Search for a Light Pseudo-Scalar Higgs Boson at e^+e^- collider

Cheng-Hsu (Bryan) Nee
Abdollah Mohammadi
Sridhara Dasu

Motivation

- **Importance of Future Colliders**:
  - Higher energy and luminosity are needed to explore uncharted territories beyond the Standard Model.
- **Exploring the Existence of Additional Higgs Bosons**:
  - The Standard Model predicts only one Higgs boson, but BSM theories suggest the existence of additional Higgs particles (e.g. 2HDM+S).
  - These additional Higgs bosons could have different masses and properties, providing a rich field for discovery.
- **Potential for Additional Lighter/Heavier Higgs Bosons**:
  - Additional Higgs bosons predicted by BSM theories could be lighter or heavier than the 125 GeV Higgs boson.
  - Specifically, (pseudo-)scalar Higgs bosons with masses less than half of the 125 GeV Higgs boson ($\mathrm{h} \rightarrow aa$) are of particular interest.
  - In our studies, the mass range of interest is 10-60 GeV.
- **Boosted Lighter a Bosons and Specialized Analysis Techniques**:
  - Lighter a bosons the Higgs boson are highly boosted, making their detection and analysis more complex.
  - Specialized analysis techniques are required to identify and study these boosted particles.

Signals and Backgrounds

To DO: $Z \to q\bar{q}$ / $\nu\bar{\nu}$

Signals ($ll = \mu^+\mu^-/e^+e^-$):

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

Backgrounds:

- $e^+e^- \to Z(\to ll)\,H$ **(Higgs decays to anything)**
- $e^+e^- \to Z(\to ll)\,Z(\to f\bar{f})$**(except muons and electrons)**

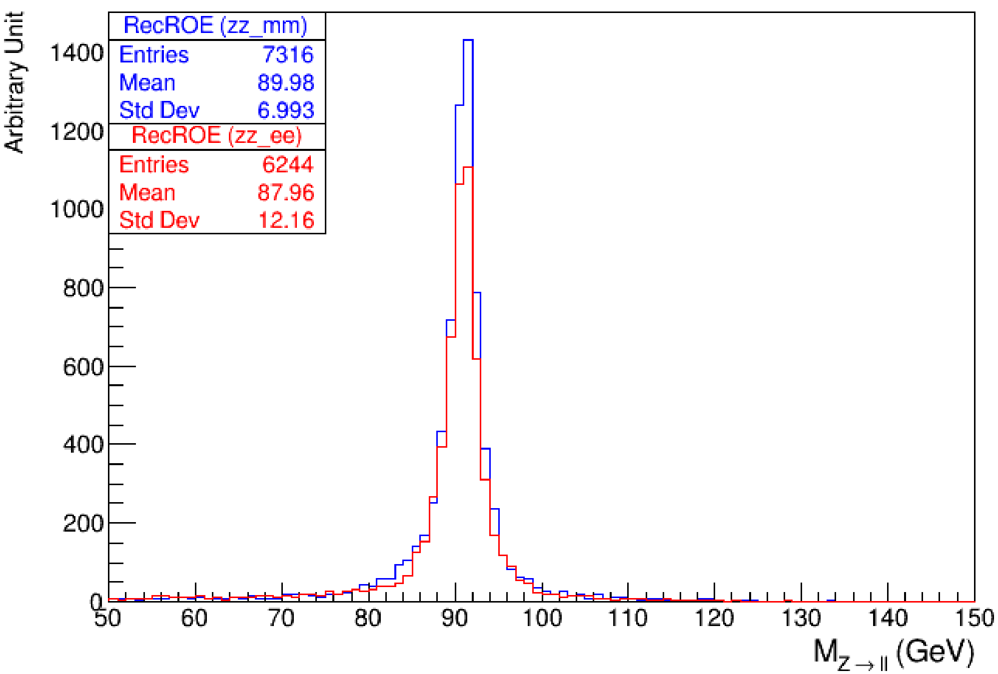
	Signals	Bkg_ZZ	Bkg_ZH
# of Events Generated	10000	1000000	1000000
a Boson Mass Range (GeV)	10 - 60		
XS (b)	6.60E-15	3.52E-14	6.60E-15

- The samples are produced at 250 GeV e^+e^- collider.
- Generators and Simulations:
  - Producing Madgragh5 based signals
  - Hadronized the signals and backgrounds Pythia8
  - Simulate for detector's response with Delphes ILC card

Event Selection and Z Boson Mass Reconstruction

- **Event Selection:**
  - 1 pair of muons/electrons with opposite charges, leading PT, and mass consistent with the Z Boson.
  - 1 pair of taus with opposite charges and leading PT.
  - Instead of selecting a pair of b-jets, we implement the Rest of Events (ROE) mechanism to represent the b-jets. (This approach will be discussed later).

- **Z Boson Mass Reconstruction:**
  - Selection Efficiency: 73%
  - The peak position sits at 90 GeV for the reconstruction level



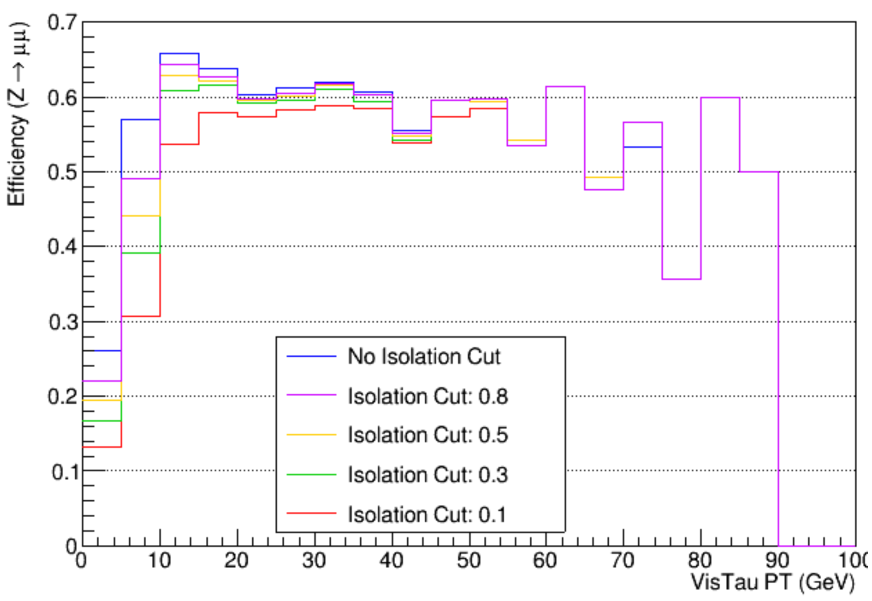
Tau Reconstruction

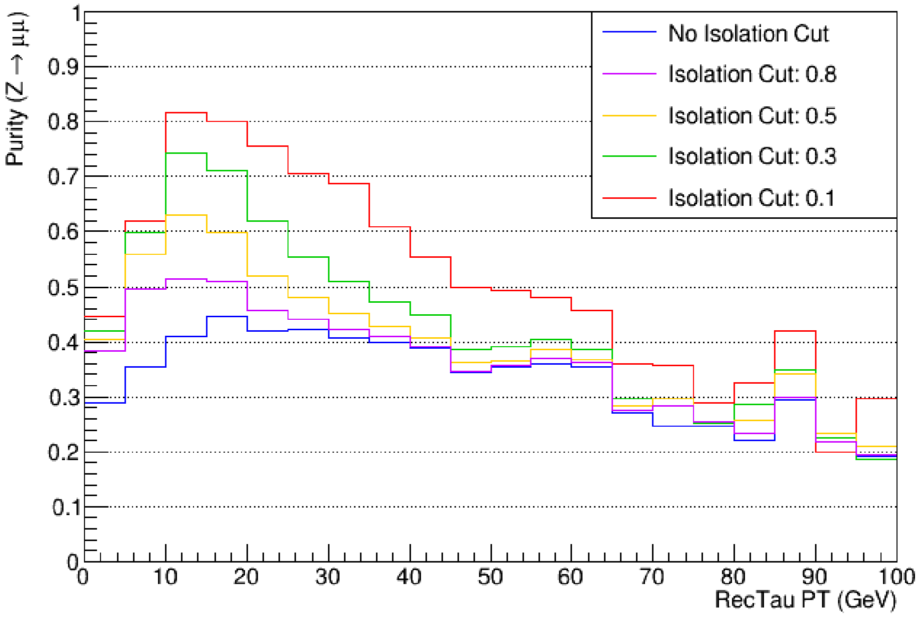
Reconstructing tau particles using energy flow (EFlow) data from tracks, photons, and neutral hadrons.

Reconstruction Process:

1. Consider tracks with PT > 2.0 GeV as potential tau remnants.
2. Add in tracks and clusters within a dynamic DeltaR signal cone around the tau candidate:
   - Signal cone: linear relationship from 0.1 (PT = 20 GeV) to 0.2 (PT = 10 GeV)
   - Calculate isolation as the sum of PT for tracks and clusters from signal cone to DeltaR 0.5.
3. Repeat the process for photons and neutral hadrons from branchEFPhotons and branchEFNHadrons
4. Only consider tau candidates with a maximum of 5 charged prongs and pass isolation ratio cuts.
5. Did consider including tau leptons seeded by a photon to improve Tau Reco efficiency, but did not lead to overall significance

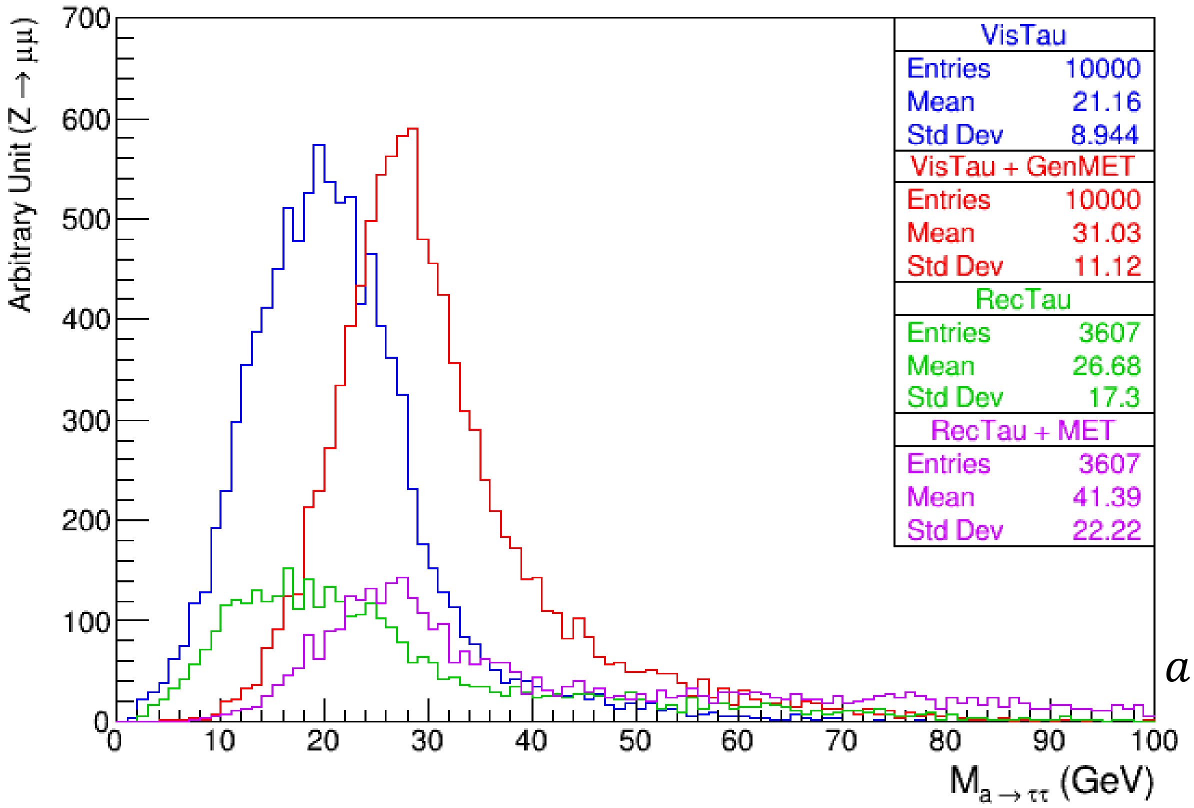
Tau Reconstruction Efficiency





- Matching: One-to-one matching has to be within $\Delta R < 0.5$
- Match Efficiency: $\frac{VisTau\ Matched\ RecTau\ PT}{VisTau\ PT}$
- Purity: $\frac{RecTau\ Matched\ VisTau\ PT}{RecTau\ PT}$
- Achieve a high efficiency/purity for the lower PT region, which is the primary focus for the tau reconstruction in this analysis.

τ-pairs Mass Reconstruction



Gen level visible τ

Gen level visible τ +
Gen level Missing ET

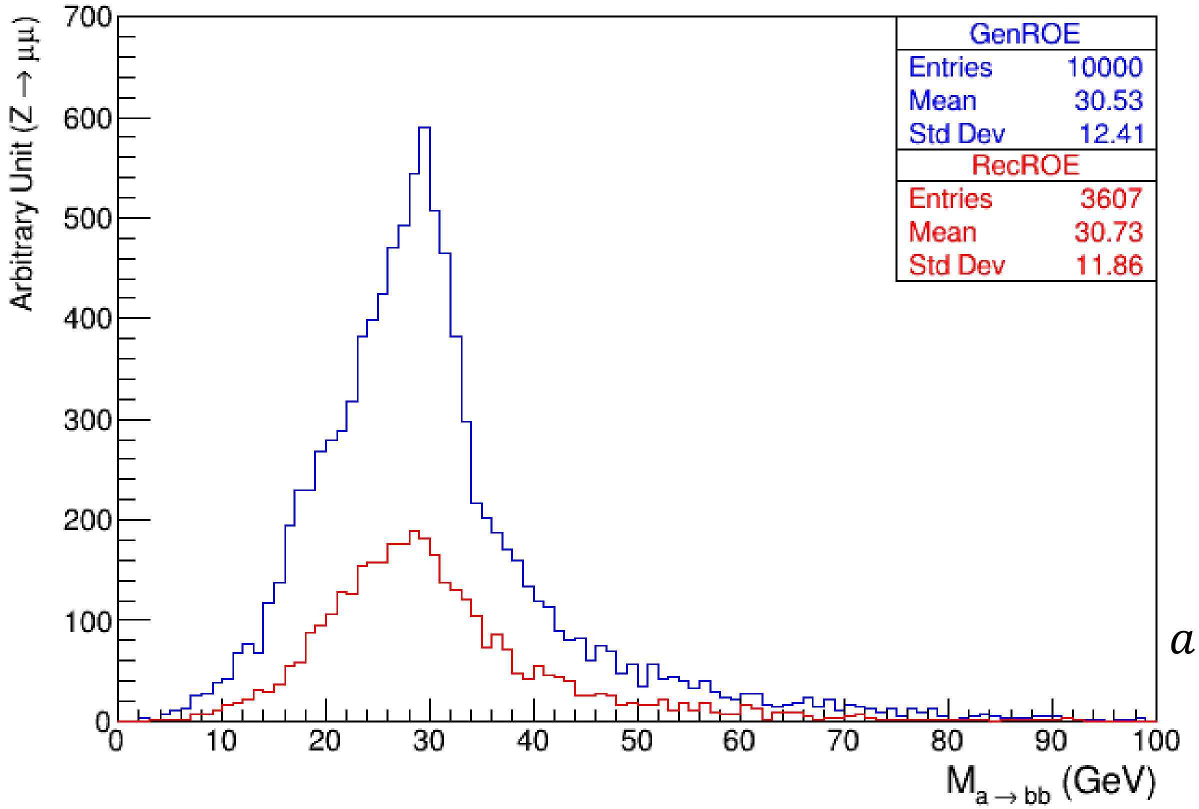
Rec level visible τ

Rec level visible τ +
Rec level Missing ET

a boson mass set to 30 GeV

- 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 the a boson invariant by adding GenMET and MET back.

