24th International Workshop on Deep-Inelastic Scattering and Related Subjects

Search for additional heavy scalar/pseudoscalar neutral Higgs bosons at CMS

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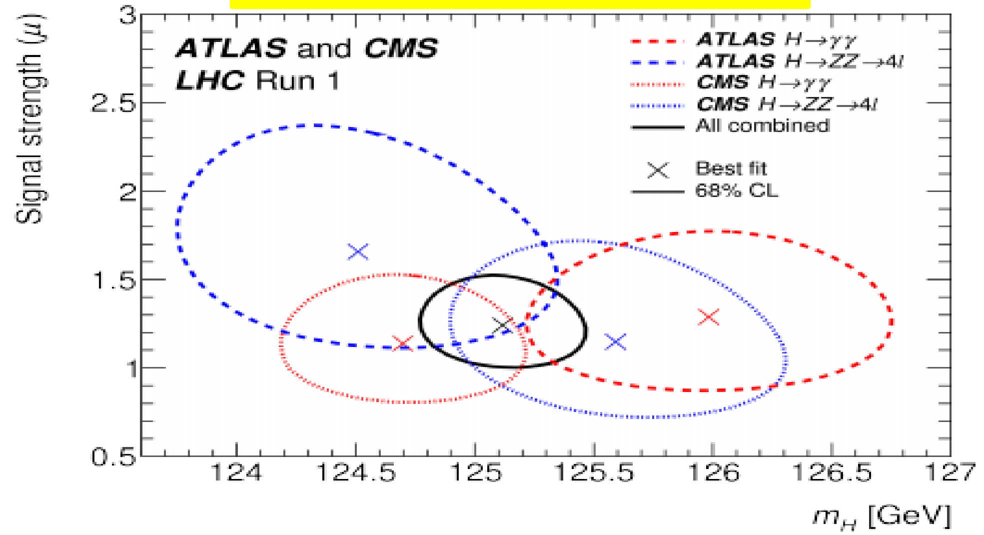
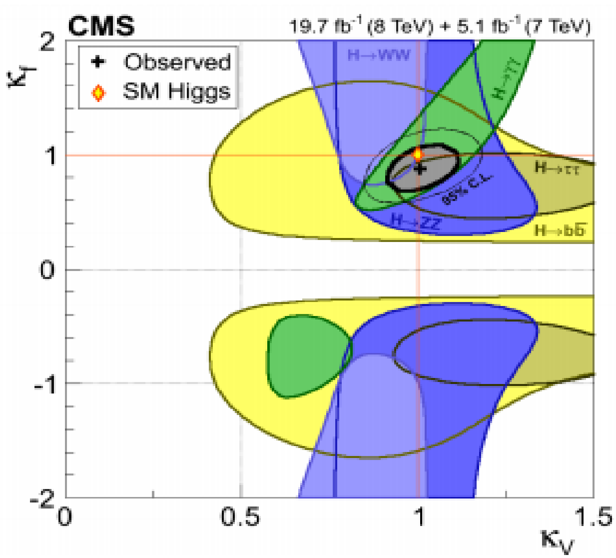
On behalf of CMS collaboration

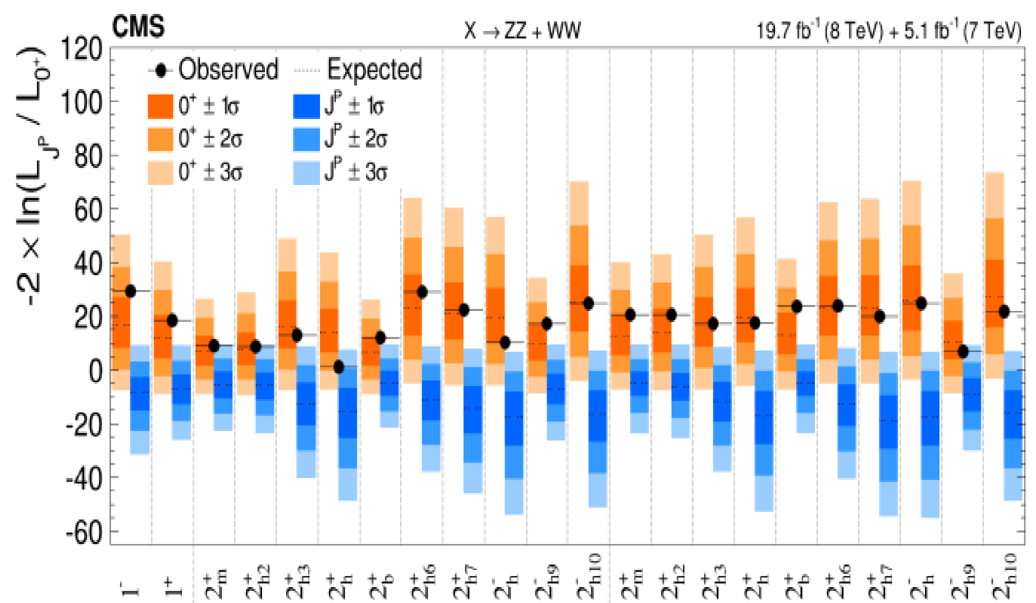
MOTIVATION

- **Discovered "a scalar" at mass 125 GeV in 2012.**
- **Measured its properties (Spin, CP, couplings …) and found it to be consistent with the SM scalar predicted by Higgs et. al.**
- **However, these measurements have large experimental uncertainty .**
  => BSM contributions can't be ruled out !
- **Besides, many BSM theories, e.g MSSM, 2HDM etc. predict a more complex scalar sector than the one in SM**
  => more scalars/pseudoscalars*

LHC Combination:
m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst)







*** Henceforth referred to as BSM higgs**

GENERAL STRATEGY

- **Search for BSM higgs bosons performed in a wide variety of theoretical scenarios in CMS using Run-1 data.**

- **In all of them, 125 GeV SM scalar interpreted as one member of a larger family of scalars and pseudo-scalars predicted by BSM theory.**

- **Most searches probed BSM higgs decays to 3rd generation down type fermions (b-quarks and taus) since most BSM theories (e.g. MSSM) predict enhancement of BSM higgs branching ratios to decay to them w.r.t SM values.**

- **Search results were interpreted in 2 broad ways:**
  - **Model Independent way: Exclusion limits set on "σ x BR" for BSM higgs production and decay => on model parameter dependence ignored.**

  - **Model Dependent way: Exclusion limits set on region of model parameter space defined by setting the model parameters to specific (benchmark) values based on latest theoretical and/or experimental constraints prior to the search.**

ANALYSIS LEVEL OBJECTS

GENERIC GUIDELINES FOLLOWED IN MOST OF THE SEARCHES

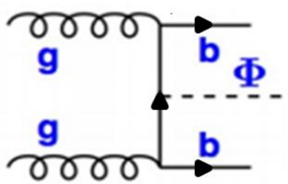
- **Particle Flow (PF) algorithm used for global event reconstruction: full use of sub-detector information.**
- **Jets reconstructed using anti-kT algorithm (R =0.5) using output of PF algorithm.**
- **b-Jets identified via a likelihood based discriminator which includes impact parameter significance and track based lifetime information.**
- **Muons identified by PF based selections designed to reduce muons fakes from pions/kaons and punch through hadrons.**
- **Electrons identified via multi-variate (BDT) based discriminators which include electron shower shape variables.**
- **Hadronic Taus identified via reconstructing the individual hadronic tau decay modes: 1Prong-0π_0, 1Prong-1π_0, 1Prong-2π_0 and 3Prong-0π_0 inside PF jets and qualifying strict isolation criteria. Dedicated multi-variate selections further reduce $e \rightarrow \tau$ and $\mu \rightarrow \tau$ fakes.**

MSSM $\phi \rightarrow \tau\bar{\tau}$ SEARCH (CMS-PAS-HIG-14-029)

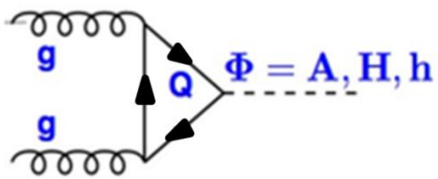
- **MSSM has 2 complex Higgs doublets → 5 Higgs Bosons: light CP even scalar (h), heavy CP even scalar (H), pseudo-scalar (A), charged ($H^{\pm}$).**

- **MSSM Higgs sector at tree level determined by 2 parameters : m_A and Tanβ (ratio b/w VEVs of the 2 higgs doublets).**

- **Main MSSM neutral Higgs (φ = h, H, A) production modes:**



b-Associated Production



Gluon Fusion

- **MSSM $\varphi \rightarrow \tau\tau$ search performed in $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$ and $\mu\mu$ channels (τ_h=> hadronic tau decay).**

MSSM CATEGORIES

B-TAG	NO B-TAG
≥ 1 B-Tagged Jets (p_T > 20 GeV), < 2 Jets (p_T > 30 GeV)	No B-Tag Jets with p_T > 20 GeV

BACKGROUNDS

$Z \rightarrow \tau\bar{\tau}$

Estimated in shape from Embedded sample comprising of $Z \rightarrow \mu\bar{\mu}$ data events in which muons are replaced by taus from simulation

