$\alpha_s(M_Z)$ and charm quark mass determination from HERA data

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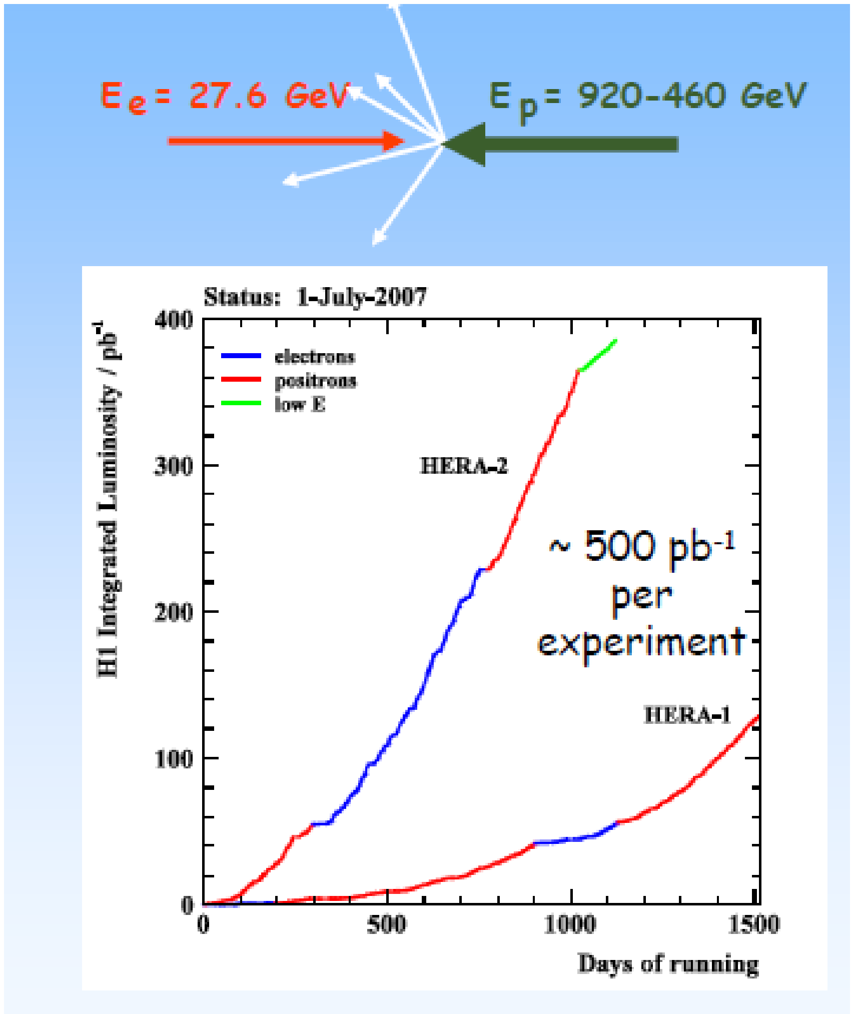
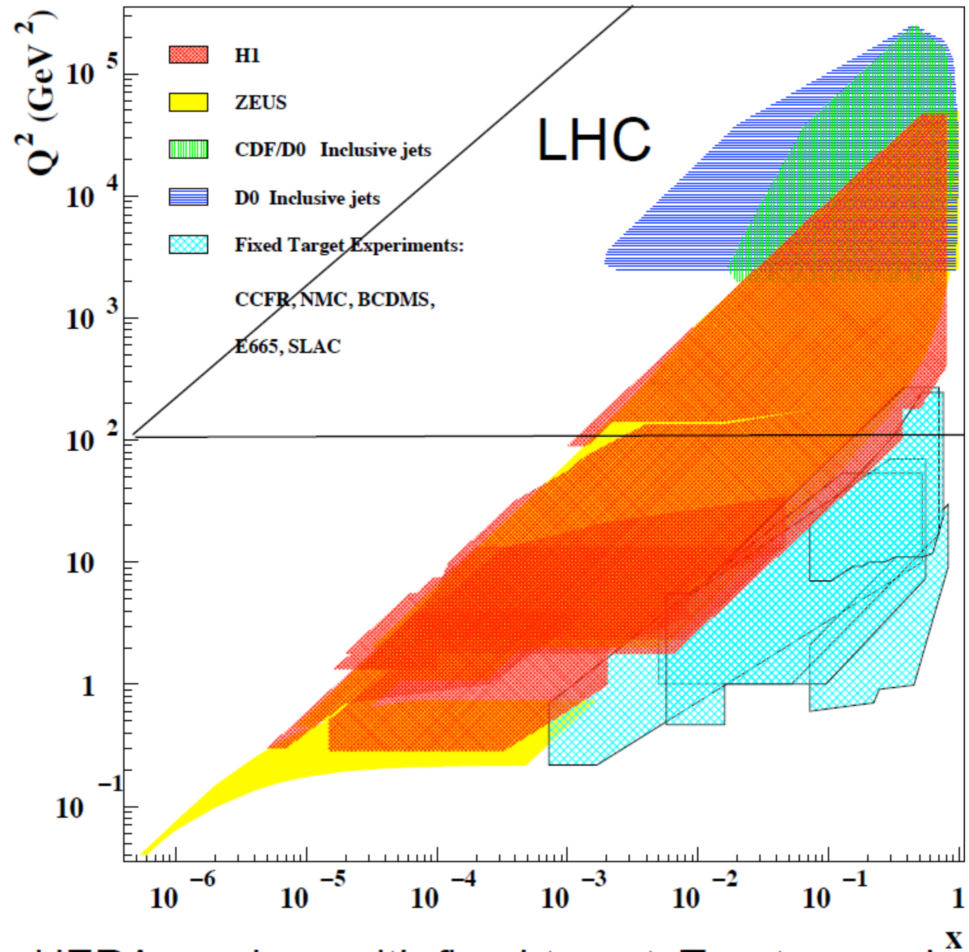
on behalf of ZEUS and H1 collaborations

HERA: protons of 920 GeV and electrons/positrons of 27.6 GeV
Centre of mass energy $\sqrt{s}$ = 318 GeV

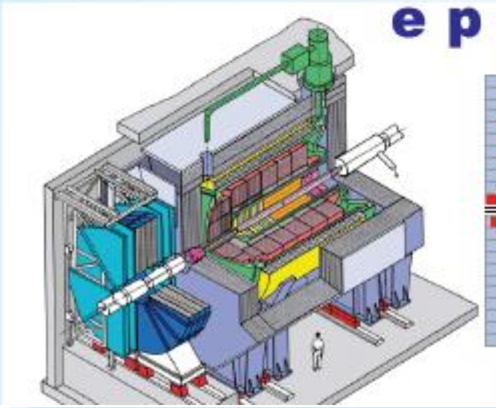


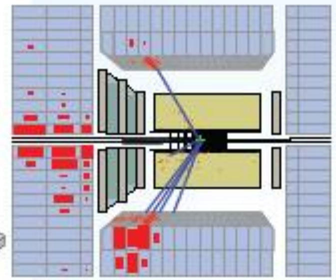


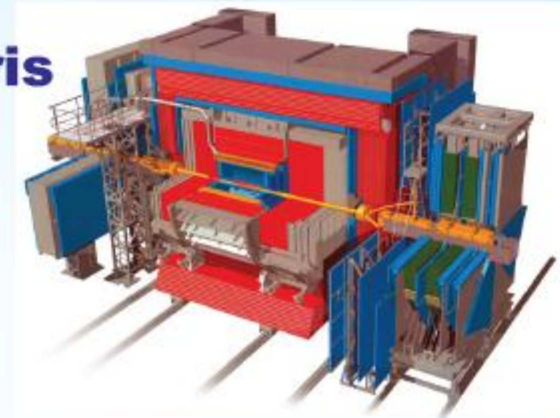
HERA overlaps with fixed-target, Tevatron and LHC experiments

That is what we measure!

e p $\rightarrow$ e (ν) debris







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

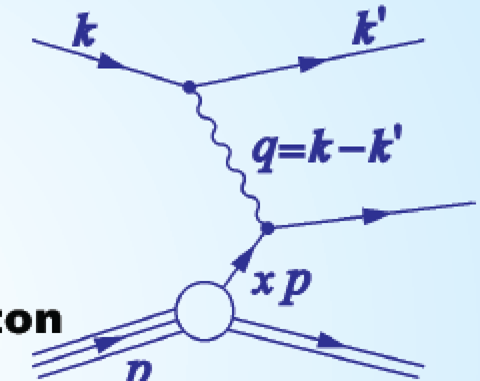
Spatial resolution of probe

$$\lambda \sim 1/\sqrt{Q^2}$$

Bjorken scaling variable:

$$x = Q^2/2pq$$

Momentum fraction of struck parton



$Q^2 = xys$

Inelasticity: $y = pk/pq$

Energy transfer to proton (in p rest frame)

Reconstruction

$$y_e = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e} \qquad Q^2_e = \frac{E'^2_e \sin^2\theta_e}{1-y_e} \qquad x_e = \frac{Q^2_e}{4E_pE_ey_e}$$

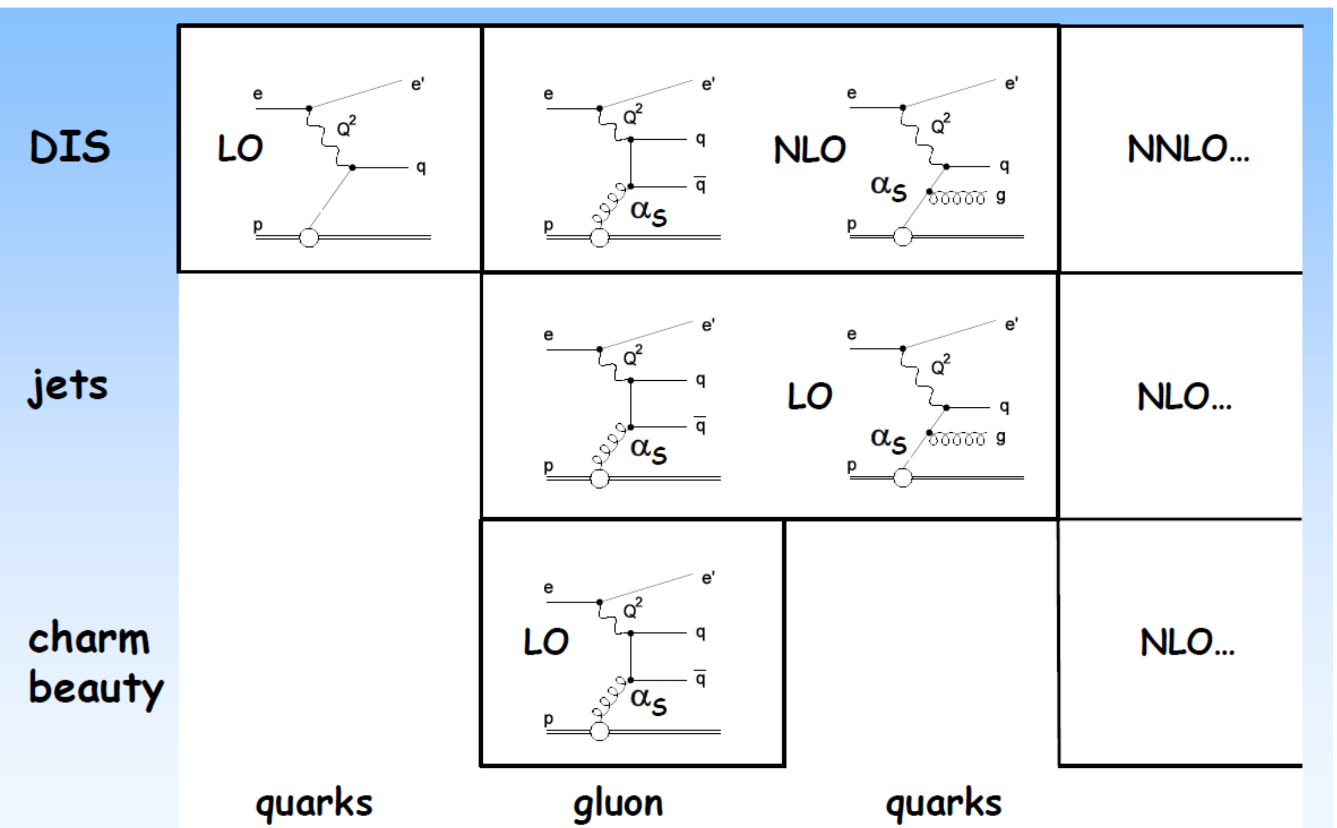
Extraction of parton densities

$$\sigma_{DIS} \sim f_P \otimes \sigma_{pert}$$

f_P : proton parton density function evolved with Q^2 by DGLAP equations.

σ_{pert} : short distance cross section calculable in pQCD.

- The structure of (parton densities in) the proton extracted from fits to DIS data.
- Use next-to-leading order (NLO) QCD, and now NNLO QCD, a series expansion in α_s



Inclusive cross sections give quark densities – gluon and α_S come from the Q^2 dependence

Jet production data depend on gluon directly, measures α_S better

Charm production also depends on gluon and α_S
But dependence on heavy quark mass and on heavy quark scheme is stronger

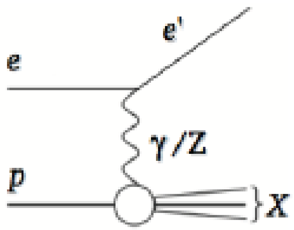
Deep Inelastic Scattering at HERA

Neutral Current:

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

$$\boxed{\sigma_r(x, Q^2) = \frac{d^2\sigma(e^{\pm}p)}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+}F_L(x, Q^2) \mp \frac{Y_-}{Y_+}xF_3(x, Q^2)}$$

NC : $e\,p \to e'\,X$



- xF_3 only sensitive at large Q^2 ($\sim M_Z^2$)
- F_L only sensitive at low Q^2 and high y
- F_2 dominates

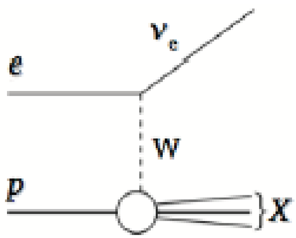
$$xF_3 \sim \sum(xq_i - x\bar{q}_i)$$

$$F_L \sim \alpha_S g$$

$$F_2 \sim \sum e_i^2(xq_i + x\bar{q}_i)$$

Charged Current: provides important flavour decomposition

CC : $e\,p \to \nu_e\,X$

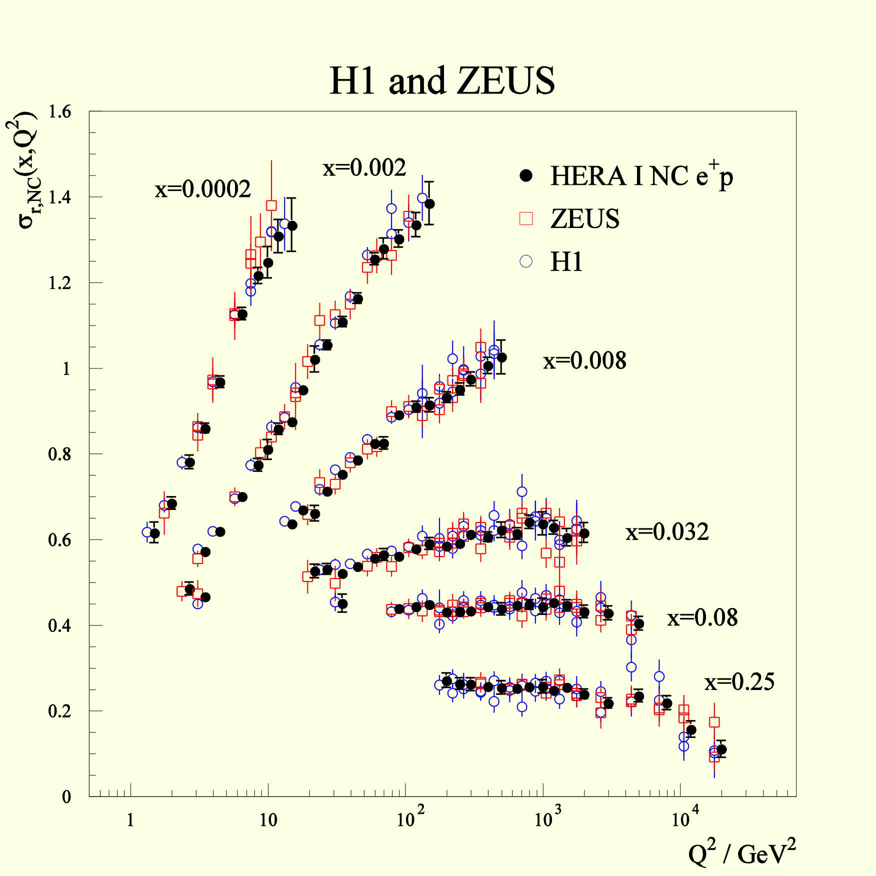


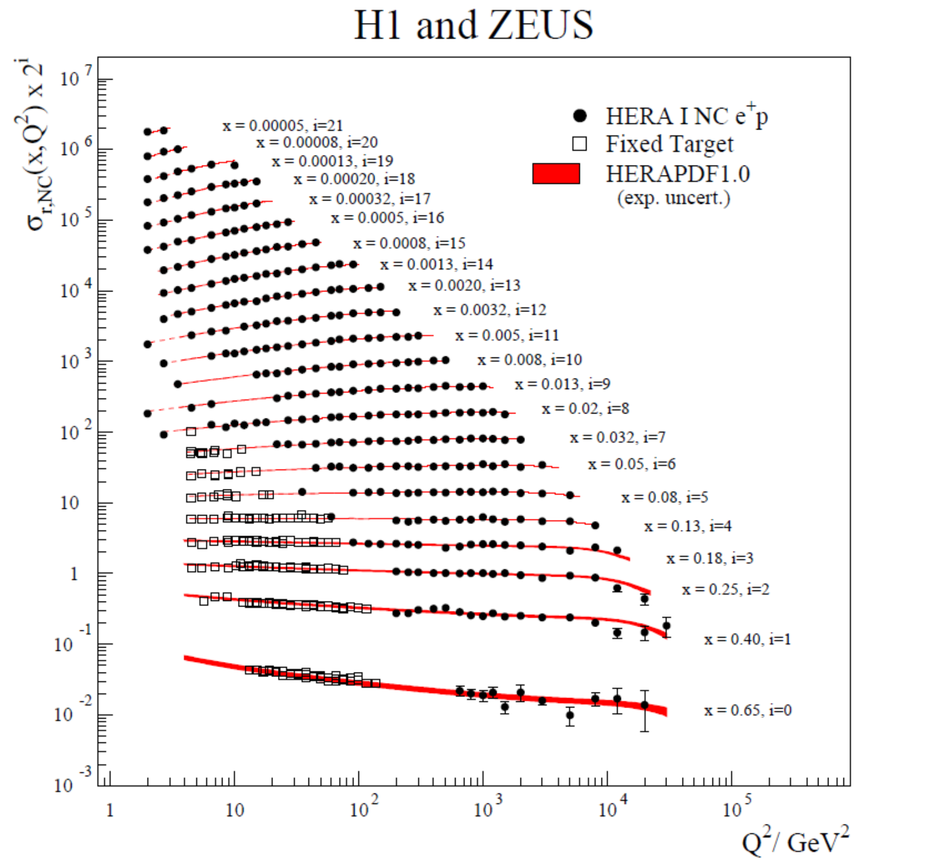
e-p: $$\frac{d^2\sigma_{CC}^-}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)\left[u + c + (1-y)^2(\bar{d} + \bar{s})\right]$$

e+p: $$\frac{d^2\sigma_{CC}^+}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)\left[\bar{u} + \bar{c} + (1-y)^2(d + s)\right]$$

