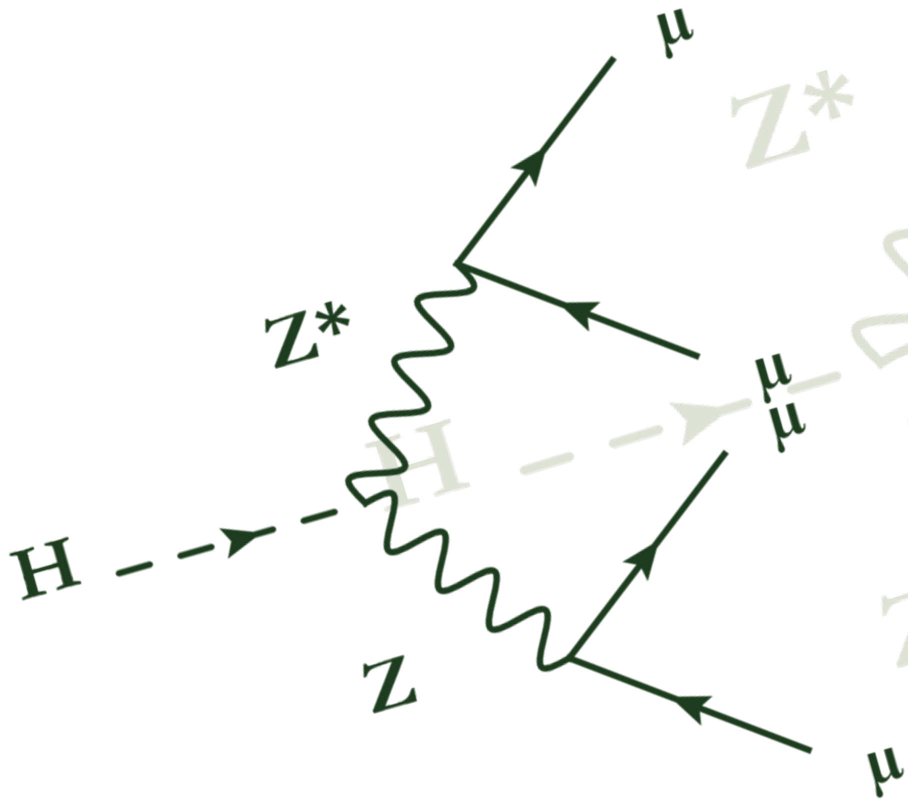
A Search for the Higgs

The Four Muon Channel



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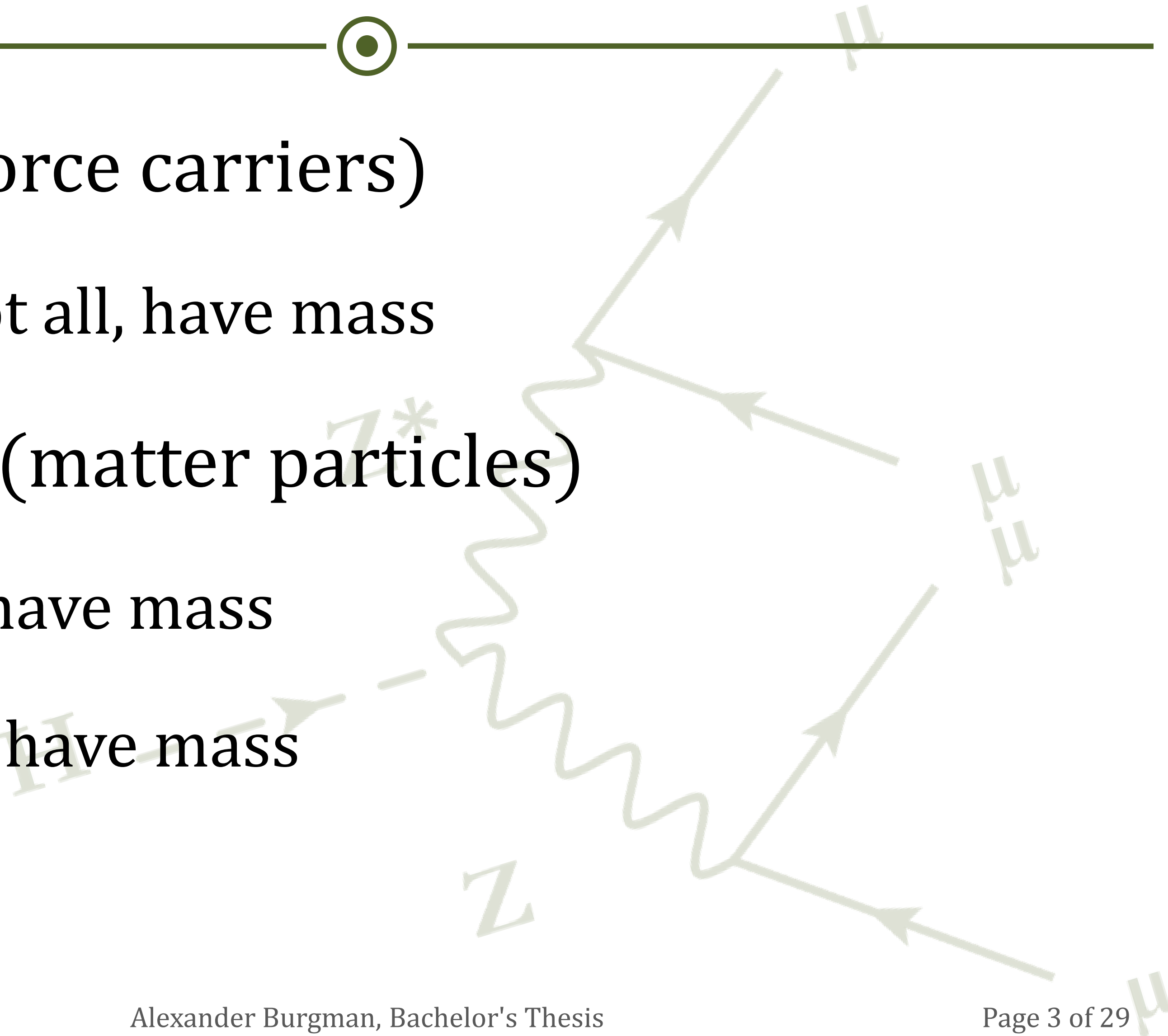
Content

- Background Facts
  - Some theoretical background
  - Machines at CERN
- This Project
  - Invariant mass calculation
  - Background ZZ estimation

The Standard Model

- Bosons (force carriers)
  - Some, not all, have mass
- Fermions (matter particles)
  - Quarks, have mass
  - Leptons, have mass

