Search of Light Pseudo-Scalar Higgs Boson at the Cool Copper Collider (C^3)

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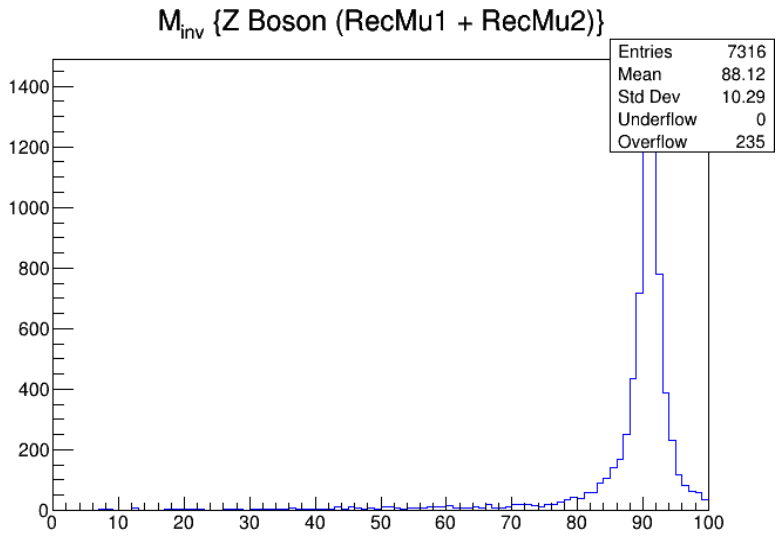
MC Simulation

- Signal sample(ZH→aa→ bbττ) & two background processes (ZZ & ZH)

$$e^+e^- \rightarrow Z\,(\rightarrow \boldsymbol{\mu^+\mu^-})\,H \rightarrow a\left(\rightarrow \boldsymbol{b\bar{b}}\right)\,a(\rightarrow \boldsymbol{\tau^+\tau^-})$$

$$e^+e^- \rightarrow Z\,(\rightarrow \boldsymbol{e^+e^-})\,H \rightarrow a\left(\rightarrow \boldsymbol{b\bar{b}}\right)\,a(\rightarrow \boldsymbol{\tau^+\tau^-})$$

- Samples have been generated using Madgraph5
- Hadronized with Pythia8
- Simulated for detector responses with Delphes

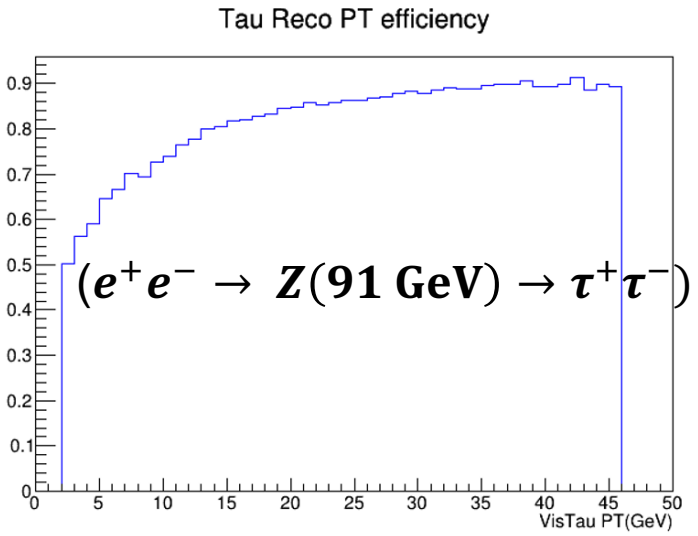


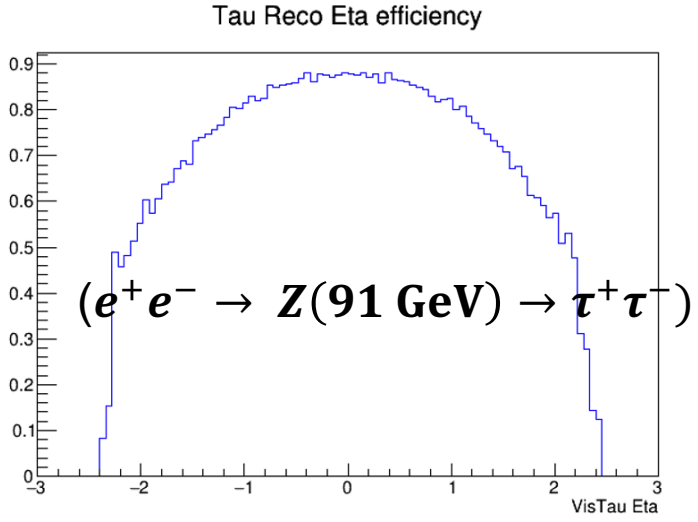
Tau Reconstruction

Reconstructing tau particles using energy flow (EFlow) from tracks, photons, and neutral hadrons.

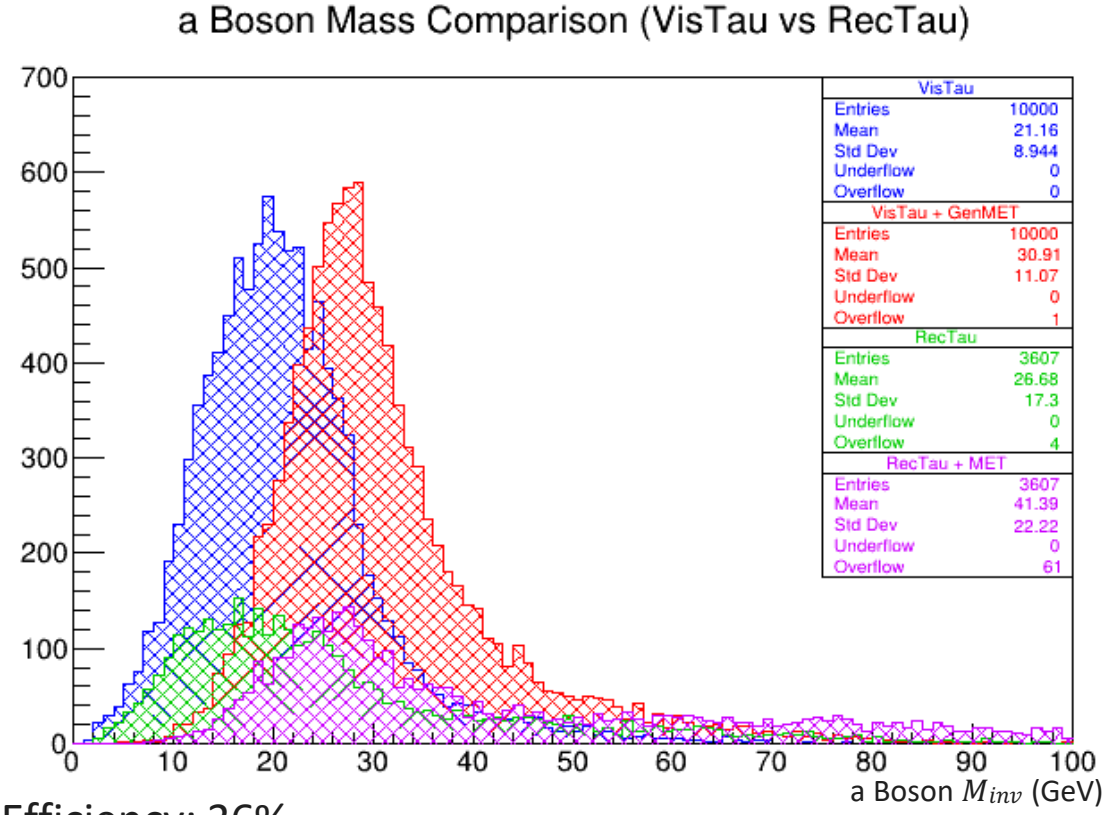
Reconstruction Process:

