QCD Studies at HERA

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What I'm not talking about

Inclusive Photoproduction of rho^0,K^{*0} and \phi Mesons at HERA

Strangeness Production at low Q^2 in Deep-Inelastic ep Scattering at HERA

Study of Charm Fragmentation into D^{*\pm} Mesons in Deep-Inelastic Scattering at HERA

Measurement of Diffractive Scattering of Photons with Large Momentum

Leading Neutron production in DIS at HERA

Diffractive photoproduction of jets with the H1 detector

Diffractive rho and phi production in DIS with the H1 detector

Study of Multiple Interactions In photoproduction at HERA

Prompt photons in photoproduction at HERA II

K*+- production at low Q2

Beauty using events with a muon and jet in photoproduction

Dstar production in photoproduction, low and high Q2 with the H1 detector

Extraction of the Charm Contribution to the Proton Structure Function F2C from D*+- Measurements in Deep Inelastic

Measurement of F_2^{cc} and F_2^{bb} using the H1 vertex Detector at HERA

Search for D*p resonance at HERA II

Measurement of Beauty Photoproduction using Decays into Muons in Dijet Events at HERA

Measurement of the charm fragmentation function in D photoproduction at HERA

Measurement of D^\pm and D^0 Production in Deep Inelastic Scattering Using a Lifetime Tag at HERA

Subjet Distributions in Deep Inelastic Scattering at HERA

Leading Proton Production in Deep Inelastic Scattering at HERA

Deep Inelastic Scattering with Leading Protons or Large Rapidity Gaps at HERA

A Measurement of the Q^2, W and t Dependences of Deeply Virtual Compton Scattering at HERA

Measurement of beauty production from dimuon events at HERA

Angular correlations in three-jet events in ep collisions at HERA

Production of excited charm and charm-strange mesons at HERA

Inclusive K0_SK0_S resonance production in ep collisions at HERA

Beauty photoproduction using decays into electrons at HERA

Energy dependence of the charged multiplicity in deep inelastic scattering at HERA

Mulit-jet cross sections in charged current e^+-p scattering at HERA

Deep inelastic inclusive and diffractive scattering at Q^2 values from 25 to 320 GeV^2 with the ZEUS forward plug calorimeter

Measurement of the energy dependence of the total photoproduction cross section with ZEUS at HERA

Title: $\alpha_s(M_Z)$ from inclusive-jet cross sections in PHP

Charm and Beauty in DIS from muons, F2c and F2b

new QCD publications and preliminary results from H1 and ZEUS in the last year

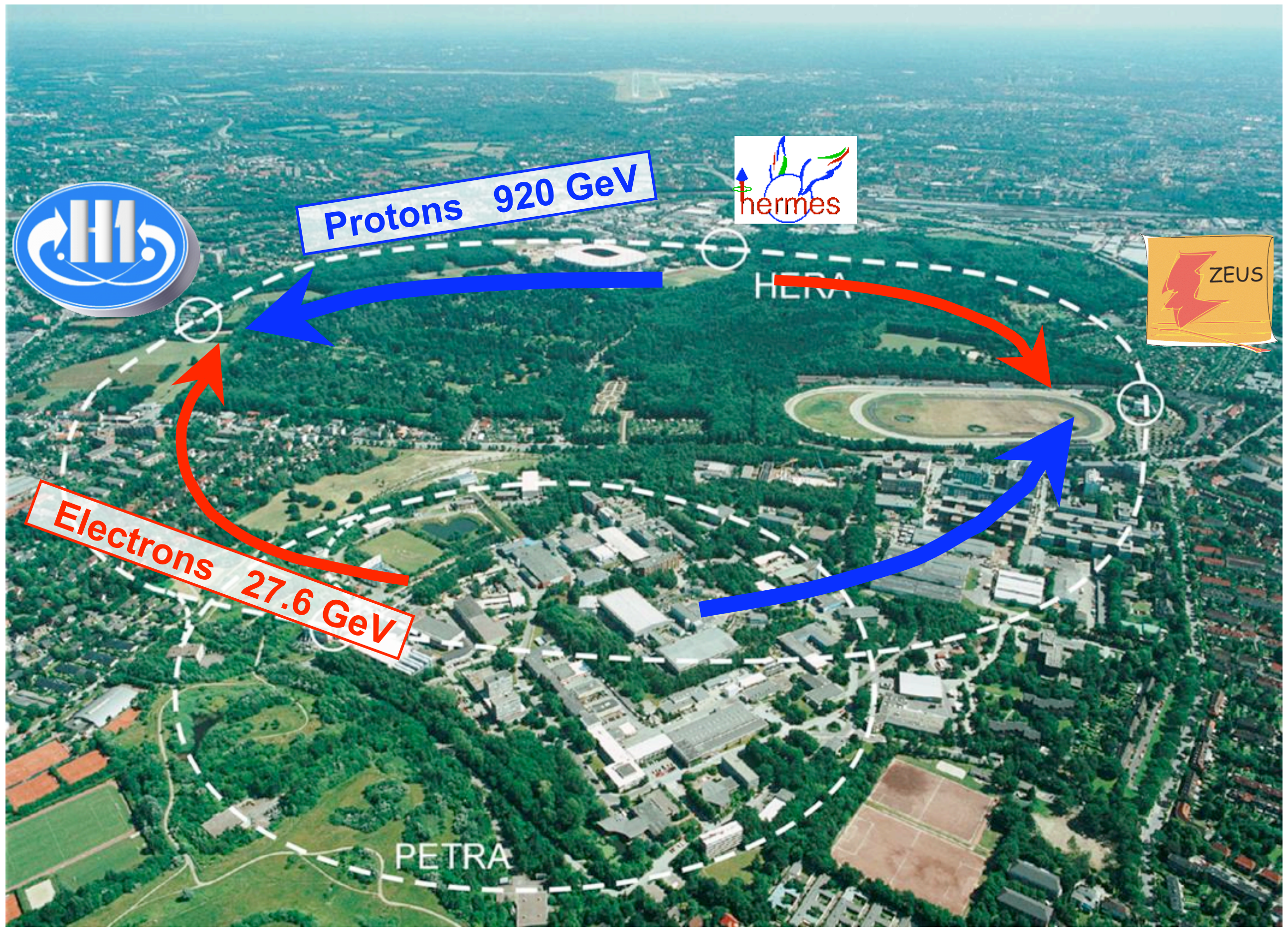
Overview

- HERA accelerator and experiments and physics.
- New neutral and charged current measurements.
- HERA data combinations and PDF fits.
- First measurement of F_L structure function.
- α_s from jets.
- Summary.

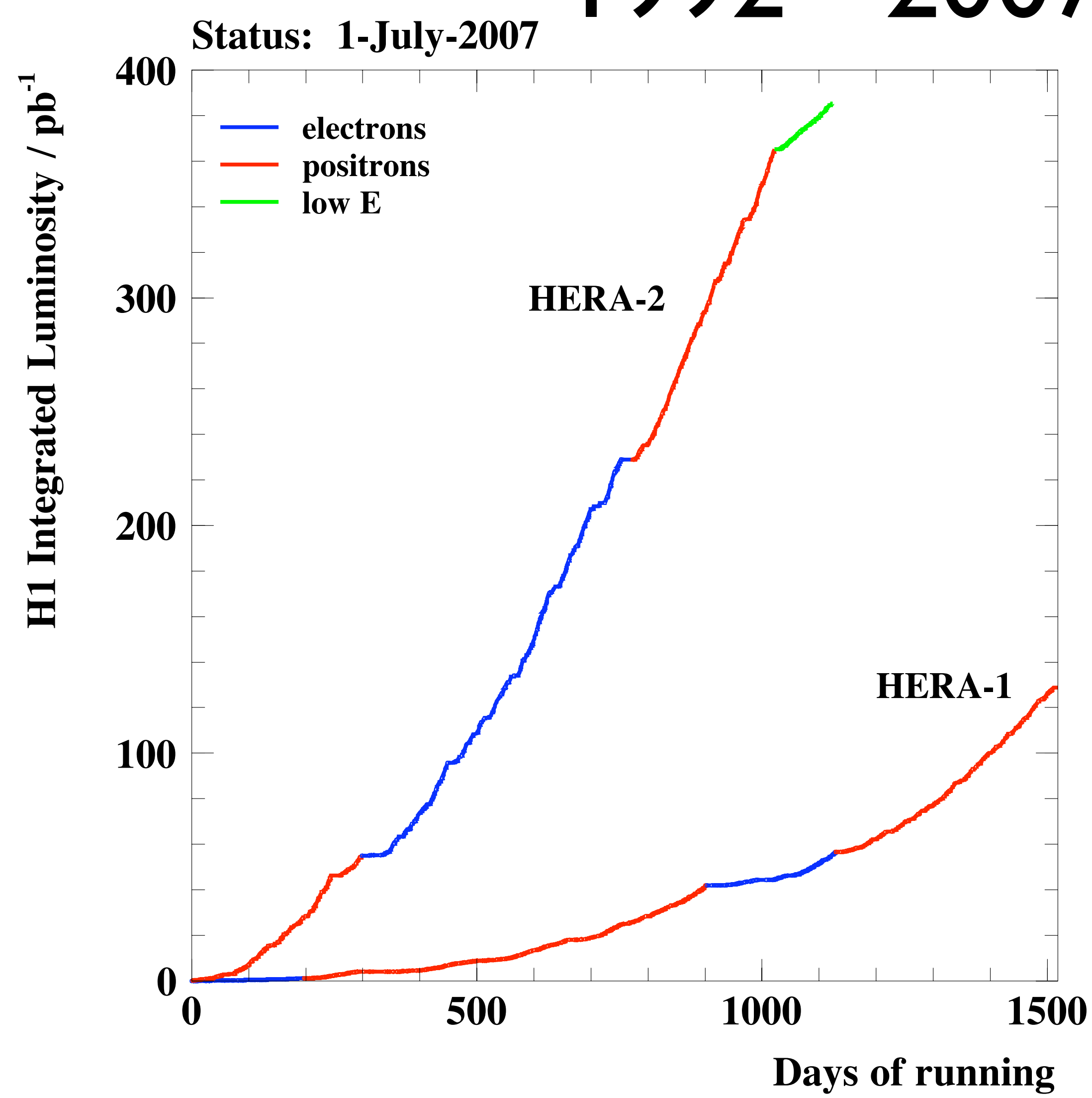
not discussed - lots! e.g. Heavy Flavour and Diffraction etc..

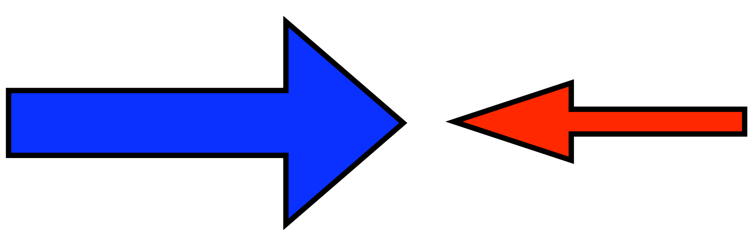
For searches see Yongdok Ri talk on Friday