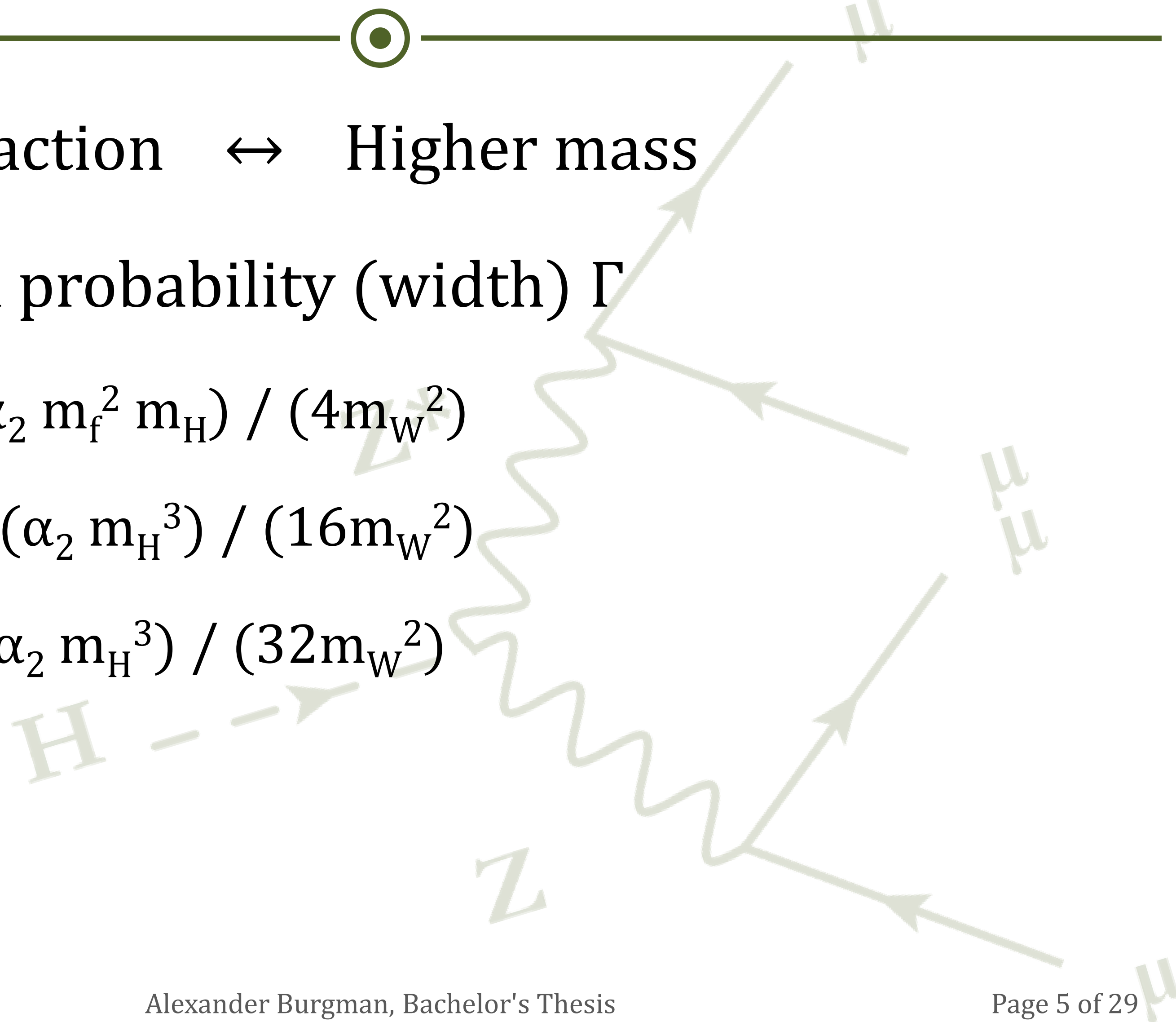


SM Higgs Boson

- Mass Mechanism (Higgs Mechanism)
  - Breaking of electro-weak symmetry
    - 3 massive vector bosons (Z, W^+, W^-)
    - 1 massive scalar boson (Higgs)
- Particle mass is gained through interaction with Higgs

SM Higgs Boson

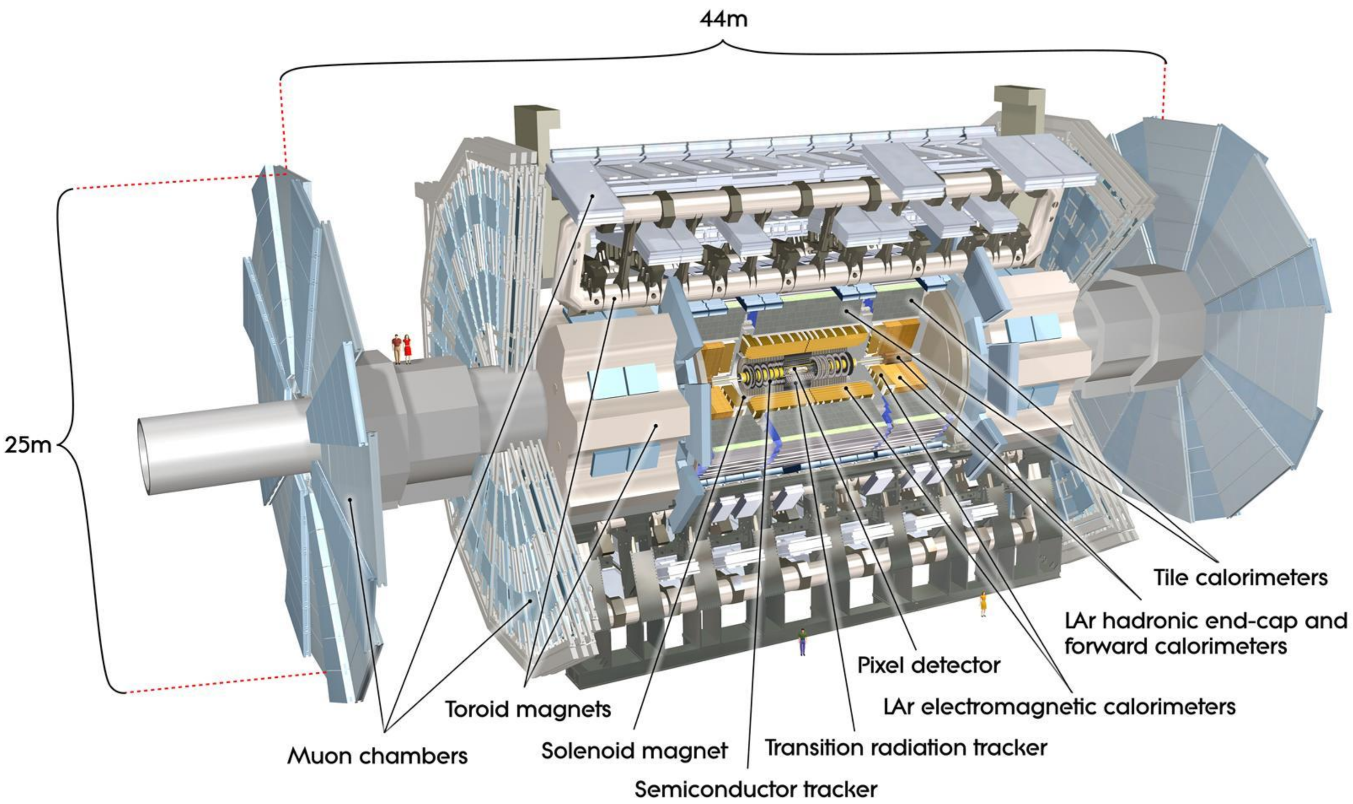
- More interaction $\leftrightarrow$ Higher mass
- Interaction probability (width) Γ
  - $\Gamma_{H\to ff} \approx (\alpha_2\, m_f^2\, m_H) / (4m_W^2)$
  - $\Gamma_{H\to WW} \approx (\alpha_2\, m_H^3) / (16m_W^2)$
  - $\Gamma_{H\to ZZ} \approx (\alpha_2\, m_H^3) / (32m_W^2)$



LHC

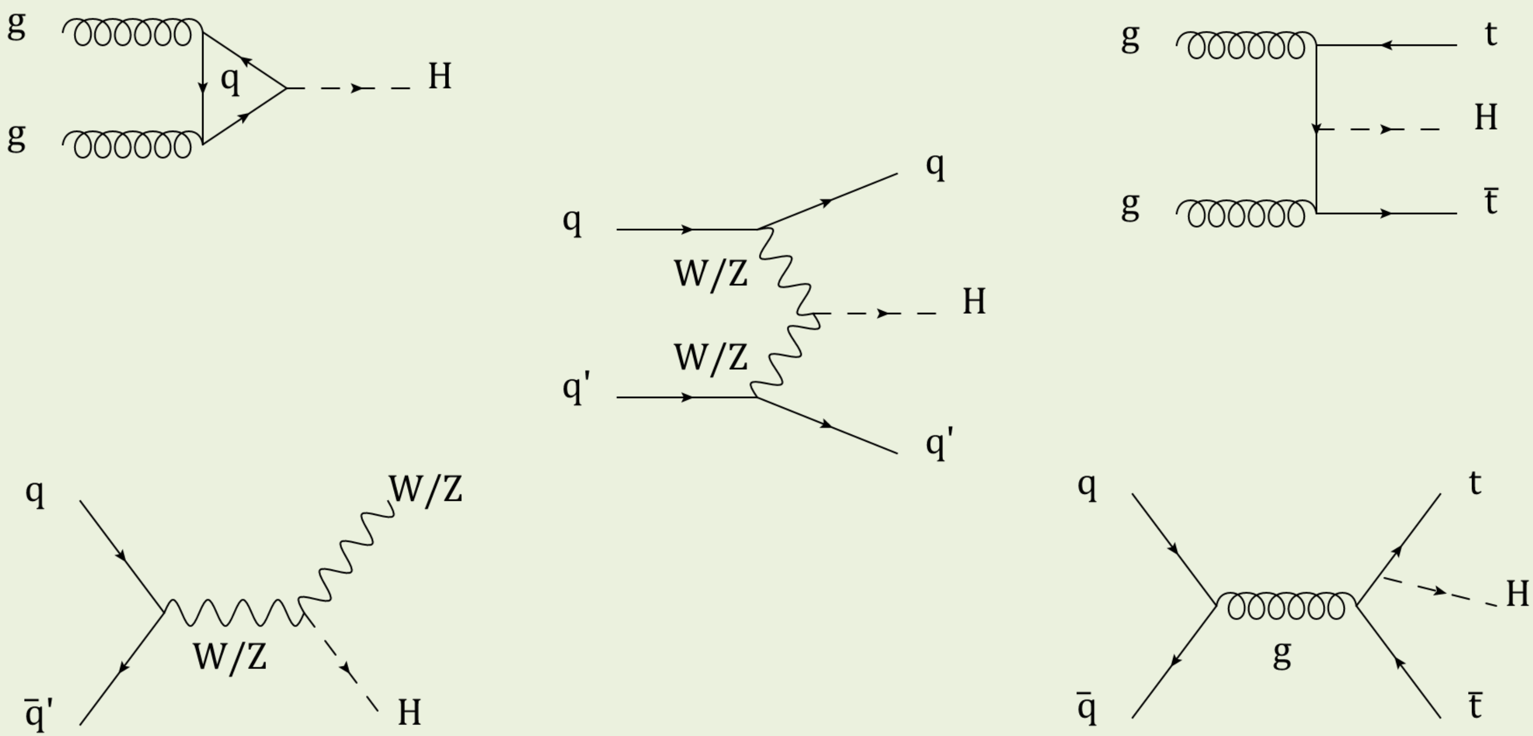
- Collides p-p, Pb-p, Pb-Pb
- Highest energy in the world
- ATLAS,   ALICE,   CMS,   LHCb
  - Results from ATLAS used in this project

