Reflections on

~~Vision for~~ using the Higgs

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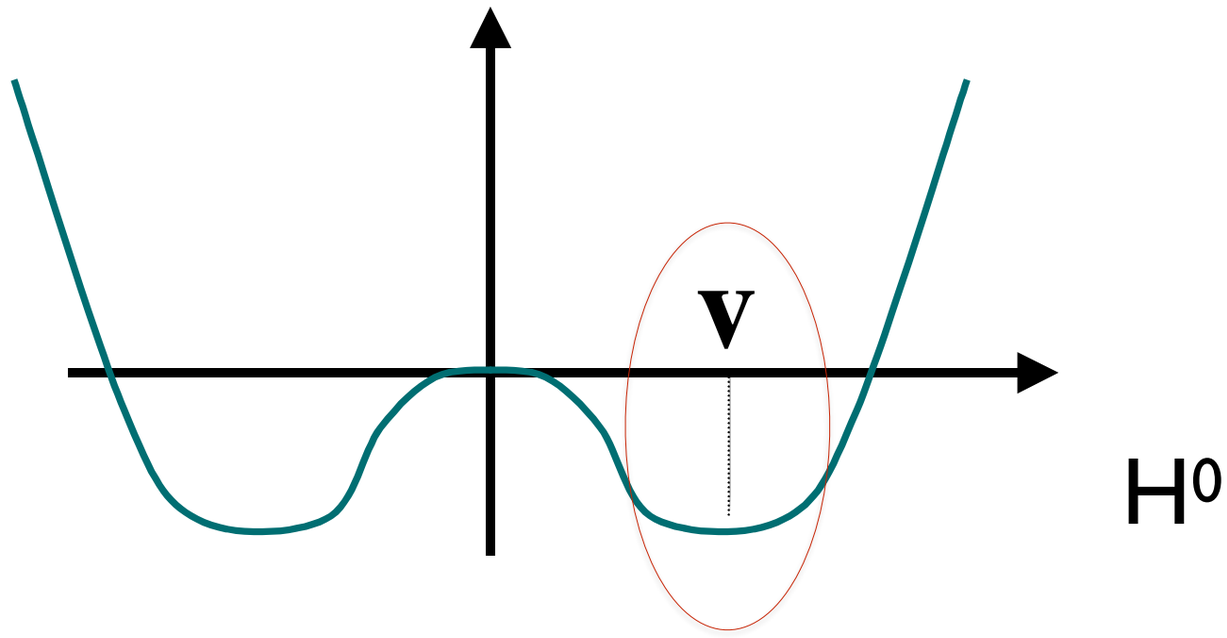
The main “use” of the Higgs?

To answer this question:



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

What sets the values of μ and λ?

