THE BOTTOM – QUARK MASS FROM HIGGS MEASUREMENTS

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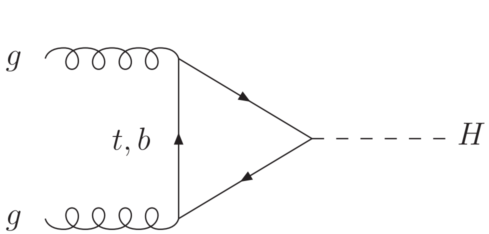
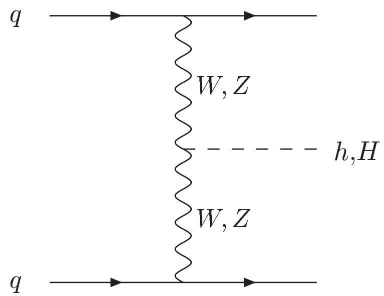
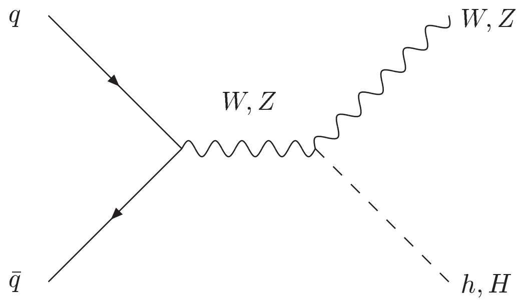
in collaboration with Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, Mateu, Tairafune, Yonamine, Tian, Dao, Moser

