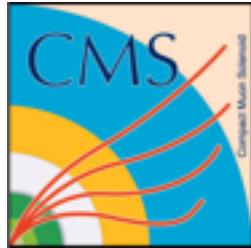


# SM HIGGS TO TAU TAU AND BEYOND AT CMS

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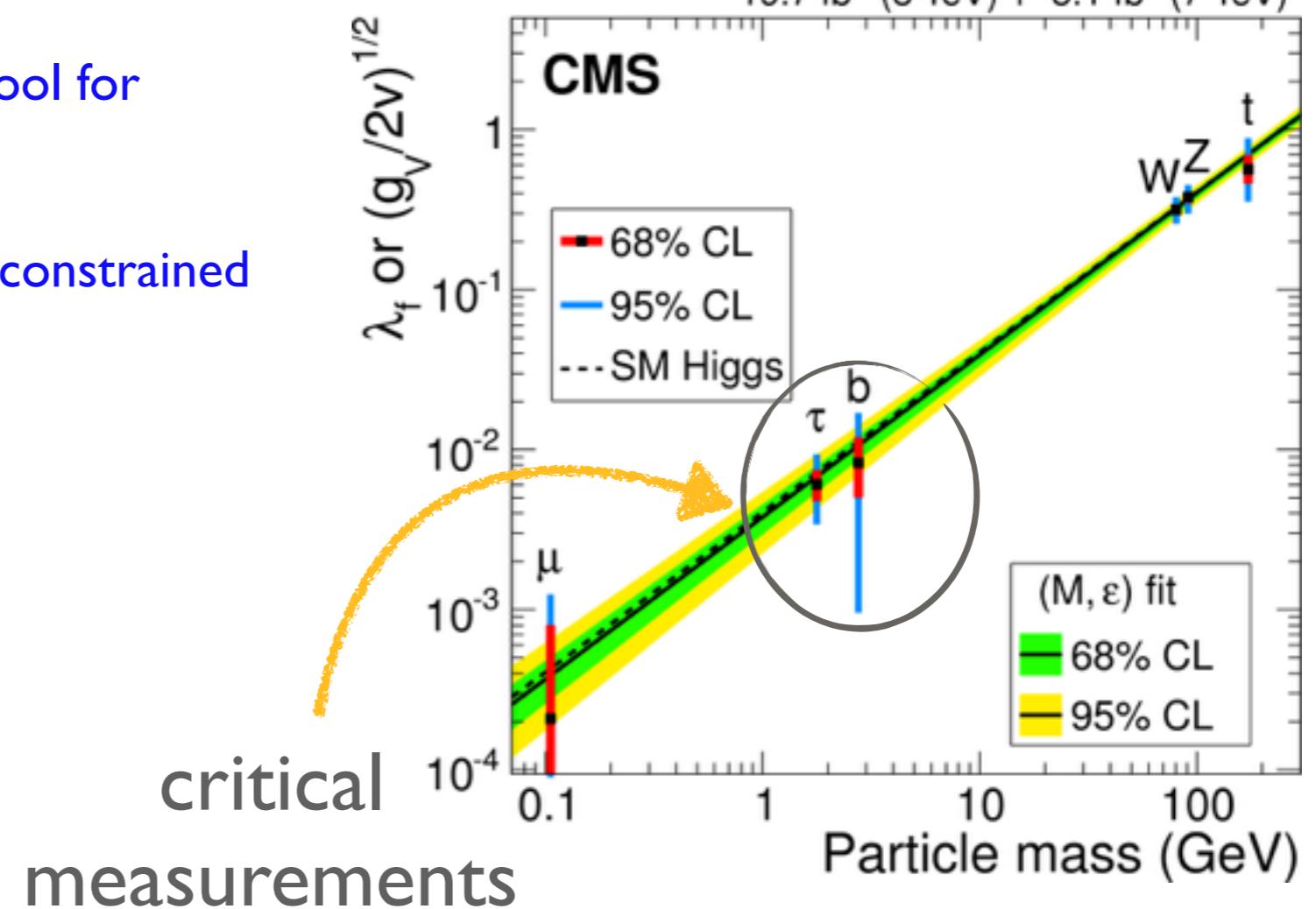
L. Dodd  
CMS Collaboration



# Overview

- CMS Standard Model Higgs to Tau Tau and Beyond
- 125 GeV Higgs decays to tau pairs
  - SM H->TT at 8TeV Analysis Overview
  - 125 GeV Higgs ->TT used as a tool for searches
    - Analysis where Di-Tau mass constrained to 125 GeV
  - And beyond
    - MSSM Higgs decays to TT
    - Light Higgs decays to TT
  - Prospects for 2016

Notation:  
 $T_e T_h$  will denote a tau decay to electron and neutrinos and a tau decaying to mesons and a neutrino





# Road Map

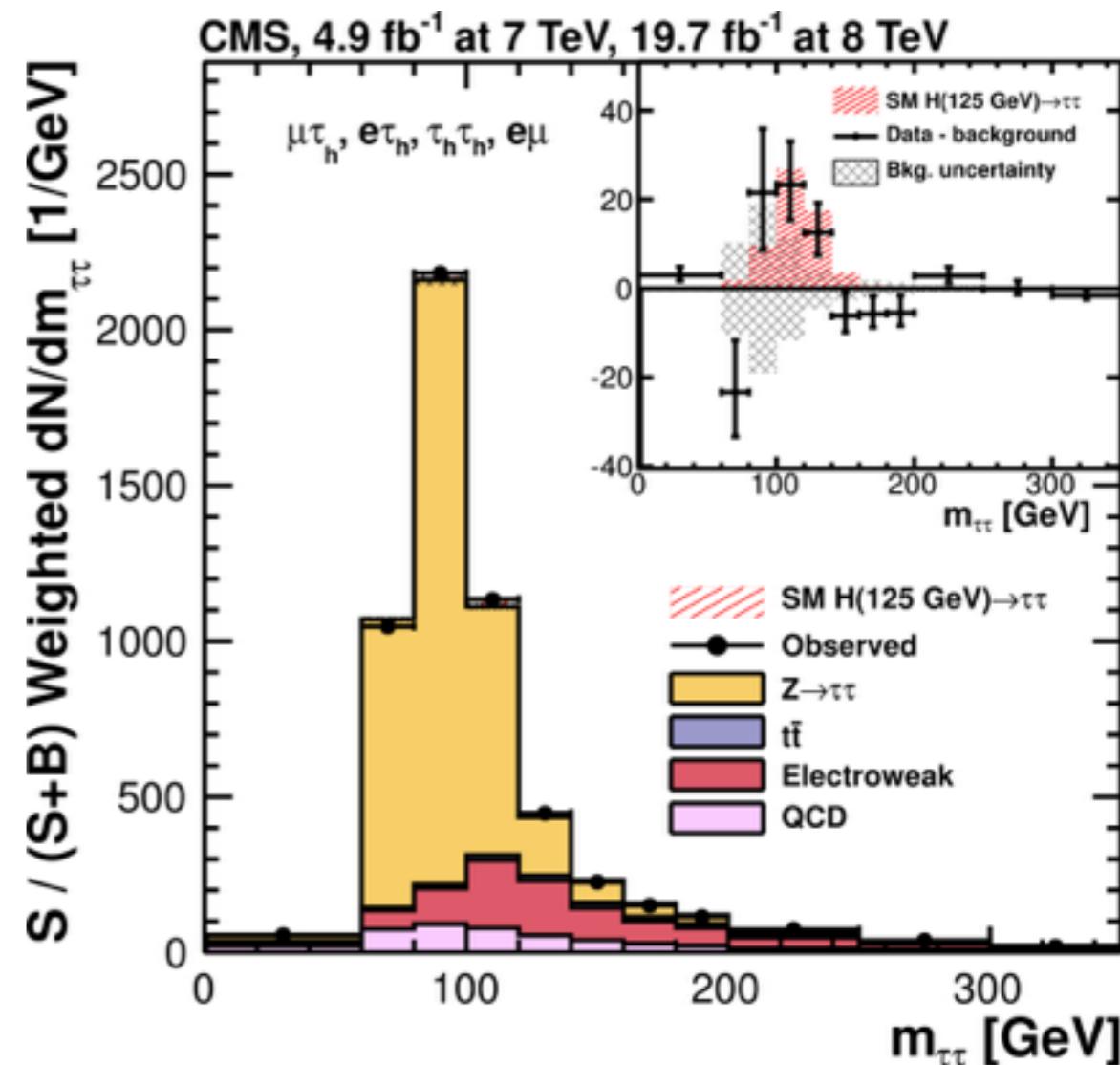
- CMS Higgs to Tau Tau
- I25 GeV Higgs
  - SM  $H \rightarrow \tau\tau$  at Run I
  - I25 GeV Higgs  $\rightarrow \tau\tau$  used as a tool for searches
  - And beyond: other masses
  - MSSM Higgs decays to taus
  - Light Higgs a
- Prospects for 2016

Please See Olivier's  
earlier talk on tau  
reconstruction and  
tau trigger within  
CMS!



# SM Higgs TauTau 8 TeV Analysis

- Straightforward mass-based analysis
- Used reconstructed invariant di-Tau mass for signal extraction.
  - Multi-Variate Analysis(MVA) correction for MET based of the decay modes of each tau.
  - SVFit
    - Mass reconstructed using likelihood fit to determine most probable 4 vectors of taus, and met.
    - Assume all met in event is from taus and need to specify what decay mode of each tau for accurate neutrino estimates
    - tau decay modes  $\tau_e \tau_h$ ,  $\tau_\mu \tau_h$ ,  $\tau_h \tau_h$ ,  $\tau_e \tau_\mu$ ,  $\tau_e \tau_e \tau_\mu \tau_\mu$  examined
    - WH/ZH addition



arXiv:1401.5041 [hep-ex]



# SM Higgs TauTau 8 TeV Analysis

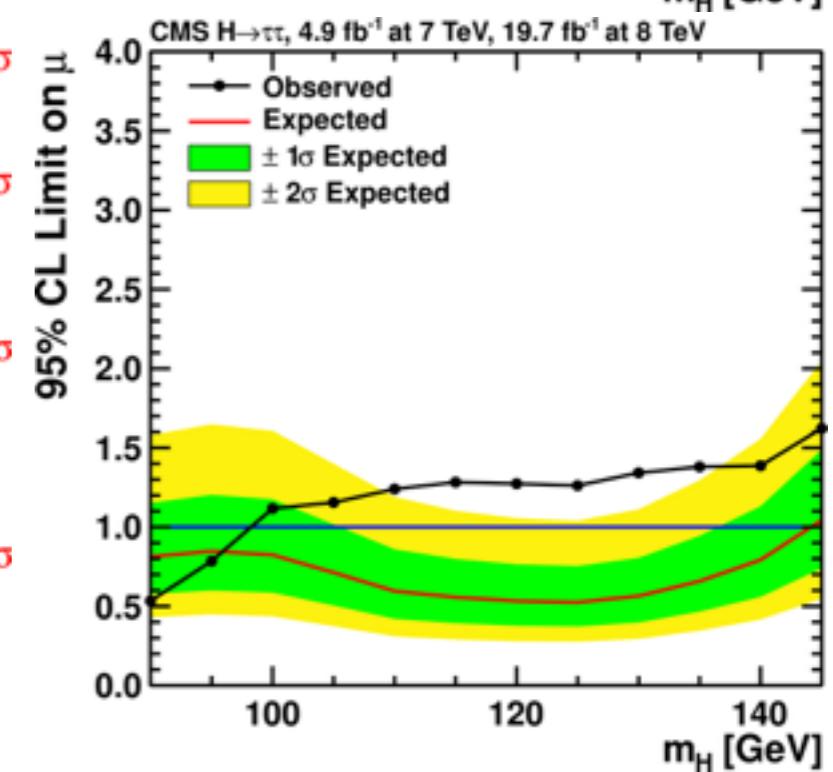
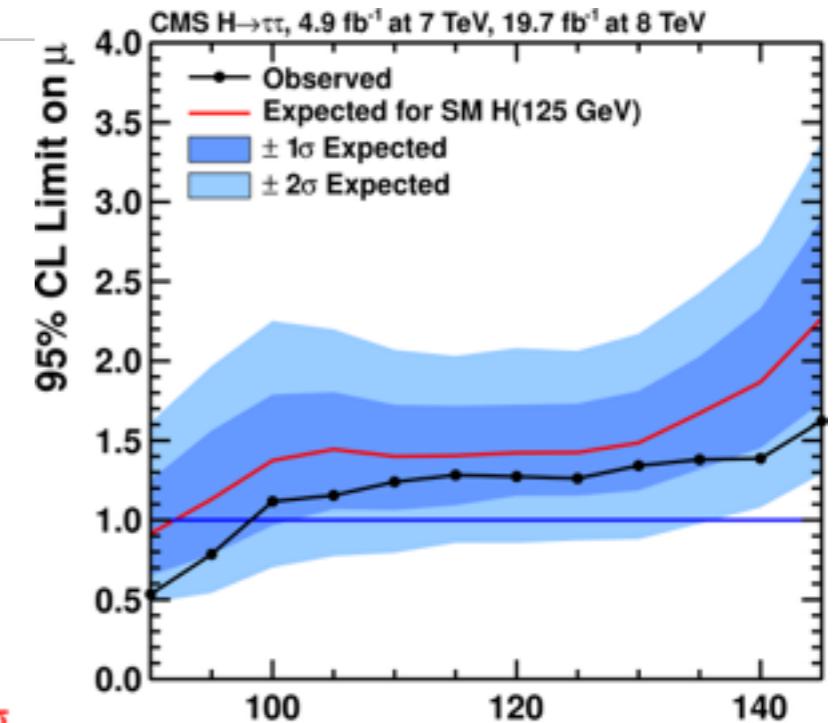
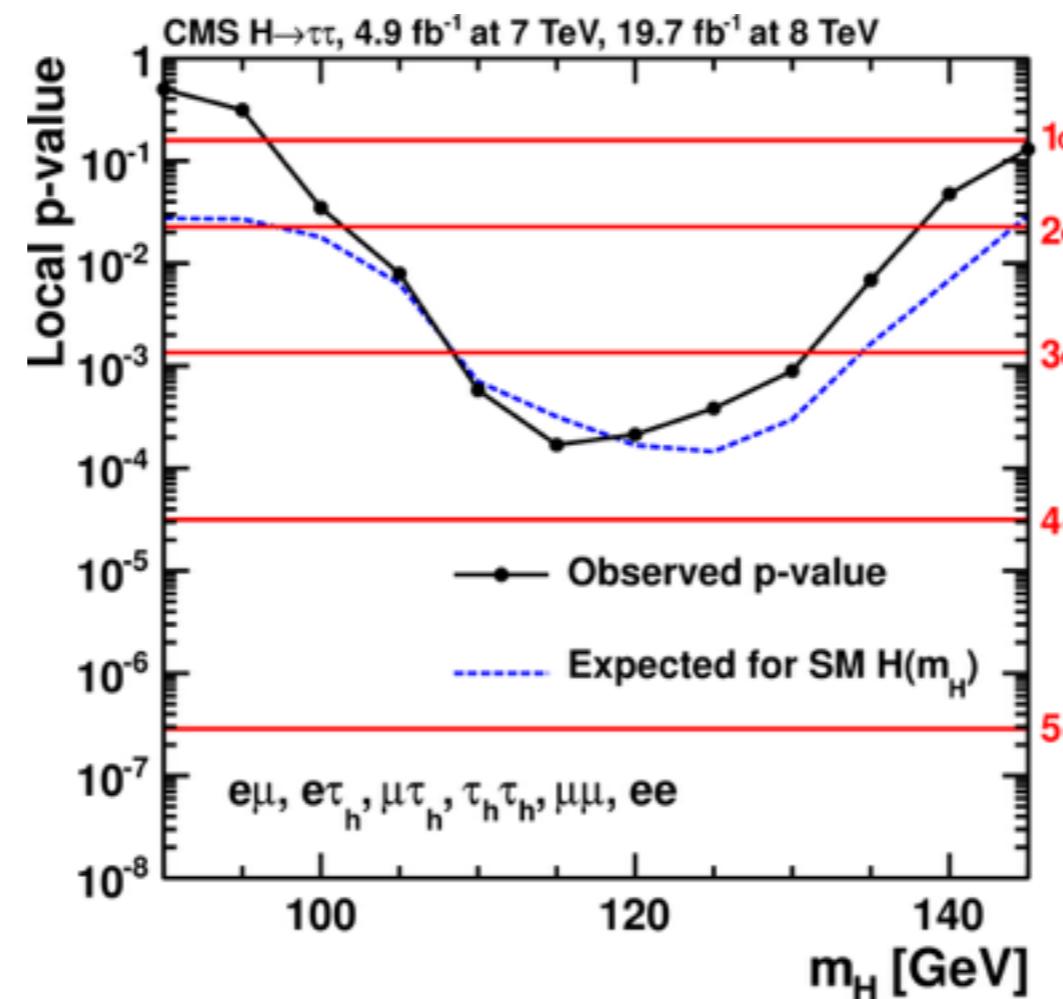
- 95% CL limits on SM  $H \rightarrow \tau\tau$  signal strength
- excess on mass spectrum from 115 GeV–135 GeV

discriminating variables used

$$M_T = \sqrt{2p_T E_T^{miss} (1 - \cos(\Delta\phi))}$$

$$p_T^{\tau\tau} = |\vec{p}_T^L + \vec{p}_T^{L'} + \vec{E}_T^{miss}|$$

$$M_{\tau\tau}^{SVfit}$$



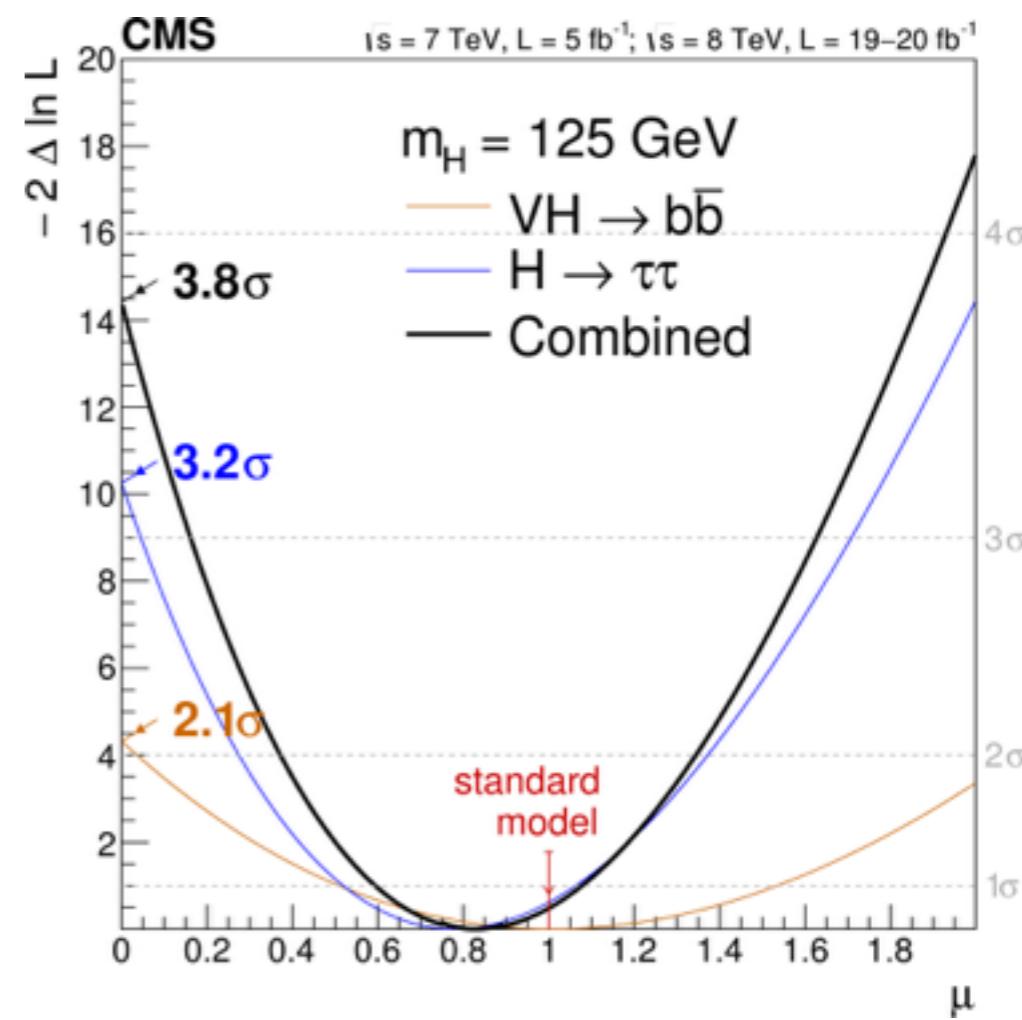
arXiv:1401.5041 [hep-ex]



# SM Higgs $\tau\tau$

- Fermionic decays of the 125 GeV Higgs Boson at  $3.8\sigma$  within CMS.
- In Run II will extend analysis with goal for  $H \rightarrow \tau\tau$  to reach  $5\sigma$  sensitivity

CMS fermionic $m_H = 125$	significance		$\mu$
	expected	observed	
$H \rightarrow \tau\tau$	3.7	3.2	$0.78 \pm 0.27$
$VH \rightarrow b\bar{b}$	2.3	2.1	$1.0 \pm 0.5$
combination	4.4	3.8	$0.83 \pm 0.24$

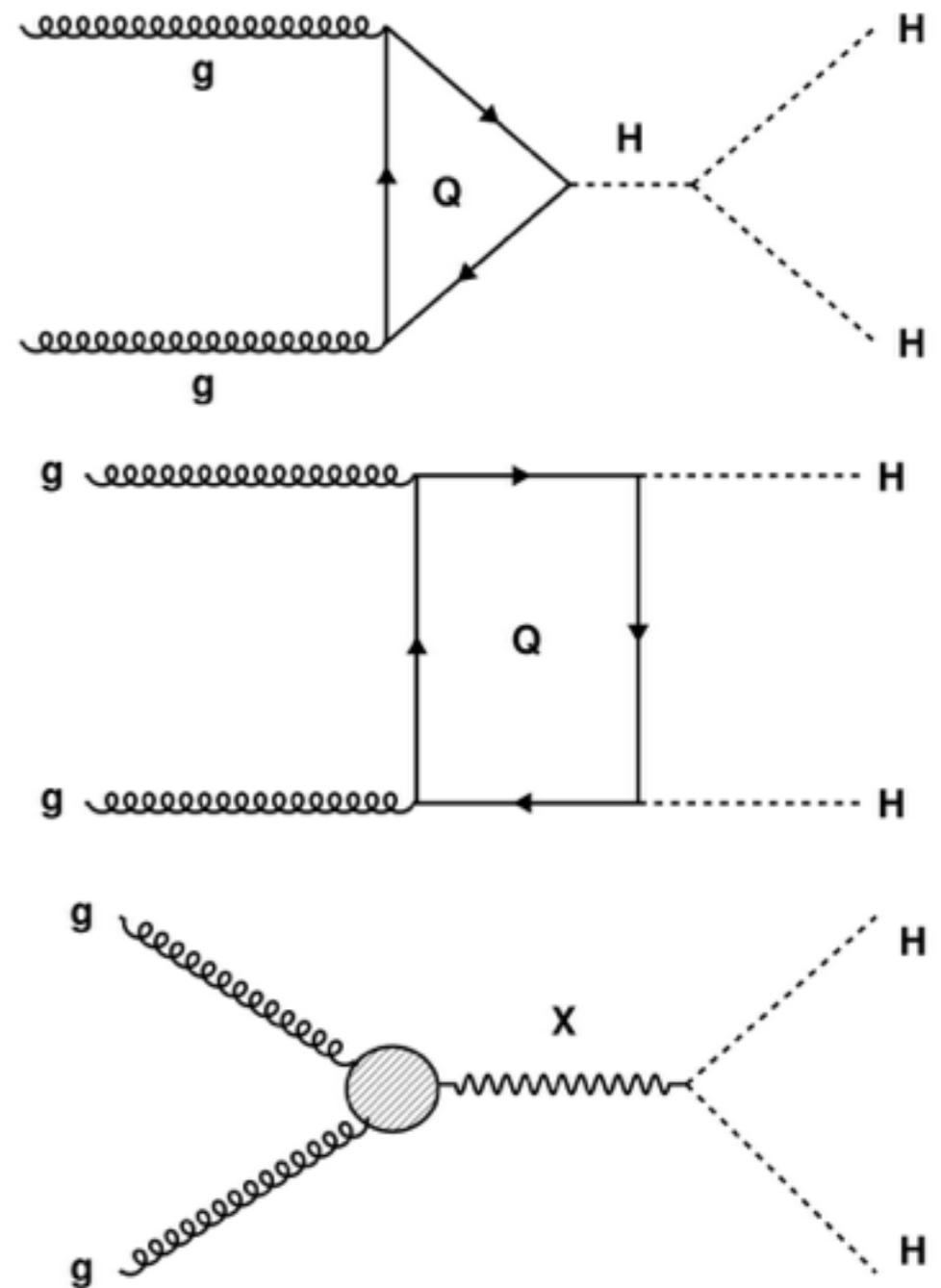


arXiv:1401.6527 [hep-ex]



