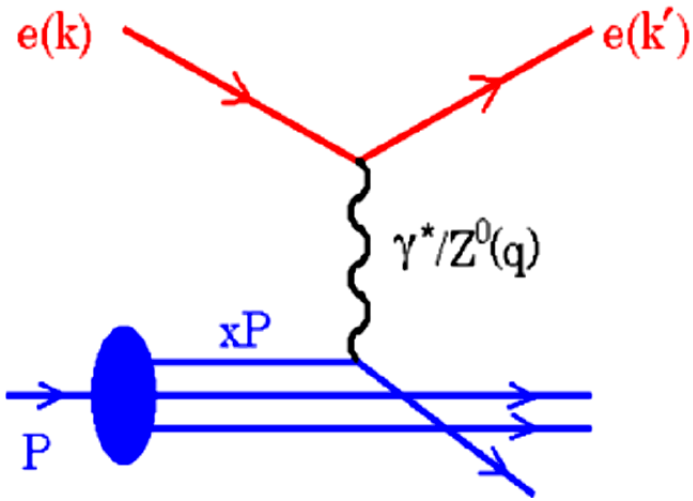
Recent Results from HERA

S. Glazov

DESY

BNL, 28 July 2009.

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

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

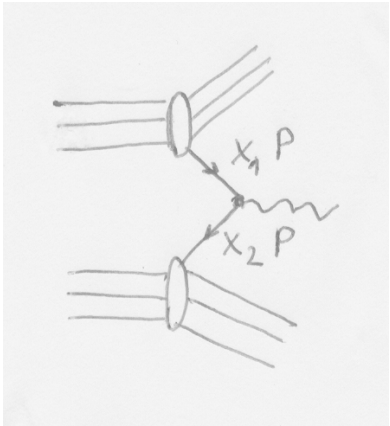
Leading order relations:

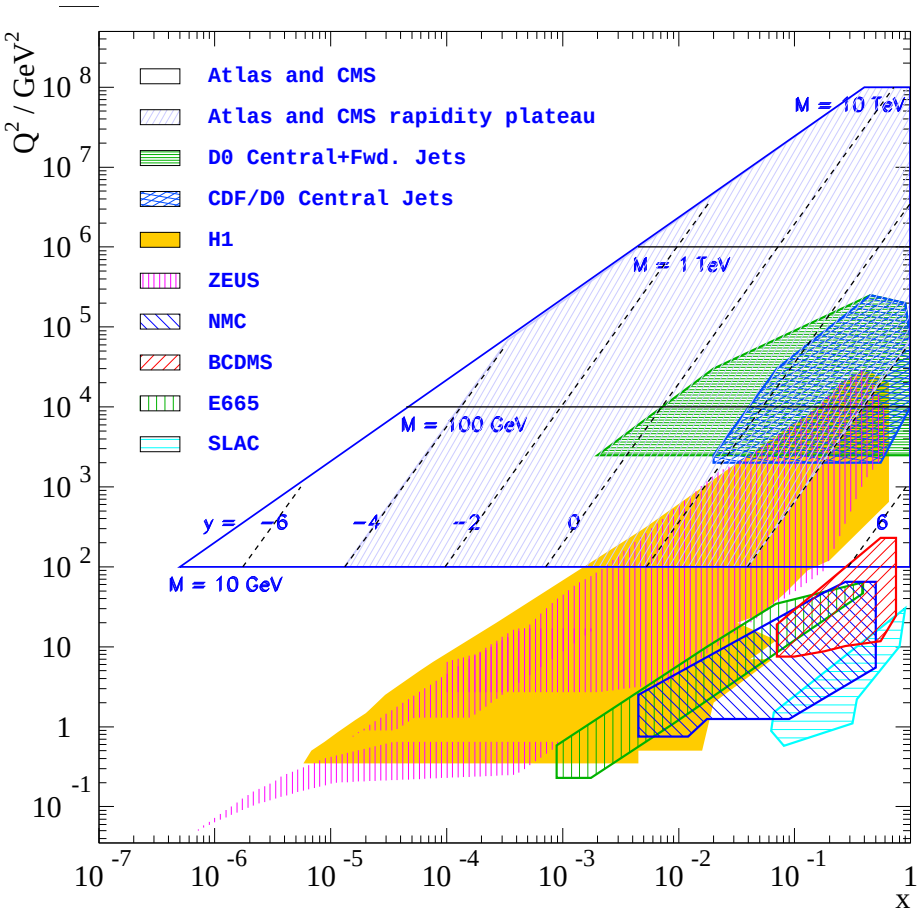
F_2	$= x\sum e_q^2(q(x)+\bar{q}(x))$
xF_3	$= x\sum 2e_q a_q(q(x)-\bar{q}(x))$
$\sigma^{CC}_{e^+p}$	$\sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s)$
$\sigma^{CC}_{e^-p}$	$\sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s})$
$pp \to (\ell\bar{\ell})X$	$\sim \sum x_1 x_2 q(x_1)\bar{q}(x_2)$

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.

HERA and LHC kinematics



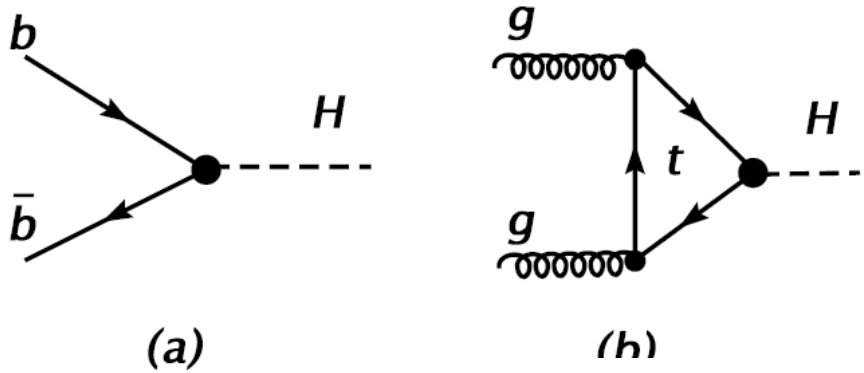


x_1, x_2 are momentum fractions. Factorization theorem states that cross section can be calculated using universal partons × short distance calculable partonic reaction.

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

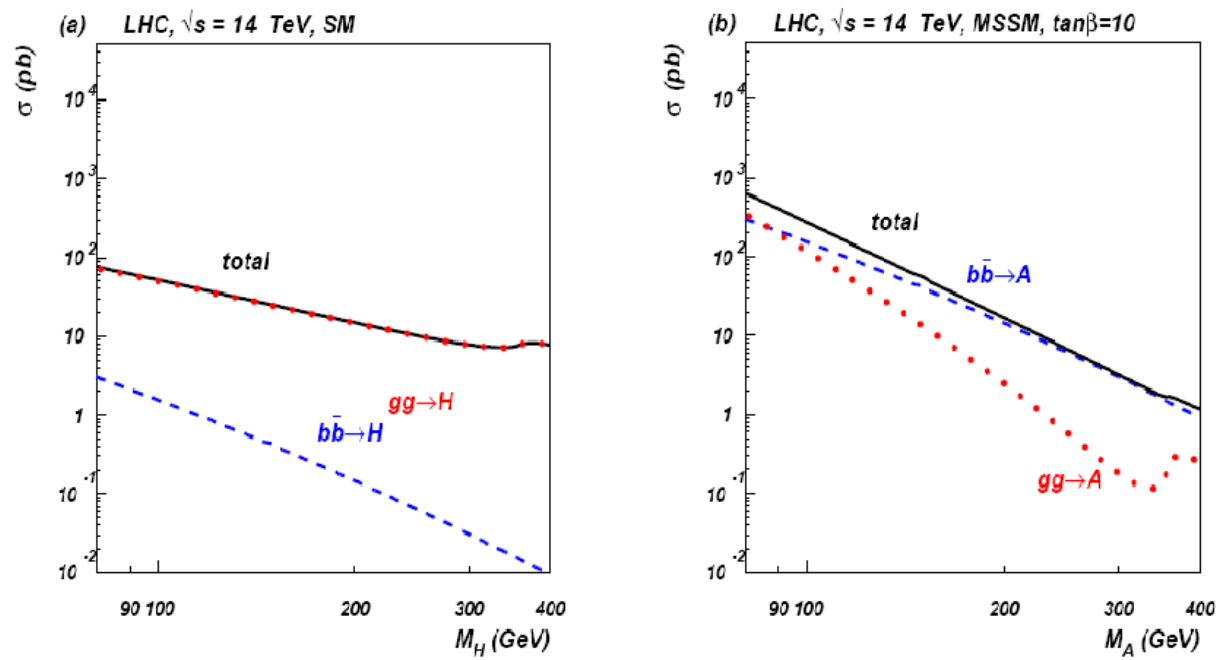
Notation clash: y – rapidity (LHC) vs y – inelasticity (HERA, $Q^2 = S\,xy$).

Case study: Higgs production at LHC, SM vs MSSM



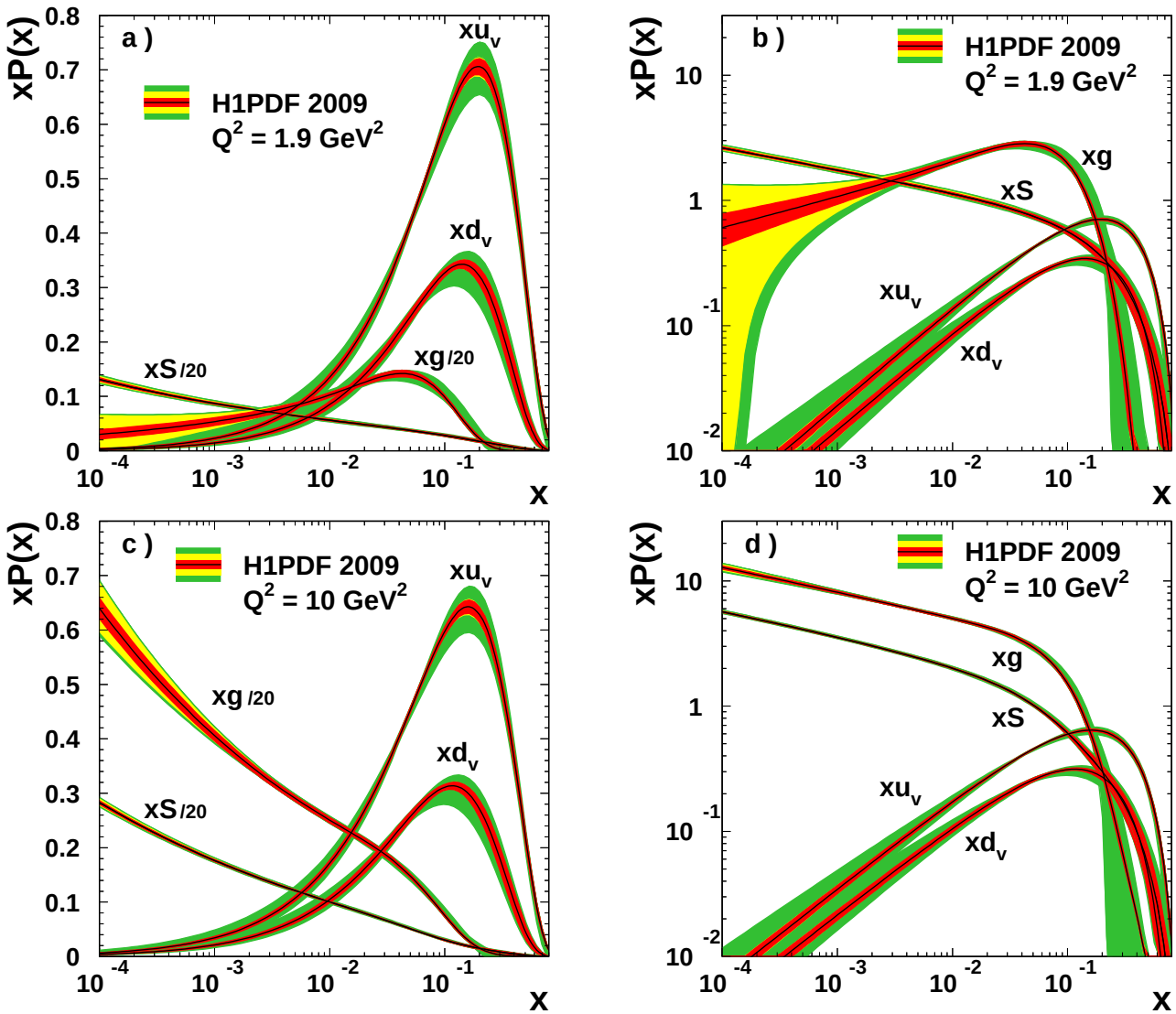
In SM, $b\bar{b} \to H$ is small vs $gg \to H$.
In MSSM, $b\bar{b} \to H$ can be enhanced by $\times \tan^2\beta$

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



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

Proton PDFs

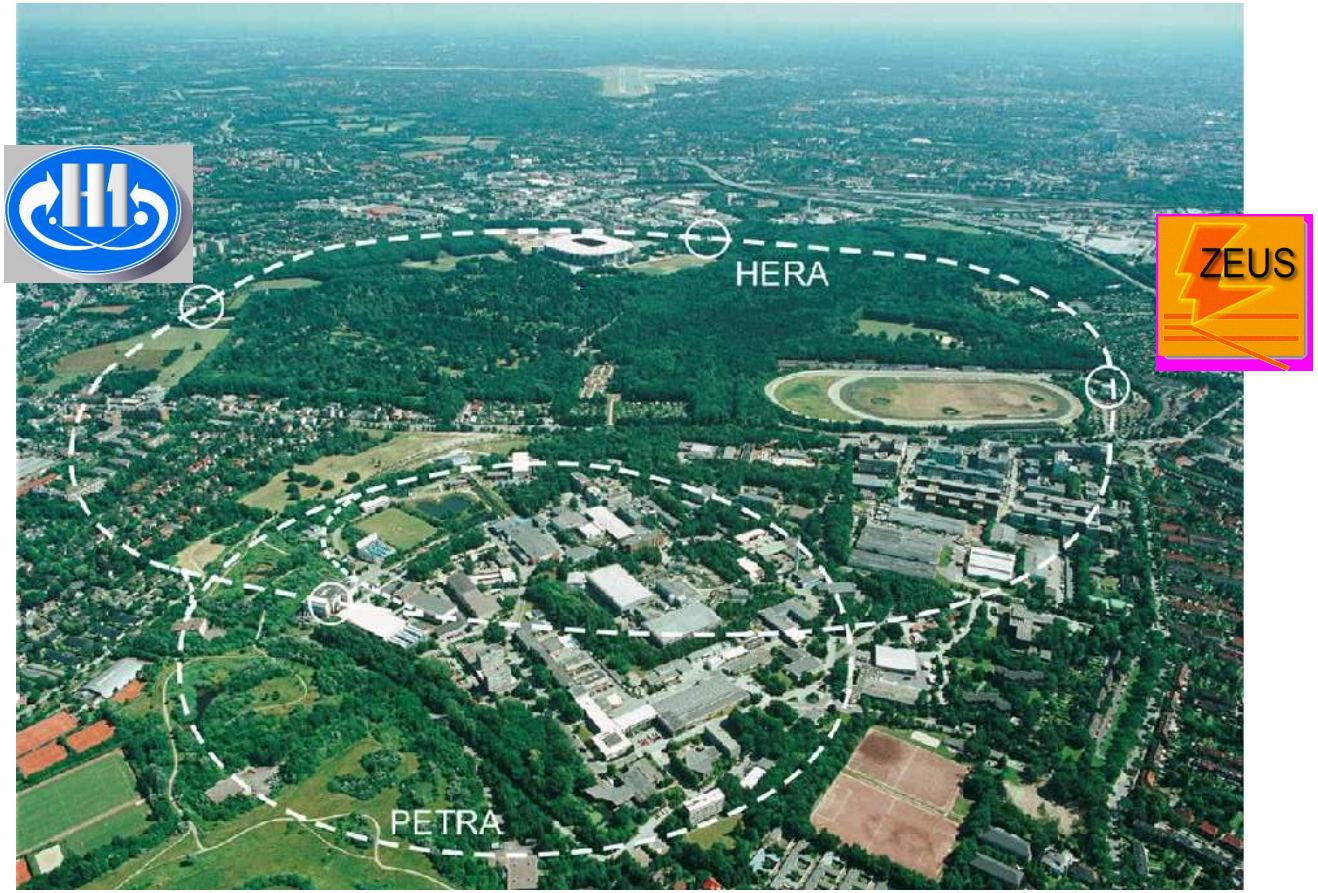


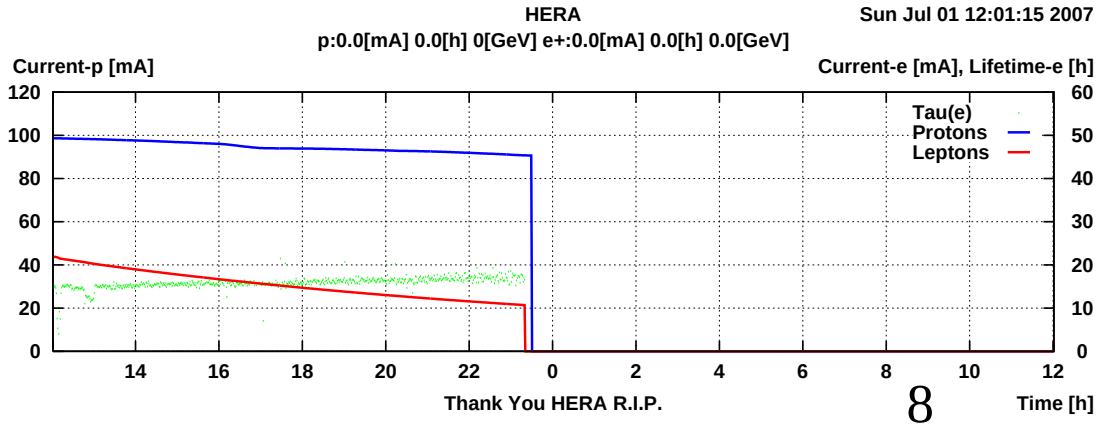
- For $x < 0.01$ xS and xG dominate.
- Very rapid evolution for xS and xG.
- Analysis based on very new H1 data.

