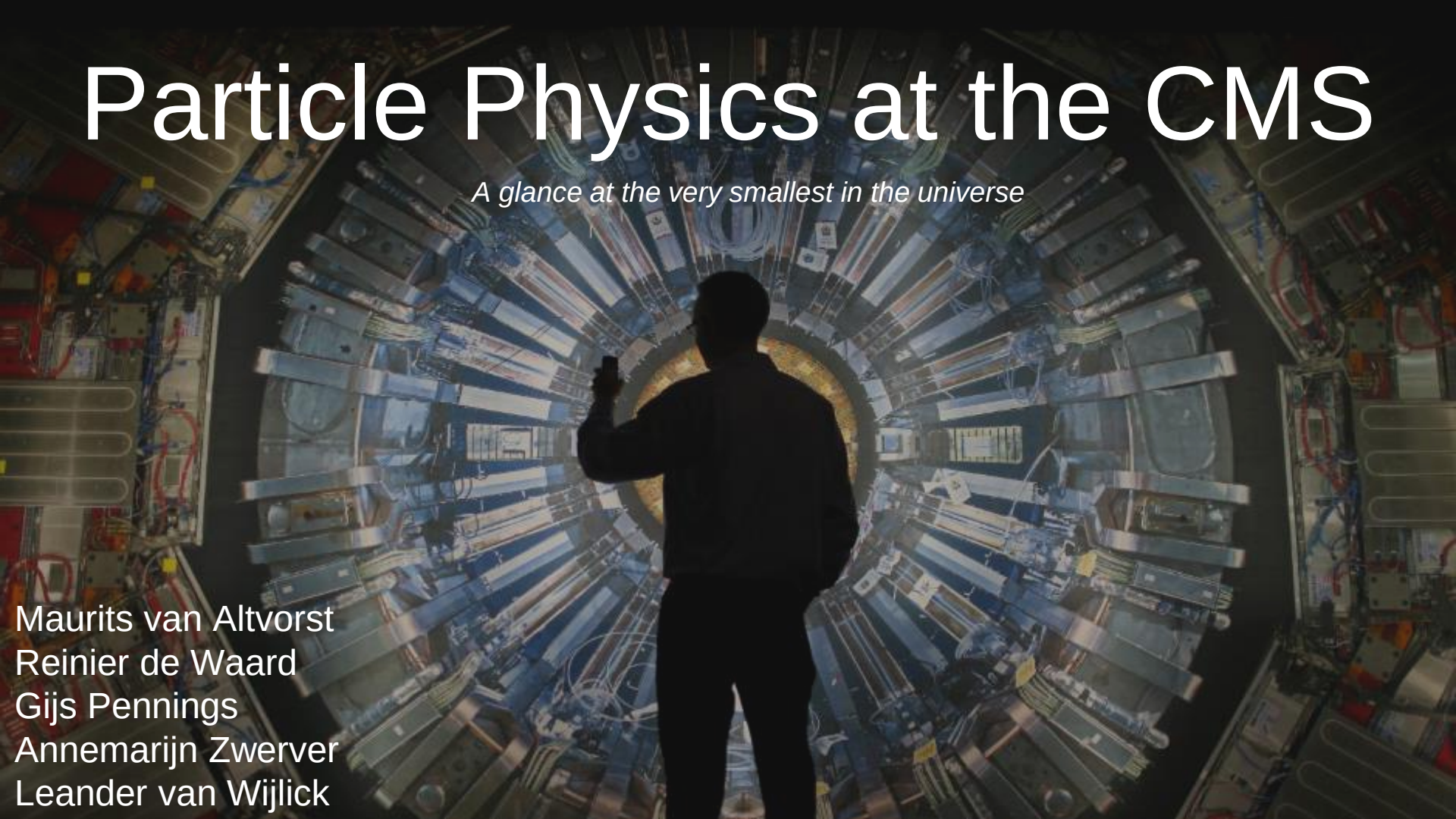
Particle Physics at the CMS

A glance at the very smallest in the universe



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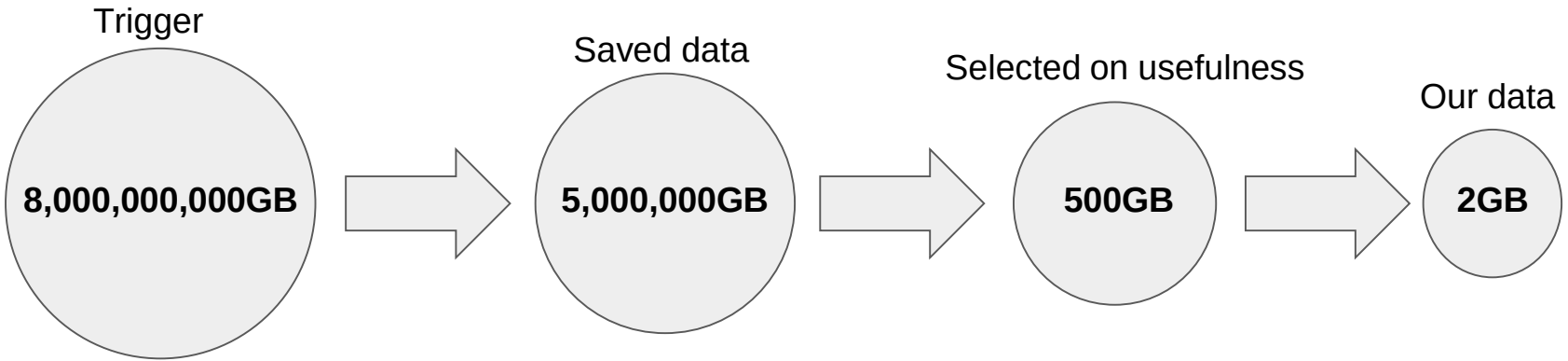
Annemarijn Zwerver
Leander van Wijlick

General Description



General Description

- Goals: find special elementary particles and their properties

```
// Structure that will contain all information for one event
struct CustomMiniEvent_t
{
  Bool_t isData;
  UInt_t run,event,lumi;
  Int_t NrLeptons;
  Int_t LeptonID[50], LeptonCharge[50];
  Float_t LeptonMass[50], LeptonPhi[50], LeptonEta[50],
          LeptonPt[50], LeptonE[50], LeptonPx[50],
          LeptonPy[50], LeptonPz[50];
};
```

ROOT

Data Analysis Framework

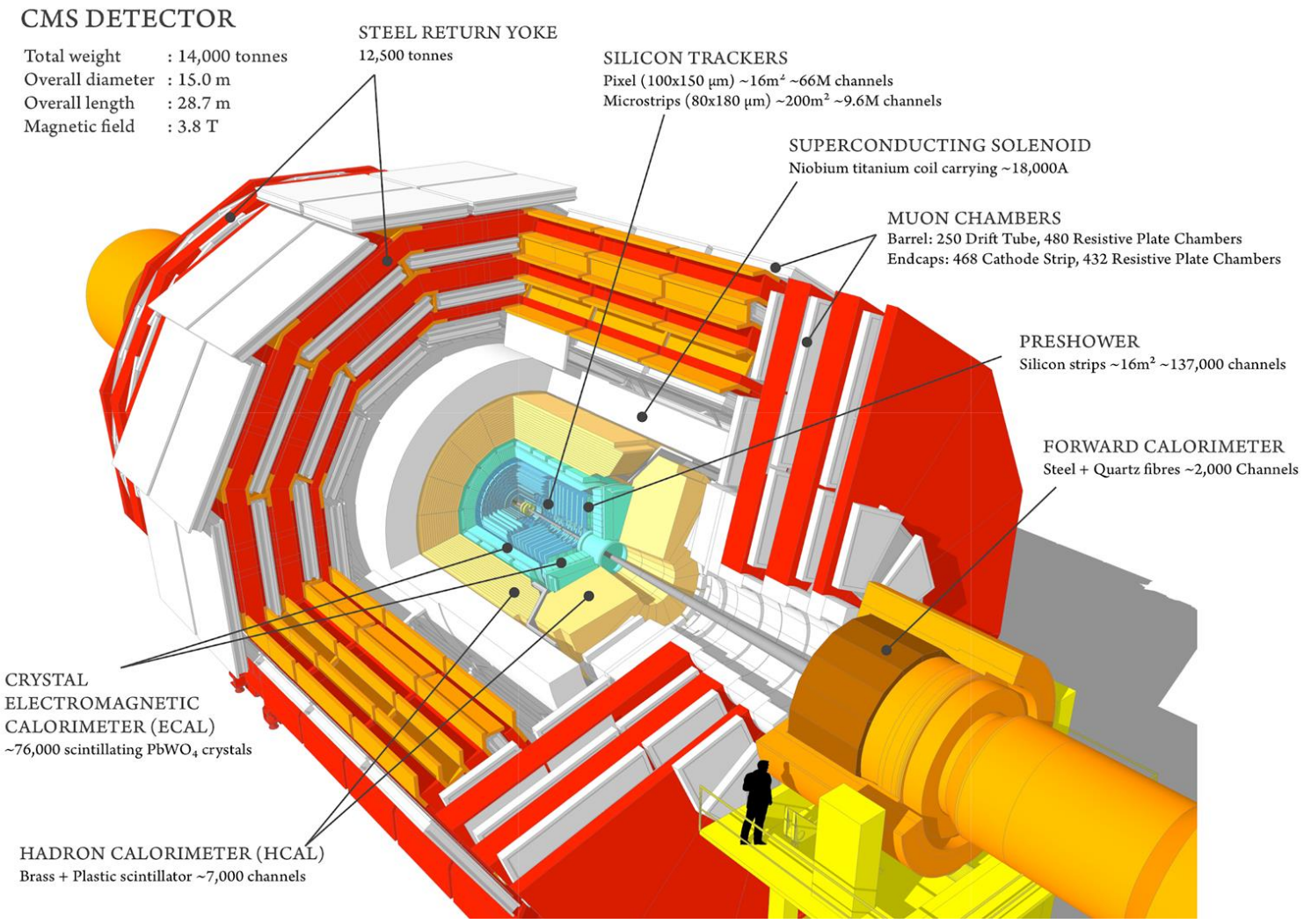
Table of Contents

Compact Muon Solenoid

- Same goals as ATLAS
- Better in detecting muons than in detecting electrons
- consist of multiple layers

TABLE 2 Main design parameters of the ATLAS and CMS detectors

Parameter	ATLAS	CMS
Total weight (tons)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

