# *The bottom quark and the Higgs boson*

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## the Higgs factory

**Everyone** (including European strategy '13+'20):

**"the highest-priority next collider is an $e^+e^-$ Higgs factory"**




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## High Energy Physics today

Since the “Higgs discovery” of 2012, the focus of the field is to study the properties and interactions of the new boson

The LHC experiments are looking – with rapidly increasing precision - for hints of BSM properties or effects

This approach is to culminate in a Higgs factory: generally agreed to be the highest-priority new facility in HEP

I - of course - share that view, but...

## An alternative view of the Higgs boson

...today we will explore an alternative view

where the Higgs boson is just another boson, and

the priority of HEP is to measure the bottom quark mass.

## The Higgs observation saga...

**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!)**

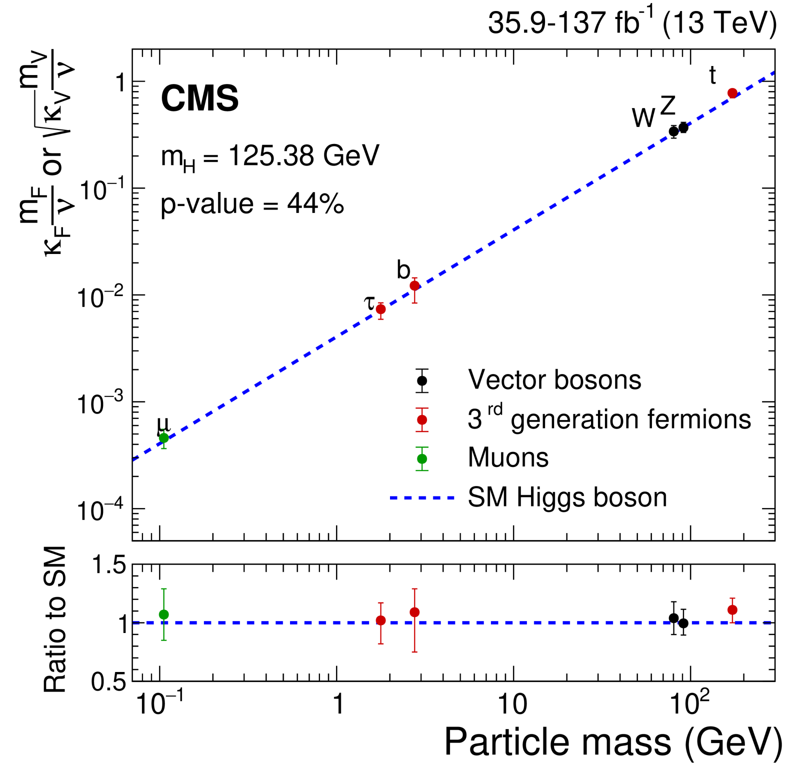
**2018: discovery of H $\rightarrow b\bar{b}$ decay (quarks!)**
**discovery of pp $\rightarrow$ VH production**
**discovery of $t\bar{t}$H production (Yukawa ~1!)**

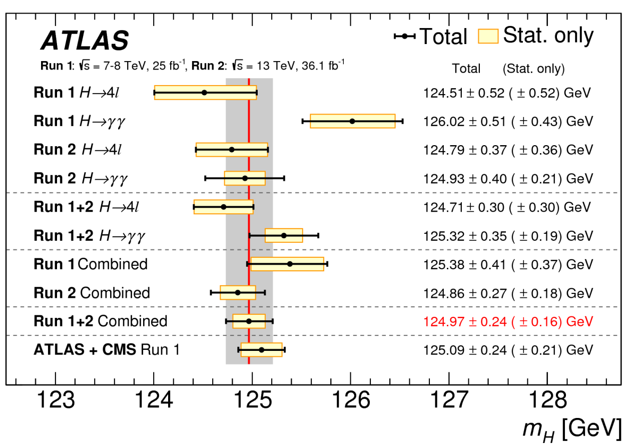
**2020: evidence for H $\rightarrow \mu\mu$ decay (2$^{nd}$ generation!)**

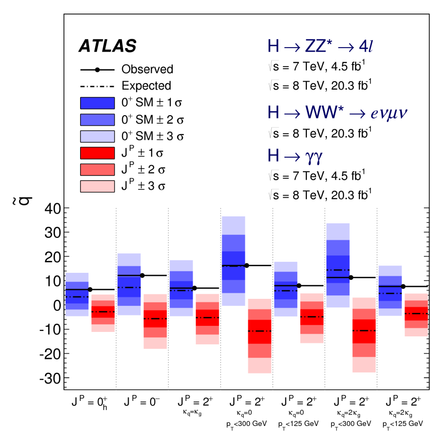
**2021: evidence for H $\rightarrow l^+l^-\gamma$ decay**