HERA



1992 - 2007





Proton
920 GeV

$e^{\pm}$
27.6 GeV

~0.5 fb^{-1} per experiment

Average polarisation ~30-40%
HERAII

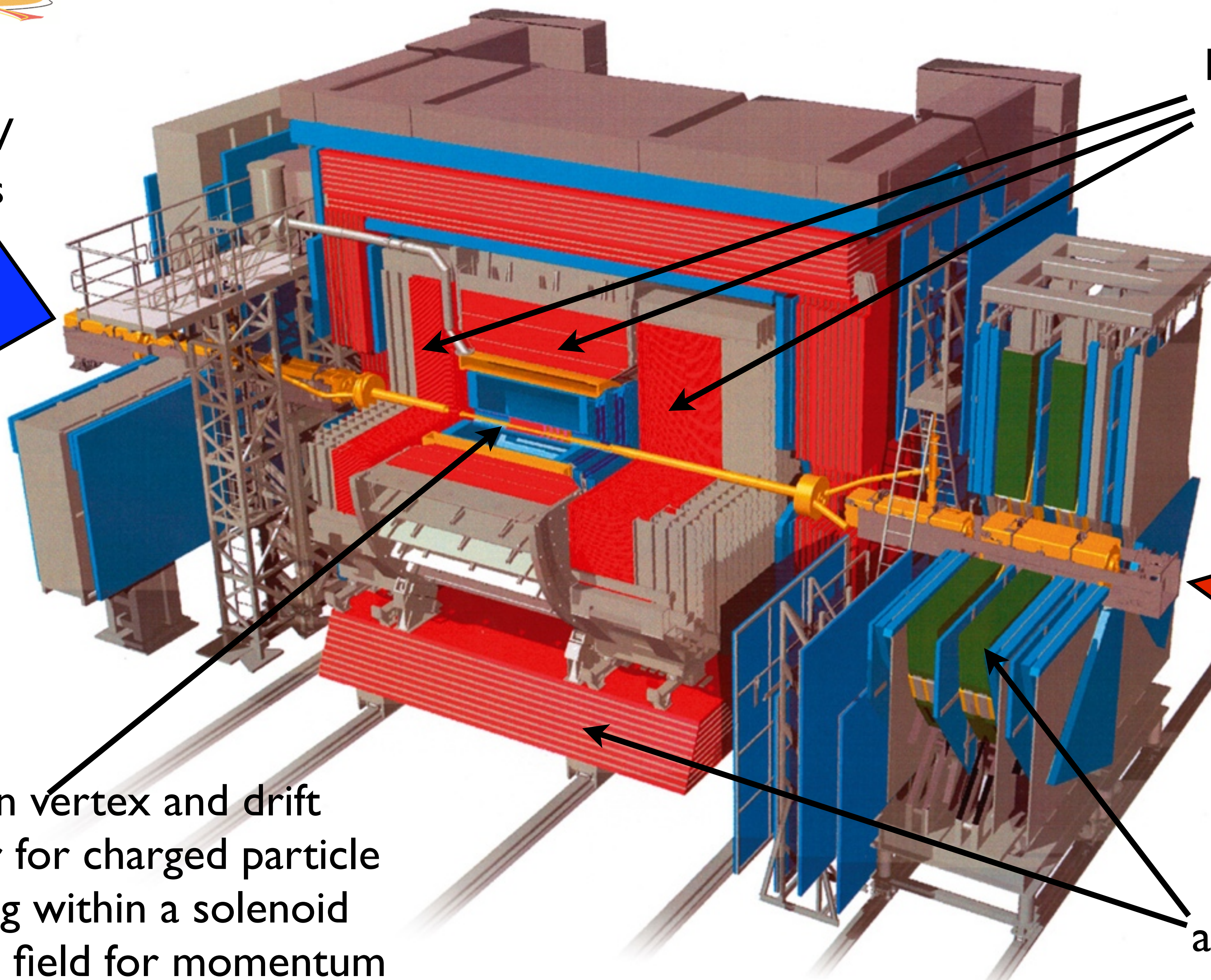
+ Low energy proton runs
to measure F_L

Typical HERA Detector

asymmetric beam energies =
asymmetric detector

electromagnetic and
hadronic calorimeters with
near 4π acceptance

920 GeV
Protons

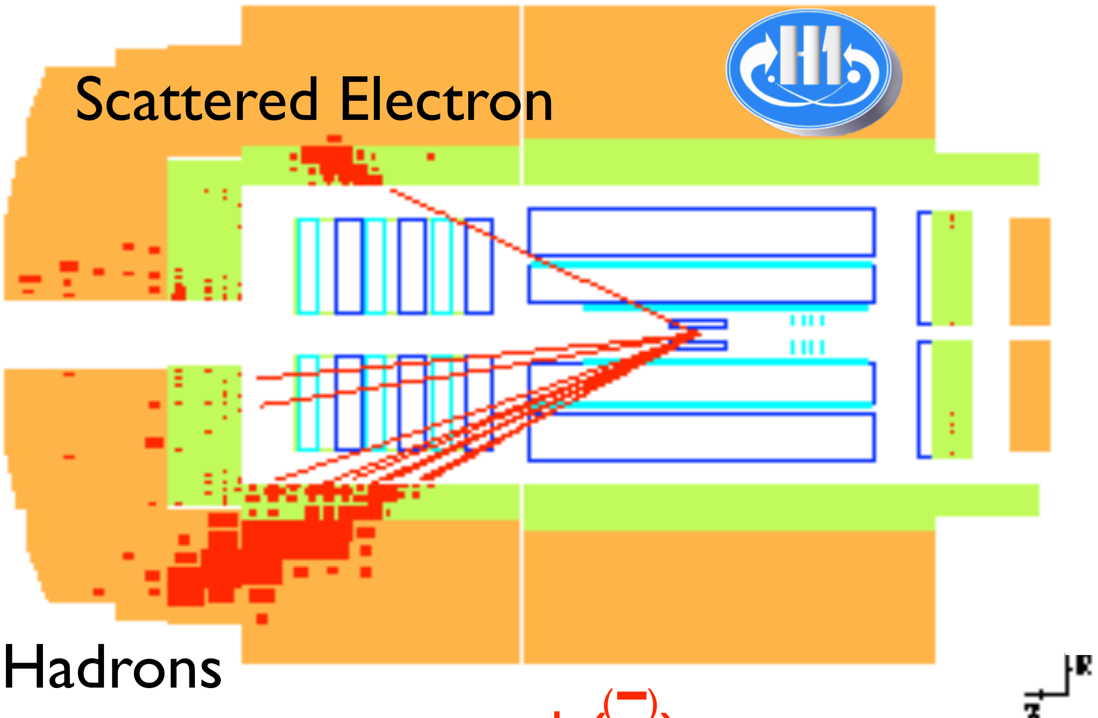


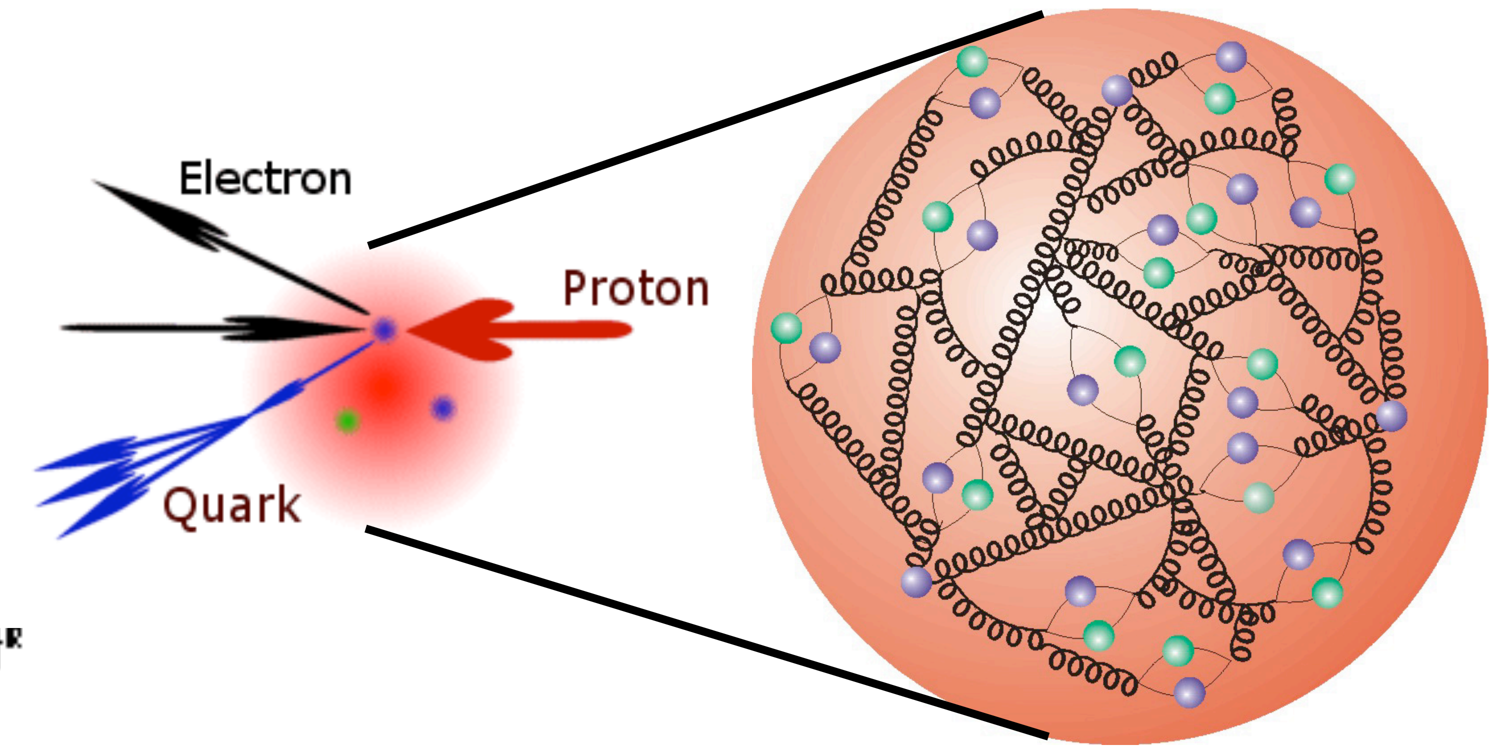
27.5 GeV
electrons

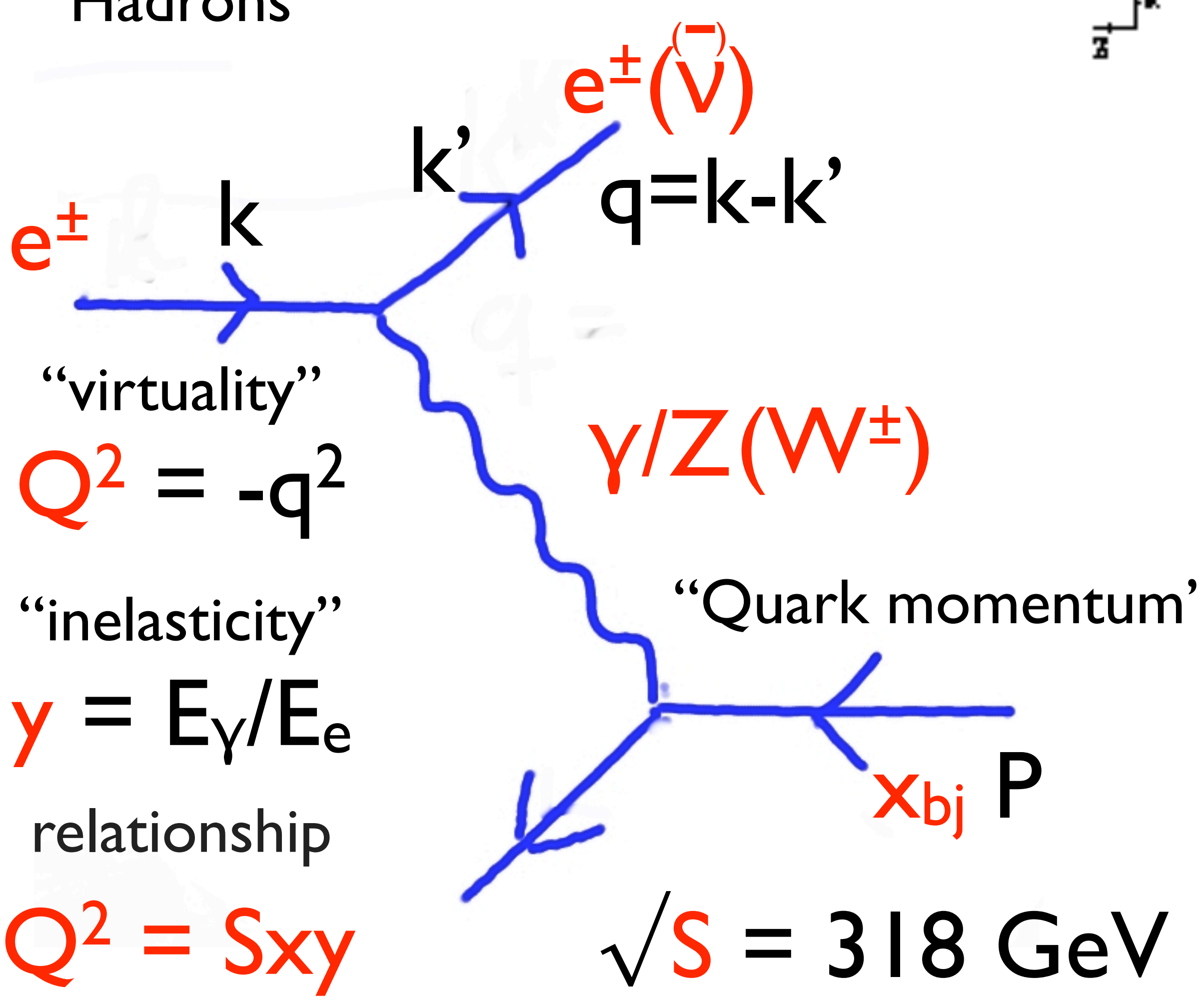
silicon vertex and drift
chamber for charged particle
tracking within a solenoid
magnetic field for momentum
measurement

muon detectors with
additional instrumentation
in the forward region

Basic Physics Picture







$\sqrt{S} = 318$ GeV

proton is a complex object, containing valence and sea quarks and gluons, that can not be calculated from first principles due to the small scales involved. Determine the proton structure from experiment!

Proton structure is driven by QCD, understand the proton - understand QCD

Vital to understand the proton for the LHC

Inclusive DIS Cross Section

Parameterise the neutral current cross section with three structure functions

$$\frac{d^2\sigma_{NC}^{(e^\mp p)}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)\right) \qquad Y_\pm = 1 \pm (1-y)^2$$

$$F_2 = x\sum e_q^2(q(x) + \overline{q}(x))$$

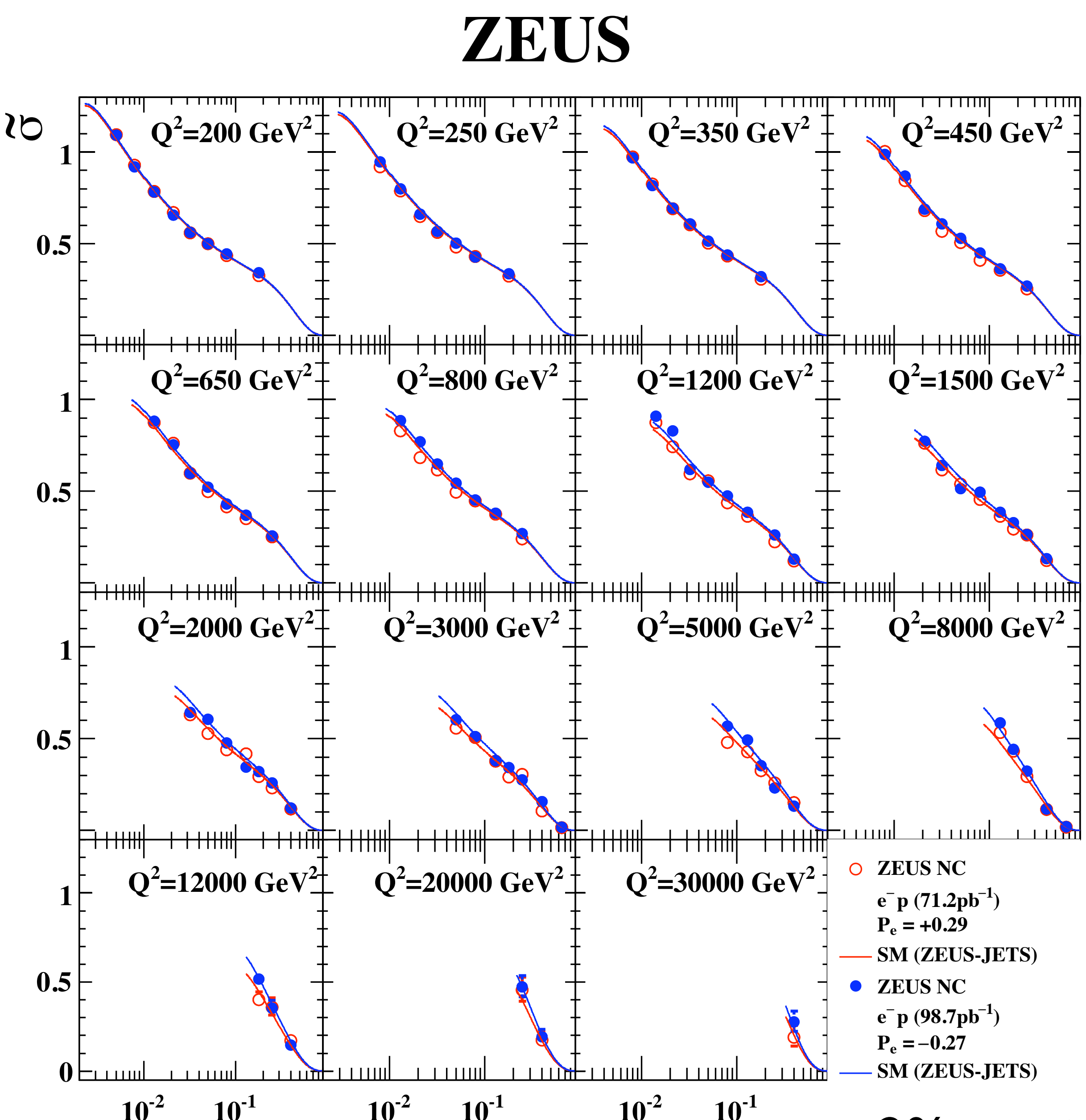
$$xF_3 = x\sum e_q^2 a_q(q(x) - \overline{q}(x))$$

F_2	F_L	xF_3
Dominant Valence + sea quarks	high y gluon	high Q^2 (large x) valence quarks

In general the gluon, xg(x, Q), is constrained by α_s, scaling violations of F_2, could also be constrained by jet cross sections, and F_L measurement

