Search for
Heavy Higgs Bosons
with the CMS experiment

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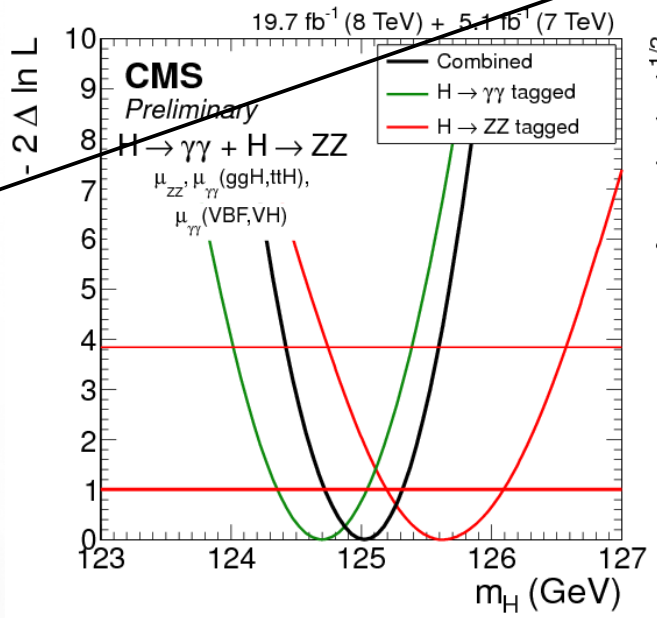
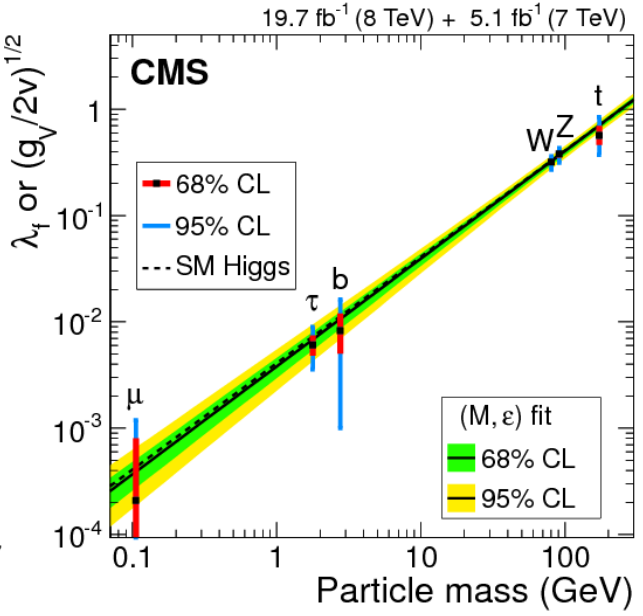
Hamburg University
on behalf of the CMS collaboration

9th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"
Hamburg, 17./18.11.2015

An Extended Higgs Sector?

Experimental proof of the Higgs mechanism





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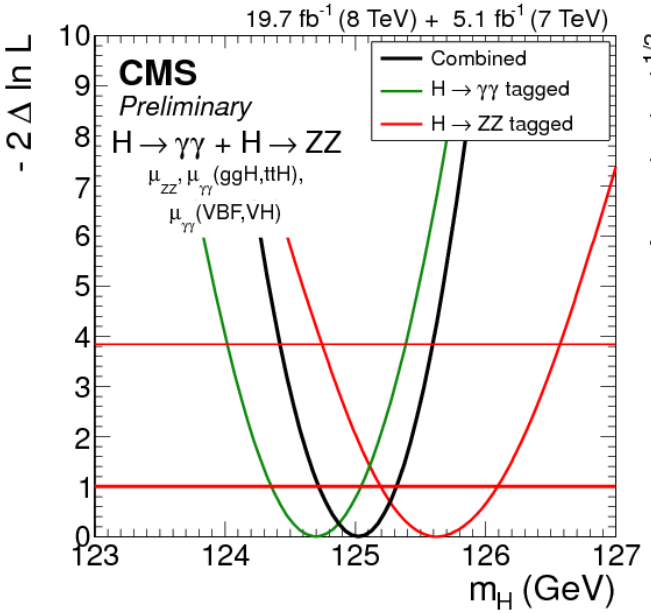
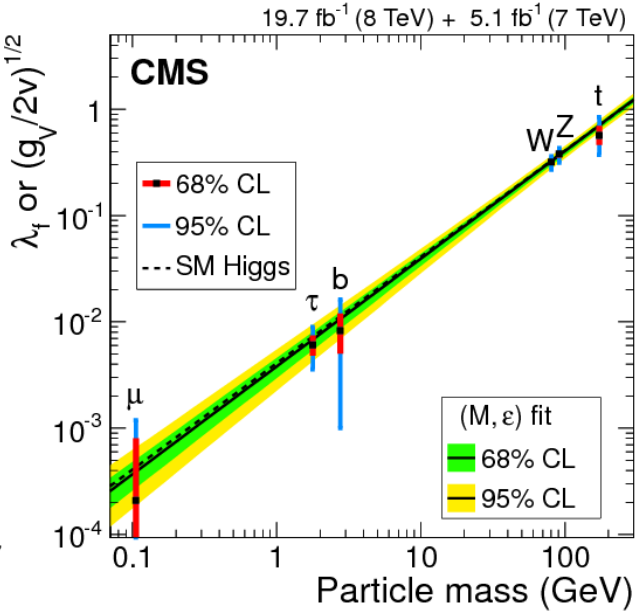




How does the Higgs mechanism work in detail?

1 Higgs Doublet

pure SM:
- 1HD sufficient to give mass to up- and down-type fermions
- **exactly one Higgs boson**

beyond SM:
- more complex structure of Higgs sector expected
- **more Higgs bosons** e.g. MSSM: h, H, A, H+, H-

more Higgs Doublets

Search for additional Higgs bosons is essential in order to explore the structure of the Higgs sector

Heavy Higgs Searches at CMS

Φ: any heavy scalar

Φ→μμ

Accepted in Phys. Lett. B
CMS-HIG-13-024

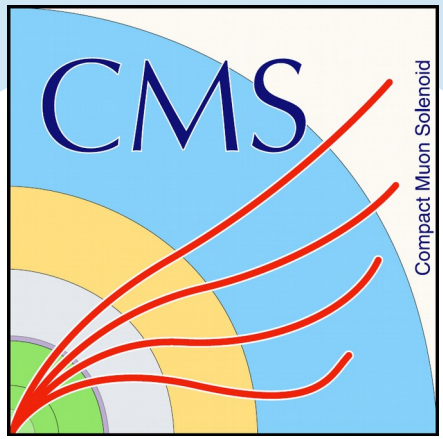
Φ→bb

Accepted in J. High Energy Phys.
CMS-HIG-14-017

direct heavy Higgs decays

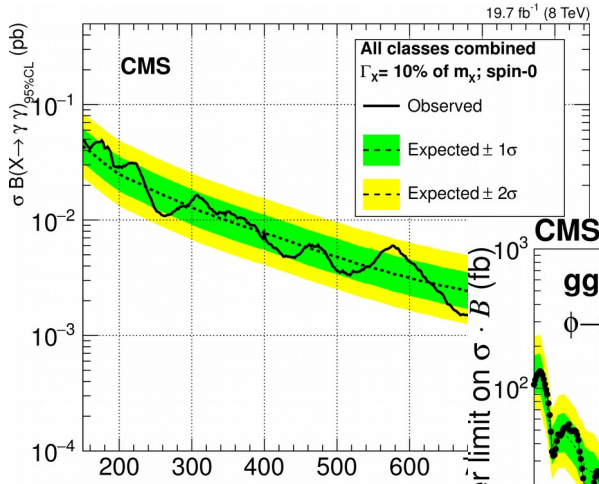
Φ→γγ

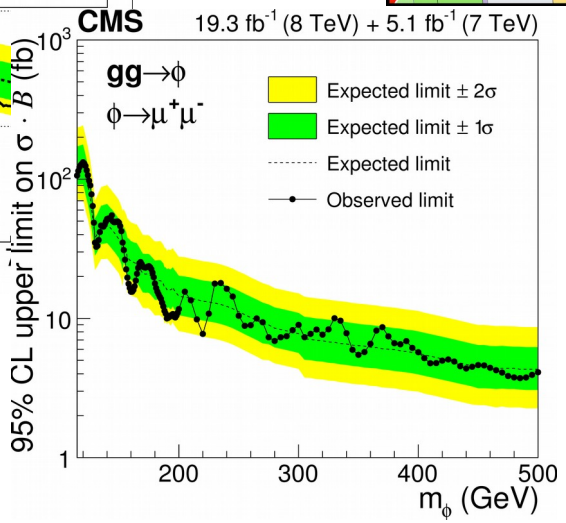
Phys. Lett. B 750 (2015) 494
CMS-HIG-14-006