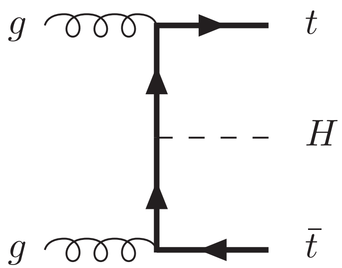
I INTRODUCTION

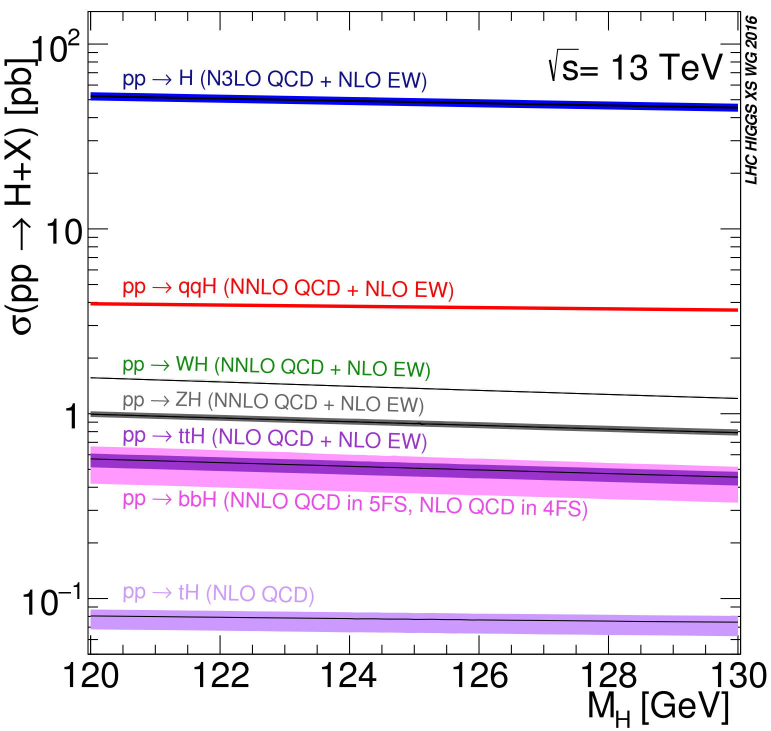
- Higgs Boson Production

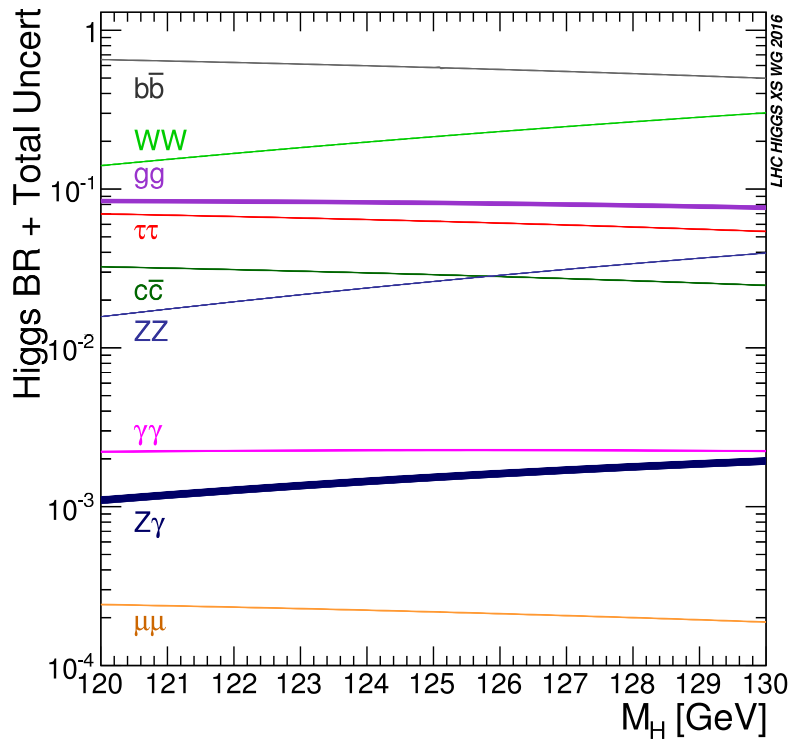






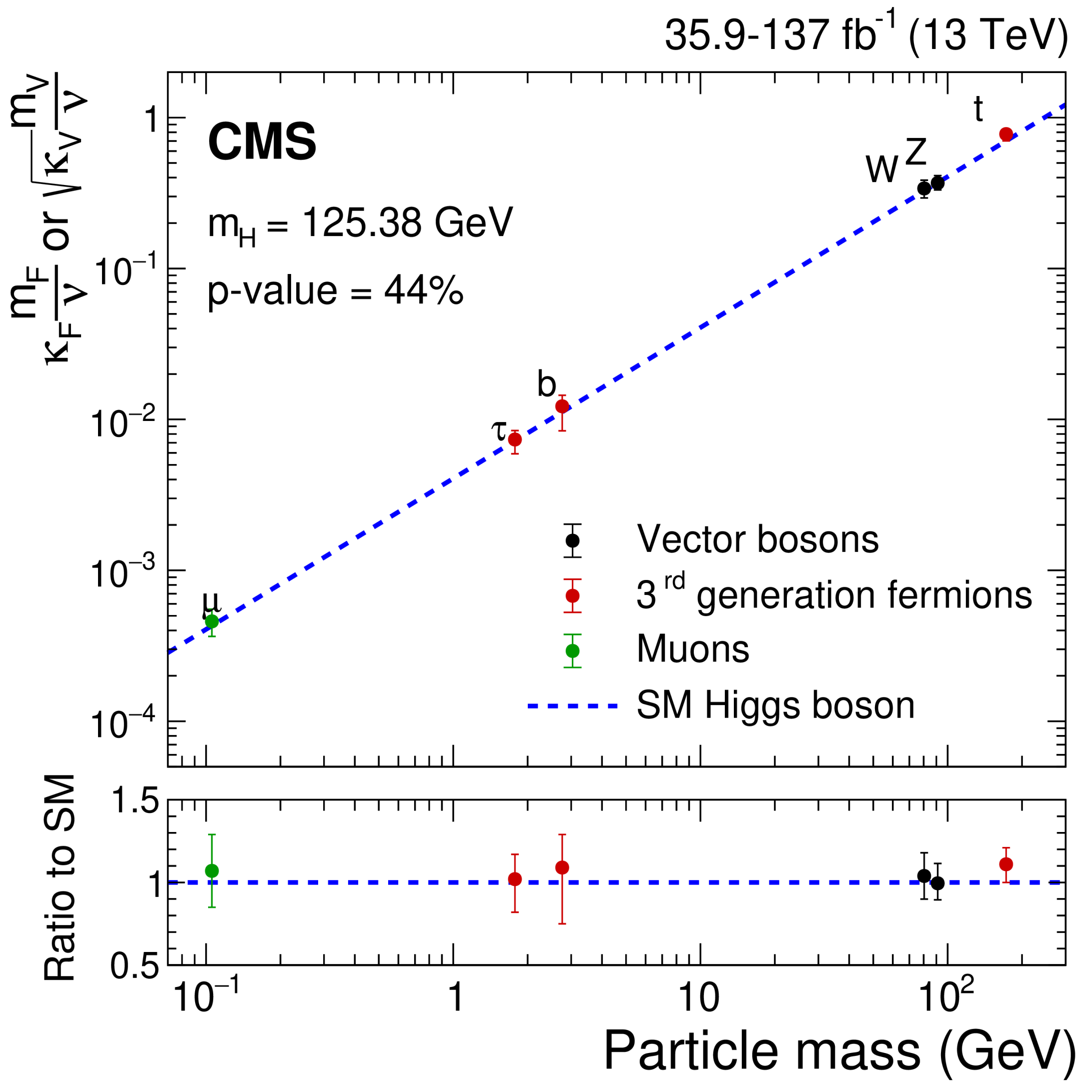






LHC Higgs XS WG

- Discovery: LHC [Tevatron]
  - → Higgs mass
  - couplings
  - spin
  - $\mathcal{CP}$
  - λ ?



II HIGGS BOSON DECAYS

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$	$\sim 0.5\%$	NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

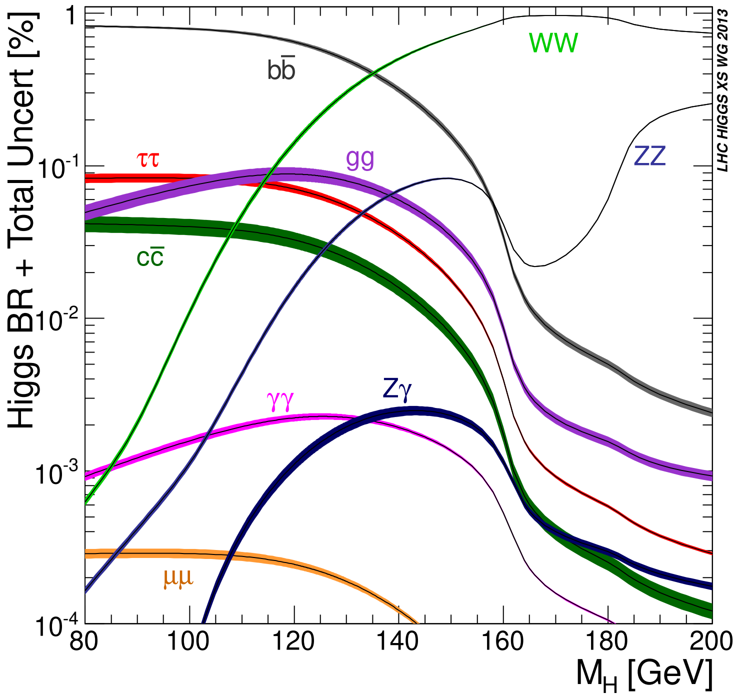
- QCD: variation $\mu_R = [1/2, 2]\mu_0$
  elw: missing HO estimated from known structure at NLO
  different uncertainties added linearly for each channel

- parametric uncertainties:
  $m_t = 172.5 \pm 1$ GeV $\qquad \alpha_s(M_Z) = 0.118 \pm 0.0015$
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $\qquad m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
  different uncertainties added quadratically for each channel

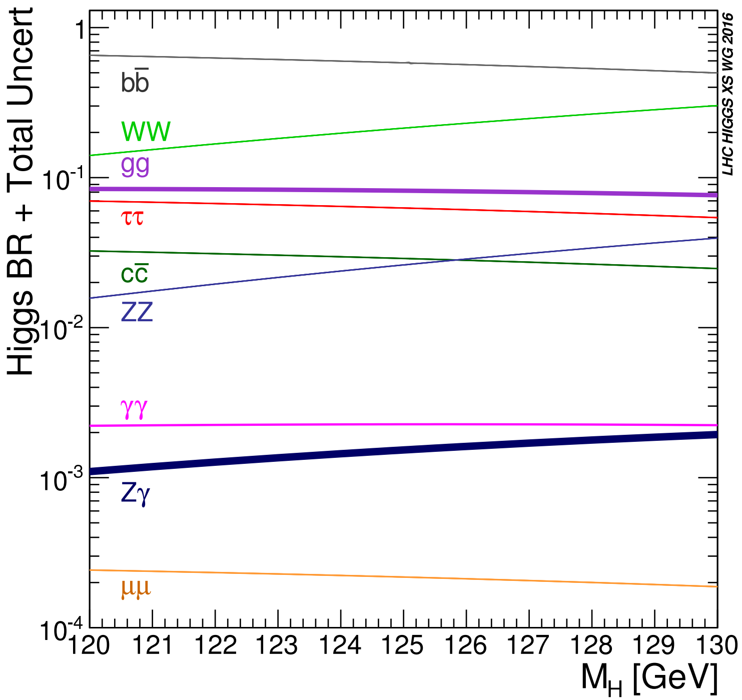
- total uncertainties: parametric & theor. uncertainties added linearly

