Search for MSSM Higgs bosons decaying to taus with CMS

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GDR Terascale – LPSC, Grenoble – 24/11/15

The Higgs sector in the Minimal Supersymmetric Standard Model

- **MSSM is a Type 2 Two-Higgs Double Model (2HDM) with a SUSY sector**

  → **Two v.e.v., 5 physical Higgs bosons**
  - **3 neutral → Φ = h (light scalar), H (heavy scalar), A (pseudoscalar)**
  - **2 charged → H^+, H^-**

  → **Protects the h_{125} mass, predicts small h_{125} coupling deviations, etc.**

- **At tree level, the MSSM is controlled by two parameters: m_A and tanβ**

→ **Other assumptions (such as the higgsino mass parameters, the stop mass, stop mixing etc.) can be used to define MSSM benchmark scenarios**

→ **Generally, results are interpreted in the m_h^{max} and more recent m_h^{mod} scenarios** *[M. Carena et al., Eur.Phys.J. C73 (2013) 2552]*

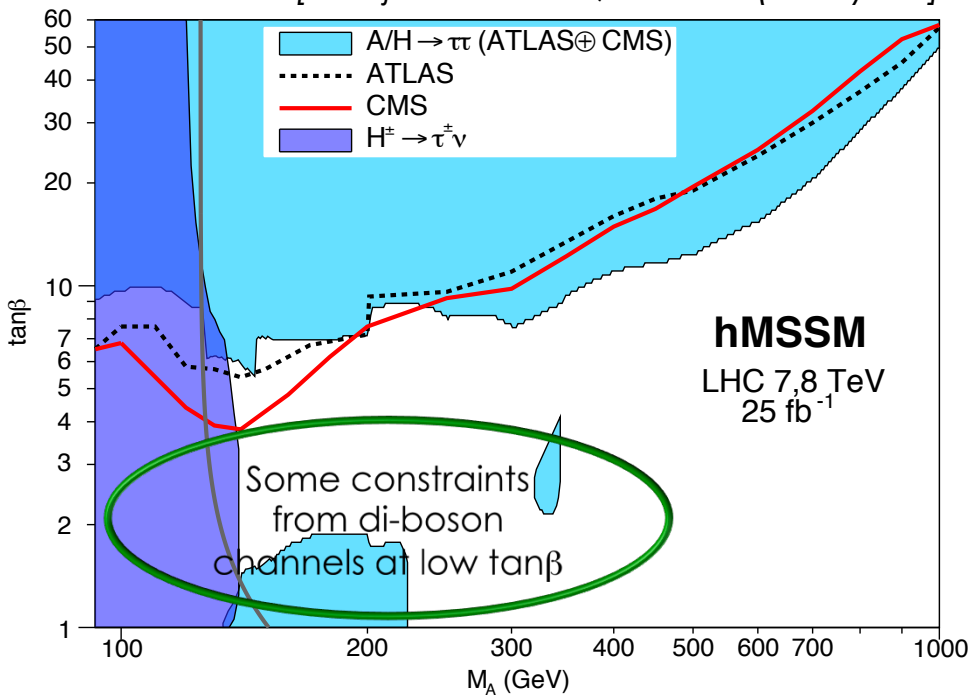
Constraints from the LHC experiments

- **Low mass region (m_A<150 GeV) excluded by $H^{\pm}\rightarrow\tau\nu$ and $\Phi\rightarrow\tau\tau$ searches**
- **Intermediate mass range allowed in tanβ 'wedge'**
- **High mass range (m_A>300 GeV) progressively covered at medium-high tanβ (mainly $\Phi\rightarrow\tau\tau$,bb) and low tanβ values (mainly di-boson final states)**

→ **Light Higgs couplings approaching (quasi-)decoupling regime**

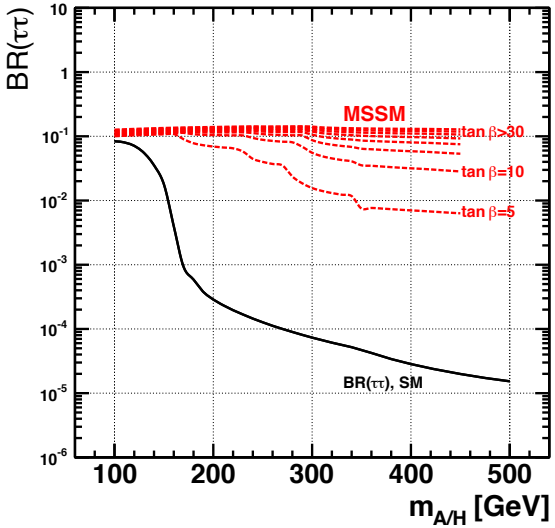
→ **Today, the CMS Run I legacy $\Phi\rightarrow\tau\tau$ result is presented**

[A. Djouadi et al., JHEP06 (2015)168]

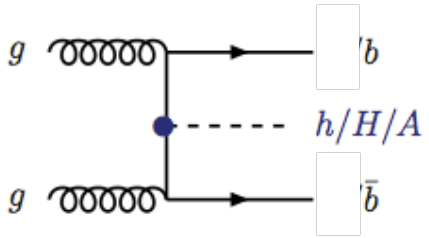


Searches for $\Phi(h,H,A) \rightarrow \tau^+\tau^-$

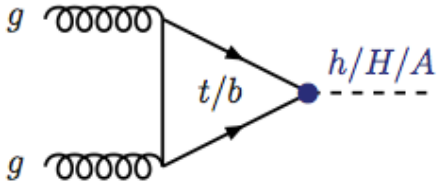
- *BR($\Phi \rightarrow \tau\tau$) ~ 10^{-1}*



Production mechanisms



≥1 b-tagged jet



No b-tagged jet

- Probing large regions of $m_A/\tan\beta$ phase space
- Challenges
  - Large kinematic regime (searching for additional resonances from ~125 GeV to 1 TeV)
  - Large $Z/\gamma^* \rightarrow \tau\tau$ background
  - ttbar/W+jets backgrounds dominate at high masses
  - QCD multijet in $\tau_h\tau_h$ channel
  - Presence of 2 to 4 neutrinos in final state

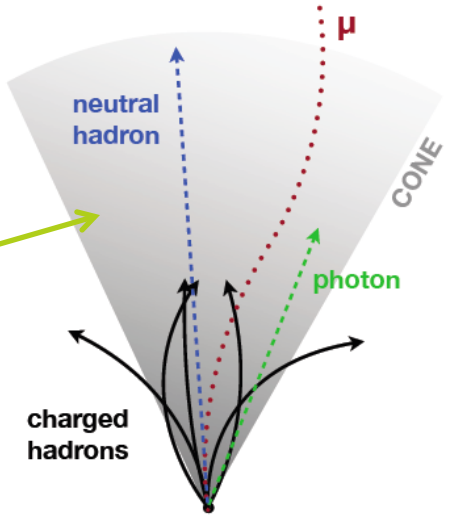
→ Challenging $M_{\tau\tau}$ reconstruction

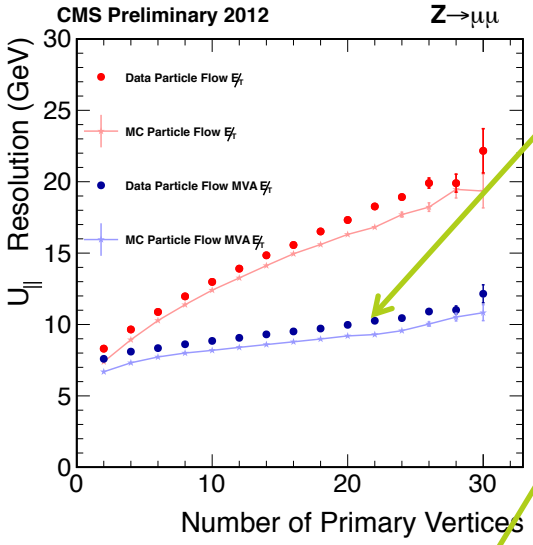
MET and di-τ mass reconstruction

- **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

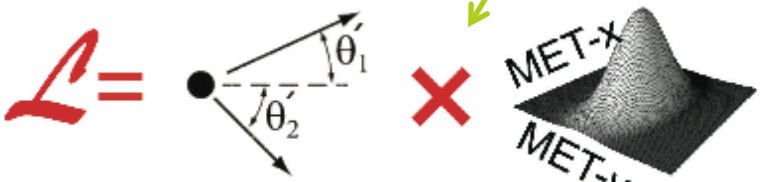




Build multivariate Missing Transverse Energy (MVA MET) to reduce degradation of resolution with pile-up

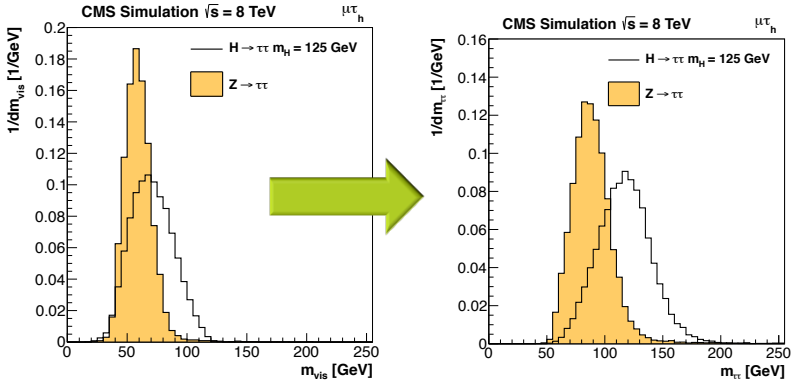
- **Di-τ mass reconstruction (SVfit)**
  - **Maximum likelihood method**
  - **Tau kinematics x phase space constraints x MET resol.**

