Search for Higgs bosons decaying to τ pairs with CMS

Erratum in slide 6 (in red)

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GDR Terascale Workshop
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Introduction

- **Higgs boson → central manifestation of EWSB**

- **a Higgs boson discovered @ the LHC by ATLAS & CMS** *Phys. Lett. B 716 (2012) 1-29* *Phys. Lett. B 716 (2012) 30*

  - **Discovery driven by di-boson channels: $ZZ^{(*)}$, $\gamma\gamma$ and $WW^{(*)}$**
  - **Current weak constraints on the Higgs properties → resonance compatible with the minimal scalar sector of the SM**
  - **What about couplings of new particle to leptons?**

  → **Search for SM $H\rightarrow\tau\tau$ and probe the Yukawa coupling** *arXiv:1401.5041 [hep-ex]*

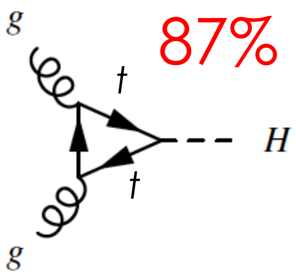
- **SM: Higgs field's self-coupling and boson's mass put by hand in the theory**

  - **Can we avoid the arbitrariness of the Higgs sector?**
  - **MSSM → theory in which the Higgs sector is predicted**
  - **Are there additional Higgs bosons? As predicted by MSSM?**

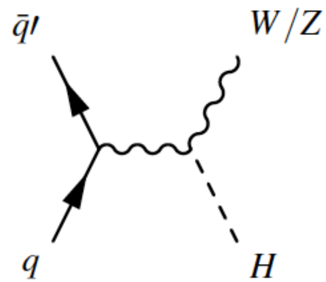
  → **Search for MSSM $h/H/A\rightarrow\tau\tau$** *CMS-PAS-HIG-13-021*

H→ττ in the SM

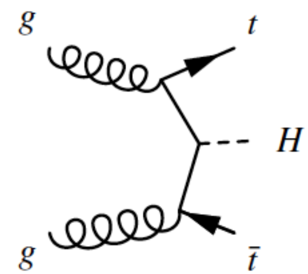
- **4 dominant Higgs production mechanisms** (fractions at $\sqrt{s}$ = 8 TeV and m_H = 125 GeV):



Gluon-gluon fusion (ggF)

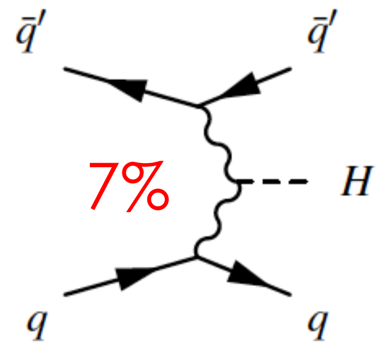


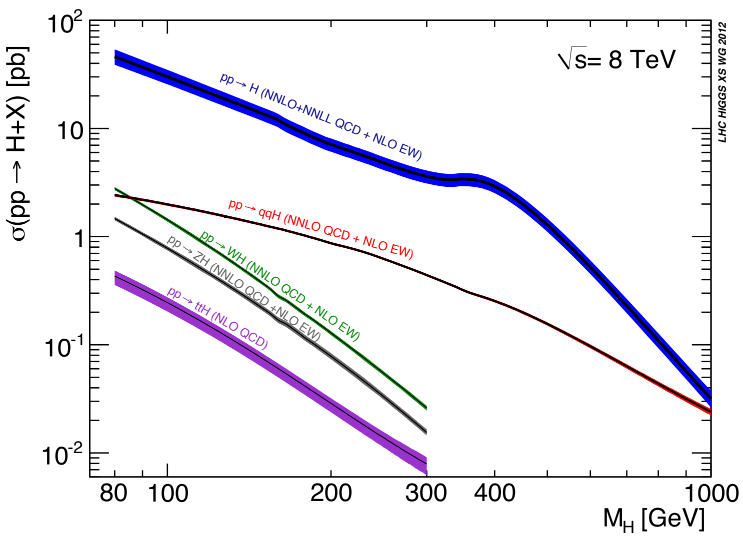
Associate production w/ a W/Z vector boson (VH)

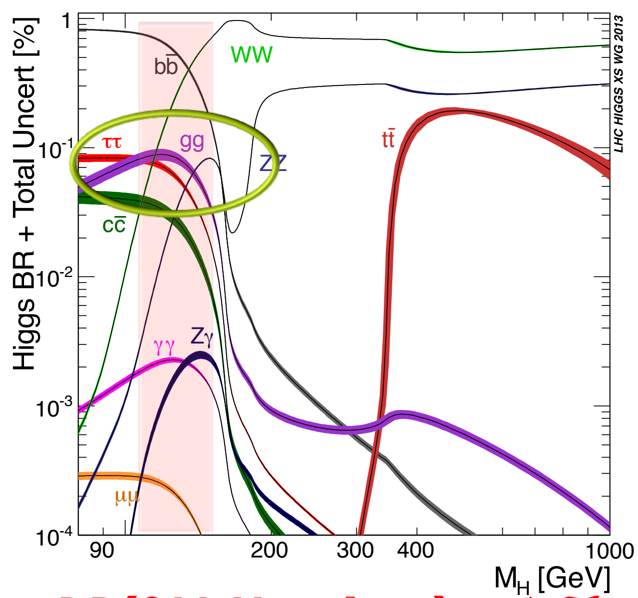


Associate production with a top-quark pair (ttH)

Vector Boson Fusion (VBF)







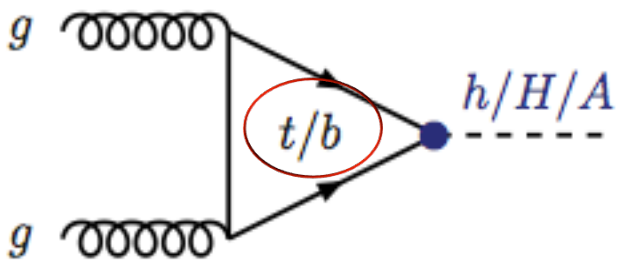
- **Favorable BR at low mass**
- **H→ττ = only channel available to probe the Higgs couplings to *leptons***

BR(SM $H_{125}\to\tau\tau$) ~ 6 %

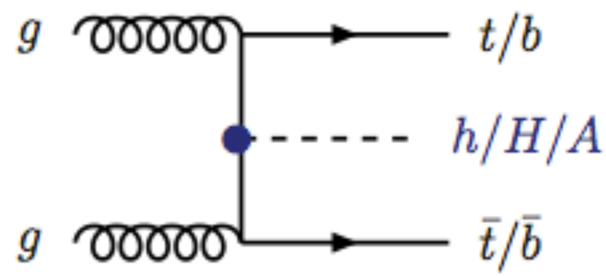
H→ττ in MSSM

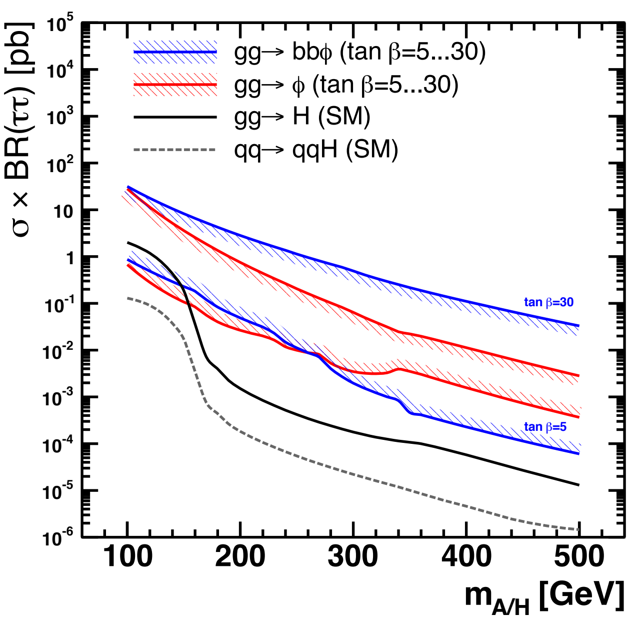
- **3 neutral Higgs bosons (h, H, A) → simultaneous search (i.e. fit of 3 components)**
- Enhanced coupling to b-quark increases cross section wrt SM
- **2 dominant Higgs production mechanisms**

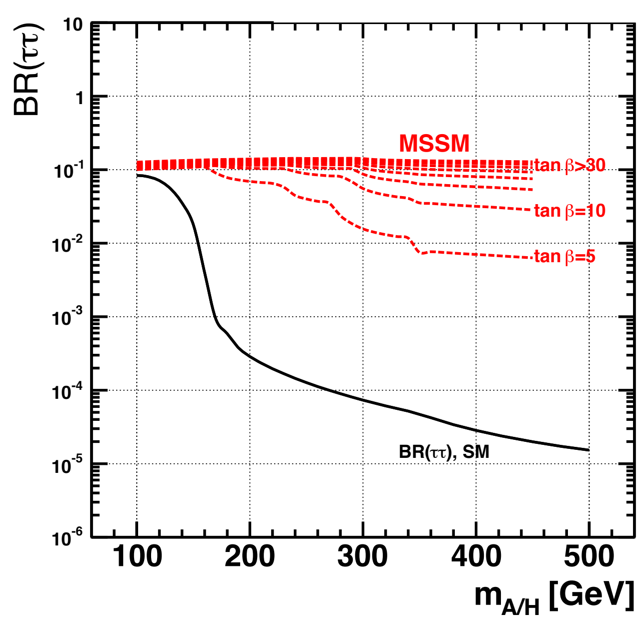
Gluon gluon fusion
(quark/squarks loops)



Associated bb/tt production





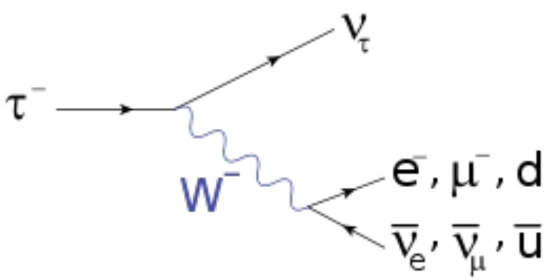


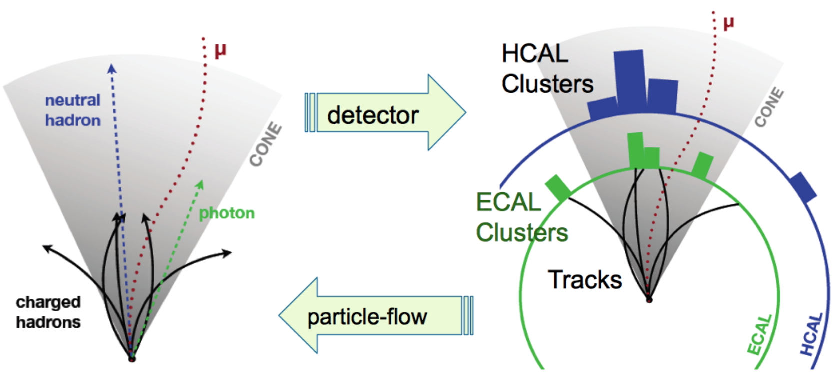
- **BR stable with Higgs mass**
- **Slight dependence on tanβ**
- ***BR ~ 10^{-1}***

- **m_A and tanβ relevant parameters in the search**

τ-lepton decay modes

- **The τ-lepton is a complex object**
- Decays rather quickly (cτ=87 μm) to leptons/hadrons + neutrino(s)





Decay channel	BR (%))
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.36
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.85
$\tau^- \to h^- \nu_\tau$	11.6
$\tau^- \to h^- \pi^0 \nu_\tau$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$	4.8
others	3.1

~35% (leptonic channels: $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, $\tau^- \to e^- \bar{\nu}_e \nu_\tau$)

~62% (hadronic channels)

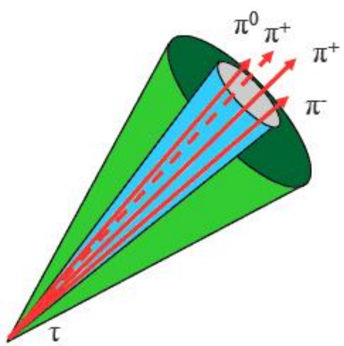
→ Reconstruction based on **Particle Flow algorithm**

Study of leptonic *and* hadronic H→ττ decays

→ μμ, eμ, ee, $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$ channels

Hadronic τ-lepton reconstruction

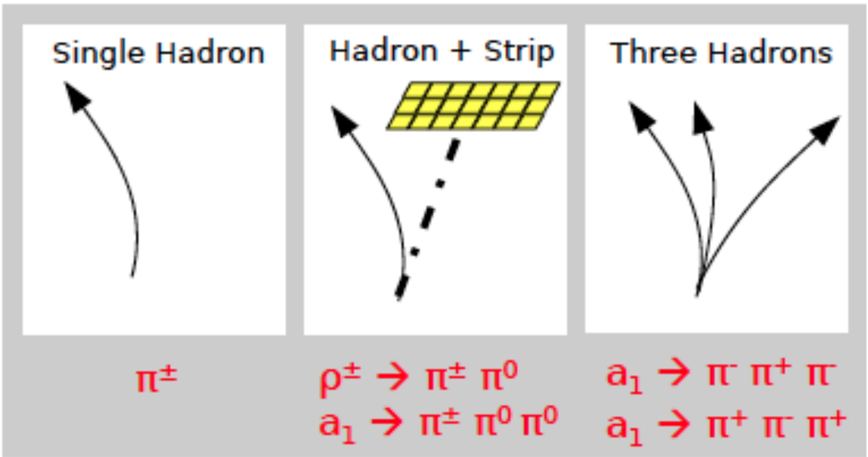
- **Decay mode reconstruction = Hadron Plus Strip (HPS) algorithm**
- Study of the different topologies + intermediate resonances

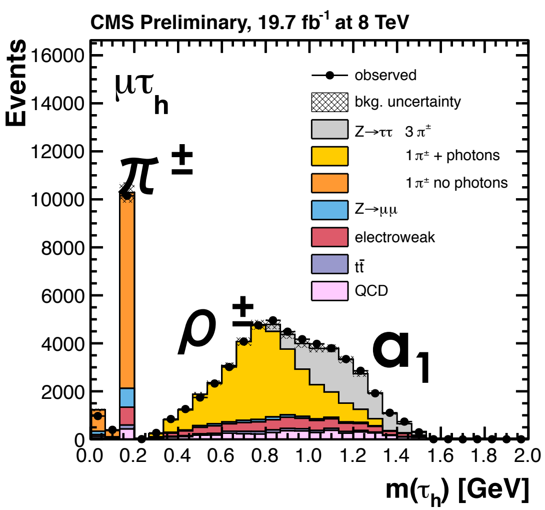


τ_h-induced jet

- 1-prong
- 1-prong + $\pi^0(\rightarrow\gamma\gamma)$
- 3-prong

[Tracker + ECAL + HCAL] integrated





- **Control of jet→τ_h fake rate through cut-based isolation**

→ **Fake rate is ~3% at ~70% signal efficiency**

- **Control of μ/e→τ_h fake rates through MVA-based discriminators**

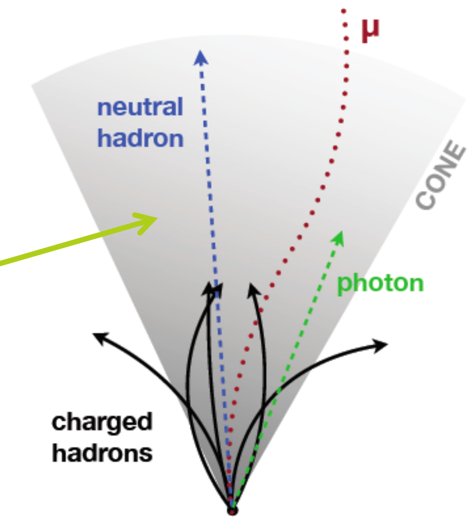
→ **μ/e fake rate are at the per-mil (per-cent) level**

