Precision QCD @ HERA

Determination of the charm quark mass and $\alpha_s(M_Z)$

Günter Grindhammer, Max-Planck-Institute for Physics, Munich

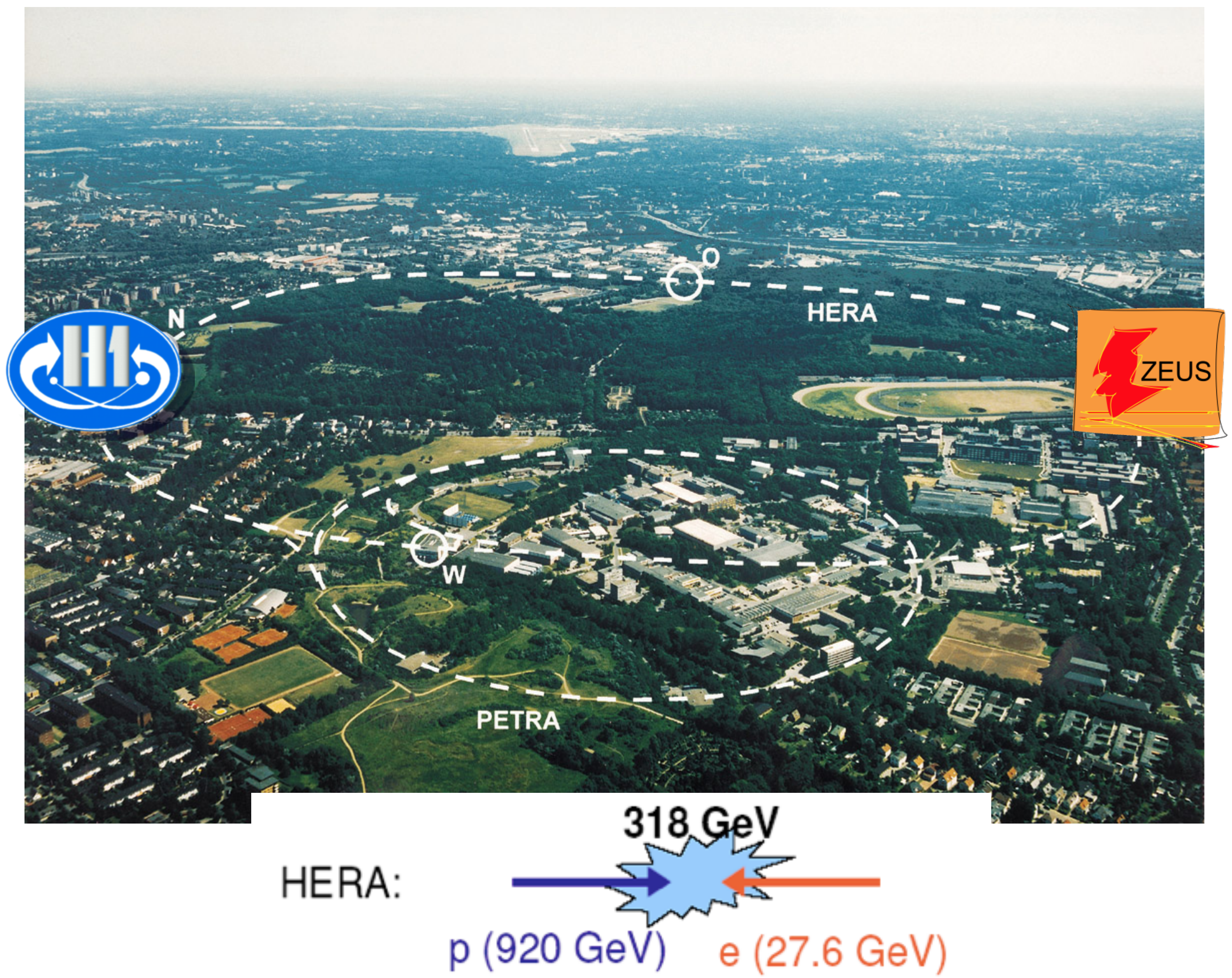
on behalf of the H1 and ZEUS collaborations

25th Rencontres de Blois, Particle Physics and Cosmology, May 26-31, 2013

pdfs & charm data

extraction of charm mass

impact on Z, W cross sections at LHC

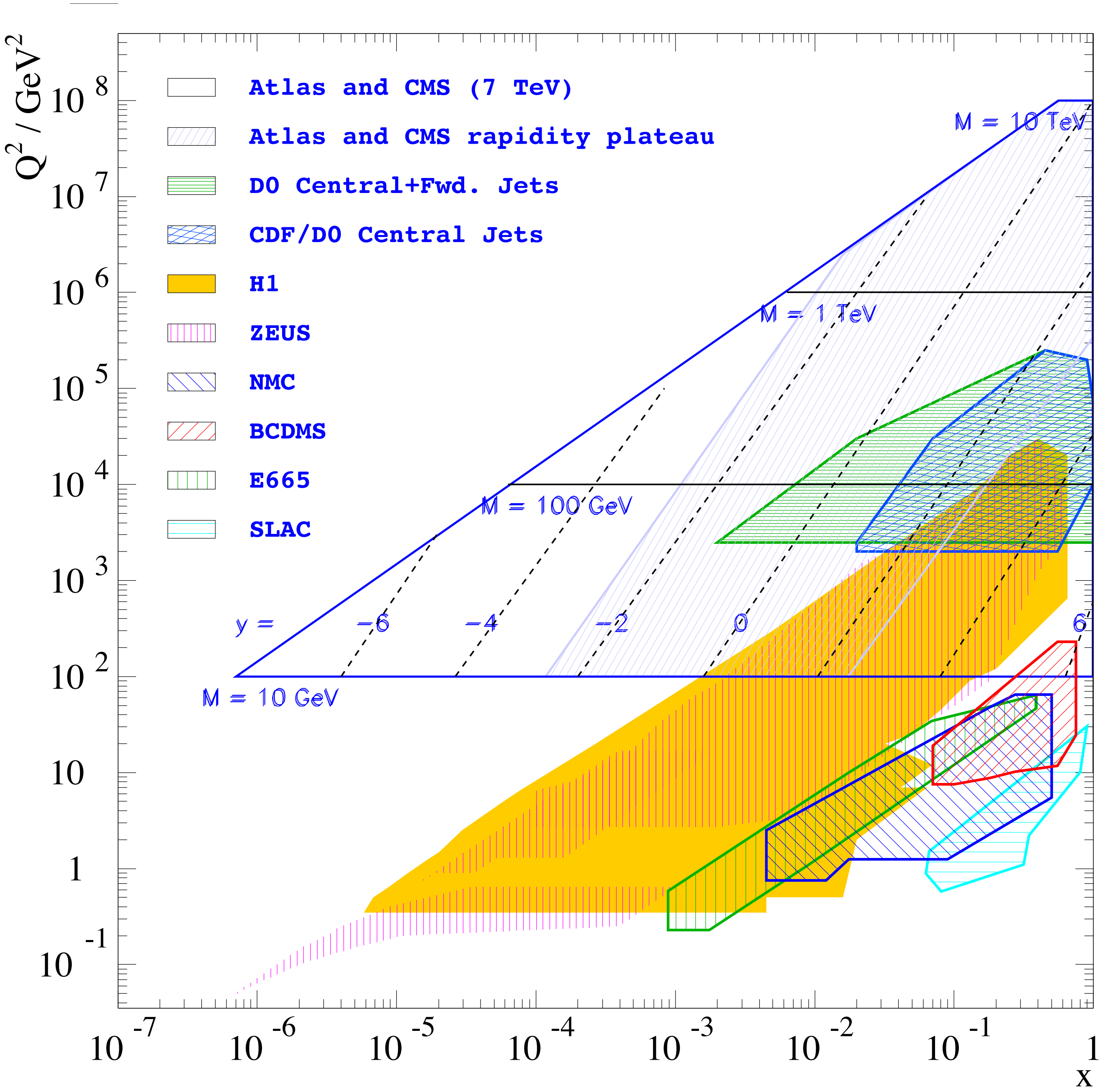


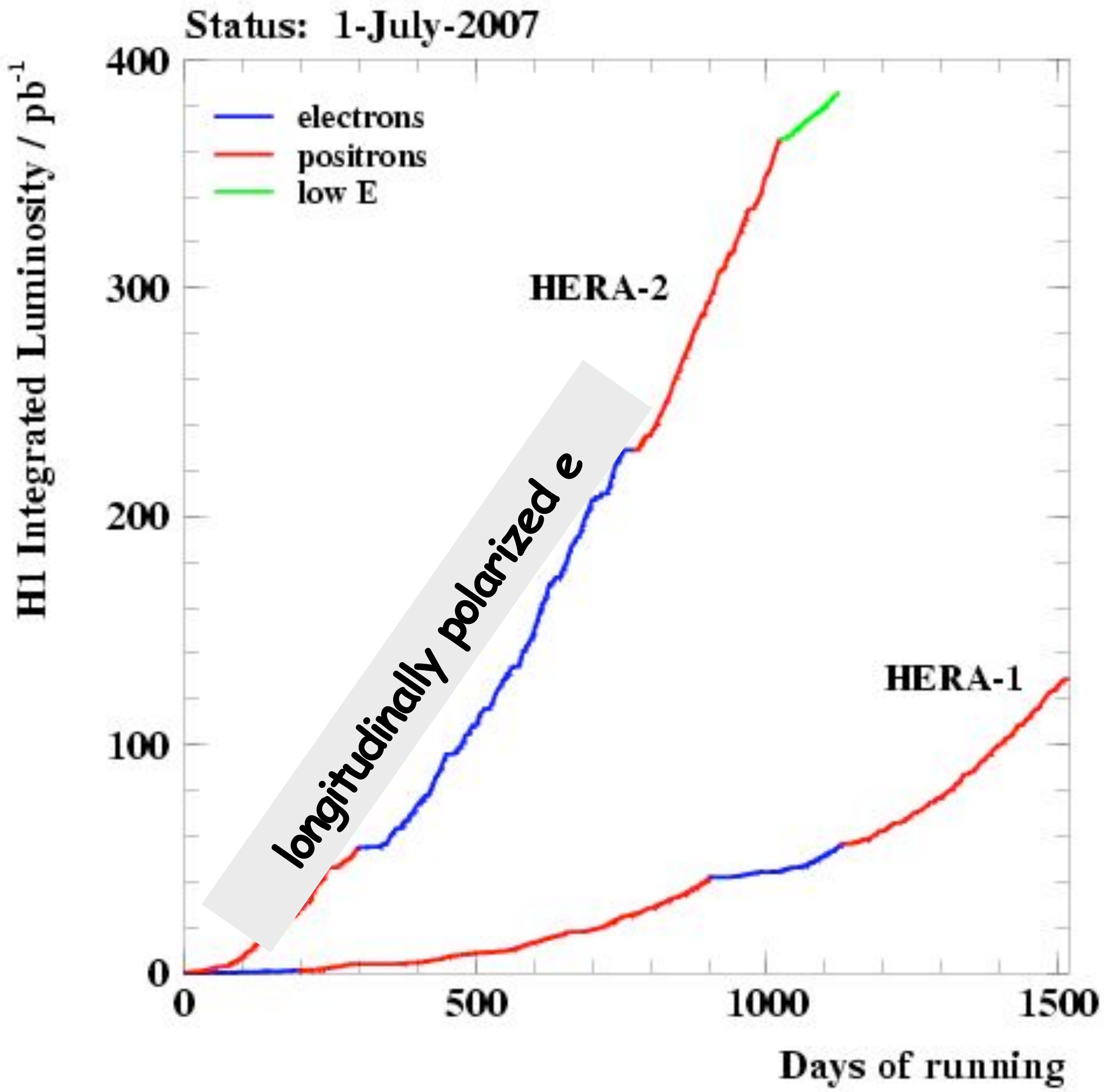
pdfs & jet data

extraction of $\alpha_s(M_Z)$ & g PDF

multijets in DIS and incl. jets in PHP & $\alpha_s(M_Z)$

Kinematic Plane & Luminosity

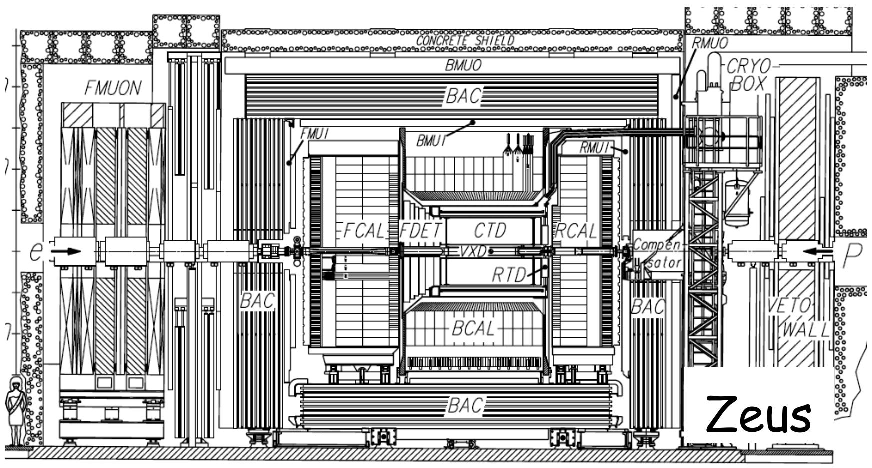




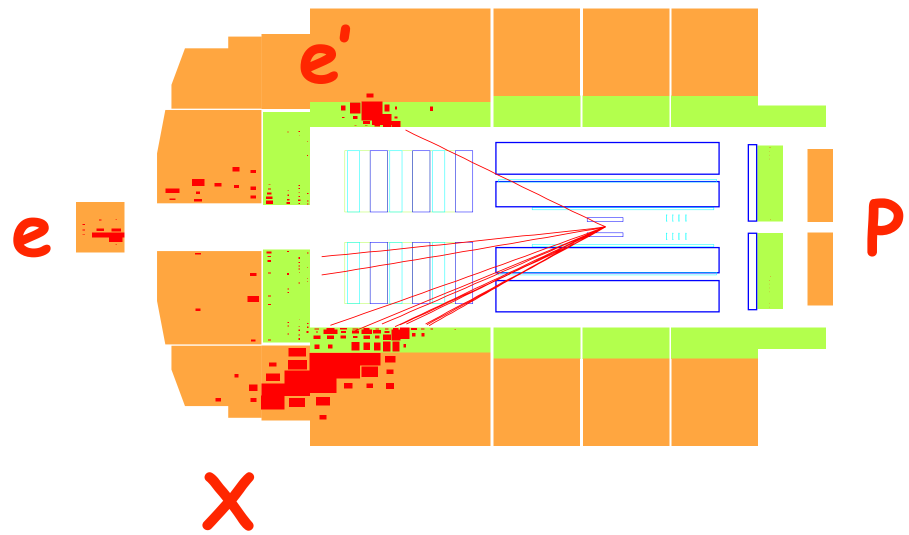
HERA overlaps with fixed target, Tevatron and LHC & provides indispensable input to PDF fits

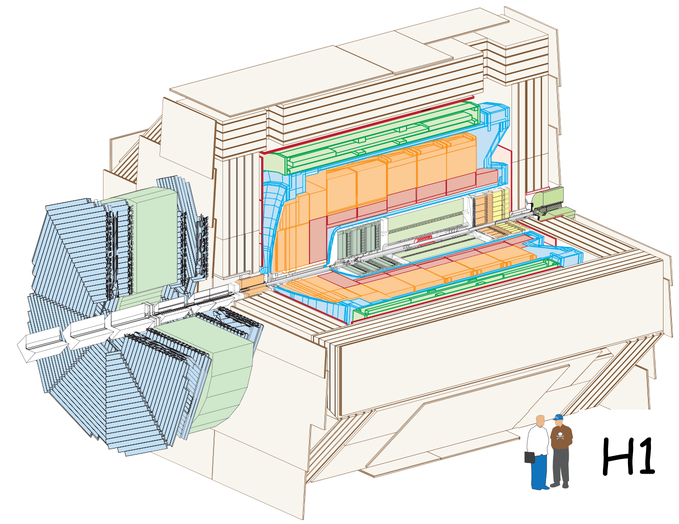
~ 0.5 fb^{-1} per experiment

Inclusive DIS kinematics

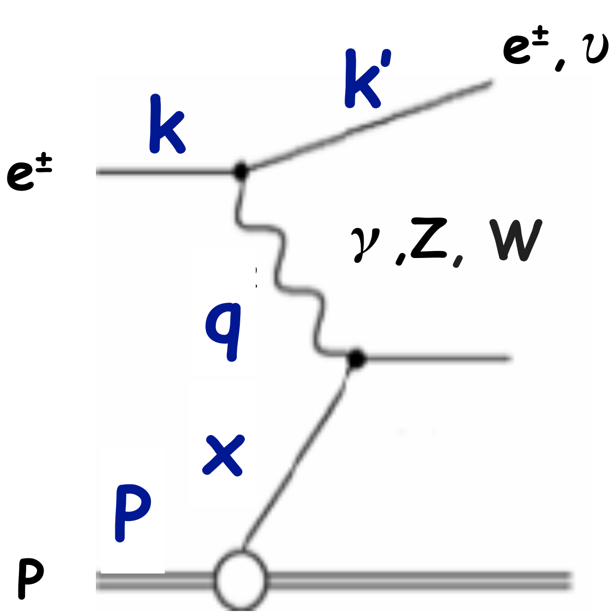


$e\,p \rightarrow e\,(\nu)\,X$





Measurement



virtuality	$Q^2 = -(k-k')^2$	$Q^2_e = \frac{E'^2_e \sin^2\theta'_e}{1-y_e}$
inelasticity	$y = (P\cdot q)/(P\cdot k)$	$y_e = 1 - \frac{E'_e}{2E_e}(1-\cos\theta'_e)$
Bjorken x	$x_{Bj} = Q^2/(2P\cdot q)$	$x_e = \frac{Q^2_e}{4E_pE_ey_e}$