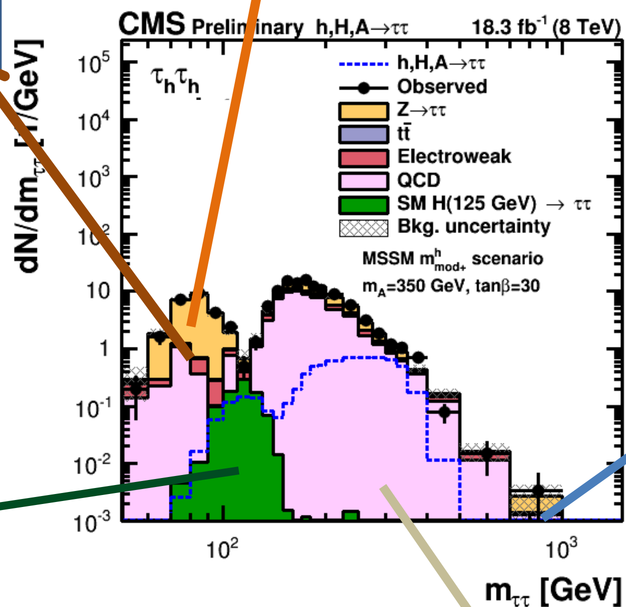
Yield is derived from $Z \rightarrow \tau\bar{\tau}$ simulation

Electroweak

This comprises of the following:

. W+Jets: Shape from simulation, yield from high m_T region in data

. Di-Boson: Estimated from simulation



$t\bar{t}$

Estimated in shape and yield from simulation which are validated in high purity regions in data from the eμ channel.

SM 125

Estimated from MC, it is the sum of SM Higgs (m_H =125 GeV) backgrounds:

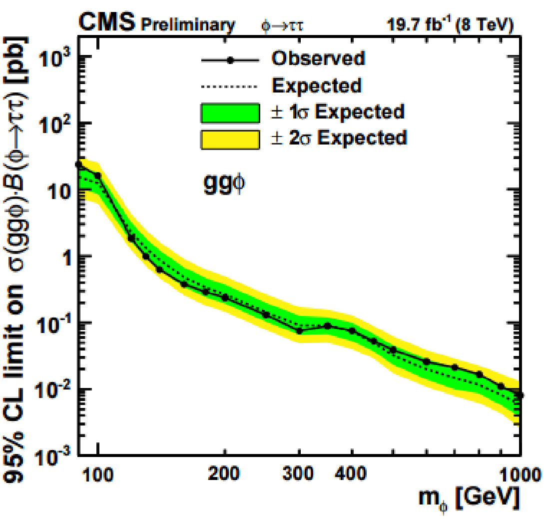
$ZH(H\rightarrow b\bar{b})$, $WH(H\rightarrow b\bar{b})$,
$VH(H \rightarrow \tau\bar{\tau})$, $qqH(H \rightarrow \tau\bar{\tau})$,
$ggH(H \rightarrow \tau\bar{\tau})$ and $H\rightarrow b\bar{b}$.

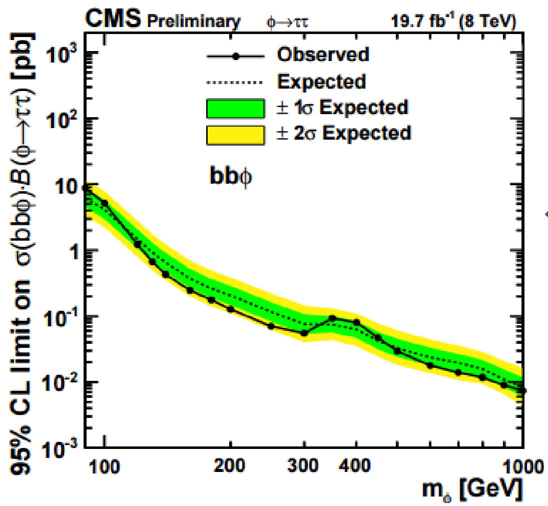
QCD

Estimated from data using sidebands defined by di-tau charge and isolation (after subtracting all other non QCD backgrounds)

RESULTS: MSSM $\phi \rightarrow \tau\bar{\tau}$

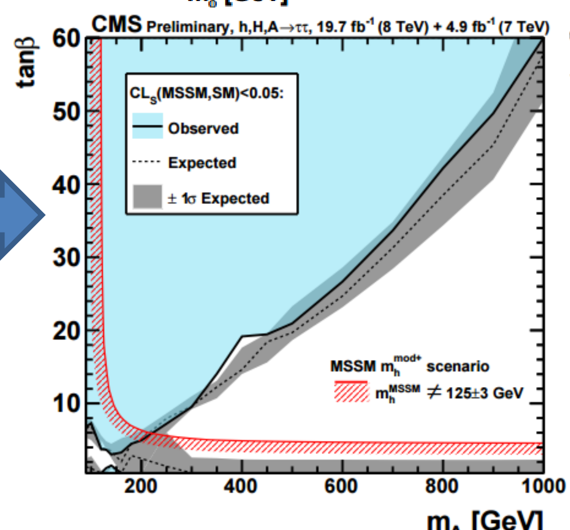
- Current MSSM $\phi \rightarrow \tau\bar{\tau}$ analysis has improved analysis sensitivity (~35%-40%) w.r.t earlier published result [JHEP 10(2014) 160] due to:
  1. Improved Hadronic Tau Identification : A Multi-Variate discriminator incorporating track based lifetime information.
  2. Tau p_T Binning : Introduction of Hadronic Tau bins optimized by sensitivity.

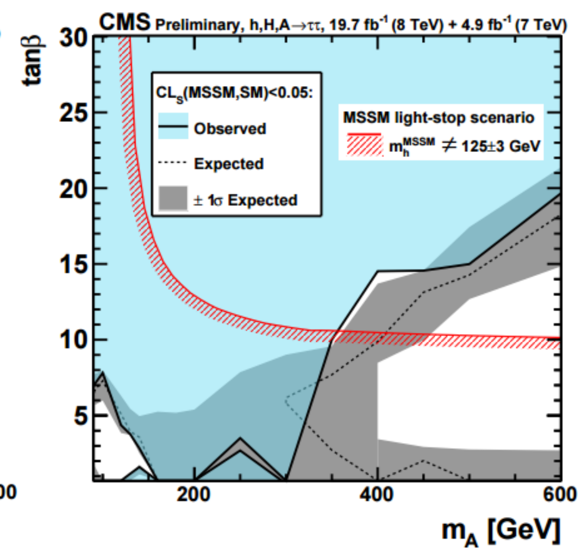




MODEL INDEPENDENT
1D LIMITS

MODEL DEPENDENT
2D LIMITS



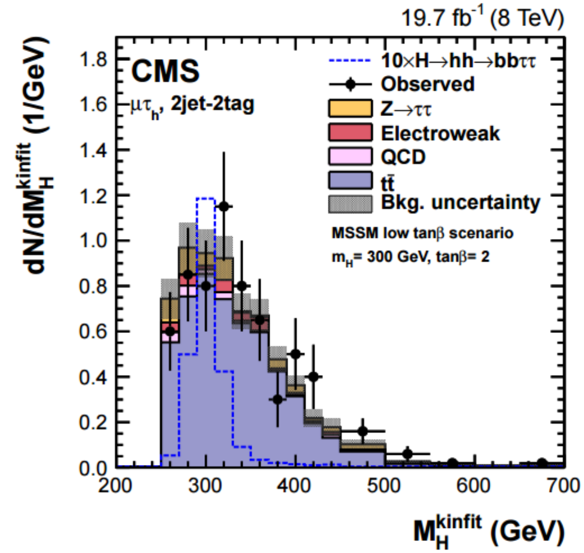


SM SCALAR INTERPRETED AS
h OF MSSM
IN MOST OF THE SCENARIOS

MSSM H→hh→ $b\bar{b}\tau\bar{\tau}$ (CMS-PAS-HIG-14-034)

- Presence of 2 b-quarks in the final state in addition to 2 taus, => 2 jets required in the event (having highest b-tag discriminator value).

- Categories are defined as:
  - 2Jet0Tag:Both jets fail offline b-tagging criterion.
  - 2Jet1Tag: Leading jet passes offline b-tagging criterion.
  - 2Jet2Tag: Both jets pass offline b-tagging criterion.



Search restricted to
260 GeV ≤ m_H ≤ 350 GeV
to stay below H→$t\bar{t}$ threshold

- Di-tau invariant mass $m_{\tau\tau}$ computed by likelihood based algorithm using constraint imposed by missing transverse energy to give best possible estimate of the true $m_{\tau\tau}$.

- Mass window cuts: 90 GeV < $m_{\tau\tau}$ < 150 GeV and 70 GeV < m_{bb} < 150 GeV applied to select the most signal like events with reconstructed m_h consistent with 125 GeV.

- Finally, kinematic fit performed where energies of the b-jets and taus is varied within their respective resolutions subject to the constraints: $m_{\tau\tau} = m_{bb} = 125$ GeV.

- The 4 body mass $m^{fit}_{bb\tau\tau}$ has an excellent shape discrimination of signal over backgrounds and is used for signal extraction.