YR3 HDECAY & Prophecy4f YR4

$\sim 10\% \rightarrow$
$\sim 10\% \rightarrow$



$\longrightarrow$



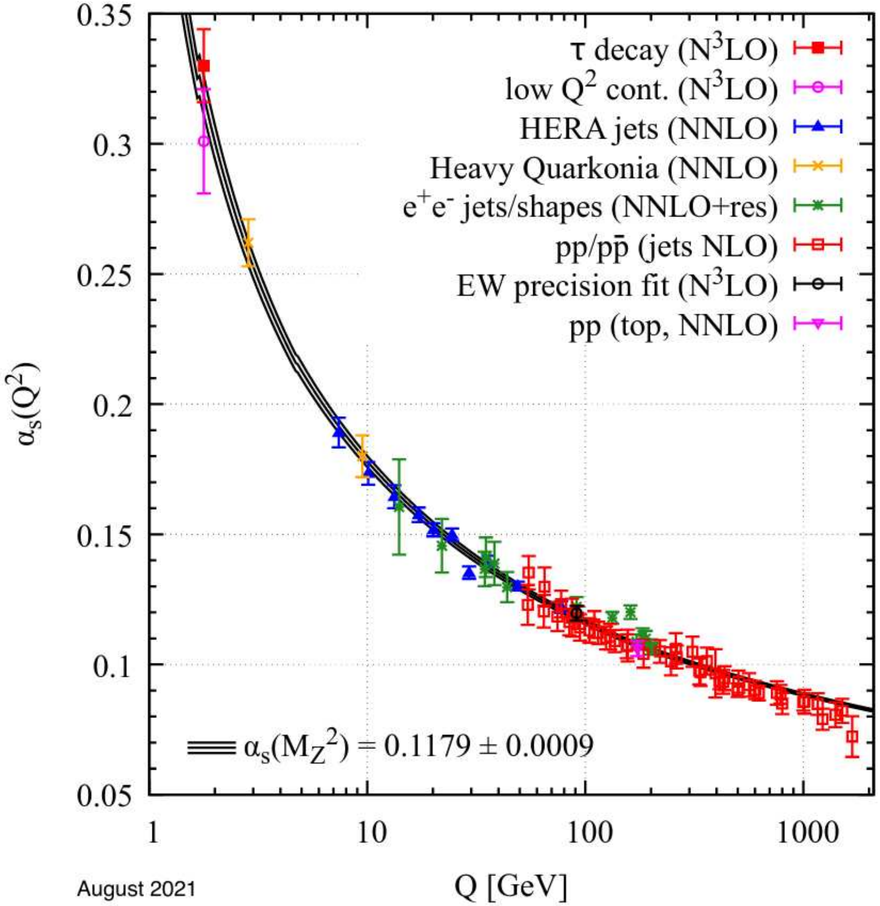
Denner, Heinemeyer, Puljak, Rebuzzi, S.

- refinements input parameters
- full NLO elw. corrections to $H \rightarrow f\bar{f}$
- NLO quark-mass effects in $H \rightarrow gg$

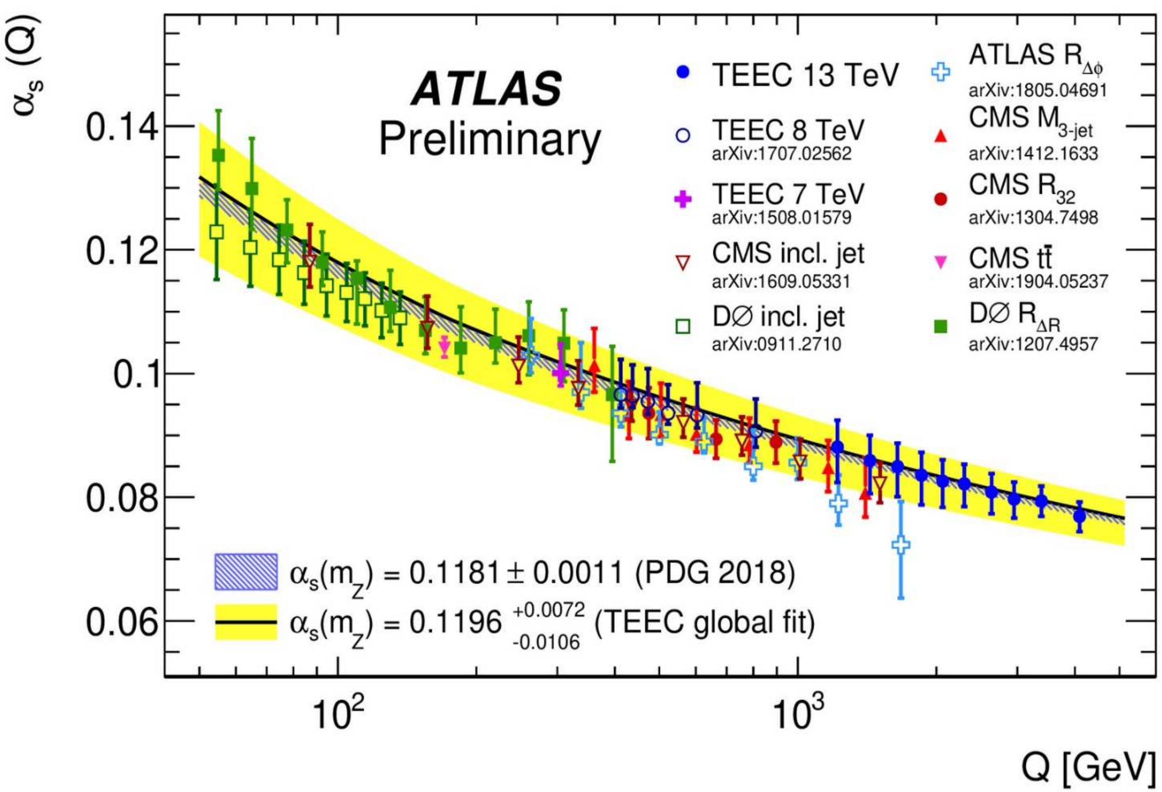
III $m_b(M_H)$

(i) running strong coupling:

$$\frac{\partial \alpha_s(\mu_R)}{\partial \log(\mu_R^2)} = \beta(\alpha_s) = -\beta_0 \frac{\alpha_s^2}{\pi} - \beta_1 \frac{\alpha_s^3}{\pi^2} + \mathcal{O}(\alpha_s^4)$$



