UNIVERSITÄT BONN

Rheinische Friedrich-Wilhelms-Universität Bonn

Physikalisches Institut

IRN TeraScale

IRN Terascale workshop, Bonn, 28/03/2022

$m_b(m_H)$

extracting the bottom quark mass from Higgs precision measurements [arXiv:2110.10202, PRL128]

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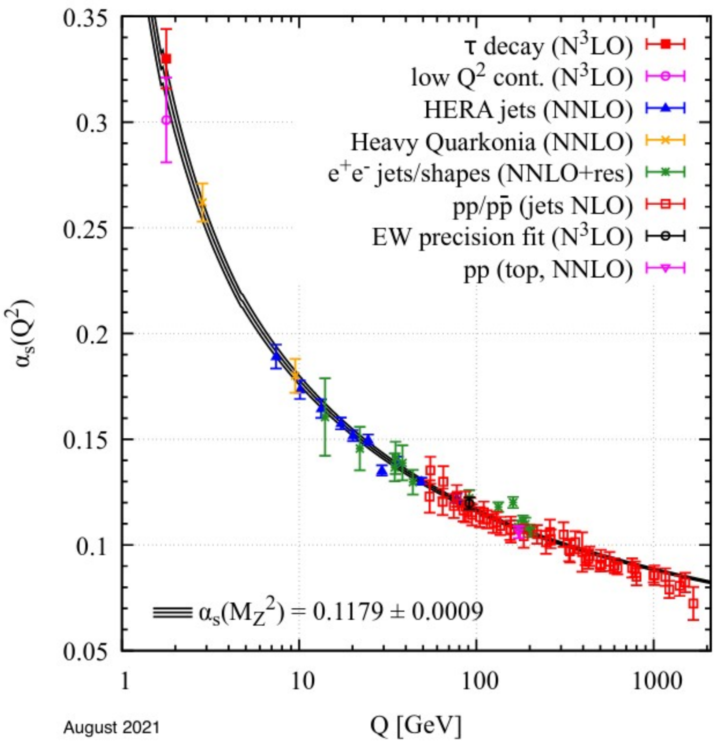
Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$



Precise determinations from 1 GeV to > 1 TeV!

Reference $\alpha_s(m_Z) = 0.118 \pm 0.001$ (PDG, <1%)

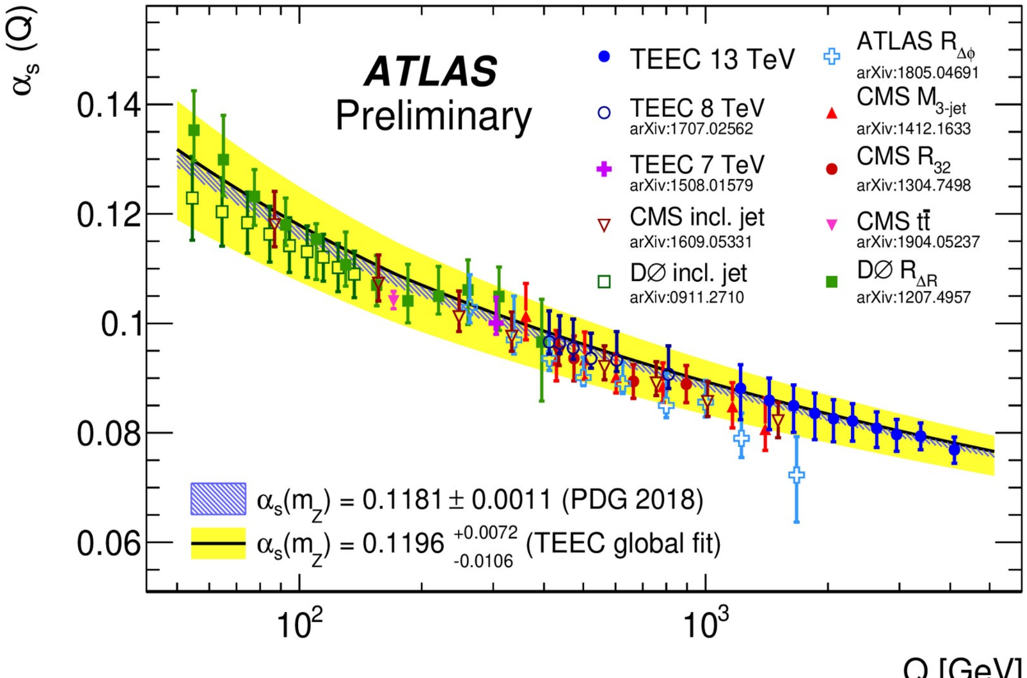
This plot collects α_s value extracted from measurements of many observables in several processes over a broad energy range

Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$

The LHC extends the range: precise determinations up to 4 TeV!



ATLAS-CONF-2020-025

Massive states with colour charge may alter the evolution:
Llorente & Nachman, NPB 936 (2018) 106
Becciolini et al., PRD91 (2015) 015010
Kaplan, Schwartz, PRL 101 (2008) 02202

Running constants

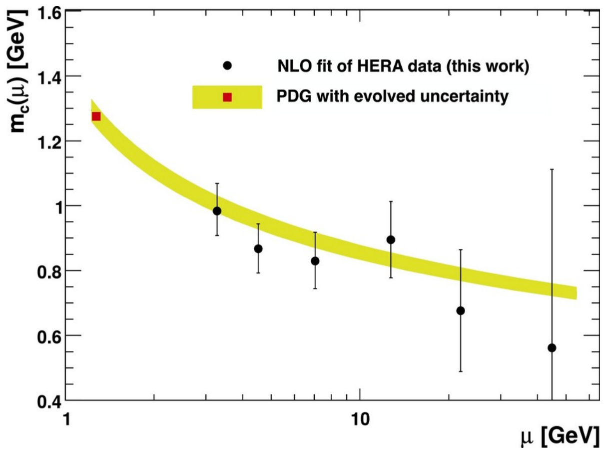
Quark masses – parameters of the QCD Lagrangian – **must run too**