- The search was done in 3 distinct di-tau channels: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$

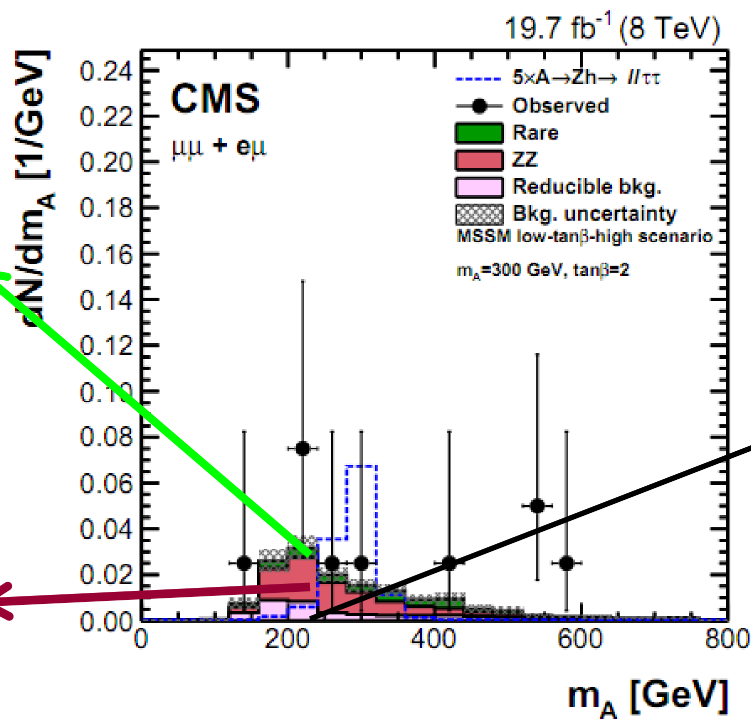
MSSM A→Zh→l^+l^- $\tau\bar{\tau}$ (CMS-PAS-HIG-14-034)

- **First a Z→μμ/ee candidate is reconstructed using well identified and isolated pair of opposite sign muons/electrons per event.**
- **Then a h→$\tau\bar{\tau}$ candidate is reconstructed in any one of the 4 di-tau final states: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ and eμ (where e/μ denote leptonic tau decays to electron/muon) using additional leptons in the event.**
- **Finally, a channel dependent cut is applied on the scalar p_T sum of the tau candidates to reduce backgrounds.**

Search restricted to 220 GeV ≤ m_H ≤ 340 GeV

Rare Backgrounds :

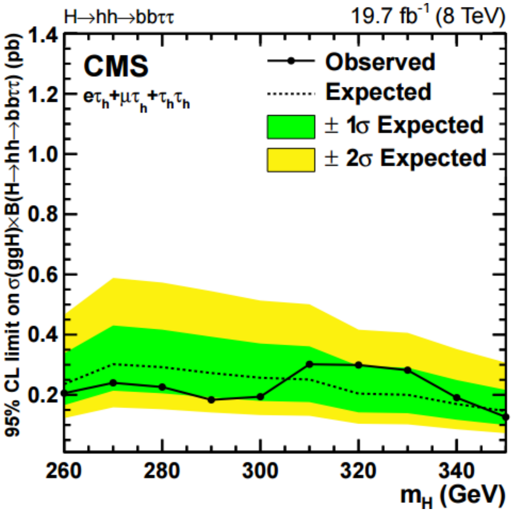
- Z→Zh → l^+l^- $\tau\bar{\tau}$
- Z→Zh →ZW^+W^-→ l^+l^- $\tau\bar{\tau}$
- Tri-boson (WWZ/WZZ/ZZZ)
- $t\bar{t}Z$ (Z→ l^+l^-, t/$\bar{t}$ → e/μ/τ)

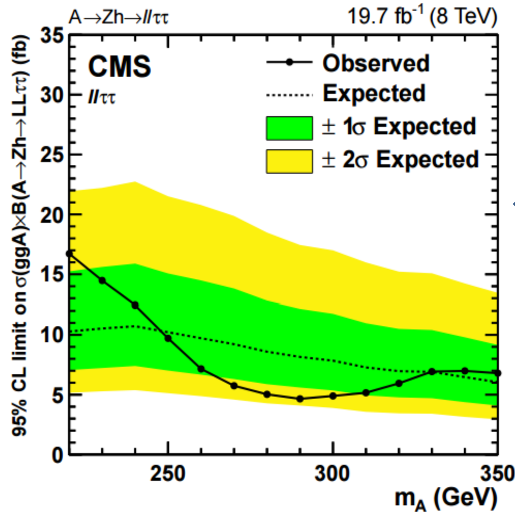


ZZ di-boson :
This is the dominant irreducible background and is estimated from Monte Carlo (NNLO).

Reducible background:
Due to Z+Jets and WZ+Jets, estimated in yield by fake rate method and in shape from Same Sign sideband region of the 2 taus

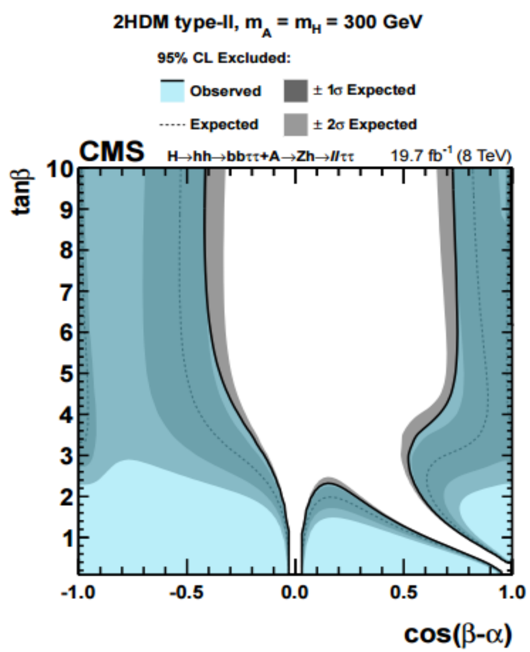
RESULTS MSSM A →Zh →l^+l^- $\tau\bar{\tau}$ /H→hh→ $b\bar{b}\tau\bar{\tau}$

