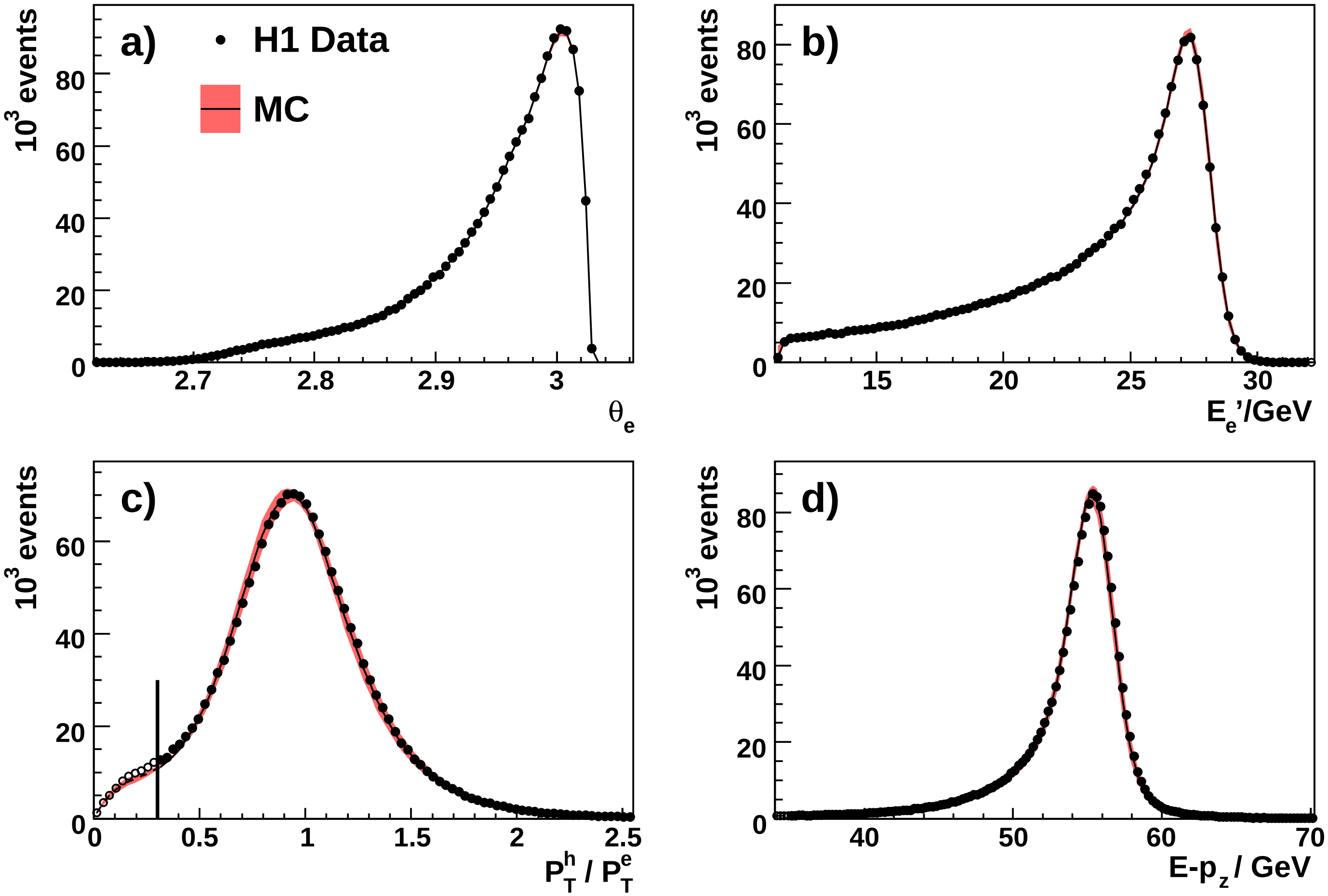
- **$\Sigma$ (Sigma) Method**:

$$y_\Sigma = \frac{(E - p_z)_{had}}{(E - p_z)_{tot}},$$

$$Q^2_\Sigma = \frac{E'^2_e \sin^2\theta_e}{1 - y_\Sigma},\quad x_\Sigma = \frac{Q^2_\Sigma}{2(E - p_z)_{had} E_p}$$

