Πανεπιστήμιο Κύπρου
Τμήμα Φυσικής

Search for an exotic decay of the Higgs boson in proton-proton collisions at CMS experiment

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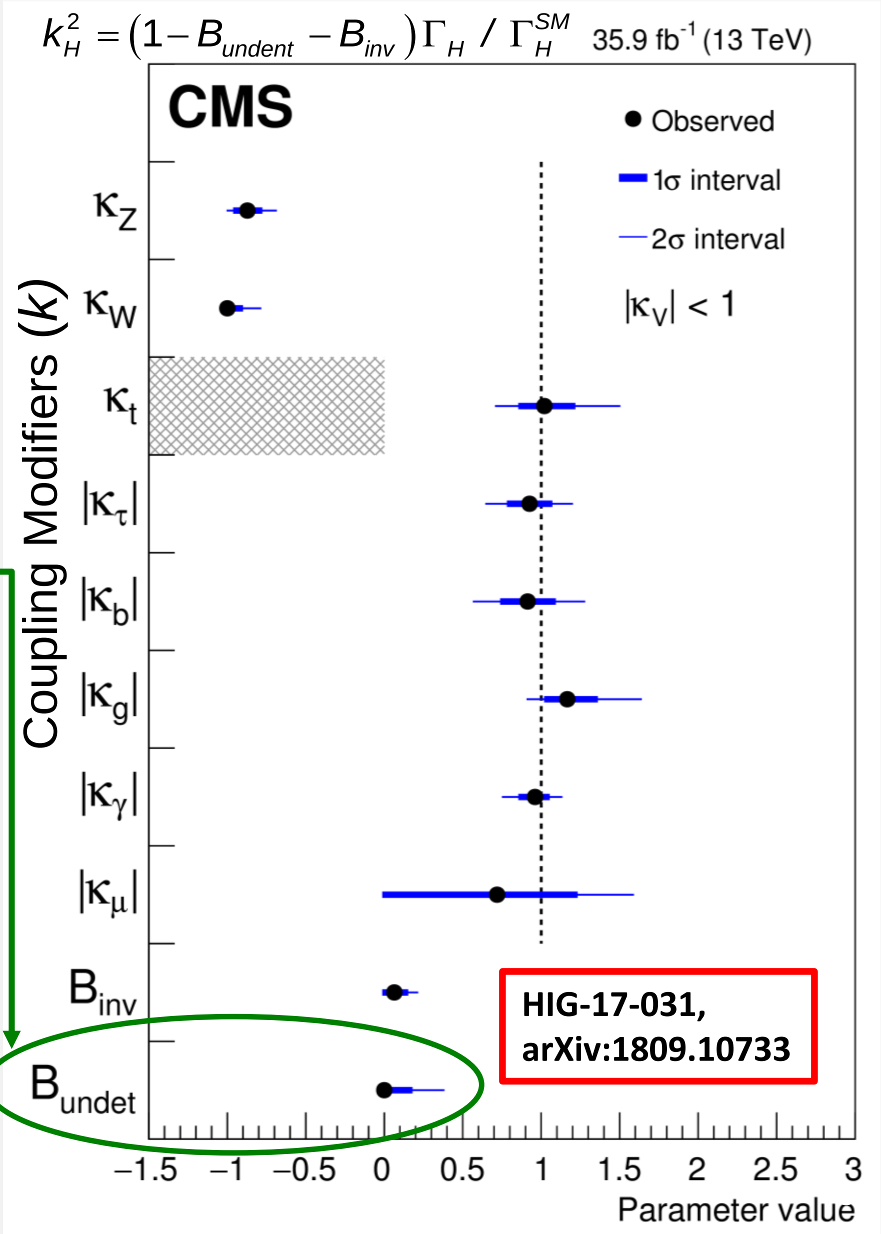
Motivation from experiment & theory

Open window for Higgs BSM Decays

- ❑ The LHC data at 13 TeV place an upper limit of
  - *BR(h → BSM) < 40%,* at 95% confidence level (CL)
- ❑ Combine Run-1 results of the CMS and Atlas:
  - *BR(h → BSM) < 34%,* at 95% CL
- ❑ future LHC projections allows BR of the 125GeV higgs boson into BSM:
  - *BR(h → BSM) < O(5% – 10%)*
- ❑ The SM Higgs boson has:
  - a very narrow width ($\Gamma_h \simeq 4.07 MeV$)
  - small coupling to another light state

  can lead to broad class of theories beyond the SM.
- ❑ Exotic Higgs decays in models with extended Higgs sector
  - ❑ (2HDM and 2HDM+S) propose a light (pseudo)scalar, *h(125)→ aa → ff*



Two Higgs Doublet Models + Singlet (2HDM + S)

- Contains 2 higgs doublets H_1 and H_2 and one additional singlet S
- After EWKSB , the 2HDM+S predicts 7 physical states:
  - 3 CP-even Higges h_1, h_2, H with $m_h < m_H$, can be SM-like (m_h = 125GeV)
  - 2 CP-odd pseuoscalar α, A
  - 2 Charged scalars $H^{\pm}$
- Four types of 2HDM+S forbid flavor changing neutral currents (FCNC) at tree level.

	Type I	Type II	Type III	Type IV
Charged leptons	H_1	H_2	H_2	H_1
Up-type quarks	H_1	H_1	H_1	H_1
Down-type quarks	H_1	H_2	H_1	H_2

- **Type 1**: the branching ratios are independent of tan*β*.
- **Type 2, Type 3 and Type 4:** BR depend on tan*β*.
  - ✓ $\tan\beta = \upsilon_2/\upsilon_1$, υ_ι vacuum expectation values (vev) of the neutral component.
- The NMSSM is a particular case of Type II that brings a solution to the μ problem.

Channels investigated

$$h(125) \rightarrow \alpha\alpha \rightarrow b\bar{b}\tau^{+}\tau^{-} \begin{cases} b\bar{b} + e\tau_h,\ b\bar{b} + \mu\tau_h,\ b\bar{b} + e\mu \\ b\bar{b} + \tau_h\tau_h,\ b\bar{b} + \mu\mu,\ b\bar{b} + ee \end{cases}$$

are discarded due to small branching fraction

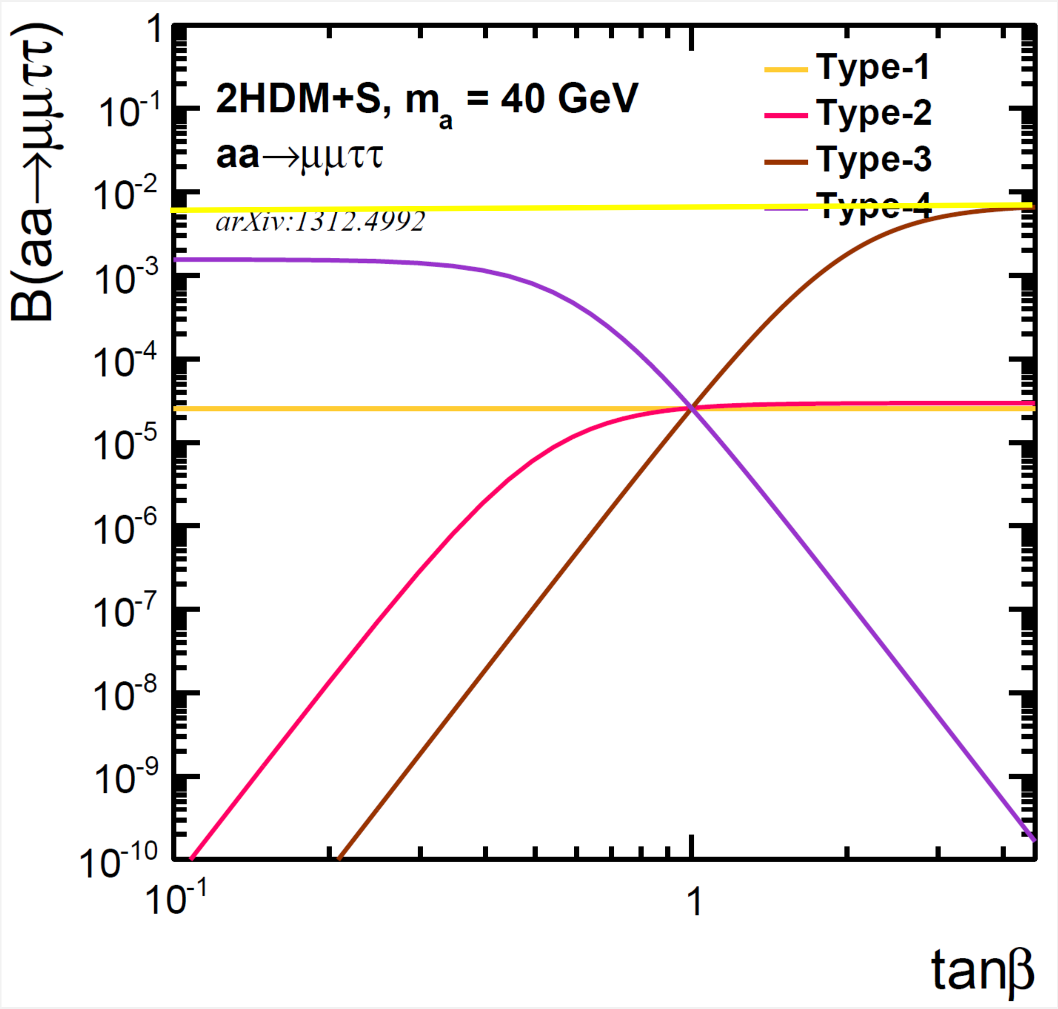
low signal acceptance due to trigger threshold (at least p_T >40 GeV offline for each τ_h)

$$h(125) \rightarrow \alpha\alpha \rightarrow \mu^{+}\mu^{-}\tau^{+}\tau^{-} \begin{cases} \mu\mu + e\mu \\ \mu\mu + e\tau_h \\ \mu\mu + \mu\tau_h \\ \mu\mu + \tau_h\tau_h \\ \mu\mu + ee \\ \mu\mu + \mu\mu \end{cases}$$

Are not considered, small BR and large irreducible background

Decay Mode	Branching Ratio (%)	
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	17.41	
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$	17.83	
$\tau^- \rightarrow \boldsymbol{l^- \bar{\nu}_e \nu_\tau}$		**35.24**
1-prong: $\tau^- \rightarrow \pi^- \nu_\tau$	11.53	**47.01**
1-prong: $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	25.95	
1-prong: $\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	9.53	
3-prong: $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	4.80	**14.6**
3-prong: $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	9.80	
Other modes with hadrons		**3.15**
All hadronic modes		**64.76**

The benchmark points $\left(h \to \alpha\alpha \to \mu^+\mu^-\tau^+\tau^-\right)$



- **Mechanism**

  gluon gluon Fusion (ggF), σ_{ggF} = 48.58pb

  vector boson fusion (VBF), σ_{qqh} = 3.93pb

- **Benchmark for the expected yield**

  BR(h → *aa*) = 10%

  BR(αα→μμττ) = 0.6%, for tanβ > 1 and m_α=40 GeV

  BR(ττ→ $\tau_h \tau_h$)=41.94%

  σ_{ggF} × BR = 12.22 fb

  σ_{qqh} × BR = 0.99 fb

- *a* → μμ: a clear peak
- Small background
- ($2m_\tau < m_\alpha < m_{h/2}$)

  Below 15 GeV, the pseudoscalar bosons are Lorentz-boosted, causing their decay products to be collimated and to fail the isolation selection criteria.

$h \rightarrow \alpha\alpha \rightarrow \mu\mu\tau^{+}\tau^{-}$

❑ Data

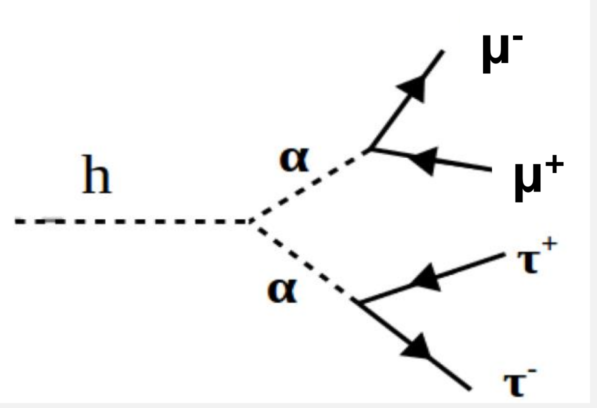
- The analysis is based on 2016 data with a corresponding integrated luminosity of 35.9 fb^{-1} at $\sqrt{s}$=13 TeV.

❑ Background

- **The Irreducible Background:** is estimated from MC
  - ✓ ttZ, WZZ, ZZZ , ZZ→4l
- **The Reducible Background:** Events where at least one jet is misidentified as a lepton
  - ✓ Z+jets, WZ+jets, ZZ→2l2q, tt and QCD multijet

❑ Signal Samples

- The MadGraph5 generator is used for the h →aa→2τ2μ



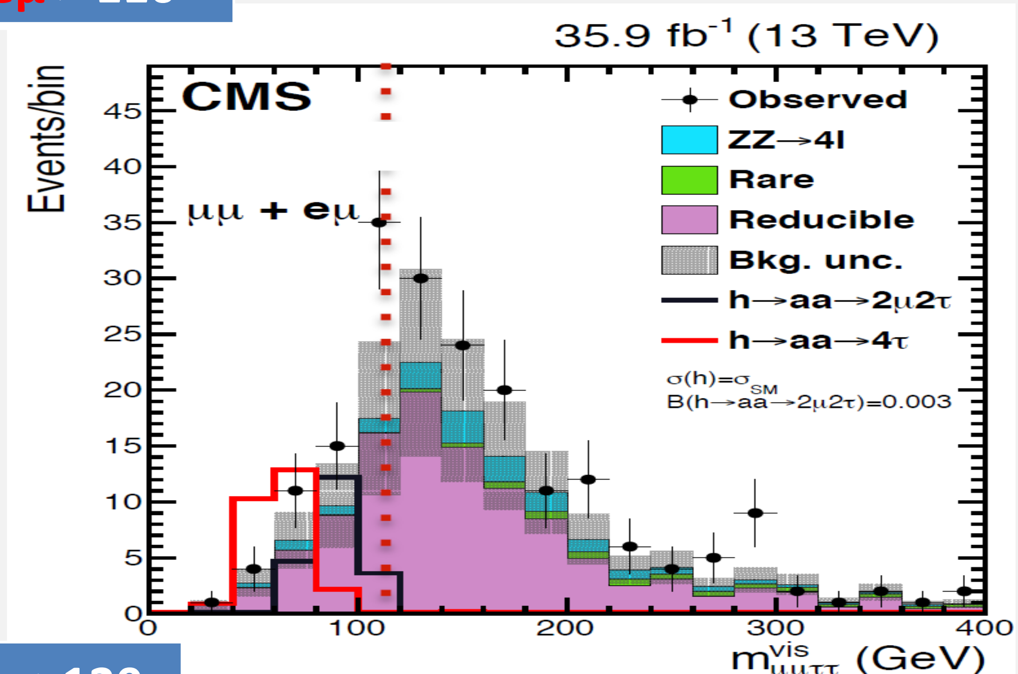
Selection criteria

$\mu\mu + e\mu, \quad \mu\mu + e\tau_h, \quad \mu\mu + \mu\tau_h, \quad \mu\mu + \tau_h\tau_h$

