



**WISCONSIN**  
UNIVERSITY OF WISCONSIN-MADISON



# *Overview of BSM Higgs boson*

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**USCMS Undergraduate Summer Internship 2022**

You don't really understand something unless you can explain it to your grandmother

*“Anonymous”*



## 1) What is the Standard Model (SM) and SM Higgs Boson?

You have already learned a lot about SM and SM Higgs boson from last weeks presentations by A. Perloff and G. Mitselmakher.

## 2) Why SM is incomplete?

Open questions in particle physics

## 3) How to complete the incomplete SM?

Beyond Standard Model theories

Let's hope you can answer these questions by the end of this presentation!





















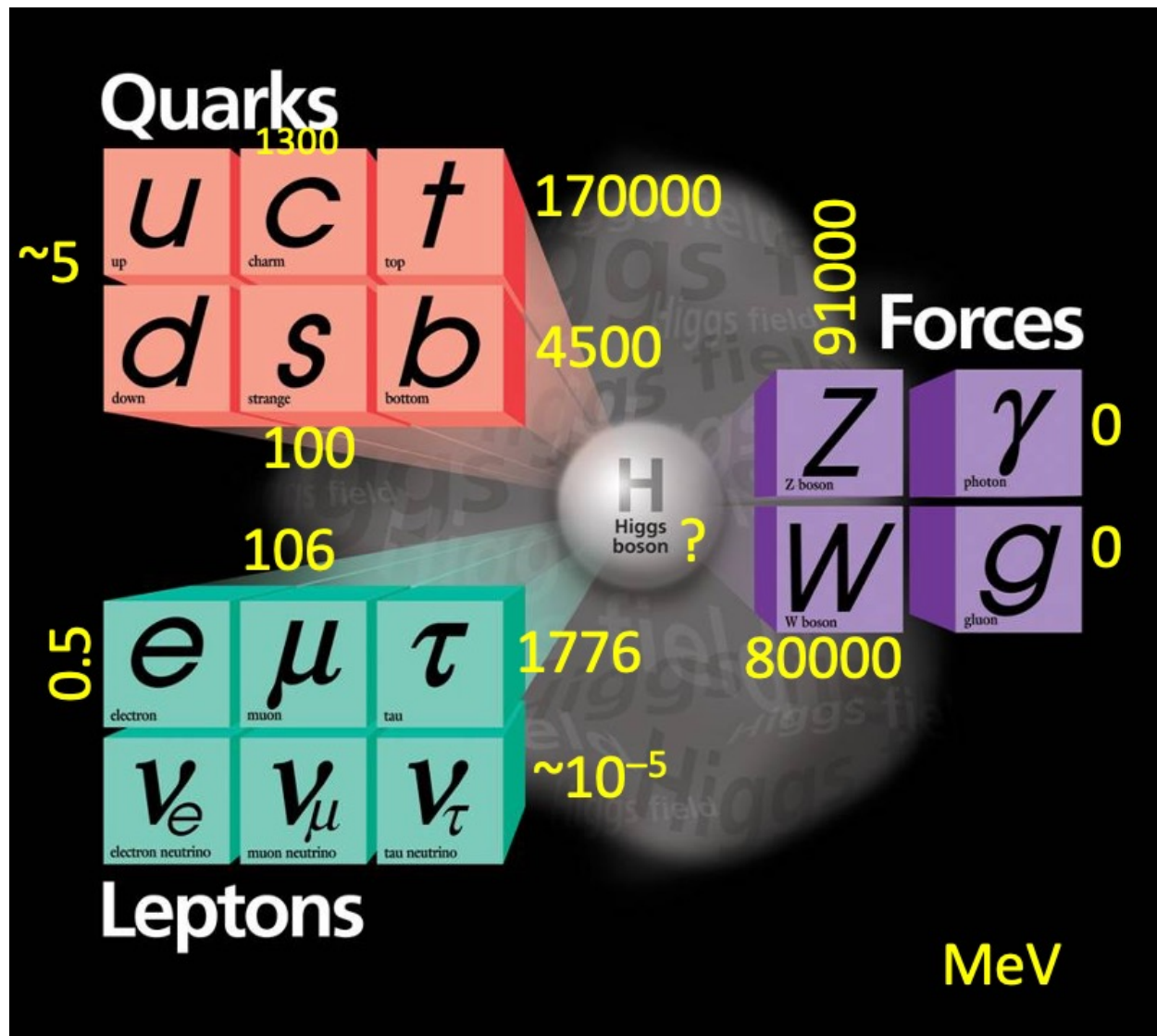
Please stop me at any time  
during this presentation if you  
have any questions!

- 1) What is the Standard Model (SM) and SM Higgs Boson?
- 2) Why SM is incomplete?
- 3) How to complete the incomplete SM?



# Fundamental Particles

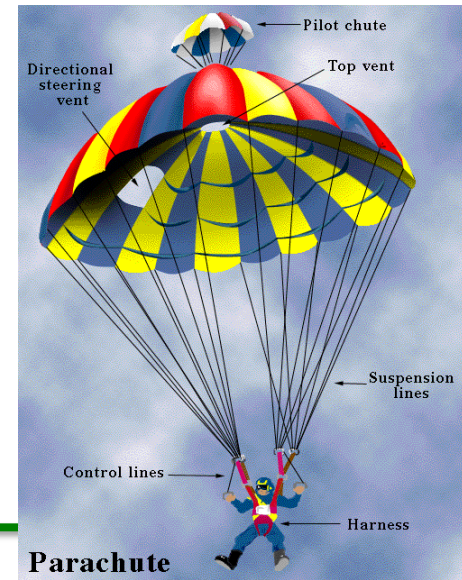
Quarks		Leptons		Bosons
 up	 down	 electron	 neutrino $e$	 photon
 charm	 strange	 muon	 neutrino $\mu$	 gluon
 top	 beauty	 tau	 neutrino $\tau$	 $Z^0 W^\pm$
				 Higgs



Widely varying masses for matter particles  
 Very troublesome: masses for force carriers

# Interactions with Higgs Field

- Which of these falls slower safely?
  - An unopened parachute
  - Fully opened parachute



The more interaction with the medium (air) the lower the speed of the drop

Higgs field permeates all space, particles interact with differing strengths with the Higgs field. The higher the interaction the larger the particle's mass.

The simplest theory with higgs fields results in a new self-interacting particle: the Higgs boson, which itself has a mass – but, theory can't predict its mass.

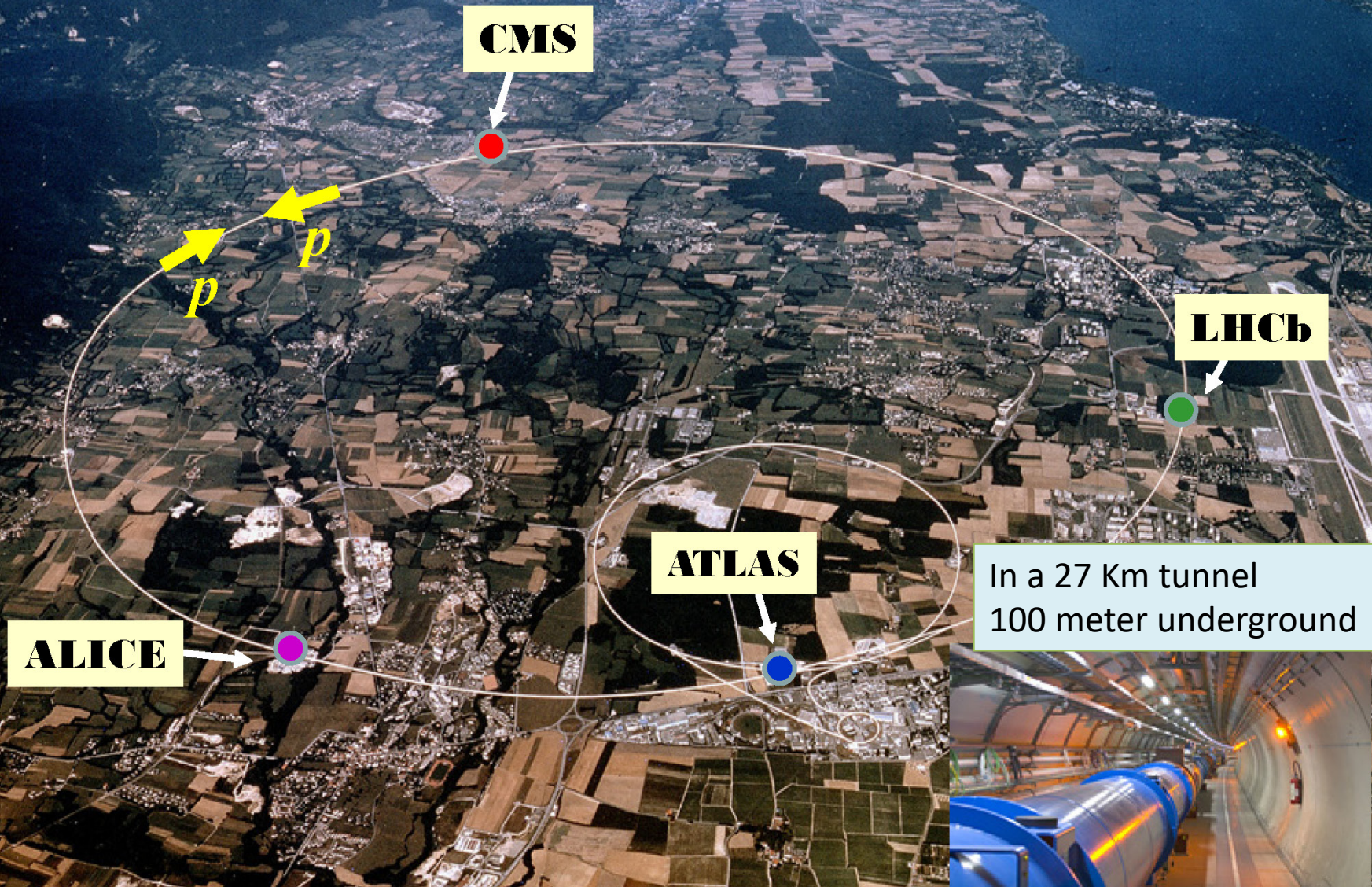


# A Cartoon Movie on Higgs

- Given high energies particles manifest from vacuum
  - Higgs particles can be created in LHC collisions
    - They are ephemeral – The LHC detectors look for its remnants



