$m_b(m_H)$

extracting the bottom quark mass from Higgs precision measurements

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High Energy Physics today

Since its discovery in 2012, the focus of HEP is to study the properties and interactions of the new H(125) boson

The LHC experiments are characterizing, with rapidly increasing precision, the couplings of the Higgs boson to SM particles:

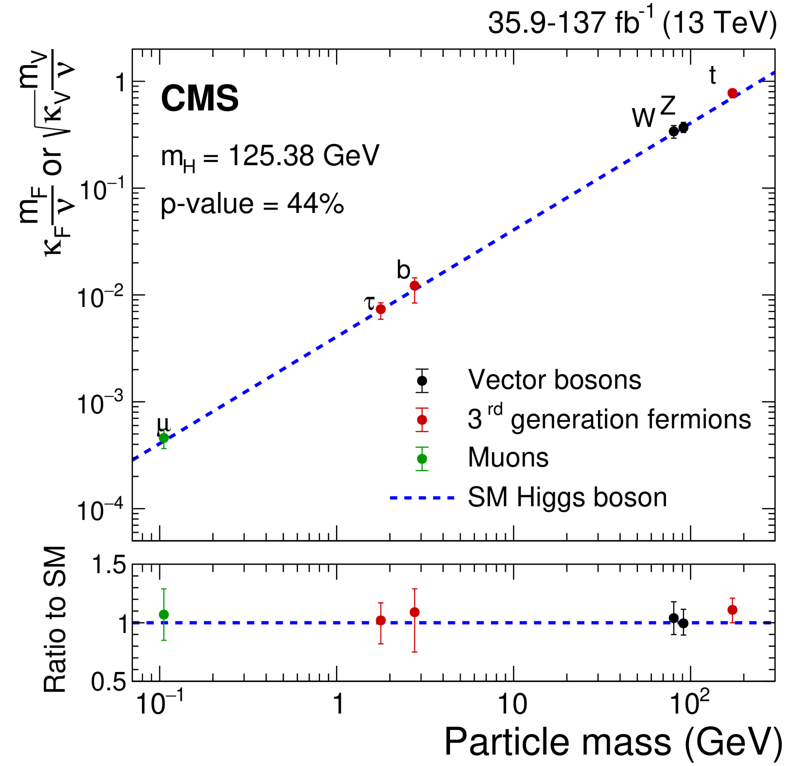
2012: discovery of pp $\rightarrow$ H, H $\rightarrow$ ZZ*, H $\rightarrow \gamma\gamma$, H $\rightarrow$ WW
2015: evidence for H $\rightarrow \tau\tau$ decay (fermions!)
2018: discovery of H $\rightarrow b\bar{b}$ decay (quarks!)
discovery of pp $\rightarrow$ VH production
discovery of $t\bar{t}$H production (Yukawa ~1!)
2020: evidence for H $\rightarrow \mu\mu$ decay (2^{nd} generation!)
2021: evidence for H $\rightarrow l^+l^-\gamma$ decay

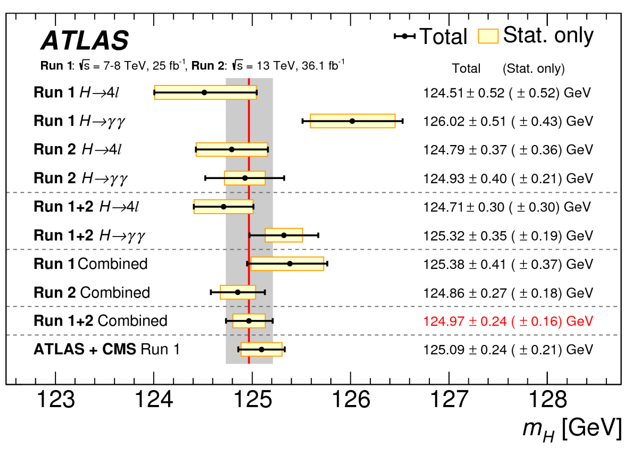
Eventually a Higgs factory will provide sub-% measurements

