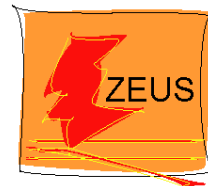


# Measurement of the Inclusive $e^\pm p$ Scattering Cross Section at High Inelasticity $y$ and of the Structure Function $F_L$

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(on behalf of the H1 & ZEUS Collaborations)



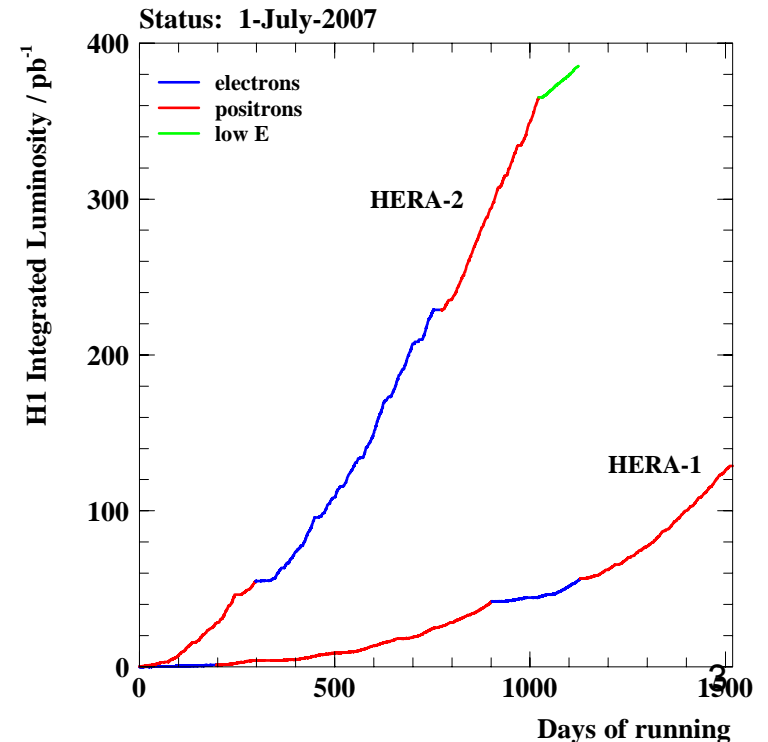
Low  $x$  Workshop 2011, Santiago de Compostela

# Content

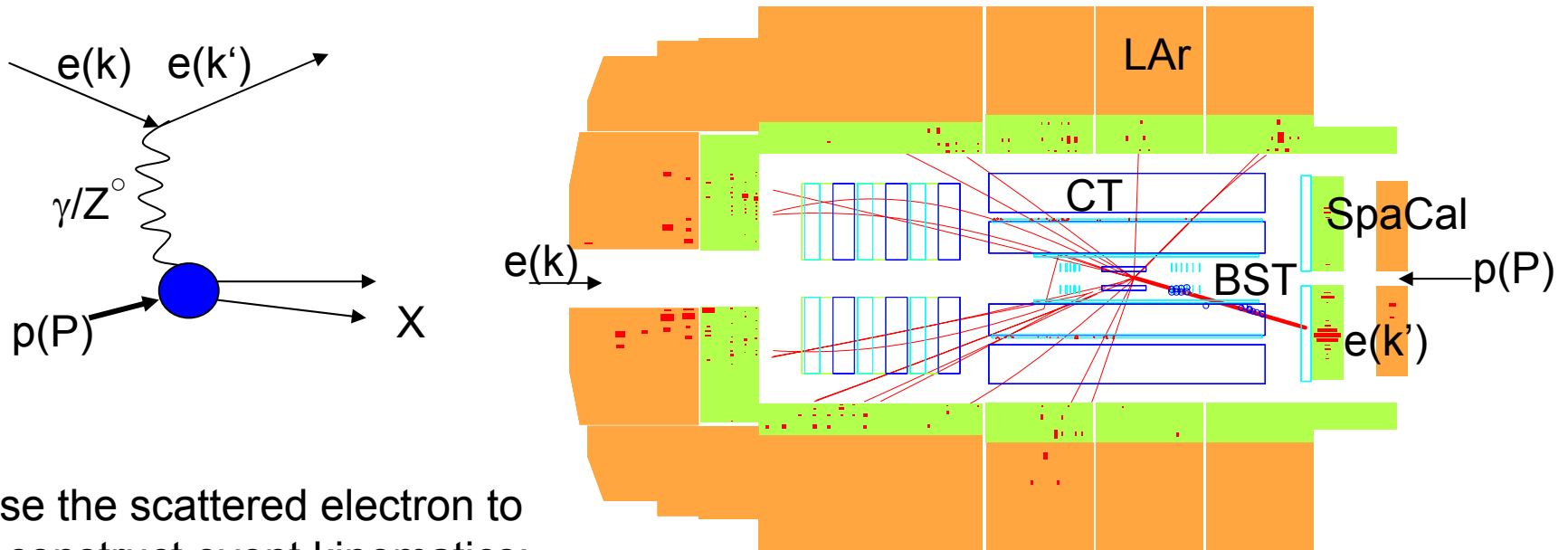
- Deep Inelastic Scattering at HERA
- DIS x-section at low  $Q^2$
- x-section measurements  
at high inelasticity  $y$
- Results on the structure function  $F_L$
- Combined data for phenomenological  
analyses
- Conclusions

# The $ep$ collider HERA

- Circumference: 6.3 km
- $27.5 \times 920(820) \text{ GeV}$ ,  $\sqrt{s_{ep}} = 319 \text{ GeV}$
- 2 collider experiments:  
H1 and ZEUS
- HERA I: 1992-2000
- Luminosity upgrade: mid 2000 – end 2001
- Higher luminosity: HERA II (2003 – 2007)



# Inclusive DIS at HERA



Use the scattered electron to  
reconstruct event kinematics:

$$Q^2 = 4E_e E_e' \cos^2 \frac{\theta_e}{2} \text{ - four momentum transfer squared in the reaction}$$

$$x = \frac{Q^2}{s} \text{ - fraction of the proton momentum carried by the parton}$$

$$y = 1 - \frac{E_e'}{E_e} \sin^2 \frac{\theta_e}{2} \text{ - fraction of the lepton's energy loss}$$

$$s = 4E_e E_p \text{ - center-of-mass energy squared}$$

# NC cross section and structure functions

**NC Reduced cross section:**  $\sigma_r(x, Q^2)$

$$\frac{d^2 \sigma_{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} Y_+ \left[ F_2 - \frac{y^2}{Y_+} F_L \right]$$

