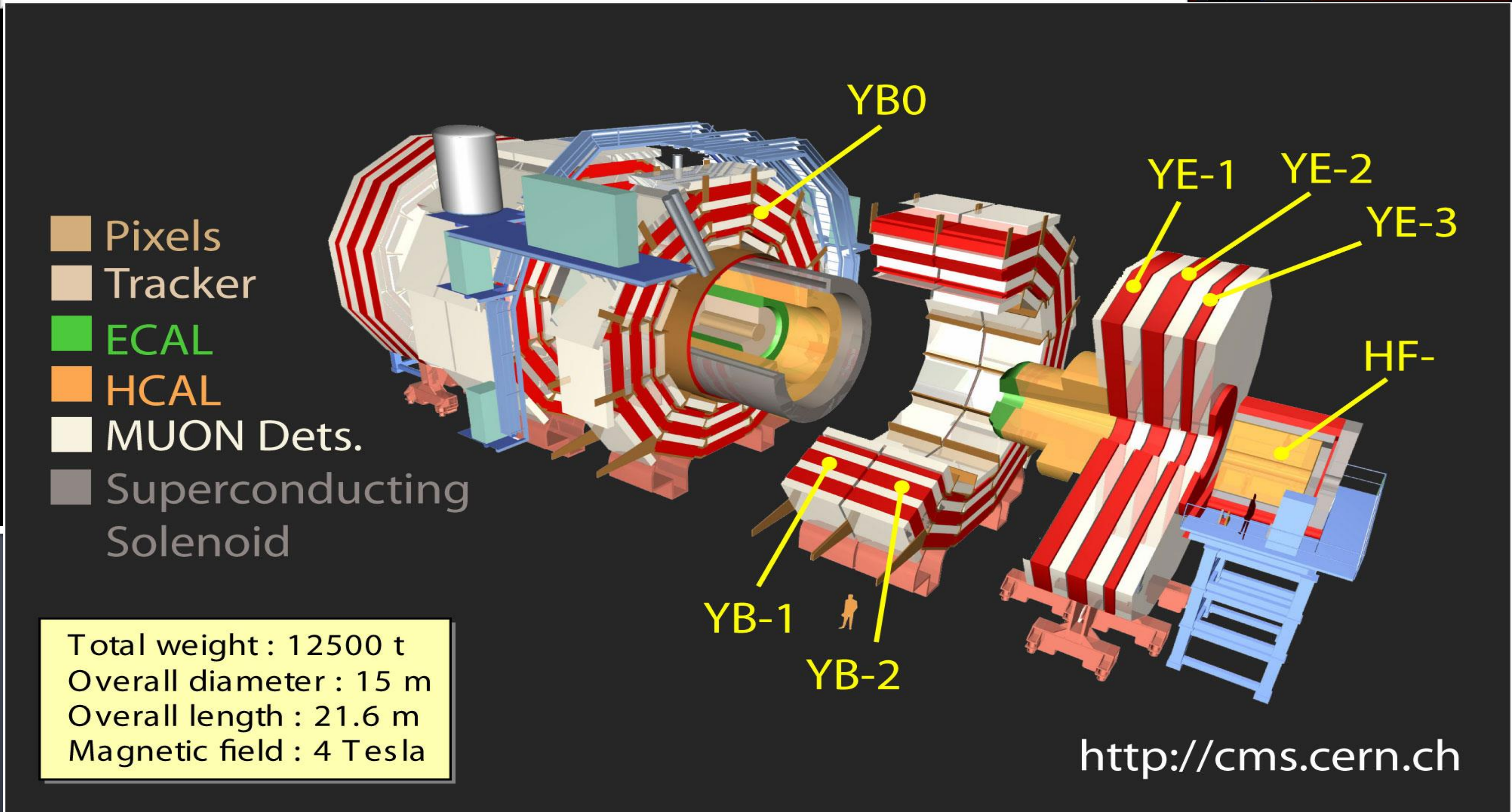
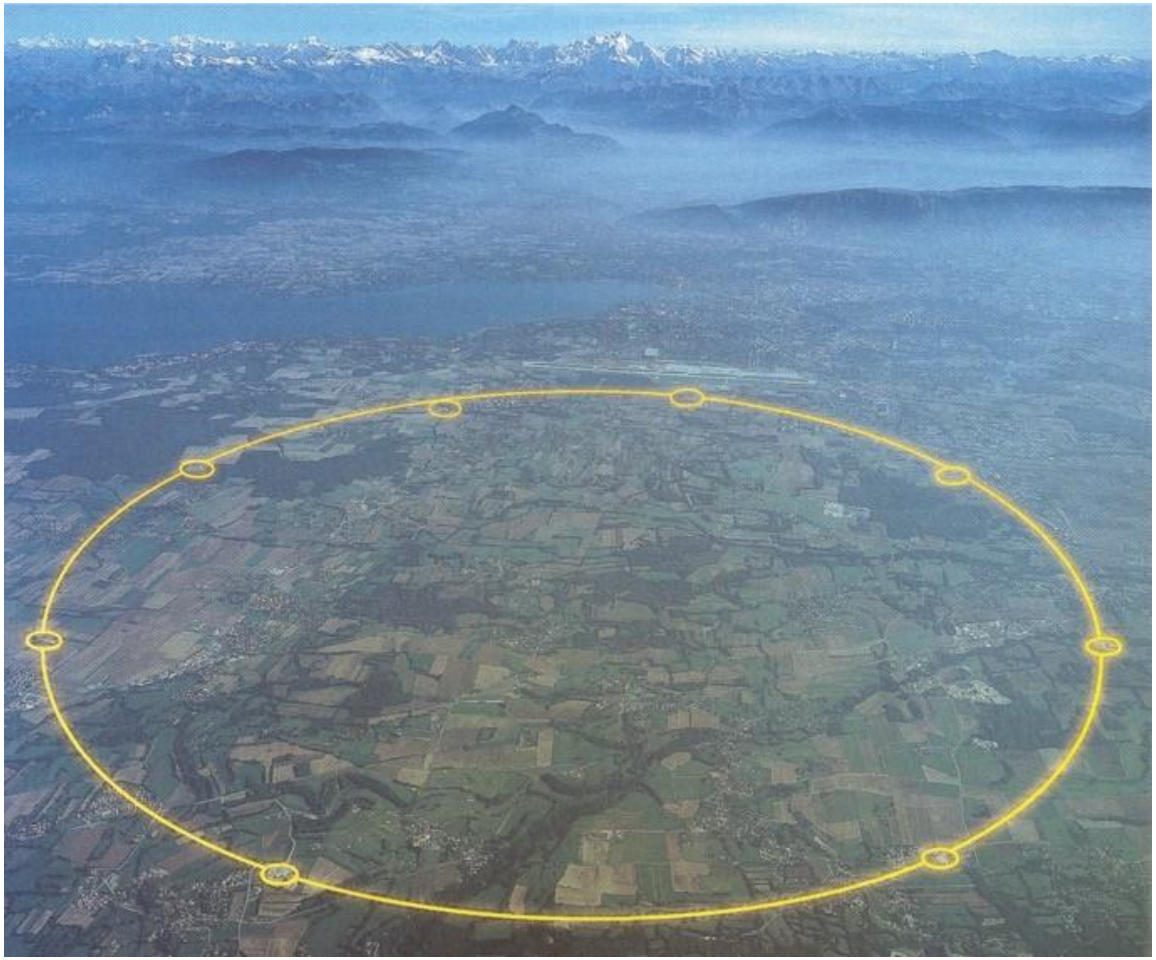
The Search for and Discovery of the Higgs Boson

Andrew Askew, July 24, 2014

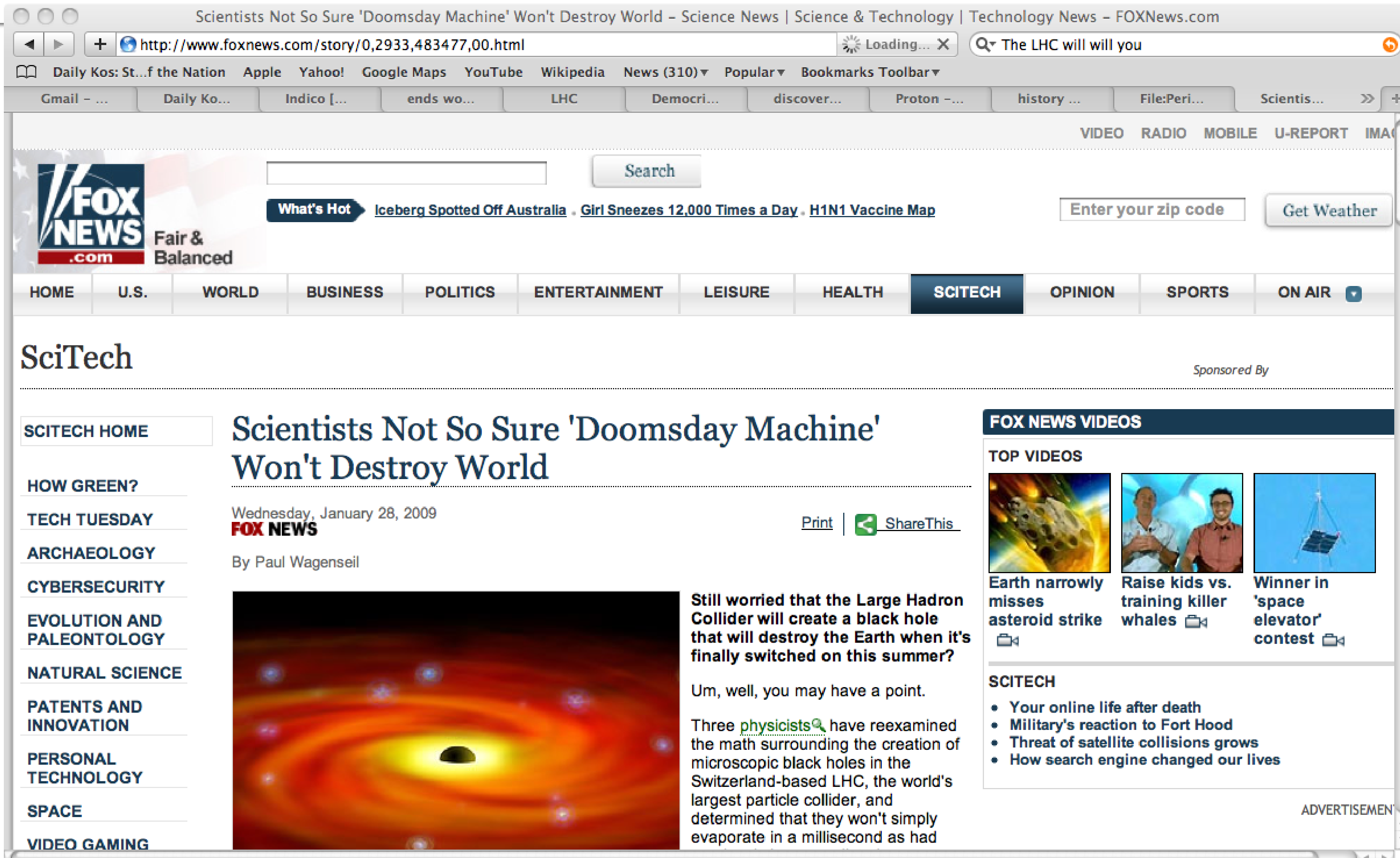


Well, there's THIS:

- The Large Hadron Collider (LHC) collides protons at the highest laboratory energy in the world.



Wasn't this the one…?



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Wednesday, January 28, 2009
FOX NEWS

By Paul Wagenseil

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Still worried that the Large Hadron Collider will create a black hole that will destroy the Earth when it's finally switched on this summer?

Um, well, you may have a point.

Three physicists have reexamined the math surrounding the creation of microscopic black holes in the Switzerland-based LHC, the world's largest particle collider, and determined that they won't simply evaporate in a millisecond as had

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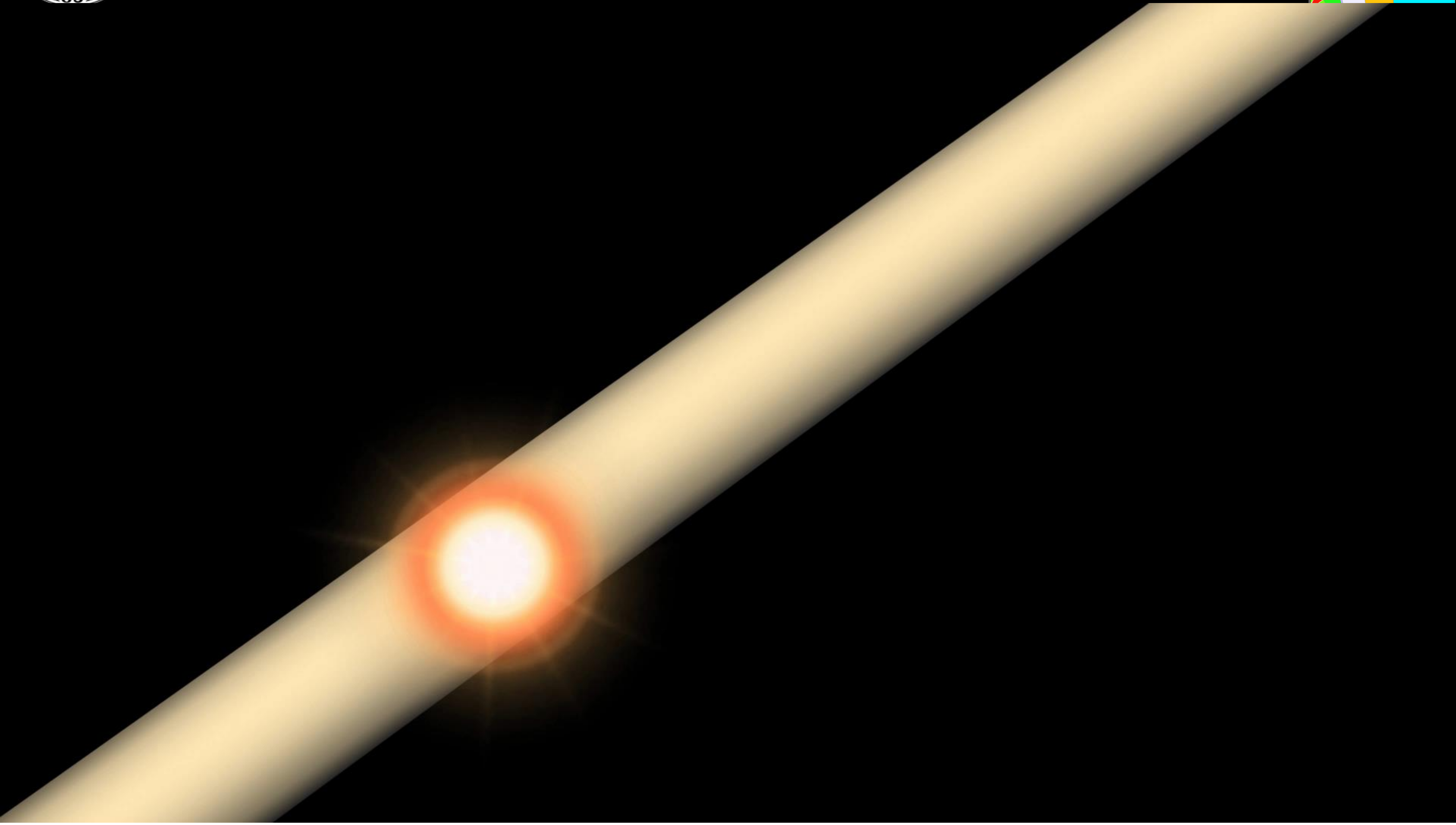
YES, it is THAT machine.