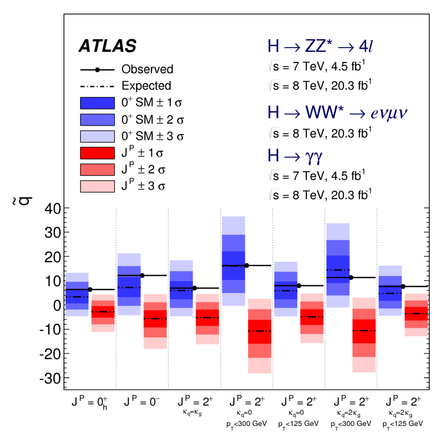
Today: these measurements enable a measurement of mb(mH)

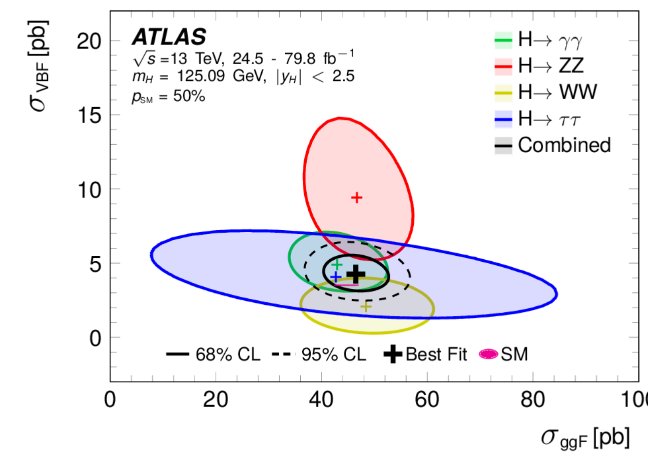
Higgs boson precision measurements at the LHC

Extensive set of measurements of multiple production and decay rates, spin, etc.,… all compatible with the SM within large, but rapidly decreasing, uncertainties









Higgs boson precision measurements at the LHC

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

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

H^0 $J = 0$

Mass $m = 125.10 \pm 0.14$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95% (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.19^{+0.12}_{-0.11}$
$\gamma\gamma = 1.10^{+0.10}_{-0.09}$
$c\bar{c}$ Final State < 110, CL = 95%
$b\bar{b} = 1.02 \pm 0.15$
$\mu^+\mu^- = 0.6 \pm 0.8$
$\tau^+\tau^- = 1.11 \pm 0.17$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 1.28 \pm 0.20$
H^0H^0 Production < 12.7
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV $=$ 57 ± 7 pb

Higgs decays and the bottom quark mass

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

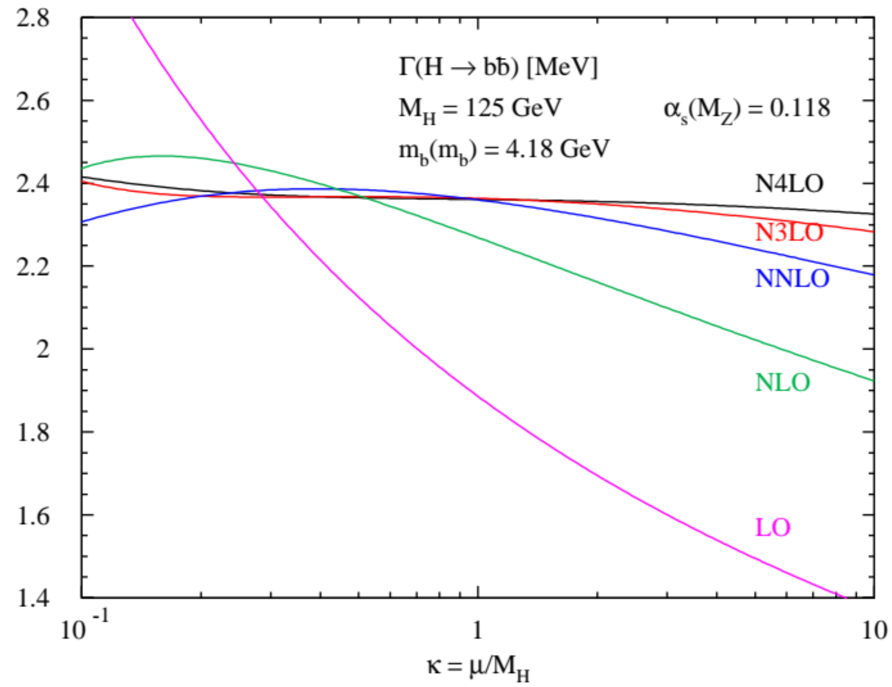
- quadratic dependence on m_b
- EW process, rate decoupled at LO from strong coupling α_s
- precise predictions available
- well-defined natural scale m_h

