Running of the Charm-Quark Mass from HERA Deep-Inelastic Scattering Data

α_s m_b m_c

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work partially done within scope of **PROSA**, **ZEUS** and **H1** collaborations

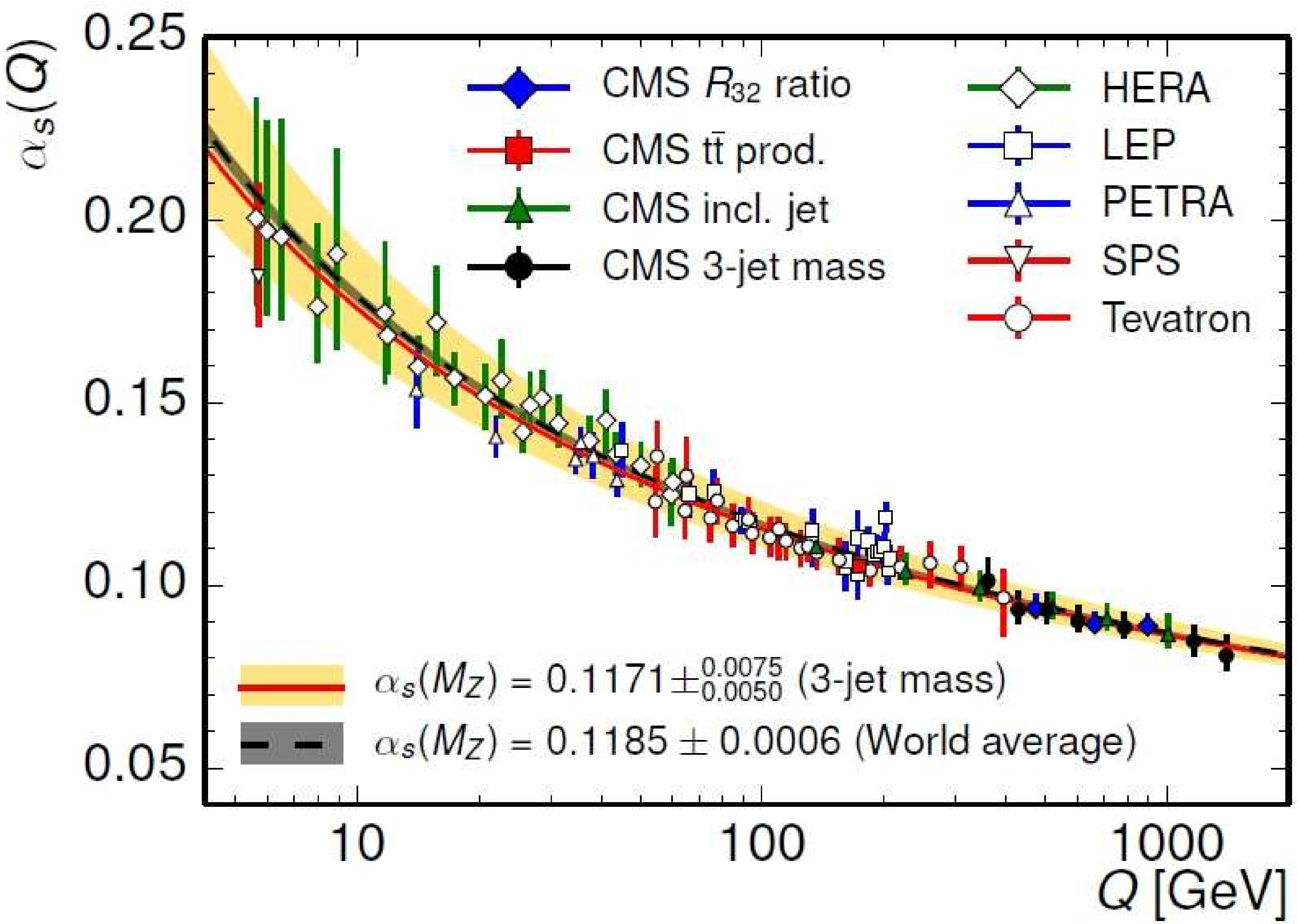
DIS 2017, Birmingham, UK, 5 April 2017

- Introduction: running of α_s and m_b
- **Final results on charm mass running:** **DESY-17-048** (on arXiv soon)
- Interpretation in terms of **Higgs Yukawa couplings:** **PoS CHARM2016 (2017) 012**

Running of strong coupling „constant“ α_s

reminder EPJC 75 (2015) 186

e.g. from jet production at e+e-, ep, and pp at DESY, Fermilab and CERN



updates see talks
K. Rabbertz
and D. Britzger

Yes,
it runs!

Running of α_s and quark masses m_Q

- **α_s running depends on number of coulours N_C and number of quark flavours n_f**

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 + \alpha_s \times (11N_C - 2n_f)/12\pi \; \ln(\mu^2/\mu_0^2)}$$

- **quark mass running depends on α_s , e.g.**

$m_Q(\text{pole}) = m_Q(m_Q)\,(1 + 4/3\ \alpha_s/\pi)$

$= m_Q(\mu)\,(1 + \alpha_s/\pi\,(4/3+\ln(\mu^2/m_Q^2))$

leading order QCD formulae

or

$$m_Q(\mu) = m_Q(m_Q) \times \left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right)^{c_0} \qquad c_0 = 4/(11 - 2n_f/3) \underset{n_f=3}{=} 4/9$$

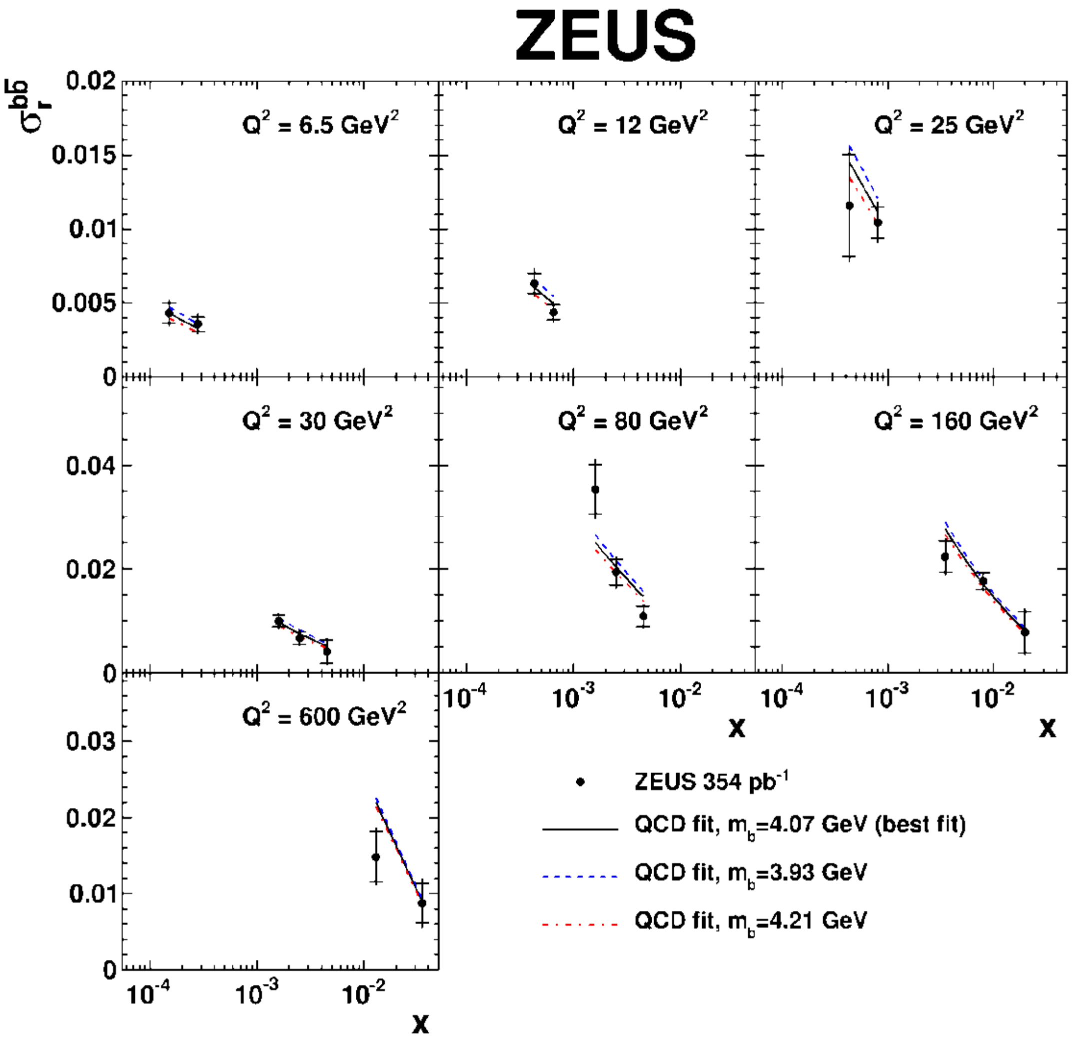
(N_C)

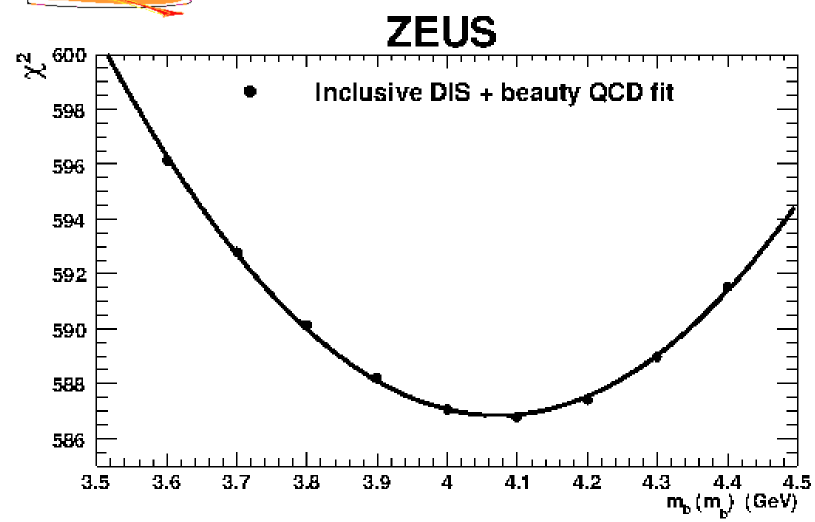
- part of gluon field around quark not 'visible' any more when 'looking' at smaller distances/larger energy scales

-> ***effective quark mass decreases***

m_b from reduced beauty cross section in DIS

reminder JHEP 1409 (2014) 127





ndf = 596

update see talk
O. Zenaiev

$m_b(m_b)$ = 4.07 ±0.14$_{fit}$ $^{+0.01}_{-0.07}$ $_{mod}$ $^{+0.05}_{-0.00}$ $_{par}$ $^{+0.08}_{-0.05}$ $_{th}$ GeV