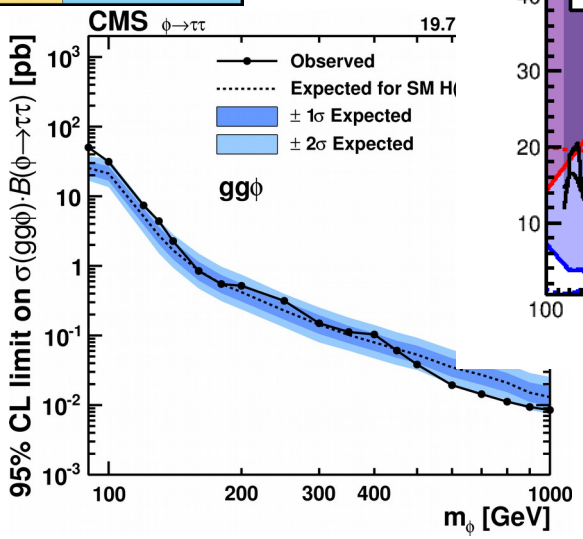


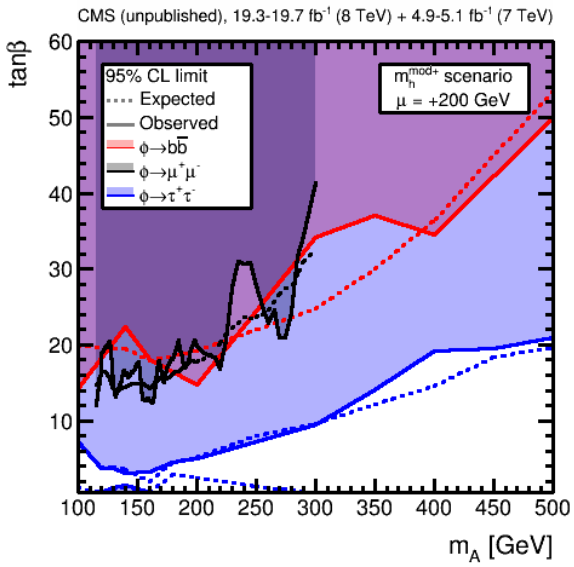
Φ→ττ

JHEP 1410 (2014) 160
CMS-HIG-13-021



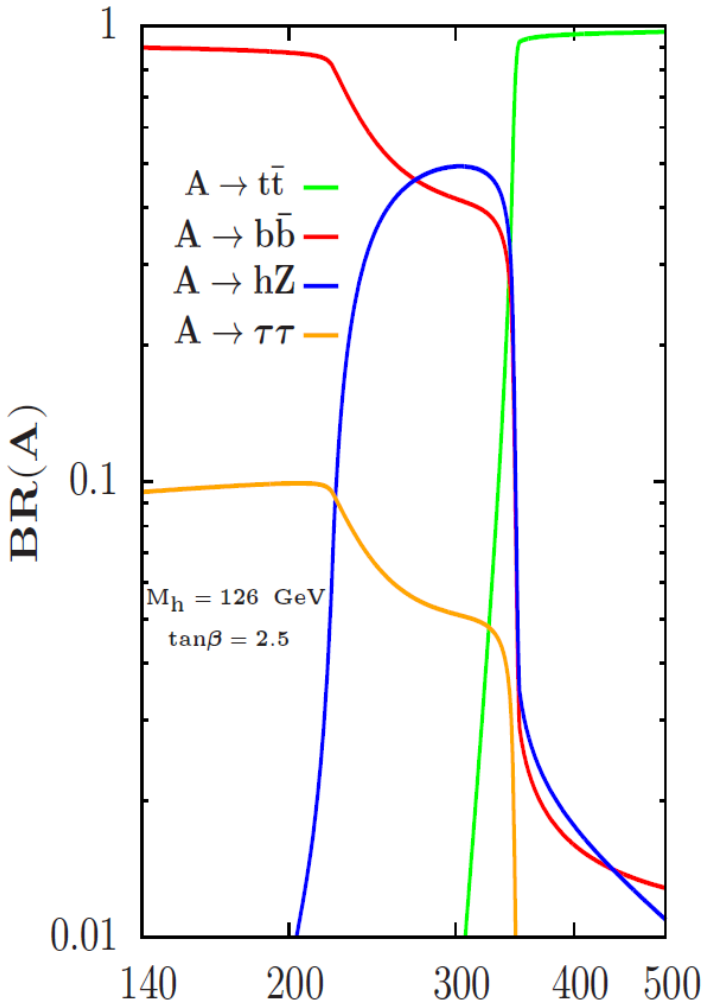


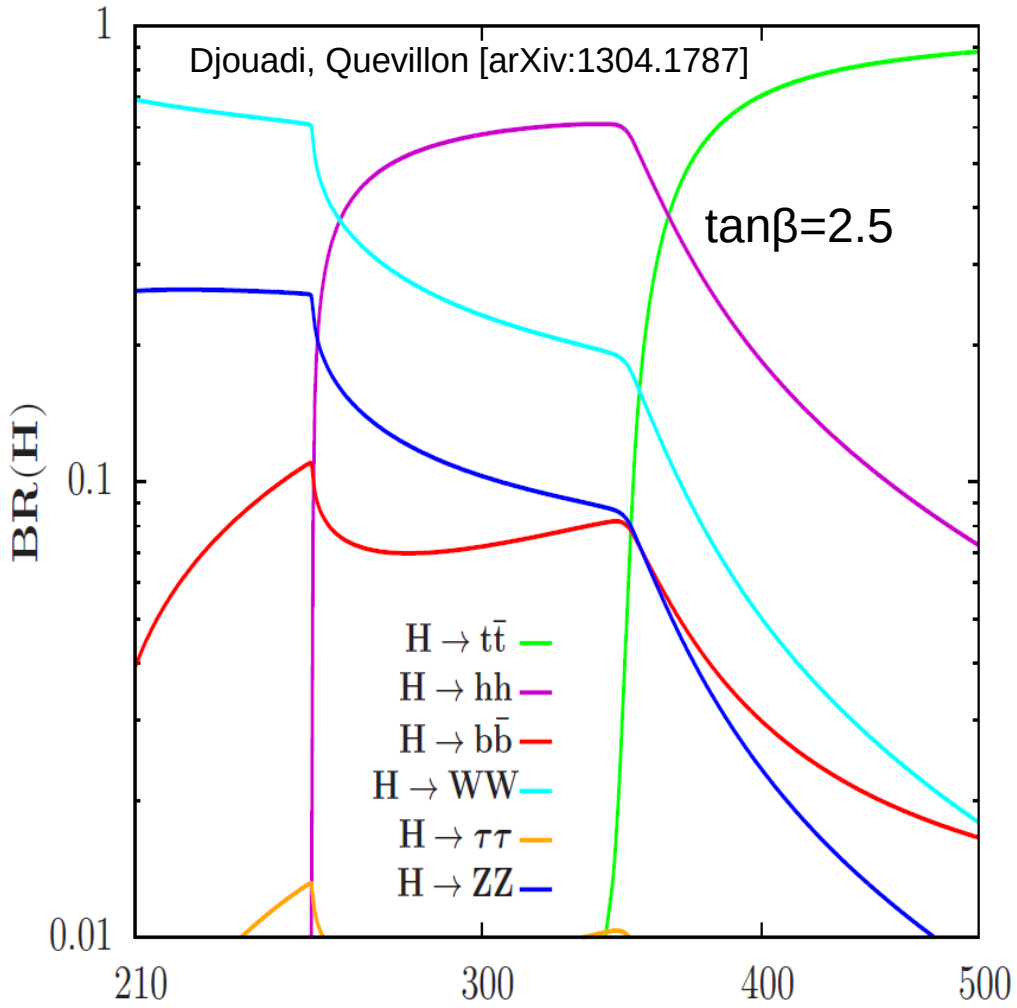




Low tanβ regime in the MSSM

- non-observation of SUSY particles suggests high SUSY scale M_S (>3TeV)
- large M_S together with measured m_h re-opens low tanβ parameter space
- λ_{Hhh} and λ_{AZh} enhanced for low tanβ





SM-like Higgs boson becomes an effective probe for an extended Higgs sector!

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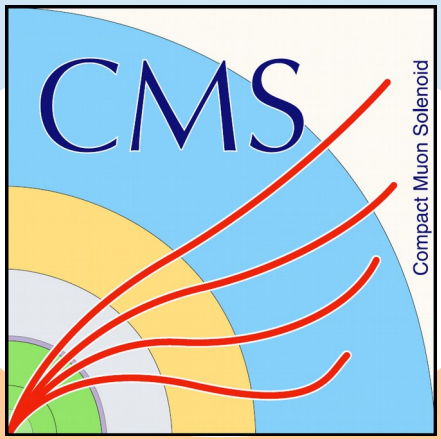

Φ→ττ
JHEP 1410 (2014) 160
CMS-HIG-13-021

H→hh→bbττ
A→Zh→llττ
Submitted to PLB
CMS-HIG-14-034

X→hh→bbbb
Phys. Lett. B 479 (2015) 560
CMS-HIG-14-013

heavy Higgs decays via SM-like h/Z resonances

A→Zh→llbb
Phys. Lett. B 748 (2015) 221
CMS-HIG-14-011

X→hh→bbγγ
CMS-PAS-HIG-13-032

A→Zh/H→hh
multi l/γ
CMS-PAS-HIG-13-025

CMS pursues a rich search program for additional Higgs bosons

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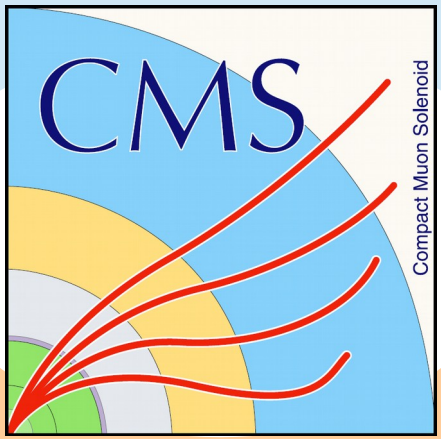

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CMS pursues
a rich search program
for additional Higgs bosons

H→hh→bbττ: Search Strategy

Channels and categories

3 search channels:

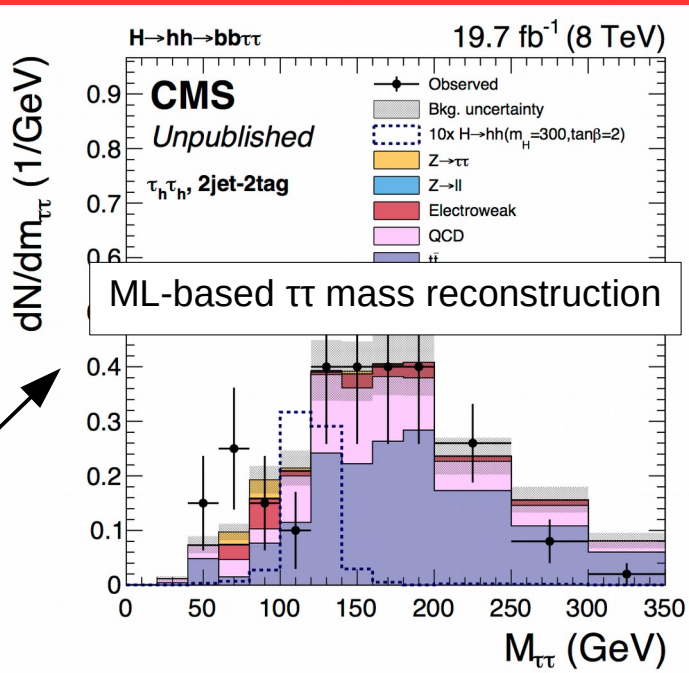
hh → bbττ → bb(eτ$_h$ | μτ$_h$ | τ$_h$τ$_h$)