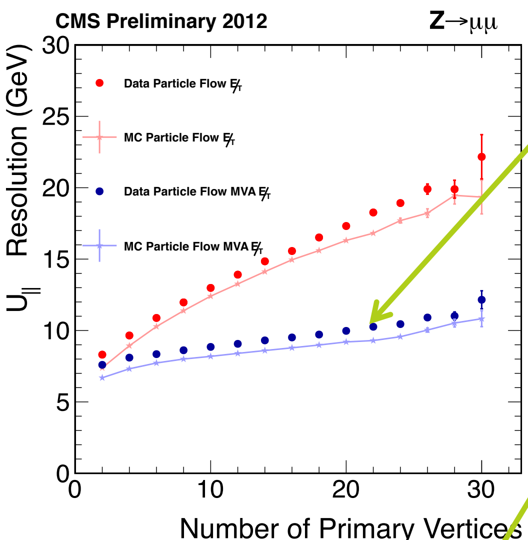
MET and di-τ mass reconstruction

MET = crucial components of di-τ mass reconstruction

$$MET = \left\| \vec{p}_T^{\,miss} \right\| = \left\| - \sum_{\text{PF particles}} \vec{p}_T \right\|$$

Jet subconstituent constribution taken into account using PF

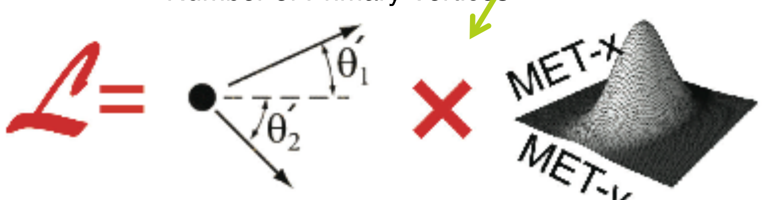




Build MVA MET to reduce degradation of resolution with pile-up

Di-τ mass reconstruction

- Maximum likelihood method
- Tau kinematics x phase space constraints x MET resol.

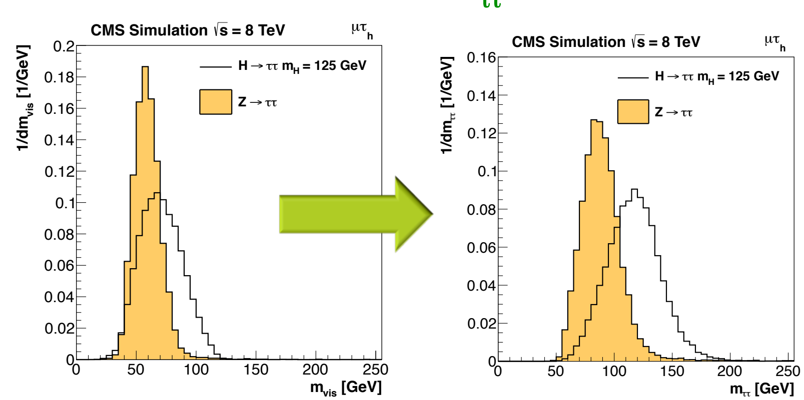


Tau decays phase-space

Expected ME_T resolution

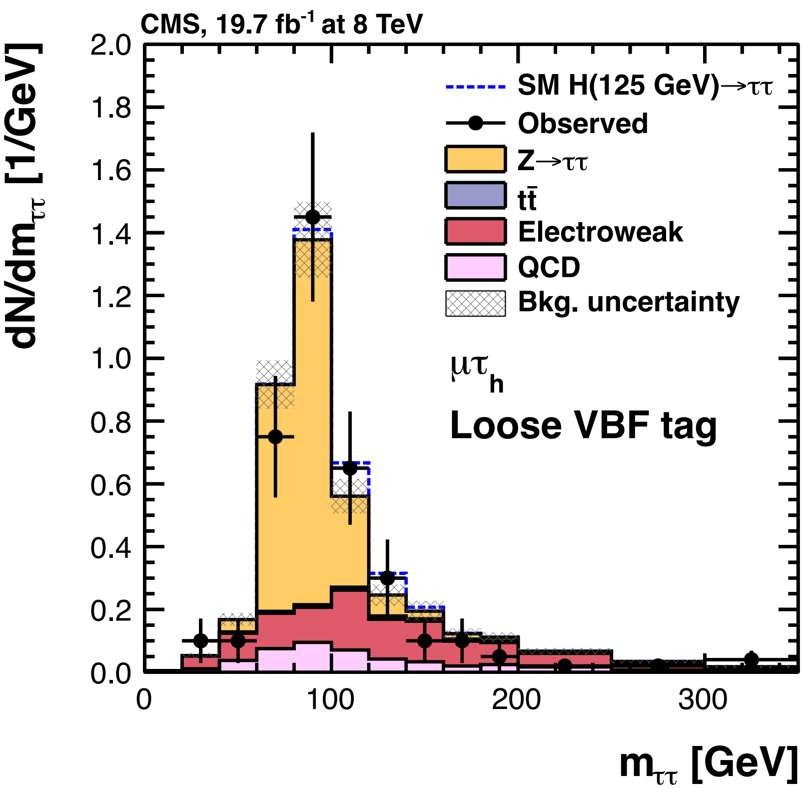
Improved separation with Z→ττ background

15-20% resolution on $M_{\tau\tau}$



Event selection

$H \rightarrow \tau\tau \rightarrow e/\mu + \tau_h$



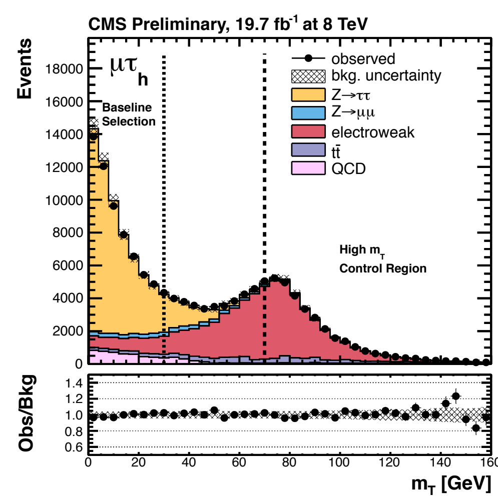
- **Common to SM and MSSM searches**

Object level

- Isolated PF [GSF e] or [μ] → $p_T > 24(20)$ GeV
- Isolated PF hadronic τ_h → $p_T > 30$ GeV

Event level

- Di-object trigger
- Opposite sign lepton and τ_h
- Low m_T to reject W+jets background



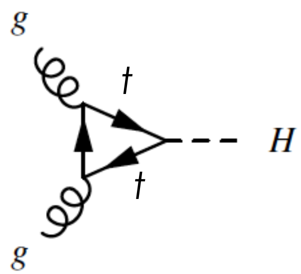
Analysis strategy

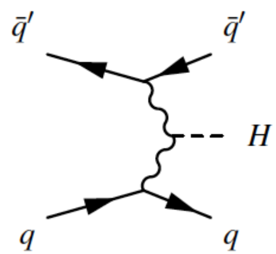
- **Search for peak(s) in the $M_{\tau\tau}$ distribution → 4.9 fb^{-1} @ 7 TeV + 19.7 fb^{-1} @ 8 TeV**
- **Test compatibility with a predicted Higgs boson: binned maximum likelihood fit**
- **Analysis combining exclusive event categories in order to increase sensitivity**

→ Sensitive to different production mode + S/B changes along categories

Study of leptonic *and* hadronic H→ττ decays
→ μμ, eμ, (ee), $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$ channels

SM search ($M_{\tau\tau}$<350 GeV)



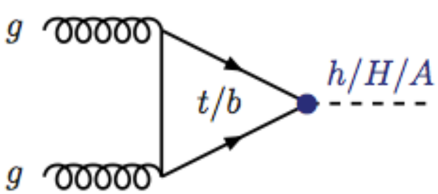


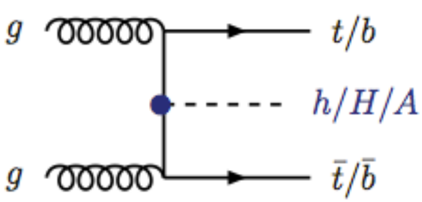
- **0, 1 jet**
- **Boosted Higgs?**

- **≥2 tagging jets**
- **Boosted Higgs**

- **Categorization used depends on the decay channel**
- **Large number of categories**

MSSM search ($M_{\tau\tau}$<1 TeV)





No b-tagged jet

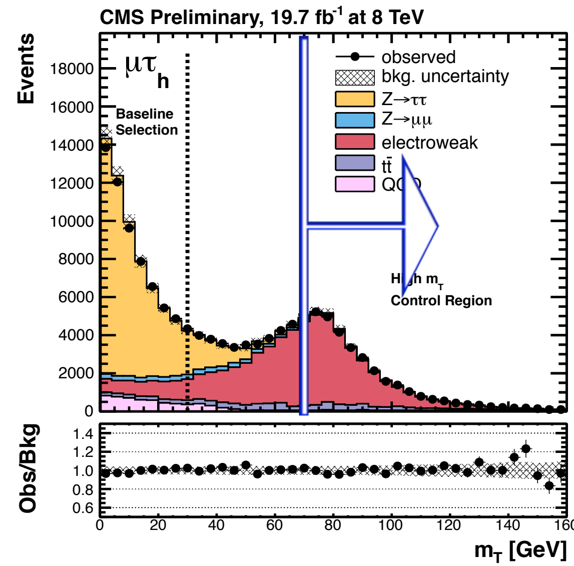
≥1 b-tagged jet

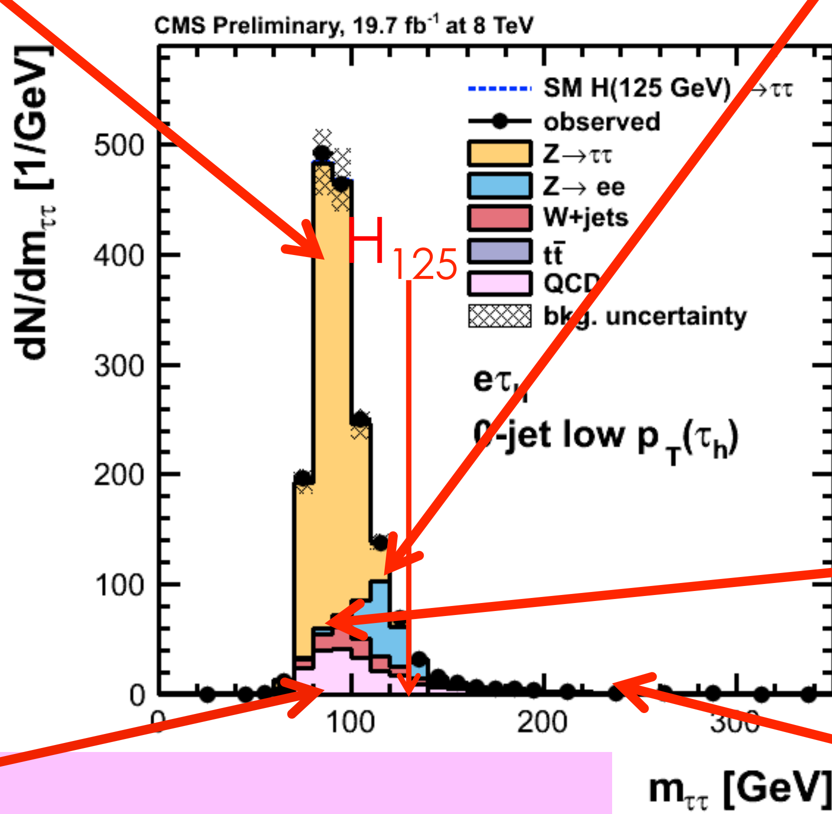
- **Simple categorization for each channel**

Background estimation

Z→ττ
- Shape = embedding technique
Data Z→μμ, μ replaced by MC τ
- Normalization = MC

Z→ee/μμ
- Shape & Norm. = MC





ElectroWeak (W+jets, di-boson, …)
- Shape = MC
- Normalization = data extrapolation (from high m_T sideband)

ttbar
- Shape & Norm. = MC simulation

QCD
- Shape & Norm. = Data driven.
(from same sign anti-isolated events)

Main sources of systematic uncertainties

Z→ττ
- τ-ID and trigger efficiencies = 8-19%
- τ-energy scale = 3% (+shape)
- Normalization = 3%
- Migrations along categories = 2-14%

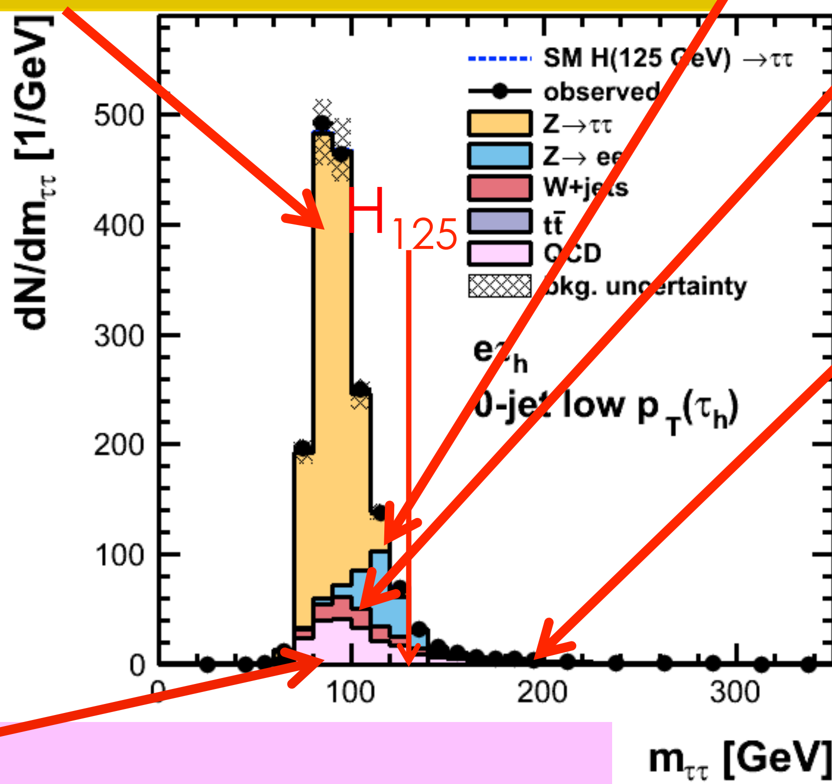
Z→ee/μμ
- Lepton to τ fake rate = 20-75%

