QCD and α_s at HERA

INSTITUTE OF PARTICLE PHYSICS

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Lake Louise Winter Institute

25 February 2012

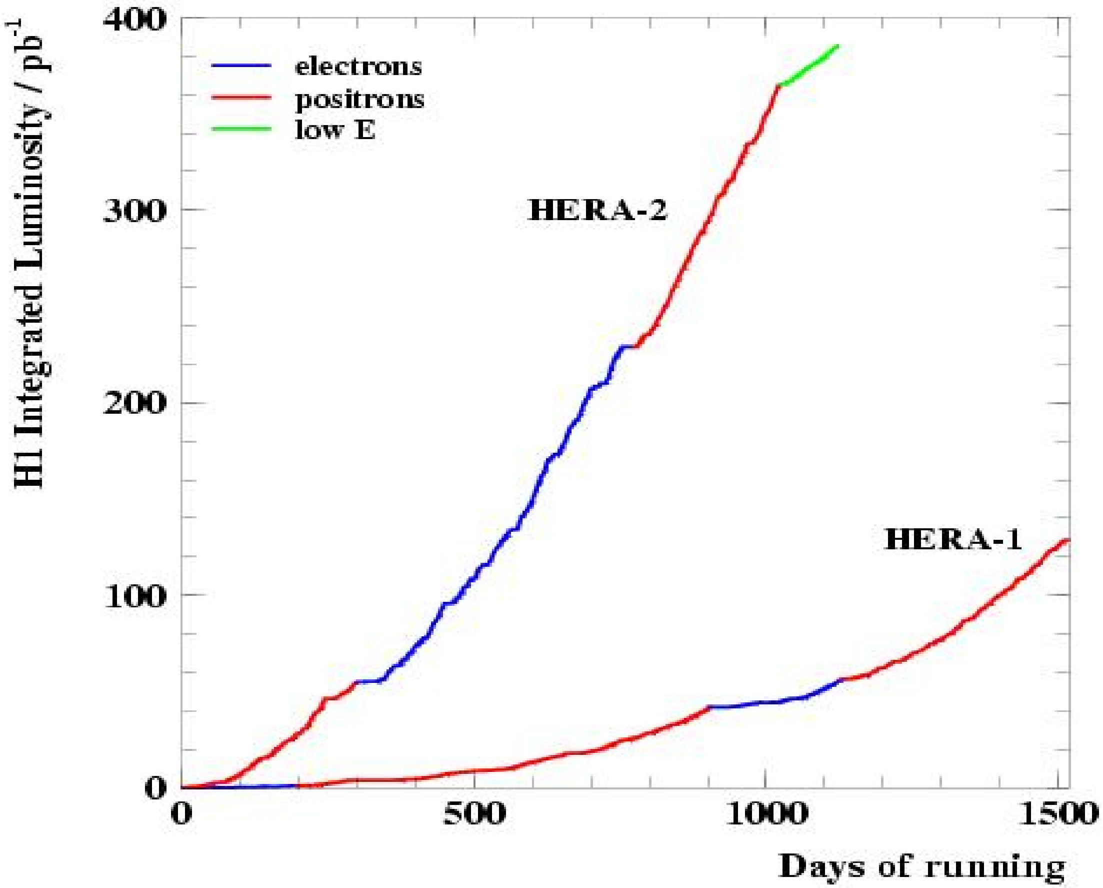
- **H1 and ZEUS at HERA**
- **Parton Distribution Functions**
- **Jets and Determination of α_s**
- **HERA and the LHC**

HERA Luminosities

HERA e$^{\pm}$p collider 1992-2007

HERA I unpolarised e$^{\pm}$ beams

HERA II polarised e$^{\pm}$ beams



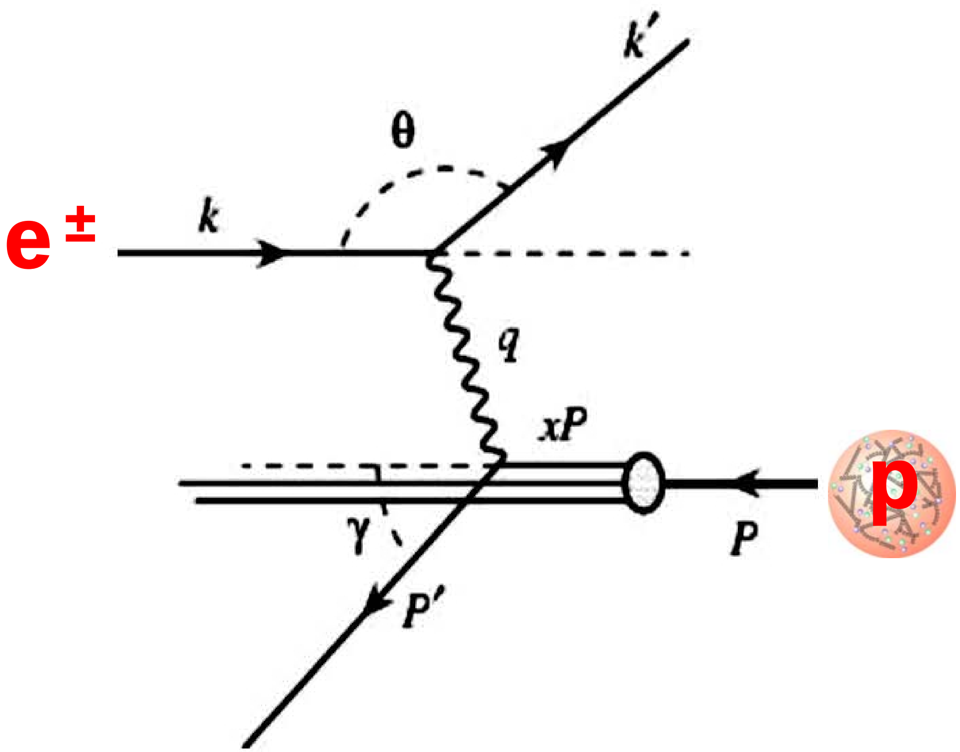
Gated luminosities

e$^{\pm}$p	H1	ZEUS
HERA I	128 pb^{-1}	143 pb^{-1}
HERA II	385 pb^{-1}	407 pb^{-1}

~ 0.5 fb^{-1} per experiment

$e^{\pm}p$ – Kinematics at HERA

27.6 GeV electrons/positrons on 920(820) GeV protons



$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

$$s = (p + k)^2 \qquad Q^2 = x \cdot y \cdot s$$

Deep Inelastic Scattering (DIS)

Neutral current (NC) via γ/Z^0 exchange

Charged current (CC) via $W^{\pm}$ exchange

Q^2 = exchanged momentum (squared)

x = Bjorken scaling variable

y = inelasticity scaling variable

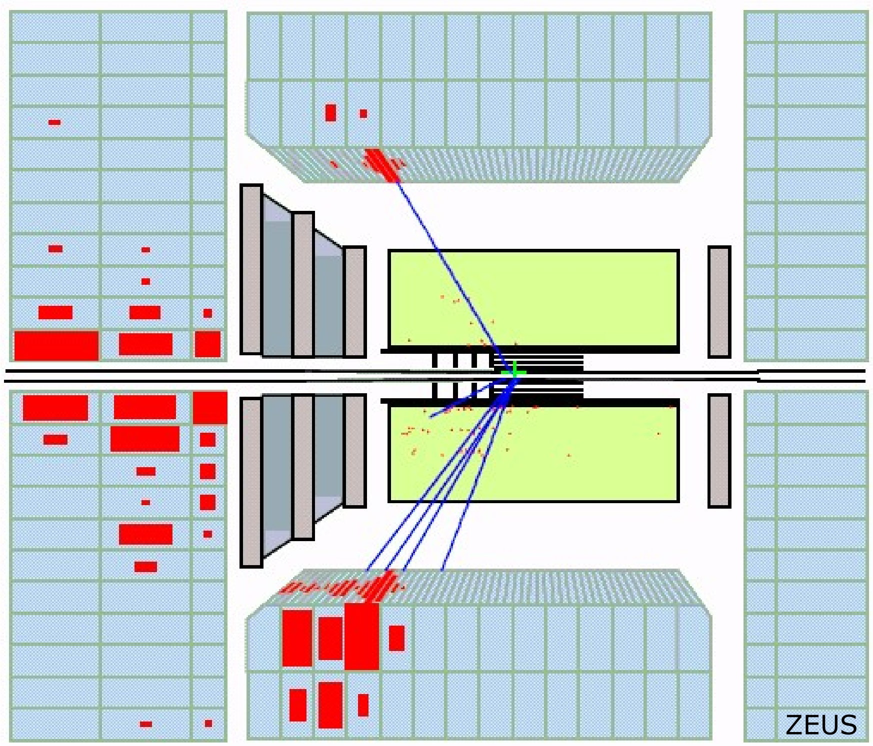
$\sqrt{s}$ = center of mass energy (~318 GeV)

Neutral Current DIS

Cross section:

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

whereby $Y_\pm = 1 \pm (1-y)^2$



With three structure functions F_i:

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

dominant, representing valence quarks, sea quarks and gluons

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

describes valence quarks at high Q^2

F_L = “longitudinal”, contributing at high y and sensitive to gluon distribution

A Simple PDF Parametrisation

$F_i(x) = F_i(x, Q^2)$

$2xF_1(x) = F_2(x)$

the term in Z^0 is neglected

$$F_2^{NC}(x) = \sum_q e_q^2 \cdot x \cdot q(x) = x\left[\frac{4}{9}u(x) + \frac{4}{9}\overline{u}(x) + \frac{1}{9}d(x) + \frac{1}{9}\overline{d}(x) + ..\right]$$

parton distribution functions (PDF's)

Assume flavor- and momentum conservation, let the gluons carry half the proton momentum and allow gluon splitting into q-q̄ pairs:

valence: $u_v(x) = 16(1-x)^7,\ d_v(x) = 8(1-x)^7$

sea: $q_s(x) = (1-2x)^4 + (3x)^{-1}(1-2x)^4$ $(x < 0.5)$

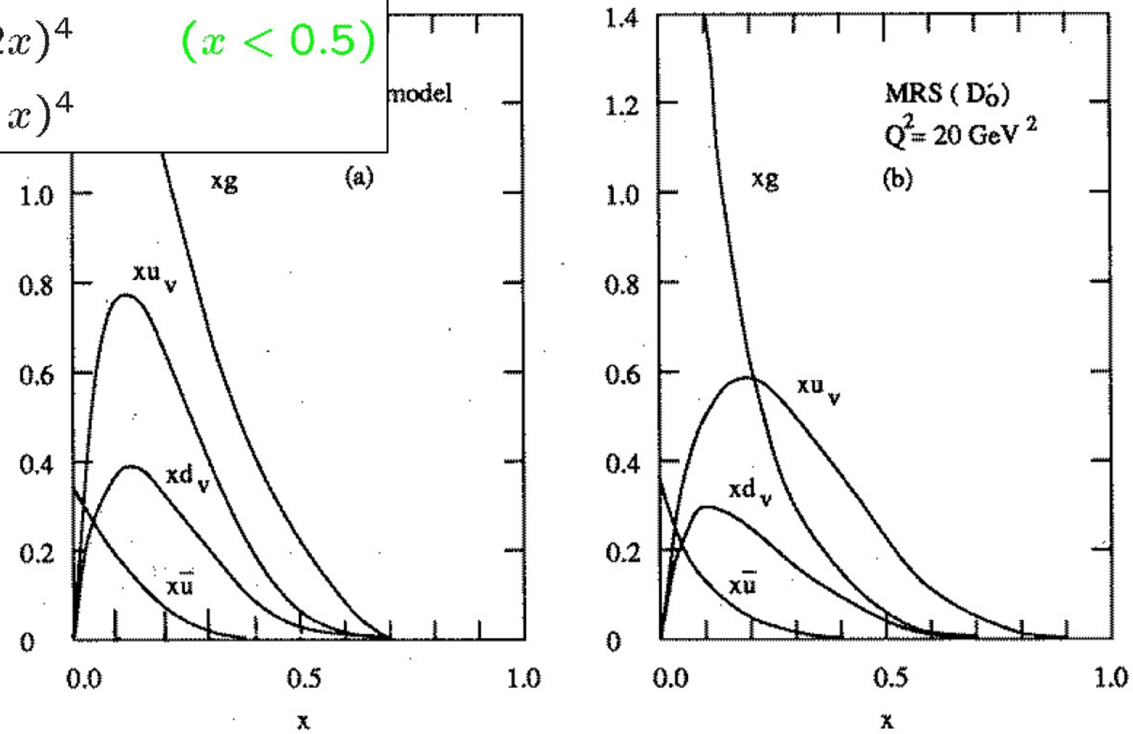
gluons: $g(x) = 3(1-x)^4 + 2x^{-1}(1-x)^4$

pre-HERA Simple model

vs

MRS parametrisation from data:

qualitative behaviours ok



HERA PDF's

The input data is restricted to HERA (H1 and ZEUS combined).