Improved separation with Z→ττ background
15-20% resolution on $M_{\tau\tau}$



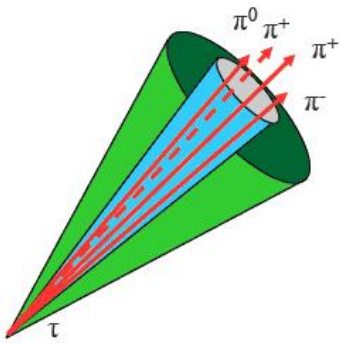
Tau decays phase-space

Expected ME_T resolution



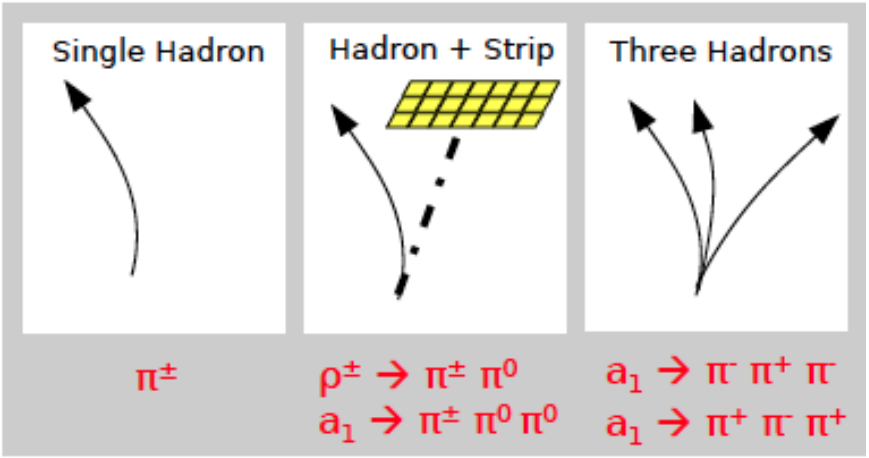
Hadronic τ-lepton reconstruction

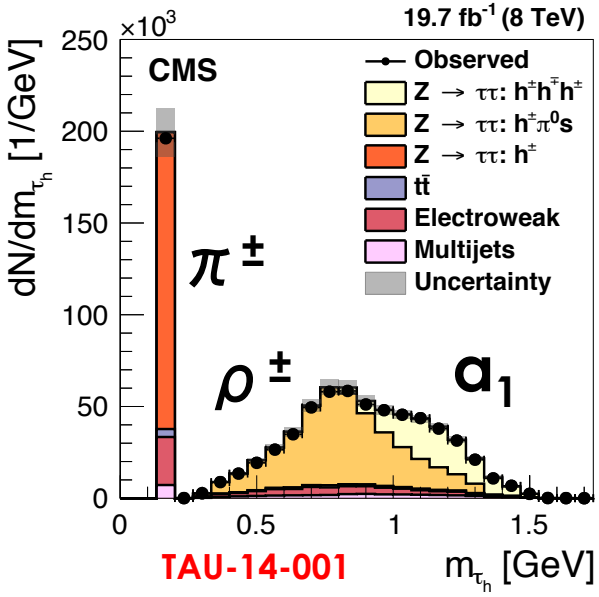
- **Decay mode reconstruction = Hadron Plus Strip (HPS) algorithm**
- Study of the different topologies + intermediate resonances



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 isolation (=τ_h-ID)**

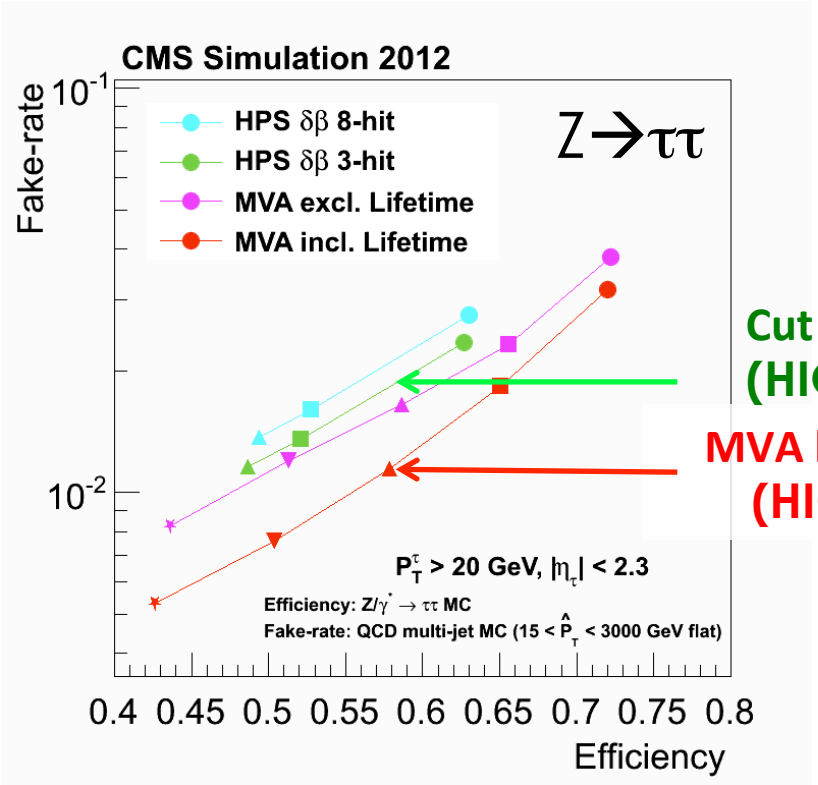
→ **Fake rate is ~3% at ~70% signal efficiency**

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

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

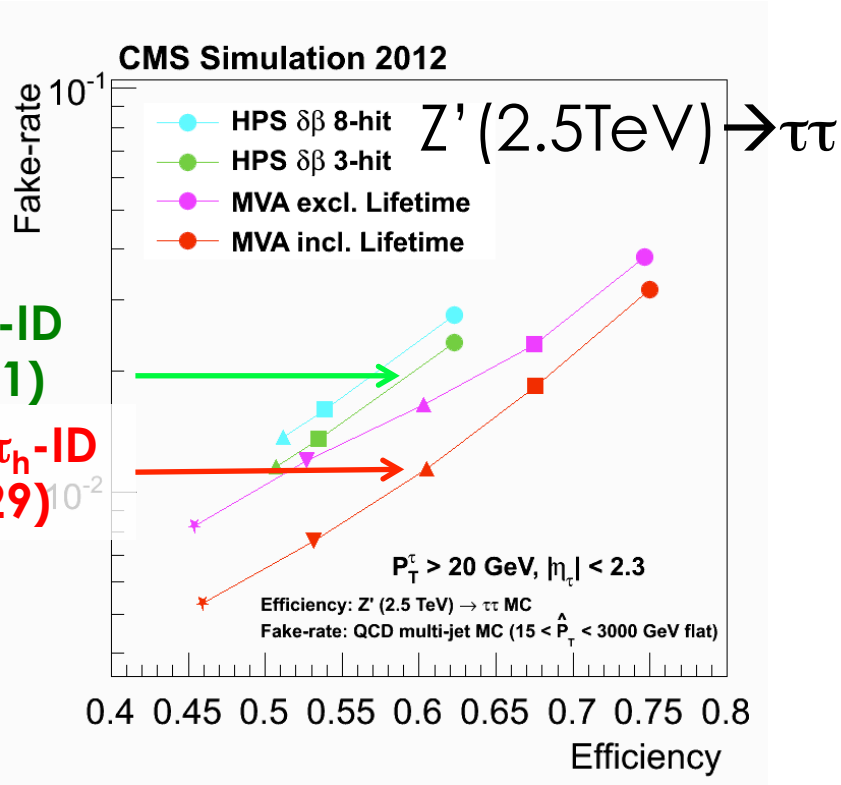
Boosted τ_h-ID

Use of MVA boosted τ_h-ID: combines isolation energy and τ lifetime information



Cut based τ_h-ID (HIG-13-021)

MVA boosted τ_h-ID (HIG-14-029)



Reduction of jet→τ_h fake rate by 40 to 50% at constant efficiency, for low p_T as well as for high p_T τ_h(s)

Updated CMS $\Phi \rightarrow \tau\tau$ search

- **Previous published CMS $\Phi \rightarrow \tau\tau$ search is HIG-13-021 [JHEP 10 (2014) 160]**

- **New analysis [CMS PAS HIG-14-029] that brings two main improvements along**

  ① **Use of MVA "boosted" identification of the hadronic taus (τ_h)**
  [documented in Run I Legacy (τ_h) paper **TAU-14-001**, submitted to J. Inst.]

