Proton structure at HERA and relation to LHC

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for the H1 and ZEUS collaborations

Hadron Structure 2013
Tatranské Matliare, Slovakia
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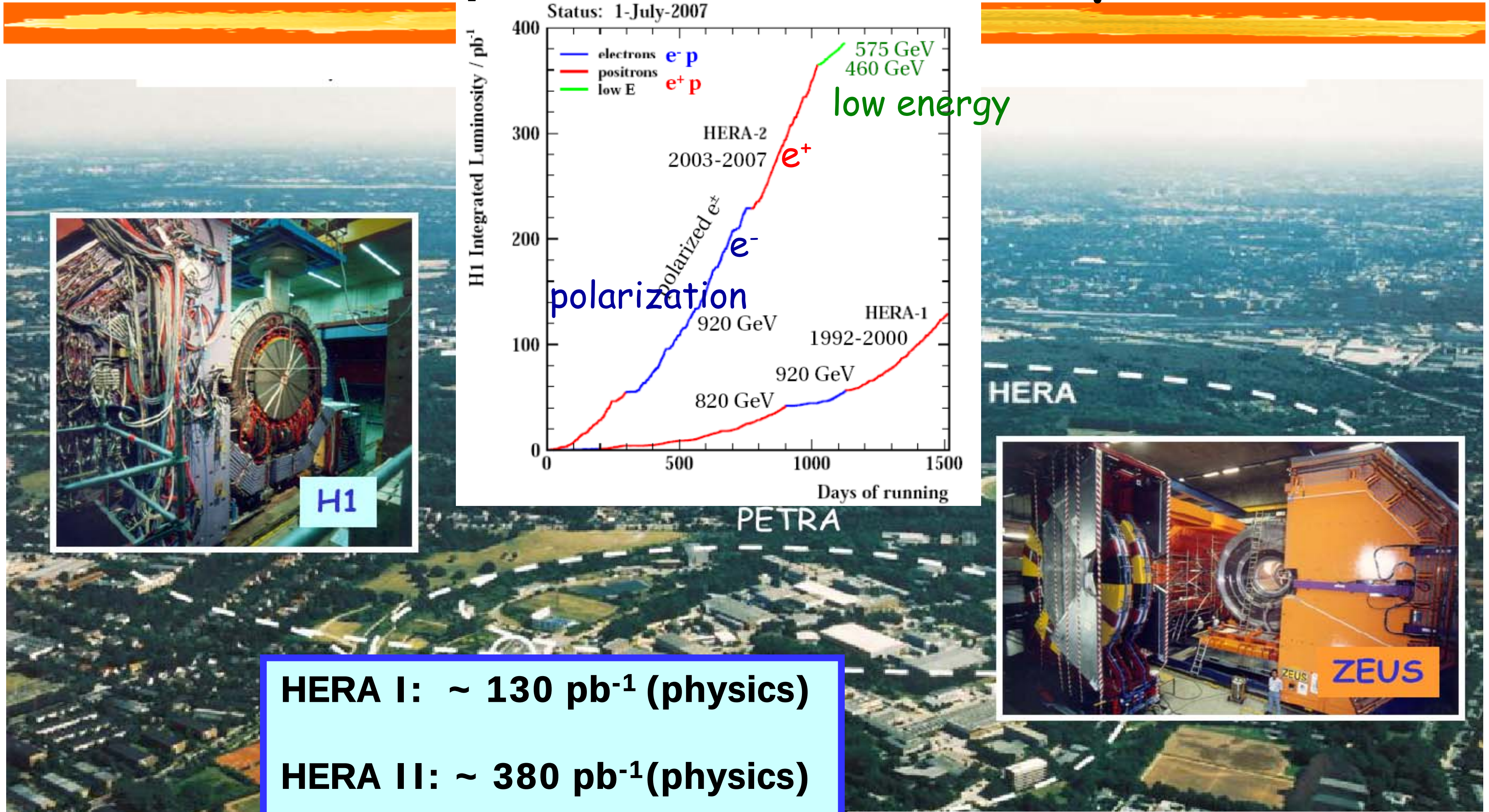
selection of recent results

- **Introduction to DIS**
- **Inclusive and electroweak results**
- **(Jets in DIS, α_s)** -> see talk S. Mikocki
- **Inclusive charm production in DIS, m_c**
- **Conclusions**

charm in PhP -> S. Mergelmeyer
single photons -> O. Kuprash
hadronic final states -> A. Baghdasarian
HERAFitter -> A. Gizhko

The HERA ep collider and experiments

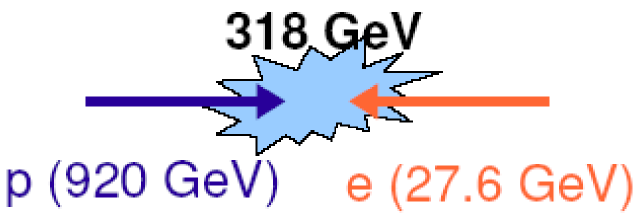


HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1}(physics)

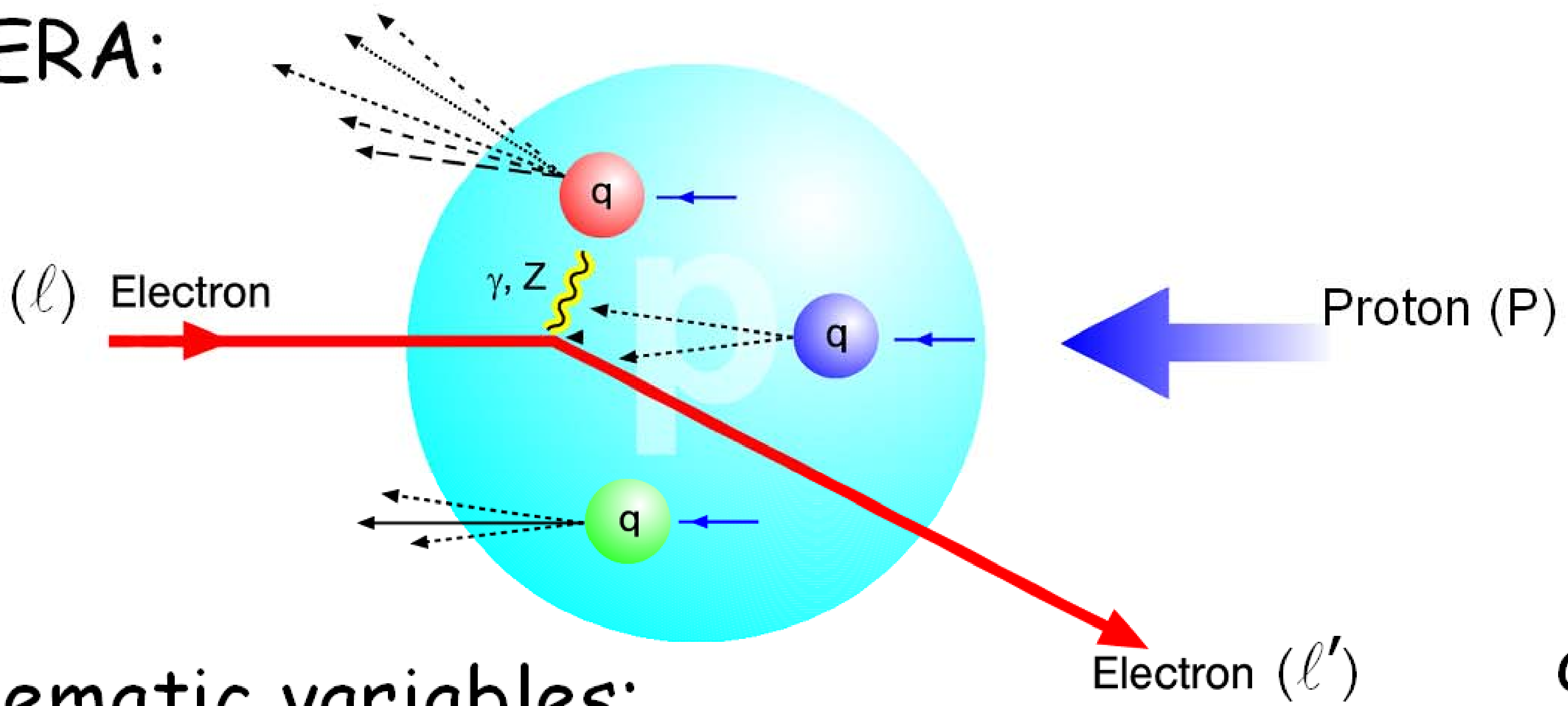
combined: ~ 2 x 0.5 fb^{-1}

HERA:



Deep Inelastic ep Scattering at HERA

HERA:



kinematic variables:

$q = \ell - \ell'$

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

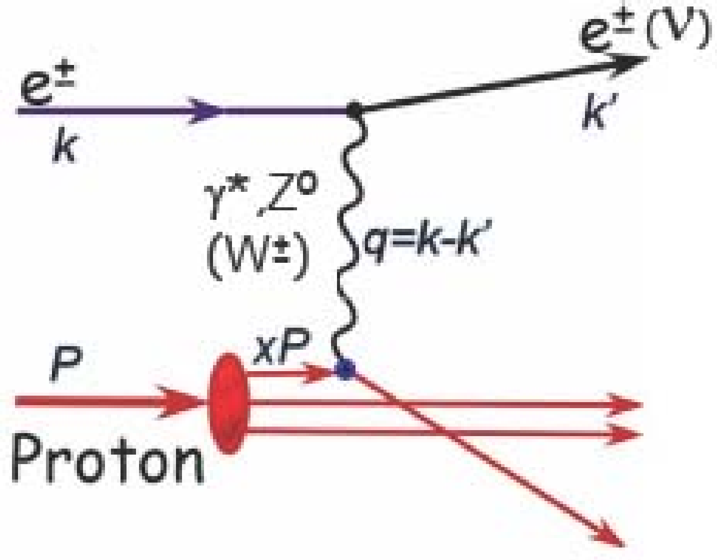
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

$Q^2 \lesssim 1\ \mathrm{GeV}^2$: photoproduction

$Q^2 \gtrsim 1\ \mathrm{GeV}^2$: DIS

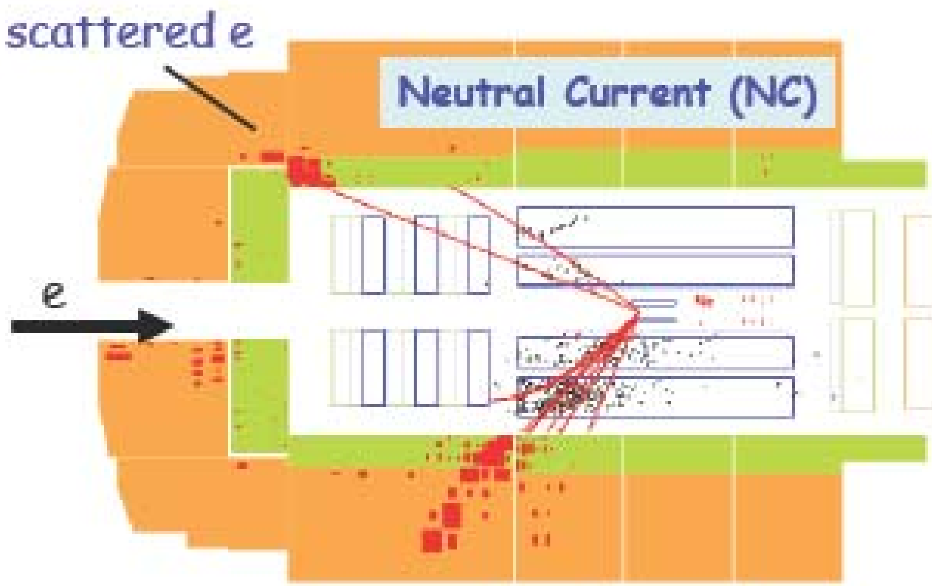
Charged current vs. neutral current

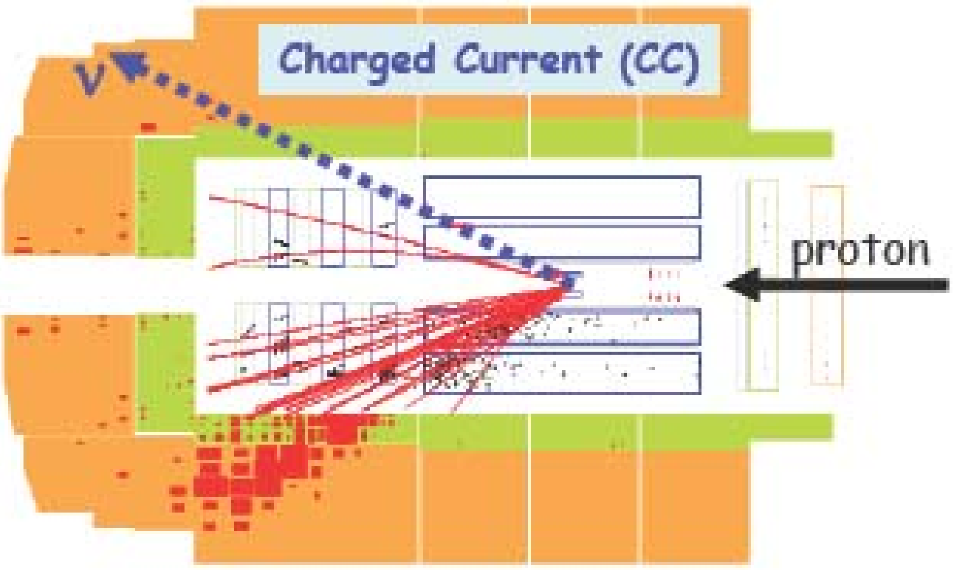


virtual boson exchange

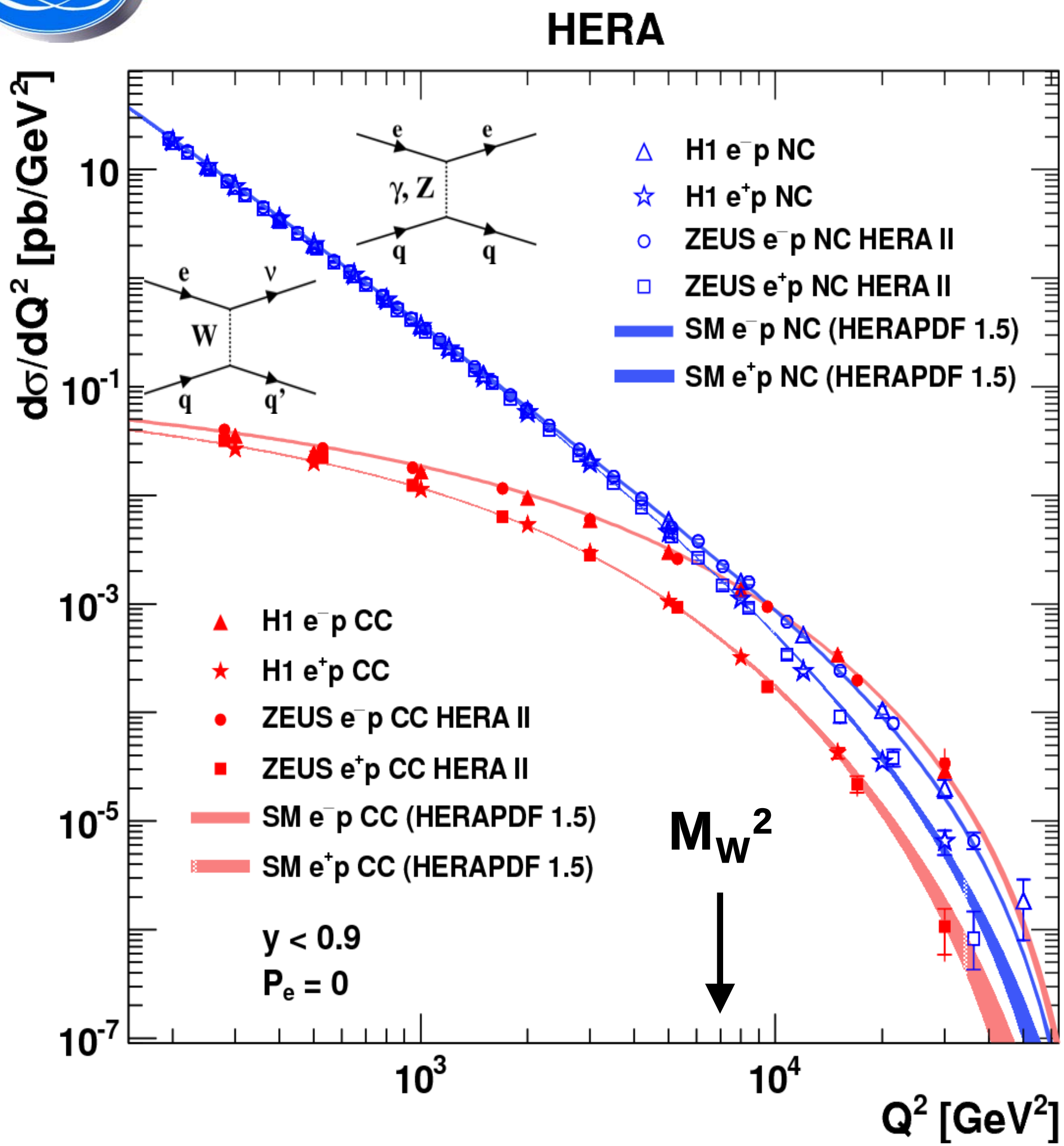
γ^*, Z* (neutral)

or $W^{\pm *}$ (charged)





Electroweak unification



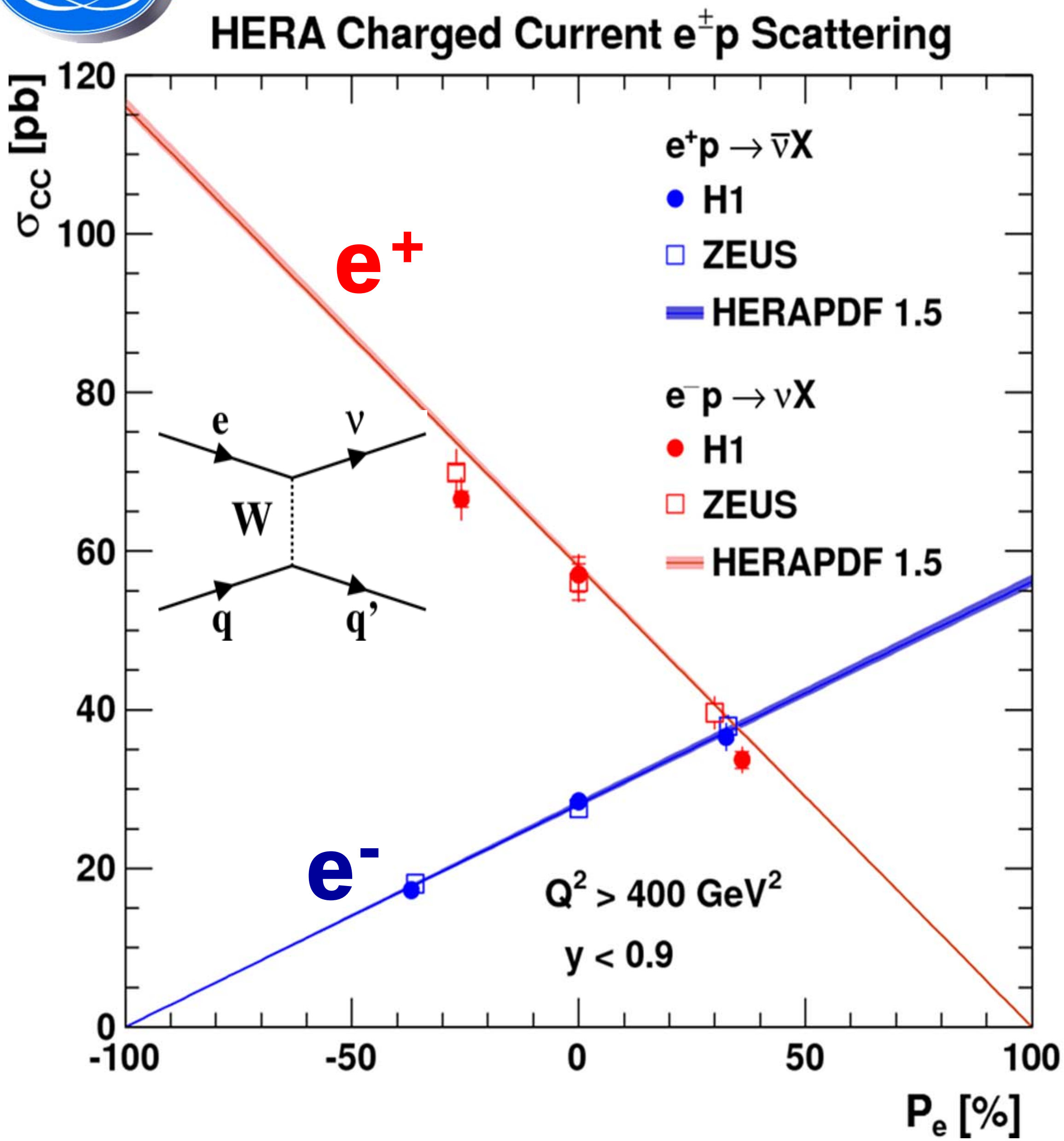
final HERA results

completed by

JHEP 1209:061 (2012)