$$Q^2 = xys \qquad s = (k+P)^2$$

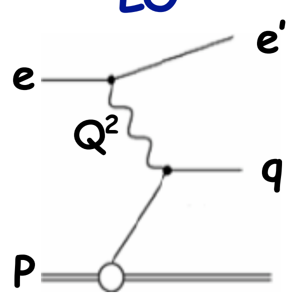
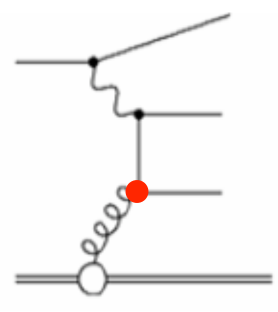
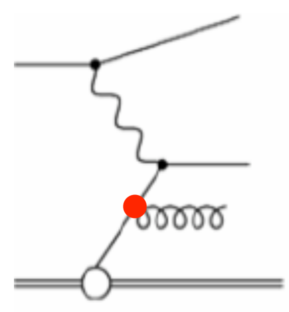
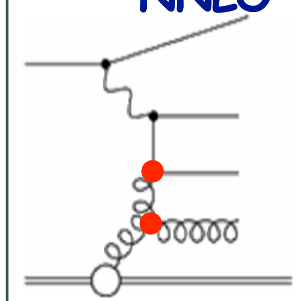
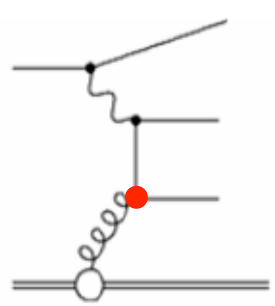
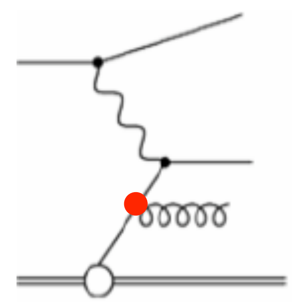
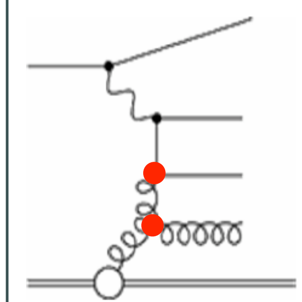
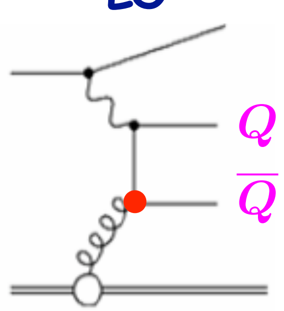
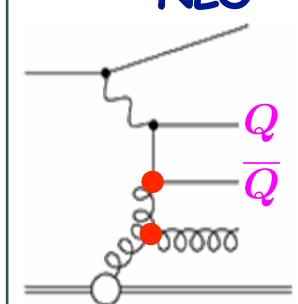
Extraction of parton dist. functions

Factorization: $\sigma \,:\, pdf(x,\mu_f) \otimes \hat{\sigma}$

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

$\hat{\sigma}$ - can be calculated in pQCD

pdf - universal pdfs determined from data and QCD (DGLAP) evolution eq.

incl. DIS	LO 	NLO  	NNLO  …
jets		LO  	NLO  …
c,b		LO 	NLO  …

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

$xF_3 \sim \sum(xq_i - x\bar{q}_i)$ at high Q^2

$F_L \sim \alpha_s g$ at low Q^2, high y

CC data sensitive to u and d

jets depend already in LO on:

$-\ \alpha_s g$ and α_s

will reduce corr. between them

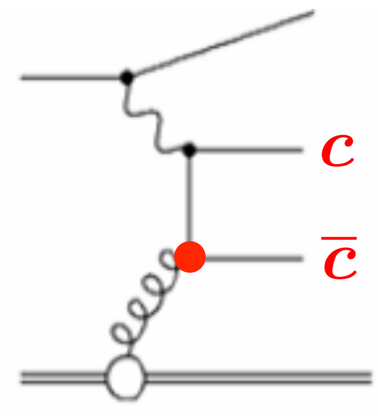
charm prod. also depends on:

$-\ \alpha_s g$

- but more on the heavy quark mass and scheme

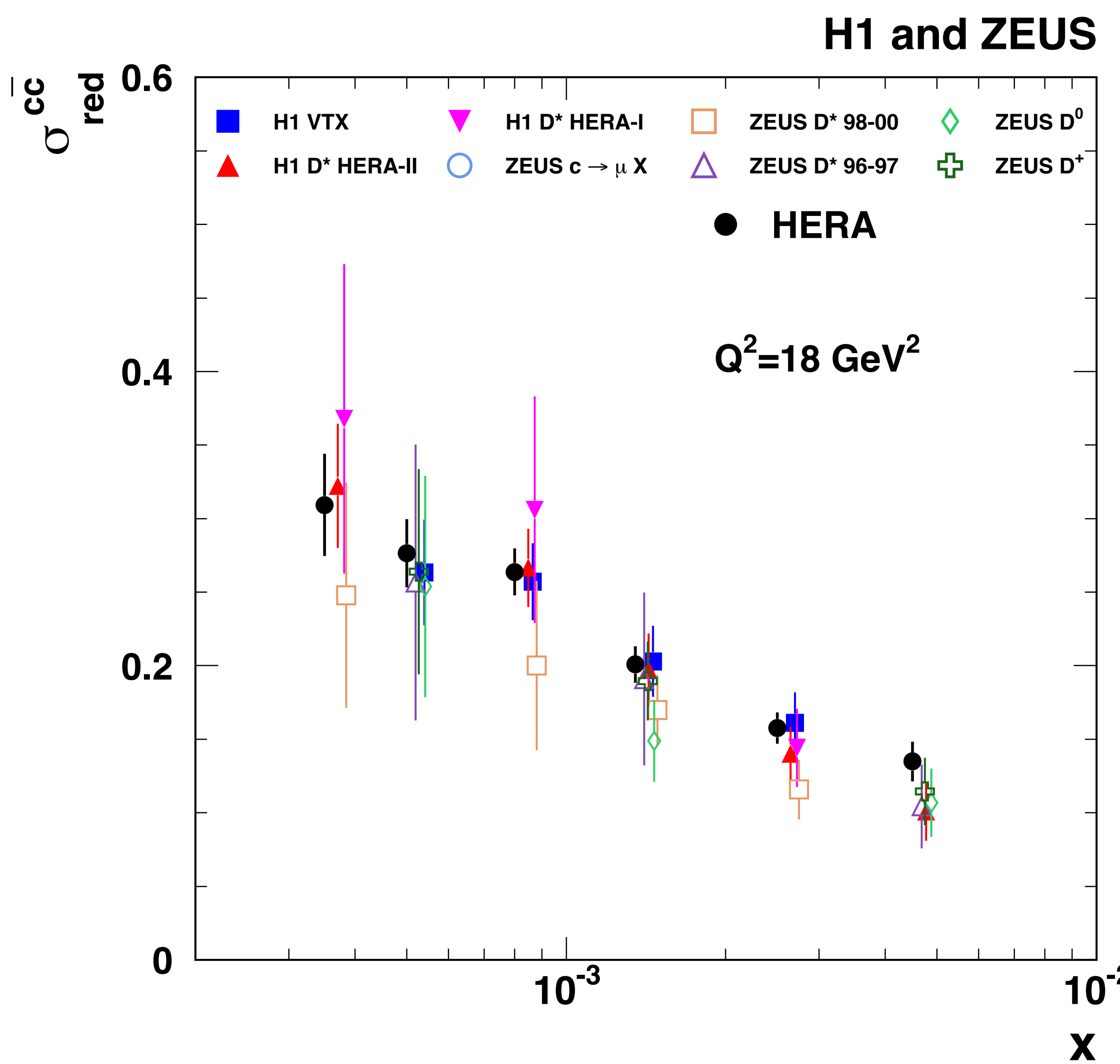
HERAPDF 1.0 and 1.5 (NLO & NNLO) have been extracted using precise (1-2%) combined inclusive DIS data from HERA

Charm data and their combination



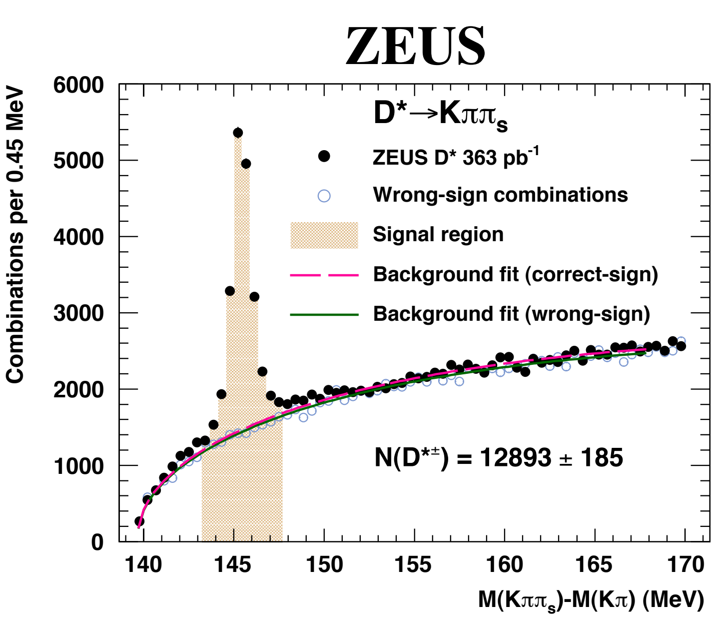
up to 30% of inclusive DIS is due to charm

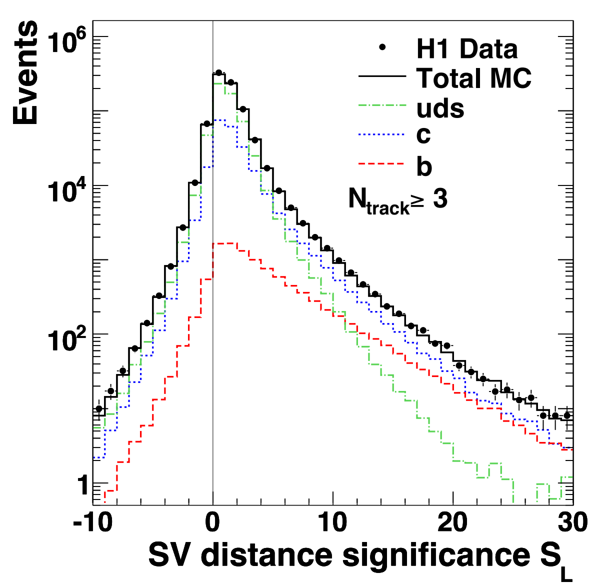
these different measurements from H1 & ZEUS are then extrapolated and combined



measurements use different charm tagging methods:

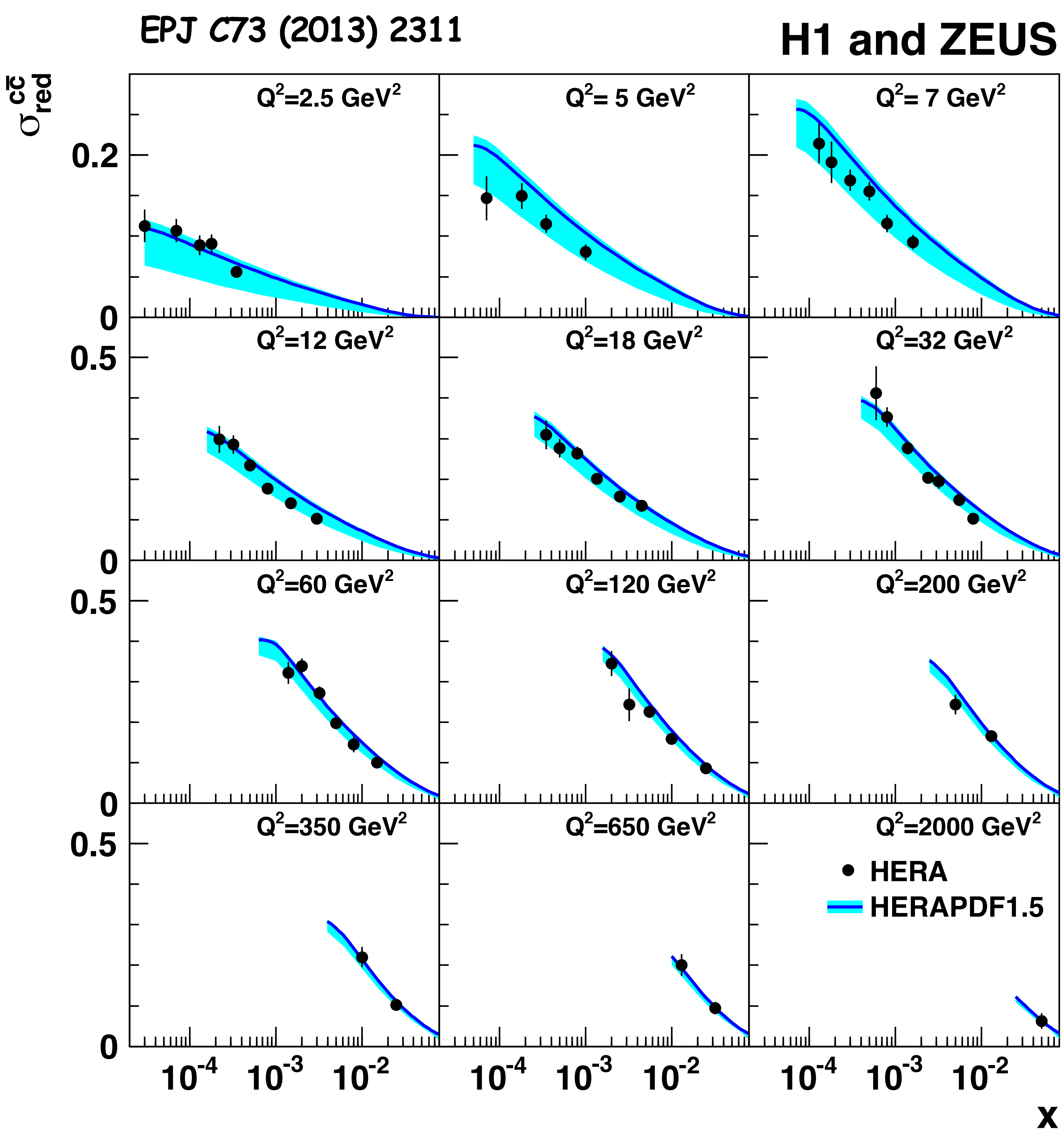
- reconstructed D* and D decays
- muons from semi-leptonic decays
- inclusive event with life-time info





precision improved by about a factor of 2 compared to best single measurement

Comparison to HERAPDF1.5 NLO



theory predictions using Roberts-Thorne GMVFNS with m_c = 1.4 GeV

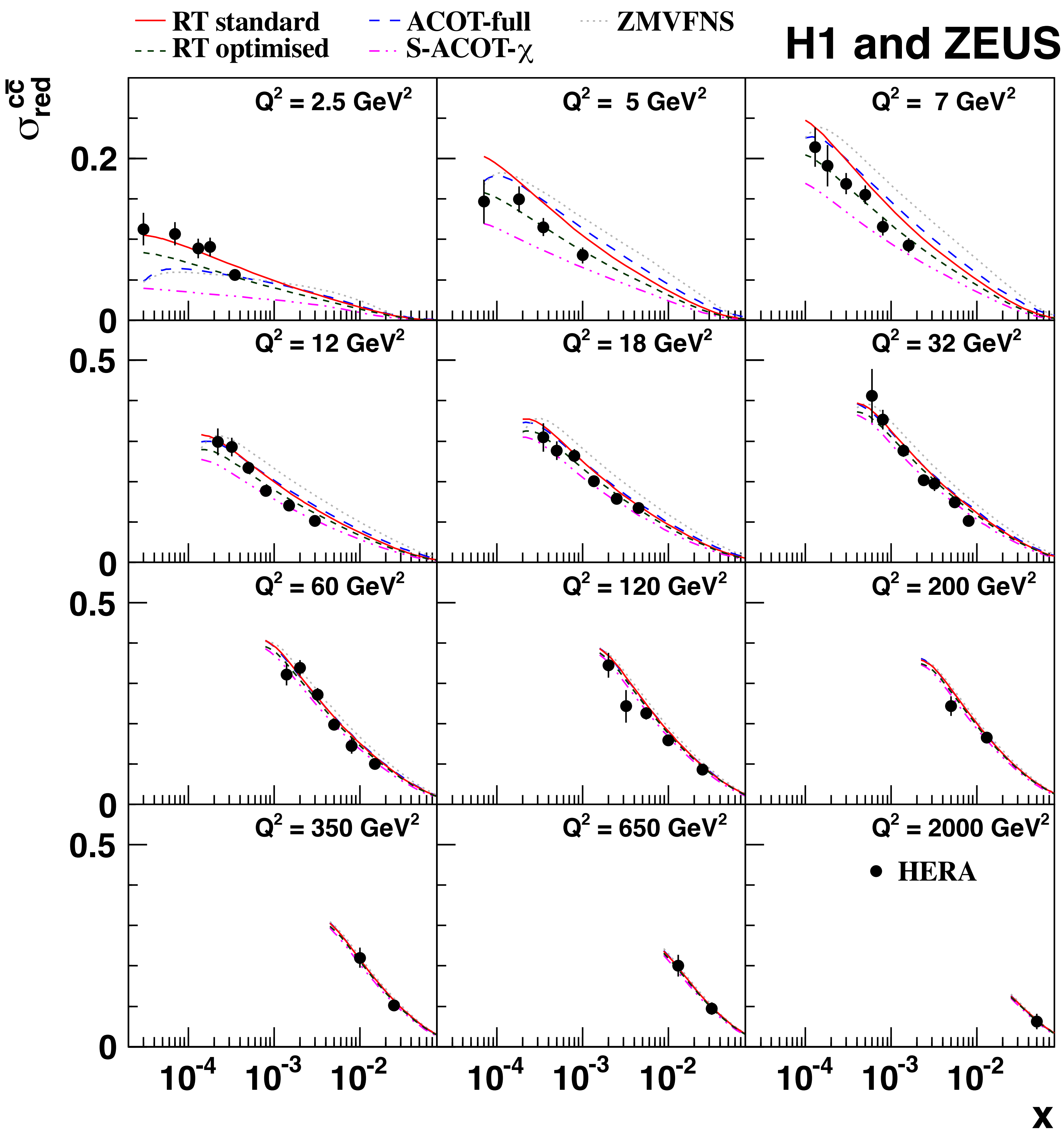
wide error band due to 1.35 < m_c < 1.65 GeV

GMVFNS - general mass variable flavor number scheme:

- very high Q^2: 5 active flavors, m_c=0, resummation of $\log(Q^2/m^2)$, ...
- very low Q^2: 3 active flavors, massive charm
- in between (most of the scale): different matching conditions, approximations, correction terms

HERAPDF1.5, extracted from inclusive DIS, provides good description of charm data

Different GMVFNS and ZMVFNS



PDF fits to HERA-1 inclusive data (HERAPDF1.0) and to combined charm data, with m_C = 1.4 GeV fixed, using different GMVFNS variants.

