



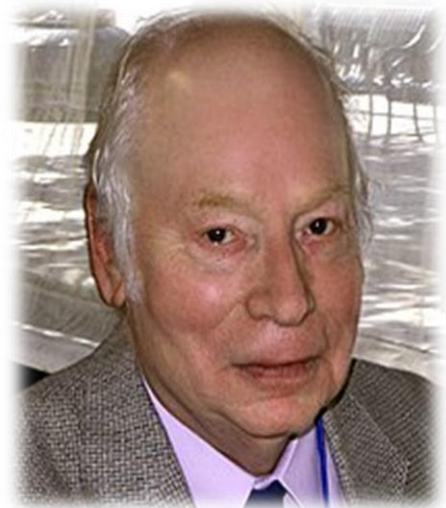
# Discovering the Higgs boson in $H \rightarrow ZZ$ channel using the ATLAS open data

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# The building blocks of our world?

- What makes up the world around us?
- What gives us mass?



# Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

**QUARKS** (purple text)

**LEPTONS** (green text)

**GAUGE BOSONS VECTOR BOSONS** (red text)

**SCALAR BOSONS** (yellow text)

**Great success!**



*Since all models are wrong, the scientist must be alert to what is importantly wrong. It is inappropriate to be concerned about mice when there are tigers abroad.*

– George Box

# Problems with the Standard Model

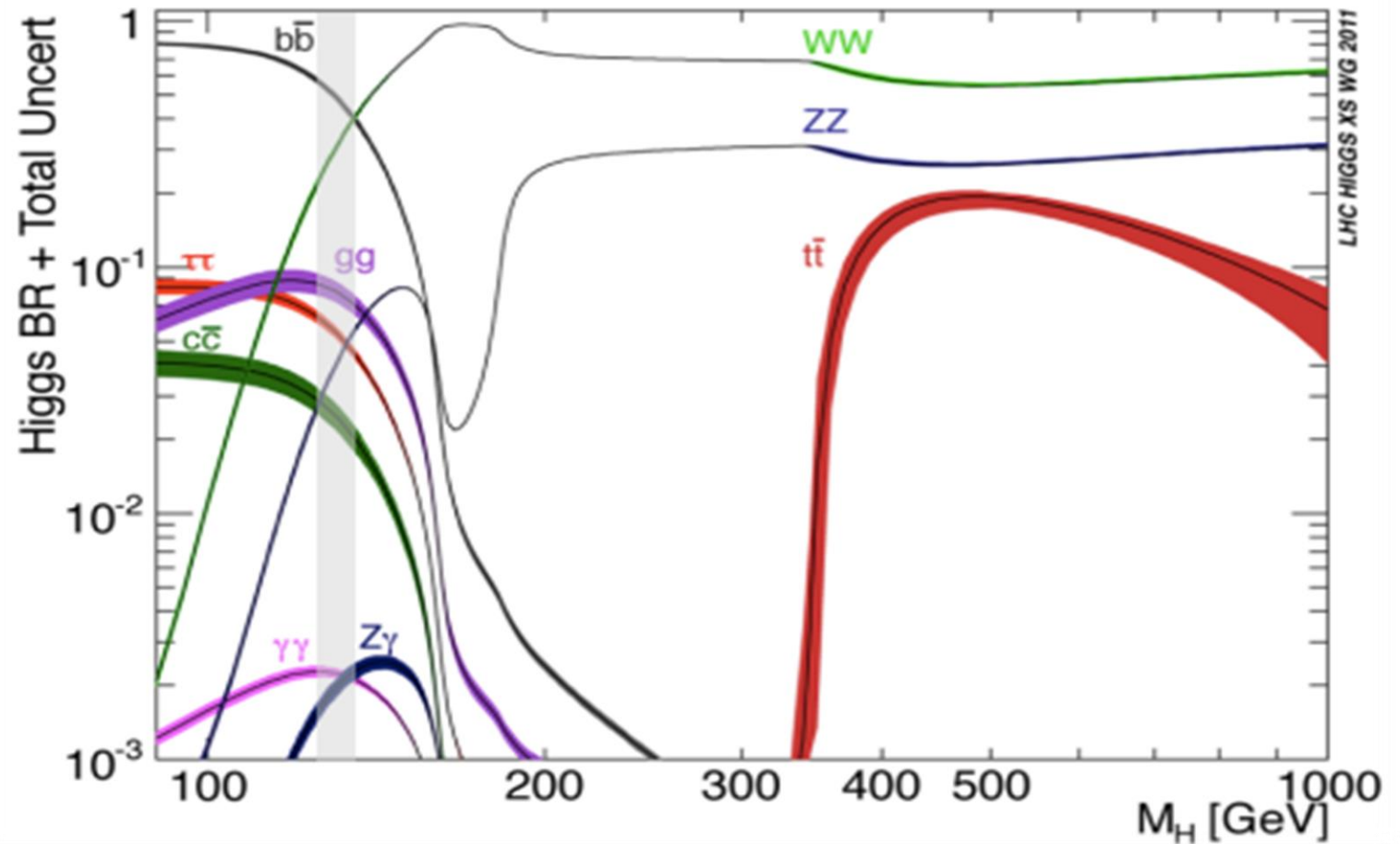


- Unexplained phenomena:
  - Grand Unified Theory? → Quantum Theory of Gravity
  - More matter than anti-matter? → Baryon asymmetry
  - Universe's accelerating expansion?
  - What is 95% of the universe made of? → Dark matter & dark energy
  - Neutrino oscillations? → Small mass of neutrinos
- Predicted particles:
  - Top quark (1995)
  - Tau neutrino (2000)
  - **Higgs boson** (2012)

