Introduction to Hadron Collider Physics

Part 4. the Higgs and Beyond the Standard Model

Caterina Doglioni - Lund University

Heavily drawing from lectures written in collaboration with Peter Christiansen & Alice Ohlson - Lund University

Note on references: all the images from experiments are taken from the experiment websites unless otherwise noted

Outline of these introductory lectures

Part 1: Introduction
- Fundamental components of matter
- Drawing particles and interactions: Feynman diagrams

10' Q&A + break

Part 2: Standard Model forces and interactions
- Electromagnetism
- Weak interactions
- Quantum Chromodynamics

Part 3: Tools
- Particle accelerators: the LHC
- Detectors for particle physics
- CERN and particle physics collaborations

10' Q&A + break

Part 4: Beyond the Standard Model
- The Higgs discovery
- Problems of the Standard Model
- Solutions beyond the Standard Model
- Dark Matter

10' Q&A + break

The discovery of the Higgs boson

How to think of the Higgs mechanism

What happens when a famous person enters a room full of people?

https://www.exploratorium.edu/origins/cern/ideas/cartoon.html

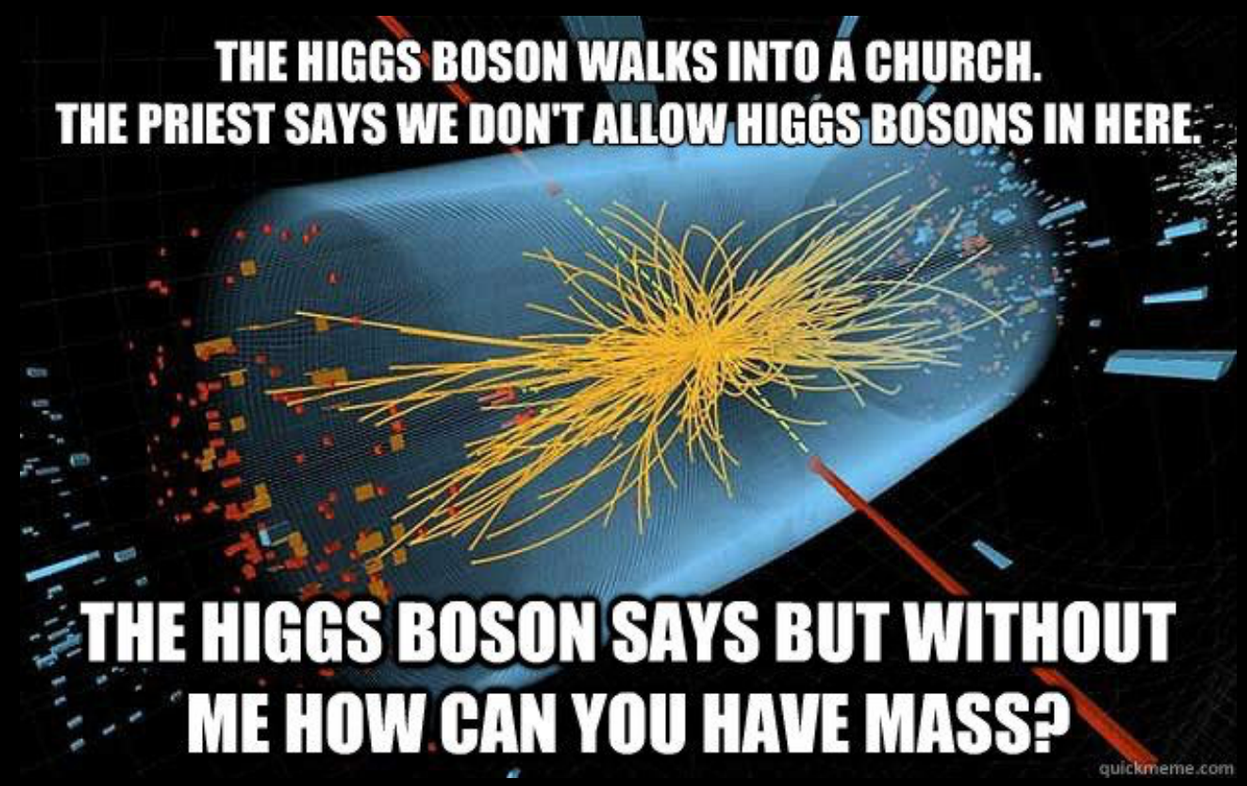
How to think of the Higgs mechanism

What happens when a rumour spreads through the room full of people?

... if a rumor crosses the room, ...

... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Bad joke to fill the empty slide space



https://www.exploratorium.edu/origins/cern/ideas/cartoon.html

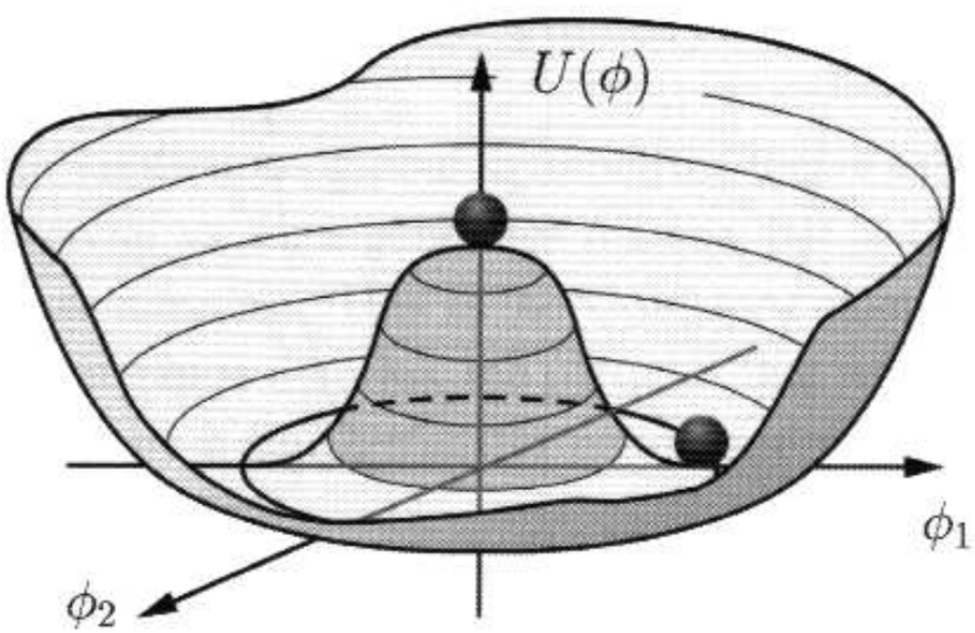
Gauge bosons and their masses

Problem (II):
all bosons are massless, adding masses by hand spoils theory

Solution (II):
Higgs mechanism!

$$\gamma = \sin\theta_W \cdot W^o + \cos\theta_W \cdot B$$ massless

$$Z^o = \cos\theta_W \cdot W^o - \sin\theta_W \cdot B$$ massive



Gauge invariance (~rotational invariance) does **not allow particles** to have **mass**

BUT with the Higgs potential

Symmetry is spontaneously broken
(~not rotationally invariant)
so **gauge bosons can have mass**
without spoiling the theory

Why so excited about this particular particle?

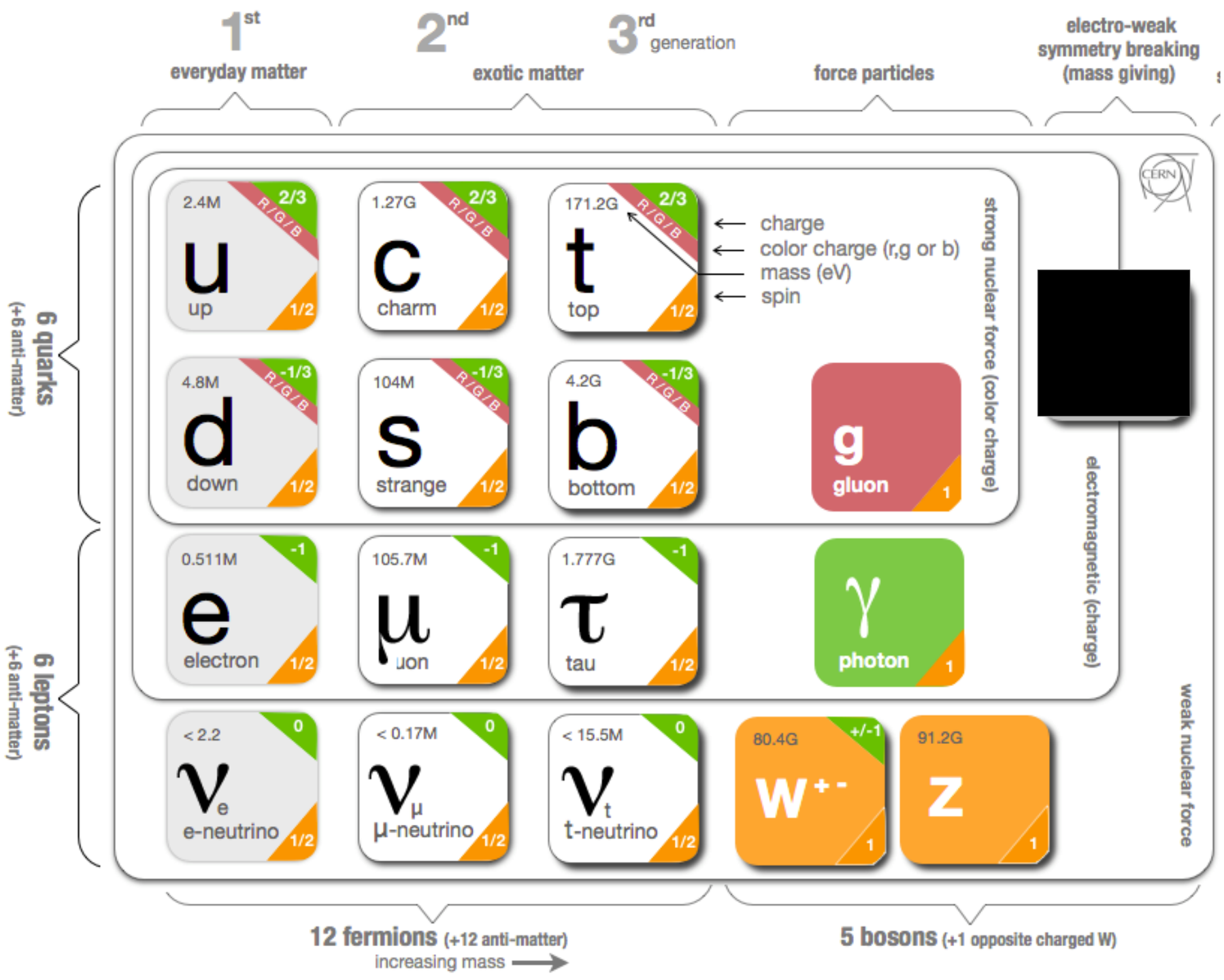
"Run! I've discovered the Higgs bison."

