Search for Neutral SUSY Higgs Bosons Decaying to Tau Leptons at 13 TeV

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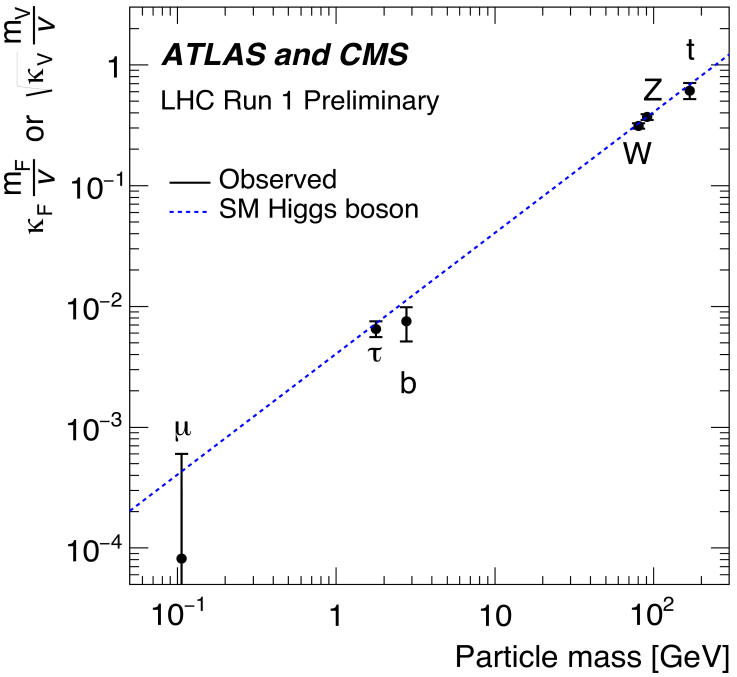
H(125) Boson and New Phyisics

- **H(125) is discovered (significance>5σ) in three bosonic and one fermionic decay mode**
  - **$H \to ZZ \to 4\ell$, $H \to WW \to 2\ell 2\nu$, $H \to \gamma\gamma$**
  - **$H \to \tau\tau$ (ATLAS+CMS combination)**

  and in two production modes
  - **gg→H**
  - **VBF (ATLAS+CMS combination)**
- **Measured properties are consistent with expectations for the SM Higgs boson**
- **Is H(125) the SM Higgs boson?**
- **Several ways to address this question**
  - **Search for deviations from the SM predictions (high precision measurements of the H(125) properties)**
  - **Search for BSM decays (invisible, LVF, etc) of H(125)**
  - **Search for new scalar bosons (topic of this talk)**



Higgs Sector in MSSM

Higgs Sector in MSSM → Two Higgs Doublet Model (2HDM)

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix}$$

5 physical states: h, H, A, $H^{\pm}$

$$\tan\beta = \nu_1/\nu_2$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

- Type II 2HDM
  - Φ_1 couples to down-type quarks and charged leptons
  - Φ_2 couples to up-type quarks
- **Modified couplings to gauge and fermion fields**

	h	H	A
W^+W^-	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
ZZ	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
$u\bar{u}$ (up-type quarks)	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$
$d\bar{d}$ (down-type quarks)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$
$\ell\bar{\ell}$ (charged leptons)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$

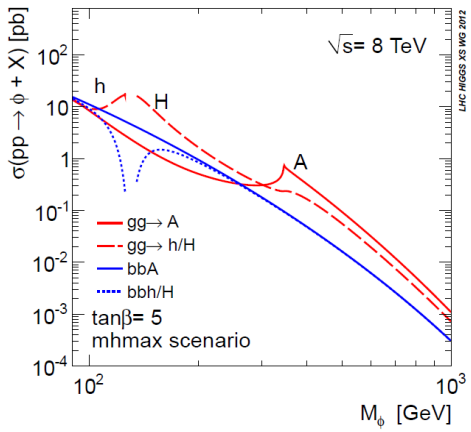
Decoupling Limit of MSSM

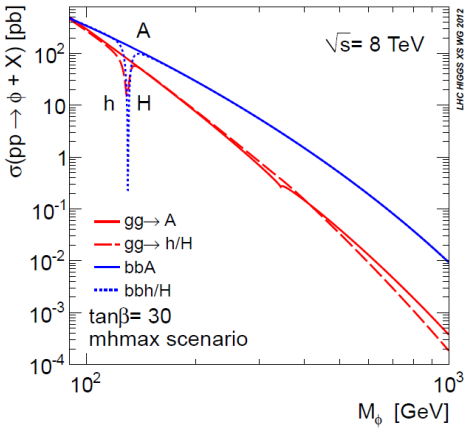
- **Unconstrained MSSM has more than 100 free model parameters**

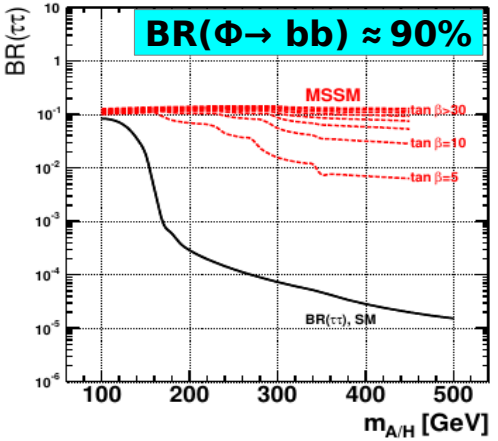
  → incomprehensible phenomenological variety of models

- **Current measurements of H(125) state are consistent with decoupling limit of MSSM**
  - $m_A \gg m_Z, m_A \approx m_H$
  - $\cos(\beta-\alpha) \to 0$ **: H decouples from W and Z**
  - $\sin(\beta-\alpha) \to 1$ **: h has properties of H_{SM} (e.g. H(125) state)**

- **high tanβ →**
  - **production rates are enhanced (bbΦ, gg → Φ)**
  - **decays to bb and ττ dominate even at high masses**



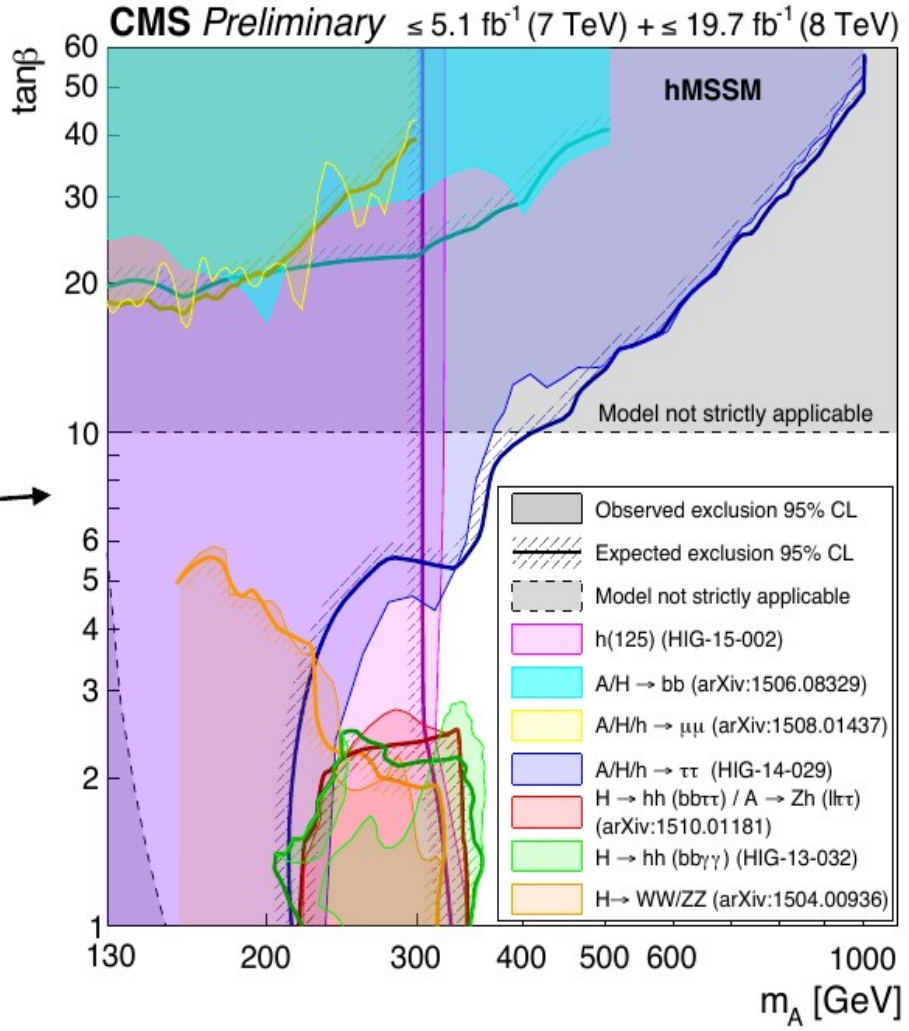




- **Decays to bottom-type fermions are the most sensitive probes of MSSM parameter domains with large m_A and high tanβ**