# Higgs boson decay into four leptons

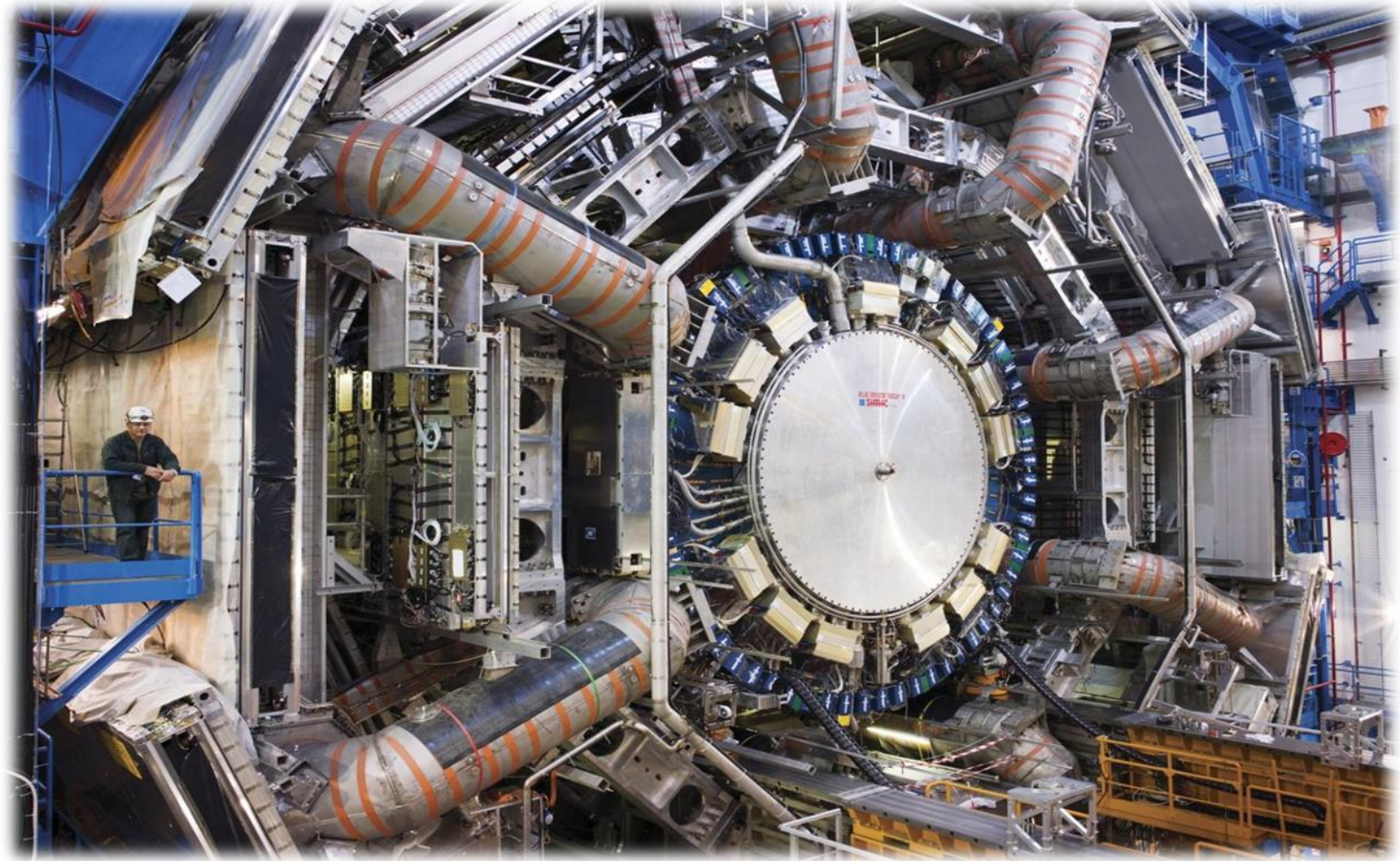
- Only **two out of 100** decay into a pair of Z bosons
- **Seven out of 100** Z bosons decay into 2 leptons (electrons or muons)
- **One out of 10000** - branching fraction