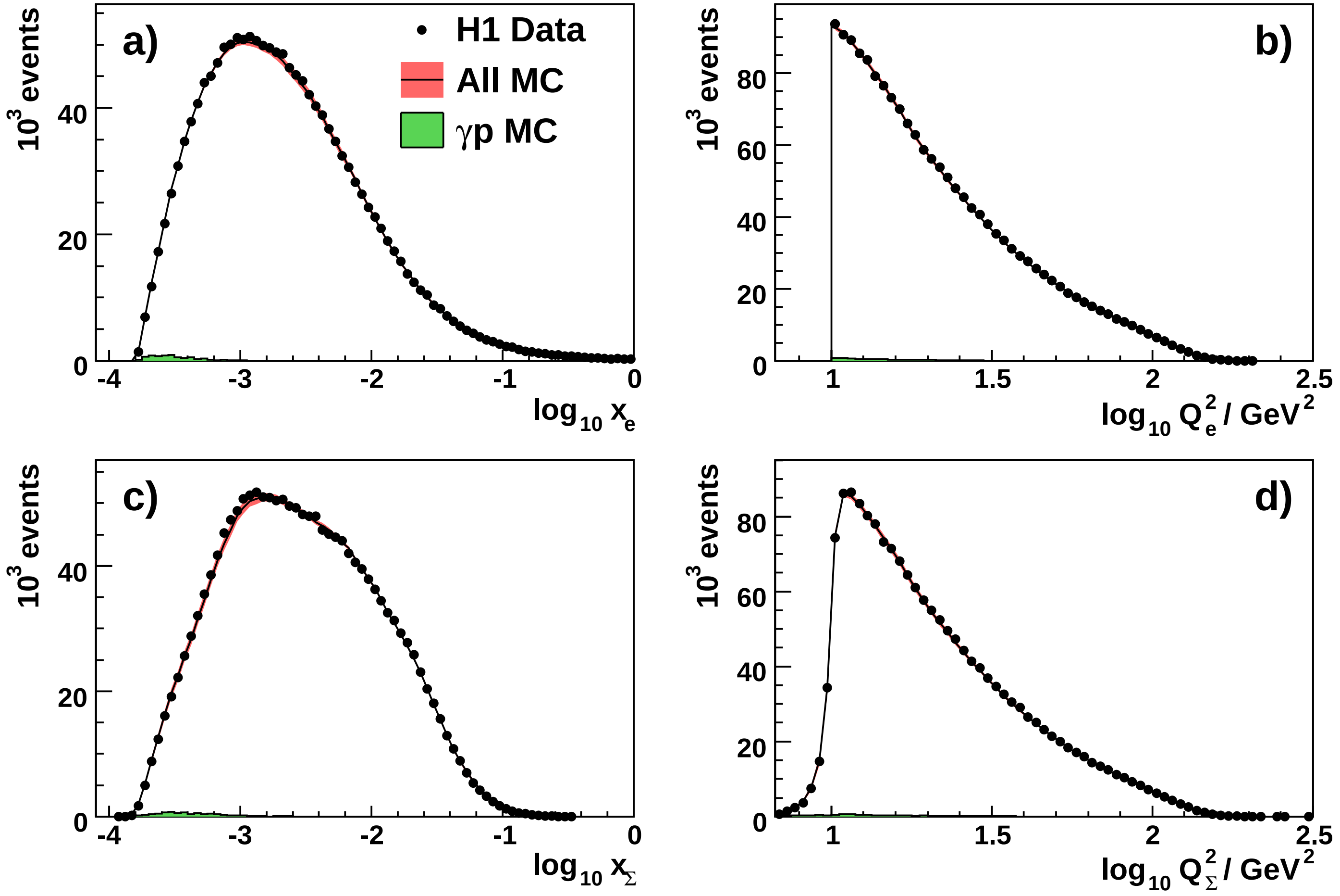
# Technical Control Plots

- Very good control over all essential measured detector quantities achieved, e.g. $\delta E'_e/E'_e \sim 0.2 - 1.0\%$, $\delta E_{HFS}/E_{HFS} \sim 2.0\%$, extra efficiency uncertainties $\sim 0.3 - 0.5\%$



# Kinematics Control Plots

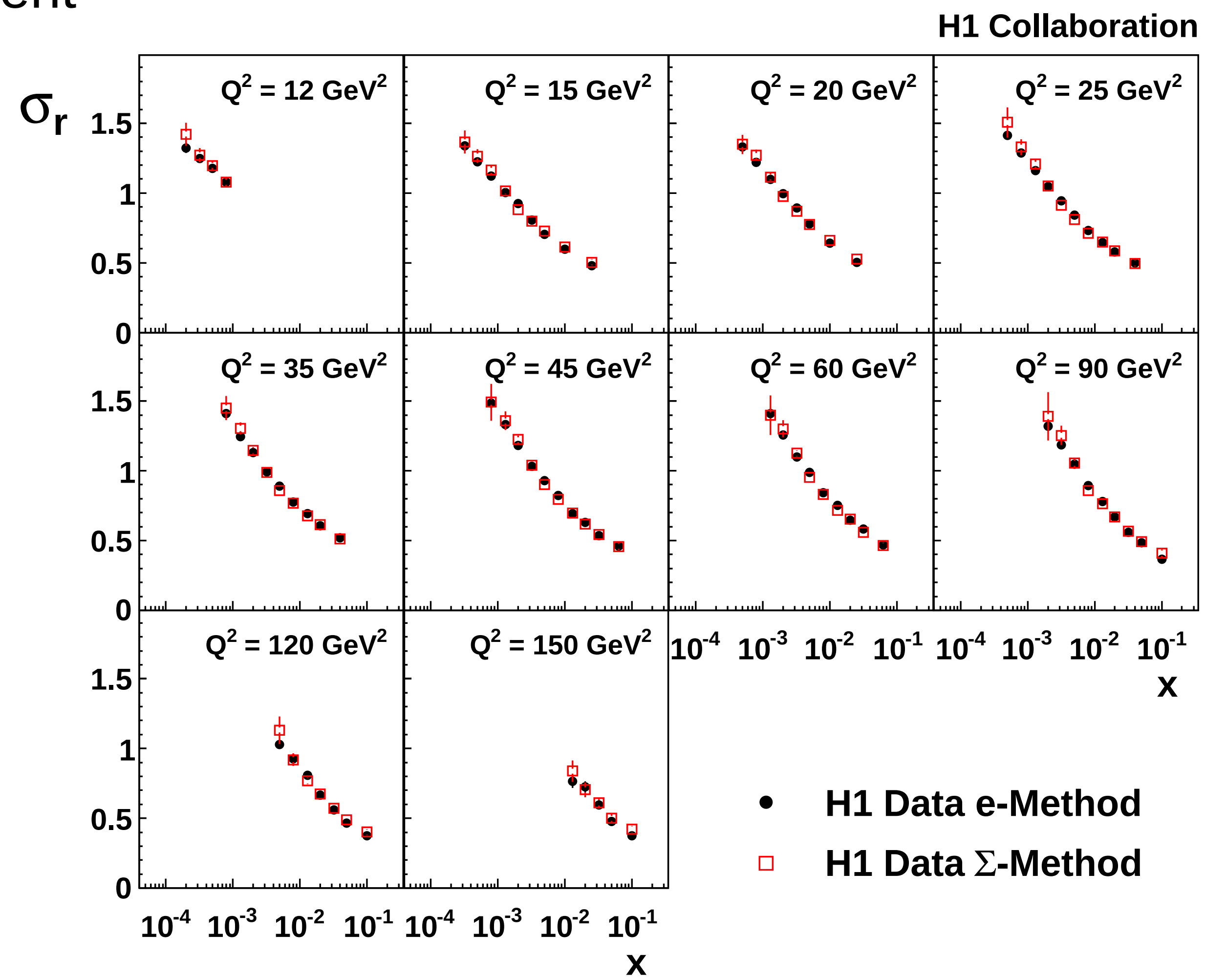
- Photo-production background is highly suppressed
- Distributions well described by MC reweighted to H1PDF 2009 structure functions (see later)



# Electron and Σ Reconstruction

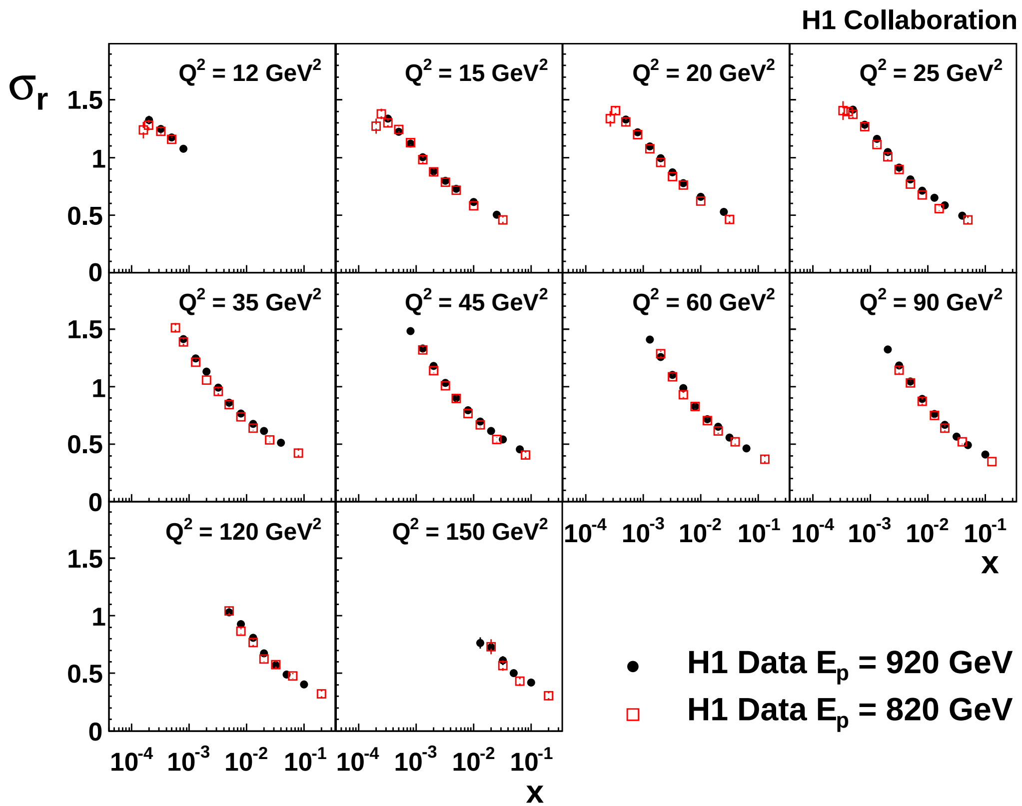
- Cross sections measured with different reconstruction methods are sensitive in different ways to systematic uncertainties
  $\Rightarrow$ Good agreement

