Charm, Beauty and Top quark mass measurements

at LEP, HERA and LHC and their relation to running Higgs Yukawa couplings

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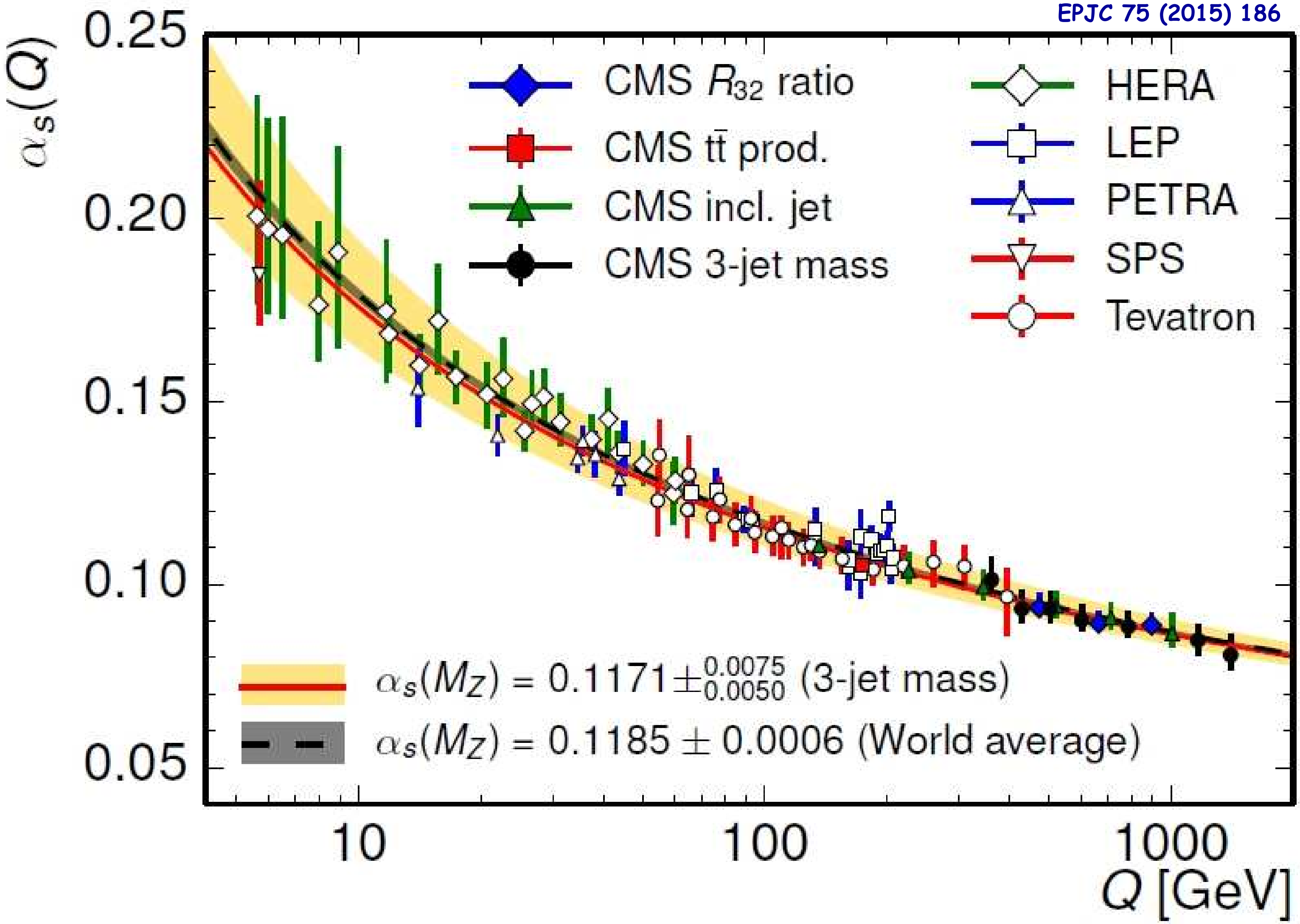
- **Introduction: running of α_s and quark masses**
- **Running of beauty quark mass**
- **Running of charm quark mass**
- **Running of top quark mass**
- **Running of Higgs Yukawa couplings**

Running strong coupling „constant" α_s

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

EPJC 75 (2015) 186



"typical" procedure for α_s running

- extract α_s from some kinematic distribution in limited scale range (e.g. jet p_T)
- express in terms of $\alpha_s(m_Z)$ separately for each bin in this distribution
- convert back to $\alpha_s(\mu)$ with appropriately chosen scale μ using renormalization group equations (which are implicitly assumed in measurement procedure)

can of course express each α_s measurement at chosen scale directly -> equivalent

running of α_s and quark masses

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

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + \alpha_s\,(11N_C - 2N_F)/12\pi\ \ln(Q^2/Q_0^2)}$$

leading order QCD formulae

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

$$m(\text{pole}) = m(m)\,(1 + 4/3\ \alpha_s/\pi)$$
$$= m(Q)\,(1 + \alpha_s/\pi\,(4/3 + \ln(Q^2/m_c^2)))$$

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

the running b quark mass at LEP

DELPHI, Eur. Phys. J. C55 (2008) 525

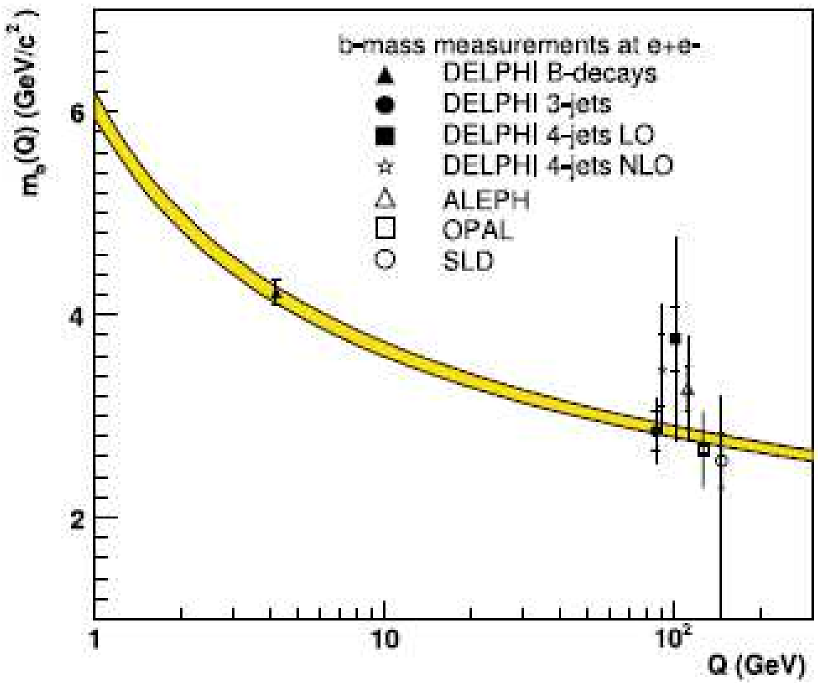


Fig. 6. The energy evolution of the $\overline{MS}$-running b-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The masses extracted from LO and approximate NLO calculations of $R_4^{b\ell}$ are found to be consistent with previous experimental results and with the reference value $m_b(Q)$ (*grey band*) obtained from evolving the average $m_b(m_b) = 4.20 \pm 0.07$ GeV/c^2 from [17] using QCD RGE (with a strong coupling constant value $\alpha_s(M_Z) = 0.1202 \pm 0.0050$ [30])

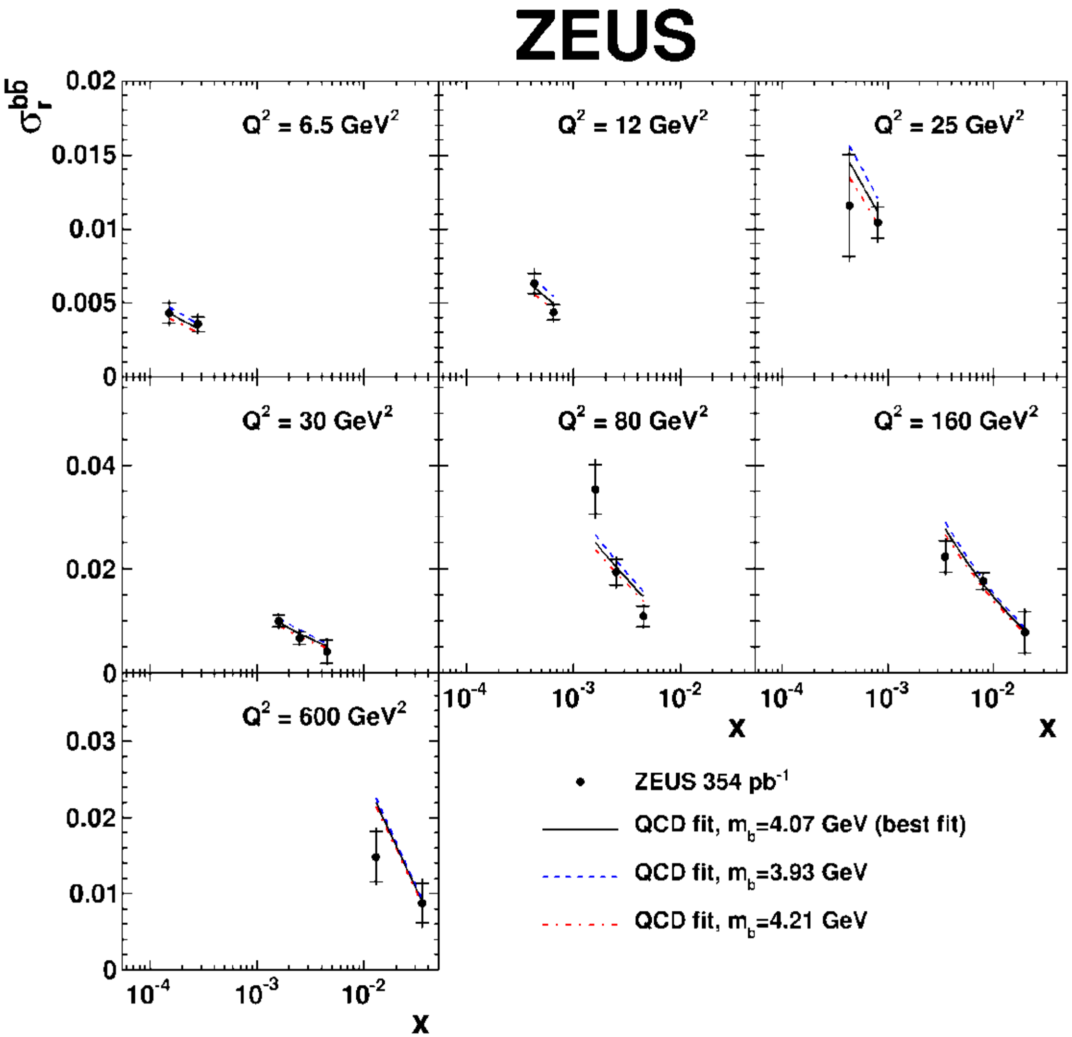
LEP: Z -> $b\bar{b}$ + gluons, measurement of phase space/ angular distributions