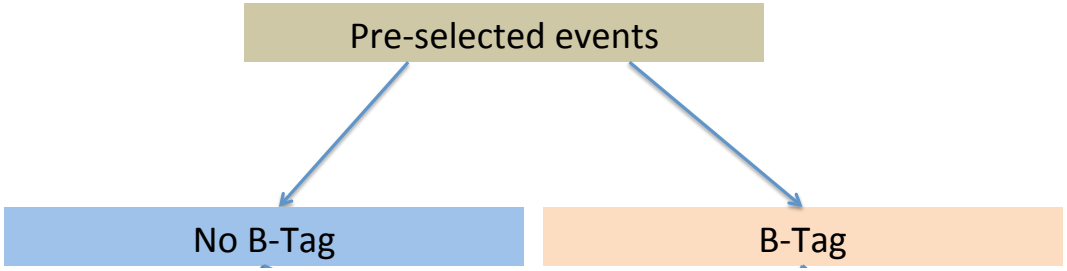
  ② **Refined event categorization which allows for a better sensitivity to the MSSM-specific kinematics**

- **Analysis of 7+8 TeV data (4.9+19.7 fb^{-1})**

  - **Channels: $\mu\mu/e\mu/\mu\tau_h/e\tau_h/\tau_h\tau_h$ (only the last three 8 TeV channels updated)**

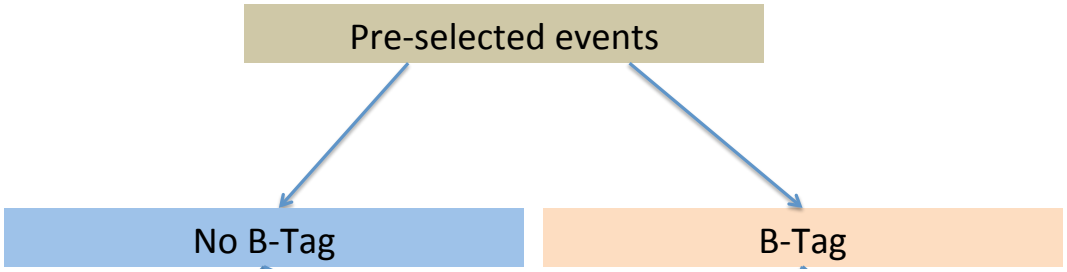
  - **Discriminant variable: SVfit mass (CMS' reconstruced $M_{\tau\tau}$)**

Refined event categories



- **Previous categorization based on presence or not of b-tagged jet**

Refined event categories



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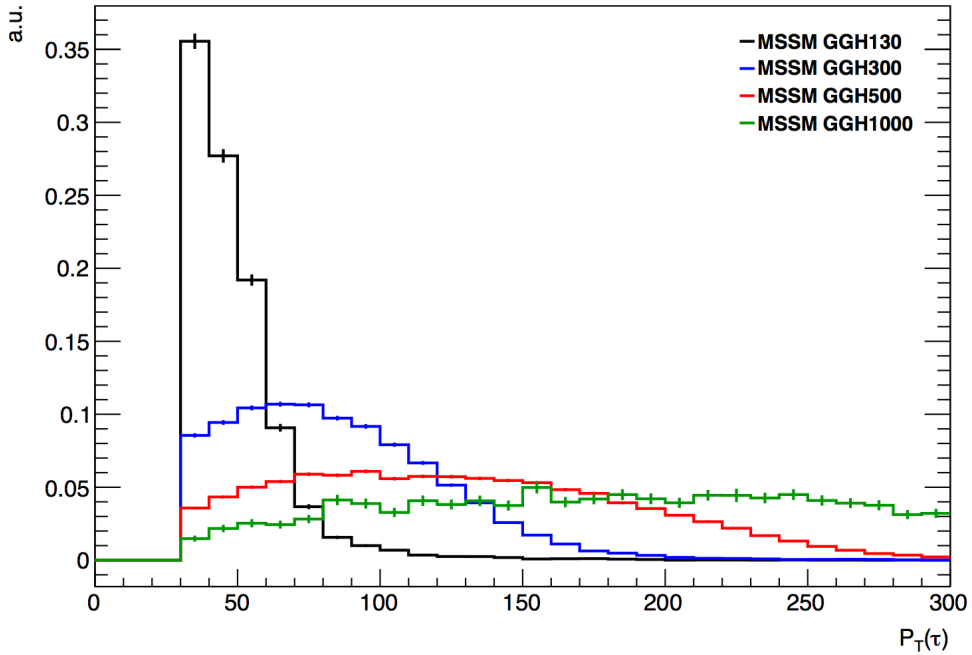
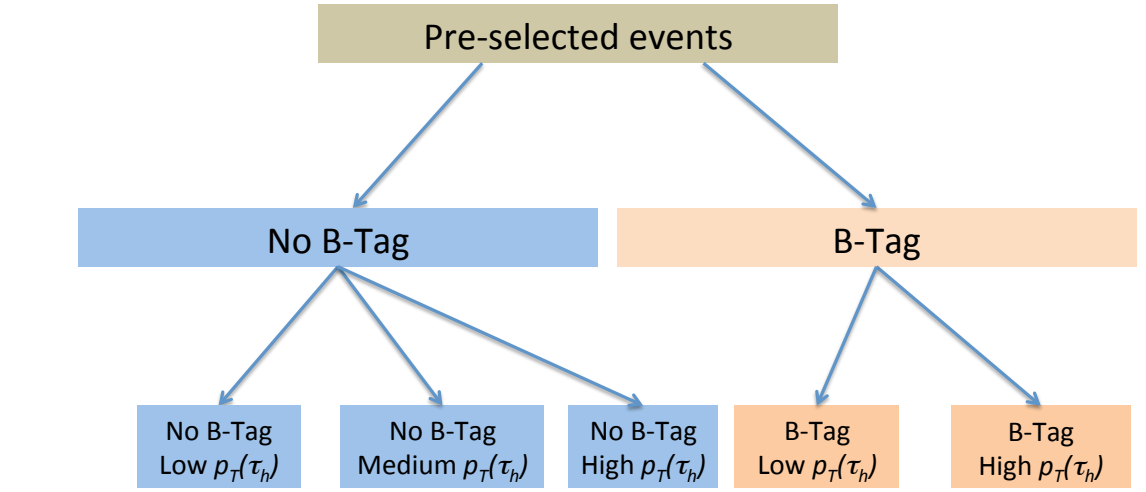


Refined event categories



→ 5 exclusive categories for each decay channel

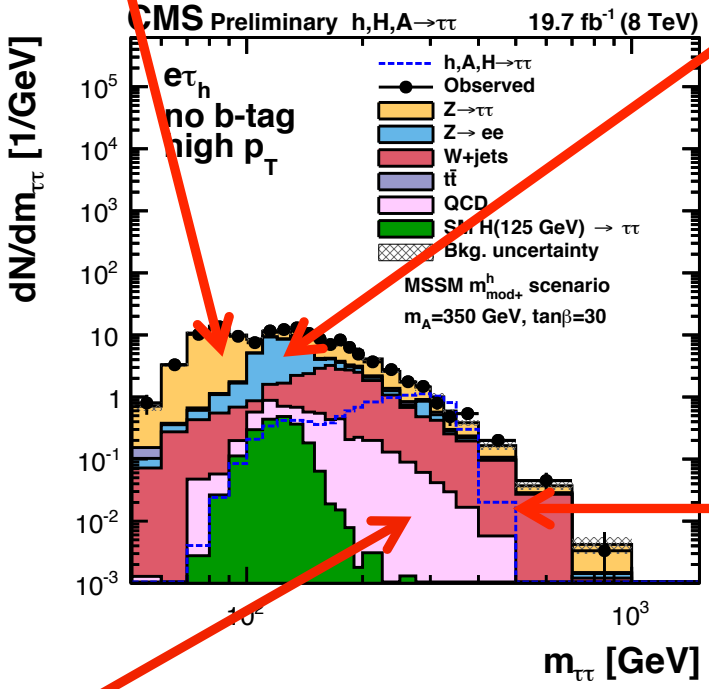
- **Further splitting using $p_T(\tau_h)$ and applied to 8 TeV most sensitive channels: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$**

- **Improved sensitivity as different kinematic regimes have different S/B ratios**
- **High-mass Higgs signals expected to contribute mostly to no-b-tag high and b-tag high categories**

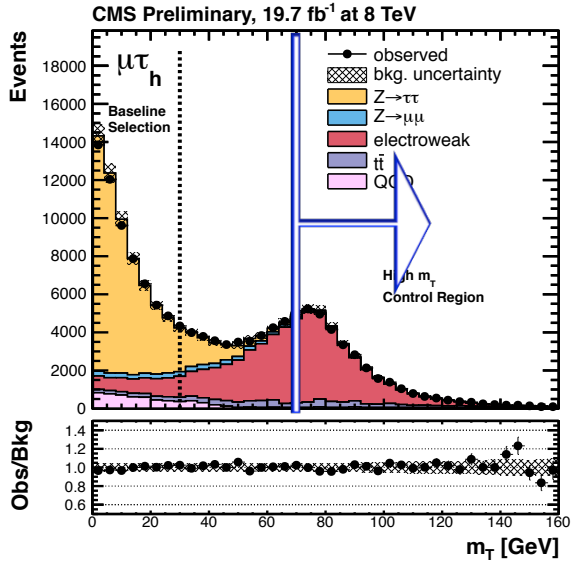
Background estimation

$Z \to \tau\tau$
- Shape = embedding technique

Data $Z \to \mu\mu$, μ replaced by MC τ
- Normalization = MC



$Z \to ee/\mu\mu$
- 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**
- **τ-energy scale**
- Normalization

