Higgs Boson as a Portal

Searching for Rare and Exotic Higgs Decays at the LHC

The 11th China LHC Physics Conference
CLHCP 2025

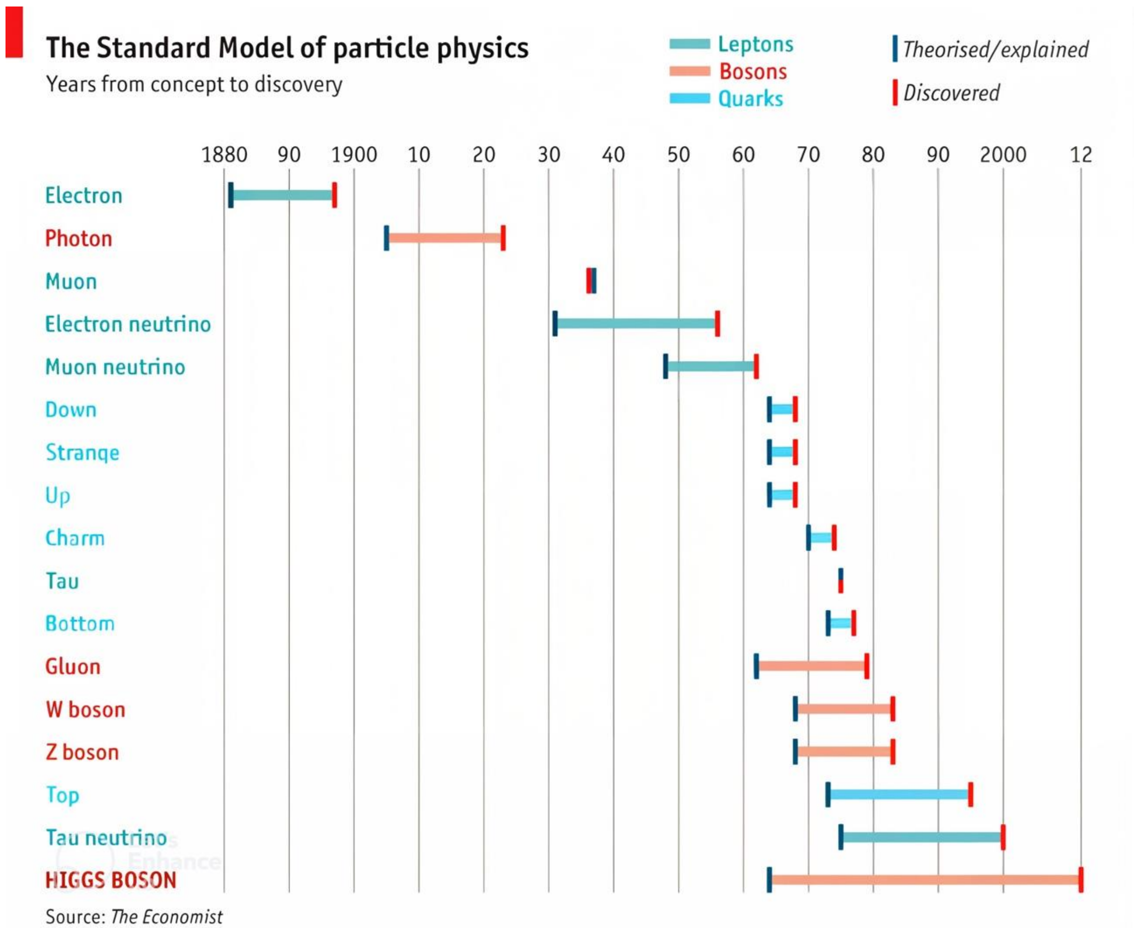
Zirui Wang

Xinxiang, Henan
2025-10-31

FUDAN UNIVERSITY

Theoretical and Experimental Particle Physics

have revealed much about the nature of our universe

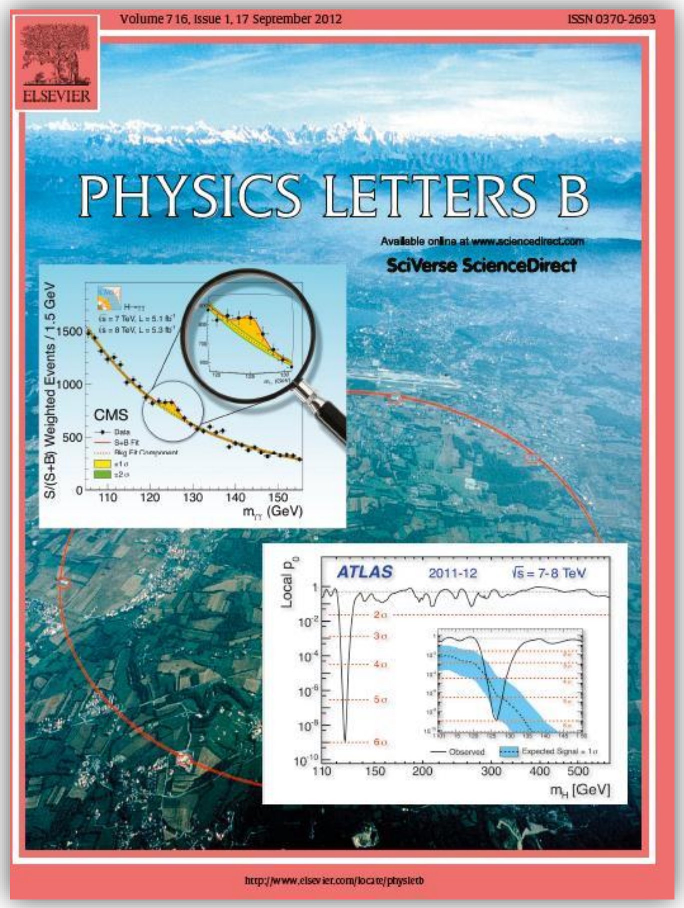


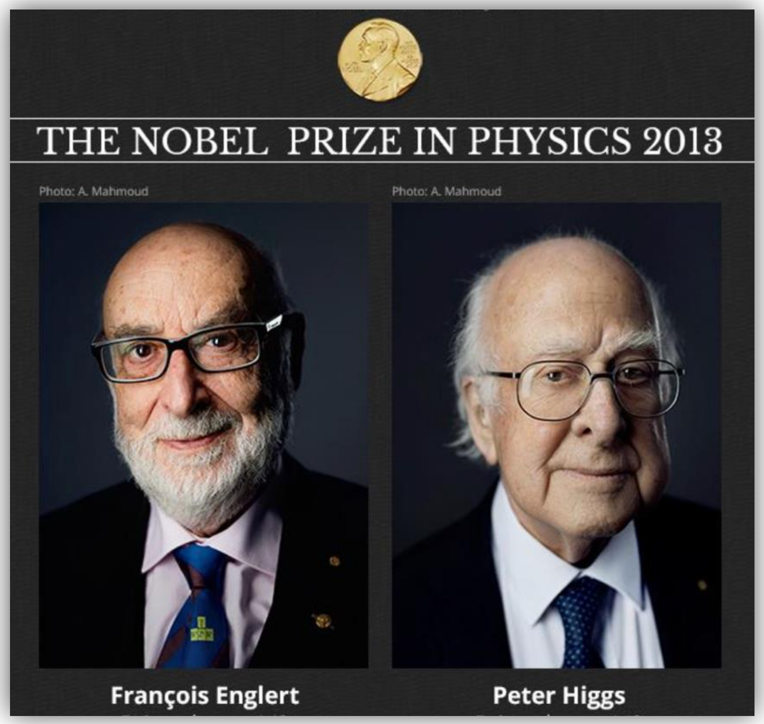
[*Economist*]

Higgs boson, with the existence predicted in 1964

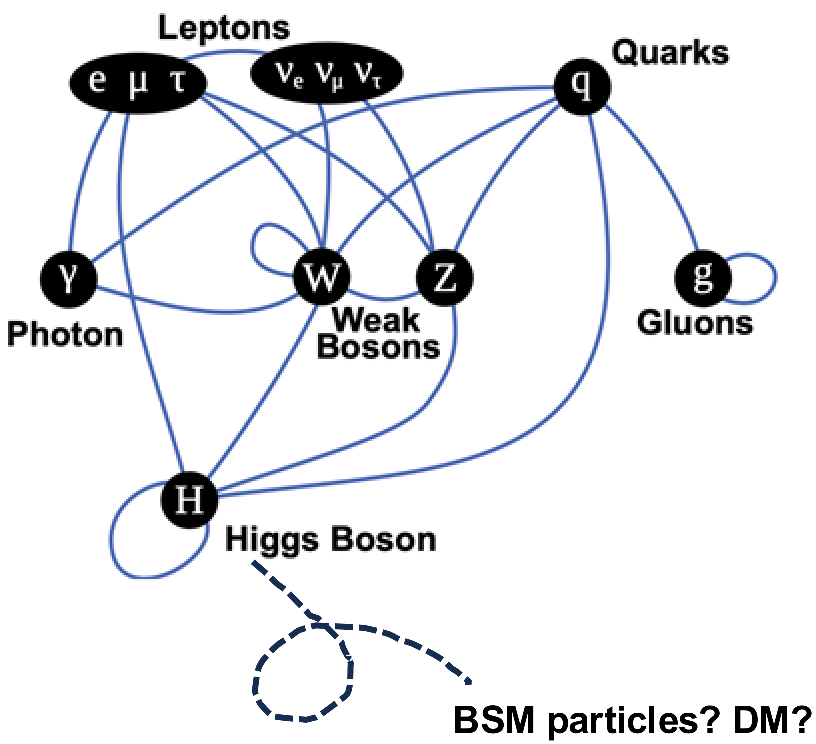
Discovered on July 4th, 2012, by **ATLAS** and **CMS** experiments on **LHC**

Higgs discovery in 2012





- 2012, **Discovery of Higgs boson** → **Last piece of the elementary particle content in SM**
- Nobel Prize in Physics in 2013 → **Peter Higgs** and **François Englert**
- **So far, the SM is very successful,** that has been tested from the low to high energy experiments.



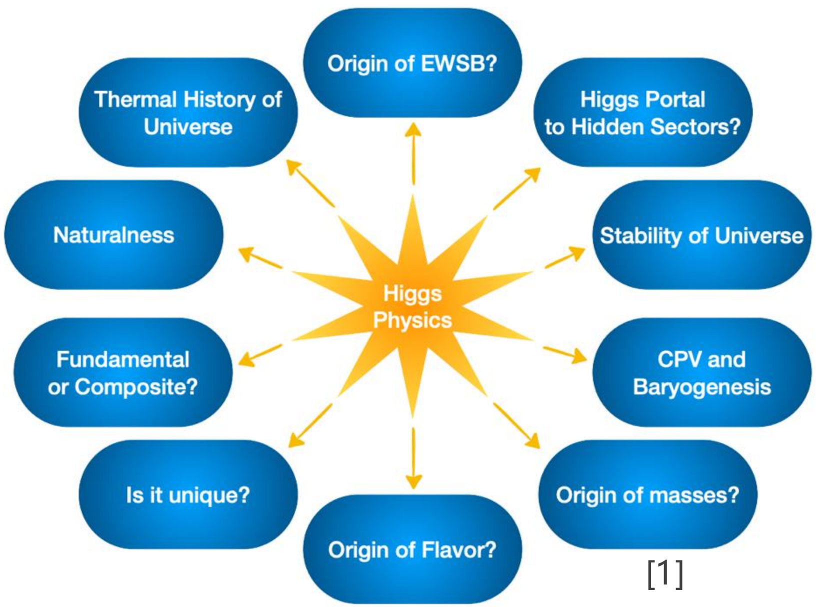
The discovery of Higgs boson completed the last piece of the SM particle content.

But **SM cannot explain**:

- What is the nature of dark matter and dark energy?
- How do neutrinos obtain their mass?
- What is the origin of matter-antimatter asymmetry
- …

As a **cornerstone of the SM**, **Higgs** holds the potential to explain those **fundamental questions**.

Could Higgs tell us more?



[1]

What is the origin of mass?

The Big Bang did not immediately produce particles with mass. After the universe cooled to a critically low temperature, an invisible field called the Higgs Field appeared. It is this field that gives particles mass. But[2]

中国科协发布2025重大科学问题、工程技术难题和产业技术问题

日期：2025年07月11日　来源：新华网　作者：系统管理员　【大 中 小】　【打印】　【关闭】

在第二十七届中国科协年会主论坛上，中国科协发布2025重大科学问题、工程技术难题和产业技术问题。

十大前沿科学问题包括：

流形的拓扑和几何分类

希格斯粒子性质和质量起源

准金属替代过渡金属用于精准合成与催化反应的可行性研究

[3]

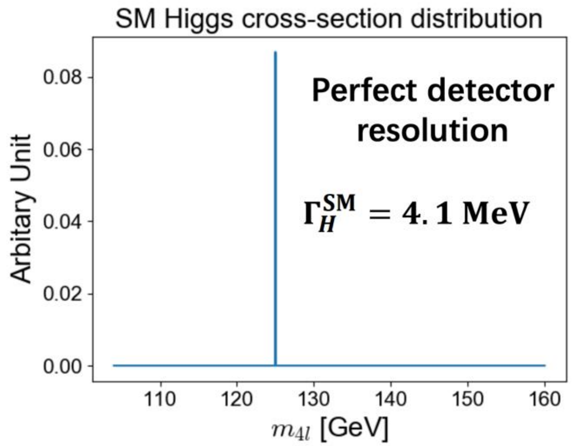
[1] Snowmass 2021 report

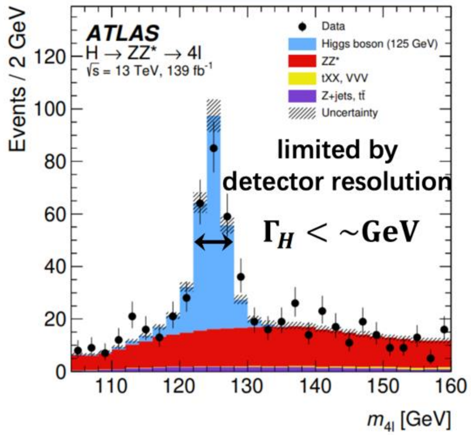
[2] Science. *125 questions: Exploration and discovery*

[3] China Association for Science and Technology (CAST). *The Top 10 Frontier Scientific Questions for 2025*

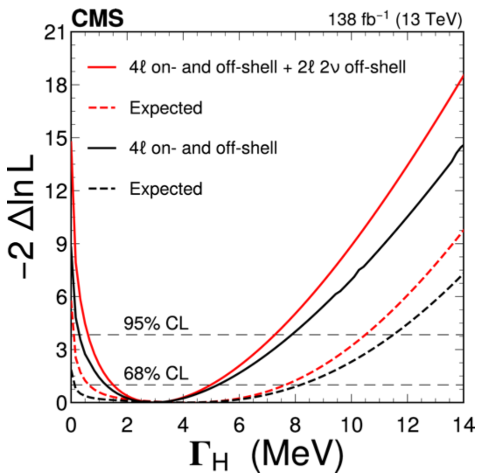
A big unknown in the Higgs decay width

- SM Higgs width: Γ_H = 4.1 MeV but could be much larger for BSM contribution



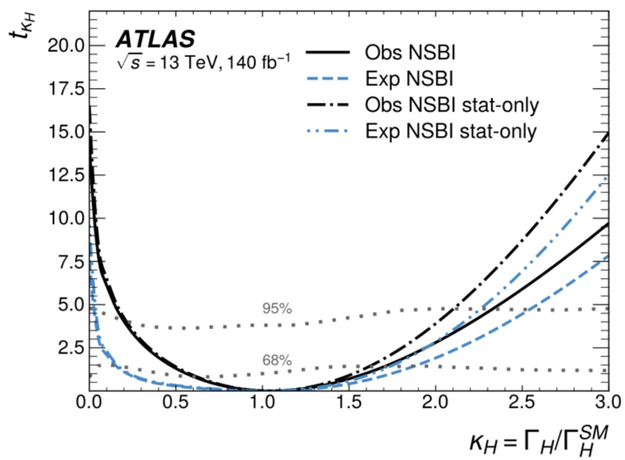


- Indirect measurement: $\Delta\Gamma_H$ ~ 50%-60%



CMS: $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV

[PRD 111 (2025) 092014]

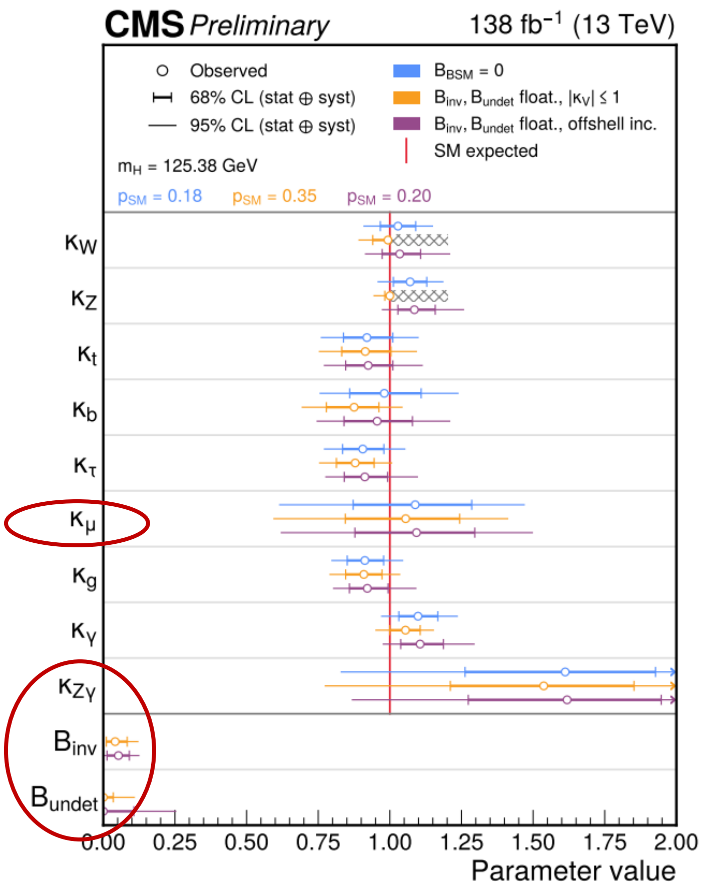


ATLAS: $\Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV

[Rep. Prog. Phys. 88 (2025) 057803]

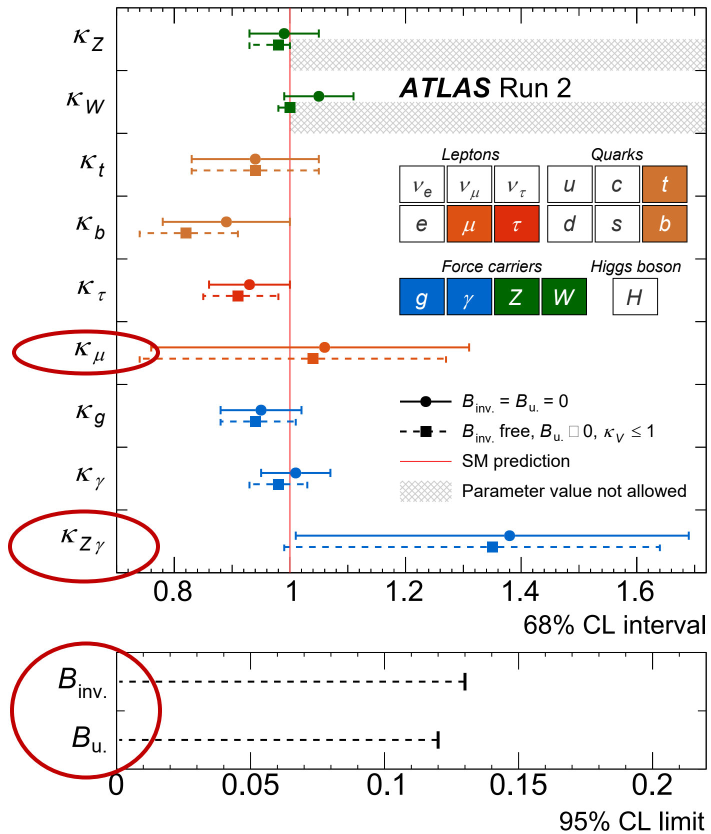
Information from the global coupling fit

- Large room left (95% C.L. upper limit) for B_{inv}/B_u from the global fit.
- Large uncertainty on the 2nd-generation fermion Yukawa coupling and $Z\gamma$ modifiers
- Important to explore Higgs rare, invisible and exotic decays.



CMS: $B_{inv} < 0.13$, $B_u < 0.25$

[CMS-PAS-HIG-21-018]



ATLAS: $B_{inv} < 0.13$, $B_u < 0.12$

[Nature 607, 52–59 (2022)]

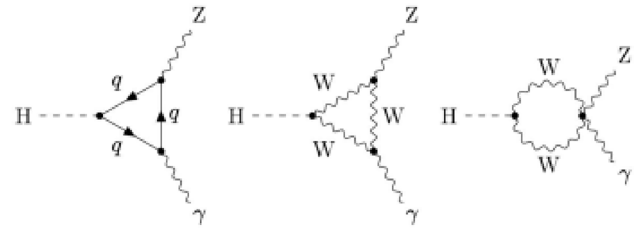
1. Search for rare Higgs decays

➤ We look into the second-generation fermion Yukawa couplings and loop-induced interactions. These studies offer deep insights into how closely the Higgs boson's behaviour aligns with the Standard Model.

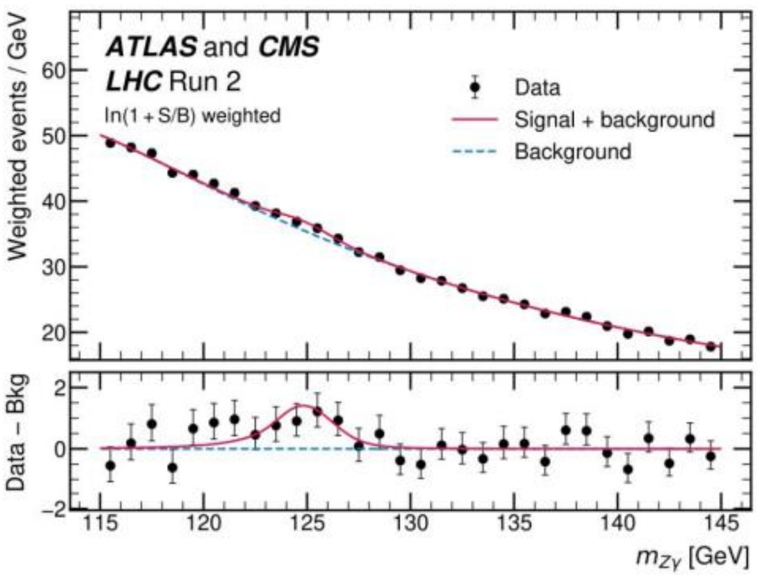
Caveats:

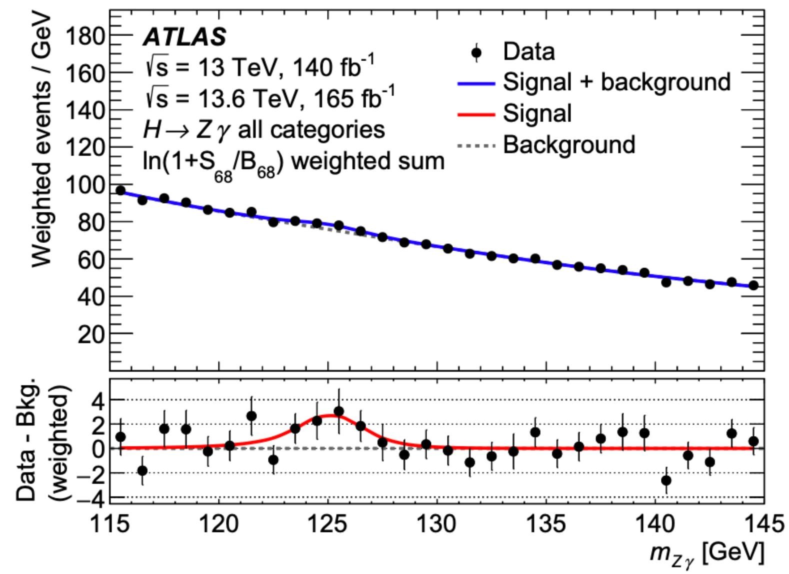
- *A personal selection of topics. Check out the ATLAS and CMS physics pages for a more comprehensive overview*

$BR_{SM}(H \to Z\gamma)$ ~1.5 x 10^{-3}



- Focus on Z boson leptonic decays ($Z \to ee/\mu\mu$)
- Main backgrounds: Z+γ, Z+jets





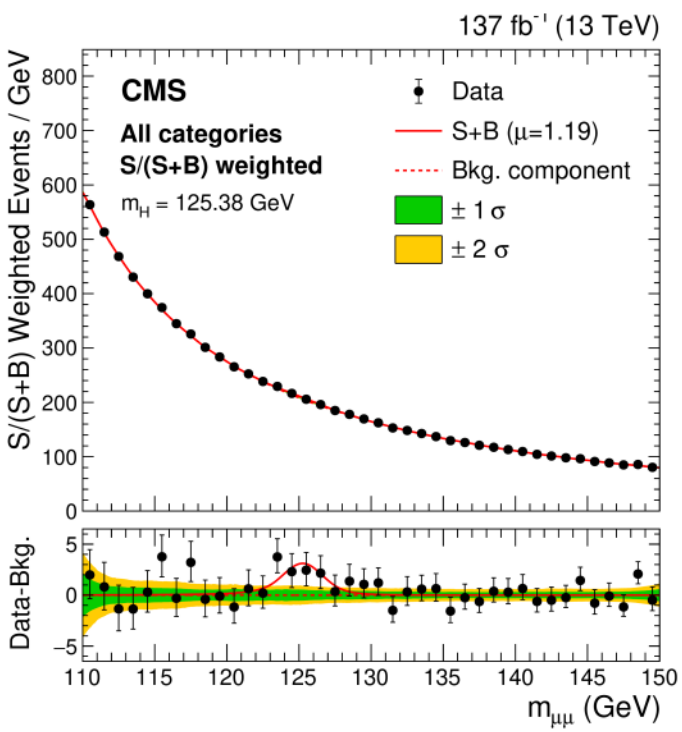
- **Run 2 results: Evidence** found for $H \to Z\gamma$ decay
  ATLAS: 2.2 (1.2) σ *PLB 809 (2020) 135754*
  CMS: 2.7 (1.2)σ *JHEP 05 (2023) 233*
  ATLAS+CMS : **3.4 (1.6) σ** *PRL 132 (2024) 021803*

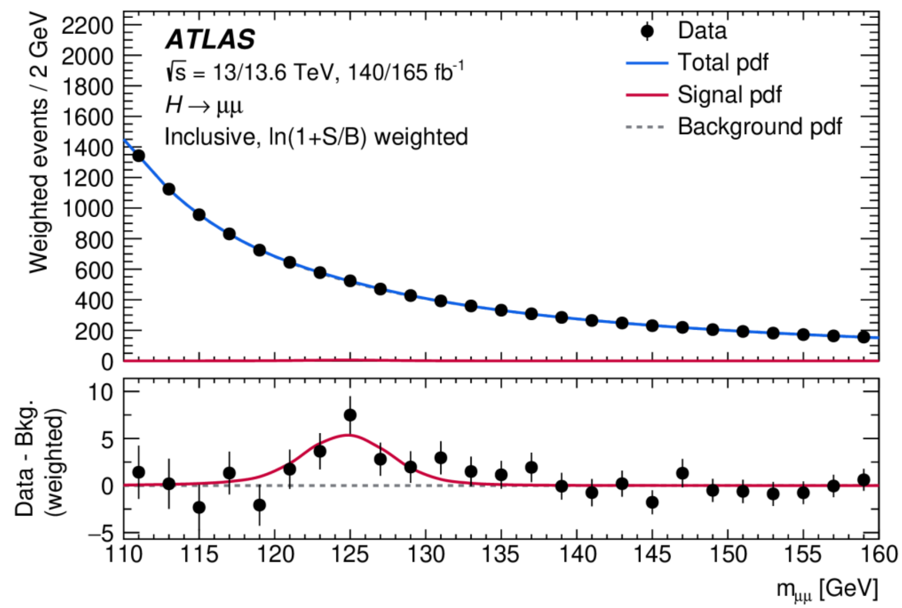
- **ATLAS Run 2+3 result:** *2507.12598*
  Run 3 only: 1.4 (1.5) σ
  Run2 + 3: 2.5 (1.9) σ

$H \rightarrow \mu\mu$

$BR_{SM}(H \rightarrow \mu\mu) \sim 2.2 \times 10^{-4}$

- Clean final state, but large Drell-Yan background:
- Both ATLAS and CMS found **clear evidence (> 3 σ)**:





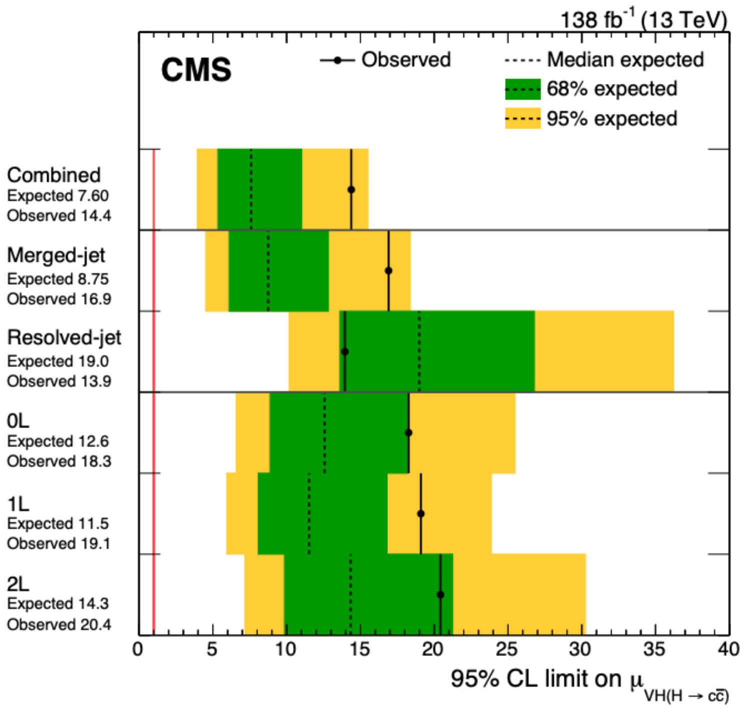
- **CMS result:** [JHEP 01 (2021) 148]
  Run 2: 3.0 (2.5)σ

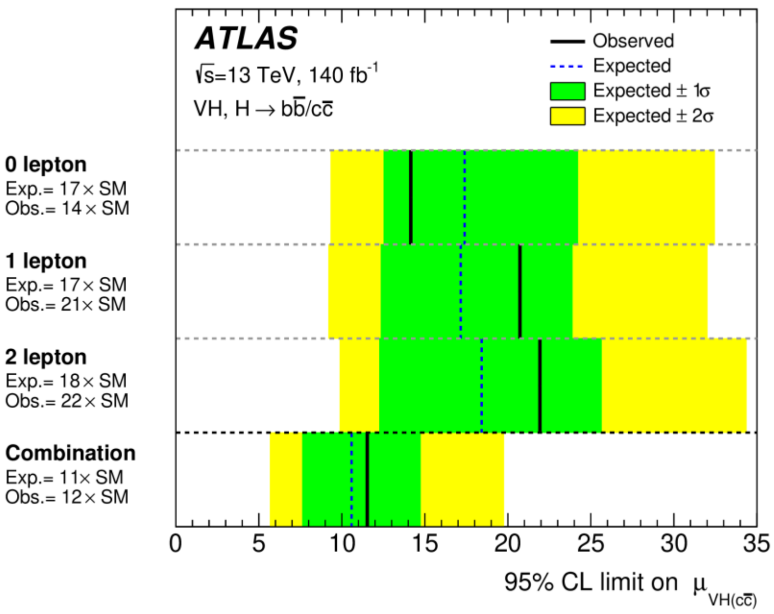
- **ATLAS Run 2+3 result:** [2507.12598]
  Run 3 only: 2.8 (1.8) σ
  Run2 + 3: 3.4 (2.5) σ

$BR_{SM}(H \to cc) \sim 3\%$

c-jet identification and **high background rate** makes it challenging:

- **VH production** and multiple decay channels offer additional handlers for signal selection and background suppression.
- **Flavour tagging** and **analysis strategy** play a central role

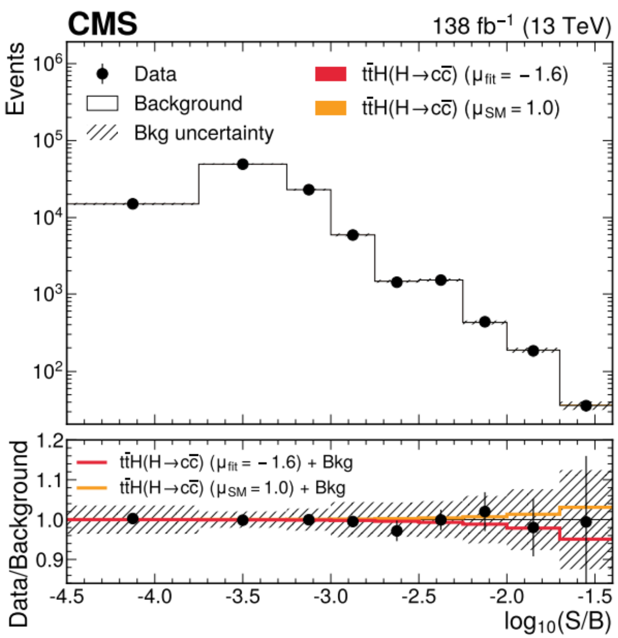


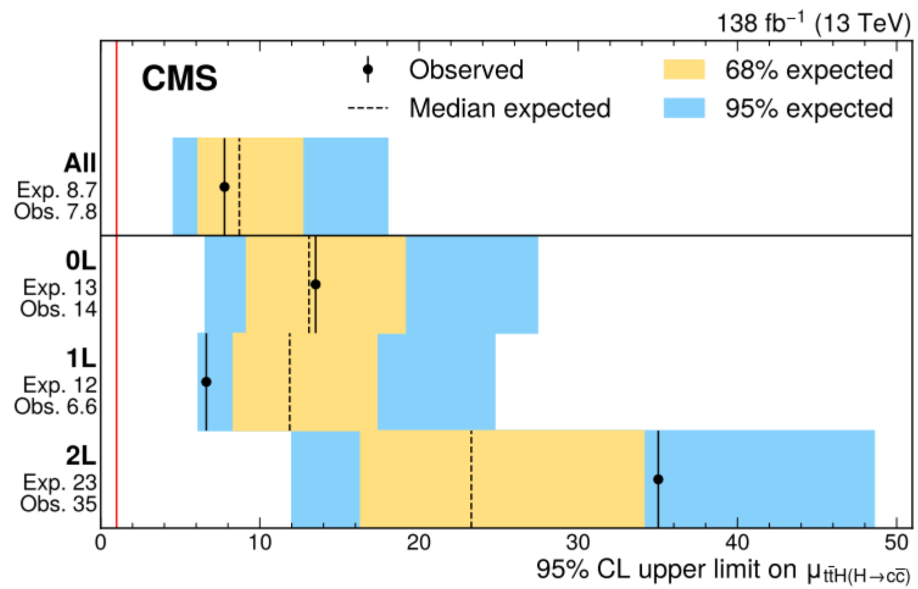


- **CMS run 2 result:**
  [Phys. Rev. Lett. 131 (2023) 061801]
  - $\mu_{VH(cc)} < 14.4\ (7.6)$
- **ATLAS Run 2 result:**
  [JHEP 04 (2025) 075]
  - $\mu_{VH(cc)} < 11.5\ (10.6)$

ttH, H→cc

New analysis from CMS **simultaneously** looking into ***ttH→ bb***, ***cc*** and ***ttZ*** SM candles





- **CMS run 2 result:** [2509.22535]

  $\mu_{ttH(cc)}$<7.8 (8.7)
- Combining with VH, H→cc:

  $|\kappa_c|$<3.5 (2.7)

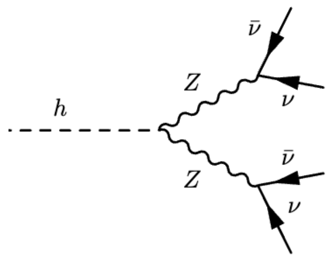
2. Search for Higgs invisible decays

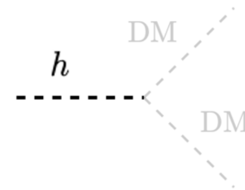
➤ We look into the higgs invisible decays, to probe if Higgs boson could serve as a "portal" to mediate interactions between SM and the dark sector.

Search for Higgs invisible decay on LHC

A unique gateway on LHC :

- H decays to a pair of stable WIMPs.

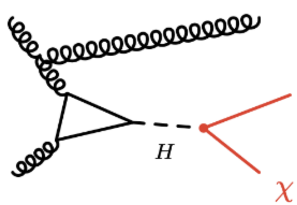




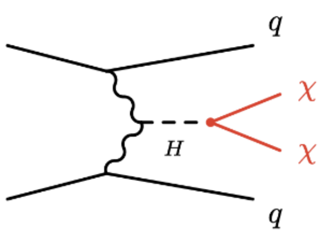
SM BR(H→inv) ~**0.12%**

DM will **increase BR(H→inv)**

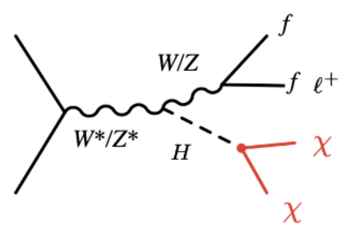
ggF (~ 49 pb)



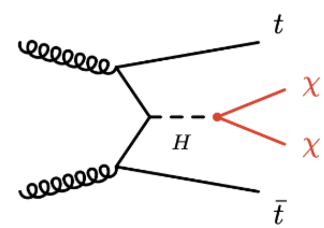
VBF (~ 3.8 pb)



VH (~ 2.3 pb)



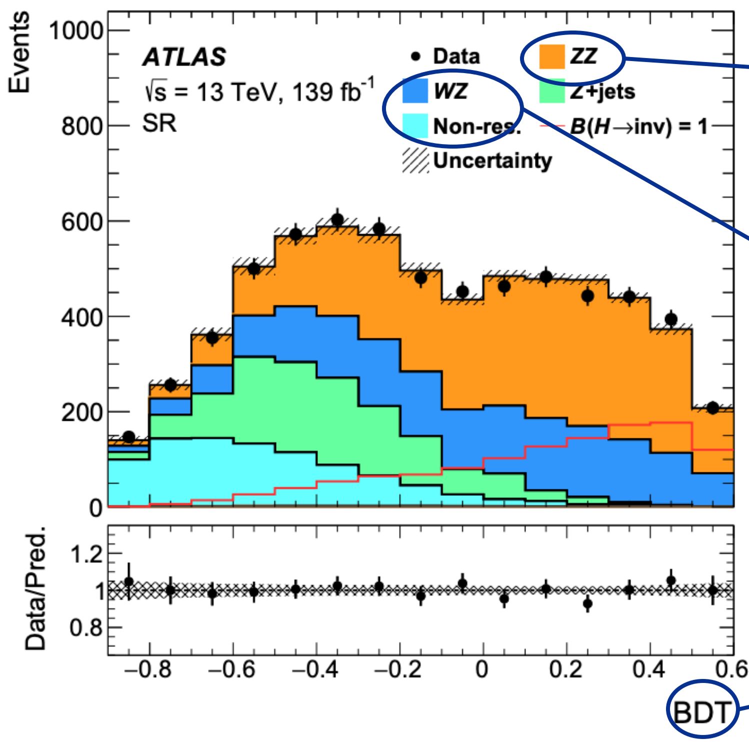
ttH (~ 0.5 pb)



Selection	high p_T ISR jet	2 forward jets in opposite hemisphere	lepton or hadron decay from W/Z	leptonic, semi-leptonic, hadronic tt
Final state	mono-jet	**VBF + MET**, VBF + MET + γ	Z(ll) + MET, mono-largeR jet	tt + MET
Sensitivity	**Low**	**High**	**Intermediate**	**Intermediate**

Hinv analyses have significantly optimized strategies at LHC, achieving **improvements beyond the increase in data size**.

For example, the ATLAS mono-Z *PLB, 2022, 829: 137066*



PLB, 2022, 829: 137066

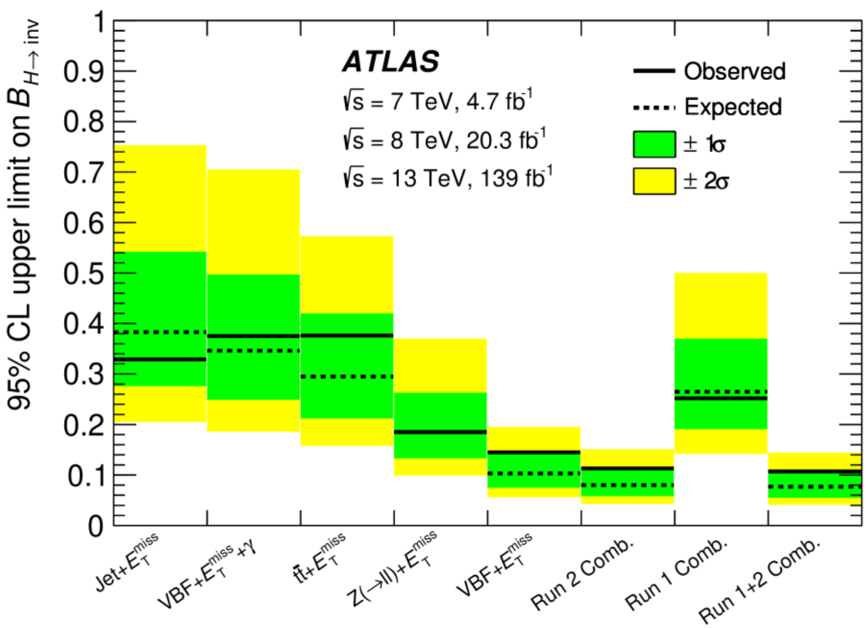
Apply the latest theoretical calculation to correct the main backgrounds

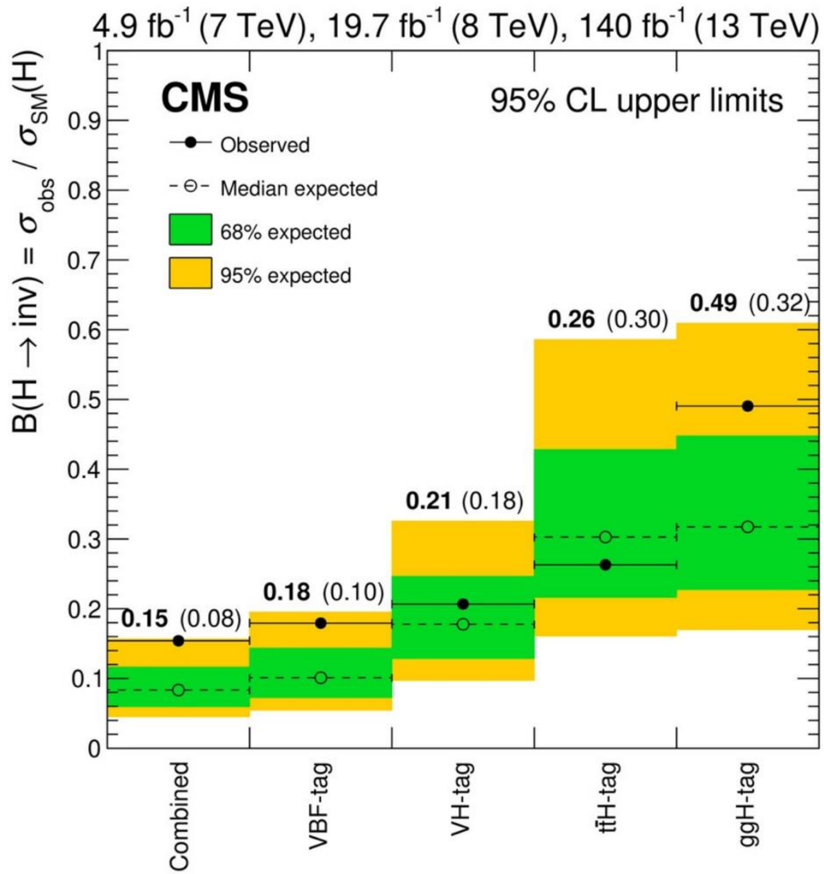
utilize data in control regions to reduce uncertainties

Use ML observables to distinguish between signal and background.

- BR(Hinv)<0.19 @ 95% CL
- Improvement of over 70% compared to the previous result of 0.67.

Put all the pieces together



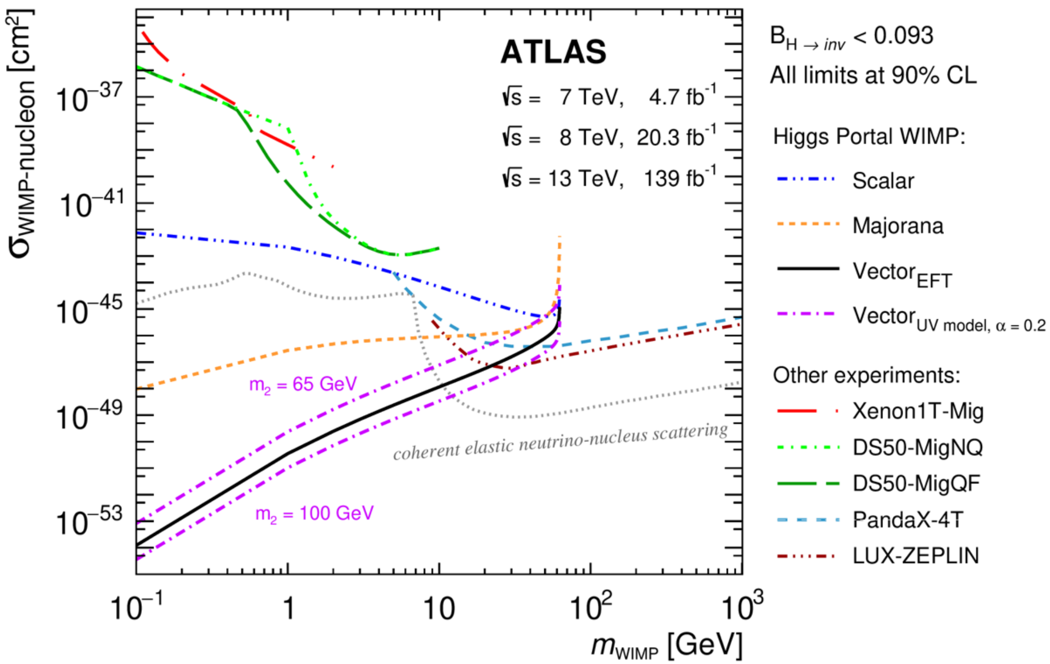


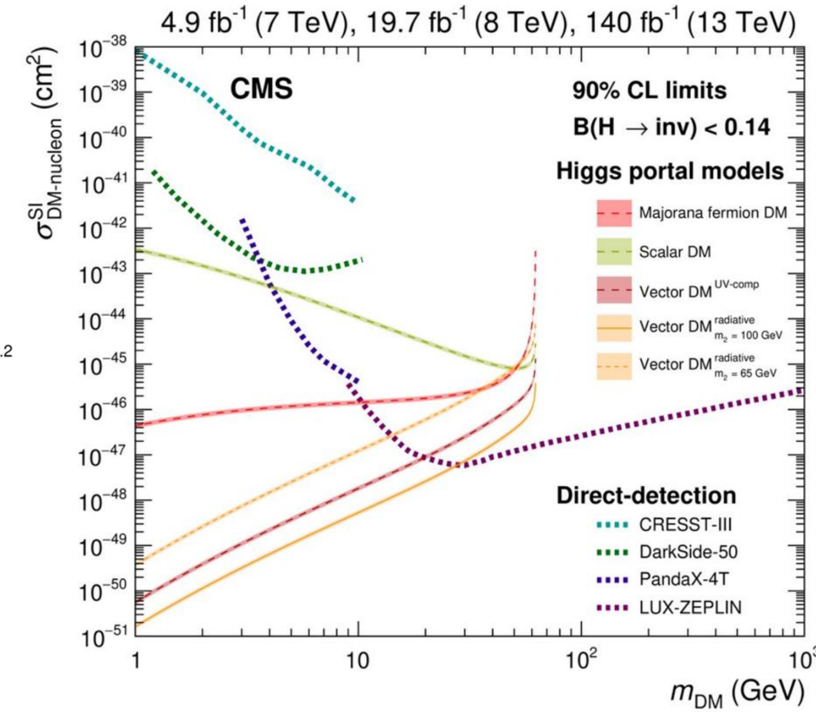
Further statistically combined All H→inv searches:

ATLAS: BR(H→inv) < 10.7% (7.7%) PLB 842 (2023) 137963

CMS: BR(H→inv) < 15% (8%) EPJC 83 (2023) 933

LHC vs Direct detection experiments





- **Significant complementarity** between LHC and direct detection experiments on DM-nucleon cross-section limits through the Higgs-portal model.

3. Search for Higgs exotic decays

➤ We look into the higgs exotic decays, to look for the evidence of non-standard interactions in the higgs sector.

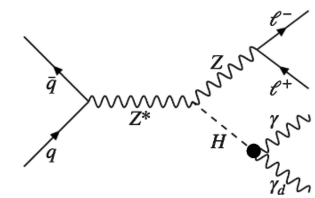
Higgs decay to dark photons

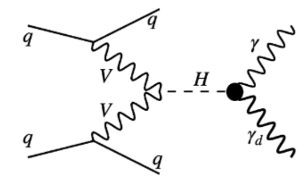
- Dark sector containing a **dark abelian gauge group $U(1)_D$**
- Massless (or ultra-light) **dark photon** leads to invisible signatures

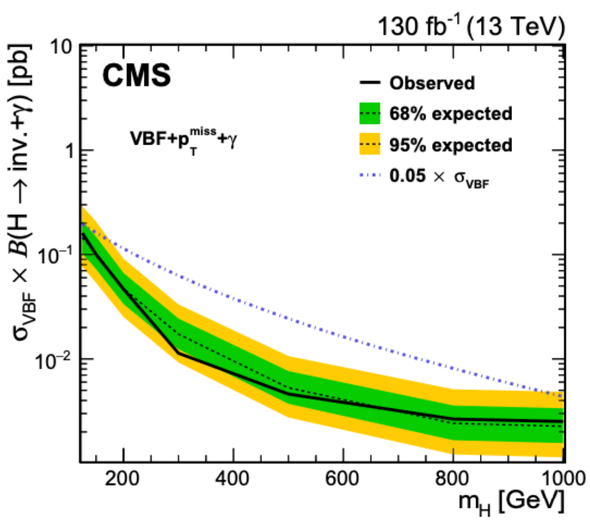
the most sensitive (as for H→inv)

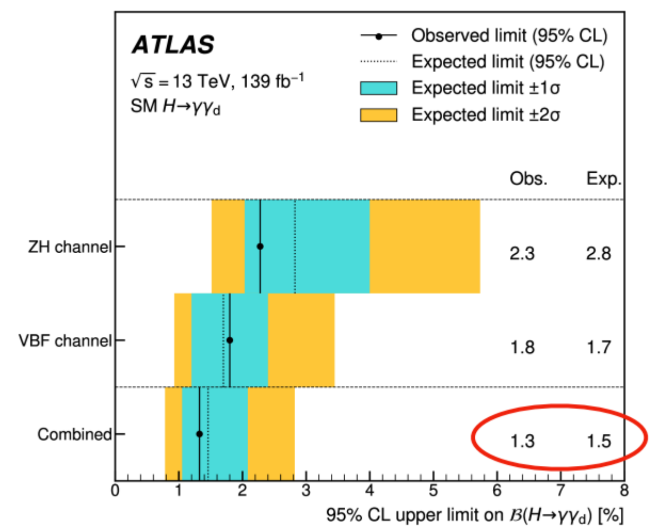
Z(ll)H channel
- BDT discriminant

VBF channel
- m_T discriminant









CMS 95% U.L. on BR($H\to\gamma\gamma_D$):

VBF channel: 3.5% (2.8%) *JHEP 03 (2021) 011*

ZH channel: 4.6% (3.6%) *JHEP 10 (2019) 139*

ZH+VBF: **2.9% (2.1%)** *JHEP 03 (2021) 011*

ATLAS 95% U.L. on BR($H\to\gamma\gamma_D$):

VBF channel: 1.8% (1.7%) *EPJC 82 (2022) 105*

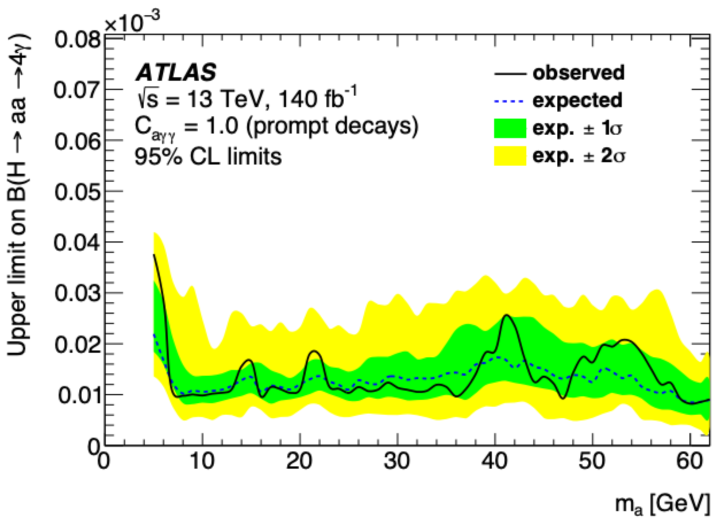
ZH channel: 2.3% (2.8%) *JHEP 07 (2023) 133*

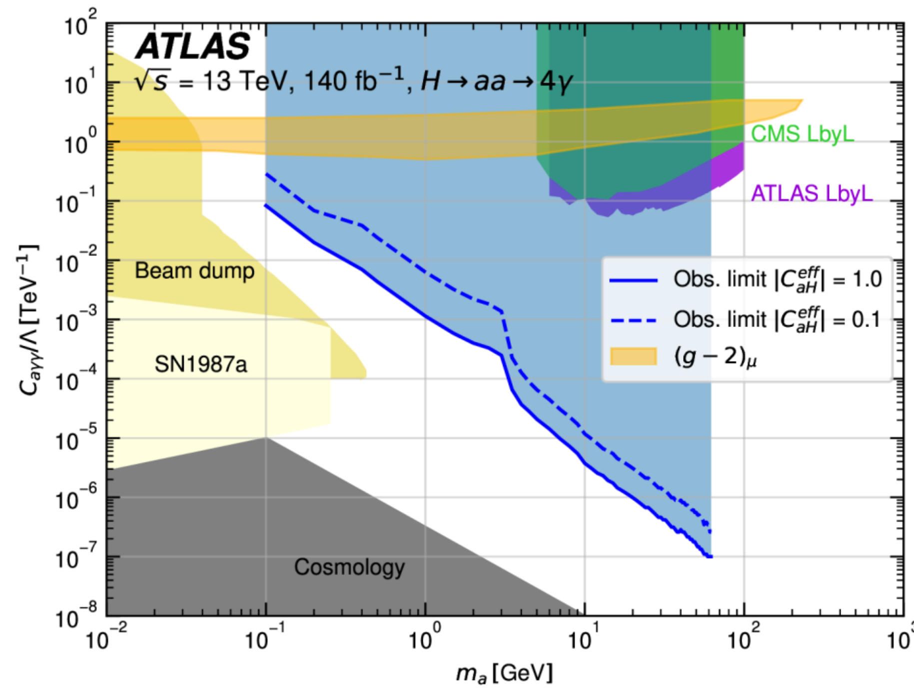
ZH+VBF: **1.3% (1.5%)** *JHEP 08 (2024) 153*

Search channel: $H \rightarrow aa \rightarrow 4\gamma$

ALP mass range probed: $0.1 < m_a < 60$ GeV Eur. Phys. J. C 84 (2024) 742

- **Collimated signature:** identified as single object when $m_a < 3.5$ GeV
- Both **Prompt (major sensitivity)** and **long-lived** signatures included



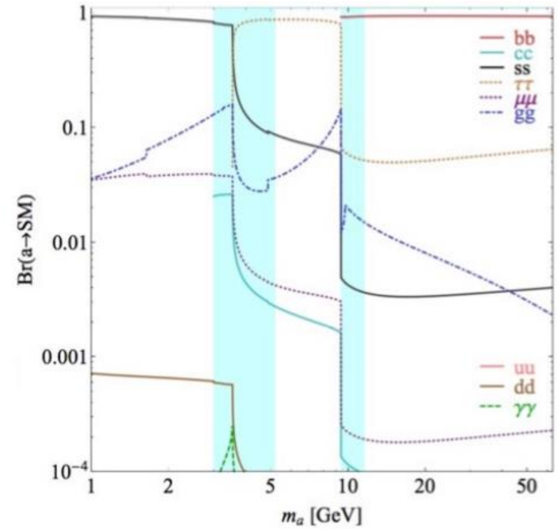


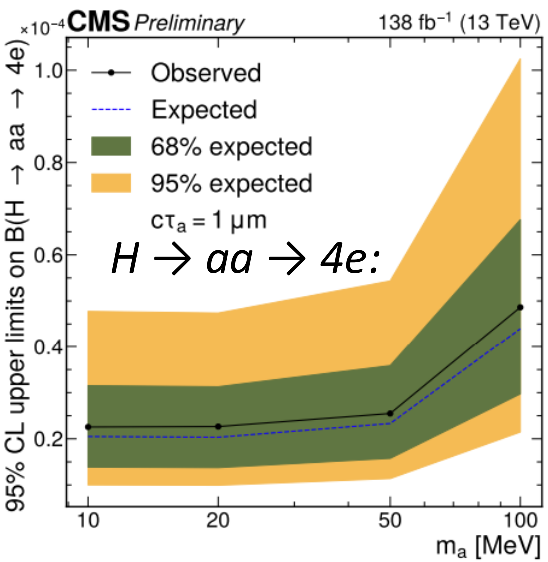
Limits on the ALP mass and coupling to photons at 95% CL, assuming $|C_{aH}^{eff}|/\Lambda^2 = 1$ TeV^{-2} (solid line) and $|C_{aH}^{eff}|/\Lambda^2 = 0.1$ TeV^{-2} (dashed line)

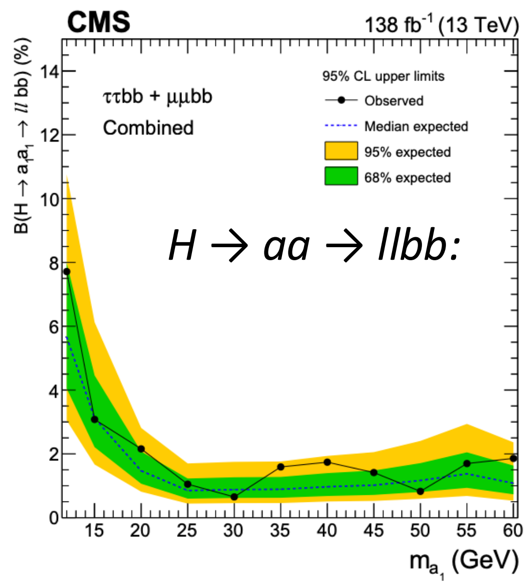
- **First time coverage of the full mass range** between 100 MeV and 62 GeV
- **Most stringent limits to date.**

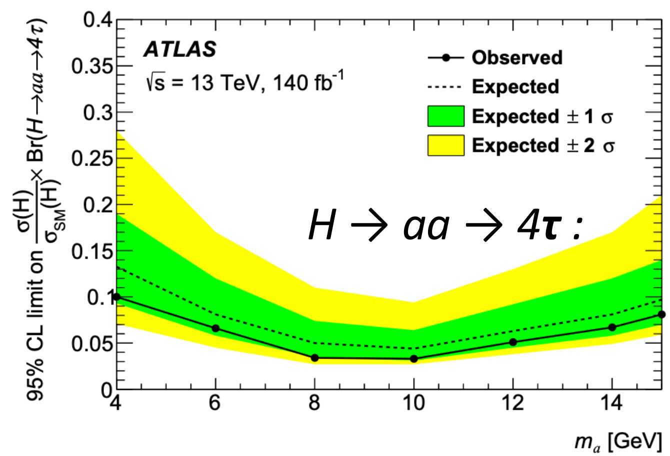
$H \to aa \to 4f$

- ***H→aa →4f*** appear in many well-motivated extensions of the SM: **ALPs, 2HDM + S, etc.** ATLAS and CMS performed various searches covering different final states.









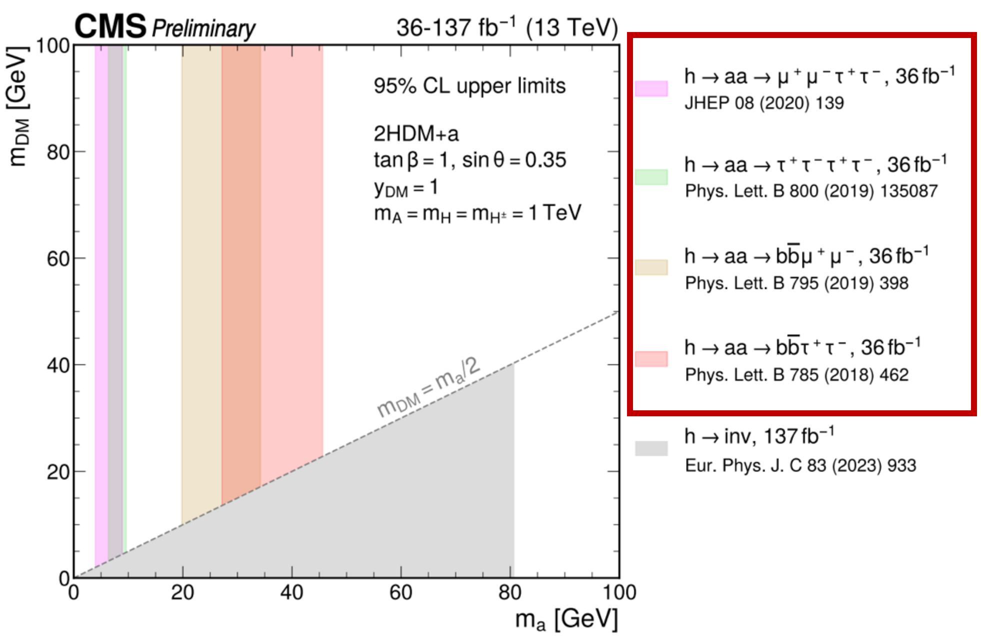
CMS explored signature with **merged electron-positron pairs**: [CMS-PAS-EXO-24-031]

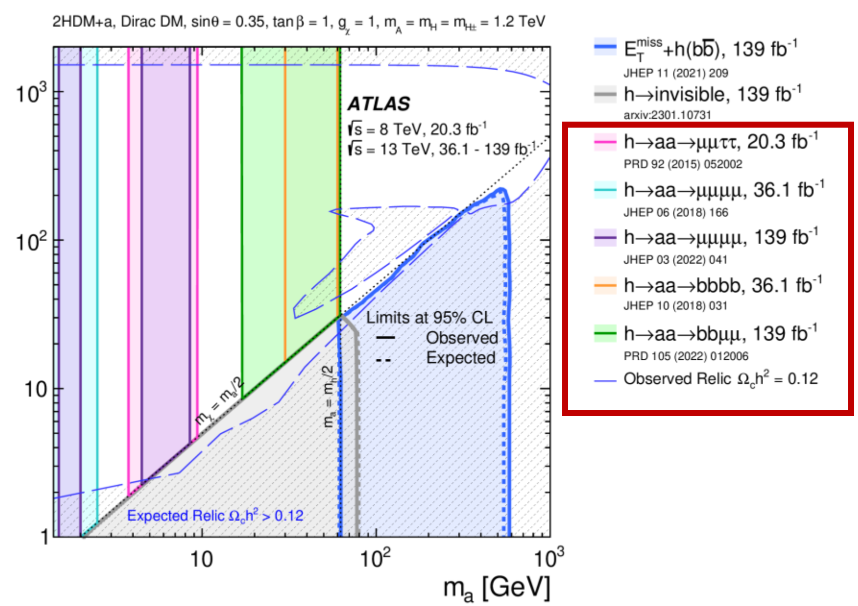
CMS searched for ***ττbb + μμbb:*** [E. Phys. J. C 84 (2024) 493]

ATLAS looked into **Boosted four-τ state** [2503.05463]

Exotic Higgs decay contributes to DM search

- *H→aa →4f* provides a **powerful** and **complementary** probe to **wider LHC search programs**—such as DM search projects in ATLAS and CMS



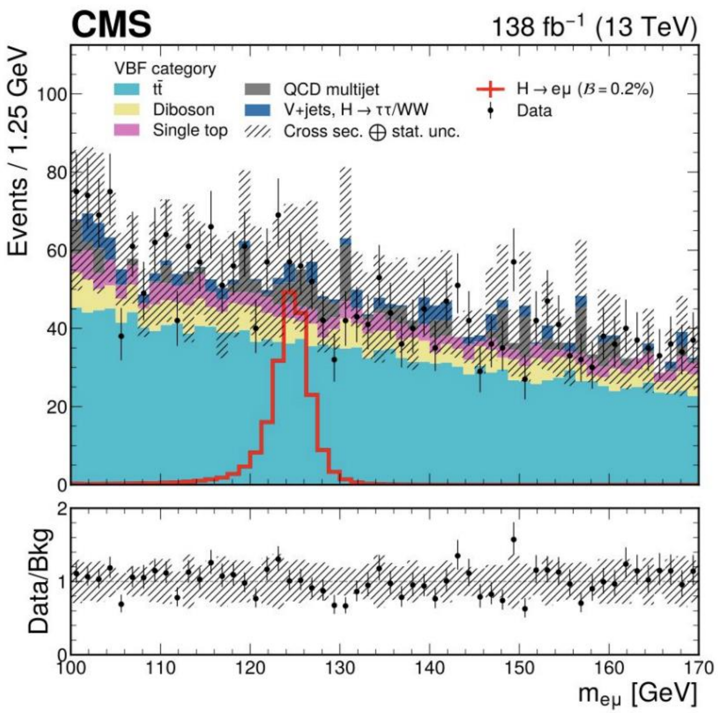


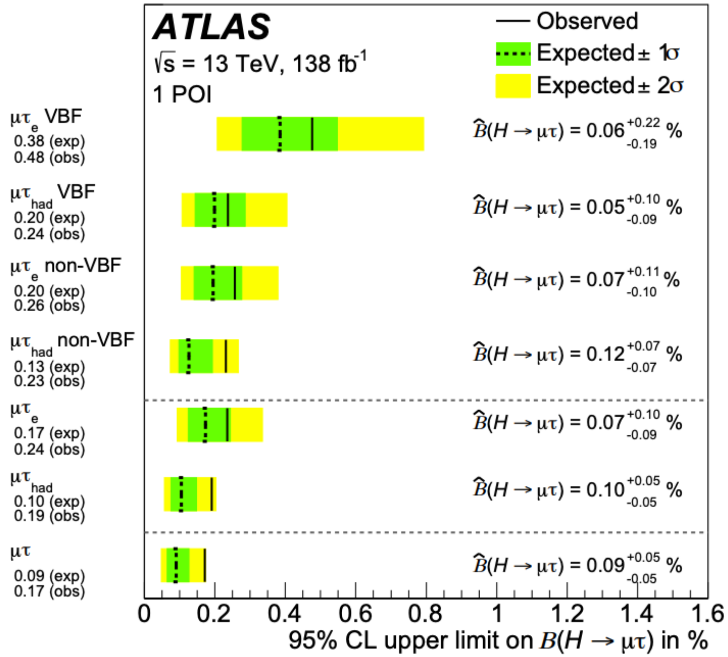
[CMS DM summary plot](#)

[Science Bulletin 69 (2024) 3005](#)

A lepton-flavor-violating **(LFV)** Higgs decay would break this SM rule and signal the presence of new physics

- additional scalar fields, heavy neutrinos, or dark-matter portals…





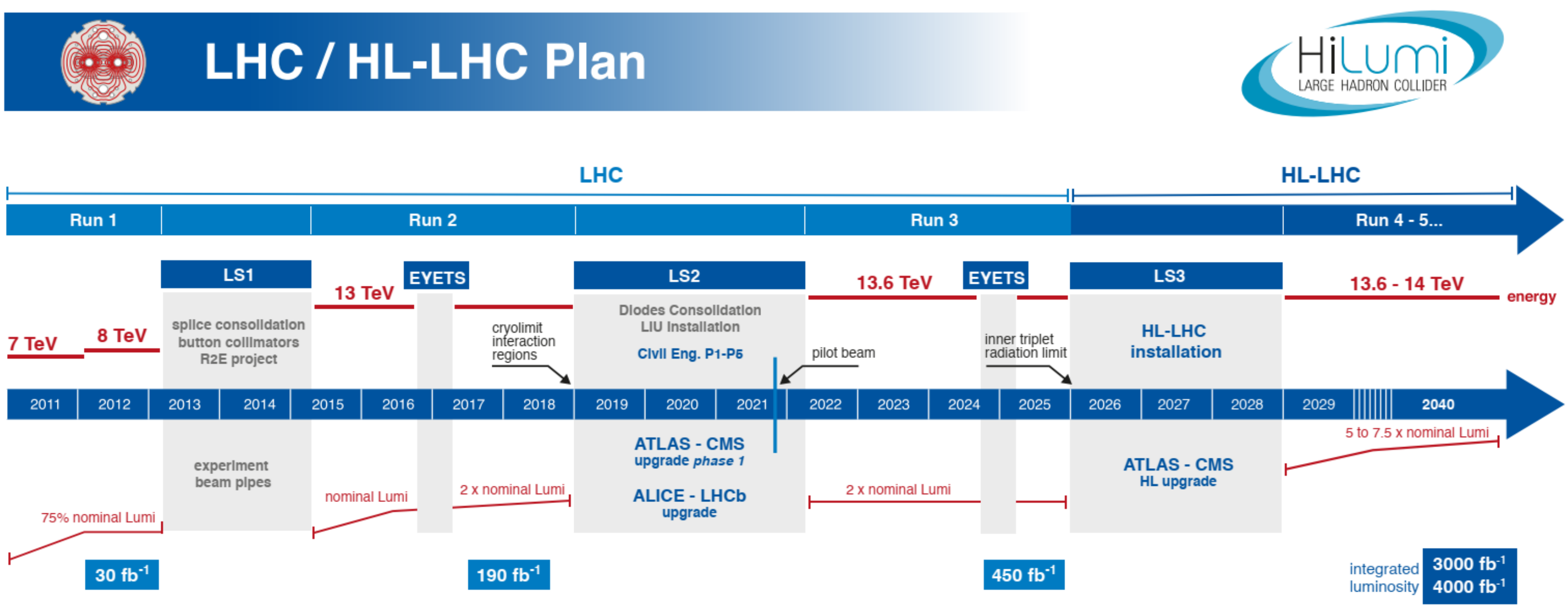
- **CMS result:** [PRD 108 (2023)]
  BR(H→eμ) < 4.4 x 10⁻⁵

- **ATLAS :** *[JHEP 07 (2023) 166]*
  BR(H→eτ) < 0.20%
  BR(H→μτ) < 0.18%

Outlook: LHC and HL-LHC

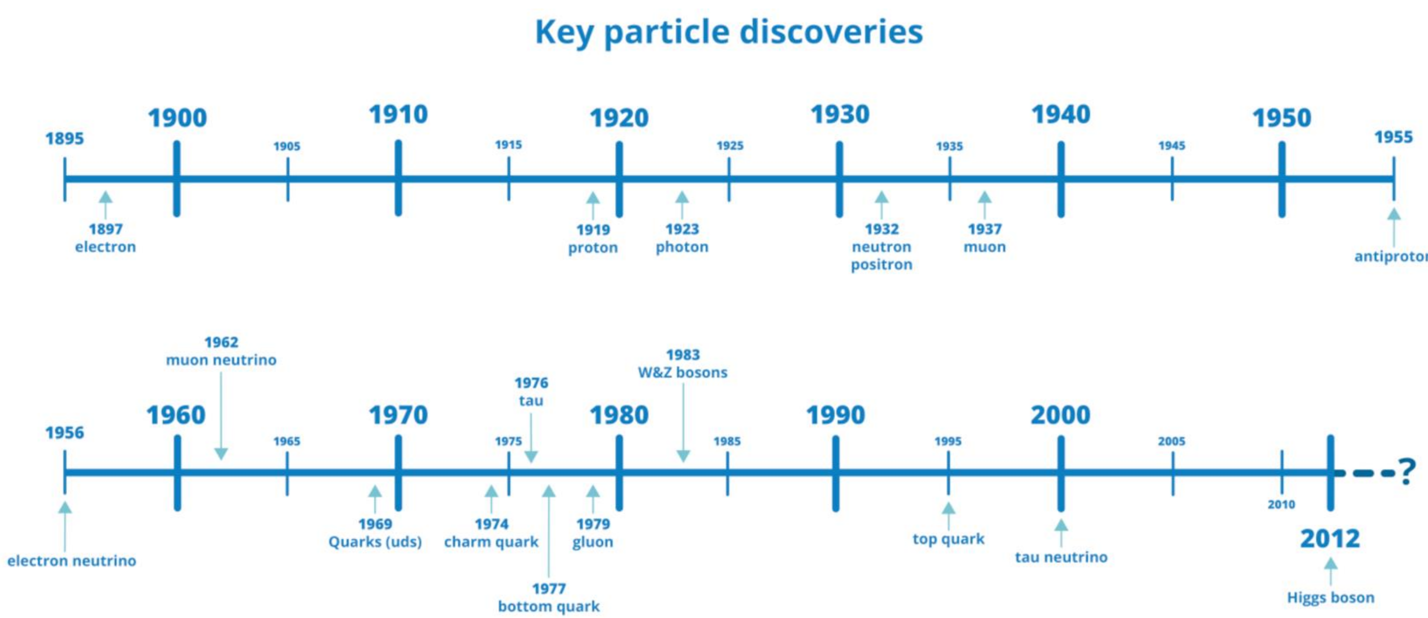
So far, the LHC has delivered **only around 10%** of its ultimate dataset, offering abundant opportunities for **high-precision measurements** and **explorations of new physics**.

Chinese LHC teams have already made substantial contributions—and are well-positioned to drive more highlight results in the run 3 and HL-LHC.



- Many theories, of various degrees of complexity, contain BSM.
- It is important to cover all this ground and also prepare for unexpected, not-yet-theorised discoveries, with **Higgs as a key portal.**

No stone must be left unturned till probing the New Physics!



Thanks

LHC

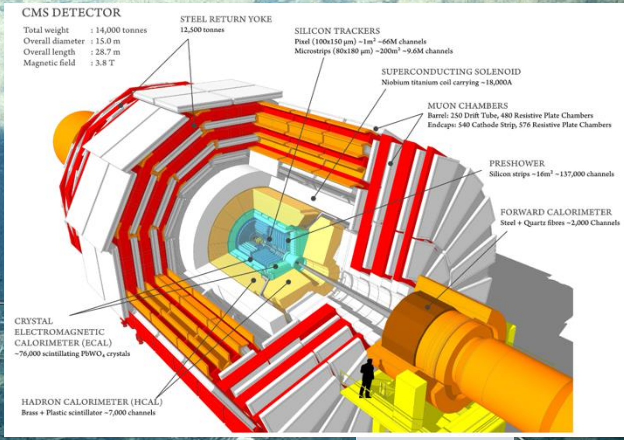
ALICE

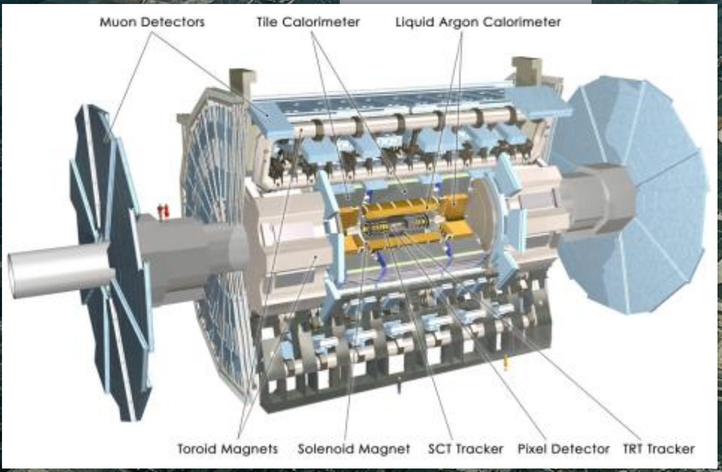
CERN

ATLAS

CMS

LHCb





LHC: 27 km, the world's largest proton-proton collider (7-14 TeV).

~10% of planned total dataset collected so far.