Intermediate Summary

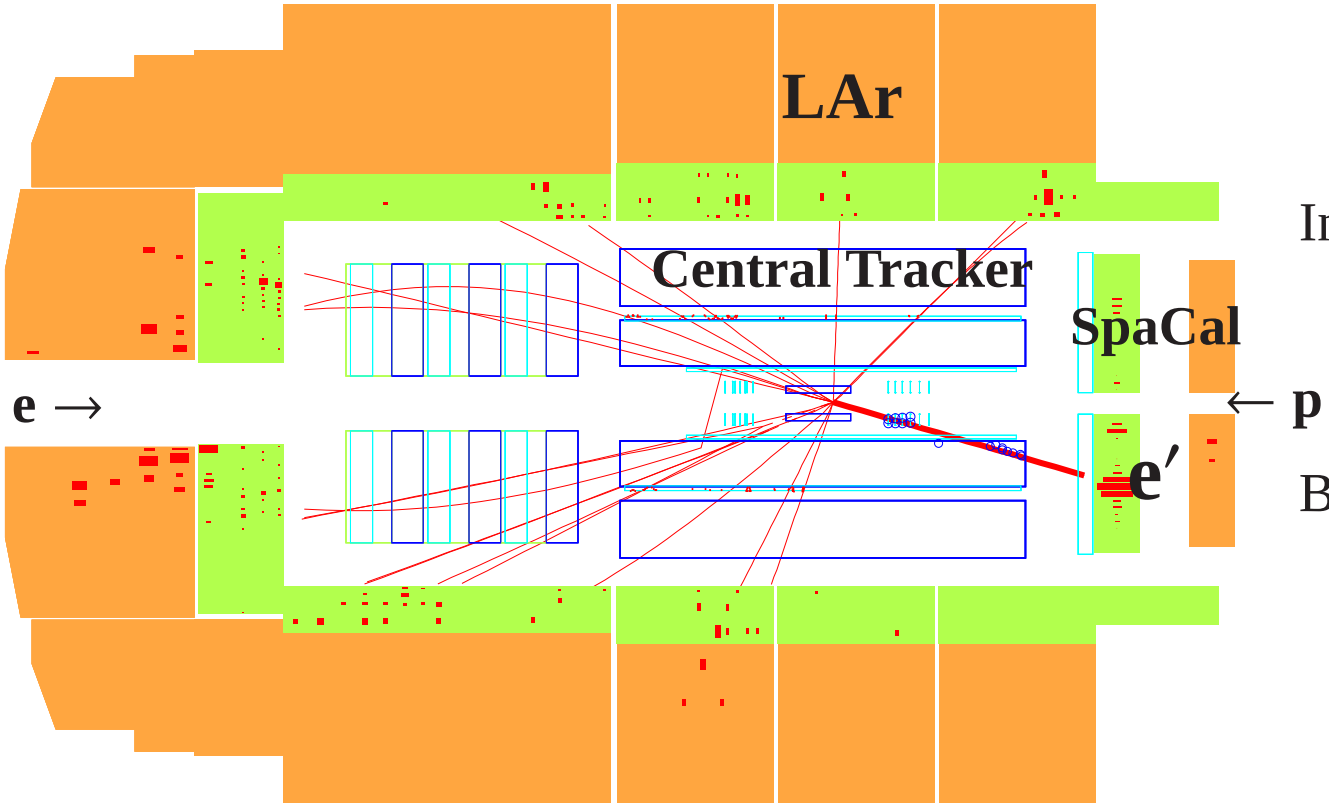
- Production of $M \sim 100$ GeV particles in the central detector region at LHC corresponds to Bjorken $0.002 < x < 0.02$.
- For this x range gluon and sea quarks dominate.
- Gluon and sea are determined from the F_2 structure function data, which for this x range come from HERA for $5 \leq Q^2 \leq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

HERA, H1 and ZEUS. 1992-2007.





DIS Event Reconstruction



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

Inelasticity:

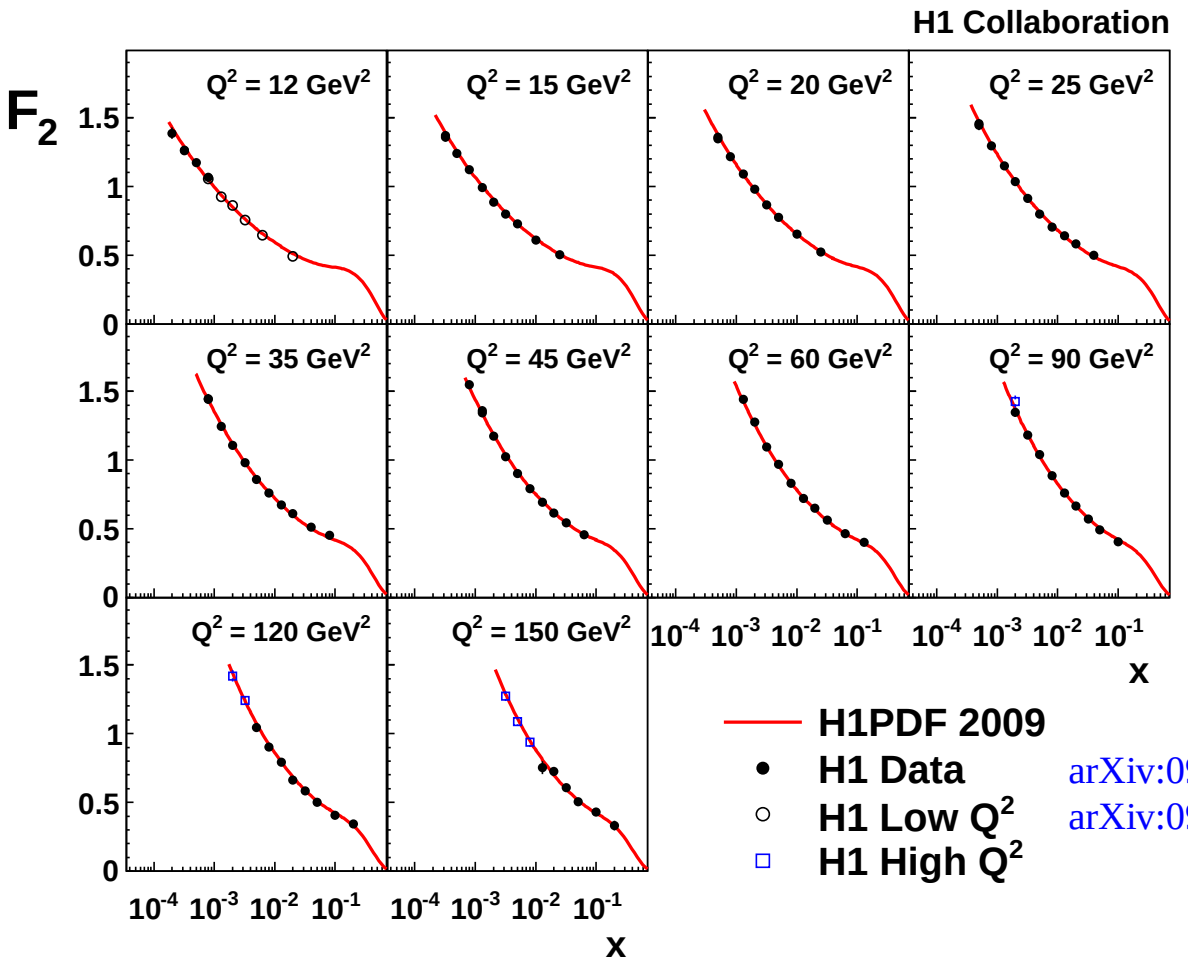
$$y = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta_e}{2}$$

Bjorken x:

$$x = \frac{Q^2}{S\,y}$$

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

Structure Function F_2 at low x

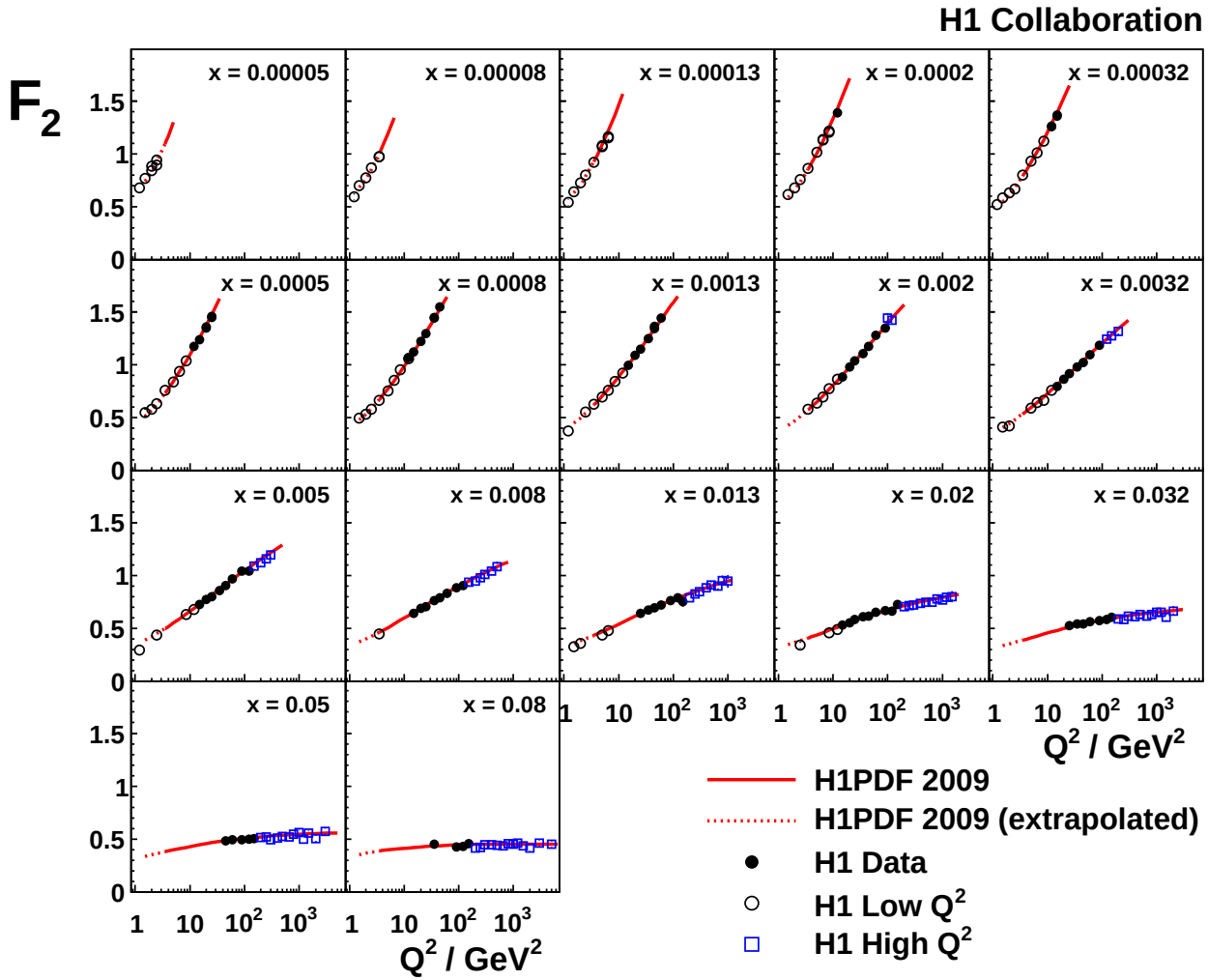


Recent measurement performed by the H1 collaboration.
Final H1 result base on HERA-I data. Precision reaches ~ 1.5%.

arXiv:0904.3513, submitted to EPJ
arXiv:0904.0929, submitted to EPJ

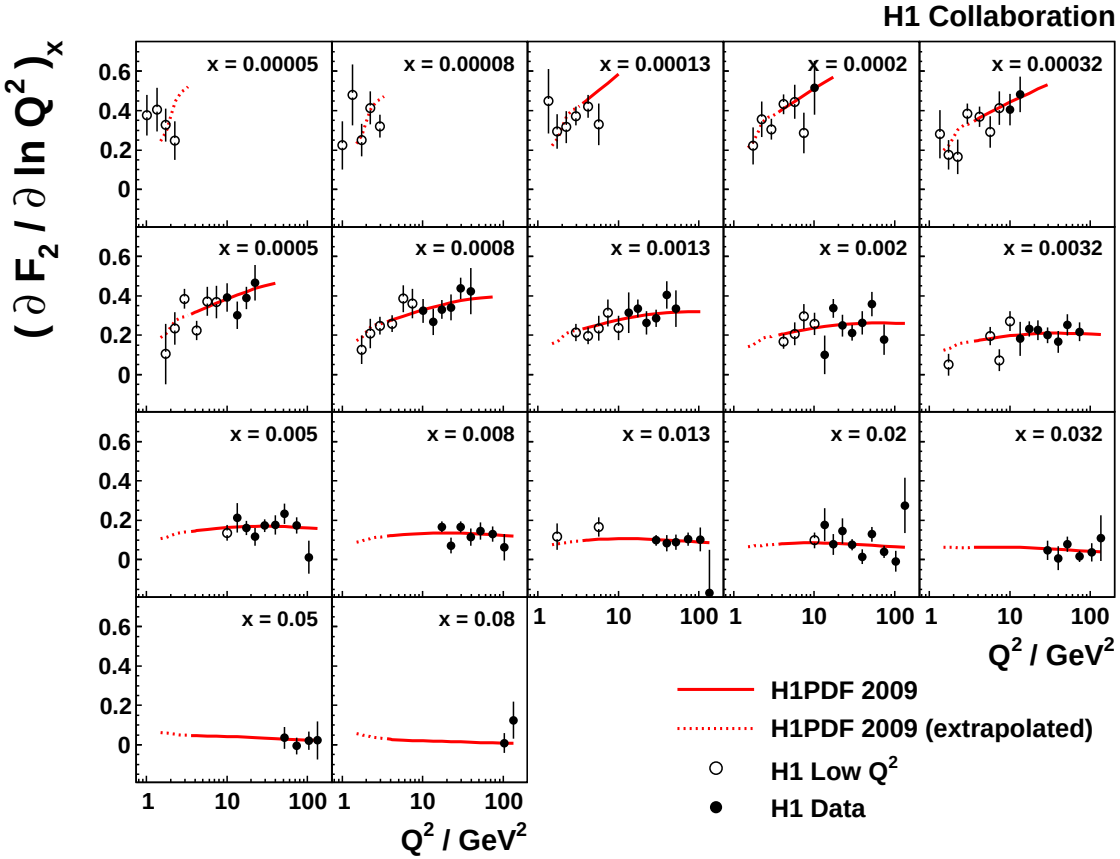
$F_2(x, Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing Q^2.