$\uparrow$  Dominant contribution       $\uparrow$  Sizeable only at high  $y$  ( $y > \sim 0.6$ )

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

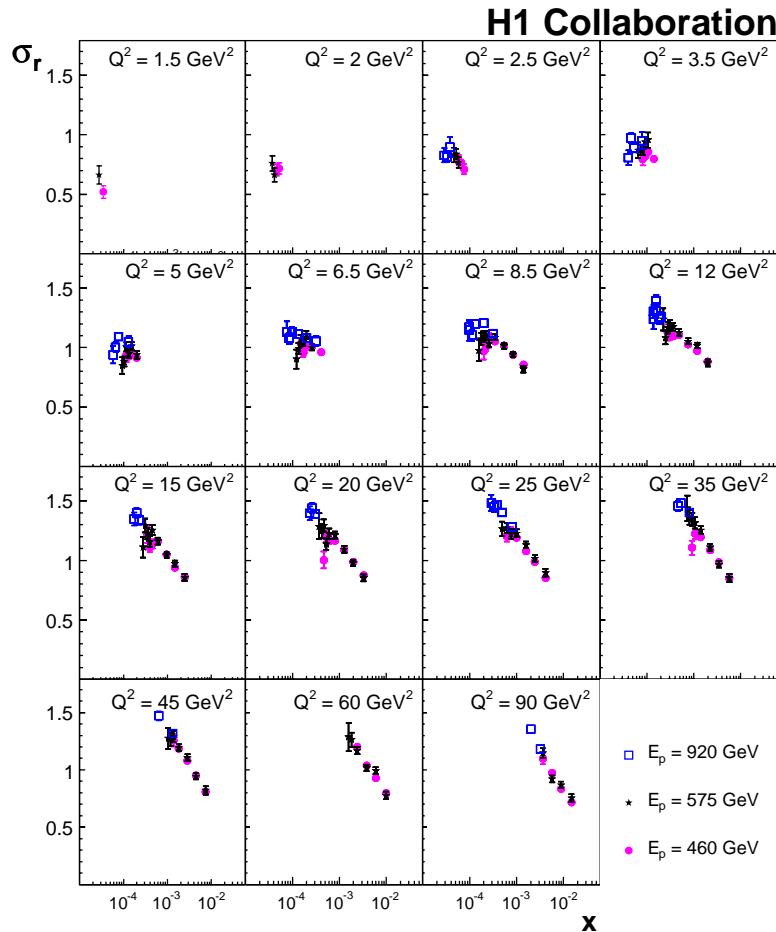
- The proton structure functions in QPM:

$$F_2(x) = \sum_i e_i^2 x [q_i(x) + \bar{q}_i(x)] - \text{sum of the (anti)quarks density distributions weighted with their electric charge squared}$$

$$F_L(x) = 0$$

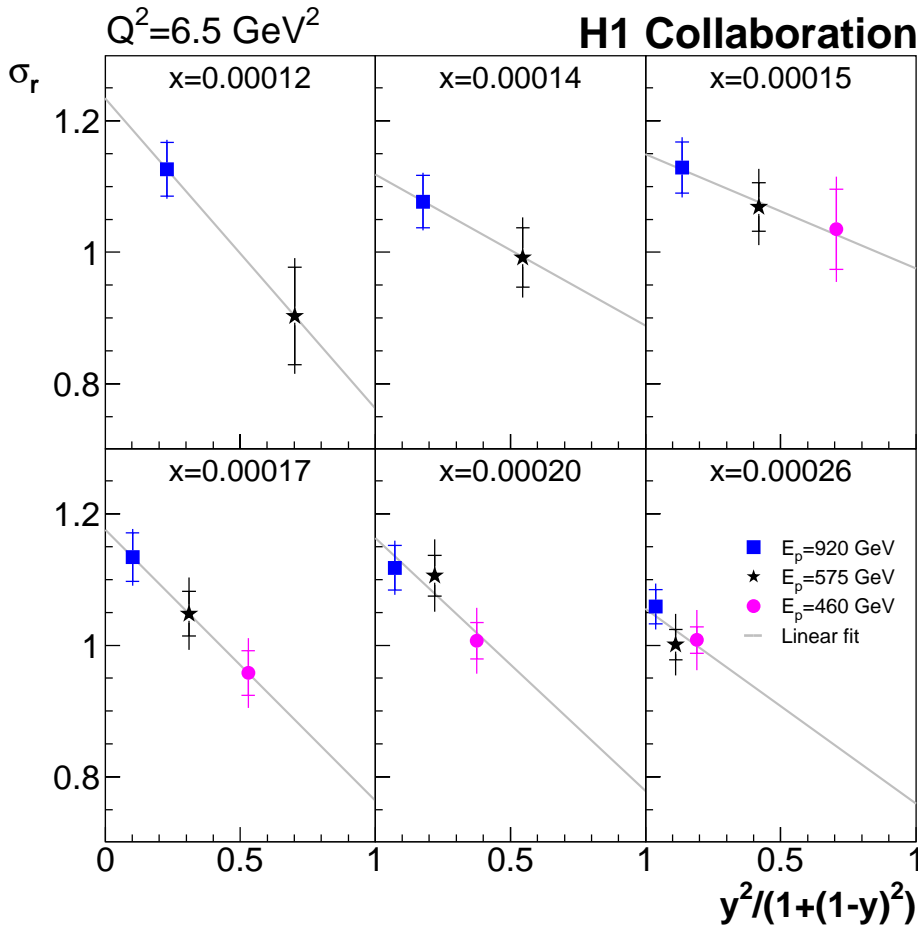
- In QCD:  $F_L(x, Q^2) \sim$  gluon density

# $\sigma_r$ for $E_p=460, 575$ and $920$ GeV



- New x-section measurements for different  $E_p$  at HERA II  
[H1 Collab., Eur.Phys.J. C71, 2011 1579]
- For  $E_p=920$  GeV, these data are combined with previous H1 measurements  
[H1 Collab., Eur.Phys.J. C63, 2009 625],  
[H1 Collab., Eur.Phys.J. C64, 2009 561],  
[H1 Collab., Eur.Phys.J. C21, 2001 33]  
leading to factor of 2 improvement in precision at high  $y$