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

CAVEAT: we have to assume that the bottom quark Yukawa coupling is standard

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Choice of mass-sensitive observable

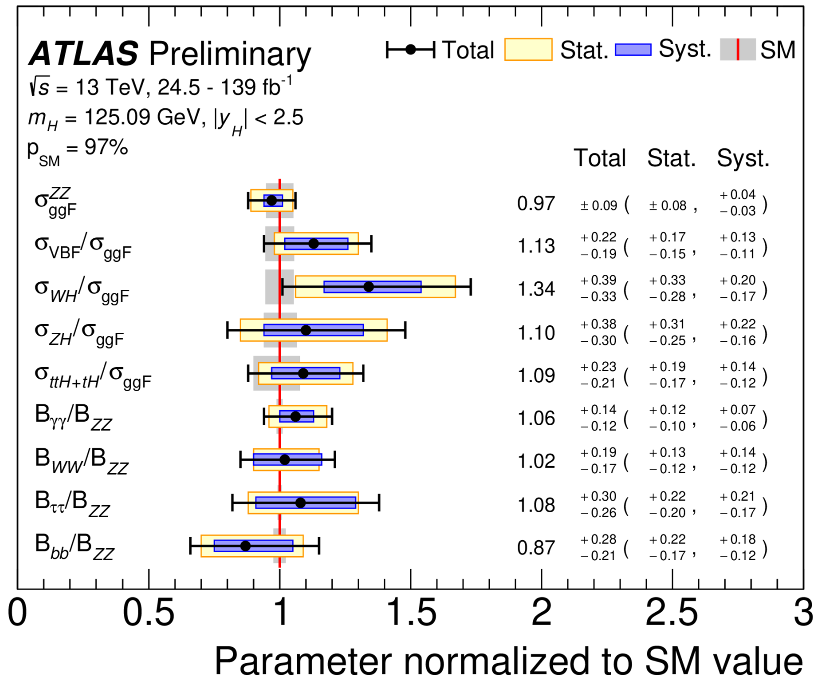
A hadron collider cannot measure absolute couplings, but ratios of prod. and decay rates can be precisely determined

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 $B_{bb}/B_{ZZ} = 22.0 \pm 0.5$

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



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We proudly present: $m_b(m_h)$

The bottom quark mass is extracted from B_{bb}/B_{ZZ}

ATLAS: $m_b(m_h) = 2.59^{+0.31}_{-0.26}(\mathrm{stat.})^{+0.26}_{-0.18}(\mathrm{syst.})\mathrm{GeV}$ [ATLAS-CONF-2020-027]

CMS: $m_b(m_h) = 2.55^{+0.38}_{-0.32}(\mathrm{stat.})^{+0.37}_{-0.26}(\mathrm{syst.})\mathrm{GeV}$ [EPJC77 (2019)5,421]

The two results are combined with Convino (arXiv:1706.01681):

$$m_b(m_h) = 2.58^{+0.36}_{-0.30}\ \mathrm{GeV} + \text{theory uncertainty}$$

Note: use of the $\overline{\mathrm{MS}}$ 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 $m_b(m_b)$)