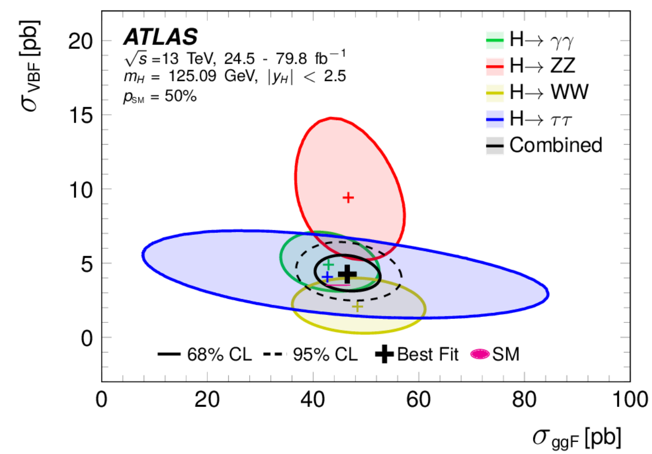
# Higgs boson precision measurements at the LHC

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



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# 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 = $57 \pm 7$ pb

## Higgs decays and the bottom quark mass

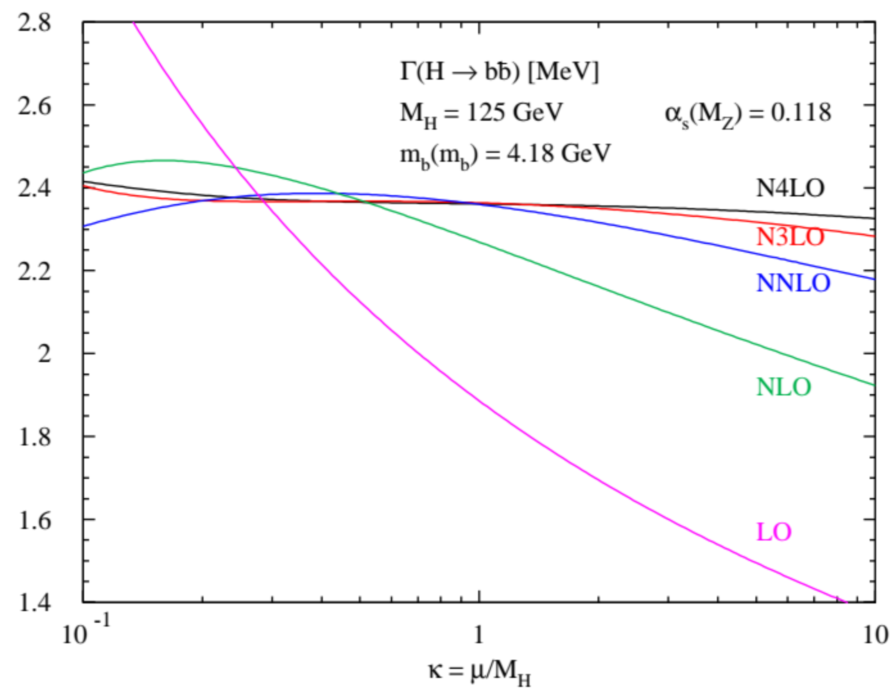
**The Higgs decay to bottom quarks is a good laboratory to study the bottom quark mass:**

- quadratic dependence on $m_b$

- EW process, rate decoupled at LO from strong coupling $\alpha_s$

- precise prediction is readily available (N4LO QCD + EW corr.)