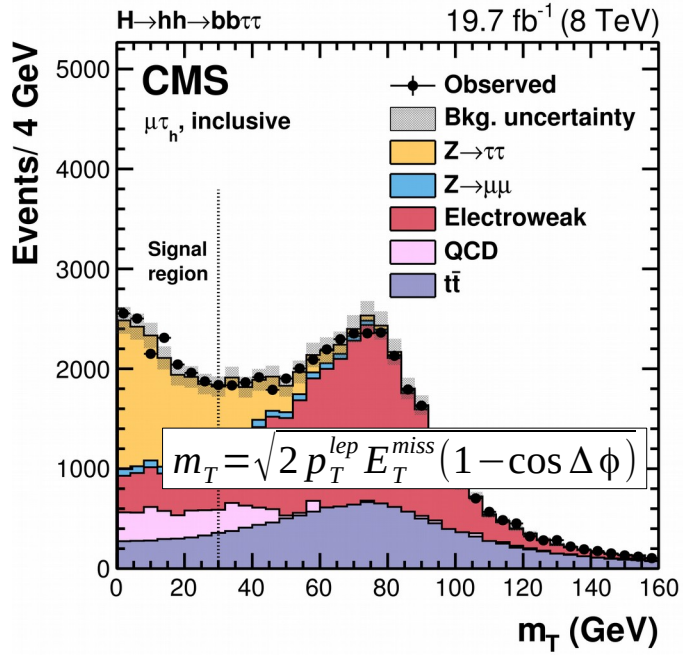
3 categories:

(0|1|2) b-taged jets

Event Selection

		$h \to e\tau_h$	$h \to \mu\tau_h$	$h \to \tau_h\tau_h$
$h \to \tau\tau$	e	$p_T > 24$ GeV, $\|\eta\| < 2.1$ Tight MVA ID, $I_{rel} < 0.1$	- -	- -
	μ	- -	$p_T > 20$ GeV, $\|\eta\| < 2.1$ Tight PF ID, $I_{rel} < 0.1$	- -
	τ_h	$p_T > 20$ GeV, $\|\eta\| < 2.3$		$p_T > 45$ GeV, $\|\eta\| < 2.1$
		3 hit isolation < 1.5 GeV		3 hit isolation < 1 GeV
		Loose anti-μ, medium anti-e MVA	Loose anti-e, tight anti-μ	Loose anti-e (tau 1) + Loose anti-e MVA (tau 2) Loose anti-μ (both)
	Charge	Opposite sign charges		
	$m_{\tau\tau}$	$90 < m_{\tau\tau} < 150$ GeV		
$h \to bb$	Jets	PF jet, $p_T > 20$ GeV, $\|\eta\| < 2.4$ Pileup jet ID		
	b-jets	CSV Medium WP		
	m_{bb}	$70 < m_{bb} < 150$ GeV		
Others	m_T	$m_T < 30$ GeV		-
	Lepton veto	No additional identified and isolated electron or muon		





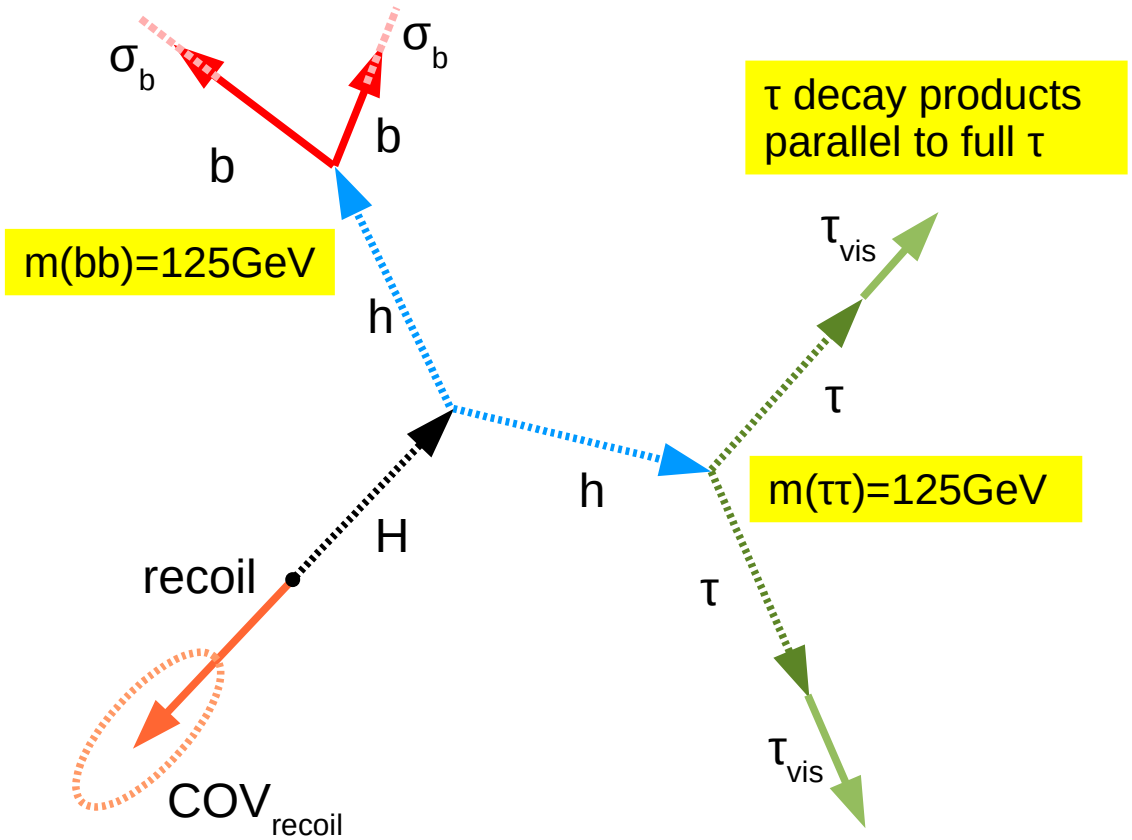
Backgrounds

- dominant in semileptonic ττ channels: **ttbar**
- dominant in full hadronic ττ channels: **QCD**

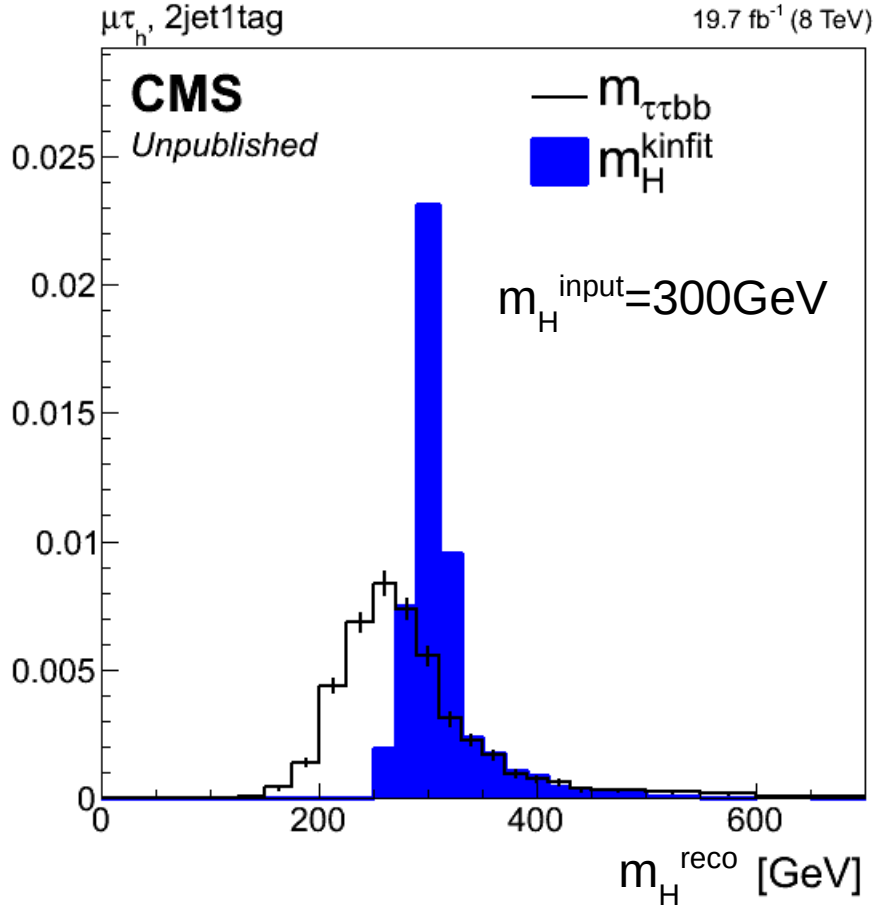
H→hh→bbττ: Kinematic Fit

- event kinematically highly constrained
- kinematic fit:
  - ➔ get a good full τ 4-vector reconstruction
  - ➔ get heavy higgs mass reconstruction

2 dimensional fit
- vary E_{b1}, $E_{\tau 1}$
- constrain E_{b2}, $E_{\tau 2}$ to fulfill inv. mass
- minimize chi2 function (considering resolutions of measured quantities)



τ decay products parallel to full τ

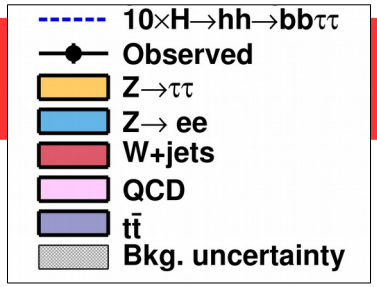


fitted heavy Higgs mass significantly improved compared to simple 4-body mass

H→hh→bbττ: Results

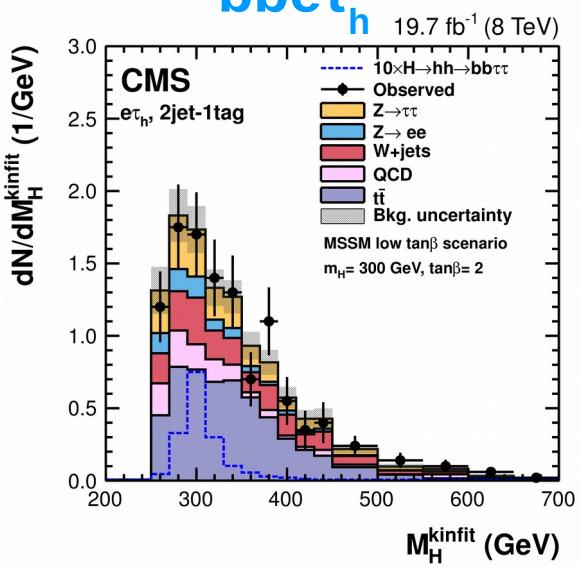
signal extracted from kinematically fitted mass
(0 tag category not shown here, BG dominated)