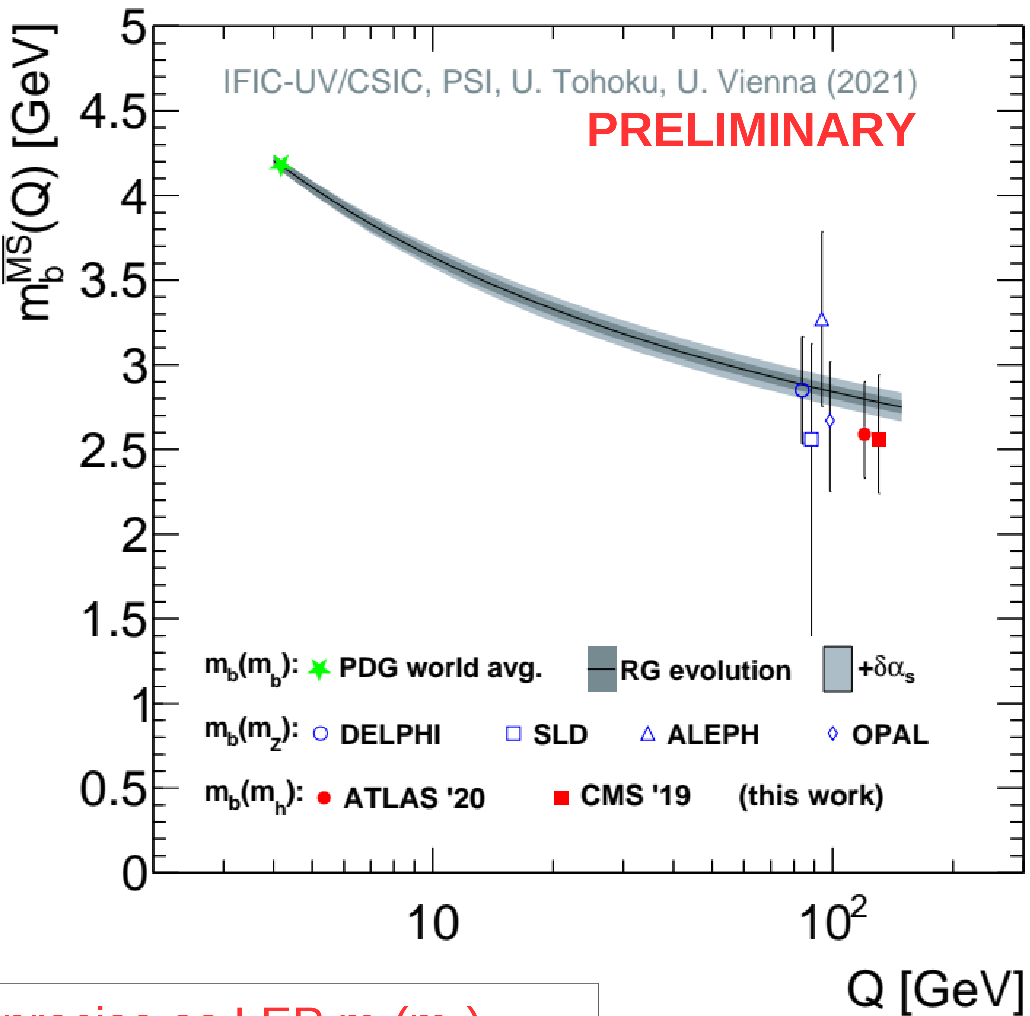
Running of the bottom quark mass

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 $m_b(m_Z)$

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Running of the bottom quark mass