Decay modes and branching ratios as function of  $m_H$



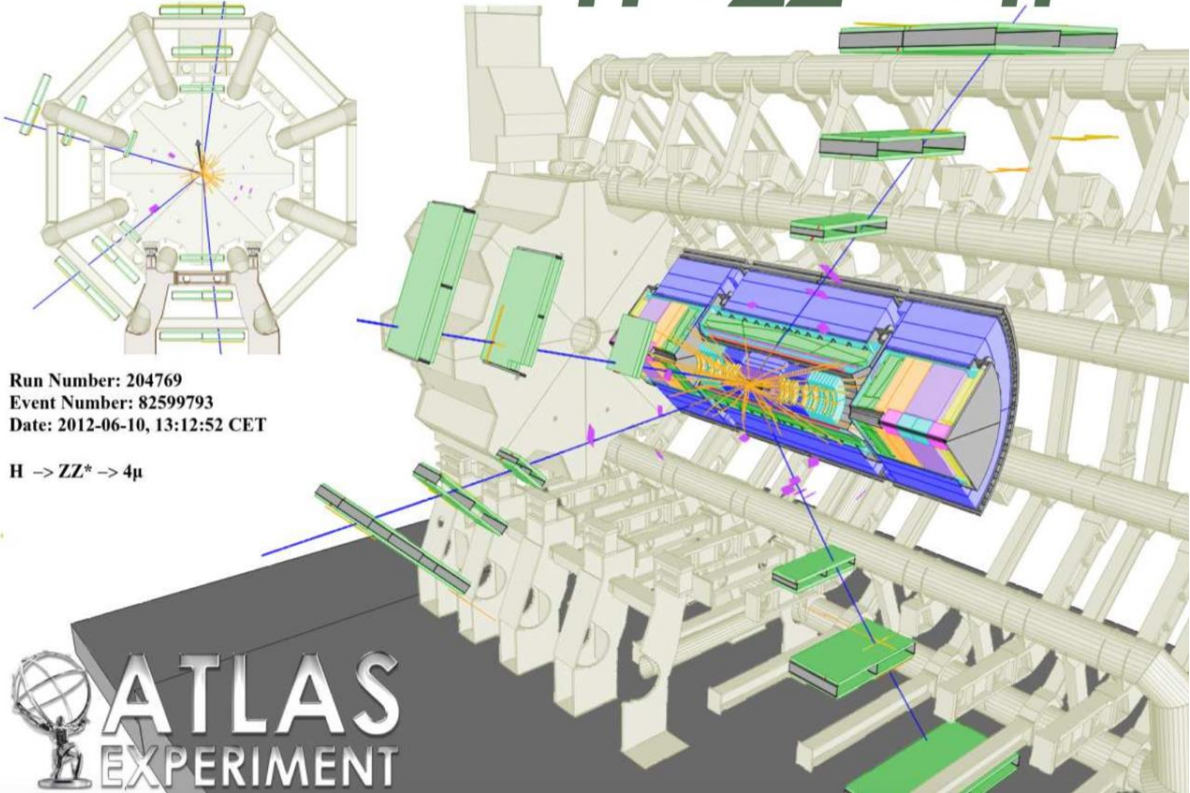
# ATLAS detector and its triggers

- The largest detector ever constructed
- Made to gather clues about the particles – speed, mass and charge
- 40 million collision events every second → only 1000 selected