- Consider tracks with PT > 2.0 GeV as potential tau cand.
- Candidates (track, photons, neutral photons) within a cone of 0.2 around leading track are considered as signal candidates and within cone of 0.2 to 0.5 are considered as isolation candidates.
- Only consider tau candidates with a maximum of 5 charged prongs.
- Relative isolation cut has been applied on taus





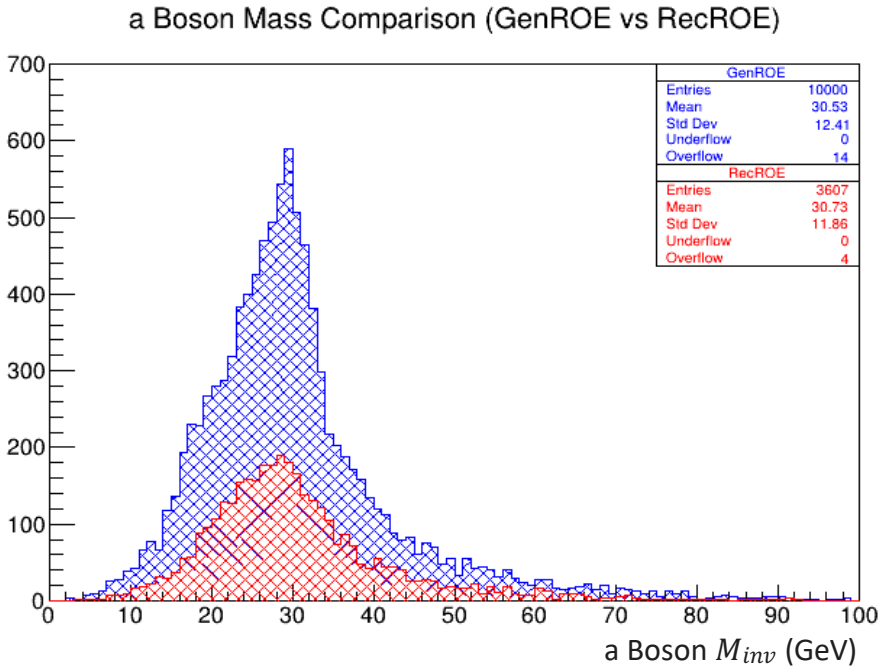
Reconstruction Tau (inner cone deltaR Cut: 0.2, Relative Isolation Cut: 0.3) ($e^+e^- \rightarrow Z(\rightarrow \boldsymbol{\mu^+\mu^-})H \rightarrow a\left(\rightarrow \boldsymbol{b\bar{b}}\right) a(\rightarrow \boldsymbol{\tau^+\tau^-})$)



- Selection Efficiency: 36%
- The peak positions for the a Boson invariant mass made from both VisTaus and RecTaus are around 20 GeV.
- The peak position will shift to around 30 GeV for both a Boson invariant by adding GenMET and MET back.

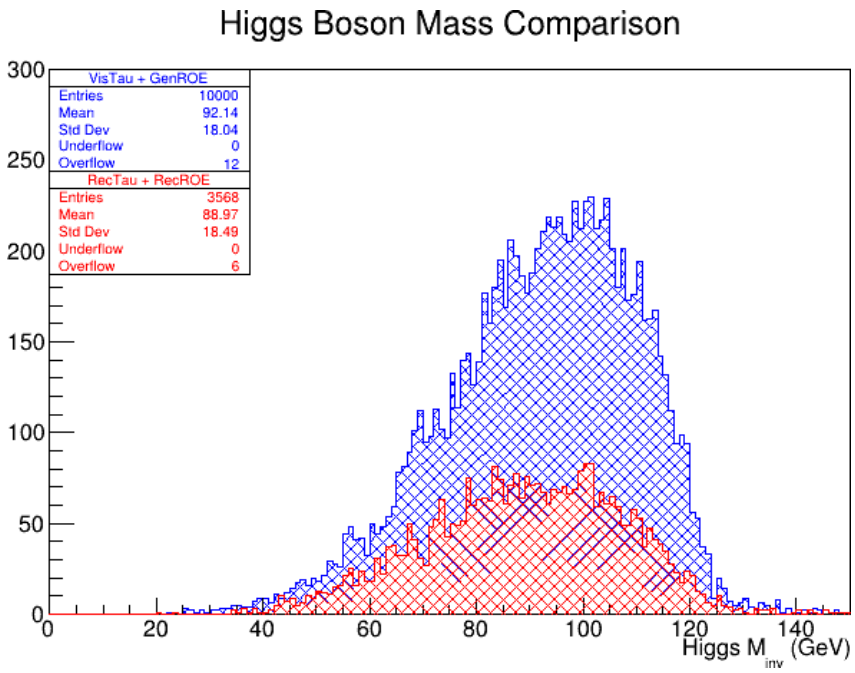
The Comparison for GenROE and RecROE

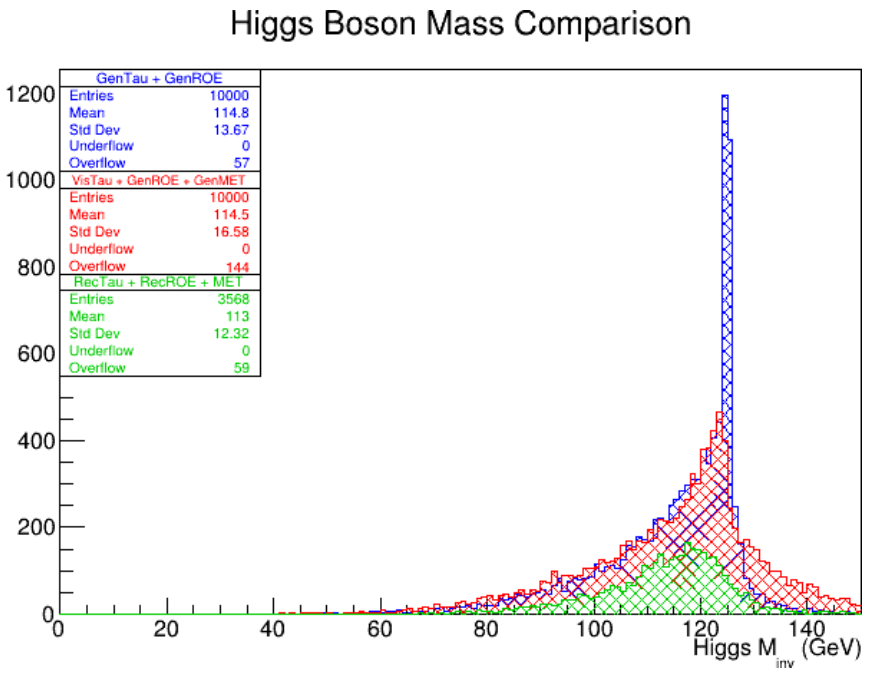
- Instead of selecting a pair of jets, we use the rest of events (ROE): whatever except pair of leptons and pair of taus are considered as dijet candidates



- RecROE = $\sum_i^{excl\ \mu\ \&\ \tau} \mathrm{track_i} + \sum_i^{excl\ \mu\ \&\ \tau} \mathrm{Photon_i} + \sum_i^{excl\ \mu\ \&\ \tau} \mathrm{NHadron_i}$

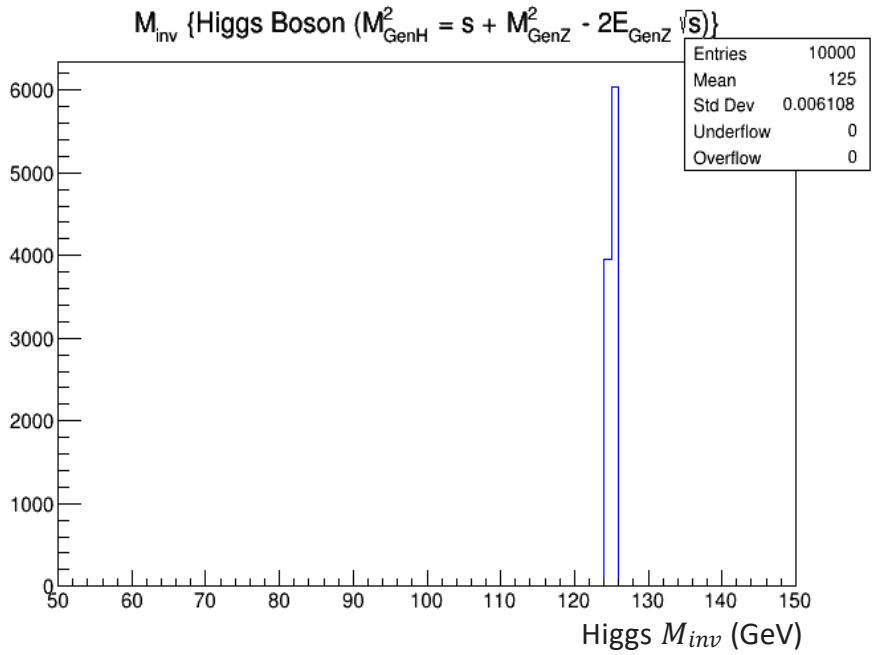
Higgs Boson Mass (from $\tau^+\tau^-$ and ROE)

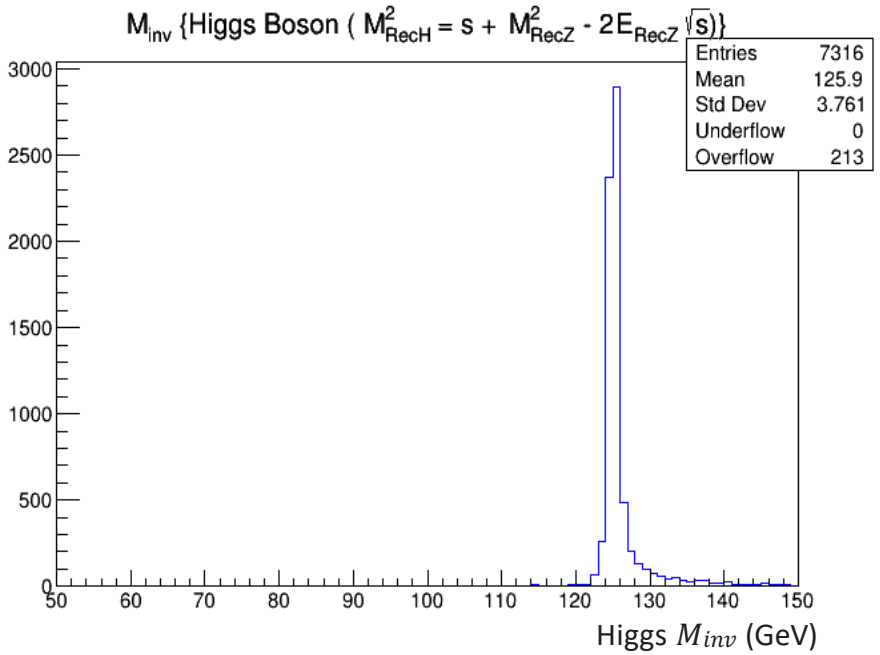




- The Higgs Boson M_{inv}(VisTau + GenROE) and Higgs Boson M_{inv} (RecTau + RecROE) both peak at around 100 GeV.
- We could sharpen those peaks and shift the peak positions toward 125 GeV by adding back the MET.

Higgs Boson Mass (from Z Boson and Beam Constraint)





- $M^2_{\text{Higgs}} = s + M_Z^2 - 2E_Z\sqrt{s} \quad \& \; s = 250\ \text{GeV}$

- The reconstruction of the Higgs Boson has significantly improved with the beam constraint method compared to the method constructing from diTau and ROE.

Final selection & significance definition

- Weighted events = $\frac{\text{XS} \times \text{BR Higgs decay} \times \text{Target Luminosity}}{\#\text{ of Events Generated}}$
- Target Luminosity = 1 ab^{-1}
- Branching Ratio for Higgs decay to a boson = 0.01

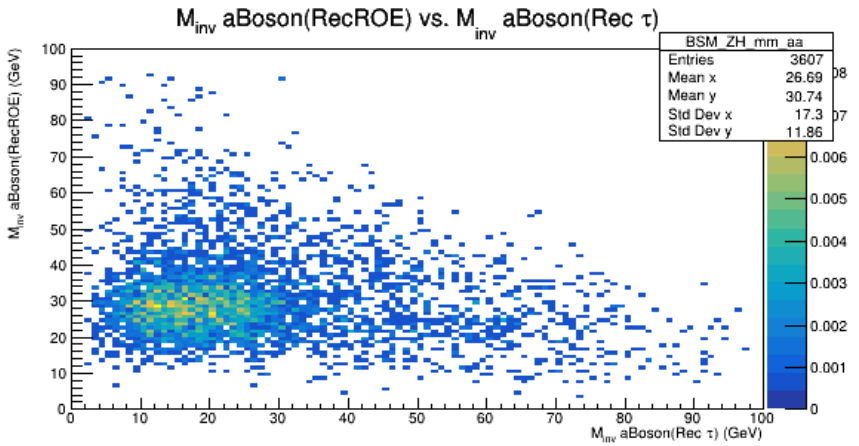
- Apply a series of kinematic cuts
  - ZBoson Mass Cuts: 80 – 100 GeV
  - aBoson (diTau) Mass Cuts: 10-30 GeV
  - aBoson (diJet) Mass Cuts: 20-40 GeV
  - Higgs Boson Mass Cuts: 120-140 GeV

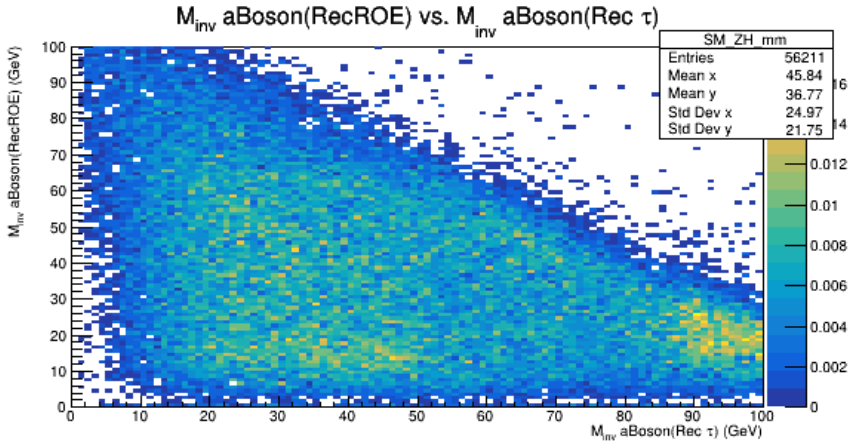
- Significance = $\frac{S}{\sqrt{S+B}}$

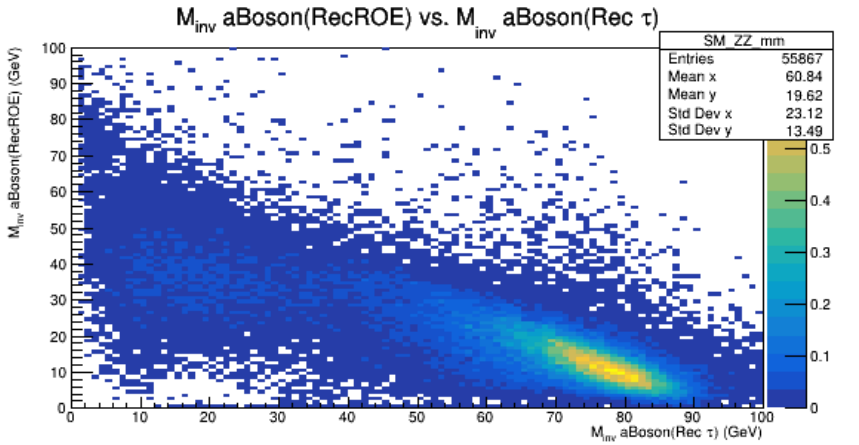
$\mu^+\mu^- b\bar{b}\,\tau^+\tau^-$ final state

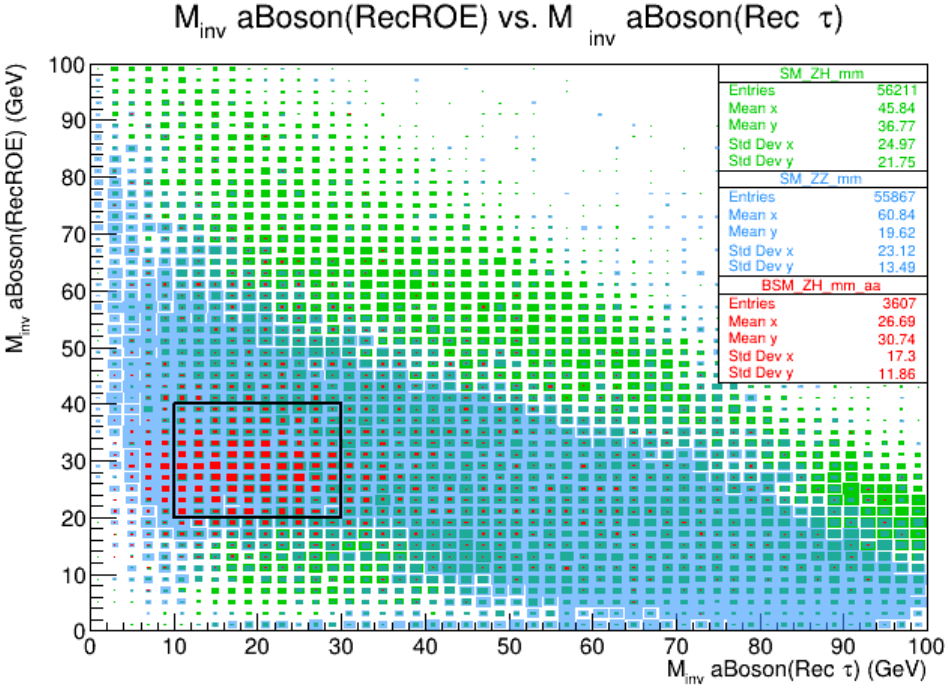
	Signal	Bkg_ZZ	Bkg_ZH
# of Events generated	10000	1000000	1000000
ZBoson [80,100] / ZBoson before [80,100] Cut %	89.45	92.34	91.05
ZBoson [80,100] / # of Events generated %	65.44	67.46	63.79
aBoson (Tau) [10,30] / aBoson (Tau) before [10,30] Cut %	62.32	14.18	23.25
aBoson (Tau) [10,30] / ZBoson [80,100] %	31.07	1.58	3.37
aBoson (Jet) [20,40] / aBoson (Jet) before [20,40] Cut %	75.50	53.84	24.97
aBoson (Jet) [20,40] / aBoson (Tau) [10,30] %	75.50	30.32	15.64
HBoson [120,140] / HBoson before [120,140] Cut %	99.28	0.53	98.21
HBoson [120,140] / aBoson (Jet) [20,40] %	99.28	0.53	98.21
XS	6.60E-15	3.52E-14	6.60E-15
BR Higgs decay	0.01	1	1
luminosity	1.00E+18	1.00E+18	1.00E+18
weighted events	10.06	0.5977	21.80
Significance	**1.77**		

- The Significance = 1.77


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
BSM_ZH_mm_aa
Entries 3607
Mean x 26.69
Mean y 30.74
Std Dev x 17.3
Std Dev y 11.86
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZH_mm
Entries 56211
Mean x 45.84
Mean y 36.77
Std Dev x 24.97
Std Dev y 21.75
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZZ_mm
Entries 55867
Mean x 60.84
Mean y 19.62
Std Dev x 23.12
Std Dev y 13.49
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)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Std Dev x 23.12
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BSM_ZH_mm_aa
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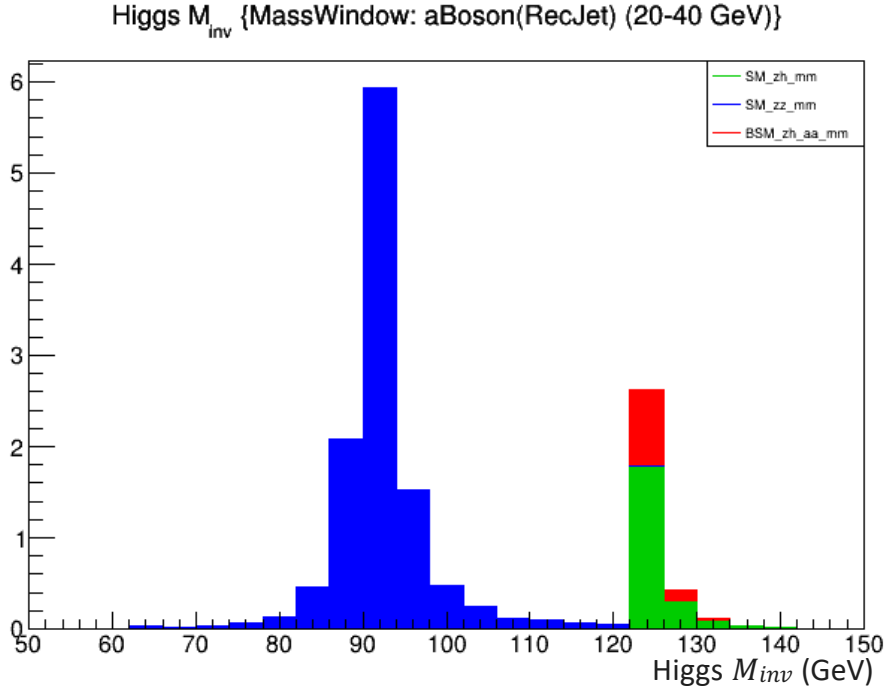
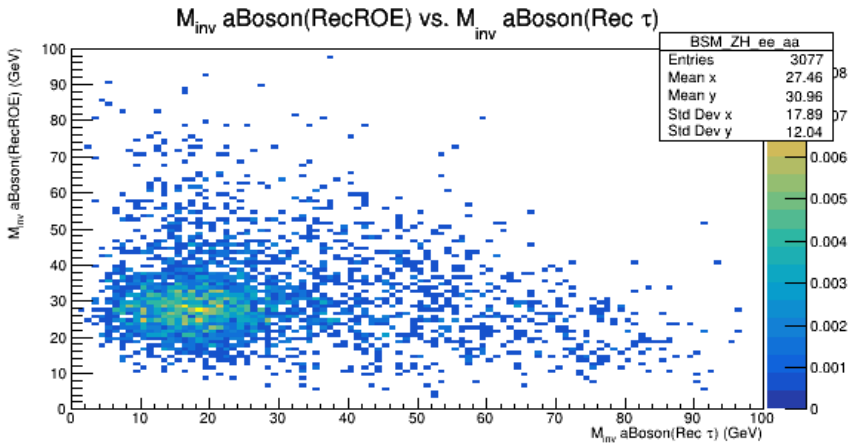
Mean y 30.74
Std Dev x 17.3
Std Dev y 11.86
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)

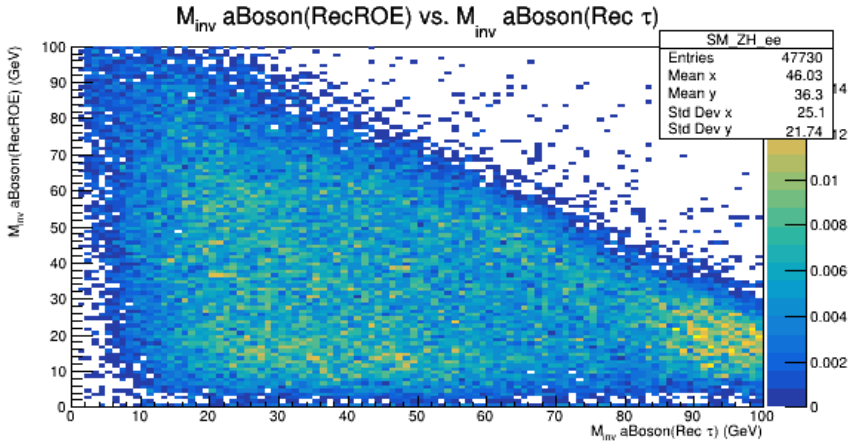

Higgs M_inv {MassWindow: aBoson(RecJet) (20-40 GeV)}
SM_zh_mm
SM_zz_mm
BSM_zh_aa_mm
Higgs M_inv (GeV)

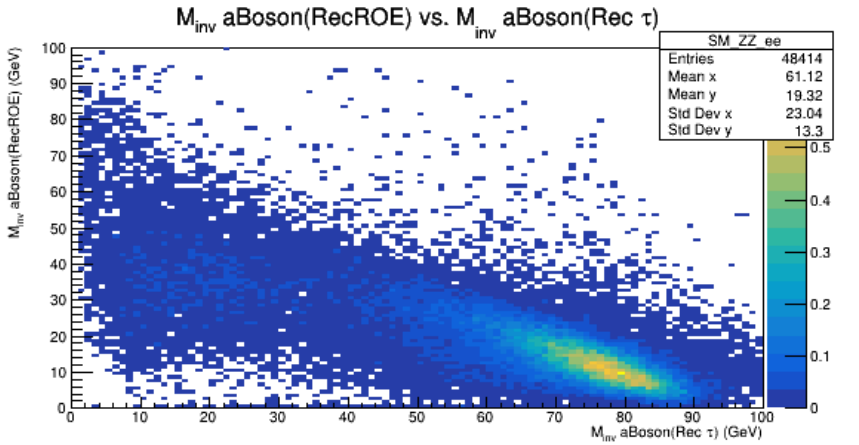
$e^+e^-\ b\bar{b}\ \tau^+\tau^-$ final state

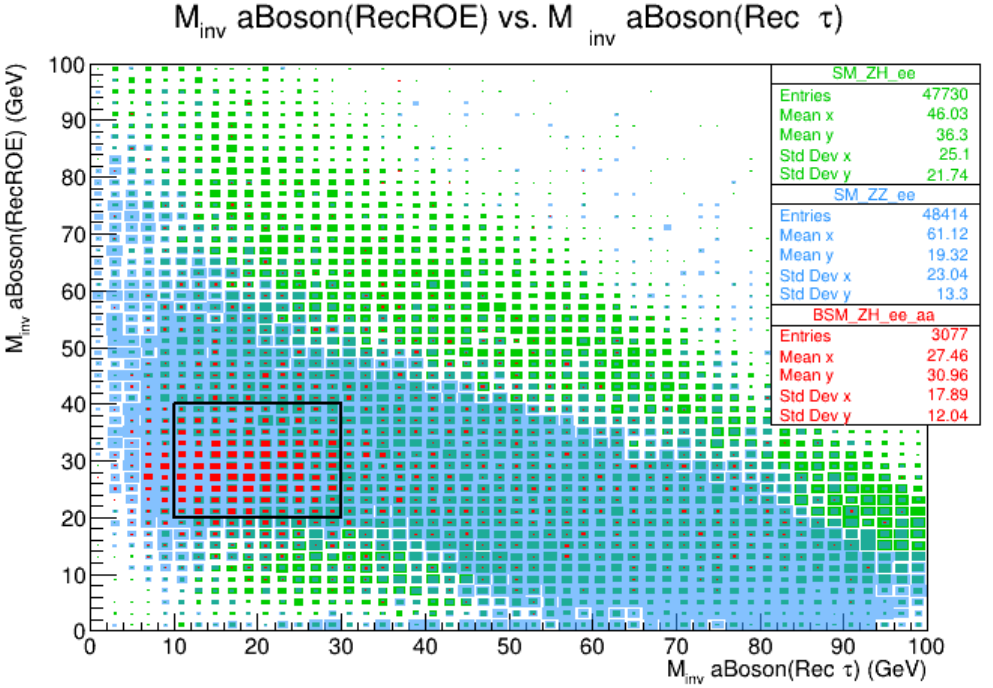
	Signal	Bkg_ZZ	Bkg_Zh
# of Events generated	10000	1000000	1000000
ZBoson [80,100] / ZBoson before [80,100] Cut %	87.16	92.32	90.58
ZBoson [80,100] / # of Events generated %	54.42	57.73	53.50
aBoson (Tau) [10,30] / aBoson (Tau) before [10,30] Cut %	61.72	14.15	23.18
aBoson (Tau) [20,40] / ZBoson [80,100] %	30.96	1.62	3.49
aBoson (Jet) [20,40] / aBoson (Jet) before [20,40] Cut %	74.66	55.20	25.01
aBoson (Jet) [20,40] / aBoson (Tau) [10,30] %	74.66	30.39	15.27
HBoson [120,140] / HBoson before [120,140] Cut %	99.84	0.11	98.42
HBoson [120,140] / aBoson (Jet) [20,40] %	99.84	0.11	98.42
XS	6.60E-15	3.52E-14	6.60E-15
BR Higgs decay	0.01	1	1
luminosity	1.00E+18	1.00E+18	1.00E+18
weighted events	8.293	0.1055	18.51
Significance	**1.60**		

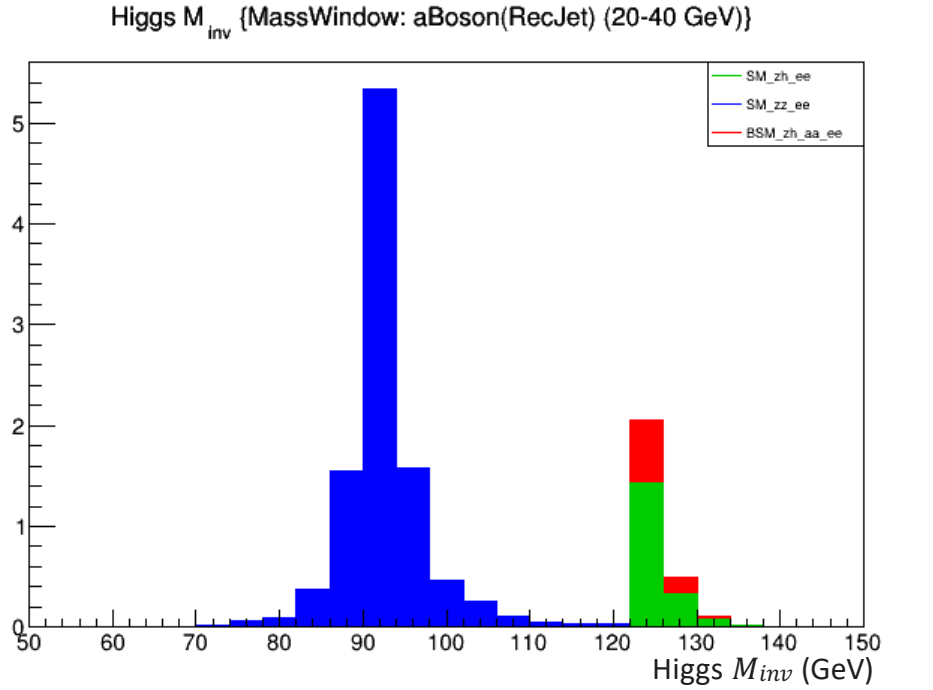
- The Significance = 1.60


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
BSM_ZH_ee_aa
Entries 3077
Mean x 27.46
Mean y 30.96
Std Dev x 17.89
Std Dev y 12.04
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZH_ee
Entries 47730
Mean x 46.03
Mean y 36.3
Std Dev x 25.1
Std Dev y 21.74
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZZ_ee
Entries 48414
Mean x 61.12
Mean y 19.32
Std Dev x 23.04
Std Dev y 13.3
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZH_ee
Entries 47730
Mean x 46.03
Mean y 36.3
Std Dev x 25.1
Std Dev y 21.74
SM_ZZ_ee
Entries 48414
Mean x 61.12
Mean y 19.32
Std Dev x 23.04
Std Dev y 13.3
BSM_ZH_ee_aa
Entries 3077
Mean x 27.46
Mean y 30.96
Std Dev x 17.89
Std Dev y 12.04
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


Higgs M_inv {MassWindow: aBoson(RecJet) (20-40 GeV)}
SM_zh_ee
SM_zz_ee
BSM_zh_aa_ee
Higgs M_inv (GeV)

Summary

- Quick look at the BSM Higgs produced from exotic SM Higgs decays in association with a Z boson at e^+e^- collider
- Results look reasonable, but there are still a lot of room for improvement i.e. Tau reconstruction algorithm, exploiting angular information, etc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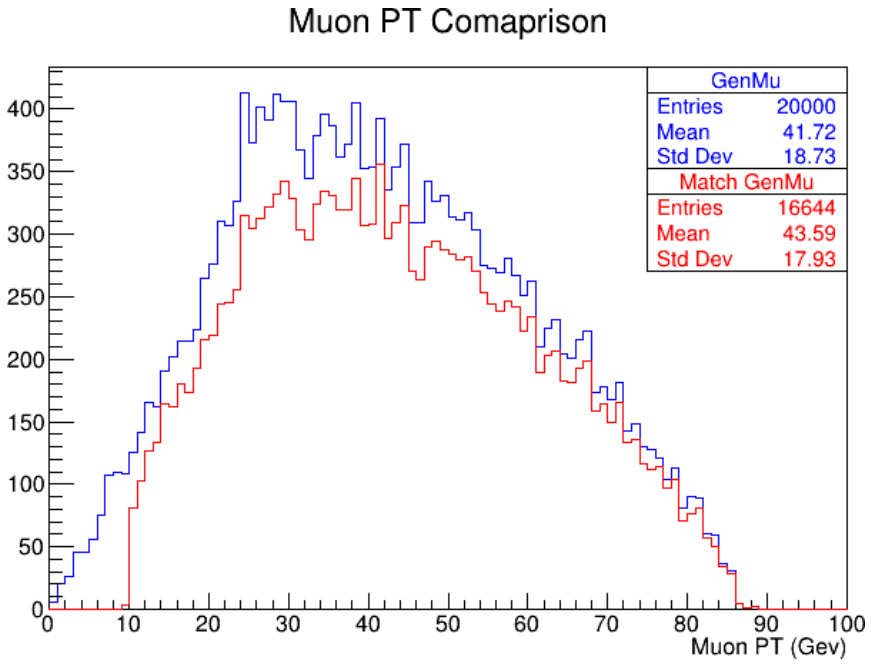
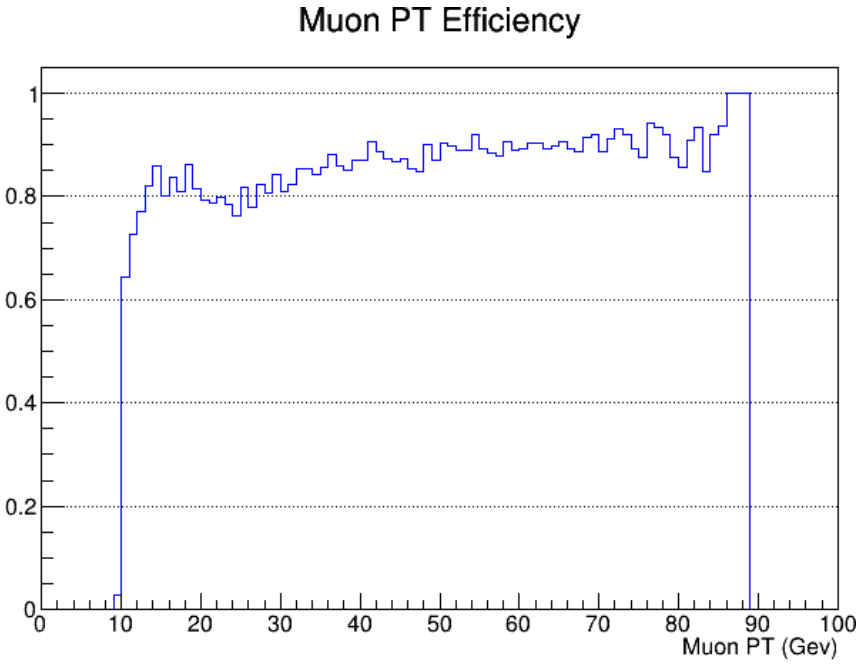
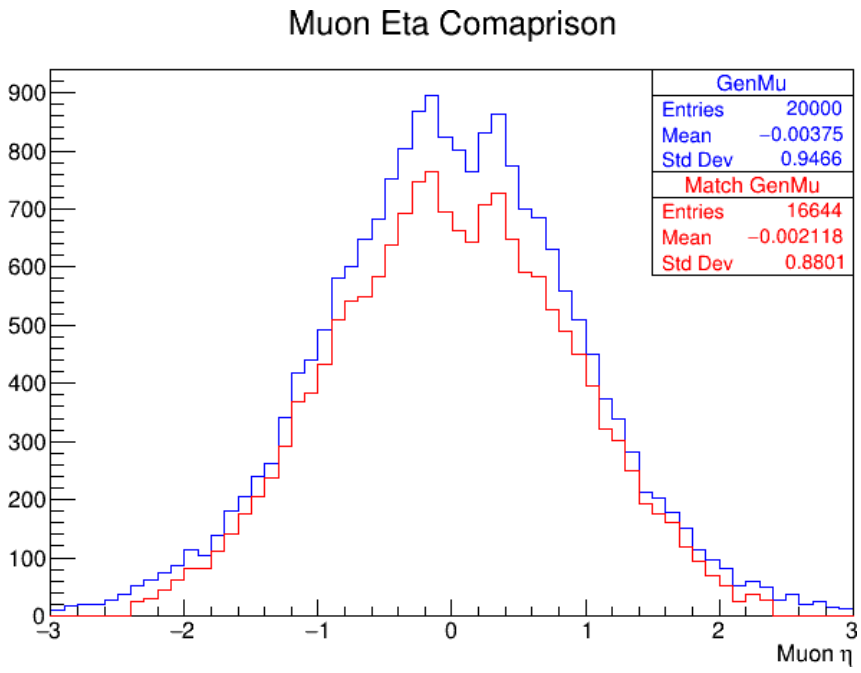
Muon PT Efficiency

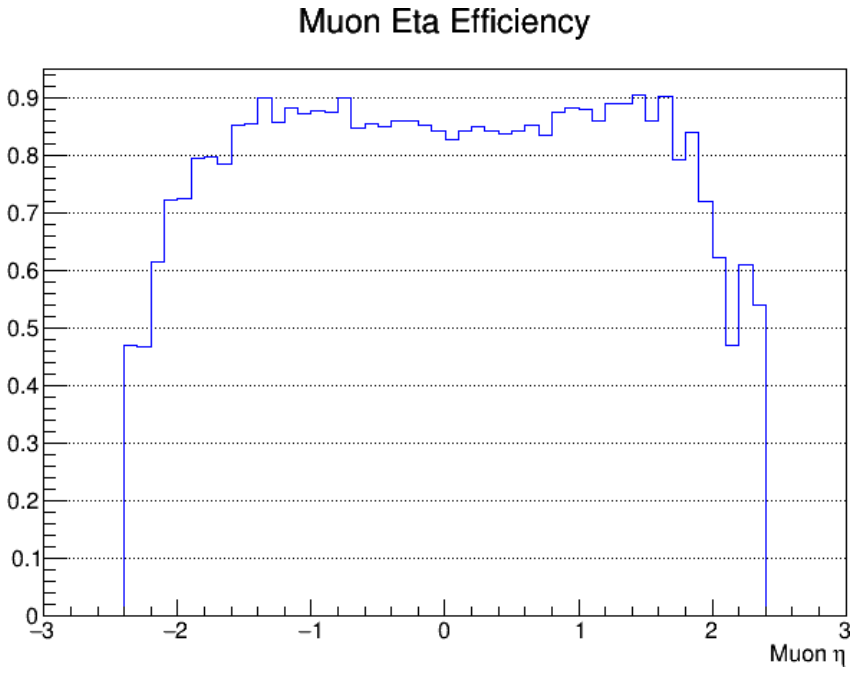




- When the PT is greater than 10 GeV, an efficiency of above 0.8 and close to 0.9 is achieved.
- Efficiency drop at around 10 GeV. Resulting from the 10 GeV PT cut on Dlephes.

Muon Eta Efficiency





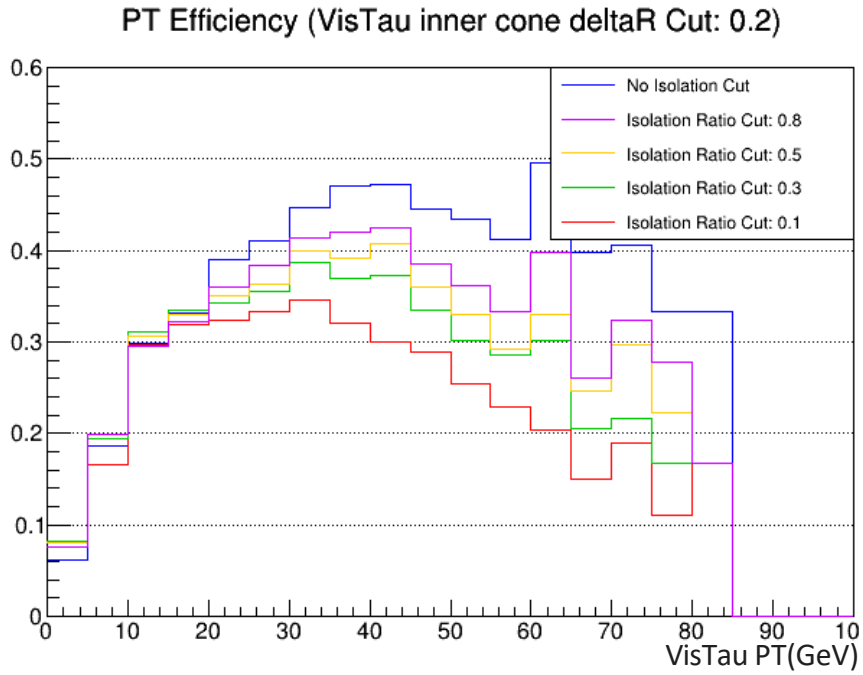
- Close to 0.9 efficiency in the eta region from -1.5 to 1.5
- Efficiency drop at around $\pm$ 2

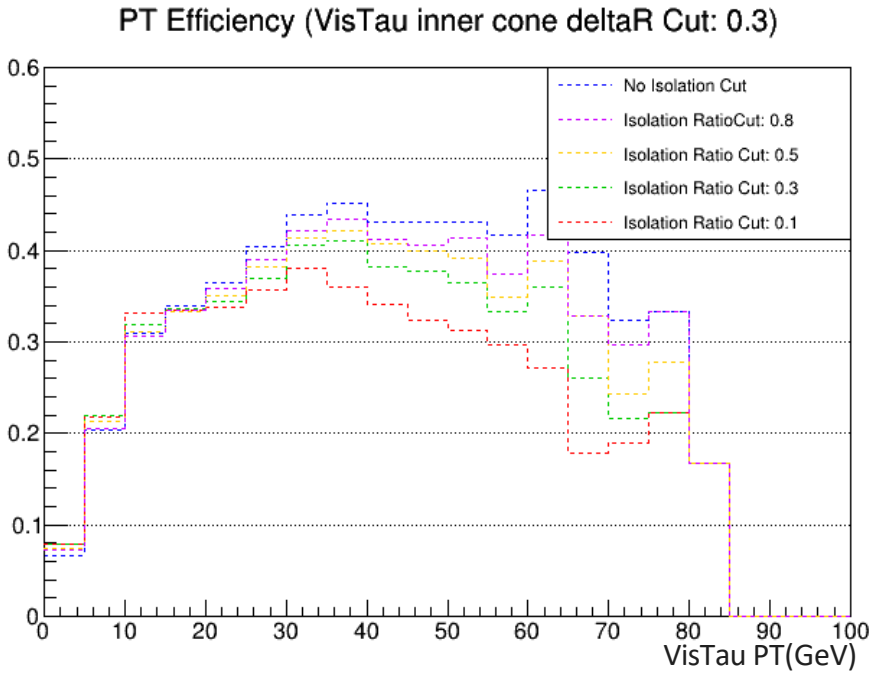
Generator level Tau

1. Loop through each particle in branchParticles:
   - Check if the particle is a tau neutrino (abs(particle->PID) == 16).
   - Trace the ancestry of the tau neutrino to find the parent tau particle.
   - Handle special cases:
     - Z or W boson decay neutrinos: Skip.
     - D or B meson decay products: Skip.
2. Extract decay products of the parent tau:
   - Identify charged prongs with the highest PT (e.g. pi+ or K+).
   - Count photons and neutral hadrons in the decay.
3. Create genTaus and visTaus objects:
   - genTaus: Information about the parent tau particle and its decay products.
   - visTaus: Information about visible tau decay (parent tau momentum - tau neutrino momentum).

Table for different Inner Cone deltaR & Isolation Ratio Cut

deltaR & Isolation Ratio Cut / a Boson Mass (RecTau)Stats	deltaR: 0.2 Isolation: 0	deltaR: 0.2 Isolation: 0.8	deltaR: 0.2 Isolation: 0.5	deltaR: 0.2 Isolation: 0.3	deltaR: 0.2 Isolation: 0.1	deltaR: 0.3 Isolation: 0	deltaR: 0.3 Isolation: 0.8	deltaR: 0.3 Isolation: 0.5	deltaR: 0.3 Isolation: 0.3	deltaR: 0.3 Isolation: 0.1
Entries	4886	4252	3925	3568	2928	4662	4441	4676	4054	3547
Mean	29.75	29.73	28.67	26.71	22.03	30.36	30.56	30.41	29.45	25.99
Std DEV	17.28	17.67	17.7	17.35	13.97	17.93	18.14	18.24	18.32	17.05

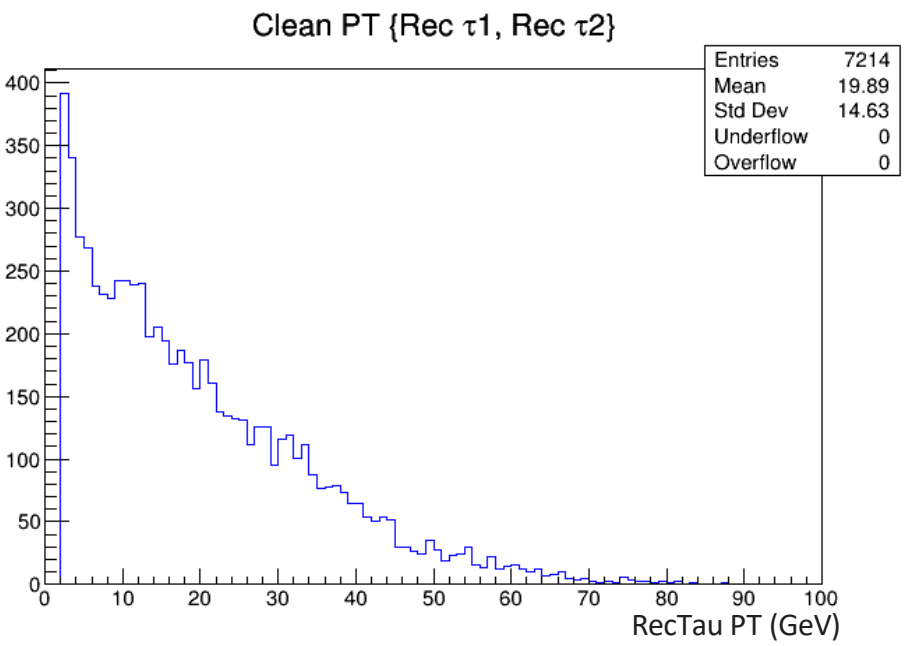


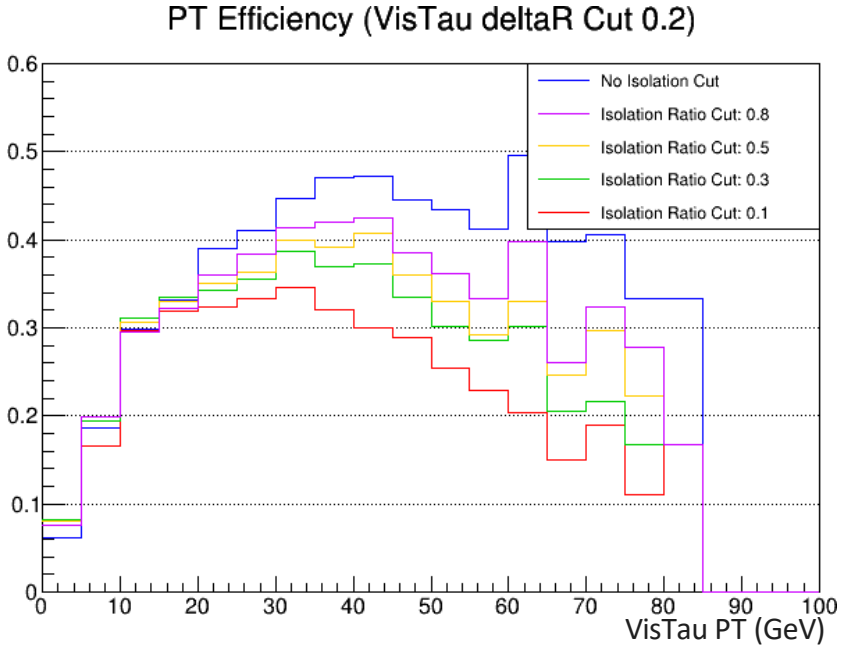


Comparison of RecTau vs VisTau (inner cone deltaR Cut: 0.2, Isolation Ratio Cut: 0.3)

Stats \ Type	VisTau	RecTau
Entries	10000	3607
Mean	21.16	26.68
std Dev	8.944	17.3

- Selection Efficiency: 36%
- Tau Reconstruction efficiency needs to be studied





- PT for the single RecTau with deltaR cut 0.2 and isolation ratio cut 0.3