ATLAS

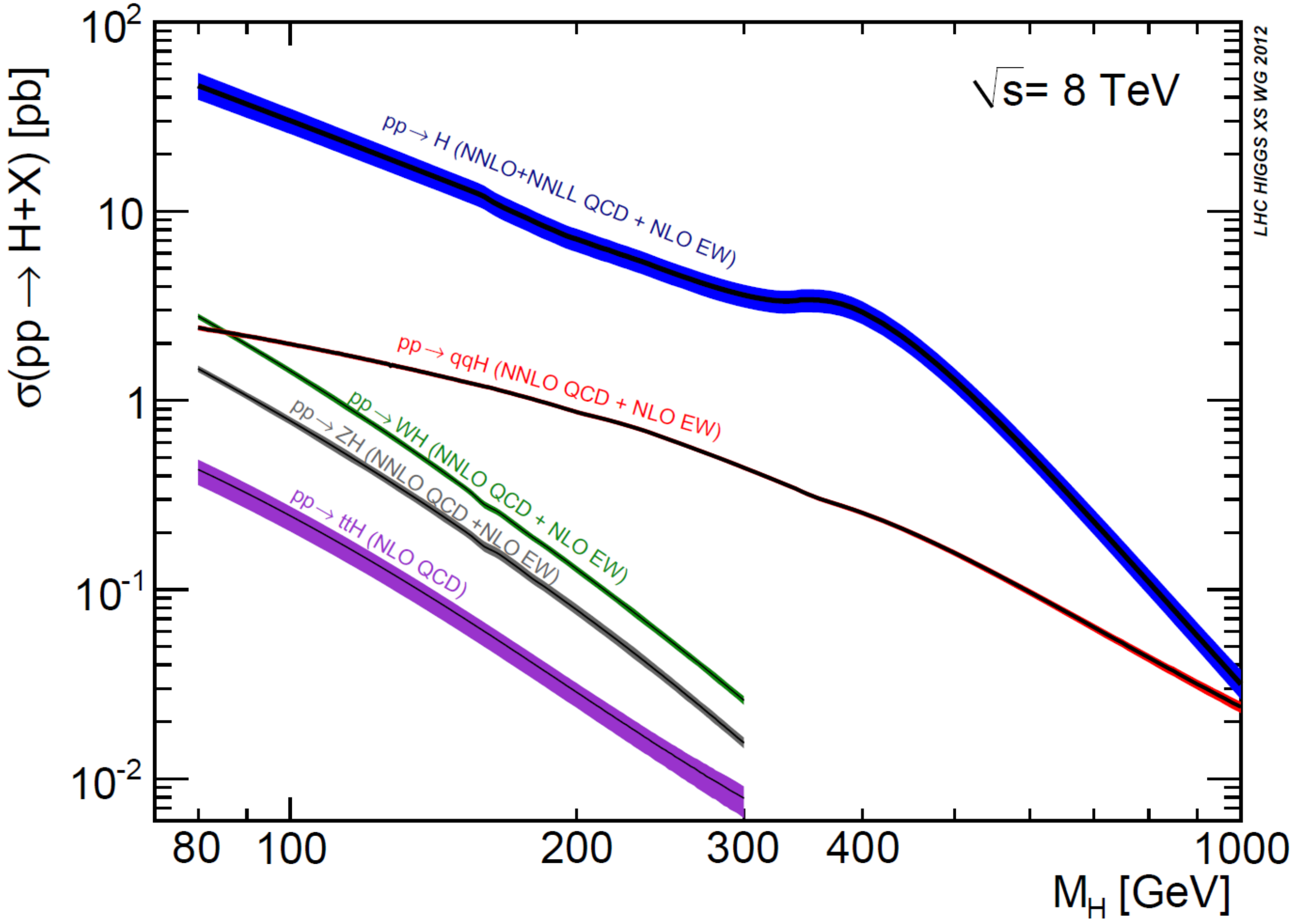


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

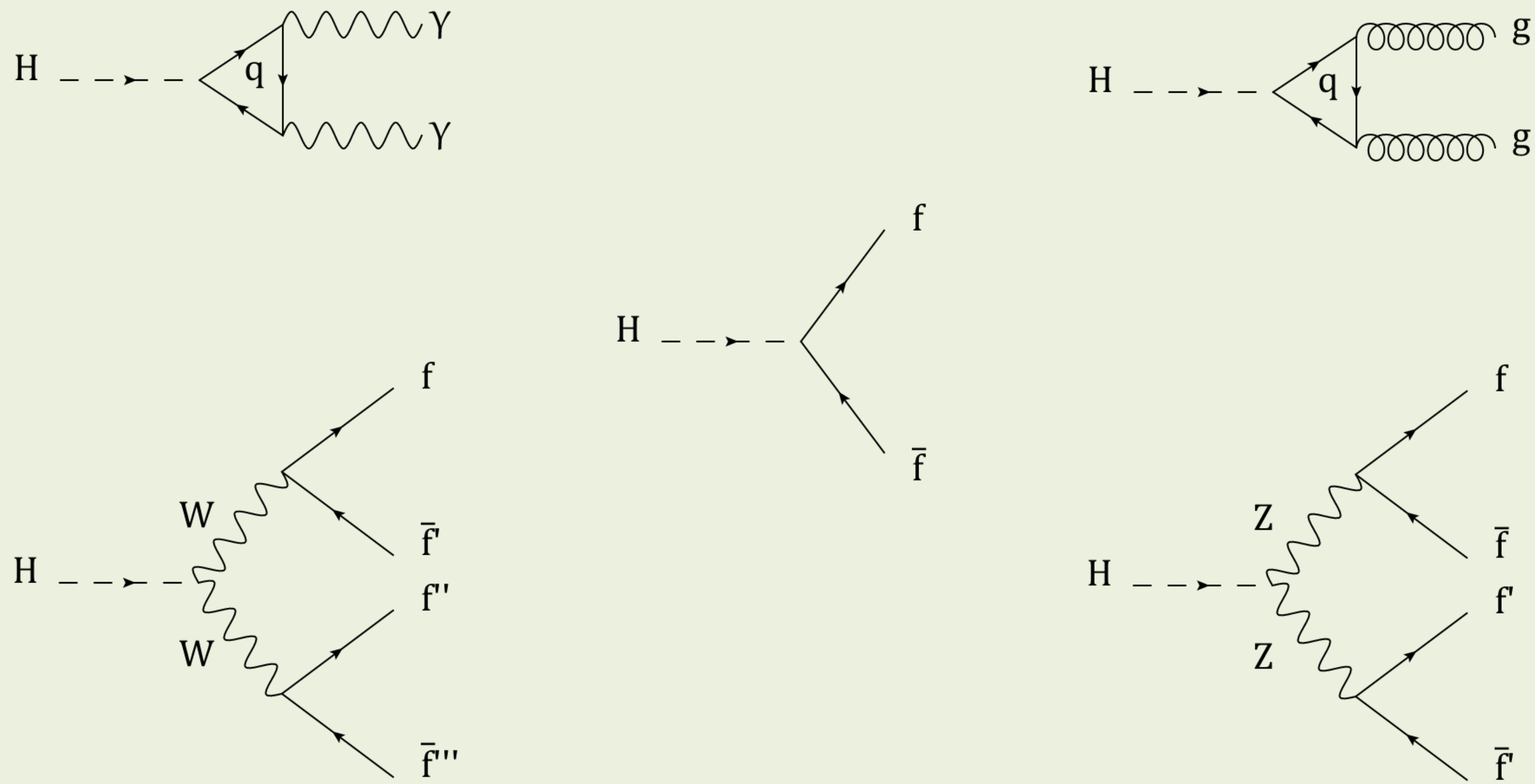
Higgs Production



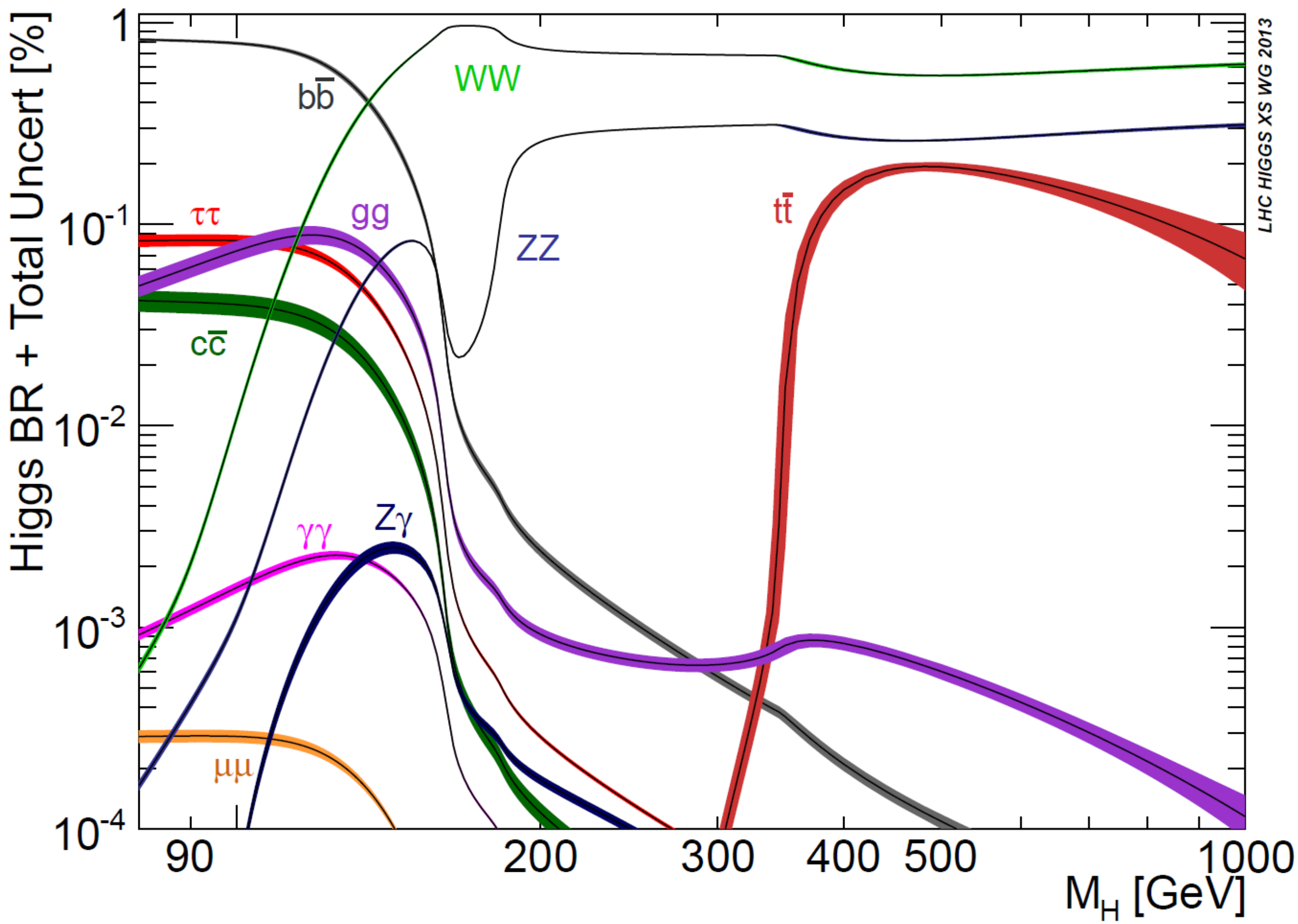
Higgs Production



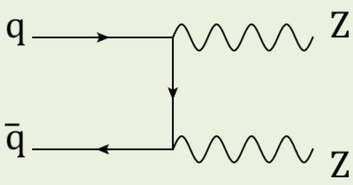
Higgs Decay

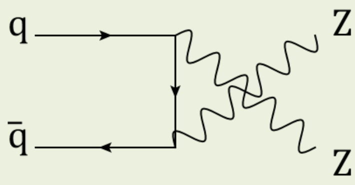


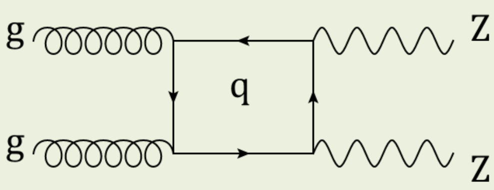
Higgs Detection

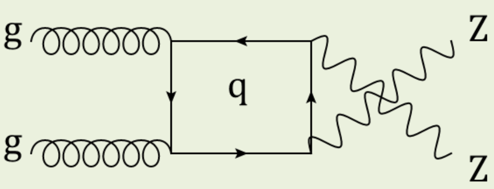


Background – Two Z









Method – Four Muons

- Invariant mass of four muon system

$$m_{4\mu} = \sqrt{(E^2 - p_x{}^2 - p_y{}^2 - p_z{}^2)}$$

$$E = E_{\mu 1} + E_{\mu 2} + E_{\mu 3} + E_{\mu 4}$$

