Quantum Tunneling in the Electroweak Vacuum

QuarkNet Workshop

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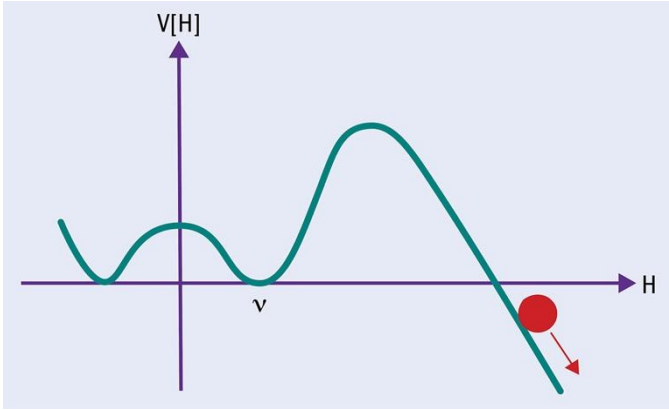
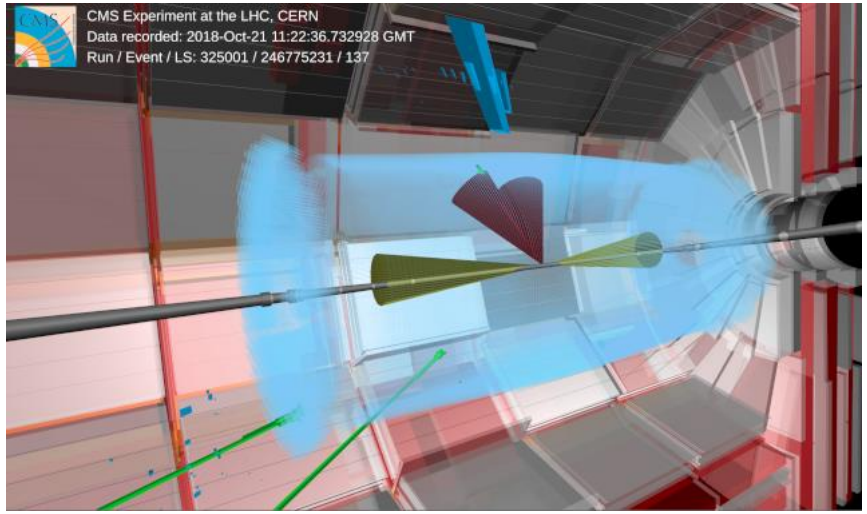
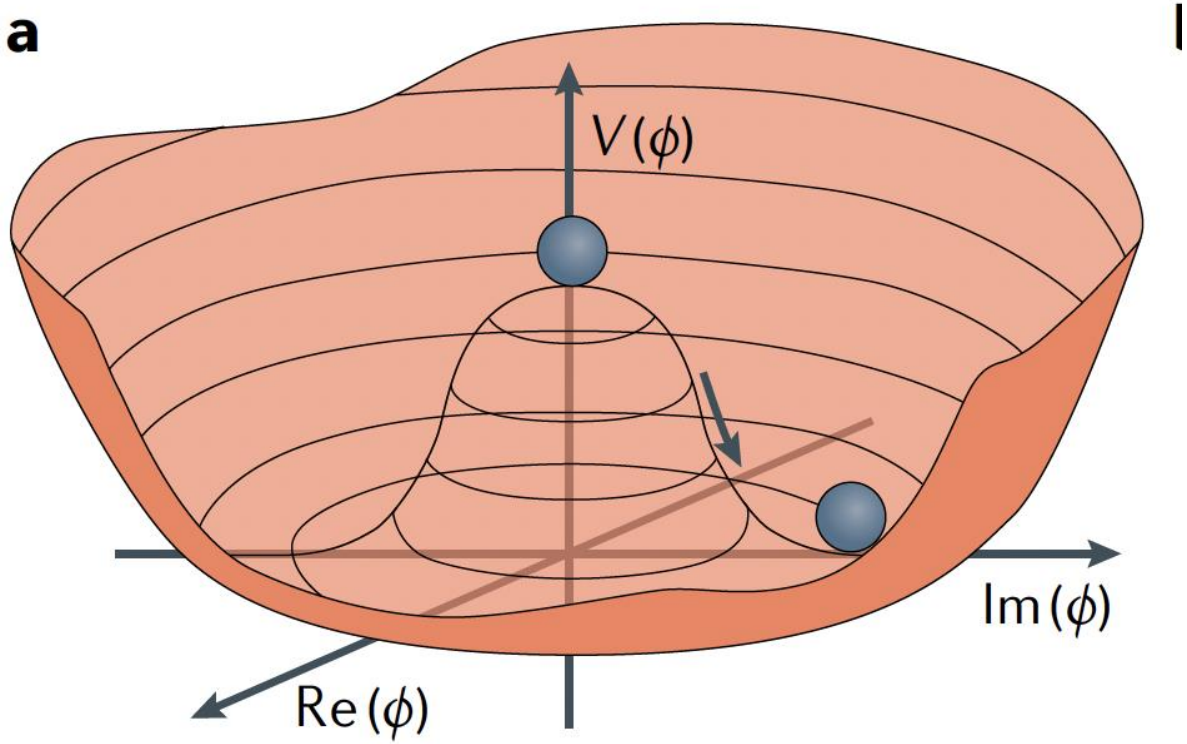
Topics for Today