# 125 GeV Higgs as a tool for discovery

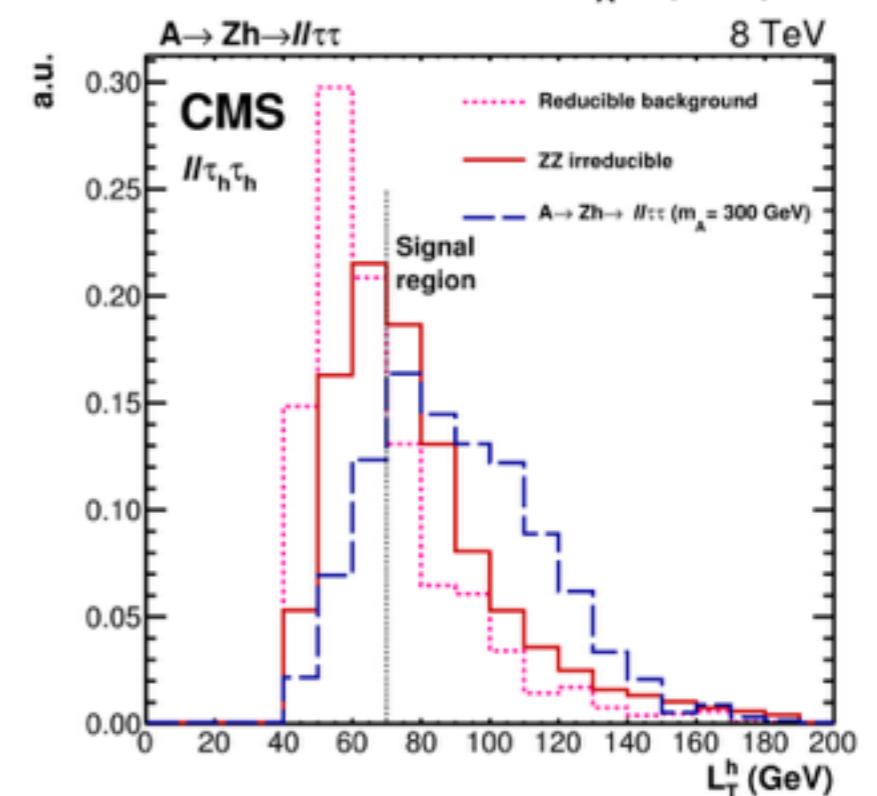
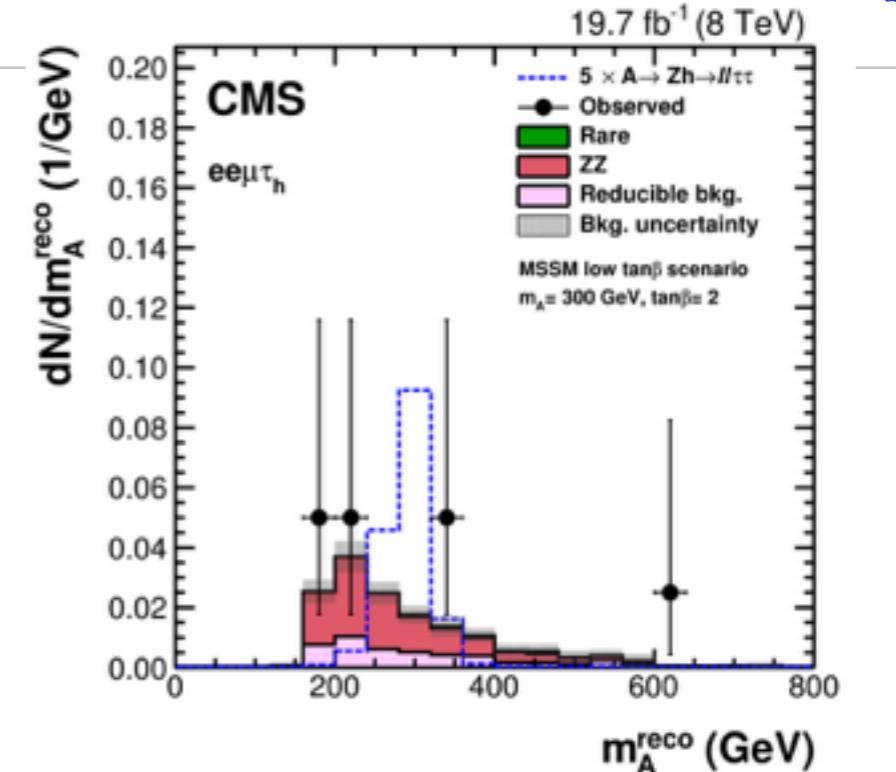
- Di-Higgs 2 main flavors
  - Measure: SM Trilinear Higgs coupling
  - Search: New heavy resonance  $X$
- Several di-Higgs  $b\bar{b}\tau\bar{\tau}$  analyses done at CMS
  - Non-resonant
    - Aims to measure trilinear Higgs coupling
  - Resonant analysis
    - Aims to reconstruct mass peak of “ $X$ ”
- VH Analysis
  - Search for resonant MSSM  $A \rightarrow Z h(125)$





# 8 TeV MSSM A->Z(ll) h(ττ)

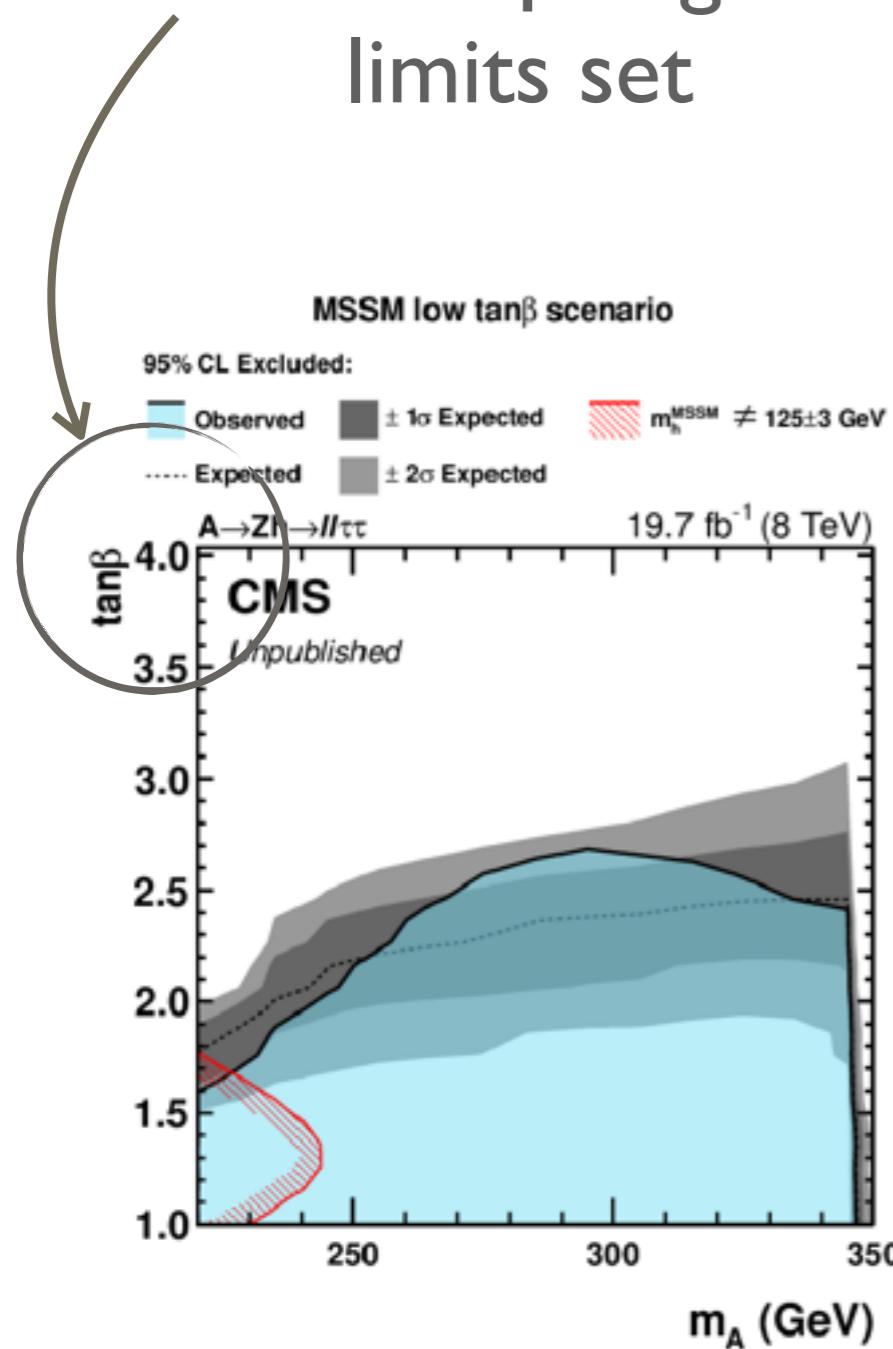
- MSSM search for Heavy pseudoscalar A decays to Zh
  - Trigger on a Z boson, and then look for h->ττ
- Low-statistics final state
  - Necessitated high BR for Higgs- 50 total events
  - SVFit used to reconstruct SM h->ττ
  - Invariant mass of Z -> ll with Z-boson mass window cut
  - Reducible backgrounds and irreducible backgrounds
  - $L_T^h$  scalar sum of transverse momentum of Higgs decay products cut at 70 GeV to reduce backgrounds, such as QCD



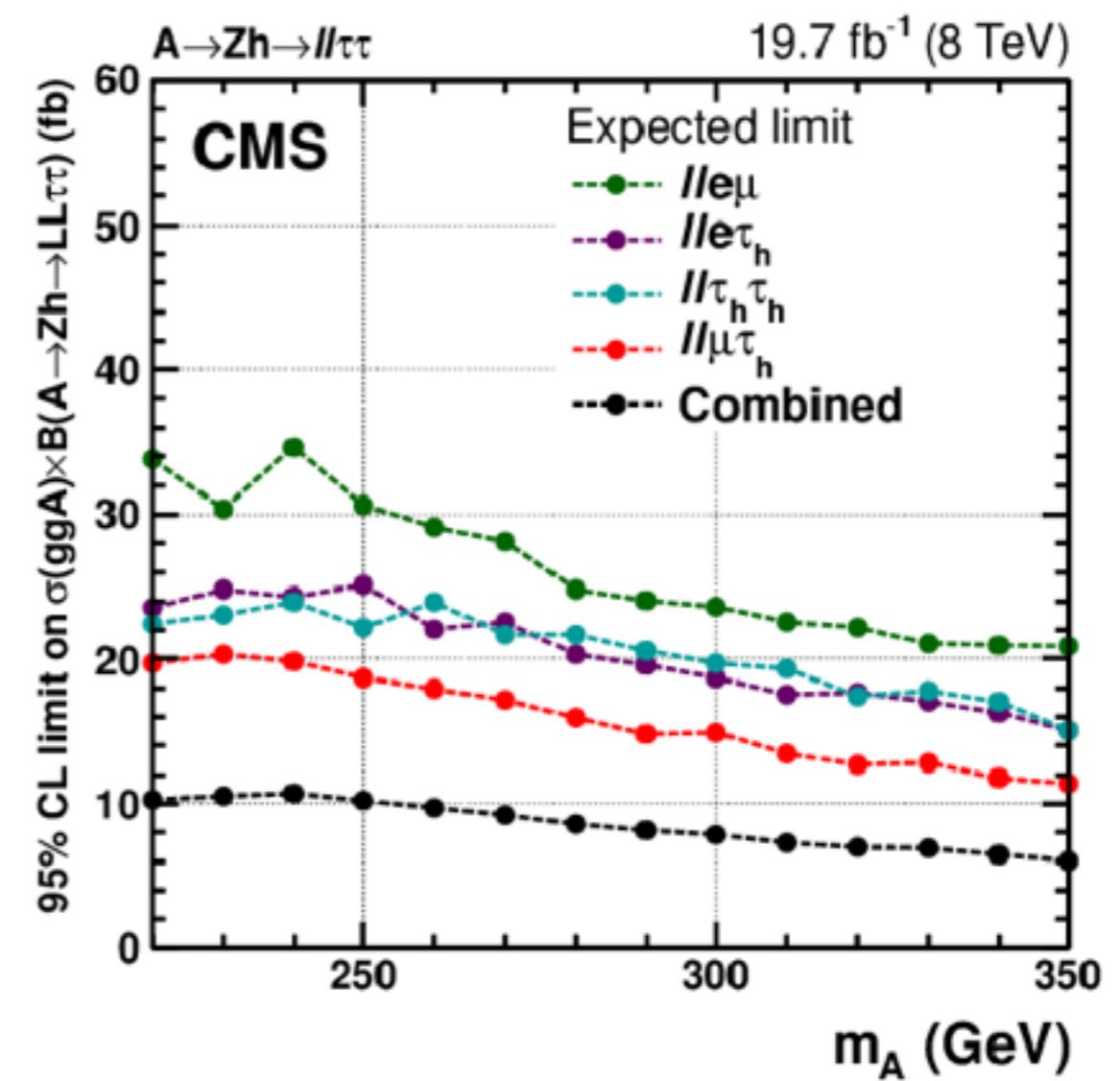


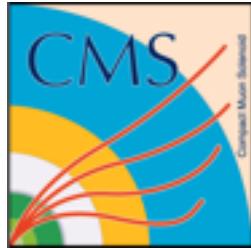
# 8 TeV MSSM A $\rightarrow$ Z(l l) h( $\tau\tau$ )

Low  $\tan\beta$  region  
limits set



Various limits depend  
on tau final states selected



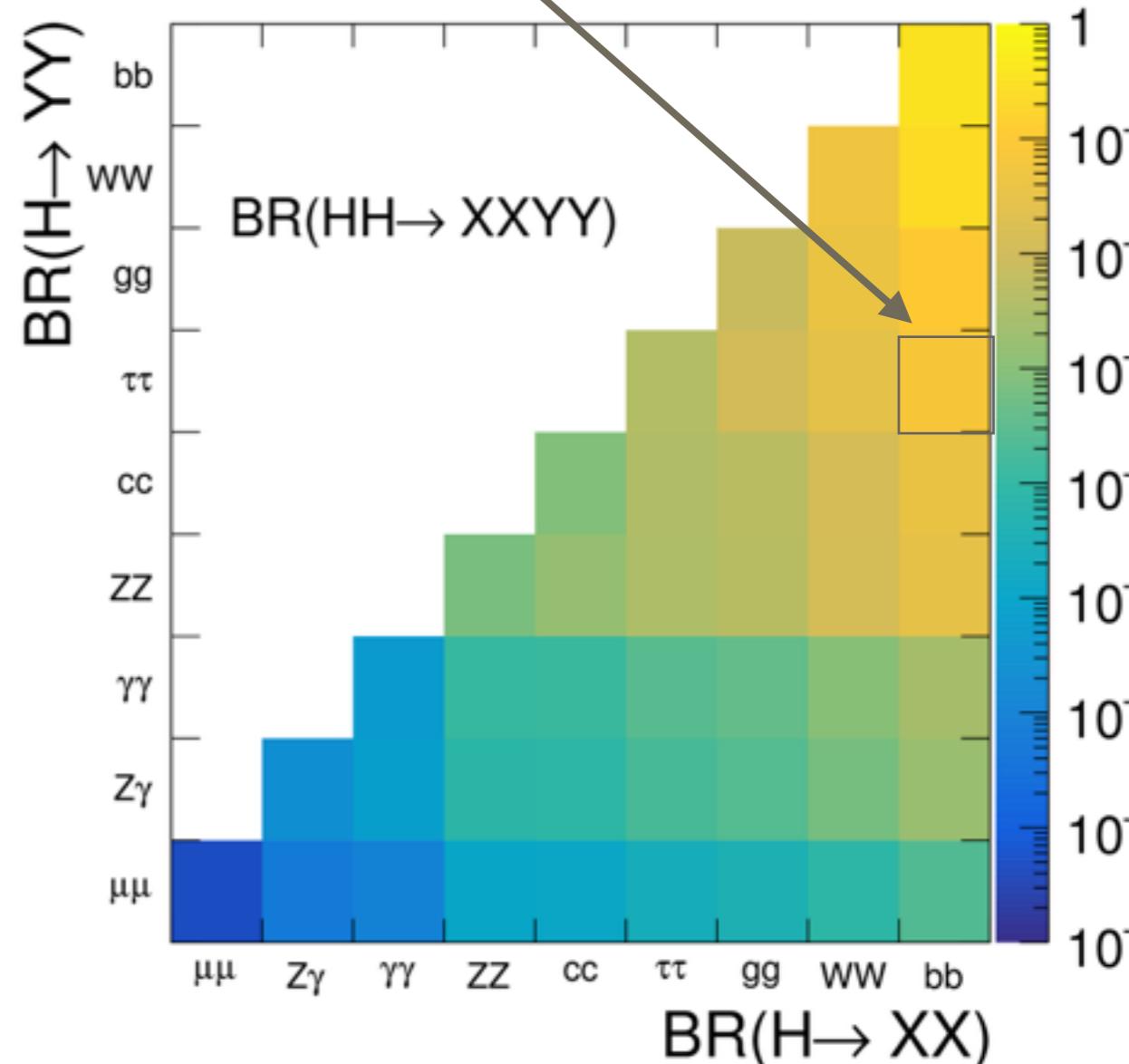


# bb $\tau\tau$



- Performed at 8 TeV
  - 8 TeV Run I in two different results
    - MSSM-driven analysis and Model Independent Analysis
  - Performed at 13 TeV in 2015 and 2016
    - 2016 Analysis has 12.9 /fb
      - Resonant and non-resonant production modes

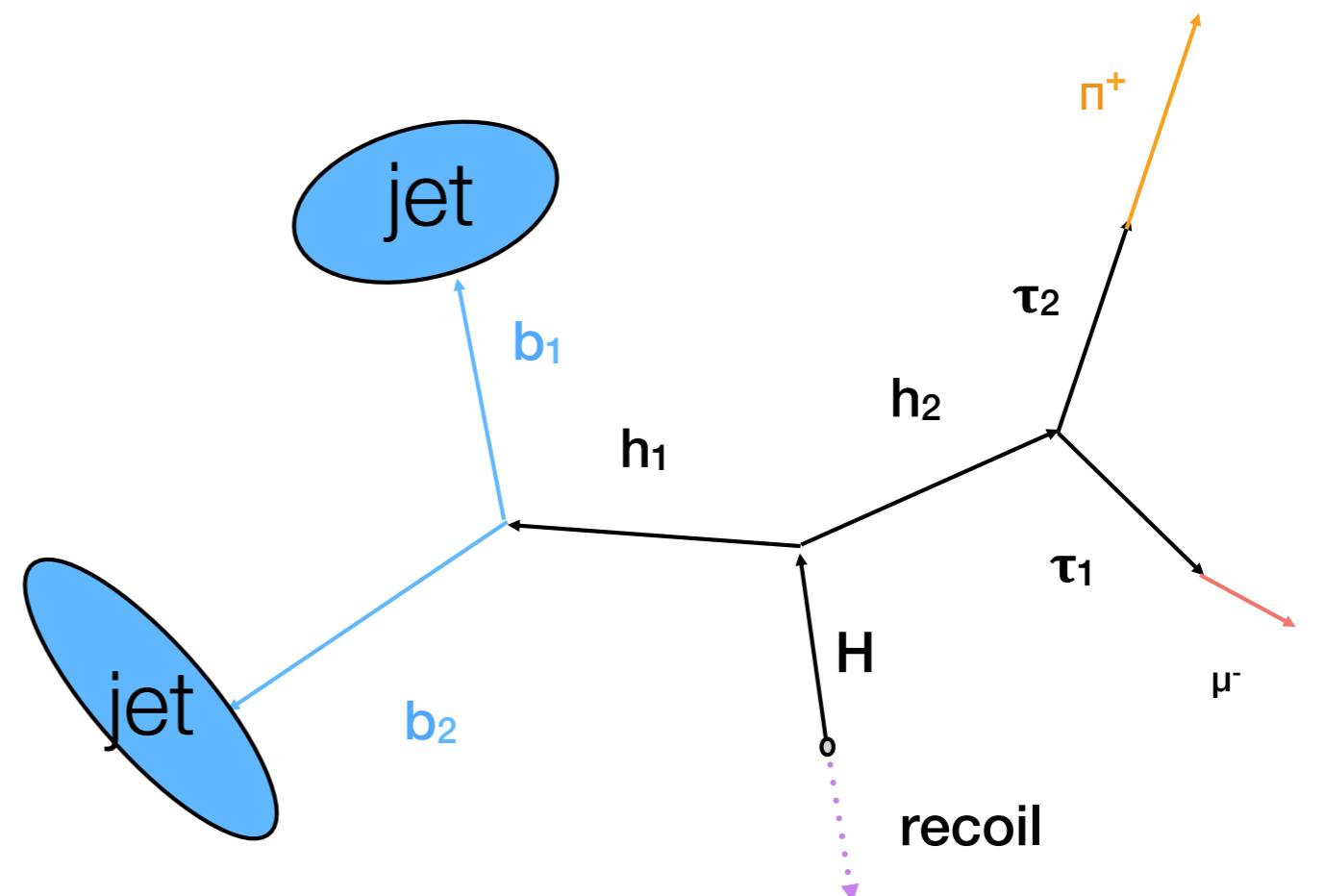
BR h(bb) h( $\tau\tau$ ) = 3.6%





- MSSM Analysis search for Heavy H decays to two 125 GeV h
- Probe low  $\tan\beta$  MSSM
- Model Independent analysis used same techniques and extended the mass range of the search
- Resonant and non-resonant