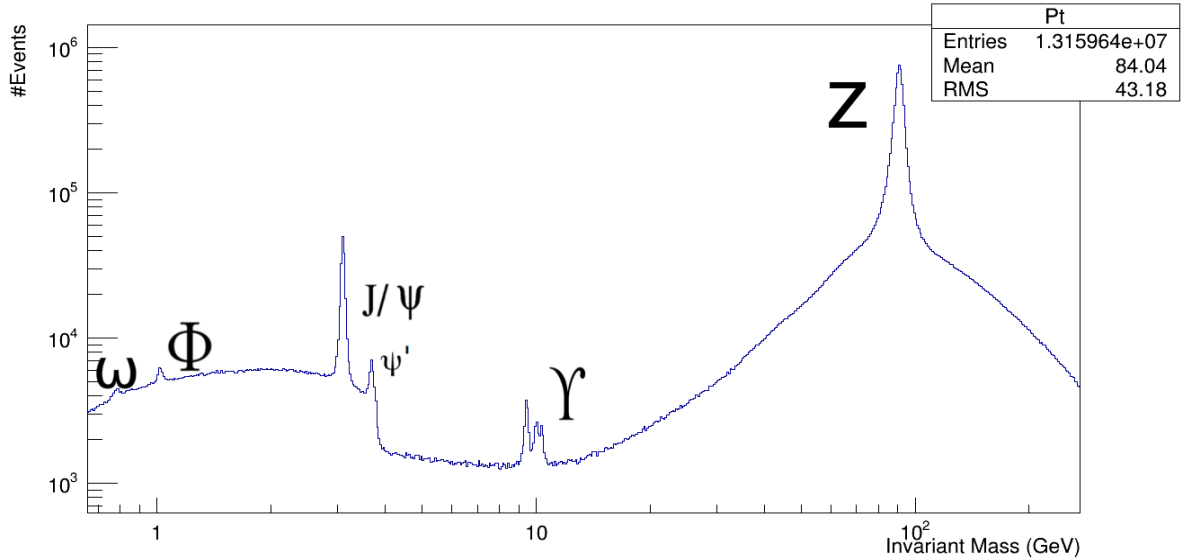
Calculated particle properties

- Newtonian mass vs. invariant mass
- $E^2 = p^2c^2 + m^2c^4$
- “Natural units”
- $E^2 = p^2 + m^2$
  - p is the sum of the momentum of all decay particles
    - Measured by the tracker
  - E is the sum of the energy of all decay particles
    - Measured by calorimeters
  - m is the invariant mass

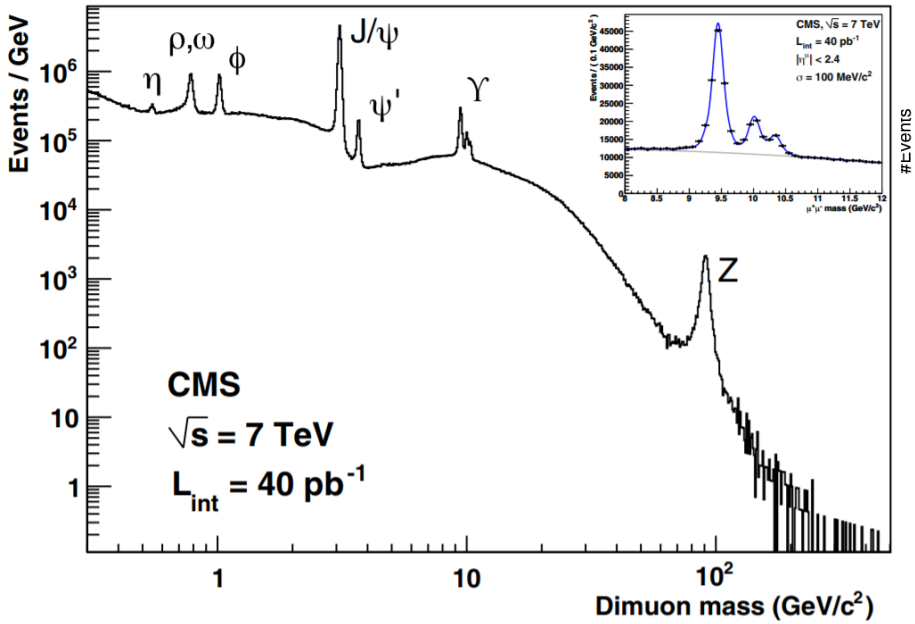
Unit	Metric value	Derivation
1 eV^{-1} of length	1.97×10^{-7} m	$= \frac{\hbar c}{1\,\mathrm{eV}}$
1 eV of mass	1.78×10^{-36} kg	$= \frac{1\,\mathrm{eV}}{c^2}$
1 eV^{-1} of time	6.58×10^{-16} s	$= \frac{\hbar}{1\,\mathrm{eV}}$
1 eV of temperature	1.16×10^{4} K	$= \frac{1\,\mathrm{eV}}{k_\mathrm{B}} \cdot \frac{2}{f}$ with $f = 2$
1 unit of electric charge (L–H)	5.29×10^{-19} C	$= \frac{e}{\sqrt{4\pi\alpha}}$
1 unit of electric charge (G)	1.88×10^{-18} C	$= \frac{e}{\sqrt{\alpha}}$

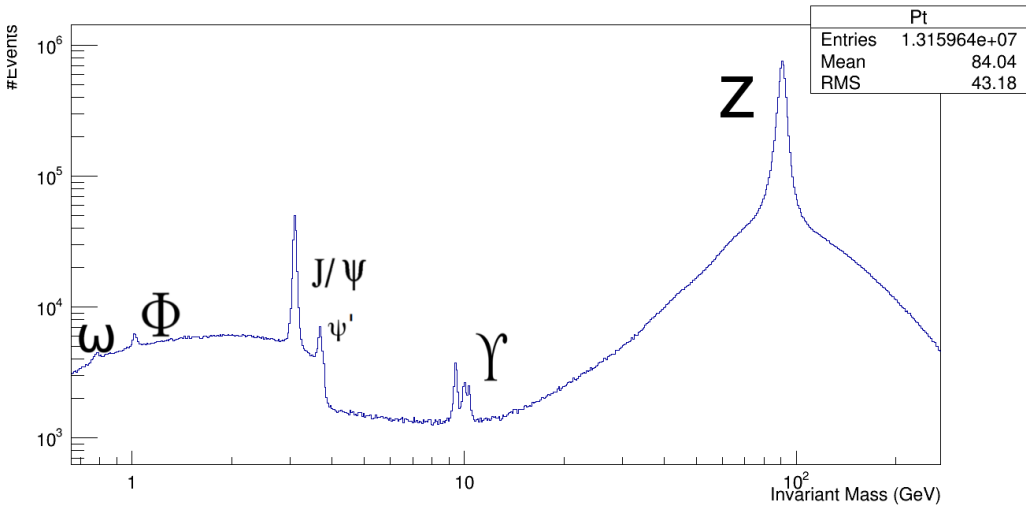
Overview of particles

- 2 leptons



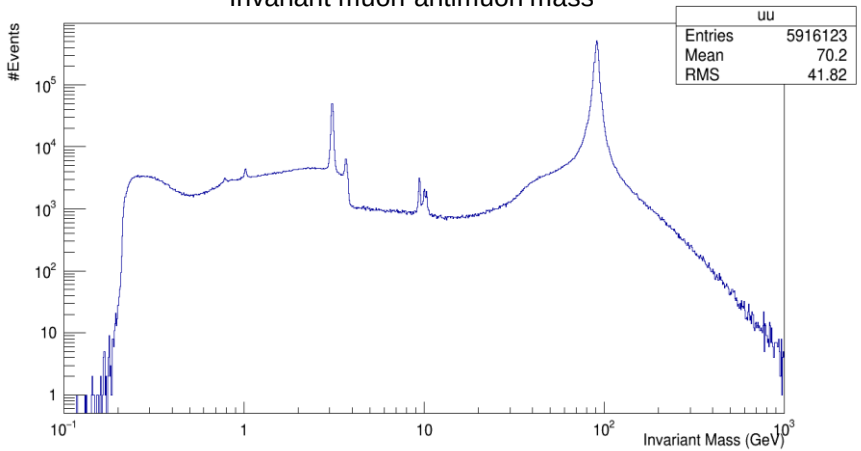
Comparison with official paper



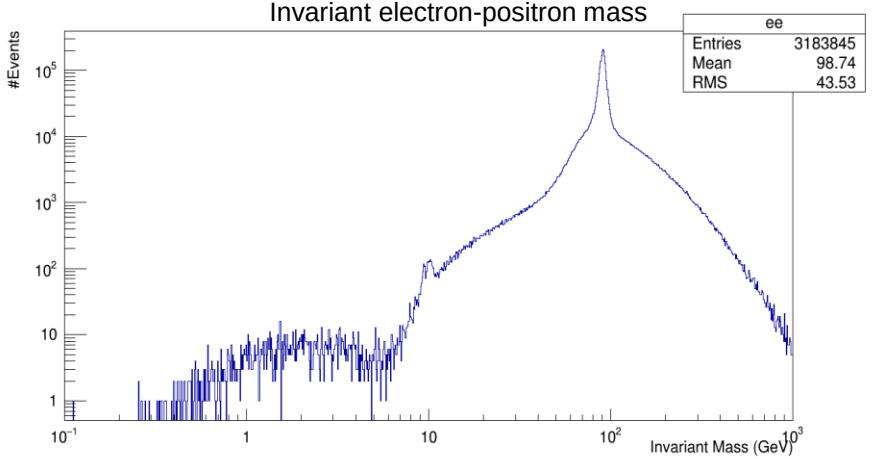


Detecting muons vs. electrons

Invariant muon-antimuon mass

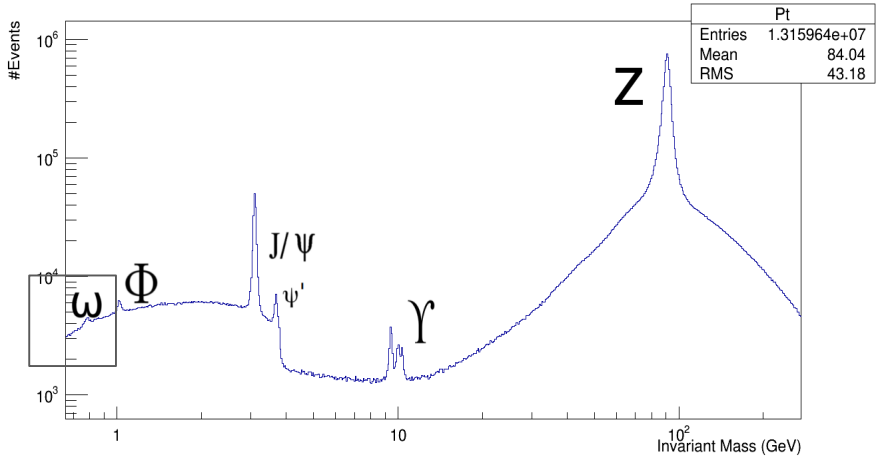


Invariant electron-positron mass



Omega (782)