Rest of the Events (ROE) Analysis

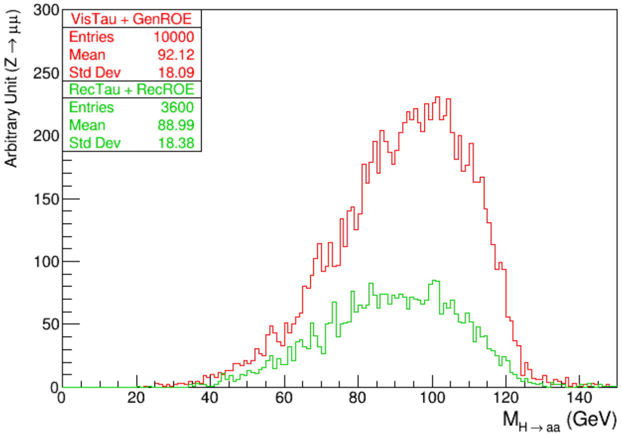


a boson mass set to 30 GeV

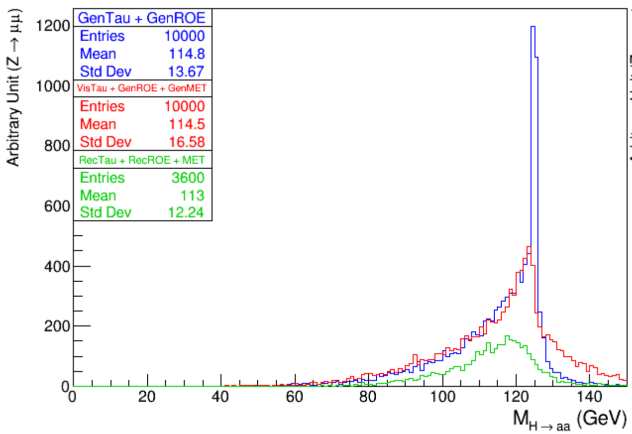
- Implementing Eflow objects for reconstruction level Rest of the Event (RecROE) to form $a \to b\bar{b}$.
- Expect higher efficiency by avoiding the Delphes jet reconstruction algorithm and associated cuts
- RecROE = $\sum_i^{excl\ \mu/e\ \&\ \tau} \mathrm{track_i} + \sum_i^{excl\ \mu/e\ \&\ \tau} \mathrm{Photon_i} + \sum_i^{excl\ \mu/e\ \&\ \tau} \mathrm{NHadron_i}$
- The peak position sits at 30 GeV for both GenROE and RecROE

Higgs Boson Mass Analysis

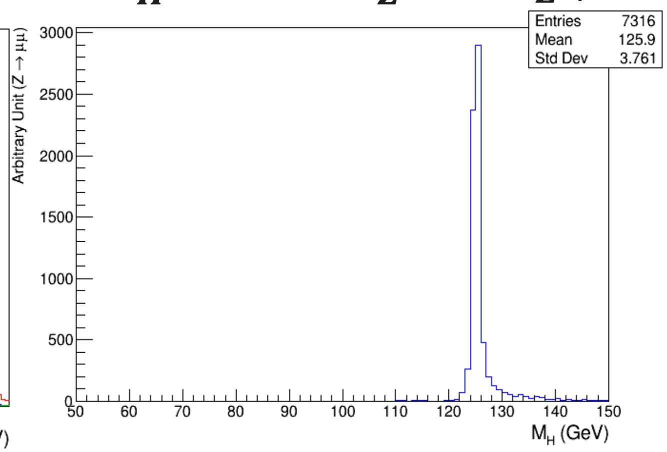
$M_{H\to aa}$



$M_{H\to aa+MET}$

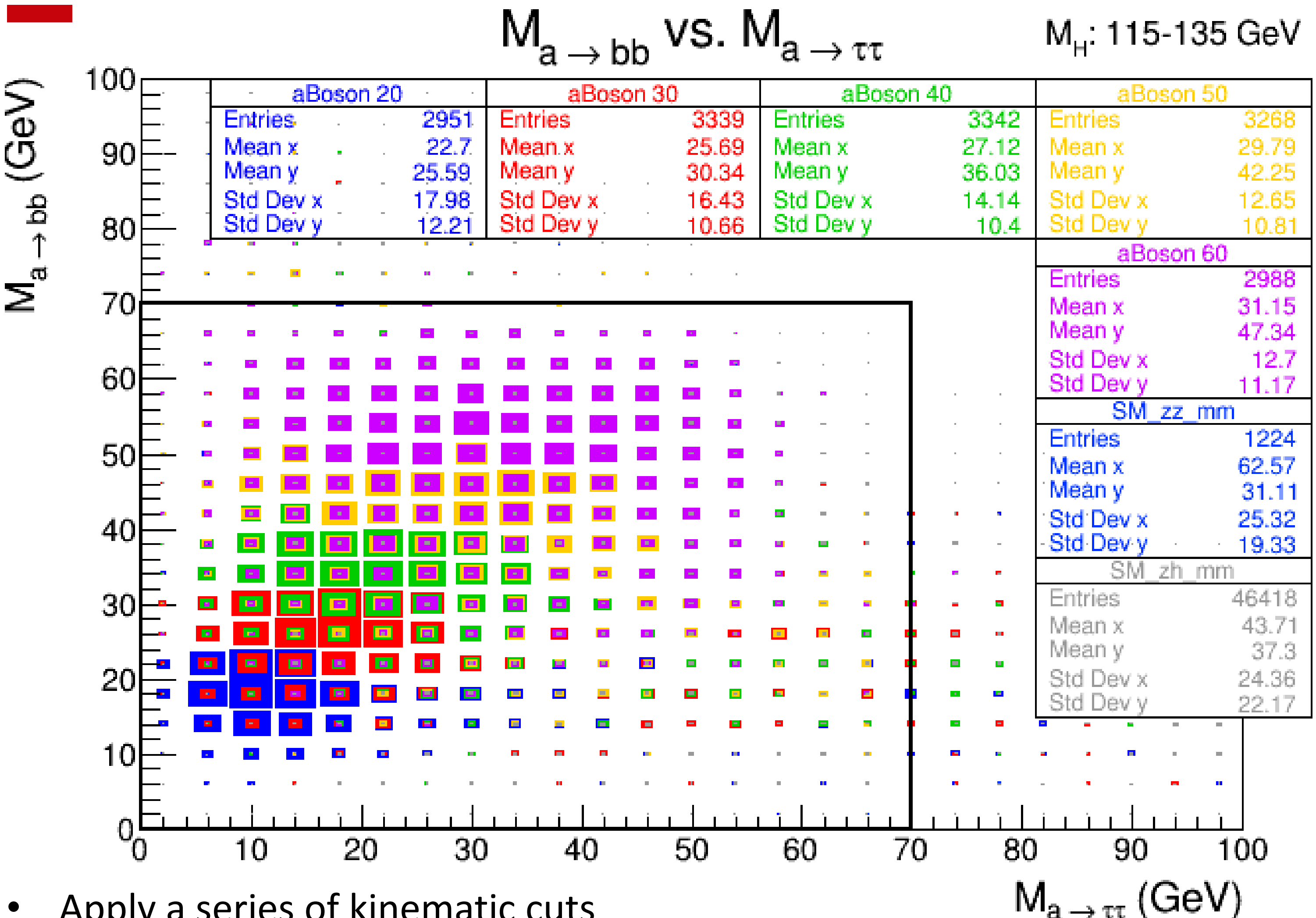


$M_H^2 = s + M_Z^2 - 2E_Z\sqrt{s}$



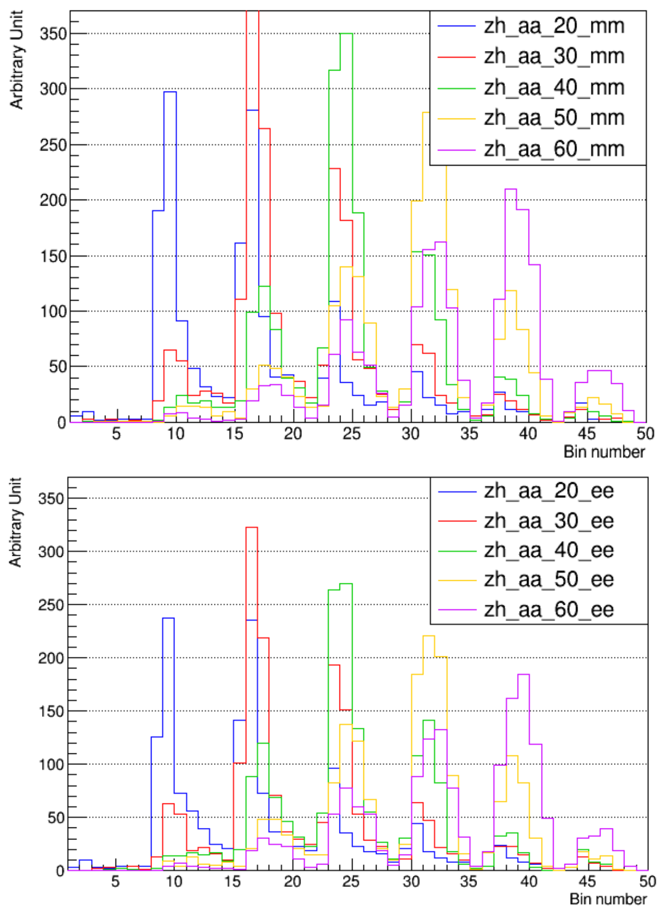
- The visible Higgs Boson M_{inv}(VisTau + GenROE) and Reco level Higgs Boson M_{inv} (RecTau + RecROE) both peak at around 100 GeV.
- We could sharpen those peaks and shift the peak positions toward 125 GeV by adding back the MET (middle).
- $M_{\text{Higgs}}^2 = s + M_Z^2 - 2E_Z\sqrt{s} \quad s = 250\ \text{GeV}$
- The Higgs Boson M_{inv} (Reco) peaks at position 125 GeV.
- The reconstruction of the Higgs Boson has significantly improved with the beam constraint method compared to the method constructed from τ-pairs and ROE.

Final Observables

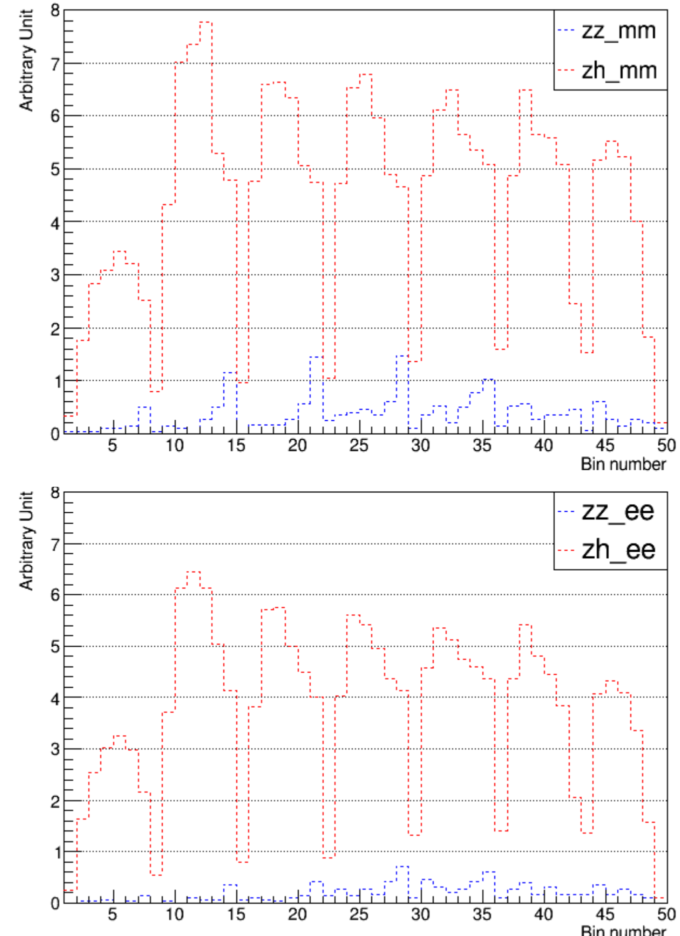


- Apply a series of kinematic cuts
  - Higgs Boson Mass Cuts: 115-135 GeV
  - aBoson (diτ) Mass Cuts: 0-70 GeV
  - aBoson (ROE) Mass Cuts: 0-70 GeV

Unrolled 2D Observables of the a Boson (Reco τ) and a Boson (RecROE) :



Unrolled 1D observables for the signal

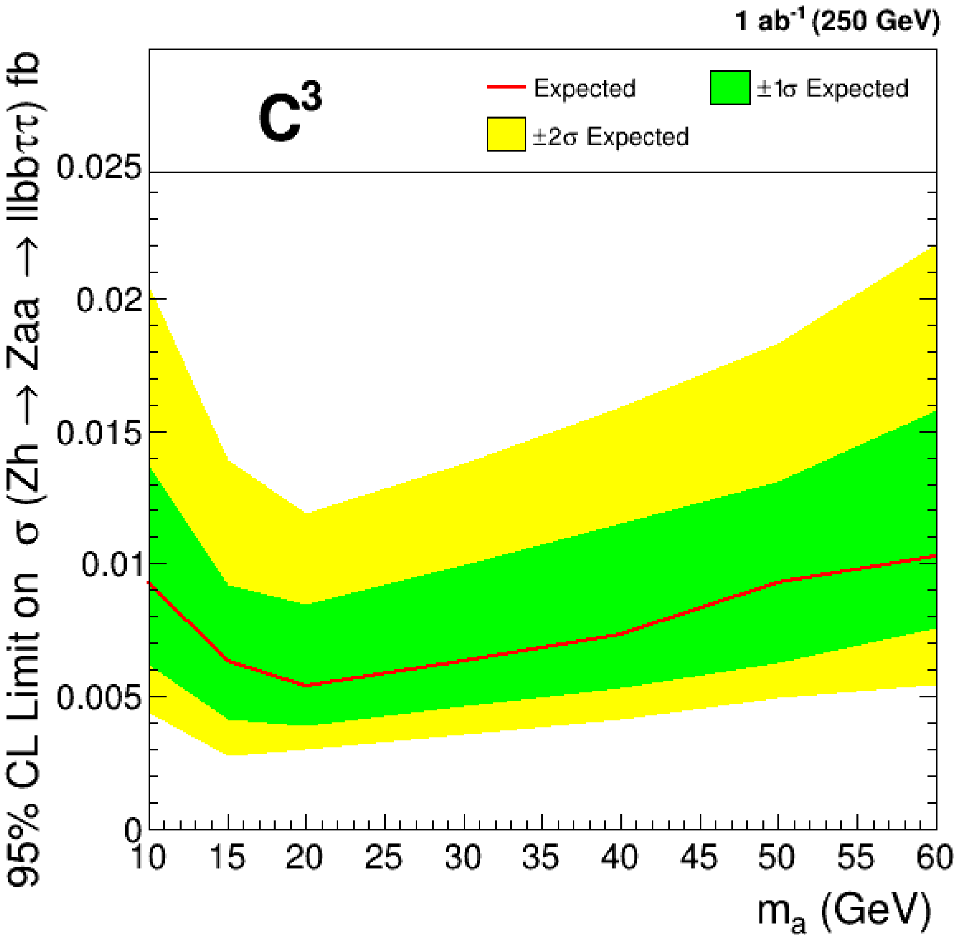


Unrolled 1D observables for the background

- We use this 1D observables' distribution to extract the limit on the Higgs boson cross-section

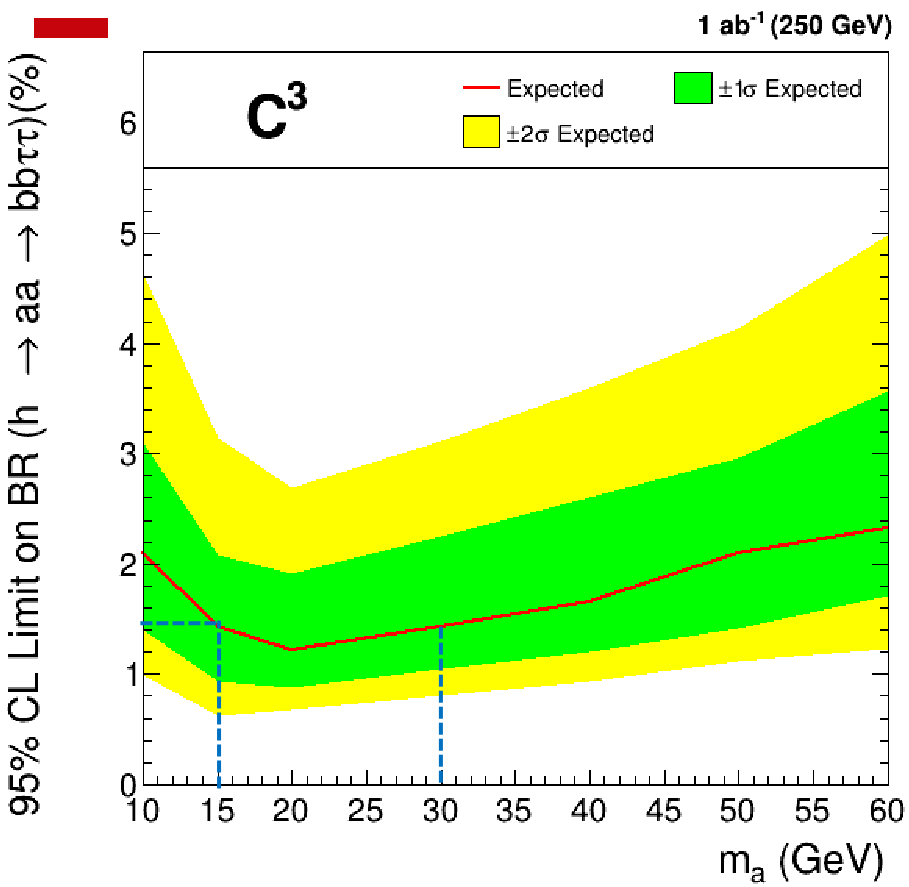
Model-Independent Limit

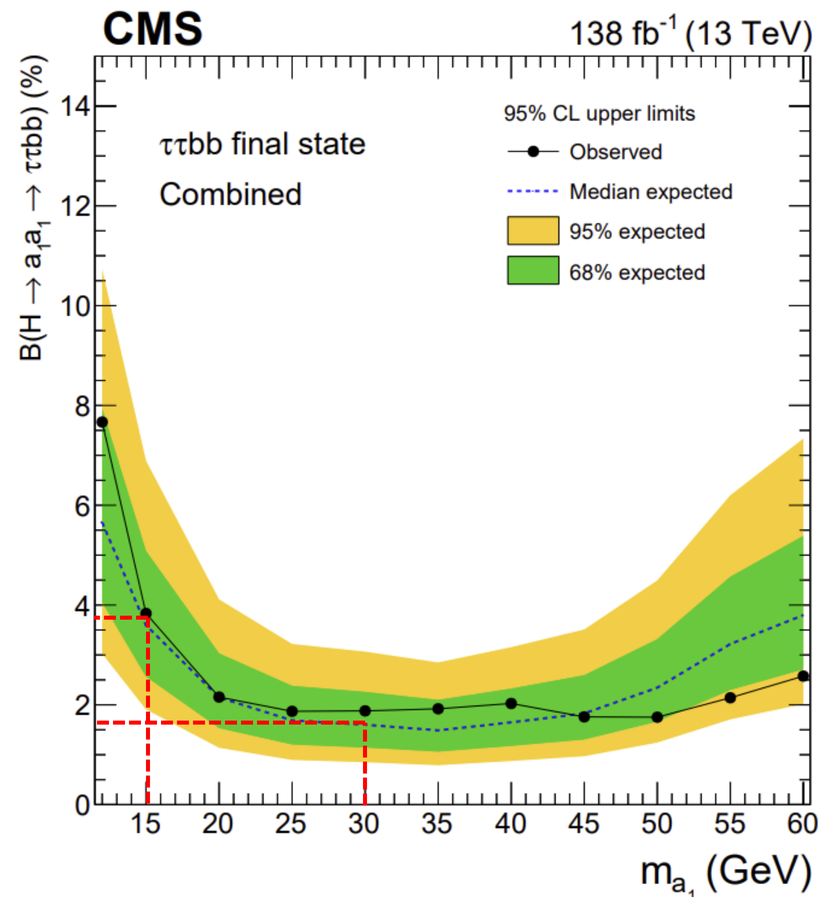
- Utilize a maximum likelihood fit method to compute the limit.
- Assumed integrated luminosity of $1\ ab^{-1}$.
- Minimal sets of systematic uncertainties:
  - 0.2% on signal and background cross sections.
  - Muons: 2%, Electrons: 2%, and Taus: 10%
- Additionally, bin-by-bin uncertainty was included to account for statistical uncertainties in each bin.
- Assume the aBoson has Standard Model-like properties.