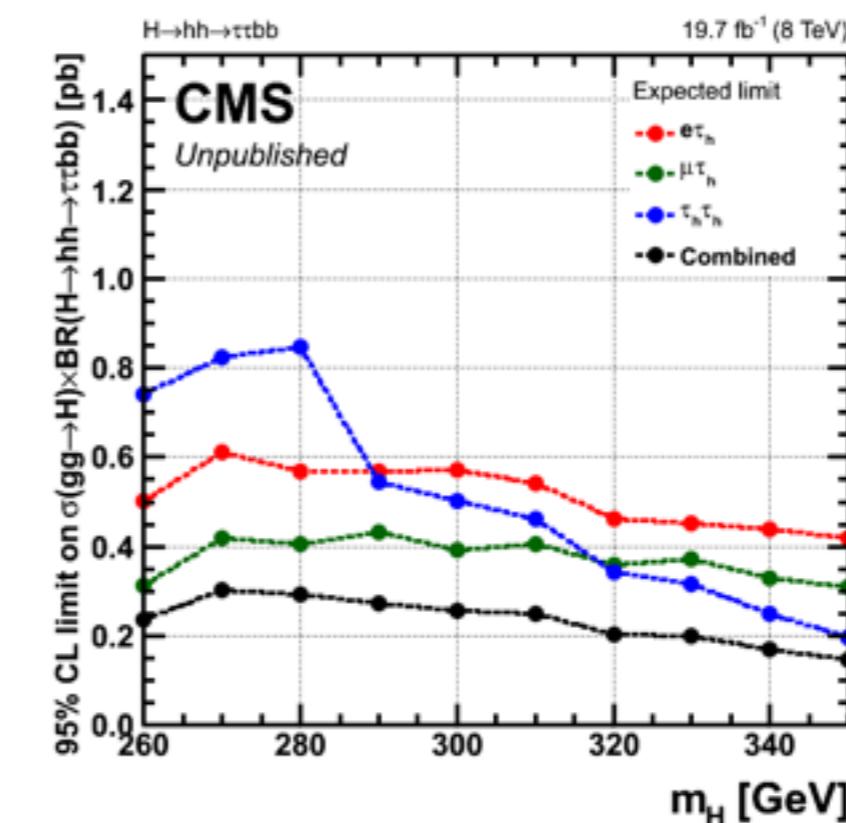
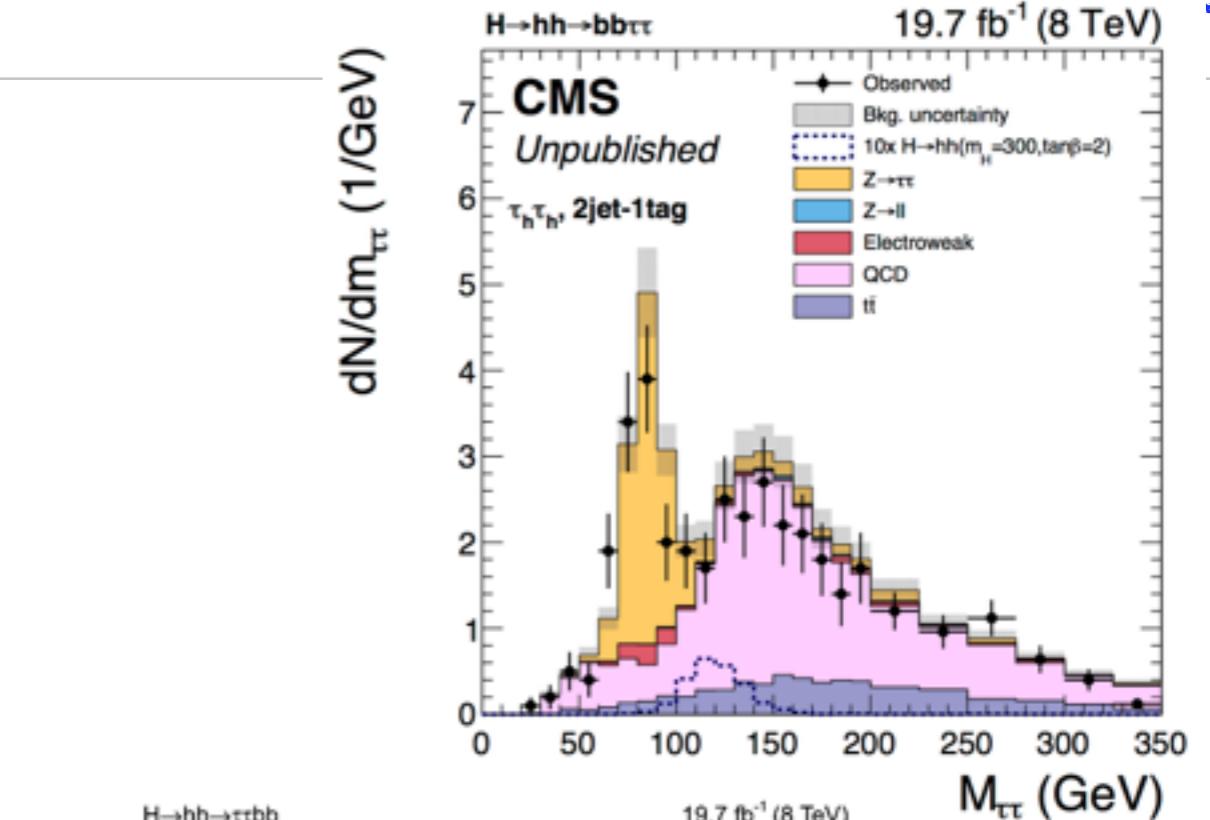
- HHKinFit
  - Maximum likelihood fit for mass Heavy Higgs, H, using the topology below.
  - Input: (1) SVfit rebuilds  $H \rightarrow \tau\tau$  first (2) 2 Reconstructed Jets
  - Di-jet invariant mass constrained to be 125 GeV





# 8 TeV MSSM $H \rightarrow hh \rightarrow bb\tau\tau$

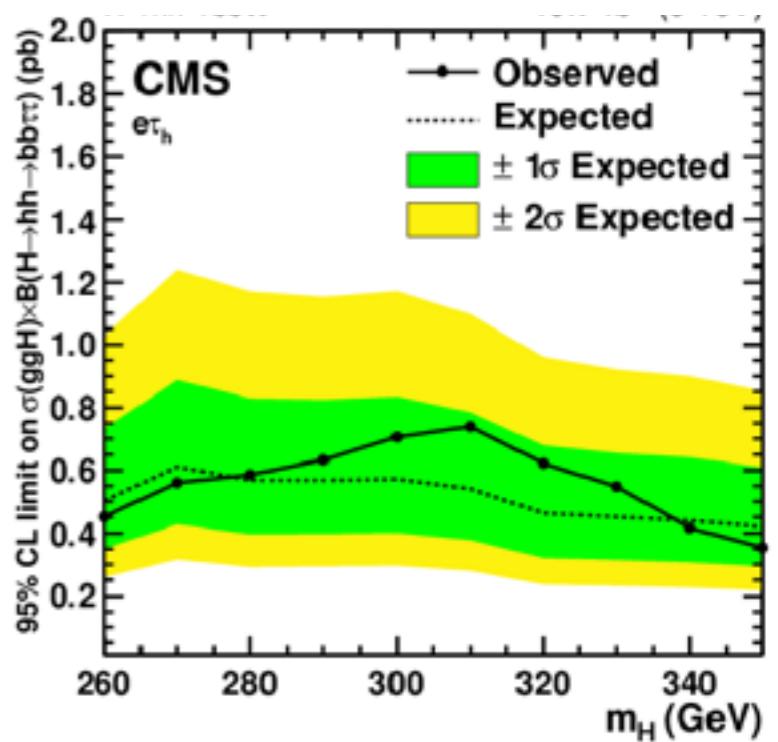
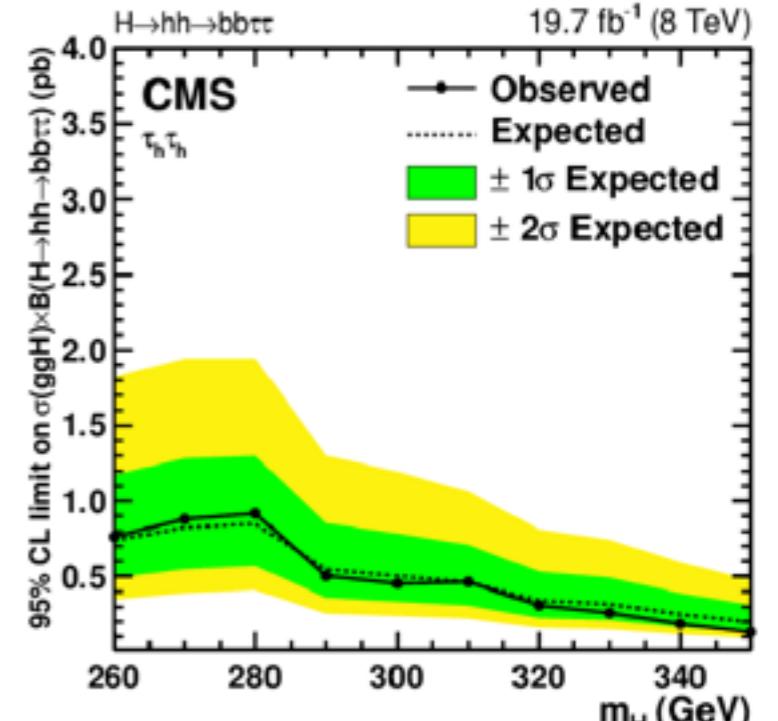
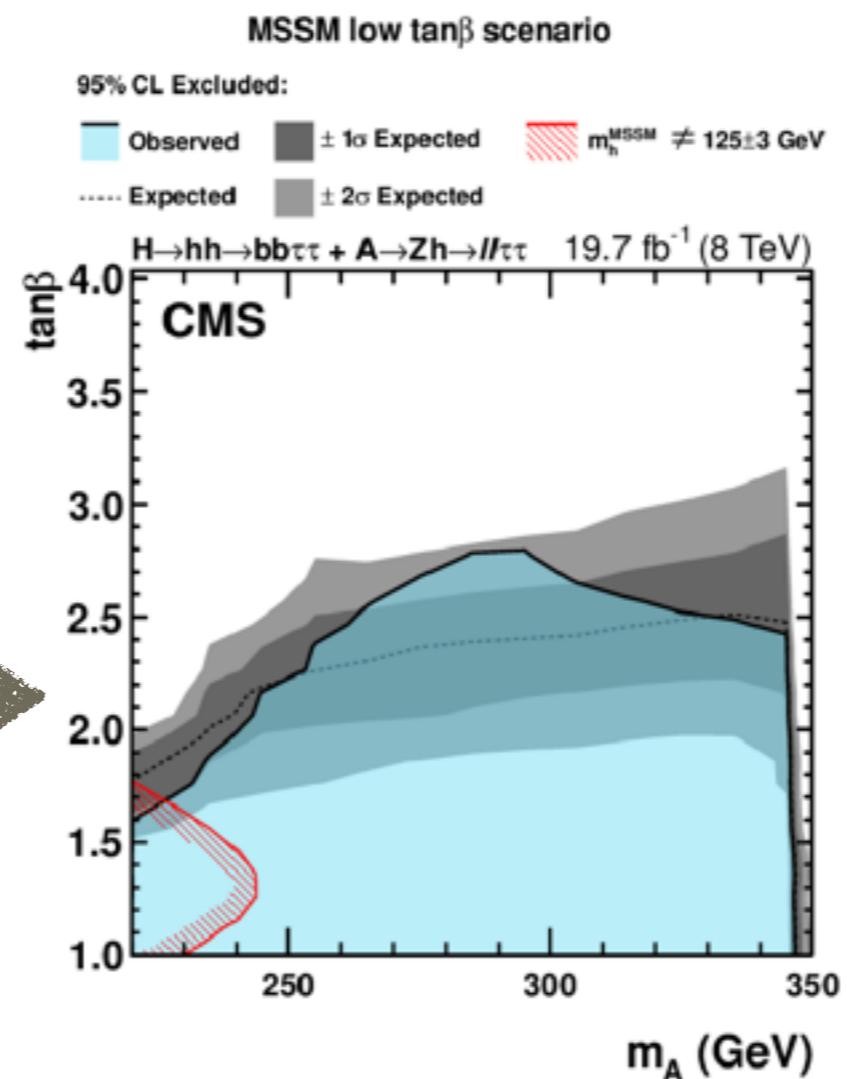
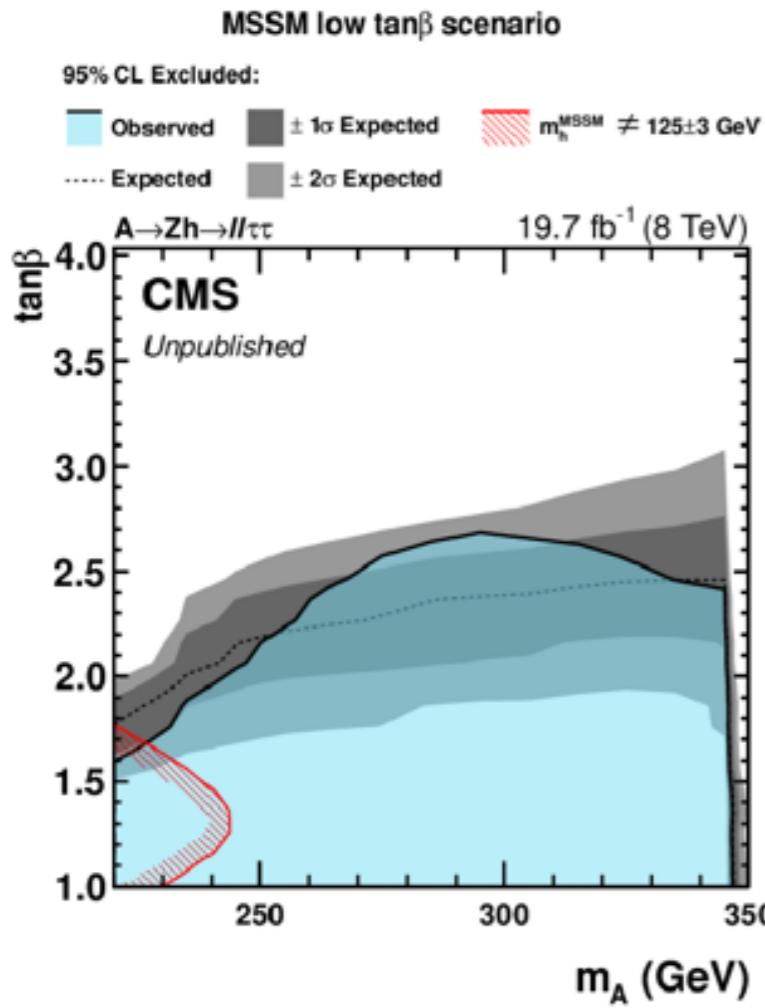
- MSSM Analysis search for Heavy H decays to two 125 GeV h
  - Kinematic fits assume no other MET in event
  - Tau decay Modes:  $\tau_e\tau_h$   $\tau_\mu\tau_h$   $\tau_h\tau_h$   $\tau_e\tau_\mu$ 
    - $\tau_\mu\tau_h$  most sensitive at low  $M_H$ - similar to Legacy SM Higgs result.
    - $\tau_h\tau_h$  drives limit at high mass.
  - Performed in tandem with  $A \rightarrow Zh$  to probe low  $\tan\beta$  MSSM





# 8 TeV MSSM $H \rightarrow hh \rightarrow bb\tau\tau$

- A $\rightarrow$ Zh set stronger limits in  $M_A$ - $\tan\beta$  plane

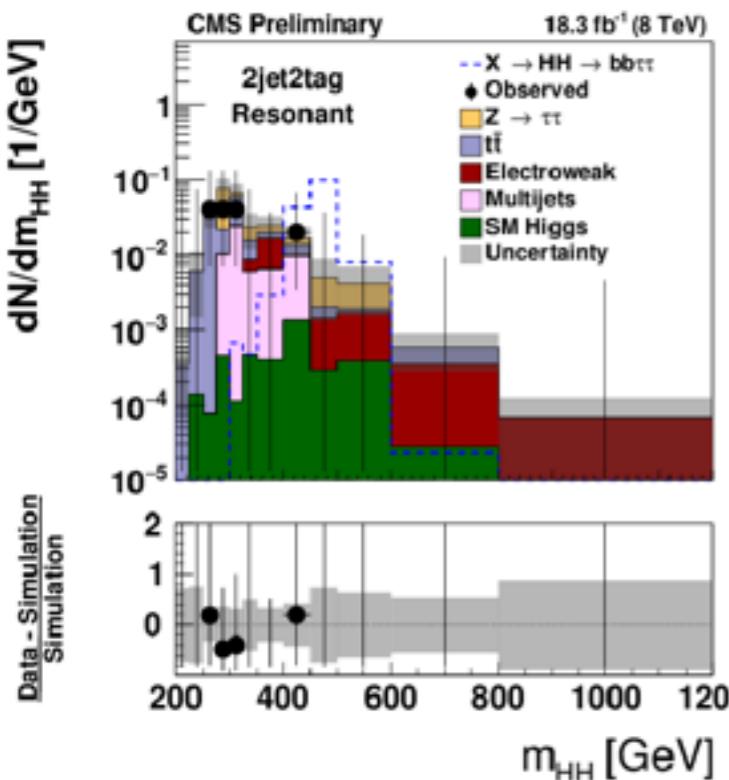




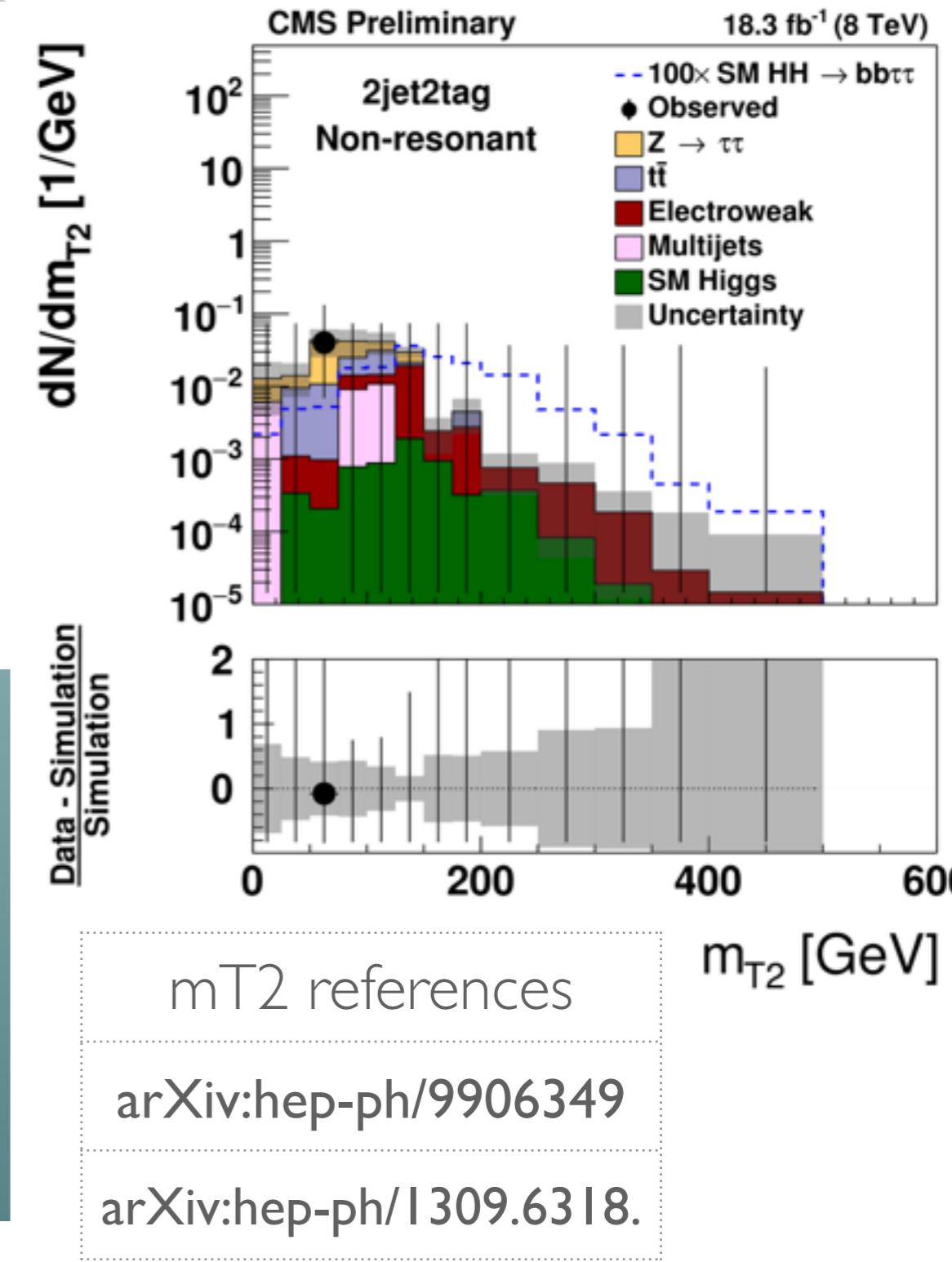
# 8 TeV Model-Independent $bb\tau\tau$

- Extend Mass range, Model Independent
- Two different mass variables used
  - Kinematic Likelihood Fit (same as MSSM  $bb\tau\tau$  Strategy)
  - new variable  $M_{T2}$  used for non-resonant search.