PRD 87, 052014 (2013)

Parity violation in charged current DIS



final HERA results
completed by
JHEP 1209:061 (2012)

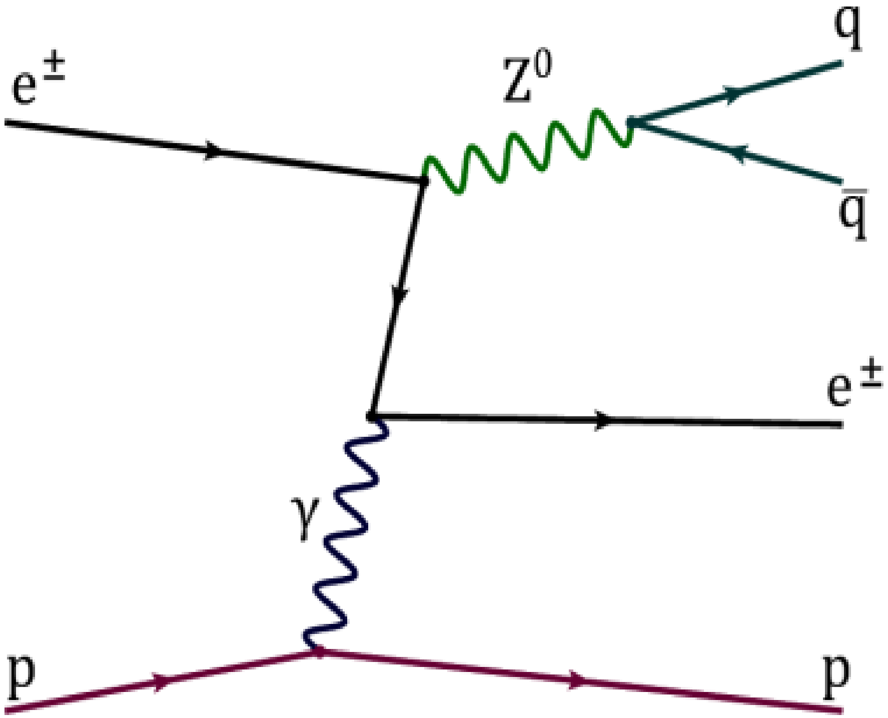
SM: CC "switched off"
for RH e- and LH e+

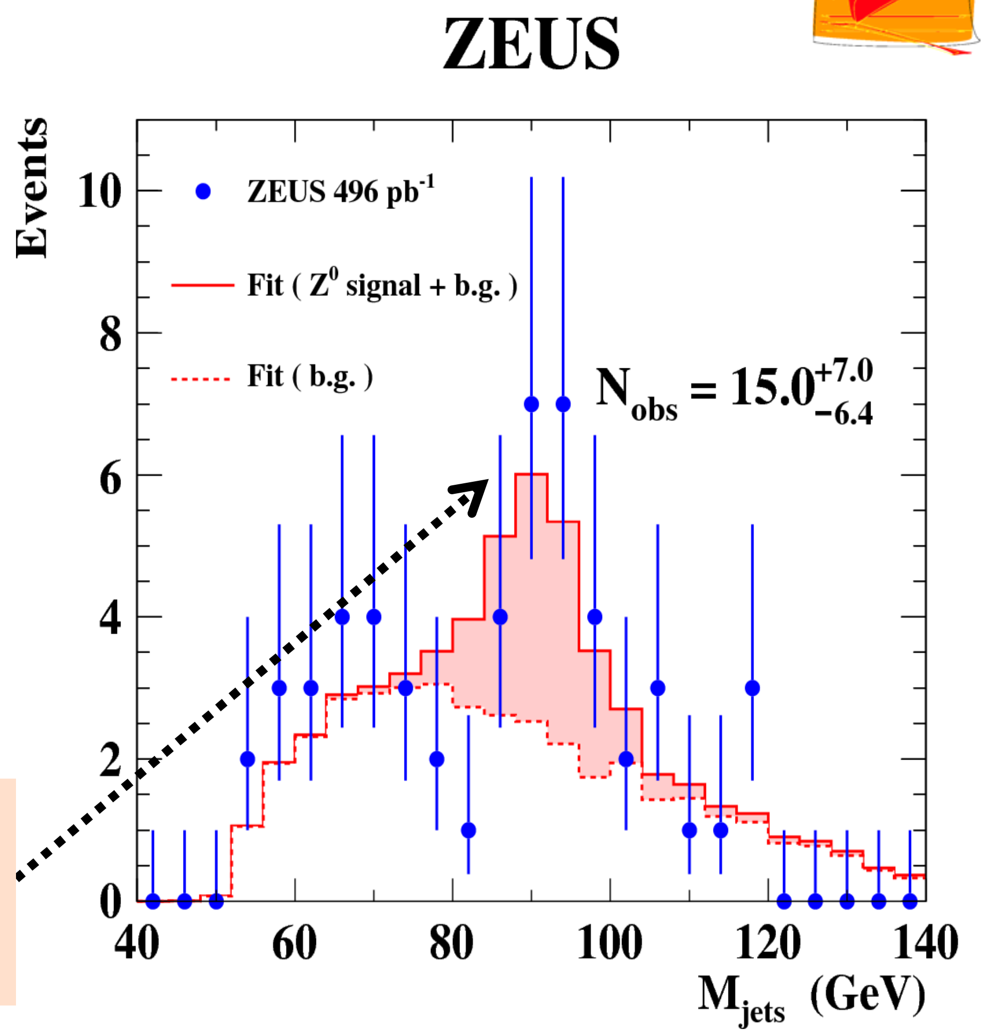
→ data agree with SM

→ rule out
$M(W_R) < 200$ GeV

Elastic real Z^0 -> jet jet production

PL B 718 (2013) 915



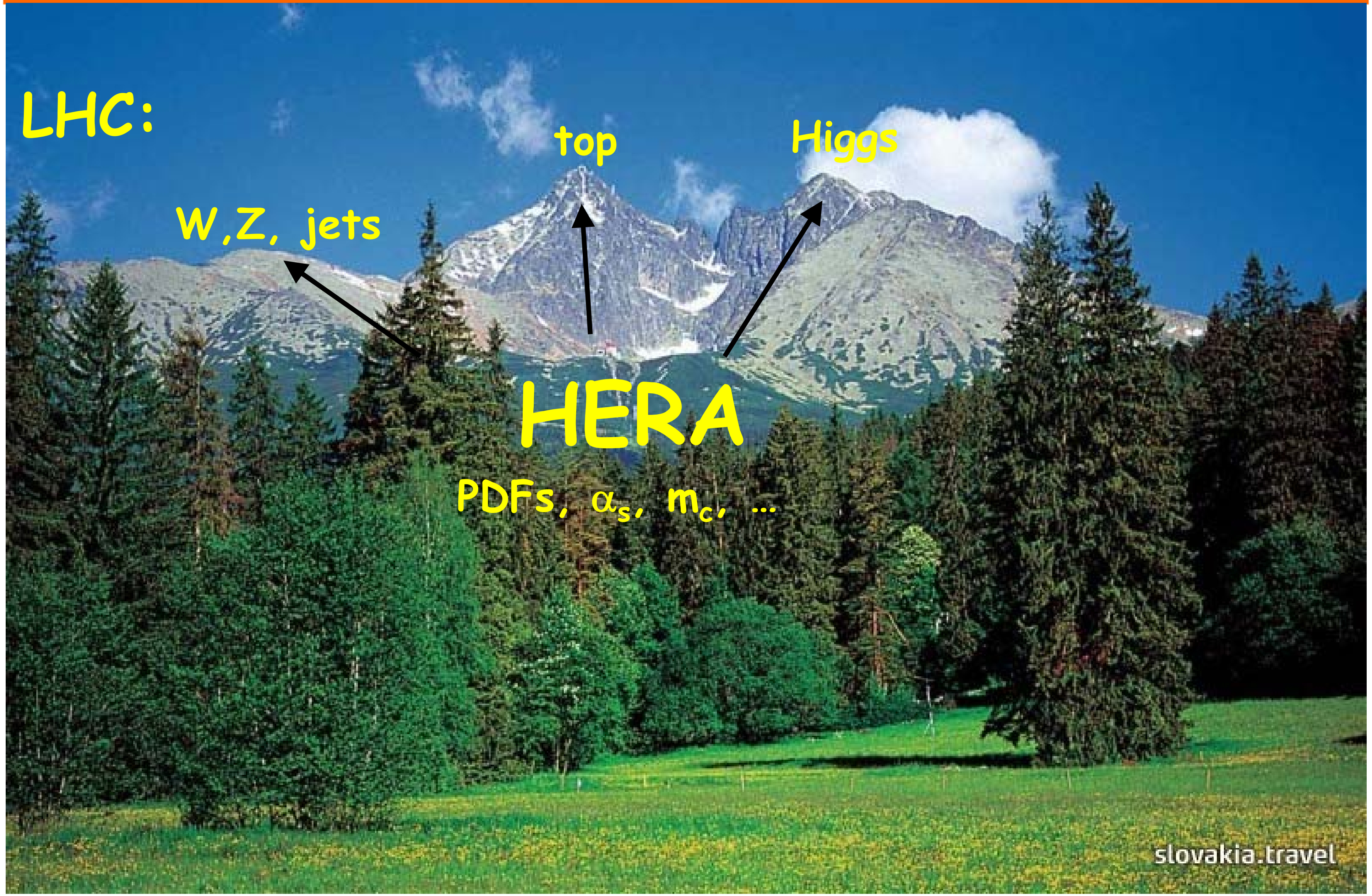


shows excellent $\sigma_E^{hadronic}$ of ZEUS Uranium scintillator calorimeter

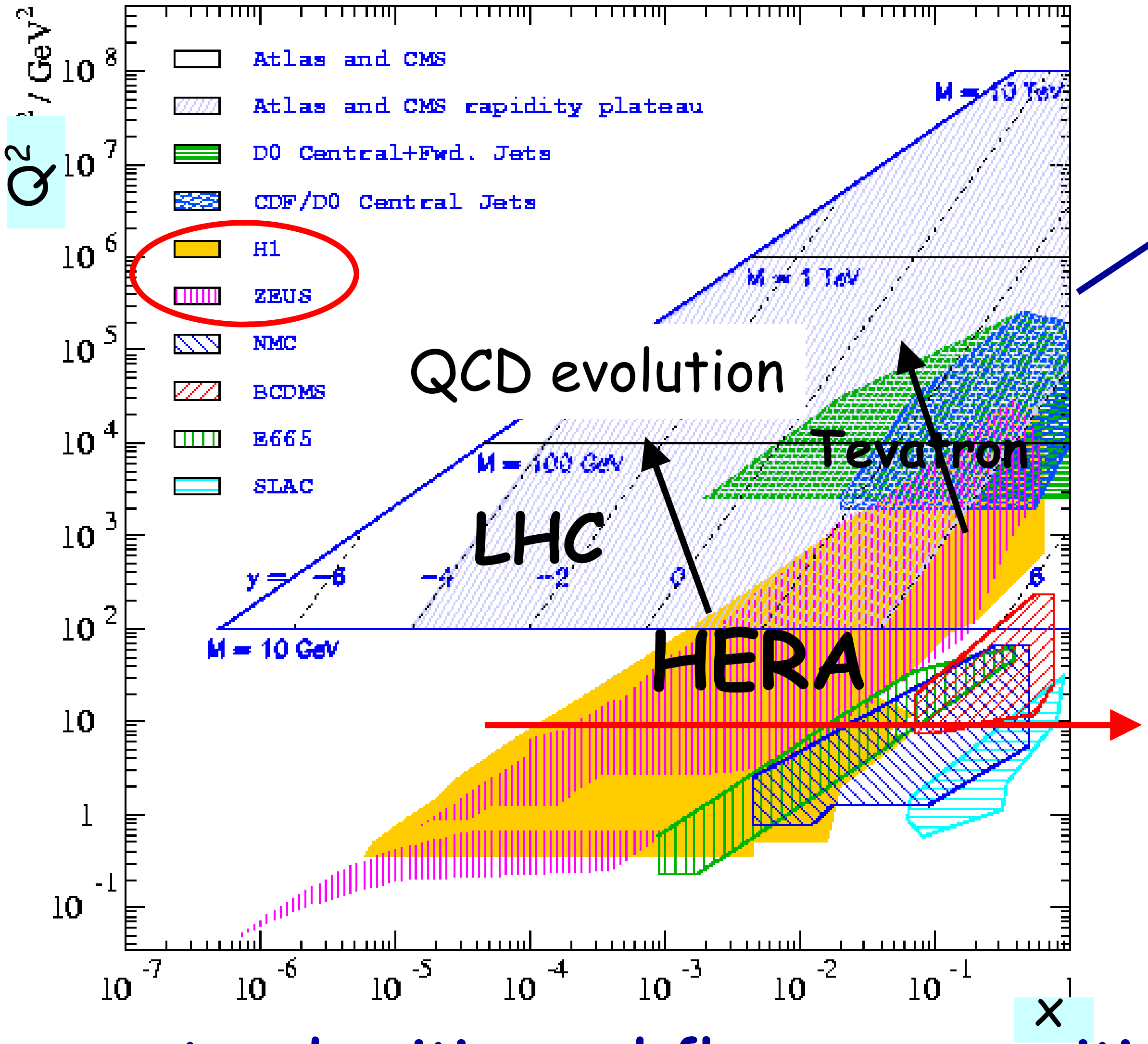
$$\sigma_{obs}\left(ep \rightarrow ep^{(*)}Z^0\right) = 0.133^{+0.060}_{-0.057}\,(\text{stat.})^{+0.049}_{-0.038}\,(\text{syst.})\ \text{pb}$$

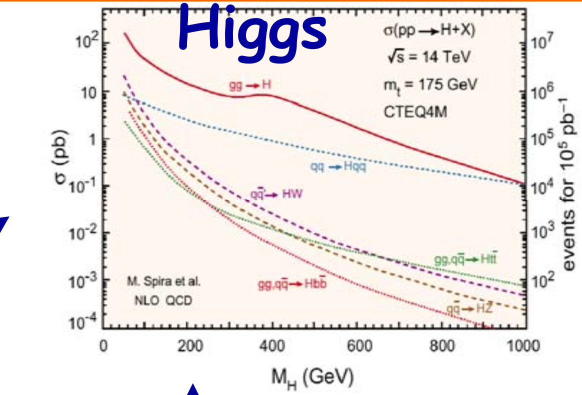
agrees with SM prediction of 0.16 pb

From HERA to LHC

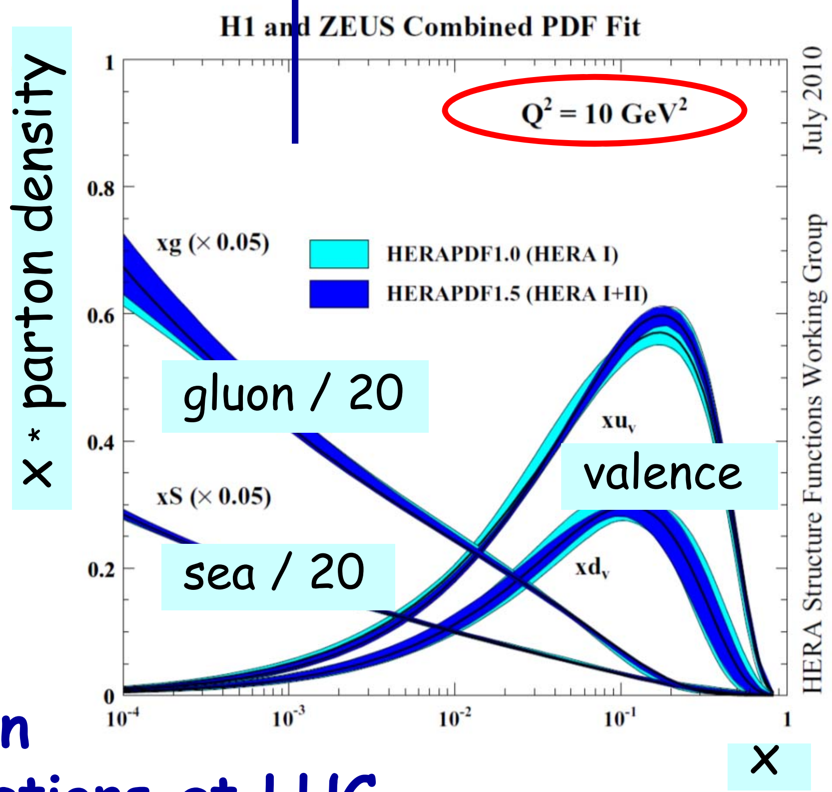


Parton density functions (PDF)