- 782.65 MeV
- Was recorded in the 1960s
- consist of down, anti-down and up anti-up



Phi (1020)

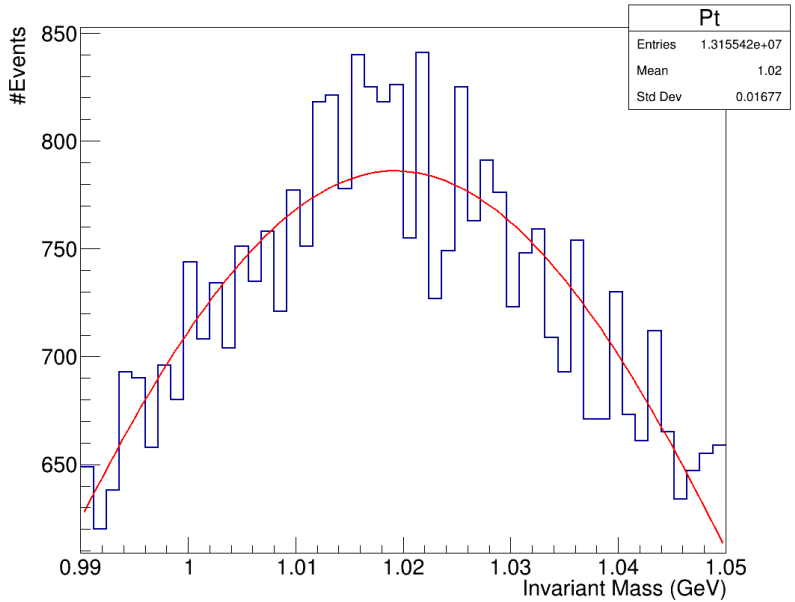
104 MeV/c^2

$-\frac{1}{3}$

$\frac{1}{2}$ S

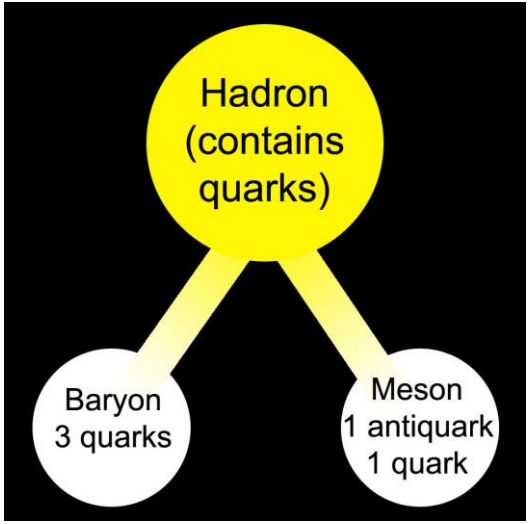
strange

- 1019 MeV
- 1972, Connolly, AGS
- strangeonium
- DAFNE
- decay
- OZI
- Gaussian fit

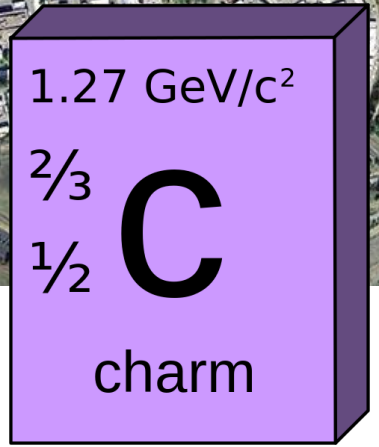


The first Quark Models

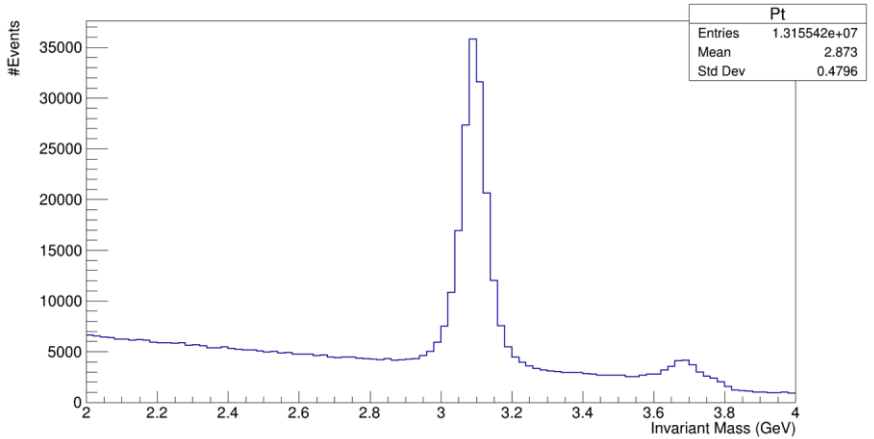
- First models: up, down and strange
- Stanford Linear Accelerator Center
- Deep inelastic scattering



J/psi meson

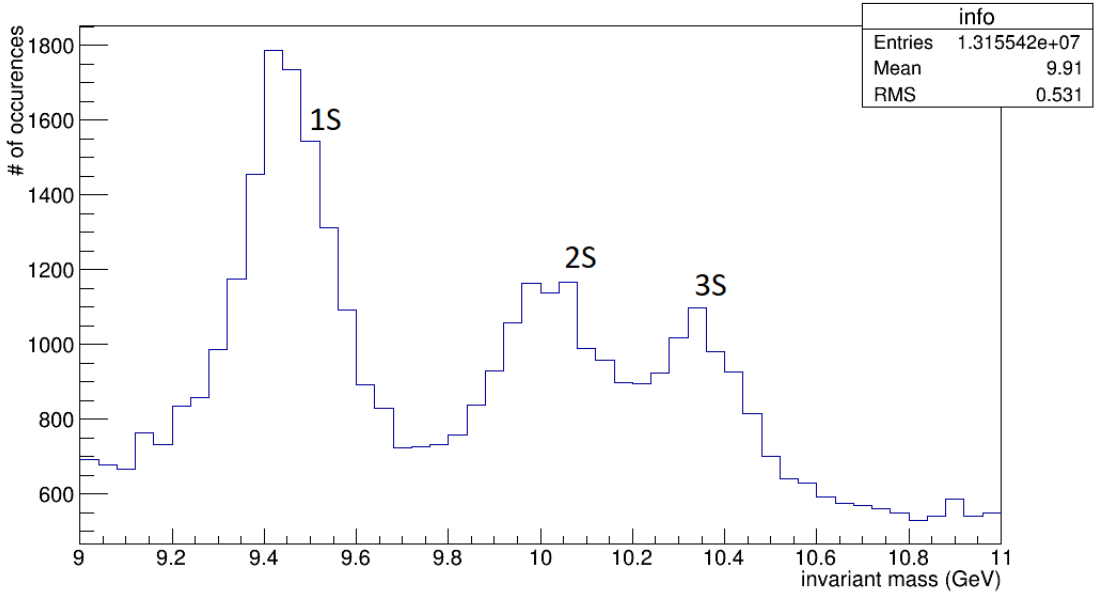


- charm, anti-charm
- SLAC and Brookhaven National Laboratory 1974
- Excited states

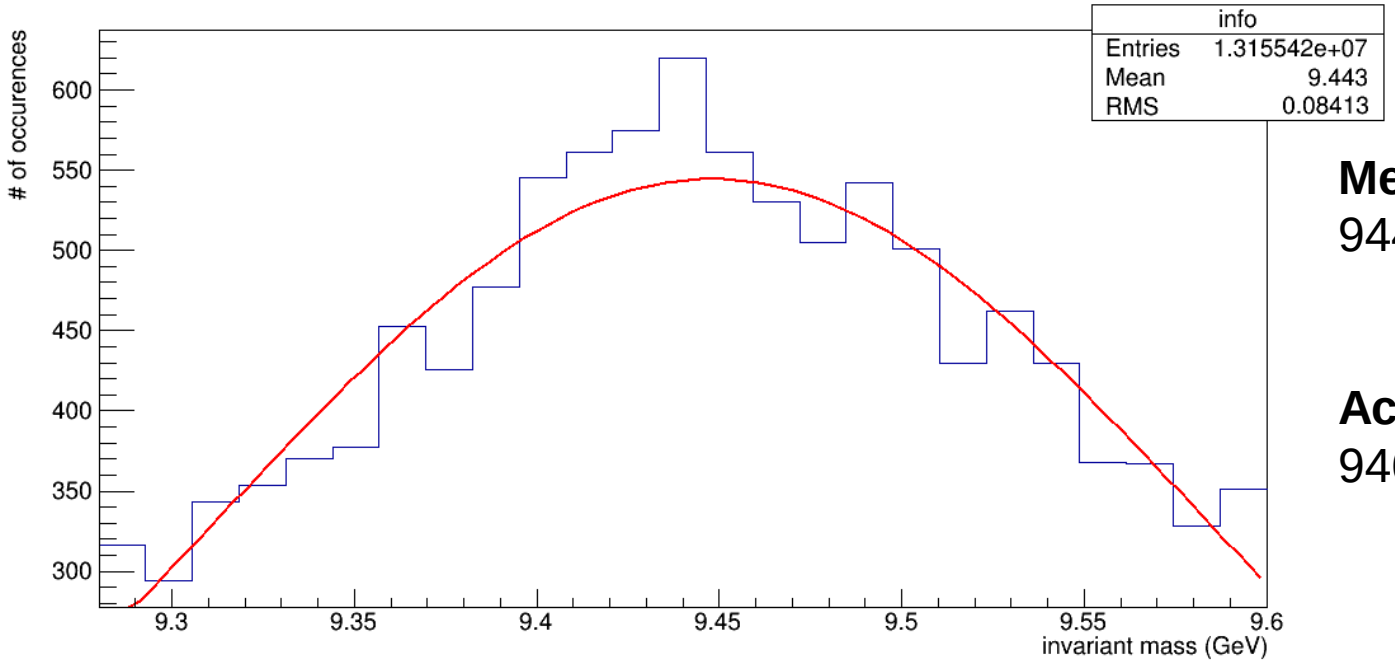


Upsilon meson (Υ)

