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m_b at m_H : the running bottom quark mass and the Higgs boson

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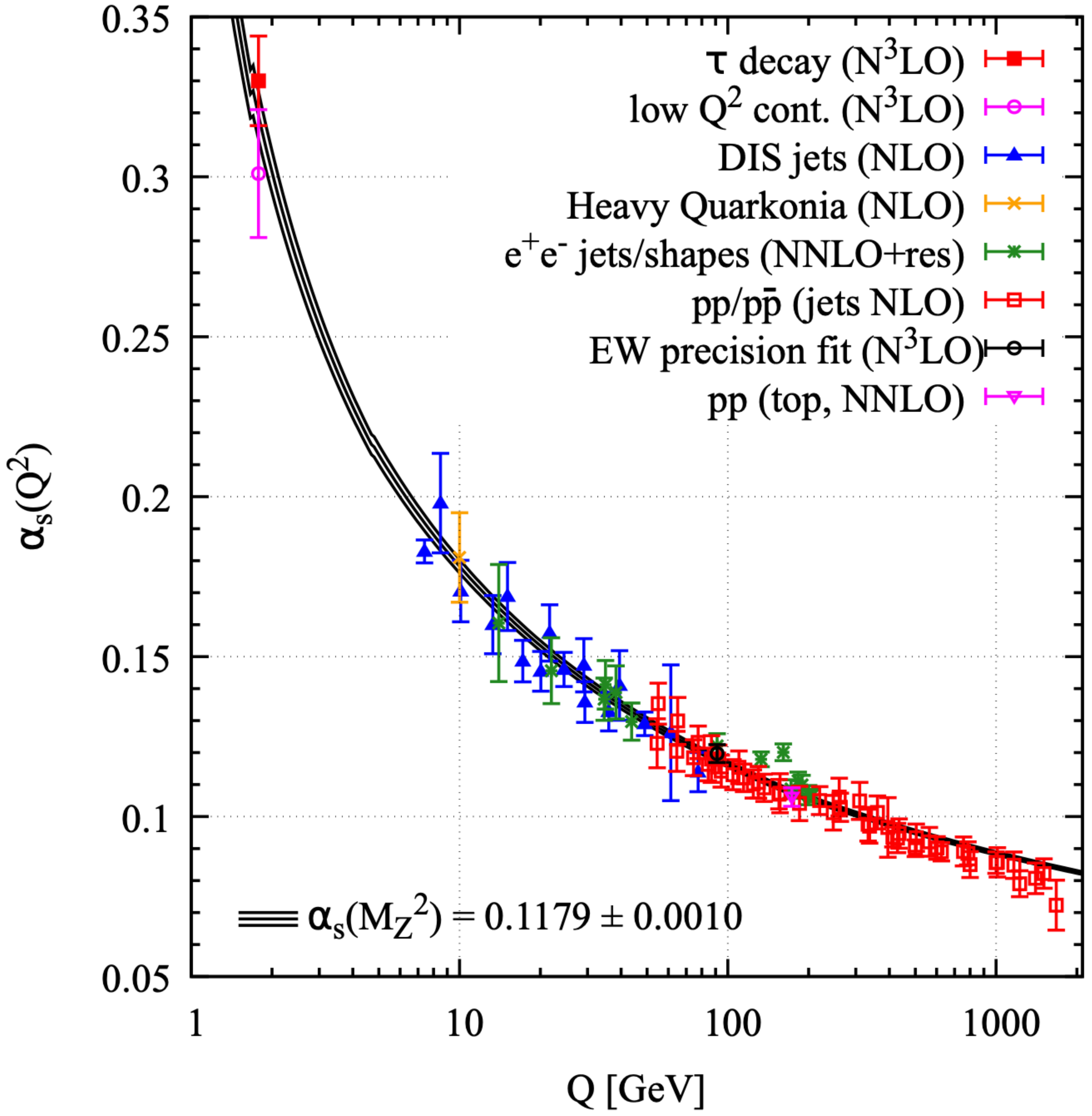
Introduction

- **Quark masses** and **coupling "constants"** are renormalized parameters in SM

  → An so renormalization scheme dependent: we consider $\overline{MS}$ scheme

  → Scale **evolution** predicted by Quantum Chromodynamics **through RGE**



PDG 2020 credits

- Experimental **measurements at different energy scales μ,** to test such running

  → Already done for bottom quark mass at LEP/SLC, charm quark at HERA, top quark at LHC

  → Higgs physics program at LHC is giving results with rapidly increasing precision.