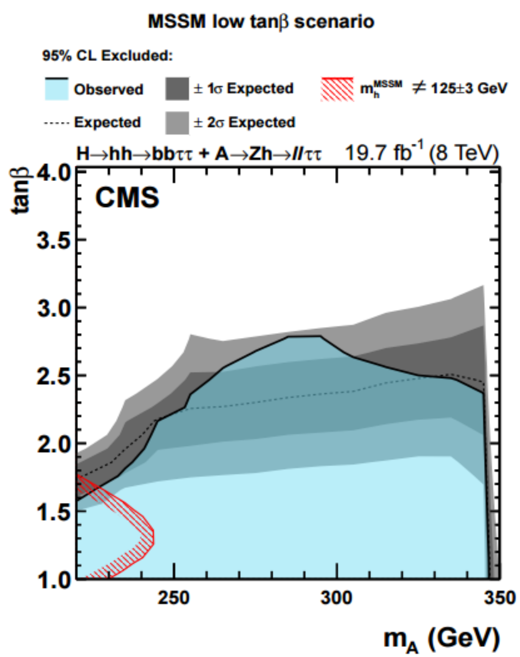




MODEL INDEPENDENT 1D LIMITS

arXiv:1510.01181

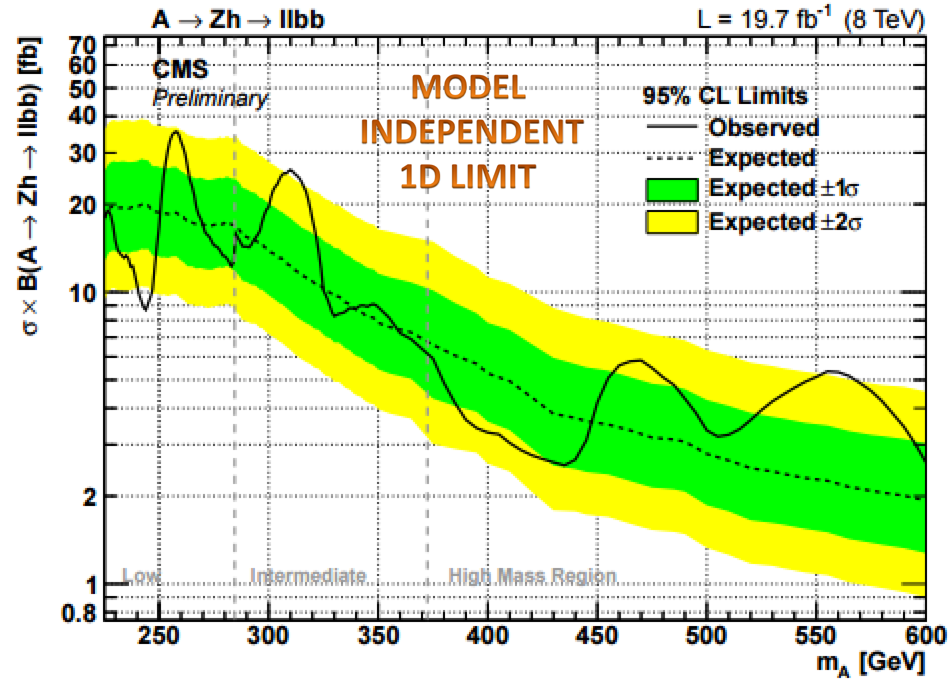




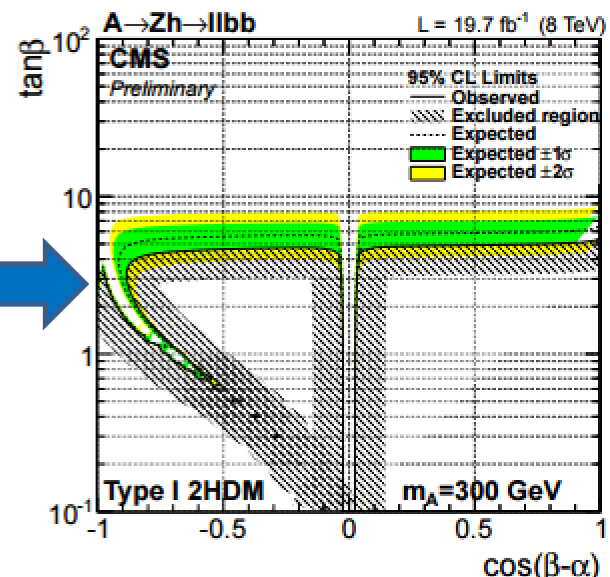
MODEL DEPENDENT 2D LIMITS

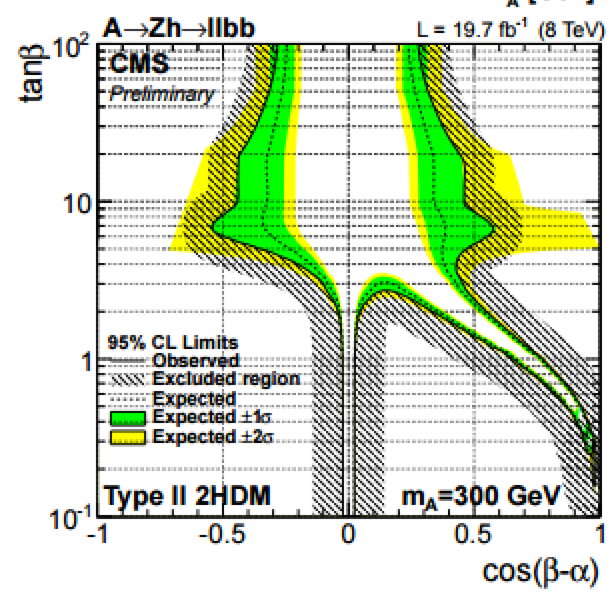
MSSM A →Zh→ l^+l^- $b\bar{b}$ (CMS-PAS-HIG-14-011)

- Similar selections for the Z→l^+l^- leg as HIG-14-034.
- For the h→$b\bar{b}$ leg, require atleast one tight b-tagged Jet and one loose b-tagged Jet.
- Mass window cuts: 75 GeV < $m_{\tau\tau}$ < 105 GeV, 90 GeV < m_{bb} < 140 GeV.
- MET compatible with zero.



MODEL DEPENDENT 2D LIMITS





MSSM $\phi \rightarrow b\bar{b}$ SEARCH (CMS-PAS-HIG-14-017)

- Events triggered if they have atleast 2 Jets (p_T^{Jet1} > 80 GeV, p_T^{Jet2} > 70 GeV, $|\eta^{Jet1/Jet2}| < 1.74$) satisfying online b-tagging criteria.

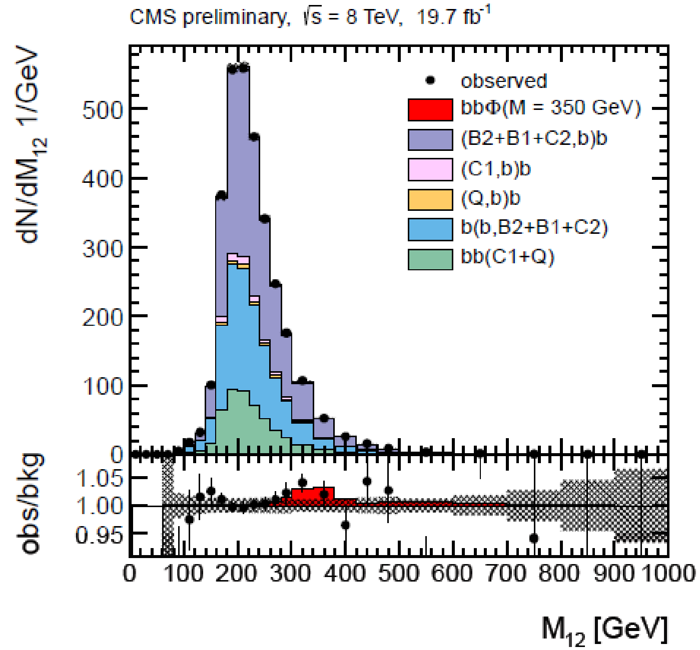
- Triggered events further required to have a 3rd Jet (p_T^{Jet3} > 20 GeV, $|\eta^{Jet1/Jet2/Jet3}| < 1.65$) and the 2 leading Jets satisfying $|\Delta\eta^{Jet1,Jet2}| \leq 1.4$.

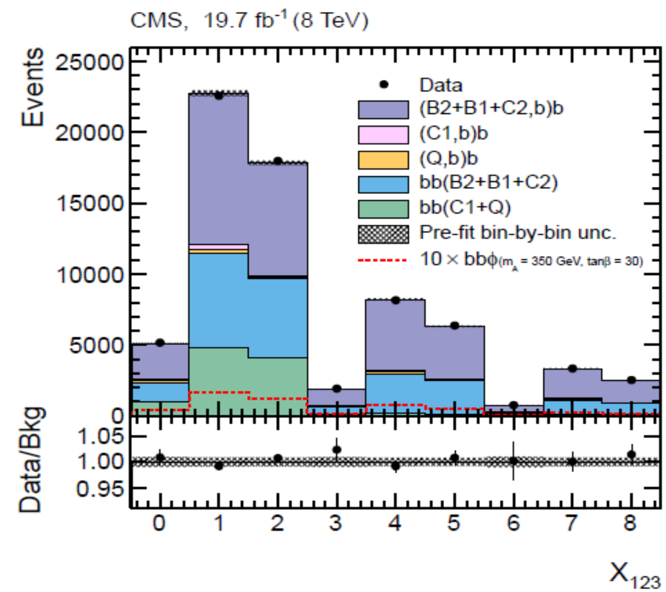
- All 3 Jets must be pair wise separated by $\Delta R > 1$.

- Events divided into triple b-tag and double b-tag categories based on number of jets (3 or 2) passing tight offline b-tag requirements.

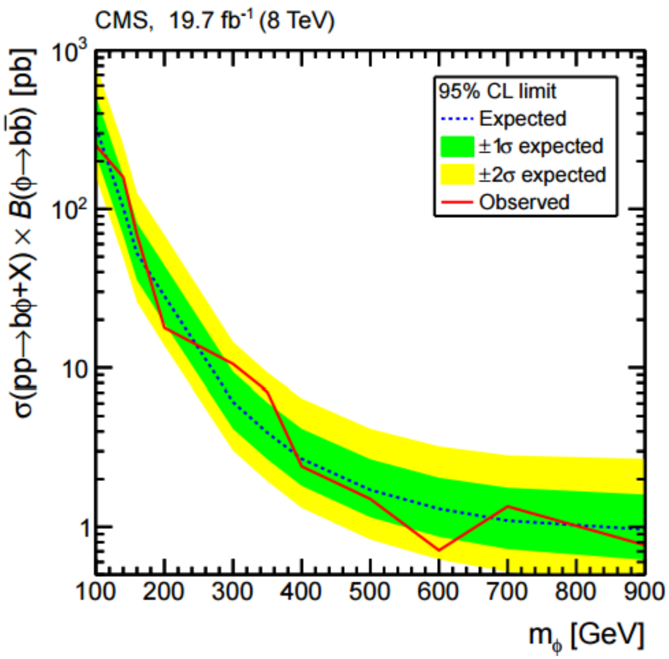
- Triple b-tag => signal extraction,
  Double b-tag => background evaluation.

- Signal extracted via 2 dimensional likelihood fit in (M_{12} , X_{123}) plane where, M_{12} is the di-Jet invariant mass of the 2 leading b-Jets and X_{123} is a compact b-tag variable for the whole event (based on Jet rank and sec. vertex info.).