$$m_{(Q)} = m_{(Q_0)} \, (1 - \alpha_s/\pi \, \ln(Q^2/Q_0^2))$$

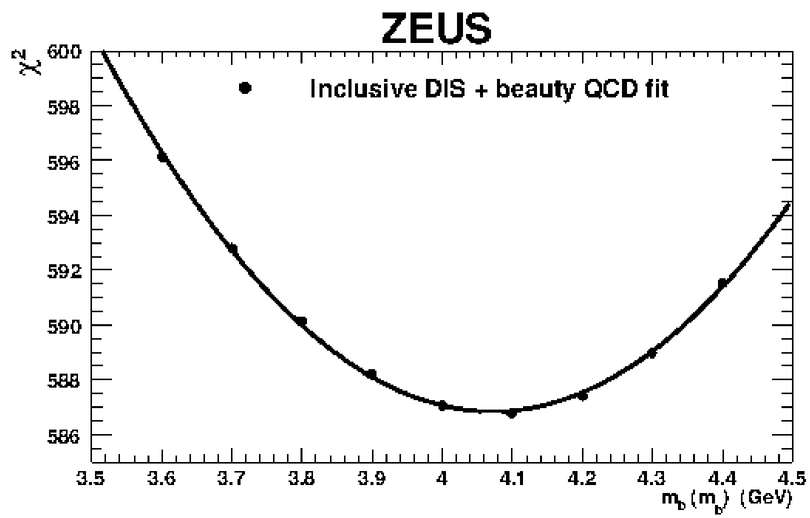
charm and top mass running not explicitly measured (so far)

m_b from HERA beauty cross section

ZEUS, JHEP 1409 (2014) 127



in DIS



uncertainty evaluation
similar to charm running case

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

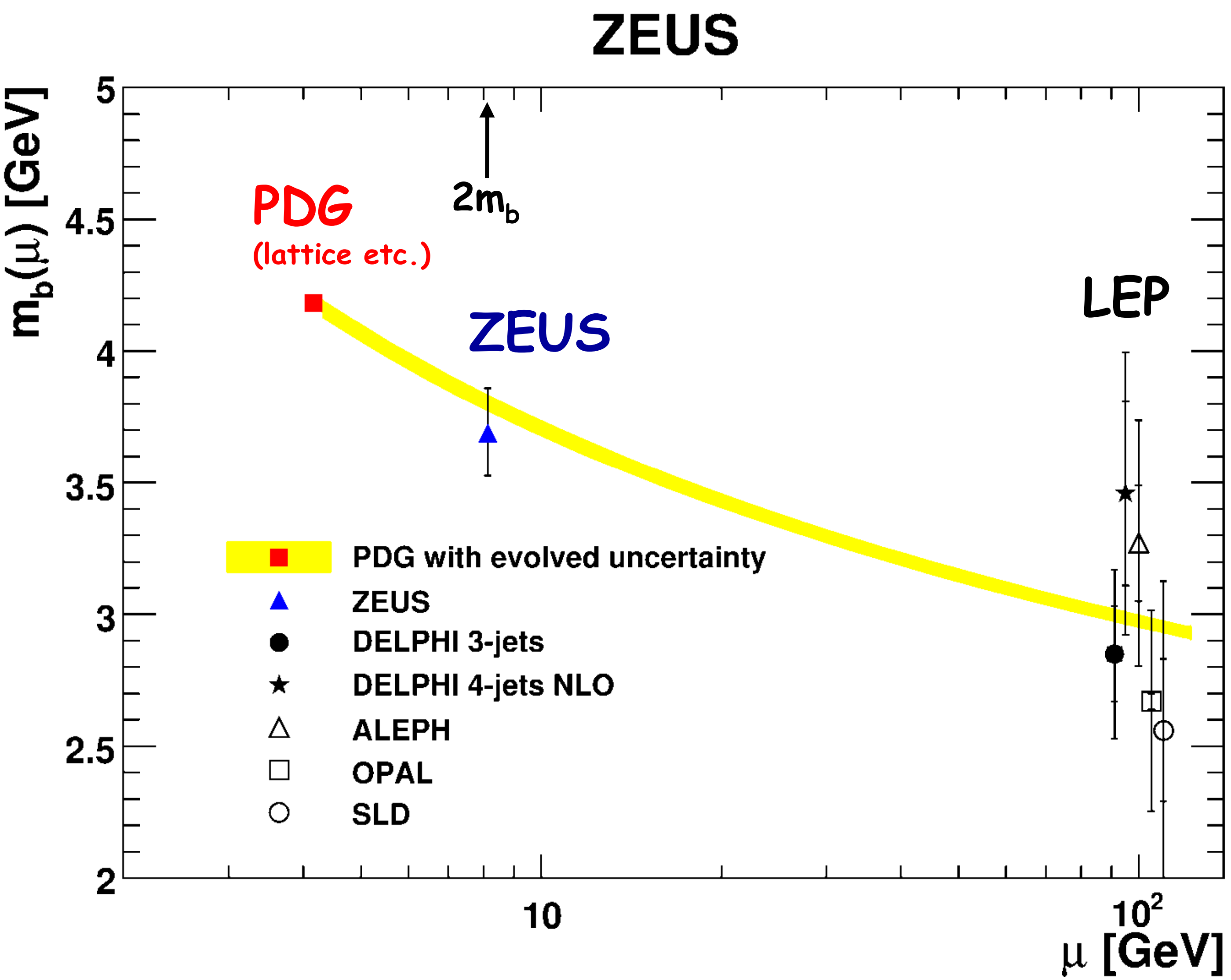
PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

the running beauty quark mass

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

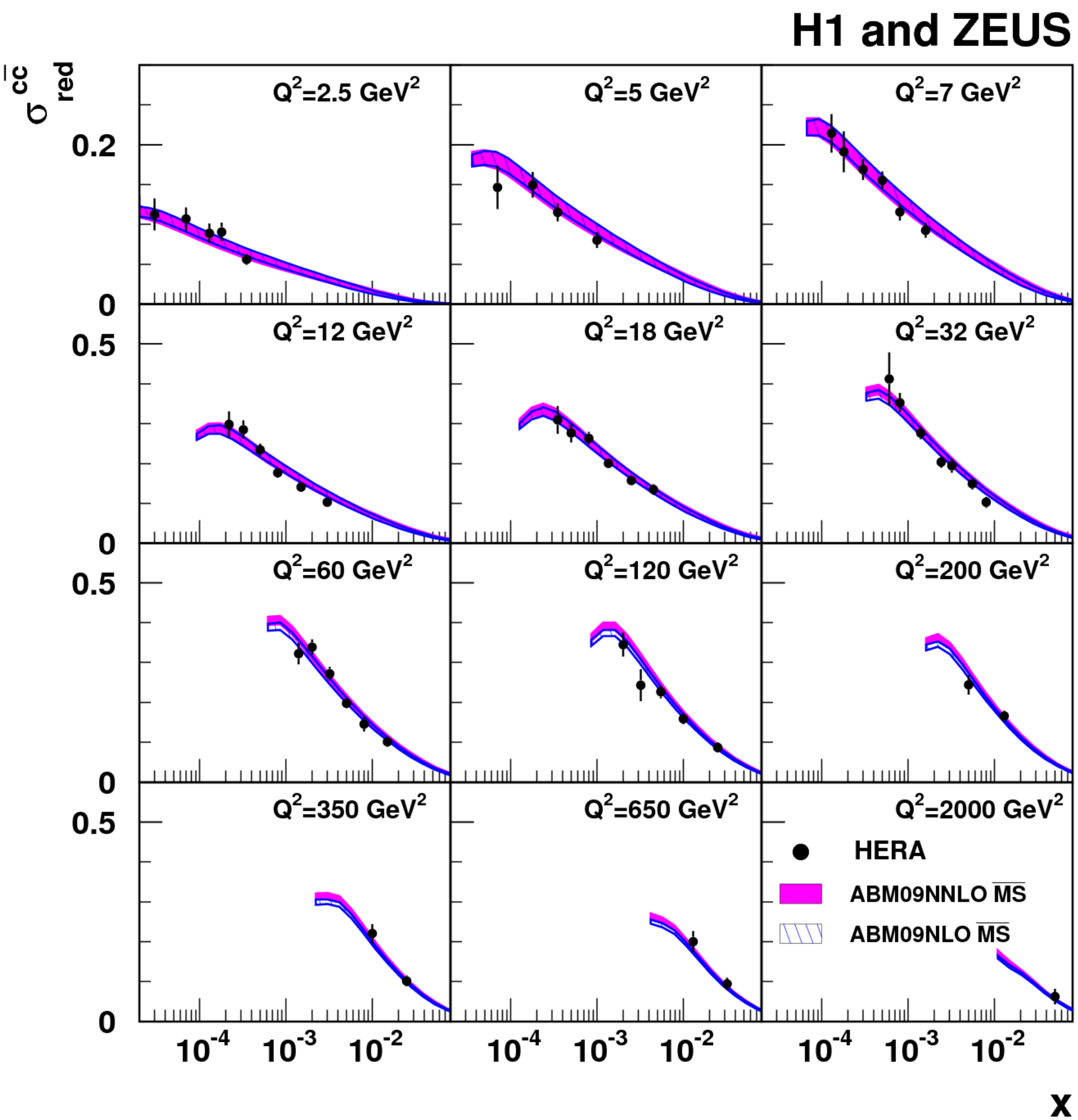
Prog. Part. Nucl. Phys. 84 (2015) 1

translate ZEUS measurement to $2m_b$



Combined HERA charm data

EPJC 73 (2013) 2311



comparison to ABM FFNS

very good description of data in full kinematic range

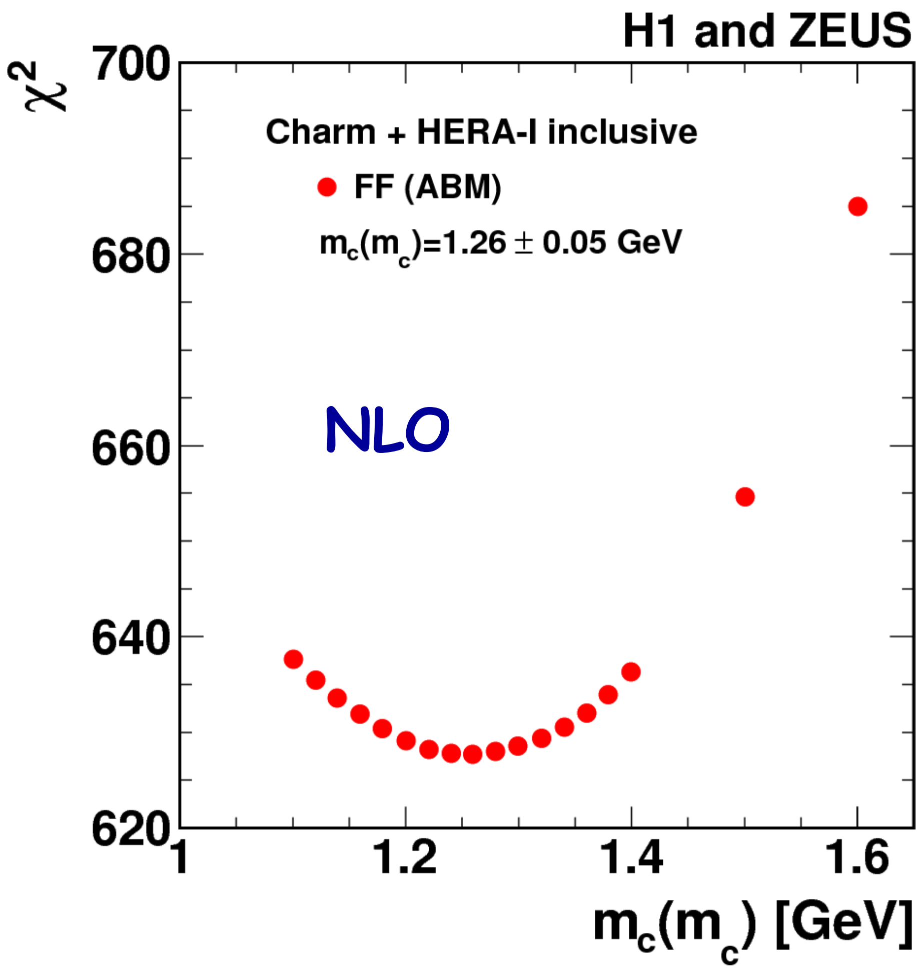
unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass

(similar predictions for pole mass)

measurement of $\overline{MS}$ charm mass

EPJC 73 (2013) 2311



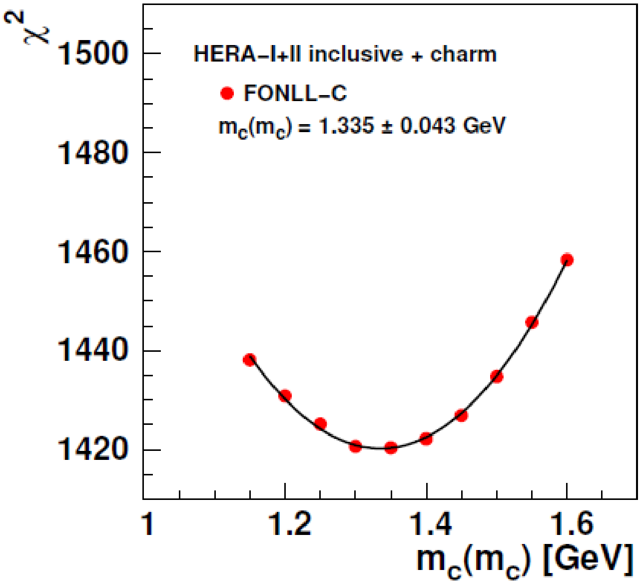
simultaneous fit of combined charm data and inclusive HERA DIS data

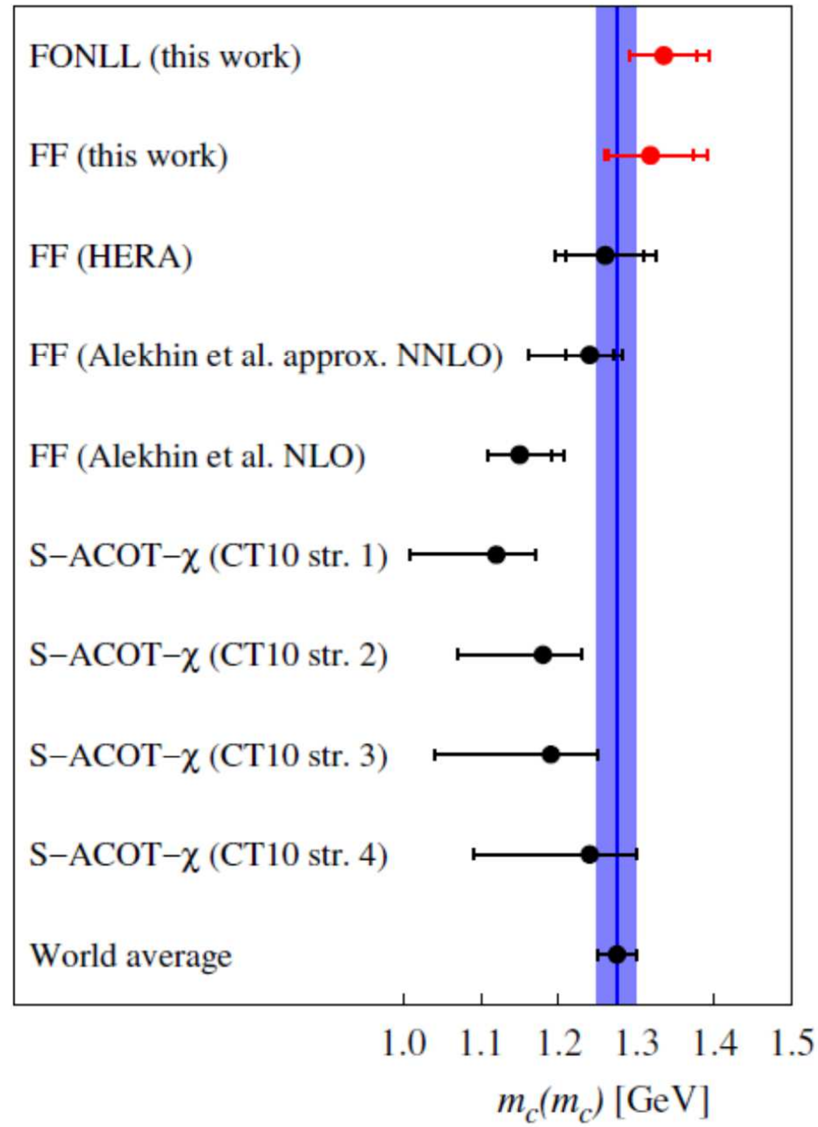
$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

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

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

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



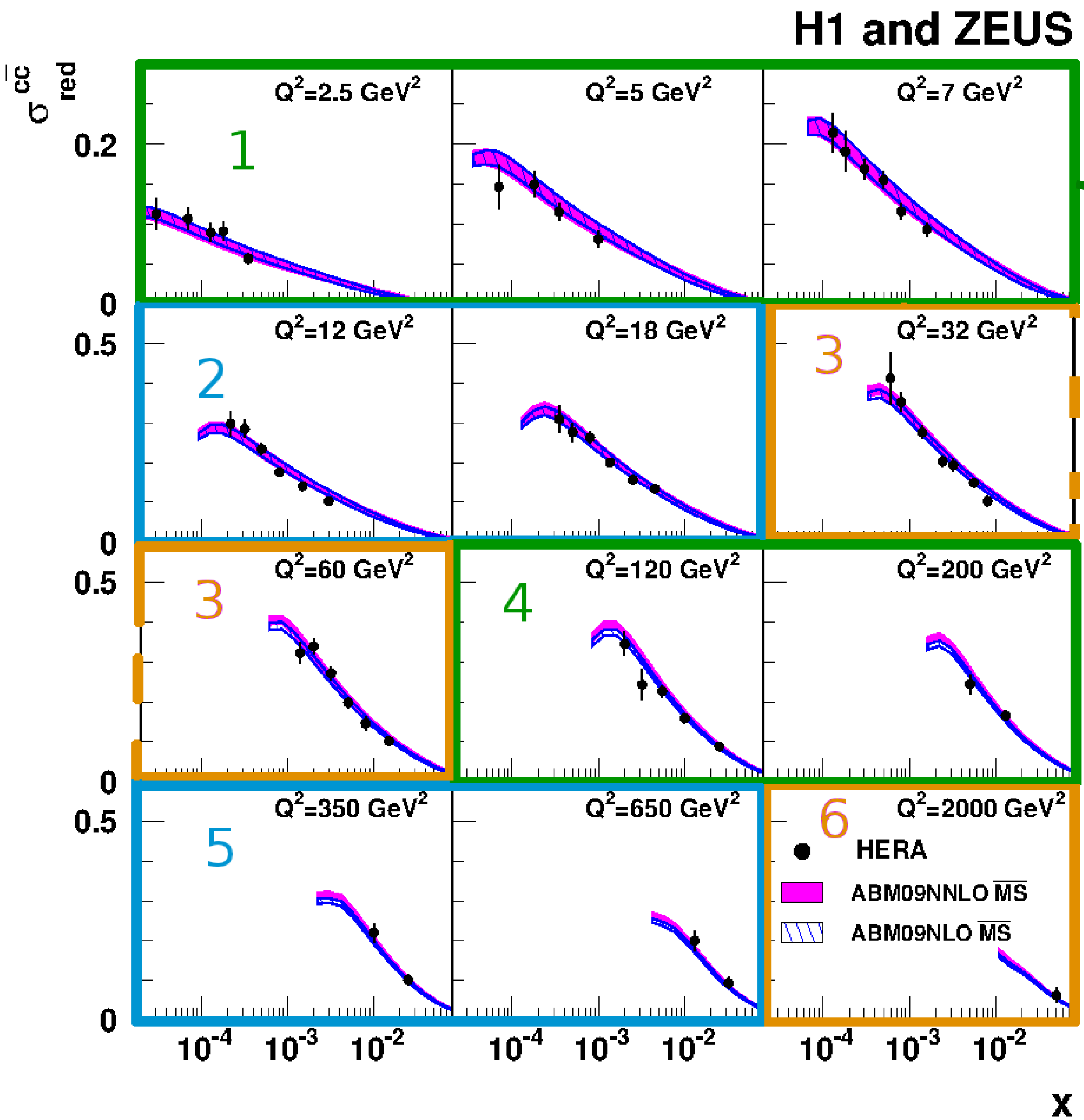


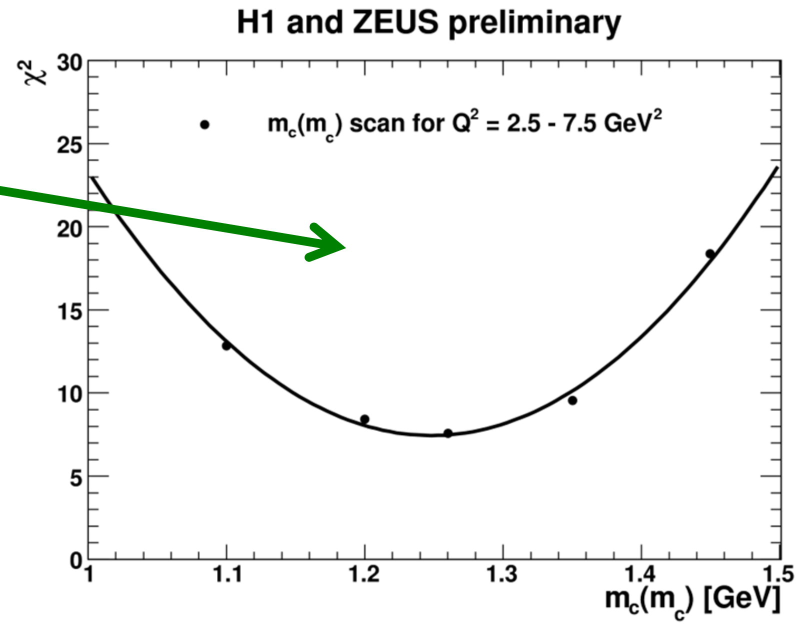
scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (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