- $b\bar{b}$ (bottomonium)
- 1977, Leon Lederman
- Tevatron, Fermilab
- ‘Oops-Leon’
- 5 excited states



Upsilon(1S) fit

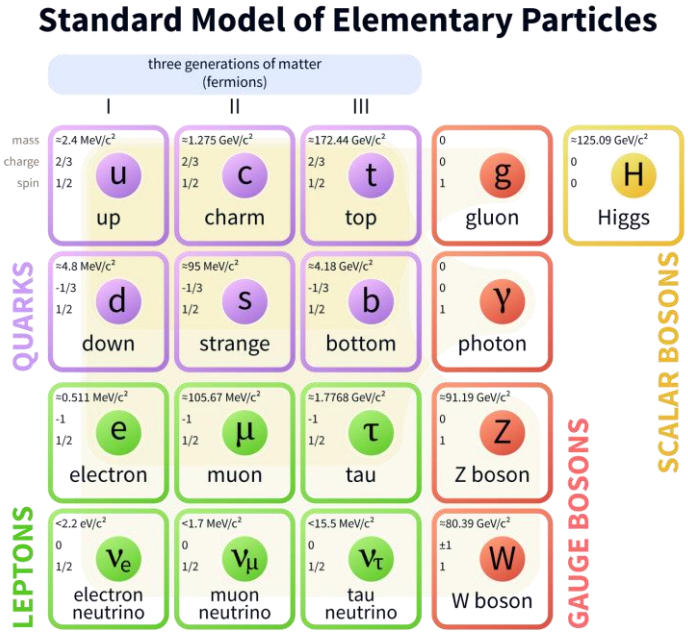


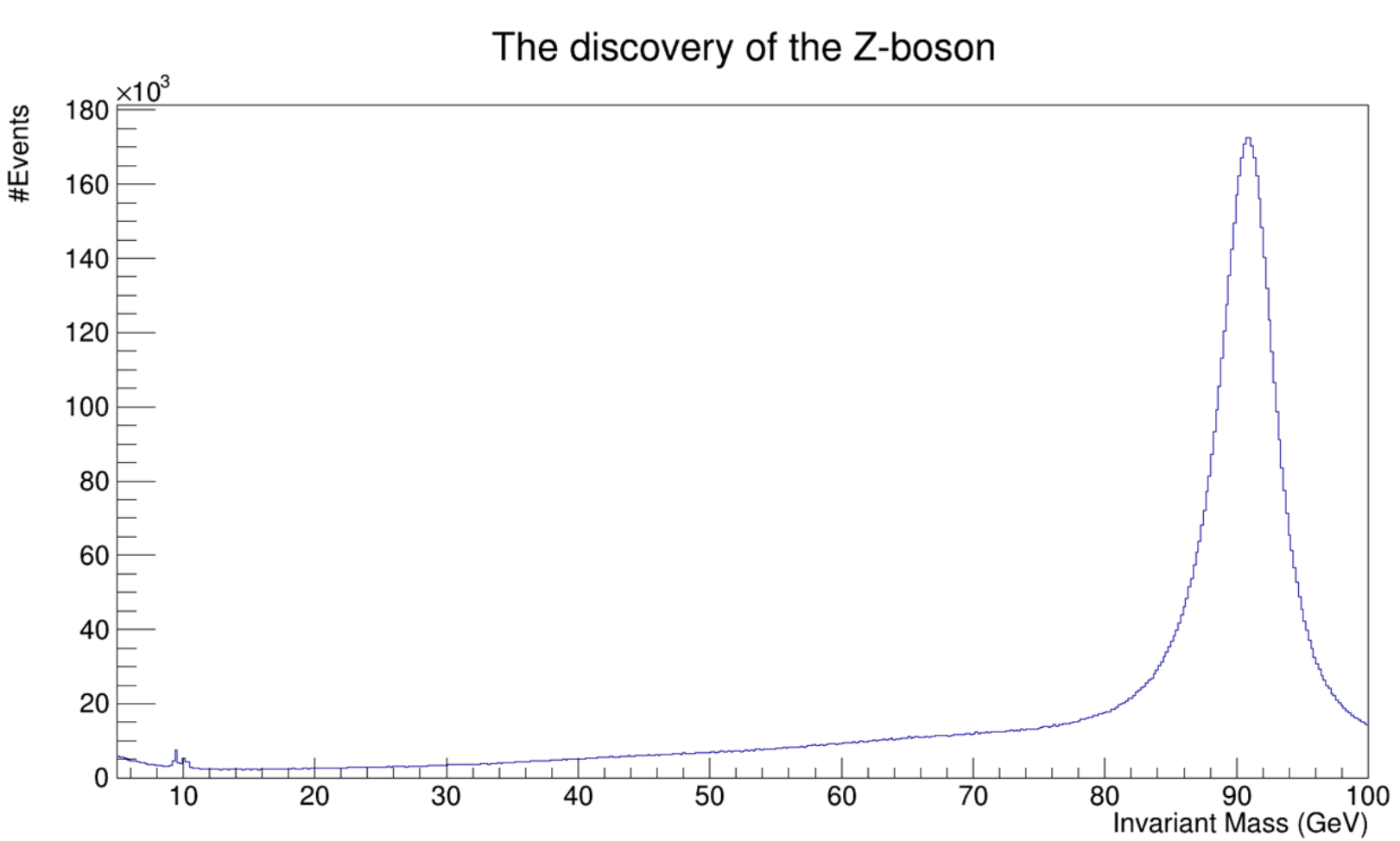
Measured mean
9447,85 MeV

Actual mean
9460,30 ± 0,26 MeV

Z-boson

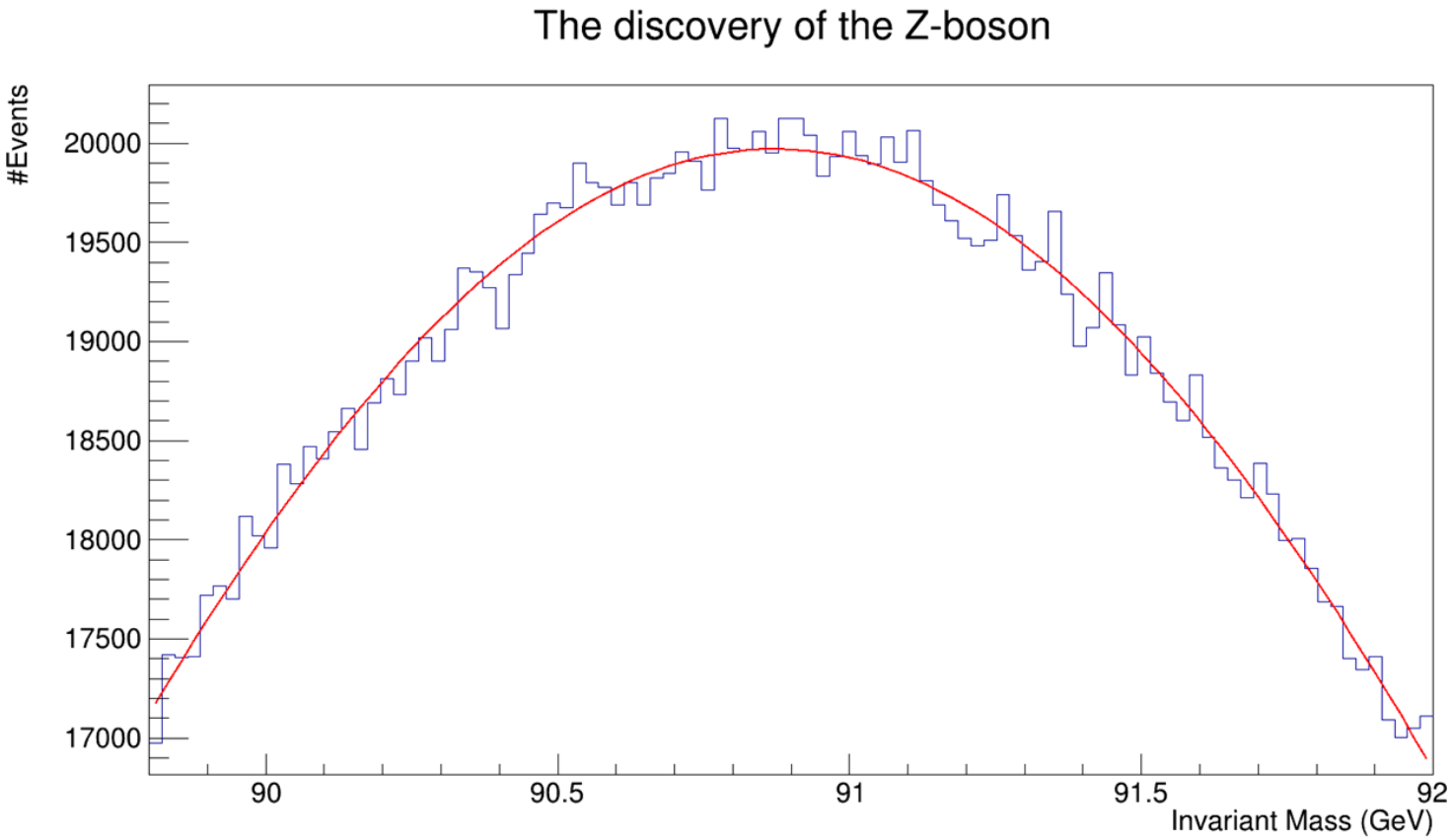
- Super Proton Synchrotron, 1983
- Weak force