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$

Anomalous mass dimension

Scale evolution or "running" experimentally confirmed:

- charm quark mass, HERA [Ghizko et al., PLB775 (2017)]



- bottom quark mass, DELPHI,SLD,ALEPH,OPAL, see cf. Kluth [hep-ex/0603011])

- top quark mass, CMS[PLB803 (2020)] (see also Catani et al., JHEP08 (2020))

Higgs measurements at the LHC

Since 2012, ATLAS and CMS have characterized, with rapidly increasing precision, the couplings of the Higgs boson to SM particles:

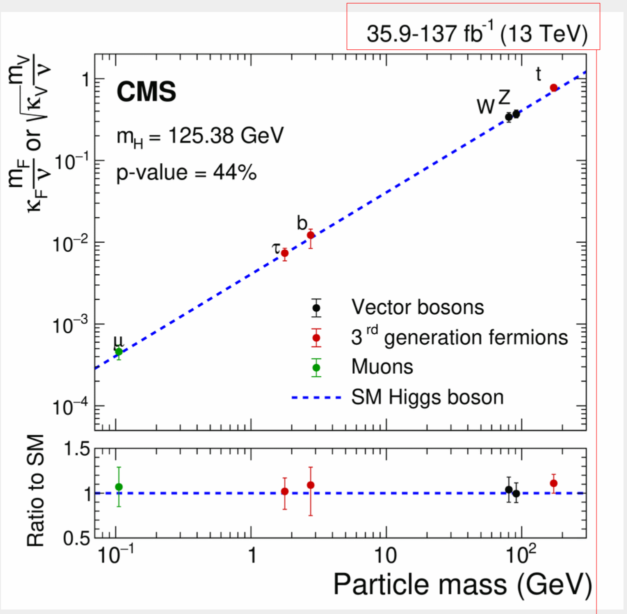
2012: discovery of pp → H, H → ZZ*, H → $\gamma\gamma$, H → WW

2015: evidence for H → $\tau\tau$ decay (fermions!)

2018: discovery of H → $b\bar{b}$ decay (quarks!)
discovery of pp → VH production
discovery of $t\bar{t}$H production (Yukawa ~1!)

2020: evidence for H → $\mu\mu$ decay (2nd generation!)

2021: evidence for H → $l^+l^-\gamma$ decay



Eventually, a Higgs factory will provide sub-% measurements

Today's talk: these measurements enable a new (and better) measurement of the bottom mass at a high scale: $m_b(m_H)$

Eagerly awaiting more, in particular legacy run 2 Higgs coupling results

Higgs boson precision measurements at the LHC

Enough data to start filling the PDG data sheet on the H^0 boson

H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States = 1.13 ± 0.06
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.06 \pm 0.09$
$\gamma\gamma = 1.11^{+0.10}_{-0.09}$
$c\overline{c}$ Final State = 37 ± 20
$b\overline{b} = 1.04 \pm 0.13$

https://pdg.lbl.gov Page 4 Created: 6/1/2021 08:29

Higgs decays and the bottom quark mass

The Higgs decay to bottom quarks is a perfect laboratory to study the bottom quark mass:

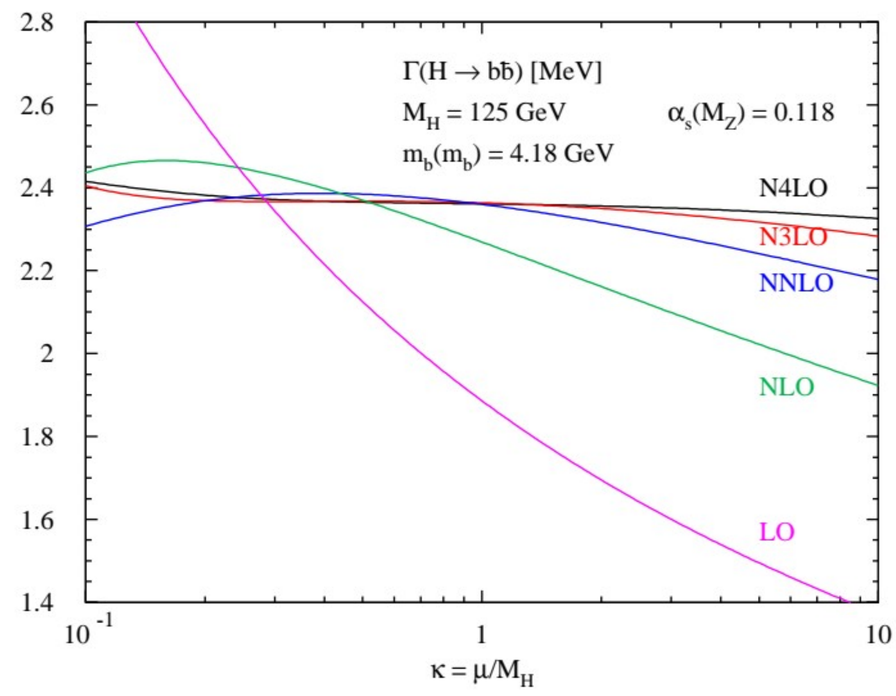
- quadratic dependence on m_b
- EW process, rate decoupled at LO from strong coupling α_s
- precise predictions available
- **well-defined natural scale m_h**

QCD series for $\Gamma(H \rightarrow bb)$ for $\mu = m_H$:

$$1 + \delta_{QCD} = 1 + 0.2030 + 0.0374 + 0.0019 - 0.0014.$$

And for $\mu = m_b$:

$$1 + \delta_{QCD} = 1 - 0.5665 + 0.0586 + 0.1475 - 0.1274.$$



See also HDECAY manual and "Handbook of LHC Higgs cross sections 4. Deciphering the nature of the Higgs sector", arXiv:1610.07922