$\overline{MS}$ $m_c(m_c)$ extractions using different HF schemes are consistent

measurement of m_c running

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch





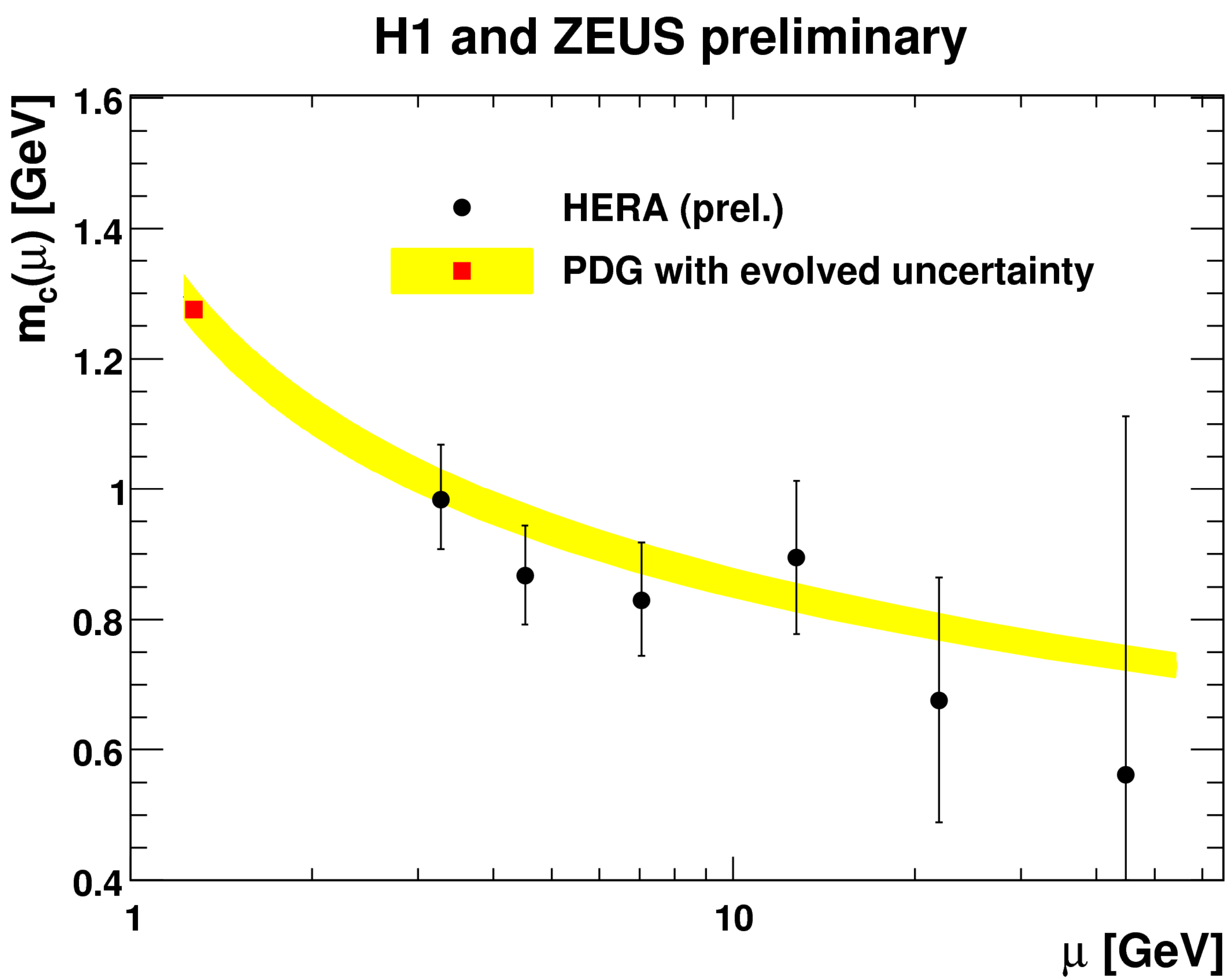
extract $m_c(\mu)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(take log average for central scale)

the running charm quark mass

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

Prog. Part. Nucl. Phys. 84 (2015) 1



running mass
concept in QCD
is self-consistent !

top quark mass running

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

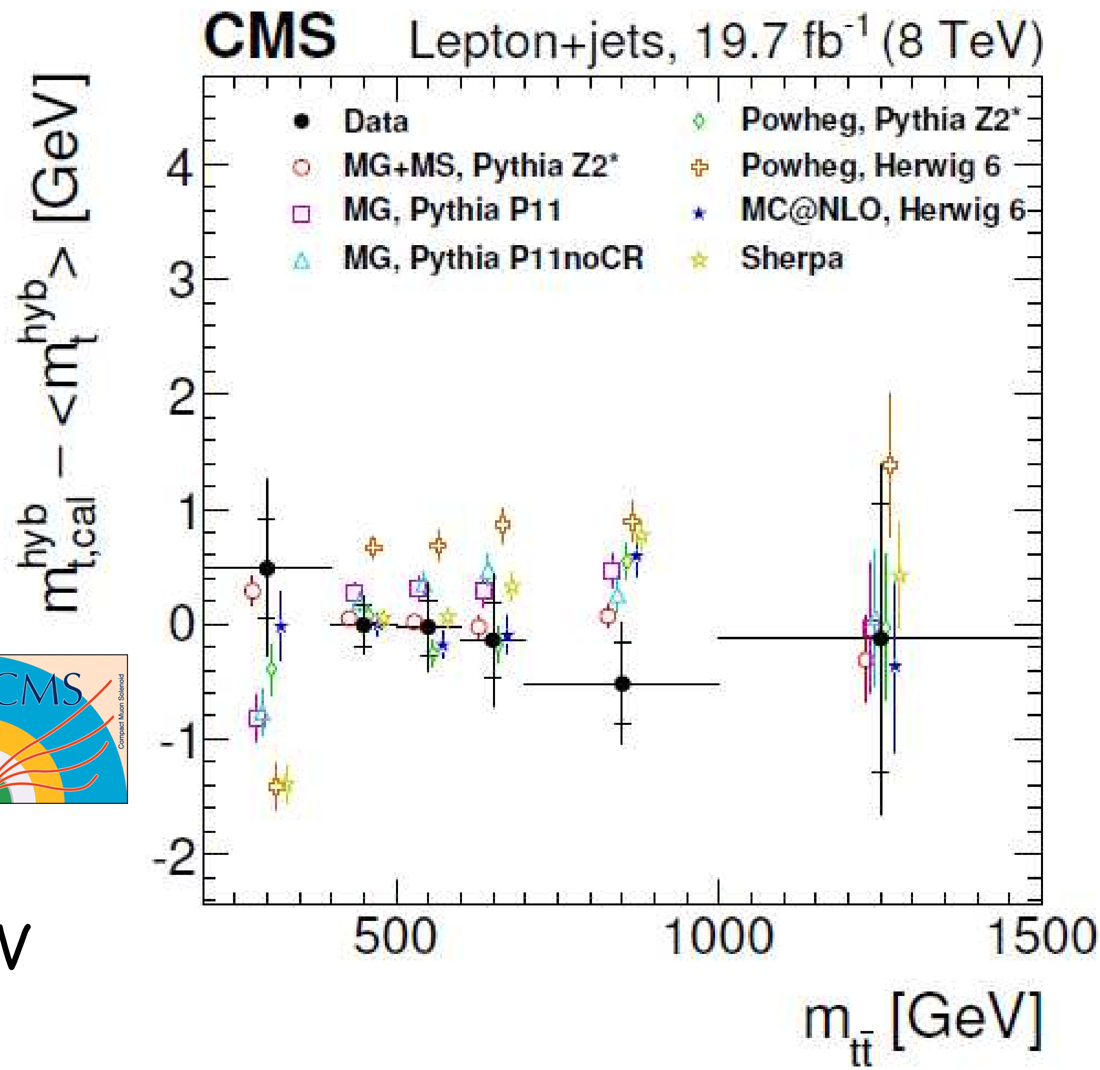
- use (conceptually constant) LO MC mass measured as function of scale-dependent quantity (e.g. $m_{t\bar{t}}$)
- check self-consistency of cross section measurements with data used for mass determination
- 'convert' LO MC mass to NLO pole mass by comparing MC and pole mass extractions from same data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

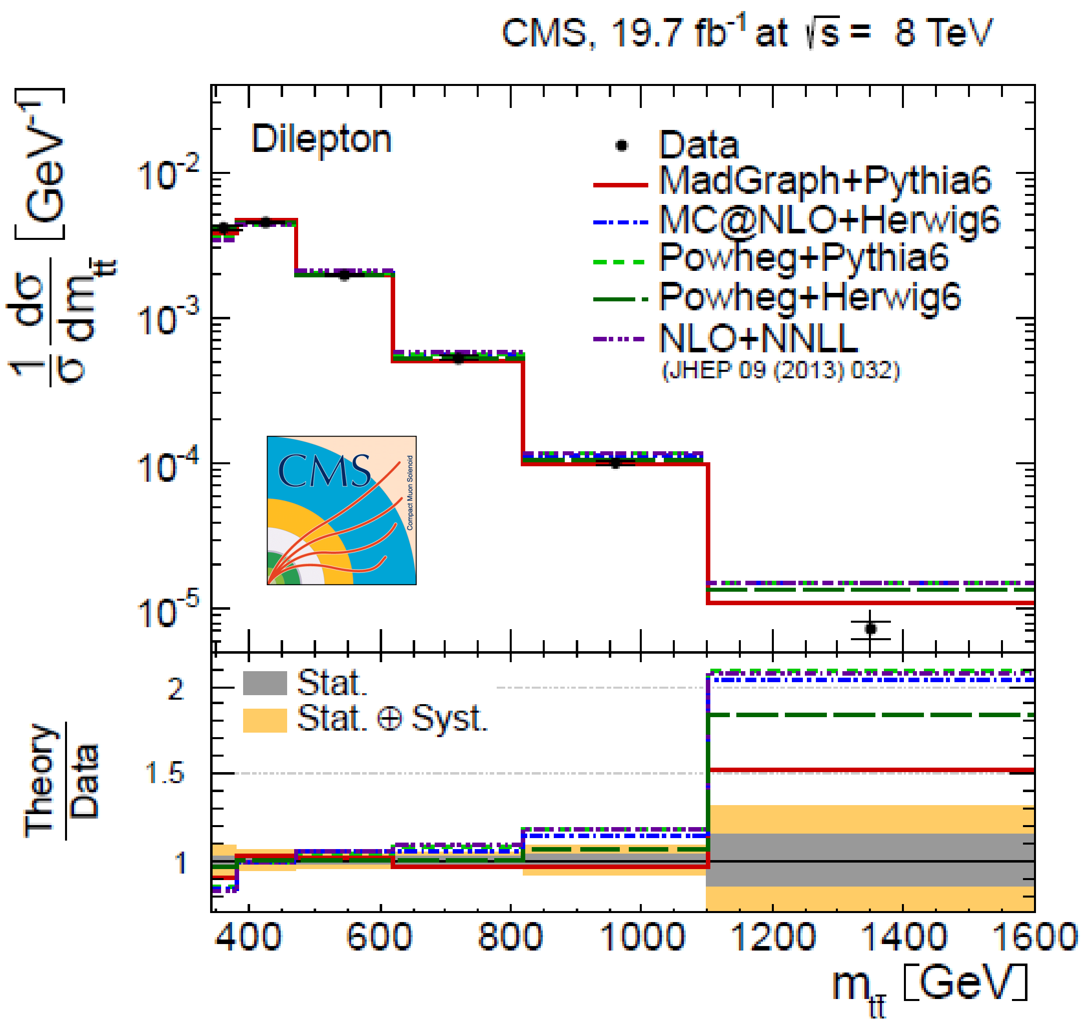
from average of

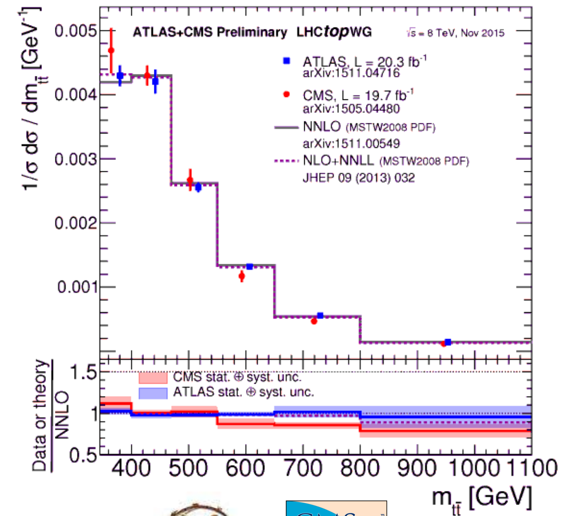
$172.35 \pm 0.16_{stat} \pm 0.48_{sys}$ GeV

