

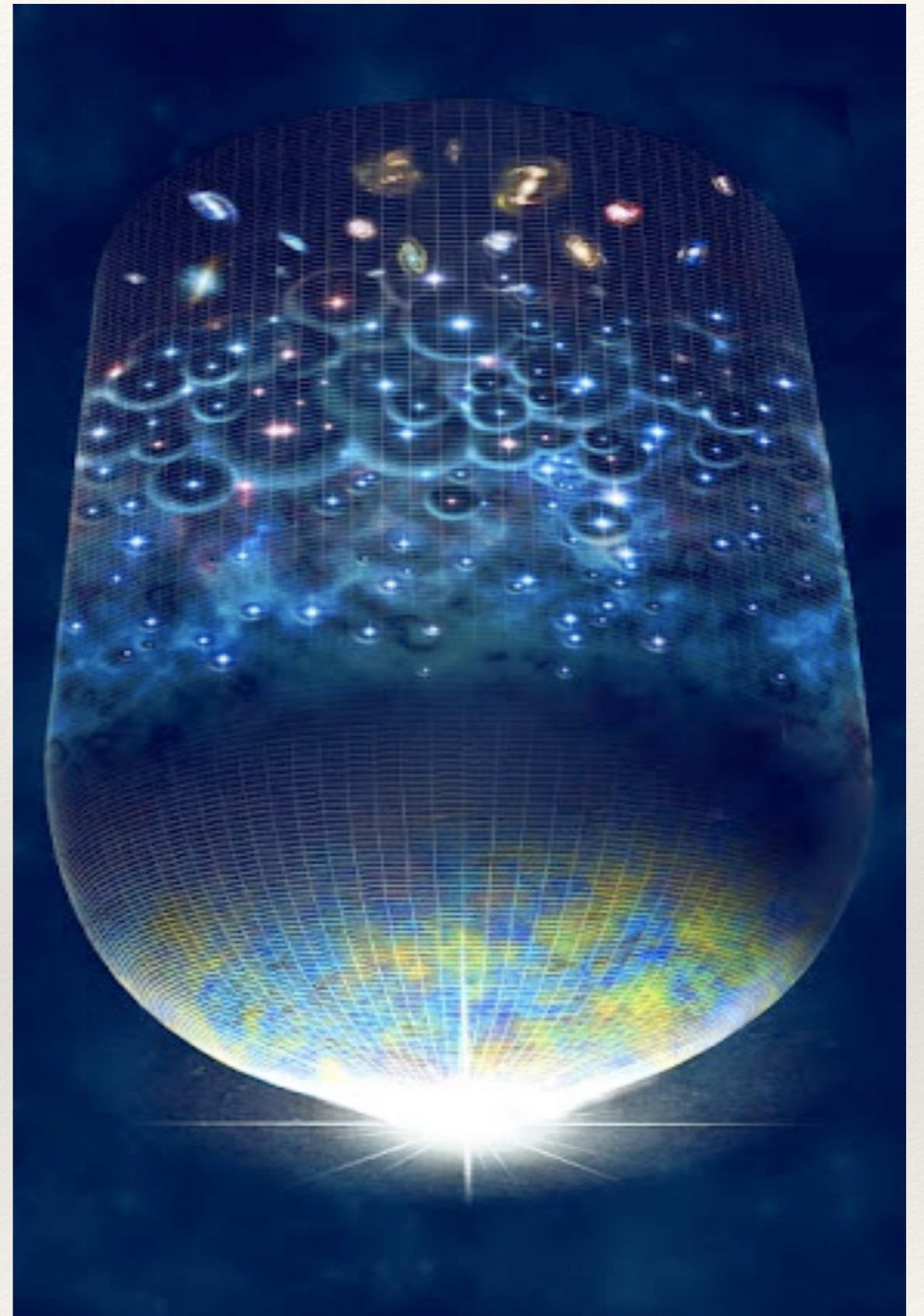
*TRIUMF Science Week*

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# Challenges and opportunities in Particle Physics

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*Veronica Sanz (IFIC-UV and Sussex)*





Long live the king Standard Model!

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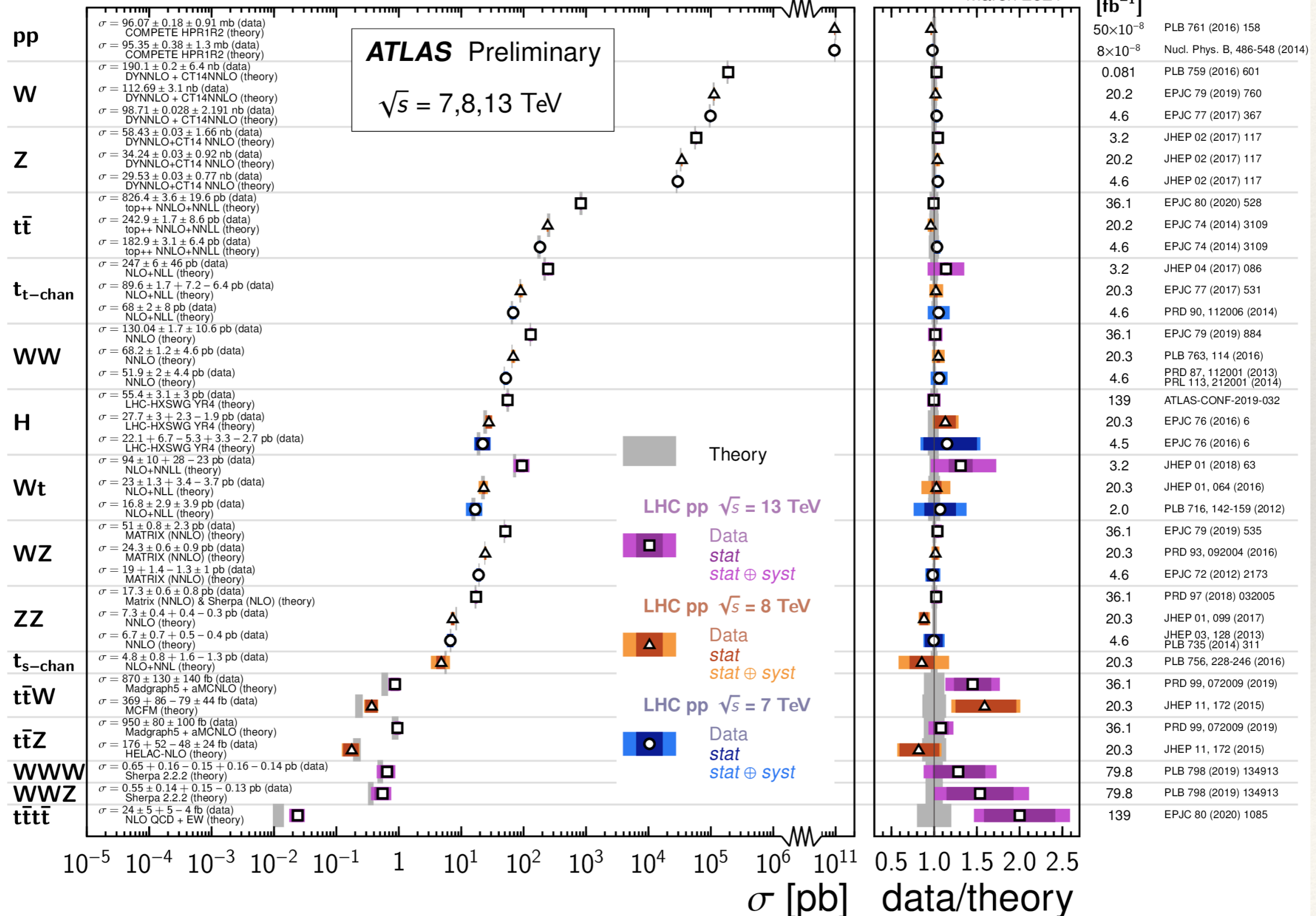
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# The Standard Model rules