Essentially 4 processes: Neutral and Charged current e+ and e- scattering determine 4-flavours: u, ubar, d,dbar

QCD scaling violations determine the gluon- very broad kinematic reach in Q^2





A very well understood consistent data set

JHEP 1001 (2010) 109 has combined data for all 4 cross sections

This page shows NC e+ combined data

Above : Results of the combination compared to the separate data sets

Right: the full NC e+ data

correlated systematic errors

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right)^2}{\left(\delta_{i,stat}\,\mu^i\right)^2 + \left(\delta_{i,unc}\,m^i\right)^2} + \sum_j b_j^2$$

statistical errors

uncorrelated systematic errors

Measurements at the same x,Q^2 must come from the same true σ

PDF determination at HERA

- HERA PDFs are determined from QCD Fits to solely HERA data of Q^2>3.5 GeV^2

PDFs $xg, xu_{val}, xd_{val}, x\bar{U} = x\bar{u}(+x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s}(+x\bar{b})$

are parametrised at Q^2_0 $xf(x, Q^2_O) = Ax^B(1-x)^C(1 + Dx + Ex^2)$

And then evolved to $Q^2 > Q^2_0$ using the QCD DGLAP equations at NLO (or NNLO)
At Q^2 values where there are measurements the evolved PDFs are convoluted with QCD coefficient functions to predict the structure functions and these predictions are then fitted to the measuremets

Imposing momentum sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

Additional Constraints:

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

In 10p fit: Buv=Bdv

The gluon PDF can also take a term which allows it to become negative

$$xf(x, Q^2_0) = Ax^B(1-x)^C(1 + Dx + Ex^2) - A'x^{B'}(1-x)^{25}$$

The assumptions made here- such as the values of Q^2_{min}, Q^2_0, f_s, m_c, m_b the value of $\alpha_s(M_Z)$=0.1176 and the form of the parametrisation are varied

Fit uses ONLY HERA DIS data

Only proton data– no nuclear corrections, no deuterium binding corrections
No strong isospin assumptions- d-quark is determined directly

All data at $W^2 > 300$ GeV^2 – no higher twist effects

Cross-section data are used not F_2– no dubious corrections for F_L used to extract F2

Data reach Q^2 ~30,000 GeV^2 so a General Mass Variable Flavour Number Scheme is used for heavy quark production ($\ln Q^2/m_c^2$) terms are resummed)

The HERA data combination procedure produces a consistent data set for the 4-cross sections NC e+, NC e-, CC e+, CC e- . Thus there is no need to introduce increased $\chi2$ tolerances to cover data inconsistencies as in some of the global PDF fits.

For the HERA combined data the correlated systematic uncertainties of the individual H1 and ZEUS data sets have been reduced by the cross-calibration of the experiments which results from the combination, so that they are less than statistical uncertainties across most of the x,Q^2 plane. Total uncertainties ~1% for $20 < Q^2 < 100$ GeV^2 and 2% for most of the rest of the kinematic plane

Sources of PDF uncertainties at HERA

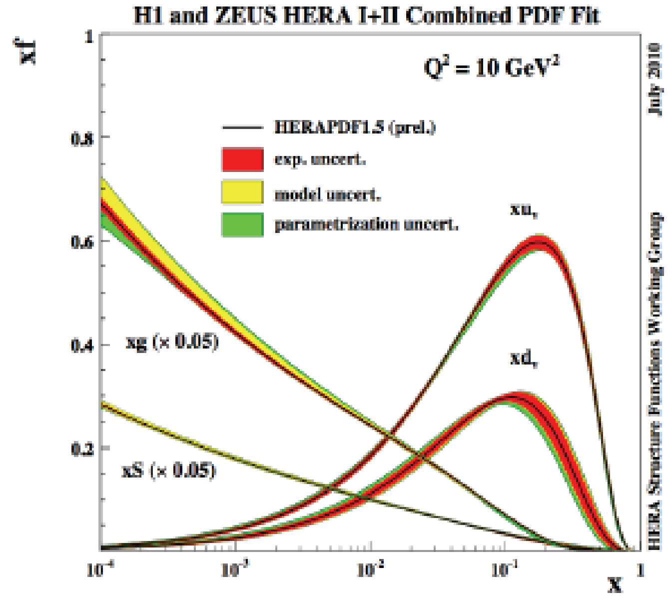
- **Experimental Uncertainties:**
  - Consistent data sets → use $\Delta\chi^2 = 1$
  - Cross checked with Monte Carlo method [PDF4LHC Interim Report arXiv:1101:0536]

- **Model Uncertainties:**
  - following variations have been considered

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	$1.35^{(a)}$	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	$1.5^{(b)}$	$2.5^{(c,d)}$

$^{(a)}Q^2_0 = 1.8$ $\quad$ $^{(c)}m_c = 1.6$

$^{(b)}f_s = 0.29$ $\quad$ $^{(d)}f_s = 0.34$



- **Parametrisation Uncertainties:**
  - An envelope formed from PDF fits using other variants of parametrisation form at the starting scale (especially sensitive to the higher x region):
    - Scanning of parameter space
    - Q_0^2 variation and a more flexible gluon parametrisation

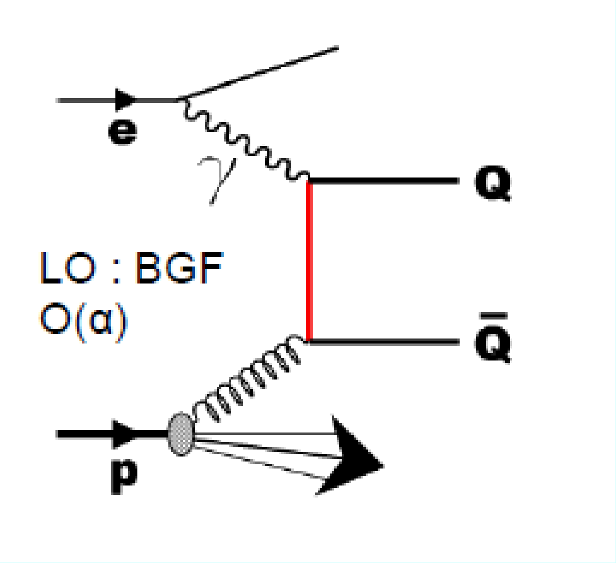
$\alpha_s(M_Z)$ uncertainty is evaluated by determining different PDFs for different fixed values of $\alpha_s(M_Z)$ from 0.114 to 0.122. The usual range considered is 0.1156 to 0.1196

Now let us move to more exclusive processes

Heavy quark production in DIS

Fixed Flavour Number Scheme (FFNS)

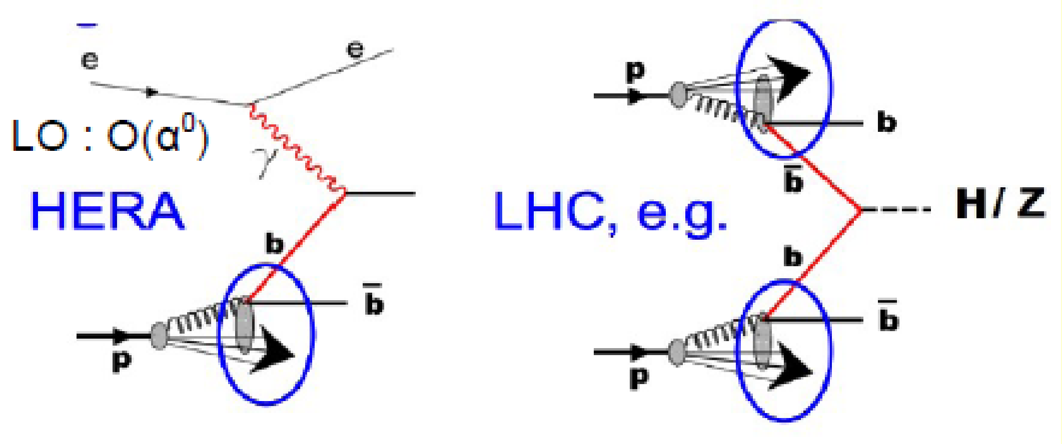
- nf=3 active flavours in p
- heavy-quarks produced in hard scattering
- mass effects correctly included



- spoiled by large logs of Q^2/m^2, p_T/m ...

Variable Flavour Number Scheme(s) (VFNS)

- c, b massless partons for $Q^2 > m_c^2$



- simplifies calculations at colliders (neglecting m_c)
- resums large $\log(Q^2/m^2)$

- **Zero Mass (ZM) VFNS**
  - neglects m_c at all Q^2s

- **General Mass (GM) VFNS**
  - FFNS at $Q^2 < m_c^2$, ZM-FNS at $Q^2 >> m^2$
  - Interpolating in between
  - different prescriptions available

Charm production in DIS

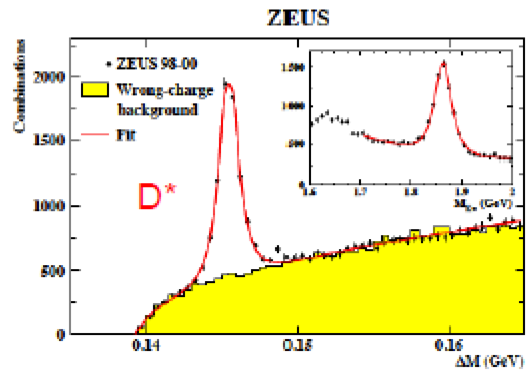
Arxiv:1211.1182
EPJC73,2311 (2013)

Reduced charm cross section defined in analogy to inclusive DIS:

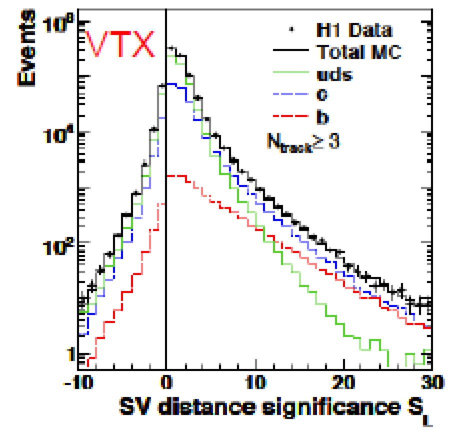
$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4}\, Y_+\, \sigma_{\rm red}^{c\bar{c}}(x,Q^2,s) \qquad Y_+ = 1+(1-y)^2$$

$$\sigma_{\rm red}^{c\bar{c}}(x,Q^2,s) = F_2^{c\bar{c}}(x,Q^2) - \frac{y^2}{Y_+}F_L^{c\bar{c}}(x,Q^2)$$

but considering events with charm in the final state



In this analysis we will combine HERA charm production measurements to extract a combined measurement of $\sigma_{\rm red}^{c\bar{c}}(x,Q^2,s)$



9 data sets used for a total of 155 points

Data Set	Period	Q^2[GeV^2]
• 1) H1 VTX	HERA I+II	5 - 2000
• 2) H1 D*	HERA I	2 - 100
• 3) H1 D*	HERA II	5 - 100
• 4) H1 D*	HERA II	100 - 1000
• 5) ZEUS D*	'96-'97	1 - 200
• 6) ZEUS D*	'98-'00	1.5 - 1000
• 7) ZEUS D0	'05	5 - 1000
• 8) ZEUS D+	'05	5 - 1000
• 9) ZEUS μ	'05	20 - 10000

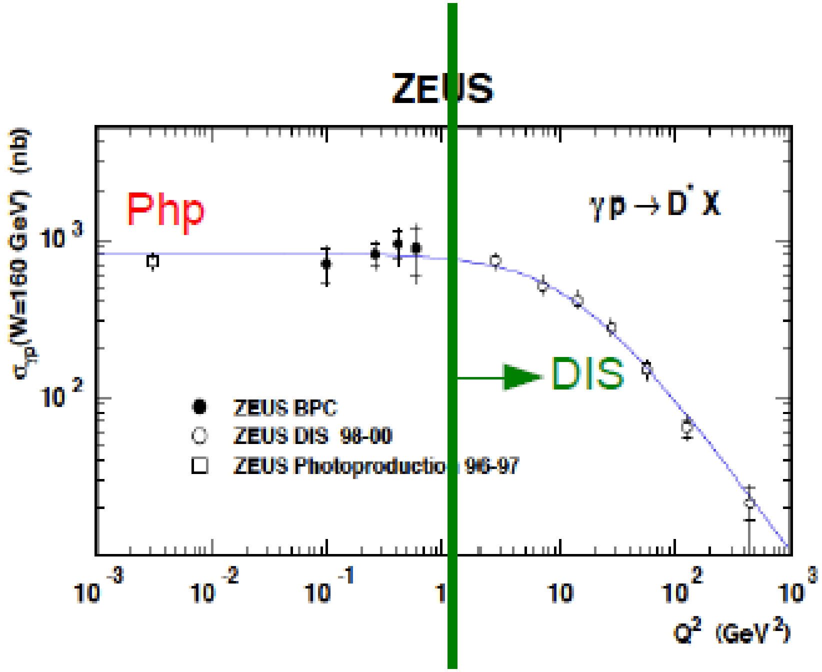
Charm measurements at HERA

Many different measurements:

- **Wide kinematic range**
  $0 < Q^2$, 10000 GeV^2

- Different methods to tag charm:
  - Full reconstruction of D and D* mesons,
  - Semileptonic decays,
  - Inclusive lifetime

  very different systematics and sensitivities



- 155 measurements are combined into 52 x,Q^2 points

- combination: measurements at the same x,Q^2 point must come from the same true $\sigma_{\rm red}^{c\bar{c}}$