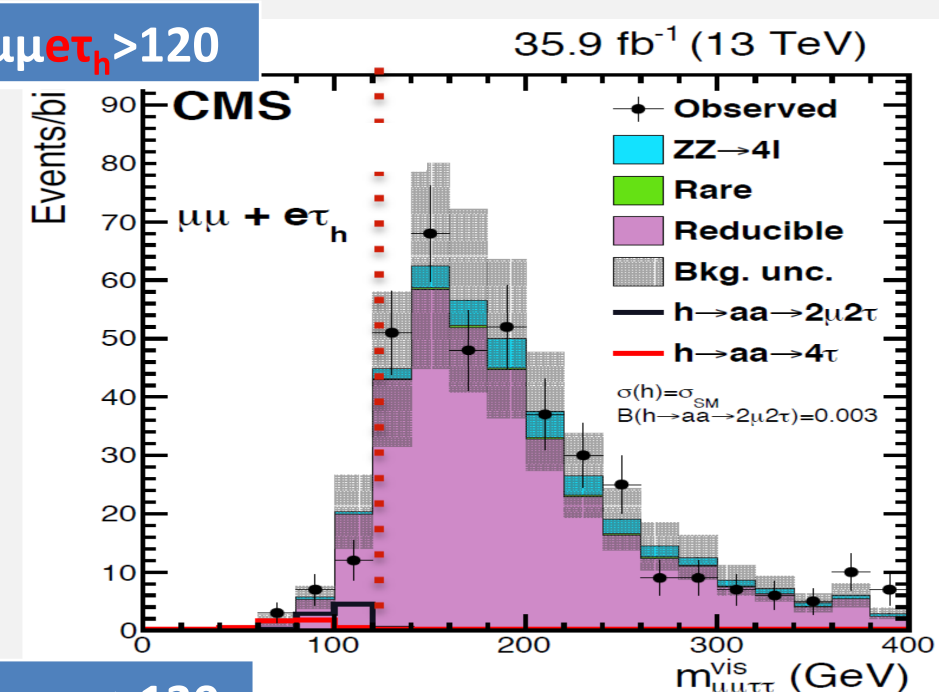
- **Triggers**: single muon (24) OR double muon (17-8)
  - OR triple muon (12-10-5) if 3 muons in the final state
- **Muons selected offline** with 1 GeV above trigger thresholds
- **Muons**: $|\eta| < 2.4$, Muon ID medium Iso < 0.2
- **Electrons:** from τ lepton decays are required to have $p_T > 7$ GeV and $|\eta| < 2.5$
- **Taus**: are required to satisfy $P_T > 18.5$ GeV and $|\eta| < 2.3$
- Opposite Sign in each pair
- **Lepton**: To avoid overlaps between final states, events with additional isolated electrons and muons are discarded in the $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ final states
- **bjet vetoes:** $P_T > 20$GeV , $|\eta| < 2.4$. Reduce the contribution of the reducible background tt and of the irreducible ttZ.
- **Selected leptons** are required to be separated from each other by $\Delta R > 0.3$, or $\Delta R > 0.4$ if there is τ_h candidate.

Event Selection – Optimization Cuts

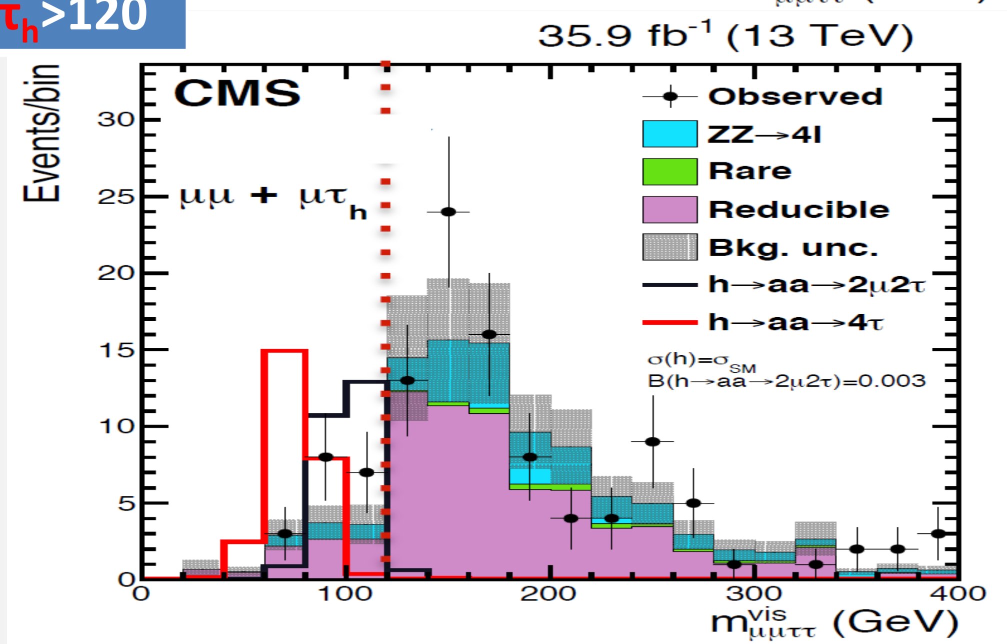
μμeμ > 110



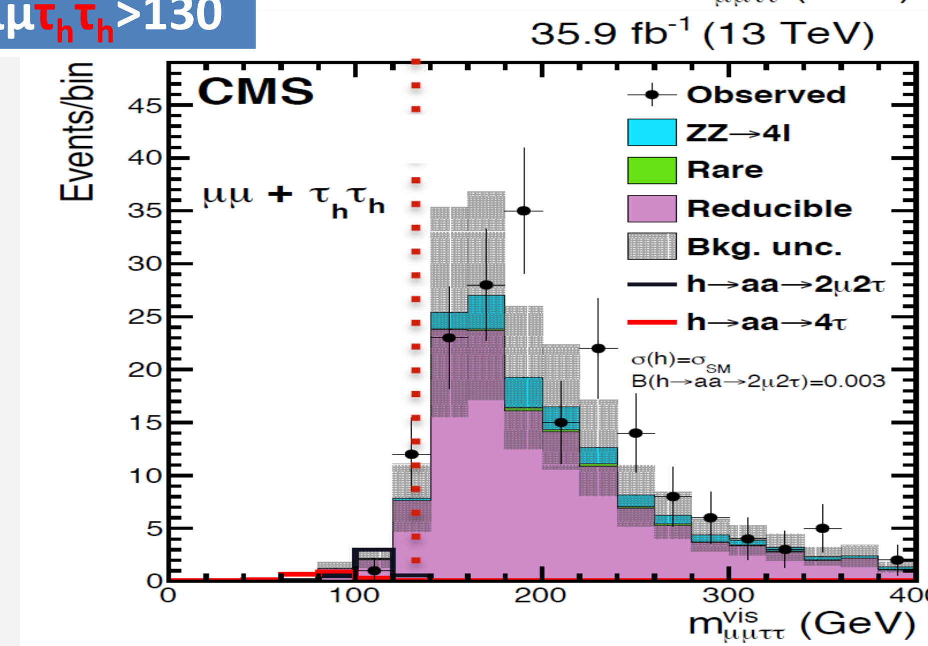
μμeτh>120



μμμτh>120

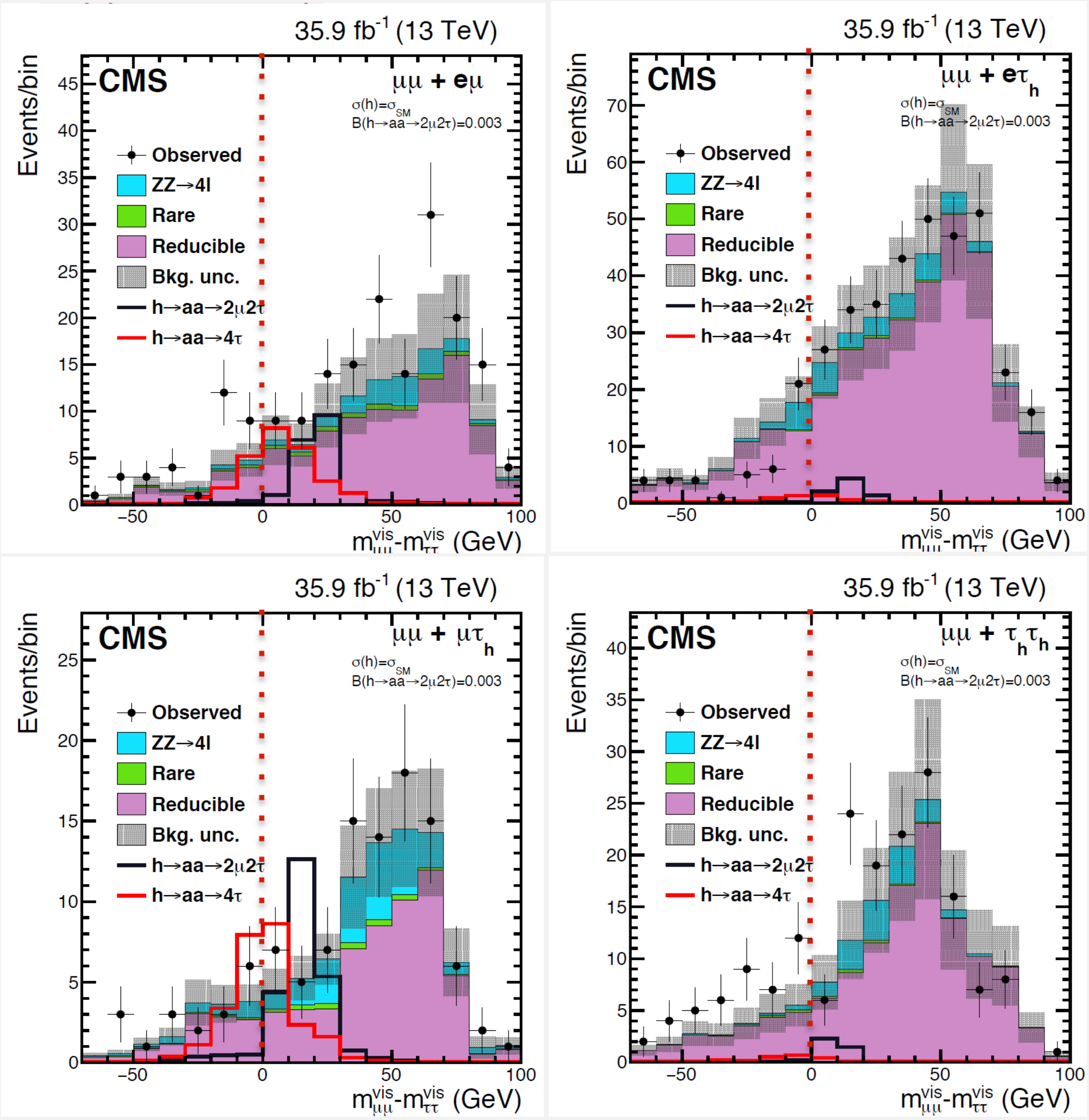


μμτhτh>130



More than 80% of the background is rejected

Selection ($m_{\mu\mu}$ - $m_{\tau\tau}$)

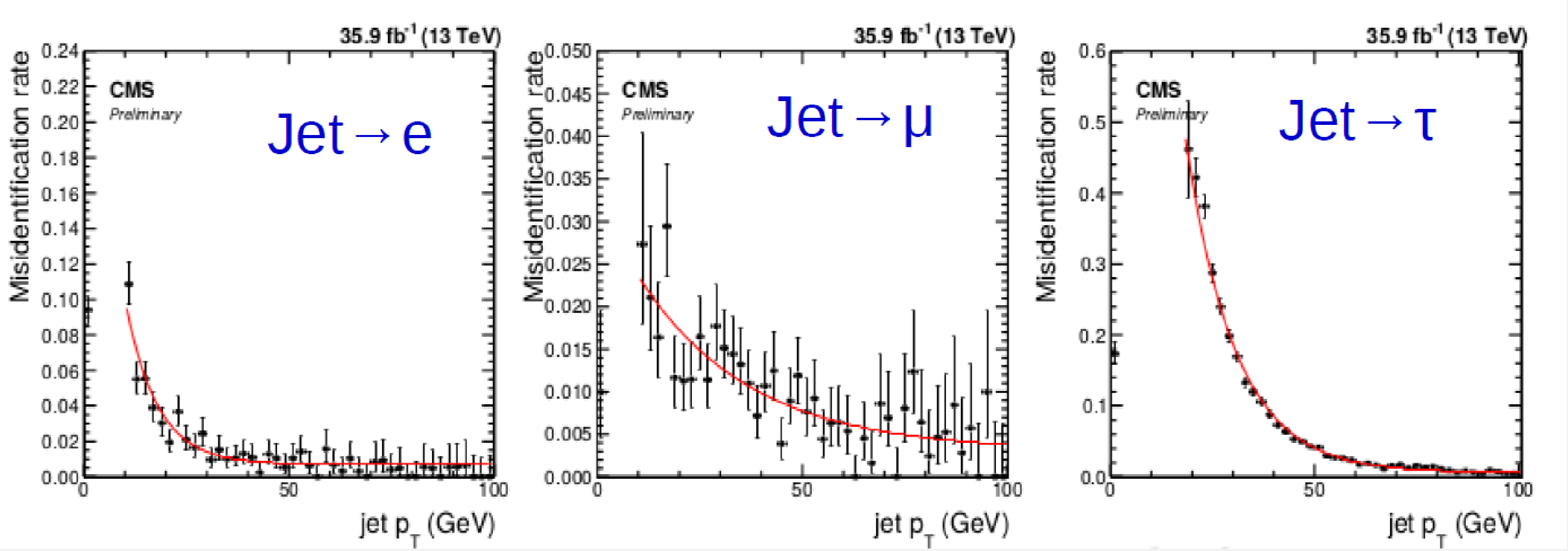


- The visible mass of the ditau is required to be smaller than the dimuon mass (Because of the neutrinos).
- After $m_{\mu\mu\tau\tau}$ cut, this cut removes ~50% of reducible background