m_H^{input}=300GeV
tanβ=2

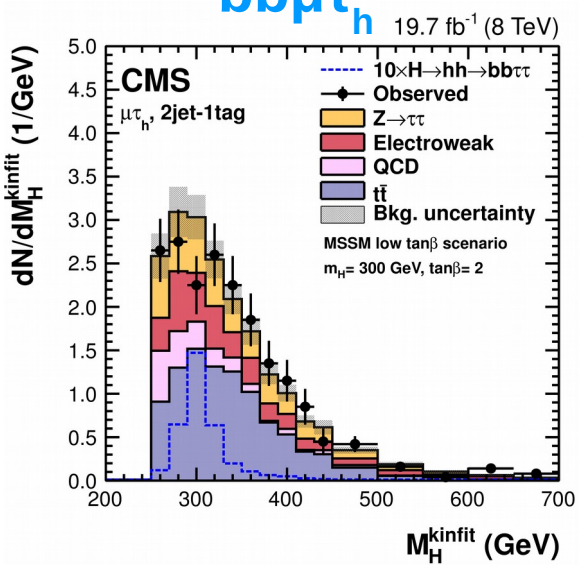


1 b-tag

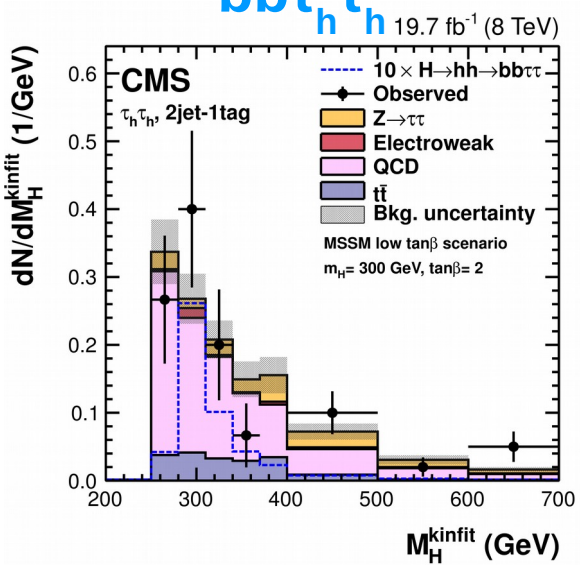
bbeτ$_h$



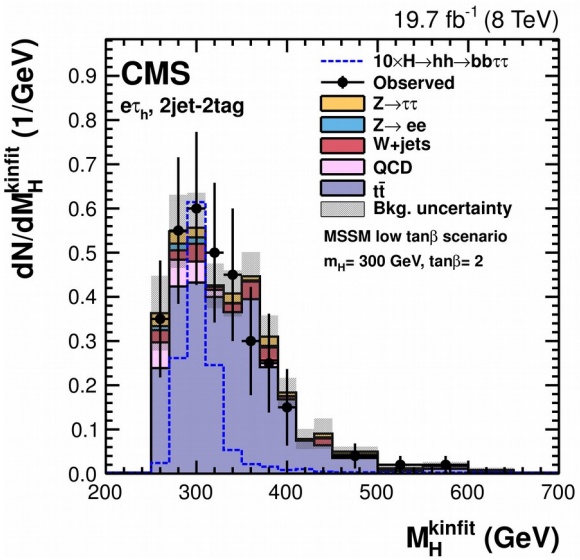
bbμτ$_h$

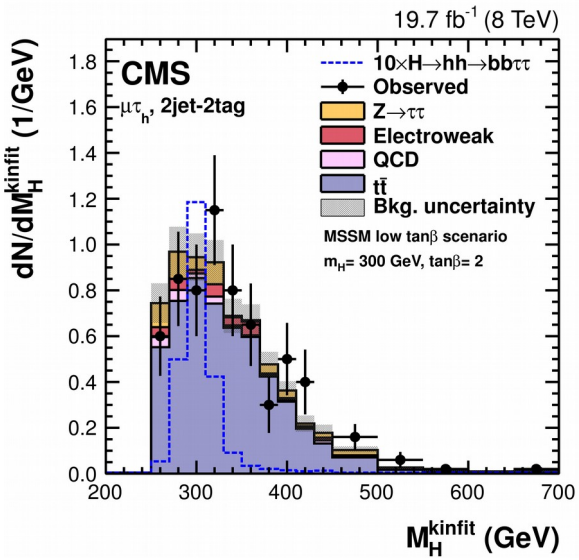


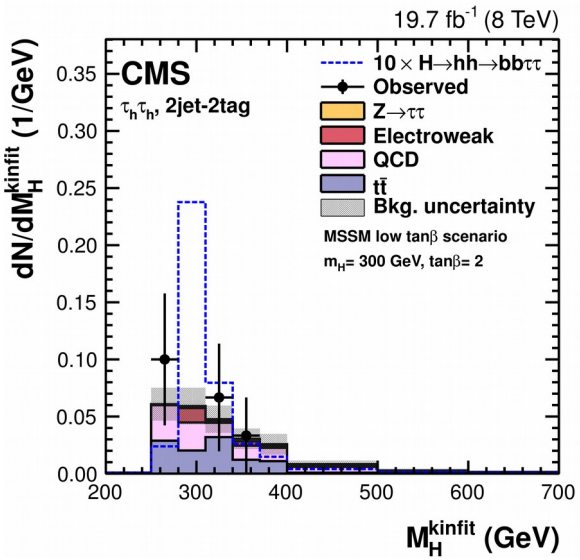
bbτ$_h$τ$_h$



2 b-tags

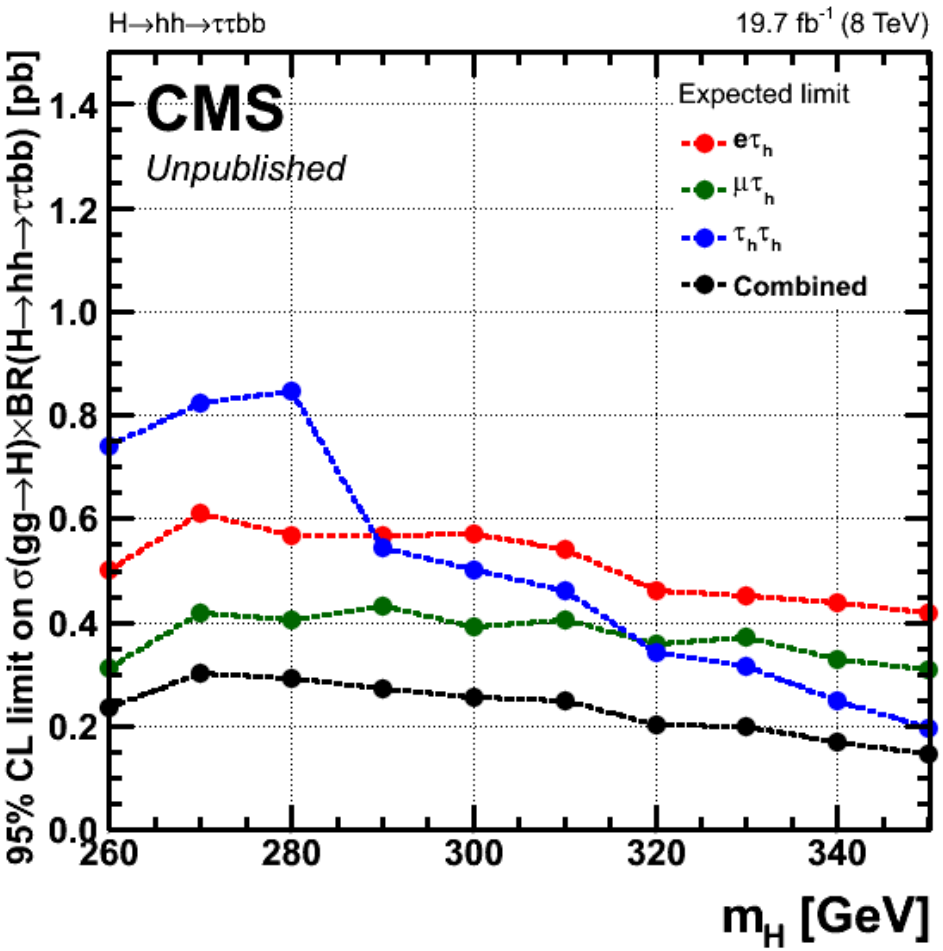




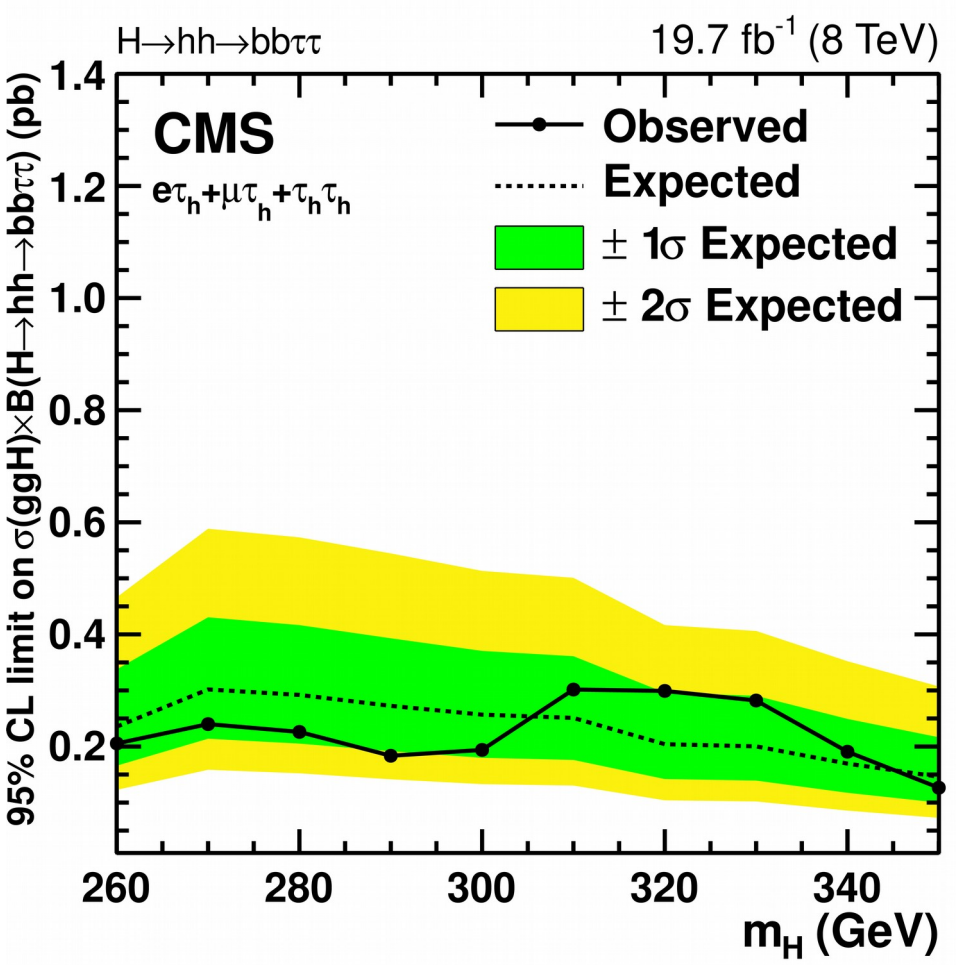


H→hh→bbττ: Limits

Sensitivity of different channels



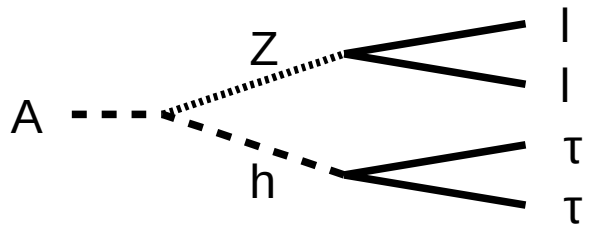
Combined observed limit



A→Zh→llττ: Search Strategy

Channels and categories

8 search channels: **Z→(ee|μμ)** x **h→ττ→(eμ | eτ$_h$ | μτ$_h$ | τ$_h$τ$_h$)**

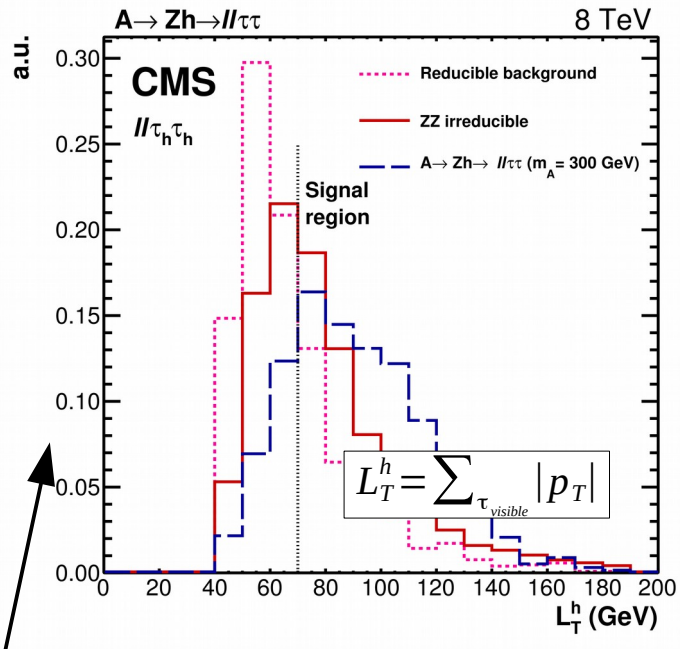


Event Selection

		$Z \to ee$	$Z \to \mu\mu$
$Z \to \ell\ell$	e	$p_T > 10/20$ GeV, $\lvert\eta\rvert < 2.5$ $I_{rel} < 0.3$, vLoose MVA ID	- -
	μ	-	$p_T > 10/20$ GeV, $\lvert\eta\rvert < 2.4$ $I_{rel} < 0.3$, Loose PF ID
	$m_{\ell\ell}$	$60 < m_{\ell\ell} < 120$ GeV	
	Charge	Opposite sign charges	

		$h \to e\mu$	$h \to e\tau_h$	$h \to \mu\tau_h$	$h \to \tau_h\tau_h$
$h \to \tau\tau$	e	$p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$		-	-