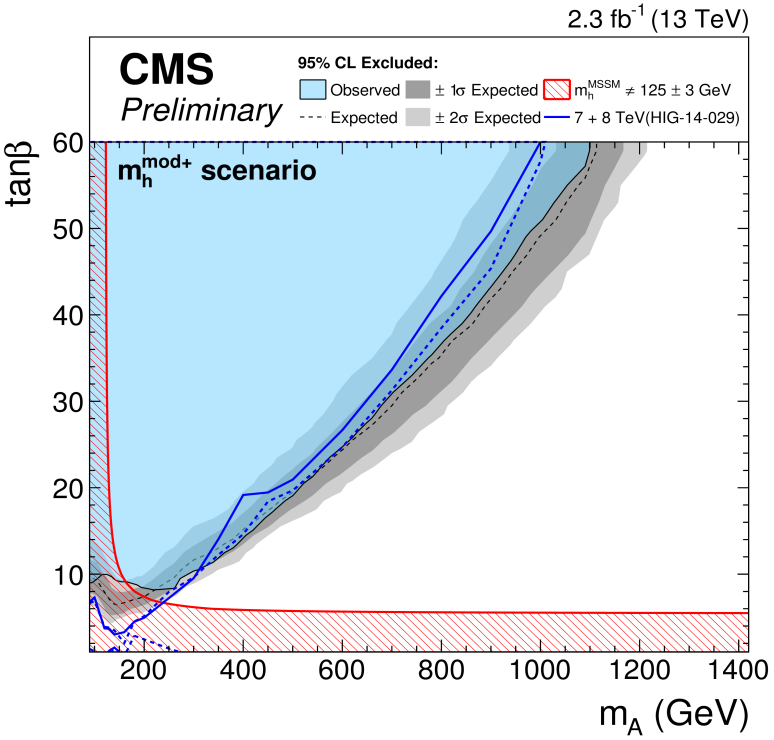
Recap of Run I Searches for MSSM Higgs bosons

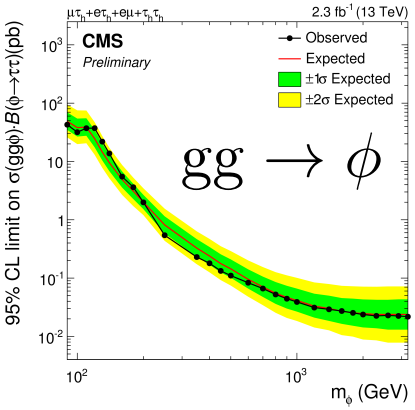
- Searches performed in many channels during Run I:
  - **H→bb**, **H→WW,H→ZZ, H→ττ**, **H→μμ**, **H→hh**, **A→Zh**, **H±→τν**,…
- Interpretations in **MSSM** - scan in m_A-tanβ plane of:
  - m_h^{mod+}
  - **hMSSM**
- Sensitivity to H→hh, A→Zh at low tanβ

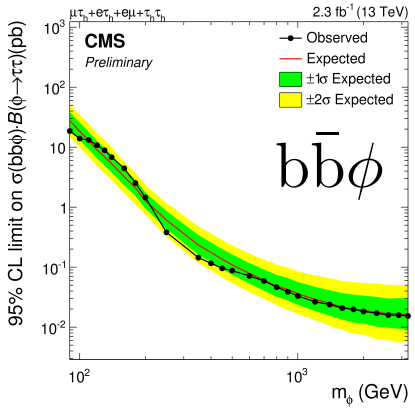


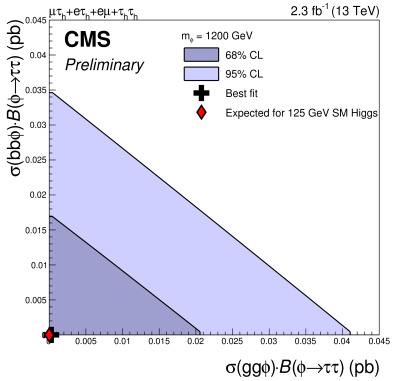
MSSM H → ττ search at CMS with early Run II data

- Previous MSSM H/A → ττ search results : CMS HIG-16-006
  - analyzed 2.3 fb^{-1} of data collected at 13 TeV in 2015
  - interpretations
    - model independent : limits on σ(bbφ/gg→φ) x BR(φ → ττ)
    - model dependent : (tanβ, m_A) limits within MSSM benchmarks
  - surpassed Run I results at high mass





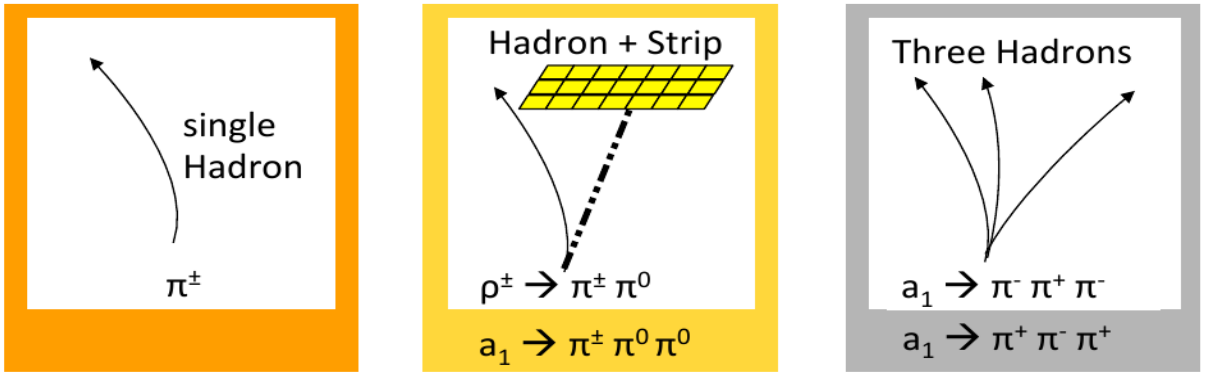




Identification of Hadronic Tau decays in CMS

Decay mode	Resonance	Mass [MeV/c^2]	Branching ratio
$\tau^- \to \pi^- \nu_\tau$	-	135	10.9%
$\tau^- \to \pi^- \pi^0 \nu_\tau$	ρ	770	25.5%
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	a_1	1200	10.8%
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	a_1	1200	9.8%
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	a_1	1200	4.5%
Total			59.2%
Other hadronic modes			5.6%

- Neutral pions are reconstructed from photons and electrons that deposit energy in ECAL → energy deposits combined in [η,φ]-strips
- Taus are reconstructed as combination of tracks and strips

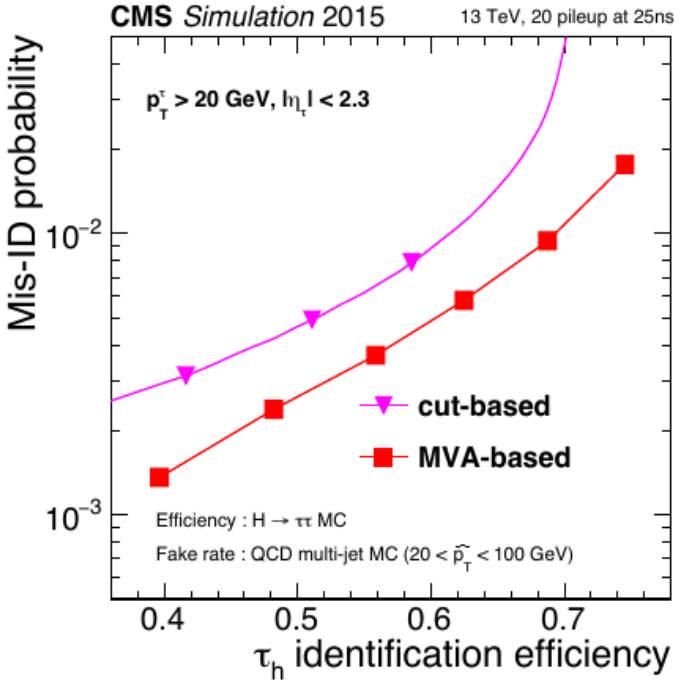


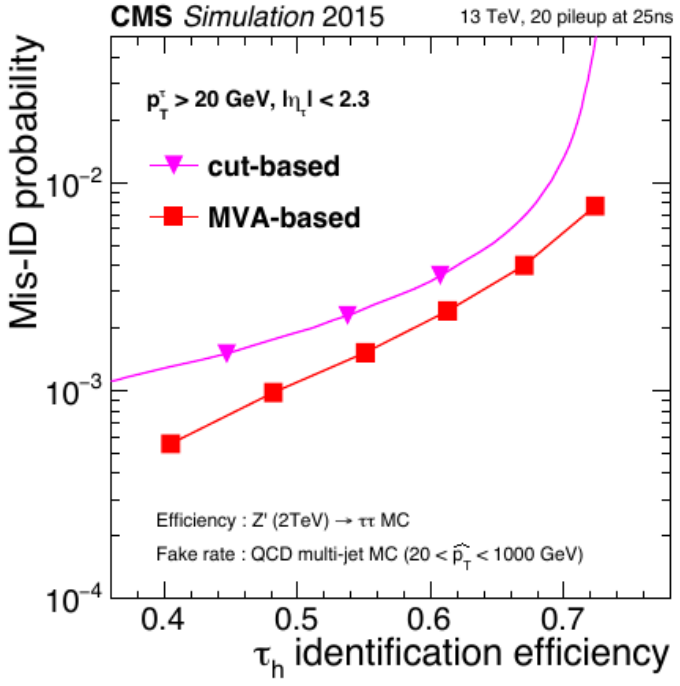
- **Invariant mass of tracks + strips should be compatible with the mass of intermediate resonance**

MVA-based tau Id

BDT based discrimination against jets

- **decay length information (track impact parameters, secondary vertex)**
- **isolation information (p_T sum of neutral objects and tracks within isolation cone)**
- **Number of photons and electrons within isolation and signal cones**