# Large Hadron Collider

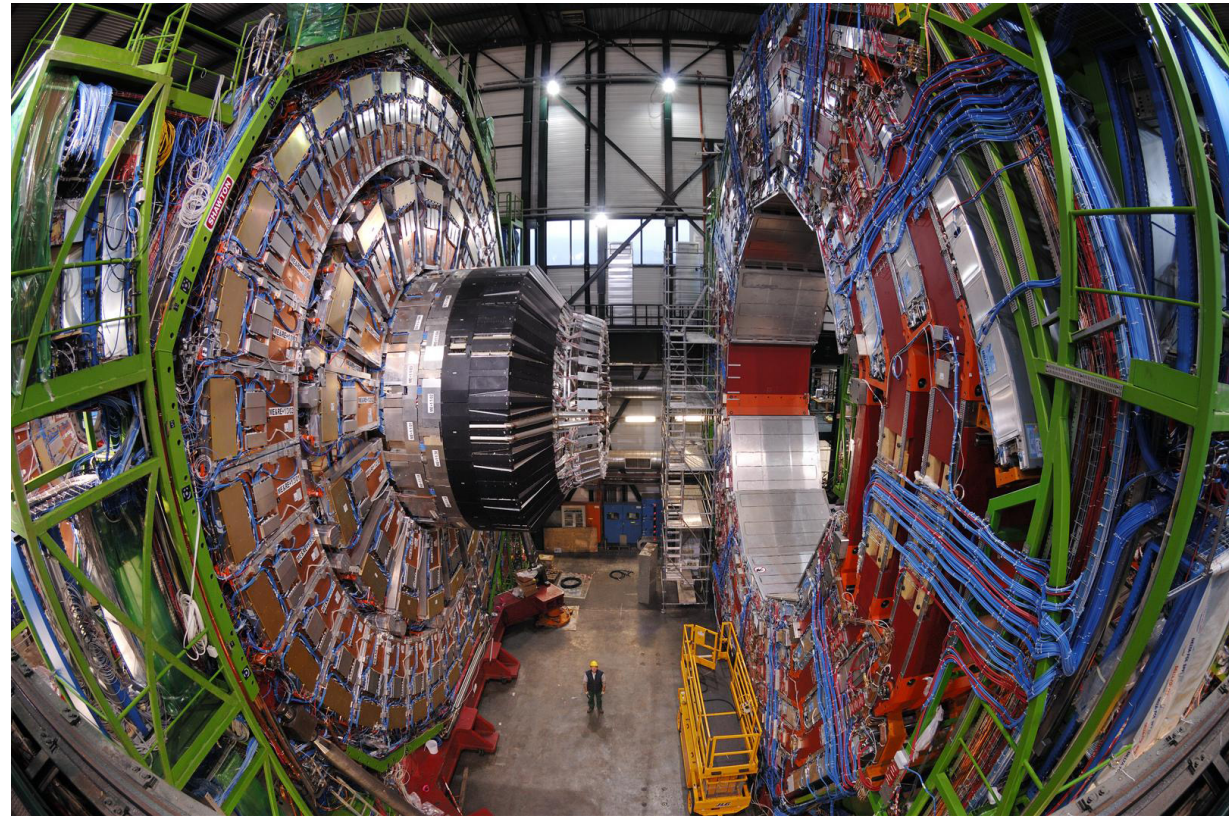




# Compact Muon Solenoid (CMS)

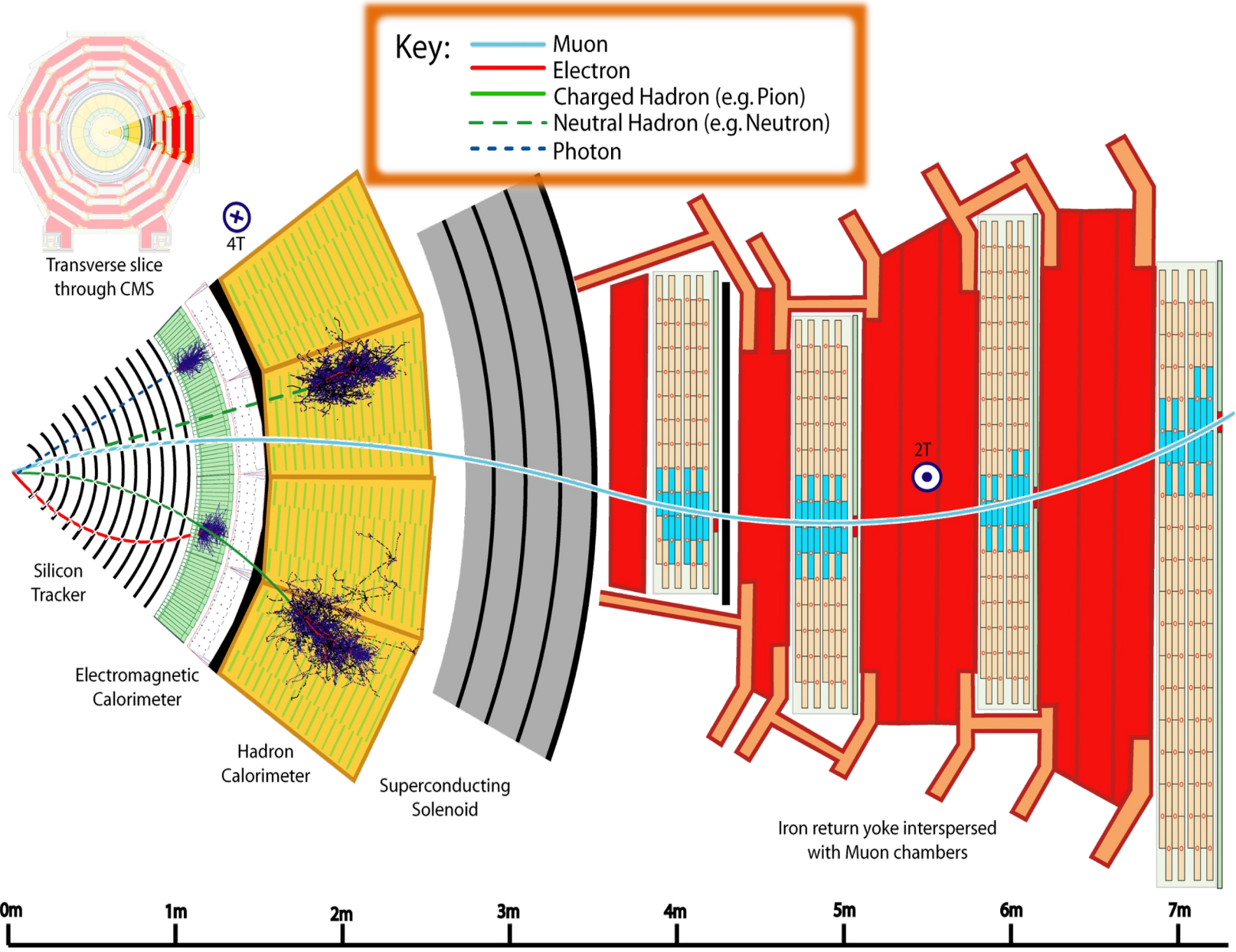


V.S.

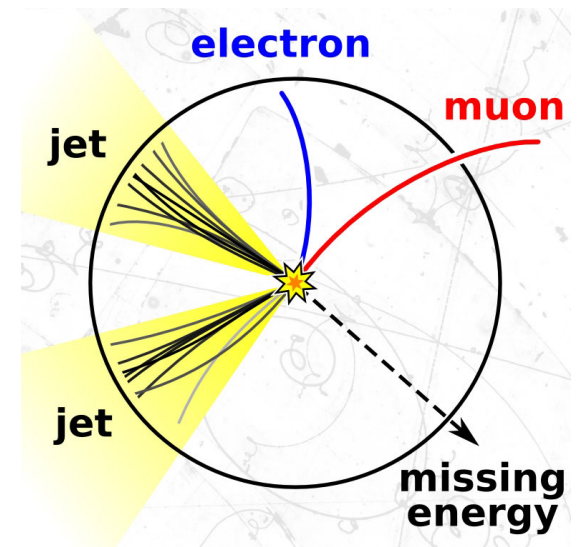
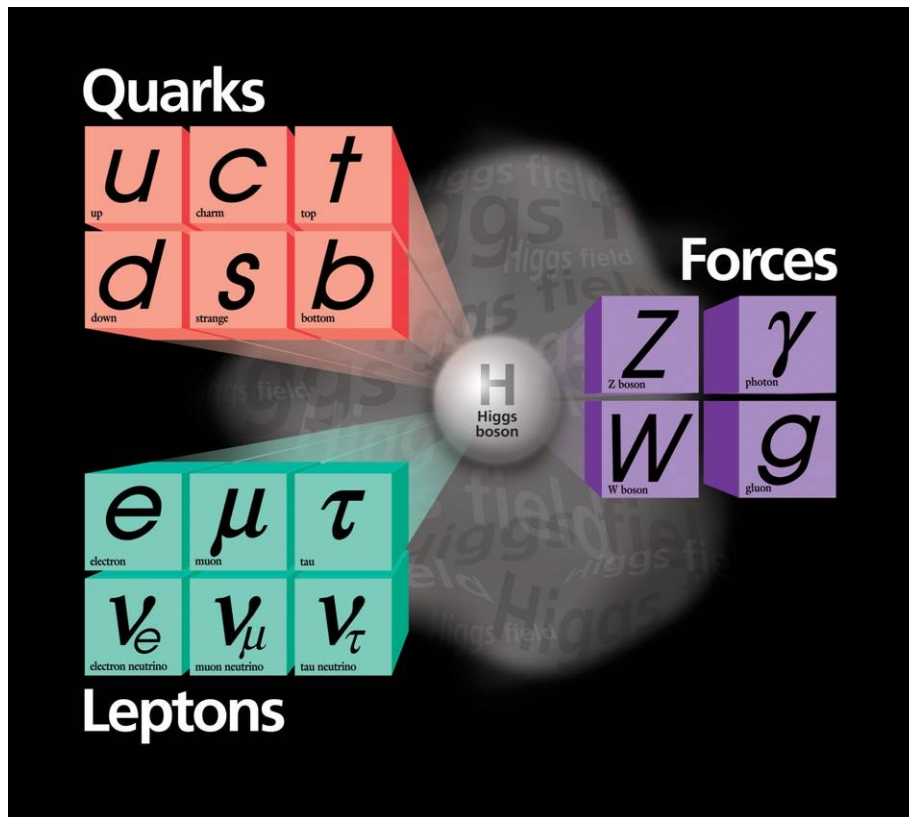


An onion-like 3D camera



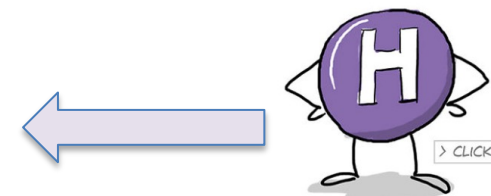


# Particle detectability in detector

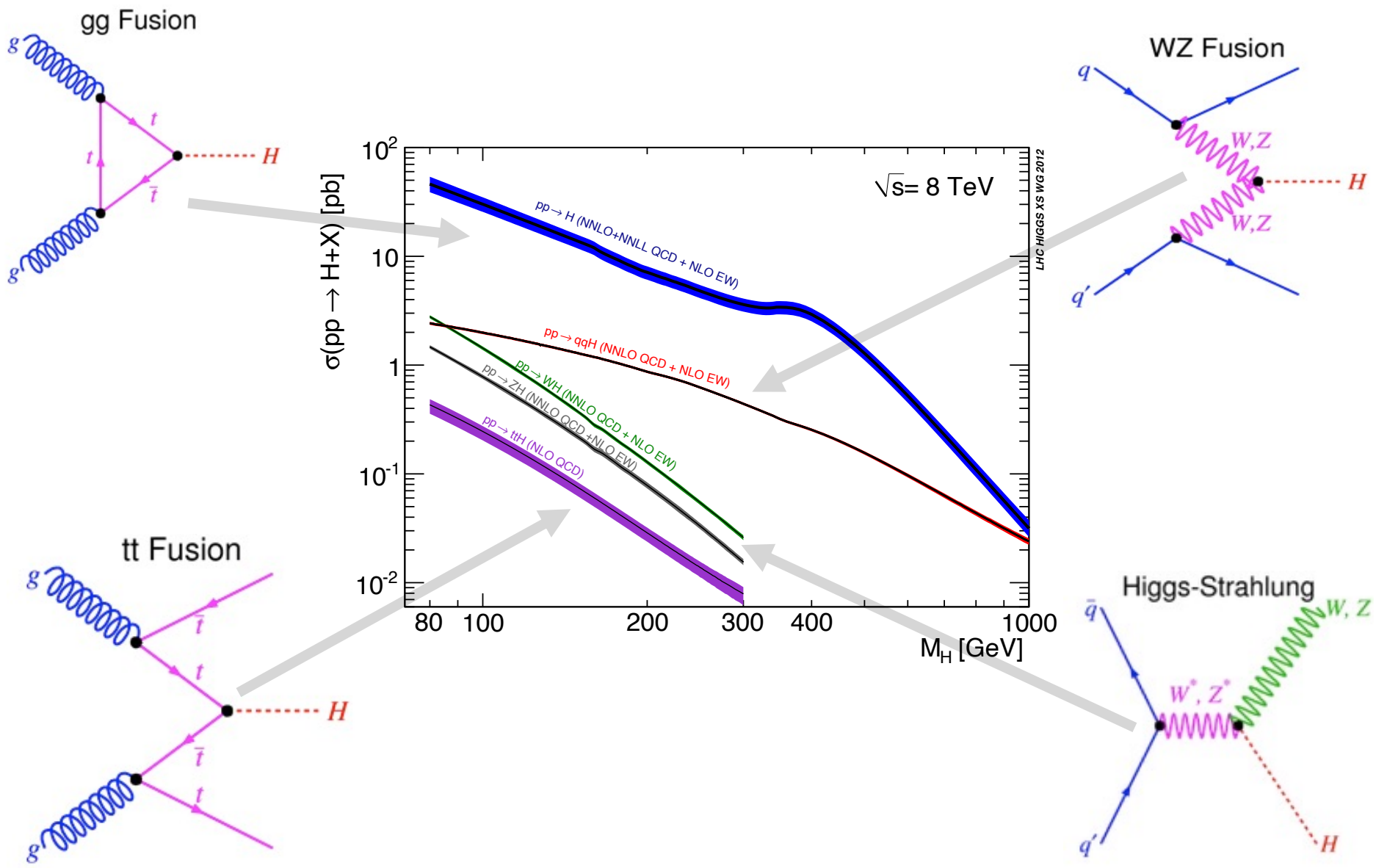


Particle categorization based on detectability:

- Interact with detector materials:  $e$ ,  $\mu$ ,  $\gamma$ ,  $q$  ...
- Escape from detector:  $\nu$
- Decay to either types of particles:  $\tau$ ,  $Z$ , ...

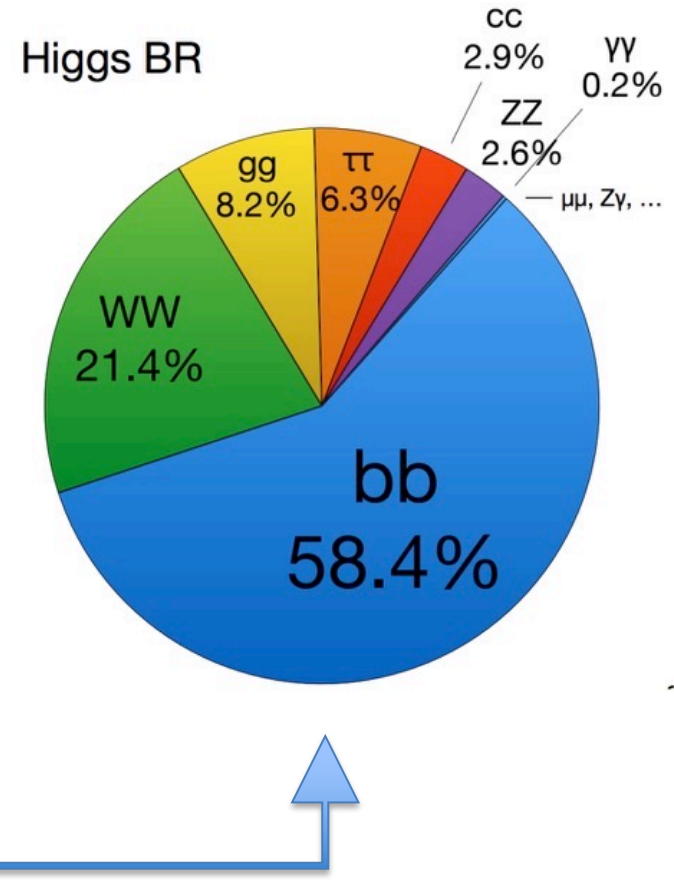
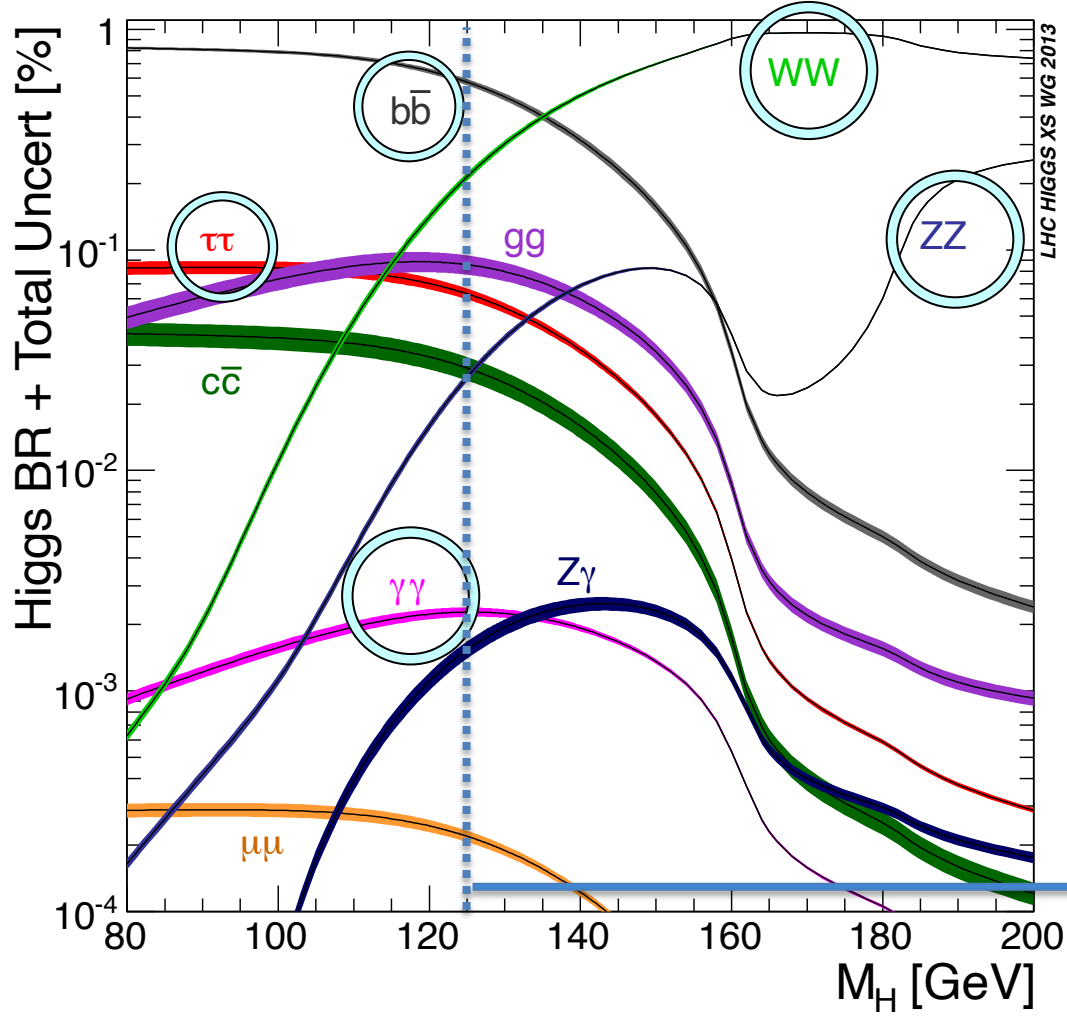