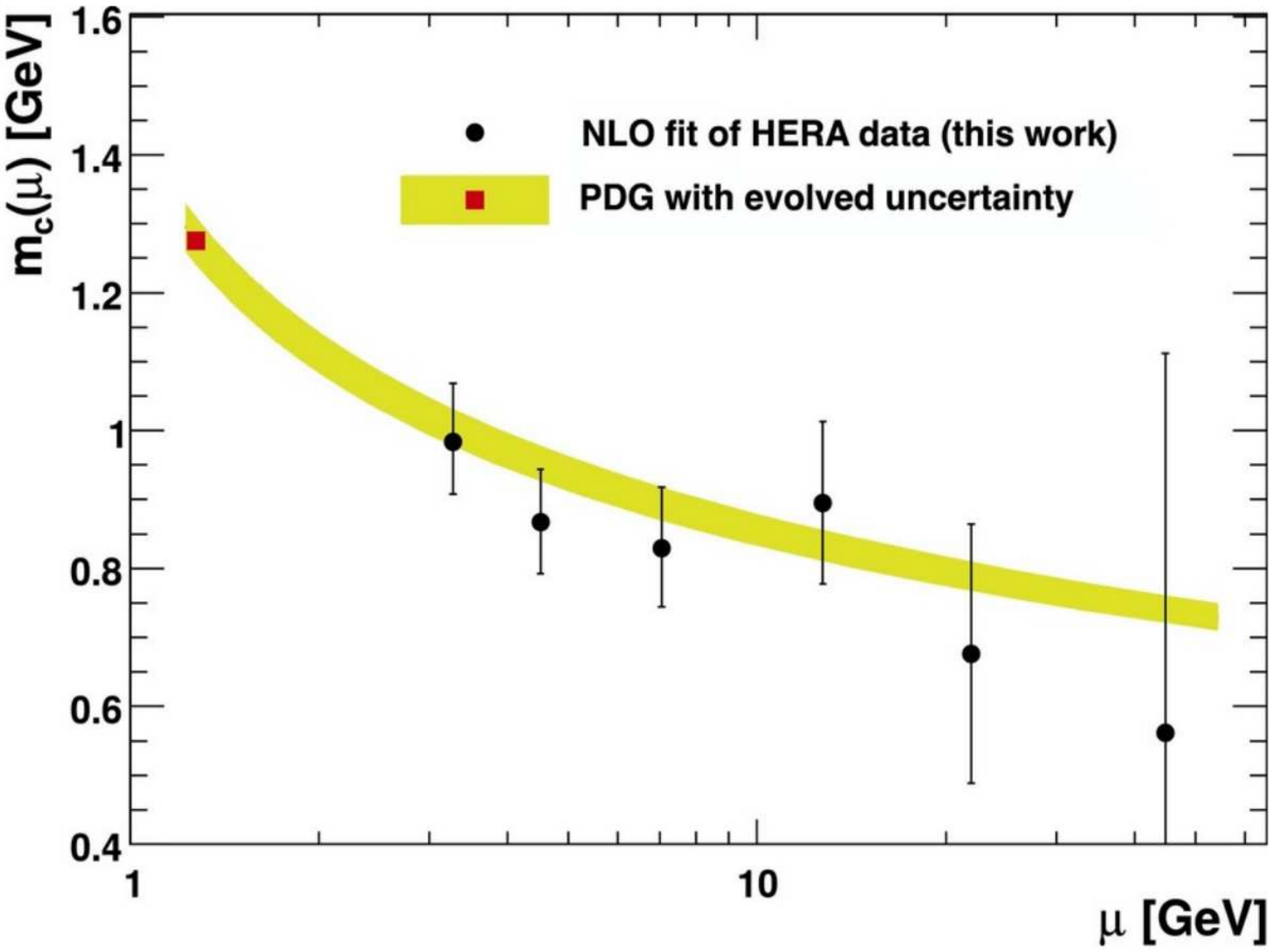
PDG 2021



ATLAS 2020

(ii) running quark mass:

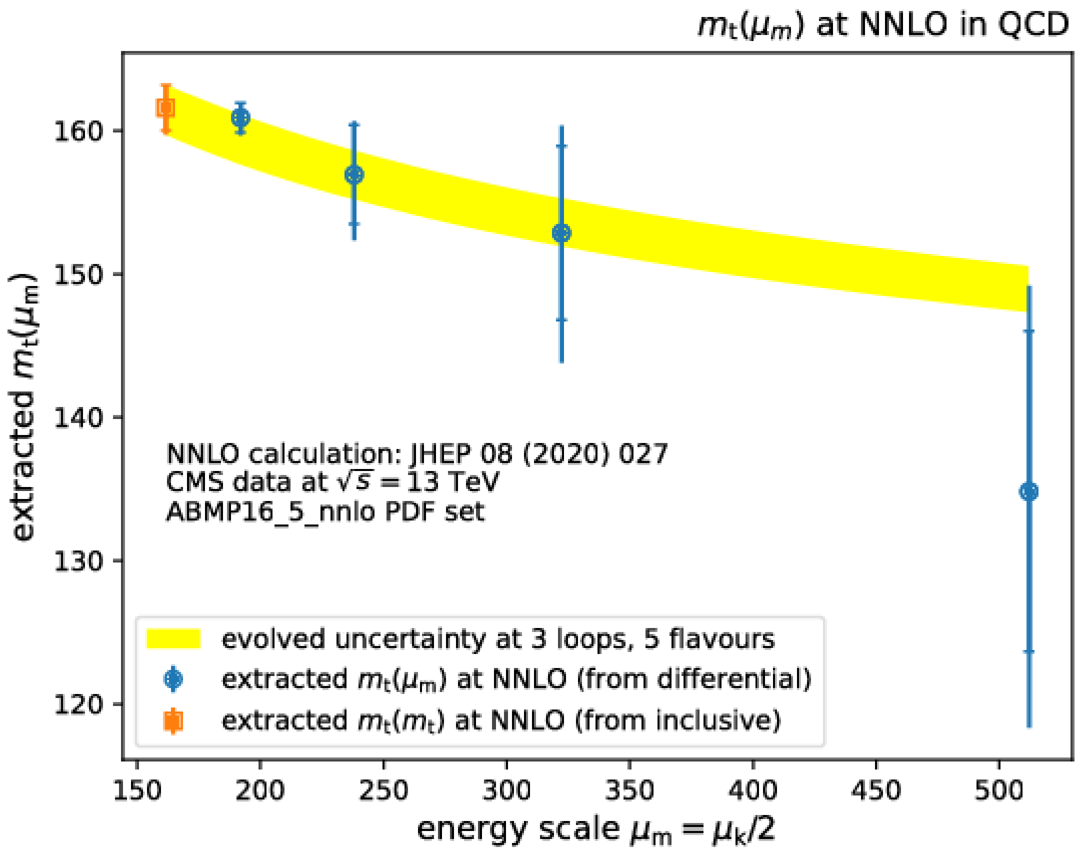
$$\frac{\partial m_q(\mu_R)}{\partial \log(\mu_R^2)} = \gamma[\alpha_s(\mu_R)] m_q(\mu_R)$$



