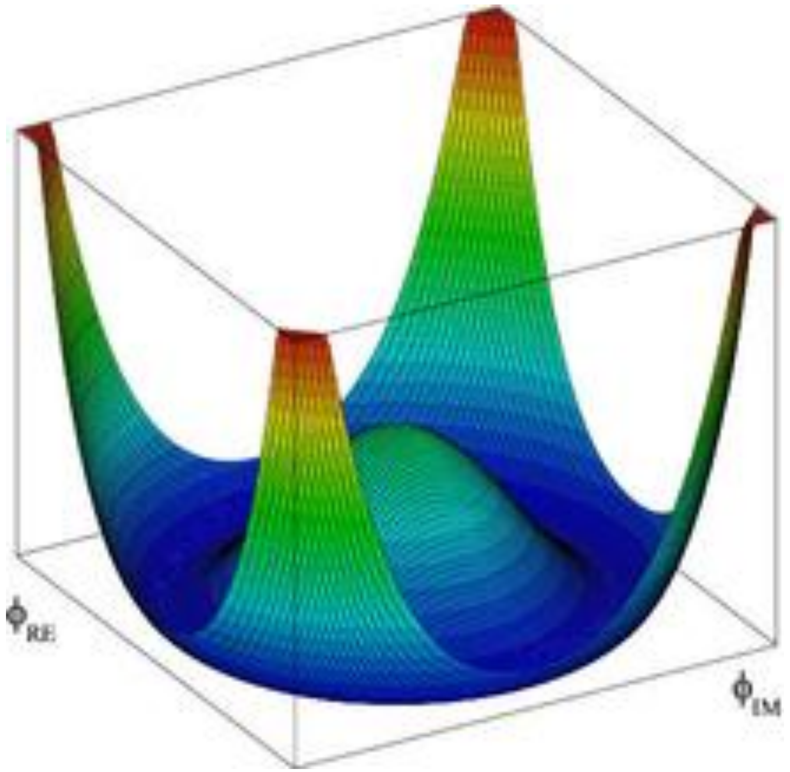
Search For the Rare Decay of $H \to \mu^+\mu^-$ at the ATLAS Experiment

Adrian Cross

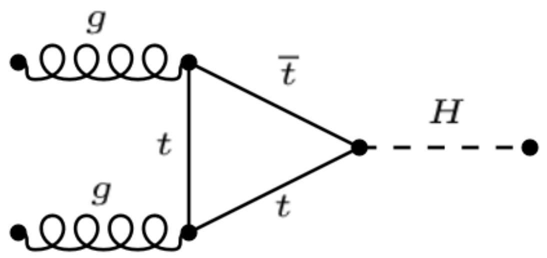
Supervisors: Paul Newman and Paul Thompson

Higgs Boson Properties



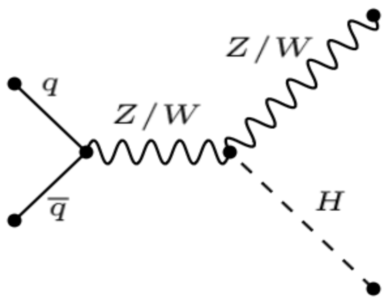
- Higgs field gives masses to gauge bosons and retains renormalisability .
- Couples to fermion fields and gives them mass.
- Measured as $125.09 \pm 0.21\ (stat.) \pm 0.11\ (syst.)\ GeV/c^2$.(March 2015)
- Parity=+1.
- Spin=0.
- No colour or electric charge.

Higgs Boson Production



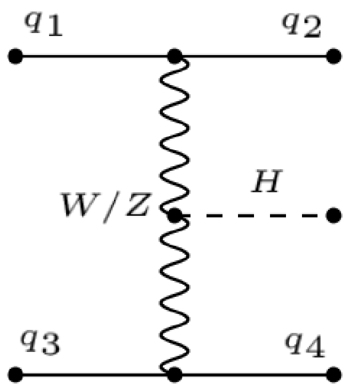
Gluon-gluon fusion

cross section: 43.92Pb



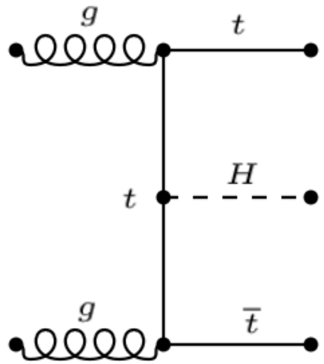
Associated production

cross section: 2.2496pb



Vector boson fusion

cross section: 3.748pb

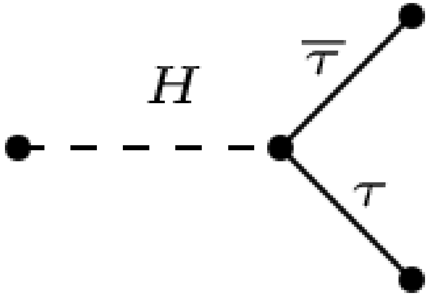


Top fusion

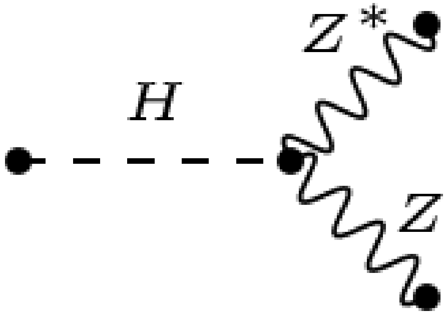
Cross section: 0.5085pb

- Gluon fusion process is roughly an order of magnitude higher than the other processes.
- All the cross section are low compared to background processes.

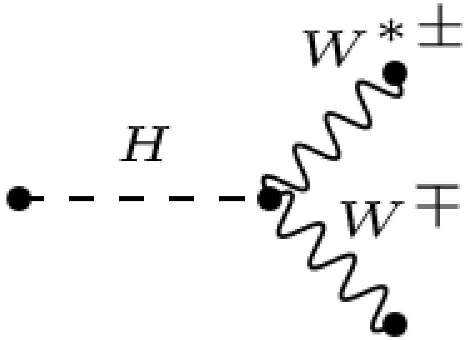
Higgs Boson Decay



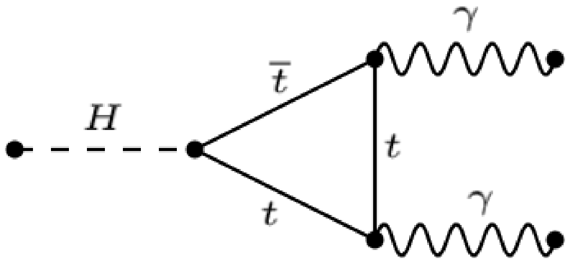
Branching ratio
$\approx 6.32 * 10^{-2}$



Branching ratio
$\approx 2.64 * 10^{-2}$



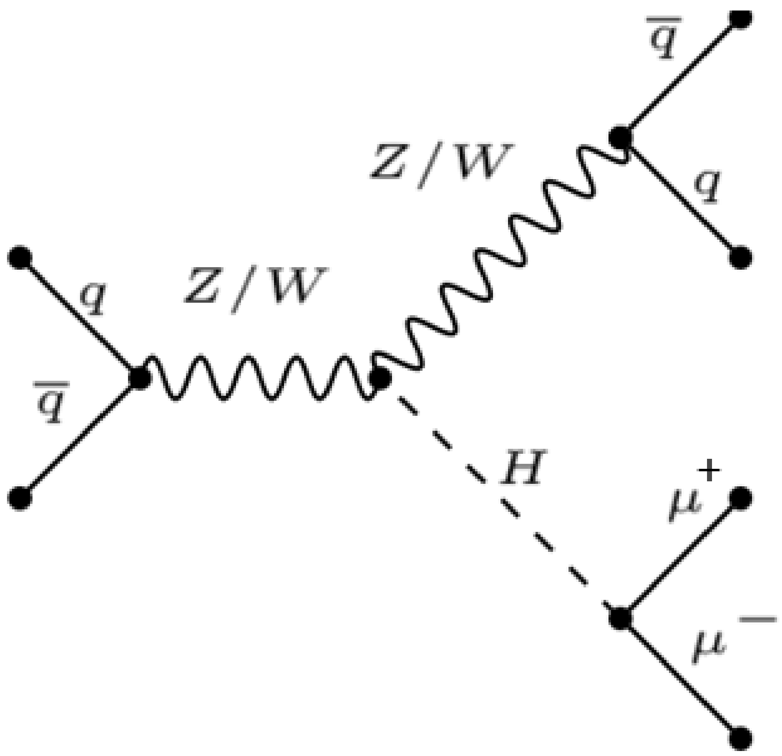
Branching ratio
$\approx 2.15 * 10^{-1}$



Branching ratio
$\approx 2.28 * 10^{-3}$

- Branching ratios of decays are proportional to the mass of decay product squared.
- Higgs decaying to higher mass particles have a higher branching ratio.

Higgs Process Investigated



$H \rightarrow \mu^+\mu^-$Branching ratio is $2.19 * 10^{-4}$

- Currently unobserved by LHC experiments.
- Rare due to the low relative mass of the muons produced.

$$\frac{\Gamma(H \rightarrow \tau^+\tau^-)}{\Gamma(H \rightarrow \mu^+\mu^-)} = \frac{{M_\tau}^2}{{M_\mu}^2} \approx 283$$

- $H \rightarrow \mu^+\mu^-$ is 283 times less likely than $H \rightarrow \tau^+\tau^-$.

Project Timeline

Electron and muon resolution studies.

→

Determining cuts to optimise signal to background ratio using simulated data.