- the combination is done similarly to the inclusive HERA combination, by minimizing

correlated systematic errors

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma_j^i m^i b_j - \mu^i\right)^2}{(\delta_{i,stat}\,\mu^i)^2 + (\delta_{i,unc}\,m^i)^2} + \sum_j b_j^2$$

statistical errors

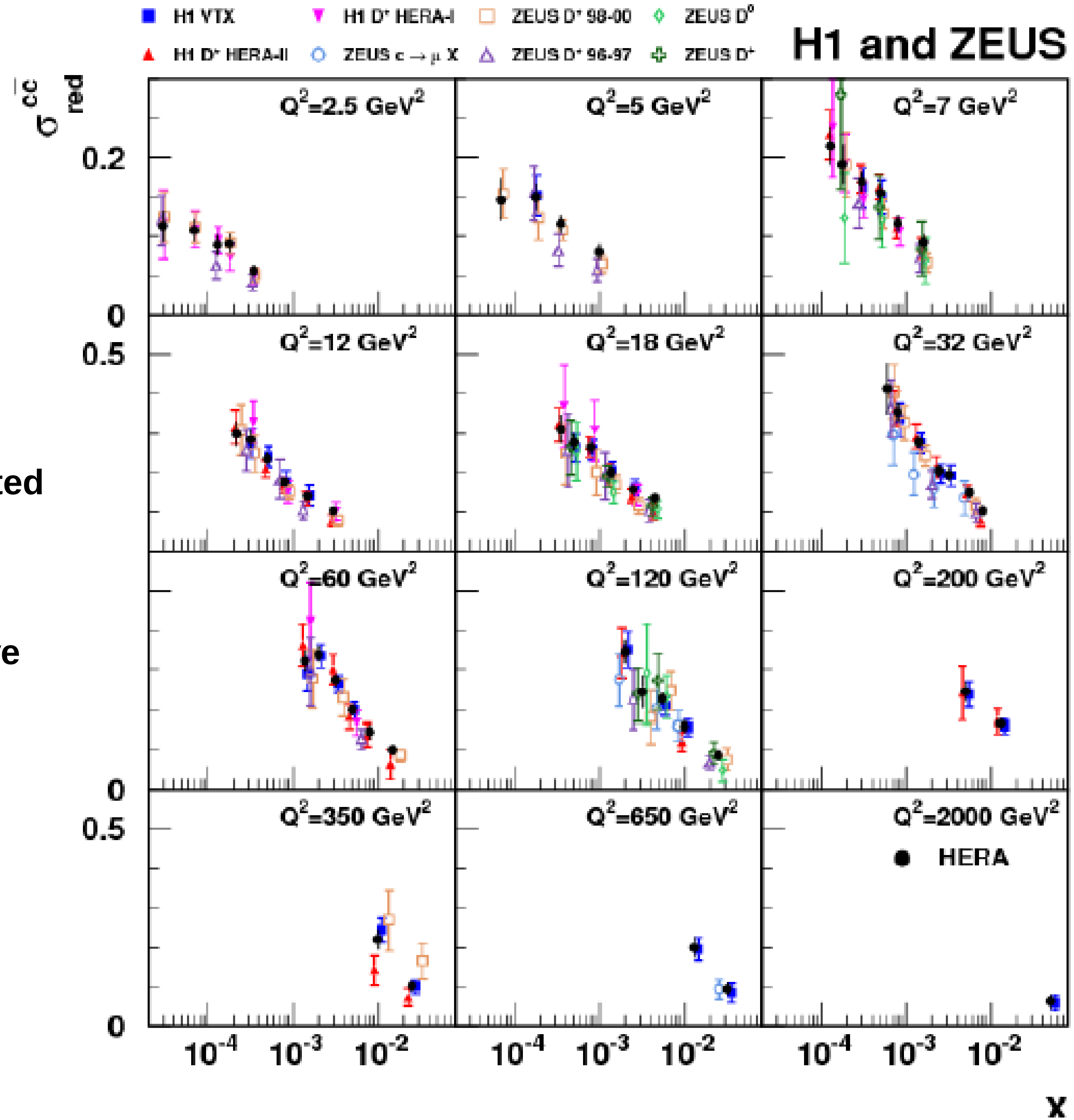
uncorrelated systematic errors

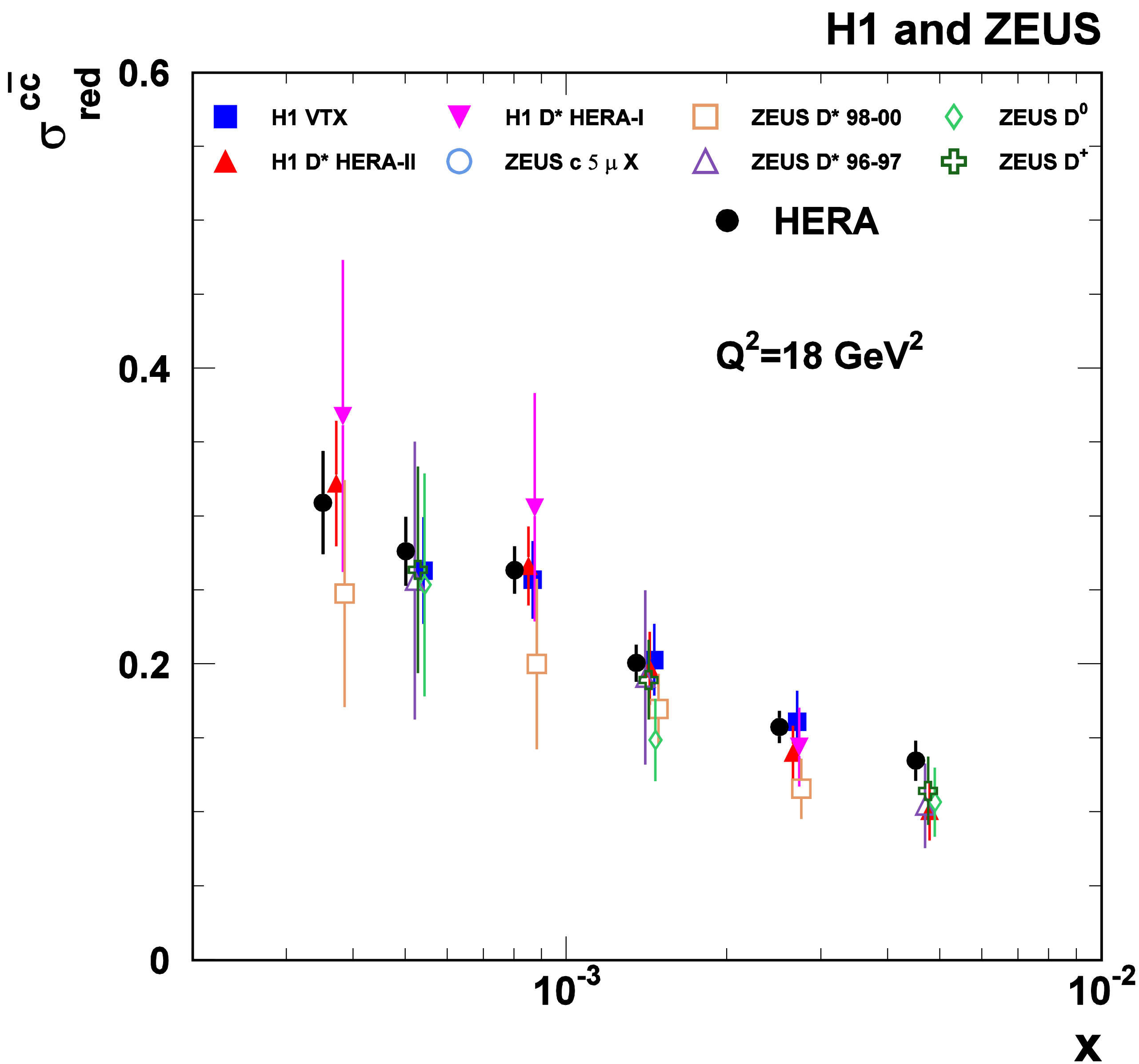
- Combined data more precise than single data sets

- Total uncertainty ~6% at medium x and $12 < Q^2 < 60$ GeV^2

- **Correlated uncertainty similar size to uncorrelated**
  → full correlation matrix provided
  → important to use it
  (in contrast with inclusive combination)

- Procedural errors small except at Q^2=350 GeV^2 (4-5%)




H1 and ZEUS
$\sigma_{red}^{c\bar{c}}$
0.6
0.4
0.2
0
H1 VTX
H1 D* HERA-II
H1 D* HERA-I
ZEUS c 5 μ X
ZEUS D* 98-00
ZEUS D* 96-97
ZEUS D^0
ZEUS D^+
HERA
Q^2=18 GeV^2
10^{-3}
10^{-2}
x

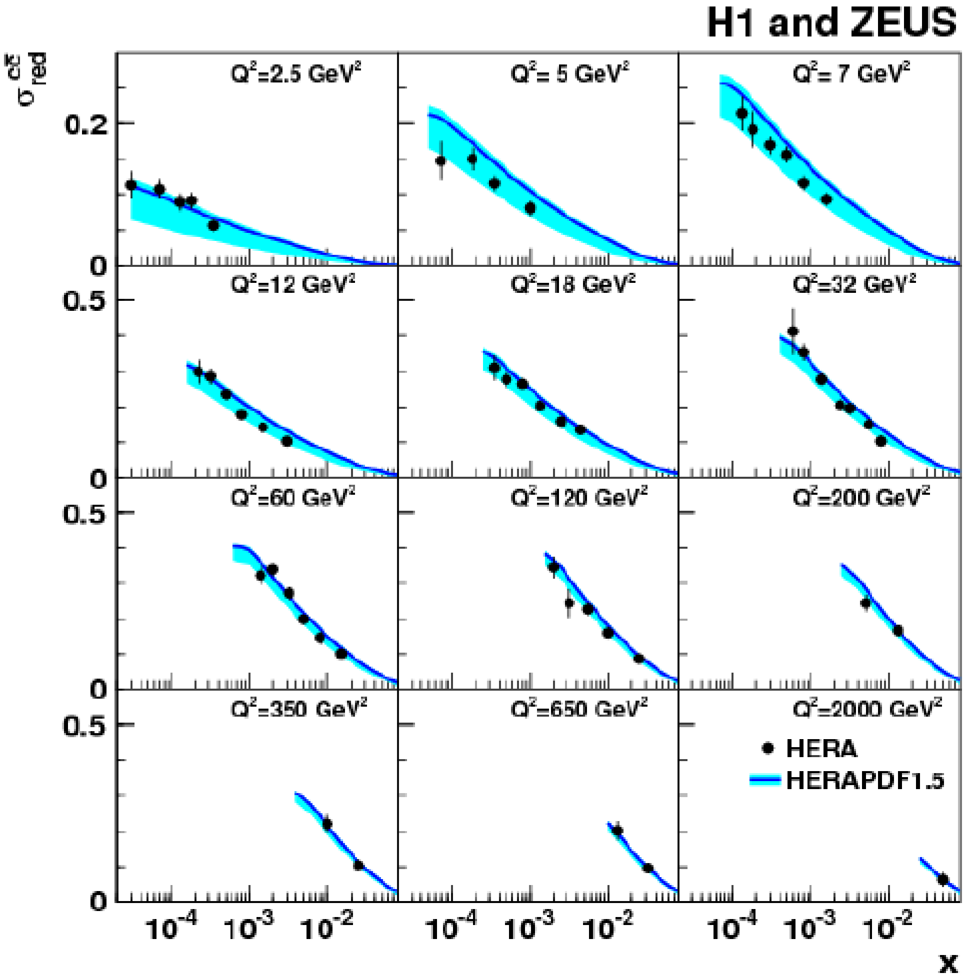
Comparison to HERAPDF1.5 NLO (note: not all the NNLO heavy quark coefficient functions for the CC processes are known)

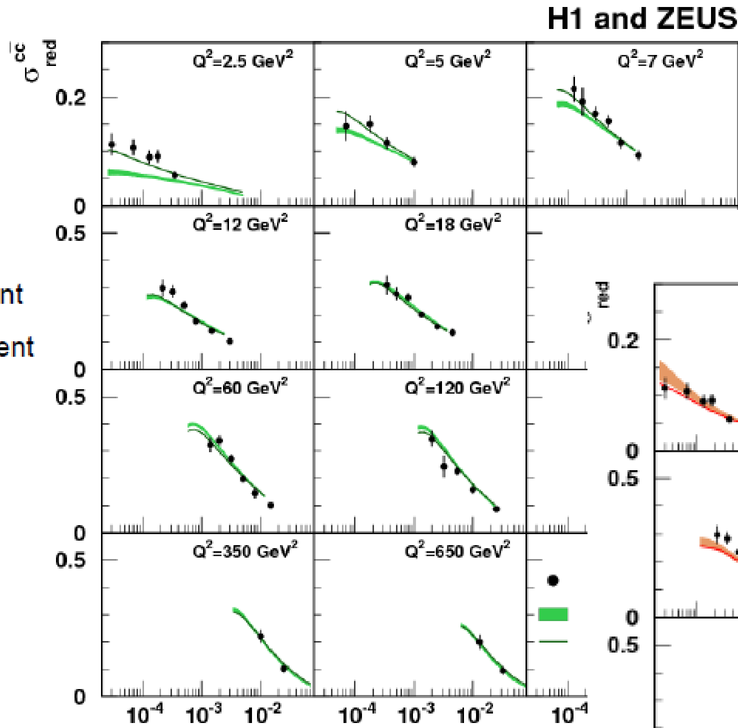
This uses the Thorne-Roberts Variable Flavour Number Scheme

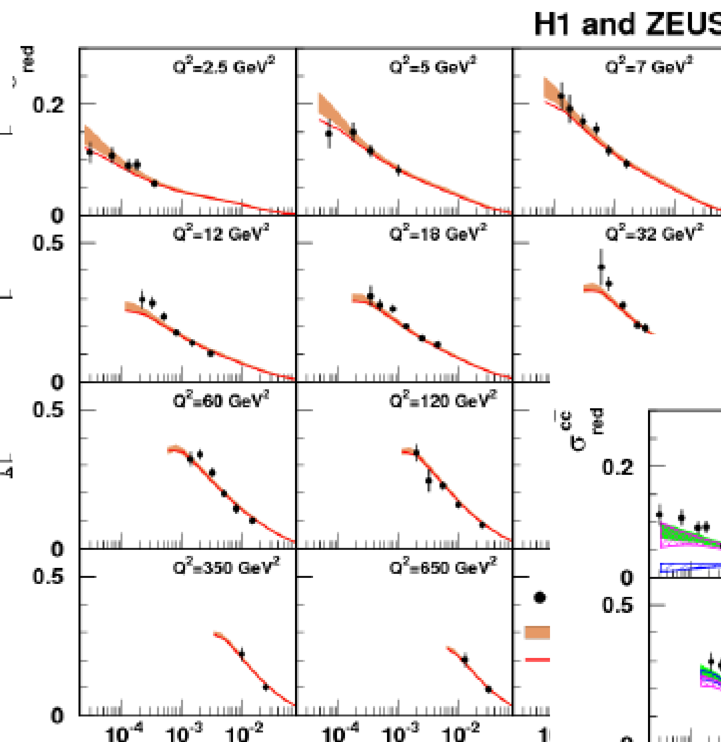
Central value of m_c=1.4 GeV

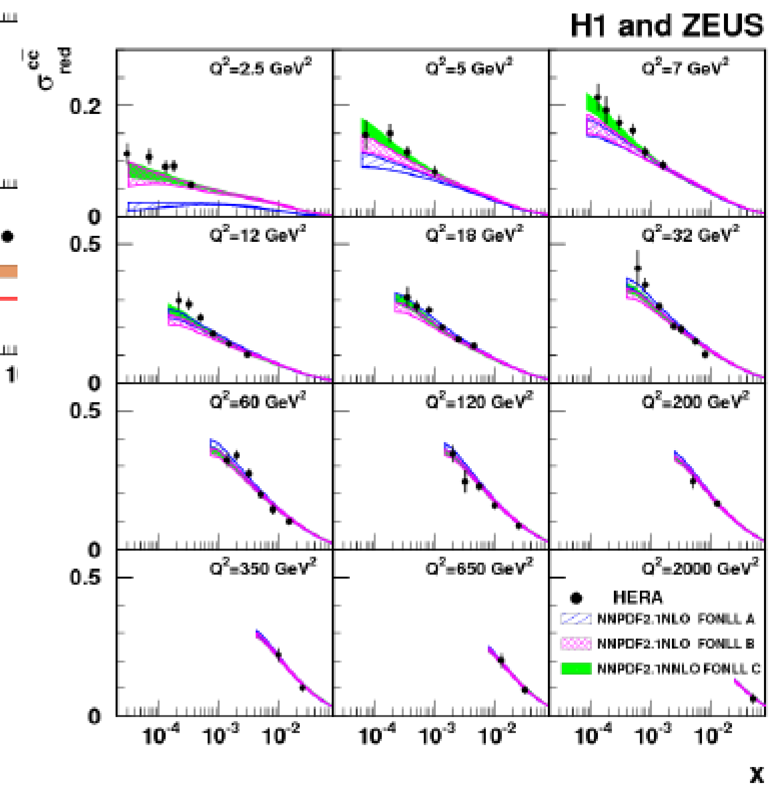
but the model dependence indicated by the blueband covers variation 1.35 < m_c <1.65 GeV

The data clearly prefer a larger value of m_c...