Choice of mass-sensitive observable

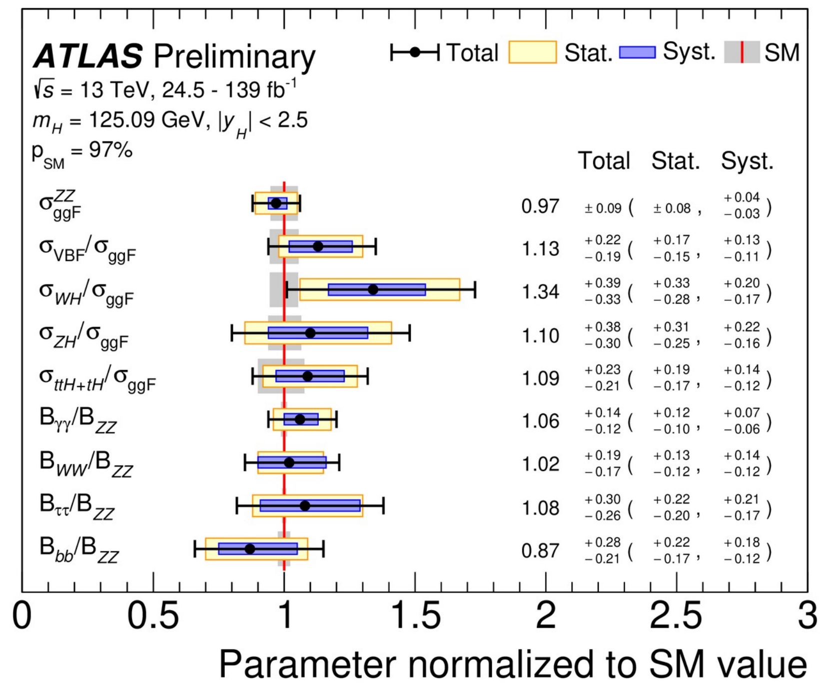
A hadron collider cannot measure absolute couplings, but ratios of prod. and decay rates can be precisely determined

Use gg → H → ZZ as standard candle to relate all other cross sections and branching fractions

Experimental and theory uncertainties cancel to some extent in ratio

SM prediction $B_{bb}/B_{ZZ} = 22.0 \pm 0.5$ (additional uncertainty due to Δm_H)

Ratio B_{bb}/B_{ZZ} known experimentally to approximately 20-30%



Higgs coupling measurements

We use the following measurements of B_{bb}/B_{ZZ}

ATLAS*: $\mu^{bb}/\mu^{ZZ} = 0.87^{+0.22}_{-0.17}(stat.)^{+0.18}_{-0.12}(syst.) = 0.87^{+0.28}_{-0.21}$ [ATLAS-CONF-2020-027]

CMS**: $\mu^{bb}/\mu^{ZZ} = 0.84^{+0.27}_{-0.21}(stat.)^{+0.26}_{-0.17}(stat.) = 0.84^{+0.37}_{-0.27}$ [EPJC77 (2019)5,421]

*Note that ATLAS has updated its result since our analysis:
$\mu^{bb}/\mu^{ZZ} = 0.75^{+0.18}_{-0.16}$ [ATLAS-CONF-2021-53]
**Note that the CMS result is based on a partial (35/fb) run-2 analysis

We proudly present: $m_b(m_h)$

Numerical results for decay widths:
H→ ZZ from Prophecy4f v3.0 [Comput. Phys. Commun. 256 (2020)],
H→ $b\bar{b}$ from HDECAY [Comput. Phys. Commun. 198 (1998) & 238 (2019)]
V6.6.1 provides results directly in terms of $m_b(m_H)$

Results from both measurements combined with Convino (arXiv:1706.01681):

The first measurement of the m_b at scale m_H:

$$m_b(m_h) = 2.60^{+0.36}_{-0.30}\ \mathrm{GeV}$$

Good agreement with $2.79^{+0.03}_{-0.02}$ GeV obtained from evolving the world average for $m_b(m_b)$ to m_H

We proudly present: $m_b(m_h)$

The mass is extracted from both measurements and the results are combined with Convino (arXiv:1706.01681):

$$m_b(m_h) = 2.60^{+0.36}_{-0.30}\ \text{GeV} + 0.06\ \text{GeV theory uncertainty}$$

Theory uncertainty includes:
- scale variations and estimate of EW corrections (0.3-0.5%, YR *arXiv:1610.07922)*
- parametric uncertainty* α_s (± 0.001 → 0.2%)
- parametric uncertainty m_H (± 240 MeV → 3%, dominant)

The theory uncertainty is small → lots of room for exp. progress

* Note: use of the $\overline{\text{MS}}$ mass of the bottom quark at the scale of the Higgs boson mass minimizes the theory uncertainty and α_s dependence of the result (cf. the more conventional $m_b(m_b)$)