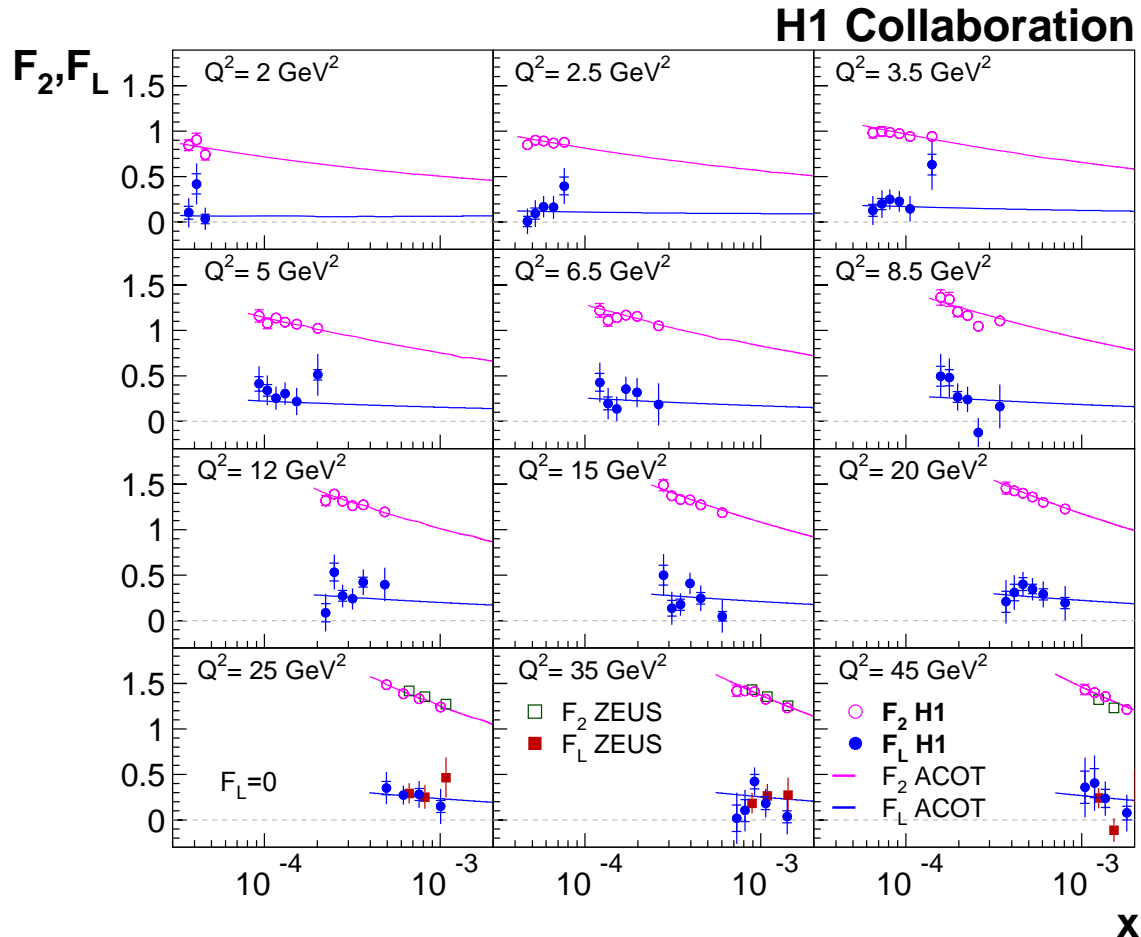
# $F_L$ determination



- $F_L$  determined from measurements at different CME
- $F_L$  is proportional to the variation of  $\sigma_r$  as a function of  $y^2/(1+(1-y)^2)$
- Improved determination procedure, taking into account correlations due to systematic uncertainties

[H1 Collab., Eur.Phys.J. C71, 2011 1579]

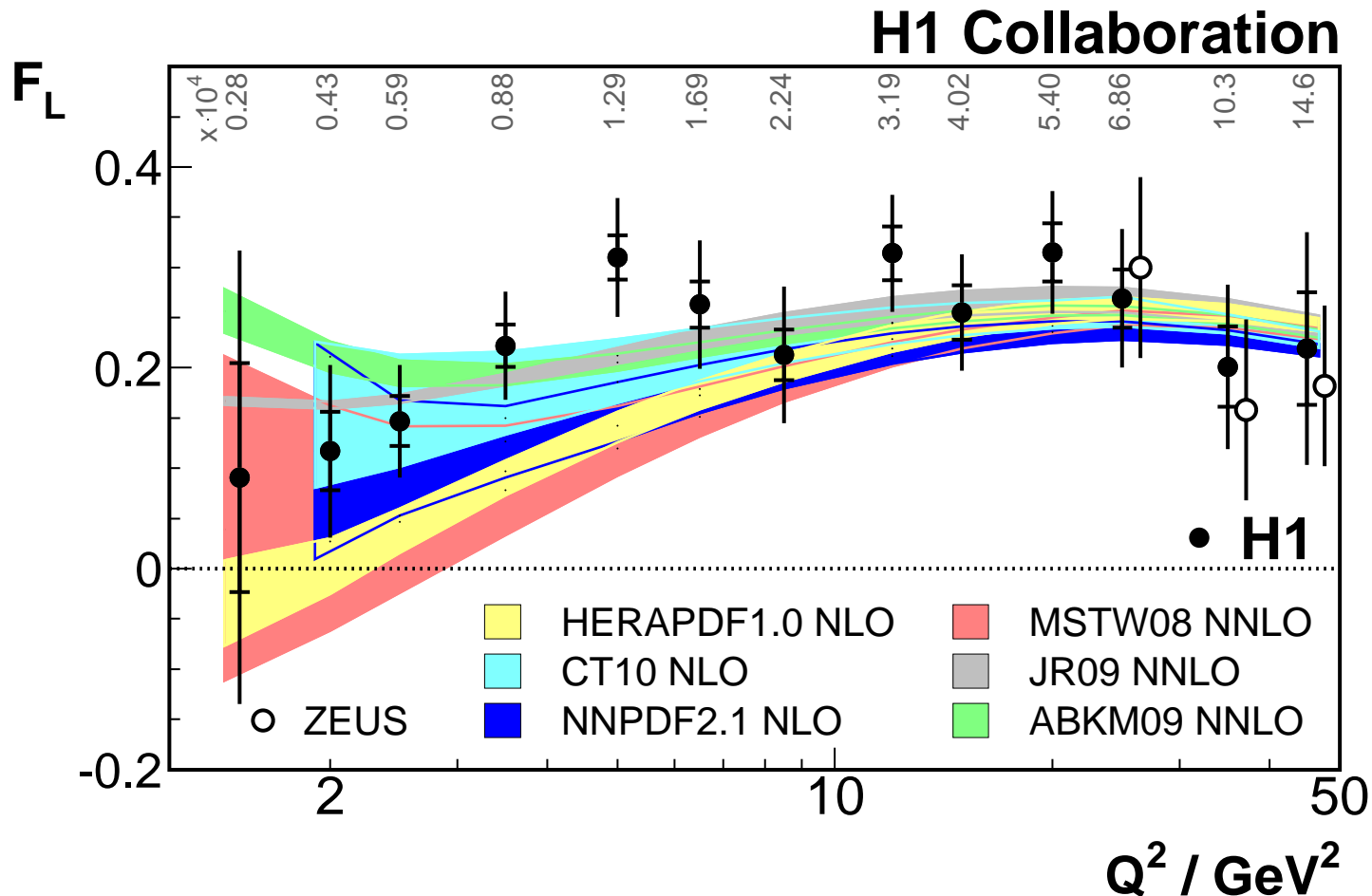
# $F_2$ and $F_L$ at low $Q^2$



- The measurement spans over 2 decades in  $x$  at low  $0.00002 < x < 0.002$
- Measured HERA  $F_2$  and  $F_L$  are consistent with predictions of the NLO DGLAP fit in the ACOT scheme