$M_{HH}^{Kin.\,fit}$



For  $t\bar{t}$  background  
 $m_{T2}$  is bounded above by the top quark mass.  
For hh signal it is not bounded



mT2 references

arXiv:hep-ph/9906349

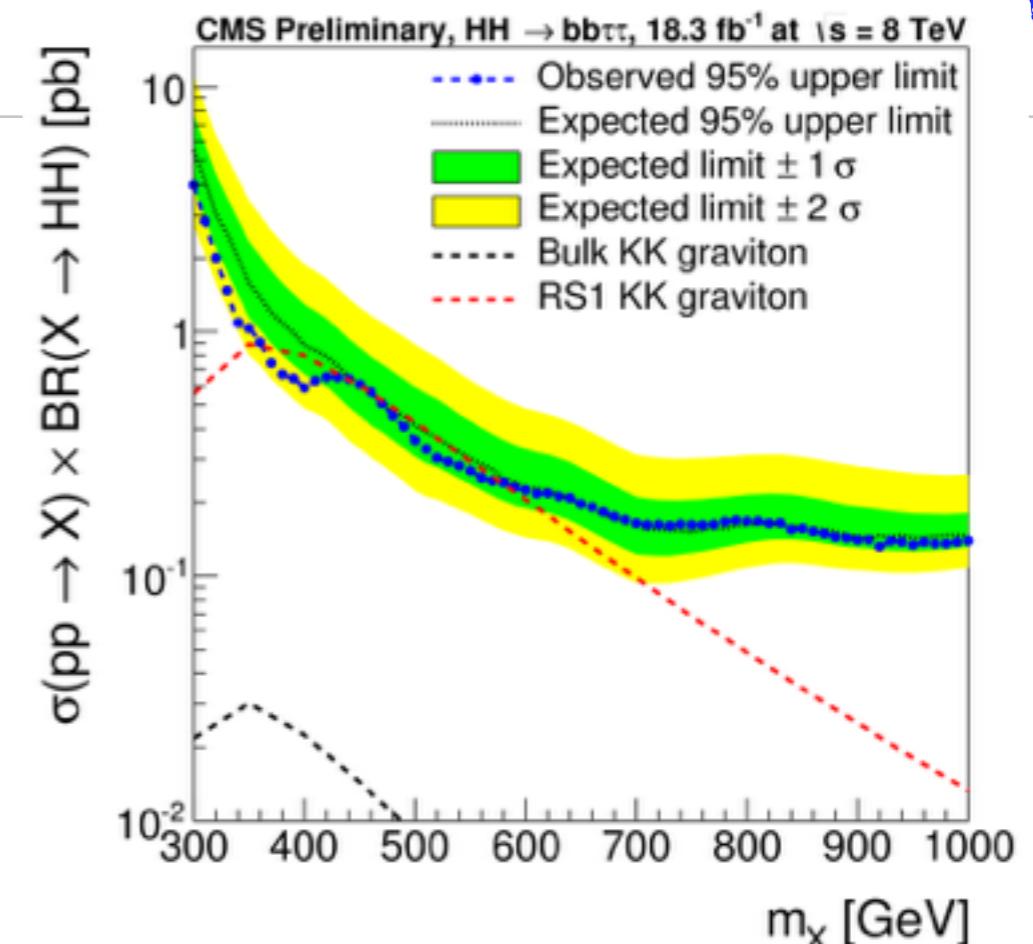
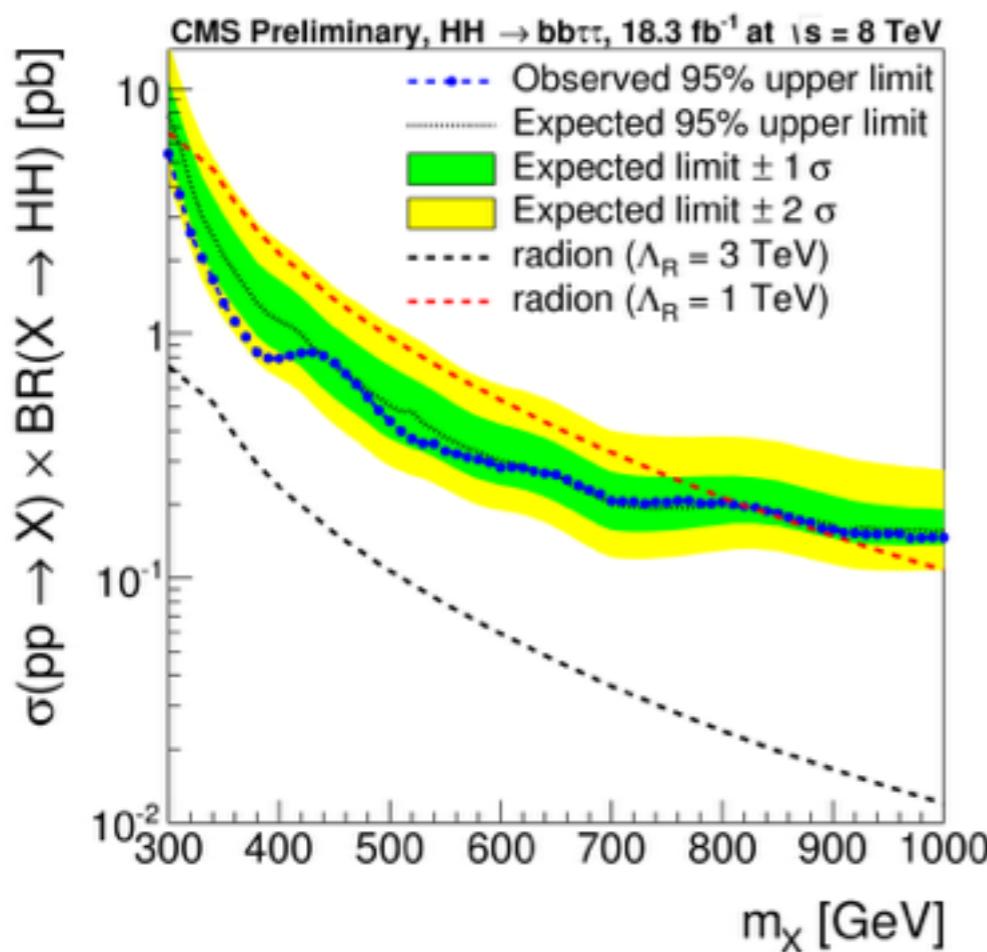
arXiv:hep-ph/1309.6318.



# 8 TeV Model-Independent $b\bar{b}\tau\tau$



- Interpreted in Spin-0 and Spin-2 models



$m_X$ [GeV]	Radion ( $J = 0$ )		Graviton ( $J = 2$ )	
	Expected	Observed	Expected	Observed
300	7.78	5.42	5.51	3.97
350	2.08	1.33	1.58	1.03
400	1.13	0.79	0.87	0.58
450	0.73	0.75	0.61	0.60
500	0.50	0.44	0.41	0.36
600	0.30	0.28	0.23	0.23
700	0.20	0.21	0.16	0.16
800	0.19	0.20	0.16	0.16
900	0.16	0.16	0.14	0.14
1000	0.15	0.14	0.14	0.14

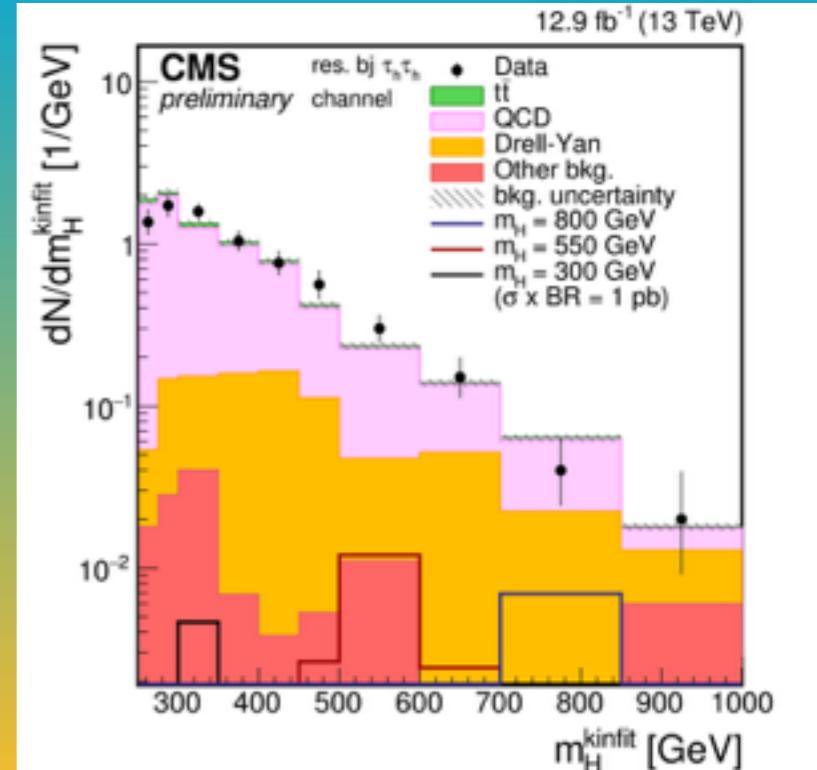
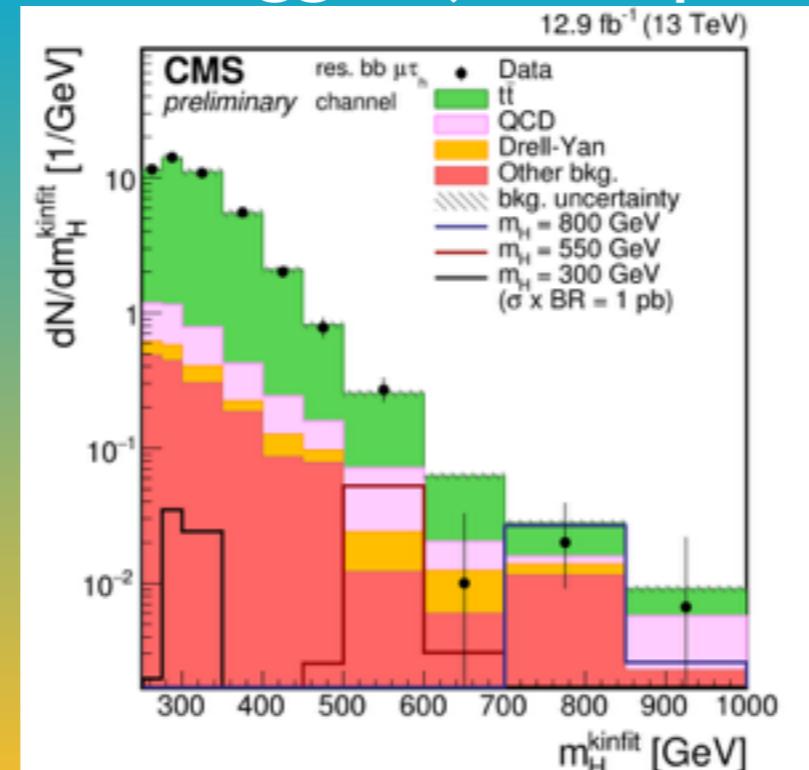
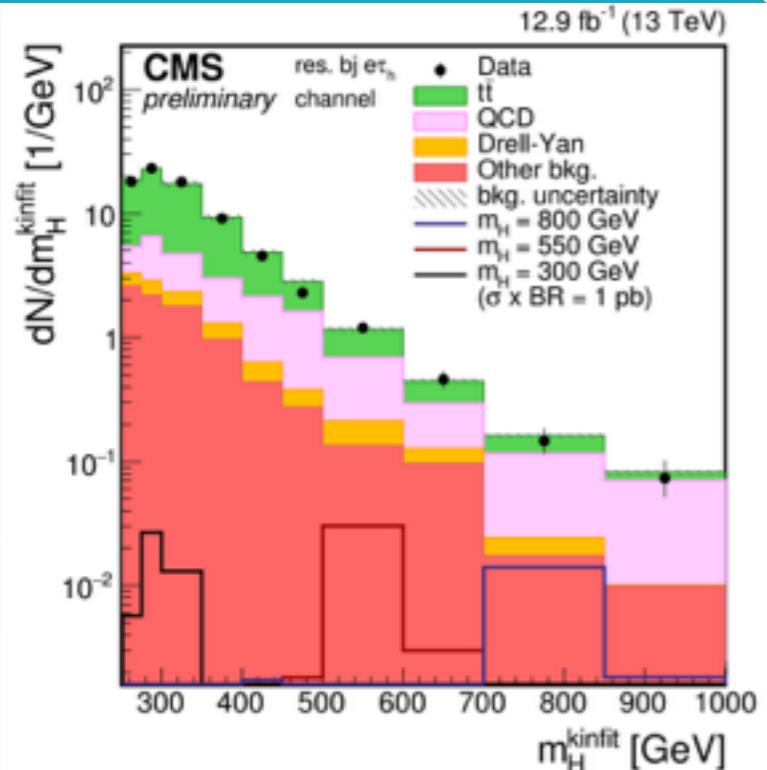


# 13 TeV bb $\tau\tau$ resonant: resolved

- At 13 TeV bb $\tau\tau$  analysis for resonant di higgs(bb $\tau\tau$ ) production was performed
- A “resolved”, where ak4 jets are reconstructed for Hbb, and a “boosted” region where the two jets are contained within an ak8 fat jet.
  - Single muon (electron) triggers used for  $\tau_\mu(\tau_e)$  final states
  - Double hadronic tau trigger was used for  $\tau_h\tau_h$  channel

Split into 2 categories  
 (1) 1-jet 1 b-tagged jet  
 (2) 2 b-tagged jets

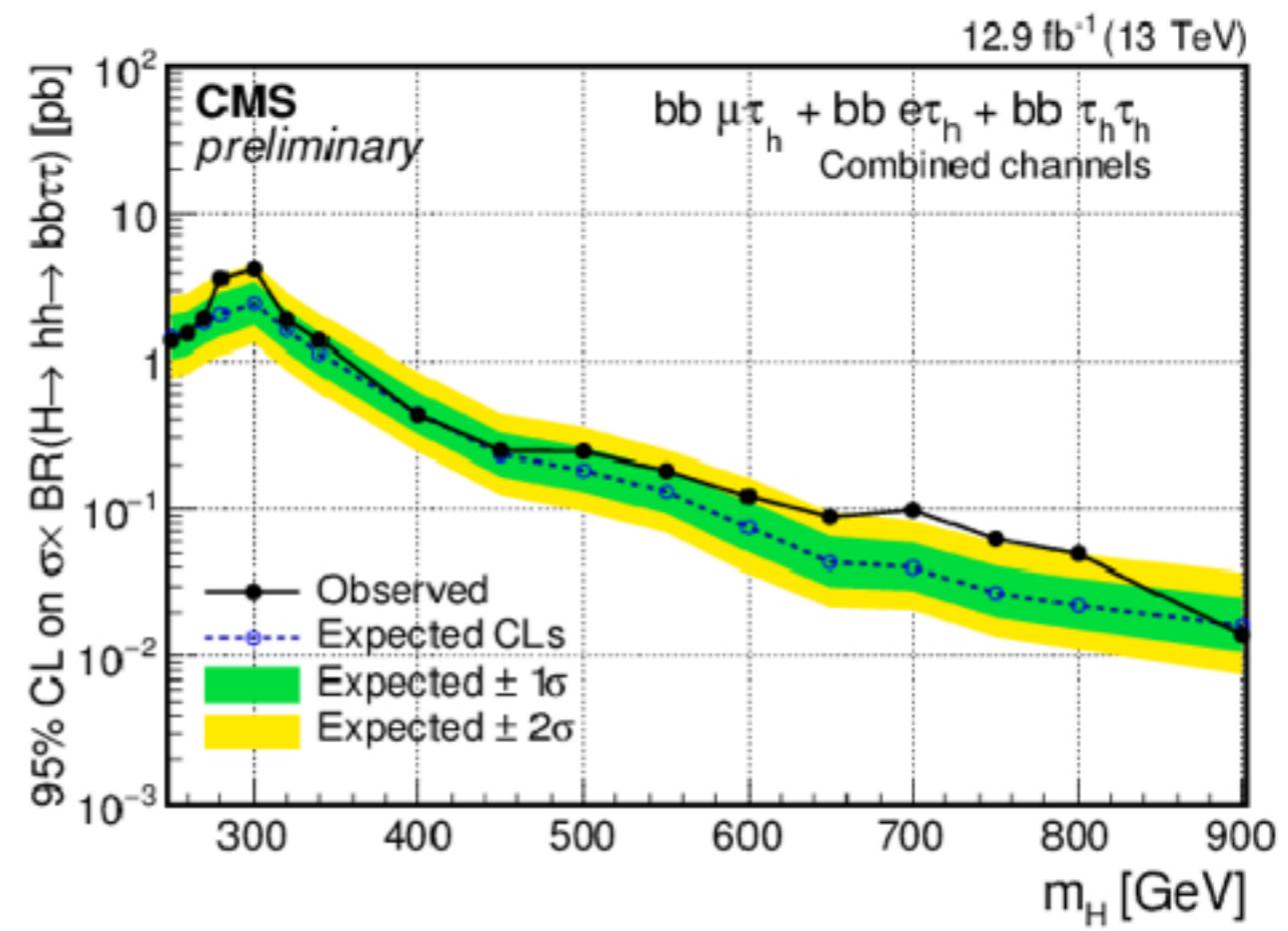
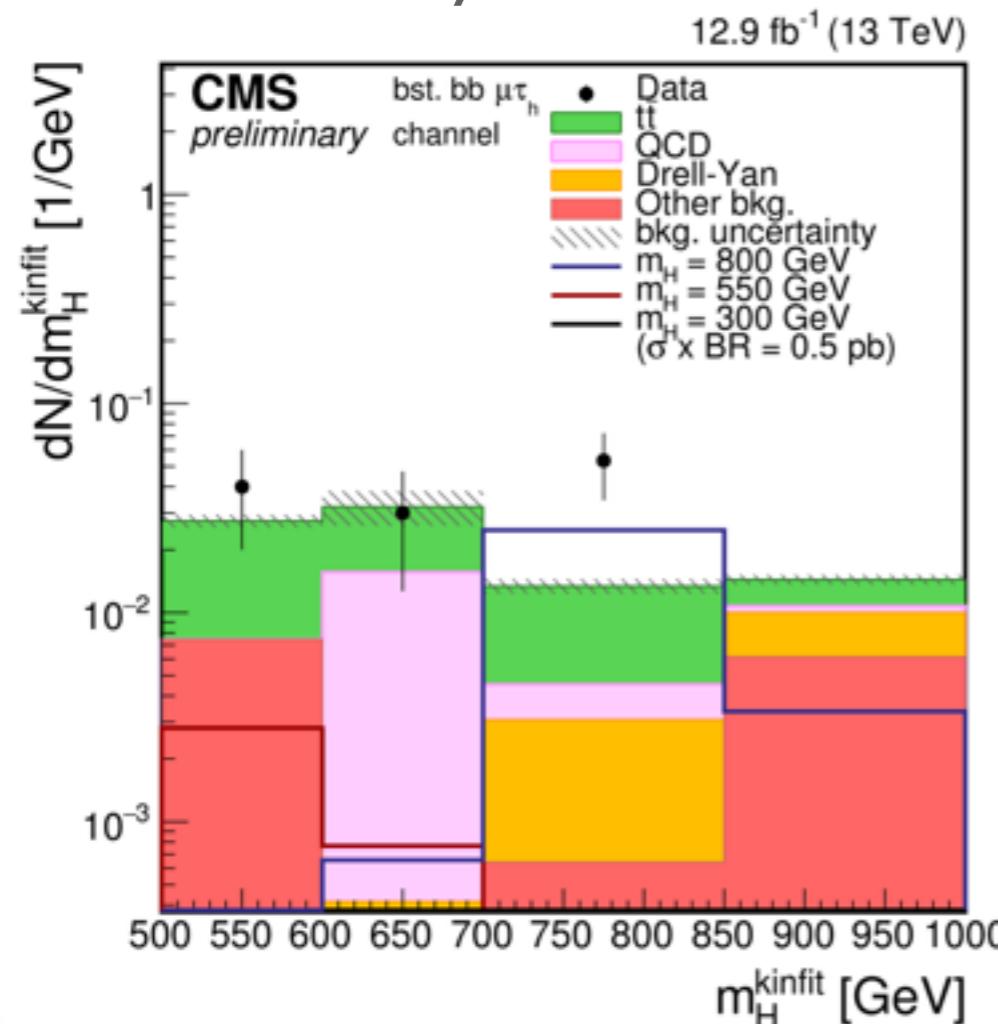
## 1-jet, 1 b-tagged jet required





# 13 TeV bb $\tau\tau$ resonant: boosted

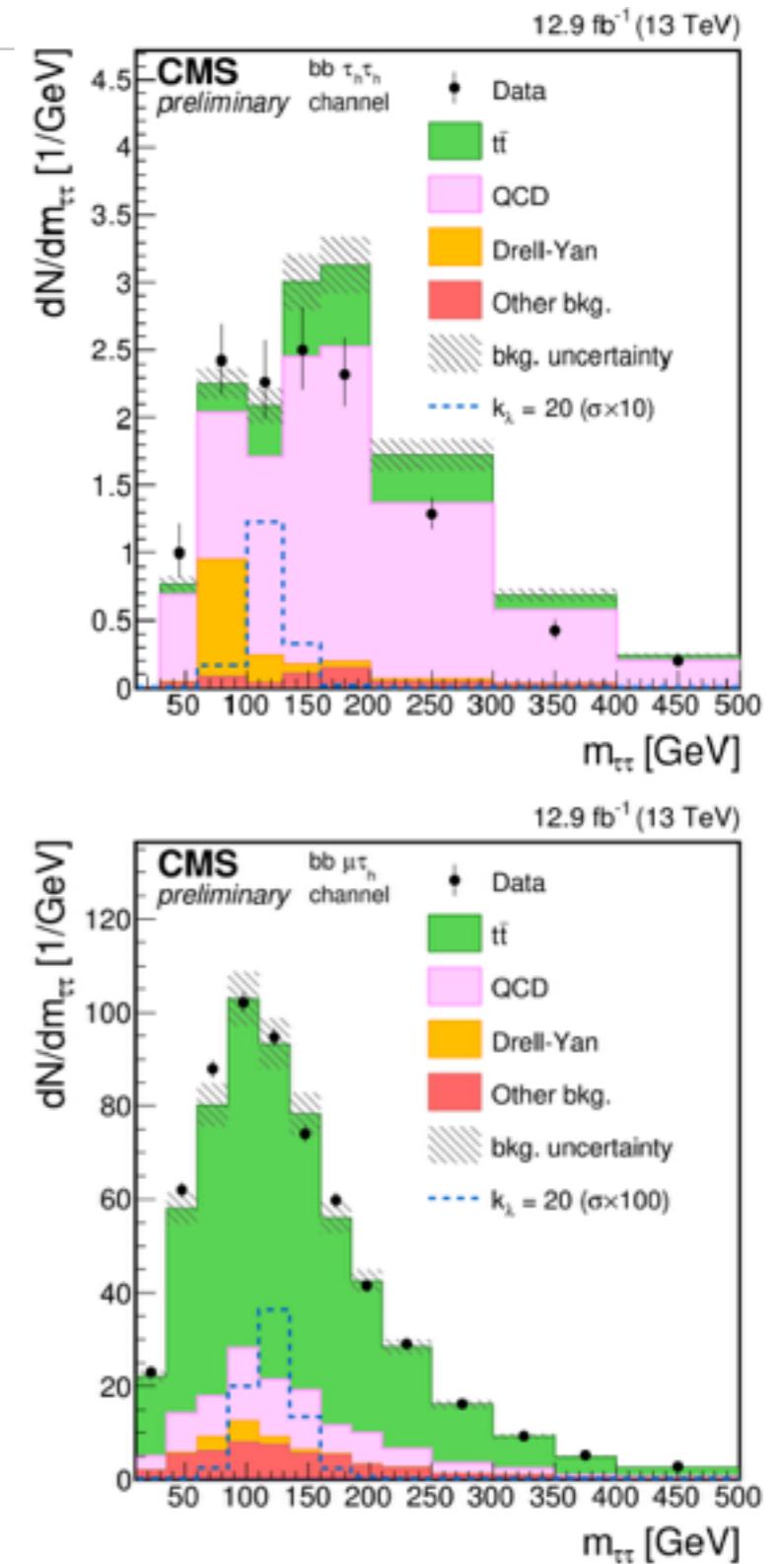
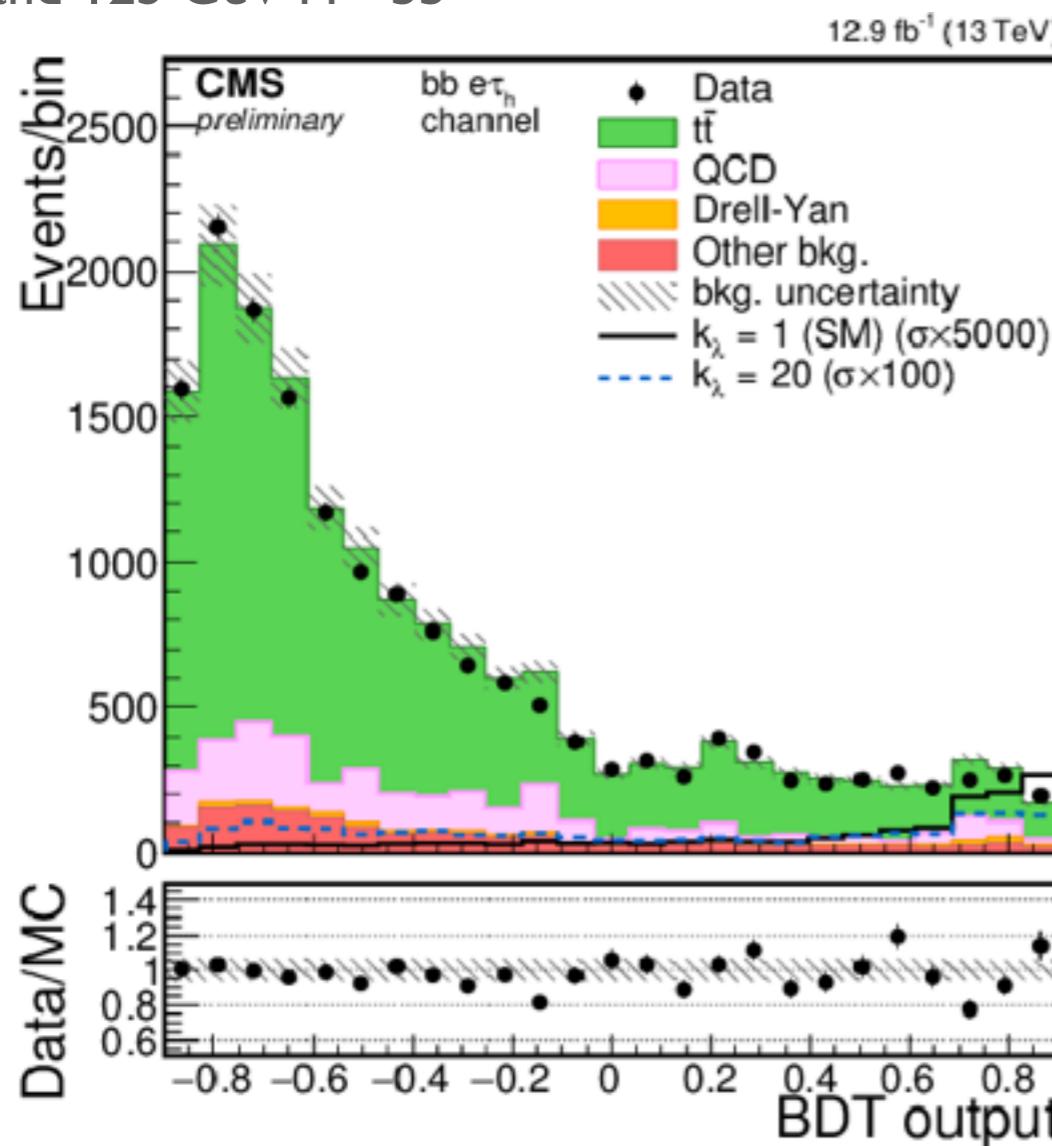
- Higgs  $p_T > 1000$  GeV will not be “resolved,”  $dR$  between higgs decay products  $< 0.4$
- Boosted tau reconstruction, where taus are seeded by fat jets
  - Tau decay modes examined:  $\tau_e \tau_h$   $\tau_\mu \tau_h$