- For the final result use method with smaller uncertainty, transition near $y = 0.1$



# Comparison with Published Results

- New measurement covers a similar kinematic domain as the previously best H1 measurement using data from 1996/97 with $E_p = 820$ GeV  Eur. Phys. J. **C21**, 33 (2001)
- The comparison and reanalysis of the older data revealed a small $Q^2$ dependant bias in the old results of $\sim 0 - 2.5\%$



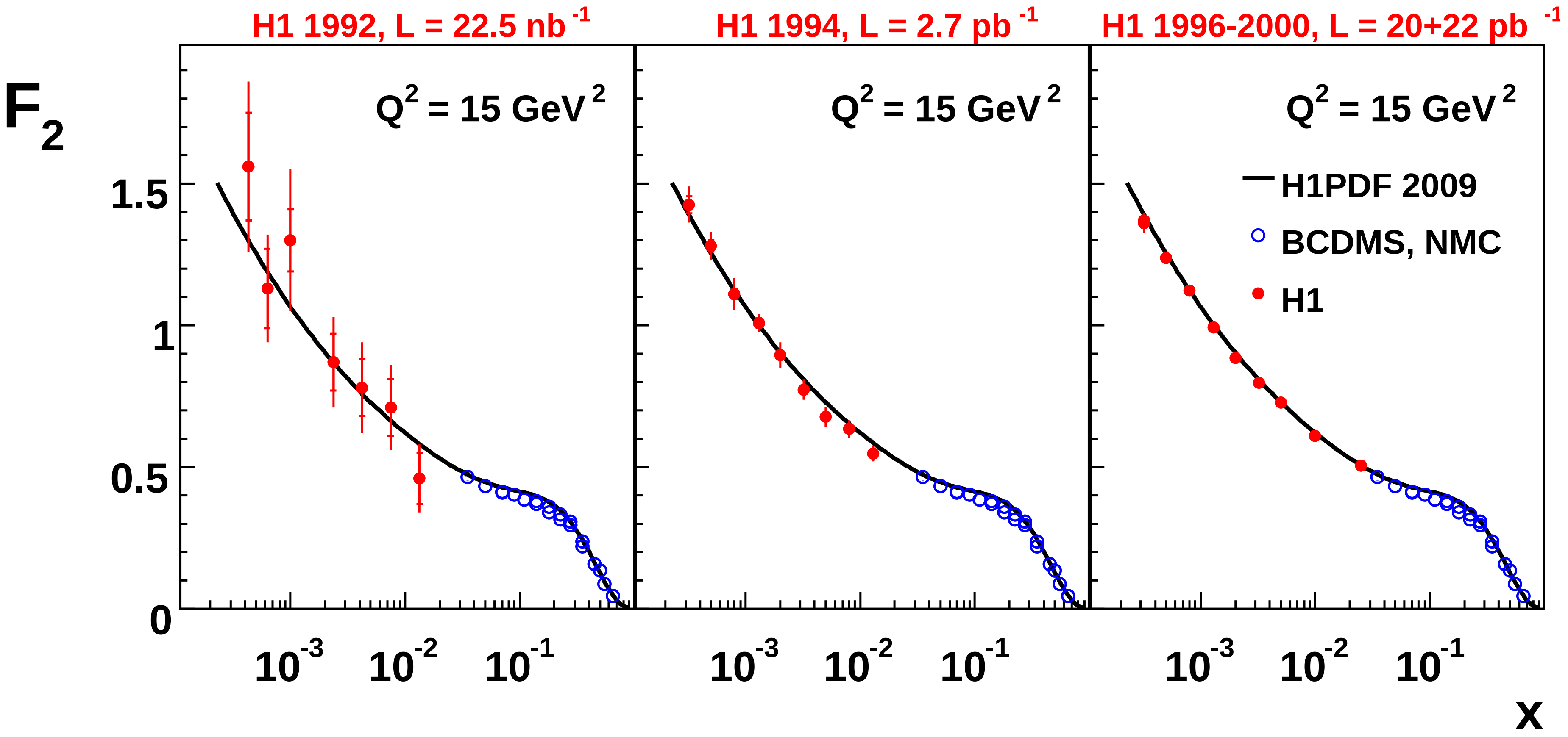

- After correction good agreement between the measurements
- Total uncertainties up to a factor $\sim 2$ better for new data

# Data Combination

- As for the analysis at lower $Q^2 \leq 12\,\mathrm{GeV}^2$ ($\rightarrow$ *A. Petrukhin*) the new measurement is averaged with the previous result
- Using the same method taking into account bin-to-bin correlated uncertainties, *also used for H1-ZEUS combination* $\rightarrow$ *E. Tassi*
- Cross sections corrected to $E_p = 920$ GeV for lower $y < 0.35$, kept separate for higher $y$
- Correlated systematic sources treated as uncorrelated between the data sets, only small shifts required
- Good consistency: $\chi^2_{\mathrm{tot}}/\,n_{\mathrm{dof}} = 51.6/61$

| **Systematic Source** | **Shift in std. dev.** 1996/97 | 2000 |
|---|---|---|
| $E'_e$ scale | $0.72$ | $0.50$ |
| $E'_e$ linearity | — | $-0.39$ |
| Polar angle $\theta_e$ | $-0.46$ | $0.09$ |
| LAr hadronic scale | $-0.86$ | $-0.13$ |
| LAr noise | $-0.22$ | $0.04$ |
| SpaCal hadronic scale | — | $0.35$ |
| $\gamma p$ background | $0.11$ | $-0.11$ |
| Luminosity | $0.64$ | $-0.46$ |