		vLoose MVA ID $I_{rel} < 0.3$	Loose MVA ID $I_{rel} < 0.2$		
	τ_h	-	$p_T > 21$ GeV, $\lvert\eta\rvert < 2.3$		
			Loose isolation Tight anti-e Loose anti-μ	Loose isolation Loose anti-e Tight anti-μ	Medium isolation Loose anti-e Loose anti-μ
	μ	$p_T > 10$ GeV $\lvert\eta\rvert < 2.4$ Loose PF ID $I_{rel} < 0.3$	-	$p_T > 10$ GeV $\lvert\eta\rvert < 2.4$ Tight PF ID $I_{rel} < 0.3$	-
	Charge	Opposite sign charges			

		$h \to e\mu$	$h \to e\tau_h$	$h \to \mu\tau_h$	$h \to \tau_h\tau_h$
Others	L_T^h	> 25 GeV	> 30 GeV	> 45 GeV	> 70 GeV
	b–Jet veto	No b–tagged jet (medium WP)			
	Lepton veto	No additional identified and isolated electron or muon			
	DR between leptons	> 0.5			



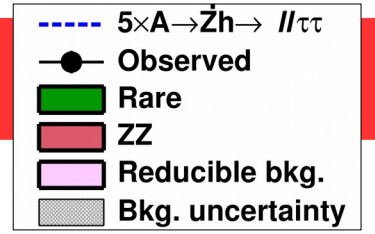
Backgrounds

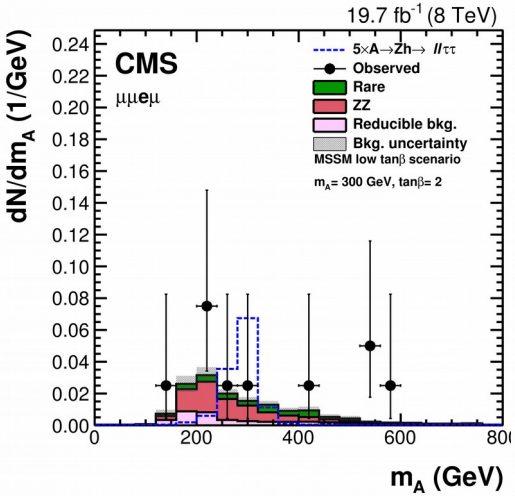
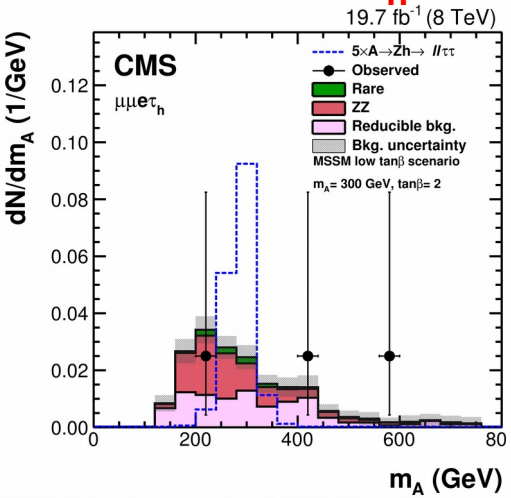
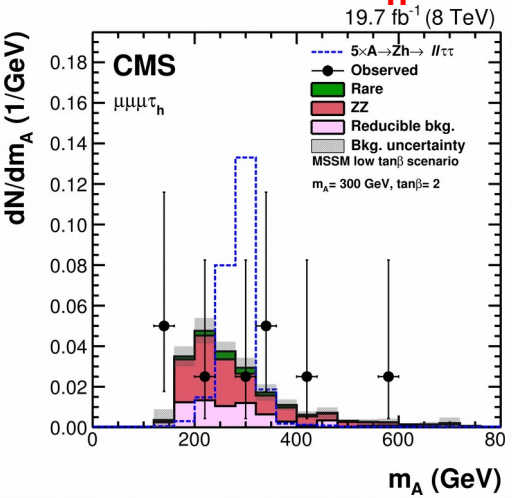
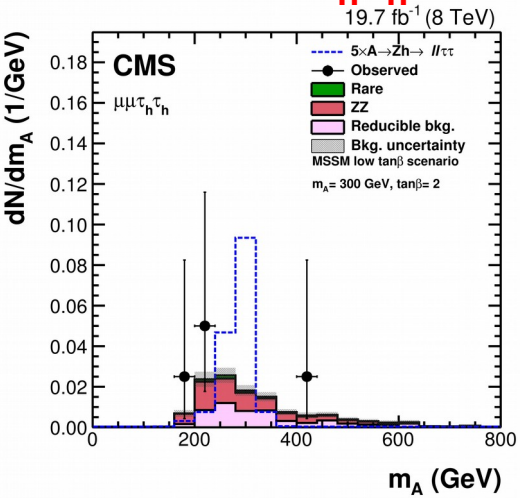
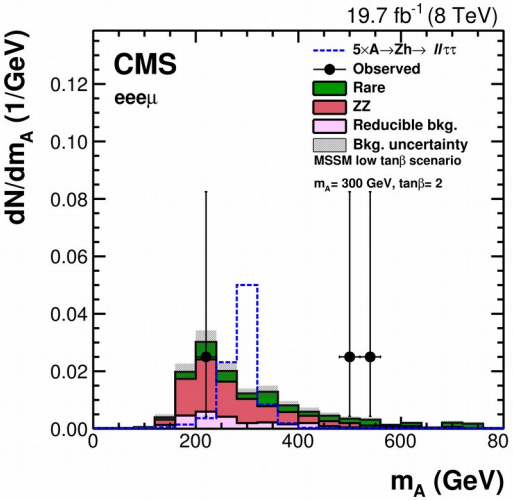
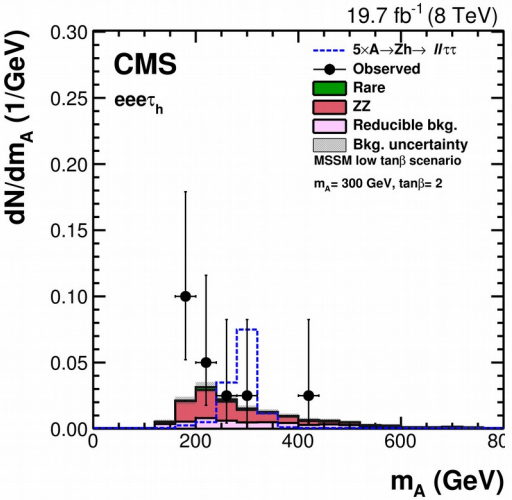
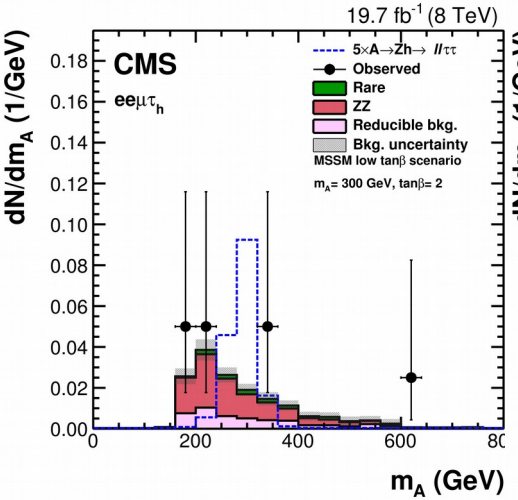
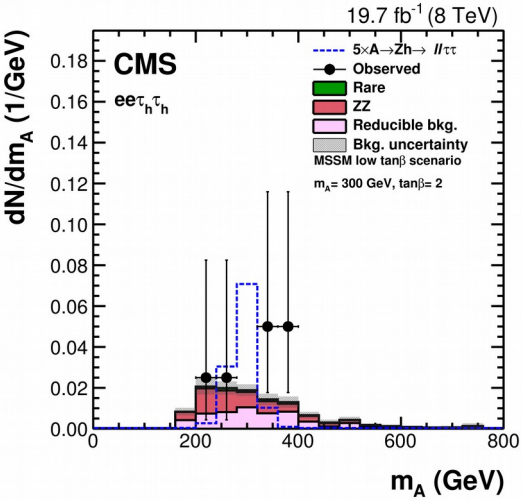
- dominant irreducible BG: **ZZ**
- dominant reducible BG: **misidentified leptons** in Z+jets, WZ+jets