Model-Independent Limit

https://arxiv.org/abs/2402.13358

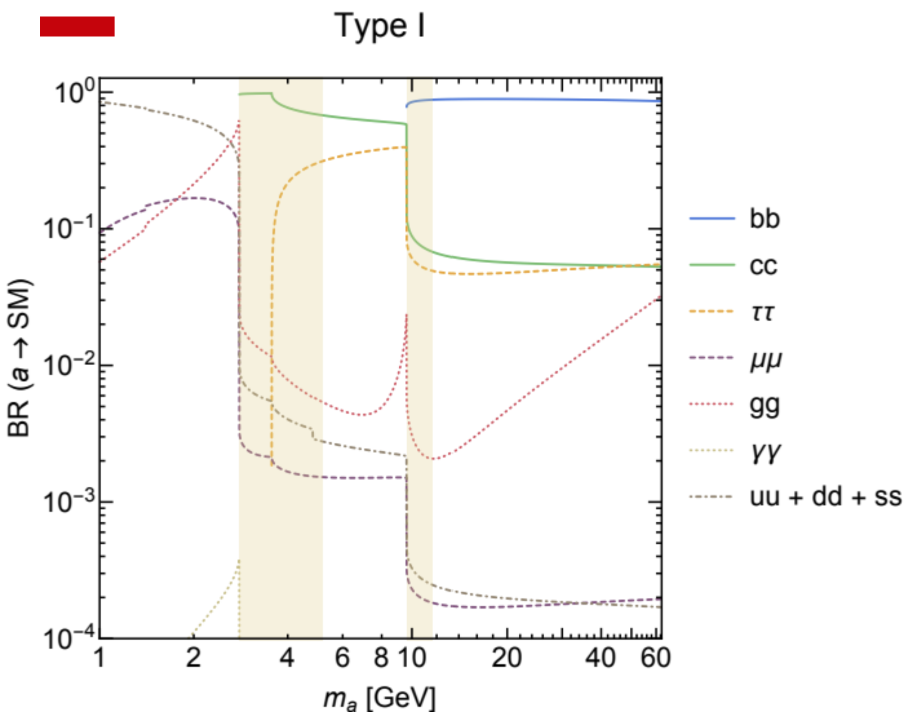




- The limit on the BR($h \rightarrow aa \rightarrow bb\tau\tau$) is obtained from $\sigma(Zh \rightarrow Zaa \rightarrow llbb\tau\tau)$ dividing σ_{SM}(6.6 fb) and BR($Z \rightarrow ll$)(0.067).
- The limit is much more sensitive in the lower mass region than the CMS RUn2 result.

a Boson Mass	C^3	CMS
15 GeV	1.5%	3.7%
30 GeV	1.4%	1.6%

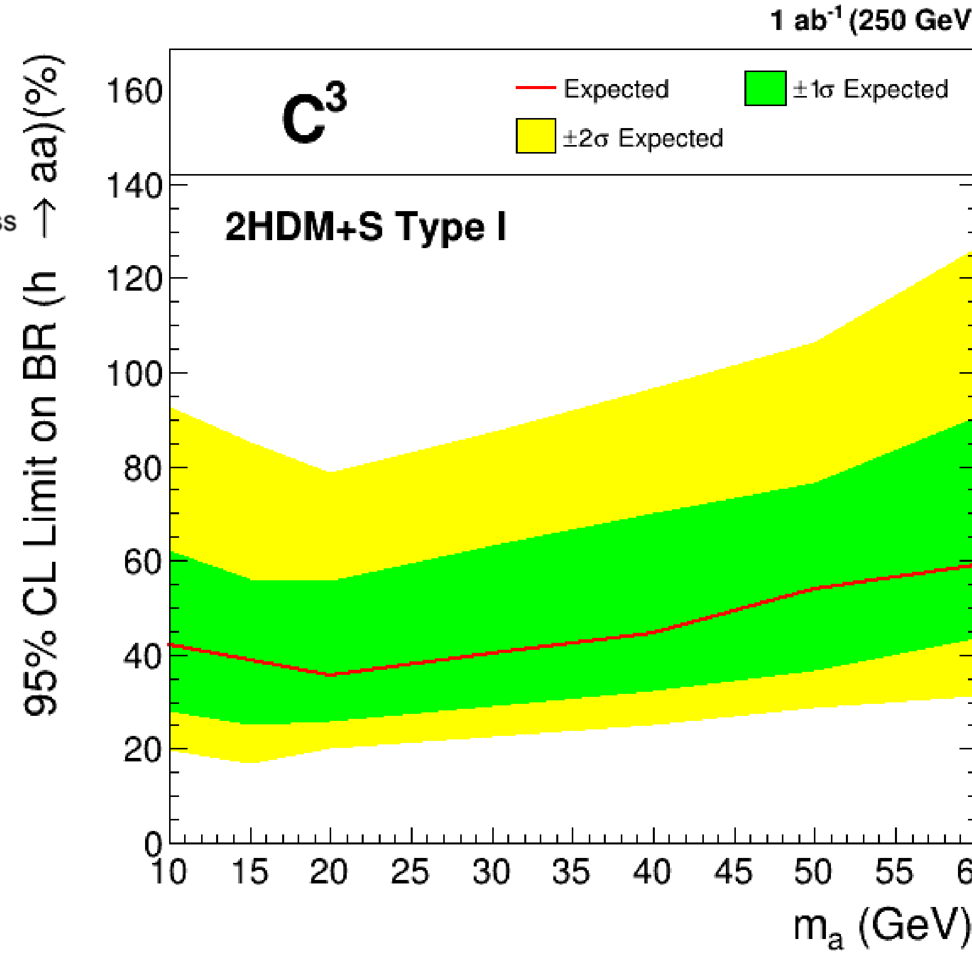
Model-Dependent Limit (2HDM+S Type I)



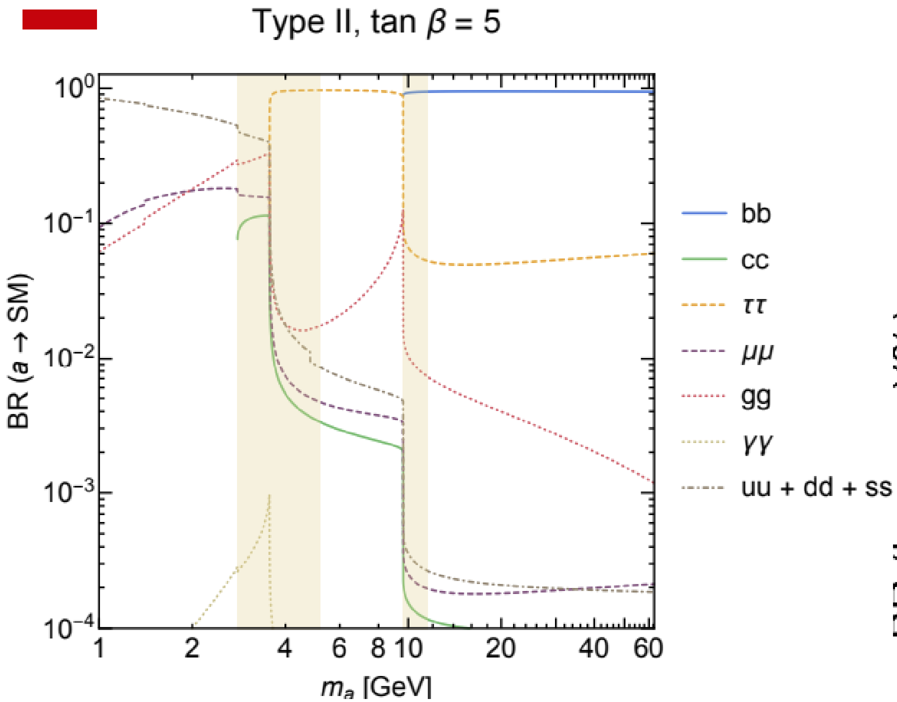
https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
10	0.78	0.064
15	0.82	0.045
20	0.9	0.038
30	0.89	0.04
40	0.885	0.042
50	0.88	0.044
60	0.875	0.045

$$\text{BR}(h \to aa) = \frac{\text{BR}(h\to aa\to bb\tau\tau)}{\text{BR}(a\to bb)\times\text{BR}(a\to\tau\tau)}$$



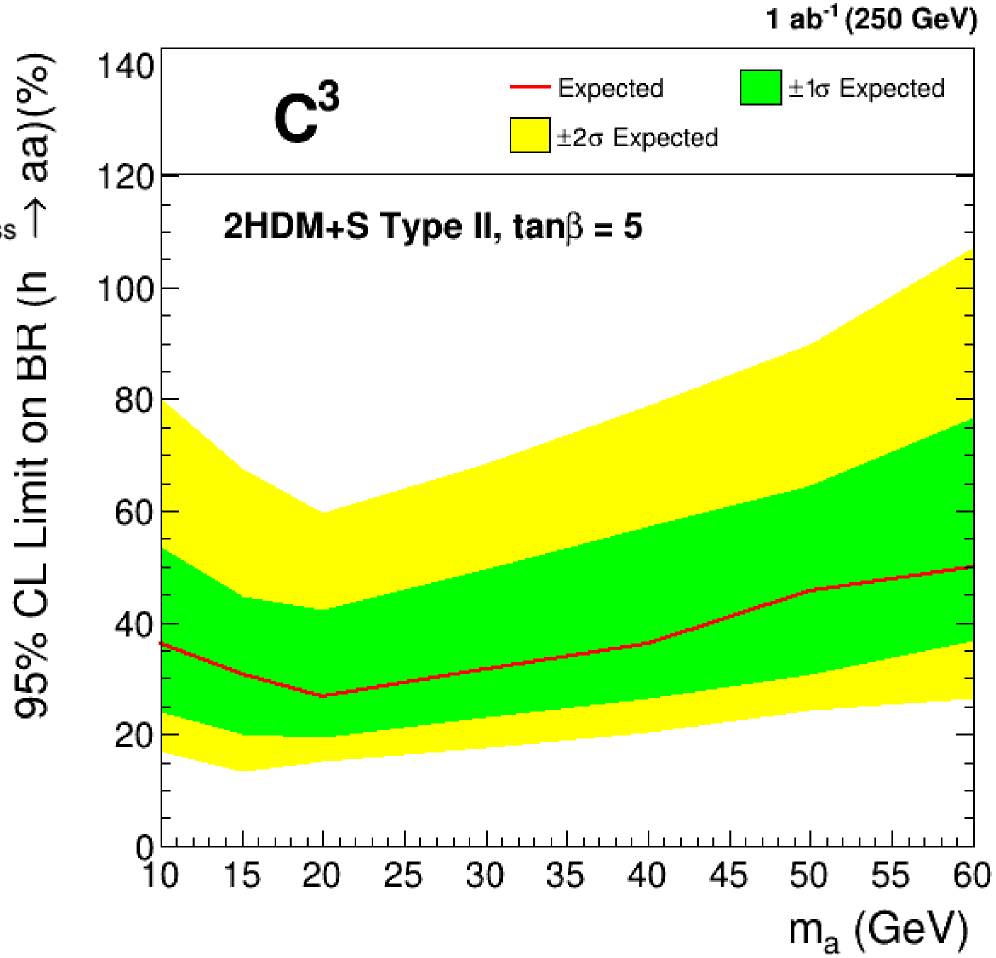
Model-Dependent Limit (2HDM+S Type II, tanβ = 5)



https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
10	0.92	0.063
15	0.93	0.05
20	0.93	0.0485
30	0.93	0.0488
40	0.93	0.049
50	0.93	0.0495
60	0.93	0.05

$$\mathrm{BR}(h \to aa) = \frac{\mathrm{BR}(h \to aa \to bb\tau\tau)}{\mathrm{BR}(a \to bb) \times \mathrm{BR}(a \to \tau\tau)}$$



Conclusion

- Feasibility study of exotic Higgs decay to two light (pseudo-)scalar bosons (a) in association with Z Boson. (Mass Range of a boson: 10–60 GeV)
- A dedicated tau reconstruction algorithm and Rest of the Events (ROE) method is employed, improving signal selection efficiency.
- In the lower mass region, our results outperform those from CMS Run II, showing higher sensitivity.
- Incorporating all Z boson decay channels could increase the signal yield, providing significant room for further enhancements.

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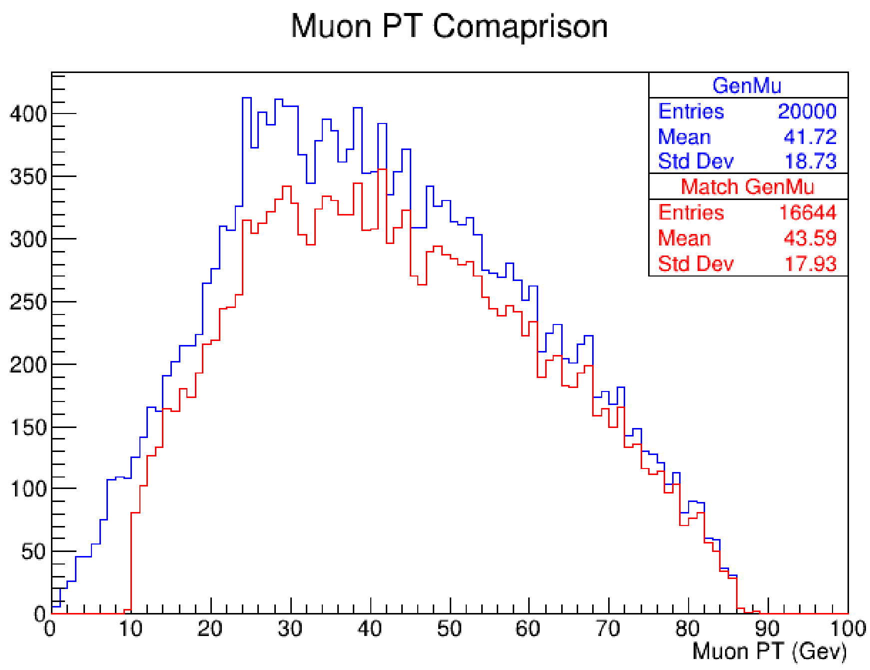
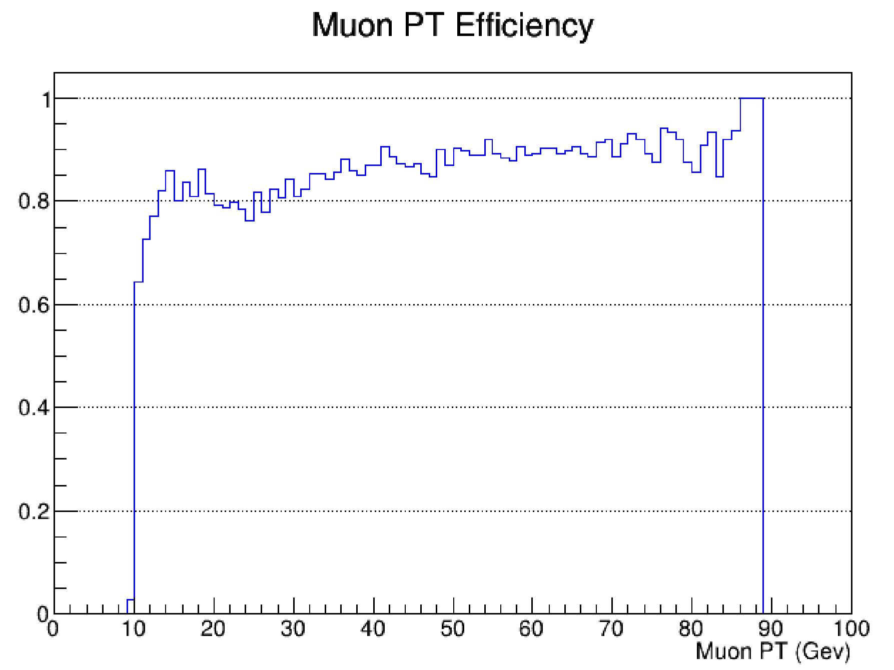
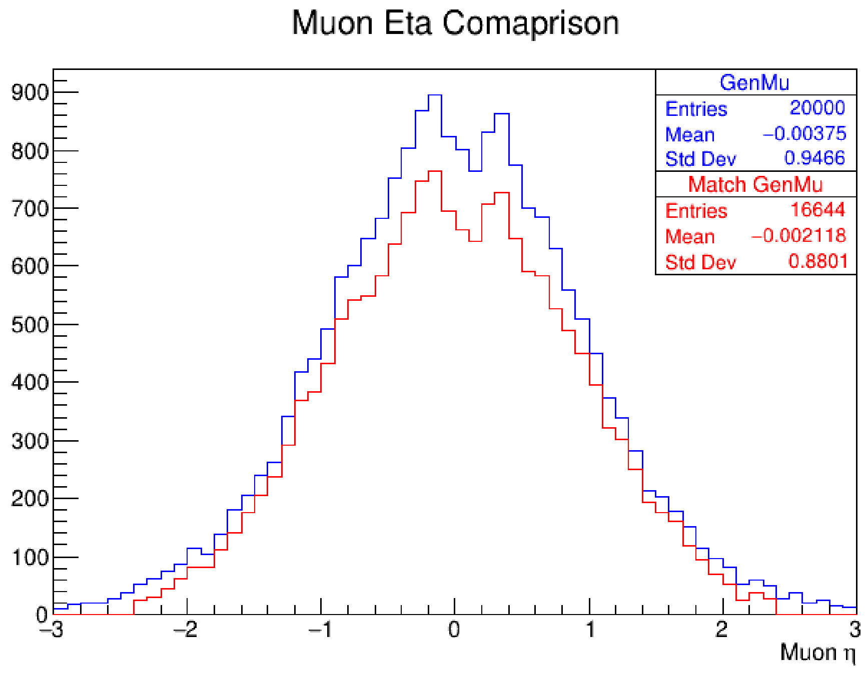
Muon PT Efficiency

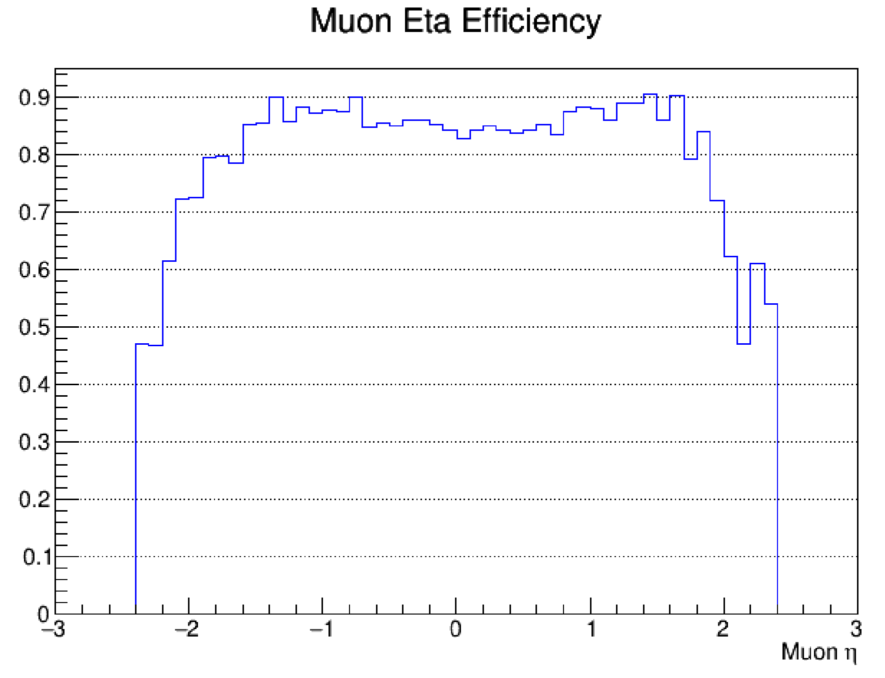




- When the PT is greater than 10 GeV, an efficiency of above 0.8 and close to 0.9 is achieved.
- Efficiency drop at around 10 GeV. Resulting from the 10 GeV PT cut on Dlephes.