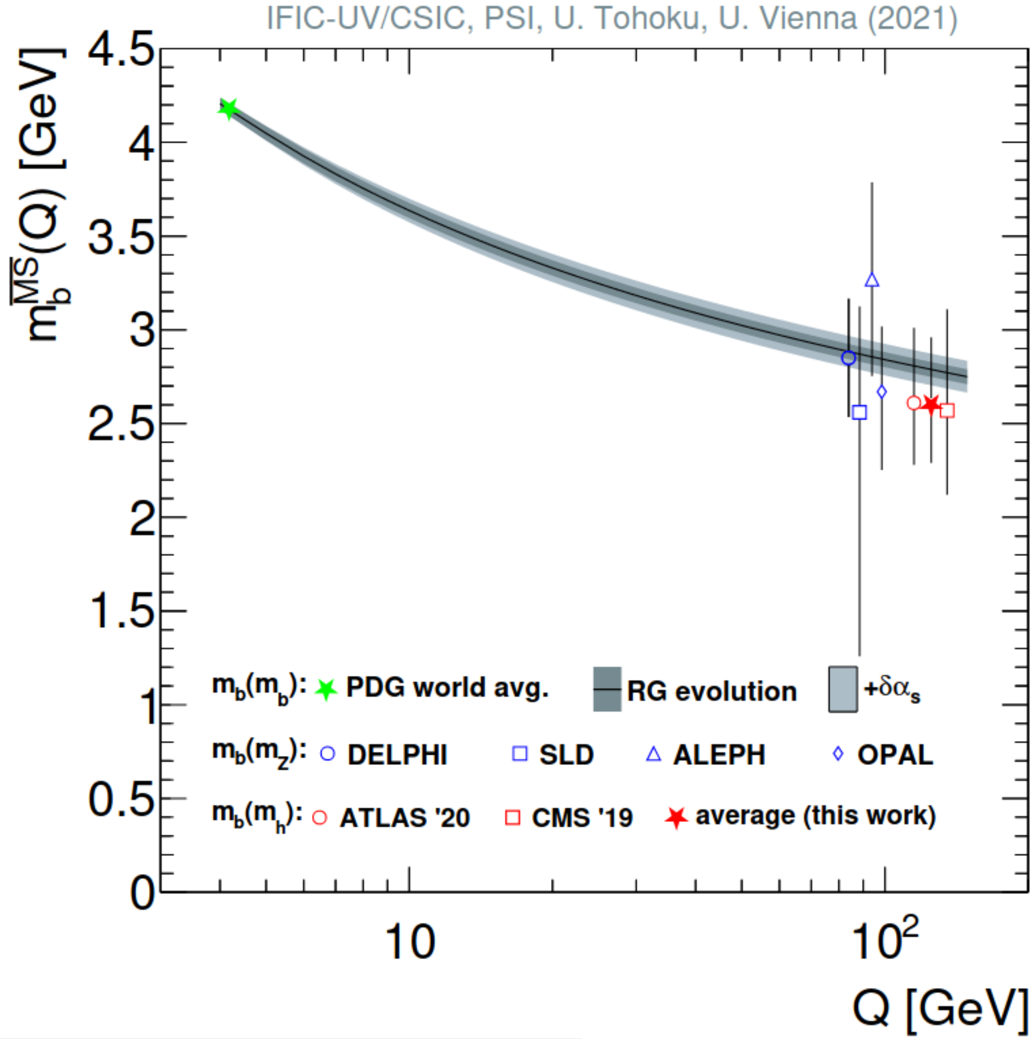
Running of the bottom quark mass

RG evolution from Revolver package, arXiv:2102.01085

Quark masses are not predicted by the SM, but QCD (RGE) does give a prescription for their scale evolution

Collecting measurements at different energies:

- $m_b(m_b)$ world average from low-energy expts
- $m_b(m_Z)$ from LEP experiments and SLD
- $m_b(m_H)$ from LHC Higgs measurements