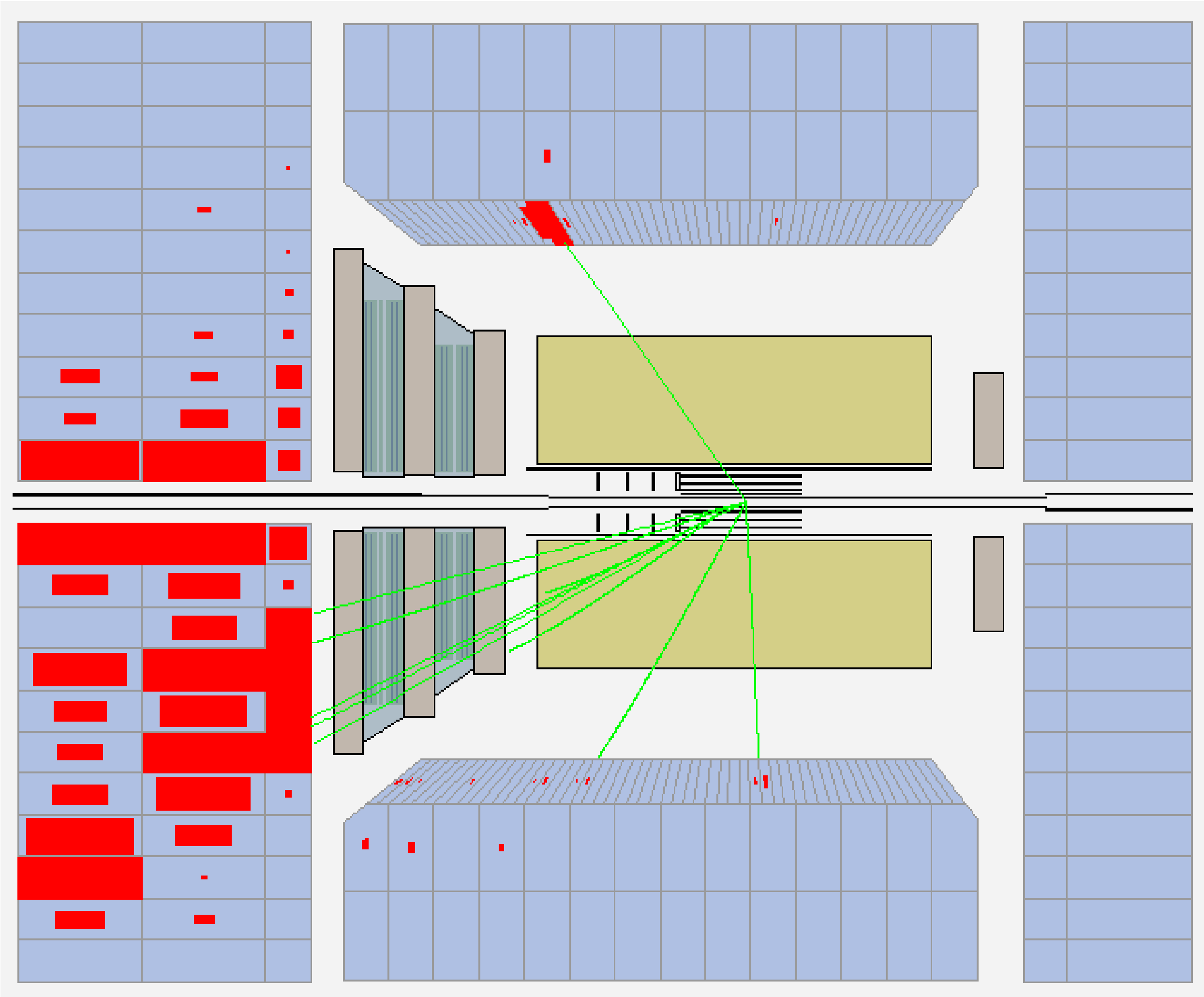
W,Z,
top,
jets,
…

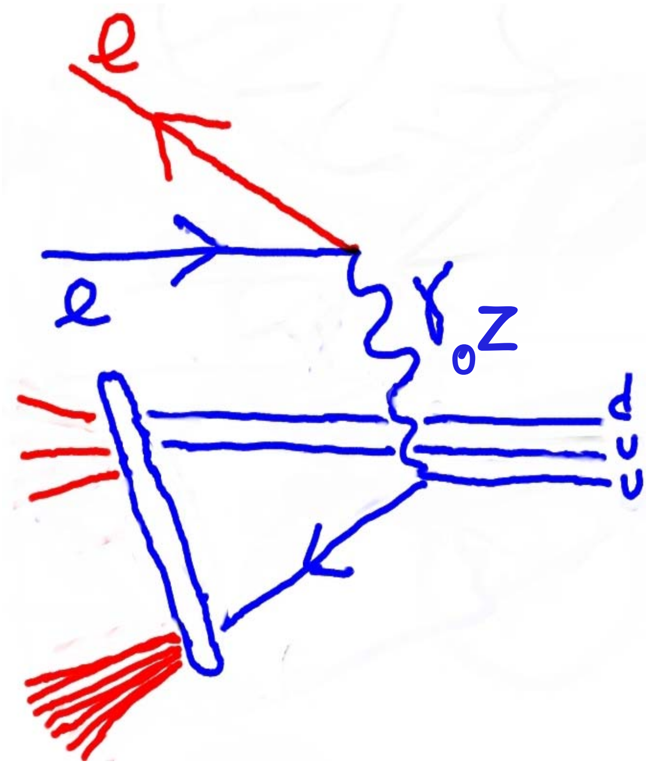


parton densities and flavour composition measured at HERA determine cross sections at LHC

Inclusive DIS at HERA (count every DIS event)

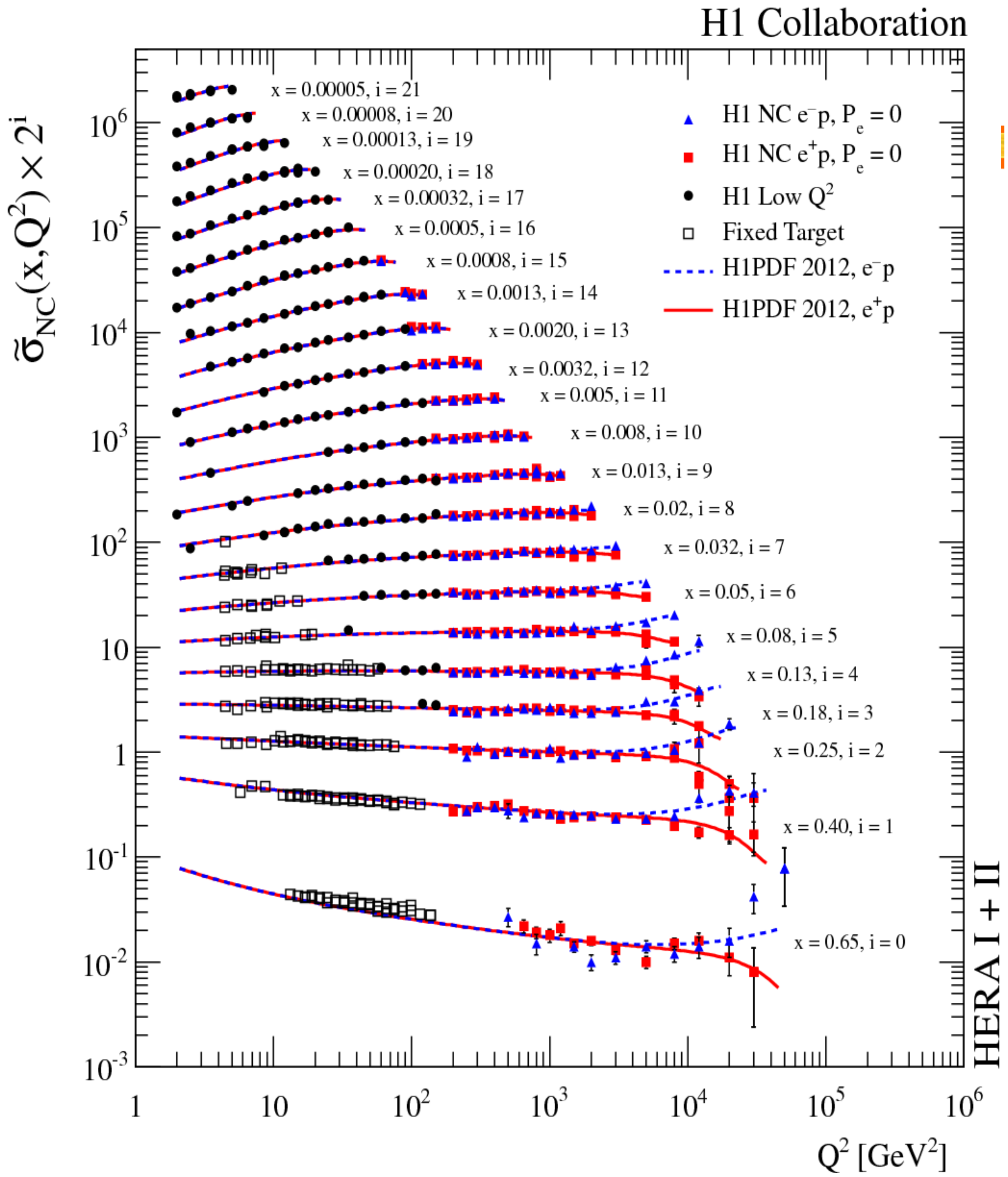
NC event





data access for
non-collaboration members
negotiable

display produced from ROOT ntuple ("ZEUS common ntuple")



Reduced NC cross sections

$$\tilde{\sigma}_{NC}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma_{NC}^{e^+p}}{dxdQ^2}$$

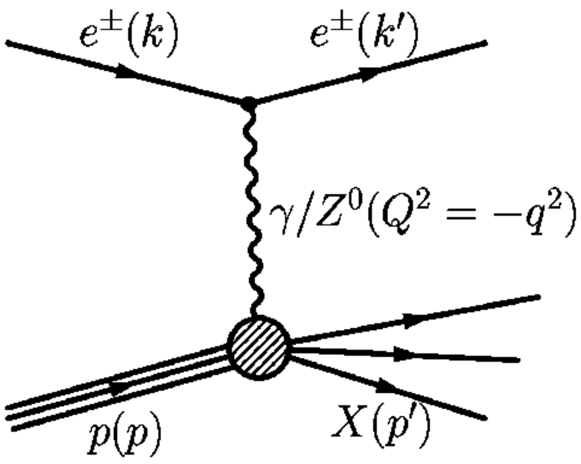
final H1 results

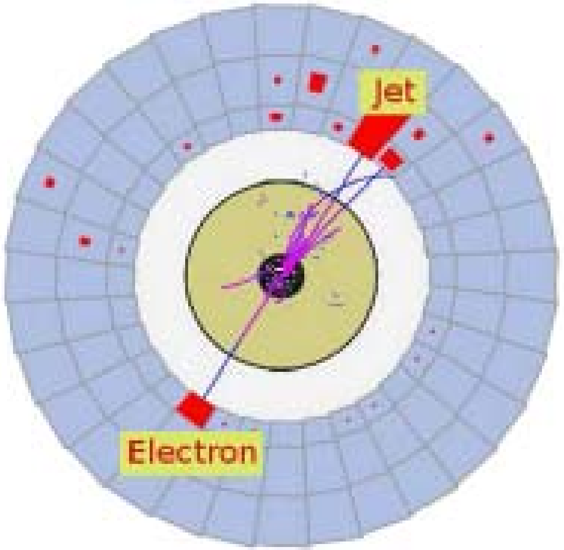
JHEP 1209:061 (2012)

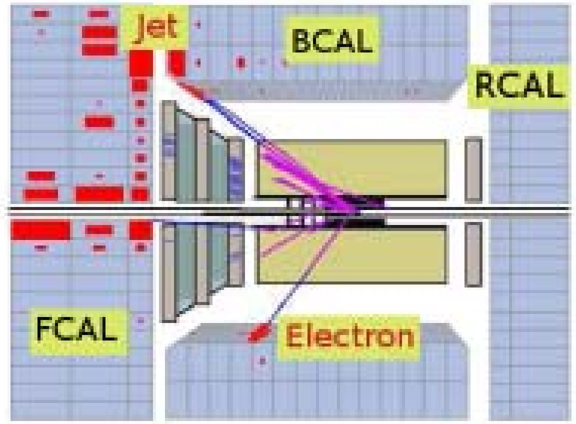
1.5% precision for $Q^2 < 500$ GeV^2

→ data well described by DGLAP NLO QCD

Unpolarized high Q^2 Neutral Current scattering







$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2) - y^2 F_L(x,Q^2) \pm Y_-\, xF_3\right\}$$

photon-Z interference

$Y_- = 1-(1-y)^2$

xF_3 term opposite sign for e^+ and e^-, q and $\bar{q}$
=> sensitivity to valence quarks

e^+ vs. e^-

reduced cross section

$$\tilde{\sigma}_{NC}^{e^{\pm}p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma_{NC}^{e^+p}}{dxdQ^2}$$

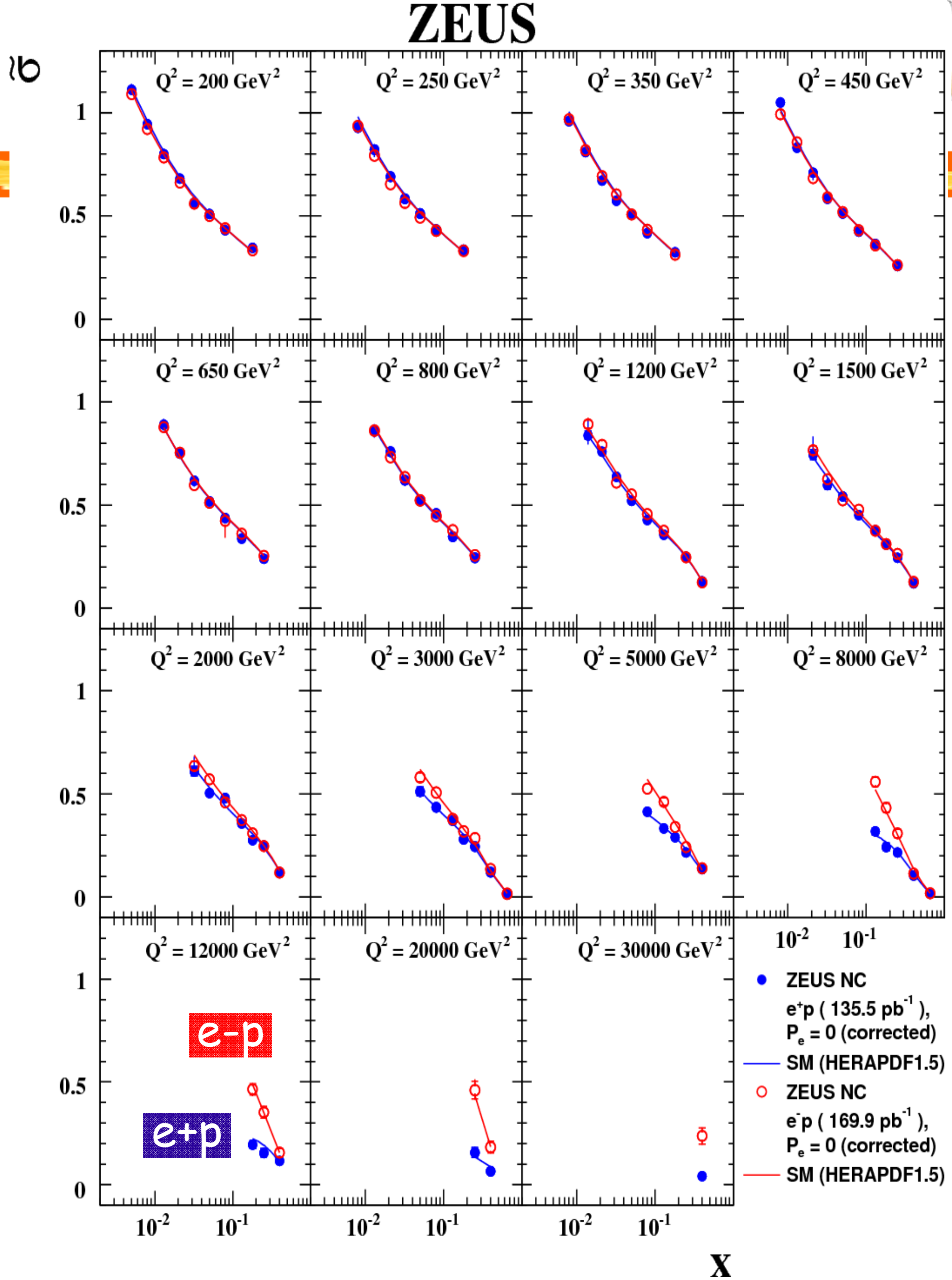
$$= \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

can use difference to extract xF_3

ZEUS final
high Q^2 HERA II results

PRD 87, 052014 (2013)

best precision ~1.5%

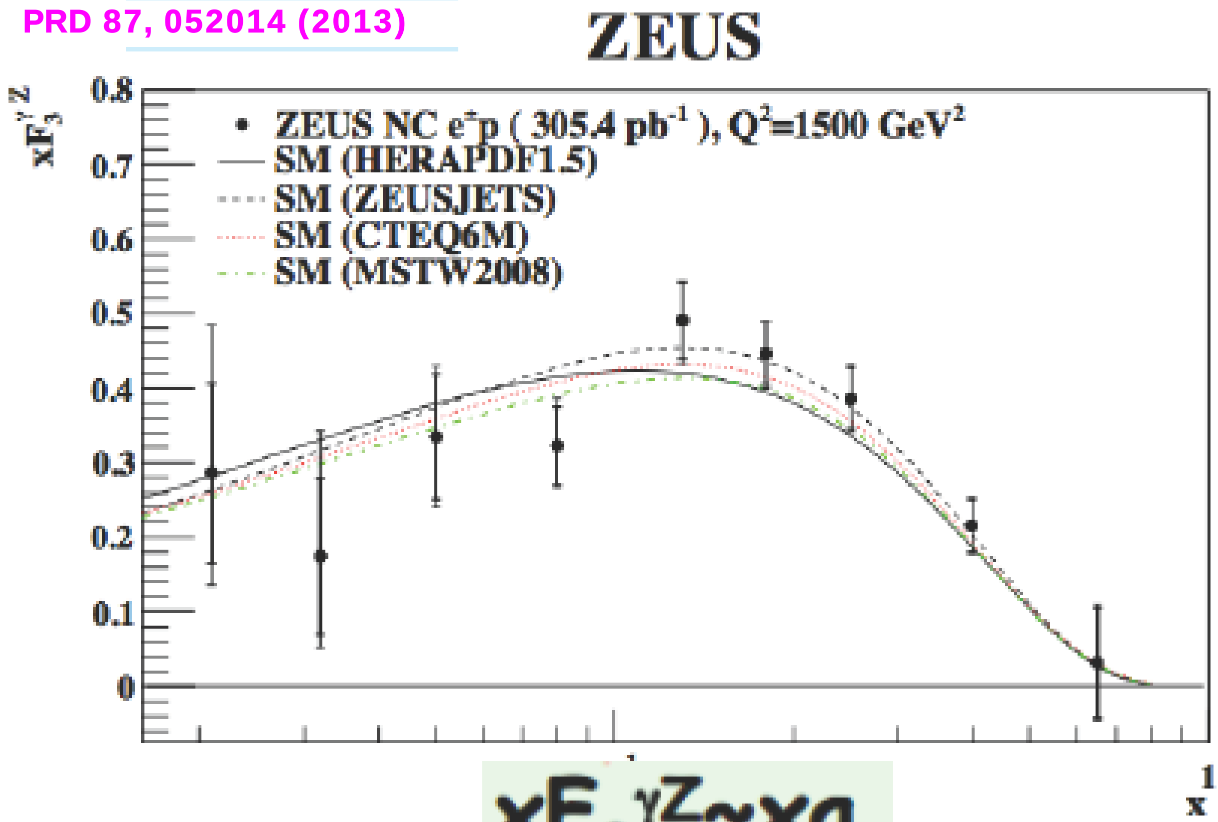


xF_3

- agrees with expectations

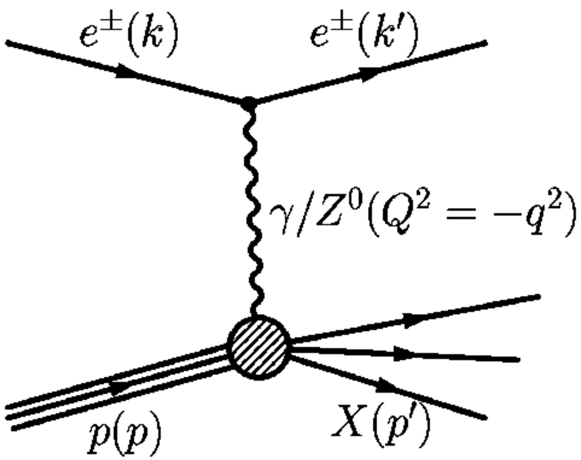
t-channel
weak interaction
contribution and
γZ interference
understood