Similar for charged current - quark flavour sensitive

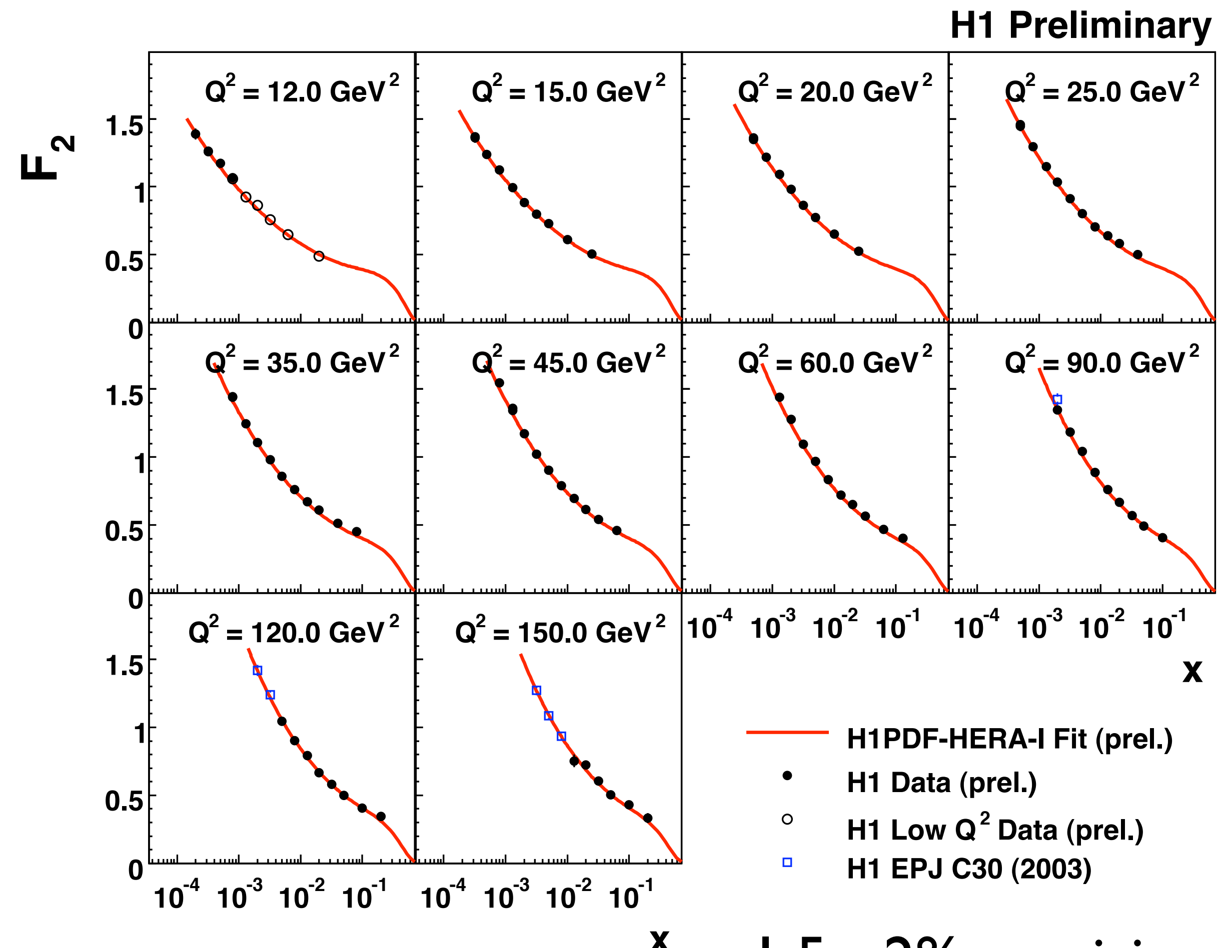
new NC measurements



2% precision

e⁻p, 169pb⁻¹ (all e⁻ data),

Q² > 185 GeV²



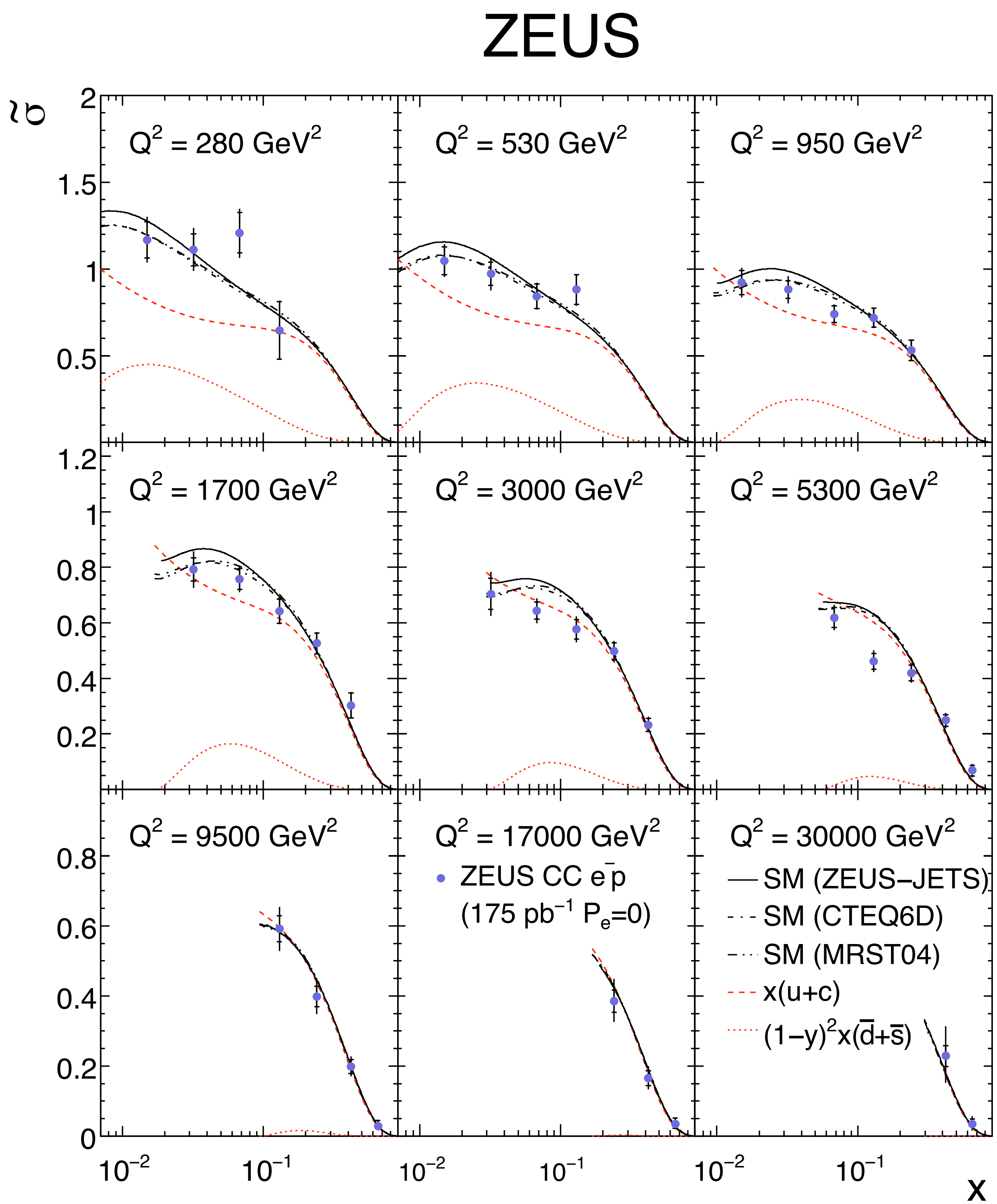
1.5 - 2% precision

e⁺p, Q²<150 GeV²

ultimate precision low Q² data

DESY-08-202 (December 2008) to be published in EPJ C

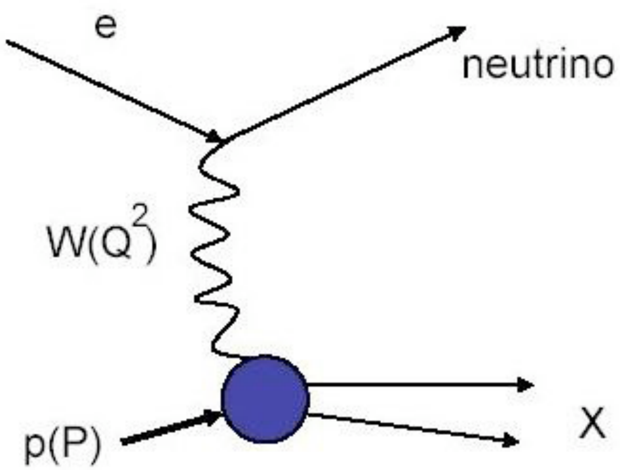
new Charged current

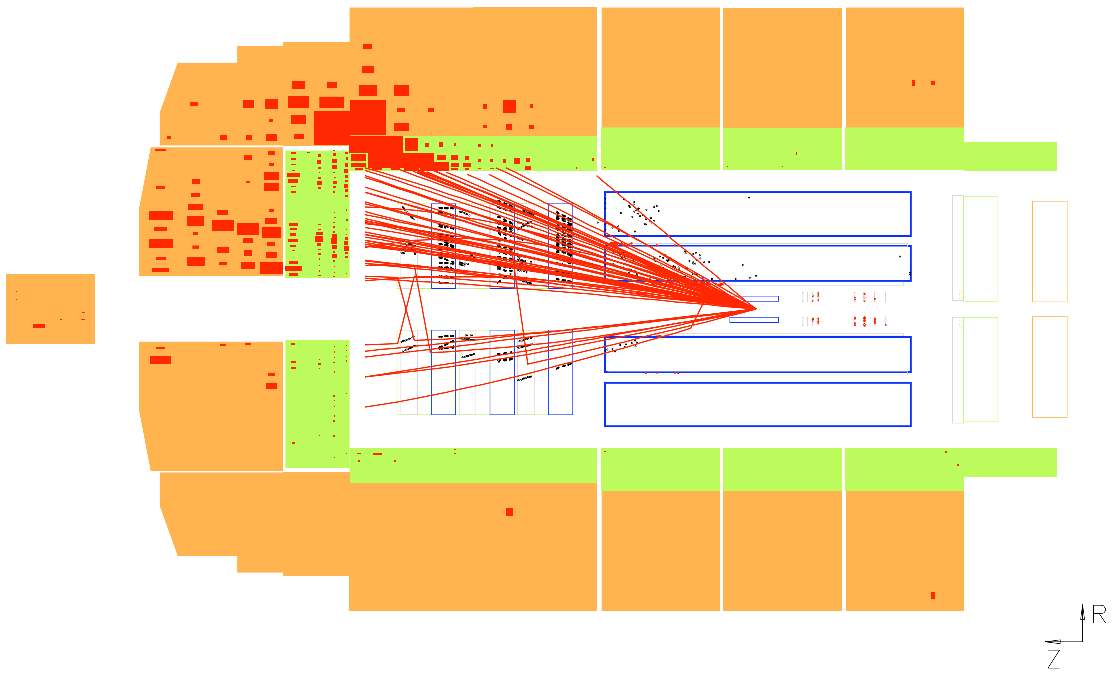


DESY-08-177 (December 2008) to be published in EPJ C

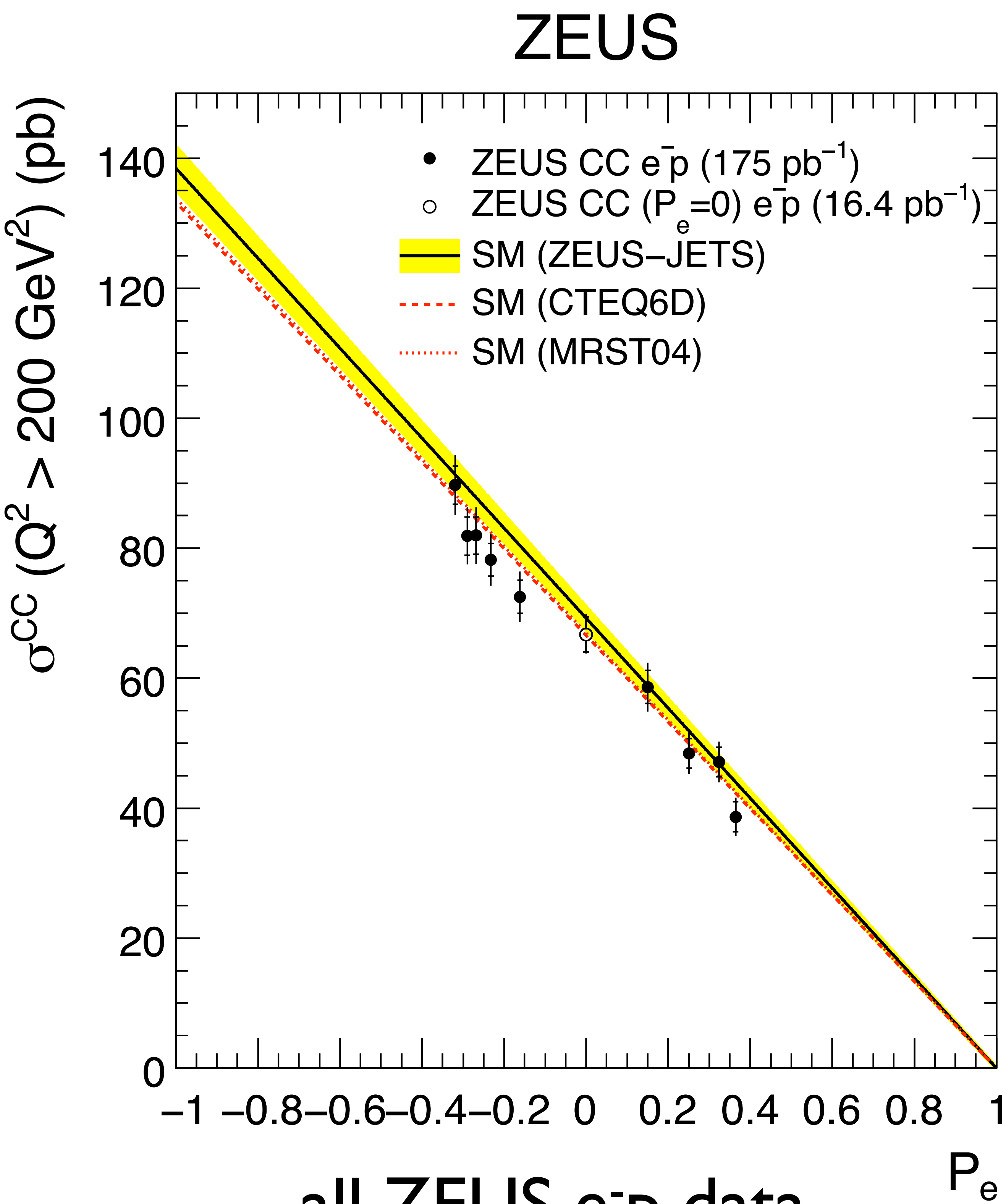
$e^-p \rightarrow \nu_e X$

$e^+p \rightarrow \bar{\nu}_e X$

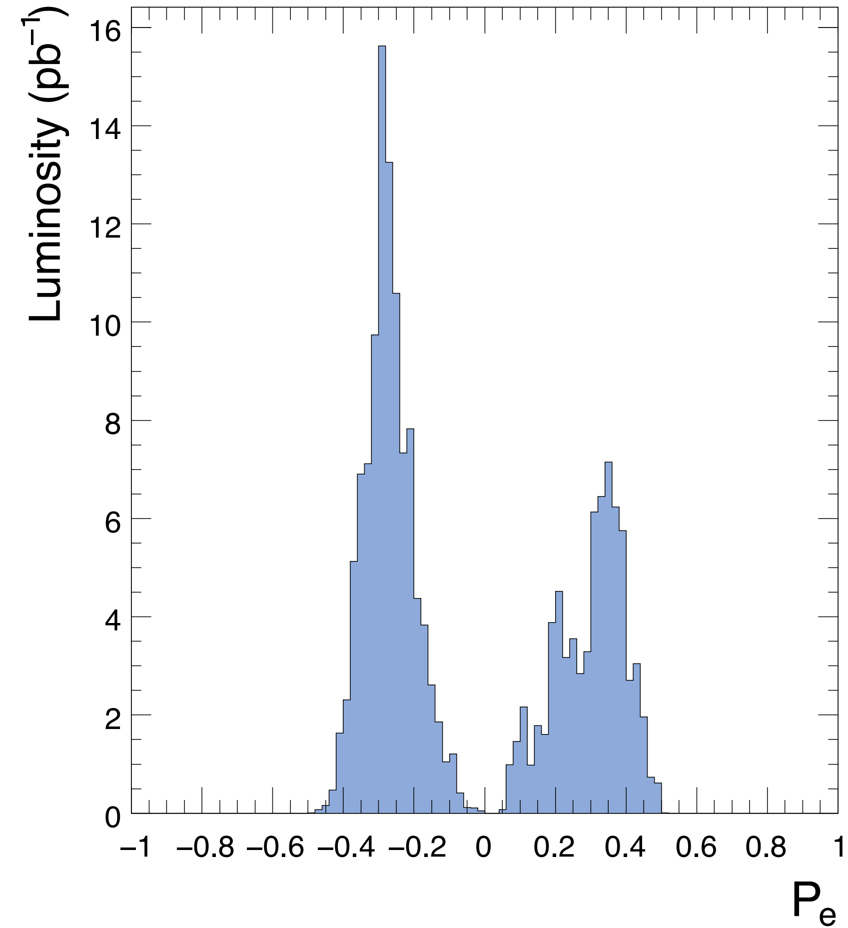




new Charged current



all ZEUS e⁻p data



polarisation of beam

cross section linearly proportional to the degree of the longitudinal beam polarisation

Consistent with no right-handed weak currents

HERA(I) Combination

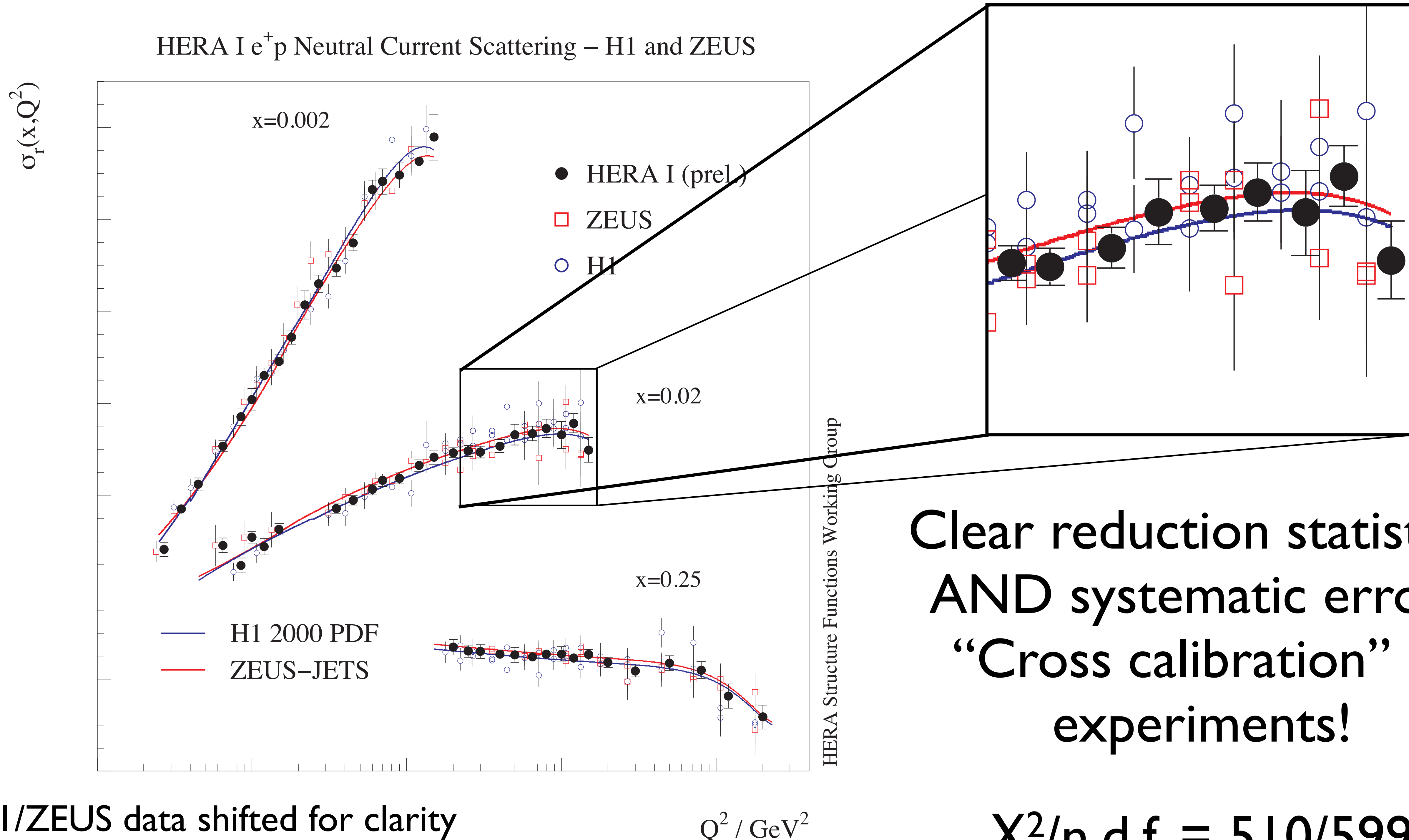
Combine published HERA1 data from H1 and ZEUS

Average H1 and ZEUS data in model independent way.
Achieved by fitting σ_r values, global normalisation and the correlated systematic uncertainties

Assumption - H1 and ZEUS measure same cross section.

Use combined data to perform a DGLAP fit and extract a proton PDF

HERA Data Combination



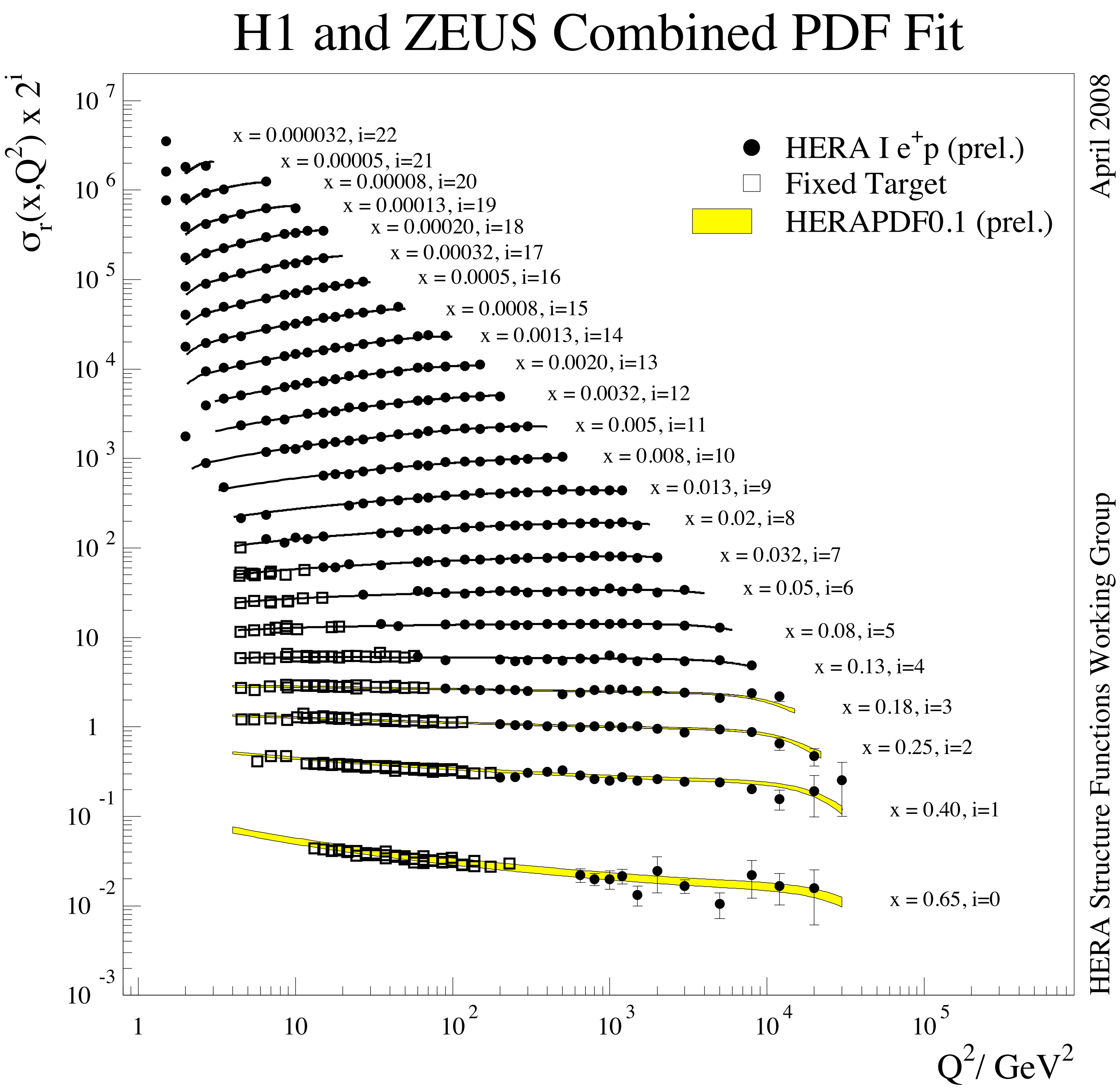
H1/ZEUS data shifted for clarity

Clear reduction statistical AND systematic errors. "Cross calibration" of experiments!

X^2/n.d.f. = 510/599

NC cross sections for 3 different x bins as a function of Q^2

HERA PDF



High precision data over 4 orders of magnitude in x and Q^2

HERA data approaches precision of fixed target data

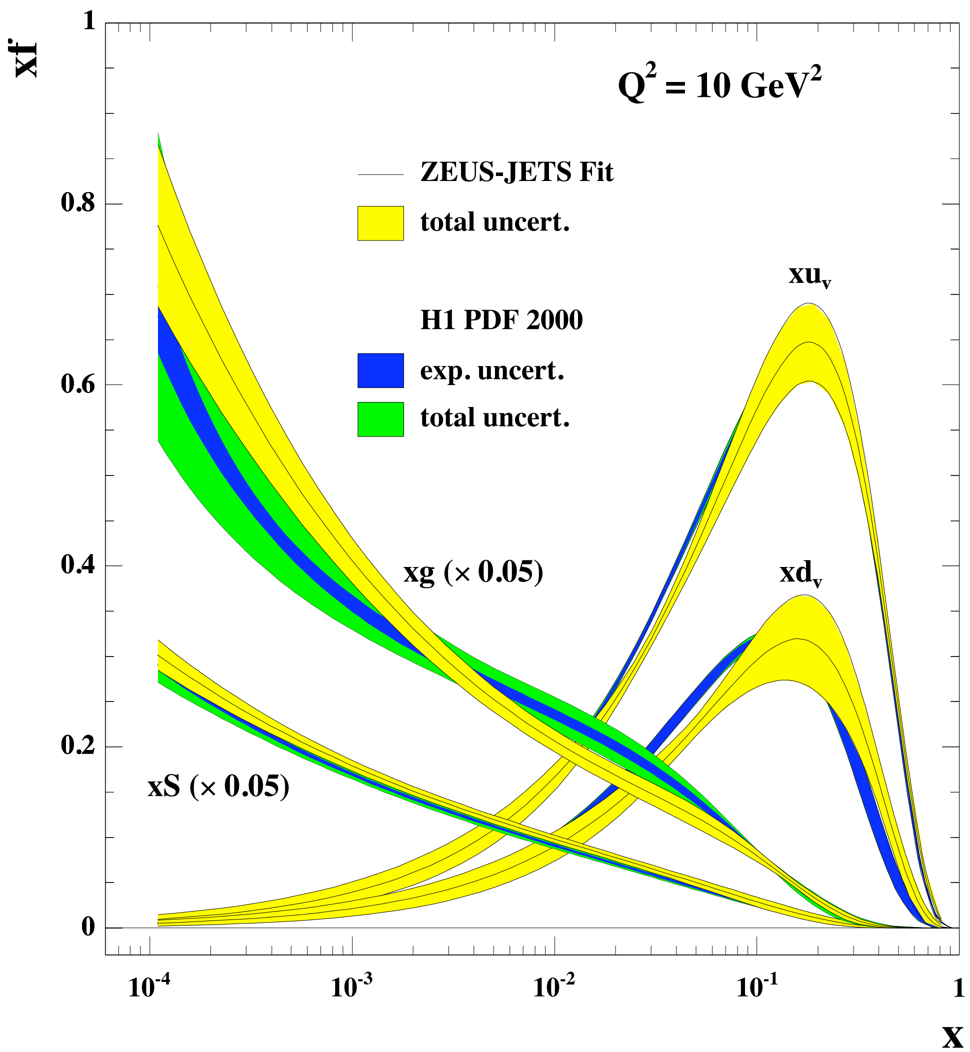
HERA PDF describes fixed target data

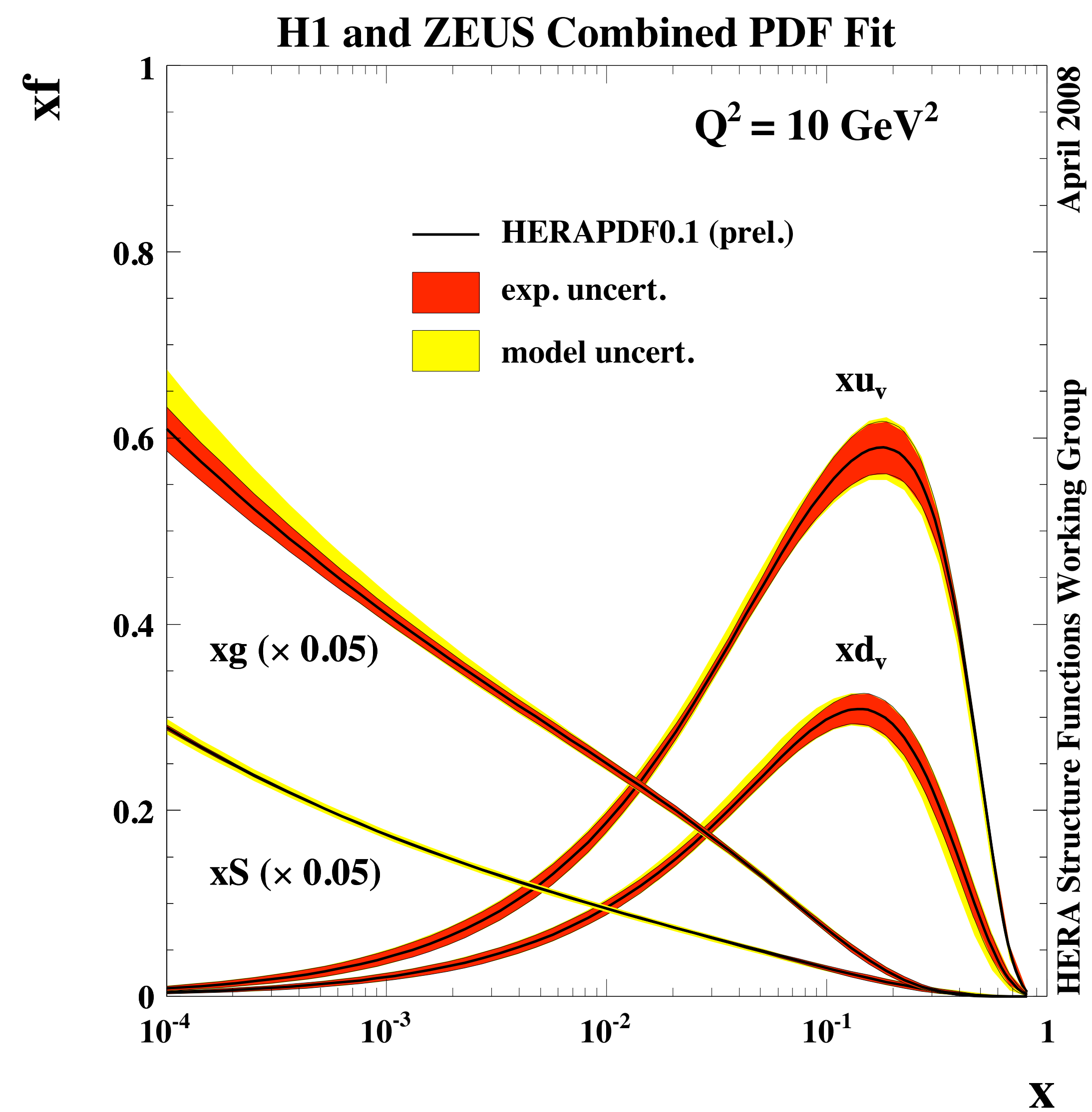
Stringent test of DGLAP evolution

errors ~1% Q^2 10GeV^2, sytematics dominated for Q^2 < 400 GeV^2

Combined HERAI data set of neutral and charged current cross sections used as sole input! + PDG α_s