## Standard Model Total Production Cross Section Measurements

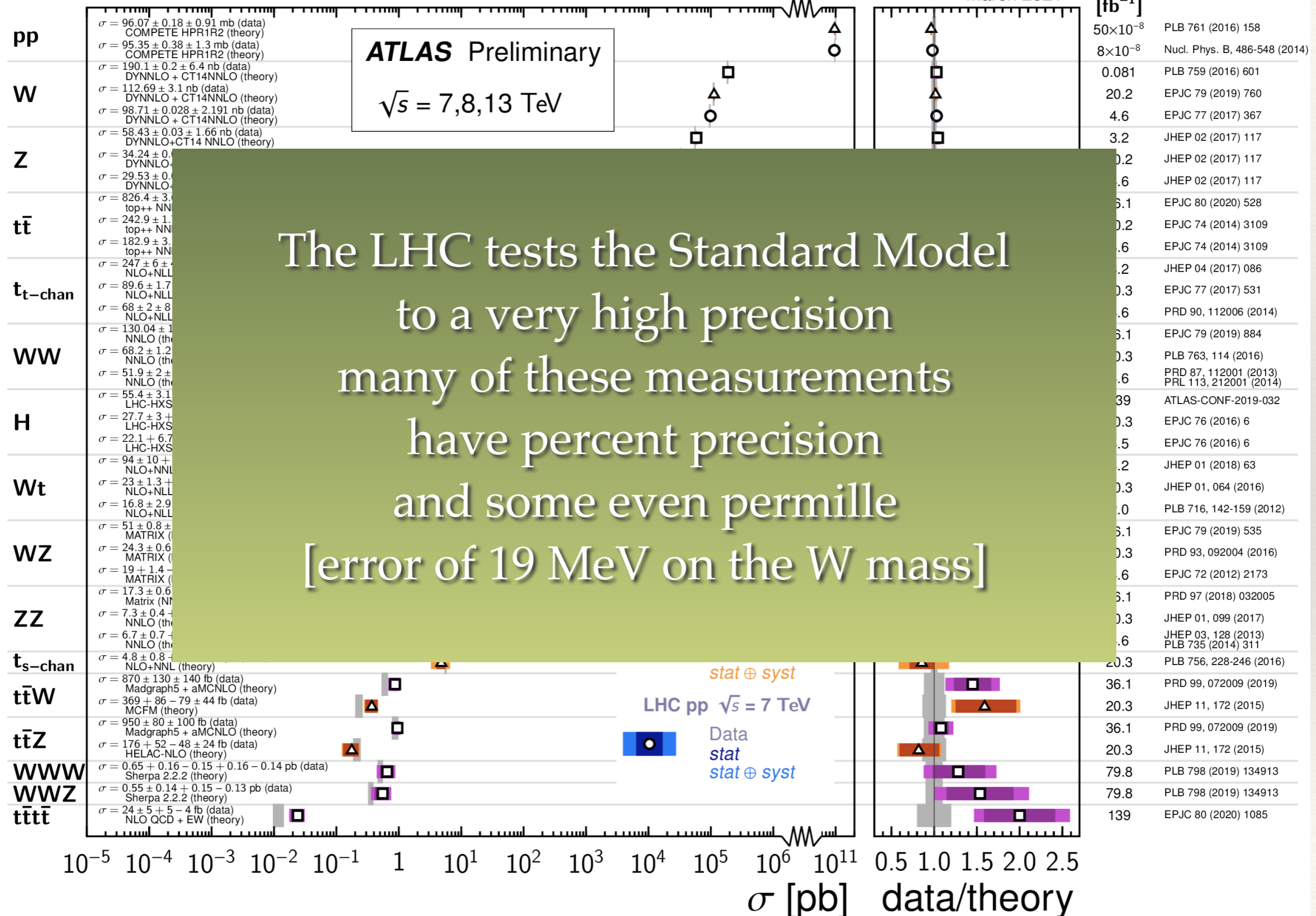
Status: March 2021



# The Standard Model rules

## Standard Model Total Production Cross Section Measurements

Status: March 2021





# Celebrating the Standard Model

Those are **impressive** achievements

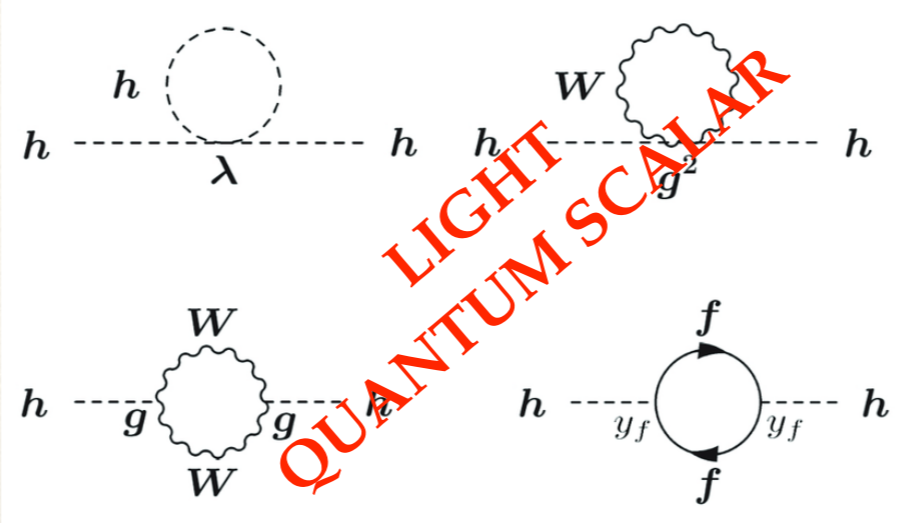
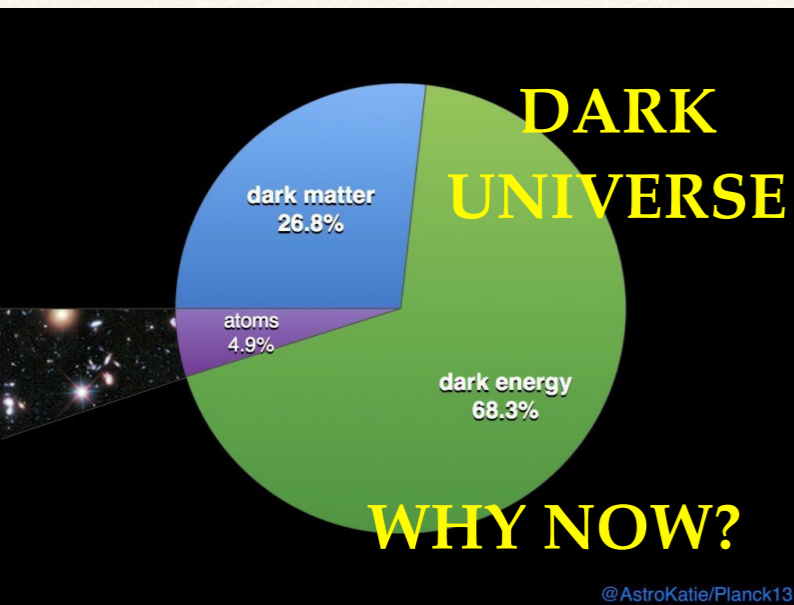
a single theory, developed long time ago  
based on rather simple building blocks

can predict Nature's behaviour  
in a huge range of energies  
with unparalleled precision  
in many kinematic situations  
involving numerous different particles

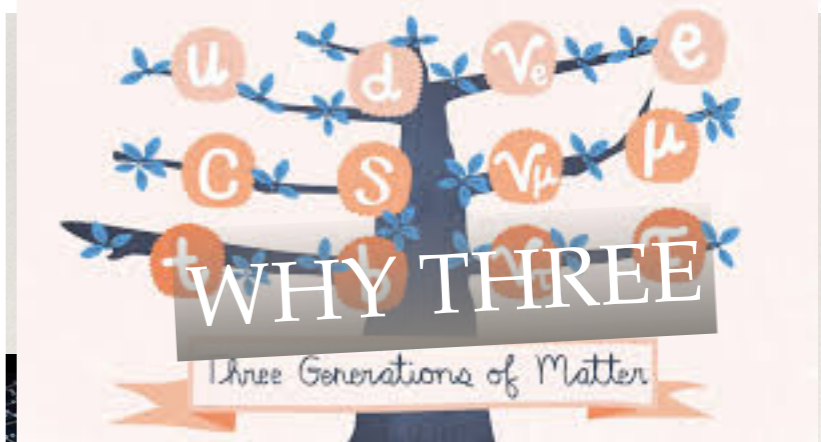
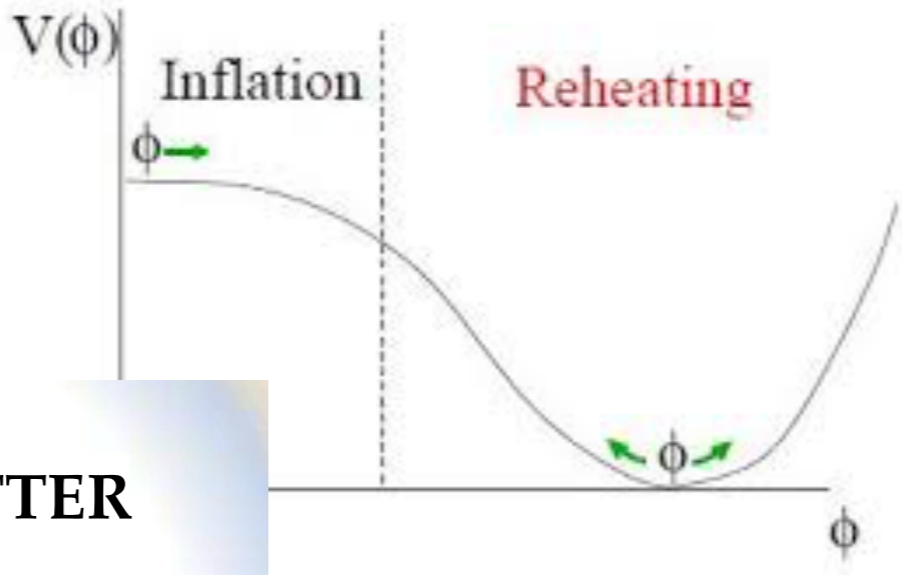
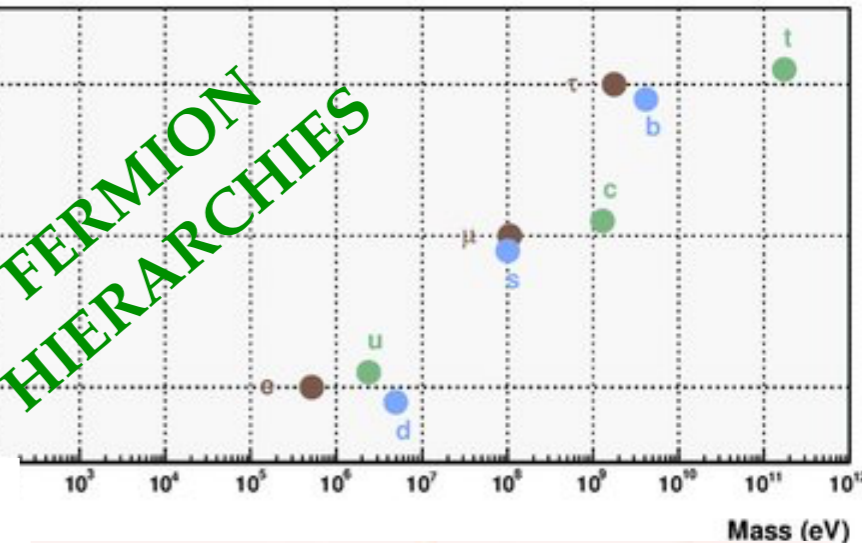
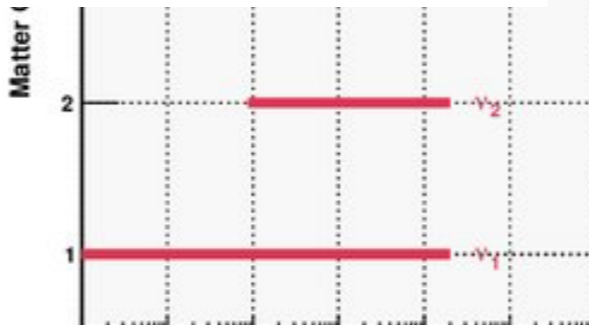
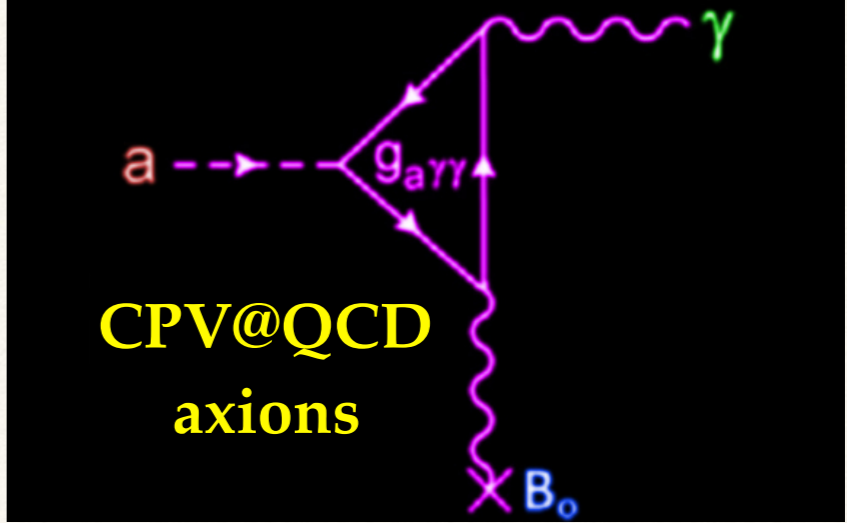
So why aren't we just **happy**?