It's a **new particle, discovered in 2012**

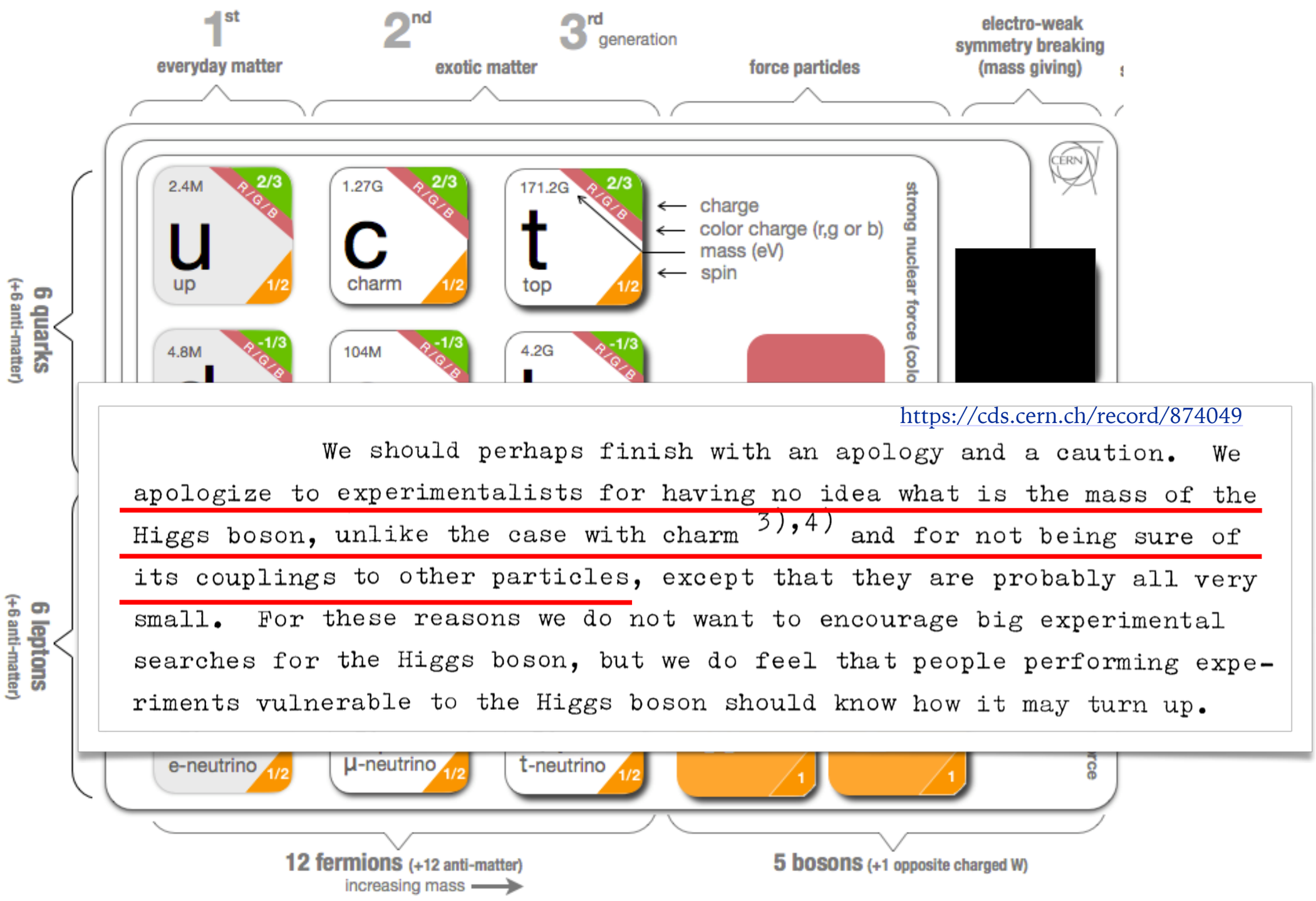
→ we knew we needed it, but:
- → we didn't know its **mass**
- → we didn't know its **properties**

We've been looking for it for 50 years, as one of the **missing pieces of the SM**

The heart of the matter



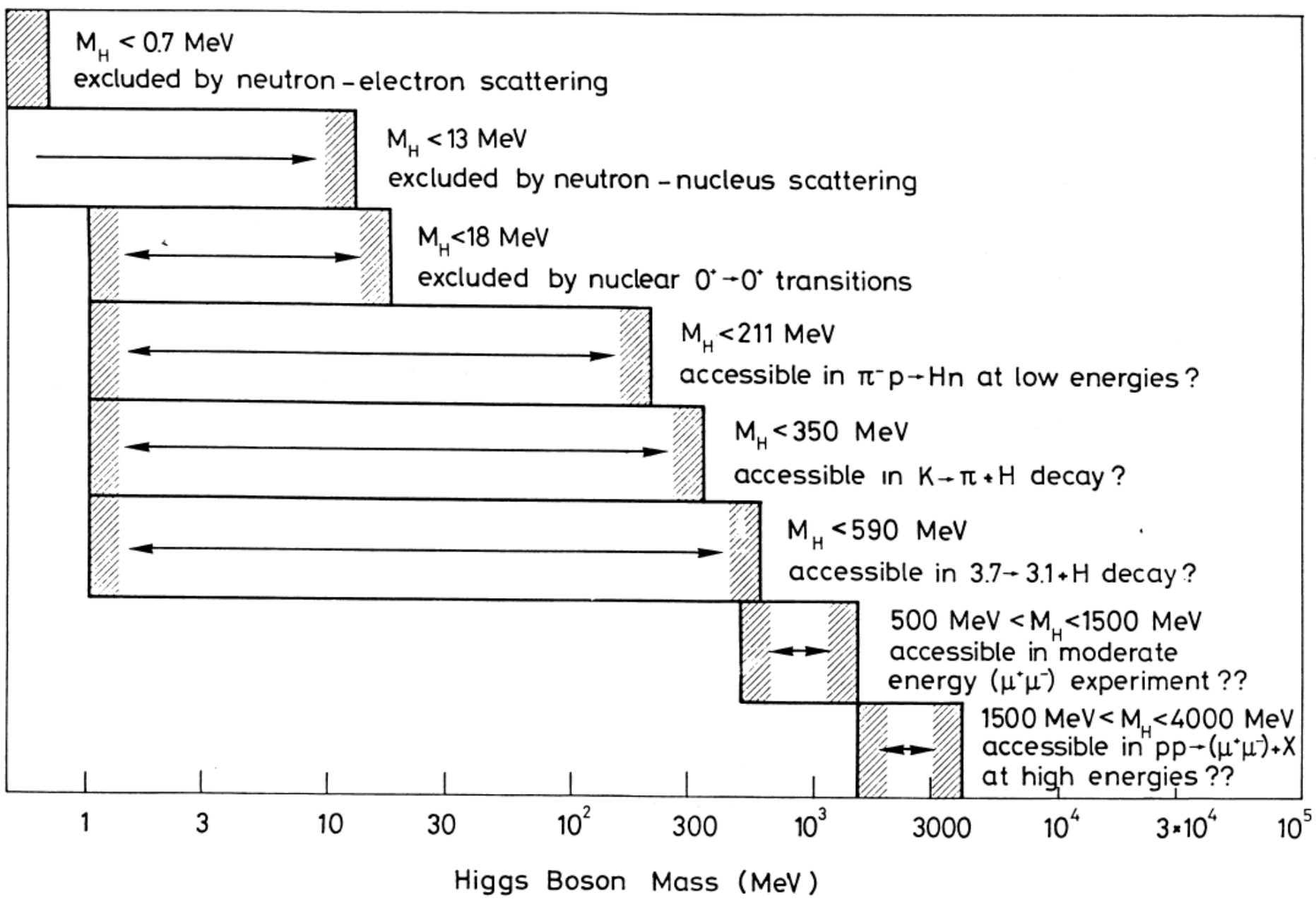
The heart of the matter



https://cds.cern.ch/record/874049

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

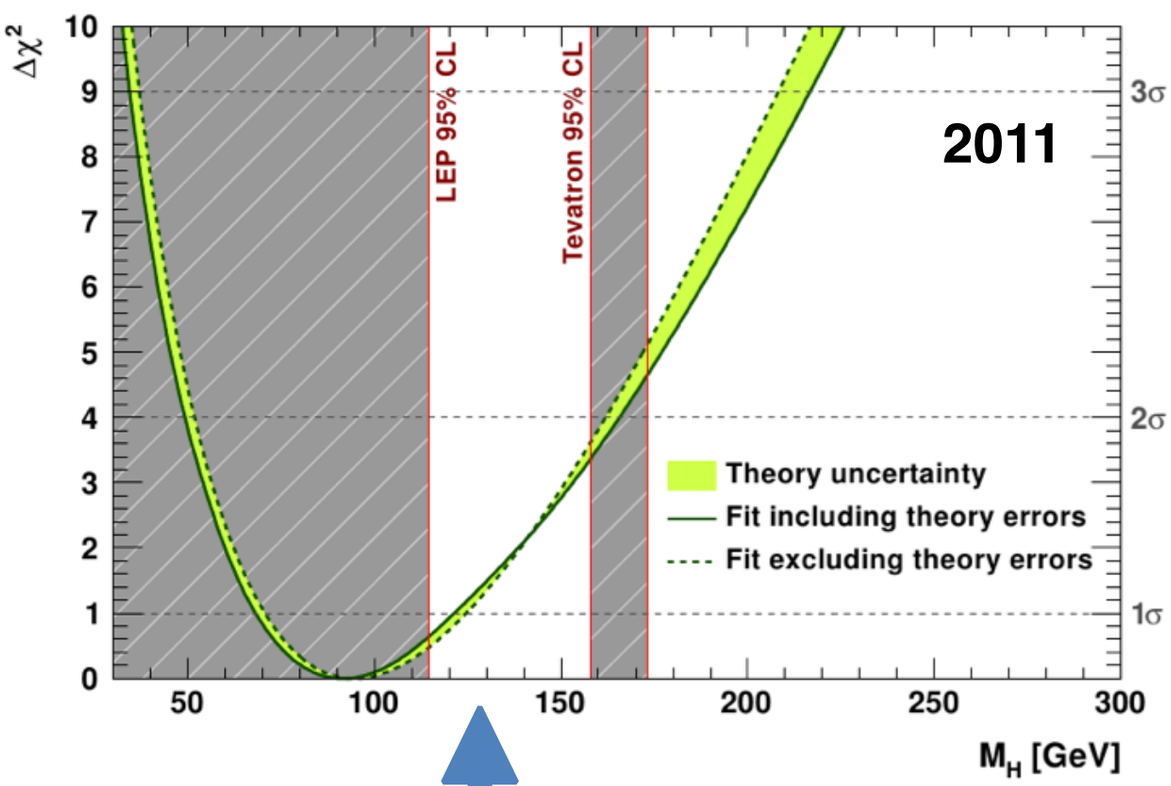
Energy step by energy step



The Standard Model led the way…

Discovery of the Higgs boson:

guided by **clues** from the **Standard Model** of particle physics



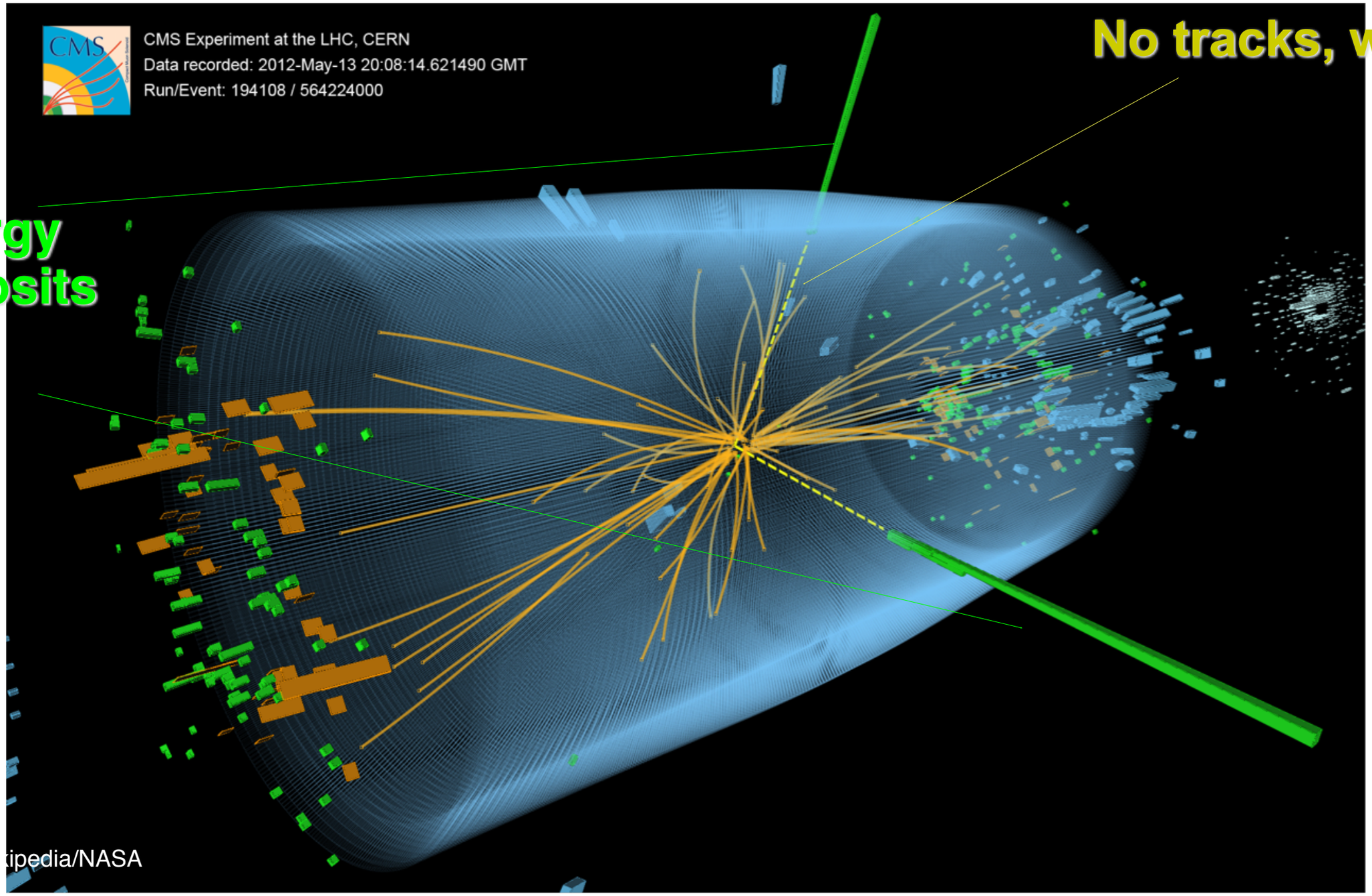
The Higgs boson mass as of May **2015**

arXiv:1503.07589

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

On the CERN message boards in 2015

The ingredients of the recipe



A 'potential' Higgs boson event?