HERA PDF



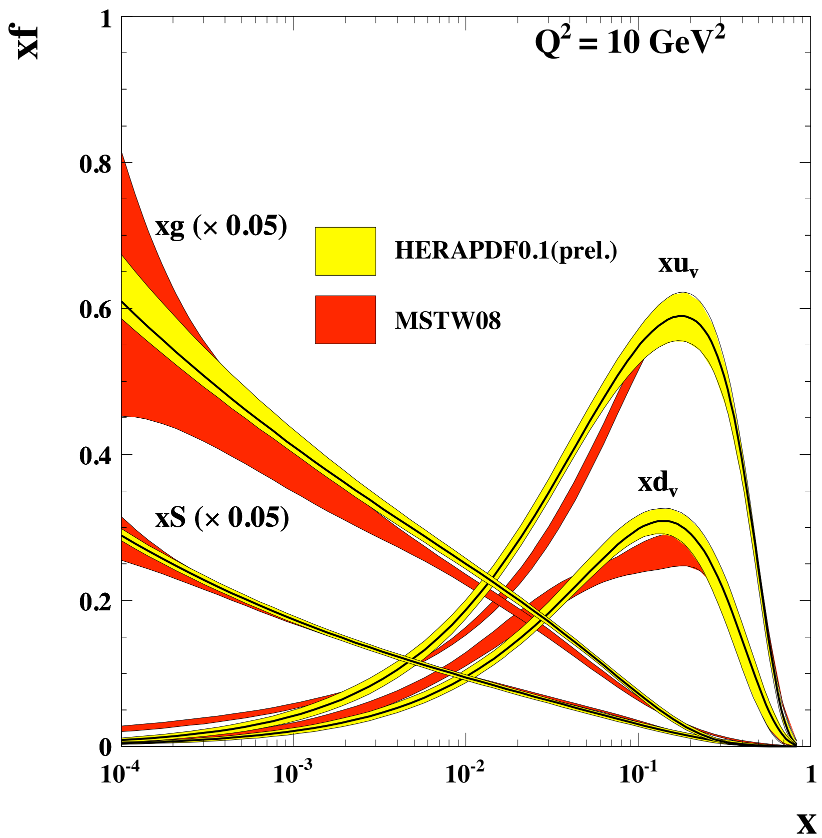


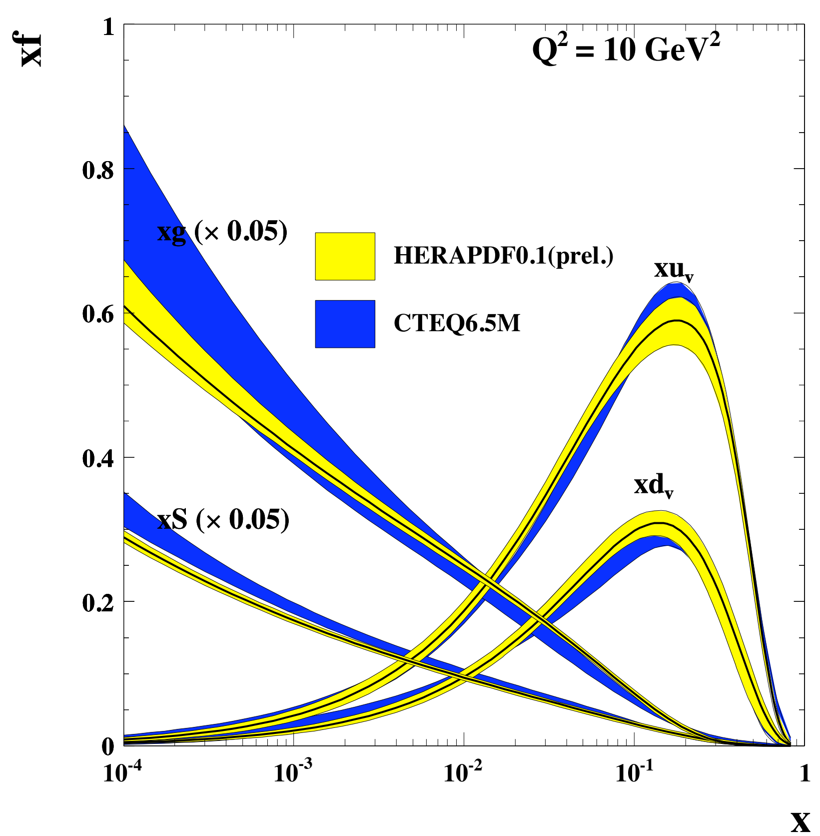
The consistent treatment of systematic uncertainties in the joint data set →$\Delta\chi^2<1$ tolerance.

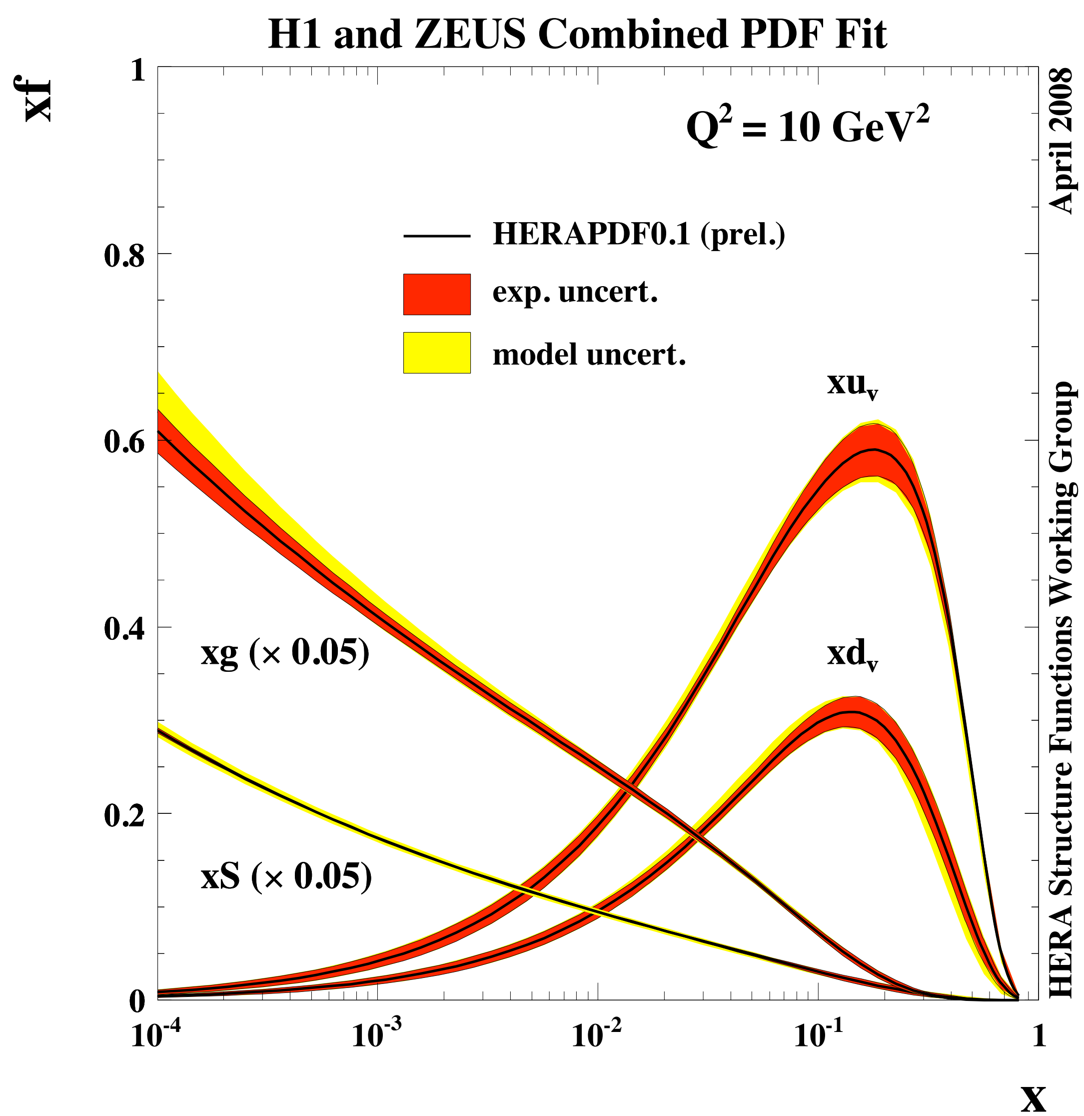
Greatly reduced experimental uncertainties compared to the separate analyses

+Common H1/ ZEUS approach to PDF fitting

HERA vs Global PDFs





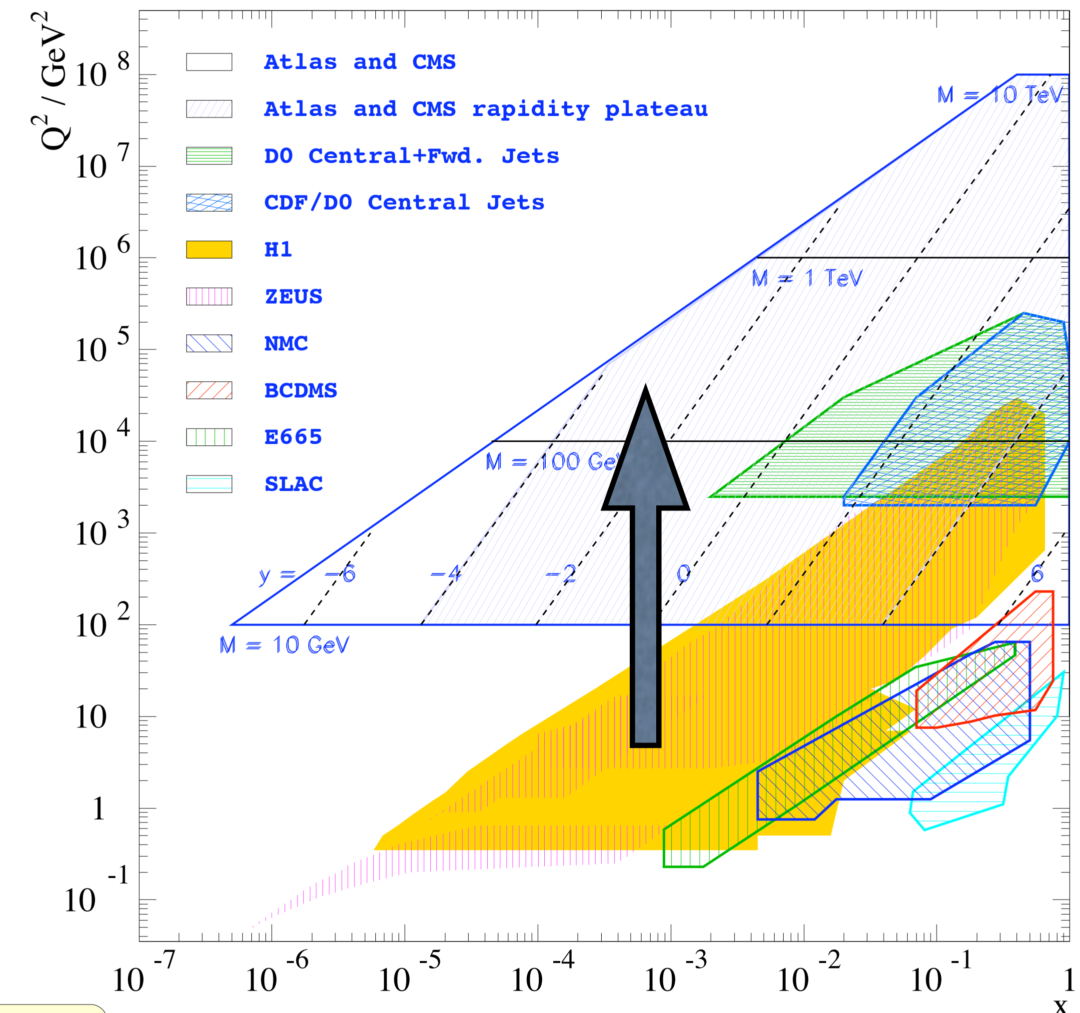


Good comparison to global fits, improved precision, however the error treatment also differs. HERA fit from HERA data alone!

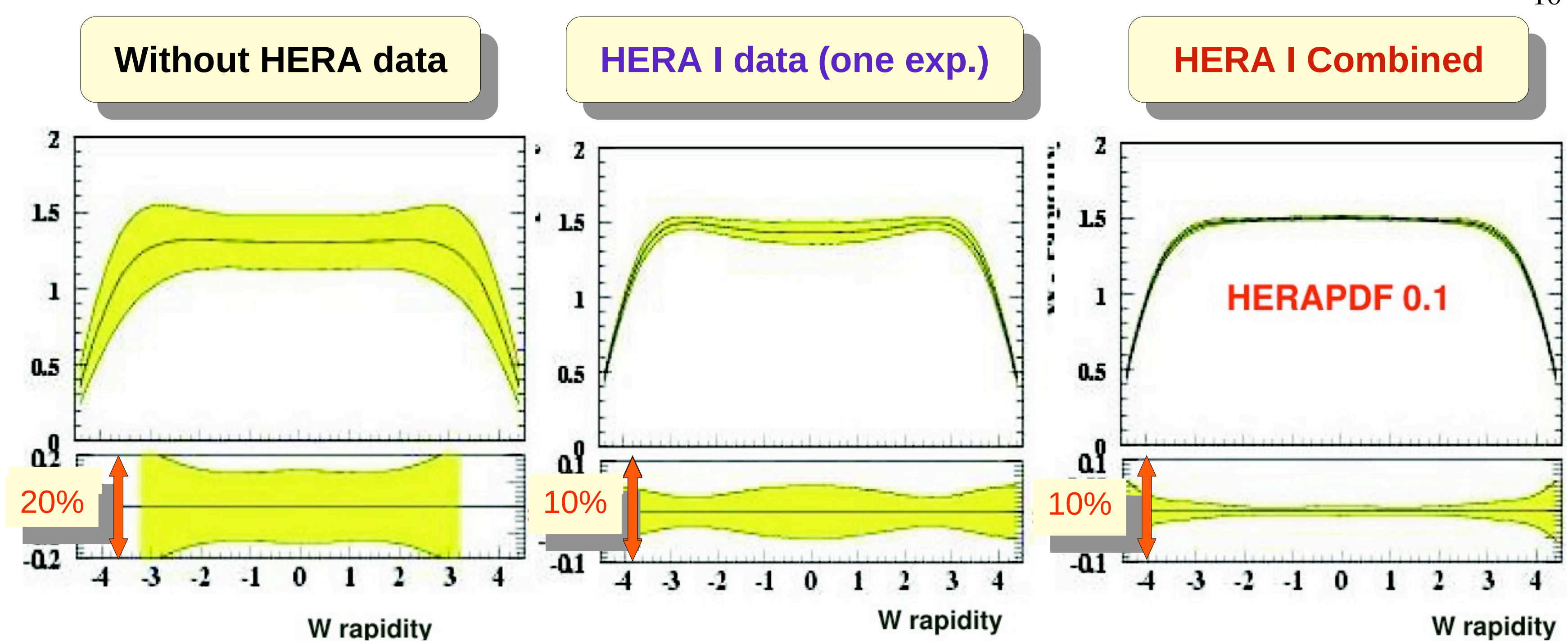
Impact on LHC

Need to know the structure of the proton to calculate cross section at the LHC.

PDFs derived from HERA data have to be evolved to the LHC phase space.



example - W cross section



Uncertainty on W cross section ~2%

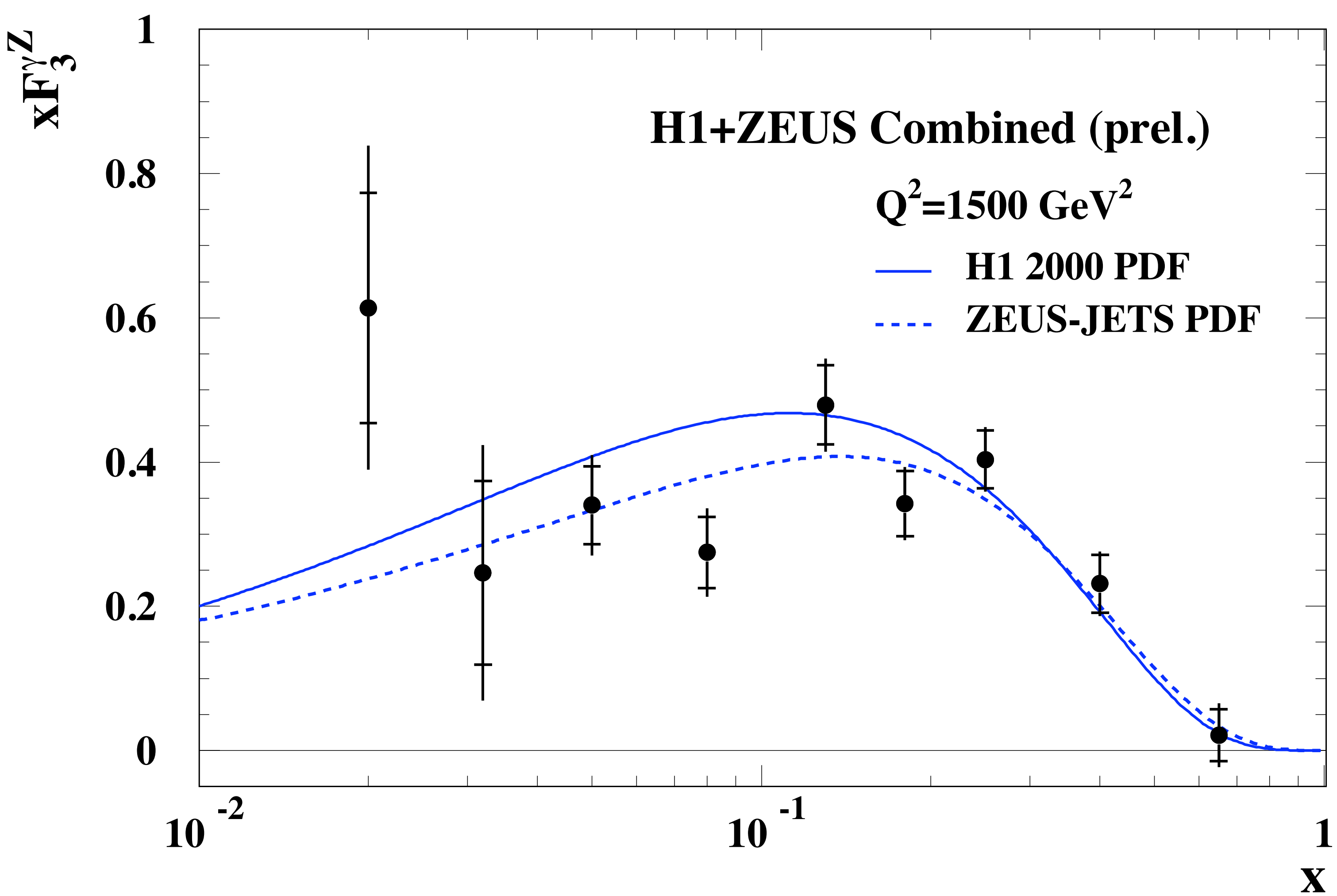
M. Cooper / E. Perez

HERA combined xF_3

at large x (Q^2), F_3 is important

$$\frac{d^2\sigma_{NC}^{(e^\mp p)}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)\right)$$

influence depends on sign of incoming lepton



$$xF_3 \sim \sigma(e^-) - \sigma(e^+)$$
$$\sim \sigma(2u_\nu + d_\nu)$$

HERA I + partial HERAII combined lumi = 480 pb^{-1}

statistical combination

F_L measurement

$y = Q^2 / Sx$

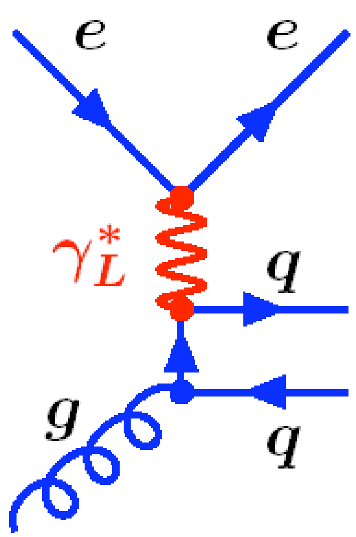
run at different proton beam energies to change S, same x and Q^2 for different y

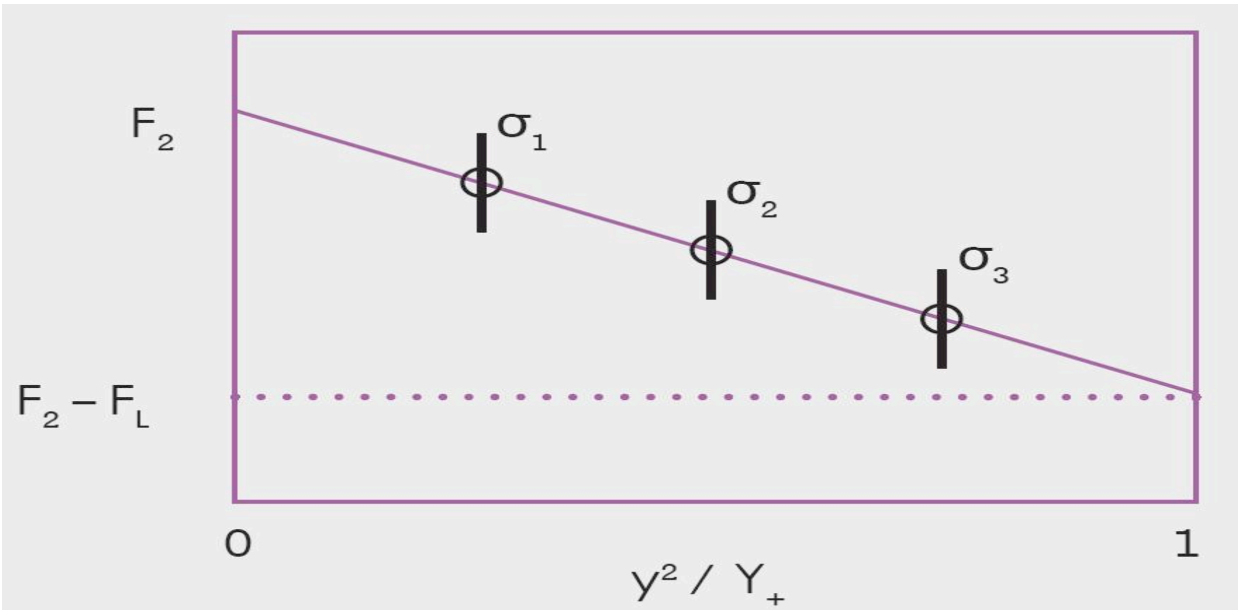
$$\frac{d^2\sigma_{NC}^{(e^\mp p)}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)\right)$$

Extraction of F_2 relies on model dependent assumptions about F_L

F_L >0 due to gluon radiation - directly sensitive to gluon density

The gluon density extracted depends on the theory assumptions.