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).

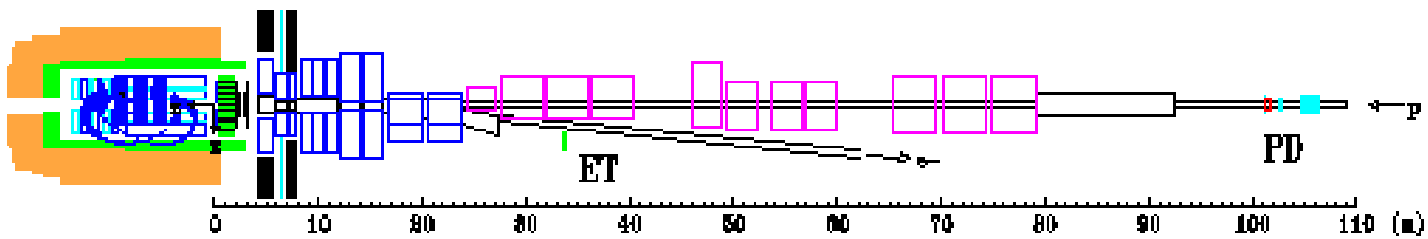
Sources of Experimental Uncertainty

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: 3σ shift generates $4.5 - 6\%$ bias with only 9 units of χ^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, σ_r^{stat} – at HERA are small for $x \sim 0.005$ range, become important for high Q^2, x.

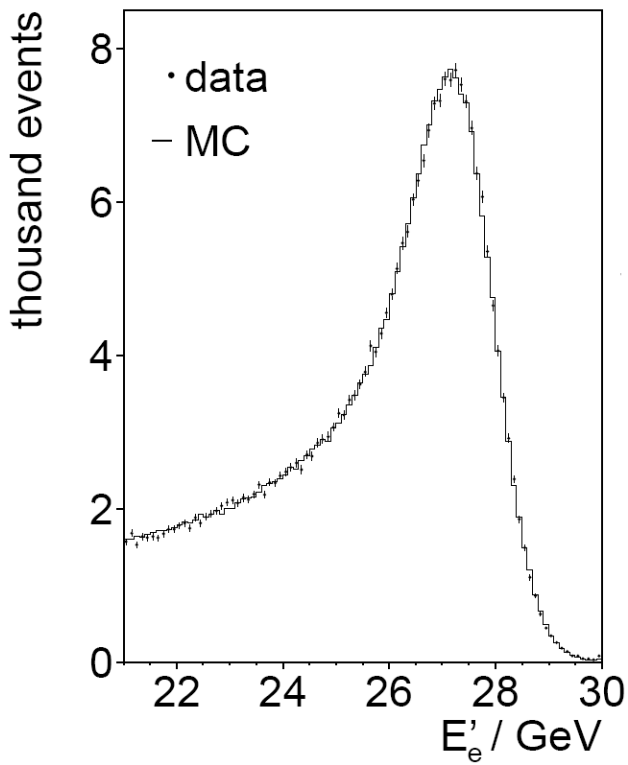
Luminosity measurement at HERA

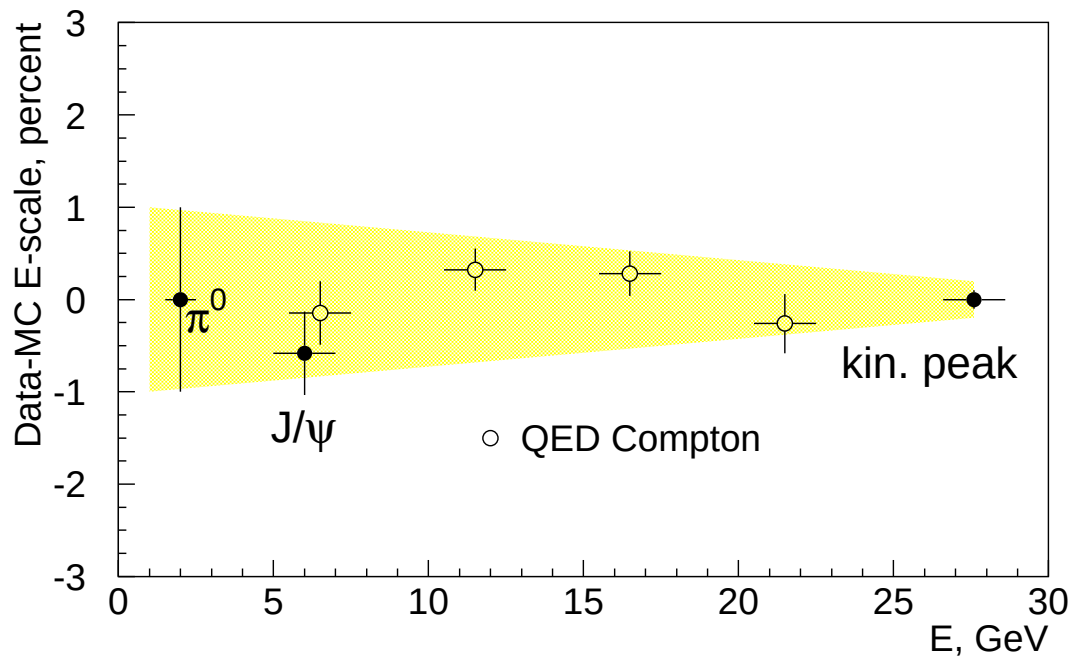


- Use $ep \to ep\gamma$ Bethe-Heitler process, detect the scattered photon in a photon tagger ~ 100 m away from the IP.
- QED prediction with 0.5% precision (effect of higher orders).
- Experimental uncertainty dominated by detector acceptance knowledge (~ 90 ± 1%), energy calibration, and beam longitudinal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

→ complicated measurement. Ultimate experimental uncertainty: 1%, uncorrelated H1 vs ZEUS.

Correlated Systematic Uncertainties

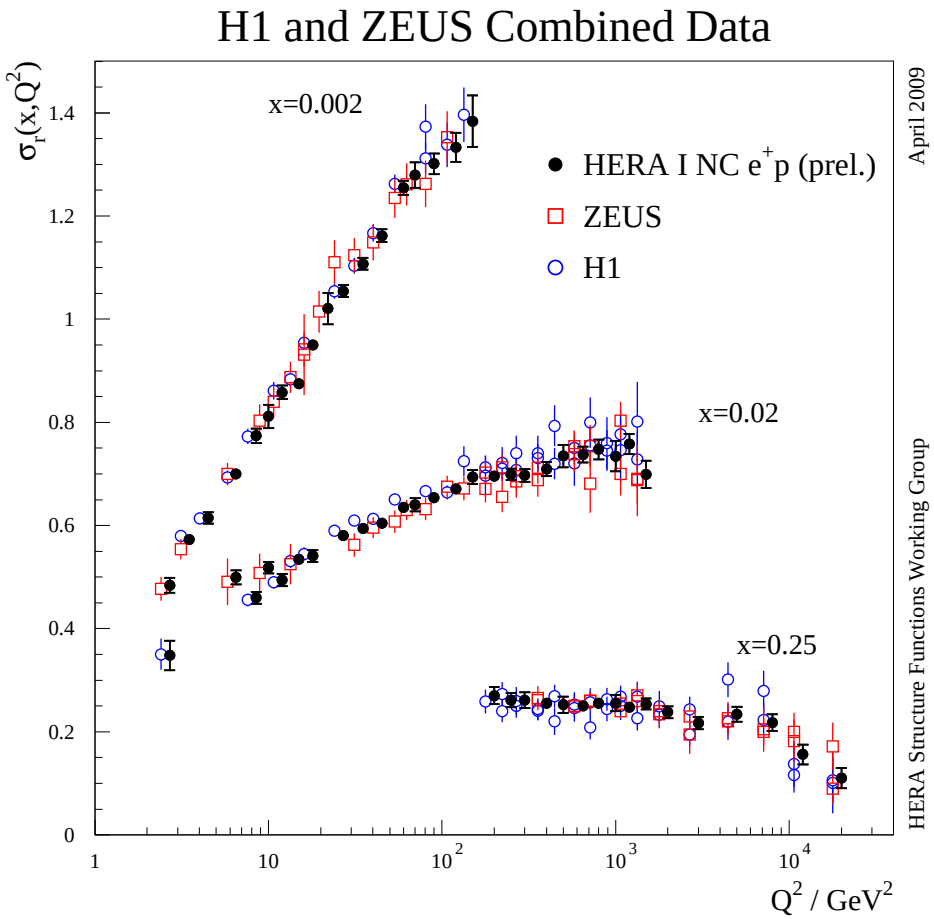




Example: scattered electron energy E'_e. Affects y, Q^2.

- 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

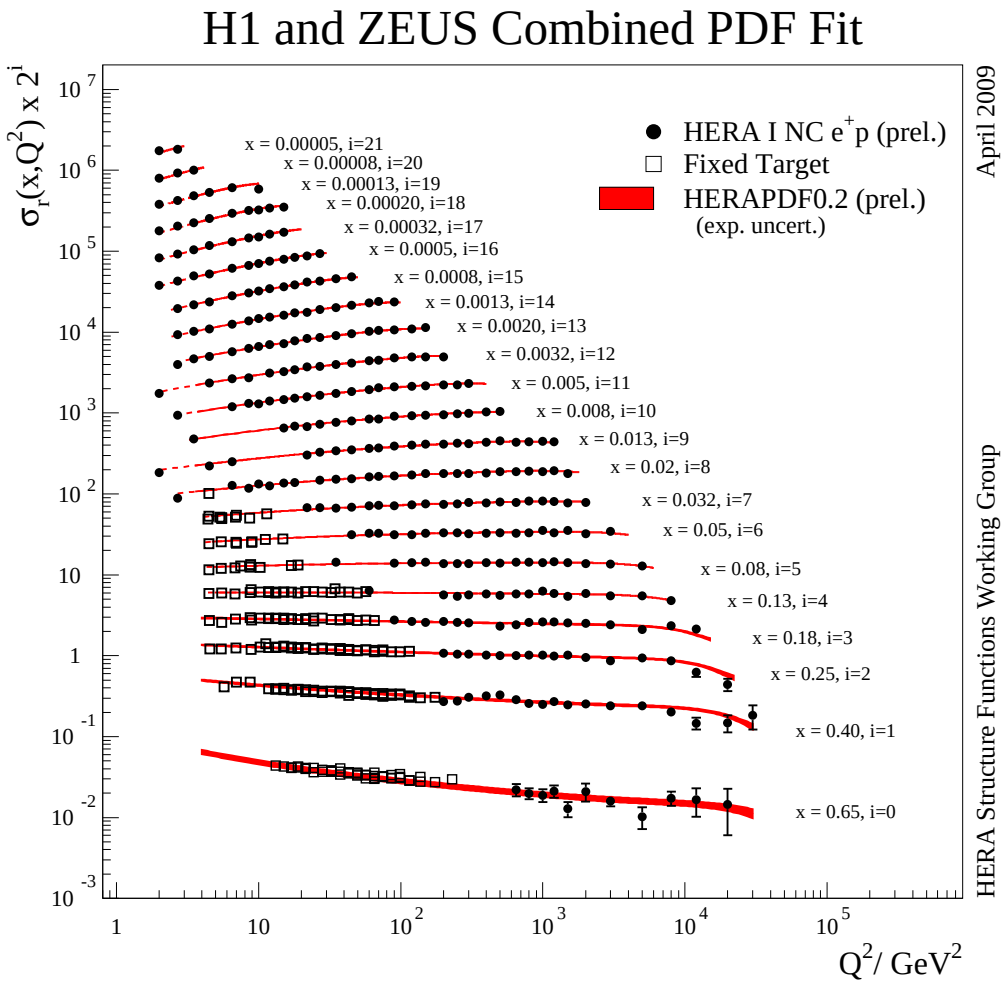


Average H1 and ZEUS data before applying QCD analysis.
Achieved by fitting σ_r values, global normalizations and the correlated systematic uncertainties.

$$\sigma_r^{\pm} = F_2 - \frac{y^2}{Y_+} \mp \frac{Y_-}{Y_+} xF_3$$

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

Combined HERA data

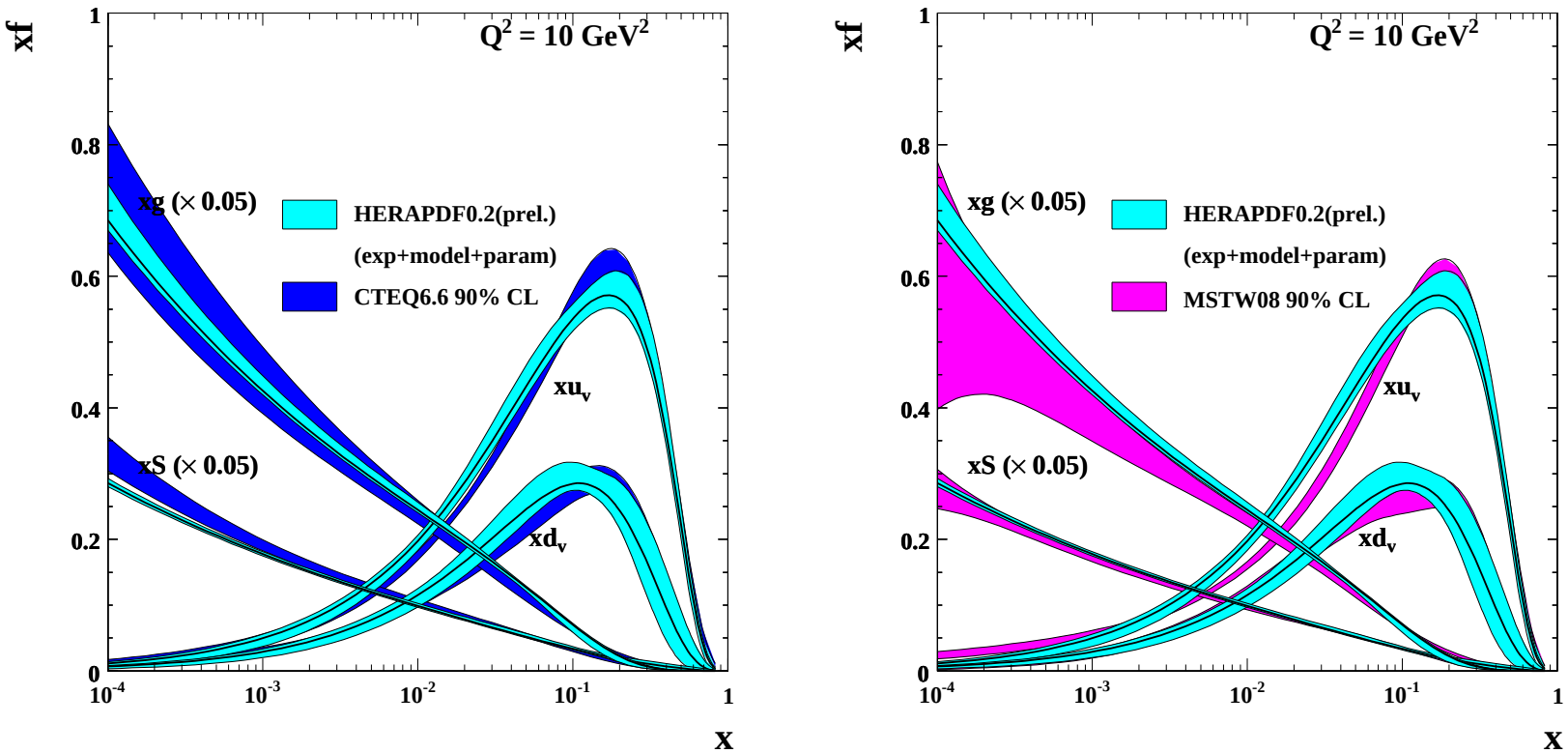


Combination of published H1/ZEUS data for CC,NC, $e^{\pm}p$ data.