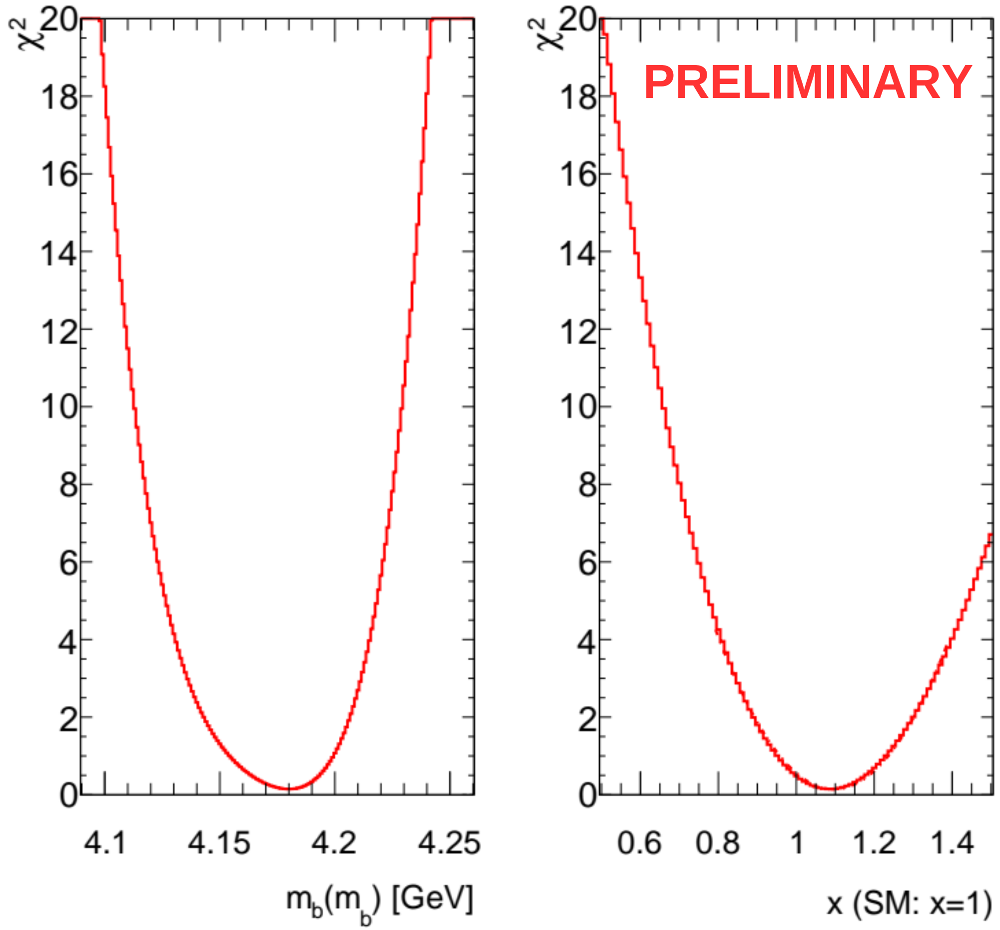
Test running hypothesis:

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

x=0 → no running
x=1 → SM prediction

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

x=1.10±0.15(exp)±0.05(α_s.)
Compatible with SM within 1σ,
Incompatible with no-running (~7σ)



Results confirm RGE scale evolution

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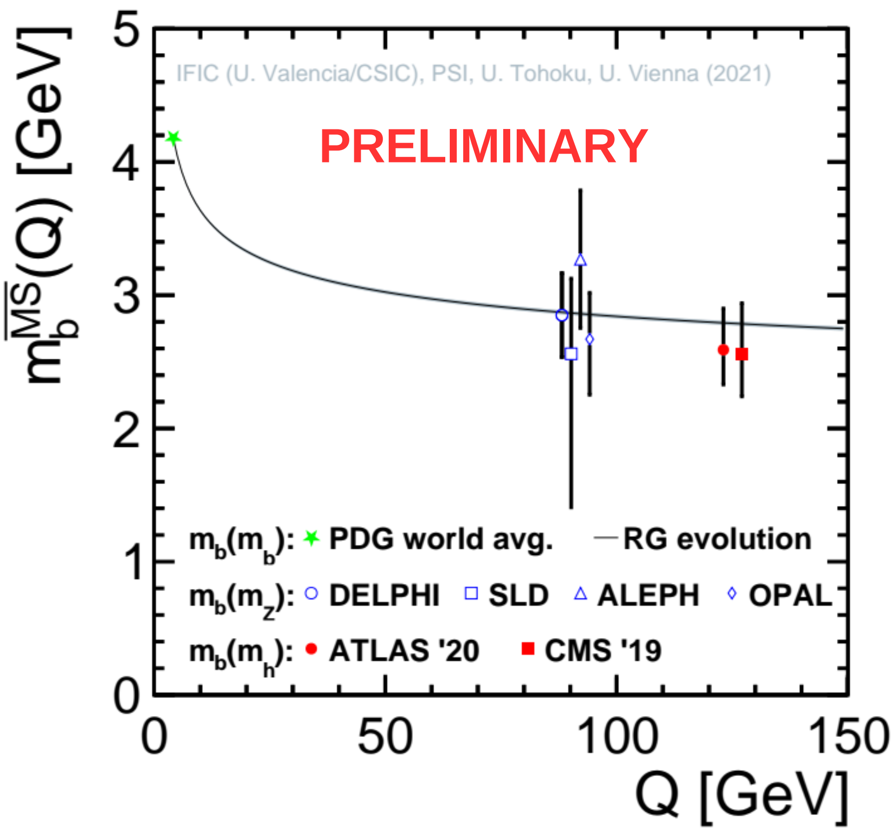
Future prospects – $m_b(m_H)$