Comparisons to predictions from CT10, MSTW NNPDF with various heavy quark schemes and masses at different $O(\alpha_s)$ with varying levels of success

Differences between predictions

Theory	Scheme	Ref.	$F_{2(L)}$ def.	m_c [GeV]	Massive ($Q^2 \lesssim m_c^2$)	Massless ($Q^2 \gg m_c^2$)	$\alpha_s(m_Z)$ ($n_f = 5$)	Scale	Included charm data
MSTW08 NLO	RT standard	[28]	$F^c_{2(L)}$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108	Q	[1,4–6,8,9,11]
MSTW08 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
MSTW08 NLO (opt.)	RT optimised	[31]			$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108		
MSTW08 NNLO (opt.)					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
HERAPDF1.5 NLO	RT standard	[55]	$F^c_{2(L)}$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.1176	Q	HERA inclusive DIS only
NNPDF2.1 FONLL A	FONLL A	[30]	n.a.	$\sqrt{2}$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.119	Q	[4–6,12,13,15,18]
NNPDF2.1 FONLL B	FONLL B		$F^c_{2(L)}$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$			
NNPDF2.1 FONLL C	FONLL C		$F^c_{2(L)}$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
CT10 NLO	S-ACOT-χ	[22]	n.a.	1.3	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.118	$\sqrt{Q^2 + m_c^2}$	[4–6,8,9]
CT10 NNLO (prel.)		[56]	$F^{c\bar{c}}_{2(L)}$	1.3 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
ABKM09 NLO	FFNS	[57]	$F^{c\bar{c}}_{2(L)}$	1.18 ($\overline{\mathrm{MS}}$)	$\mathcal{O}(\alpha_s^2)$	-	0.1135	$\sqrt{Q^2 + 4m_c^2}$	for mass optimisation only
ABKM09 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	-			

- Different perturbative orders of FFN / VFN parts
- Different matching prescriptions between FFN and VFN parts
- Different mc, α_s
- Different scales
- Different fitted data sets (in general including some HERA charm data)

But not only do schemes, orders and masses differ, the PDF assumptions and value of $\alpha_s(M_Z)$ also differ. We want a consistent approach to the various schemes

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Perform a QCD fit to the HERA combined charm data together with HERA combined inclusive data
Use different heavy quark schemes and masses– see what the data tells us

- Different GM-VFNS schemes used:

  - RT NLO with "standard" and "optimal" matching between FFN/VFN parts (as in MSTW)

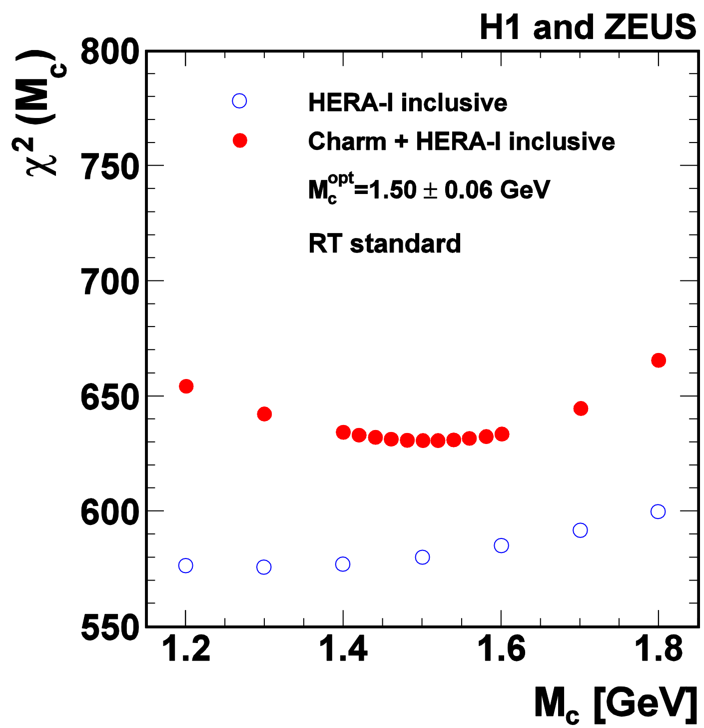
    ($O(\alpha_s^2)$ for FFN part, $O(\alpha_s)$ for VFN part)

  - ACOT-full NLO and S-ACOT-χ NLO (as in CT10 NLO, *all $O(\alpha_s)$*)

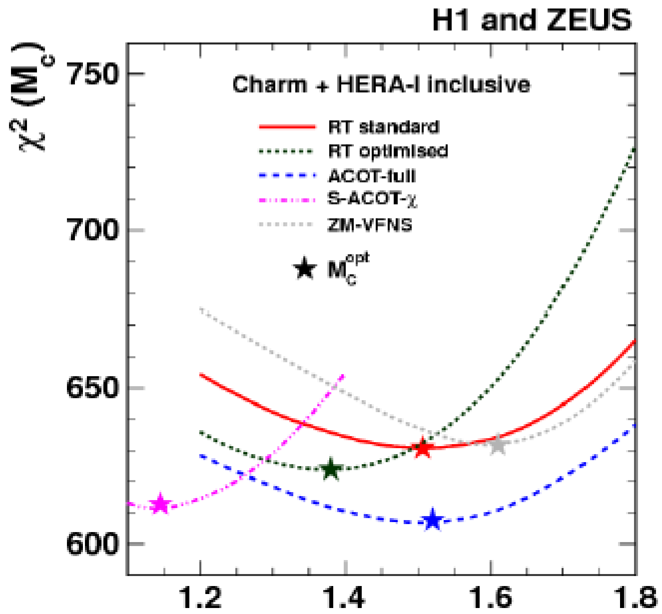
  - ZM-VFNS NLO (*$O(\alpha_s)$*)

Charm mass is treated as a free parameter of the fit
For the schemes listed above this is a pole-mass

The combined charm data show a clear minimum of χ2...
But this plot is for just one scheme RT-Standard



The preferred value of charm mass depends on the scheme used..
The best fit to HERA data is from ACOT-full
But the best fit to HERA charm data is from RT-Standard. All are acceptable fits



Below we give the preferred charm masses with systematic uncertainties resulting from

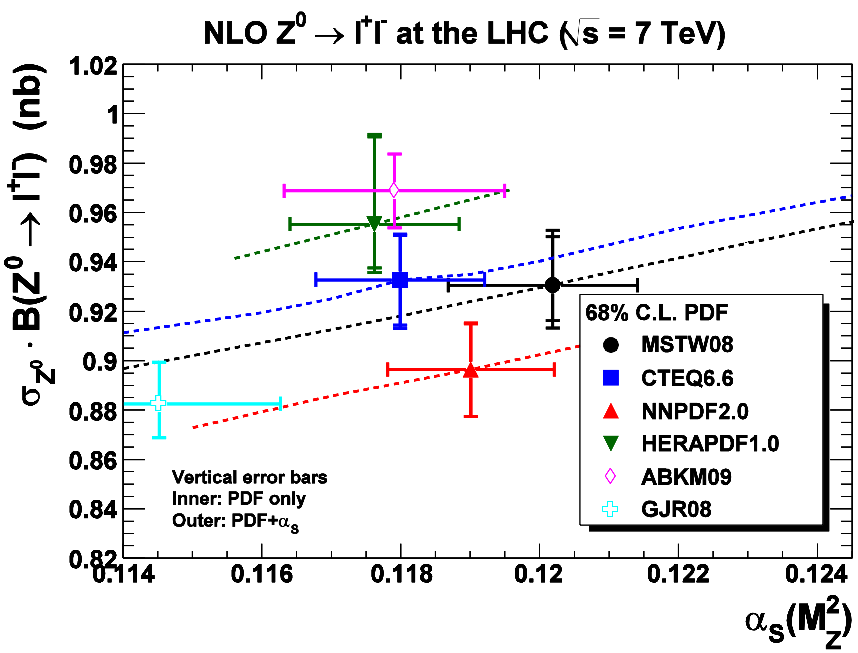
- differing model assumptions in the QCD fit
- different choices of parametrisation
- different values of $\alpha_s(M_Z)$

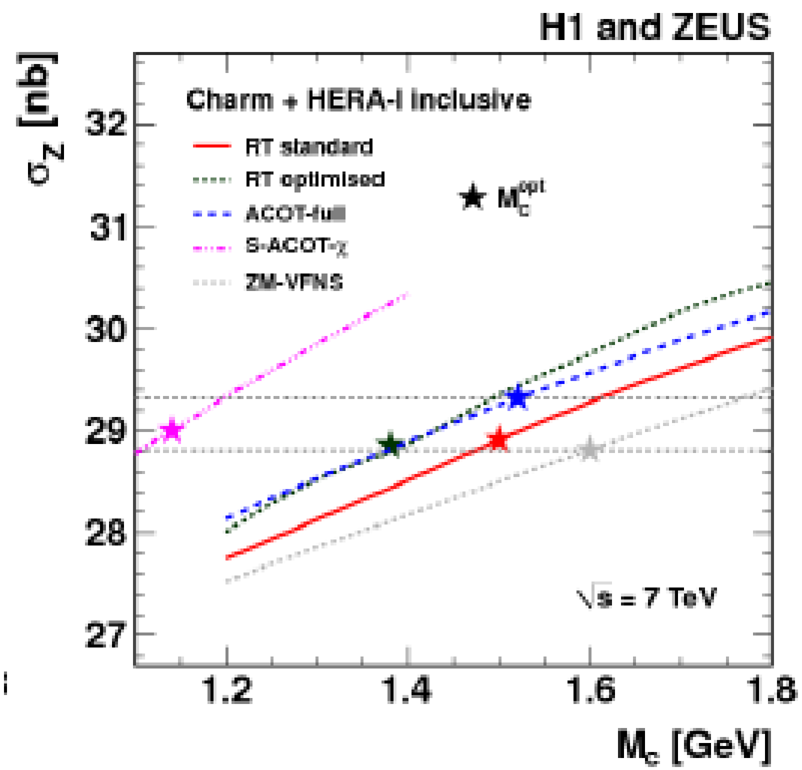
scheme	M_c^{opt} [GeV]	χ^2/n_{dof} $\sigma_{\mathrm{red}}^{NC,CC}+\sigma_{\mathrm{red}}^{c\bar{c}}$	χ^2/n_{dp} $\sigma_{\mathrm{red}}^{c\bar{c}}$
RT standard	$1.50 \pm 0.06_{\mathrm{exp}} \pm 0.06_{\mathrm{mod}} \pm 0.01_{\mathrm{param}} \pm 0.003_{\alpha_s}$	630.7/626	49.0/47
RT optimised	$1.38 \pm 0.05_{\mathrm{exp}} \pm 0.03_{\mathrm{mod}} \pm 0.01_{\mathrm{param}} \pm 0.01_{\alpha_s}$	623.8/626	45.8/47
ACOT-full	$1.52 \pm 0.05_{\mathrm{exp}} \pm 0.12_{\mathrm{mod}} \pm 0.01_{\mathrm{param}} \pm 0.06_{\alpha_s}$	607.3/626	53.3/47
S-ACOT-χ	$1.15 \pm 0.04_{\mathrm{exp}} \pm 0.01_{\mathrm{mod}} \pm 0.01_{\mathrm{param}} \pm 0.02_{\alpha_s}$	613.3/626	50.3/47
ZM-VFNS	$1.60 \pm 0.05_{\mathrm{exp}} \pm 0.03_{\mathrm{mod}} \pm 0.05_{\mathrm{param}} \pm 0.01_{\alpha_s}$	631.7/626	55.3/47

The value of the effective charm mass has consequences for the predictions of W and Z cross sections at the LHC- the larger the mass the larger the cross-section- although the argument is subtle.

Currently predictions from different PDF groups differ by ~7-8%.

Part of the reason is a non-optimal choice of charm mass for the corresponding heavy quark scheme





CTEQ	MSTW	NNPDF	
1.3	1.4	1.414	(Mc in GeV chosen)
1.15	1.5	1.6	(optimal choice)

Predictions differ by~6% for a fixed value of Mc

But only by ~ 2% for an optimal choice

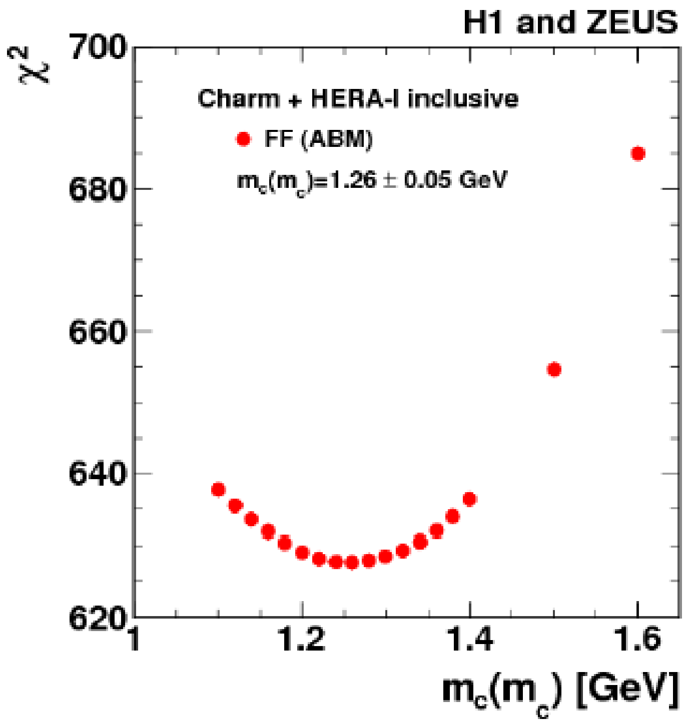
But so far we have not considered FFN schemes

An FFN fit can be done using a running mass rather than a pole mass

As implemented by the ABM group

FFN schemes fit the charm data well– although they are not used for HERA very high Q^2 inclusive data (because of $\ln(Q^2/mc^2)$ terms)

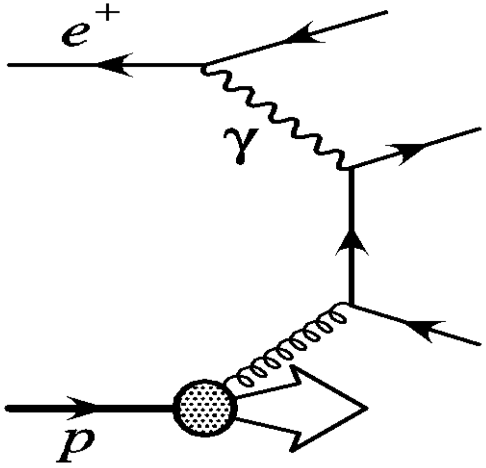
A determination of the MSbar mass can be made



Result: $m_c(m_c) = 1.26 \pm 0.05_{\rm exp} \pm 0.03_{\rm mod} \pm 0.02_{\rm param} \pm 0.02_{\alpha_s}$ GeV

PDG : $m_c(m_c) = 1.275 \pm 0.025$ GeV

Jet production in Deep Inelastic Scattering and in Photoproduction can be used to extract $\alpha_s(M_Z)$ and to improve the determination of the gluon PDF



The value of $\alpha_S(M_Z)$ is strongly correlated to the gluon PDF shape in fits to inclusive data alone because the gluon is determined from the scaling violations

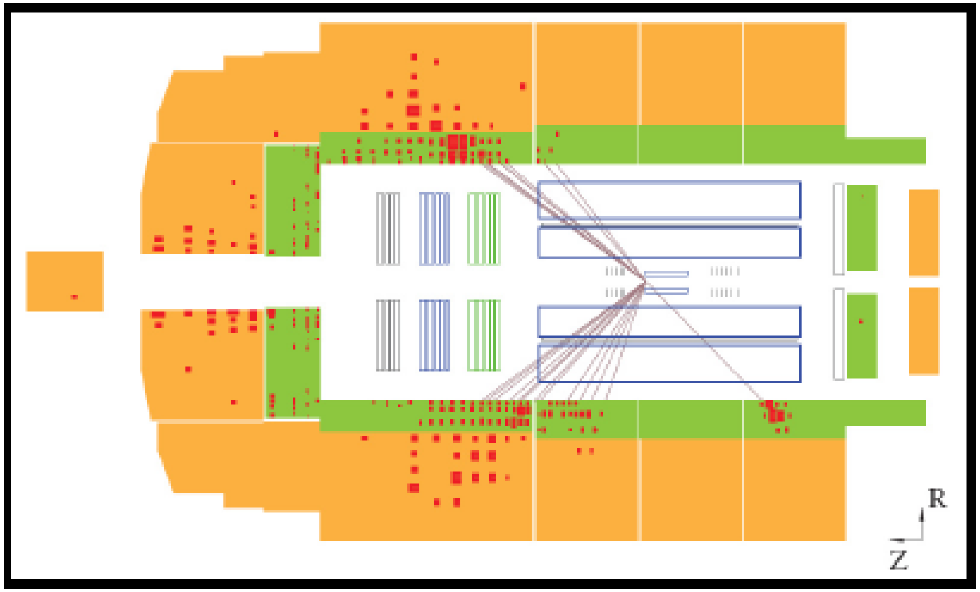
Jet data give us a cross-section which depends directly on the gluon PDF.

This extra information reduces the strong correlation

The DIS jet cross-sections have small correlated errors (~5%) from the Jet Energy Scale of ~1%. This is much smaller than the correlated systematic uncertainties achieved forTevatron jets at the end of Run-II.