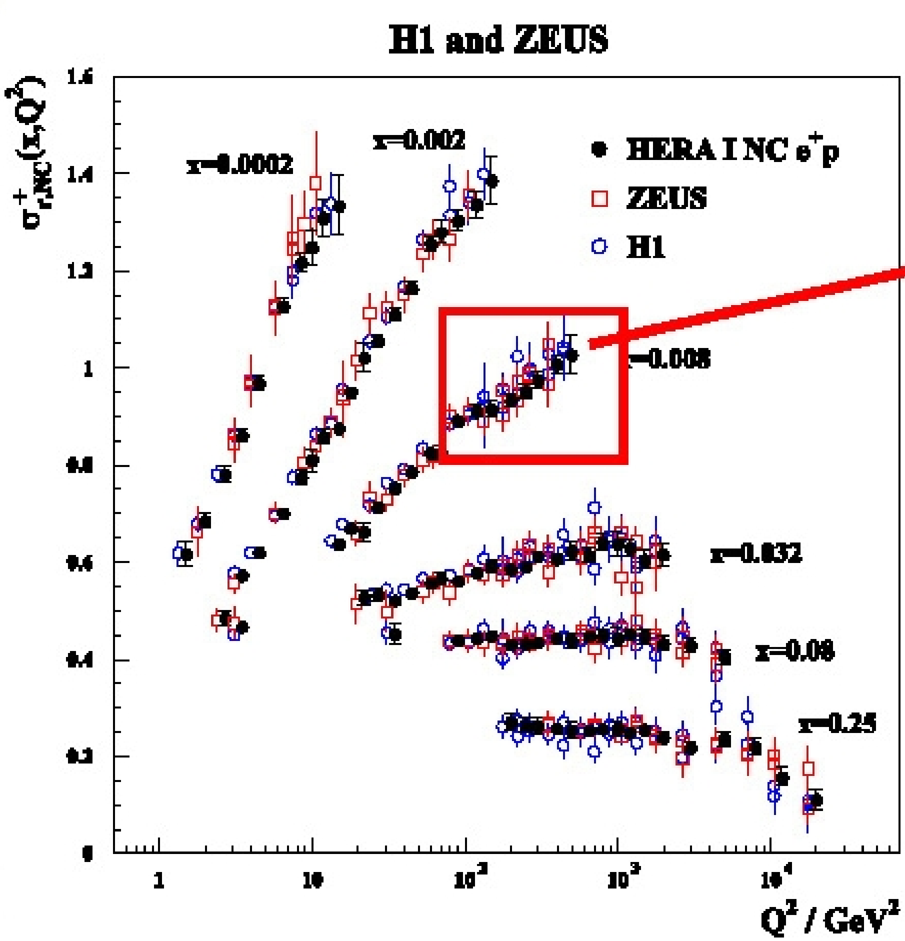
Version	Order	HERA	Low E_p	Jets	Charm	Date
1.0	NLO	I				2009/11
	NNLO	I				2010/04
1.5	NLO	I+II(part)				2010/07
	NNLO	I+II(part)				2011/03
1.6	NLO	I+II(part)		√		2011/03
1.7	NLO	I+II(part)	√	√	√	2011/06

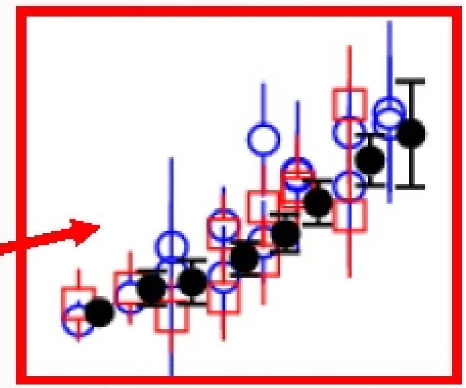
↑ Inclusive data

A large program is underway at HERA to finalize the data analyses.

Combining H1+ZEUS Data

- increase statistics, check the consistency of the data between the two detectors
- reduce the systematic errors through detector cross-calibration (2% or better)
- combine both measurements in a model independent way, huge data sets available
- data as input for DGLAP QCD analysis → extract new proton PDF's for HERA





This example:

all of NC and CC data from HERA I

full error correlations (e.g. energy scale)

averaging procedure uncertainties

Significantly improved precision!

HERAPDF1.0

QCD NLO fits using only HERA data (H1+ZEUS) for consistency

Model assumptions: α_s (0.1176) , strangeness fraction (0.31) , c-mass (1.4 GeV), b-mass (4.75 GeV), Q^2_0 (1.9 GeV^2), Q^2_{min} (3.5 GeV^2)

Parametrisation: $$xf(x, Q_0) = A \cdot x^B \cdot (1-x)^C \cdot (1 + \epsilon\sqrt{x} + Dx + Ex^2)$$

momentum and quark sum rules + other standard assumptions

10 free parameters for:

the gluon (g), valence quarks (u,d) and sea quarks:

$$\mathrm{B_g, C_g, B_u, C_u, C_d, A_{\bar{d}}, B_{\bar{d}}, C_{\bar{d}}, C_{\bar{u}}, E_u}$$

Results: for HERA-I data

(numbers to be compared

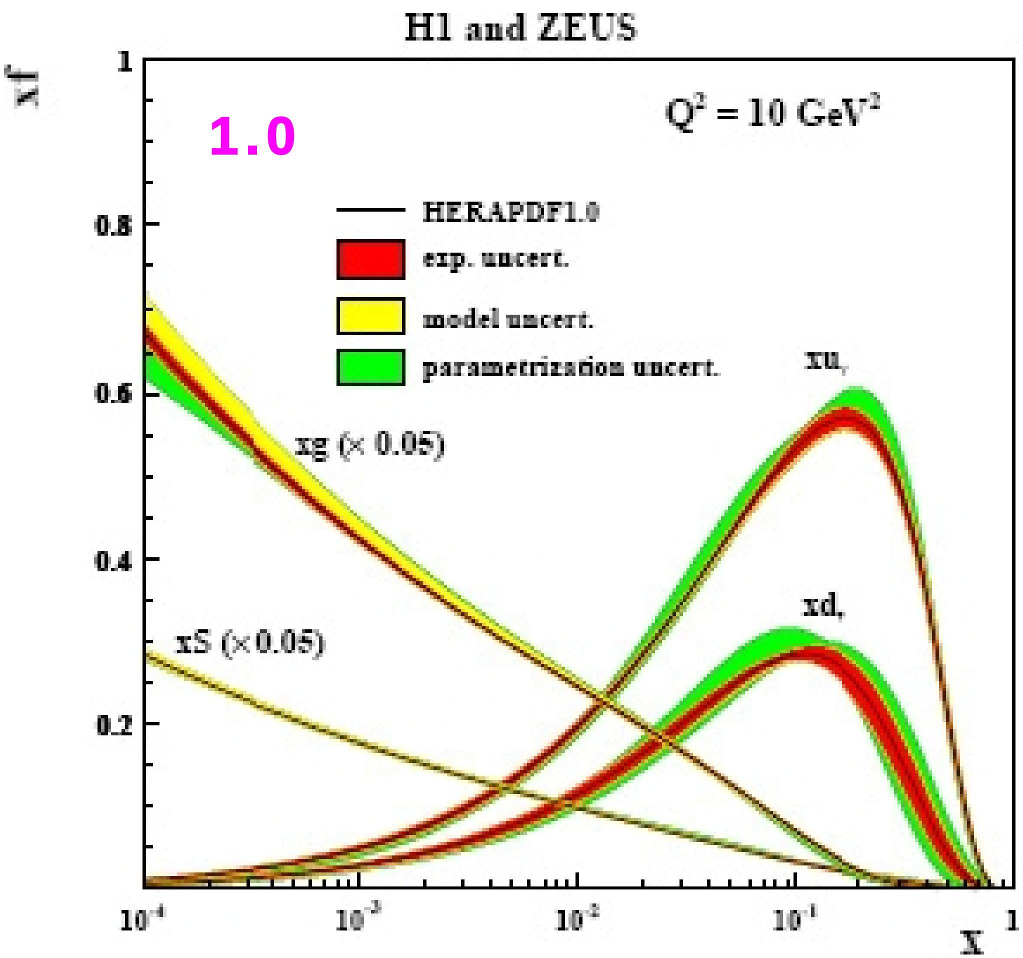
to simple model of slide 5)

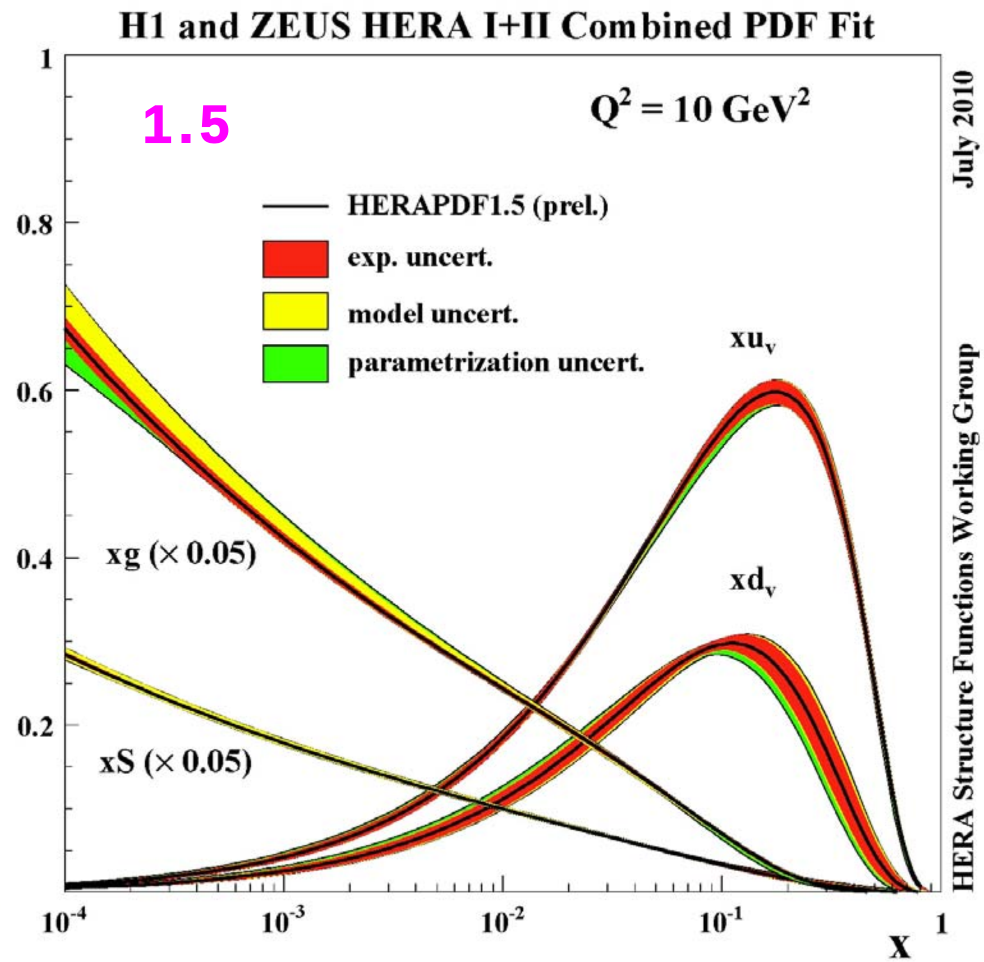
	A	B	C	E
xg	6.8	0.22	9.0	
xu_v	3.7	0.67	4.7	9.7
xd_v	2.2	0.67	4.3	
xU-bar	0.113	-0.165	2.6	
xD-bar	0.163	-0.165	2.4	

HERAPDF1.5 (+HERA II)

H1prelim-11-034, ZEUS-prel-11-001

The HERA II data is added through an averaging procedure:

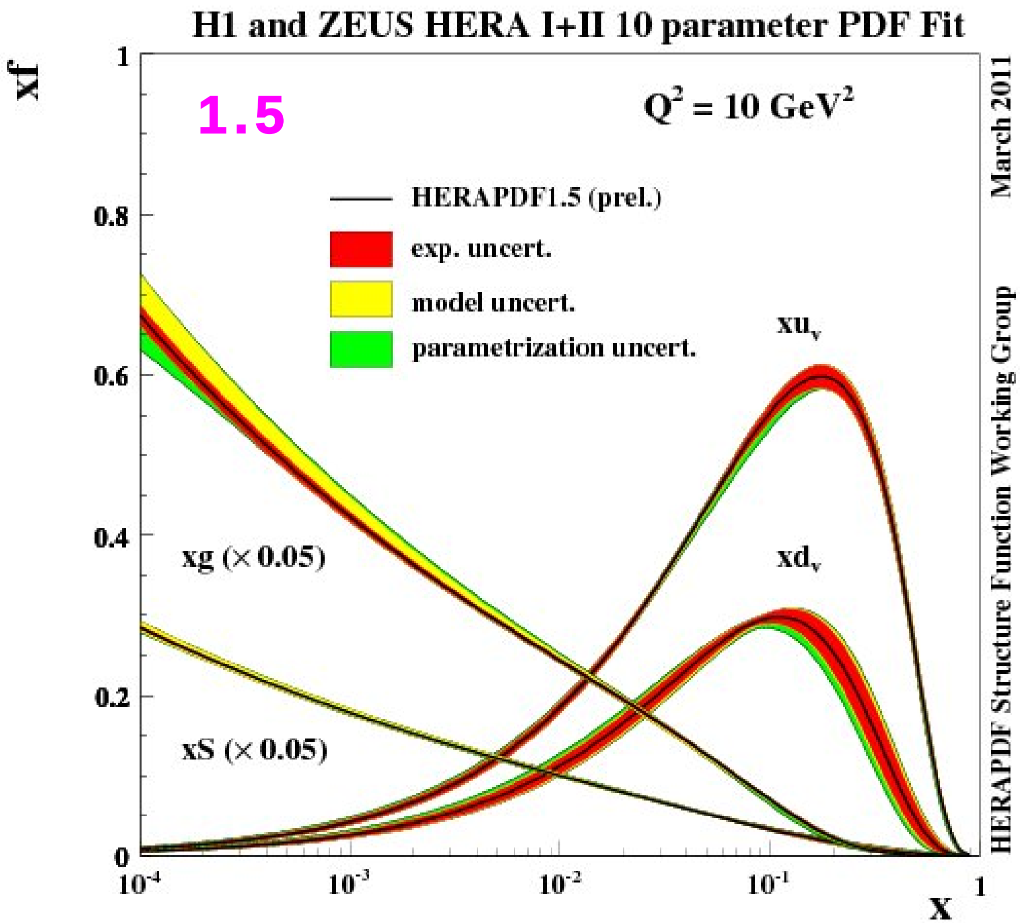


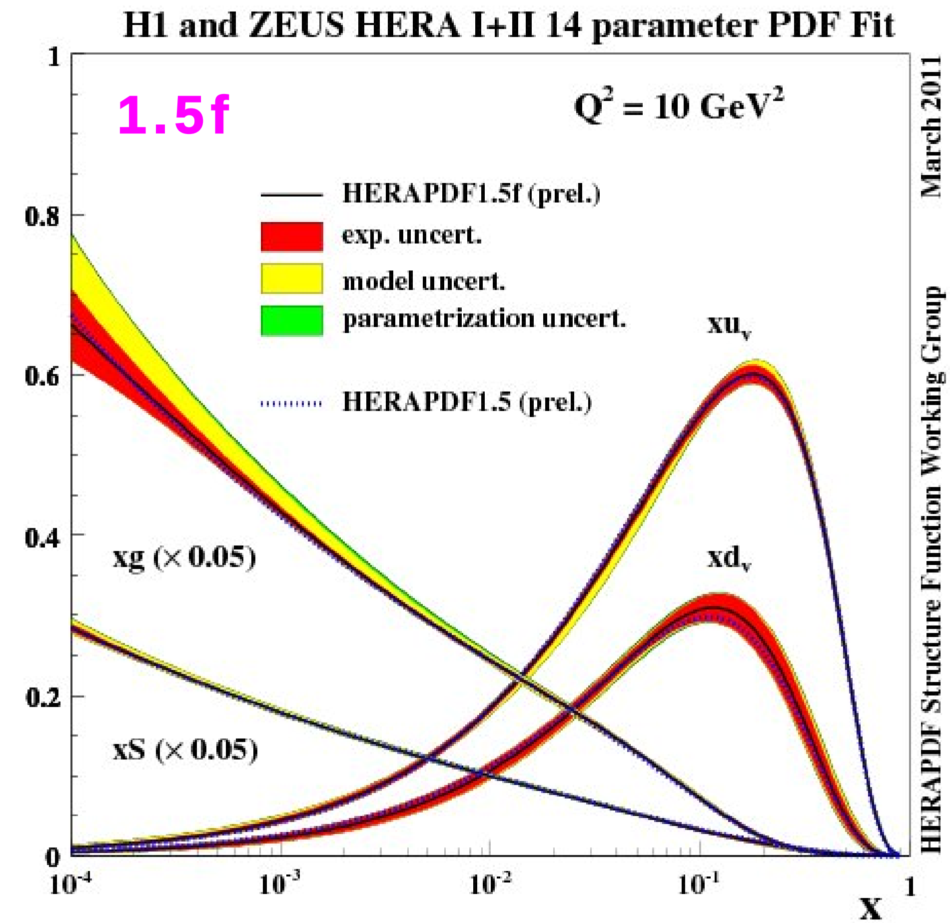


The consistency of the results is preserved and their precision is greatly improved, especially at high x.

HERAPDF1.5f (14 parameters)

An extended parametrisation exists with 14 free parameters, allowing for more flexibility at low x for gluons and valence quarks (also for NNLO).

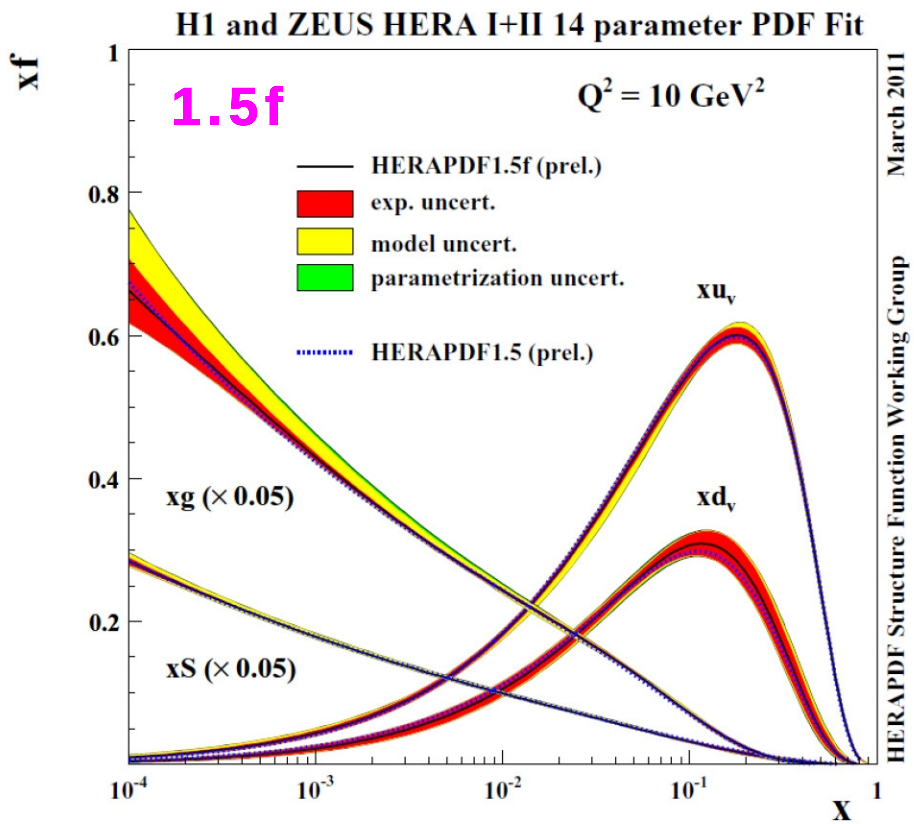




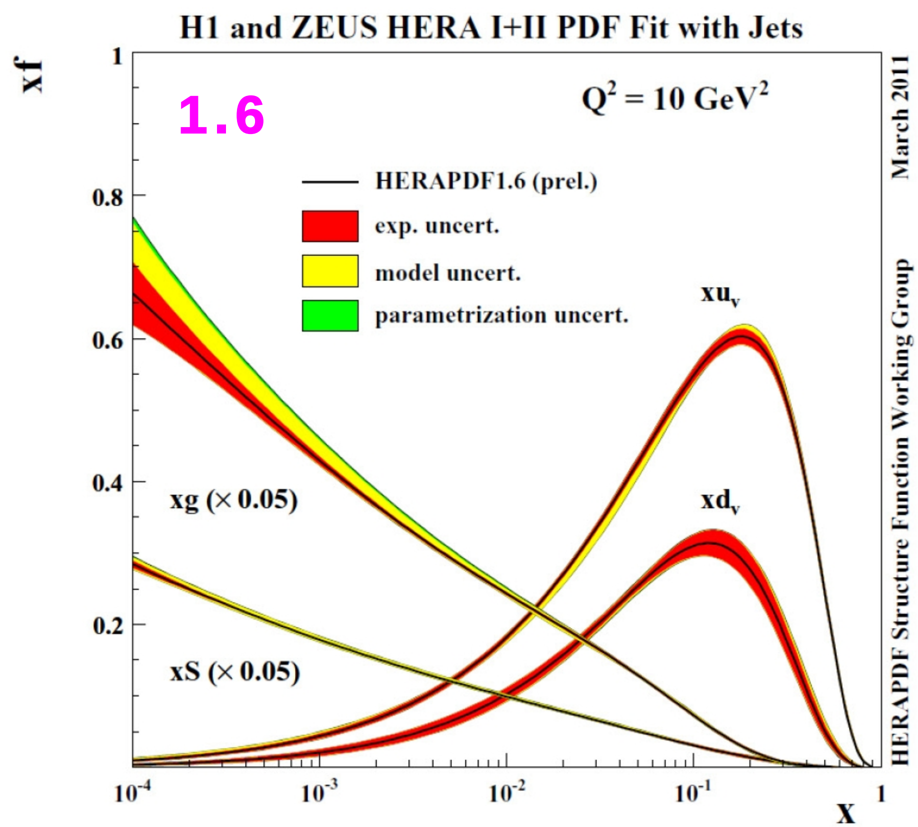
Balance reached between parametrisation and experimental uncertainties, especially visible at the low-x end of the gluon distribution.

HERAPDF1.6 (+jets)

When the jet data is added, α_s is kept fixed at 0.1176.