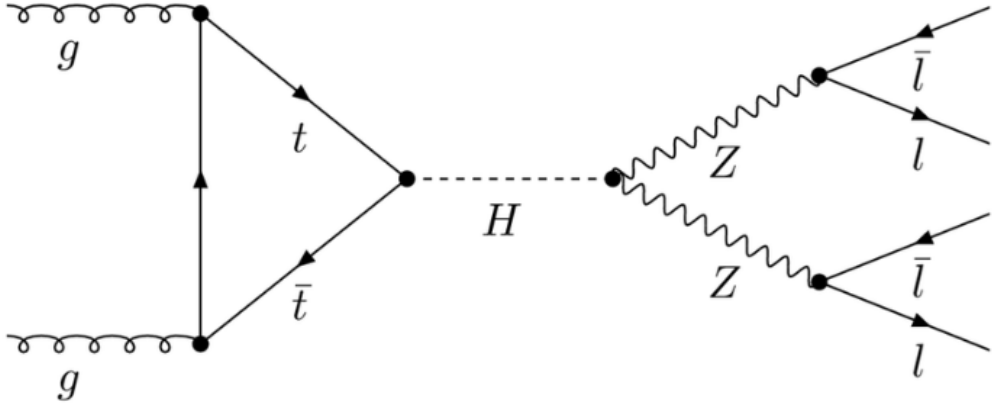
# HZZ decay – real event

**$H \rightarrow ZZ^* \rightarrow 4l$**



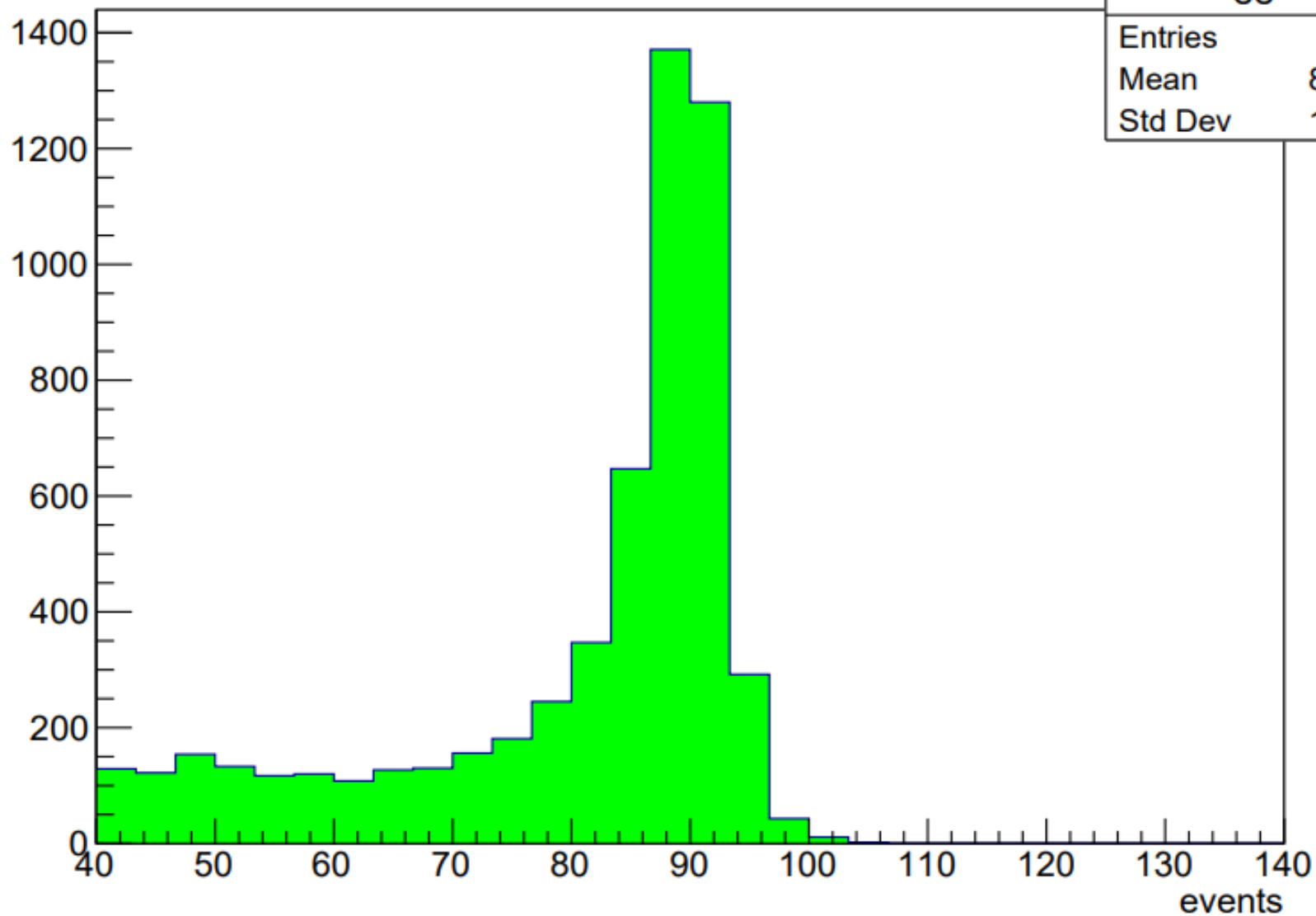
Run Number: 204769  
 Event Number: 82599793  
 Date: 2012-06-10, 13:12:52 CET

$H \rightarrow ZZ^* \rightarrow 4\mu$



- Actual 2012 event
- Production of 4 muons
- Higgs boson production and decay diagram