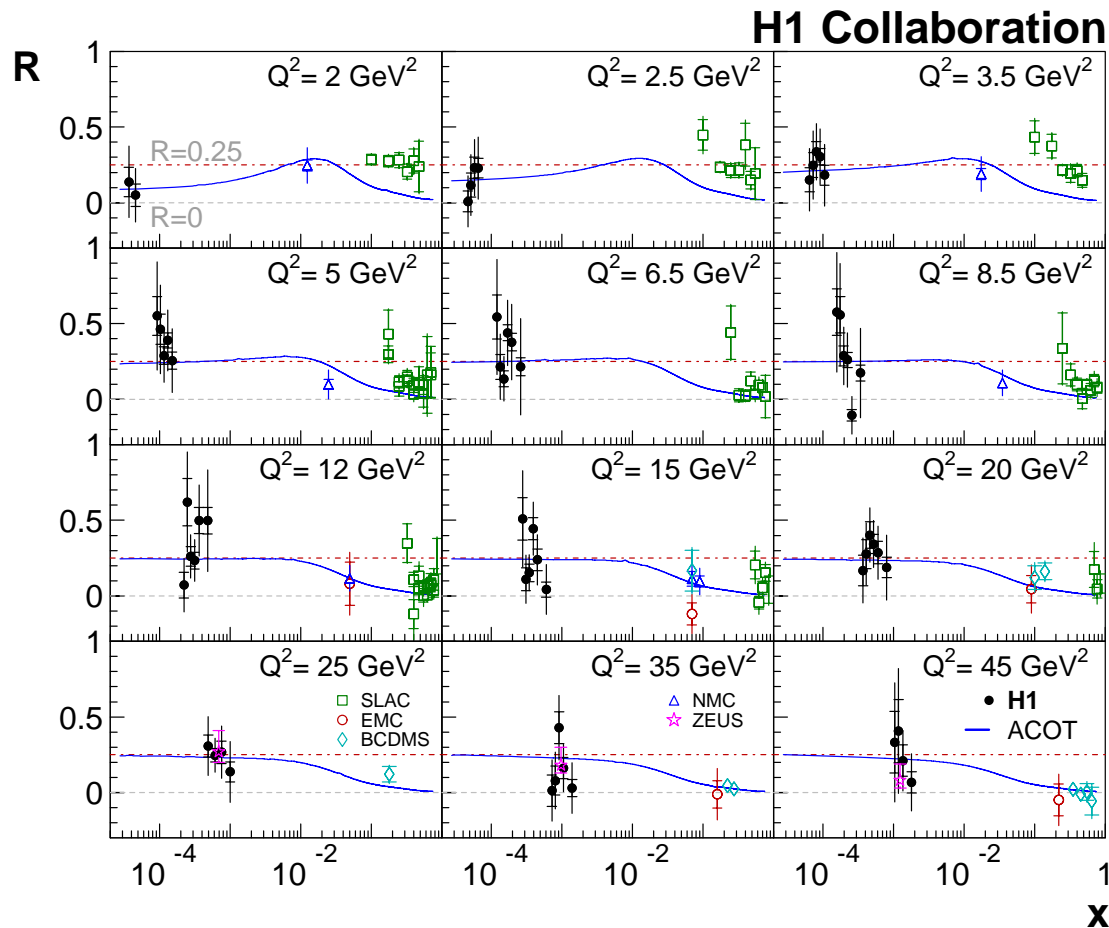


# HERA $F_L$ and different predictions



- New measurement extends to  $Q^2 \geq 1.5 \text{ GeV}^2$
- Within the uncertainties all predictions describe the data reasonably well
- Good agreement between H1 and ZEUS measurements