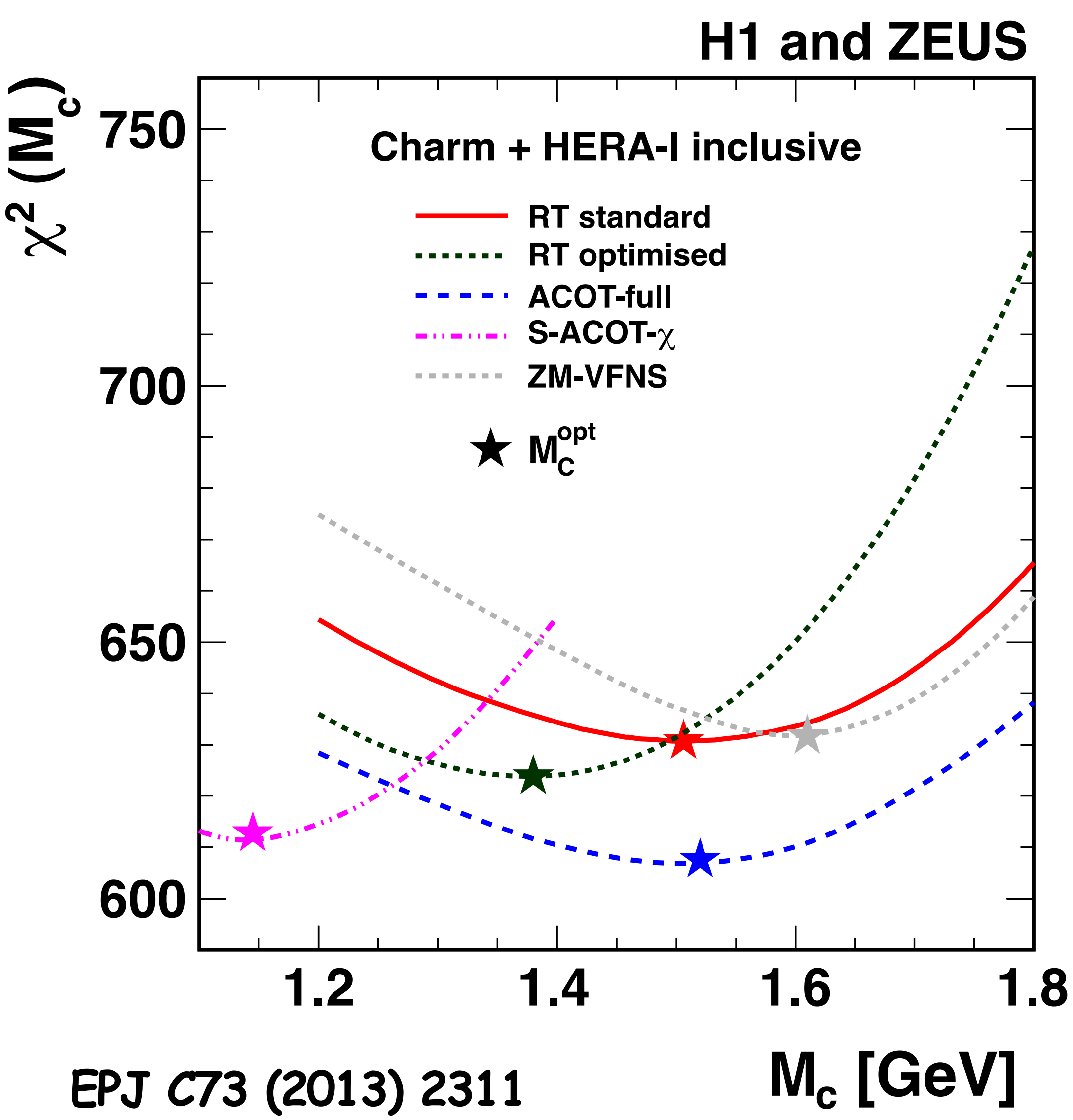
(m_C should be the pole mass)

at lower Q^2 the calculations differ significantly - due to differences in terms neglected and in matching low/high Q^2

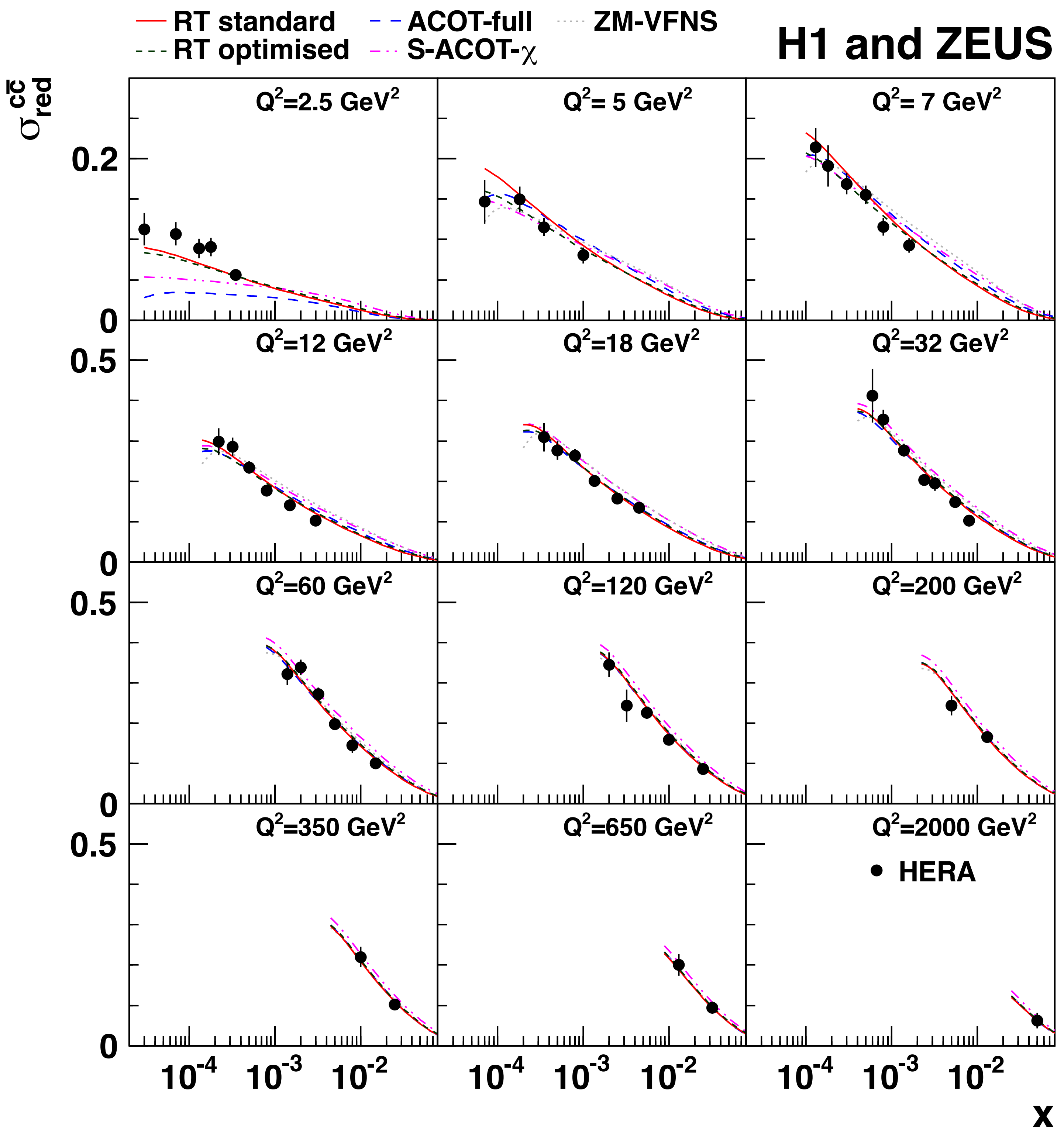
➥ consider charm mass as mass parameter M_C to be determined from data

Fit charm mass parameter M_c^{opt}

perform scans of M_C to the same data (as on previous slide) using different VFNS implementations



EPJ C73 (2013) 2311

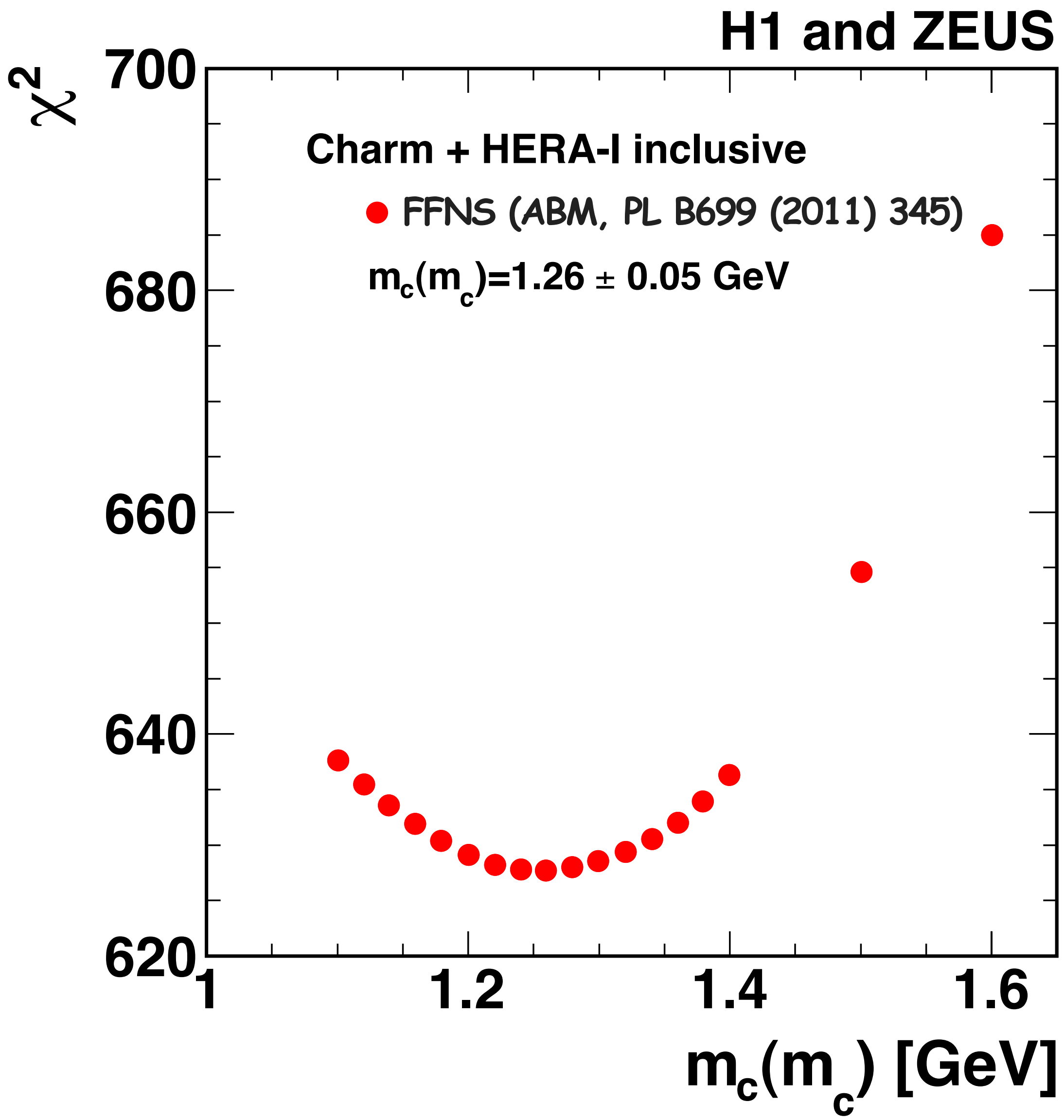


charm data well described for $Q^2 \geq 5$ GeV^2 with $M_c = M_c^{opt}$

Running $\overline{MS}$ charm mass in FFNS

FFNS:

- no charm in the proton, just 3 active flavors
- full kinematical treatment with massive charm
- calculation uses running $\overline{MS}$ mass, which is well defined



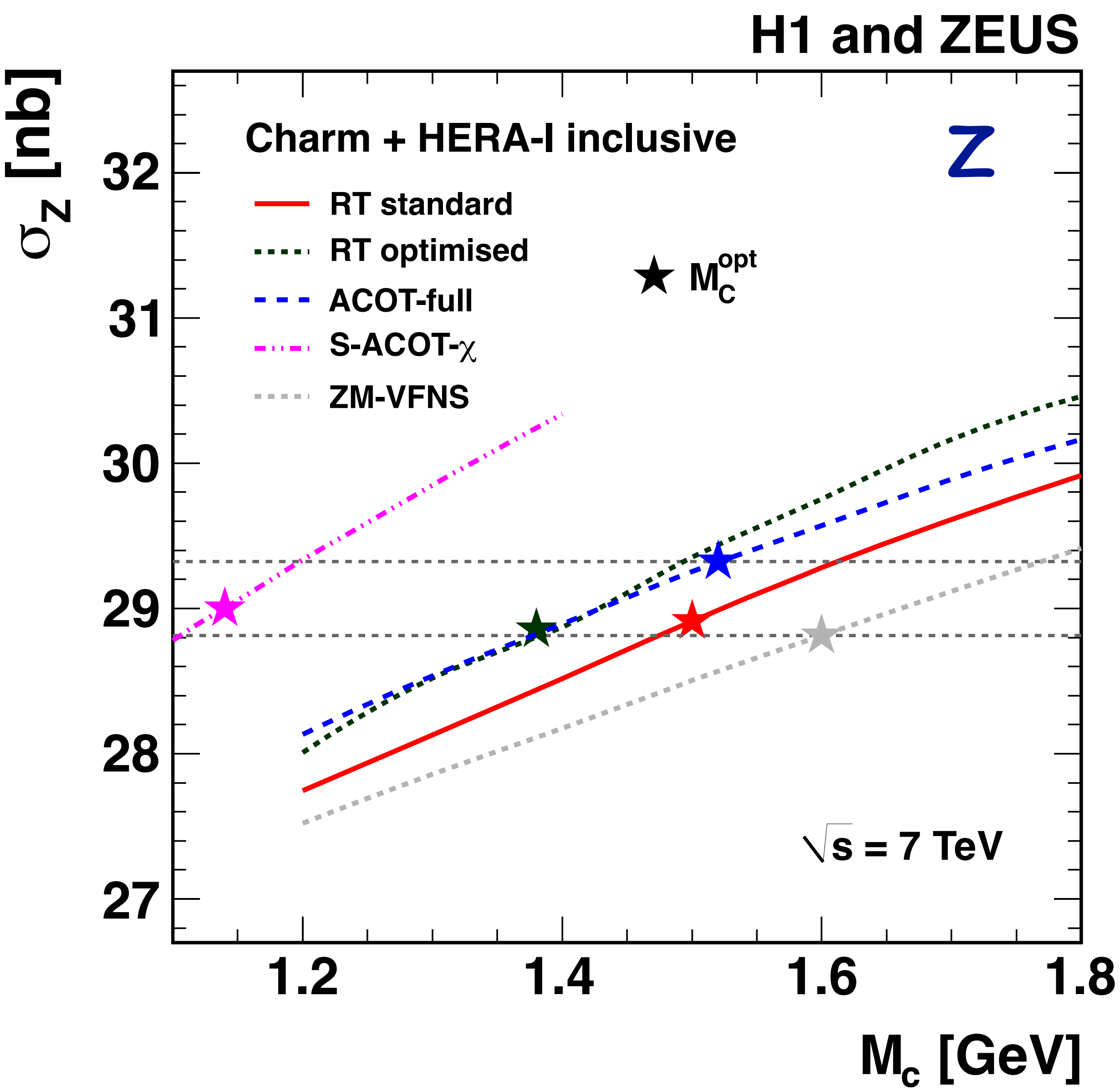
perform scan of $m_c(m_c)$ of the QCD fit to HERA-1 inclusive and combined charm data

model: vary f_s, m_b, Q^2_{min}

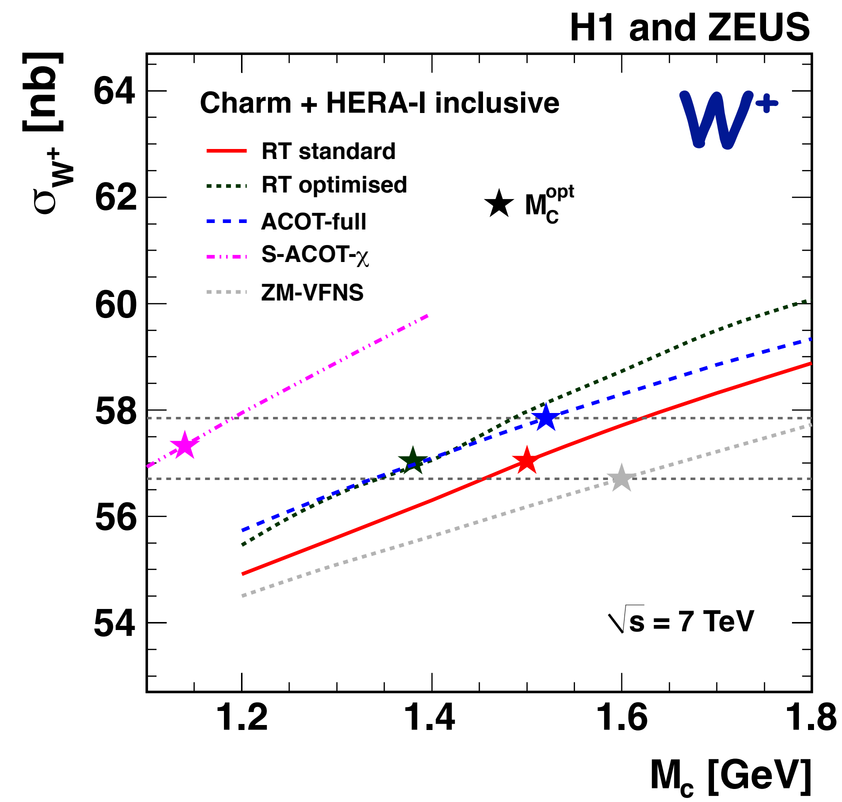
$$m_c(m_c) = 1.26 \pm 0.05\,(\mathrm{exp}) \pm 0.03\,(\mathrm{model/param}) \pm 0.02\,(\alpha_s) \quad \text{GeV}$$