A→Zh→llττ: Results

signal extracted from 4-body mass

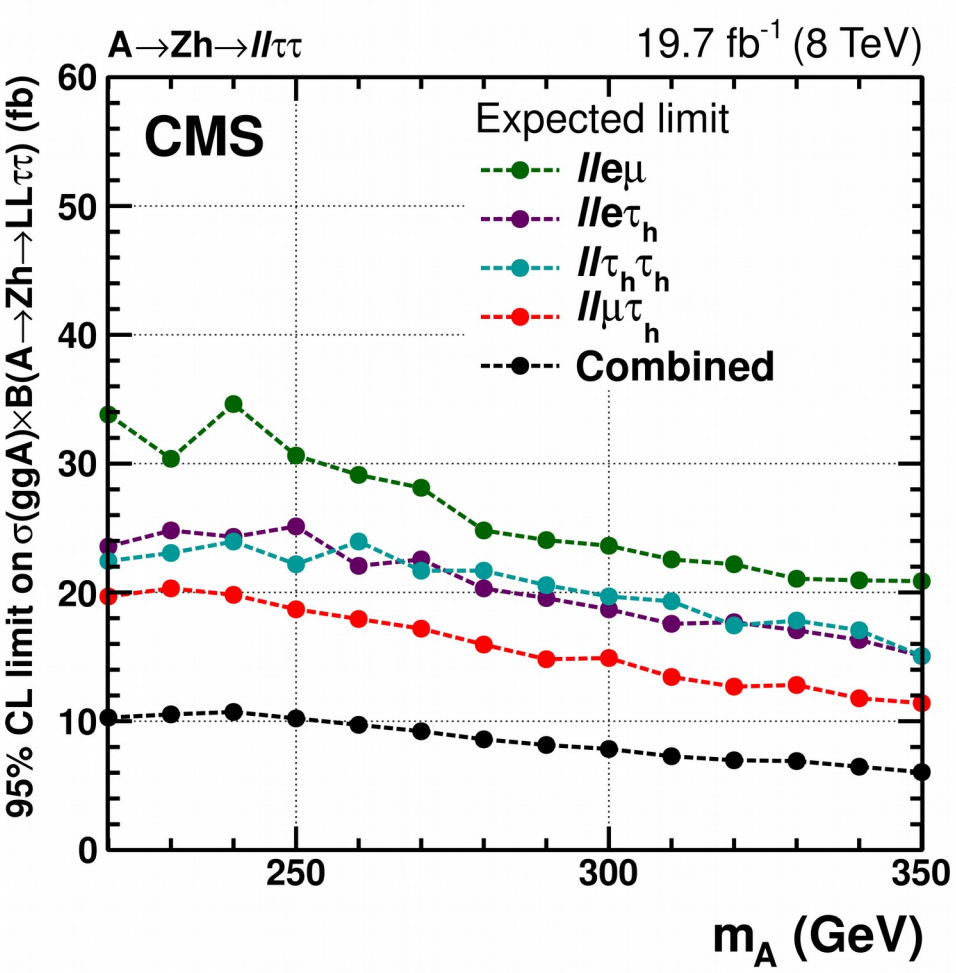
m_A^{input}=300GeV
tanβ=2



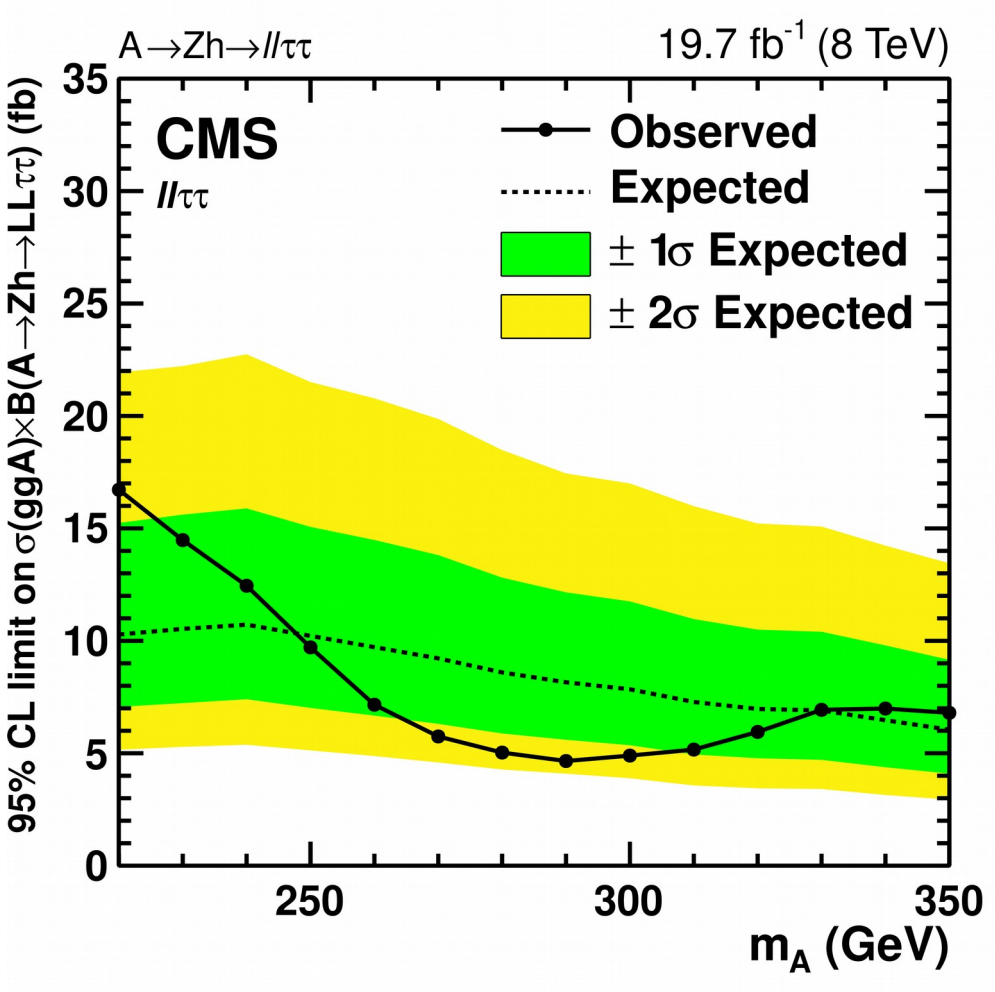
	ττ → eμ	ττ → eτ$_h$	ττ → μτ$_h$	ττ → τ$_h$τ$_h$
Z → ee				
Z → μμ				

A→Zh→llττ: Limits

Sensitivity of different channels



Combined observed limit



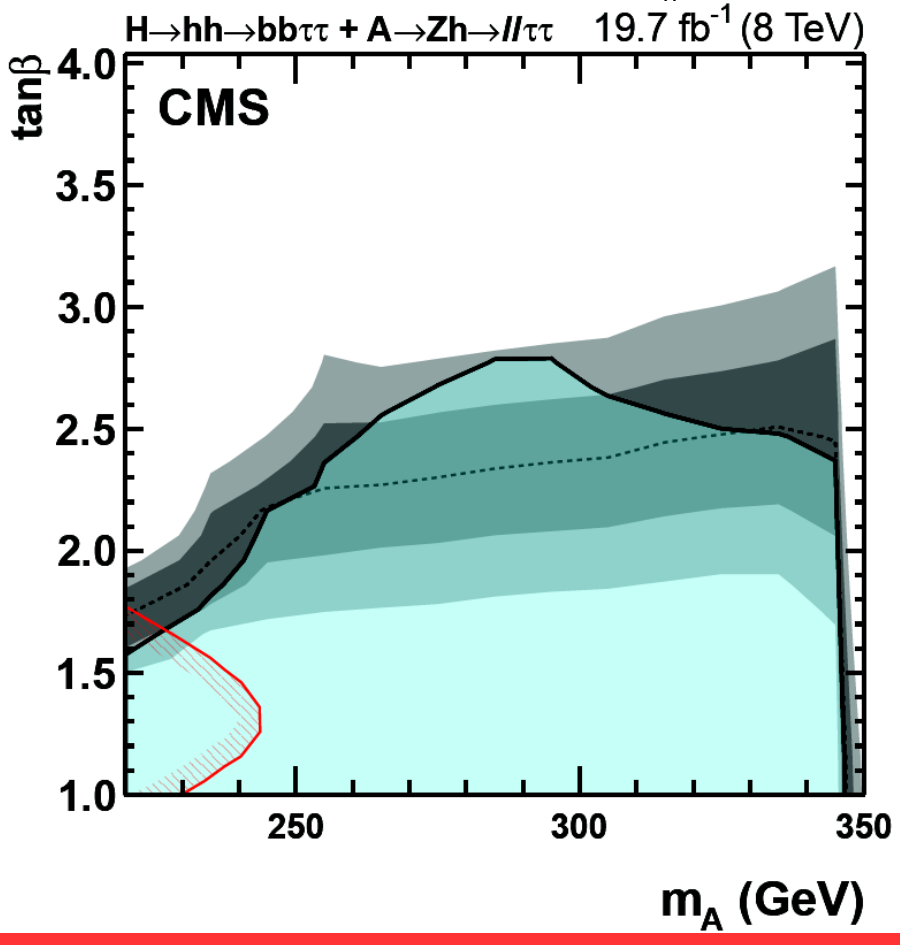
Combined MSSM low tanβ Interpretation

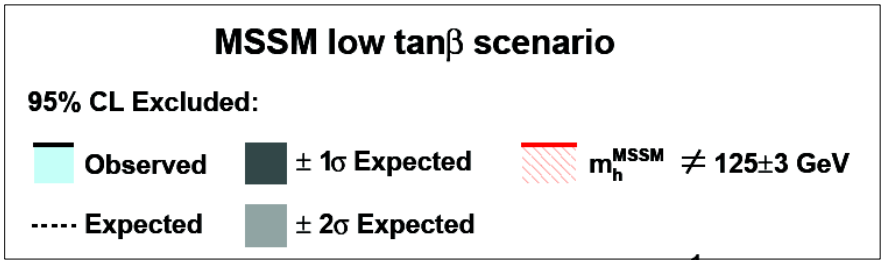
low tanβ scenario as defined by the LHC Higgs Cross Section Working Group:
(LHCHXSWG-2015-002)

parameter space:
- 0.5<tanβ<10
- 150GeV<mA<500GeV

constraint
- from high-precision calc.: $m_h \approx 125$GeV

remaining parameter choices:
- soft sfermion/gluino masses = m_{SUSY}
- m_{SUSY}: few TeV-100TeV
  (special relations between m_{SUSY}, tanβ, X_t)
- trilinear couplings=2TeV, μ=1.5TeV,
- M_2=2TeV, M_1 via GUT relation





