Higgs to Diphoton Decay Analysis

Befriending the Background

Theo Broxton

Brief Introduction

Cuts

Background fits

Cross sections

Conclusion

Introduction

- Wish to 'find' Higgs

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- Wish to 'find' Higgs
- ATLAS 13 TeV data

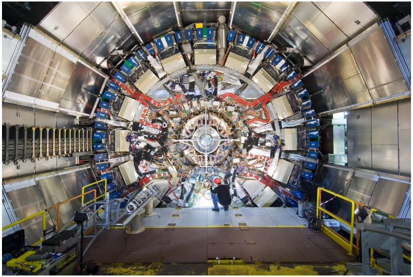

Figure: ATLAS inner detector endcap. Taken from `https://atlas.cern/Discover/Detector/Inner-Detector`.

Introduction

- Wish to 'find' Higgs
- ATLAS 13 TeV data
- $H \rightarrow \gamma\gamma$
  - $\mathcal{BR} = 0.227$ % [3]

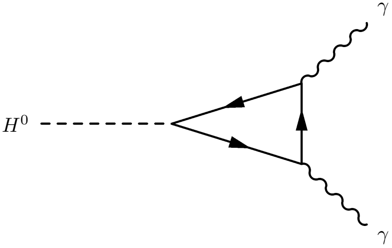

Figure: Feynman diagram for $H \rightarrow \gamma\gamma$. Taken from FDL https://www.physik.uzh.ch/~che/FeynDiag/index.php.

Invariant mass

$$m^{\gamma\gamma} = \sqrt{2p_{T1}p_{T2}\left(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)\right)}$$

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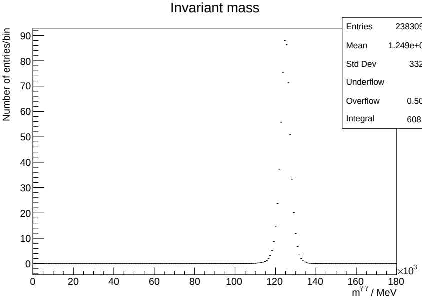

Figure: Monte Carlo invariant mass distribution.

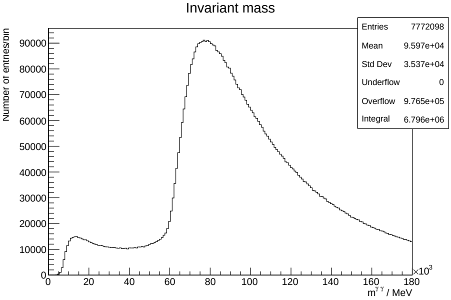

Figure: ATLAS data invariant mass distribution.

Cuts

What to cut...

To determine how effective the selection cuts are, calculate the statistical significance.

$$\text{significance} = \frac{S}{\sqrt{B}}$$

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- Signal - Hyy
- Background - yy

What to cut...

To determine how effective the selection cuts are, calculate the statistical significance.

$$\text{significance} = \frac{S}{\sqrt{B}}$$

Maximise!

Transverse momentum

$$p_T[0] > 35\text{ GeV} \quad , \quad p_T[1] > 25\text{ GeV } [1]$$

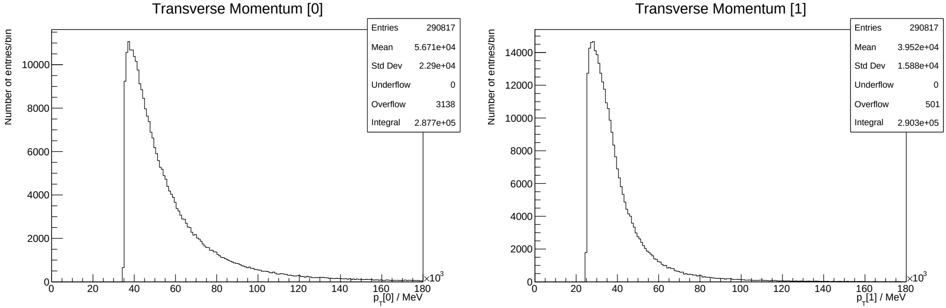

Figure: ATLAS data: $p_T[0]$ and $p_T[1]$ with cuts applied.

$$\sigma_{\text{stat}} = 2.01$$

The cones

- Isolation variables

The cones

- Isolation variables
- ptcone - charged particles

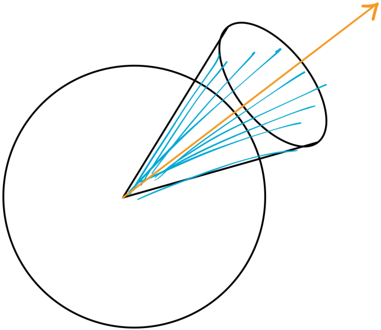

Figure: Artistic rendition of ptcone.

The cones

- Isolation variables
- ptcone - charged particles
- etcone - charged and neutral particles [2]

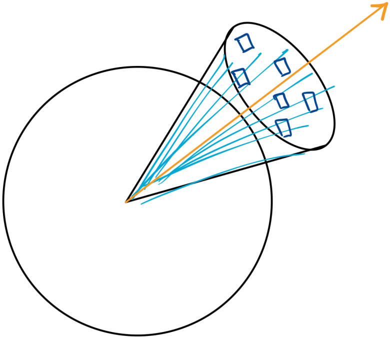

Figure: Artistic rendition of etcone.

ptcone

- Tried ranges from 2 GeV to 10 GeV

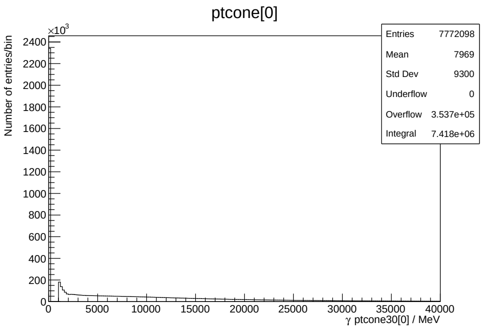

Figure: ATLAS data: ptcone[0] without any selection cuts.

ptcone

- $\text{ptcone}[0,1] < 3\,\text{GeV}$
- $\sigma_{\text{stat}} = 2.69$

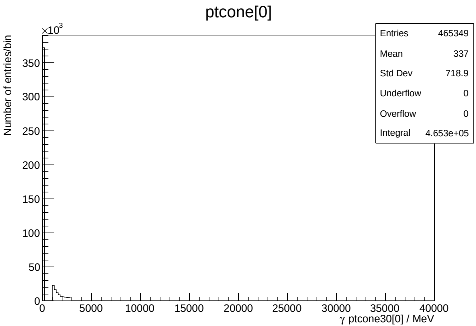

Figure: ATLAS data: ptcone[0] with upper bound selection cut of 3 GeV.