LHC $m_b(m_h)$ today is as precise as LEP $m_b(m_Z)$

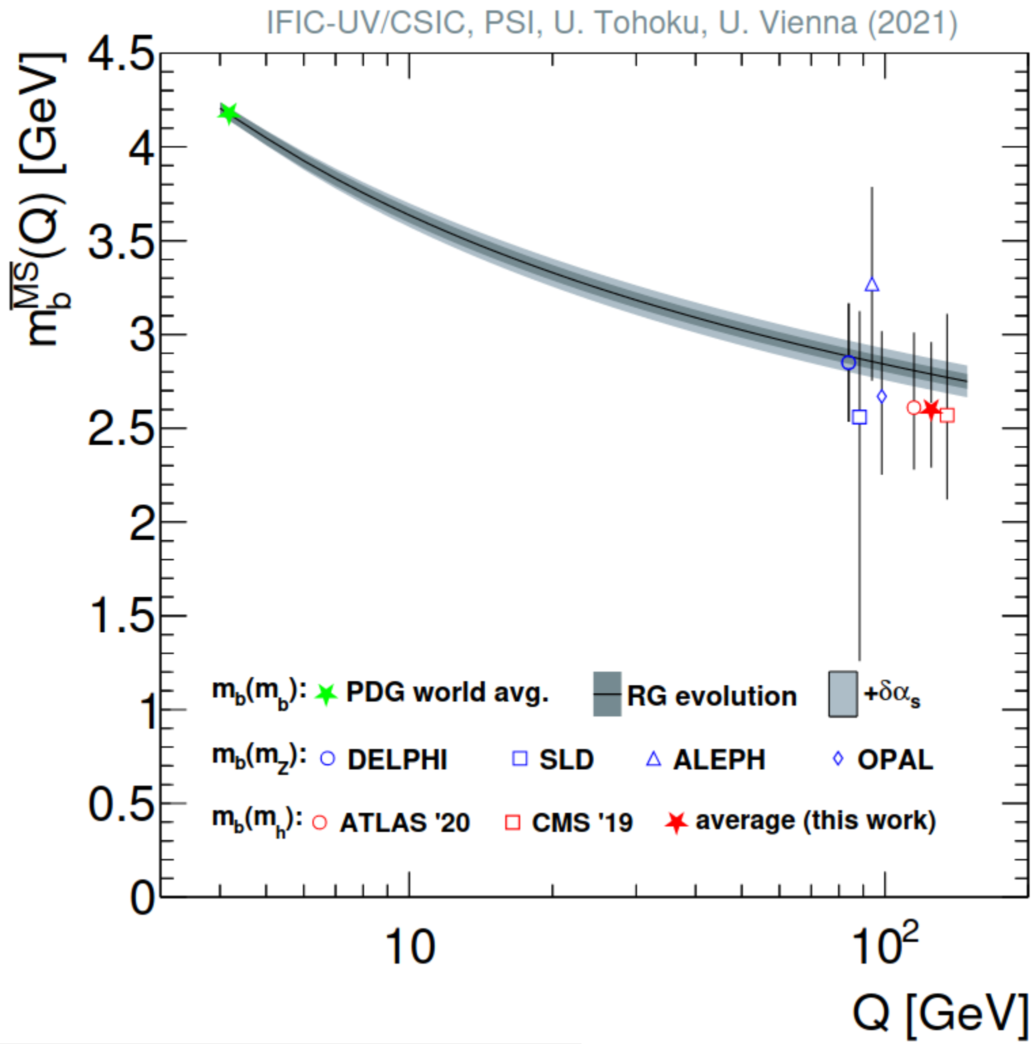
Running of the bottom quark mass

RG evolution from Revolver package, arXiv:2102.01085

Quark masses are not predicted by the SM, but QCD (RGE) does give a prescription for their scale evolution

Uncertainties on evolution:

- reference $m_b(m_b)$ → PDG
- α_s ± 0.001 (PDG $\alpha_s(m_Z)$ [dark grey box])
- α_s ± 0.004 (BSM evolution [light grey box])
- missing higher orders (negligible)



LHC $m_b(m_h)$ today is as precise as LEP $m_b(m_Z)$

Running of the bottom quark mass

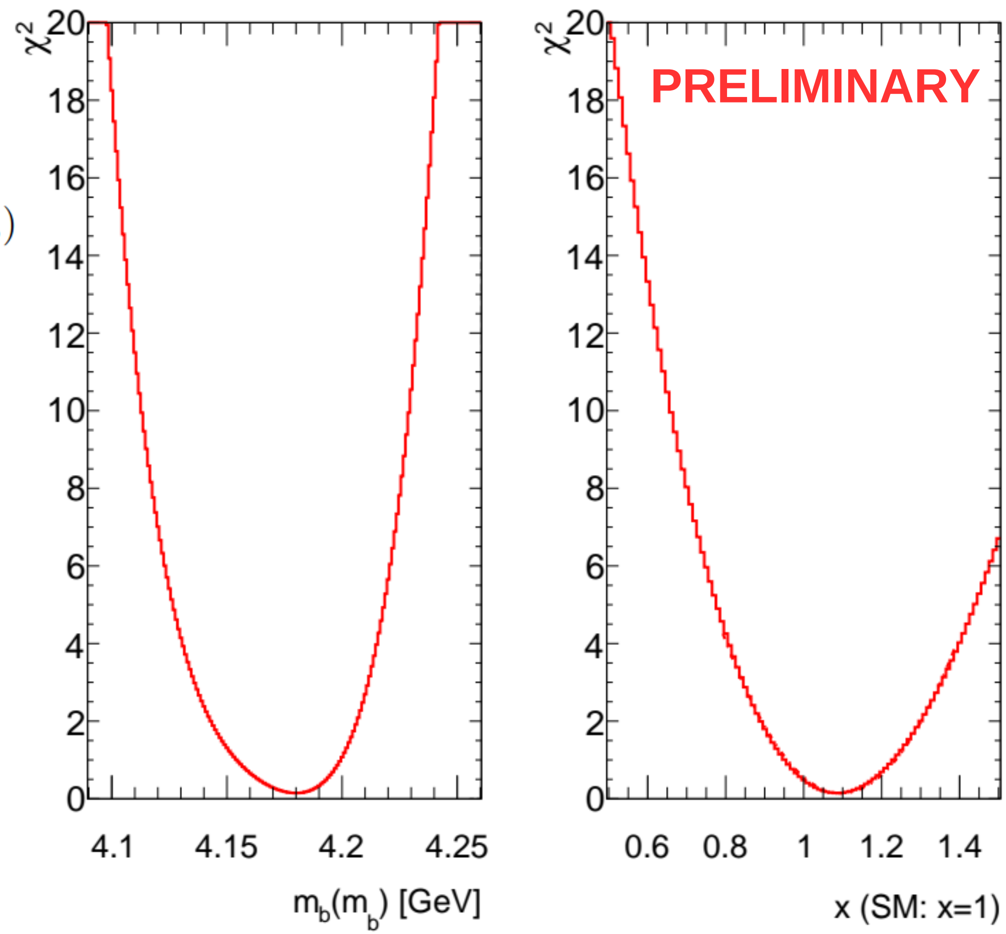
Test running hypothesis:

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

$x=0$ → no running
$x=1$ → SM prediction

$m_b(m_b) = 4.18^{+0.03}_{-0.02}$ GeV,
compatible with very precise input from PDG world average

$x=1.08\pm0.15(\mathrm{exp})\pm0.05(\alpha_s)$
Compatible with SM within 1σ,
Incompatible with no-running ($\sim7\sigma$)