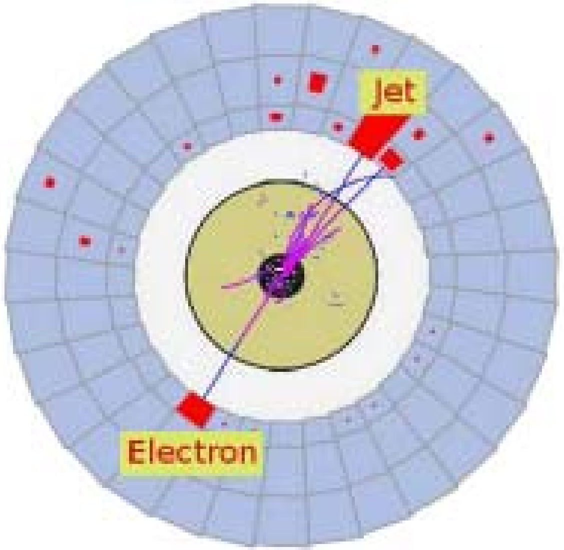
PRD 87, 052014 (2013)

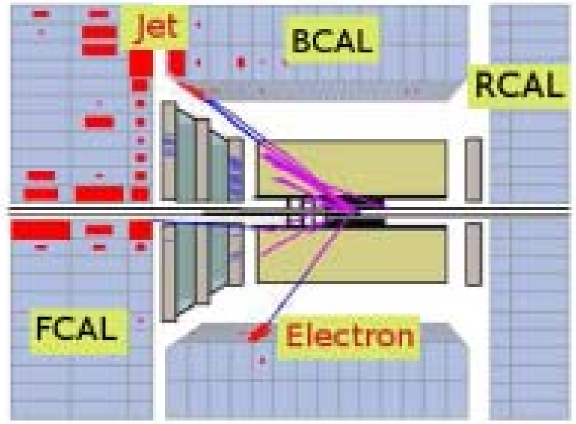


$xF_3^{\gamma Z} \sim xq_v$

Polarized Neutral Current Scattering







$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2) - y^2 F_L(x,Q^2) \;+\!-Y_-\; xF_3\right\}$$

$$F_2^{L,R} = \sum_q [xq(x,Q^2) + x\bar{q}(x,Q^2)]\cdot A_q^{L,R},$$

$$xF_3^{L,R} = \sum_q [xq(x,Q^2) - x\bar{q}(x,Q^2)]\cdot B_q^{L,R}.$$

photon-Z interference

$Y_- = 1-(1-y)^2$

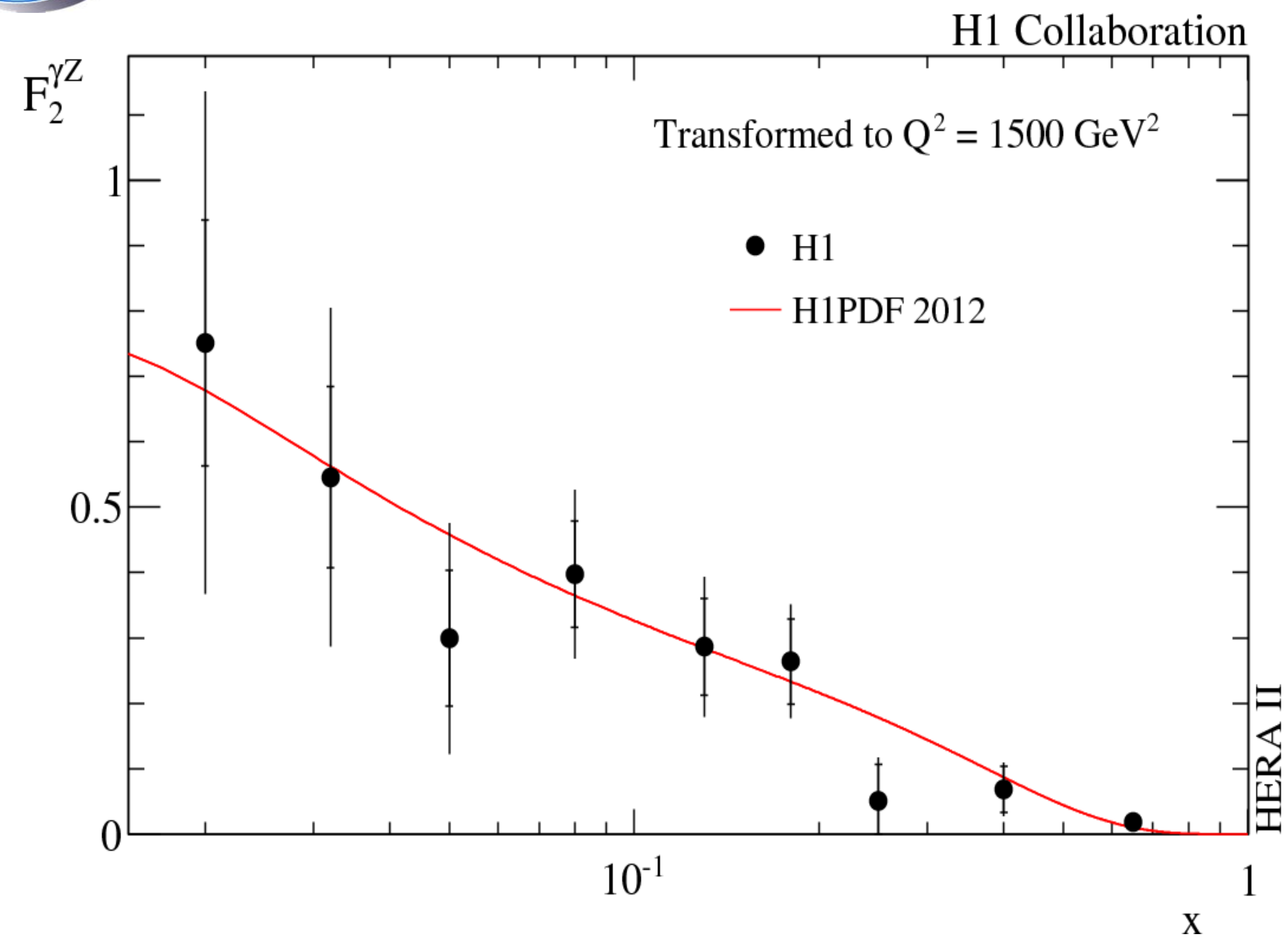
$$A_q^{L,R} = Q_q^2 + 2Q_eQ_q(v_e \pm a_e)v_q\chi_Z + (v_e \pm a_e)^2(v_q^2 + a_q^2)(\chi_Z)^2,$$

$$B_q^{L,R} = \pm 2Q_eQ_q(v_e \pm a_e)a_q\chi_Z \pm 2(v_e \pm a_e)^2 v_q a_q(\chi_Z)^2,$$

additional polarization dependence

Reduced NC cross sections: $F_2^{\gamma Z}$

JHEP 1209:061 (2012)

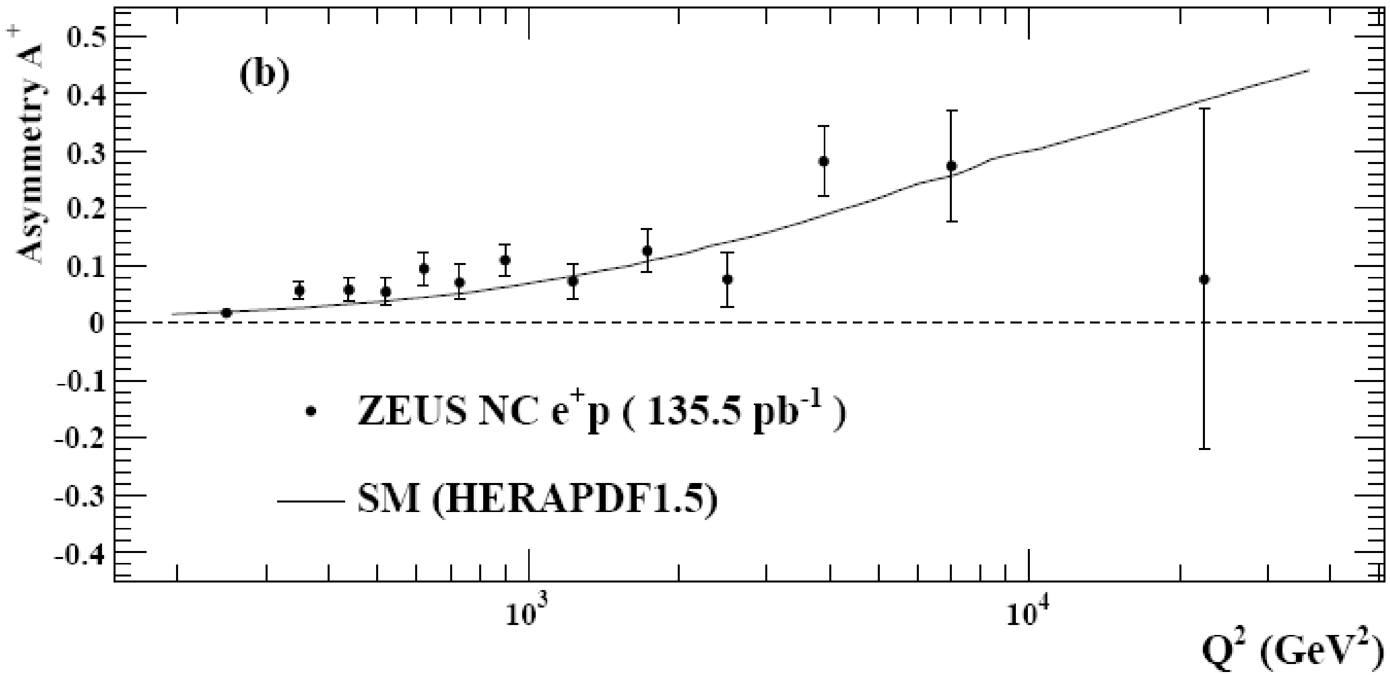


first measurement

→ Data well described by DGLAP NLO QCD

Cross section polarization asymmetry

$$A^{+} = \frac{2}{P_{+} - P_{-}} \frac{\sigma^{+}(P_{+}) - \sigma^{+}(P_{-})}{\sigma^{+}(P_{+}) + \sigma^{+}(P_{-})}$$



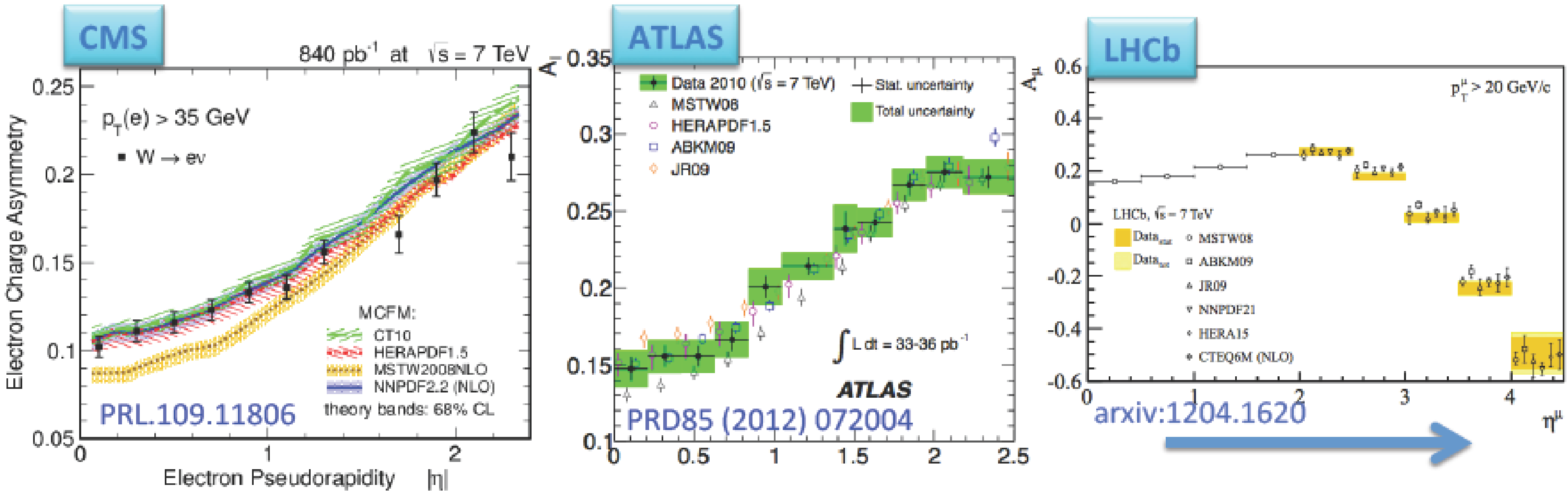
- increasing Z contribution with increasing Q^2
- -> increasing asymmetry, as expected

(these data not included in prediction)

HERAPDF, LHC predictions

- **HERAPDF1.5:** PDF fit to preliminary version of HERA II inclusive DIS data, **performs very well**
- example: W asymmetry at LHC

  - W-asymmetry $A_W = [\sigma(W^+) - \sigma(W^-)] / [\sigma(W^+) + \sigma(W^-)] = (u_v - d_v) / (u_v + d_v + 2\,\text{qbar})$ at x1=x2

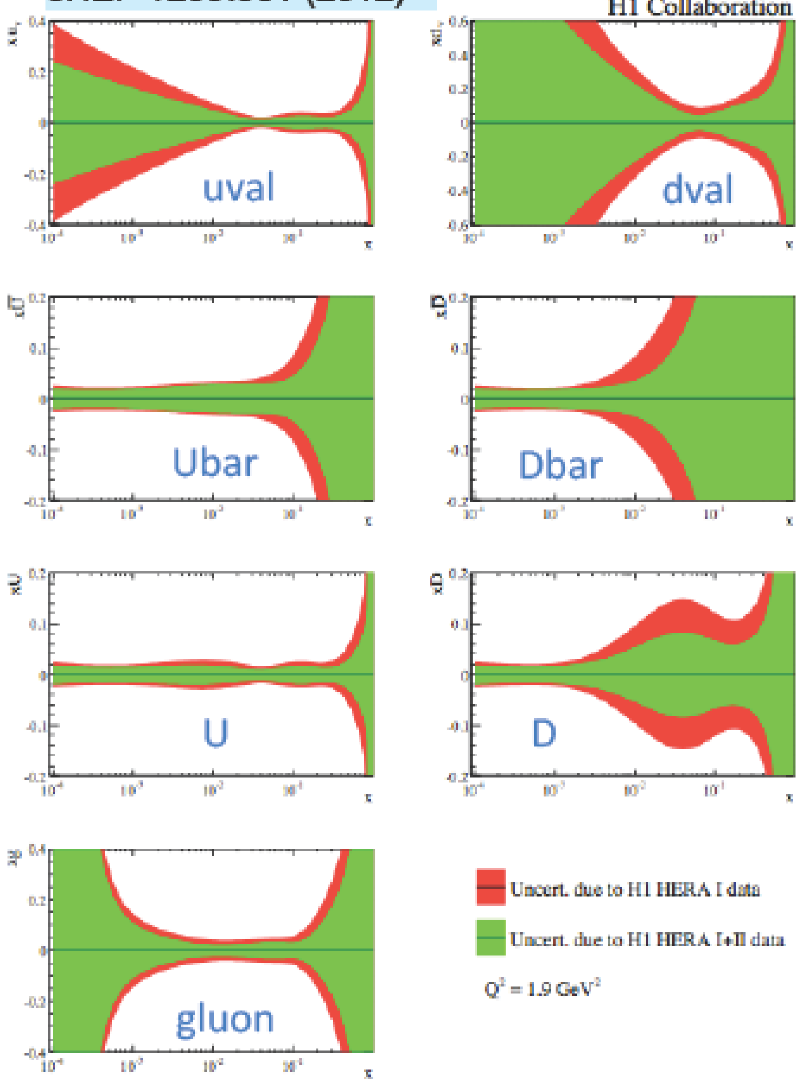


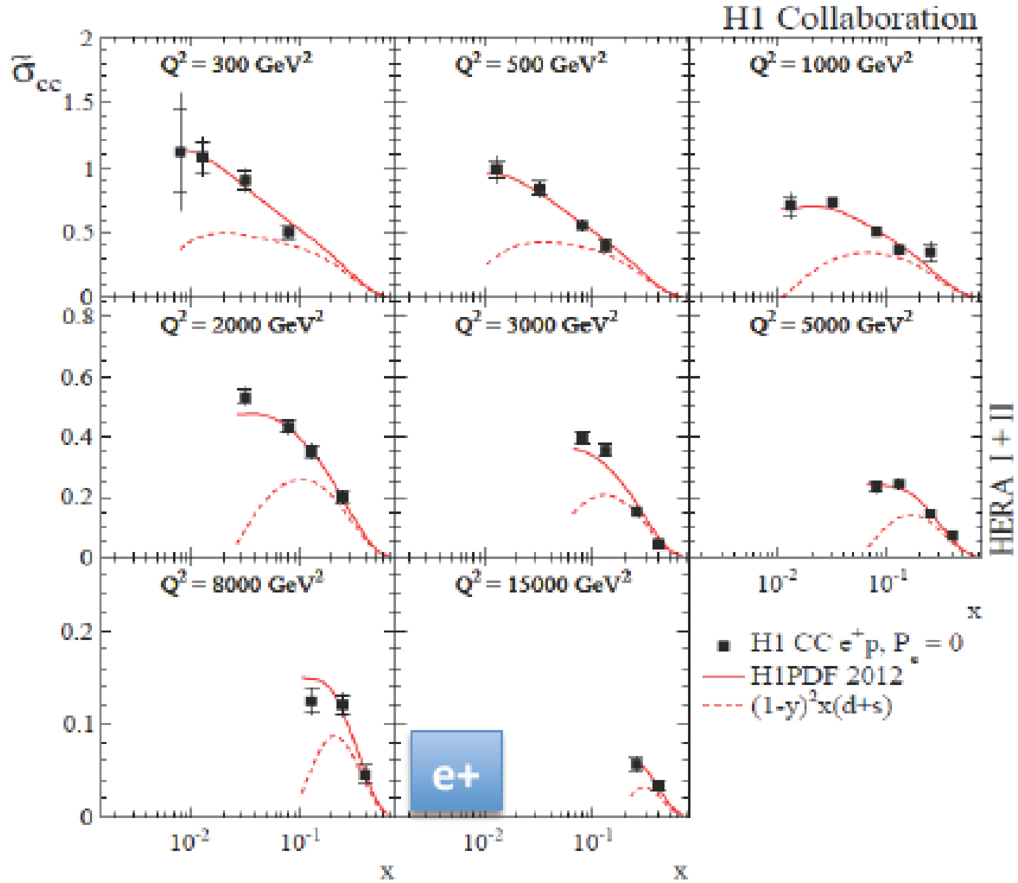
- similar performance for jet production

Towards HERAPDF2.0: impact of HERA II

HERA II luminosity for e+(e-)p improved by factor 3 (10)

JHEP 1209:061 (2012)