W+jets
- Normalization = 10-100%

Di-boson
- Normalization = 15-45%

Z+jets
- Jet to τ fake rate = 20-80%
- Shape = bin-by-bin

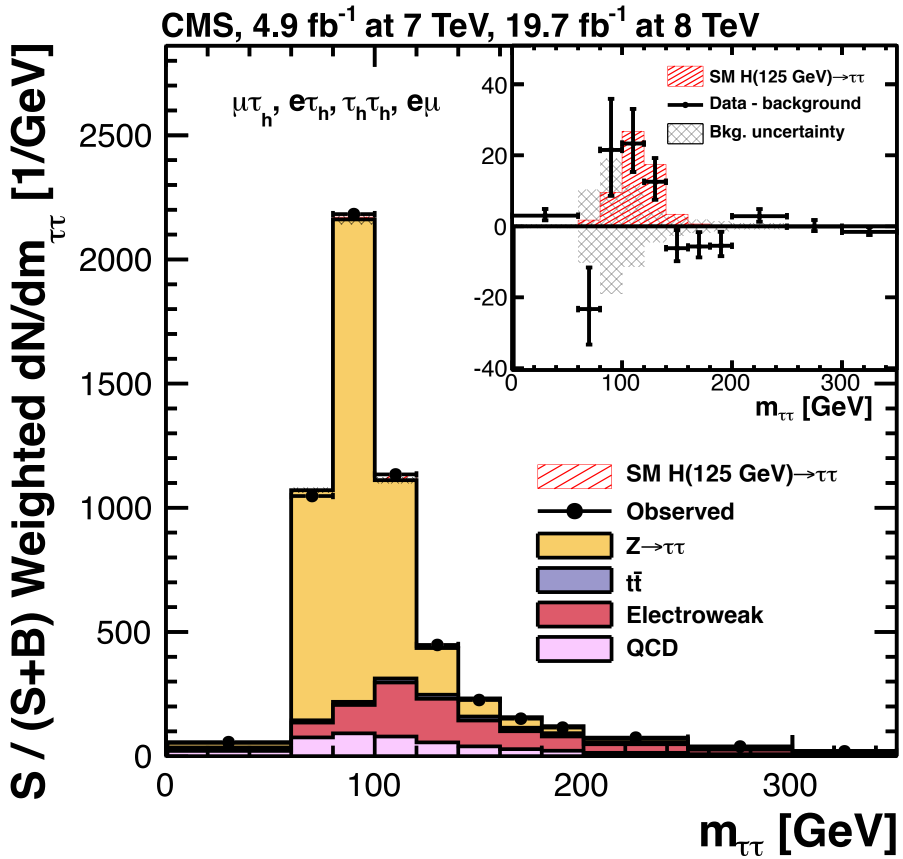
ttbar
- Normalization = 8-35%

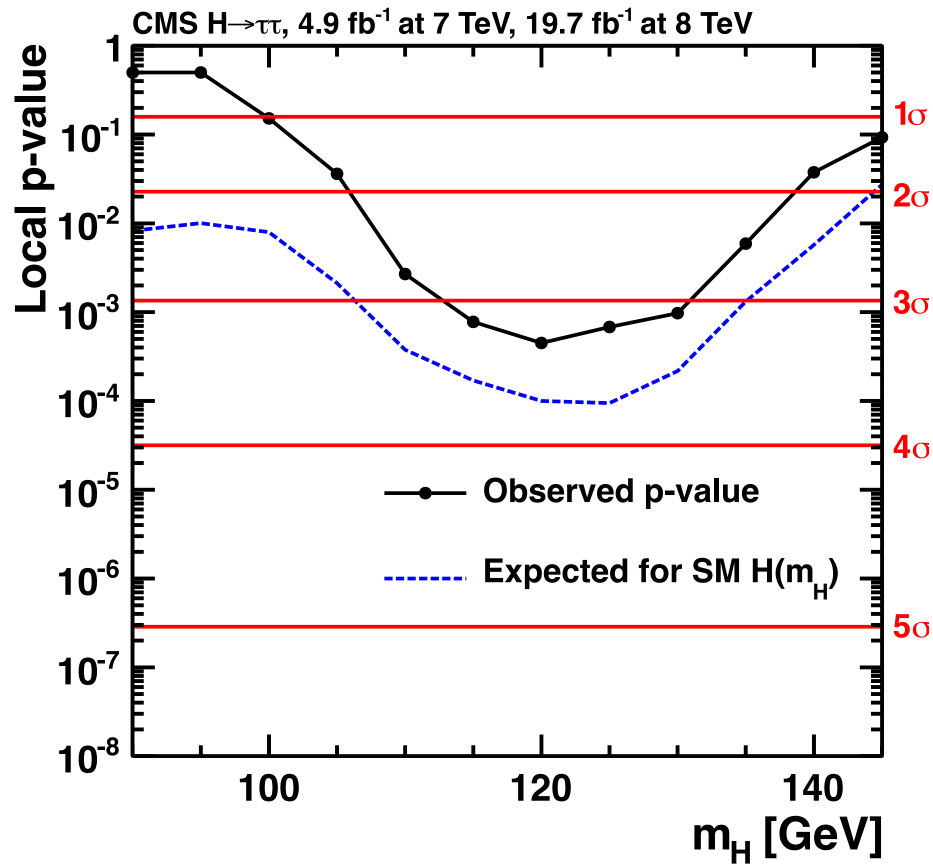


QCD
- Normalization = 6-70%
- Shape = bin-by-bin

Signals / common systematics
- e/μ selection efficiency = 2-6%
- jet energy scale & resol. = 0-20%
- MET resolution = 1-12%
- PDFs = 4-10%
- Scale variations = 3-41%
- Underlying event = 2-10%

SM H→ττ results (1/2)





Excess is present

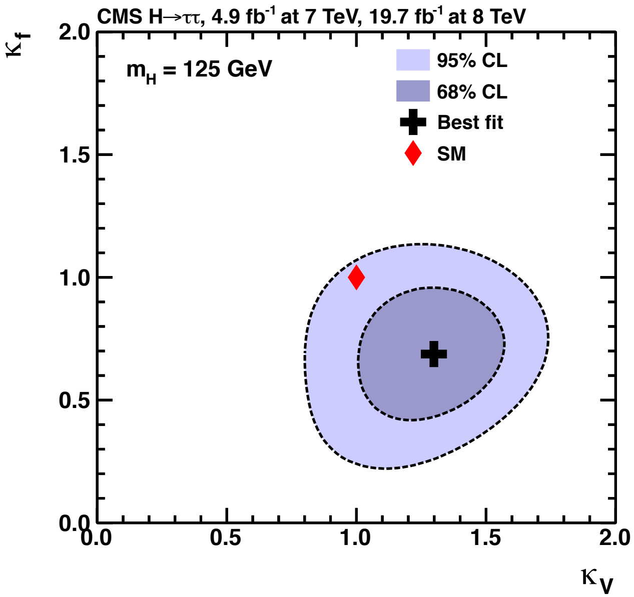
- Located around 125 GeV with low resolution
- Close to expectation

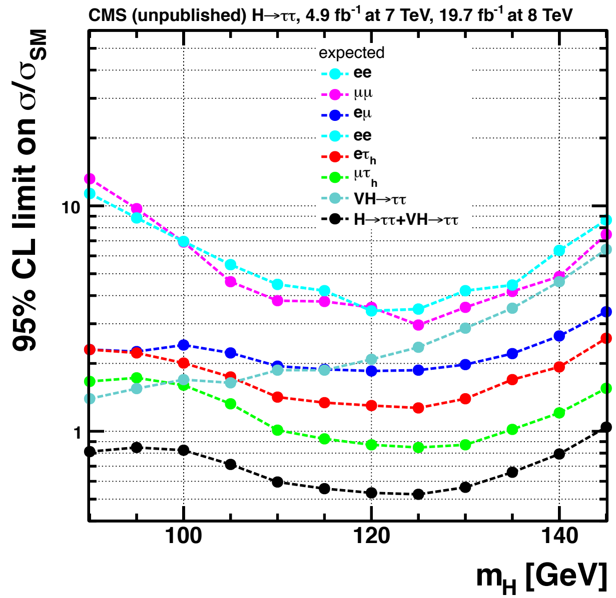
Excess quantified @ m_H = 125 GeV

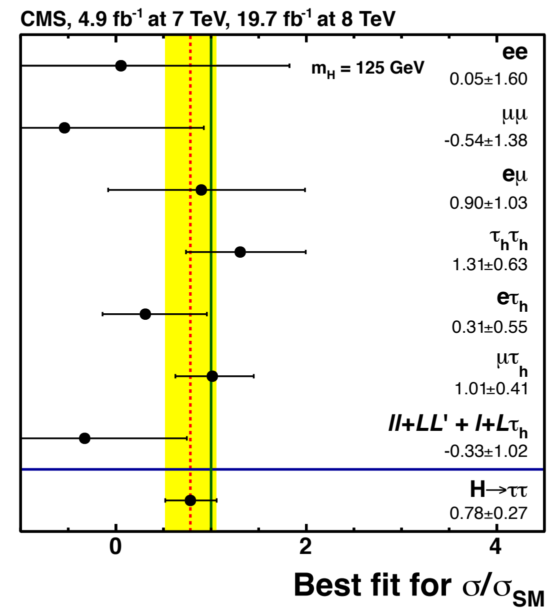
- Observed (expected) p_0 = 3.2σ (3.7σ)

Evidence for H→ττ!

SM H→ττ results (2/2)







Coupling modifier for fermions κ_f is consistent with expectation from the minimal SM scalar sector

$\mu\tau_h$ channel provides most sensitivity

Excess is consistent along decay channels studied

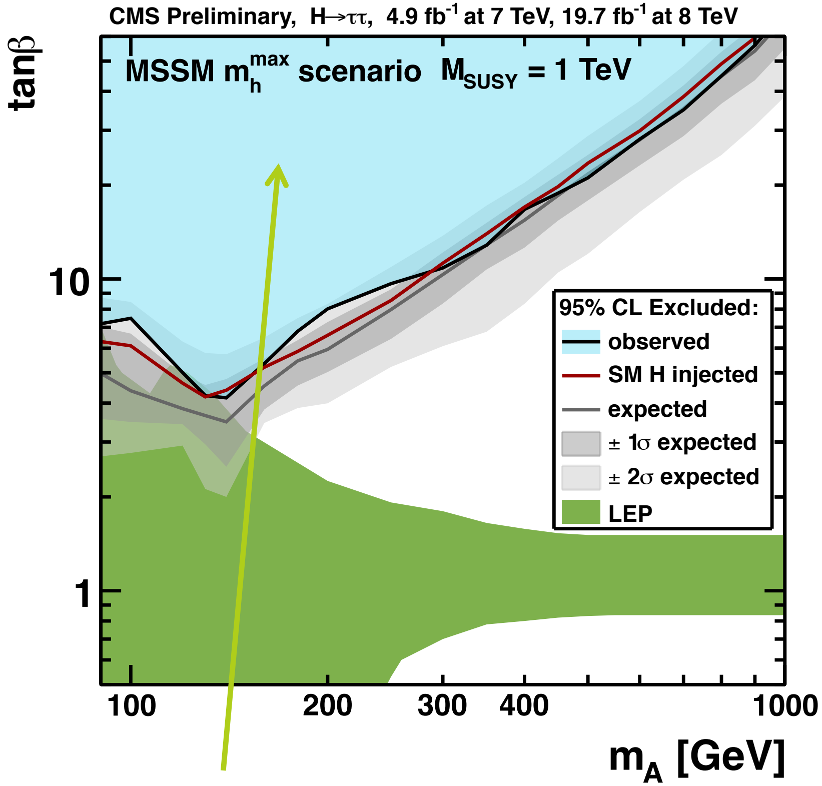
- μ (= N_{obs}/N_{SM}) **= 0.78 ± 0.27**
- **Compatibile with SM**

- **H→μμ not observed**

→ Higgs boson coupling to fermions is not universal

→ The scalar sector may be related to the generation of fermion families

MSSM H→ττ results

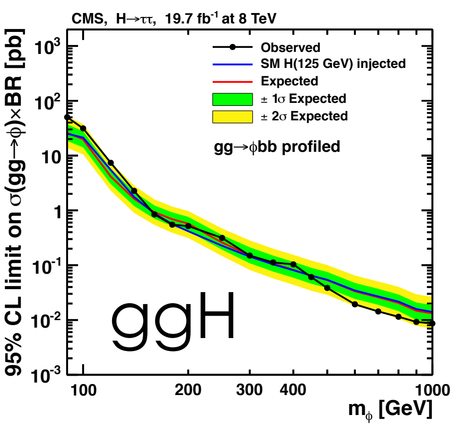


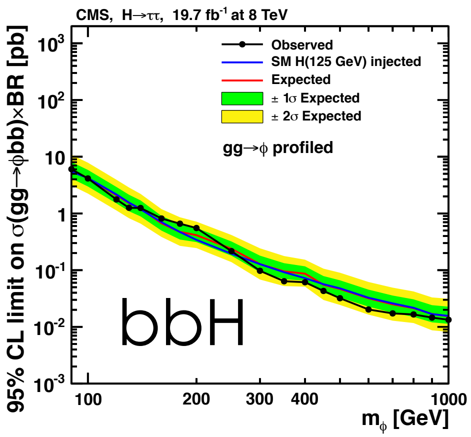
Large region of MSSM parameter space excluded @ 95% C.L.

- Complementary to LEP limit
- Low mass / high tanβ almost ruled out
- Starting to explore low tanβ regions!