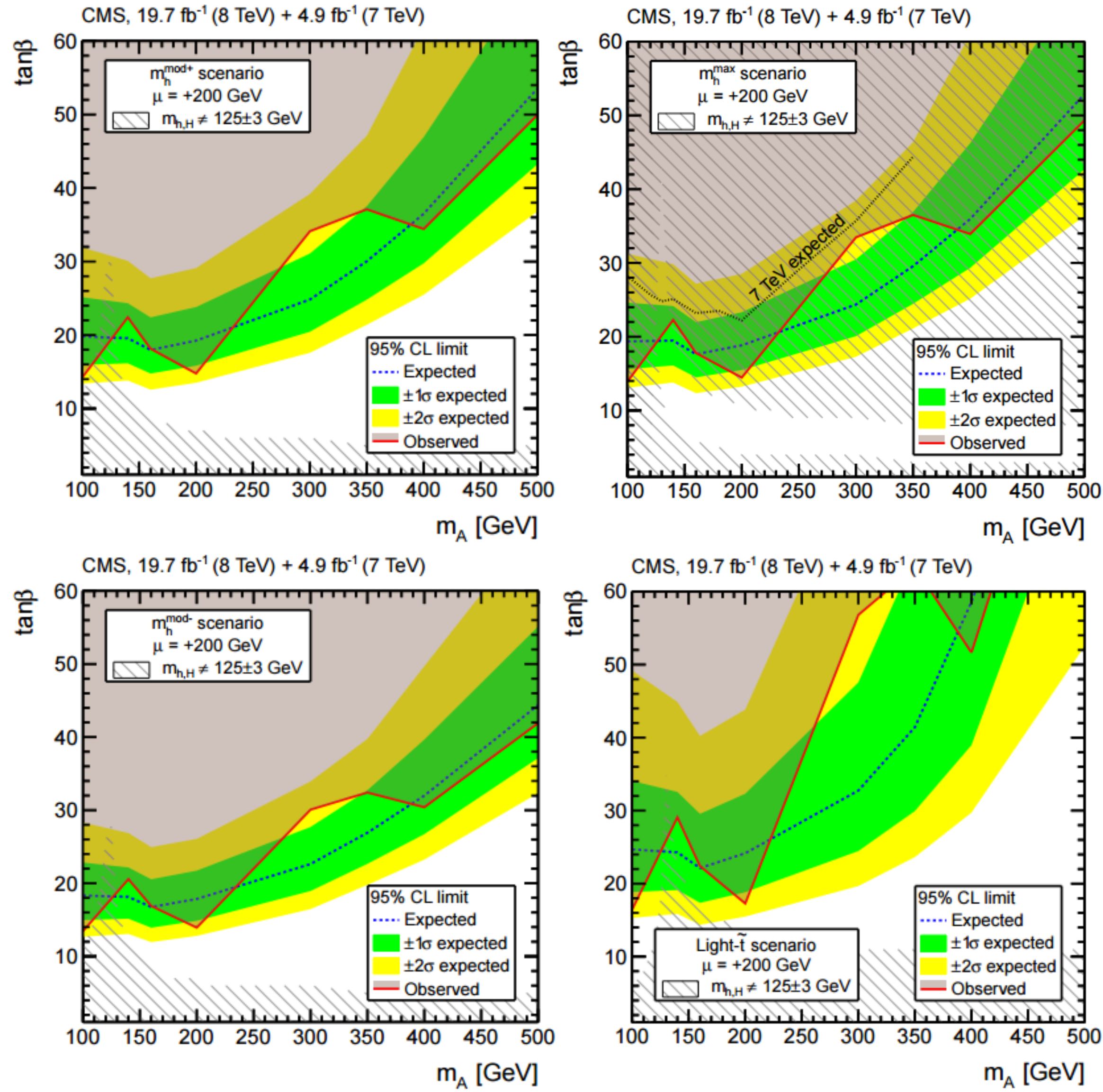




RESULTS: MSSM $\phi \to b\bar{b}$ SEARCH (CMS-PAS-HIG-14-017)



MODEL INDEPENDENT 1D LIMIT



MODEL DEPENDENT 2D LIMITS

CONCLUSION

- **CMS has performed a thorough search for additional heavy neutral scalar/pseudo-scalar higgs bosons in Run-1 data.**

- **No evidence of signal has been found so far and strong exclusion limits have been set on the cross section times branching ratio for these exotic particles.**

- **Exclusion limits have also been placed on large regions of theory parameter space that is consistent with the 125 GeV higgs discovery.**

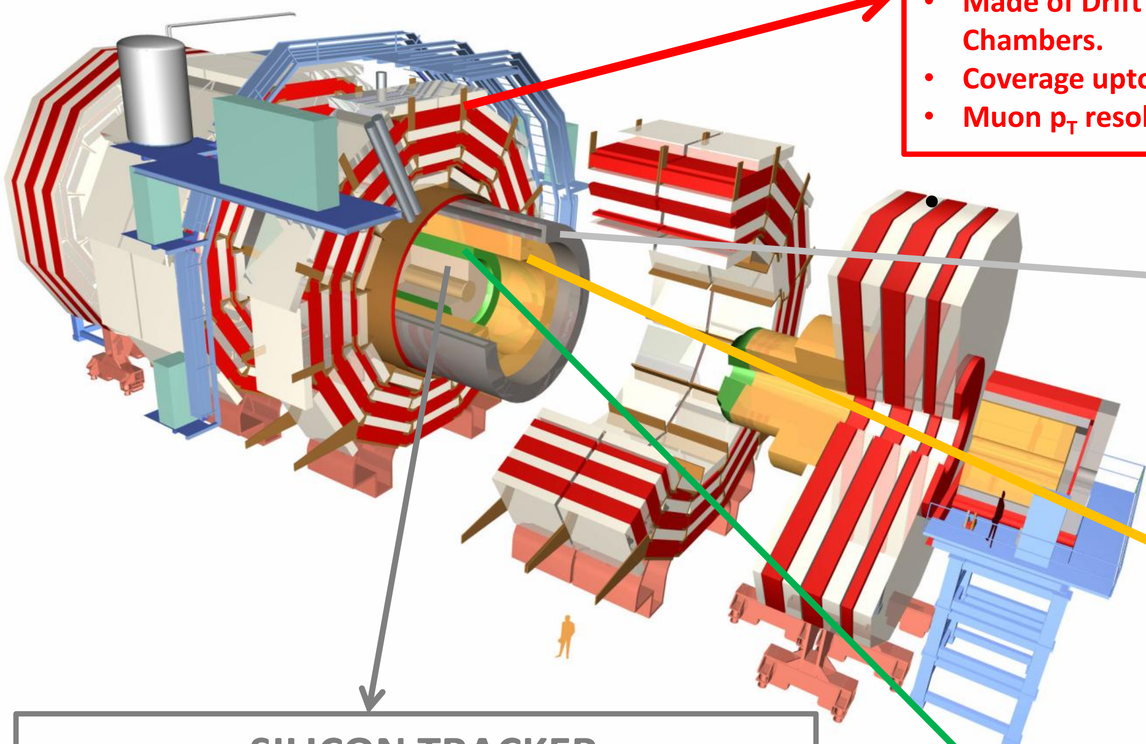
- **The searches have predominantly targeted the decays of the BSM higgs to b-quarks and tau leptons as theories predict enhanced branching fractions for them.**

- **Run-2 searches are ongoing and eagerly awaiting more 13 TeV data in 2016.**


YOU MAY HAVE FOUND THE “SM SCALAR” BUT YOU ALSO KNOW THAT IS NOT THE END OF THE STORY
JOKER
SO STAY CALM AND KEEP SEARCHING
THANK YOU!

BACKUP SLIDES

CMS DETECTOR



MUON CHAMBERS

- Made of Drift Tubes, Cathode Strip Chambers and Resistive Plate Chambers.
- Coverage upto $|\eta| < 2.4$
- Muon p_T resolution 1-1.5% upto p_T^{μ} = 1 TeV

MAGNET

- Superconducting Nb-Ti coil , 12m long and 6m diameter.
- Design Magnetic field : 4 Tesla

HADRON CALORIMETER

- Sampling calorimeter made of alternating layers of Brass and plastic scintillator.
- WLS fibres used for collection of signal. measured by HPDs.
- Energy resolution 10% for 100 GeV pion.