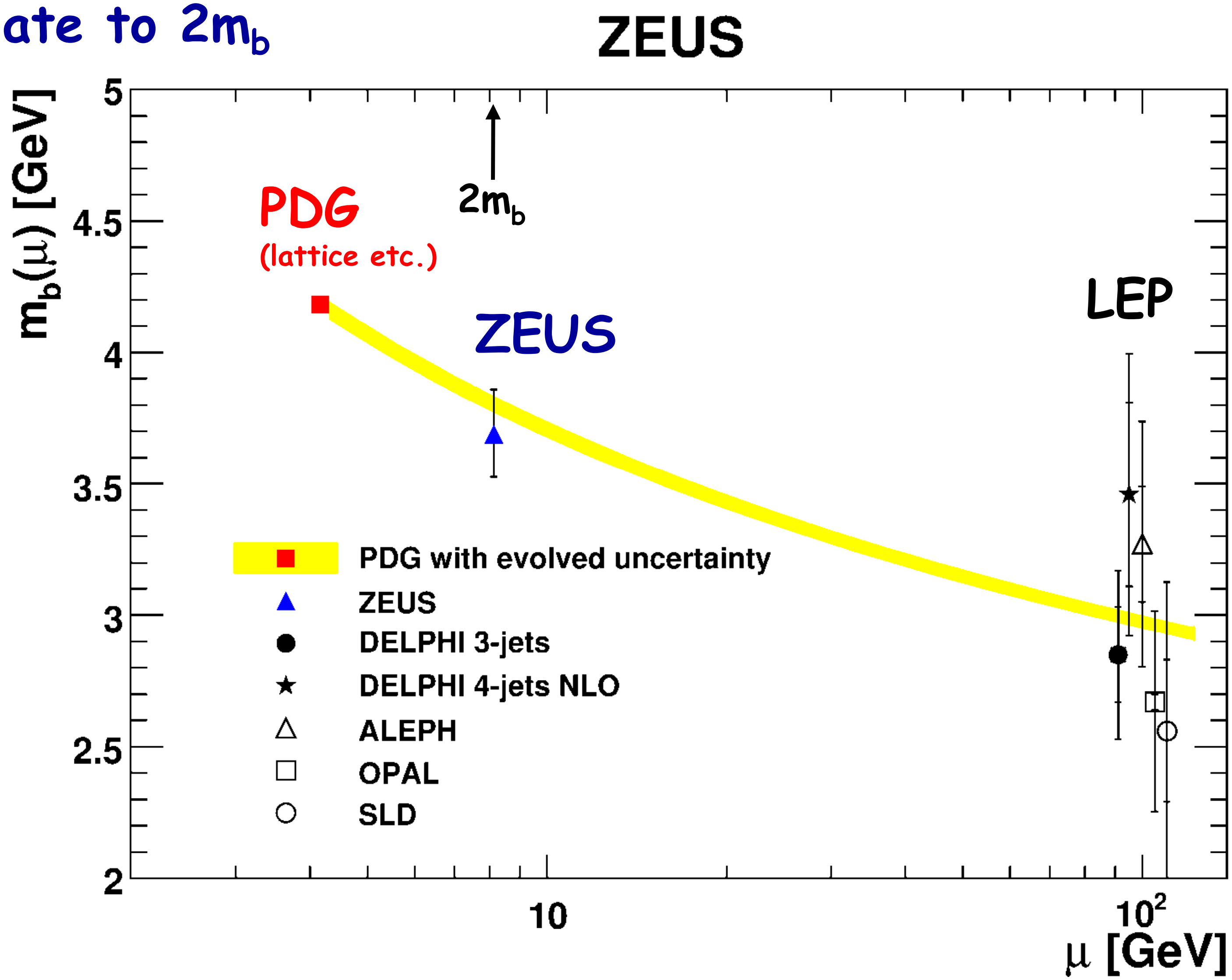
PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

The running beauty quark mass

ZEUS, JHEP 1409 (2014) 7; review,arXiv:1506.07519

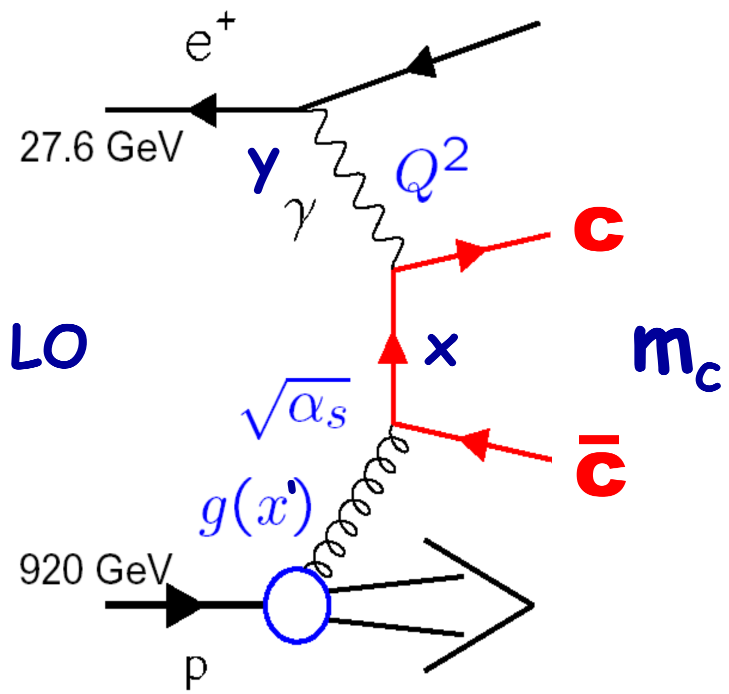
LEP, Eur. Phys. J. C55 (2008) 525 Prog. Part. Nucl. Phys. 84 (2015) 1

translate to $2m_b$



MSbar scheme

Fixed Flavour Number Scheme (FFNS)



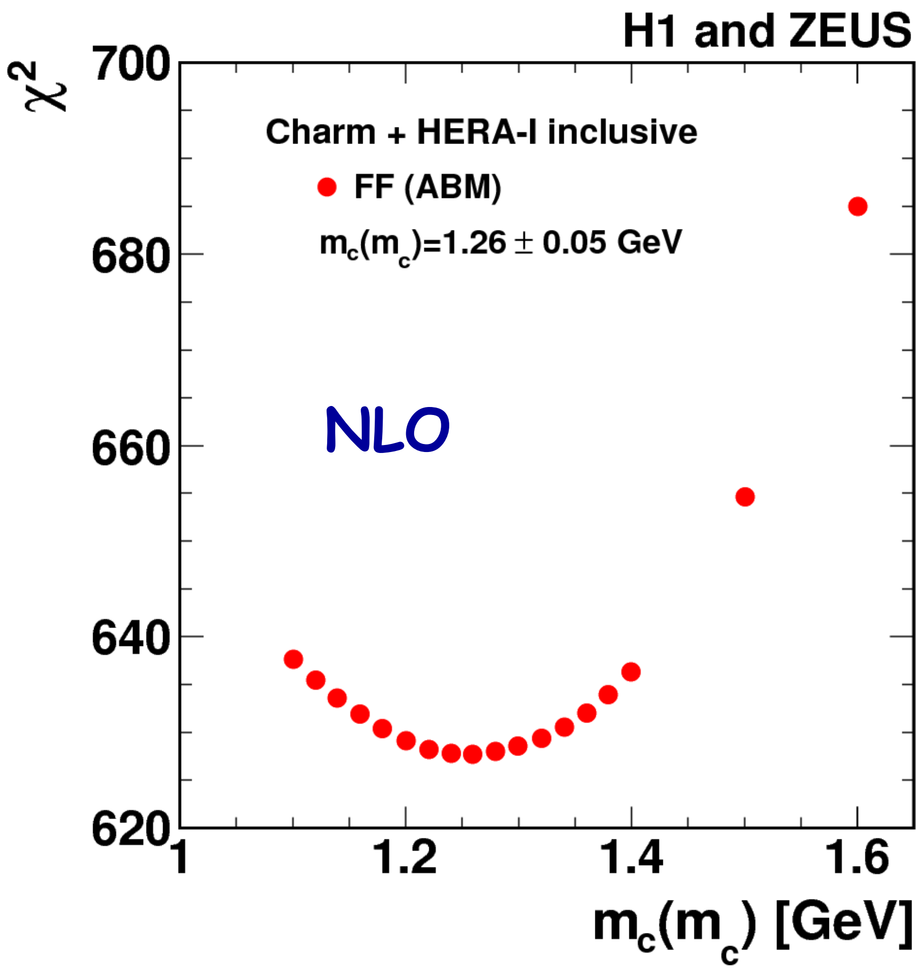
+ NLO (+partial NNLO) corrections,

"natural" scale:
$\mu^2 = Q^2 + 4m_c^2$

- no charm in proton
- full kinematical treatment of charm mass ☺
  (multi-scale problem: Q^2, p_T, m_c -> logs of ratios)
- no resummation of logs ☹
- no extra matching parameters ☺

Measurement of $\overline{MS}$ charm mass

reminder EPJ C73 (2013) 2311



simultaneous
mass + PDF fit of
combined charm data and
inclusive HERA I DIS data

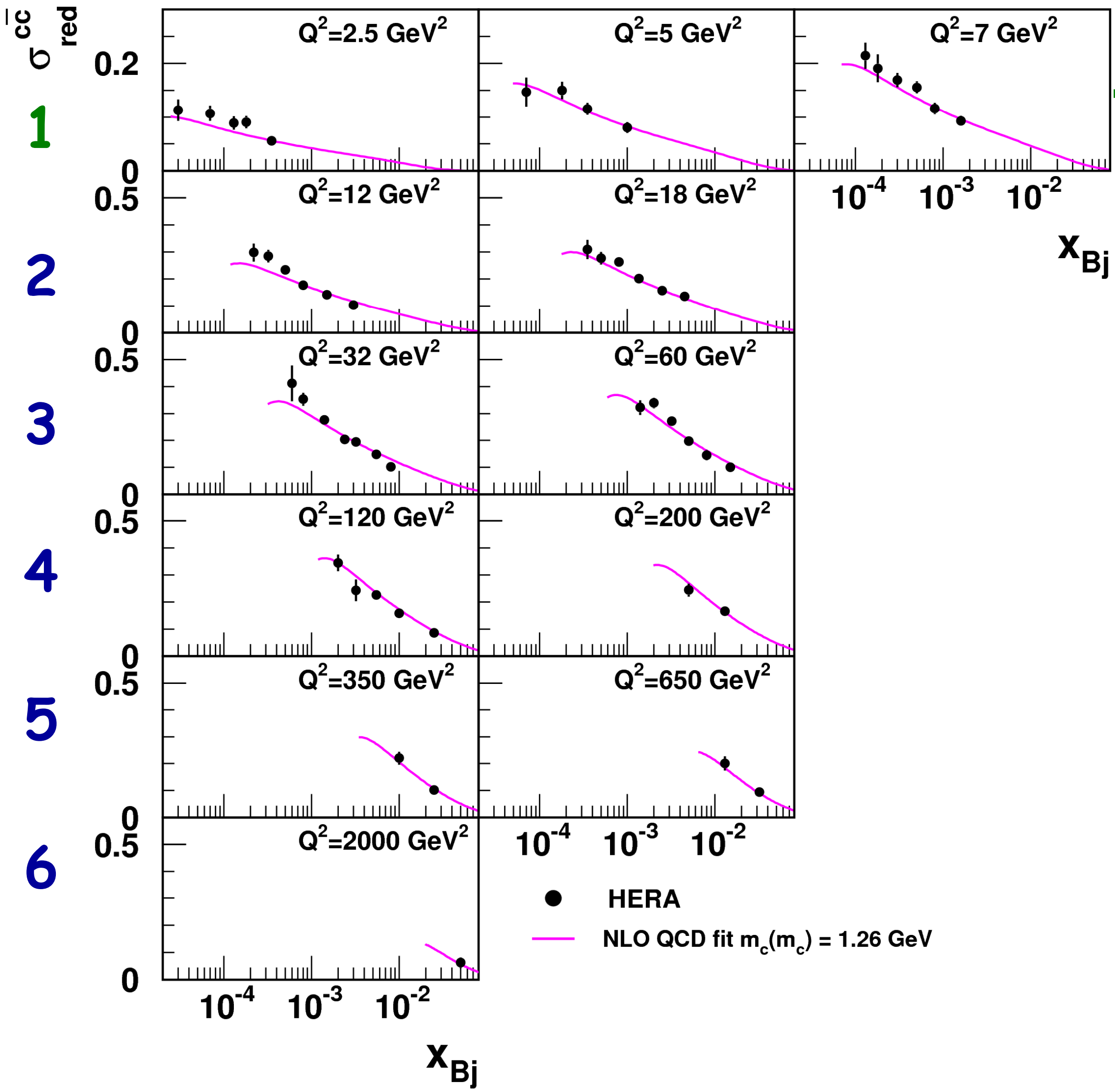
update see talk
O. Zenaiev

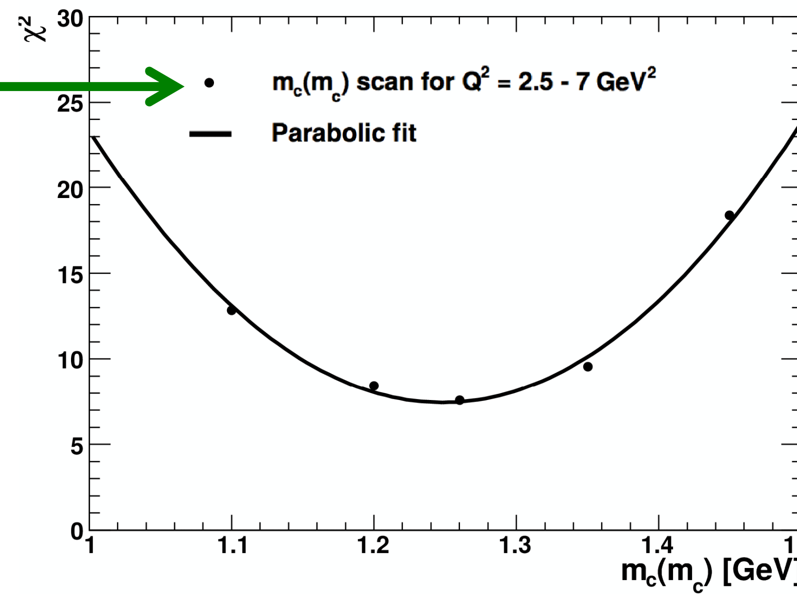
$m_c(m_c)$ = 1.26 $\pm 0.05_{exp}$ $\pm 0.03_{mod}$ $\pm 0.02_{\alpha s}$ GeV