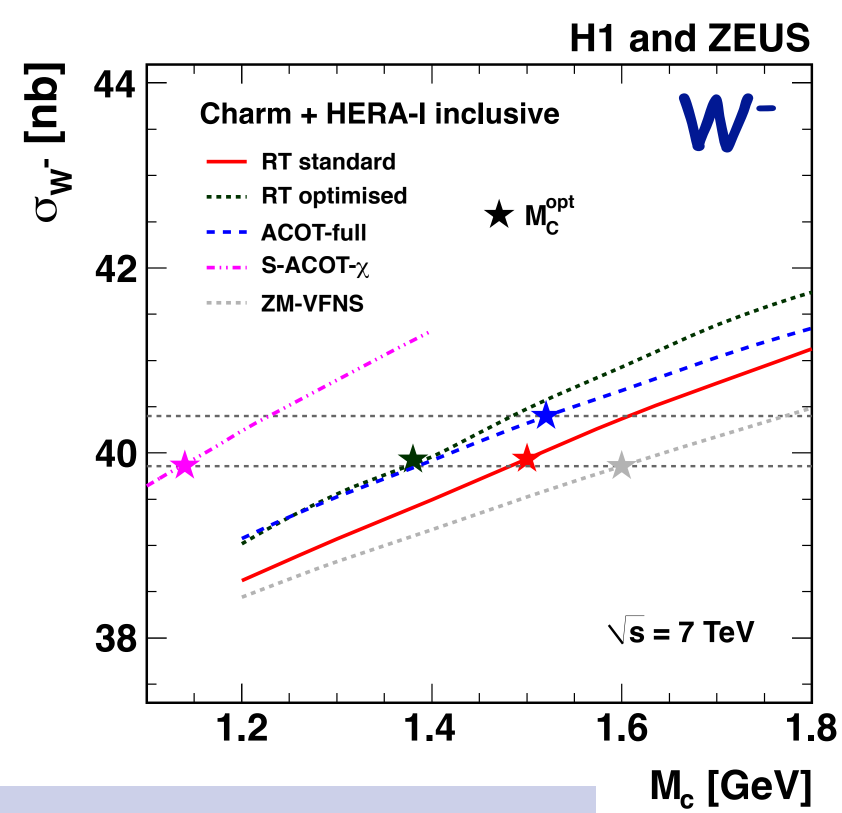
$$\mathrm{PDG:} \quad 1.275 \pm 0.025\,\mathrm{GeV} \quad (\mathrm{lattice\ QCD\ and\ time-like\ processes})$$

Impact on Z, W± predictions for LHC



MCFM
7 TeV

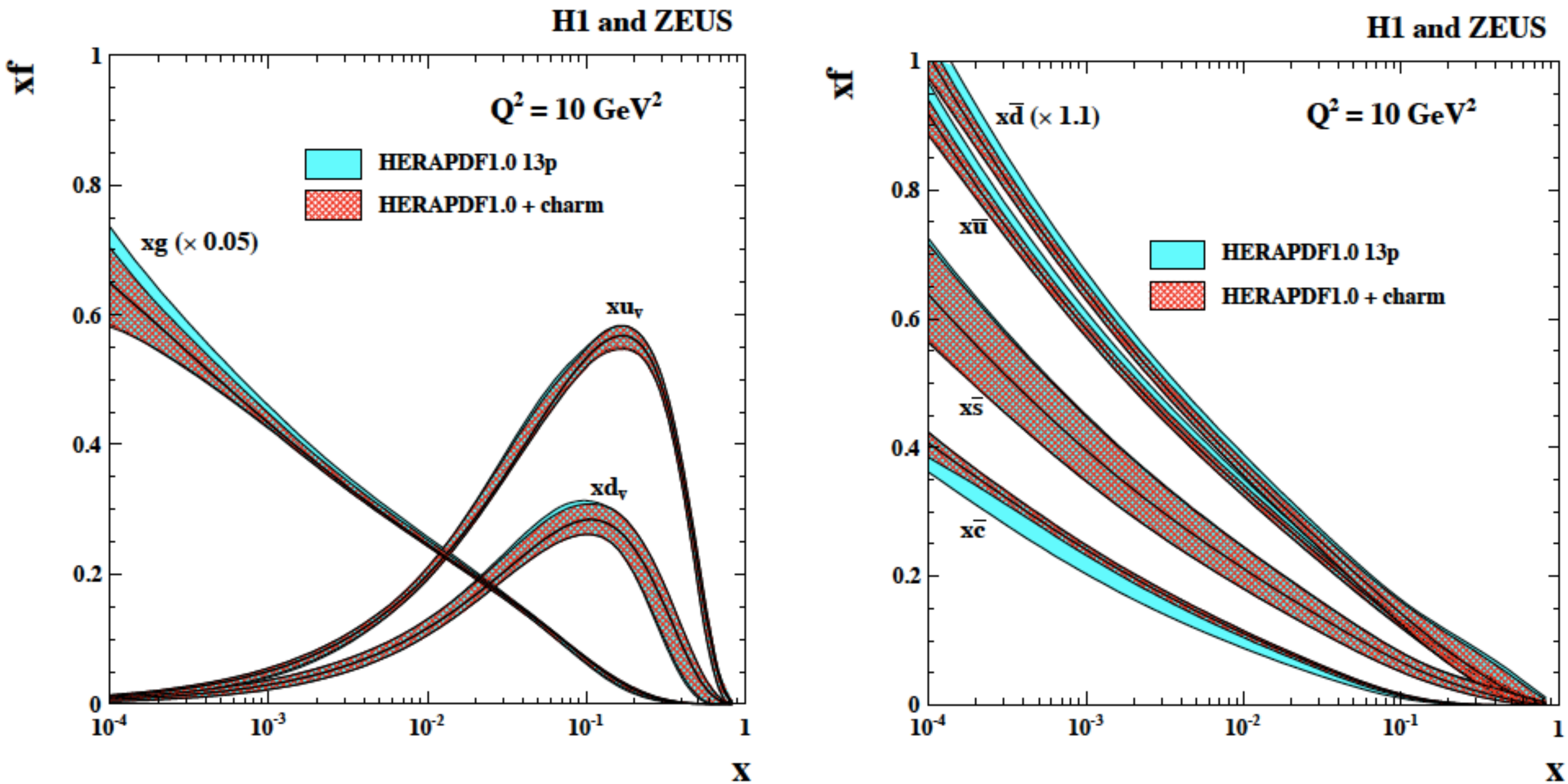




Different implementations of GMVFNS with M_C=1.4 GeV give a spread in predictions of 6%

$M_C = M_C^{opt}$ reduces uncertainty due to the charm mass to < 2%

Impact of charm data on PDFs



significant reduction in uncertainty of charm density

$$\text{more } \bar{c}\ (g \to c\bar{c}) \longrightarrow \text{ less } g,\ \text{less } \bar{u}, \bar{d}$$

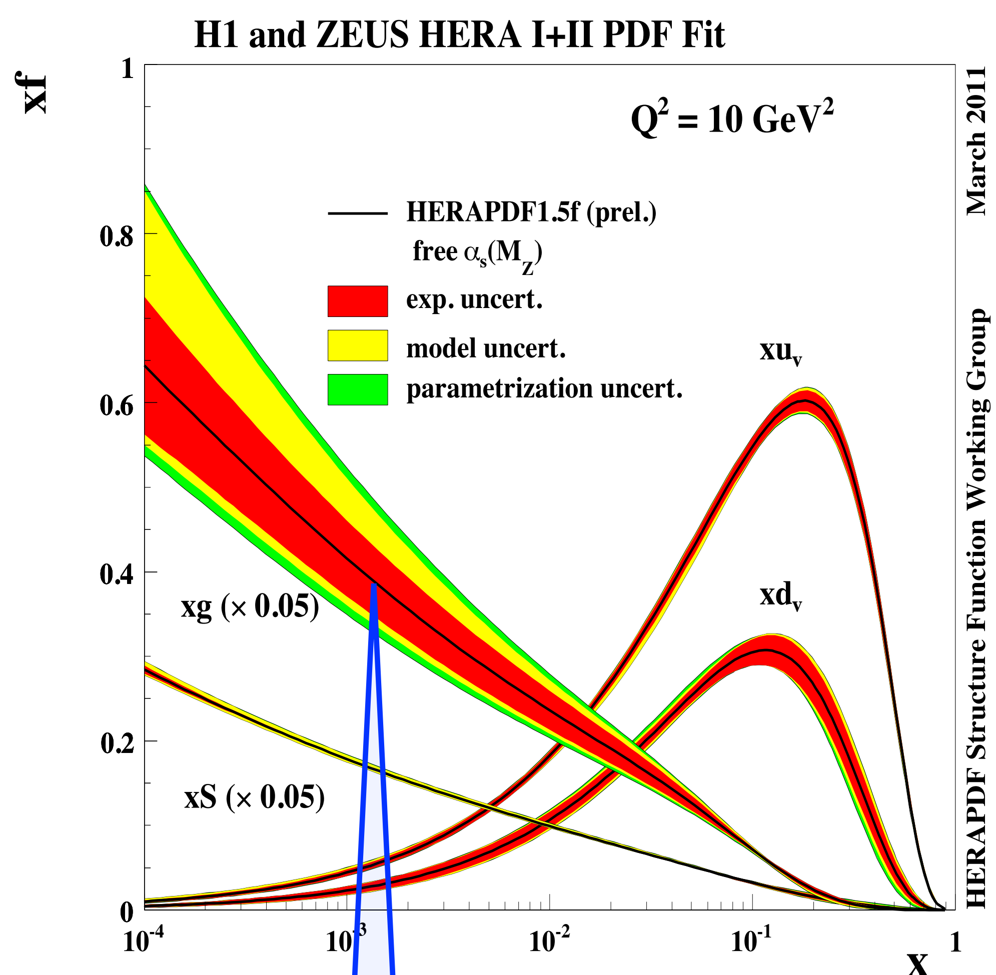
Inclusive jets in DIS in PDF fits

Inclusive jets from H1 and ZEUS in bins of Q^2 and P_T are added in the PDF fit

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

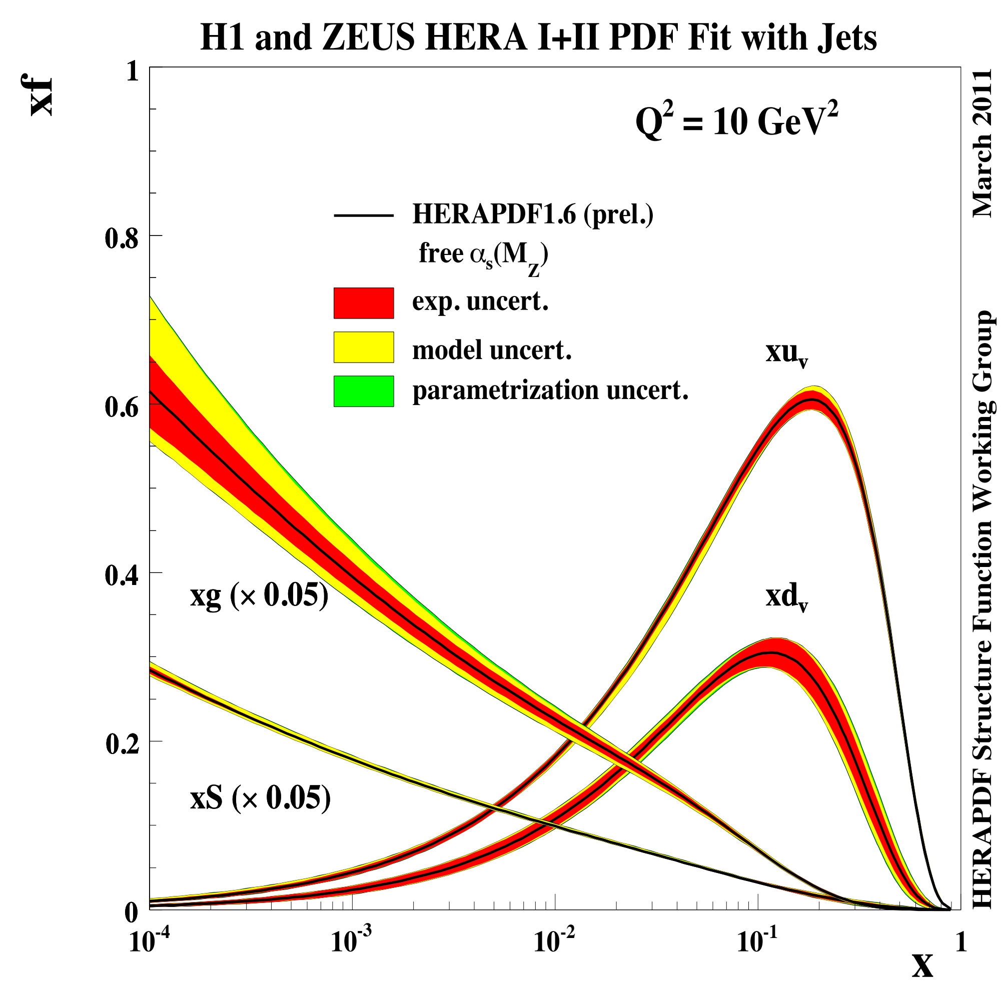
reminder: jets are sensitive in LO to $\alpha_s \otimes g$ (BGF) and α_s (QCDC)

no jets, $\alpha_s(M_Z)$ free



the gluon uncertainty at low-x blows up

+ jets, $\alpha_s(M_Z)$ free

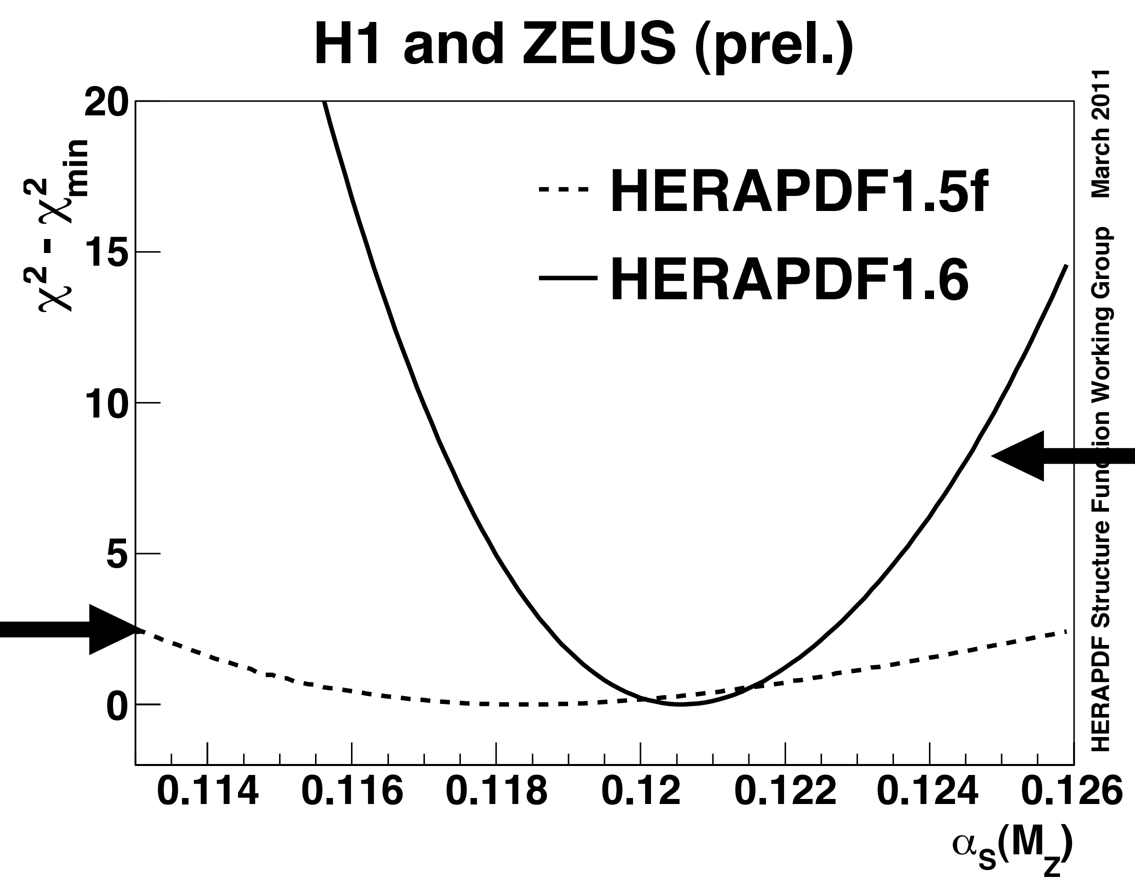


adding jet data dramatically decreases the low-x gluon uncertainty, not only the experimental but also the model and parameterization uncertainties

$\alpha_s(M_Z)$ from incl. DIS & jets in DIS

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

inclusive DIS data only



inclusive DIS + jets data

desparately seeking NNLO

➡ adding jet data successfully reduces the correlation between α_s and the gluon

$$\alpha_s(M_Z) = 0.1202 \pm 0.0019(\mathrm{exp/model/param/hadronization})\ ^{+0.0045}_{-0.0036}(\mathrm{scale})$$

1.6% uncertainty + 3-3.7% scale unc.

scale uncertainty from variation of renormalization & factorization scale by a factor of $\frac{1}{2}$ and 2

stay tuned for HERAPDF2.0: will include all final inclusive data, charm and jets

$\alpha_s(M_Z)$ from norm. multijet cross sect.