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object

- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking

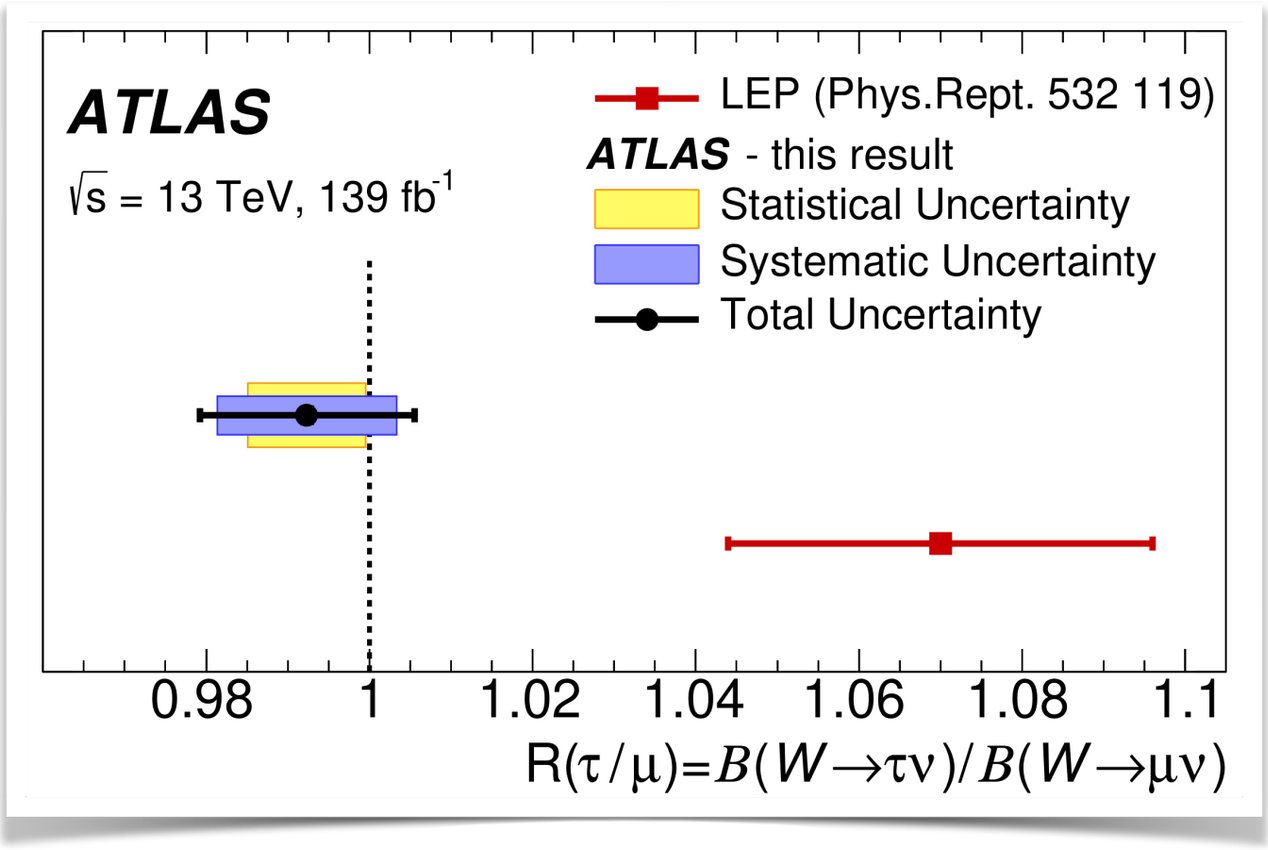
- …

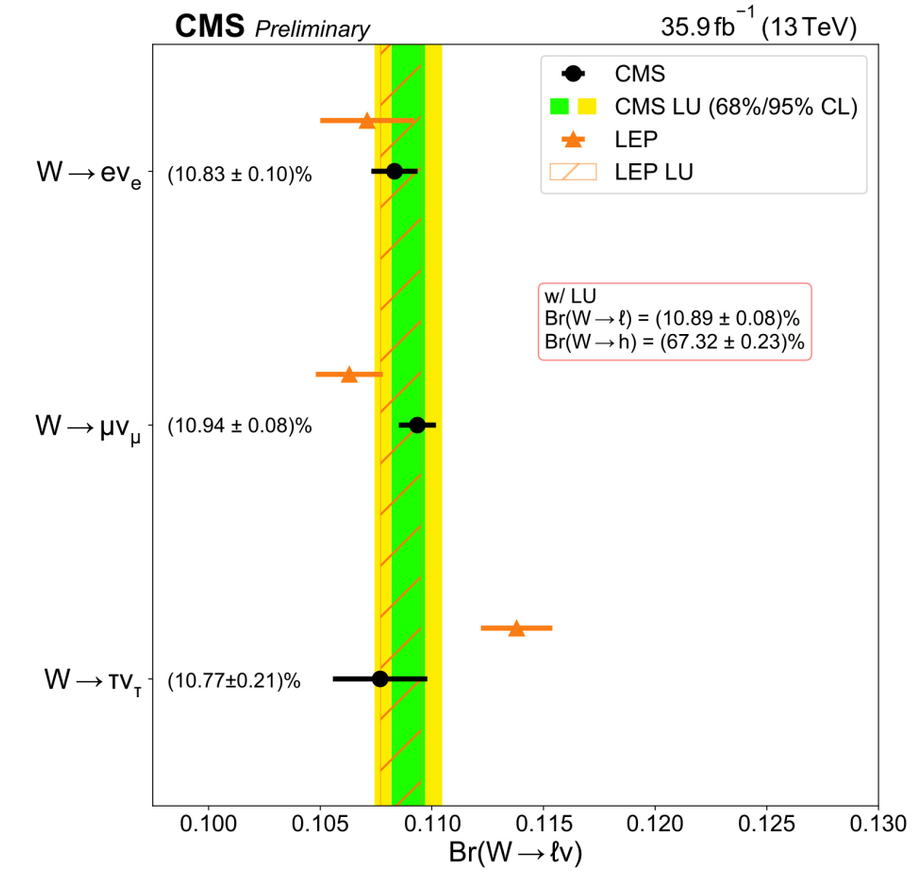
Plenty of other important open questions on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^{\pm}, A^0, H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do I_3=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field as I_3=–1/2 fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H \to \mu\tau$? $H \to e\tau$? $t \to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ ***the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which require the LHC and a future generation of colliders***

Still exploring the W at age 38 (1983→2021)





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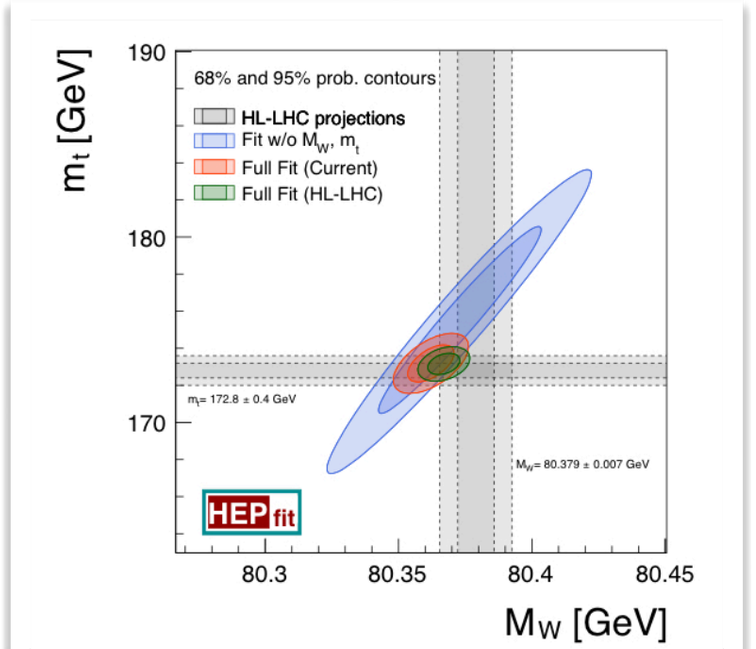
Search for the rare decay of the W boson into a pion and a photon in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

[3] G. Perez, Y. Soreq, E. Stamou, K. Tobioka, Prospects for measuring the Higgs boson coupling to light quarks, Phys. Rev. D 93 (2016) 013001, https://doi.org/10.1103/PhysRevD.93.013001, arXiv:1505.06689.