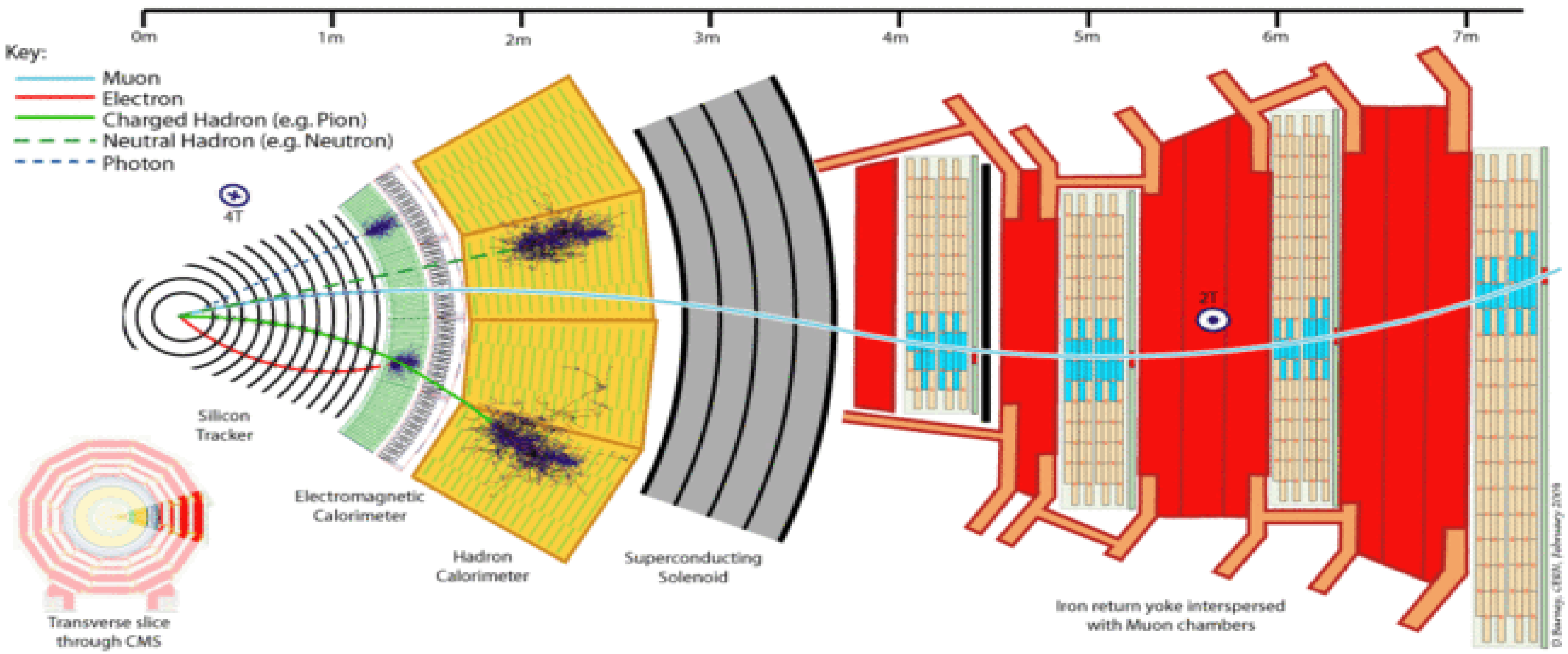
SILICON TRACKER

- Inner most 3/2 layers in the Barrel/Endcap comprising 100 x 150 μm^2 pixels (66 million channels)
- Outermost 10/12 layers in the Barrel/Endcap made of strip detectors.
- p_T resolution 0.5% for 10 GeV charged track.

ELECTROMAGNETIC CALORIMETER

- Homogeneous calorimeter made of PbWO4 crystals .
- Signal measured by Avalanche Photo diodes.
- Energy resolution of 1% for 30 GeV e/γ.

EVENT RECONSTRUCTION (PARTICLE FLOW)

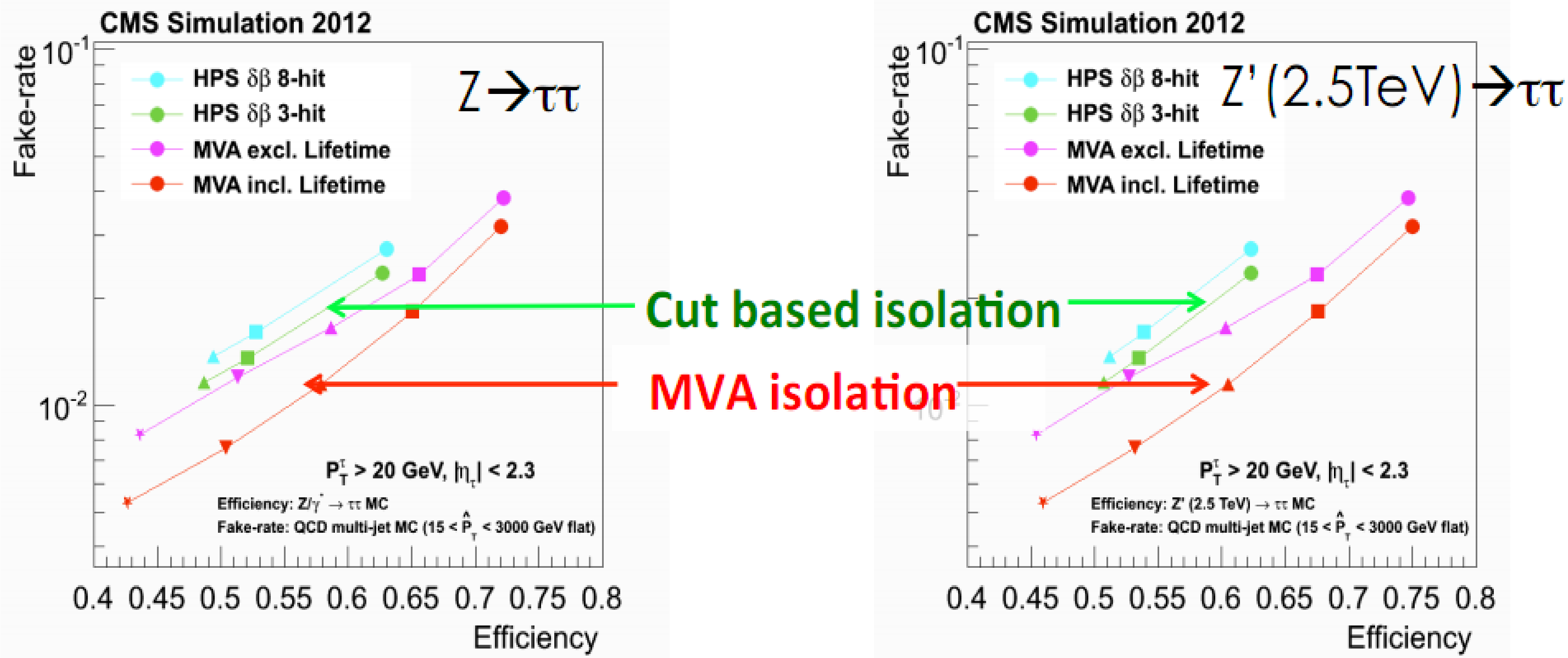


- Muons: Tracker hits, Calo Energy deposits (ECAL + HCAL), Muon chamber hits
- Charged Hadrons: Tracker hits, Calo Energy deposits (ECAL + HCAL)
- Electron/Photon (Converted): Tracker hits, Calo Energy deposits (ECAL)
- Neutral Hadron: Calo Energy deposits (ECAL + HCAL)
- Photon (Unconverted): Calo Energy deposits (ECAL)

TAU ID PERFORMANCE: MVA vs CUT BASED

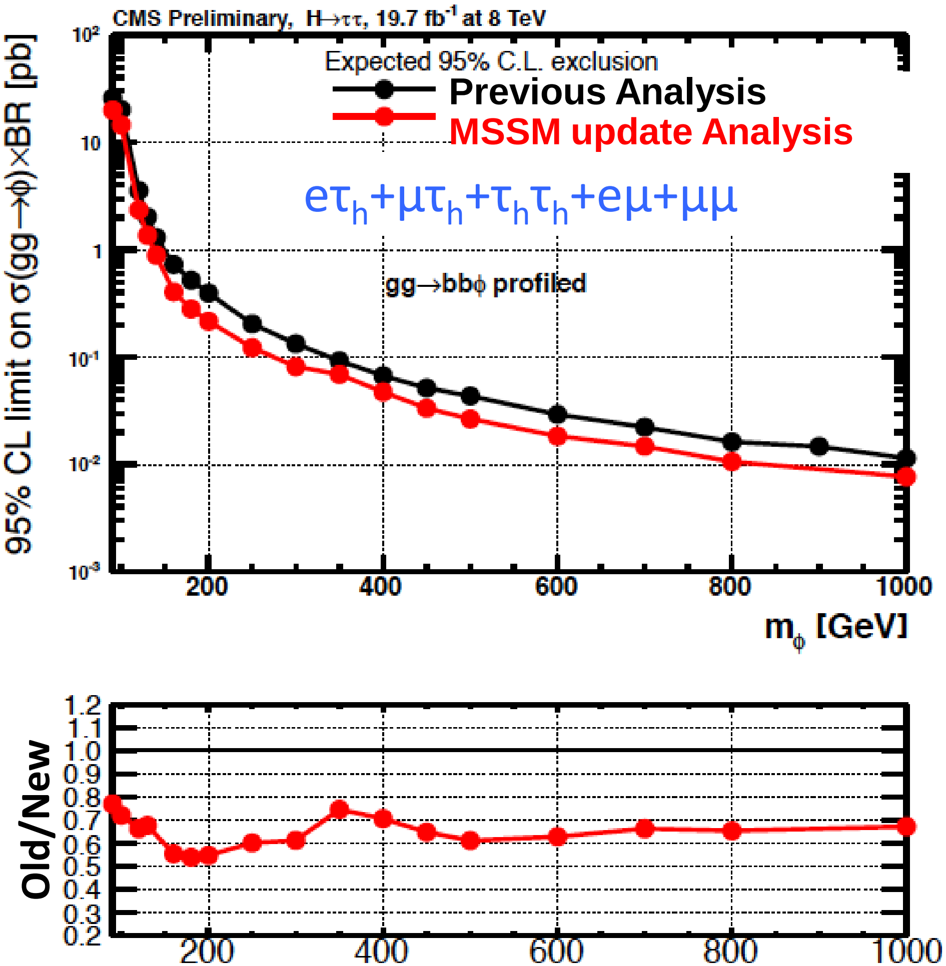
Reduction of fake rate by 40 to 50%
at constant efficiency, for low p_T as well as for high p_T τ(s)