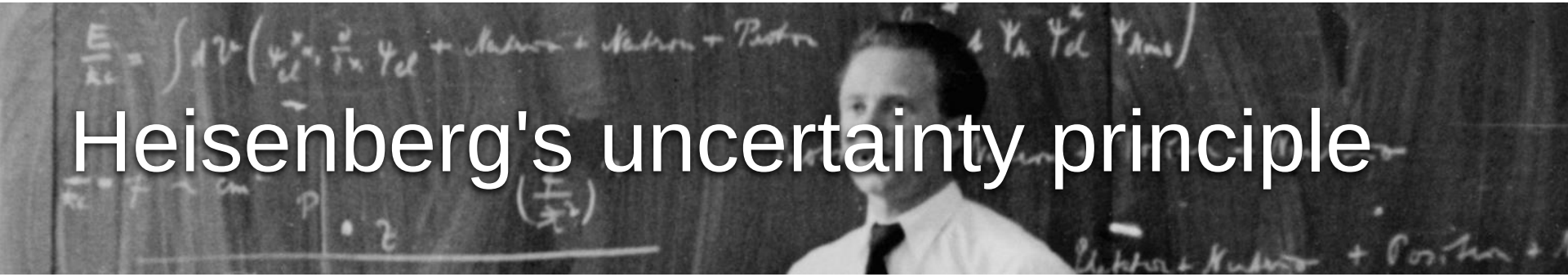



The discovery of the Z-boson
#Events
×10^3
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
Invariant Mass (GeV)

Measured mean
90,872 GeV

Actual mean
91,118 ± 0,0021 GeV





Heisenberg's uncertainty principle

- The shorter the lifetime, the more uncertain the energy/mass
- Lifetime (τ) can be implied from energy uncertainty (ΔE)

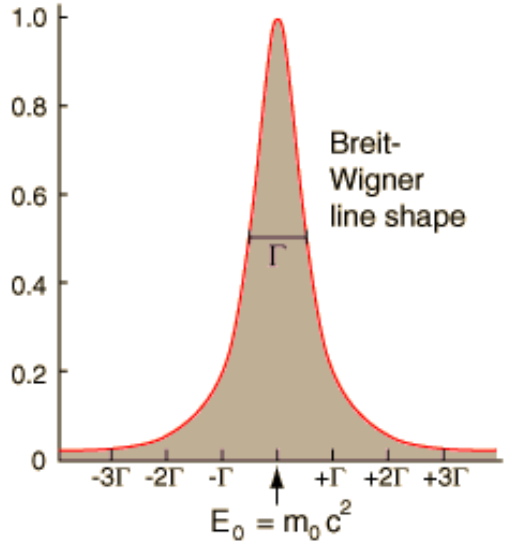
$$\Delta E \Delta t > \frac{\hbar}{2}$$

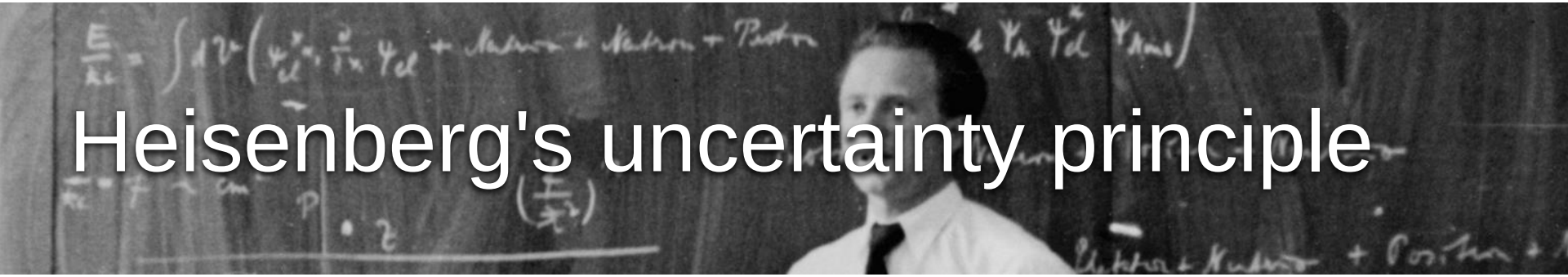
$$\Delta t > \frac{\hbar}{2\Delta E}$$

$$\Delta t = \tau$$

$$\Delta E = \frac{\Gamma}{2}$$

$$\tau_{min} = \frac{\hbar}{\Gamma}$$

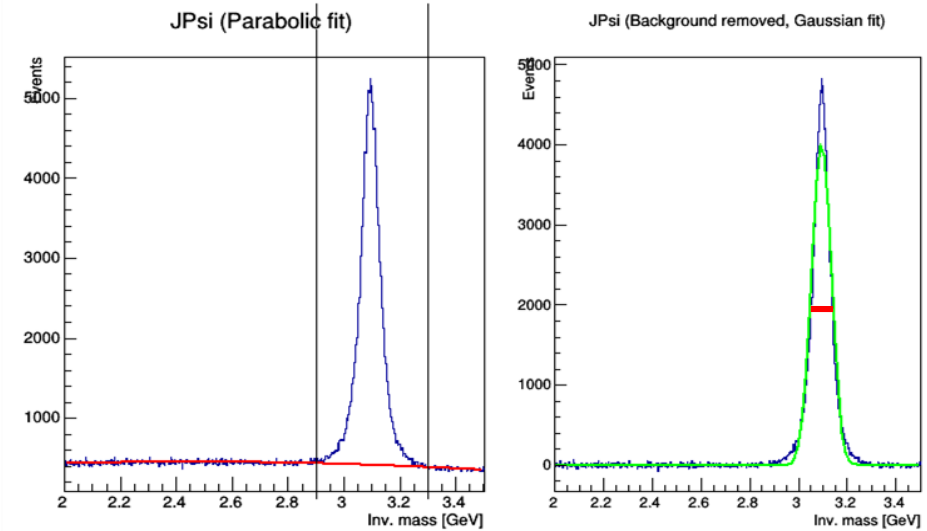




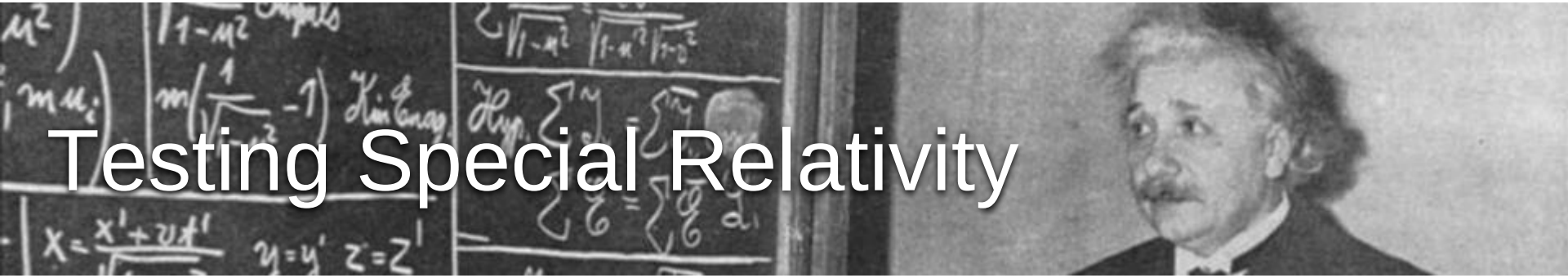
Heisenberg's uncertainty principle

$$\tau_{min} = \frac{\hbar}{\Gamma} = \frac{6{,}582 \times 10^{-16}}{(3{,}14 - 3{,}05) \times 10^{9}} = 7{,}00 \times 10^{-24}\ s$$

Actual lifetime
7×10^{-21} s



- 1000× smaller
- Actual peak much more narrow
- Resolution (1%)
- ‘Smear’