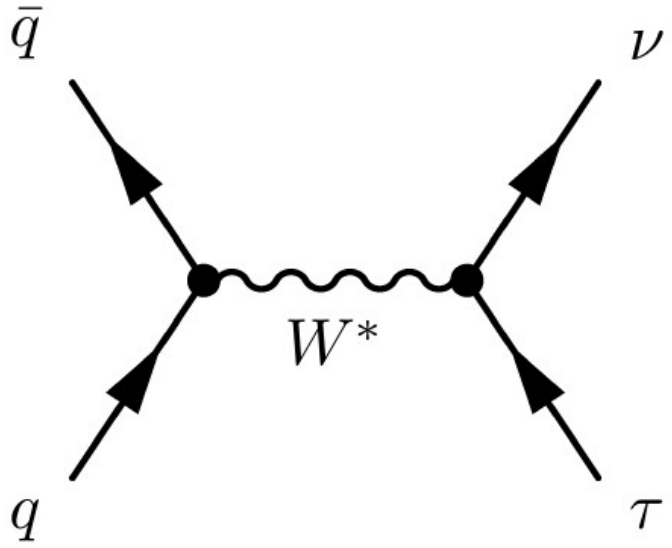


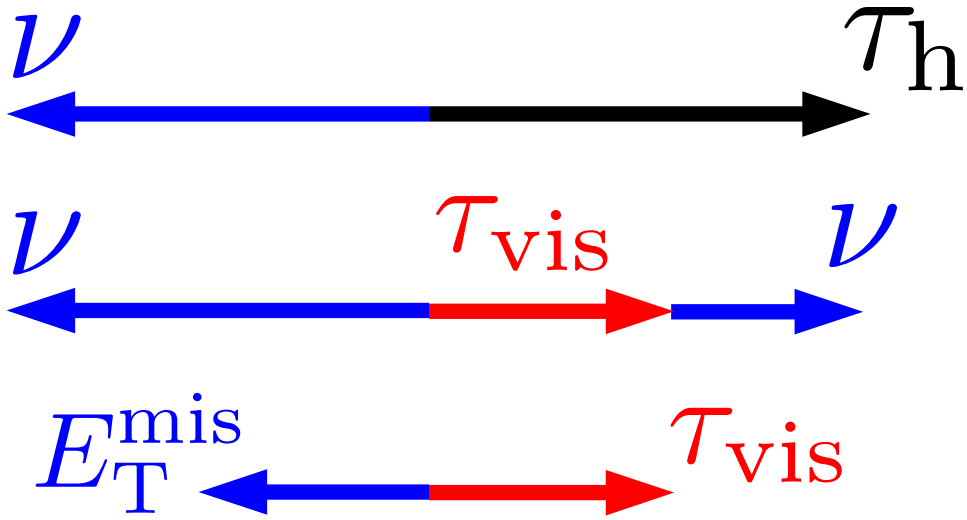


Tau ID measurement for high p_T taus

- **Tau ID efficiency of high p_T taus essential for heavy resonance searches :** $X^0 \to \tau^+\tau^-,\ X^\pm \to \tau^\pm\nu_\tau$
  - **high p_T tau-leptons can be accessed in the W*→τ+ν sample**

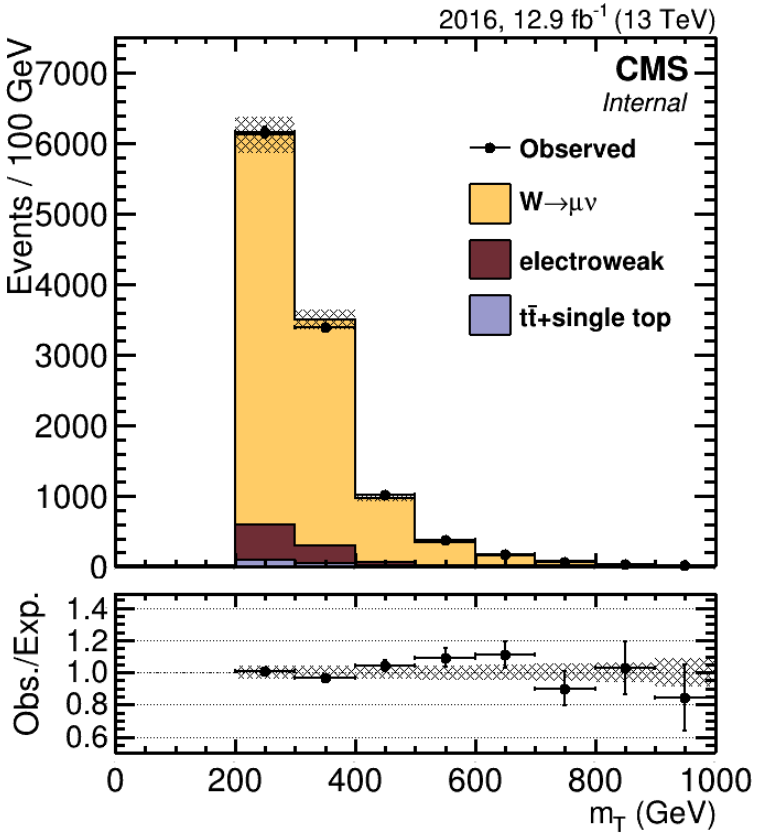
    → highly virtual W* production with little hadronic activity

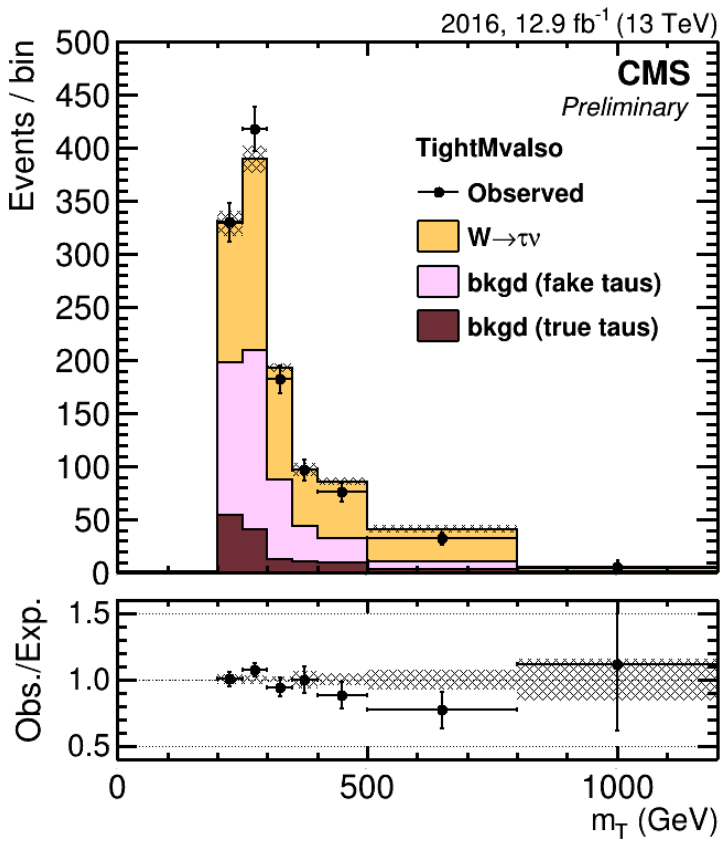




- **Signatures : single jet (tau), balanced with MET**

Tau ID measurement for high tau p_T

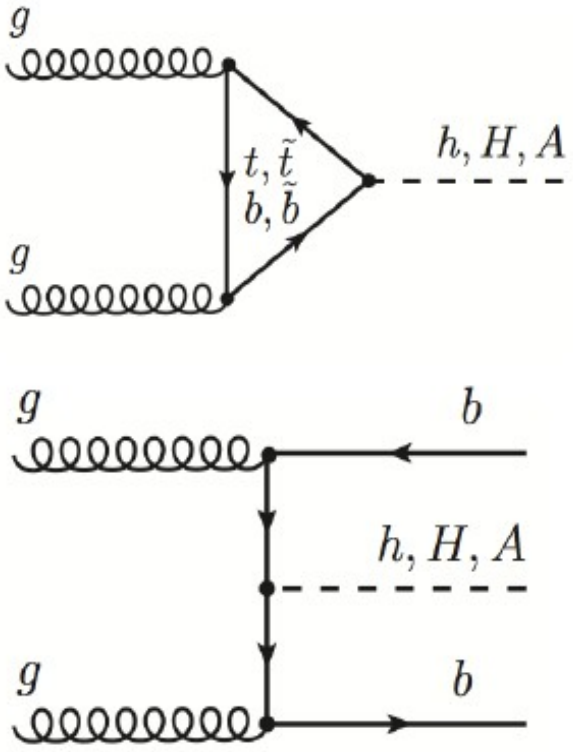




- data/siumlation τ Id scale factors are derived from fits of m_T(lepton,MET) in selected samples of W* → μν and W* → τν events
  - W* → μν sample is used to constrain fiducial yield of W* production with $m_{W^*} \geq 200$ GeV
- scale factors are found to be consistent with unity within measurement errors of 10-15%

MSSM Φ → ττ search at 13 TeV

- Exploited production mechanisms



- Exploited di-tau decay modes

$$\mu\tau_{\mathrm{h}}, e\tau_{\mathrm{h}}, \tau_{\mathrm{h}}\tau_{\mathrm{h}}, e\mu,$$

- new τ_{h}identification using lifetime information and dynamic strip reconstruction of neutral pions (TAU-16-002 PAS)
- Event categorization
  - no b-jets (p_T > 20 GeV, |η| < 2.4)
  - ≥ 1 b-jet (p_T > 20 GeV, |η| < 2.4)

    < 2 jets (p_T > 30 GeV, |η| < 4.7)
- Major backgrounds : Drell-Yan, TTBar, VV, W+Jets, QCD
- Signal extracted using total transverse mass of leptons and E_T(mis)

Selection

- **Triggers :**
  - **single lepton (e/μ) triggers with relatively low thresholds in the e+τ and μ+τ channels**
  - **e+μ cross triggers with asymmetric thresholds in the e+μ channel**
  - **double hadronic-tau trigger in the τ+τ channel**
- **Offline selection of opposite sign isolated di-lepton events**
- **Additional topological cuts involving missing E_T related variables to further suppress backgrounds**