- The exploration of the Higgs will take decades, and will need successive generations of accelerators and experiments
- Like for W, Z and top, the Higgs will soon become background
- The precise measurement and modeling of the Higgs will enrich both our understanding of its properties, and the opportunities to use it as a search and discovery tool

The theoretical challenge

The study of the Higgs is stimulating a massive and unprecedented effort to improve theoretical calculations

Ex: $\delta_{TH}\ \sigma(pp \to H)_{N3LO}$

Anastasiou, et al. `15

Bonetti, Melnikov, Tancredi `18
Anastasiou, del Duca, et al. `19
Mistlberger `18
Becchetti, Bonciani, et al. `21
Czakon, Harlander, Klappert, **Niggetiedt** '21

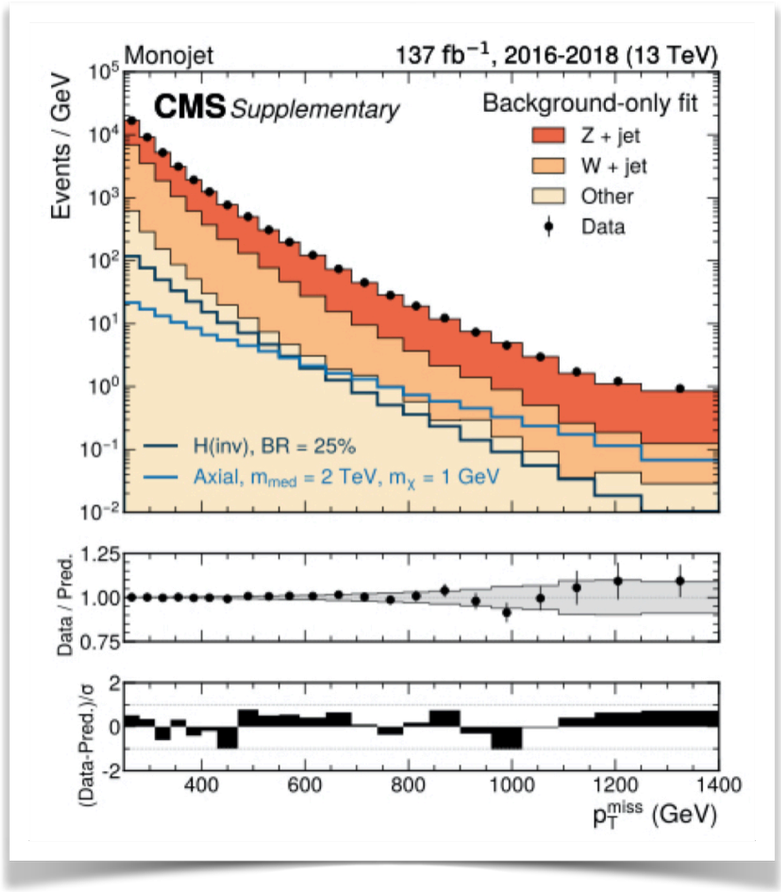
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \text{pb}}_{-1.15\ \text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

The HL-LHC YR target of halving the TH systematics by the mid-2030's appears more credible day by day…

The theoretical challenge

- This progress will positively reflect on all areas of collider physics, from the Higgs to BSM searches to SM measurements (eg PDFs)

- The estimates of TH systematics, however, require validation. The thorough campaign of experimental measurements of QCD and EW dynamics is a critical component of this effort.

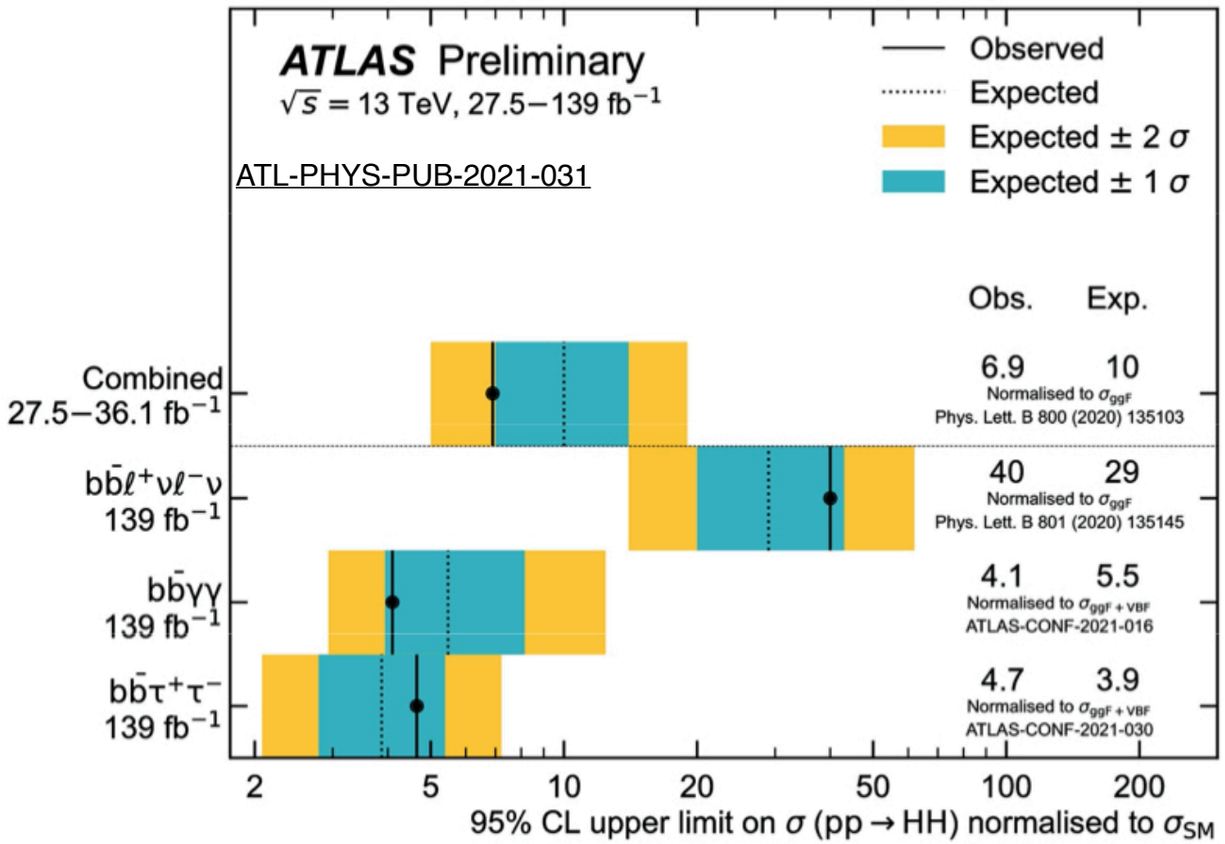


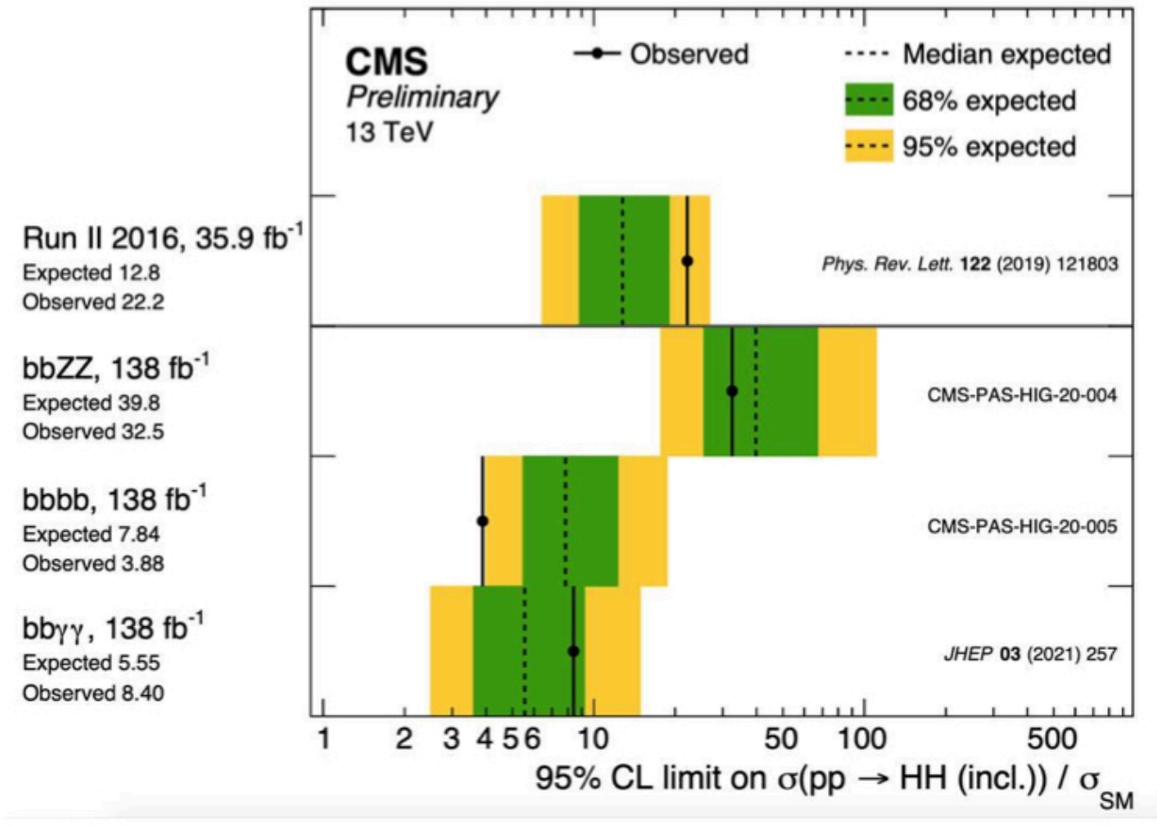
- Precision measurements of jets, heavy quarks, DY, etc, are necessary to give confidence in the reliability of the theoretical modeling and to further improve the determination of PDFs

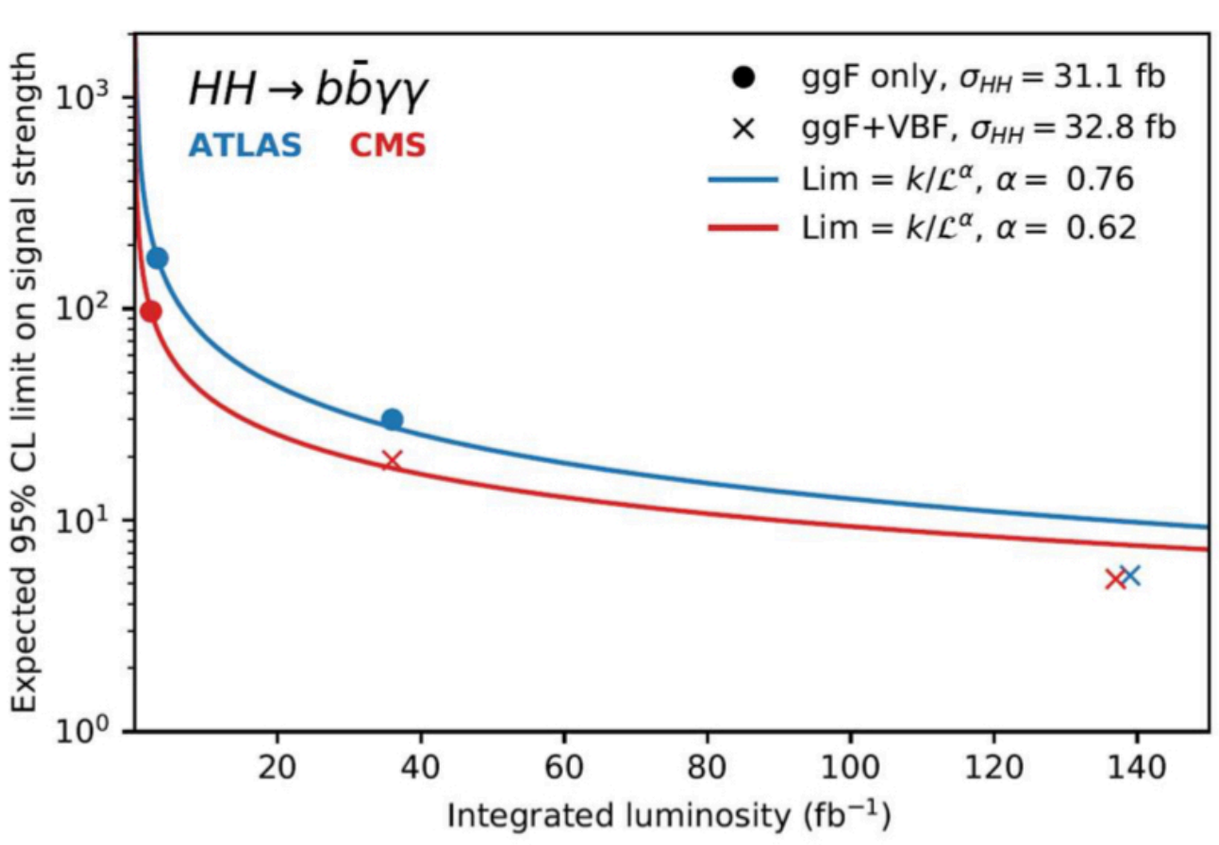
  - The Higgs itself presents rather unique production features ($gg \to H$), which make it interesting *per se* from the QCD perspective

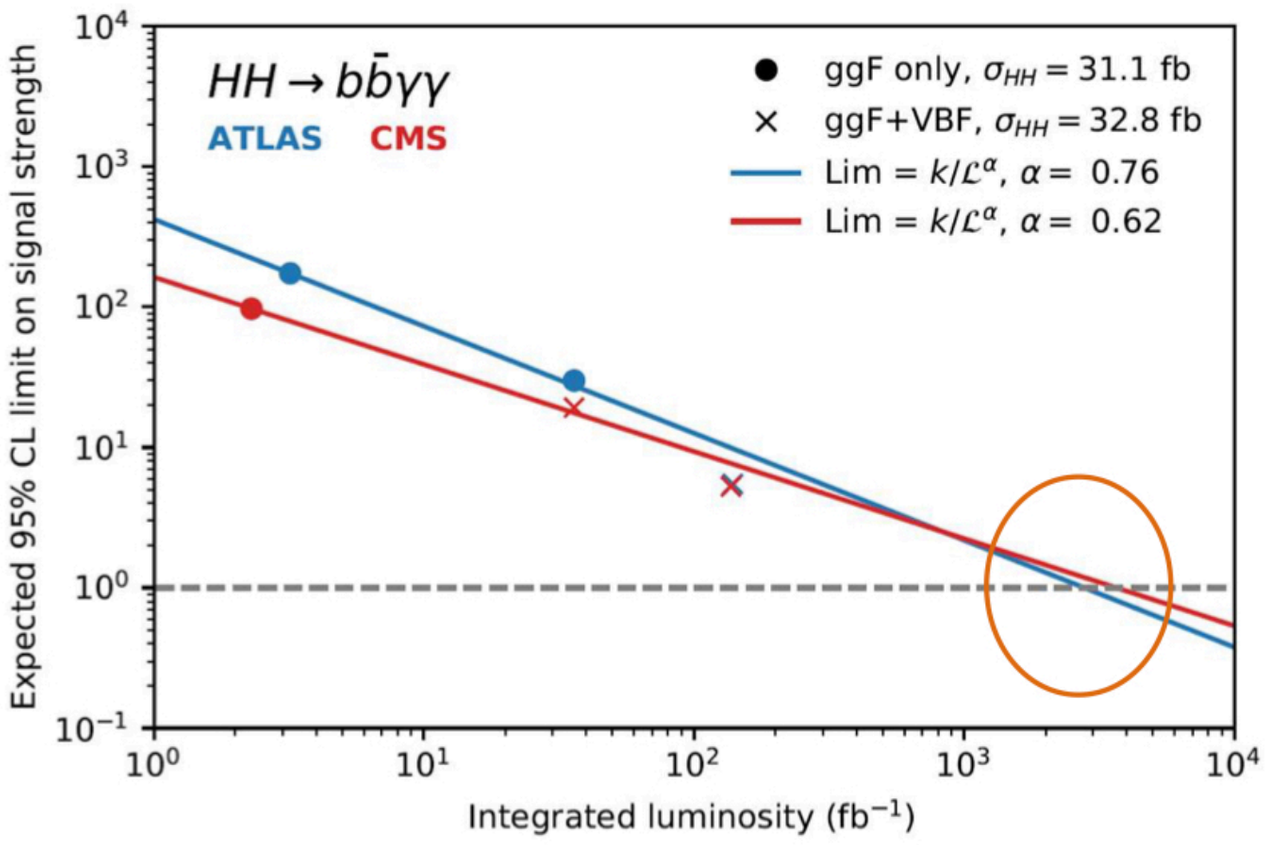
The experimental challenge

- Performance projections based on the Run 1 and early Run 2 experience have been fulfilled by the analysis of the full Run 2 data, and are in line with the HL-LHC YR projections
- Notable exceptions exist, where the precision appears to progress faster than statistics allows!









@ Higgs Hunting 2021

Plots from M. Kagan & R. Teixeira de Lima

Importance of standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen'n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

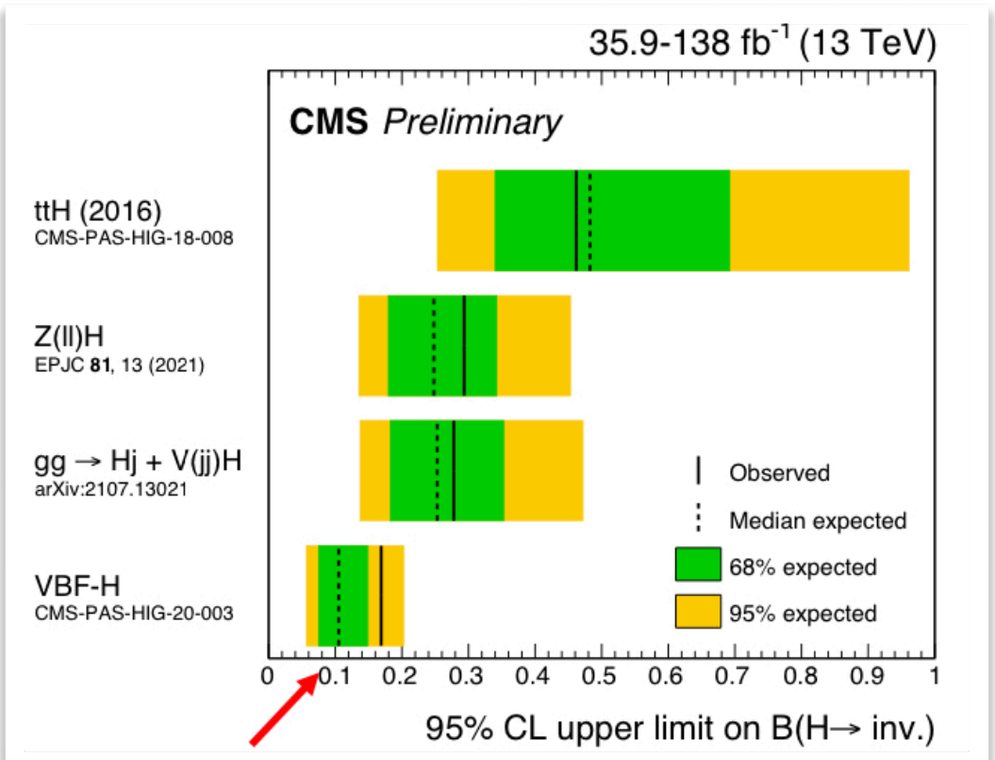
different EW charges in the loops of the two procs