One of the (hard) tasks of a physicist is **how to distinguish**

the **signal**
(Higgs boson decaying into two photons)

From the **background**
(any other particle decaying into two photons, or QCD processes where jets are identified as photons)

→ no one tells us whether the event display is signal or background!

We'd like to have a tag on every particle we record, but we have to identify them ourselves

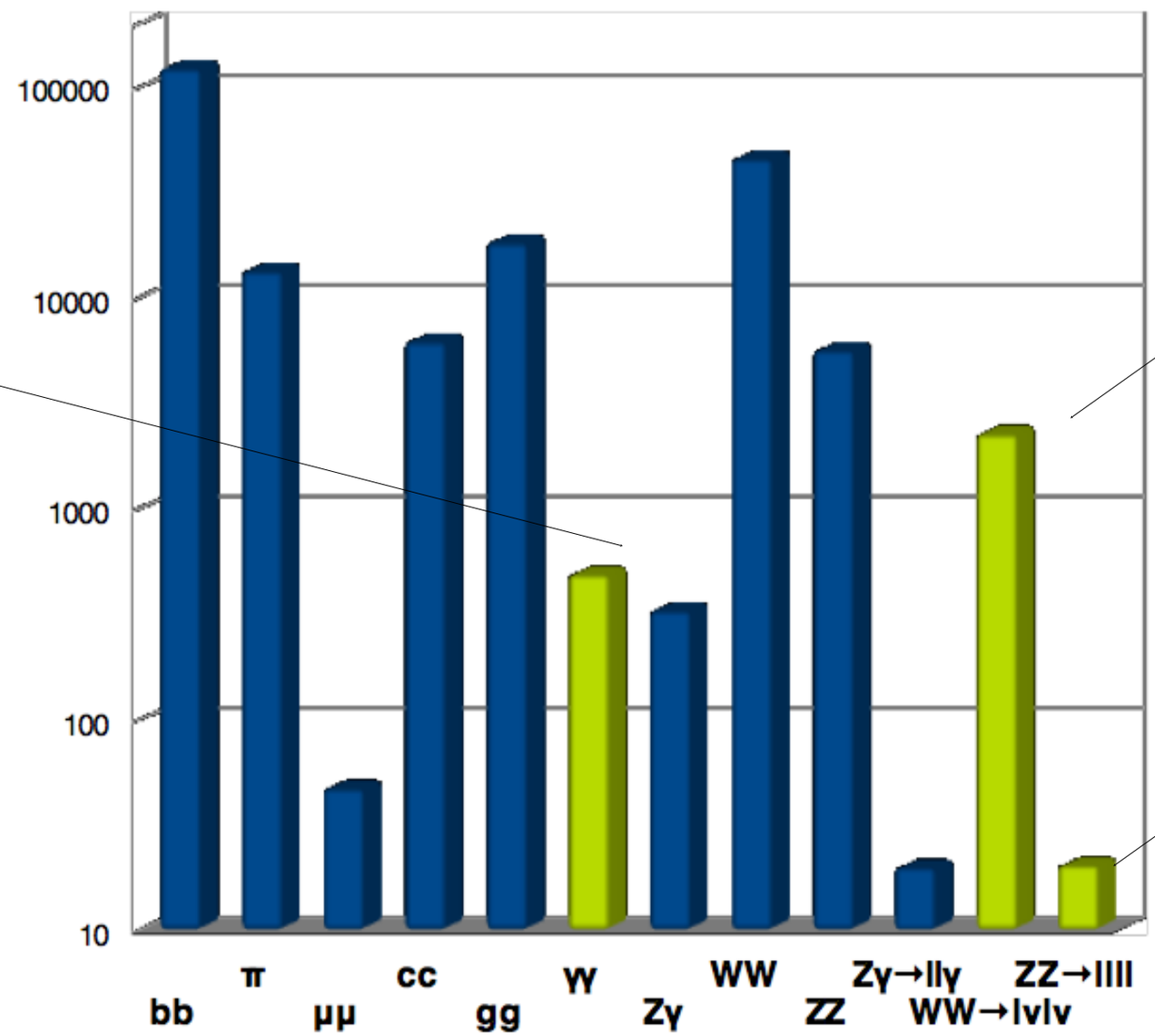
The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe get its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

Wool felt with gravel fill for maximum mass.

Higgs signals...

Until Summer of 2012 we should have seen:
(in the hypothesis of a Standard Model Higgs boson)

500 decays in two photons



1100 decays in two visible and two invisible leptons

15 decays in 4 visible leptons

Bill Murray

...and backgrounds

Multiply
1000000000 times

background reduction is a
key point for physics analysis at the LHC

background

1) *trigger system*

When data is taken, this system chooses interesting events based on the raw properties of the events/ particles in the event

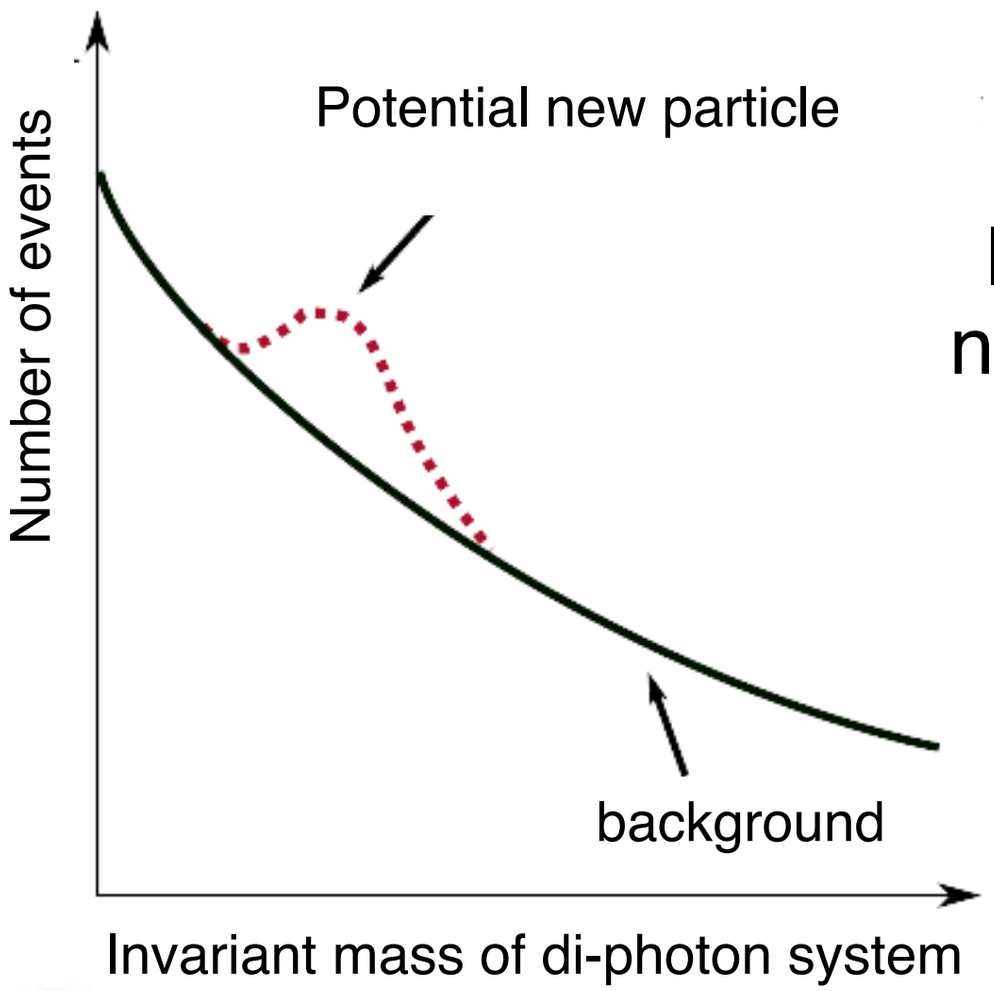
2) data analysis

After data is taken, we write software to reconstruct the particles within the event, and only select the interesting ones (e.g only two-photon events)

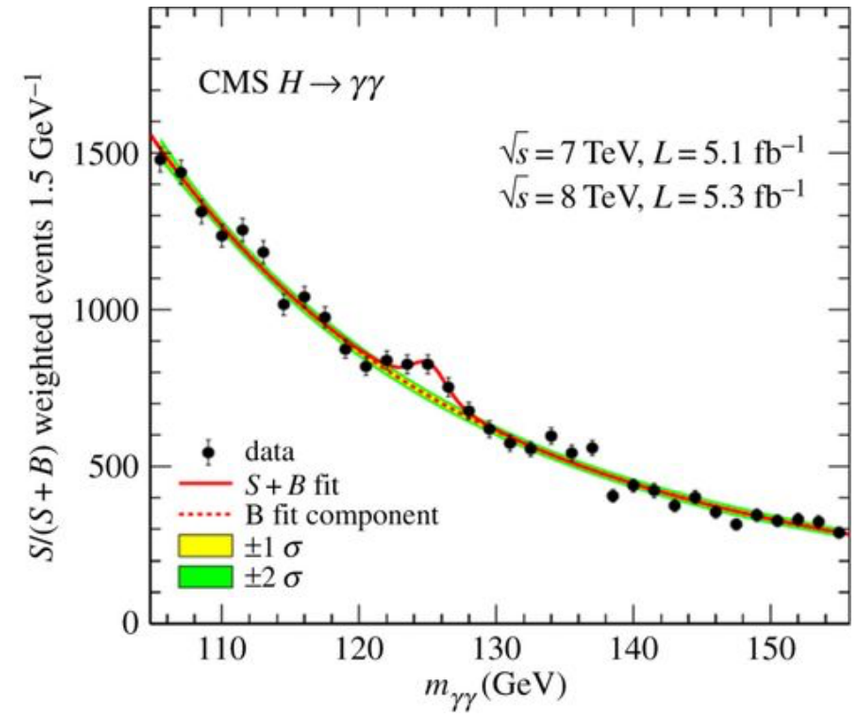
Higgs ‘golden channels’: photons and electrons in final state

Diphoton invariant mass

After having selected the interesting events, we can look for the **invariant mass** of the particles that can be identified as the **Higgs decay products**



In plots like this, new particles look like "bumps" = excesses of events wrt the background



https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0384

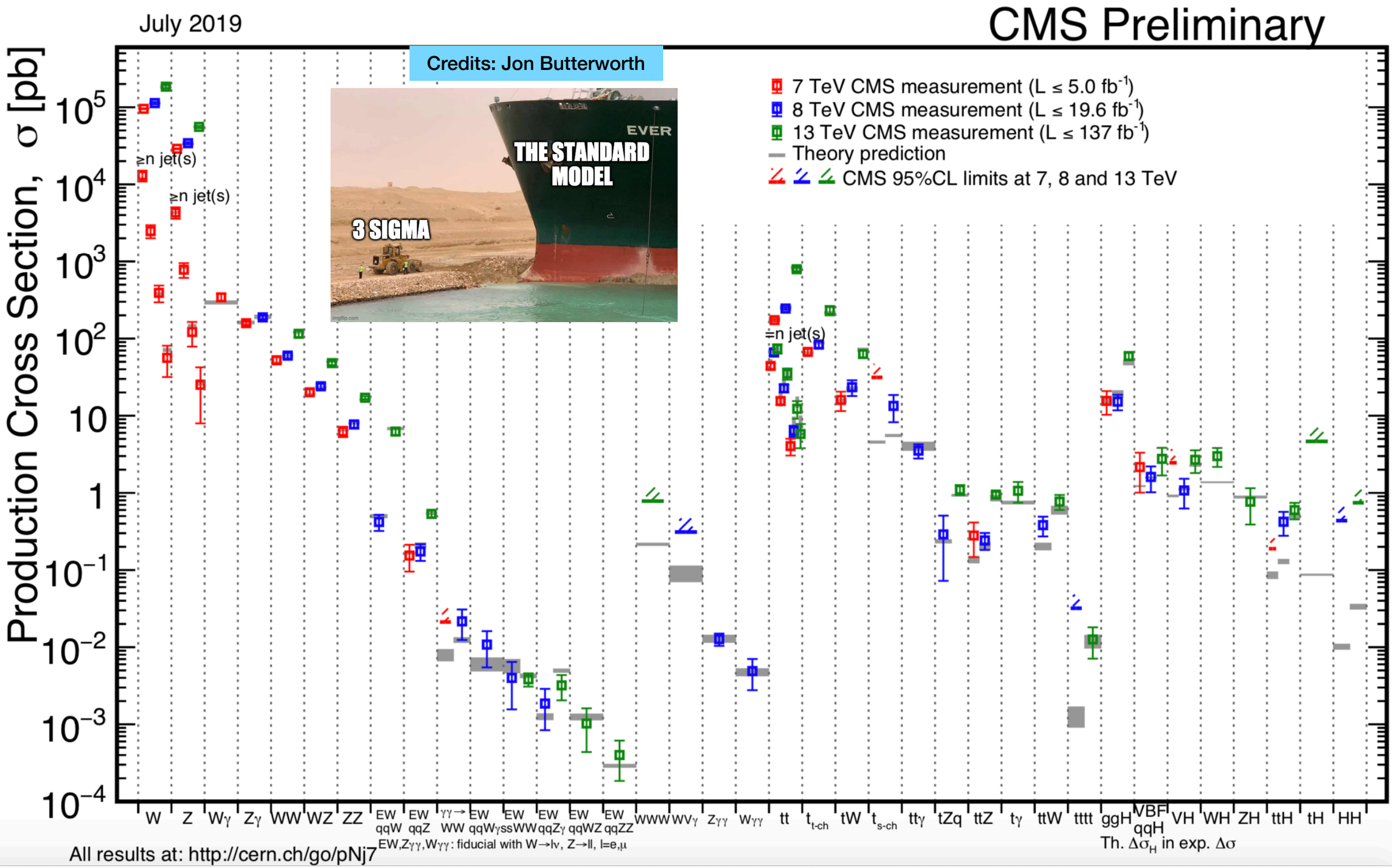
Higgsdependence day (2012)

http://resonaances.blogspot.se/2012/07/h-day-live.html

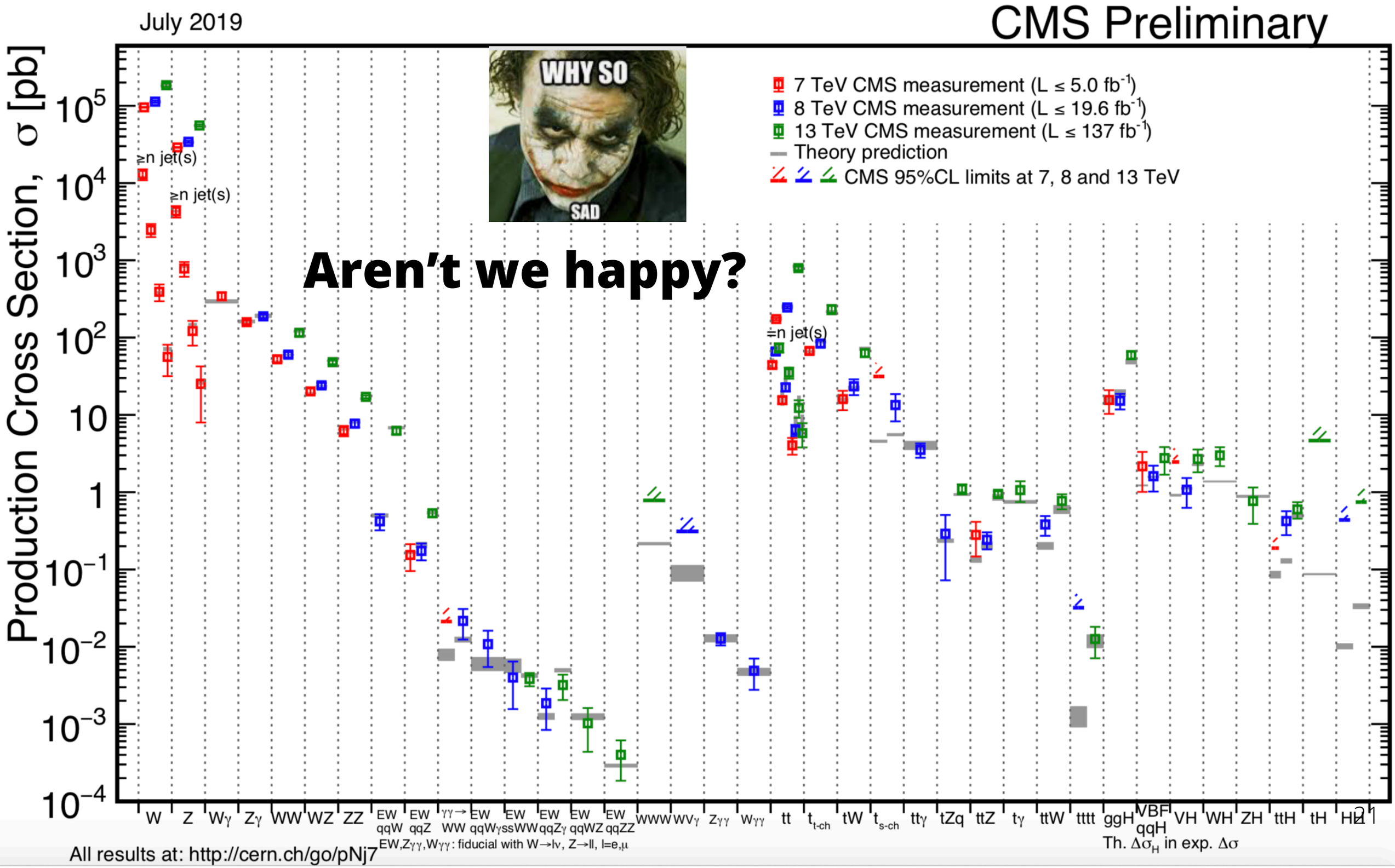
8:38 The audience is a funny mix. One half are 60+ big shots who could get themselves a sit reservation, the other half are 20-something Higgs groupies who had a strength to queue all night.

The problems with the Standard Model (even after the Higgs discovery!)

The SM in its full experimental glory



The SM in its full experimental glory



The SM in its full experimental glory

A list of problems with the SM

Aesthetic

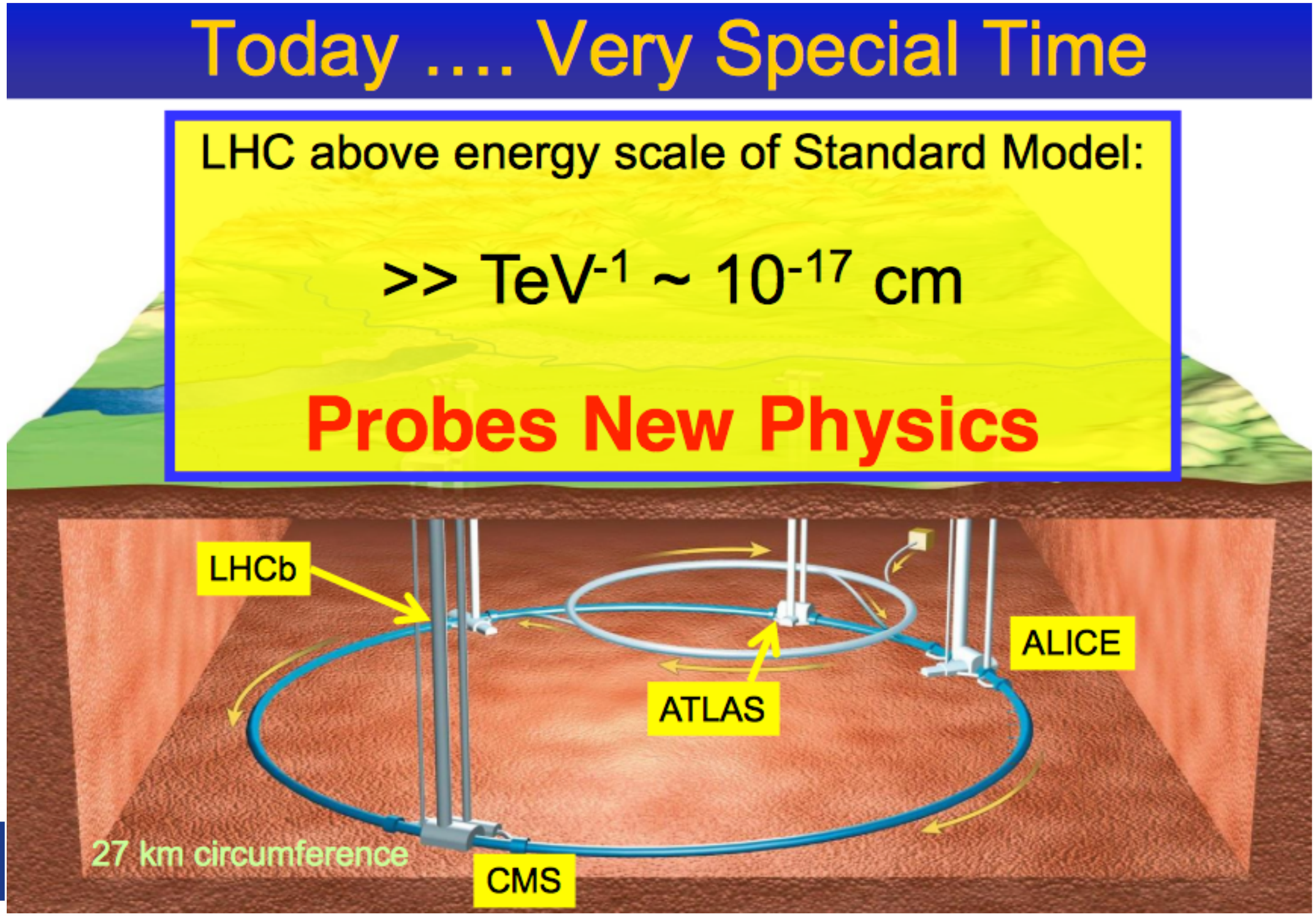
- Fine-tuning needed for Higgs mass
- Large difference in scales of particles & forces (hierarchy problem)
- Free SM parameters
- …

Empirical

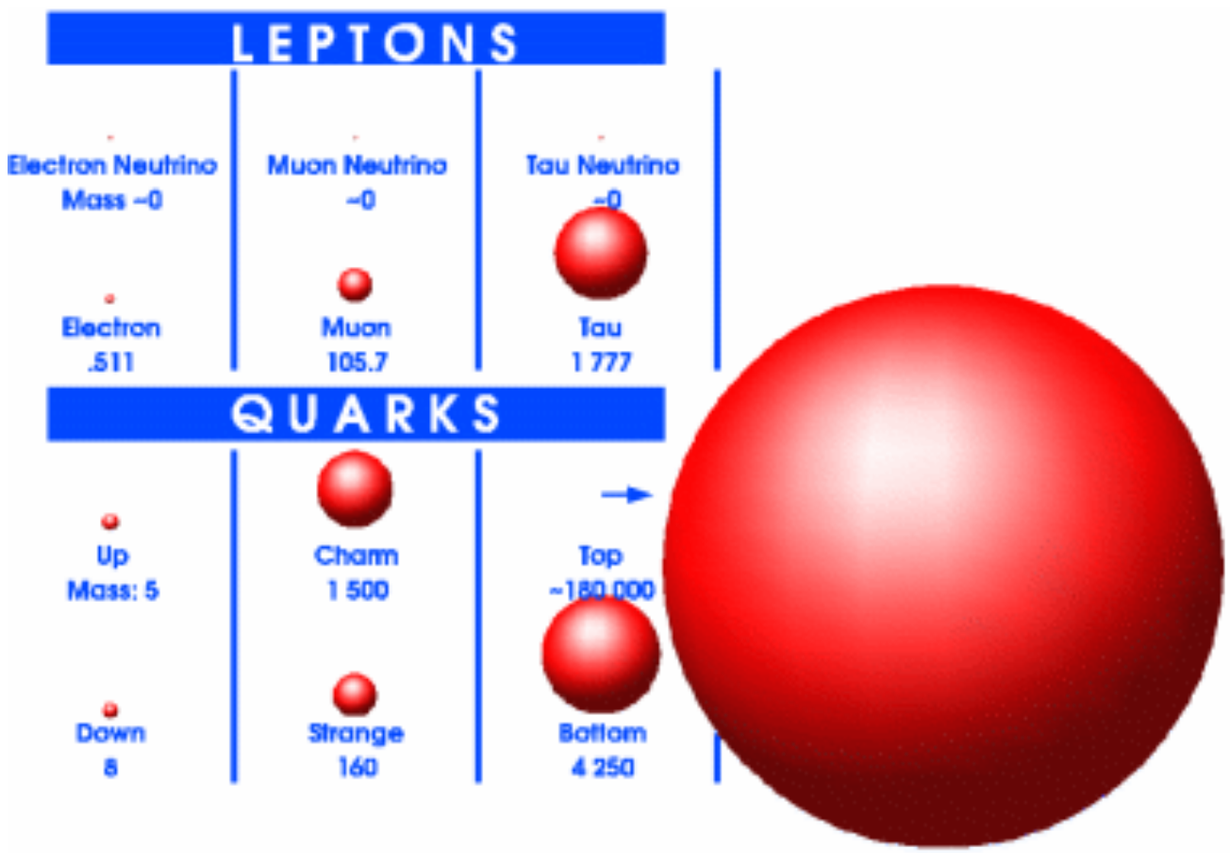
- Dark matter (DM)
- Dark energy
- Matter vs antimatter
- Weakness of gravity
- Neutrino masses