Previous b-quark mass measurements

At $\mu = m_b$ scale from B-factories *(PDG world average)*

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

At $\mu = m_Z$ scale from LEP and SLC* *(our average of DELPHI, ALEPH, OPAL and SLD results)*

$$m_b(m_Z) = 2.82 \pm 0.28\ GeV$$

… At $\mu = m_H$ scale from LHC?

→ Higgs boson decay rate to bottom quarks can be precisely measured and predicted.

$\Gamma(H \to b\bar{b})$ and the b-quark mass

Theory calculations available at $N^4LO + N^2LL$ in QCD, including NLO EW corrections. In the limit of small m_b, it holds

$$\Gamma(H \to b\bar{b}) \propto m_b^2(\mu)(1 + \delta_{QCD} + \ldots)$$

where we assume that the bottom quark Yukawa coupling is standard.

Fo scale choice $\mu = m_H$, pQCD shows excellent convergence:

$$1 + \delta_{QCD} = 1 + 0.2030 + 0.037 + 0.0019 - 0.0014$$

so Higher-Order corrections are small.

b-quark mass extraction from Higgs rates (I)

We use the **ratio of bottom and Z boson decay rates** and parameterize the dependence with $m_b(m_H)$:

$$\frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to ZZ)} = 2.81 \frac{m_b^2}{GeV^2} - 0.0014 \frac{m_b^4}{GeV^4} + \mathcal{O}(m_b^6)$$

Numerical results for $\Gamma(H \to b\bar{b})$ and $\Gamma(H \to ZZ)$ with HDECAY and Prophecy4l, respectively.

Breakdown of uncertainties in such parametrization:

Souce	Variation	Impact (%)
Missing H.O. in α_s	$\Delta\mu_R \in (1/2,2)$	0.2%
$m_H = 125.1\ GeV$	$\Delta m_H = 240\ MeV$	3.0%
$\alpha_s(m_Z) = 0.1179$	$\Delta\alpha_s(m_Z) = 0.001$	0.2%
EW corrections	Beyond NLO	0.5%

→ Total uncertainty on $m_b(m_H)$ from parametrization is 60 MeV

b-quark mass extraction from Higgs rates (II)

→ ATLAS and CMS measurements at $139\ fb^{-1}$ and $35\ fb^{-1}$ each:

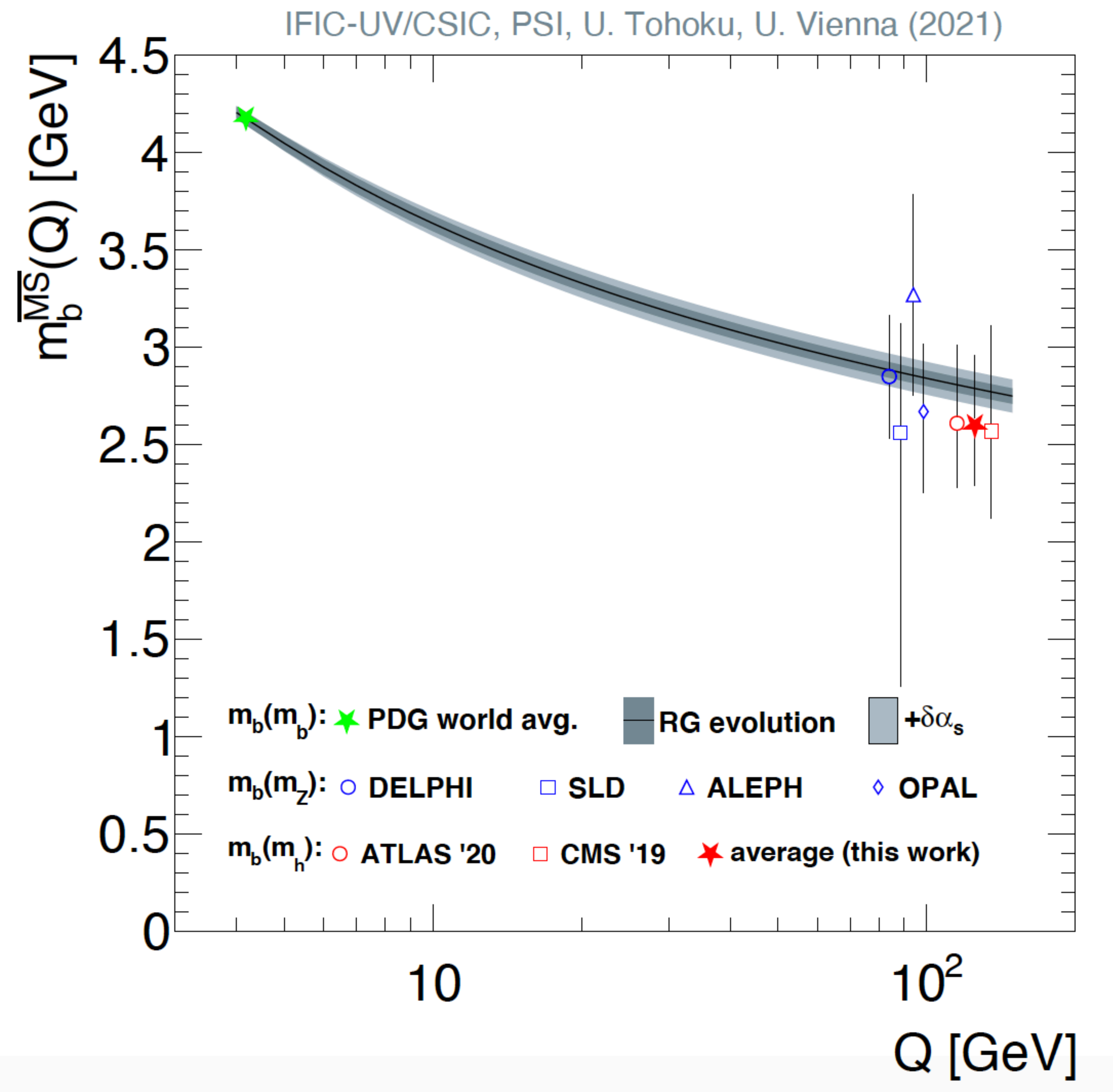
	$\Gamma^{b\bar{b}}/\Gamma^{ZZ}$	$m_b(m_H)$
ATLAS	$0.87^{+0.22}_{-0.17}\ (stat.)^{+0.18}_{-0.12}\ (syst.)$	$2.61^{+0.32}_{-0.27}\ (stat.)^{+0.26}_{-0.19}\ (syst.)\ GeV$
CMS	$0.84^{+0.27}_{-0.21}\ (stat.)^{+0.26}_{-0.17}\ (syst.)$	$2.57^{+0.39}_{-0.35}\ (stat.)^{+0.37}_{-0.28}\ (syst.)\ GeV$

Both results are combined into (with convino):

$$\boxed{m_b(m_H) = 2.60^{+0.36}_{-0.31}\ GeV}$$

(50% / 100% corr. in exp. and syst.)

The running b-quark mass (I)



Test the running mass hypothesis:

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

where x adjust the RGE evolution

$x = 0 \rightarrow$ No-running scenario

$x = 1 \rightarrow$ SM scenario

Experimental $m_b^{exp}(\mu_i)$ are compared to RGE prediction for evolution from $m_b(m_b)$ with variable x:

$$\chi 2(m_b(m_b), x) = \frac{\sum_{\mu_i}(m_b^{exp}(\mu_i) - m(\mu_i; x, m_b(m_b)))^2}{\sigma_i^2}$$

$\mu_i = m_b, m_Z, m_H$

The running b-quark mass (II)