- The Higgs mechanism and the Electroweak vacuum
  - beyond the “Mexican hat”
- Higgs potential (vacuum) shape possibilities
  - stable, unstable, metastable
  - tunnelling time
- Relevant experimental particle physics measurements
  - Higgs boson mass ✅
  - top quark mass ✅
  - di-Higgs production cross section ❓





Does the brim of the ”Mexican Hat” turn down?



Vacuum potential before spontaneous symmetry breaking:

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4.$$

minimum at

$$|\phi| \equiv \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}.$$

Tunneling of the vacuum

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4.$$

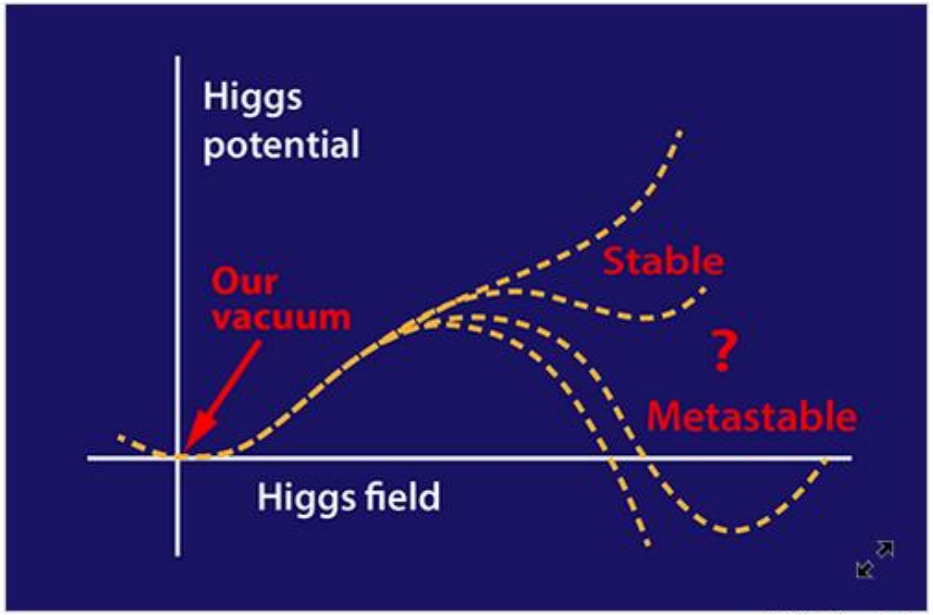
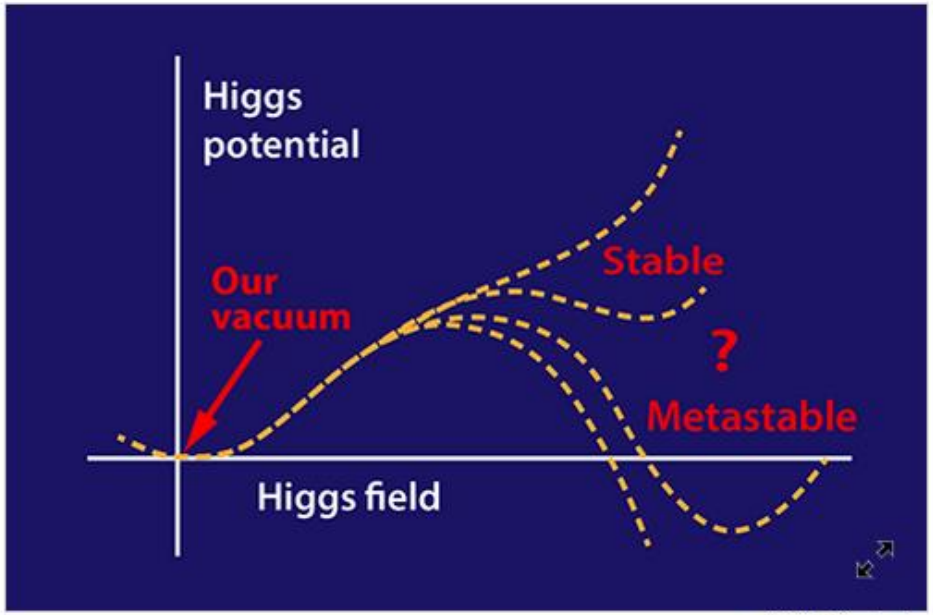


Figure 1: The ground state of the Universe depends on the potential of the Higgs field. If the Universe lies in the global minimum of the potential (a "true" vacuum state), then it is stable. But if the minimum is local and a deeper minimum exists, the vacuum is "false," and the Universe might catastrophically tunnel out into the true vacuum state.

λ is not a constant, but evolves with energy

- Stable
  - our present vacuum is at the absolute minimum. No tunnelling possible
- Unstable
  - a true minimum is close by, and the universe should tunnel to it rapidly
- Metastable
  - a lower true minimum exists, but the tunneling time (like half-life) is very long
  - longer than the age of the universe?

Well-measured: top quark mass and Higgs boson mass



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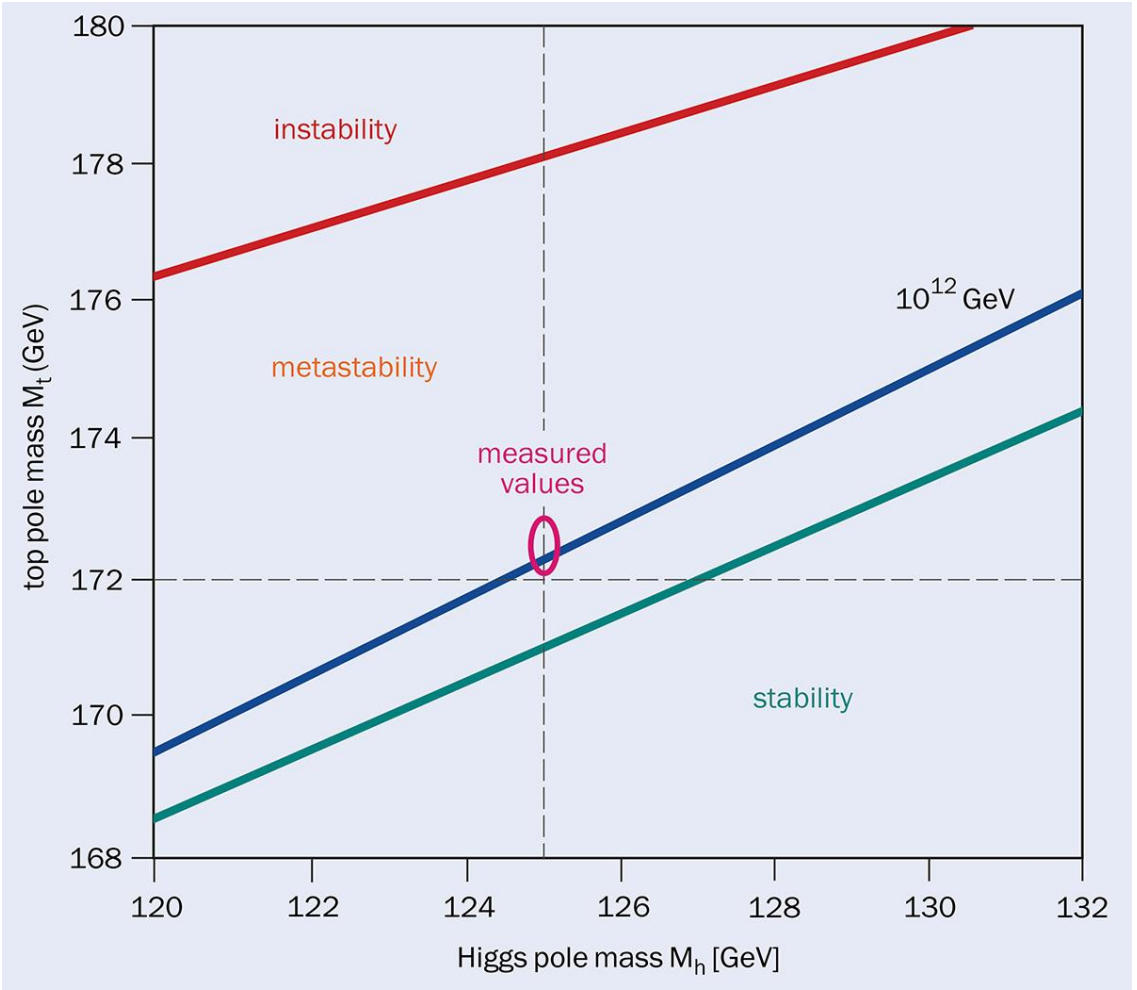
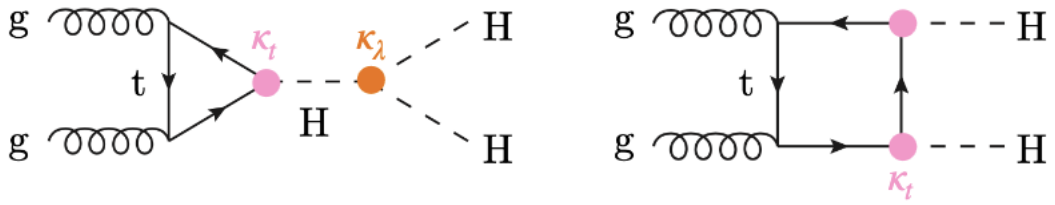


Critical experimental input needed: Higgs self-coupling (λ)

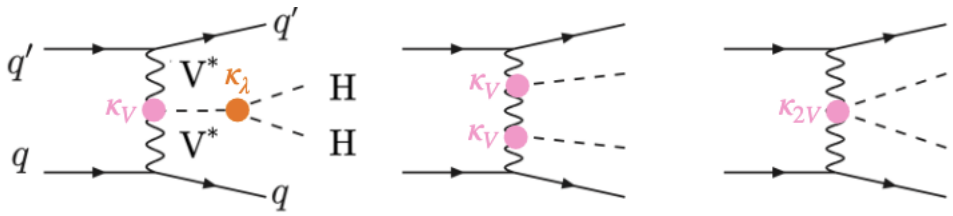
- Di-Higgs
  - production rate is proportional to λ
  - if you can measure the cross section for di-Higgs production, you can measure λ at a higher energy and observe its evolution
- How many events produced so far?
  - CMS integrated luminosity ~300 fb^{-1}
  - ~500 di-Higgs events produced in VBF
  - so where are they?



DESTRUCTIVE INTERFERENCE

$\sigma_{ggF} = 34.1$ fb

(13 TeV)

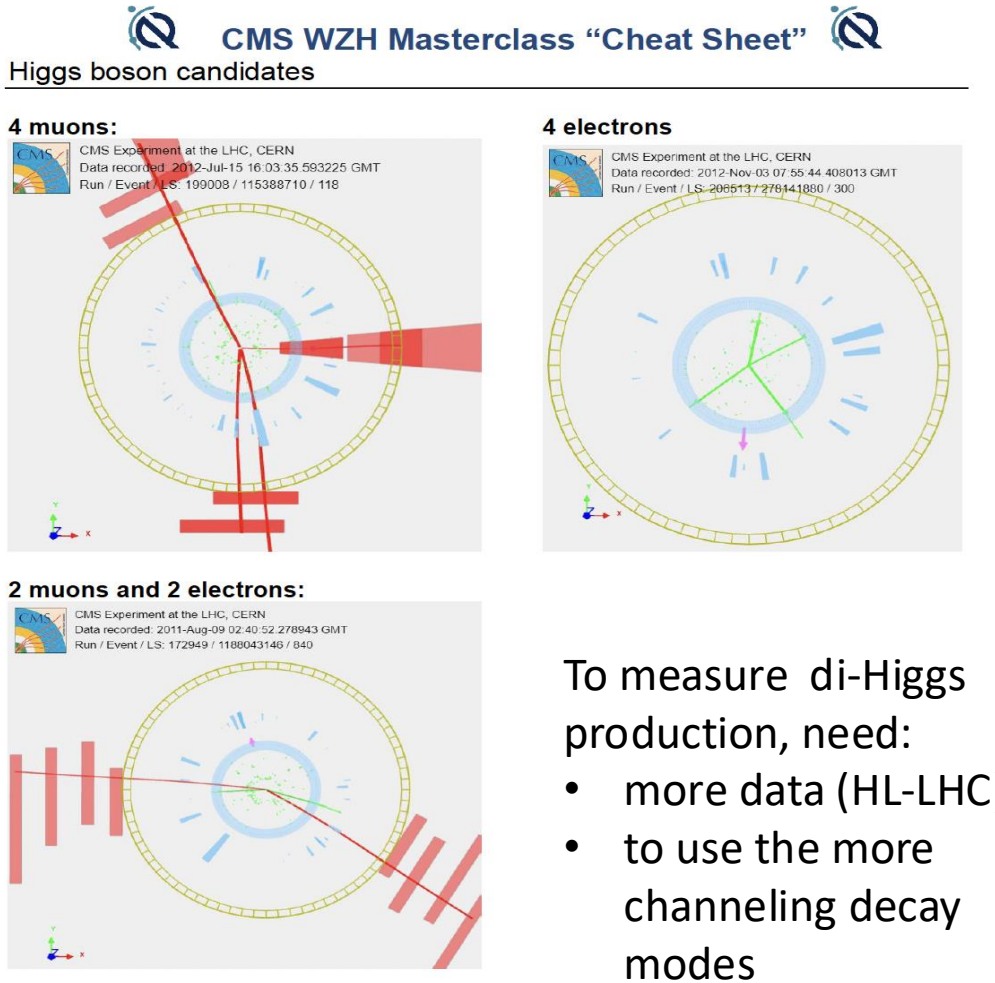


DESTRUCTIVE INTERFERENCE

$\sigma_{VBF} = 1.87$ fb

Challenge of rare decays is multiplied in di-Higgs

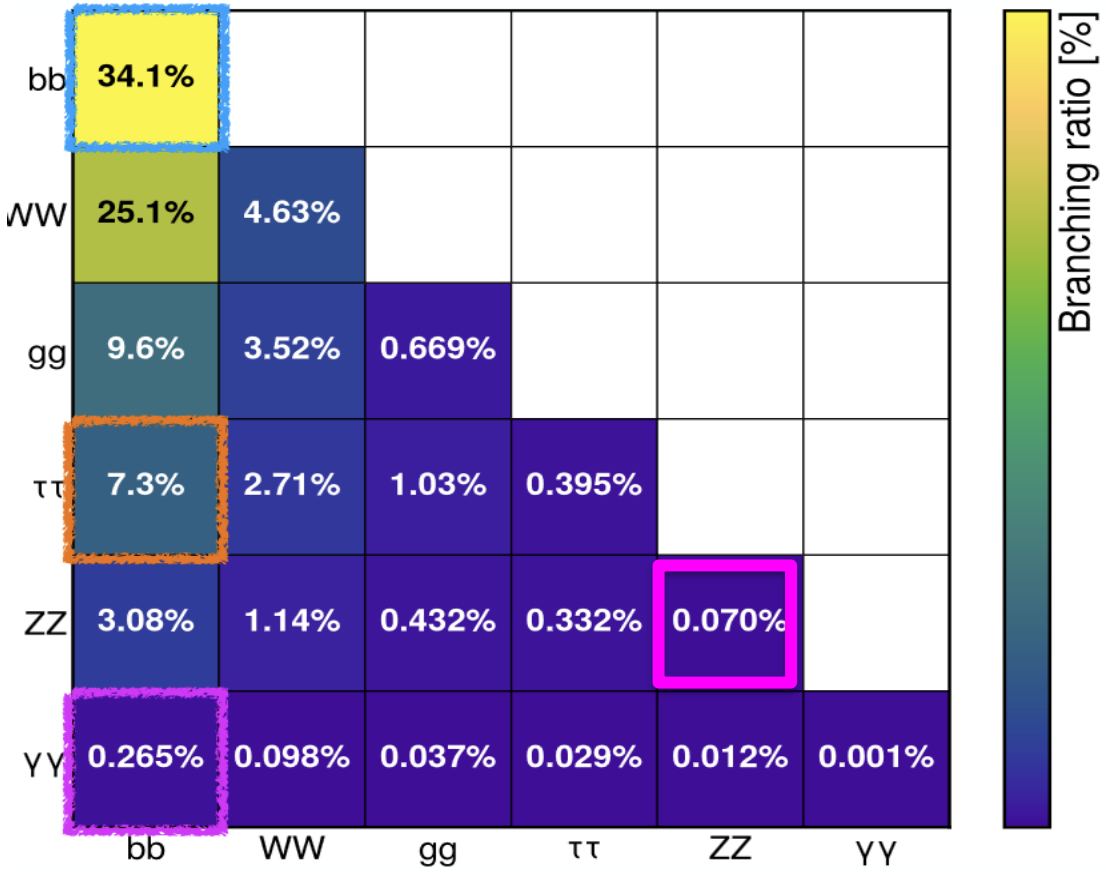
Remember what one Higgs looks like at CMS?



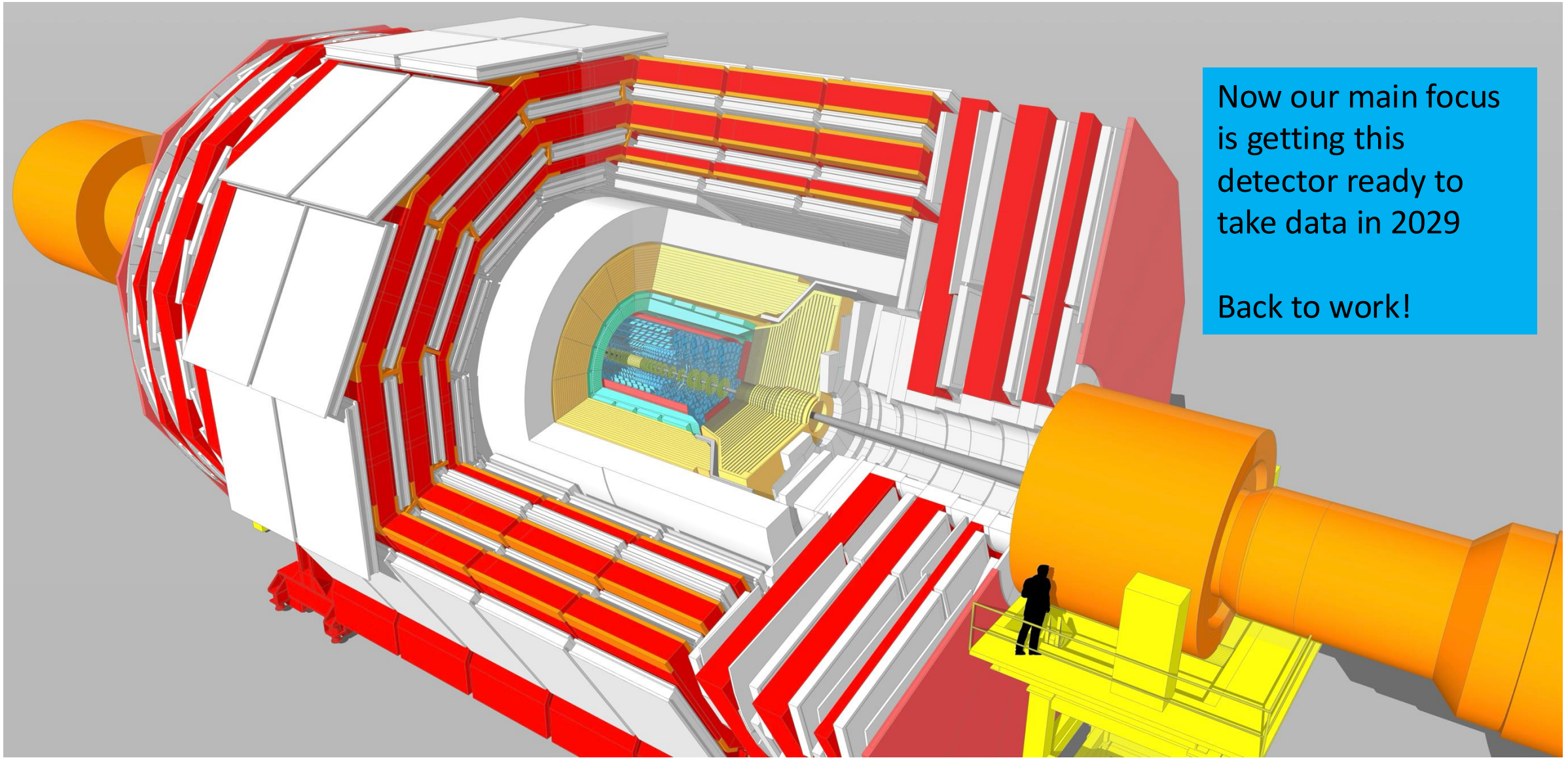
To measure di-Higgs production, need:

- more data (HL-LHC)
- to use the more channeling decay modes

Less than 0.5 events expected in the HH->ZZ, before event considering that Z's decay to e or mu only 6% of the time



The New CMS


Now our main focus is getting this detector ready to take data in 2029
Back to work!