# 13 TeV bb $\tau\tau$ non-resonant

- Similar selection to resonant analysis: Tau decay modes: e $\tau_h$ ,  $\mu\tau_h$ , and  $\tau_h\tau_h$ .
- Since the reconstructed mass of the heavy H is not needed, a Boosted Decision Tree (BDT) is used to identify 125 GeV H $\rightarrow\tau\tau$  and 125 GeV H $\rightarrow bb$

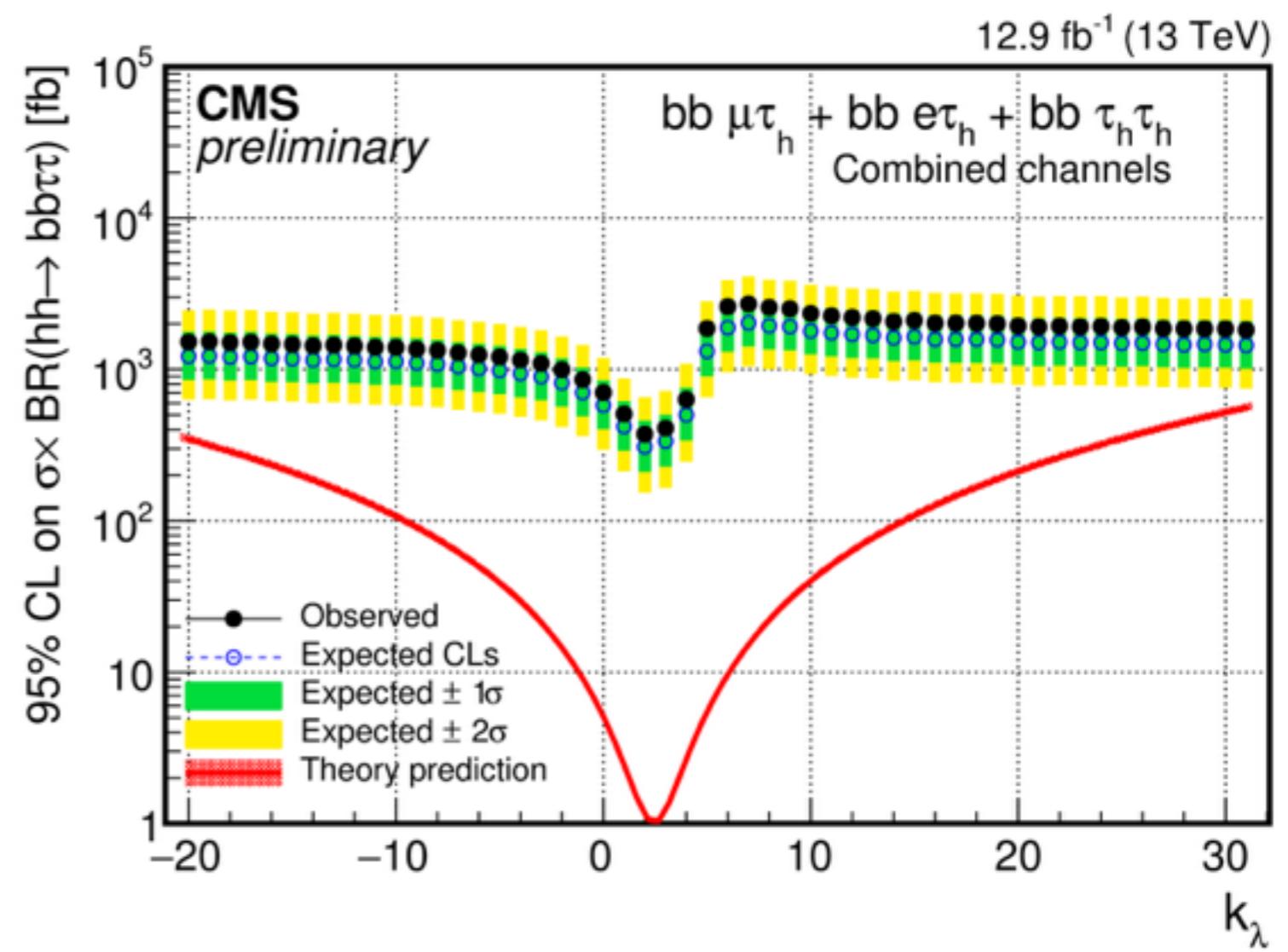




# 13 TeV $b\bar{b}\tau\tau$ non-resonant

- For non-resonant Higgs boson pair production at  $k\lambda=k\lambda=1$  the observed (expected) 95% CL upper limit on  $\sigma(pp \rightarrow hh \rightarrow b\bar{b}\tau\tau)\sigma(pp \rightarrow hh)$  amounts to 508 (420) fb.
- This value corresponds to approximately 200 (170) times the SM prediction

More luminosity needed  
to get closer to SM limit.  
Couplings could be  
enhanced in several BSM  
models





# Talk Road Map

- CMS Higgs to Tau Tau
- I25 GeV Higgs
  - SM  $H \rightarrow \tau\tau$  at 8TeV
  - I25 GeV Higgs  $\rightarrow \tau\tau$  used as a tool for searches
  - And beyond: other masses
  - MSSM Higgs decays to taus
  - Light Higgs, a decays to taus
- Prospects for 2016

HIGGS TO TAU TAU  
MASS NO LONGER  
CONSTRAINED TO  
I25 GEV



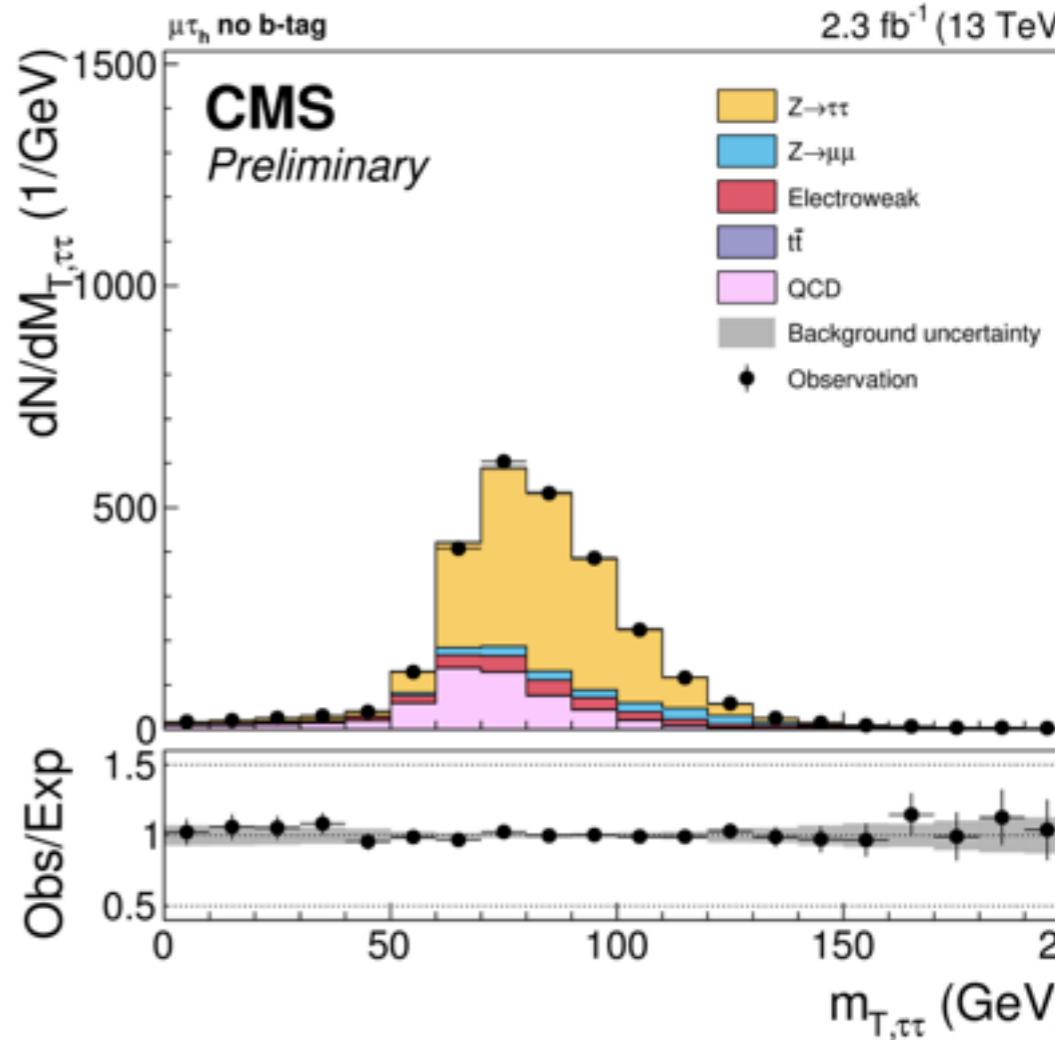
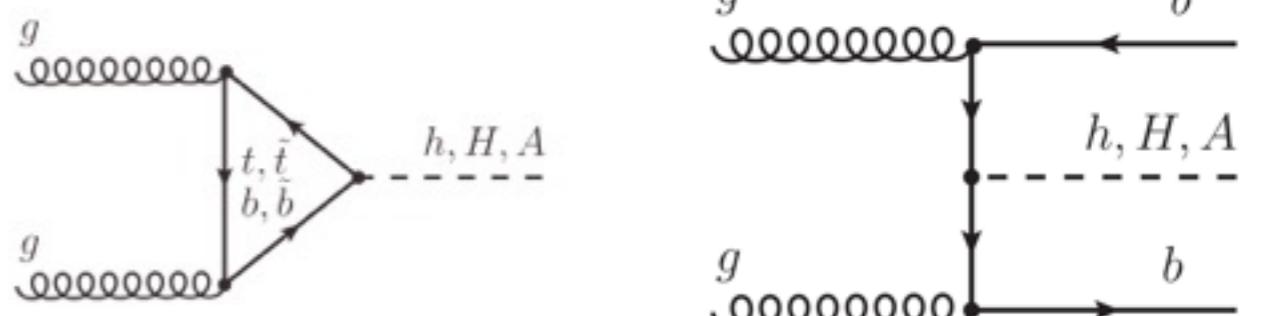
# MSSM Higgs TauTau

$$m_{T,\tau\tau} = \sqrt{(E^{\tau_1} + E^{\tau_2})^2 - ((p_x^{\tau_1} + p_x^{\tau_2})^2 + (p_y^{\tau_1} + p_y^{\tau_2})^2)}$$

- MSSM Higgs  $\tau\tau$  search with 2.3 /fb in 2015 at 13 TeV

- Gluon-gluon fusion and associated-b production

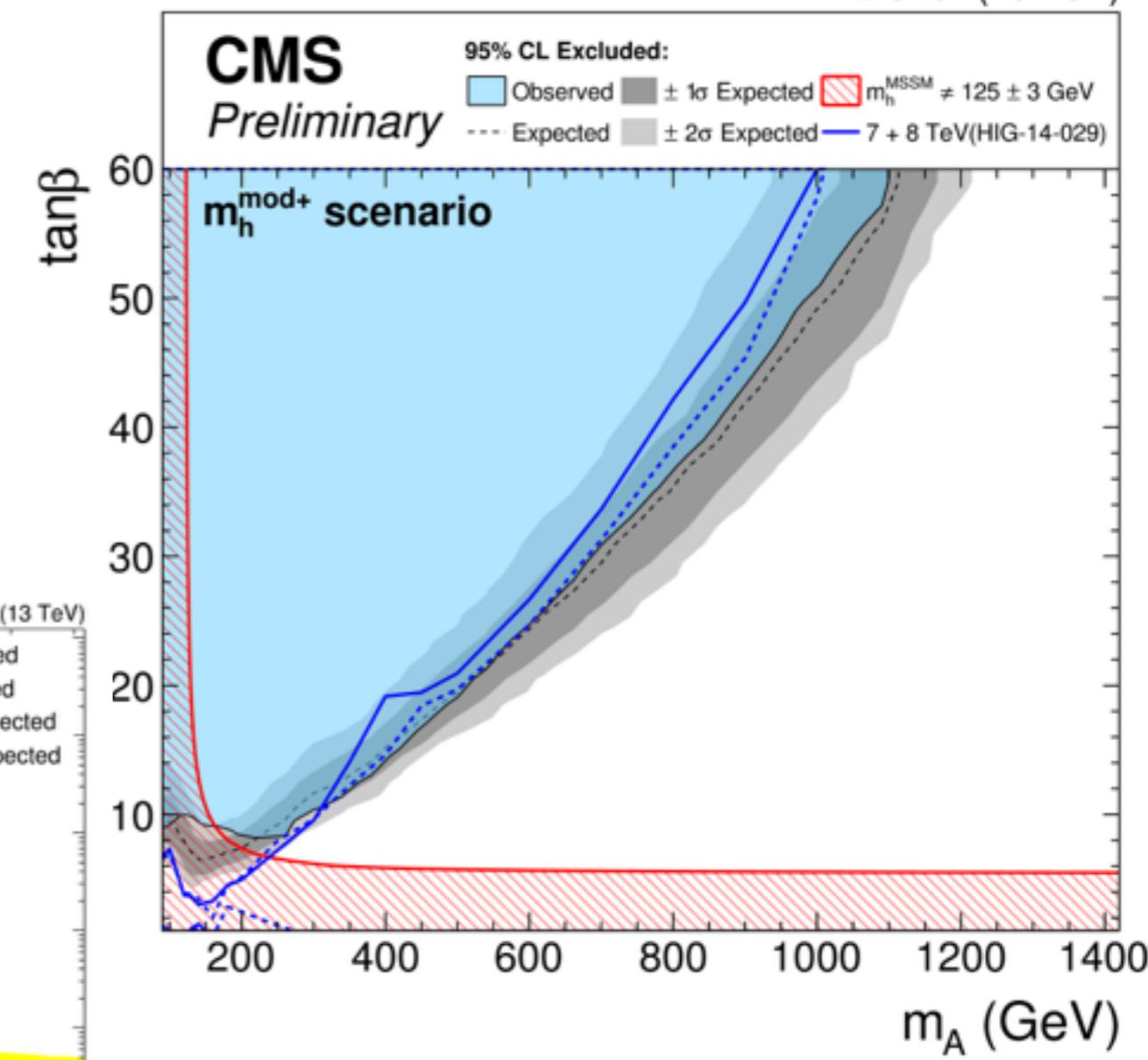
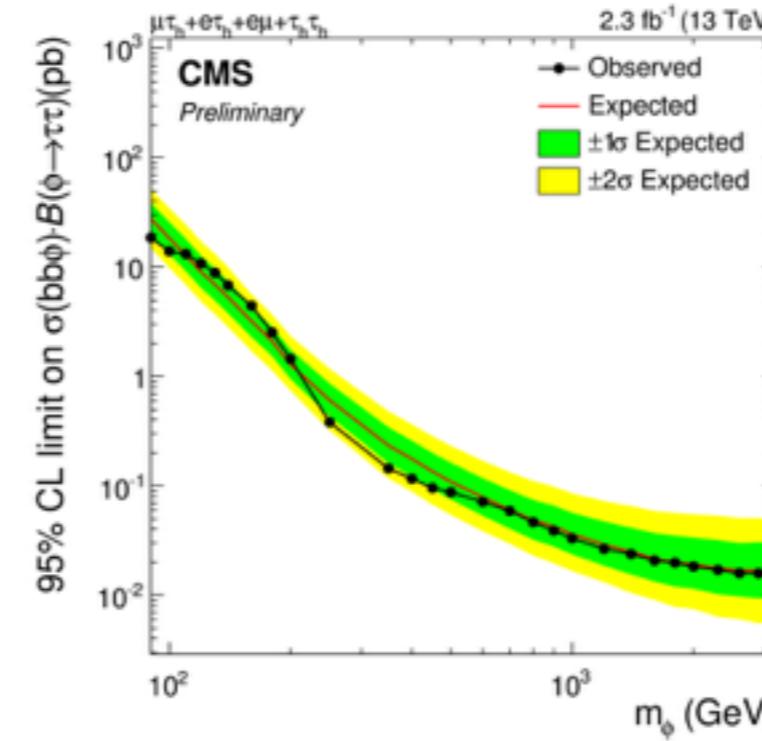
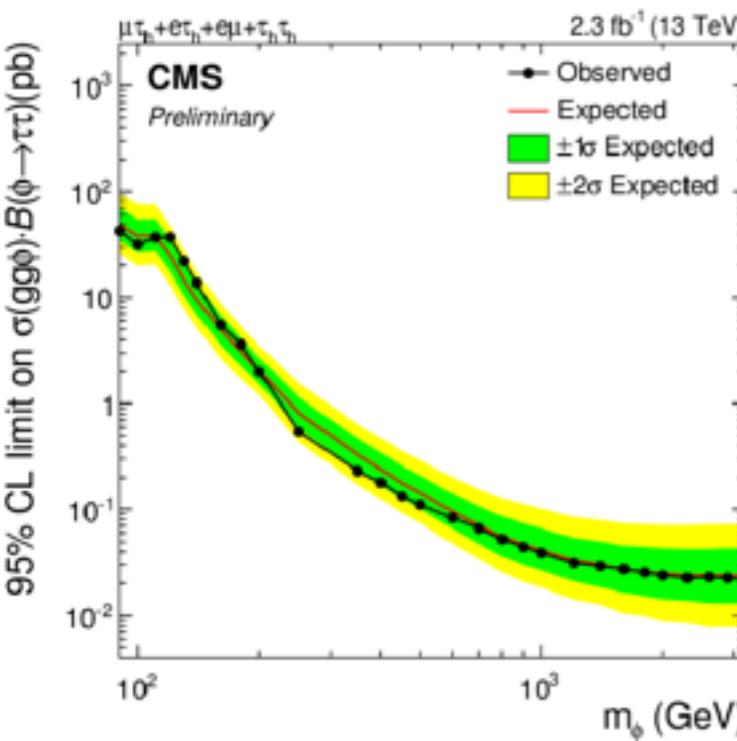
- 2 categories: one b-tagged jet, no b-tagged jets using medium working point.
- Very similar analysis strategy and event selection to SM Higgs- $\rightarrow\tau\tau$ 
  - However, single lepton triggers used. No trigger requirement for the tau was applied.
  - SVFit is used. The  $M_{T,\text{tot}}$  variable rebuilt from svFit output performed better than  $M_{\tau\tau}$  variable





# MSSM Higgs TauTau

- Event selection optimized for high mass
- $M_{T,\text{tot}}$  used to set limits
- Compared to 8TeV better high mass limits, but not as sensitive to the low mass as 8TeV