charm-quark mass

HERA 2017

$$\frac{\partial m_q(\mu_R)}{\partial \log(\mu_R^2)} = \gamma[\alpha_s(\mu_R)] m_q(\mu_R)$$



top-quark mass

Defranchis, Kieseler, Lipka, Mazzitelli

(iii) running bottom mass:

$$\frac{\partial m_q(\mu_R)}{\partial \log(\mu_R^2)} = \gamma[\alpha_s(\mu_R)] m_q(\mu_R)$$

$$\Gamma[Z \to b\bar{b}] \;=\; \frac{G_F M_Z}{4\sqrt{2}\pi}\left[1 - \frac{4}{3}s_W^2 + \frac{8}{9}s_W^4\right] \left\{\Delta^0_{\mathrm{QCD}} + \frac{\overline{m}_b^2(M_Z)}{M_Z^2}\Delta^1_{\mathrm{QCD}} + \cdots\right\}$$

- bottom-mass effects subleading
  [same in 3j final states]

$\Rightarrow$ sizeable uncertainties right from the start

$$\frac{\partial m_q(\mu_R)}{\partial \log(\mu_R^2)} = \gamma[\alpha_s(\mu_R)] m_q(\mu_R)$$

$$\Gamma[H \to b\bar{b}] = \frac{3 G_F M_H}{4\sqrt{2}\pi} \overline{m}_b^2(M_H)\, \Delta_{\mathrm{QCD}}$$

$\uparrow$

log resummation $\to \sim$ factor 1/2
(larger than BSM effects!)

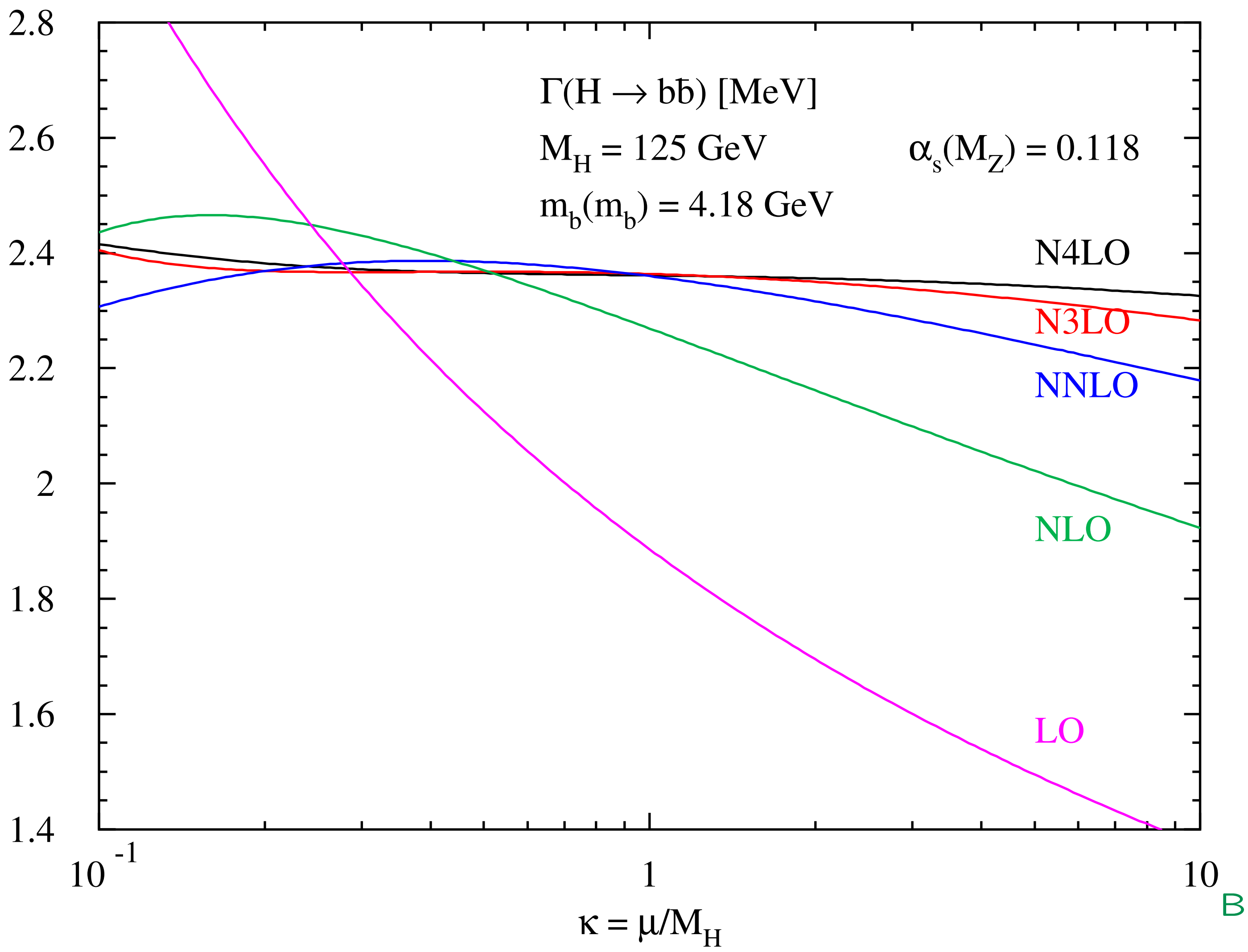
- had. coll.: ratio to elw. decay $\to$ canc. exp. & TH unc.
  [to large extent]

  $$\frac{B_{b\bar{b}}}{B_{ZZ}} \approx \frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to ZZ)} = 22.0 \pm 0.5 \qquad \text{(exp. known to 20–30\%)}$$