excluding jet data

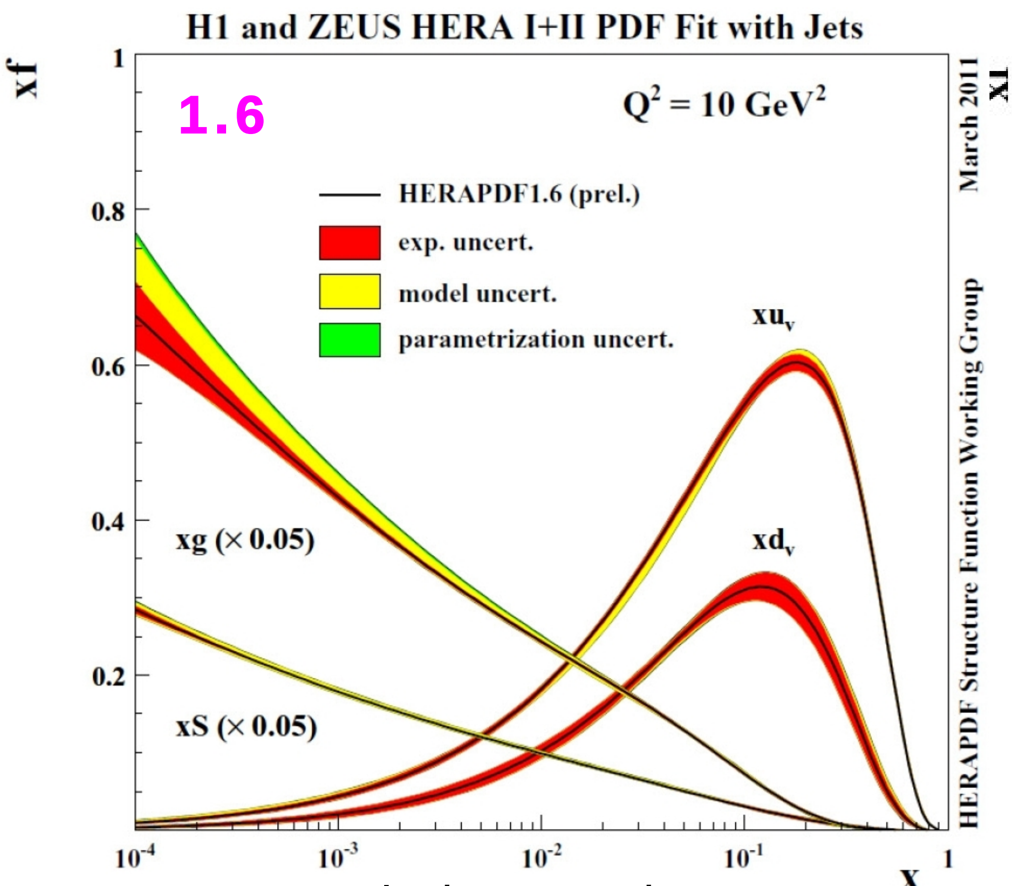


including jet data

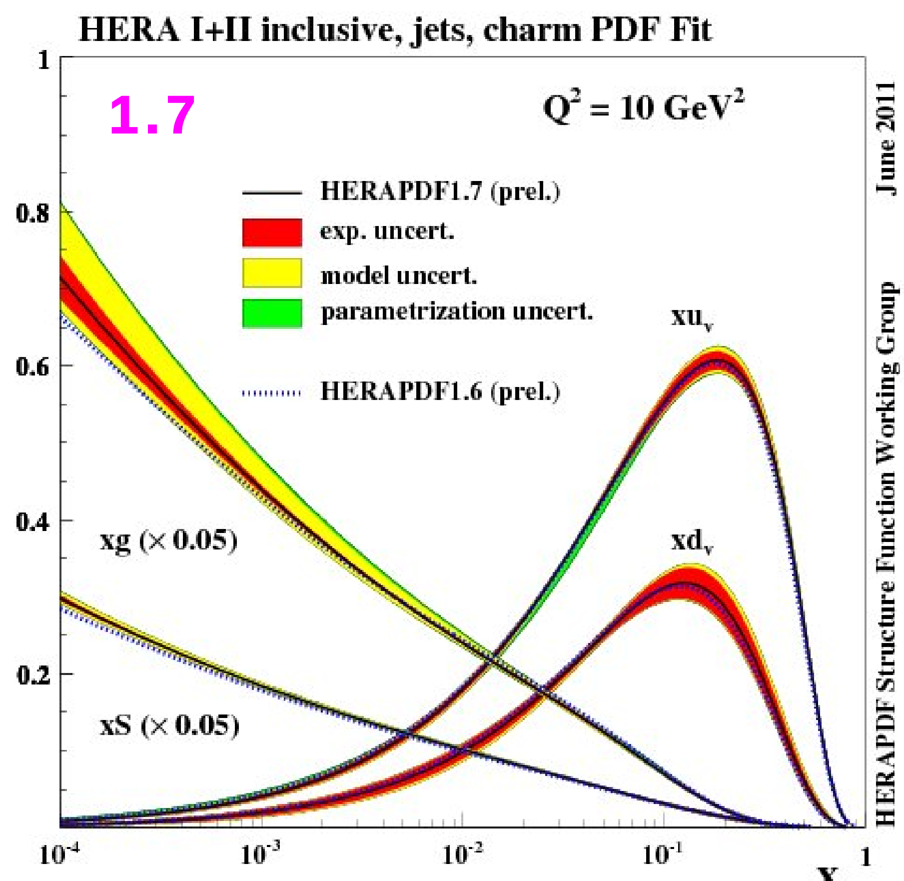
Essentially little effect is observed.

HERAPDF1.7 (+charm+)

The charm data is now added, together with data from low energy runs.



including jet data

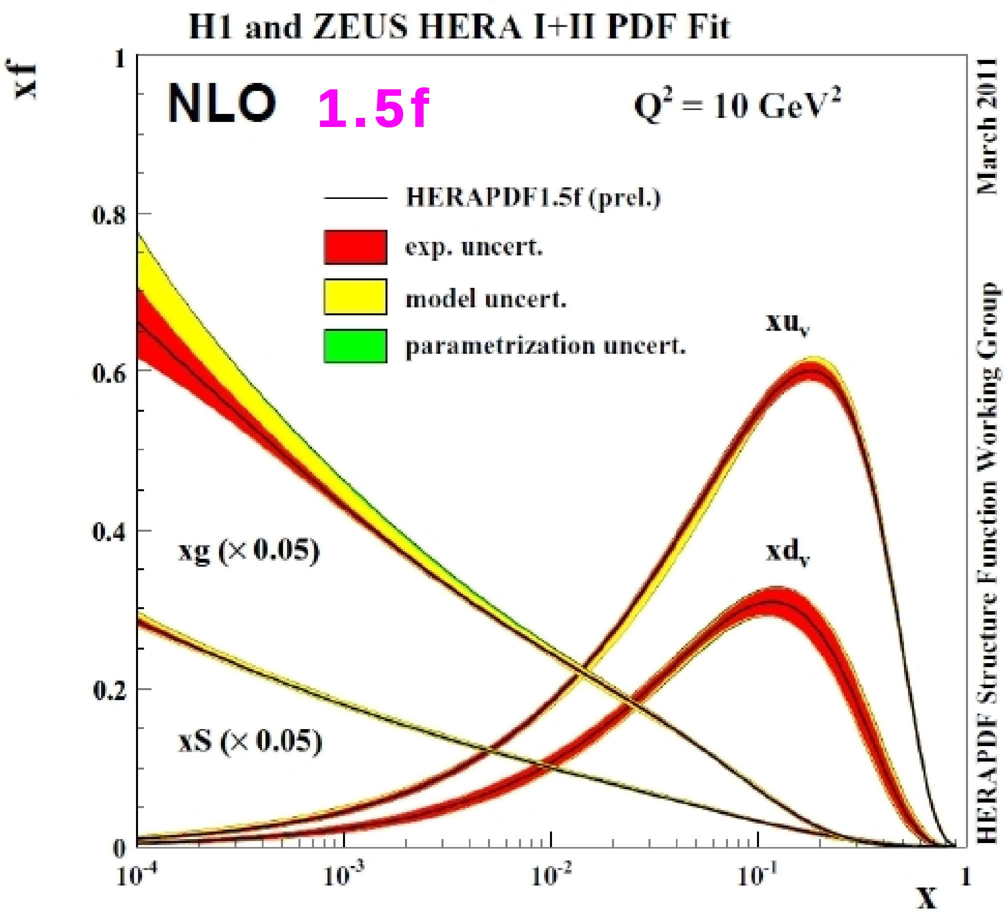


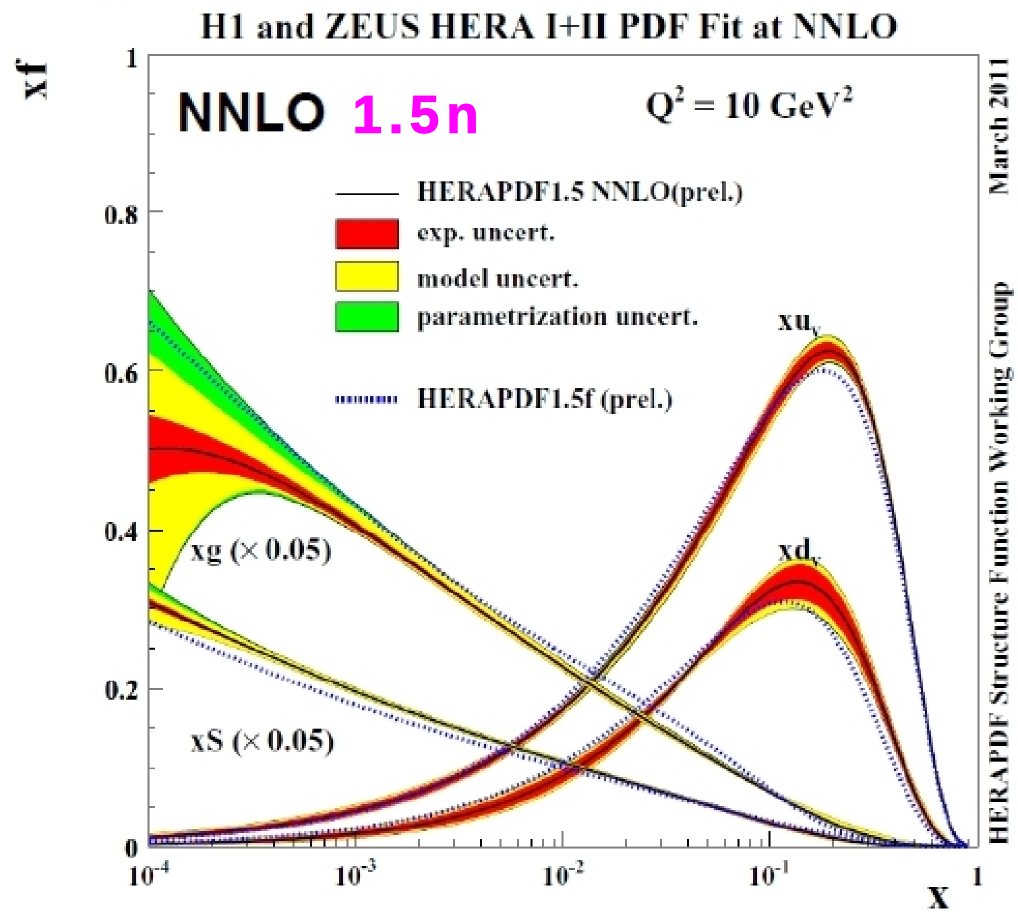
including jet+charm+lowE data

α_s is still fixed at 0.1176. Small changes observed in the PDF's, and all data sets are still very compatible with each other.

HERAPDF1.5 (NNLO vs NLO)

Only inclusive data are used since jets cannot be fitted at NNLO



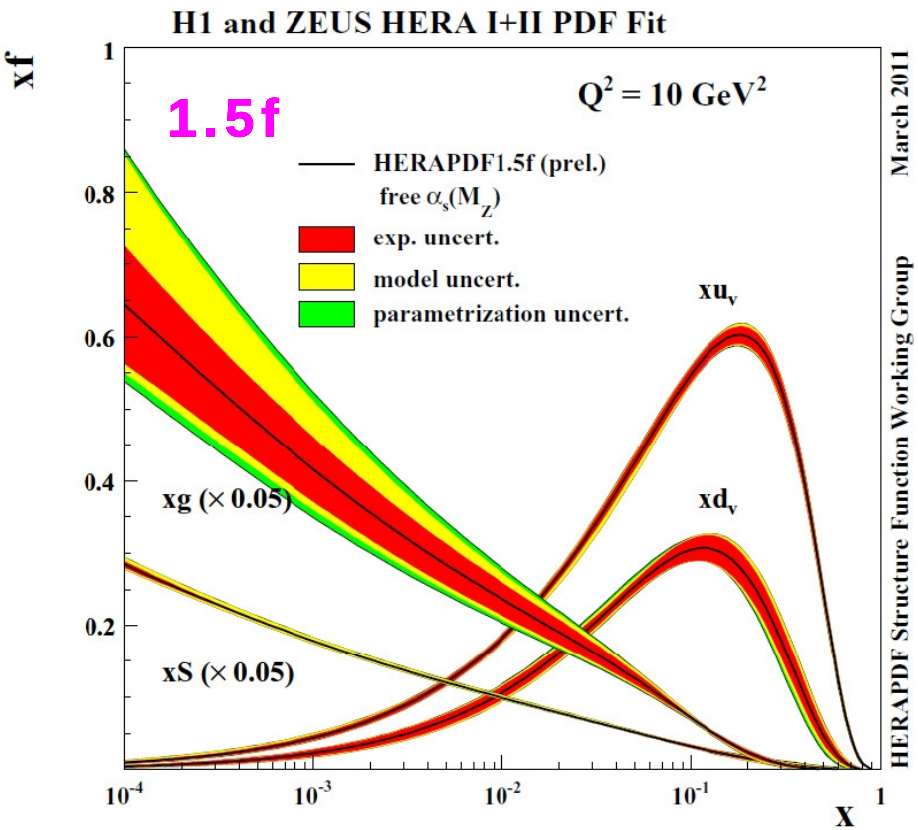


$\alpha_s = 0.1176.$

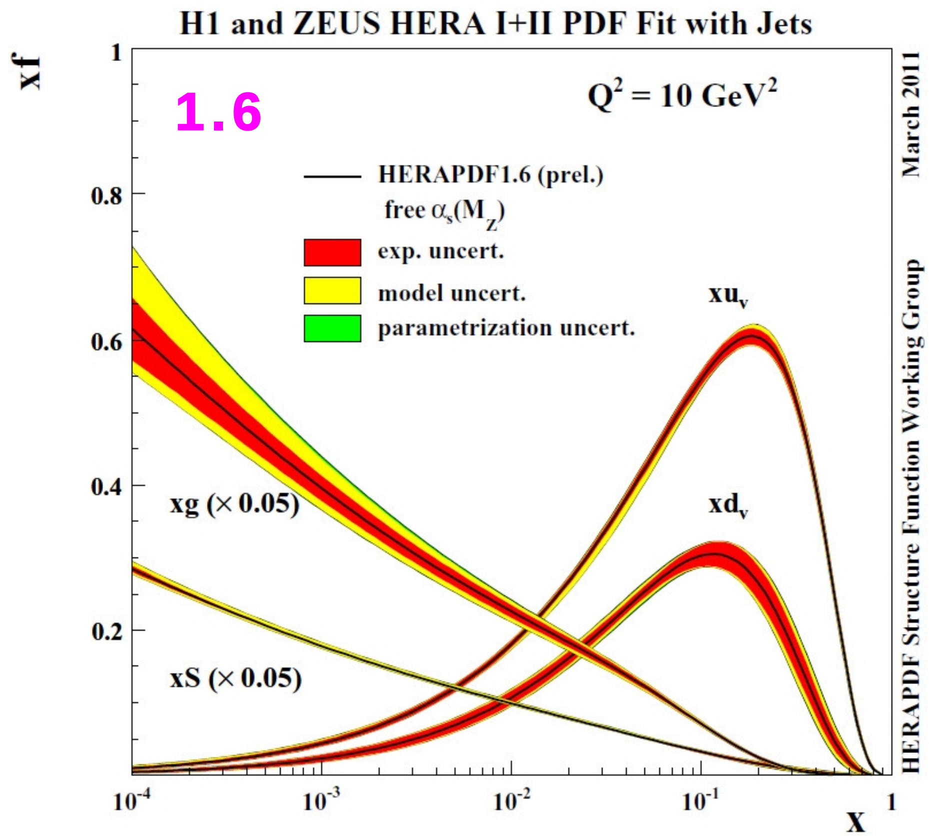
valence distributions change somewhat
sea becomes steeper
low-x **gluon** shows larger uncertainties