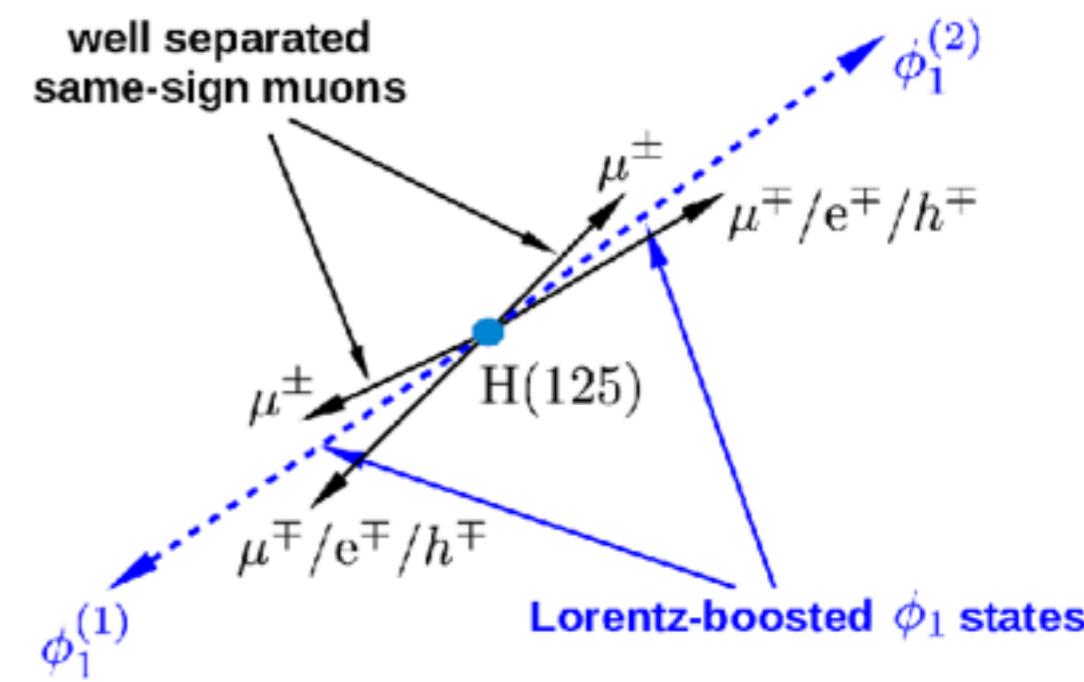
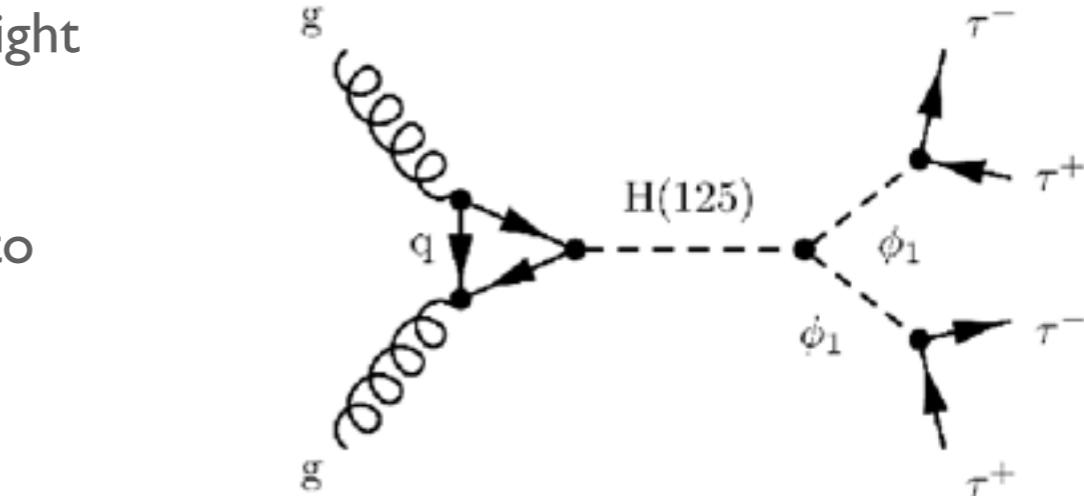
# 8 TeV NMSSM $a \rightarrow \tau\tau$

- I25 GeV Higgs, produced via gluon-gluon fusion, decays to two light scalars,  $\varphi$ , where  $\varphi$  decays to taus.
- Scalar masses between  $4 < m_h < 8$  GeV predominately decays to taus in the mass range
- Trigger off of  $2 \tau \rightarrow \mu$  decays: muons  $P_T > 17$  and  $P_T > 8$
- The other tau decays to either electron, muon, or “single prong” tau. The sign of this charged track is opposite sign of the triggered  $\mu$ . **Track is used instead of a HPS reconstructed tau.**
- 2 Boosted tau pairs
  - The invariant mass between the muon and the nearby charged track (from the  $\varphi$  decay)

I25 GeV Higgs is:

decays to:

$h_2$	$h_1 h_1$
$h_2$	$a_1 a_1$
$h_1$	$a_1 a_1$



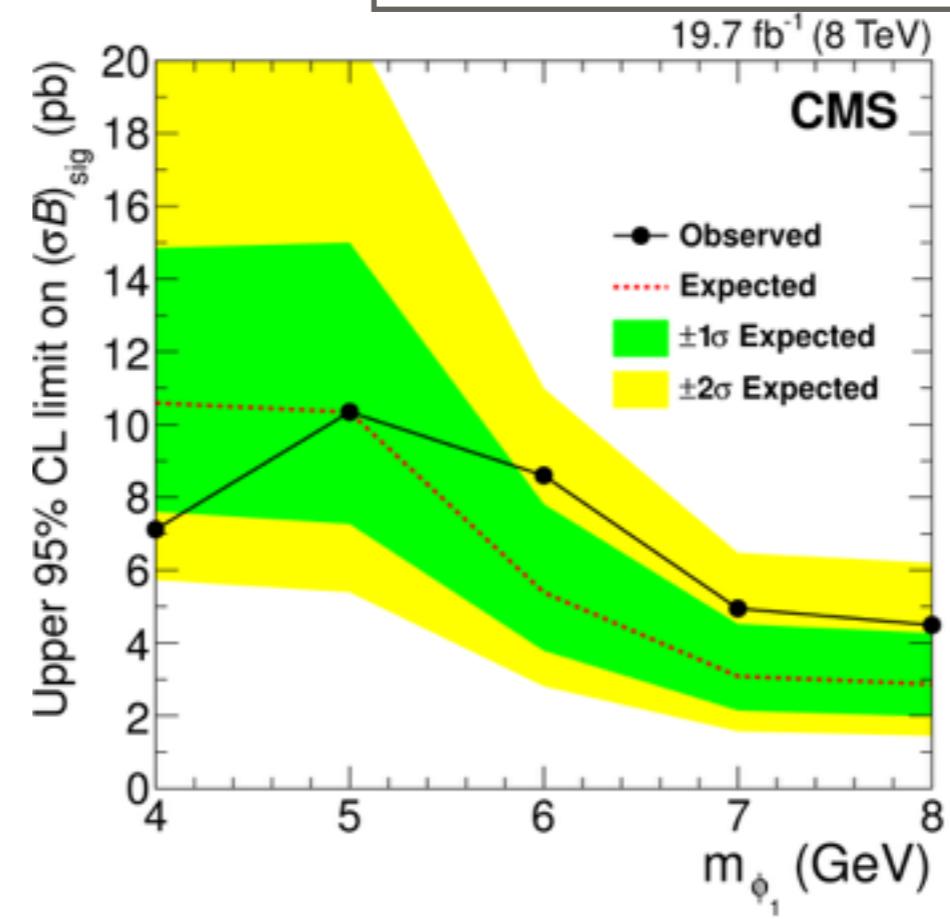
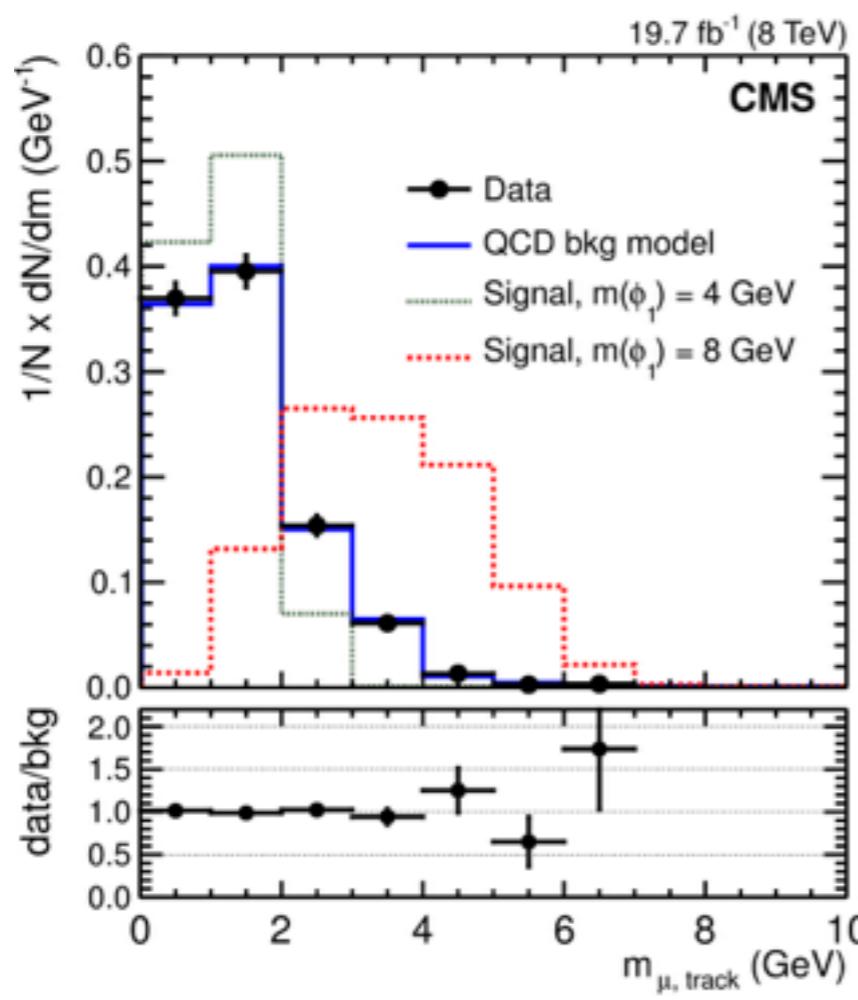
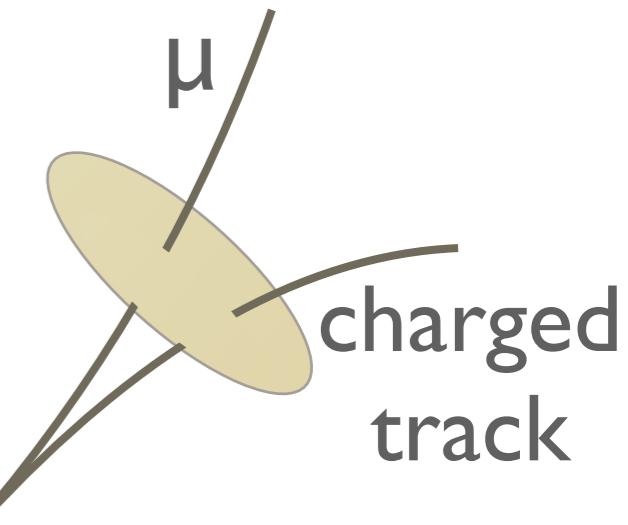
arXiv:1510.06534 [hep-ex]



# 8 TeV NMSSM $a \rightarrow \tau\tau$

- Each mu+track pair event contributes two entries to the invariant mass distribution
- Limits are set for mass  $\varphi$  one of the light NMSSM scalars

reminder:  
tau pair  
topology

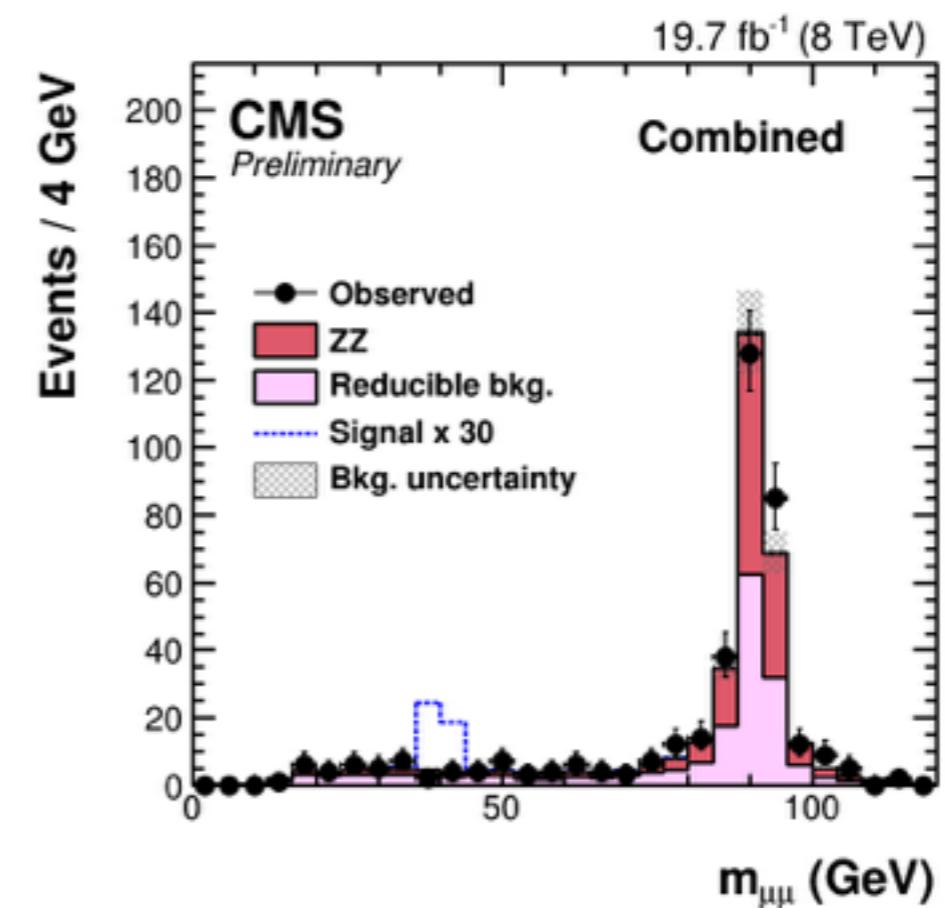
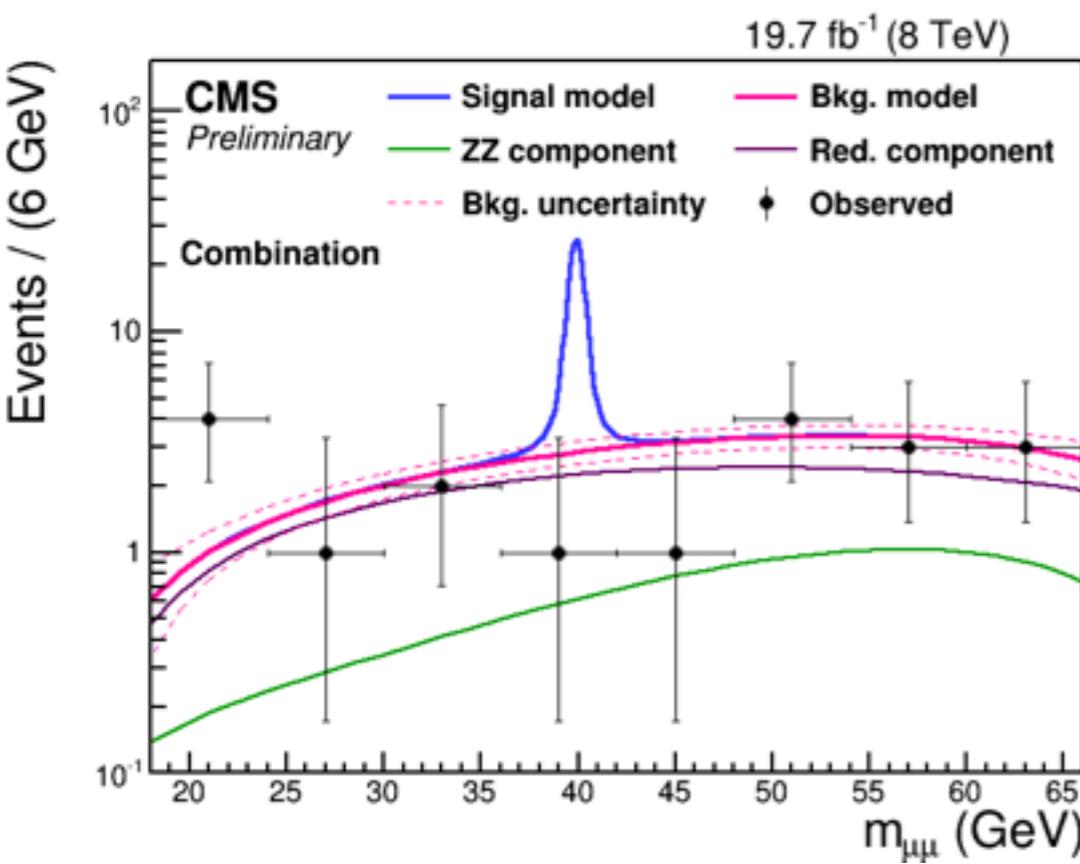


arXiv:1510.06534 [hep-ex]



# Light Higgs aa $\rightarrow \mu\mu\tau\tau$

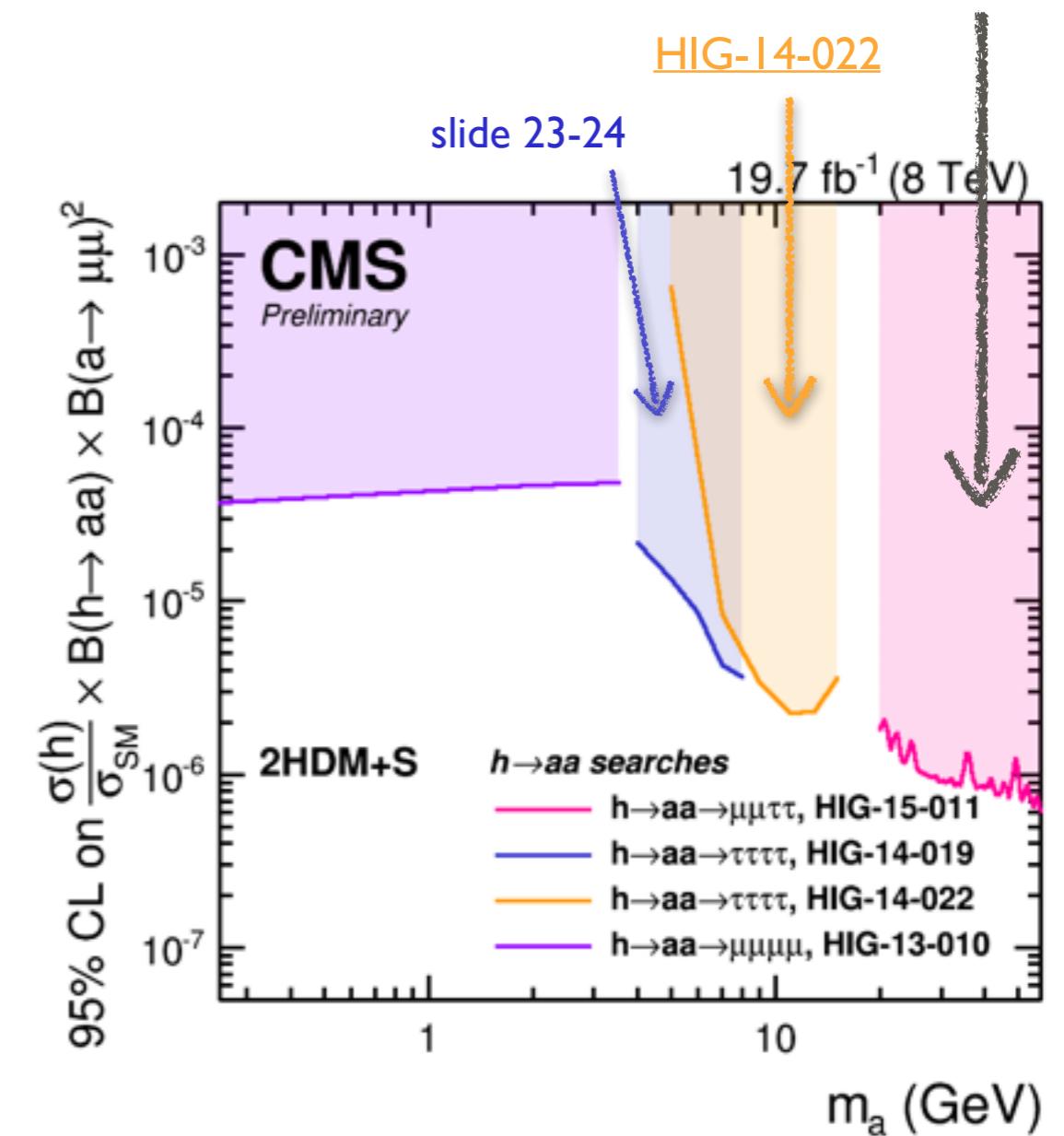
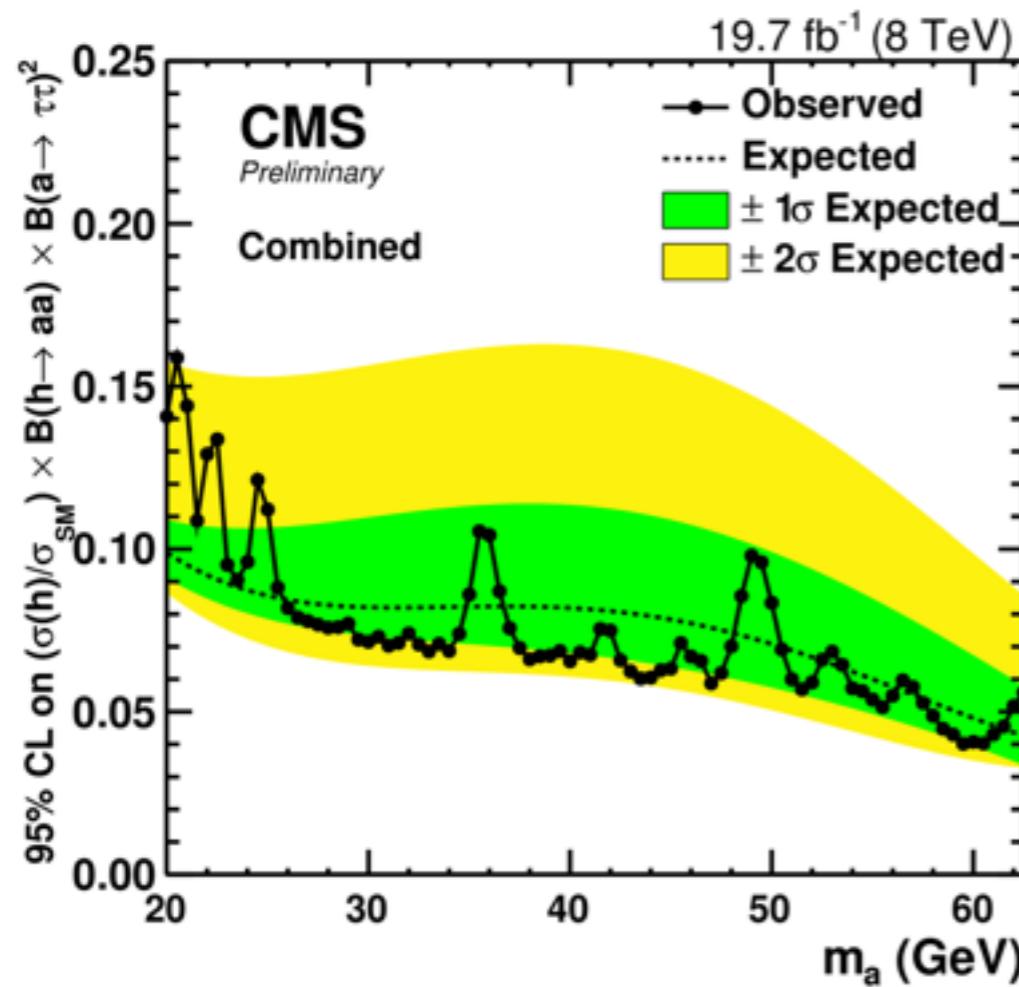
- CMS measured  $B(h \rightarrow \text{BSM}) < 32\%$  at 95% CL. Set tighter limits on light higgs a BR.
- $H(125) \rightarrow aa \rightarrow \mu\mu\tau\tau$ . Use  $\mu\mu$  to search for  $\tau\tau$  at moderately low mass  $20 < m_a < m_h/2$ 
  - Require two taus in the event and look at the di-muon mass in the presence of the two other taus to search for low mass, a.
- Mass window cut for 4 lepton( $\mu\mu\tau\tau$ ) invariant mass 100-150 GeV