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

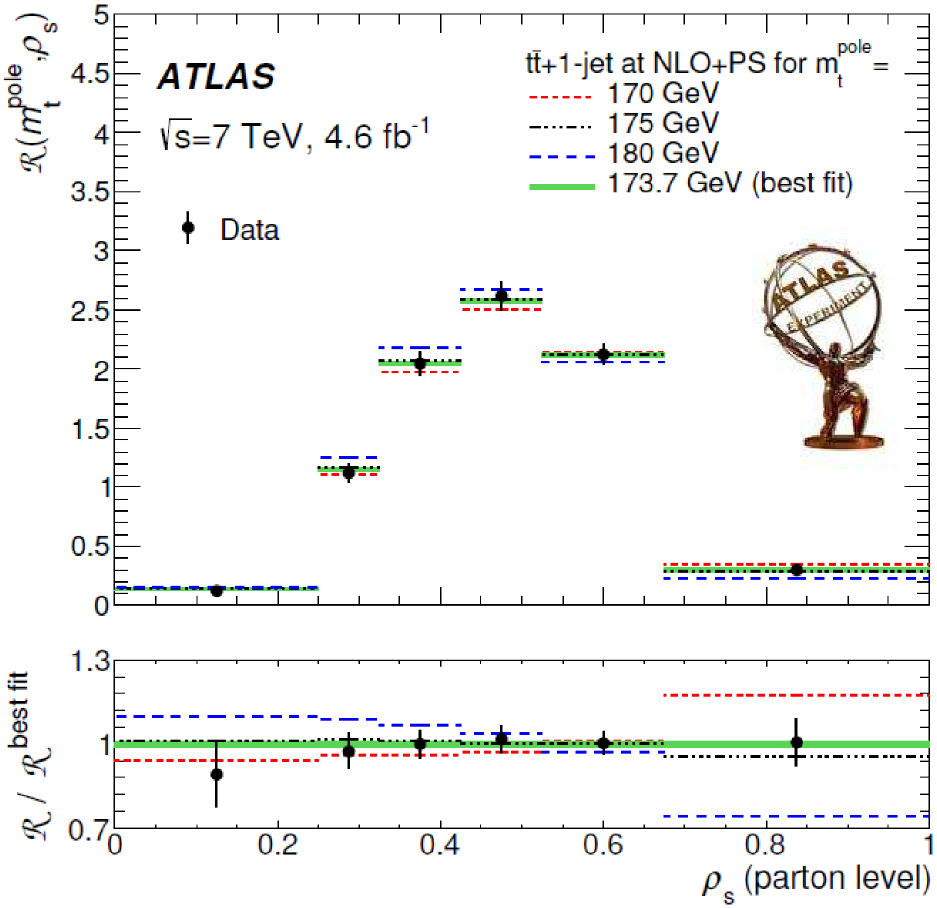
similar results
for lepton+jets
channel only

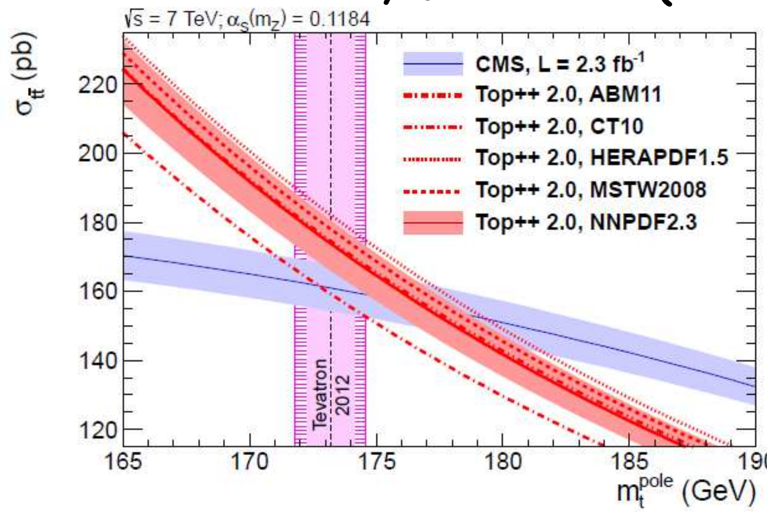
-> measurements and LO+PS/NLO theory are self-consistent
and consistent with ATLAS and NNLO

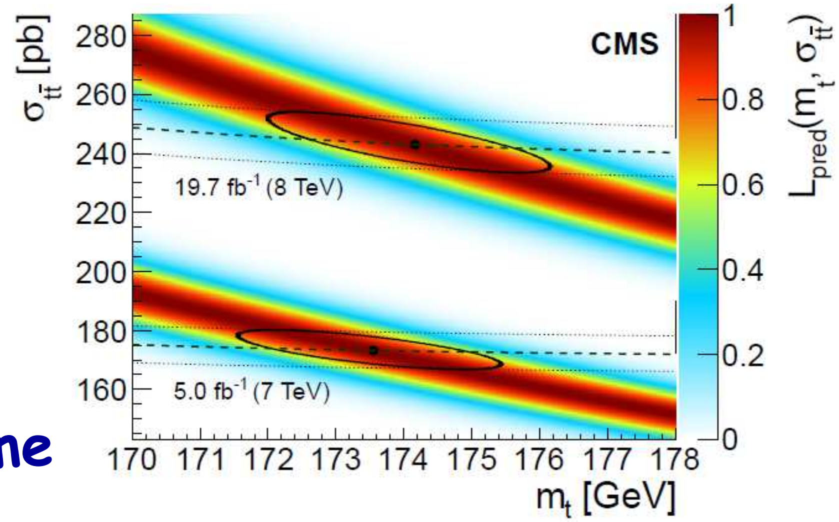
convert top MC mass to pole mass

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

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







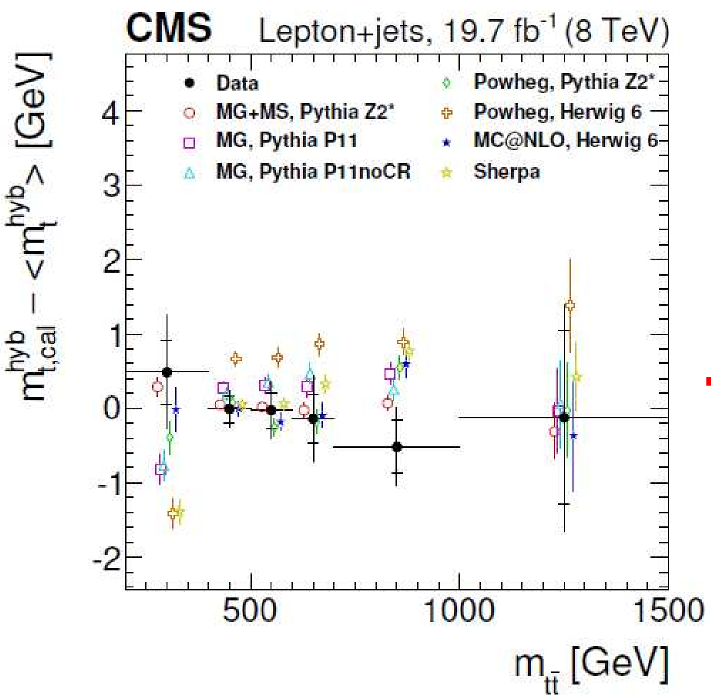
"MC" and pole masses almost the same

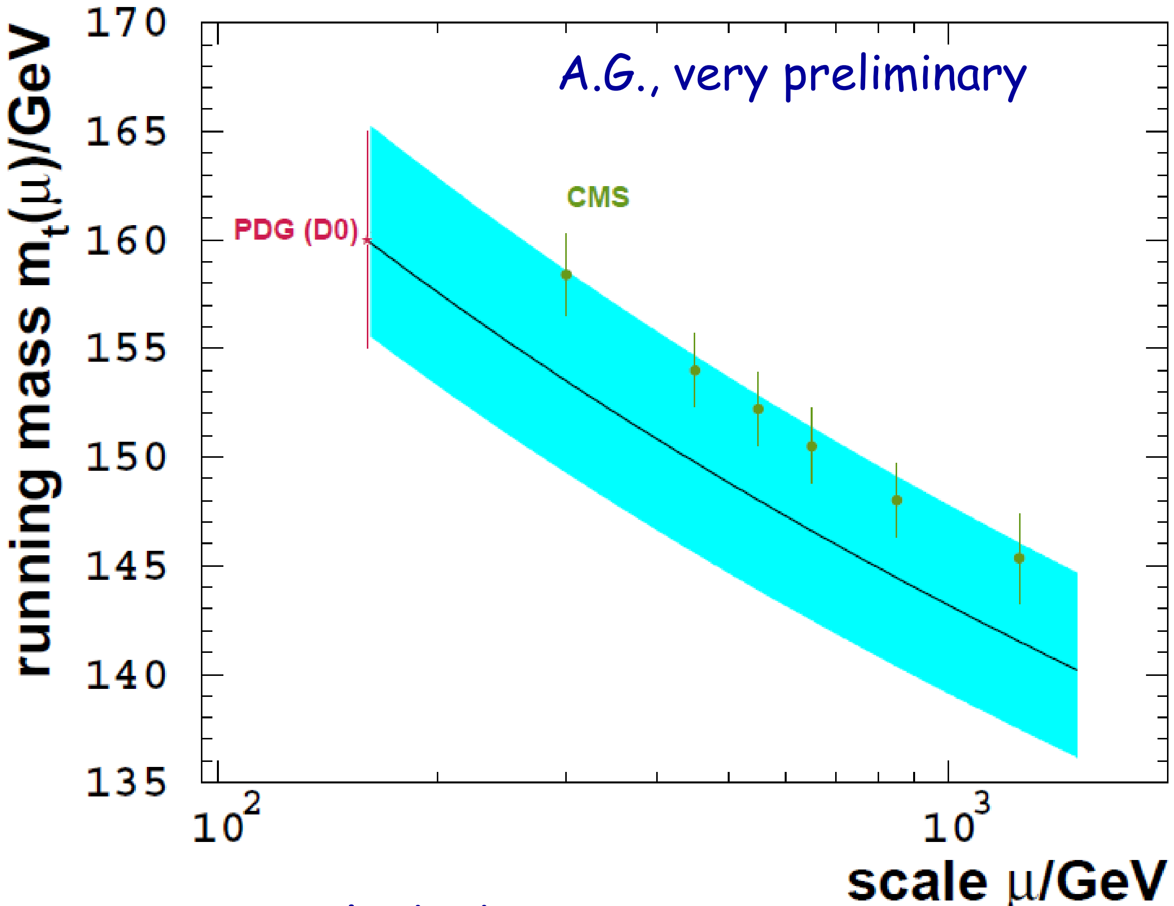
ATLAS: m_t(pole) = 173.7 ±1.5$_{stat}$ ±1.4$_{syst}$ +1.0−0.5$_{th}$ GeV

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

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

convert pole masses to running mass





caveat:

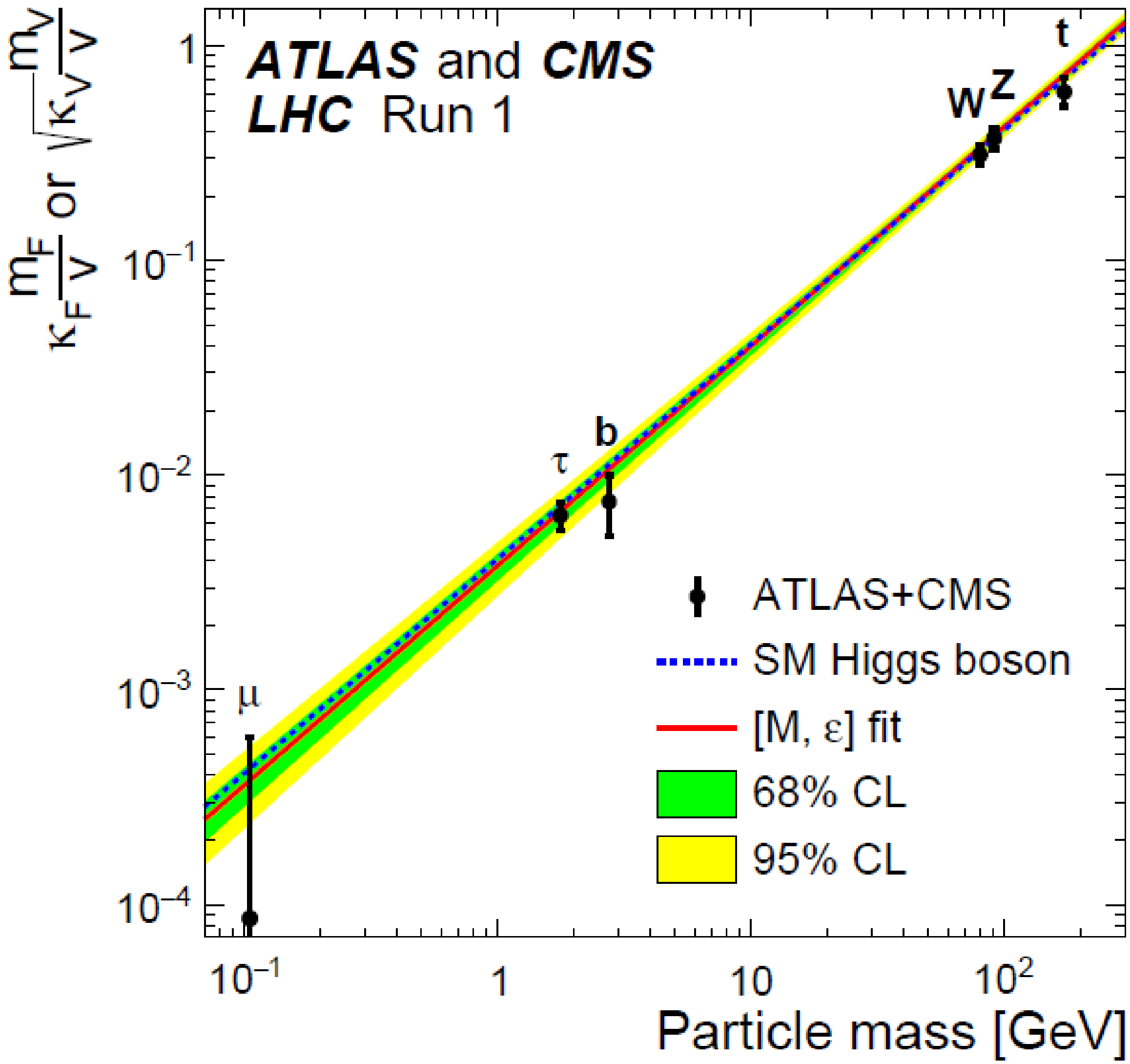
not all uncertainties from conversion included

(needs theoretically better defined procedure!)

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

direct measurements of Higgs Yukawa couplings

ATLAS and CMS, JHEP08 (2016) 045

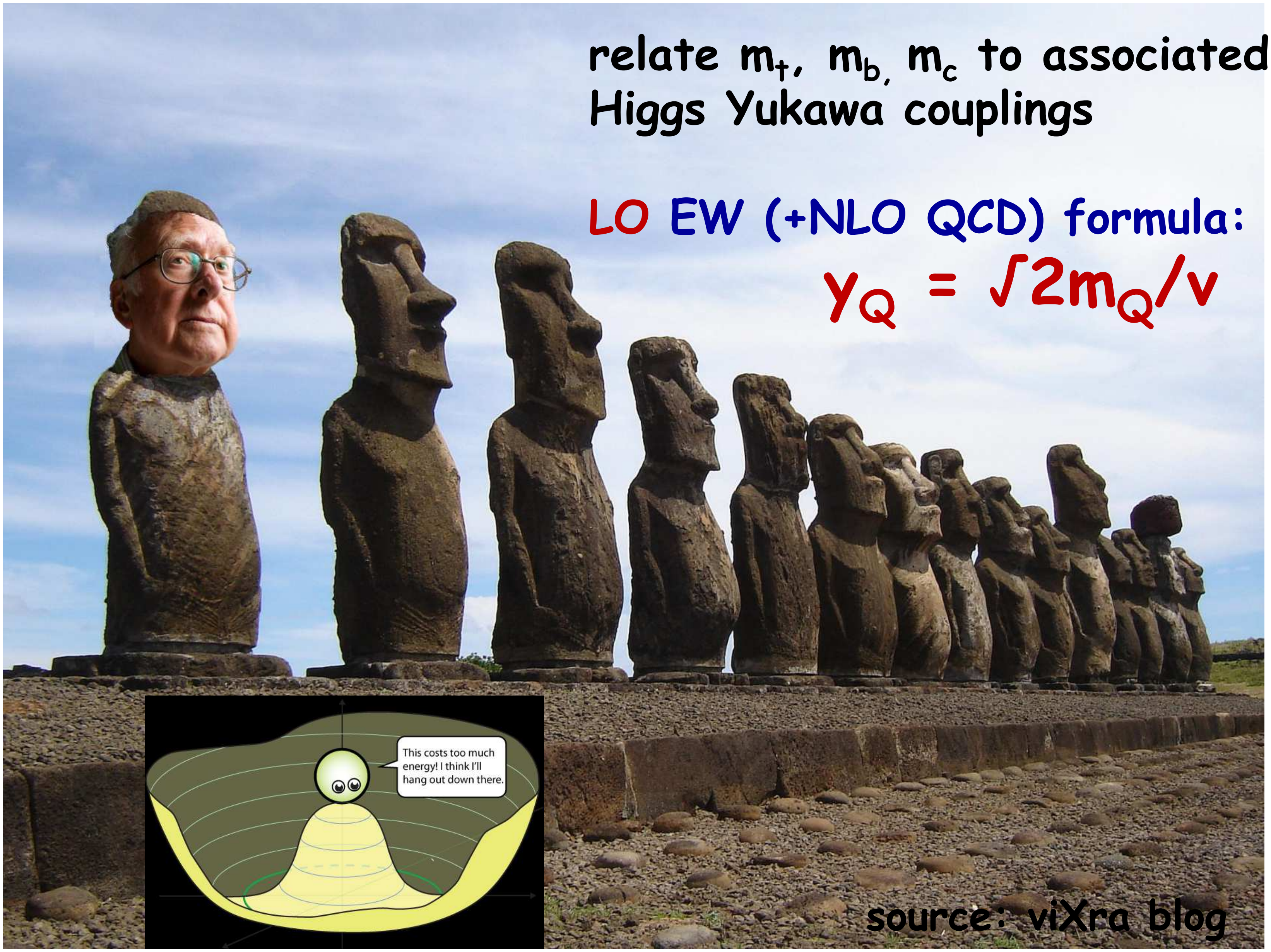


Higgs couplings from m_Q

relate m_t, m_b, m_c to associated Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

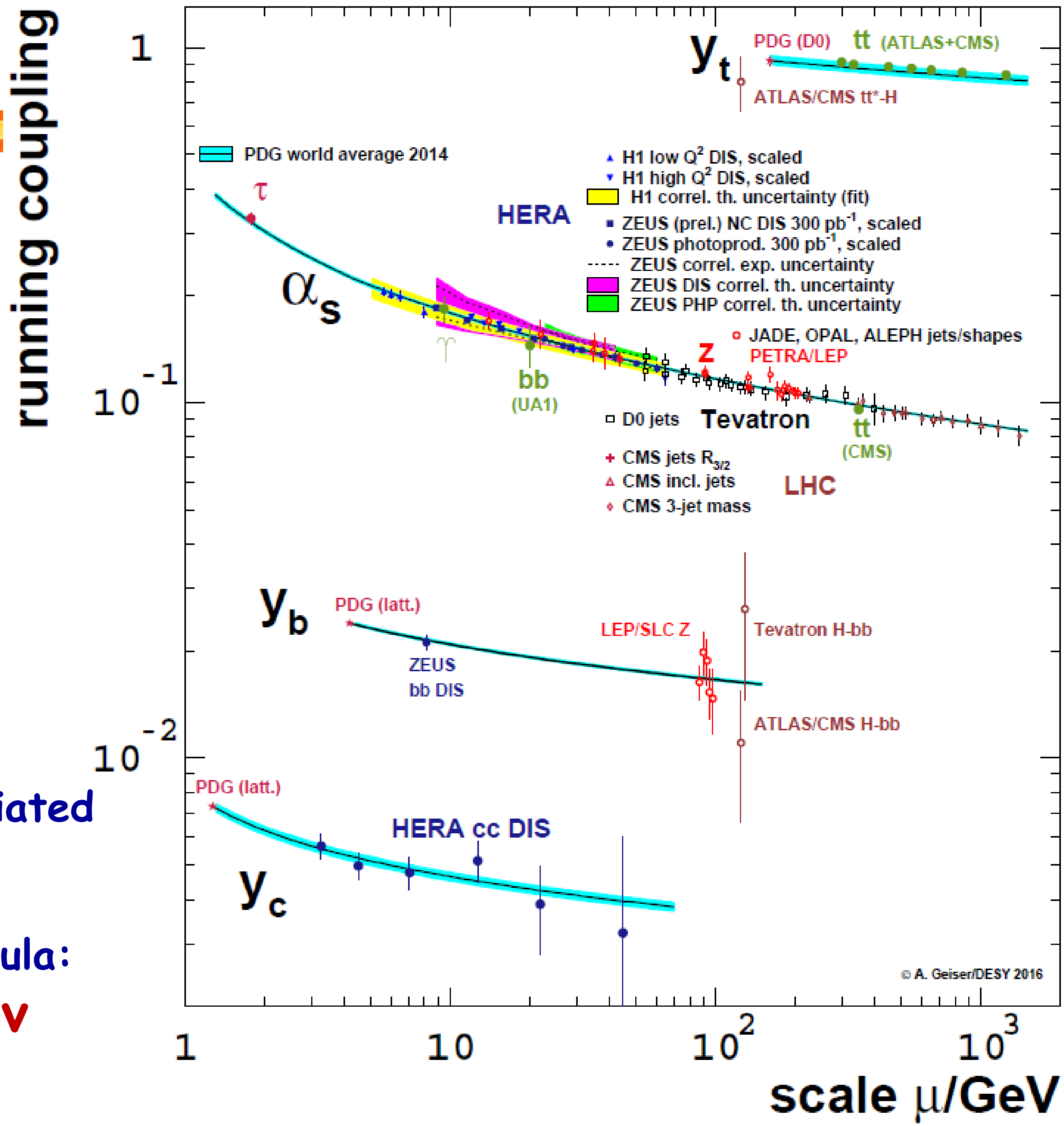
$$y_Q = \sqrt{2} m_Q / v$$



source: viXra blog

Running

of
strong coupling
and
heavy quark
Yukawa couplings
(very preliminary)



relate m_t, m_b, m_c to associated Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

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

Discussion

of future conceptual improvements ?

- avoid MC mass and pole mass intermediate steps for top
  -> extract $m_t(\mu)$ directly from data (e.g. cross sections)
  need NLO QCD theory for LHC using running mass

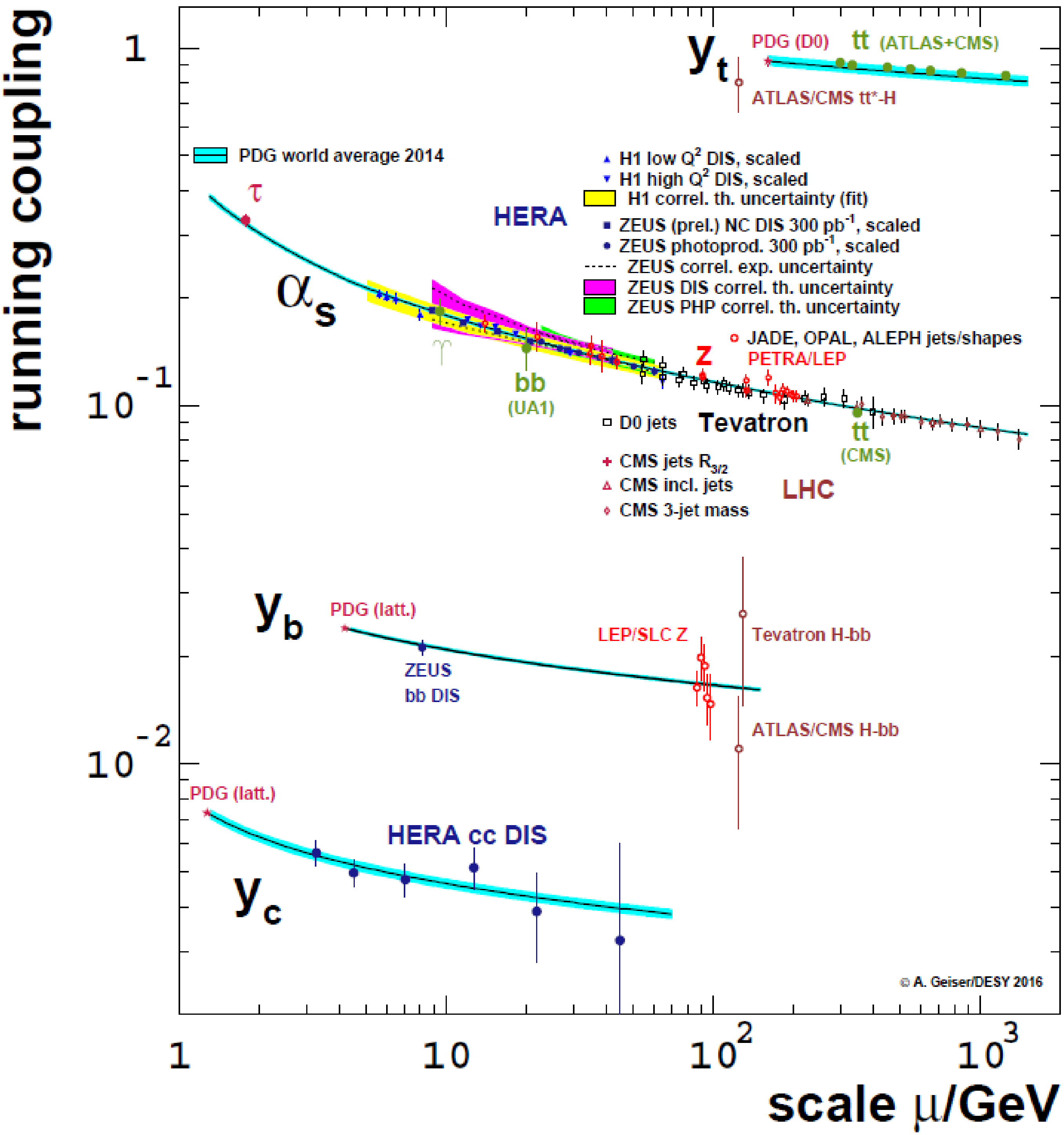
- extend LO EW + NLO QCD approach
  (running of Higgs couplings is purely QCD-induced!)
  to NLO EW + NNLO QCD + interference
  highly non-trivial but eventually necessary
  (Standard model is not QCD only)

Conclusion

experimental representation of running Yukawa couplings obtained for the first time

heavy quark physics is also QCD + Higgs physics

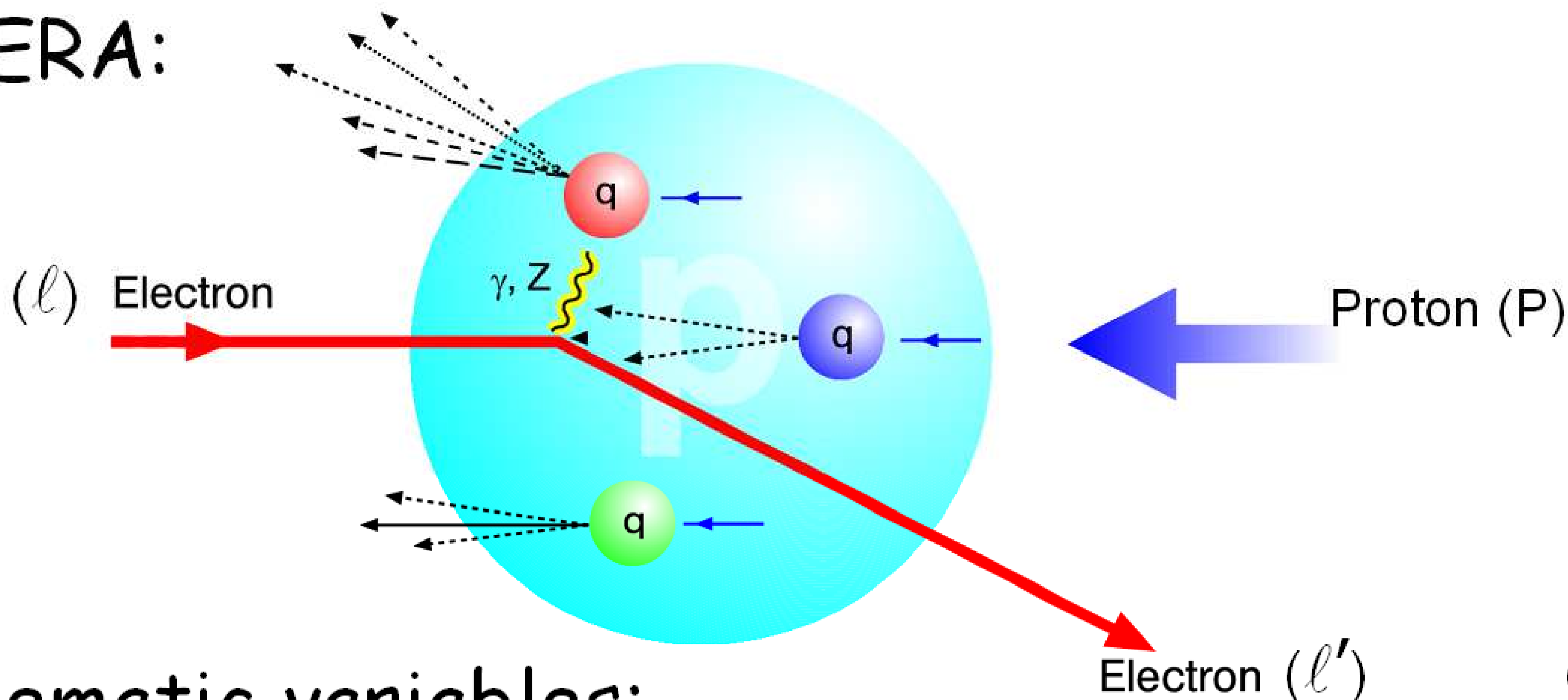
so far, Higgs couplings and their running as obtained from quark masses are consistent with directly measured Higgs couplings



Backup

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

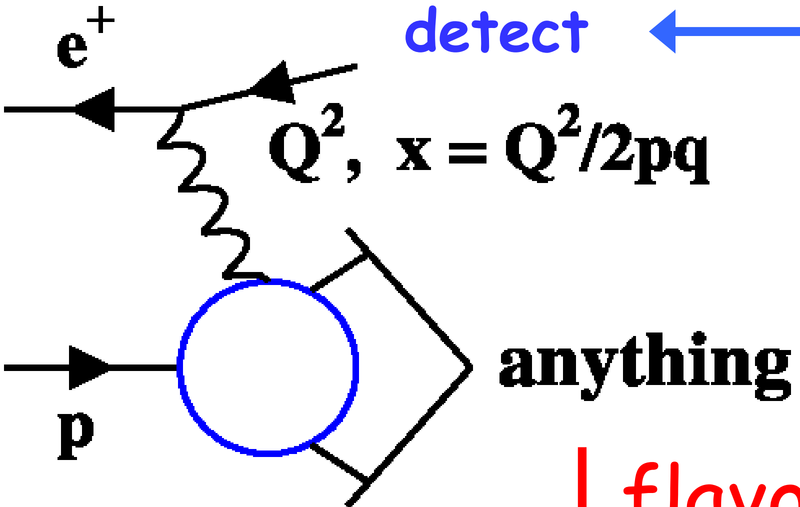
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ 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