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).

Tau Reconstruction

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

Reconstruction Process:

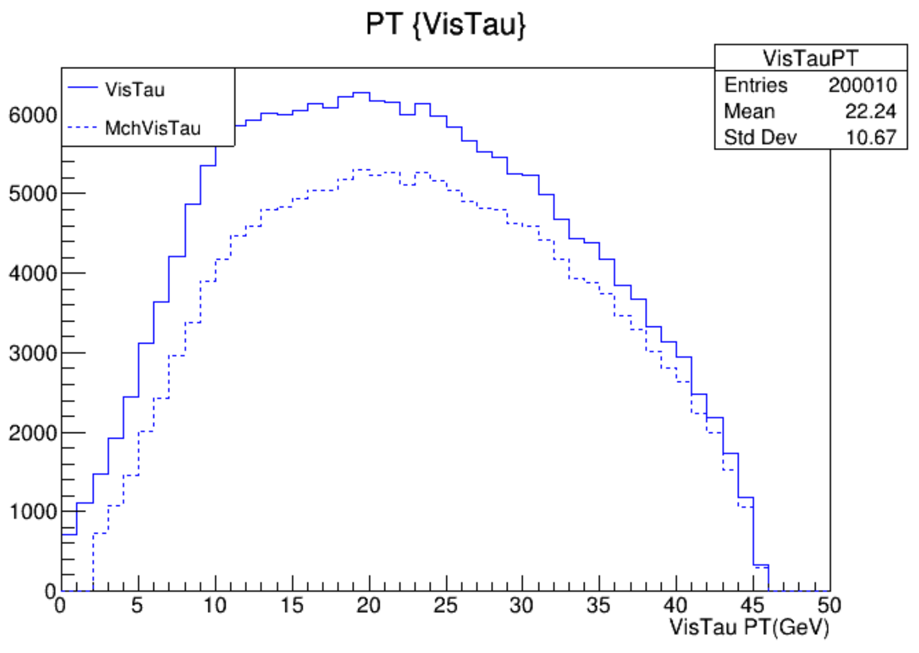
1. Loop through each track in branchEFTracks:
   - Consider tracks with PT > 2.0 GeV as potential tau remnants.
   - Create a tau candidate with the track's PT, eta, phi, and mass.
   - Compute isolation and sum charge of the tracks in the tau candidate.
2. Add in tracks and clusters within a 0.3 DeltaR cone around the tau candidate:
   - Calculate isolation as the sum of PT for tracks and clusters in the 0.3-0.5 DeltaR range.

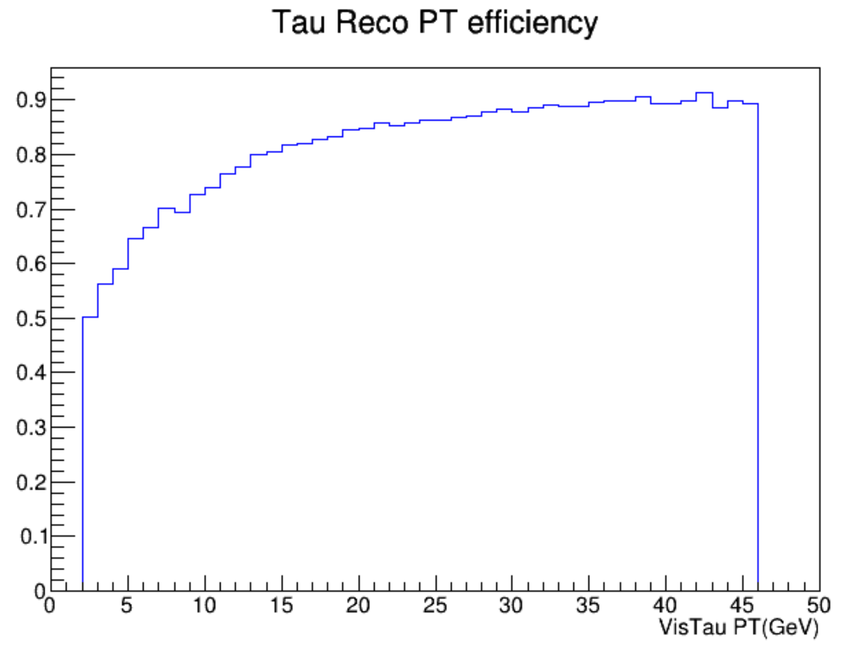
4. Repeat the process for photons and neutral hadrons from branchEFPhotons and branchEFNHadrons

5. Apply selection criteria to the tau candidates:
   - Only consider tau candidates with a maximum of 5 charged prongs.

Reconstruction Efficiency

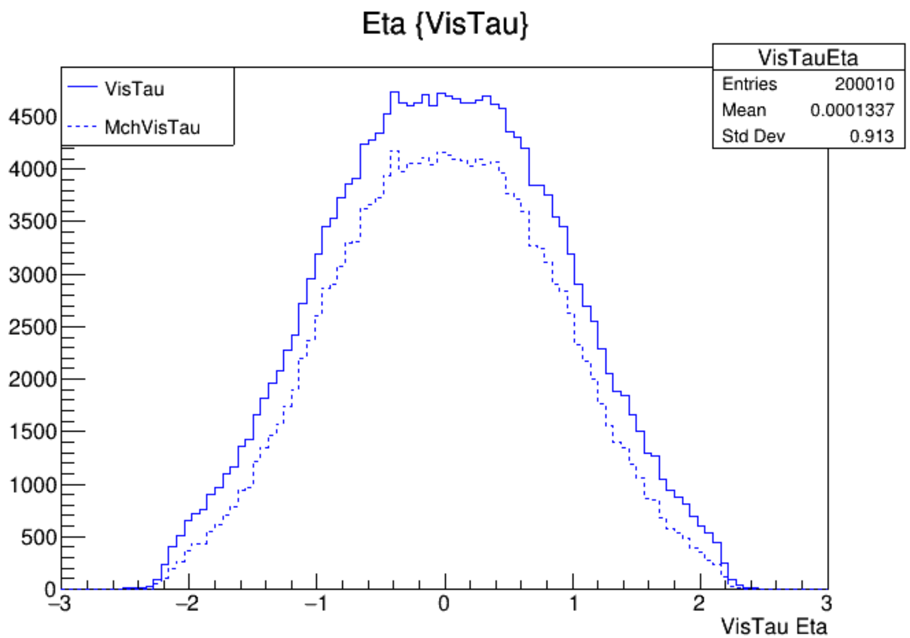
$(e^+e^- \rightarrow Z(91\ \mathrm{GeV}) \rightarrow \tau^+\tau^-)$

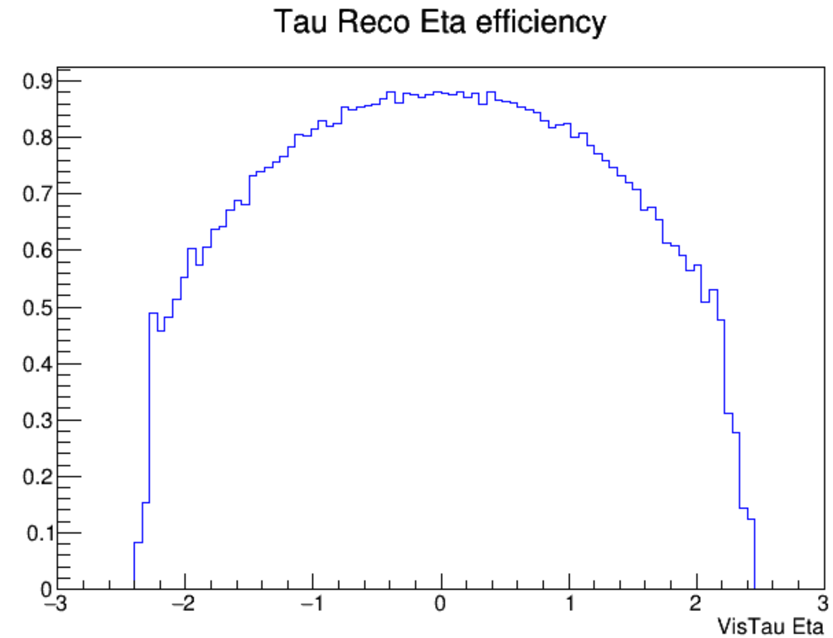




- No isolation cut is applied.
- Good efficiency in the high PT region.
- Efficiency starts dropping approaching the low PT region.

Reconstruction Efficiency
$(e^+e^- \rightarrow Z(91\ \mathrm{GeV}) \rightarrow \tau^+\tau^-)$

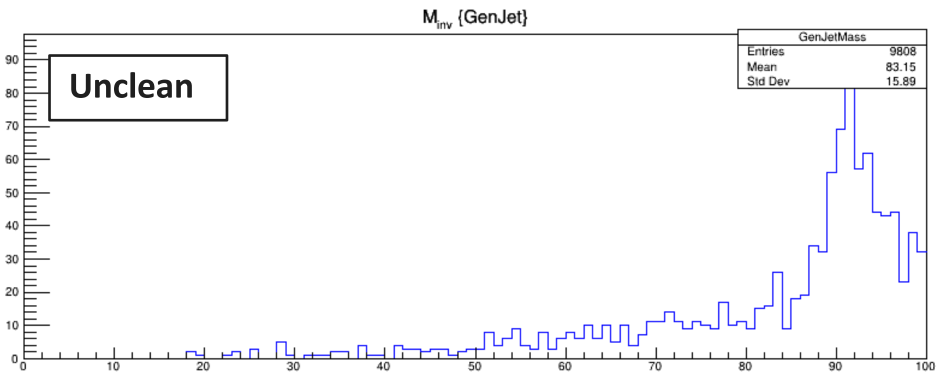


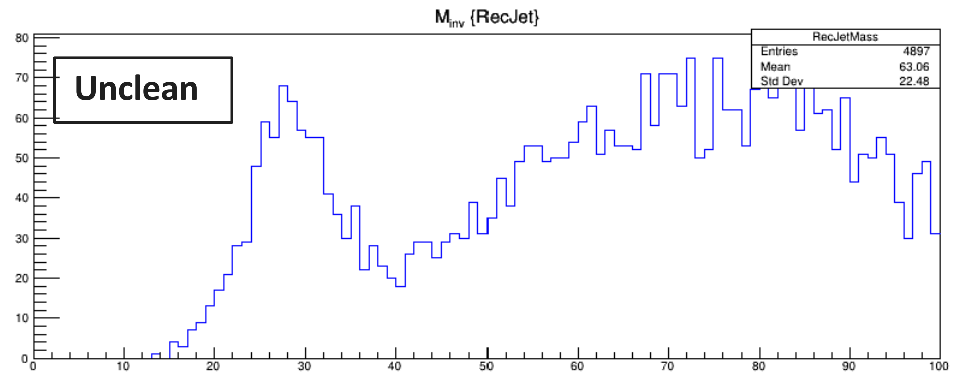


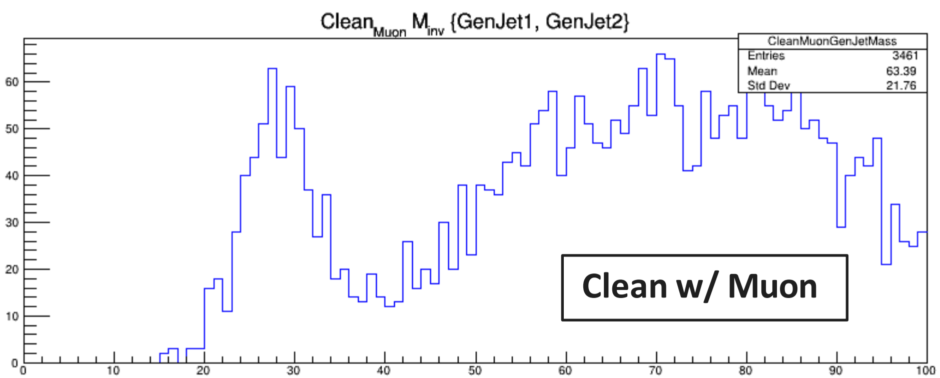
- No isolation cut is applied.
- Good efficiency in the low eta region.
- Efficiency starts dropping when eta increases.

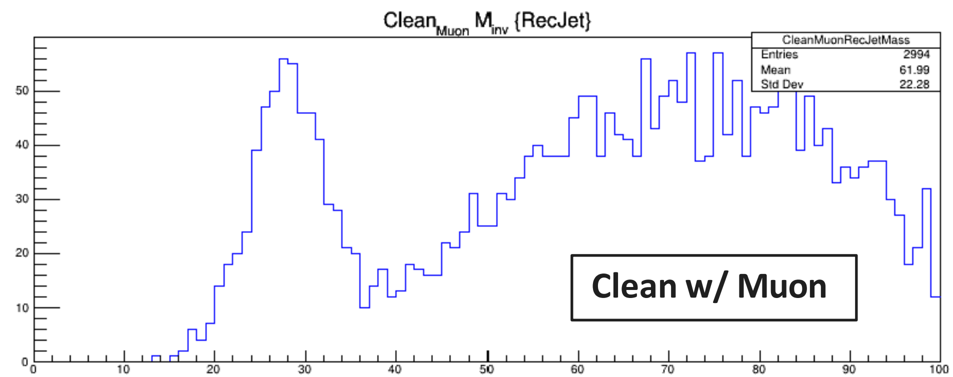
JetCleaning

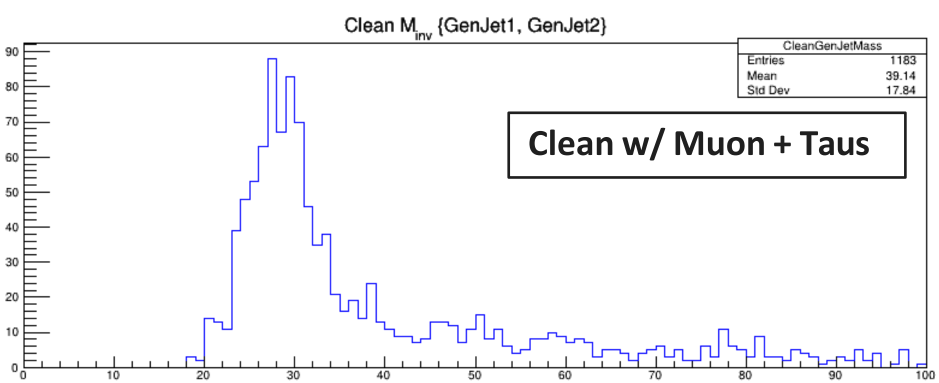
Gen Type	Entries	Rec Type	Entries
GenJet	9808	RecJet	4897
GenJet (Clean: Muon)	3461	RecJet (Clean: Muon)	2994
GenJet (Clean: Muon + Tau)	**1183**	RecJet (Clean: Muon + Tau)	**1176**

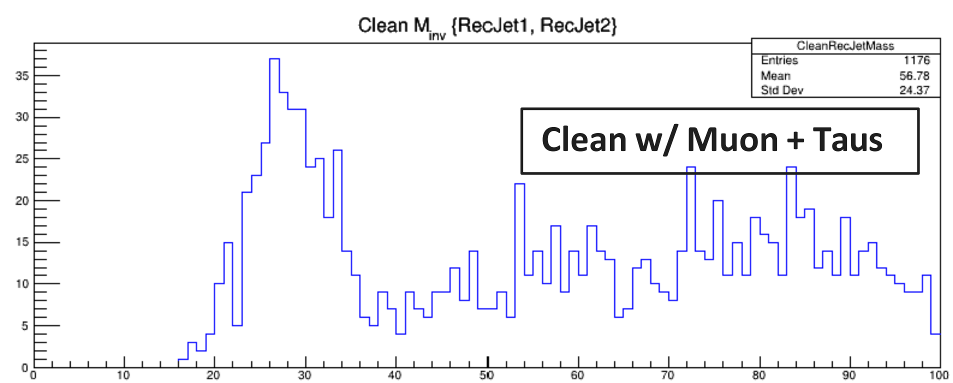












GenROE Analysis:

1. If there are particles in the branchParticles, two genTaus, and two genMuons:
   - Loop over the particles from branchParticles.
   - Select stable particles (status 1).
   - Exclude initial state electrons based on their PID values.
2. Calculate deltaR between the current stable particle and genTaus as well as muons GenROE Cleaning:
   - Update the particles as GenROE

- GenROE = $\sum_i \mathrm{StableParticle_i}$

RecROE Analysis

1. If there are entries in branchEFTracks and more than one entry in branchMuon and the size of clean_recTaus is 2:
   - The track's proximity to other particles like clean_recTaus and muons is checked using Delta R.
   - If the track is sufficiently separated from these particles (DeltaR >= 0.2), classify it as RecROE.
2. If there are entries in branchEFPhotons and a track has been selected:
   - The code loops over all photon entries and checks their proximity to clean_recTaus and muons.
   - If they are separated, they are added to the invariant mass and momentum sums and histograms are updated.
3. Same for branchNHadrons

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

Table for Comparison of Delphes Jet and Rest Of Events (ROE)

Stats \ Type	GenJet	GenROE	RecJet	RecROE
Entries	**1183**	**10000**	**1176**	**3607**
Mean	**39.14**	**30.53**	**54.76**	**30.73**
std Dev	**17.84**	**12.14**	**29.37**	**11.86**

- Delphes Jet selection efficiency: **11%** → ROE selection efficiency: **36%**
- ROE selection efficiency is more than 3 times that of Delphes Jet

Data Processing

- 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 aBoson = 0.01

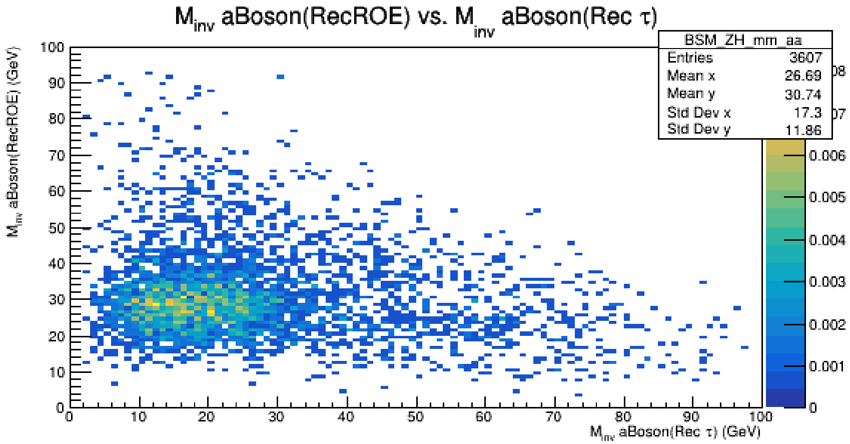
- Apply a series of kinematic cuts
  - ZBoson Mass Cuts: 80 – 100 GeV
  - aBoson (diTau) Mass Cuts: 10-30 GeV
  - aBoson (diJet) Mass Cuts: 20-40 GeV
  - Higgs Boson Mass Cuts: 120-140 GeV