The NNLO DGLAP fit is not necessarily better, especially at low x, Q^2

HERAPDF with free $\alpha_s(M_Z)$



without jet data

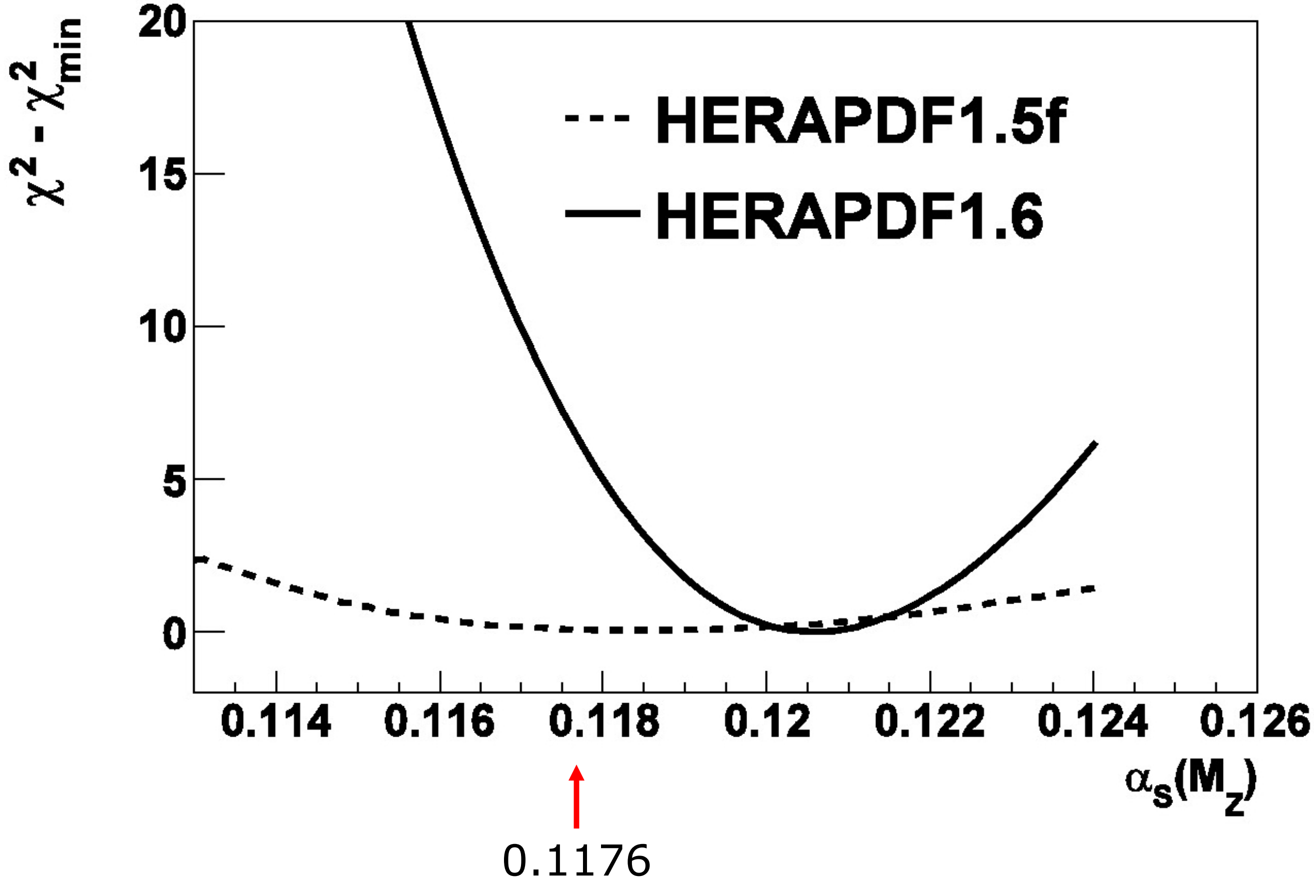


including jet data + free α_s

The dependence of the uncertainty of the gluon PDF from α_s is much reduced by the inclusion of jet data.

α_s Scan with HERAPDF1.6

χ^2 scan performed as function of $\alpha_s(M_Z)$ for HERAPDF1.5f (DIS without jet data) and HERAPDF1.6 (DIS with jet data):



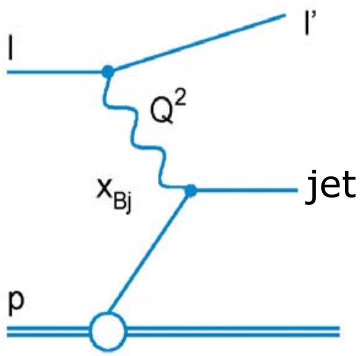
adding jet data reduces strongly the correlation between α_s and the gluon.

Extracted value for α_s:

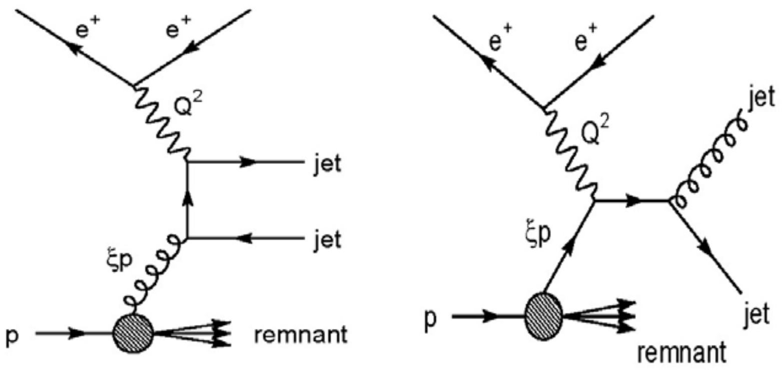
$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{model/param}) \pm 0.0012(\text{hadronization})\ ^{+0.0045}_{-0.0036}(\text{scale})$$

Deep Inelastic Scattering

Born level:



Leading order (LO):



2 jets, rate of production proportional to α_s

proton momentum's fraction carried by emerging parton:

$$\xi = x\left(1 + \frac{M_{12}^2}{Q^2}\right)$$

Next to leading (NLO) and higher orders: 3 jets (α_s^2), 4 jets (α_s^3), ..

Technical tip:

When events are boosted in the Breit Frame (2xP+q=0), the sensitivity to α_s and the **gluon PDF** is much increased since only hard processes generate significant p_T in the BF.

α_s Measurement from Jets

H1prelim-11-032

New H1 analysis on multi-jet production at high Q^2

Larger statistics available

Improvements in the reconstruction of tracks

New calibration of the hadronic energy in Liquid Argon

↓

Jet energy scale uncertainty of ~ 1% (was 2%)

Better jet energy resolution

NLO QCD predictions using $\alpha_s(M_Z)$ = 0.118, HERAPDF1.5

Factorization and renormalisation scales = $\sqrt{(Q^2 + P_T^2)/2}$

Cross sections: inclusive (Q^2,P_T), dijet and trijet (Q^2,$\langle P_T \rangle$,ξ)

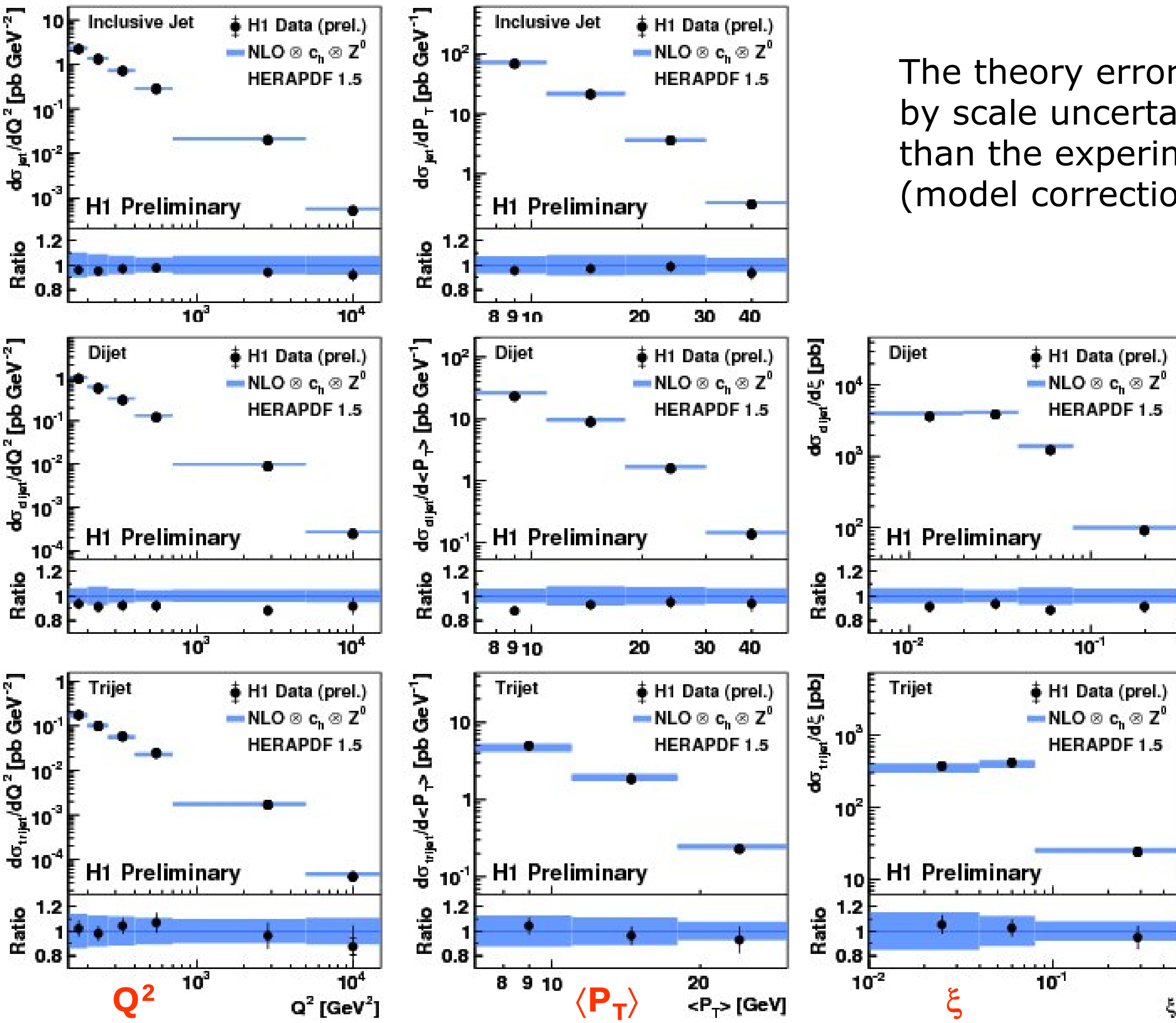
(also double differential ones)