No MSSM signal observed

- Sensitivity to production modes





No sign of SUSY (just yet)

Potential analysis improvements

→ **SM-like analysis suboptimal for MSSM**

Improved search at high masses

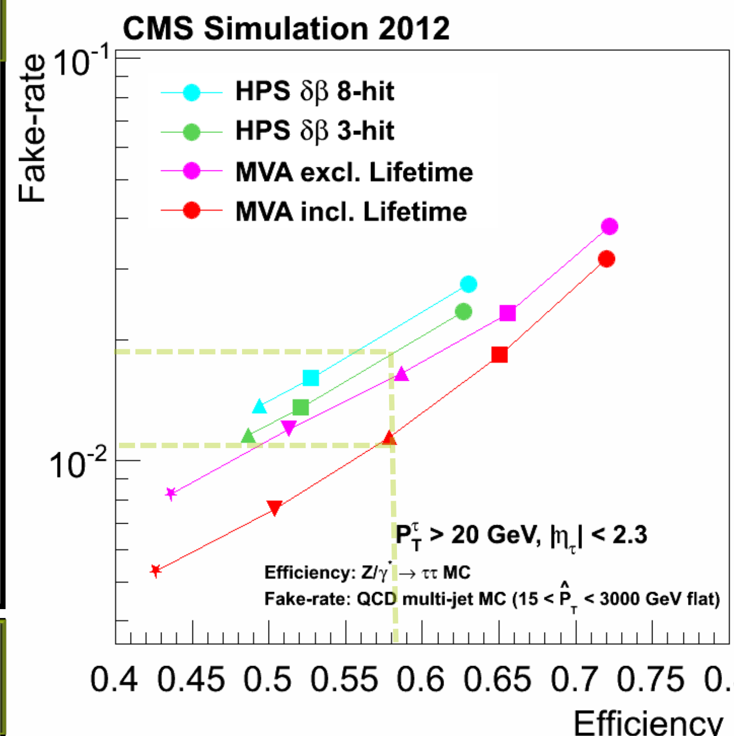
- **Improved τ_h (decay mode) reconstruction**
  Relaxed cuts
  Better treatment of p_T-dependence
  → Flatter τ efficiency and energy scale w/ τ p_T
  → Efficiency increased at high τ p_T
- **MVA τ_h isolation**
  Exploits τ lifetime information
  Correlations between the isolation variables fully exploited
  → reduced jet fake rate at high τ p_T

Improved search at low masses

- **Categorization using τ_h p_T for MSSM $H \rightarrow \tau\tau$**
  - Higgs resonances → boosted τ(s)
  - Build categories with different S/B
  - $Z \rightarrow \tau\tau$ background quickly falls with p_T

  → Increased sensitivity

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsPFT/tau_dps.pdf



A constant signal efficiency = fake rate is reduced by ~50% using MVA isolation

Conclusions

- **Studies of H→ττ are central in the understanding of the Higgs sector**

  → (Current) *only* handle to measure coupling between Higgs and leptons
  → In SUSY: most sensitive channel for h/H/A searches

- **Evidence for H(125 GeV)→ττ: achieved!**

  → Rate compatible with minimal scalar sector of the SM
  → Combination with H→bb → *strong evidence (~4σ) for Higgs coupling to fermions*
  → >5σ observation likely to be achieved in LHC Run II

  → This H(125 GeV) boson imposes constraints on MSSM → decoupling limit?

- **No sign yet for extra Higgs bosons (from MSSM's perspective)**

  → Larger regions of parameter space excluded
  → Still some room for SUSY at always lower tanβ and higher m_A values
  → Ways to improve the analysis & keys to handle harsh Run II pile-up conditions

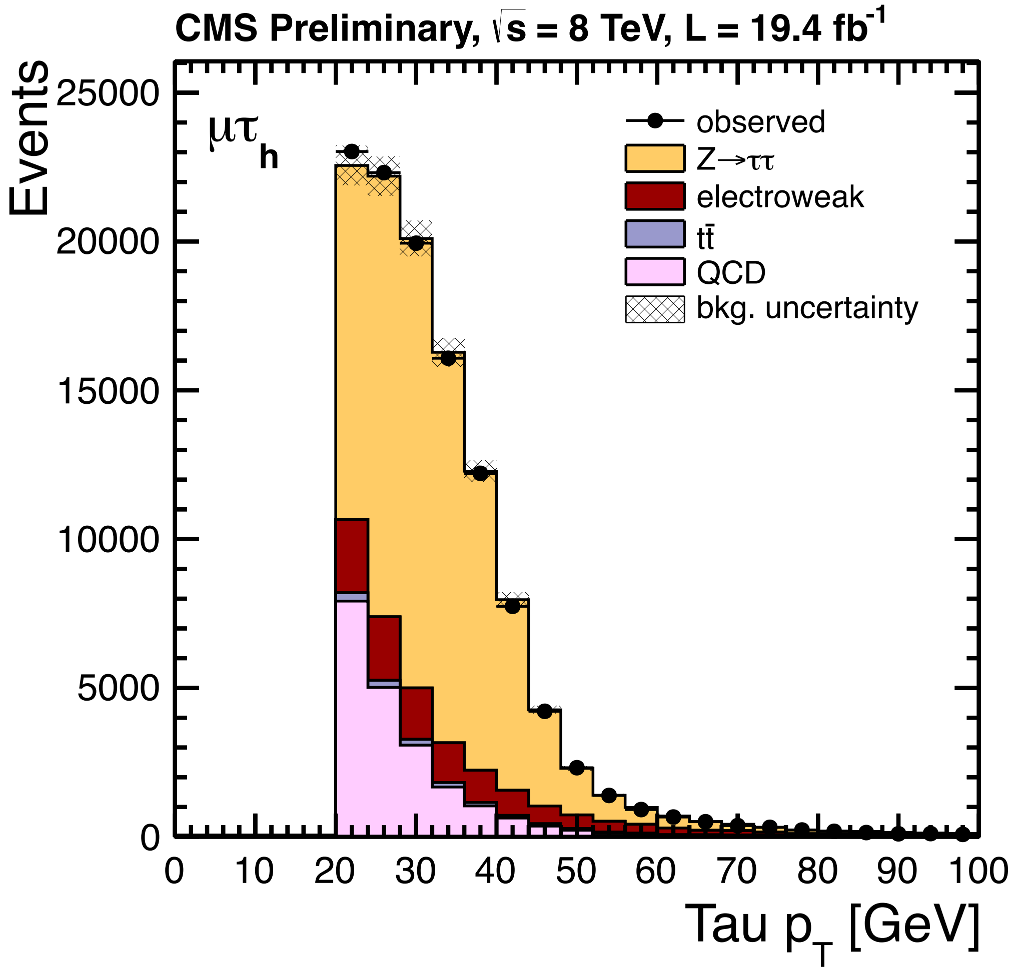
H→ττ teaches us a lot
Please expect new results soon ☺

Backup material

Intermidate resonances for τ_h

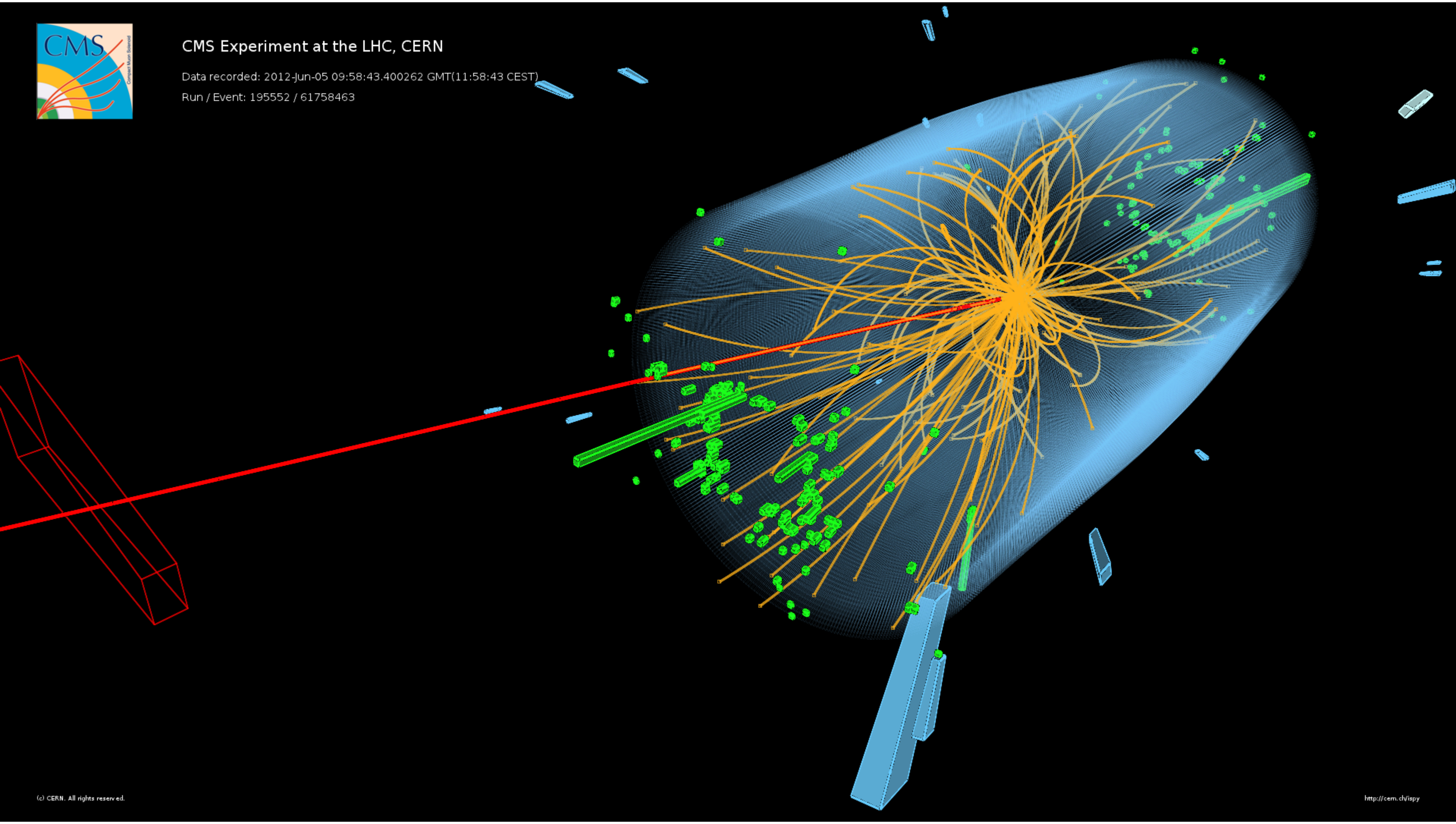
Decay Mode	Resonance	Mass (MeV/c^2)	Branching Ratio (%)
$\tau^- \to h^- \nu_\tau$	π	139.6	11.6 %
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ	770	26.0 %
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1	1200	10.8 %
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1	1200	9.8 %
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8 %

τ p_T

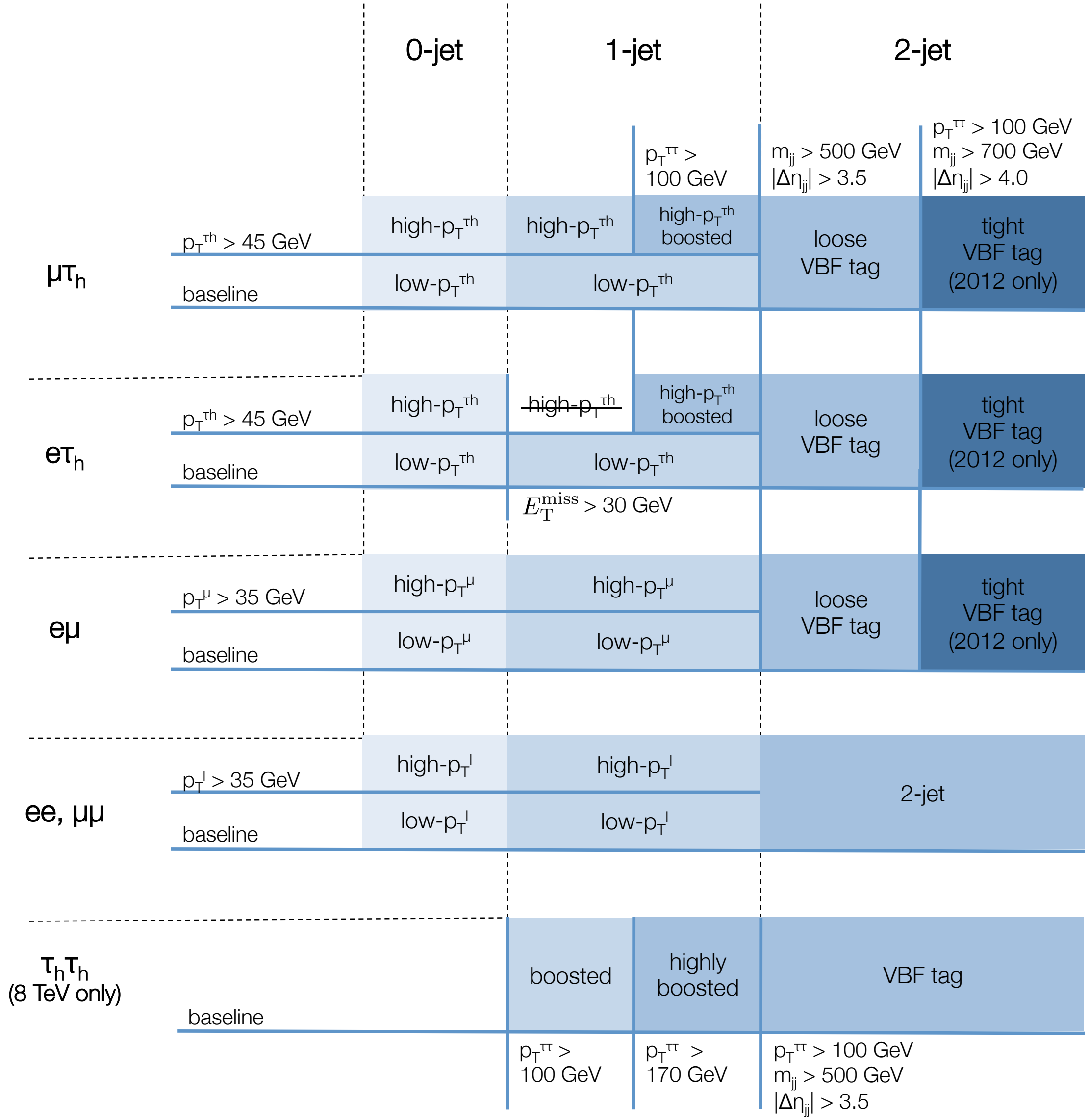

CMS Preliminary, √s = 8 TeV, L = 19.4 fb-1
Events
25000
20000
15000
10000
5000
0
μτh
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
0
10
20
30
40
50
60
70
80
90
100
Tau pT [GeV]