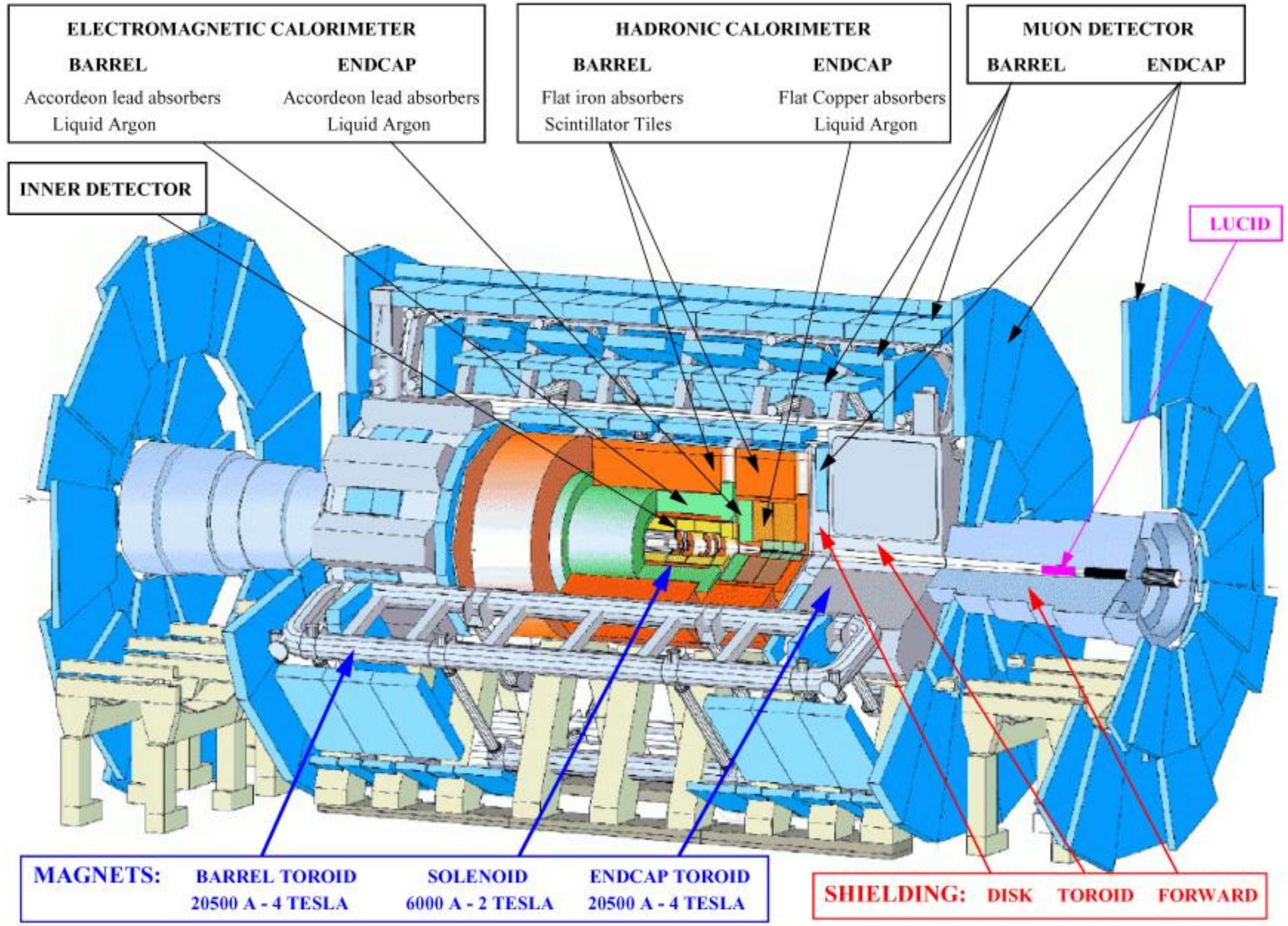
→

Apply cuts to data.

→

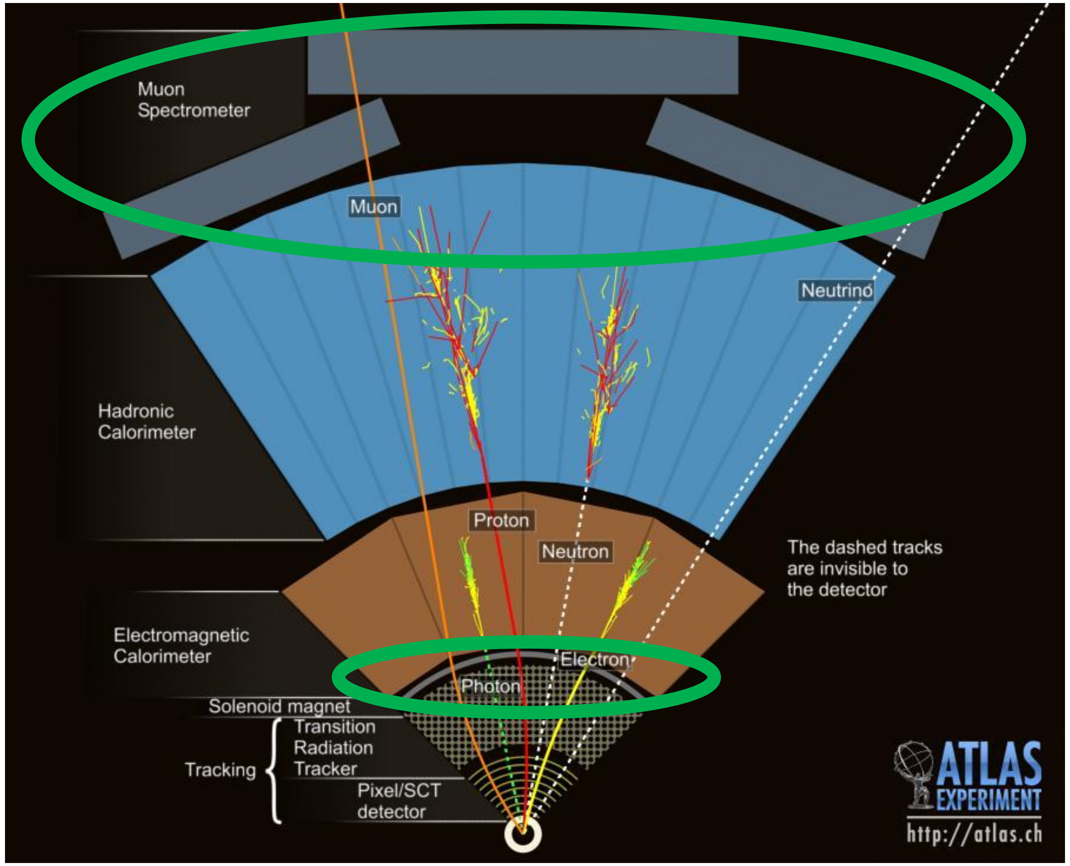
Determine the signal excess required to detect the process and compare to ATLAS data.

ATLAS Experiment



- ATLAS has completed a $7TeV$ run collecting $5fb^{-1}$ of data and an $8TeV$ run collecting $20fb^{-1}$ of data.
- Currently running at a centre of mass energy of $13TeV$ with approximately $3fb^{-1}$ of data collected so far.
- Analysis is currently based on $100fb^{-1}$ of data.

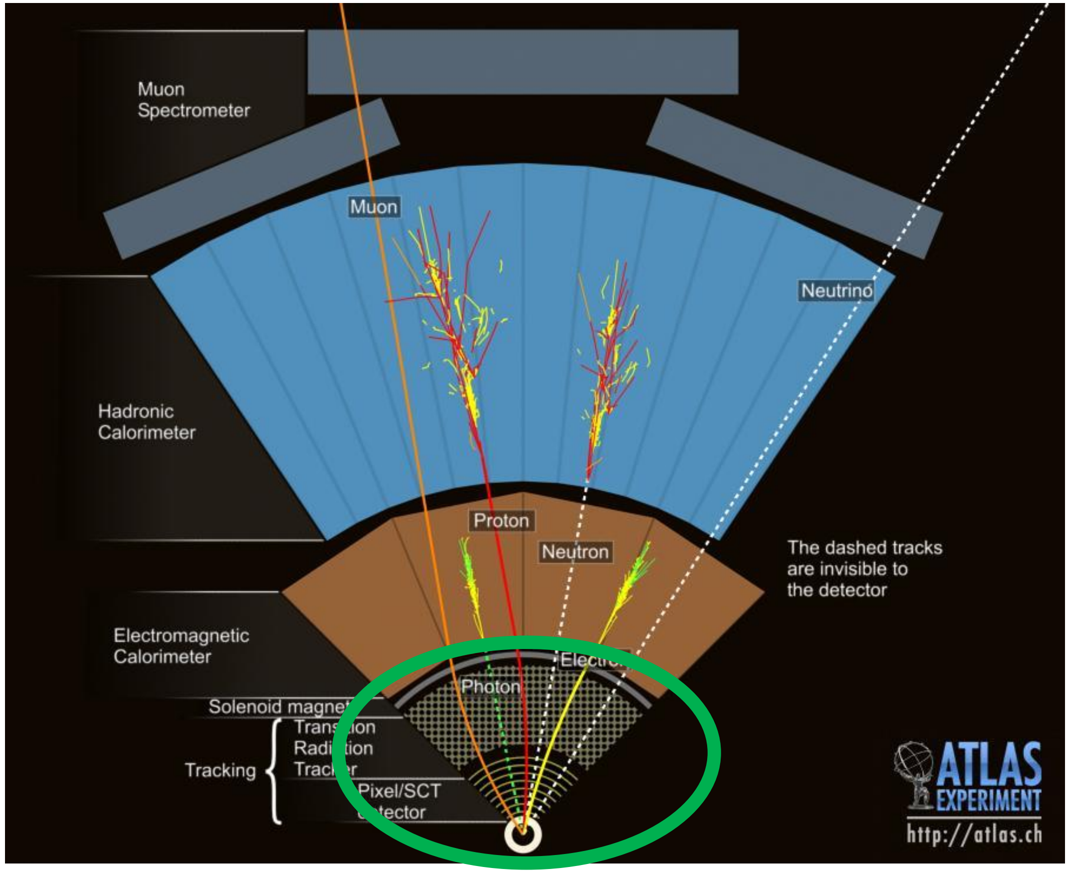
Atlas Experiment: Magnet System



- Solenoid: Surrounds the inner detector with a magnetic field strength of 2T.
- Toroidal magnets: 8 barrel, 2 end cap toroidal loops interweaved with the muon detector facilitating the measurement of muons outside of the tracker.
- Toroidal magnets produce a non uniform magnetic field.