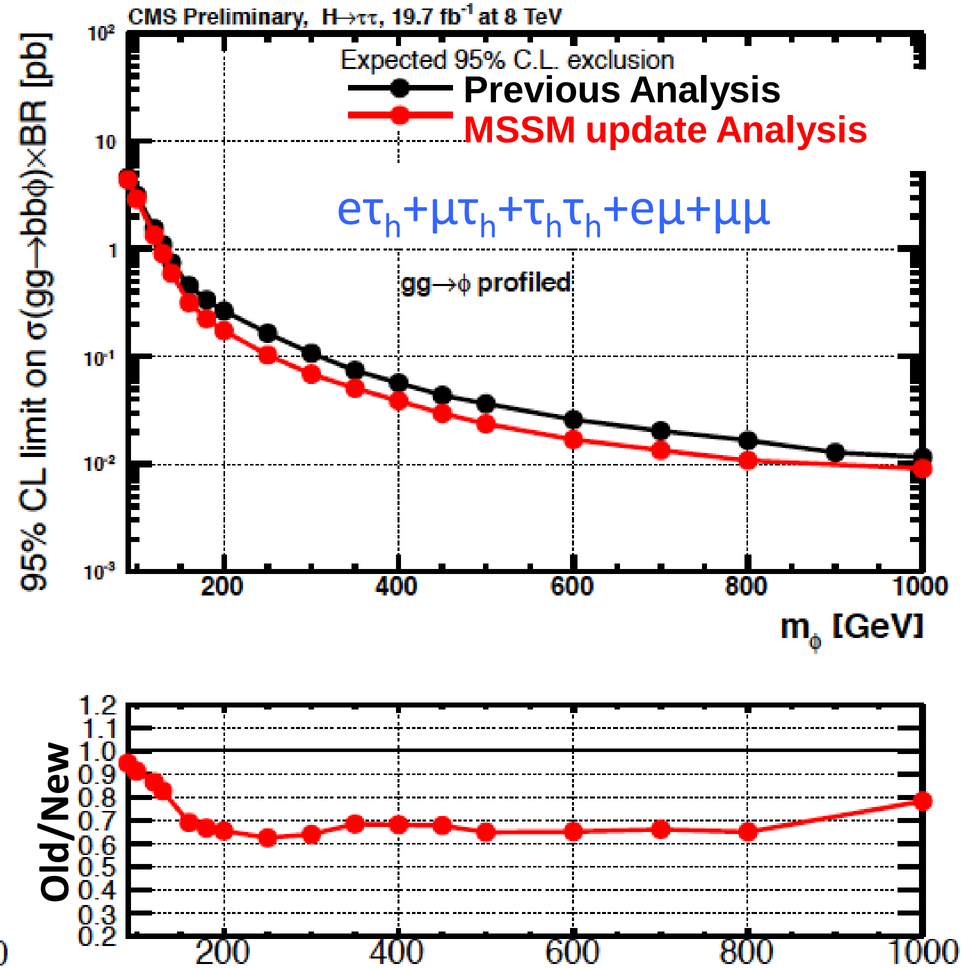
CMS-DP-14-015



CMS-DP-14-015

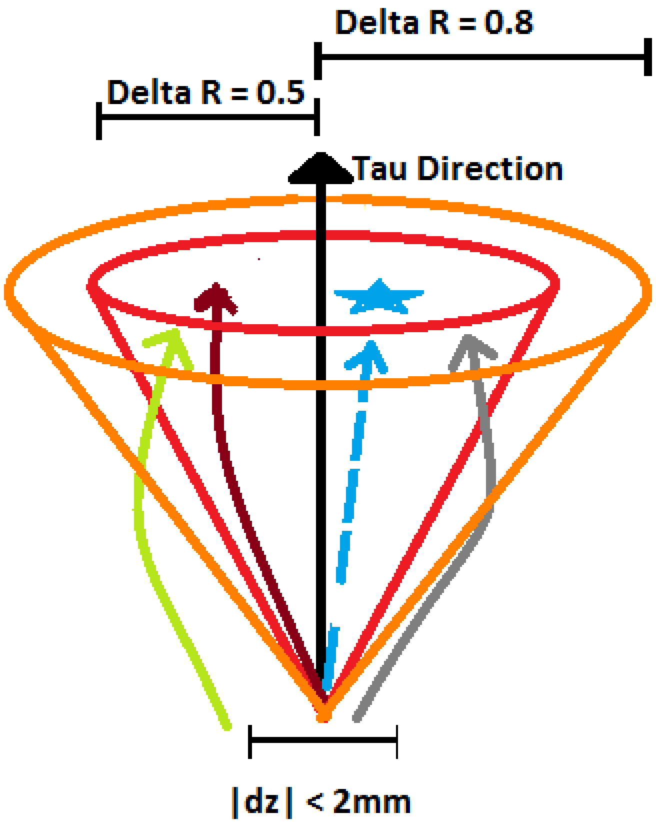
Gain in Analysis Sensitivity (Overall)





MSSM update analysis **improves sensitivity by 30-40%** compared to previous analysis, corresponding to **factor 3-4 gain in luminosity**

HADRONIC TAU ISOLATION: CUT BASED



$$I_\tau = \sum p_T^{charged}(\Delta z < 2mm) + max(p_T^\gamma - \Delta\beta, 0)$$

$$\Delta\beta = 0.4576 \cdot \sum p_T^{charged}(\Delta z > 2mm)$$

- **Tau Isolation P_T Sum Input: PFCharged Hadrons ($P_T >$ 0.5 GeV) and PFPhotons ($E_T >$ 0.5 GeV) within dZ < 2mm from production vertex within a cone of ΔR < 0.5 .**
- **Production vertex: Has highest probability of association with the leading (Highest P_T) track of the Tau candidate.**
- **PFCharged Hadrons and Photons forming the Tau candidate, excluded from the sum.**
- **Pile Up contribution accounted for by applying Δβ corrections.**
- **Δβ corrections: Computed by summing the P_T of PFCharged Hadrons having dZ > 2mm from production vertex within a cone of ΔR < 0.8.**
- **They are scaled by a factor (0.4576) to make them insensitive to Pile Up.**
- **Working Points: Loose (< 2GeV), Medium (< 1GeV) and Tight (< 0.8 GeV).**

HADRONIC TAU ISOLATION: MVA BASED

- **BDT based Isolation uses the following input variables :**
  1. **P_T and η of the reconstructed τ_h candidate and the reconstructed decay mode.**
  2. **Charged Particle Isolation P_T sum :**

     $$\sum P_T^{Charged} \; (\Delta z < 2\,\mathrm{mm})$$

  3. **Neutral Particle Isolation P_T sum :**

     $$\sum P_T^{\gamma}$$

  4. **$\Delta\beta$ corrections.**
  5. **Transverse Impact parameter (d_0) of the leading track of the τ_h candidate and its significance (d_0/σ_{d0}) for 1Prong0π0 and 1Prong1π0 decay modes.**
  6. **Distance b/w τ_h production and decay vertex and its significance for 3Prong0π0 decay mode :**

     $$\left|\vec{r}_{PV} - \vec{r}_{SV}\right| \;,\quad \left|\vec{r}_{PV} - \vec{r}_{SV}\right| \big/ \sigma_{\left|\vec{r}_{PV} - \vec{r}_{SV}\right|}$$

- **MVA trained on simulated $\Phi \to \tau\tau$, $Z \to \tau\tau$, $Z' \to \tau\tau$ and $W' \to \tau\nu$ "Signal" samples (~ 10^6 events each) and QCD multijets, WJets and $Z \to ll$ ($l = e/\mu$) "background " samples covering 20 GeV to 2000 GeV in Gen Tau P_T.**

RESULTS: 2D (MODEL DEPENDENT) LIMITS

- **Six (CP conserving) Phenomenological scenarios proposed by the LHC Higgs cross section working group based on bounds set by LEP, Tevatron and LHC searches are used to set exclusion limits in the (mostly) 2 dim. "Tanβ – m_A" plane (Carena et al., Eur.Phys.J.C73, 2552 (2013)).**

- **They all fulfill the criterion that one of the MSSM scalars have mass 125 ± 3 GeV (where the uncertainty is theory dominated).**

- **h is SM like for most of the parameter space (but exceptional scenarios exist).**

Parameter	Definition
m_t	Top Quark mass (172.5 GeV)
m_b	Bottom Quark mass (4.16 GeV)
M_{SUSY}	Mass scale of 3^{rd} Gen. squarks (stops and sbottoms)
μ	Higgsino mass
$M_{\tilde{l}3}$	3^{rd} Gen. slepton mass (stau)
M_1	U(1) gaugino mass parameter
M_2	SU(2) gaugino mass parameter
A_t, A_b, A_τ	Trilinear couplings of stops, sbottoms and staus
X_t, X_b, X_τ	Mixing parameters of stops, sbottoms and staus

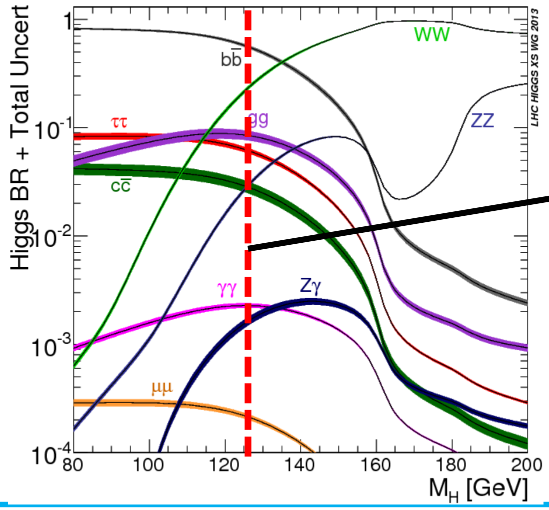
Radiative SUSY parameters used to define scenarios

Values in Next Slide!