- H/A→hh/Zh constrain tanb-mA-plane from below
- complementary to H/A→ff searches

Type-II-2HDM Interpretation

2HDM in the "physics basis"

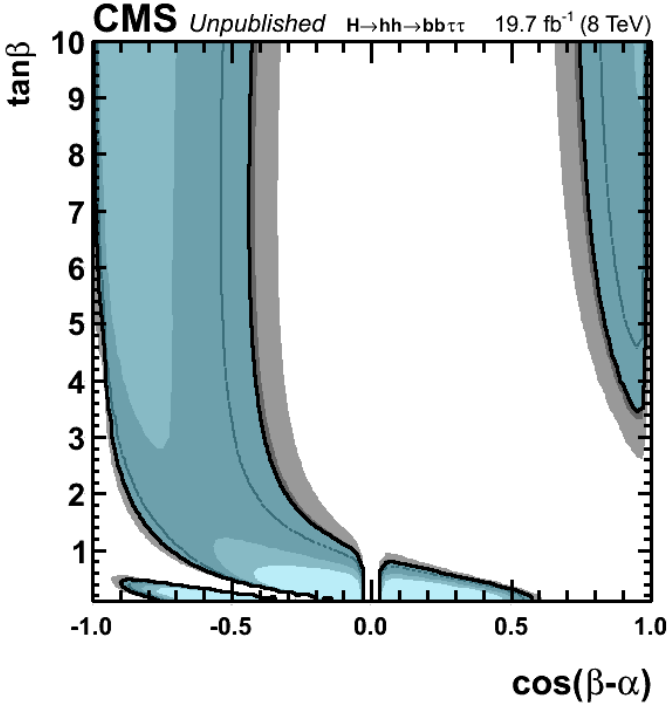
parameter space:

- Higgs boson masses (m_h, m_H, m_A, m_{H+})
- ratio of vevs: tanβ
- mixing angle of CP-even higgses: α

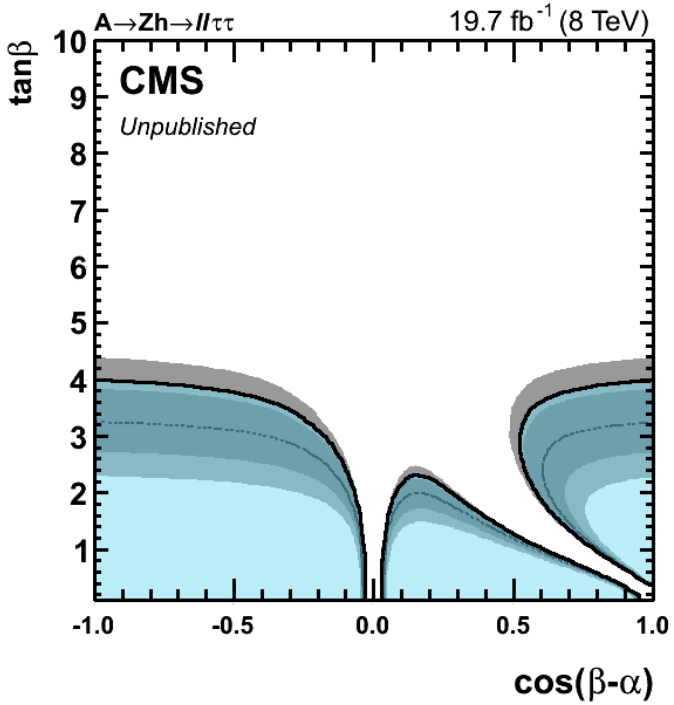
assumptions:

- m_h=125GeV
- m_H=m_A=m_{H+}=300GeV

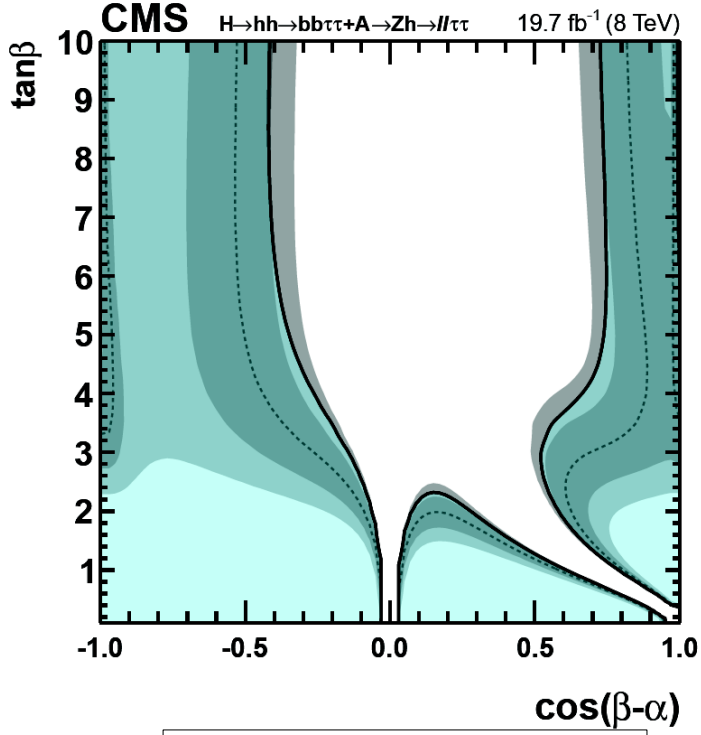
H→hh→bbττ



A→Zh→llττ



combined

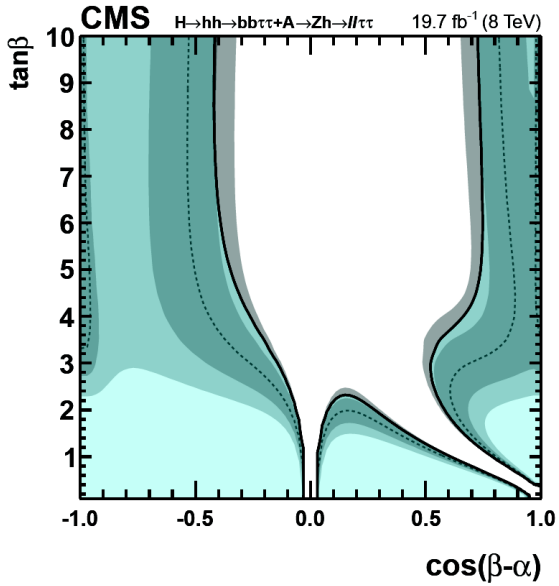


CP even (H) and CP odd (A) searches constrain different regions of the Type-II-2HDM parameter space

Conclusions

- CMS pursues a versatile search program in the extended Higgs sector
- SM-like Higgs boson becomes effective probe for an extended Higgs sector in low tanβ regime
- CMS heavy Higgs search with τ final states recently submitted to PLB:

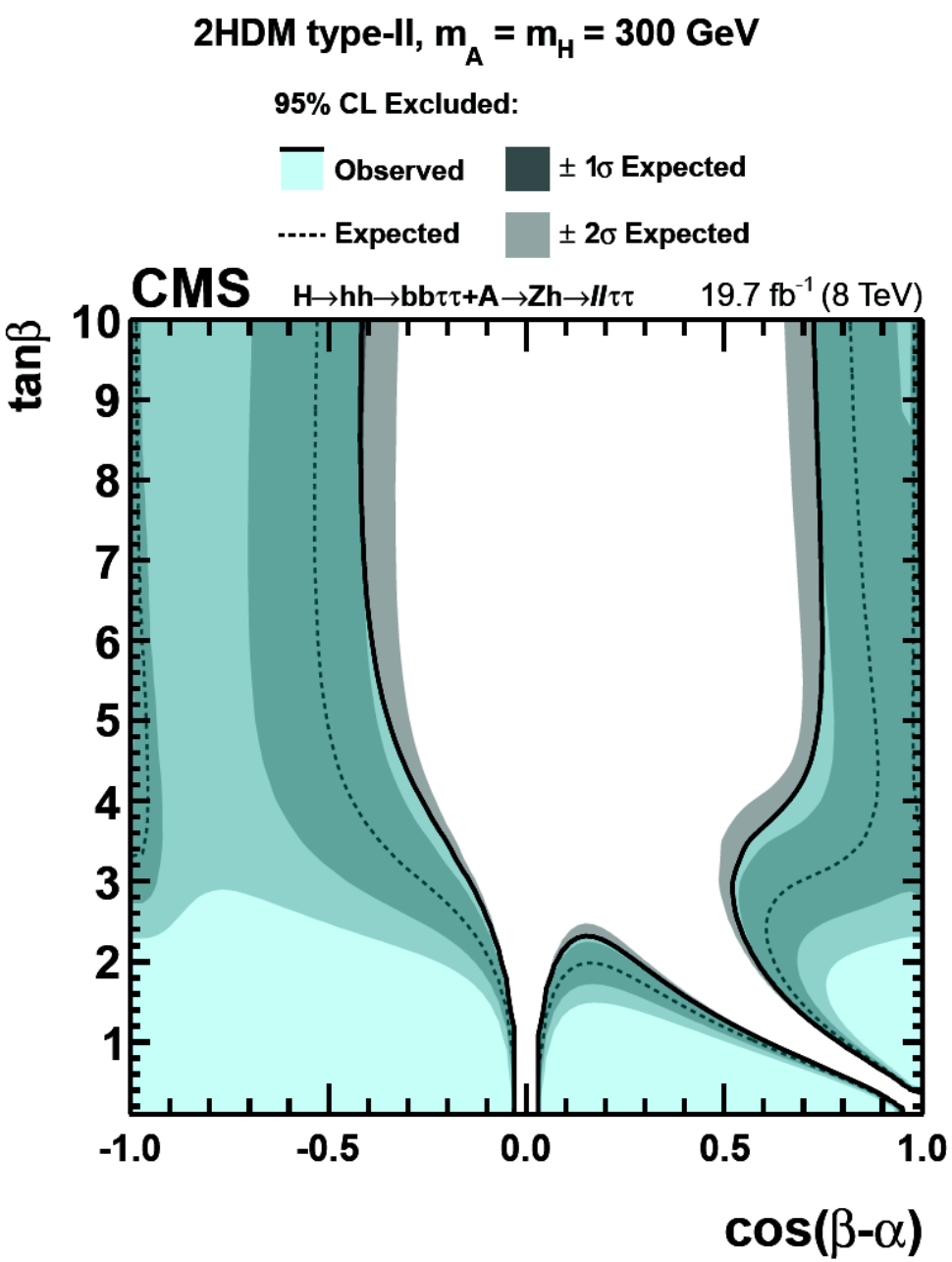
> Searches for a heavy scalar boson H decaying to a pair of 125 GeV Higgs bosons hh or for a heavy pseudoscalar boson A decaying to Zh, in the final states with $h \to \tau\tau$