- c

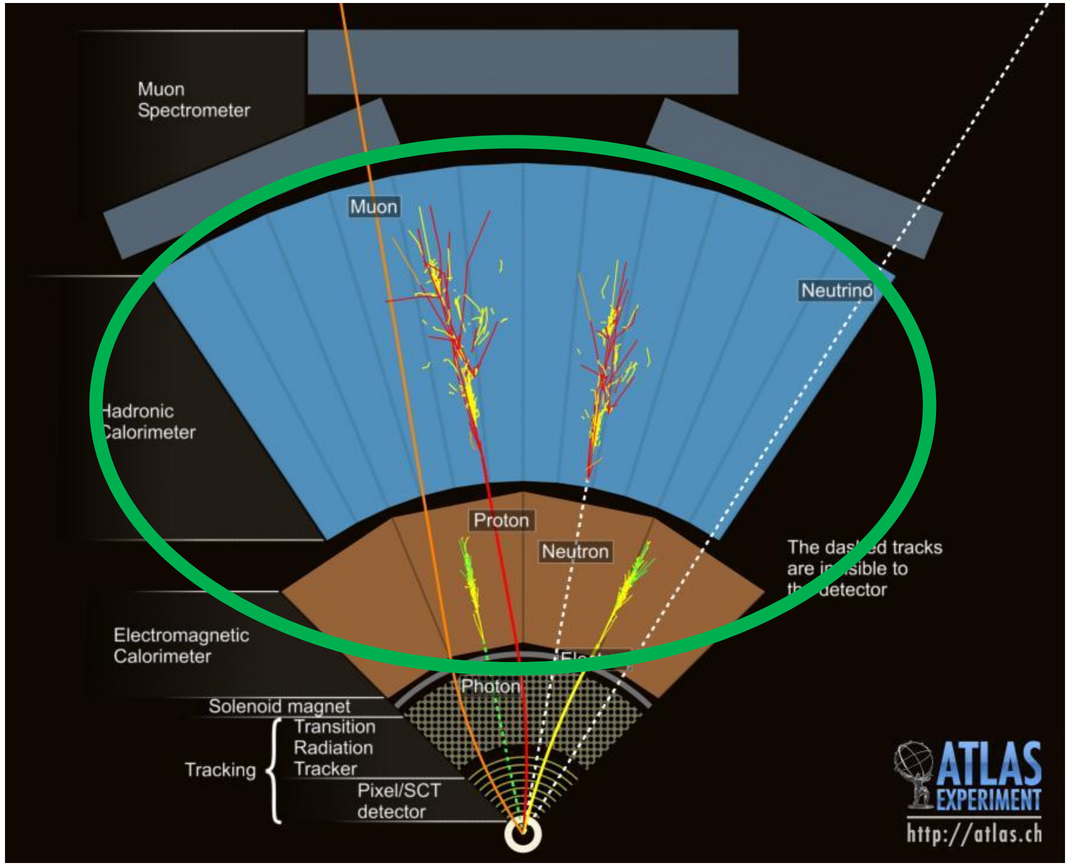
Atlas Experiment: Inner Detector



- Total resolution of $\frac{\sigma P_T}{P_T} = 0.05\% P_T \oplus 1\%$

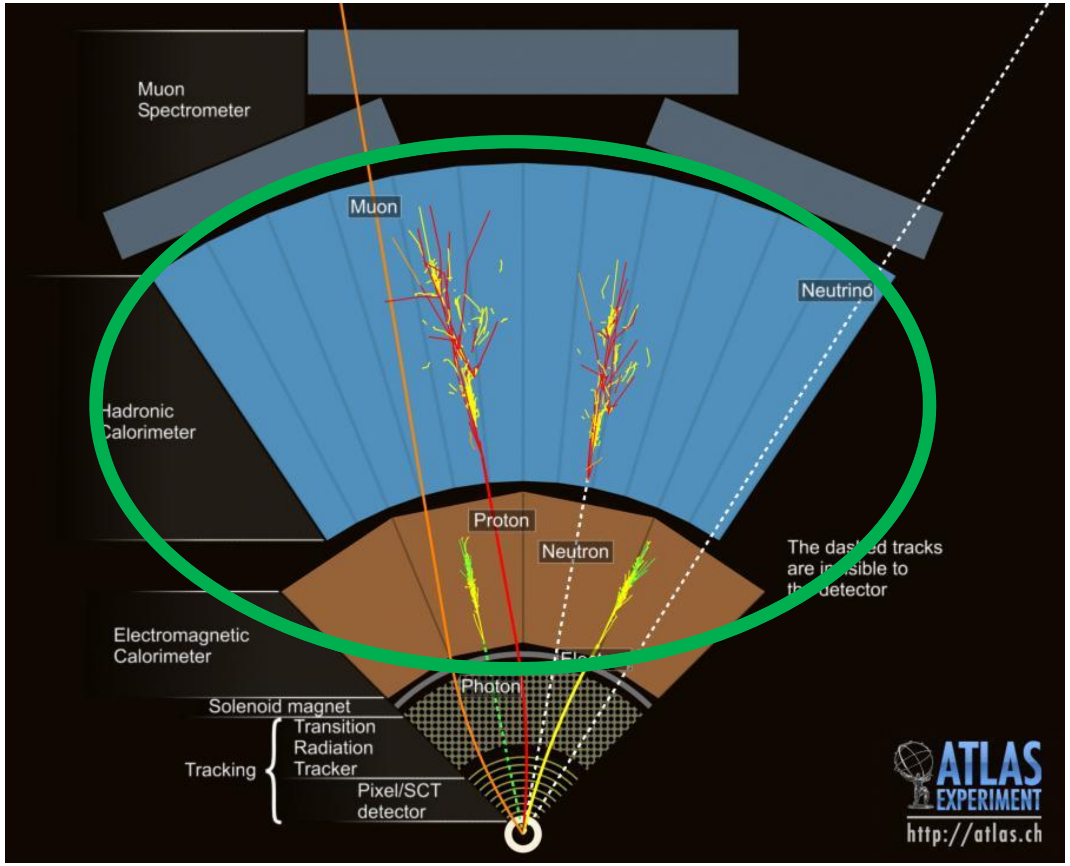
- Tracks charged particles bending in magnetic field (2T)
- Consists of 3 distinct layers:
- Pixel detector: 3 layers of silicon pixels up to 122.5mm radius $|\eta|$<2.5.
- SCT: 8 layers of silicon strips with slight angle between them $|\eta|$<2.5.
- TRT: Consists of straw tubes filled with a mixture of ,$X_e(70\%)$, $CO_2(27\%)$ and $O_2(3\%)$ which ionise when charged particles pas through them$|\ \eta|$<2.5.

Atlas Experiment: EM Calorimeter



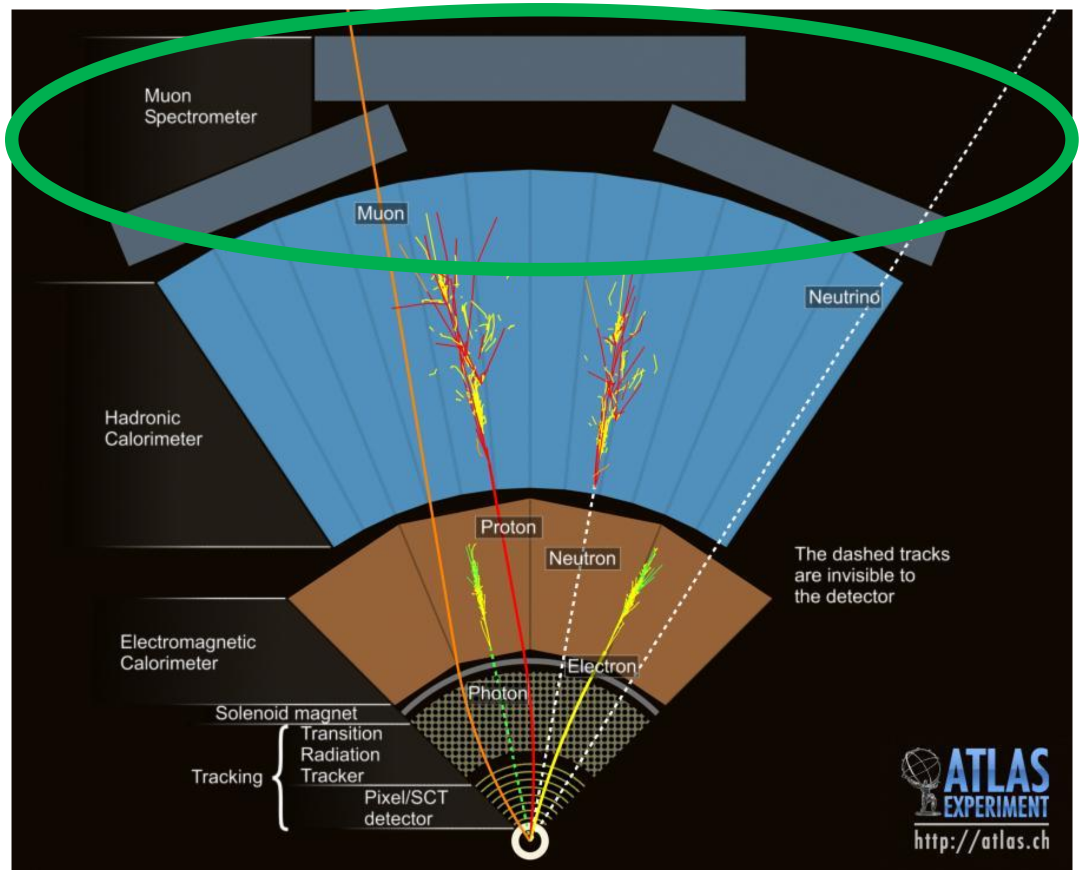
- Sampling calorimeter consisting of a barrel calorimeter with lead as the absorber material and liquid argon as the active medium. $|\eta|<1.475$.
- End caps consists of the same material with $1.375<|\eta|<3.2$.
  - ECAL resolution $\frac{\sigma E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Atlas Experiment: Hadronic Calorimeter



- Barrel: Tile calorimeter with steel as an absorber material and scintillating tiles as the active medium $|\eta|<1.475$.
- End cap: Copper as the absorber material and liquid argon as the active medium. $1.5<|\eta|<3.2$.
- Forward calorimeter consists of 1 layer using copper as the absorber and 2 layers using tungsten with liquid argon as the active medium. $3.1<|\eta|<4.9$.
  - HCAL resolution (barrel and end cap) $\frac{\sigma E}{E} = \frac{50\%}{\sqrt{E}} \bigoplus 3\%$
- HCAL resolution (Forward calorimeter) $\frac{\sigma E}{E} = \frac{100\%}{\sqrt{E}} \bigoplus 10\%$

Atlas Experiment: Muon Detector



Precision chambers:

- Muon drift chamber $|\eta|$<2.
- Cathode strip chamber 2<$|\eta|$<2.7.