- well-defined natural scale $m_h$




*See also HDECAY manual and "Handbook of LHC Higgs cross sections 4. Deciphering the nature of the Higgs sector", arXiv:1610.07922*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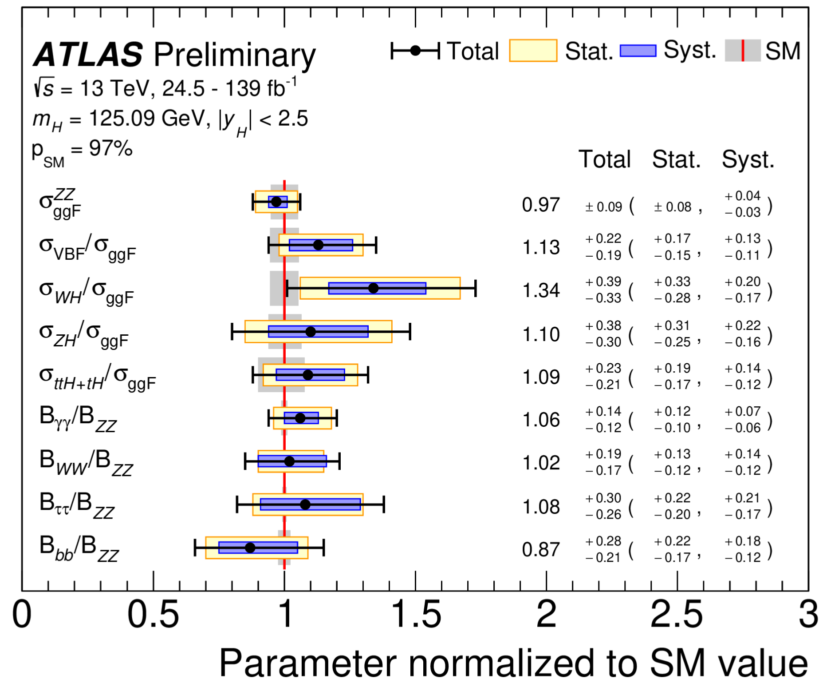
# Choice of mass-sensitive observable

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

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



# We proudly present: $m_b(m_h)$

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

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

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

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

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

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 $\alpha_s$ dependence of the result (cf. the more conventional $m_b(m_b)$)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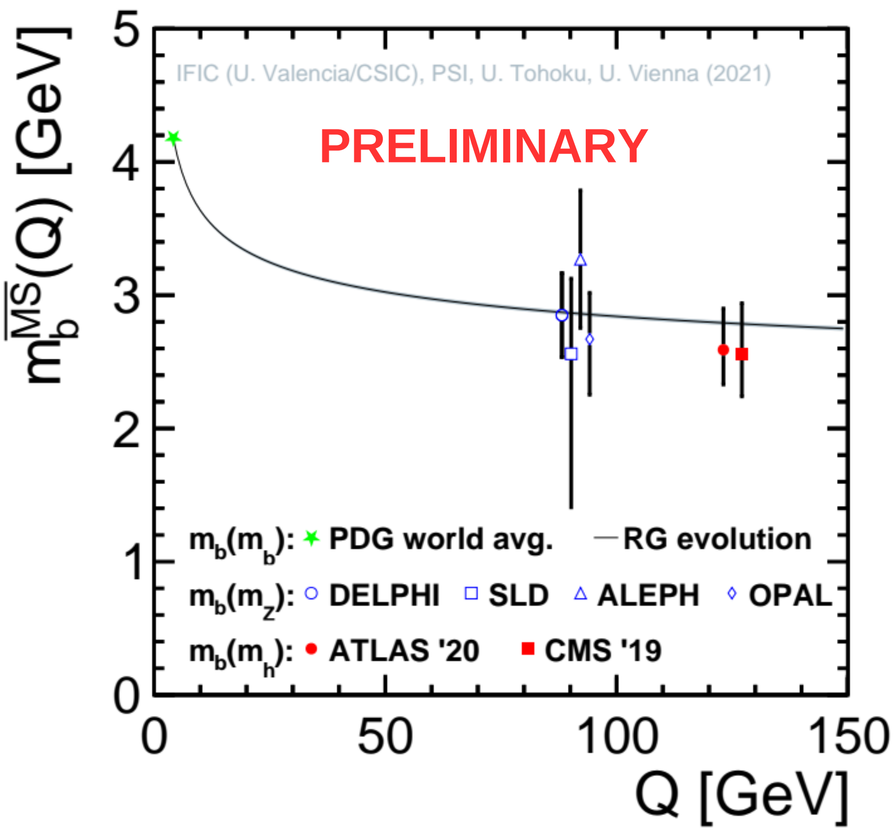
# Running of the bottom quark mass

*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




Measurements of $m_b(m_h)$ are already as precise as LEP results for $m_b(m_Z)$
The 3 sets of results are consistent with the scale evolution predicted by RGE

