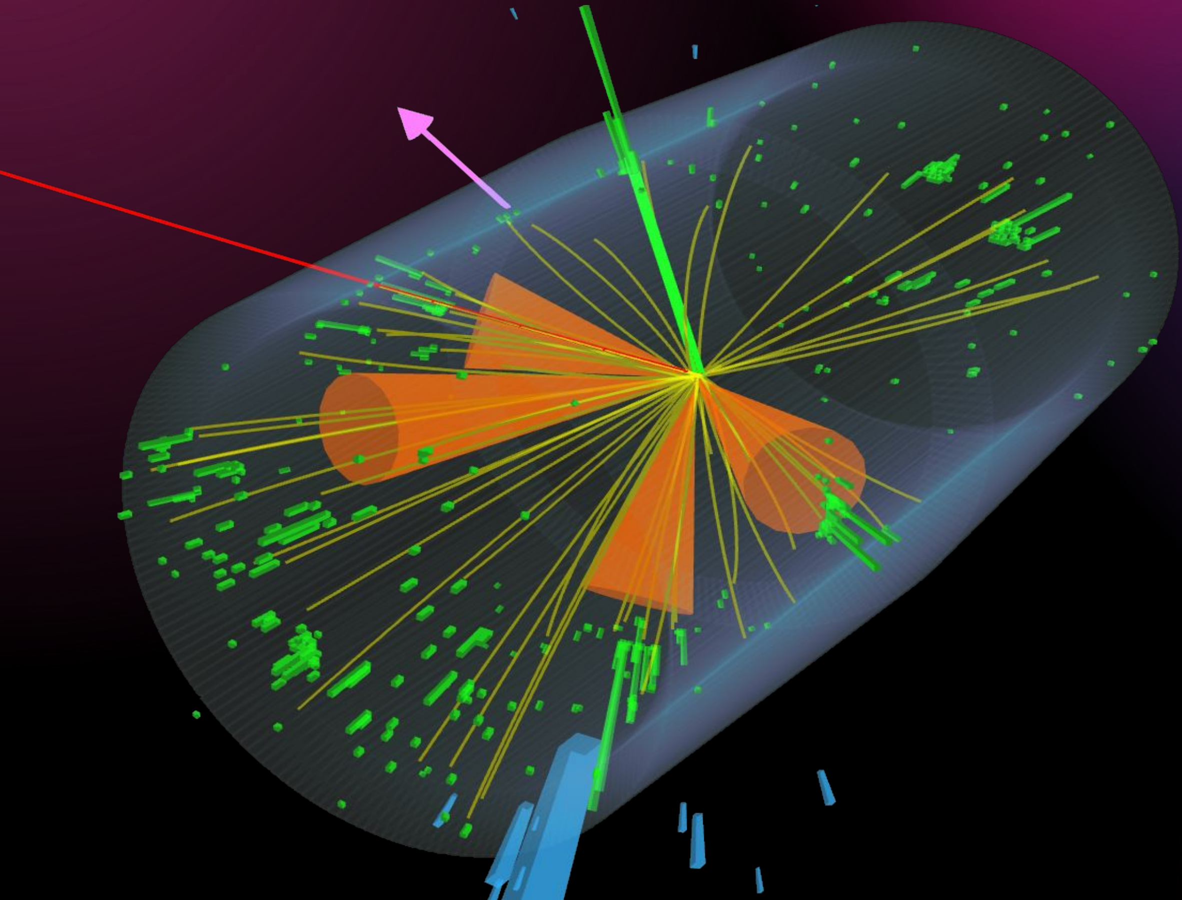
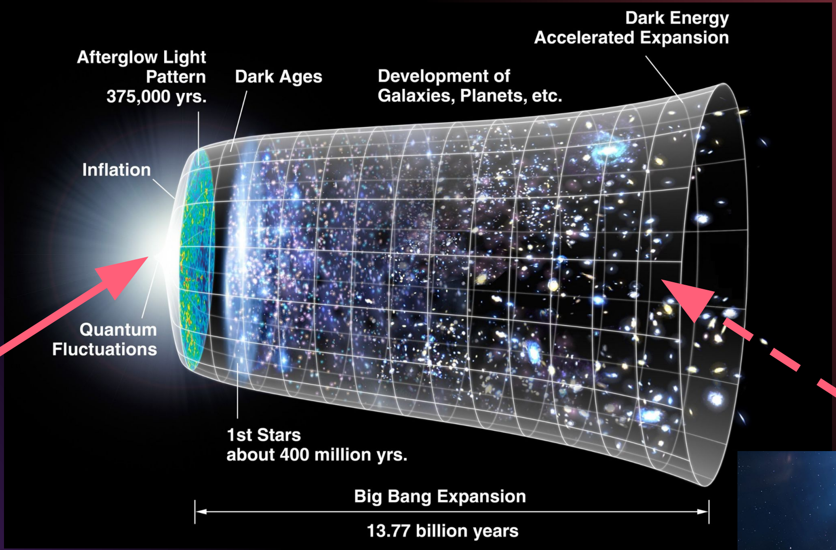
The Energy Frontier @ CMS



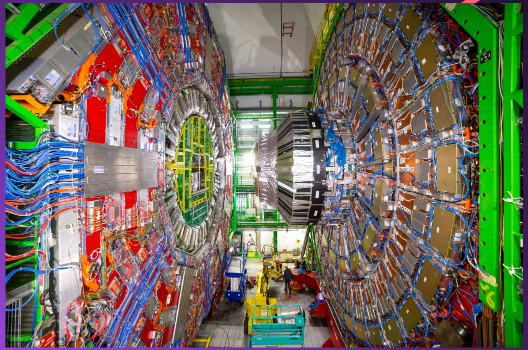
Tom Runting

Our mission

- Understand how the universe evolved from the Big Bang to what we see today



LHC



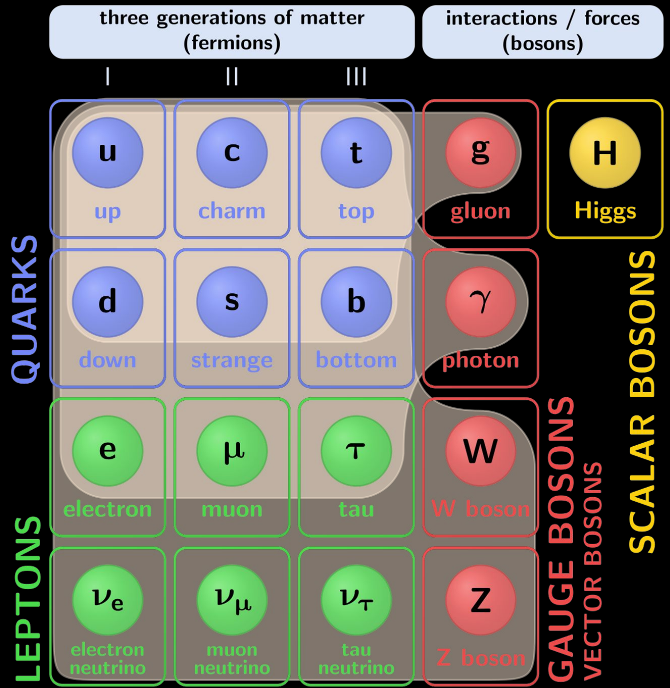
Particle observatory

James Webb

Infrared telescope

What we know

- The **Standard model** is a “periodic table” of building blocks
- Makes *testable* predictions for what we expect to see in colliders

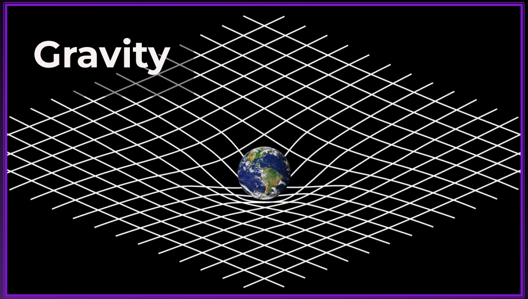


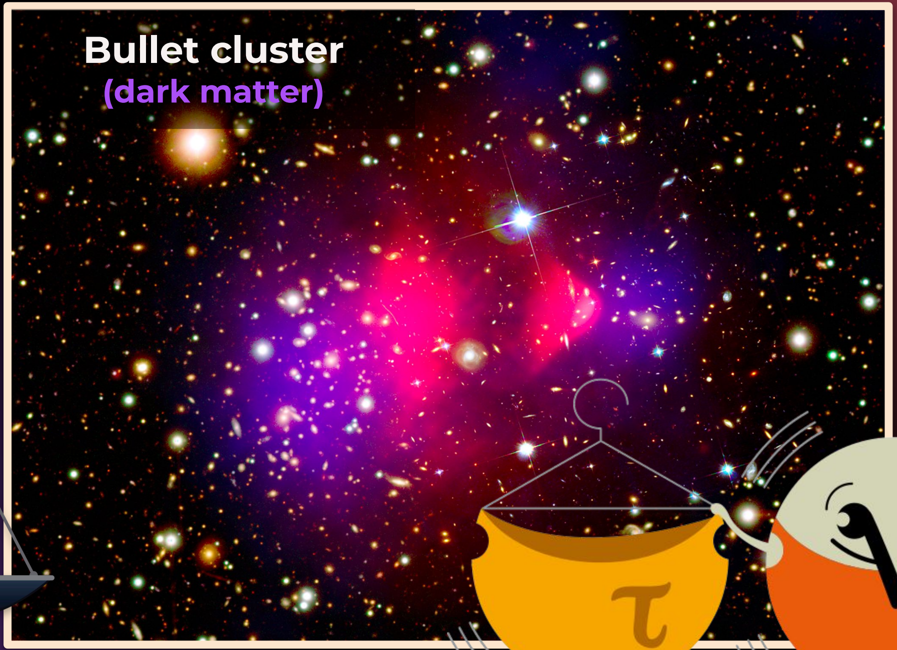
Mathematical model of the early universe

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\operatorname{tr}\left(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right) - \frac{1}{2}\operatorname{tr}\left(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}\right) && (U(1),\ SU(2),\ \text{and } SU(3) \text{ gauge terms}) \\
& + (\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \binom{\nu_L}{e_L} + \bar{e}_R \sigma^\mu i D_\mu e_R && (\text{lepton kinetic terms}) \\
& - \frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R M^{e\dagger}\phi^\dagger \binom{\nu_L}{e_L}\right] && (\text{electron, muon, and tau Yukawa terms}) \\
& + \left(\bar{u}_L, \bar{d}_L\right)\tilde{\sigma}^\mu i D_\mu \binom{u_L}{d_L} + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R && (\text{quark kinetic terms}) \\
& - \frac{\sqrt{2}}{v}\left[\left(\bar{u}_L, \bar{d}_L\right)\phi M^d d_R + \bar{d}_R M^{d\dagger}\phi^\dagger \binom{u_L}{d_L}\right] && (\text{down, strange, and bottom Yukawa terms}) \\
& - \frac{\sqrt{2}}{v}\left[\left(\bar{u}_L, \bar{d}_L\right)\tilde{\phi} M^u u_R + \bar{u}_R M^{u\dagger}\tilde{\phi}^\dagger \binom{u_L}{d_L}\right] && (\text{up, charm, and top Yukawa terms}) \\
& + \left(D_\mu \phi\right)^\dagger D^\mu \phi - \frac{m_h^2}{2v^2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2 && (\text{Higgs kinetic and potential terms})
\end{aligned}
$$

What we know (that we don't know)

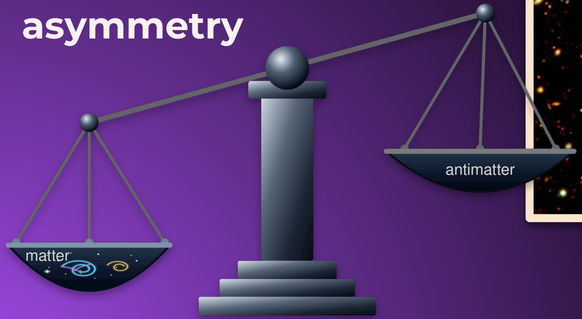
- Many phenomena left **unexplained**

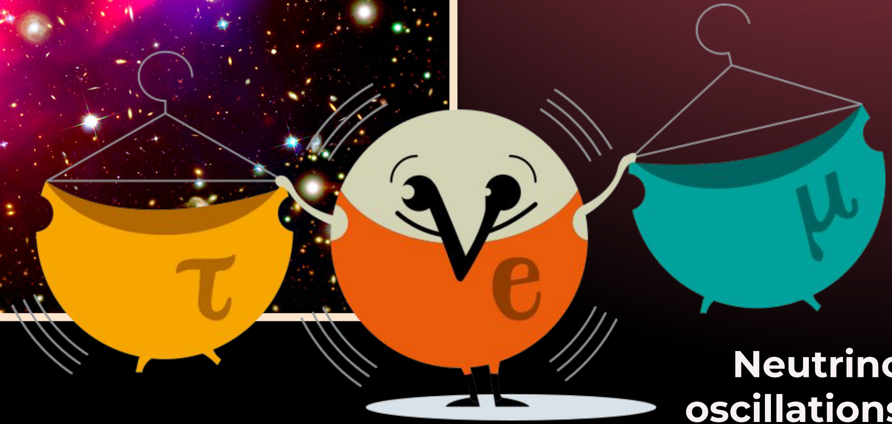




Hierarchy problem

Matter-antimatter asymmetry





Neutrino oscillations

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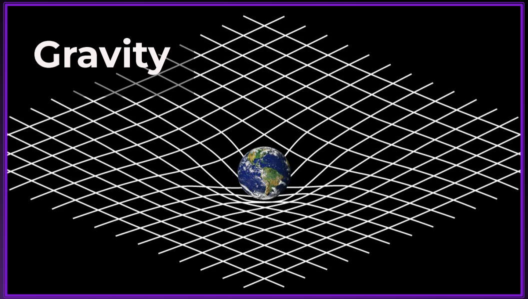

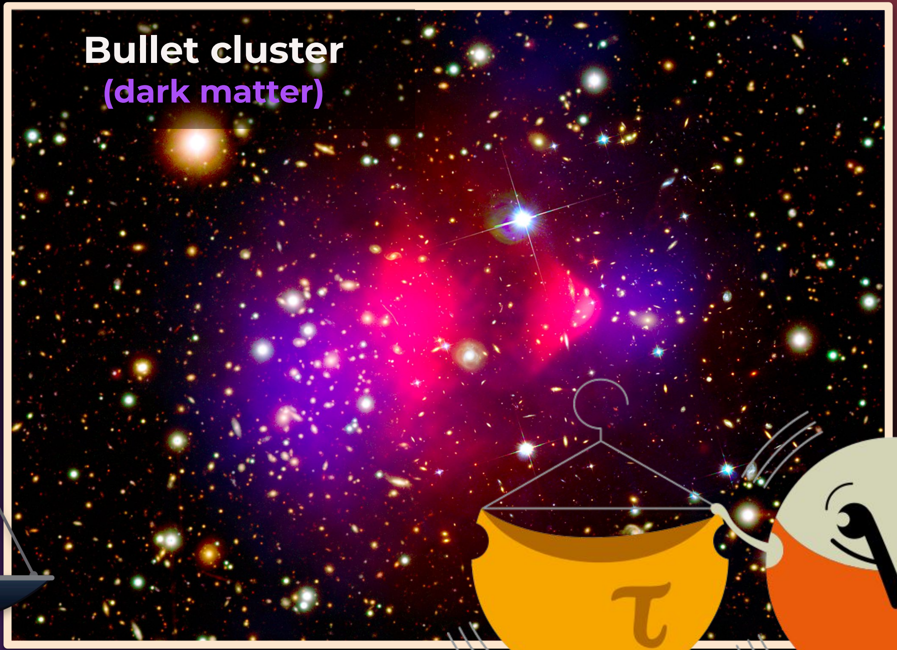

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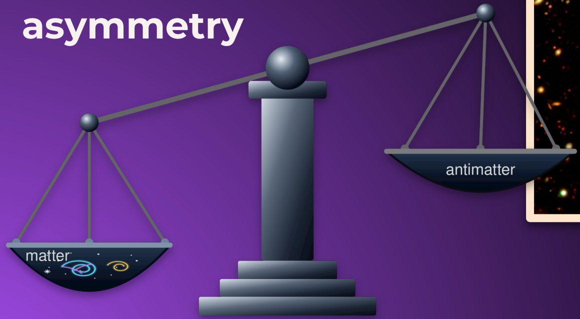


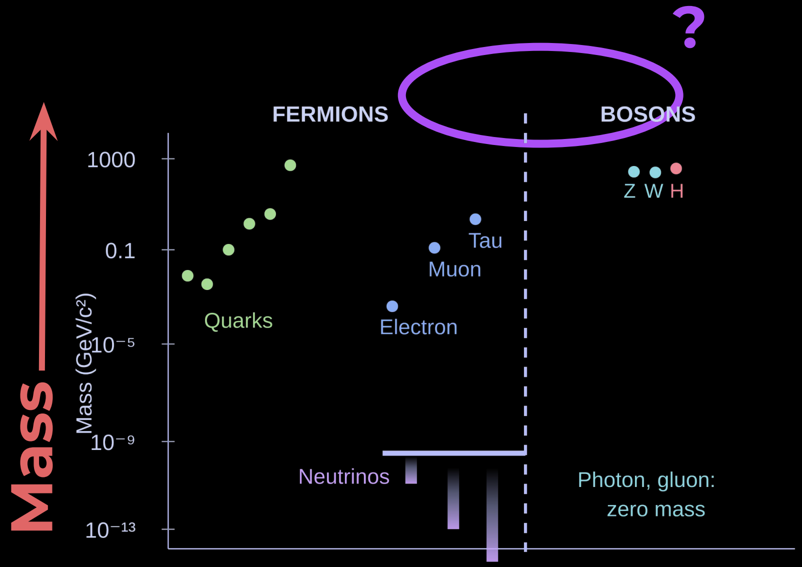
Neutrino oscillations

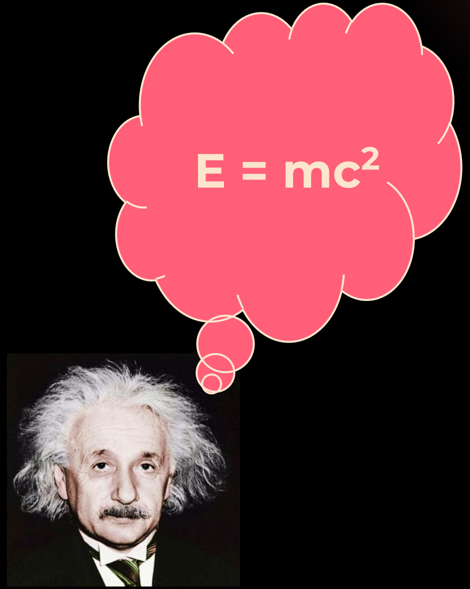
Upside: there must be new physics to discover!

How to discover the secrets of the universe

- Directly produce **new particles** to study
- Indirectly via **precisely testing** the Standard model's predictions

- Both require **high energy** and **high intensity…**





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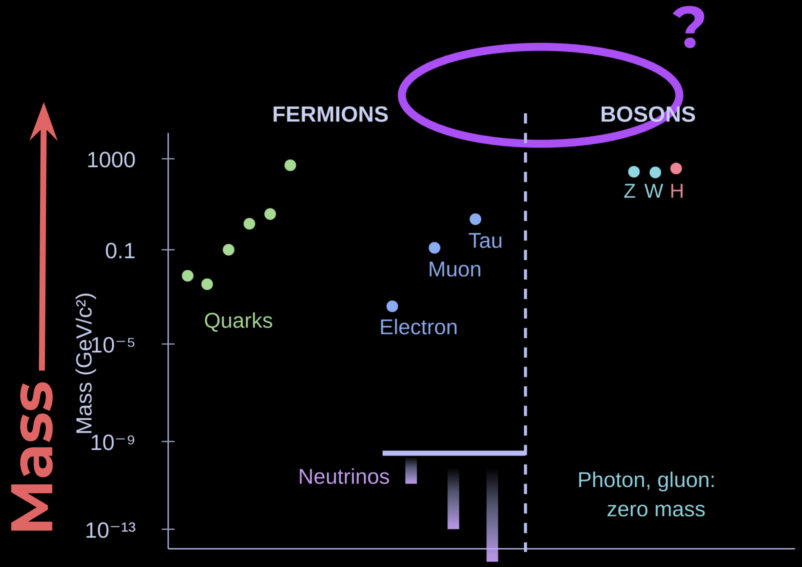
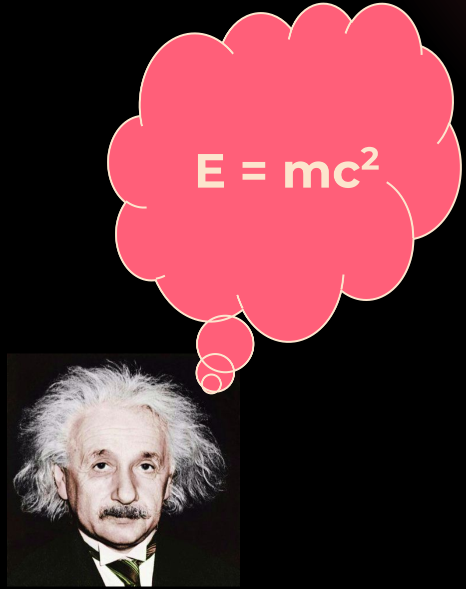
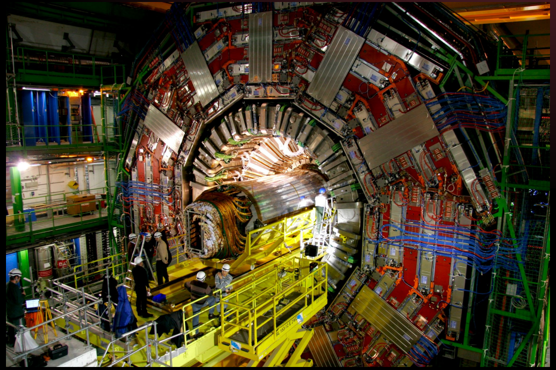




Particle colliders!



A brief history of colliders

This talk's focus

- Accelerate particles to very high kinetic energy in two opposing beams: **circular** or linear
    - Circular requires bending beams using extremely strong magnetic field
- Collide the beams and measure what stuff comes out
- Sufficiently **high energy** can produce new particles

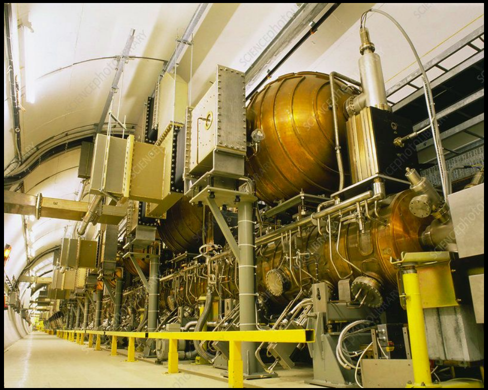
1950s-1970s

Proton synchrotron
Circumference: 628m

~1980s ***W + Z bosons***

Super Proton synchrotron
Circumference: ~7 km

~1990s ***Precision***



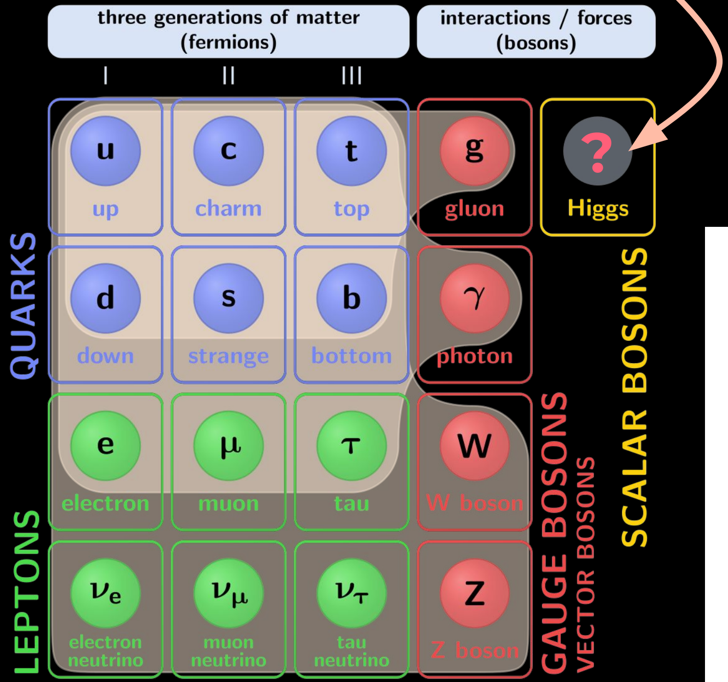
LEP
Circumference: 27 km

1990s-2000s ***Top quark***

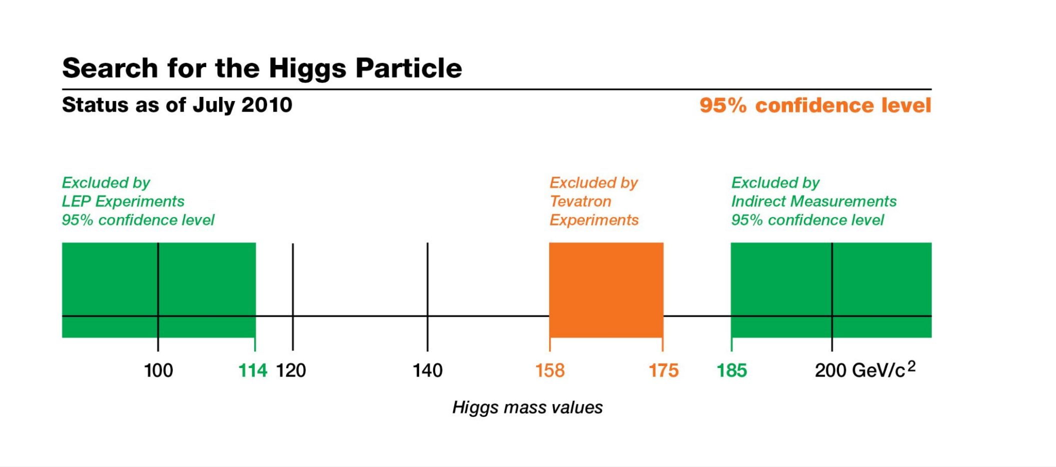
Tevatron
Circumference: 6.3 km

The missing piece of the puzzle

- In the early 2000s, there was just one piece of the Standard Model missing



We also knew where it **wasn't**, but needed a machine capable of filling in the gaps



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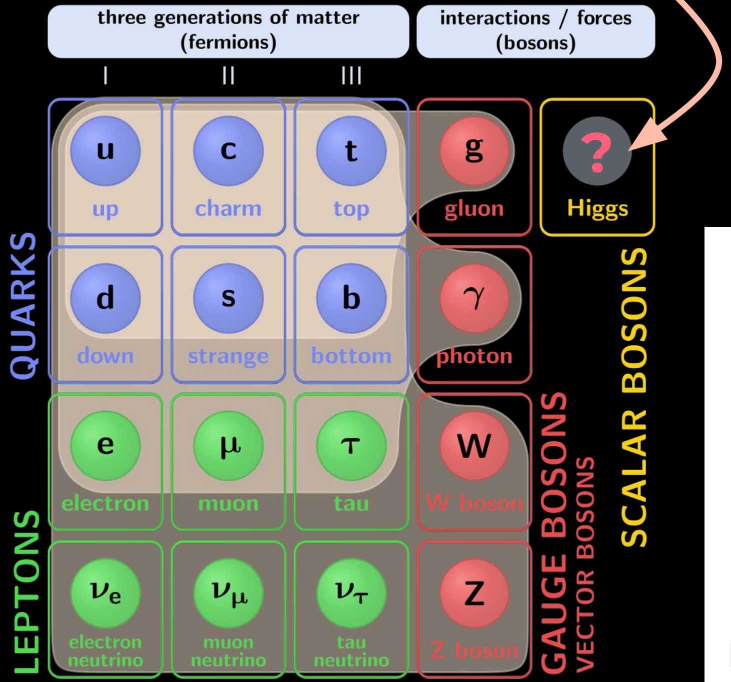

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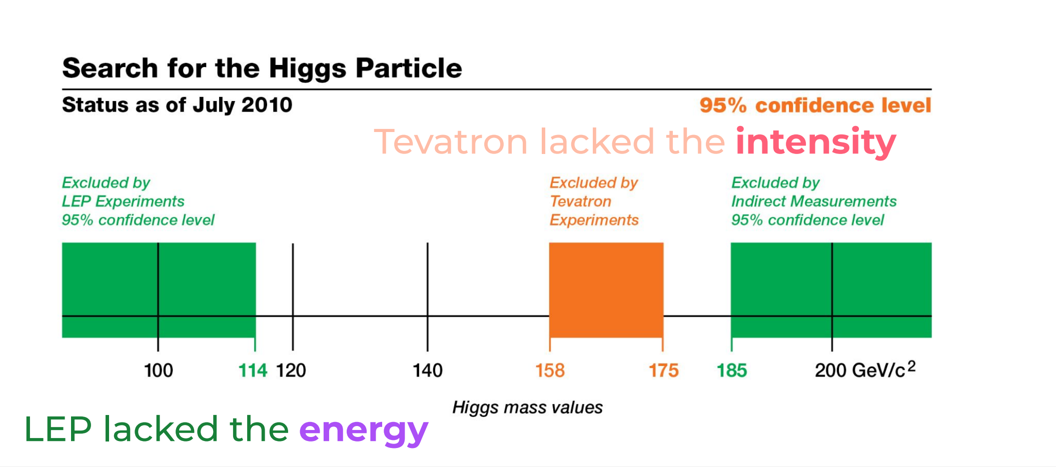
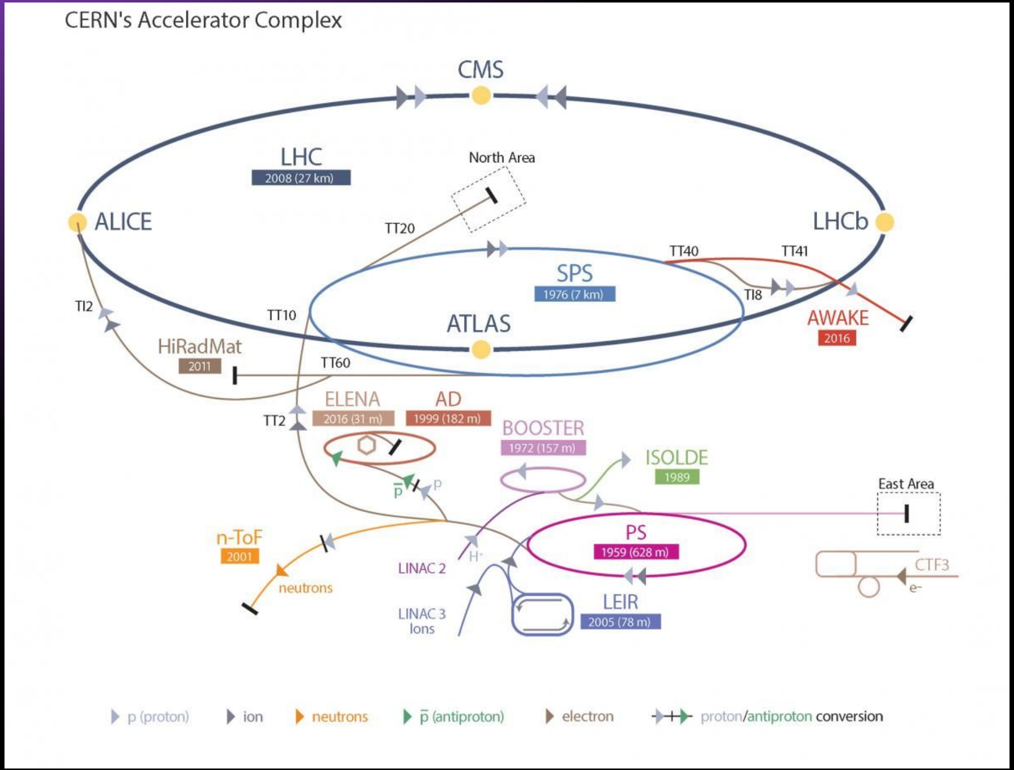
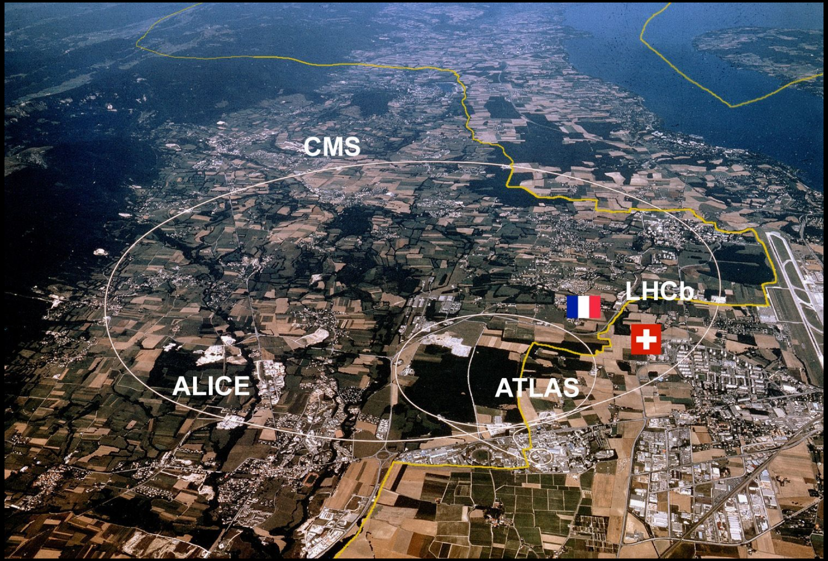


Enter the LHC

- **L**arge **H**adron **C**ollider (LHC)





Large = 27km ring of superconducting magnets, 100m underground French-Swiss border

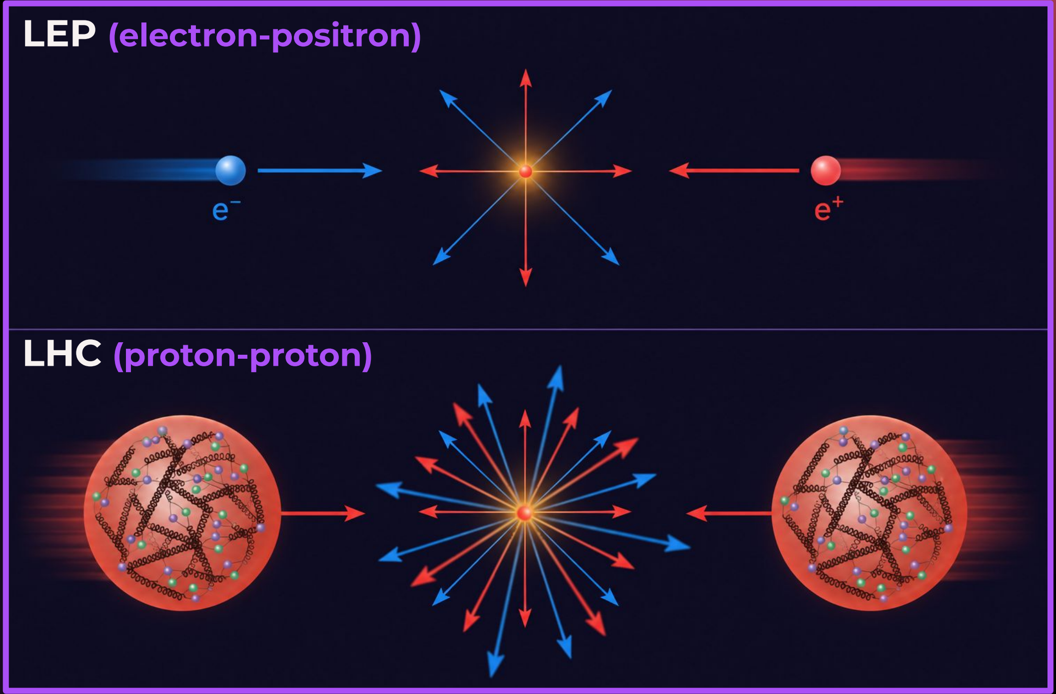
Hadron = accelerate protons (hadrons) to almost the speed of light

Collider = two proton beams collide 40 million times a second at four points around the ring

New collider, same address

- The LHC is in the same tunnel as the previous LEP (**L**arge **E**lectron **P**ositron) collider

	LEP	LHC
Beam energy (GeV)	208	13,600
Operation	1989-2000	2010-2026



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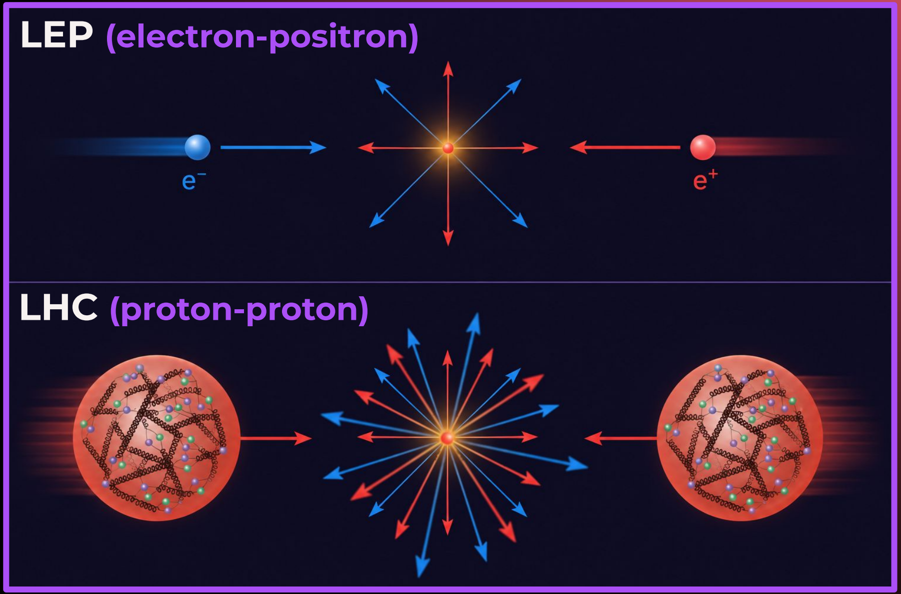


Bending charged particles causes them to emit **synchrotron radiation**, carrying away energy

The power loss scales as

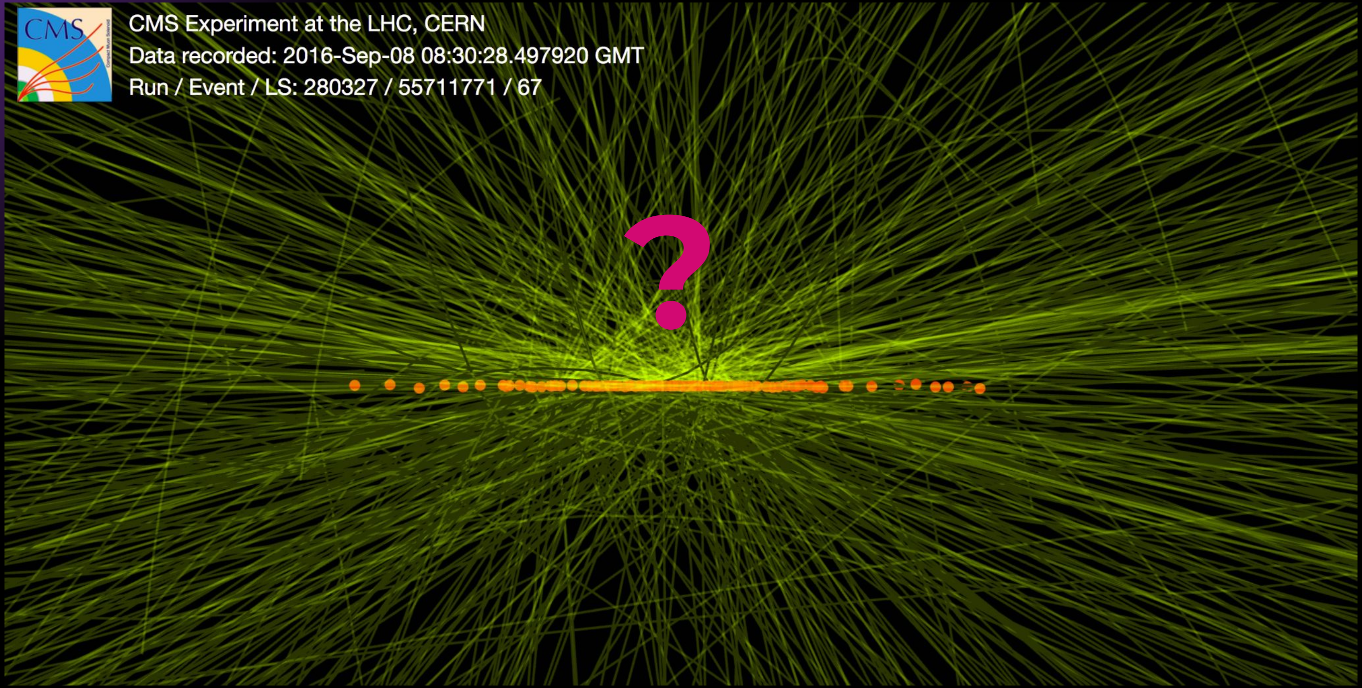
$$P \propto \frac{1}{R_{\text{ring}}^2}\left(\frac{E_{\text{beam}}}{m}\right)^4$$

For electrons vs protons

$$\frac{P_{\text{electron}}}{P_{\text{proton}}} = \left(\frac{m_{\text{proton}}}{m_{\text{electron}}}\right)^4 = 10^{13}$$

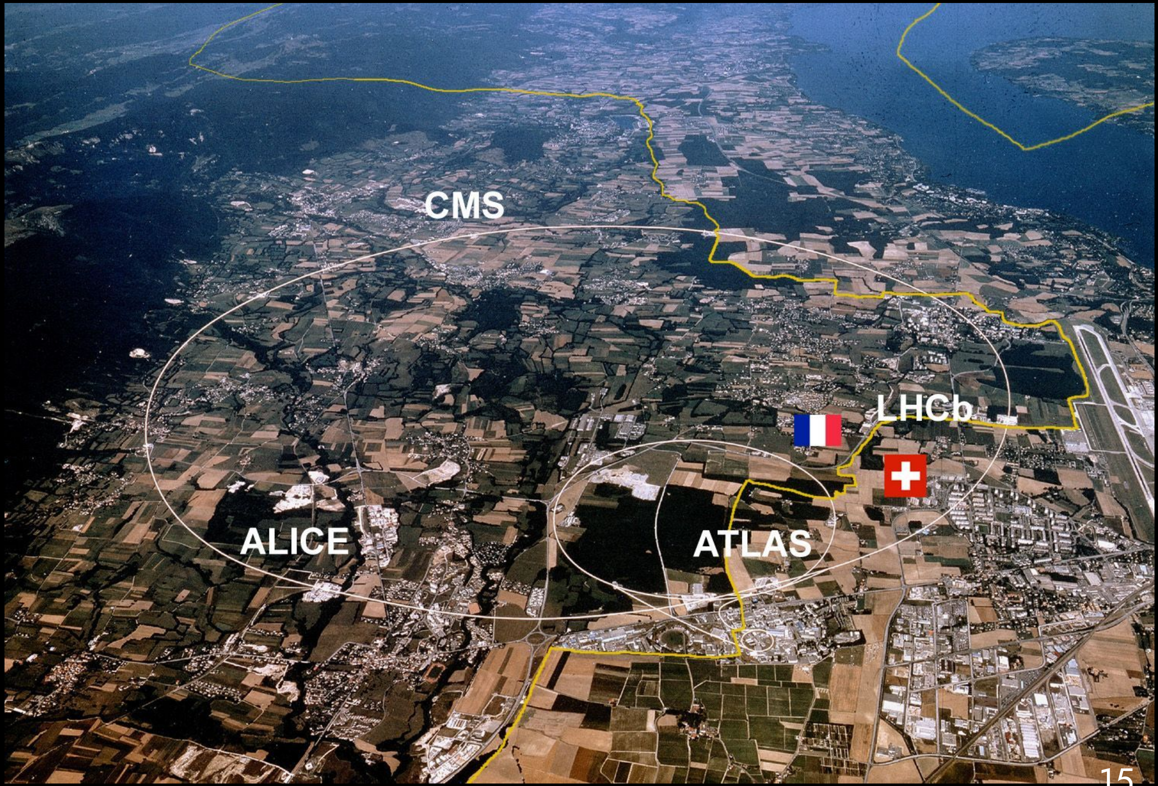
Proton-proton collisions

When the proton beams collide, interaction points collision fragments are “photographed” with massive detectors



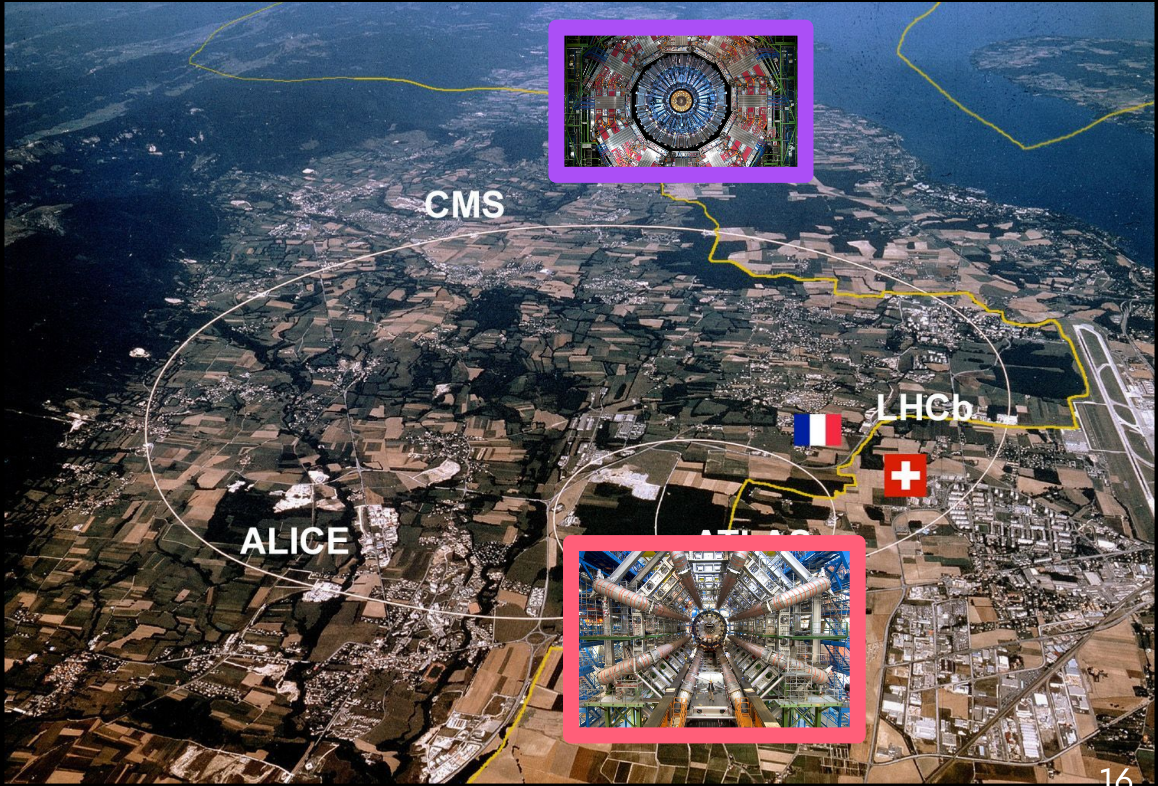
Proton collisions are messy! Requires advanced detector technology...

Detectors at the LHC



Detectors at the LHC

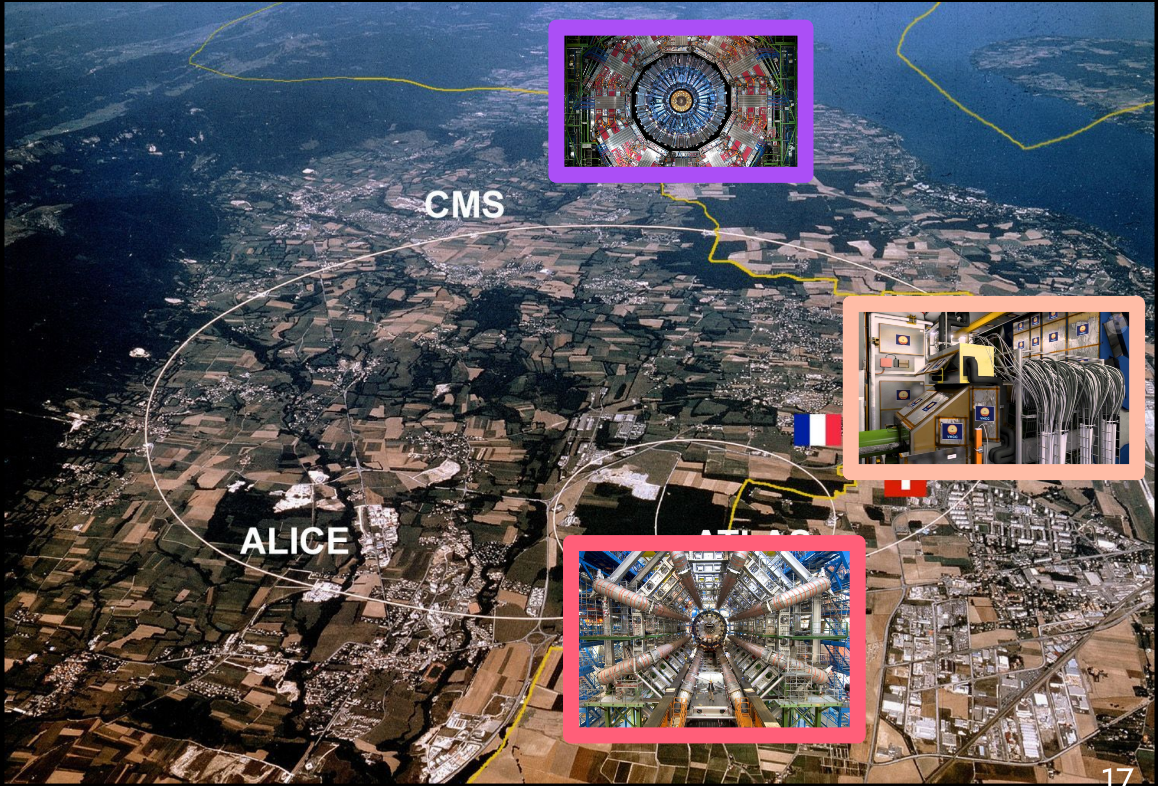
Two “general purpose” detectors



Detectors at the LHC

Two “general purpose” detectors

One dedicated flavour-physics detectors (**see Sophie’s talk later**)



Detectors at the LHC

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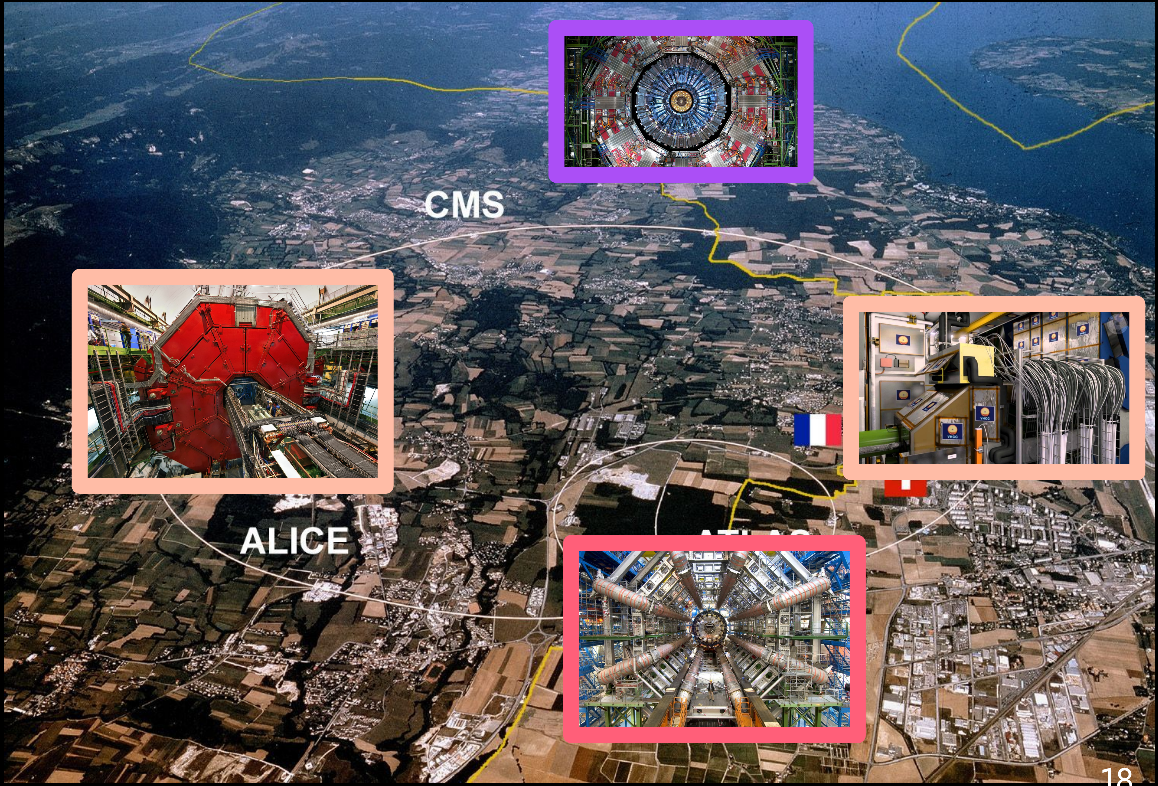
One dedicated heavy-ion detector



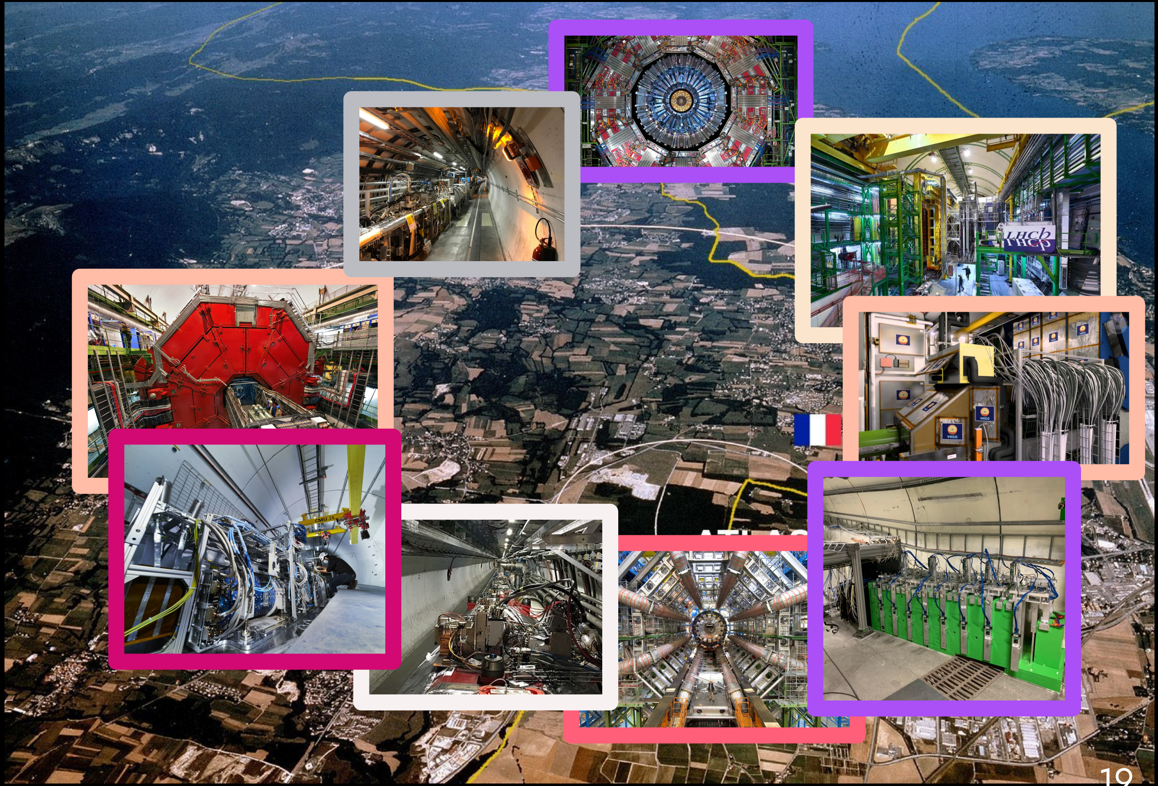
Detectors at the LHC

Two “general purpose” detectors

One dedicated flavour-physics detectors (**see Sophie’s talk later**)

One dedicated heavy-ion detector

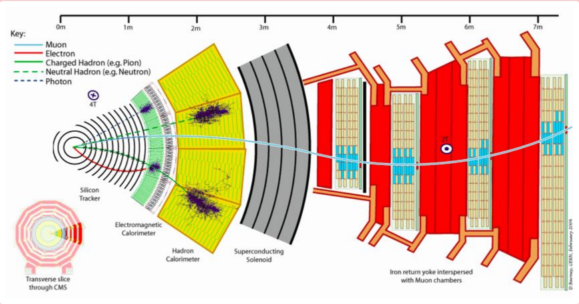
Several smaller experiments each doing very specific research



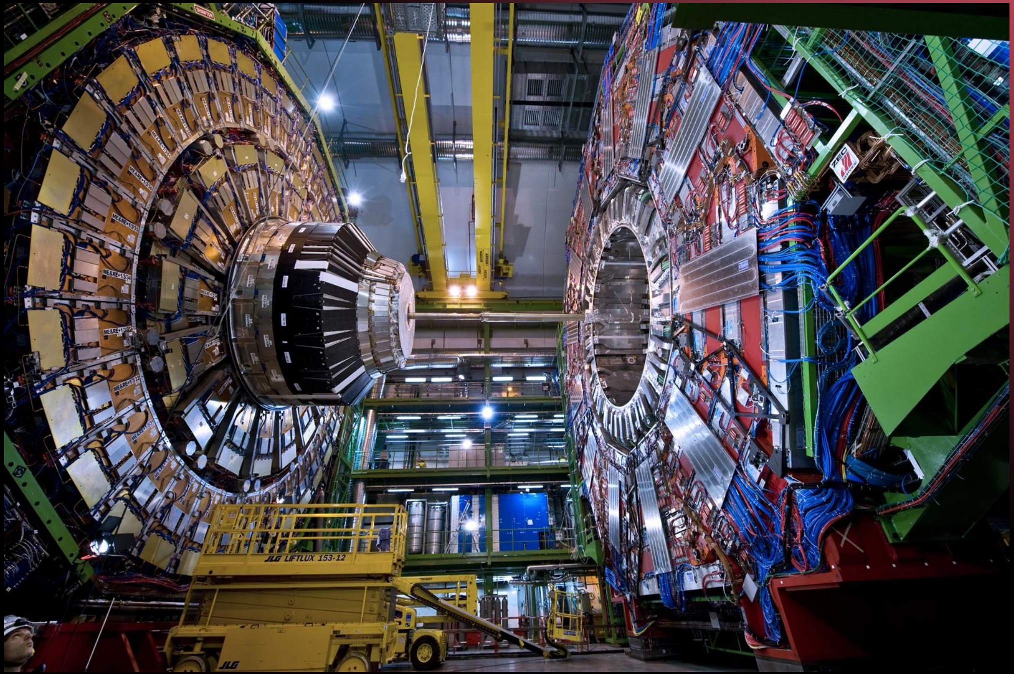
The CMS experiment

- One of two general purpose detectors at the LHC: ATLAS and CMS
  - *"Giant camera" operating at 40,000,000 frames per second!*

Compact **M**uon **S**olenoid



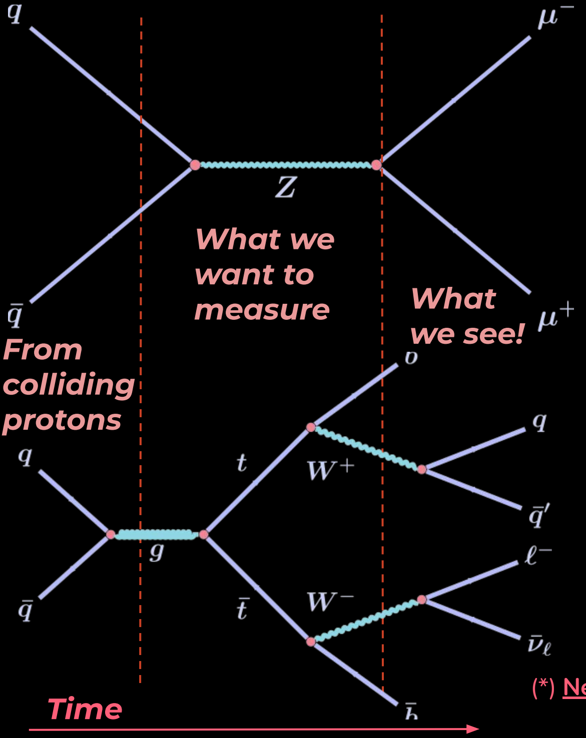
Length: 28m
Diameter: 15m
Weight: 14,000 tonnes
Superconducting solenoid: 3.8T
Readout channels: O(100) million
Radiation environment: Extreme

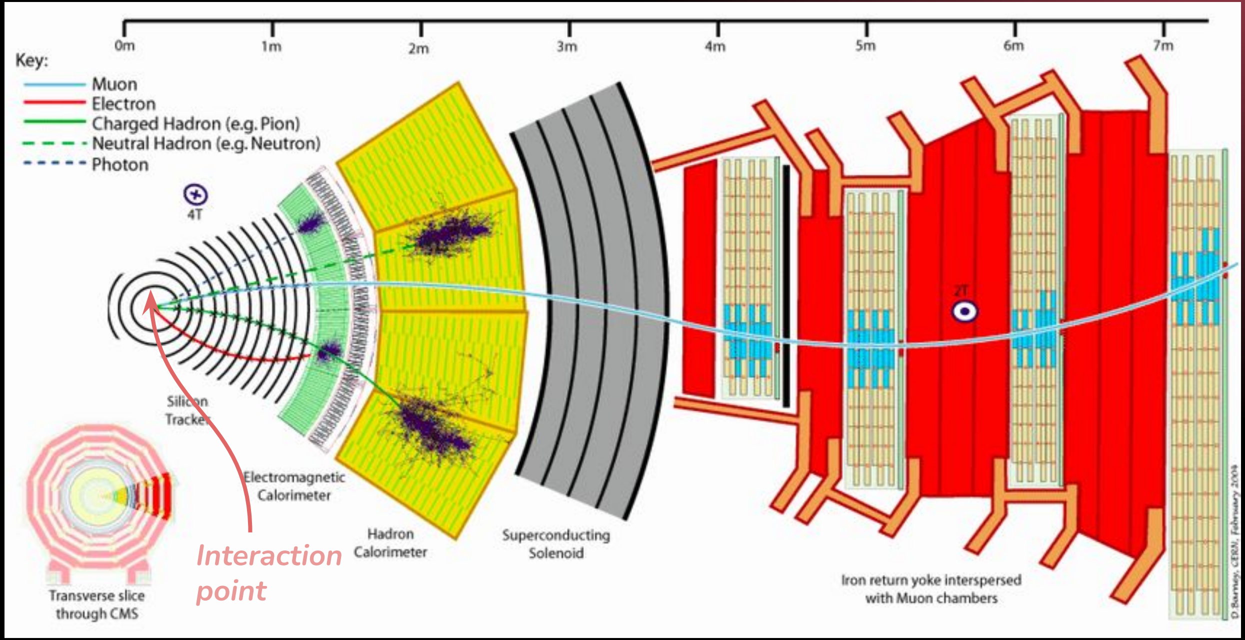


Layers of "sub"-detectors each with a different purpose: "a cylindrical onion"

Collision event at CMS

- "Interesting" physics is unstable (Higgs, top quark, W and Z bosons)
- Combination of sub-detectors enables reconstruction of all final state particles (*)
- Infer the presence of "interesting" physics... and measure it!

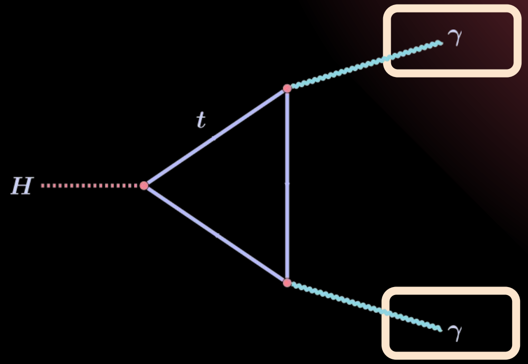




(*) Neutrinos are an exception as they do not interact with detector but can be inferred from conservation of momentum.

Let there be light

- Higgs boson decays instantaneously
    - One way this can happen is to **two photons** (0.2%): two clusters of energy in ECAL
- Measure energy and position of photons -> calculate **mass!**



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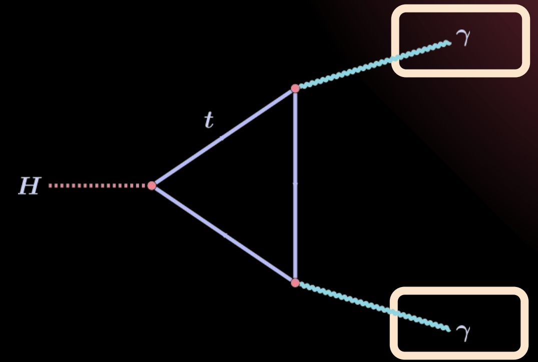

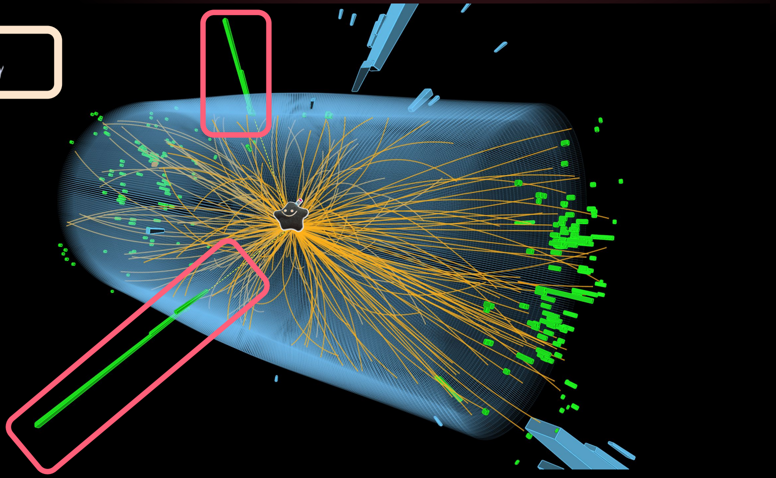

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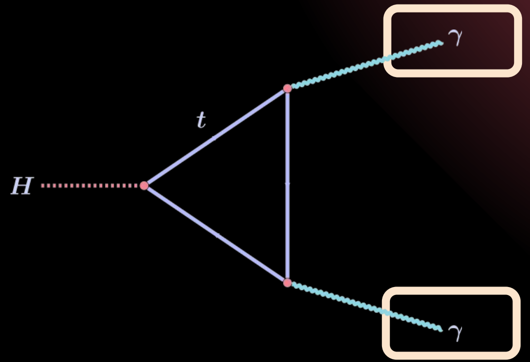
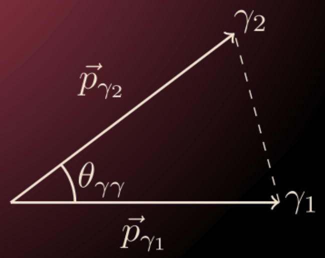
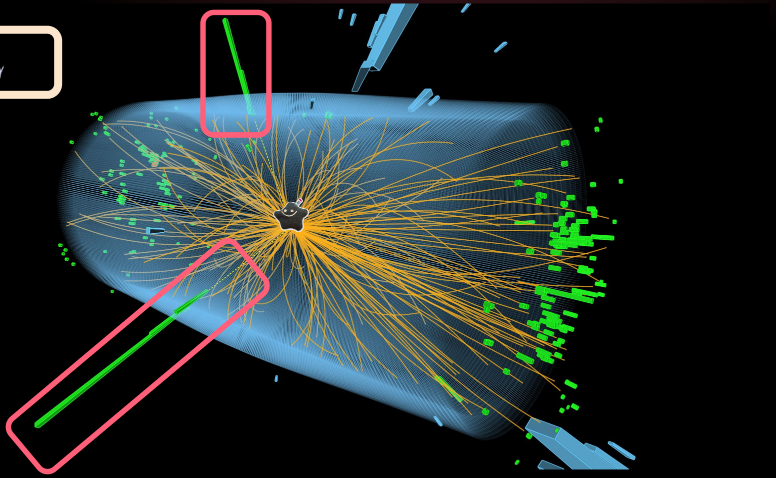


$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\theta_{\gamma\gamma}\right)}$$





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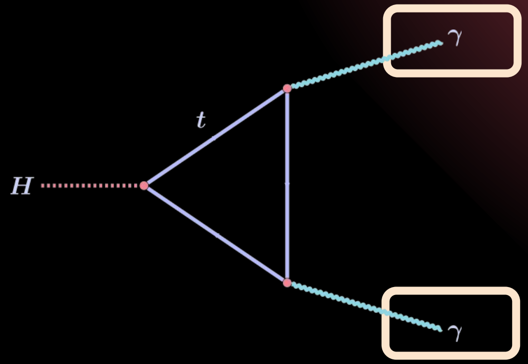

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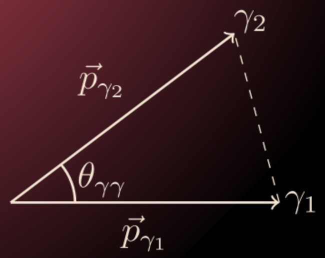
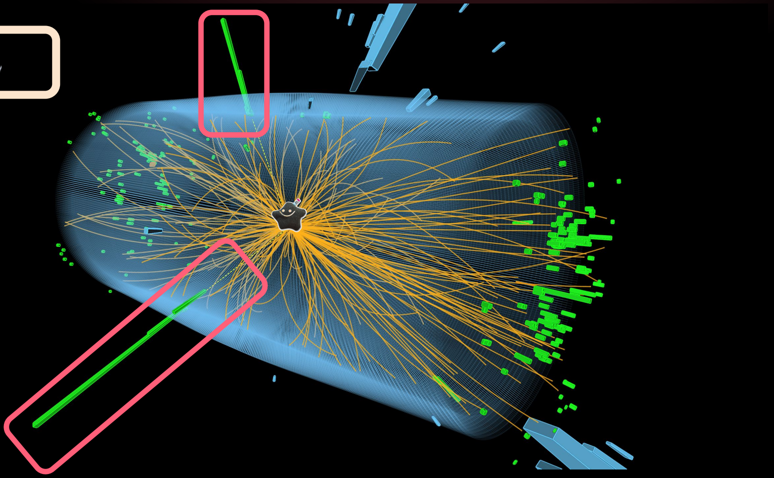
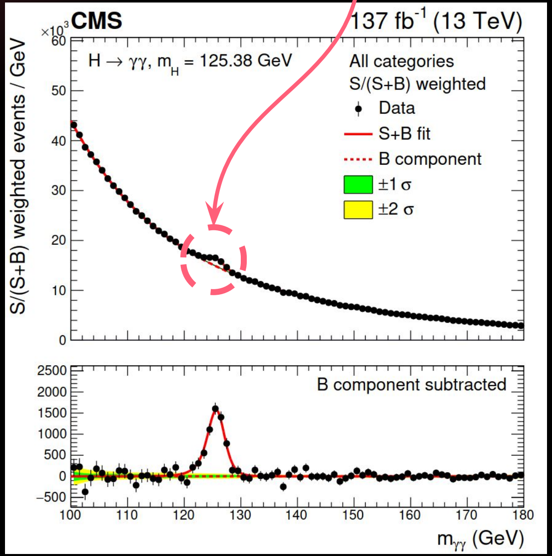


Higgs boson appears as bump above background!

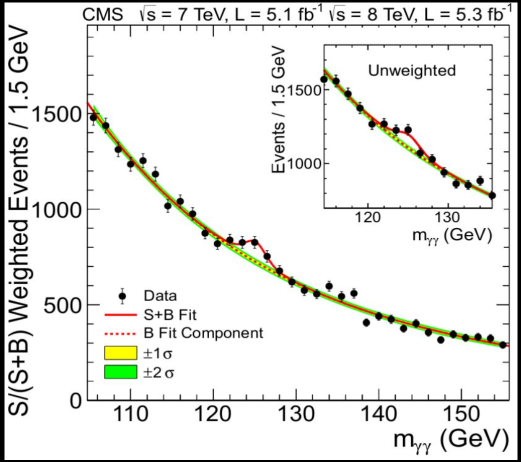




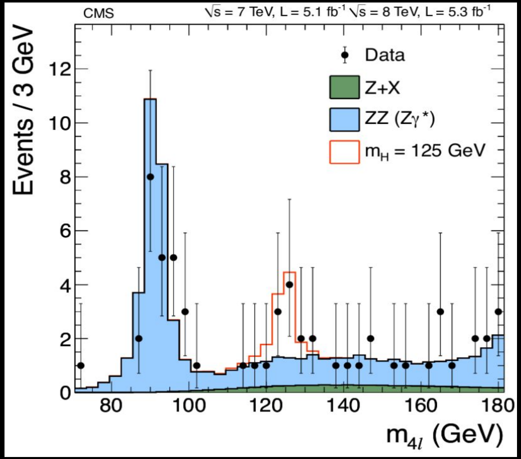
Higgs boson discovery

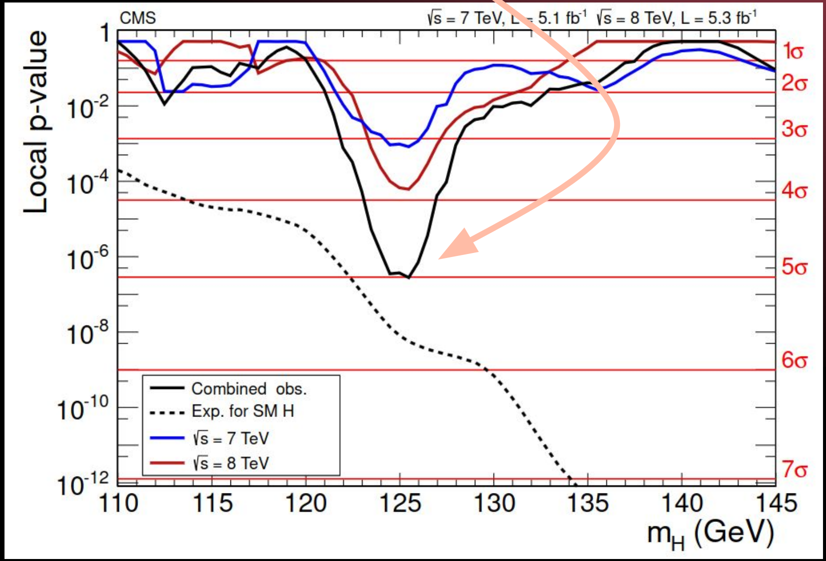
- Higgs boson production is very rare: only 1 in 10 billion pp collisions
  - *Requires sophisticated analysis techniques e.g. Machine Learning to find the needle in the haystack*
- On **4th July 2012**, ATLAS + CMS announced observation of Higgs boson with **5σ significance**

$H \to \gamma\gamma$



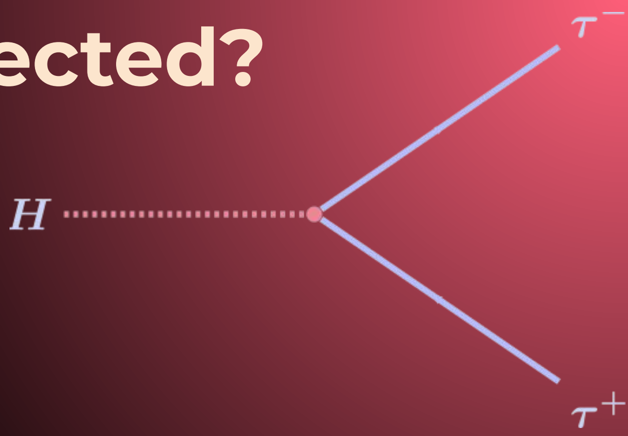
$H \to ZZ^* \to 4\ell$



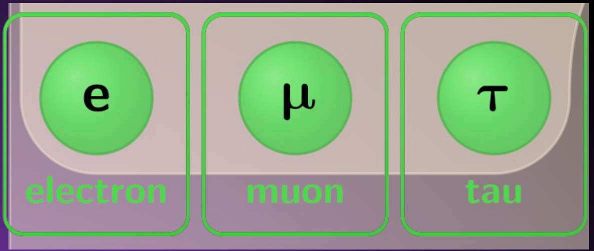


But does it behave as the SM predicts?

Does the Higgs behave as expected?

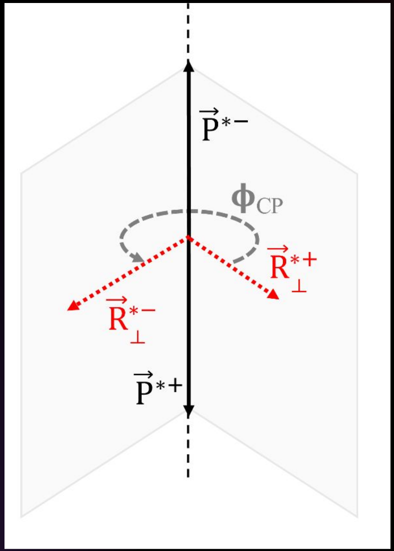


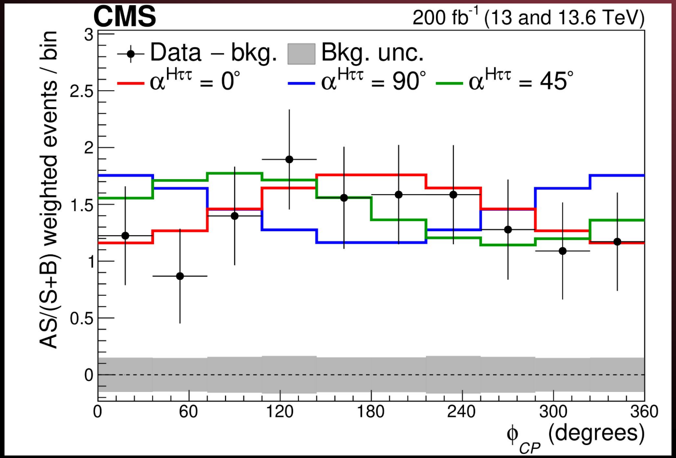
- Measurement how the Higgs interacts with **tau leptons**
  - Tau leptons notoriously difficult to reconstruct in the detector, so advanced techniques were needed



Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8

Many different tau decay modes, each with their own challenges



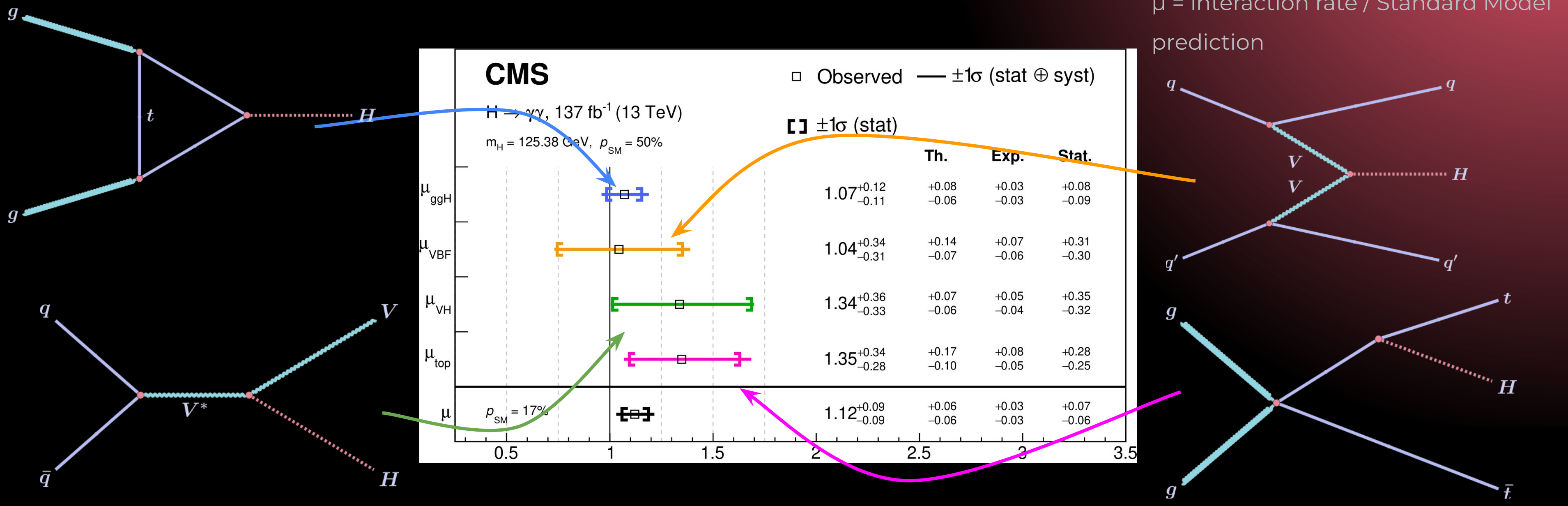


Data agrees with the Standard Model

Does the Higgs behave as expected?

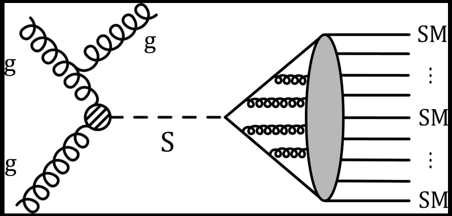
- Used two photon decay channel to probe different interactions which produce a Higgs
- Measure <u>rate of interactions</u> and compare to Standard Model predictions

μ = interaction rate / Standard Model prediction



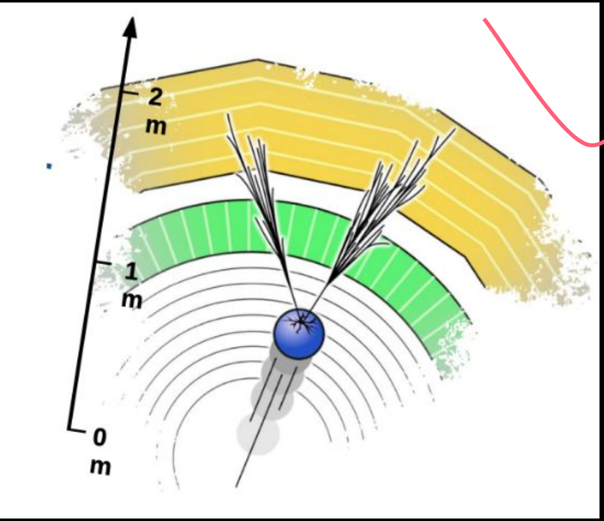
- Large data set + sophisticated analysis techniques e.g. <u>machine learning</u> for high statistical precision
- No clear sign of new fundamental physics… but could it be hiding within the uncertainties?
  - Take more data!

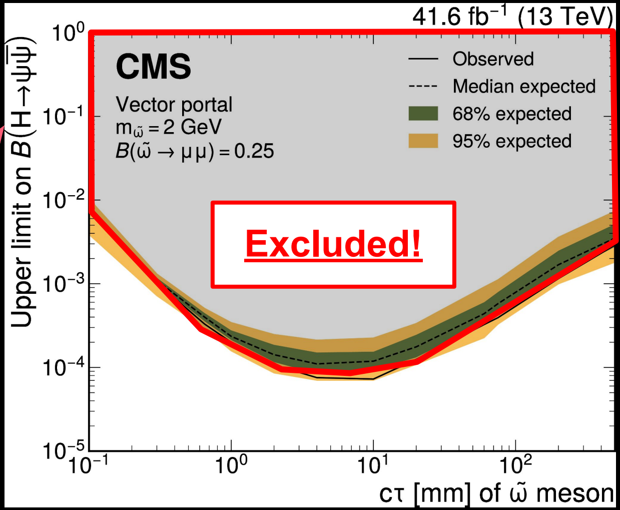
Searching for something new

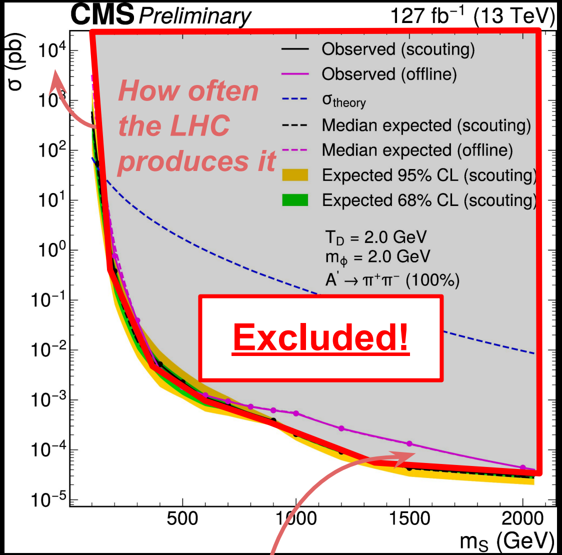


- We also search for **direct** signatures of new particles. Examples at Imperial...
  - Long-lived particles that decay within the CMS silicon tracker
  - Search for new particles that decay into sprays of low-energy particles
- Something new may provide solutions to the biggest questions: dark-matter, supersymmetry, flavour anomalies, ...

Coupling to Higgs sector







How often the LHC produces it

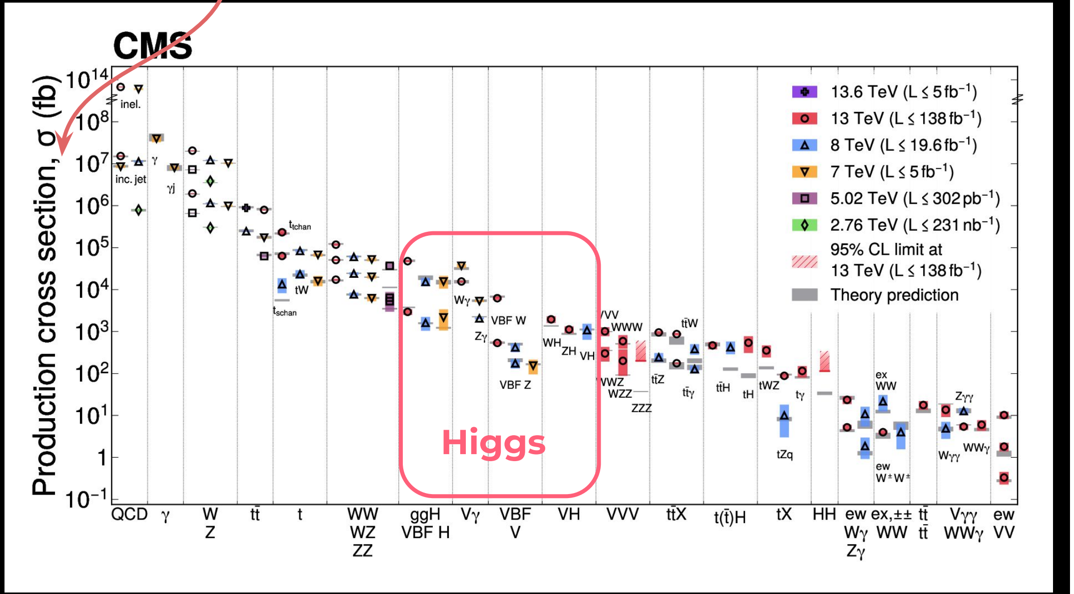
Distance new particle travels

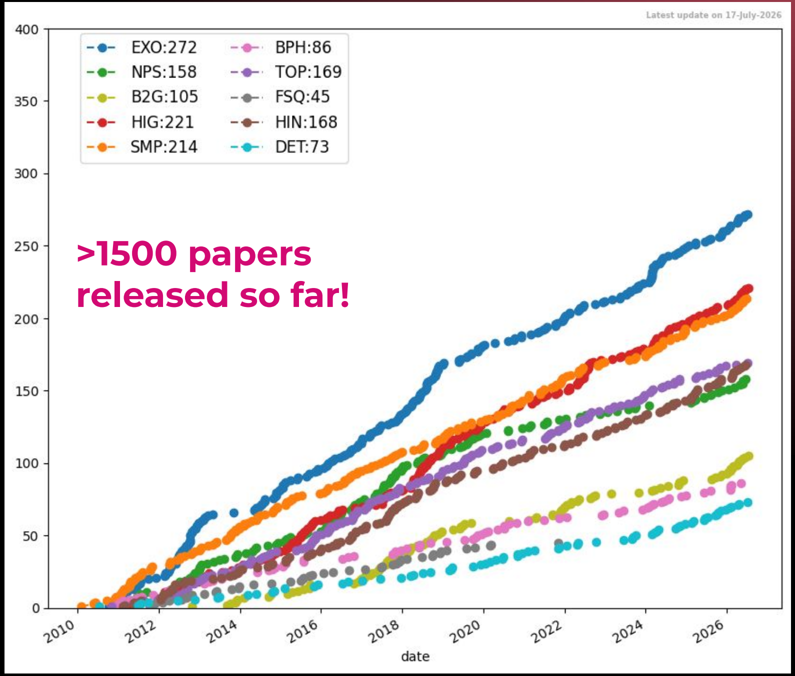
Mass of new particle

A myriad of physics

- Not all about the Higgs! At CMS we measure many different interactions
  - Aiming to observe a deviation from the Standard Model predictions

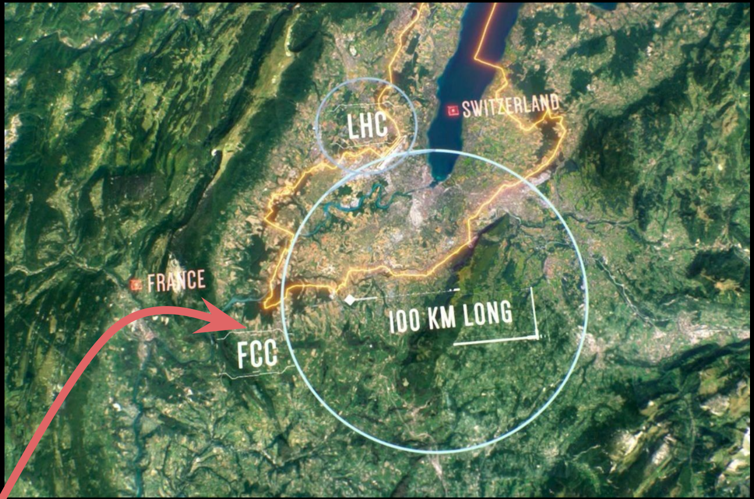
Probability of interaction





What does the future hold?

HiLumi
HL-LHC PROJECT



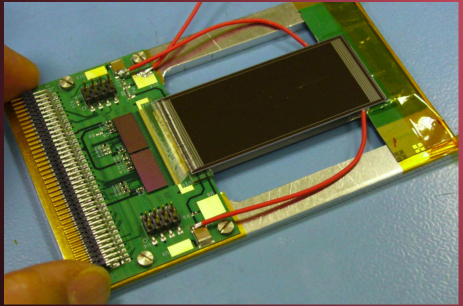
- Increase rate of collisions: starting ~2031
  - Unprecedented volume of data to play with

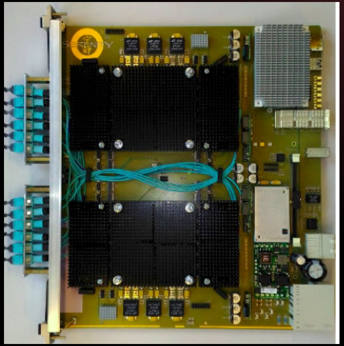
- Increase energy of collisions: starting ~2050+
  - directly produce new particles?

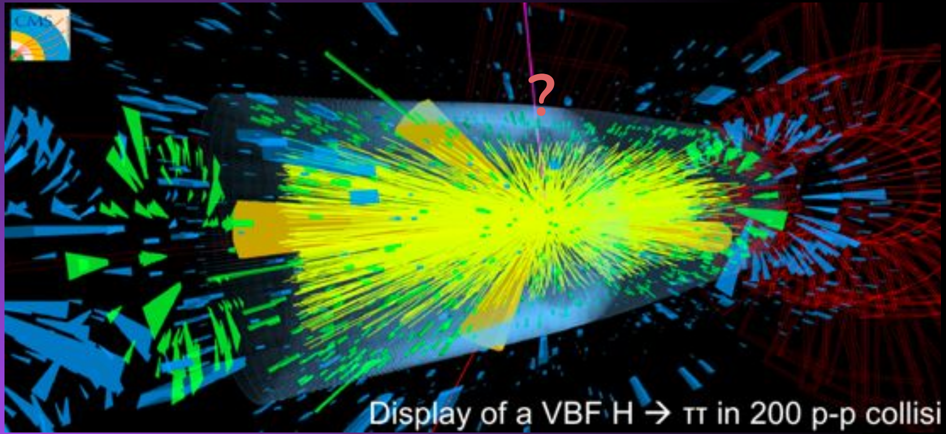
Maybe you will play a role?

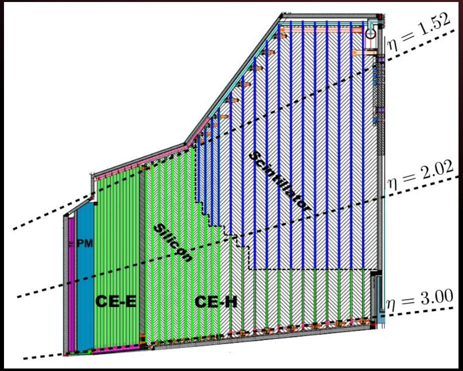
A technical challenge

- Increasing the rate of proton-proton collisions means a <u>much messier environment</u>!
- CMS detector will undergo a substantial upgrade for the High-Luminosity LHC
  - At Imperial we are involved with many aspects of this upgrade
- Improvements to the detector will help towards **<u>discovering new physics in the future!</u>**

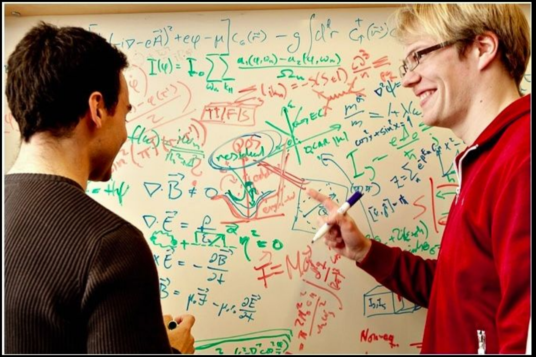


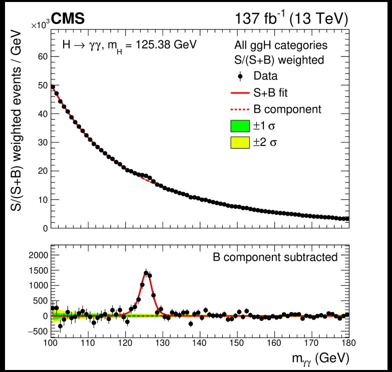


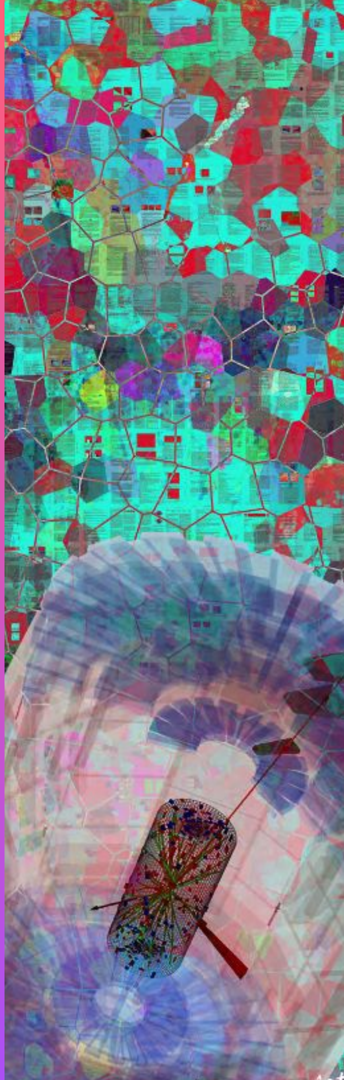




High energy physics is a team effort







Something for everyone!

Thank you

Any questions?