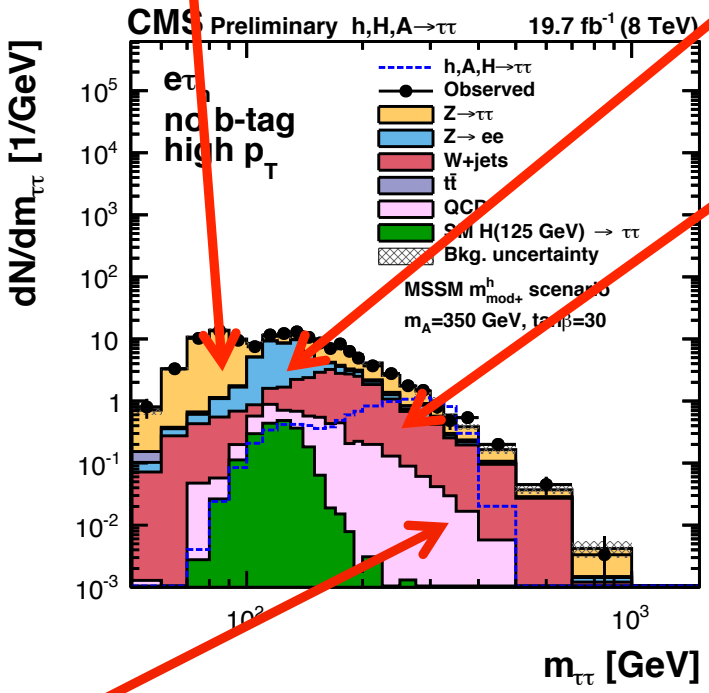
Z→ee/μμ
- **Lepton to τ fake rate**

W+jets
- **Normalization from extrapolation**

Di-boson
- Normalization

Z+jets
- Jet to τ fake rate

ttbar
- **Normalization**



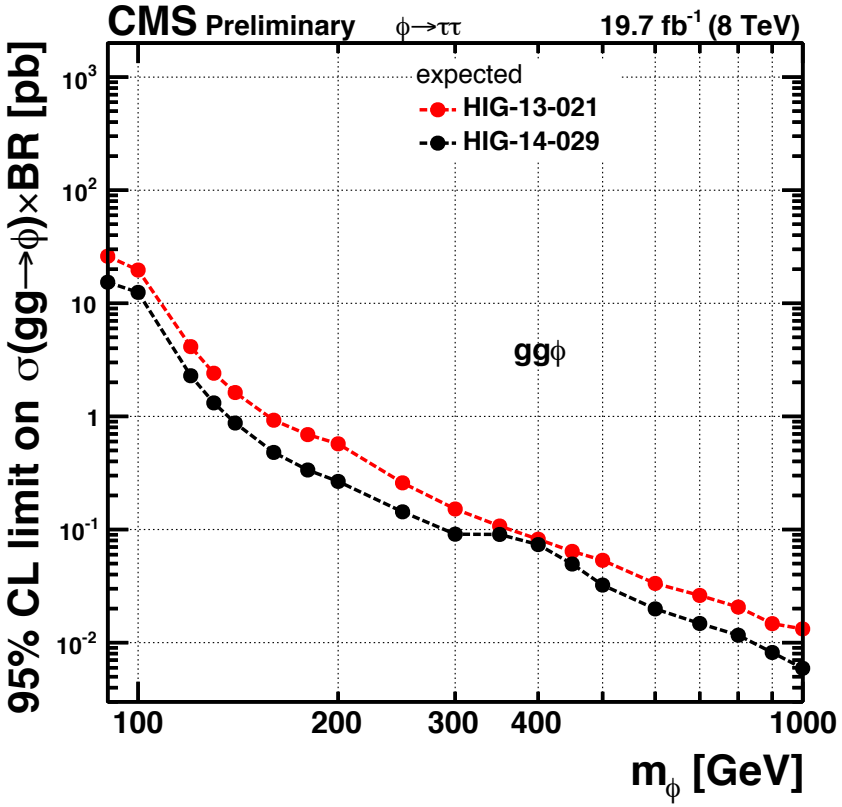
QCD
- **Normalization**
- **Shape = extrap.**

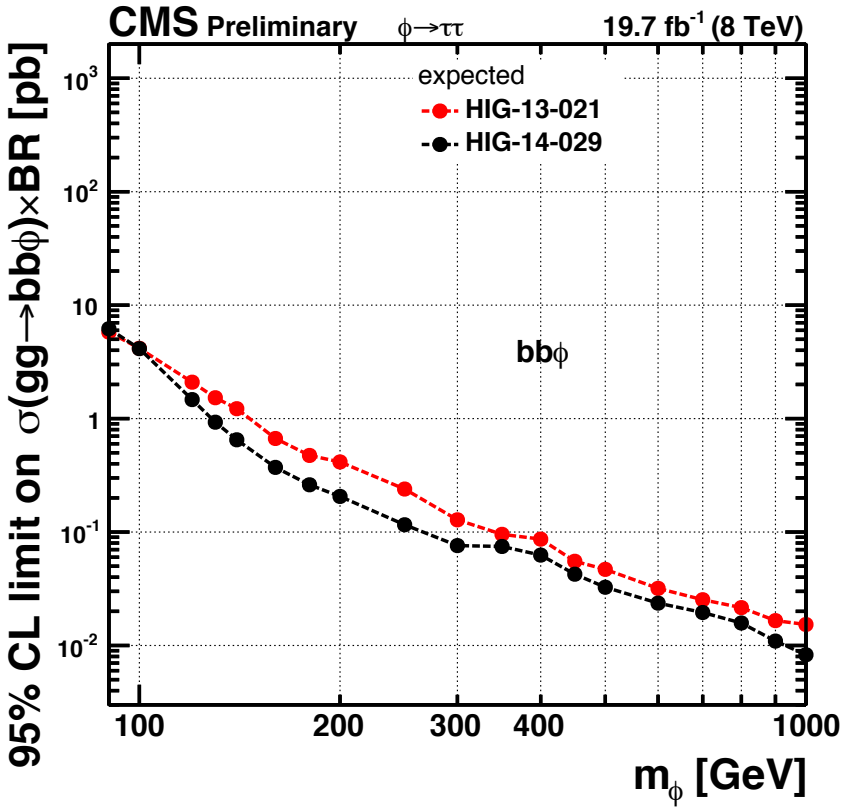
+ shape syst. from limited statistics when applicable

Signals / common systematics
- e/μ selection efficiency
- **jet energy scale & resol.**
- **MET resolution**
- **PDFs**
- **Scale variations**
- Tanβ dependence (new)
- Underlying event