$$p_x = p_{x,\mu 1} + p_{x,\mu 2} + p_{x,\mu 3} + p_{x,\mu 4}$$

$$p_y = p_{y,\mu 1} + p_{y,\mu 2} + p_{y,\mu 3} + p_{y,\mu 4}$$

$$p_z = p_{z,\mu 1} + p_{z,\mu 2} + p_{z,\mu 3} + p_{z,\mu 4}$$

Method – Four Muons

- $m_Z = \sqrt{(E_{\mu 1} + E_{\mu 2})^2 - (p_{x,\mu 1} + p_{x,\mu 2})^2 - (p_{y,\mu 1} + p_{y,\mu 2})^2 - (p_{z,\mu 1} + p_{z,\mu 2})^2}$
- Leading Z boson: muon pair with the mass closest to m_Z
- Sub-leading Z boson: remaining muon pair with highest mass

Method – Selection Criteria

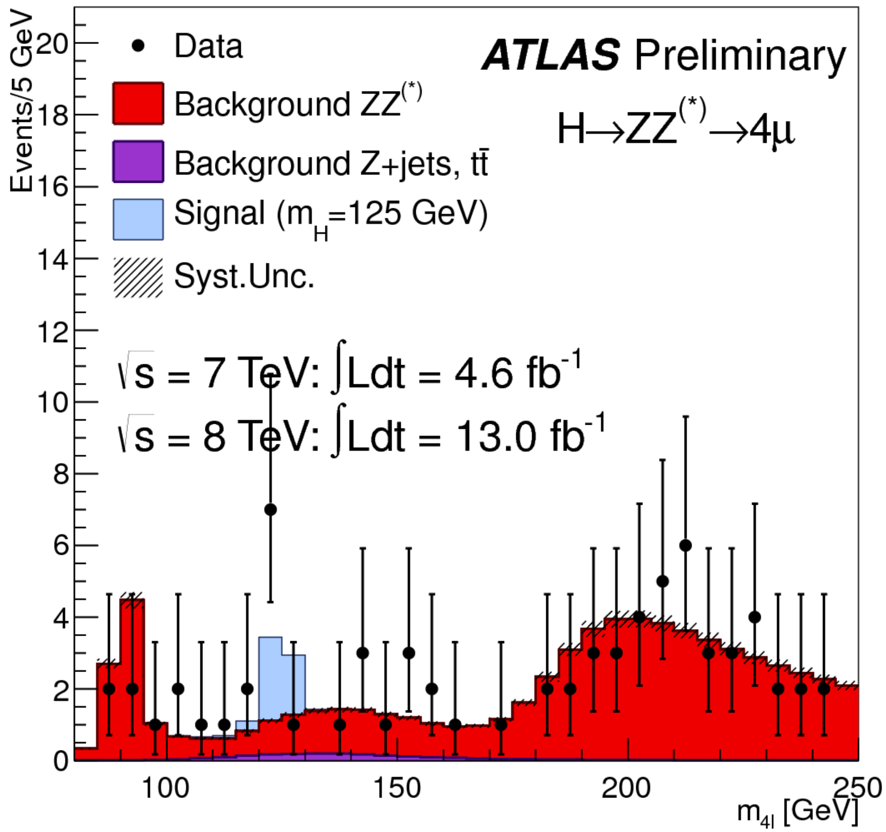
- Uncharged Z bosons
- p_T-triggers
- Additional p_T criteria
- Restrictions on Z masses
- Pseudorapidity (polar angle) restriction