# Higgs production mechanisms at the LHC





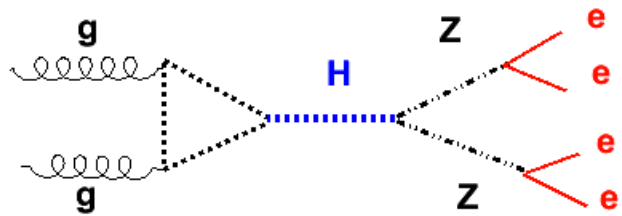
# Higgs decay channels



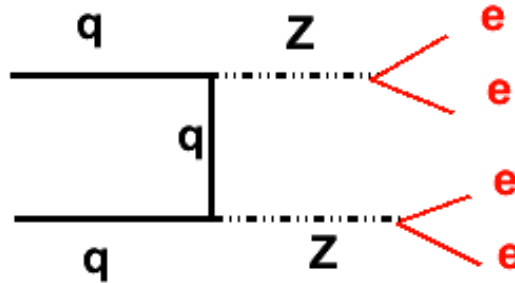
Observing Higgs boson in some of these final states are complicated than the others

# Signal and Backgrounds

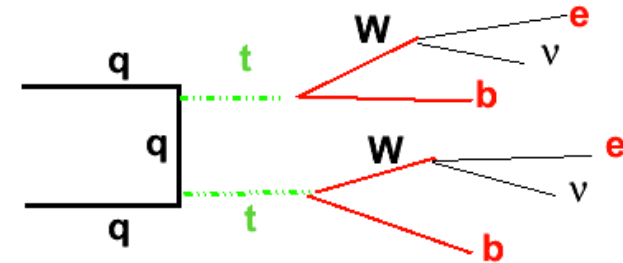
Signal



background



background



What we see as a signal might not be a real signal !

# Signal v.s. Backgrounds

In low luminosity phase

$$10^{33}/\text{cm}^2/\text{s} = 1/\text{nb}/\text{s}$$

Approximately

- $4 \times 10^7$  pp interactions
- $10^6$  bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

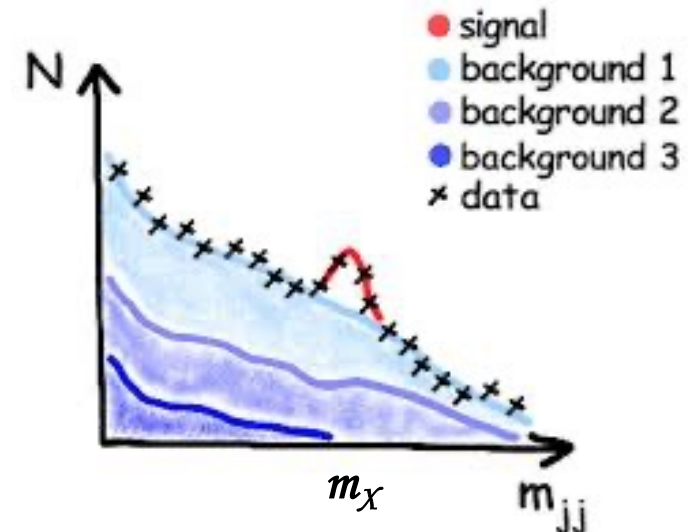
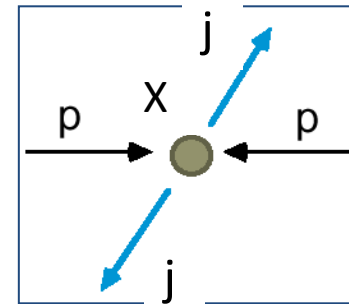
will be produced per **second**

- 1 Higgs boson

per **minute!**

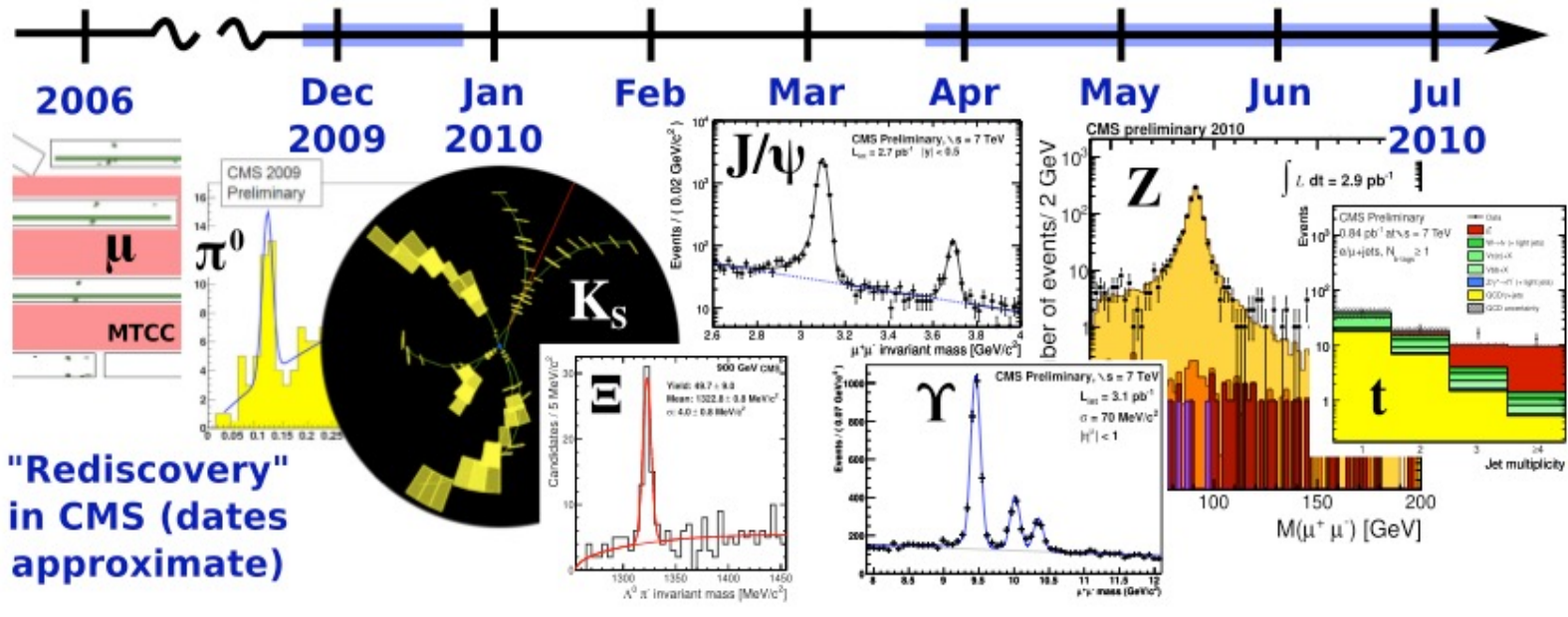
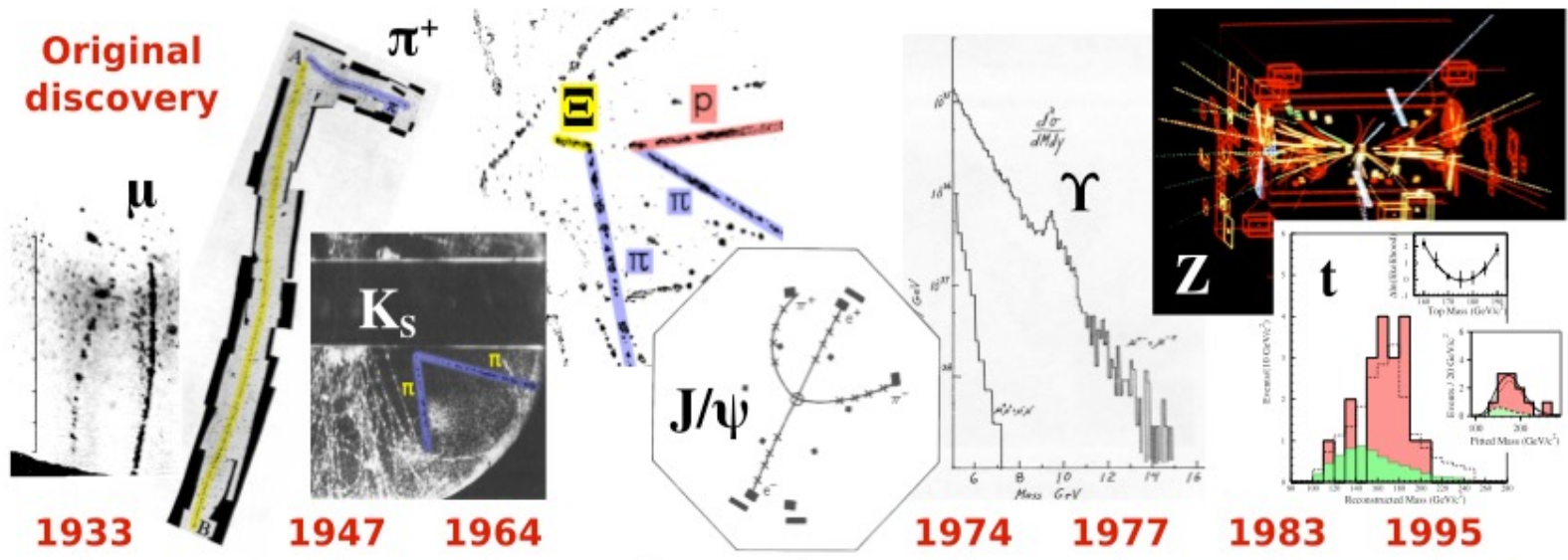
The major effort is separating signal from background

Mass is the particle's fingerprint





# Re-discovery of the SM particles



WHAT NEXT?

And finally, 4<sup>th</sup> of July 2012



CERN



Melbourne



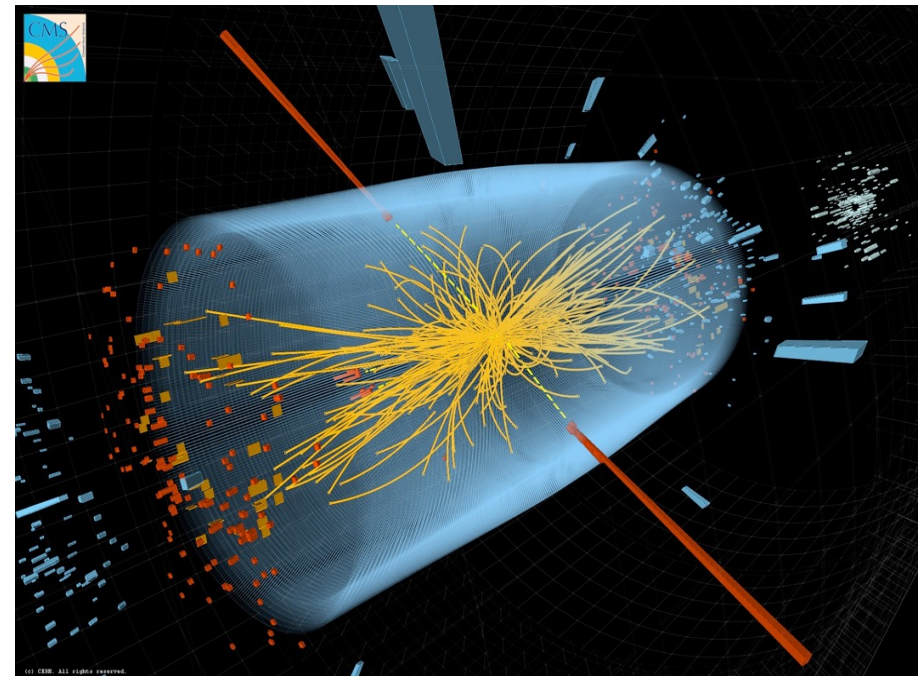
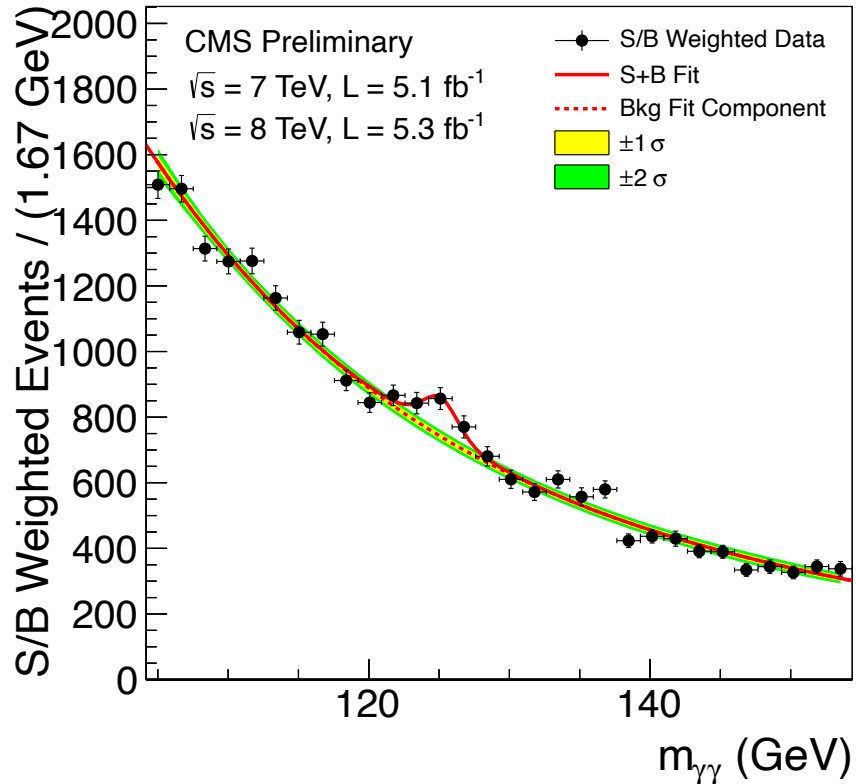
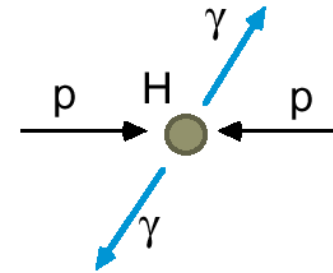
Rolf Heuer:

*'We have it!'*

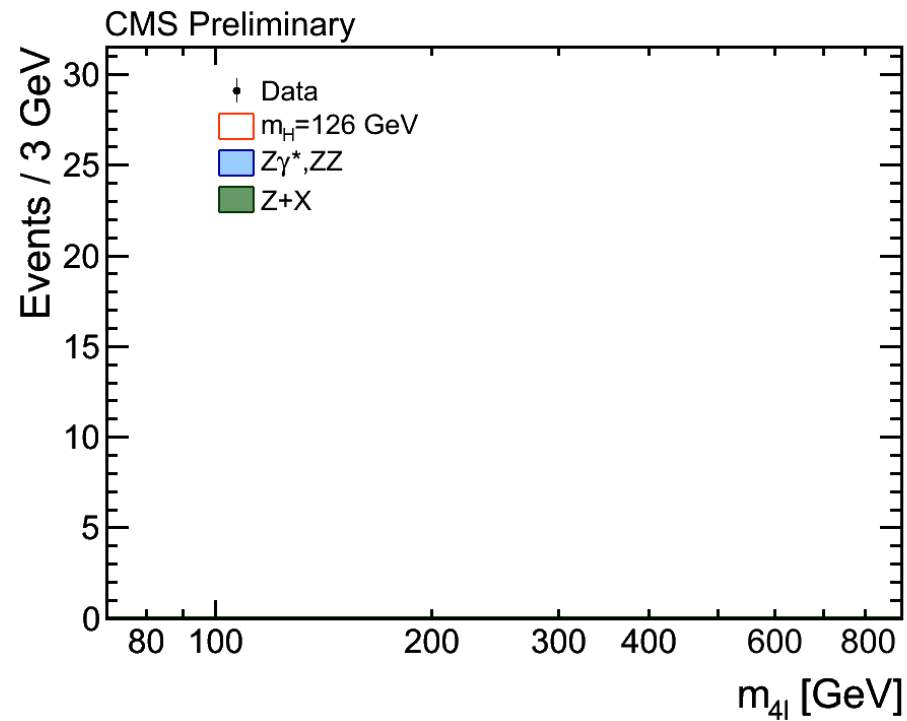
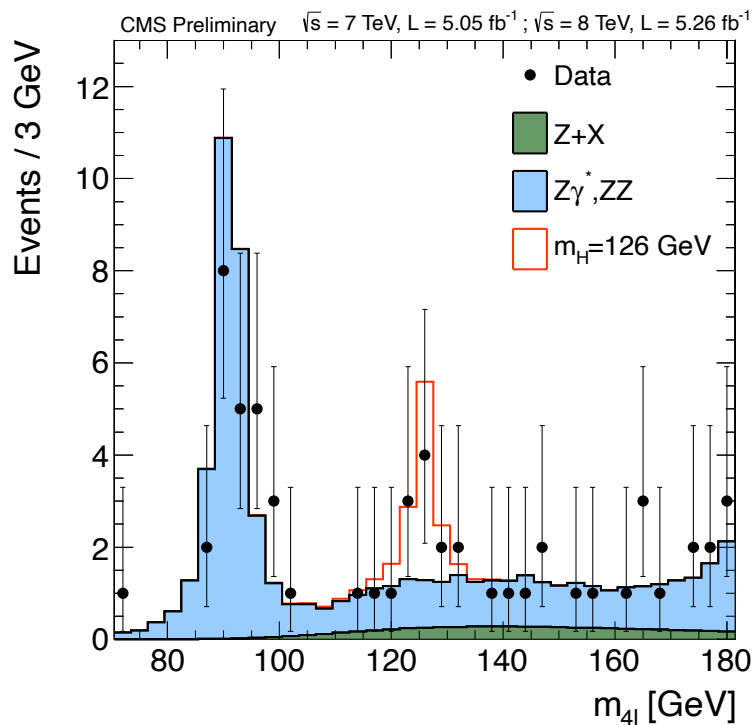
4<sup>th</sup> of July 2012 – new Higgs-like particle discovery



# The first two discovery channels ( $H \rightarrow \gamma\gamma$ )

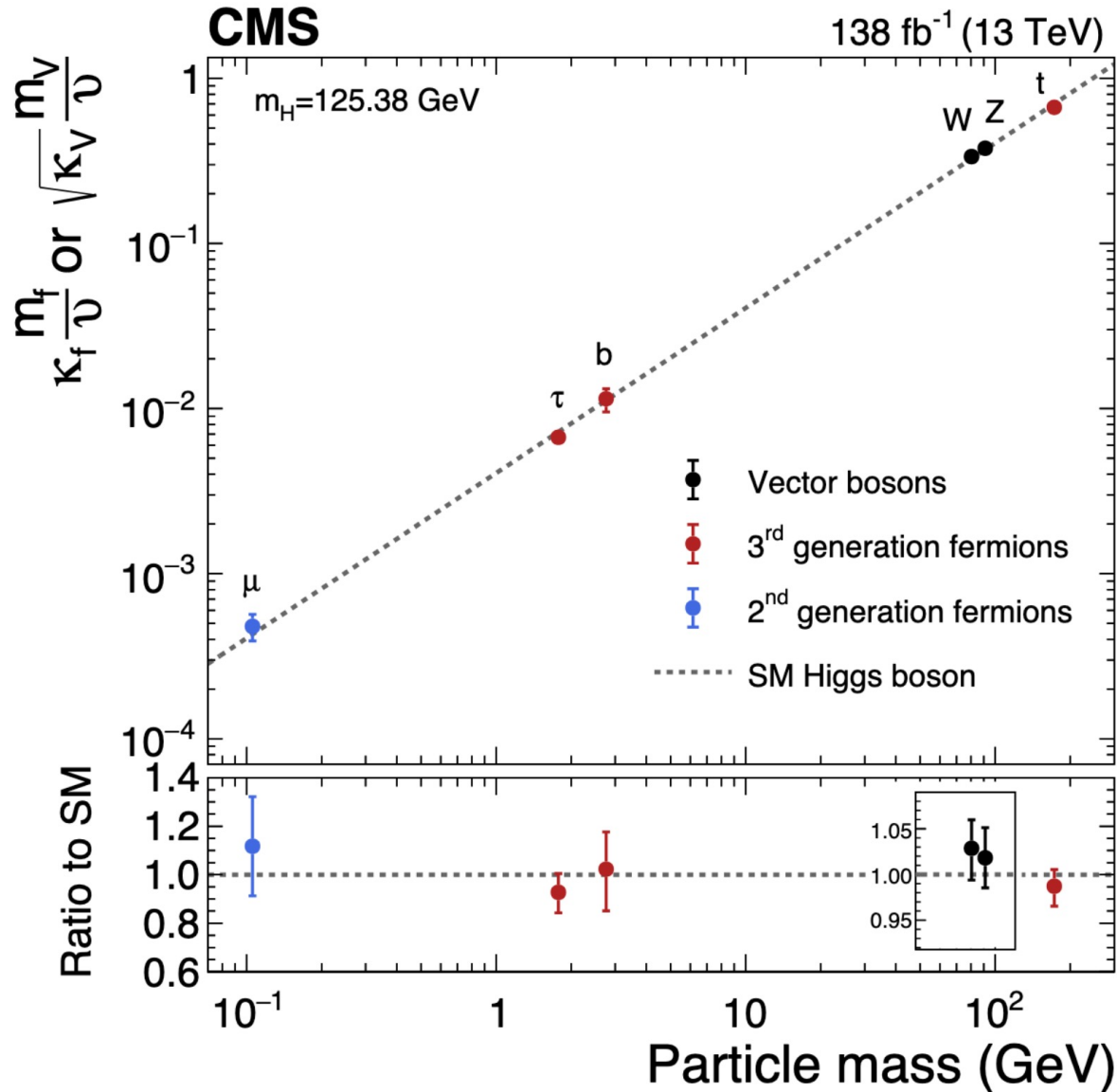


# The first two discovery channels ( $H \rightarrow ZZ$ )





# A portrait of the Higgs boson by the CMS experiment



We have found the Higgs boson 😊 and SM seems complete...

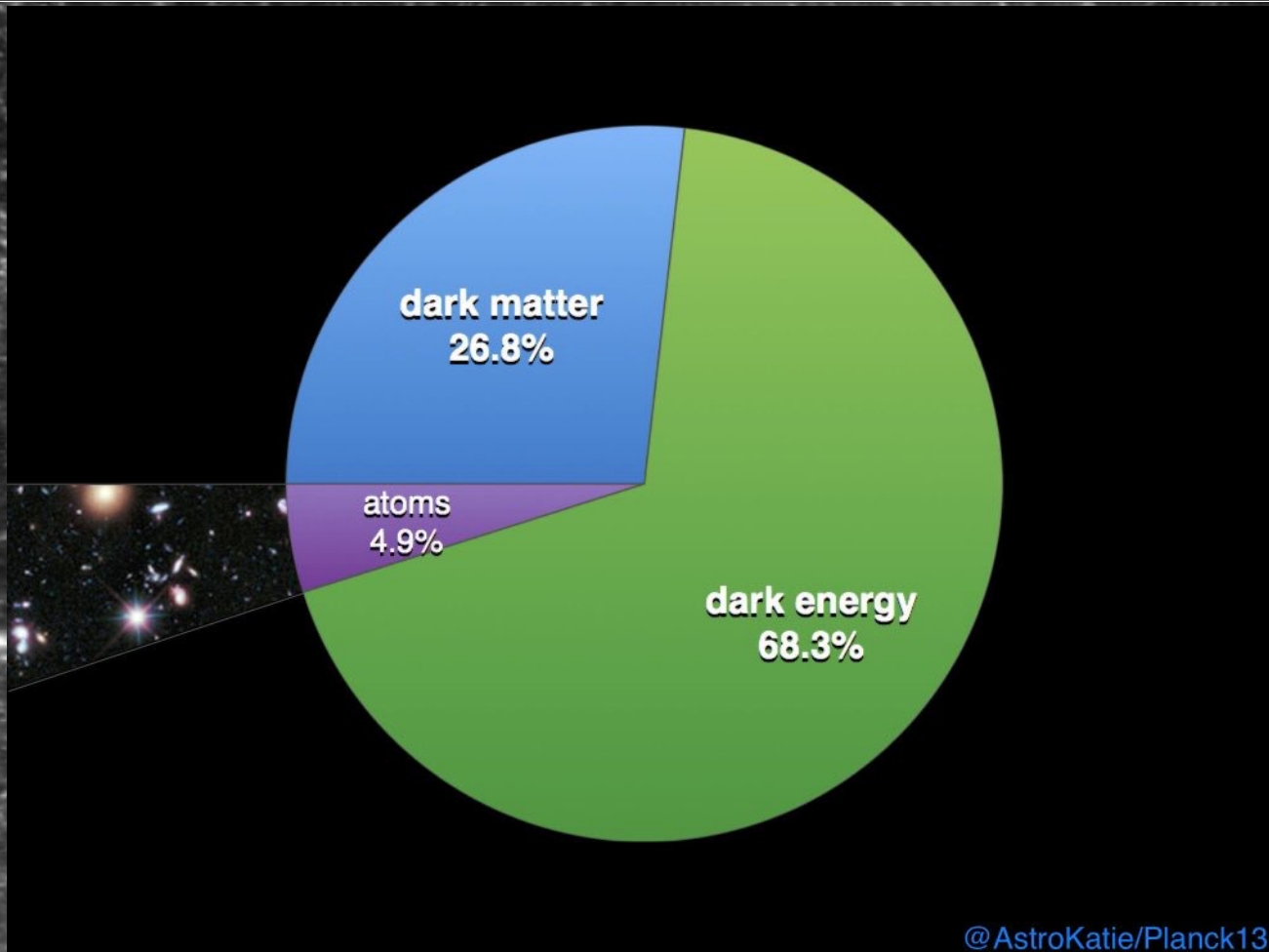


... but SM is not capable of addressing all of our questions 😞

i.e. Hierarchy problem, dark matter candidate, matter-antimatter asymmetry, ...

- 1) What is the Standard Model (SM) and SM Higgs Boson?
- 2) Why SM is incomplete?
- 3) How to complete the incomplete SM?

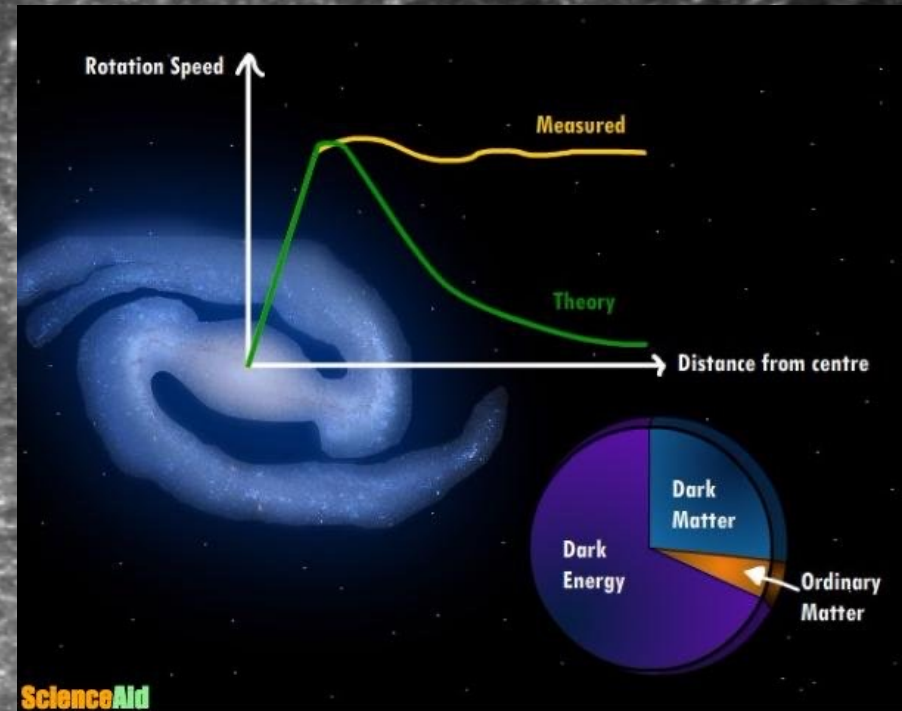
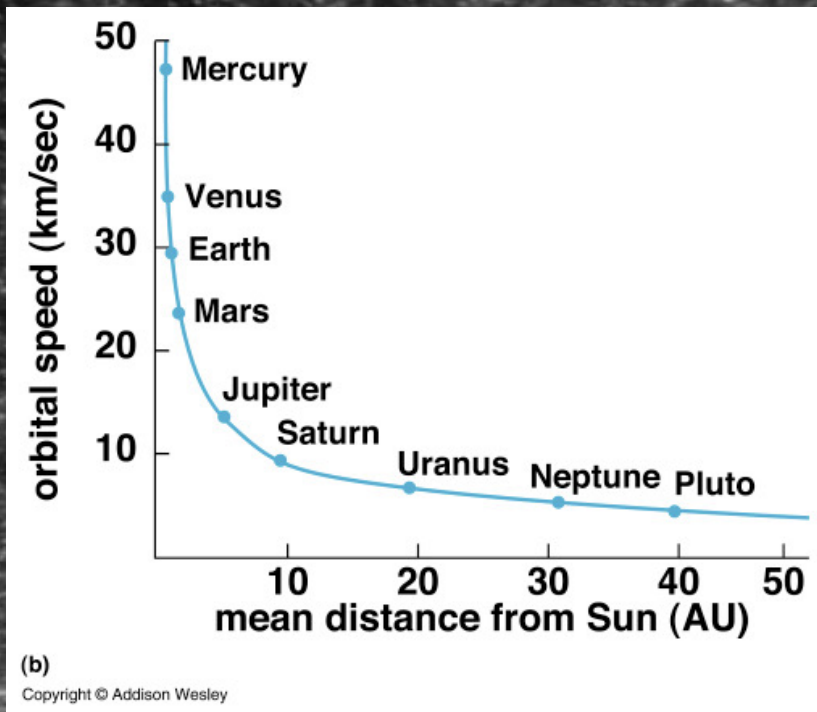
# Looking for unobservables?