$\Phi \rightarrow \tau^+\tau^-$ results from CMS

- **Comparison with previous published CMS analysis (HIG-13-021)**

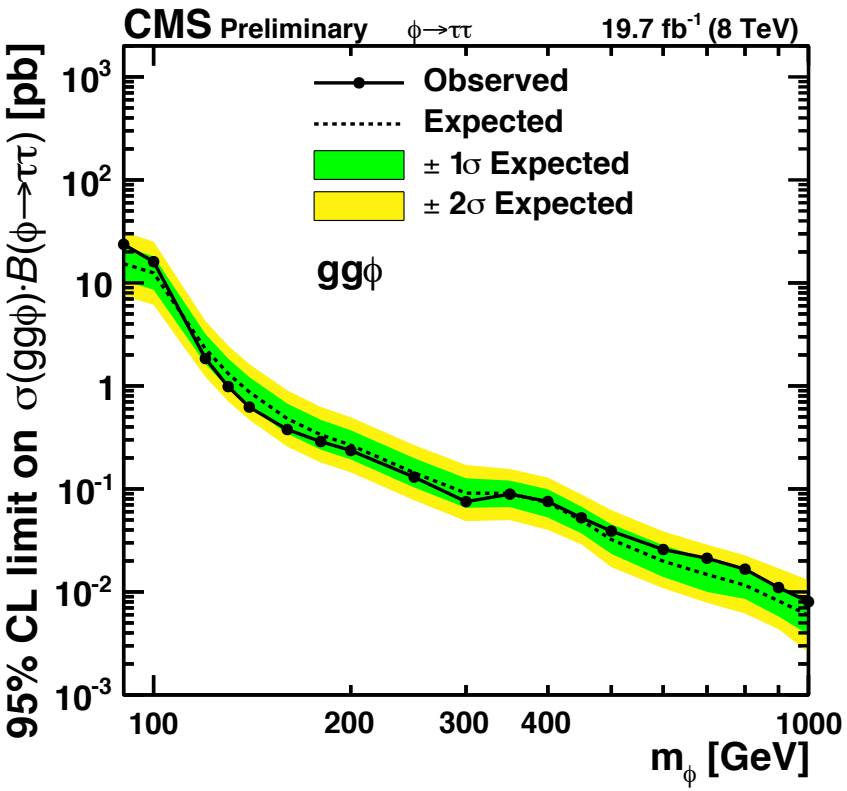




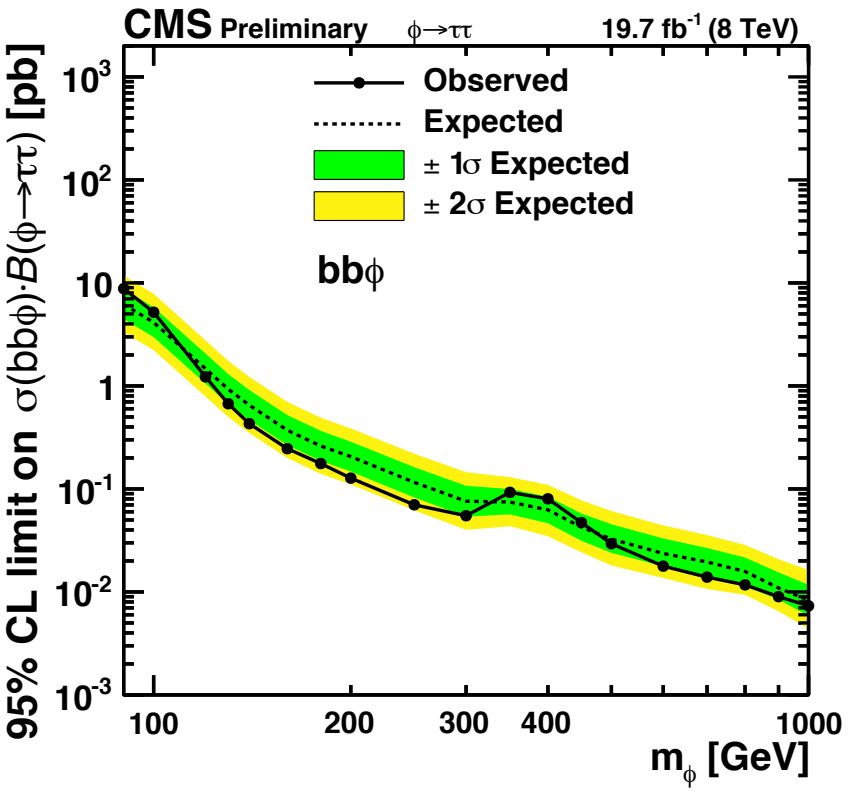
For most of the mass points, the improvement in expected sensitivity is > 20% and up to 50%

$\Phi \rightarrow \tau^+\tau^-$ results from CMS

$gg\Phi$



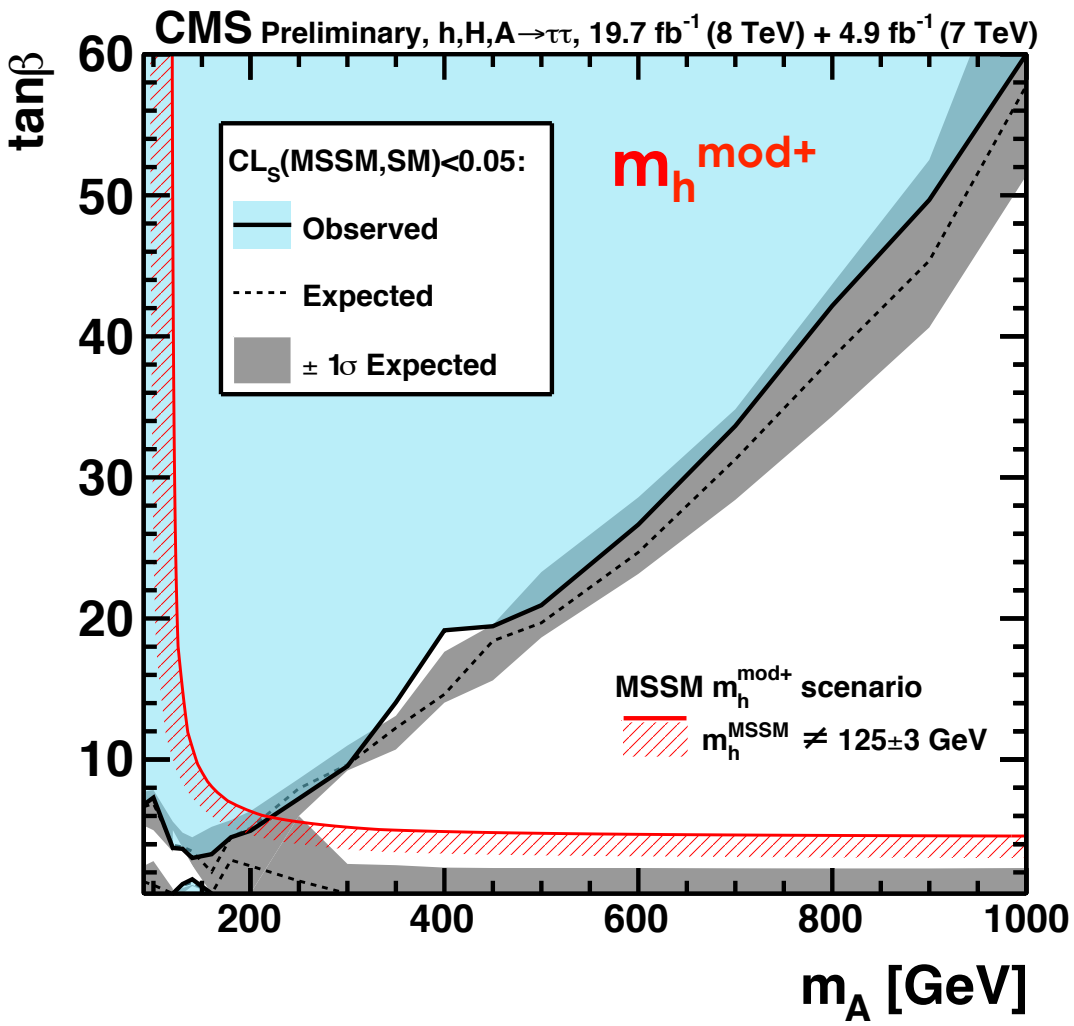
$bb\Phi$



- No significant excess found
- Limits range
  - O(10) pb for m_Φ~100 GeV
  - O(10^{-2}) pb for m_Φ~1000 GeV

$\Phi \rightarrow \tau^+\tau^-$ results from CMS

- **Model dependent 95% CL limits in (m_A,tanβ) plane**

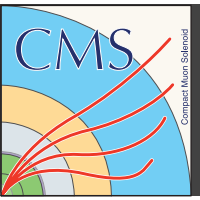


- **Search excludes low m_A region except tanβ <10-20**
- **Larger masses and tanβ ~ 20-50 still allowed**
- **Run II will extend search to masses beyond 1 TeV**

Conclusions & prospects

- Using LHC Run I data, CMS has searched for neutral Higgs bosons in the $\Phi \to \tau\tau$ channel, implementing two significant changes
  - Efficient MVA τ_h-identification using lifetime information
  - Improvement of the categorization to better target MSSM phase space
  - → Limits are set: for example, $m_A < 400$ GeV with $\tan\beta > 12$ is excluded
- No evidence of an extra Higgs boson found just yet
- Stringent limits on extra resonances and MSSM parameter space were set
- This analysis is now the reference and benchmark for future $\Phi \to \tau\tau$ searches
- LHC Run II data will allow to explore further the Higgs sector
  - Highest production cross section and reach due to increased c.o.m.
  - Other channels ($H \to hh$, $A \to Zh$, etc.), sensitive at low $\tan\beta$, will have a complementary role with $\Phi \to \tau\tau$
  - → In 2015, CMS has collected ~2.5 fb^{-1} of 13 TeV data → currently under analysis ☺

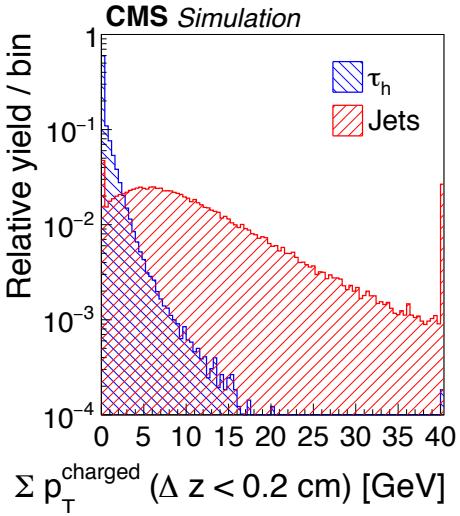
The scalar sector offers unique discovery potential in Run II
The $\Phi \to \tau\tau$ channel is by far the flagship of this effort