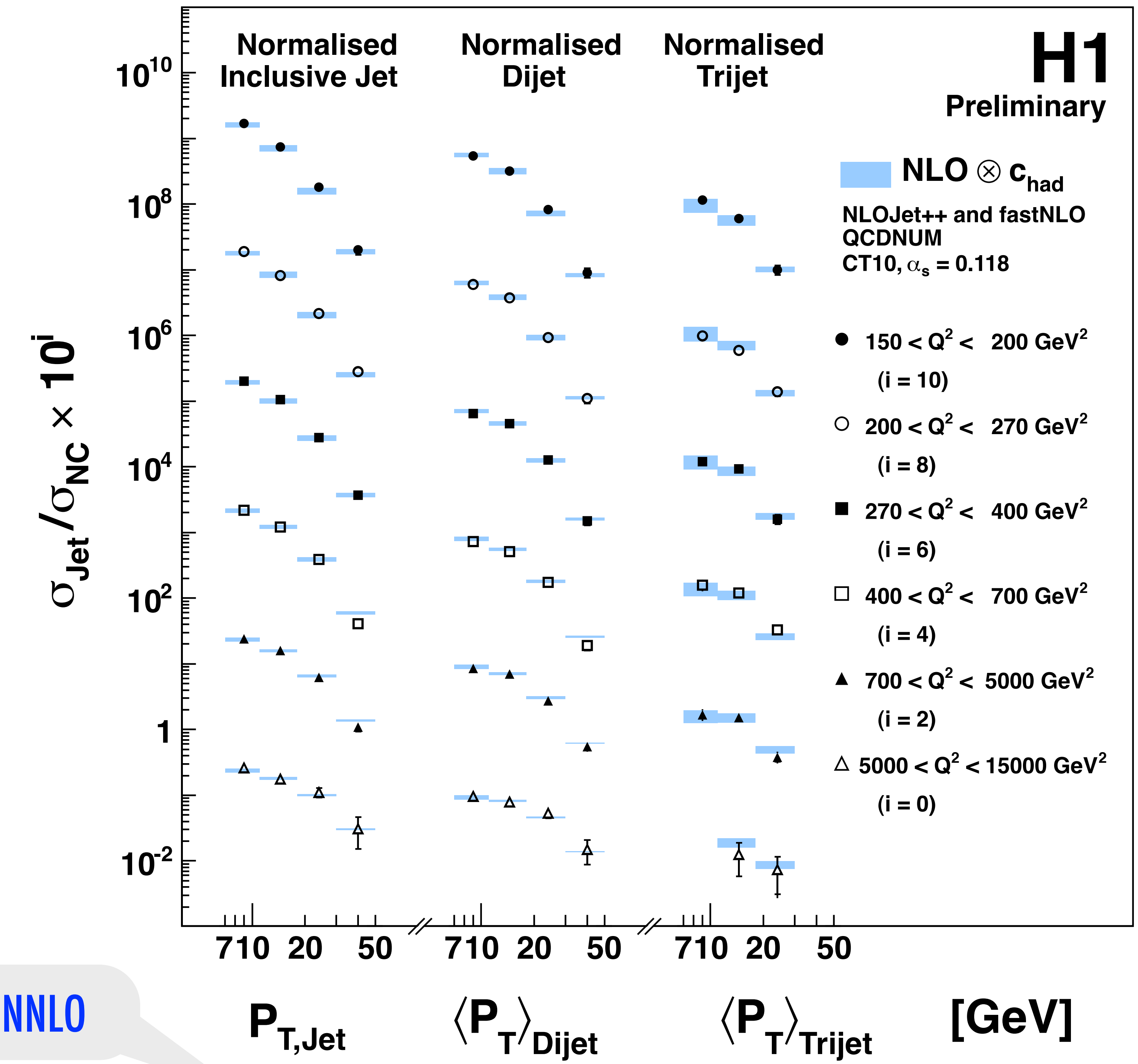
Multijet production in DIS using regularized unfolding (H1prelim-12-031)

jet energy scale uncertainty 1%,
effect on cross sections 3-10%

NLO predictions:
NLOJet++, fastNLO, QCDNUM
CT10 PDF, $\alpha_s(M_Z)$=0.118

$\mu_f^2 = Q^2$
$\mu_r^2 = (Q^2+P_T^2)/2$

Extract $\alpha_s(M_Z)$ by fitting each jet cross sections singly and also all 3 simultaneously, with covariance matrix from unfolding and syst. errors treated as penalty terms

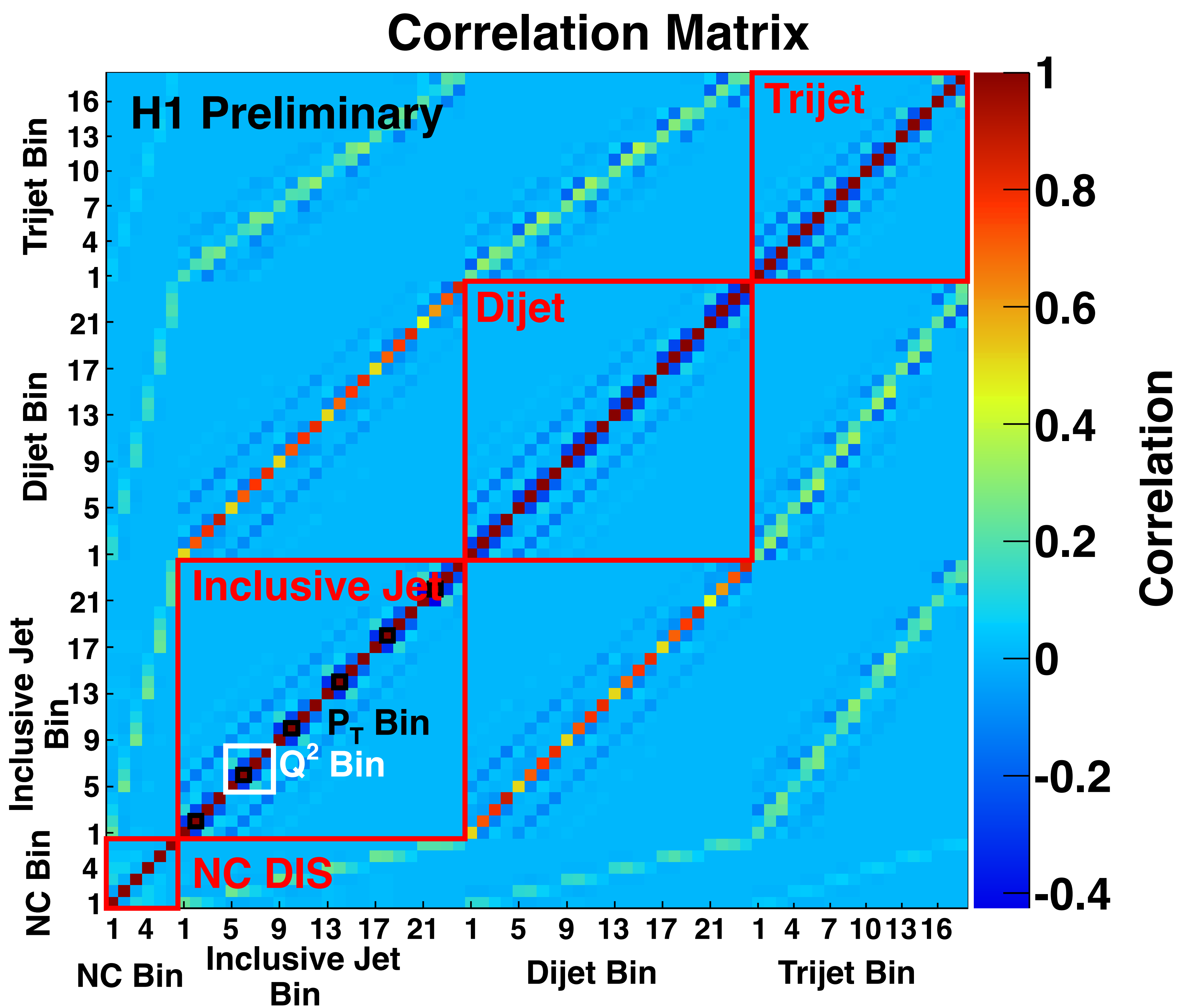


desparately seeking NNLO

$$\alpha_s(M_Z) = 0.1163 \pm 0.0011\,(\text{exp}) \pm 0.0040\,(\text{theo}) \pm 0.0014(\text{pdf})$$

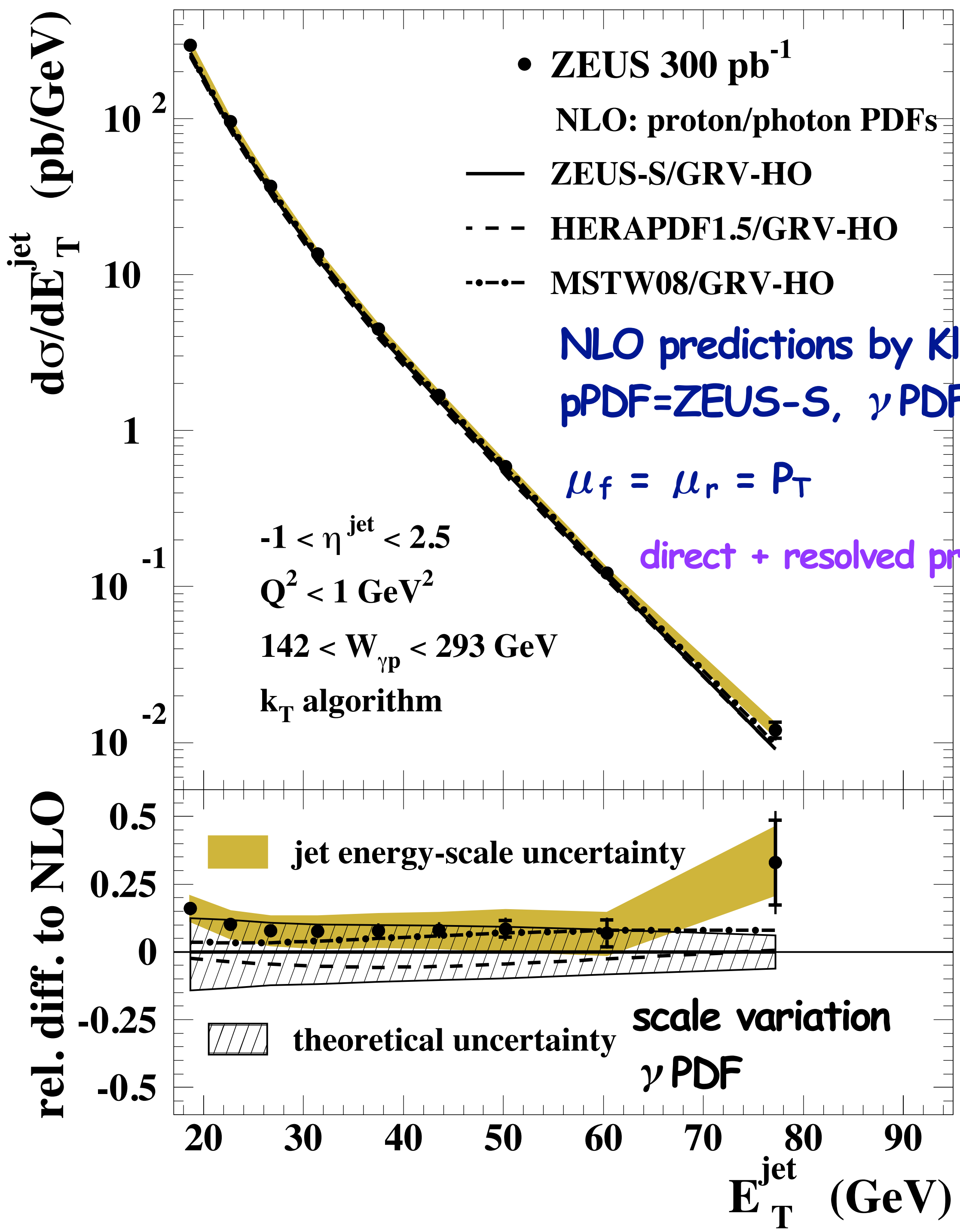
uncertainty: 1% exp and 3.6% from theory and pdf

NC DIS + Multijet correlation matrix



$\alpha_s(M_Z)$ from inclusive jets in PHP

NPB 864 (2012) 1

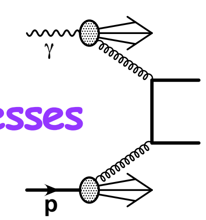


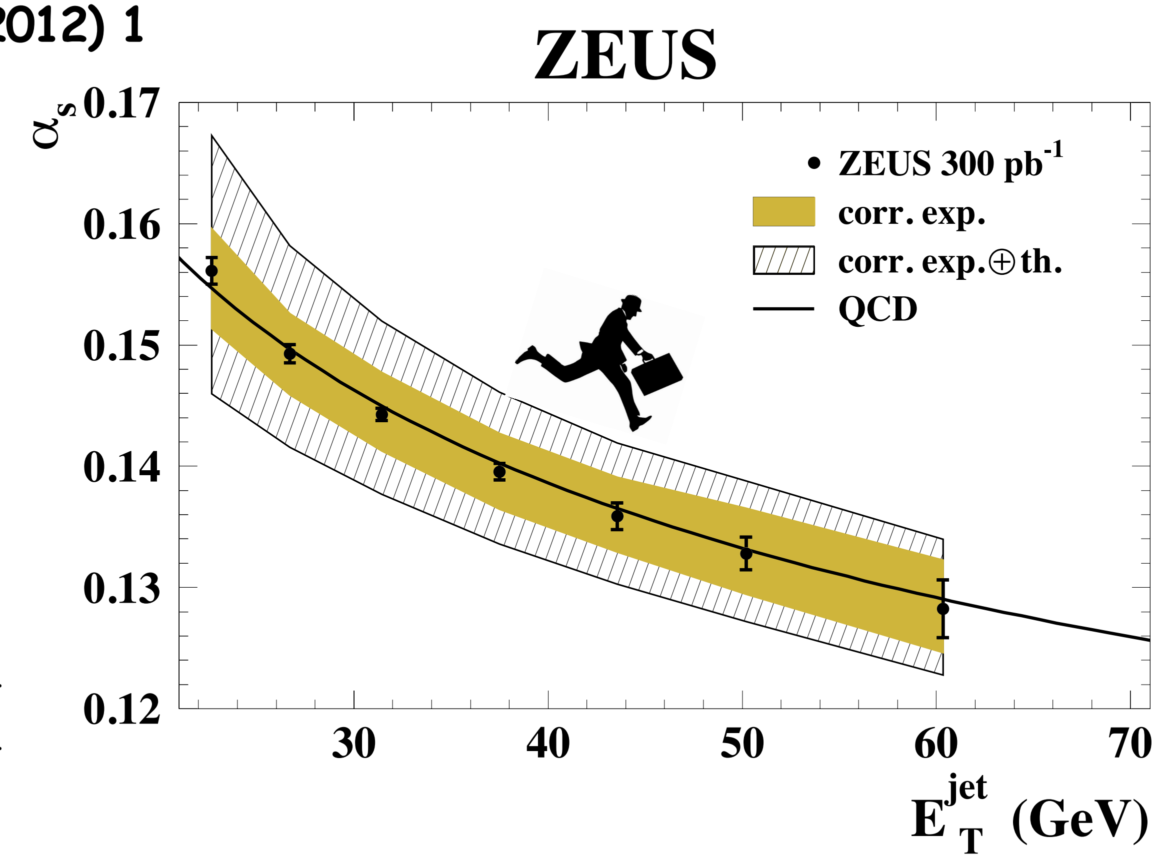
NLO predictions by Klasen et al.
pPDF=ZEUS-S, γPDF=GRV-HO