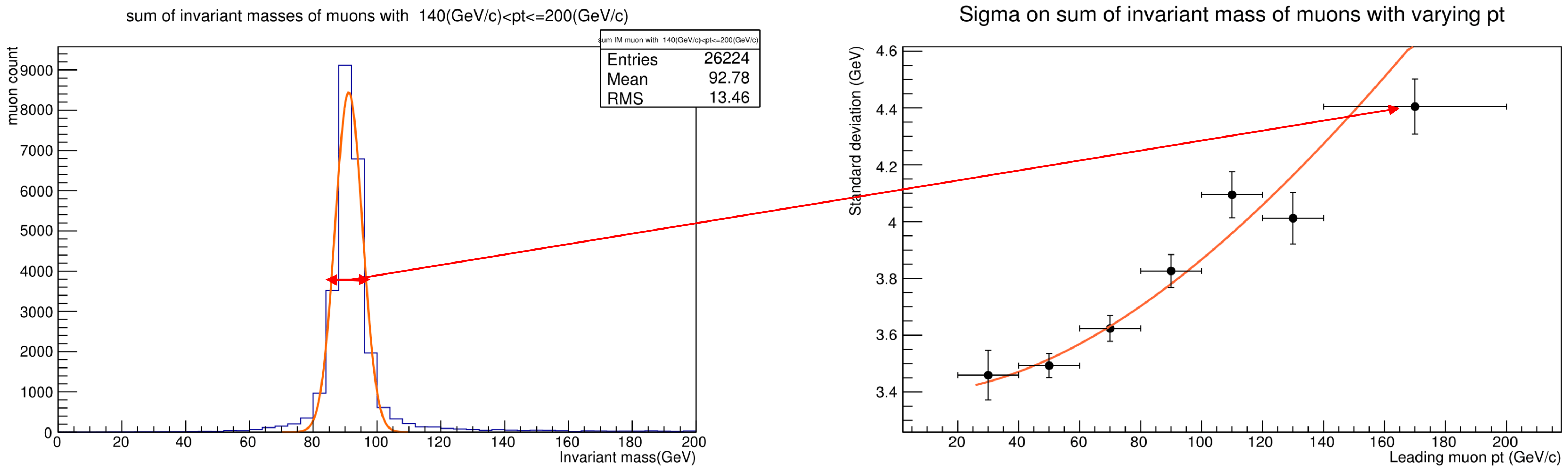
Trigger chambers:

- Resistive plate chamber $|\eta|$<1.05
- Thin gap chamber 1.05<$|\eta|$<2.4

- Muon detector resolution $\frac{\sigma P_T}{P_T} = 3\%$ at $P_T = 100GeV/c$

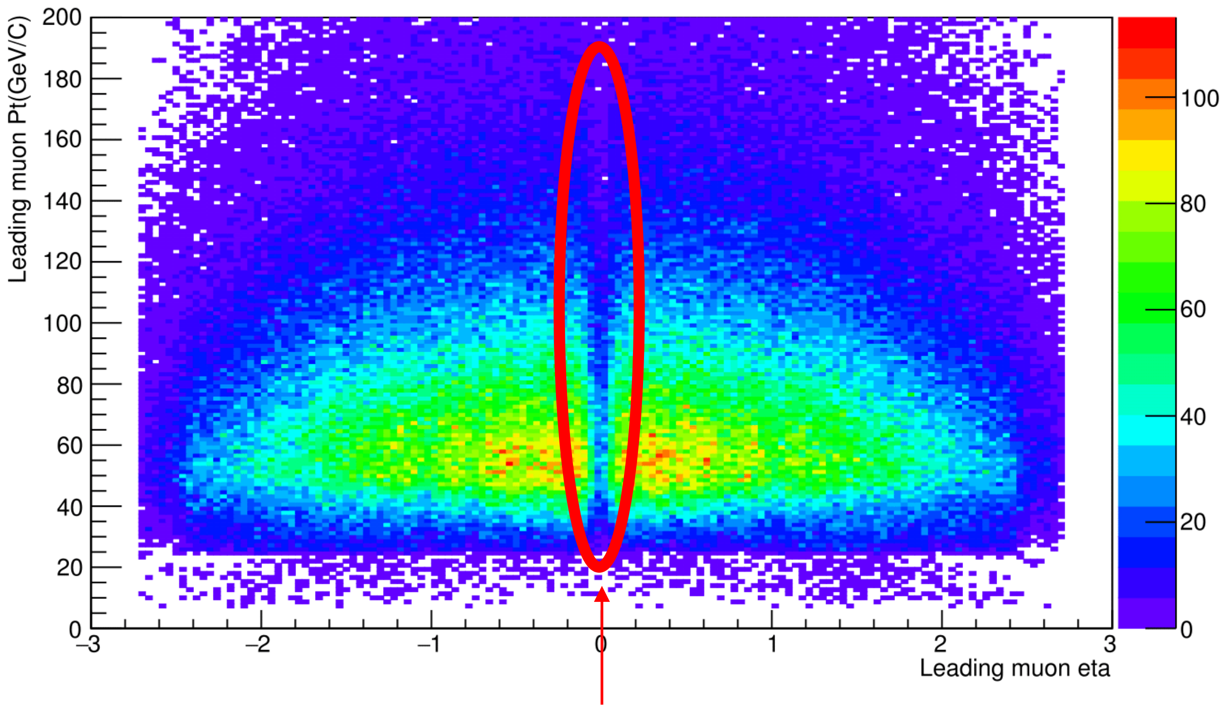
Resolution Studies

- Using Gaussian fits on muon invariant mass in different momentum bounds can build a picture of the tracker resolution.



Simulated Data

Leading Muon Transverse Momentum against Pseudorapidity

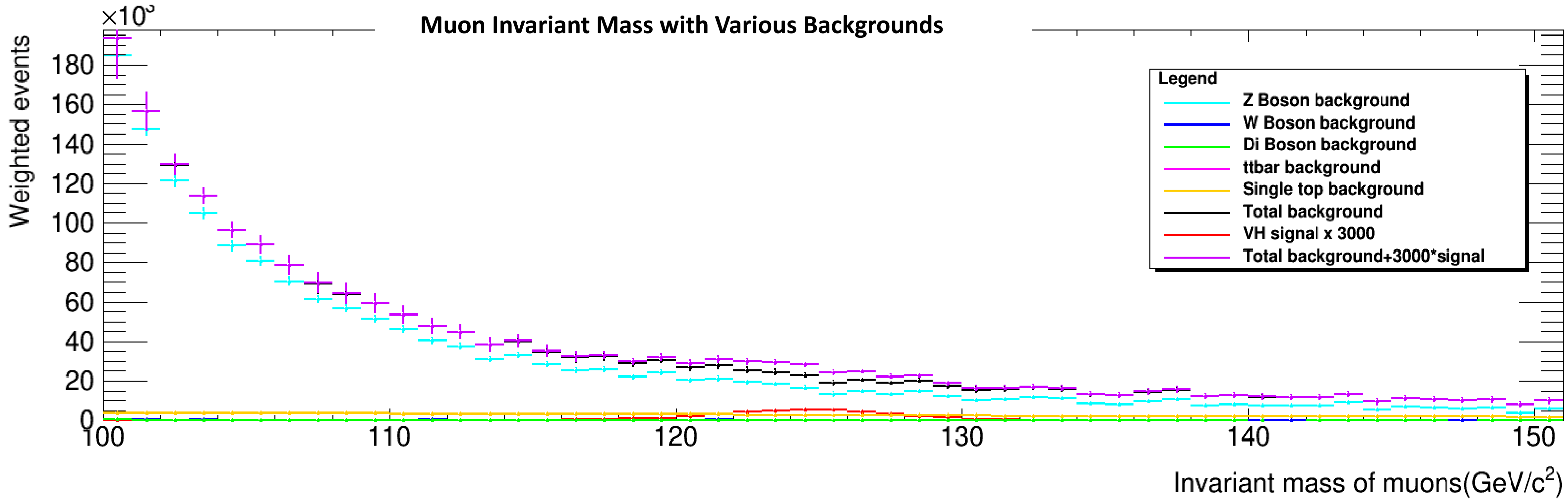


Simulated data should accurately represent the measurements made by the detector including 'holes'.