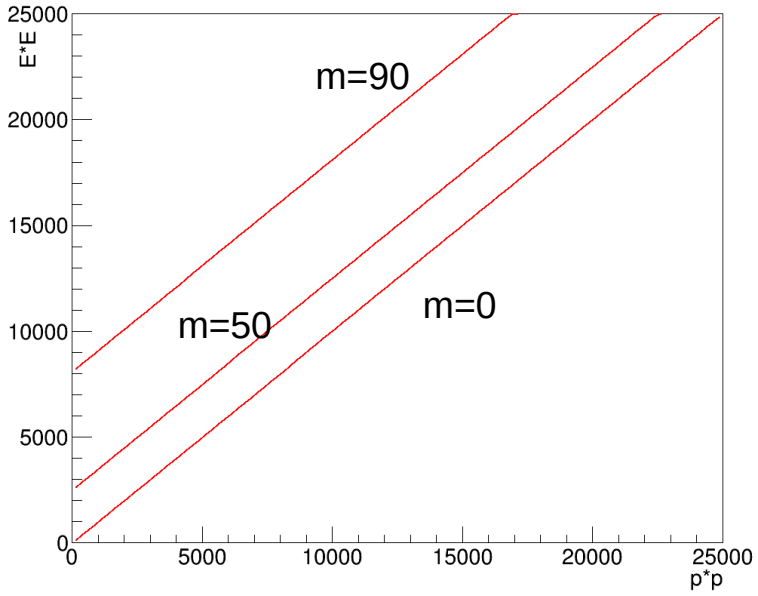


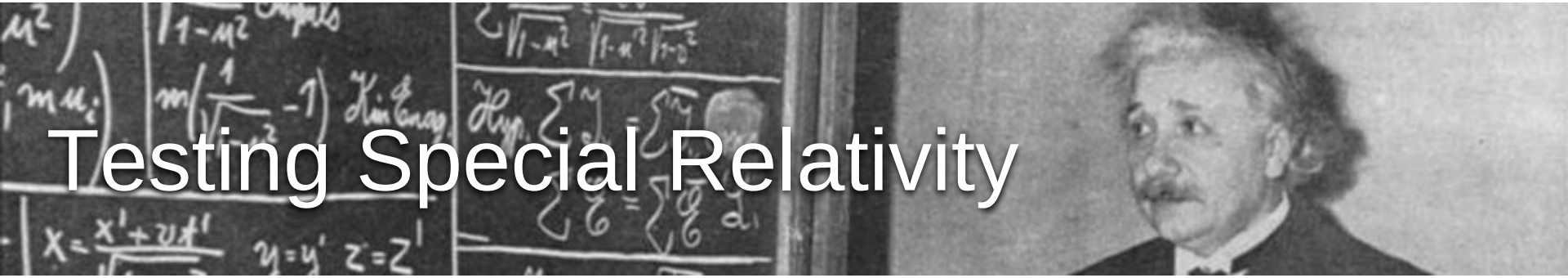
Testing Special Relativity

Special relativity

$$E^2 = p^2 + m^2$$

Linear graph



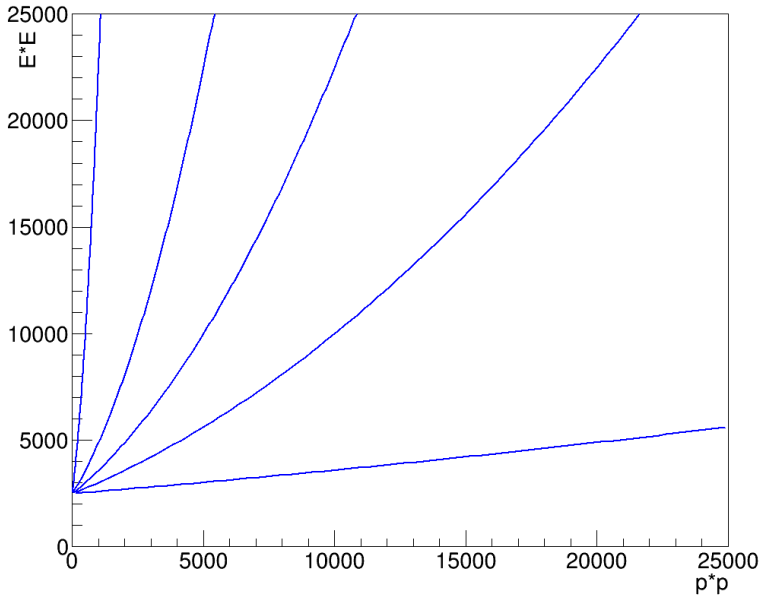


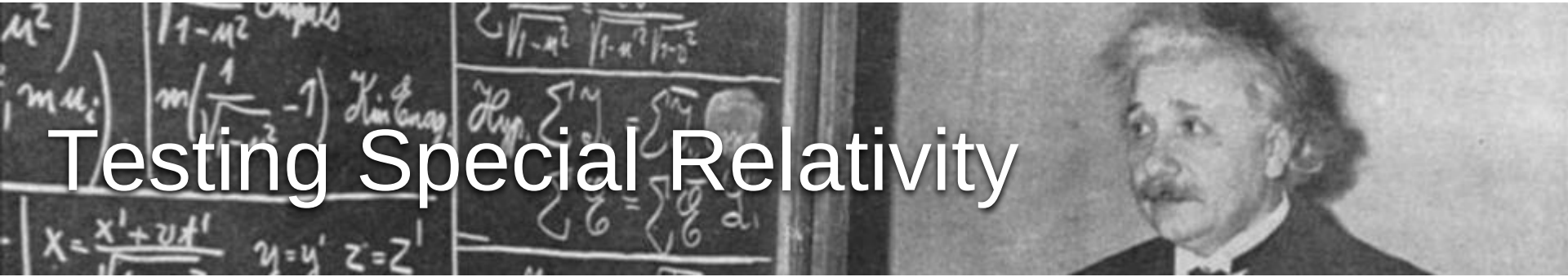
Testing Special Relativity

Classic mechanics

$$E^2 = (E_0 + \frac{p^2}{2m})^2$$

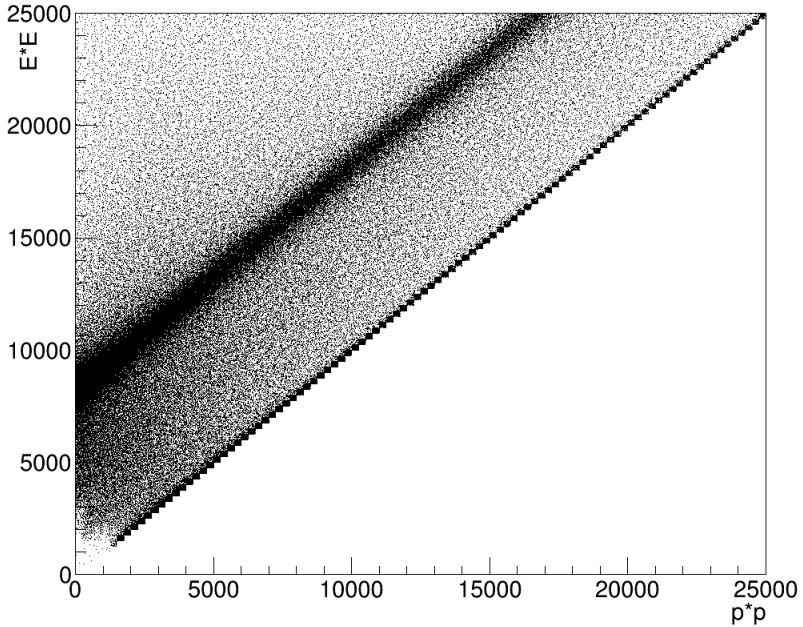
Quadratic graph

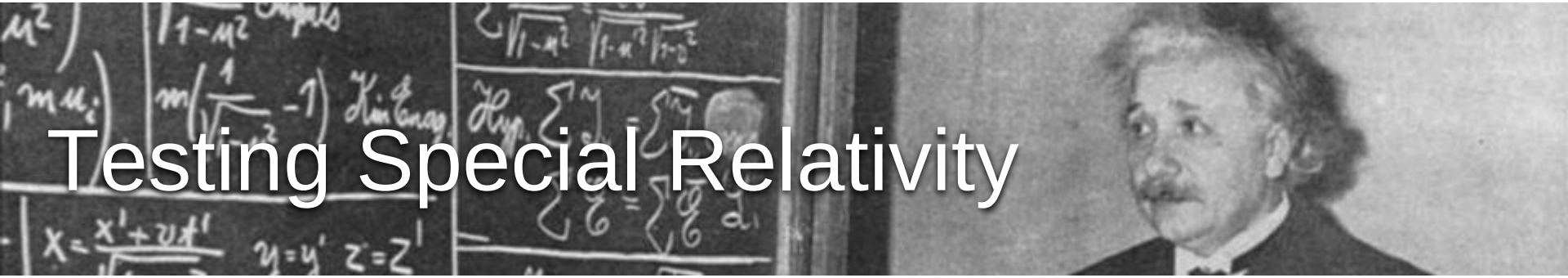




Testing Special Relativity

Plotting using actual data





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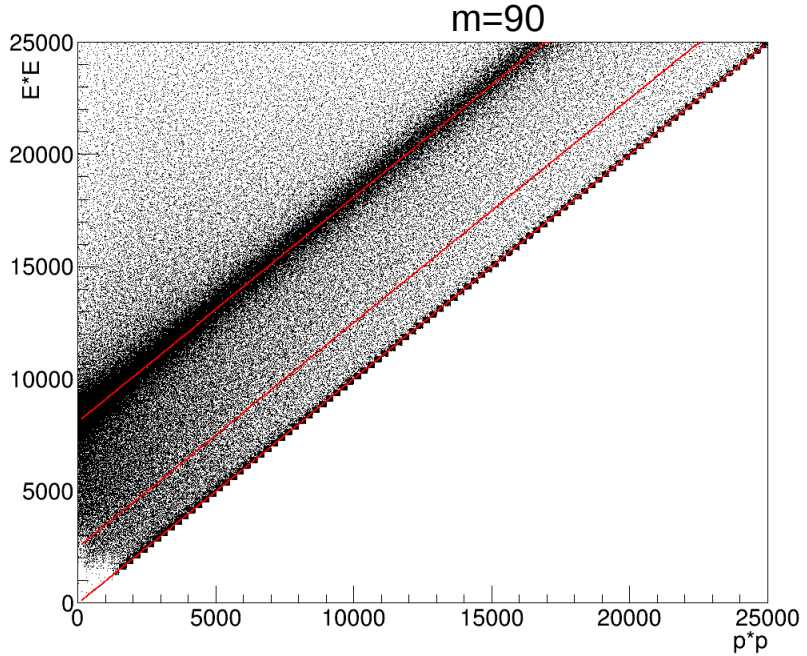