SM

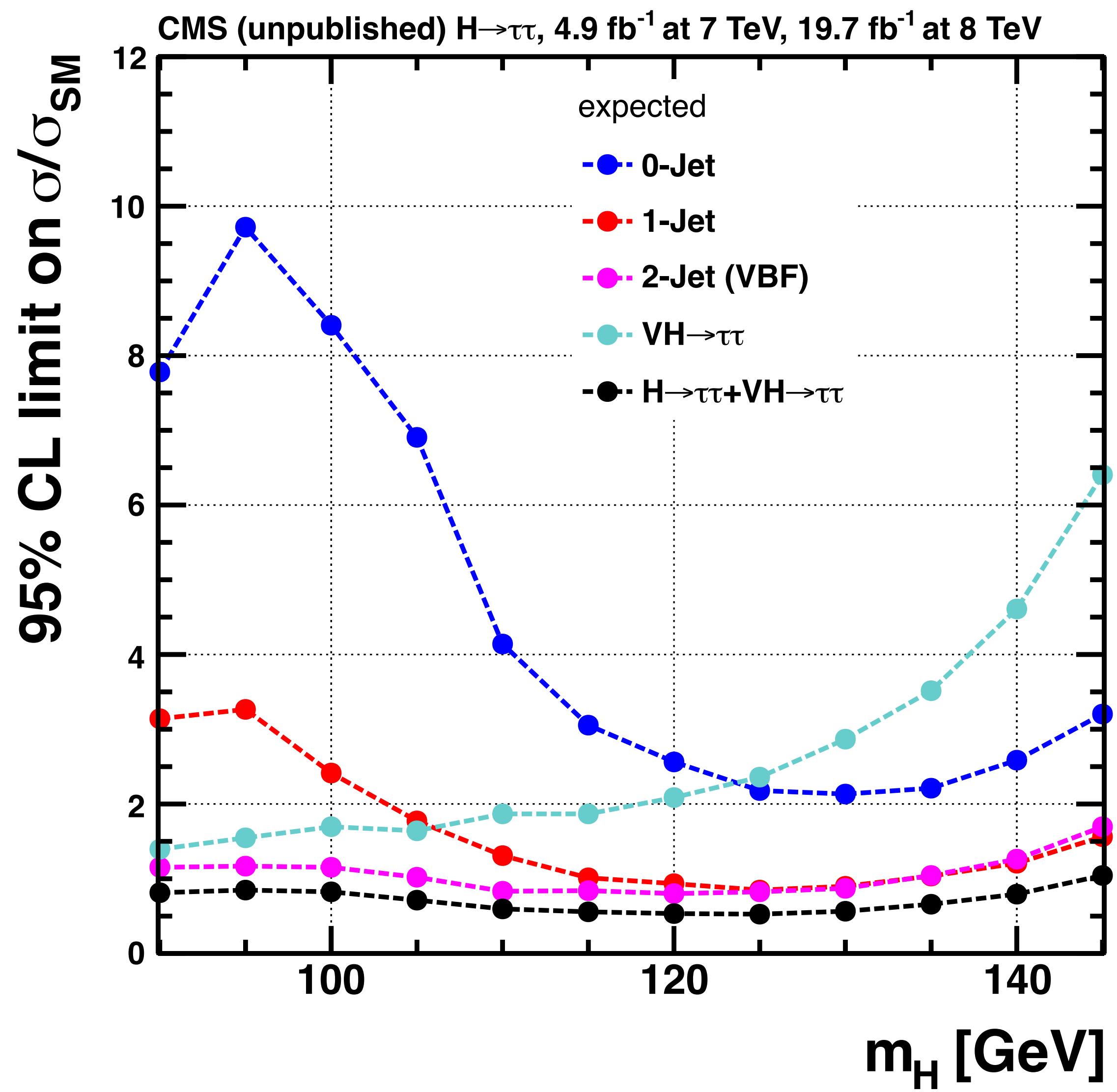
$\mu\tau_h$ event display: VBF candidate



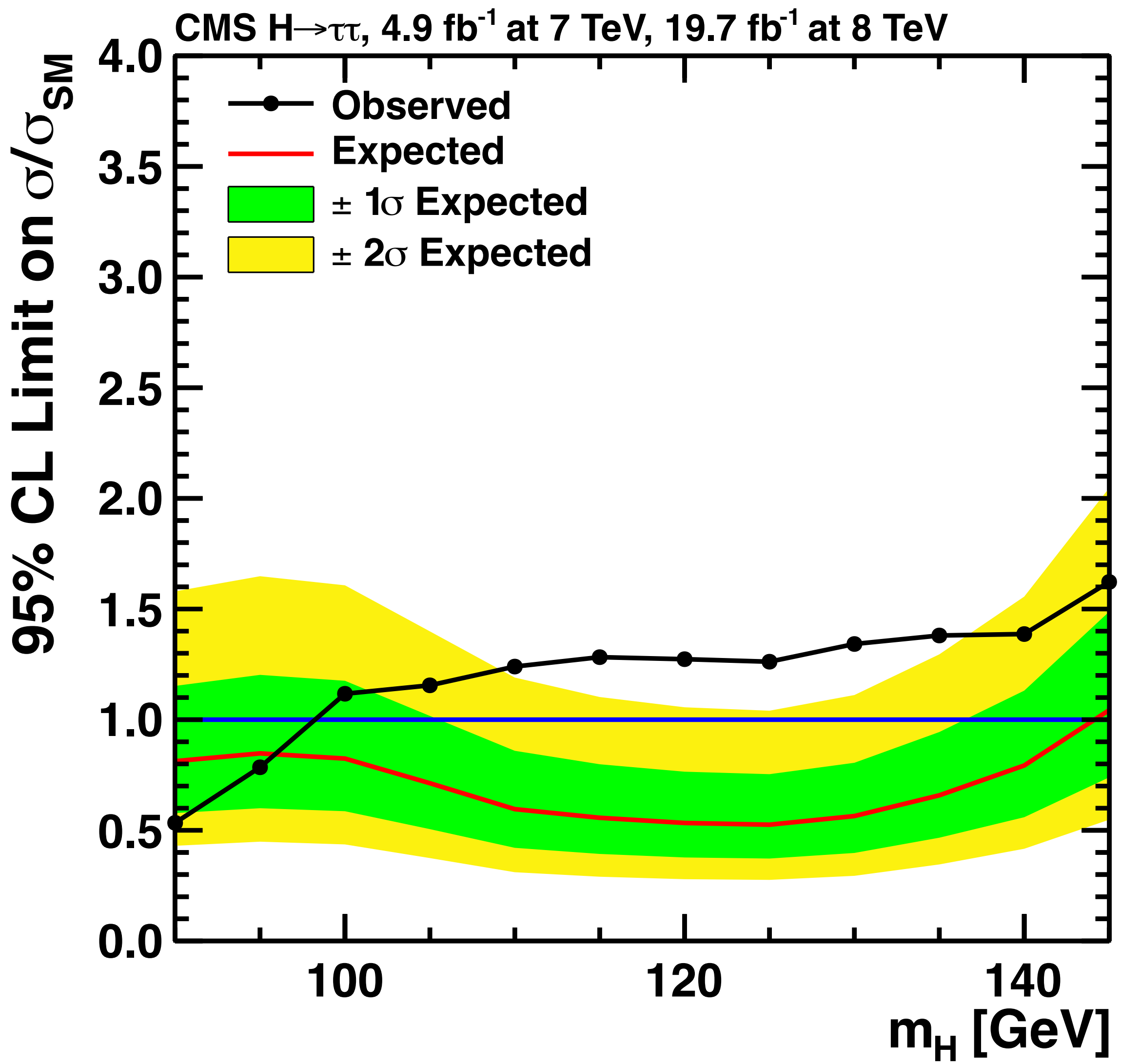
Categories in SM 8 TeV



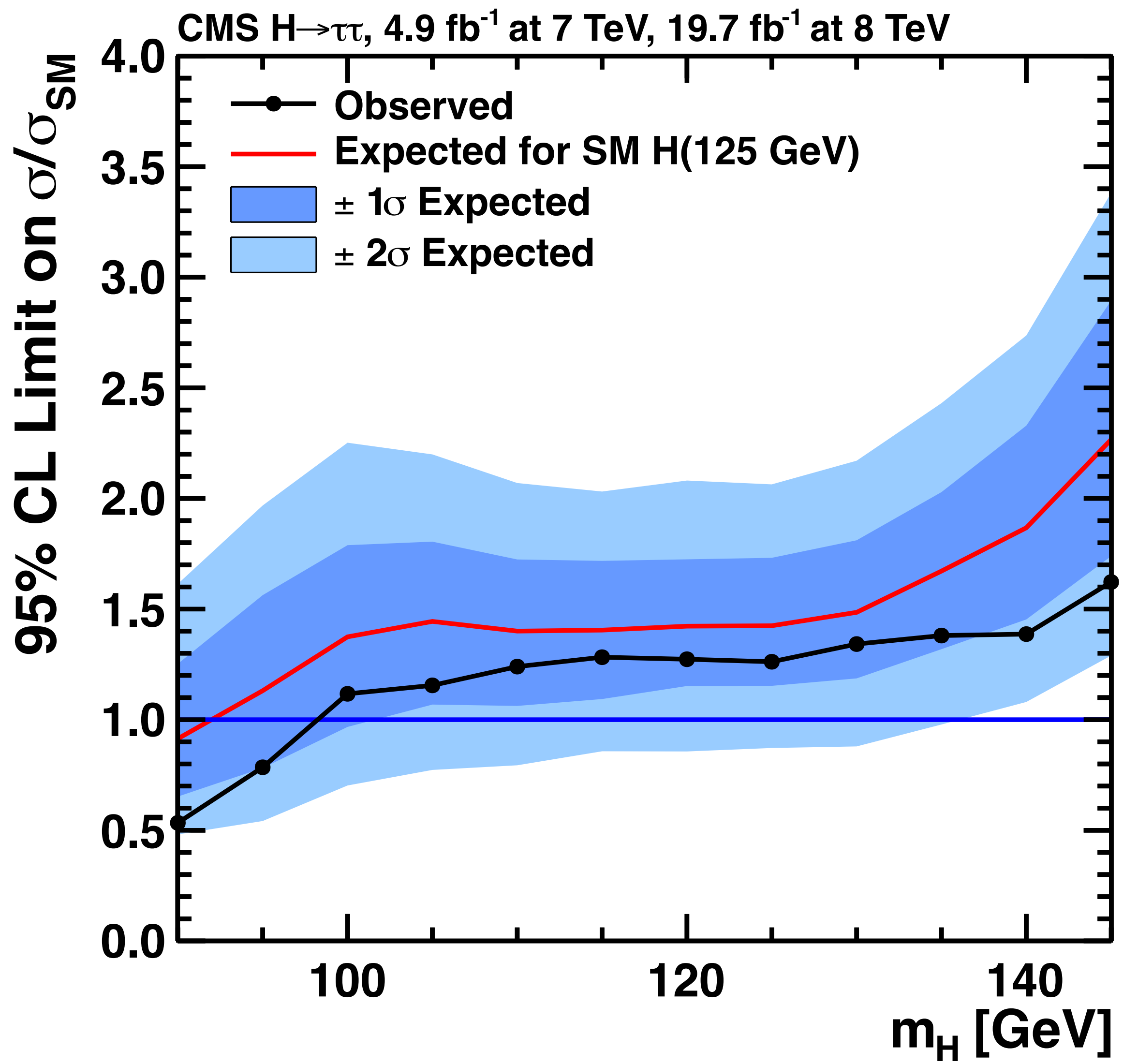
SM: expected limit



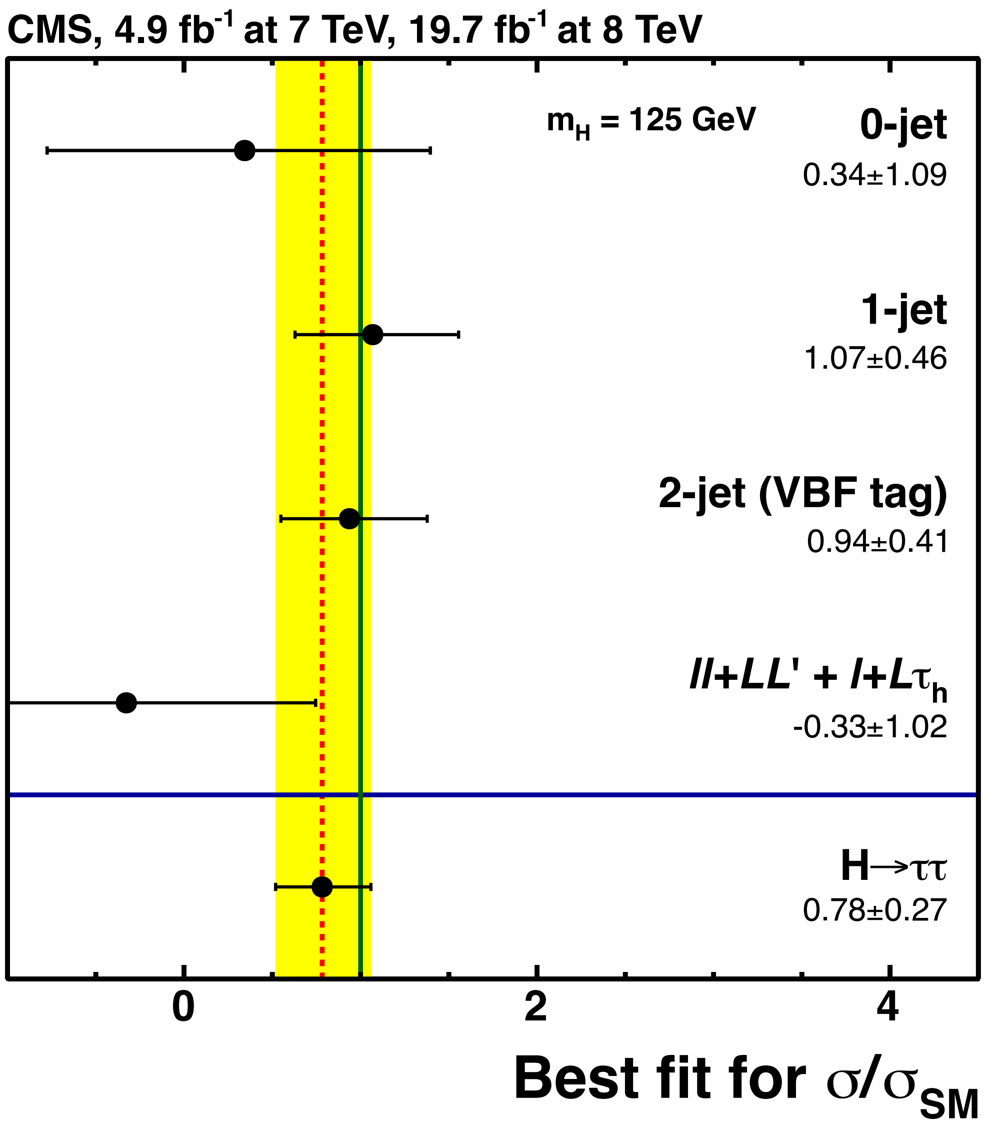
SM: CLs limit


CMS H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
Observed
Expected
± 1σ Expected
± 2σ Expected
95% CL Limit on σ/σSM
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
120
140
mH [GeV]