HERA –jet measurements contribute to the gluon and $\alpha_s(M_Z)$ measurements in global PDF fits

H1 normalised multi-jet cross sections H1-Prel-12-031



Normalized Jet Measurment

Normalized Jets

$d\sigma_{Jet} / d\sigma_{DIS}$

Four Ingredients

(inclusive) DIS Measurement	$d\sigma/dQ^2$
Inclusive Jet	$d\sigma/dQ^2dP_T$
Dijet	$d\sigma/dQ^2d\langle P_T\rangle$
Trijet	$d\sigma/dQ^2d\langle P_T\rangle$

Phase Space

Neutral current phase space

$150 < Q^2 < 15000$ GeV^2

$0.2 < y < 0.7$

Jet phase space

$-1.0 < \eta_{Lab} < 2.5$

Inclusive Jet

$7.0 < P_T < 50$ GeV

Dijet and Trijet

$5 < P_T < 50$ GeV

$7 < \langle P_T\rangle < 50$ GeV

$M_{12} > 16$ GeV

Kinematics

DIS Event = scattered electron

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

$y \quad = q{\cdot}P / k{\cdot}P$ (Inelasticity)

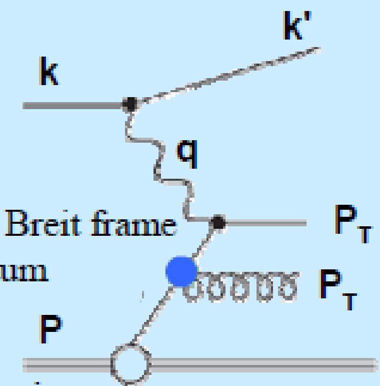
Jet kinematics

p_T = jet transverse momentum in Breit frame

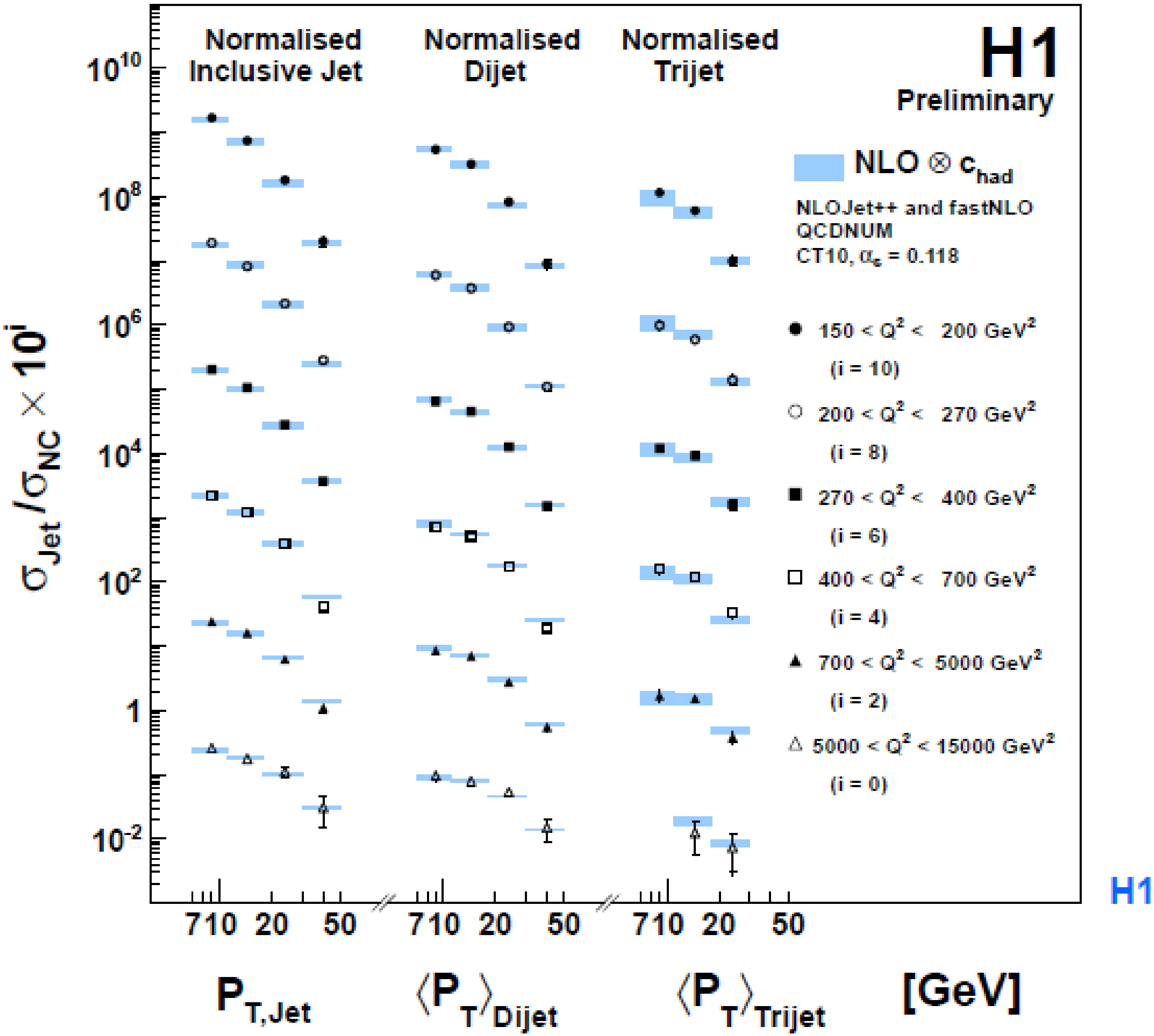
$\langle p_T\rangle$ = Average transverse momentum of 2 (resp. 3) jets

η = pseudorapidity of Jet

M_{12} = invariant mass of two leading jets



Normalized Multijet cross sections



$\alpha_s(M_Z)$ Extraction Fitting Technique

NLO calculations depend on PDF and α_s

- Keep PDF fixed and determine $\alpha_s(M_Z)$

Jet cross sections

- NLOJET++, FastNLO v2.0
- $\mu_r^2 = (Q^2 + E_T^2)/2$
- $\mu_f^2 = Q^2$

NC-DIS cross sections

- QCDNUM
- $\mu_f^2 = \mu_r^2 = Q^2$

NLO × Had. corrections

PDF: CT10

Hessian Method

- Minimise χ^2
- TMinuit
- Comparable to Eur. Phys. J. C65, 363

$$\chi^2(\alpha_s, \varepsilon_k) = \vec{\tilde{\sigma}}^T \cdot V^{-1} \cdot \vec{\tilde{\sigma}} + \sum_k^{SysErr} \varepsilon_k^2$$

$$\vec{\tilde{\sigma}}_i = \sigma_i^{Data} - \sigma_i^{Theo}(\alpha_s, f(\alpha_{s,fix})) \cdot \left(1 - \sum_k^{SysErr} \Delta_{i,k}(\varepsilon_k)\right)$$

Usage of full covariance matrix V from unfolding

- All correlations are respected in fit

Systematic errors as penalty terms

α_s Fits to Individual Measurements

Normalized Inclusive Jet

$$\alpha_s = 0.1197 \pm 0.0008\,(\text{exp}) \pm 0.0014\,(\text{PDF}) \pm 0.0011\,(\text{had}) \pm 0.0053\,(\text{theo})$$

$\chi^2 / \text{ndf} = 28.7/23 = 1.24$

Fit Quality
- Reasonable χ^2 / ndf
- Penalty parameters $-1<\varepsilon<1$

Experimental Error
- Cancellations of some systematic errors
- All normalization uncertainties cancel

Theoretical/systematic errors

Repeated fit with offset method

PDF Error
- Error on cross section from PDF Eigenvectors
- Neglecting correlations from EV

Hadronisation Error
- Error on hadronisation correction
- Sherpa
  - Lund Fragmentation
  - Cluster Fragmentation

Theory Error
- Scan μ_r and μ_f independently
  - $0.5 < c < 2.0$
  - Largest and lowest cross section
- Add error on cross section from μ_r and μ_f variation in quadrature

NNLO calculations are not available for DIS jet production

Normalized Inclusive Jet

$$\alpha_s = 0.1197 \pm 0.0008\,(\text{exp}) \pm 0.0014\,(\text{PDF}) \pm 0.0011\,(\text{had}) \pm 0.0053\,(\text{theo})$$

$$\chi^2 / \text{ndf} = 28.7/23 = 1.24$$

Normalized Dijet

$$\alpha_s = 0.1142 \pm 0.0010\,(\text{exp}) \pm 0.0016\,(\text{PDF}) \pm 0.0009\,(\text{had}) \pm 0.0048\,(\text{theo})$$

$$\chi^2 / \text{ndf} = 27.0/23 = 1.17$$

Normalized Trijet

$$\alpha_s = 0.1185 \pm 0.0018\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0016\,(\text{had}) \pm 0.0042\,(\text{theo})$$

$$\chi^2 / \text{ndf} = 12.0/16 = 0.75$$

Combined Fit

$$\alpha_s = 0.1177 \text{ +/- } 0.0008\,(\text{exp})$$

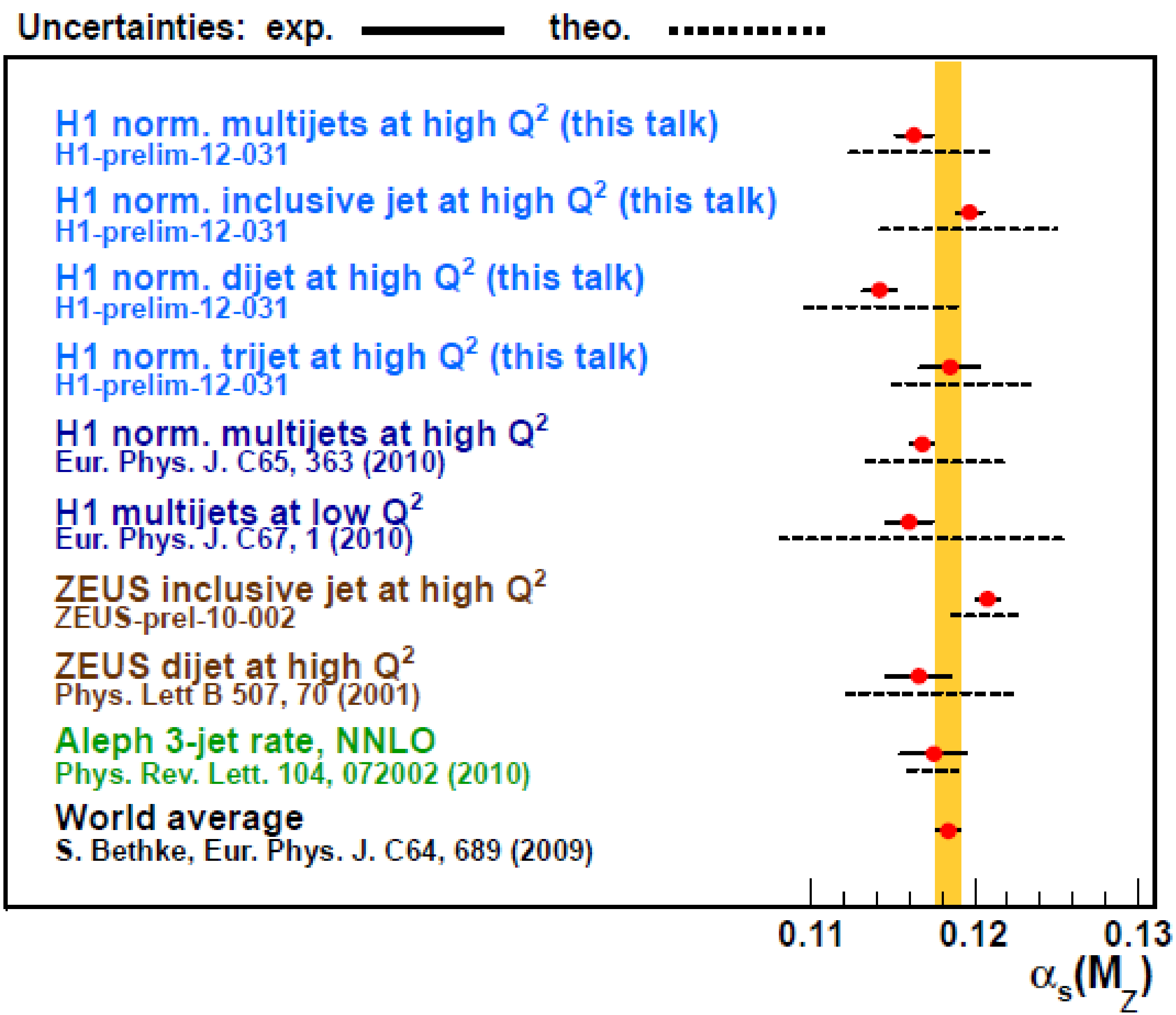
$$\chi^2 / \text{ndf} = 104.608 / 64 = 1.634$$

Tension between di-jet result and inclusive jet result. Resolve this by only using points for which the NLO corrections are less than 30%

Normalized Multijet (k-factor < 1.3)

$$\alpha_s = 0.1163 \pm 0.0011\,(\text{exp}) \pm 0.0014\,(\text{PDF}) \pm 0.0008\,(\text{had}) \pm 0.0039\,(\text{theo})$$

$$\chi^2 / \text{ndf} = 53.2 / 41 = 1.30$$



Uncertainties: exp. theo.
H1 norm. multijets at high Q2 (this talk)
H1-prelim-12-031
H1 norm. inclusive jet at high Q2 (this talk)
H1-prelim-12-031
H1 norm. dijet at high Q2 (this talk)
H1-prelim-12-031
H1 norm. trijet at high Q2 (this talk)
H1-prelim-12-031
H1 norm. multijets at high Q2
Eur. Phys. J. C65, 363 (2010)
H1 multijets at low Q2
Eur. Phys. J. C67, 1 (2010)
ZEUS inclusive jet at high Q2
ZEUS-prel-10-002
ZEUS dijet at high Q2
Phys. Lett B 507, 70 (2001)
Aleph 3-jet rate, NNLO
Phys. Rev. Lett. 104, 072002 (2010)
World average
S. Bethke, Eur. Phys. J. C64, 689 (2009)
0.11
0.12
0.13
αs(MZ)

ZEUS photoproduced jets Nucl.Phys B864(2012)1 arXiv:1205.6153

Data

- data from 2005 - 2007
- luminosity: $300 pb^{-1}$

Data selection

- no electron in detector: $Q^2 < 1 GeV^2$
- $142 < W_{\gamma p} < 293 GeV$
- $E_T^{jet} > 17 GeV$
- $-1 < \eta^{jet} < 2.5$

jet search

- using k_T algorithm with radius set to unity

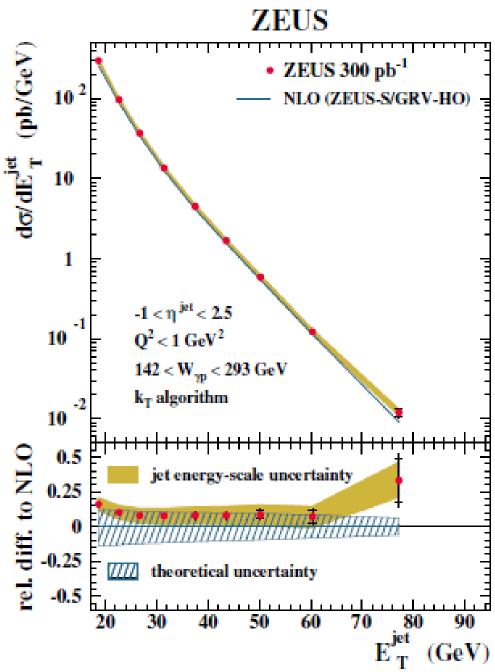
NLO-QCD predictions

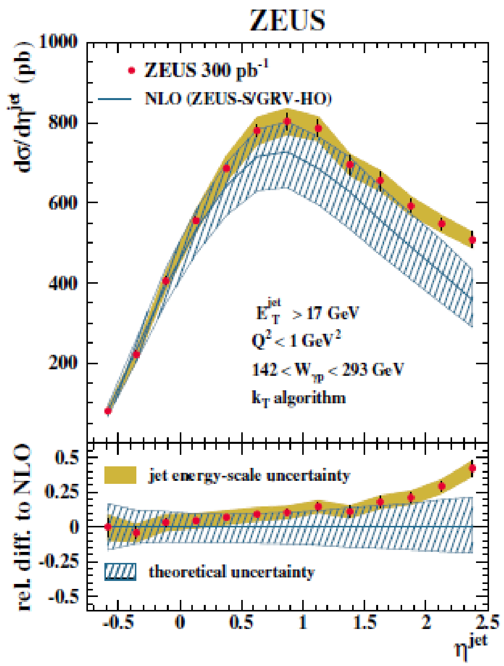
- calculations with program of Klasen, Kleinwort and Kramer ref: EPJ Direct C1 (1998) 1

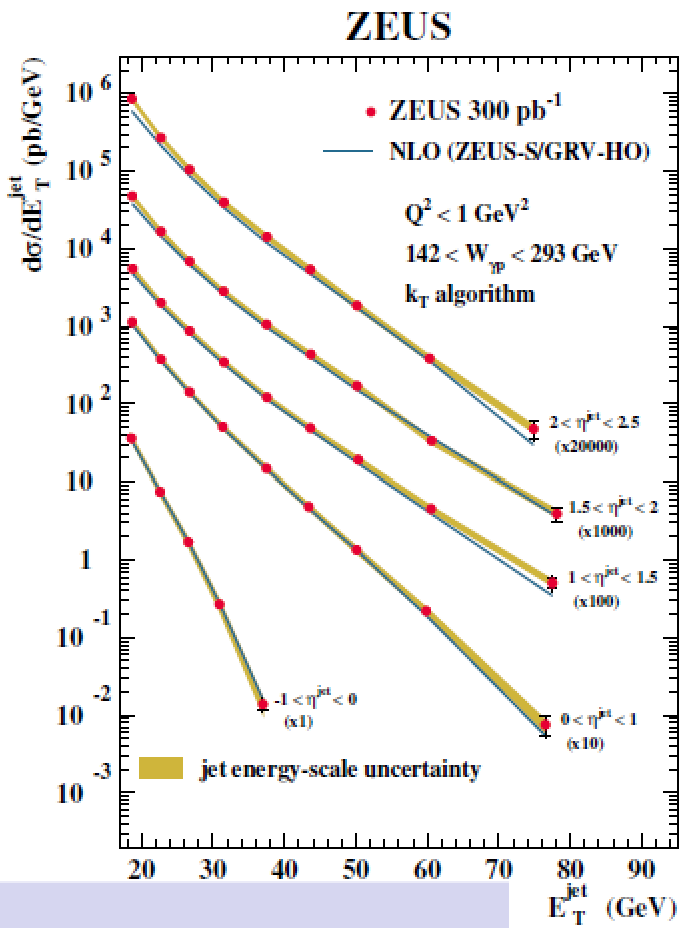
Features

- $\mu_R = \mu_F = \mu = E_T^{jet}$
- ZEUS-S for the proton PDFs
- GRV-HO for the photon PDFs
- Predictions refer to a jet of partons
- MC simulations (PYTHIA and HERWIG) were used to correct predictions to hadron level
- MC simulations including multi-parton scatterings (PYTHIA-MI) were used for comparisons