Background Estimation

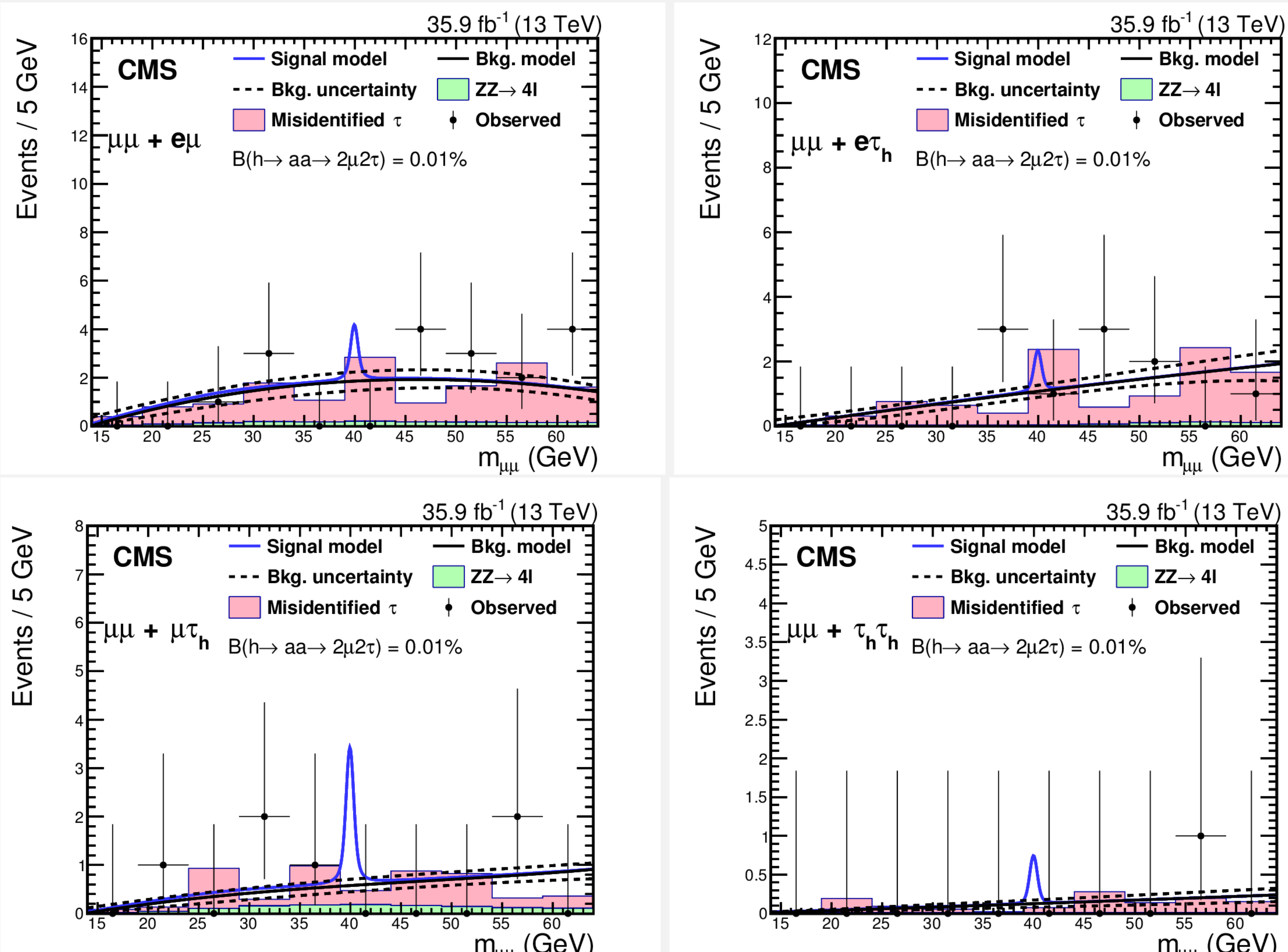
- Reducible Background: The background composed of events where at least one jet is misidentied as one of tau candidates (e, μ, τ_h)
- The yield and the distributions of backgrounds are estimated from data via:
    1) The shape of the reducible background is obtained selecting events where the tau candidates have same sign charge.
    2) The yield of the reducible background is estimated with the fake rate method.

$$\text{Fake rate} = \frac{\text{Events passing identification criteria + Isolation}}{\text{Events with loosened identification criteria + Isolation}}$$



Results

Global maximum likelihood fit based on the unbinned mass distributions



- ❑ $m_{\mu\mu}$ distribution for each channel with the best fit for the background model and signal model including uncertainties
- ❑ **Signal model**

Voigt profiles: Lorentzian + Gaussian

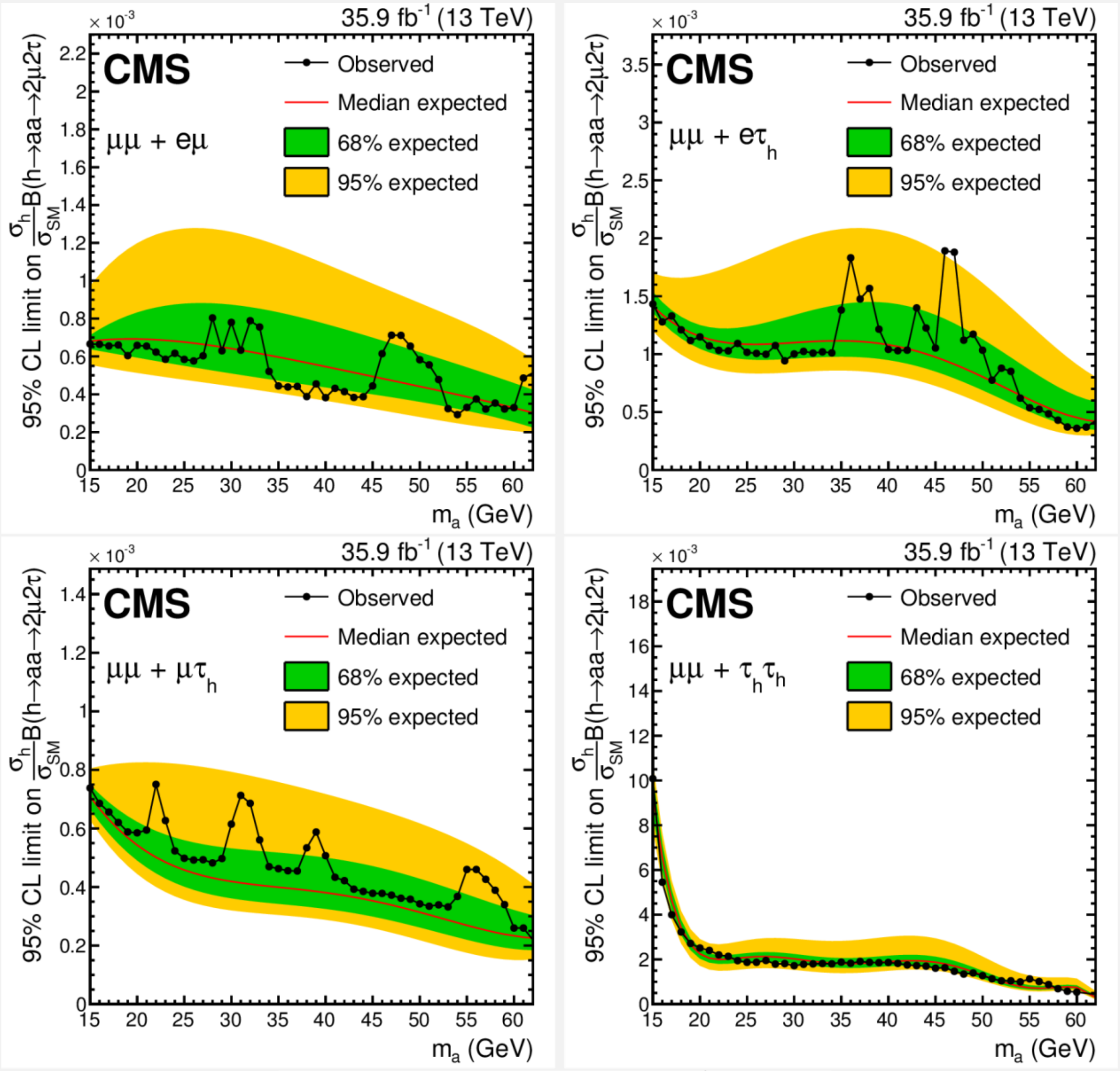
- ❑ **Background model**

Bernstein polynomials (The number of degrees determined via F - test)

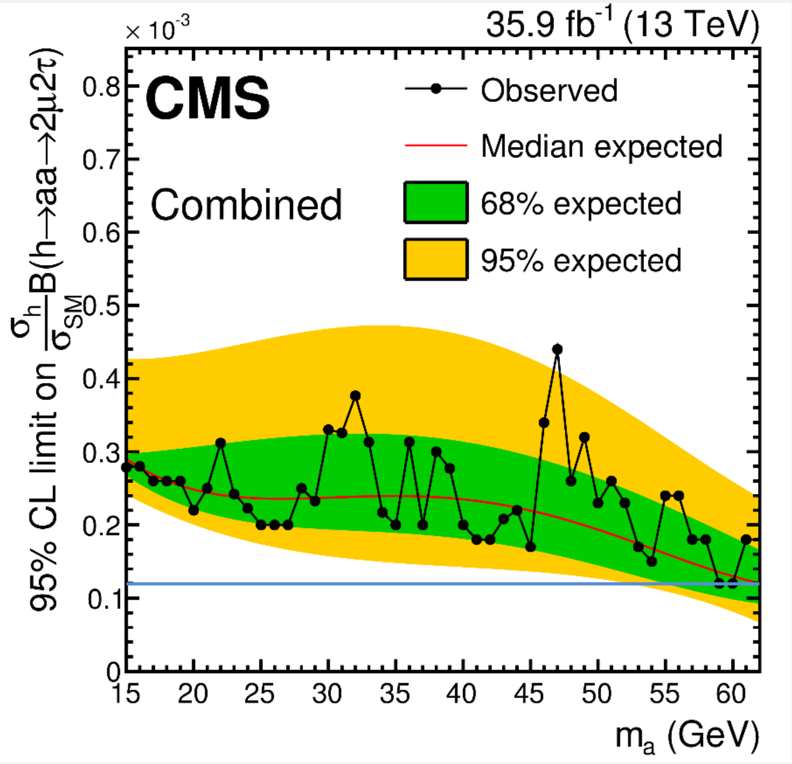
$$B_{i,n}(t) = \binom{n}{i} t^i (1-t)^{n-i}$$

$$i = 0, 1, \ldots, n$$

Expected Limits on σ_h/σ_{SM} x BR(h(125) → αα → 2μ2τ)



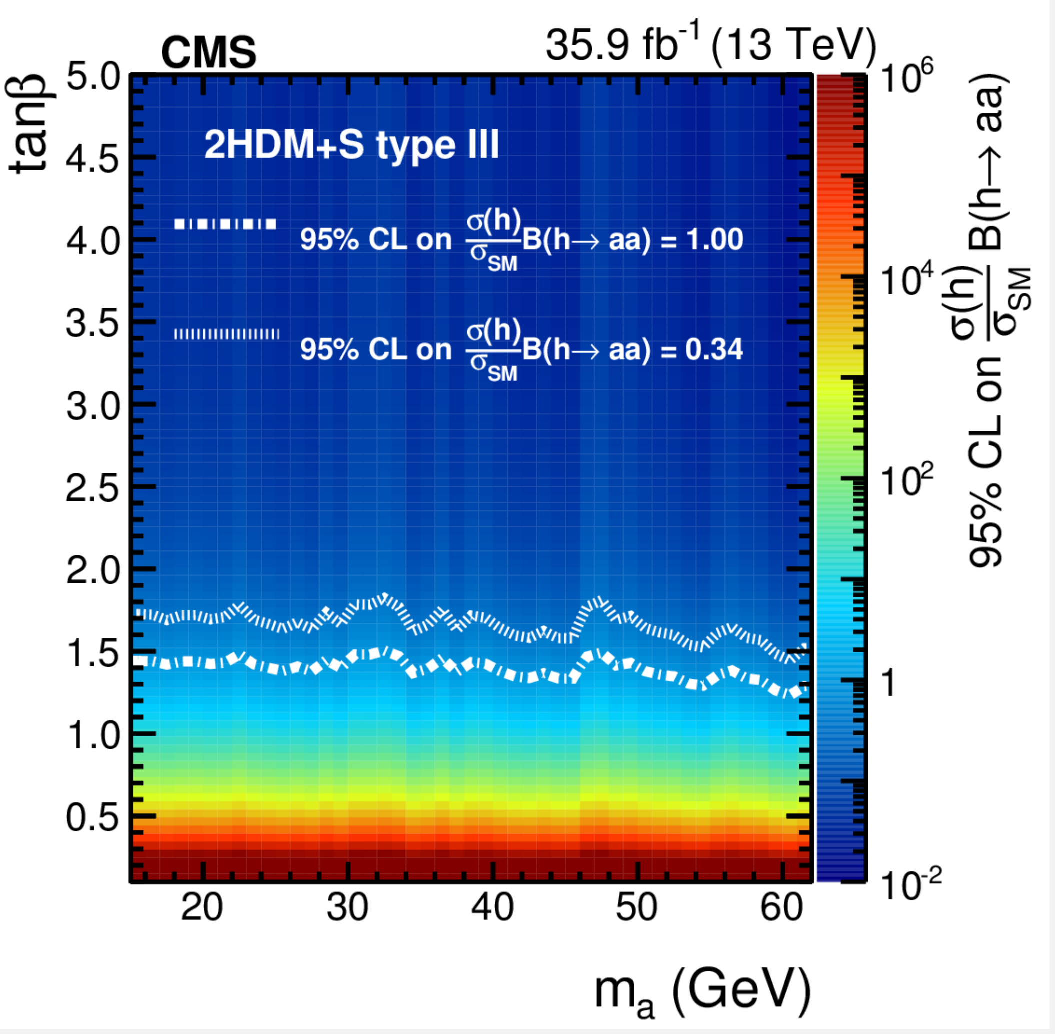
- No significant excess of data is observed above the expected SM background.
- Upper limits at 95% CL on σ_h/σ_{SM} x B(h → αα) for masses of α between 15 and 62.5 GeV are as low as 1.2 x 10^{-4}.