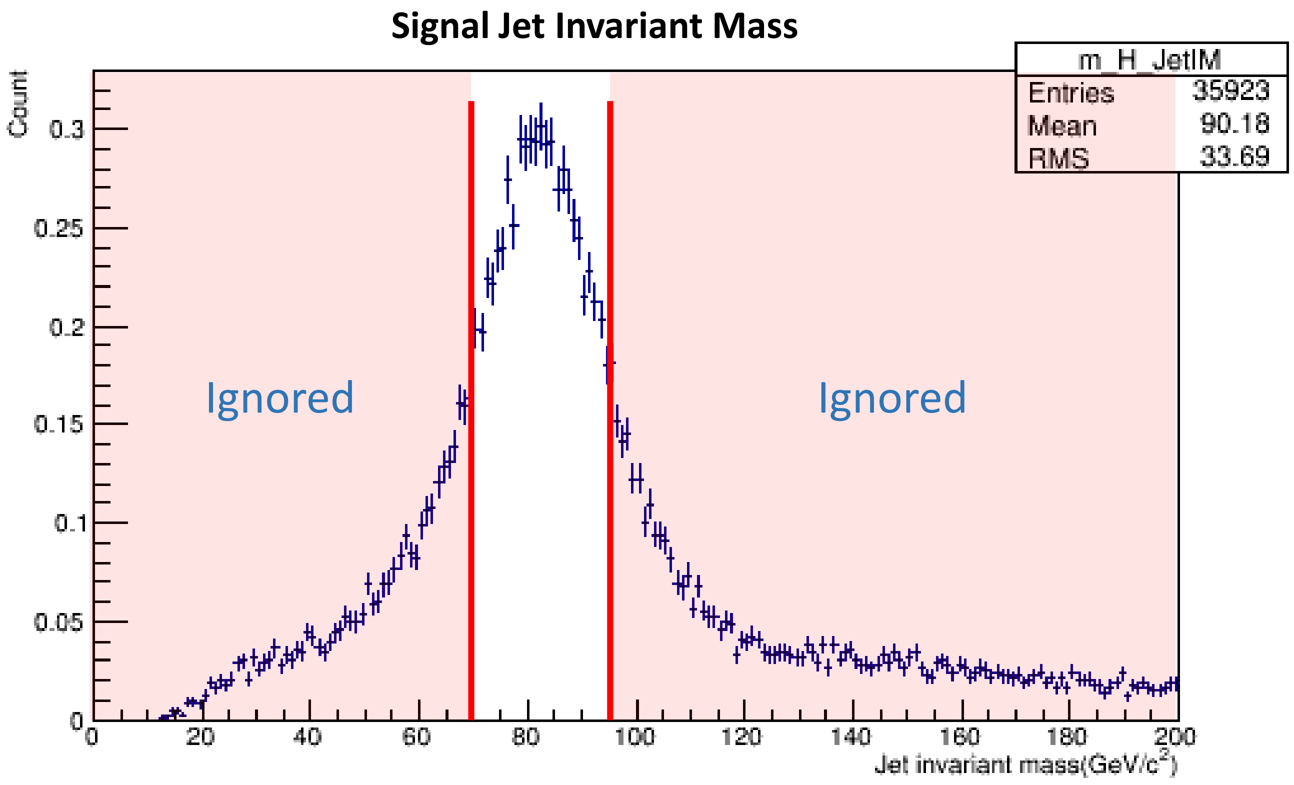
- Data has been simulated using Monte Carlo software.
- Geant4 is then used to simulated the particles passing through the ATLAS detector.
- Monte Carlo data has been weighted depending on event cross section and total luminosity.

Sources of Background

- Main source of background is $Z \rightarrow \mu^+\mu^-$ + Jets.
- Cuts are applied to data to maximise background reduction but minimise signal reduction



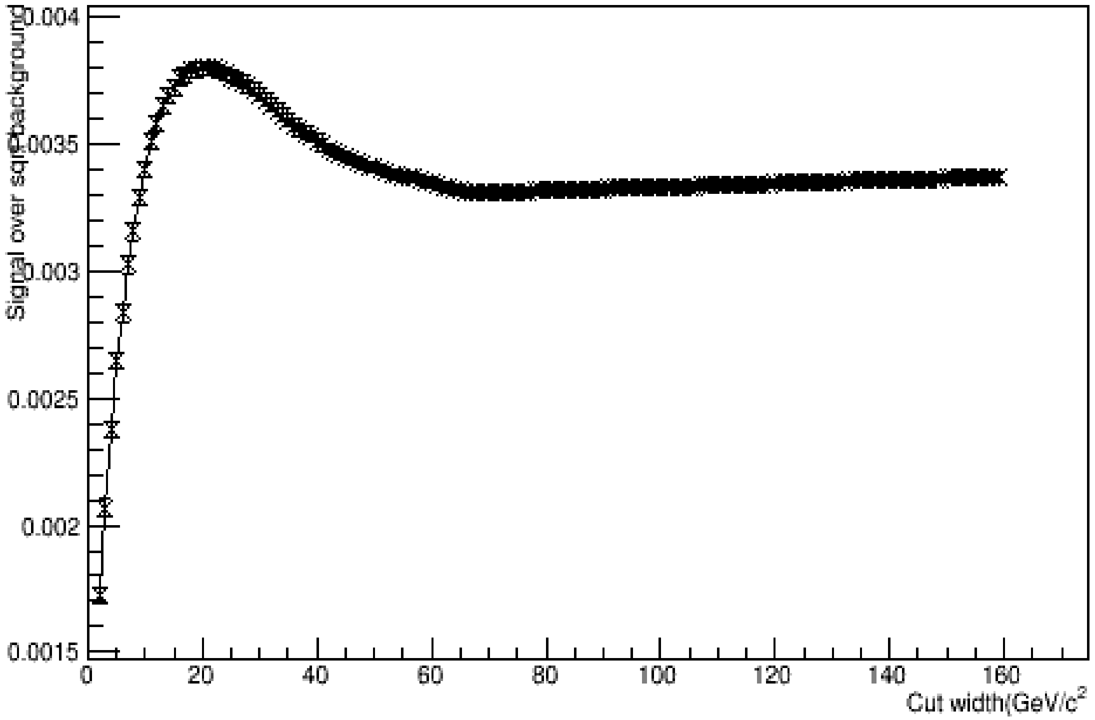
Selection Cuts



- By applying limits on the particle properties the background can be reduced relative to the signal.
- This is done by ignoring all events which are outside a certain range.
- Cuts can be done on different properties of particles and on different particles.

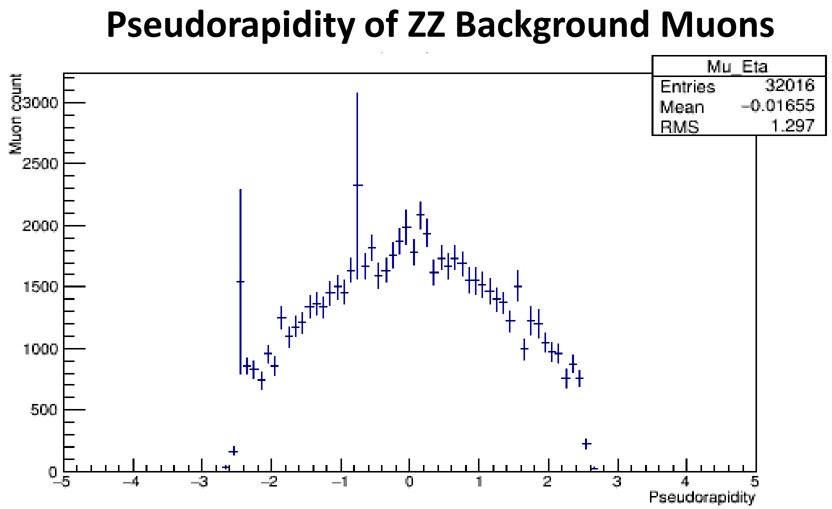
Determining Cut Value

Significance for Varying Jet Invariant Mass Cuts



- The value of the cuts are determined by systematically cutting on the signal and all sources of background.
- The significance ($\frac{Signal}{\sqrt{Background}}$) is plotted for each cut value.
- Finding the maximum for these graphs retains the most amount of signal events while reducing background.

Preselection Cuts



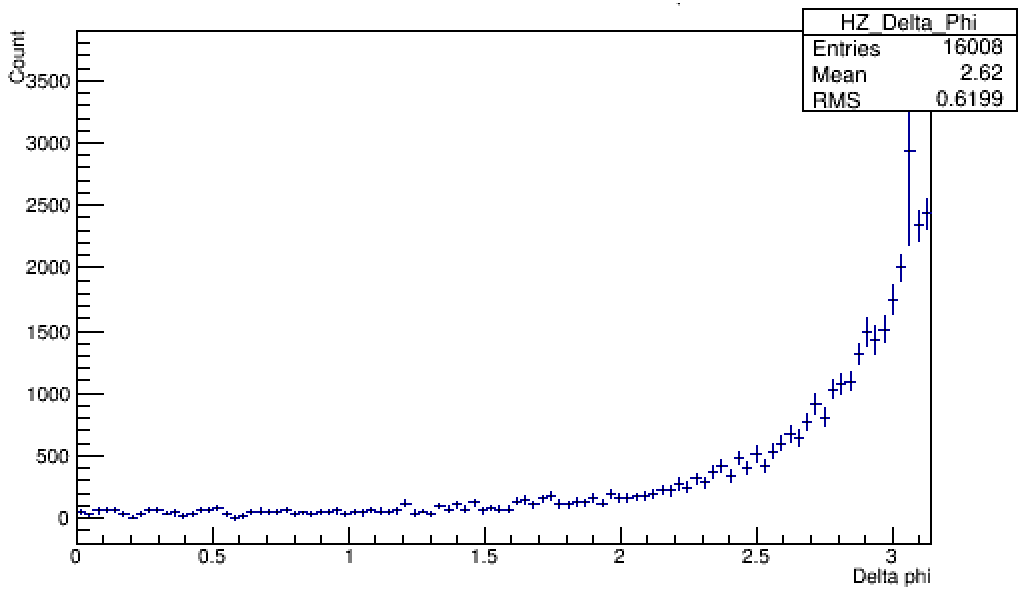
- Several cuts are made before processing the data.
- $\eta < 2.5$
- $Jet\ P_T > 25GeV/c$
- More than 2 Jets and exactly 2 muons in the event.

Polar Angle in the Transverse Plane (Ø)

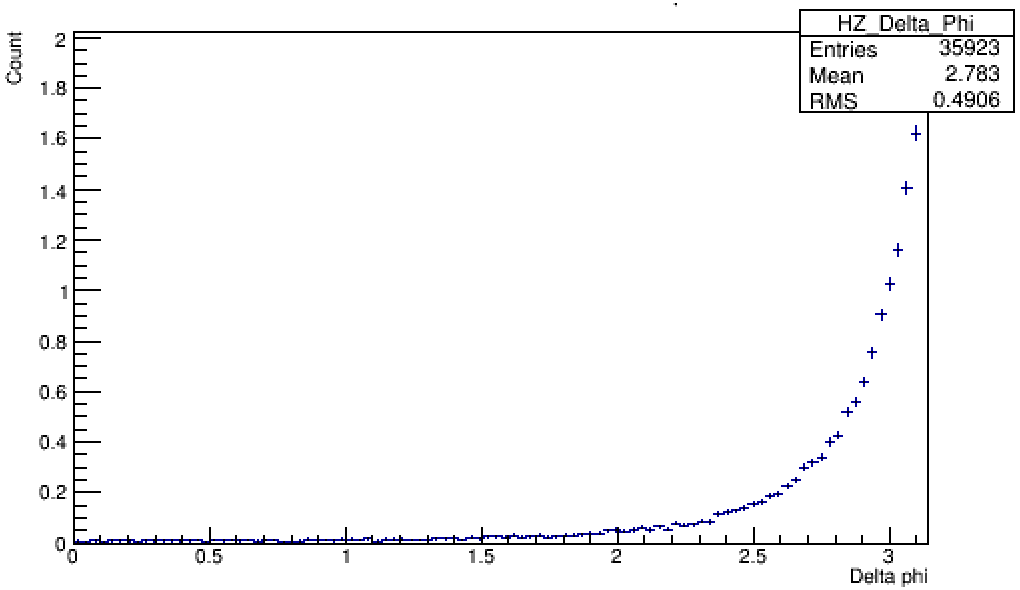
- This is the angle around the beamline.
- Cuts have been made on ΔØ (the angle between 2 particles.)
- $|\Delta Ø(HV)| > 2.6$: Signal Retained=79.7%

Background retained: 49.1%

HV ΔØ on Background

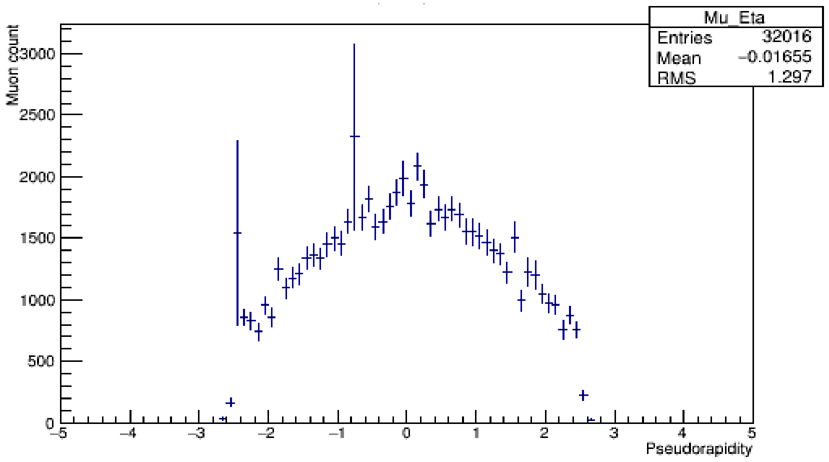


HV ΔØ on Signal

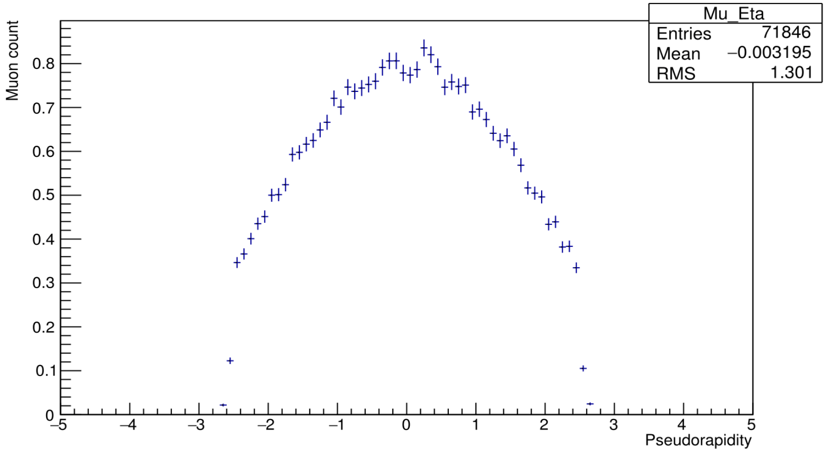


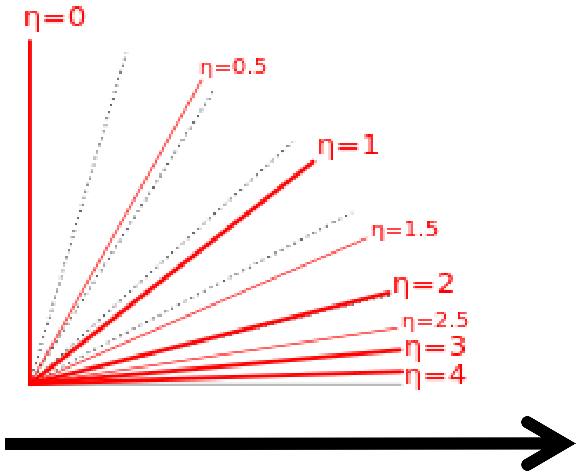
Pseudorapidity (η)

Pseudorapidity of ZZ Background Muons



Pseudorapidity of Signal Muons





- Spatial coordinate used to describe the angle of a particle to the beamline.

- $|\Delta\eta(HV)| < 1.7$: Signal Retained=65.7%

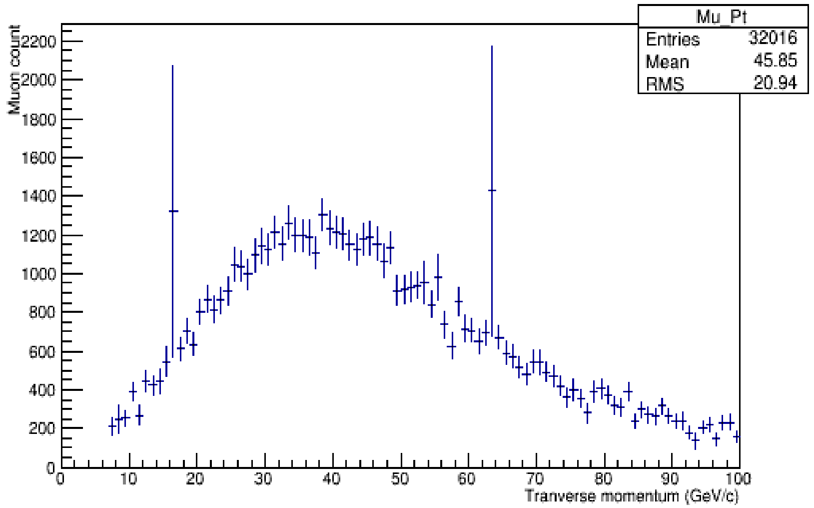
  Background retained: 24.8%

Transverse Momentum

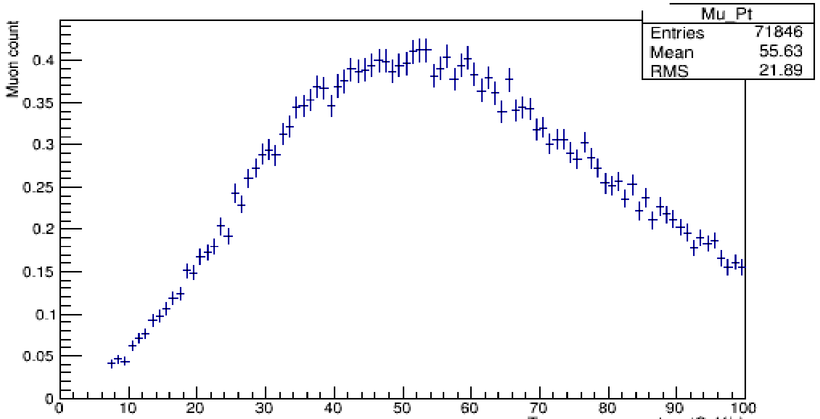
- Momentum perpendicular to the beamline

- $P_t(Jets) > 77GeV/c$: Signal Retained=56.7%
  Background retained: 16.8%
- $P_t(Muons) > 76GeV/c$: Signal Retained=53.6%
  Background retained: 13.2%

Background Transverse Momentum of Muons



Signal Transverse Momentum of Muons

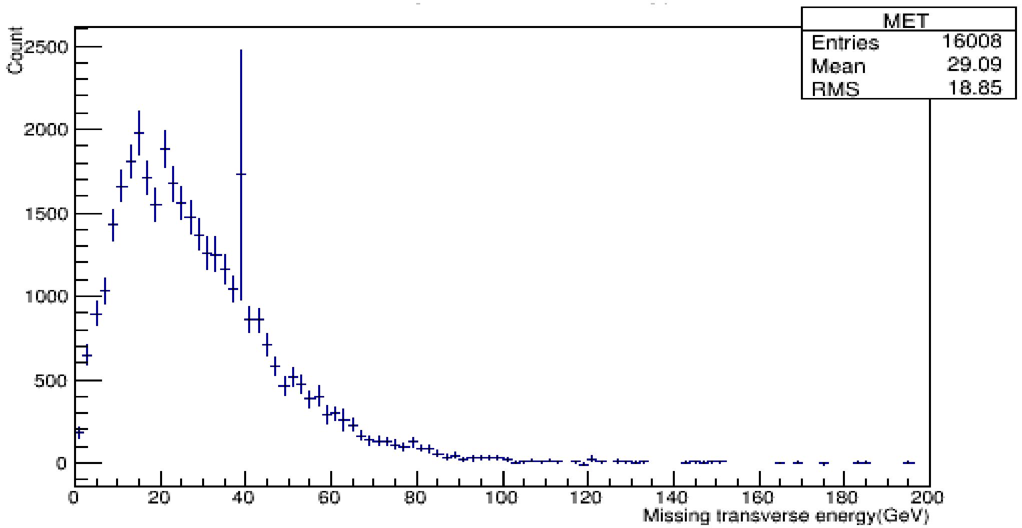


Missing Transverse Energy (MET)