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

Measurement of m_c running

A. Gizhko et al., DESY-17-048





Step 1:
extract $m_c(m_c)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(take log average for central scale)

m_c fit and uncertainties

A. Gizhko et al., DESY-17-048

use appropriate PDF set for each mass (from inclusive DIS data only), fit charm data

Fit uncertainty

- Was estimated by taking $\triangle\chi^2 = 1$ (dominant uncertainty)

Parametrisation

- Adding extra parameter in the PDF parametrisation

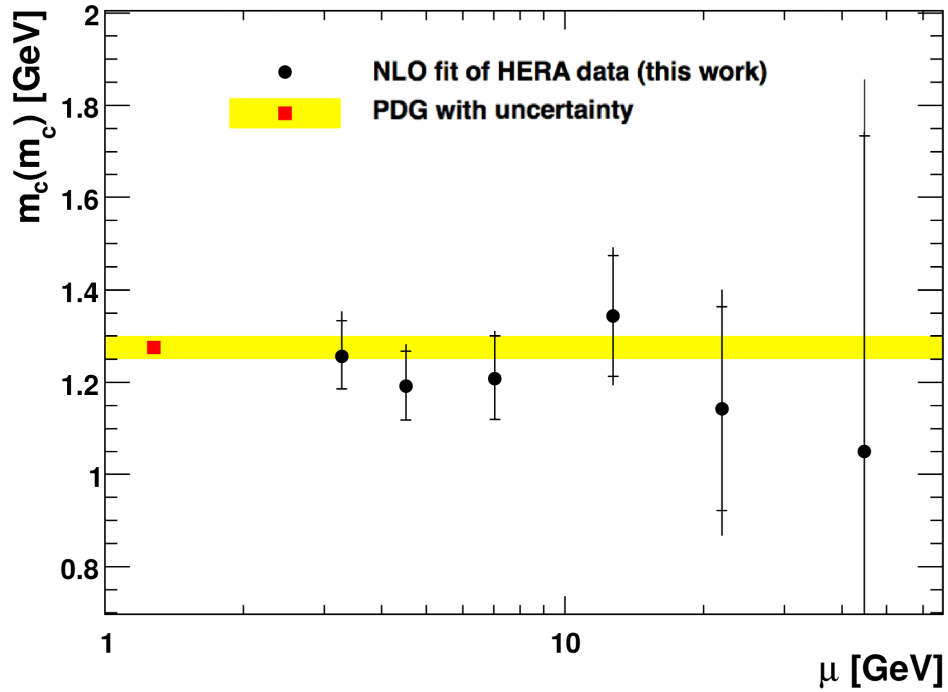
Model uncertainty

- Variation of the strangeness supression factor
- Lower cut on Q^2 for inclusive data
- The evolution starting scale
- The b-quark mass

Theory

- Variation of α_s
- Variation of the factorisation and renormalization scales of heavy quarks by factor 2

-> outer error bar



sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

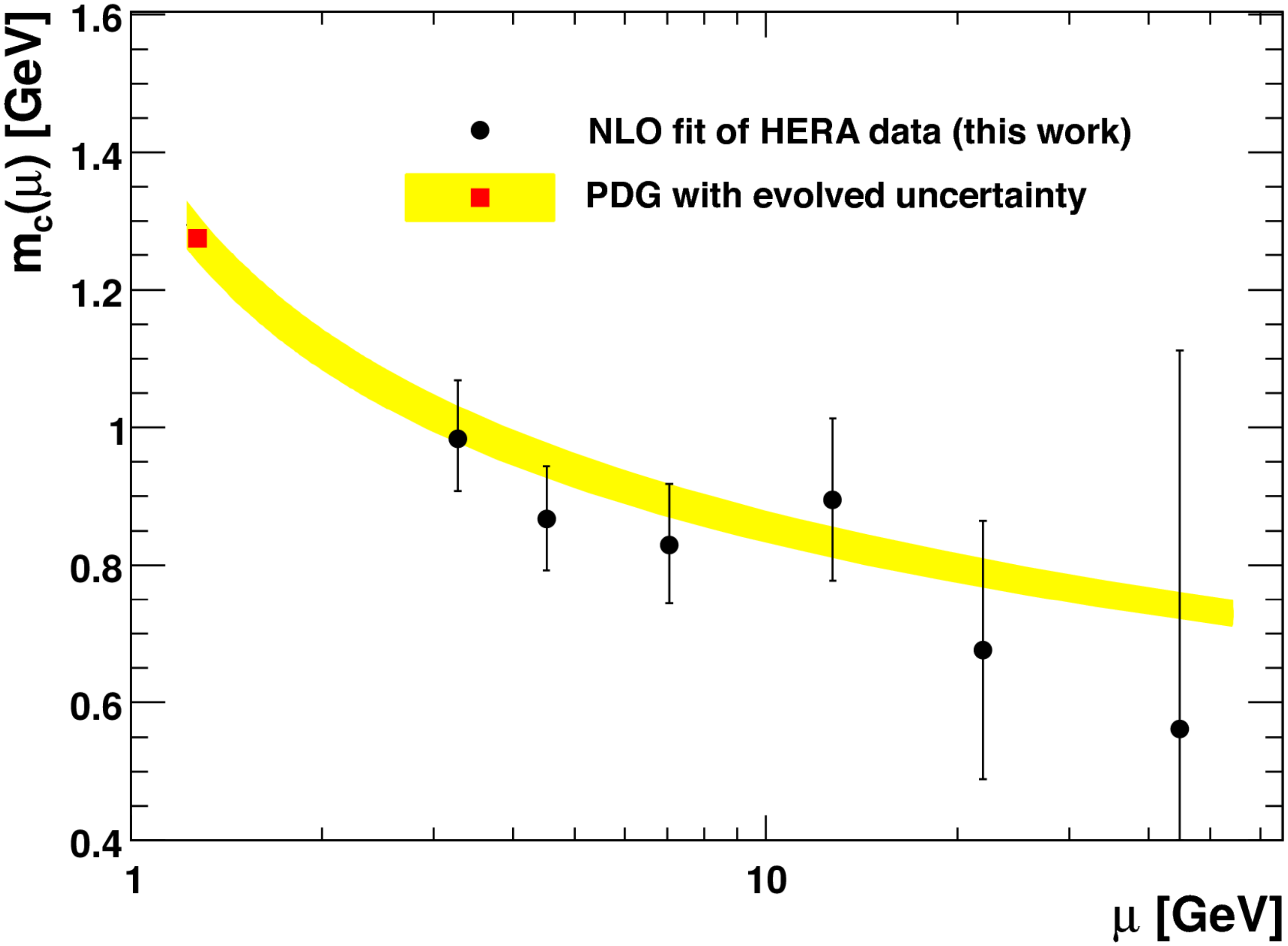
'in reality', have measured $m_c(\mu)$ at each scale

The running charm quark mass

A. Gizhko et al., DESY-17-048

Step 2: translate back to $m_c(\mu)$, which was actually measured, using LO formula consistent with NLO $\overline{MS}$ QCD fit

(OpenQCDrad, Alekhin et al.)



running mass concept in QCD is self-consistent !

Numerical details

A. Gizhko et al., DESY-17-048

Subset	N_{dat}	Q^2 range [GeV^2]	μ [GeV]	$m_c(m_c)$ [GeV] fit scale	$m_c(\mu)$ [GeV] fit
1	15	2.5–7	3.3	$1.256\ ^{+0.078}_{-0.070}\ ^{+0.054}_{-0.000}$	0.984 ± 0.061
2	12	12–18	4.5	$1.192\ ^{+0.075}_{-0.073}\ ^{+0.043}_{-0.000}$	0.867 ± 0.055
3	13	32–60	7.0	$1.208\ ^{+0.092}_{-0.088}\ ^{+0.045}_{-0.000}$	0.830 ± 0.063
4	7	120–200	12.7	$1.344\ ^{+0.130}_{-0.131}\ ^{+0.073}_{-0.074}$	0.895 ± 0.087
5	4	350–650	21.9	$1.143\ ^{+0.222}_{-0.221}\ ^{+0.133}_{-0.163}$	0.676 ± 0.132
6	1	2000	44.8	$1.050\ ^{+0.684}_{-0.760}\ ^{+0.400}_{-0.149}$	0.562 ± 0.412

Table 1: Values of $m_c(m_c)$ at different scales μ, determined from six different subsets, and corresponding values of $m_c(\mu)$. The first uncertainty (fit) corresponds to the uncertainty $\delta_{\mathrm{fit}}^{\mathrm{exp}}$ added in quadrature with the symmetrised systematic uncertainties $\delta_1 - \delta_6$. The second uncertainty (scale) of $m_c(m_c)$ corresponds to the scale variation uncertainty δ_7. No scale uncertainty is quoted for $m_c(\mu)$ (see text). The range of Q^2 values contributing to the six data subsets shown in Fig. 1 is given. Also given is the corresponding logarithmic average scale μ for each subset according to Eq. (2), and the number N_{dat} of charm data points contributing to each measurement.

Breakdown of uncertainties on m_c

A. Gizhko et al., DESY-17-048

Subset	$\delta_{\rm fit}^{\rm exp}$ [%]	δ_1 (m_b) [%]	δ_2 (α_s) [%]	δ_3 (f_s) [%]	δ_4 (Q_0) [%]	δ_5 ($Q^2_{\rm min}$) [%]	δ_6 (param) [%]	δ_7 (scale) [%]
1	± 5.4	$^{+0.1}_{-0.4}$	$^{-1.2}_{+2.6}$	$^{-0.4}_{+0.2}$	+0.5	+1.4	+0.5	$^{+3.1}_{+4.3}$
2	± 6.0	$^{+0.2}_{-0.5}$	$^{-0.9}_{+0.7}$	$^{-0.5}_{+0.2}$	+0.3	+1.0	+0.9	$^{+2.4}_{+3.6}$
3	± 7.2	$^{+0.3}_{-0.7}$	$^{-0.4}_{+0.3}$	$^{-0.8}_{+0.3}$	+1.7	+0.3	+1.8	$^{+0.1}_{+3.7}$
4	± 9.6	$^{+0.5}_{-0.8}$	$^{+0.7}_{-0.6}$	$^{-0.8}_{+0.5}$	+0.5	–1.2	+0.1	$^{-5.5}_{+5.4}$
5	± 19.2	$^{+0.5}_{-1.2}$	$^{+1.6}_{-1.8}$	$^{-1.2}_{+0.5}$	–0.5	+2.1	–1.7	$^{-14.3}_{+11.6}$
6	± 63.8	$^{-7.4}_{-2.9}$	$^{+5.9}_{-5.7}$	$^{-3.0}_{-7.6}$	+6.5	–33.3	+9.5	$^{+38.1}_{-14.2}$

Table 2: Summary of the systematic uncertainties in the $m_c(m_c)$ determinations. The definitions of the uncertainty sources, the meaning of the symbols in the first and second row and related details are given in the text. In cases where opposite variations of a variable yield uncertainties with the same sign, only the larger one is considered for the uncertainty combination in Table 1. Except for δ_7, these uncertainties also apply to $m_c(\mu)$.