# Light Higgs aa $\rightarrow \mu\mu\tau\tau$

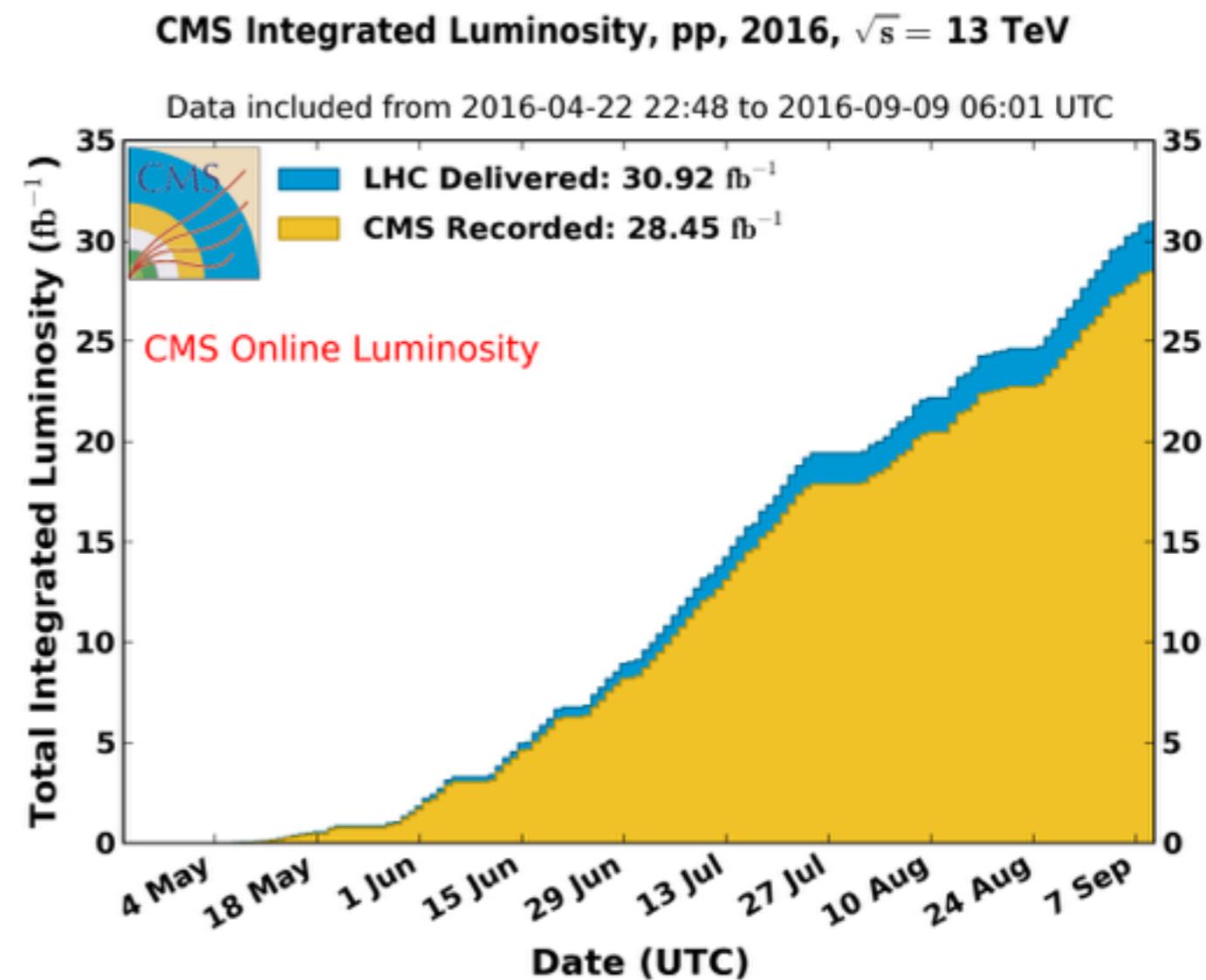
- Tau decay modes examined:  $\mu\mu\tau_e\tau_e$ ,  $\mu\mu\tau_e\tau_\mu$ ,  $\mu\mu\tau_e\tau_h$ ,  $\mu\mu\tau_\mu\tau_h$  and  $\mu\mu\tau_h\tau_h$
- Upper limits between 4 and 15% are set on the branching fraction of the Higgs boson to two light pseudoscalar bosons, under the hypothesis that the pseudoscalar aa does not decay to quarks.
- Set limits for a masses between  $20 < m_a < m_h/2$





# Prospect for 2016 Run

- Collecting data now!
- SM Higgs Analysis
  - Measure fermionic couplings,  $K_f$
- Expect more public results soon!





# Summary

- SM Higgs  $\tau\tau$  to be done at 13 TeV
- Various methods to look at Higgs decays to taus
  - Likelihood fits to reconstruct mass
    - 8 TeV SM Higgs
    - di-Higgs  $h(bb)$   $h(\tau\tau)$
    - MSSM heavy Higgs searches
  - BDTs in non resonant di-Higgs models
  - Di-Muon Mass
  - $\mu$ -track invariant mass

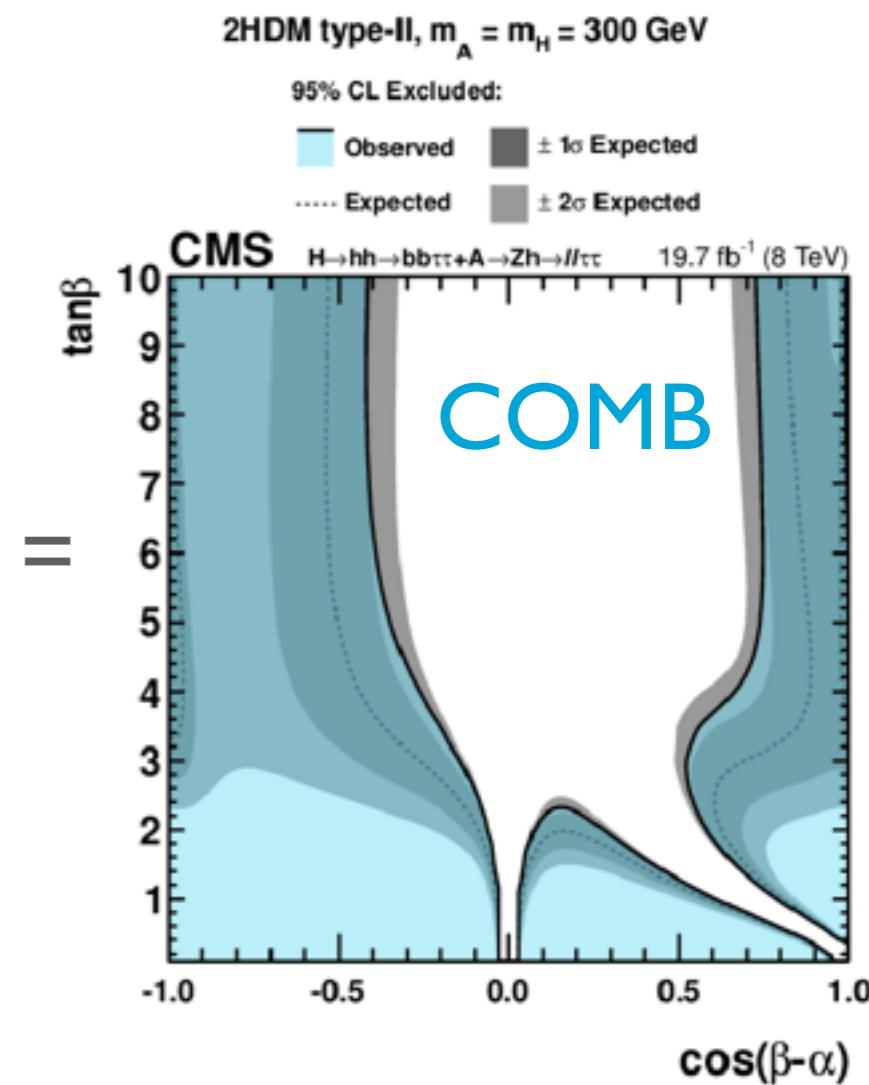
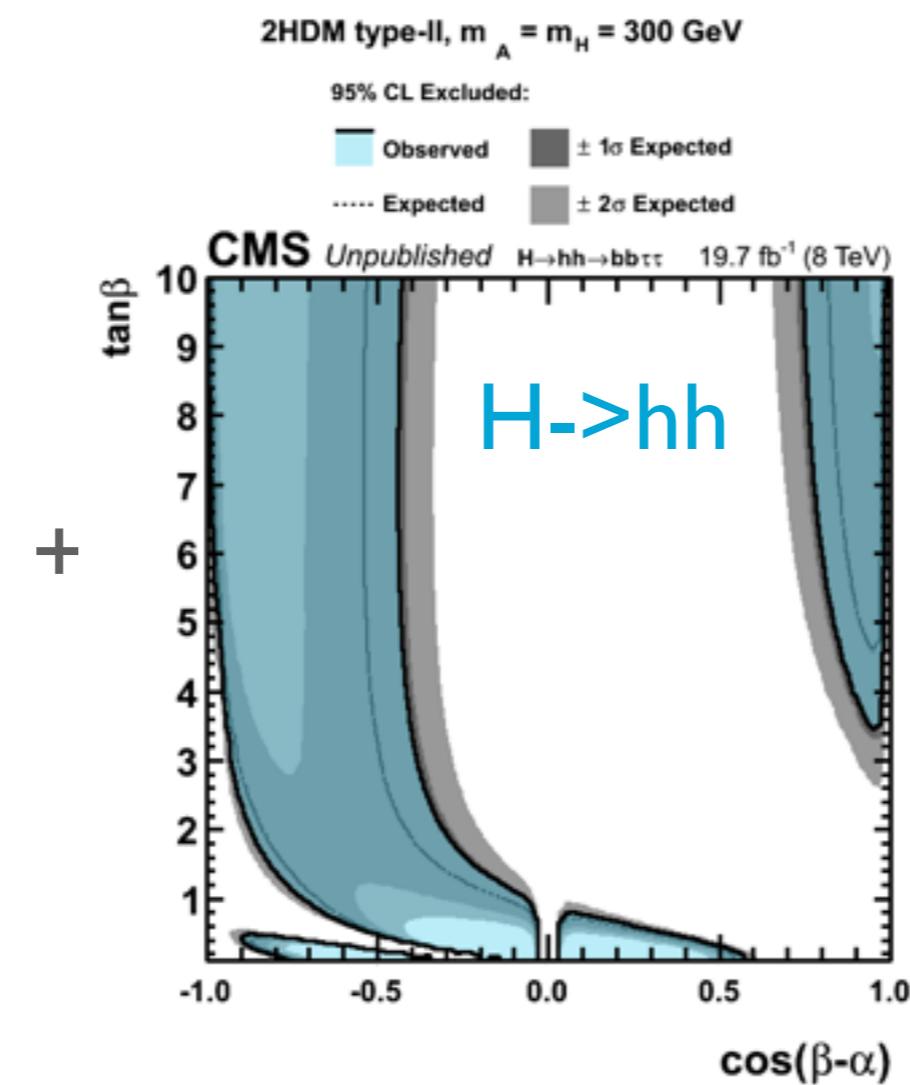
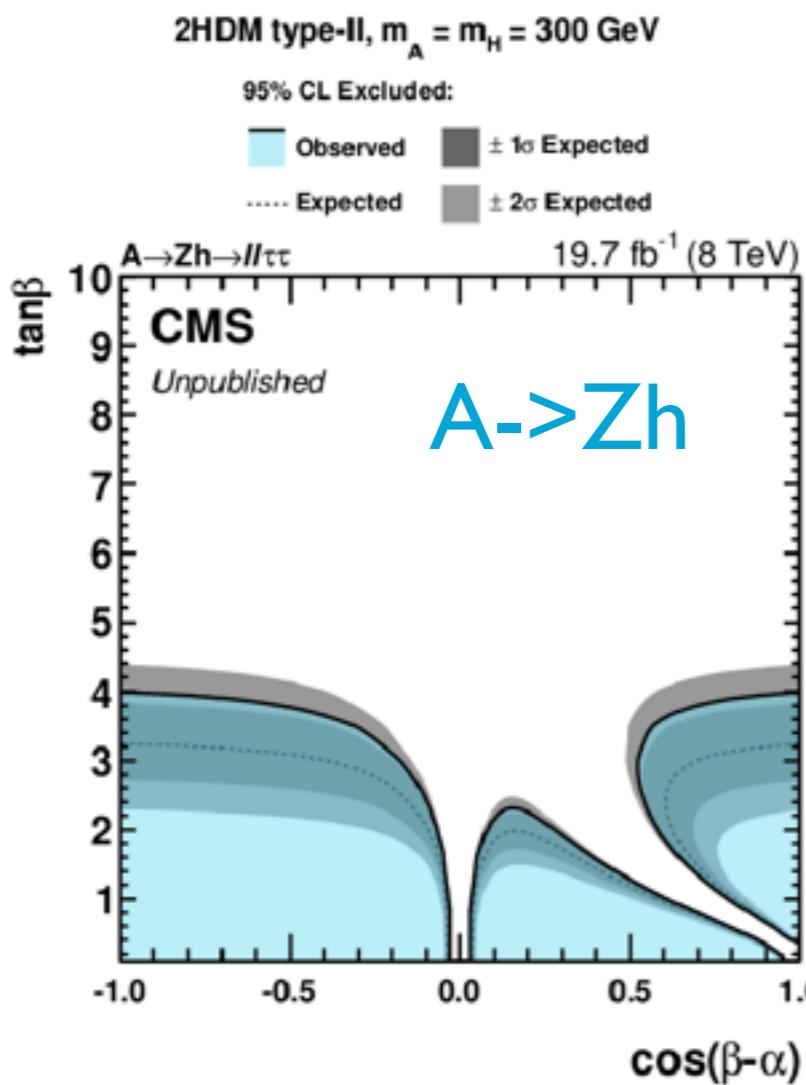


# BACKUP



# 8 TeV MSSM $bb\tau\tau + l\bar{l}\tau\tau$

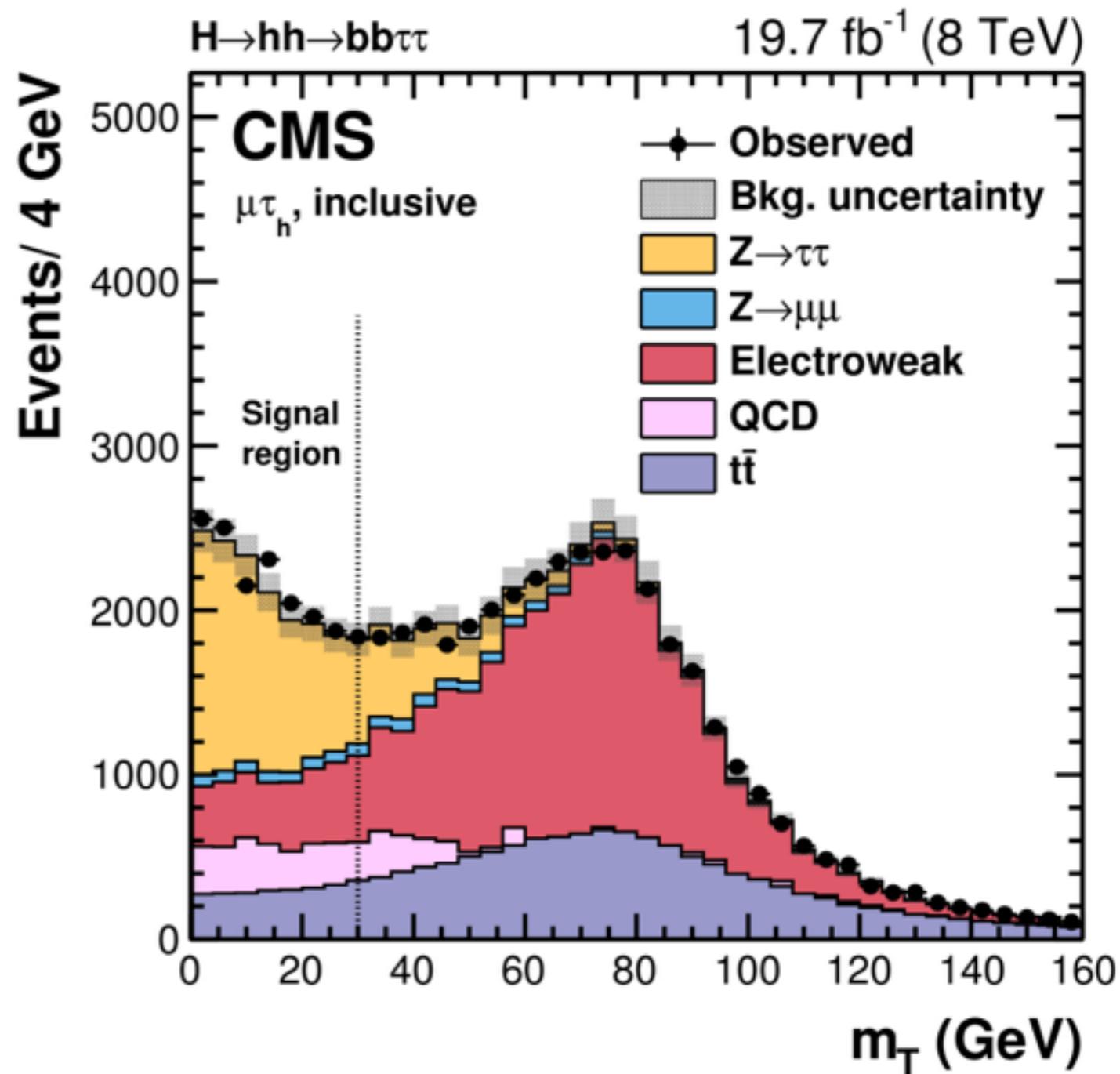
- Observed limits can be set in the generic 2 Higgs Doublet Model (2HDM) interpretation
- Combination of the MSSM hh, Zh limits





# 8 TeV MSSM $bb\tau\tau + l\bar{l}\tau\tau$

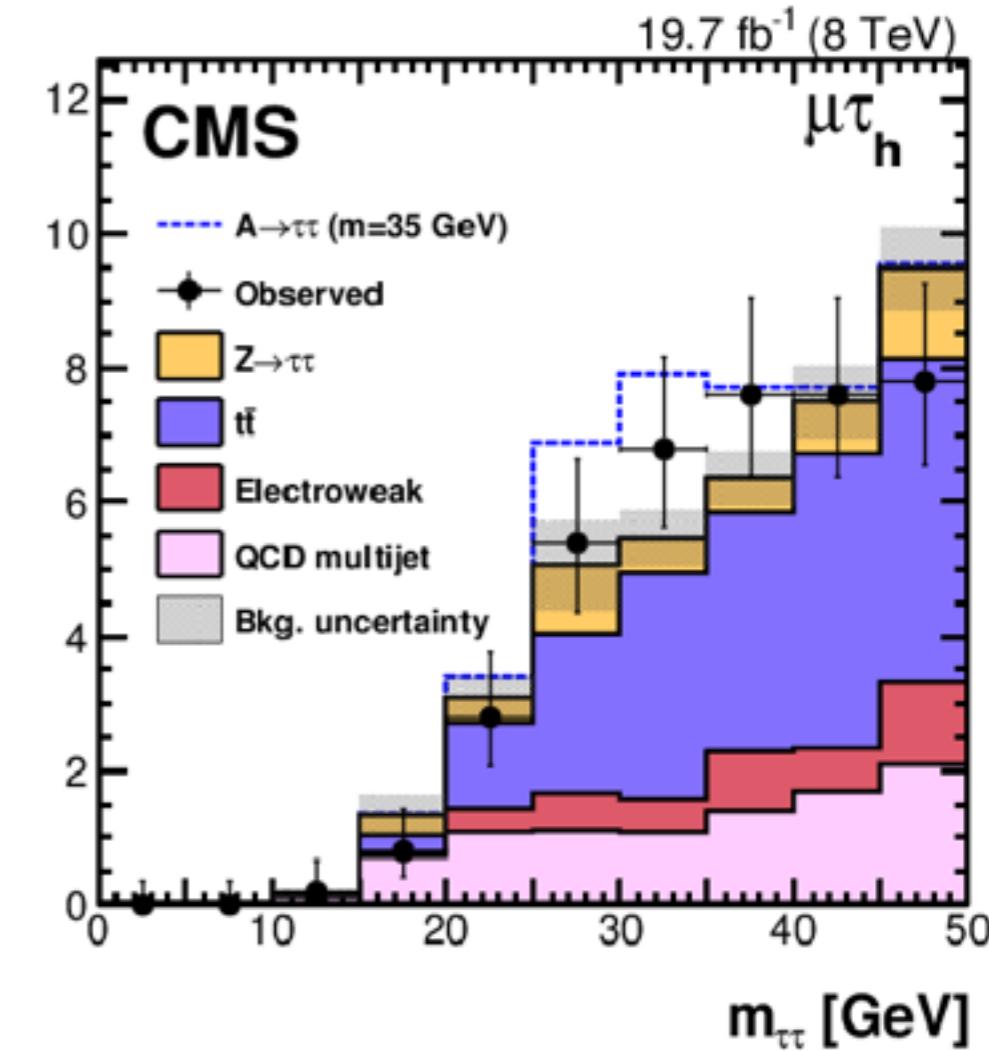
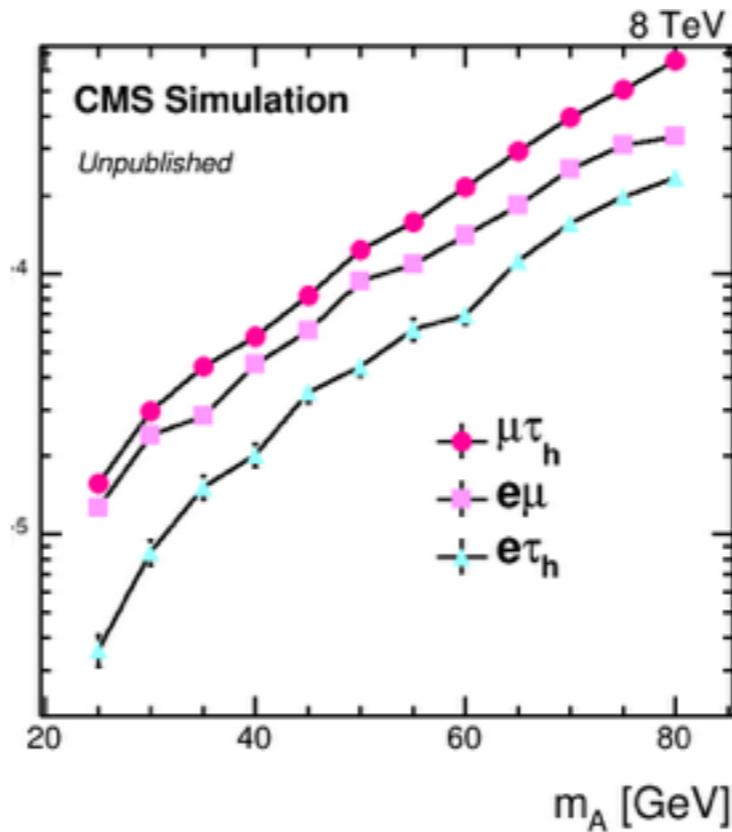
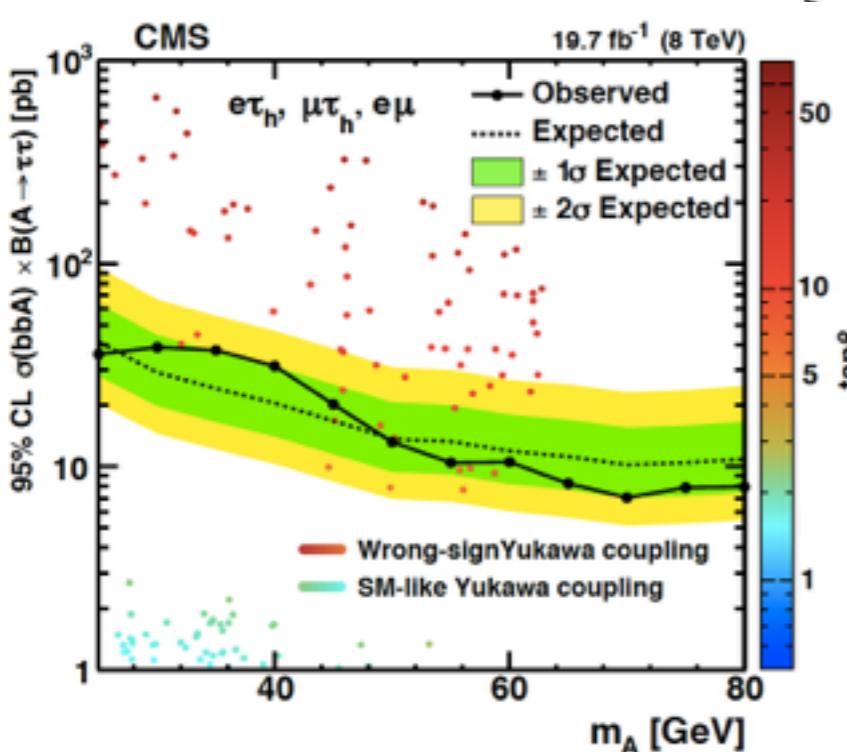
## Transverse Mass Distribution