NC DIS Cross Sections

Inclusive

Dijets

Trijets



Q^2 **$\langle P_T \rangle$** **ξ**

The theory error (dominated by scale uncertainty) is larger than the experimental error (model corrections and E_{scale})

slightly below for low P_T data

important test of pQCD and α_s running

Extraction of α_s

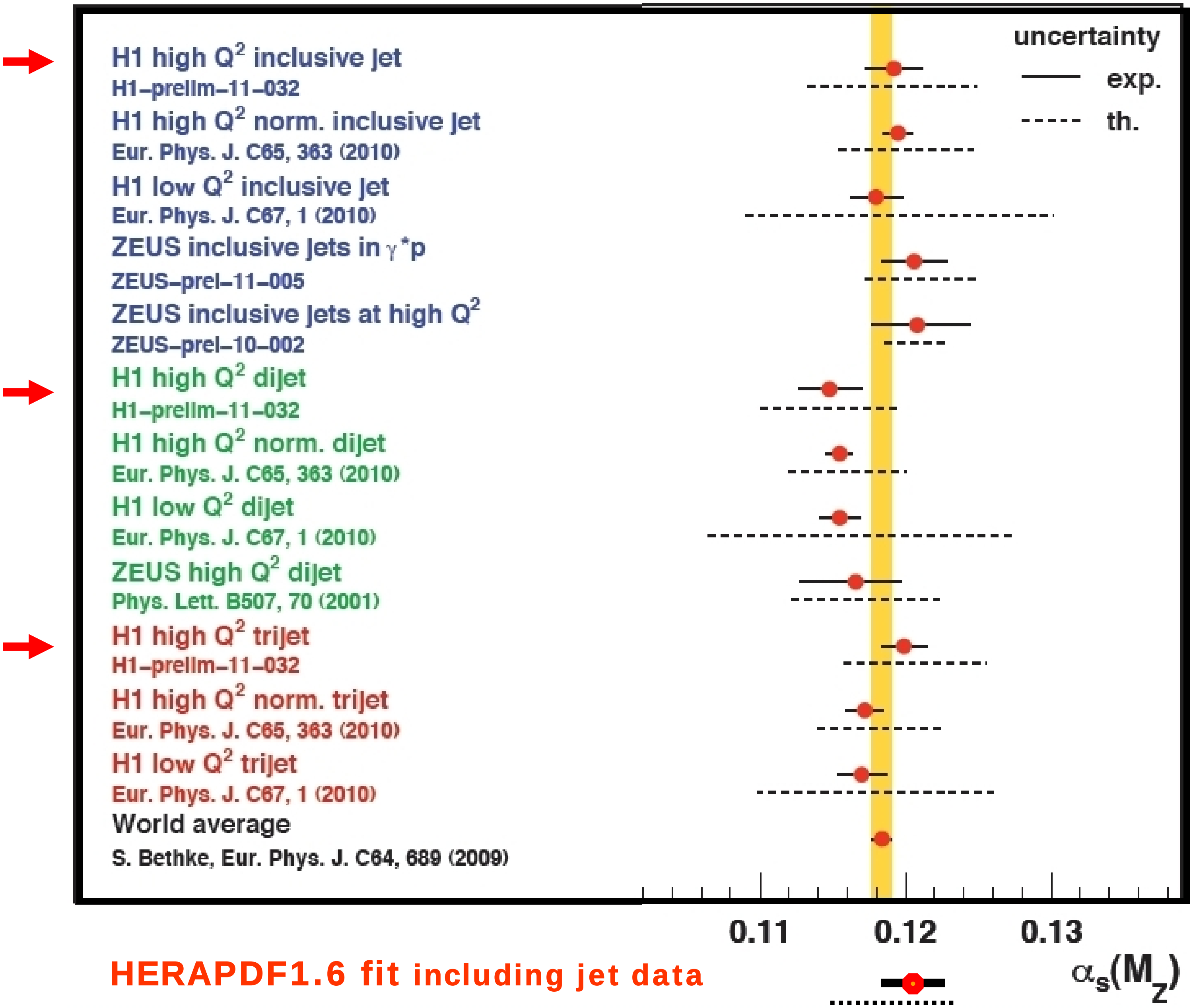
QCD NLO fit:

- HERA II data with CT10 PDF's (Tevatron, HERA I, others,..but not HERA II)
- coherent treatment of renormalisation and factorisation scale dependencies
- χ^2-minimisation using the Hessian method
- consideration of experimental correlation uncertainties
- largest theory uncertainties come from the missing higher orders

Measurement	$\alpha_S(M_Z)$	Uncertainty			χ^2/ndf
		experimental	theory	PDF	
inclusive jet	0.1190	0.0021	$^{+0.0050}_{-0.0056}$	0.0020	30.2/23
dijet	0.1146	0.0022	$^{+0.0044}_{-0.0045}$	0.0021	25.5/23
trijet	0.1196	0.0016	$^{+0.0055}_{-0.0039}$	0.0010	18.6/17

Consistent with the value extracted from the HERAPDF1.6 fits (with jets)

α_s from HERA Jet Data



lower α_s values for dijets?

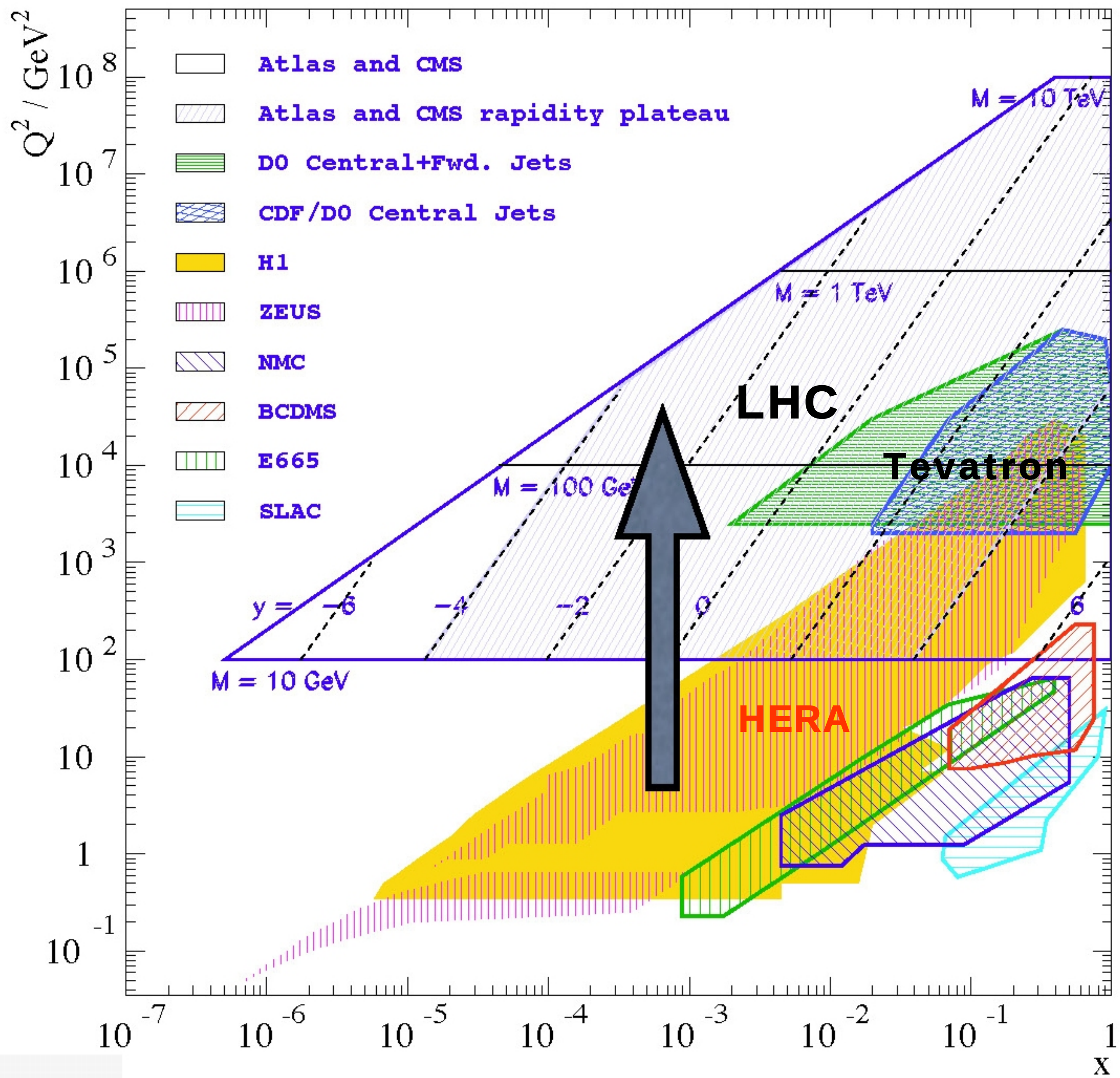
consistent with world average

At the LHC

Knowledge of the proton structure is necessary to calculate cross sections at the LHC

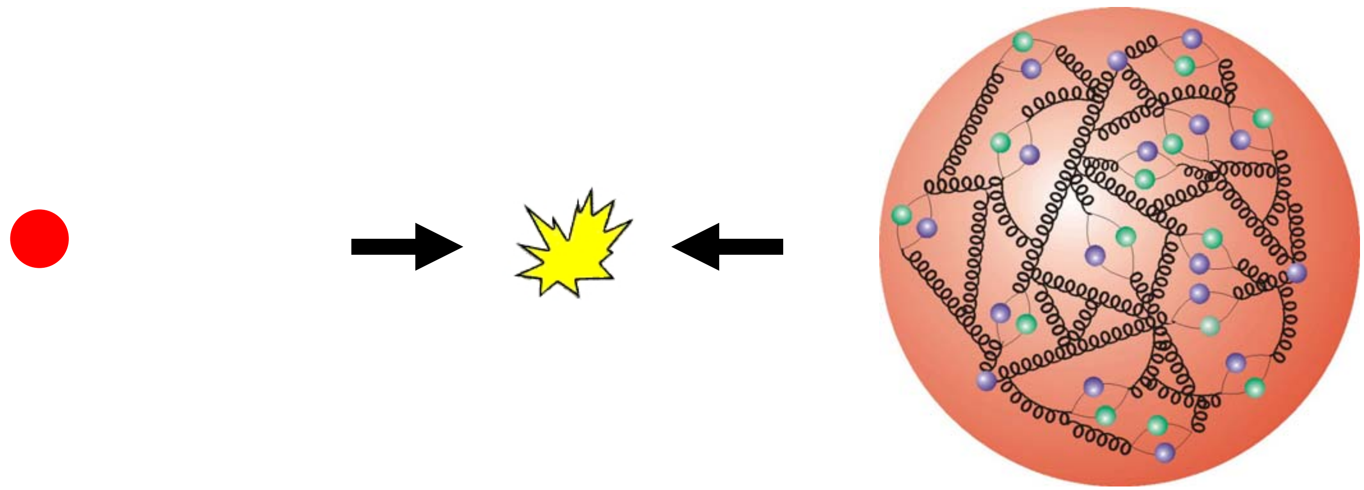
The HERA PDF's must therefore be evolved into the LHC phase space (using the DGLAP evolution equations)

Numerous sensitivity studies done e.g. at dedicated HERA-LHC workshops.