# The ratio $R$



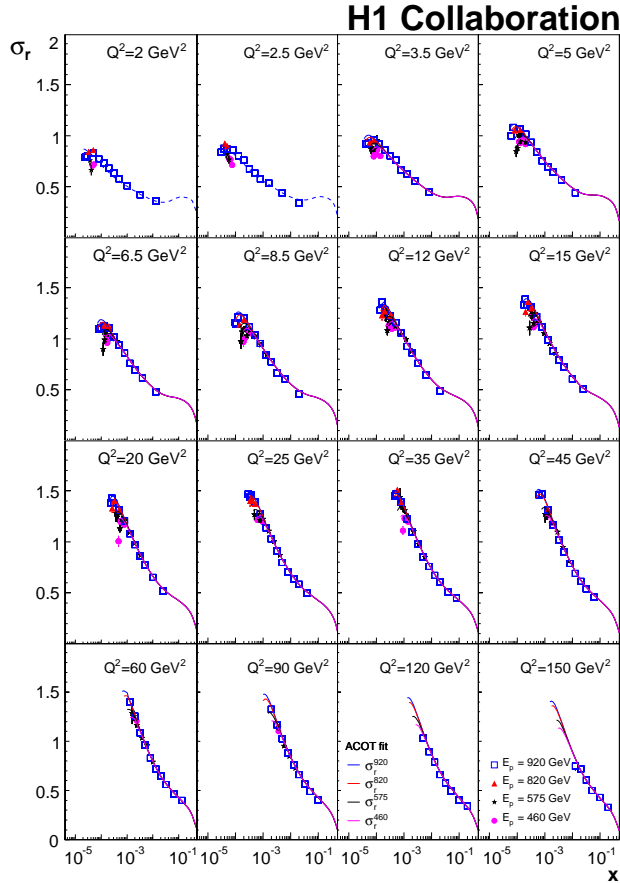
$$R = \frac{F_L}{F_2 - F_L}$$

HERA data are consistent with const  $R = 0.26 \pm 0.05$

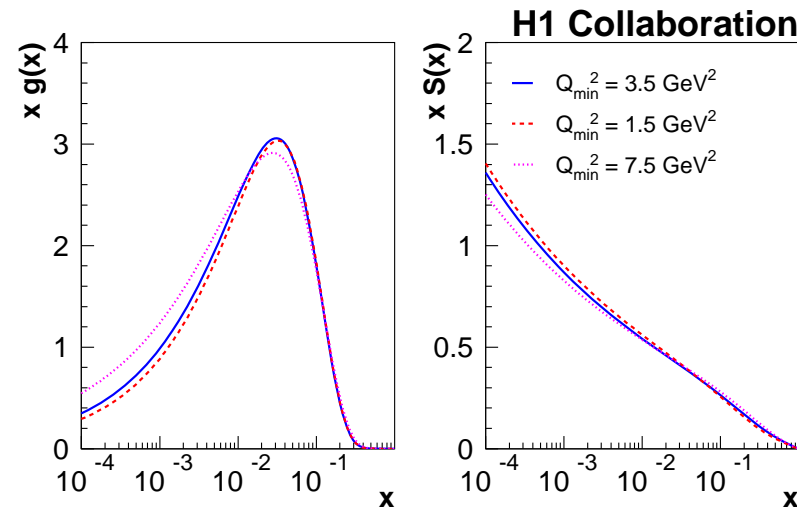
# Phenomenological analysis settings

- Combined H1 data for  $E_p=820\text{--}920$  GeV,  $0.2\leq Q^2\leq 150$  GeV<sup>2</sup> [H1 Collab., Eur.Phys.J. C63, 2009 625], [H1 Collab., Eur.Phys.J. C64, 2009 561], [H1 Collab., Eur.Phys.J. C21, 2001 33]
- Combined for  $y_{460}\leq 0.35$  low  $E_p=460$  and 575 GeV data
- ‘H1fitter’ fitting program, based on NLO DGLAP QCDNUM [arXiv:1005.1481] evolution code. The fitter has been extended to include non-DGLAP models (dipole,  $\lambda$ -fit)
- See more about HERA fits in talk of Voica Radescu

# $\sigma_r$ and QCD fits

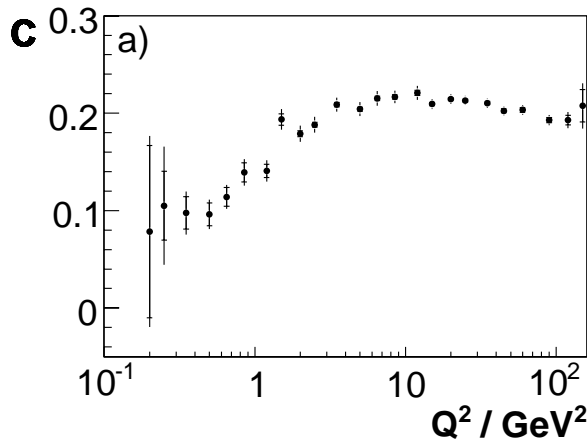


- Two calculation schemes for QCD fits: ACOT and RT with different computation of the heavy quark structure functions and of the structure function  $F_L$
- Better quality of ACOT fit:  $\chi^2/\text{dof}=715/781$  vs RT fit with  $\chi^2/\text{dof}=765/781$
- With increasing of  $Q_{\min}^2$  cut:
  - fit quality is improved
  - gluon is increased, sea becomes smaller at low  $x$



$Q_{\min}^2 / \text{GeV}^2$	1.5	2	2.5	3.5	5	7.5
$\chi^2 / n_{\text{dof}}$	824.8/834	777.9/818	748.7/801	715.2/781	677.6/759	626.9/712

# $\lambda$ fit

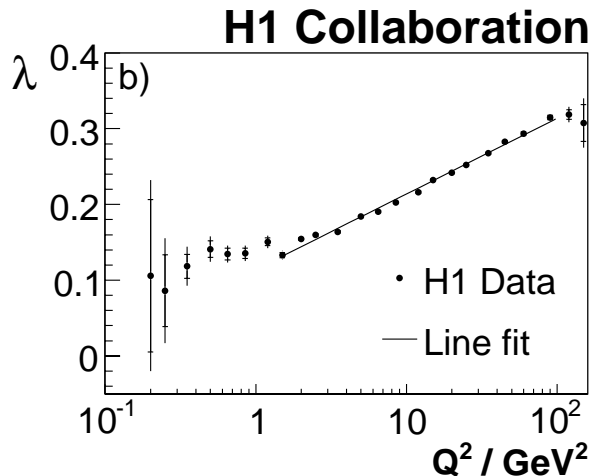


- At low  $Q^2$  and  $x \rightarrow 0$  rise of  $F_2$  towards low  $x$  may be described by

$$F_2(x, Q^2) = c(Q^2) \cdot x^{-\lambda(Q^2)}$$

- Fit  $x$ -dependences of  $\sigma_r$  in  $Q^2$  bins with two free parameters  $c(Q^2)$ ,  $\lambda(Q^2)$  and fixed  $R=0.26$

$$\sigma_r(x, Q^2) = F_2(x, Q^2) \cdot \left[ 1 - \frac{y^2}{1 + (1 - y)^2} \cdot \frac{R}{1 + R} \right]$$



- Fit results
  - For  $Q^2 \geq 2 \text{ GeV}^2$ 
    - $\lambda$  exhibits a linear increase as function of  $\ln Q^2$
    - Normalisation  $C$  is constant
  - For  $Q^2 < 2 \text{ GeV}^2$ 
    - $\lambda$  deviates from that linear dependence
    - Normalisation  $C$  rises with increasing of  $Q^2$