Additional topological cuts

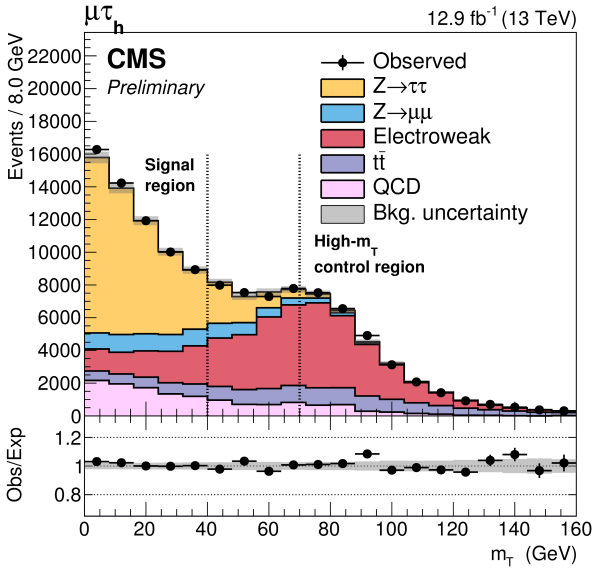
$\mu\tau_h$, $e\tau_h$:

cut on m_T to reduced W+Jets

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

$\mu\tau_h$: $m_T < 40$ GeV

$e\tau_h$: $m_T < 50$ GeV



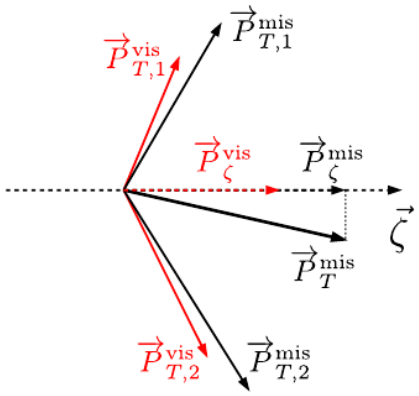
$e\mu$:

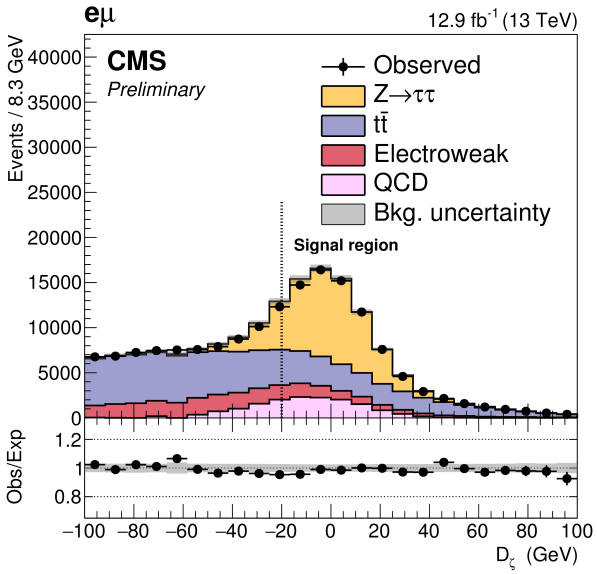
cut on D_ζ to reduced TTBar and VV

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

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

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





Choice of final discriminant

- Previous analysis used transverse mass of fully reconstructed di-tau system
- This variable is found to be sub-optimal in the e+μ channel

eμ channel differs from other channels ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) in that tt+jets is by far dominant background to high mass Higgs signals

Direction of MET vector in tt+jets events not "aligned" with e and μ

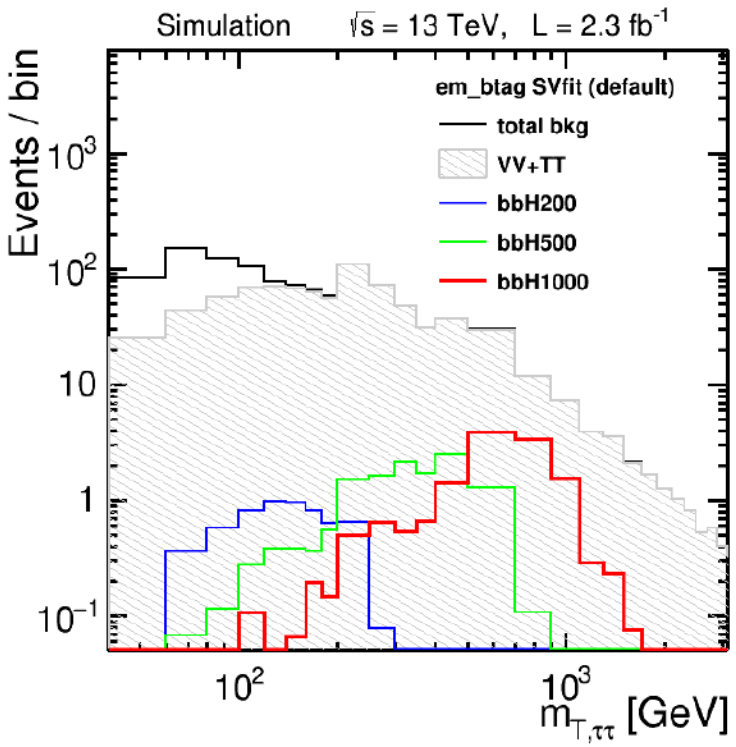
➔ SVfit likelihood typically broad in tt+jets events, as direction of MET vector does not match expected signal topology for signal of any mass

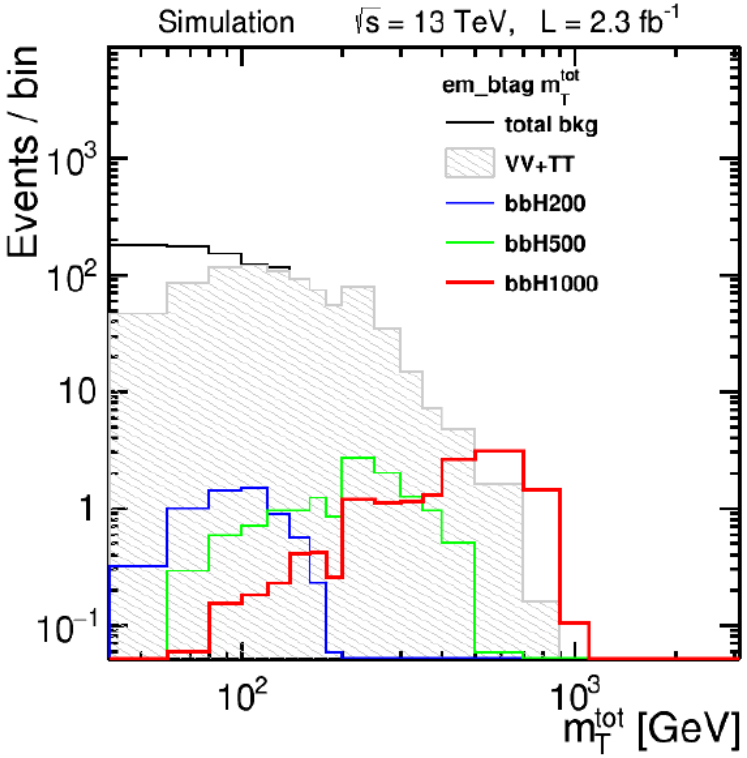
➔ Broad likelihood function can cause high mass tails in SVfit reconstruction

- Use total transverse mass (variable introduced by ATLAS in their MSSM H → ττ search)

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(\mathrm{e}, \mathrm{MET}) + m_{\mathrm{T}}^2(\mu, \mathrm{MET}) + m_{\mathrm{T}}^2(\mathrm{e}, \mu)}$$