- All of the matter only constitutes less than 5% of the entire universe.
- The rest are dark matter (DM) and dark energy
- There are cosmological evidences for the existence of the DM

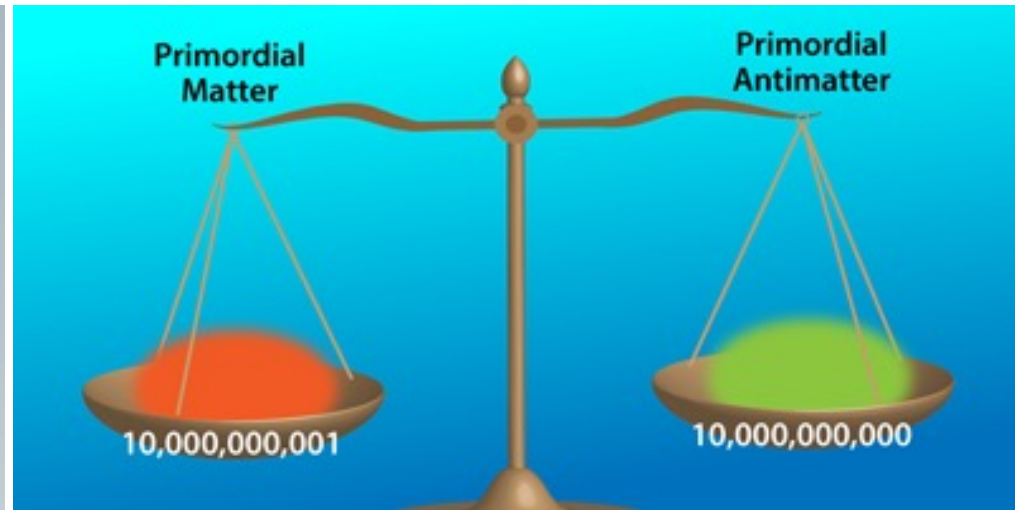
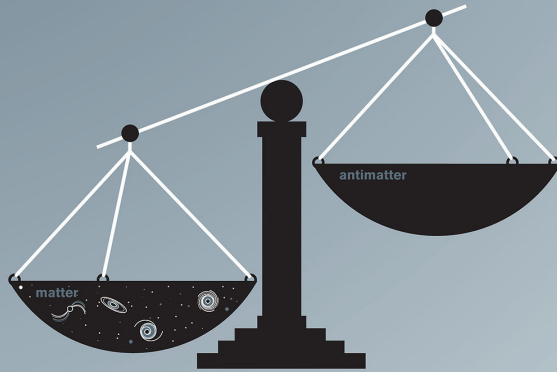


# Galactic rotation curve



- As you get further from the galactic center, the rotation speed remains almost constant !!!
- Dark matter emanates and absorbs no light
- Is constituted by Weakly Interacting Massive Particles (WIMPs) that interact only across gravity and the weak force → BSM

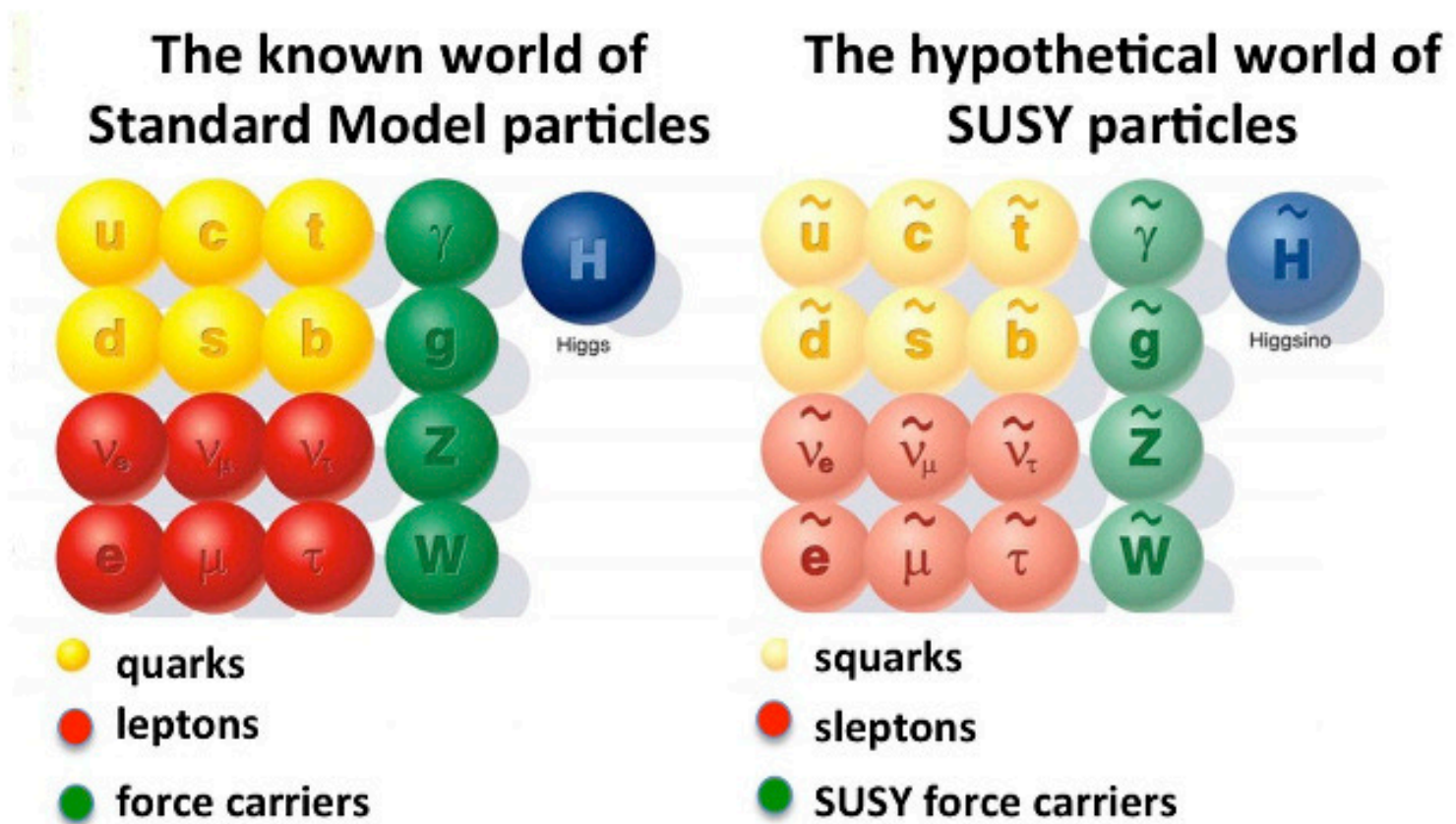
# Matter-antimatter asymmetry ?!



- Most existing laws of nature treat matter and antimatter equally.
- At the early universe and right after the Big-Bang we had the same amount of matter and antimatter
- But why we are left with only matter now?

- 1) What is the Standard Model (SM) and SM Higgs Boson?
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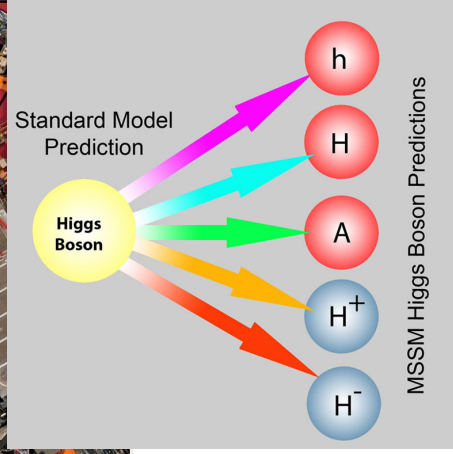
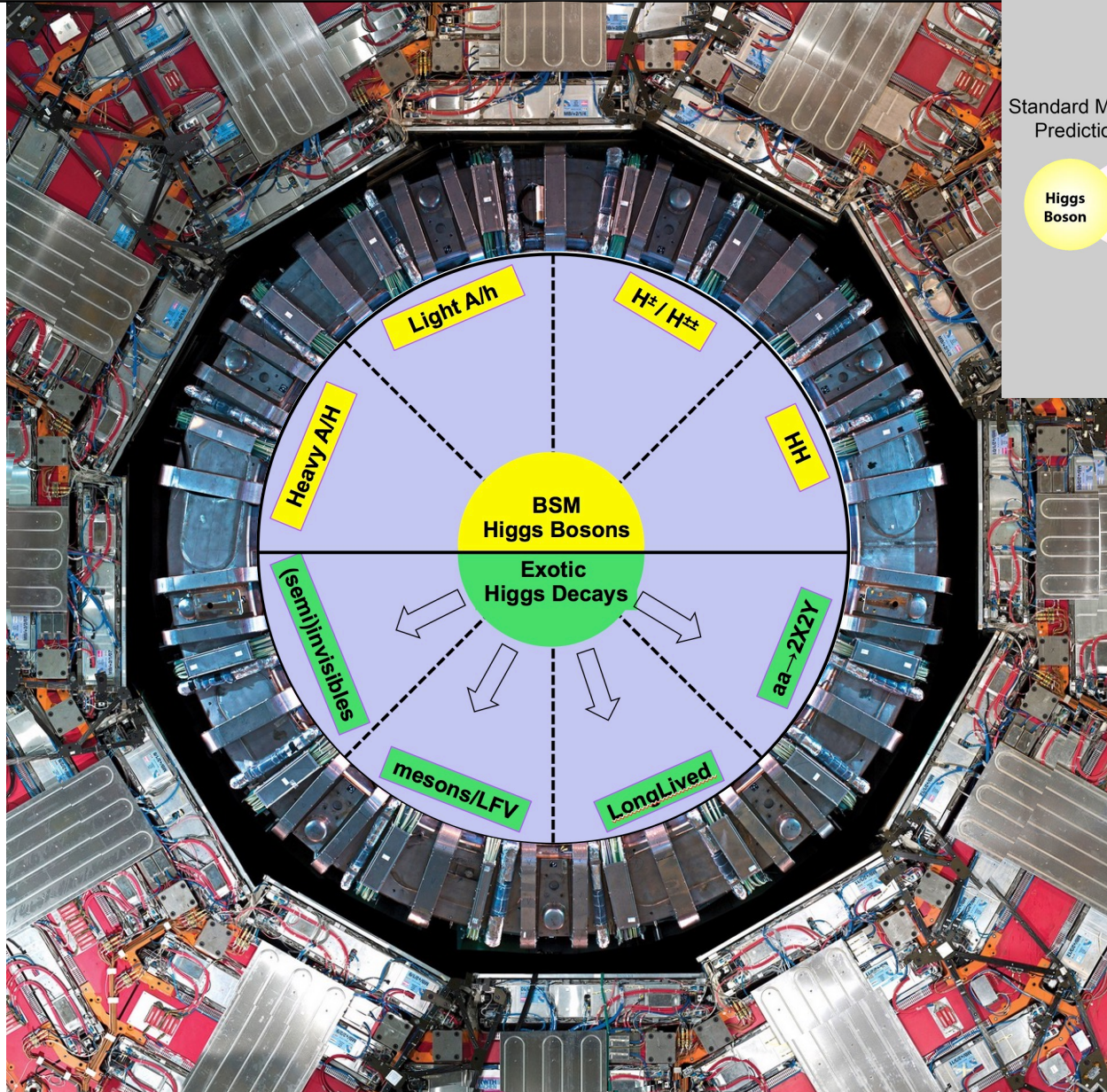
# Beyond Standard Model