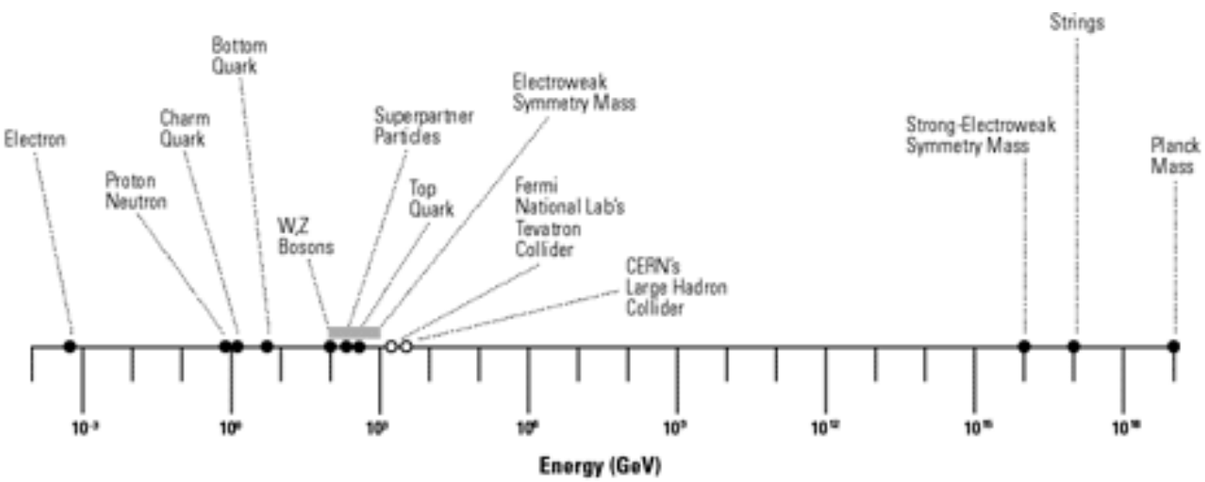
Preferred (by LHC enthusiasts?) mass range for answers: **TeV-scale**

Why is the LHC interesting? (from C. Issever)



Hierarchy problems

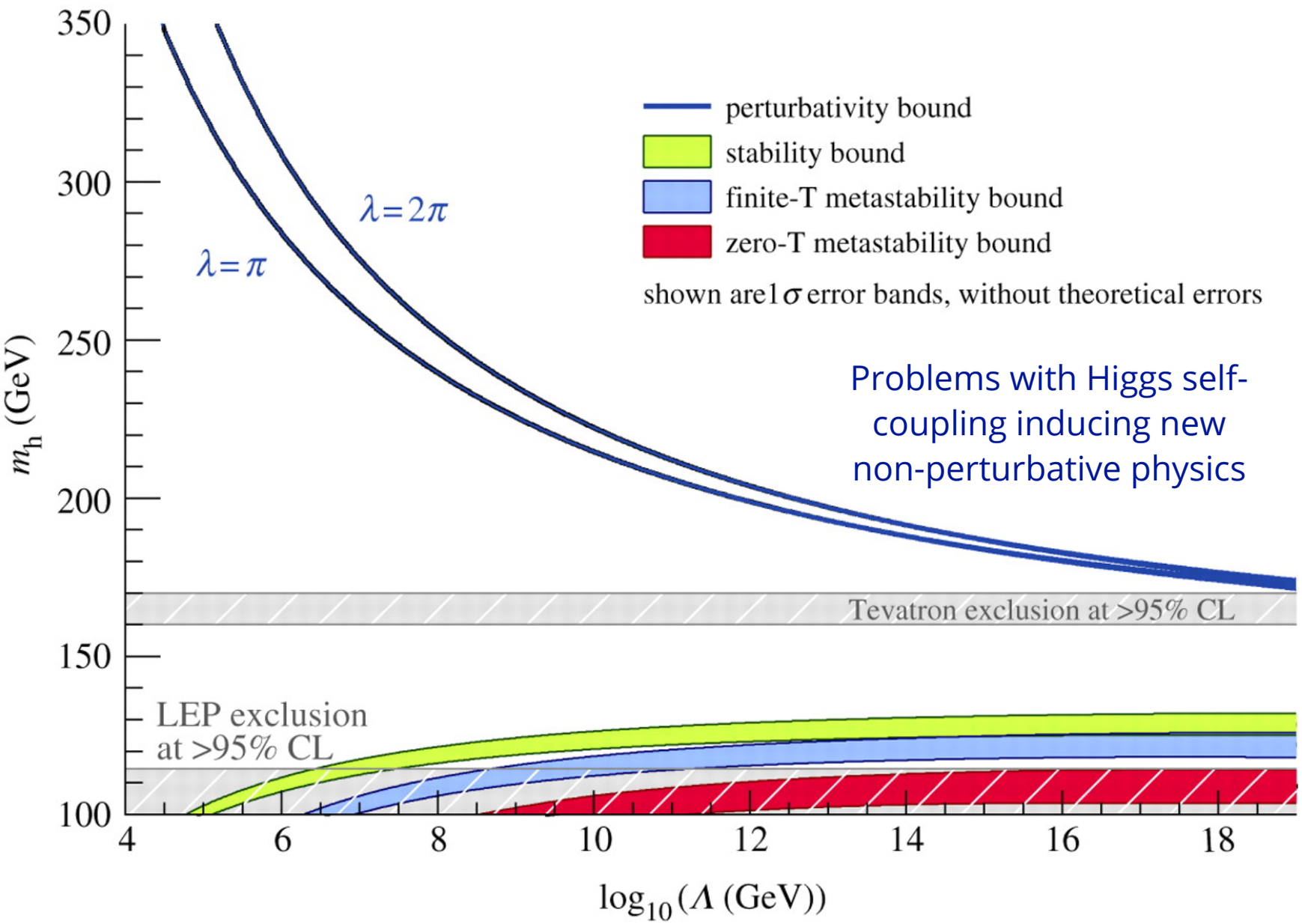




Why are the scales of the SM forces and the masses of its particles so far apart?
[Why three families? Why masses not predicted?]

Can the Higgs indicate the scale of new physics? Not directly

http://rsta.royalsocietypublishing.org/content/370/1961/818 (2012)



Problems with Higgs self-coupling inducing new non-perturbative physics

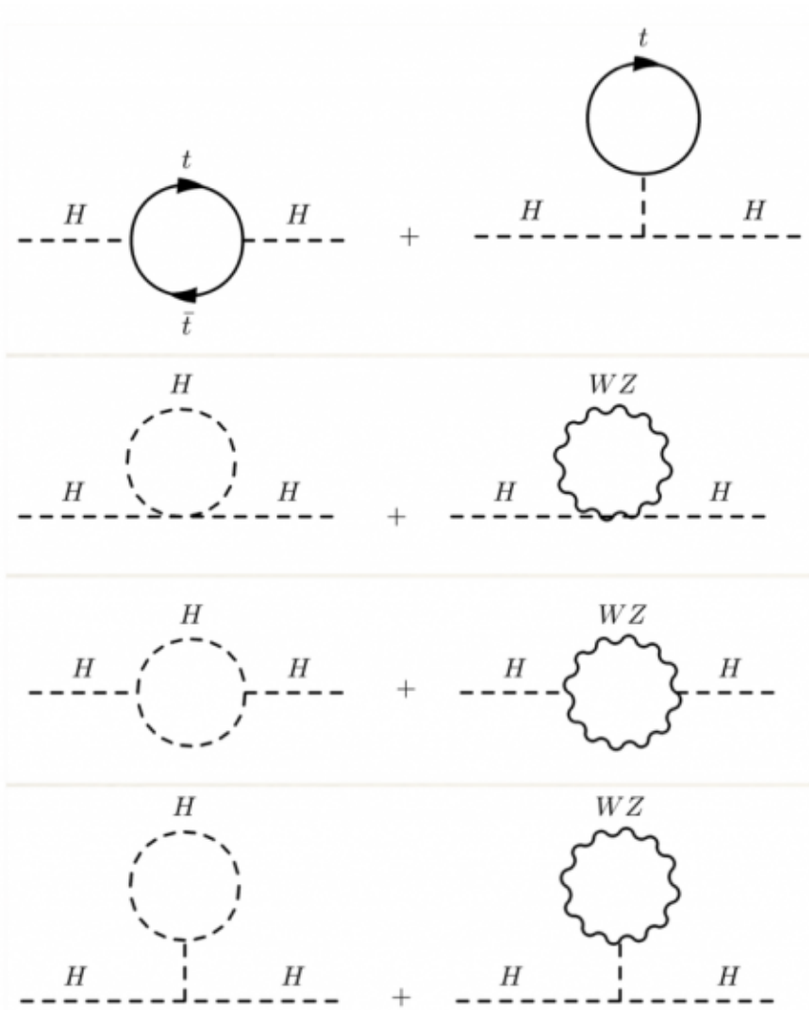
"Only a narrow range of $m_h \in (130,180)$ GeV is compatible with the survival of the Standard Model at all scales up to the Planck mass. This could be the 'maximal conceivable disaster' scenario for the LHC: a single Standard Model Higgs boson and nothing else!"

Problems with stability of the vacuum

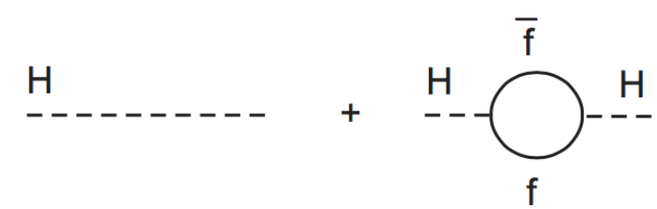
Higgs mass and fine tuning

Slides by P. Athron, D. Miller

Observed (Higgs mass)^2: 10^{32} times smaller than predicted



Think **renormalisation**:
Large loop corrections needed
to the Higgs mass
OR
cut-ff the theory at scale Λ



$$m_H^2 = m_o^2 + \delta m^2$$

$$\delta m^2 \sim \Lambda^2,$$

No indication of what this scale Λ is (from previous slide)…
could be limit of current physics knowledge (Planck scale)

Higgs mass and fine tuning

Tobias Golling's talk

Is this natural?

$$36127890984789307394520932878928933023 -$$
$$36127890984789307394520932878928917398 =$$
$$= m^2_H = 125^2$$

Unnatural cancellation or fine-tuning: $O(10^{32}) - O(10^{32}) = O(1)$

In analogy to: $0.7 - 0.4 \neq O(10^{-32})$

Higgs mass and fine tuning

Slides by P. Athron, D. Miller

Is this natural?

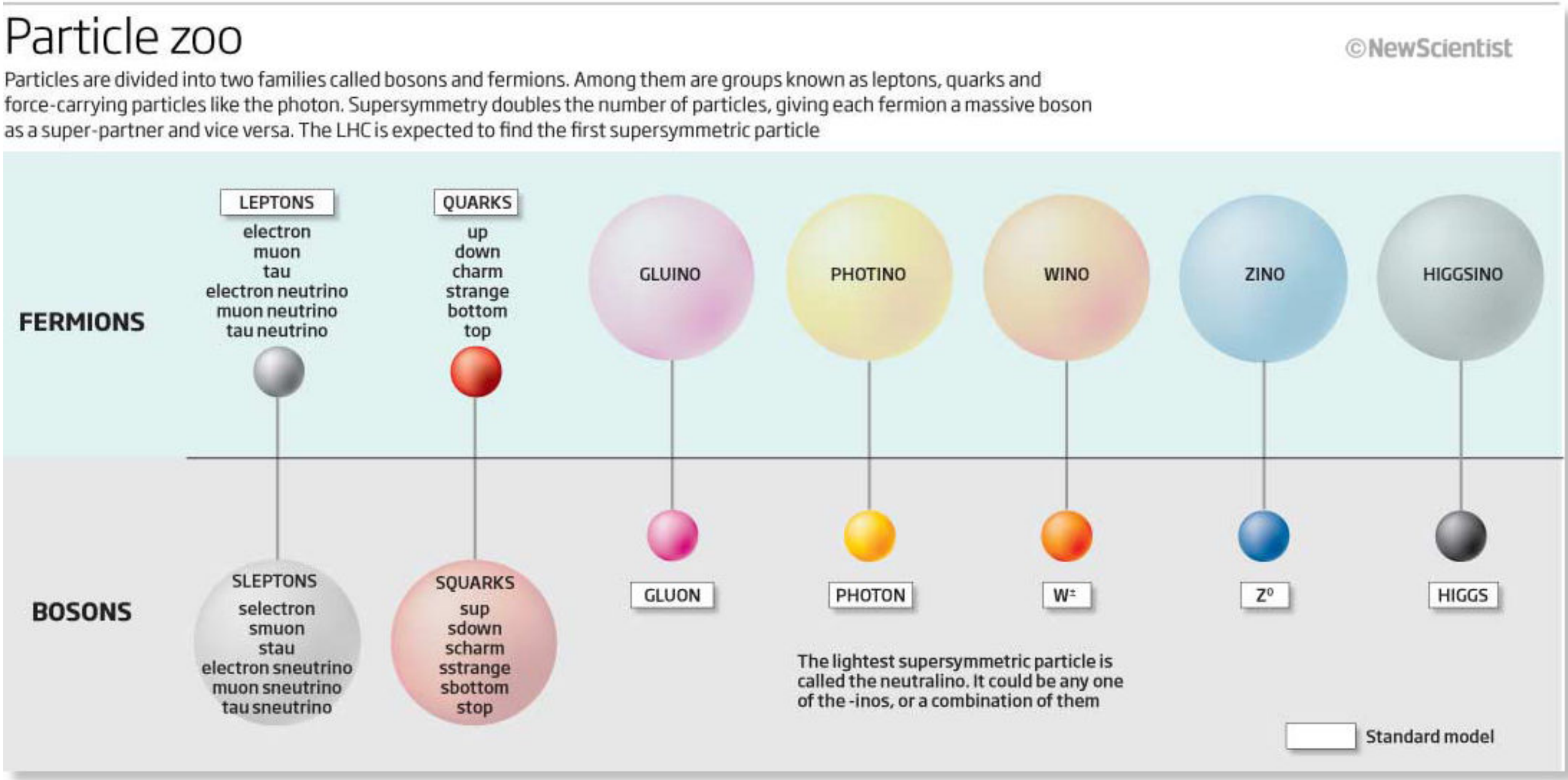
Fine-tuning in nature:

- Eclipse (moon and sun aligned to 1 %)
- A pen perfectly balanced on its tip

For further digressions: see http://discovermagazine.com/2000/nov/cover/

But also: *"Whatever combination of physical constants may exist, it would be one of a kind."* T. Drange

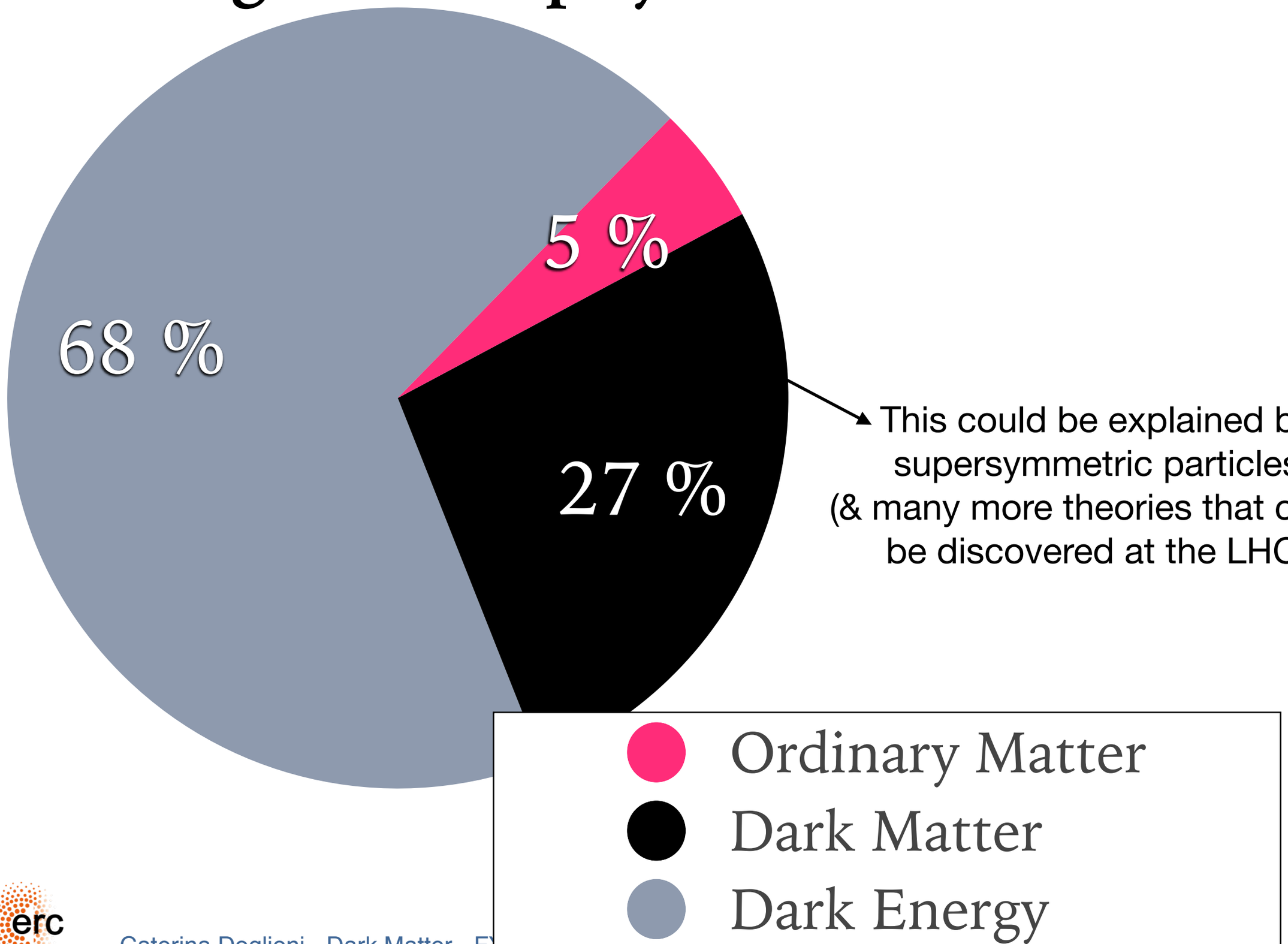
Supersymmetry: a new particle zoo solving these problems & more



Each supersymmetric particle "compensates" a SM one in the current theory

...and it has more answers!

The state of the matter(-energy) according to astrophysics observations

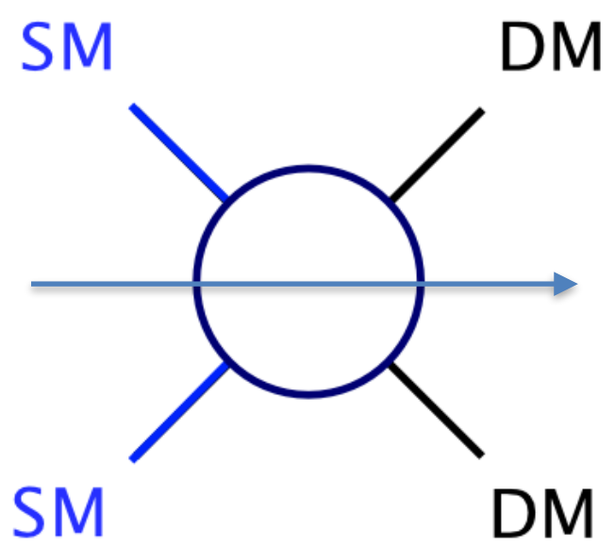


Motivation for dark matter @ colliders / LHC

How do we search for DM at colliders, depending on its properties?

- Generally assume some properties for the DM particle, our assumptions:
  - interacts with SM particles → we can **produce it at colliders**

known particle collision



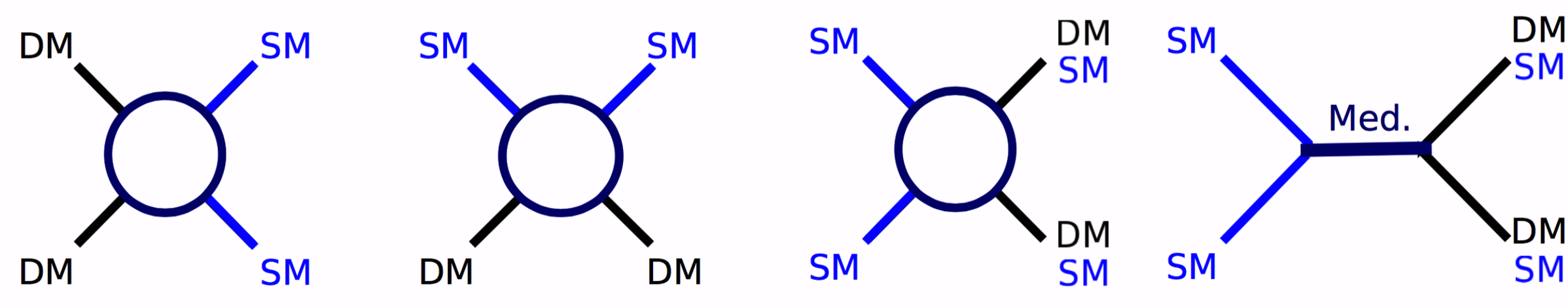
production of DM particles

Caveat: very simplified diagram

- dark, stable → **invisible to detectors**

Particle accelerators, direct and indirect detection

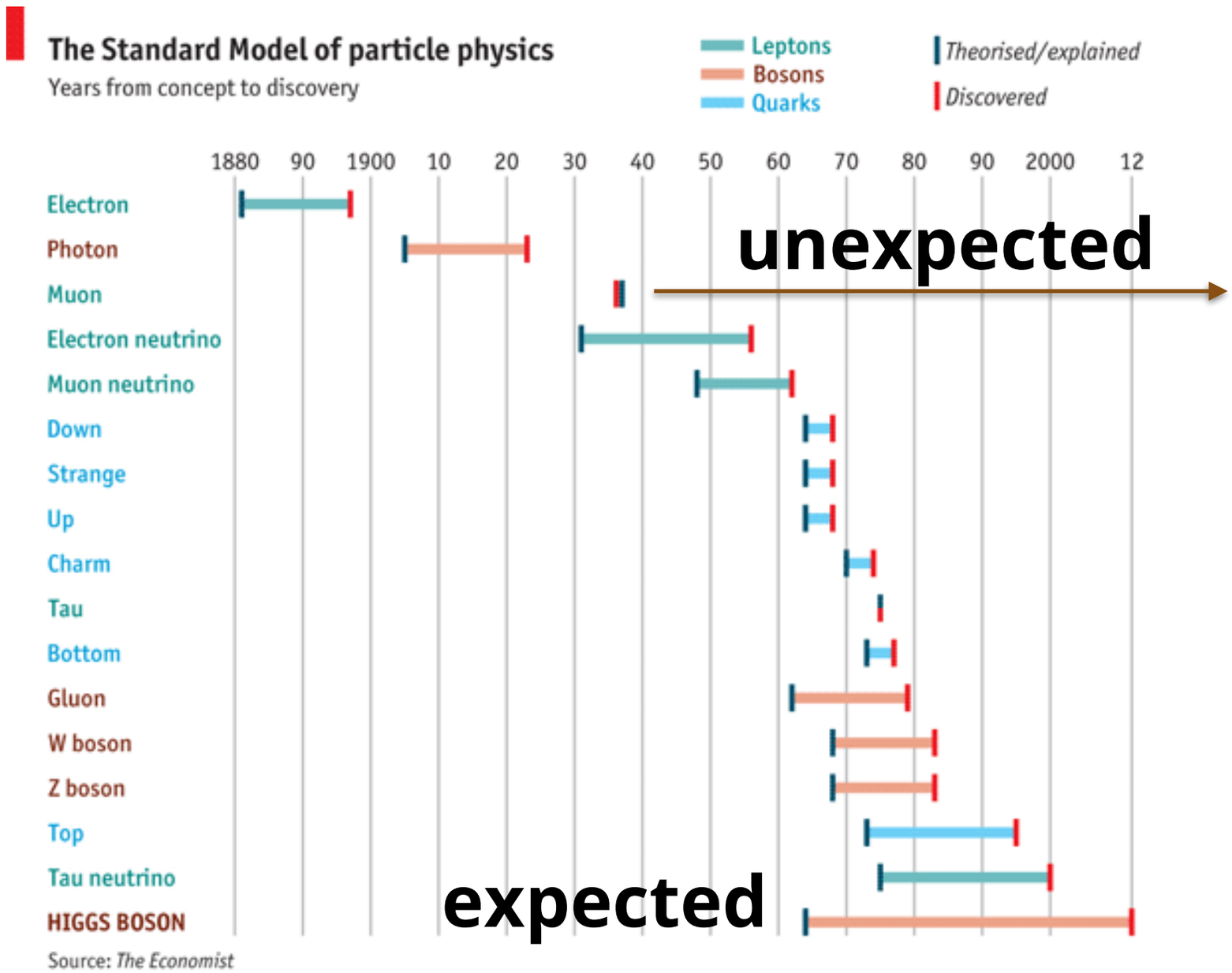
- **Important note:** any LHC DM discovery need complementary experiments that involve DM with **cosmological origin** / can **produce DM**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays
  - Accelerators/colliders can produce DM and **probe the dark interaction**

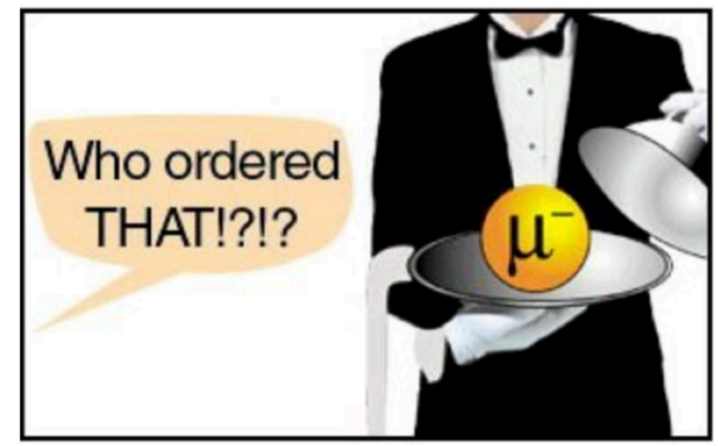


Indirect Detection Direct Detection Particle Accelerators (colliders & extracted beam lines)

Note also that many DM experiments have many **common challenges**, e.g. strategies to handle **large amounts of data,** particle **detectors and instrumentation**

Final words: expected & unexpected discoveries





The Economist

ML-powered searches: a change in mindset?

Maurizio Pierini's talk at IWAPP 2021

Re-embracing the scientific method

- Research under the scientific method starts gathering information about nature
- Instead, our baseline is the SM, which was formed once these informations were gathered
- We are victim of our success:
  - Since 1970s, we start always from the same point
  - We have lost the value of learning from data
  - Not by chance, we totally endorsed blind analysis as the ONLY way to search

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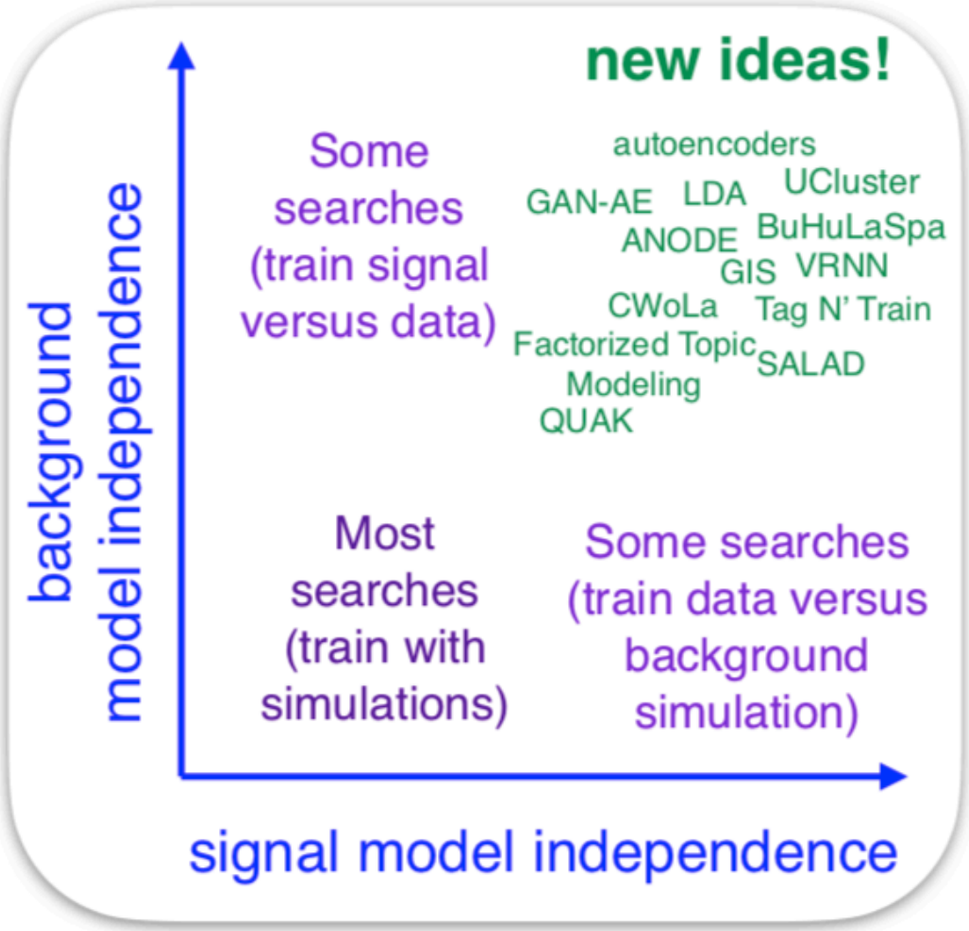
A possibility that many of us (including school attendants) are interested in: **outlier detection**

Ongoing tests in controlled conditions, e.g. LHC Olympics

Ben Nachman's talk at the 2021 Reinterpretation Workshop

New Methods



There are many new ideas that make use of modern machine learning

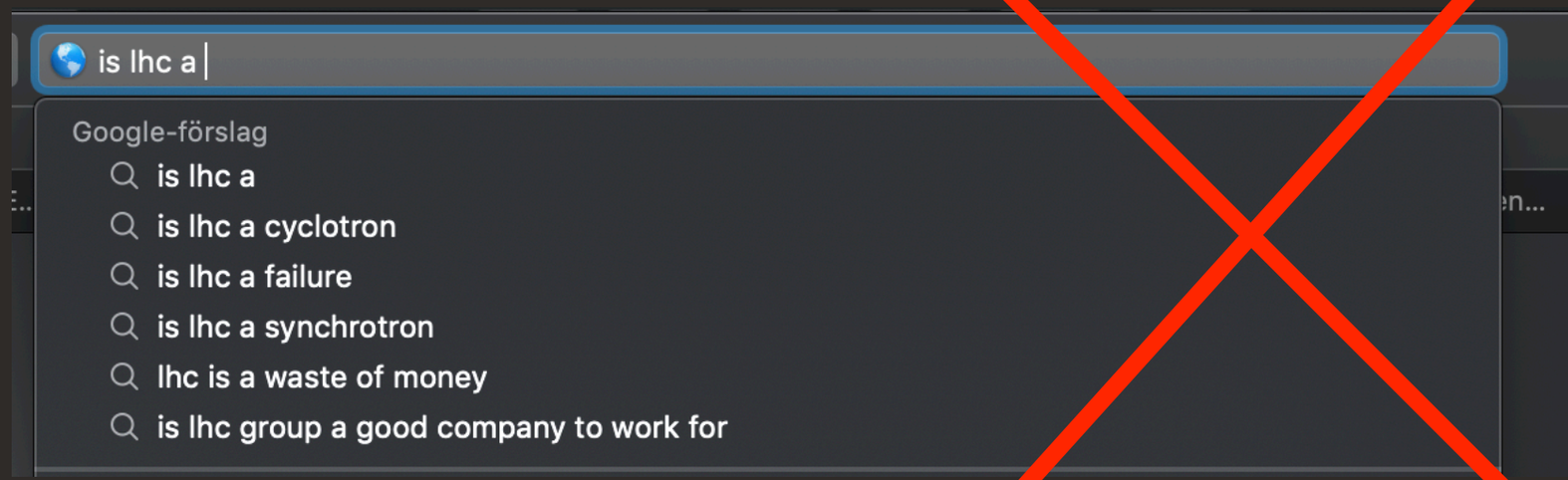
The goal is to learn **directly from data**, injecting as little bias as possible

*N.B. this is just for signal sensitivity - there is **also model dependence** for determining the background*

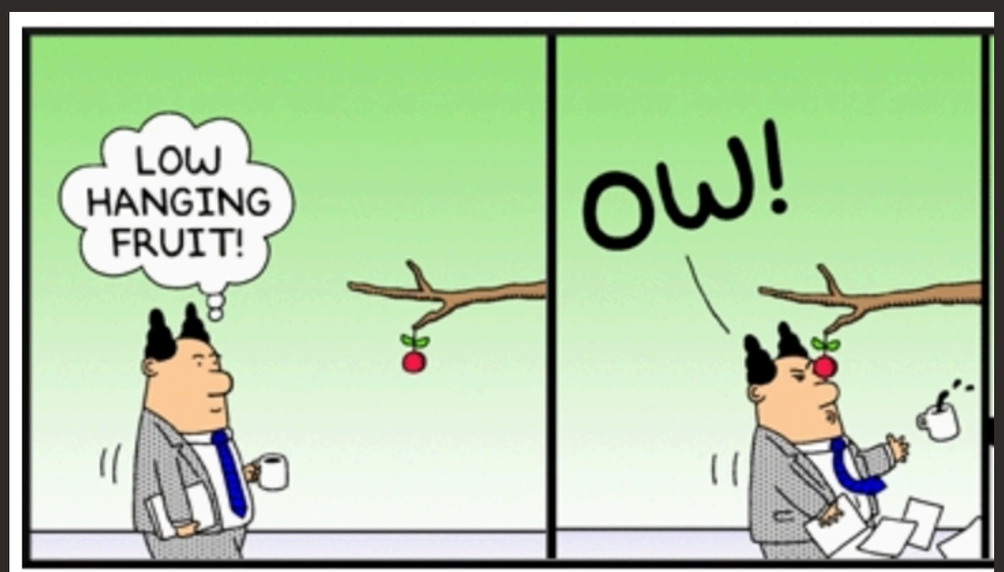
Adapted from BN and D. Shih, 2001.04990

Something similar also happening for Dark Matter in *DarkMachines*

Naysayer's feeling about future LHC physics:



My feeling about future LHC physics:



Dilbert comics

Let's keep looking!

New physics could still manifest in:

1. deviations through precision
2. rare, unusual processes

The SM <u>still</u> has some unexplained issues that needs an answer!

Thanks for your attention!

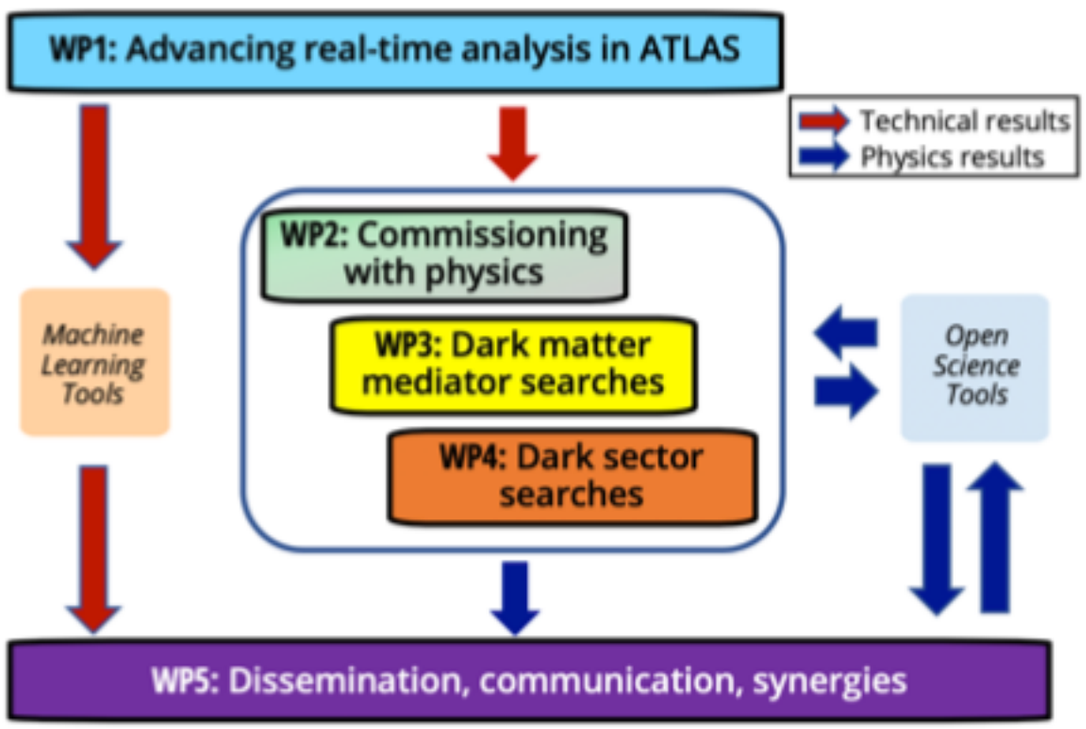
Bonus slides:
My research in the next 5 years / 3 slides

The REALDARK Project (ERC Consolidator)

Hiring a team of: **2 PhDs, 2 Post-docs, 1 Research Software Engineer (@ U of Manchester)**

Upgrade ATLAS trigger for next LHC run with new data-taking workflows (Partial Event Building)

Make **real-time analysis** widely usable for searches and measurements in ATLAS (and at the LHC)



Further exploration of the electroweak scale @ LHC(~100 GeV)

Sustainability and reusability of LHC/DM analyses, in terms of data and pipelines

Machine learning for data compression

DM @ colliders complementarity with accelerator experiments & astrophysics

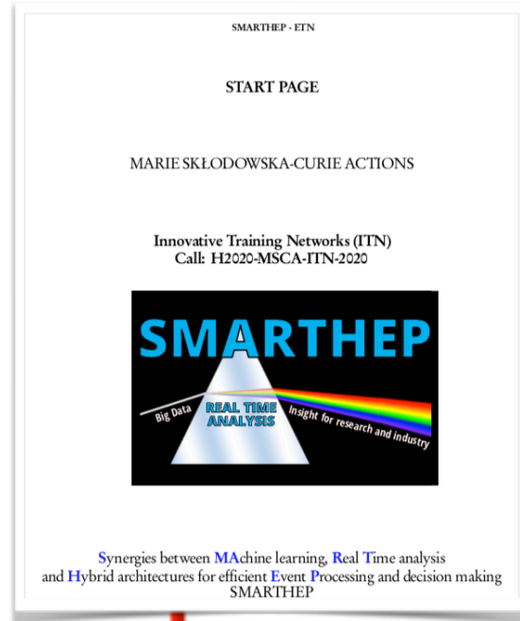
Non-WIMP dark matter searches with non-standard jet signatures

European Research Council
Established by the European Commission

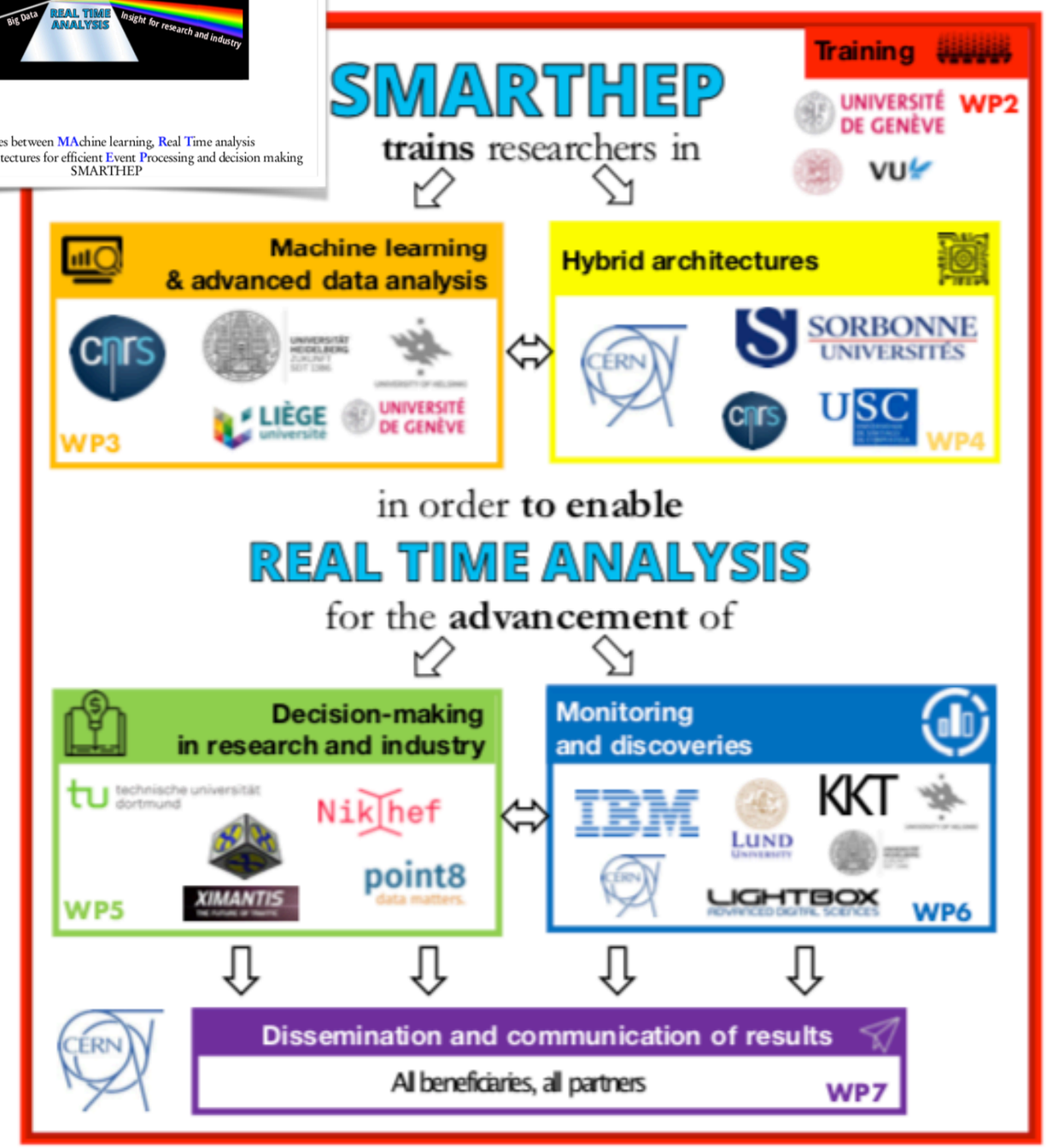
ATLAS EXPERIMENT

The SMARTHEP European Training Network

- **“Too much data”** problem by no means unique to LHC physics
- Data is abundant in industry → fast decision-making (short **time-to-insight**) crucial
- **Solution:** real-time analysis (RTA)
  - Tools to accelerate **RTA in industry & research**: machine learning, hybrid computing architectures (GPU, FPGA)



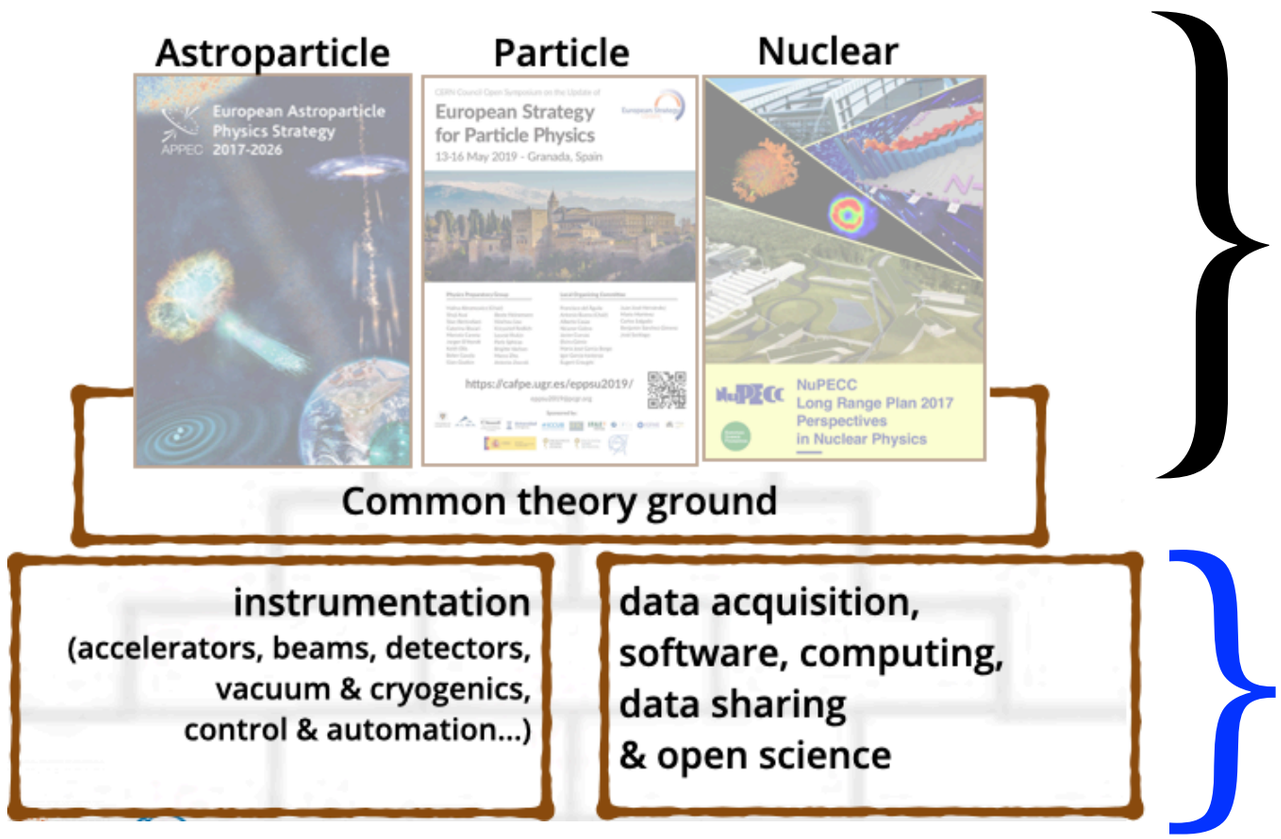
SMARTHEP trains
12 (+N) **PhD students**
20 participants:
industries, labs and academic institutions



Putting dark matter and software in context

scientific outcome:

searches & interpretation



foundations:

(open) data & software tools

JENAA
Joint ECFA-NuPECC-APPEC Activities

Initiative for Dark Matter in Europe and Beyond (iDMEu) Link

Online platform / series of meetings to discuss dark matter synergies across all experiment & theory fields, endorsed by European particle / astroparticle and nuclear physics communities

+ Snowmass 2021 (Topical Group convenor for DM at Colliders & liaison between Energy & Cosmic Frontiers)

ESCAPE
European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

Dark Matter Test Science Project Link

5 postdocs working in European institutes on reproducible and sustainable dark matter analysis (colliders, DD, ID) in the European Open Science Cloud

erc
European Research Council
Established by the European Commission

ATLAS EXPERIMENT