# Mass of the Z boson

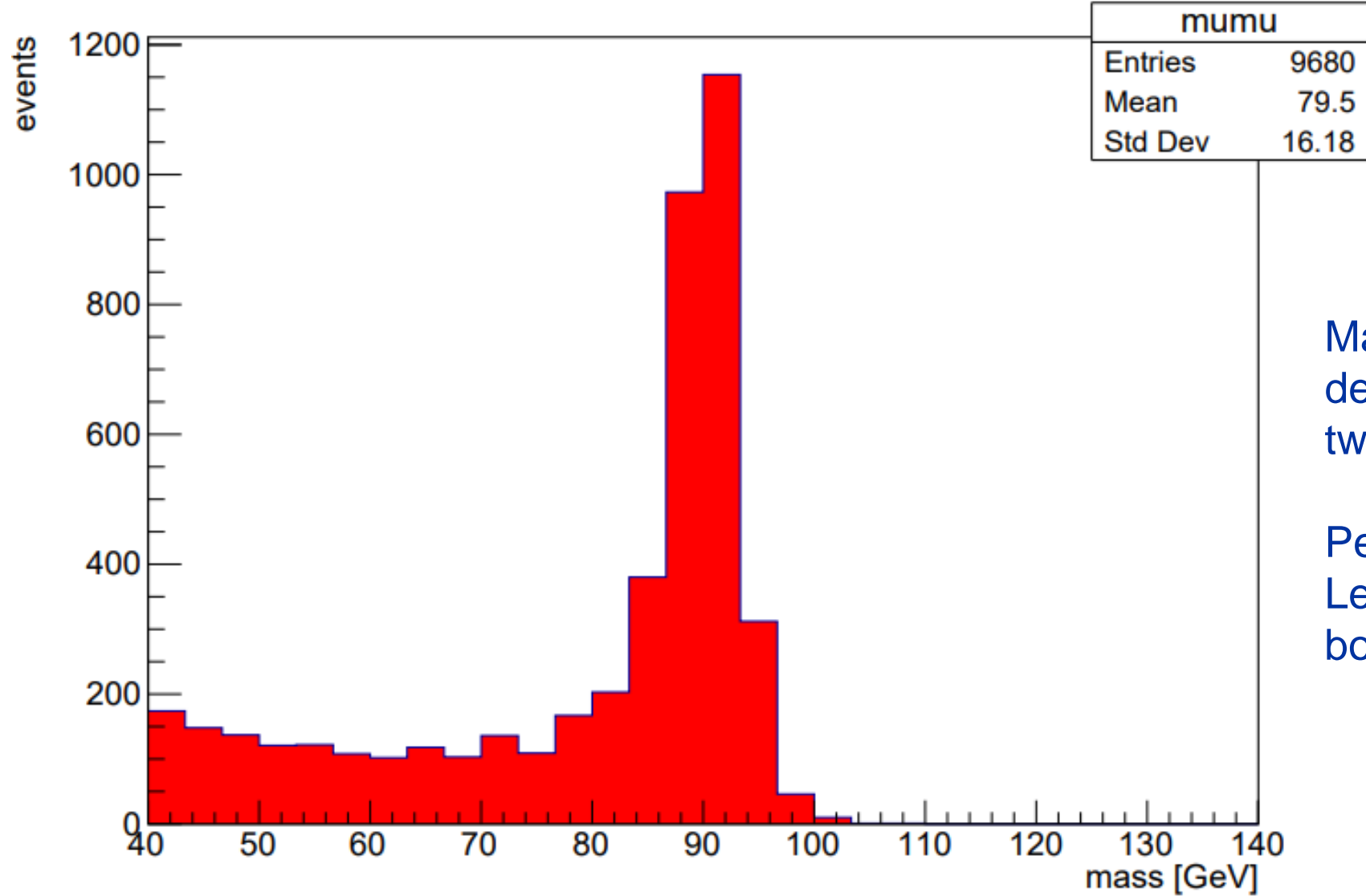


Mass of the Z boson derived from the mass of two electrons

Peak at 90 GeV  
Left tail: one off-shell Z boson



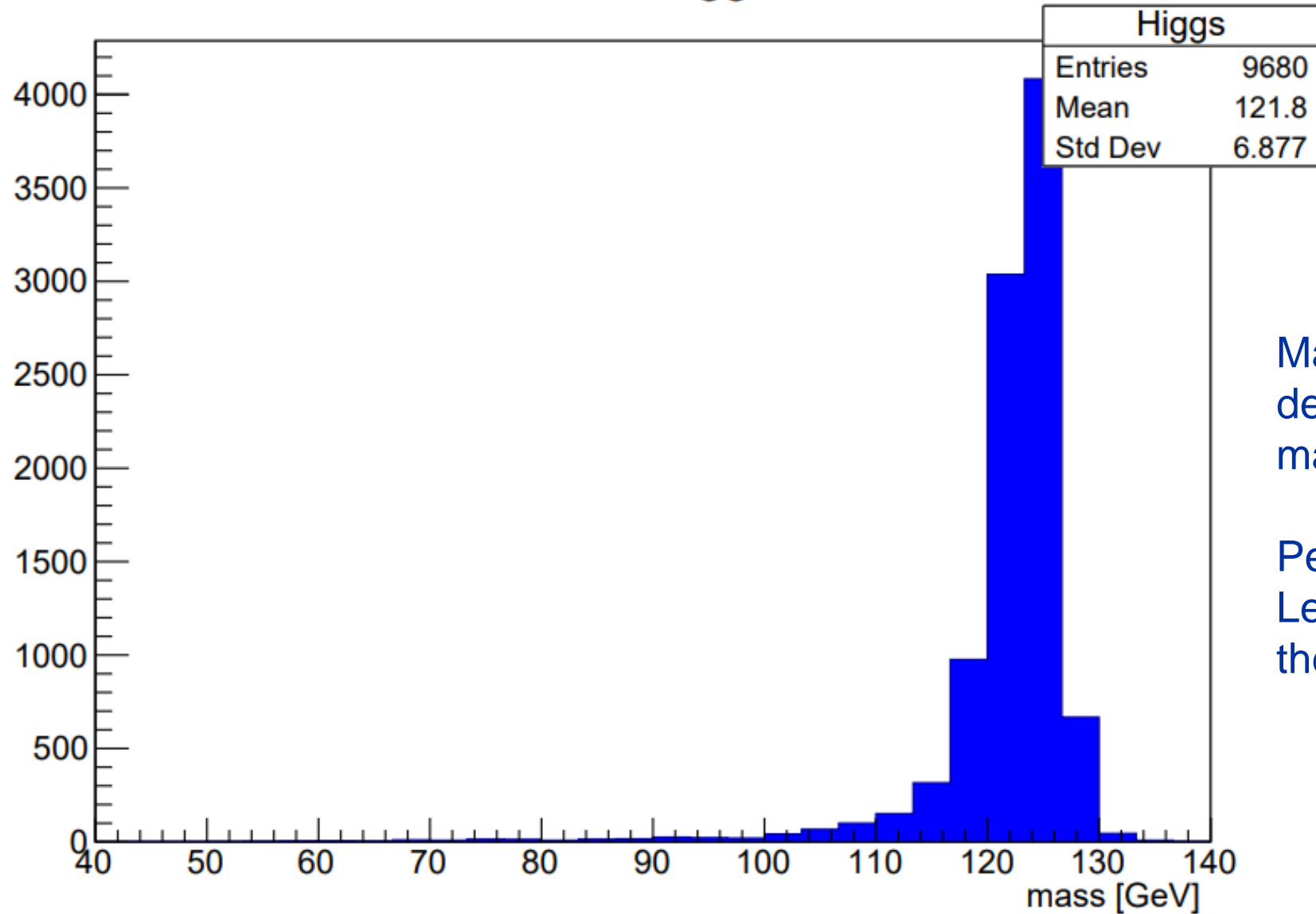