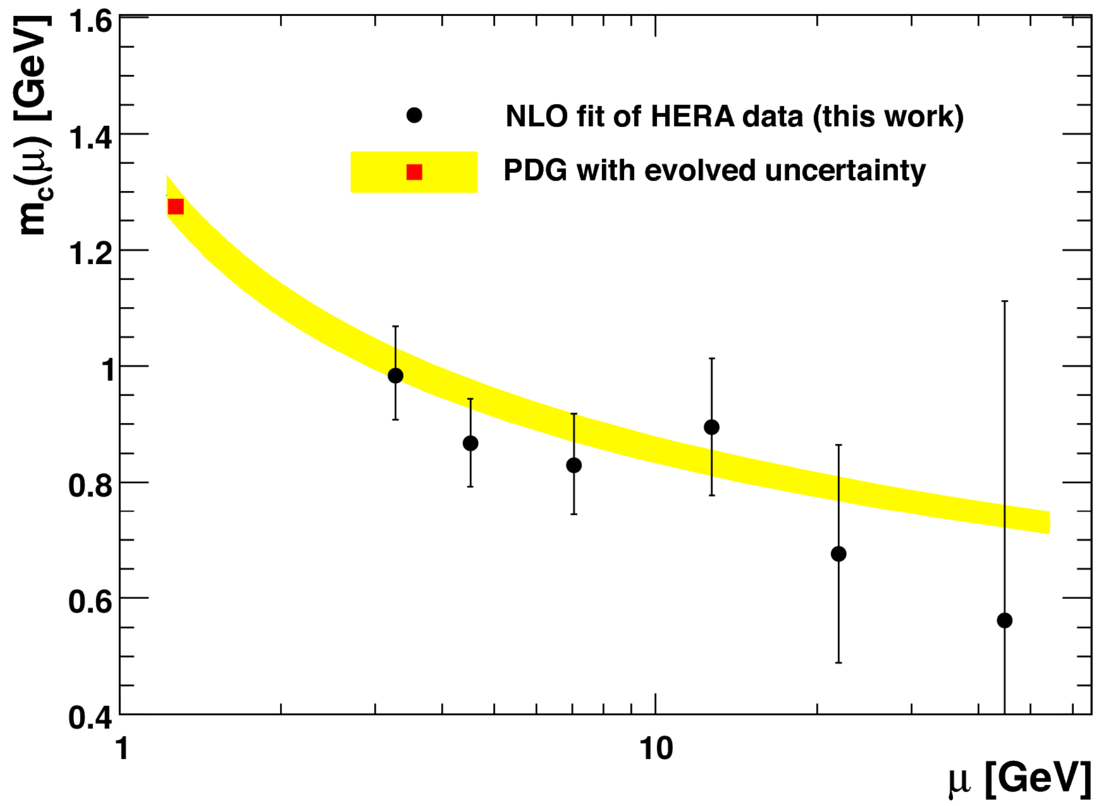
Conclusions, part I

A. Gizhko et al., DESY-17-048

- Subdividing HERA DIS charm data into 6 kinematic intervals, running of charm-quark mass in MSbar scheme has been determined for the first time
(conceptually similar to running of α_s from jets)

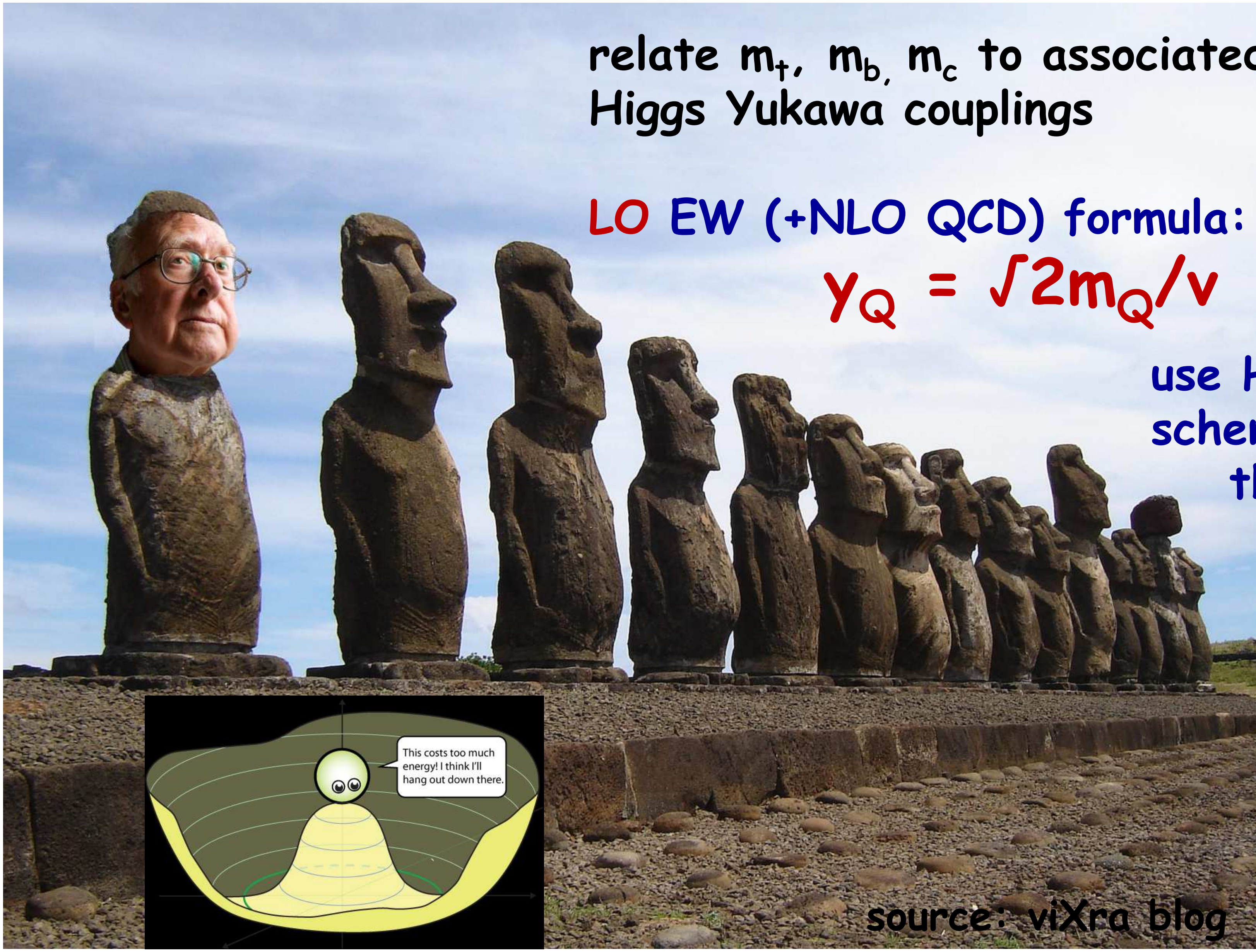
- Interplay/treatment of correlations between mass and PDF fits nontrivial, details see DESY-17-048

- Charm-quark mass running consistent with QCD



Higgs Yukawa couplings from m_Q

PoS CHARM2016 (2017) 012



relate m_t, m_b, m_c to associated Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

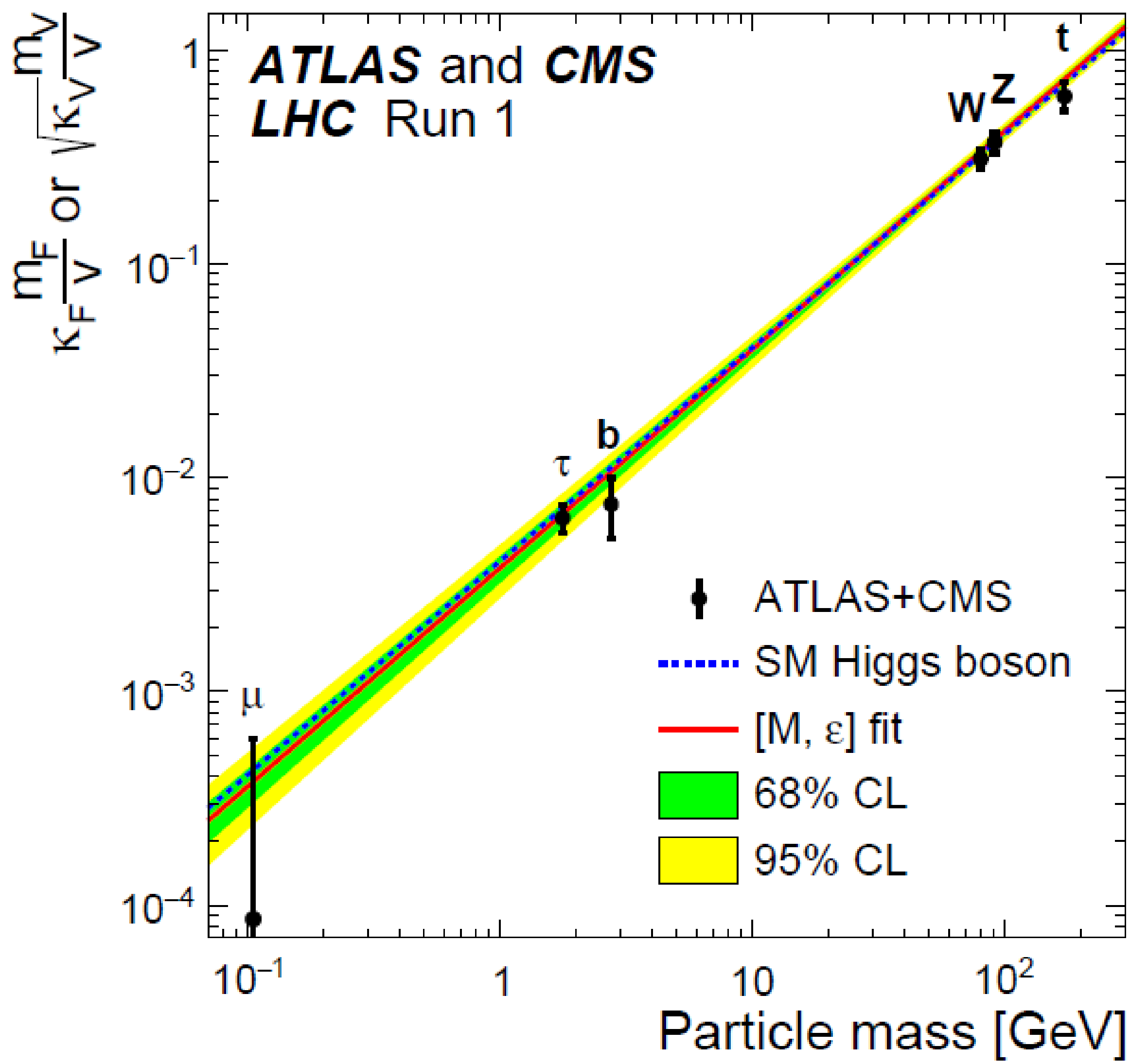
$$y_Q = \sqrt{2} m_Q / v$$

use Higgs/EW scheme in which this relation is exact !

source: viXra blog

Direct measurements of Higgs Yukawa couplings

ATLAS and CMS, JHEP08 (2016) 045



Running of α_s and quark Yukawa couplings

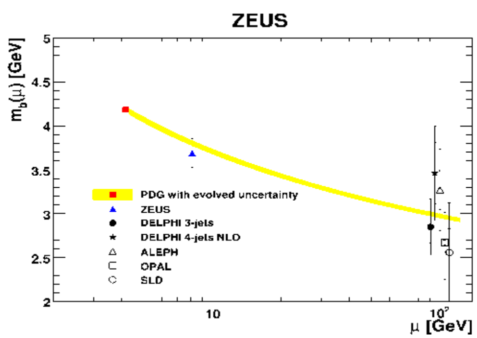
PoS CHARM2016 (2017) 012

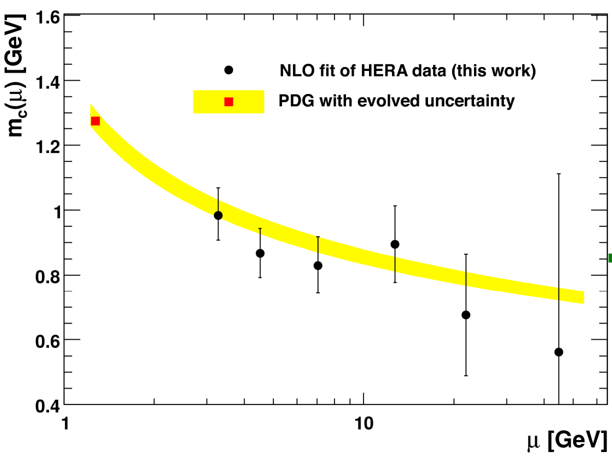
relate m_t, m_b, m_c to associated Higgs Yukawa couplings