Results confirm RGE scale evolution: no-running scenario ruled out at 7σ

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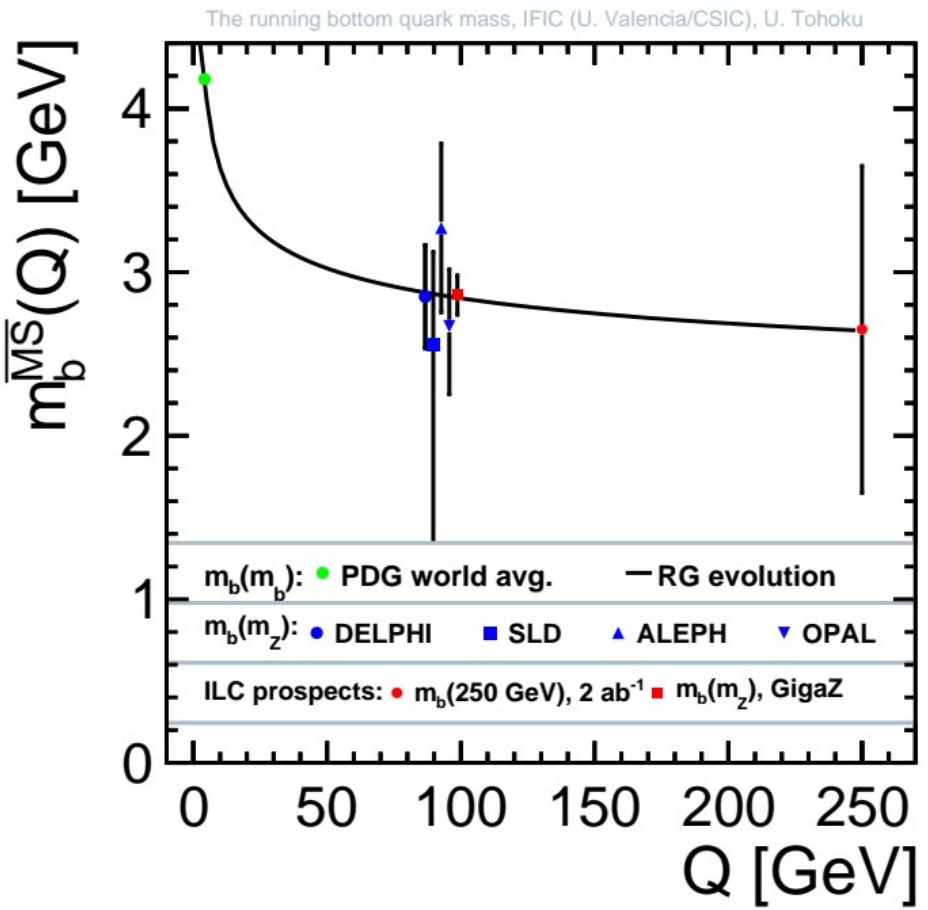
Future prospects – $m_b(m_Z)$, $m_b(250)$ at Higgs factories

Electron-positron colliders can add further points:

- Extend the reach measuring m_b(250 GeV) from 3-jet rates
  ILD-PHYS-PUB-21-001
  S. Tairafune, arXiv:2104.09924

- Return to the Z-pole (TeraZ or rad.return, 3-jet rates or R_b)
  ILD-PHYS-PUB-21-001
  + S. Kluth, arXiv:2202.02417



The Higgs factory improves $m_b(m_Z)$ considerably, with some theory/MC progress; m_b(250 GeV) is limited by poor mass sensitivity

Future prospects – $m_b(m_H)$ from Higgs decays

HL-LHC expectation [M. Cepeda et al., YR7 (2019), arXiv:1902.00134] :

- 4.4% precision on B_{bb}/B_{ZZ} (HL-LHC-S2)

  → **60 MeV** exp. uncertainty on m_b(mH)

A Higgs factory [ILC, J. Tian, private communication, arXiv:1910.11775]:

- 0.86% precision on B_{bb}/B_{WW} (ILC250)

  → **12 MeV** exp. uncertainty on m_b(mH)

- 0.46% precision on B_{bb}/B_{WW} (ILC250+500)

  → **6 MeV** exp. uncertainty on m_b(mH

What about theory?

Param. unc. (m_H, α_s) will come down, EW corrections to NNLO needed

The HL-LHC and ILC have to potential to improve the experimental precision of $m_b(m_h)$ to ± 60 MeV (HL-LHC) and even 12 MeV (ILC250) or 6 MeV (ILC250+500)

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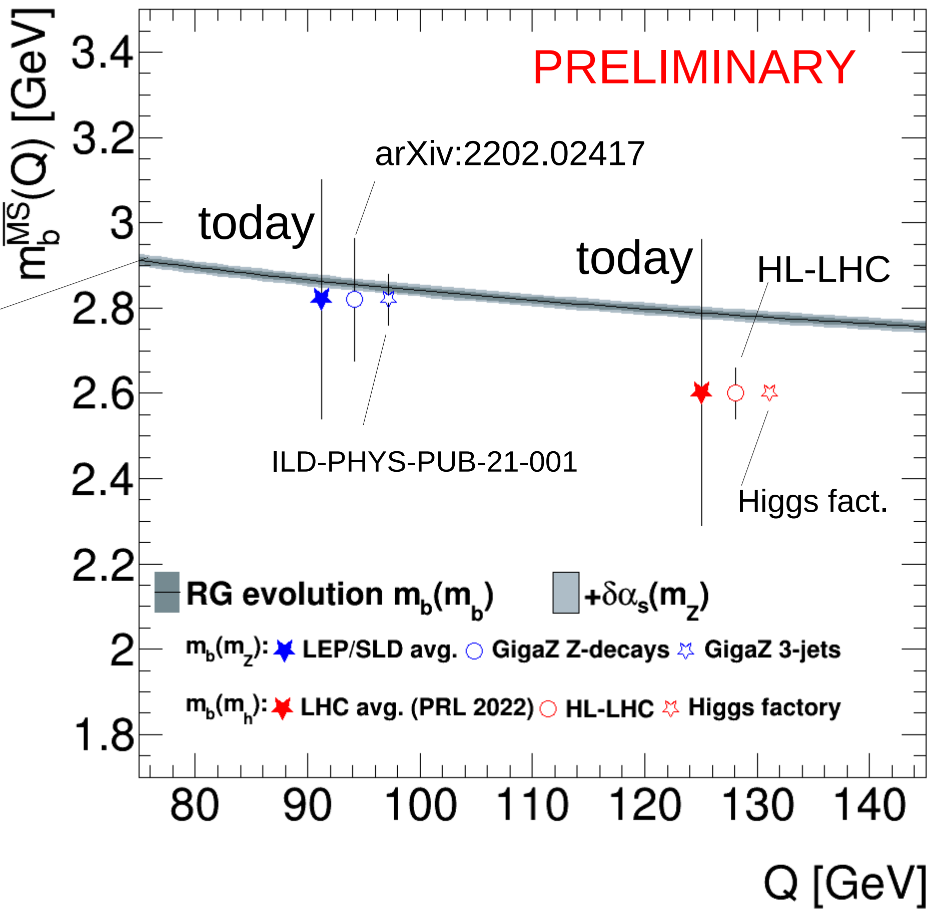
Future prospects – the complete picture