$$\chi^2/dof = 637/656$$

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

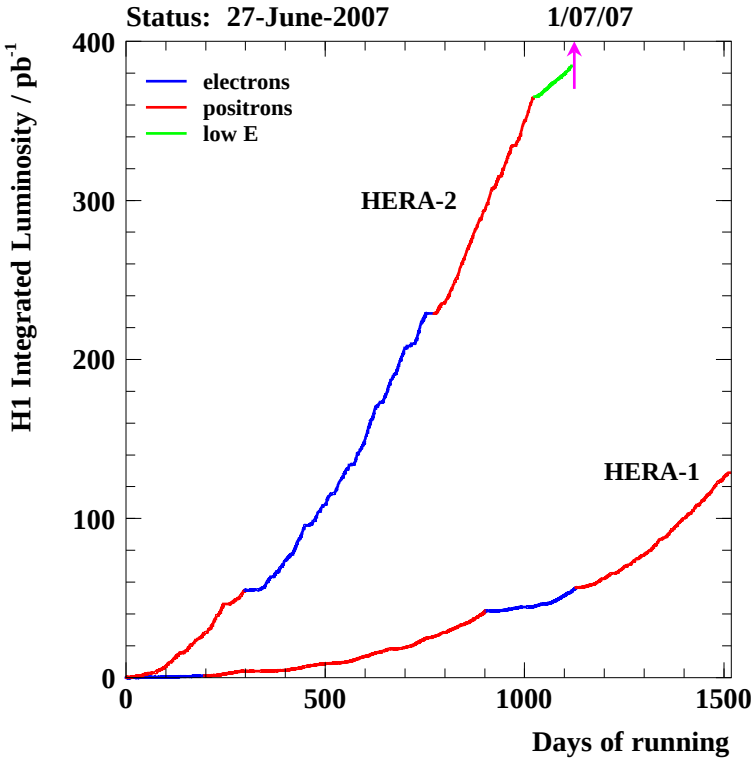
PDFs extraction

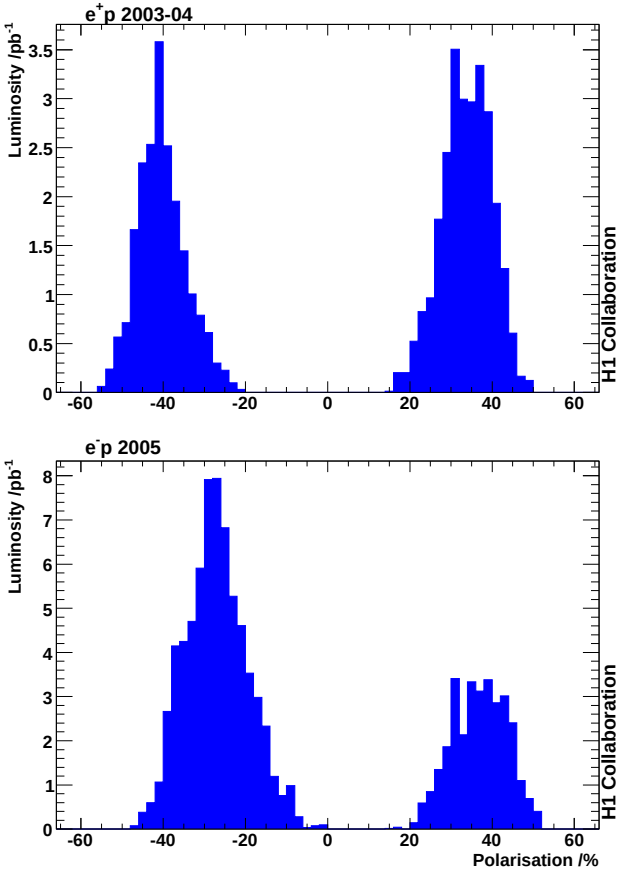


Sea S and gluon g are far more important at low x. Mind the $\times 0.05$ scale factor for them.

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.

HERA-II Results

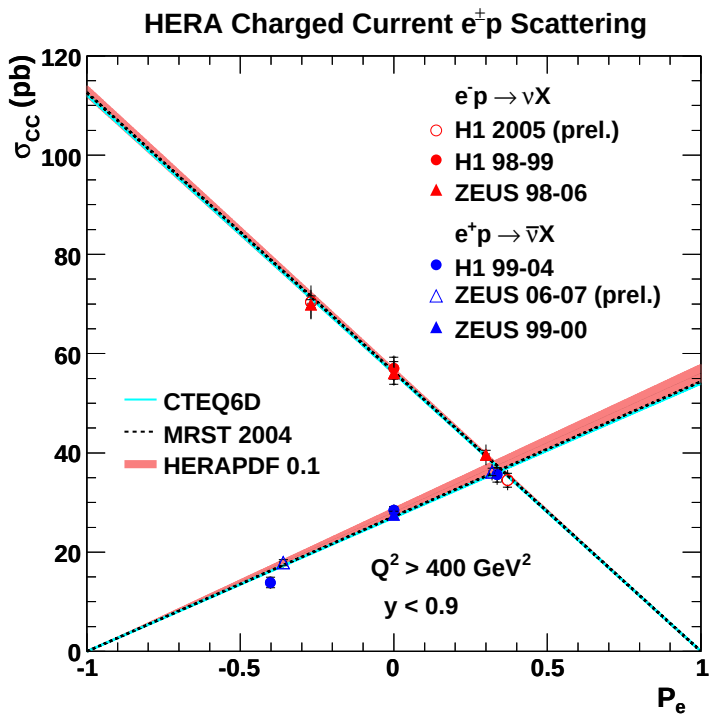




HERA-II upgrade provides better instantaneous luminosity and longitudinal beam polarization.

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

Charged Current Cross Section

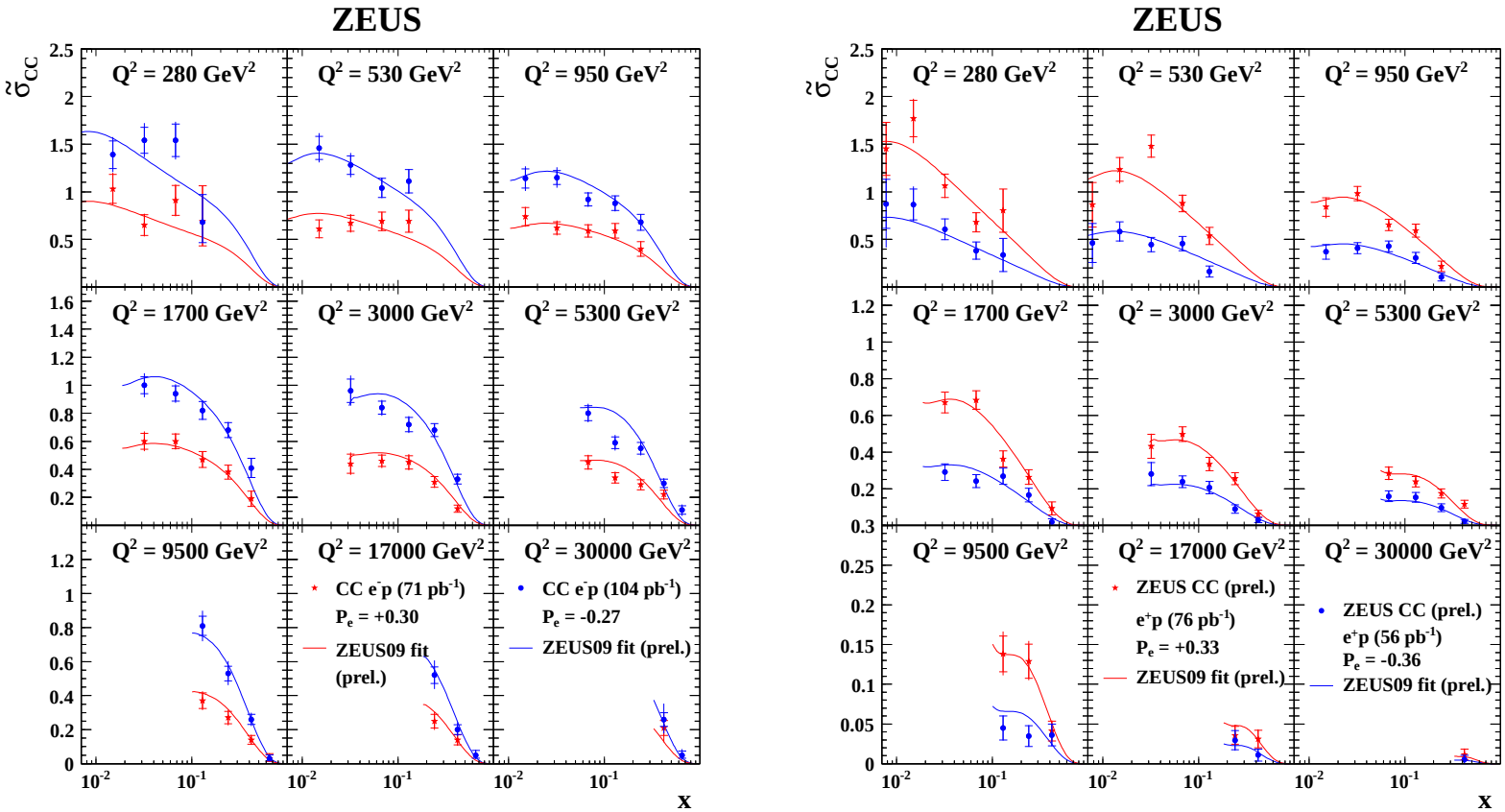


CC cross section is linearly proportional to the degree of the longitudinal beam polarization:

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

Consistent with no right-handed weak currents

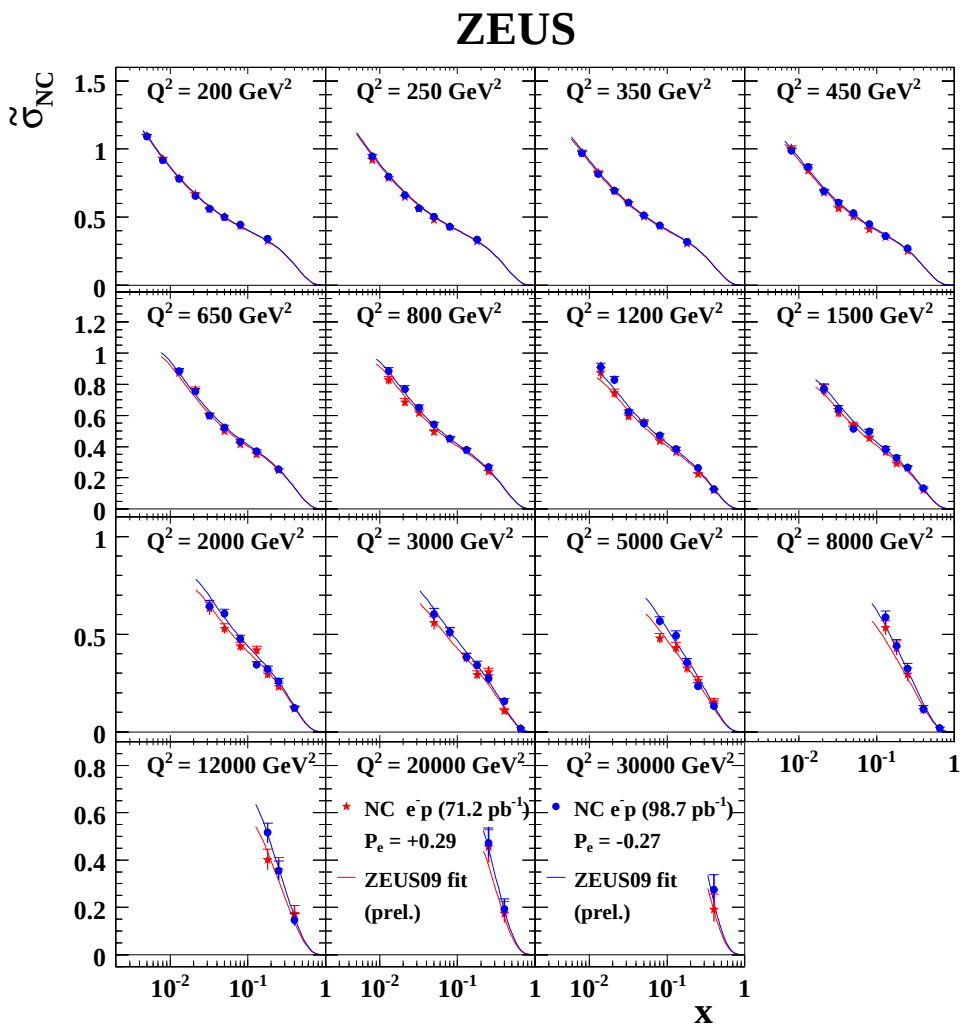
Charged Current Double Differential Cross Section



Recently ZEUS published analysis of the complete $e^- p$ sample. CC data allows to measure $D, \bar{U}$ and $U, \bar{D}$ separately.

(DESY-08-177, accepted by EPJ C)

NC Cross Section Polarization Dependence



Neglecting pure Z exchange term, generalized F_2:

$$\tilde{F}_2^{\pm} \approx F_2 + k(-v_e \mp P a_e) F_2^{\gamma Z}$$

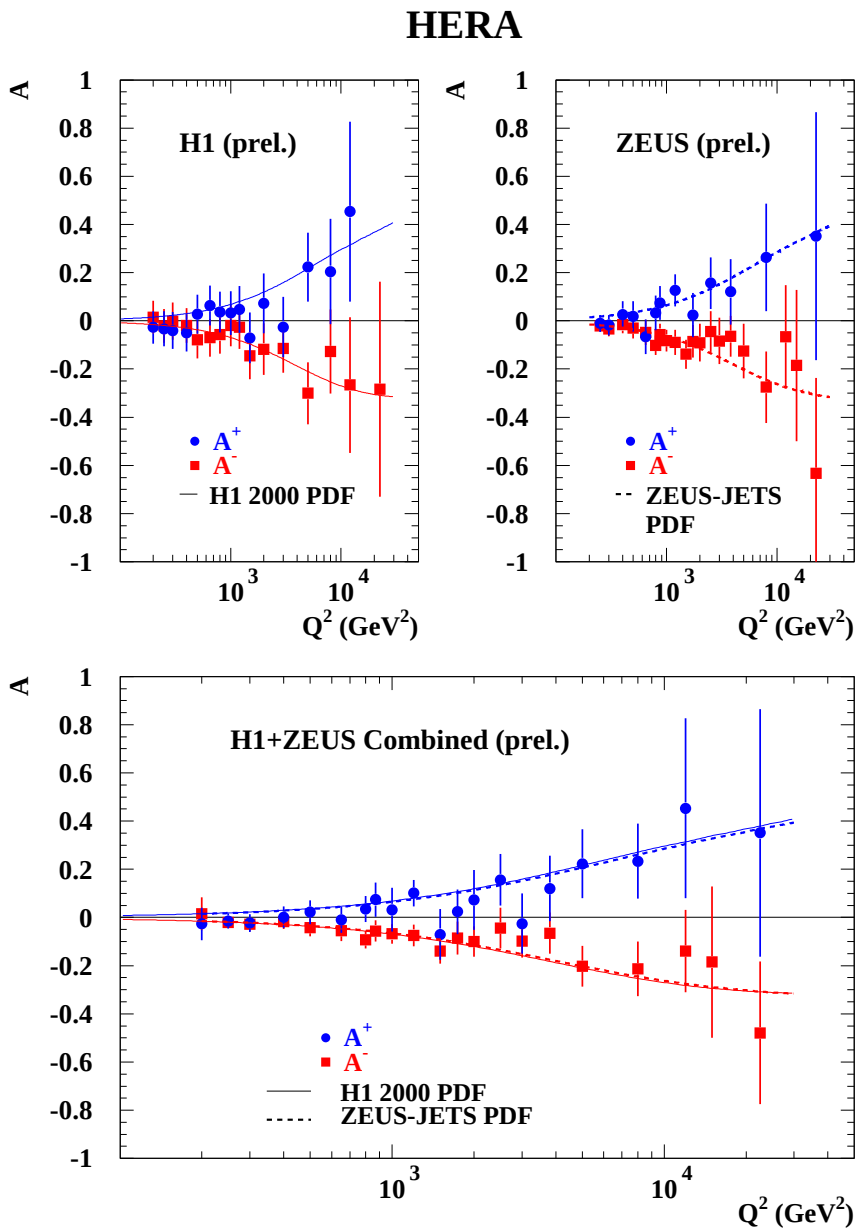
where $k = \frac{1}{4\sin^2\theta_W \cos^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$

At leading order

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

(DESY-08-202, accepted by EPJ C, Complete HERA-II sample).