# Mass of the Z boson



Mass of the Z boson derived from the mass of two muons

Peak at 90 GeV  
Left tail: one off-shell Z boson

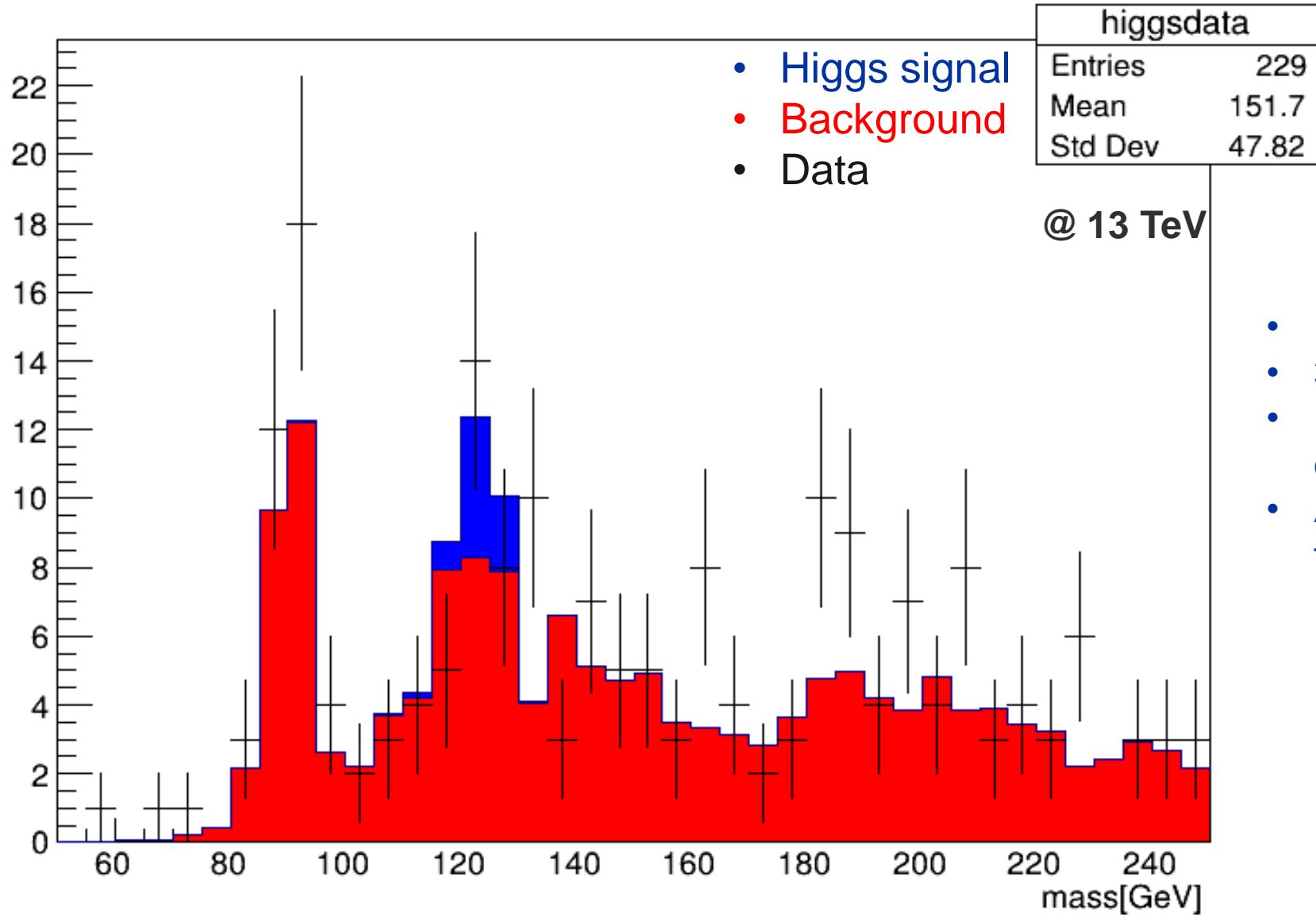