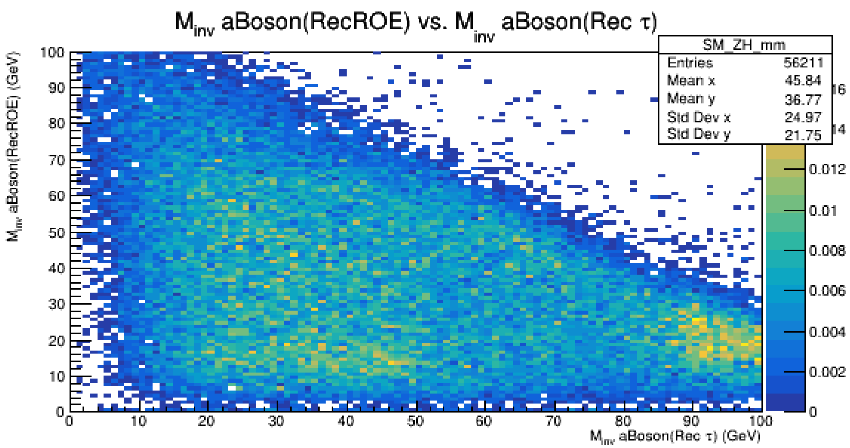
- Significance = $\frac{\text{S}}{\sqrt{\text{S+B}}}$

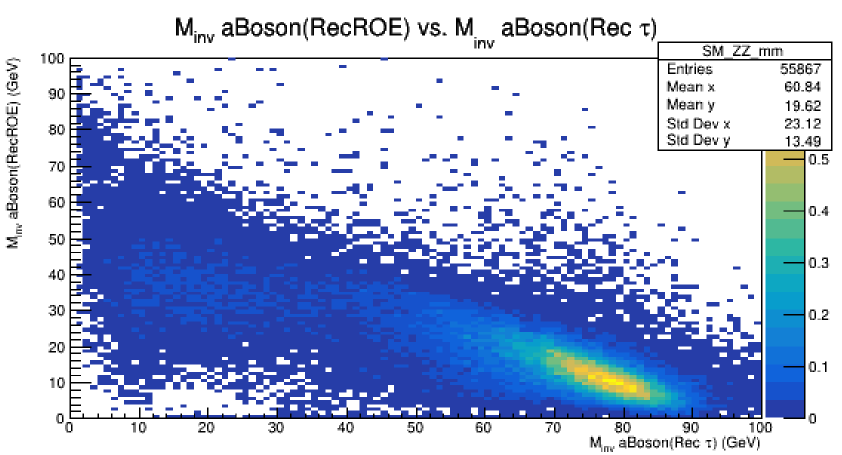
$\mu^+\mu^-\ b\bar{b}\ \tau^+\tau^-$ final state

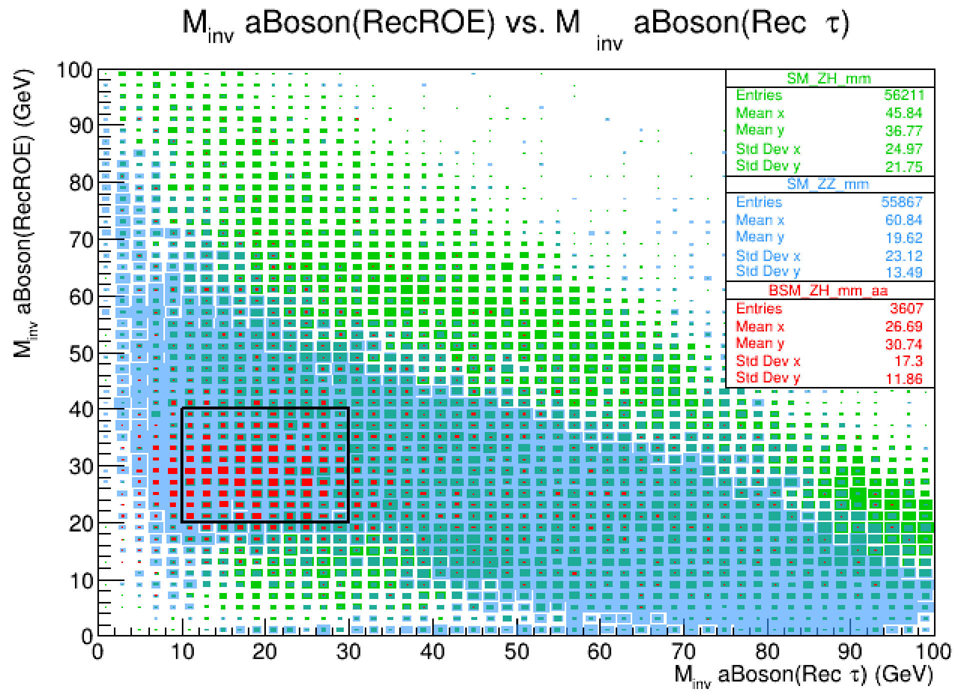
	Signal	Bkg_ZZ	Bkg_ZH
# of Events generated	10000	1000000	1000000
ZBoson [80,100] / ZBoson before [80,100] Cut %	89.45	92.34	91.05
ZBoson [80,100] / # of Events generated %	65.44	67.46	63.79
aBoson (Tau) [10,30] / aBoson (Tau) before [10,30] Cut %	62.32	14.18	23.25
aBoson (Tau) [10,30] / ZBoson [80,100] %	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	**1.766**		

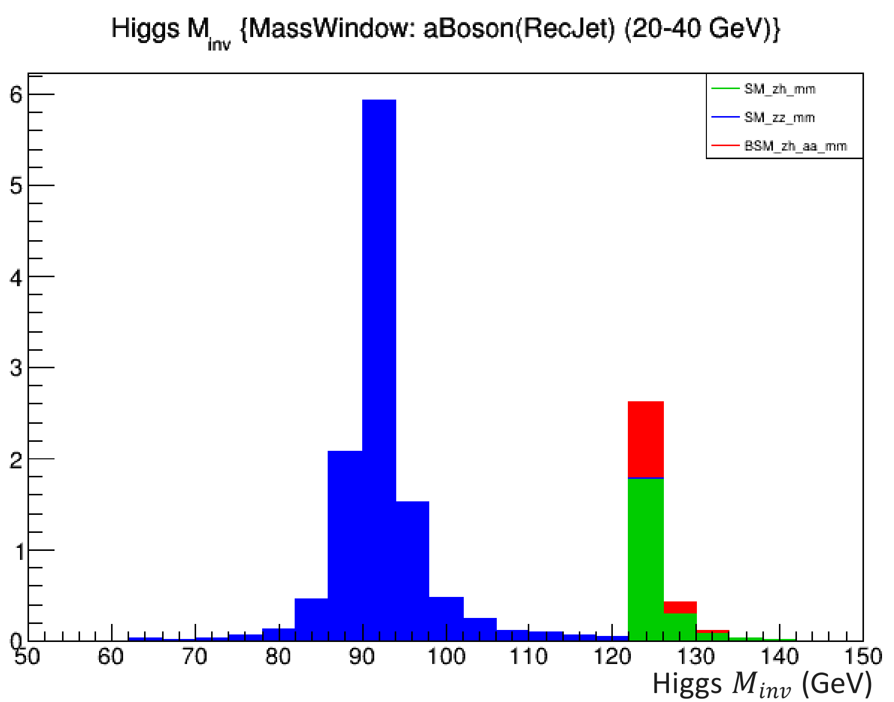
- The sequence of rapid cuts significantly decreased the background, particularly for the background noise of Bkg_ZZ.
- The Significance = 1.766


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)

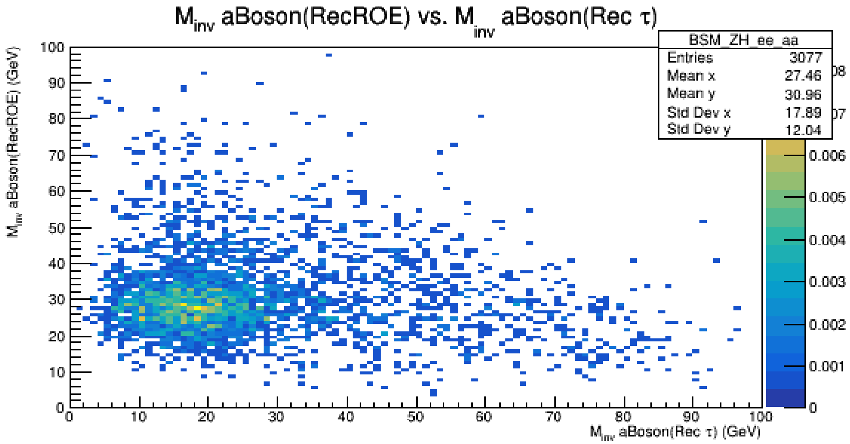

M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZH_mm
Entries 56211
Mean x 45.84
Mean y 36.77
Std Dev x 24.97
Std Dev y 21.75
SM_ZZ_mm
Entries 55867
Mean x 60.84
Mean y 19.62
Std Dev x 23.12
Std Dev y 13.49
BSM_ZH_mm_aa
Entries 3607
Mean x 26.69
Mean y 30.74
Std Dev x 17.3
Std Dev y 11.86
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)

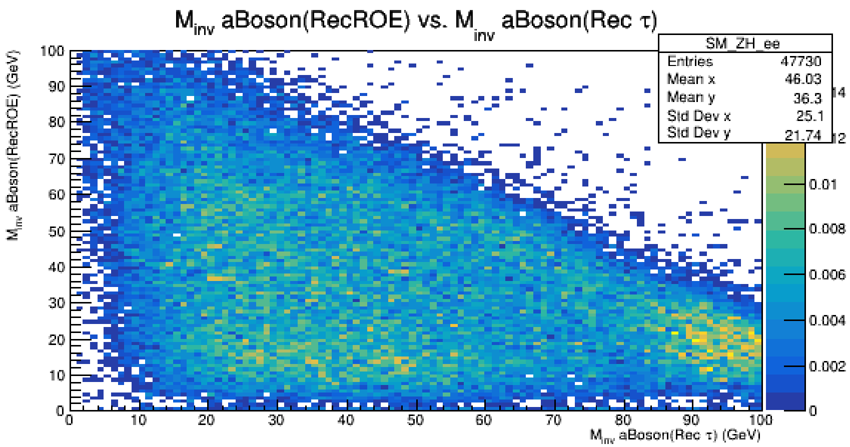

Higgs M_inv {MassWindow: aBoson(RecJet) (20-40 GeV)}
SM_zh_mm
SM_zz_mm
BSM_zh_aa_mm
Higgs M_{inv} (GeV)

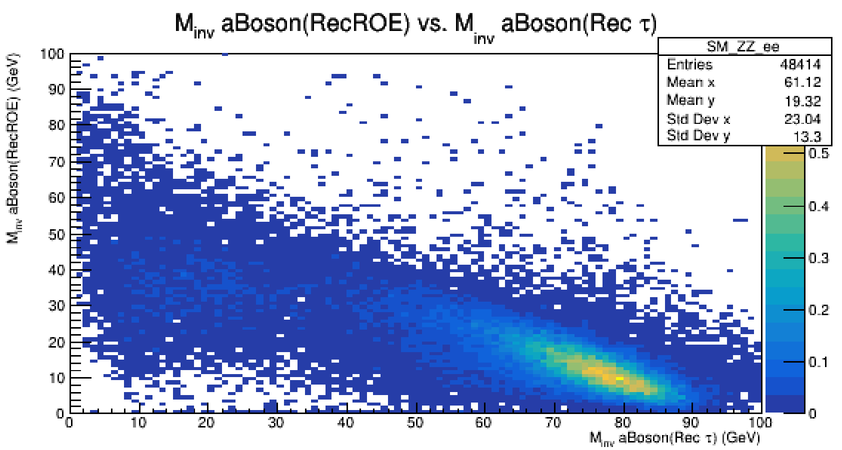
$e^+e^- \; b\bar{b} \; \tau^+\tau^-$ final state

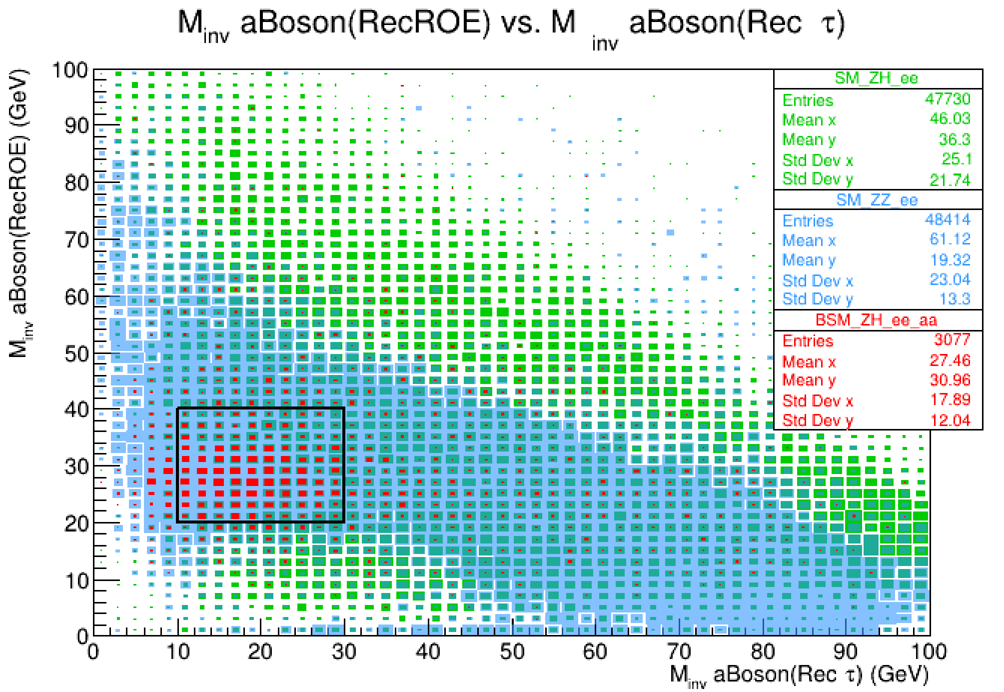
	Signal	Bkg_ZZ	Bkg_Zh
# of Events generated	10000	1000000	1000000
ZBoson [80,100] / ZBoson before [80,100] Cut %	87.16	92.32	90.58
ZBoson [80,100] / # of Events generated %	54.42	57.73	53.50
aBoson (Tau) [10,30] / aBoson (Tau) before [10,30] Cut %	61.72	14.15	23.18
aBoson (Tau) [20,40] / ZBoson [80,100] %	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	**1.599**		

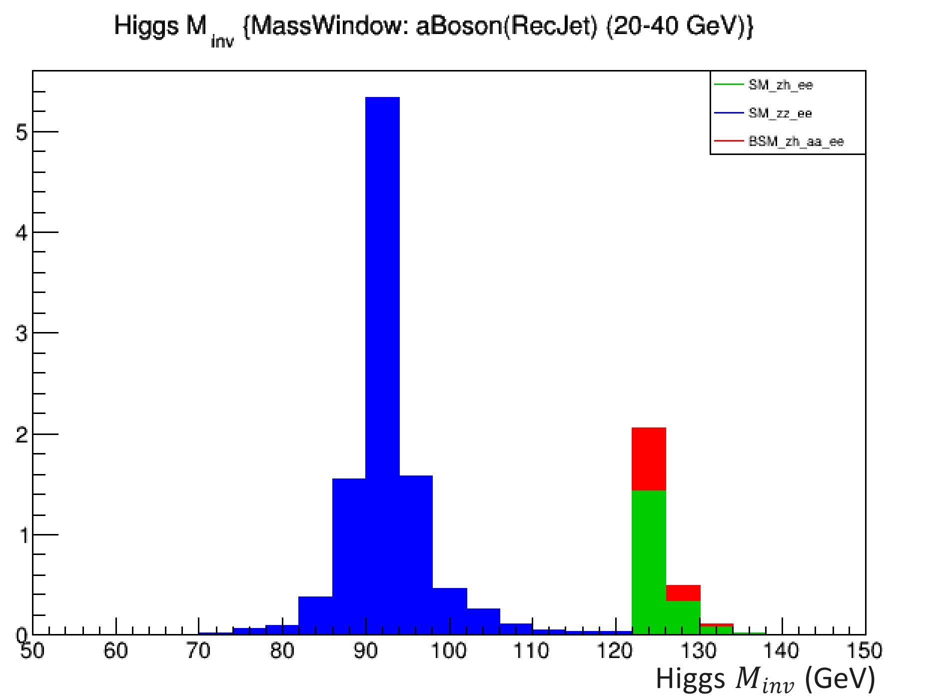
- The sequence of rapid cuts significantly decreased the background, particularly for the background noise of Bkg_ZZ.
- The Significance = 1.599