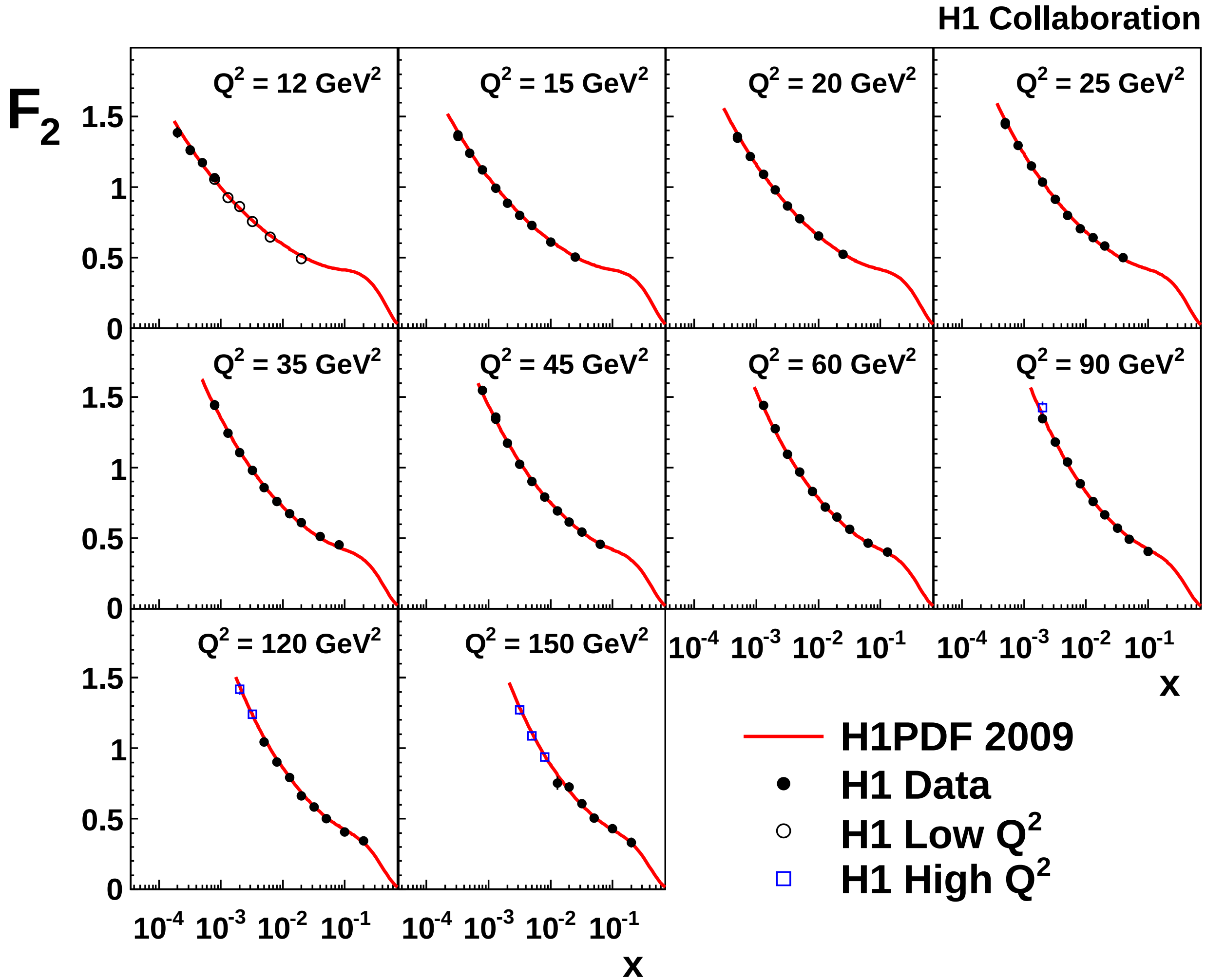
# History of H1 $F_2$ Measurements




- Accuracies starting from $\sim 20 - 30\%$, reaching $\sim 4 - 6\%$, last publication using 1996/97 data $\sim 2 - 3\%$, and finally $\sim 1.3 - 2\%$

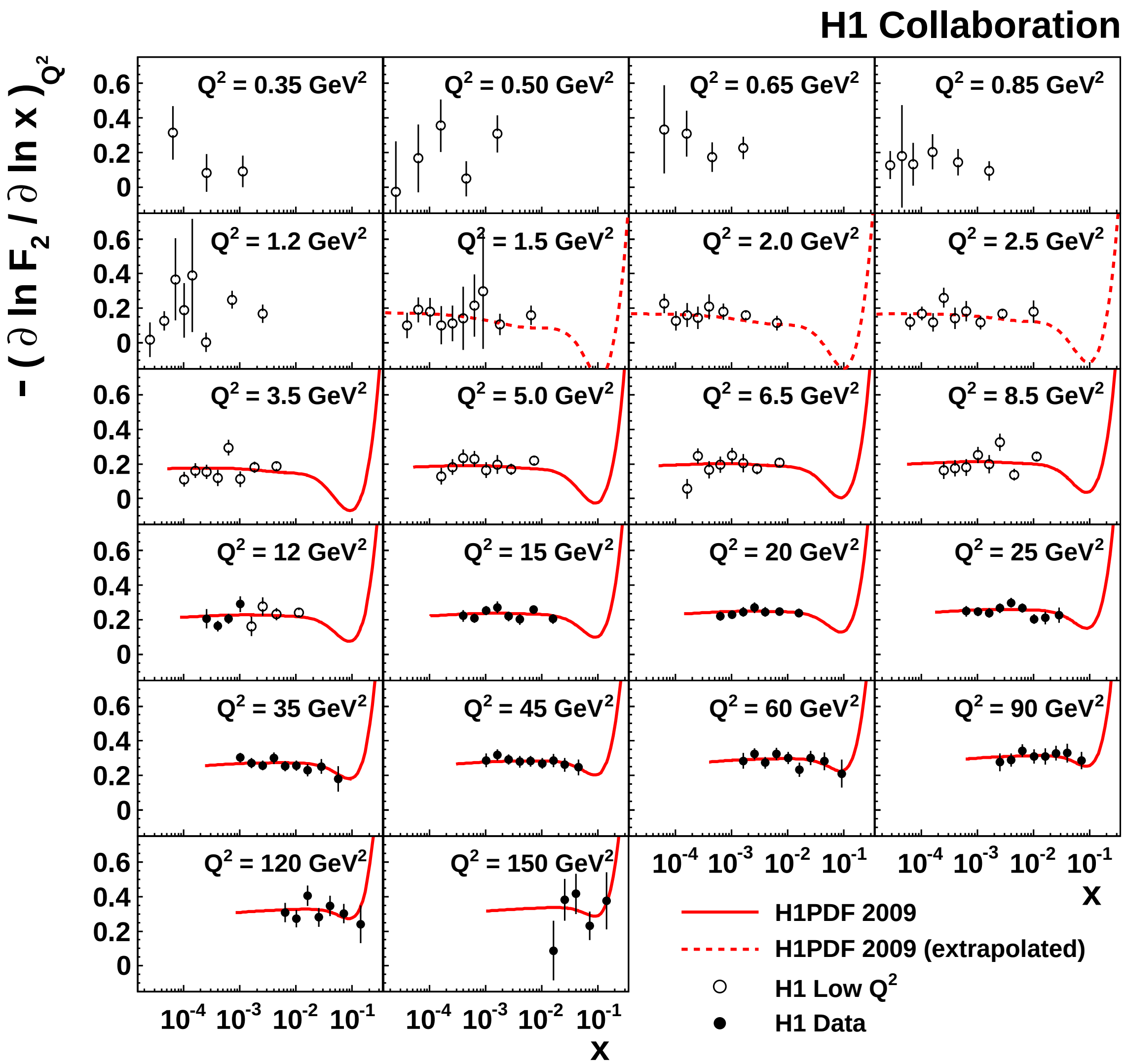
# $F_2$ at fixed $Q^2$

- $F_2$ is extracted for $y < 0.6$ using $R$ given by the QCD fit
- Steep rise of $F_2$ towards low $x$, well described by QCD fit