NC Cross Section Polarization Dependence



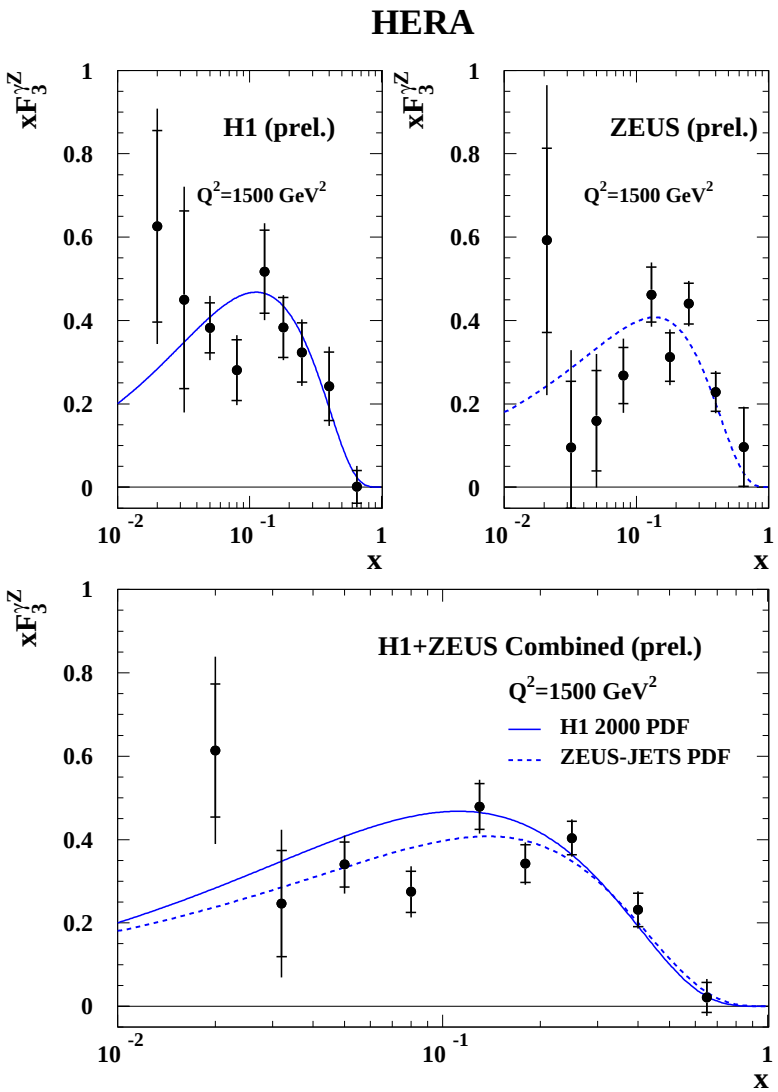
Polarization asymmetry

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx$$

$$\approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

measures directly NC parity violation.

Neutral Current Cross Section and xF_3

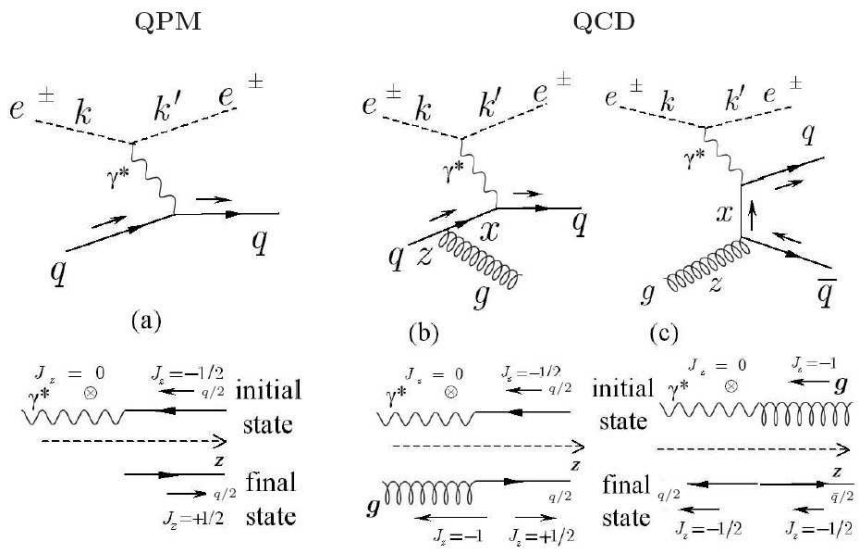


$$xF_3 = x \sum 2e_q a_q (q(x) - \bar{q}(x))$$

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.

The Proton Structure Functions at low Q^2



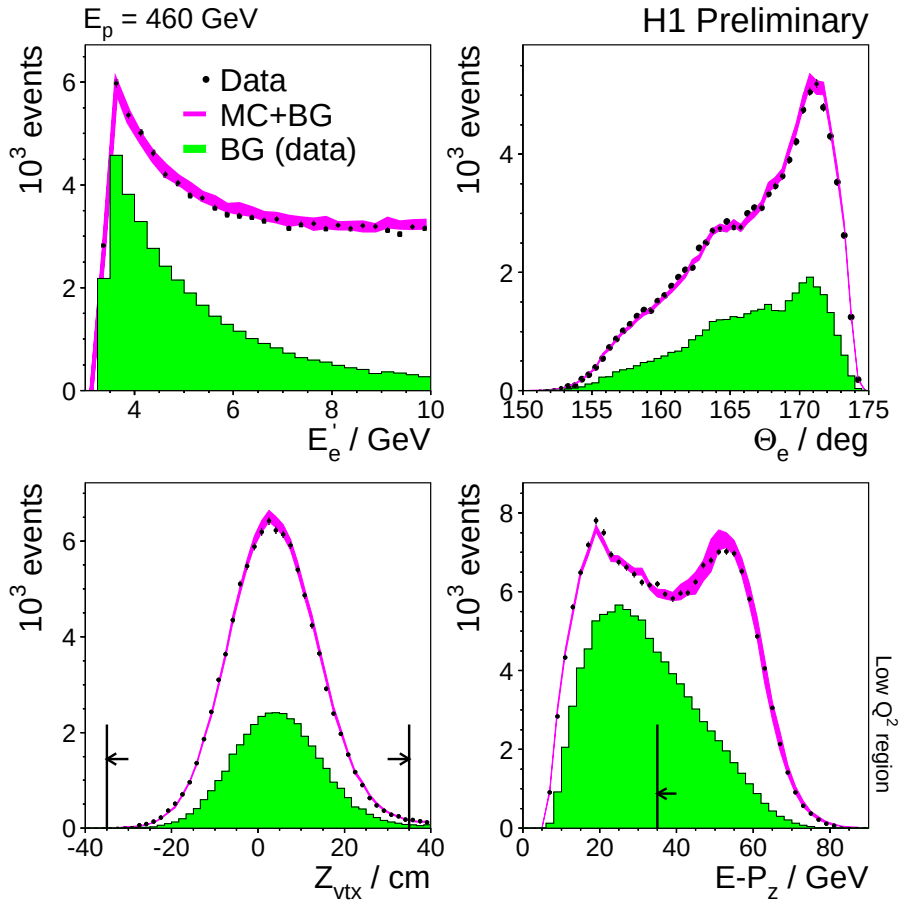
For low Q^2:

$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L \quad F_2 \sim \sigma_L + \sigma_T \quad F_L \sim \sigma_L$$

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.

Measurement of F_L.



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

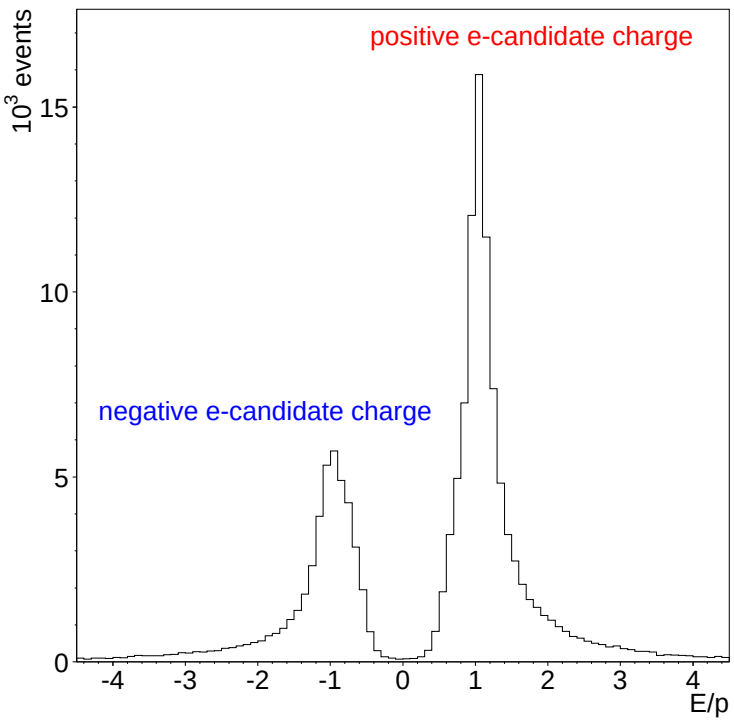
H1 estimates background directly from data using the measured charge of the electron candidate.

Background Estimation

e^+p scattering:

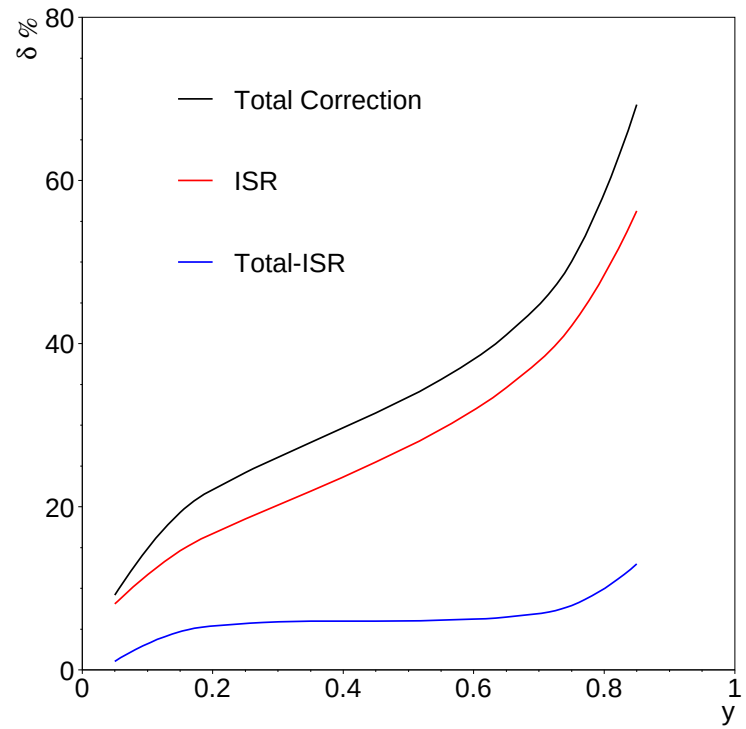
- $+$ Scattered lepton has the beam charge (positive).
- $-$ Background from hadronic particles, γ conversions is almost charge symmetric: $N^+_{bg} \approx N^-_{bg}$

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



Radiative Corrections

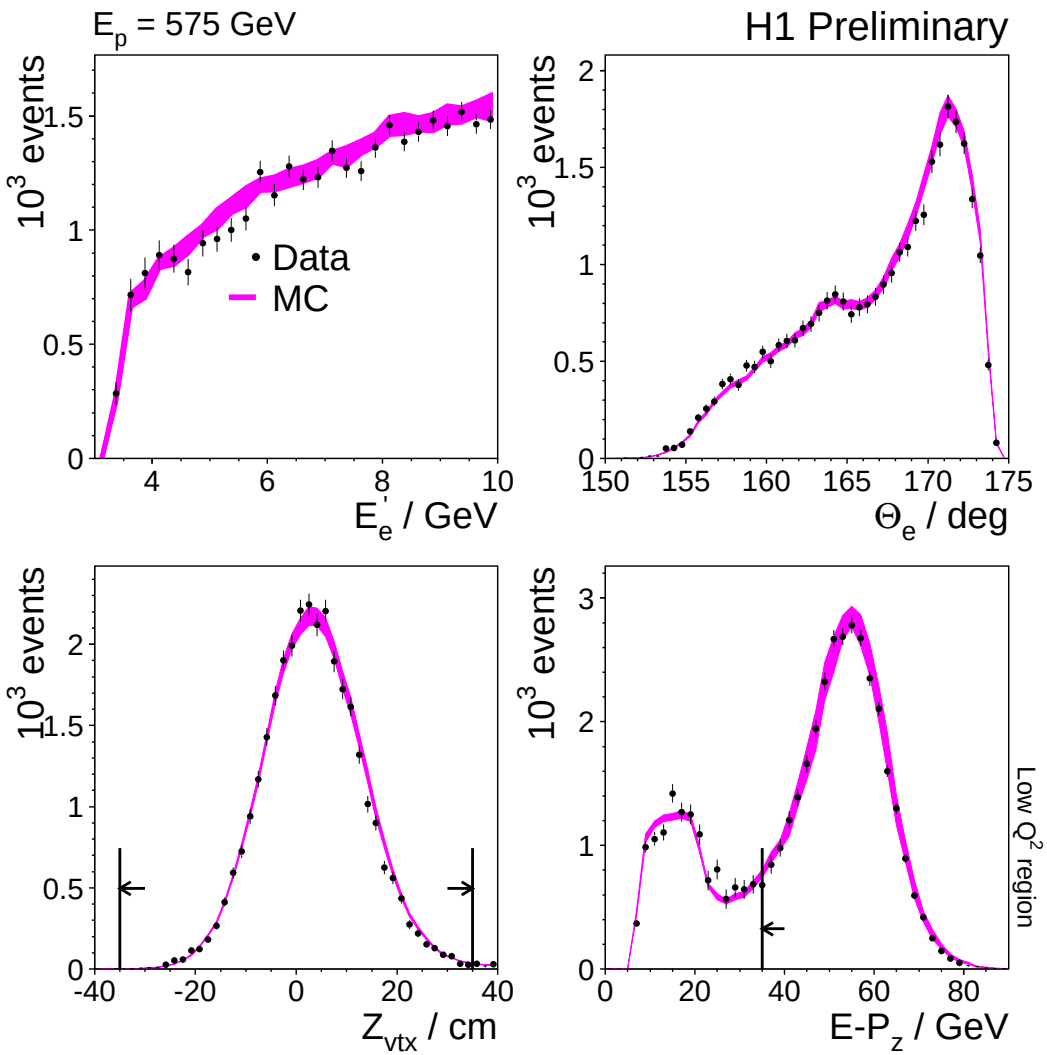
- Radiative corrections are large at high y, $\delta = \frac{\sigma_{\text{total}}}{\sigma_{\text{born}}} - 1 > 50\%$.
- Simulated in DJANGO MC, checked with HECTOR program.
- Mostly from initial state radiation (ISR) - radiative return to low y and low Q^2 ($\sigma \sim 1/y$ and $\sigma \sim 1/Q^4$).