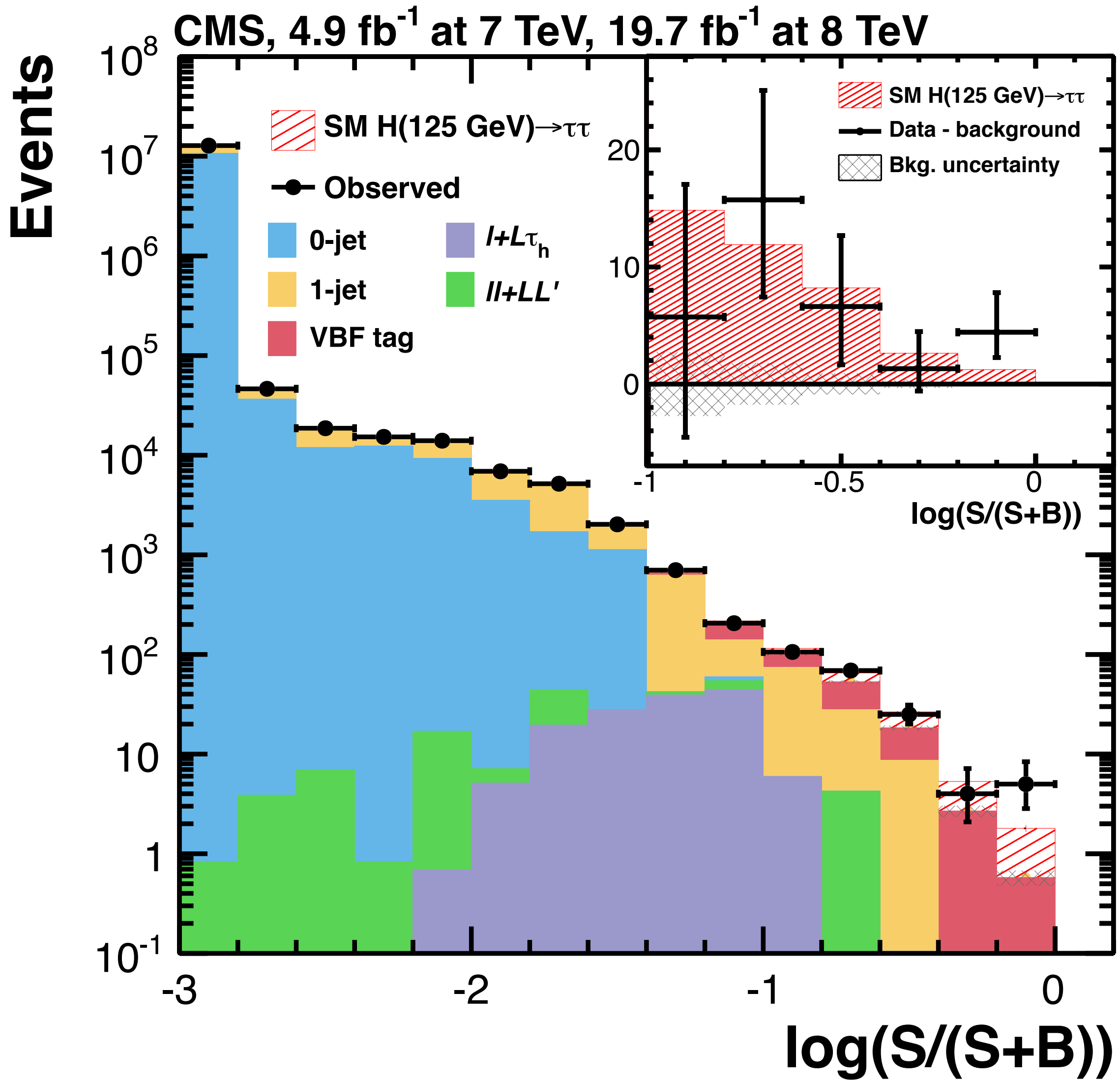
SM: CLs limit with injection



SM: breakdown per category



SM: different view of the excess



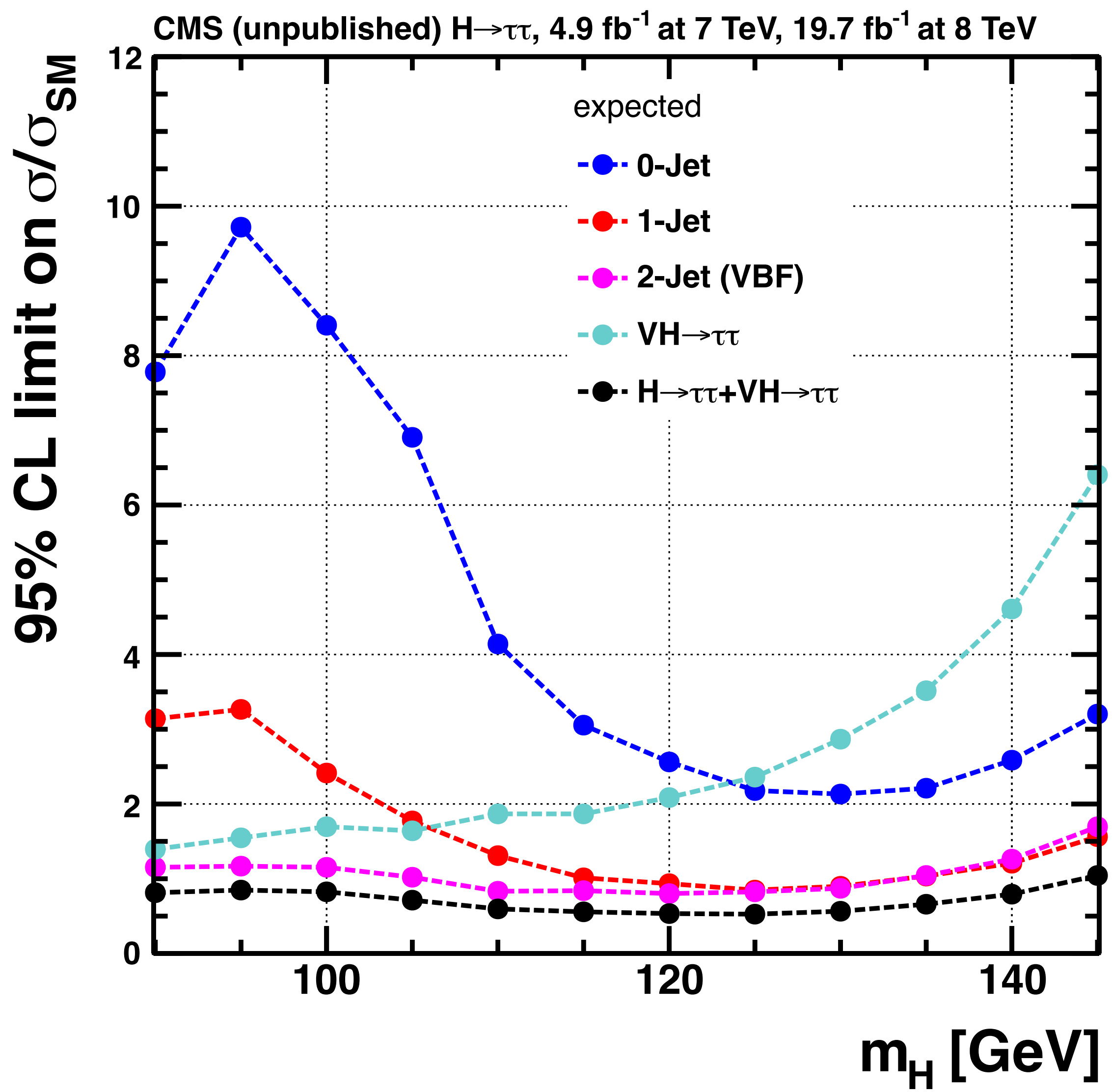
SM: detailed selection

Channel	HLT requirement	Lepton selection		
$\mu\tau_h$	$\mu(12–18)$ & $\tau_h(10–20)$	$p_T^{\mu} > 17–20$	$\lvert\eta^{\mu}\rvert < 2.1$	$R^{\mu} < 0.1$
		$p_T^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.4$	$I^{\tau_h} < 1.5$
$e\tau_h$	$e(15–22)$ & $\tau_h(15–20)$	$p_T^{e} > 20–24$	$\lvert\eta^{e}\rvert < 2.1$	$R^{e} < 0.1$
		$p_T^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.4$	$I^{\tau_h} < 1.5$
$\tau_h\tau_h$ (2012 only)	$\tau_h(35)$ & $\tau_h(35)$ $\tau_h(30)$ & $\tau_h(30)$ & jet(30)	$p_T^{\tau_h} > 45$	$\lvert\eta^{\tau_h}\rvert < 2.1$	$I^{\tau_h} < 1$
$e\mu$	$e(17)$ & $\mu(8)$	$p_T^{\ell_1} > 20$	$\lvert\eta^{\mu}\rvert < 2.1$	$R^{\ell} < 0.1–0.15$
	$e(8)$ & $\mu(17)$	$p_T^{\ell_2} > 10$	$\lvert\eta^{e}\rvert < 2.3$	
$\mu\mu$	$\mu(17)$ & $\mu(8)$	$p_T^{\mu_1} > 20$	$\lvert\eta^{\mu_1}\rvert < 2.1$	$R^{\mu} < 0.1$
		$p_T^{\mu_2} > 10$	$\lvert\eta^{\mu_2}\rvert < 2.4$	
ee	$e(17)$ & $e(8)$	$p_T^{e_1} > 20$	$\lvert\eta^{e}\rvert < 2.3$	$R^{e} < 0.1–0.15$
		$p_T^{e_2} > 10$		
$\mu + \mu\tau_h$	$\mu(17)$ & $\mu(8)$	$p_T^{\mu_1} > 20$	$\lvert\eta^{\mu}\rvert < 2.4$	$R^{\mu} < 0.1–0.2$
		$p_T^{\mu_2} > 10$		
		$p_T^{\tau_h} > 20$	$\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\tau_h} < 2$
$e + \mu\tau_h$ /	$e(17)$ & $\mu(8)$	$p_T^{\ell_1} > 20$	$\lvert\eta^{e}\rvert < 2.5$	$R^{\ell} < 0.1–0.2$
$\mu + e\tau_h$	$e(8)$ & $\mu(17)$	$p_T^{\ell_2} > 10$	$\lvert\eta^{\mu}\rvert < 2.4$	
		$p_T^{\tau_h} > 20$	$\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\tau_h} < 2$
$\mu + \tau_h\tau_h$	$\mu(24)$	$p_T^{\mu} > 24$	$\lvert\eta^{\mu}\rvert < 2.1$	$R^{\mu} < 0.1$
		$p_T^{\tau_{h,1}} > 25$	$\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\tau_h} < 2–3$
		$p_T^{\tau_{h,2}} > 20$		
$e + \tau_h\tau_h$	$e(20)$ & $\tau_h(20)$	$p_T^{e} > 24$	$\lvert\eta^{e}\rvert < 2.1$	$R^{e} < 0.1–0.15$
	$e(22)$ & $\tau_h(20)$	$p_T^{\tau_{h,1}} > 25$	$\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\tau_h} < 2$
		$p_T^{\tau_{h,2}} > 20$		

SM: systematic uncertainties

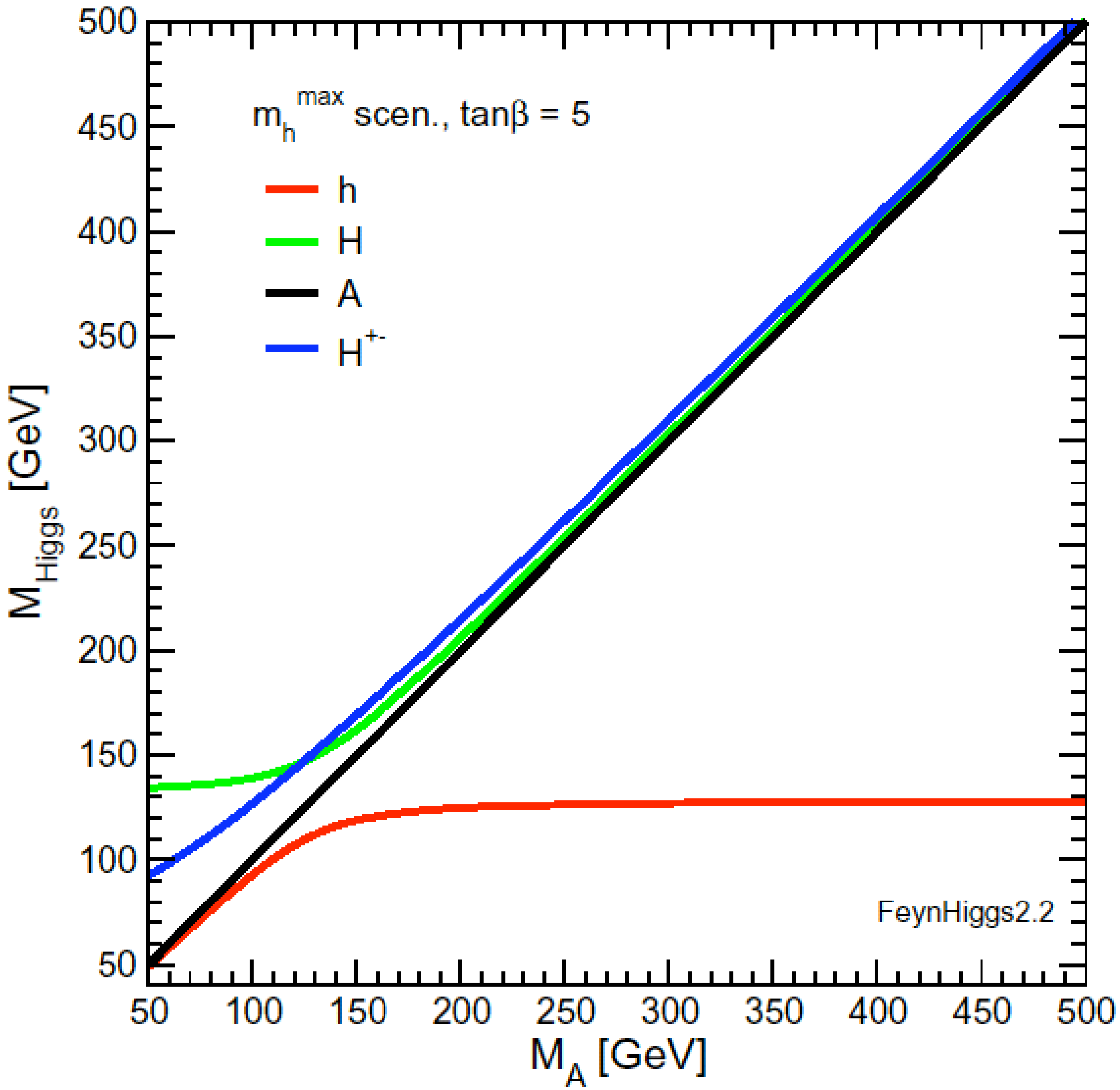
Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	$Z \to ee$	20–74%
μ misidentified as τ_h	$Z \to \mu\mu$	30%
Jet misidentified as τ_h	$Z + \text{jets}$	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	up to 13%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \to \tau\tau$ category	$Z \to \tau\tau$	2–14%
Norm. $W + \text{jets}$	$W + \text{jets}$	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t} + Z$	$t\bar{t} + Z$	50%
Scale variation	signal	3–41%
Underlying event & parton shower	signal	2–10%
Limited number of events	all	shape only

SM: expected limit



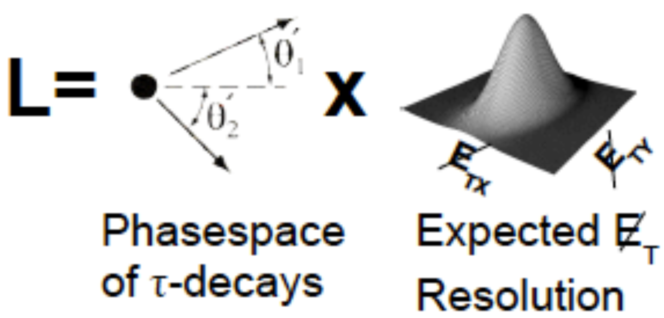
MSSM

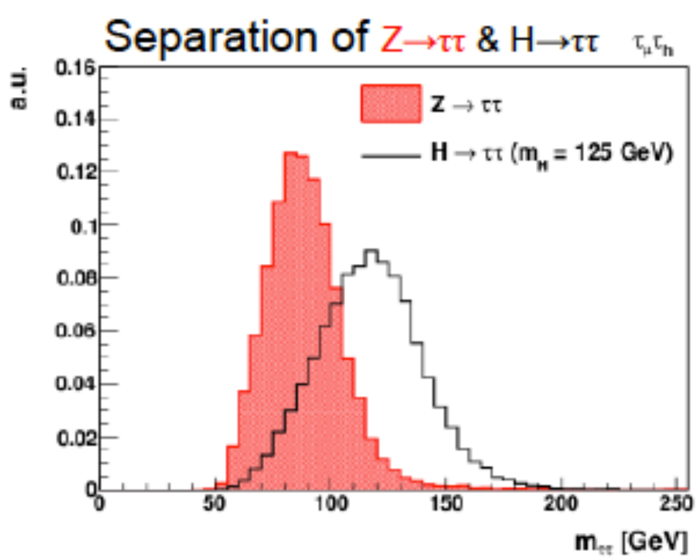
Mass of Higgs bosons in SUSY



Di-τ mass reconstruction

- Determine invariant mass of di-τ system with maximum likelihood method.