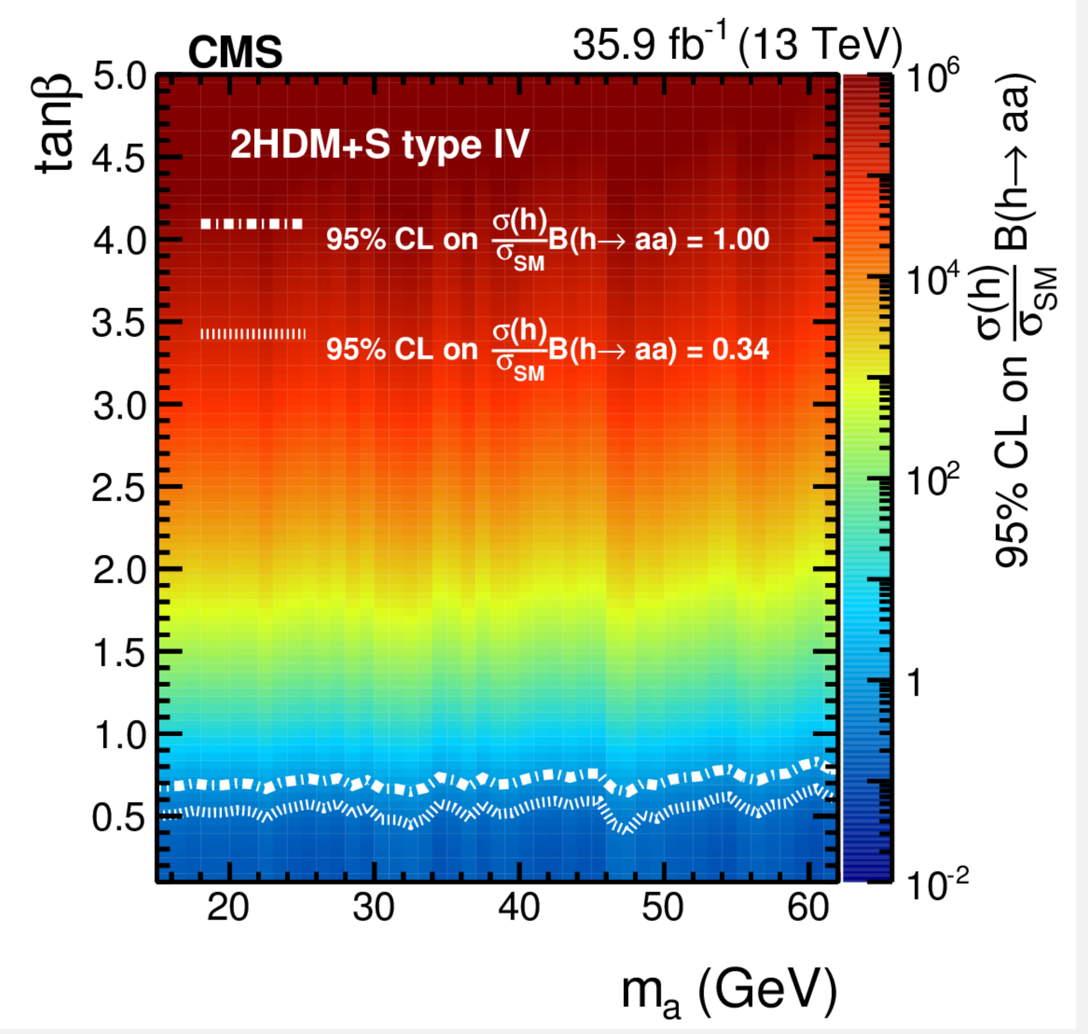


The expected limits are the tightest for the μμ+μτ$_h$ final state:

- The lepton p_T thresholds are lower than in the μμ+ eτ$_h$ and μμ+ τ$_h$τ$_h$ final states.
- The BR is larger than in the μμ + eμ final state.

Upper limits on σ_h/σ_{SM} x BR($h \rightarrow \alpha\alpha$) in the different 2HDM+S models

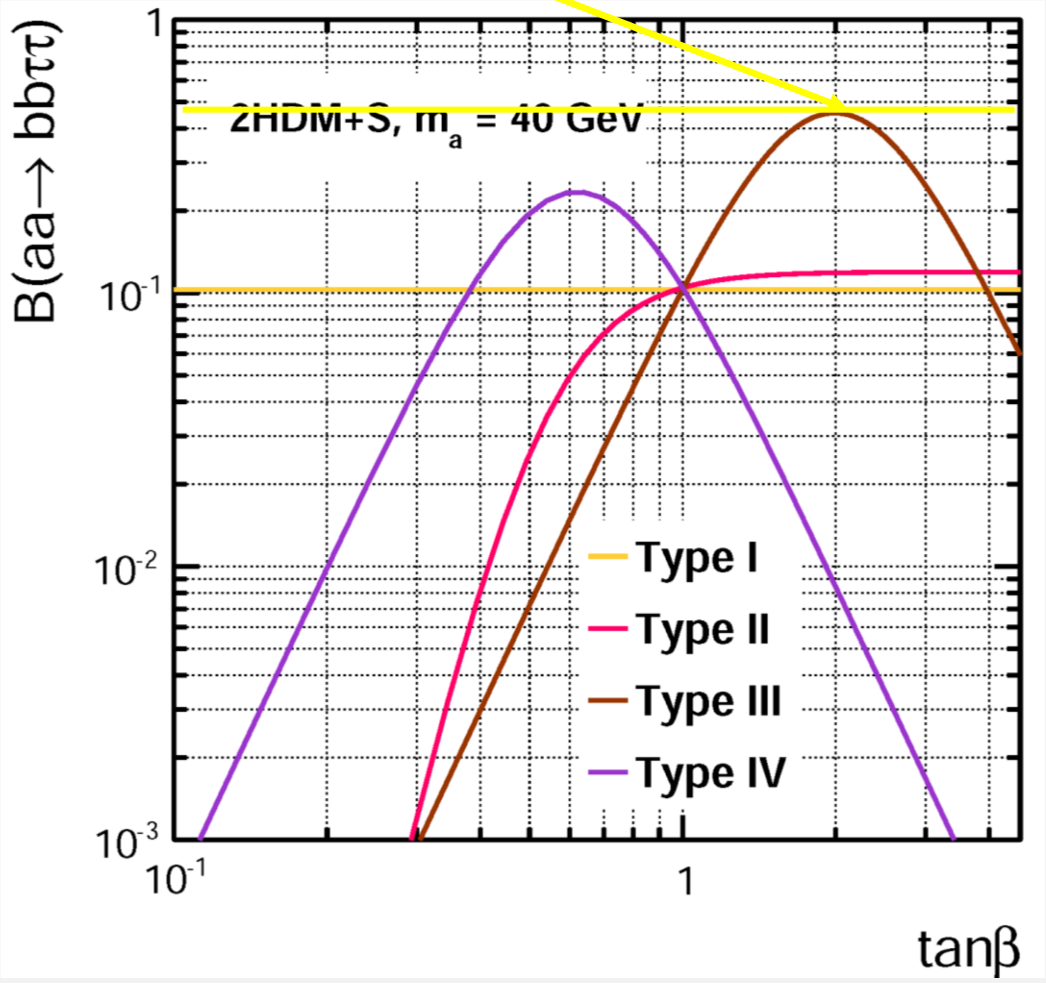




The most stringent limits are obtained in 2HDM+S type III at large tanβ, where the couplings to leptons are enhanced, and where limits of approximately 3% are set for tanβ > 3.

The benchmark points $h \to \alpha\alpha \to b\bar{b}\tau^+\tau^-$

In 2HDM+S type-3, $Br(\alpha a \to bb\tau\tau)$ can reach 45%



- Final state ($2m_b < m_\alpha < m_{h/2}$) with good sensitivity because of the large branching fractions to τ and b quarks in most models.
- Sensitive final states and analysis techniques depend on m_α :
  - m_α < 3.5 GeV: α→bb and α→ττ channels not open.
  - m_α < 15 GeV: decay products are boosted
  - m_α > 15 GeV: all channels open and decay products not boosted
- **Mechanism**

  gluon gluon Fusion (ggF), σ_{ggF} = 48.58 pb

  vector boson fusion (VBF), σ_{qqh} = 3.93 pb
- **Benchmark for the expected yield**

  BR(h → *aa*) = 10%

  BR(αα→bbττ) = 45%,   for tanβ = 2

  σ_{ggF} × BR = 2.19 pb

  σ_{qqh} × BR = 0.18 pb

$$h \rightarrow \alpha\alpha \rightarrow b\bar{b}\tau^{+}\tau^{-}$$

❑ Data

- The analysis is based on data collected in 2016, amounting to 35.9 fb^{-1} at √s=13 TeV

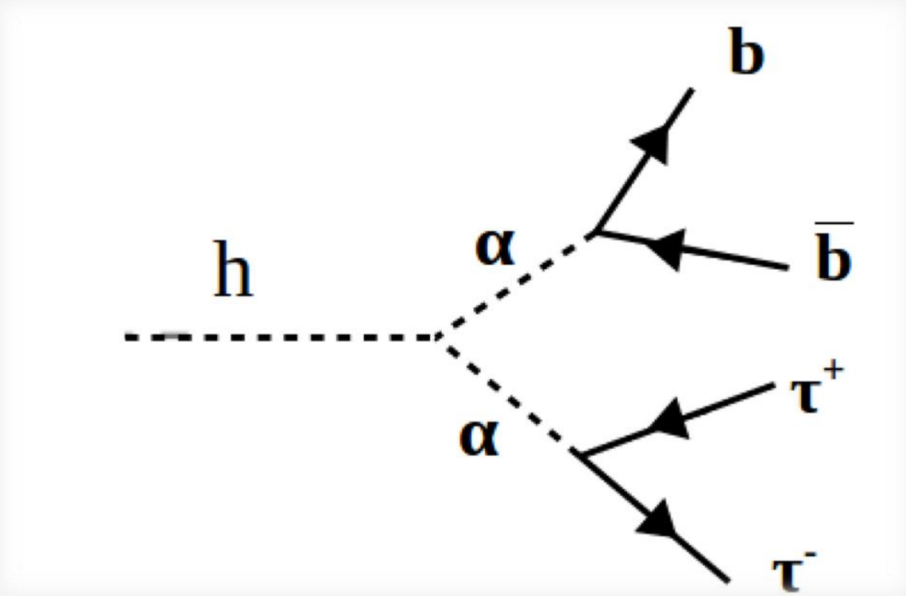
❑ Background

- Drell–Yan (DY) +jets: samples (MADGRAPH), 2–3% probability for electrons to be misidentified as electron is misidentified as τ_h.
- ttbar + Single top: (POWHEG), is one of the main backgrounds in the eμ channel
- W + jets samples: (MADGRAPH), *W* boson decays leptonically and a jet is misidentified as τ_h
- Diboson samples, (WW, ZZ, and WZ):
- $WZ^*/\gamma^*(\rightarrow \tau^+\tau^-)b\bar{b}$: has the $b\bar{b}$ pairs from a virtual gluon splitting, the $\tau^+\tau^-$ pair from an intermediate Z^*/γ^* and the charged lepton plus missing energy from *W* boson.

❑ Signal Samples

- The MadGraph5 generator is used for the h →aa→2τ2b

Selection



$e\tau_h$ channel

- **Trigger**: Single Electron
- **Electron:** p_T > 26GeV, |η| < 2.1, MVA ID (80%), iso(ΔR=0.3) <0.10
- **Tau:** p_T > 25GeV, |η| < 2.3, isolation MVA,
- **Electron and τ_h:** are OS and are separated by ΔR > 0.4

$\mu\tau_h$ Channel

- **Trigger**: Single muon OR Muon + Tau
- **Muon**: p_T > 20GeV, optimized threshold to reduce Jet → τ_h fake background, |η| < 2.1, isolation (ΔR=0.4) < 0.15
- **Tau**: p_T > 25GeV, |η| < 2.3, isolation multivariate analysis (MVA)
- **Muon and Tau** are OS (opposite sign) and are separated by ΔR > 0.4

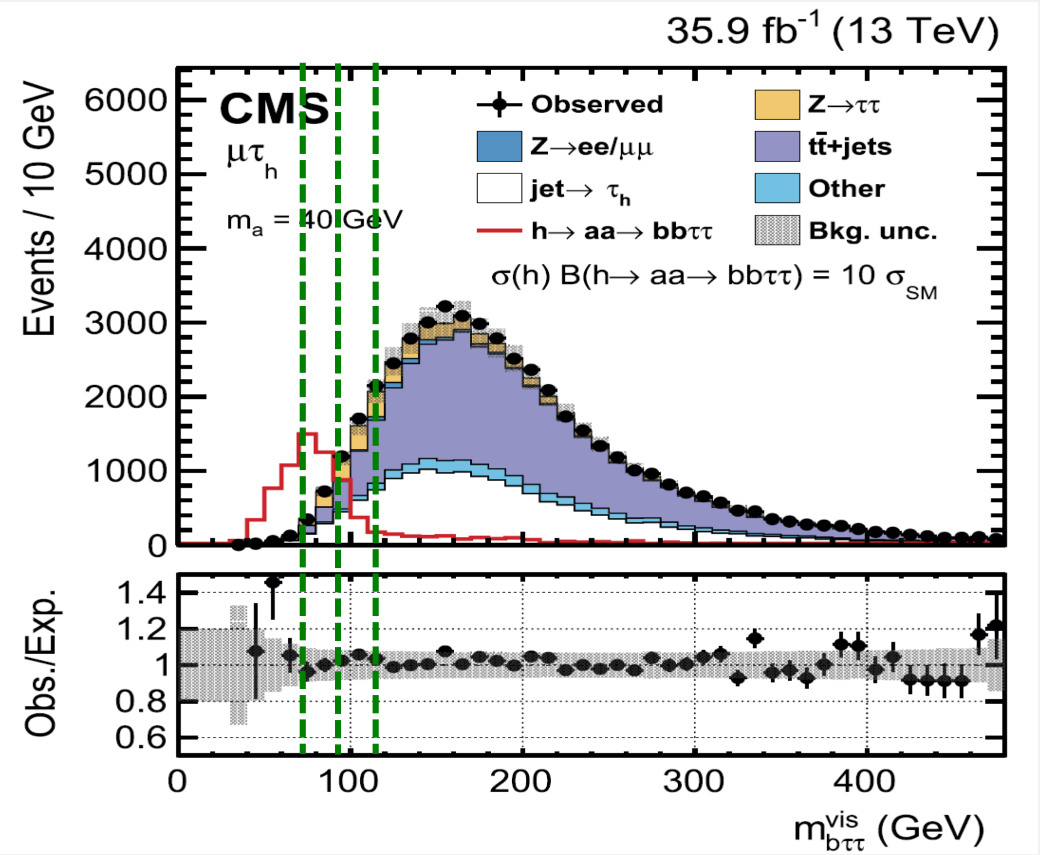
eμ channel

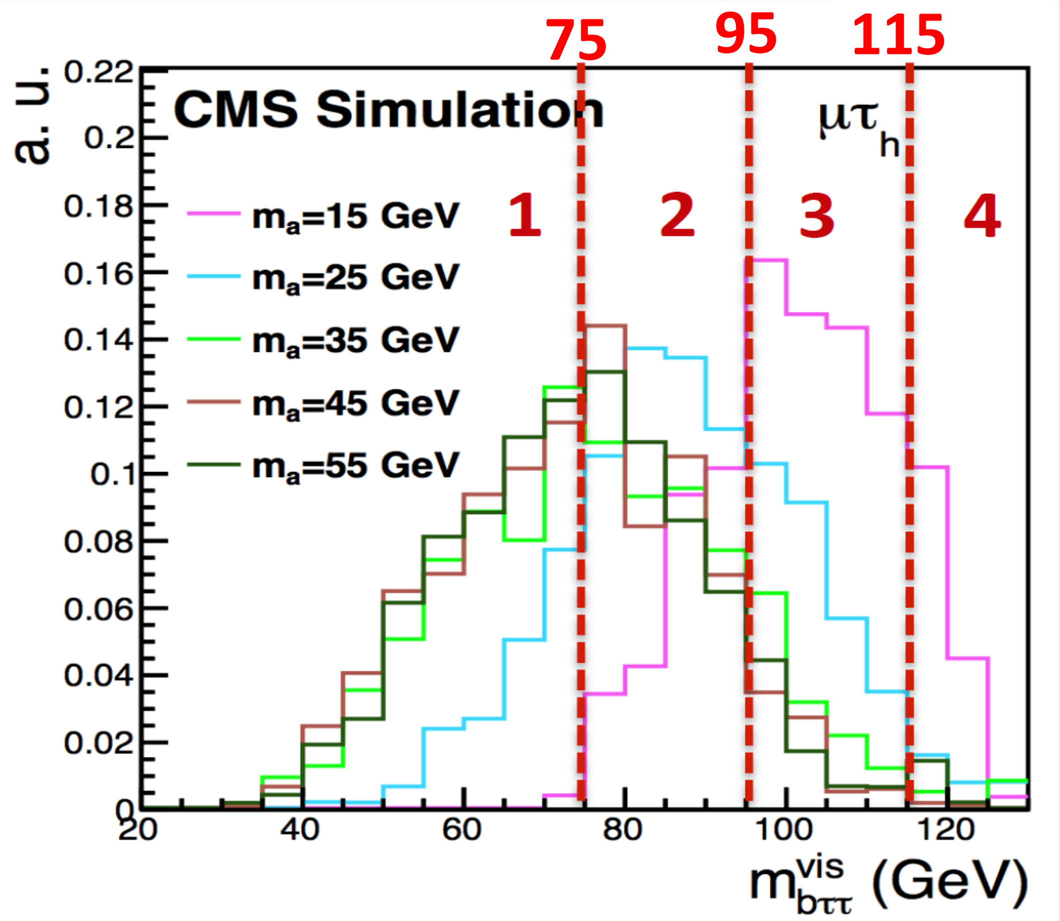
- **Trigger:** Electron + Muon
- **Muon:** p_T >24/10 GeV, |η|< 2.4, iso(cone size of 0.4) <0.15
- **Electron:** p_T >13/24 GeV, |η|<2.5, iso(cone size of 0.3) <0.10
- **The electron and the muon**: are separated by ΔR > 0.3 and should have OS

Categorization

To increase the sensitivity of the analysis, events in each final state are separated into four categories with different signal-to-background.