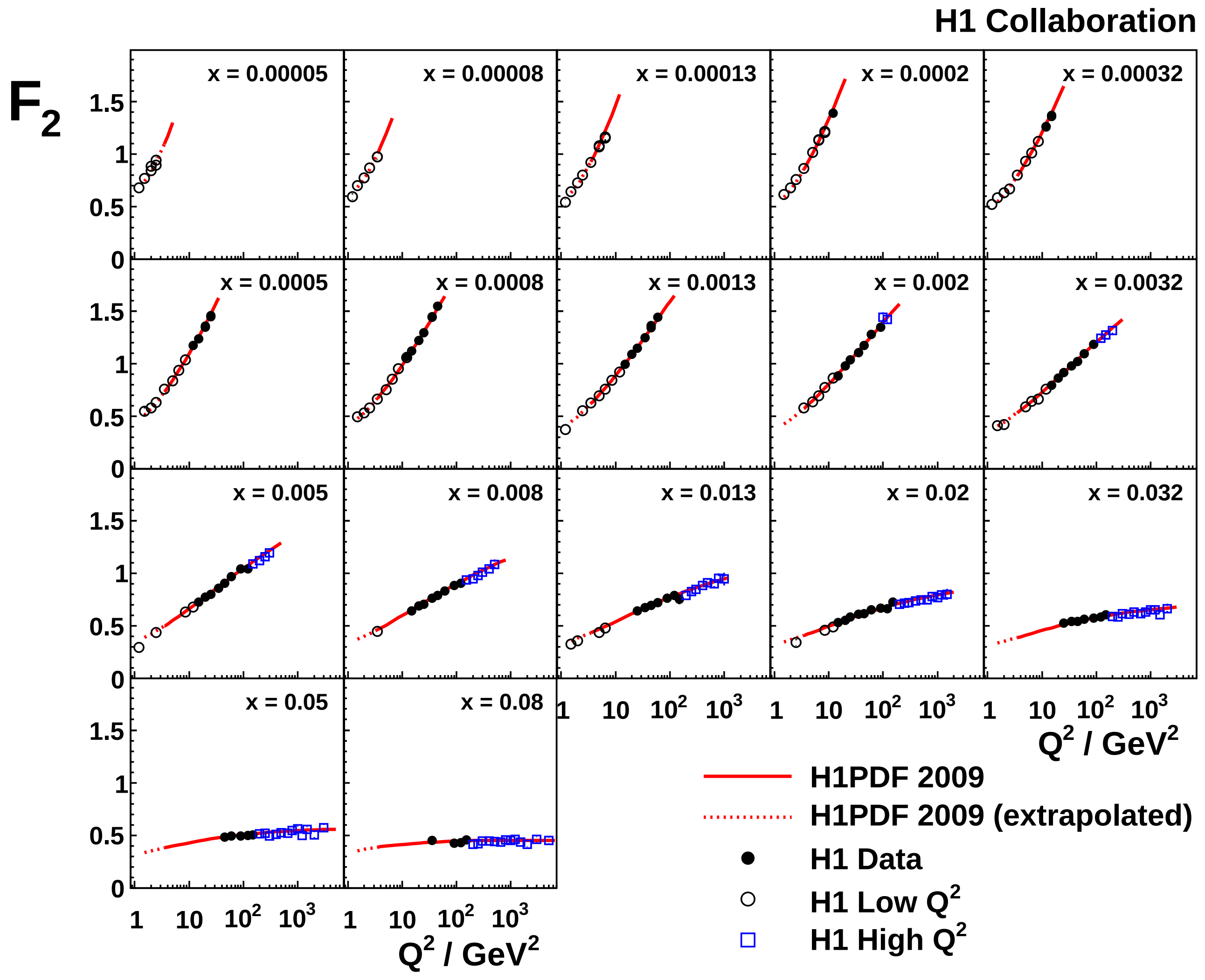
# $\partial \ln F_2/\partial \ln x$ at fixed $Q^2$

- At low $x < 0.01$, $\partial \ln F_2/\partial \ln x \approx$ const.
  $\Rightarrow$ Rise of $F_2$ towards low $x$ compatible with power law $F_2 \propto x^{-\lambda}$
- Small dependance of $\lambda$ on $x$ also possible