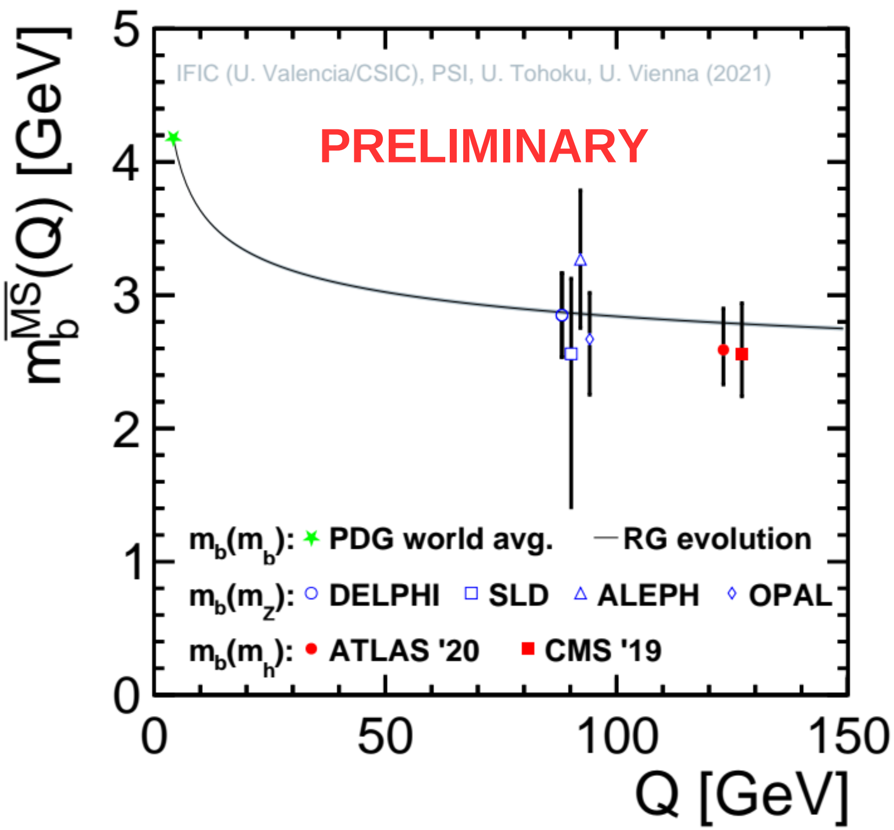
# Future prospects – $m_b(m_h)$

*RG evolution from Revolver package, arXiv:2102.01085*

**More precise measurement is expected at HL-LHC:**
- 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 ILC can improve the measurement of $m_b(m_h)$ to a precision of tens of MeV and - more importantly – can verify the key assumption of this method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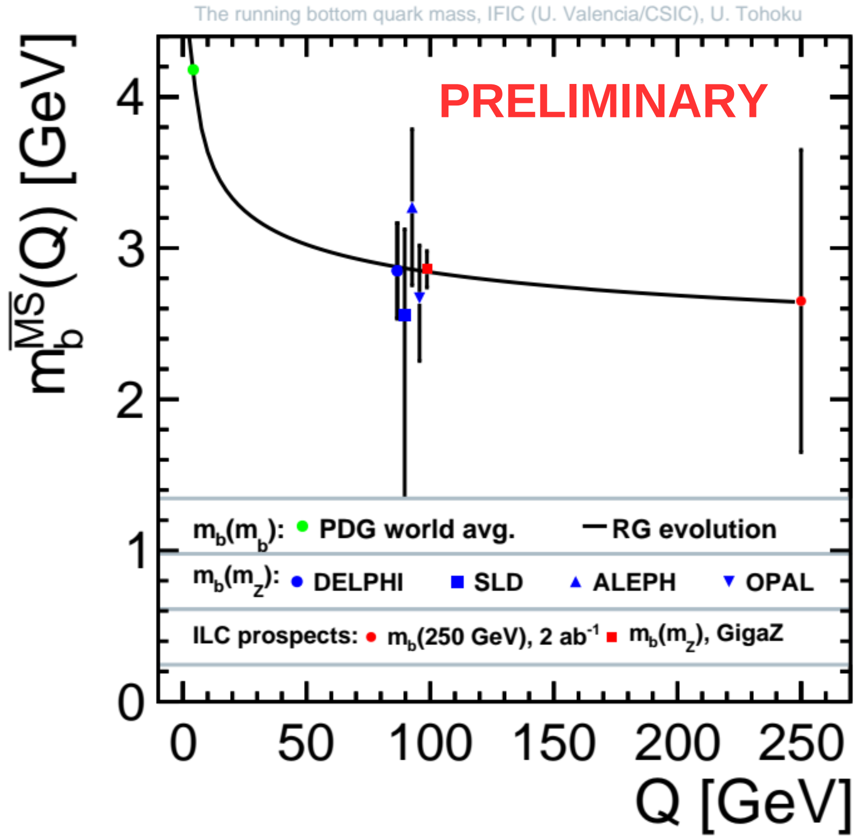
# Future prospects – other scales