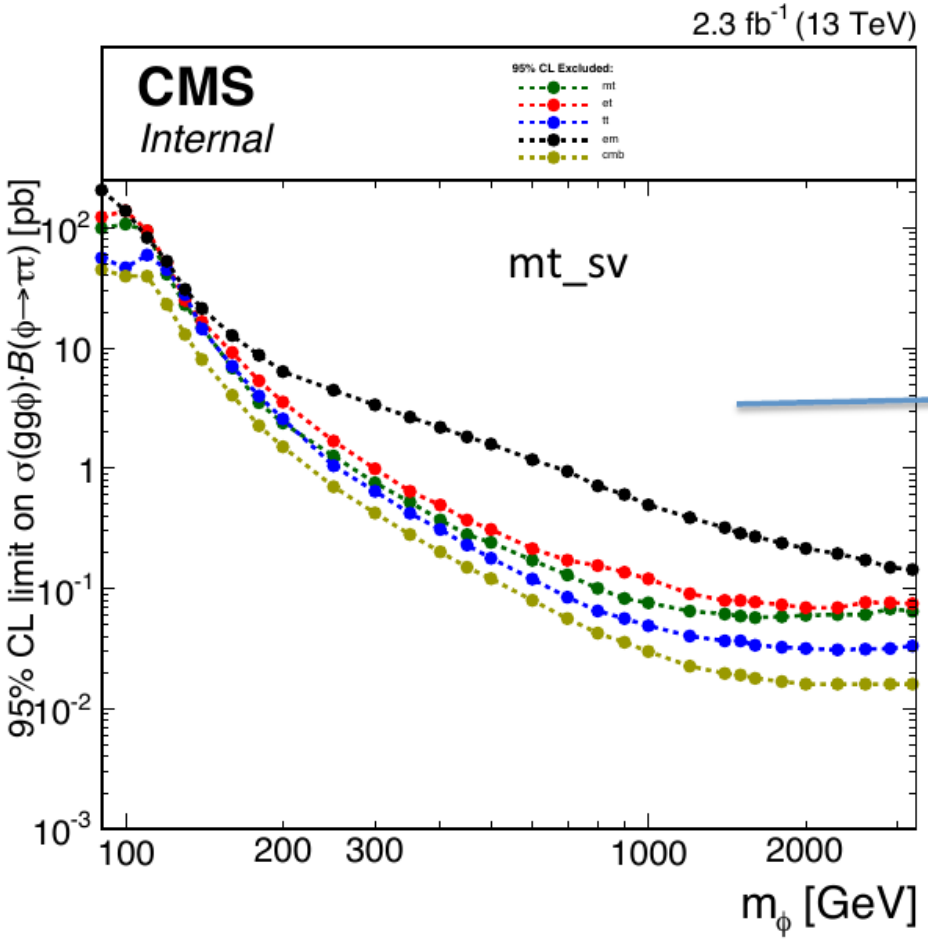
Choice of final discriminant

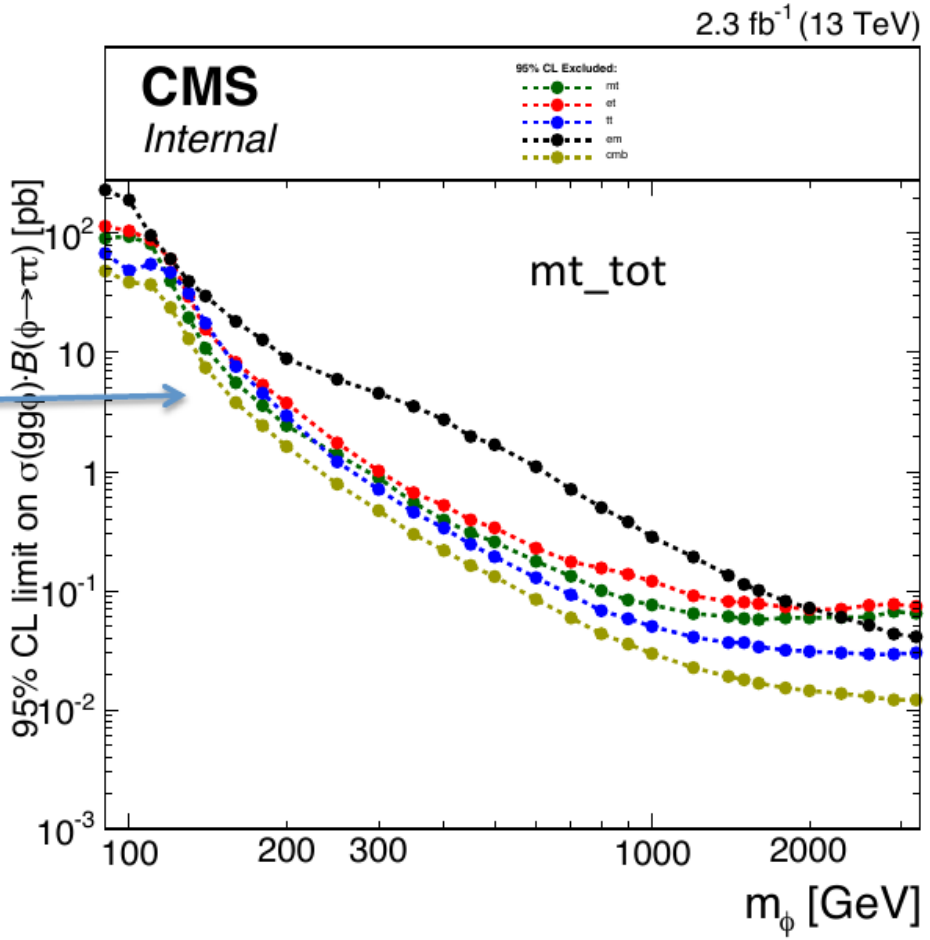




- Much better signal/background separation at high masses in e+μ channel is attained by using total transverse mass instead of transverse mass of reconstructed di-tau system

Choice of final discriminant



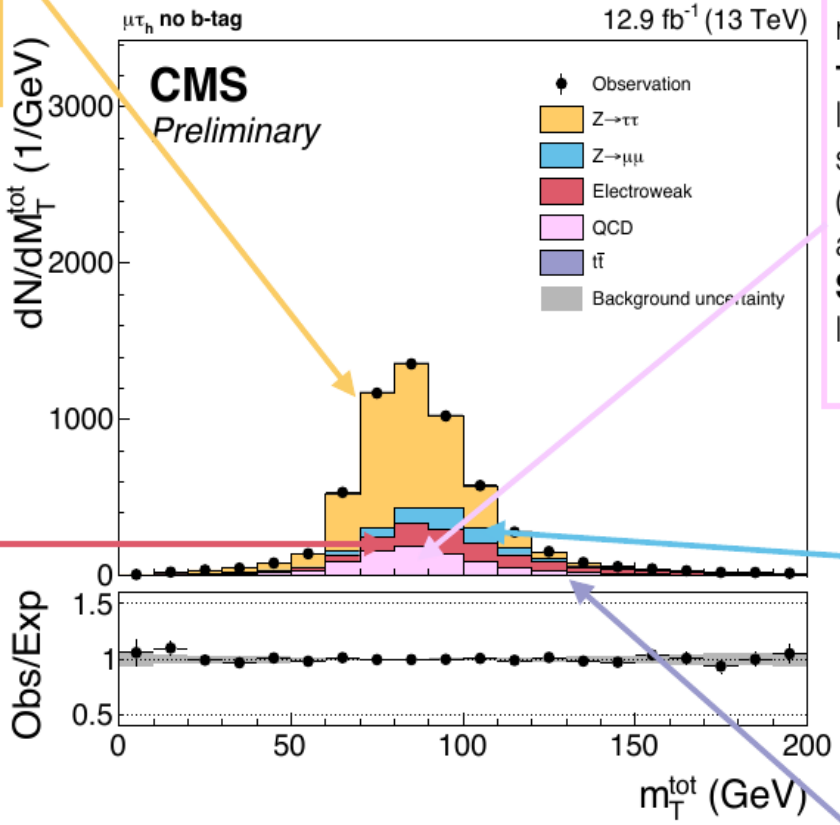


- With m_T^{tot} as the final discriminant e+μ channel outperforms e+τ_h and μ+τ_h at high masses (m_φ > 2 TeV)
- Usage of of m_T^{tot} instead of $m_{T,\tau\tau}$ does not deteriorate performance in other channels

Background Estimation Techniques

Z—>ττ*: Norm and shape from MC, with data-driven correction applied

W+Jets: μτh,eτh: Norm** from high m_T control region **shape** from MC
τhτh,eμ: Norm and shape from MC



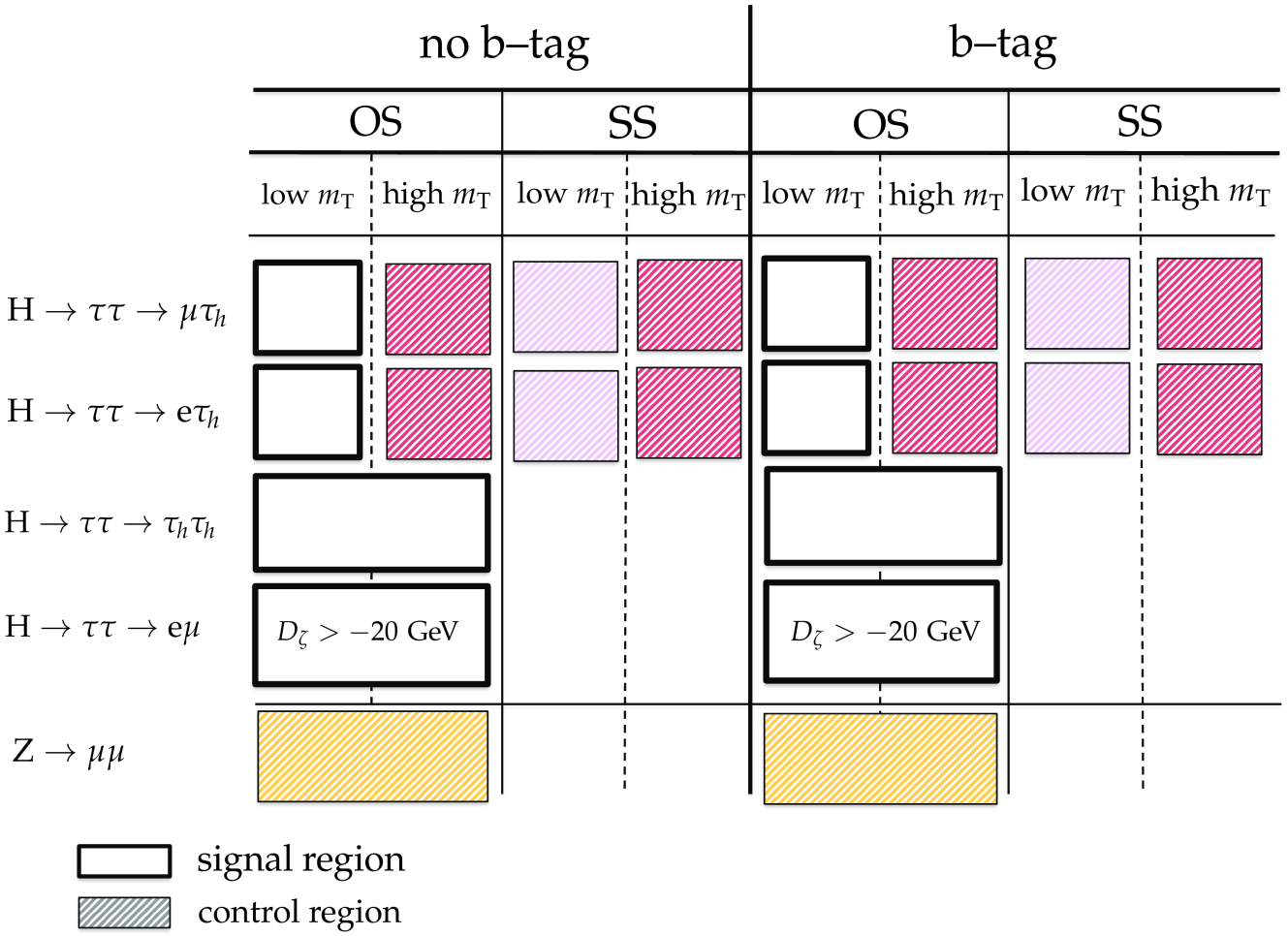
QCD: Fully data-driven**
μτh,eτh,eμ: Norm from SS with other backgrounds subtracted, and OS/SS ratio applied, **shape** from SS
τhτh: Norm from OS region with loosened isolation (SR excluded), scale factor loose—>tight isolation (measured in equivalent SS regions) applied.
Shape from OS region with loosened isolation

Z—>ll: Norm and shape from MC

ttbar: Norm and shape from MC, with data-driven corrections

*Control regions included in fit for this background, affecting the post-fit normalisation of **all channels**
** Control regions included in fit for this background affecting the post-fit normalisation of the **μτh and eτh channels only**

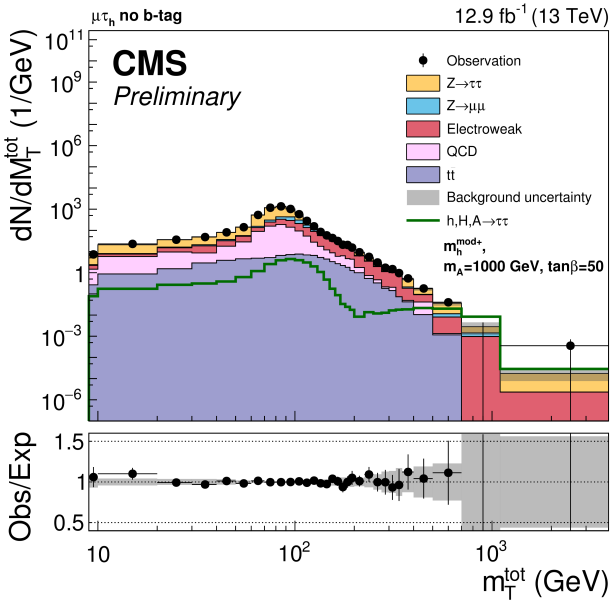
Control regions

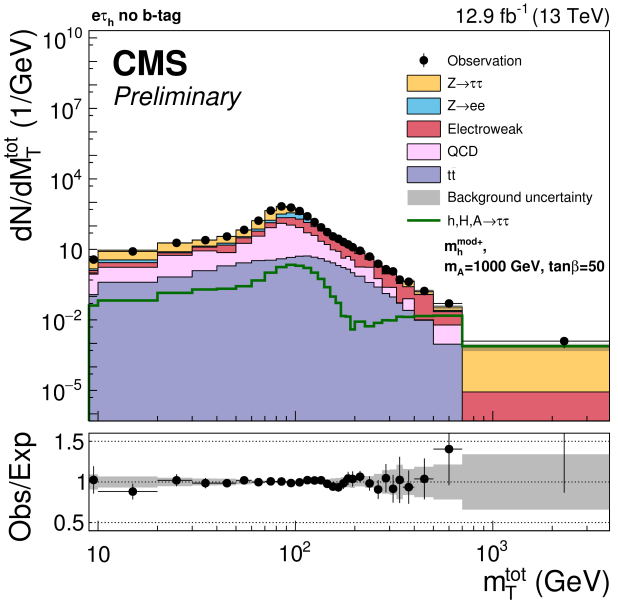


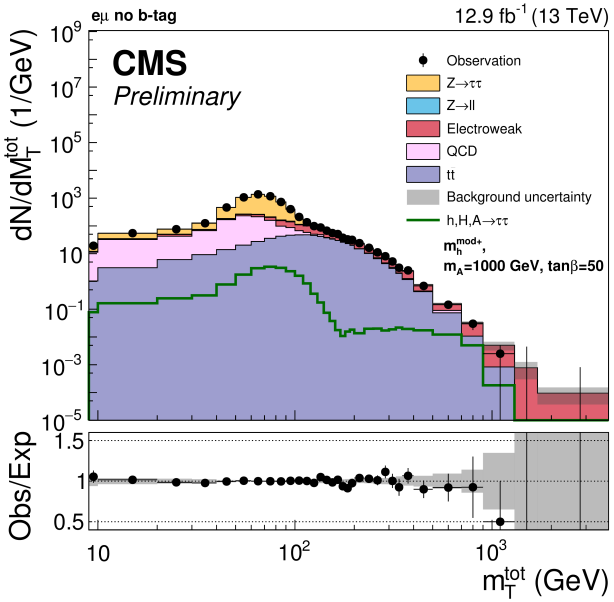
- Backgrounds constrained by control regions:

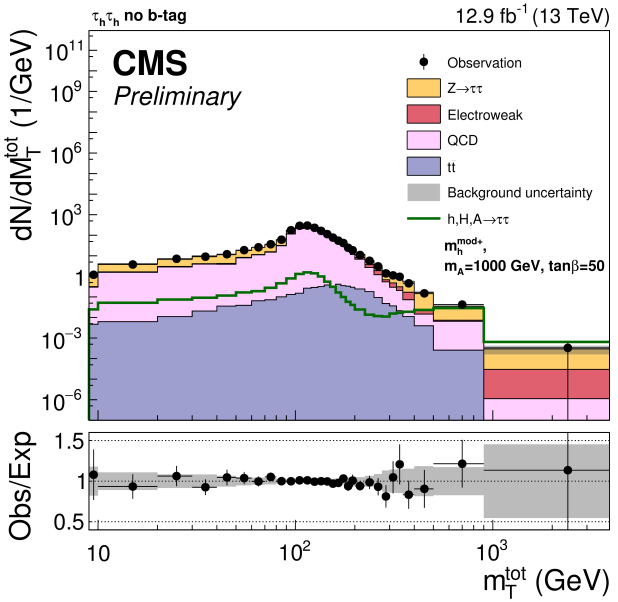
$Z \to \tau\tau$ W+Jets QCD

Postfit distributions of m_T^{tot} (no btag category)

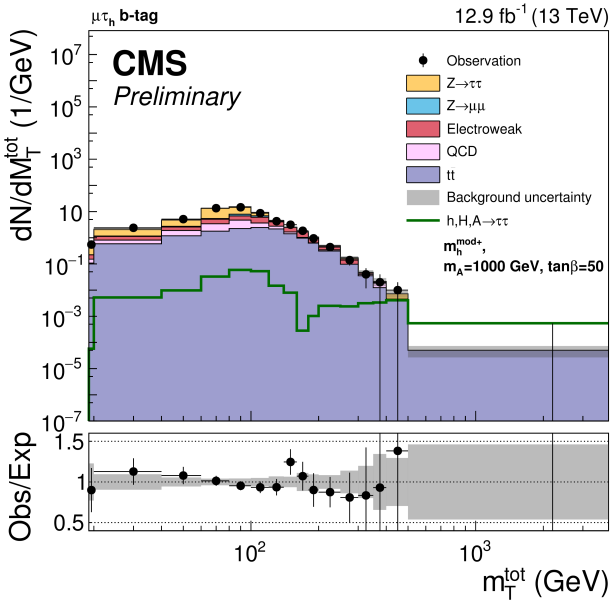


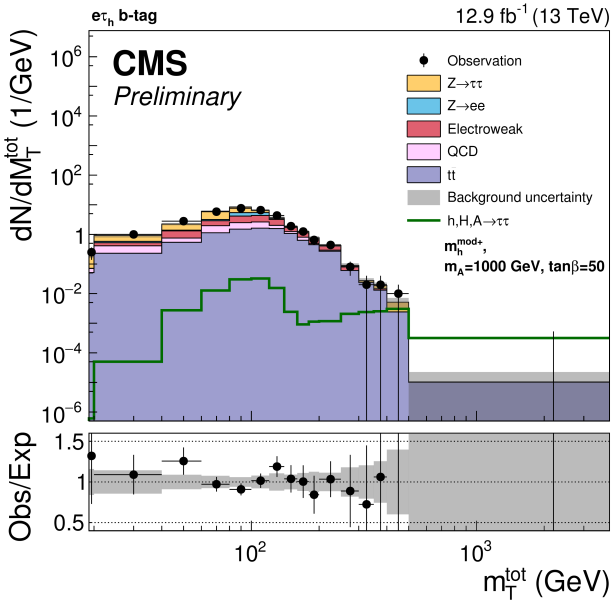


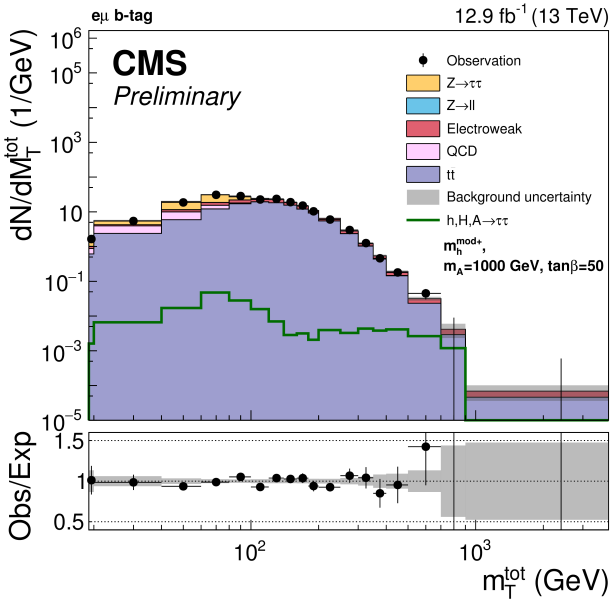


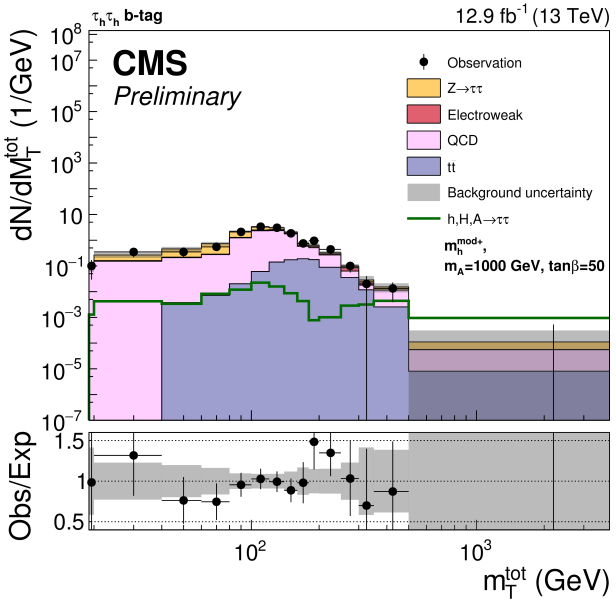


Postfit distributions of m_T^{tot} (btag category)







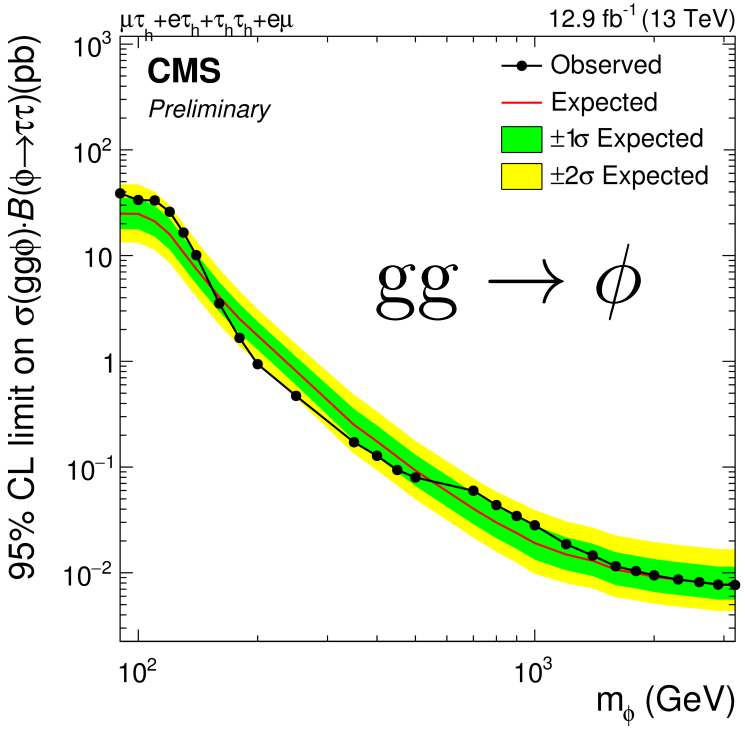


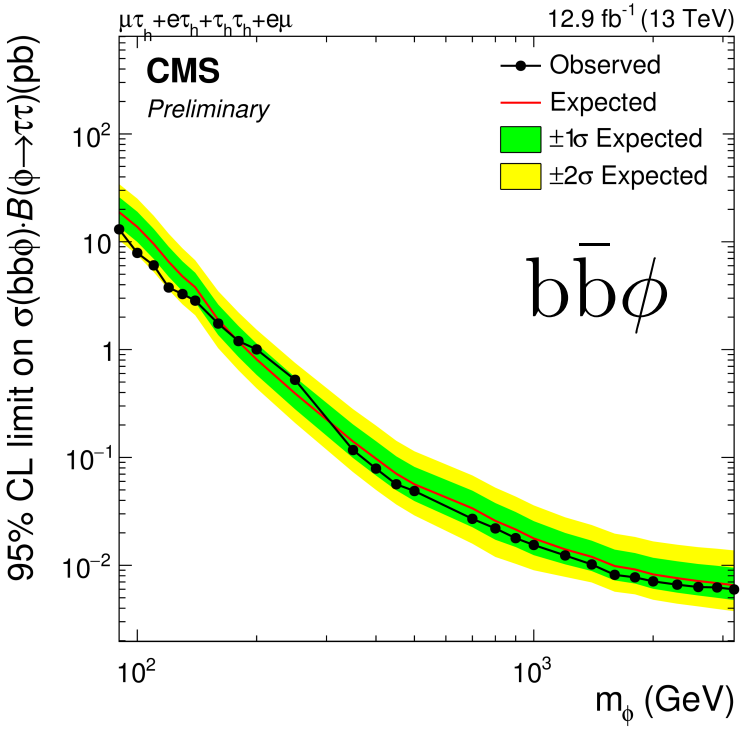
Model Independent Interpretation

- No evidence of signal found
- Model independent result : constraints on signal production cross section times BR (search for narrow $\Phi \rightarrow \tau\tau$ resonance)

  set limits on each process

  (other process is profiled)

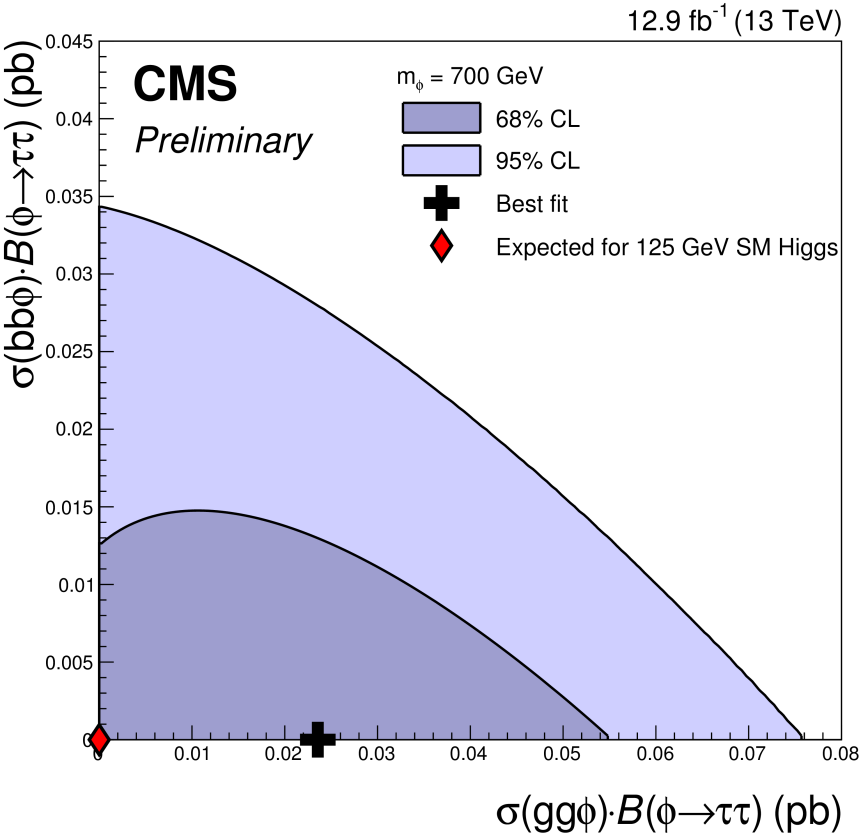


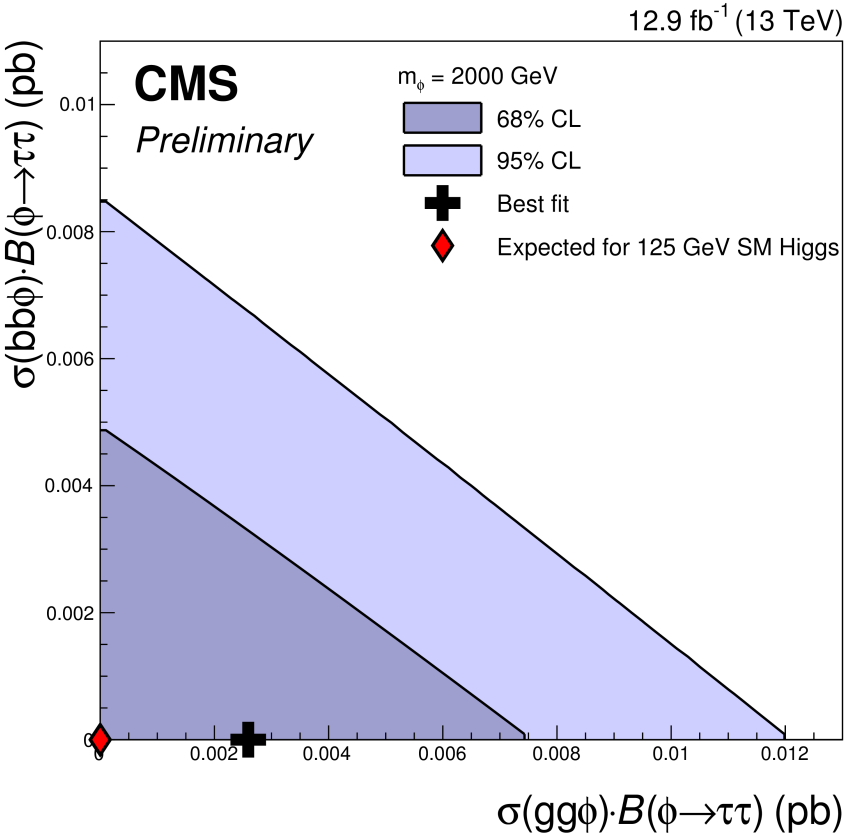


Model independent interpretation

- **Limits in 2D plane**

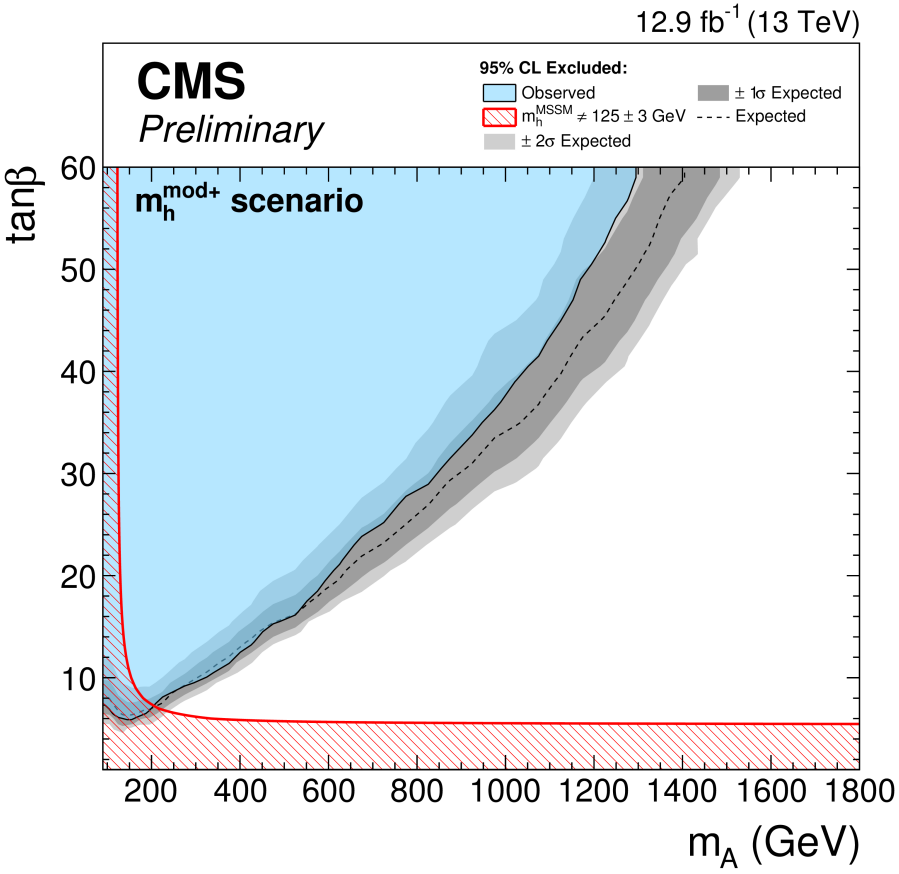
$$\sigma(\mathrm{gg} \to \phi)\mathcal{B}(\phi \to \tau\tau) \quad \text{vs.} \quad \sigma(\mathrm{bb}\phi)\mathcal{B}(\phi \to \tau\tau)$$