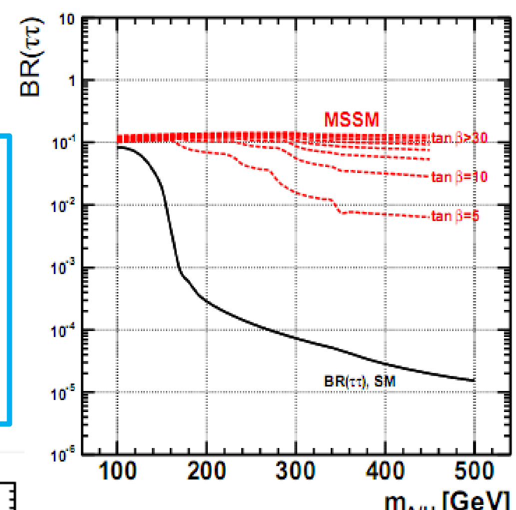
RADIATIVE SUSY PARAMETERS FOR ALL MSSM SCENARIOS

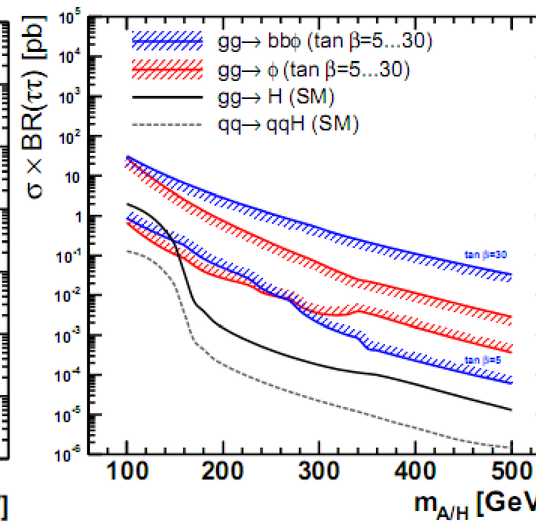
parameter	m_h^{max}	m_h^{mod+}	m_h^{mod-}	*light stop*	*light stau*	*τ-phobic*	*low-M_H*
m_b [GeV]	4.16	4.16	4.16	4.16	4.16	4.16	4.16
m_t [GeV]	172.5	172.5	172.5	172.5	172.5	172.5	172.5
m_A [GeV]	90–1000	90–1000	90–1000	90–600	90–1000	90–1000	110
$\tan\beta$ [ ]	0.5–60	0.5–60	0.5–60	0.7–60	1.0–60	0.5–60	1.5–9.5
μ [GeV]	200	200	200	400	500	2000	300–3100
$M_{\tilde{q}_{1,2}}$ [GeV]	1500	1500	1500	1500	1500	1500	1500
M_{SUSY} [GeV]	1000	1000	1000	500	1000	1500	1500
X_t [GeV]	$2.0M_{SUSY}$	$1.5M_{SUSY}$	$-1.9M_{SUSY}$	$2.0M_{SUSY}$	$1.6M_{SUSY}$	$2.45M_{SUSY}$	$1.5M_{SUSY}$
$M_{\tilde{l}_{1,2}}$ [GeV]	500	500	500	500	500	500	500
$M_{\tilde{l}_3}$ [GeV]	1000	1000	1000	1000	245	500	1000
M_1 [GeV]	fixed by GUT relation to M_2			340	fixed by GUT relation to M_2		
M_2 [GeV]	200	200	200	400	200	200	200
$m_{\tilde{g}}$ [GeV]	1500	1500	1500	1500	1500	1500	1500
$A_{f_{1,2}}$ [GeV]	0	0	0	0	0	0	0
A_t [GeV]	fixed by $X_t = A_t - \mu\cot\beta$						
A_b [GeV]	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ [GeV]	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	$= A_t$	$= A_t$

MOTIVATION-2

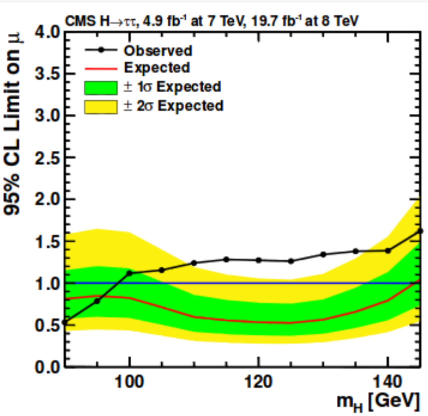


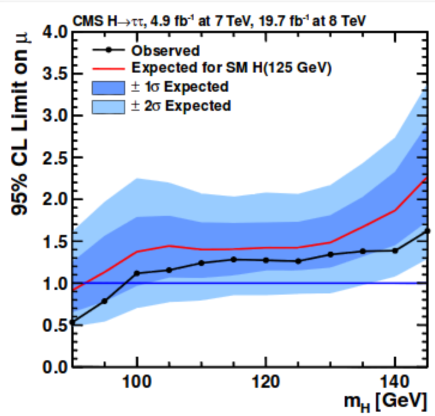
- Di-Tau final state is an important channel in Higgs searches.
- H→ττ in SM has 3rd highest Branching Ratio (~6.3% next only to bƃ and WW) at 125 GeV.
- Only channel that constrains well Higgs couplings to fermions (Over whelming background in H→bƃ).





- H→ττ : Important in MSSM.
- σ x BR(ττ) is enhanced w.r.t SM values for large Tanβ due to enhanced bottom Yukawa coupling.





- > 3σ observation of SM Higgs decay to Taus
  http://dx.doi.org/10.1007/JHEP(2014)104
- Triggered interest in interpreting this particle in context of BSM physics scenarios (esp. SUSY).

SYSTEMATICS

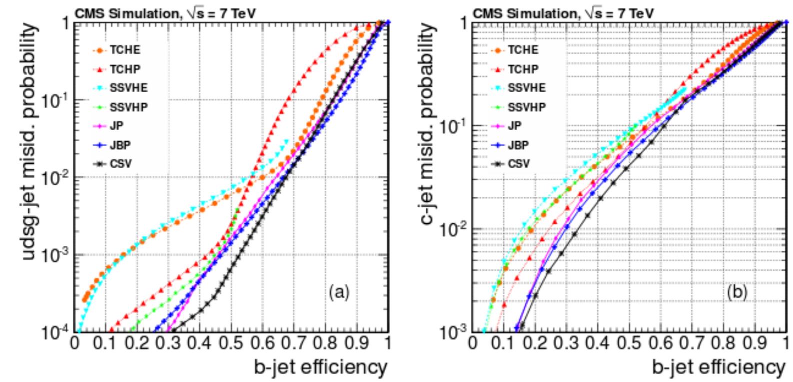
Systematic uncertainty source	Value	Comments
e/μ identification efficiency	2%	applied flat for all p_T and η
τ_h identification efficiency	$6\% \oplus 20\% \cdot \frac{p_T}{1000 GeV}$	p_T dependent part for extrapolation to high τ_h p_T
τ_h trigger efficiency	4.5%	applied per leg of the trigger
$Z/\gamma^* \rightarrow \tau\tau$ MC yield	5%	applied to embedded samples inclusively
Di-Boson MC yield	15%	-
$t\bar{t}$+Jets MC yield	15%	-
Single top MC yield	15%	-
W+Jets yield	30%	-
e$\rightarrow$ τ_h fake rate	30%	-
$\mu \rightarrow \tau_h$ fake rate	30%	-
Luminosity	2.6%	-

Systematic uncertainty source	Comments
τ_h energy scale	obtained by varying the τ_h energy by $\pm 3\%$
Jet energy scale	applied as a function of jet p_T and η
b-tagging efficiency	applied as a function of b-jet p_T and η
b mistag rate	applied as a function of b-jet p_T and η
QCD background	both normalization and shape varied by varying the jet$\rightarrow$ τ_h fake rate weights between unity and twice the nominal value
Higgs p_T reweighting	estimated by taking difference between the MSSM higgs templates for $tan\beta = 1$ (pure t-loop) and $tan\beta = 60$ (pure b-loop)
Top quark p_T reweighting	estimated by varying the corrections between unity and twice the nominal value

b-TAGGING

Sec. Vtx. Candidate selection

- 100 μm < $|d_{(Prim.Vtx-Sec.Vtx)}|$ < 2.5 cm
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}| > 3$
- Invariant mass of charged particles assoc. to Sec. Vtx < 6.5 GeV
- Sec. Vtx incompatible with K^0_s decay (having 2 OS charge tracks having inv. Mass within ± 50 MeV around K^0_s mass[497 MeV]).



Sec. Vtx. Candidate events divided into 3 categories

Reco. Vtx. (>1 Sec. Vtx)

- Invariant mass of charged particles of Sec. Vtx.
- Charged particle multiplicity
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}|$
- $E_{Sec.Vtx\ Chg\ partcles}/E_{Jet\ Chg\ particles}$
- Charged particle rapidity

Pseudo Vtx. (0 Sec. Vtx)

- Charged hadron tracks incompatible with Prim. Vtx.

No Vtx.

- Complement of other 2 categories.

All these variables are combined into 1 single discriminator using likelihood ratio