Remove/check ISR radiation using the measured lepton beam energy:

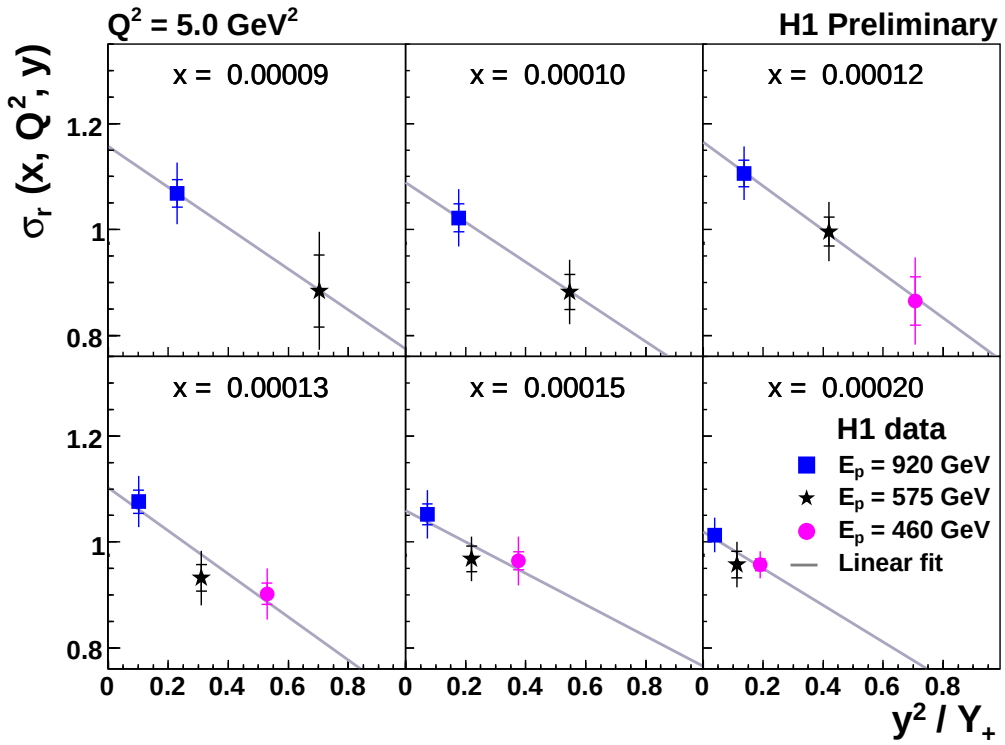
$$2E_e \approx E - p_Z|_{in} = E - p_Z|_{out} = \sum_h \left(E^h - p_Z^h\right) + \sum_e \left(E^e - p_Z^e\right) \equiv E - p_Z$$

Control plots: High y low Q^2 (SpaCal)



- After background subtraction
- $E_p = 460$ GeV
- $E'_e > 3.4$ GeV.
- Lines indicate cut values
- $E - p_z$ is effective against ISR radiation

F_L extraction



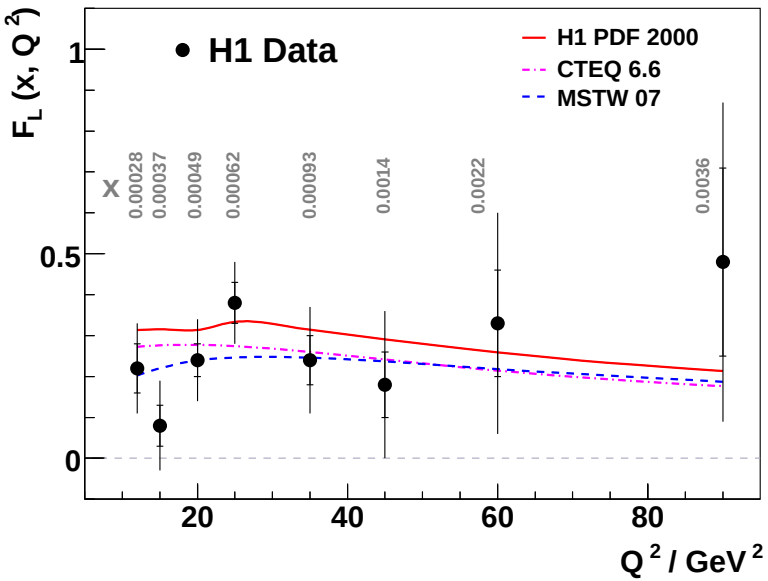
$$\sigma_r(y) = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

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

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

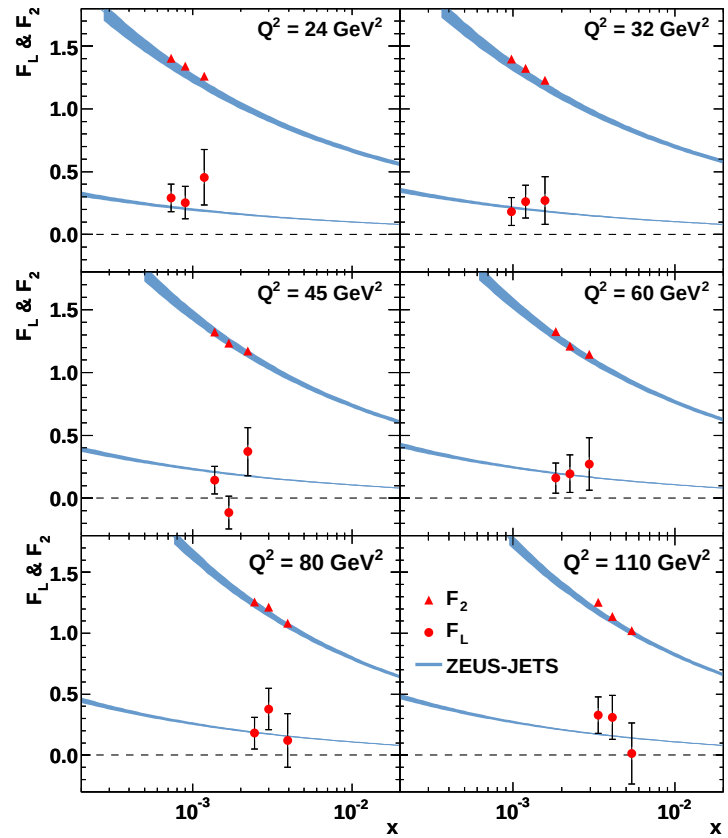
Consistent slope — consistent F_L for different x bins.

Published H1 and ZEUS F_L results



Phys.Lett. **B665** 139, 2008.

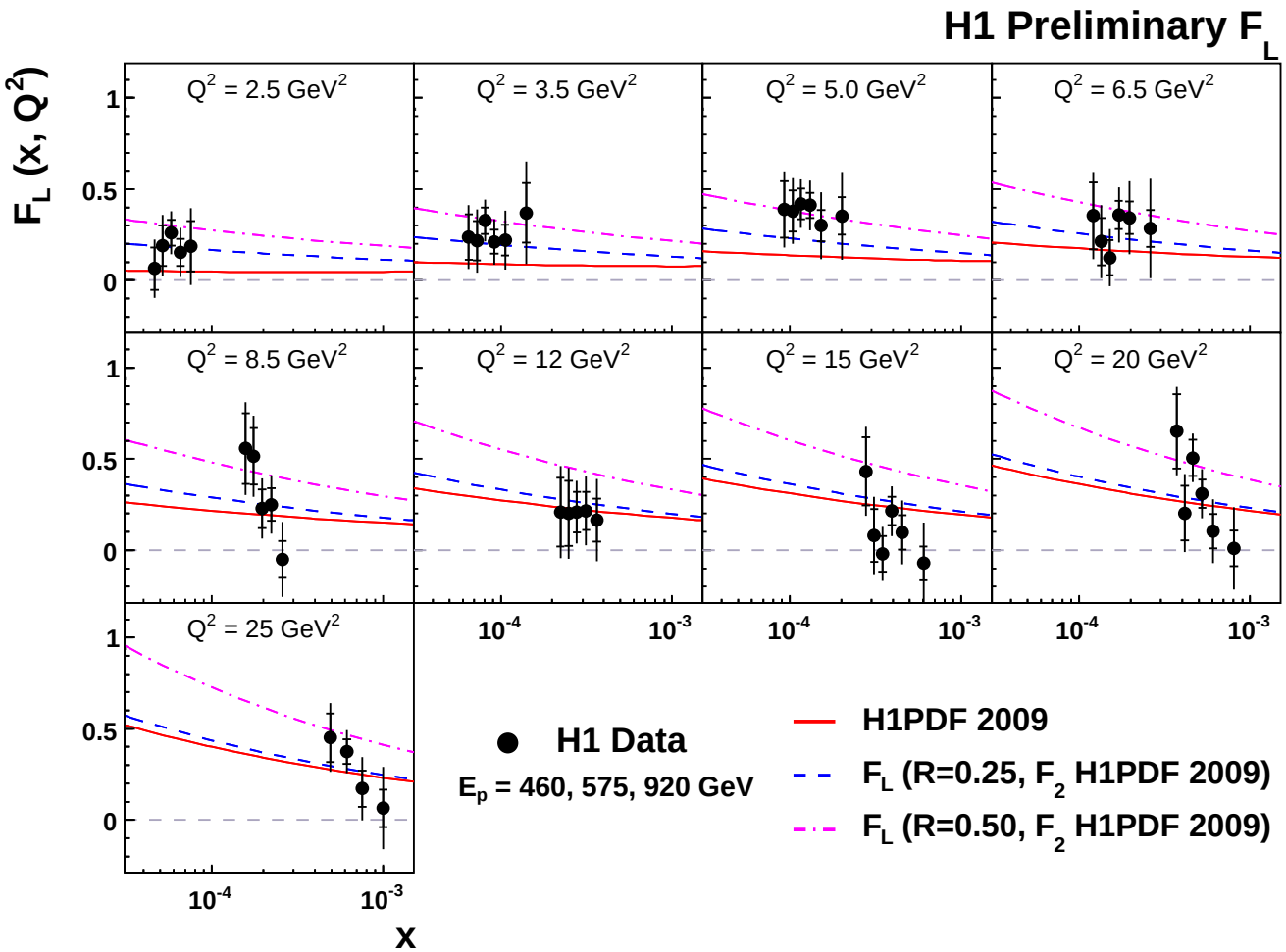
ZEUS



DESY-09-046, to be published in Phys. Lett. B

Both H1 and ZEUS collaborations published their first measurements of F_L. ZEUS also extracts F_2 without any assumption on F_L.

H1 extension to low Q^2



Using the backward silicon tracker, H1 extended the measurement to low Q^2.

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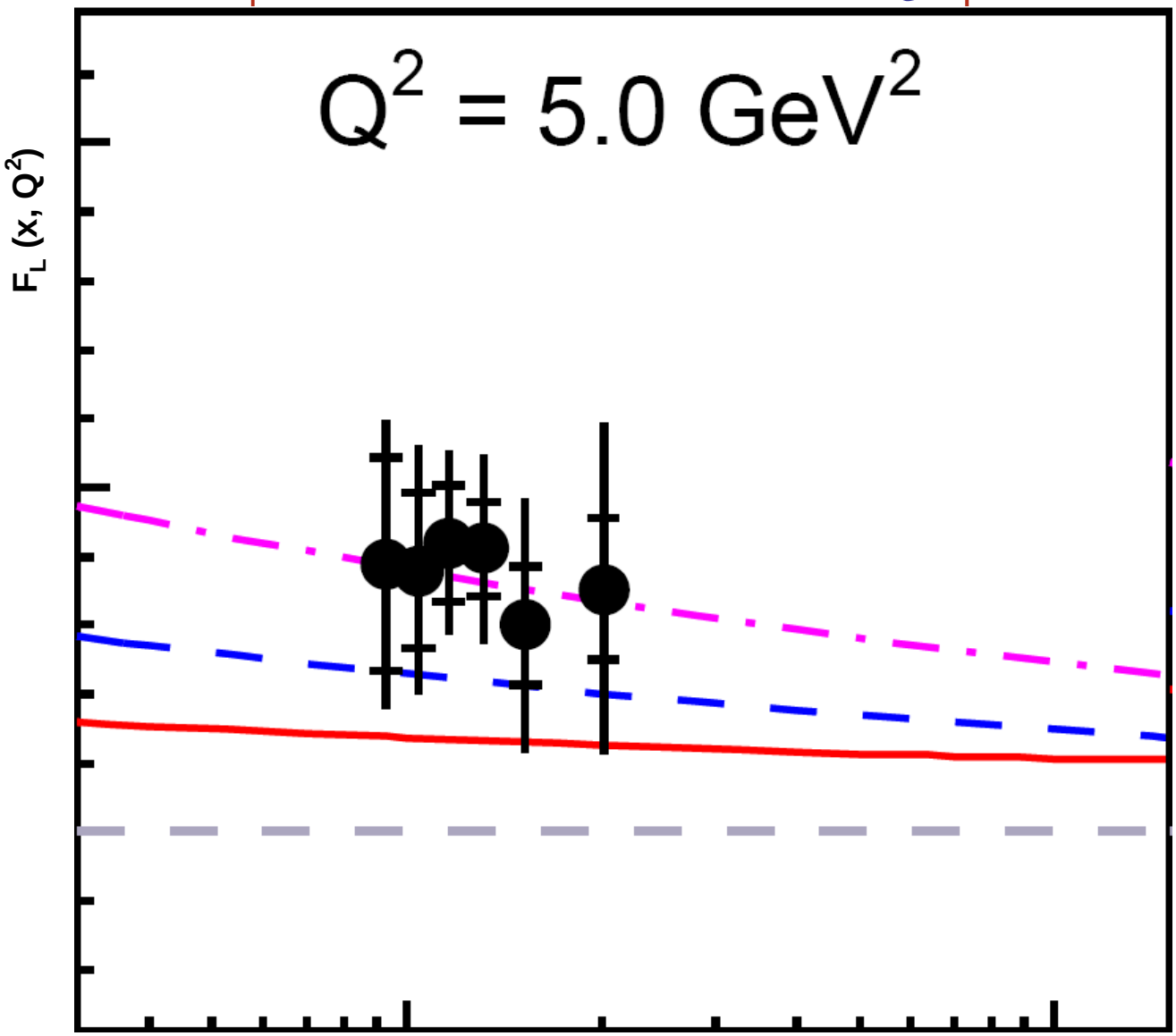
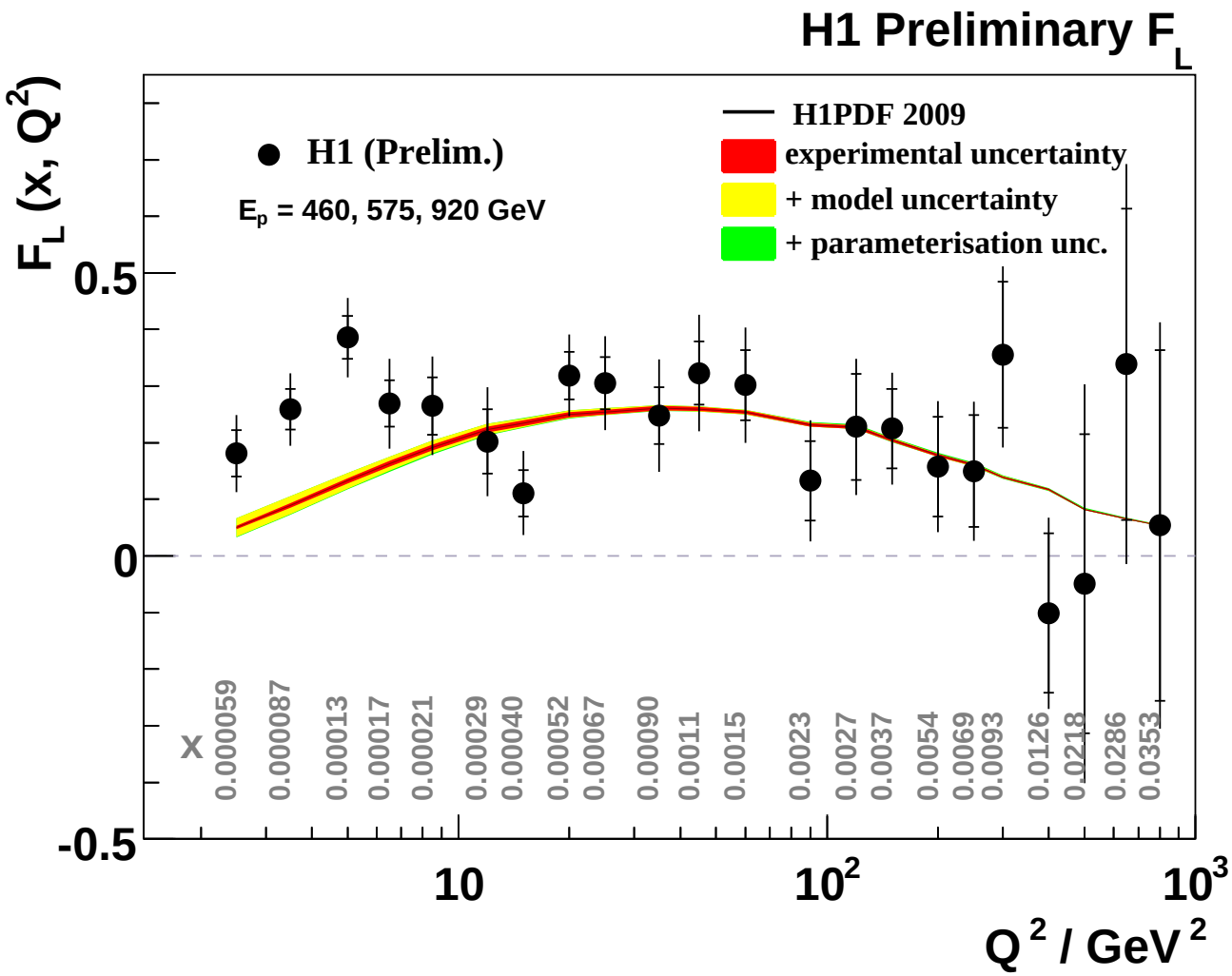