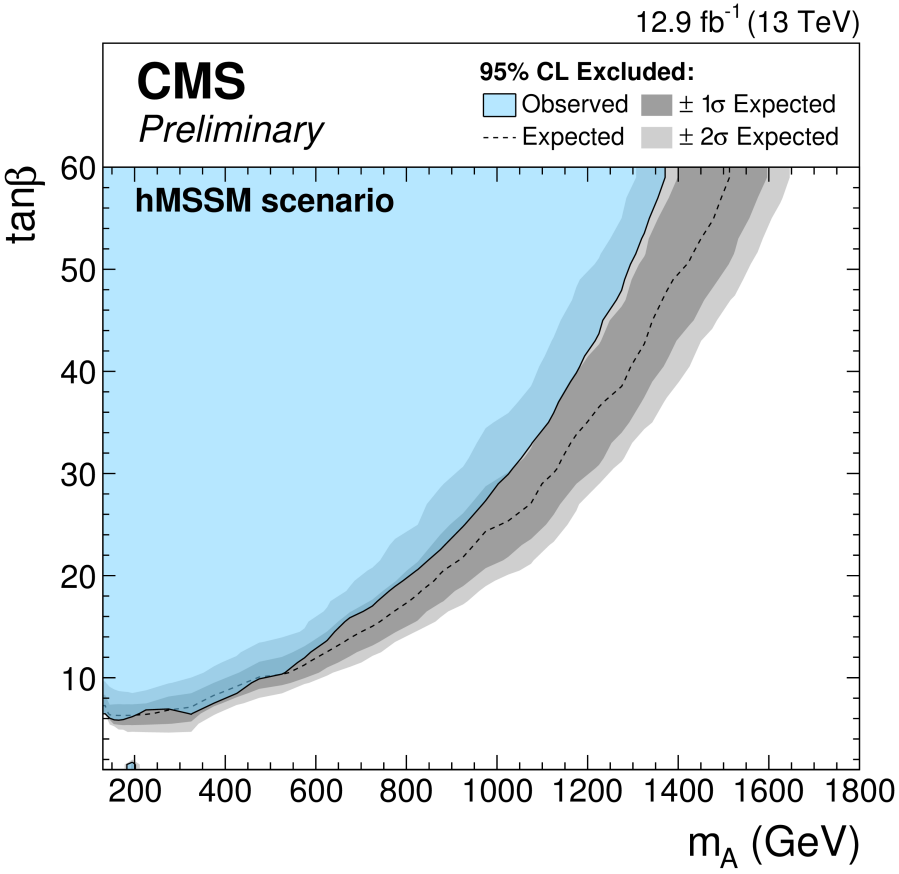




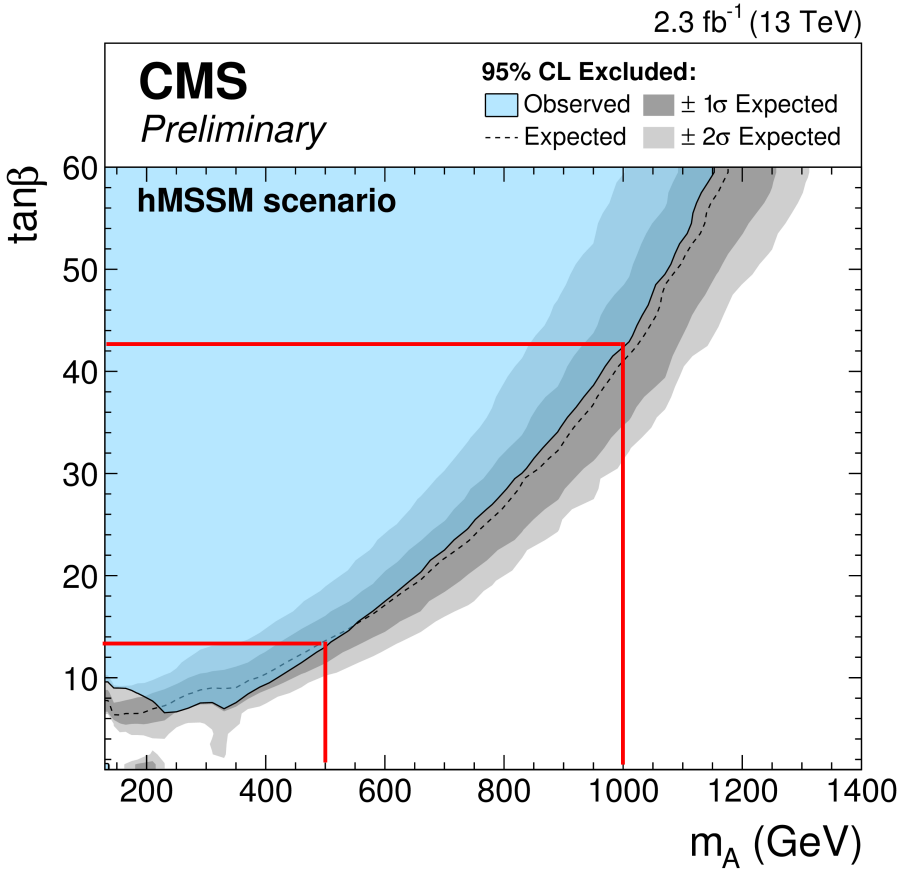
Model Dependent Interpretation

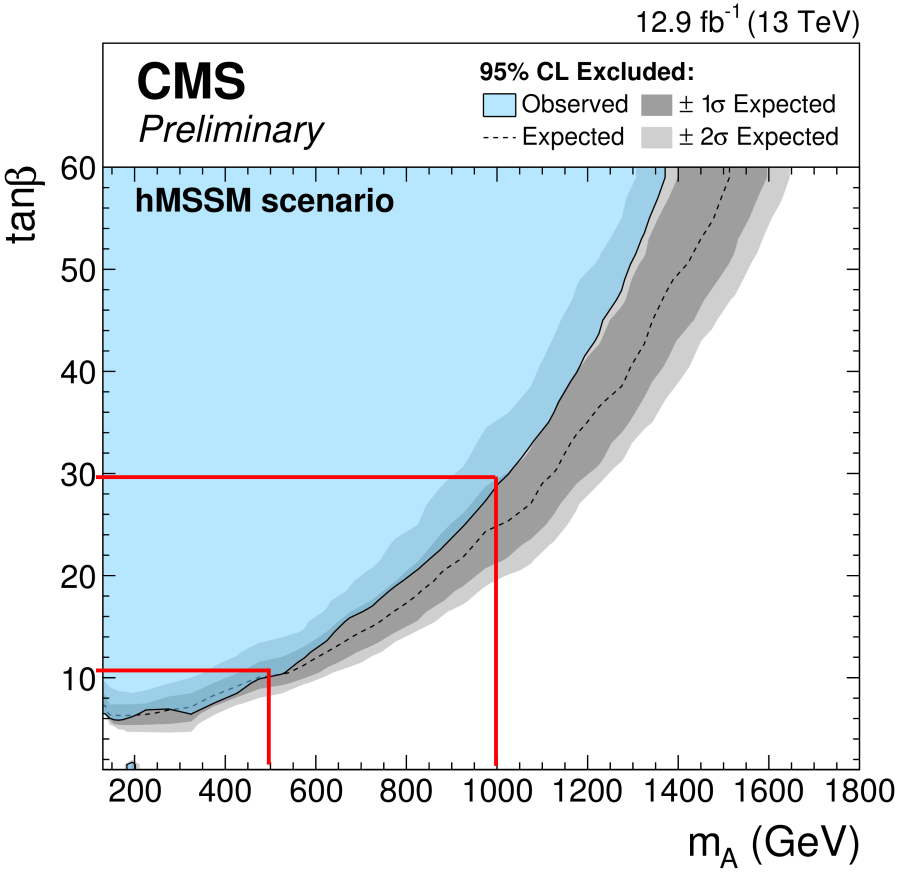
- **limits in (m_A,tanβ) plane**
- **m_h-mod+ and hMSSM benchmarks : post-discovery scenarios accommodating h(125) state**





Comparison with previous results





Summary

- **Search for neutral SUSY Higgs bosons is performed with 12.9 fb^{-1} of 2016 data**
  - **no indication of signal yet**
  - **results of the search are interpreted in a model independent and model dependent ways**
    - **limits on x BR for two major productions mechanisms : $bb\Phi$ and $gg \rightarrow \Phi$**
    - **limits on $\tan\beta$ as a function of m_A within benchmark scenarios**
- **Analysis performed on full 2016 dataset (L ~ 36 fb^{-1}) is being finalized**
  - **Plan to release updated results at the time scale of EPS'17 Conference**