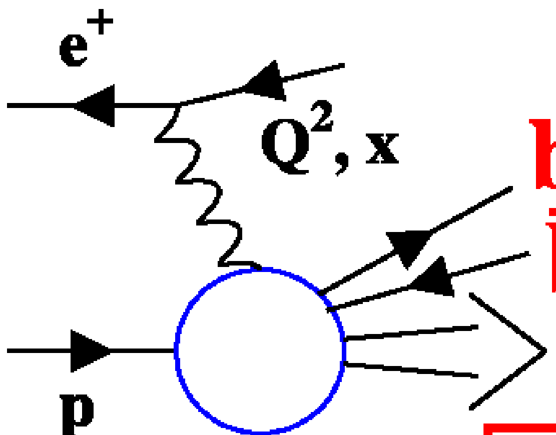


detect ⟷

Measure cross section

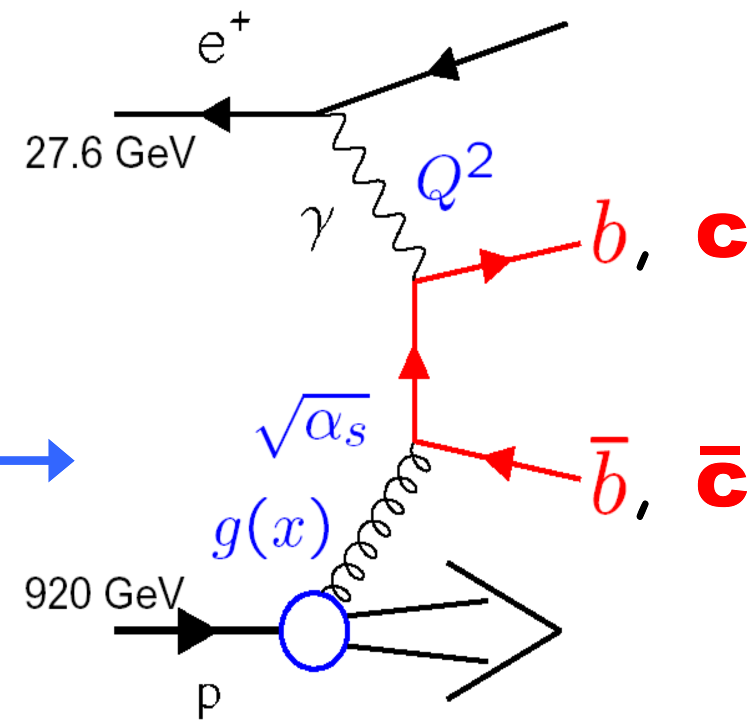
$$\frac{d^2\sigma}{dx\,dQ^2} \simeq \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2)\right.$$

flavour tagging



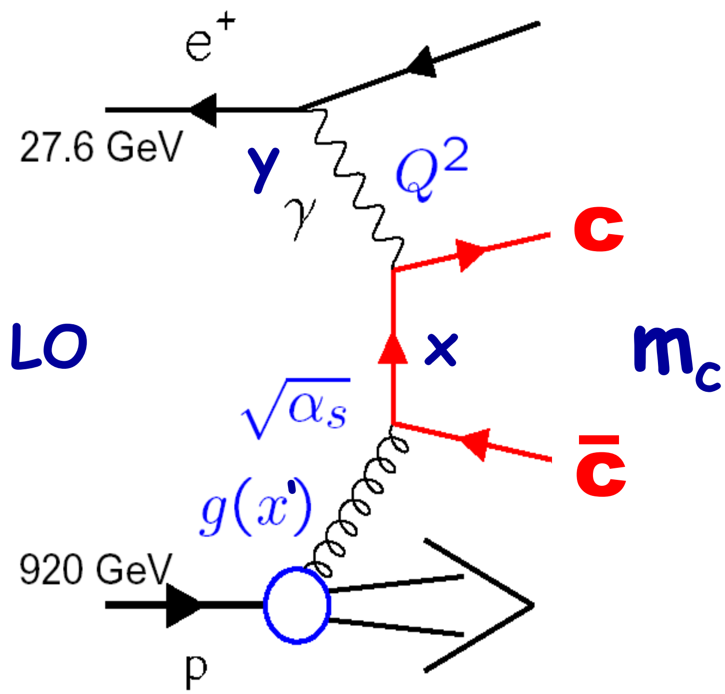
b $\bar{b}$ or c $\bar{c}$

QCD ⟷



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

fixed flavour number scheme (FFNS)



+ NLO (+partial NNLO) corrections,

"natural" scale: $Q^2 + 4m_c^2$

- 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

m_c fit and uncertainties

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

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

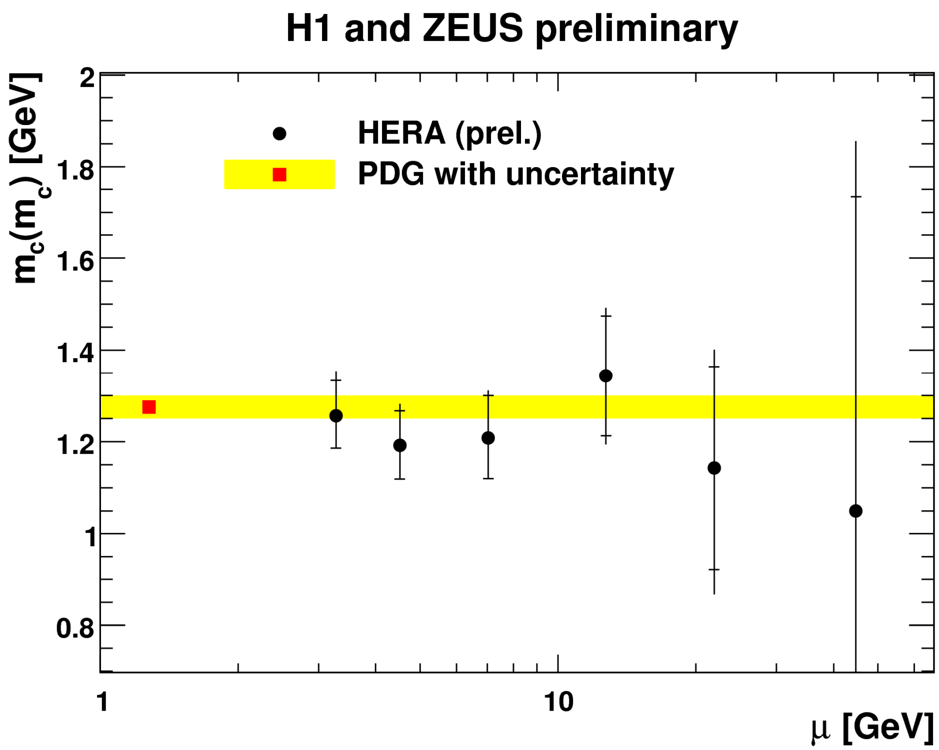
- Adding extra parameter in the PDF parametrisation

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



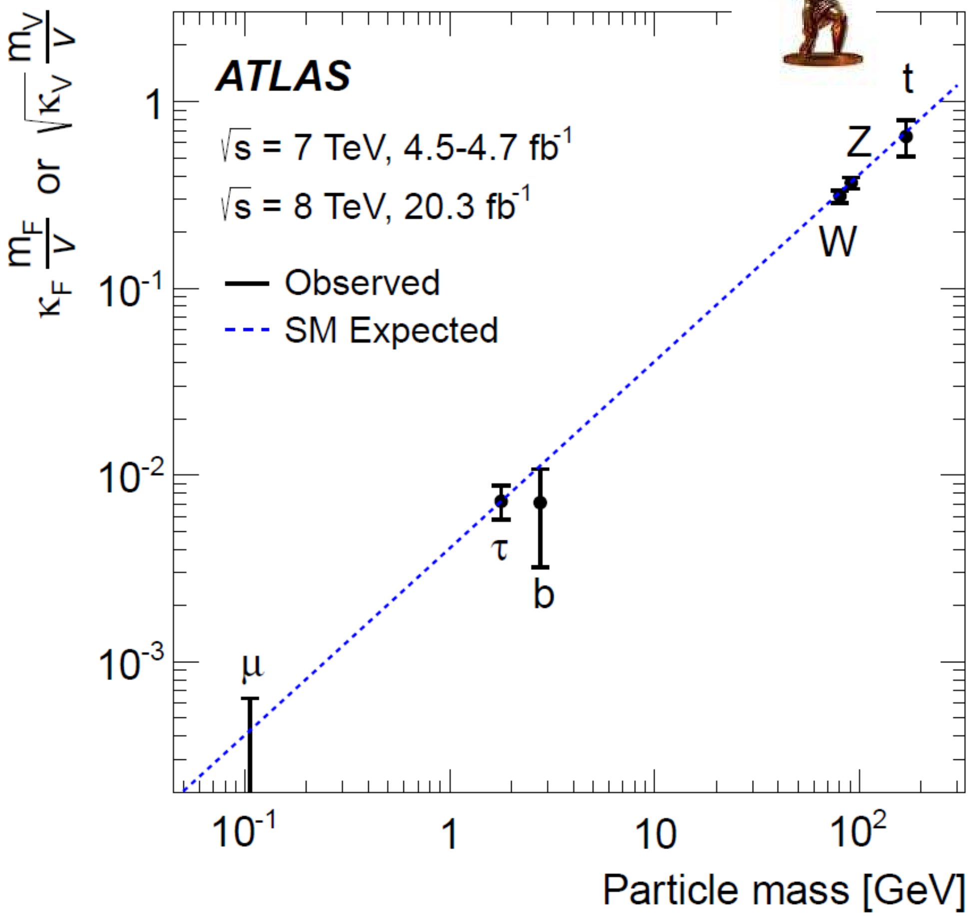
sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

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

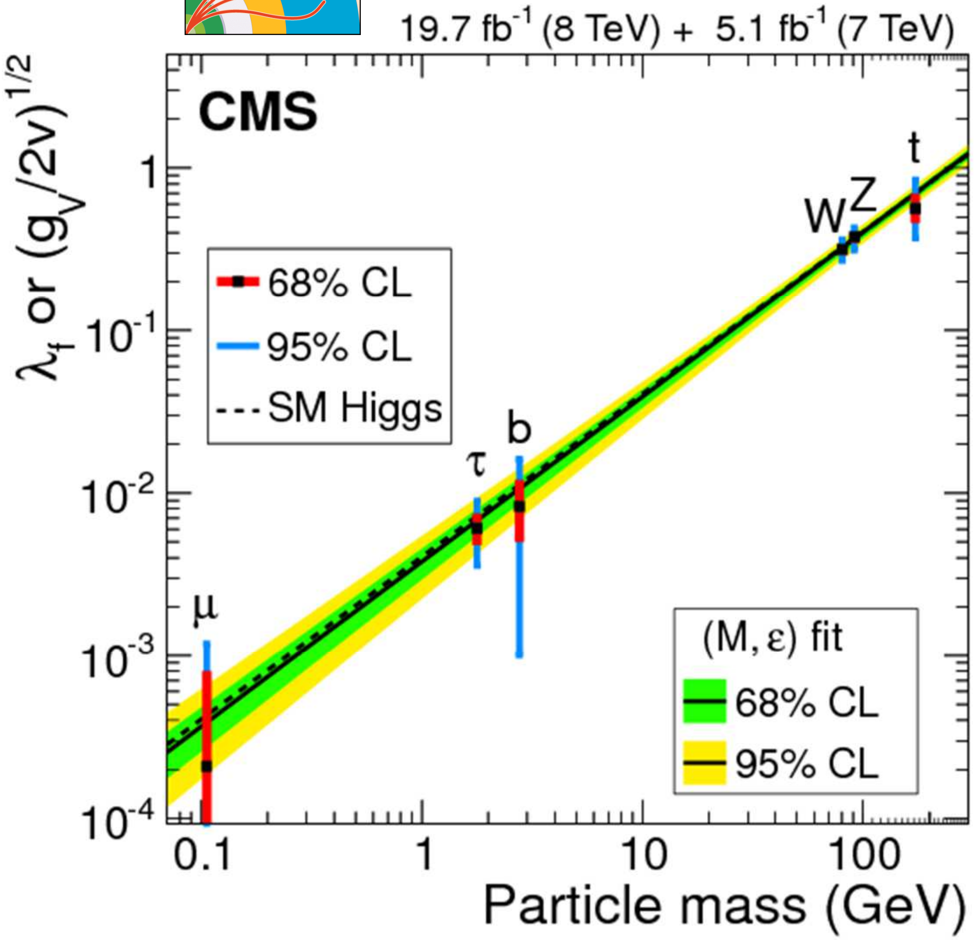
Direct measurements of Higgs Yukawa couplings

vs. mass

arXiv: 1507.04548, EPJC 76 (2016) 6



EPJC 75 (2015) 212



Hbb updated from PRD 92 (2015) 032008

to be updated from JHEP08 (2016) 045