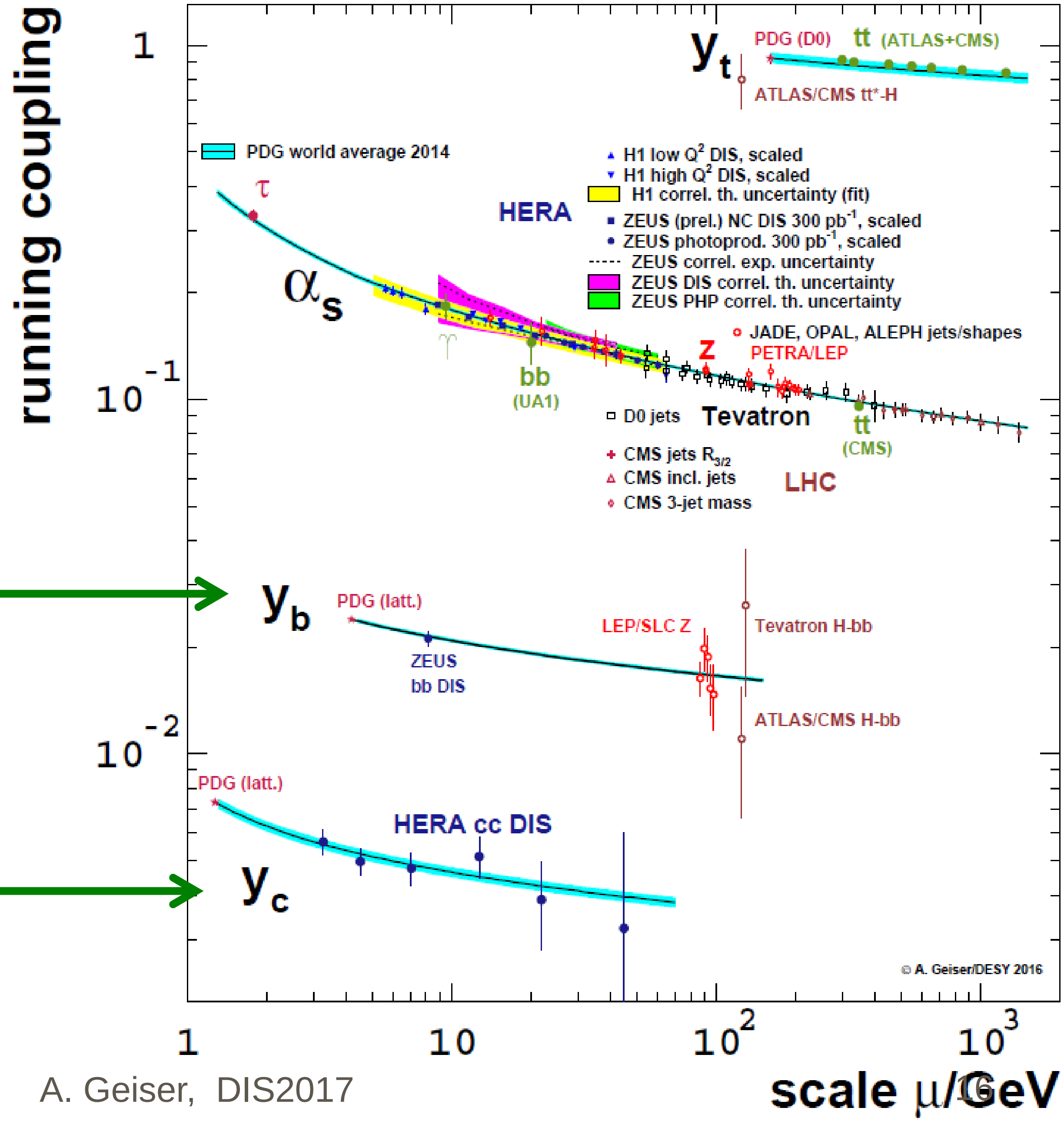
LO EW (+NLO QCD) formula:

$$y_Q = \sqrt{2}m_Q/v$$

for top see backup







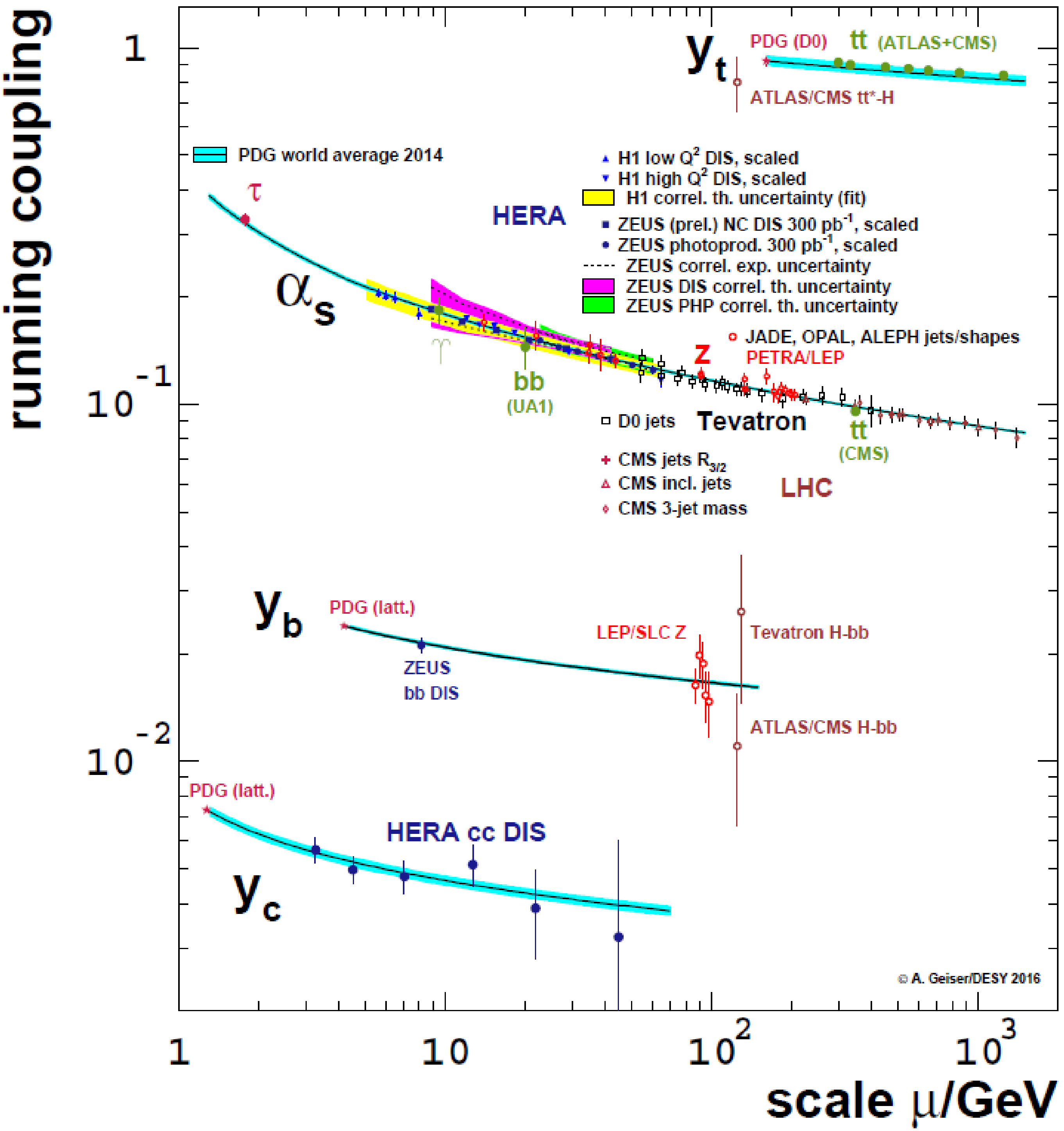
Conclusion

Part II

experimental representation of running Yukawa couplings obtained for the first time

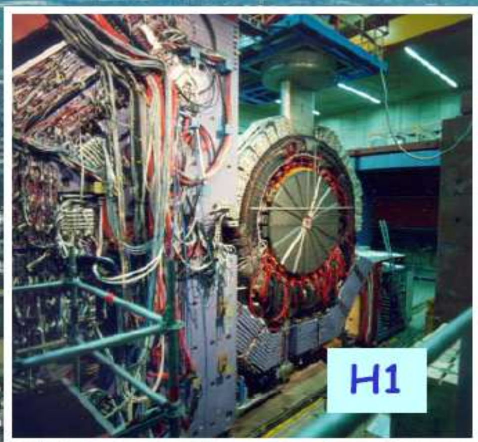
heavy quark physics is also QCD + Higgs physics

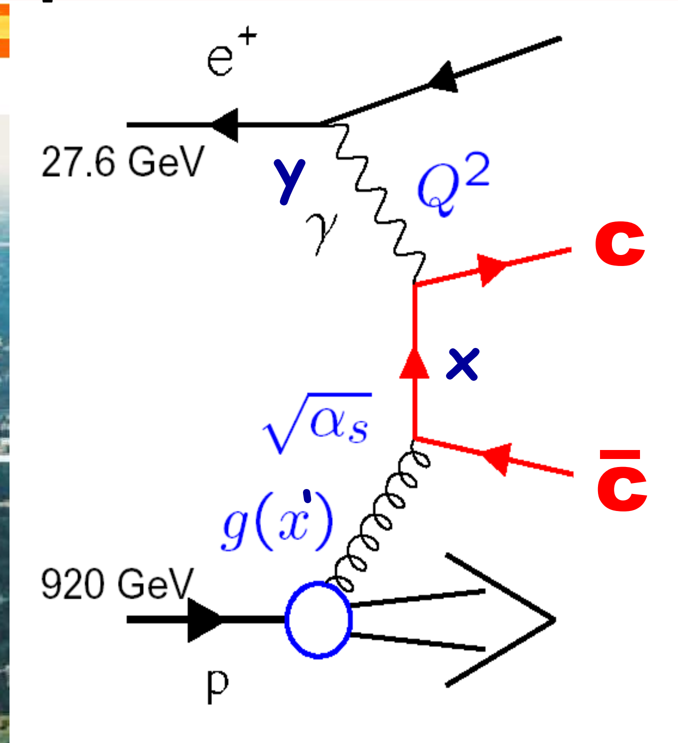
so far, Higgs couplings and their running as obtained from quark masses are consistent with directly measured Higgs couplings