$\mu_f = \mu_r = P_T$

direct + resolved processes

scale variation
γPDF





running of α_s in a single experiment

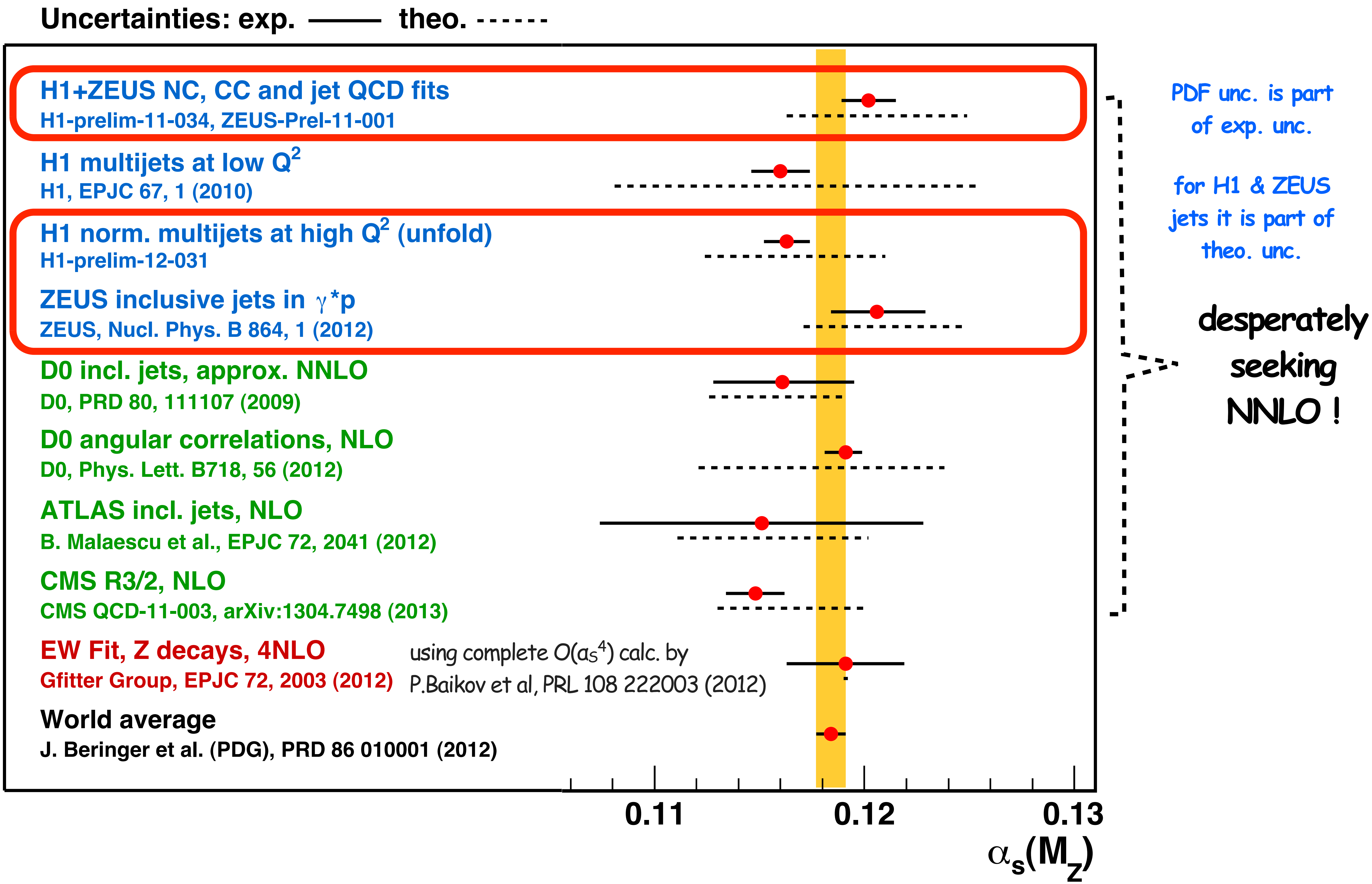
in good agreement with RGE (2-loops)

desparately seeking NNLO

$$\alpha_s(M_Z) = 0.1206\ ^{+0.0023}_{-0.0022}\,(\text{exp})\ ^{+0.0042}_{-0.0035}(\text{theo})$$

uncertainty: 1.9% exp and 3.6% from theory (includes pdf)

Comparison of recent $\alpha_s(M_Z)$-values



Summary

- combination of charm data yields significantly improved precision
- good description of charm data by different VFNS variants, after fitting "optimal" charm mass for each variant.
- running $\overline{MS}$ charm mass: $m_c(m_c) = 1.26 \pm 0.05\,(\mathrm{exp}) \pm 0.03\,(\mathrm{mod/par}) \pm 0.02\,(\alpha_s)$ GeV
- including charm data in PDF fit significantly reduces the uncertainty on charm from the sea.
- including jet data in PDF fit allows to determine $\alpha_S(M_Z)$ & gluon pdf.
- $\alpha_S(M_Z)$-values from jets at HERA reach exp. precision of 1%, as good as or better than other measurements, but with 3-4% uncertainty from NLO theory.
- desperately seeking NNLO !

Extras

HERAPDFs

- idea: use only HERA data (combined H1 & ZEUS) in the PDF fits
  - precise data set with total uncertainties between 1-2% over most of the phase space
  - systematic correlated and uncorr. uncertainties well controlled, allowing for $\Delta\chi^2 = 1$ uncertainty criterion
  - $e^{\pm}p$ data only, i.e. no need for deuterium corrections and heavy target corrections
  - for central fit use parameterizations with minimum number of parameters
  - param. uncertainty ⇒ vary number of parameters (and parametrization) and Q_0^2, the starting scale of the parameterizations (default = 1.9 GeV^2)
  - model uncertainty ⇒ vary m_c, m_b, f_s, Q^2_{min} (defaults: 1.4 GeV, 4.75 GeV, 0.31, 3.5 GeV^2)

HERAPDF parametrizations I

- x·uv, x·dv, x·Ubar, x·Dbar and x·g are parametrized according to:

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

- starting scale Q_0^2 = 1.9 GeV^2 (below m_c), NLO DGLAP evolution (RT-VFNS)
- constraints:
  - momentum sum rules, quark sum rules
  - x·sbar = f_s x·Dbar strange sea is a fixed fraction f_s of Dbar at Q_0^2
  - B_{Ubar} = B_{Dbar} and Buv = Bdv
  - Sea = 2x·(Ubar+Dbar)
  - Ubar = Dbar at x=0
- 10 free parameters are used up to HERAPDF1.5 fitting HERA-1 data:
  - B_g, C_g, B_{uv}, C_{uv}, C_{dv}, A_{Dbar}, B_{Dbar}, C_{Dbar}, C_{Ubar}, E_{uv}
- 14 free parameters are used for HERAPDF1.5f, HERAPDF1.6 fitting HERA-1 and HERA-2 data (more data require a more flexible parametrization):
  - \- $A'_g \cdot x^{B'g} \cdot (1-x)^{Cg}$ term for low-x gluon and $B_{uv} \neq B_{dv}$ to free low-x uv from dv

HERAPDF parametrizations II

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

extended gluon parametrization: $Ag \cdot x^{Bg} \cdot (1-x)^{Cg} \cdot (1+Dx+Ex^2) - A'g \cdot x^{B'g} \cdot (1-x)^{Cg}$

	A	B	C	D	E	ε
uv	Sum rule	free	free	free	free	var
dv	Sum rule	free	free	var	var	var
UBar	=(1-fs)ADbar	=BDbar	free	var	var	var
DBar	free	free	free	var	var	var
glue	Sum rule	free	free	var	var	var

A'g	B'g
free	free

HERAPDF1.5f & HERAPDF1.6:

- additional parameters: Bdv, Duv, A'g, B'g
- estimate of parametrization uncertainty: indicated parametrization variations, Q_0^2
- estimate of model uncertainties: m_c, m_b, f_s, Q^2_{min} are varied

HERA Combined results

HERA results

H1 home page

ZEUS home page

HERAPDF table https://www.desy.de/h1zeus/combined_results/herapdftable/

NAME	NC and CC DIS	NC, lower E(p_beam)	Jets	Charm	Docu	Grids	Data comparison	Date
HERAPDF1.7 NLO	HERAI + partial HERAII	H1+ZEUS	H1 and ZEUS(1)	H1+ZEUS	Figures	N.A.		June 2011
HERAPDF1.6 NLO	HERAI + partial HERAII	---	H1 and ZEUS(1)	---	Writeup and figures	N.A.		March 2011
HERAPDF1.5 NNLO	HERAI + partial HERAII	---	---	---	Figures	LHAPDF beta 5.8.6		March 2011
HERAPDF1.5 NLO	HERAI + partial HERAII	---	---	---	Figures	LHAPDF beta 5.8.6		July 2010
Charm mass scan	HERAI	---	---	H1+ZEUS	Writeup and figures	---		August 2010
HERAPDF1.0 NNLO	HERAI	---	---	---	ICHEP2010 writeup and figures	Docu for LHAPDF		April 2010
	HERAI	H1+ZEUS	---	---	Writeup and figures	N.A.		April 2010
	HERAI	---	---	H1+ZEUS	DIS2010 writeup and figures	N.A.		April 2010
HERAPDF1.0 NLO PUBLISHED	HERAI	---	---	---	Paper HERAPDF1.0 page	LHAPDF	Benchmarking HERAPDF1.0	Nov. 2009

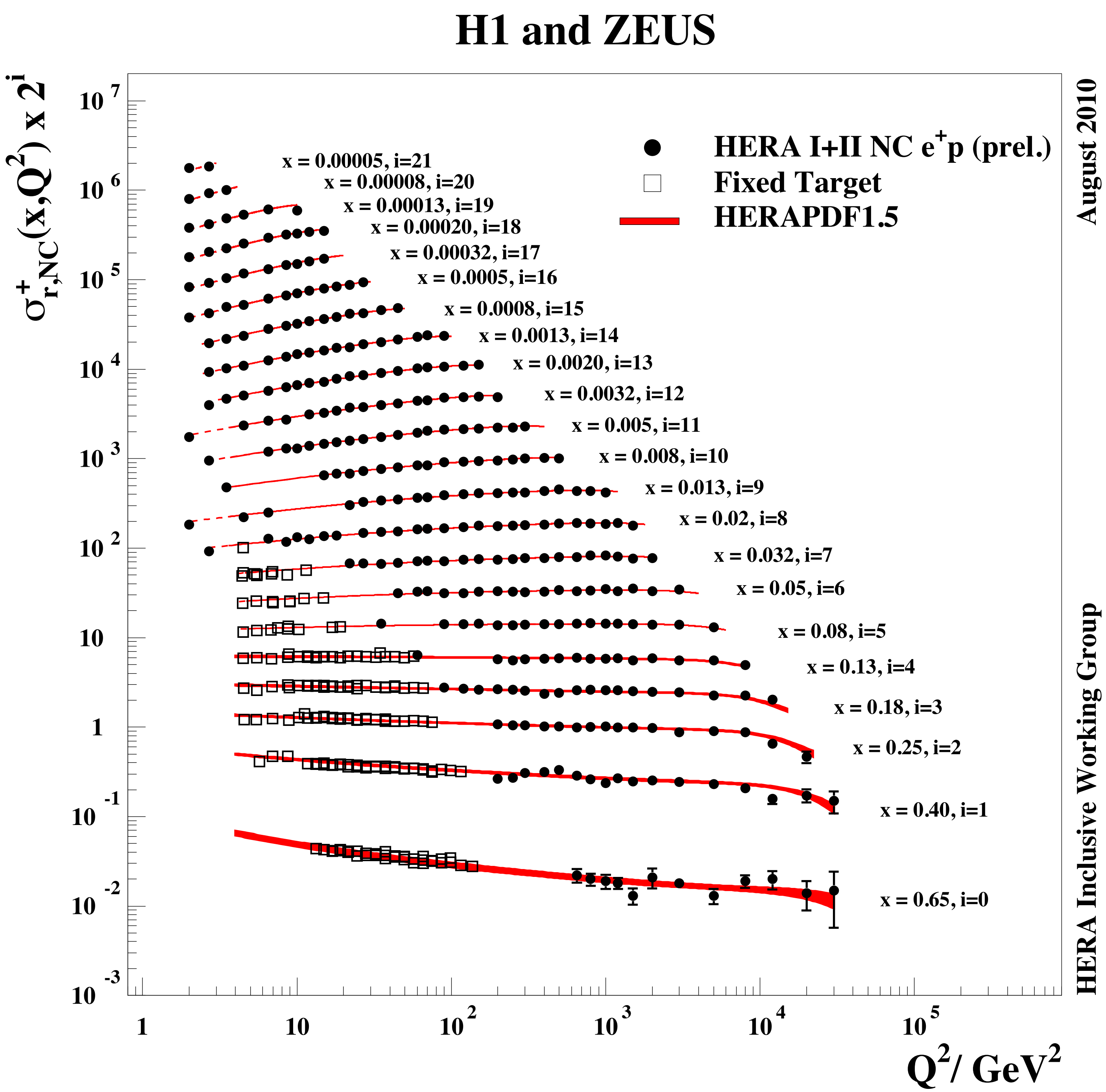
(1) H1 jets data: 1 and 2 , ZEUS jets data: 1 and 2 .

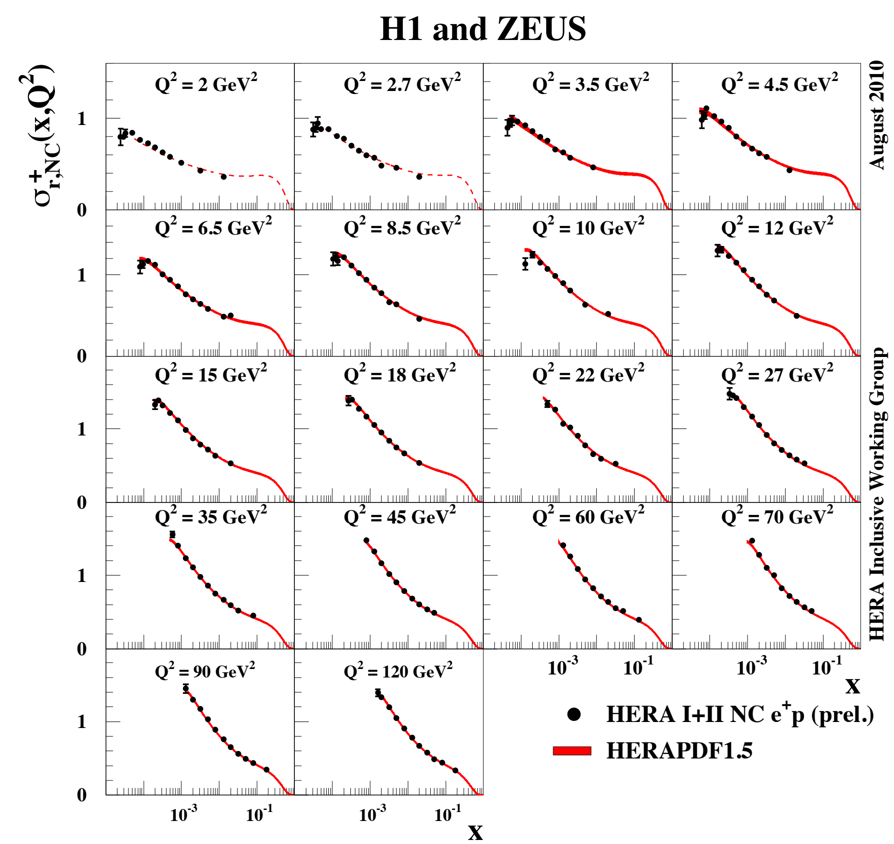
More information on the results can be obtained from the contact persons and/or from the H1 and ZEUS management.

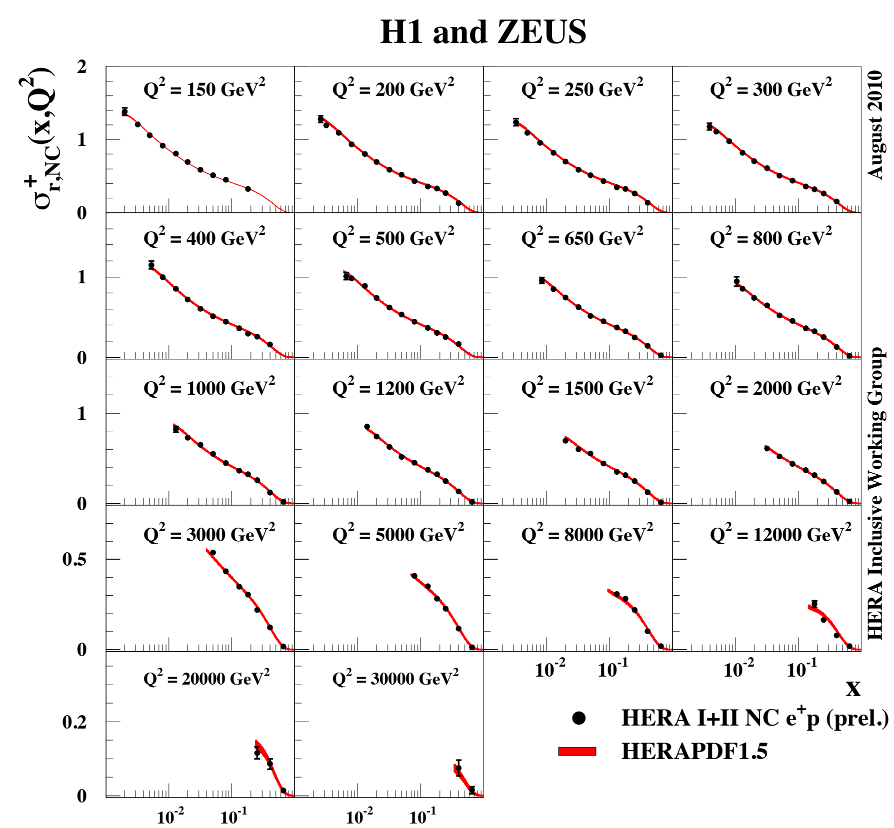
Last modified: Wed Jul 13 16:32:06 CEST 2011

Incl. HERA NC e+p cross sections

- HERA PS: $0.045 < Q^2 < 3 \cdot 10^4$ GeV^2, $5 \cdot 10^{-5} < x < 0.65$
- combine H1 & ZEUS data