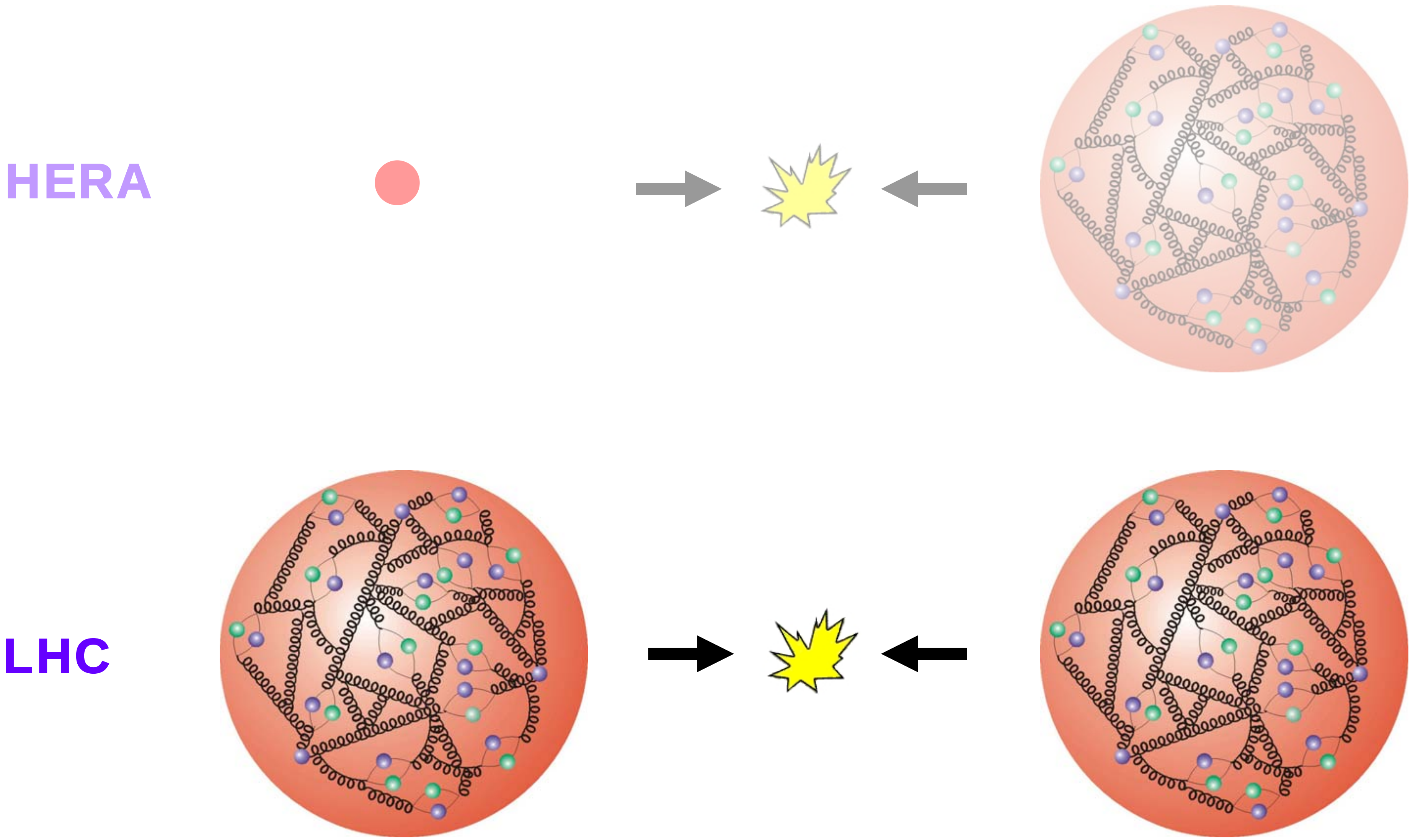


HERA

HERA



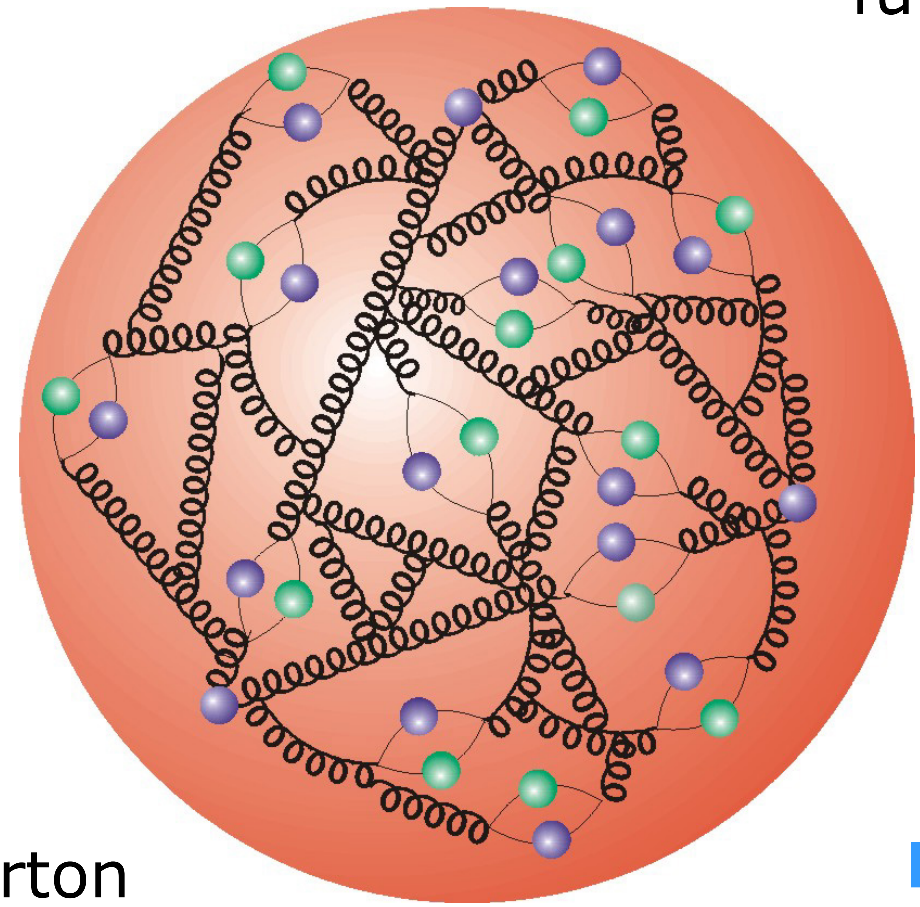
HERA vs LHC



Summary and Outlook

H1 and **ZEUS** have an active program to combine all HERA data

All proton structure functions could be determined at **HERA**



Precise HERA **P**arton **D**istribution **F**unctions are being produced: **2.0**

PDF's and α_s will have an impact on the measurements at the **LHC**

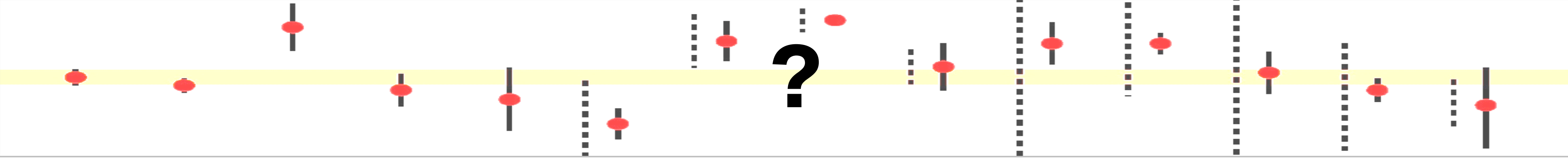
More

LLWI 2012 Hockey

Lake Louise Winter Institute 2012 - Two Ice Hockey Teams - Higgs vs Bosons

http://www.physics.mcgill.ca/~corriveau/projects/hockey/llwi2012hockey.html

Many pictures received, will be updated!



Abstract

QCD and α_s at HERA

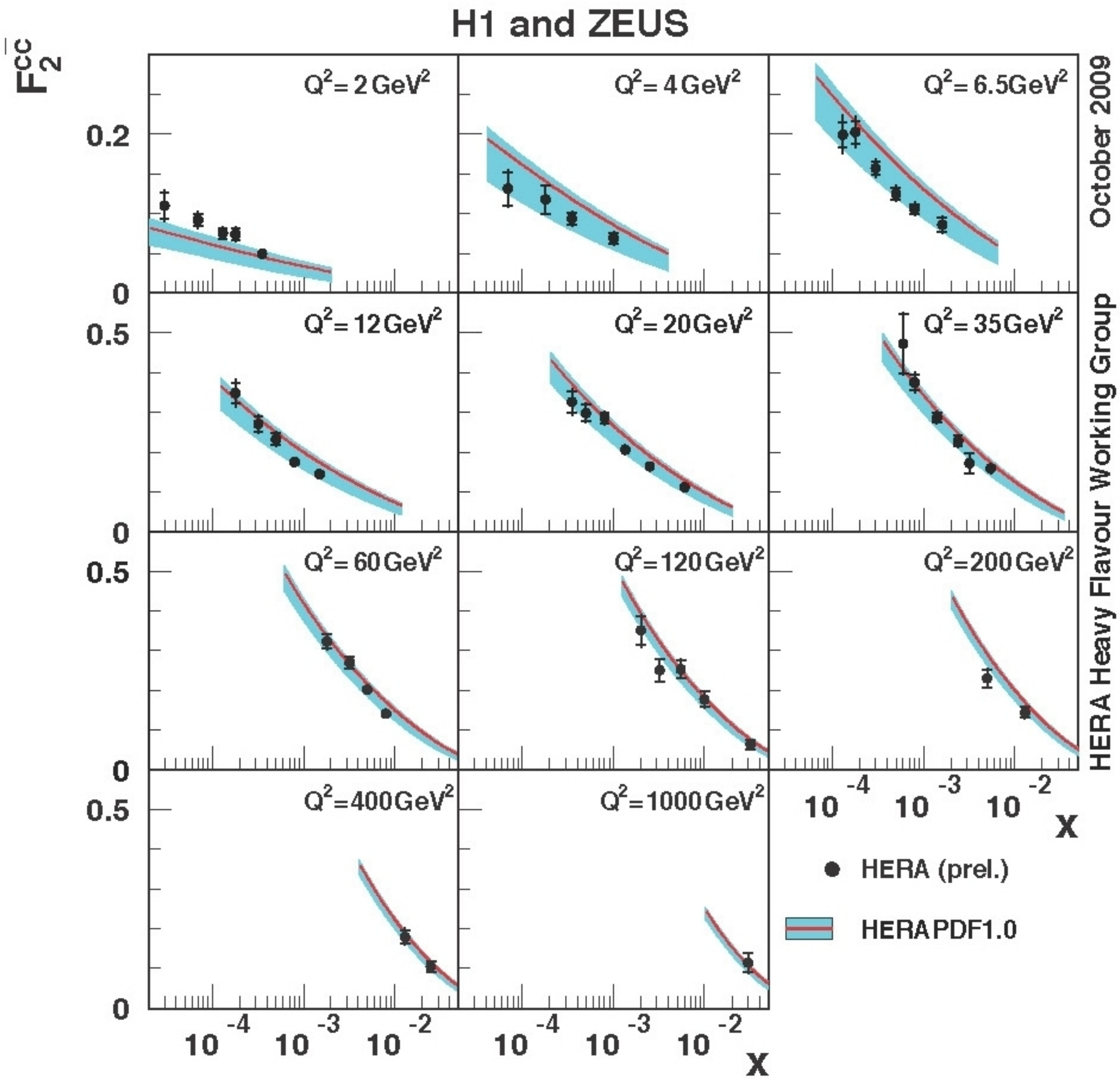
The HERA accelerator collided electrons on protons and provided a unique laboratory for precise studies of QCD. Both the H1 and ZEUS experiments investigated in depth the parton structure of the proton and the physics of jets. The most recent combined QCD analysis results will be presented and compared with their NLO predictions, including the determination of the parton distribution functions and of the α_s strong coupling constant. A short review of the current analyses will also be performed.

Adding the HERA F_2 Charm

The H1 and ZEUS charm data were also combined beforehand.

The uncertainty band comes from the assumed mass of the charm in HERAPDF1.0:

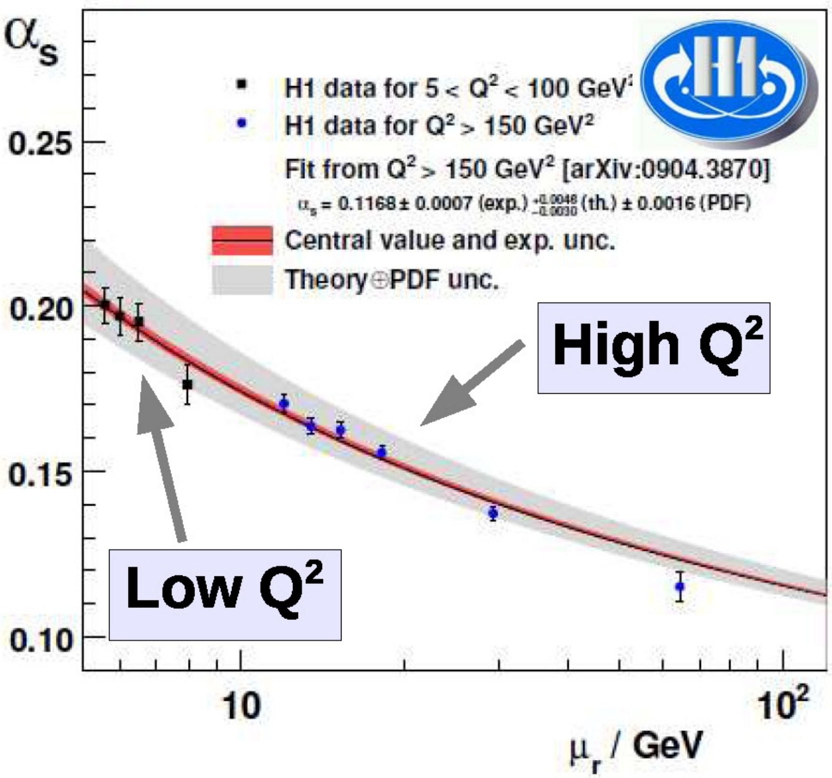
$1.35 < m_c < 1.65$ GeV

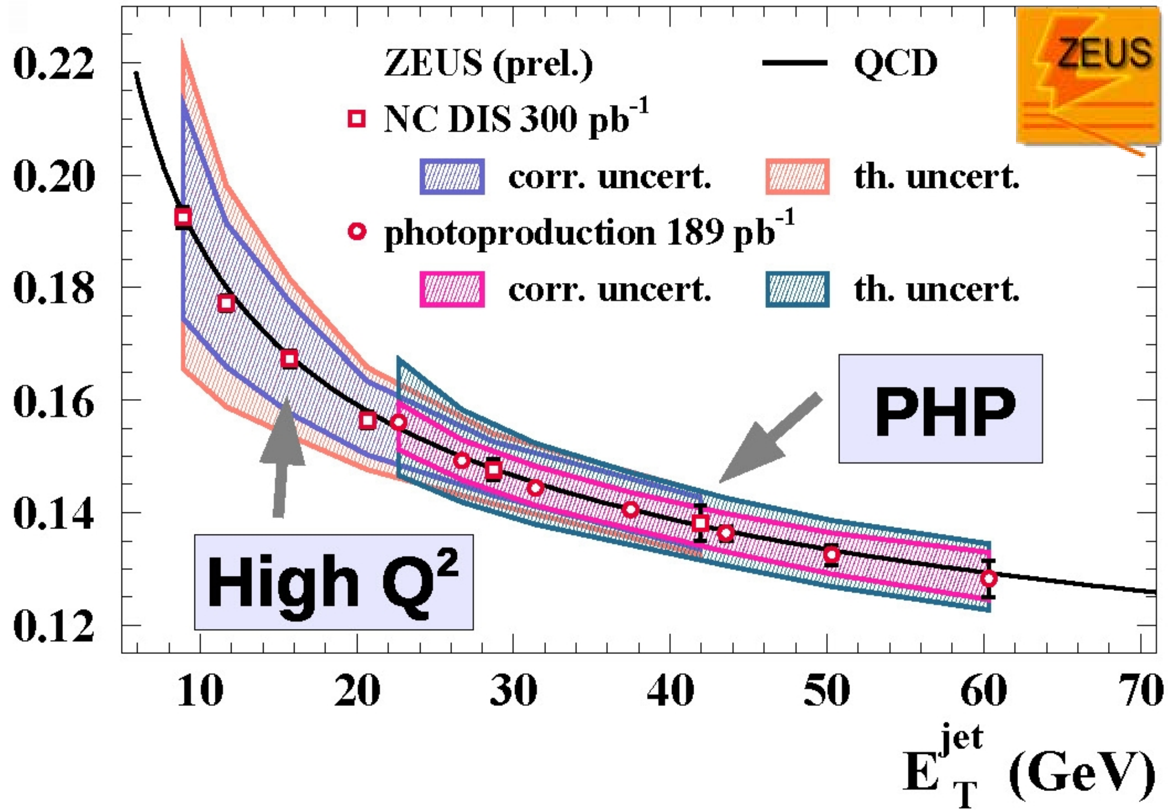


Adding the charm data should help improve the PDF's

Running of α_s

This was already shown last year at LLWI by Krzysztof Nowak



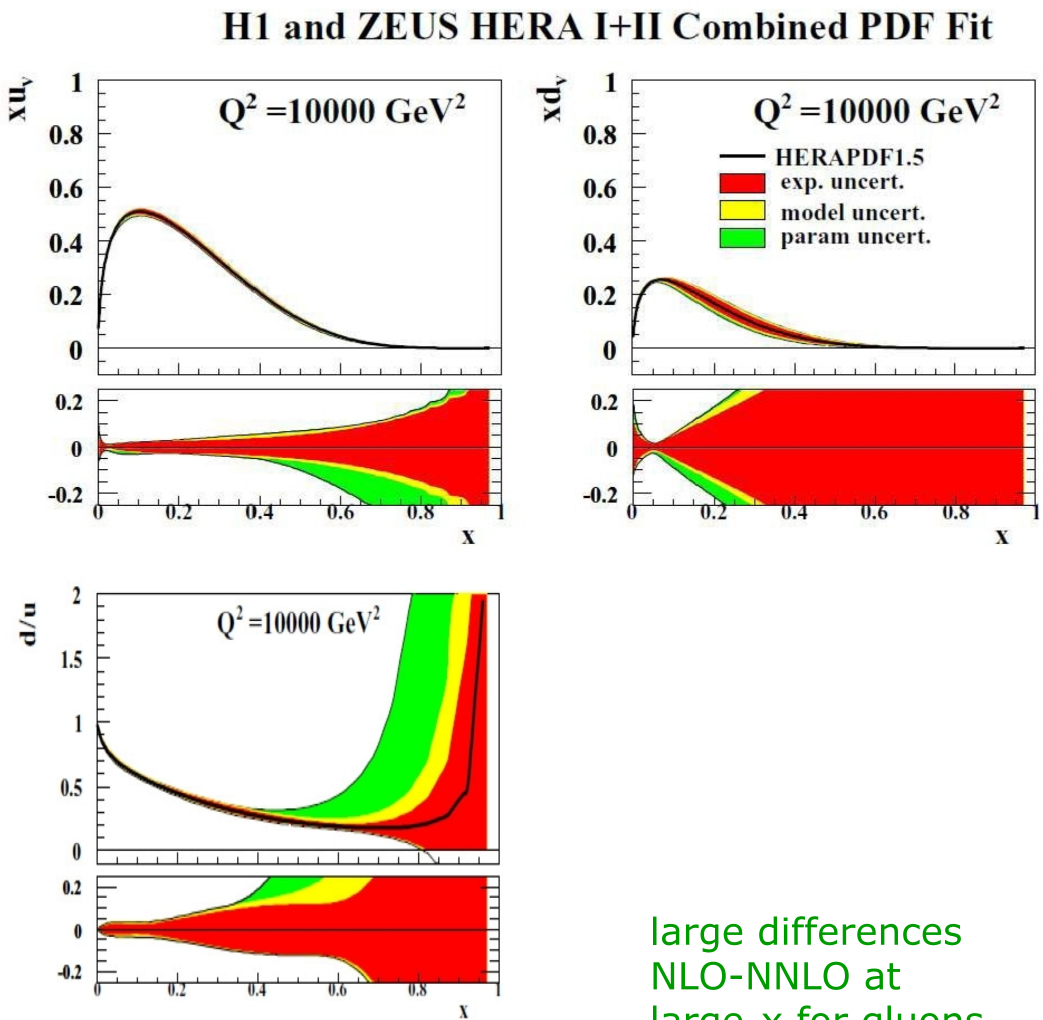


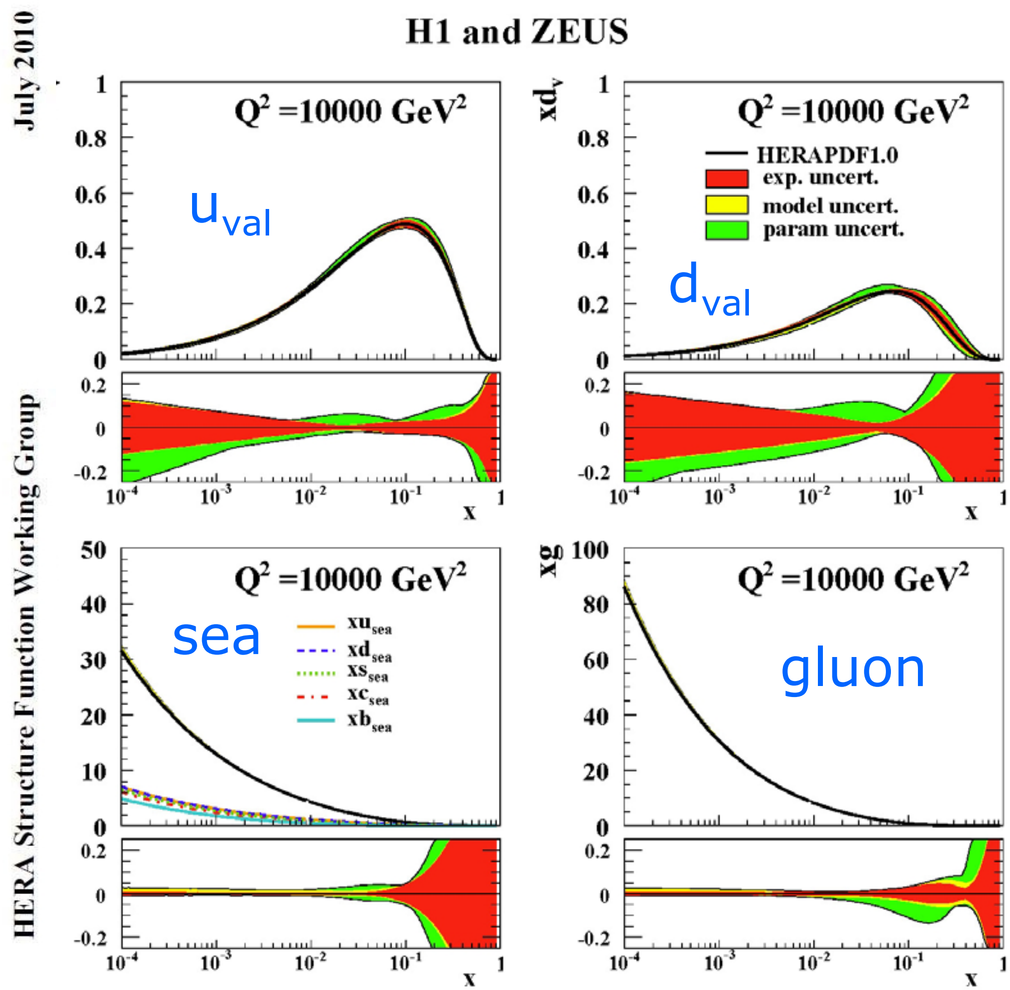
Good determination of the α_s running for both HERA experiments and understanding of the correlated uncertainties.

Sensitivity at the LHC Q^2 Scale

PDF's very precise (parametrisation uncertainties dominate at high-**x**)

(previous study results with HERA I data only)

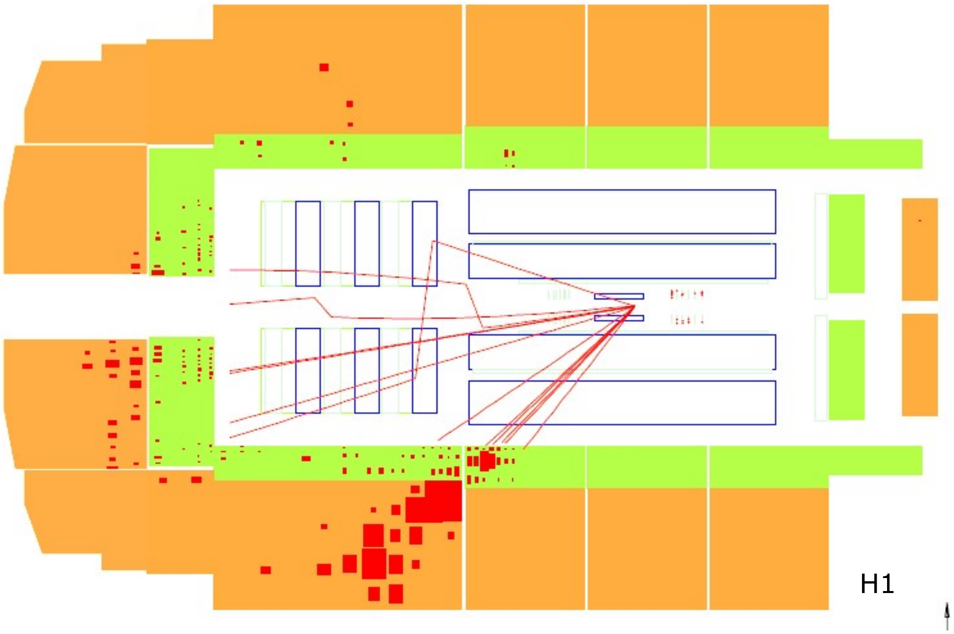




large differences NLO-NNLO at large-x for gluons

Charged Current DIS

mediated by exchange of $W^{\pm}$



Similarly to the NC case, the cross section can be written in terms of structure functions F_i

$$\tilde{\sigma}_{cc}^{e^-p} \sim u + c + (1-y)^2(\bar{d} + \bar{s})$$

$$\tilde{\sigma}_{cc}^{e^+p} \sim \bar{u} + \bar{c} + (1-y)^2(d + s)$$

i.e. disentangle d and u contributions

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[Y_+ F_2^{CC}(x,Q^2) \mp Y_- x F_3^{CC}(x,Q^2)\right]$$

P_e is the lepton polarisation (HERA II only, =0 for HERA I)