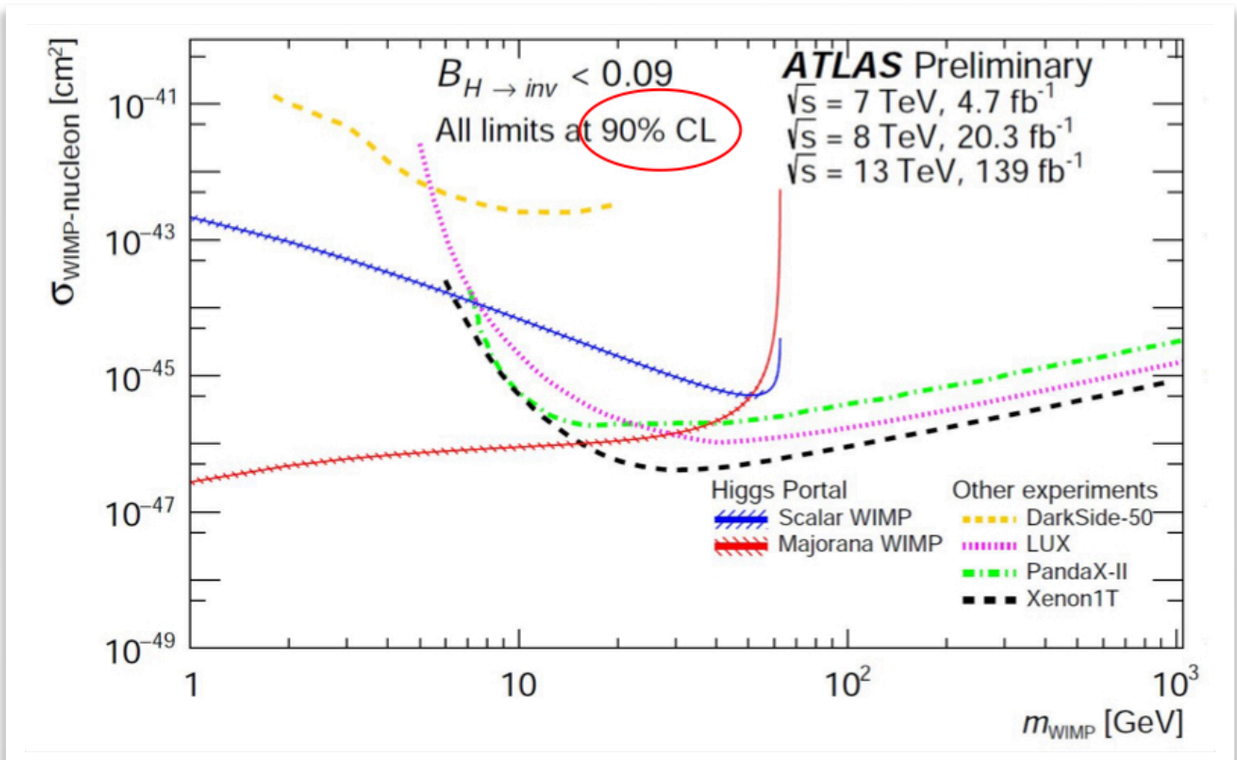
BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

Setting targets

- The road to the end of HL-LHC and to the achievement of its ultimate precision/exploration targets is still long
- Intermediate targets and milestones, matching the luminosity growth through Run 3, 4 etc, will help keep focus and motivation
- Obvious ones exist: $H \to \mu\mu$ @ 5σ, $Z\gamma$@ $3\sigma, 5\sigma$, HH@$1\sigma, 2\sigma, \ldots$
- It would be useful to develop milestones or benchmarks for each area of Higgs studies. Eg for $H \to$ inv a ref benchmark is the comparison against the progress of direct DM search expts:





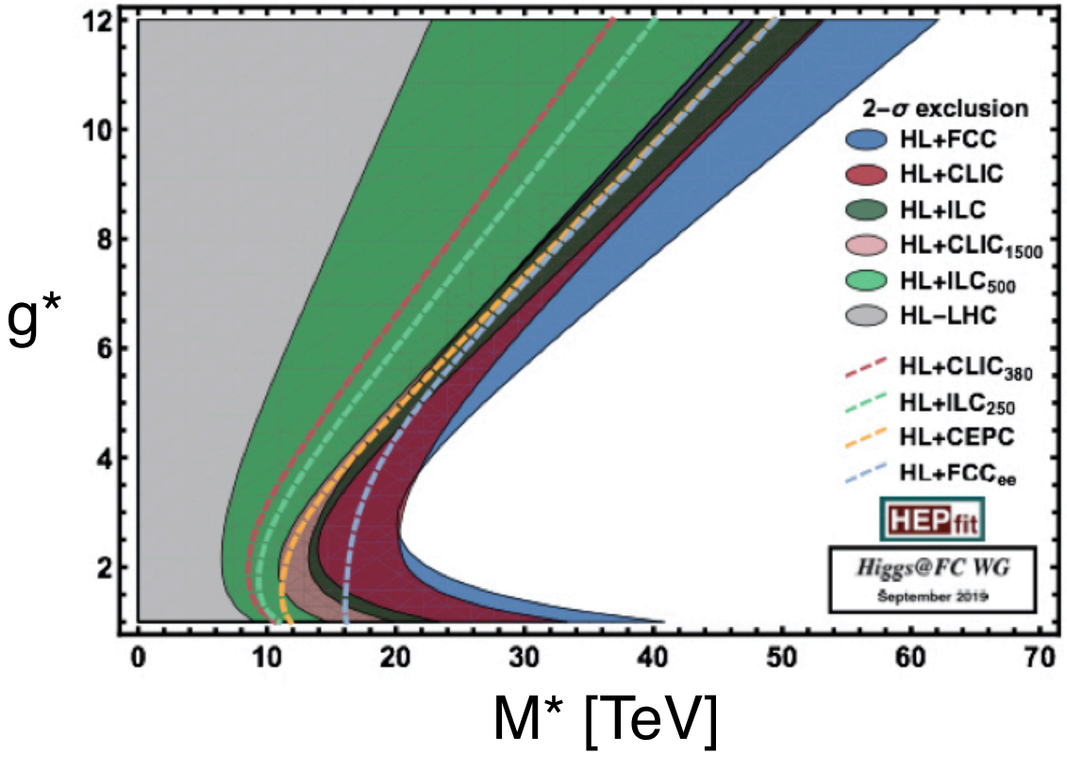
Setting BSM targets

- EFT by itself doesn't easily lead to the introduction of tangible targets, except in the cross-comparison among different facilities (eg reach of HL-LHC vs ILC vs CLIC …).
- Concrete BSM models remain the best way to define benchmarks, to connect the search results/projections to other measurements, and to *engage colleagues in other areas of HEP*
- Eg what are the implications of crossing the $\kappa_{charm} < 5, 3, 2$ thresholds? Any specific BSM models that get tested/excluded? Document the milestones that concrete BSM scenarios can set on EFT coefficient measurements, to stimulate and monitor the progress

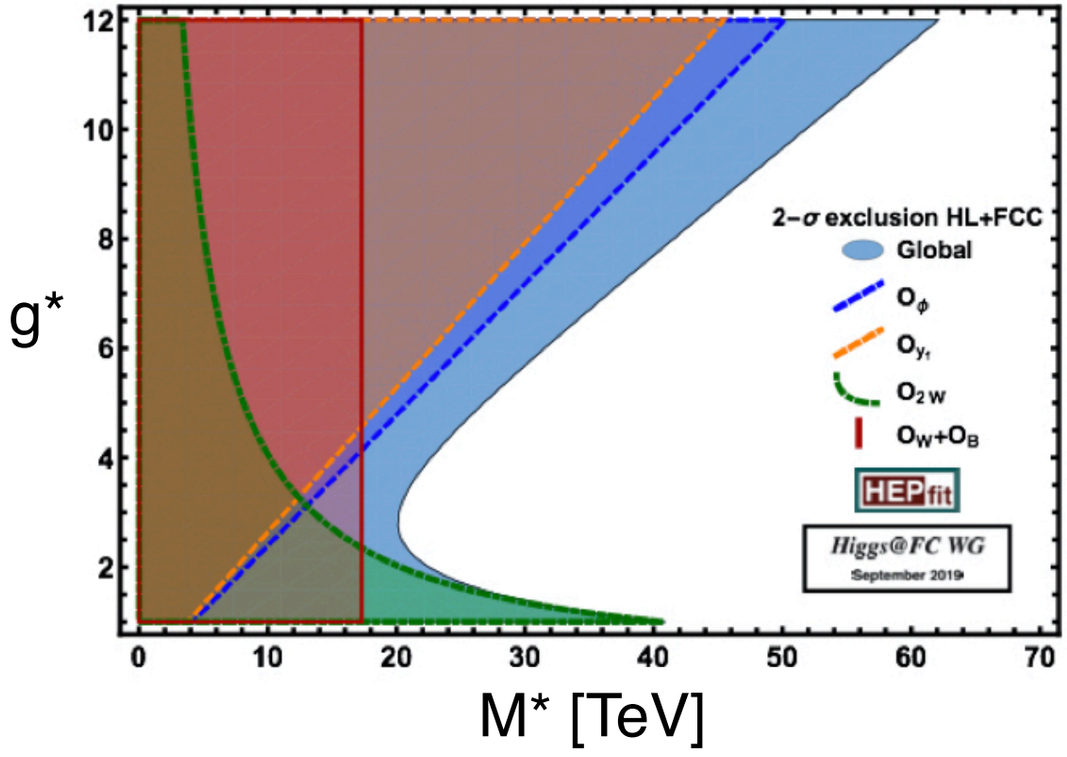
Setting BSM targets

- More effort should be put in exploring the interplay of potential EFT deviations in precision (or "high-Q2") Higgs measurements and concrete manifestations of the possible underlying new physics. ⇒ *more targets*

Ex: composite Higgs models,
De Blas et al, arXiv:1905.03764



g* , m* (coupl & mass of new resonances) ↔
EFT ops' coefficients



Beyond HL-LHC

- As the LHC keeps exceeding expectations, the bar for the performance of future colliders keeps being raised
  - The Higgs case for future colliders needs continuous review and update, to preserve the quantum leap in precision that we expect from them, and that is needed to justify their construction.
- The approval of the next facility to study the Higgs, beyond HL-LHC, cannot be taken for granted. We need to educate ourselves on the best way to explain the value of the Higgs physics program.
- We need to better articulate the value of improved Higgs measurements, in a way that our non-collider colleagues can appreciate, and especially in case they end up agreeing with the SM.
  - what <u>new</u> do we learn about nature if the Higgs proves to act SM-like down to precision x% ?

Final remarks

- Higgs physics is the pillar supporting the future development of HEP and accelerator physics. It presents exceptional experimental and theoretical intellectual challenges, which by themselves provide the adrenalin that lets us engage in this multi-decades enterprise.
- But sharing our enthusiasm with the external world, starting from our neighboring colleagues in non-collider domains of particle physics, is not easy, and we must work harder to find the proper language, defining targets and milestones that are meaningful and compelling even outside our circles
- Nothing of what I said is particularly original. This Conference provided ample evidence that our community is taking care of most of what I said. But I felt it important to underscore some of these points as we wrap Higgs 2021 up
- I encourage all of you to take responsibility in improving the narrative!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THANKS
to the organizers and the programme committee, for setting up a fantastic and flawless event!!
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