Proton energy

920 GeV
575 GeV
460 GeV

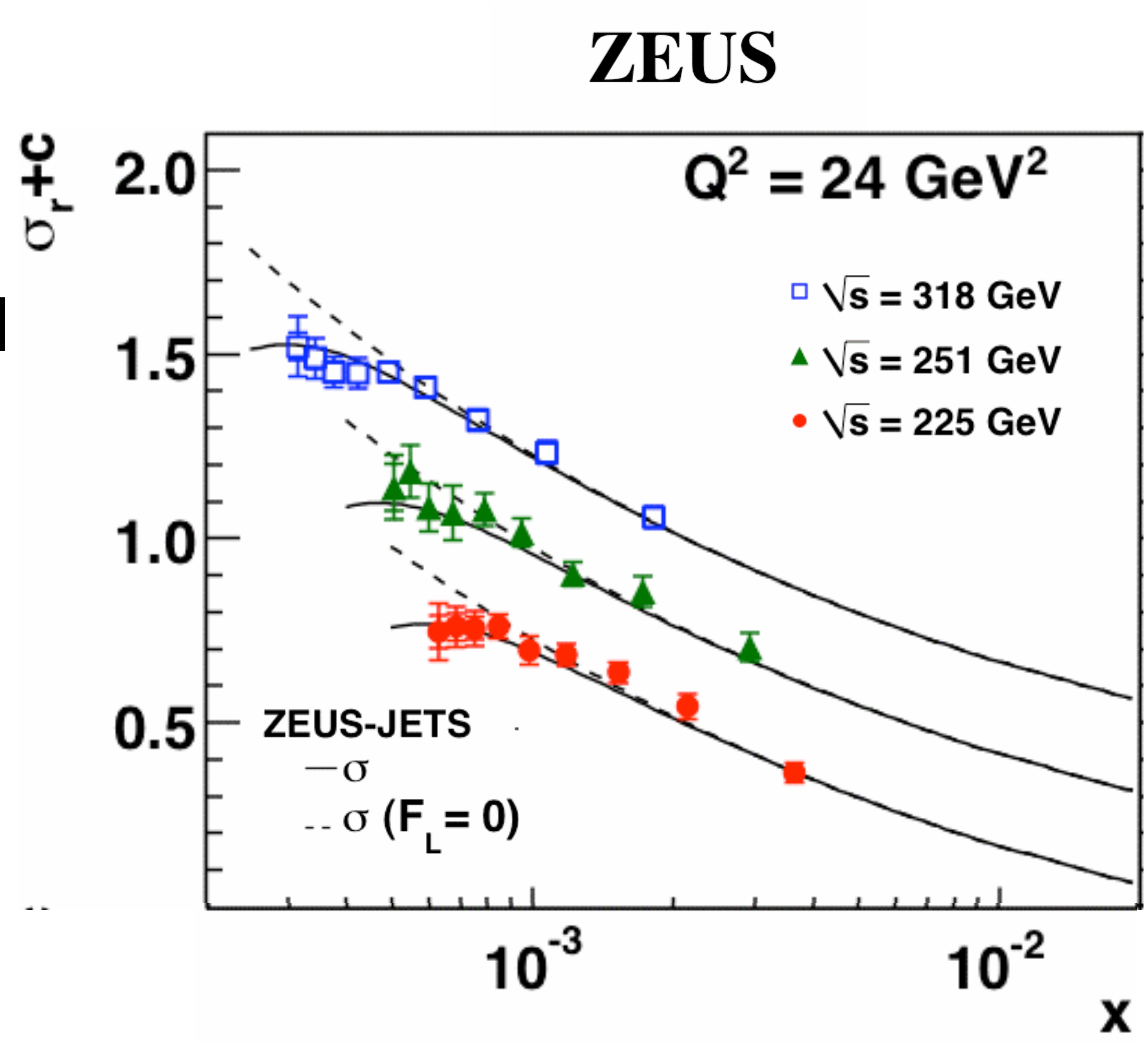
F_L measurement

$\sigma_r(x)$ in bins of Q^2 for each $\sqrt{S}$ energy

Compared to prediction based on ZEUS-JETS PDF set with expected F_L and F_L=0

F_L causes a suppression at low x. Different for each $\sqrt{S}$ energy - basis of F_L extraction

Small effect but data tend to turn over as expected



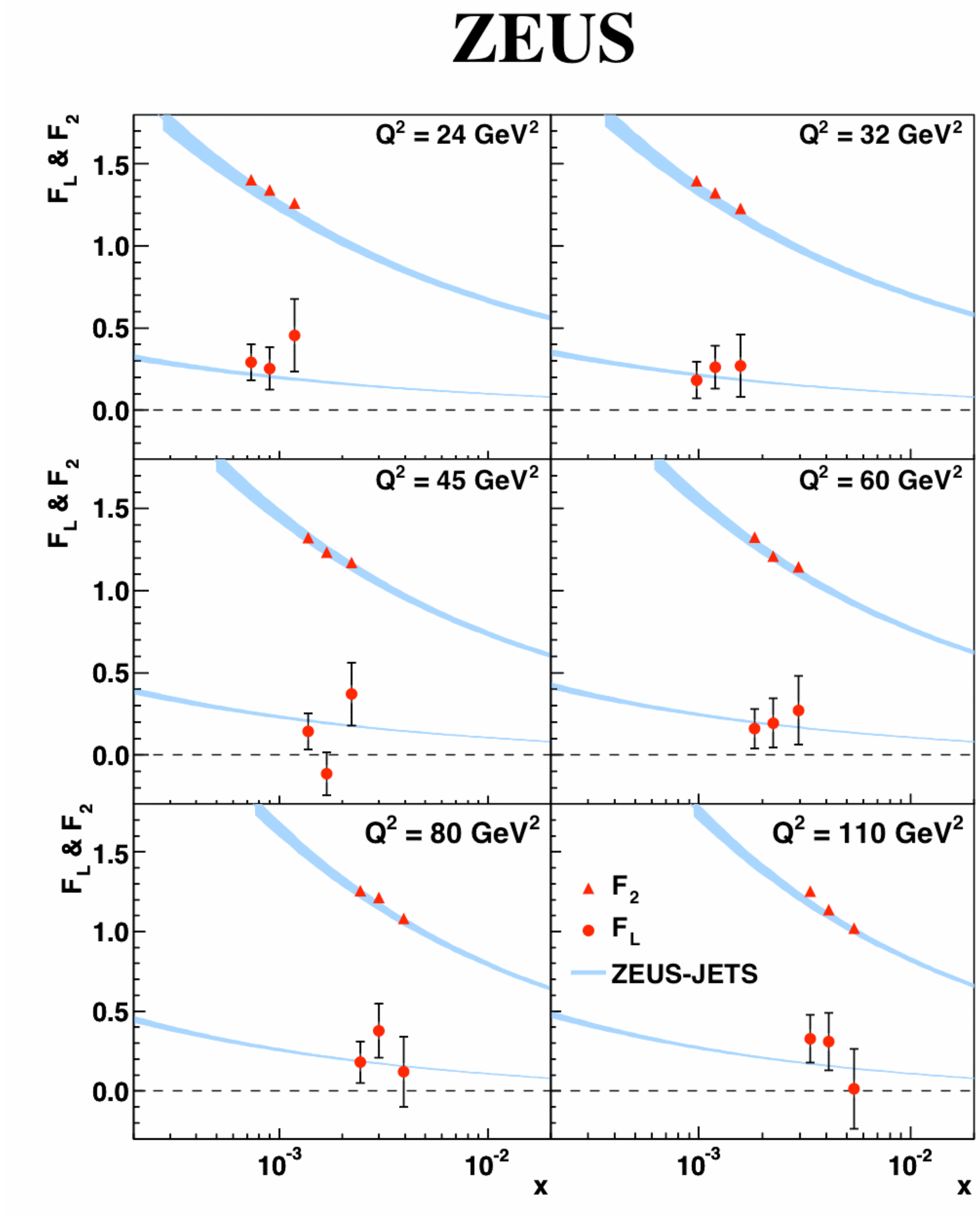
F_L measurement

$F_2(x)$ and $F_L(x)$ in bins of Q^2

Data support a non-zero F_L

compared to the ZEUS-JETS PDF prediction

Predictions consistent with F_L and F_2 data



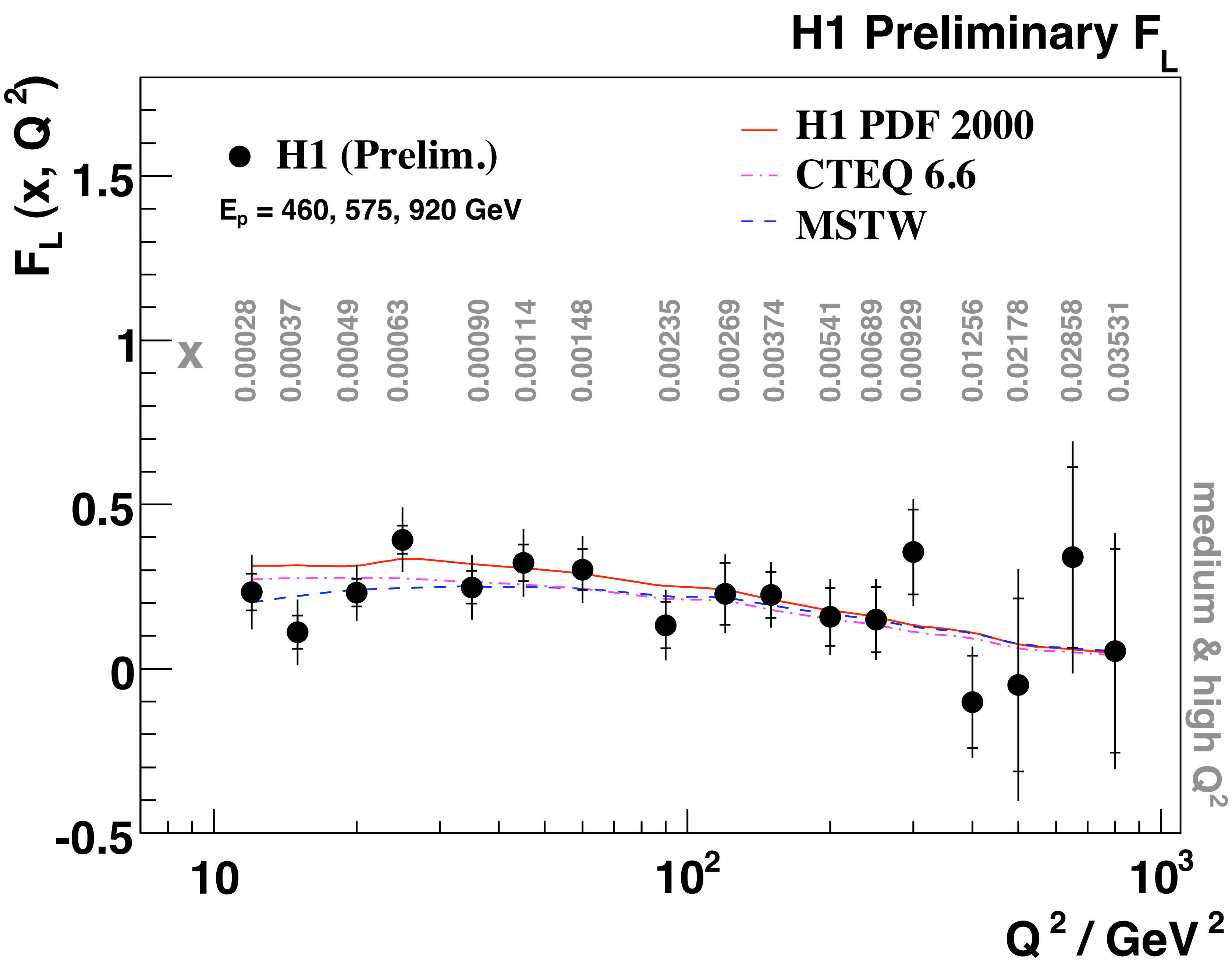
F_L measurement

$F_L(Q^2)$ formed by averaging and quoted at the x values given

F_L clearly non-zero

compared with NLO predictions

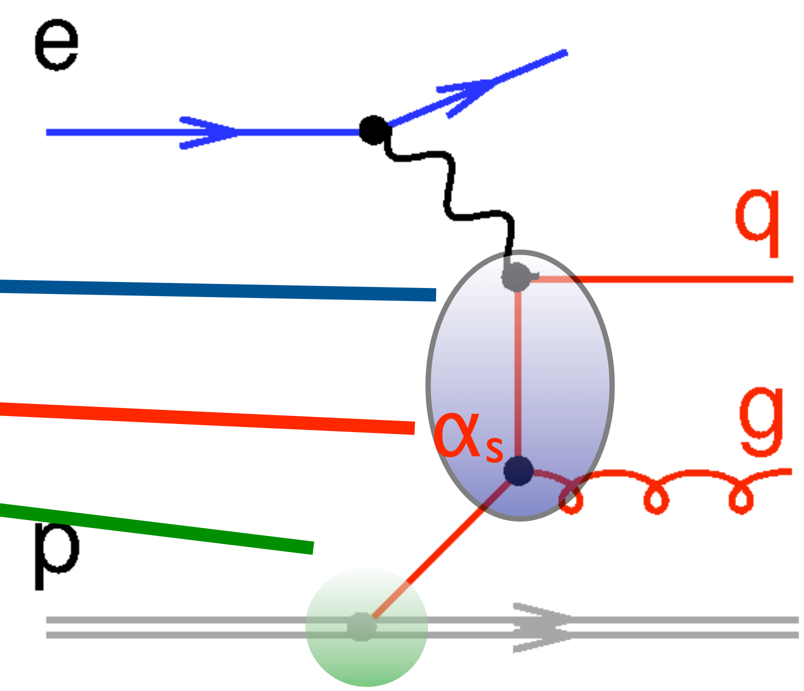
all are consistent with the data



Analyses will be extended to lower Q^2 where there is greater sensitivity to different theory

H1 Collab., F.D. Aaron et al., Phys. Lett. B665 (2008) 139-146

HERA α_s from Jets

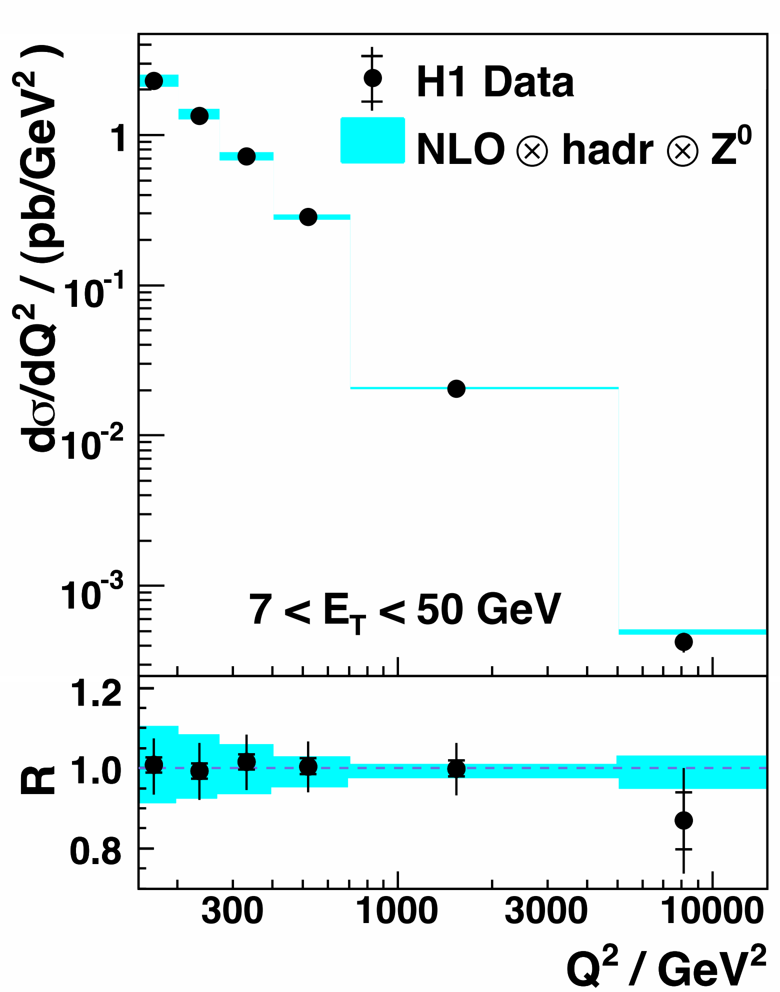


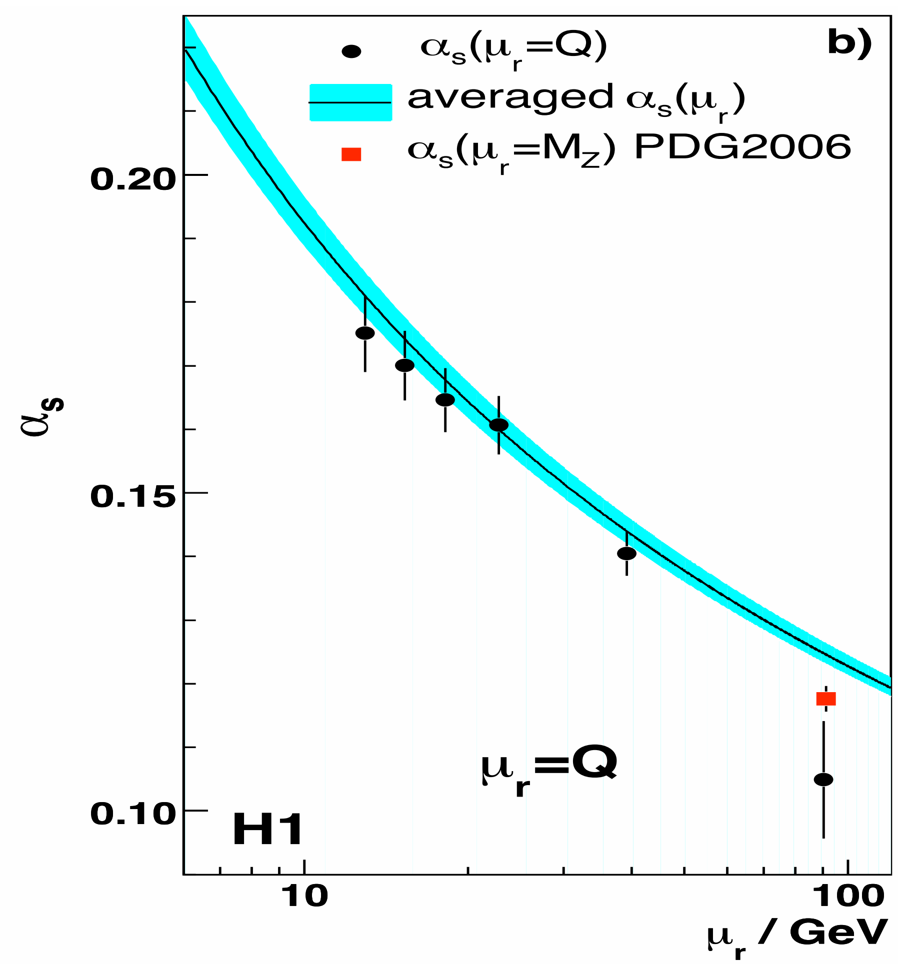
Count all jets in phase space as function of Q^2