Currently working to collect complete prospects:
$\alpha_s(m_b)$, $\alpha_s(m_Z)$, $\alpha_s(m_H)$, $m_b(m_b)$, $m_b(m_Z)$, $m_b(m_H)$
Snowmass White Paper, arXiv:2203.XXXXX

Projected evolution from m_b scale

$m_b(m_b)$ < 10 MeV [Mateu/Hoang]
$\alpha_s(m_b)$ < 0.5%) [FLAG]
$\alpha_s(m_Z)$ < 0.1% [d'Enterria/FCCee]
See report α_s workshop 2022



The next years at the LHC will see rapid progress in $m_b(m_H)$; the Higgs factory will further improve $m_b(m_H)$ and $\alpha_s(m_Z)$

Small print

DISCUSSION & OUTLOOK

Caveat. When the Higgs decay rates are used for a determination of the bottom quark mass, we must assume that physics beyond the SM has a neligible impact. The procedure followed by the ATLAS and CMS experiments is quite robust against certain new physics effects. The contribution of unknown "invisible decays" to the Higgs width cancels in the ratio and other assumptions, e.g. on the Higgs boson production cross sections, can be tested to good precision. A shift of the bottom quark Yukawa coupling (and none of the other Higgs couplings) would, however, lead to a bias in the mass measurement. The results in this Letter are strictly valid only for a SM bottom quark Yukawa coupling.

Summary

We proudly present a new measurement of the bottom quark mass at the scale of the Higgs boson mass:

$m_b(m_H) = 2.60^{+0.36}_{-0.30}$ GeV

CAVEAT: under the assumption that the bottom quark Yukawa coupling is standard

A new method with very nice theory properties and ample potential to improve the precision (run 2, run 3, HL-LHC, Higgs factory)

New and better high-energy measurements of $m_b(m_Z)$, $m_b(m_H)$,…) provide a high-precision test of the scale evolution predicted by QCD

Possible future projects: joint fit of scale evolutions of α_s and m_b to derive bounds on massive coloured objects, simultaneous measurement of Yukawa coupling and bottom quark mass (more info in Q&A session)

Backup: anomalous mass dimension

Backup: Anomalous mass dimension

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$

Focusing on the first term in the expansion $\gamma_m[\alpha_s] = \gamma_0 \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)$, we obtain, in leading-log (LL) approximation:

$$\gamma_0 = -\beta_0 \log\left(\frac{m_q(\mu^2)}{m_q(\mu_0^2)}\right) / \log\left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right) . \qquad (10)$$

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

Backup: Can I have my cake and eat it?

Can we measure the bottom Yukawa AND the mass?

In principle, yes, a precise measurement of the i.e. the 3-jet rate in Higgs decays would yield a shape sensitive to mass effects, while the rate is primarily driven by the Yukawa coupling

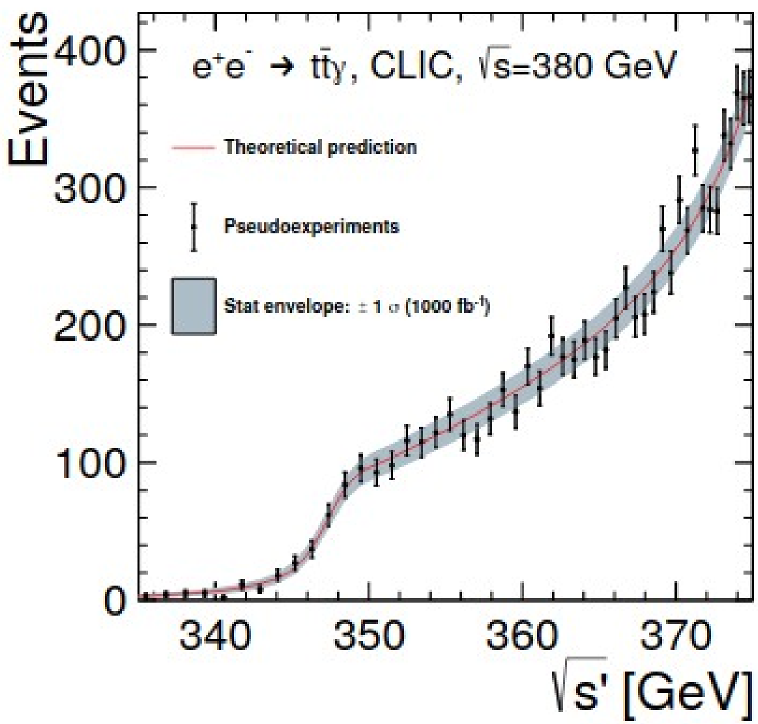
The NNLO calculation of differential Higgs decay rates to bottom exists: Bernreuther, Chen and Si (JHEP 07 (2018))