**Higgs factories can also:**
- Extend the reach, and measure $m_b$(250 GeV), albeit with limited precision
- Return to the Z-pole, with the GigaZ run, or using radiative-return events

See S. Tairafune, LCWS21

*The 250 GeV point was studied in detail as part of Seidai's master's thesis, the GigaZ prospect is an extrapolation based on LEP*




The ILC can improve the measurement of $m_b(m_Z)$ considerably, assuming progress in theory and Monte Carlo
$m_b$(250 GeV) is challenging, as the mass sensitivity decreases, but feasible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## Summary

**Proudly presenting 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

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

One major caveat: we assume that $H^0$ is the minimal Higgs boson of the SM; this hypothesis must be verified at a future Higgs factory

*See also S. Tairafune's talk at this workshop*

## Bonus material: running top quark mass


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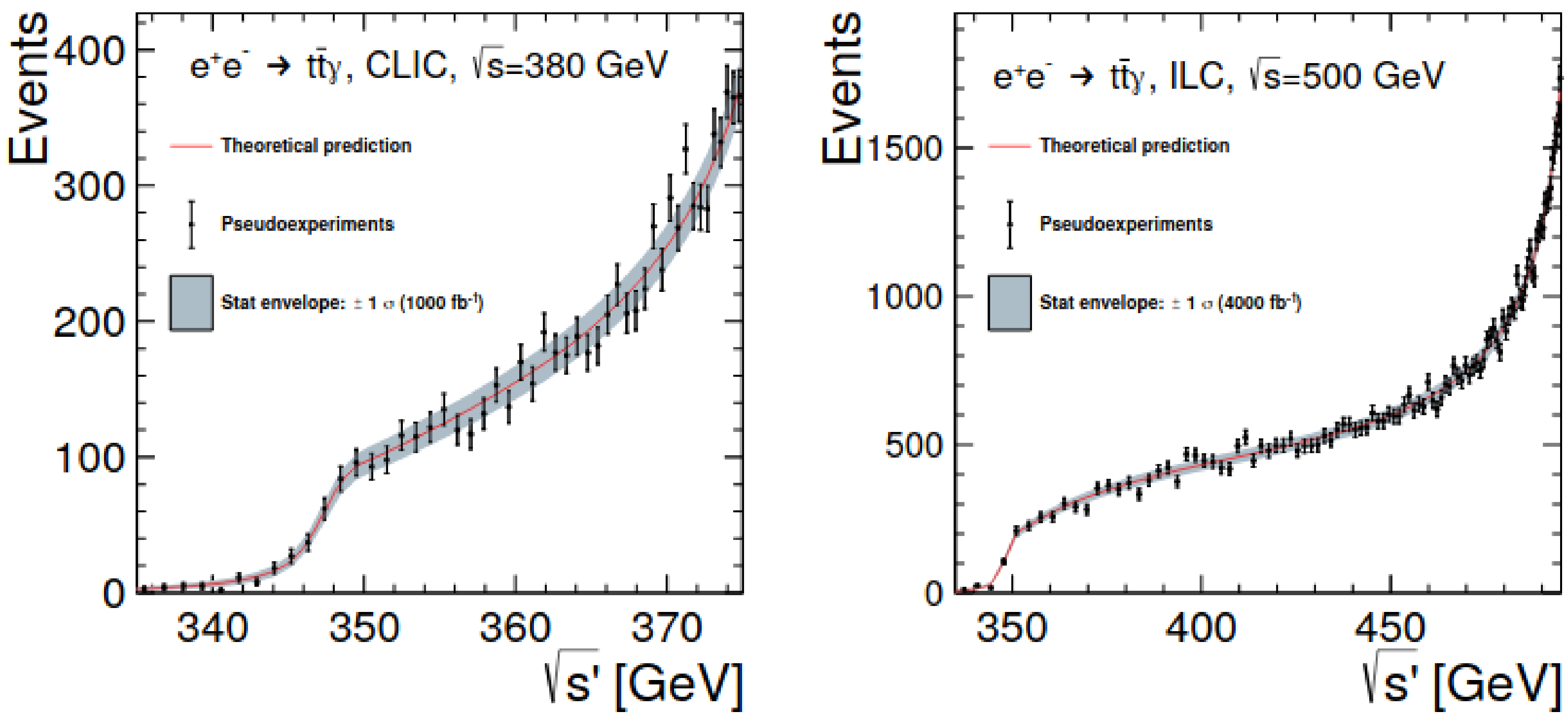
# Top quark mass from radiative events