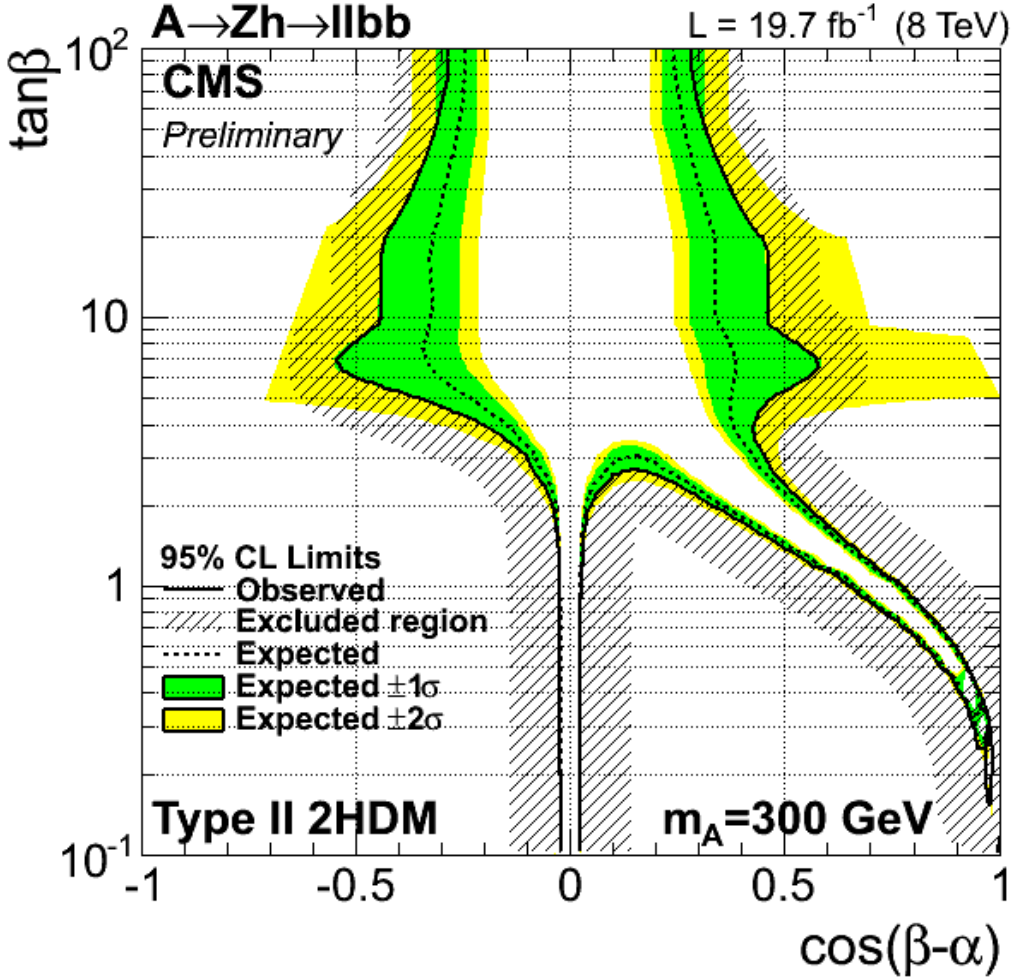


- no hint for new physics found …… yet!

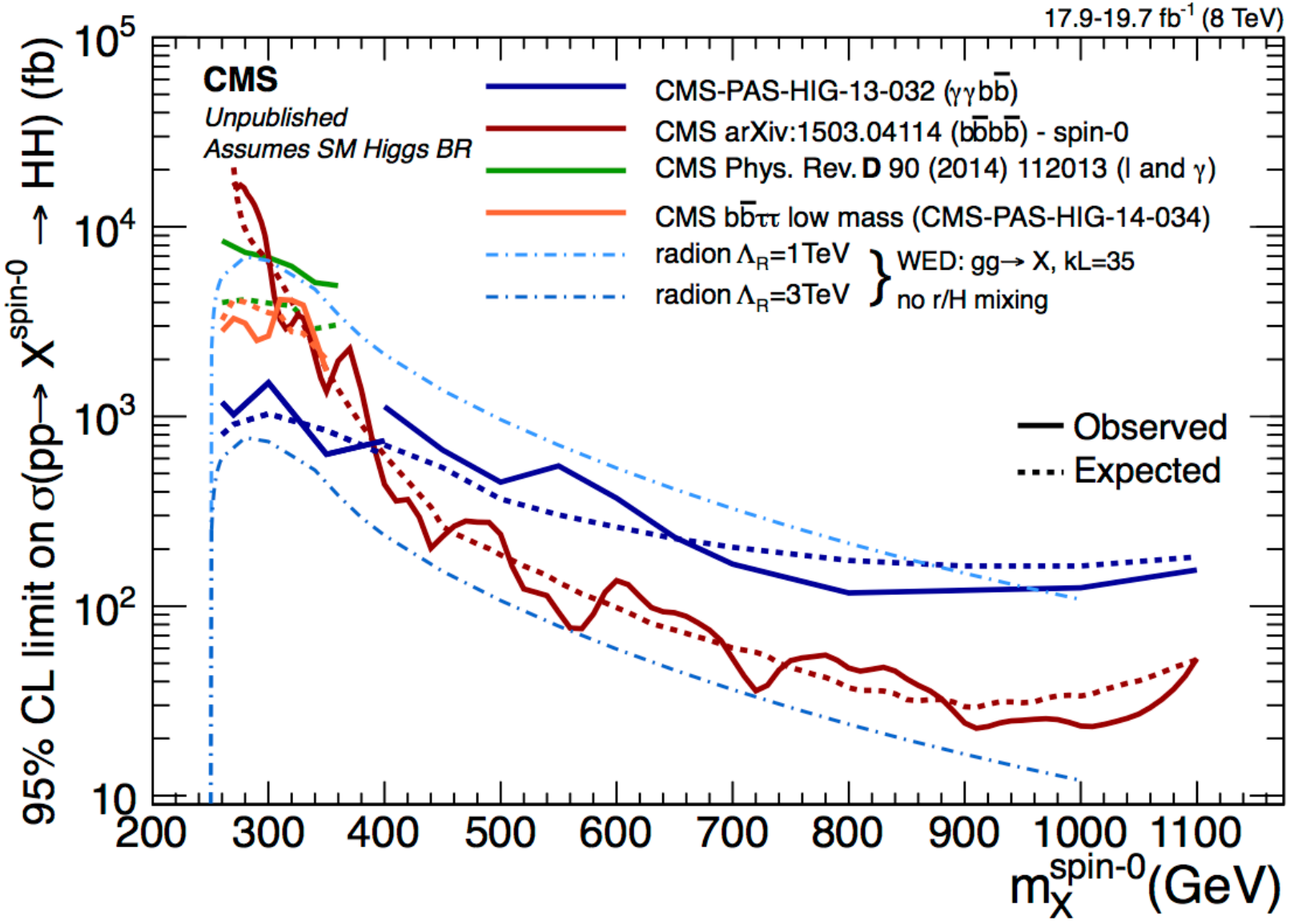
Thank you very much for your attention!

Comparison with A→Zh→llbb





Sensitivity of Different Heavy Higgs Searches



Signal Sample Cut Flow

$A \to Zh \to ll\tau\tau$:

	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Initial Number		457250	
$h \to \tau\tau$ inclusive preselection	4647	7958	1134
$m_T < 30\,\text{GeV}$	2809	5198	-
$n_{jets} \geq 2$	2166	3946	1032
$70 < m_{bb} < 150\,\text{GeV}$ and $90 < m_{\tau\tau} < 150\,\text{GeV}$	1352	2421	712
Kinematic fit convergence	1330	2362	686

$H \to hh \to bb\tau\tau$:

	$\mu\mu\tau_h\tau_h$	$\mu\mu e\tau_h$	$\mu\mu\mu\tau_h$	$\mu\mu e\mu$	$ee\tau_h\tau_h$	$eee\tau_h$	$ee\mu\tau_h$	$eee\mu$
Initial number	99 794							
Trigger	61 577							
At least 4 loose leptons	12 136	11 717	6 212	2 876	8 504	7 310	5 755	1 865
b-Jet veto	10 109	10 276	5 551	2 660	7 018	6 332	5 045	1 711
Z candidate	7 825	7 758	4 571	2 142	4 903	5 266	2 720	1 340
h candidate	1 106	919	1 485	718	764	735	950	531
L_T^h cut	842	919	1 362	707	612	735	892	522

Systematic Uncertainties

Common Experimental Uncertainties	
Source	Uncertainty
Luminosity Measurements	2.6%
Electron ID and trigger	2–3%
Muon ID and trigger	2–3%
τ lepton ID and trigger	6–19%

$H \to hh$ **Experimental Uncertainties**		
Source	$\mu\tau_h$-eτ_h	$\tau_h\tau_h$
E_T^{miss}	1–10%	–
b tagging efficiency	1–70[1]%	2–5%
b mistag rate	1–5%	2.5%
Z production	3.3%	3.3%
$Z \to \tau\tau$: category selection	5%	6–175[1]%
$Z \to \tau\tau$ due to $t\bar{t}$ embedded	–	5–49%
$t\bar{t}$	10%	10%
Diboson	15%	15%
QCD multijet	10–100%	10–40%
W+jets	10–100%	20%
$Z \to ee$: e misidentified as τ_h	20–40%	–
$Z \to \mu\mu$: μ misidentified as τ_h	30–60%	–
Z+jets: jet misidentified as τ_h	20–90%	–
$Z \to ll$: jet and l misidentification	–	30–67%

$A \to Zh$ **Experimental Uncertainties**	
Source	Uncertainty
Reducible background estimate	15–50%
$\sigma_{triboson}$ and σ_{ttZ}	50%
b jet veto	1%