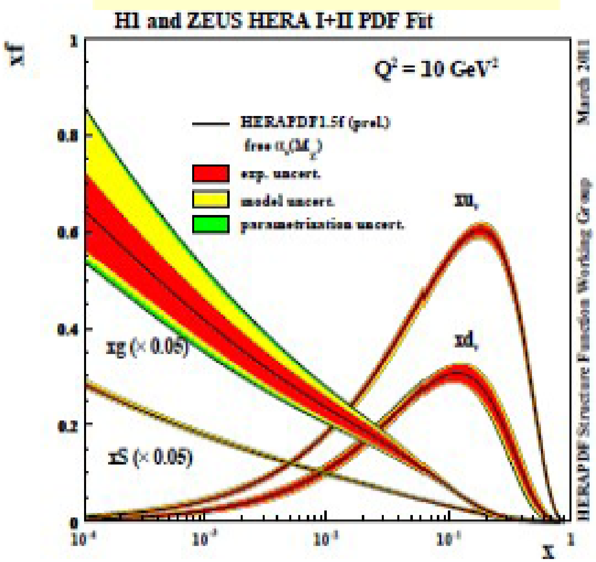


New measurements improve the PDF uncertainties at high x, in particular D=d+s

Including jets in PDF fit

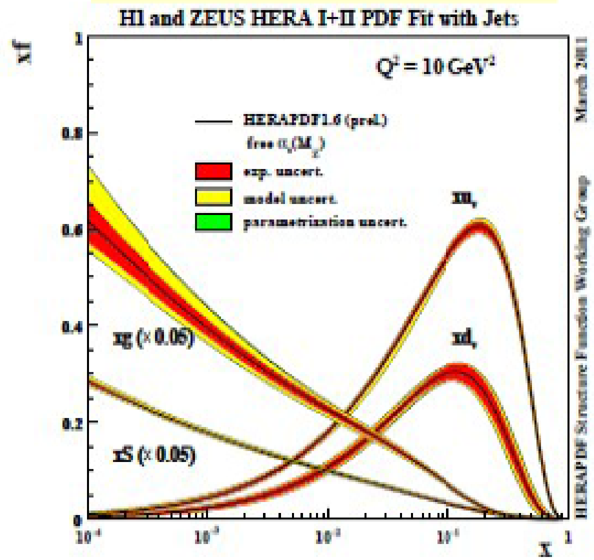
- Jets in DIS: see talk S. Mikocki

No Jets, $\alpha_s(M_z)$ free



Adding jets

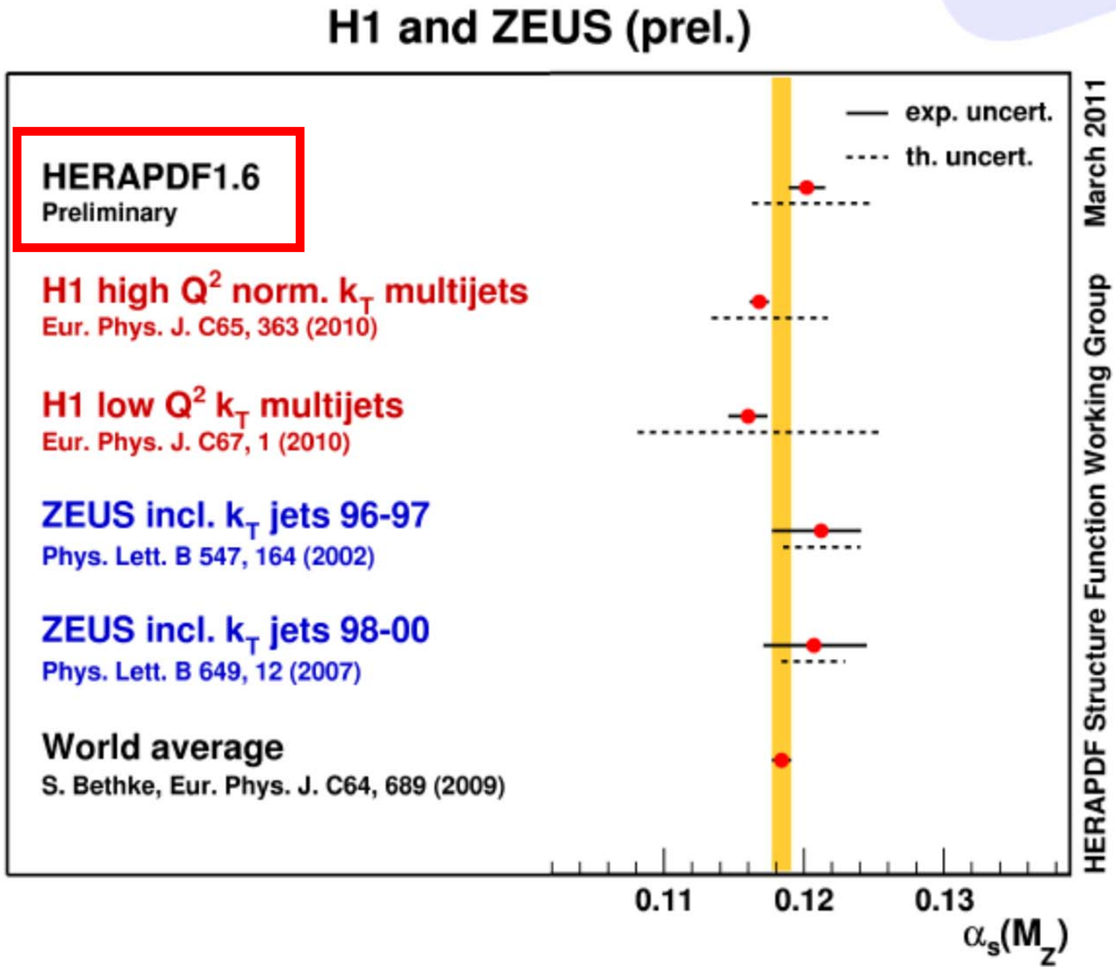
+ Jets, $\alpha_s(M_z)$ free



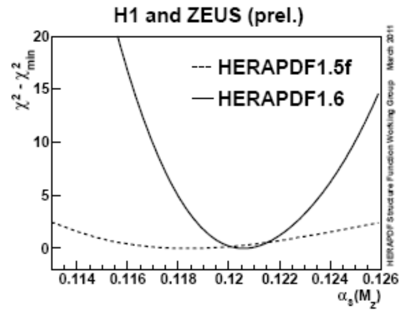
Adding jet data dramatically decreases
the low-x gluon uncertainty, not only
the experimental but also
the model and parametrization uncertainties

PDF fit including Jets + free α_s

ZEUS-prel 11-001
H1-prelim 11-034



$$\alpha_s = 0.1202 \pm 0.0013(exp) \pm 0.0007(mod/par) \pm 0.0012(hadr) {}^{+0.0045}_{-0.0036}(scale)$$



decorrelates α_s and gluon

agrees well with world average

uncertainty dominated by NLO theory, need NNLO !

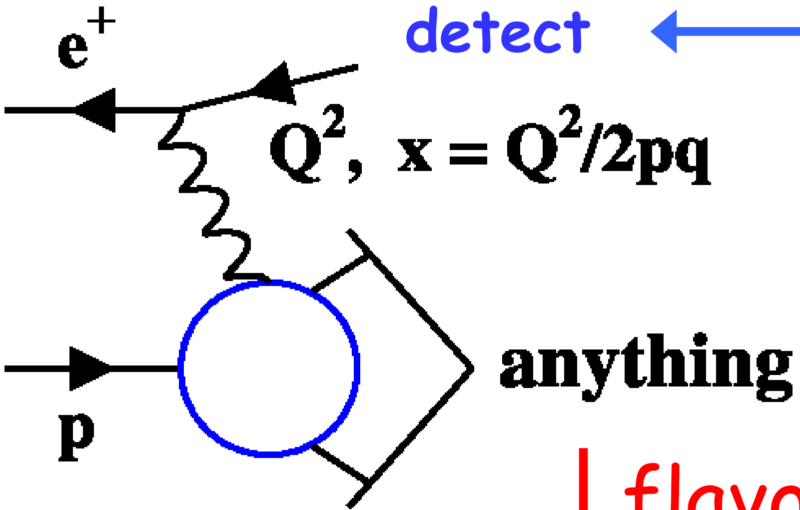
The Charm of HERA

Combination and QCD analysis of charm production cross section measurements in DIS at HERA

technical details:
DESY 12-172, EPJ C73 (2013) 2311

- data combination
- PDF fits
- measurement of m_c
- impact on LHC cross sections

Heavy flavour contributions to F_2

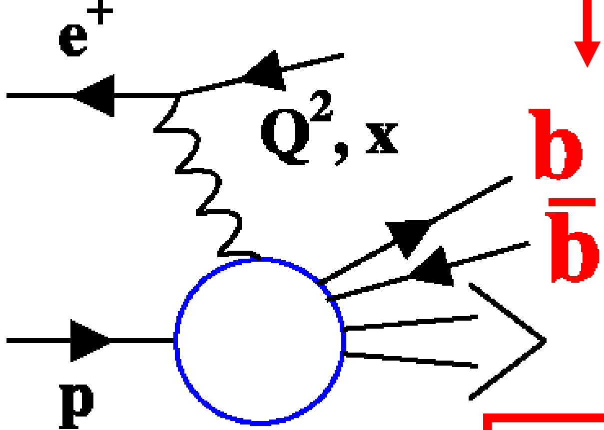


detect ⟷

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2)\right.$$

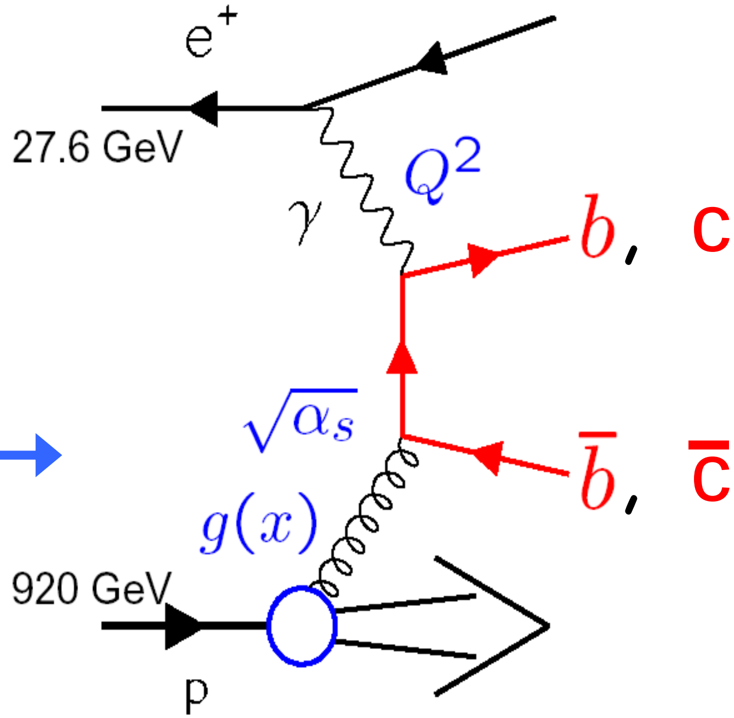
flavour tagging



-> $F_2^{b\bar{b}}$, $F_2^{c\bar{c}}$

QCD ⟷

\+ ...



Why are heavy flavours important?

- charm contribution to DIS data up to 40%!
- **kinematic effect of mass**
- **competing scales for perturbative expansion**

  e.g. m, Q^2, p_T -> terms $\log Q^2/m^2$

  $\log p_T^2/m^2$ etc.

=> "**massless**" treatment allows resummation, but fails near "mass threshold" -> avoid !

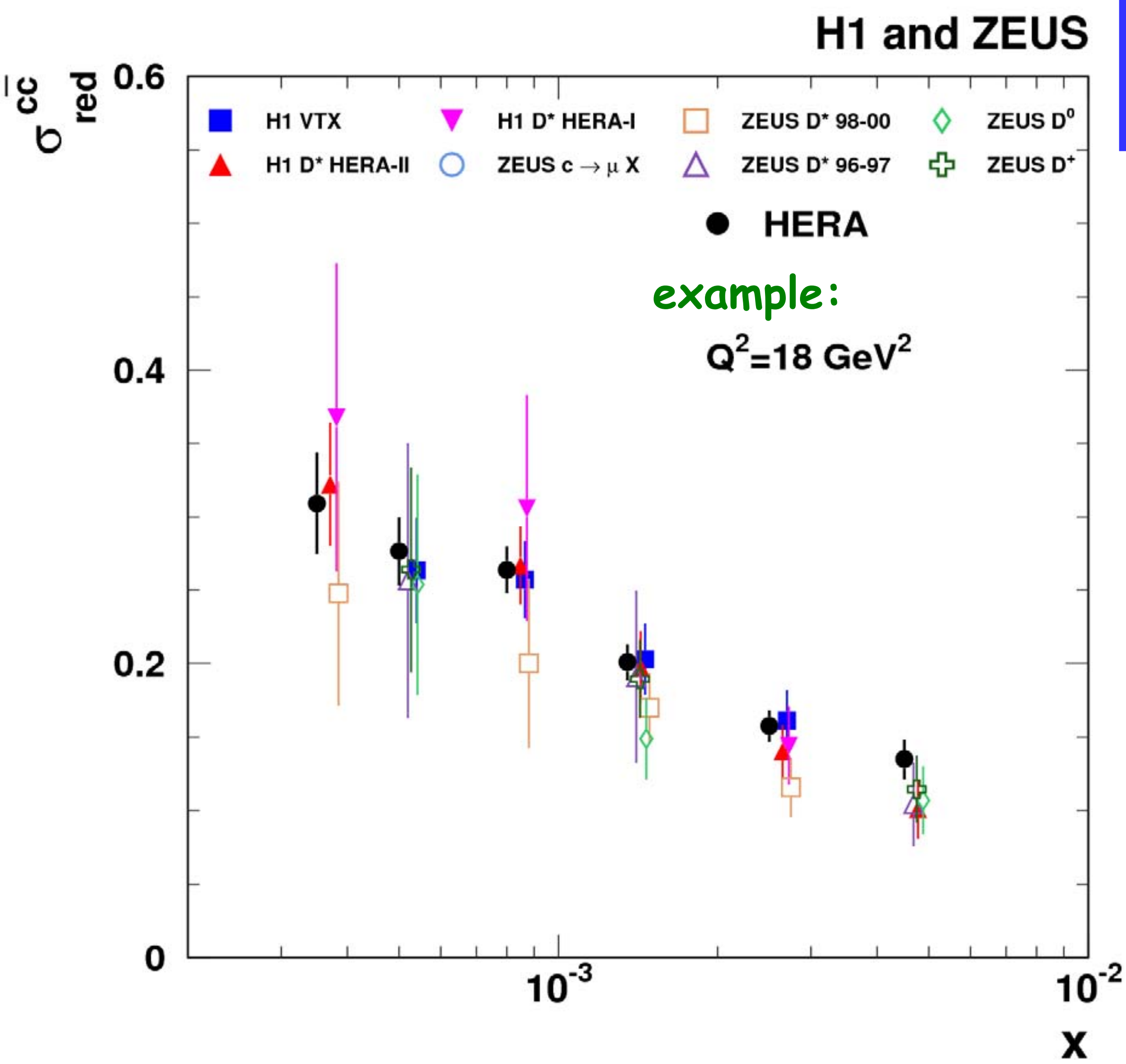
=> "**massive**" treatment gets kinematics right, but does not allow resummation (fixed flavour number schemes) or induces ambiguities in QCD corrections near flavour threshold (variable flavour number schemes)

check different schemes against HERA data

HERA charm data combination

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[1+(1-y)^2\right]\sigma_{red}^{cc}$$



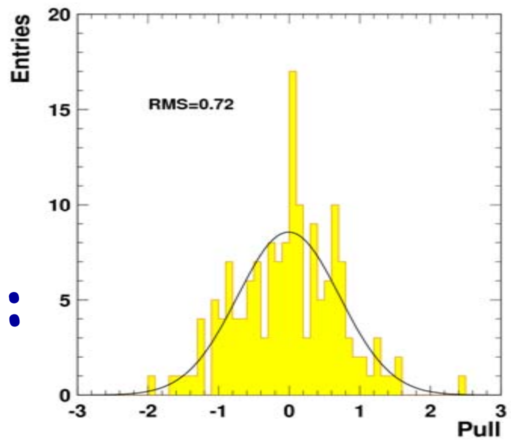
9 data sets
(HERA I, HERA II)

5 charm tagging methods
-> see talk S. Mergelmeyer

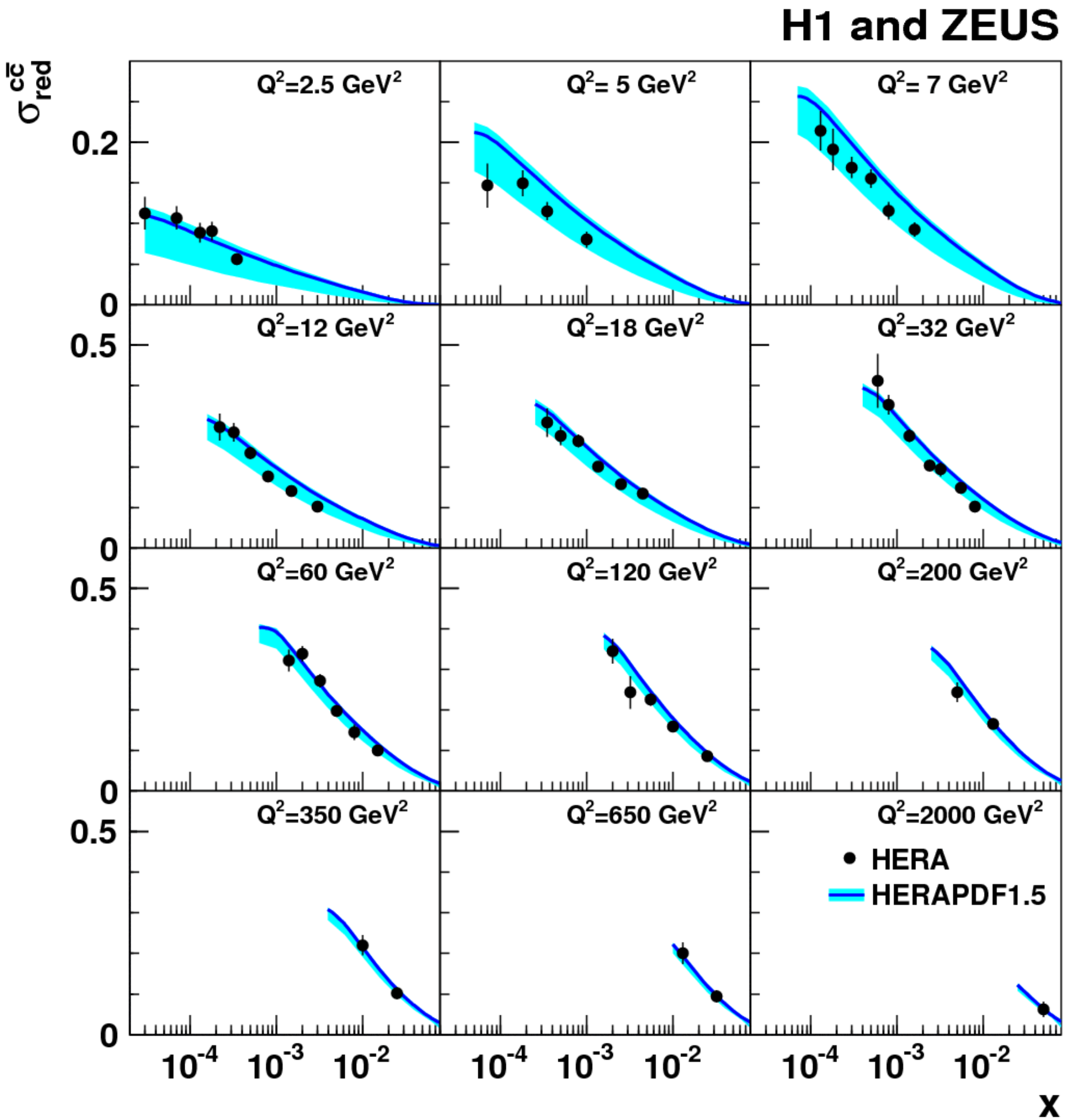
155 -> 52 data points

48 correlated systematic uncertainties

very good self-consistency of data:



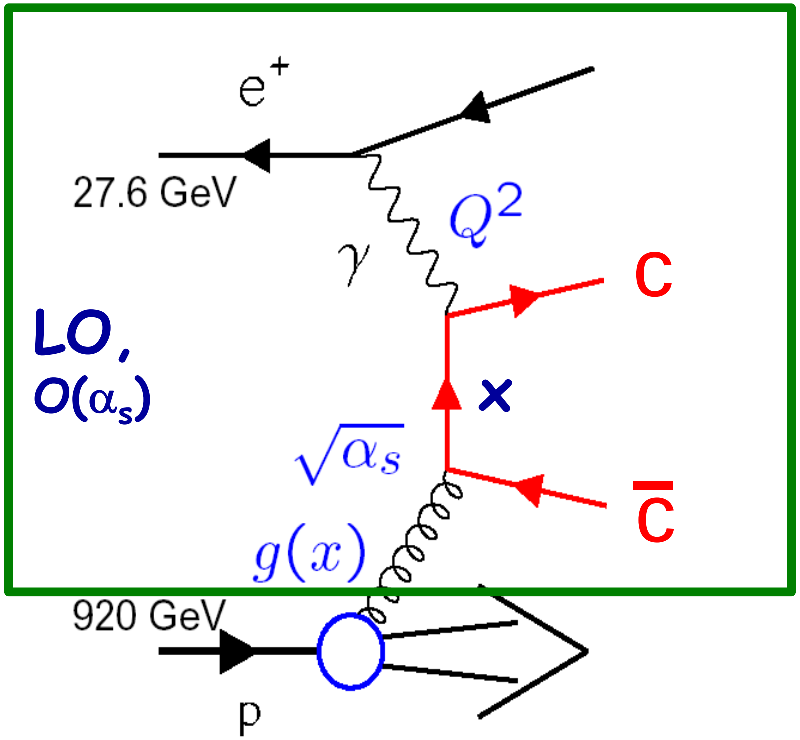
Combination result



well described using HERAPDF1.5
(fitted from inclusive DIS only)

strong charm mass dependence
(blue band: 1.35-1.65 GeV)

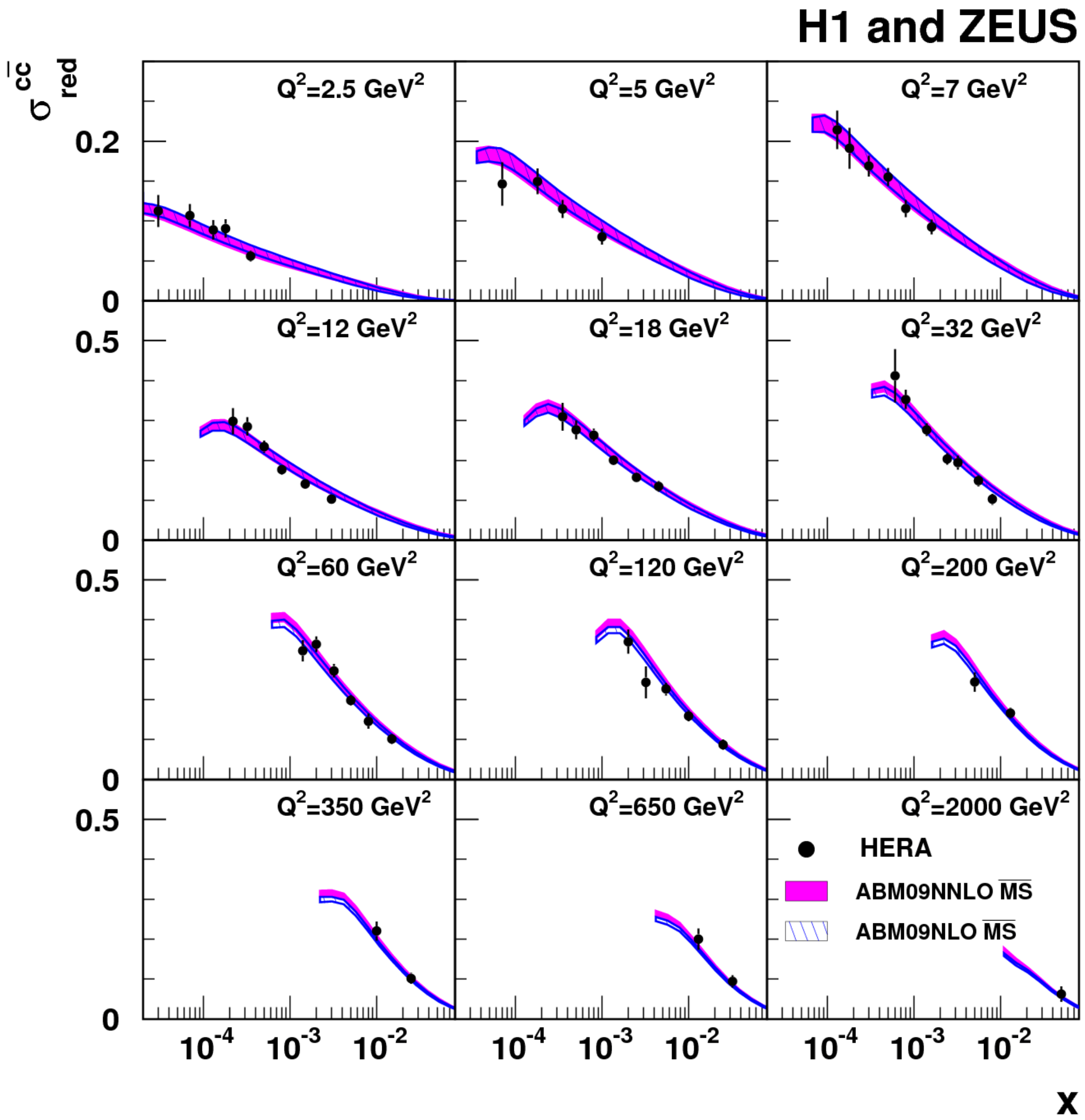
Fixed Flavour Number Scheme (FFNS)



+ NLO, O(α_s^2)
(+partial NNLO, O(α_s^3))
corrections

- no charm in proton
- full kinematical treatment of charm mass
  (multi-scale problem:
  Q^2, p_T, m_c -> logs of ratios)
- on-shell (pole) or $\overline{MS}$ mass renormalization
- no resummation of logs

comparison to ABM FFNS



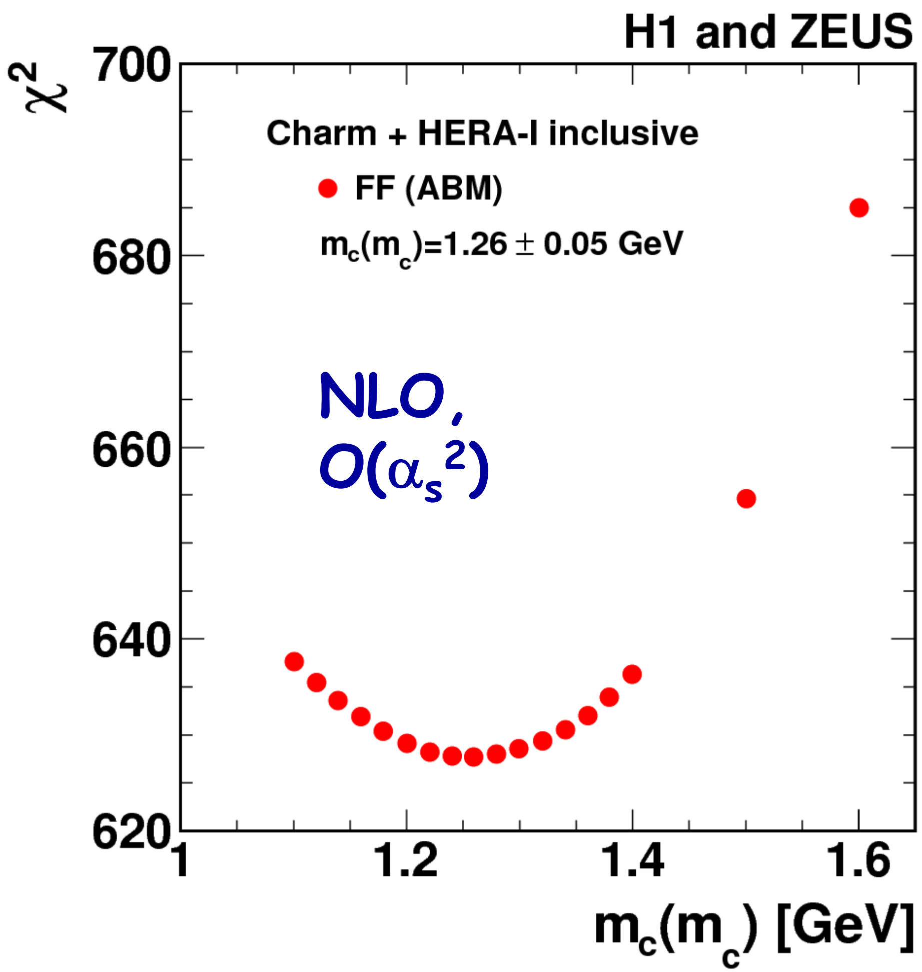
very good description of data in full kinematic range

unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass NLO, partial NNLO

(similar predictions for pole mass)

measurement of $\overline{MS}$ charm mass



simultaneous fit of combined charm data and inclusive HERA I DIS data (HERAFitter)

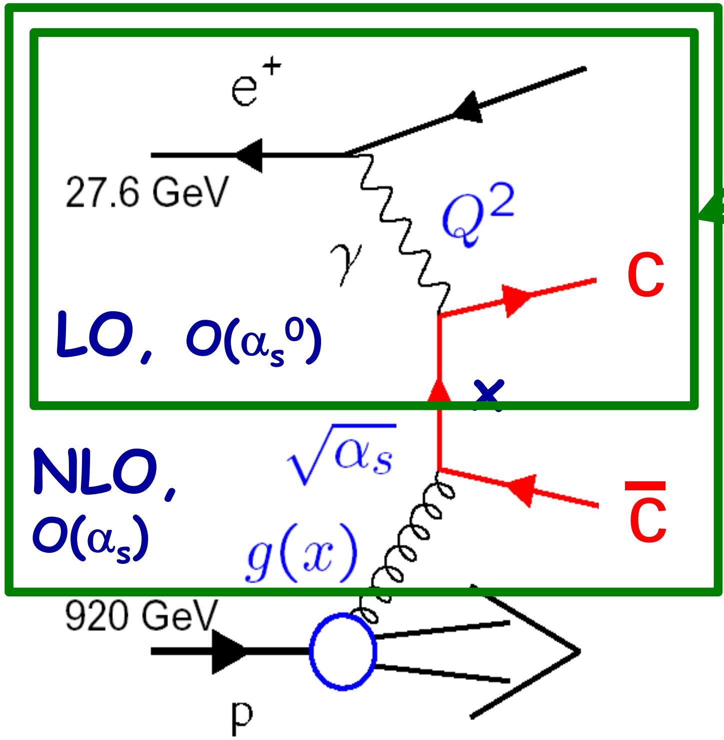
$\chi 2$ = 628/626, 44/47 (charm)

mod: vary f_s, m_b, Q^2_{min}, PDF param

$m_c(m_c)$ = 1.26 ±0.05$_{exp}$ ±0.03$_{mod}$ ±0.02$_{\alpha s}$ GeV

PDG: 1.275 ±0.025 GeV (lattice QCD + time-like processes)

Variable Flavour Number Scheme (GM-VFNS)



+ NNLO, O(α_s^2) corrections

very high Q^2:

- massless charm in proton
- resummation of $\log(Q^2/m^2)$ etc.

very low Q^2:

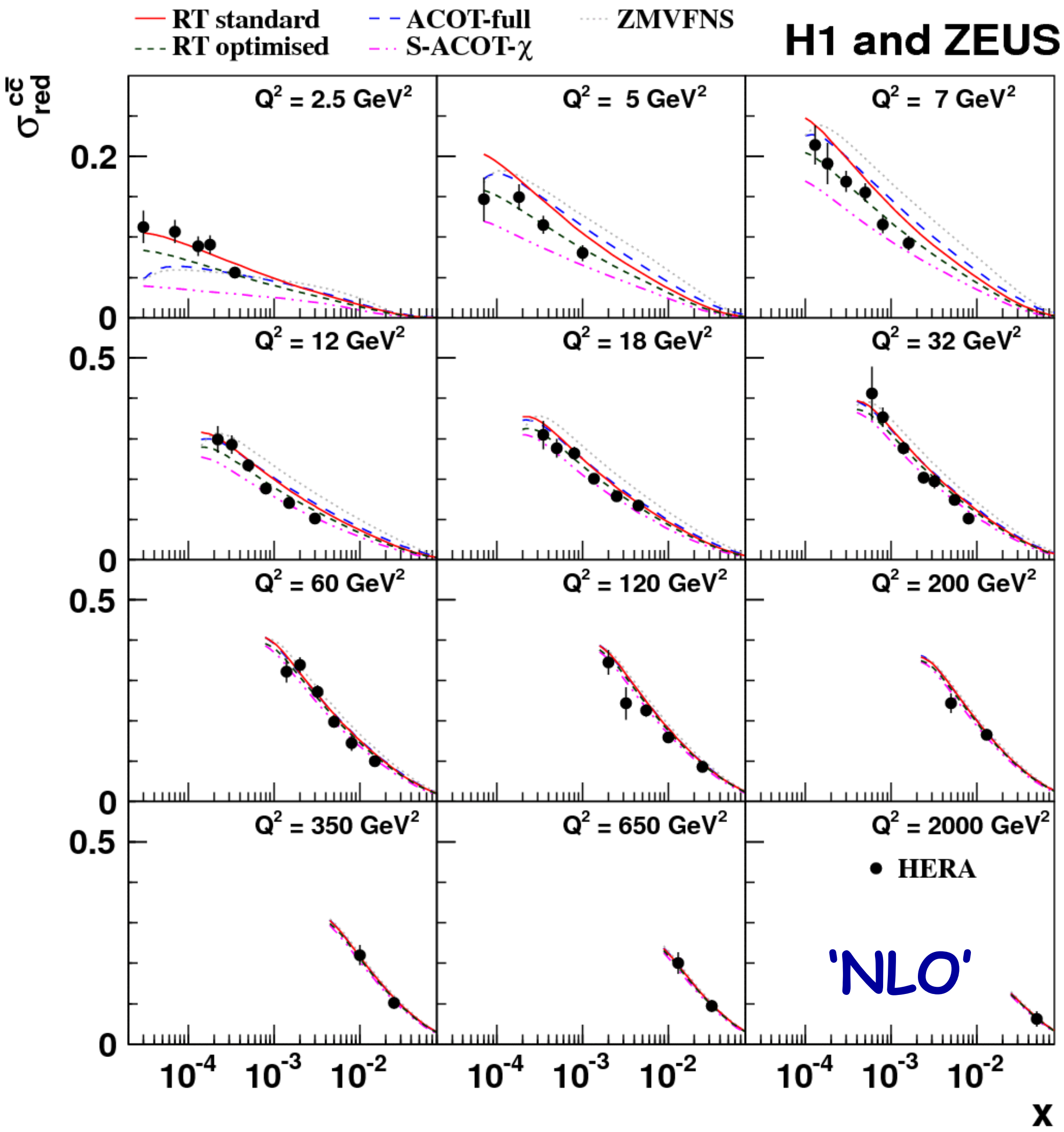
- massive calculation (pole mass)

in between (almost everywhere):

- kinematic interpolation and/or correction terms

comparison to various VFNS

more comparisons see paper



as implemented in HERAFitter (talk A. Gizhko)

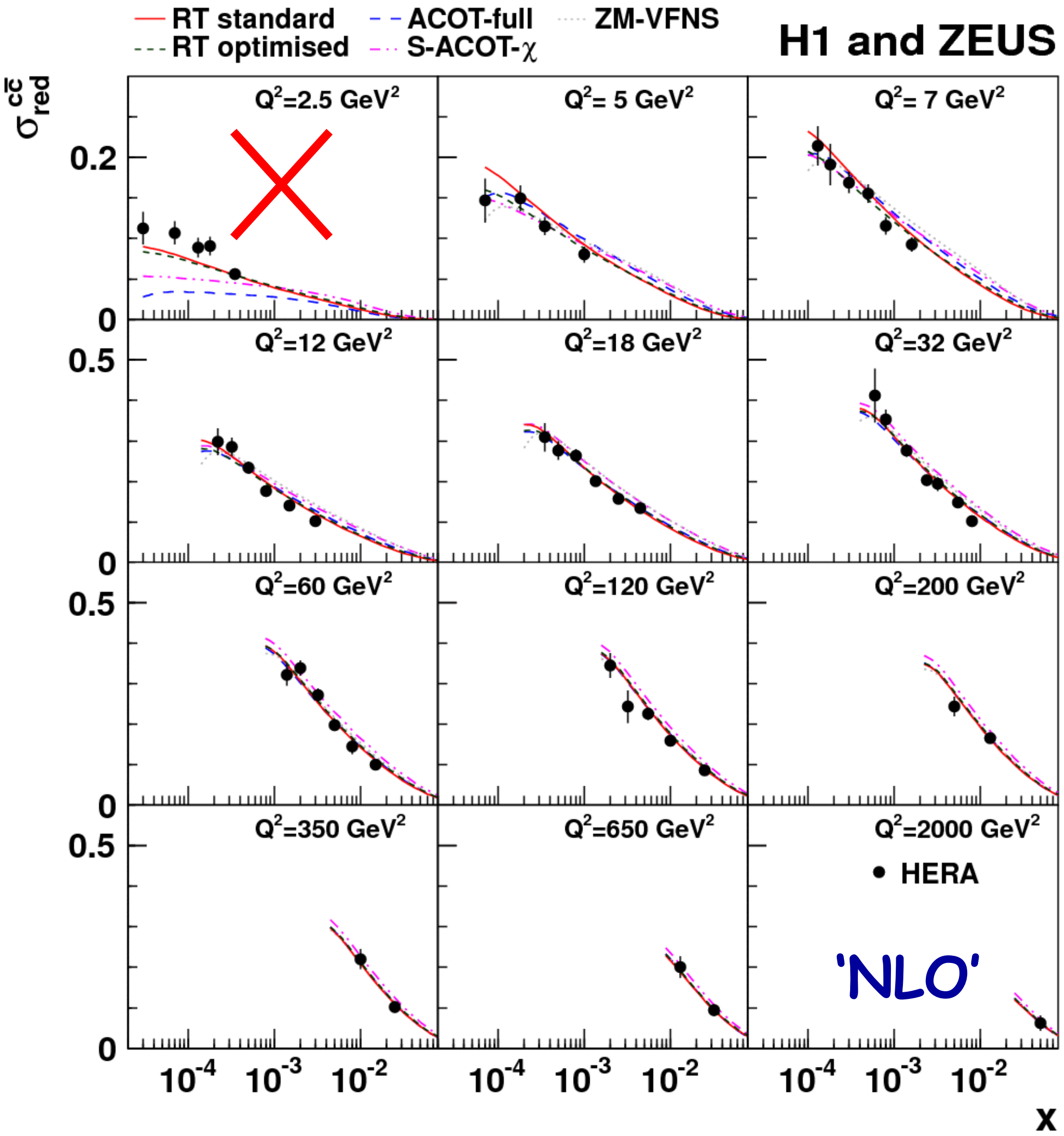
m_c (pole) fixed to 1.4 GeV

differences mainly due to different matching schemes of massive and massless parts