# Mass of the Higgs boson



Mass of the Higgs boson derived from muon and electron mass measurements

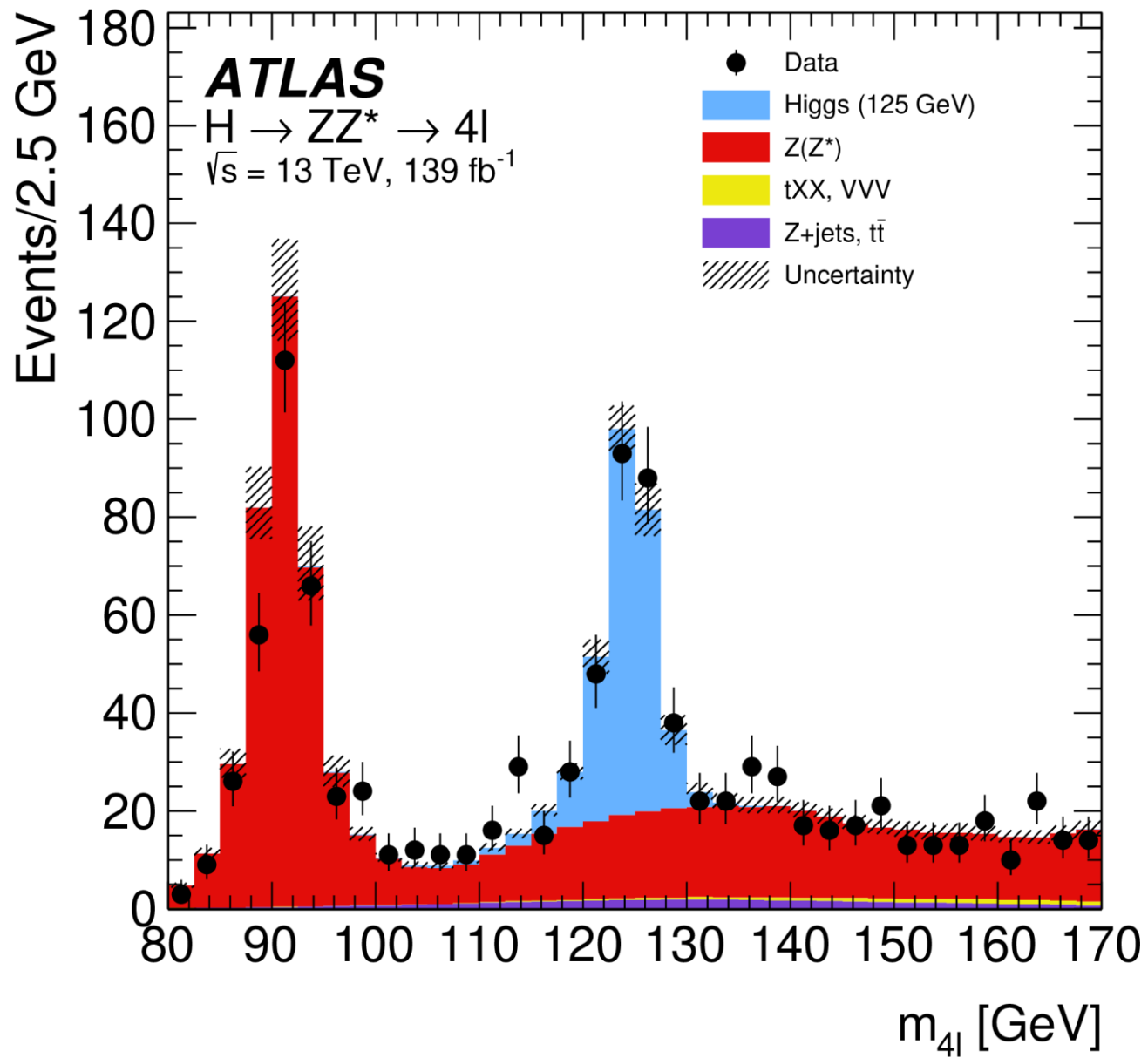
Peak at 125 GeV  
Left tail: small loss of energy on the lepton