Backup

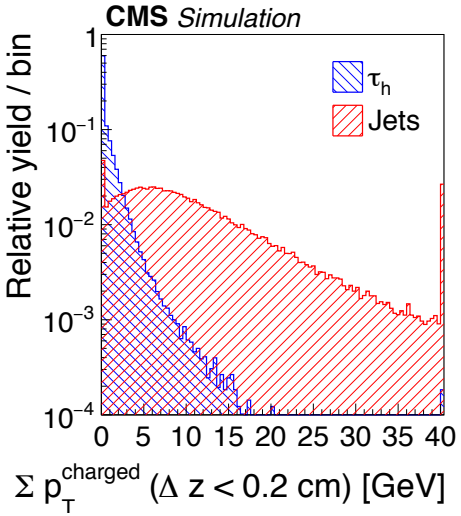
MVA τ_h-isolation

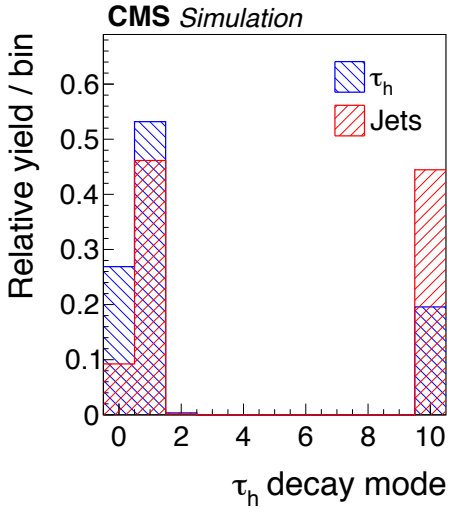
- **8 variables as input: isolation p_T**



MVA τ_h-isolation

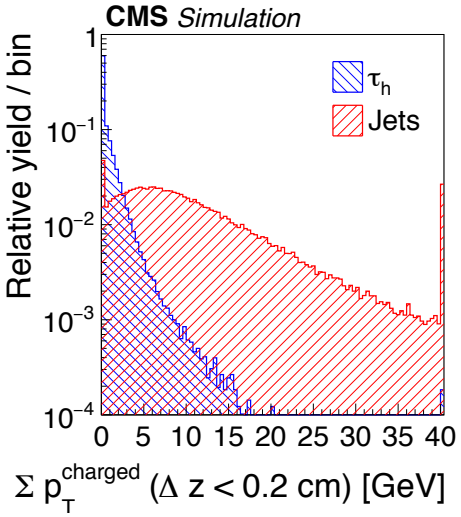
- **8 variables as input: isolation p_T, decay mode**

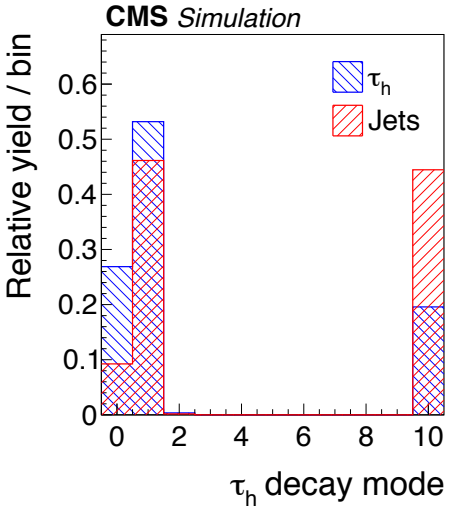


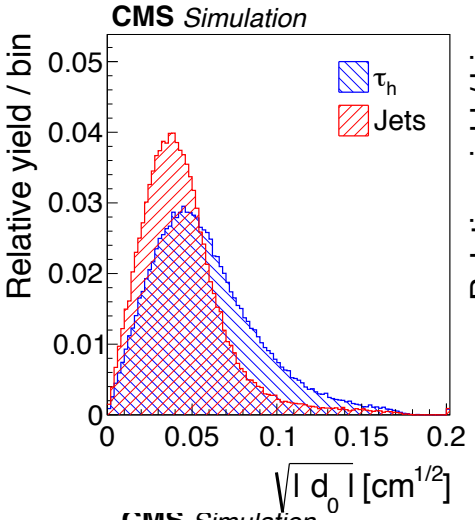


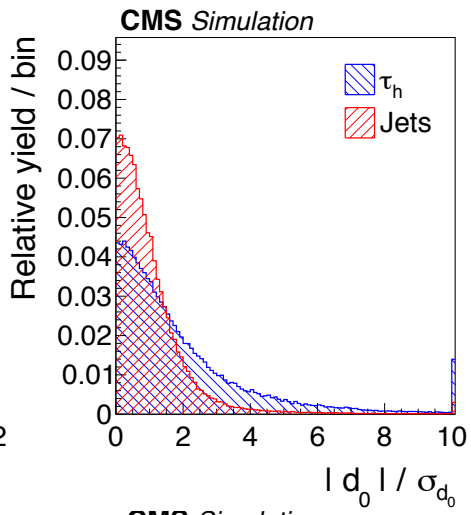
MVA τ_h-isolation

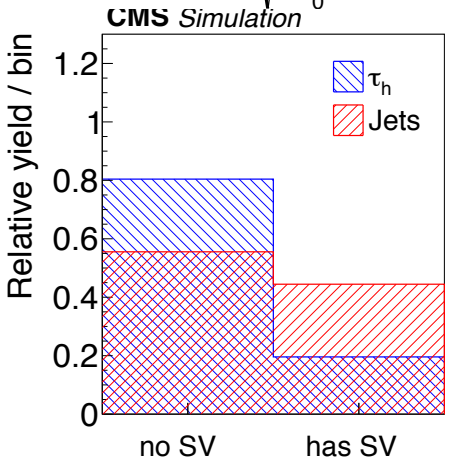
- **8 variables as input: isolation p_T, decay mode, and variables related to τ lifetime**

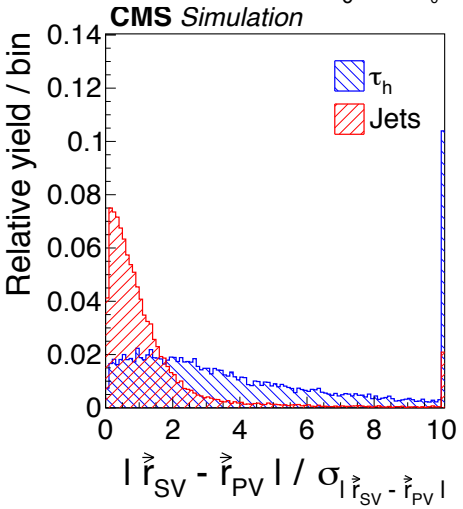






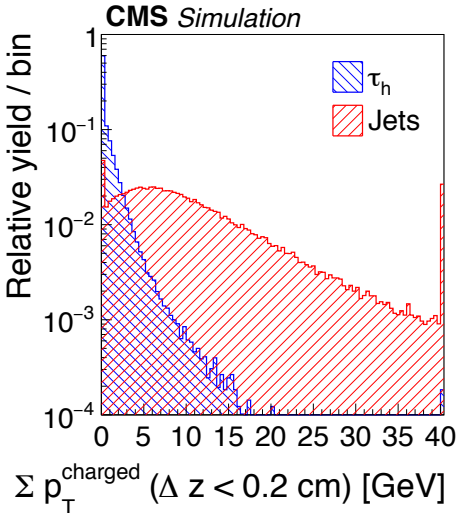


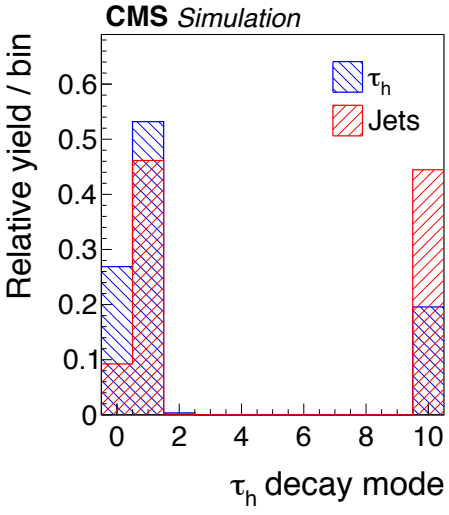


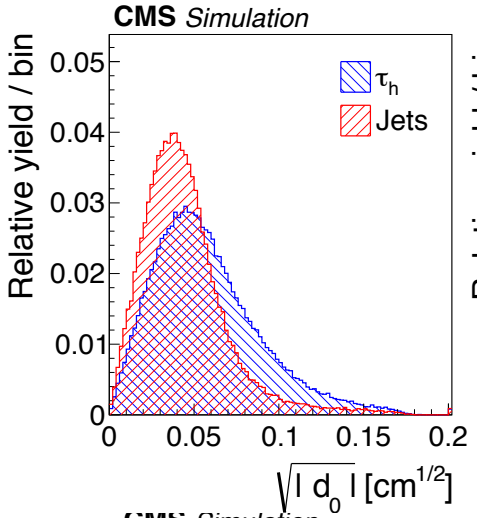


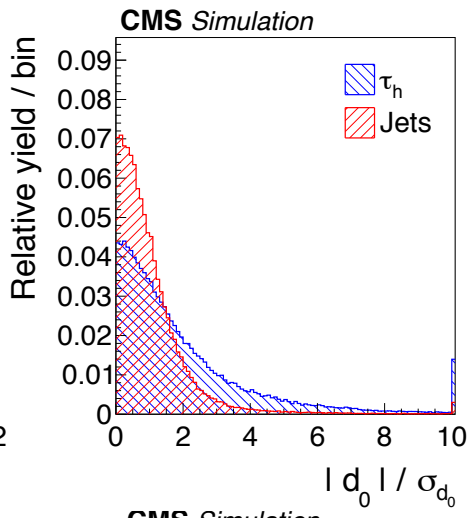
MVA τ_h-isolation

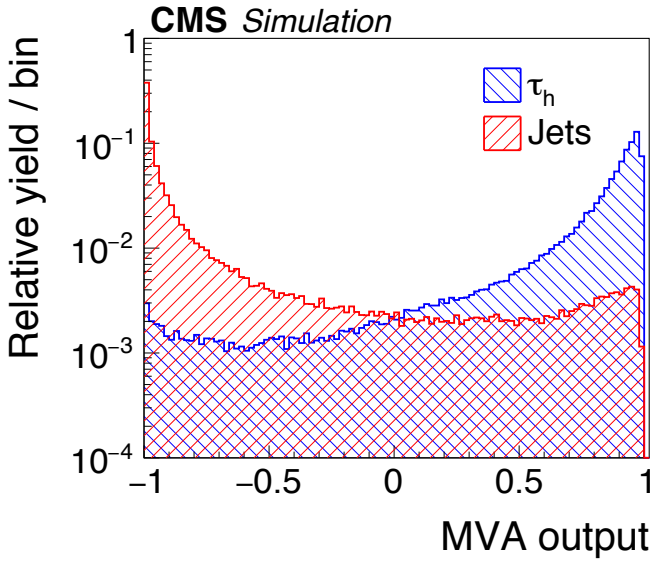
- **8 variables as input: isolation p_T, decay mode, and variables related to τ lifetime**