RG evolution from Revolver package, arXiv:2102.01085

HL-LHC expectation:
- 4.4% precision on B_{bb}/B_{ZZ}

A Higgs factory is the ideal machine for this study:
- ILC250 expects to measure B_{bb}/B_{WW} to 0.86%
- High-energy run can improve this to 0.46%
[source: Junping Tian]

A detailed assessment of theory uncertainties is needed for a final projection



The HL-LHC and ILC have to potential to improve the experimental precision of $m_b(m_h)$ to ± 80 MeV (HL-LHC) and 15 MeV (ILC250) and 8 MeV (ILC250+500)

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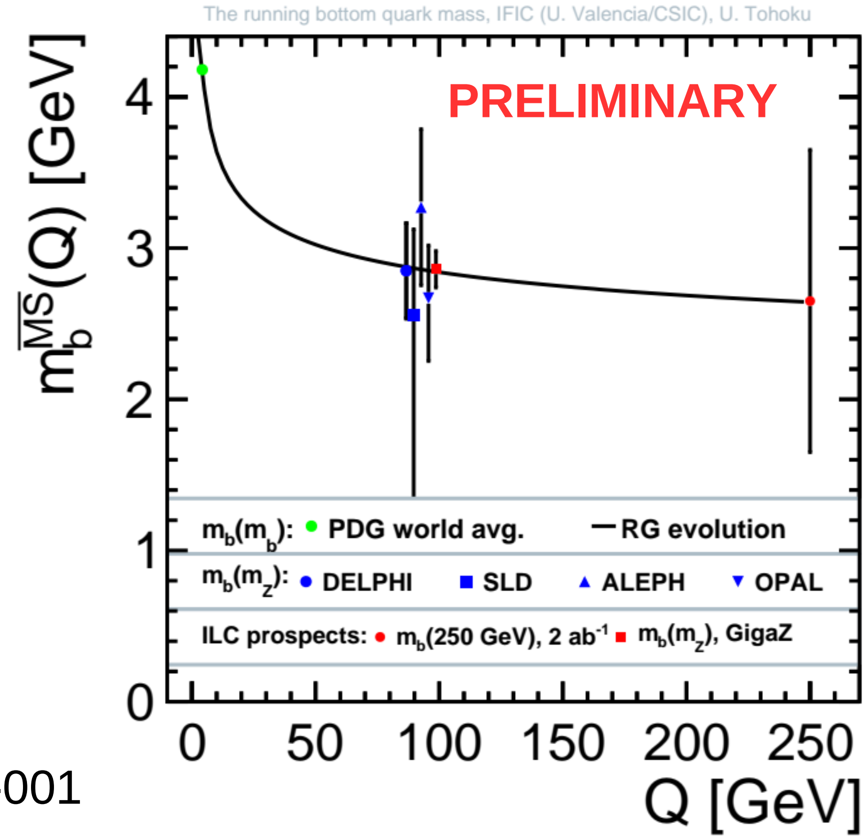
Future prospects – other scales

Higgs factories can also:

- Extend the reach, and measure $m_b(250\ \mathrm{GeV})$, albeit with limited precision
- Return to the Z-pole, with the GigaZ run, or using radiative-return events



See S. Tairafune, LCWS21
arXiv:2104.09924, ILD-PHYS-PUB-21-001

The ILC improves $m_b(m_Z)$ considerably, assuming progress in theory & Monte Carlo
$m_b(250\ \mathrm{GeV})$ is challenging, as the mass sensitivity decreases, but feasible

Summary

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

$m_b(m_H) = 2.58^{+0.36}_{-0.30}$ 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 (HL-LHC, Higgs factory)

New high-energy measurements ($m_b(m_Z)$, $m_b(m_H)$,…) can be used to test the scale evolution predicted by QCD

Bonus material: running top quark mass

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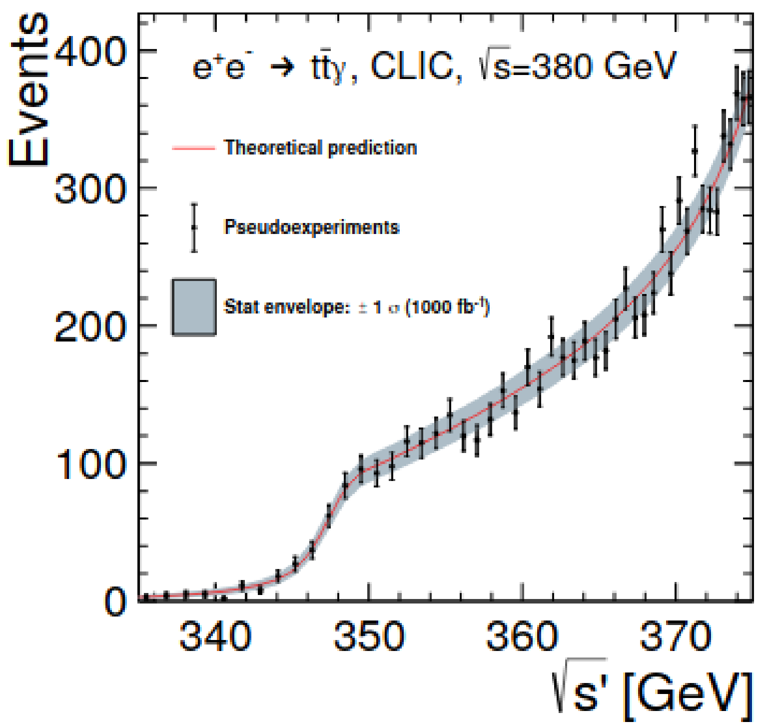
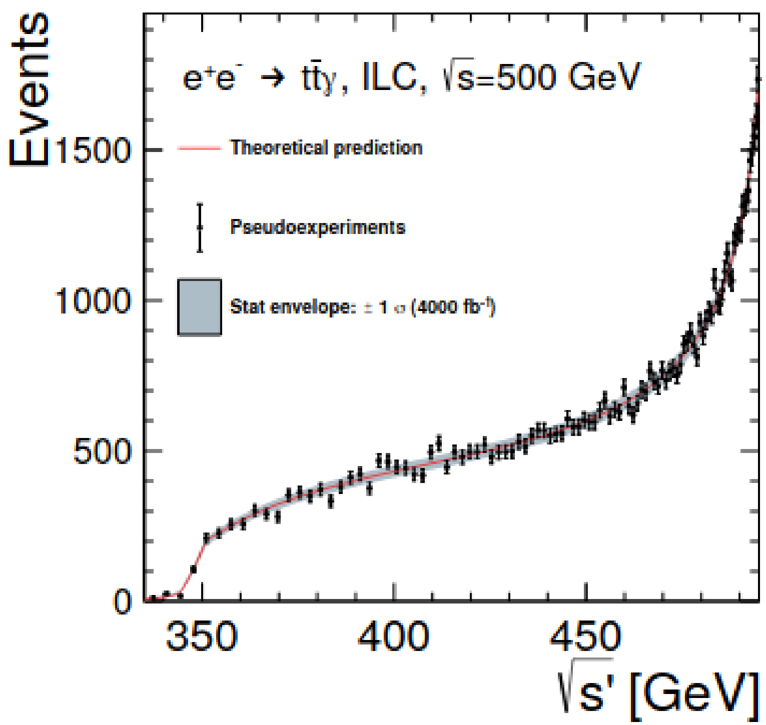
Top quark mass from radiative events