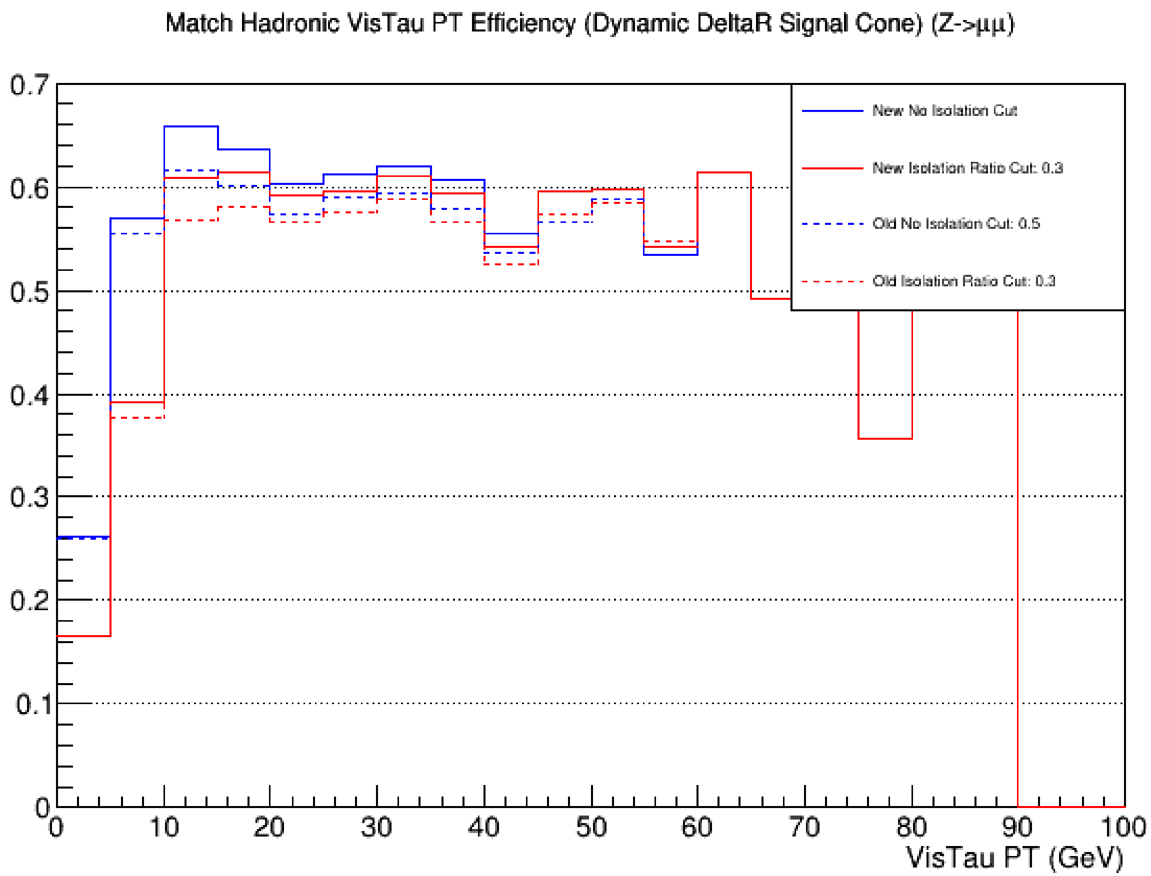

M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
BSM_ZH_ee_aa
Entries 3077
Mean x 27.46
Mean y 30.96
Std Dev x 17.89
Std Dev y 12.04
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


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)

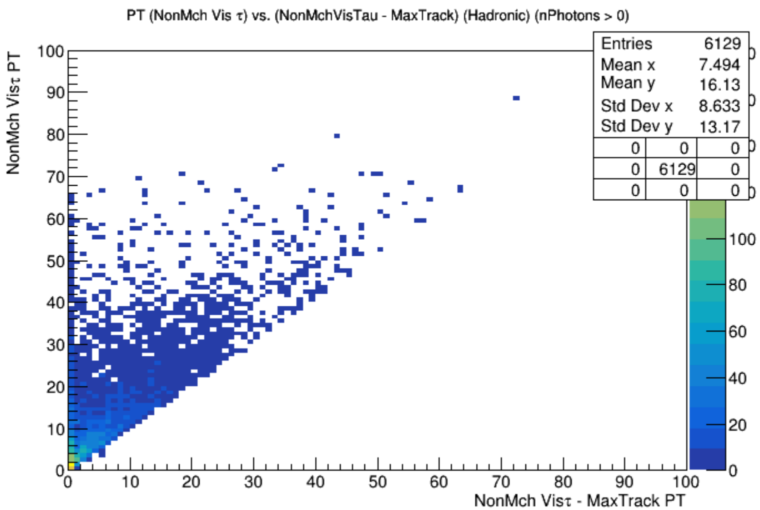

M_inv aBoson(RecROE) vs. M_inv aBoson(Rec τ)
SM_ZZ_ee
Entries 48414
Mean x 61.12
Mean y 19.32
Std Dev x 23.04
Std Dev y 13.3
M_inv aBoson(RecROE) (GeV)
M_inv aBoson(Rec τ) (GeV)


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)

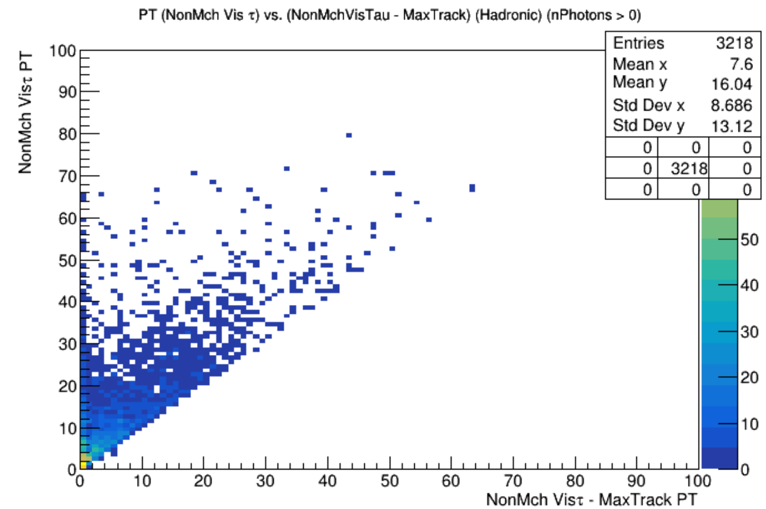

Higgs M inv {MassWindow: aBoson(RecJet) (20-40 GeV)}
SM_zh_ee
SM_zz_ee
BSM_zh_aa_ee
Higgs M_{inv} (GeV)



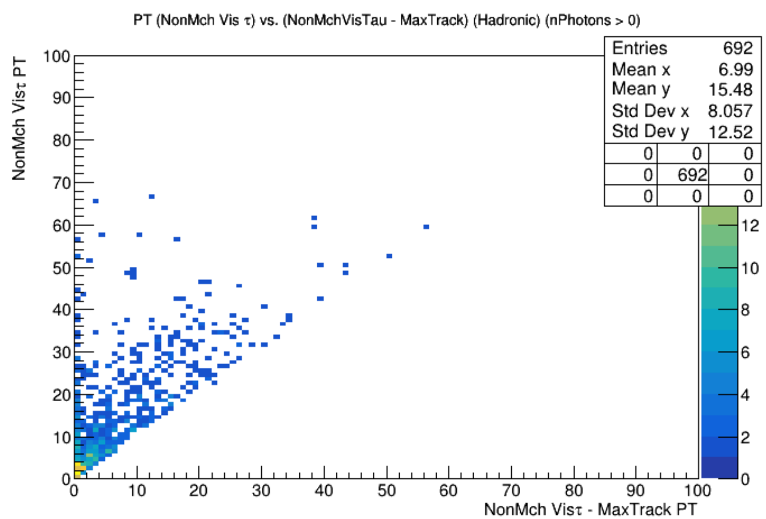
Match Hadronic VisTau PT Efficiency (Dynamic DeltaR Signal Cone) (Z->μμ)
New No Isolation Cut
New Isolation Ratio Cut: 0.3
Old No Isolation Cut: 0.5
Old Isolation Ratio Cut: 0.3
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
VisTau PT (GeV)



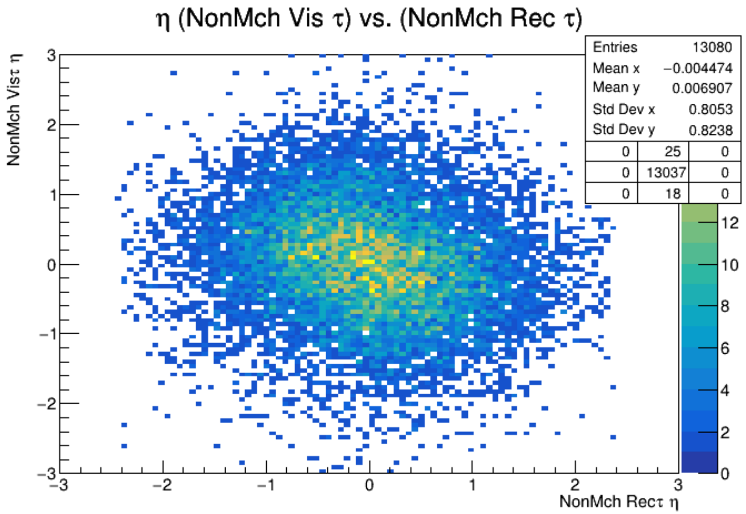
No isolation Ratio Cut



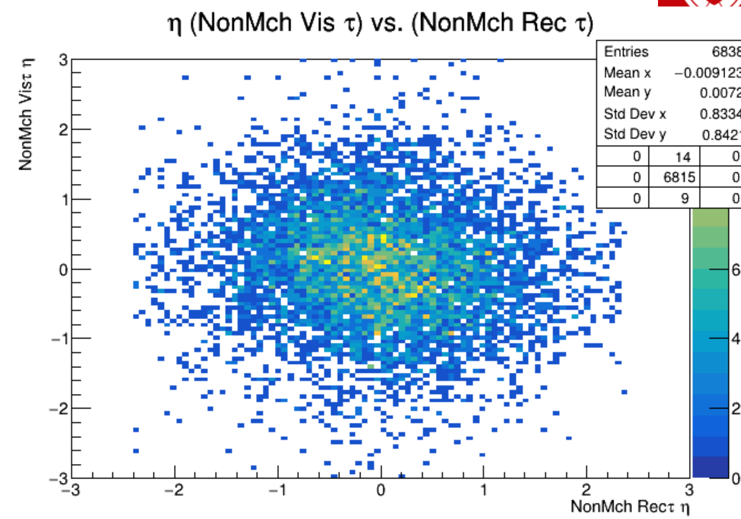
isolation Ratio Cut: 0.5



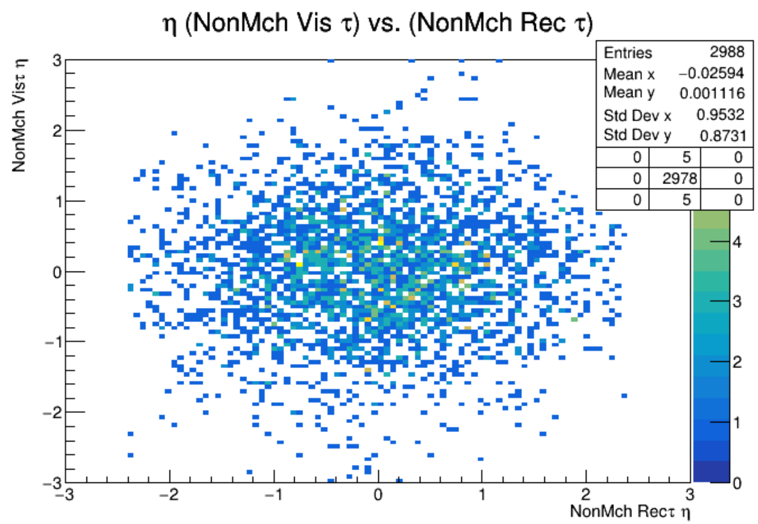
isolation Ratio Cut: 0.1



No isolation Ratio Cut

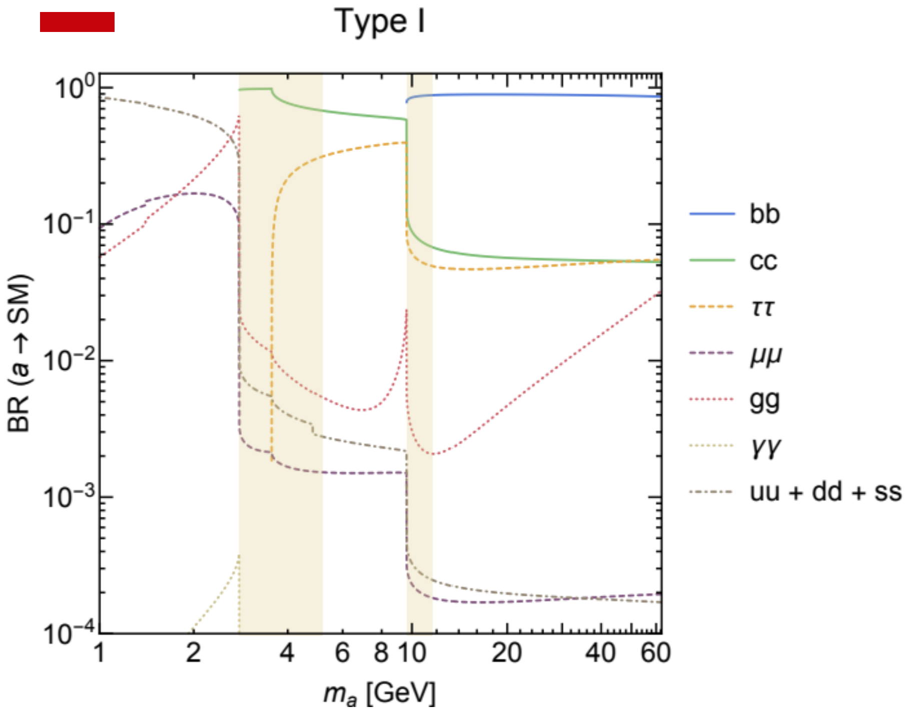


isolation Ratio Cut: 0.5



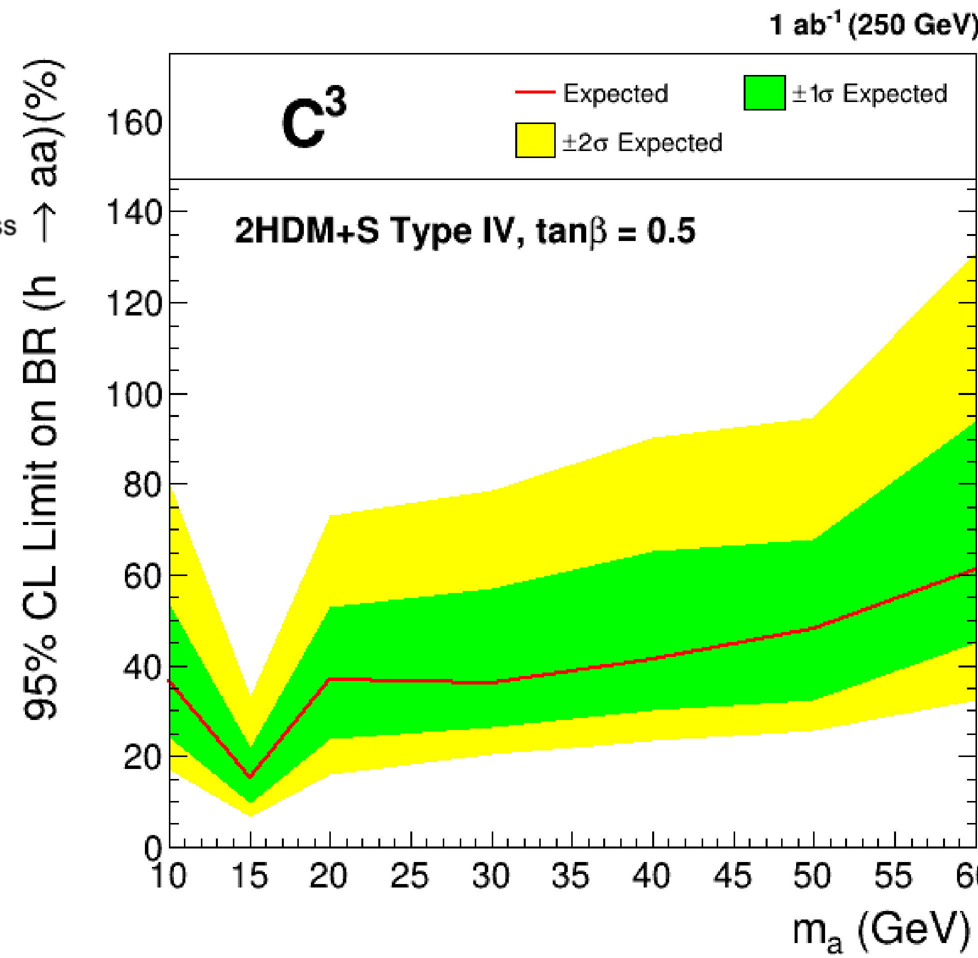
isolation Ratio Cut: 0.1

Model-Dependent Limit (2HDM+S Type IV, tanβ = 0.5)



https://www.arxiv.org/pdf/1312.4992

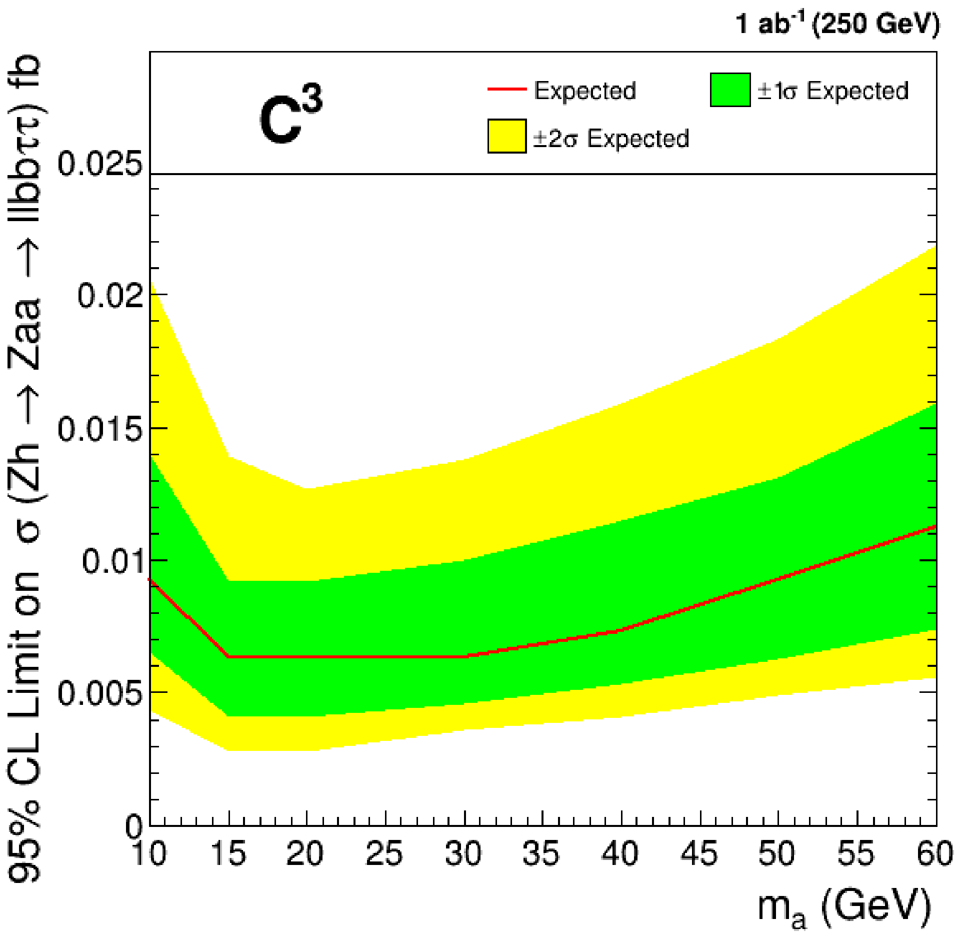
$$\mathrm{BR}(h \to aa) = \frac{\mathrm{BR}(h\to aa\to bb\tau\tau)}{\mathrm{BR}(a\to bb)\times \mathrm{BR}(a\to\tau\tau)}$$



a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
10	0.18	0.32
15	0.34	0.28
20	0.23	0.17
30	0.22	0.18
40	0.21	0.19
50	0.208	0.2
60	0.19	0.21

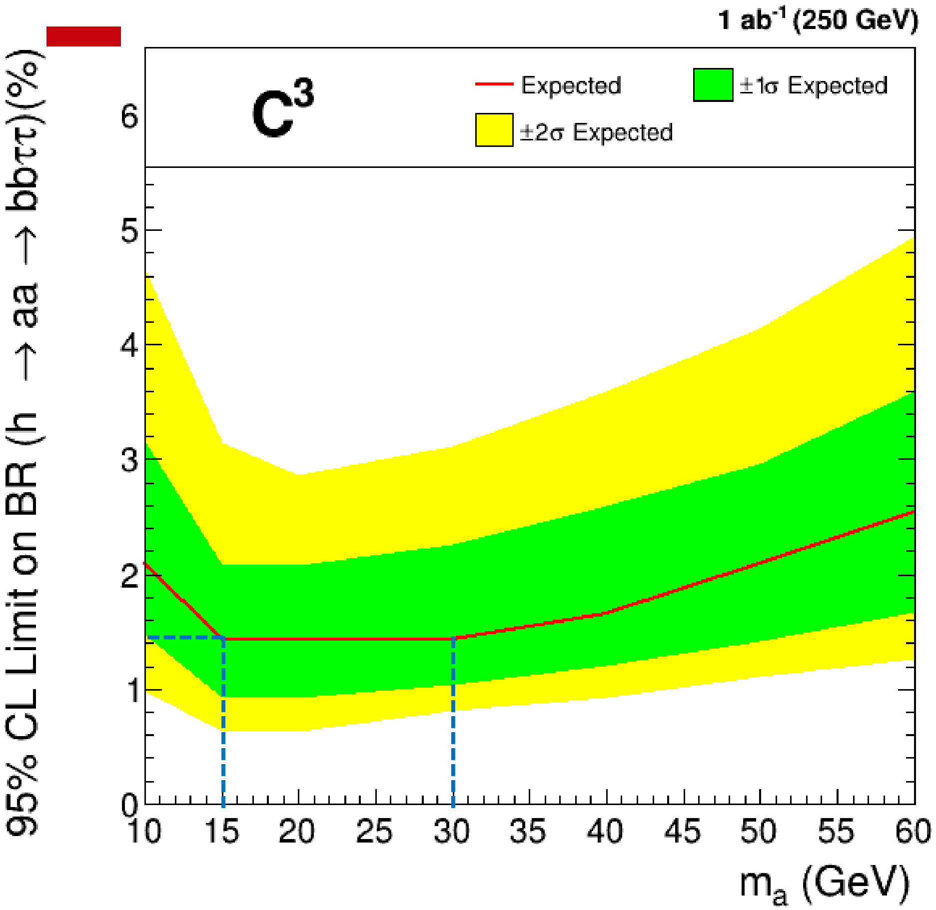
Model-Independent Limit

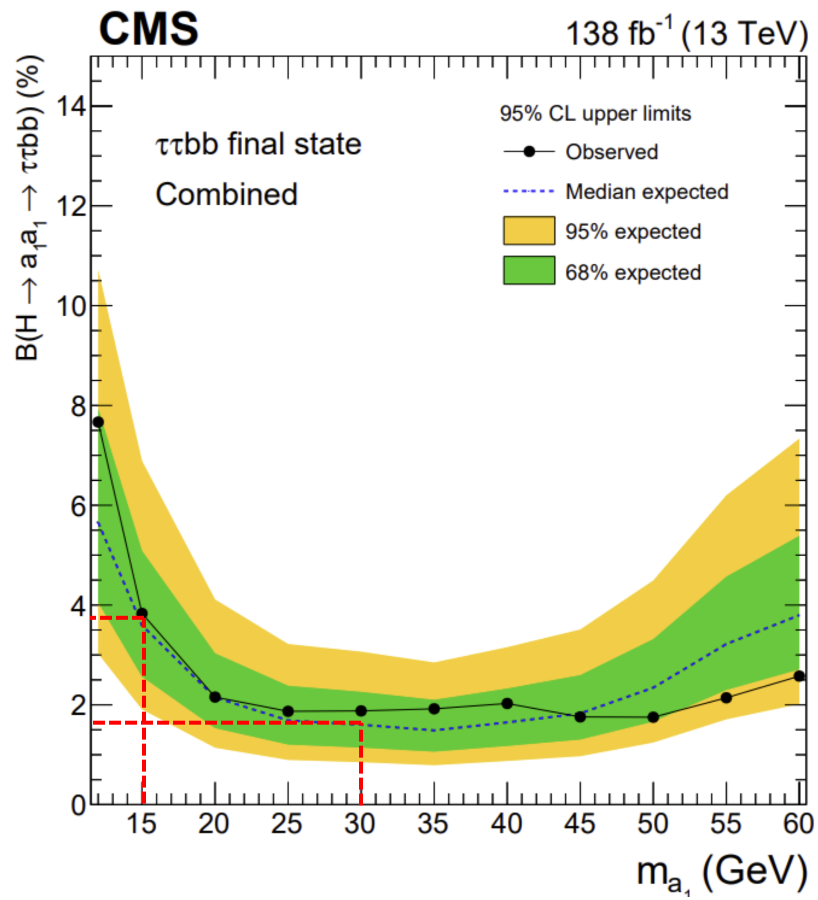
- Utilize a maximum likelihood fit method to compute the limit.
- Assumed integrated luminosity of $1\ ab^{-1}$.
- Minimal sets of systematic uncertainties:
  - 5% on signal and background cross sections.
  - Muons: 2%, Electrons: 2%, and Taus: 10%
- Additionally, bin-by-bin uncertainty was included to account for statistical uncertainties in each bin.
- Assume the aBoson has Standard Model-like properties.



Model-Independent Limit

https://arxiv.org/abs/2402.13358

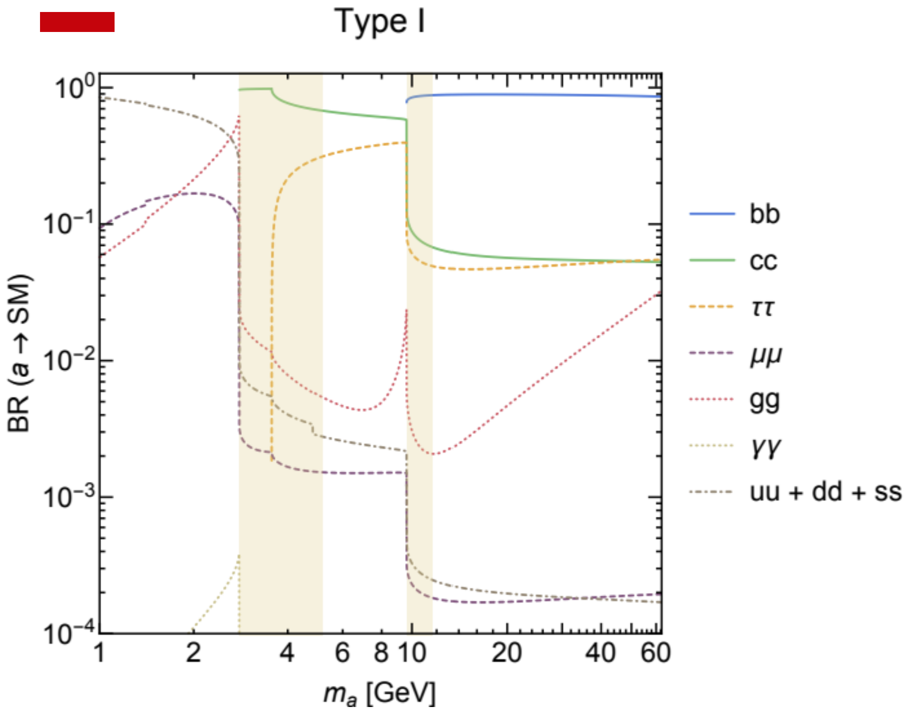




- The limit on the BR$(h \rightarrow aa \rightarrow bb\tau\tau)$ is obtained from $\sigma(Zh \rightarrow Zaa \rightarrow llbb\tau\tau)$ dividing σ_{SM}(6.6 fb) and BR$(Z \rightarrow ll)$(0.067)
- The limit is much more sensitive in the lower mass region than the CMS RUn2 result.

a Boson Mass	C^3	CMS
15 GeV	1.5%	3.7%
30 GeV	1.4%	1.6%

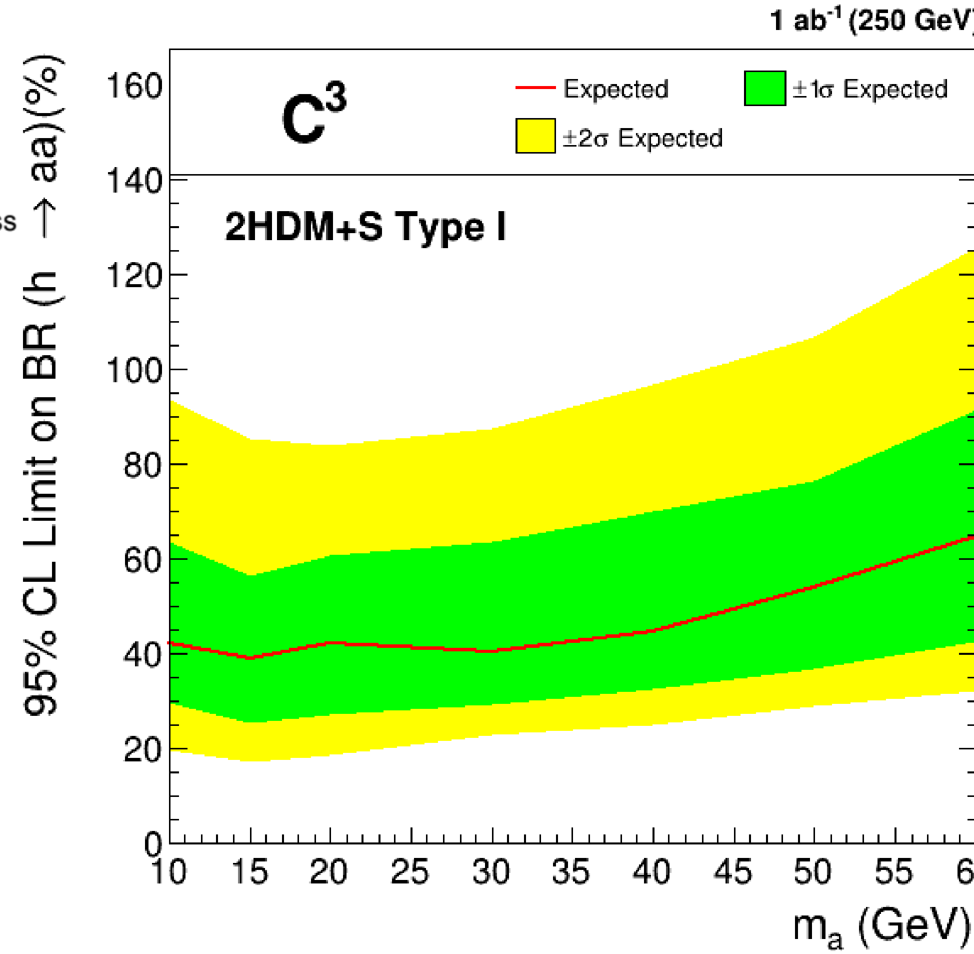
Model-Dependent Limit (2HDM+S Type I)



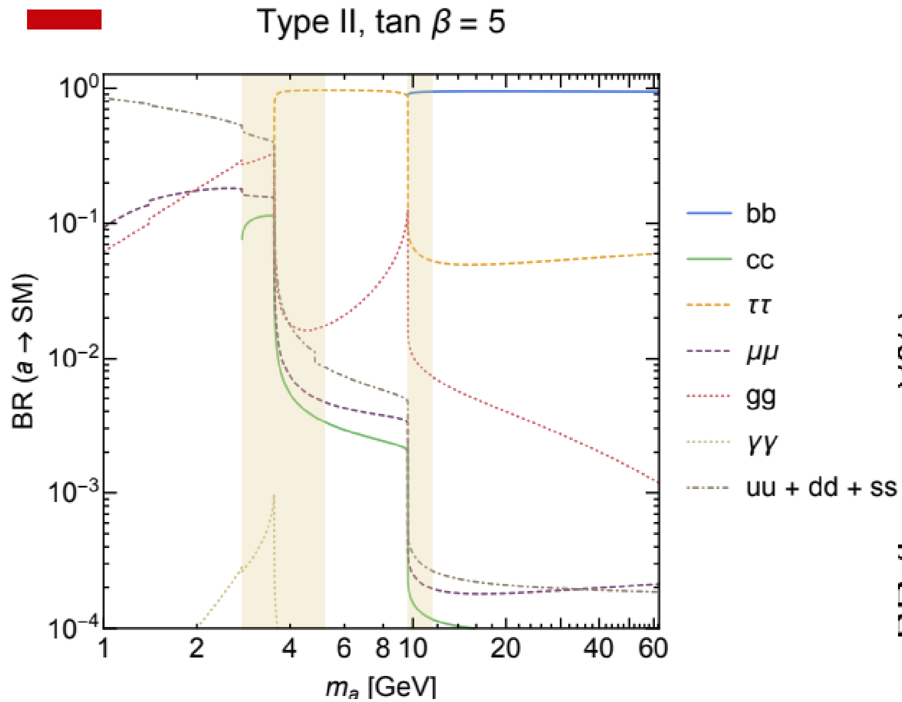
https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
10	0.92	0.063
15	0.93	0.05
20	0.93	0.0485
30	0.93	0.0488
40	0.93	0.049
50	0.93	0.0495
60	0.93	0.05

$$\mathrm{BR}(h \to aa) = \frac{\mathrm{BR}(h \to aa \to bb\tau\tau)}{\mathrm{BR}(a \to bb) \times \mathrm{BR}(a \to \tau\tau)}$$



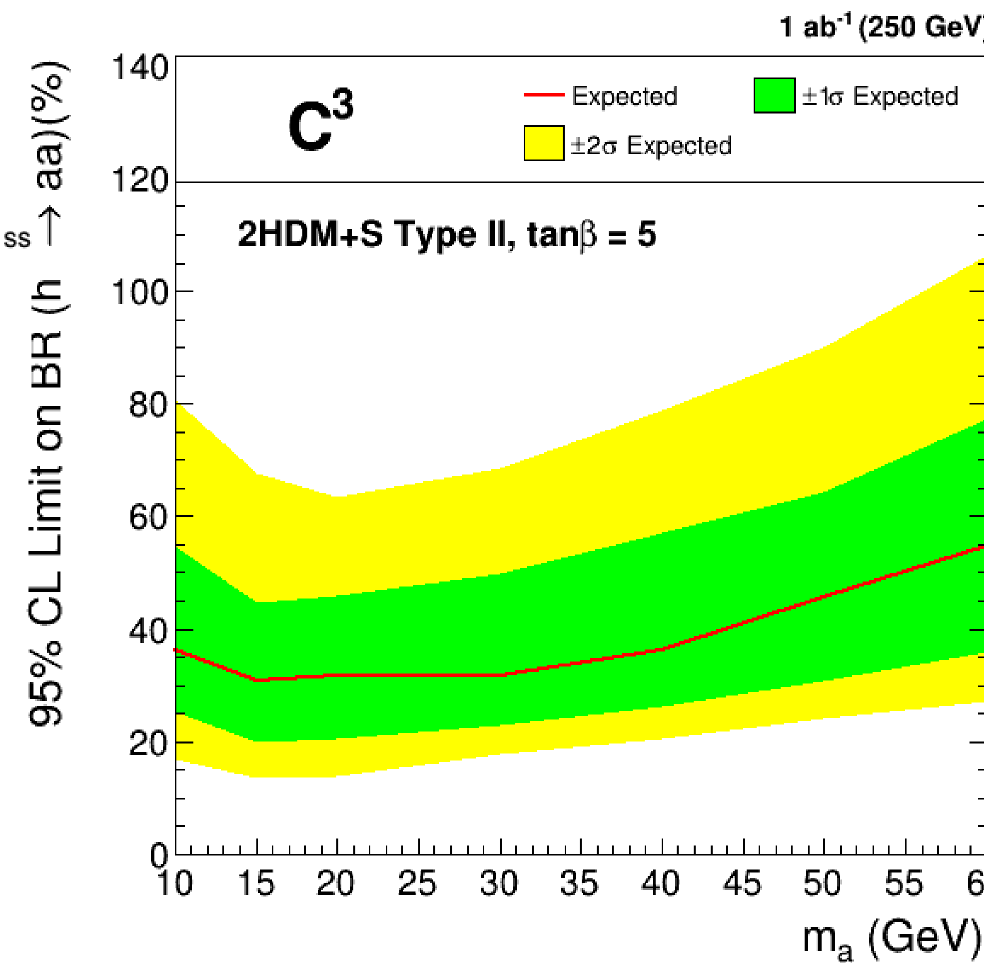
Model-Dependent Limit (2HDM+S Type II, tanβ = 5)



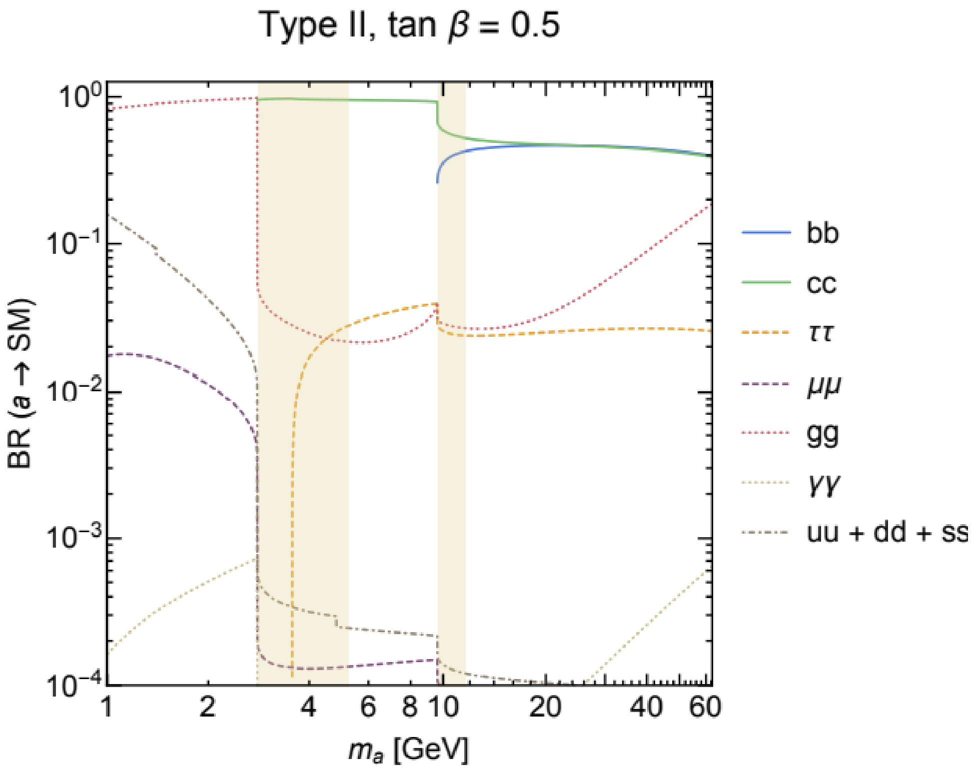
https://www.arxiv.org/pdf/1312.4992

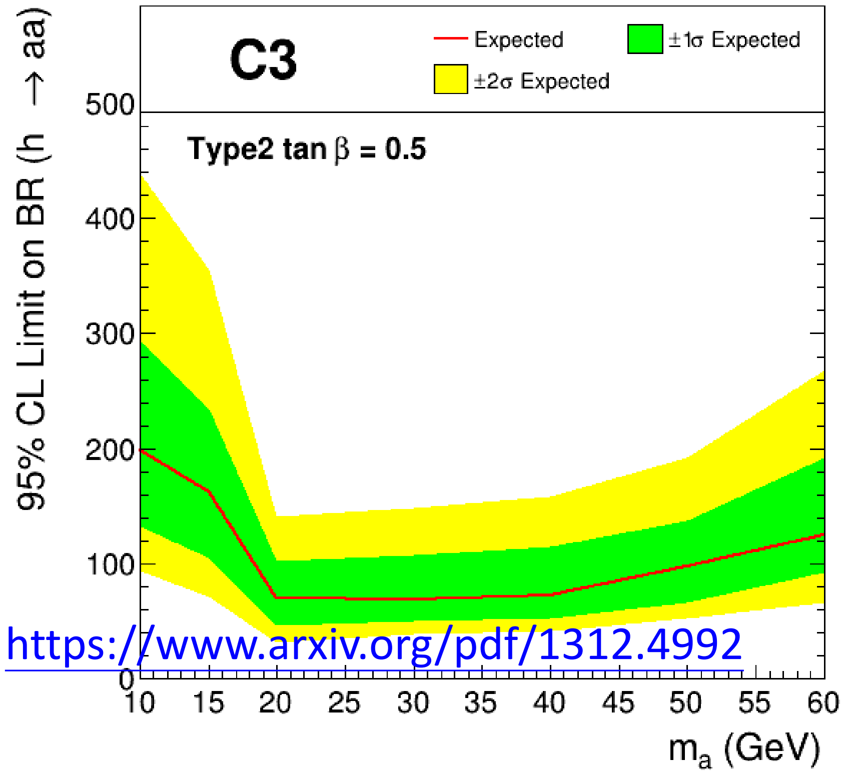
$$\text{BR}(h \to aa) = \frac{\text{BR}(h\to aa\to bb\tau\tau)}{\text{BR}(a\to bb)\times\text{BR}(a\to\tau\tau)}$$

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
10	0.78	0.064
15	0.82	0.045
20	0.9	0.038
30	0.89	0.04
40	0.885	0.042
50	0.88	0.044
60	0.875	0.045



Branching Ratio Limit (Type 2, tanβ = 0.5)



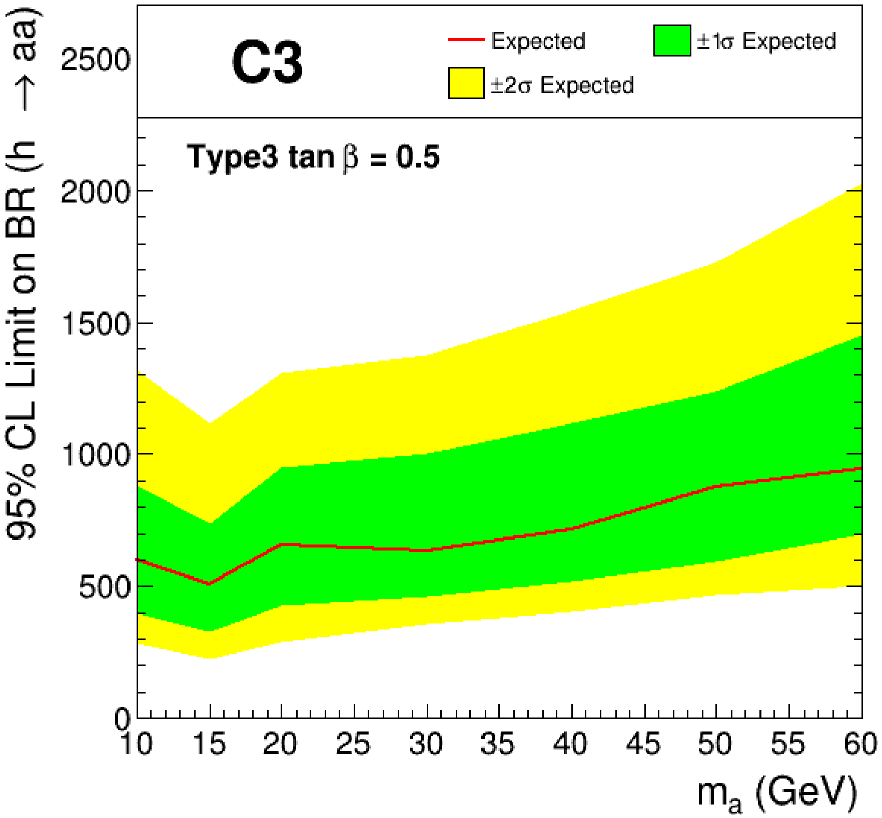


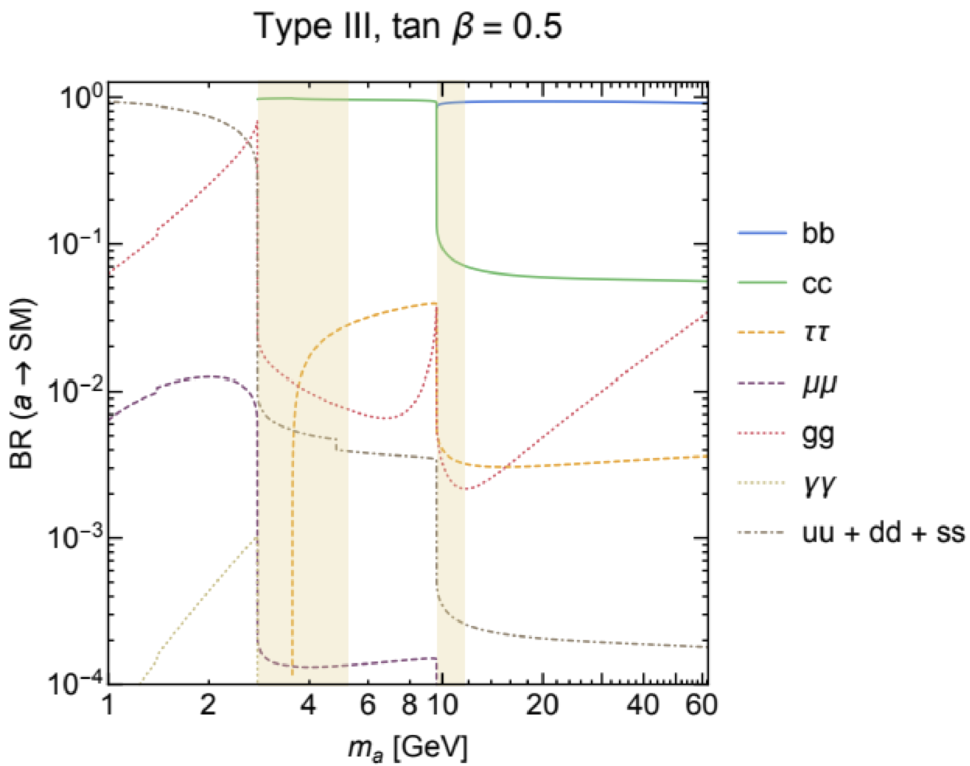
https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
20	0.34	0.06
30	0.338	0.062
40	0.335	0.068
50	0.332	0.065
60	0.3	0.062

Branching ratio for $a \to b\bar{b}$ and $a \to \tau^+\tau^-$

Branching Ratio Limit (Type 3, tanβ = 0.5)



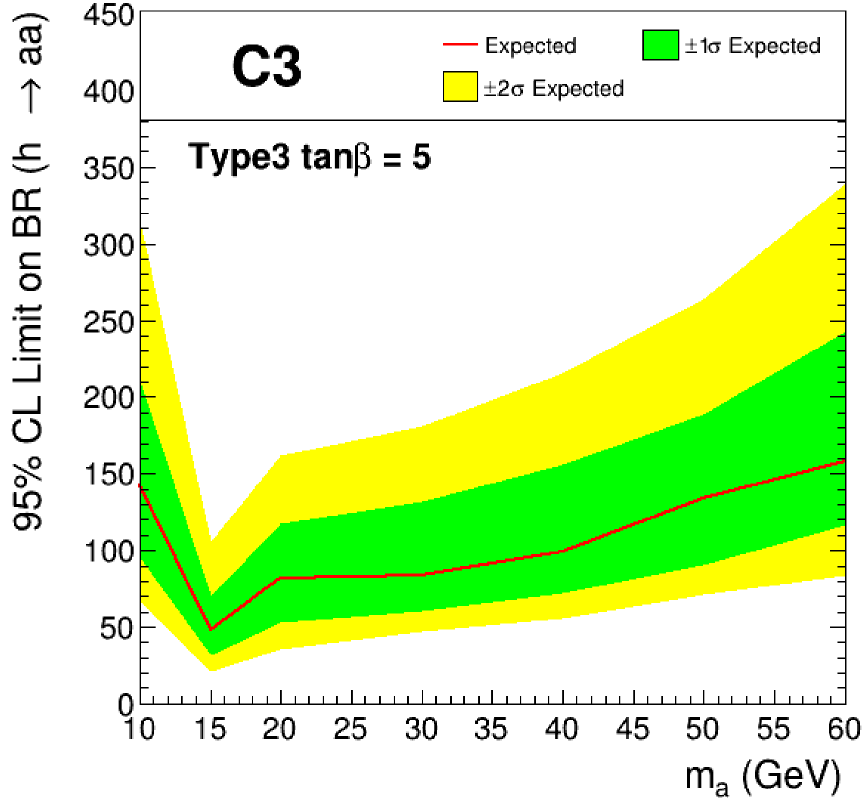


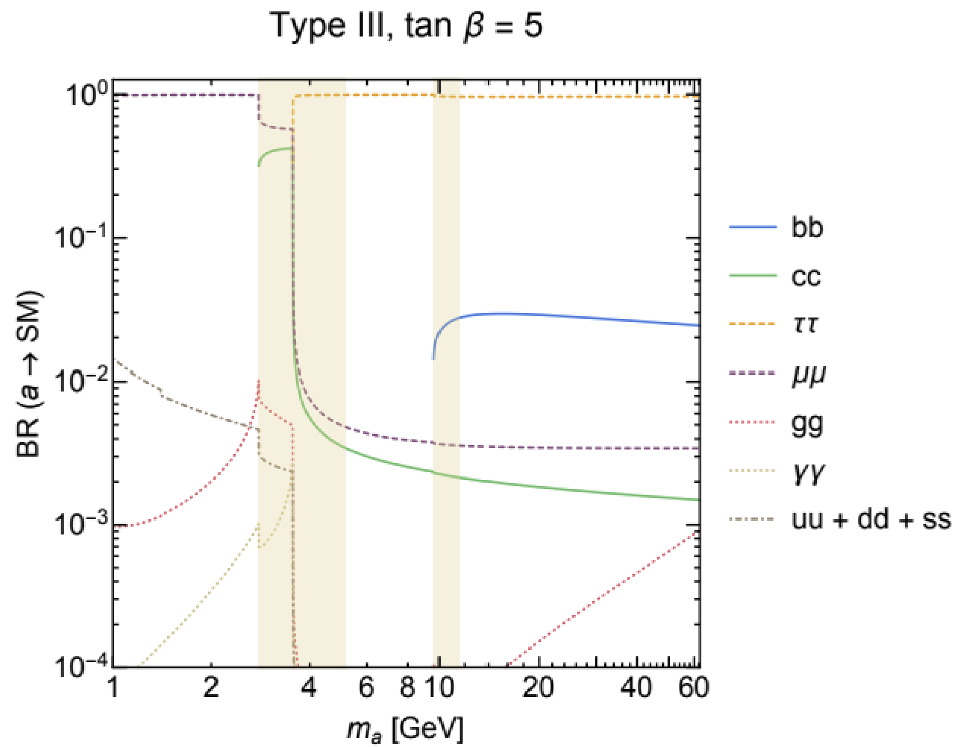
https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
20	0.95	0.0023
30	0.94	0.0024
40	0.93	0.0025
50	0.92	0.0026
60	0.91	0.0027

Branching ratio for $a \rightarrow b\bar{b}$ and $a \rightarrow \tau^+\tau^-$

Branching Ratio Limit (Type 3, tanβ = 5)



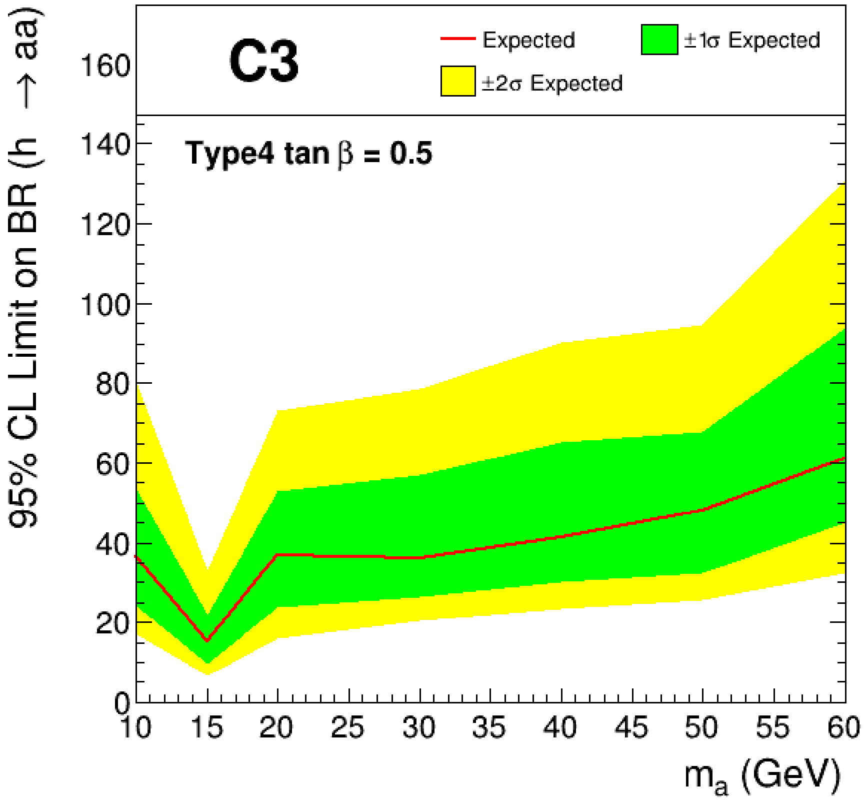


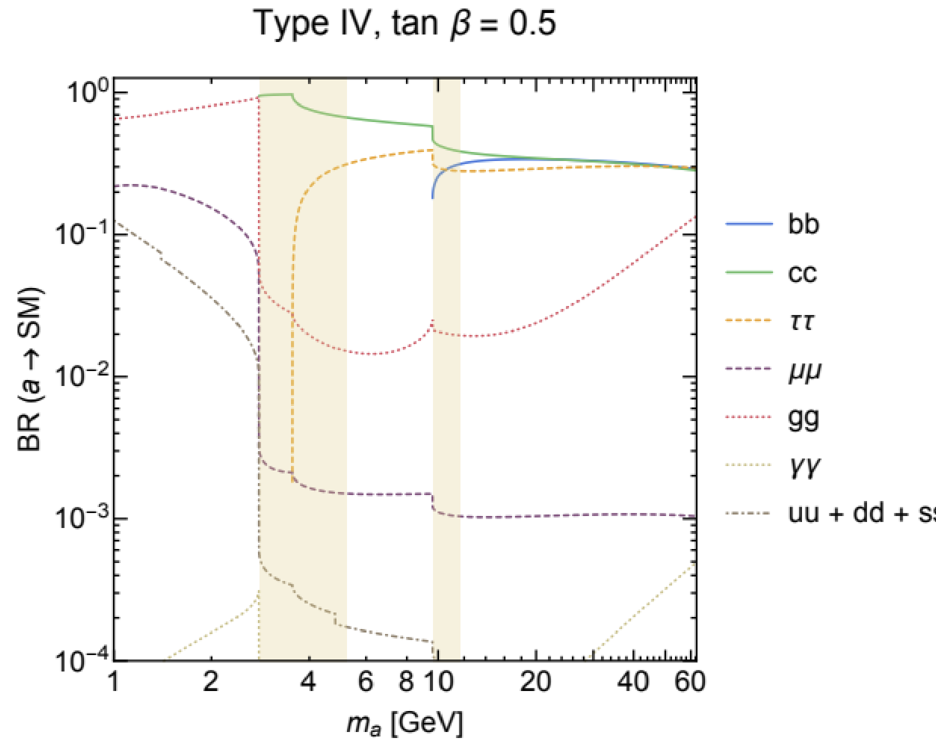
https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
20	0.018	0.098
30	0.0175	0.098
40	0.017	0.098
50	0.016	0.098
60	0.015	0.098

Branching ratio for $a \to b\bar{b}$ and $a \to \tau^+\tau^-$

Branching Ratio Limit (Type 4, tanβ = 0.5)





https://www.arxiv.org/pdf/1312.4992

a Boson Mass (GeV)	$b\bar{b}$	$\tau^+\tau^-$
20	0.23	0.17
30	0.22	0.18
40	0.21	0.19
50	0.208	0.2
60	0.19	0.21

Branching ratio for $a \rightarrow b\bar{b}$ and $a \rightarrow \tau^+\tau^-$