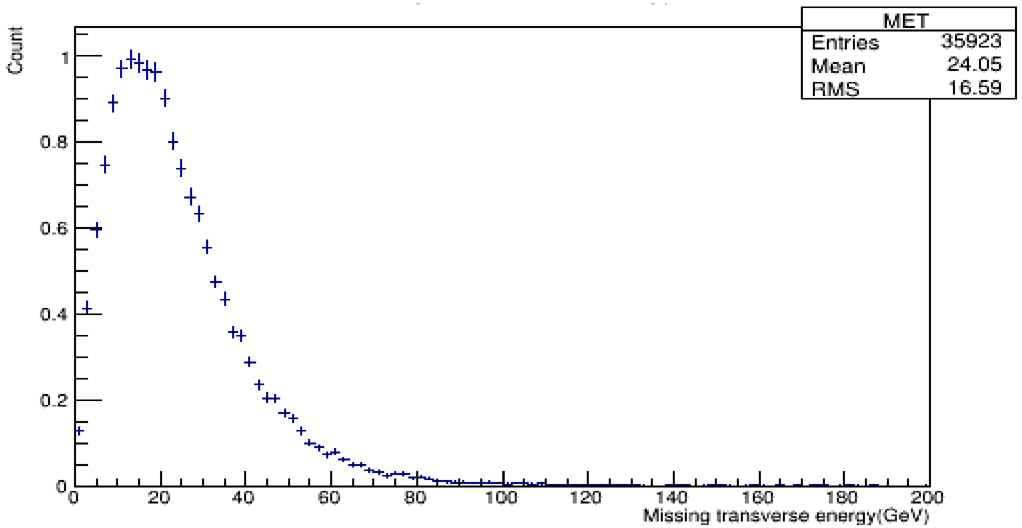
- This is the missing energy from the collision.
- Caused by neutrino’s carrying energy away or particles escaping the calorimeter.
- $MET < 53GeV$: Signal Retained=46.3%

Background retained: 10.5%

Background Missing Transverse Energy



Signal Missing Transverse Energy

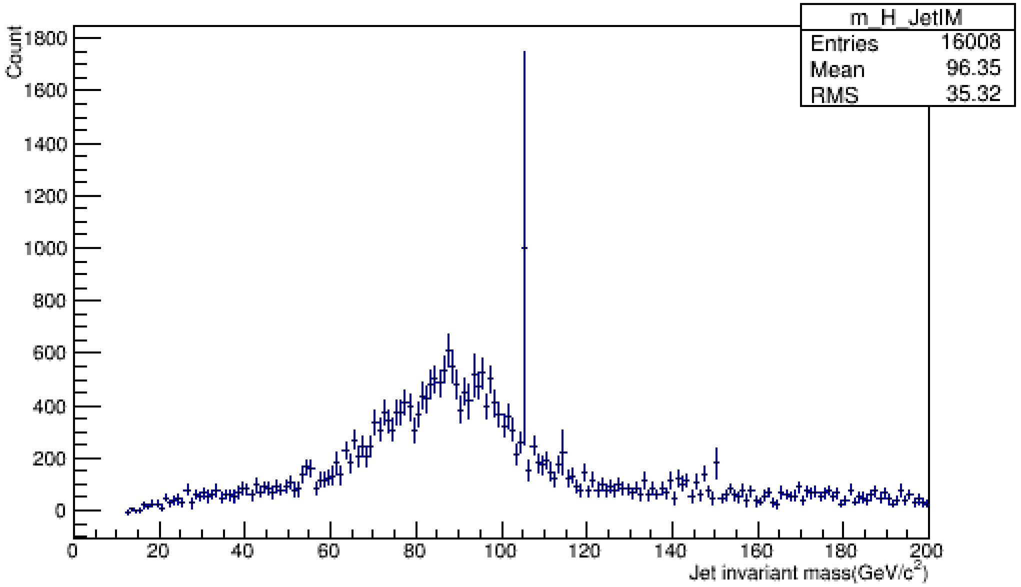


Jet Invariant Mass (Jet IM)

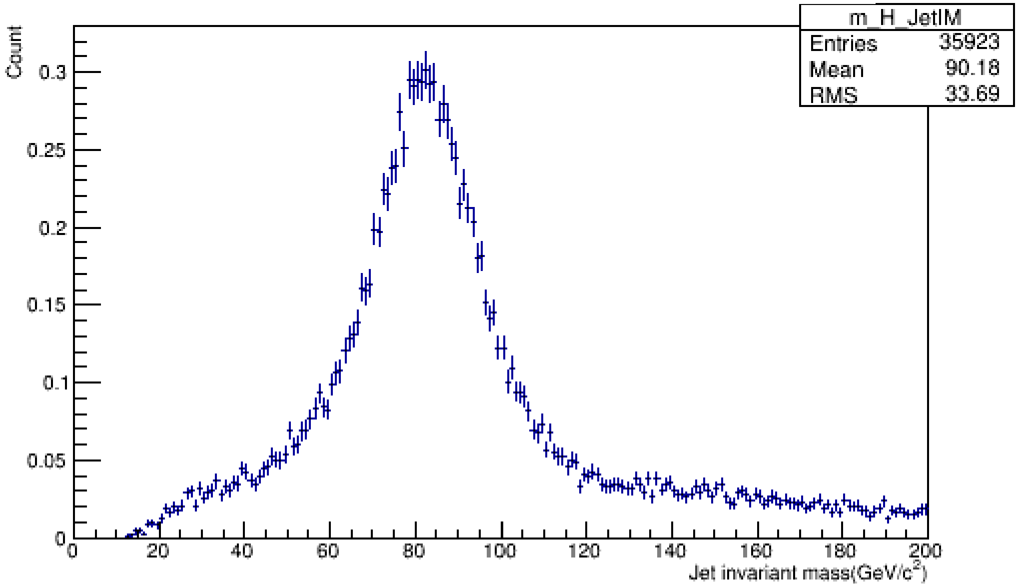
- Cut on Jet IM has been made by taking a peak at 83GeV and applying a cut width (calculated as 22GeV).
- $61GeV \leq IM(Jets) \leq 105GeV$ Signal Retained=32.0%

Background retained: 2.7%

Jet IM on Background

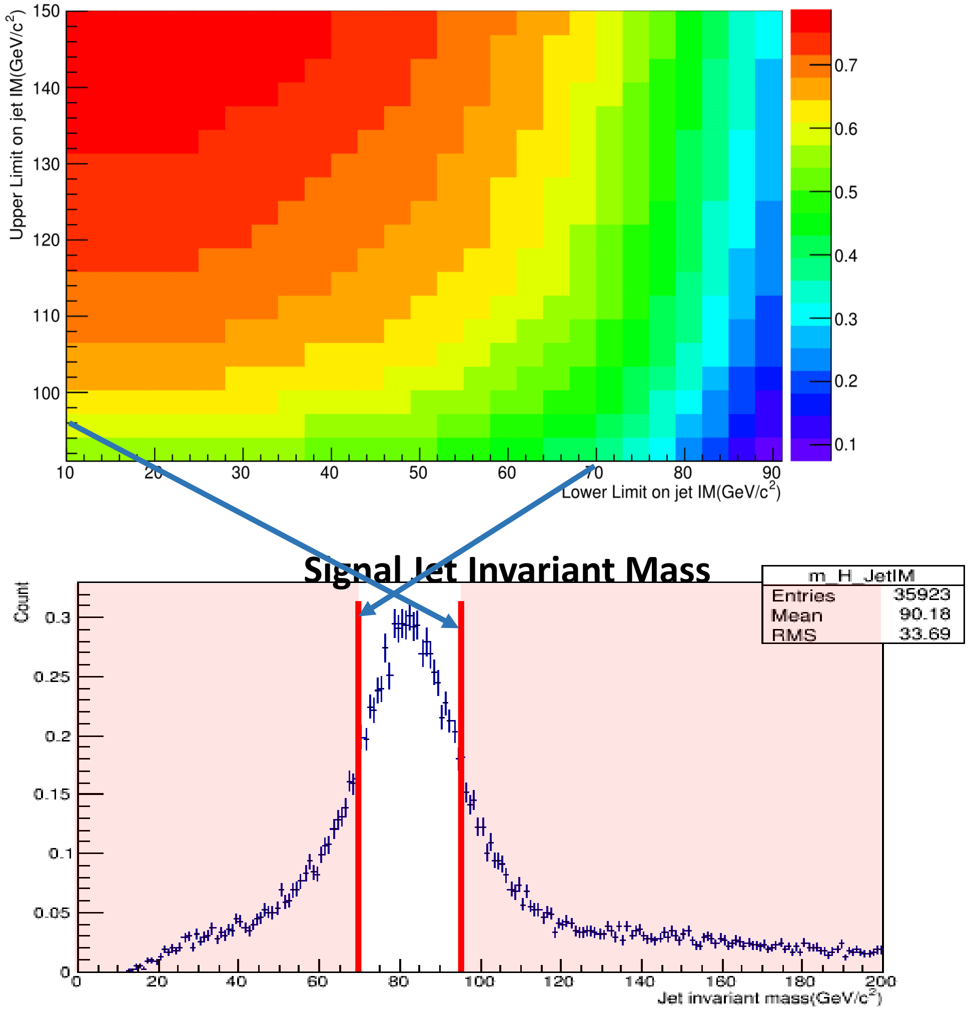


Jet IM on Signal



2D Cuts

Fraction of Signal Events Retained Depending on Jet IM Limits



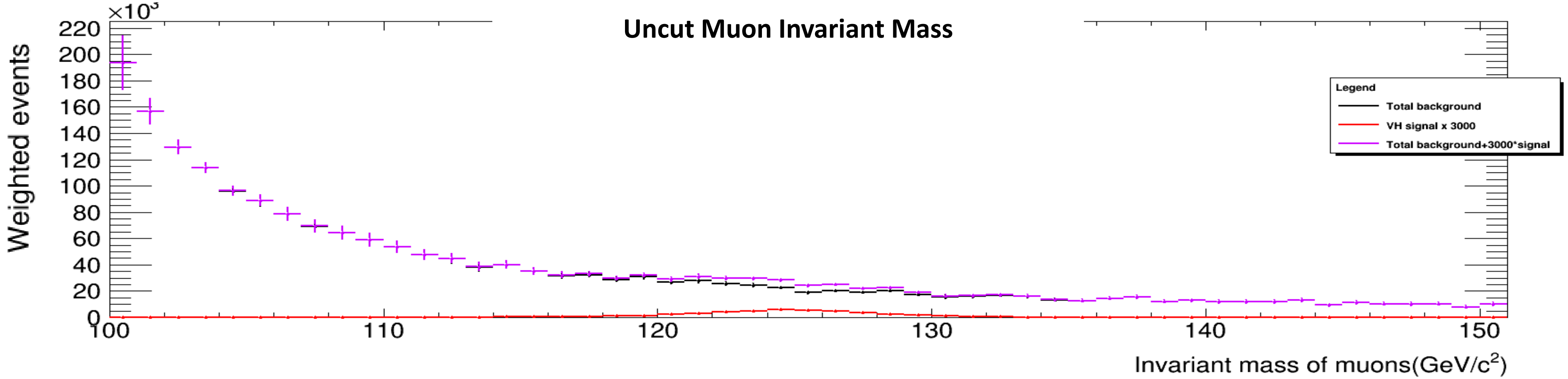
- When applying limits around a central value a different value for the lower and upper cuts could optimise the selection
- In practise this is computationally intensive
- Instead apply a cut with a ‘width’ around the Z/W peak (83GeV)