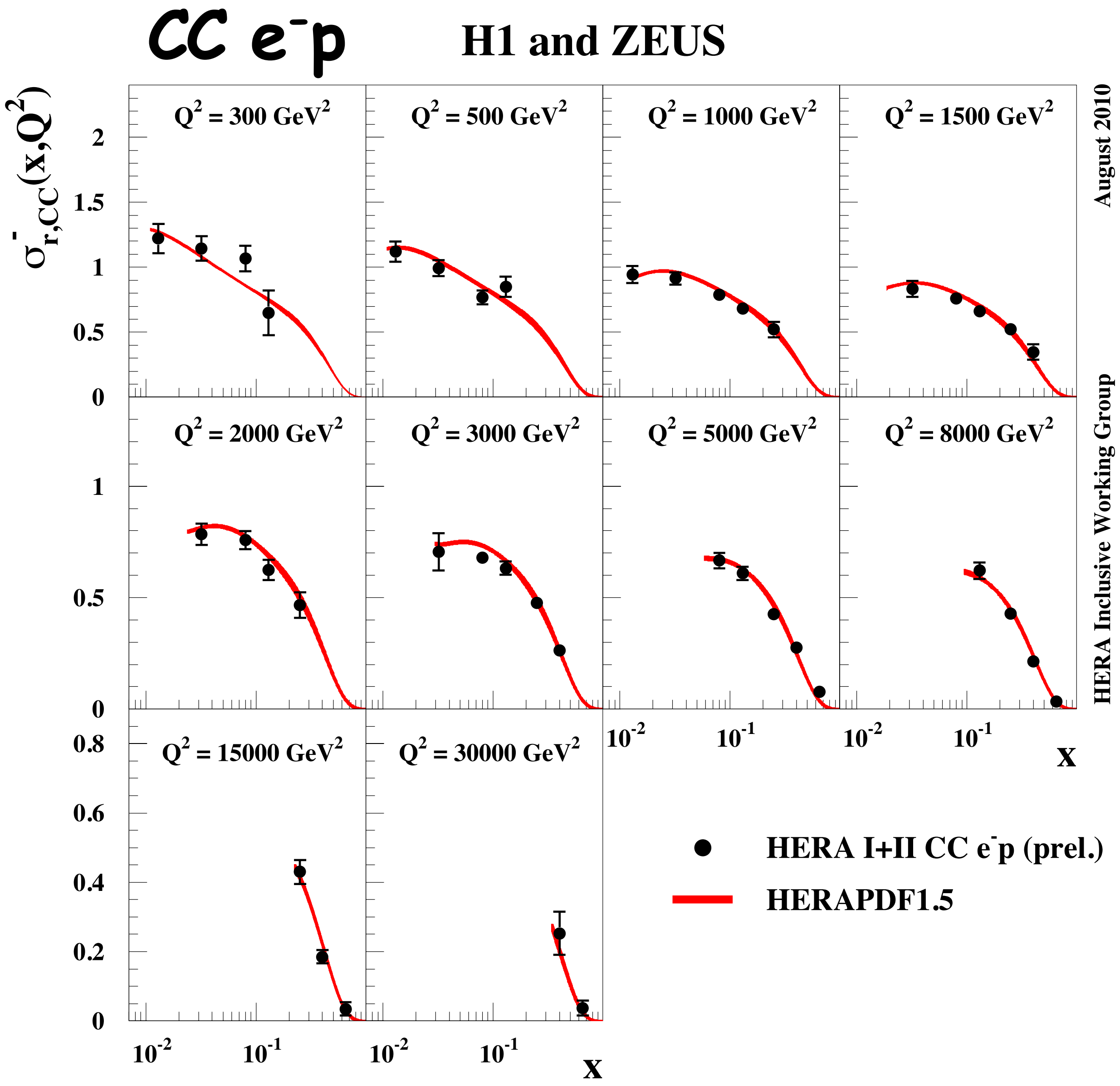


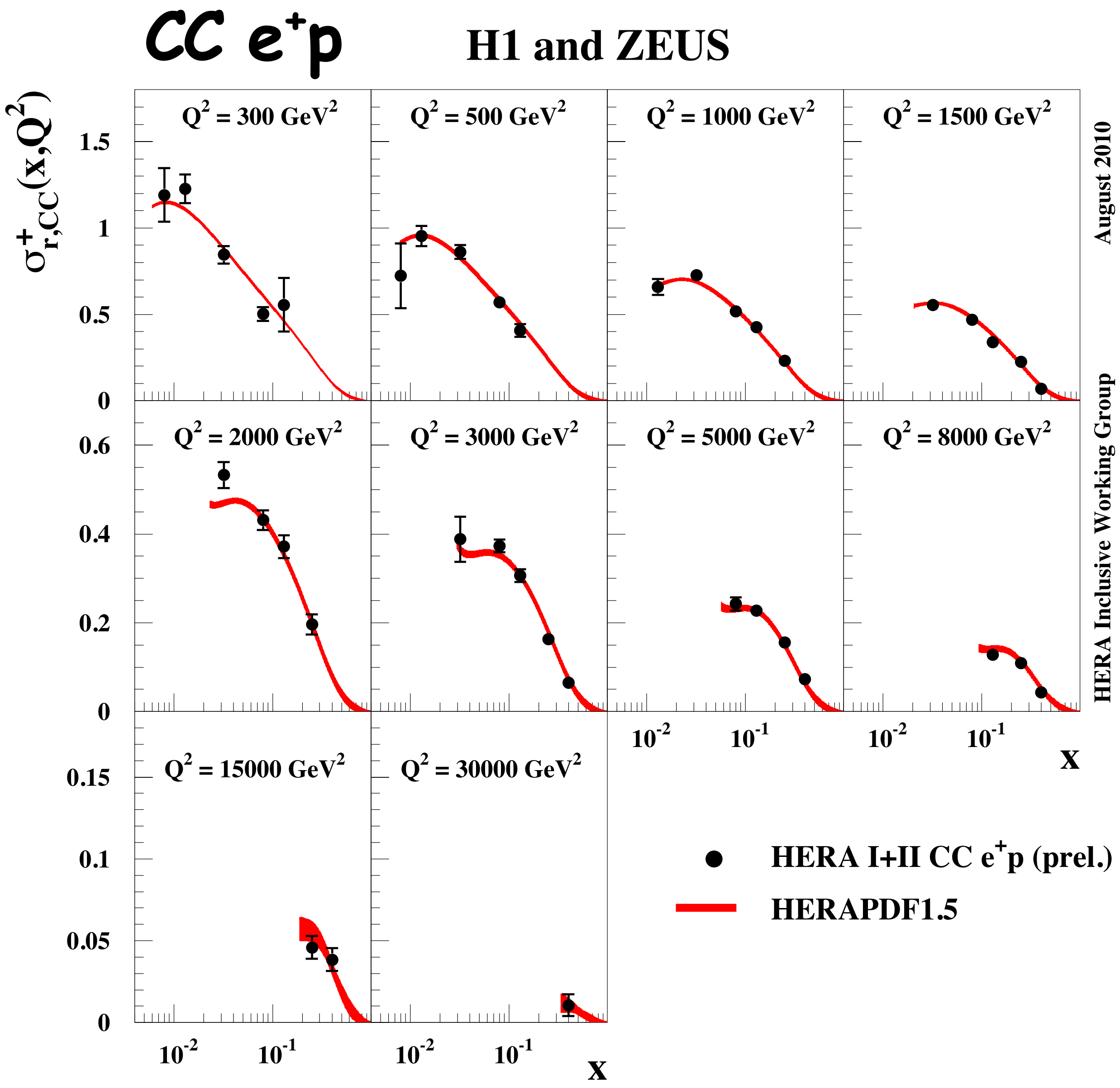




see H1 & ZEUS, JHEP 1001 109 (2010) + updates

Incl. HERA CC e±p cross sections





$$\frac{d^2\sigma^-_{CC}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[u + c + (1-y)^2(\bar{d}+\bar{s})\right]$$

$$\frac{d^2\sigma^+_{CC}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right]$$

Combining H1 & ZEUS charm data

Datasets:

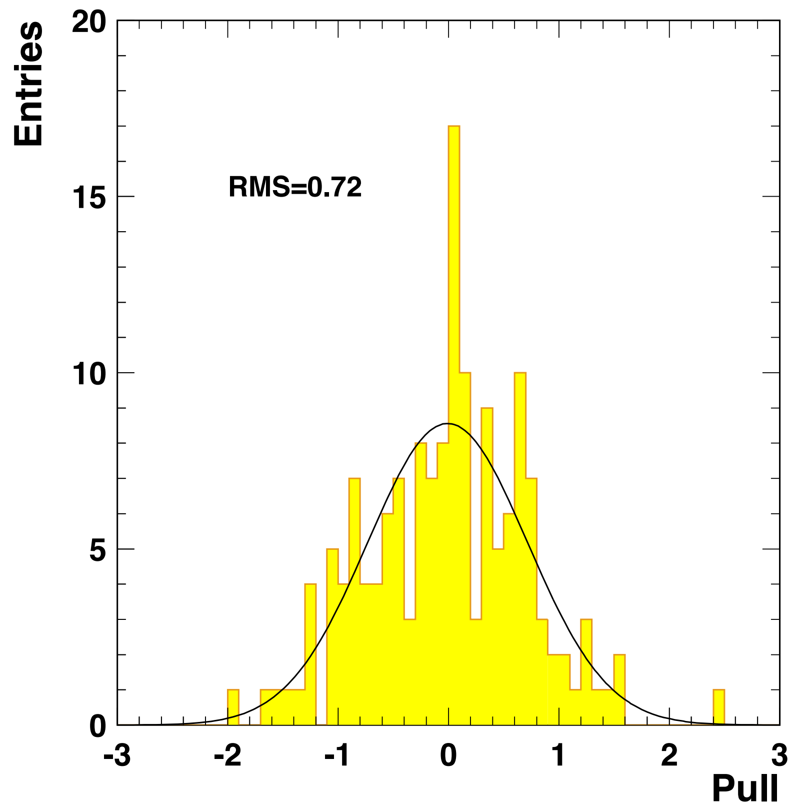
	Data set	Tagging method	Q^2 range [GeV^2]	N	$\mathcal{L}$ [pb^{-1}]
1	H1 VTX [14]	Inclusive track lifetime	5 – 2000	29	245
2	H1 D^* HERA-I [10]	D^{*+}	2 – 100	17	47
3	H1 D^* HERA-II [18]	D^{*+}	5 – 100	25	348
4	H1 D^* HERA-II [15]	D^{*+}	100 – 1000	6	351
5	ZEUS D^* (96-97) [4]	D^{*+}	1 – 200	21	37
6	ZEUS D^* (98-00) [6]	D^{*+}	1.5 – 1000	31	82
7	ZEUS D^0 [12]	$D^{0,\mathrm{no}D^{*+}}$	5 – 1000	9	134
8	ZEUS D^+ [12]	D^+	5 – 1000	9	134
9	ZEUS μ [13]	μ	20 – 10000	8	126

- Correct visible cross sections to total cross sections
- Correct most data points to a common (Q2,x) grid

Combination method:

The χ^2 function takes into account the correlated systematic uncertainties for the H1 and ZEUS cross section measurements.
The χ^2 function is defined for an individual data set e by

$$\chi^2_{\mathrm{exp},e}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma_j^{i,e} m^i b_j - \mu^{i,e}\right)^2}{(\delta_{i,e,\mathrm{stat}}\,\mu^{i,e})^2 + (\delta_{i,e,\mathrm{uncor}}\,m^i)^2} + \sum_j b_j^2$$



Calculations from different groups

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 ($\overline{\text{MS}}$)	$\mathcal{O}(\alpha_s^2)$	-	0.1135	$\sqrt{Q^2 + 4m_c^2}$	for mass optimisation only
ABKM09 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	-			

M_c^{opt} in different schemes

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

Hessian method for fitting $\alpha_s(M_Z)$

$$\chi^2 = \sum_i^{allBins} \vec{\tilde{\sigma}}^T V^{-1} \vec{\tilde{\sigma}} + \sum_k^{SysErr} \varepsilon_k^2$$

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

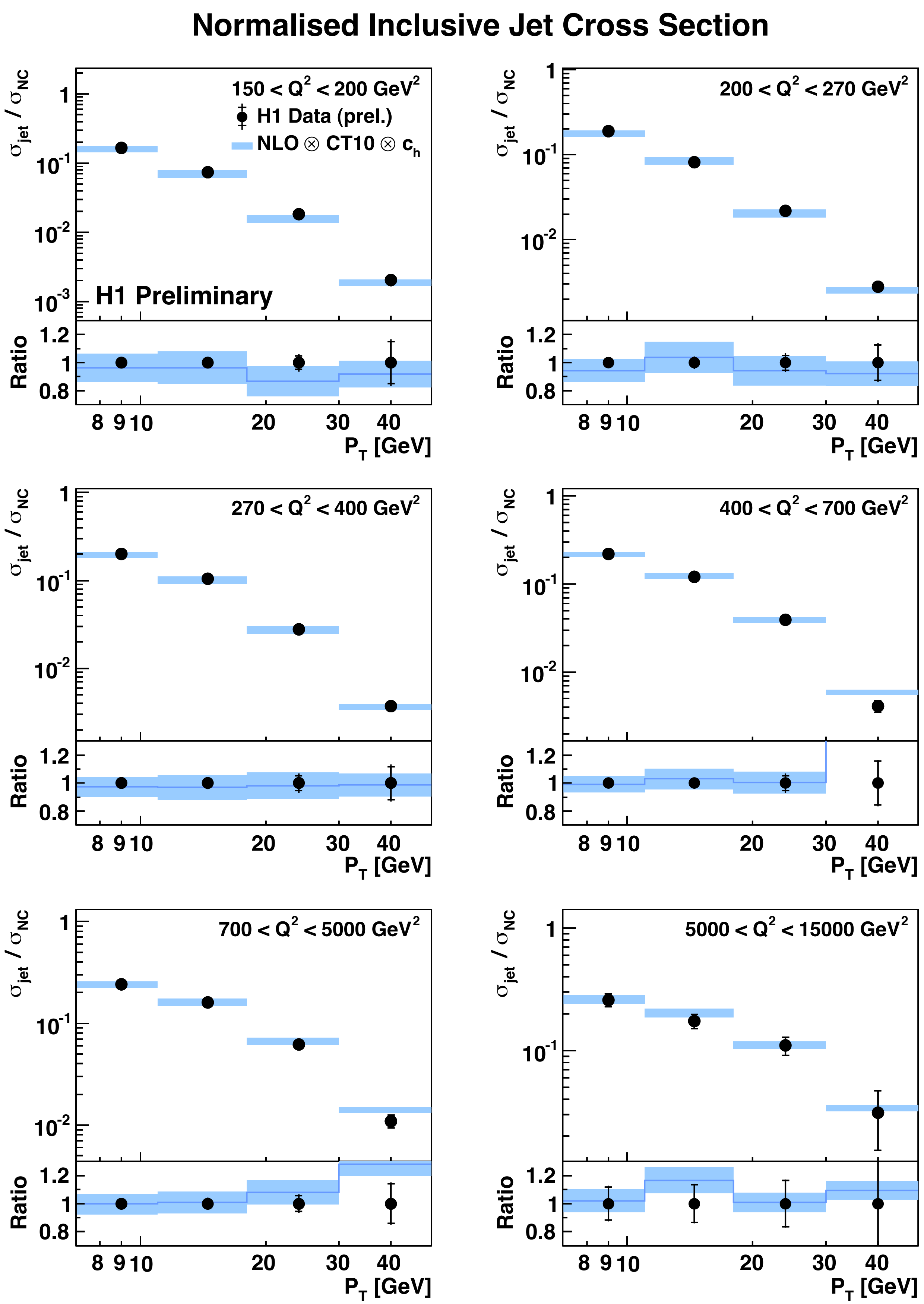
$$V = V_{stat} + V_{ii,uncorr}$$

$\alpha_s(M_Z)$-values from norm. multijets

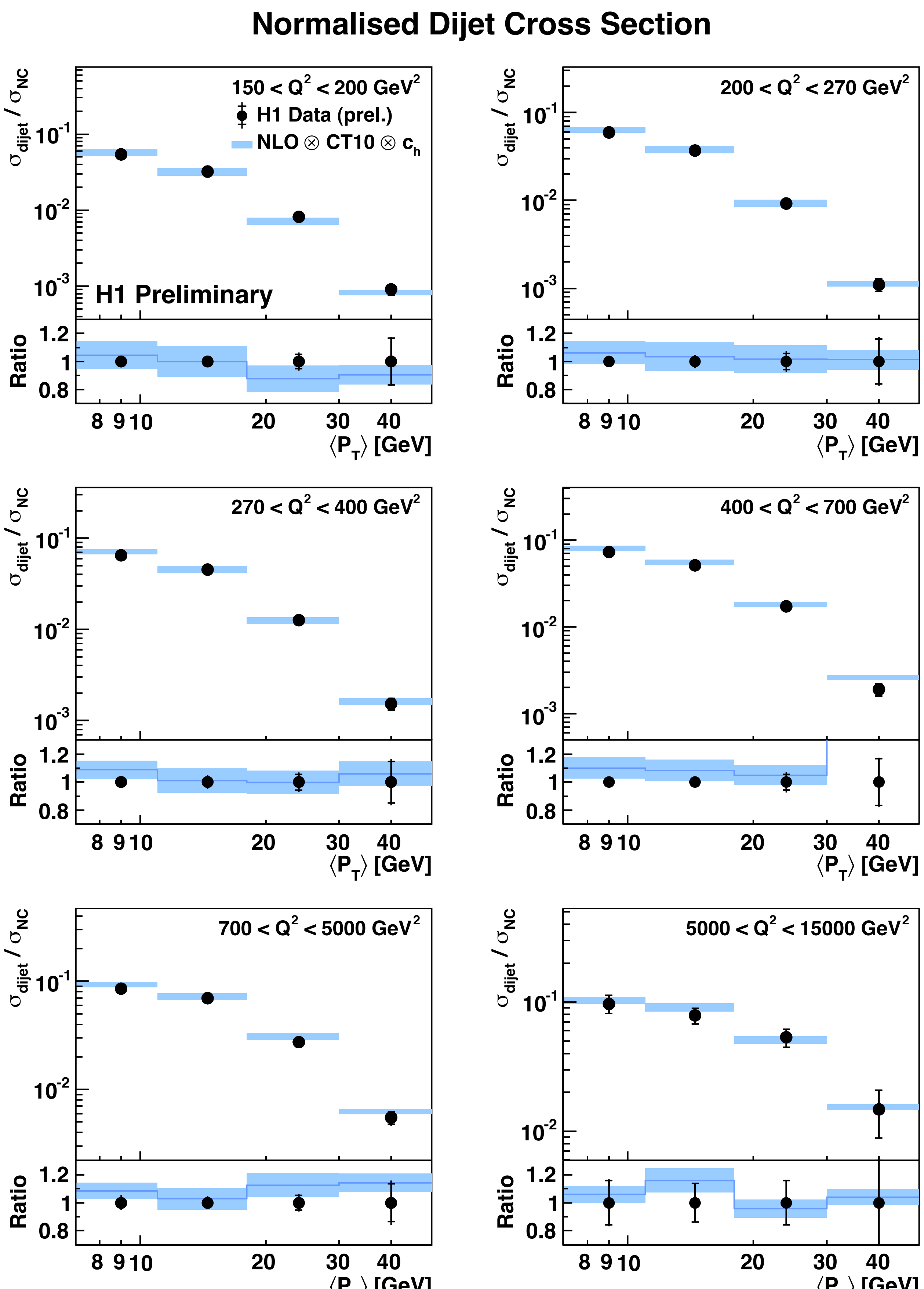
NC DIS Selection	$150 < Q^2 < 15000\,\mathrm{GeV}^2 \quad 0.2 < y < 0.7$		
Inclusive jet	$7 < P_T < 50\,\mathrm{GeV}$		$-1.0 < \eta_{\mathrm{lab}} < 2.5$
Dijet	$5 < P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}} < 50\,\mathrm{GeV}$	$M_{12} > 16\,\mathrm{GeV}$	
Trijet	$5 < P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}},\ P_T^{\mathrm{jet3}} < 50\,\mathrm{GeV}$		