- First categories have very few backgrounds.
- Intermediary categories contain low m_α signal.
- High category constrains the backgrounds.





Selection optimization

$$D_\zeta = P_\zeta - 1.85 P_\zeta^{vis}$$

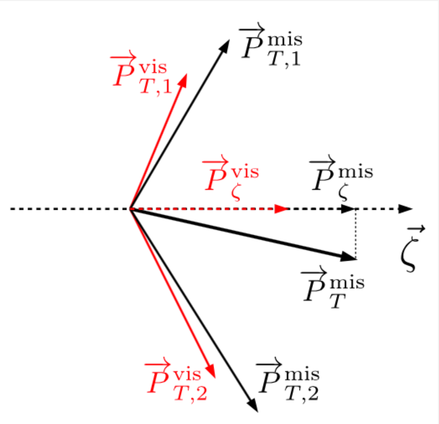
$$\text{with } P_\zeta = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis} + \vec{P}_T^{\text{mis}}) \frac{\vec{\zeta}}{|\vec{\zeta}|}$$

$$\text{and } P_\zeta^{vis} = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis}) \frac{\vec{\zeta}}{|\vec{\zeta}|}$$

- Limits optimized By cutting on 3 other variables:

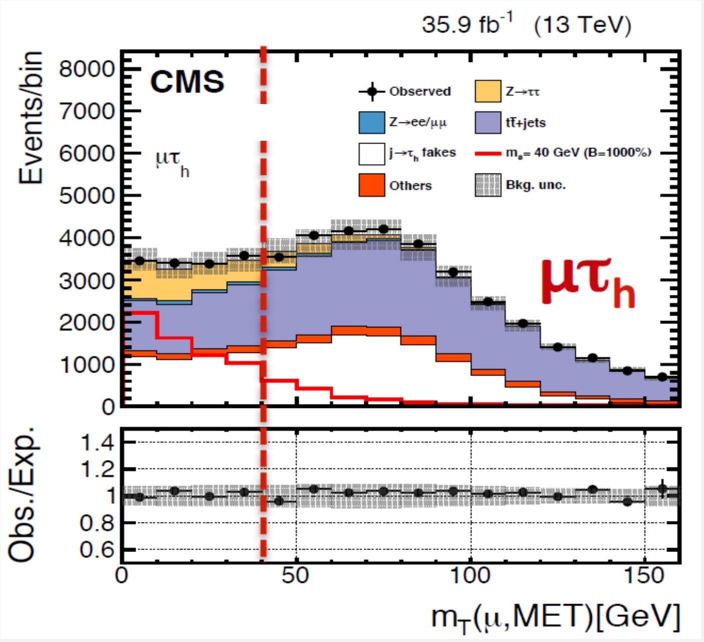
  (1) $m_T(\mu,\text{MET})$, (2) $m_T(\tau_h,\text{MET})$, (3) D_ζ

$$m_T\left(\ell, \vec{p}_T^{miss}\right) = \sqrt{2 p_T^{\ell} p_T^{miss}\left[1 - \cos\left(\Delta\phi\right)\right]}$$

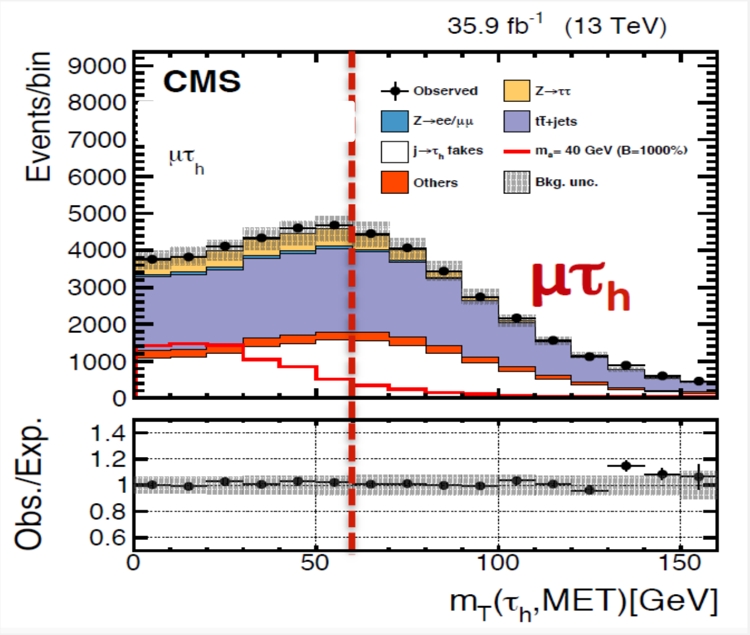


- Selecting events with low m_T strongly reduces the backgrounds from W +jets and tt events, which are characterized by a larger
- The Z →ττ background typically has D_ζ values close to zero because is approximately collinear to the ττ system.

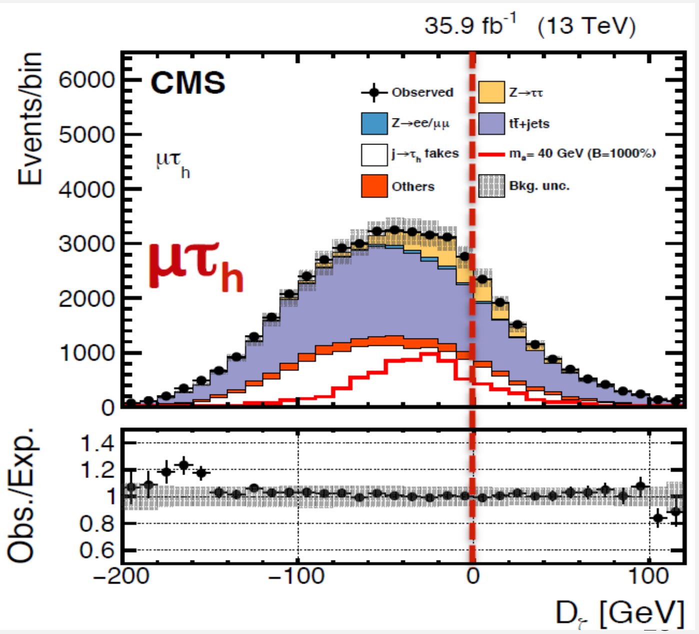
$m_T(\mu,\text{MET})$



$m_T(\tau_h,\text{MET})$



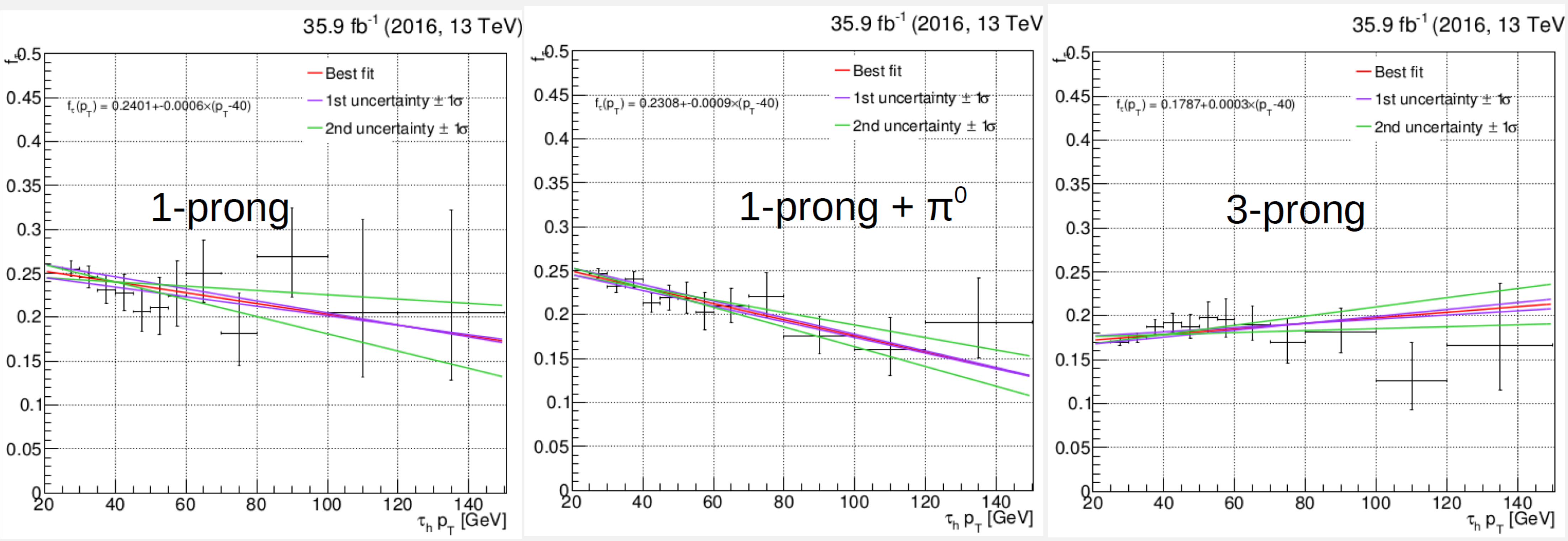
D_ζ



Background Estimation

- Backgrounds with a jet misidentified as a τ_h candidate are estimated from data (W +jets, QCD multijet , tt, diboson, and single top quark).
- All other backgrounds (Z+jets, ttbar+jets, single top and diboson) estimated from MC.
- The Data passing the very loose working point was reweighed by $f/(1-f)$.

  Where f is the probability for jets to be misidentified as τ_h candidates.

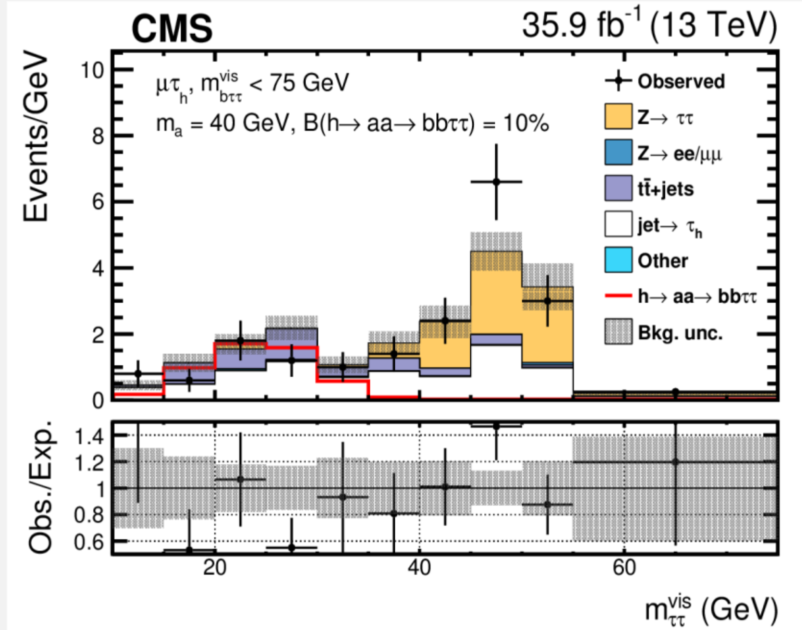


Landau distributions

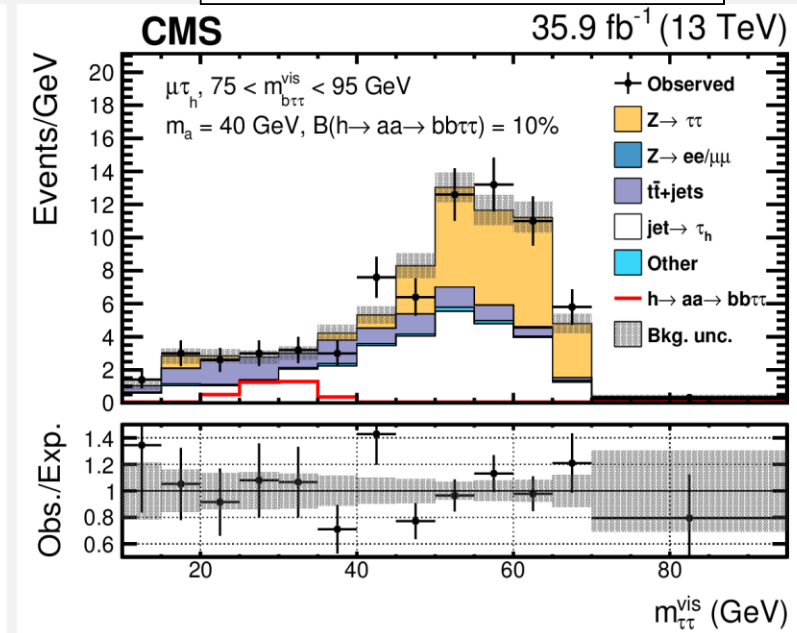
Fit Method

The search for an excess of signal events over the expected background involves a global binned maximum likelihood fit based on the $m_{\tau\tau}^{vis}$ distributions in the different categories.