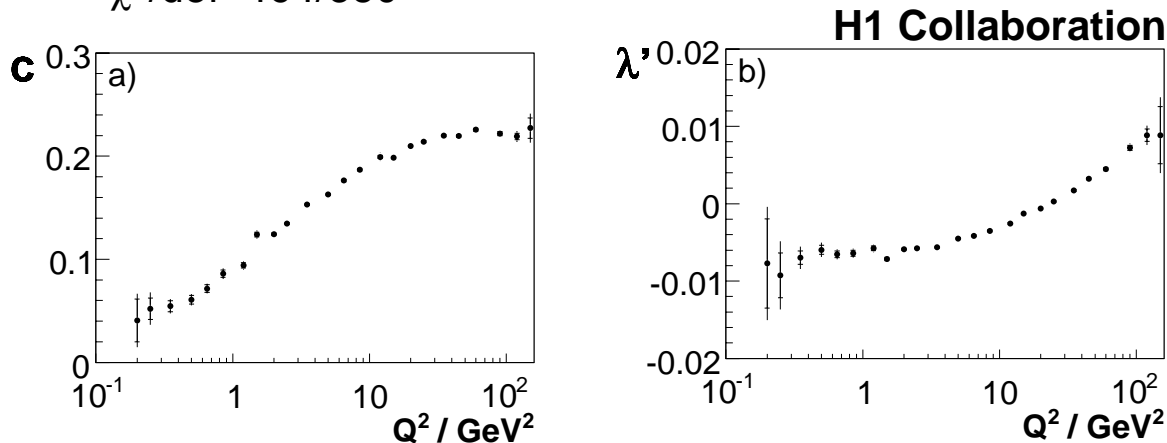
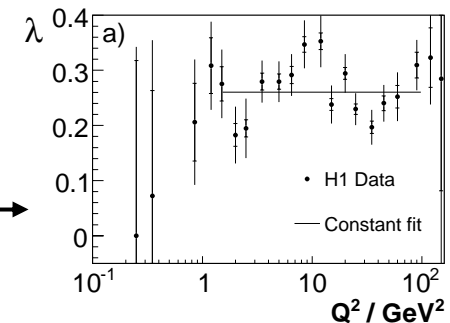
With offset method for syst. errors quality of the fit is poor:  $\chi^2/\text{dof}=538/350$

# Introduce a $\lambda'$ fit

- Parameterisation of the  $F_2$  is extended by one parameter to allow for deviations from a simple power law

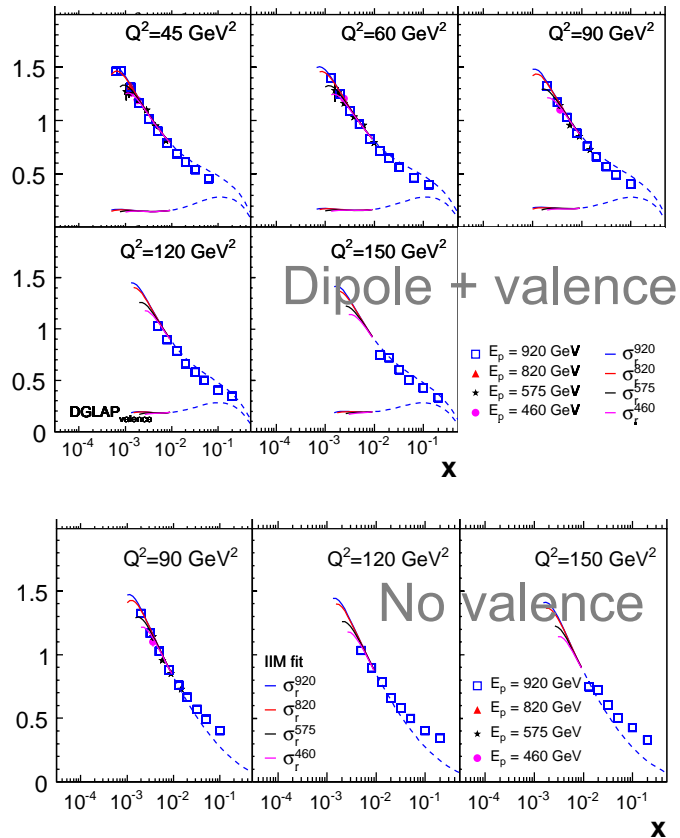
$$F_2(x, Q^2) = c(Q^2) \cdot x^{-\lambda(Q^2) + \lambda'(Q^2) \ln x}$$

- Fit returns significantly improved  $\chi^2/\text{dof}=405/326$ 
  - $\lambda$  exhibits a constant behaviour ( $\lambda \sim 0.25$ )
  - strong correlations between  $\lambda$  and  $\lambda'$
- Fix  $\lambda=0.25$  and let  $C(Q^2)$ ,  $\lambda'(Q^2)$  float which yields  $\chi^2/\text{dof}=464/350$



Confirms a QCD prediction  
[A. De Rujula et al., Phys. Rev. D10,  
1649 (1974)] :  
rise of  $F_2$  slower than power  
 $1/x$ , faster than power  $\ln 1/x$