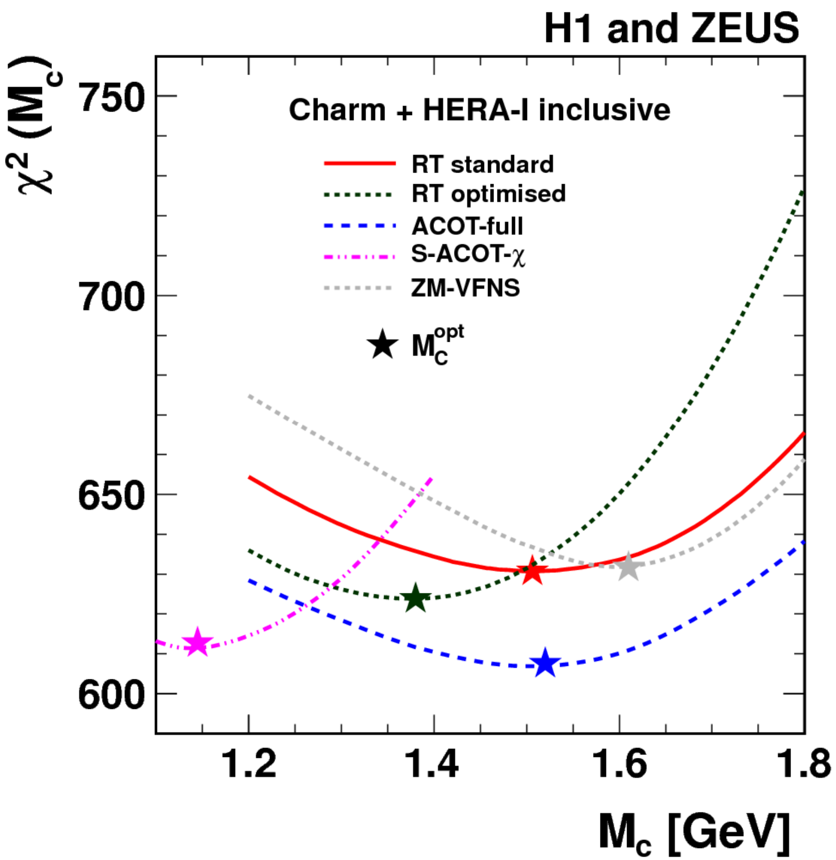
+ corresponding additional parameters in interpolation terms

-> we treat mass in VFNS as effective parameter

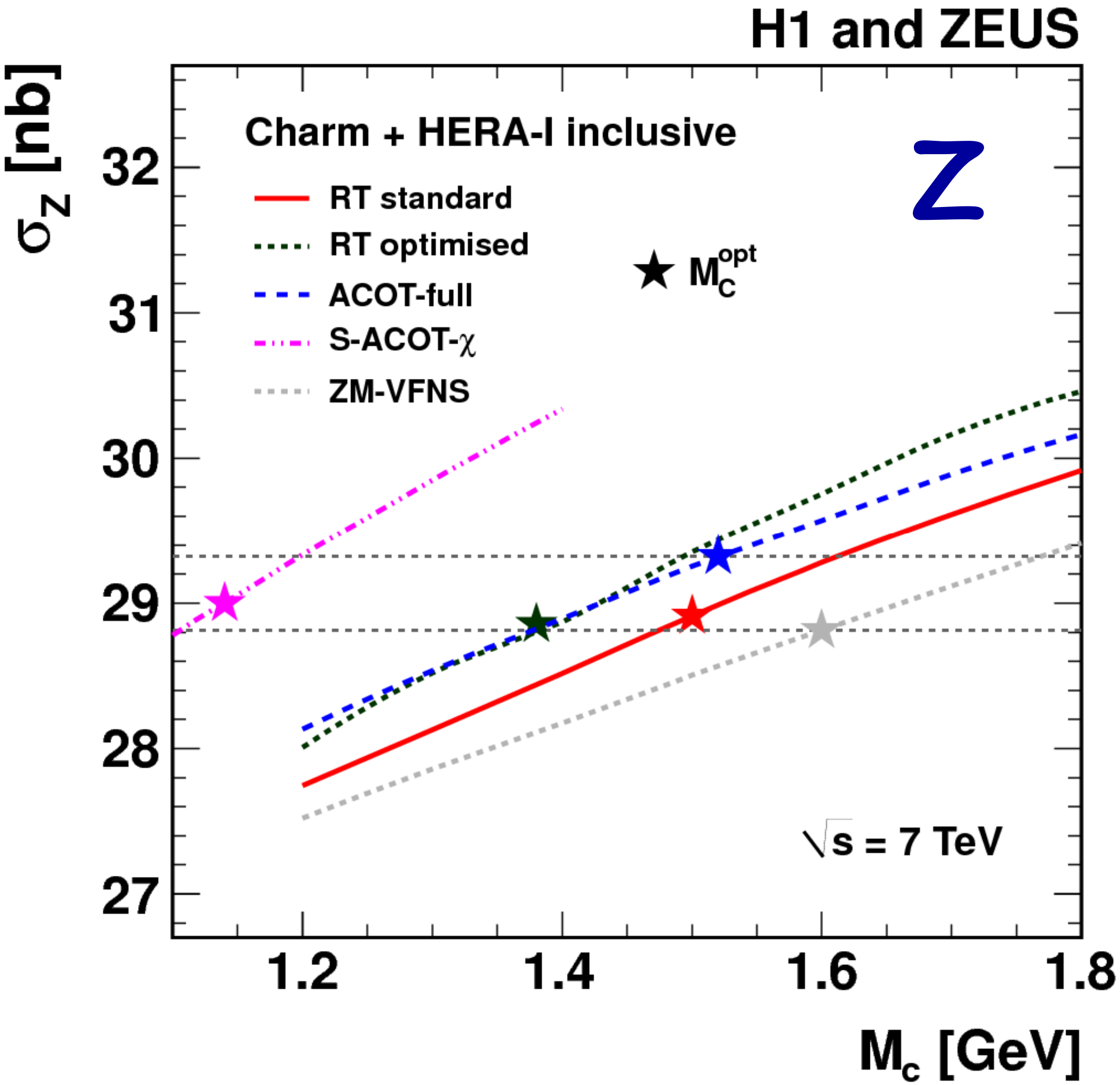
comparison to various VFNS

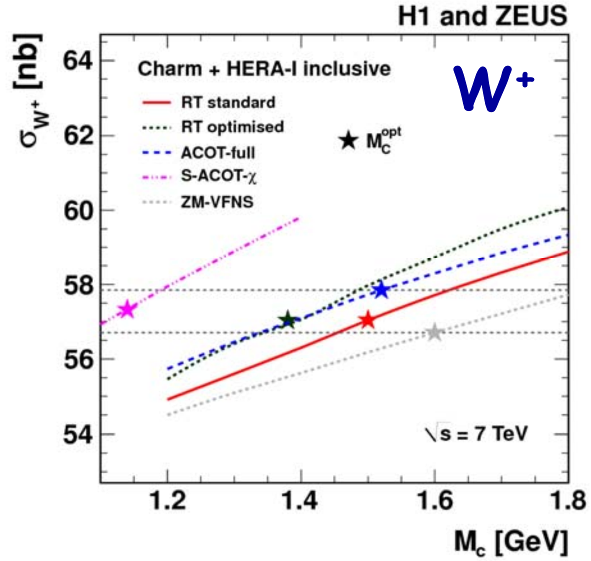


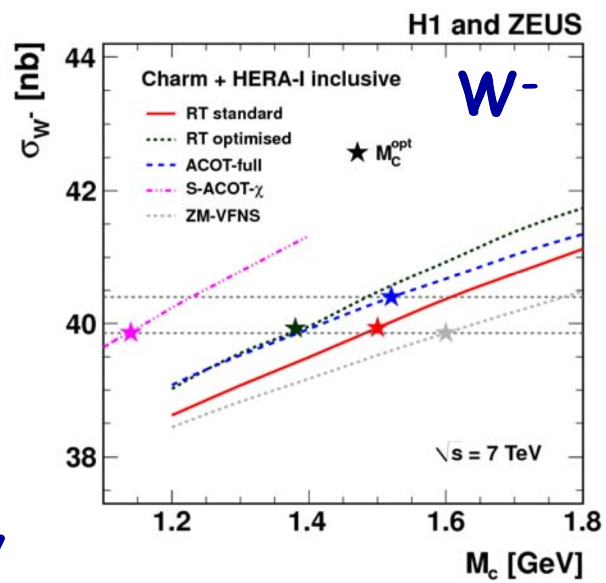
fit optimal mass for each scheme ($Q^2 > 3.5$ GeV²)



Z, W cross section predictions for LHC



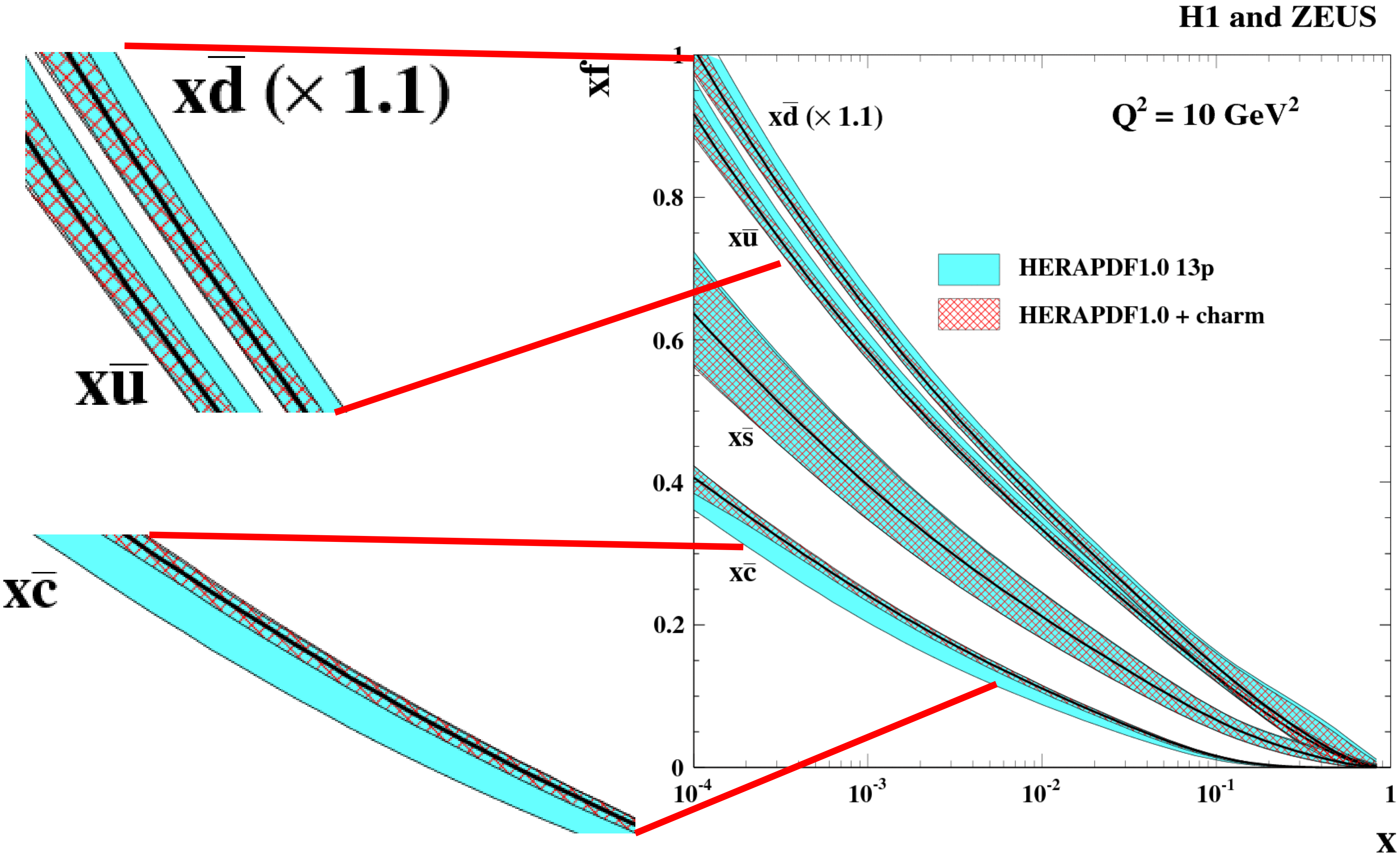




optimal M_c significantly reduces uncertainty

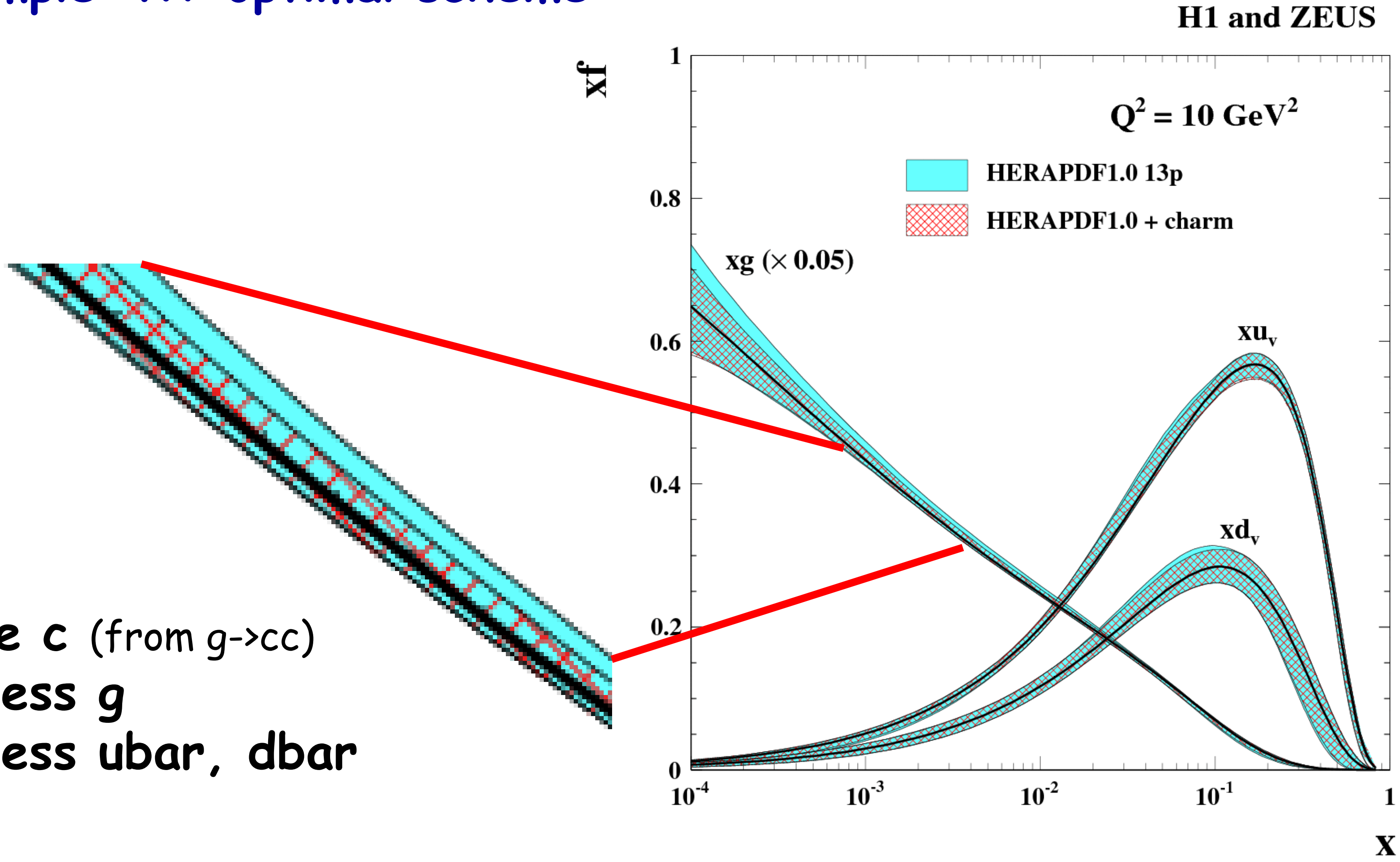
Charm data stabilize sea flavour composition

example: RT optimal scheme



and reduce gluon uncertainty

example: RT optimal scheme



more c (from g->cc)
-> less g
-> less ubar, dbar

-> expect reduced uncertainty also for Higgs cross section

New charm results in DIS: D* and D+

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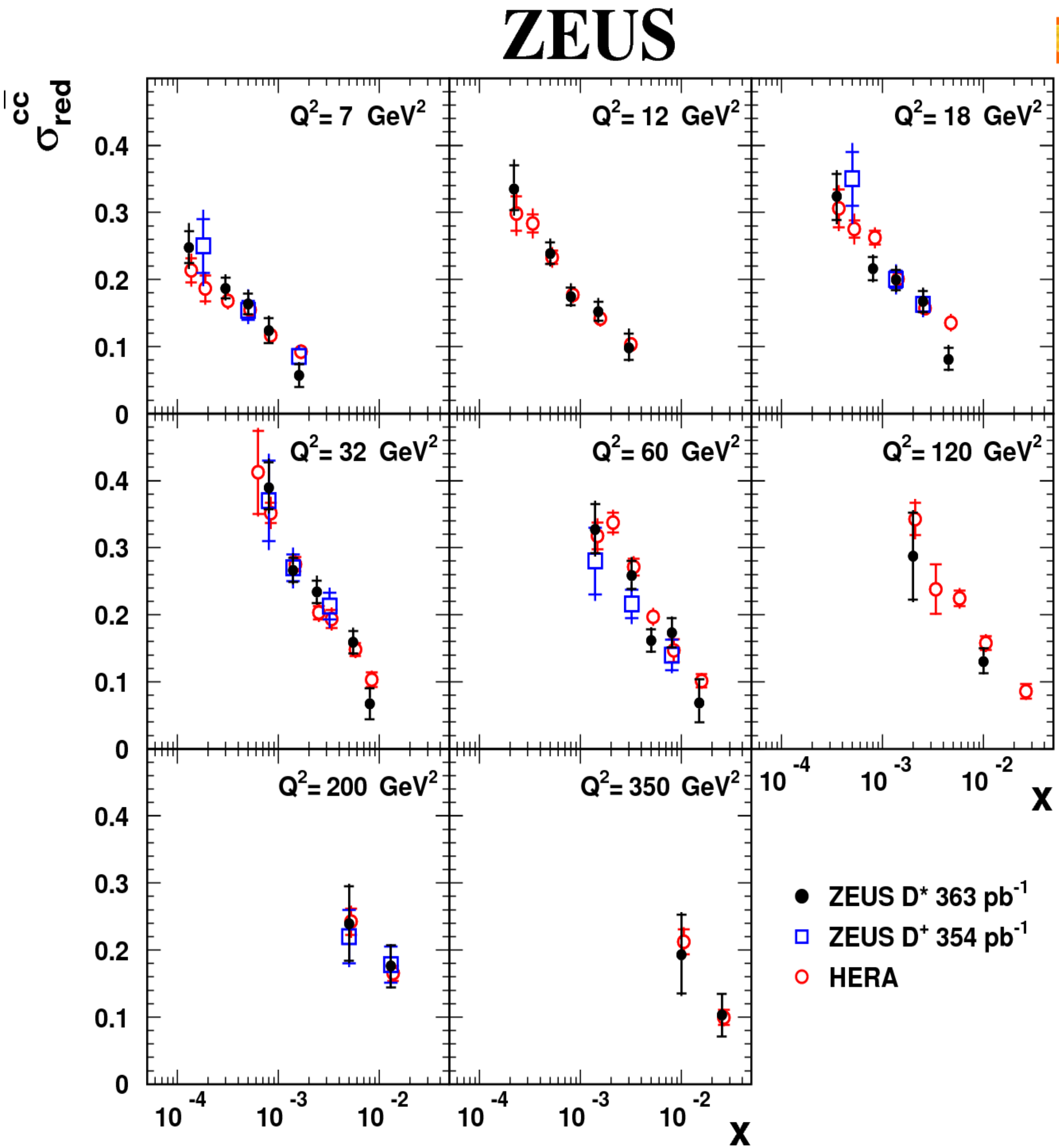
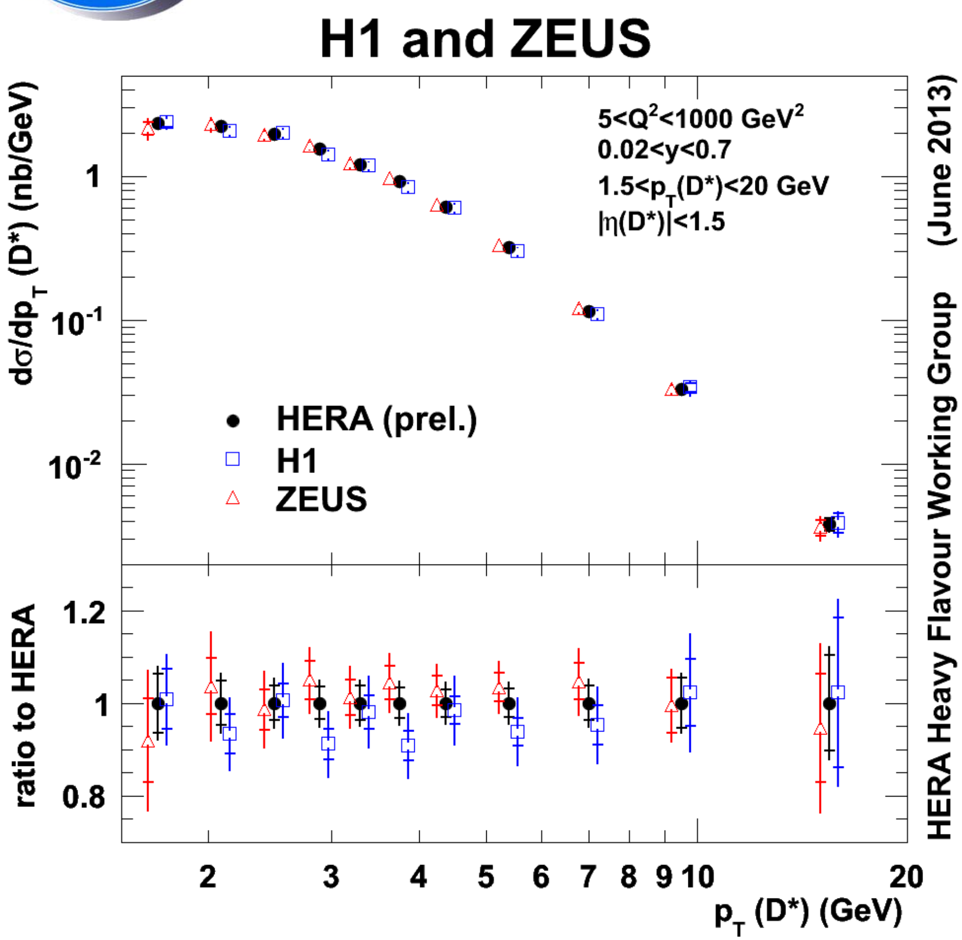
JHEP 05 (2013) 097