# Mass of the Higgs boson

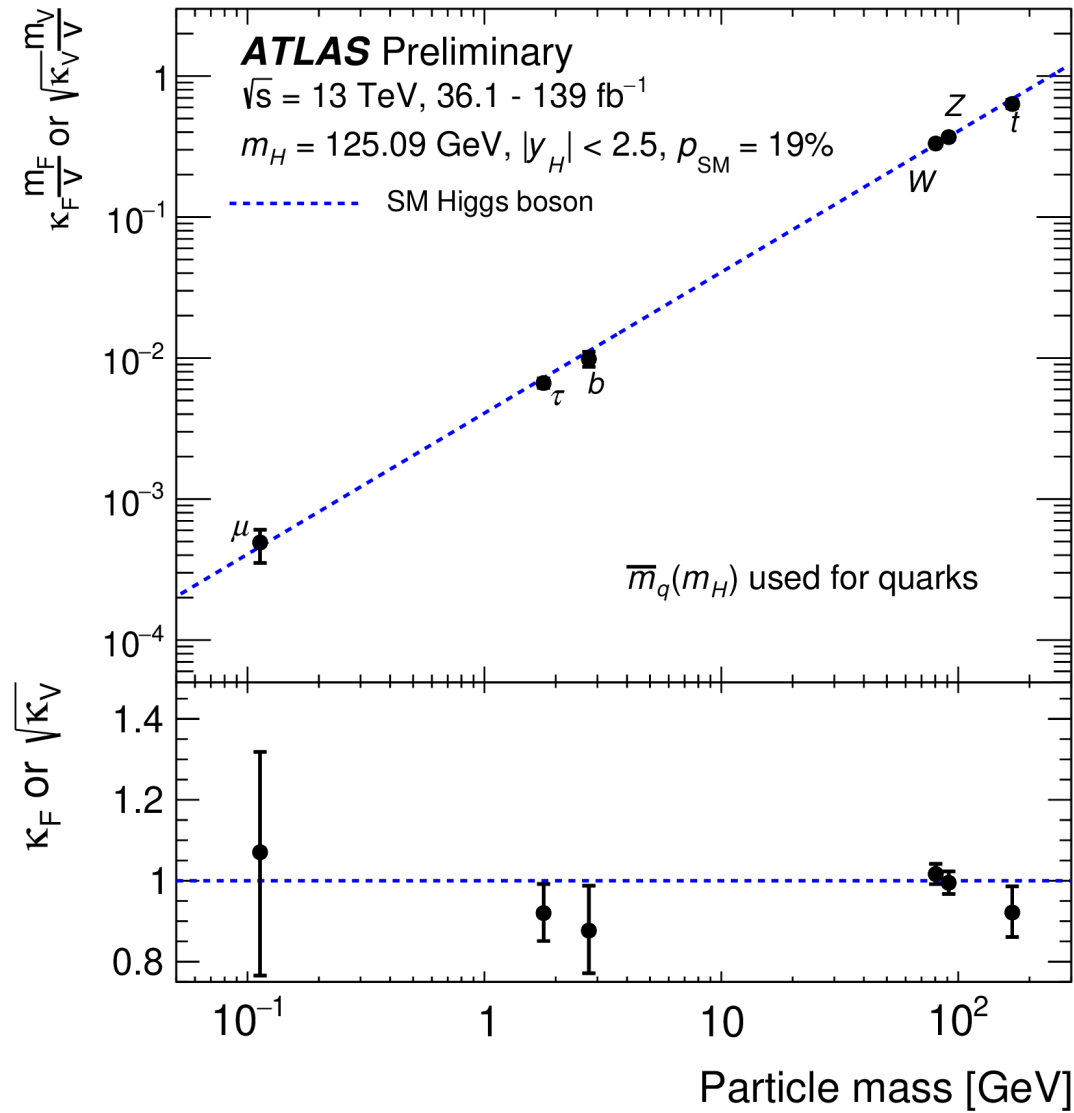


- Higgs signal
- Background
- Data

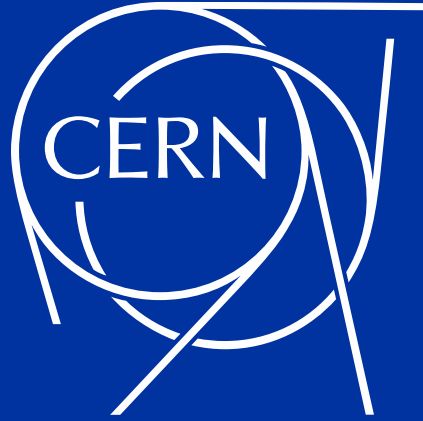
- Higgs peak at 125 GeV
- 30 events
- Peak at Z mass (likely from Z decay to four lepton)
- A small bump at 180 GeV (possibly from two Z background)



- Ten years after the discovery (more precise)
- How well do we compare?
- Two peaks, little uncertainty

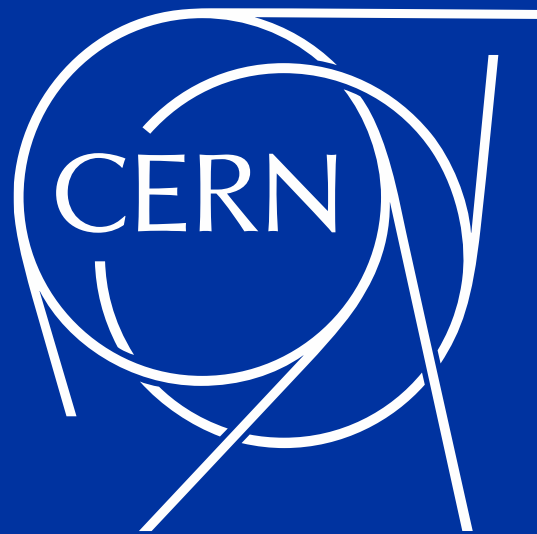


- Standard Model → a very successful theory
- So far measured interaction of Higgs boson with: top, Z, W, bottom, tau, muon
- Left to measure: Higgs, charm, strange, down, up, electron



*The need to do research is a part of our  
humanity... So, I think there will always be  
a CERN.*

– Maria Fidecaro



Thank you for your attention!