etcone

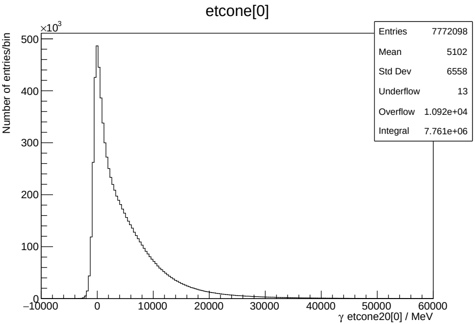

Figure: ATLAS data: etcone[0] without any selection cuts.

etcone

- $\text{etcone}[0,1] < 5\,\text{GeV}$
- $\sigma_{\text{stat}} = 2.79$

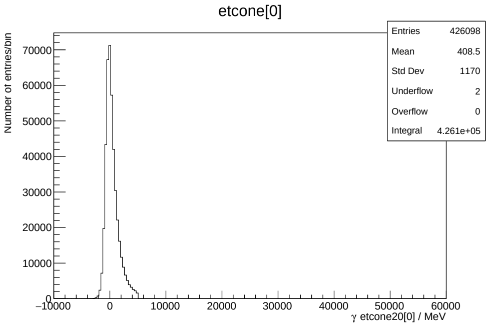

Figure: ATLAS data: etcone[0] with upper bound selection cut of 5 GeV.

Final Cuts

- photon_pt[0] > 35 GeV && photon_pt[1] > 25 GeV
- photon_n $== 2$
- photon_isTightID$[0, 1] == 1$
- photon_ptcone30$[0, 1] < 3$ GeV
- photon_etcone20$[0, 1] < 5$ GeV
- trigP $== 1$
- abs(photon_eta$[0, 1]$) < 1.37 || $1.52 <$ abs(photon_eta$[0, 1]$) < 2.37 [1]

Final Cuts

Applying these cuts improved the significance

$$\sigma_{\text{stat}} : 0.86 \to 2.79$$

Job done..?

Job done..?

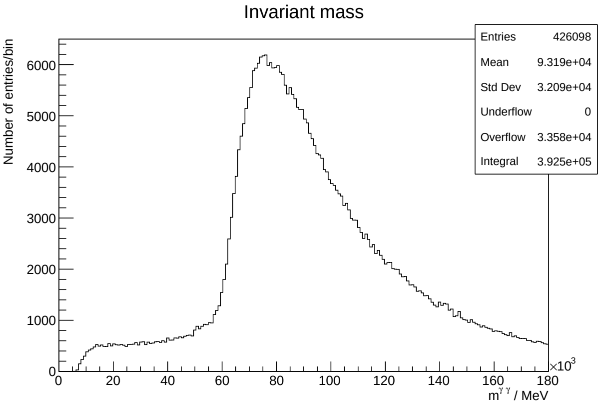

Figure: ATLAS data: Invariant mass distribution with final selection cuts applied.

Background fits

Why fit the background?

- Tiny Higgs signal but a large, smooth background from SM processes

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- Fit background and subtract to isolate Higgs signal

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- Tiny Higgs signal but a large, smooth background from SM processes
- Fit background and subtract to isolate Higgs signal
- Precise background minimises systematic uncertainty

What's a good fit?

- Used χ^2_ν
- $\chi^2_\nu \sim 1$ - good fit

Functional forms

- pol
- pol*exp
- pol+exp
- exp(pol)
- pol(-1)*exp(pol)
- pol(-1)+exp(pol)
- pol(-1)+pol
- pol(-1)*pol

- gauss
- pol+gauss
- pol+gauss+expo
- landau
- landau+pol
- exp
- landau+exp

Background fit

With $\chi^2_\nu = 1.2799$, the best fit was

$$x^{-1} \cdot \exp\left(p_0 x^2 + p_1 x + p_2\right)$$

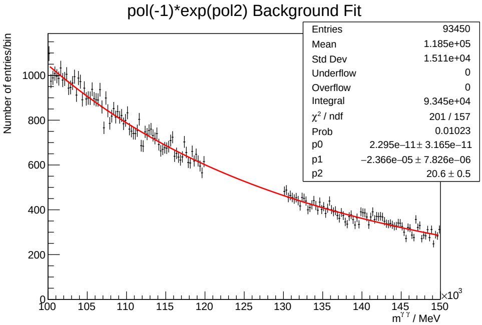

Figure: ATLAS data: Background fit for 200 bins, 100-150 GeV.

Background fit (100-180 GeV)

With $\chi^2_\nu = 1.0560$, the best fit was

$$\exp\left(p_0 x^2 + p_1 x + p_2\right)$$

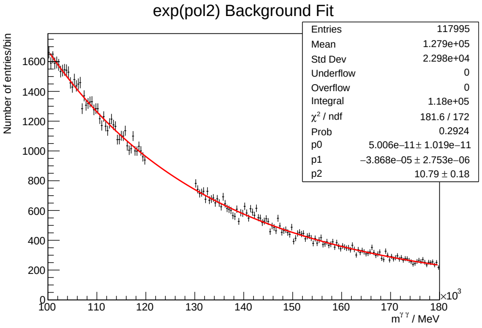

Figure: ATLAS data: Background fit for 200 bins, 100-180 GeV.

Background fit (80 bins)

With $\chi^2_\nu = 1.1365$, the best fit was

$$\exp\left(p_0 x^2 + p_1 x + p_2\right)$$

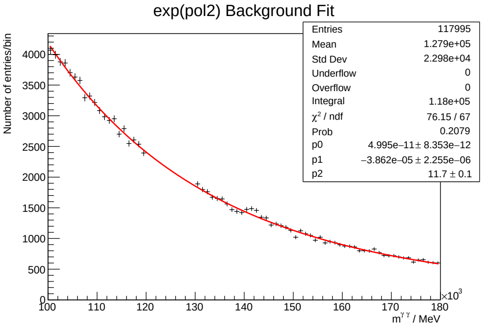

Figure: ATLAS data: Background fit for 80 bins, 100-180 GeV.

Background fit

With $\chi^2_\nu = 1.0560$, the best overall fit was

$$\exp\left(p_0 x^2 + p_1 x + p_2\right)$$

with

$$p_0 = (5.005\,94 \pm 1.019\,20) \times 10^{-11}$$
$$p_1 = (-3.867\,62 \pm 0.275\,28) \times 10^{-5}$$
$$p_2 = (1.078\,980 \pm 0.018\,036) \times 10^{1}$$

for 200 bins over the range 100-180 GeV.

Cross sections

Cross section

$$\sigma = \frac{N^{\text{selected}} - N^{\text{background}}}{\epsilon \int L \, \mathrm{d}t}$$

Cross section

$$\epsilon = \frac{\sum_{\text{sel.}} w_i}{\sum_{\text{tot.}} w_i}$$

$$\int L \, \mathrm{d}t = 10.064 \text{ fb}^{-1} \pm 1.7\%$$

Methods

- Subtract background
- Scale signal fit

Background subtraction

$$\exp\left(p_0 x^2 + p_1 x + p_2\right)$$

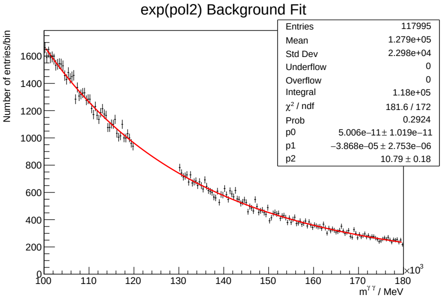

Figure: ATLAS data: Background fit for 200 bins, 100-180 GeV.

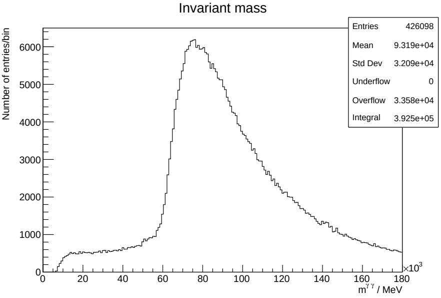

Figure: ATLAS data: Invariant mass distribution with final cuts.

Background subtraction

$$\exp\left(p_0 x^2 + p_1 x + p_2\right)$$

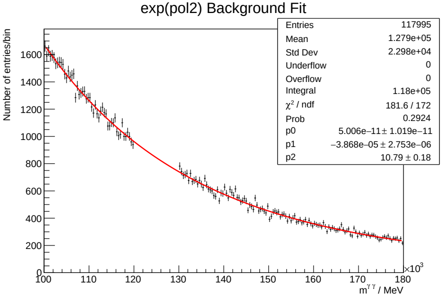

Figure: ATLAS data: Background fit for 200 bins, 100-180 GeV.

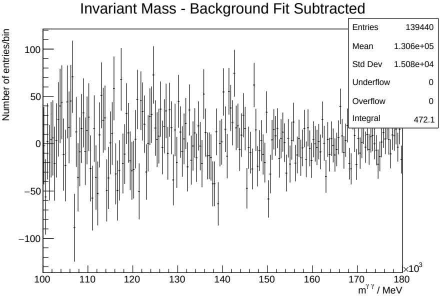

Figure: ATLAS data: Invariant mass distribution after background subtraction.

oh..

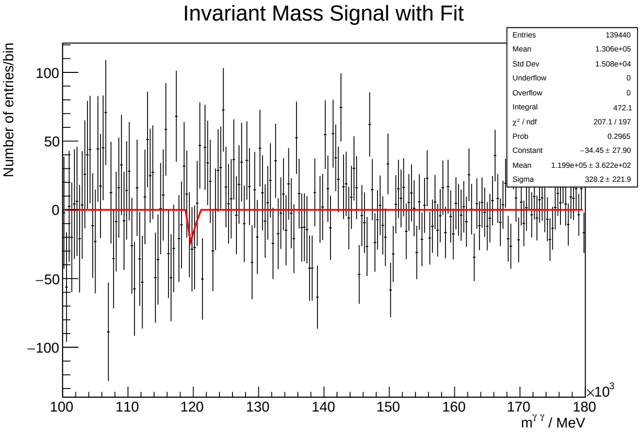

Figure: ATLAS data: Free Gaussian fit on background subtracted invariant mass distribution.

Background subtraction

- Calculate integral in region 120-130 GeV
- $N^{\text{selected}} - N^{\text{background}}$

Background subtraction

- Calculate integral in region 120-130 GeV
- $N^{\text{selected}} - N^{\text{background}}$
- $\sigma = (88 \pm 39)\,\text{fb}$

Scaling signal fit

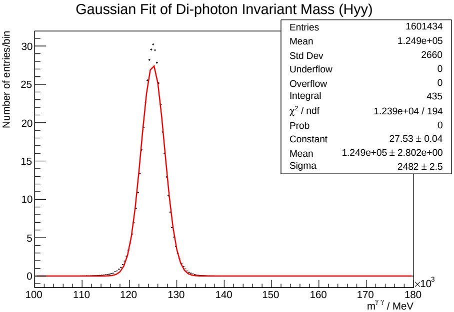

Figure: MC data: Gaussian fit of Higgs peak.

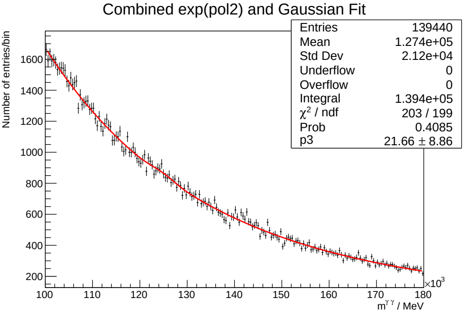

Figure: ATLAS data: Combined background and Gaussian fit.

Scaling signal fit

- Get linear scale factor

Scaling signal fit

- Get linear scale factor
- Apply to MC integral value to get number of signal events in ATLAS

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- Get linear scale factor
- Apply to MC integral value to get number of signal events in ATLAS
- $\sigma = (85 \pm 34)\,\mathrm{fb}$

Cross section

$$\sigma = \text{value} \pm XXX(\text{stat.}) \pm YYY(\text{syst.}) \pm ZZZ(\text{lumi.})$$

Estimating systematic uncertainty

Reran cross section analysis with different changes

- Fit function chosen to model background
- Bin number
- Range

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- Range

Recorded in ‘Cross sections.xlsx’ and then ‘cross_sections_data.csv’ for analysis

Estimating systematic uncertainty

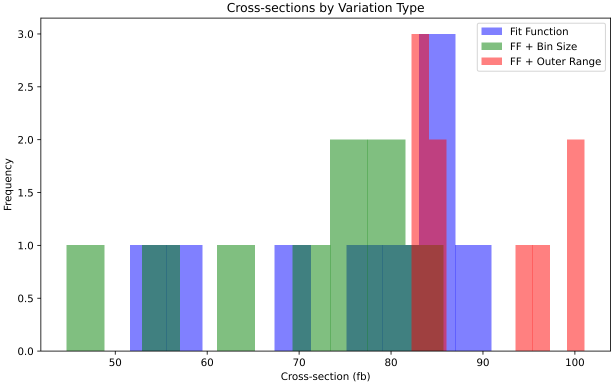

Figure: Coloured histogram showing different sources of cross sections.

Estimating systematic uncertainty

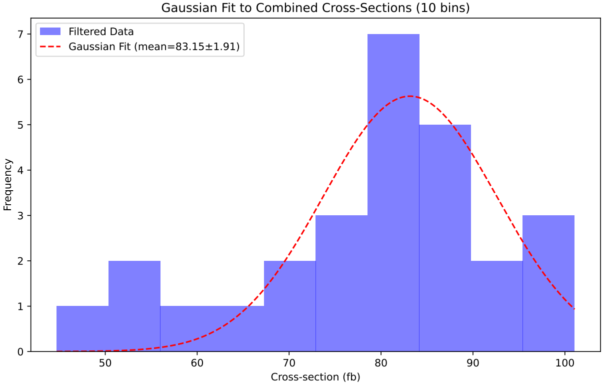

Figure: Combined cross section histogram with Gaussian fit.

Estimating systematic uncertainty

Also changed selection cuts

Estimating systematic uncertainty

Also changed selection cuts

- ptcone,etcone
- 1 to 10 GeV
- Steps of 0.5 GeV

Do they impact the syst. uncertainty?

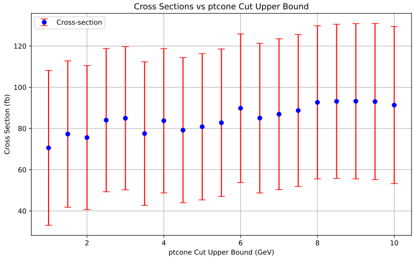

Figure: Cross section as a function of ptcone upper bound cut.

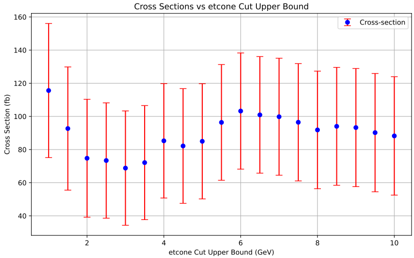

Figure: Cross section as a function of etcone upper bound cut.

Estimating systematic uncertainty

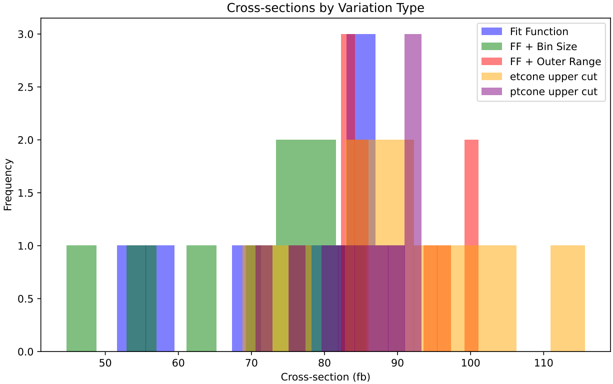

Figure: Coloured histogram showing different sources of cross sections - including etcone and ptcone.

Estimating systematic uncertainty

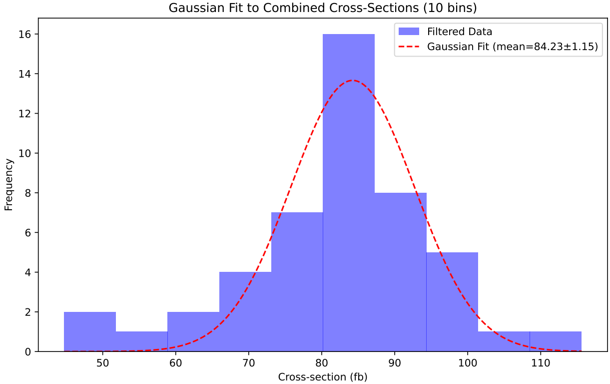

Figure: Combined cross section histogram with Gaussian fit.

Estimating systematic uncertainty

Some options are

- Standard deviation
- FWHM
- Range/2
- RMS

Estimating systematic uncertainty

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- Standard deviation
- FWHM
- Range/2
- RMS

Took average as systematic uncertainty

Final cross section

Taking the mean of the Gaussian fit on the combined histogram as the cross section value,

$$\sigma = 84 \pm 35(\text{stat.}) \pm 19(\text{syst.}) \pm 1(\text{lumi.})\,\text{fb}$$

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Taking the mean of the Gaussian fit on the combined histogram as the cross section value,

$$\sigma = 84 \pm 35(\text{stat.}) \pm 19(\text{syst.}) \pm 1(\text{lumi.})\,\text{fb}$$

$$\text{i.e. } 29 < \sigma < 140$$

Conclusion

- Goal was to study $H \to \gamma\gamma$
- Optimised selection cuts
- Modelled background
- Calculated cross sections
- Accounted for statistical and systematic uncertainties

Conclusion

$$\sigma = 84 \pm 35(\text{stat.}) \pm 19(\text{syst.}) \pm 1(\text{lumi.})\,\text{fb}$$

Bibliography (I)

[1] G. Aad *et al.*, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Physics Letters B*, vol. 716, no. 1, pp. 1–29, Sep. 17, 2012, ISSN: 0370-2693. DOI: 10/jb7. Accessed: Oct. 20, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S037026931200857X.

[2] S. Moortgat, *Lepton Isolation Using Particle Flow Objects for the ATLAS Detector*, 2014. Accessed: Nov. 26, 2024. [Online]. Available: https://cds.cern.ch/record/1756841.

Bibliography (II)

[3] "Vol. 2 (2017): Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector — CERN Yellow Reports: Monographs,", Accessed: Nov. 28, 2024. [Online]. Available: https://e-publishing.cern.ch/index.php/CYRM/issue/view/32.

Appendices

Appendices (I)

A - No cuts

B - Cuts 1 (p_T)

C - Cuts 7 (ptcone)

D - Cuts 9 (etcone)

E - etcone isolation

F - Crystal Ball fit

G - Bin number & xs histogram

H - Extra p/etcone plots

I - In future..

No cuts

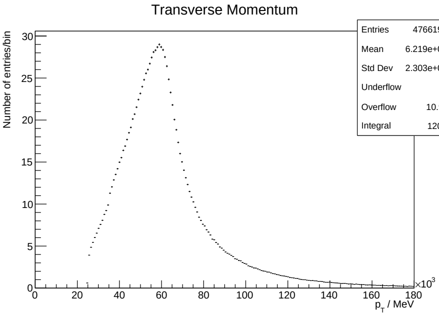


Figure: Monte Carlo: Photon transverse momenta.

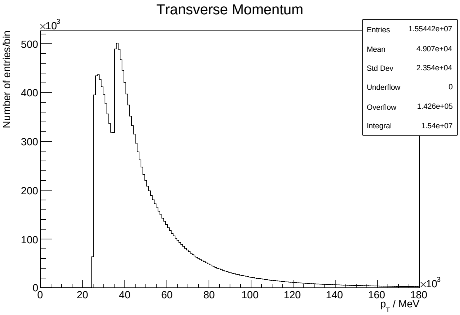


Figure: ATLAS data: Photon transverse momenta.

No cuts

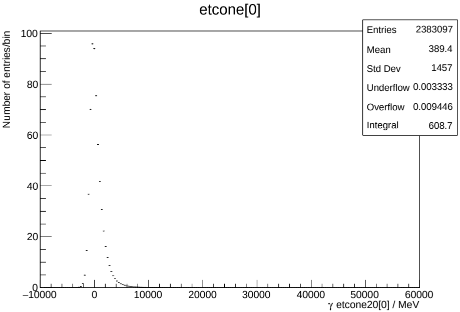


Figure: MC data: etcone[0] - no cuts.

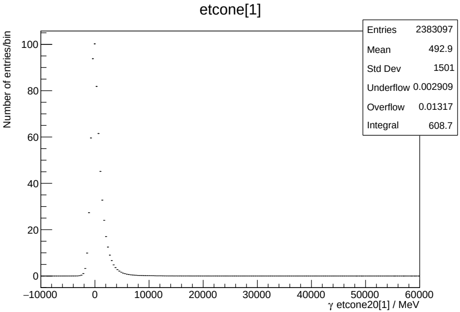


Figure: MC data: etcone[1] - no cuts.

No cuts

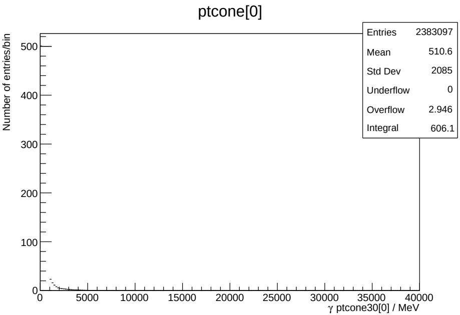


Figure: MC data: ptcone[0] - no cuts.

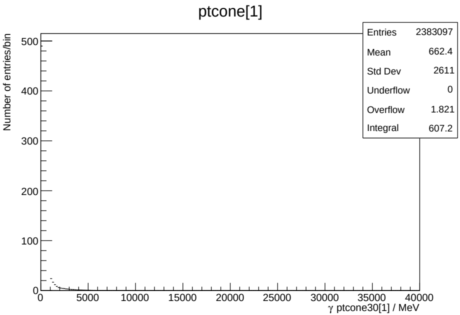
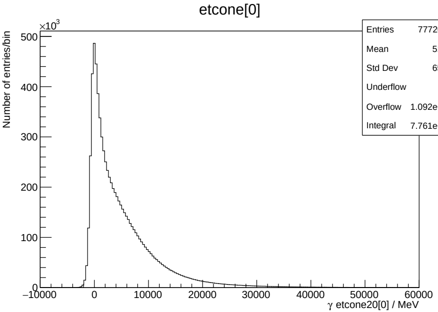


Figure: MC data: ptcone[1] - no cuts.

No cuts



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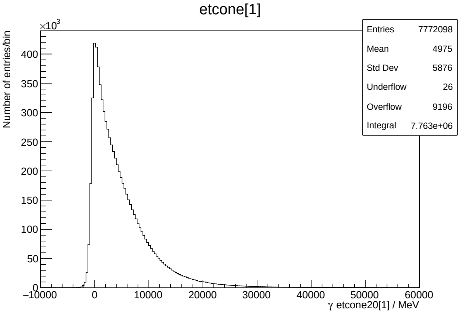

Figure: ATLAS data: etcone[1] - no cuts.

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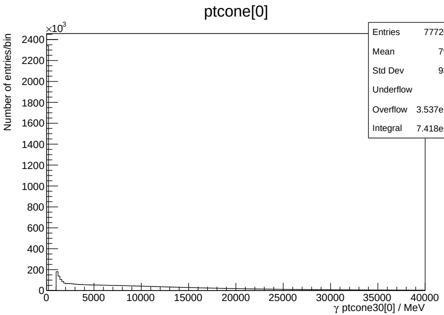

Figure: ATLAS data: ptcone[0] - no cuts.

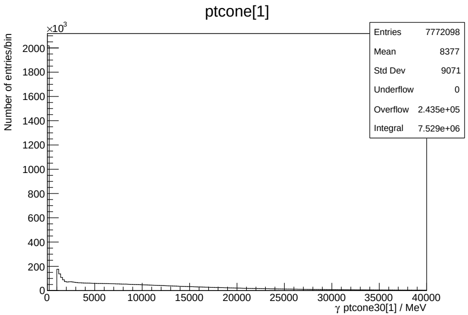

Figure: ATLAS data: ptcone[1] - no cuts.

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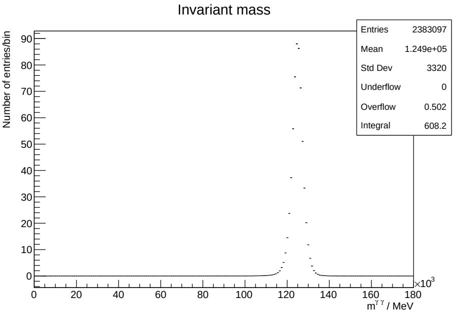


Figure: MC data: Invariant mass - no cuts.

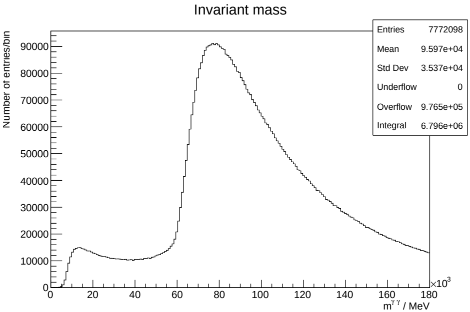


Figure: ATLAS data: Invariant mass - no cuts.

Cuts 1 - Transverse Momentum

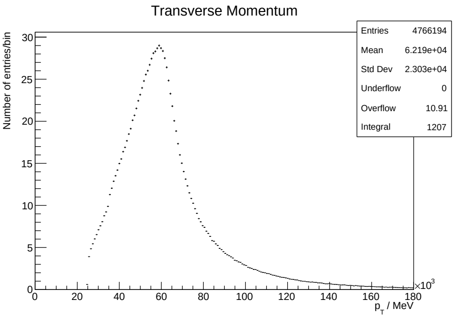
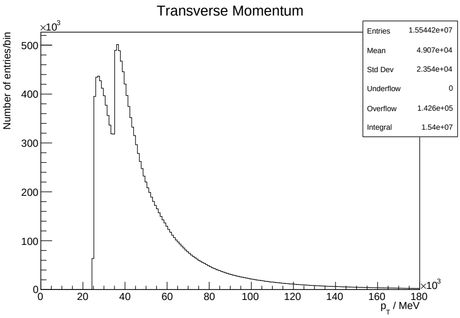


Figure: Monte Carlo: Photon transverse momenta.



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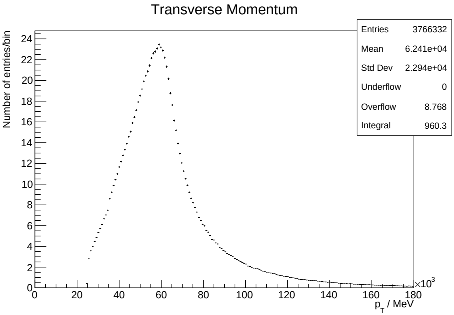
Cuts 1 - Transverse Momentum

$$p_T[0] > 35e3 \quad , \quad p_T[1] > 25e3$$



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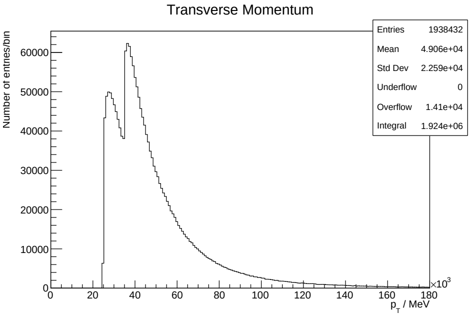

Figure: ATLAS data: Photon transverse momenta.

$$\sigma_{\text{stat}} = 2.01$$

Cuts 1 - Transverse Momentum

$$p_T[0] > 35e3 \quad , \quad p_T[1] > 25e3$$

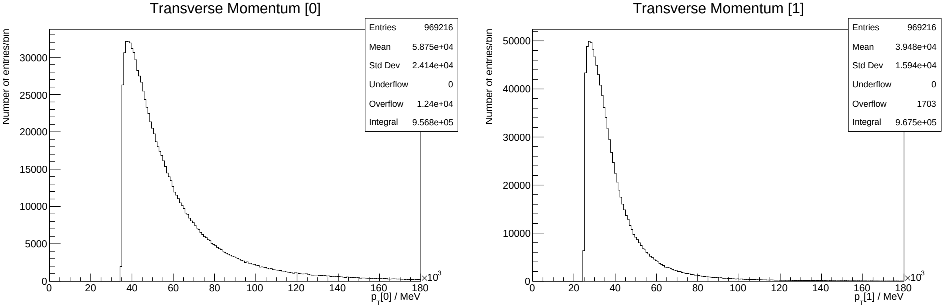

Figure: Monte Carlo: $p_T[0]$ and $p_T[1]$ with cuts applied.

$$\sigma_{\text{stat}} = 2.01$$

Cuts 1 - Transverse Momentum

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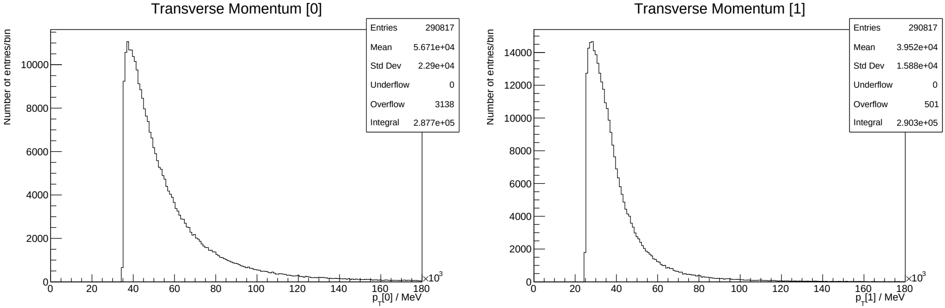

Figure: ATLAS data: $p_T[0]$ and $p_T[1]$ with cuts applied.

$$\sigma_{\text{stat}} = 2.01$$

Cuts 7 - ptcone

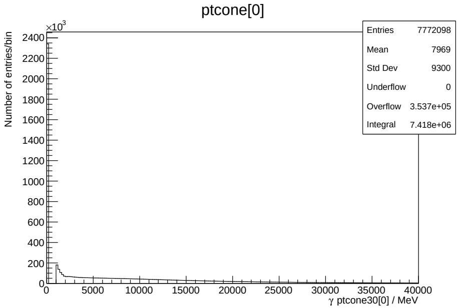

Figure: ATLAS data: ptcone[0] and ptcone[1] without cuts applied.

Cuts 7 - ptcone

$$\text{ptcone}[0,1] < 3e3$$

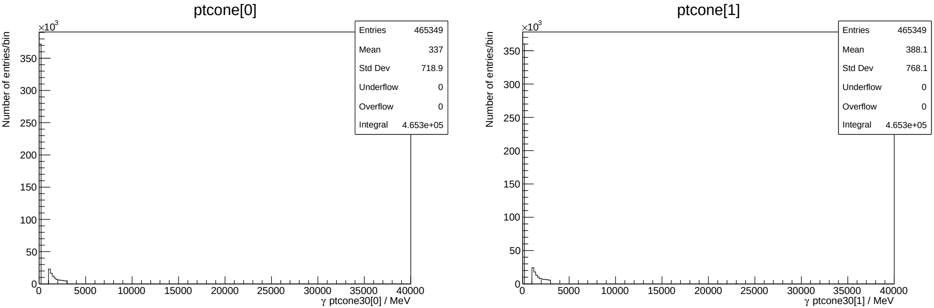

Figure: ATLAS data: ptcone[0] and ptcone[1] with cuts applied.

$$\sigma_{\text{stat}} = 2.69$$

Cuts 7 - ptcone

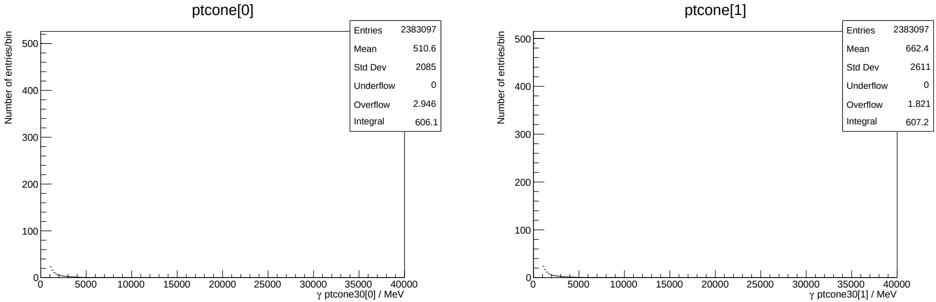

Figure: MC data: ptcone[0] and ptcone[1] without cuts applied.

Cuts 7 - ptcone

$$\text{ptcone}[0, 1] < 3e3$$

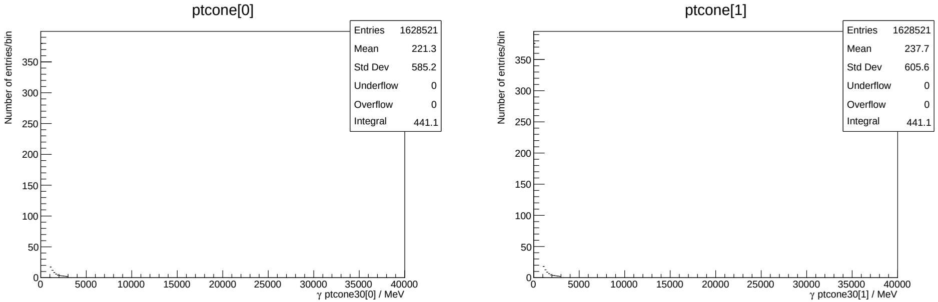

Figure: MC data: ptcone[0] and ptcone[1] with cuts applied.

$$\sigma_{\text{stat}} = 2.69$$

Cuts 9 - etcone

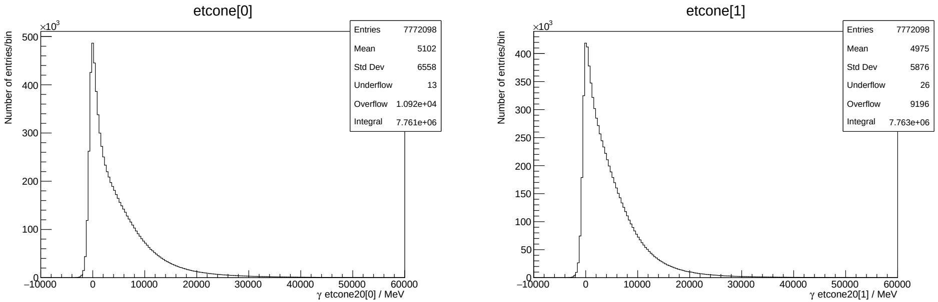

Figure: ATLAS data: etcone[0] and etcone[1] without cuts applied.

Cuts 9 - etcone

$$\text{etcone}[0,1] < 5e3$$

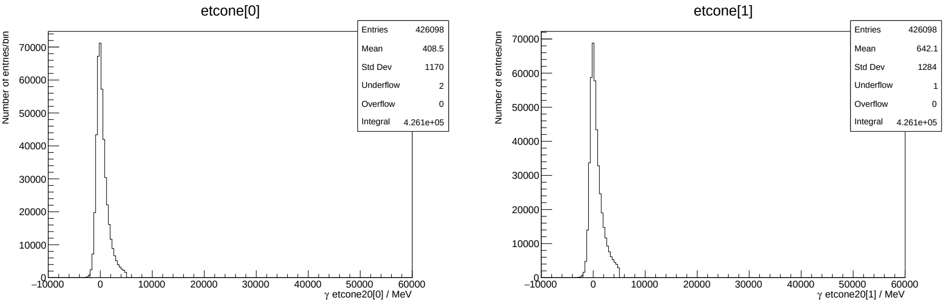

Figure: ATLAS data: etcone[0] and etcone[1] with cuts applied.

$$\sigma_{\text{stat}} = 2.79$$

Cuts 9 - etcone

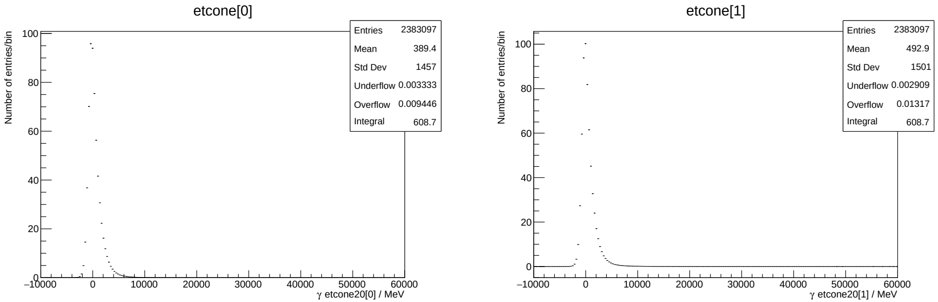

Figure: MC data: etcone[0] and etcone[1] without cuts applied.

Cuts 9 - etcone

$$\text{etcone}[0, 1] < 5e3$$

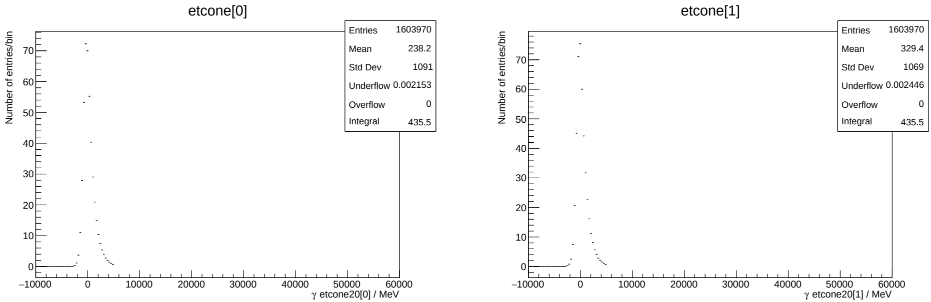

Figure: MC data: etcone[0] and etcone[1] with cuts applied.

$$\sigma_{\text{stat}} = 2.79$$

etcone Isolation

Calorimeter detects

- charged particles - via ionisation
- neutral particles - via EM interactions or hadronic processes

etcone Isolation

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- neutral particles - via EM interactions or hadronic processes

Cannot precisely determine which directions particles come from

etcone Isolation

Cannot precisely determine which directions particles come from
Exclude:

- neutral pile-up
- underlying events
- extraneous - detector noise, cosmic rays

etcone Isolation

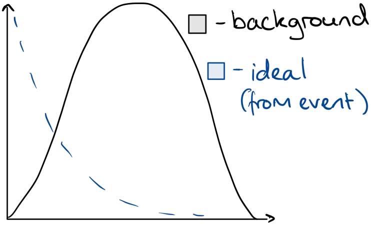

Figure: Ideal etcone function alongside background.

etcone Isolation

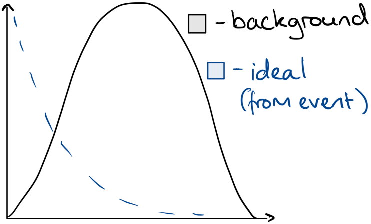

Figure: Ideal etcone function alongside background.