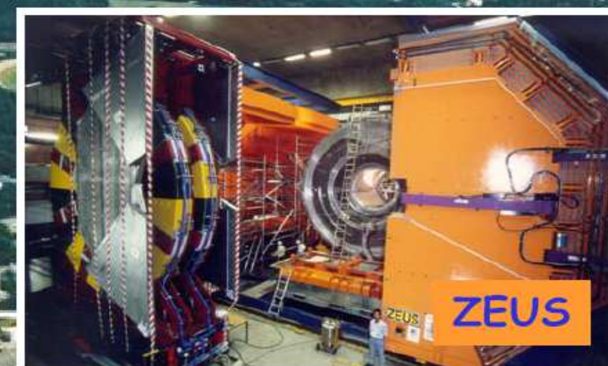
Backup

The HERA ep collider and experiments





up to 30% of cross section



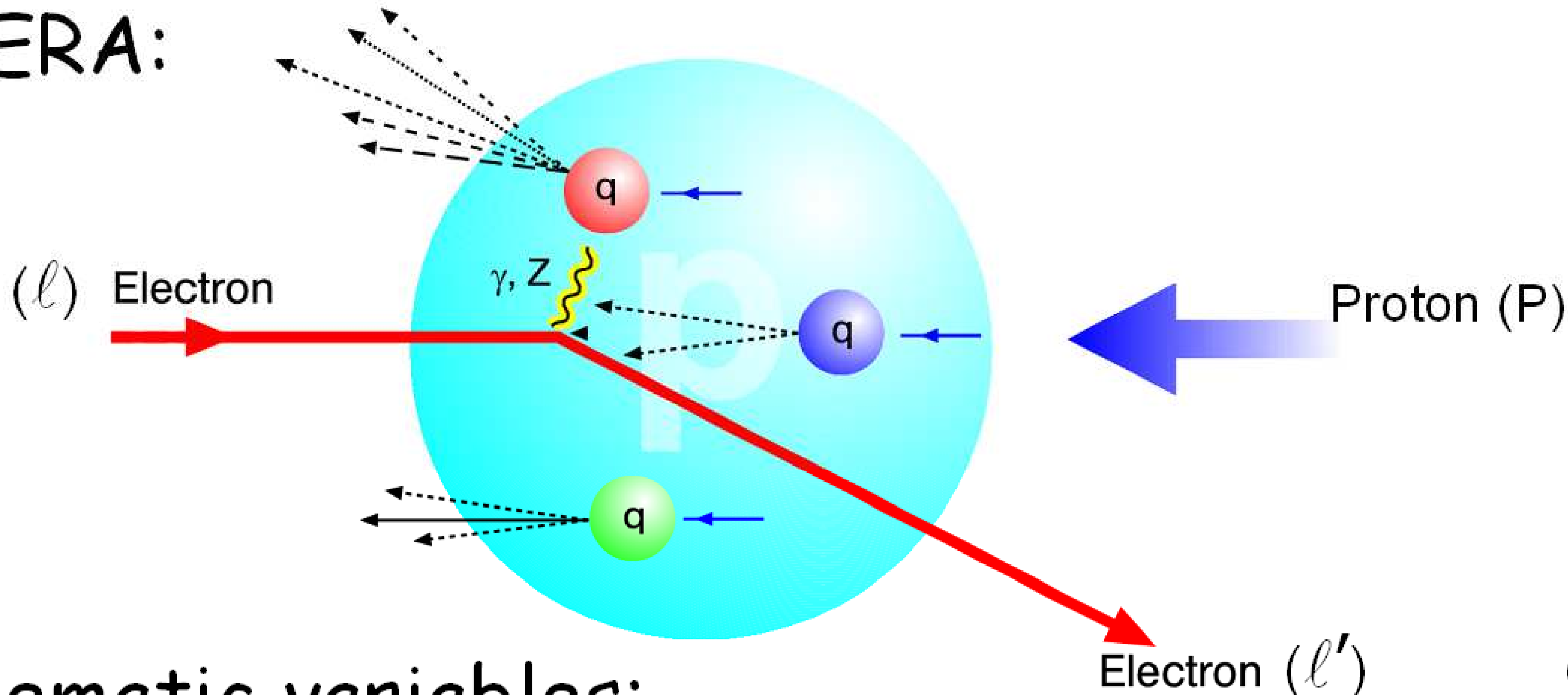
HERA I: ~ 130 pb^{-1} (physics)

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

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

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

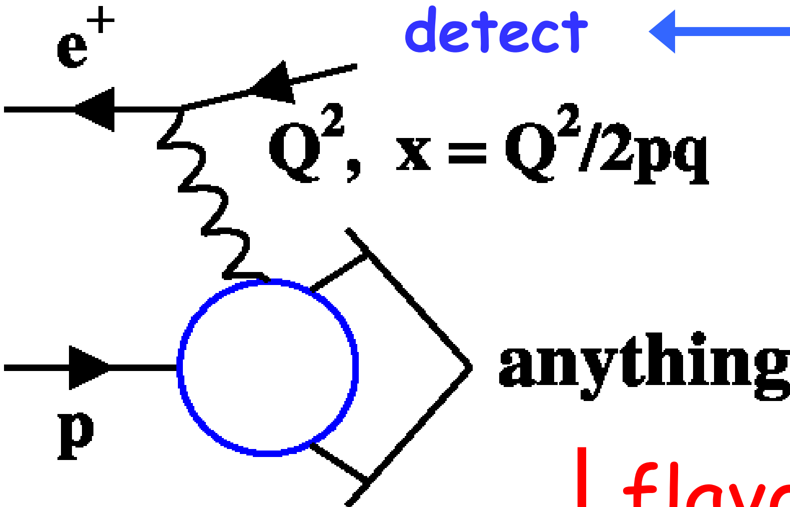
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

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

$Q^2 \lesssim 1$ GeV^2: photoproduction

$Q^2 \gtrsim 1$ GeV^2: DIS

Heavy flavour contributions to F_2

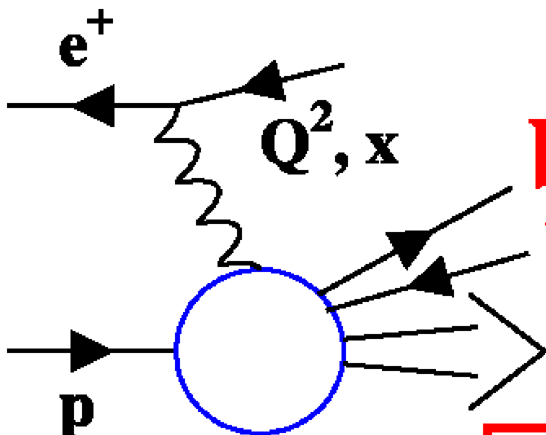


detect ⟷

Measure cross section

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

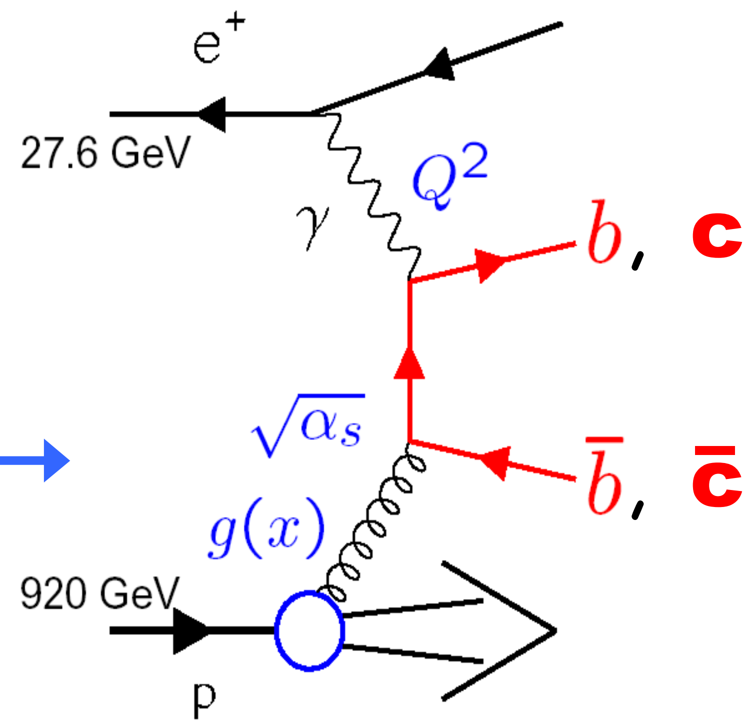
flavour tagging



b or **c**
$\bar{\mathbf{b}}$ $\bar{\mathbf{c}}$

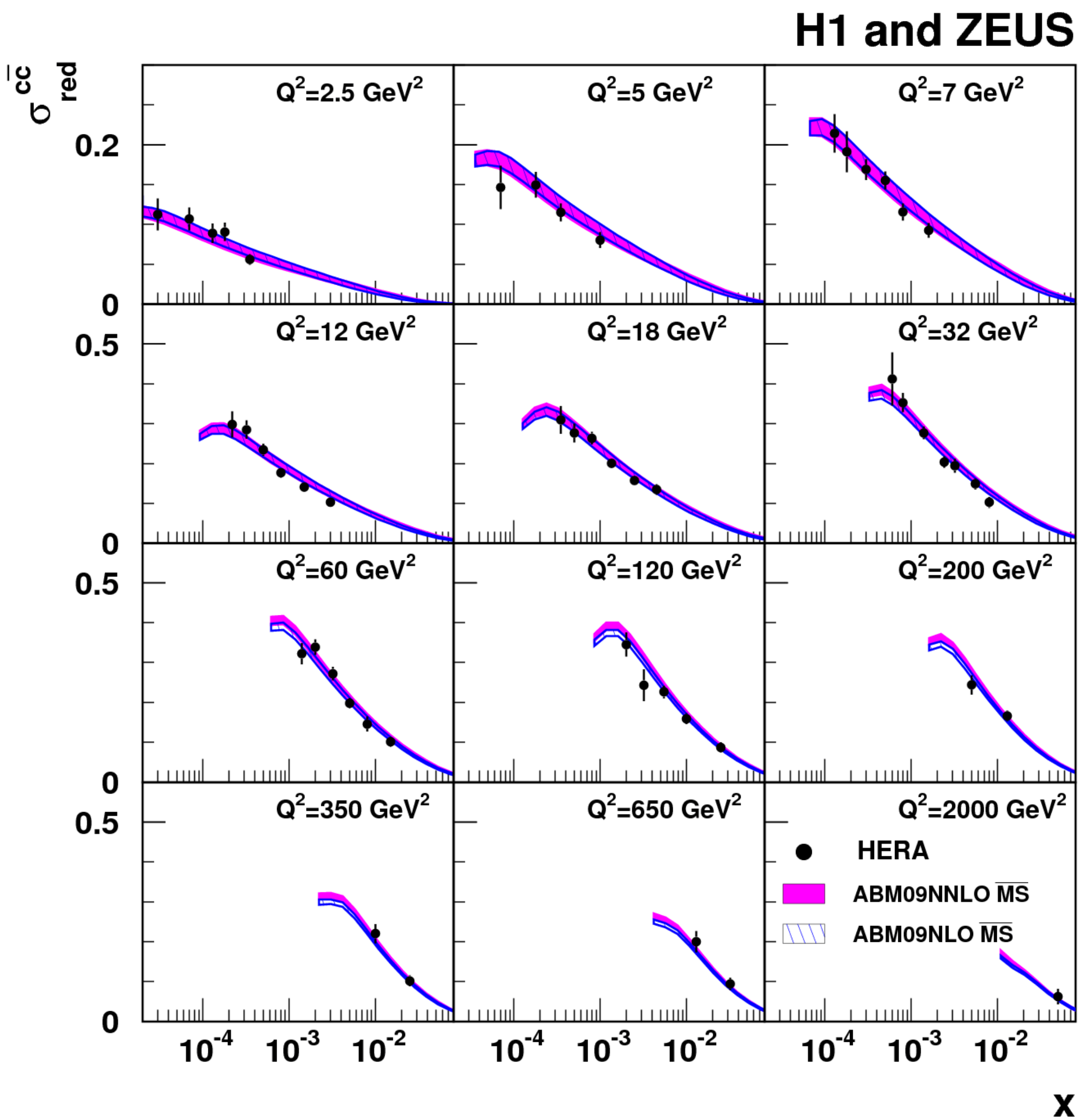
-> $\sigma_r^{b\bar{b}}$, $\sigma_r^{c\bar{c}}$

QCD ⟷



comparison to ABM FFNS

EPJ C73 (2013) 2311



very good description of data in full kinematic range

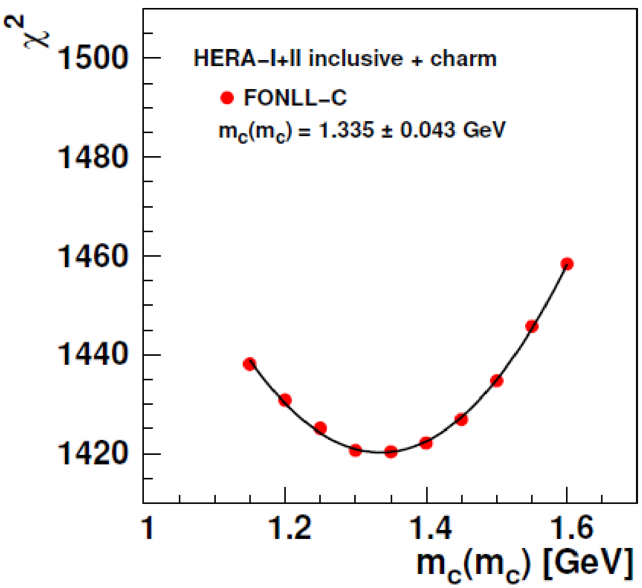
unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass

(similar predictions for pole mass)