# Light Higgs $h \rightarrow \tau\tau$ with b-jets

- Performed at 8 TeV with 19.7 /fb
- Light pseudoscalar Higgs boson, A, decaying to  $\tau\tau$  leptons, produced in association with a b-jet pair
- $25 \text{ GeV} < m_{\tau\tau} < 80 \text{ GeV}$
- $\tau_\mu T_h$  has highest acceptance

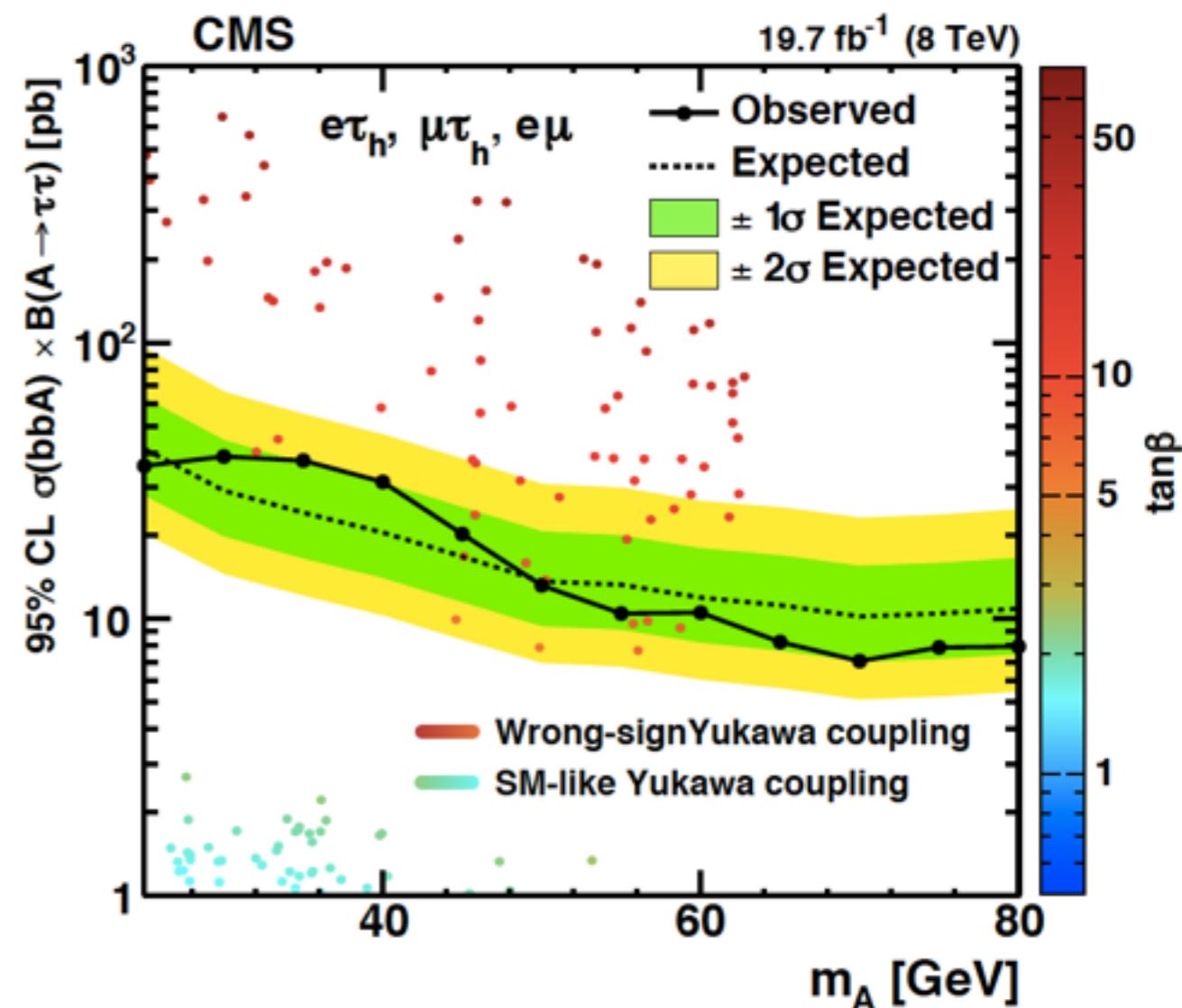


arXiv:1511.03610 [hep-ex]



# Light Higgs $h \rightarrow \tau\tau$ with b-jets

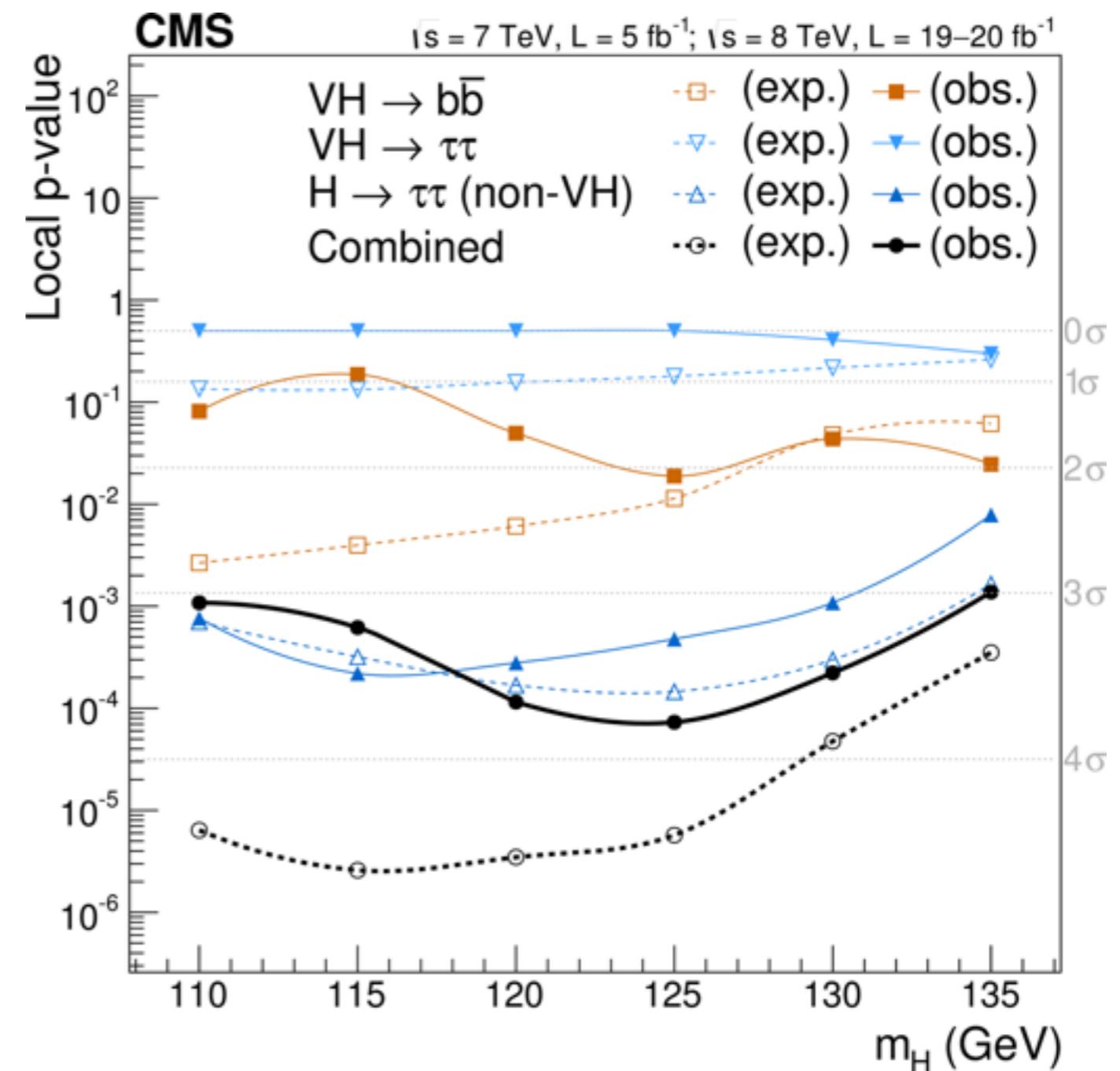
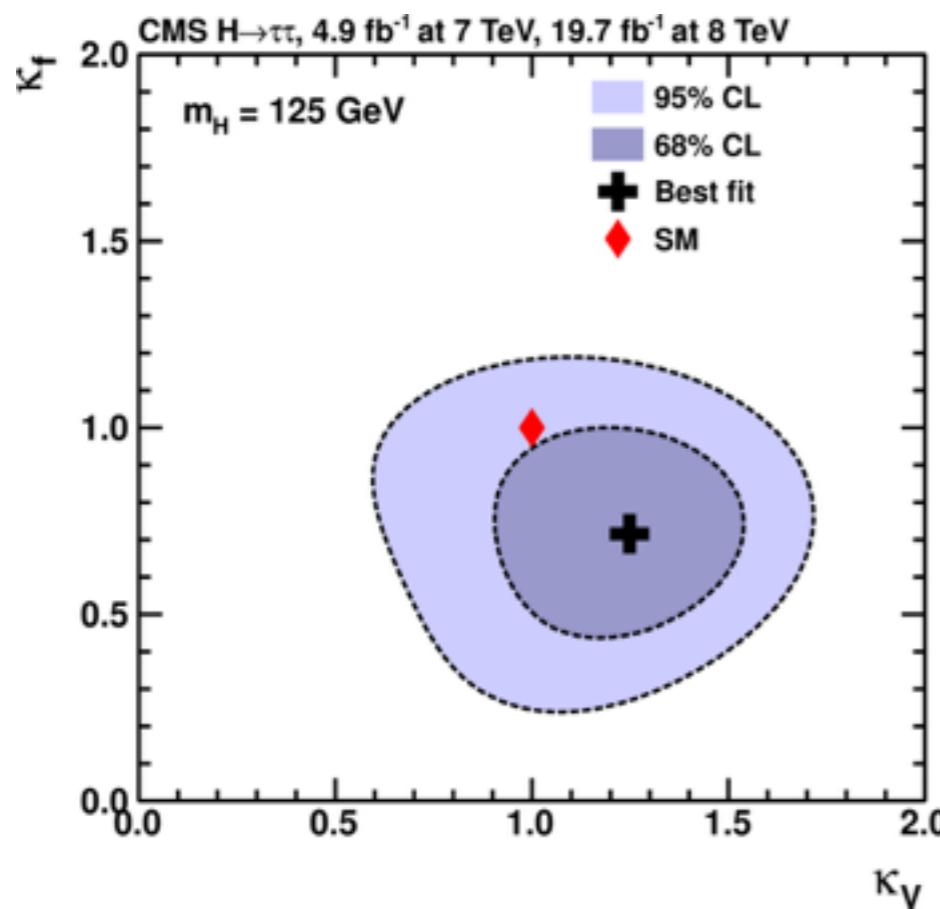
- Performed at 8 TeV with 19.7 /fb
- Light pseudoscalar Higgs boson, A, decaying to  $\tau\tau$  leptons, produced in association with a b-jet pair
- $25 \text{ GeV} < m_{\tau\tau} < 80 \text{ GeV}$
- Pseudoscalar A excluded 95% CL for wrong sign Yukawa coupling hypothesis.



arXiv:1511.03610 [hep-ex]

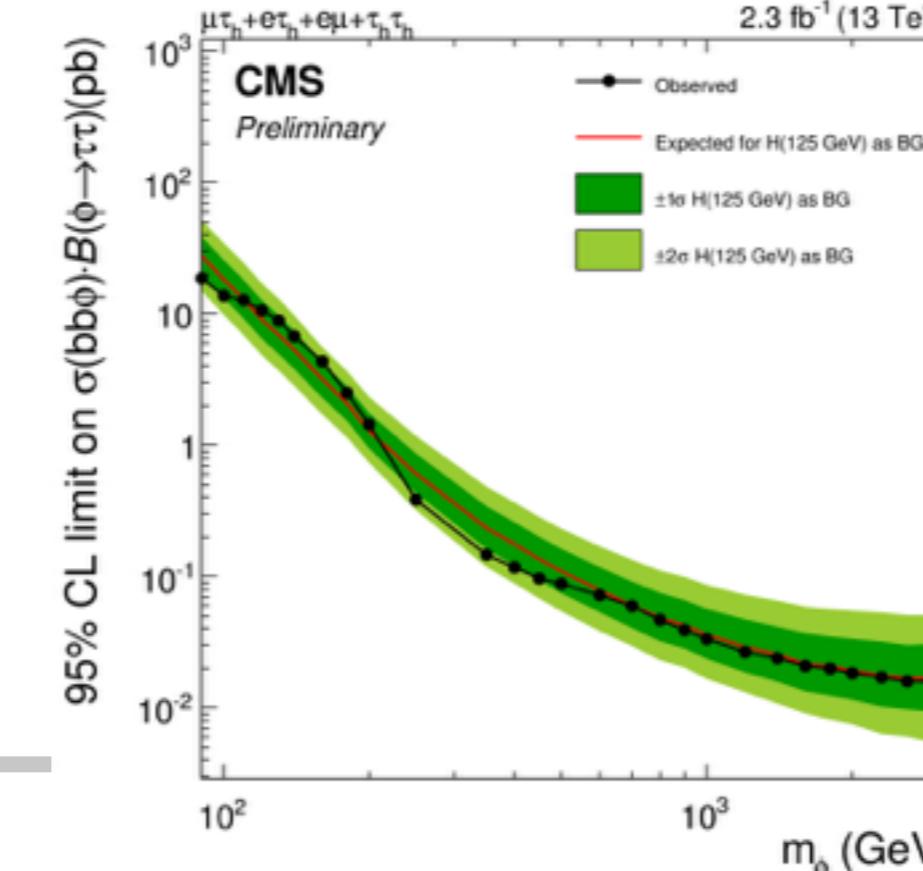
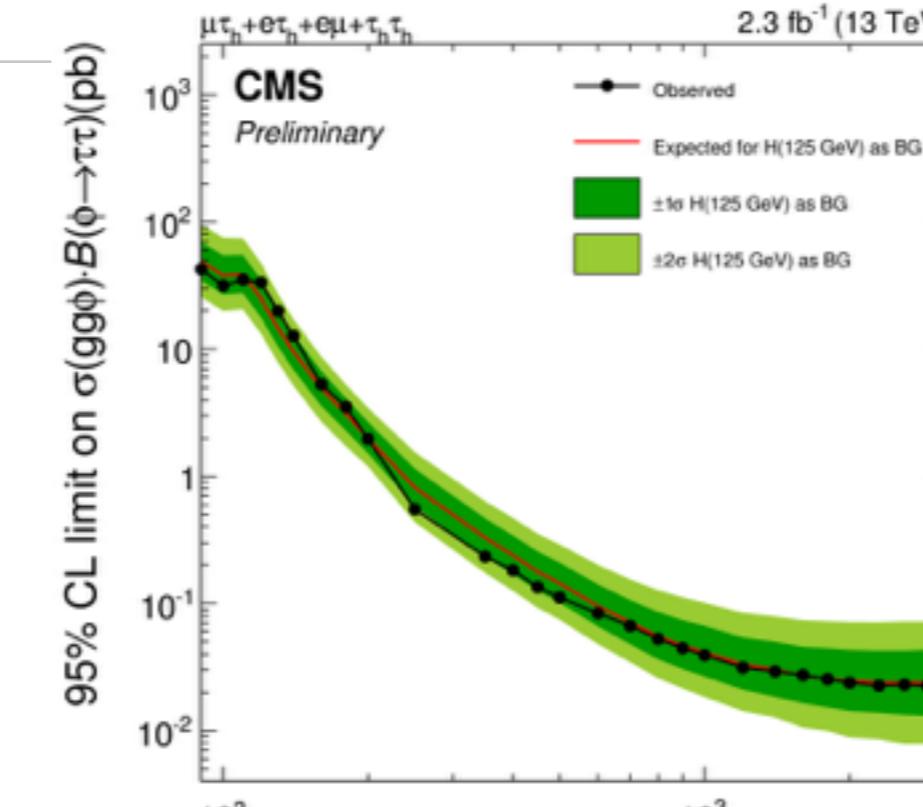
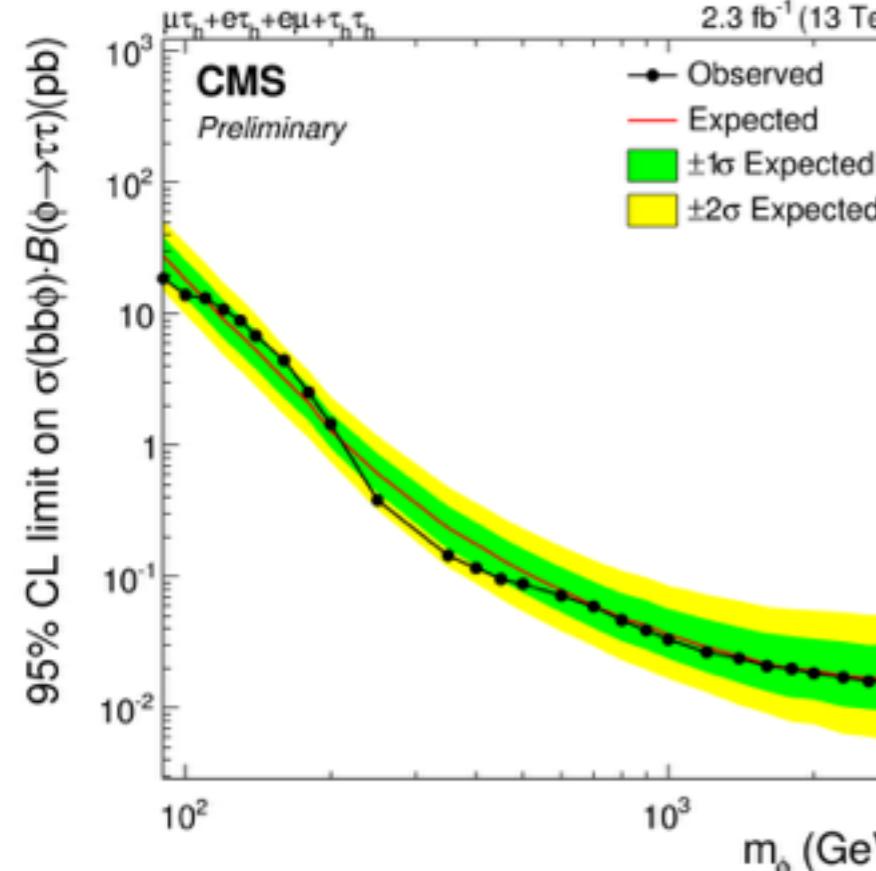
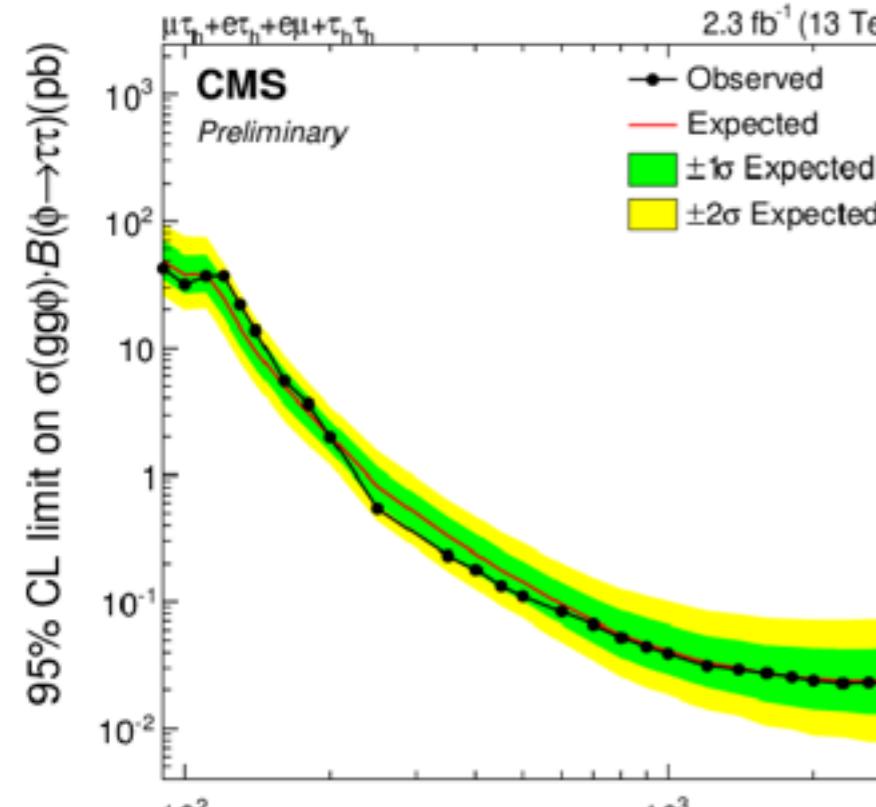


# Higgs Decays to $\tau\tau$ combination with Higgs to $bb$





# MSSM Higgs TauTau Limits



comparison with  
I25 H  
as background