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



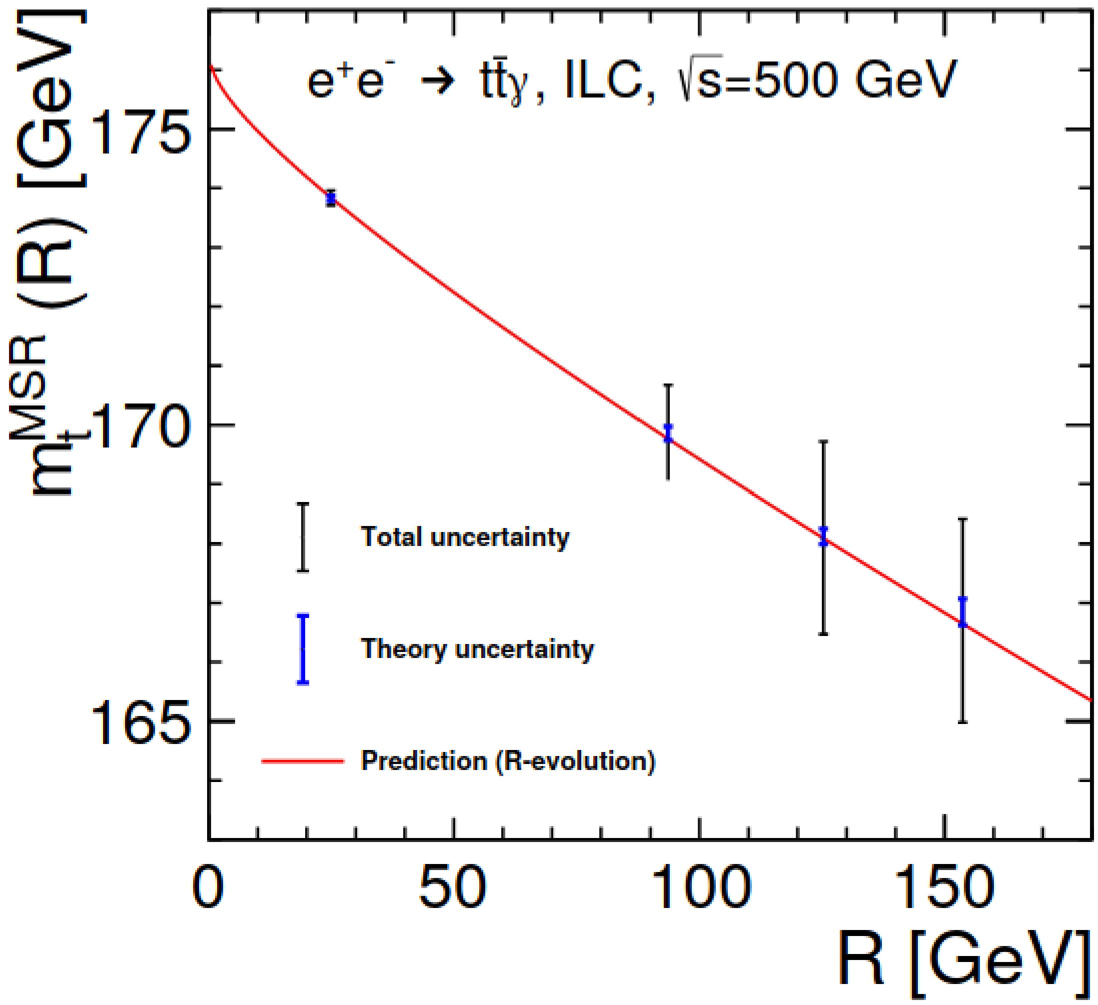

*Radiative "return to threshold" in e+e- → tt$\gamma$ events*

**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




**5$\sigma$ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone**