Search for Higgs Boson Decaying to Delayed and Non-Pointing Photons using the ATLAS experiment at the LHC

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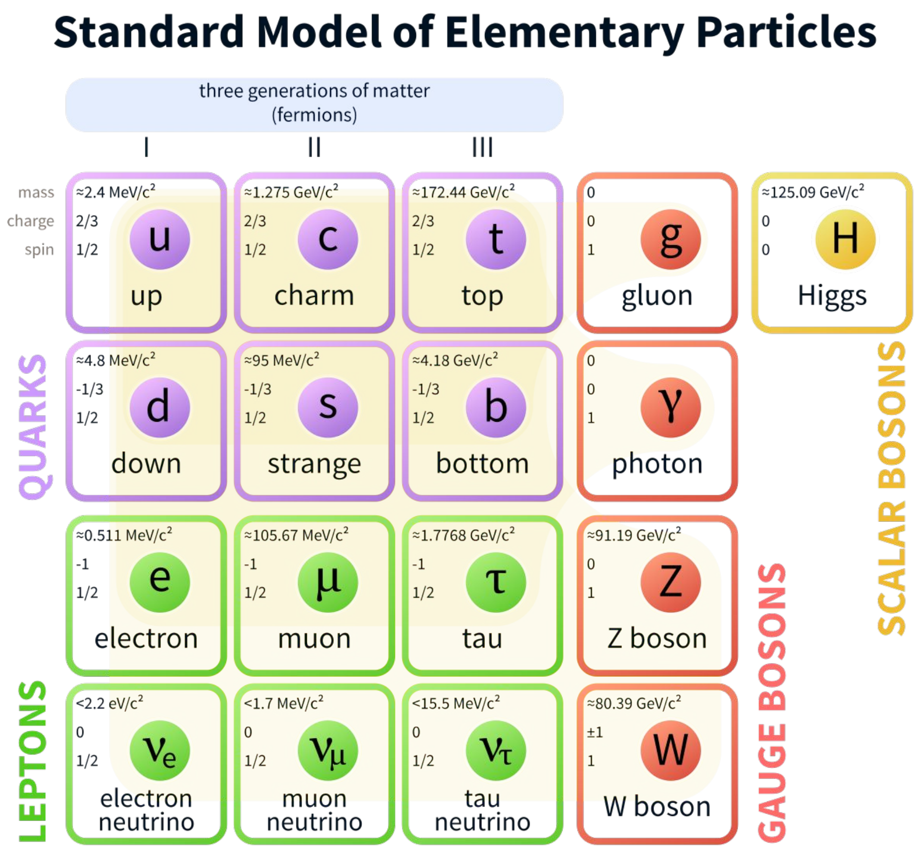
Introduction

- You have heard from Prof. Heather Gray and Dr. Maurice Srivas-Garcia about ATLAS a few weeks ago
- We are a large group, with three faculty members from campus, more than twelve scientists from LBL, seven graduate students, nine postdocs, and many visitors and undergraduates

Heather and Maurice’s talks are high-level. I will discuss one specific piece of work, out of many ongoing activities in the group, as example, for what we do



$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
&+ i\bar{\psi}\not{D}\psi + h.c. \\
&+ \psi_i y_{ij} \psi_j \phi + h.c. \\
&+ |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

new particles, new interactions ⇔ addition/modification of the SM Lagrangian

Particle Physics Experiments

Open questions:

- why is electroweak interaction so much stronger than gravity?
- what is the nature of dark matter?
- why is there an imbalance between matter and antimatter?
- is there any extra spatial dimension in the Universe?
- why are there three generations of leptons and quarks? Do they have internal structures?

...

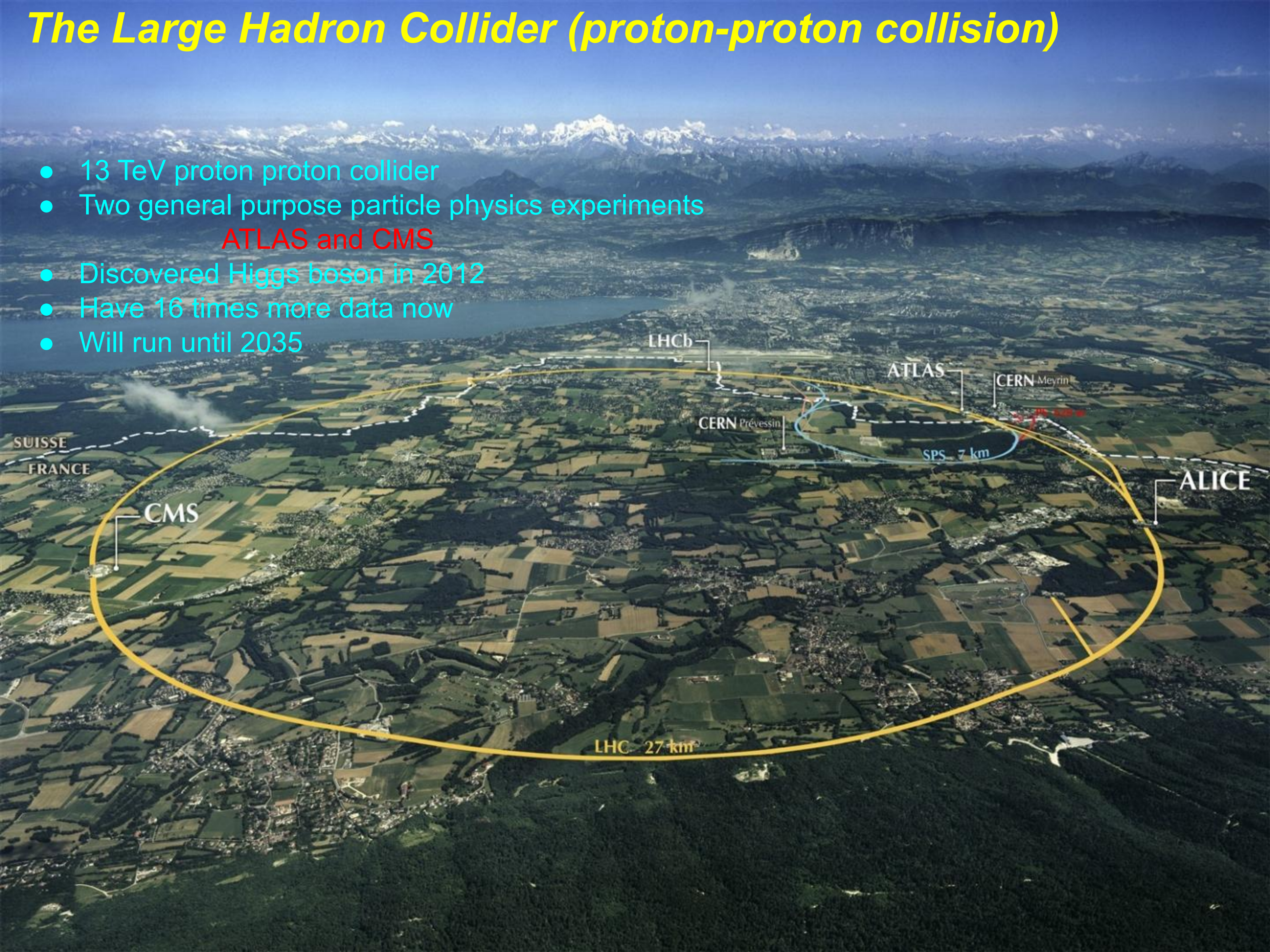
Particle physics experiments try to answer these questions

- **accelerator based**: **collider (ATLAS, CMS)**, fixed target, neutrino (DUNE)
- **non-accelerator:** cosmic rays or dark matter from the space, nuclear reactor (reactor neutrino experiment)

Why high energy collider?
higher energy ⇒ smaller probe ⇒ more fundamental structure and heavier particles

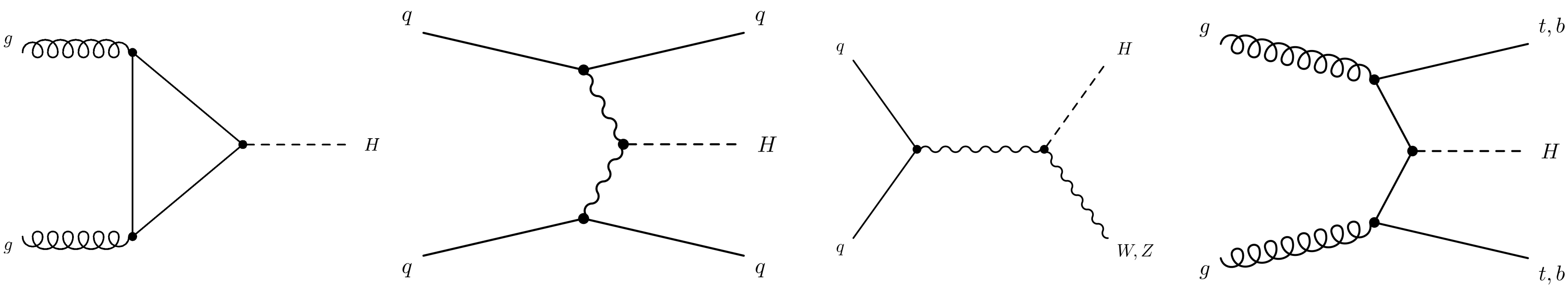
The Large Hadron Collider (proton-proton collision)

- 13 TeV proton proton collider
- Two general purpose particle physics experiments
  ATLAS and CMS
- Discovered Higgs boson in 2012
- Have 16 times more data now
- Will run until 2035

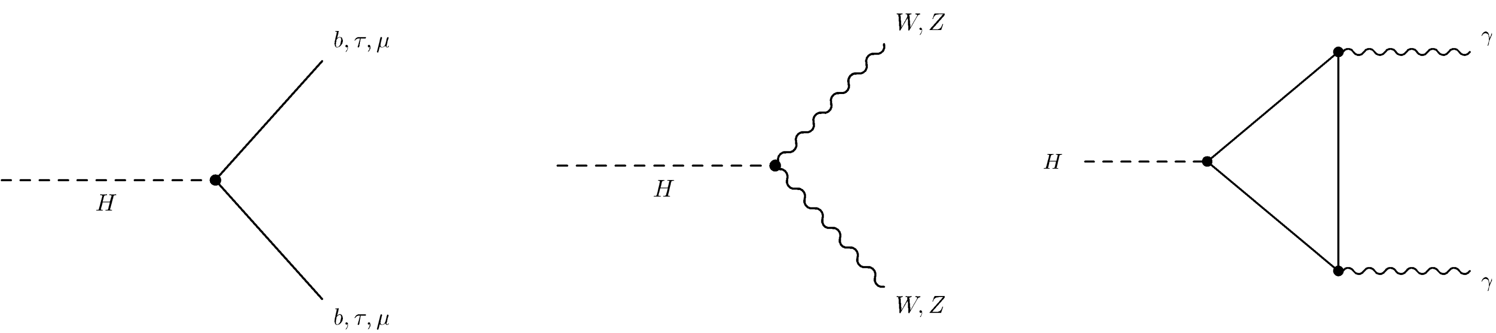


Main Higgs production mode at the LHC

Possible ways to produce Higgs boson in proton collisions



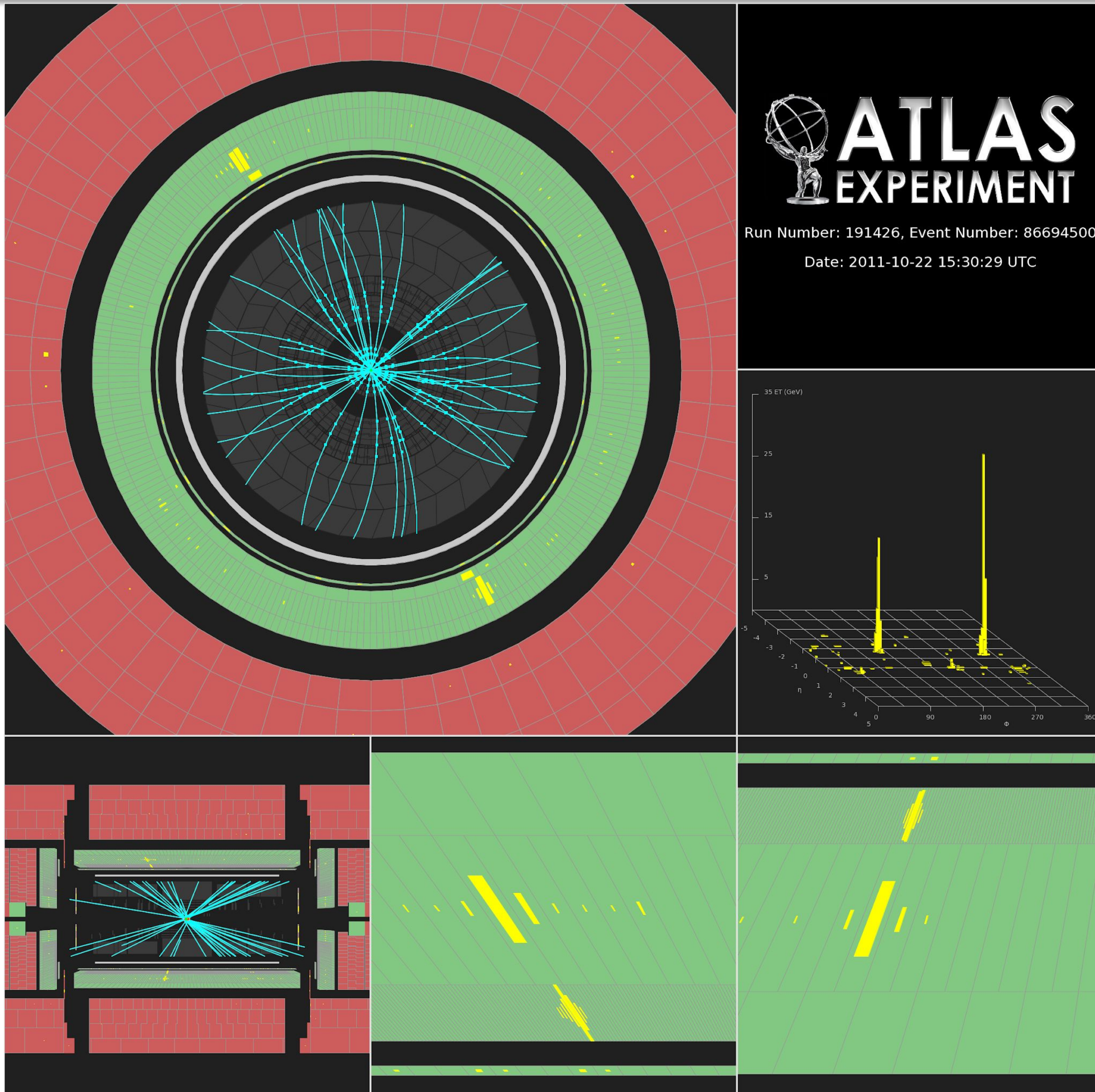
Possible Higgs boson decay final states

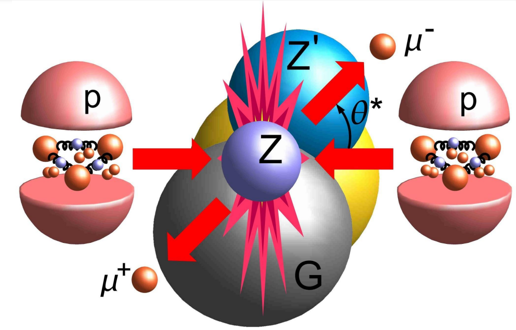


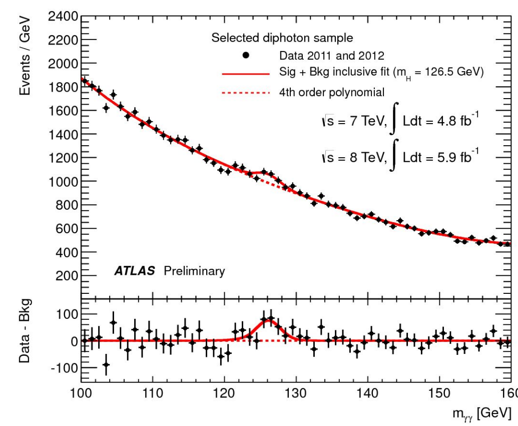
Production and decay rates are related the coupling between the Higgs boson and other elementary particles

⇒ Rate measurements allow us to study Higgs interaction, to test Standard Model, and to search for subtle effects from new physics

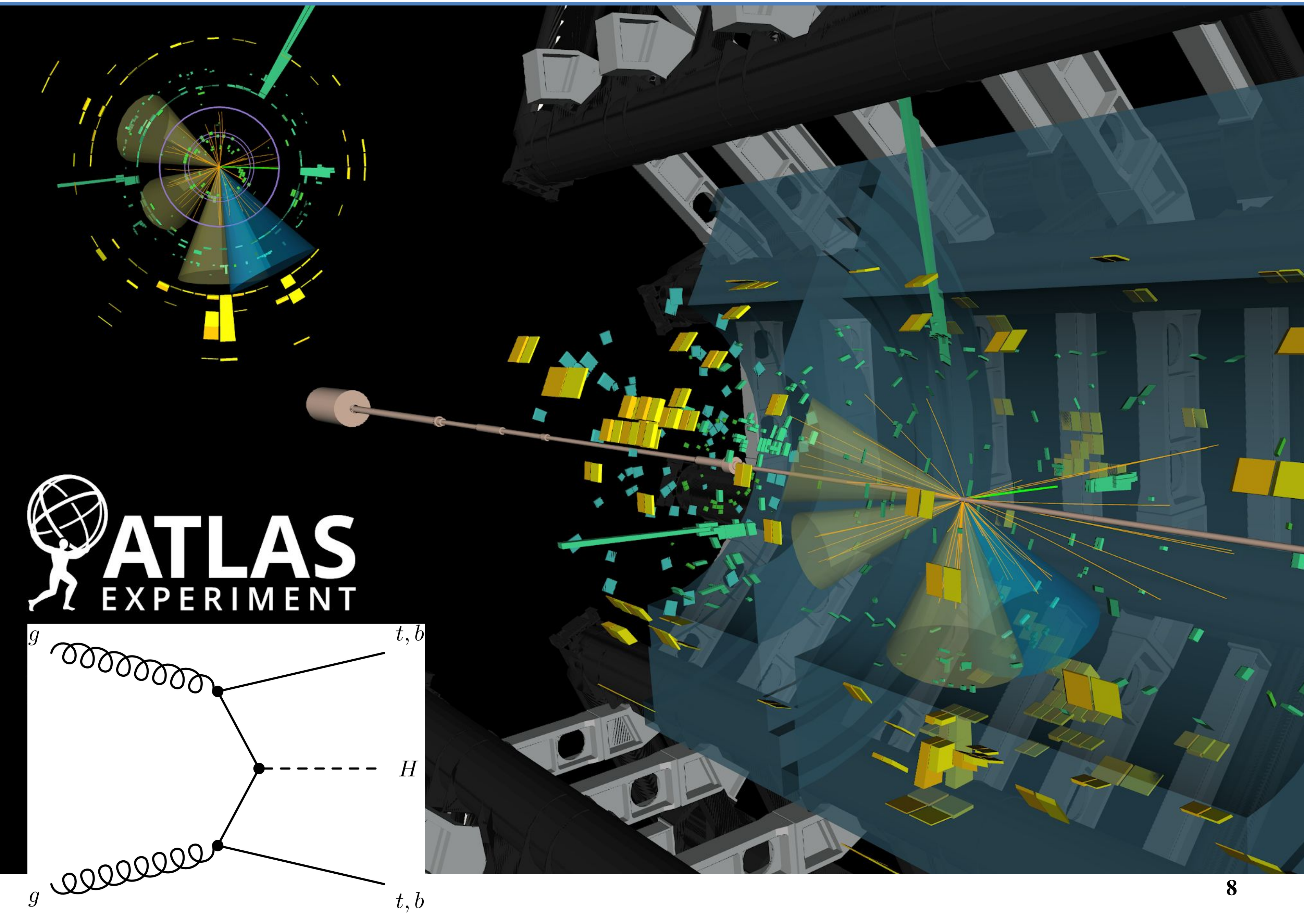
$H \to \gamma\gamma$



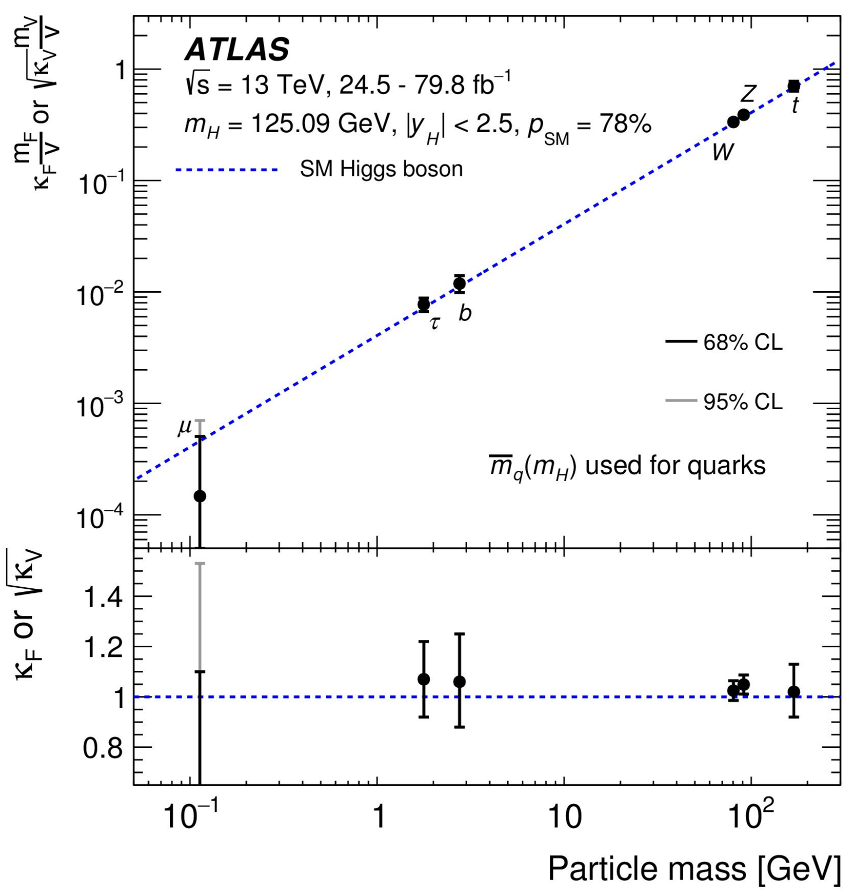




$ttH \rightarrow \gamma\gamma$

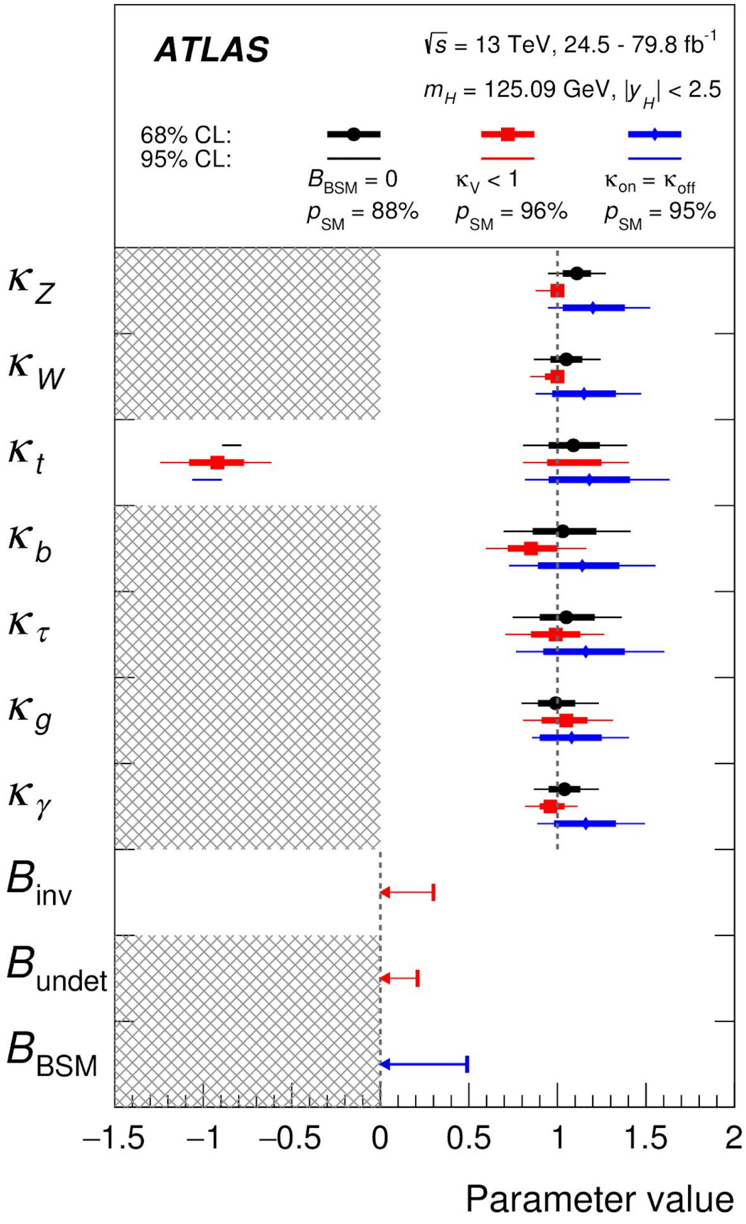


Our knowledge about Higgs couplings as of October 2019



Particle mass ⇔ Strength of coupling to Higgs

From what is observed and how strong they are, we can estimate how much room is left for unexpected Higgs decays



Search for Higgs boson's exotic decays

O(20%) of the Higgs bosons produced at the LHC could have decayed to particles not predicted by the Standard Model

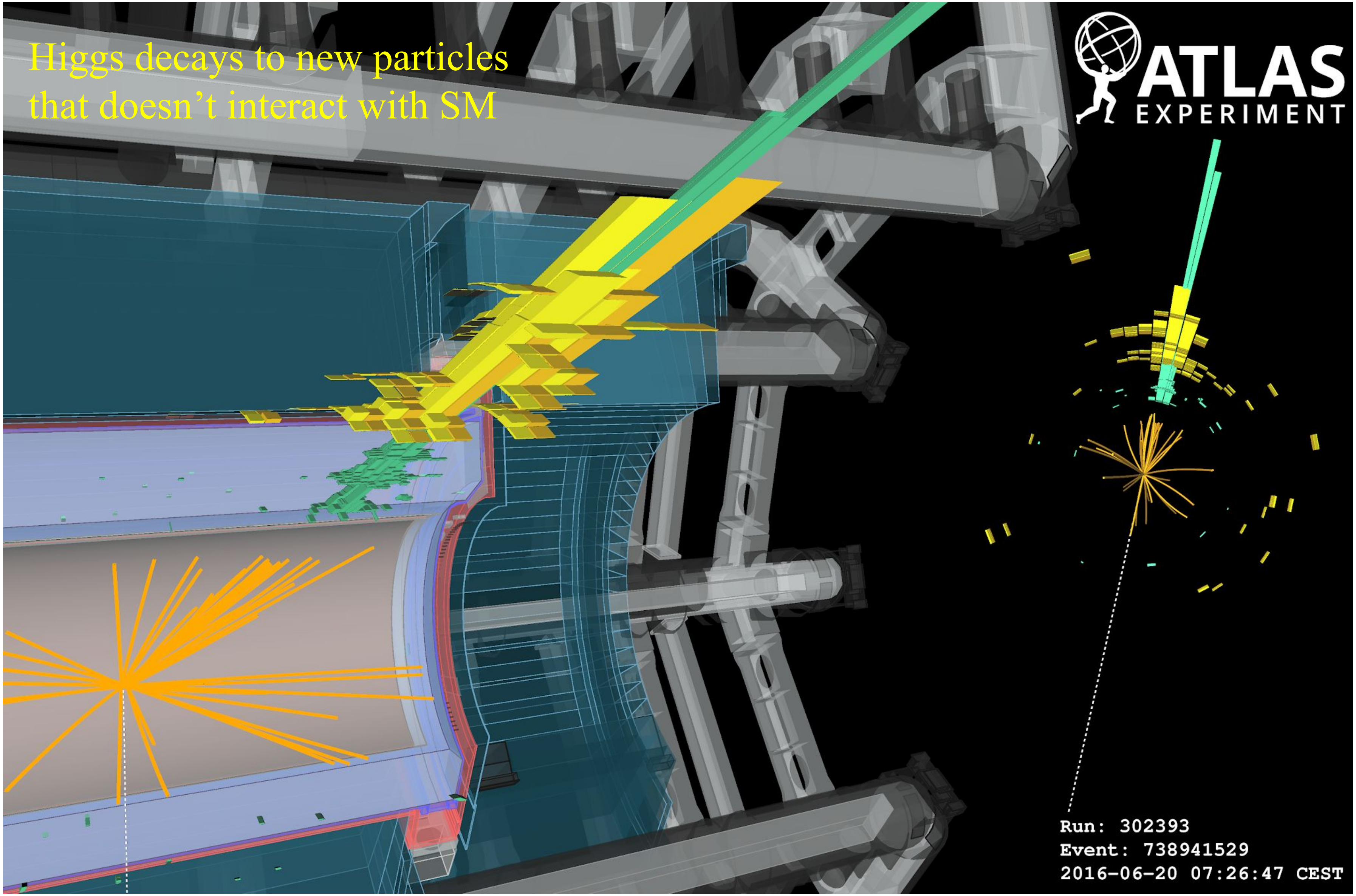
- corresponding to ~ 1.5 million Higgs bosons produced at the LHC, out of a total of ~ 7 million

This is a wide open field

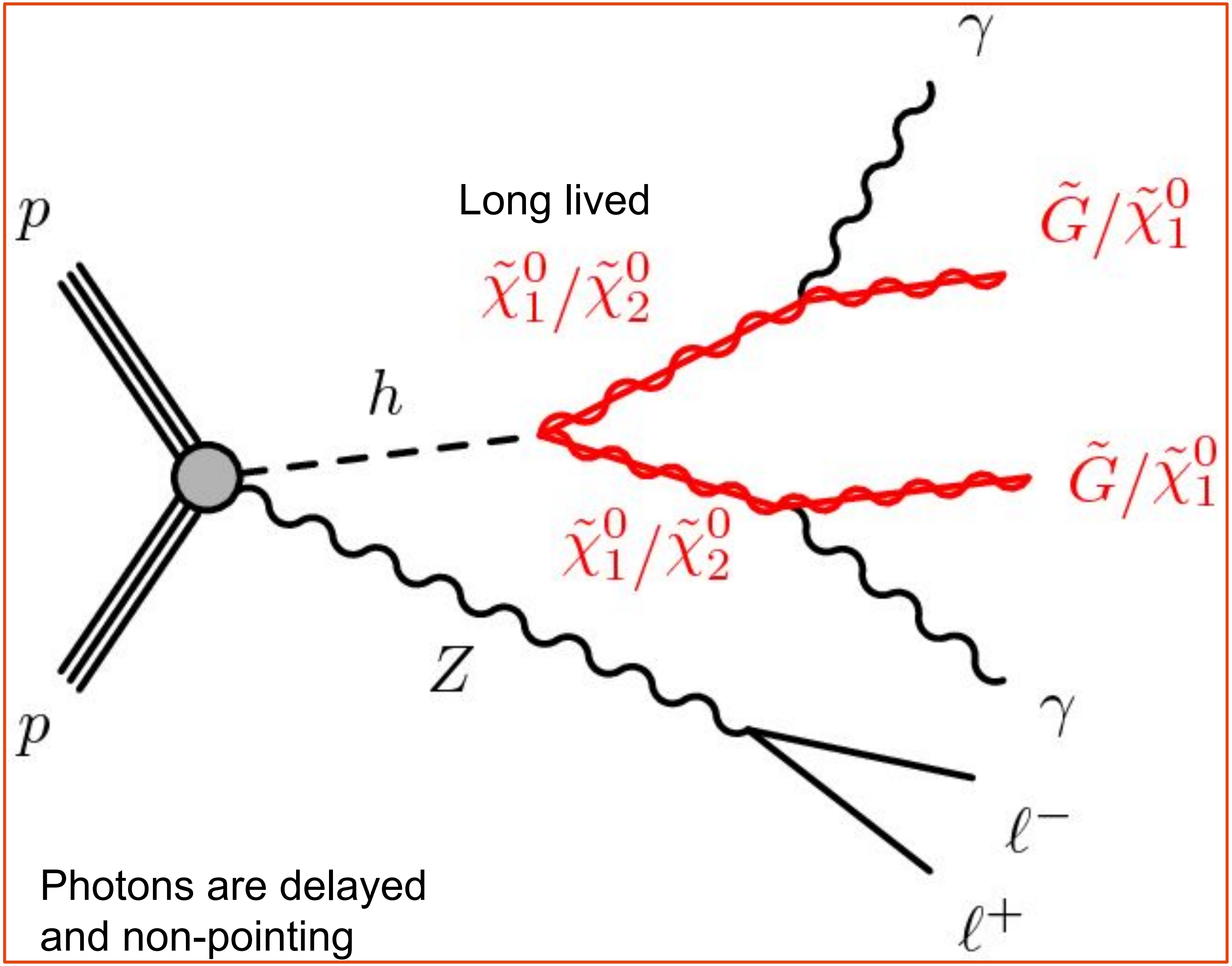
- all sorts of signals are possible

I will discuss our ongoing search for one such possible exotic Higgs boson decays

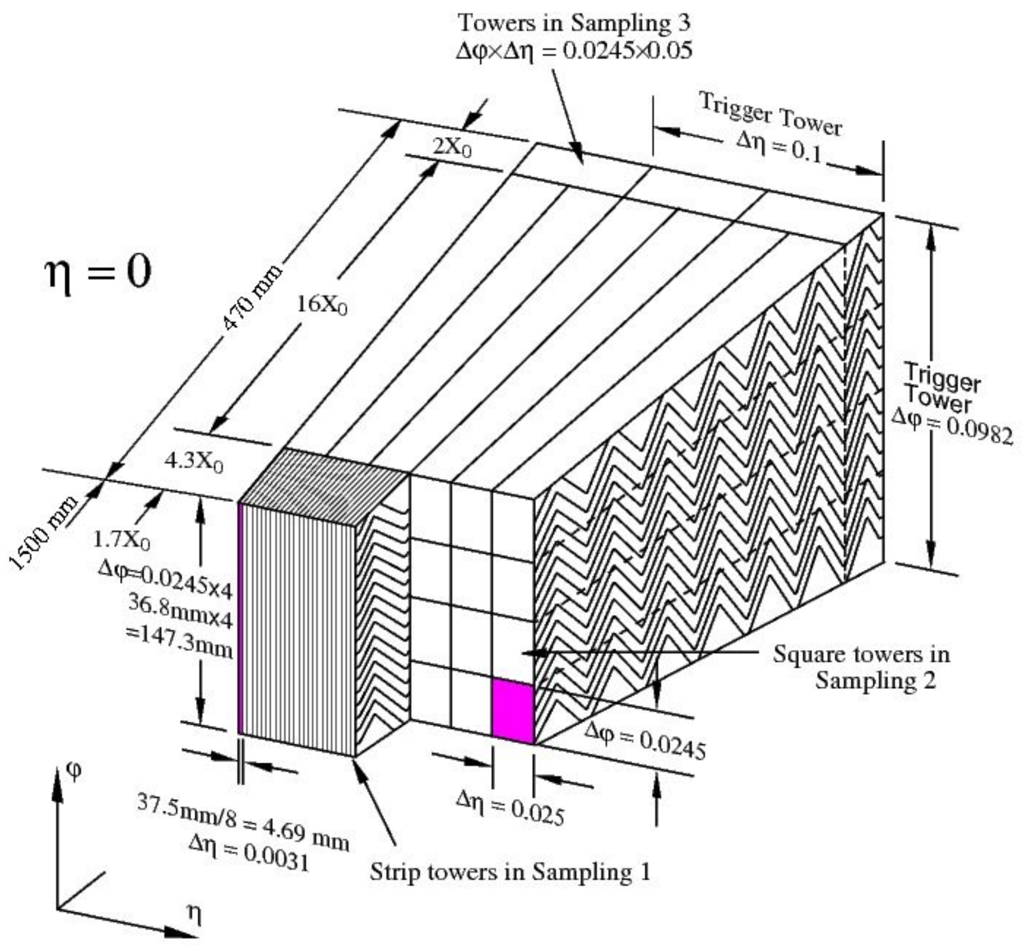
Higgs decays to “invisible” particles

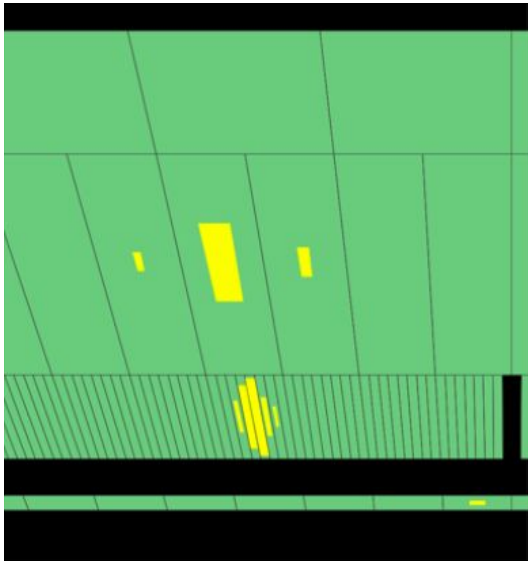


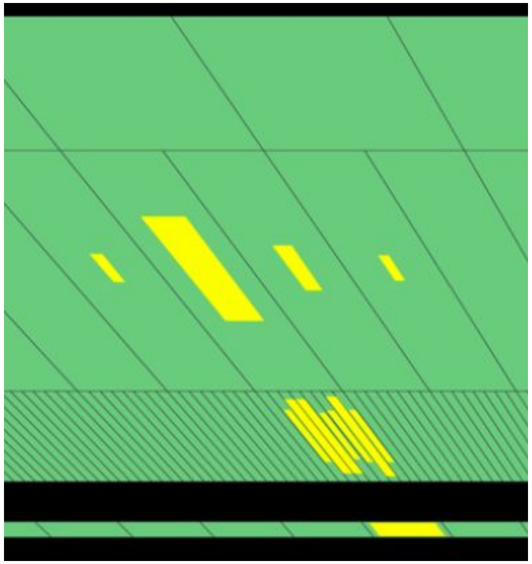
Higgs decays to long-lived particles



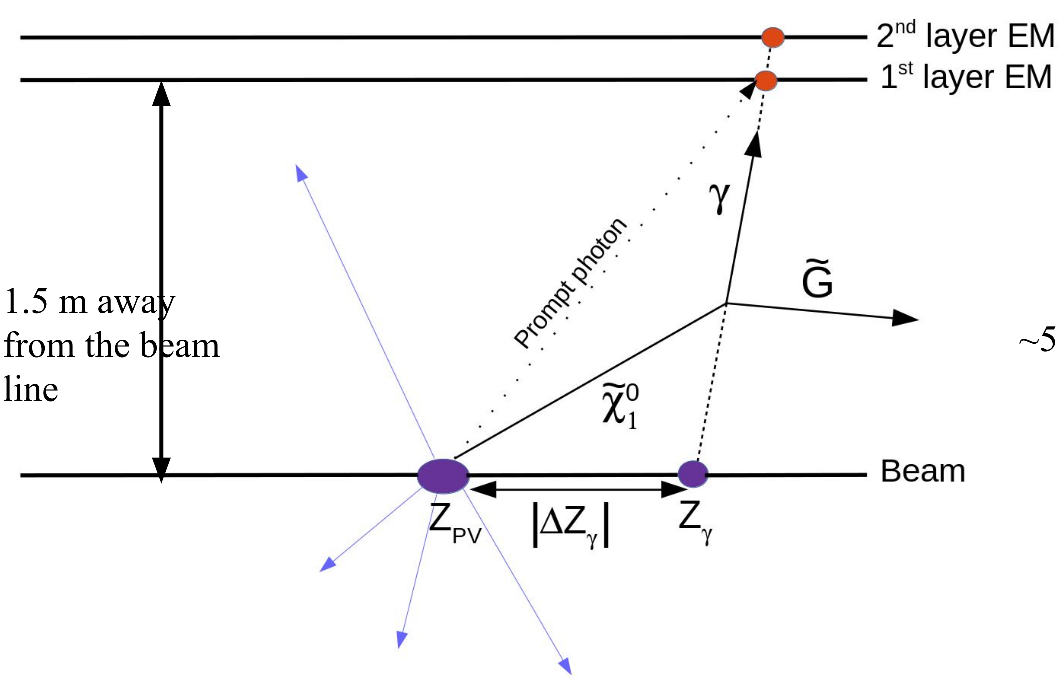
How we measure photons



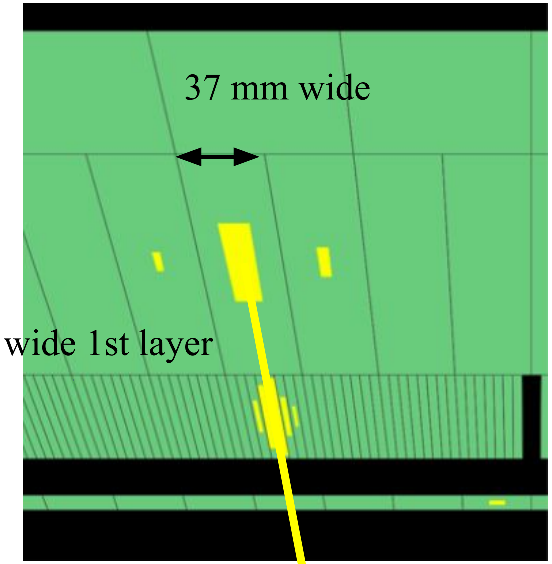




How to charaterize the displacement



1.5 m away from the beam line

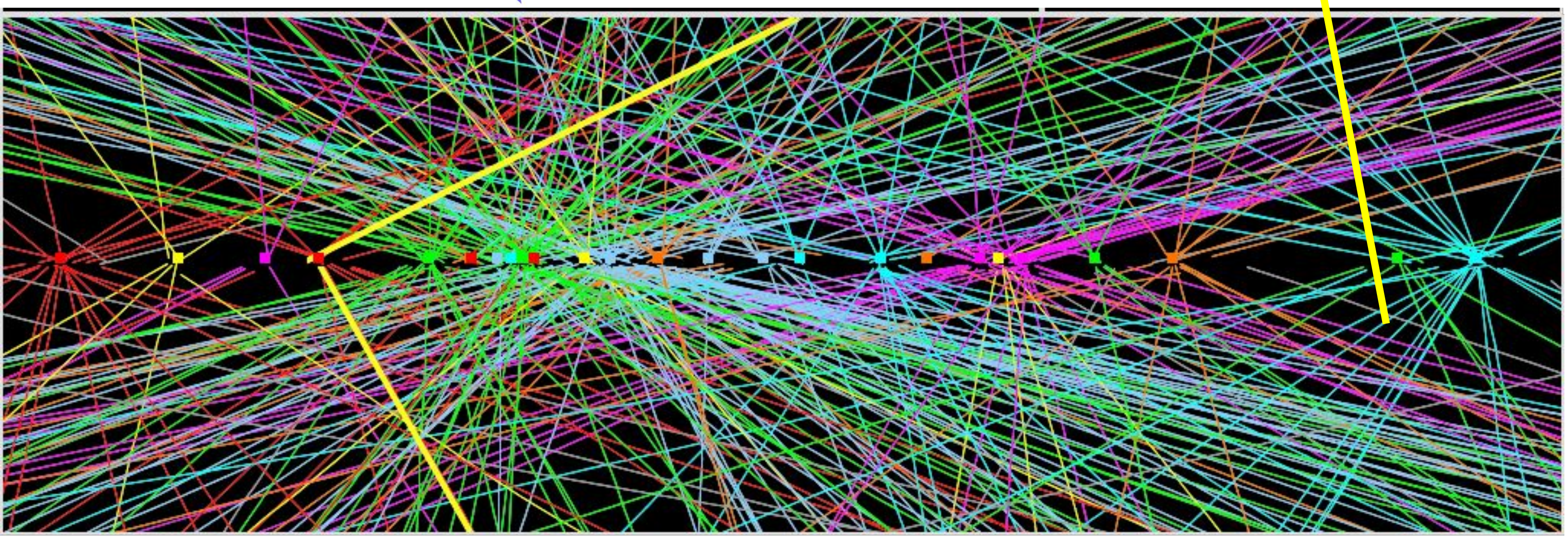


~5 mm wide 1st layer

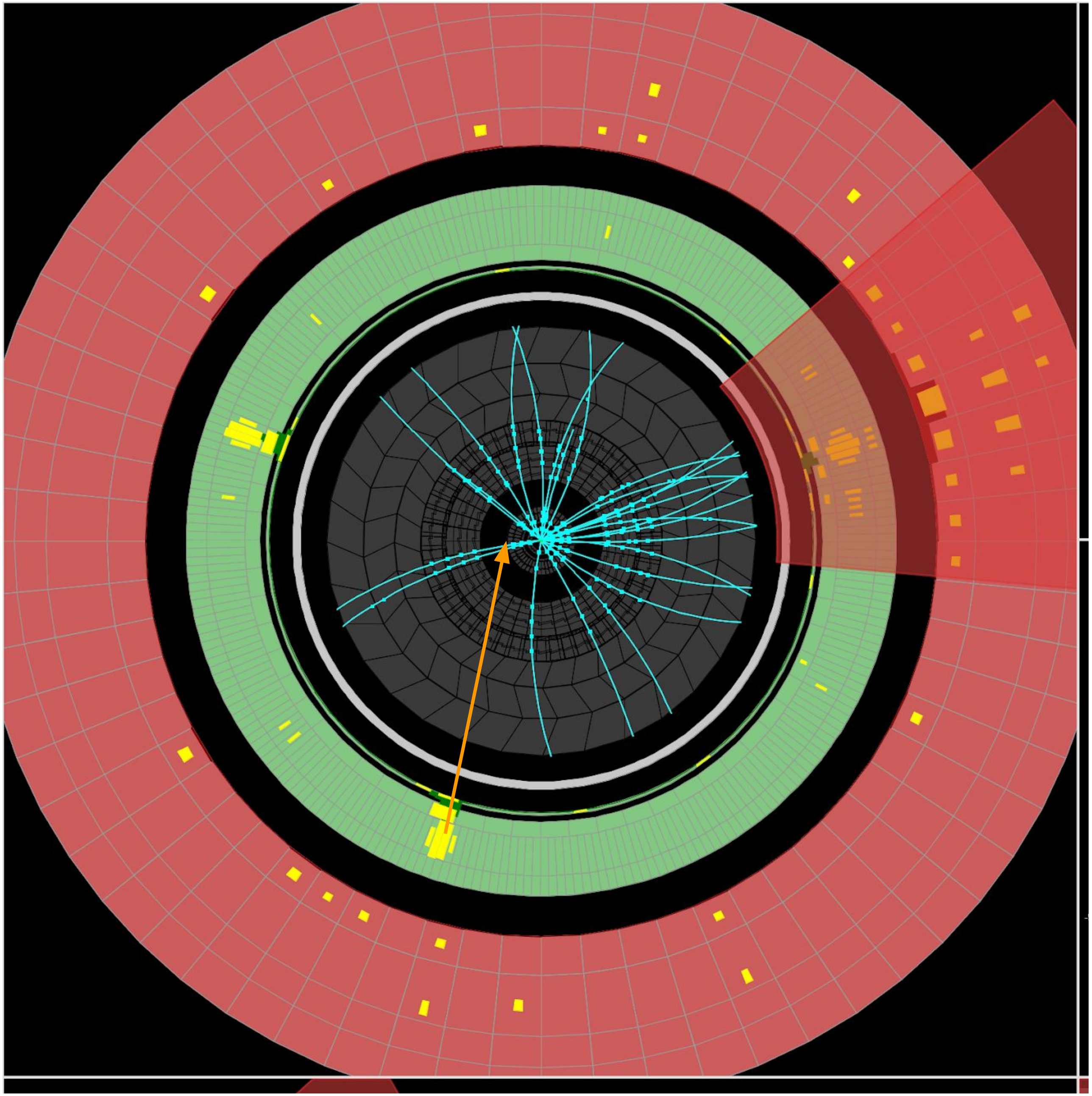
← 2nd layer

← 1st layer

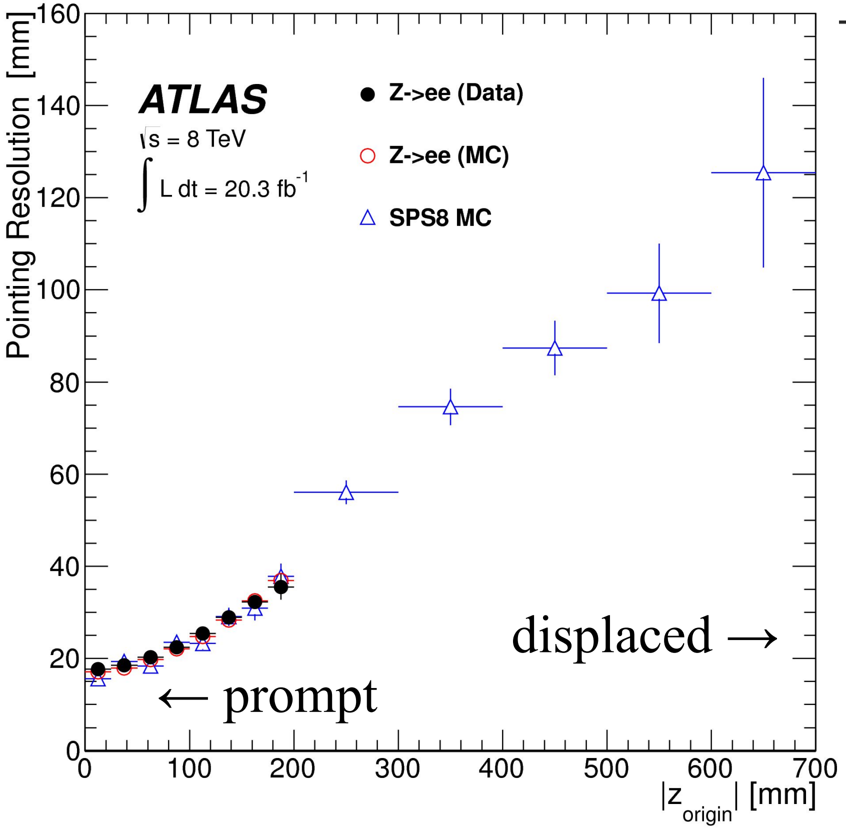
1.5 m away from the beam line

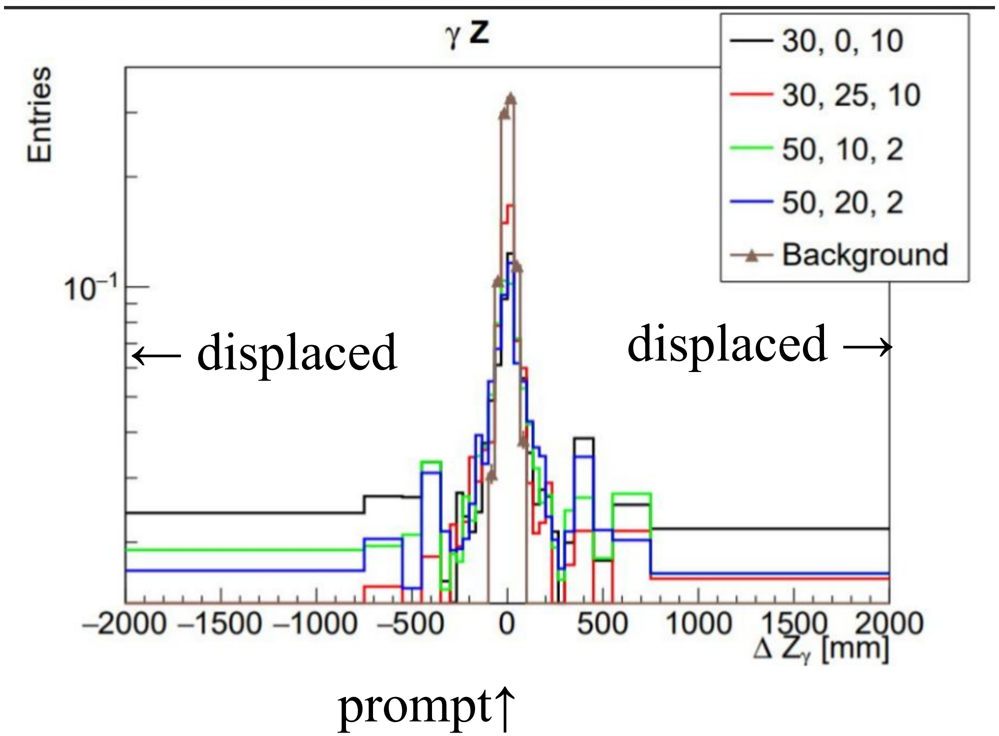


Photon Pointing



Resolution of Photon Pointing

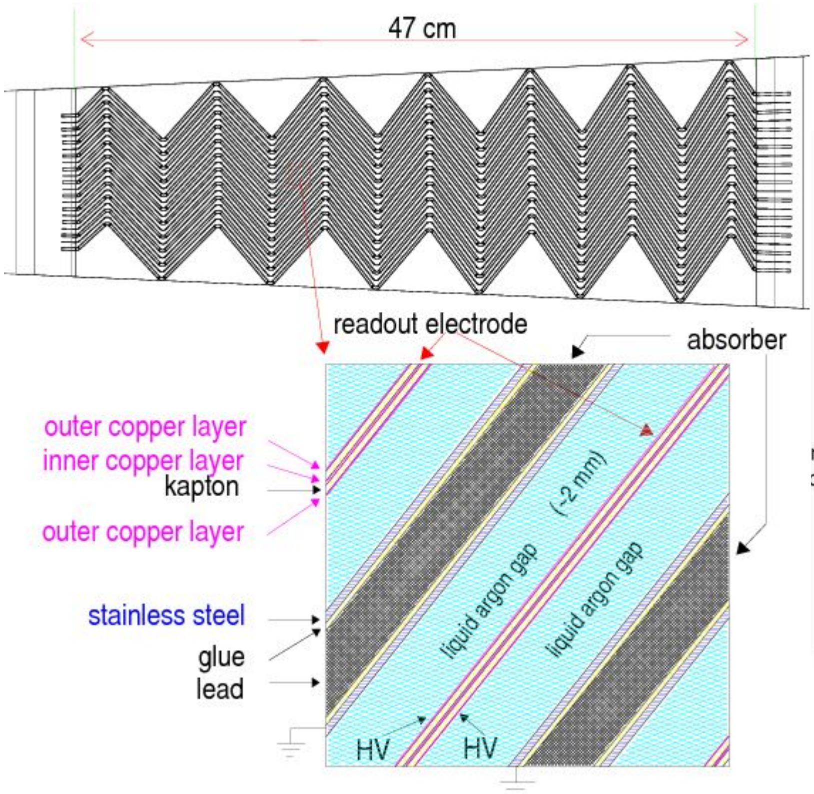


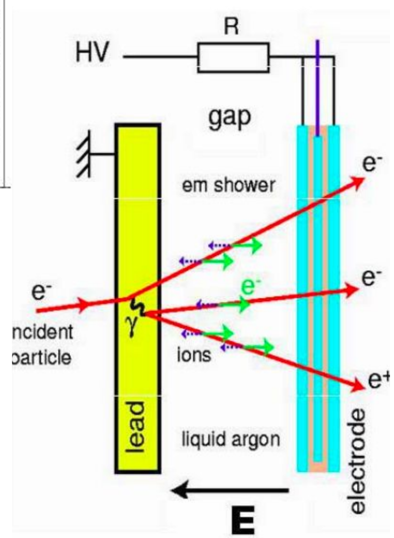


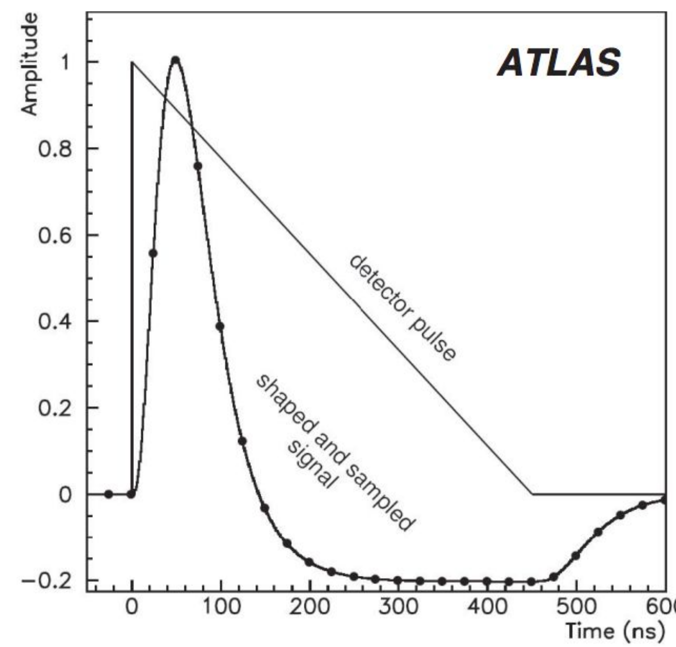
Resolution is ~ 20 - 25 % with respect to the displacement

for prompt cases, resolution can be validated using electrons from Z decays

How we measure timing



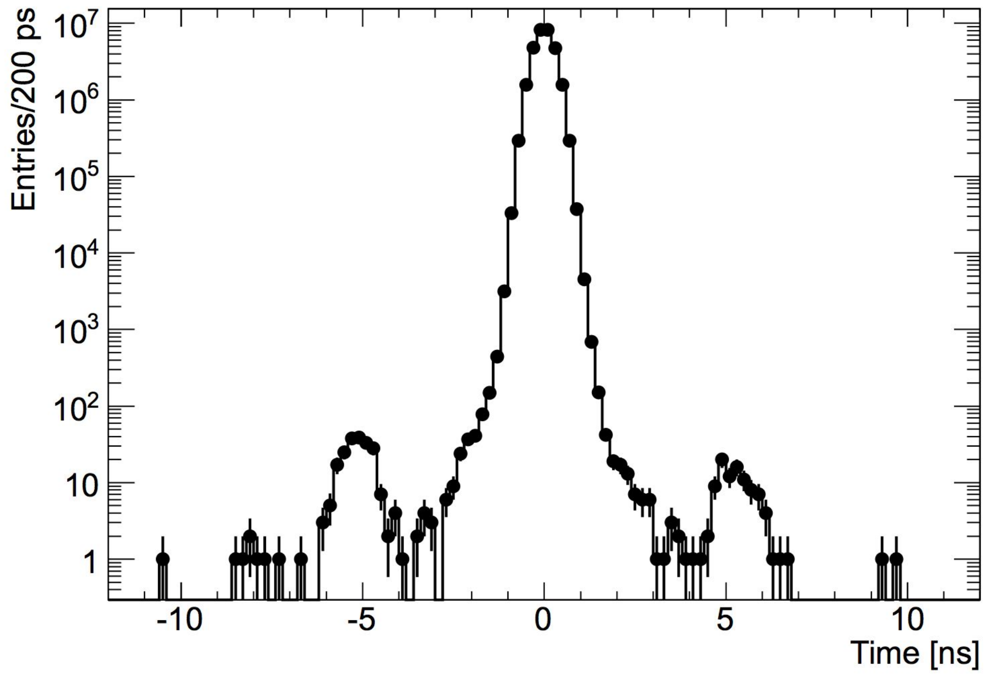




Ionization signal pulse is shaped to a known form

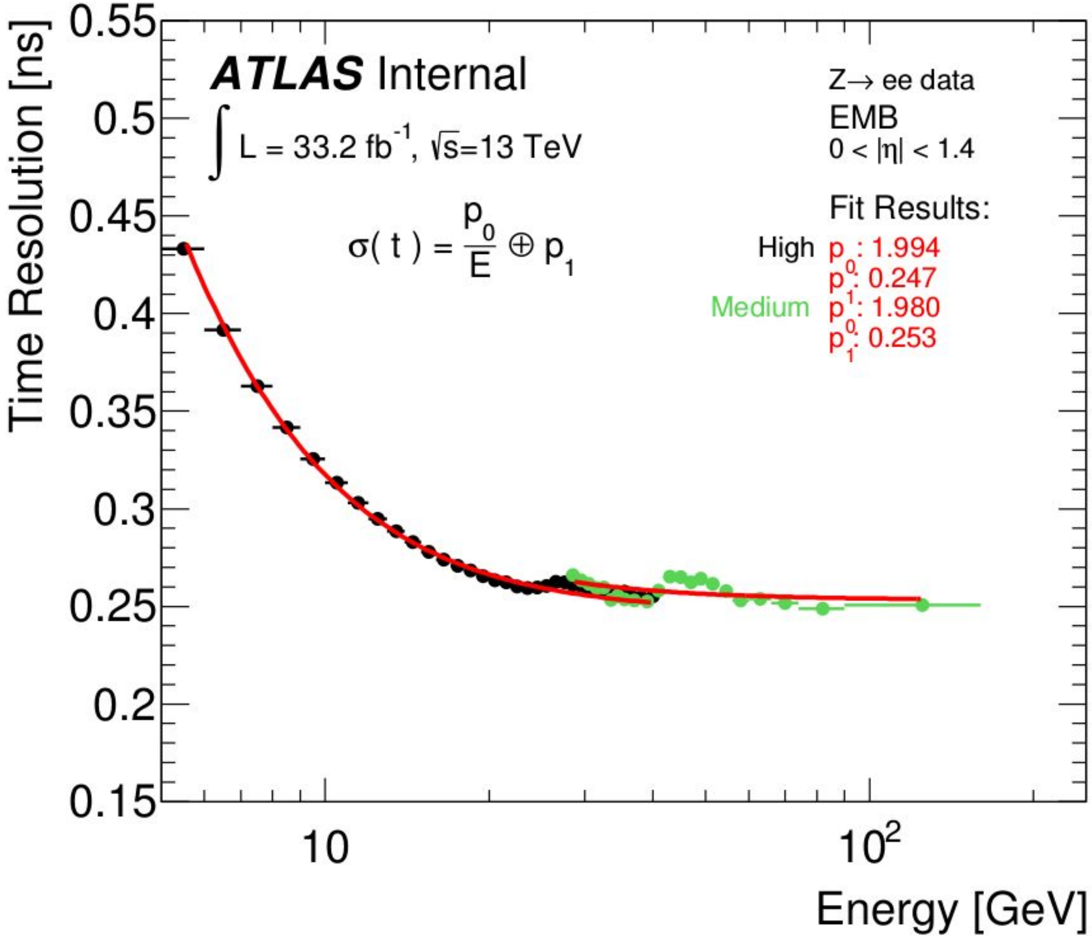
Five samplings determine the amplitude and timing

Verify timing measurement with "satellite" collisions



- LHC main accelerator bunch spacing - 25 ns
- upstream accelerators run at higher RF - bunch spacing ~ 5 ns
  - small fraction "leaked" to the main accelerator
  - collisions at +/- 5 ns, known as "satellite collisions"
- Verified using $Z \rightarrow ee$ events
  - every entry has a pair of electrons, with mass = m_Z
  - so they are not junks

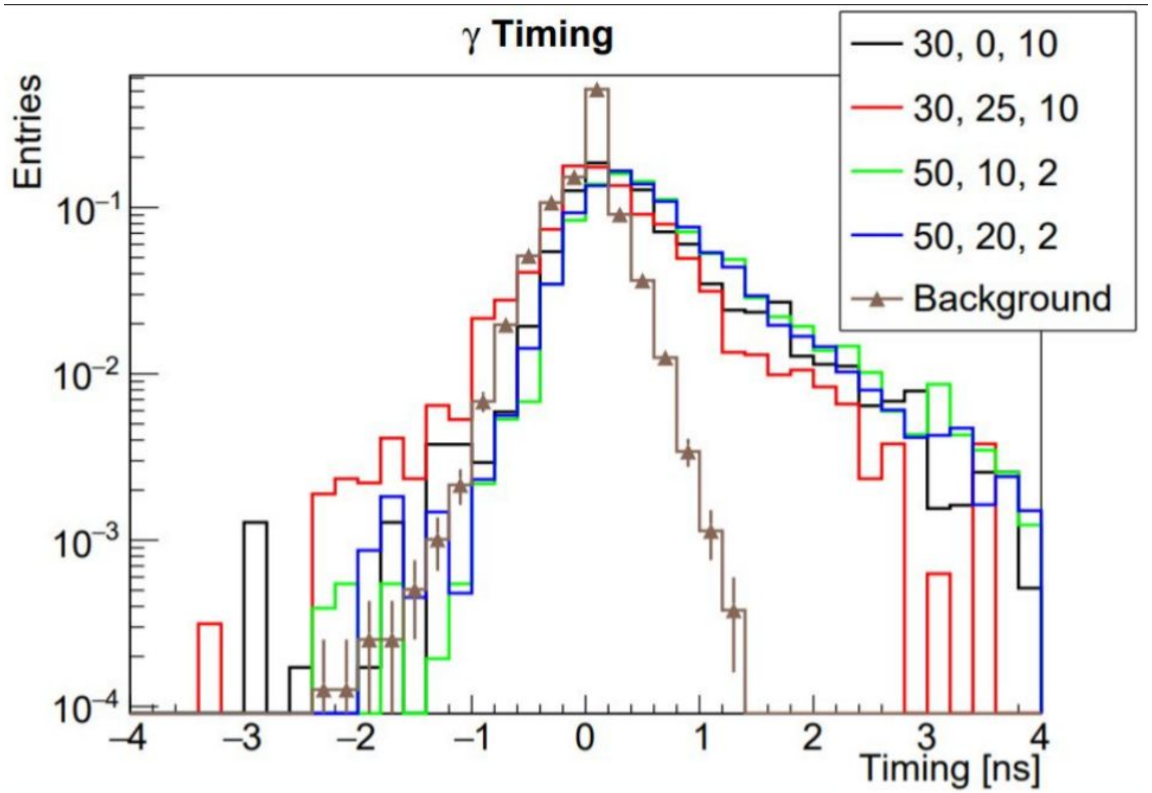
Resolution of timing



can be as good as 250 ps

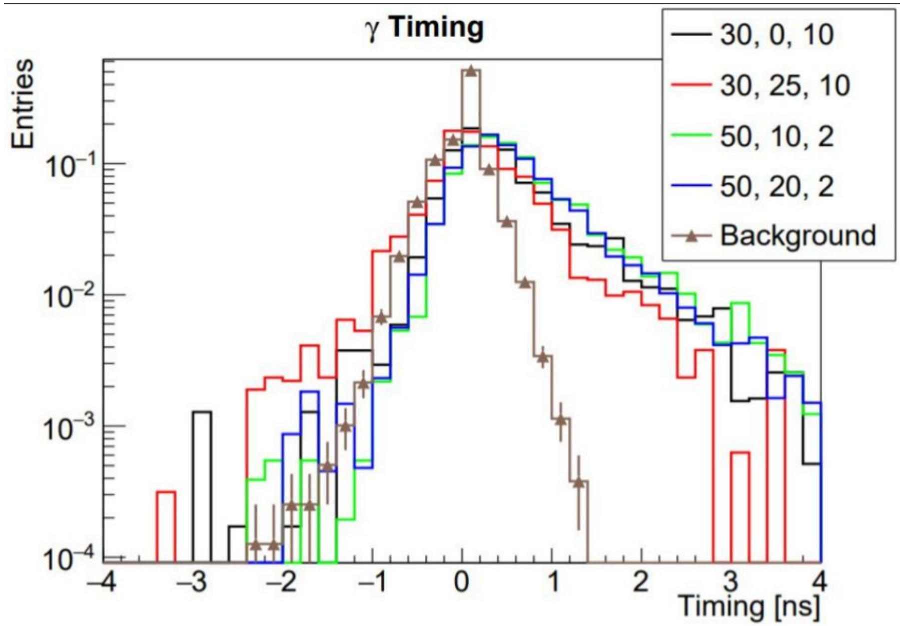
sensitive to photons delayed by 1 ns or more

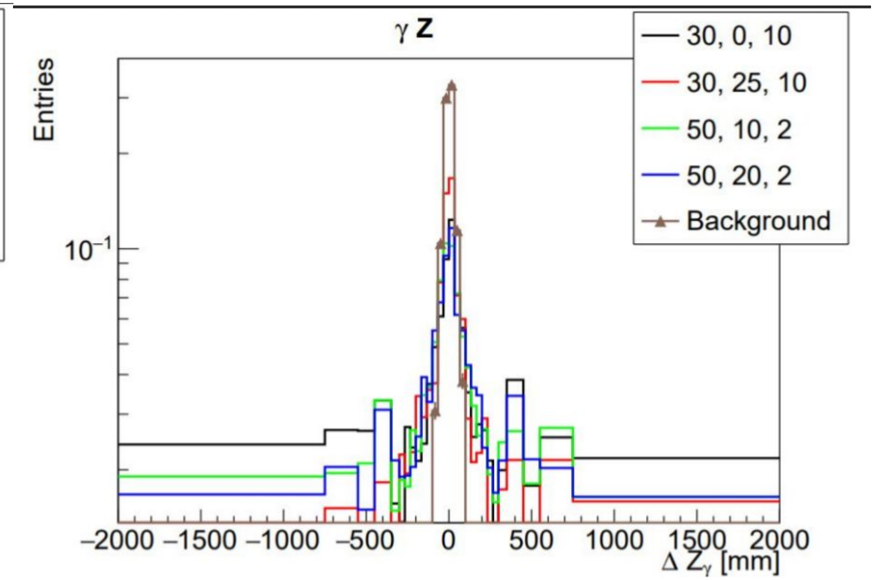
How does signal look like?



Signals are more likely to show up at region with large timing values (i.e., delayed)

How does signal look like?





- In the final analysis, we will combine timing and pointing
    - There is still a lot development and optimization
- We project that our sensitivity is at ~ 2% level in terms of Higgs decay branching ratio

Closing remark

- I discussed one search project that uses unique capabilities of our detector. I hope this gives you a sense about what we do with the ATLAS experiment

- The physics program at the LHC is very rich

  Higgs boson ✅
  Supersymmetry?
  Extra space dimensions?
  Dark Matter particles?
  New source of CP-violation?
  Flavor violation?
  New quarks and leptons?
  Heavy neutrinos?
  New interactions?