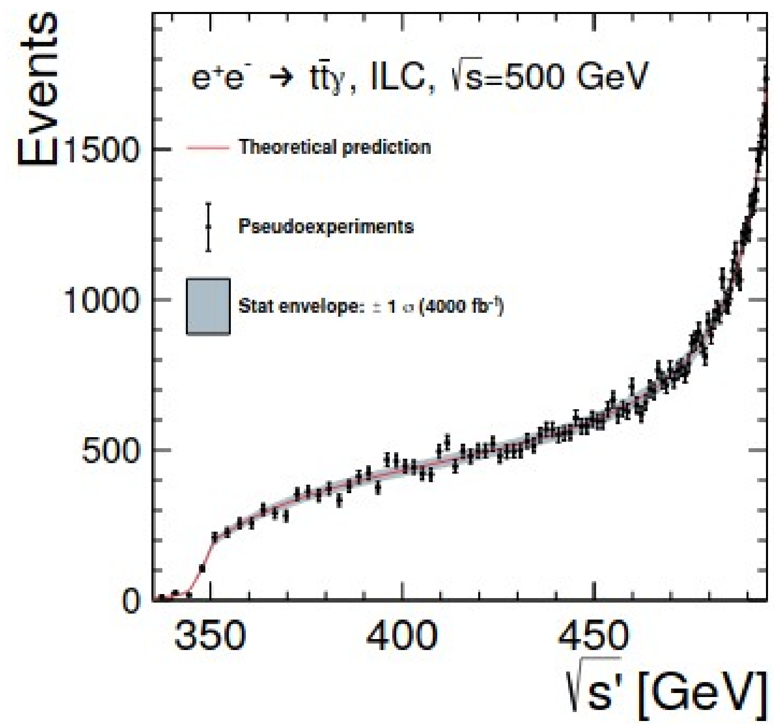
In practice, the precision of the mass will be limited and a differential three-jet rate measurements may be challenging at the LHC

Bonus material: running top quark mass

Top quark mass from radiative events

Ph.D. Pablo Gomis, UV, jan. 2020





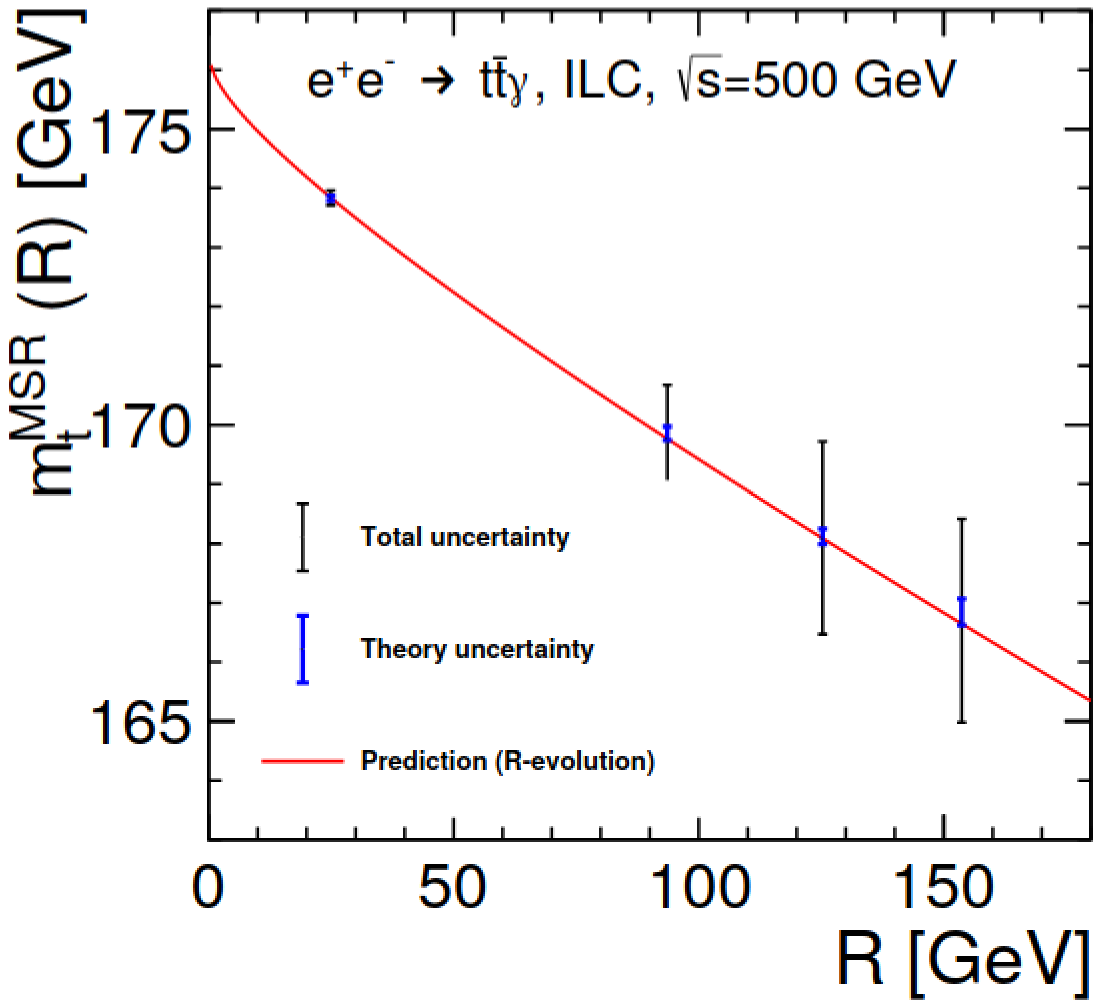
Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance MSR mass with rigorous interpretation and competitive precision:

CLIC380 (1/ab): 50 MeV (theory), 110 MeV total

ILC500 (4/ab): 50 MeV (theory), 150 MeV total

Top quark mass from radiative events



5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone