The Course to New Physics

Recent Highlights from CMS

Cosmo-Astro-Particle Symposium (CAP 2025)
The 19th TeV Workshop

Zirui Wang

Beijing China
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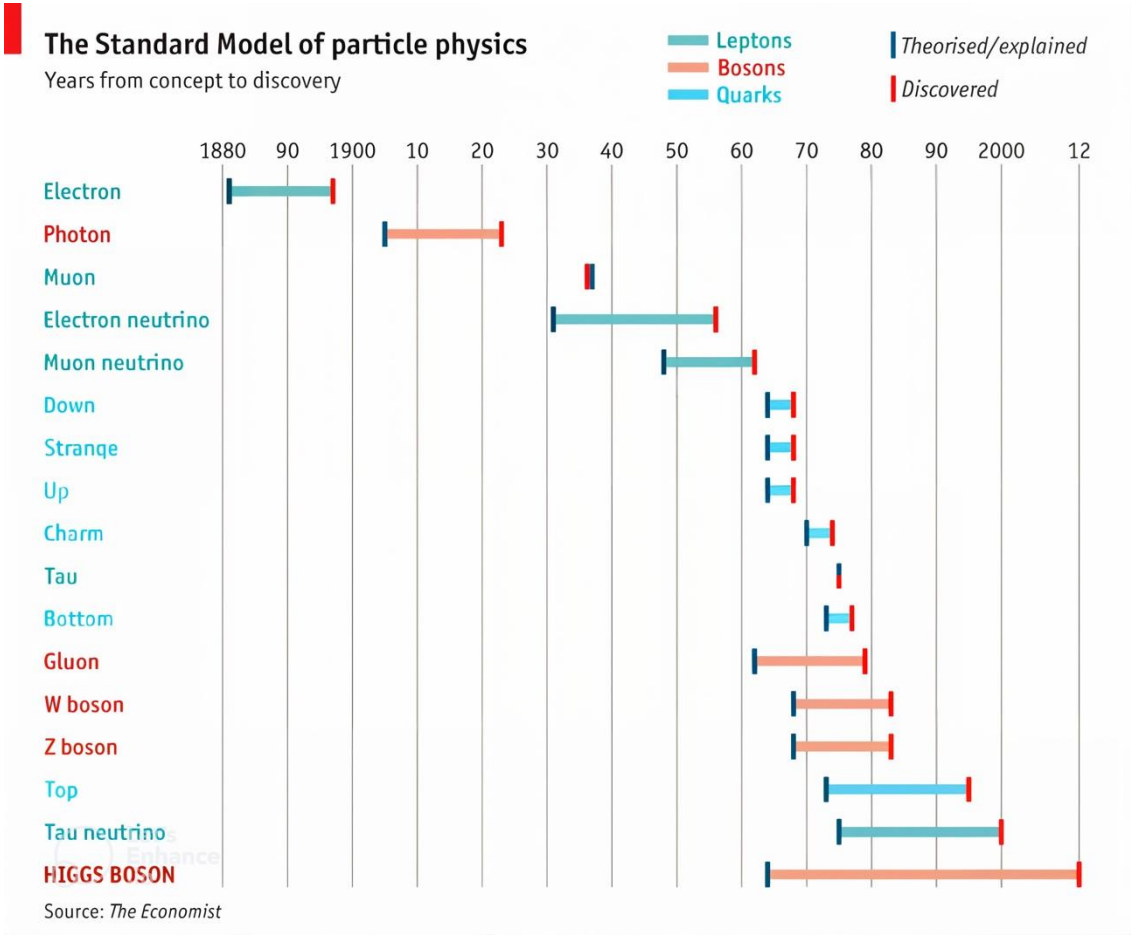
FUDAN UNIVERSITY

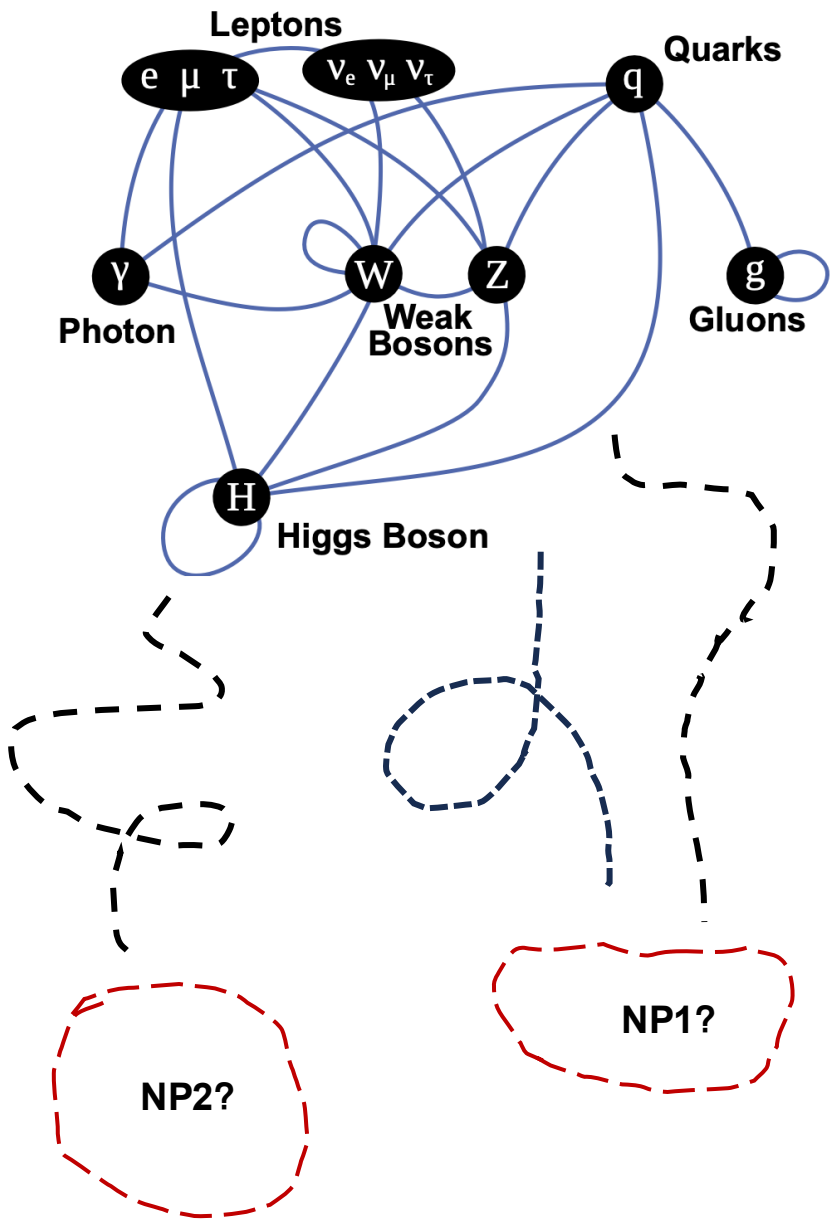
Theoretical and Experimental Particle Physics
have revealed much about the nature of our universe



Economist

Higgs boson, discovered on July 4th, 2012, by **ATLAS** and **CMS** experiments on **LHC**
Completed the last piece of the SM particle content.

Chart the course to BSM



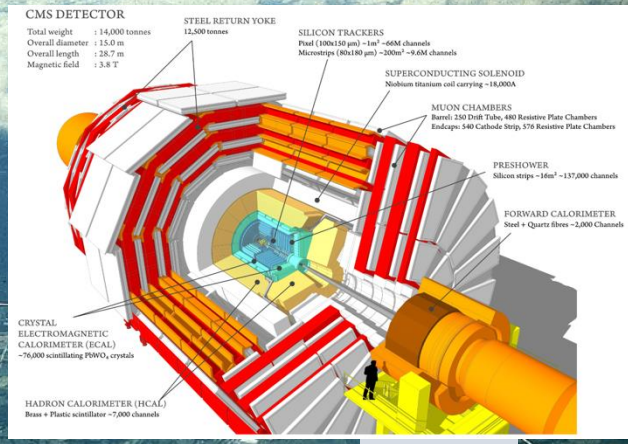
The discovery of Higgs boson completed the last piece of the SM particle content.

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
- …

Many **new physics** aiming to address those fundamental scientific questions. The experimental search for them is the crucial course we must chart.

LHC and CMS



CMS

ALICE

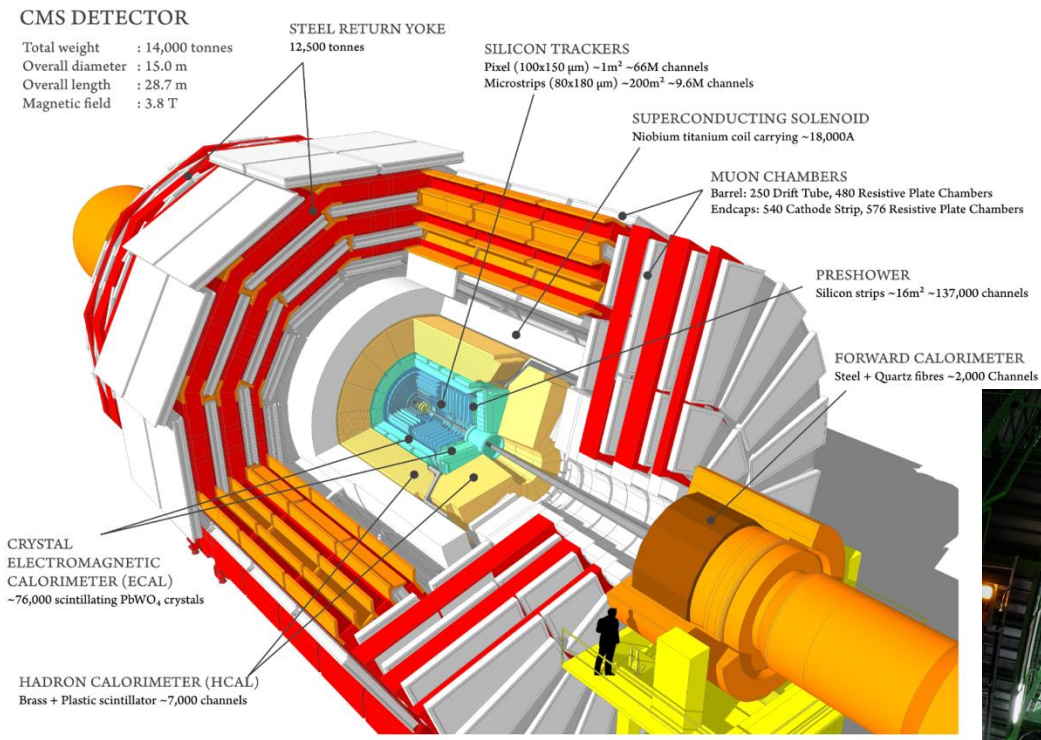
CERN

ATLAS

LHC: 27 km, the world's largest proton-proton collider (7-14 TeV).
~10% of planned total dataset collected so far.

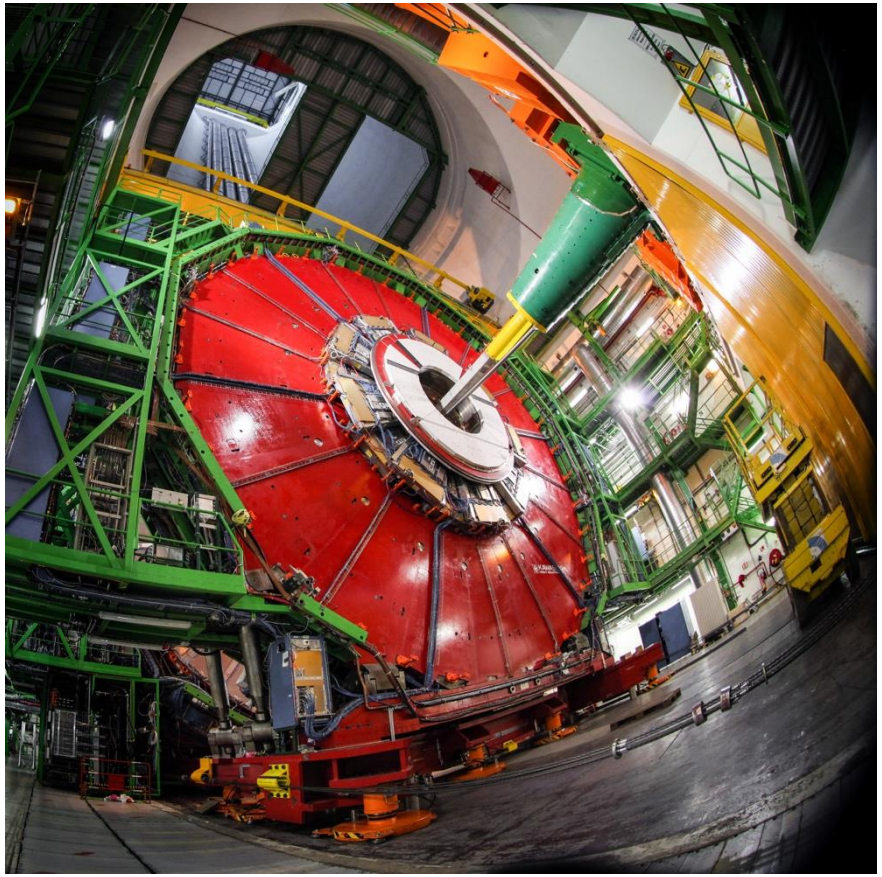
LHCb

CMS: Compact Muon Solenoid



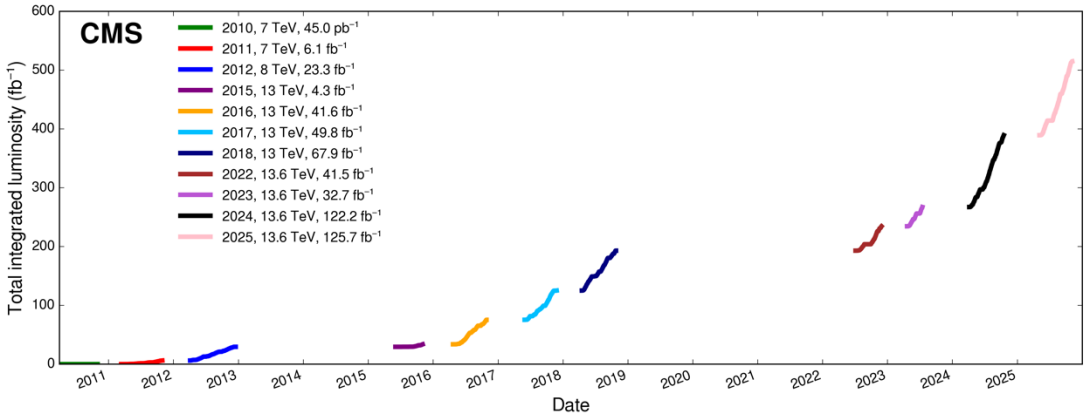
Multi-purpose experiment: Higgs sector physics, SM precision measurements, BSM searches…

Several sub-detectors nested around the LHC collision interaction point



Run 3 Data Taking

LHC pp collision integrated luminosity



Run 3

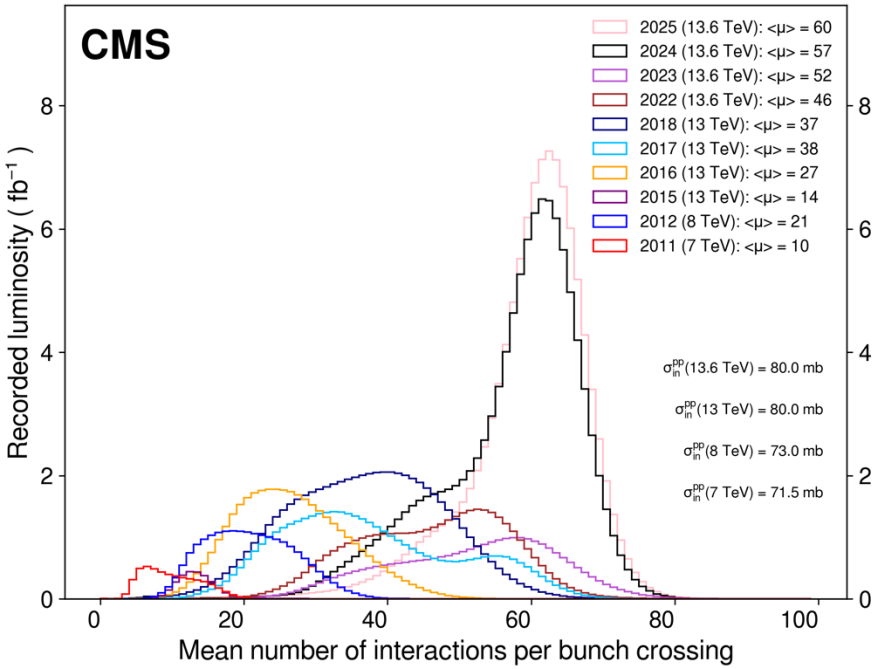
322 fb^{-1} (13.6 TeV, as of 2025)

Run 2

165 fb^{-1} (13 TeV)

Run 1

6 fb^{-1} (7 TeV) + 23 fb^{-1} (8 TeV)



Higher luminosity

larger pileup + vertex density

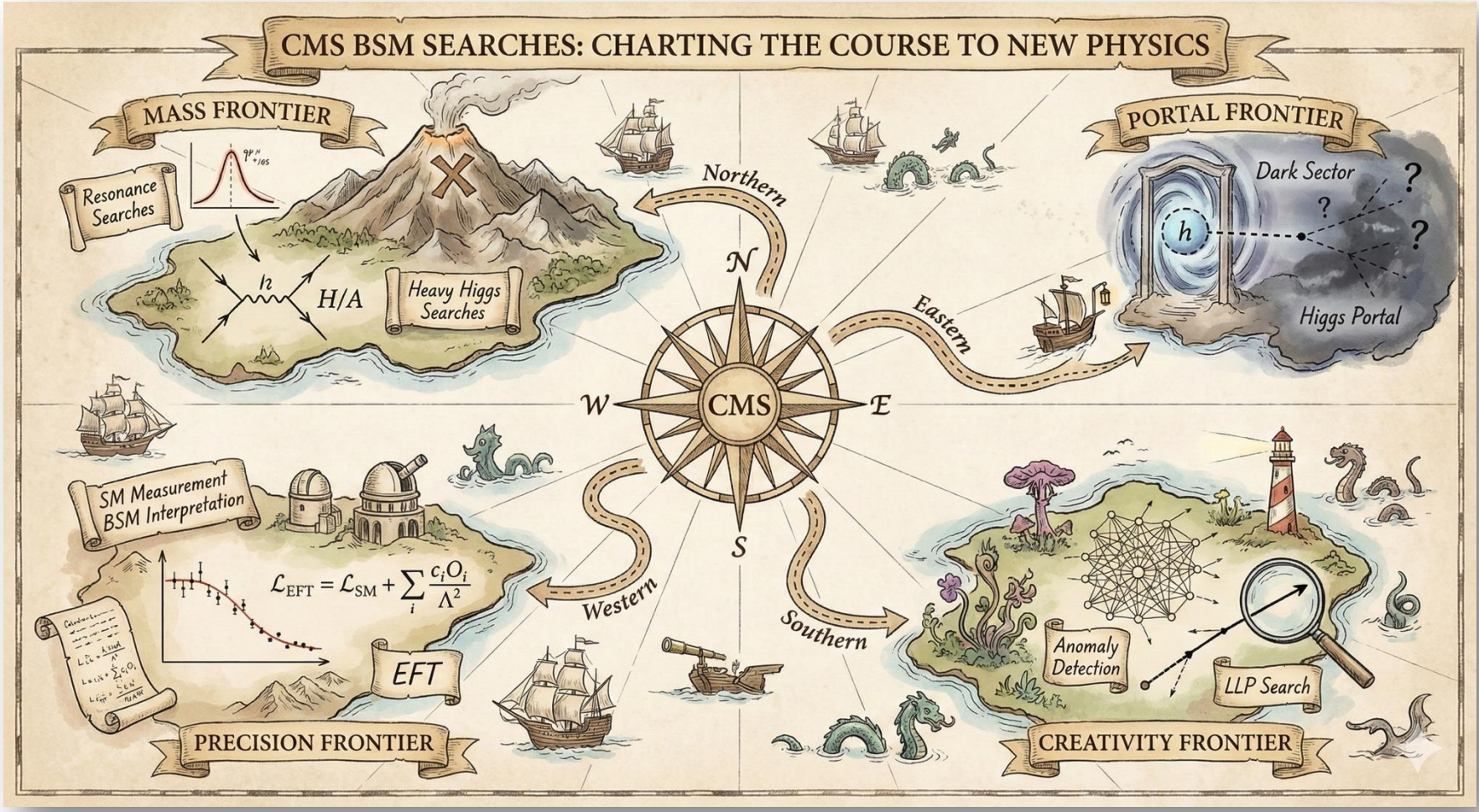
The Collaboration and CMS China Group

The CMS collaboration:

- 58 Countries/Regions
- 246 Institutes
- 6,100 Active CMS Members
  - 2,100 Scientists
  - 1,200 PhD Students

CMS China Group:

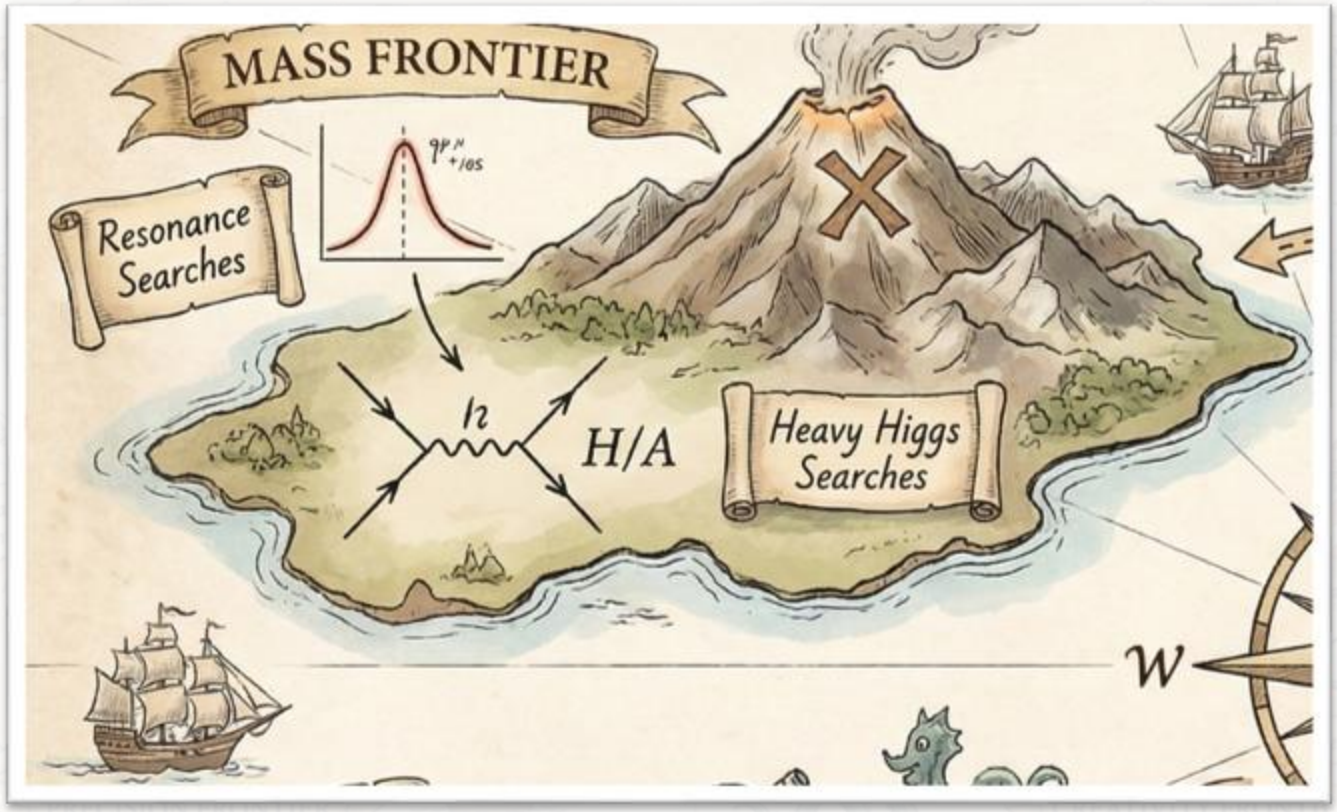
- 11 Institutes
- Over 200 members



Let's explore recent CMS highlights from these frontiers (credit: Nano Banana)

Caveats:

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

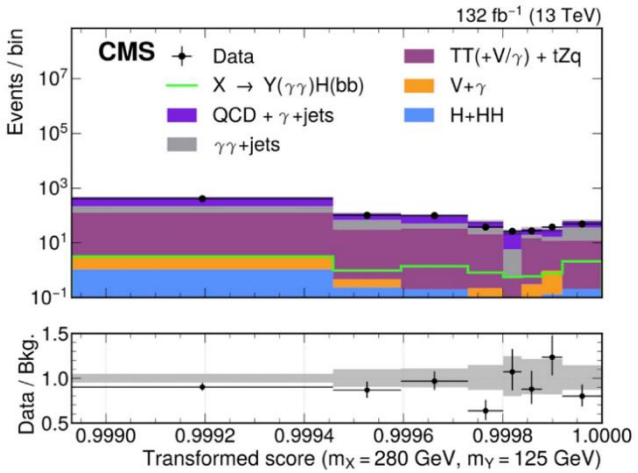


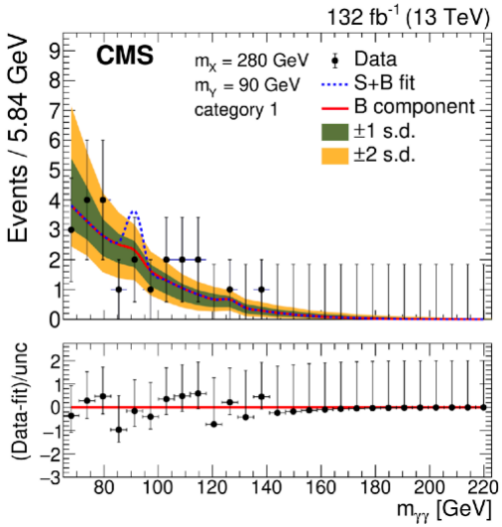
➤ Focus on searches for hypothetical particles that would appear as high-mass resonances, **using the full energy of the LHC**. This is where the highest TeV scale searches live.

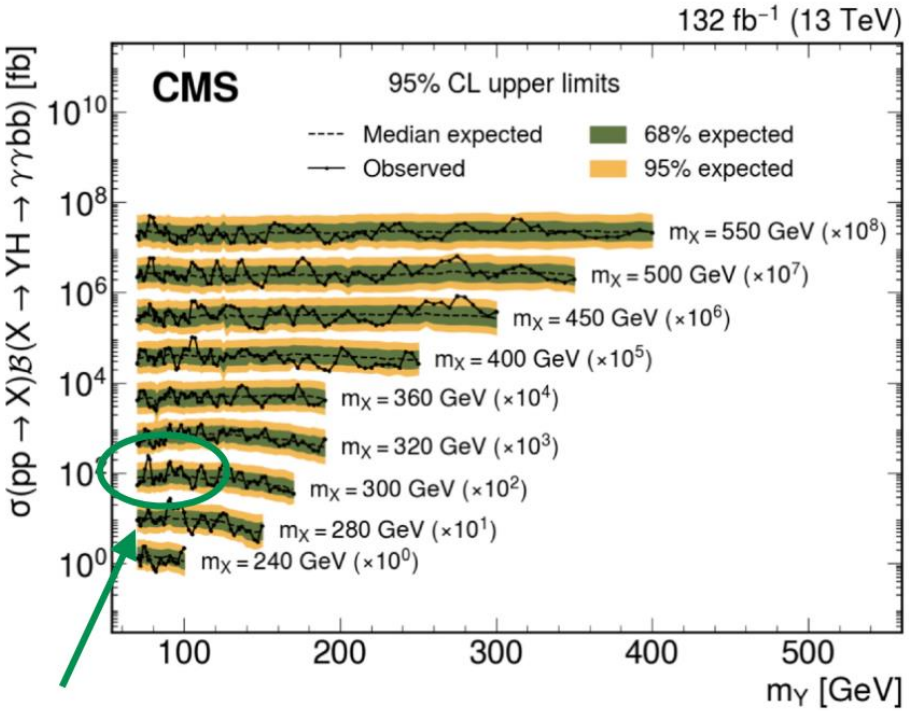
$X \rightarrow Y h_{125} \rightarrow \gamma\gamma bb$

- **Search range:** 240 -1000 GeV for resonance X and 70-800 GeV for scalar Y
- **Discriminant:** parametrised NN and $m_{\gamma\gamma}$ spectrum
- **95% CL observed upper limits**: 0.05-2.69 fb

2508.11494



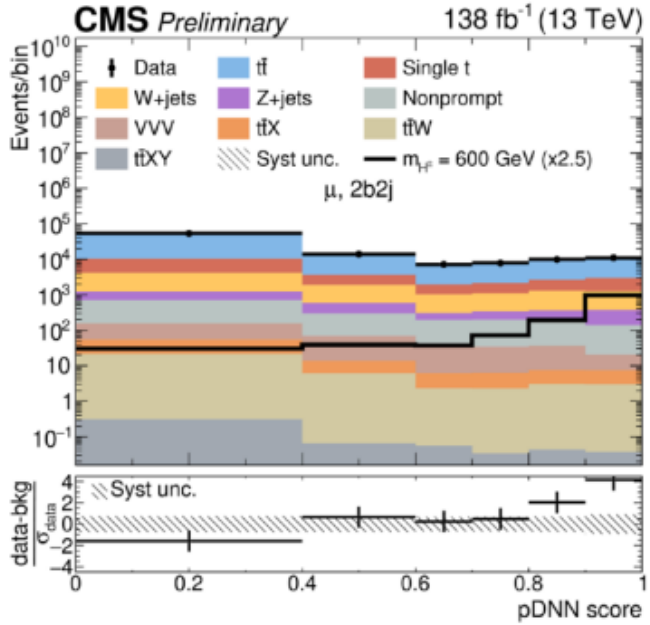


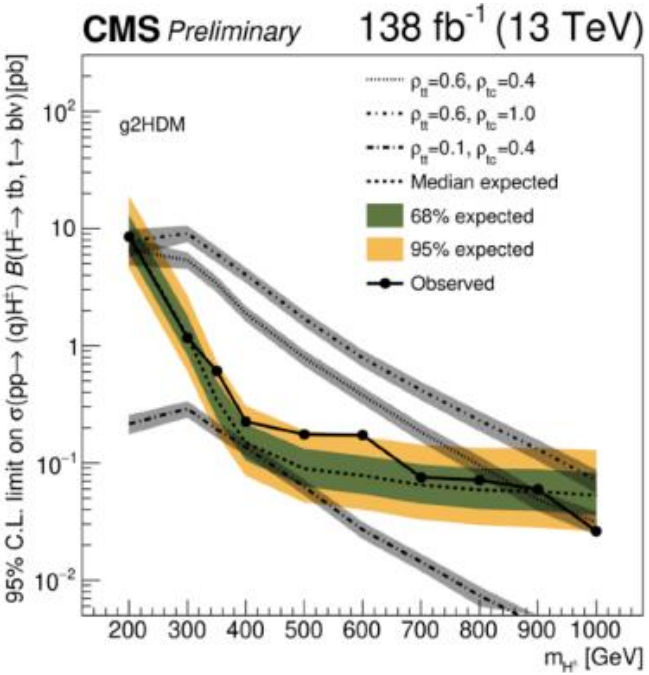


excess at $m_X = 300$ GeV, $m_Y = 77$ GeV

local (global) significance 3.33 (0.65)σ

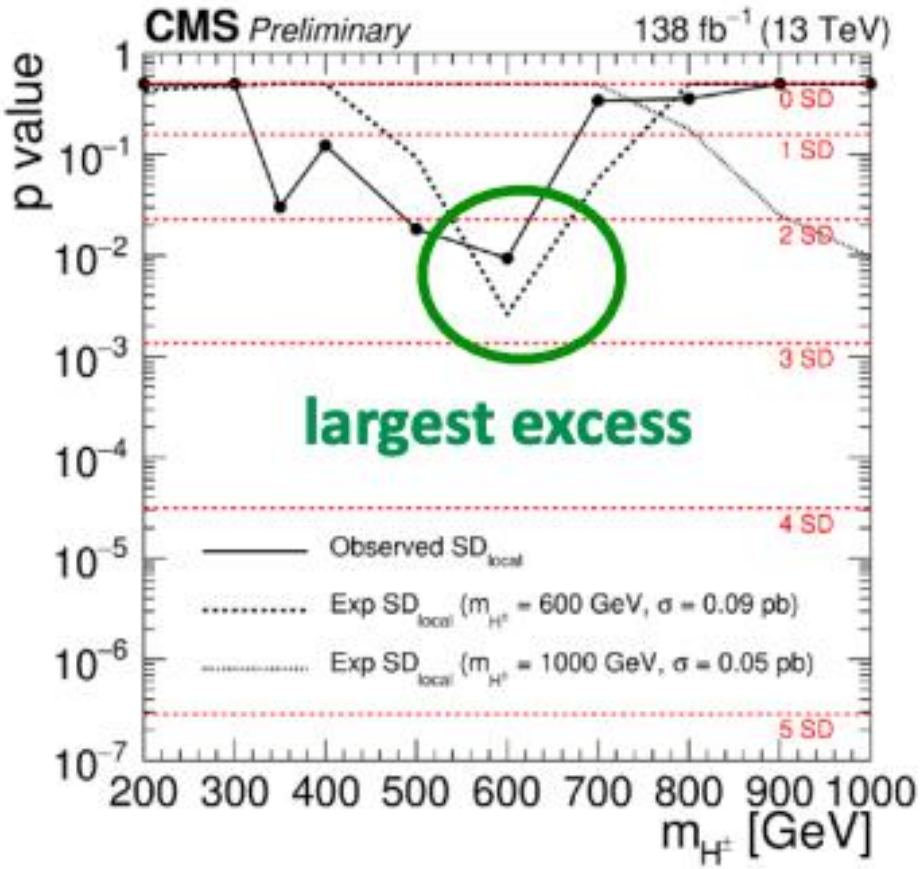
$H^{\pm} \longrightarrow tb$





[CMS-PAS-B2G-24-008]

- **Searching range:** 200-1000 GeV
- **Discriminant:** PNN parametrised by the signal mass



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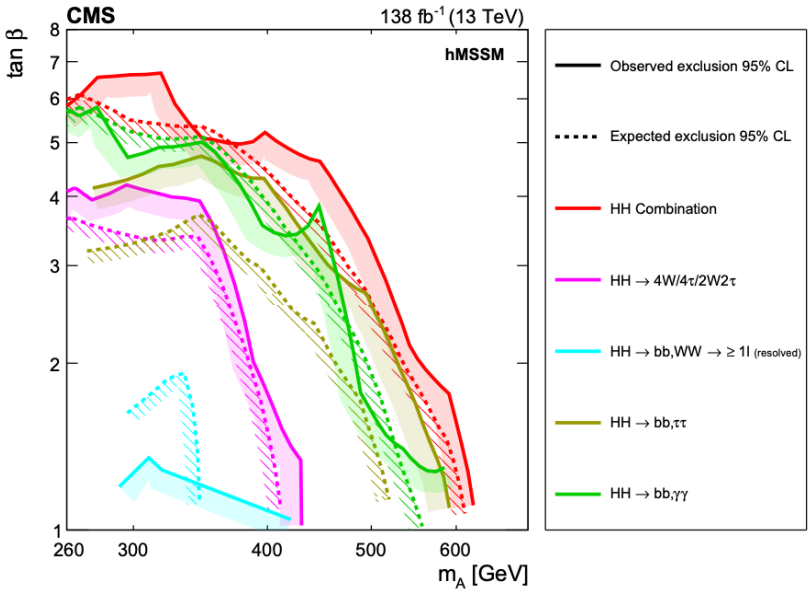
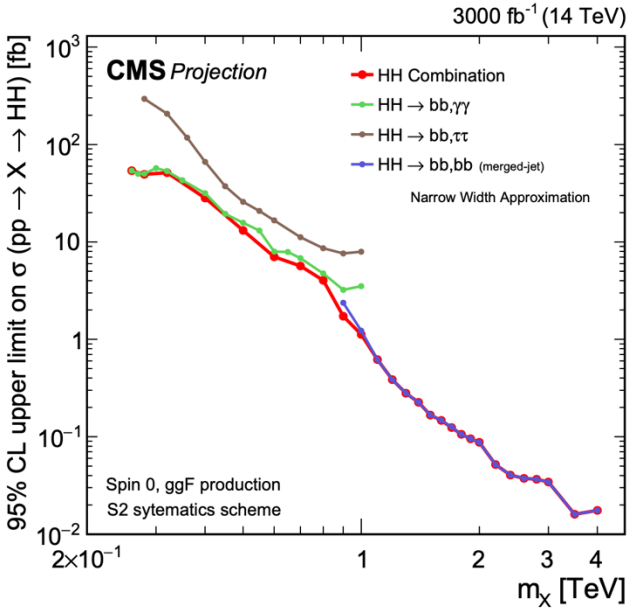
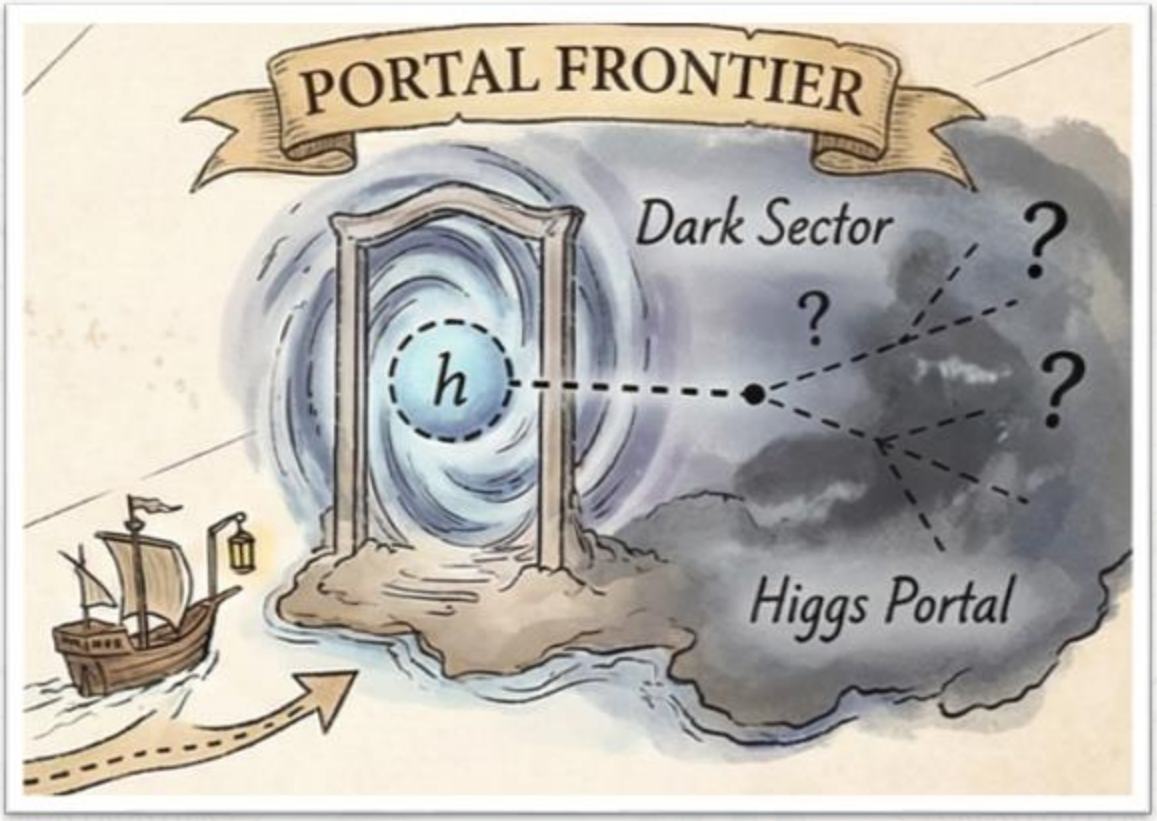
Comprehensive Review: Covers all CMS Run 2 searches for heavy resonances X decaying into at least one Higgs boson.





- First systematic CMS study on the validity of the **NWA** in resonant HH searches.
- Discovery potential extrapolated to HL-LHC
- Limits set on production cross-sections vs. Mass for various benchmarks, driving the strategy for Run 3.

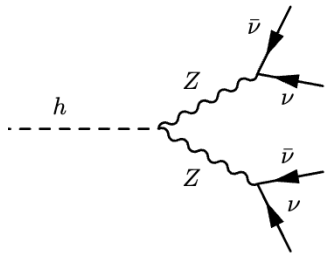


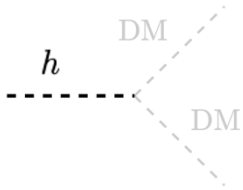
➤ Focus on searches that look for "portals" or mediators connecting the Standard Model particles to the **hypothetical exotic particles** and **dark matter.**

Search for Higgs invisible decay on LHC

A unique gateway on LHC :

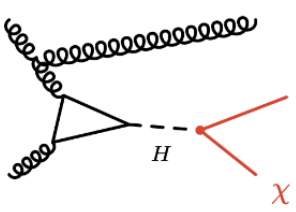
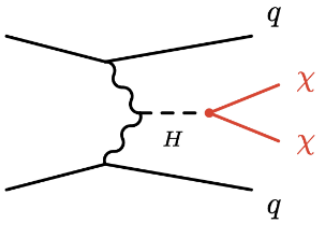
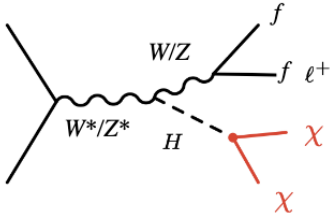
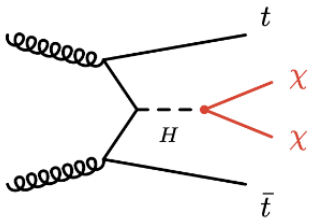
- H decays to a pair of stable WIMPs.



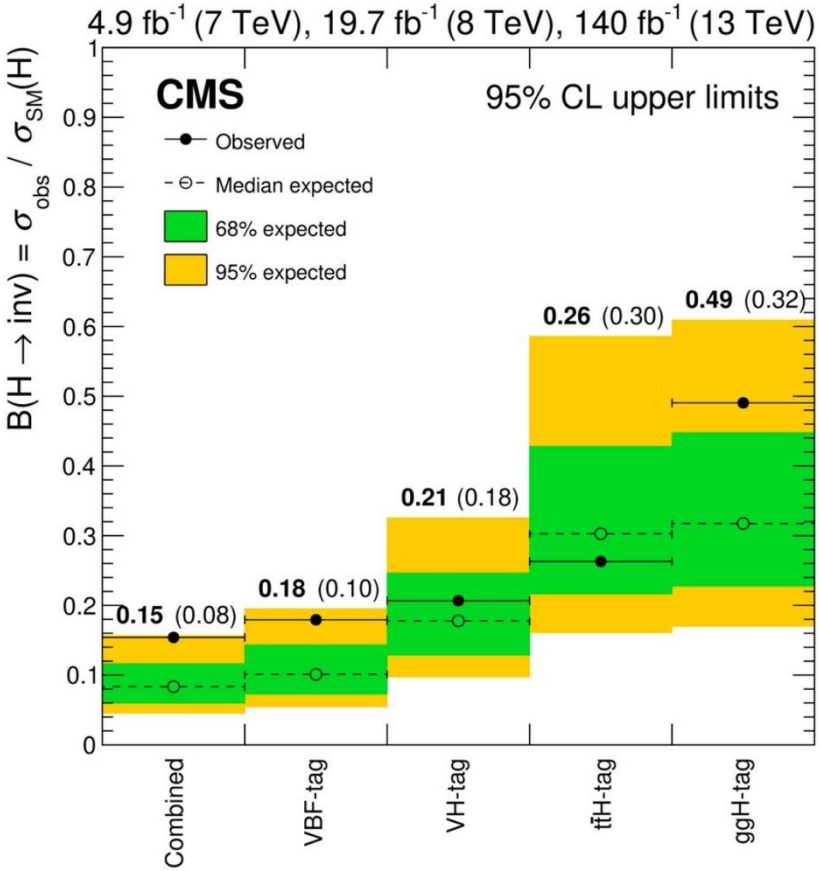


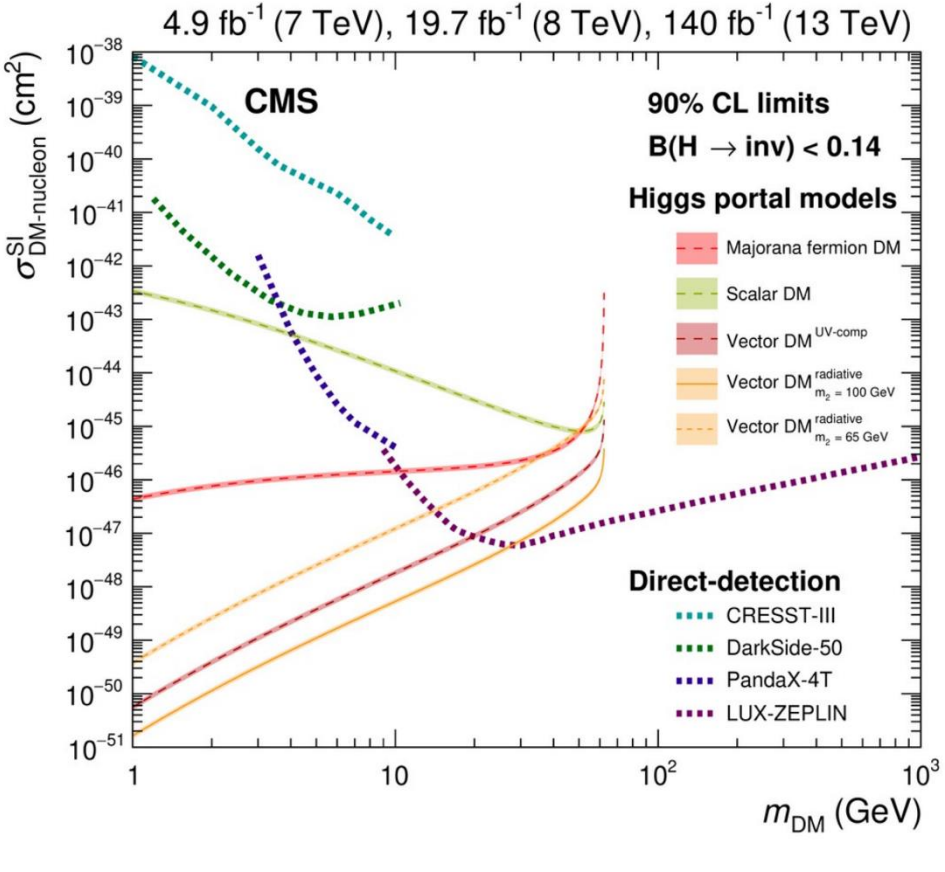
SM BR(H→inv) ~**0.12%**

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 + ɣ	Z(ll) + MET, mono-largeR jet	tt + MET
Sensitivity	**Low**	**High**	**Intermediate**	**Intermediate**

H→inv combination





Statistically combined All H→inv searches:

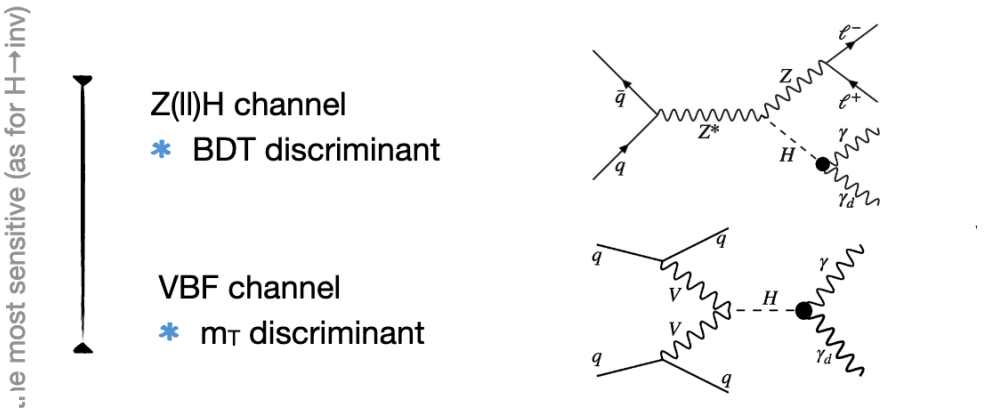
CMS: BR(H→inv) < 15% (8%) EPJC 83 (2023) 933

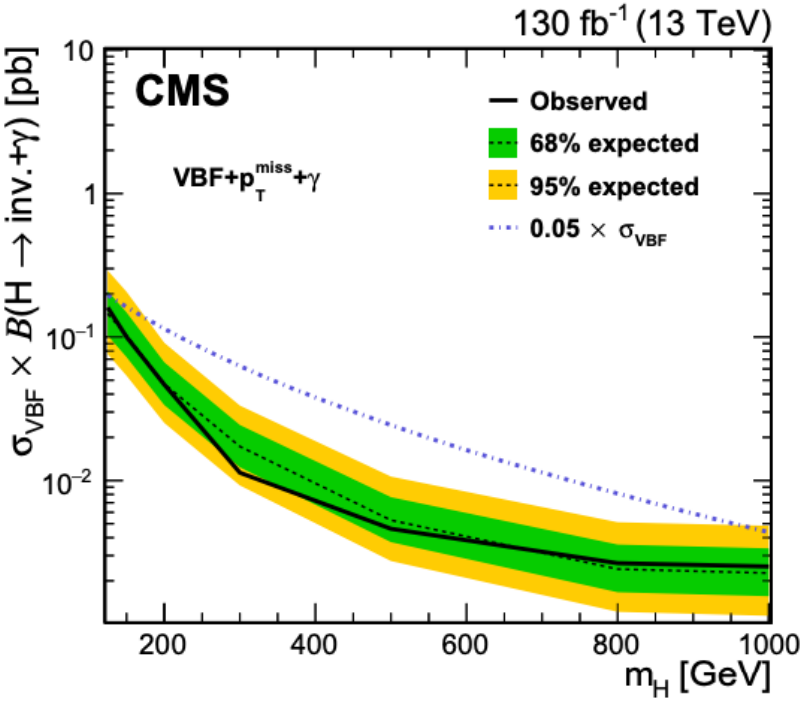
ATLAS: BR(H→inv) < 10.7% (7.7%) PLB 842 (2023) 137963

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

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





95% U.L. on BR($H_{125}\rightarrow\gamma\gamma_D$):

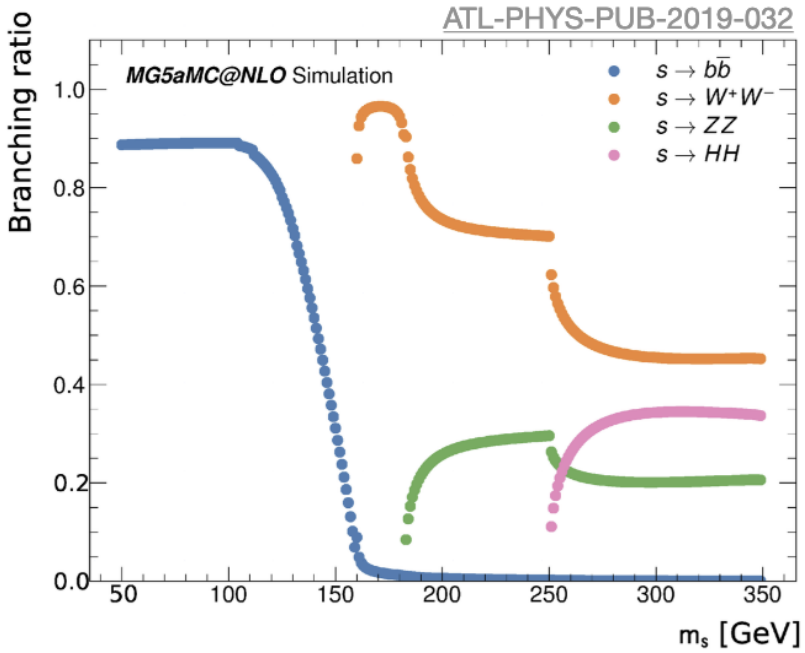
VBF channel: 3.5% (2.8%) *JHEP 03 (2021) 011*

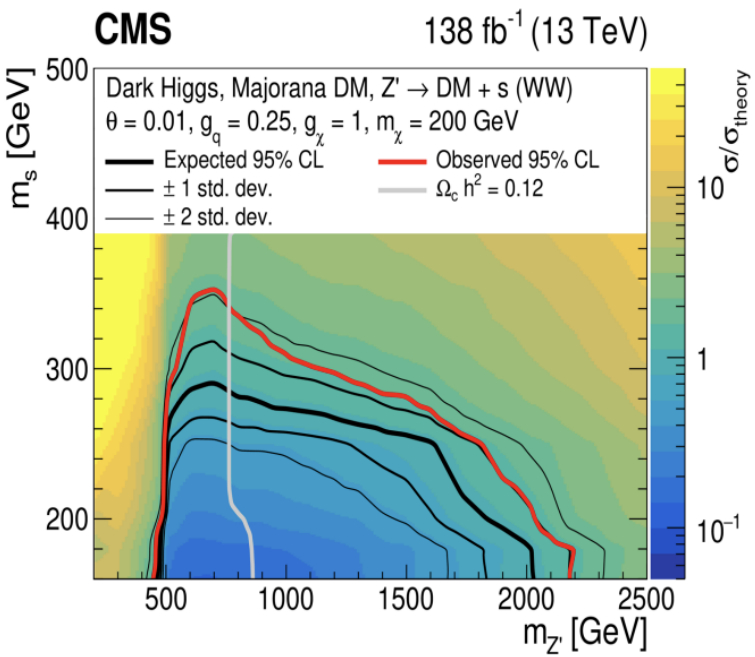
ZH channel: 4.6% (3.6%) *JHEP 10 (2019) 139*

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

Search for "Dark Higgs"

- **Dark sector model** with **a scalar** (dark Higgs)
- Mediator *Z'* coupling to DM g_χ floating in different benchmarks.

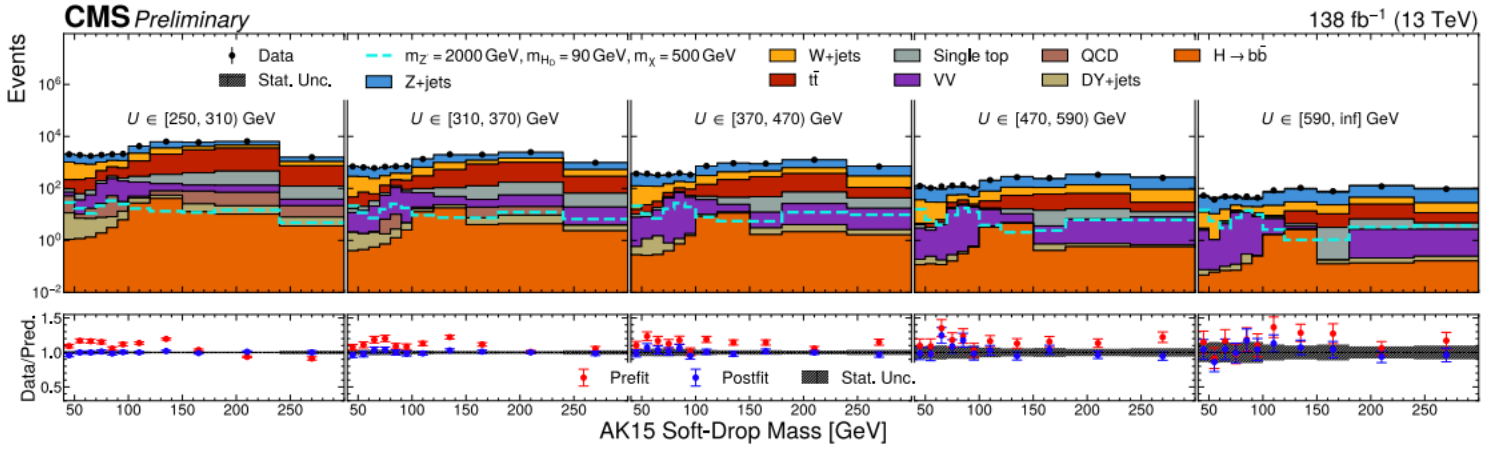




CMS existing result: ***s → WW→2l2ν/lνqq'***
JHEP 03 (2024) 134

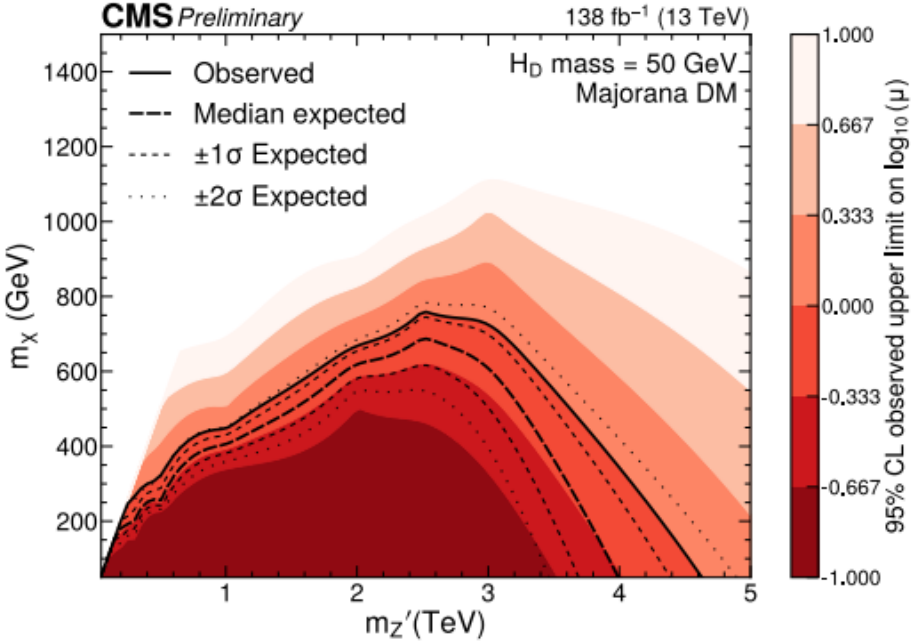
Parameter space: Mases of BSM particles and couplings
Yukawa-like couplings favours different final states for different mass scenarios.

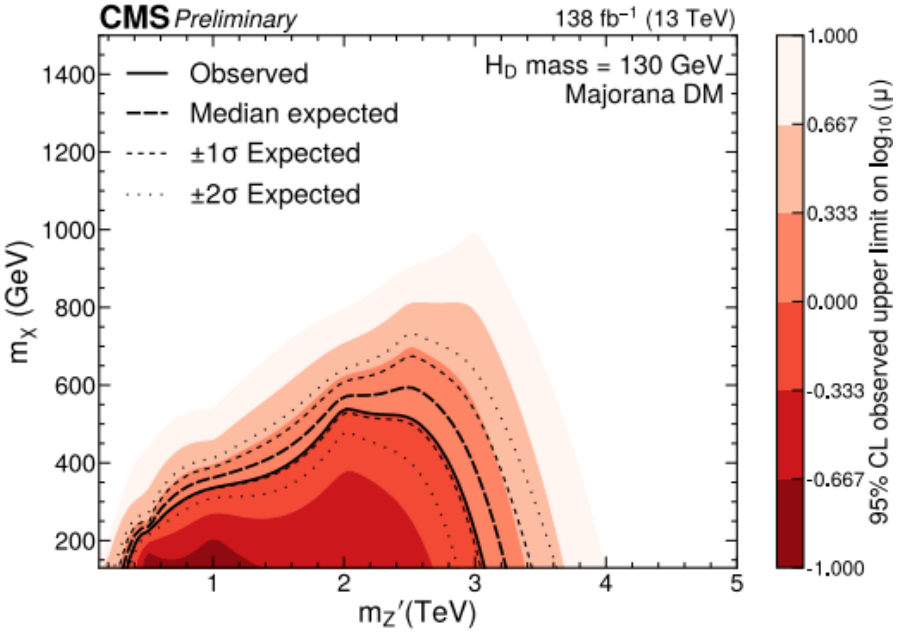
1st time investigate s ⟶ bb on CMS



Z' candidate p_T reconstructed by the hadronic recoil (>250 GeV)

PAS-SUS-23-013

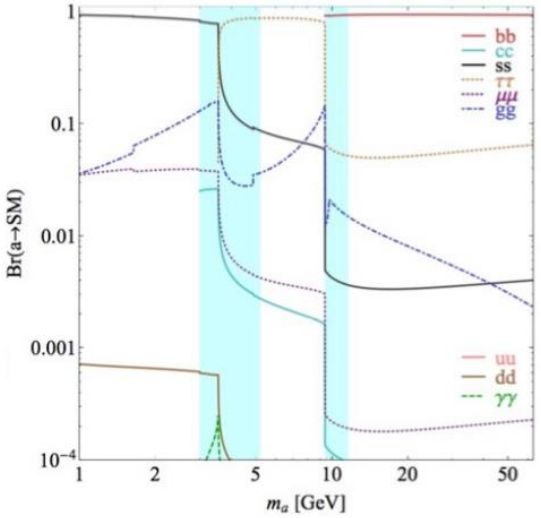


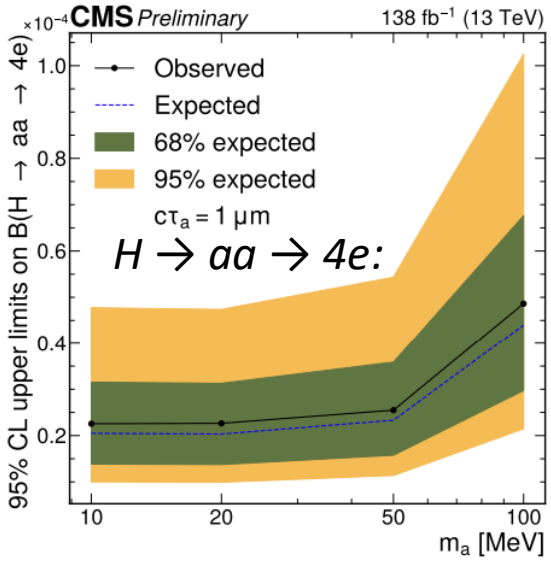


Z' between 2.5—4.5 TeV excluded depending on the Dark Higgs mass (<150 GeV)

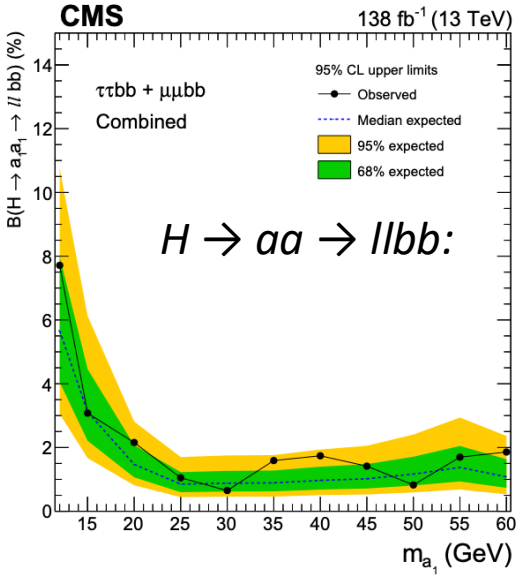
Higgs exotic decay

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





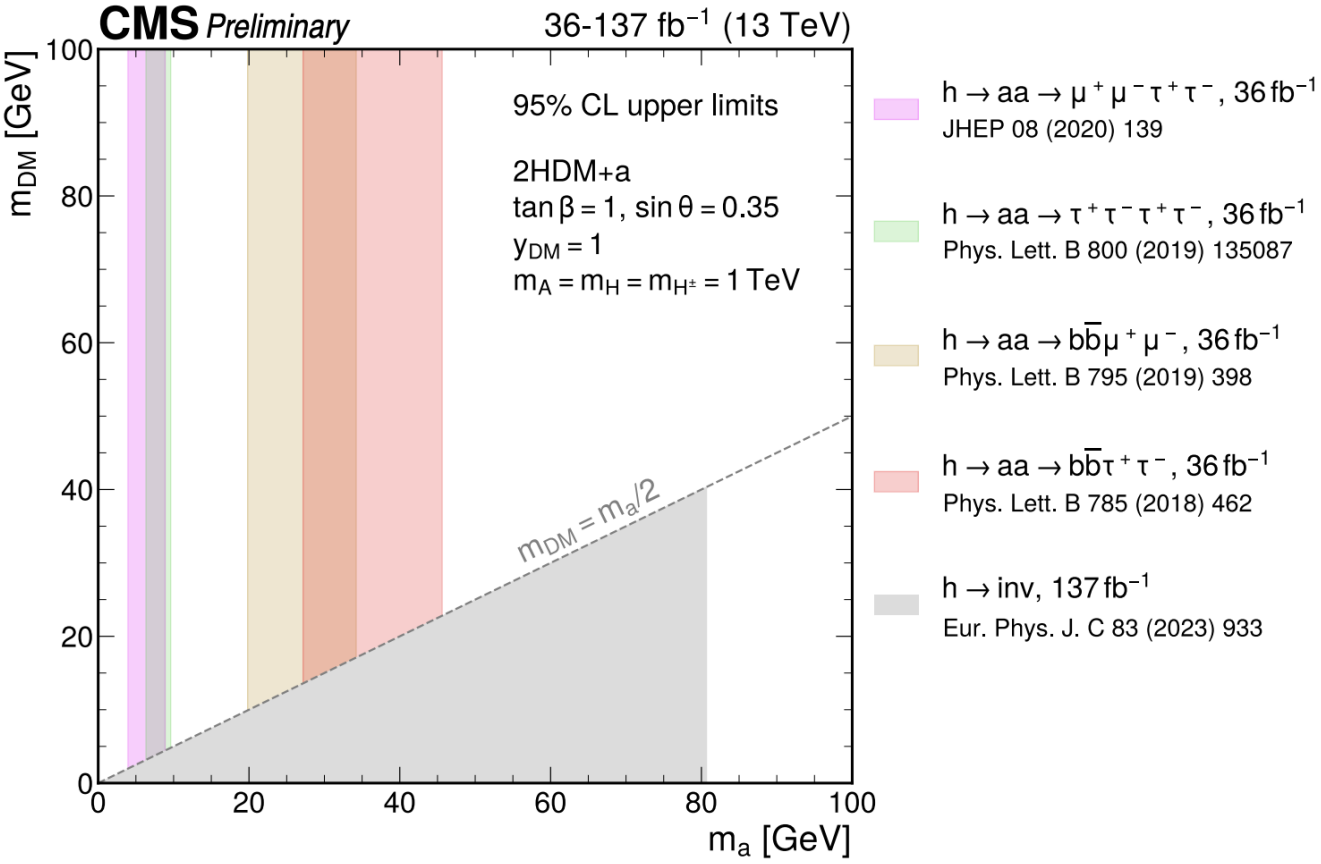
merged electron-positron pairs:
[CMS-PAS-EXO-24-031]



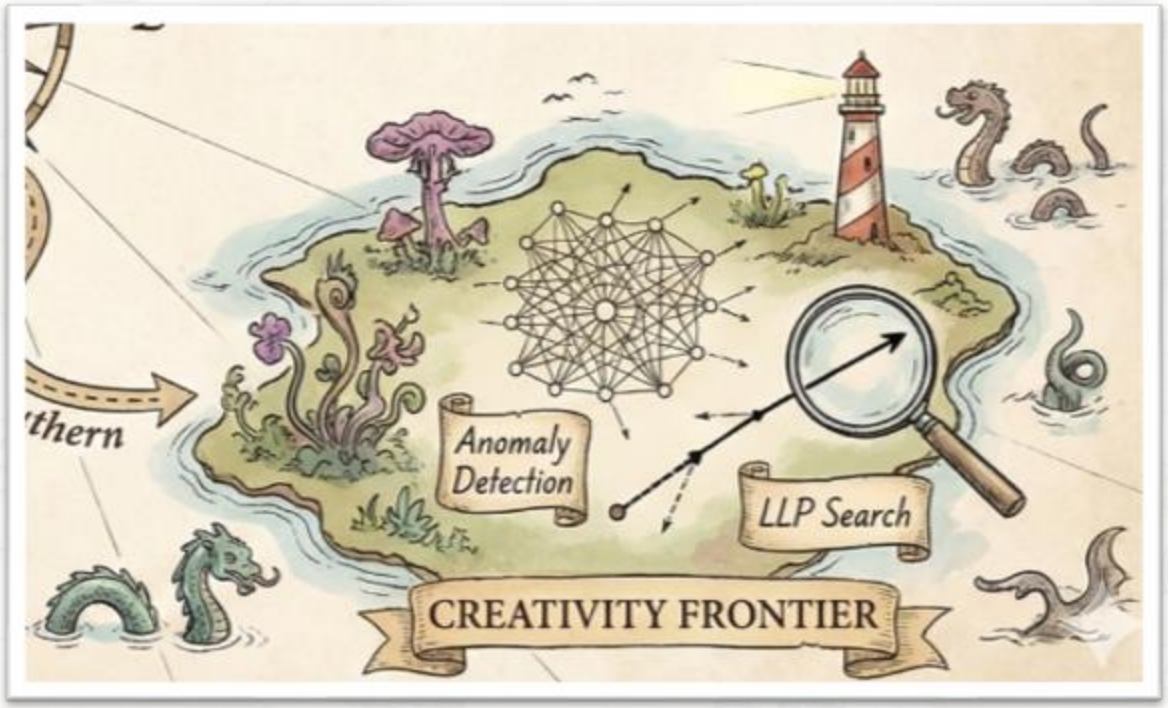
ττbb + μμbb:
[E. Phys. J. C 84 (2024) 493]

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



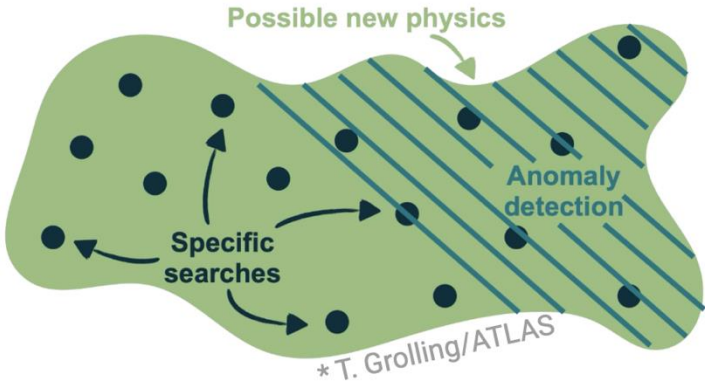
➤ This is a hot, unique area that often requires innovative detector techniques, dedicated reconstruction algorithms and search strategies.

First Anomaly Detection Result from CMS

When we search for BSM

- Have we looked for the **right model**?
- Have we even **imagined the right model**?

- Model-independent, ML-enhanced anomaly detection searches cover these cases

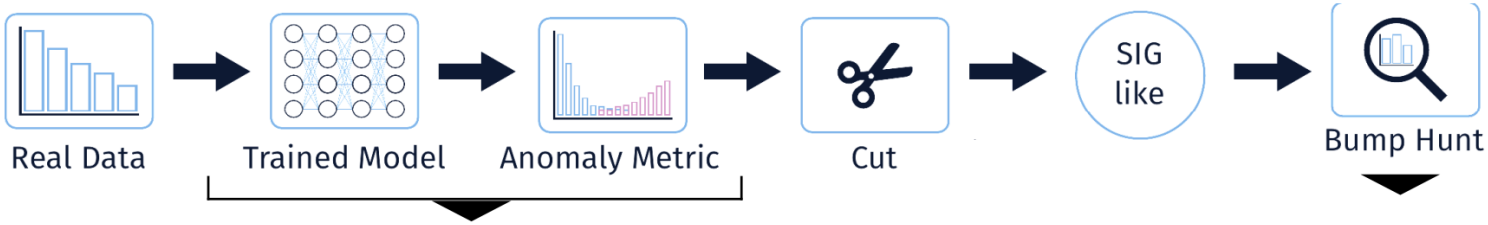


Rep. Prog. Phys. 88 (2025) 067802

Start from data

Anti-k_T jets with $R = 0.8$
Basic selection criteria

Keep ~1% most anomalous events



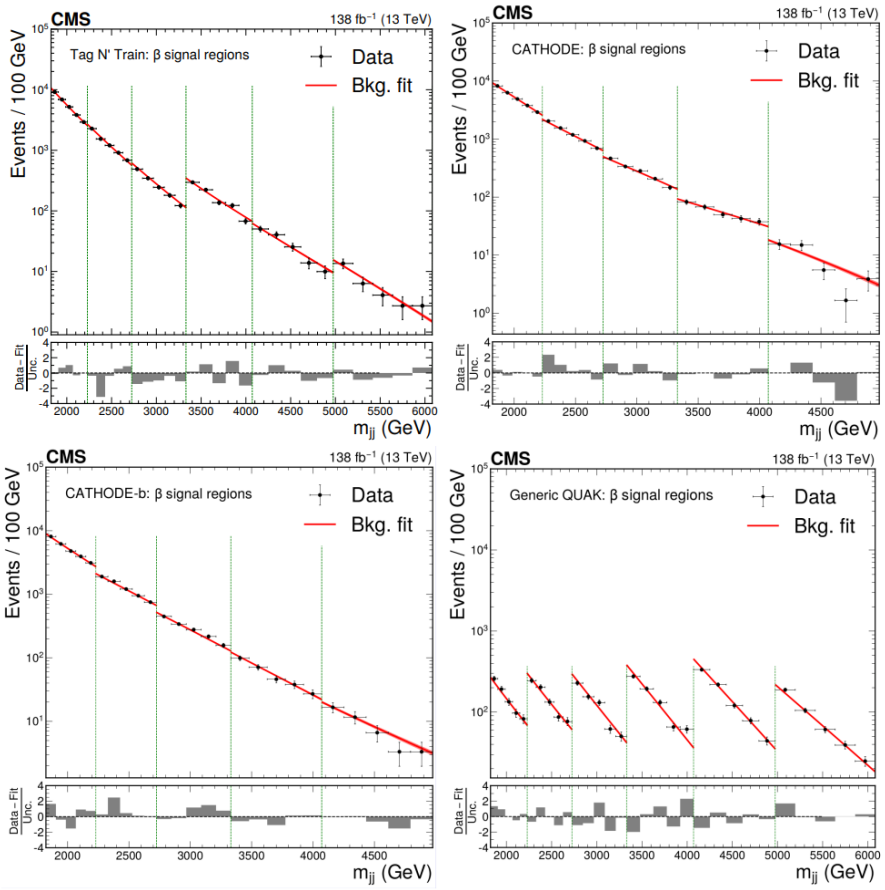
5 anomaly detection methods

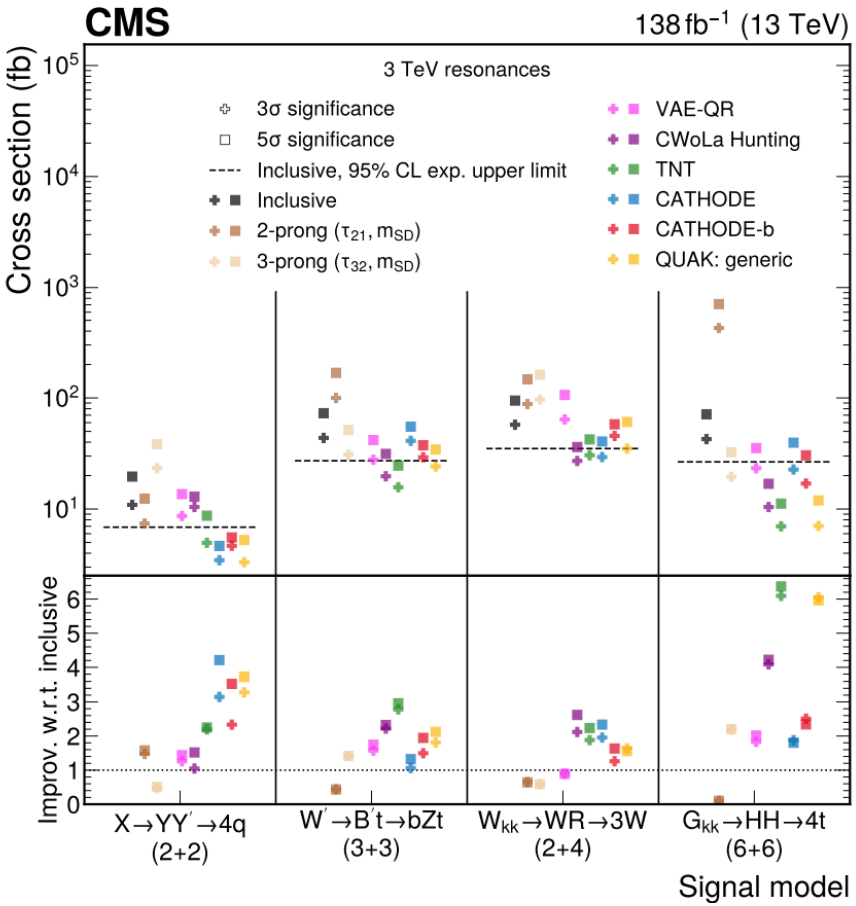
CWoLa Hunting / TNT / CATHODE(-b) / VAE-QR / QUAK

Resonance?

Fit m_{jj} spectrum and obtain significance

First Anomaly Detection Result from CMS





Results extracted from bump hunt in m_{jj}

- Selection differs per signal region
- **No significant excess from any method**
- **Most comprehensive constraint** on model-agnostic new physics signals

AD improve over an inclusive m_{jj} fit on all 4 signal models

- **Large discovery potential**

Search for Long Lived Particles

LLPs are common in many BSM scenarios

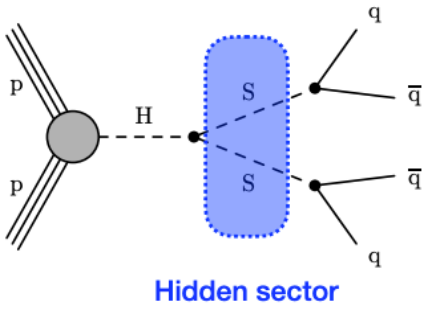
- Small relevant coupling
- Suppressed decay
- Small allowed final state phase space

Rich signatures produced by BSM LLPs

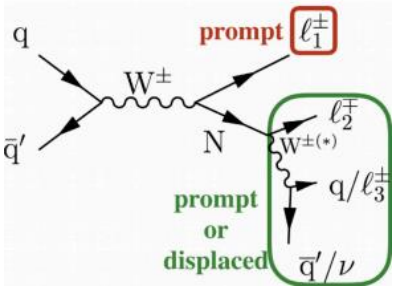
Call for experimental innovations

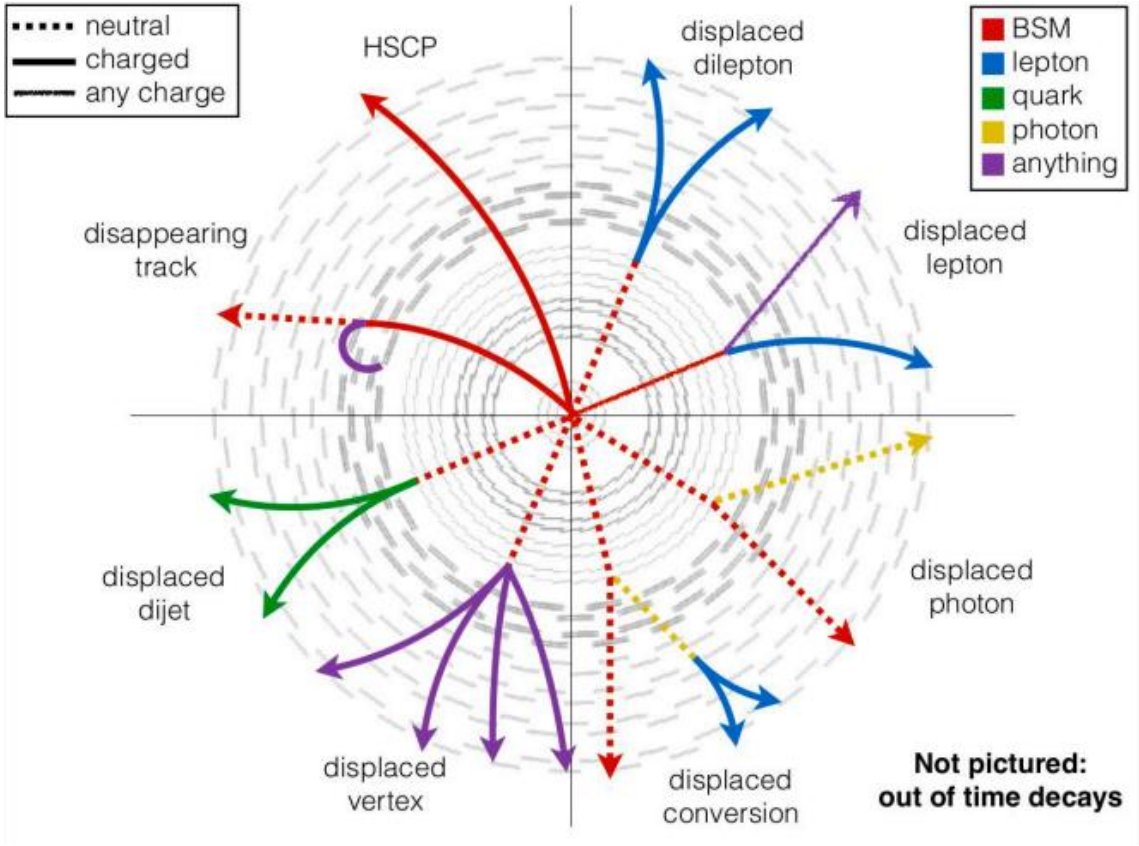
- Specialized trigger, reco, dedicated ID, etc.

Hidden Sector



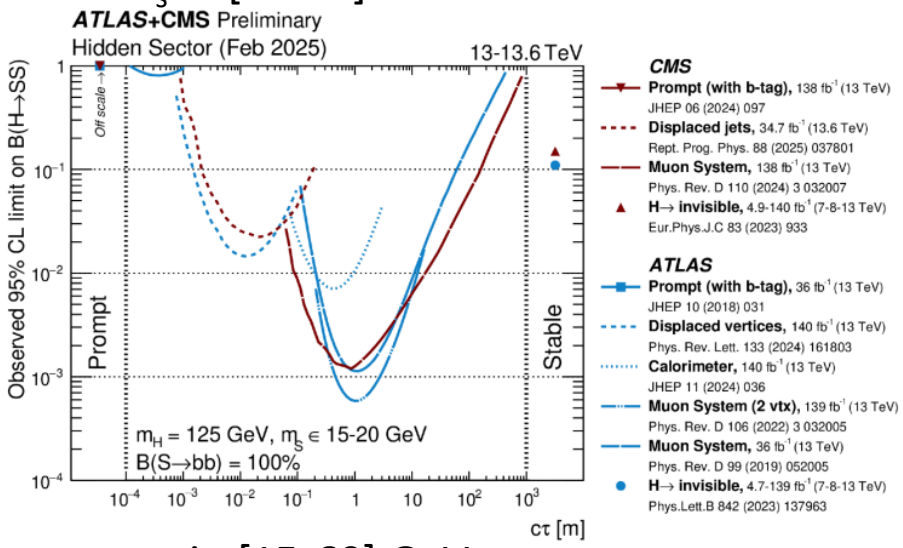
Heavy neutral leptons



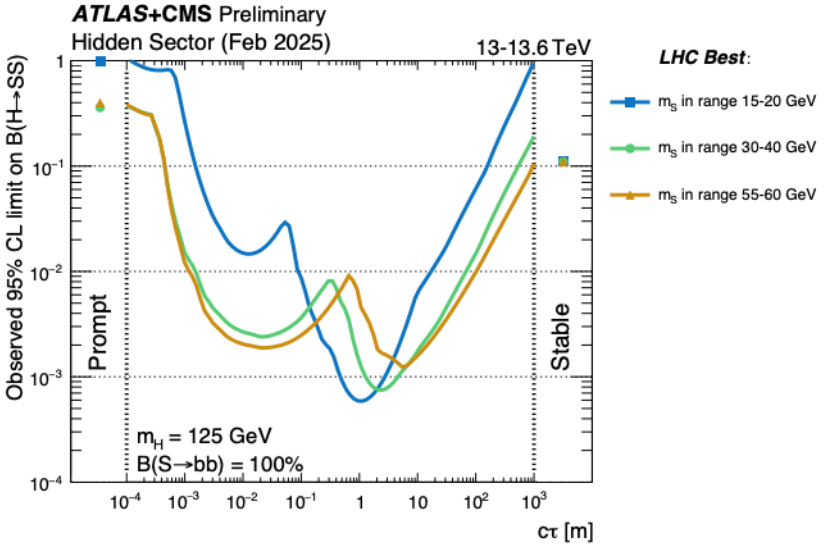


Hidden Sector H→SS

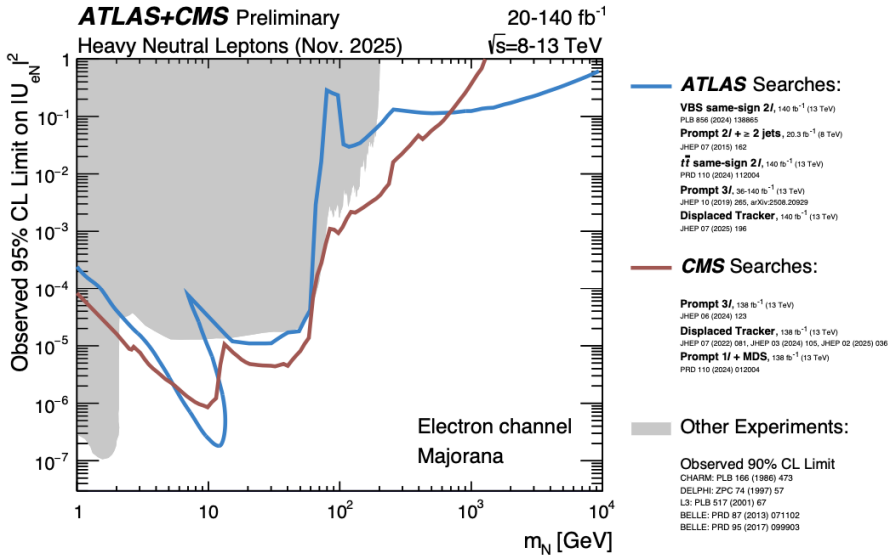
m_s in [15-20] GeV



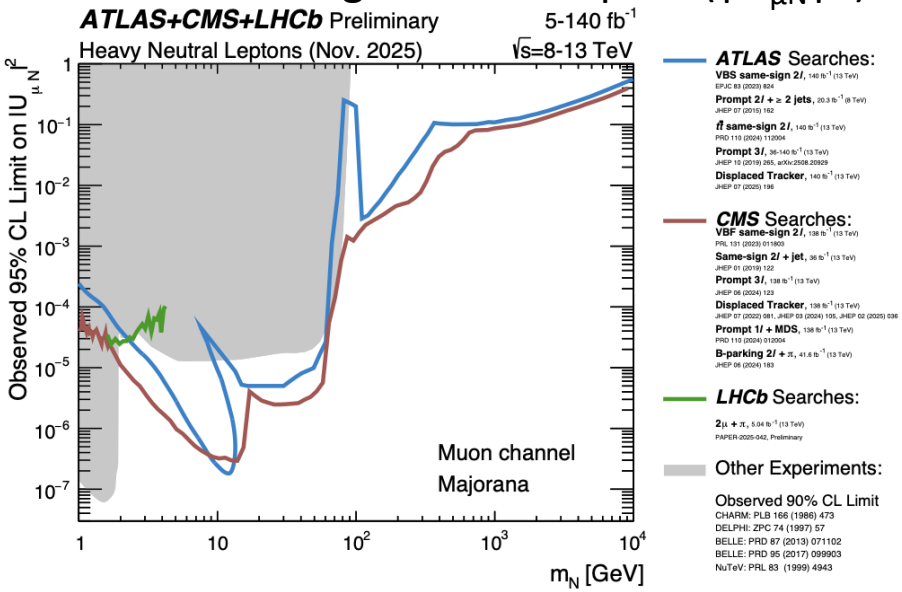
m_s in [15-60] GeV



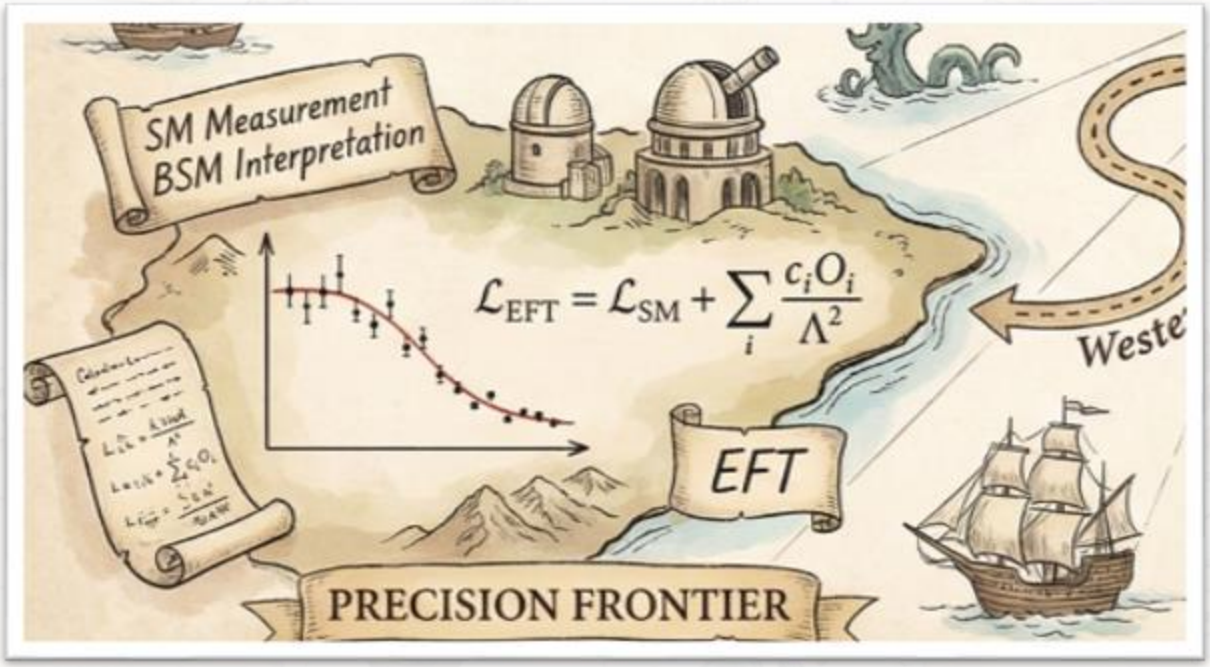
HNL first generation lepton ($|U_{eN}|^2$)



HNL second generation lepton ($|U_{\mu N}|^2$)



4. Measurement ⇔ Search



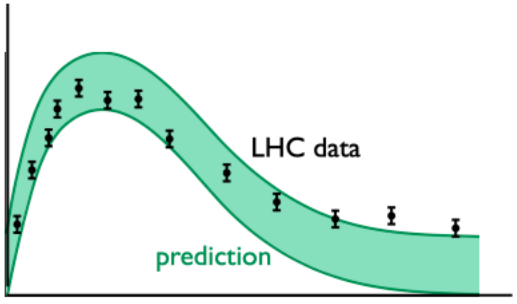
➤ **Measurements contribute to the big picture as much as searches**. The Precision Frontier constrains new physics by measuring Standard Model processes with high accuracy.

Why precision matters?

- The SM makes **extremely precise predictions** for observable quantities:
  - cross-sections, decay rates, couplings, etc.
- Any new physics NP at high energy scales will **indirectly influence** these SM observables.
  - **e.g. Small corrections on higgs coupling** expected in many BSM scenarios

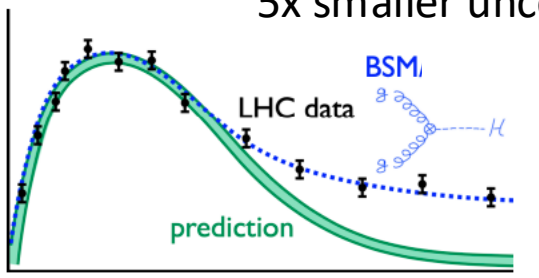
	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%

A gedankenexperiment:



Miss discovering new physics

5x smaller uncertainty

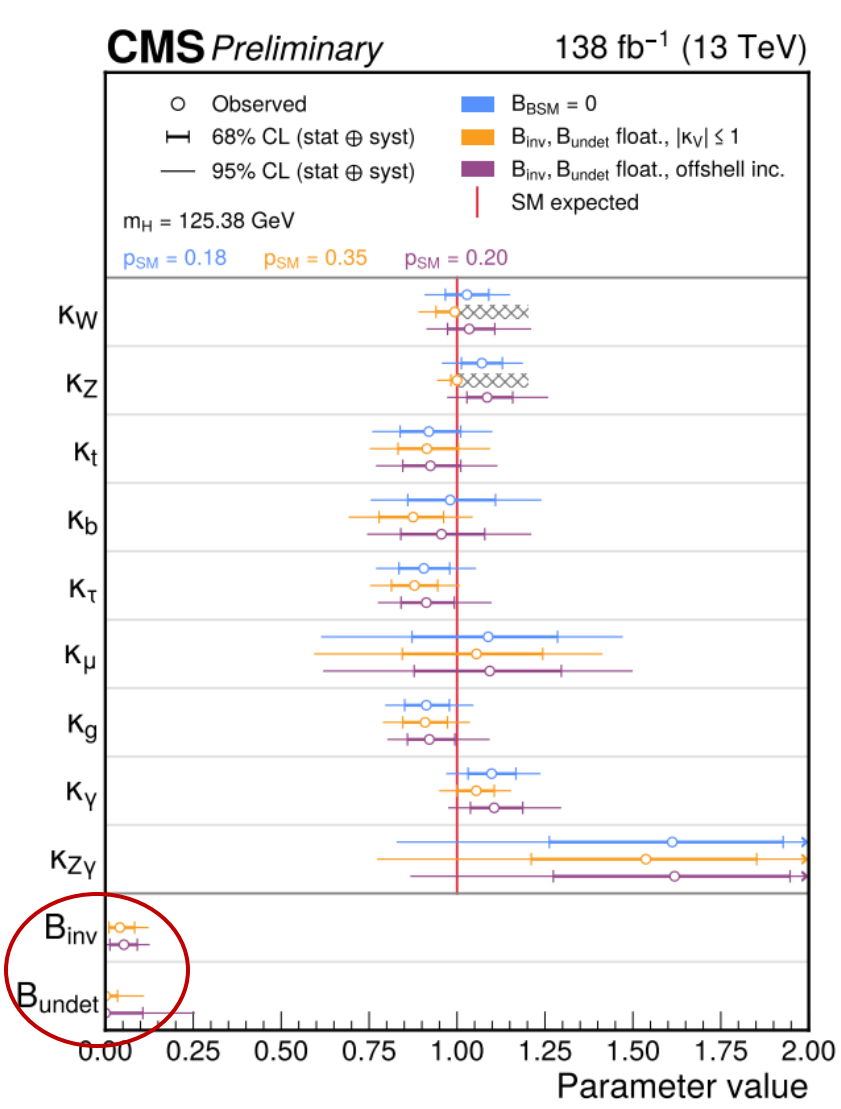


Discovery!

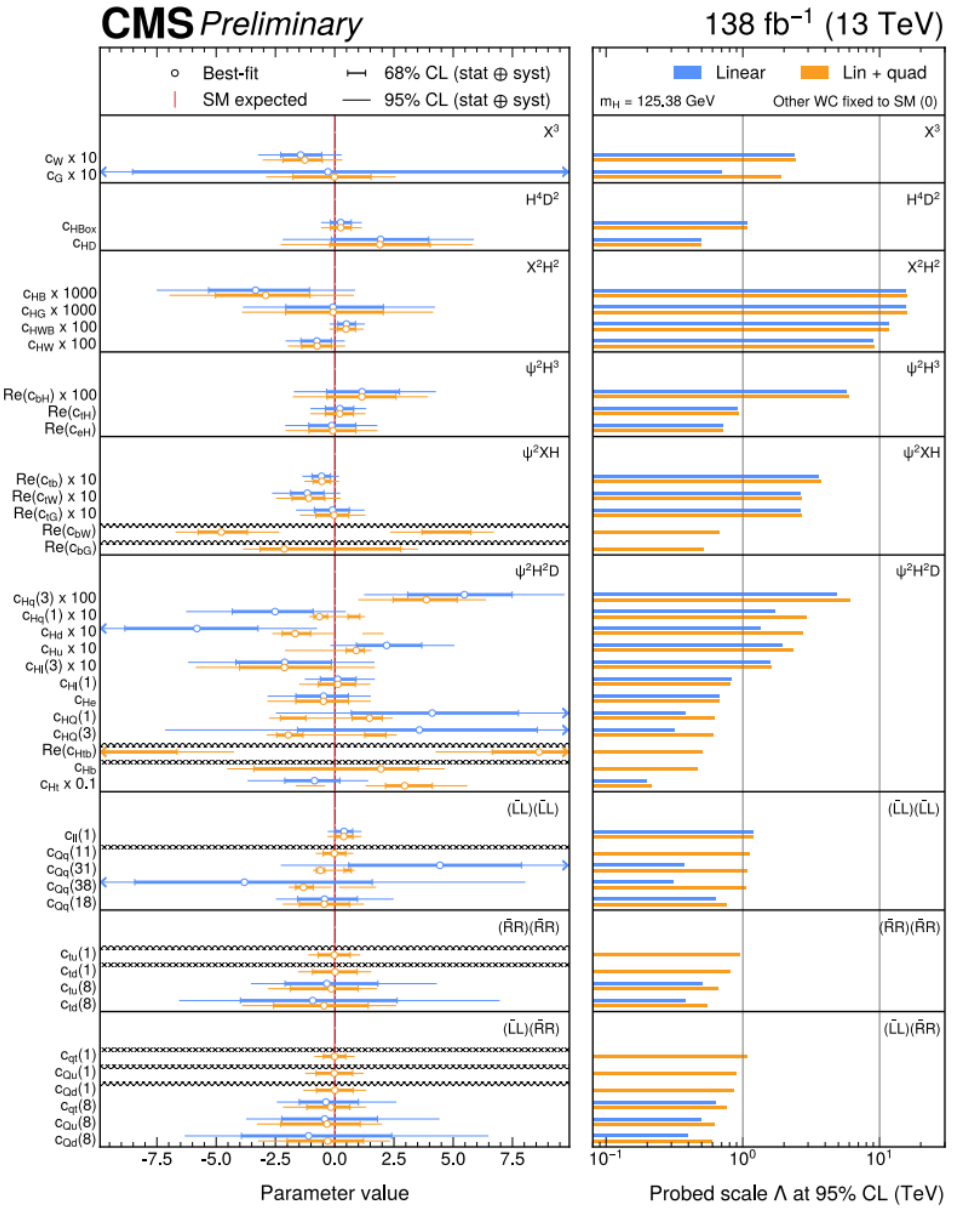
- **Higher precision** can be translated into **higher discovery reach.**

Higgs Sector: kappa and EFT interpretations

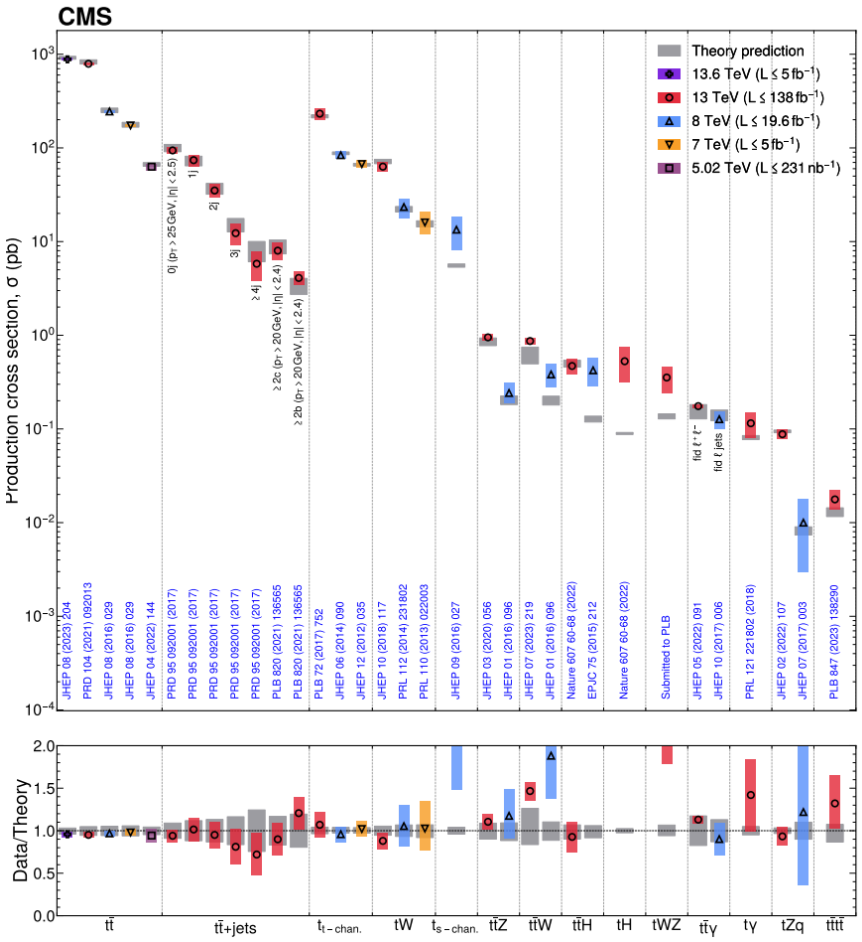
CMS-PAS-HIG-21-018



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



Top Sector: Deviation in rare processes



[CMS top results summary page]

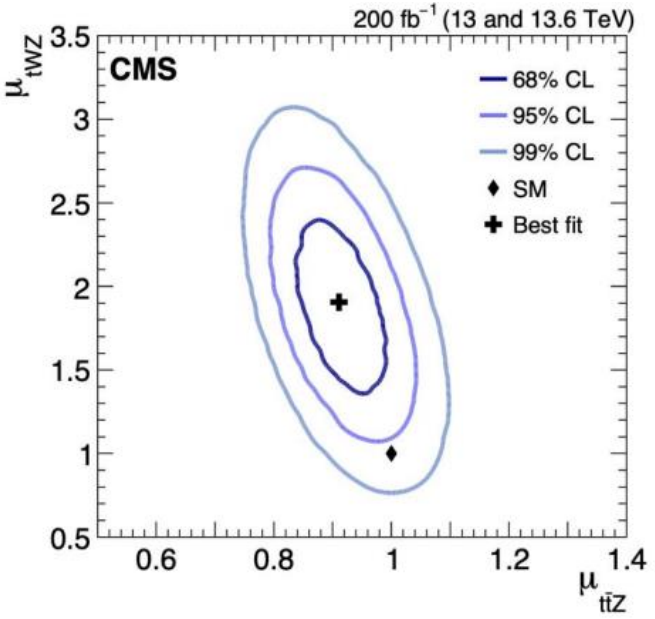
xs measurements + EFT interpretations

ttbar production:

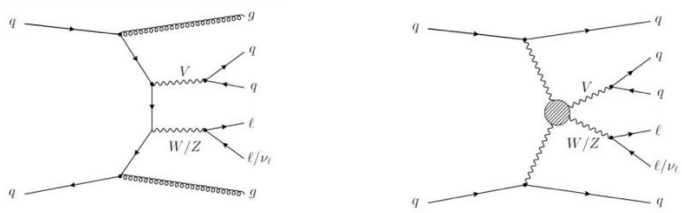
- Large cross section O(100 M) events
- Dedicated studies of the tails

Rare processes (top+boson, multiple tops)

- O(1000) events in Run 2+3 (or less)
- Sensitivity to BSM physics
  - Tension in tWZ with SM [2410.23475]

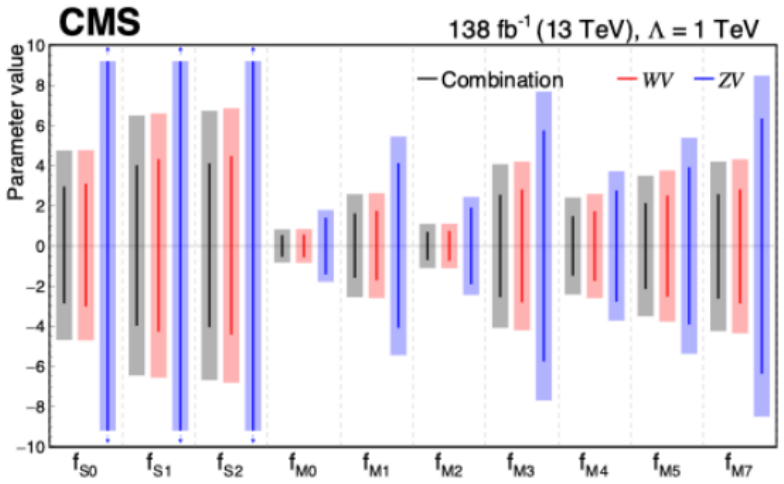


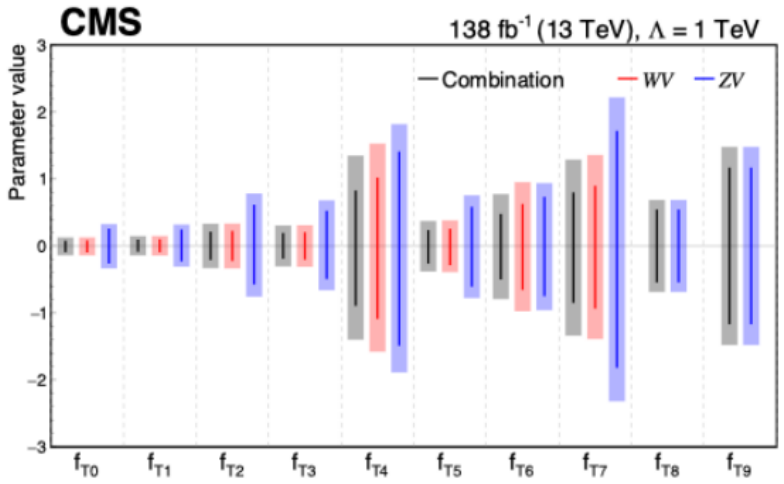
EW Sector: ZV via VBS and aQGC constraint



arXiv.2510.00118

- Measuring $Z \to \ell^+\ell^- + V \to qq' +$ two forward jets
- Observed (expected) significance of 1.3 (1.8) σ



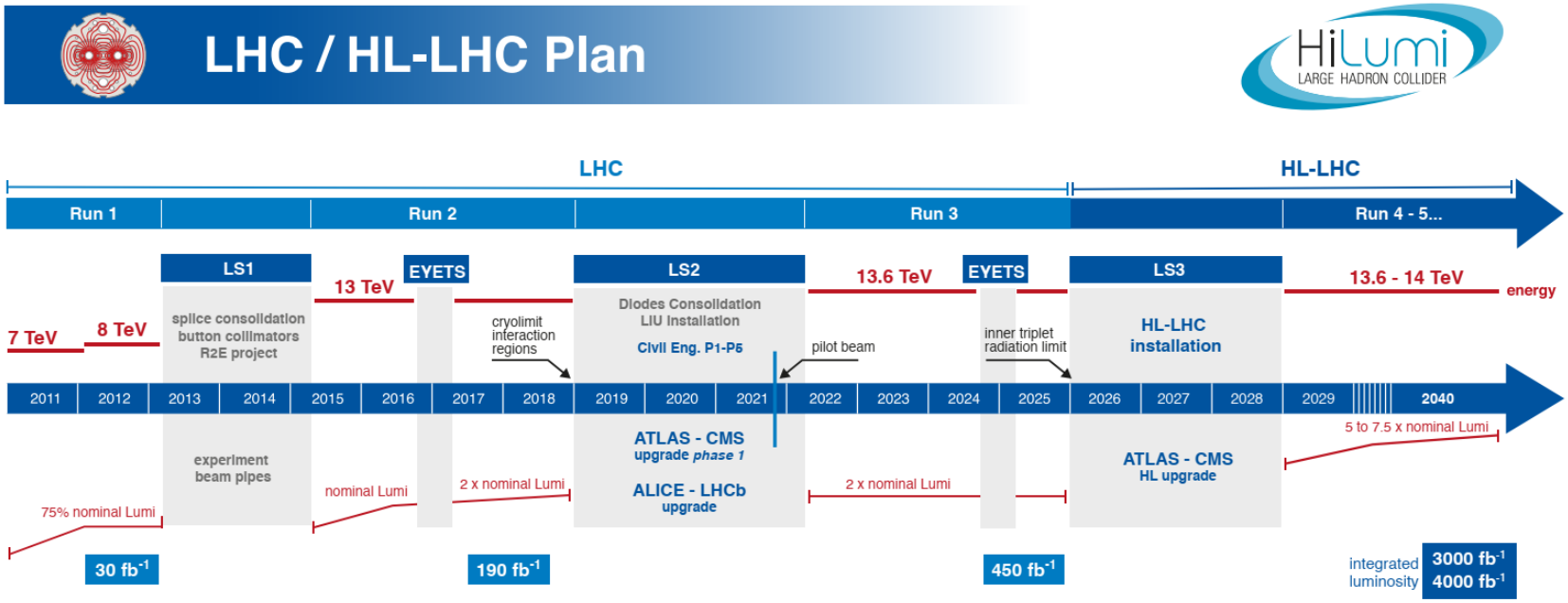


Combined with the WV channel, test aQGC and SMEFT

- World's leading constraints on dim-8 operators

Outlook: LHC and HL-LHC

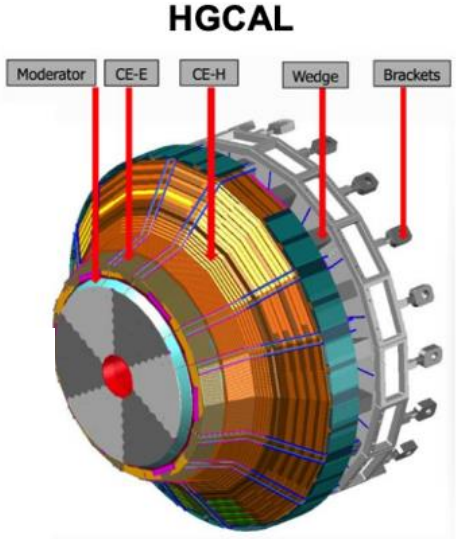
So far, the LHC has delivered **only around 10%** of its ultimate dataset, offering abundant opportunities for **high-precision measurements** and **explorations of new physics**.



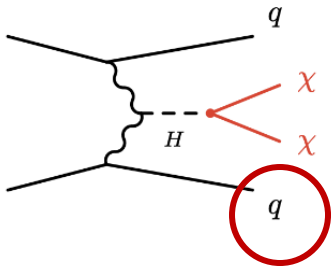
Detector Upgrade to Expend Search Reach

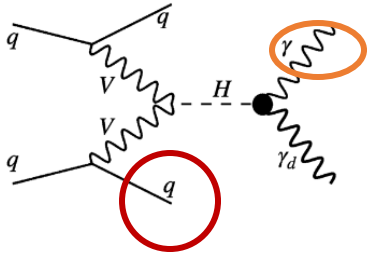
- **e.g. the High-Granularity Calorimeter (HGCAL)** will replace the current endcap in the HL-LHC.

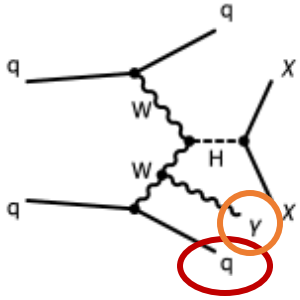
The 1st 5D calorimeter (energy, X, Y, Z, t)



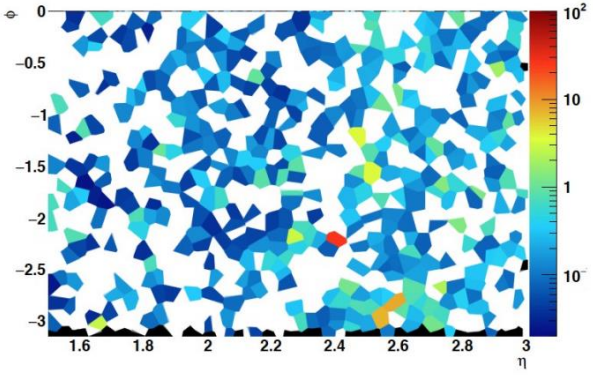
- HGCAL: **mitigate large PU** &**provide high resolution and acceptance** on **forward physics**
  - significantly boosting **Higgs portal searches** (VBF Hinv, dark photons).



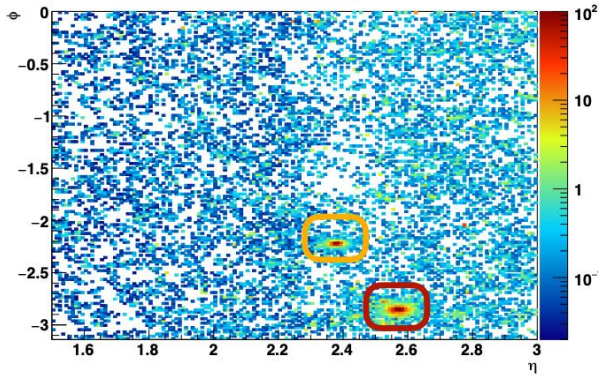




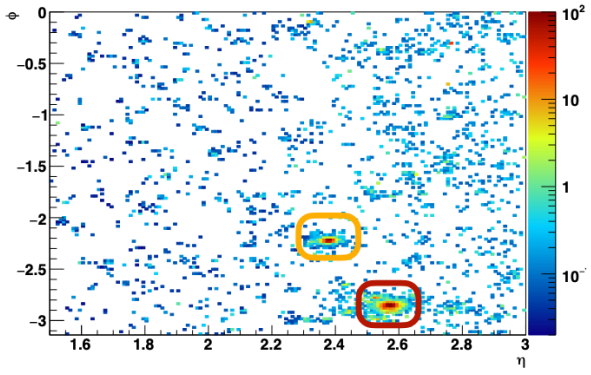
200 PU, current spatial granularity



200 PU, HGCAL granularity



200 PU, HGCAL granularity + precision timing



Boosting BSM Searches Through LHC Collaboration

Newly established LHC BSM WG:
A unified structure to guide and connect BSM searches

- Builds on grassroots community initiatives (**DM**, **LLP**, **SUSY**)
- Formalizes **Reinterpretation Forum** as an official WG
- Umbrella structure for all BSM searches
- Fosters synergies across experiments & theory

WG home page
Indico category

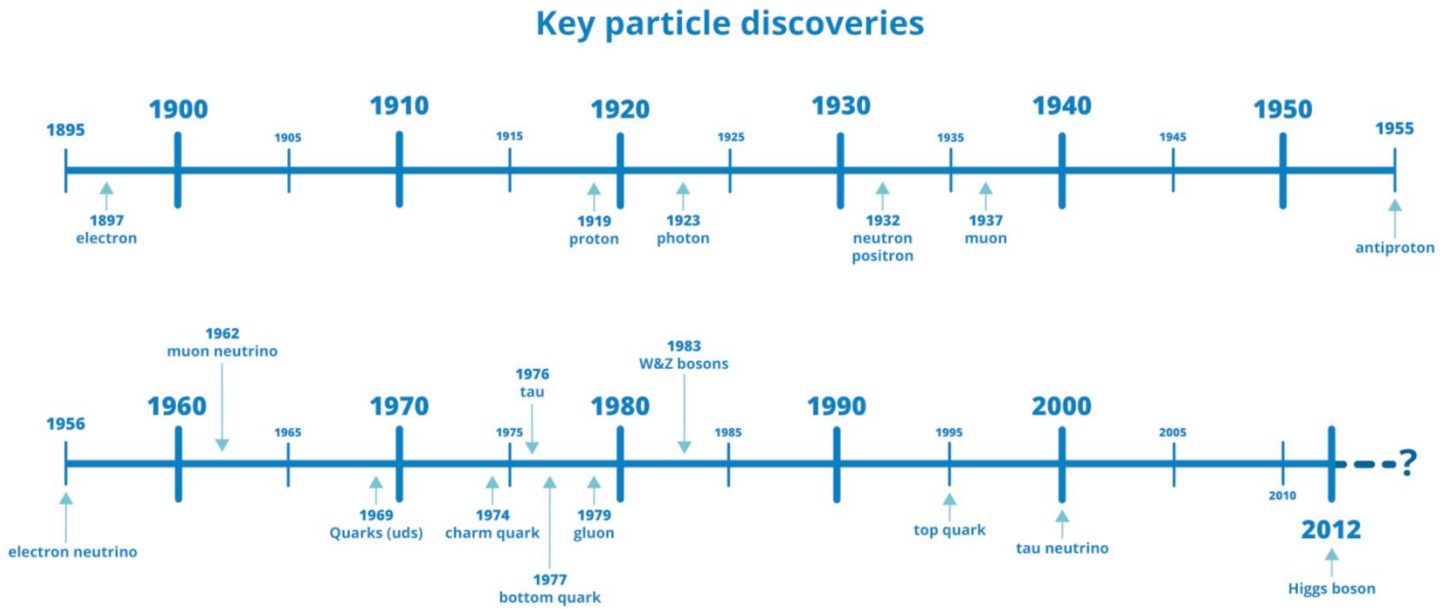
Recent WG focus:

- **Tracking Tensions:** Launch a centralized public initiative to document and preserve all observed data excesses.
- **Full Re-Exploitability:** Achieve 100% re-exploitability of all BSM search results through standardized archiving and data preservation.
- …

Summary

- 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

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



Thanks