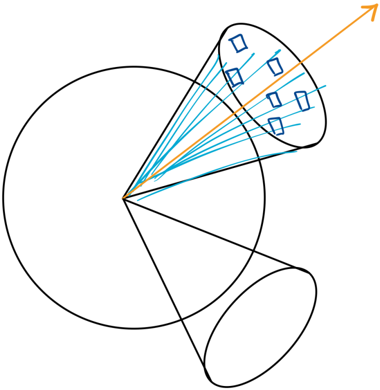

Figure: Estimating background density.

etcone Isolation

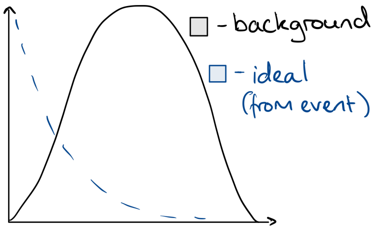

Figure: Ideal etcone function alongside background.

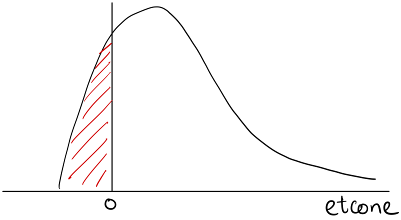

Figure: Corrected etcone distribution.

Crystal Ball fit

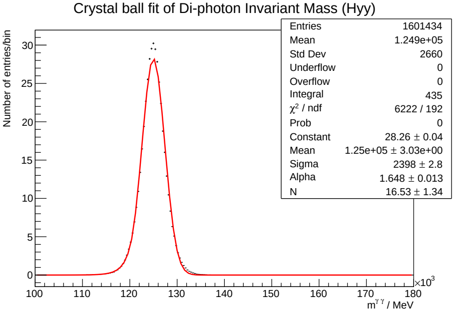

Figure: Crystal Ball background fit.

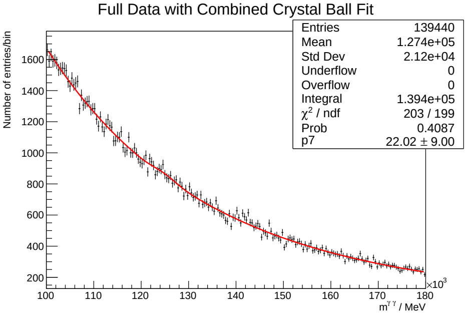

Figure: Combined background and Crystal Ball signal fit.

$$\sigma = (84 \pm 34)\,\text{fb}$$

Bin number & xs histogram

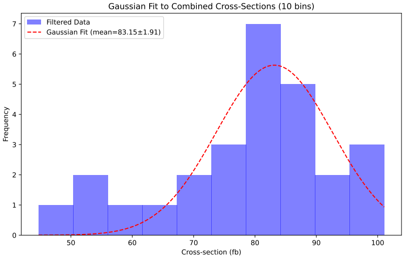

Figure: Combined cross section histogram with Gaussian fit (10 bins).

Bin number & xs histogram

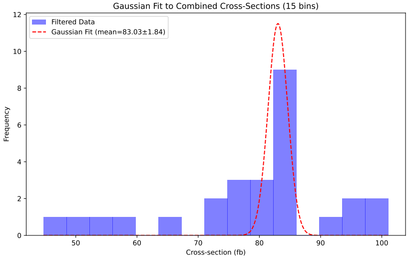

Figure: Combined cross section histogram with Gaussian fit (15 bins).

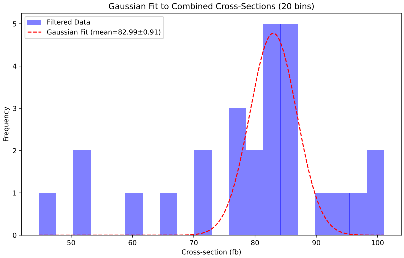

Figure: Combined cross section histogram with Gaussian fit (20 bins).

Bin number & xs histogram

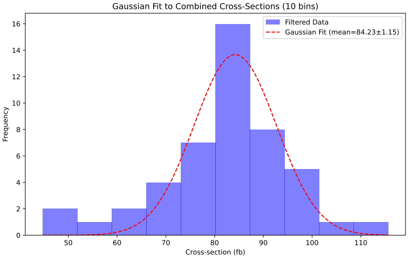

Figure: Combined cross section histogram with Gaussian fit (10 bins).

Bin number & xs histogram

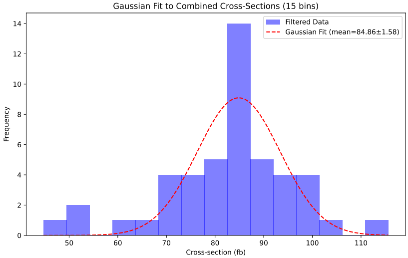

Figure: Combined cross section histogram with Gaussian fit (15 bins).

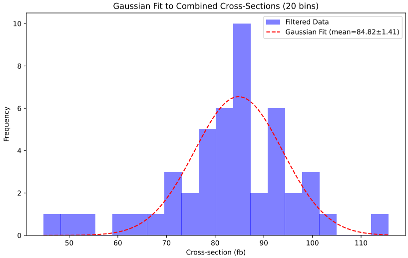

Figure: Combined cross section histogram with Gaussian fit (20 bins).

Extra ptcone plots

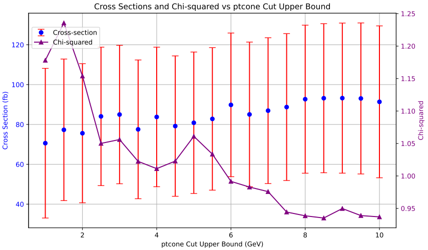

Figure: Combined cross section and chi-squared vs ptcone upper cuts.

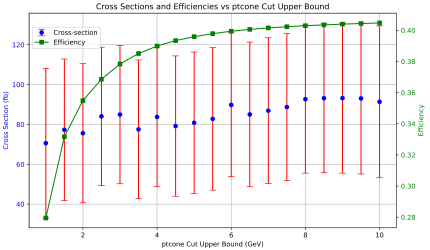

Figure: Combined cross section and efficiency vs ptcone upper cuts.

Extra etcone plots

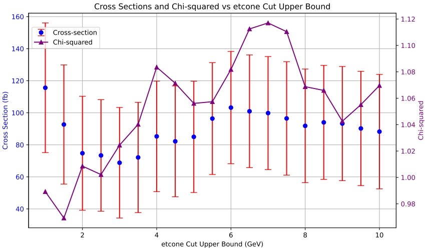

Figure: Combined cross section and chi-squared vs etcone upper cuts.

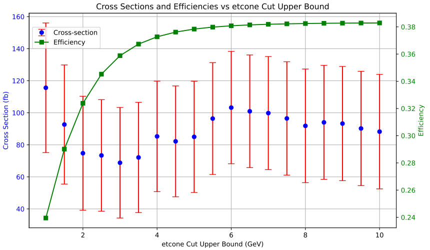

Figure: Combined cross section and efficiency vs etcone upper cuts.

In future..

- Higher luminosity data
- Machine learning, neural networks
- Better visualisation
- Detector upgrades