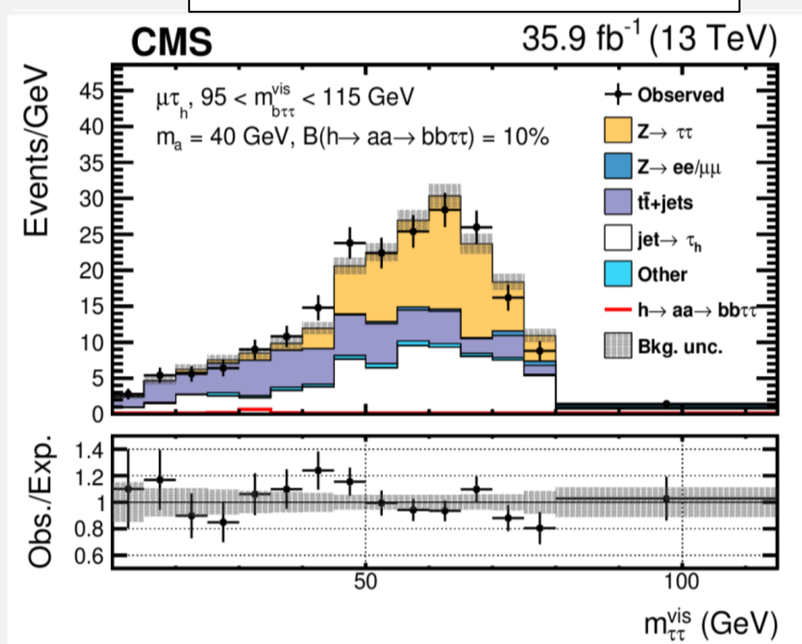
$m_{\tau\tau}^{vis} < 75\text{GeV}$



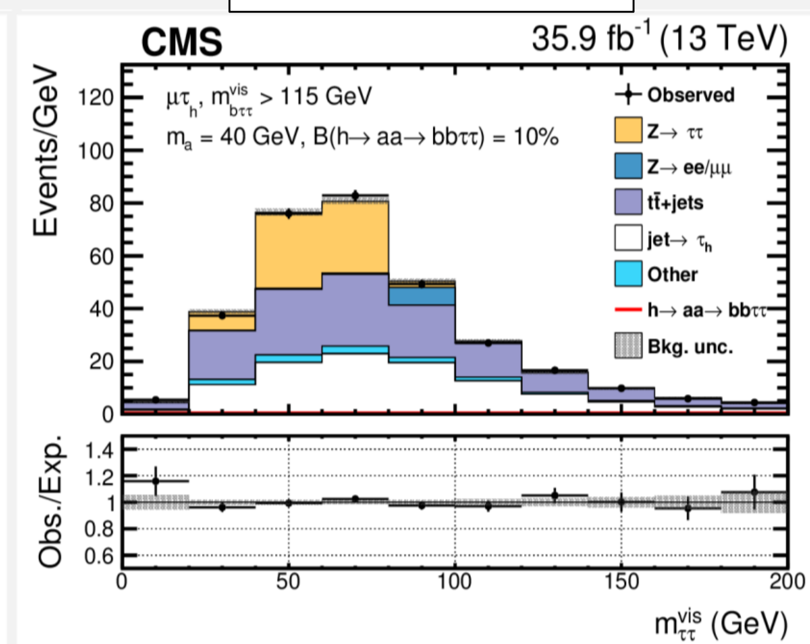
$75 < m_{\tau\tau}^{vis} < 95\text{ GeV}$



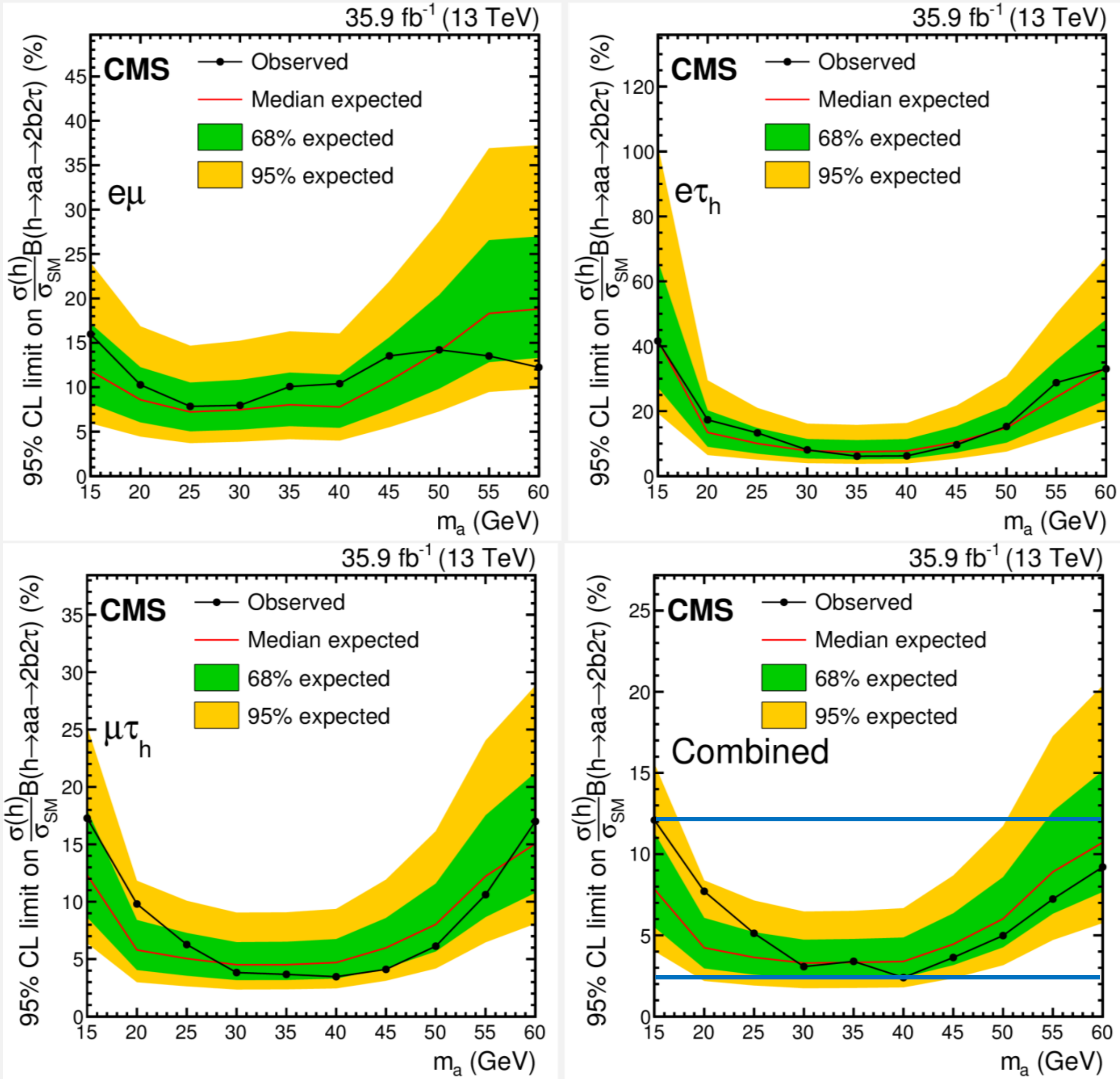
$95 < m_{\tau\tau}^{vis} < 115\text{ GeV}$



$m_{\tau\tau}^{vis} > 115\text{ GeV}$

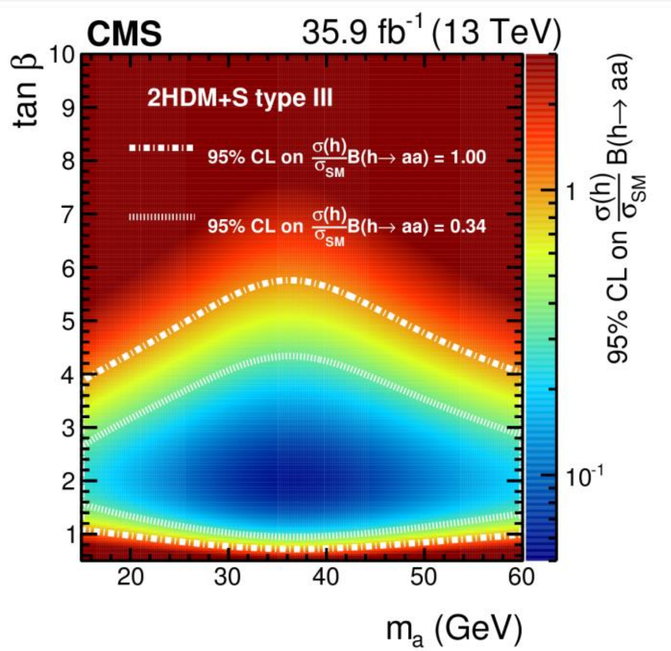


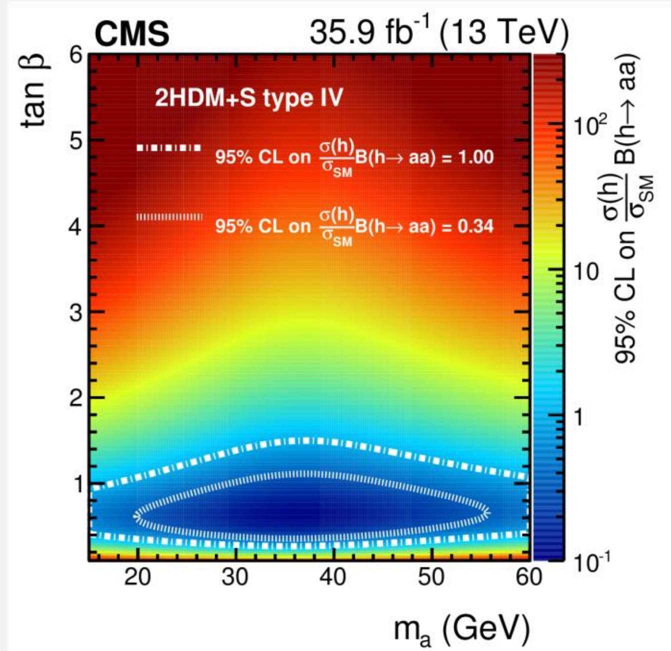
Expected Limits on σ_h/σ_{SM} x BR(h(125) → αα → 2b2τ)

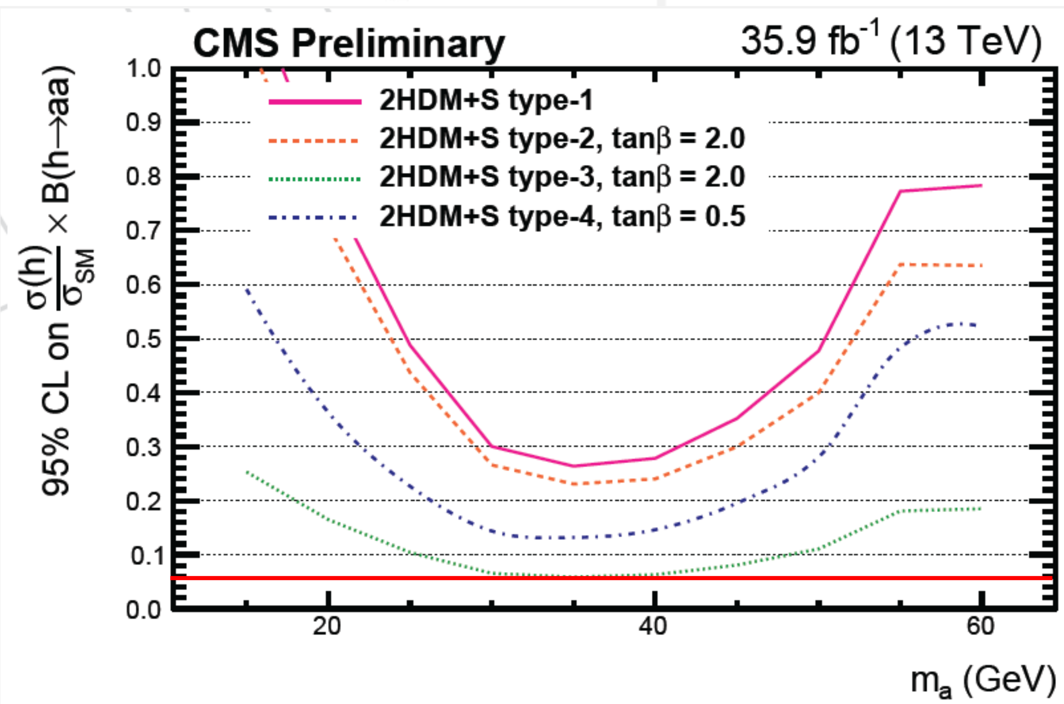


- No excess is observed relatively to the SM background prediction.
- $\mu\tau_h$ channel is the most sensitive channel:
  - $e\tau_h$ channel suffers from higher trigger thresholds and lower object identification efficiency.
  - eμ channel suffers from a lower BR.
- The combined limit at intermediate mass is as low as 3% on σ_h/σ_{SM} x BR(h →aa→2τ2b), and is up to 12% for the lowest mass point m_α=15 GeV.

Expected Limits at 95% CL on σ_h/σ_{SM} x BR(h → αα) for 2 types of 2HDM+S







- The Higgs boson pair production rate σ_h/σ_{SM} x BR(h → αα) for all types of 2HDM+S depends on tan β

2HDM+S	BR(αα → bbττ)
Type I	0.10 – 0.11
Type II	0.11 – 0.13
Type III	0.44 – 0.46
Type IV	0.16 – 0.21

- In the scenario with the highest branching fraction, 2HDM+S type-3 with tan β = 2, the expected limit is as low as 6% for m_α = 35 GeV.

Summary

❑ $h(125) \rightarrow \alpha\alpha \rightarrow \mu^+\mu^-\tau^+\tau^-$

- Limits are set at 95% confidence level on the σ_h/σ_{SM} x BR(h(125) → αα → 2μ2τ for the masses of the pseudoscalar between 15.0 and 62.5 GeV, and are as low as 1.2×10^{-4} for a mass of 60 GeV.
- No significant excess of data is observed above the expected SM background.
- **Published in JHEP 1811 (2018) 018**

❑ $h(125) \rightarrow \alpha\alpha \rightarrow b\bar{b}\tau^+\tau^-$

- The combined limit at intermediate mass is as low as 3% on σ_h/σ_{SM} x BR(h →aa→2τ2b), and is up to 12% for the lowest mass point.
- In the scenario with the highest branching fraction, 2HDM+S type III with tanβ=2, the expected limit is 6% at intermediate m_a.
- No excess is found over the SM backgrounds
- **Published in Phys. Lett. B785 (2018) 462**

Thank you

Two Higgs Doublet Models (2HDM)

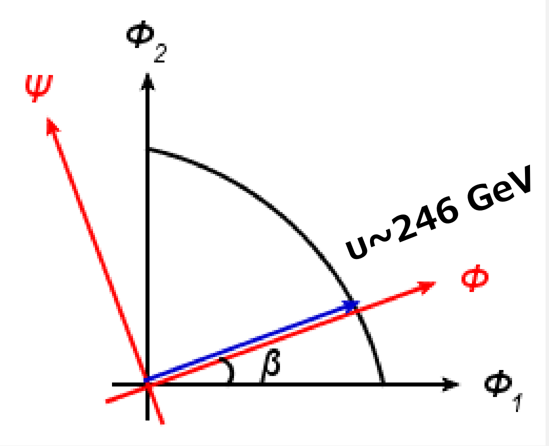
- We consider a model with an $SU(2)_L$
- Two doublets - ϕ_1 and ϕ_2

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

$\tan\beta = \upsilon_2/\upsilon_1$

$$\upsilon_1^2 + \upsilon_2^2 = \upsilon^2$$

υ_ι vacuum expectation values (vev) of the neutral component.



Goldstone bosons (**NG**)

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix}$$

Charged Higgs

$$\Psi = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

α: The mixing angle between cp-even boson

SM-like Higgs with 125 GeV

Two Higgs Doublet Models (2HDM)

- The 2HDM Lagrangian for Φ_i

$$L = \sum_i \left| D_\mu \phi_i \right|^2 - V(\phi_1, \phi_2) + L_{yuk}$$

Kinetic term for the two Higgs doublets

The 2HDM potential

Yukawa interaction between Φ_i and the SM fermions

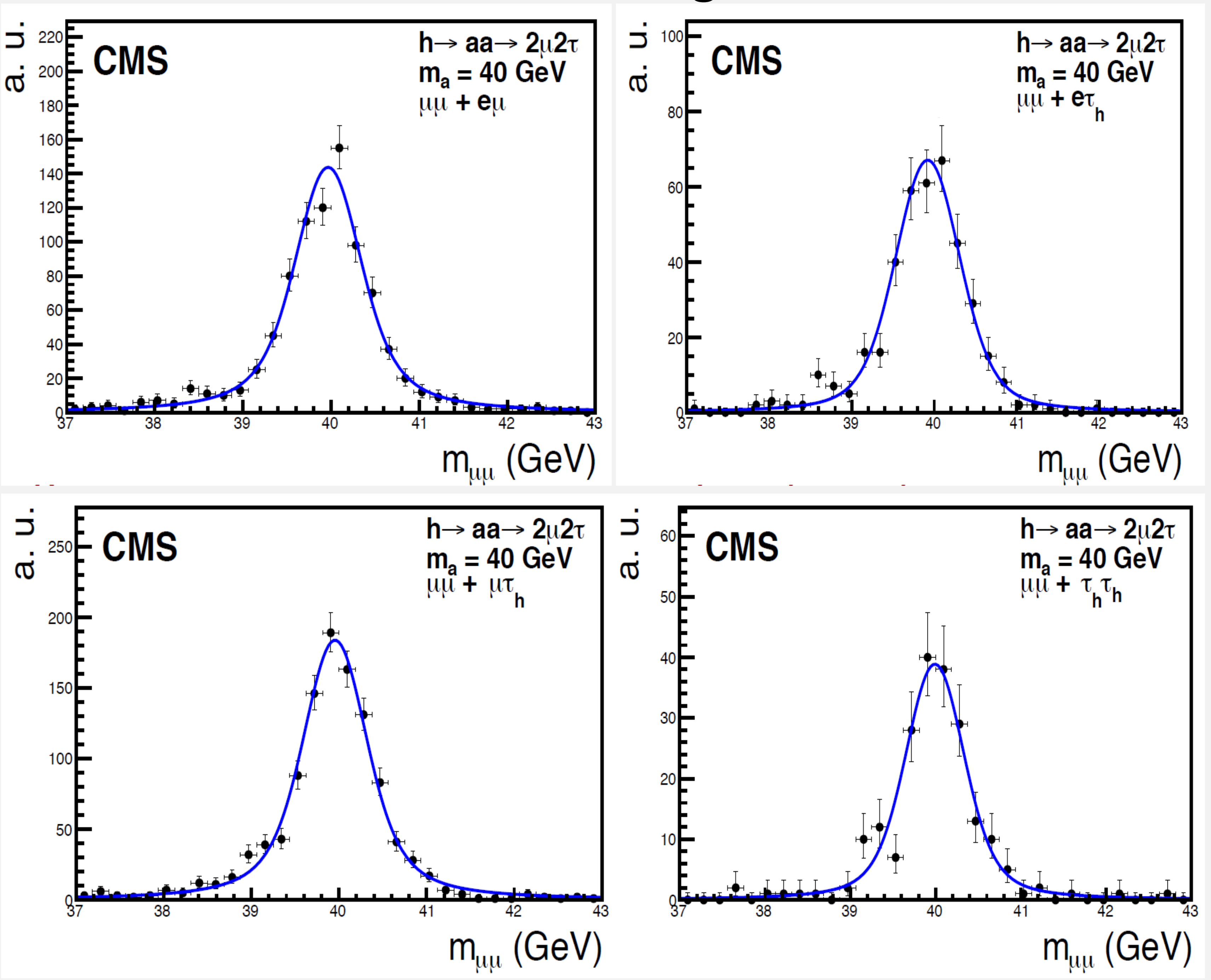
$$V(\phi_1,\phi_2) = m_1^2 \phi_1^+\phi_1 + m_2^2 \phi_2^+\phi_2 - m_{12}^2 \left(\phi_1^+\phi_2 + \phi_2^+\phi_1\right) + \frac{1}{2}\lambda_1(\phi_1^+\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^+\phi_2)^2$$
$$+ \lambda_3(\phi_1^+\phi_1) + (\phi_2^+\phi_2) + \lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1) + \frac{1}{2}\lambda_5\left[(\phi_1^+\phi_2)^2 + (\phi_2^+\phi_1)^2\right]$$

After EW symmetry breaking, the physical scalar spectrum of five states:

1) Two CP-even Higges h, H with $m_h < m_H$, can be SM-like
2) CP-odd scalar A
3) Charge scalar pair $H^\pm$

Three of these are absorbed and given mass to the $W^\pm$ and Z boson

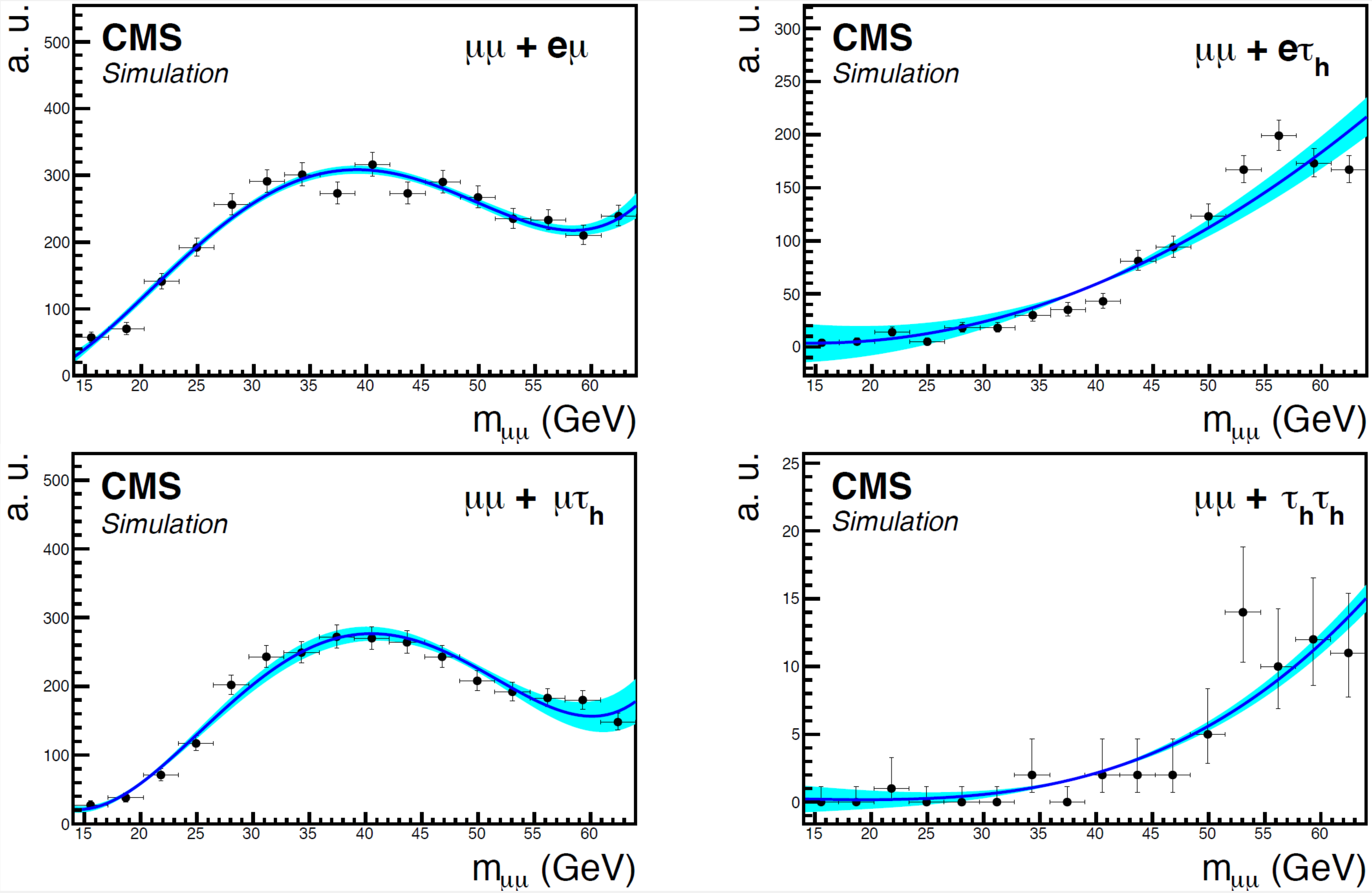
Signal model



Voigt profiles:
3 parameters:
- mean
- α Lorentzian
- σ Gaussian

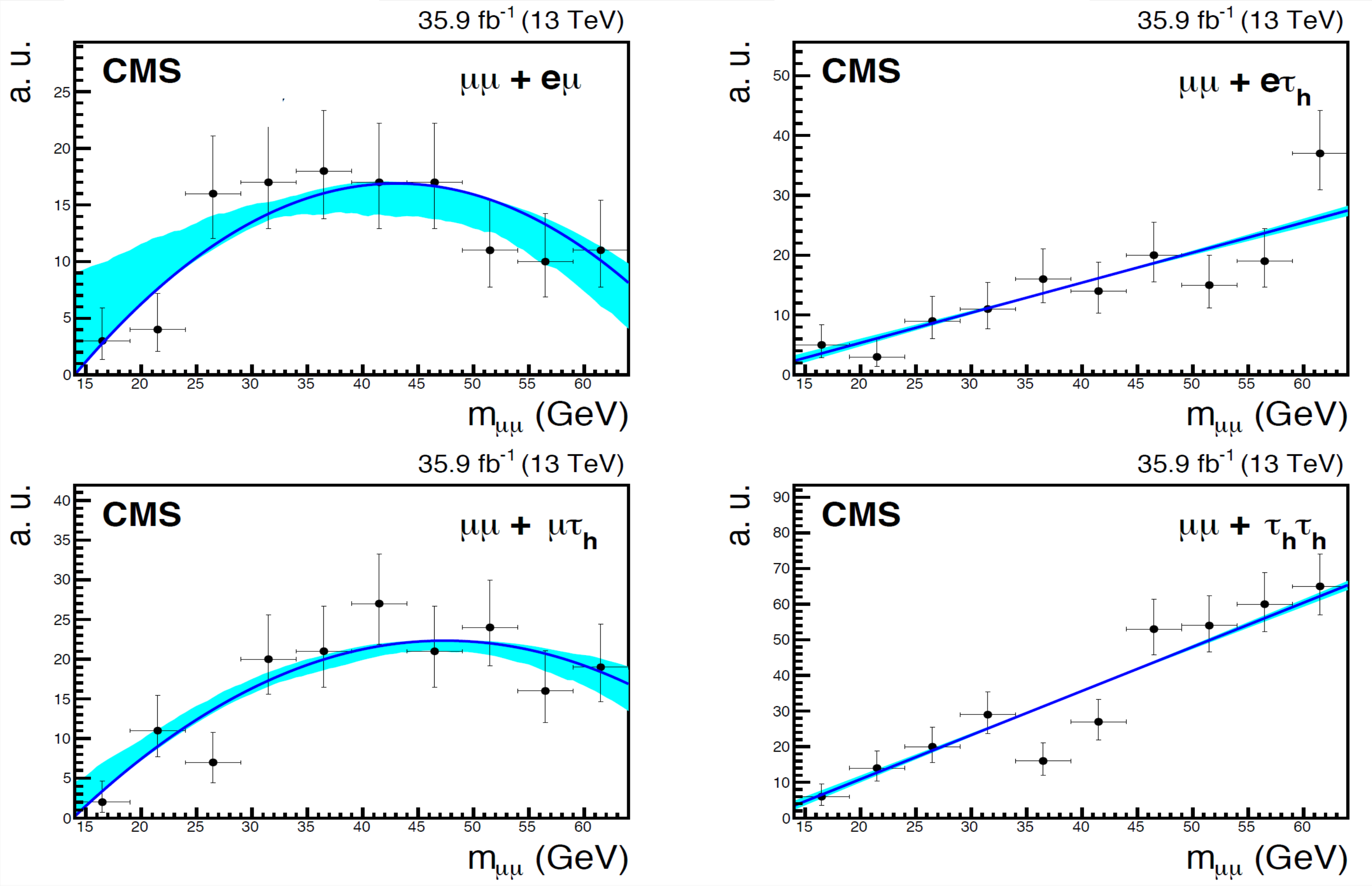
Fit to simulation for each mass point and each final state

Irreducible background model



Bernstein polynomials (degree determined via F - test) $B_{i,n}(t) = \binom{n}{i} t^i (1-t)^{n-i}, \quad i = 0,1,\ldots,n$

Reducible background model



Bernstein polynomials (degree determined via F - test) $B_{i,n}(t) = \binom{n}{i} t^i (1-t)^{n-i}, \quad i = 0,1,\ldots,n$

Results

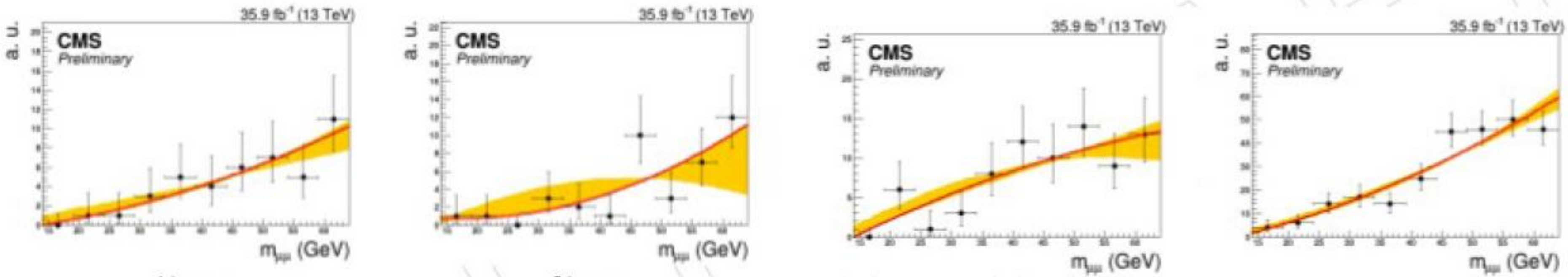
- ❑ The expected background and signal yields in the four final states