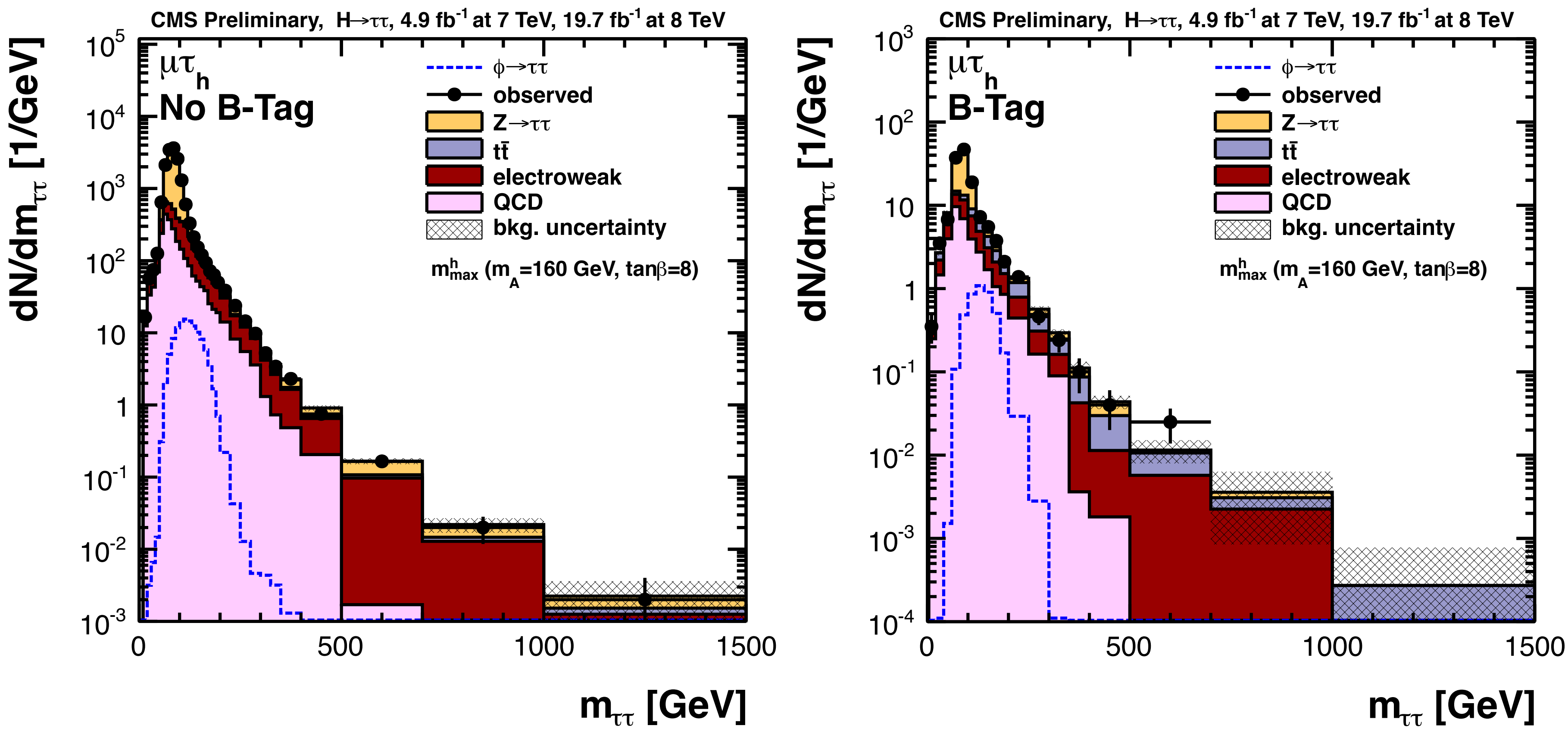




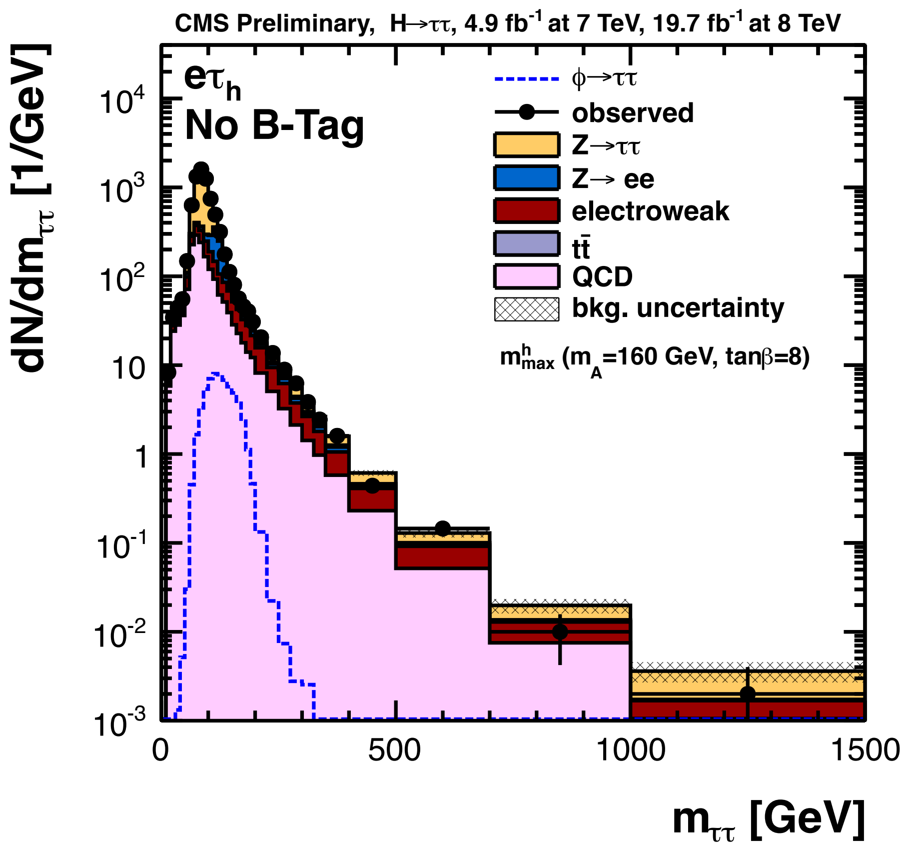
- Estimate for di-τ system, to be real for given value of $m_{\tau\tau}$.
- Inputs: four-vector information of visible leptons, x- and y- component of $\not{E}_T$ on event by event basis.
- Free parameters: φ, θ*, ($m_{\nu\nu}$) per τ-lepton (4-6 parameters).
- Full integration of kernel. Scan of $m_{\tau\tau}$ from m_τ up to 2TeV.
- 15-20% resolution of the reconstructed $m_{\tau\tau}$ mass.

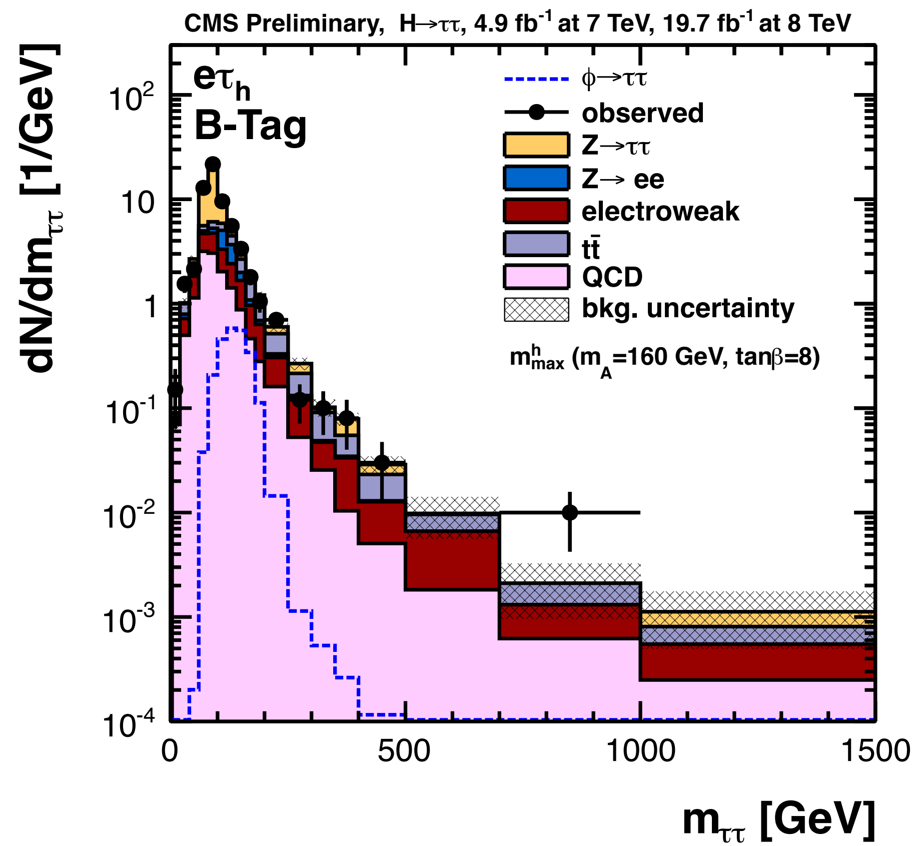
6

MSSM: $M_{\tau\tau}$ in $\mu\tau_h$ channel

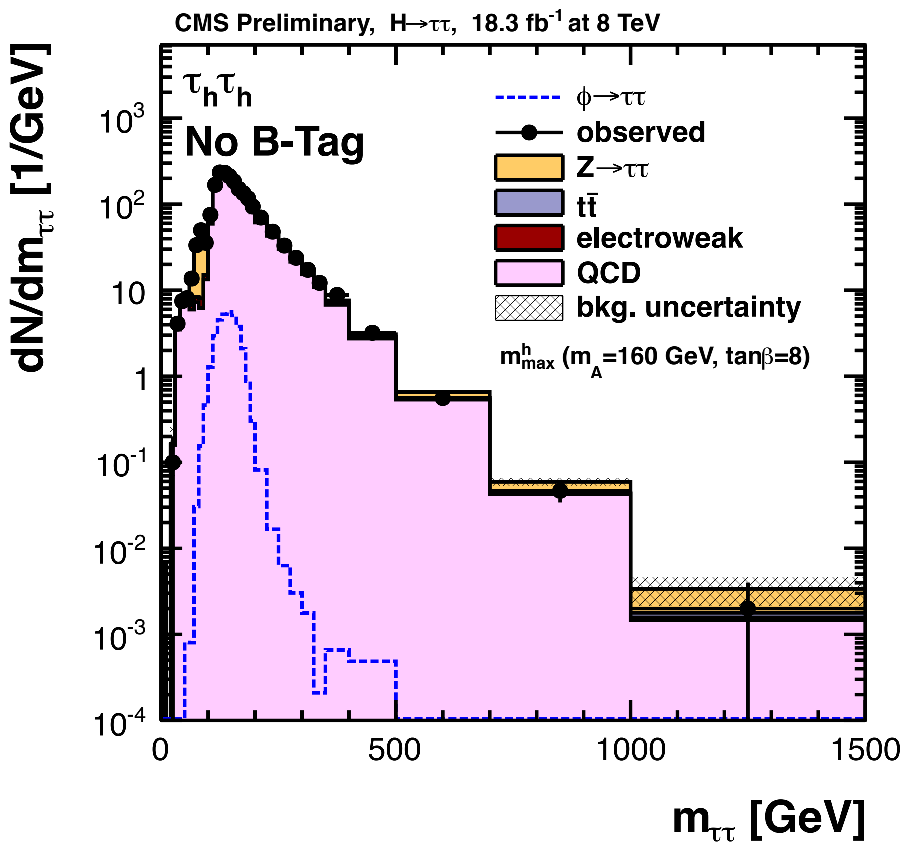


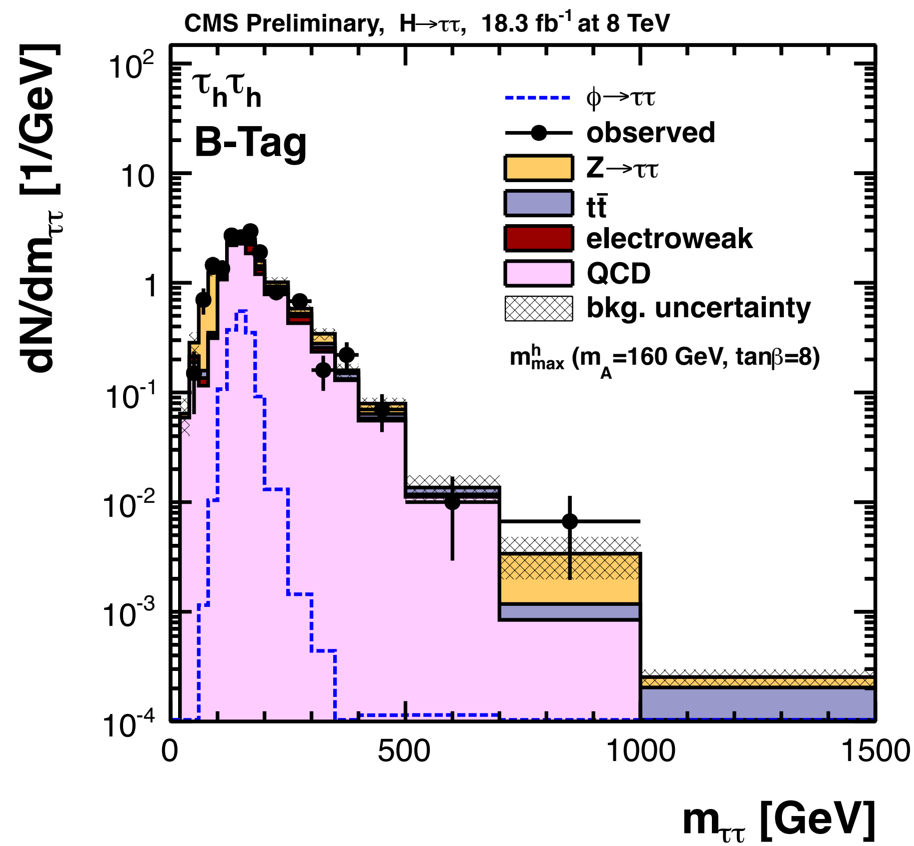
MSSM: $M_{\tau\tau}$ in $e\tau_h$ channel