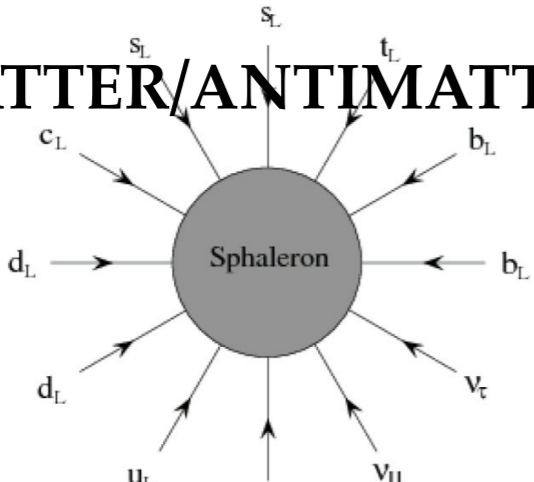
# Because that can't be it



**LIGHT QUANTUM SCALAR**

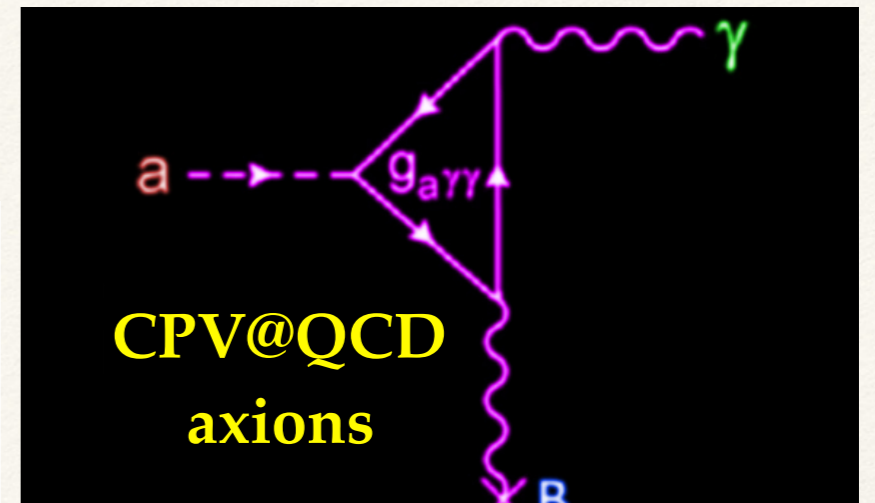
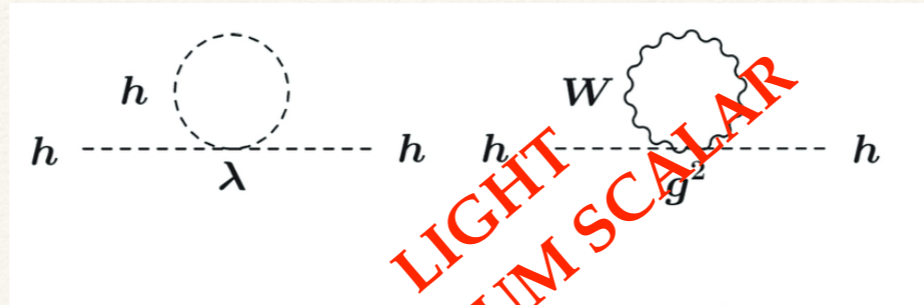
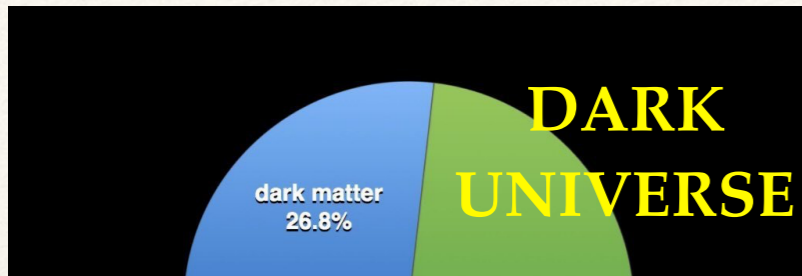


## MATTER/ANTIMATTER

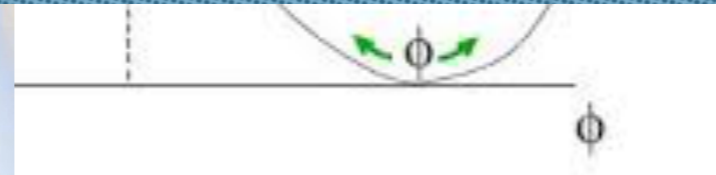
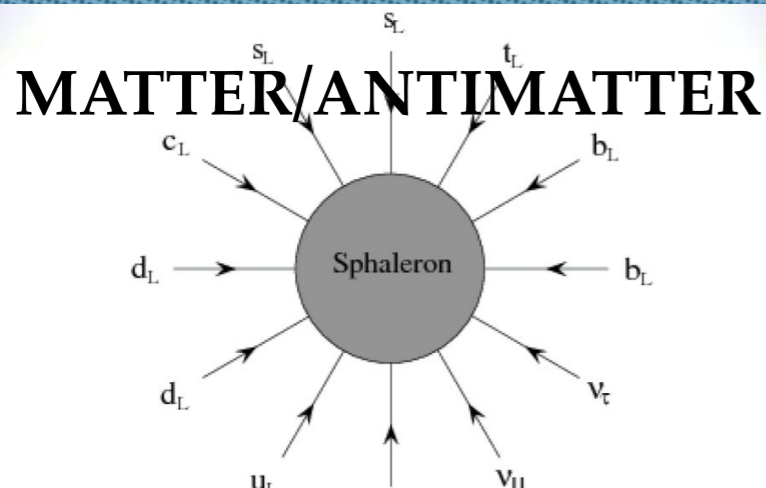




# Because that can't be it



WHY NOW?  
**THERE ARE MANY MYSTERIES TO SOLVE**  
**MANY DISCOVERIES TO BE MADE**  
Discovery=understanding a new principle,  
a new way to think about Nature



Three Generations of Matter





# So here we are

Light Higgs

Inflation

Neutrinos

Matter/Antimatter

Unification

CP QCD

Dark Matter

Dark Energy

Quantum Gravity



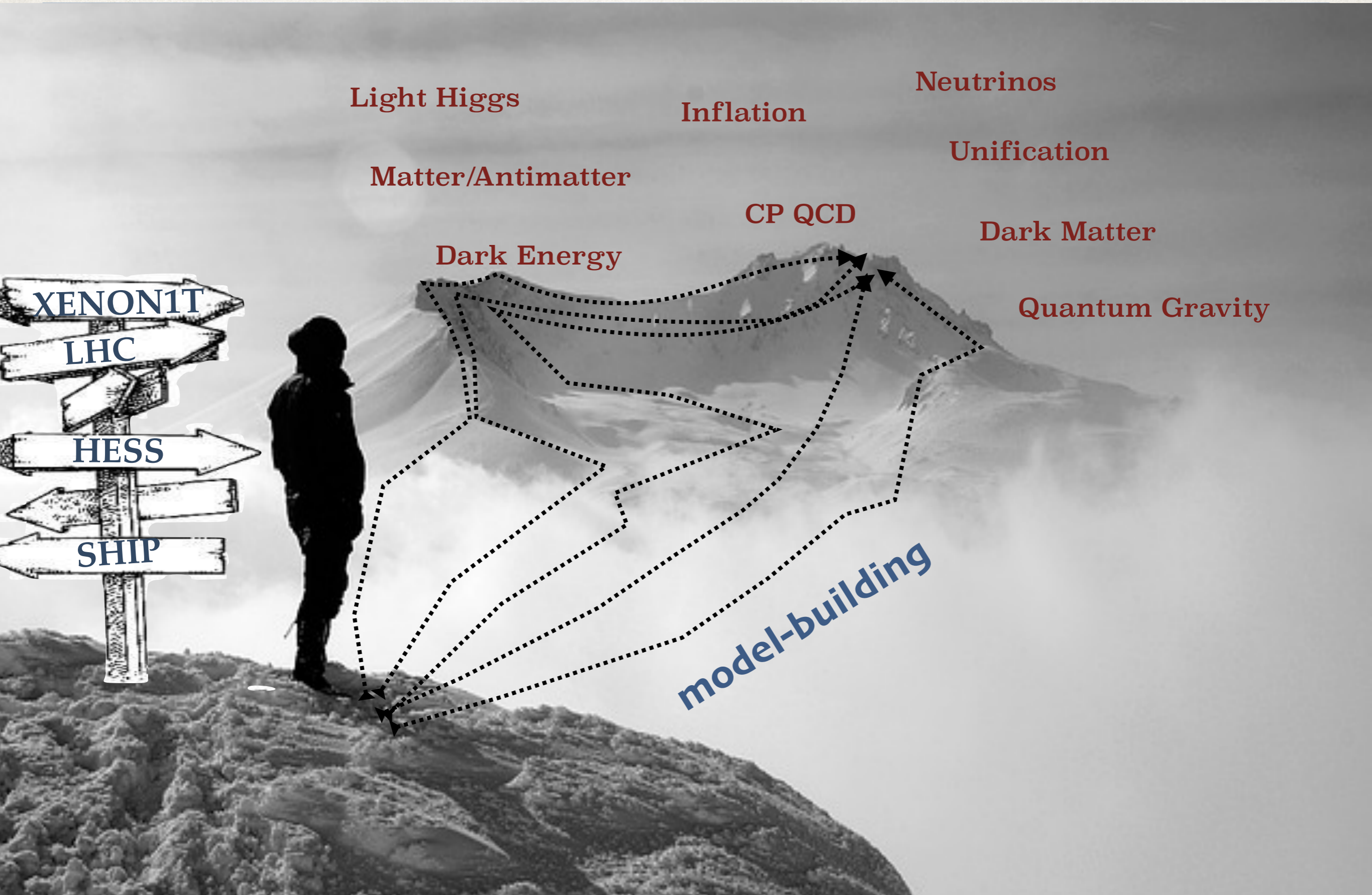
finding our path through **SYMMETRIES & DYNAMICS**

aiming for a **UNIFIED FRAMEWORK**

**SM+GR**



# Empirical science



Light Higgs

Inflation

Neutrinos

Matter/Antimatter

Unification

CP QCD

Dark Matter

Dark Energy

Quantum Gravity

XENON1T

LHC

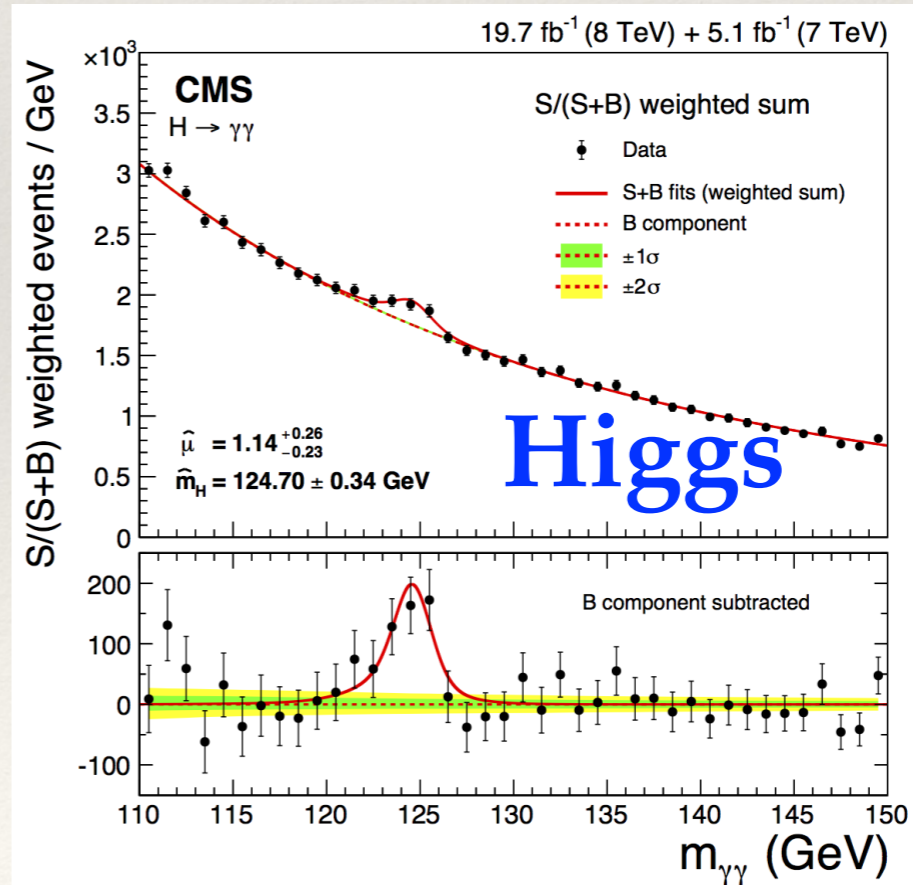
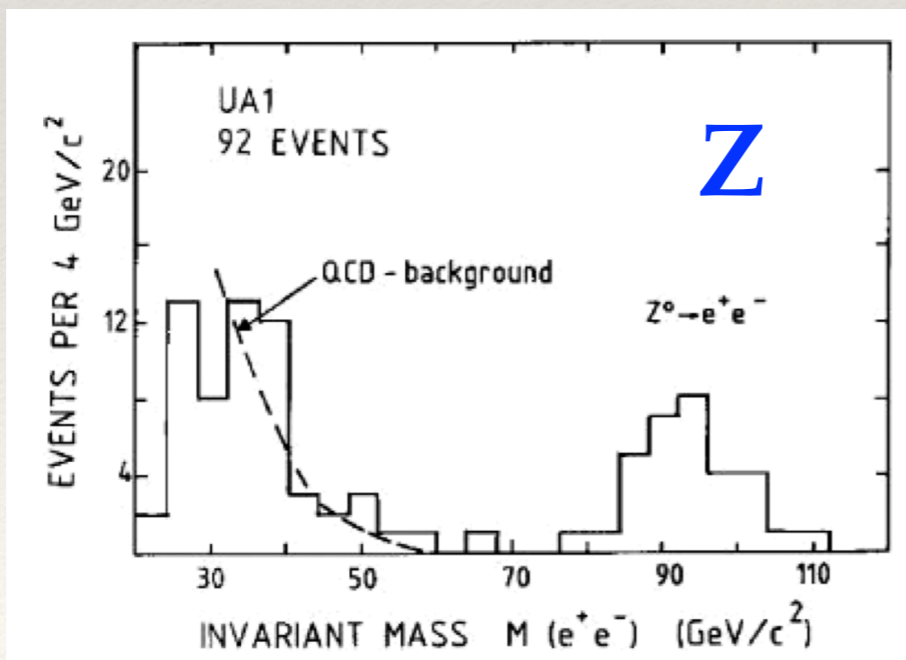
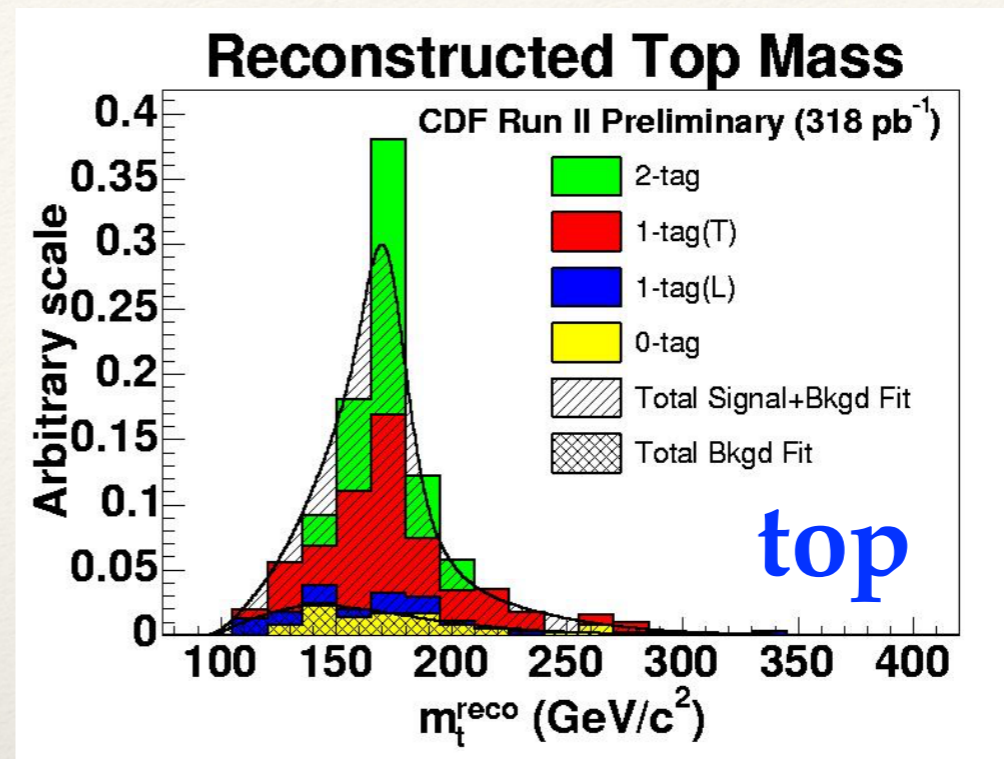
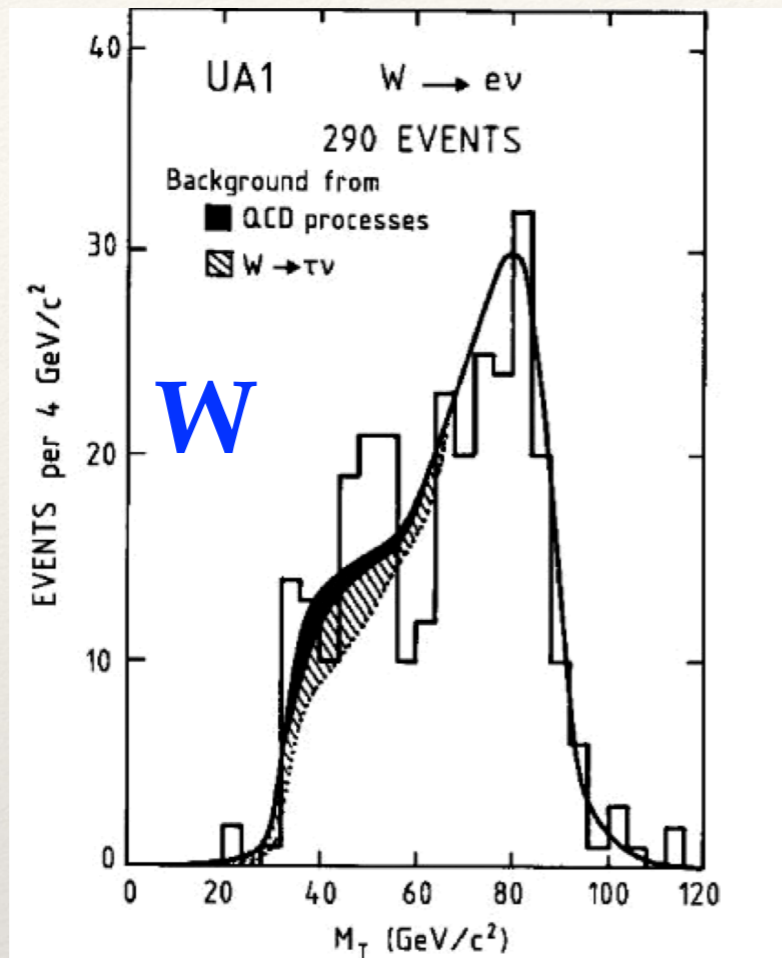
HESS

SHIP

model-building



# Discoveries = Resonances?



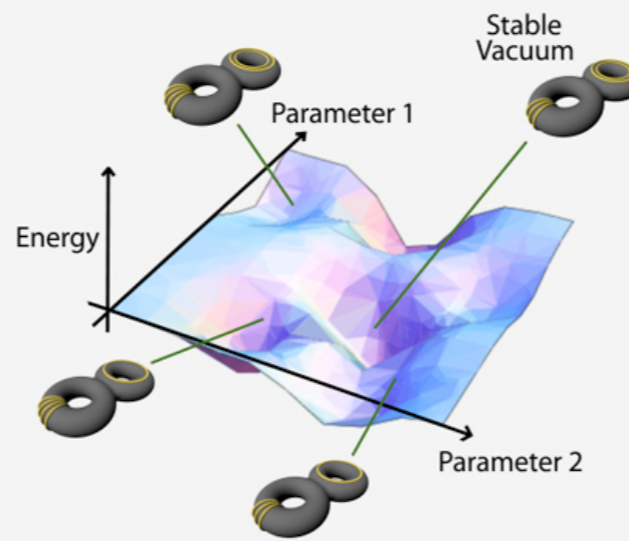


# The nature of the Higgs is still a mystery

What fundamental principle could be behind a light scalar in Nature?