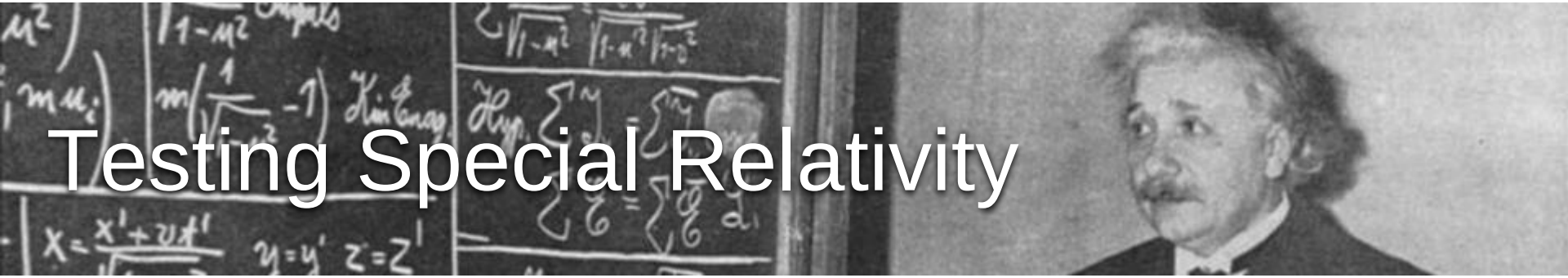

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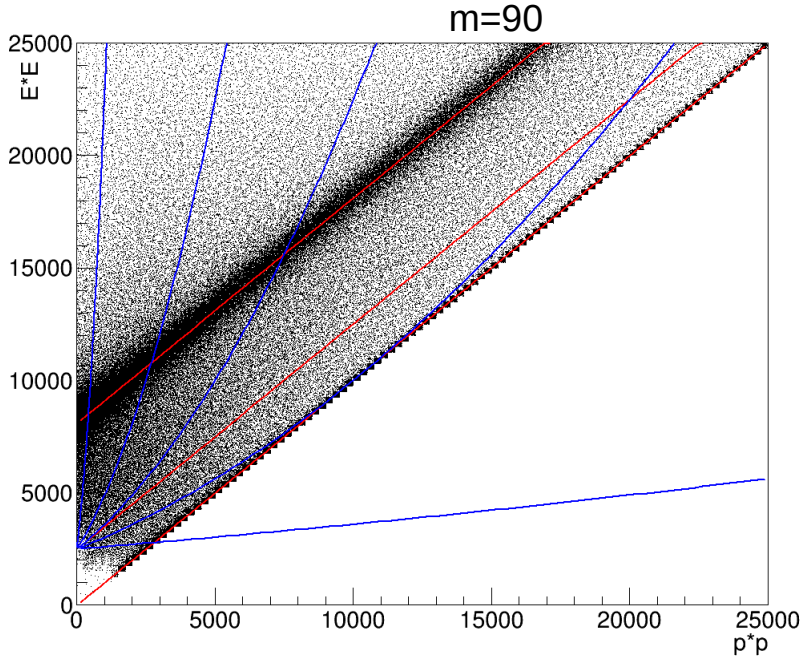
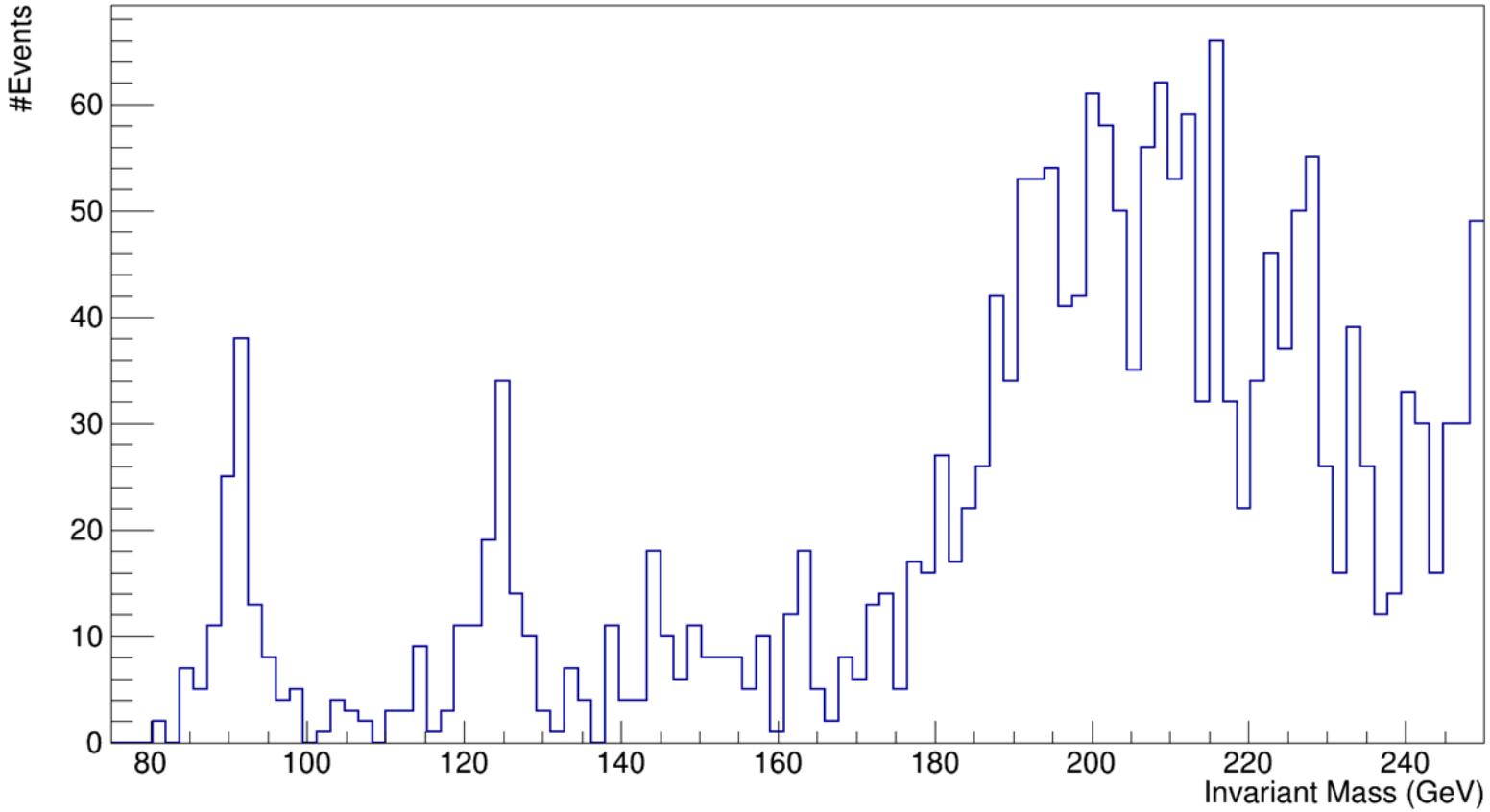


Thank you!

One more thing...

Four lepton decay (with some event selection)



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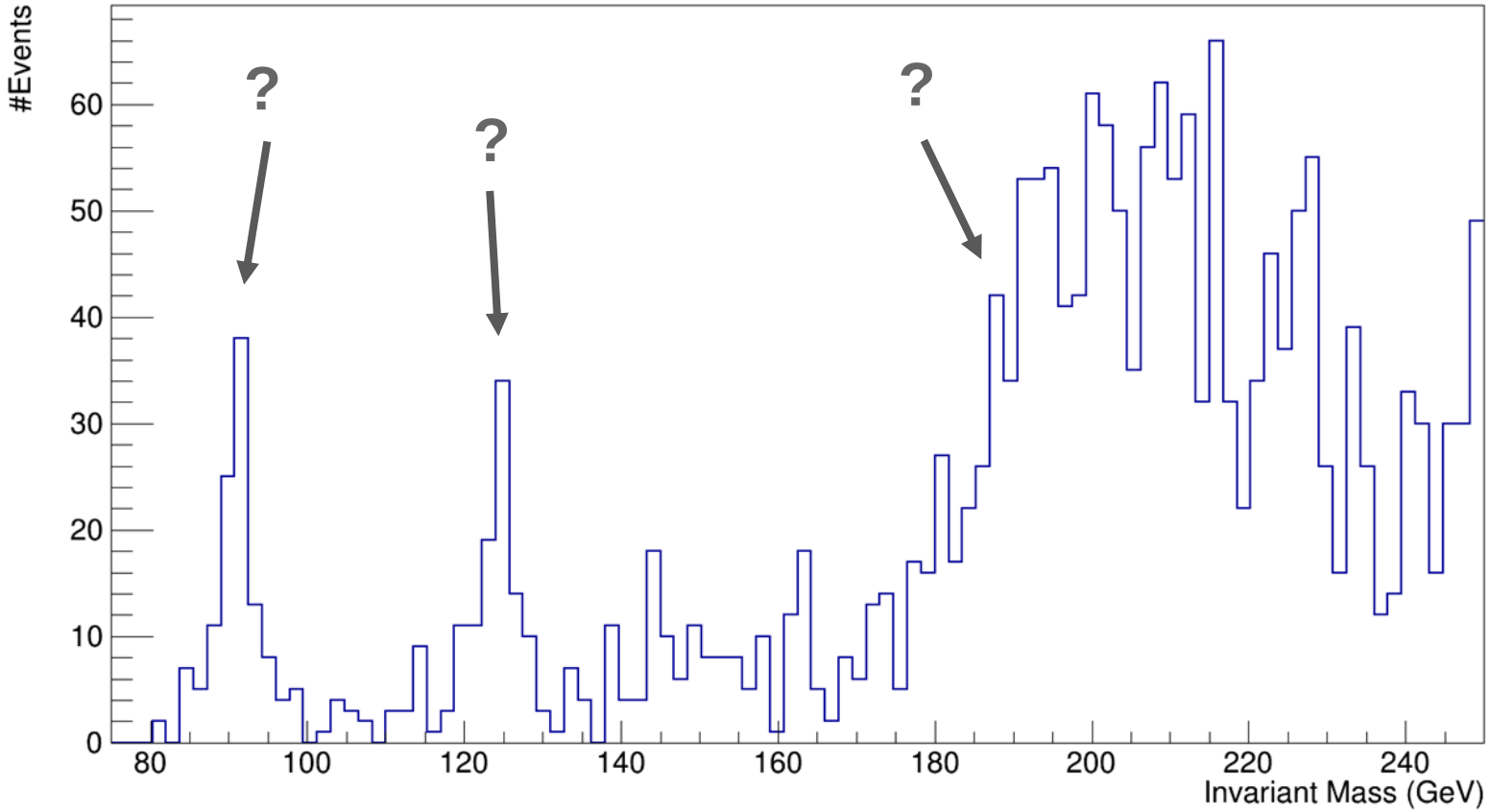

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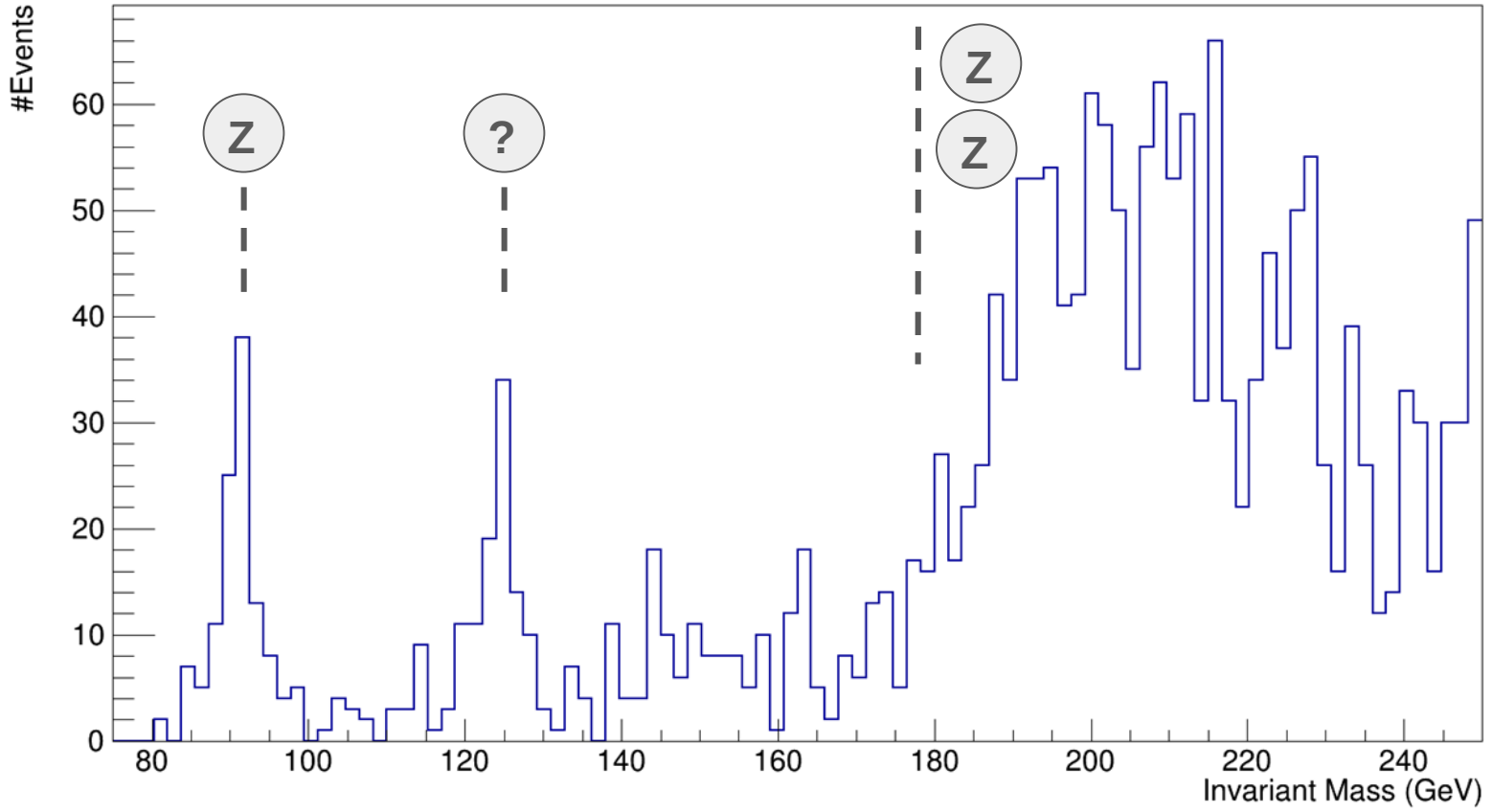
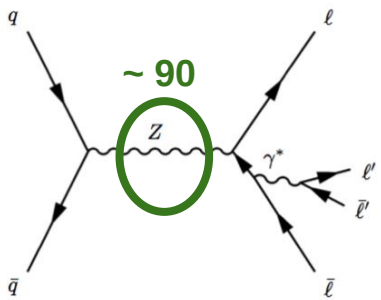