Method – Selection Criteria

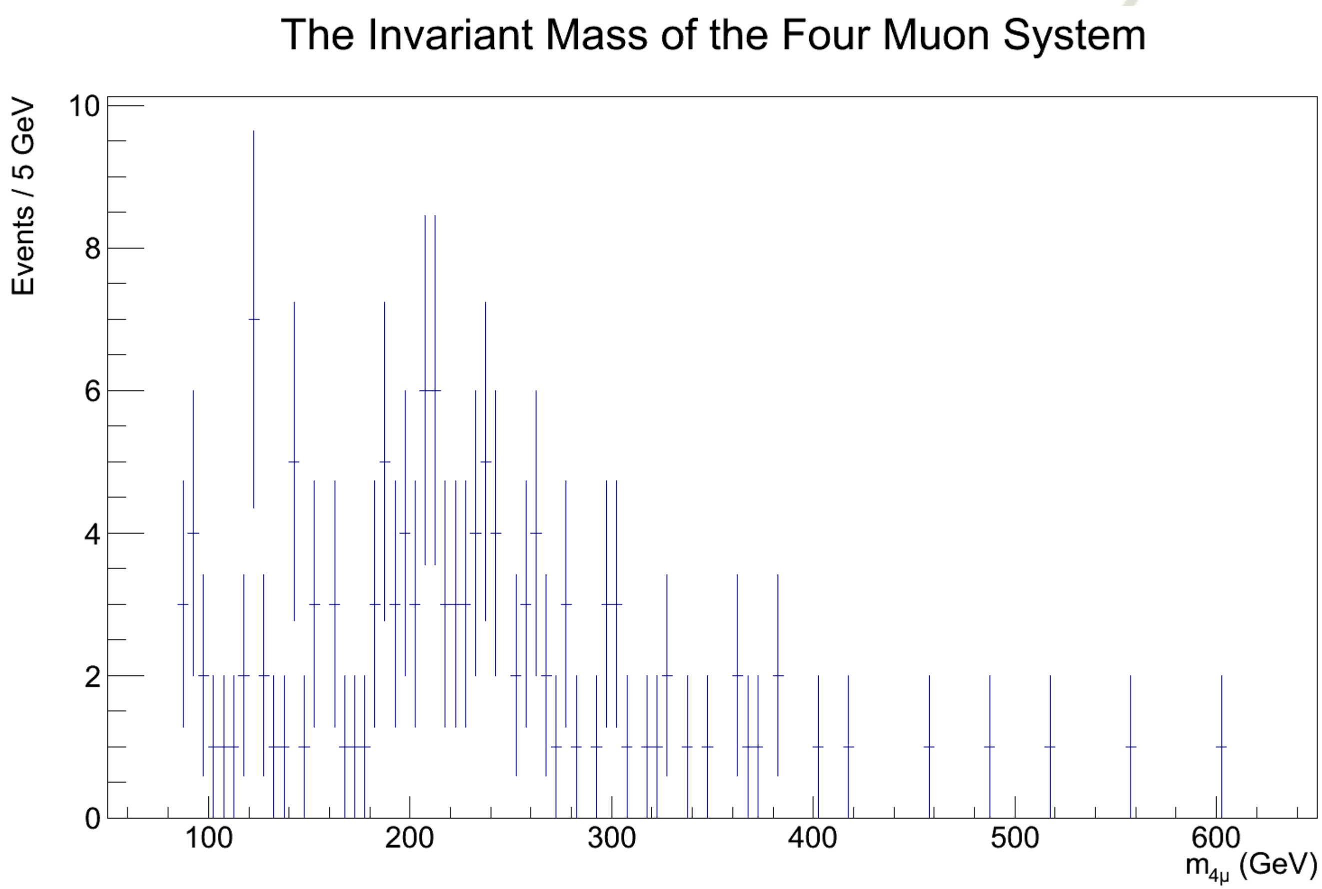
- Separation in the quadruplet
- Track isolation
- Proximity to the primary vertex (d_0, z_0)
- All possible opposite charge muon pairs:

  $m_{\mu\mu} > 5$ GeV

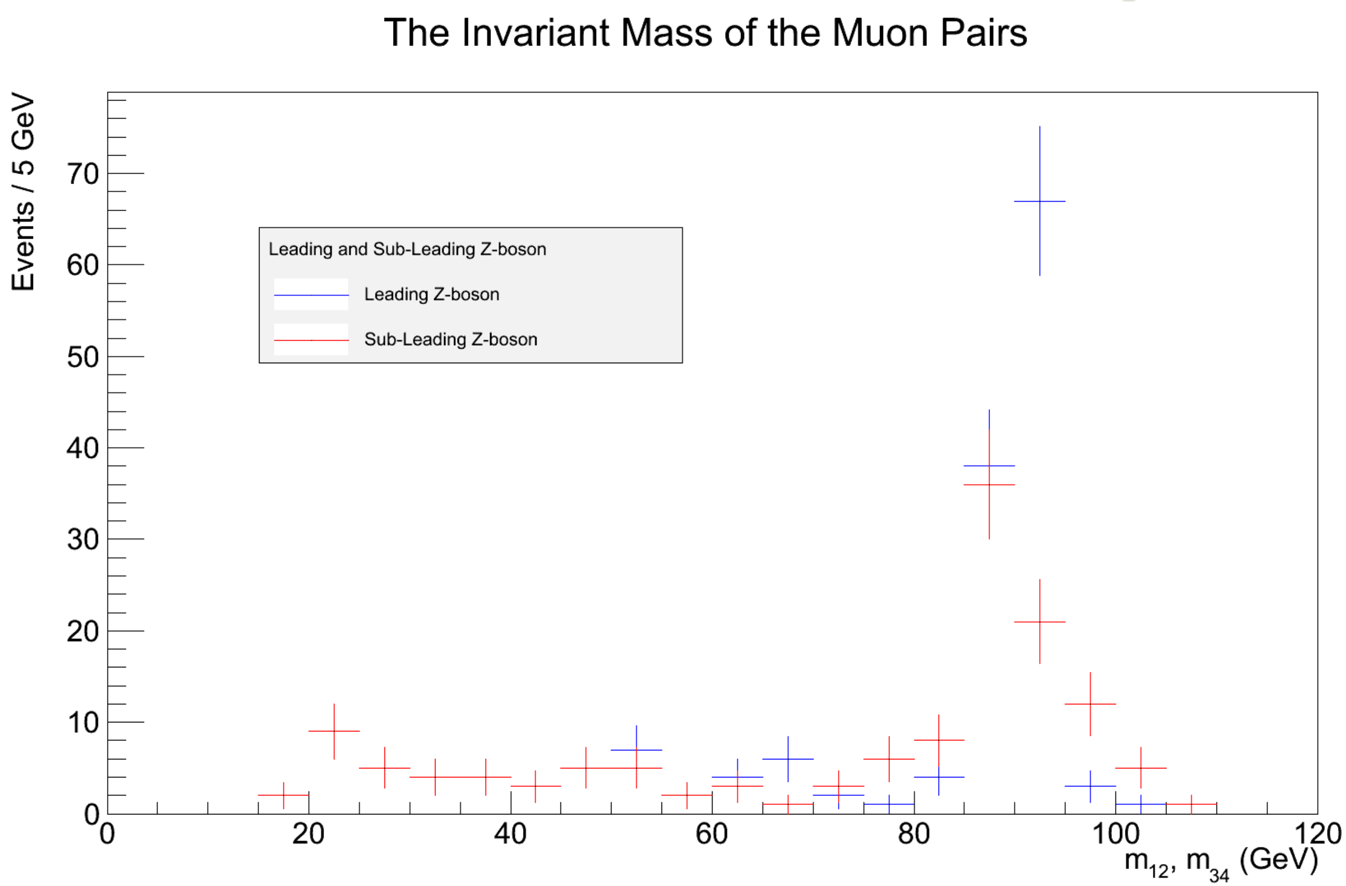
Results – ATLAS Official



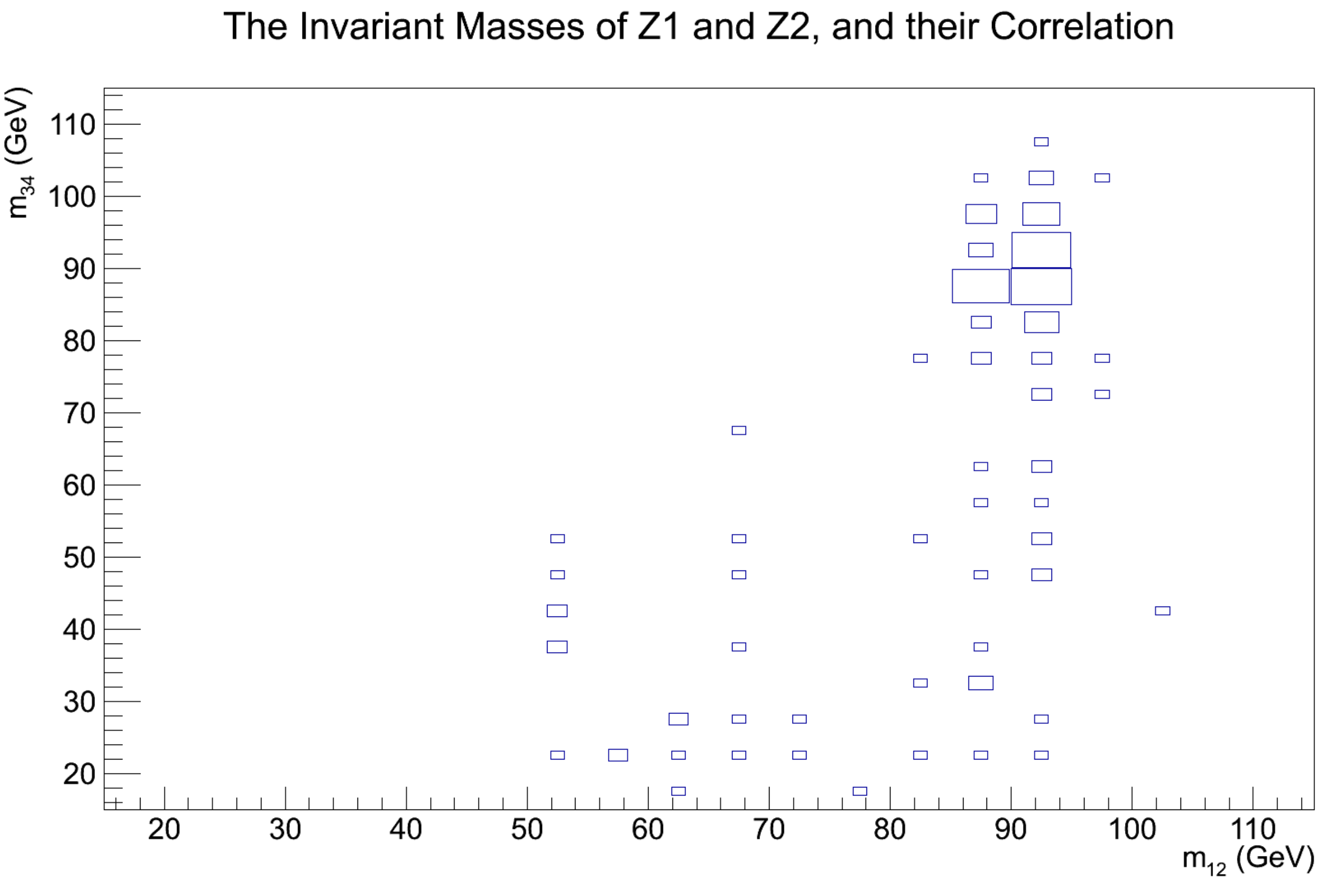
Results – Muon Quadruplet



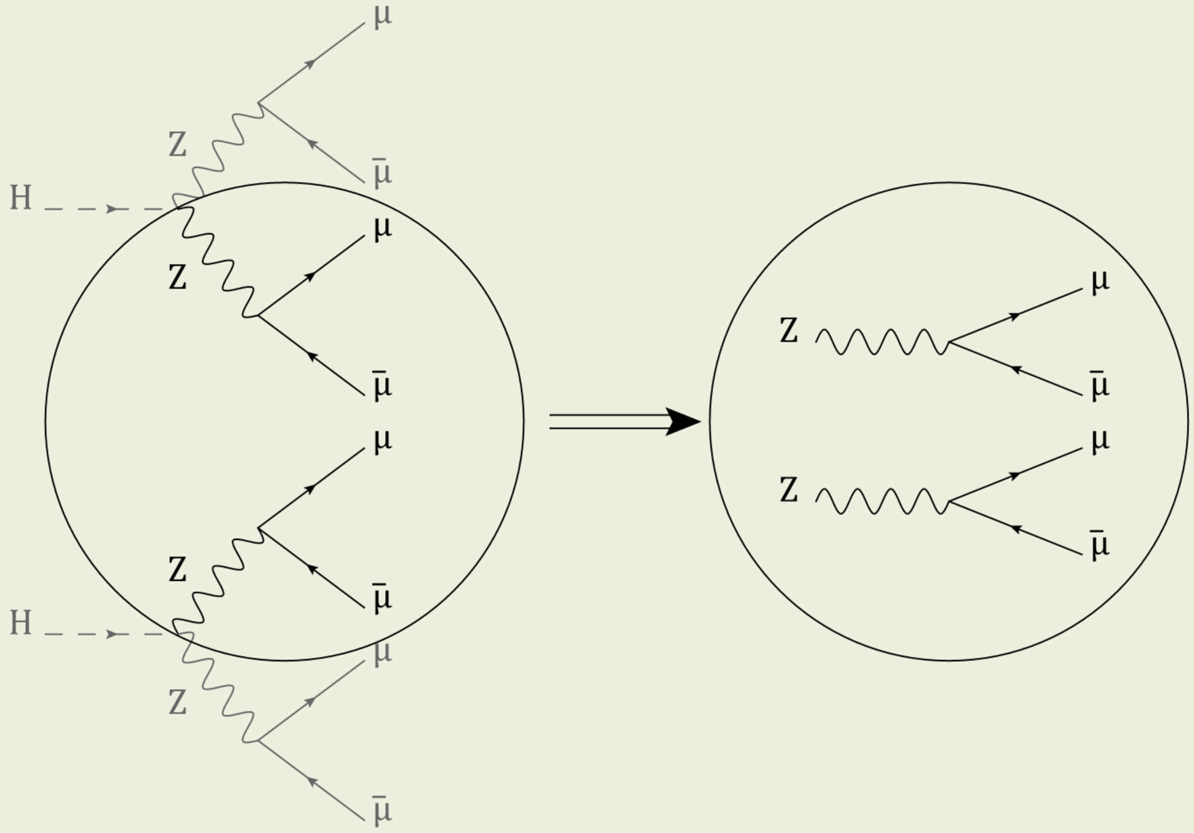
Results – Muon Pairs



Results – Muon Pairs