L-H-C

- Large: Don't think I really need to explain this one. The machine is 27 km (16.7 miles) around.
- Hadron: hadrons are particles, in this case protons. Neutrons are also hadrons.
- Collider: Well, since it's a hadron collider, one presumes it "collides" things

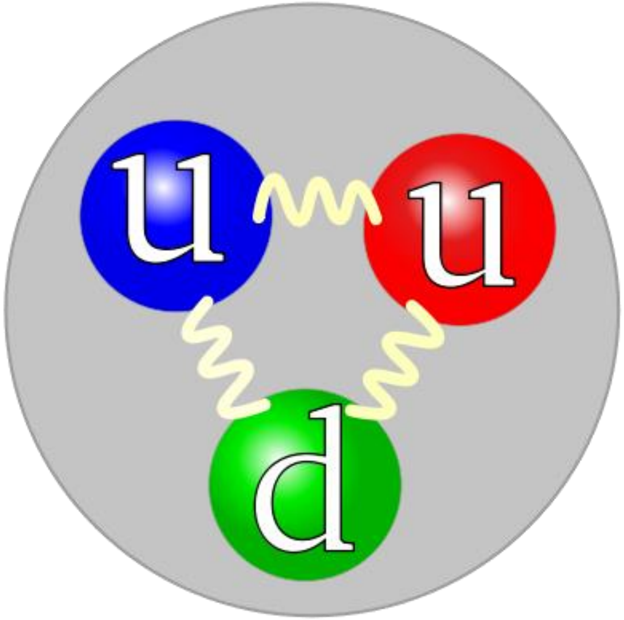


A Common Picture:

- A lot of the time, physics outreach centers will have a very simplified picture of colliders.
- Two billiard balls collide with each other.
- This isn't quite the right picture…

A closer picture:

- Protons aren't billiard balls though, they're made of quarks.
  - That's what's meant by "hadron"
- A closer description would be a balloon that has three billiard balls in it.
  - And fill the remaining space with jello.
- Now take this new picture and imagine a collision!

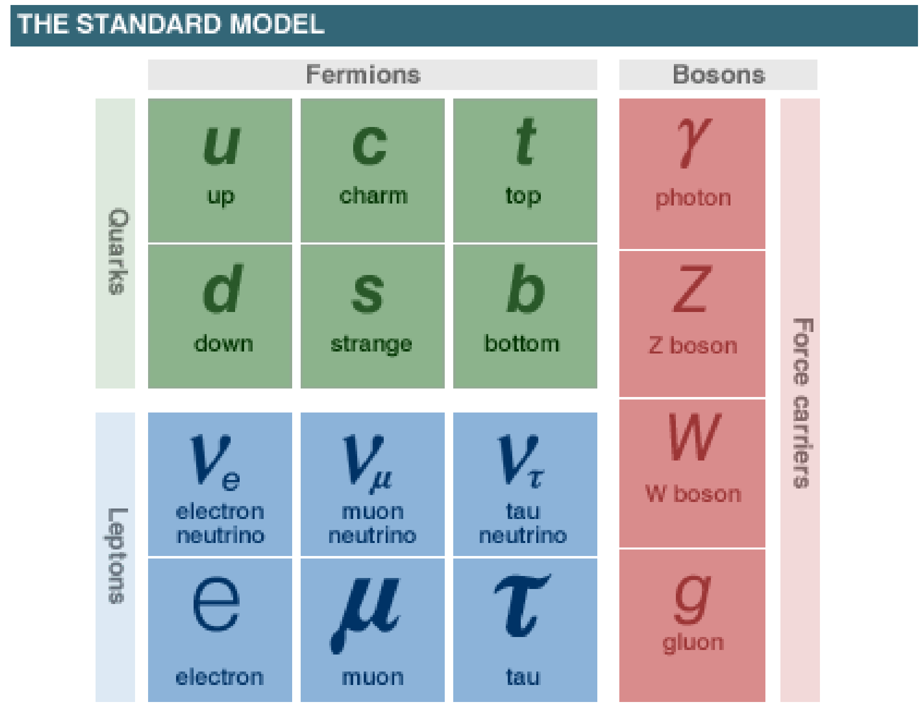


More over:

- So if I threw this balloon (with jello and billiard balls) at you, then the momentum is shared among the stuff inside.
- And if I smashed two of them together…well
  - You can try this at home…
- To be perfectly blunt: I'm loading up protons with a lot of energy. And when the "stuff" collides via $E=mc^2$, I can produce new massive particles, and that includes the Higgs.

Stuff we already know about:

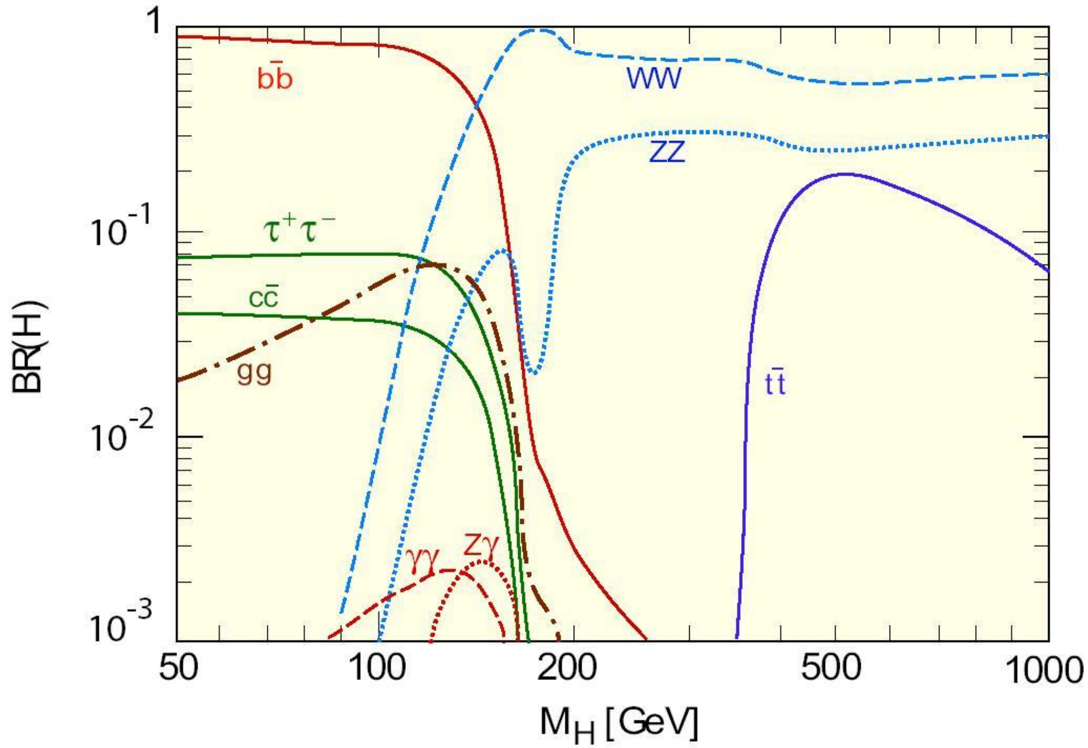
- These are the known quarks, leptons and bosons.
- Three different “generations” of particles, which have different masses.



Source: AAAS

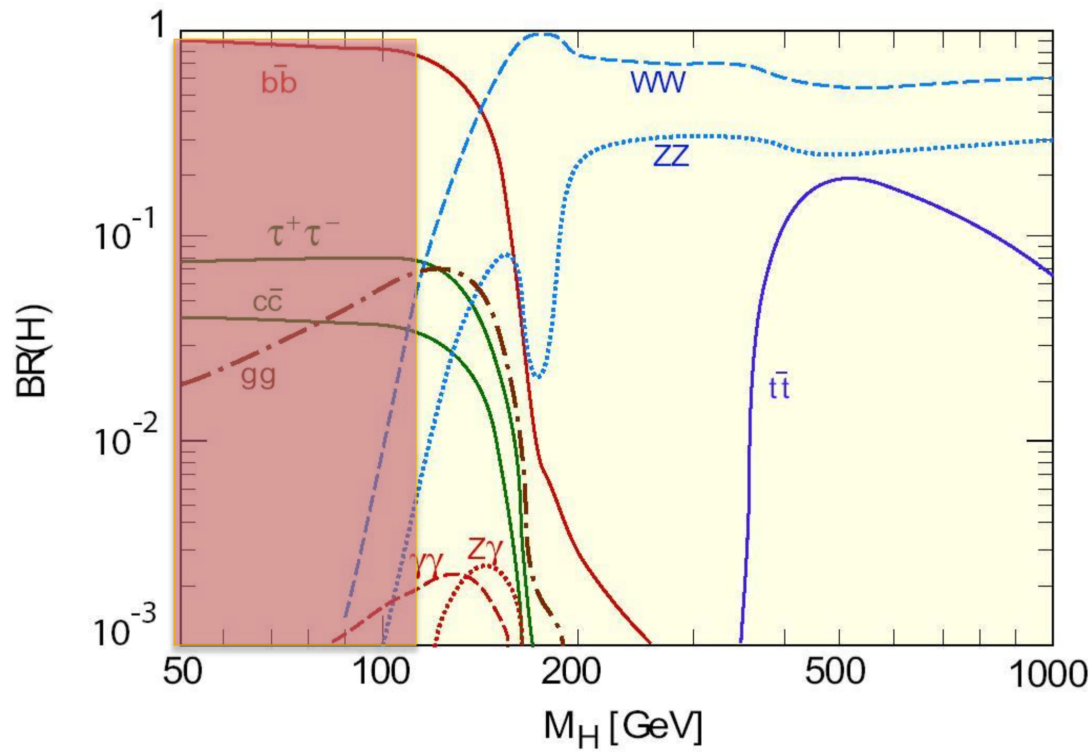
How do we find a Higgs?

- So I can use the LHC to make Higgs bosons.
- If the Higgs really does like massive things, that also controls how it decays.



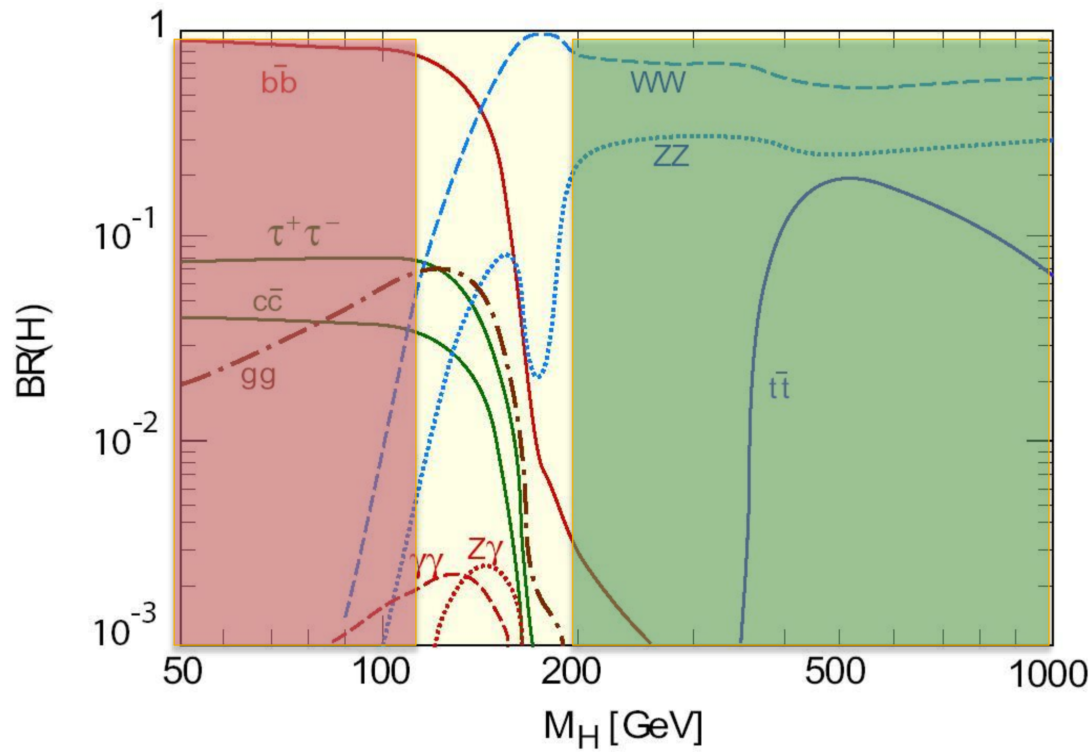
Where is the Higgs NOT?

- There have been other experiments (at LEP, the previous occupant of the tunnel where the LHC lives), which pretty much block out this region.



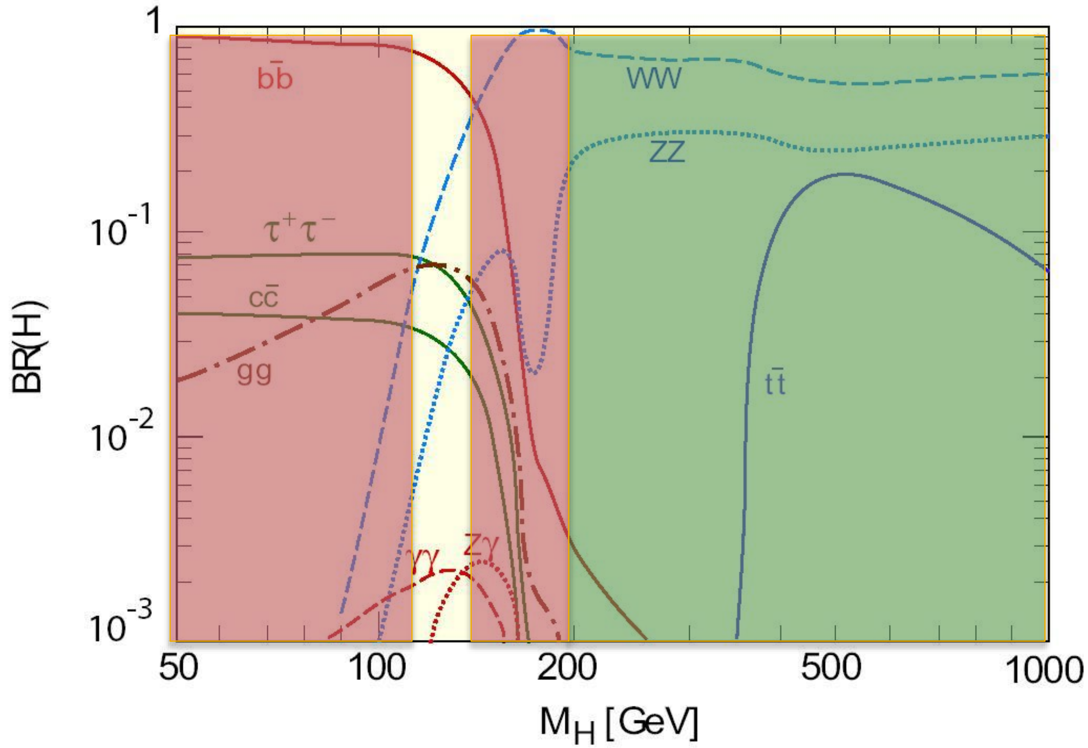
Where is the Higgs NOT (2)?

- The relationship of the Higgs to other particles, tends to exclude this area.



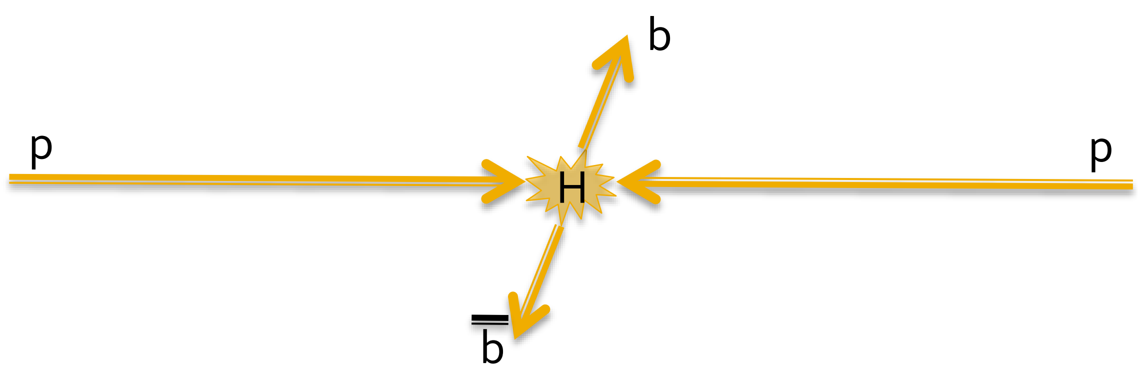
Where is the Higgs NOT (3)?

- More of this space got excluded before, because we didn't "find" anything.
- More on how we find stuff in a second.



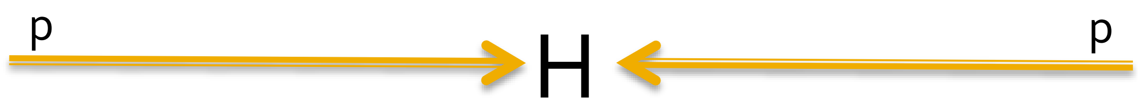
So how do I find a Higgs?

- So since we now know around where it should be, how do we find it?
  - Well, the top line on the previous slide was the Higgs decaying to two b-quarks. So I should just look for two b-quarks, calculate their invariant mass, and look for a bump.
  - ...right?



Aside: Invariant Mass

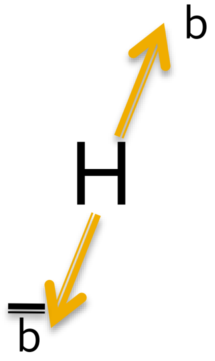
- If I produce some heavy particle, then a lot of the energy of the collision goes into creating that mass:



Aside: Invariant Mass

- If I produce some heavy particle, then a lot of the energy of the collision goes into creating that mass:

Most particles (including the Higgs) decay very, VERY rapidly.



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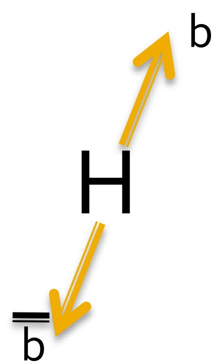
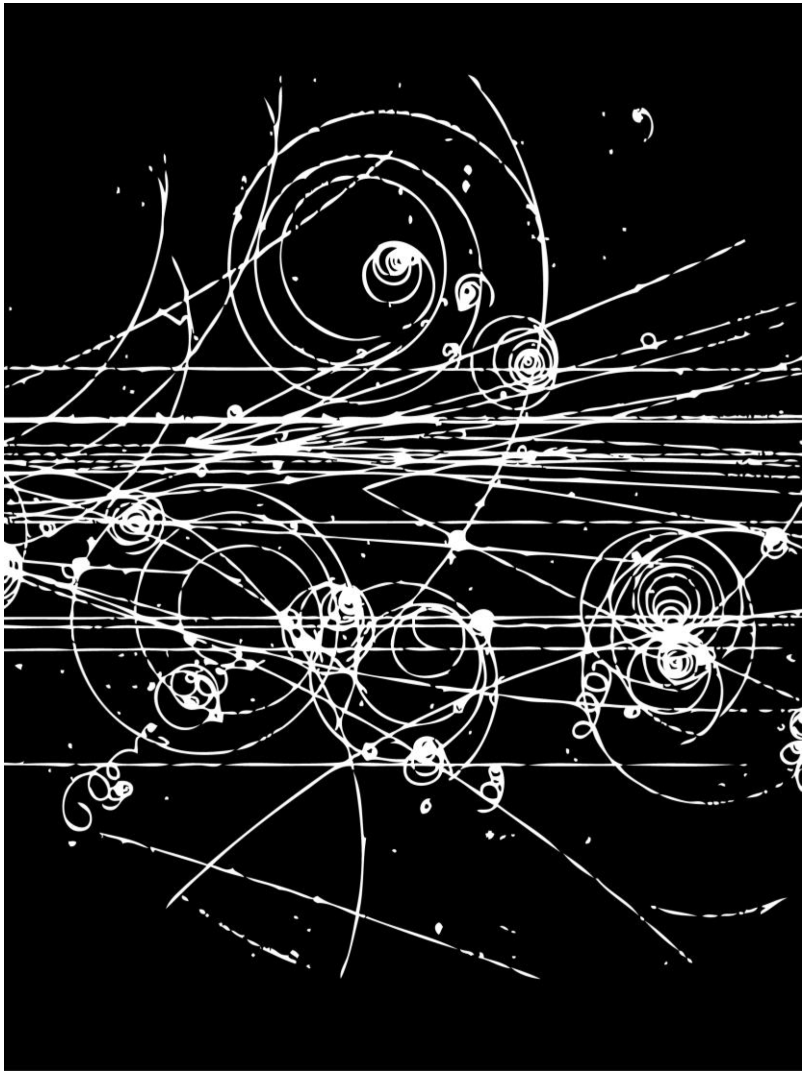


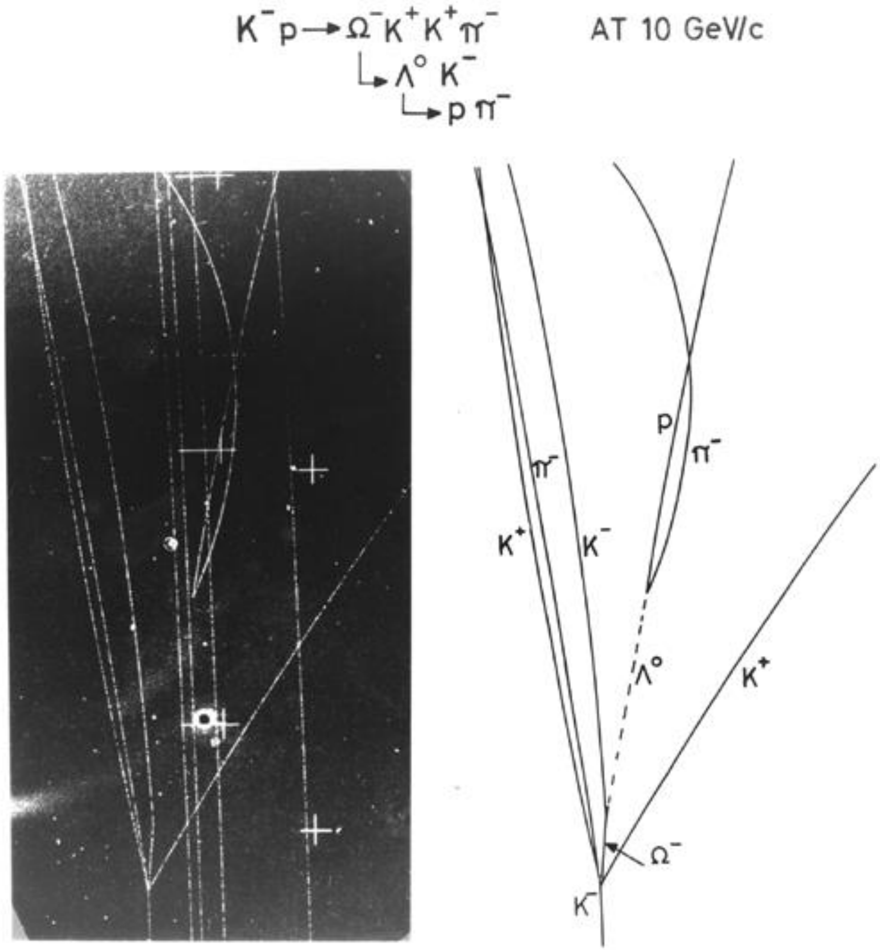
I still have to conserve mass/Energy though, which means that the mass of the Higgs then goes into the mass and momentum of the b-quarks. So if I measure those, I can calculate the Higgs mass.

Detector Then:

- What is it I mean by this?
- Back in the day, when bubble chambers were used:
  - Just before beam would come, the chamber would expand (oversaturating the air inside), and the charged particles would leave trails.
  - You'd take an actual picture of the chamber and it would look something like this

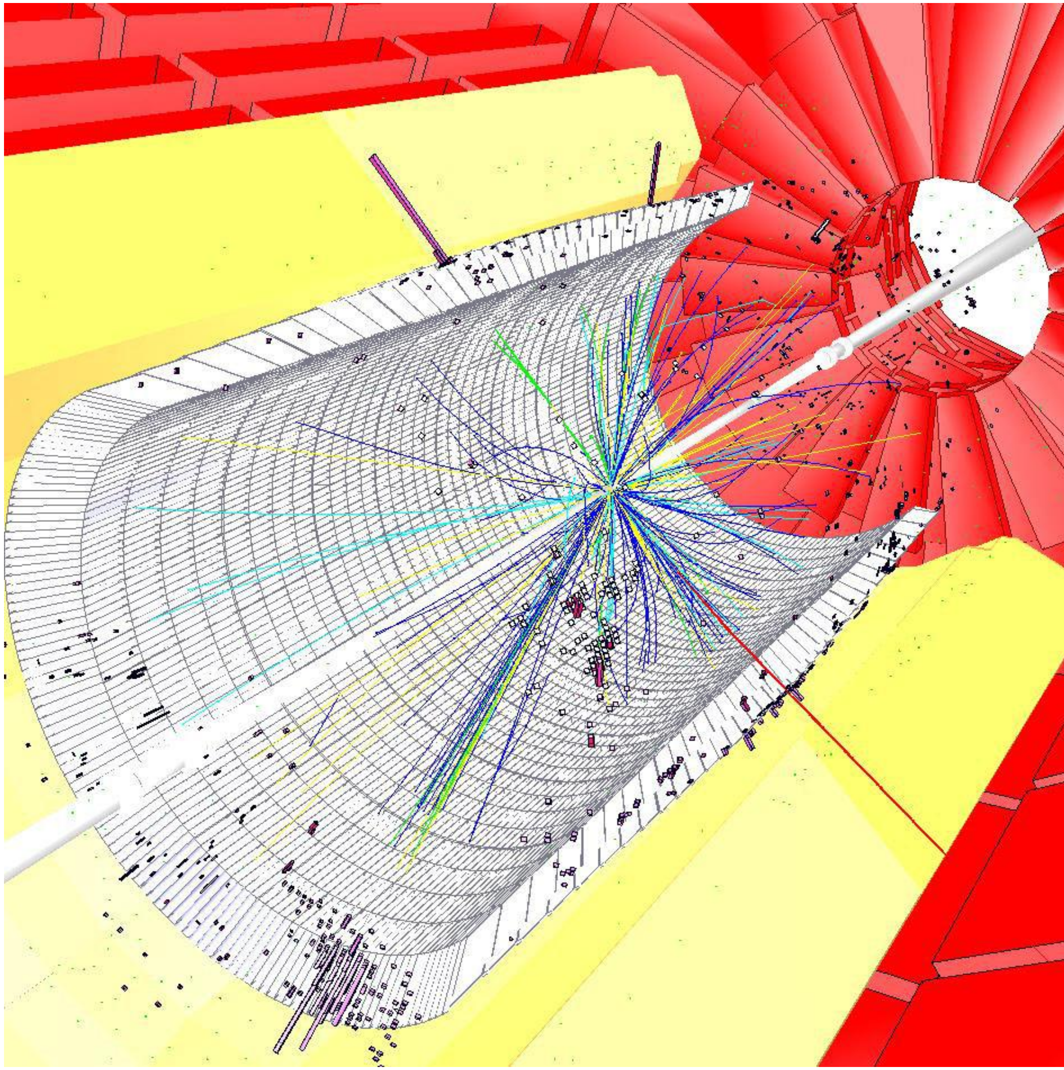


- The actual picture of the bubble chamber is on the left, the lines of all the particles with their labels is on the right.
- Philosophically, this is still what we do today…

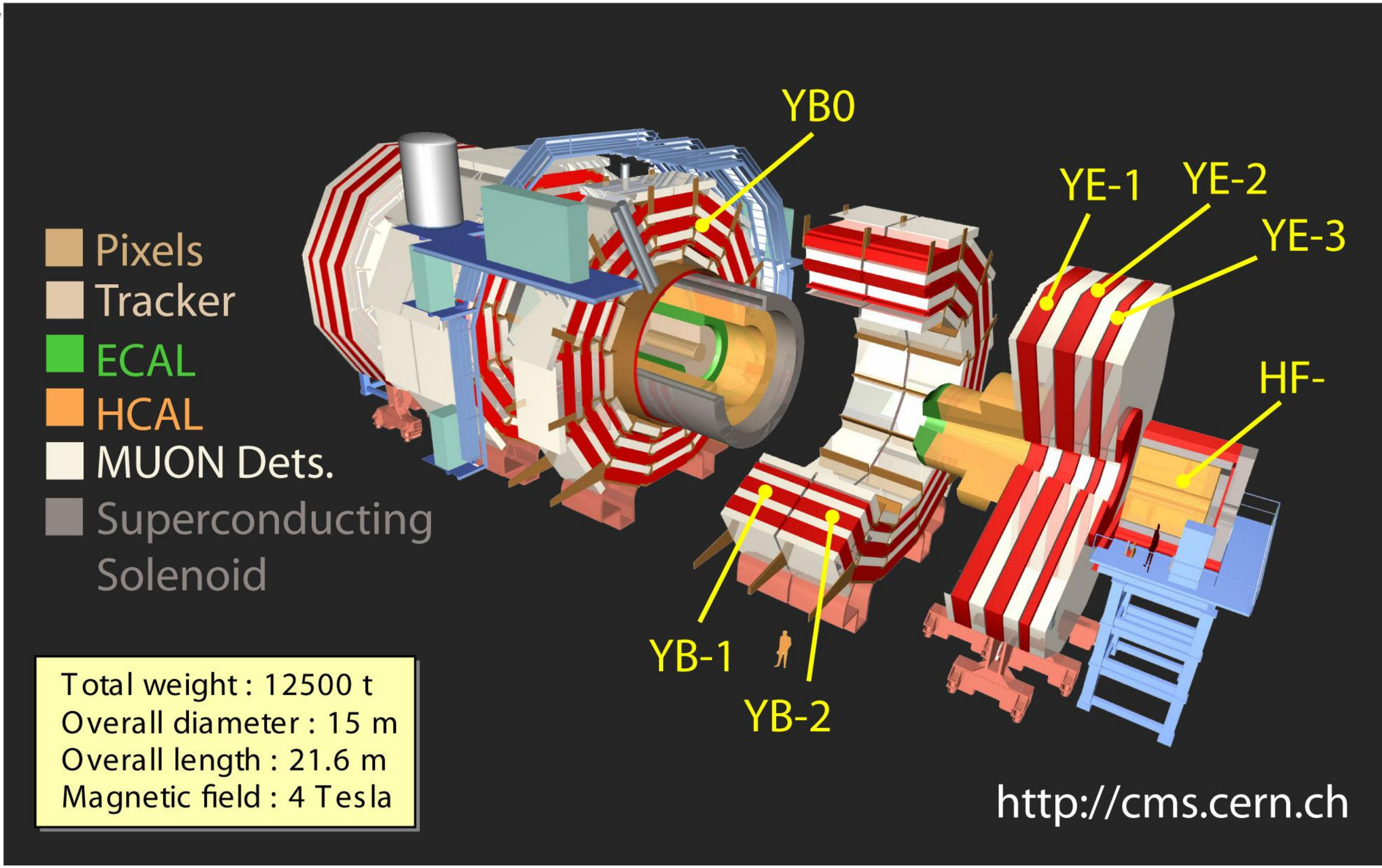


We now “see” through our detectors:

- Only in a slightly more high-tech vein.
- Just like in the bubble chamber, the particles leave traces in the detector.

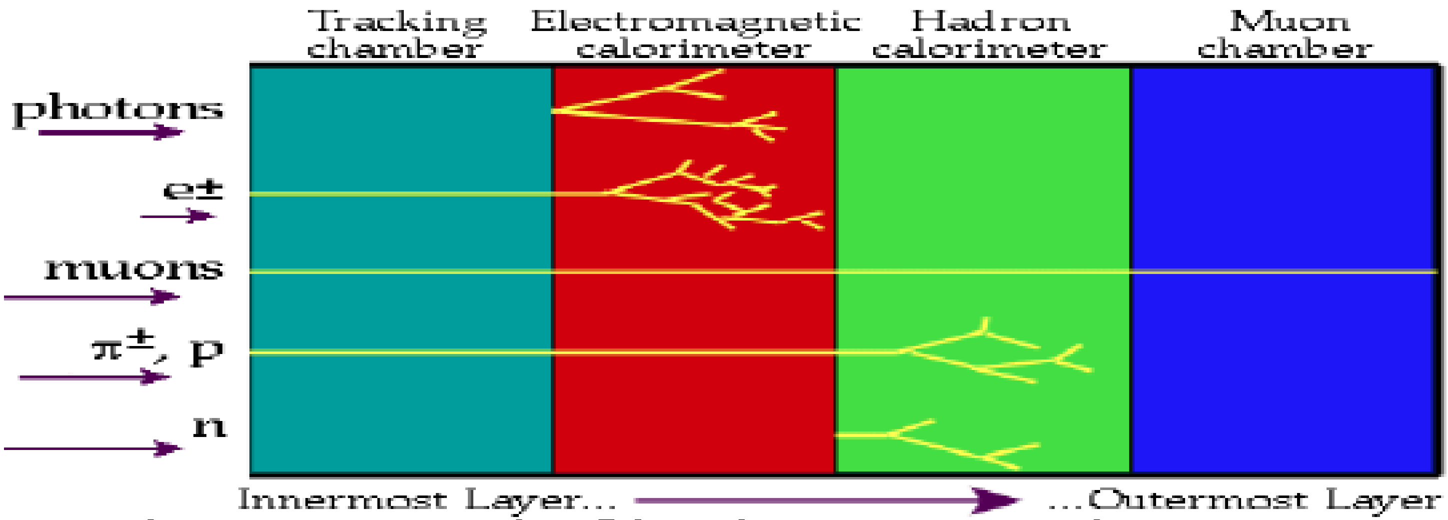


The CMS Experiment



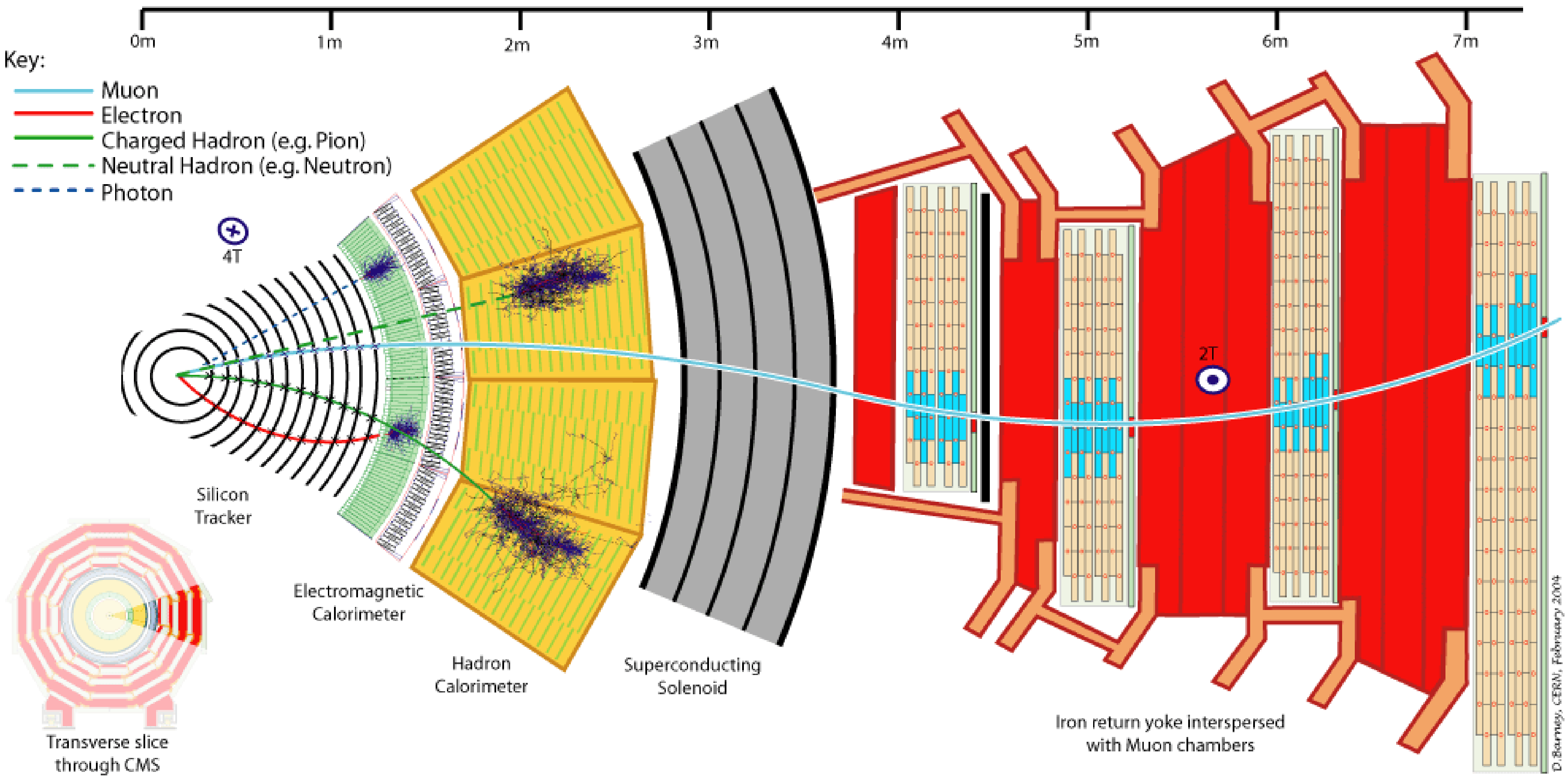
Who does the labeling?

- This is generically how particles interact with the detector



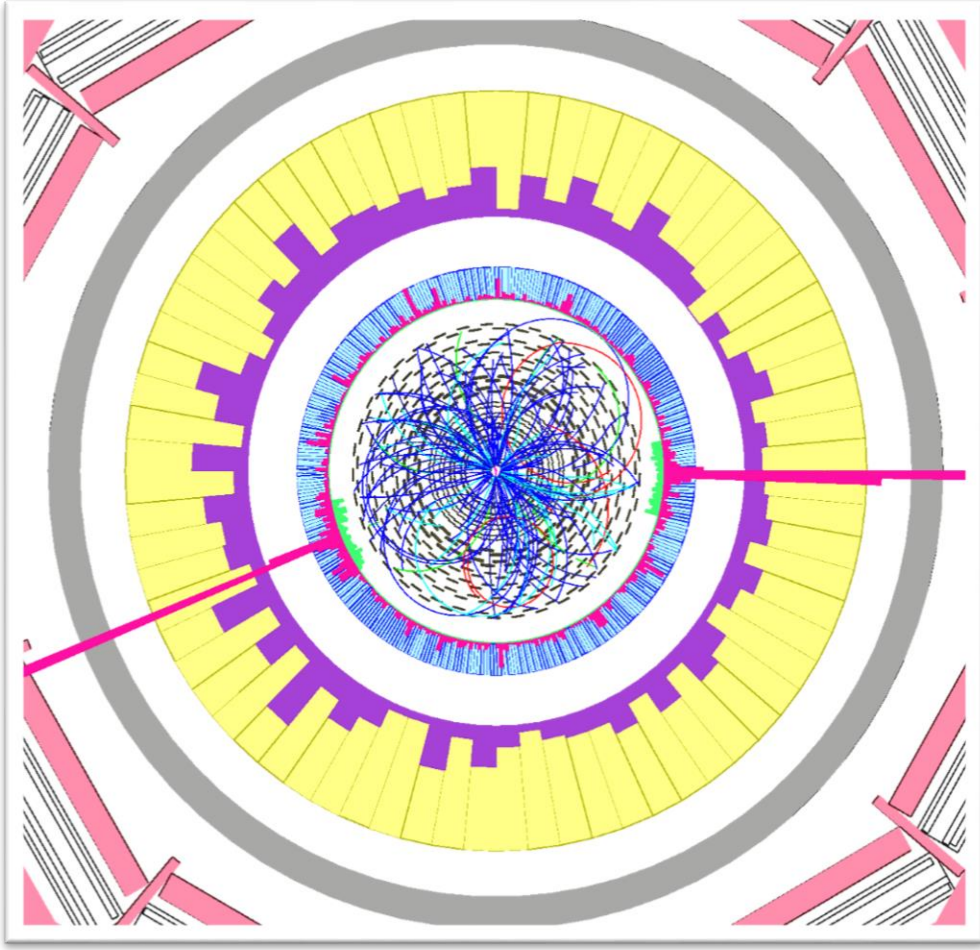
These days instead of looking at each picture individually, we teach the computers how to recognize the different particles and how they appear within our device. Then we try to figure out what's interesting.

Another view:

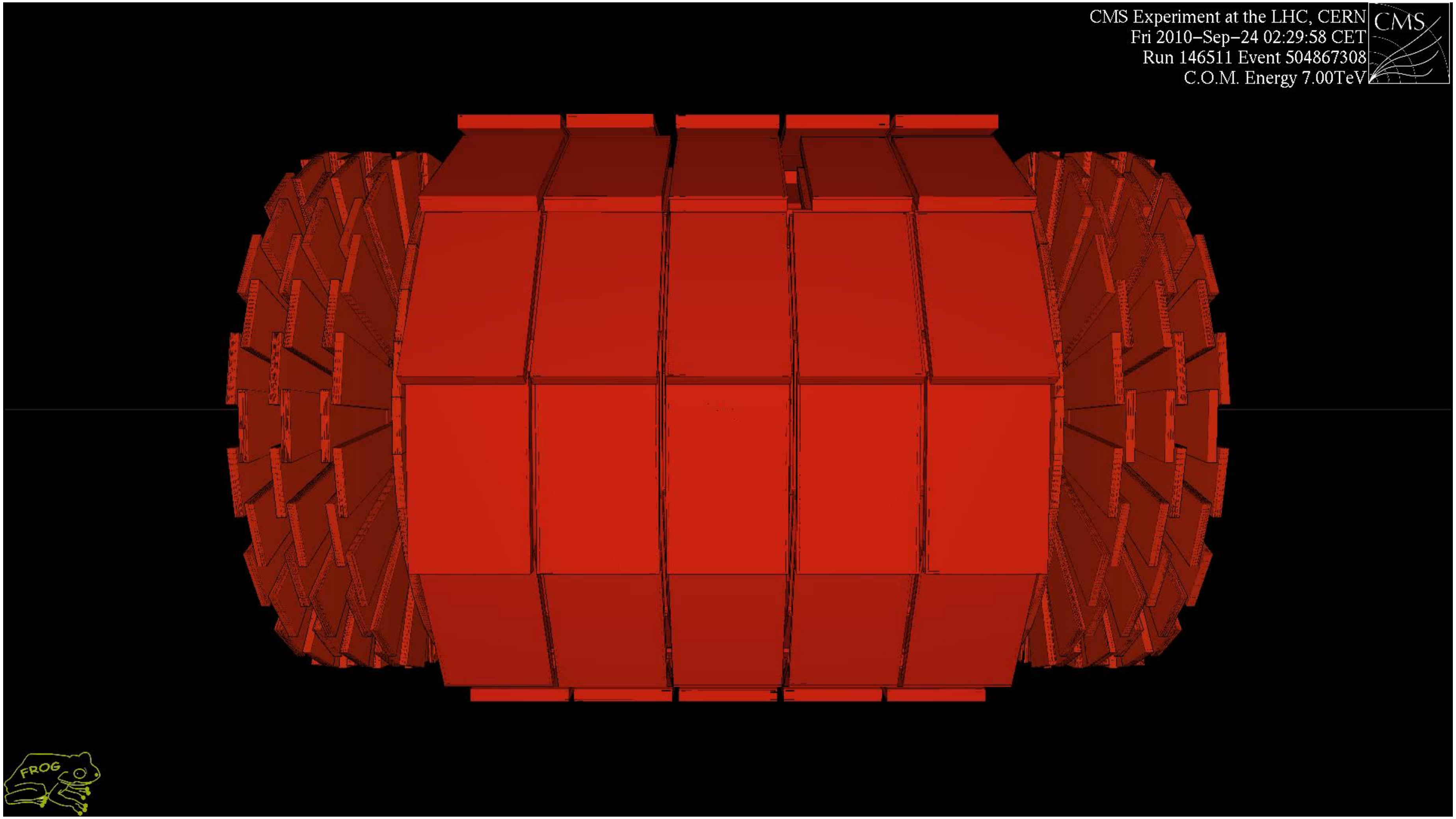


Detectors Now:

- You can STILL think of the detector as a camera:
  - A five story
  - 80 megapixel camera
  - Taking pictures at 40 million times a second.
- But still, a camera nonetheless.
- Today a lot of the staring is done by computers.
  - The humans then, tend to end up staring at the computers.



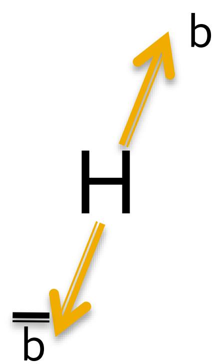
A Quick Animation:



Back to finding the Higgs!

- If I produce some heavy particle, then a lot of the energy of the collision goes into creating that mass:

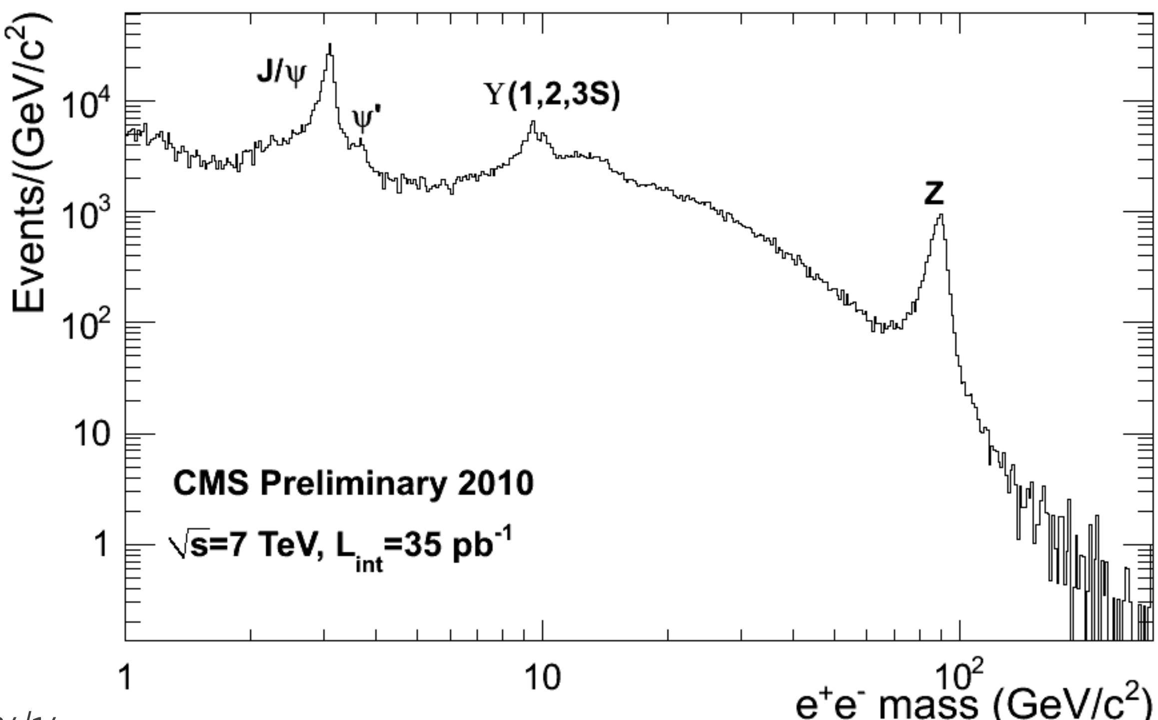
Most particles (including the Higgs) decay very, VERY rapidly.



I still have to conserve mass/Energy though, which means that the mass of the Higgs then goes into the mass and momentum of the b-quarks. So if I measure those, I can calculate the Higgs mass.

A brief tangent:

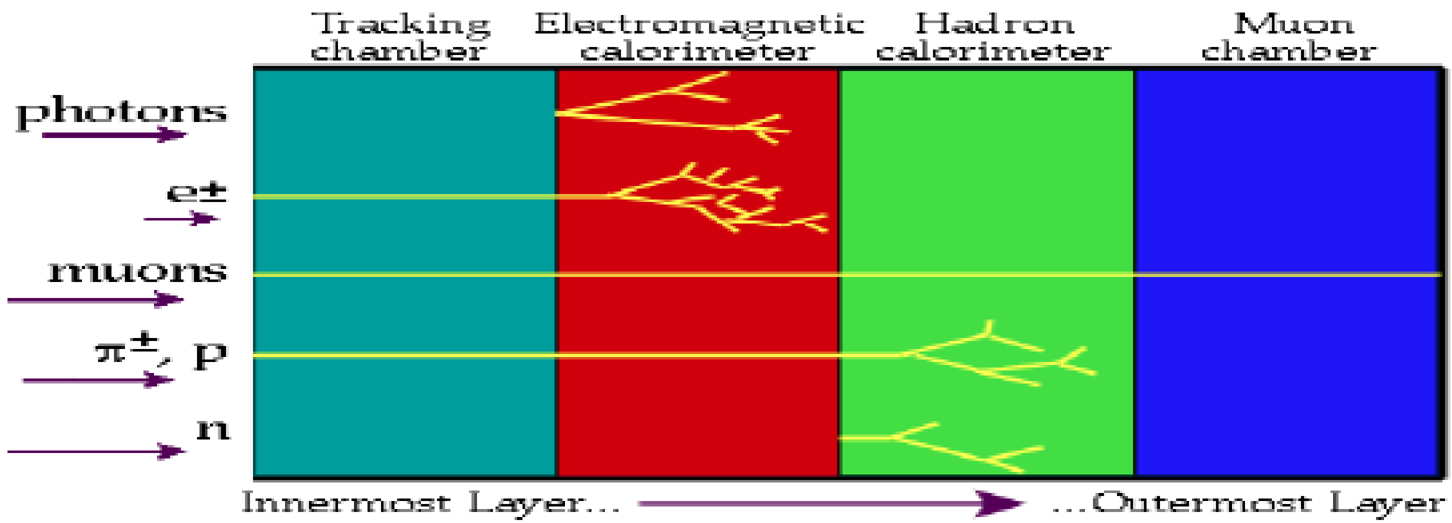
- "Bump Hunting" has a long and dignified history. There's even a simple example from CMS:
  - Just calculate the invariant mass of all events with electron pairs, and see what you get.



These are all well-known Standard model particles which decay to electrons. Pretty simple, and every time there is a particle, you see a "bump".

We're also really good at measuring electrons, more on that later.

Who does the labeling?



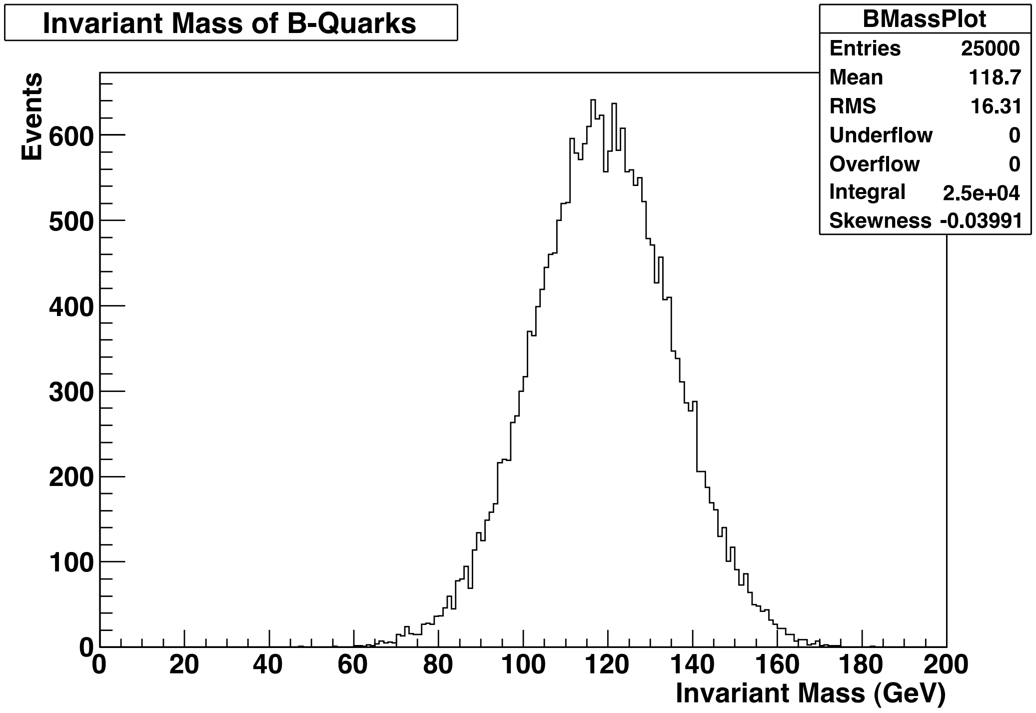
What I omitted is that measuring hadrons (protons, neutrons, pions) is difficult and imprecise.

B-quarks "fragment" into many of these hadrons.

We're really pretty bad at measuring these.

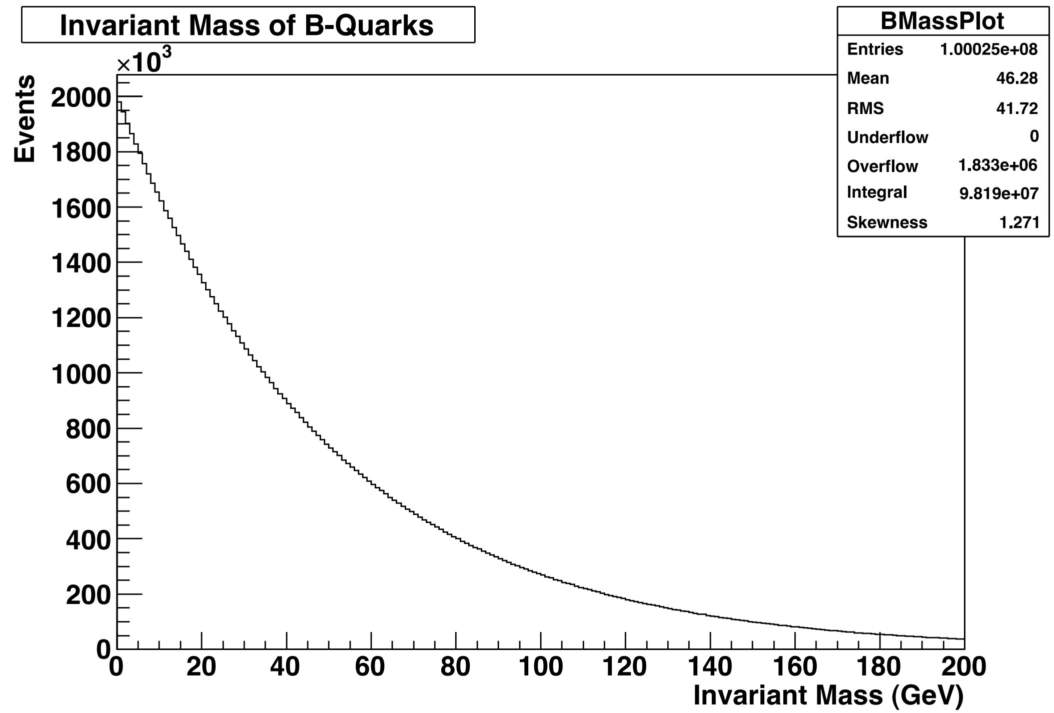
So if all you were doing is producing Higgs…

- The mass would look something like the plot on the right.
- Really pretty ugly compared to what I showed for electrons.
- But how is this a problem?



Problem the Second:

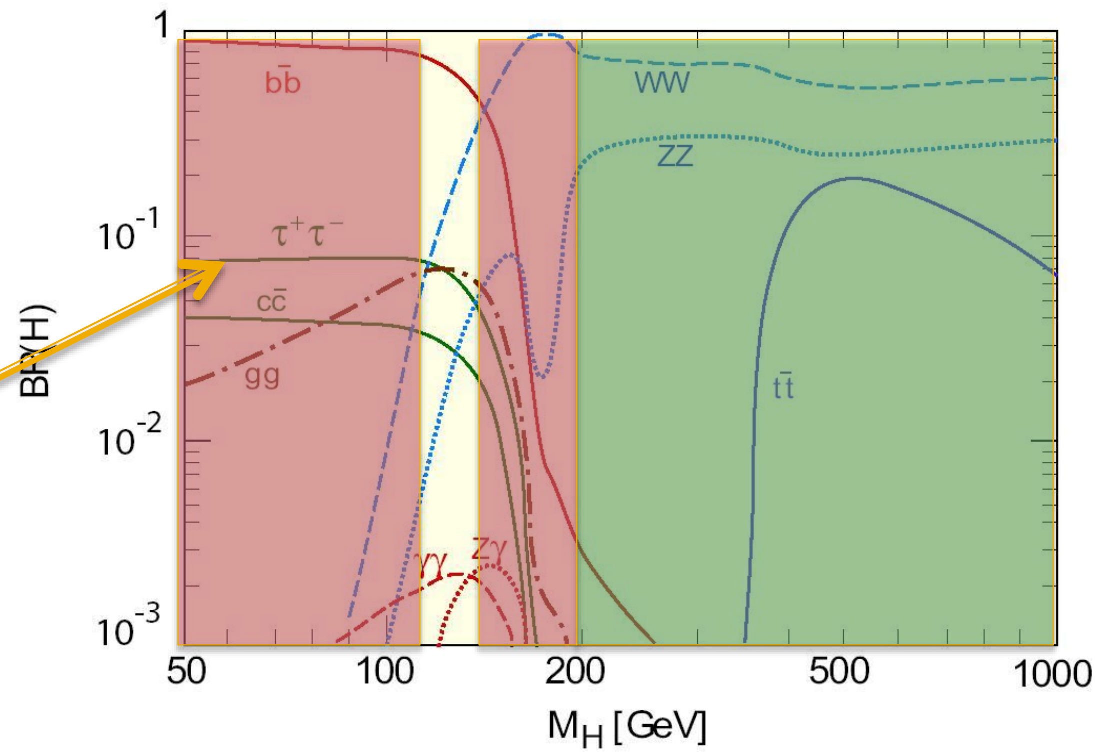
- There are a LOT of b-quarks produced in collisions. Most of which have nothing to do with the Higgs.
  - In fact, these are a factor of roughly a million more common.



The bump from the previous slide is still here, I promise. You just can't see it for the ENORMOUS background.

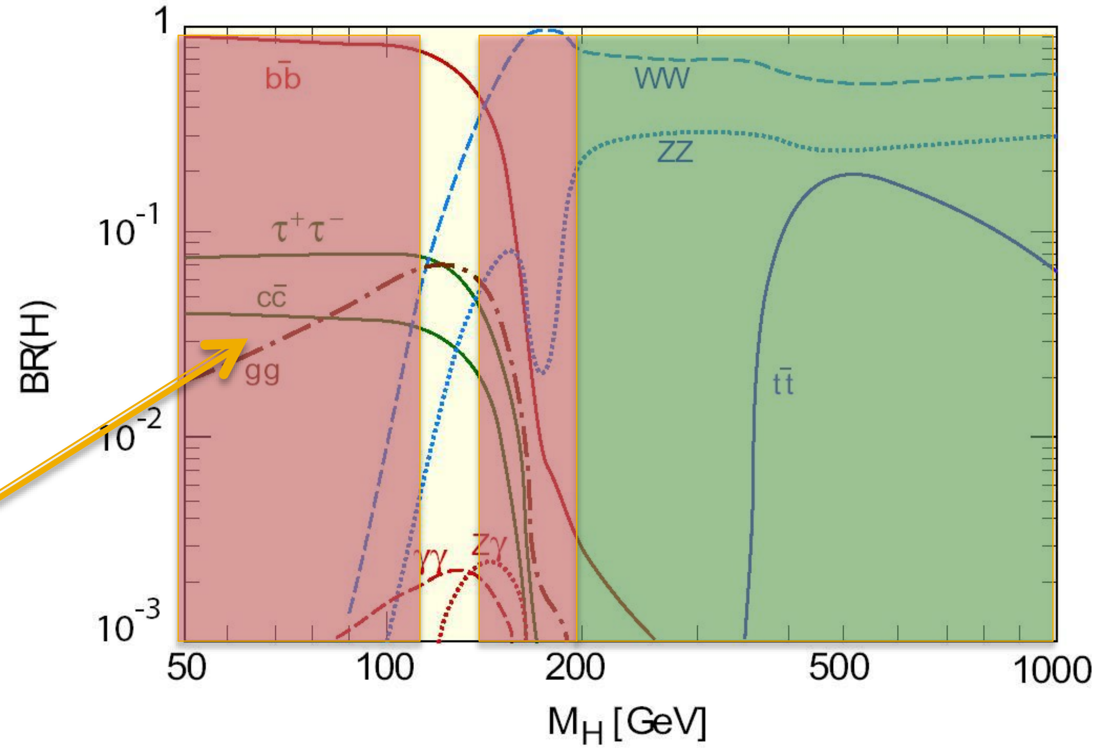
Okay, so that sucks.

- So I can't look in b-quarks. Crap.
- What is there left?
  - $\tau\tau$ suffers a pretty similar fate.



Okay, so that sucks.

- So I can't look in b-quarks. Crap.
- What is there left?
  - ττ suffers a pretty similar fate.
  - cc is even worse than bb.



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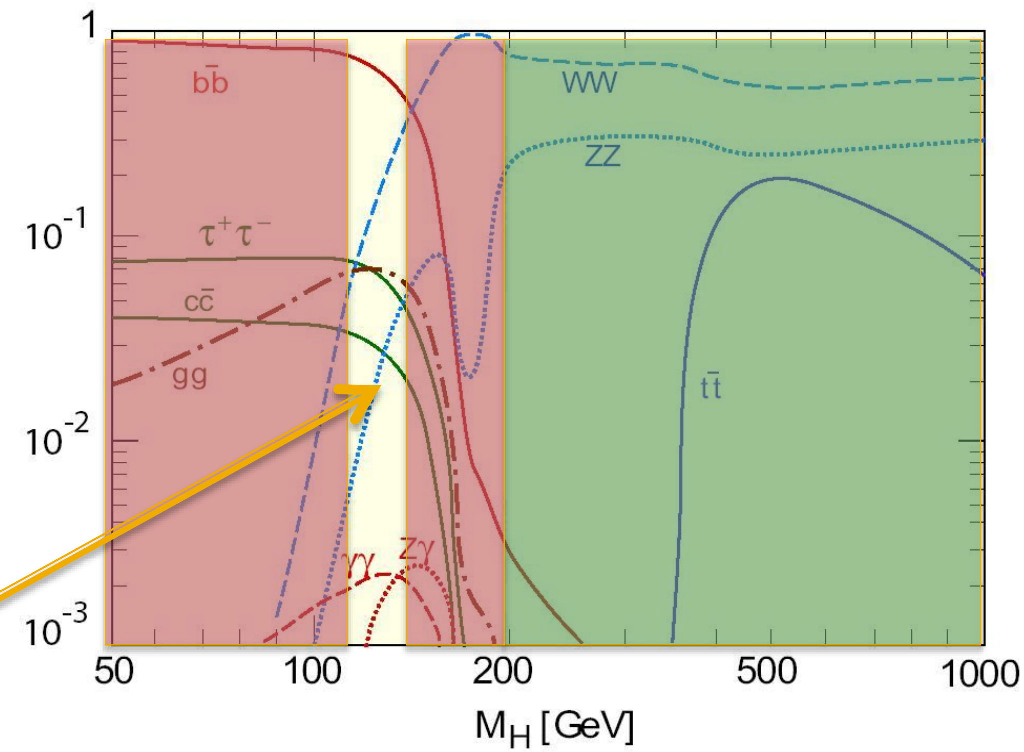
  - ZZ we use, but the rate is really small.



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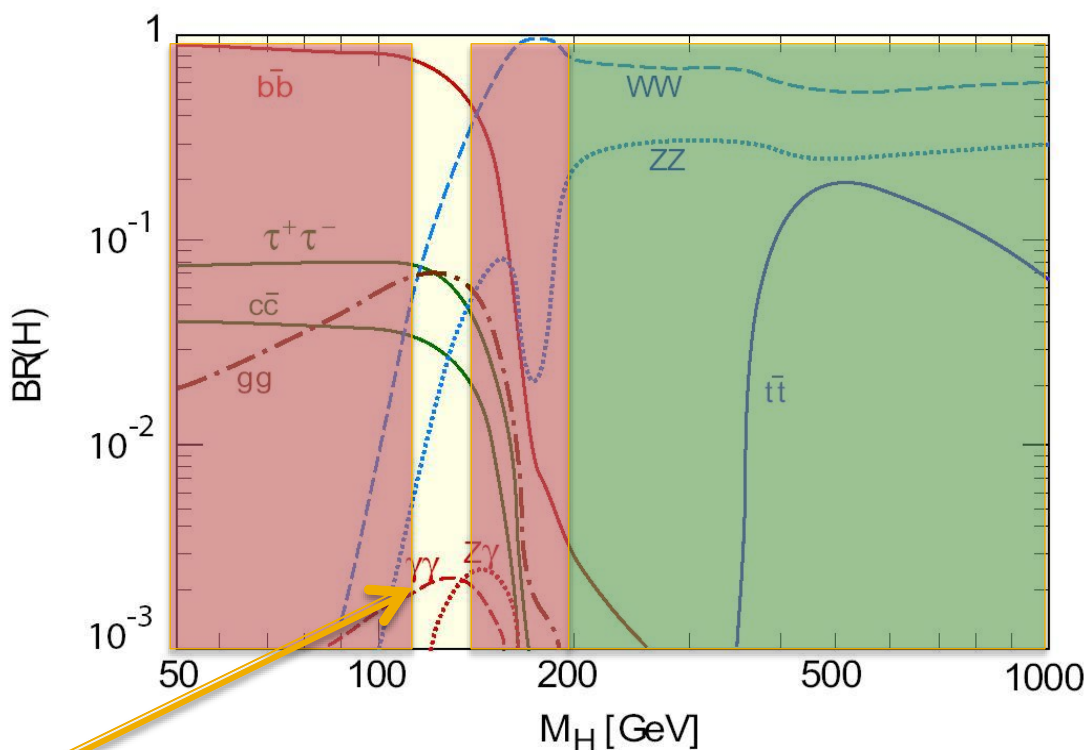
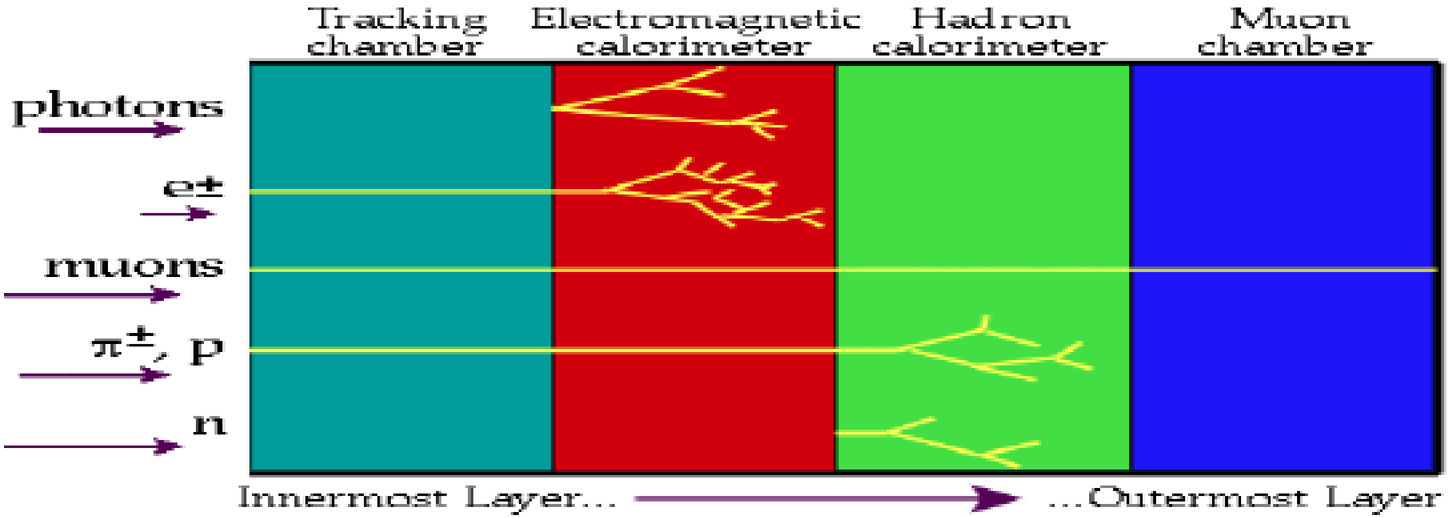
- So I can't look in b-quarks. Crap.
- What is there left?
  - ττ suffers a pretty similar fate.
  - cc is even worse than bb.
  - ZZ we use, but the rate is really small.
  - What about this guy down here?



H→γγ even as small a rate as it is, is still a VERY key decay.

Is that even possible?

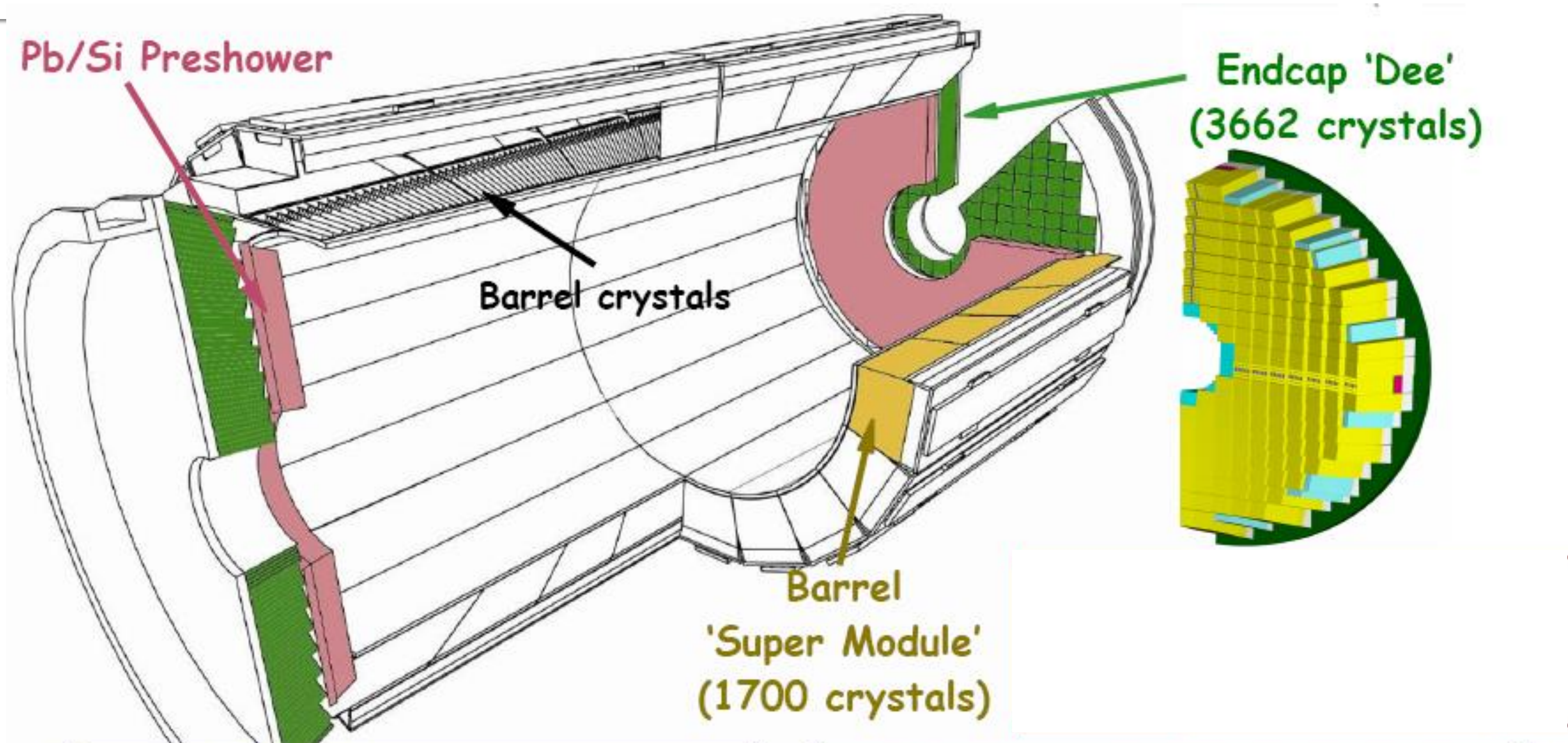
- Well, photons are a lot less plentiful at the LHC than b-quarks.



Looking back at this diagram, in principle I can measure photons even better than electrons.

If I have the right detector that is…

CMS Ecal:

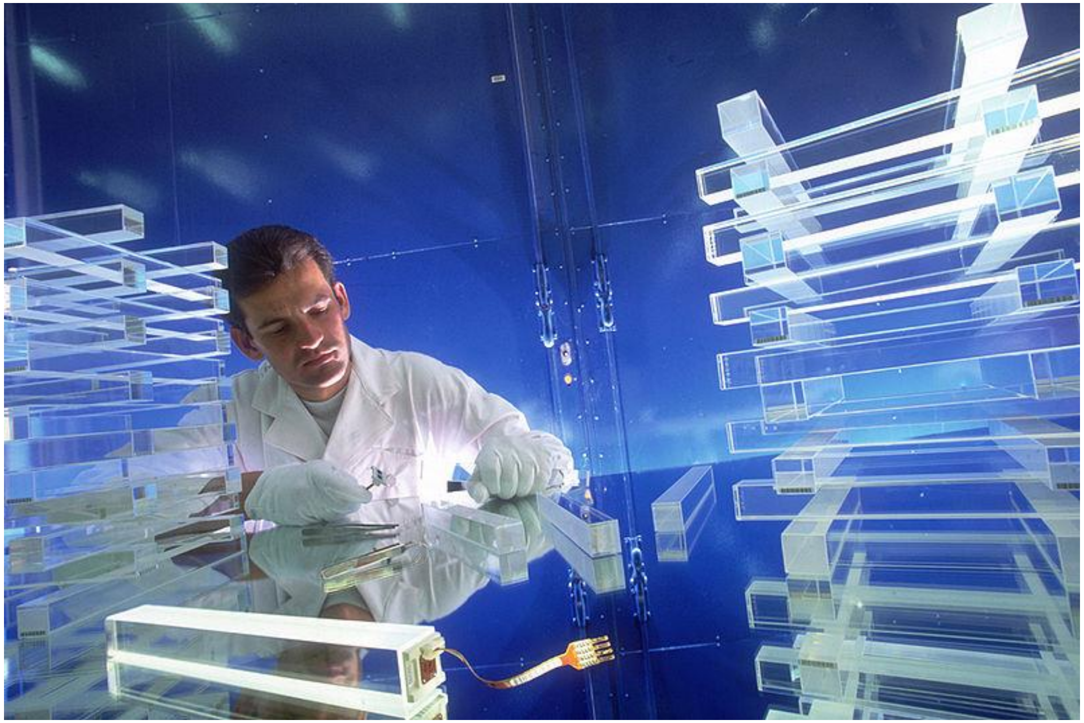


Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2 x 2 x 23 cm^3)

Endcaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3 x 3 x 22 cm^3)

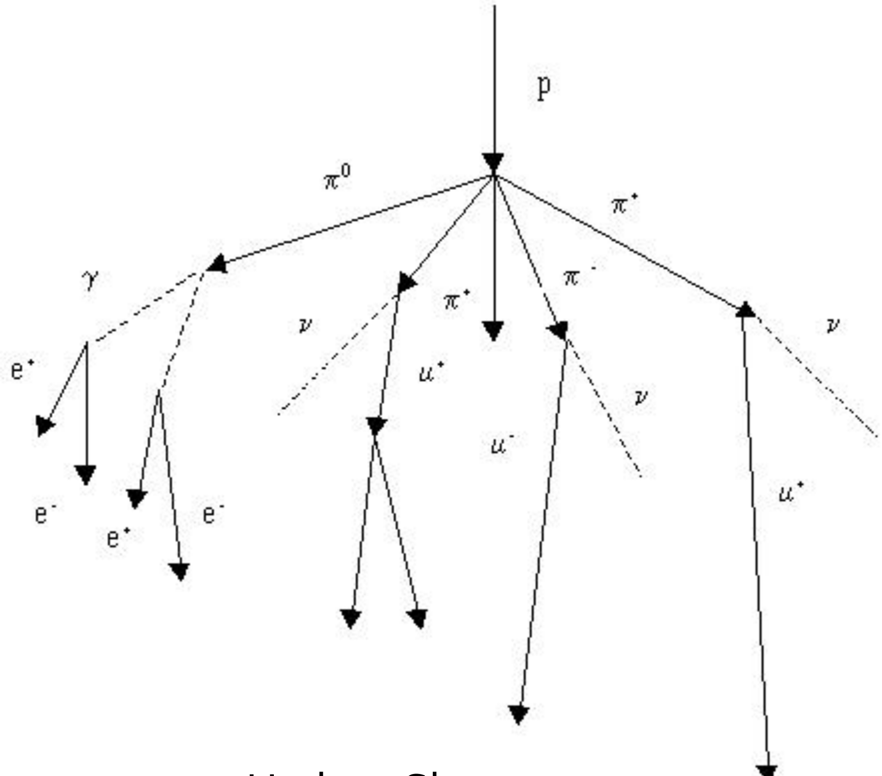
Total Absorption Calorimeter:

- The CMS electromagnetic calorimeter is composed of Lead Tungstate Crystals.
- Totally contain the shower and measure the energy.

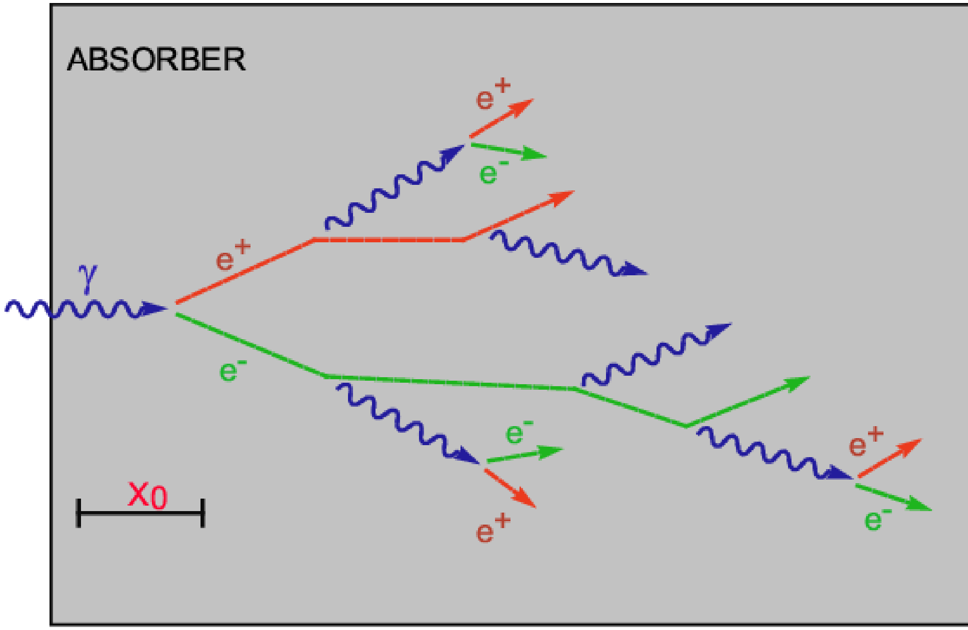


- most modern calorimeters are "sampling calorimeters" - separate layers of high density material ("absorber") to force shower development, and "sensitive" layer to detect charged particles in the shower.

How Well?



Hadron Shower

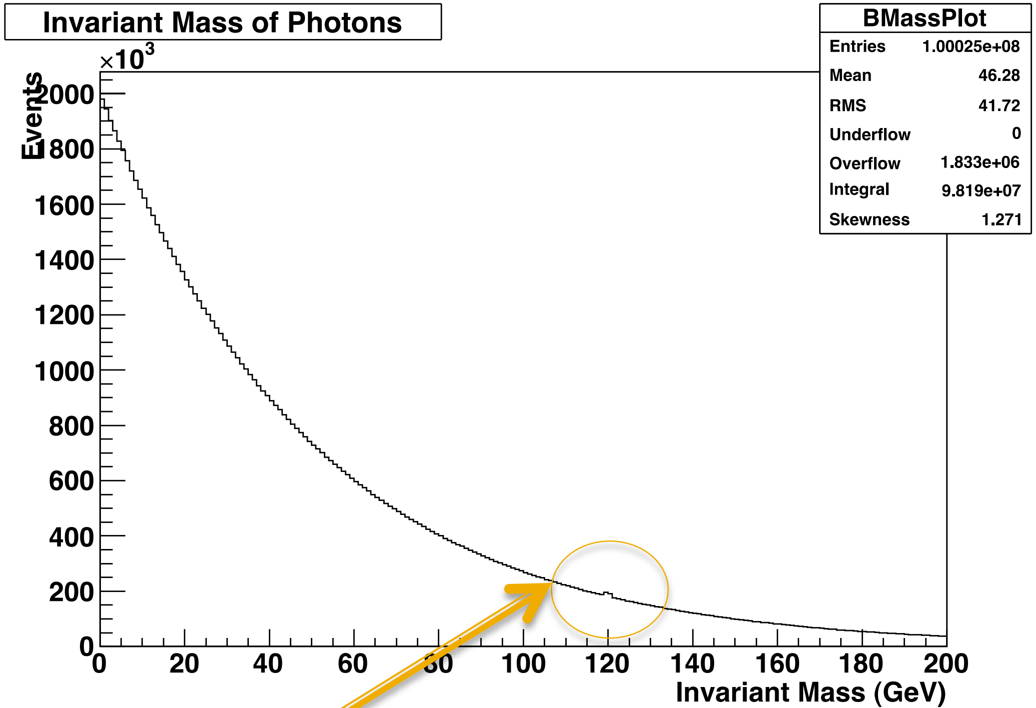


Photon Shower

- Here's the difference between hadronic and electromagnetic showers.
- EM showers are so regular, they can be cleanly identified, and measured to VERY high precision…

Like THIS High Precision:

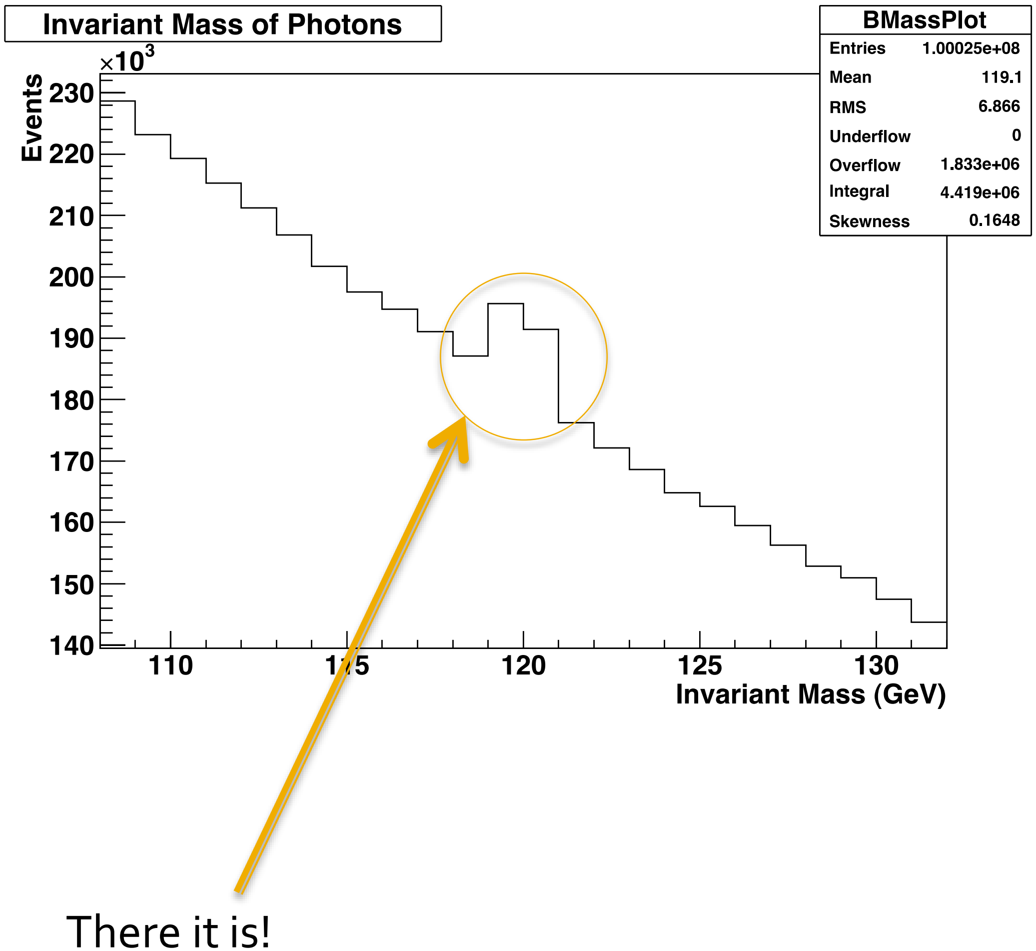
- This is actually the same plot I showed before, but with the ECAL design resolution for photons.



Wait, what's THIS now?

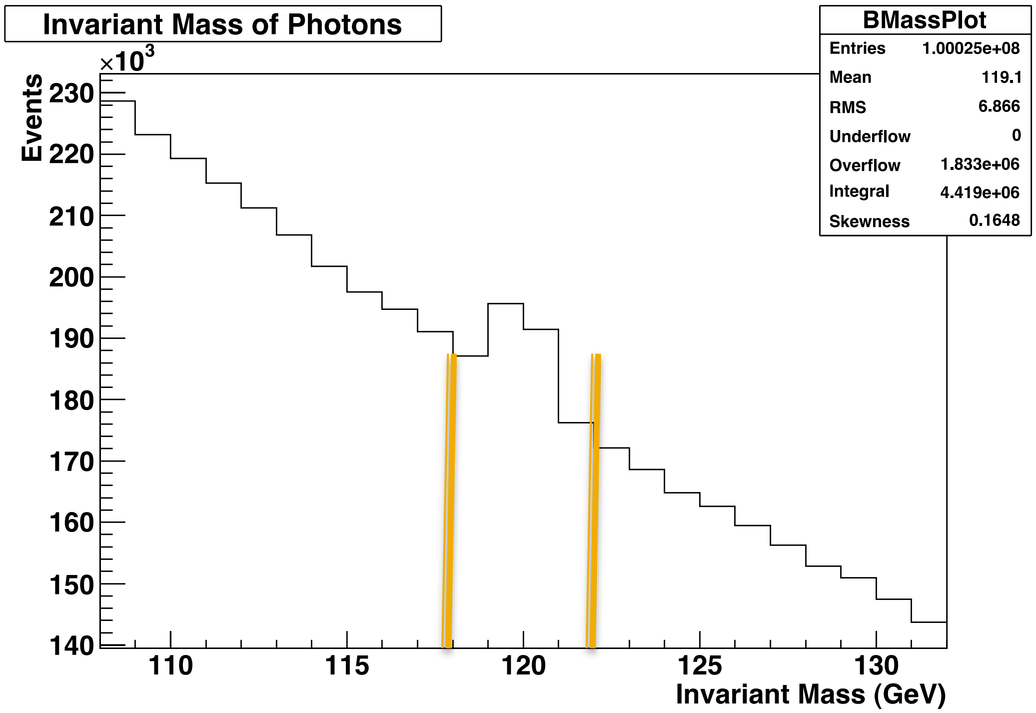
Like THIS High Precision:

- This is actually the same plot I showed before, but with the ECAL design resolution for photons (basically 0.5% for each photon).
- Still small compared to background, but visible!



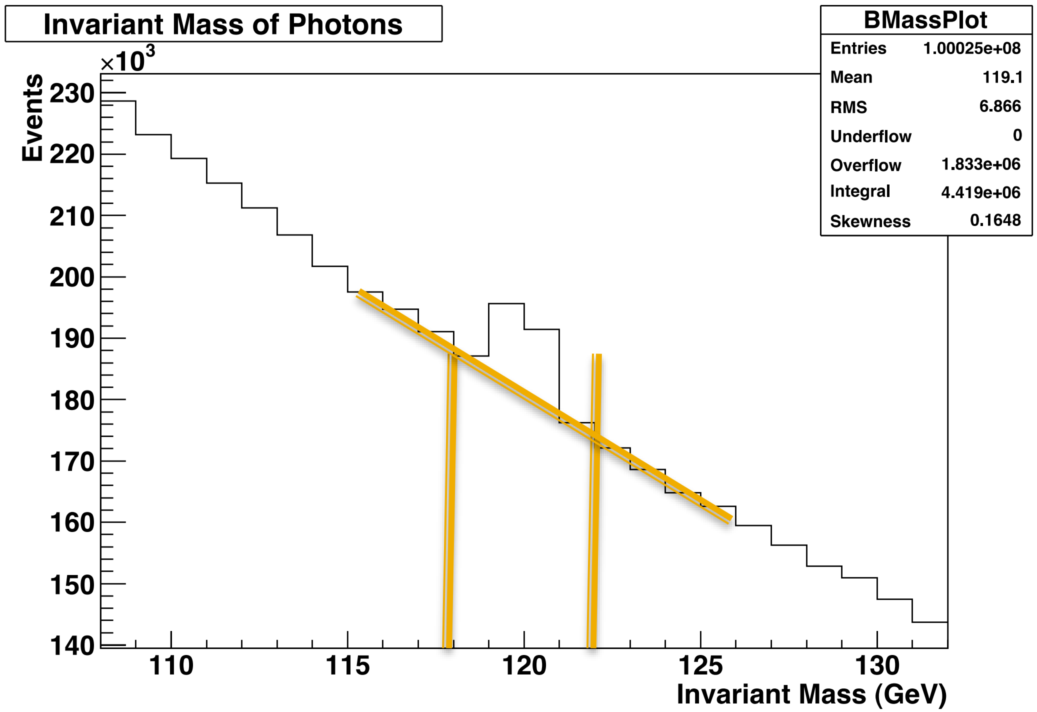
More on bump hunting:

- Typically when one looks merely for a "bump":
  - Work your way down the distribution. Pick a "window".



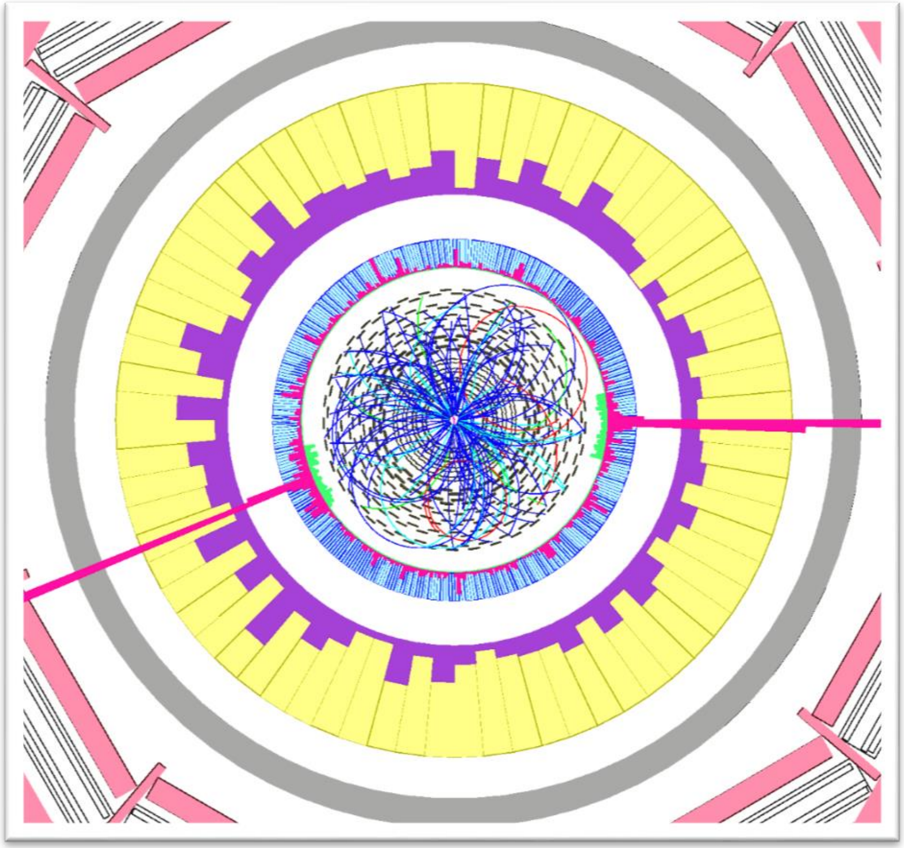
More on bump hunting:

- Typically when one looks merely for a "bump":
  - Work your way down the distribution. Pick a "window".
  - Extrapolate across it.
  - Figure out how much remains above the expected background.



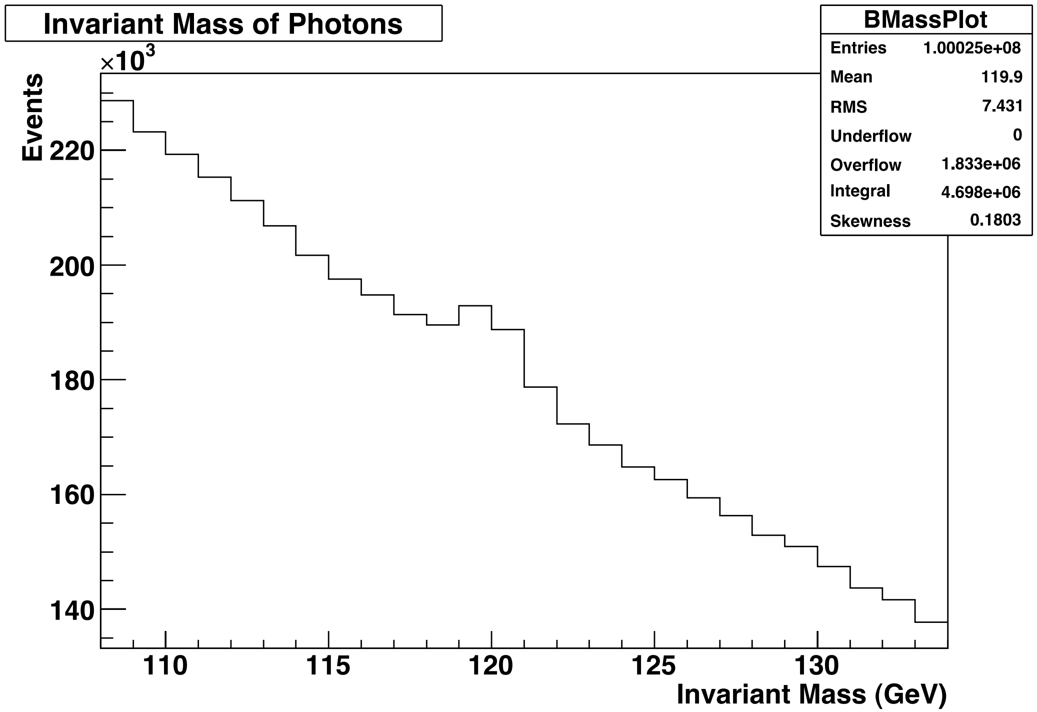
Sounds good, but…

- Half a percent resolution. For photons. This is not just ambitious, it's downright unprecedented for an experiment in this environment.
- It's messy in there. And crowded.



But the bottom line is:

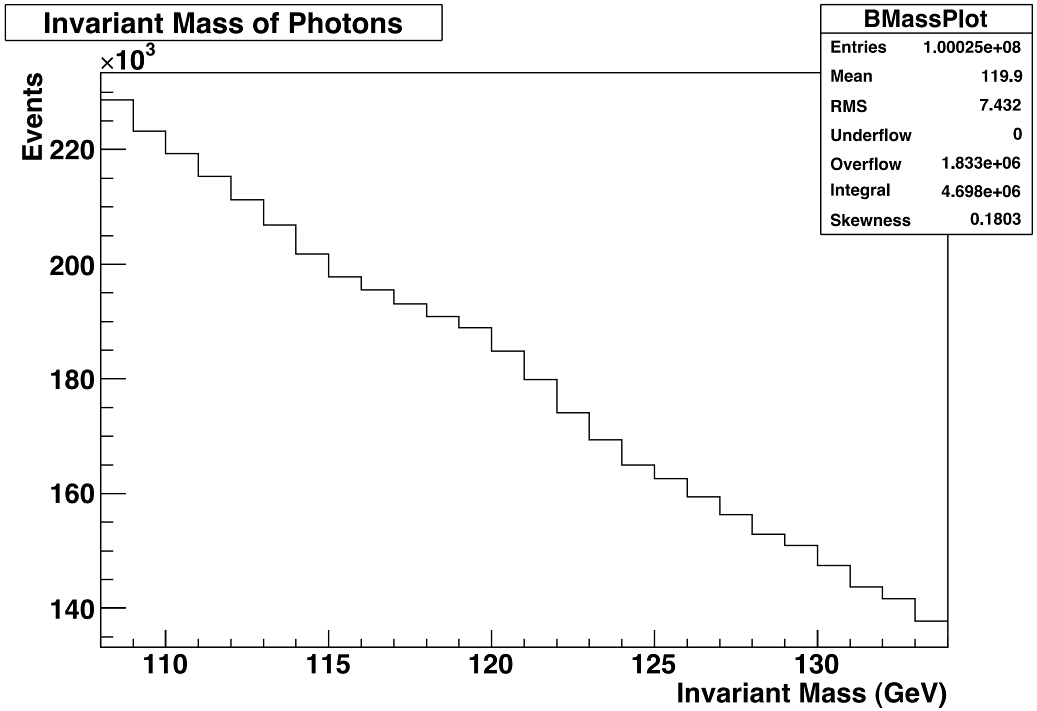
- If you don't have THAT kind of precision, you can't see the peak as clearly…



1% resolution

But the bottom line is:

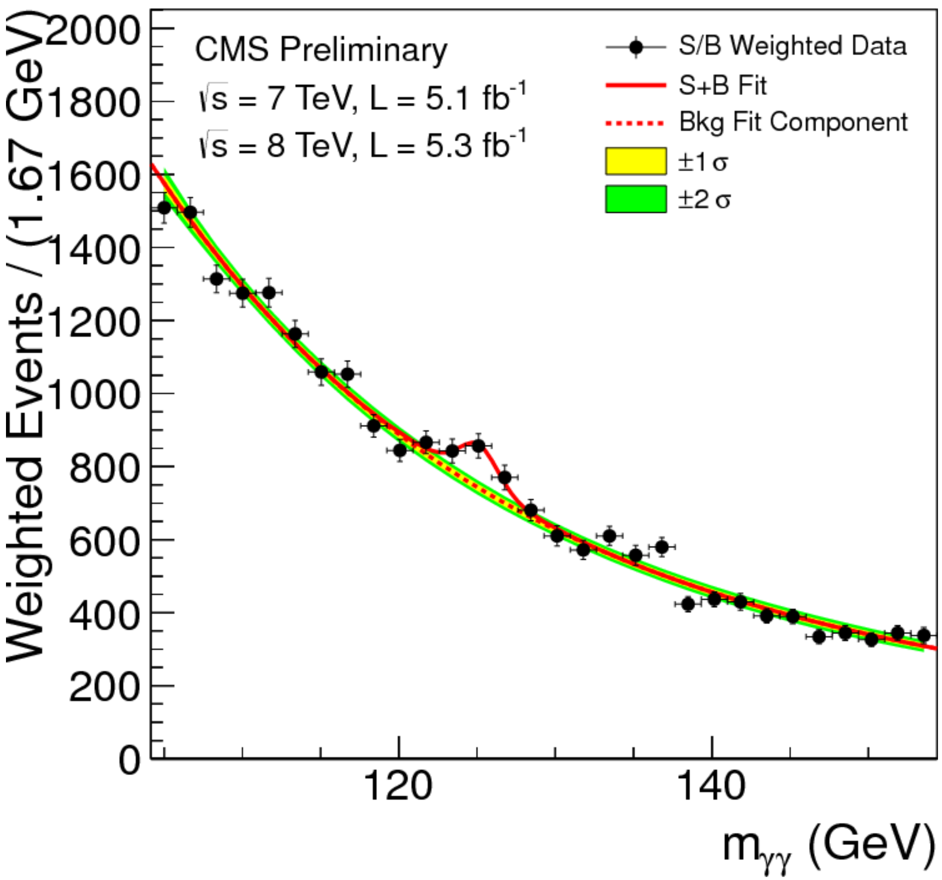
- If you don't have THAT kind of precision, you can't see the peak as clearly…
- Or at ALL.



2% resolution

What we saw for discovery:

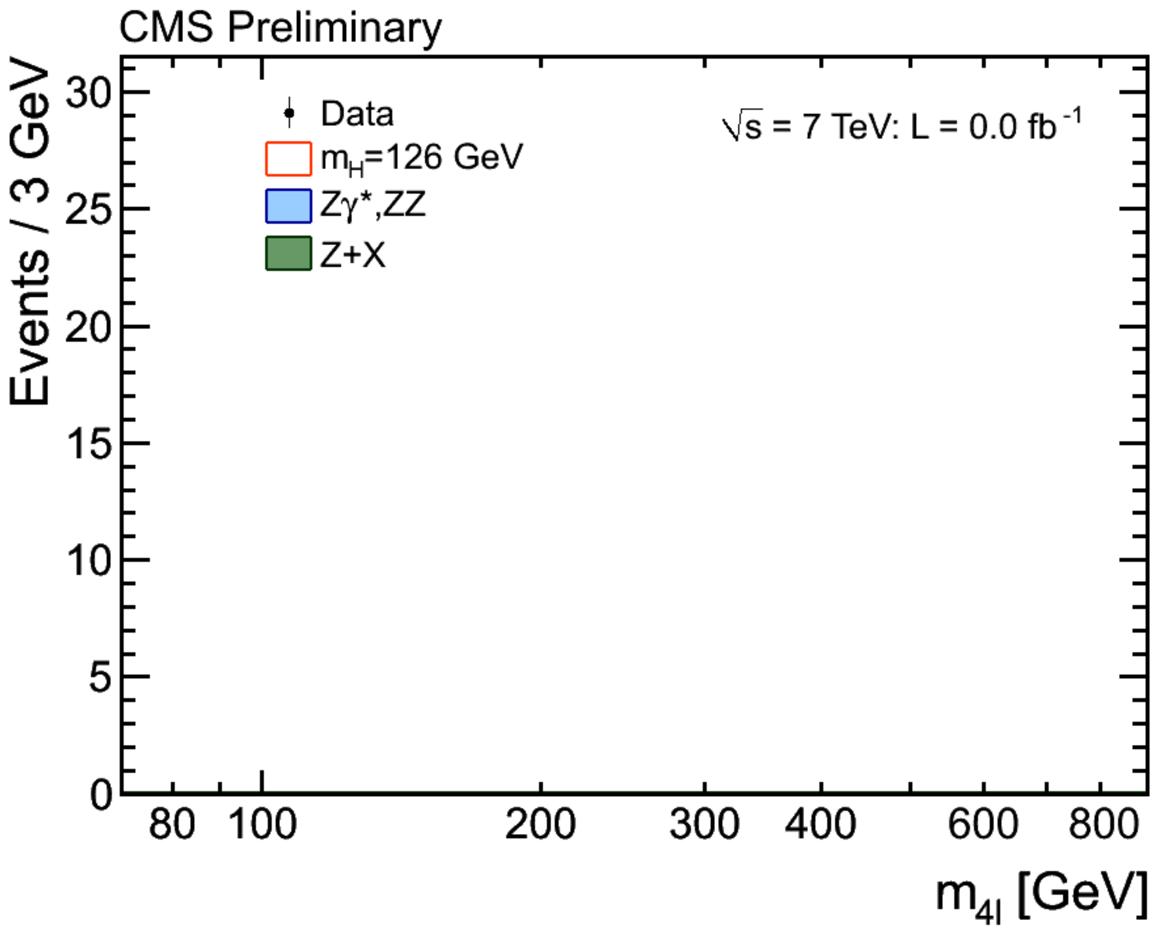
- This is what we saw after an enormous amount of work.
- That's a brand new particle.
- This makes me feel like cheering.



Another peak:

- Animated version of this for H->ZZ->llll

https://twiki.cern.ch/twiki/pub/CMSPublic/Hig13002TWiki/HZZ4l_animated.gif



Standing on the shoulders of, the shoulders of, the shoulders of…

- There has only ever been ONE LHC. The fact that it operates at all, much less as terrifically as it does is astounding.
- There has only even been ONE CMS detector. And the design had requirements so ambitious that one wouldn't swear it was even possible.
- And because of all the work that went into this over all the years, we can finally see this particle.

But is it…

- Is it really the Higgs boson? We don't really know.
- Finding it was just the first step, NOW is the fun part. We get to study it and see if it actually IS the particle that we expected.

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Summary:

- We've seen something!
  - It might be a Higgs! It looks more like the Higgs than it looks like anything else.
  - This is STILL ONLY THE BEGINNING! We'll have even higher energy collisions (13 TeV expected) when the downtime is over (which by the way is NEXT YEAR). More energy means potentially producing even more massive particles, and more Higgs events!