Further Cut Optimisation

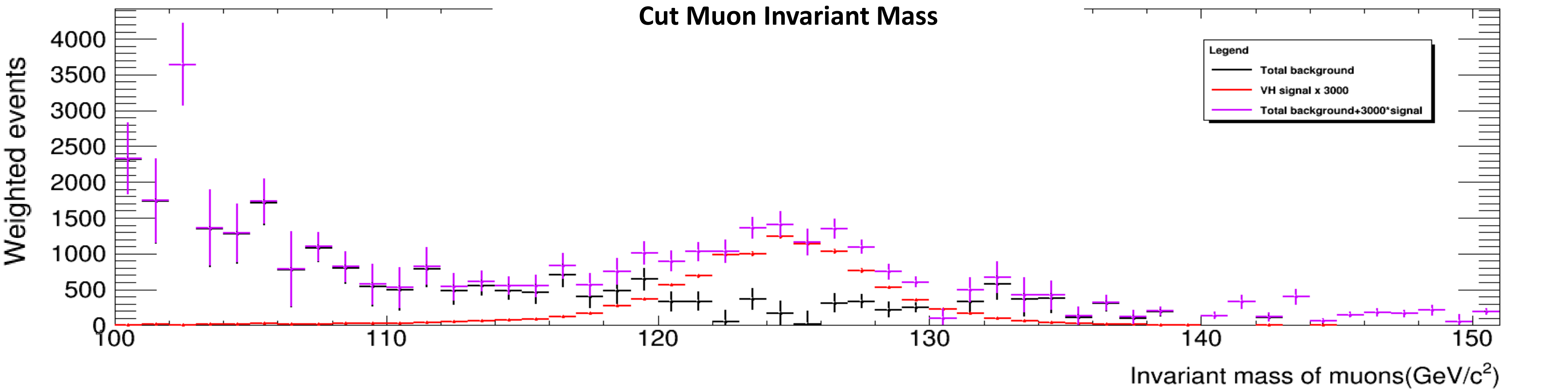
- Cuts have been optimised by altering the cut parameters and seeing how it affects the confidence limit (CLs) using the Tlimit function.
- By systematically altering the cuts an improvement on the cuts can be made.

Previous Cuts	Optimised Cuts
$\lvert\Delta\text{Ø}(HV)\rvert > 2.6$	$\lvert\Delta\text{Ø}(HV)\rvert > 2.8$
$\lvert\Delta\eta(HV)\rvert < 1.7$	$\lvert\Delta\eta(HV)\rvert < 1.7$
$P_t(Jets) > 77GeV/c$	$P_t(Jets) > 50GeV/c$
$P_t(Muons) > 76GeV/c$	$P_t(Muons) > 50GeV/c$
$MET < 53GeV$	$MET < 40GeV$
$61GeV \leq IM(Jets) \leq 105GeV$	$70GeV \leq IM(Jets) \leq 96GeV$
Total signal retained: 32.0%	Total signal retained: 22.3%
Total background retained: 2.7%	Total background retained: 1.4%

Cut Plots



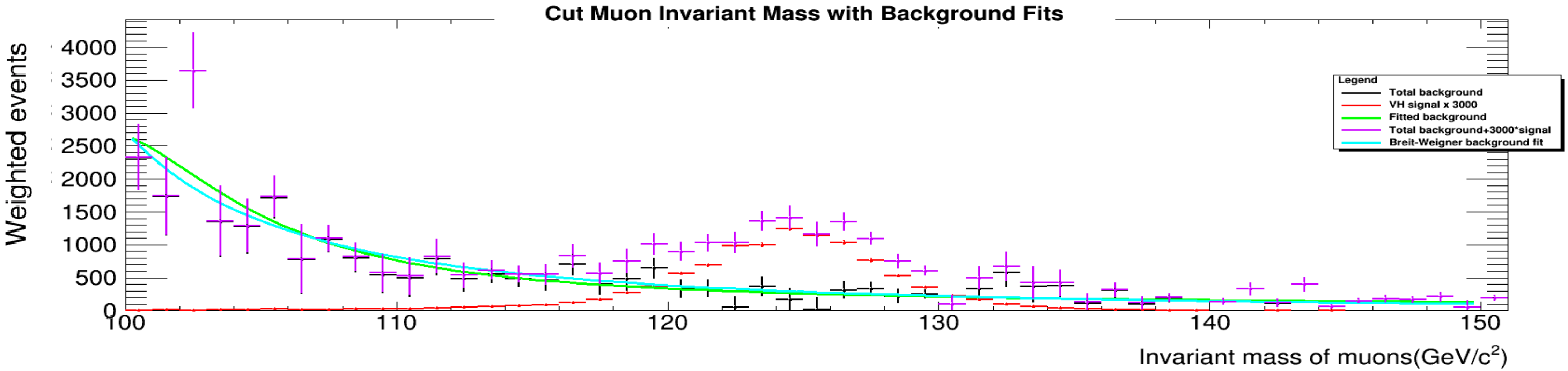
Uncut Muon Invariant Mass
×10³
220
200
180
160
140
120
100
80
60
40
20
0
Weighted events
100
110
120
130
140
150
Invariant mass of muons(GeV/c²)
Legend
Total background
VH signal x 3000
Total background+3000*signal



Cut Muon Invariant Mass
4000
3500
3000
2500
2000
1500
1000
500
0
Weighted events
100
110
120
130
140
150
Invariant mass of muons(GeV/c²)
Legend
Total background
VH signal x 3000
Total background+3000*signal

Systematic Errors

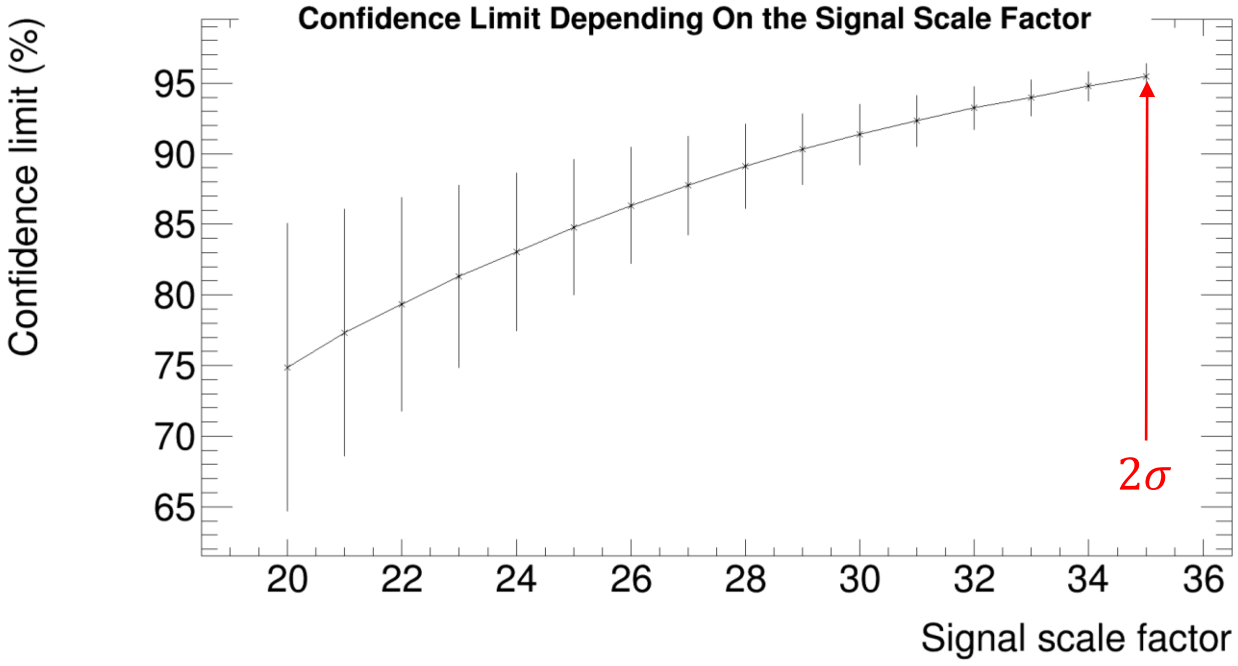
- Systematic errors are caused by performing a fit to the Monte Carlo data (the Monte Carlo data has large fluctuations).
- By finding the difference between different fits we can estimate the systematics.
- Currently investigating the effect of this on the final result.



Fits Used

- Smoothed Monte Carlo background (using the smooth function.)
- Breit-Wigner equation:
- $f(m_{\mu\mu}) = \dfrac{\beta}{(m_{\mu\mu} - m_Z) + \frac{\Gamma^2}{4}}$
- Background fit equation:
- $f(m_{\mu\mu}) = \dfrac{\beta C_1 e^{-\lambda m_{\mu\mu}}}{(m_{\mu\mu} - m_Z) + \frac{\Gamma^2}{4}} + \dfrac{1}{{m_{\mu\mu}}^2}(1 - \beta) C_2 e^{-\lambda m_{\mu\mu}}$

Calculating the Scaling Factor



- Signal must discerned from the background.
- This requires scaling up the signal.
- In order to get a confidence limit of 2σ (95%) a signal scale factor of 35 is required.

Summary

- Investigating the currently unseen $H \rightarrow \mu^+\mu^-$ via associated production at $100fb^{-1}$.
- In order to investigate the $H \rightarrow \mu^+\mu^-$ channel data has been simulated using Monte Carlo and put through the Geant4 detector simulator.
- Cuts have been applied to increase the signal relative to the background. Signal retained = 22.3%, background retained = 1.4%.
- Systematic errors have been estimated by applying different fits to the simulated data and finding the difference.
- Have found that in order to observe this channel to 2σ requires the signal being scaled up by a factor of 35.

TLimit

- Input the signal and background histograms.
- Calculates confidence limit given background only.
- Gives you a CLs which is the confidence limit of the signal+background/confidence limit of the background