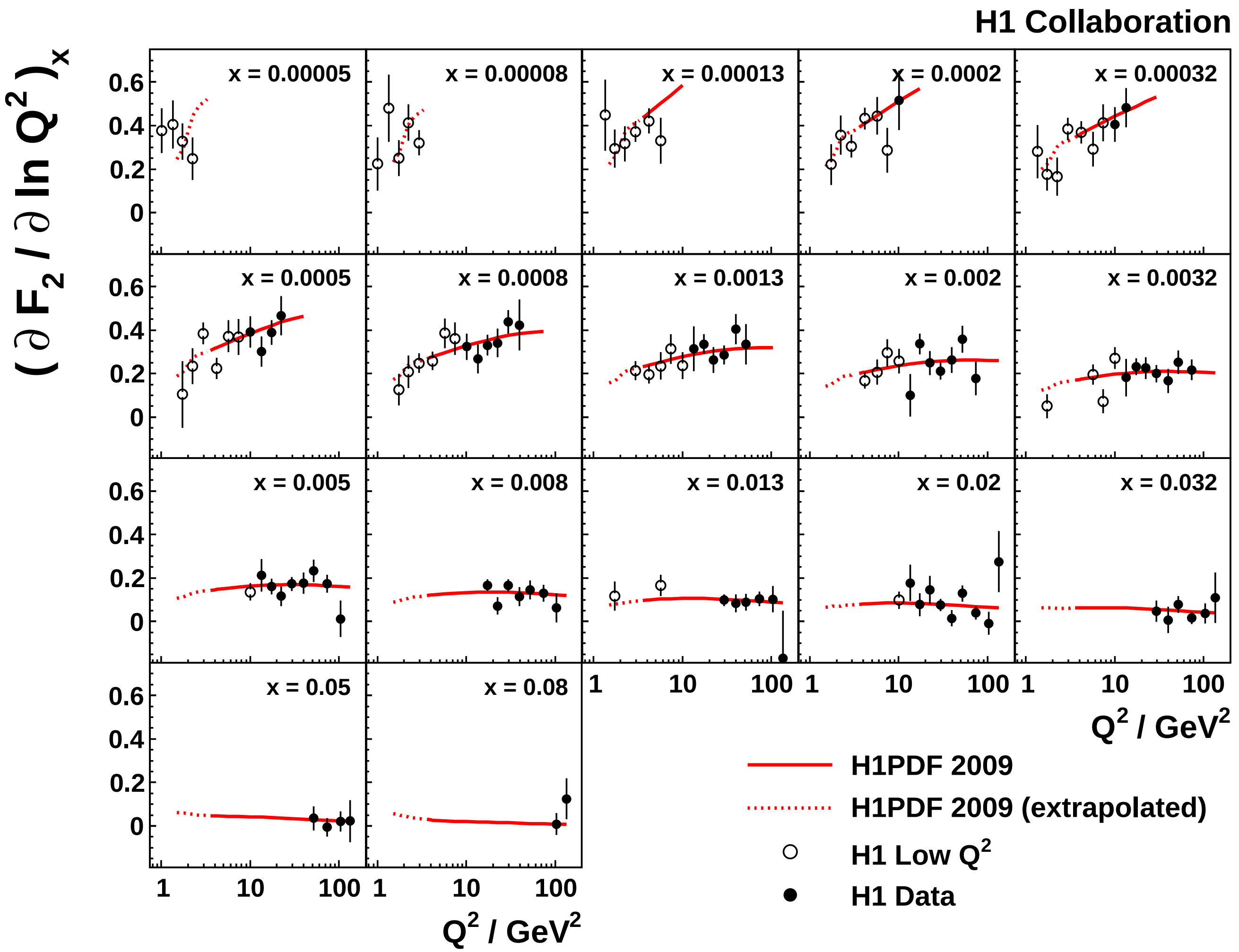
# $F_2$ at fixed $x$

- Strong scaling violations at low $x$, approximate scaling behaviour for $x \sim 0.1$



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

- Effect of the gluon dynamics at low $x$, well described by the QCD fit to low $Q^2 \sim 1.5\,\mathrm{GeV}^2$



# H1PDF 2009 - A new QCD Fit

- Using only inclusive cross section data by H1, a new QCD based on DGLAP evolution equations (NLO) was performed
- Compared to the previously published fit (H1PDF 2000):
  - Data for $Q^2 \leq 150\,\mathrm{GeV}^2$ more precise
  - Improved theoretical treatment of heavy quark threshold effects (GM-VFNS, TR scheme)

| Data set | Process | $Q^2$ range | |
|---|---|---|---|
| H1 combined low $Q^2$ $1995-2000$ | $e^+p$ NC | 0.2 | 12 |
| H1 combined medium $Q^2$ $1996-2000$ | $e^+p$ NC | 12 | 150 |
| H1 high $Q^2$ $94-97$ | $e^+p$ NC | 150 | 30 000 |
| H1 high $Q^2$ $94-97$ | $e^+p$ CC | 300 | 15 000 |
| H1 high $Q^2$ $98-99$ | $e^-p$ NC | 150 | 30 000 |
| H1 high $Q^2$ $98-99$ | $e^-p$ CC | 300 | 15 000 |
| H1 high $Q^2$ $98-99$ | $e^-p$ NC | 100 | 800 |
| H1 high $Q^2$ $99-00$ | $e^+p$ NC | 150 | 30 000 |
| H1 high $Q^2$ $99-00$ | $e^+p$ CC | 300 | 15 000 |

# Parameterisation

- The set chosen PDFs same as for **HERAPDF 0.2** fit:
  $\rightarrow$ *V. Radescu*
  $$xu_v,\ xd_v,\ xg,\ x\bar{U} = x(\bar{u}+\bar{c}),\ x\bar{D} = x(\bar{d}+\bar{s}+\bar{b})$$
- Parameterised at low $Q_0^2 = 1.9\,\mathrm{GeV}^2$ ($x\bar{c} = x\bar{b} = 0$) as
  $$xP = Ax^B(1-x)^C(1+Dx+Ex^2+\ldots)$$
- $6$ parameters are fixed by model assumptions
- Remaining $9$ $A, B, C$ parameters are the basic parameterisation
- Additional $D, E, \ldots$ parameters are added in an iterative $\chi^2$ optimisation procedure with additional conditions:
  - $F_2 \geq 0$ and $F_L \geq 0$ $\Rightarrow$ *otherwise discarded*
  - all PDFs $\geq 0$
    $\Rightarrow$ *otherwise considered for parameterisation uncertainty*
  - Valence not too low compared to sea at high $x \gtrsim 0.2$
    $\Rightarrow$ *otherwise considered for parameterisation uncertainty*

# Parameterisation

- This optimisation procedure leads to the choice

| | $A$ | $B$ | $C$ | $D$ | $E$ |
|---|---|---|---|---|---|
| $xg$ | mom. sum rule | | | | |
| $xu_v$ | quark count. rule | | | | |
| $xd_v$ | quark count. rule | $= B_{u_v}$ | | | |
| $x\bar{U}$ | $A_{\bar{D}}(1 - f_s)$ | | | | |
| $x\bar{D}$ | | $= B_{\bar{U}}$ | | | |

- The fit has a good $\chi^2_{\mathrm{tot}} / n_{\mathrm{dof}} = 587/644$, no significant tension in the systematic uncertainties
- Alternative parameterisations with similar or better $\chi^2$, which are discarded due to the additional optimisation conditions, are used to estimate an additional **parameterisation uncertainty**
- Envelope of all those considered fits is formed, using e.g.

| | $A$ | $B$ | $C$ | $D$ | $E$ |
|---|---|---|---|---|---|
| $xg$ | | | | | |
| $xu_v$ | | | | | |
| $xd_v$ | | | | | |
| $xU$ | | | | | |
| $x\bar{D}$ | | | | | |

| | $A$ | $B$ | $C$ | $D$ | $E$ |
|---|---|---|---|---|---|
| $xg$ | | | | | |
| $xu_v$ | | | | | |
| $xd_v$ | | | | | |
| $xU$ | | | | | |
| $x\bar{D}$ | | | | | |