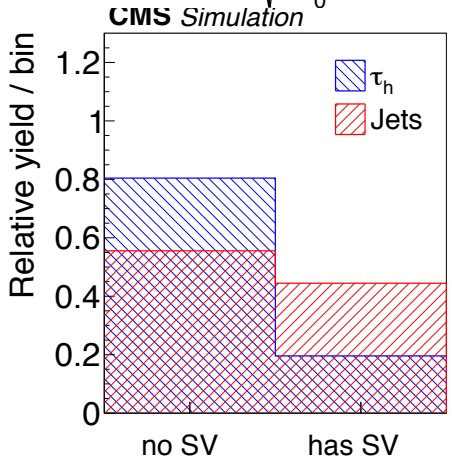


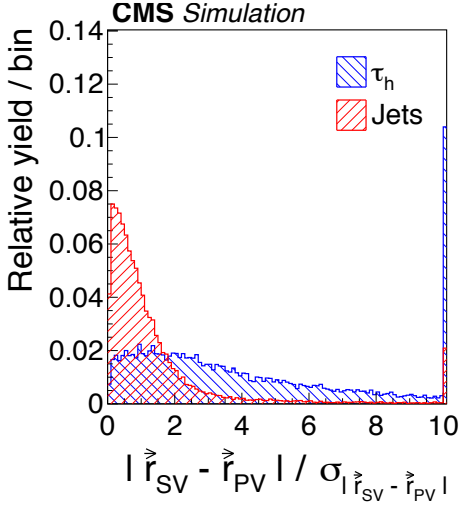












Excellent τ_h / jet discrimination

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

JHEP 11 (2014) 056

- **Analysis of 8 TeV data (19.5 – 20.3 fb^{-1})**
  - Channels: $e\mu/\mu\tau_h/e\tau_h/\tau_h\tau_h$
  - Two variables are used as final discriminators:

① **Missing Mass Calculator (MMC) in $e\mu$, $e\tau_h$, $\mu\tau_h$**

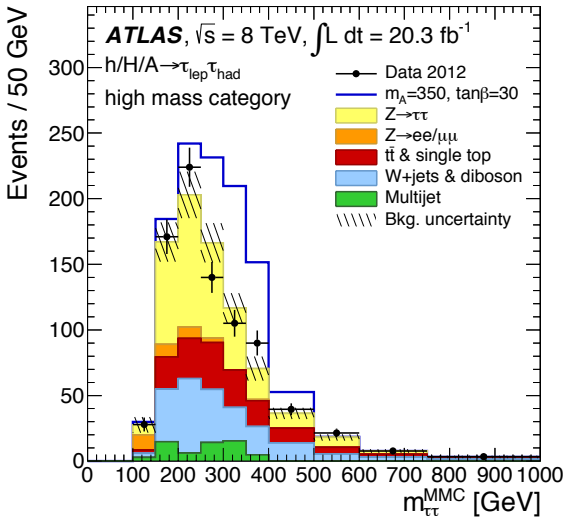
② **Total transverse mass in $\tau_h\tau_h$ channel**

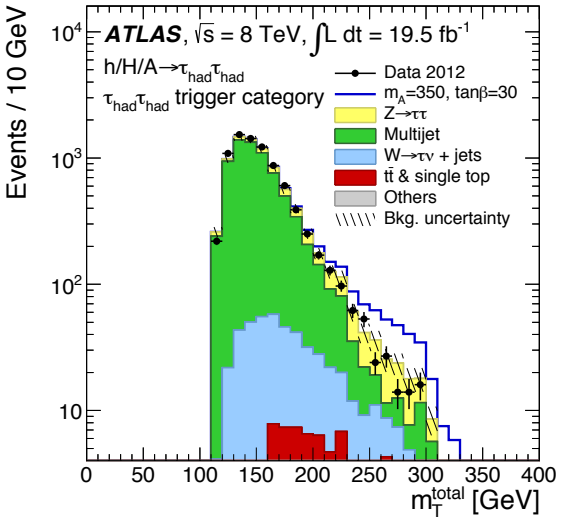
❖ **Categories based on:**

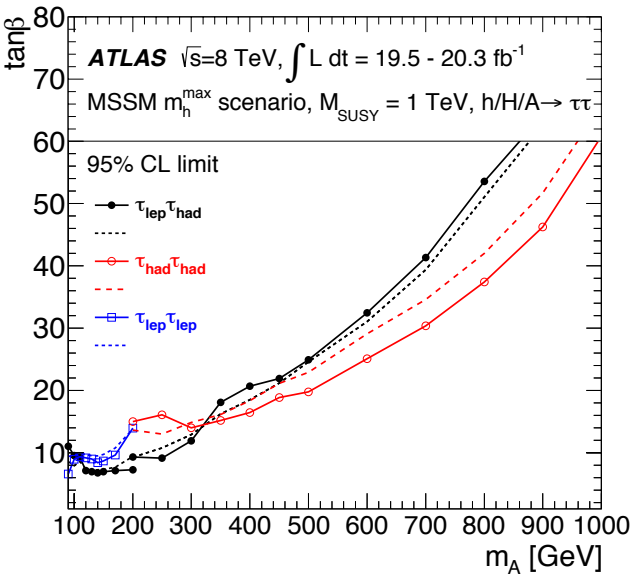
① number of b-tagged jets for $e\mu$, $e\tau_h$, $\mu\tau_h$ channels

② low m_A / high m_A specific cuts for $e\tau_h$ and $\mu\tau_h$ channels

③ Trigger used in $\tau_h\tau_h$ channel







❖ **each channel is used in the mass range for which it is most sensitive**

(e.g. $\tau_h\tau_h$ only used at high masses)

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

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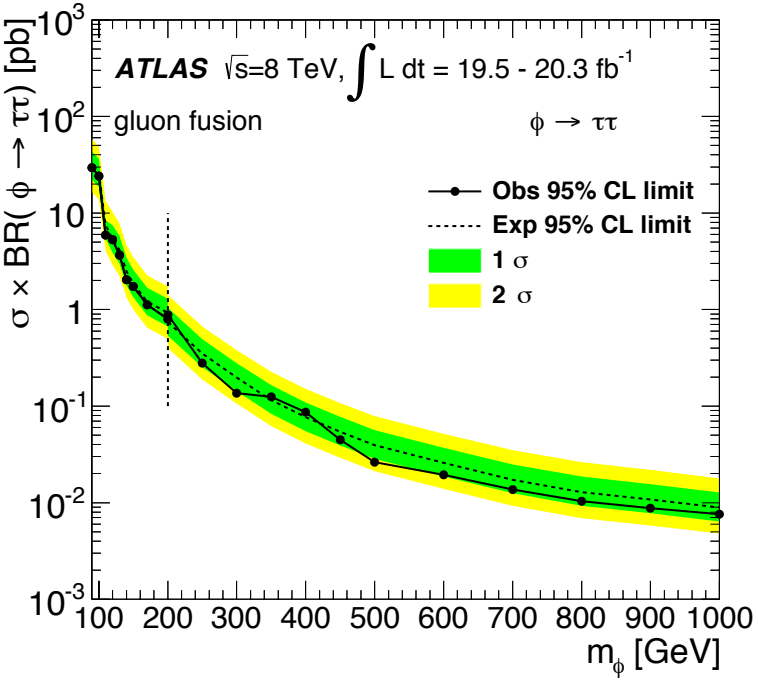
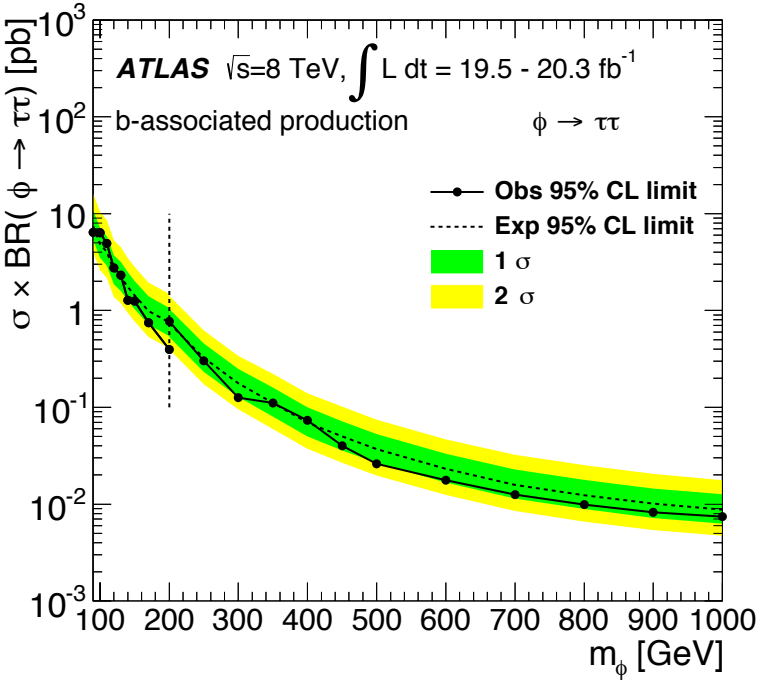
- **95% CL limits on $gg\Phi$ and $bb\Phi$ production cross section x BR**