Cross section depends on:

1. QCD matrix elements.
2. *Strong coupling α_S.*
3. Parton density functions of the proton.

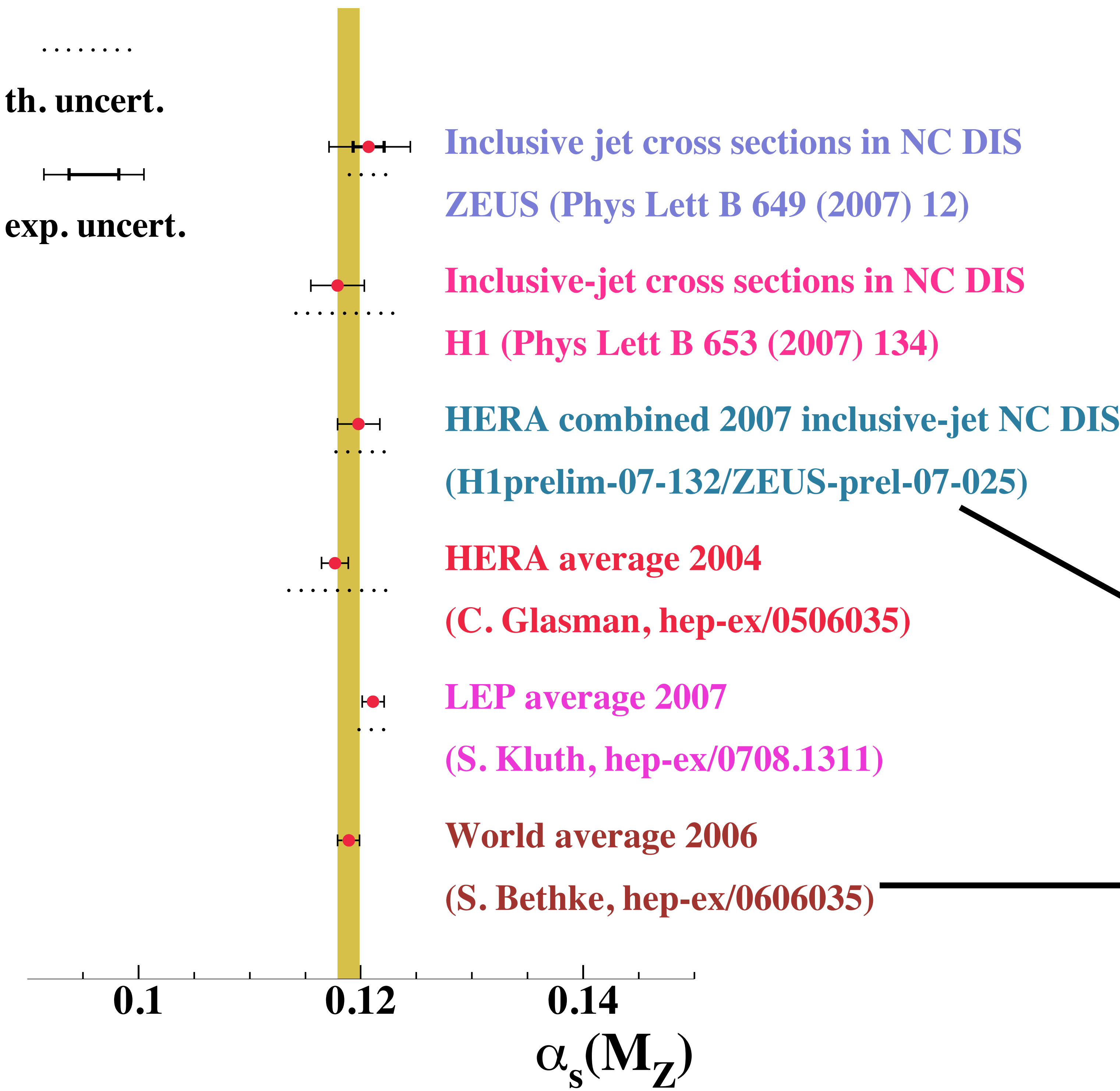
Determine a α_S by fitting the theory to data

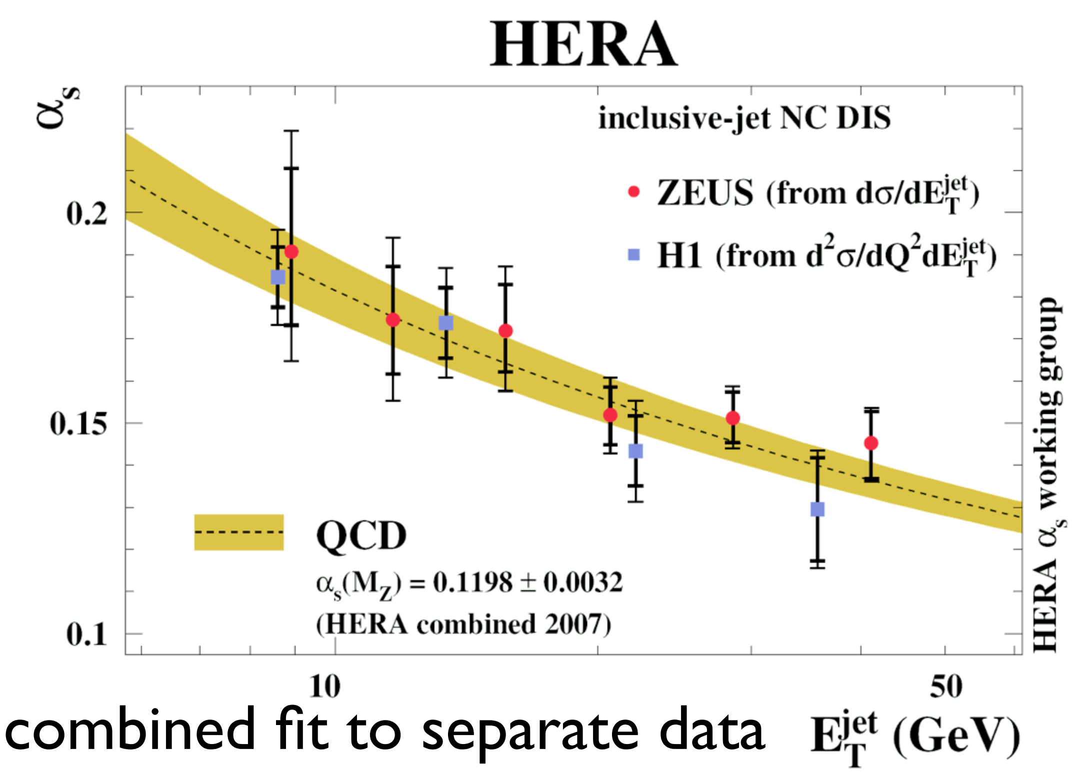




HERA α_s from Jets

$\alpha s(M_Z) = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(\text{th.})$



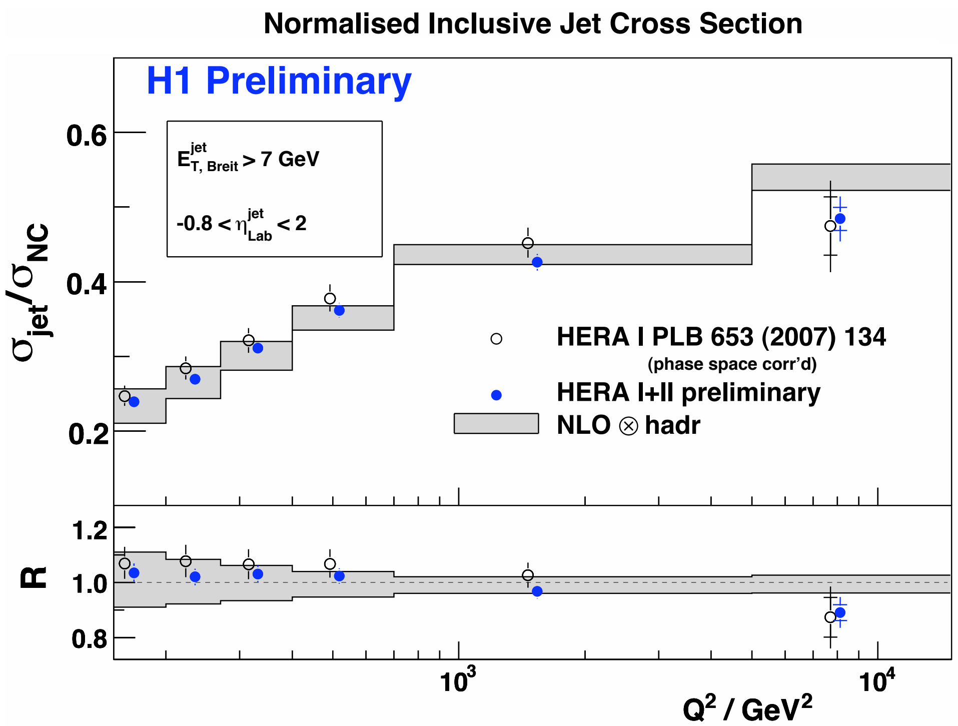


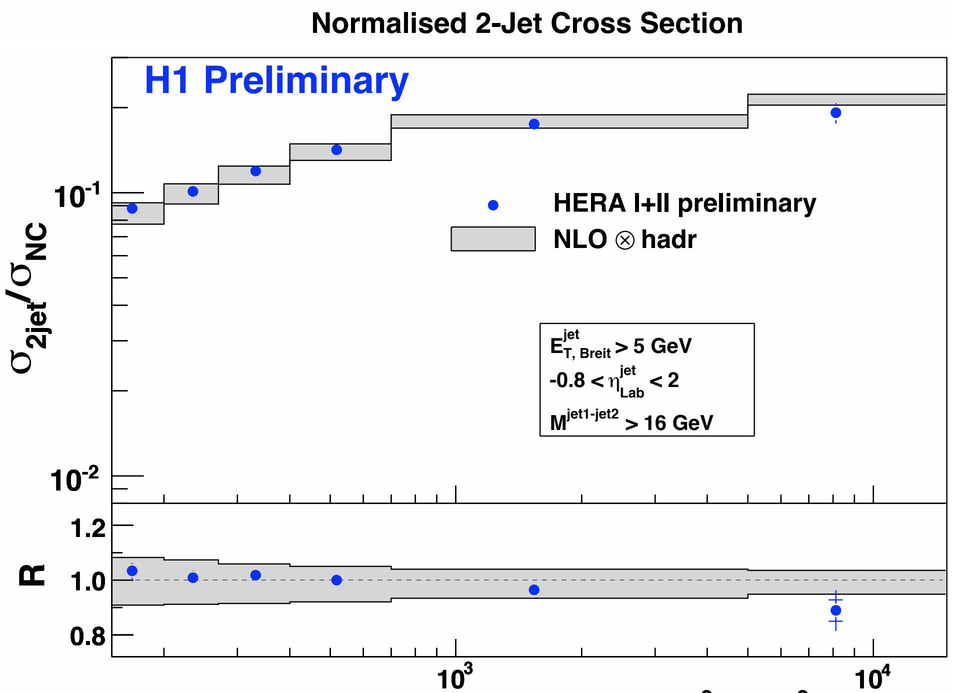
combined fit to separate data

HERA combined 2007 (2.7%)

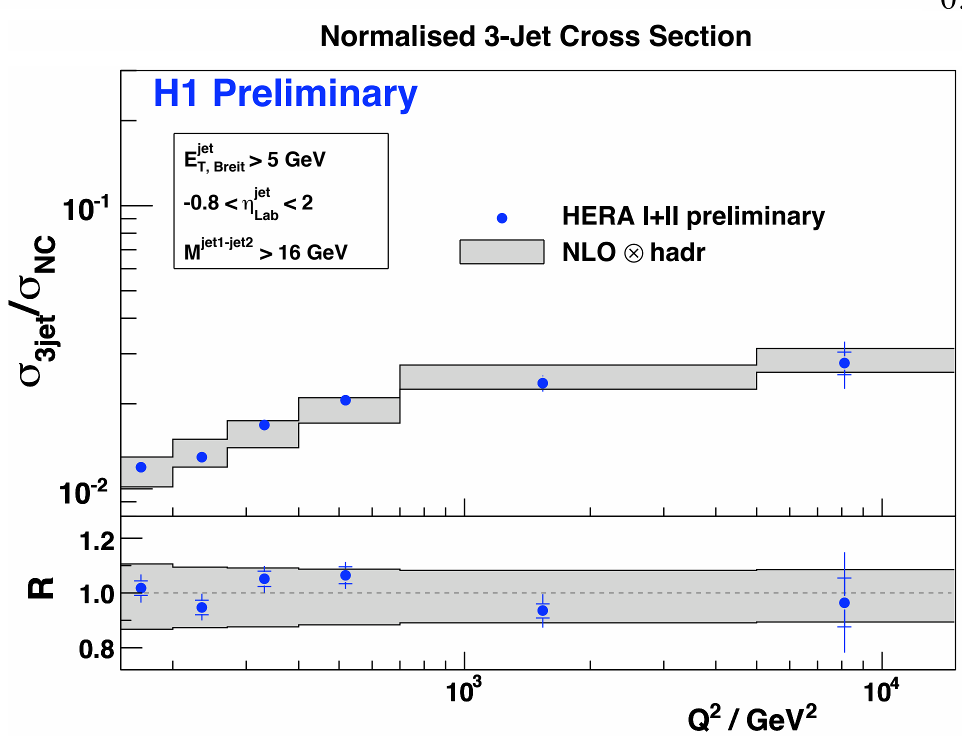
World average (0.8%)

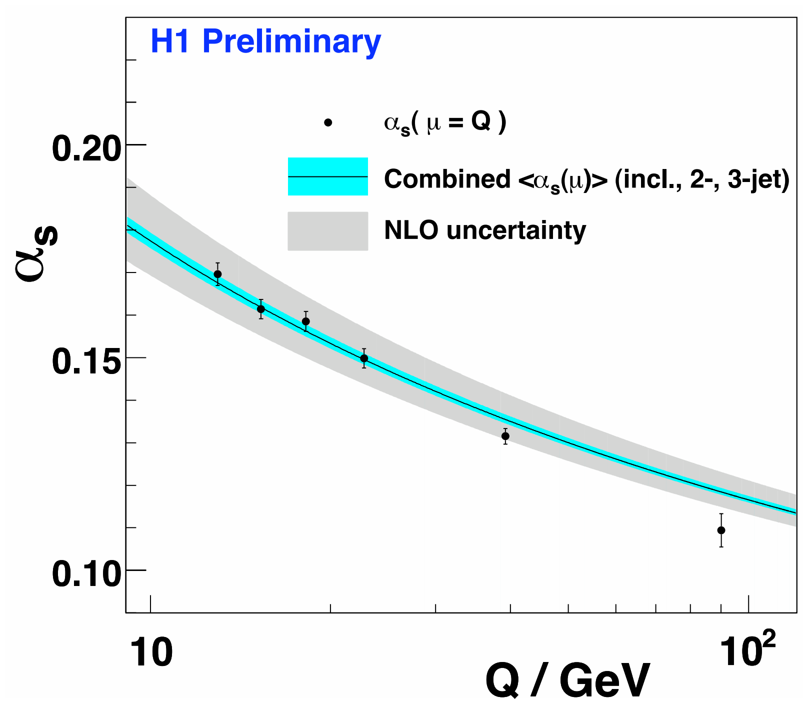
New α_s Measurements





0.1182 0.0008 +0.0041 -0.0031 0.0018 55.8/53





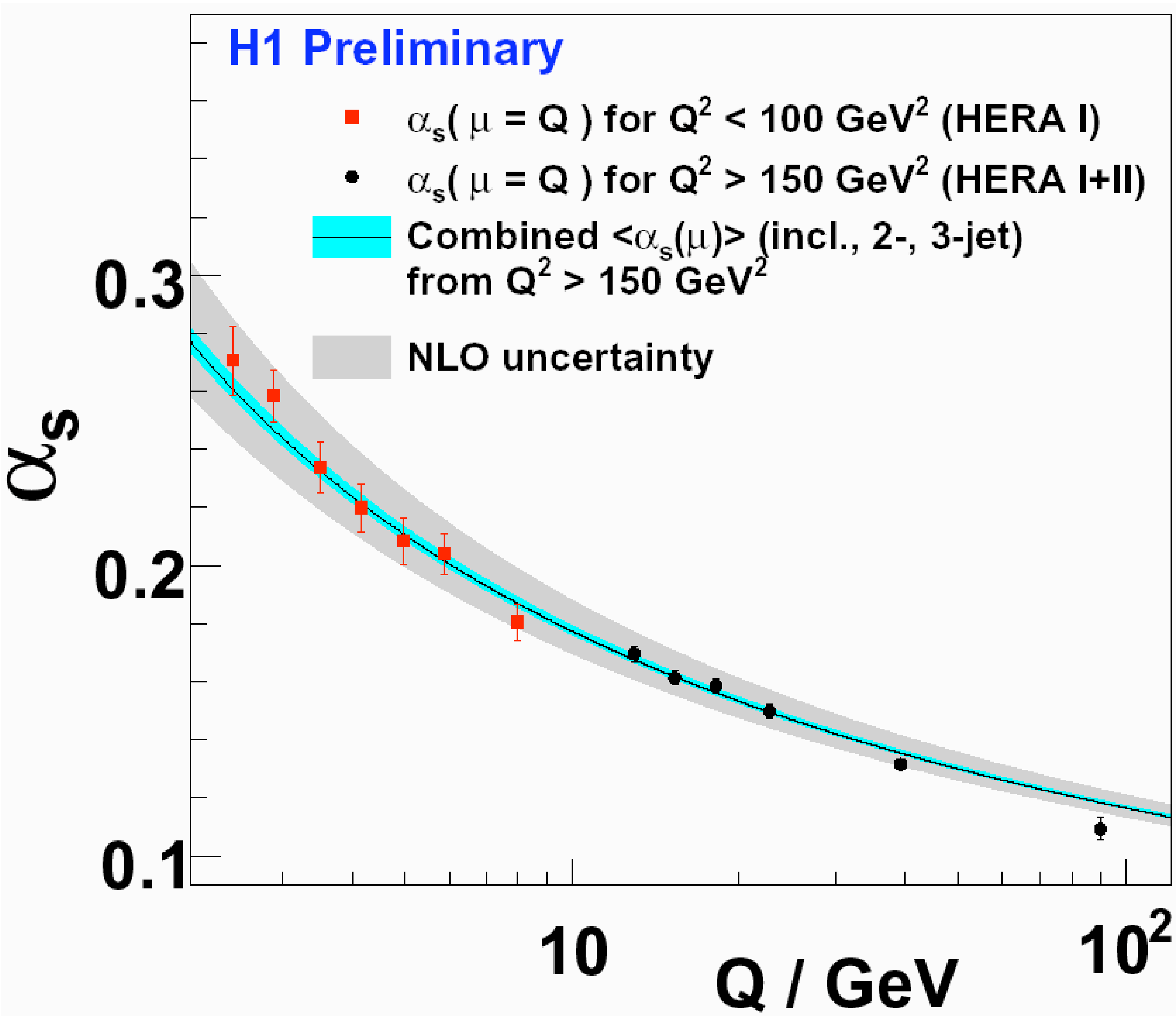
full H1 920GeV data set! ~400pb^{-1}

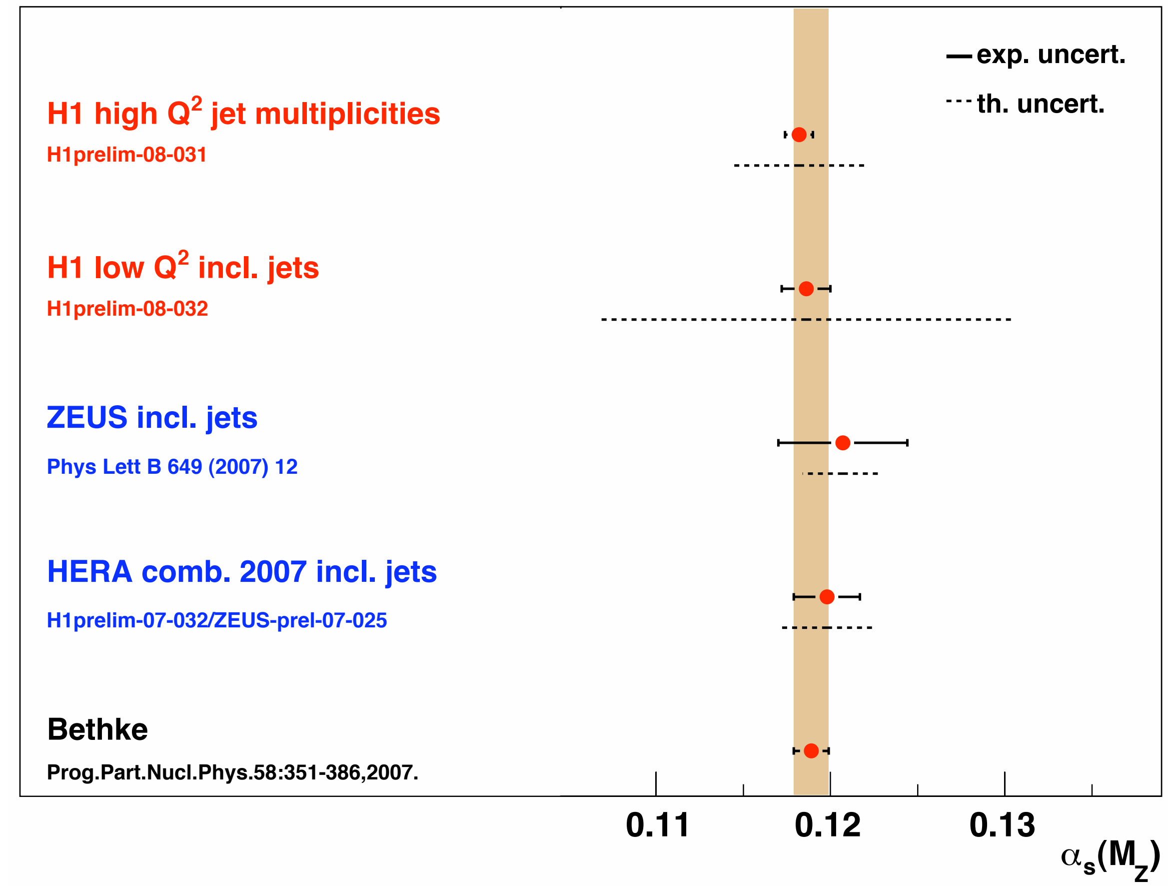
normalised to the DIS cross section - partial cancelation of systematic and theory errors