	$\mu\mu + e\mu$	$\mu\mu + e\tau_h$	$\mu\mu + \mu\tau_h$	$\mu\mu + \tau_h\tau_h$
$ZZ \to 4\ell$	1.5 ± 0.2	0.5 ± 0.1	1.2 ± 0.2	0.03 ± 0.01
Misidentified τ	13.2 ± 5.5	9.7 ± 2.5	4.0 ± 1.2	1.2 ± 0.5
$h \to aa \to 2\mu 2\tau, m_a = 20\,GeV$	0.39	0.25	0.47	0.10
$h \to aa \to 2\mu 2\tau, m_a = 40\,GeV$	0.57	0.28	0.68	0.14
$h \to aa \to 2\mu 2\tau, m_a = 60\,GeV$	0.94	0.85	1.18	0.52
Observed	17	10	6	1

Background Parametrization $h \to \alpha\alpha \to \mu\mu\tau^{+}\tau^{-}$

Reducible

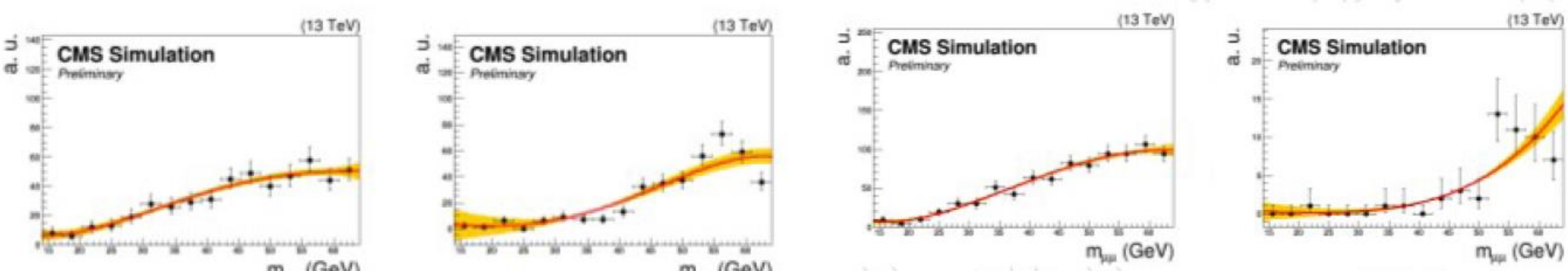
- 3rd degree Bernstein polynomials⟶ Good fit quality in all the final states



(a) $\mu\mu e\mu$ (b) $\mu\mu e\tau_h$ (c) $\mu\mu\mu\tau_h$ (d) $\mu\mu\tau_h\tau_h$

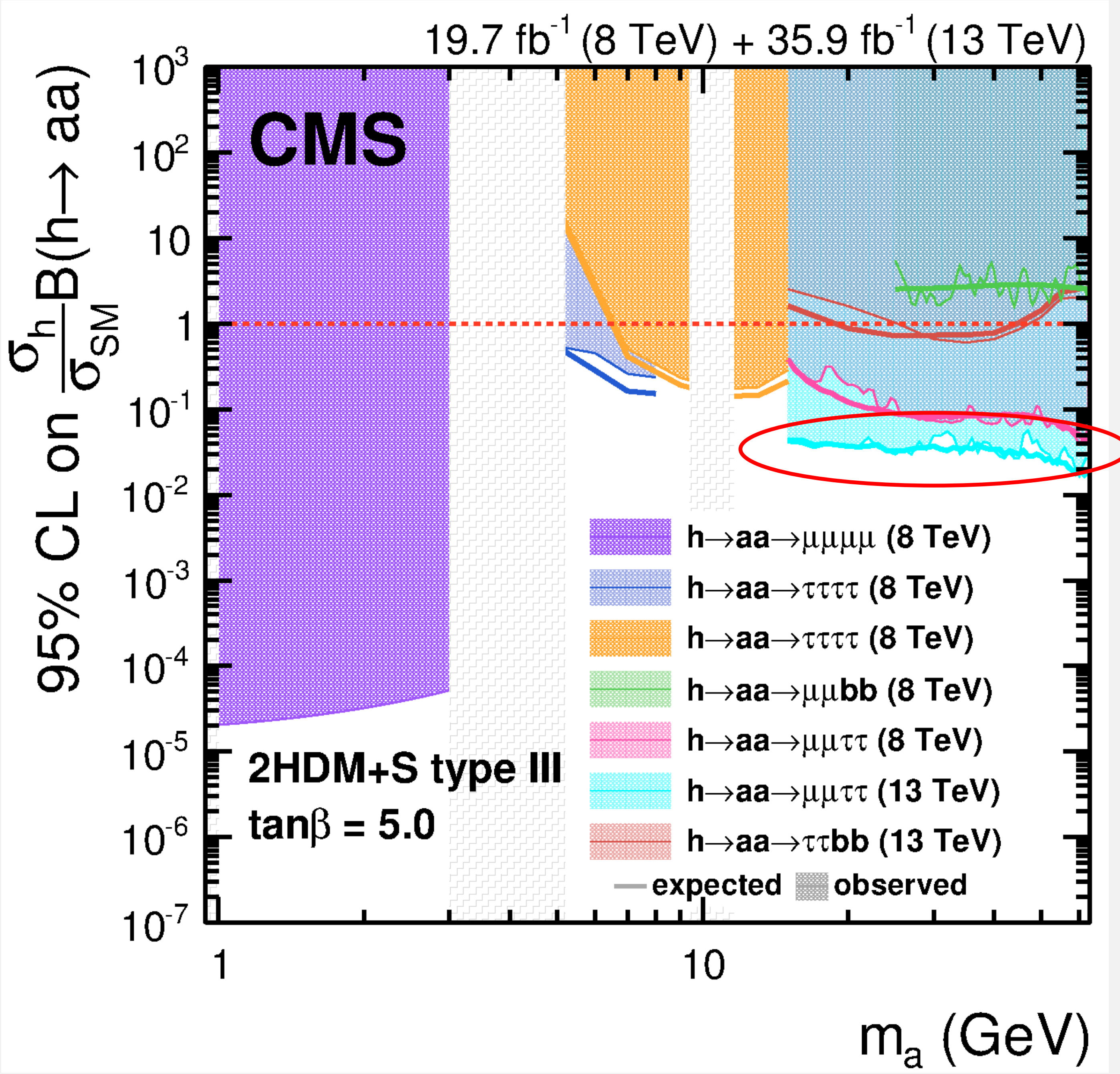
Irreducible

- 5th degree Bernstein polynomials⟶ Good fit quality in all the final states



(a) $\mu\mu e\mu$ (b) $\mu\mu e\tau_h$ (c) $\mu\mu\mu\tau_h$ (d) $\mu\mu\tau_h\tau_h$

Expected and observed 95% CL limits on σ_h/σ_{SM} X BR h(→ αα) in 2HDM+S type III for tan *β* = 5.

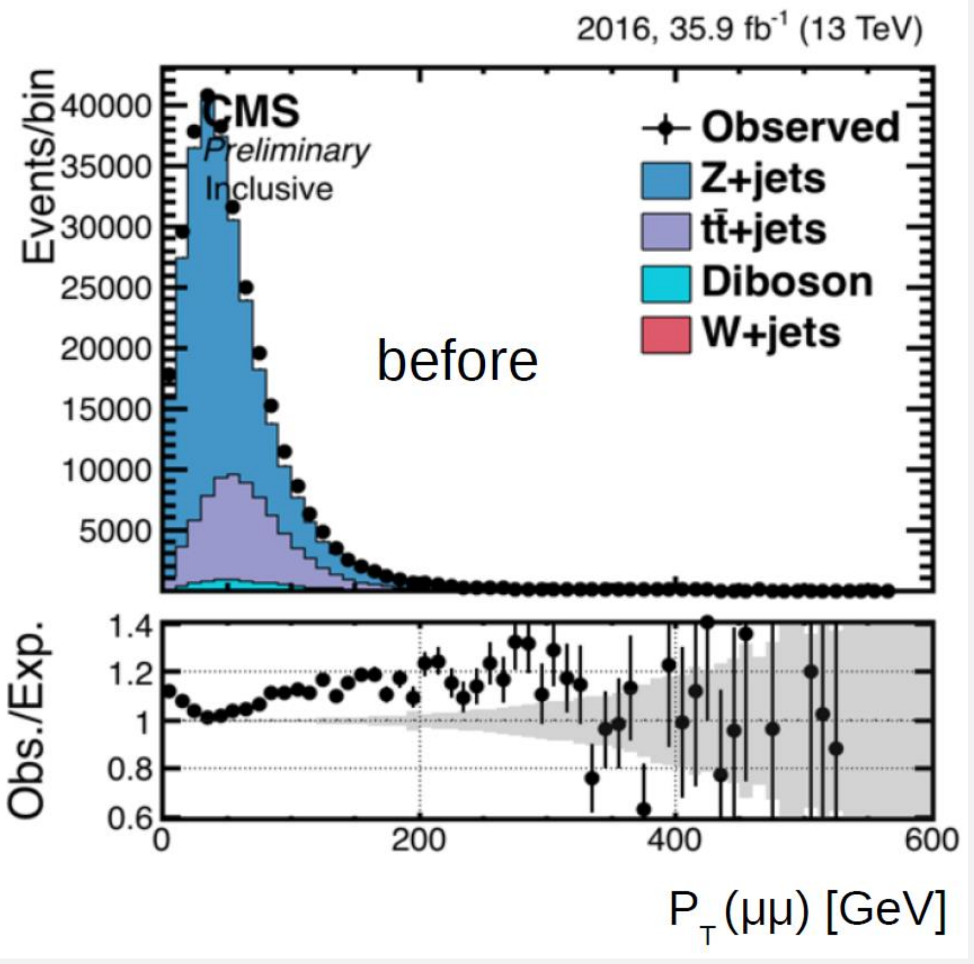


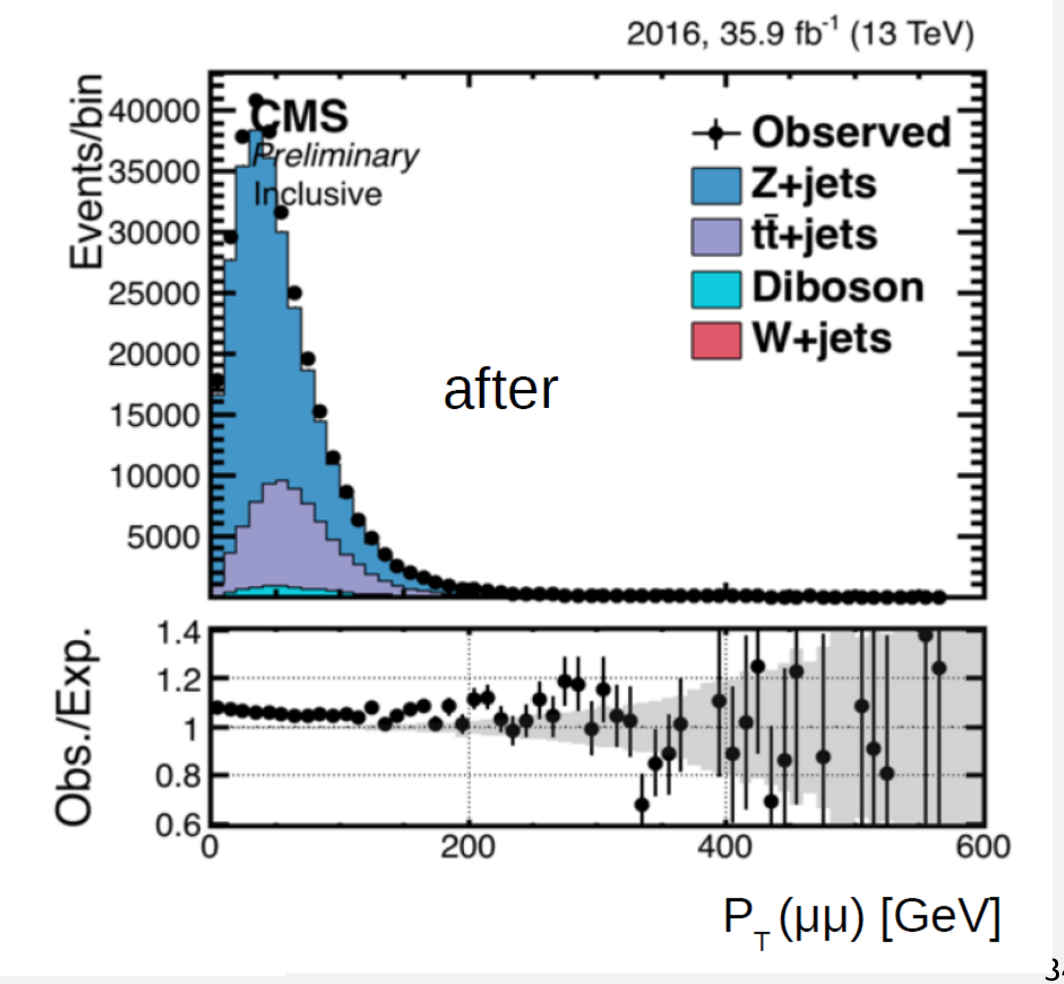
Limits improved by ~factor 2 for 20 < m_α < 62.5 GeV, and by one order of magnitude for 15 < m_α < 20 GeV

Corrections to Simulated samples

Z p_T corrections:

- Z p_T distribution disagreement between simulations and Data in $Z \rightarrow \mu\mu$ control region with ≥ 1bjet
- The correction has been re-measured and applied to $Z \rightarrow \tau\tau$ / $\ell\ell$ (signal region)





Corrections to Simulated samples

- **τ_h energy scale** :

-1.8%	**1 prong**
+1.0%	**1 prong + π^0**
+0.4%	**3 prong**

- **e/μ energy scale:** It depends on the reconstructed decay mode.
- **τ_h identification efficiency:** fs = 0.95, with tag and probe method.
- **e/μ identification efficiency:** is strongly depends on the pseudorapidity of the fake **τ_h**
- **recoil correction:** Recoil corrections for W+jets, Z+jets, and Higgs boson events .
- **Top p_T reweighting:** Corrections to tt bar simulation depend on the generated p_T of the top and anti top quarks.
- **B tagging efficiency:** depends on jet p_T and hadron flavor.
- **Pileup reweighting:** MC events are reweighted using minimum bias cross section equal to 69.2 mb