  [additional uncertainty due to ΔM_H]

- $H \to ZZ$: Prophecy4f — Bredenstein, Denner, Dittmaier, Weber

  $H \to b\bar{b}$: Hdecay — Djouadi, Kalinowski, Mühlleitner, S.



Braaten, Leveille
Drees, Hikasa
Kataev,. . .
Chetyrkin,. . .
etc.

→ HDECAY

Djouadi, Kalinowski, Mühlleitner, S.

$$\begin{aligned}\Delta_{QCD} &= 1 + 0.2030 + 0.0374 + 0.0019 - 0.0014 \qquad (\mu_R = M_H)\\ &= 1 - 0.5665 + 0.0586 + 0.1475 - 0.1274 \qquad (\mu_R = m_b)\end{aligned}$$

- ATLAS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.87^{+0.28}_{-0.21}$

- CMS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.84^{+0.37}_{-0.27}$

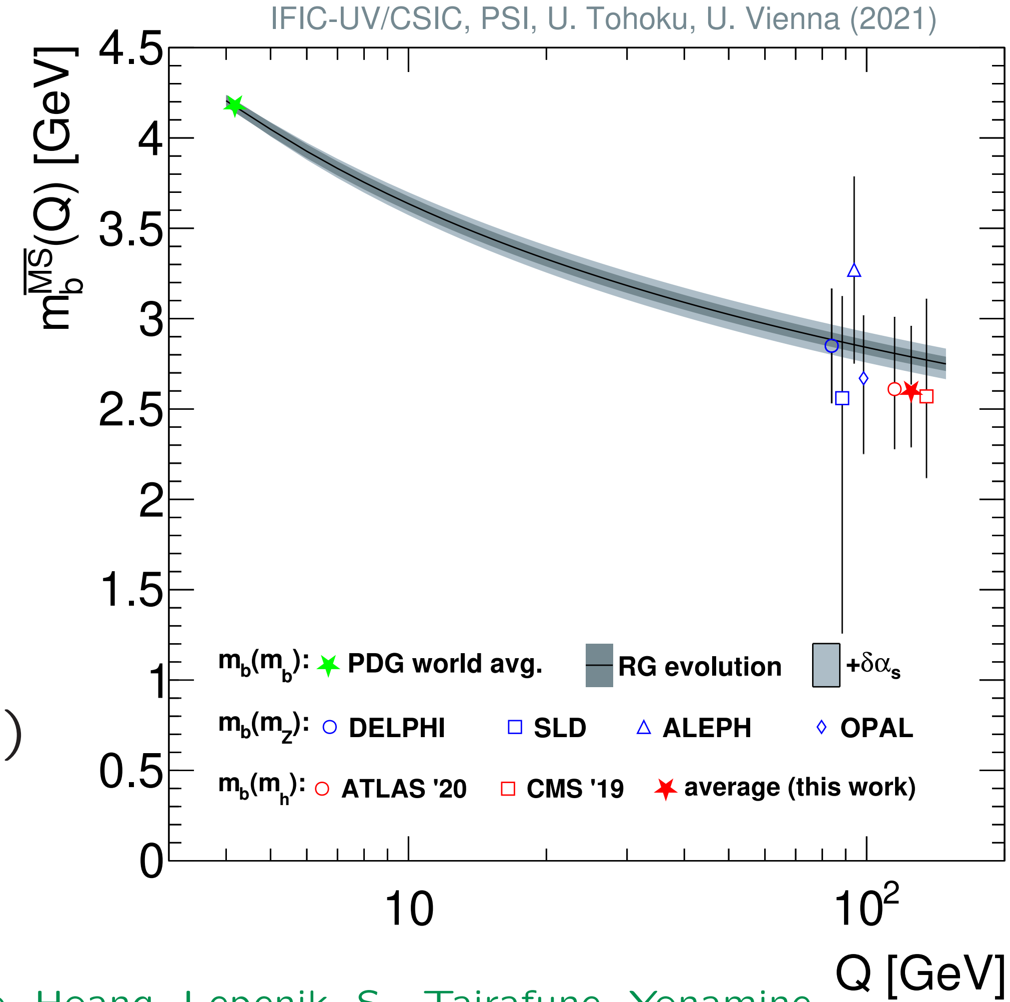
$\Rightarrow \overline{m}_b(M_H) = 2.60^{+0.36}_{-0.31}$ GeV

(Convino) Kieseler

RG-evolution: REvolver

Hoang, Lepenik, Mateu

$\alpha_s(M_Z) = 0.1179 \pm 0.001$ (0.004)



Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tairafune, Yonamine

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$\Rightarrow \overline{m}_b(M_H) = 2.60^{+0.36}_{-0.31}$ GeV $\pm$ 0.06 GeV (THU)

- scale & elw. corr. (0.3–0.5%)
  $\alpha_s(M_Z) = 0.1179 \pm 0.001$
  $M_H = (125.1 \pm 0.240)$ GeV

Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tairafune, Yonamine

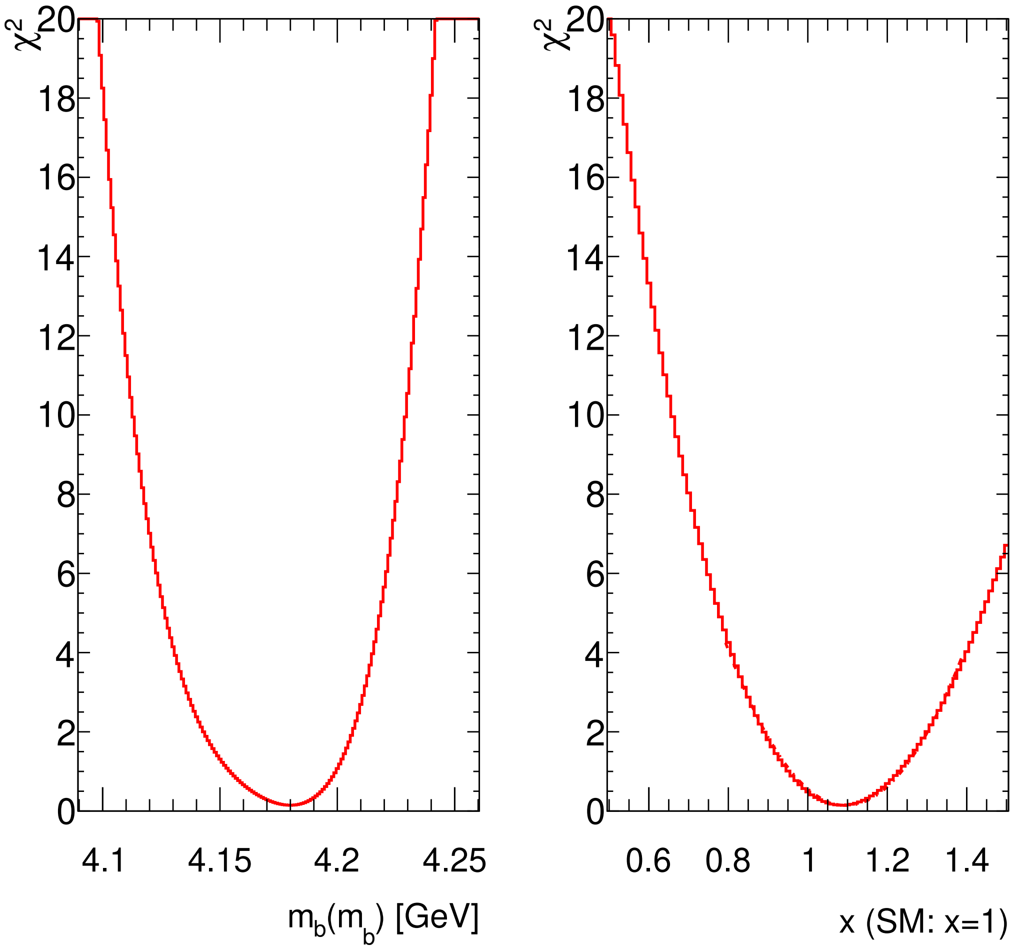
- test of running hypothesis ($x = 0$: no running, $x = 1$: SM running):

$$m(\mu; x, m_b(m_b)) = m_b(m_b) + x\ [m_b^{\text{RGE}}(\mu, m_b(m_b)) - m_b(m_b)]$$

$m_b(m_b) = 4.18^{+0.03}_{-0.02}$ GeV

$x = 1.08 \pm 0.15(exp) \pm 0.05(\alpha_s)$

$\Rightarrow$ running @ 7σ



Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tairafune, Yonamine

• anomalous mass dimension:

$$\frac{\partial m_q(\mu_R)}{\partial \log(\mu_R^2)} = \gamma[\alpha_s(\mu_R)] m_q(\mu_R) = \left\{ \gamma_0 \frac{\alpha_s(\mu_R)}{\pi} + \gamma_1 \left(\frac{\alpha_s(\mu_R)}{\pi} \right)^2 + \cdots \right\} m_q(\mu_R)$$

$$\gamma_0 \approx -\beta_0 \log \left(\frac{m_b(M_H)}{m_b(m_b)} \right) \ / \ \log \left(\frac{\alpha_s(M_H)}{\alpha_s(m_b)} \right)$$

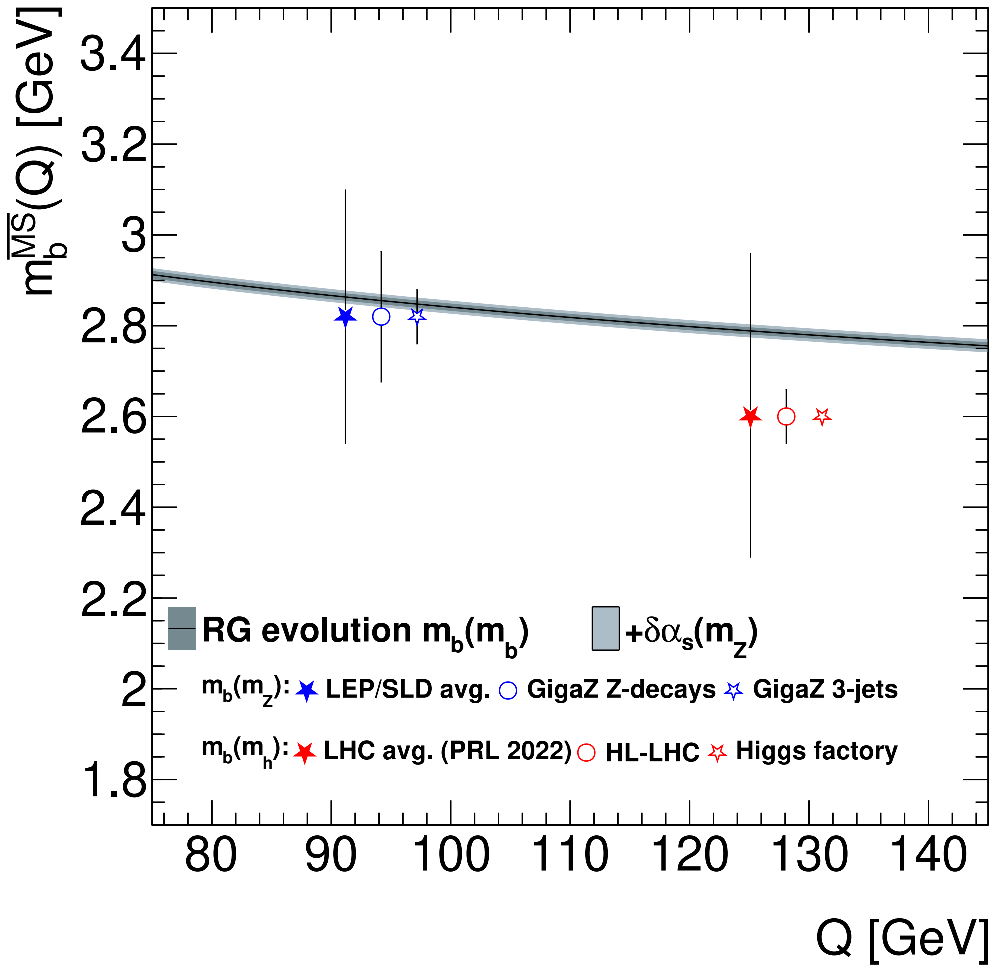
[THU $\sim$ 12% (NLL)]