(H1prelim-12-031) Measurement	$\alpha_S(M_Z)$	Uncertainty				χ^2/ndf
		experimental	had.	theory	PDF	
normalised inclusive jet	0.1197	0.0008	0.00118	$^{+0.0054}_{-0.0053}$	0.0014	28.663/23 = 1.246
normalised dijet	0.1142	0.0010	0.0009	$^{+0.0050}_{-0.0046}$	0.0017	27.037/23 = 1.176
normalised trijet	0.1185	0.0018	0.0016	$^{+0.0050}_{-0.0035}$	0.0013	12.013/16 = 0.751
normalised multijet	0.1177	0.0008	0.0011	$^{+0.0052}_{-0.0049}$	0.0014	104.61/64 = 1.634
normalised multijet ($k < 1.3$)	0.1163	0.0011	0.0008	$^{+0.0044}_{-0.0035}$	0.0014	53.257/41 = 1.299

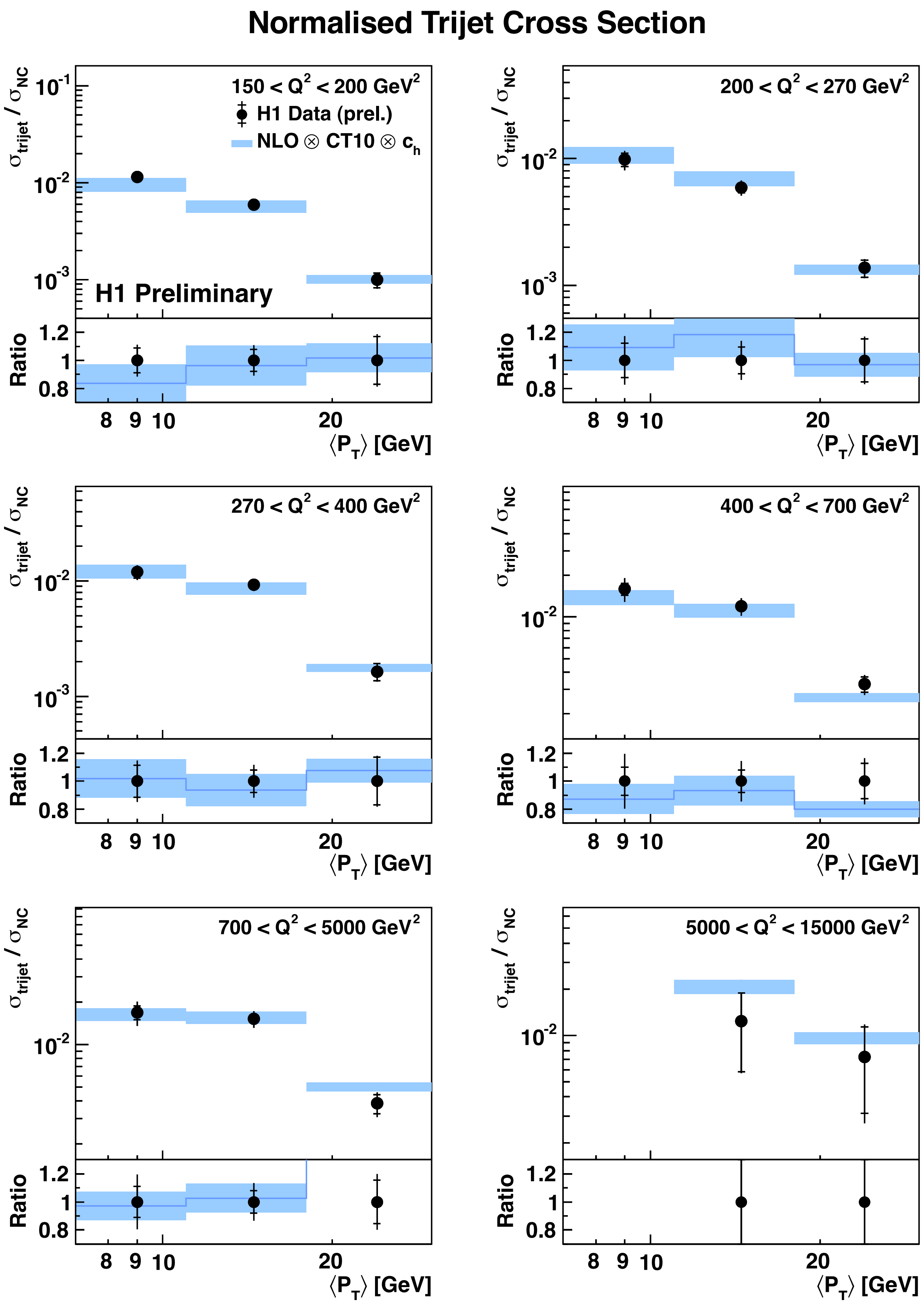
Norm. inclusive jet cross sections



Normalized dijet cross sections



Normalized trijet cross sections



Inclusive jets in PHP

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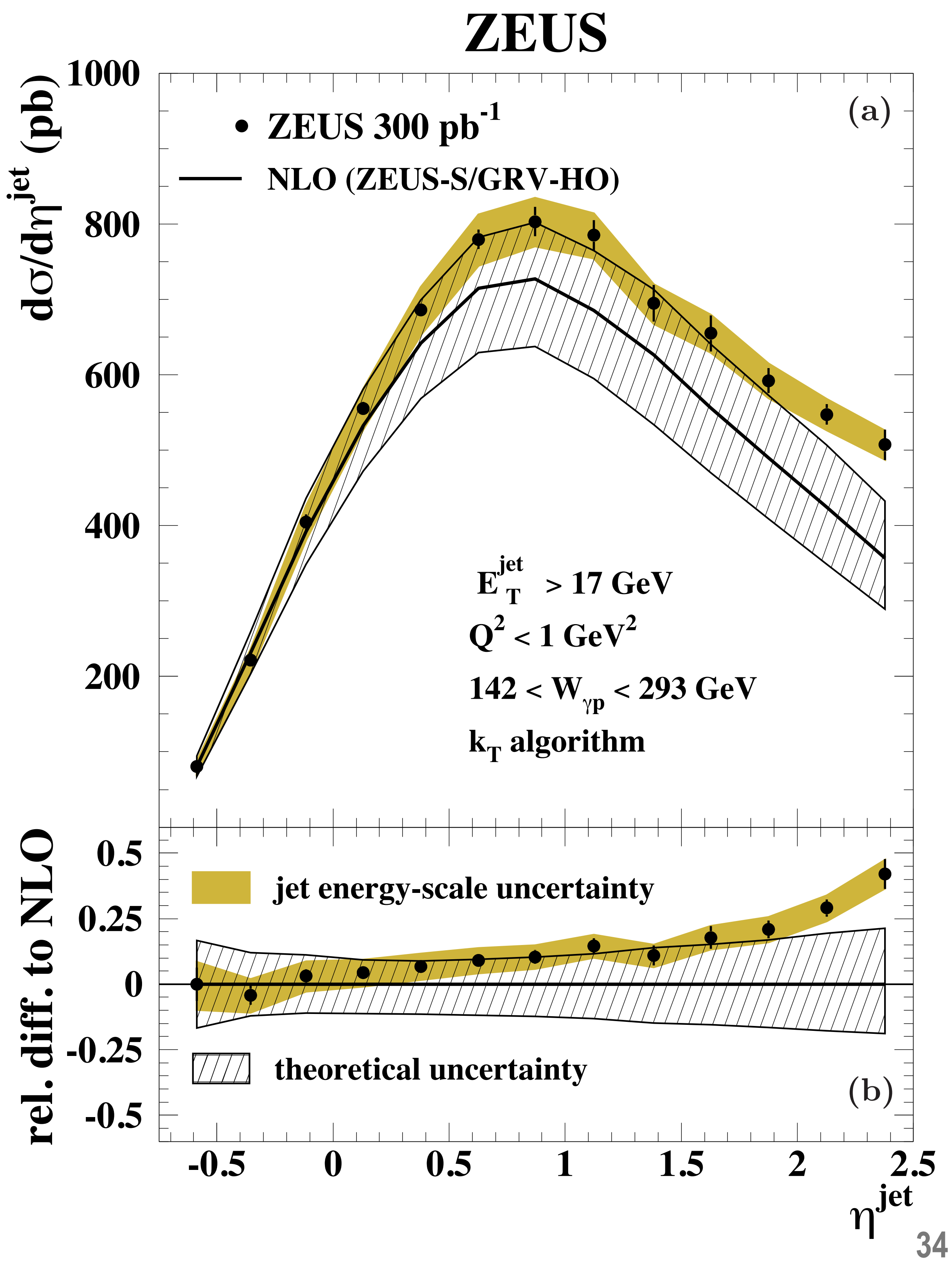
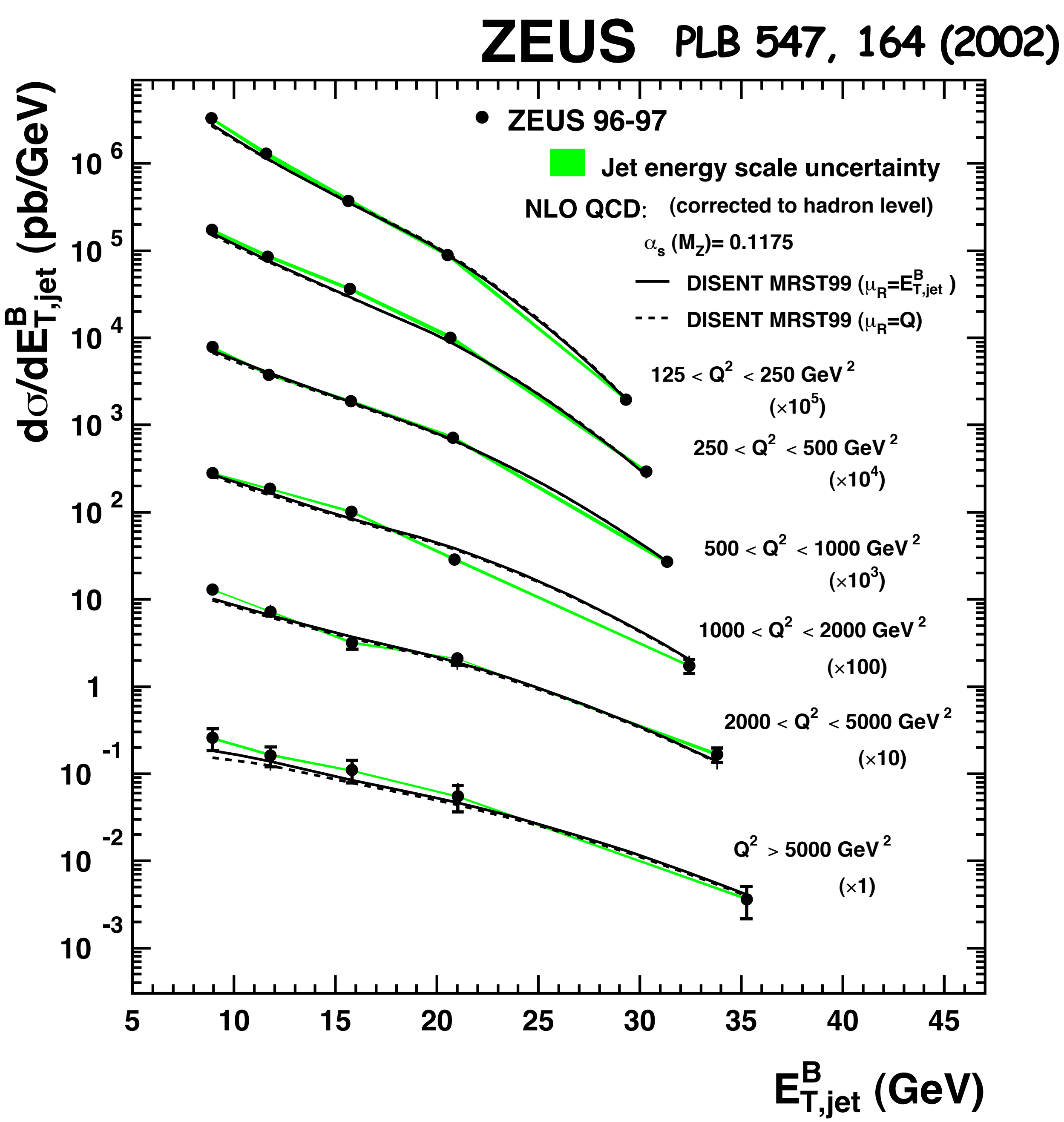
includes in addition:
- double differential cross sections in bins of ET and rapidity of the jets

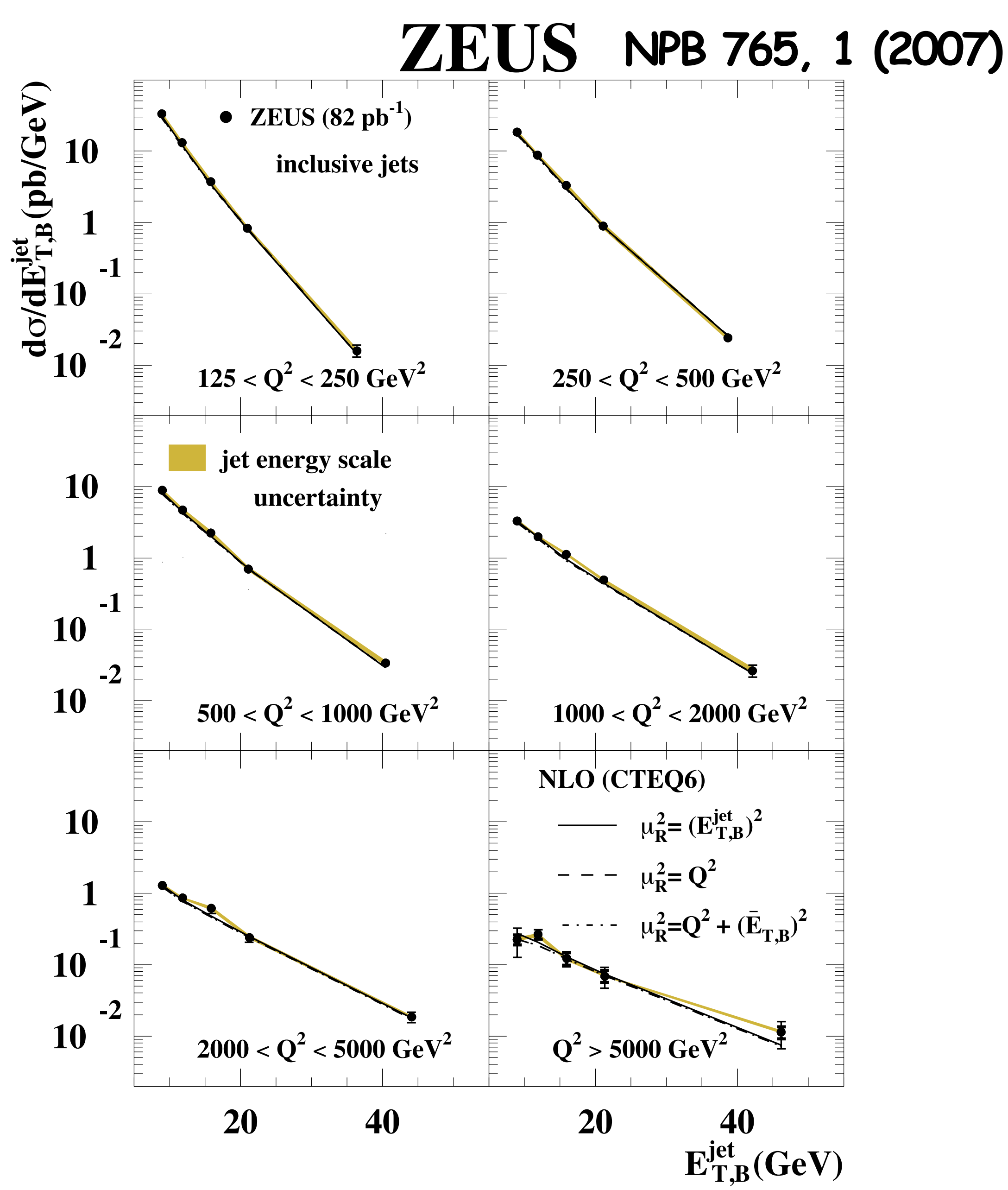
- investigation of effects of:
  - kt,anti-kt and SIScone
  - MPI interactions
  - different photon PDFs

$$\alpha_s(M_Z)|_{k_T} = 0.1206 \,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0042}_{-0.0035}\,(\text{th.}),$$
$$\alpha_s(M_Z)|_{\text{anti}-k_T} = 0.1198 \,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0041}_{-0.0034}\,(\text{th.}),$$
$$\alpha_s(M_Z)|_{\text{SIScone}} = 0.1196 \,^{+0.0022}_{-0.0021}\,(\text{exp.})\,^{+0.0046}_{-0.0043}\,(\text{th.}).$$



Incl. jet cross sections (ZEUS)





exp. uncertainty for inclusive jets at high Q^2: ~ 15% uncorrelated, 4% correlated