# Model Parameters and Variation

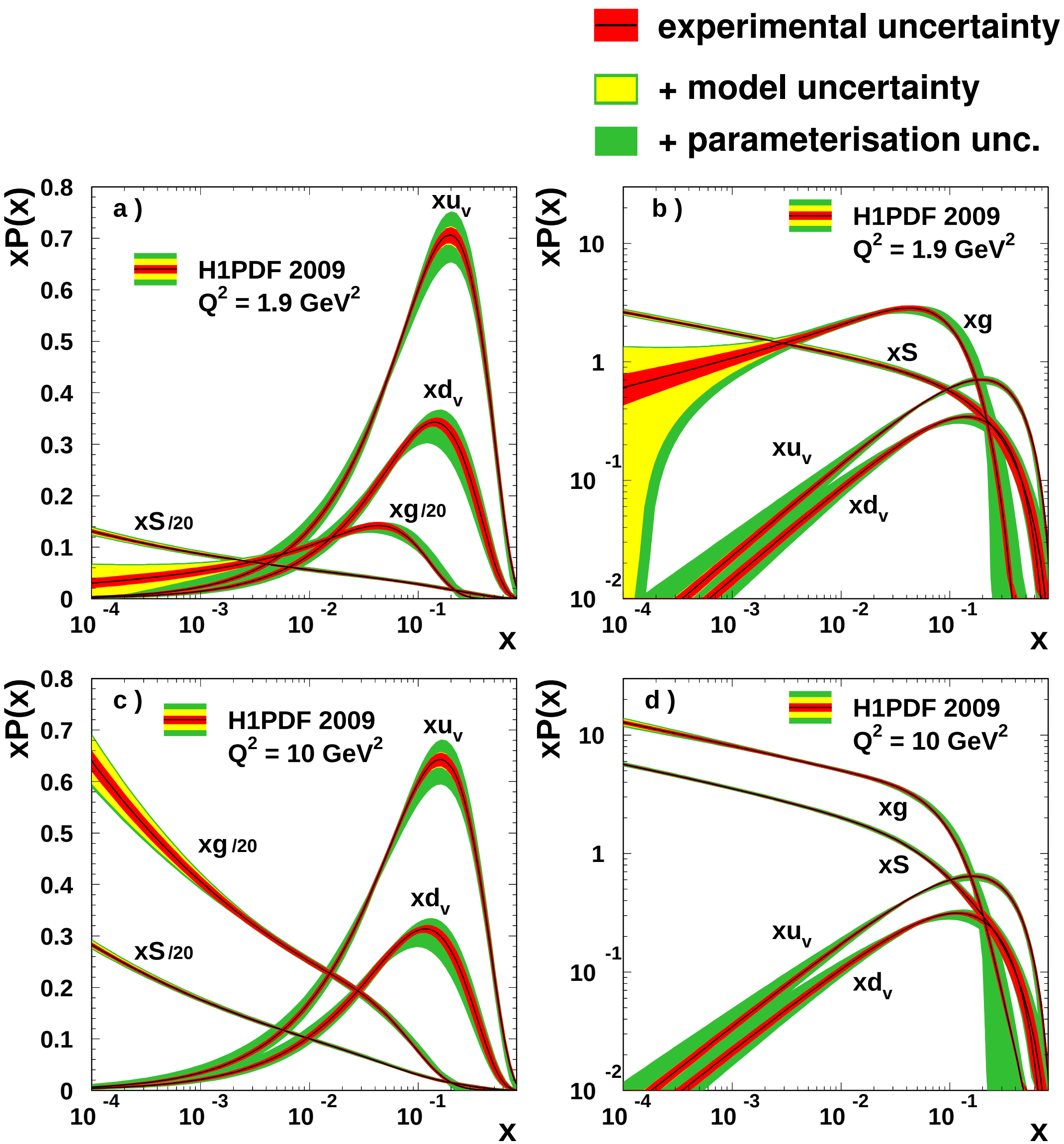
- Typically “conventional” choices for H1 fits, also mostly like **HERAPDF 0.2**
- The choice VFNS scheme dictates $Q_0^2 \leq m_c^2$, which limits either of those variations

| Parameter | Central Value | Variation |
|---|---|---|
| $\alpha_s$ | $0.1176$ | fixed |
| $Q_0^2$ | $1.9\,\mathrm{GeV}^2$ | down to $1.5\,\mathrm{GeV}^2$<br>– error symmetrised |
| $Q_{min}^2$ | $3.5\,\mathrm{GeV}^2$ | $2.5 - 5.0\,\mathrm{GeV}^2$ |
| $m_c$ | $1.4\,\mathrm{GeV}$ | $1.38 - 1.47\,\mathrm{GeV}$ |
| $m_b$ | $4.75\,\mathrm{GeV}$ | $4.3 - 5.0\,\mathrm{GeV}$ |
| $f_s$ | $0.31$ | $0.25 - 0.40$ |

- The largest effect at low $x$ is due to the $Q_0^2$ variation

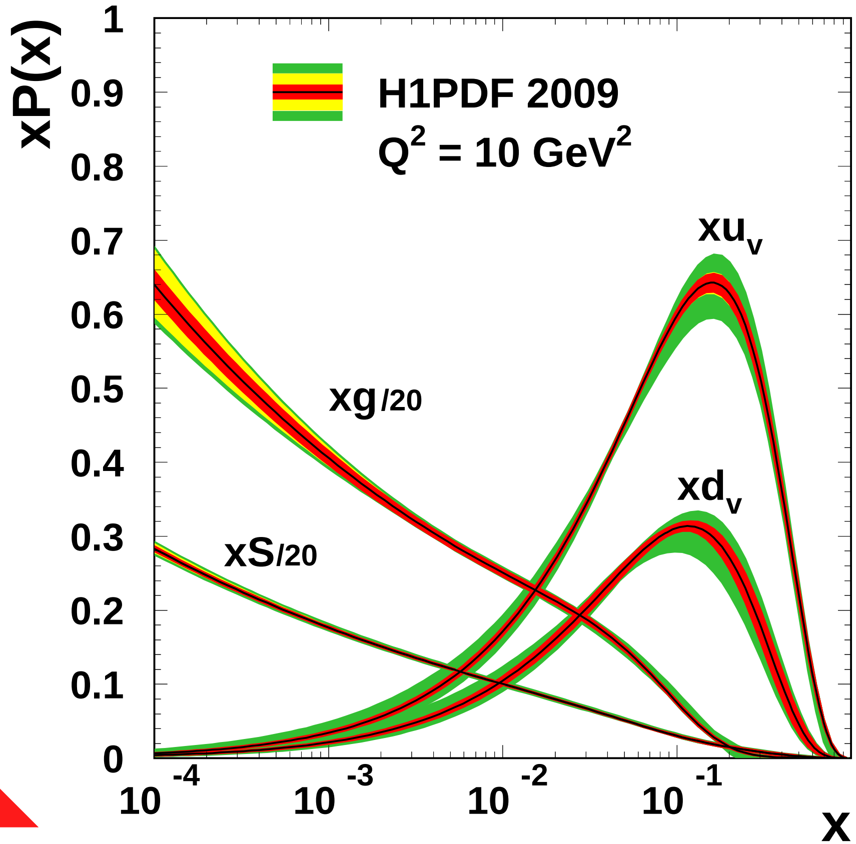
# H1PDF 2009 Result

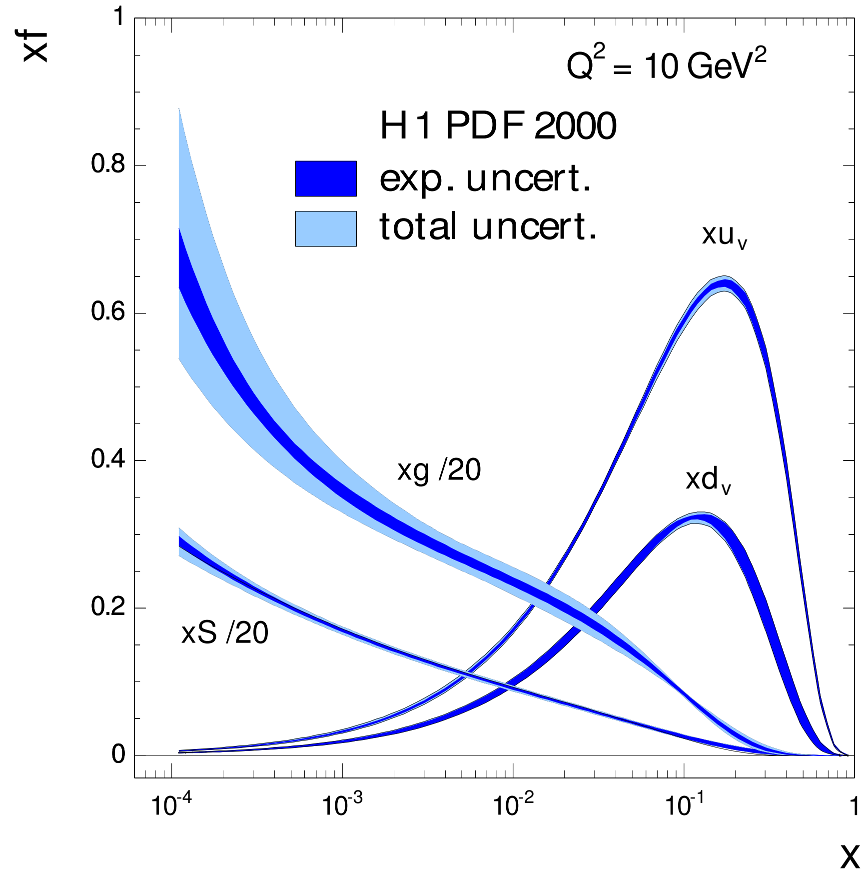
- At $Q^2 = 1.9\,\mathrm{GeV}^2$ gluon has valence-like shape, low $x$ dominated by sea quarks
- At $Q^2 = 10\,\mathrm{GeV}^2$ the gluon clearly dominates low $x$
- Parameterisation uncertainty dominates at high $x$