Something like  
Superconductivity?



Landscape of  
String Theory?



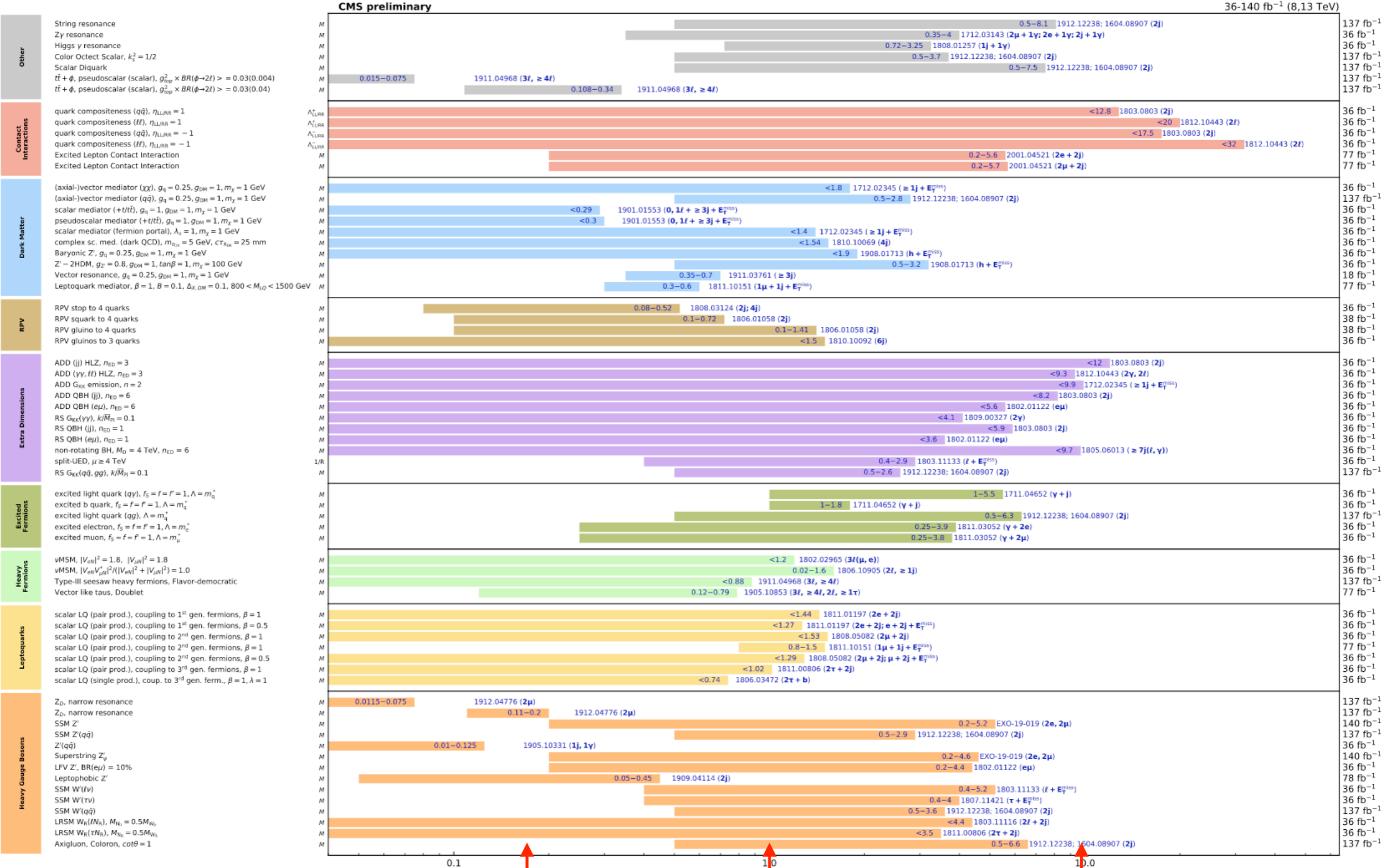
New dimensions?  
Supersymmetry?

Many, many possible realisations (phenomenology)  
Predict new states, to be discovered  
(SUSY partners, techni-baryons and mesons, spin-two...)  
AND induce deviations in the Higgs behaviour



# And resonances have been searched for, indeed!

## Overview of CMS EXO results



EW

1 TeV

10 TeV



# And resonances have been searched for, indeed!

Overview of CMS EXO results



**PROMPT, DISPLACED, DISAPPEARING...**  
**+ excellent agreement in SM observables**  
**no stone unturned**



# Angst, anyone?

Thanks to the LHC, we have witnessed a large-scale mobilisation of talent behind the idea of

understanding Nature

a selfless, intellectual drive



It is a remarkable success and its continuation requires re-focusing as we learn more about Nature



Lack of discoveries since the Higgs and guidance on where to look:  
a sort of *identity crisis*

as PP seems to be all about new particle discoveries

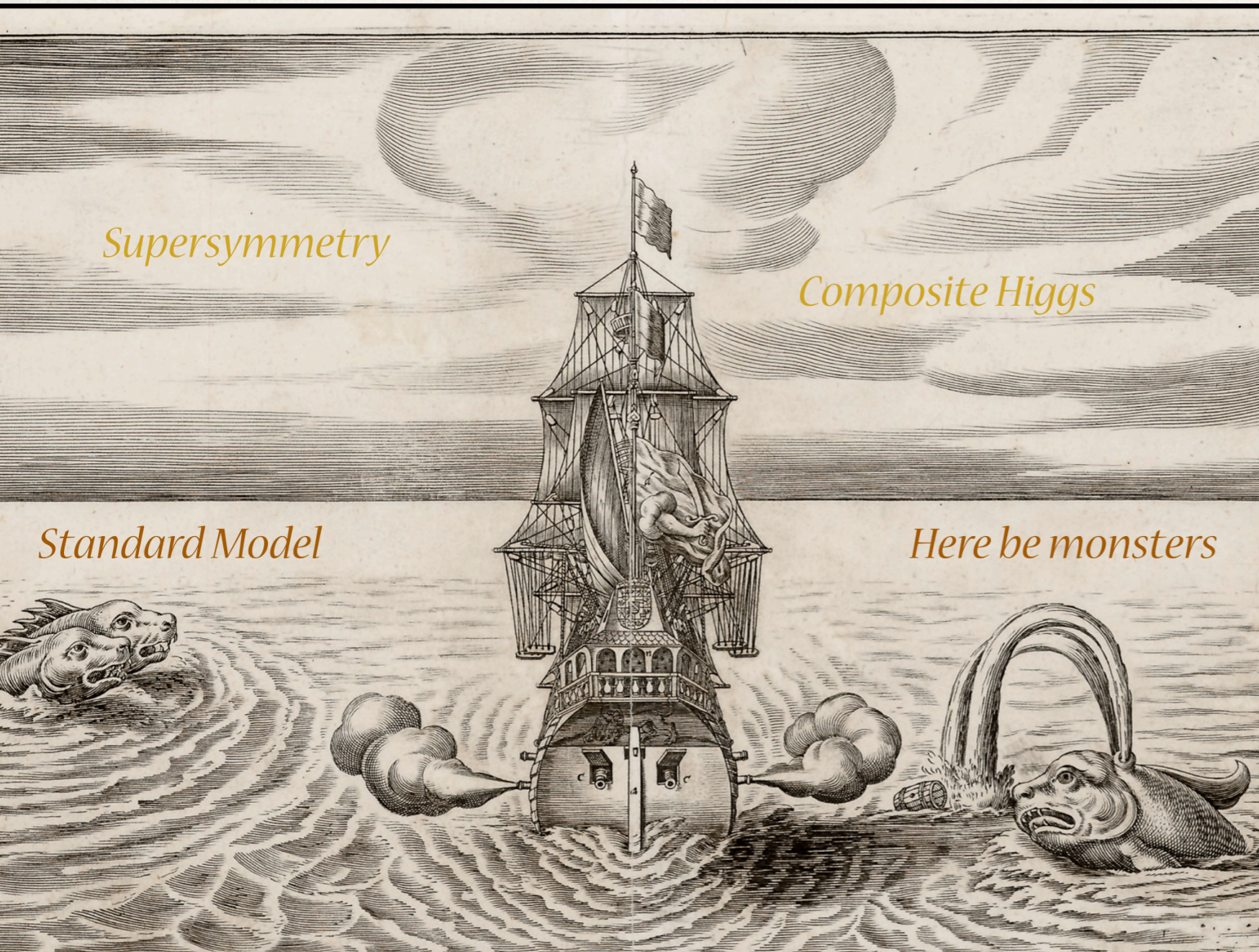


*Supersymmetry*

*Composite Higgs*

*Standard Model*

*Here be monsters*



# Then what?

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Sailing towards *terra incognita*



# Connecting ideas with experiments

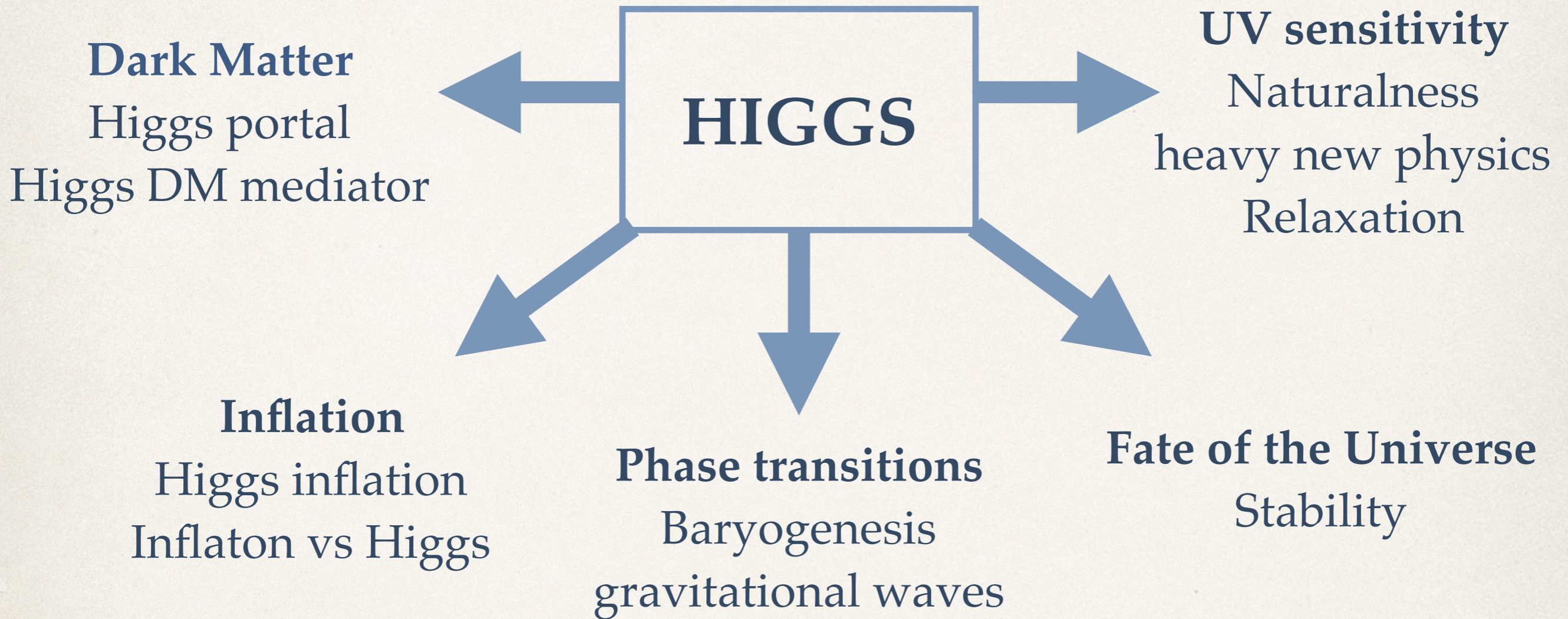
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# A cosmological Higgs

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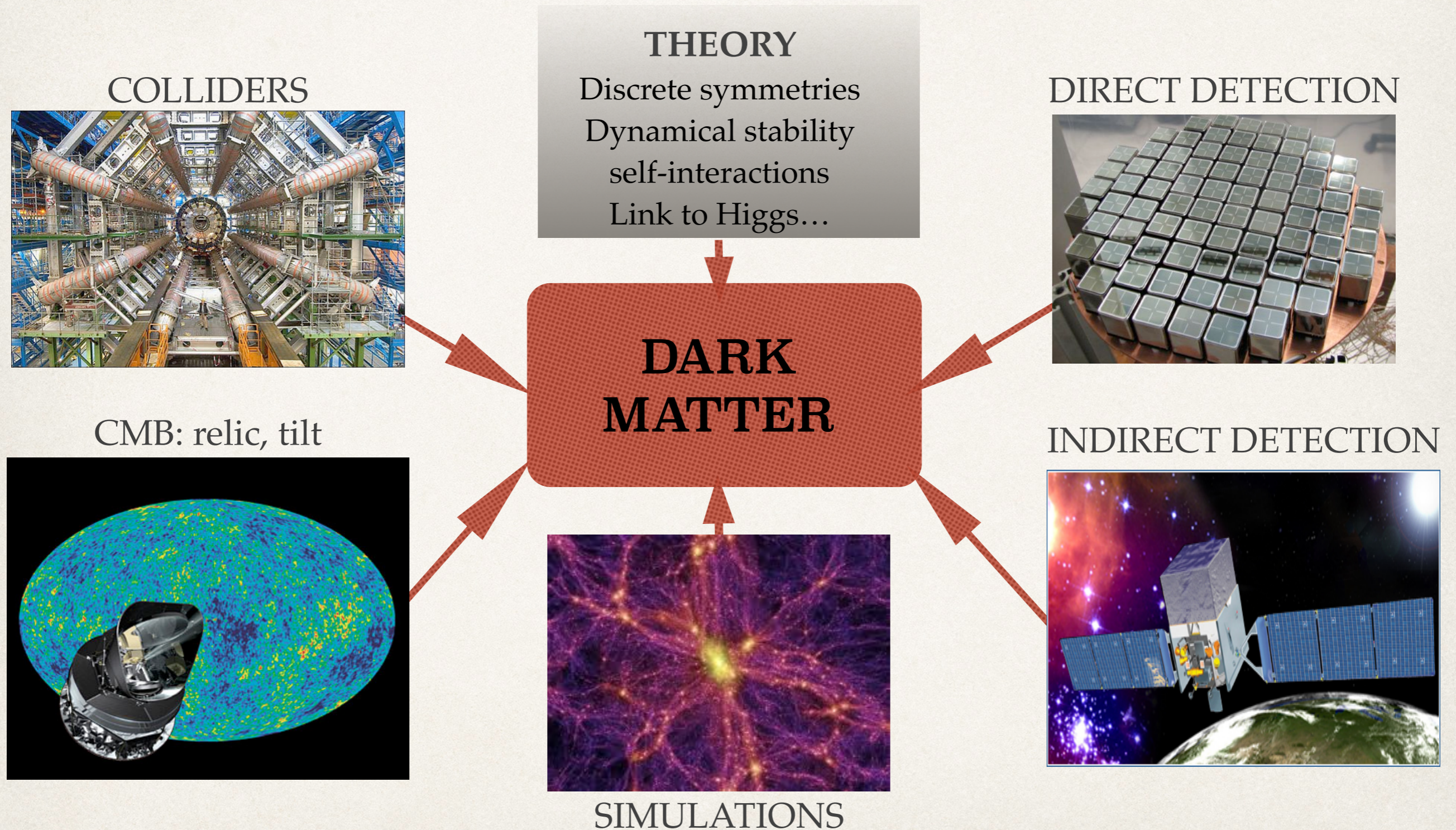
The LHC provides the **most precise, controlled** way of studying the Higgs and direct access to TeV scales

Exploiting complementarity with cosmo/astro probes

**Similar story for Axions and ALPs, scalars are versatile**



# Many faces of Dark Matter





# New opportunities at the LHC

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# Run3 and beyond

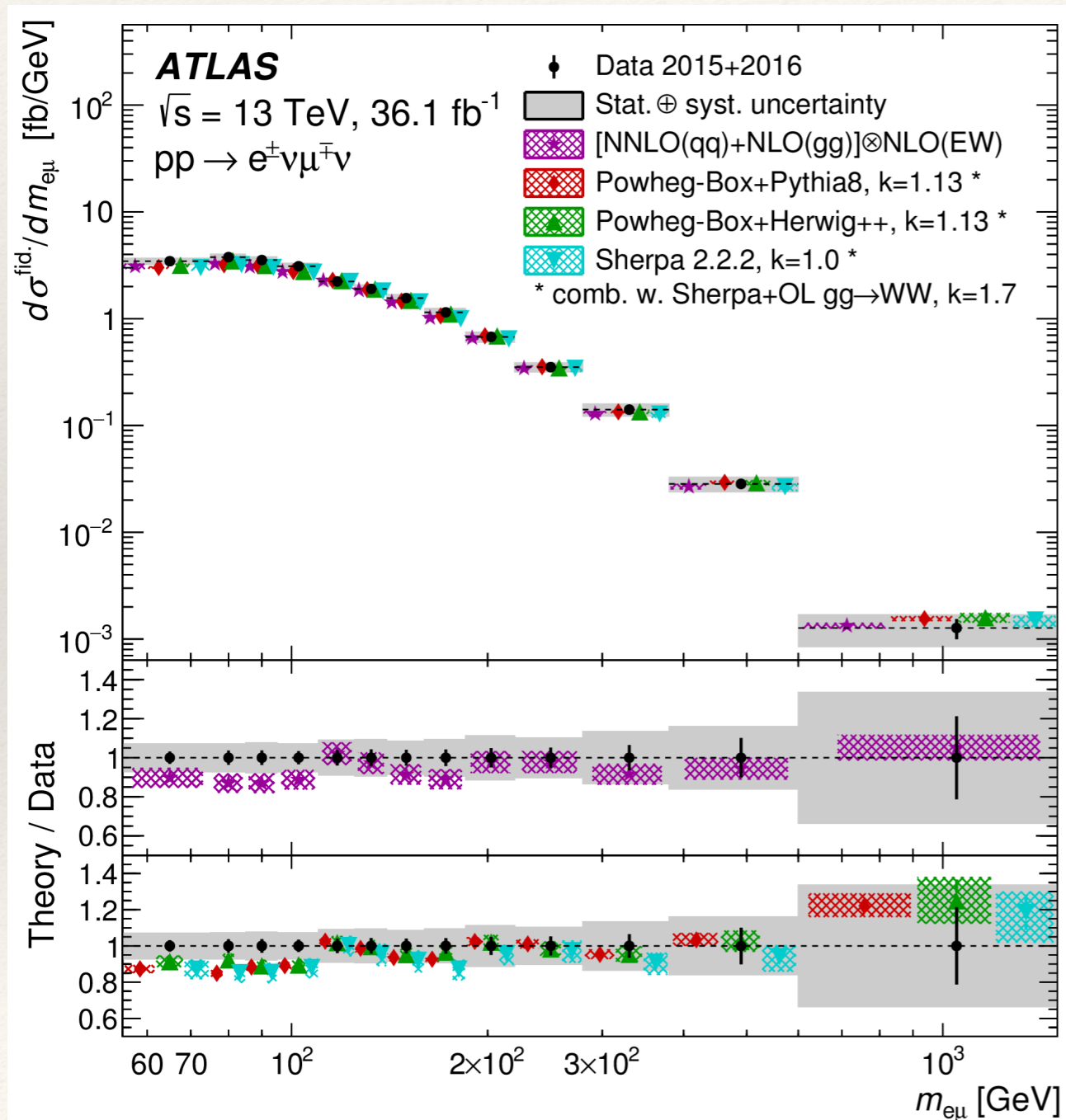
The LHC is a hadron machine, a **discovery** machine  
yet it had to re-invent itself to become a **precision** machine

**Precision LHC-> new opportunity**

Traditional resonant searches have  
been so far unfruitful

On the other hand, more statistics and  
better understanding of the experiment  
allows diving into extreme kinematic  
regions

Let's embrace this state-of-affairs to  
perform different searches for new  
phenomena, beyond resonances



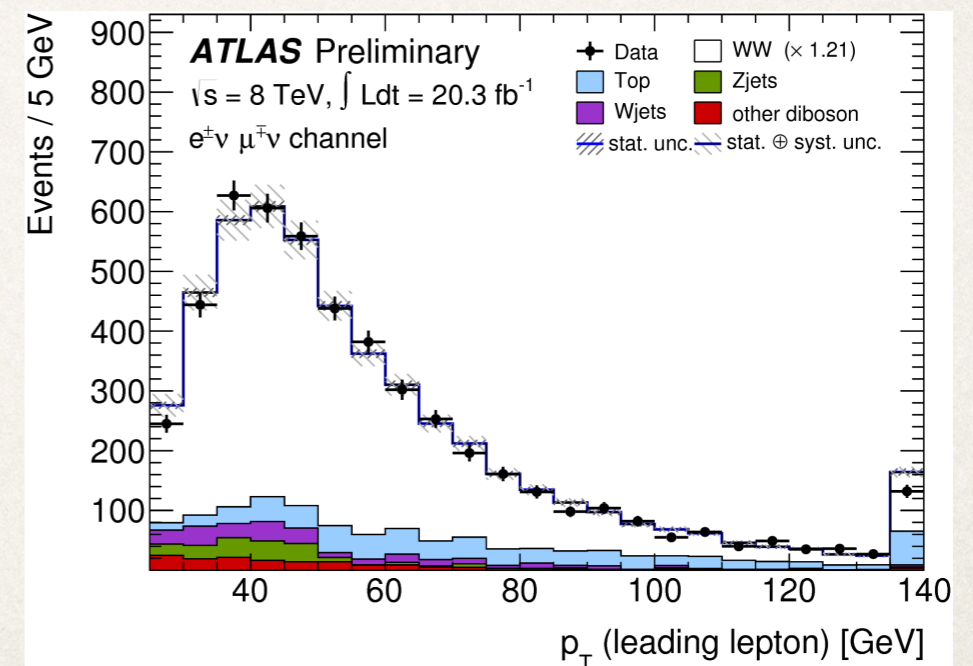
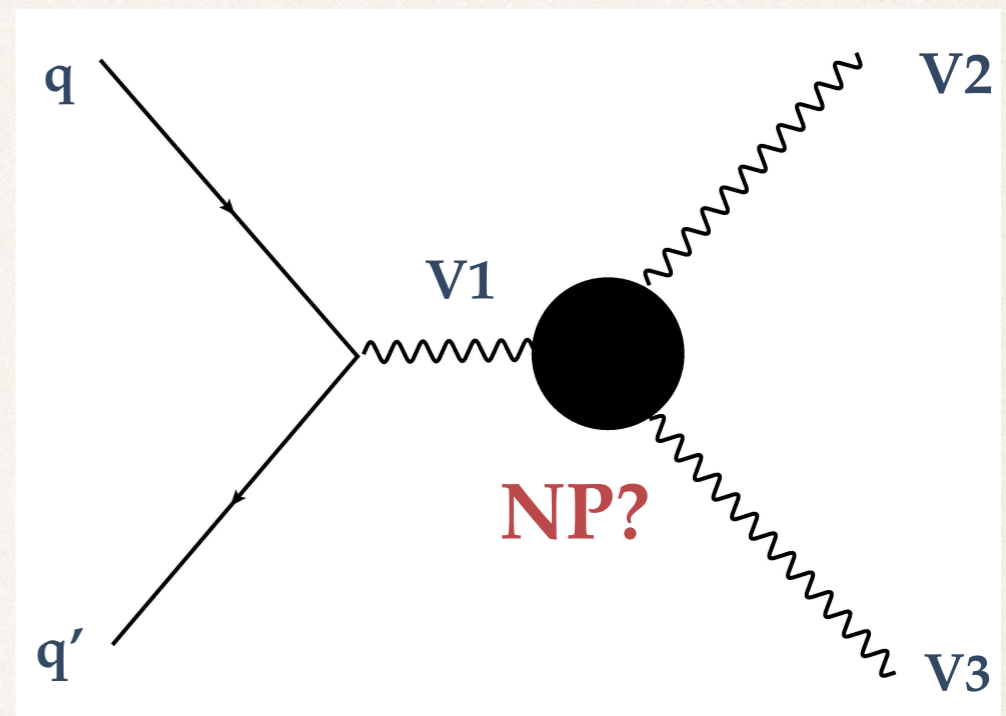


# Change in paradigm: Indirect searches

Focus on SM particles' behaviour  
precise determination of couplings  
and kinematics  
comparison with SM,  
**search for deviations**

Indirect searches using the Higgs  
**since 2012, relatively new**  
Higgs as a window to NP  
expect deviations in its behaviour  
Run2 data and beyond  
**precision Higgs Physics**

e.g. Anomalous trilinear gauge  
couplings, aka TGCs







# EFT is the new black

I assume you roughly know what is SMEFT  
and also know this is a word increasingly present in  
LHC analyses

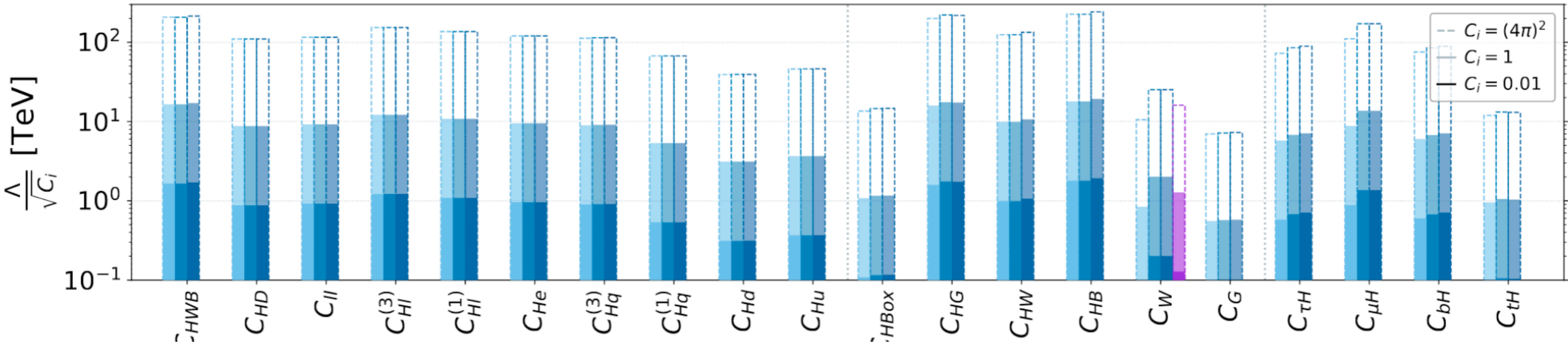
There are good theoretical reasons to adopt (NOW) an EFT  
interpretation of the LHC data  
no light NP, nice / tractable framework...

And experiments, after lots of tensioning and some reticence,  
are also adopting it as a default option to re-interpret SM  
measurements

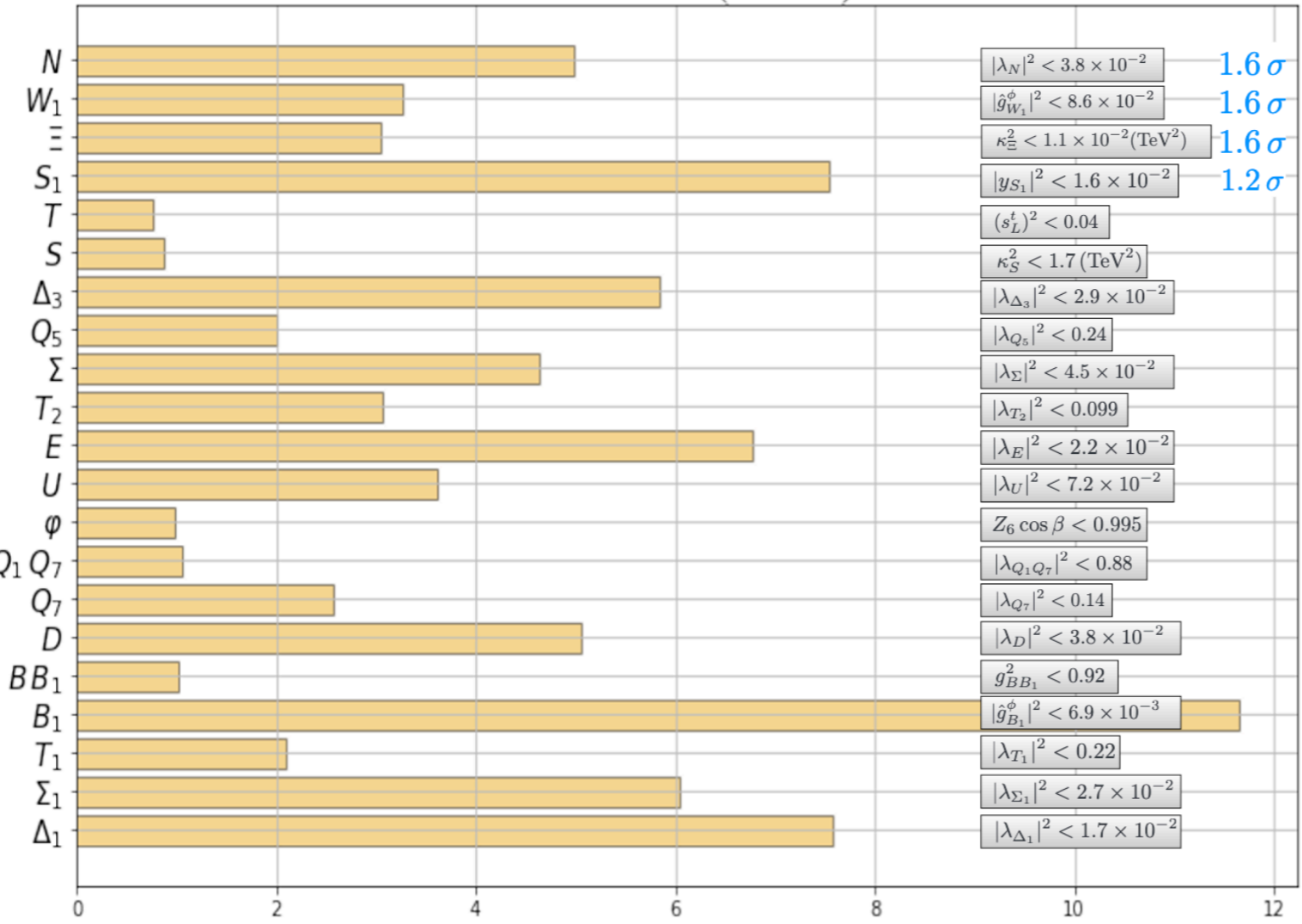


# Current SMEFT constraints reach the TeV for most of the param space

Ellis, Madigan, Mimasu, VS, You  
2012.02779, JHEP



Mass limits (in TeV)



And when translated into vanilla extensions of the SM, the mass limits are also probing the TeV scale

*Lots of work needed to advance this area: higher-order calculations, optimisation of strategies, better exp understanding of correlations...*



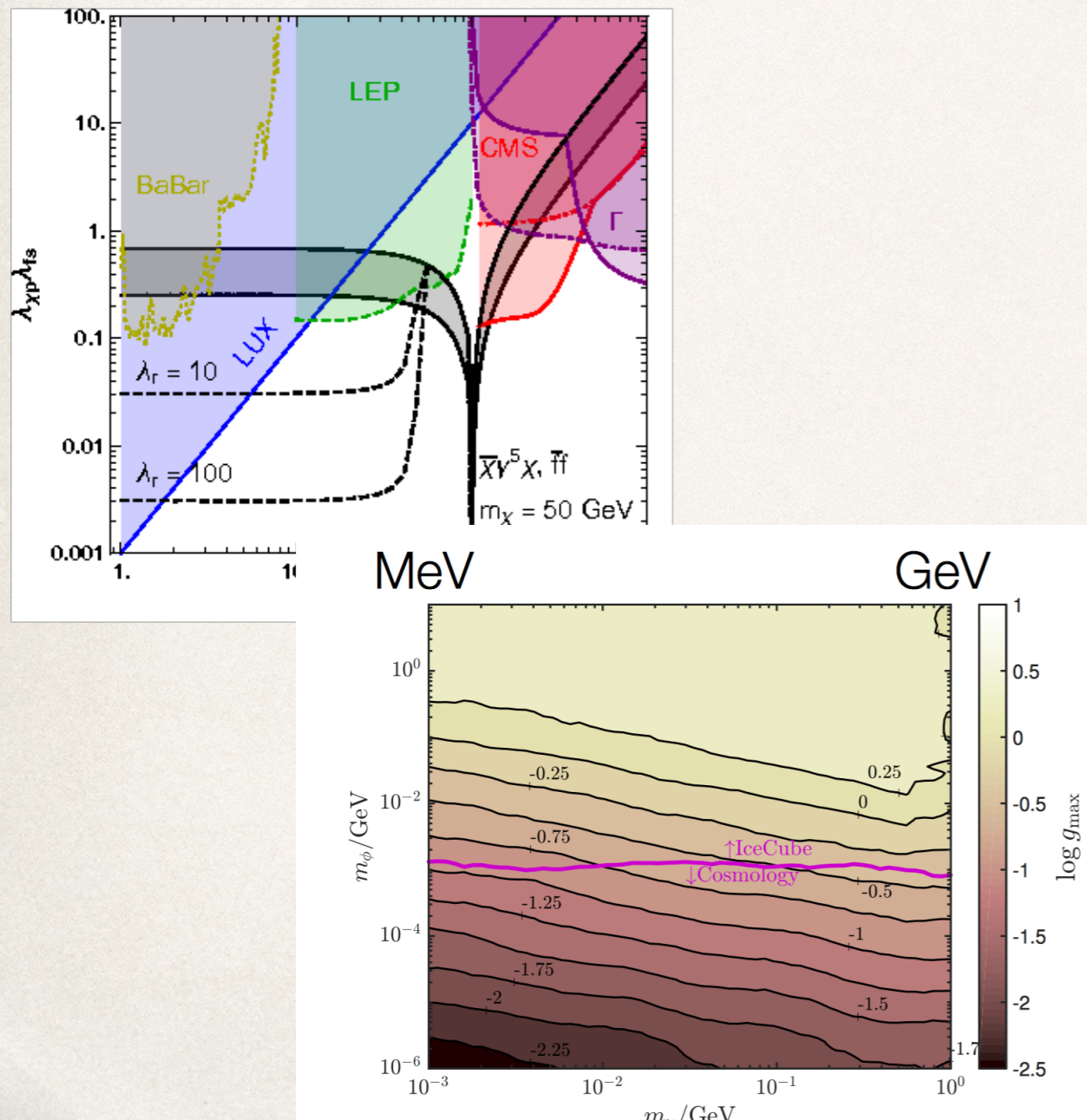
# Complementarity

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# These days we think a lot more about **complementarity**

One idea can be tested by many experiments beyond LHC  
*neutrino observatories/reactors, high-intensity/precision at low  
energies (flavour,  $g-2$ ), gravitational waves...*



1. New experiments, ways they present results, access to data
2. Simple straw-man models
3. Development of public tools, or recasting, so we can tackle complex processes and focus on the fundamental ideas



Experiments keep coming in:

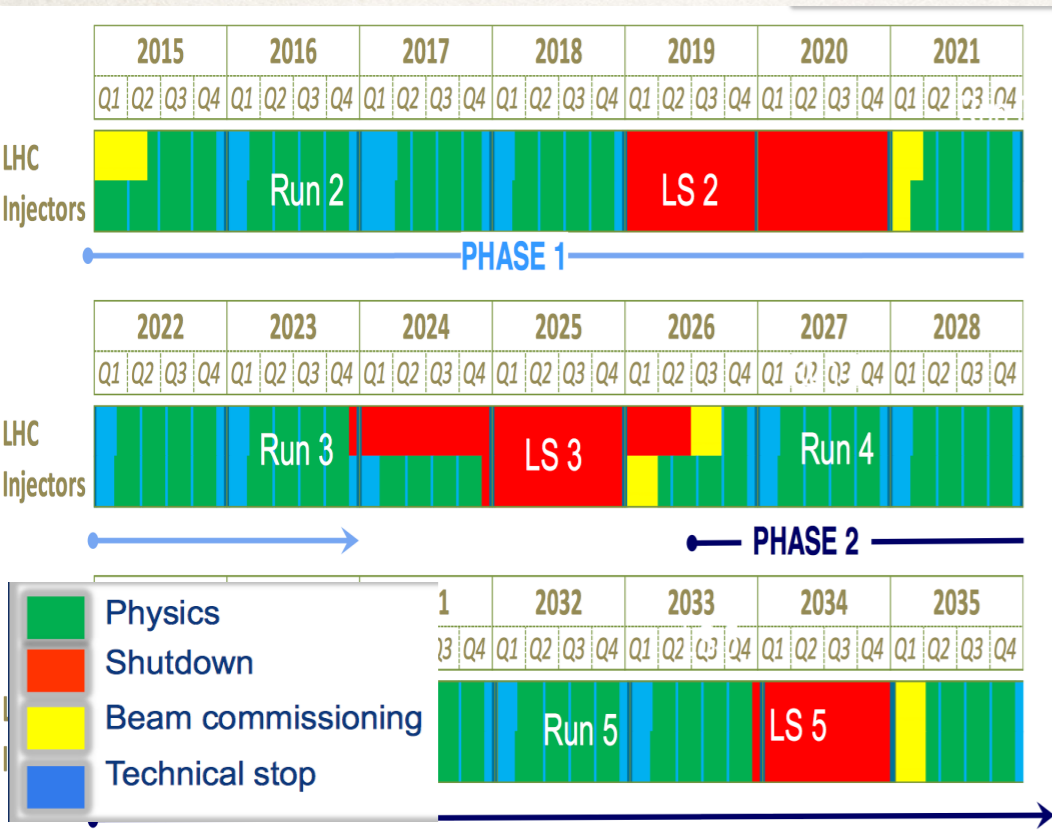
There is a lot to explore ahead of us

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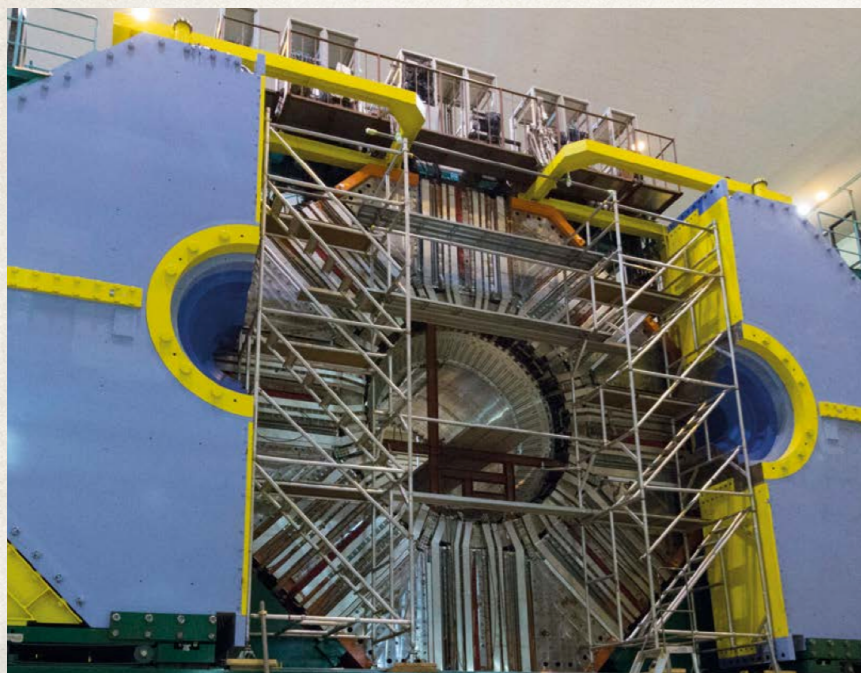
# For the LHC, this is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data.  
Funding ensured beyond 2035.



LHC hopefuls

- gains from more data and better understanding of the environment
- Testing non-standard kinematic features
- Reaching high-precision in Higgs physics
- Searches for invisible particles (monoX)
- Blind spots (DV, disap. tracks, quirks)



and, of course, **FLAVOUR**  
with Belle-II, NA62 complementing LHCb



# Smaller experiments may be key

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LHC is our best probe into the SM **but**  
other, smaller and narrower-focus experiments are also important  
**cheaper, shorter time-scale**  
**develop creative experimental techniques**  
**often enlarge the initial physics focus**





# *A comment on theory*

---



# And what about the cool/crazy stuff?

---

LHC, g-2, Direct Detection, B-factories, Axion experiments...

all these probes seem to be in a **high-precision stage**

with a well-established methodology

progress is just a matter of working harder...

*is this hubris?*



# And what about the cool/crazy stuff?

---

LHC, g-2, Direct Detection, B-factories, Axion experiments...

all these probes seem to be in a **high-precision stage**

with a well-established methodology

progress is just a matter of working harder...

*is this hubris?*

Theorists need to keep challenging well-established paradigms

*There are lots of mostly unexplored ideas, and pursuing them may not lead to a discovery but to inspire new ways to think about Nature*

some examples:      Dark Energy and its interaction with us

Alternatives to space-time symmetries (e.g. emergent gravity)

Very light dark matter (new exp techniques)

Dark moments in the Universe's history, pre-BBN

Connections between IR and UV physics, e.g. BHs



# Conclusions

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- Here we are, looking for a way to advance our understanding of nature, to reach **discovery**
- Scaling back from an ambitious program to find *the* theory of everything. Facing the challenges & opportunities that more data brings, testing in the darkness of **no guidance from theory** of where to look
- Keeping at the edge of the interpretation of data: bringing many towards **precision** (e.g. SMEFT) and to **Artificial Intelligence** techniques (NNs and the likes) yet we should not lose track of the importance of supporting **speculative explorations**

In 2021 Particle Physics lives in **interesting times**:  
with so many **experimental probes**  
and so many **new ideas and techniques**,  
Particle Physics will continue reinventing itself  
to push the limits of what we know