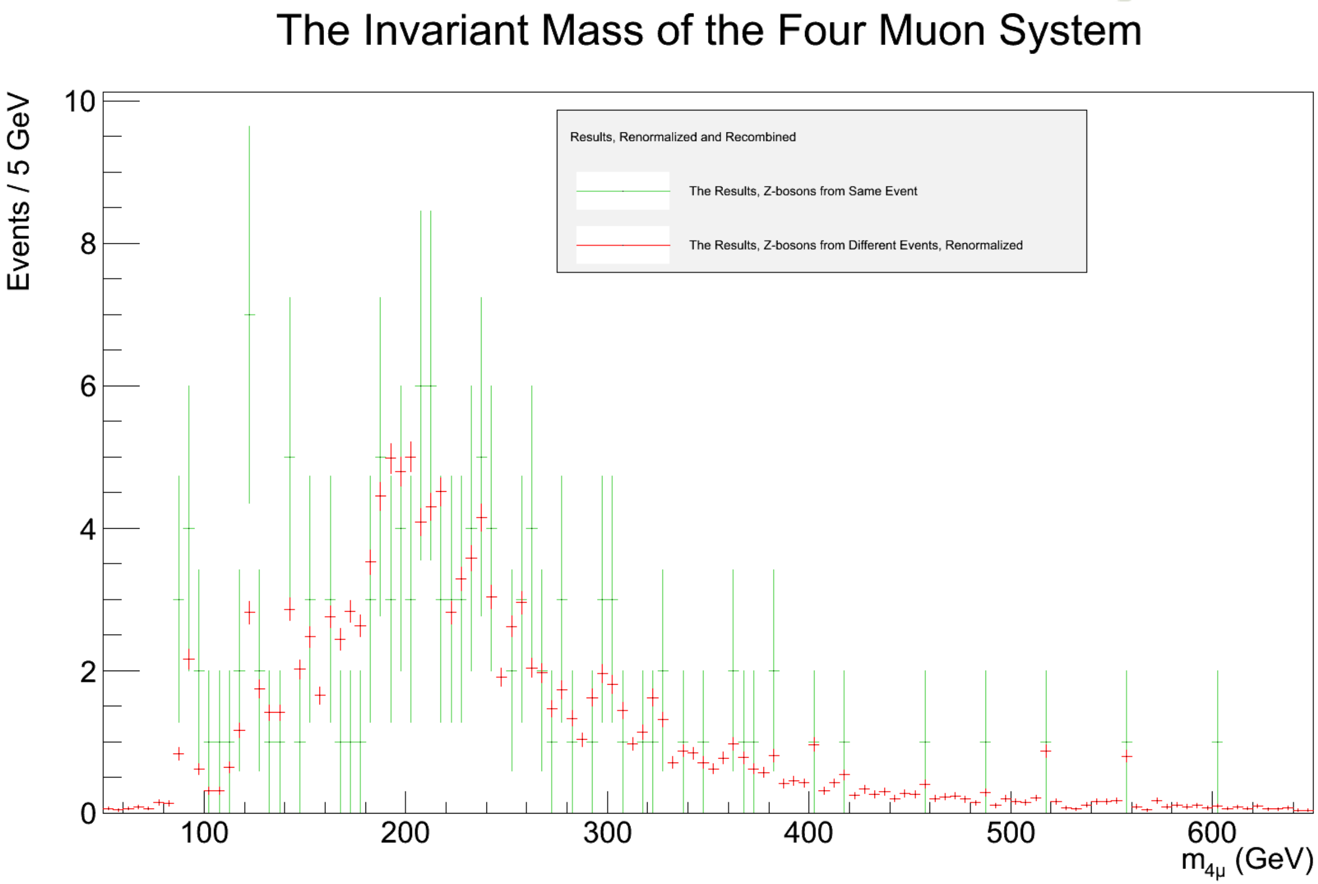
Method – Recombining Z



Method – Recombining Z

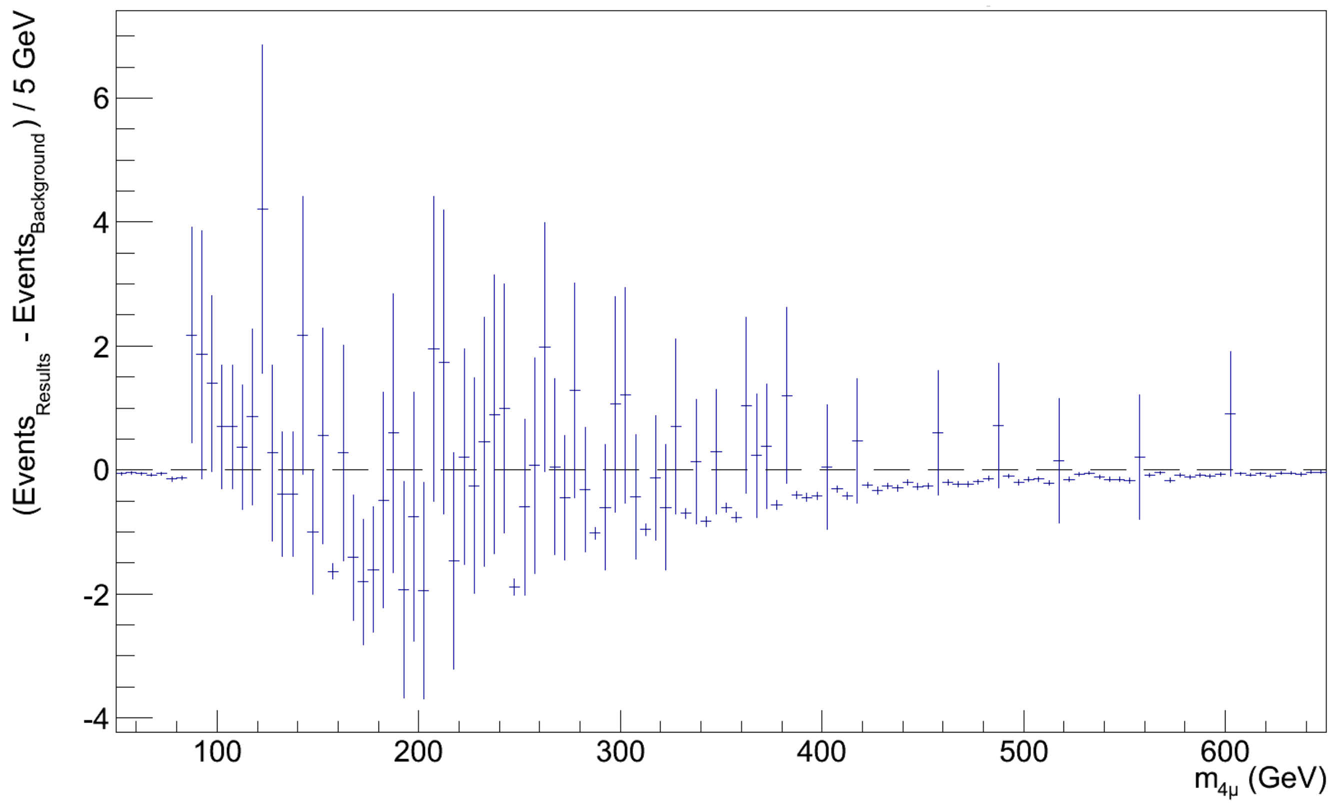
- Same selection criteria
- Estimates the invariant mass of a system of non-related Z bosons
  - ONLY good estimator for ZZ background
  - NOT other background