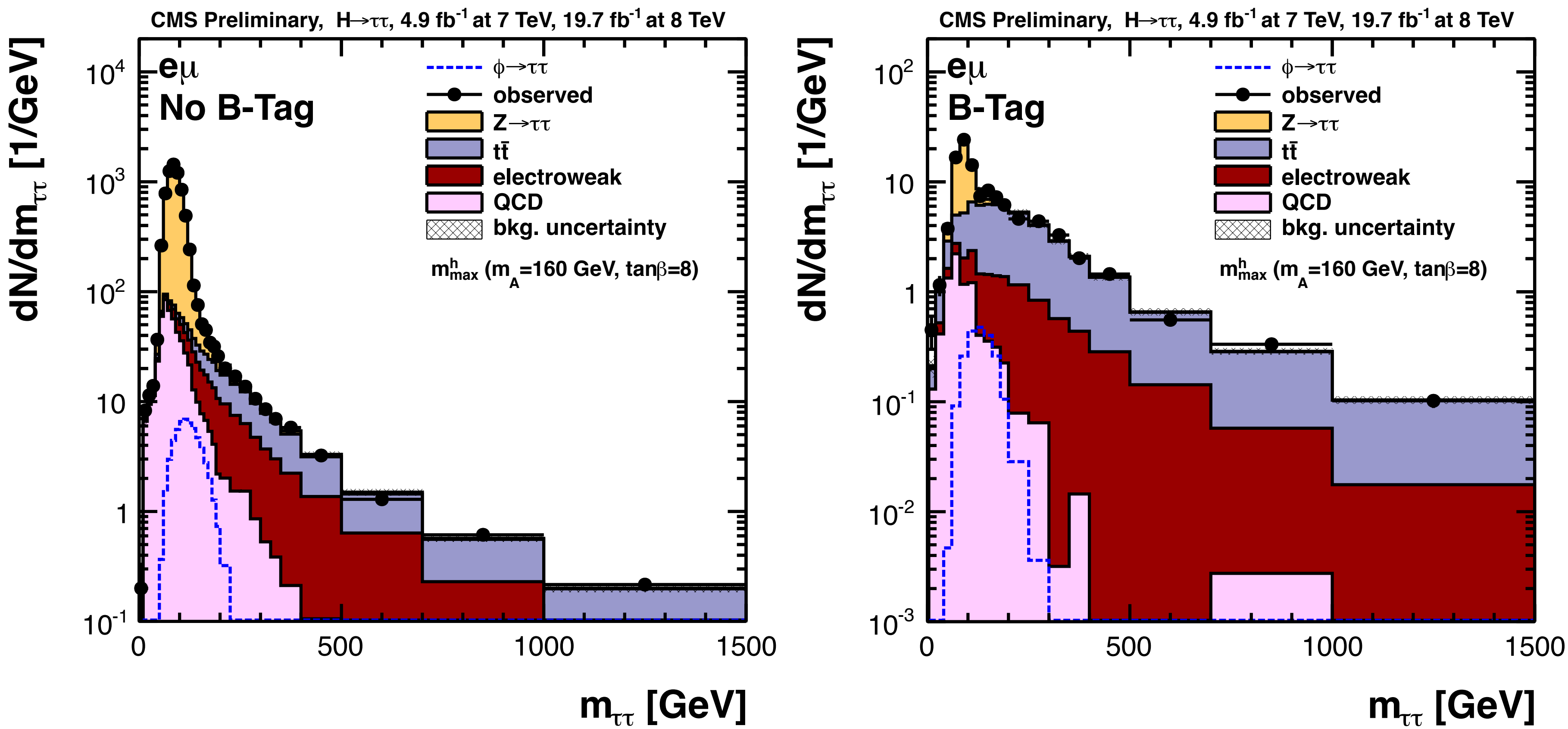


MSSM: $M_{\tau\tau}$ in $\tau_h\tau_h$ channel

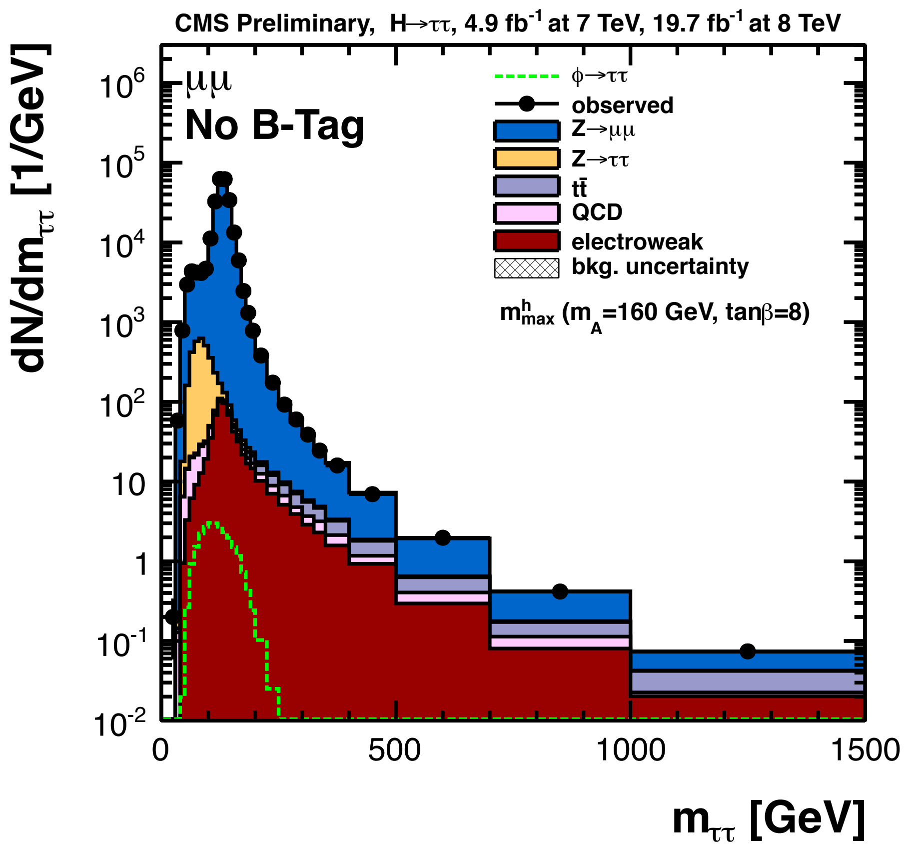


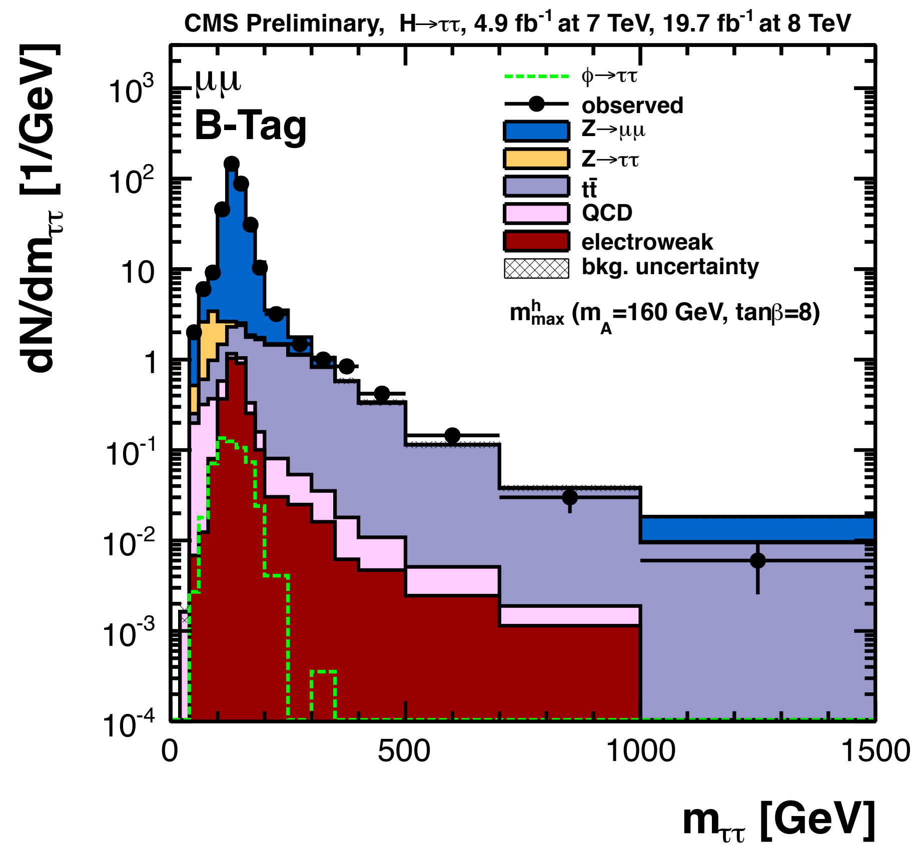


MSSM: $M_{\tau\tau}$ in eμ channel

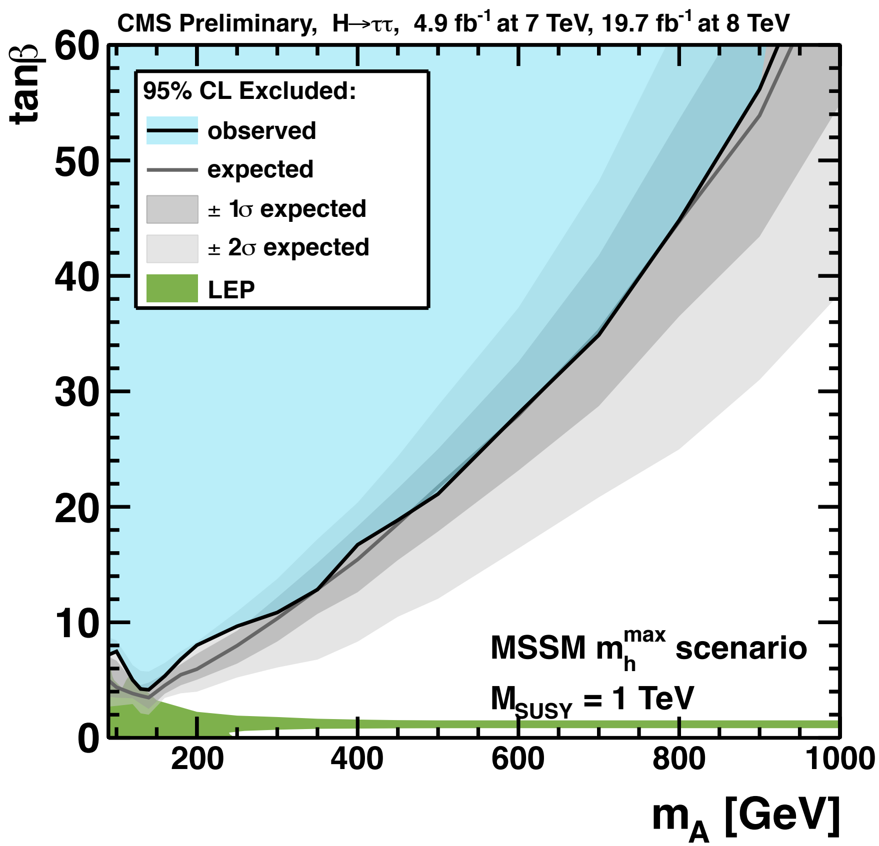


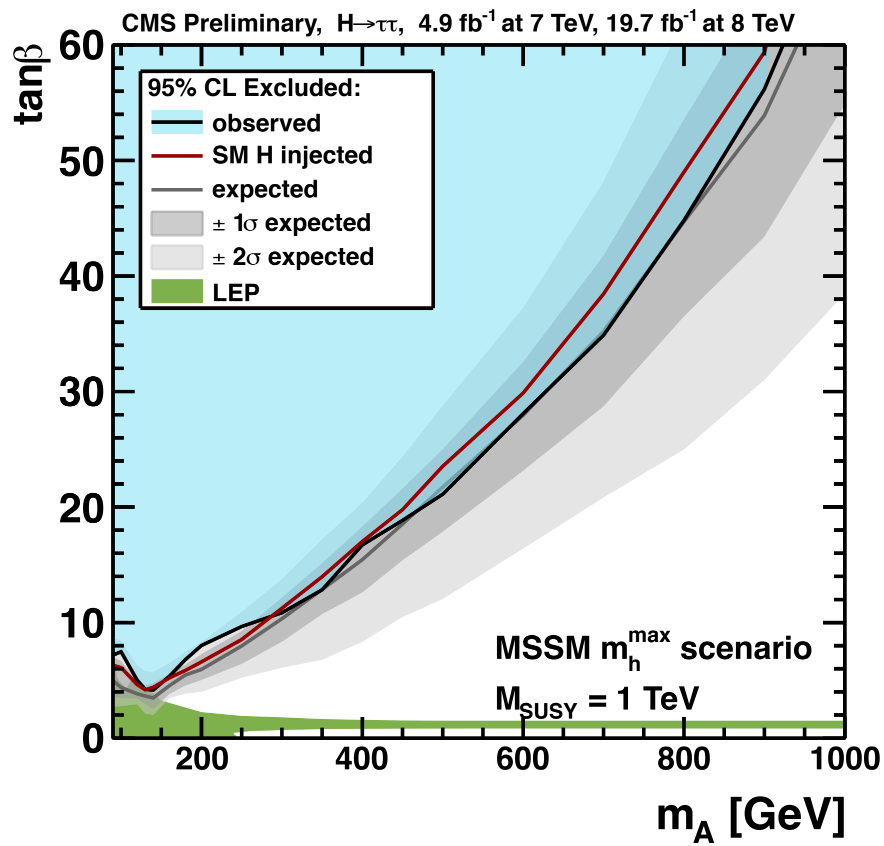
MSSM: $M_{\tau\tau}$ in μμ channel





MSSM: m_A tanβ limit





MSSM: m_A tanβ limit