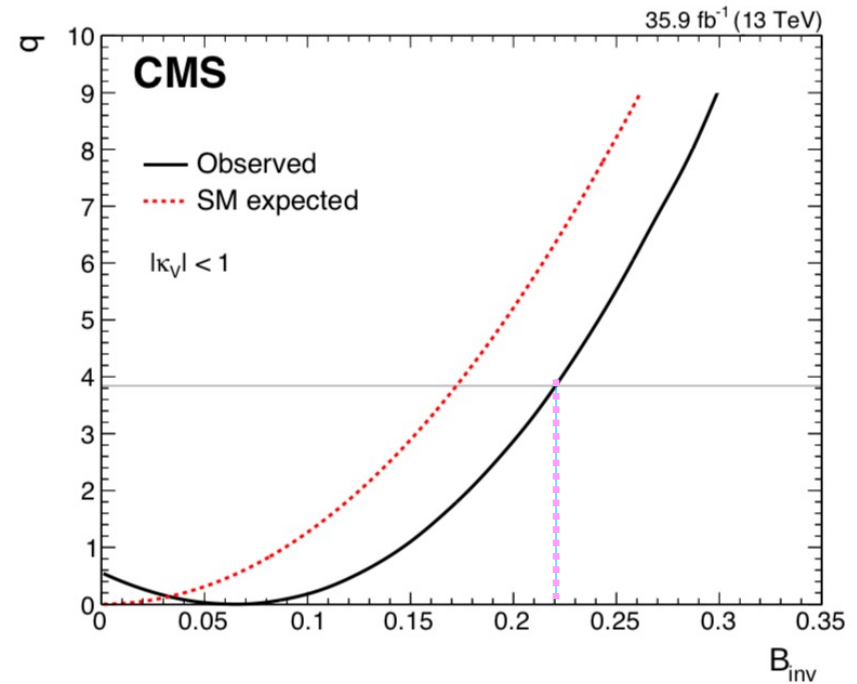
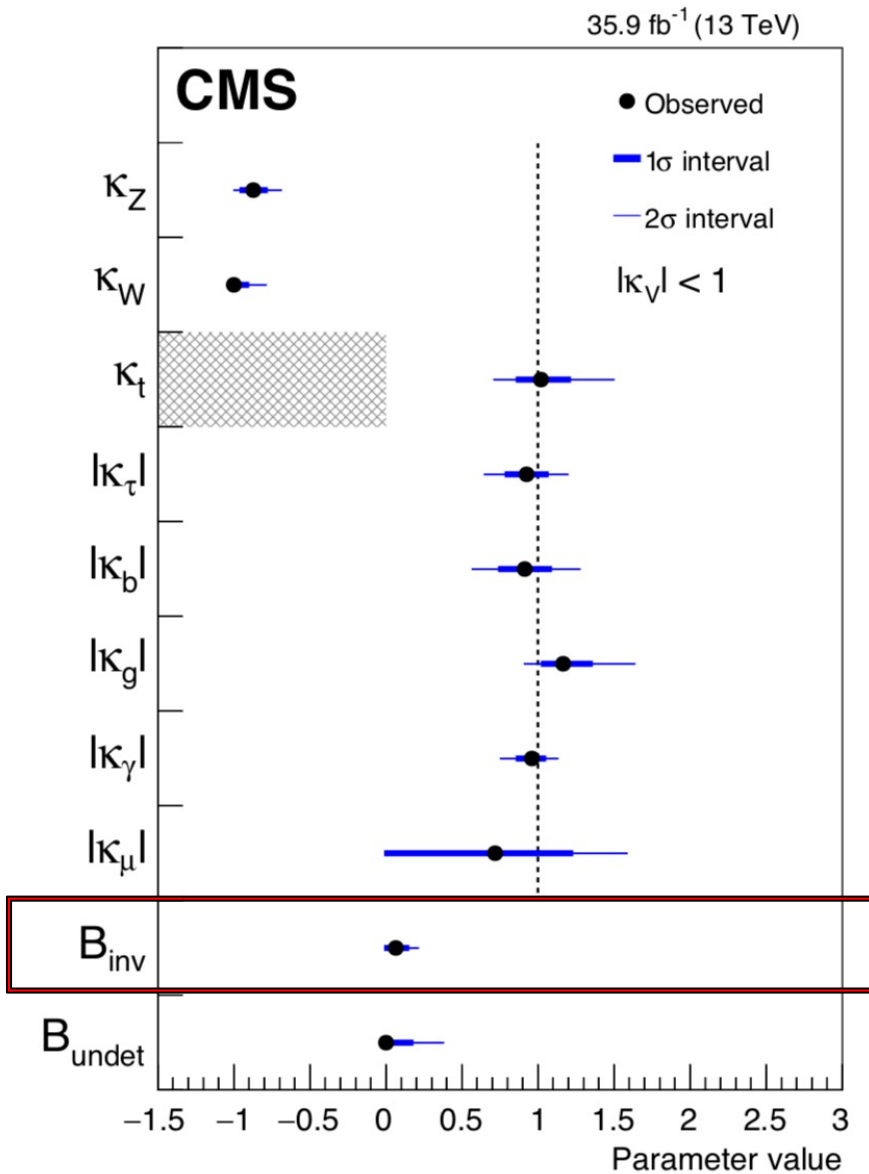
- Supersymmetry is one of the BSMs that is capable of answering many open questions in HEP.



# BSM Higgs boson



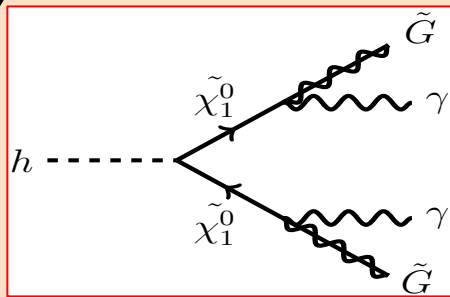
# Higgs coupling measurements



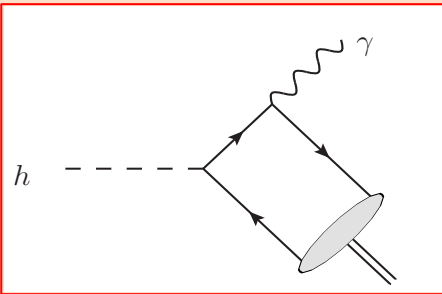
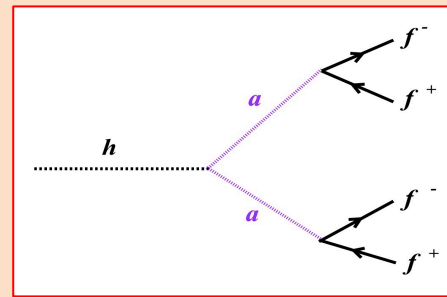
• Combining all searches, still offer a large chance for non-SM decays (~ 22%)

# Higgs Exotic Decays Overview

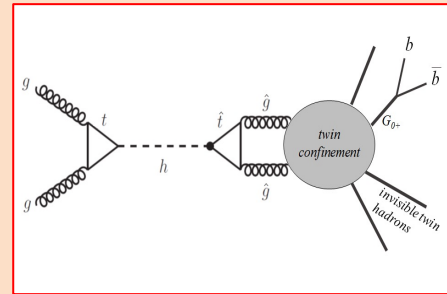
$h \rightarrow (\text{semi})\text{invisibles}$



$h \rightarrow aa \rightarrow 4X$



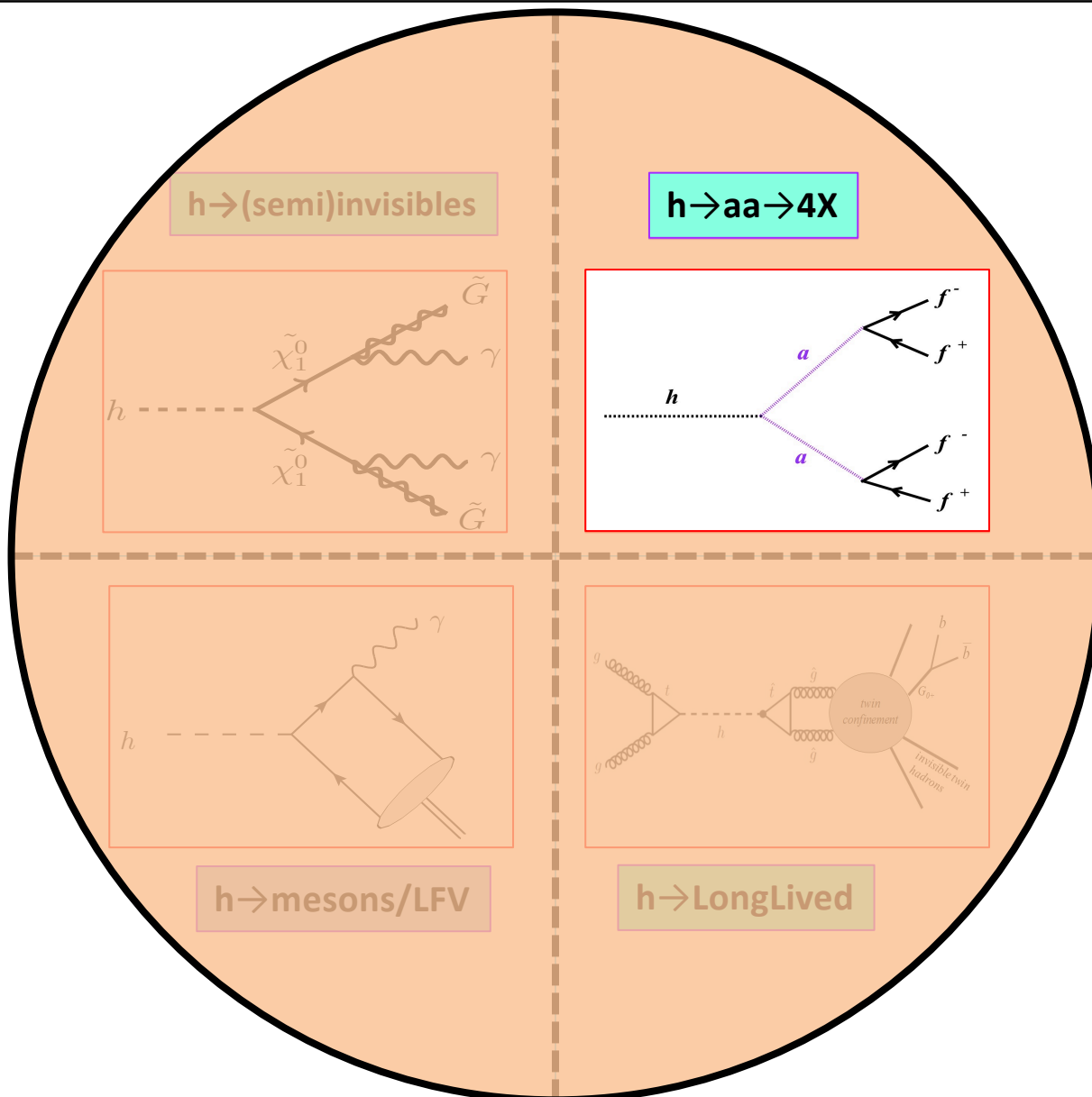
$h \rightarrow \text{mesons}$



$h \rightarrow \text{LongLived}$

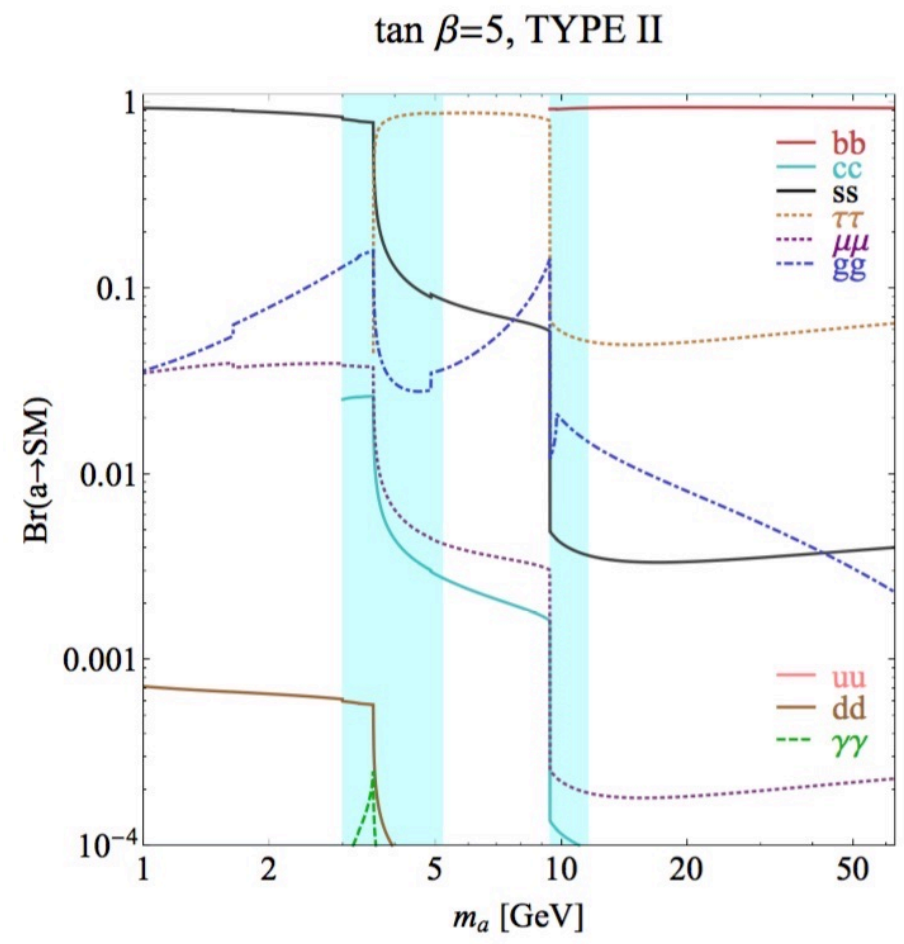


# $h \rightarrow aa \rightarrow 4X$

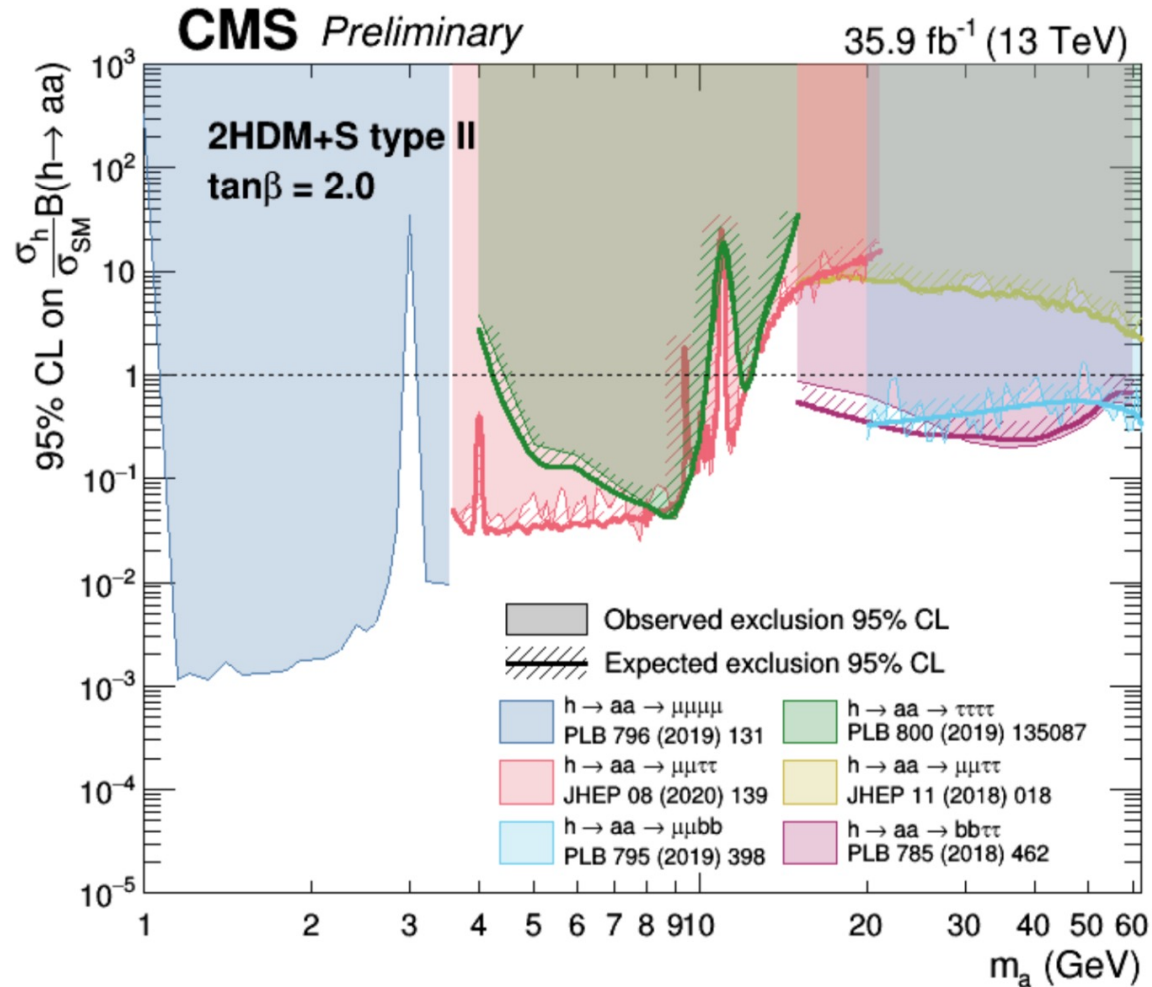


# $h \rightarrow aa \rightarrow 4X$ Motivation

- This exotic decays is generic prediction of many well-motivated theories of BSM. i.e. extended Higgs sector (NMSSM, ...),
- The final states SM particles are usually fermions (b, tau and muons), but can be photons and gluons as well
- Branching fraction to SM particles depends on the mass of a bosons, and models/model parameters.



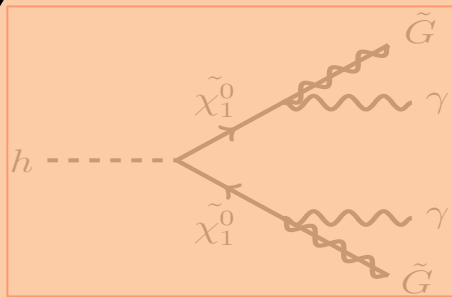
# Summary for Higgs exotic decays [ $h \rightarrow aa \rightarrow 2X2Y$ ]



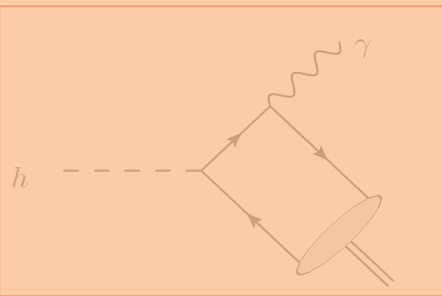
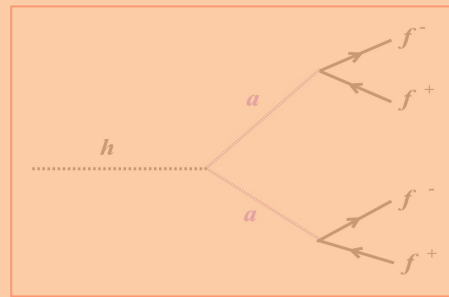
- This plot covers many searches sensitive in different range of the pseudoscalar mass.

# $h \rightarrow$ LongLived

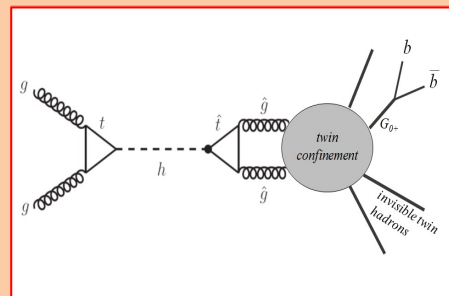
$h \rightarrow$  (semi)invisibles



$h \rightarrow aa \rightarrow 4X$



$h \rightarrow$  mesons/LFV

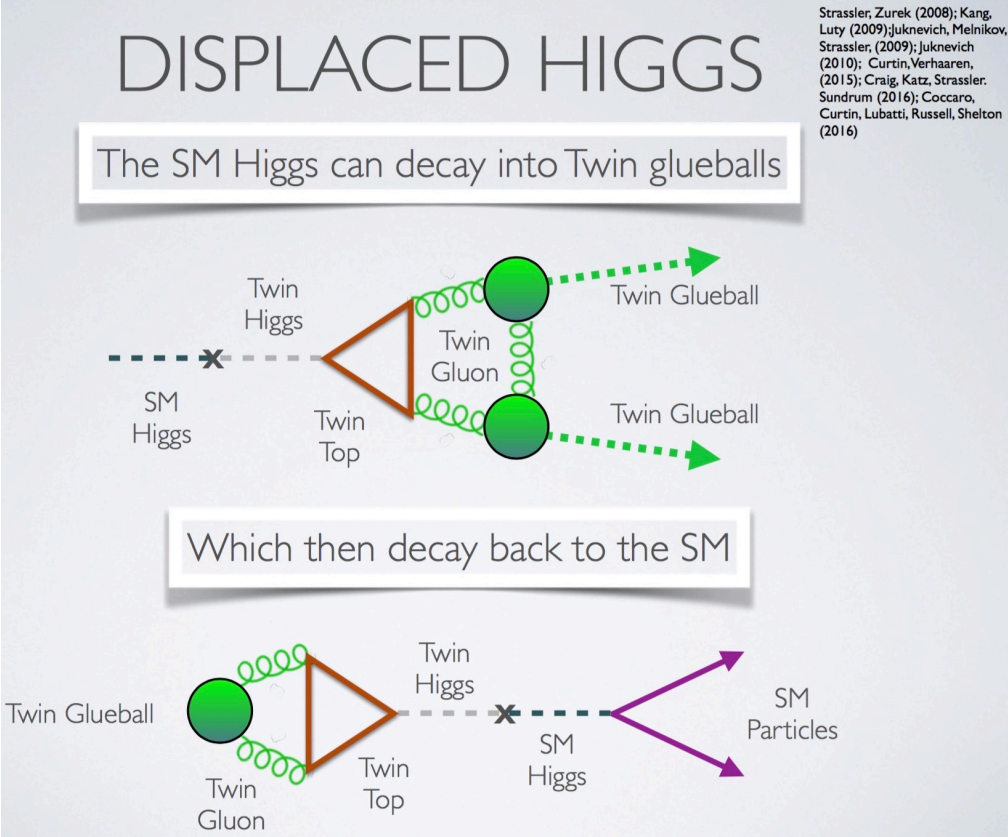


$h \rightarrow$  LongLived



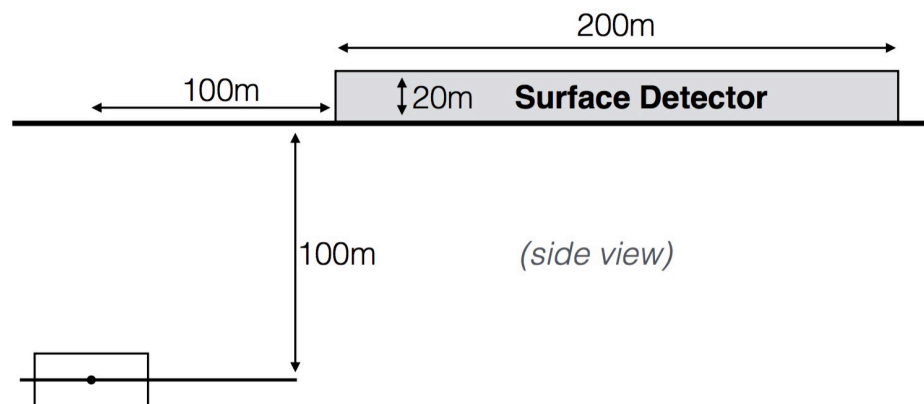
# Displaced Higgs

- LLPs arise in large variety of BSM scenarios
- Once produced at LHC, decays within detector volume with measurable displacement from primary vertex:
  - Challenge: ATLAS and CMS were not specifically optimized → tough to trigger and reconstruct them
  - Opportunity: such events are relatively background free!



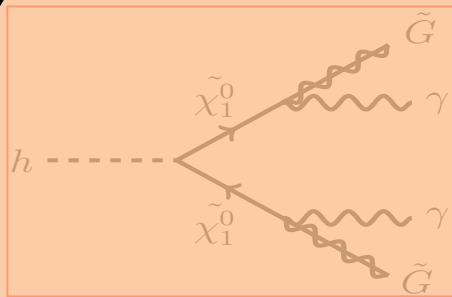
## MAssive Timing Hodoscope for Ultra-Stable Neutral PArticles

- A dedicated **surface detector** for ultra-long-lived particle (ULLP) decays
- ~5% geometric coverage
- Minimal RPC/scintillator instrumentation required
- Can be virtually background free

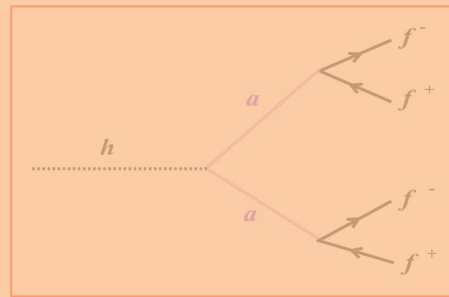


# $h \rightarrow \text{mesons/LFV}$

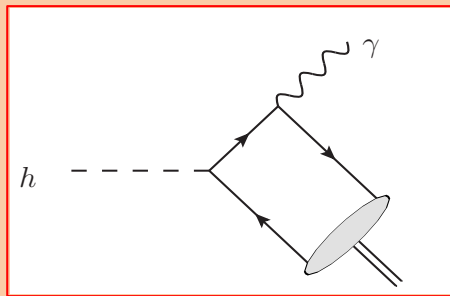
$h \rightarrow (\text{semi})\text{invisibles}$



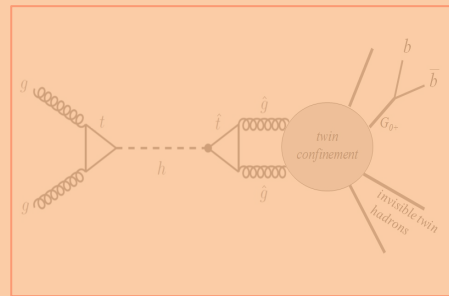
$h \rightarrow aa \rightarrow 4X$



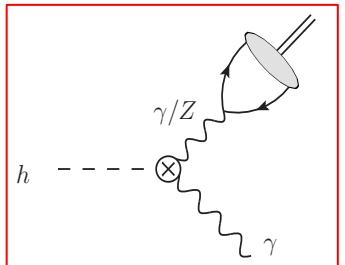
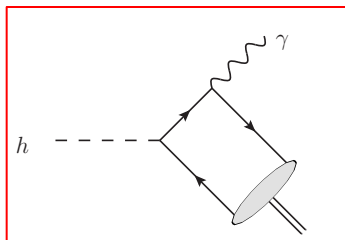
$h \rightarrow \text{mesons}$



$h \rightarrow \text{LongLived}$



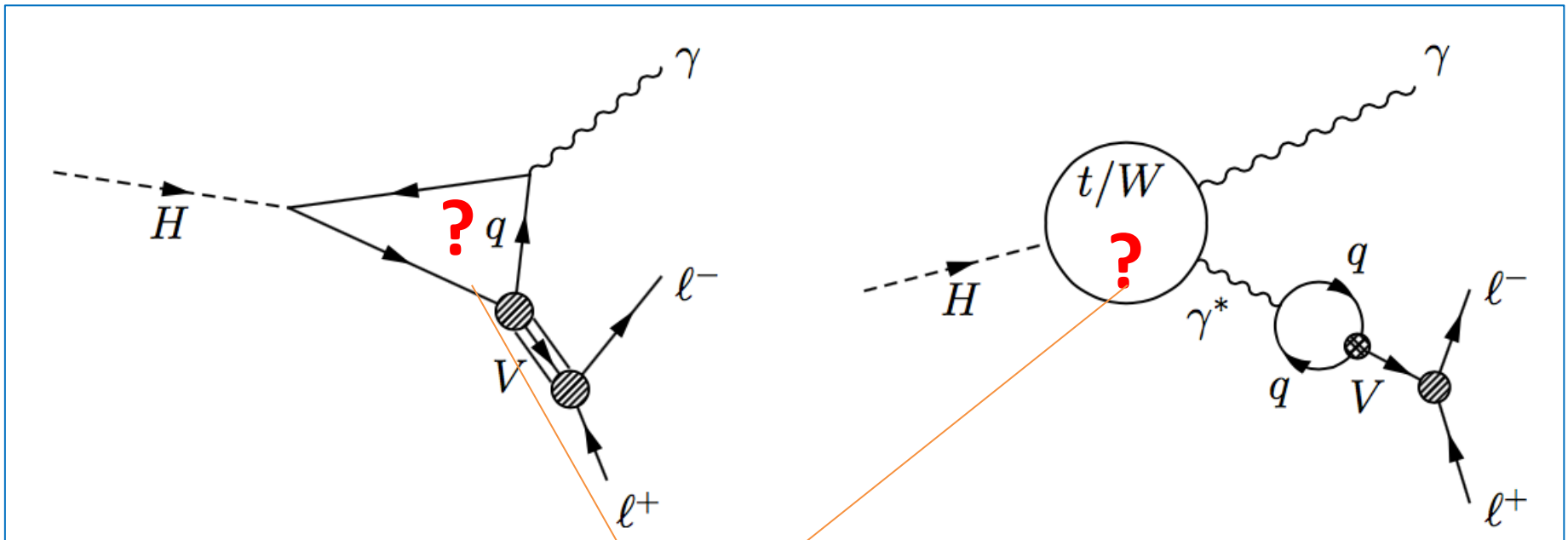
Direct production



Indirect production

# Exclusive mesonic Higgs decays

- Rare exclusion decay of Higgs to mesonic final state ( $h \rightarrow M\gamma/Z$ ) is a unique window on the (light) quark Yukawa coupling
- $H \rightarrow bb$  and  $H \rightarrow cc$  (mainly in  $W/Z$  AP), but no way for lighter quark coupling
- Branching ratios are very small  $\sim 10^{-6}$

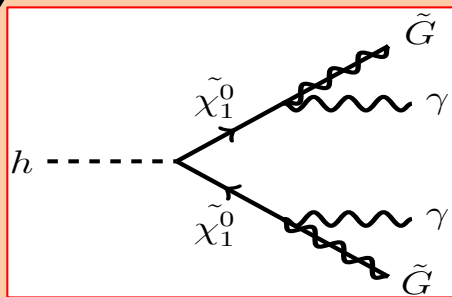


**What happens if new particles are involved in the loop?**

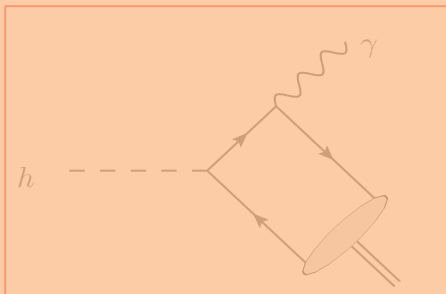
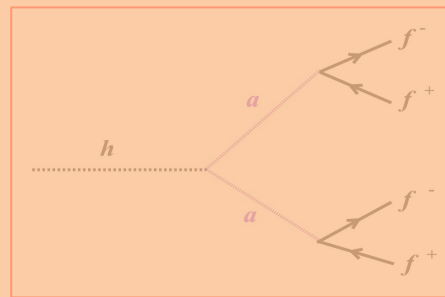


# $h \rightarrow (\text{semi})\text{invisibles}$

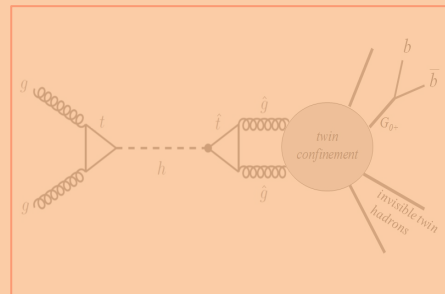
$h \rightarrow (\text{semi})\text{invisibles}$



$h \rightarrow aa \rightarrow 4X$

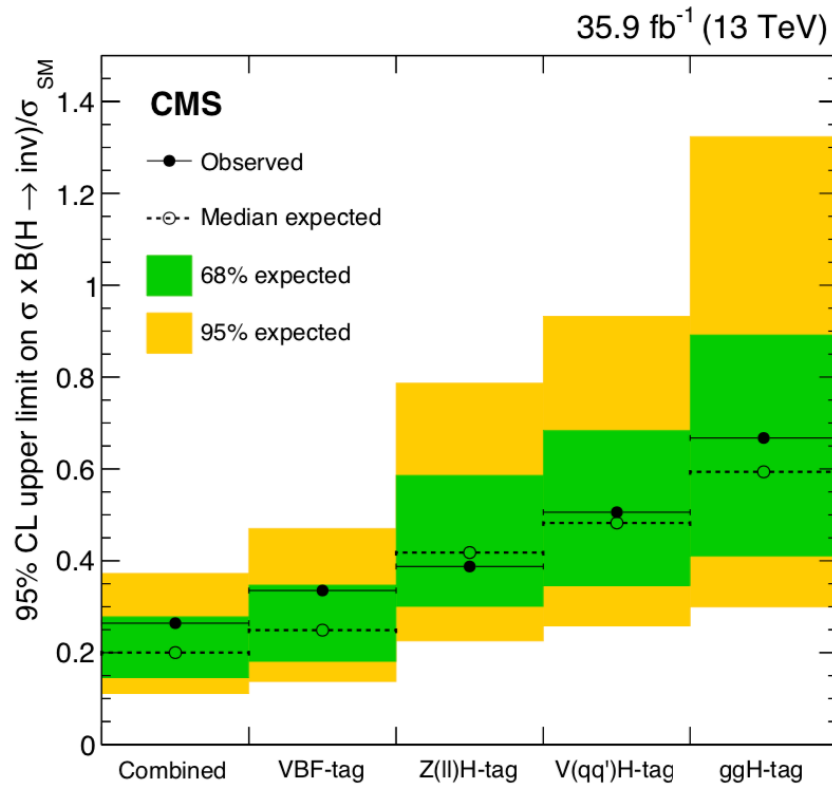
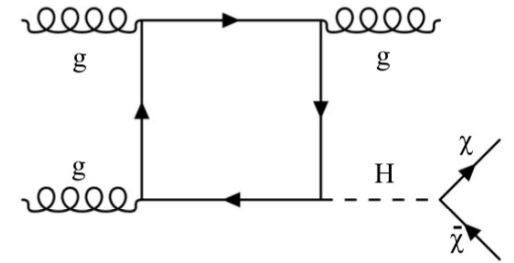
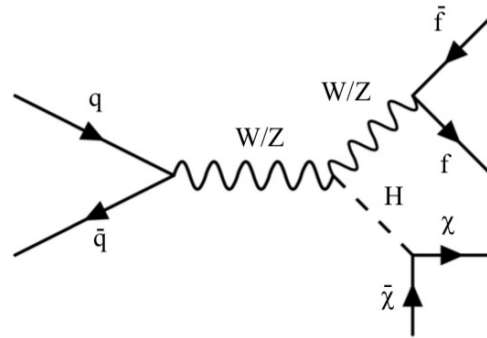
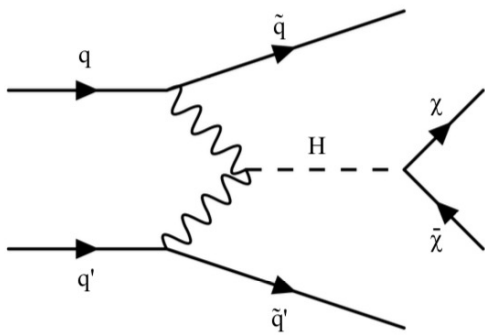


$h \rightarrow \text{mesons/LFV}$



$h \rightarrow \text{LongLived}$

# Higgs $\rightarrow$ Invisibles



# After a decade, where we stand now and where we go ...

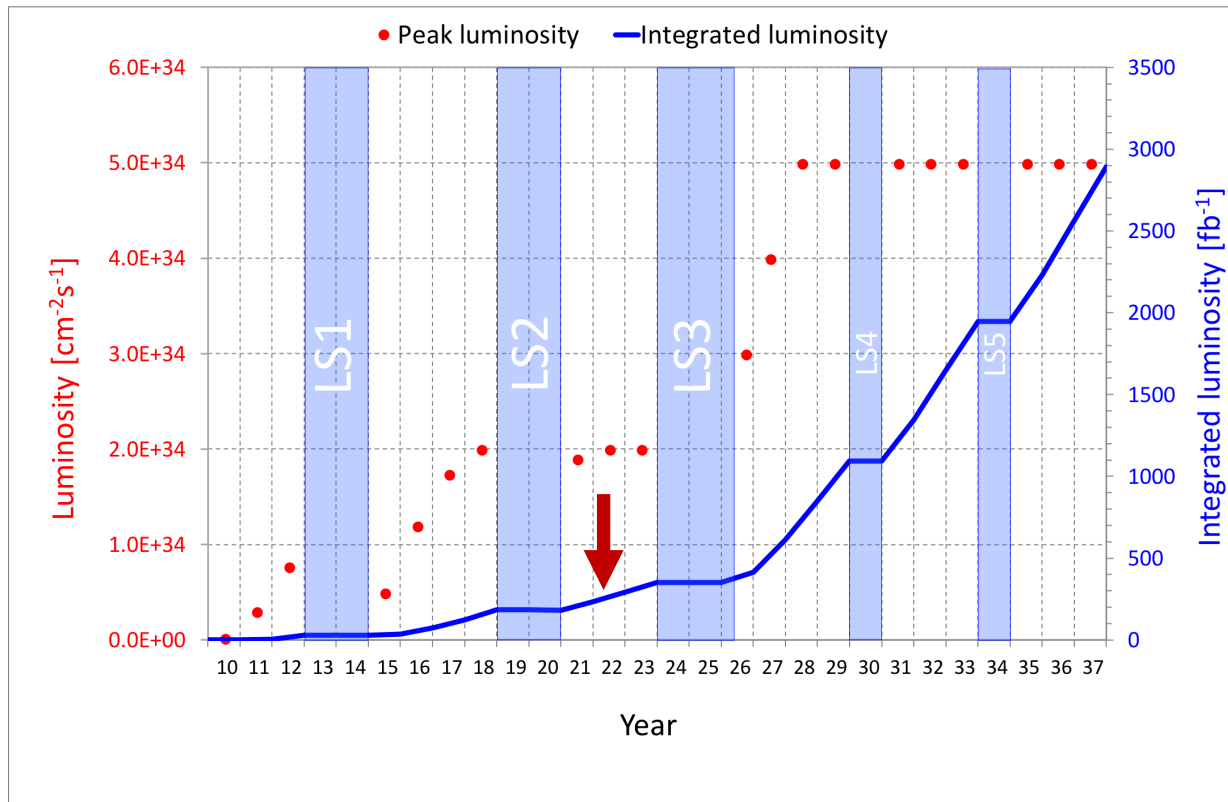
Measured SM  
more precisely

Found SM  
Higgs boson

No clue for  
new Physics



# Future Plan

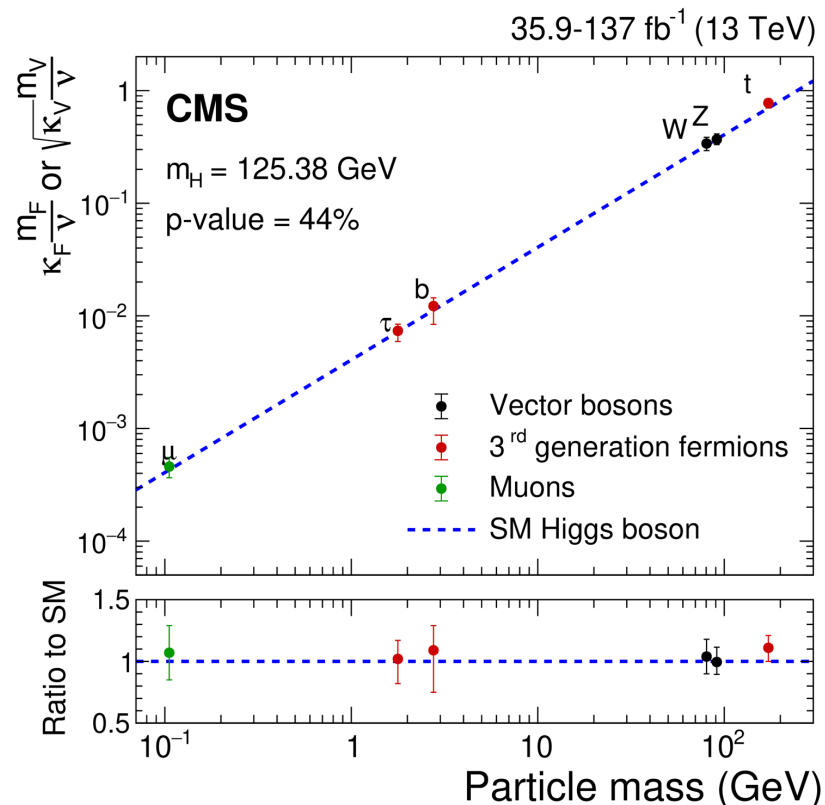


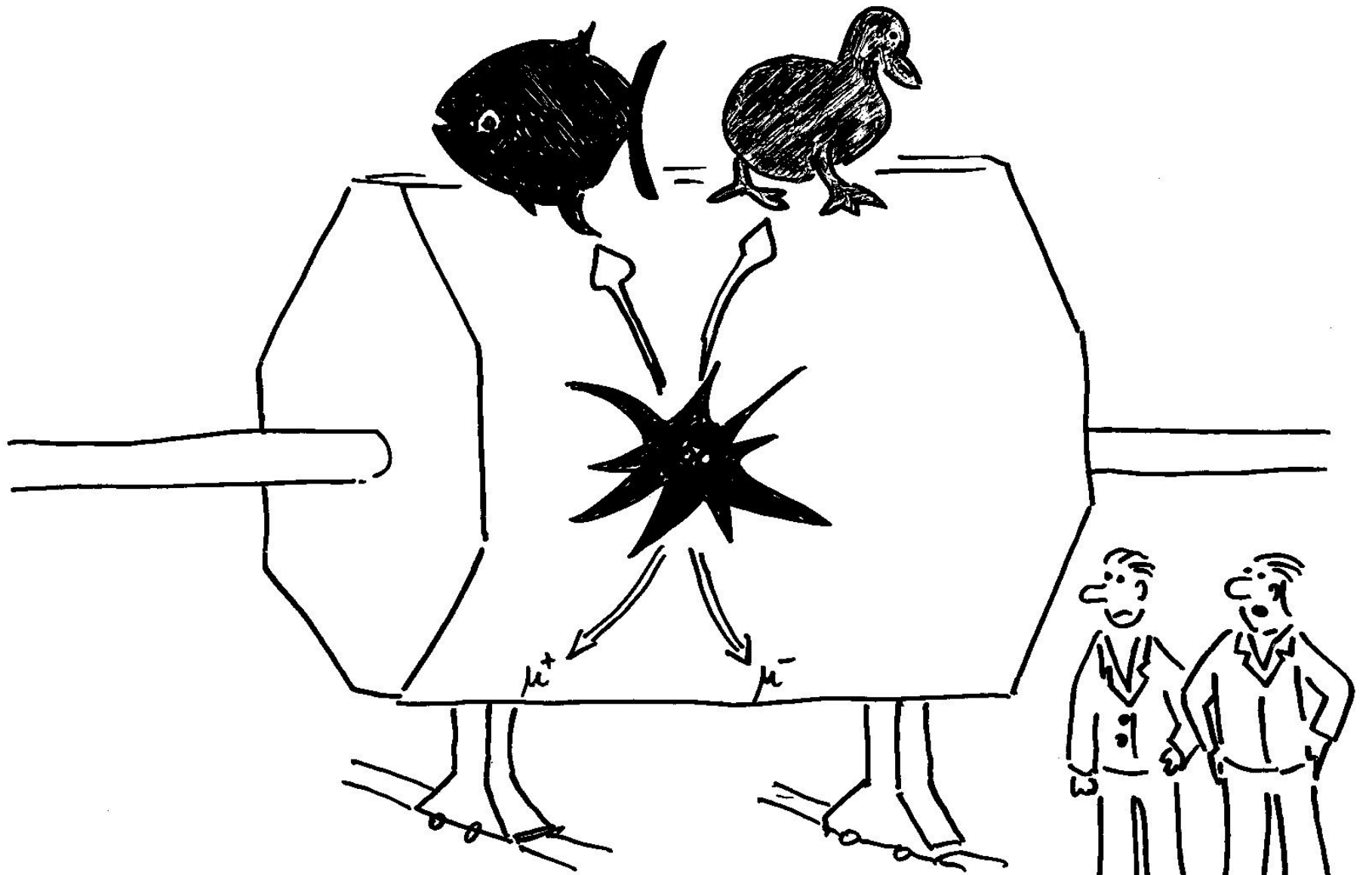
- The current analyzed data is just a few % of the total data planned to be collected by the entire life of the LHC (particularly, during HL-LHC)



# Summary

- Thanks to the excellent performance of the LHC in the last decade, particle physicists have a better understanding of the rules governing our universe
  - Most spectacular one is the unraveling the particles' mass origin puzzle
- No significant sign for new Physics yet, in spite of extensive attempts.
- Need to look everywhere. New physics might just be on the corner!





“This is not exactly, what theory predicted for the Higgs decay!”