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



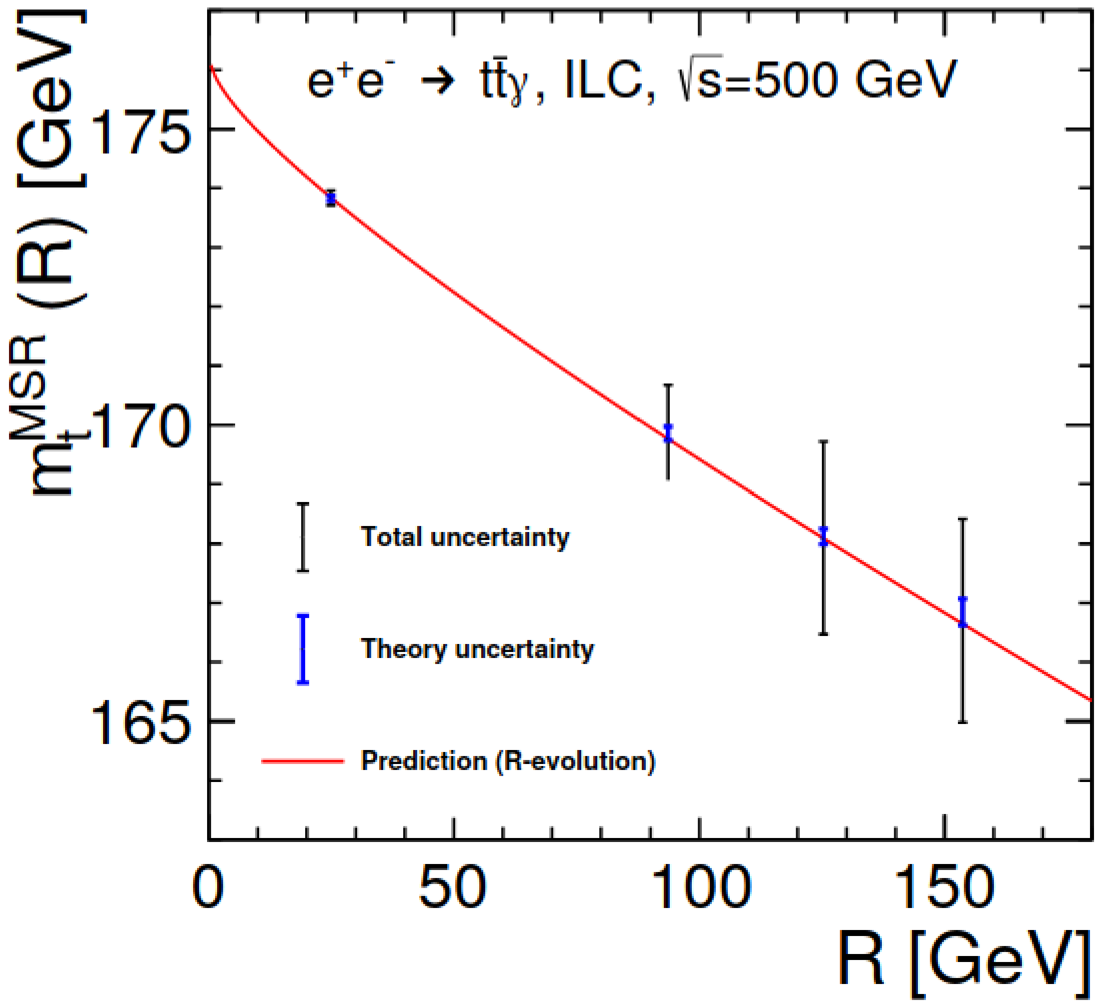


Radiative "return to threshold" in e+e- → ttγ events

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