# H1PDF 2009 vs. H1PDF 2000

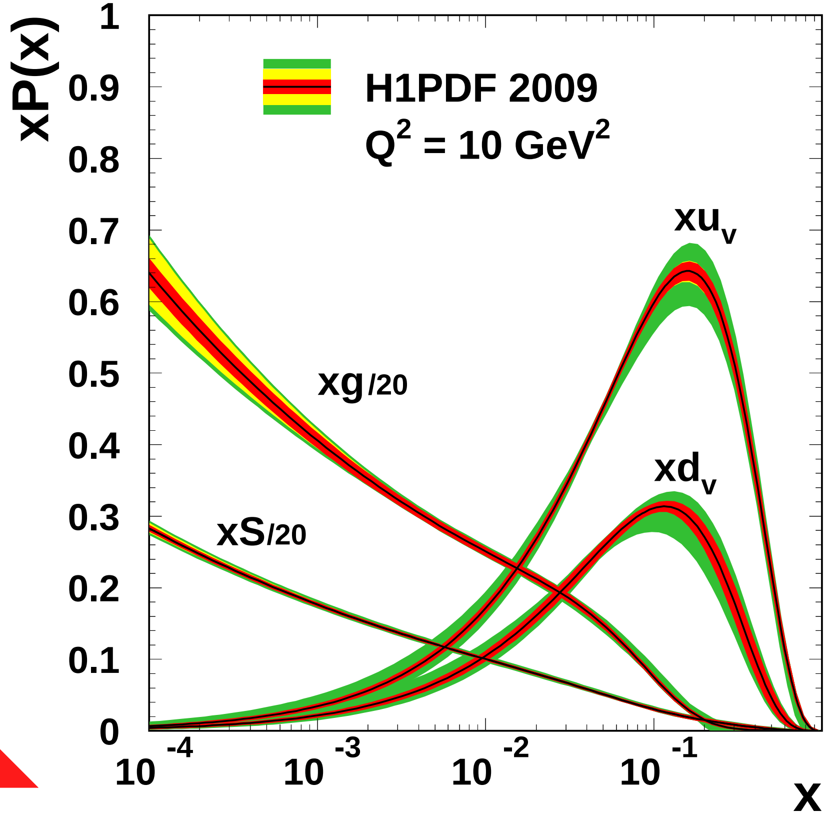
- Low $x$ uncertainties reduced
- Uncertainties at high $x$ larger and more realistic:
  - New parameterisation using $xu_v$ instead of $xU = x\bar{U} + xu_v$
  - New uncertainty for parameterisation choice

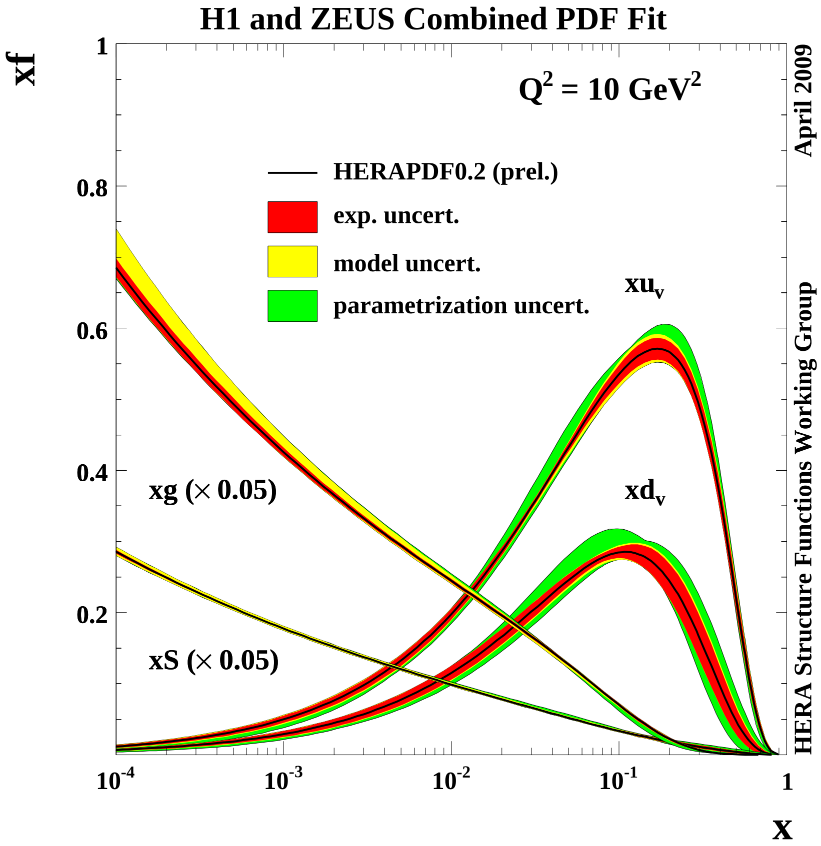


# H1PDF 2009 vs. HERAPDF 0.2

- Parametrisation optimisation procedure leads to different choices: additional $D_g$ vs. $E_{u_v}$ parameter
- Low $x$ gluon uncertainty dominated by $Q_0^2$ variation: symmetrised for H1PDF 2009, but not for HERAPDF 0.2



# Conclusions

- A new measurement of the inclusive DIS cross section at medium $12\,\mathrm{GeV}^2 \leq Q^2 \leq 150\,\mathrm{GeV}^2$ is performed using H1 data from the year 2000
- The new measurement is combined with the published 1996/97 data, after correction of a small bias in the older result
- The result is the most accurate measurement in this kinematic domain to date with typical total uncertainties of $1.3-2\%$
- A QCD analysis, H1PDF 2009, is performed using the improved new data at $Q^2 \leq 150\,\mathrm{GeV}^2$ and published H1 high $Q^2$ inclusive cross section measurements