Cross sections in comparison to NLO-QCD predictions(I)







- Experimental errors: bars + yellow band for error of jet-energy scal
- Theoretical errors: mainly due to terms beyond NLO and photon PDFs

Observations

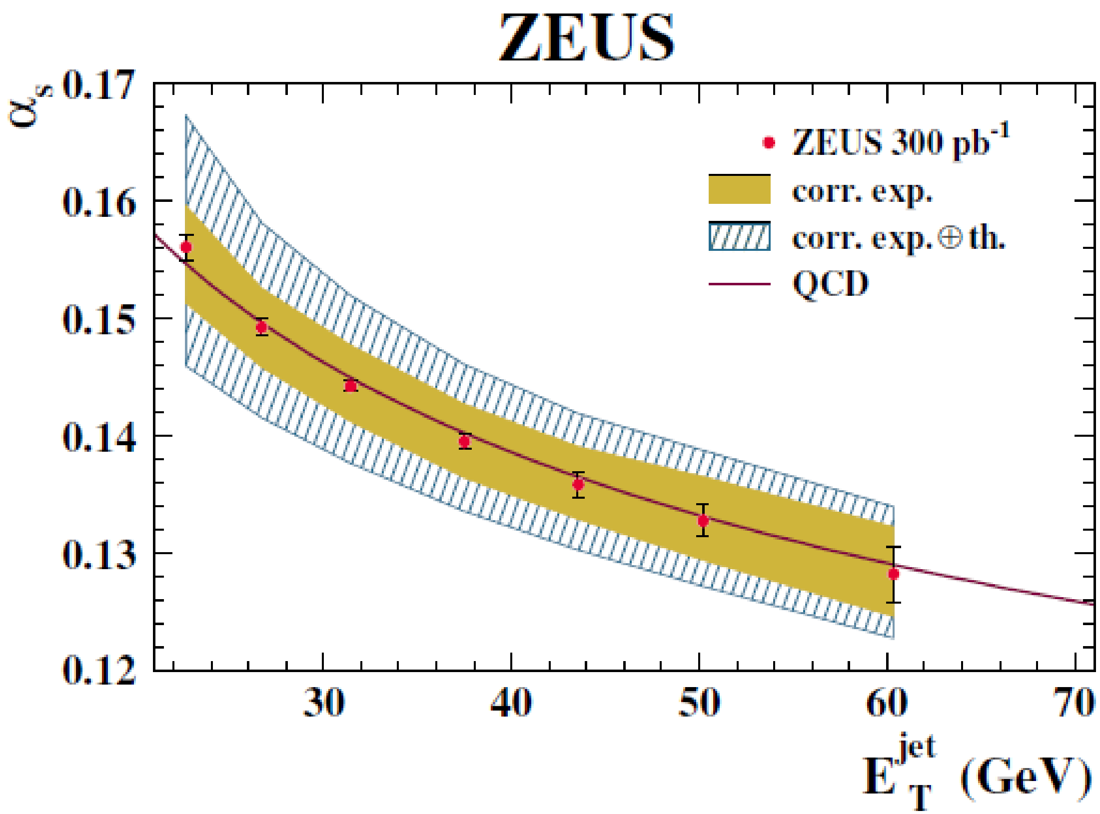
- Reasonable description for most of the data points
- data above prediction for $\eta^{jet} > 2$ and low E_T^{jet}

Studies

- Comparison of jet algorithms
- Effect of multi-parton interactions

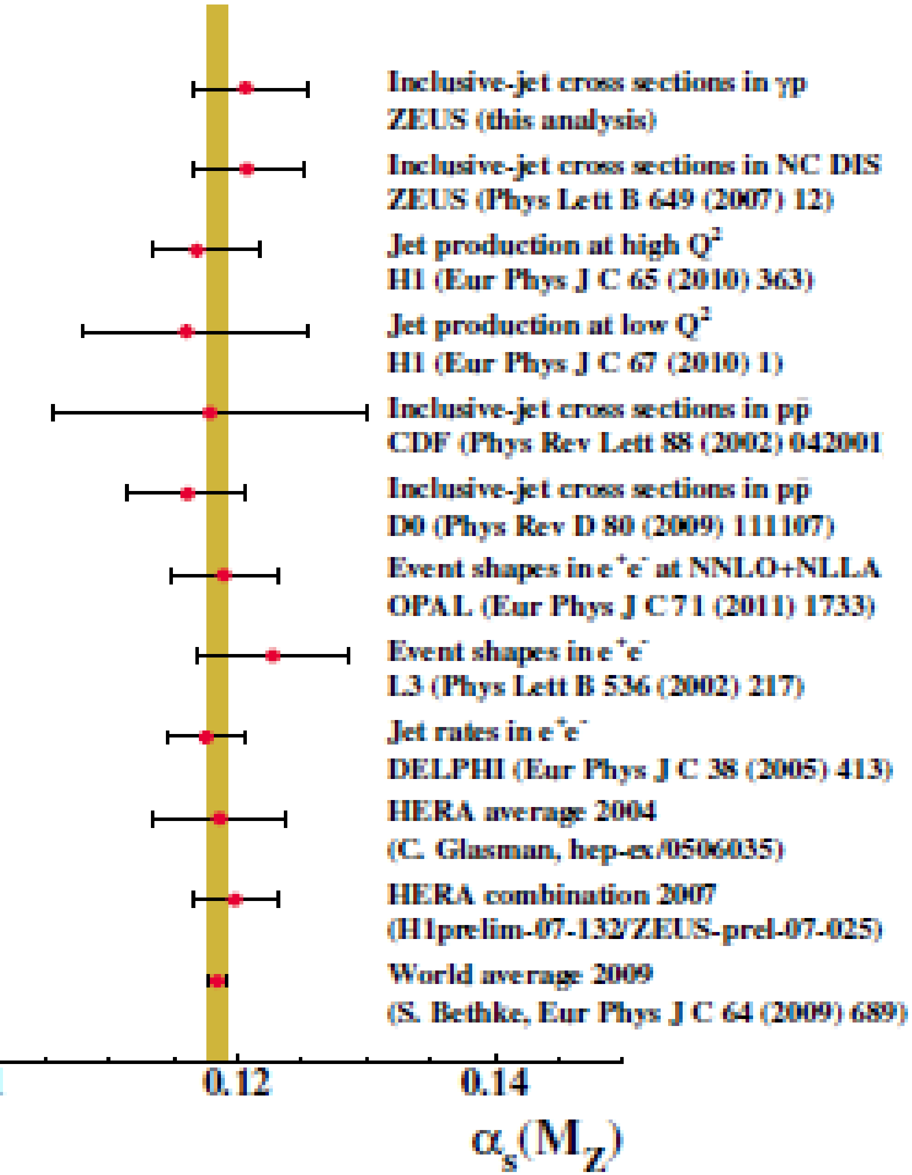
Studies of different photon PDFs

Dependence of α_s on E_T^{jet} as scaling variable



Running of α_S seen in a single experiment

- The measurement confirms running of α_s over a wide range of E_T^{jet}
- The observed running is in good agreement with NLO-QCD



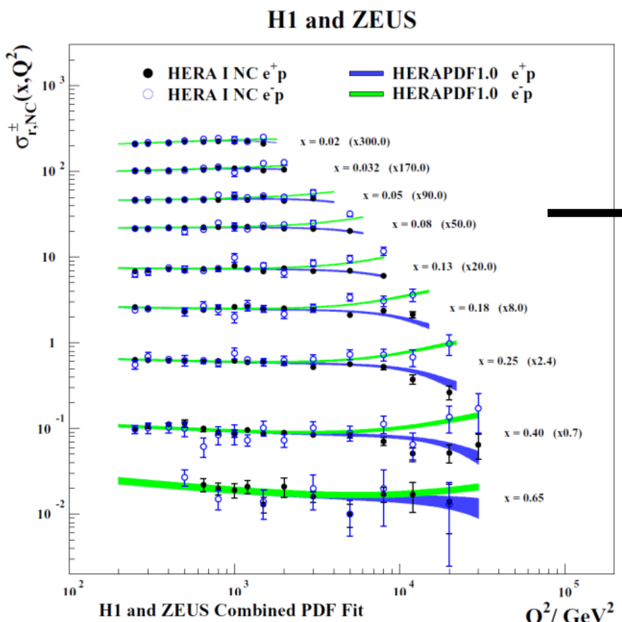
Result (based on k_T):

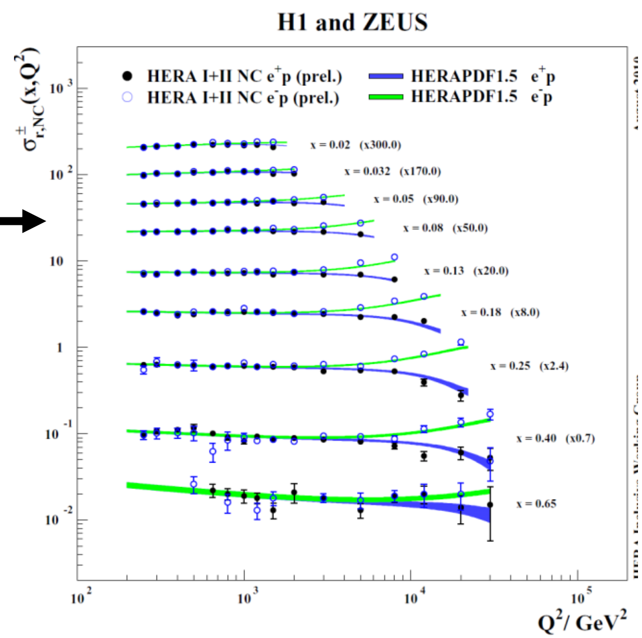
- Fit of NLO-QCD to $d\sigma/dE_T^{jet}$ (ZEUS, PL B 547 (2002) 164)
- Result (based on k_T): $\alpha_S(M_Z) = 0.1206^{+0.0023}_{-0.0022}(exp.)^{+0.0042}_{-0.0035}(th.)$ consistent with world average
- Consistent values obtained with the other jet algoritms

These jet based measurements of $\alpha_s(M_Z)$ use fixed proton PDFs and assess uncertainty due to this choice

We could fit $\alpha_s(M_Z)$ and the PDFs simultaneously.

We do this starting with the HERAPDF1.5 which has an update of data and fit compared to HERAPDF1.0



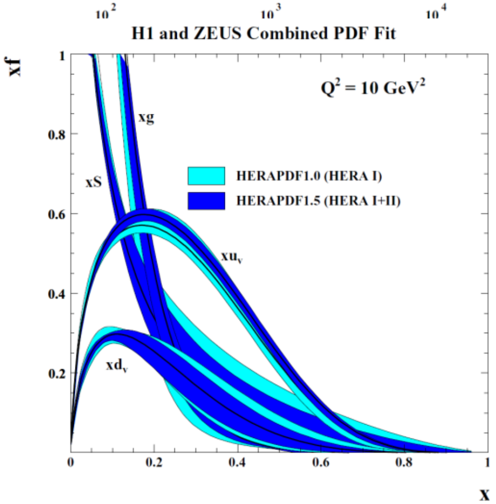


Uses preliminary HERA I+II data combination (ZEUS-prel 10-018, H1prelim-10-042) in addition to the published HERA-1 combined data

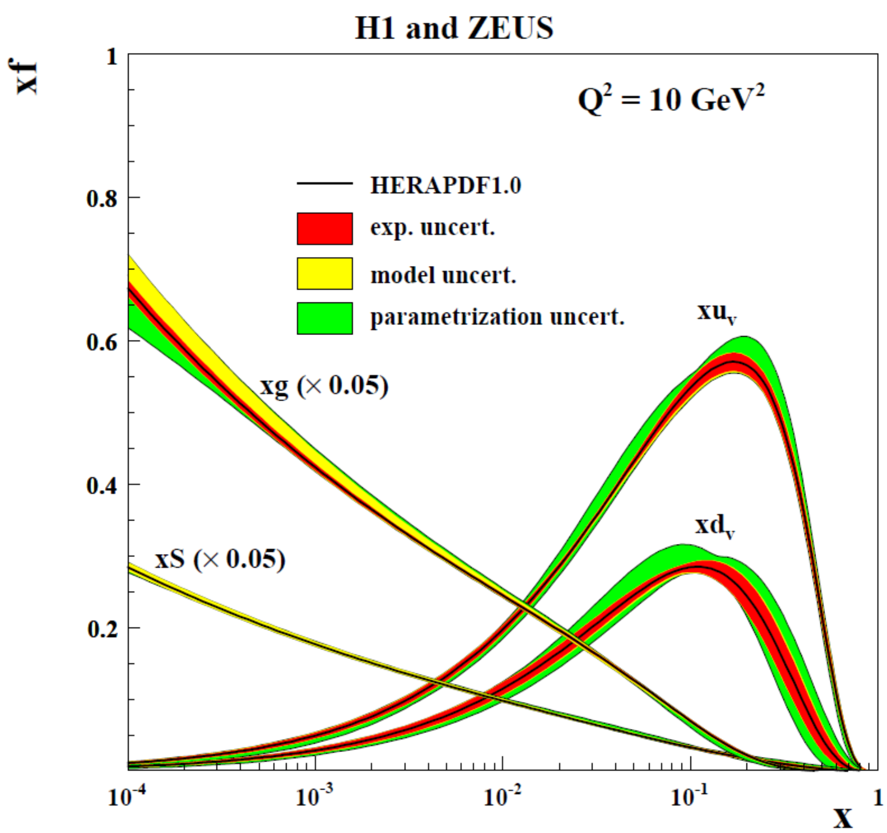
~200pb^{-1} HERA-I

~700pb^{-1} HERA-II

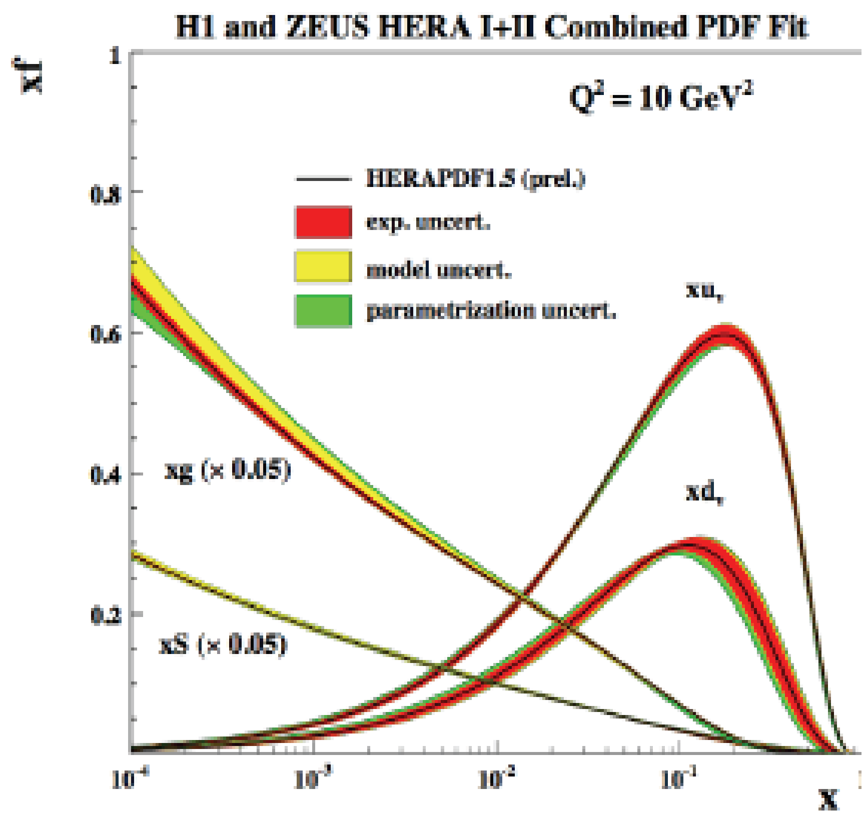
e- increases by ~factor 10



Gives increased precision at high-x



HERAPDF1.0



HERAPDF1.5

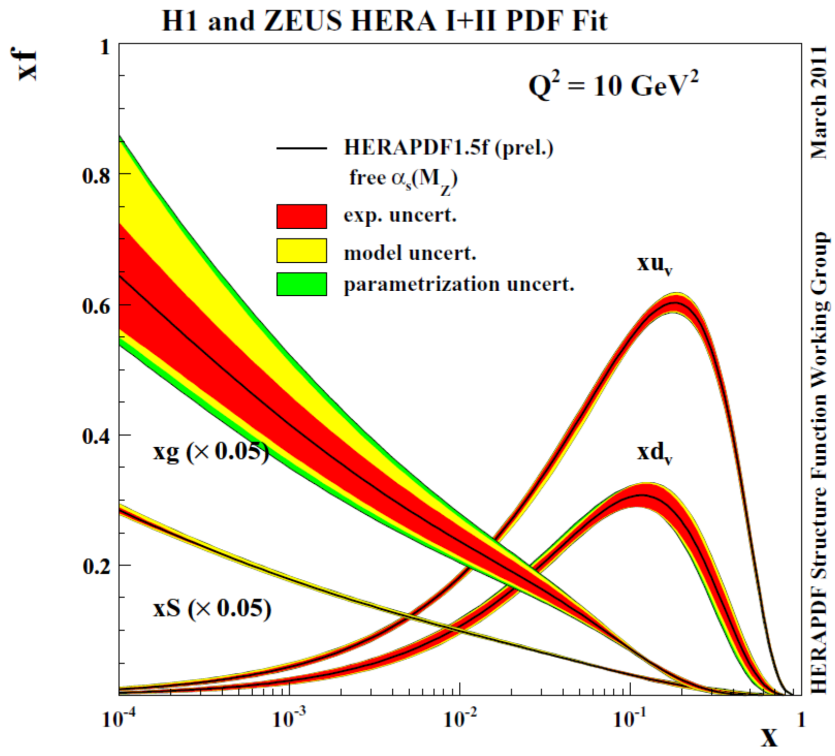
Most PDFs are supplied at fixed $\alpha_s(M_Z)$, what happens when we free it?