experimental error on α_s ~0.6%

$$\alpha_s = 0.1182 \pm 0.0008(exp)^{+0.0041}_{-0.0031}(th.) \pm 0.0018(PDF)$$

New α_s Measurements





However theoretical error (scale uncertainty), blows up at low Q

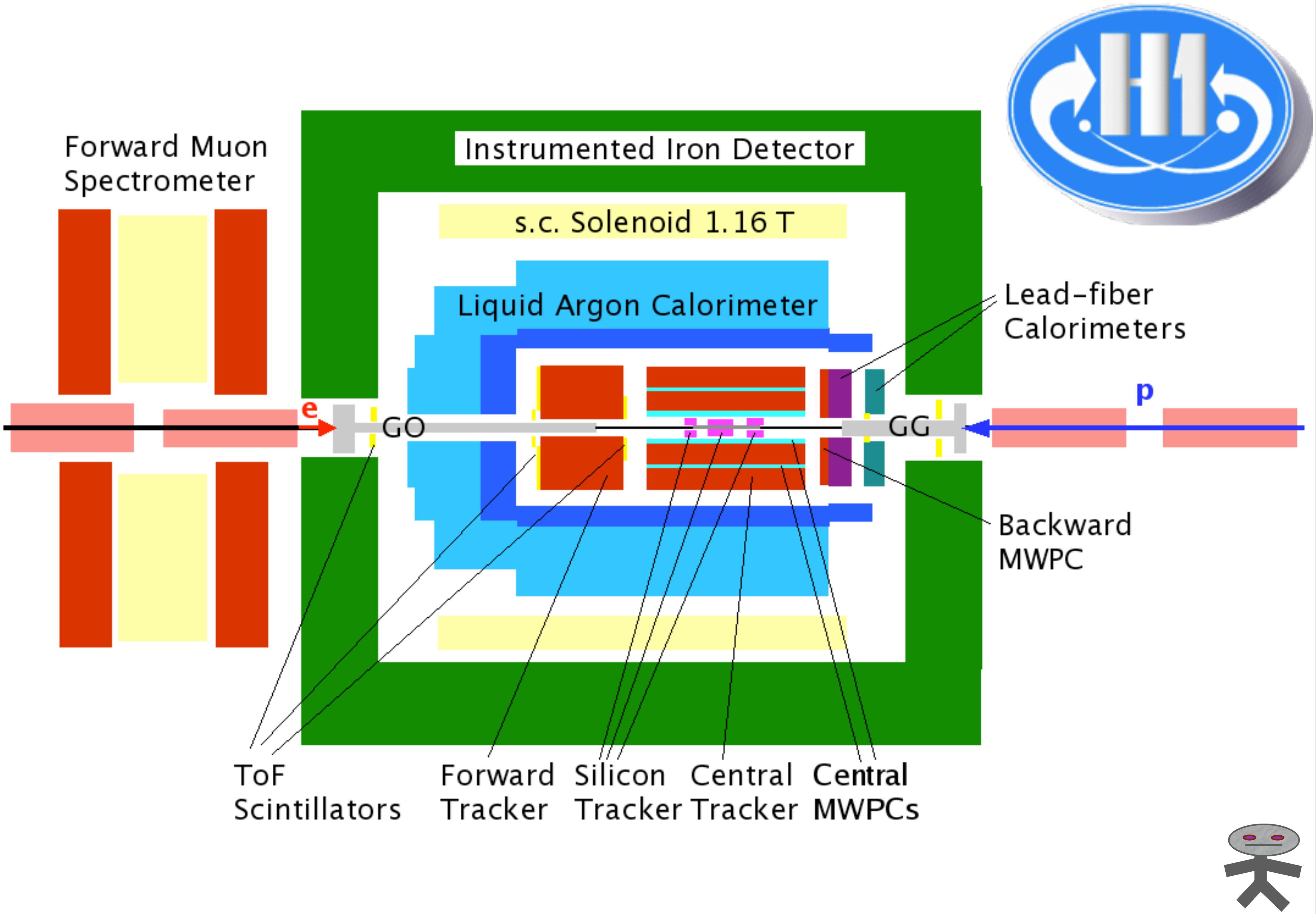
Include HERAI low Q^2 data to get running of α_s over two orders of magnitude in one experiment

need reduced theory uncertainty - NNLO?

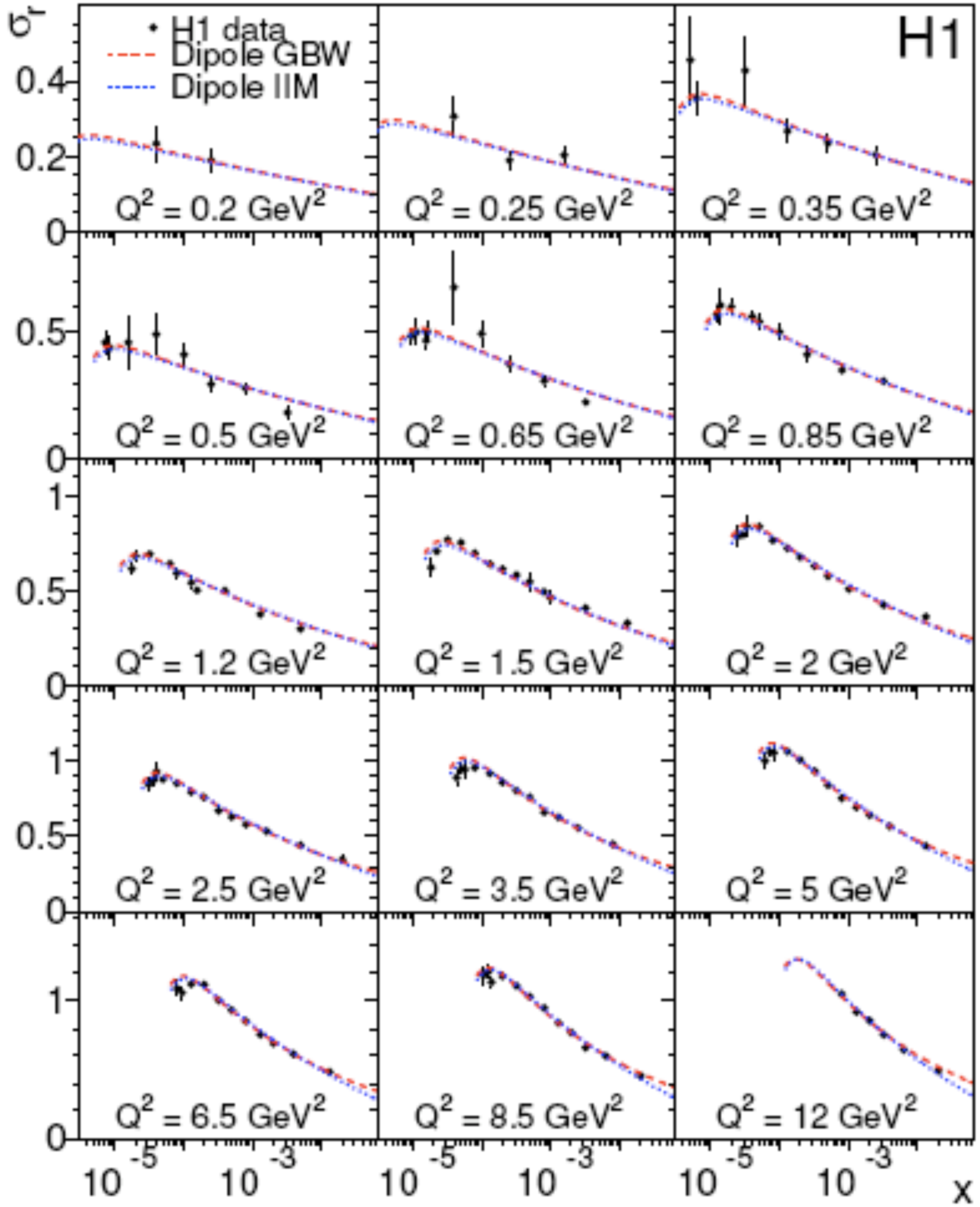
Summary

- HERA provides most precise inclusive structure function measurements, significant improving our knowledge of the proton structure.
- Combination of H1 and ZEUS published data has brought significantly improved precision.
- New measurements still provide an improved understanding of QCD.
- Final results with ultimate precision are being published now!

Backup



Forward Muon
Spectrometer
Instrumented Iron Detector
s.c. Solenoid 1.16 T
Liquid Argon Calorimeter
Lead-fiber
Calorimeters
e
GO
GG
p
Backward
MWPC
ToF
Scintillators
Forward
Tracker
Silicon
Tracker
Central
Tracker
Central
MWPCs

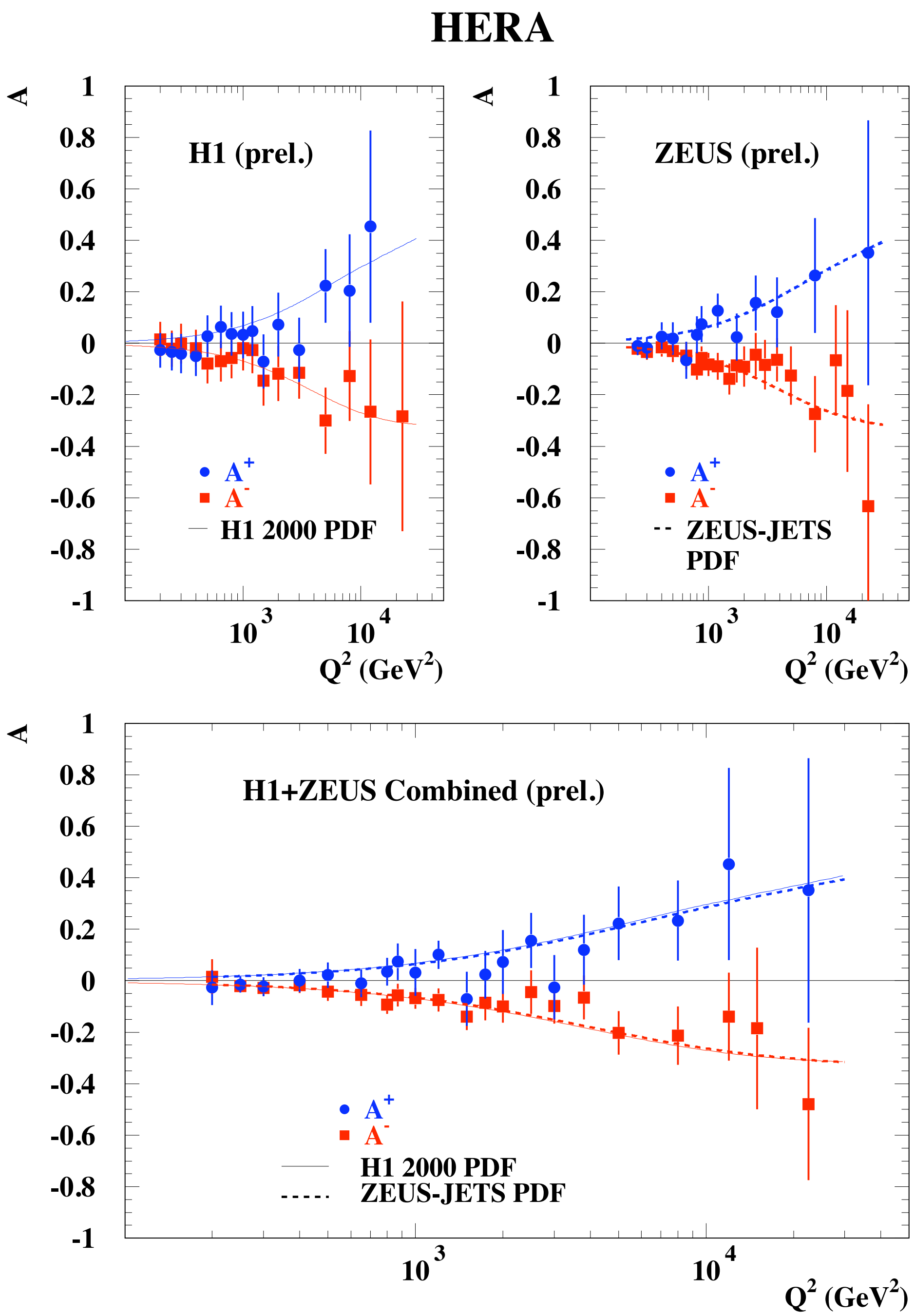


$0.2 < Q^2 < 12$ GeV^2, $5\mathrm{x}10^6 < x < 0.02$

DESY-08-171 (February 2009) submitted to EPJ C

HERA combined xF3

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

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

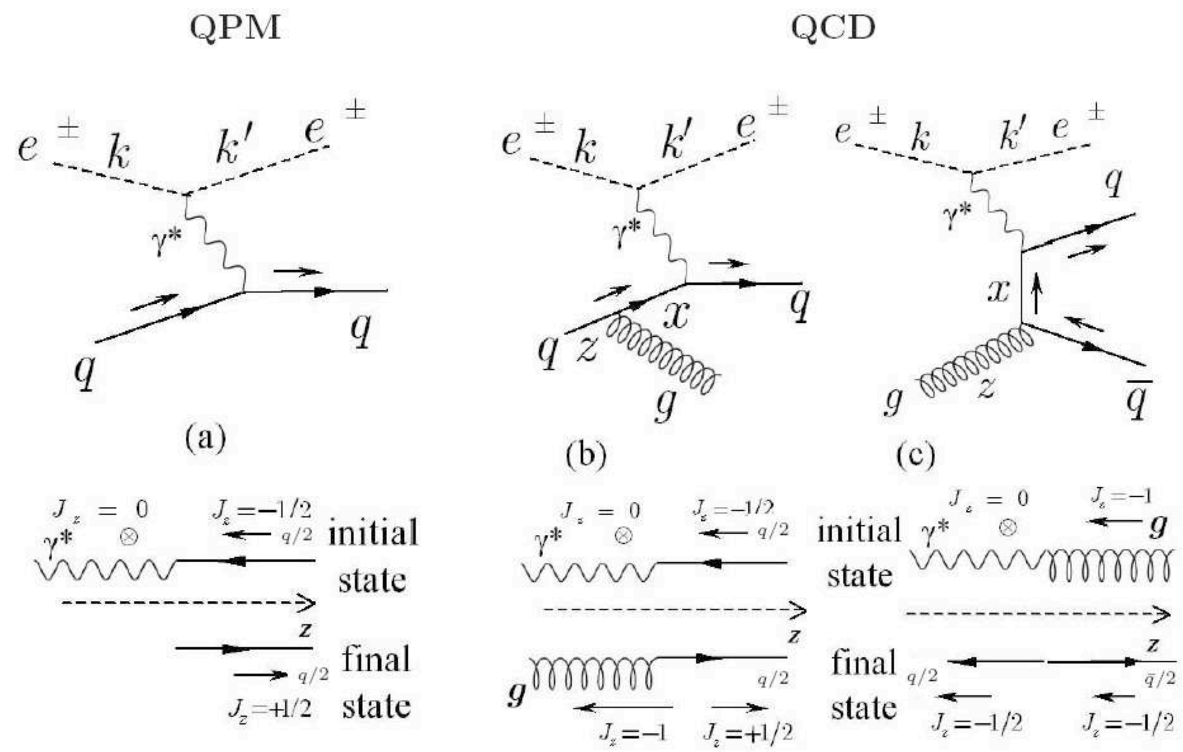
Defined as

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

directly measures NC parity violation.

F_L measurement

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.

F_L measurement

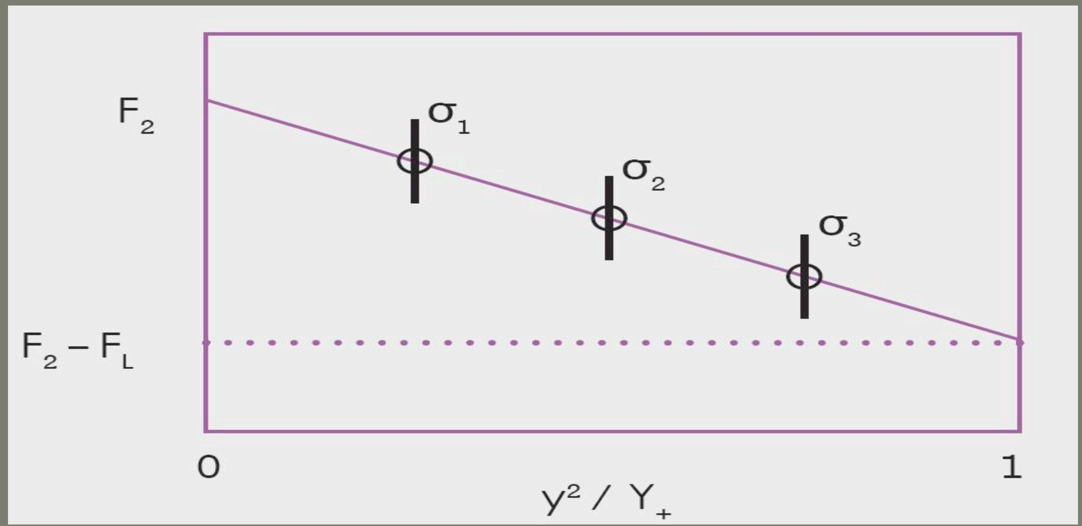
Analysis strategy

- From DIS cross section formula:

$$F_2(x,Q^2) = \sigma_r(x,Q^2,y=0)$$

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

Rosenbluth plot



- hence need to measure σ_r at fixed *(x,Q²)* but with varying *y*
- In *ep* collisions, kinematic variables *(x,Q²,y)* are related via:

$$\sqrt{s} = \sqrt{Q^2/xy}$$

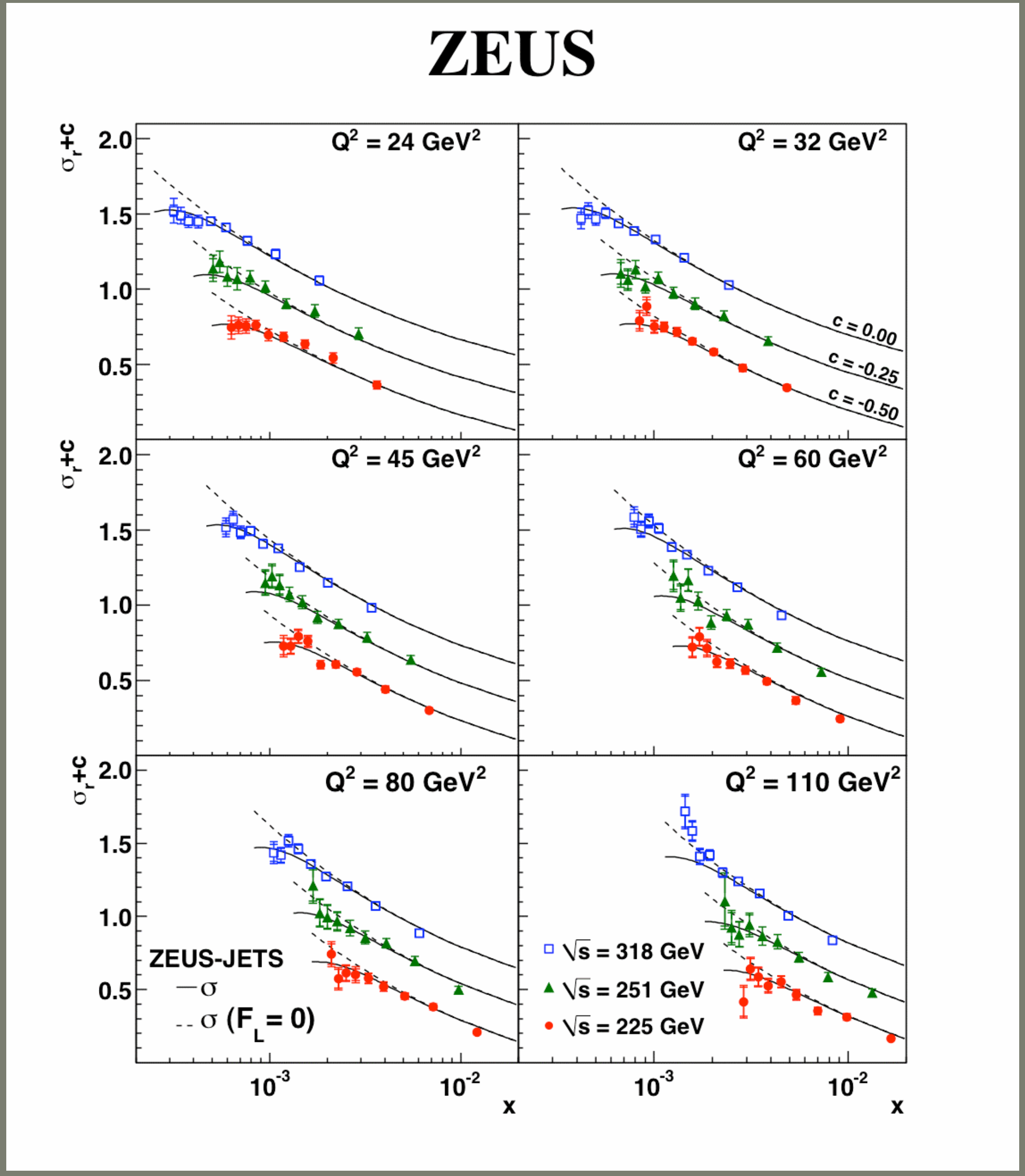
- where $\sqrt{s}$ is the beam centre-of-mass (CoM) energy
- so **need *ep* data at multiple CoM energies**