Results – Recombined Z

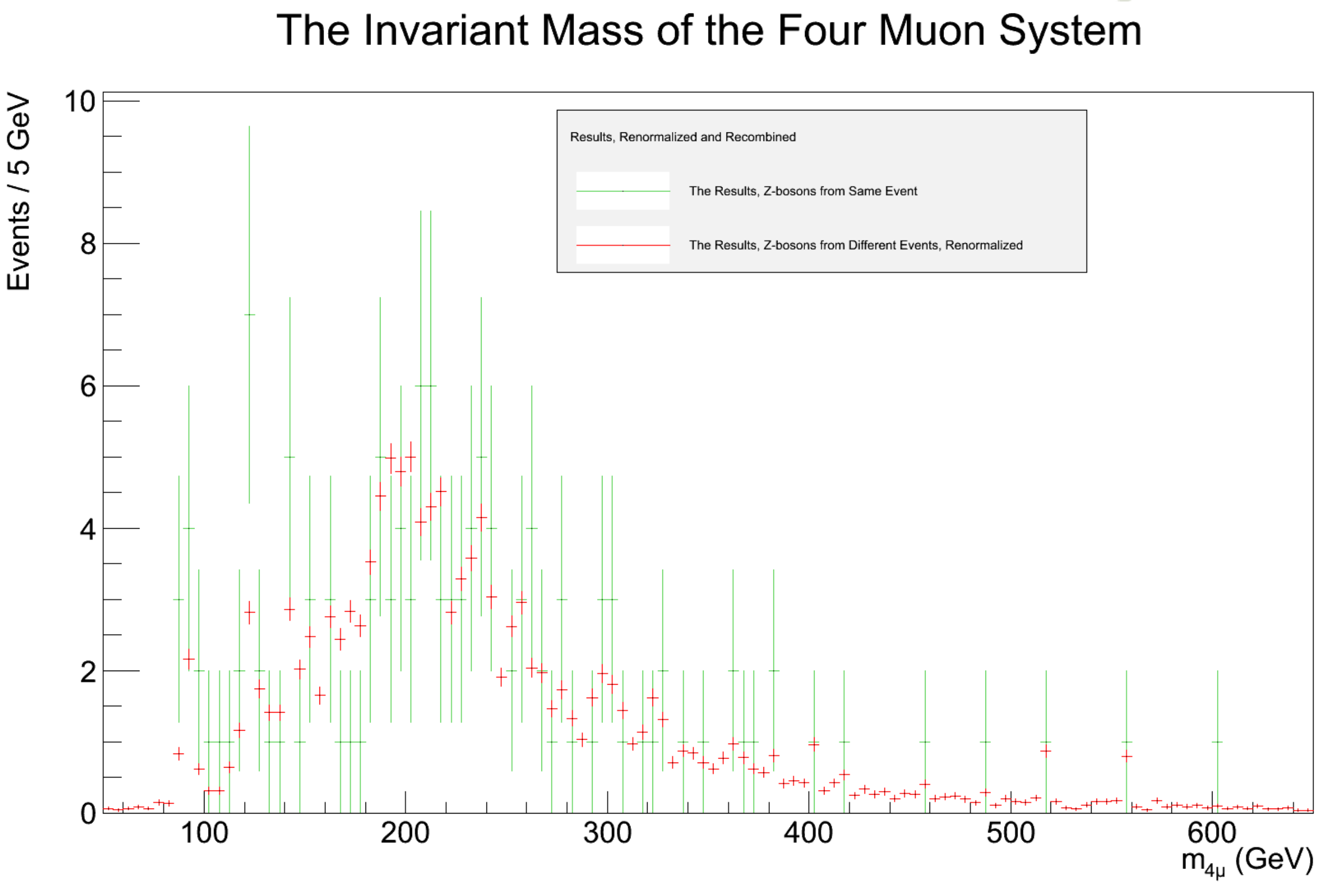


Results – Recombined Z

The Invariant Mass of the Four Muon System, Estimated Background Subtracted



Results – Recombined Z



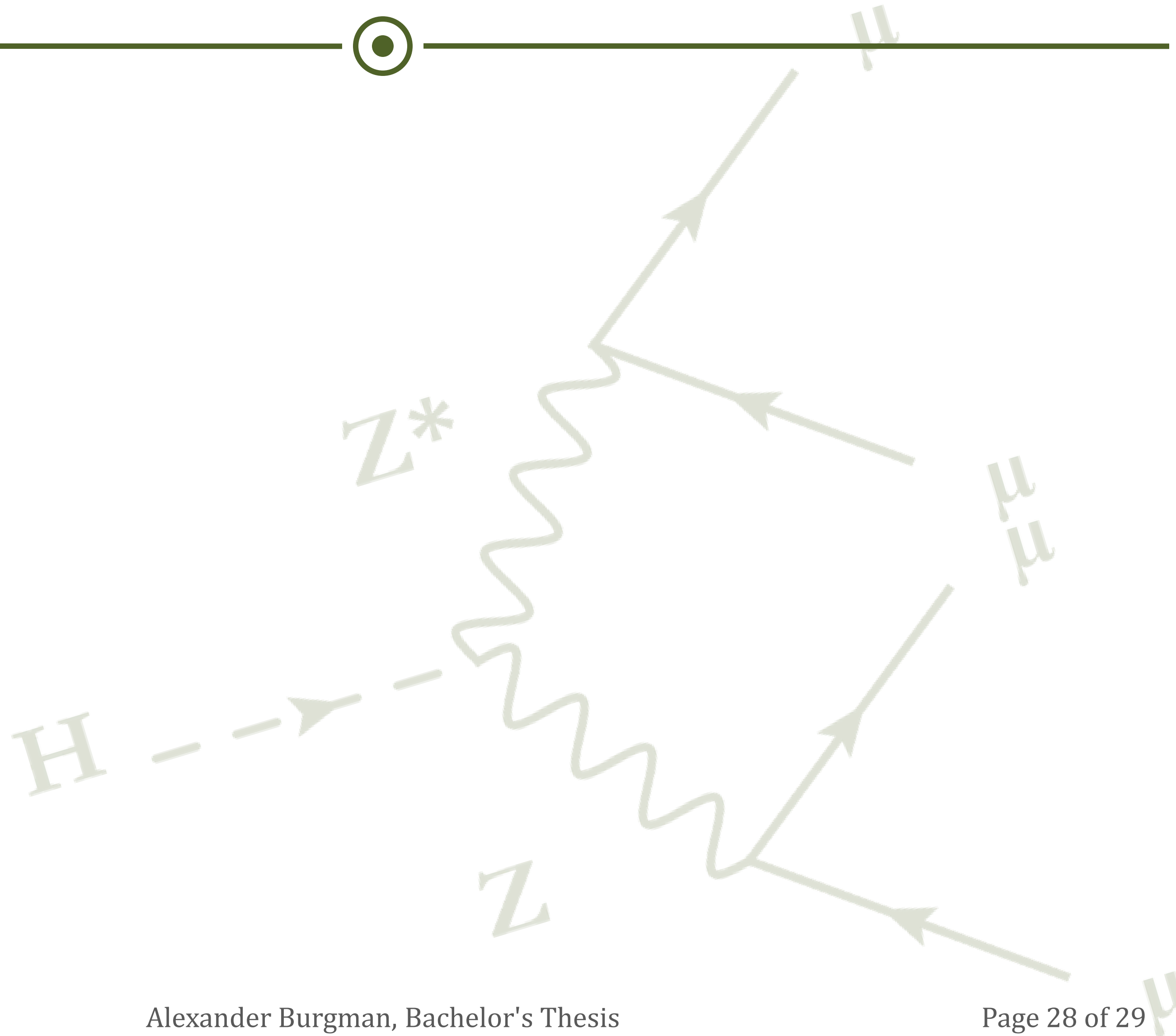
Expansion of this Project

- Data analysis
  - MC simulation to estimate FSR
  - MC simulation to estimate Higgs signal
- Recombination of Z
  - Why some Z bosons deviated
  - MC simulation to investigate recombination

Conclusion

- Peak at 120-125 GeV
  - More prominent than any other
  - Remained (significantly) more prominent after background subtraction
- Conclusion: $120\ \mathrm{GeV} \lesssim m_H \lesssim 125\ \mathrm{GeV}$
- ATLAS results: $m_H = 126\ \mathrm{GeV}$

Thank you



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Extra Slide – The Standard Model

Fermion-Type	Particles	Charge	Mass (MeV)
Quarks	u c t	2/3	2.3 1 280 174 000
	d s b	−1/3	4.8 95 4 180
Leptons	e μ τ	−1	0.511 106 1 780
	ν_e ν_μ ν_τ	0	$\lesssim 1 * 10^{-6}$

Boson-Type	Particles	Charge	Mass (GeV)
Guage	Γ	0	0
	Z	0	91.2
	W^+ W^-	+1 −1	80.4
	g	0	0
Scalar	H	0	[Unknown]

Extra Slide – Data Treatment – TDAQ

Part of TDAQ	Method	Incoming Event Rate (s^{-1})	Outgoing Event Rate (s^{-1})	Reduction Factor
Level 1	Hardware, special purpose processors	40 000 000	100 000	400
Level 2	Software, computing farms	100 000	3 000	33.3
Event Filter (Level 3)	Software, computing farms	3 000	200	15
Entire TDAQ	Both hardware and software	40 000	200	200 000

1.6 Mb / event → 1 Mb / event → 0.1 Mb / event

Extra Slide – Data Treatment – STACO

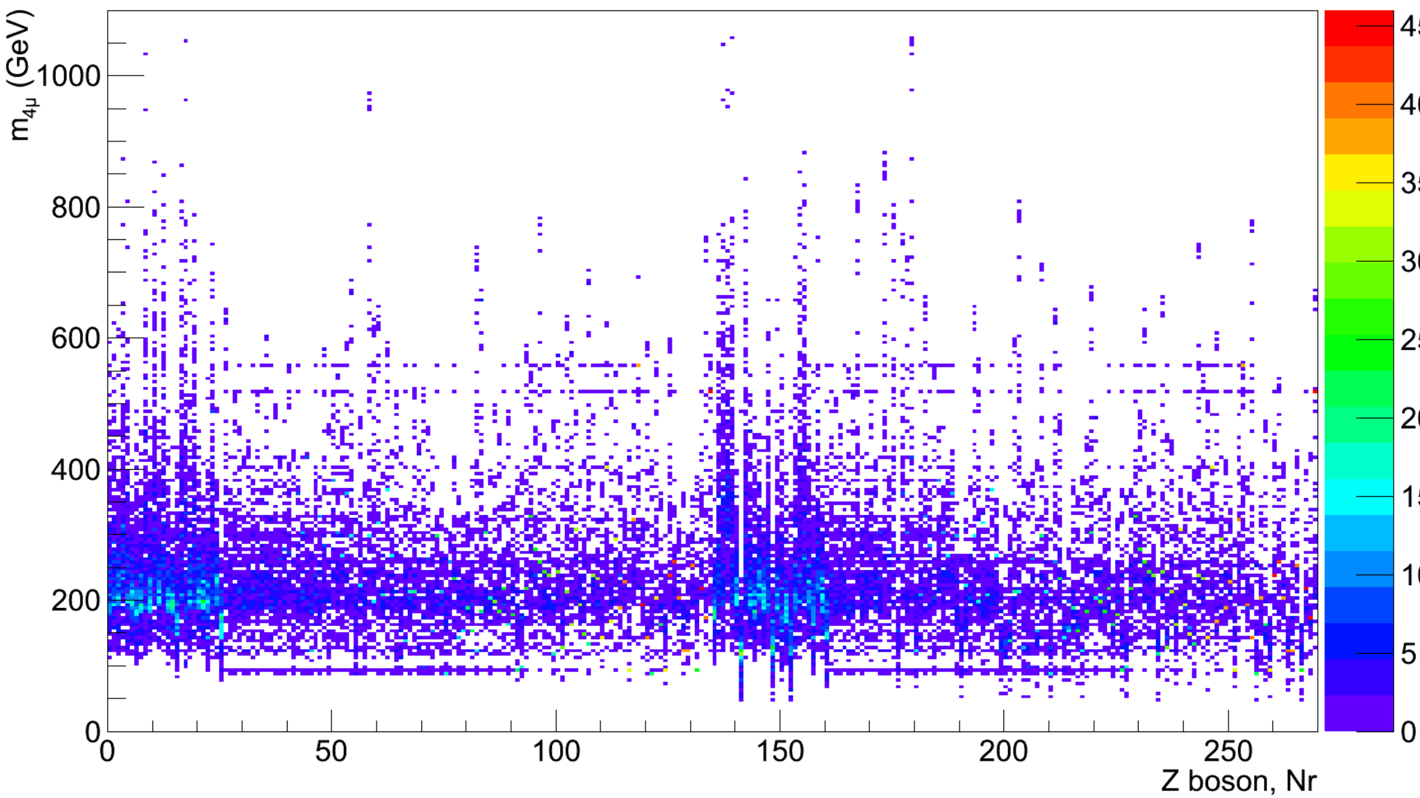
- Algorithm for muon data
- Statistically combines tracks from
  - The ID (Inner Detector)
  - The MS (Muon Spectrometer)
- Done for all muon-tracks in ID and MS, until there are no more possible combinations

Extra Slide – Data Treatment – ROOT

- Object oriented framework
  - Mostly for HEP, also used in astronomy, biology, medicine, finance
- Built-in HEP applications
  - ROOT data format
  - Histograms and graphics

Extra Slide – Results – Recombined Z

The Invariant Mass of H, Correlated with the Z1 and Z2 it came from



Extra Slide – Results – Recombined Z