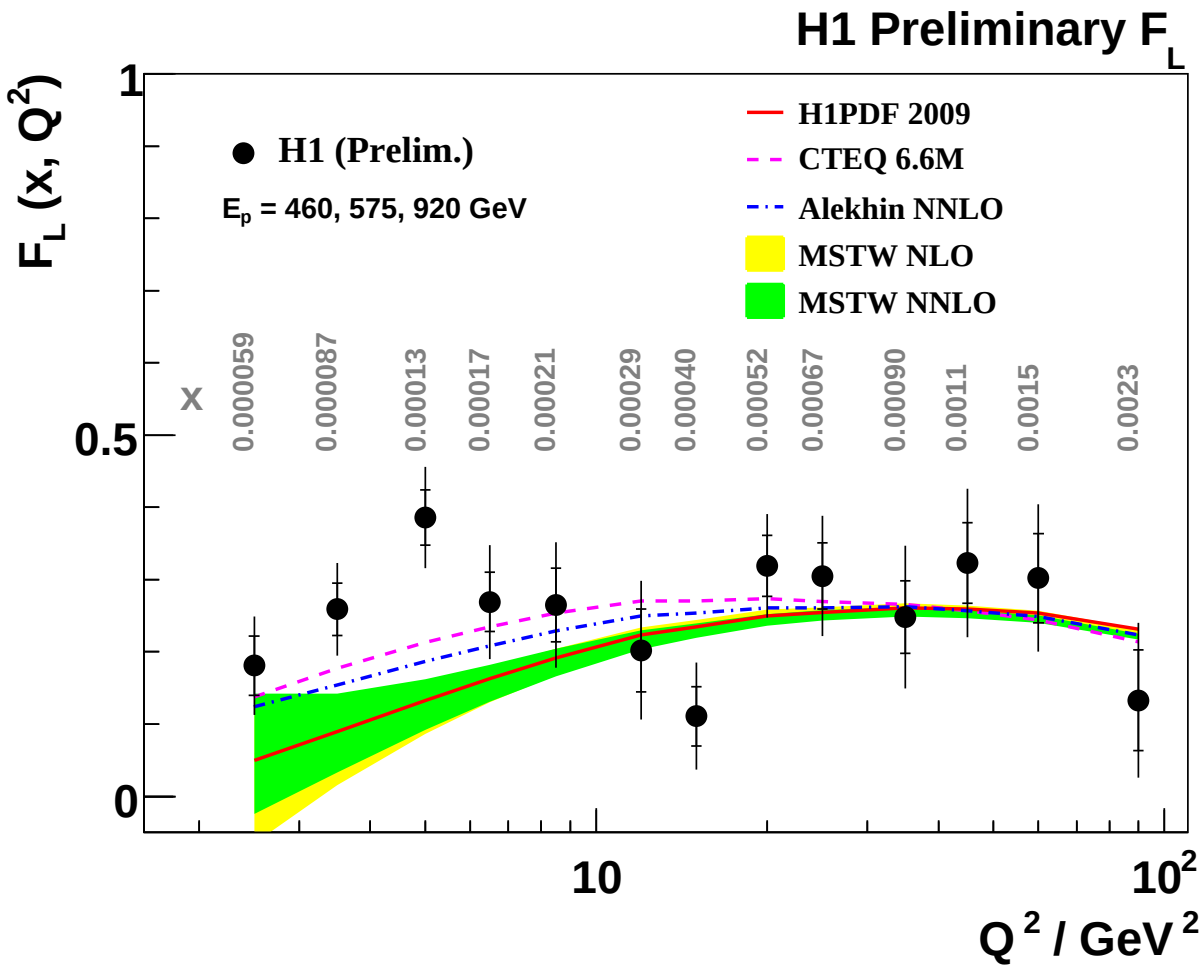
Using the backward silicon tracker, H1 extended the measurement to low Q^2.

F_L measured by H1



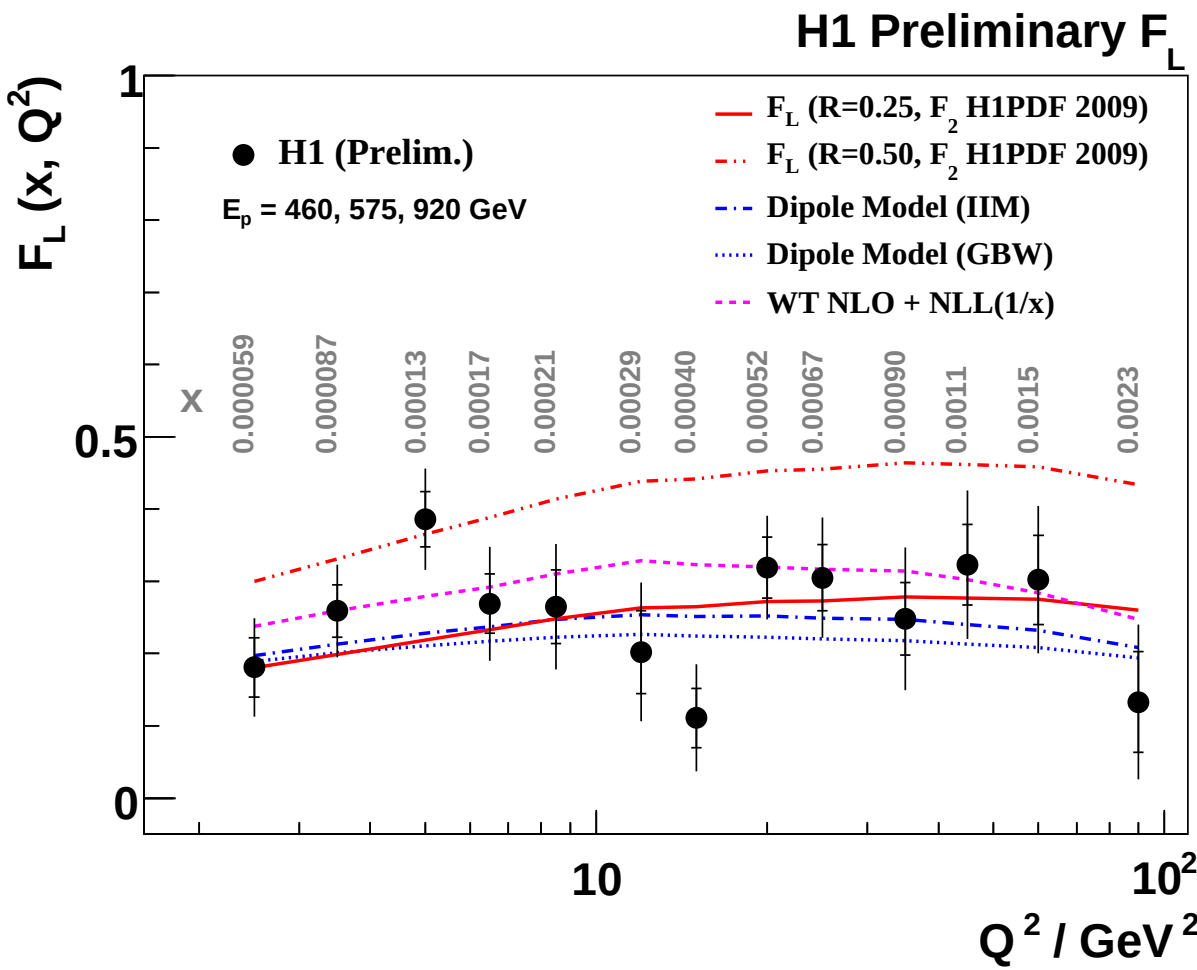
H1 measurements cover $2.5 \leq Q^2 \leq 800$ GeV^2 and $0.00005 \leq x \leq 0.04$ range
For $Q^2 \geq 10$ GeV^2, agree well with H1PDF 2009 prediction.

F_L measured at $Q^2 < 100$ GeV^2



MSTW and H1PDF 2009 predictions use the same scheme to calculate F_L.
Data agree better with calculation of CTEQ.

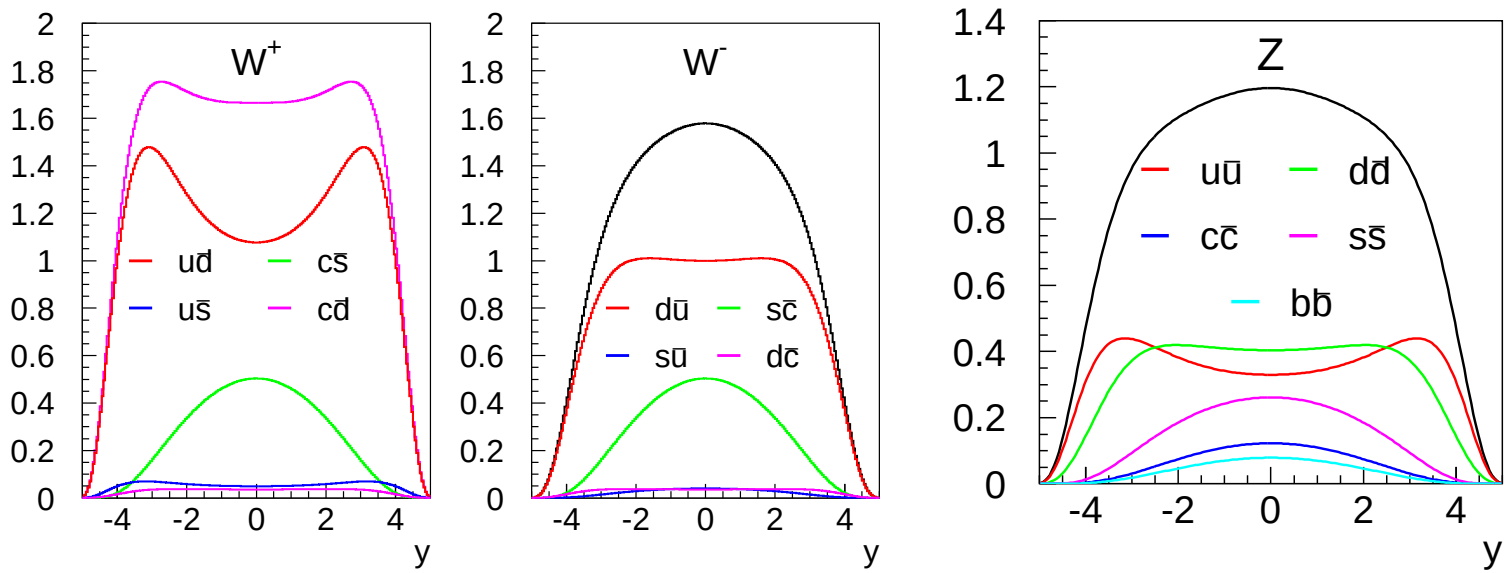
F_L vs phenomenological models.



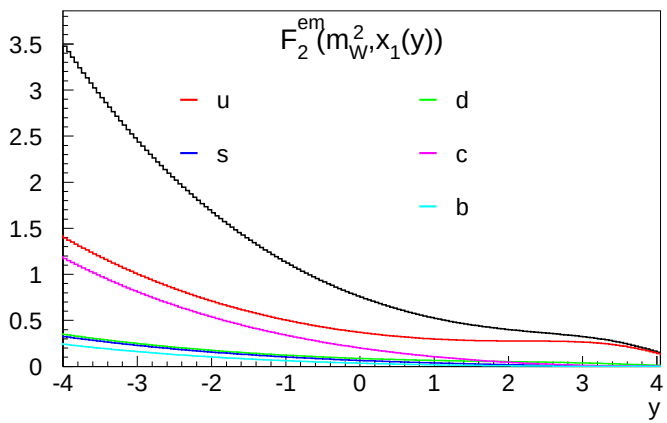
Dipole Models:
fits to low Q^2 H1 data

Data is consistent with constant $R \sim 0.25$.
Good agreement with IIM and GBW dipole models, NLL(1/x) prediction.

Flavor Decomposition for processes at the LHC

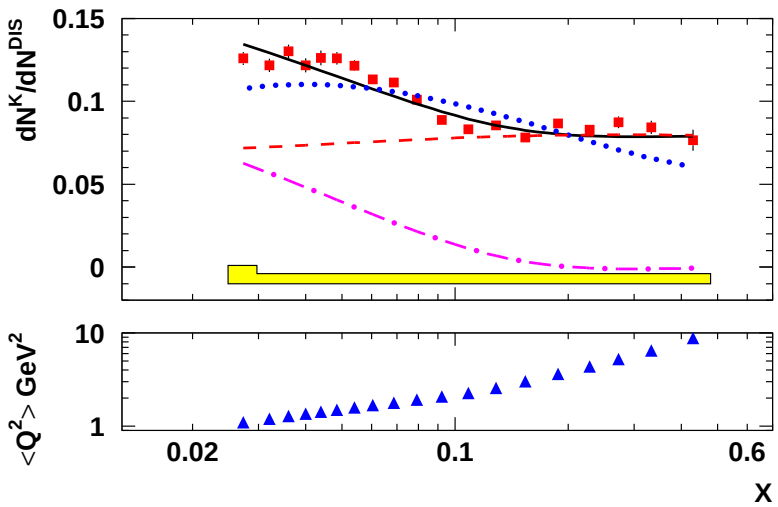


We want to have
predictions for W^+, W^-, Z with the main experimental input from F_2^{em}:



- For LHC, more important d, s quarks
- For Z, significant contribution from b.