16th February, 2009 Tim Namsoo (DESY) 7

F_L measurement

Reduced cross sections - ZEUS

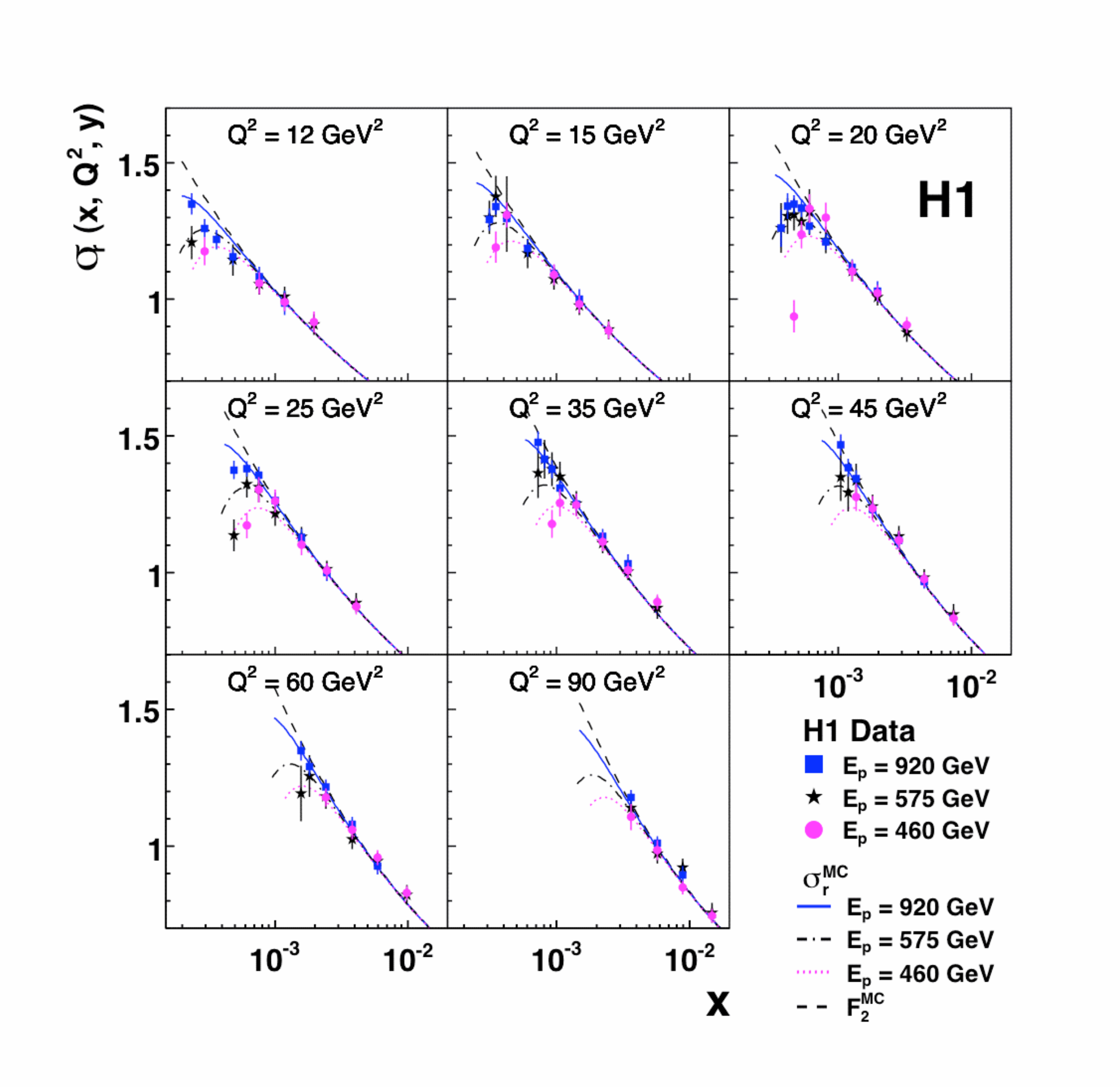
- $\sigma_r(x)$ in bins of Q^2 for each COM energy offset along *y*-axis for clarity
- compared to prediction based on ZEUS-JETS PDF set with expected F_L and $F_L=0$
- F_L causes a suppression at low *x*. Different for each CoM energy - basis of F_L extraction
- small effect but data tend to turn over as expected



F_L measurement

Reduced cross sections - H1

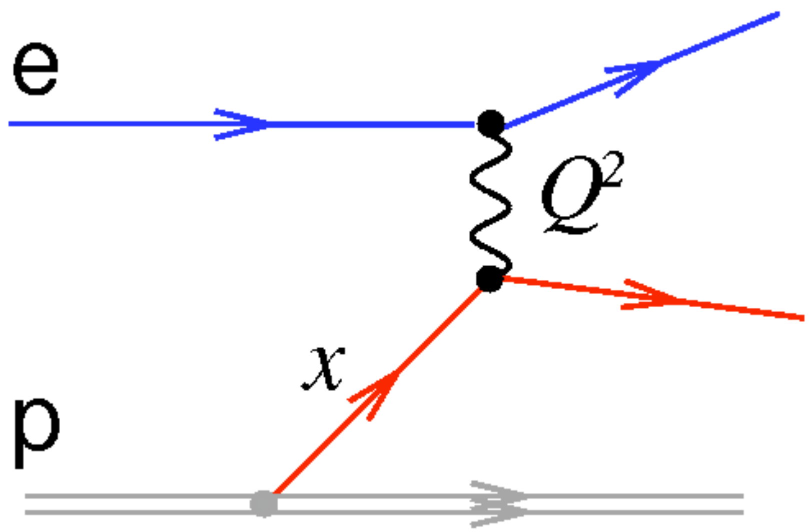
- $\sigma_r(x)$ in bins of Q^2 for each COM energy
- H1 mid-Q^2 analysis
- compared to prediction based on H1 2000 PDF set with expected F_L and F_L=0
- Suppression at low *x* different for each CoM energy - basis of F_L extraction



Frame of reference

LAB

Born level

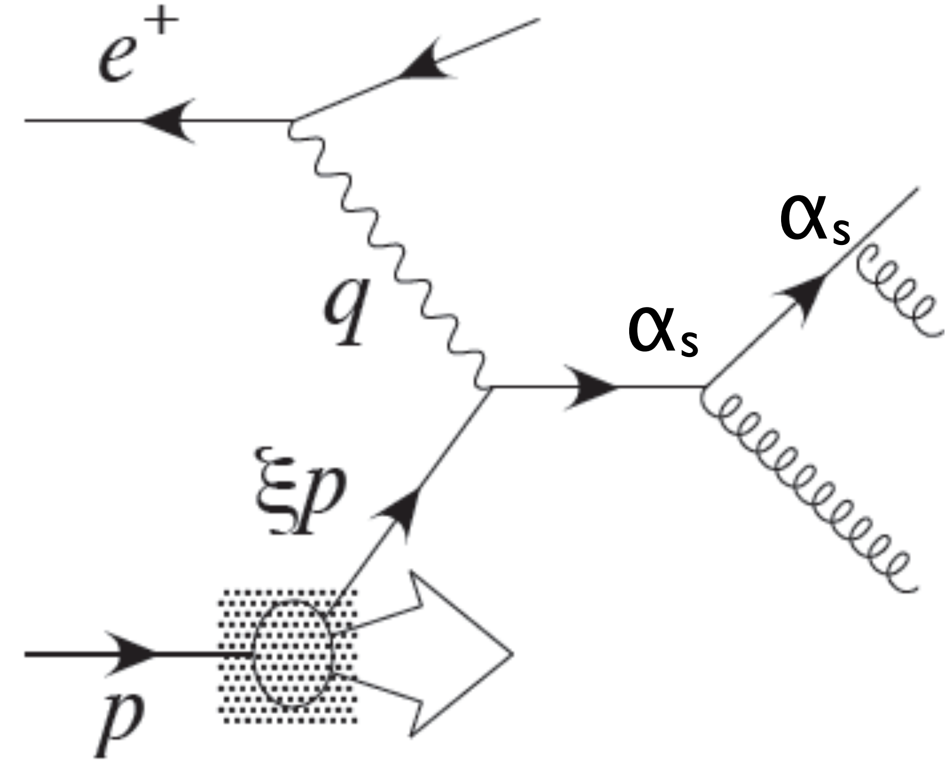


0'th order α_s

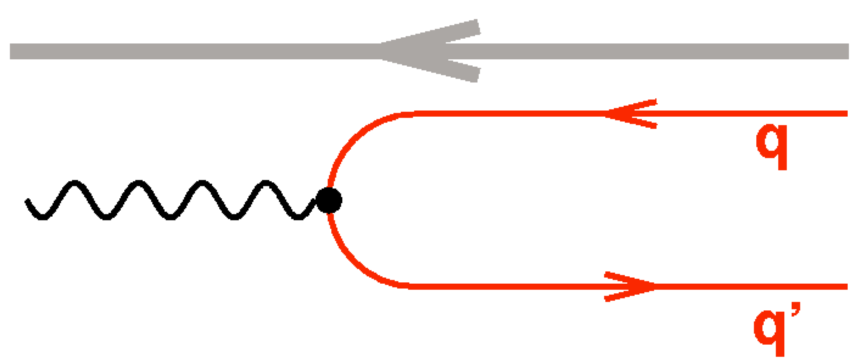
no hard QCD radiation

One jet in Lab frame

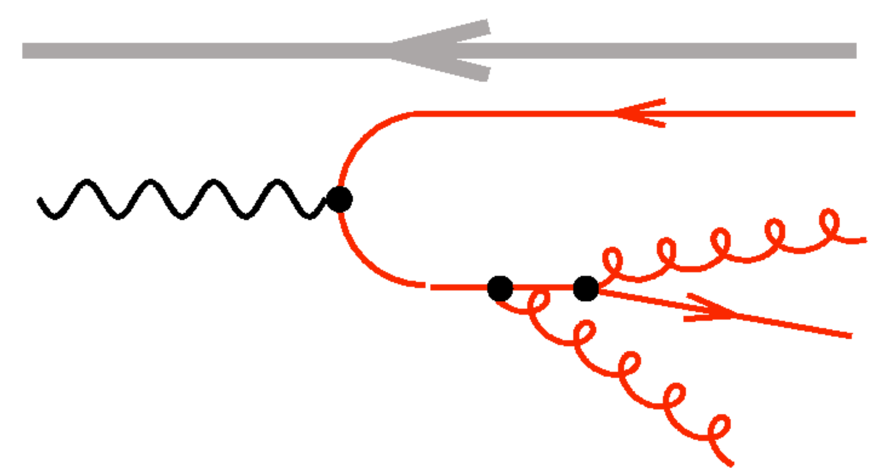
order α_s^2, NLO pQCD



BREIT



No E_T ,
No jets in Breit frame!



In the Breit frame, QCD radiation generates E_T

NLO pQCD Theory

NLOJet++ (Zoltan Nagy)

Proton PDF

Matrix Element

Hadronisation correction

$$\sigma_{jet} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x, \mu_F, \alpha_S)\, \hat{\sigma}_{QCD}(x, \mu_F, \mu_R, \alpha_S(\mu_R)) \cdot (1 + \delta_{had})$$

CTEQ6.5
error: ± 20 eigenvectors
±5%

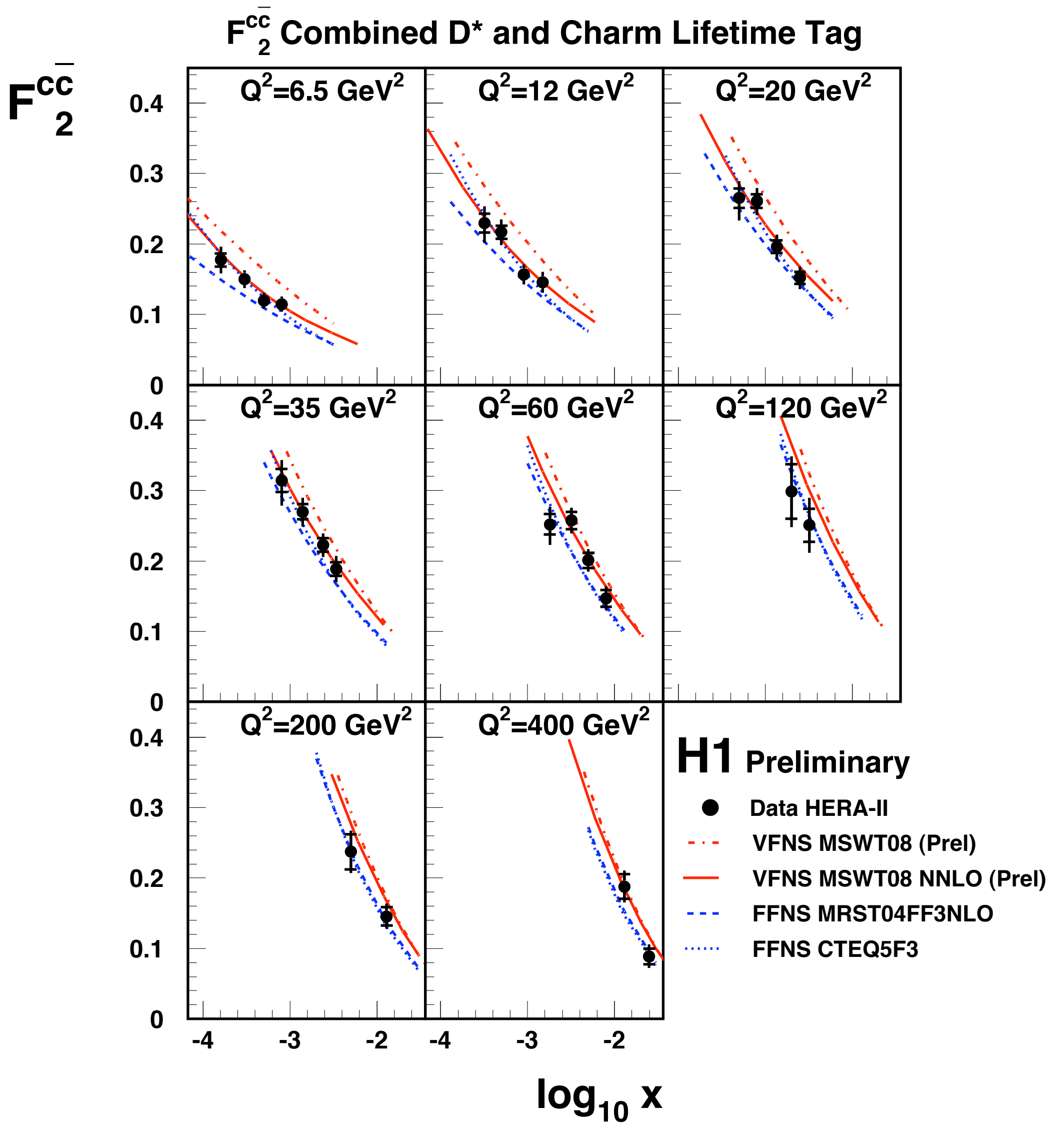
Apply hadronisation correction (δhad) to parton level predictions to be able to compare with data
uncertainty taken from difference of Monte Carlo models (PS /CDM)

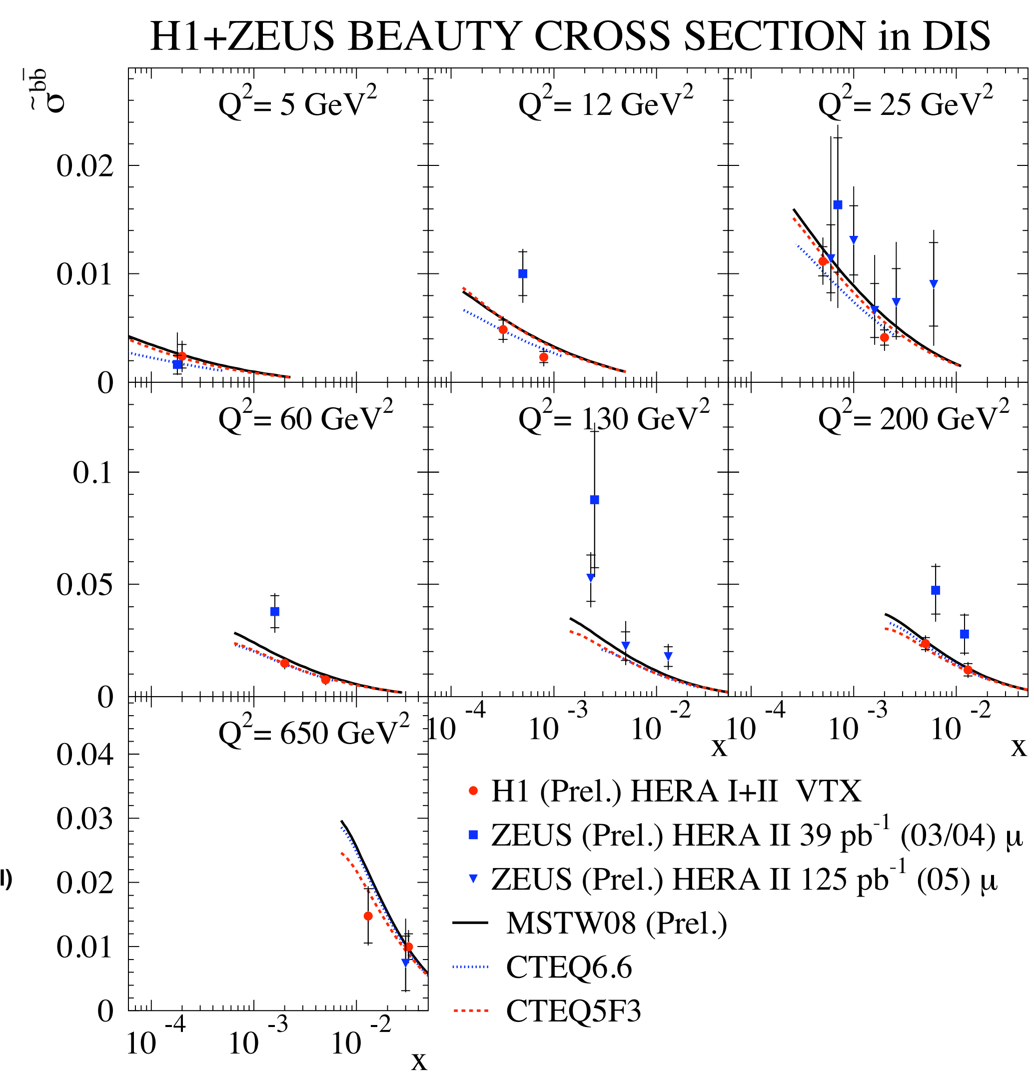
±2%

Assess theoretical uncertainty due to missing higher orders through μ_R (and μ_F) dependence of σ_{jet}
convention : $\mu_{R,F}$ ↑ x2 and $\mu_{R,F}$ ↓ x0.5
±5%

F_2^c and F_2^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 and c/b quark using secondary vertex.