The HERAPDF1.6 fit does this (H1prelim-11-034, ZEUS-prel-11-001)

Note these are NLO fits since DIS jet production at NNLO is not available.

Most PDFs are supplied at fixed $\alpha_s(M_Z)$, what happens when we free it?

This shows the HERAPDF1.5 fit with free $\alpha_s(M_Z)$,



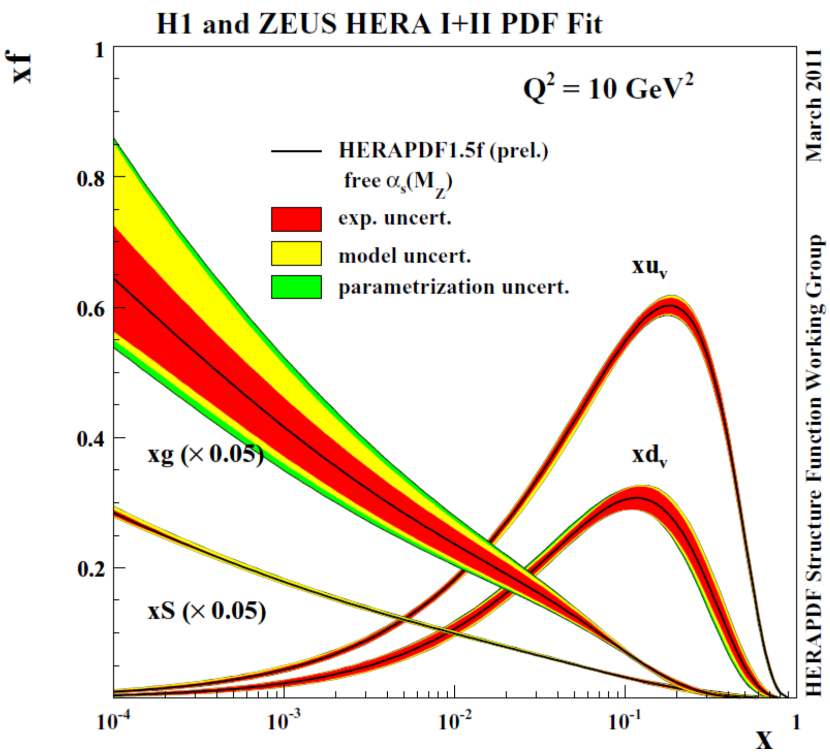
The gluon PDF uncertainty at low-x blows up

What happens if we add jet data to this fit? (HERAPDF1.6)

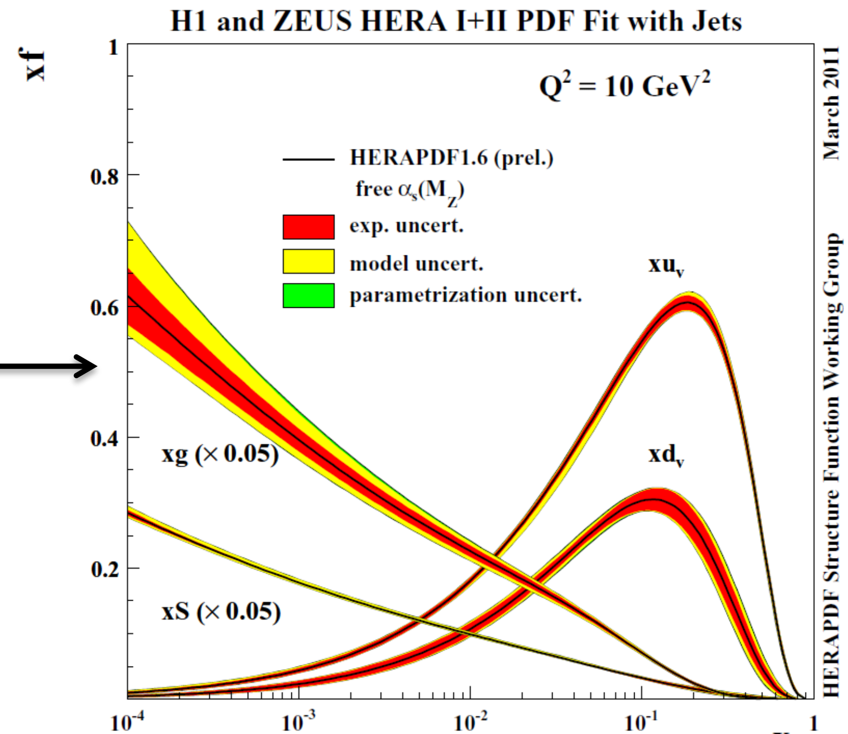
Now add jet data- **inclusive jet data at low (5-100 GeV²) and high (125-15000 GeV²) Q^2**

H1 data: 395pb^{-1} EPJC65,363(2010) and 43.5pb^{-1} EPJC67,1(2010)

ZEUS data: 38.6pb^{-1} PLB547,164(2002) and 82pb^{-1} NPB765,1(2007)



Free $\alpha_S(M_Z)$ no jets



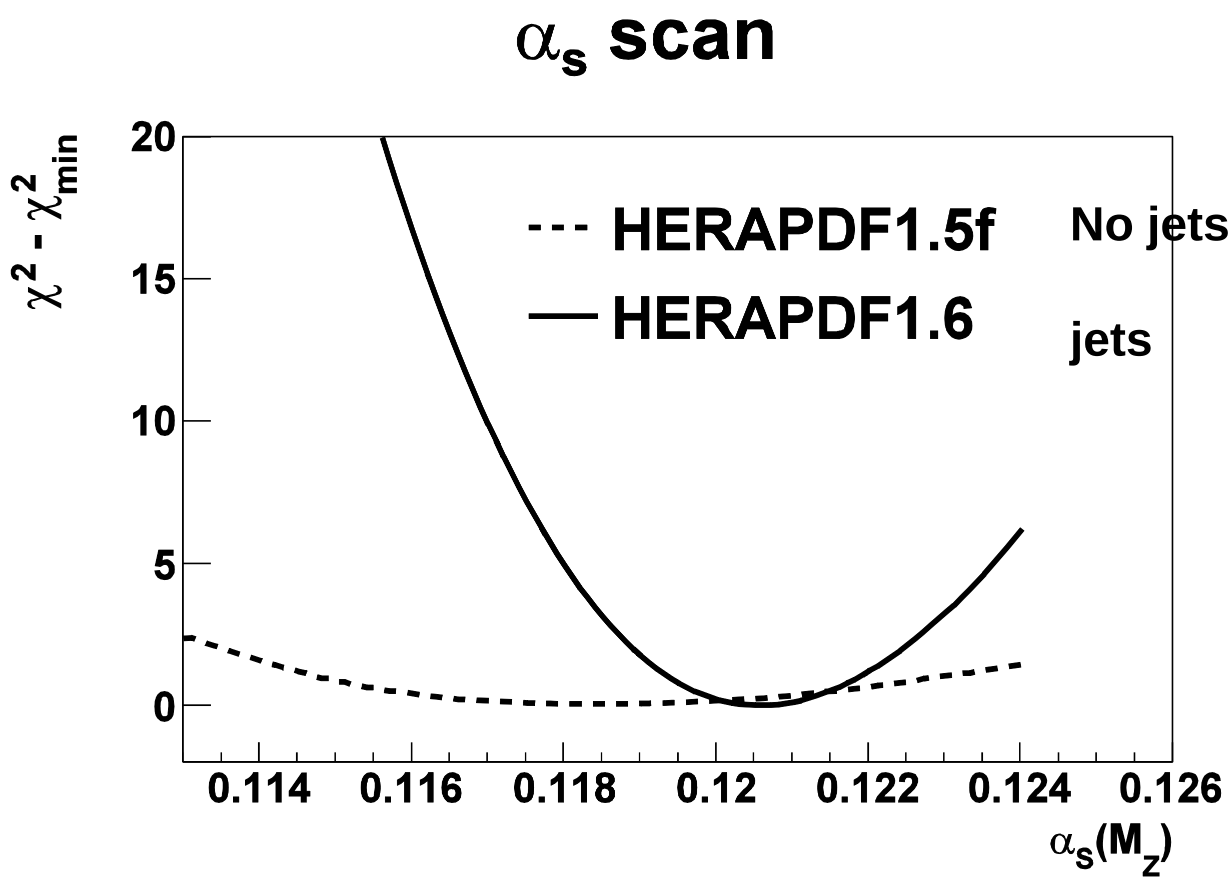
Free $\alpha_S(M_Z)$ with jets

The addition of the jet data ensure that the **PDF uncertainty on the gluon due to the uncertainty on $\alpha_S(M_Z)$ is not very large**

AND ....What happens to the freed value of $\alpha_S(M_Z)$?

The jet data allow us to make a competitive measurement of $\alpha_S(M_Z)$

The $\chi 2$ scan of HERAPDF1.5f (no jets) and HERAPDF1.6 (with jets) vs $\alpha_S(M_Z)$



$\alpha_S(M_Z)$ =0.1202 ± 0.0013 (exp) ± 0.0007(model/param) ± 0.0012(hadronisation)

+0.0045/-0.0036 (scale)

$\alpha_S(M_Z)$ = 0.1202 ± 0.0019 ± scale error

Summary

HERA data on inclusive neutral and charged current cross section for e+ and e- beams has been combined and used as the input to the HERAPDF QCD parton fit

HERA data on charm production has been combined to give accurate charm structure function data which can be used to determine the charm mass in various heavy quark-schemes.

The running mass is $m_c(m_c) = 1.26 \pm 0.05_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.02_{\text{param}} \pm 0.02_{\alpha_s}$ GeV

HERA data on jet production has also been used to determine $\alpha_s(M_Z)$:
H1 normalised inclusive, di-jet and tri-jet cross-sections yield

$$\alpha_s = 0.1163 \pm 0.0011\ (\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0039\ (\text{theo})$$

ZEUS photo-produced jets yield

$$\alpha_S(M_Z) = 0.1206^{+0.0023}_{-0.0022}(exp.)^{+0.0042}_{-0.0035}(th.)$$

And a simultaneous fit of parton distributions functions together with HERA inclusive jet production at low and high Q^2 from both experiments yields:

$\alpha_S(M_Z) = 0.1202 \pm 0.0019(\text{exp.}) \pm 0.004\ (\text{th}).$

These are all NLO determinations such that the theory uncertainty is scale uncertainty– we need NNLO calculations

D*/D/μ measurements are "visible" D*/D/μ cross sections ($\sigma_{\text{vis,bin}}$) in bins of Q^2, y (or x), pt, η

Reduced cross sections are obtained as

$$\sigma_{\text{red}}^{c\bar{c}}(x, Q^2) = \sigma_{\text{vis,bin}} \frac{\sigma_{\text{red}}^{c\bar{c},\text{th}}(x, Q^2)}{\sigma_{\text{vis,bin}}^{\text{th}}}.$$

This method accounts for extrapolation to full phase space

The theory used for this "extrapolation" is FFNS at NLO : HVQDIS

Parameters (and systematic variations) used for HVQDIS:

- $m_c = 1.5 \pm 0.15$ GeV;
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_c^2}$, varied up/down by factor 2;
- $\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$;

- PDF: HERAPDF1.0, FFNS variant
  m_c, μ, α variations done simultaneously in HVQDIS and in PDF fit.

To produce visible D*, D, μ cross section a fragmentation model is used:

- Longitudinal fragmentation function : Kartvelishvili with variable α_K ($\hat{s}$)
  $\hat{s}$ = γ*g cms energy squared,
  based on D* fragmentation mesurements in ep:

$\hat{s}$ range	$\alpha_K(D^*)$	α_K(g.s.)	Measurement
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9	4.6 ± 0.7	[47] D^*, DIS, no-jet sample
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4	3.0 ± 0.3	[47] D^*, DIS, jet sample
$\hat{s} > \hat{s}_2$	2.67 ± 0.31	2.19 ± 0.24	[11] D^* jet photoproduction

$$\hat{s}_1 = 70 \pm 40 \text{ GeV}^2$$
$$\hat{s}_2 = 324 \text{ GeV}^2$$

- Fragmentation for ground-state D meson was softened wrt D* to account for D* decays (based on e+e- data and kinematics)

- transverse fragmentation (kT of D wrt c direction): based on e+e- data:
  <kt> = 0.35 +- 0.15 GeV

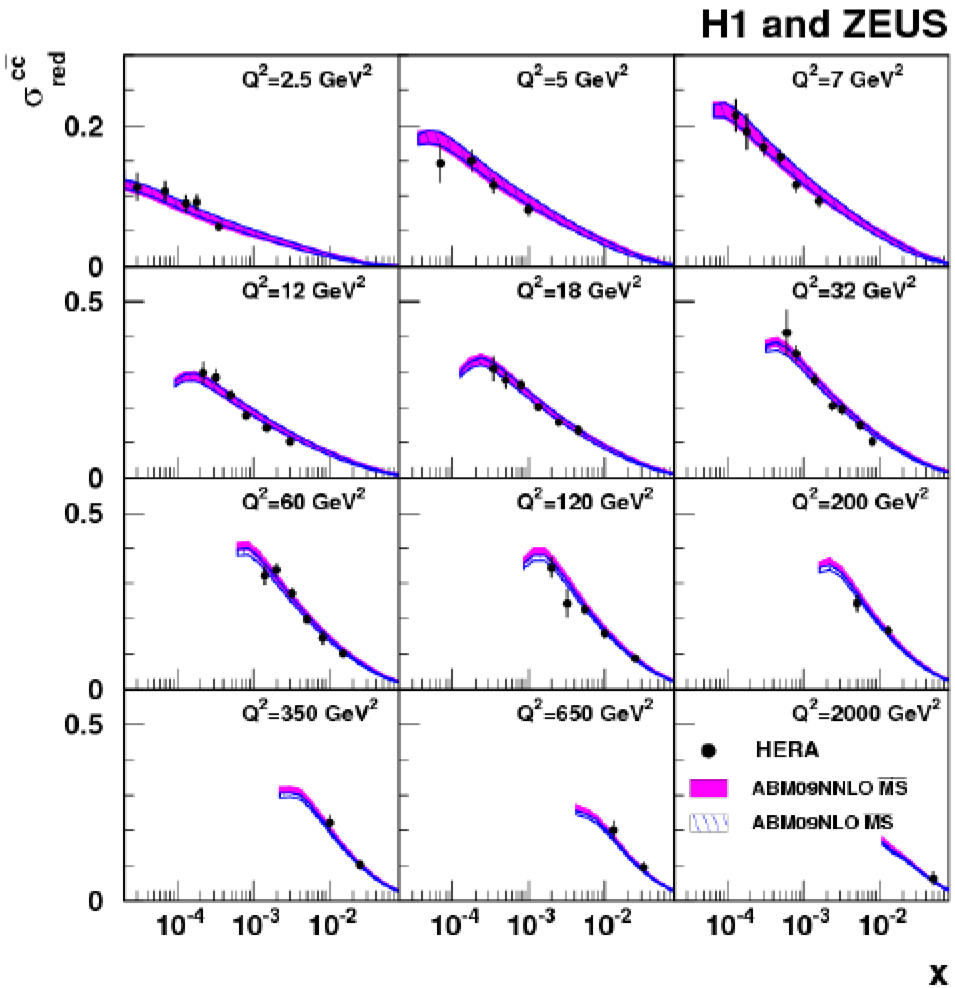
- Fragmentation fractions, updated average of e+e- and ep data (arXiv:1112.3757)

$f(c \to D^{*+})$	0.2287 ± 0.0056
$f(c \to D^+)$	0.2256 ± 0.0077
$f(c \to D^{0,\mathrm{not}\,D^{*+}})$	0.409 ± 0.014
$B(c \to \mu)$	0.096 ± 0.004

Comparison with FFNS (ABM)

