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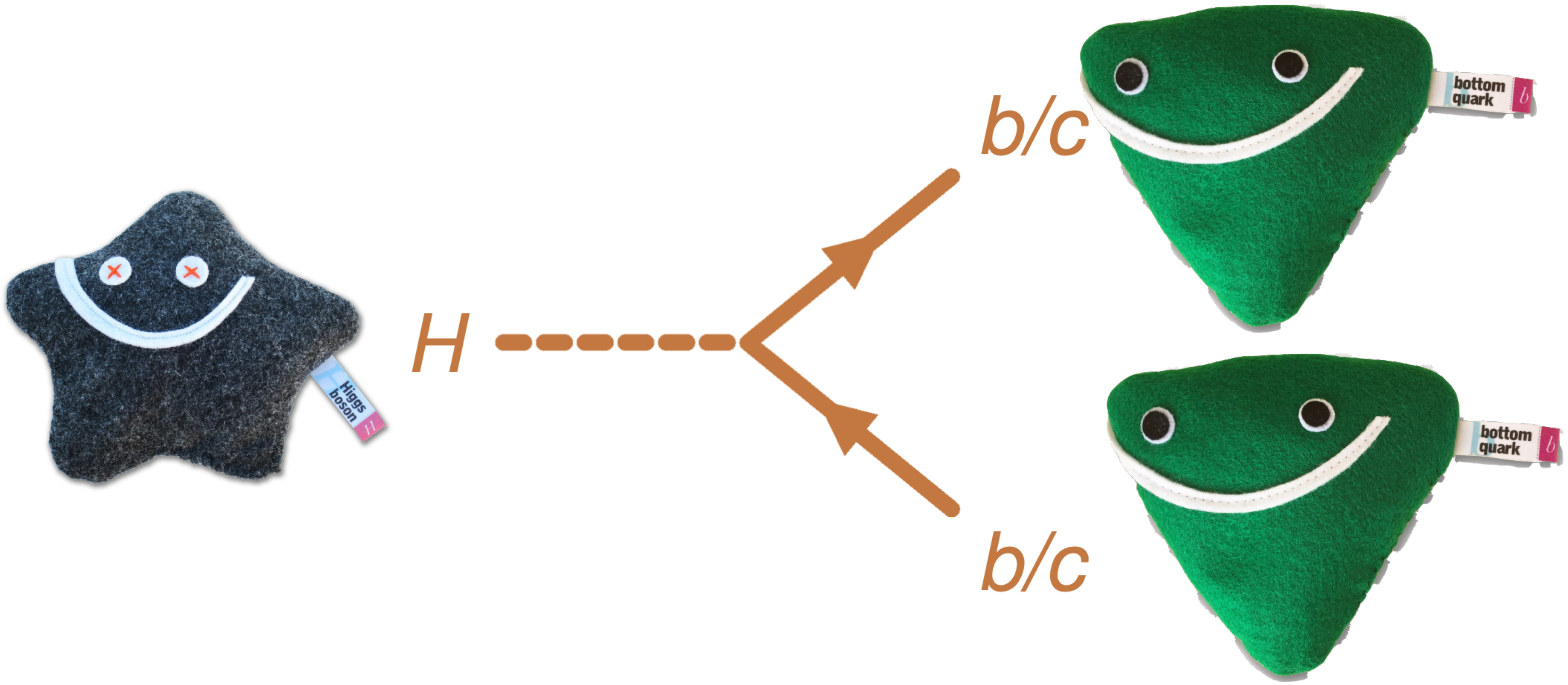
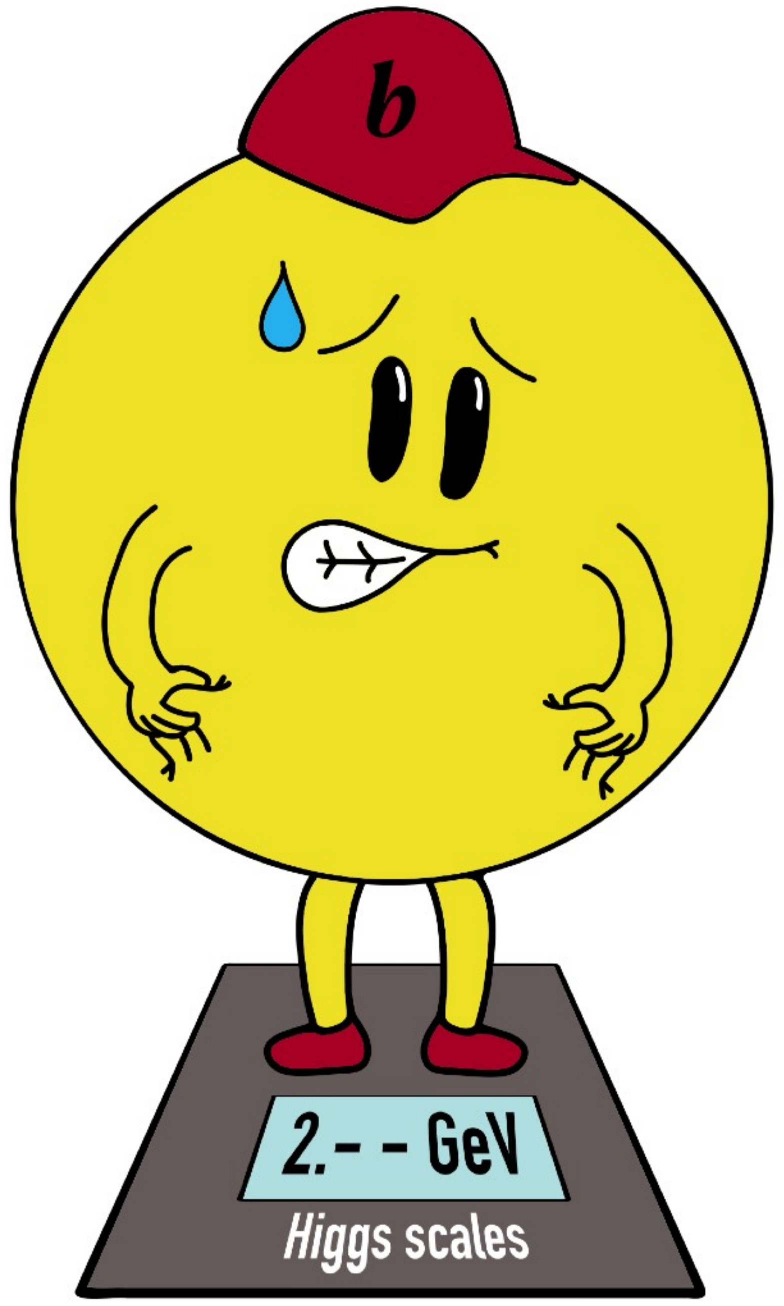
ATLAS Experiment





The bottom quark mass at high scale

Juan Ramírez Alfaro, María Moreno Llácer & Marcel Vos || IFIC (UV-CSIC)

Introduction & Motivation

Running parameters

- Free parameters of the Standard Model (SM) Lagrangian have two key properties:
  - Their values must be **determined experimentally**
  - When renormalized (*), they depend on the dimensional renormalization scale μ (or Q) i.e. they are **running constants**.
- For QCD parameters such as the strong coupling $\alpha_s(\mu)$ and quark masses $m_q(\mu)$, theory yields precise prescription for their running: **Renormalization Group Equations** (RGE). Software to compute it: **REvolver** [1].

Performing **several measurements** at **different energy scales** allows us to **test** the renormalization **scale dependence** of these parameters **experimentally**!

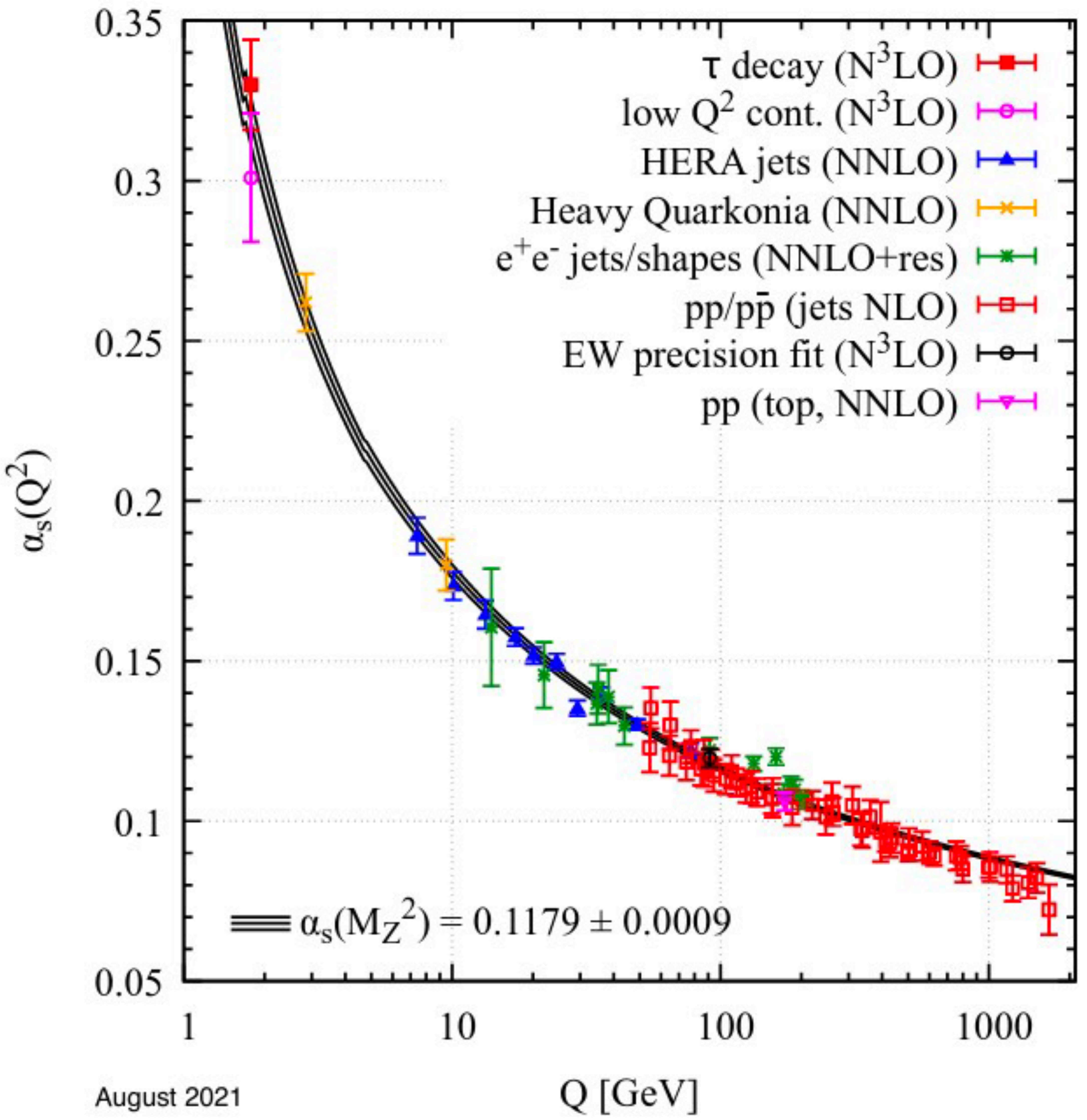
(*): Throughout this work, we consider the most popular renormalization scheme, the *modified minimal subtraction* or $\overline{MS}$ scheme. So, whenever we mention a mass, we are implicitly considering $m_b \equiv m_b^{\overline{MS}}$

Running parameters: $\alpha_s(\mu)$

- Scale evolution of **strong coupling** predicted by QCD:

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

- Numerous **determinations**, from many different measurements, over a broad range of energies (1 GeV to >1TeV), **confirms this evolution with great precision**.
- **Reference scale for RGE evolution**: Z boson mass m_Z, $\alpha_s(m_Z) = 0.1180 \pm 0.0009$ (PDG reference value, <1% rel. prec.)



From [2].

Running parameters: $m_q(\mu)$

- QCD also predicts the running of the **quark masses** (in terms of the *anomalous mass dimension* γ_m):

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

- Evidence already found for the charm quark mass running & ongoing studies for the top quark as well.
- **Bottom quark mass** m_b has been measured mainly at two scales:
  - m_b itself, $m_b(m_b)$: great precision, relatively low energy. "World average" from PDG [2]:

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

  - m_Z, $m_b(m_Z)$: most precise ones are performed with LEP & SLD data (ALEPH, DELPHI, OPAL, SLD). Their average [3] is:

$$\boxed{m_b(m_Z) = 2.82 \pm 0.28\ \mathrm{GeV}}$$

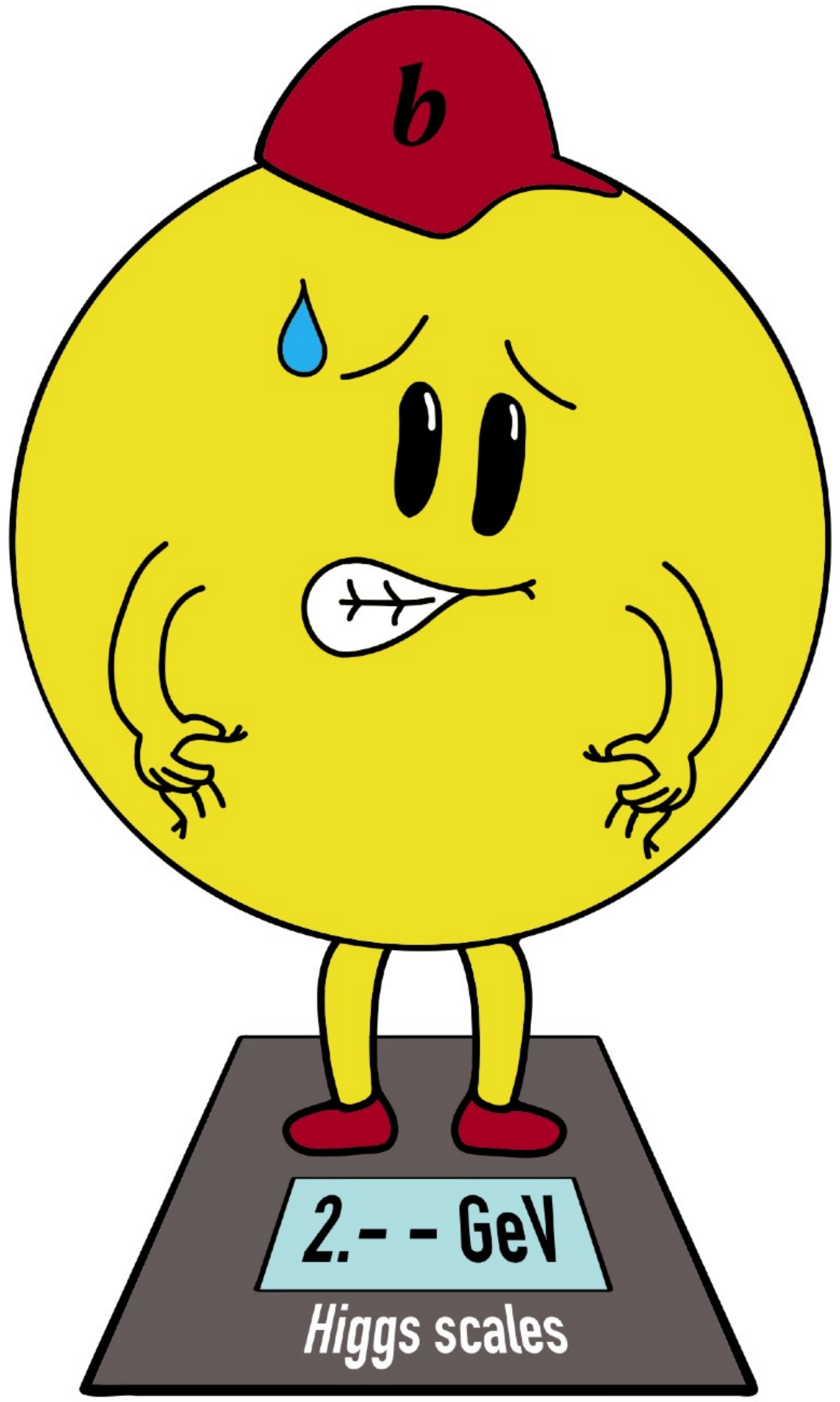
m_b at m_H from Higgs Decay

- Since discovering the **Higgs Boson**, the **LHC** has measured its coupling to SM particles with increasing precision. These measurements provide a **new way of measuring m_b at a high scale**, the one of the **Higgs boson mass m_H**.
- **Higgs decay to bottom quarks, $H \to b\bar{b}$**, is our lab for studying this measurement $m_b(m_H)$:

$$\Gamma(H \to f\bar{f}) = \frac{1}{32\pi}\frac{g^2 m_f^2}{m_W^2} N_C^f m_H \left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2}$$

  - At LO, **quadratic dependence on m_b** & **decoupled from α_s:**
  - **Precise predictions** available.
  - m_H represents the **characteristic dynamical scale of the process** (convergence of perturbative series)
- **First result of this method** (ATLAS+CMS data) on [3],

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



m_b at m_H from Higgs Decay

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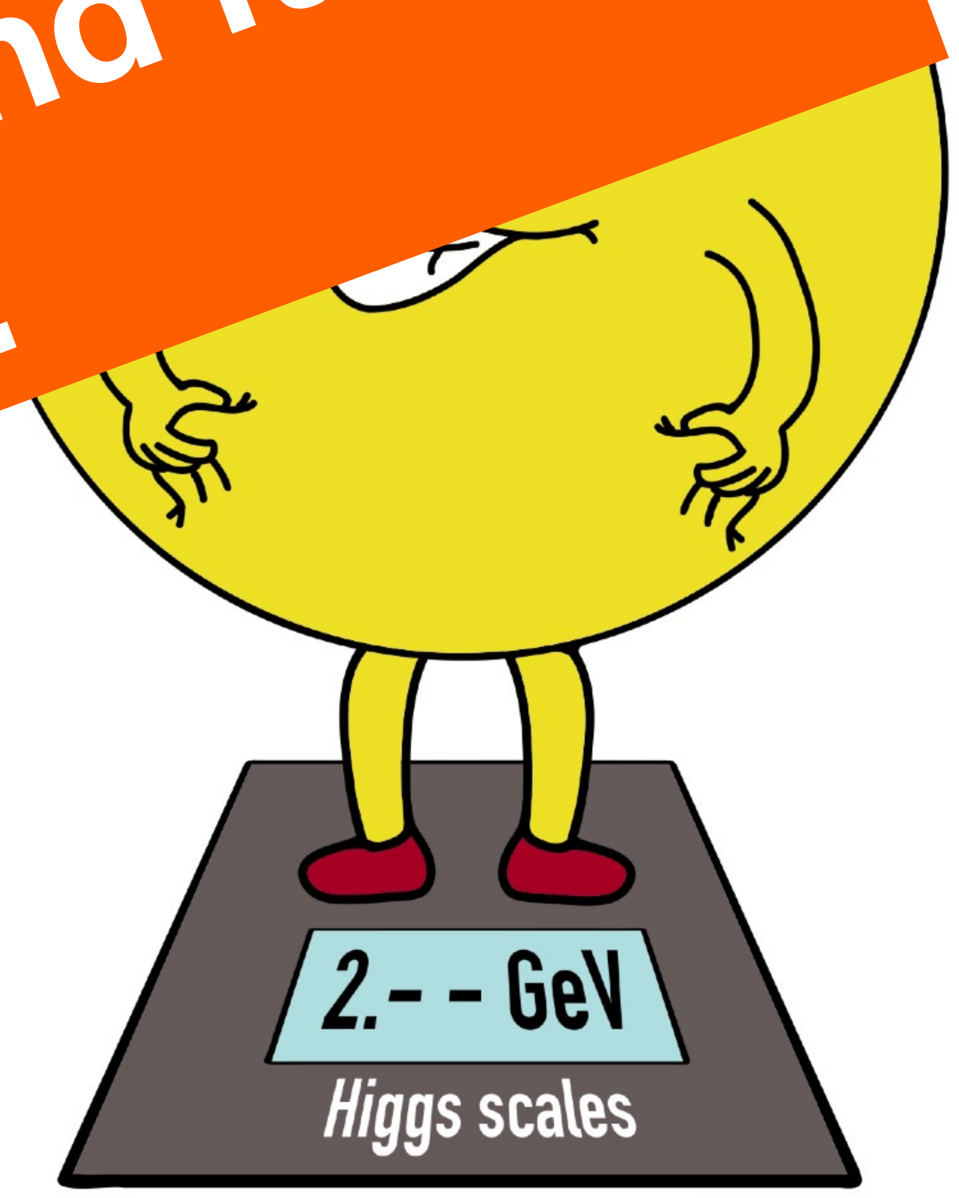
Updated results on $m_b(m_H)$ can turn the study on m_b running into a precise test of the SM & QCD, and future colliders can further enhance this potential !!!!



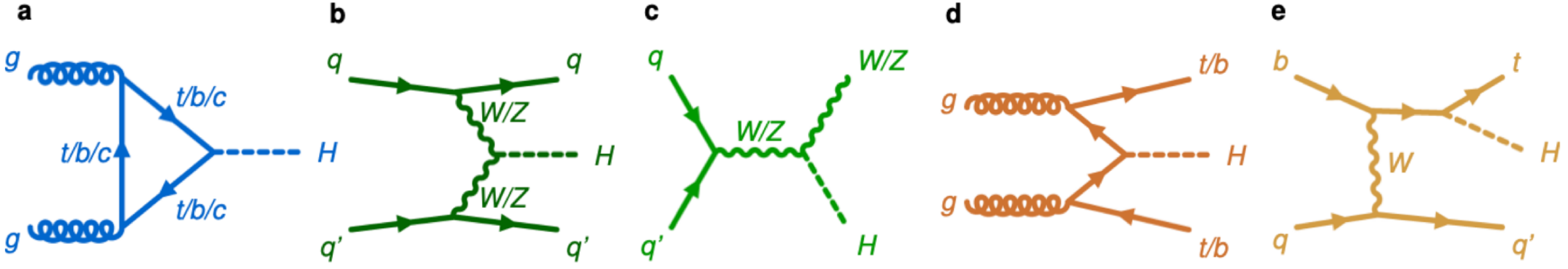
$m_b(m_H)$ measurement at LHC with updated ATLAS data

Input measurements

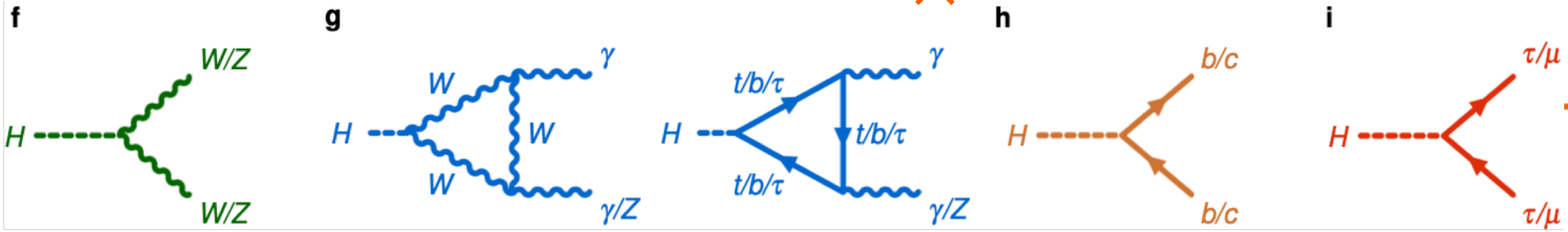
- **ATLAS-CONF-2025-006** [4]: Updated ATLAS measurements on Higgs boson at $\sqrt{s} = 13$ TeV and $L = 140$ fb^{-1}. **Combination** of production cross-sections σ_i and decay rates B_f, $\sigma_i \times B_f$, relative to their SM prediction, as well as the **full correlation matrix.**

σ_i :

a. ggF
b. VBF
c. VH (WH/ZH)
d. ttH/bbH
e. tH



$\times$



B_f :

f. $H \rightarrow WW/ZZ^*$
g. $H \rightarrow \gamma\gamma/\gamma Z$
h. $H \rightarrow bb/cc$
i. $H \rightarrow \tau\tau/\mu\mu$

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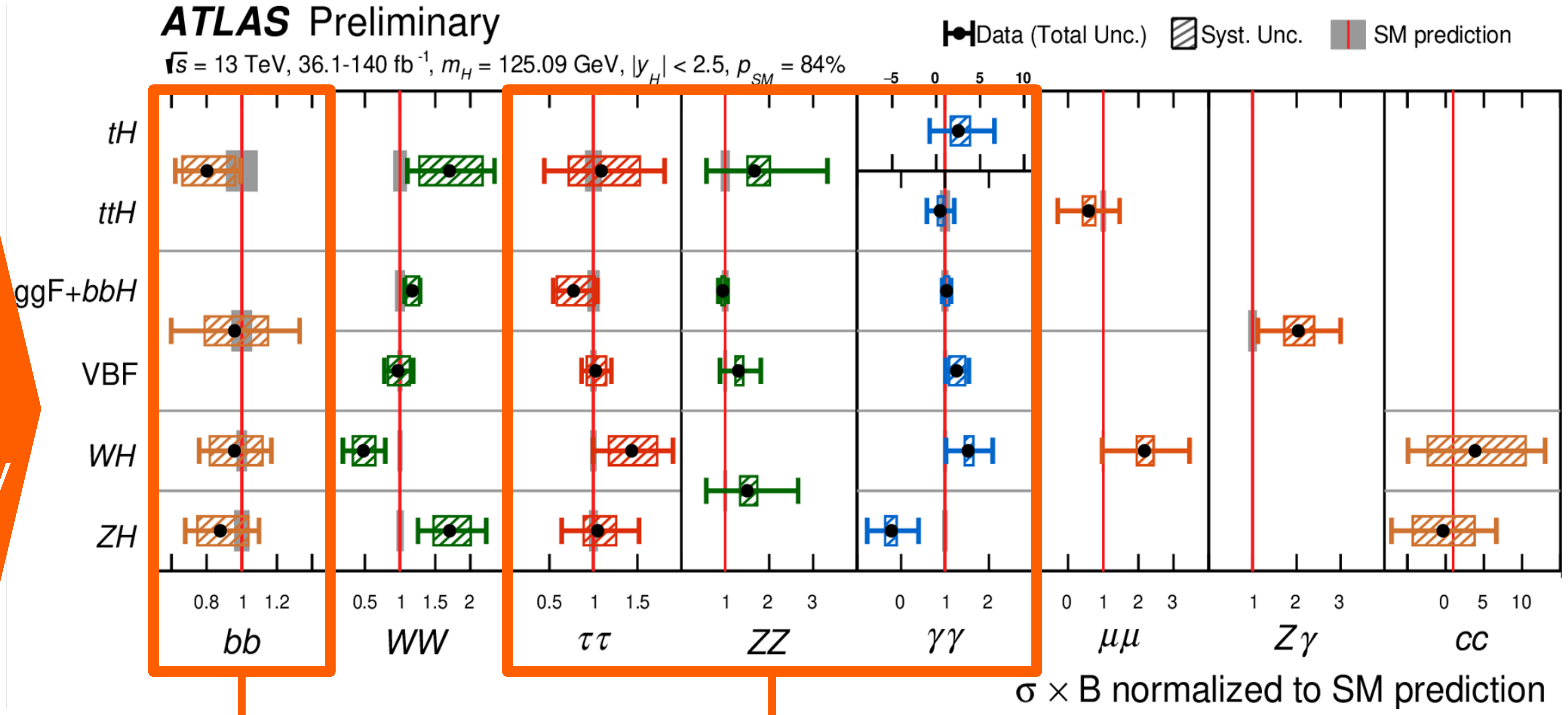
Each measurement targets **individual** production & decay processes



Relevant measurements used in this work

Decay mode	Prod. mode	Ratio to SM
$H \to bb$	ggF + bbH + VBF	1.0 ± 0.4
	WH	$0.96^{+0.21}_{-0.20}$
	ZH	$0.88^{+0.22}_{-0.20}$
	$ttH + tH$	$0.80^{+0.19}_{-0.18}$
$H \to \tau\tau$	ggF + bbH	$0.77^{+0.27}_{-0.23}$
	VBF	$1.03^{+0.18}_{-0.16}$
	WH	$1.4^{+0.5}_{-0.4}$
	ZH	$1.1^{+0.5}_{-0.4}$
	$ttH + tH$	$1.1^{+0.7}_{-0.6}$
$H \to ZZ^*$	ggF + bbH	$0.94^{+0.11}_{-0.10}$
	VBF	$1.3^{+0.5}_{-0.4}$
	VH	$1.5^{+1.2}_{-0.9}$
	$ttH + tH$	$1.7^{+1.7}_{-1.1}$
$H \to \gamma\gamma$	ggF + bbH	1.04 ± 0.10
	VBF	$1.26^{+0.28}_{-0.25}$
	WH	$1.5^{+0.6}_{-0.5}$
	ZH	-0.2 ± 0.6
	ttH	$0.89^{+0.32}_{-0.30}$
	tH	$2.5^{+4.0}_{-3.3}$

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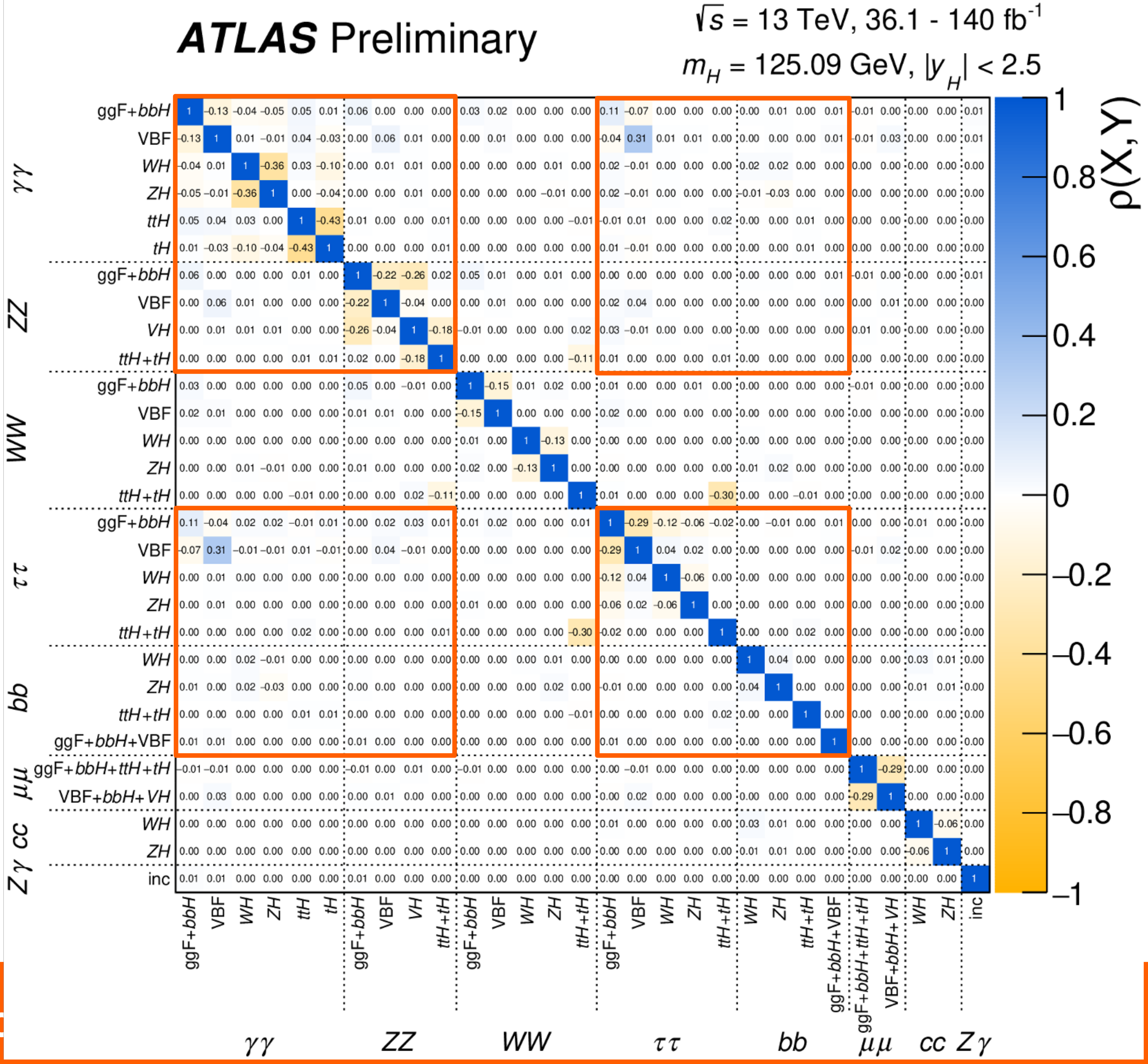
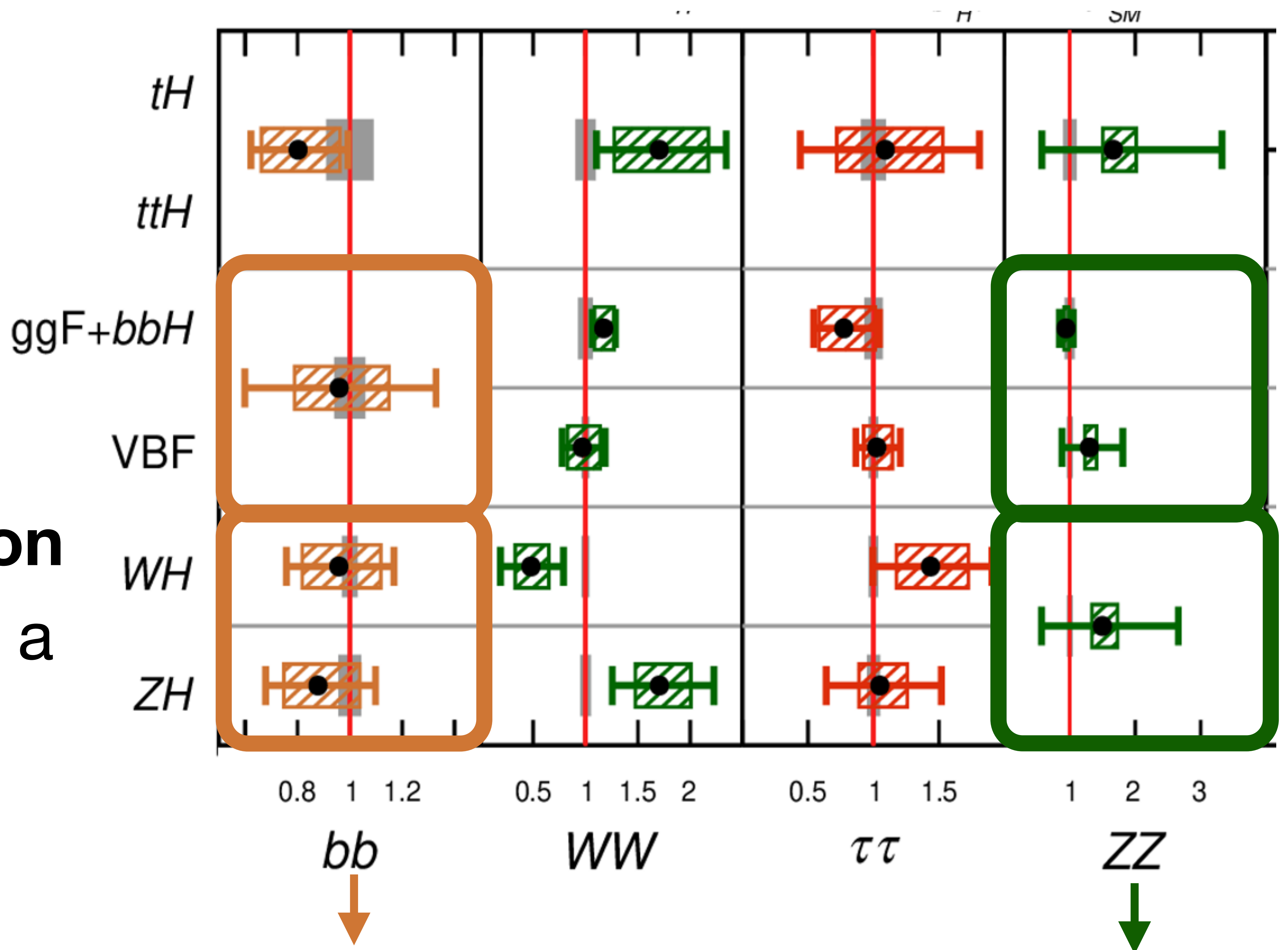


Extraction of $m_b(m_H)$ from decay rates

- The $m_b(m_H)$**-sensitive observables chosen** are ratios of decay rates normalized to SM predictions: $H \rightarrow bb$ divided by $H \rightarrow ZZ^*/\gamma\gamma/\tau\tau$, namely μ_{bb/ZZ^*} , $\mu_{bb/\gamma\gamma}$ and $\mu_{bb/\tau\tau}$ (Note that $(\sigma_i \times B_{bb})/(\sigma_i \times B_{XX}) = (B_{bb}/B_{XX})_i \equiv \mu_{bb/XX,\,i}$).
- These ratios are first **computed for each production channel** σ_i, $\mu_{bb/XX,\,i}$. Then, they are **combined** into a correlated weighted average to get a **single value** $\mu_{bb/XX}$. Combination done analytically & cross-checked with Convino [5].
- If the **decay rates** of a ratio **don't share the same** σ_i's, a **combination is performed beforehand**. Consider, for example, the ratio bb/ZZ:



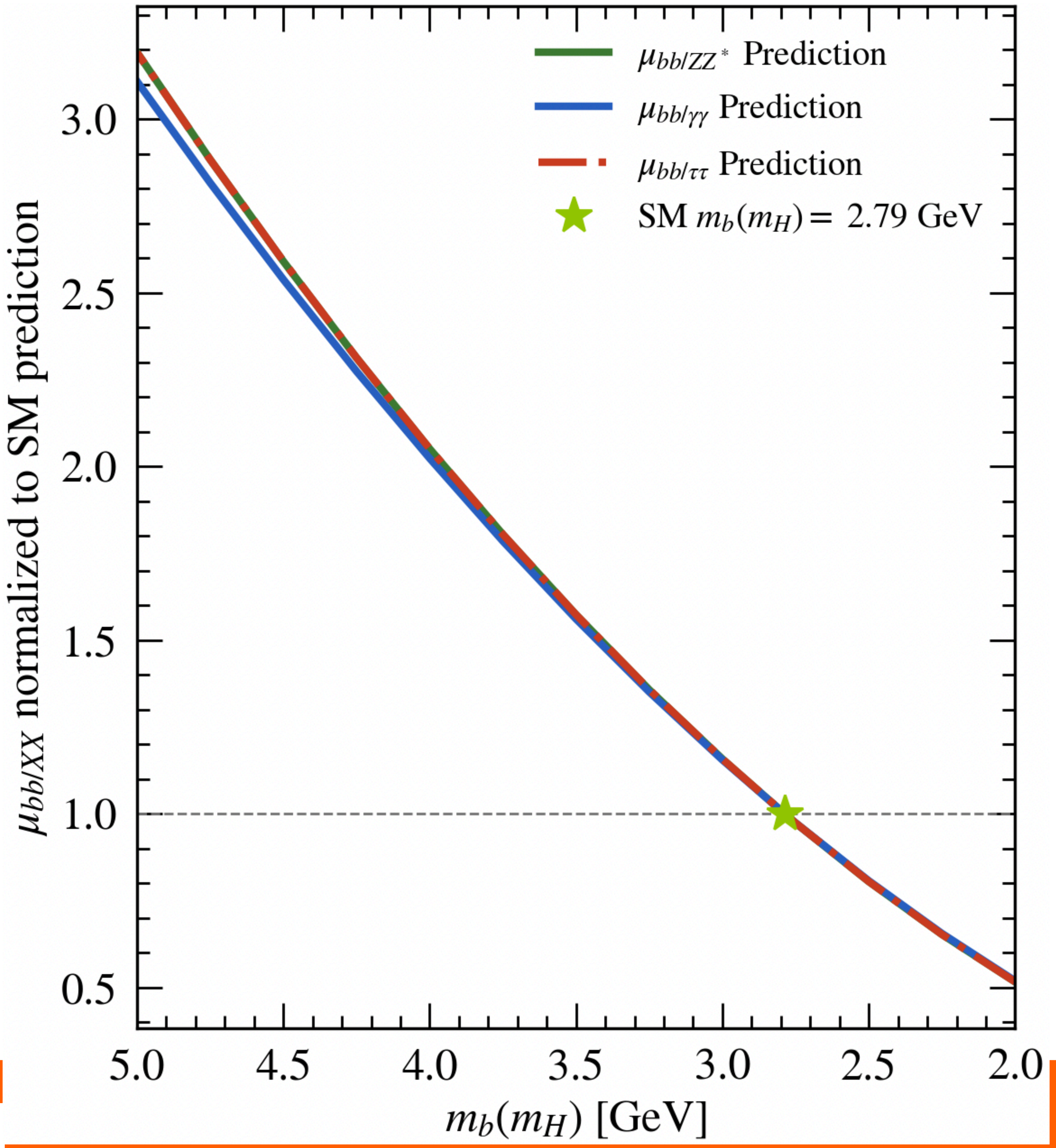
For **bb**, ggF+bbH and VBF are combined and WH and ZH are given independently

BUT

For **ZZ**, ggF+bbH and VBF are split, while WH and ZH are combined into VH

Extraction of $m_b(m_H)$ from decay rates

- Each measured $\mu_{bb/XX}$ is then fed to a **parametrization** of its **prediction** (obtained from **HDecay** [6]) as a **polynomial of** $m_b(m_H)$, $\mu_{bb/XX} = f(m_b(m_H))$, **giving a value for** $m_b(m_H)$**!**
- The masses **for each ratio** are **extracted independently** of each other. If they are found to be **compatible**, they are combined using a correlated weighted average to provide a **single, final value for** $m_b(m_H)$.



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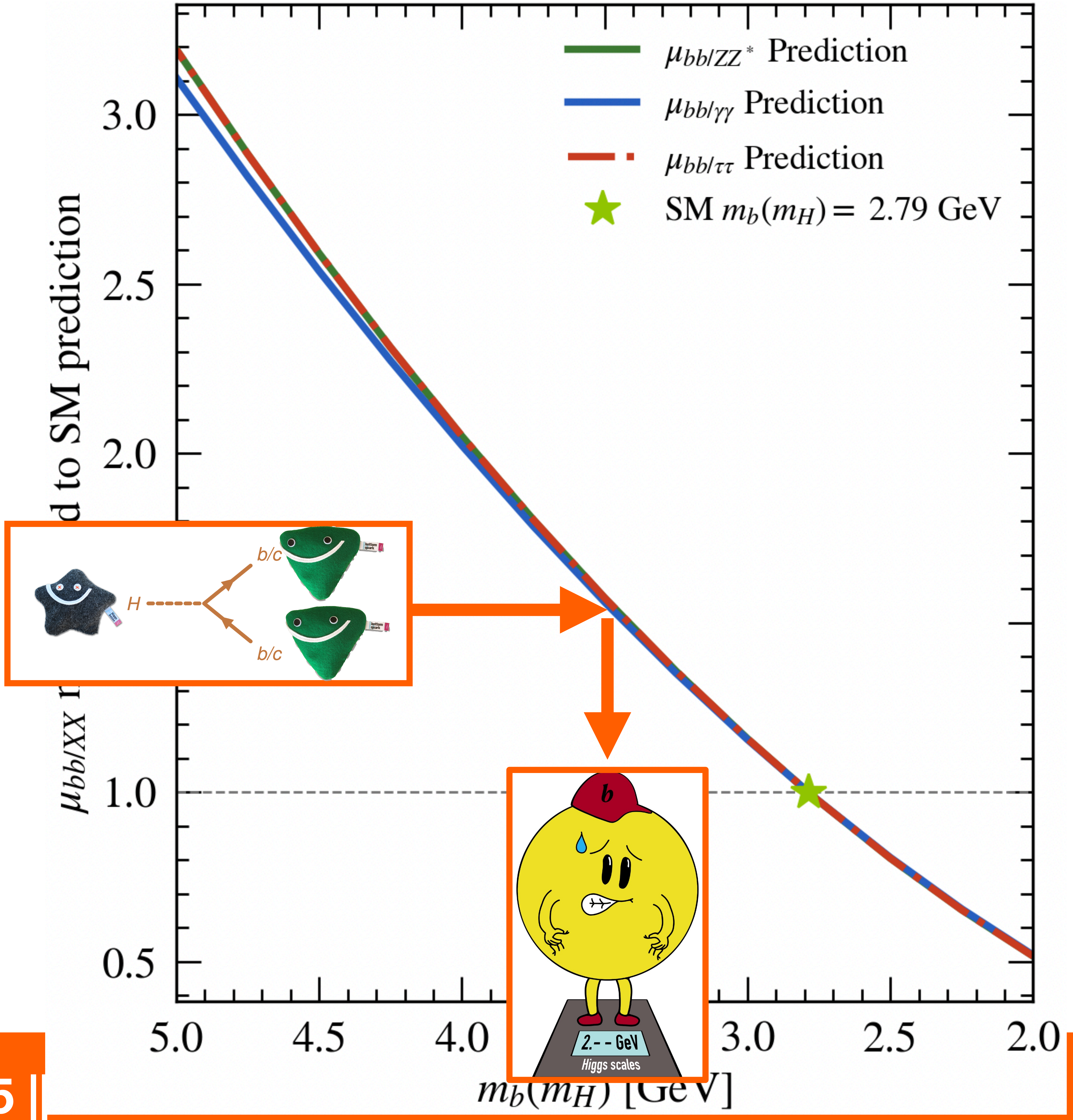


Prospects for future Linear Collider Facility (LCF)

The Linear Collider Facility (LCF) at CERN

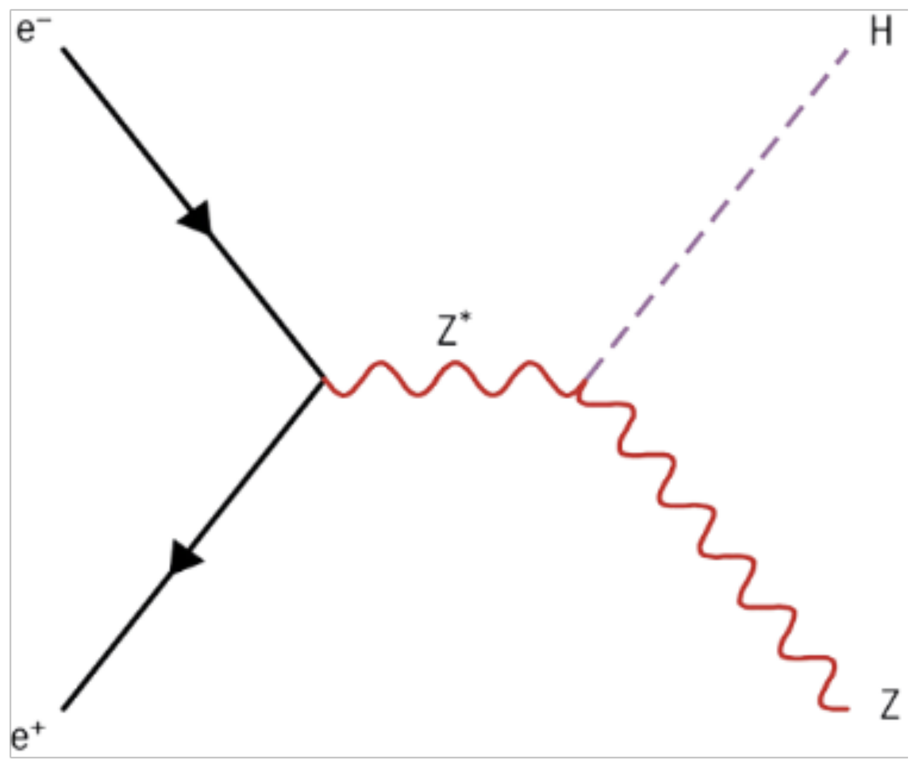
- 2020 update of the European Strategy for Particle Physics: "*An **electron-positron Higgs factory** is the **highest-priority** next collider*" [7]. Why?
  - Most of the open problems in particle physics stem from the Higgs sector of the SM, so ***"Many important opportunities remain for studies at higher precision with the potential to reveal the influence of new physics on the Higgs boson"***.
  - An e^+e^- **collider** is an **ideal** machine to perform these **precision measurements**: its different features **minimize systematic uncertainties** w.r.t. pp collisions, making it possible to **measure small deviations** from the SM with **high confidence and credibility**.
- The **LCF at CERN** implements the Higgs factory program with SuperConducting Radio Frequency Cavities. Its **baseline program** envisages operation at **two** $\sqrt{s}$ [7]:

Centre of Mass Energy →	$\sqrt{s}$ [GeV]	250	550
Integrated Luminosity →	$\int \mathcal{L}$ [ab^{-1}]	3	8
Beam Polarization →	$P(e^-)/P(e^+)$ [%]	80 / 30	80 / 60

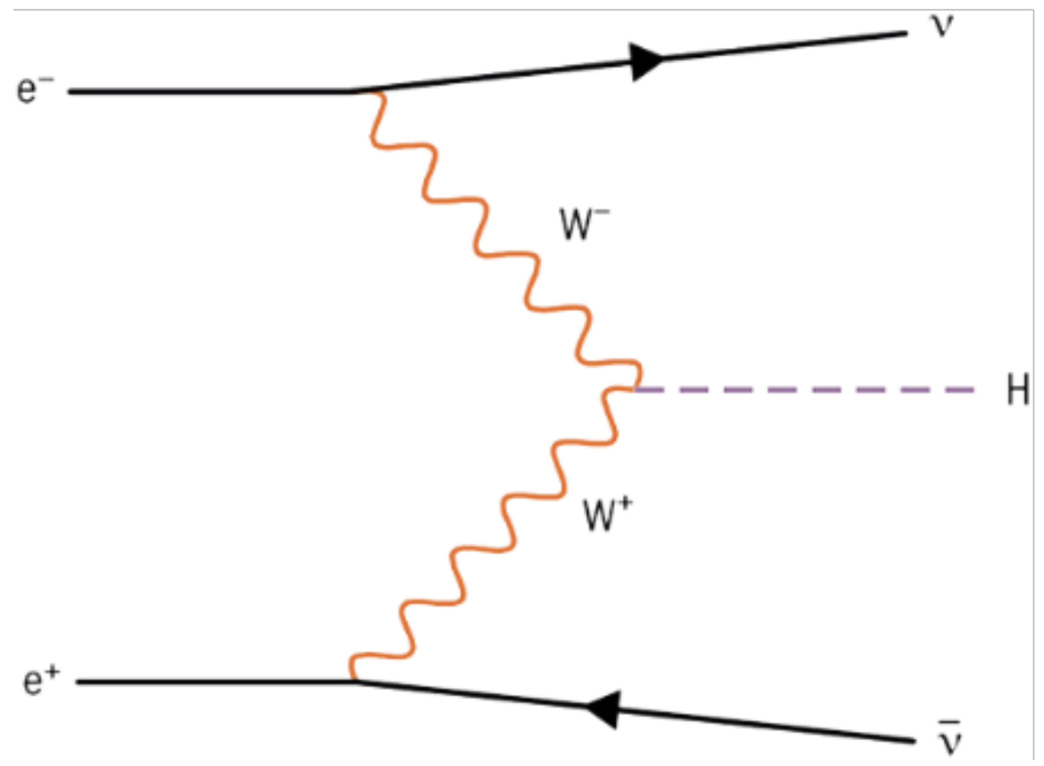
The two **operation points** are labelled as **LCF250** and **LCF550**

Higgs Boson couplings at the LCF

- Higgs couplings are expected to be **measured at the LCF with unprecedented precision** [7]:
  - $H \rightarrow bb/\tau\tau/cc$ projected to reach **sub-% relative precision**
  - $H \rightarrow WW^*/gg$ will reach **high precision** as well. However, $H \rightarrow ZZ^*$ **won't be that competitive** (smaller BR in comparison).
  - Rare decays like $H \rightarrow \gamma\gamma$ are also **limited by their small BRs** and won't be measured with the same precision as in the HL-LHC.
- **Best prospect** for $m_b(m_H)$ analysis: bb/WW^* **ratio**, expected to achieve **sub-% precision**:



$e^+e^- \rightarrow ZH$, dominant production mode for LCF250



WW fusion, dominant production mode for LCF550

Operation	Relative precision on $BR(H \rightarrow bb)/BR(H \rightarrow WW^*)$
LCF250	0.65 %
LCF550	0.38 %
LCF250+550	0.33 %

Preliminary predictions, kindly provided by Junping Tian (Tokyo U., ICEPP)

Results at LHC & future LCF

ATLAS 2025 Result

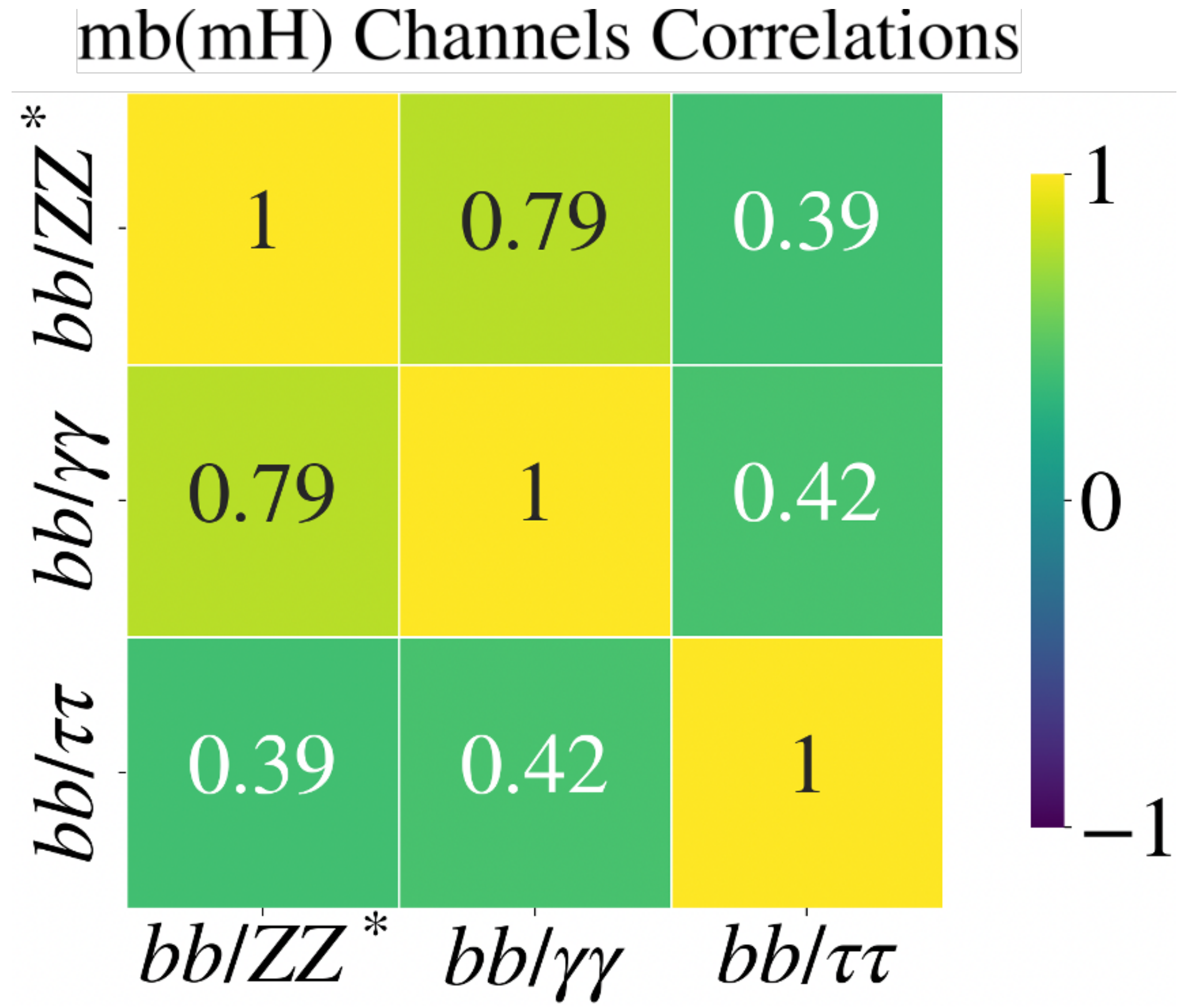
- **Independent extraction** of $m_b(m_H)$ for each ratio provides **compatible results: combination makes sense**!

Ratio	μ_{bb}/μ_{XX}	$m_b(m_H)$ [GeV]
bb/ZZ^*	$0.69^{+0.25}_{-0.20}$	$2.31^{+0.41}_{-0.32}$
$bb/\gamma\gamma$	$0.71^{+0.18}_{-0.16}$	$2.34^{+0.30}_{-0.26}$
$bb/\tau\tau$	$0.78^{+0.20}_{-0.17}$	$2.45^{+0.31}_{-0.26}$

- **Combination** of the $m_b(m_H)$ values (obtained with the simultaneous extraction of μ_{bb/ZZ^*}, $\mu_{bb/\gamma\gamma}$ and $\mu_{bb/\tau\tau}$), i.e. **OUR RESULT**:

$$m_b(m_H) = 2.38^{+0.24}_{-0.21}\ \mathrm{GeV}$$

- **Relative precision** of **~10%**, could **improve** with a combination with CMS.
- **Uncertainty reduced** w.r.t. PRL result by **33%**.
- **Uncertainty** from **parametrization of HDecay** predictions on **sub-% level**: **negligible**.



Correlation Matrix obtained from Convino [5].

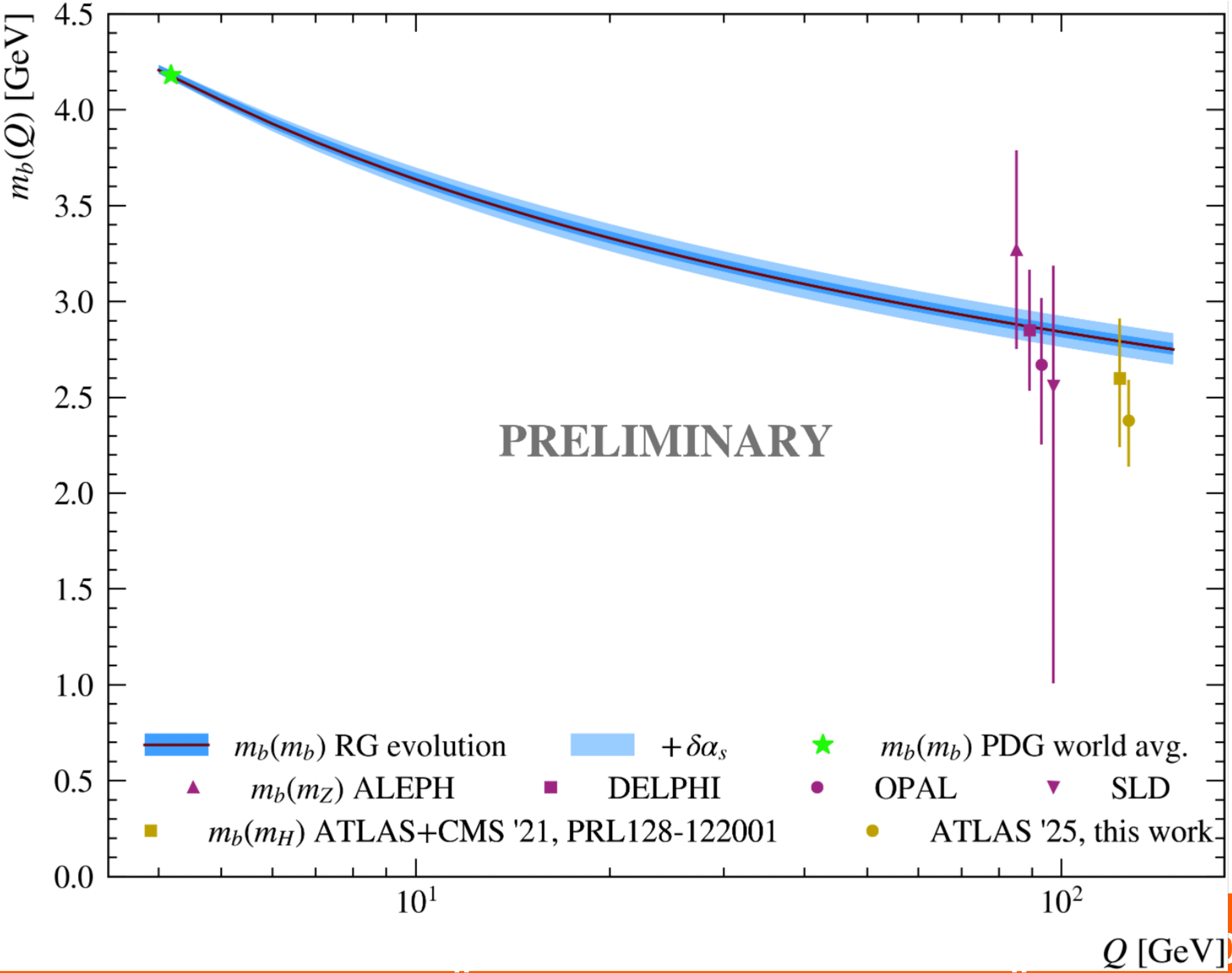
ATLAS 2025 Result

- **Combination** of the $m_b(m_H)$ values (obtained with the simultaneous extraction of μ_{bb/ZZ^*}, $\mu_{bb/\gamma\gamma}$ and $\mu_{bb/\tau\tau}$), i.e. **OUR RESULT**:

$$m_b(m_H) = 2.38\,^{+0.24}_{-0.21}\ \mathrm{GeV}$$ ± 0.03 GeV theo. unc.

- **Theoretical uncertainties** include:
  - Higher-Order QCD corrections (Scale variations) and EW corrections (estimated from Higgs Yellow Report [8]): **0.3% - 0.5%**
  - Parametric uncertainty from α_s [2]: $\Delta\alpha_s(m_Z) = 0.0009 \rightarrow$ **0.2%**
  - Parametric uncertainty from m_H [9]: $\Delta m_H = 0.11$ GeV $\rightarrow$ **1.4%** **Leading**, but **reduced over 1/2 w.r.t. PRL**
- Taking a **conservative** approach, **uncertainties** are **added up linearly**. These uncertainties were estimated for bb/ZZ^* originally in Ref. [3], but for this work they are considered for the full combination (following the conservative line).

Running of the bottom quark mass



- Testing the running hypothesis following parametrization from [3]:

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

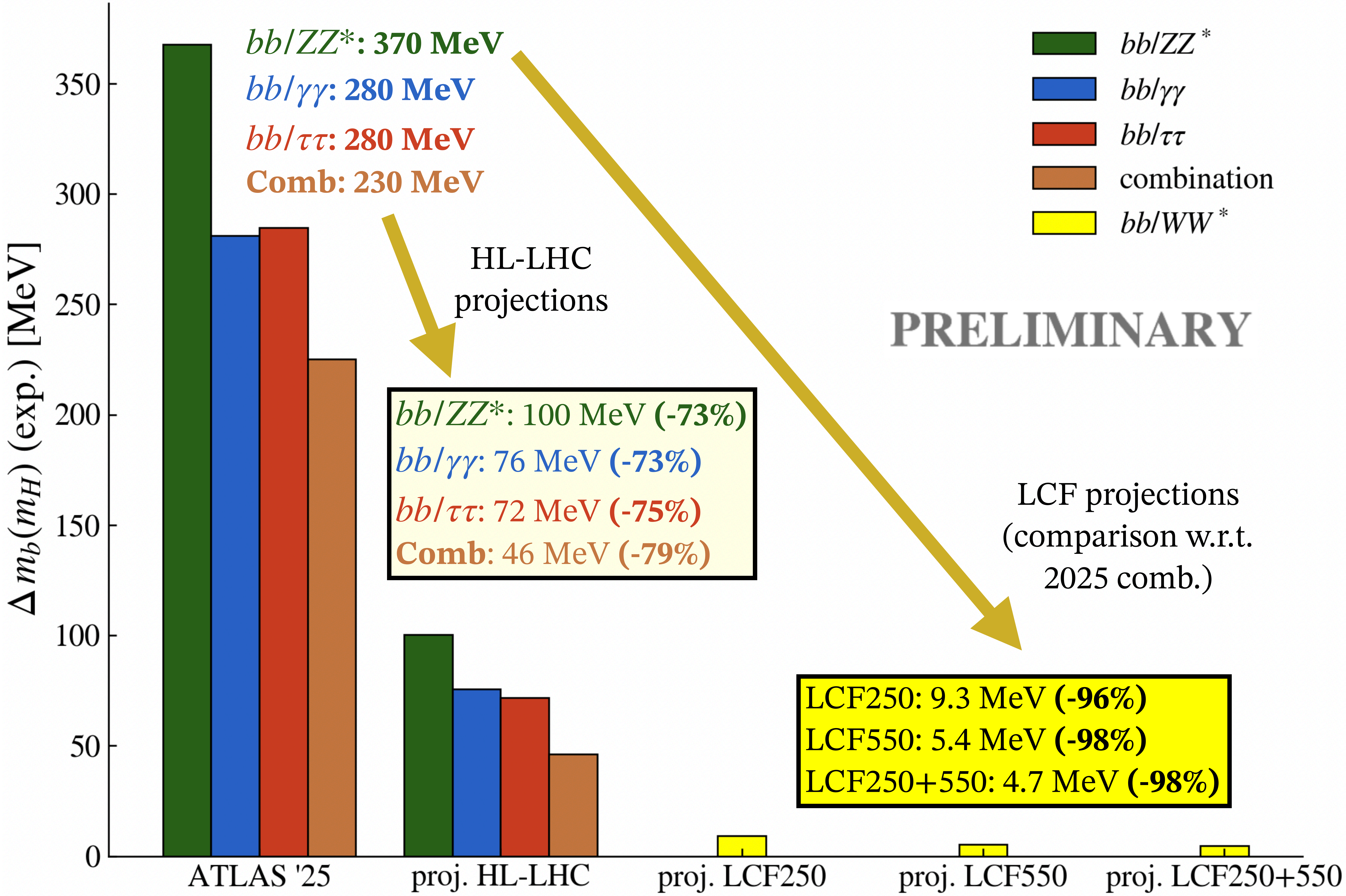
- $x = 0$ is no running; $x = 1$ is SM.
- Fitting the experimental points give

$$x = 1.20 \pm 0.13\,(\mathrm{exp}) \pm 0.05\,(\alpha_s)$$

- $> 9\sigma$ deviation with no running
- Compatible with SM within 1.5σ

Projected uncertainties for LCF & HL-LHC

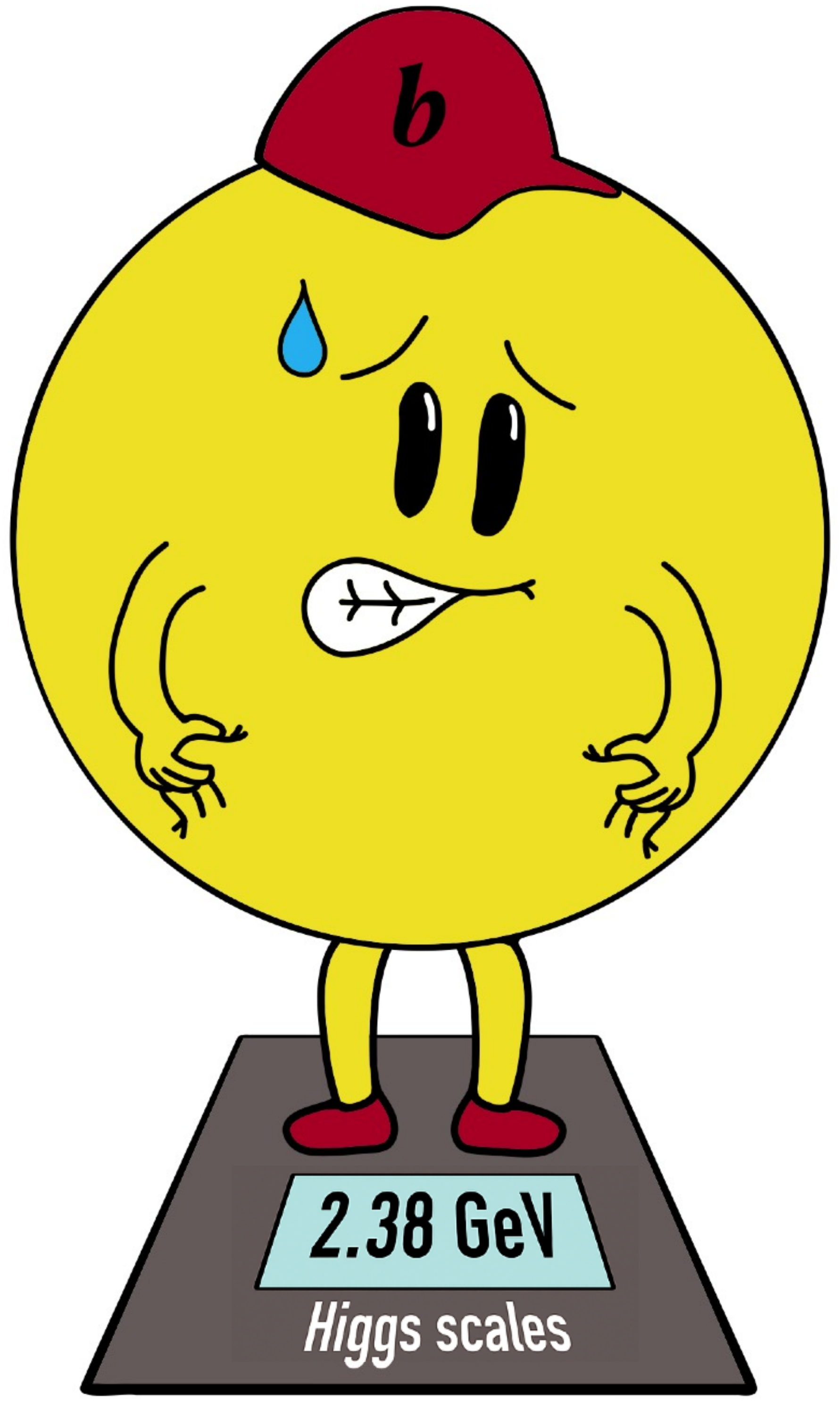
- Projected **theo. uncertainties** [10]:
  - 10 MeV uncertainty on $m_b(m_b)$
  - 0.5% relative precision on $\alpha_s(m_Z)$
- **HL-LHC projections** (preliminarily) estimated by scaling the ATLAS ’25 exp. uncs. with the integrated lumi L as $1/\sqrt{L}$ (Scenario 2, with $L = 3$ ab^{-1} for HL-LHC).
- **LCF projections** come from bb/WW^* ratio precisions.



Conclusion & outlook

Conclusion & Outlook

- **Scale evolution** of QCD parameters is **experimentally testable.**
- **Updated measurement** of bottom quark mass at high scale → $m_b(m_H) = 2.38^{+0.24}_{-0.21}$ GeV
  - Full Correlation matrix allows to **significantly decrease uncertainty** (**33%**) via **combination.**
  - Provides **proof for running of quark masses**; **no running ruled out by 9σ**.
- **Future Colliders** have a **high potential for improvement**, particularly **Linear** Facilities: **experimental uncs. projected to reach the level of today's theoretical ones!**
- **Near Future:**
  - **Integrate within ATLAS** analysis groups to further develop & refine the measurement
  - Address the **elephant in the room**: we inevitably **assume SM for Higgs decays**
    - Simultaneous measurement of b-Yukawa & m_b
    - Design scenarios for different effects of new physics
  - **Refine the prediction for LCF**, reproduce "covariance matrix treatment" (Junping Tian & Jorge De Blas).



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[8]: D. de Florian *et al*. (LHC Higgs Cross Section Working Group), 2/2017 (2016), 10.23731/CYRM-2017- 002, arXiv:1610.07922 [hep-ph].

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[10] J. Aparisi et al., arXiv: 2203.16994 [hep-ex]

Backup

Backup: Extraction of $m_b(m_b)$ & $m_b(m_Z)$

- Most precise **measurements of $m_b(m_b)$** combine:
  - Experimental input from mass of bottomium bound states & $e^+e^- \to$ hadrons xsec.
  - QCD sum rules & perturbative QCD computations. Also lattice QCD groups involved, achieving 0.3% precision.
  - Realistic future predictions assume that the total uncertainty can go below 10 MeV [10].
- A method for the **extraction of $m_b(m_Z)$** was developed at LEP and SLC relying on the sensitivity to subleading mass effects on the **three-jet rates**.
  - Measurements done by DELPHI using LEP data, and by ALEPH, OPAL & DELPHI with SLD data.
  - Precision can be improved in future e^+e^- colliders. Also, the method can also be used to **extend the running analysis** to higher energies (probe effects of colored states with masses above m_H): at 250 GeV, expected precision of 1 GeV [10].

Backup: Measurements of $m_b(m_Z)$

TABLE I. Measurements of the bottom-quark $\overline{\text{MS}}$ mass at the renormalization scale $\mu = m_Z$, from three-jet rates with bottom quarks in e^+e^- collisions at the Z-pole at LEP and SLD. For ALEPH and DELPHI the hadronization uncertainty is added in quadrature with the experimental uncertainty to yield the total systematic uncertainty.

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.)

From [3].

The result

$$m_b(m_Z) = 2.82 \pm 0.28\ \text{GeV}$$

used in this work is obtained with the **Convino** method [5], propagating the reported asymmetric uncs. and taking into account correlations:

- Theo. uncs. assumed to be 100% correlated (same prediction)
- Exp. uncs. assumed to be 50% correlated (hadronization unc.)

Backup: Identifying natural energy scale for Higgs decay

- The point can be illustrated by considering the **convergence of the perturbative series** [3]. When taking $\mu = m_H$ as the renormalization scale for both m_b and α_s, the leading QCD correction series for $H \to b\bar{b}$ when expanding in m_b^2/m_H^2 takes the form:

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

- However, when taking $\mu = m_b$ the convergence is much poorer and presents large perturbative uncertainties due to logarithmic uncertainties $\ln(m_H/m_b)$, which are otherwise resumed to all orders in $\mu = m_H$:

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

- Renormalization scales can also be chosen independently for m_b and α_s. However, the **best results** for the convergence are obtained when **both scales** are in the **order of m_H.**

Backup: A brief history of $m_b(m_H)$

- **First measurement** from [3] relied on ATLAS & CMS analyses that **directly provided the ratio** B_{bb}/B_{ZZ^*}; $m_b(m_H)$ was computed for **this ratio only**.
- When ATLAS published the "**Higgs 10th anniversary**" (*Nature 607 (2022) 52-59 & 60-68*), with partial Run2 data, the measurement of the ratio was no longer made public. However, the **full set of** $\sigma_i \times B_f$ **measurements**, together with the corresponding **covariance matrix**, were provided. From this new input, an update on $m_b(m_H)$ was made (unpublished work by M. Vos, B. Moser & V. Dao), following the methodology described in this talk, considering other ratios rather than bb/ZZ^* only:
- **This work** represents an update on the Nature paper result, using the same methodology for extracting the masses but with Legacy Run2 data, with the new addition of **combining the masses** from the different ratios.

Backup: A brief history of $m_b(m_H)$

Experiment	Input	Ratio	mb(mH) [GeV]
ATLAS + CMS, partial Run2	Direct ratio	bb/ZZ	2.60 +0.36 -0.31
ATLAS, partial Run2	Full σ x B covariance matrix	bb/ZZ	2.55 +0.29 -0.32
		bb/$\gamma\gamma$	2.52 +0.25 -0.28
ATLAS, Legacy Run2	Full σ x B covariance matrix	bb/ZZ	2.31 +0.41 -0.32
		bb/$\gamma\gamma$	2.34 +0.30 -0.26
		bb/$\tau\tau$	2.45 +0.31 -0.26
		bb/ZZ & bb/$\gamma\gamma$ & bb/$\tau\tau$	2.38 +0.24 -0.21

Backup: ATLAS '25 update vs Nature

Table 1: Input analyses to the combination with their integrated luminosity ($\mathcal{L}$), reference to the original publication and STXS granularity. Analyses initially reporting results corresponding to a Run 2 integrated luminosity of 139 fb^{-1} are rescaled to the updated 140 fb^{-1} value for the combination. In the last column, *New analysis* denotes analyses not present in the combination reported in Ref. [3]; *Full Run 2* refers to analyses that used a partial Run 2 dataset and have been updated to the full dataset; and *Reanalysis* to cases where an improved analysis of the full Run 2 dataset is used.

Analysis	Prod. modes	$\mathcal{L}$ (fb^{-1})	Reference	STXS stage	Improvements relative to Ref. [3]
$H \to ZZ^* \to 4\ell$	All	140	[19]	1.2	-
$H \to WW^* \to \ell\nu\ell\nu$	ggF,VBF	140	[20]	0	Reanalysis
$H \to WW^* \to \ell\nu\ell\nu$	VH	140	[21]	1.2	Full Run 2
$H \to \gamma\gamma$	All	140	[22]	1.2	-
$H \to Z\gamma$	All	140	[23]	0	-
$H \to \tau\tau$	All	140	[24]	1.2	Reanalysis
$H \to \tau\tau$	VH	140	[25]	0	New analysis
$H \to \mu\mu$	All	140	[26]	0	-
$H \to bb$	VBF	126	[5]	1.2	-
$H \to bb, cc$	VH	140	[27]	1.2	Reanalysis
$H \to$ multileptons	ttH	36.1	[4]	0	-
$H \to bb$	ttH	140	[28]	1.2	Reanalysis

- Summary of the updates in the 2025 ATLAS CONF note with respect to the Higgs' 10th anniversary combination. Taken from [4].

Backup: Combination of production channels for Branching function's ratios

- **Perform the bb/XX ratio for each production channel, so that $(\sigma_i \times B_{bb})/(\sigma_i \times B_{XX}) = (B_{bb}/B_{XX})_i \equiv \mu_{bb/XX,\,i}$. Then, combine all of the $\mu_{bb/XX,\,i}$ into a single $\mu_{bb/XX}$ by performing a correlated weighted average.**
- Considering these ratios allow us to **discard production**, and any assumption related to it i.e. **we don't consider any particular model for σ**!
- However, note that for this methodology to work, σ_i must be the same for both decay rates; in other words, **the two decays must share the same production channels.**
- **This is not always the case**, as some production channels can be split in two different analyses for some decay rate, while for a different rate they might be combined into a single analysis due to statistical limitations.
- Therefore, before performing the ratios, a **previous combination** is due.

Backup: Combination of production channels for Branching function's ratios

- **Logic behind the previous combination**: the absolute measurements (not SM-normalized) can be added directly because they are measured as Number of events, so $N_{A+B} = N_A + N_B$. For the signal strengths (measurements normalized to SM), this turns into a "weighted average" with the SM production predictions as weights:

$$\mu^{\sigma_{A+B}}_{BR_X} = \frac{(\sigma_A^{SM} \times BR_X^{SM})\,\mu^{\sigma_A}_{BR_X} + (\sigma_B^{SM} \times BR_X^{SM})\,\mu^{\sigma_B}_{BR_X}}{\sigma_A^{SM} \times BR_X^{SM} + \sigma_B^{SM} \times BR_X^{SM}} = \frac{\sigma_A^{SM}\,\mu^{\sigma_A}_{BR_X} + \sigma_B^{SM}\,\mu^{\sigma_B}_{BR_X}}{\sigma_A^{SM} + \sigma_B^{SM}}$$

- Production predictions are taken from YR [8], for $\sqrt{s} = 13$ TeV & $m_H = 125.09$ GeV:

Production Mode	Cross-Section [fb]
ggF	48 510
VBF	4 006
WH	1 370.00
ZH	882.10
ttH	506.5
tH	74.26
bbH	486.30

Backup: Combination of production channels for Branching function's ratios

- **What channels do we combine for each ratio?** We distinguish between the individual/independent extraction of the ratios & the simultaneous one performed to ultimately extract the combined value for $m_b(m_H)$. For the latter, we impose that the four involved decay rates share the same production channels:

Ratio	**Common σ's**	**Channels to combine**
bb/ZZ, indep.	ttH+tH // (ggF + bbH)+VBF // VH	WH & ZH, [bb] (ggF+bbH) & VBF, [ZZ]
bb/$\gamma\gamma$, indep.	ttH+tH // (ggF + bbH)+VBF // WH // ZH	ttH & tH, [$\gamma\gamma$] (ggF+bbH) & VBF, [$\gamma\gamma$]
bb/$\tau\tau$, indep.	ttH+tH // (ggF + bbH)+VBF // WH // ZH	(ggF+bbH) & VBF, [$\tau\tau$]
bb/ZZ, bb/$\gamma\gamma$, bb/$\tau\tau$, sim.	ttH+tH // (ggF + bbH)+VBF // VH	WH & ZH, [bb, $\gamma\gamma$, $\tau\tau$] (ggF+bbH) & VBF, [ZZ, $\gamma\gamma$, $\tau\tau$] ttH & tH, [$\gamma\gamma$]

Backup: Correlation treatment

- Starting from the **ATLAS full Covariance matrix** and the **reported uncertainties** as input, we apply the **standard formalism of uncertainty propagation** in the case of multiple, multi-variable functions, **all the way to the final** $m_b(m_H)$:
  - Have a set of <u>N variables</u> $x_i\,,\ \ i = 1, 2\ldots, N$, with <u>uncertainties</u> $\{\sigma_i\}$ that are correlated according to the <u>correlations</u>, $\rho_{ij} = \sigma_{ij}/(\sigma_i\,\sigma_j)$ where σ_{ij} is the <u>covariance</u> b/w the variables x_i and x_j, and it holds that $\sigma_{ii} = \sigma_i^2$.
  - Then, if we define a series of <u>M functions</u> $f_k(x_i)\,,\ \ k = 1, 2\ldots, M$ that <u>depend on the variables</u> x_i, we can compute their <u>covariances</u> (and thus their <u>correlations</u> and <u>uncertainties</u> by using identical definitions as the ones for x_i) as:

$$\{\mathcal{V}[x]\}_{ij} = \sigma_{ij}(x)$$

Covariance matrix of the variables

$$\boxed{\mathcal{V}[f] = \mathcal{S}^T\,\mathcal{V}[x]\,\mathcal{S}}$$

$$\{\mathcal{V}[f]\}_{ij} = \sigma_{ij}(f)$$

Covariance matrix of the functions

$$\{\mathcal{S}\}_{ij} = \frac{\partial f_j}{\partial x_i}$$

Columns (j): functions

Rows (i): variables

Matrix of derivatives

Backup: Correlated weighted average

- For the combination of correlated measurements (either the ratios per prod. chan. or the final $m_b(m_H)$), we perform a **correlated weighted average**, following the analytical formulae:
  - For asymmetric uncertainties, we would have 2 covariance matrices, C^+ & C^-, from which we define a symmetric covariance matrix (and from that the correlation matrix) C.
  - With these 3 matrices, and the set of measurements $\{x_i\}$ to be combined, the **weighted average** x_{avg} and its **uncertainty** (both up and down, $\sigma_{avg,\pm}$) are defined as

$$C_{ij} = \frac{C^+_{ij} + C^-_{ij}}{2}$$

$$x_{avg} = \frac{1}{\sum_{p=1}^{N}\sum_{q=1}^{N}(C^{-1})_{pq}} \left\{ \sum_{i=1}^{N} x_i \left[\sum_{j=1}^{N} (C^{-1})_{ij} \right] \right\}$$

$$\sigma^2_{avg,\pm} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} \left\{ \left[\sum_{s=1}^{N} (C^{-1})_{si} \right] \left[\sum_{r=1}^{N} (C^{-1})_{rj} \right] (C^{\pm})_{ij} \right\}}{\left(\sum_{p=1}^{N}\sum_{q=1}^{N} (C^{-1})_{pq} \right)^2}$$

Backup: Correlated weighted average

- The correlated combinations are **cross-checked with Convino** [5], *specifically developed to perform combinations* based on a method that only takes into account the *central values and their covariance* → a χ^2 **minimization**, where each measurement result and stat. unc. contribute to the χ^2, following either a *Neyman* or *Pearson* χ^2 definition:
  - <u>Neyman</u>: the uncertainty is fixed for each measurement. According to Kieseler, this is better suited to compute a single quantity
  - <u>Pearson</u>: the uncertainty is scaled with the combined value. According to Kieseler, this works best when measuring different quantities.
  - For more details on this, we refer to the documentation.

Backup: Correlated weighted average

- Since Convino asks for only one covariance/correlation matrix as input, the technical computation is done 3 times for each computation: one with C as input (to get the nominal result), and two for C^{+}/C^{-} (to get up and down uncertainties & covariances).
- The **Neyman definition reproduces the same central value** as the analytical formulae (up to the precision that the Convino results are given), for both the combination of ratios & of the final masses, while the results from Pearson diverge more → **we take the "analytical"/Neyman result as the nominal**, and keep Pearson's as an alternative.
- **NOTE**: **Convino** is **critical** to perform the **simultaneous combination** of the different ratios by production channel into the final single values for each of the 3 ratios, since it is (as of now) the **only way that we have to produce the correlation/covariance matrix between multiple correlated weighted averages**.

Backup: e^+e^- colliders as Higgs factories

An e^+e^- collider is the ideal machine for precision measurements. Because electron and positrons are elementary particles, their reactions are simple and display the structure of the underlying interactions directly. Backgrounds are dominated by electroweak processes, and these are also simple and — more importantly — precisely understood at the part-per-mil level. The low event rates relative to proton collisions allow the construction of low-material-budget, high-precision detectors and of trigger-less data taking. All of these features minimize systematic uncertainties. This makes it possible to measure small deviations from the SM with high confidence and credibility.

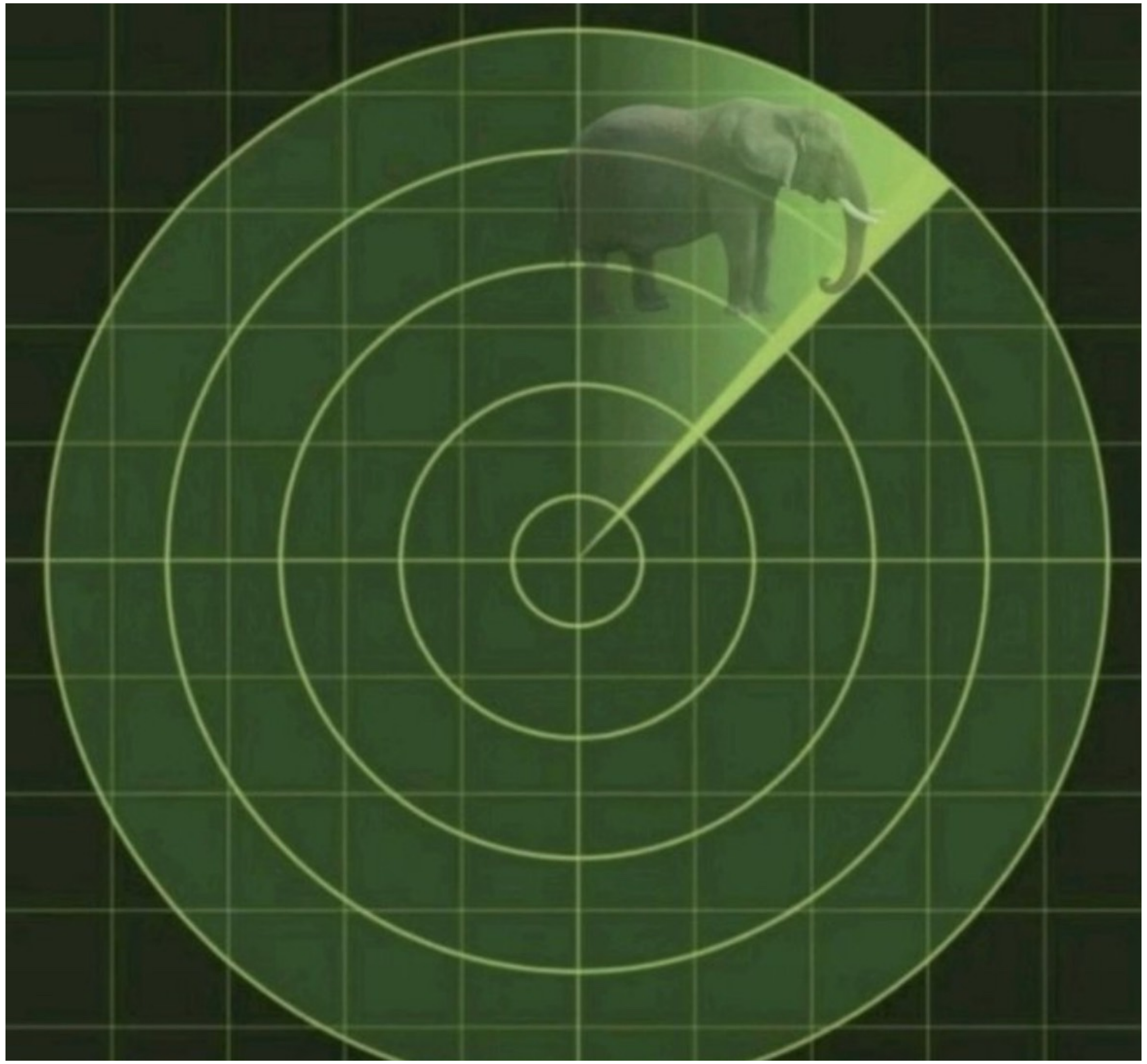
The choice of a linear e^+e^- collider redoubles these advantages. Electroweak physics is intrinsically chiral, with, for example, the left- and right-handed electron giving different information. Linear colliders will have high beam polarisation to take advantage of the new observables that this produces. Higgs bosons are produced in a number of different reactions that complement one another, as is well appreciated at the LHC. Because linear collider designs have luminosities that increase with the centre-of-mass energy, they can study directly not only the reaction $e^+e^- \to ZH$ that is most important at low energies but also WW fusion, reactions involving the top quark Yukawa coupling, multiple reactions with Higgs boson pair production, and at the highest energies even constrain triple-production of Higgs bosons. They can also carry out a program of precision measurements on

Extracted from [7].

Linear colliders thus provide a large number of distinct observables covering the full range of interactions of the Higgs boson and its closest relatives in the SM. These observables will be crucial to discover deviations from the SM through precision measurement, and also to re-discover it in a variety of processes. This program

Backup: New physics effects on $m_b(m_H)$

- **Elephant in the room**: we are assuming SM for the Branching ratios.
- Ideally, we would like to implement a **simultaneous measurement** of bottom quark Yukawa coupling y_b (from Higgs decays) and m_b (radiation from b-quark gluons, similarly to how $m_b(m_Z)$ is measured).
- In touch with theorists on how to implement this (Germán Rodrigo, Pier Paolo Giardino).
- Alternatively, we would try to test some **scenarios to quantify the effect of new physics** in the measurement.



Backup: New physics effects on $m_b(m_H)$

1. **Best-case scenarios** 😇: New physics that only affect production, to show that the measurement isn't influenced by this.
2. **Not-so-great scenarios** ☹️: The branching ratios get affected. This way, we would expect different results for $m_b(m_H)$ on each different ratio bb/XX.
3. **Worst-case scenario (for us)** 💀: The only thing that changes is y_b, and nothing else. In this case, the only clue for this that we can expect is $m_b(m_H)$ failing to align with $m_b(m_b)$ and $m_b(m_Z)$ in the RG evolution.