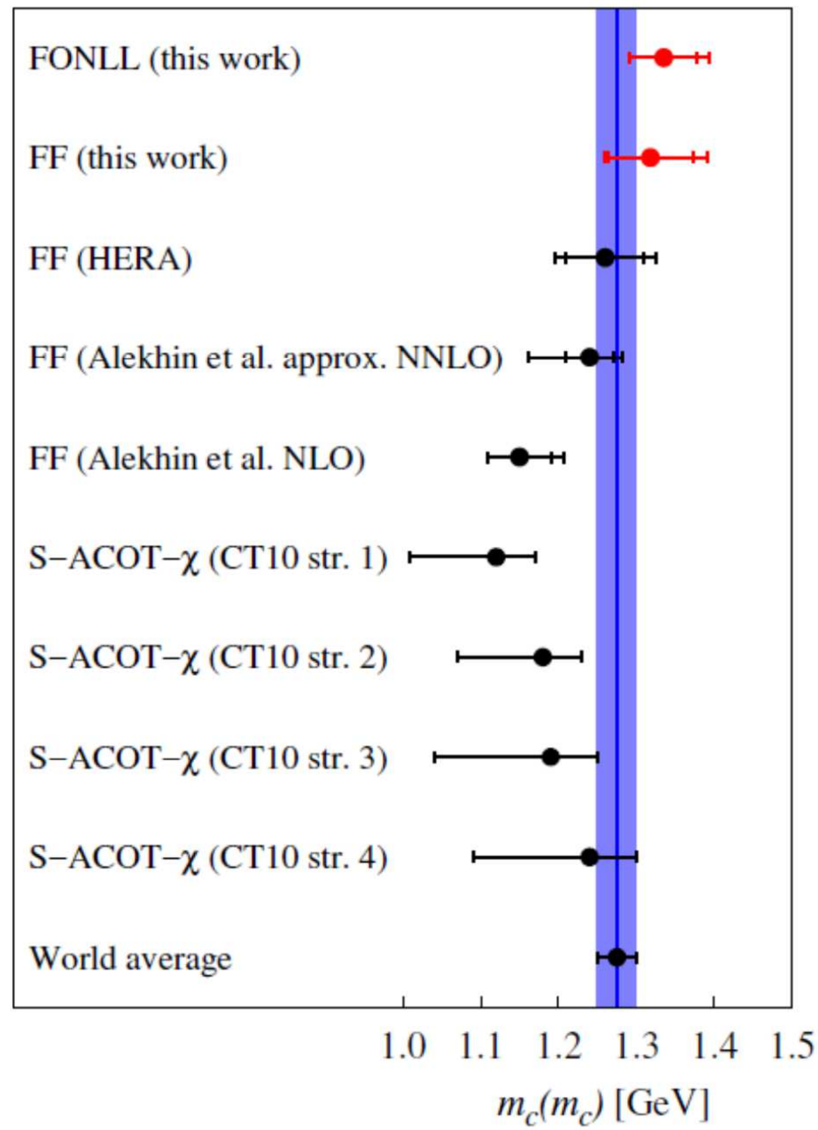
$m_c(m_c)$ from FONLL fit of HERA data

V. Bertone et al., arXiv 1605.01946, JHEP 1608 (2016) 050



xFitter APFEL

scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (HERA) [9]	$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\text{param}) \pm 0.02(\alpha_s)$
FFN (Alekhin *et al.*) [24]	$1.24 \pm 0.03(\text{exp})^{+0.03}_{-0.02}(\text{scale})^{+0.00}_{-0.07}(\text{th})$ (approx. NNLO)
	$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)
S-ACOT-χ (CT10) [29]	$1.12^{+0.05}_{-0.11}$ (strategy 1)
	$1.18^{+0.05}_{-0.11}$ (strategy 2)
	$1.19^{+0.06}_{-0.15}$ (strategy 3)
	$1.24^{+0.06}_{-0.15}$ (strategy 4)
World average [53]	1.275 ± 0.025



top quark mass running

PoS CHARM2016 (2017) 012

very preliminary procedure (with caveats, "cheated" a bit):

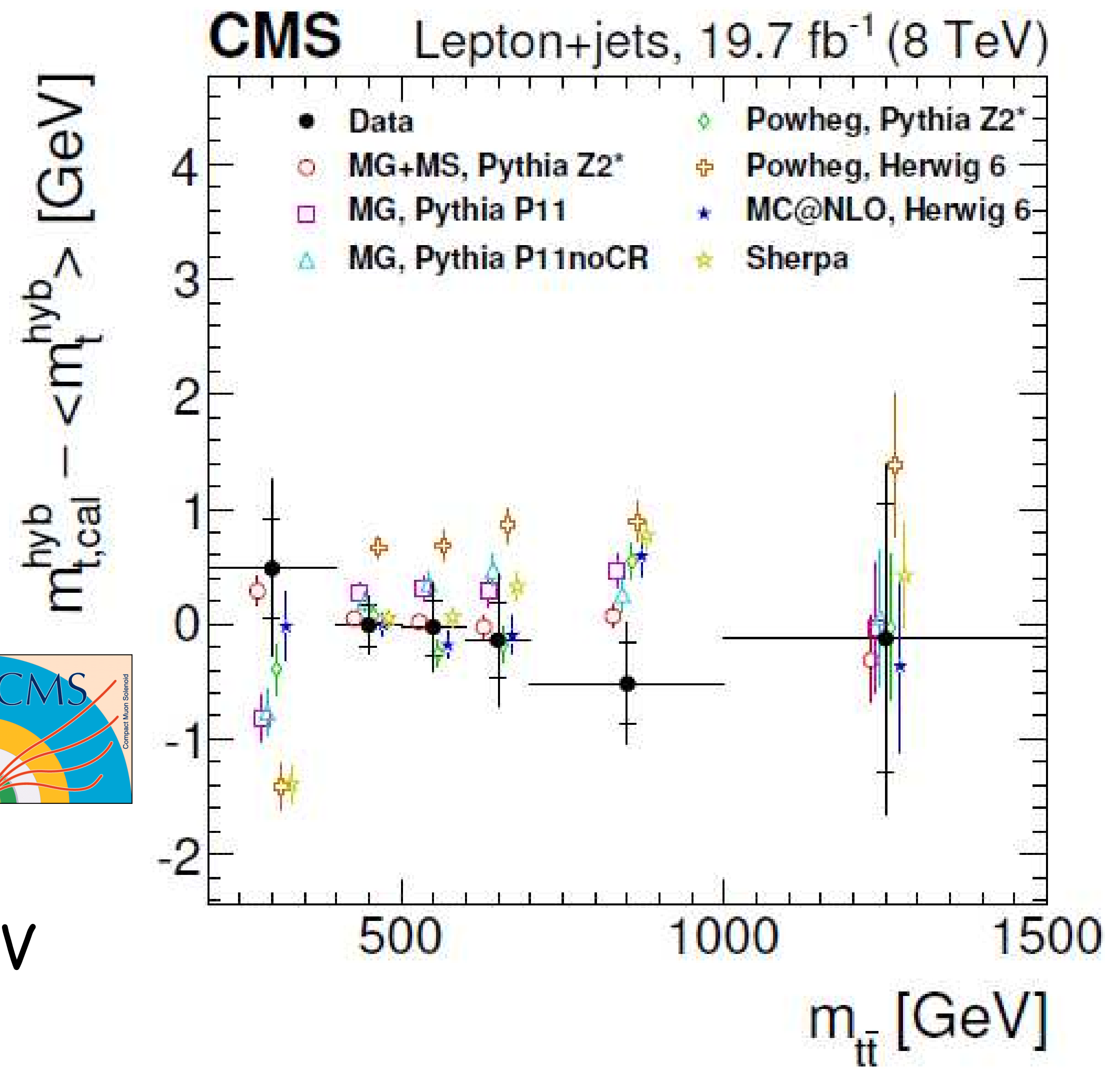
- use (conceptually constant) LO MC mass measured as function of scale-dependent quantity (e.g. $m_{t\bar{t}}$)
- check self-consistency of cross section measurements with data used for mass determination
- 'convert' LO MC mass to NLO pole mass by comparing MC and pole mass extractions from same data
- convert pole mass to $\overline{MS}$ mass using 3-loop QCD
- use 1-loop evolution for actual running (NLO QCD)

(in the future, like for m_c and m_b, extract NLO (or NNLO) running mass directly from data, e.g. cross section, in each kinematic bin)

top quark mass as function of $m_{t\bar{t}}$

CMS-TOP-14-022, Phys. Rev. D93 (2016) 072004

"MC mass"



deviation

from average of

172.35 $\pm 0.16_{stat}$ $\pm 0.48_{sys}$ GeV

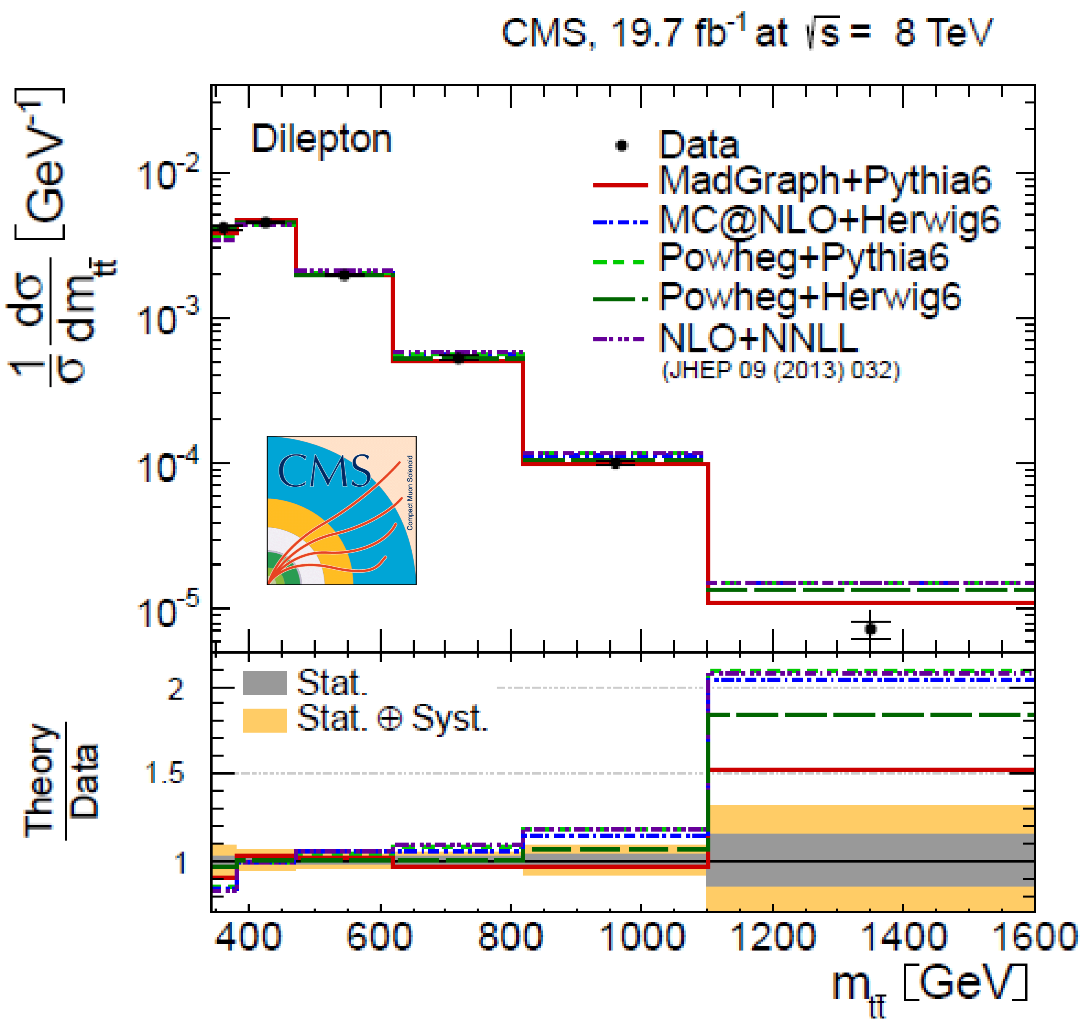
differential top cross section shape consistent with NLO

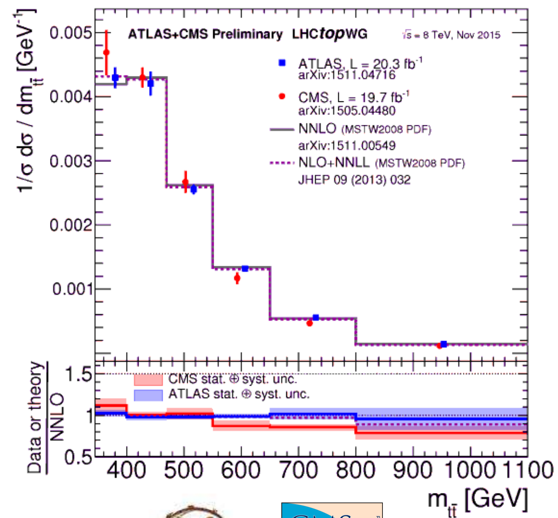
CMS-TOP-12-028, Eur. Phys. J. C75 (2015) 542 LHCtopWG

NLO theory
uses
pole mass
scheme

use CMS to
be consistent
with previous
slide

similar results
for lepton+jets
channel only



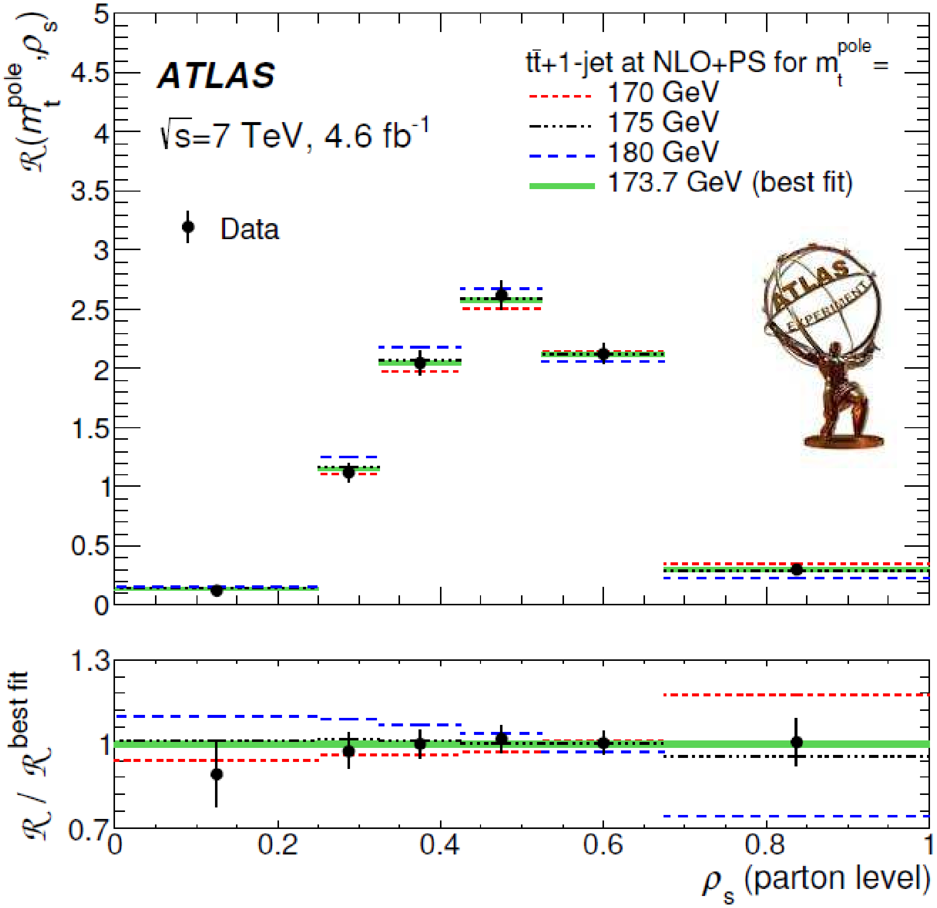


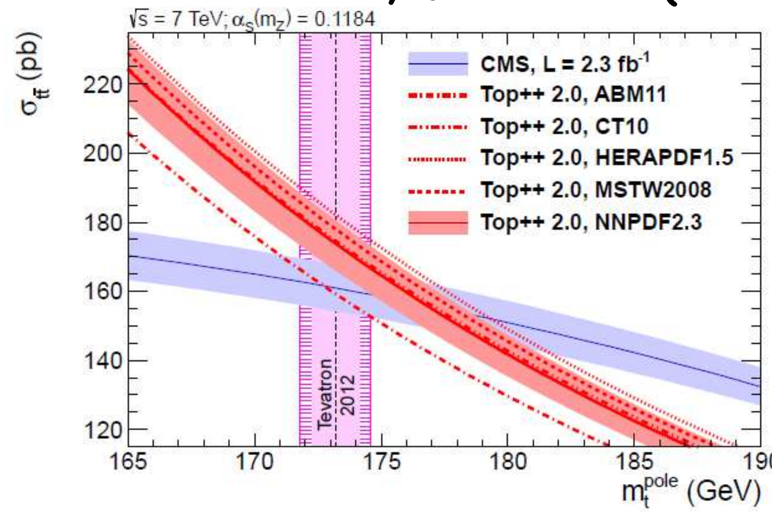
-> measurements and LO+PS/NLO theory are self-consistent and consistent with ATLAS and NNLO

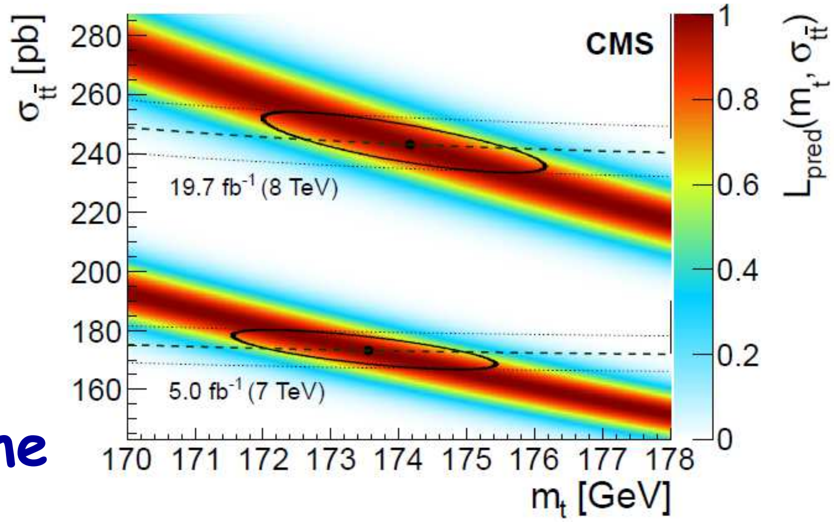
convert top MC mass to pole mass

ATLAS, JHEP10 (2015) 121, CMS-TOP-12-022, Phys. Lett. B728 (2014) 526

CMS-TOP-13-004, JHEP 1608 (2016) 029







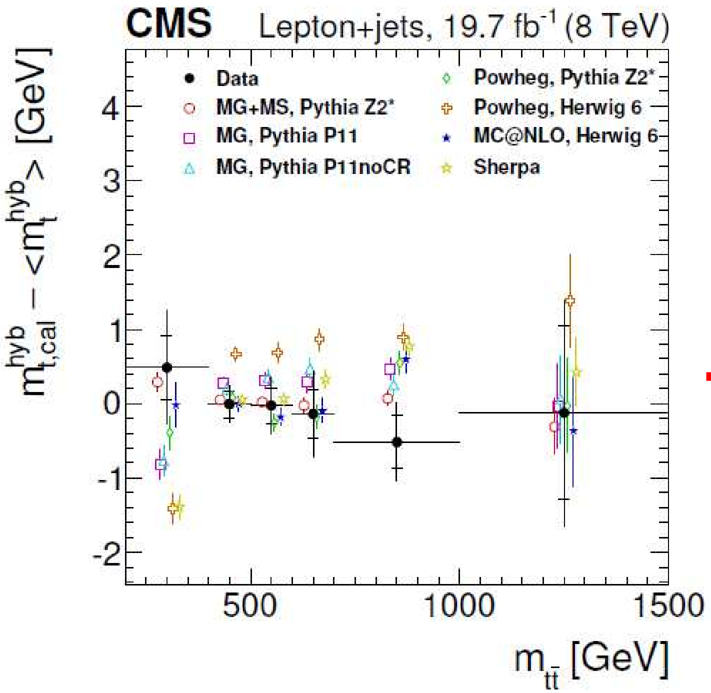
"MC" and pole masses almost the same

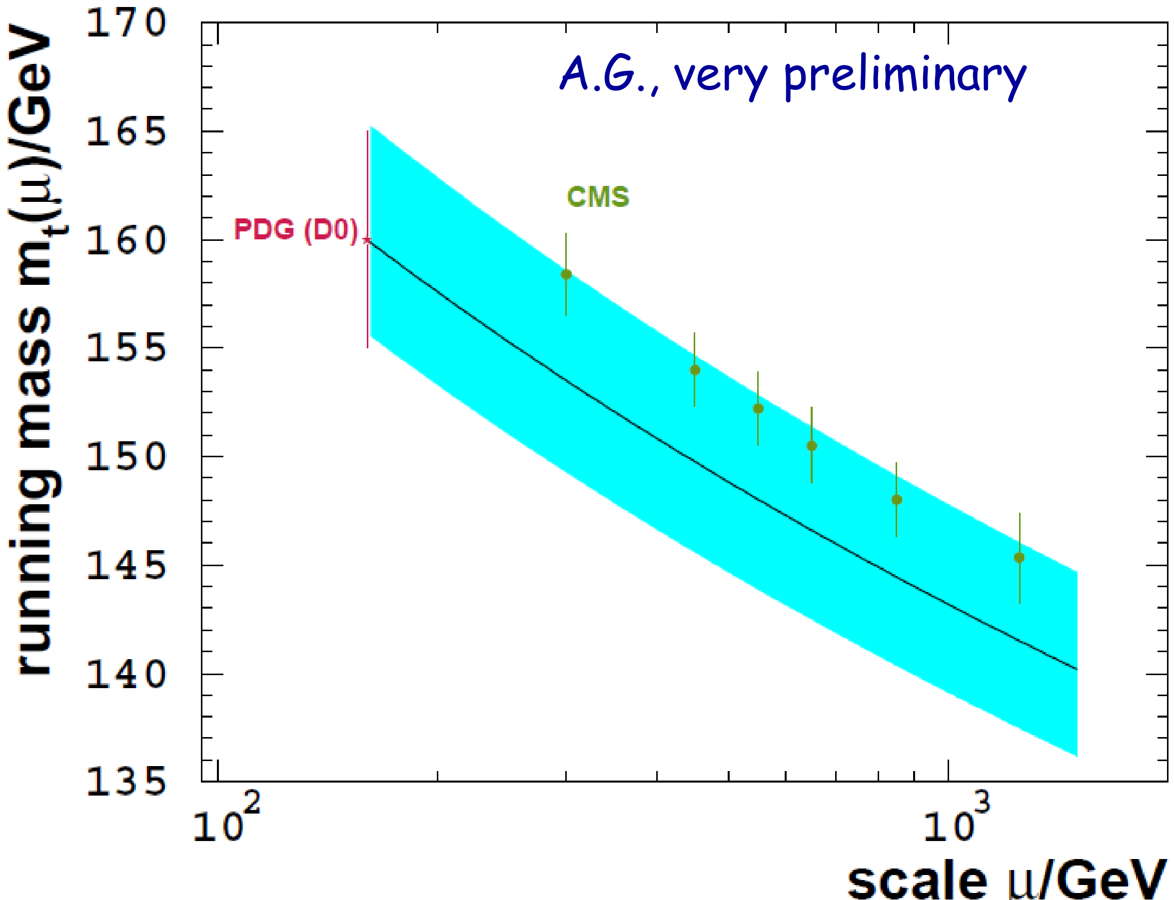
ATLAS: m_t(pole) = 173.7 $\pm 1.5_{stat}$ $\pm 1.4_{syst}$ $+1.0-0.5_{th}$ GeV

CMS: m_t(pole) = 173.8 $+1.7-1.8_{total}$ GeV <-> $m_t(MC_{CMS,l+jets})$=172.35 $\pm 0.16_{stat}$ $\pm 0.48_{sys}$ GeV

PDG: m_t(pole) = 176.7 $\pm$4.0-3.4 GeV, "m_t(MC)" =173.21 $\pm 0.51_{stat}$ $\pm 0.71_{sys}$ GeV

convert pole masses to running mass





caveat:

not all uncertainties from conversion included

(needs theoretically better defined procedure!)

-> take with grain of salt, **for illustration purposes**

Discussion

of future conceptual improvements

- avoid MC mass and pole mass intermediate steps for top

  -> extract $m_t(\mu)$ directly from data, as already done for b,c

  (e.g. from absolute m_{tt} cross sections in CMS-TOP-16-008)

  need NLO QCD theory for LHC using running mass

- extend LO EW + NLO QCD approach

  (running of Higgs couplings is purely QCD-induced!)

  to NLO EW + NNLO QCD + interference

  highly non-trivial but eventually necessary

  (Standard Model is not QCD only)