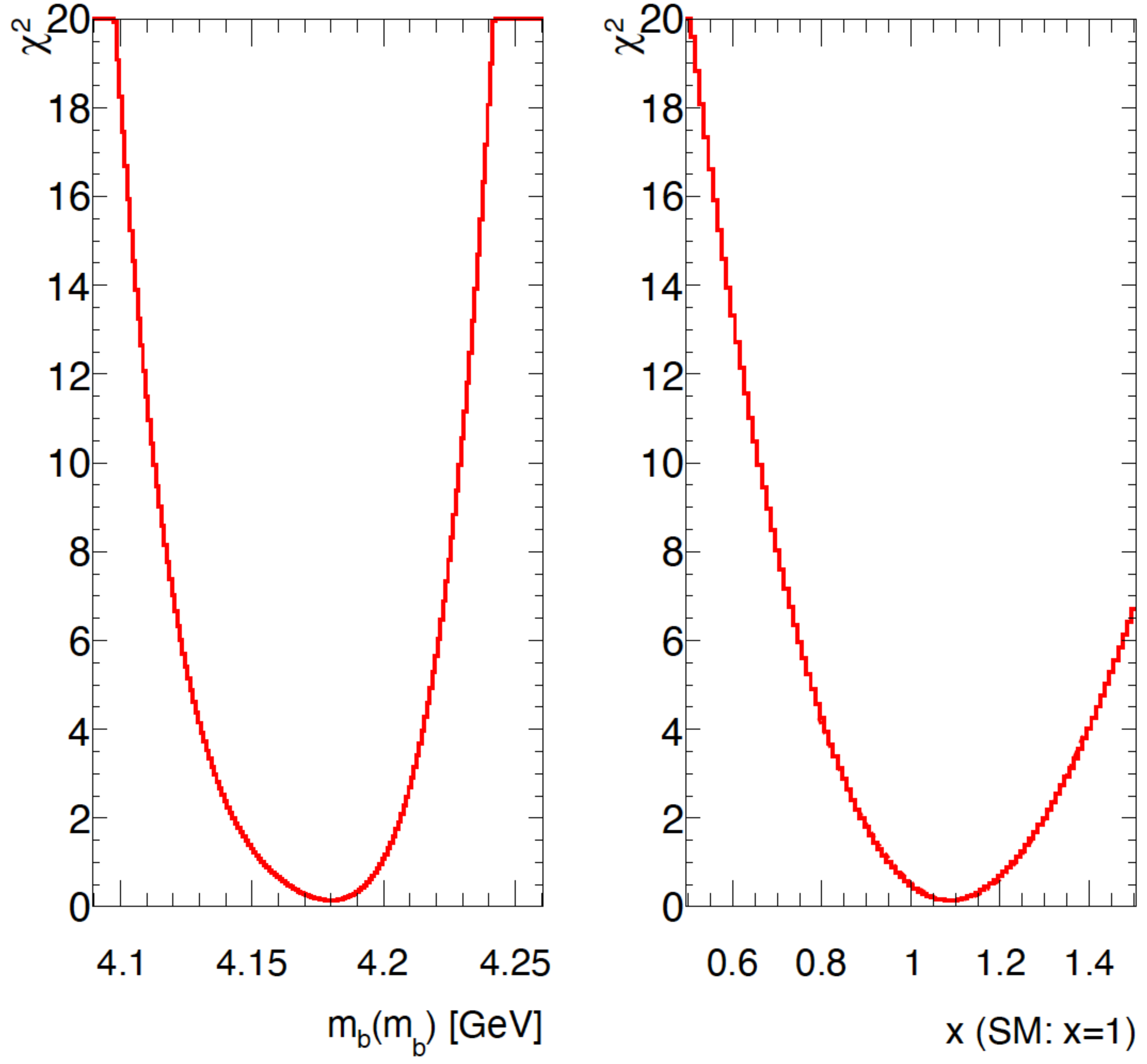
$\rightarrow \chi2(x, m_b(m_b))$ *minimisation gives:*

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

Compatible with PDG world average, as expected!

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

Compatible with RGE evolution ($x = 1$) at 1σ, disfavours no-running scenario ($x = 0$) at 7σ.



Prospects in future colliders

Collider	Channel	Expected experimental unc. on channel meas.	Expected experimental unc. on $m_b(m_H)$
HL-LHC	$BR(H \to b\bar{b})$	$4\,\%$	$\pm 63\ MeV$
ILC:250	$\frac{BR(H \to b\bar{b})}{BR(H \to WW)}$	$0.86\,\%$	$\pm 12\ MeV$
ILC:250+500		$0.47\,\%$	$\pm 6\ MeV$

→ Very competitive measurements are possible with this method.
The prospects for theory uncertainties need to be carefully assessed.

Summary

- We present the first measurement of the bottom quark mass at the Higgs mass scale,

$$\boxed{m_b(m_H) = 2.60^{+0.36}_{-0.31}\ GeV}$$

(still) dominated by the experimental statistical uncertainty.

- Confronting this new measurement with $m_b(m_b)$ and $m_b(m_Z)$, we confirm the predicted RGE running of m_b.

- Excellent prospects for $m_b(m_H)$ at HL-LHC and a future Higgs factory

Bonus slides

$m_b(m_Z)$ combination from LEP and SLC

experiment	$m_b(m_Z)$ [GeV]
ALEPH[14]	3.27 ± 0.22 (stat.) ± 0.44 (syst.) ± 0.16 (theo.)
DELPHI[16]	2.85 ± 0.18 (stat.) ± 0.23 (syst.) ± 0.12 (theo.)
OPAL[15]	2.67 ± 0.03 (stat.) $^{+0.29}_{-0.37}$ (syst.) ± 0.19 (theo.)
SLD[12, 13]	2.56 ± 0.27 (stat.) $^{+0.28}_{-0.38}$ (syst.) $^{+0.49}_{-1.48}$ (theo.)