- ABM FFNS describe data well in the full HERA range

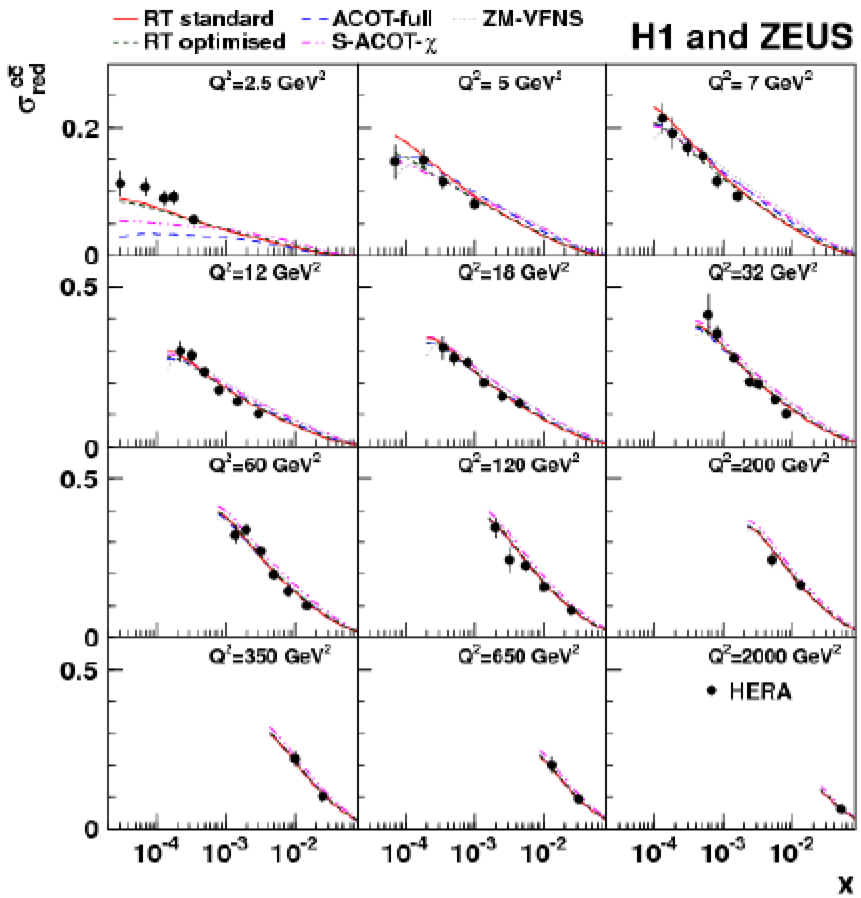
- $m_c(m_c)$=1.18 GeV ($\overline{MS}$)



Fit results compared to charm data

- Using the optimized Mc all the fits describe data reasonably well, including ZM-VFNS

- Largest deviations observed In the lowest Q^2 bin (not included in the fit)



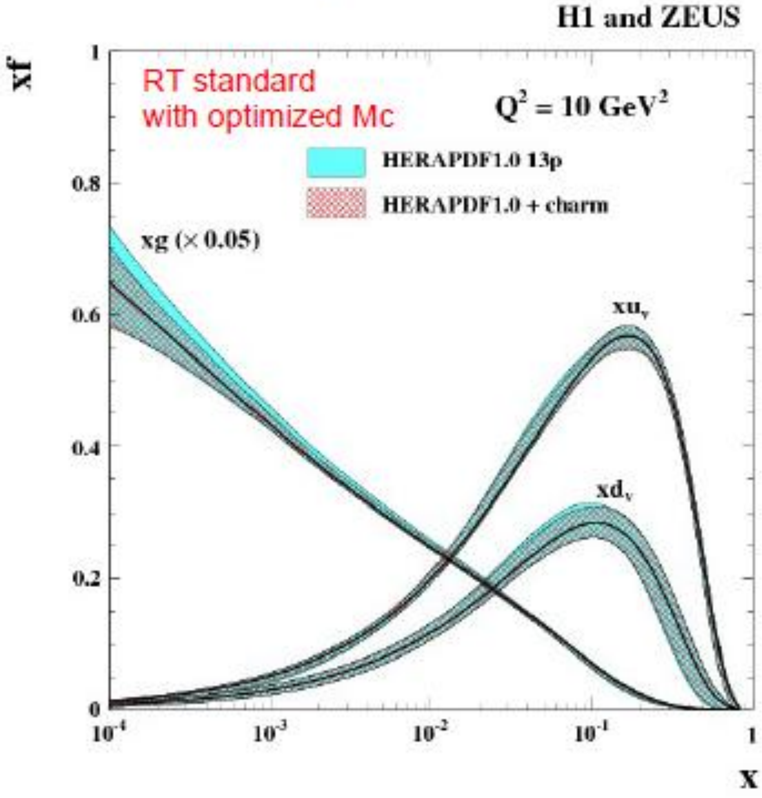
Impact on PDFs

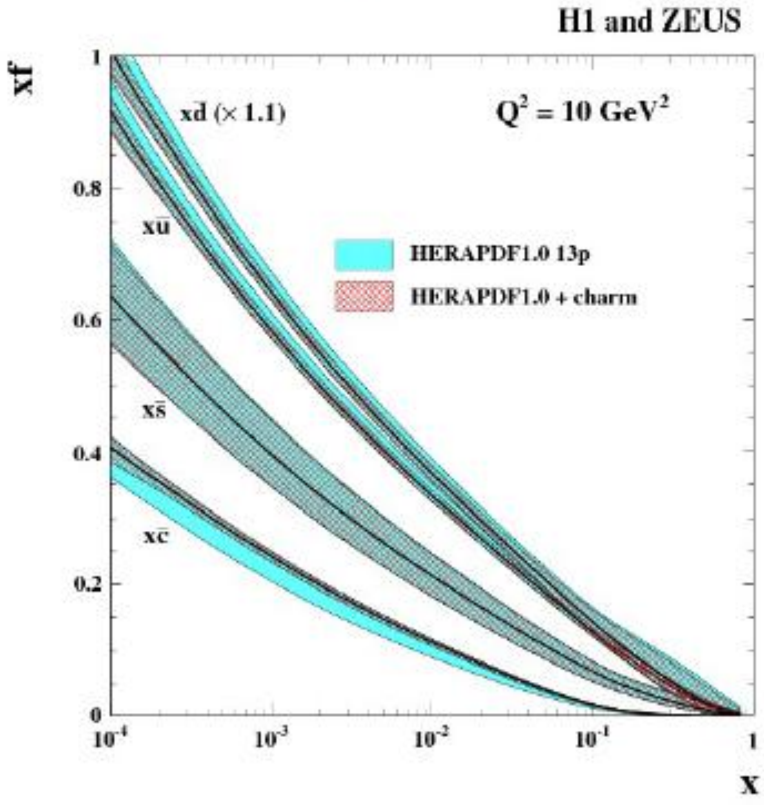
RT "standard" fit, with optimized Mc

- Uncertainty on g(x) reduced due to the reduced range allowed for Mc variation in the parametrization uncertainty

- Uncertainty on c(x) reduced significantly

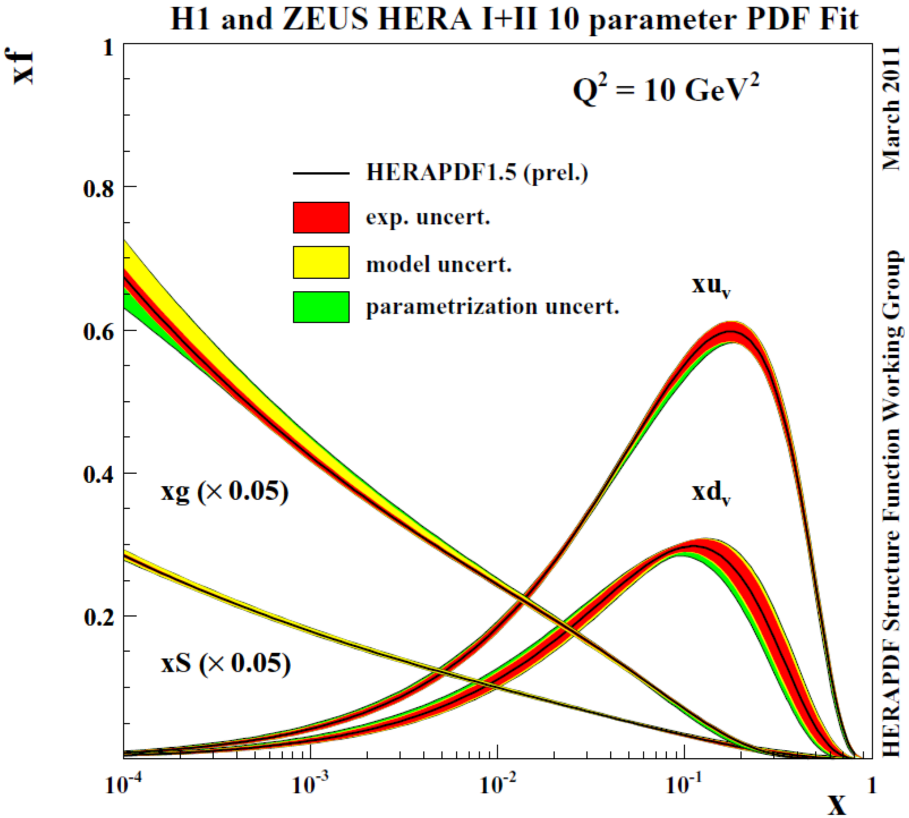
- Uncertainty on light sea reduced because of reduced uncertanty of charm component

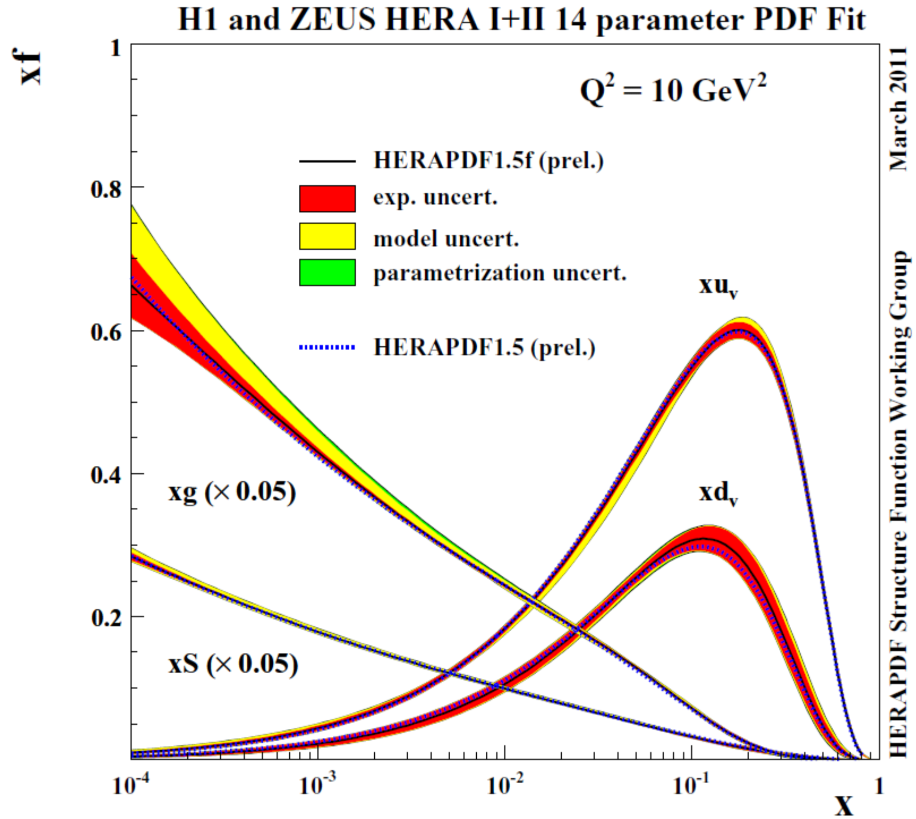




How does the extended parametrisation affect the NLO PDFs?- not much

HERAPDF1.5 **HERAPDF1.5f**



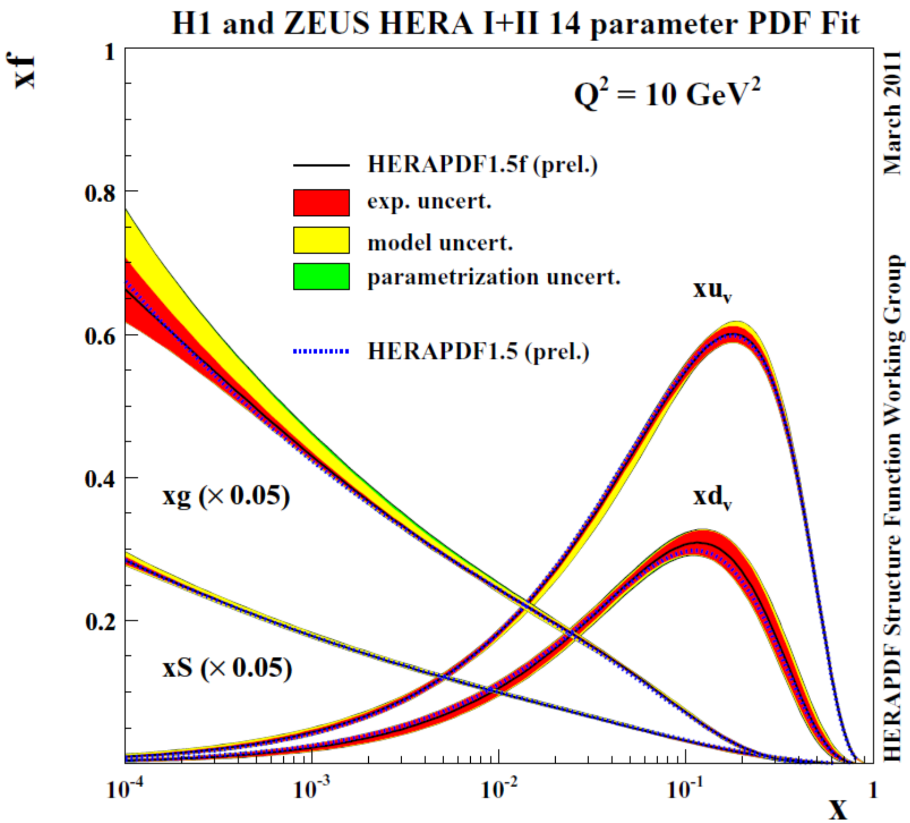


i) The level of total uncertainty is similar- but we swap parametrisation uncertainty for experimental uncertainty- and there is slightly more uncertainty on low-x gluon

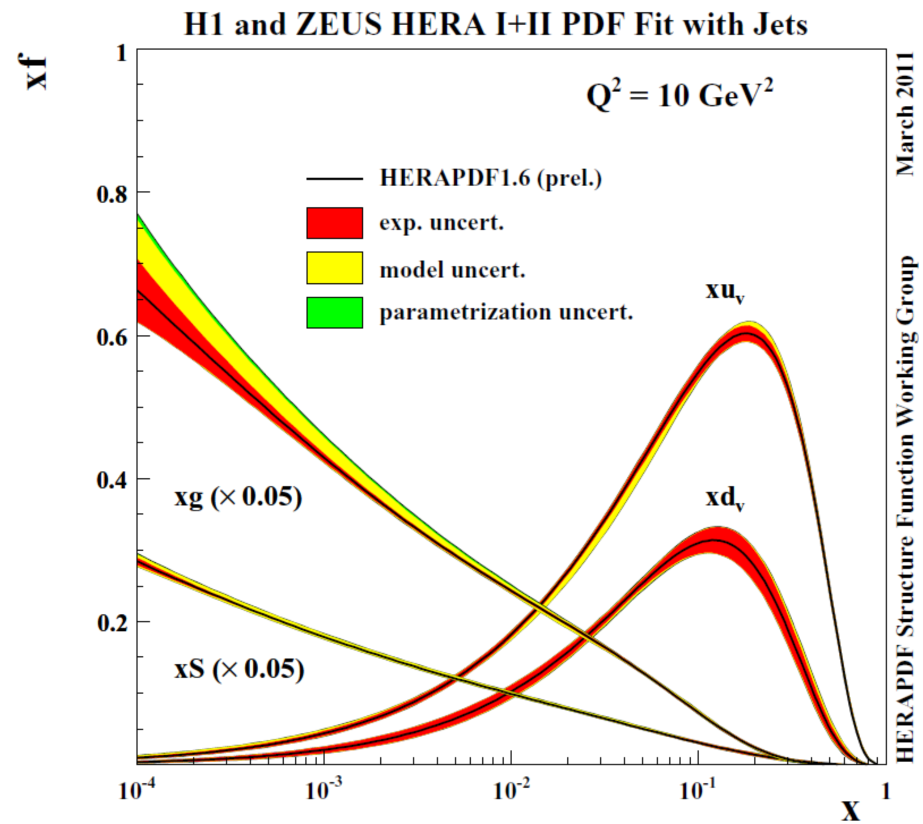
ii) The central values have shifted such that the flexible parametrisation has a softer high-x Sea and a suppressed low-x d-valence- but these changes are within our error bands

Add HERA jet data to the fit but keeping $\alpha_s(M_Z)$ fixed

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



Without jets



With jets

There is little difference in the size of the uncertainties after adding the jet data –but there is a marginal reduction in high-x gluon uncertainty.