Explanation of the 4-lepton peaks

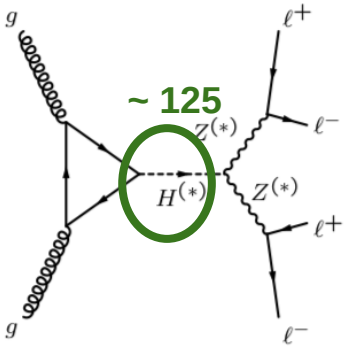
$(m_{ZZ})^2 = 2\ m_Z^2 + 2\ p_Z^2$

with p_Z the Z momentum in the ZZ rest frame (assuming equal masses for the two Z bosons, and equal but opposite momenta)

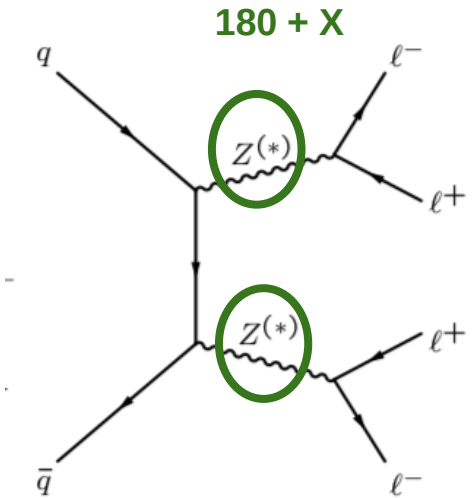
$Z \rightarrow 4l$



$H \rightarrow 4l$



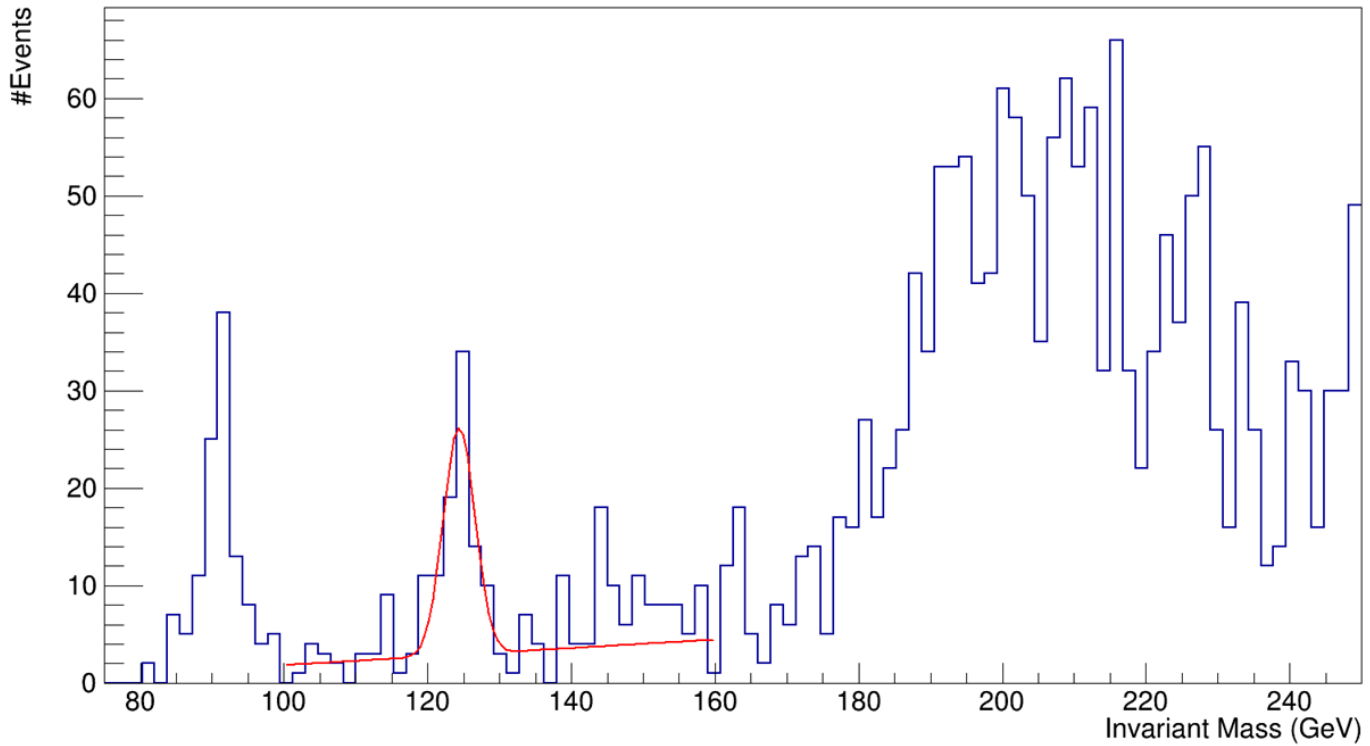
$\ldots \rightarrow ZZ \rightarrow 4l$



Our measured mass (ZZ, 13 TeV, 46 fb^{-1}, 2017) 124.37 ± 0.3 GeV

ATLAS + CMS mass (ZZ + γγ, 7-8 TeV, 50 fb^{-1}, 2010-12) 125.09 ± 0.24 GeV

The discovery of the Higgs boson



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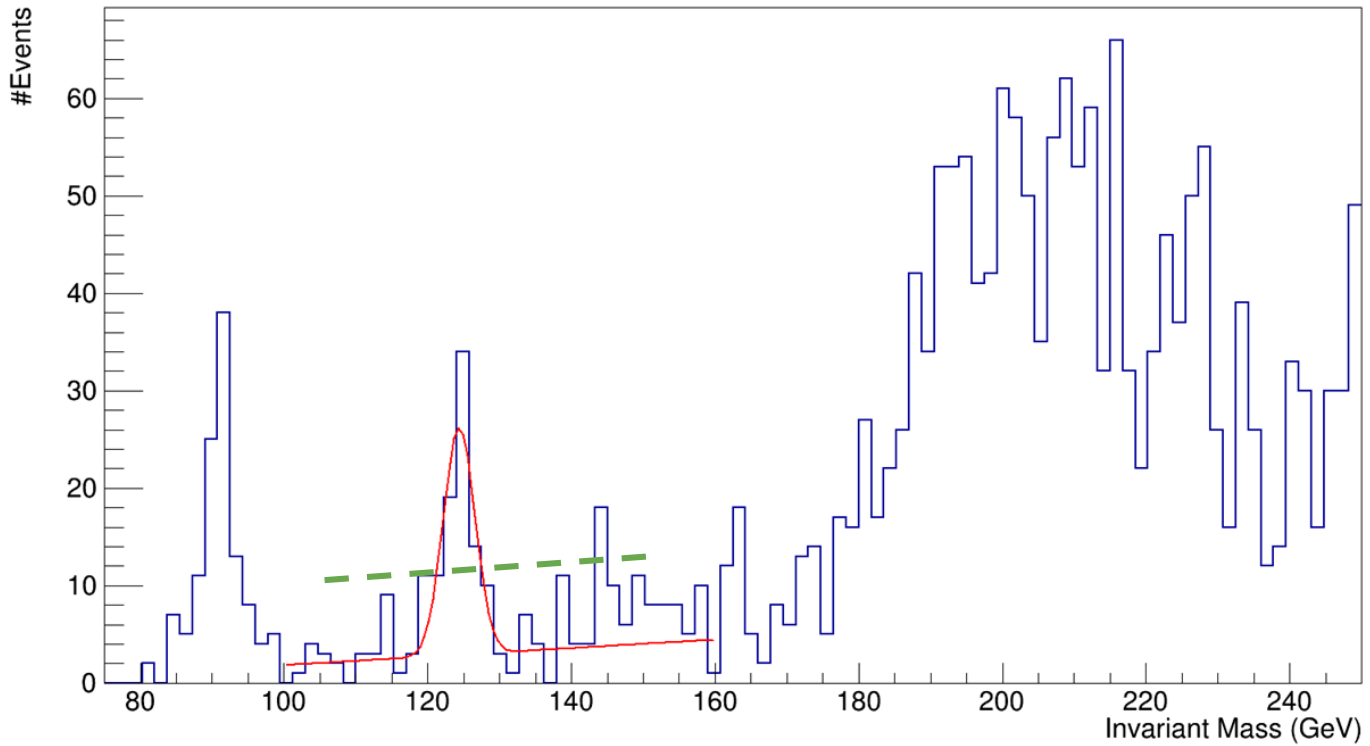

Approximate
5σ line (2 bins)
(1 : 3,500,000)


Are there any questions?