Measurement of $xS(x)$ by HERMES

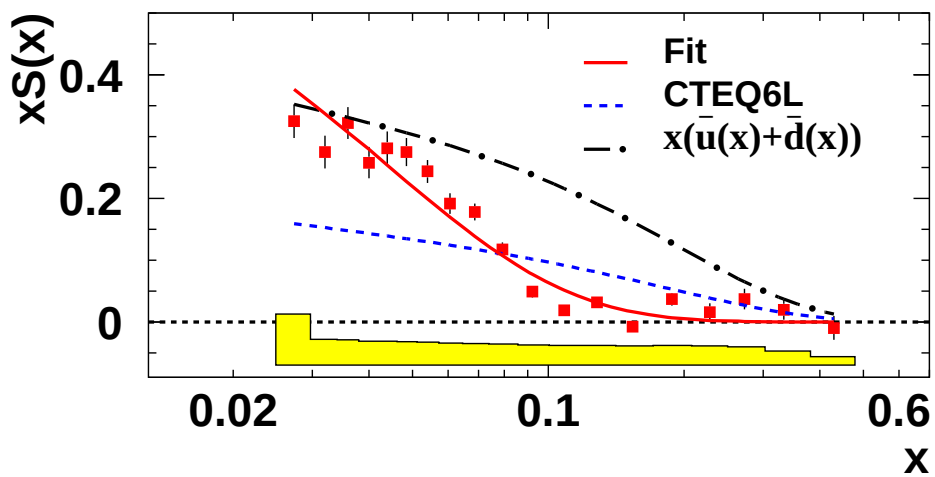


Measure $K^{\pm}$ prduction on deuteron target compared to inclusive DIS.

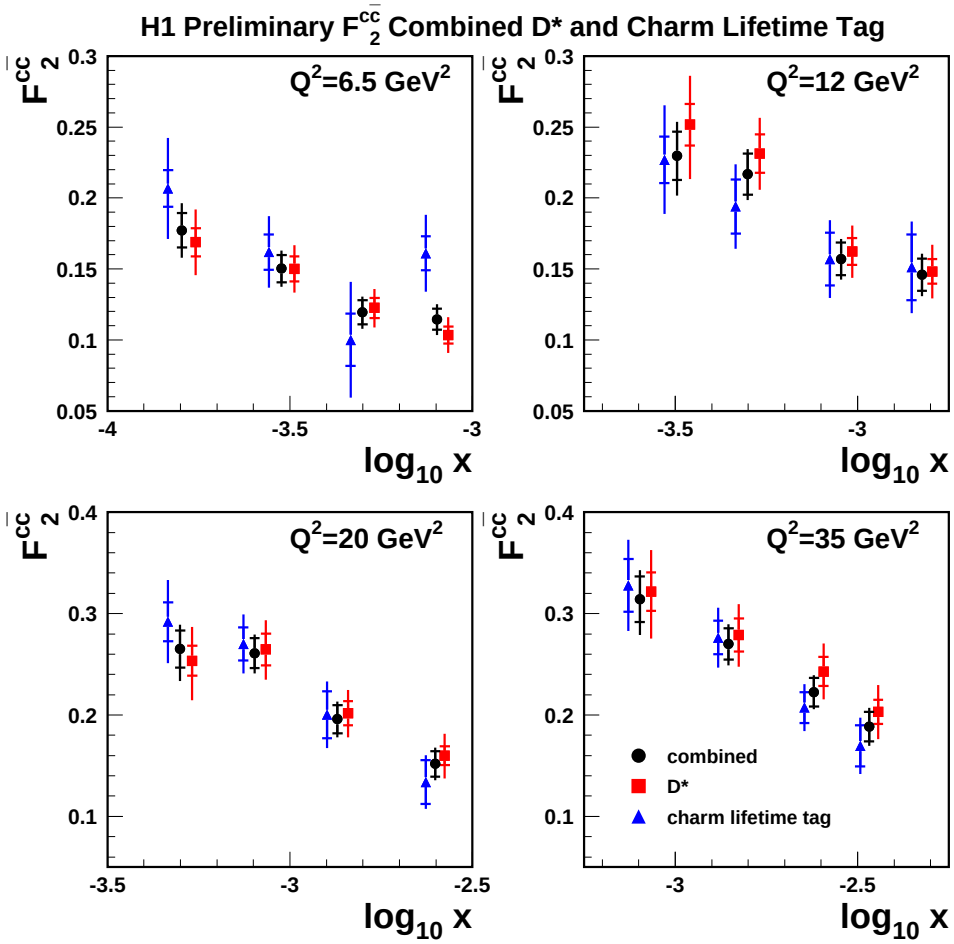
$$S(x)\int D_S^K(z)dz \approx Q(x)\left[5\frac{d^2N^K(x)}{d^2N^{DIS}(x)} - \int D_Q^K(z)dz\right]$$

Based on flatness of $dN^K(x)/dN^{DIS}(x)$ for high x, assume $S(x) = 0$ for $x > 0.15$, measure the fragmentation function $\int D_Q^K(x)dz$.

Subtracting the contribution of $\int D_Q^K(x)dz$, evolving to Q^2=2.5 GeV^2 and using an external value of the fragmentation function $\int D_S^K(x)dz$, $xS(x)$ distribution is obtained:



Measurements of $F_2^{c\bar{c}}$

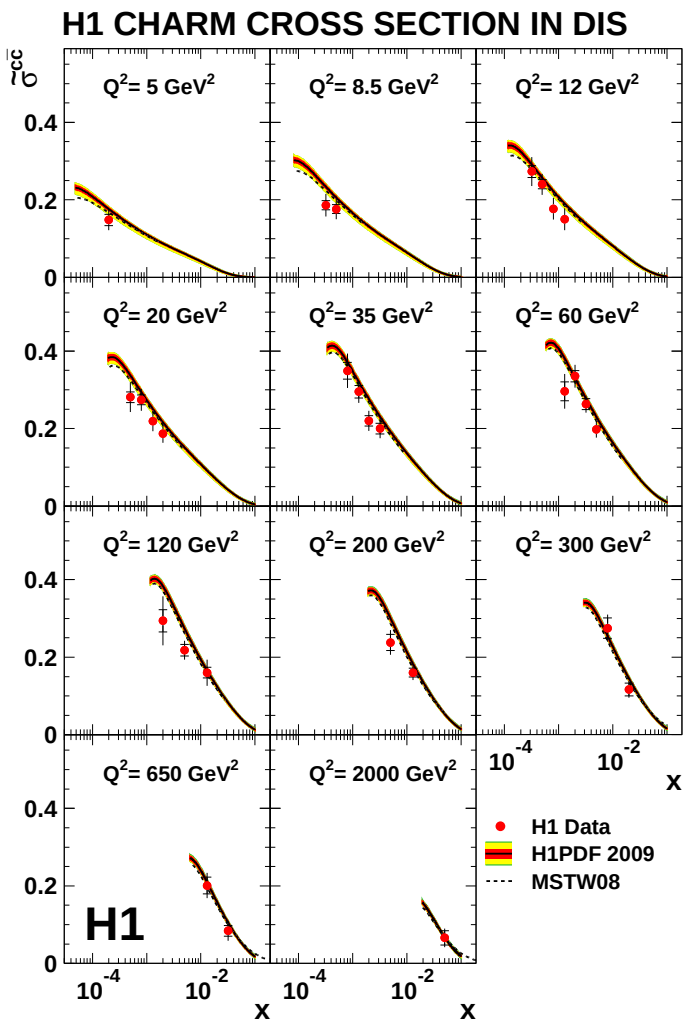


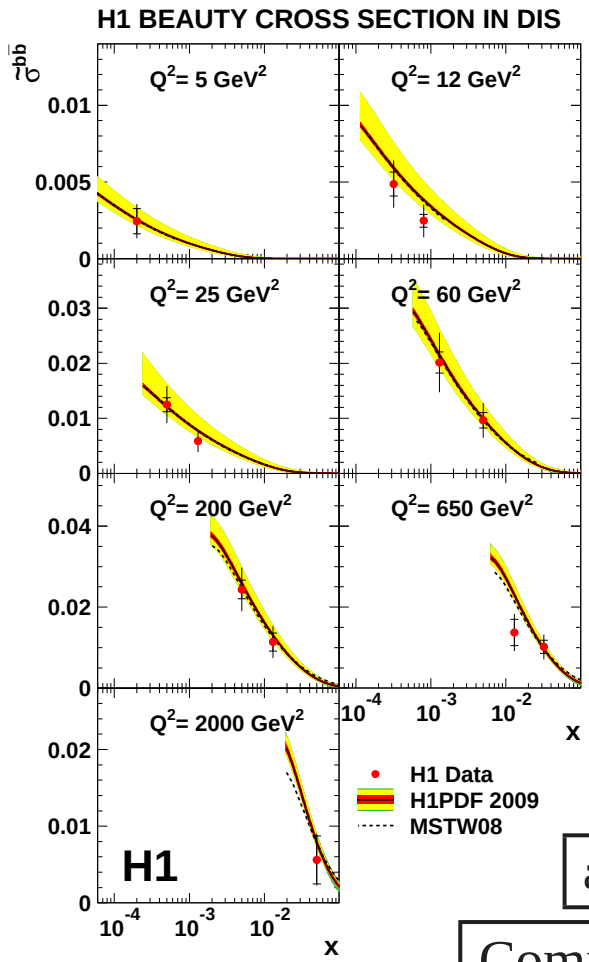
Different methods to measure $F_2^{c\bar{c}}$

- Displaced secondary vertex (lifetime tag).
- Tagging by measuring D^* meson production.

Methods have different experimental/theoretical uncertainties: combine taking into account correlations, significant reduction of the uncertainty.

Measurements of c, b using displaced vertex.



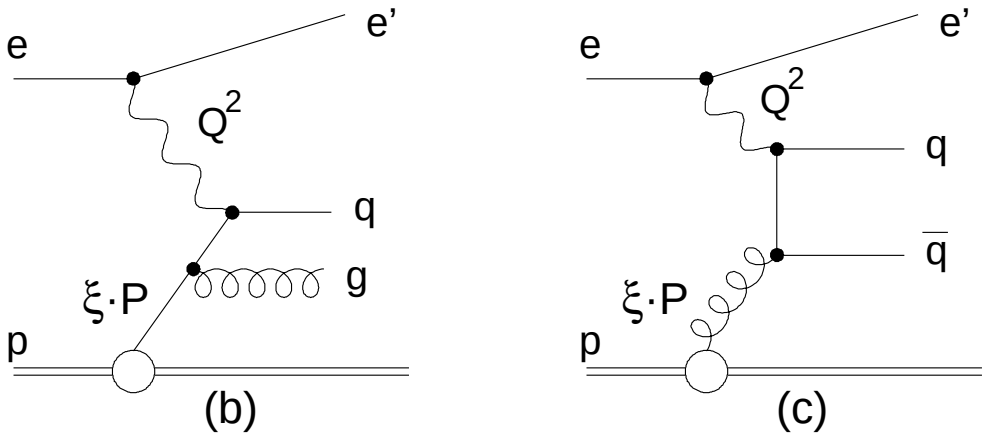


arXiv:0907.2643

Complete HERA dataset

Larger contribution to σ_r allows to determine $\sigma_r^{c\bar{c}}$ more precisely than $\sigma_r^{b\bar{b}}$. Data agree well with H1PDF2009/MSTW08 predictions.

DIS jet cross section

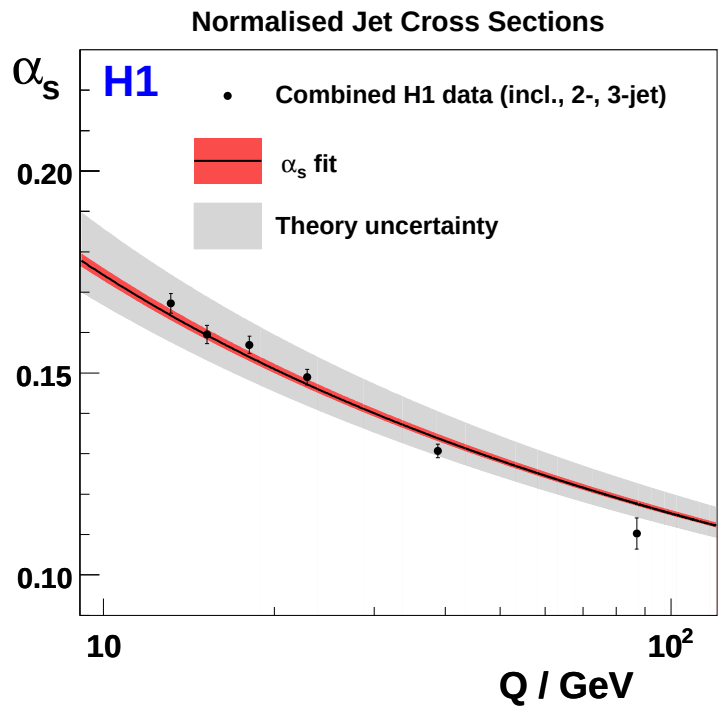


High P_t jets provide information on α_S and $xG(x)$.

H1 Analysis based on complete HERA sample (395 pb^{-1}).

$$\alpha_S(M_Z) = 0.1168 \pm 0.0007\ (\text{exp})$$
$$^{+0.0046}_{-0.0030}\ (\text{th.}) \pm 0.0016\ (\text{PDF}).$$

arXiv:0904.3870, Submitted to EPJC.



Summary

- HERA enables precise determination of PDFs for the LHC kinematic range.
- DGLAP evolution works very well so far.
- More information will come with finalization of HERA analyzes, combination of H1/ZEUS data, from the measurements of heavy flavors and of F_L.

Extras

Combination χ^2

$$\chi^2_{\text{exp}}(\boldsymbol{m}, \boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\text{stat}}\, \mu^i \left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\text{uncor}}\, m^i\right)^2} + \sum_j b_j^2.$$

- μ^i — measured central value at point i
- γ^i_j, $\delta_{i,\text{stat}}$, $\delta_{i,\text{uncor}}$ — relative correlated systematic, statistical and uncorrelated systematic uncertainty.

The function χ^2_{exp} depends on the set of underlying physical quantities m^i (vector $\boldsymbol{m}$) and the set of systematic uncertainties b_j ($\boldsymbol{b}$).

All(normalization, correlated, uncorrelated) systematic uncertainties are assumed to be **multiplicative** and statistical errors are rescaled based on estimated (instead of measured) number of events.
Extra procedural error for if only normalizations are considered multiplicative.

Alternative: average/fit $\log \sigma_r$, in this case all uncertainties should be treated as additive (also normalizations). Consistent resulting average.

Combination Procedure

- All NC,CC $e^{\pm}p$ data are combined in one step. This allows for coherent propagation of the systematic uncertainties.
- Before the combination, the data are corrected to a common x, Q^2 grid using parameterizations of NC,CC cross section. QCD fit is used for $Q^2 \geq 4$ GeV^2 and fractal model fit for $Q^2 < 4$ GeV^2 data.
- The data collected at $E_p = 820$ GeV are corrected to $E_p = 920$ GeV for all point excluding $y > 0.35$ NC data. The model uncertainty arising from this CME correction is negligible compared to experimental errors.
- The correlated systematic uncertainties are considered uncorrelated between H1 and ZEUS. To study importance of this approximation, similar sources were identified and assumed to be correlated. Additional **procedural** uncertainties are introduced for possible correlation of photoproduction background and hadronic final state simulation.