• using $\beta_0 = (33 - 2N_F)/12 = 23/12$ [SM]:

$$\boxed{\gamma_0 = -1.23 \pm 0.22(exp.) \pm 0.14(TH) \pm 0.06(\alpha_s)}$$

in good agreement with SM value $\gamma_0 = -1$

• future prospects:

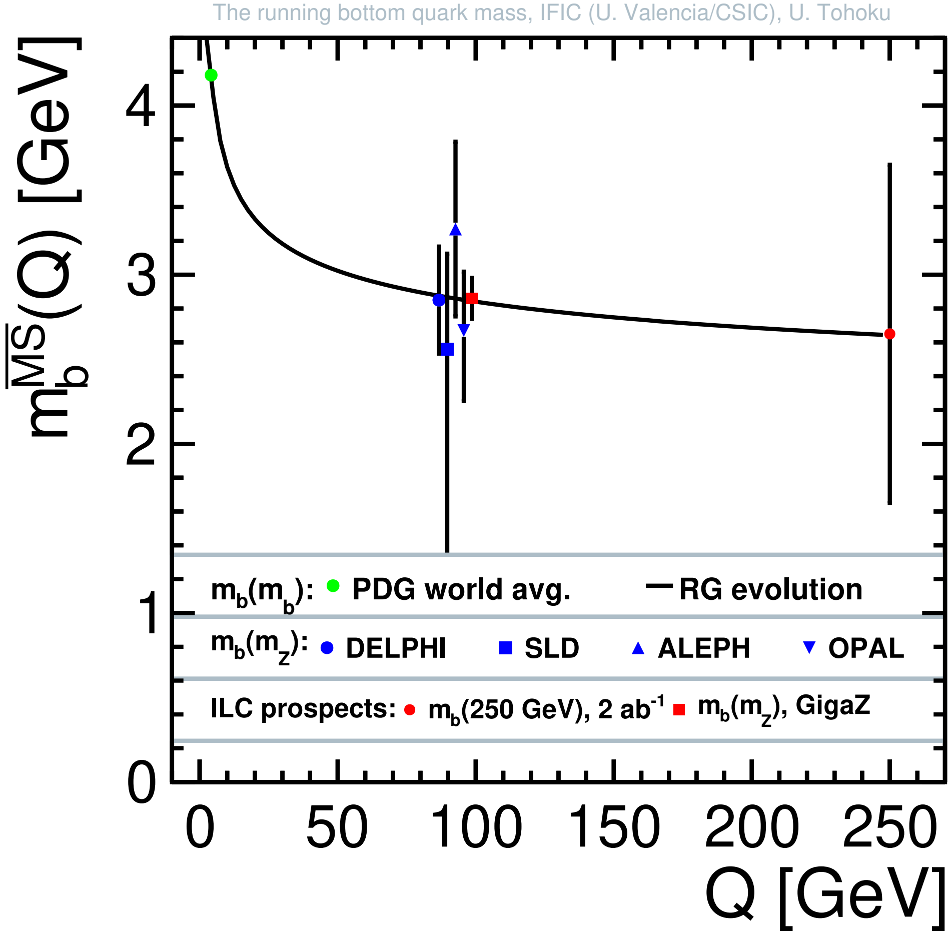


Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, Mateu, S., Tairafune, Yonamine, Tian

• assuming pure SM contributions to $H \to b\bar{b}, ZZ$ [i.e. BSM negligible]

• disentangling bottom mass and Yukawa coupling in a model-independent way? [future Higgs factories will help a lot!]

• future prospects:



Fuster, Irles, Rodrigo, Tairafune, Vos, Yamamoto, Yonamine

• measurement of m_b(250 GeV) at HE e^+e^- collider

IV CONCLUSIONS

- partial Higgs boson decay widths reach valuable accuracies @ LHC
- important HO corrs known $\Rightarrow$ extraction of Higgs couplings reliably
- THUs small for $\Gamma(H \to b\bar{b}, ZZ)$
- high sensitivity of $\Gamma(H \to b\bar{b})/\Gamma(H \to ZZ)$ to running b mass $m_b(M_H)$
- first extraction of

$$\boxed{m_b(M_H) = 2.60^{+0.36}_{-0.30}\ \text{GeV}}$$

- anomalous mass dimension at LL compatible with SM
- add. info by $\Gamma(H \to b\bar{b})/\Gamma(H \to \gamma\gamma)$?
- future prospects very motivating for Higgs fact. and HE e^+e^- collider

BACKUP SLIDES

$$
\begin{aligned}
m(\mu^2) &= m(\mu_0^2)\ \left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right)^{-\frac{\gamma_0}{\beta_0}} \frac{1+1.175\frac{\alpha_s(\mu^2)}{\pi}}{1+1.175\frac{\alpha_s(\mu_0^2)}{\pi}} \\
\log\frac{m(\mu^2)}{m(\mu_0^2)} &= -\frac{\gamma_0}{\beta_0}\log\left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right) + \log\left(\frac{1+1.175\frac{\alpha_s(\mu^2)}{\pi}}{1+1.175\frac{\alpha_s(\mu_0^2)}{\pi}}\right) \\
&= -\frac{\gamma_0}{\beta_0}\log\left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right) + \delta \\
\delta &= 1.175\ \frac{\alpha_s(\mu^2)-\alpha_s(\mu_0^2)}{\pi} + \mathcal{O}(\alpha_s^3) \\
\log\frac{m(\mu^2)}{m(\mu_0^2)}\ -\ \delta &= -\frac{\gamma_0}{\beta_0}\log\left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right)
\end{aligned}
$$

Using $\beta_0 = 23/12$ we obtain for the anomalous mass dimension:

$$
\begin{aligned}
\gamma_0 &= -1.000 && \text{(1-loop)} \\
\gamma_0 &= -1.120 && \text{(5-loop, w/o } \delta) \\
\gamma_0 &= -1.007 && \text{(5-loop, w/ } \delta)
\end{aligned}
$$