$gg\Phi$



$bb\Phi$



- **No excess found**
- **Limits range**
  - **O(10) pb for m_Φ~100 GeV**
  - **O(10^{-2}) pb for m_Φ~1000 GeV**

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

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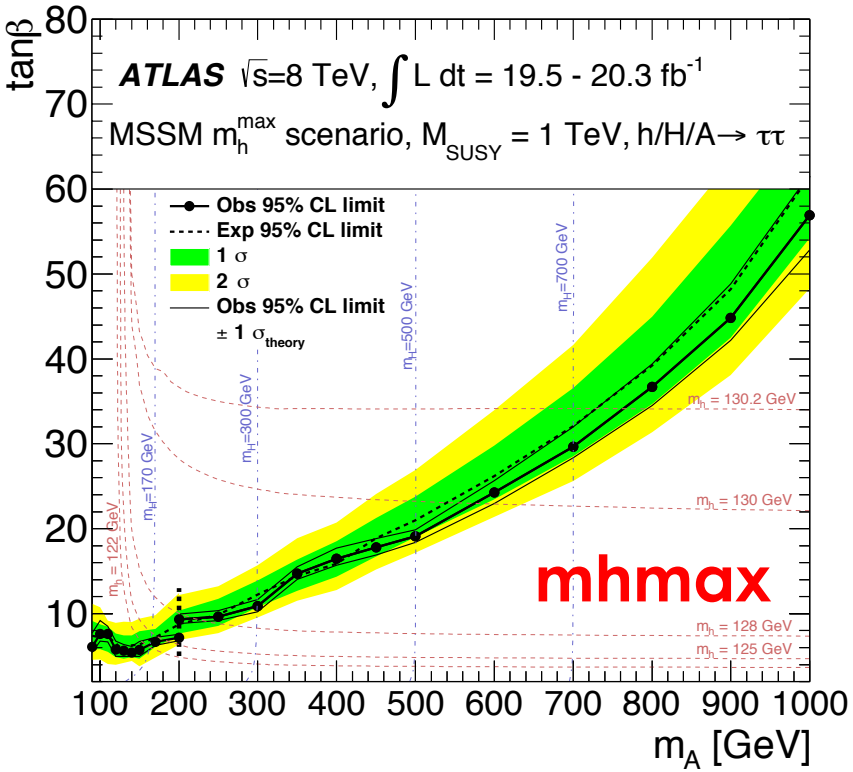
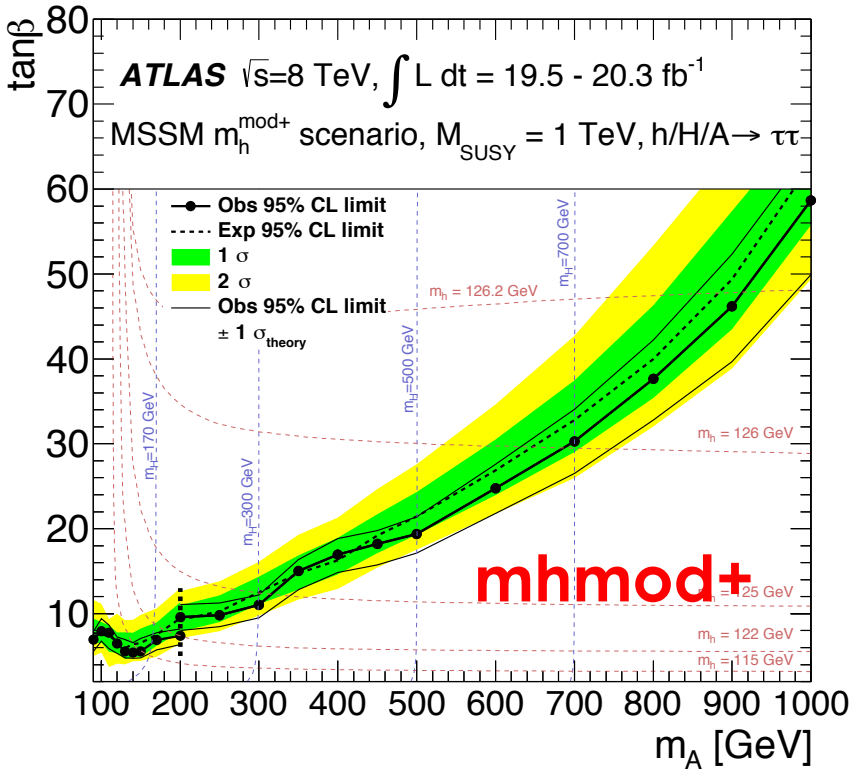
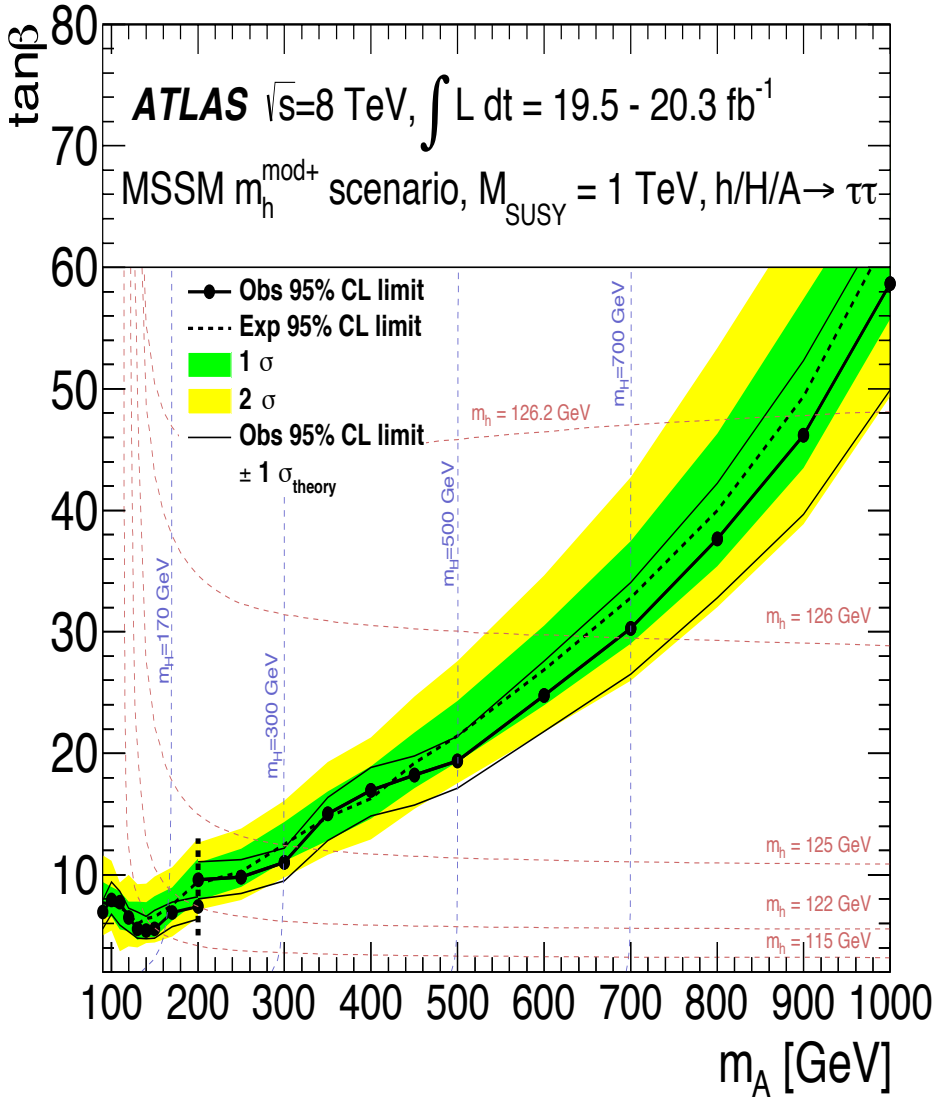
- **Model dependent 95% CL limits in (m_A,tanβ) plane**





- **Search excludes low m_A region except for low tanβ (<10-20)**
- **Larger masses and moderate tanβ (<20-50) still allowed**

ATLAS/CMS comparison



m_h^{mod+}