# $\sigma_r$ and Dipole Model fits

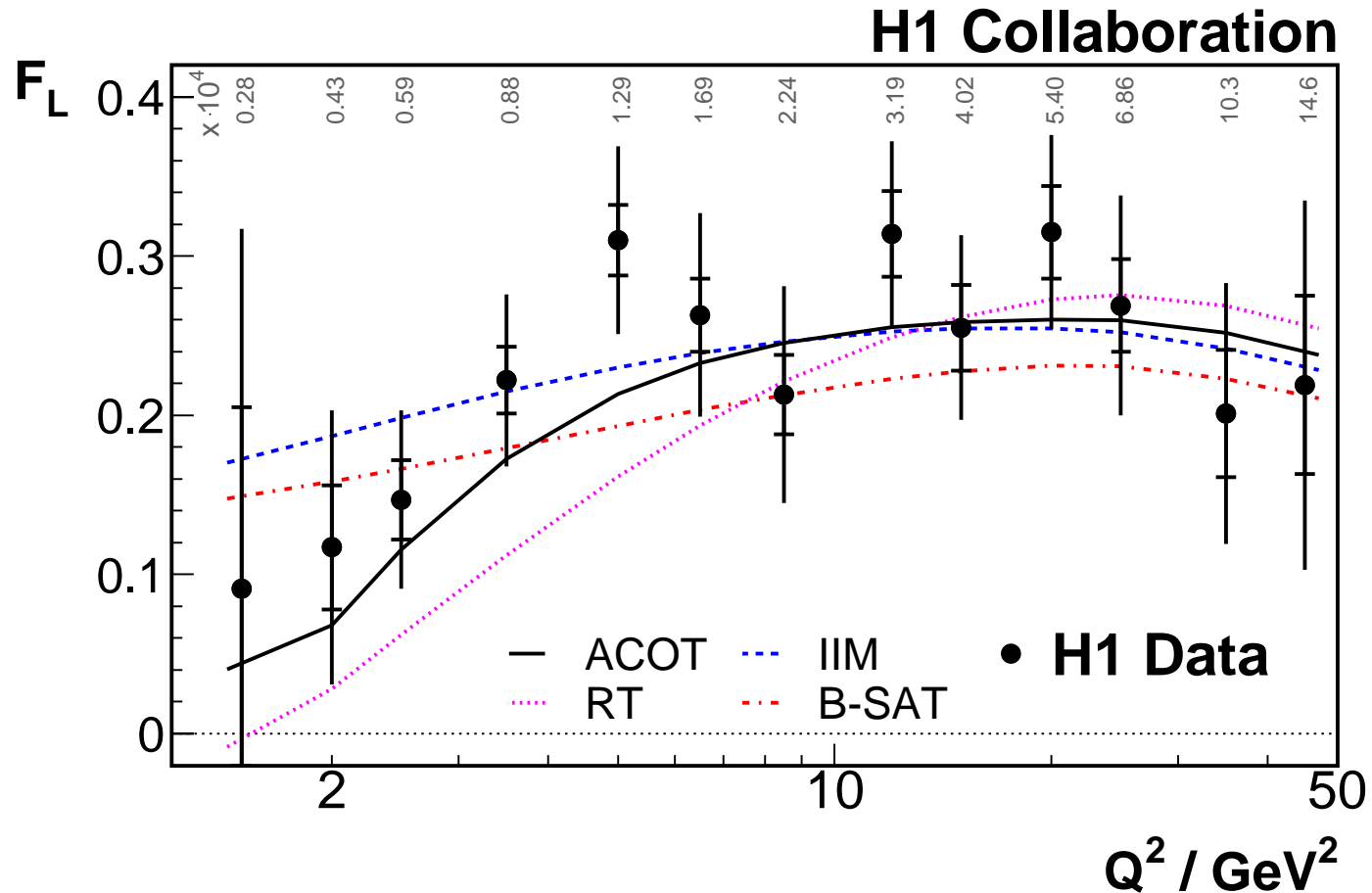


- Test DModels with and without DGLAP-based correction for valence contribution
- Fits to data in  $3.5 \leq Q^2 \leq 150$  GeV<sup>2</sup> and  $x < 0.01$  where both DM and DGLAP are working
- The addition of valence contribution improves description of the data at high  $x$  but overall fit quality is not better

Fit Conditions	GBW	IIM	$\chi^2/n_{\text{dof}}$ B-SAT	ACOT	RT
Nominal fit	718.8/352	397.6/352	424.9/352	715.2/781	764.5/781
$Q^2 \geq 3.5$ GeV <sup>2</sup>	559.7/252	259.4/252	261.7/252	248.3/249	288.8/249
DGLAP <sub>valence</sub>	739.5/252	287.6/252	371.4/252	248.3/249	288.8/249

⇒ Best fit for DGLAP-ACOT, closely followed by IIM

# $F_L$ vs phenomenological models

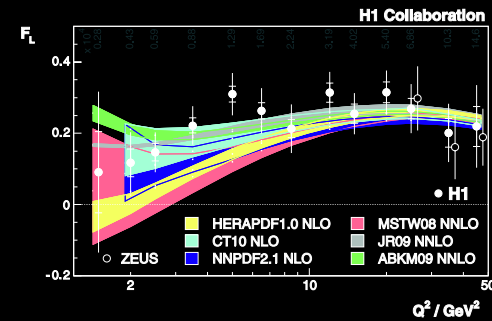


- At  $Q^2 > 10 \text{ GeV}^2$ : good agreement between data and all considered models
- At low  $Q^2$ : RT fit falls below data. Other models describe measured  $F_L$  well



# Summary

- The new most precise HERA measurement of the inclusive  $e^\pm p$  scattering cross section at high inelasticity  $y$  and of the structure function  $F_L$  is presented
- The analysis is published in EPJC [H1 Collab., Eur. Phys. J. C71, 2011 1579. arXiv:1012.4355 [hep-ex]]
- $F_L$  is measured for the first time at HERA down to  $Q^2 = 1.5 \text{ GeV}^2$
- Data are consistent with constant  $R \sim 0.26$  and generally well described by the phenomenological models
- From the considered models NLO DGLAP ACOT fit provides the best description of HERA data

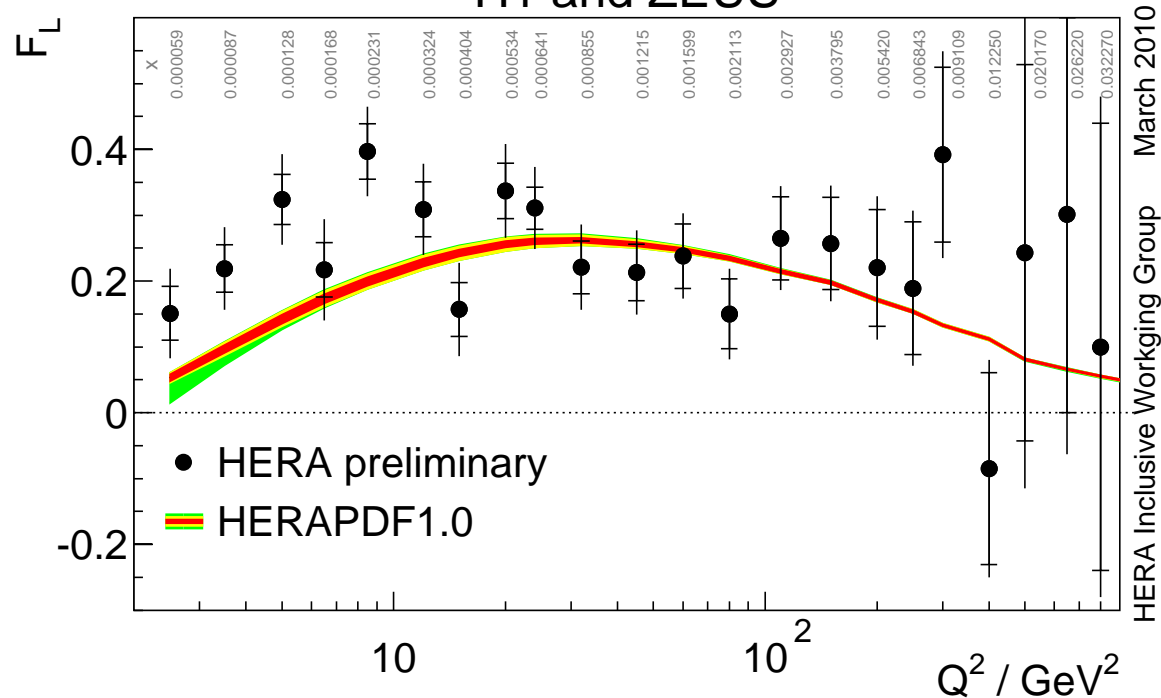


An improved determination and extended measurement range of the proton structure function  $F_L$ —shown as a function of  $Q^2$  and the corresponding average  $x$  values—and comparison with relevant theoretical calculations. From the H1 Collaboration: Measurement of the inclusive  $e^+p$  scattering cross section at high inelasticity  $y$  and of the structure function  $F_L$ .