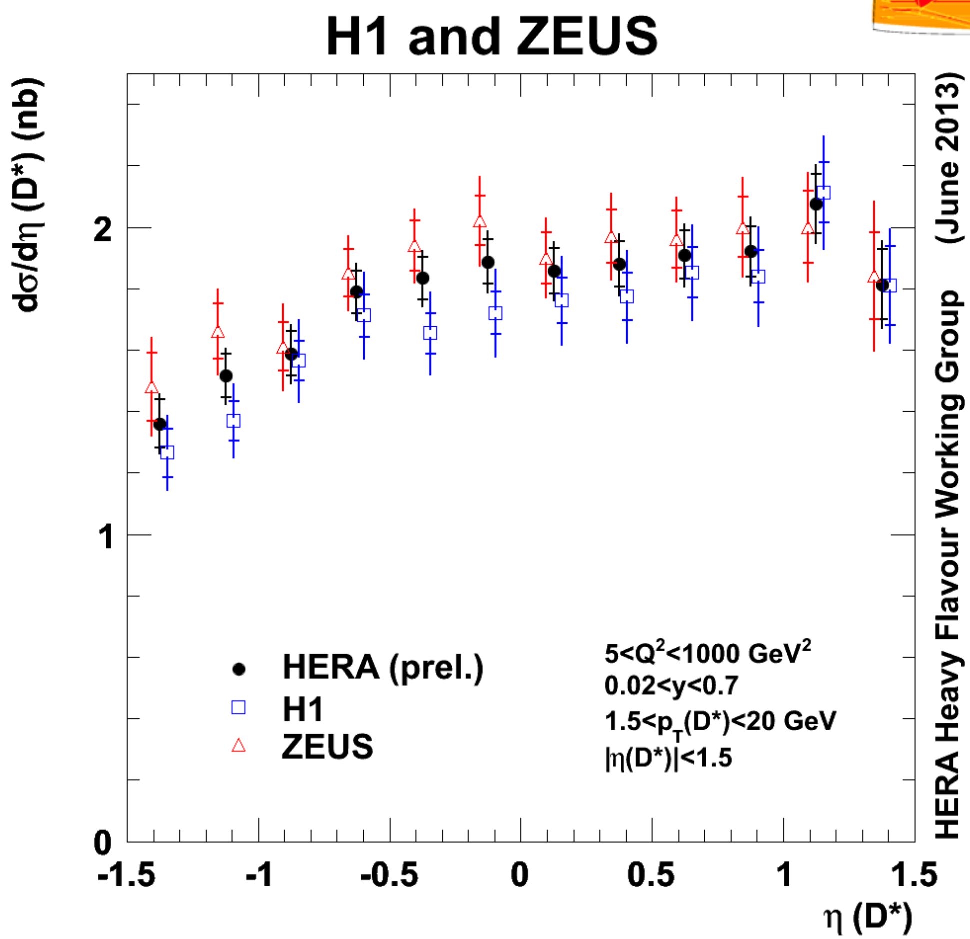


→ consistent findings
→ new ZEUS results will further improve combination, PDF and m_c fits

H1/ZEUS D* cross section combination

ZEUS-prel 13-002, H1-prelim 13-141

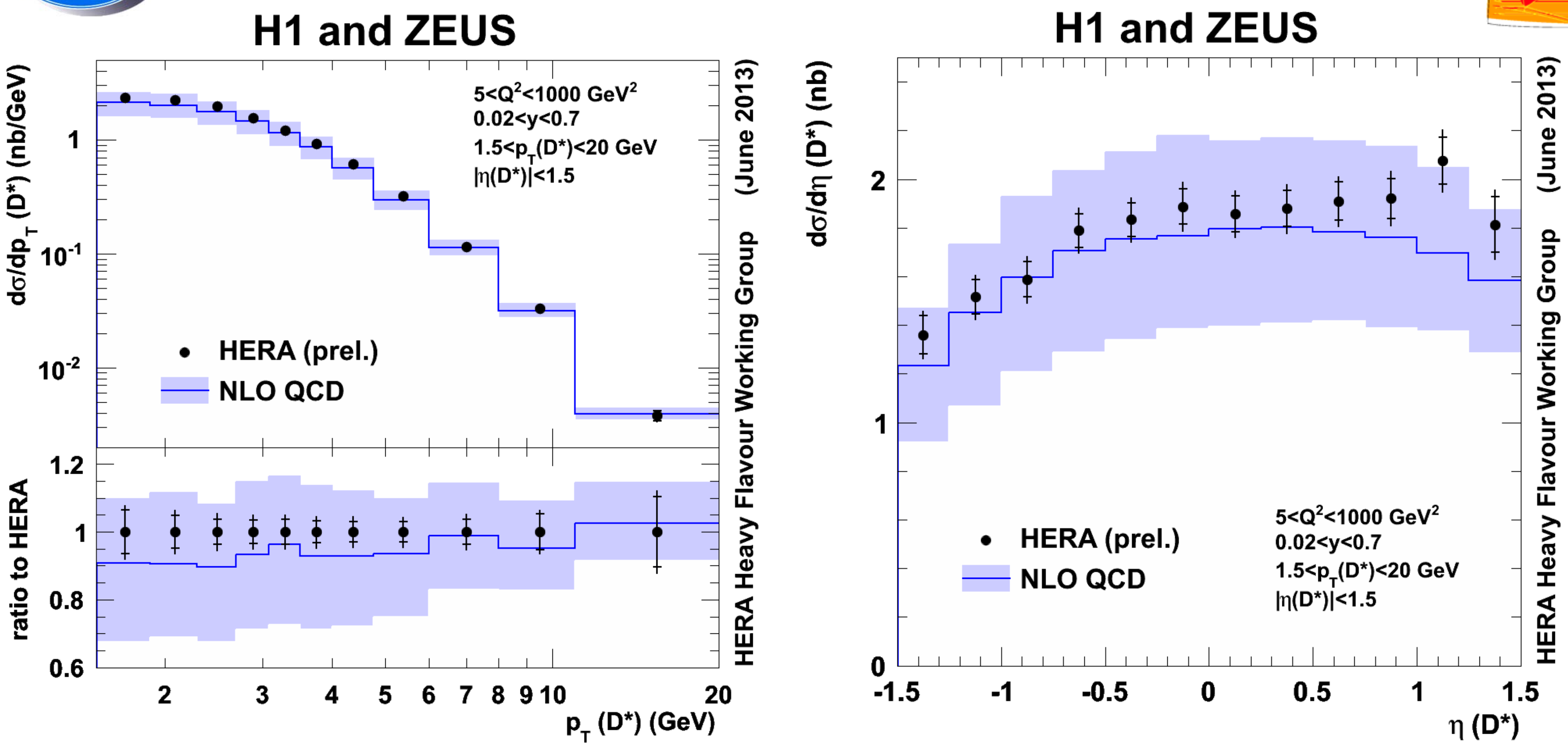




- good agreement between experiments

H1/ZEUS D* cross section combination

ZEUS-prel 13-002, H1-prelim 13-141



and with massive NLO QCD calculations

Summary and conclusions

- **Final HERA inclusive DIS data have been published by H1 and ZEUS**
  well described by DGLAP NLO (and NNLO) QCD
  final versions of textbook plots for electroweak unification and lefthandedness of CC

- **Virtual γ-Z interference** has been measured and is well described by Stand Model.
  Real Z production has been observed (smallest cross section ever measured at HERA)

- **HERA DIS Charm data have been combined**
  very good consistency, reduced uncertainties, very well described by NLO QCD in FFNS
  -> measure running charm mass ($\overline{MS}$): $m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

- **different VFNS variants prefer different optimal charm masses**
  (additional parameter(s) for interpolation between massless and massive calculations)
  -> good description of data with 'optimal' mass in all variants

- **PDF fits including jet and/or charm data significantly reduce PDF uncertainties**
  (more precise gluon, stabilization of flavour composition)
  -> reduced uncertainties for predictions at LHC

- **-> towards including final inclusive DIS data, charm, and jet data in HERAPDF2.0**

Backup

Table of different heavy quark schemes

Theory (PDF)	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.-$\mathcal{O}(\alpha_s^3)$	-			

Table 6: Calculations from different theory groups as shown in figures 5-8. The table shows the heavy flavour scheme used and the corresponding reference, the respective $F_{2(L)}$ definition (section 2), the value and type of charm mass used (equation (3)), the order in α_S of the massive and massless parts of the calculation, the value of α_s, the renormalisation and factorisation scale, and which HERA charm data were included in the corresponding PDF fit. The distinction between the two possible $F_{2(L)}$ definitions is not applicable (n.a.) for $\mathcal{O}(\alpha_s)$ calculations.

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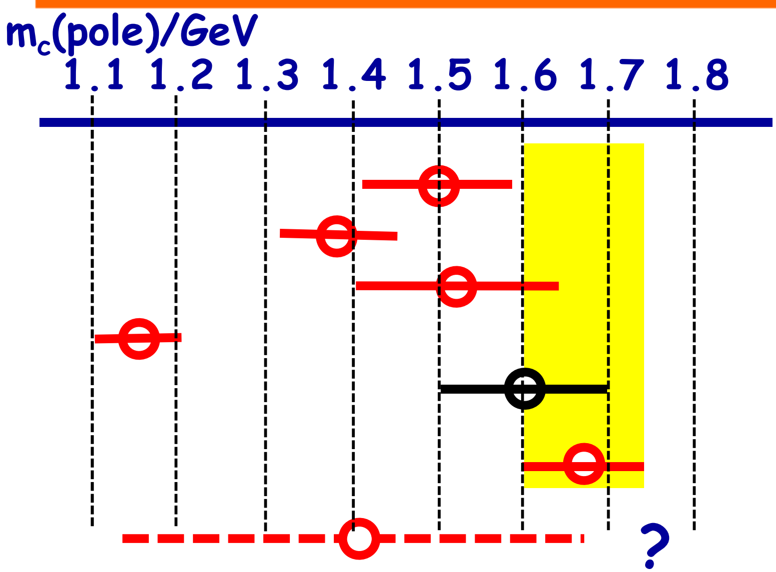
some personal remarks



this work, 'NLO'

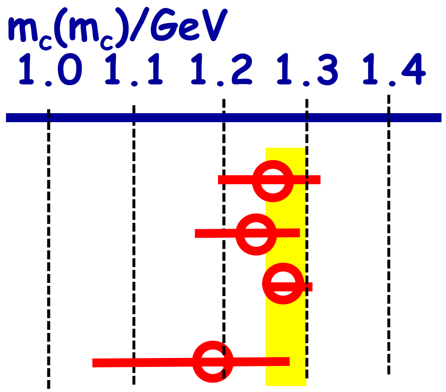
scheme VFNS	$M_c^{\rm opt}$ [GeV]	$\chi^2/n_{\rm dof}$ $\sigma_{\rm red}^{NC,CC}+\sigma_{\rm red}^{c\bar{c}}$	$\chi^2/n_{\rm dp}$ $\sigma_{\rm red}^{c\bar{c}}$
RT standard	$1.50 \pm 0.06_{\rm exp} \pm 0.06_{\rm mod} \pm 0.01_{\rm param} \pm 0.003_{\alpha_s}$	630.7/626	49.0/47
RT optimised	$1.38 \pm 0.05_{\rm exp} \pm 0.03_{\rm mod} \pm 0.01_{\rm param} \pm 0.01_{\alpha_s}$	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

PDG pole mass

effect smaller at 'NNLO', but will not disappear completely

-> in VFNS not fully obvious to use world average to reduce uncertainties

-> use "effective" mass values, or live with larger m_c uncertainty?



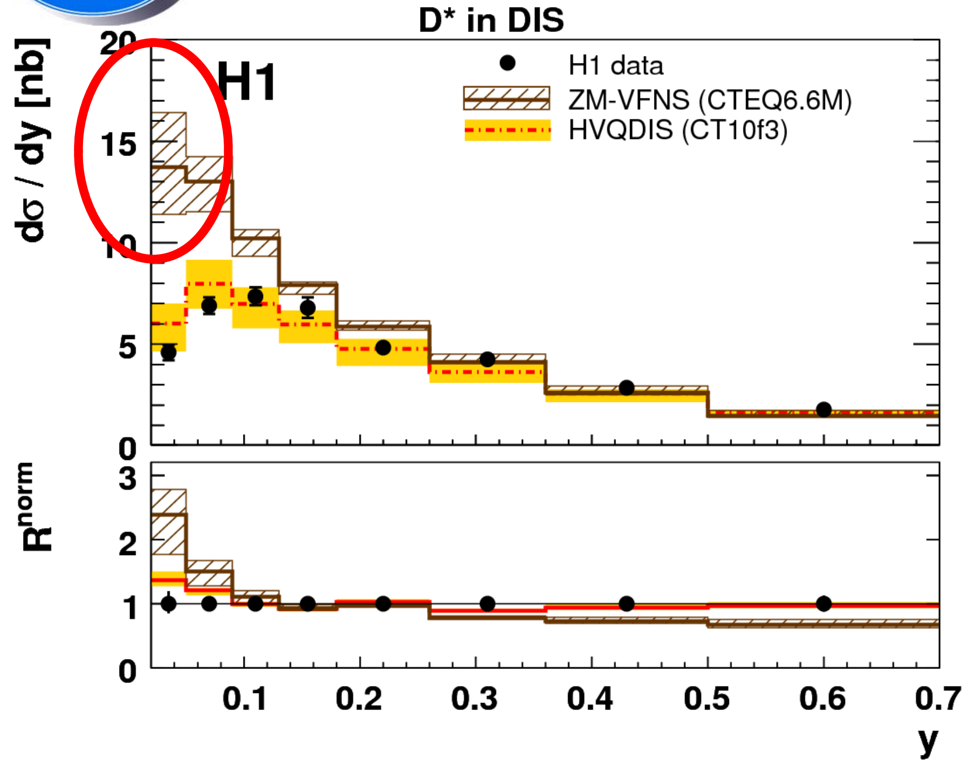
this work, FFNS NLO, $\Delta\chi^2=1$

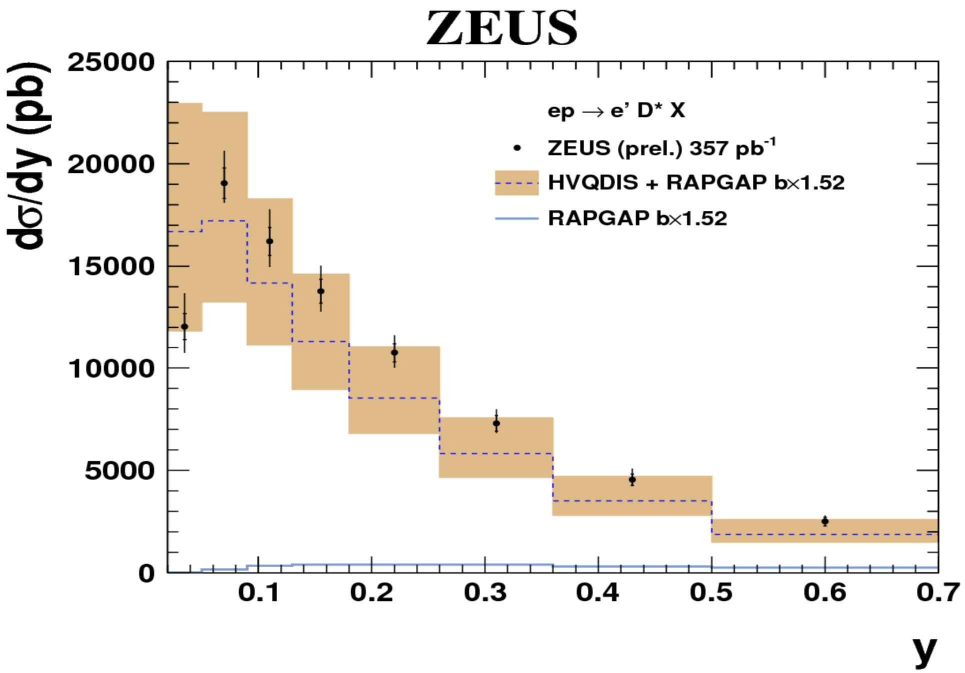
Alekhin et al. 2012/2013, FFNS appr. NNLO, $\Delta\chi^2=1$

PDG $m_c(m_c)$, $\overline{\rm MS}$ -> can use as external constraint?

Gao, Guzzi, Nadolsky, 2013, GM-VFNS NNLO, $\Delta\chi^2$~15-50

D* cross section vs. inelasticity y





- good agreement between experiments and with massive NLO QCD calculations
- massless NLO calculation (ZM-VFNS) fails at low y