Back up

# $F_L$ at HERA

H1 and ZEUS



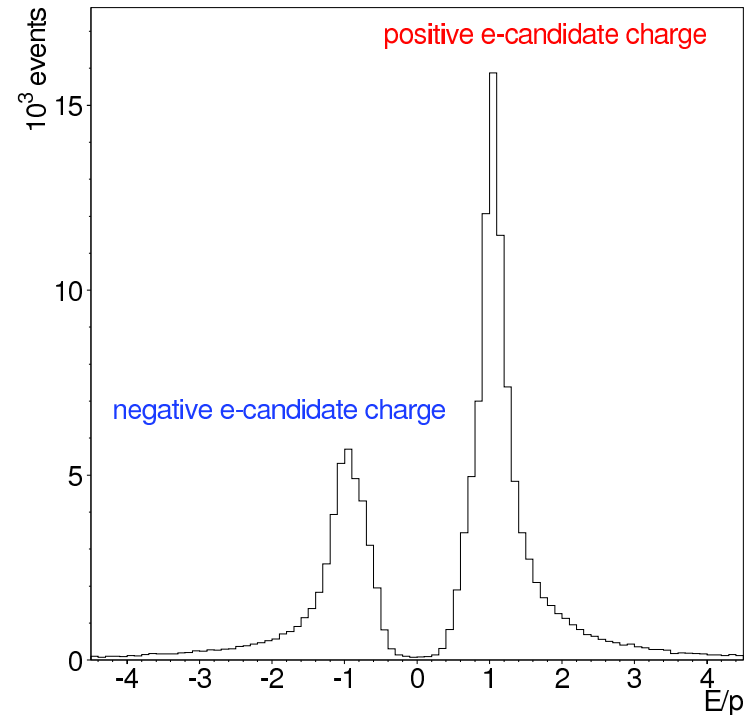
- The preliminary combined measurement of  $F_L$  cover the range of  $2.5 \leq Q^2 \leq 800 \text{ GeV}^2$  and  $0.00005 \leq x \leq 0.06$
- Data are in a good agreement with HERAPDF1.0 for  $Q^2 > 10 \text{ GeV}^2$

# Background estimation

- Measure particle charge using curvature of the associated track
- $e^+p$  scattering:
  - + Scattered lepton has the beam charge (positive)
  - Background from hadronic particles,  $\gamma$  conversions is almost charge symmetric:

$$N_{BG}^+ \approx N_{BG}^-$$

- Require **positive** charge for the signal sample. Estimate remaining background using **negative** sample



# F<sub>2</sub>-F<sub>L</sub> Fitter: new method

Instead of  $\sigma$ -average, extract  $F_2/F_L$  directly

$$\chi^2(F_2, F_L, \alpha) = \sum_i \frac{[(F_2^i - f(y^i)F_L^i) - \sum_j \Gamma_j^i \alpha_j - \mu^i]^2}{\Delta_i^2} + \sum_j \alpha_j^2 + \sum_i \left( \frac{F_L^i - \frac{R}{R+1} F_2^i}{\Delta_{F_L}} \right)^2$$

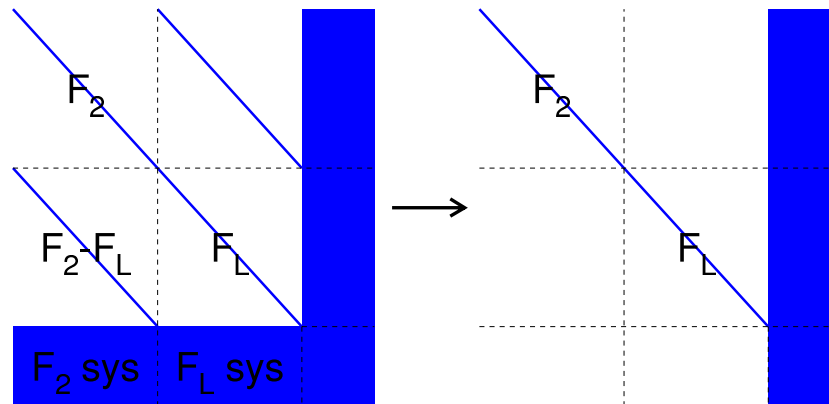
Minimization vs  $F_2, F_L$  and syst. sources  $\alpha$  leads to a simple system of linear equations:

$$R = \frac{F_L}{F_2 - F_L} \approx 0.25$$

$\mu^i$  – measured x - section

$\Delta_i$  – its uncertainty

$\alpha_j$  – correlated error sources



Plays role at low  $y$  only

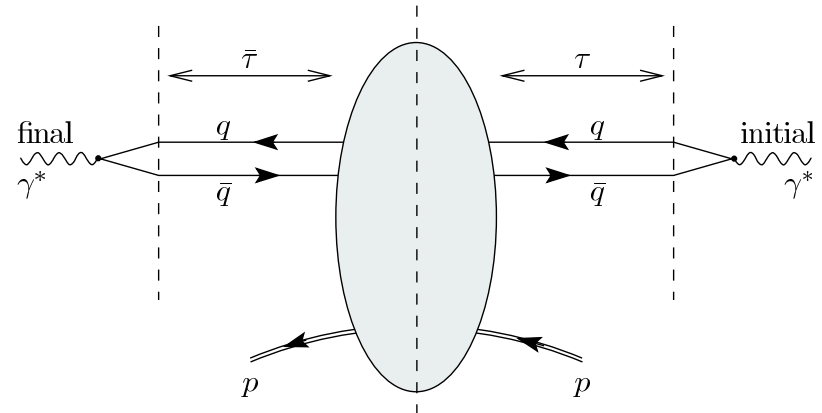
which can be easily solved numerically.

# Dipole model fits

- At low  $x$  and  $Q^2$  the virtual photon-proton scattering can be described using the color dipole model (CDM):

$$\gamma^*(q) + p(p) \rightarrow \gamma^*(q) + p(p)$$

the initial  $\gamma^*$  splitting into a quark-antiquark pair (dipole), this pair scattering on the proton and the  $q\bar{q}$  subsequently fusing into the final state  $\gamma^*$



- We consider here three CDM as representative for a much larger variety of Dipole models: GBW (Golec-Biernat & Wusthoff), IIM (Iancu, Itakura & Munier) and B-SAT (Kowalski, Motyka & Watt)
- CDM are applicable for  $x < 0.01$  where the gluon and sea dominate. All models neglect valence contributions which are sizeable: 5-15%