Search for Higgs boson in models beyond SM at CMS

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Overview

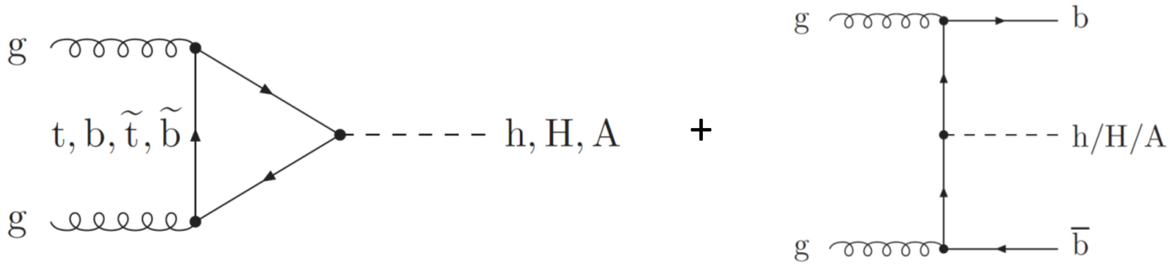
- Higgs boson in MSSM
  - Neutral Higgs boson : h/H/A → bb, ττ
  - Charged Higgs boson : $H^{\pm} \rightarrow \tau\nu$

- Higgs boson in Next-to-MSSM
  - A very light CP odd scalar boson :

    $\boldsymbol{h \rightarrow 2a \rightarrow 4\mu}$, ($m_a < 2m_\tau$)

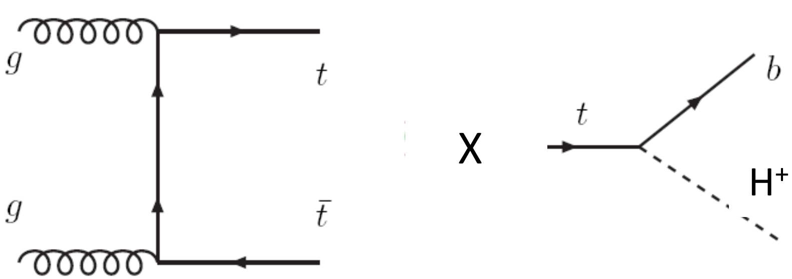
MSSM Higgs production at LHC

- MSSM Higgs Sector :
  - Two Higgs doublet => 5 physical bosons : h, H (CP even), A (CP odd) and $H^{\pm}$
  - Controlled by two parameters at tree level : m_A and $\tan\beta$
- Neutral Higgs production and decay :



- Dominant decay mode : bb and ττ

- Charged Higgs production and decay :



For $M_{H+} \leq m_{top}$:

$pp \to t\bar{t} \to bH^{\pm}\bar{b}W^{\mp}$ with $t \to bH^{+}$

For $M_{H+} \geq m_{top}$: $pp \to tbH^{\pm}$

For large $\tan\beta$, $Br(H^{+} \to \tau\nu) \approx 1$

MSSM Higgs search channels

- pp → φb, φ → bb
  - Semileptonic b decays (jet containing a muon)
  - Hadronic b decays

φ : h, H, A

- pp → φ, φ → ττ
  - e+μ (very clean channel, low statistics)
  - e+τ_{had} (larger background, high statistics)
  - μ+τ_{had} (smaller background, high statistics)
  - μ+μ (low sensitivity)

τ_{had}: hadronic τ decay

- pp → tt, t → H^+b, H^+ → τν

(1) $H^{\pm} \to \tau_h \nu, W^{\mp} \to q_i \bar{q}_j$ (2) $H^{\pm} \to \tau_h \nu, W^{\mp} \to \ell \nu$

(3) $H^{\pm} \to \tau \nu, \tau \to e(\mu)\nu, W^{\mp} \to \mu(e)\nu$

MSSM Higgs → bb

Analysis divided in two sub-categories

- Semileptonic b decays (jet containing a muon)
- Hadronic b decays

$pp \rightarrow \varphi b,\ \varphi \rightarrow bb,\ \varphi : h, H, A$

di-Jet mass in semi-leptonic final state

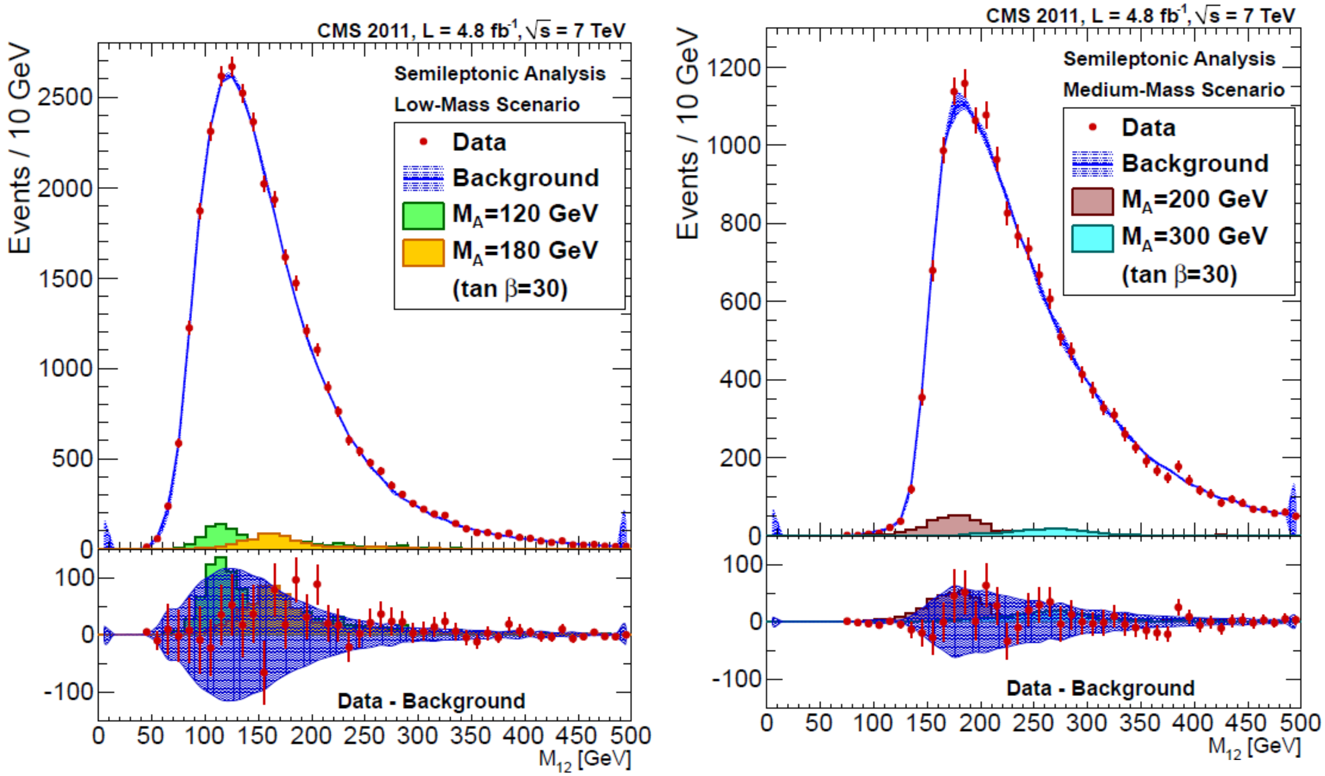
Event Selection :

Trigger :
diJet OR muon+jet triggers, with one or more b-tagged jets

Offline :
>= 3 b-tagged jets
(Thresholds vary according to analysis)

One of the jet contains a muon in semi-leptonic analysis.

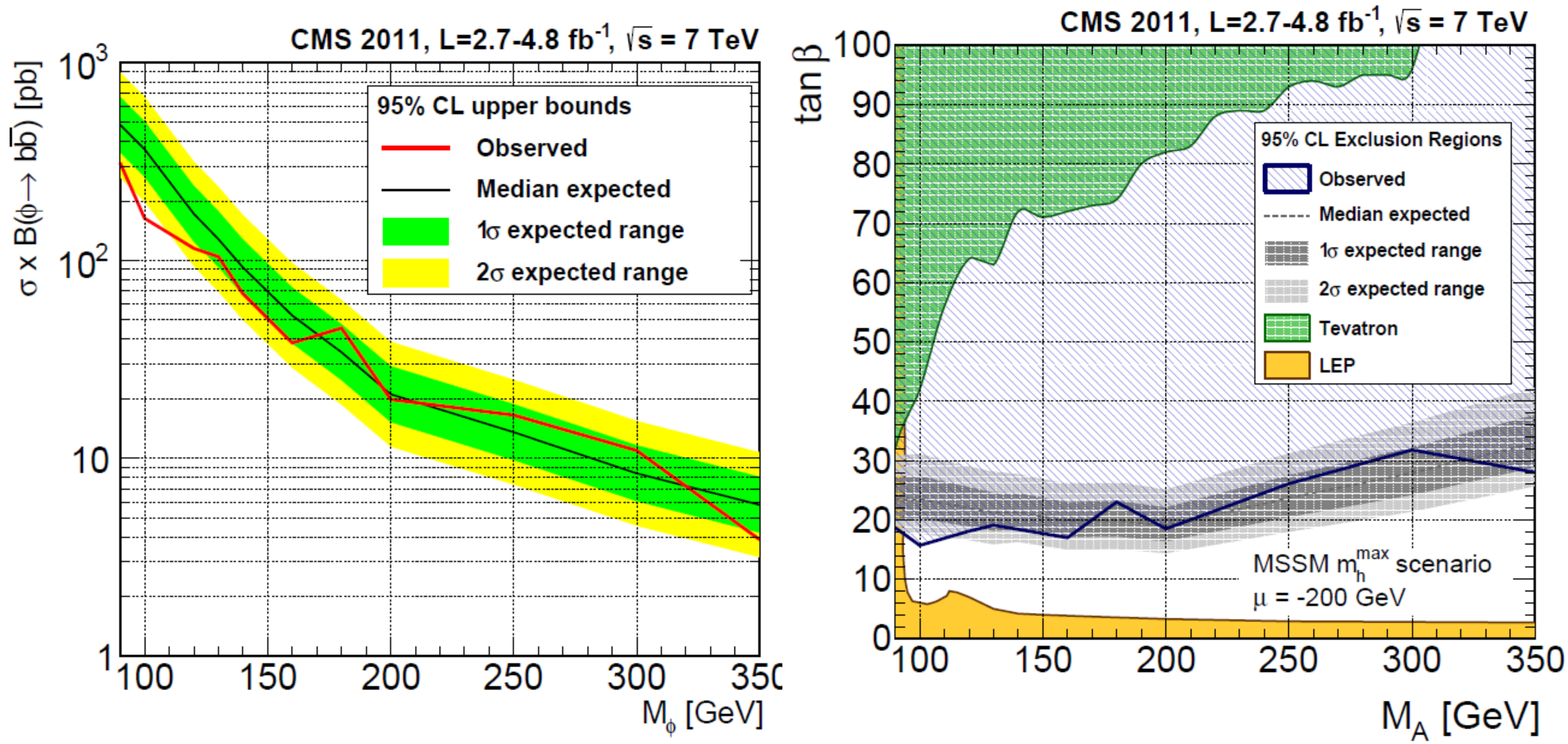
Backgrounds :
Major background : qcd bbbar
Measured from data



Data in Agreement with background prediction
M_{12} Resolution ~15%

φ → bb Exclusion Limits

arXiv:1302.2892, CMS-HIG-12-033



Upper Limit on pp → φb, φ→bb production by fitting observed M_{12} distribution.
Non-observation of φ →bb Signal excludes region of large tanβ in MSSM Parameter space

MSSM Higgs → ττ

$pp \to \varphi,\ \varphi \to \tau\tau$, φ : h, H, A

Analysis performed in 4 final states :

$e+\mu$, $e+\tau_{had}$, $\mu+\tau_{had}$, $\mu+\mu$

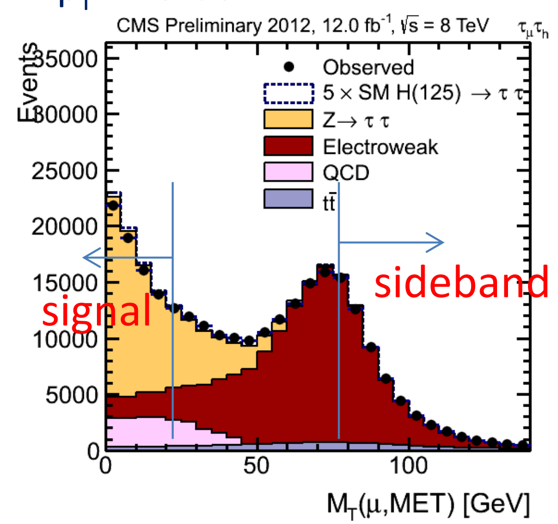
Event Selection

- Events triggered by $e+\mu$, $e+\tau_{had}$ and $\mu+\tau_{had}$ Triggers
- Opposite Charged isolated Lepton Pair ($\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$)
- Veto Events with additional isolated Leptons

- Selected Events analyzed in 2 Categories: non-b-Tag and b-Tag
  - **b-Tag** : ≤ 1 jet with p_T > 30 GeV, ≥ 1 b-Tagged Jet with p_T > 20 GeV **(enhance bbH signal)**
  - **Non b-Tag** : ≤ 1 jet with p_T > 30 GeV, No b-Tagged Jet with p_T > 20 GeV

Backgrounds :

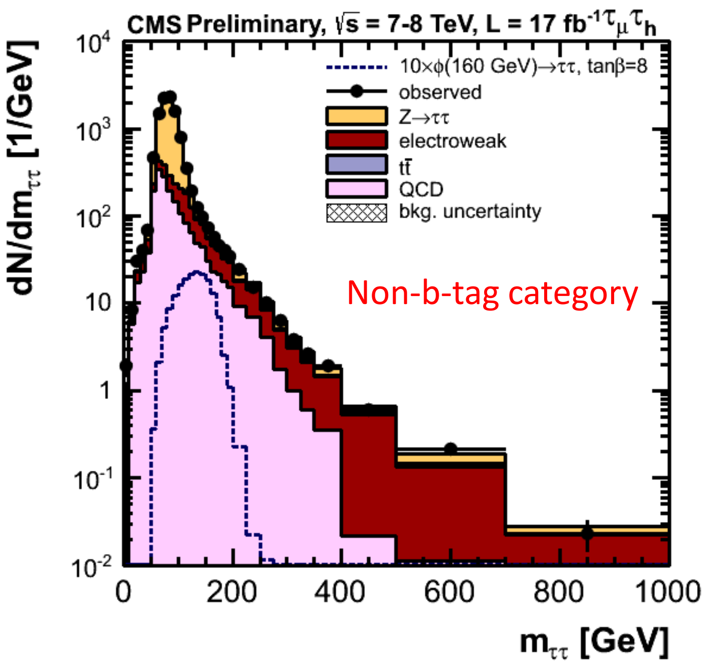
- $Z \to \tau\tau$, $Z \to ee$, $\mu\mu$, QCD, W+Jets, ttbar, diboson.
- $Z \to \tau\tau$ is estimated using $Z \to \mu\mu$ events, where muon is replaced by a simulated tau.
- W+jets and ttbar is suppressed by requiring m_T < 20 GeV
- W+jets estimated from high m_T (m_T > 70) sideband.
- QCD is estimated from data using same-sign lepton pairs.

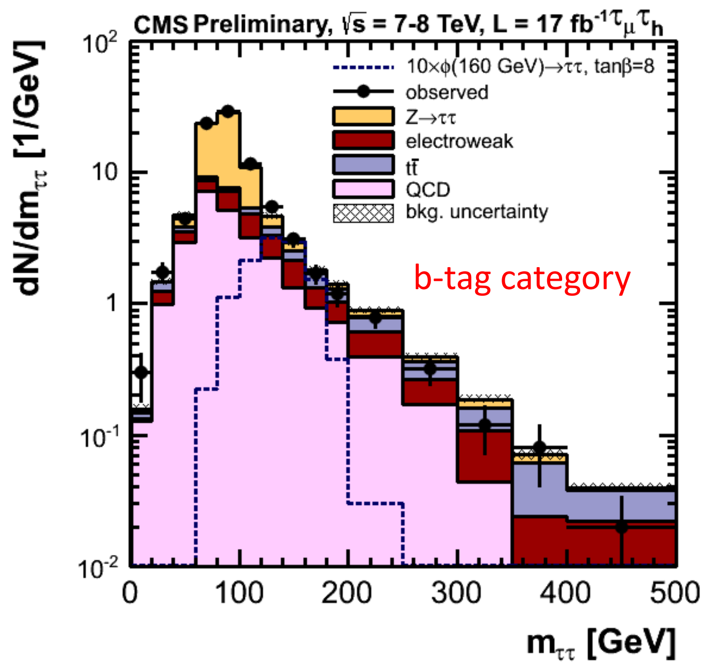


di-Tau mass reconstruction

- Mass of τ Lepton pair reconstructed via Likelihood technique, based on:
  - τ decay Kinematics
  - Compatibility of reconstructed E_T^{miss} with Neutrino hypothesis
- $m_{\tau\tau}$ Resolution ~20% (almost Gaussian)

$\mu\tau_h$ final state





- Distribution observed in Data in agreement with background expectation

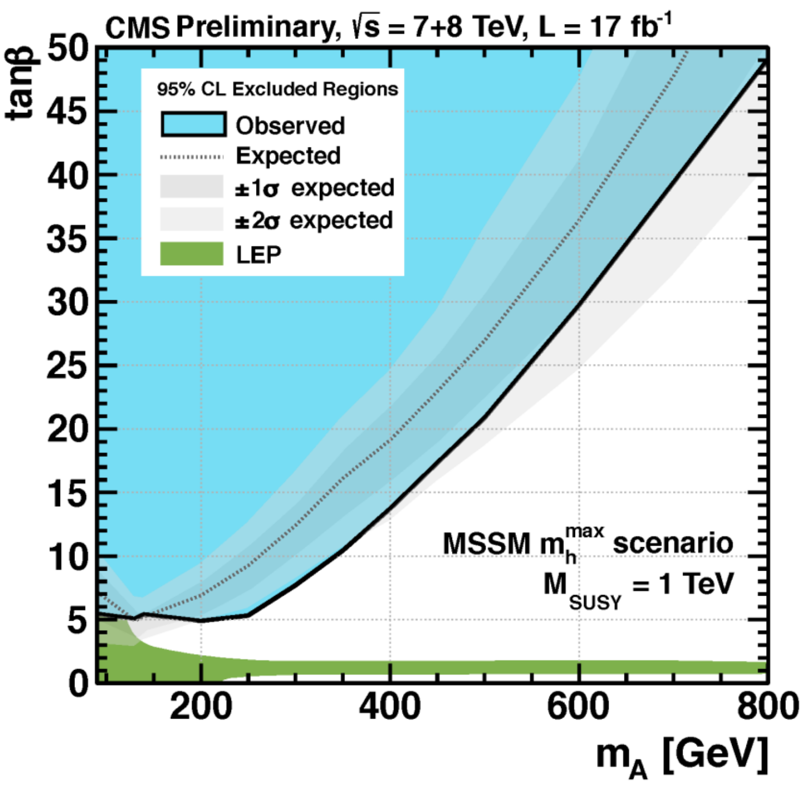
More details on tau-ID and di-tau mass reconstruction is in SM H→ ττ talk.

$\varphi \rightarrow \tau\tau$ Exclusion Limit

CMS-PAS-HIG-12-050

- Limit obtained by scanning $\tan\beta$ for each mass hypothesis M_A:
- Cross-section × BR for $gg \rightarrow \varphi$ and $bb \rightarrow \varphi$ computed as function of M_A, $\tan(\beta)$

- Dependence of M_h and M_H on $\tan\beta$ taken into account



Charged Higgs

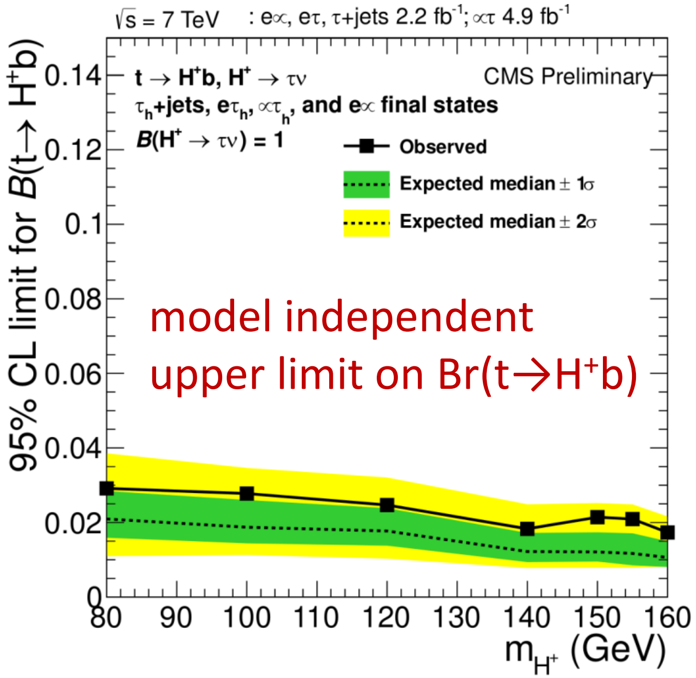
Search for a charged Higgs in top quark decay

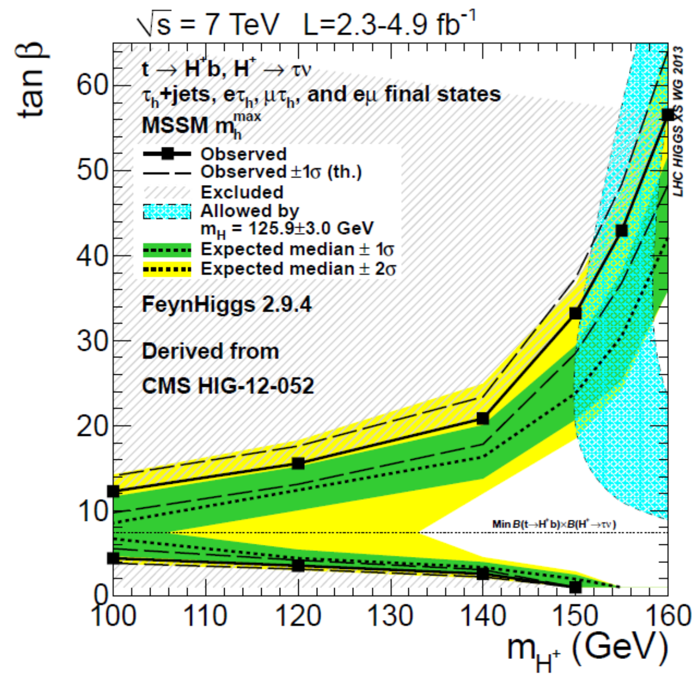
CMS-PAS-HIG-12-052

$pp \rightarrow tt,\ t \rightarrow H^{+}b,\ H^{+} \rightarrow \tau\nu$

4 final states analysed ($e\mu$, $e\tau_h$, $\mu\tau_h$, τ_h+jets)

Shape based analysis using m_T ($\tau+E_T^{miss}$) or p_T(leading track)/$p_T(\tau)$





Upper limit on BR($t \rightarrow H^{+}b$) excludes region of large $\tan\beta$ in MSSM Parameter space for $M_{H+} / M_A \leq M_{top}$ (arXiv:1307.1347)

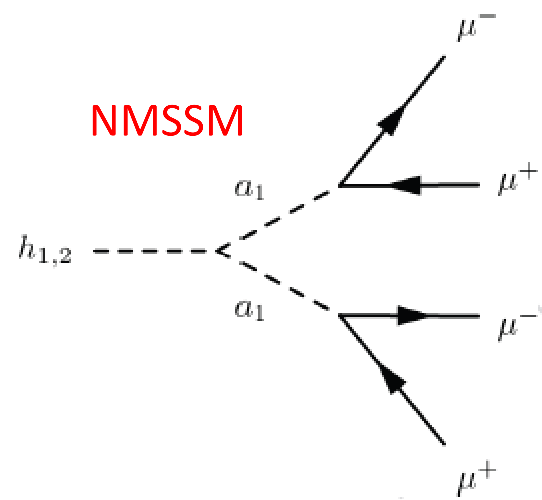
Search for $h \rightarrow 2a \rightarrow 4\mu$

- Generic search for non-SM decay of Higgs boson to a pair of new light bosons (a), which subsequently decay to boosted pairs of oppositely charged muons.
- Predicted in several models (NMSSM, dark SUSY)

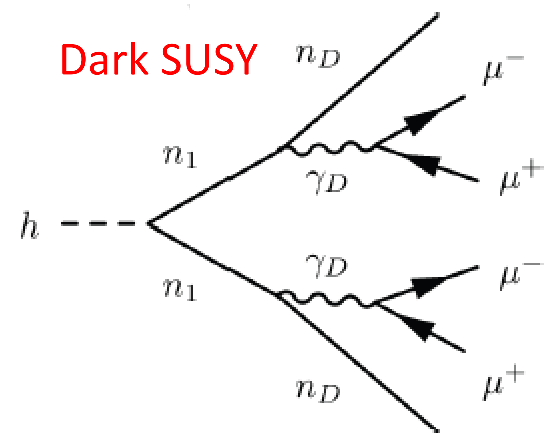
- Benchmark Scenarios :
  - NMSSM Higgs Sector : 3 CP−even: $h_{1,2,3}$, 2 CP-odd:$a_{1,2}$
    - Possible Signature at LHC : $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$
    - Typical Higgs masses : $90 \lesssim m_{h1} \lesssim 120$–135 GeV
    - Search assumption : $0.25 < m_{a1} < 3.55$ GeV
      $(2m_\mu \lesssim m_{a1} \lesssim 2m_\tau)$
  - Dark Susy : New light dark boson γ_D
    - Possible Signature at LHC :
      $h1 \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu$
    - Search assumption : $0.25 < m_{\gamma D} < 3.55$ GeV

$h \rightarrow 2a + X \rightarrow 4\mu + X$

NMSSM



Dark SUSY



Analysis Strategy

Event Selection

- di-muon trigger (p_T > 17 GeV, 8 GeV)
- Exactly two distinct, opposite charged, muon pairs ($m_{\mu\mu}$ < 5 GeV)
- Di-muons are required to be isolated to suppress qcd bb background.
- No limit on no. of unpaired muons.

- Search for di-muon resonance peaks on diagonal of 2D distribution of the di-muons mass

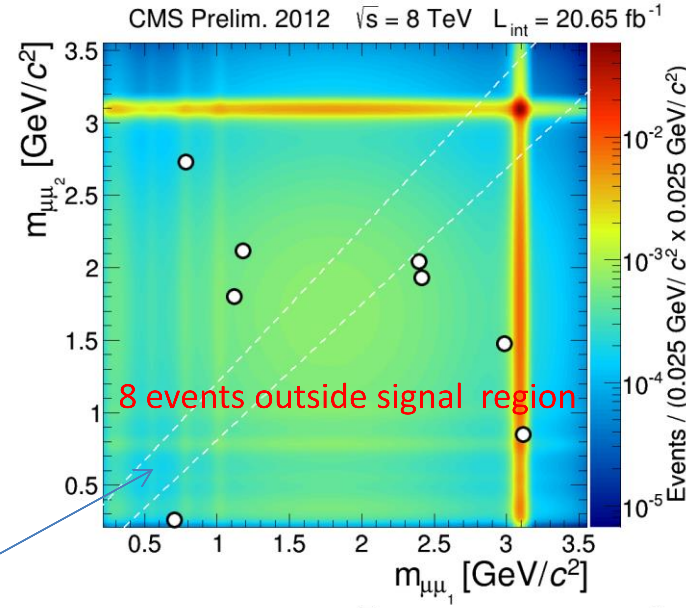
Signal Region :

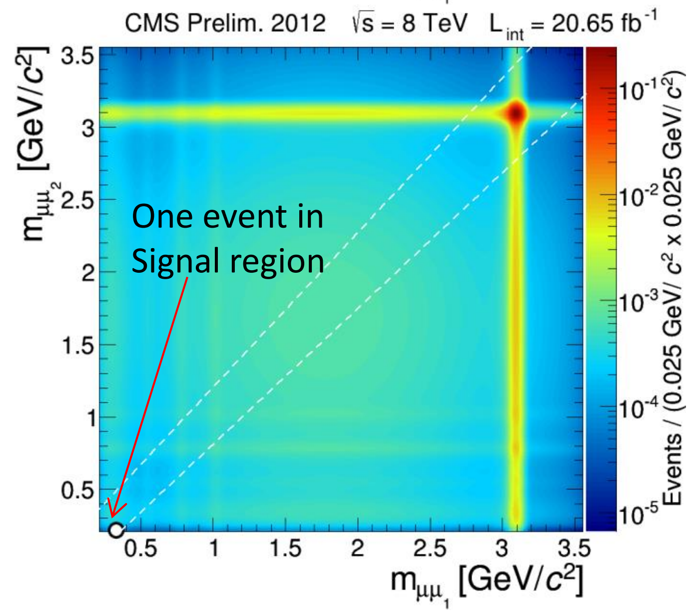
$$m_{\mu\mu1} - m_{\mu\mu2} < 5\sigma = 0.13 + 0.065 \cdot (m_{\mu\mu1} + m_{\mu\mu2})/2$$

(detector resolution)

- Backgrounds :
  - bbbar : Measured from data using orthogonal sample of bbbar events with exactly one di-muon and one unpaired muon.
  - J/ψ : Estimated using simulation
  - Total background in the signal region : 3.8 ± 2.1

(background expectation shown as the intensity of the shading)





Exclusion Limits

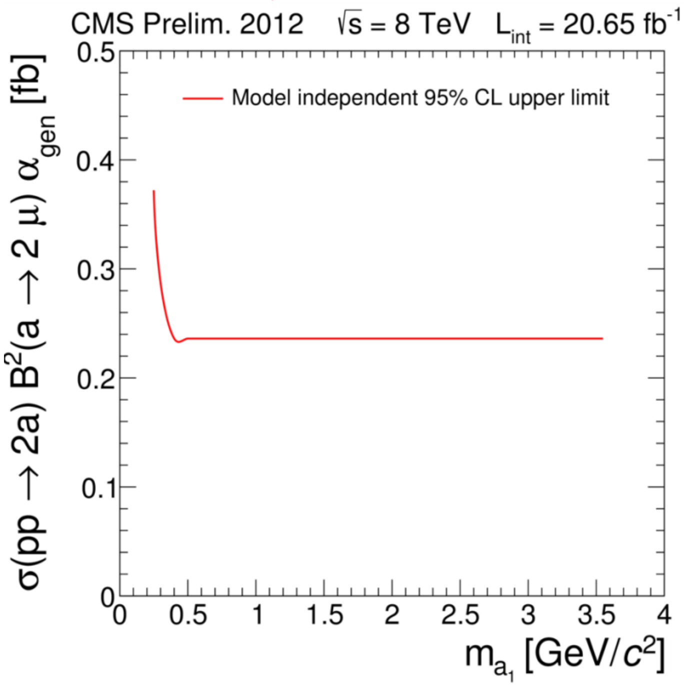
CMS-PAS-HIG-13-010

Model independent 95% CL upper limit on

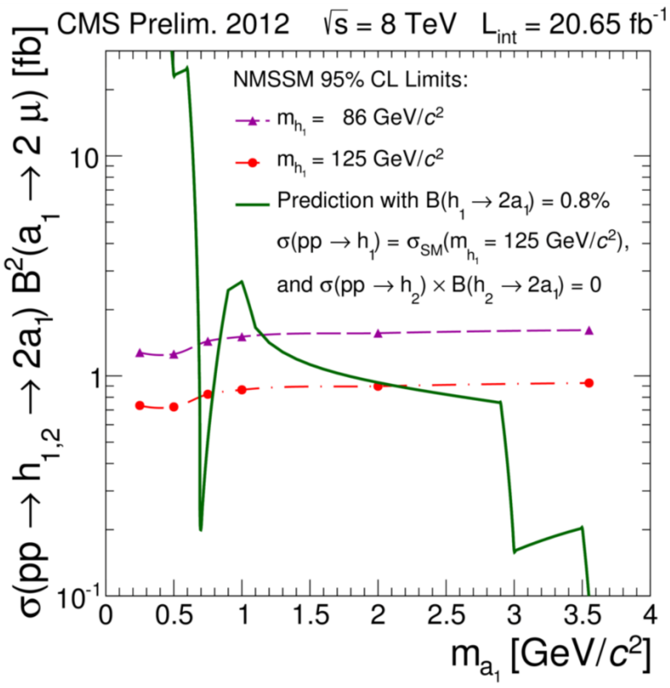
$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen}$$

- where α_{gen} is geometric and kinematic acceptance calculated using generated information.
- The efficiency of detector and analysis selection requirements have very weak dependence on the model, Thus allowing to set limit on any arbitrary new physics model predicting similar signature.

Model Independent Exclusion Limit



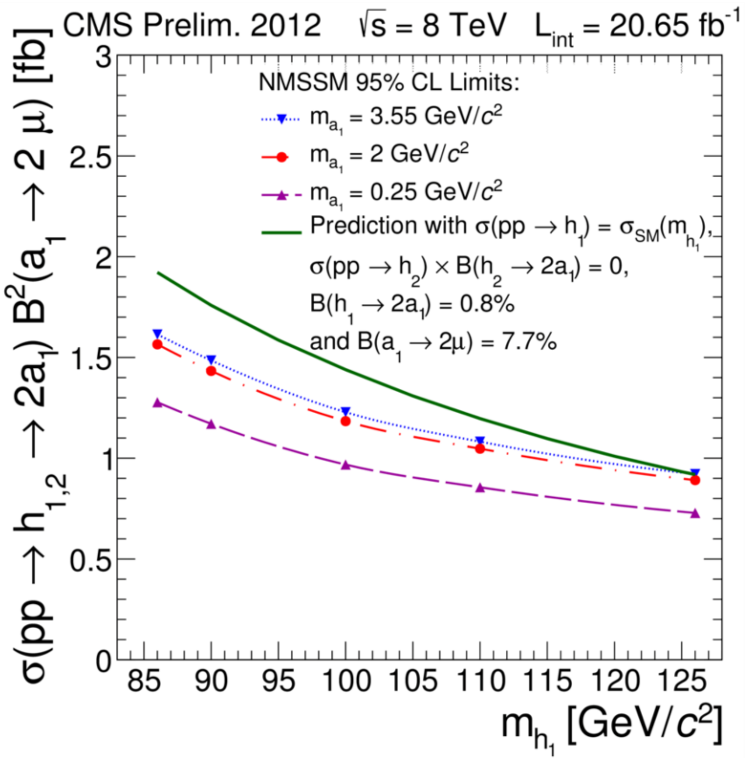
Exclusion Limits on Higgs boson in NMSSM



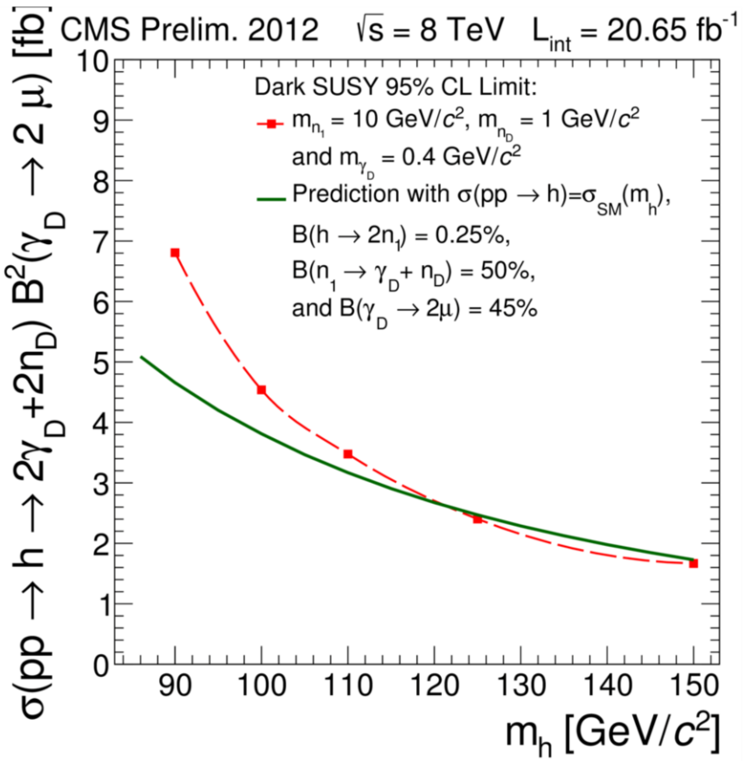
Exclusion Limits (II)

95% CL upper limit as functions of m_h

NMSSM



dark-SUSY



Summary

- CMS explored the search for Higgs boson in many promising models beyond SM.
- Results are presented for the search of Higgs boson in MSSM, NMSSM and other exotic models.
- No evidence of any excess above Standard Model backgrounds.
- Stringent limit set on the production of Higgs boson in most of the models beyond SM.
- An update on the MSSM Higgs results with full 7TeV+8TeV data is expected soon.

backup

Higgs boson in MSSM

- Two Higgs doublet => 5 physical bosons
  - Three neutrals : h, H (CP even), A (CP odd)
  - Two charged : $H^{\pm}$
- Controlled by two parameters at tree level
  - m_A and $\tan\beta$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$M_{H^+}^2 = M_A^2 + M_W^2$$

$$M_{h/H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 cos^2 2\beta}\right)$$

Other SUSY parameters are important at higher order corrections

$\varphi \to bb$ Event Selection

	Semileptonic	Hadronic
• **Trigger :**	Muon+1/2 Jets ≥ 1/2 b-tagged	2/3 Jets ≥ 2 b-tagged
• **Offline :**		
Muon	$P_T > 15$ GeV (no Isolation applied)	
Jets	≥ 2 Jets of $P_T > 30$ GeV + 3rd Jet of $P_T > 20$ GeV $\lvert\eta\rvert$(jets) < 2.6, all 3 b-tagged Muon is within one of two leading jets	≥ 3 Jets: P_T 1st > 46 (60) GeV P_T 2nd > 38 (53) GeV P_T 3rd > 20 GeV $\lvert\eta\rvert$(jets) < 2.2 all 3 b-tagged

The major background, QCD, is estimated from data.
The other minor backgrounds, ttbar and Z(bb)+jets
Is taken from MC.

Jet P_T Threshold depends on Higgs Mass hypothesis: lower (higher) Thresholds used for $M\varphi < 180$ GeV ($M\varphi > 180$ GeV), driven by Trigger Thresholds

$\varphi \rightarrow \tau\tau$ Analysis

Event Selection

- Trigger

Events triggered by $e+\mu$, $e+\tau_{had}$ and $\mu+\tau_{had}$ Triggers, P_T thresholds 10-20 GeV/c

- Lepton Selection

Electrons	Muons	τ_{had}
$P_T > 10\text{-}20$ GeV	$P_T > 10\text{-}20$ GeV	$P_T > 20$ GeV
$\|\eta\| < 2.1$ (2.3 for $e + \mu$)	$\|\eta\| < 2.1$	$\|\eta\| < 2.3$
isolated	isolated	Tau Identification
		Veto against e/μ

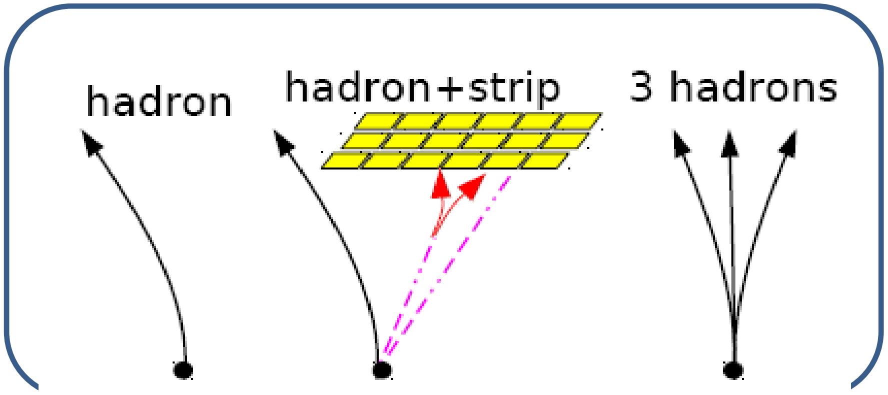
- Opposite Charge Lepton Pair

- Veto Events with additional isolated Leptons

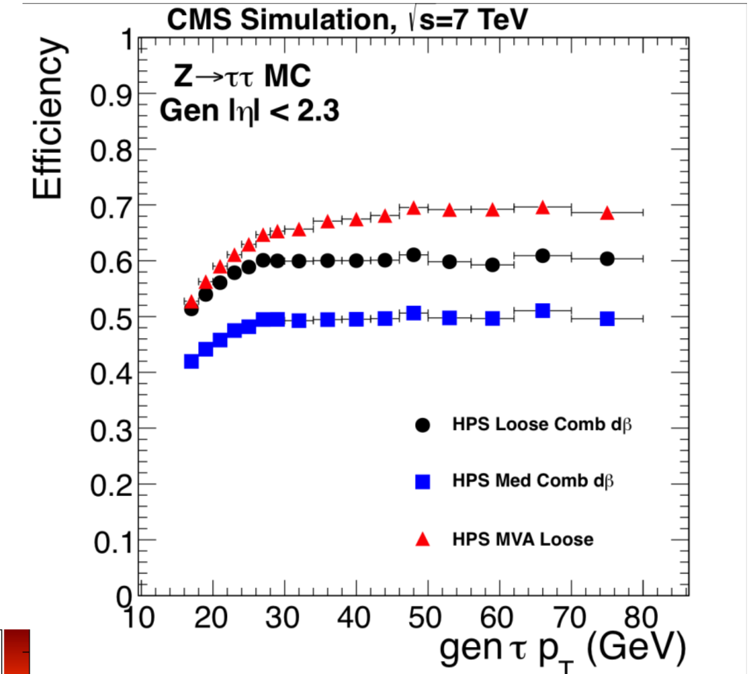
- Selected Events analyzed in 2 Categories: non-b-Tag and b-Tag
  - b-Tag : ≤ 1 jet with $p_T > 30$ GeV, ≥ 1 b-Tagged Jet with $p_T > 20$ GeV
  - Non b-Tag : ≤ 1 jet with $p_T > 30$ GeV, No b-Tagged Jet with $p_T > 20$ GeV

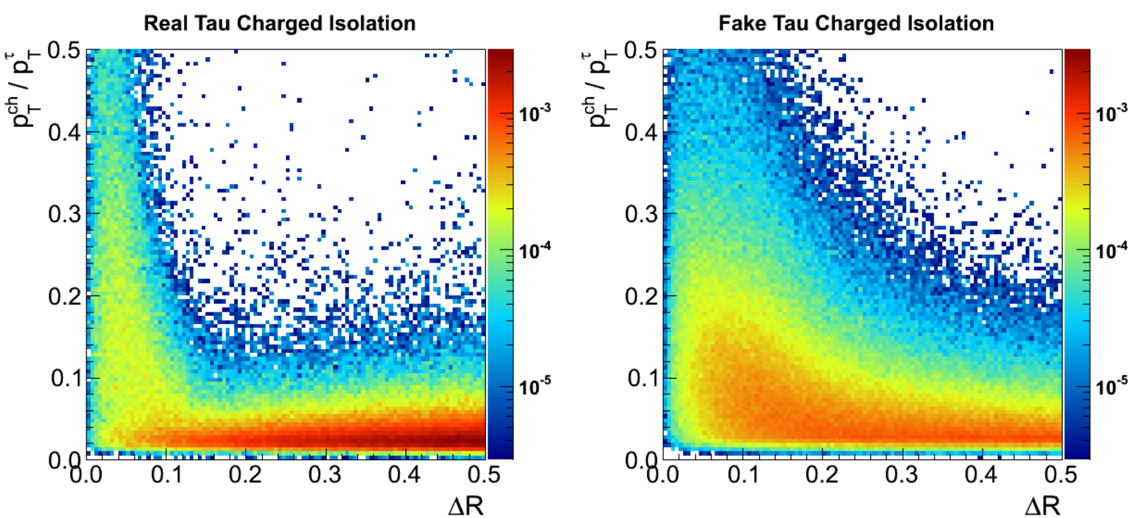
Tau Identification @ CMS

Hadron + Strips Algorithm



π^+/K^+ , $\rho^+ \rightarrow \pi^+\pi^0$ and $a_1 \rightarrow \pi^+\pi^-\pi^+(\pi^+\pi^0\pi^0)$

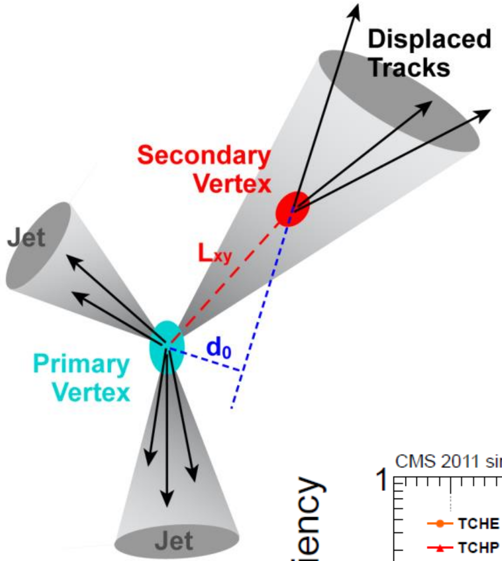




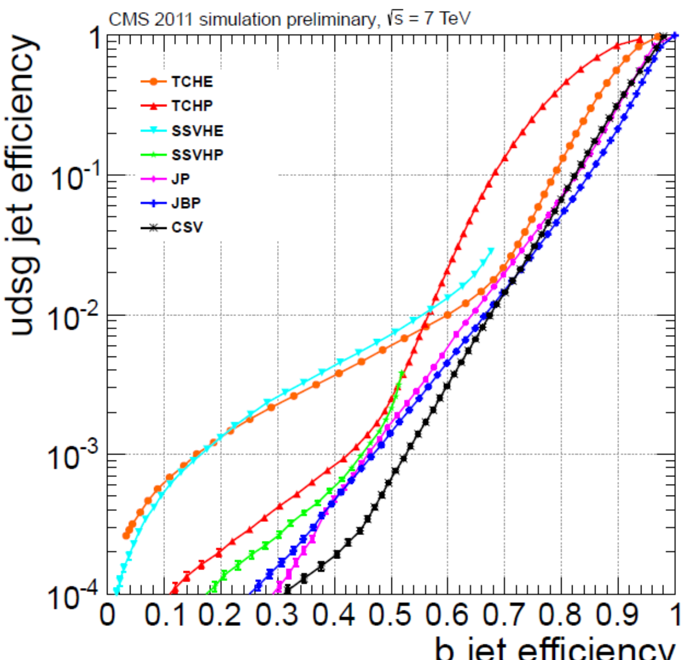
Ring-Based Isolation :

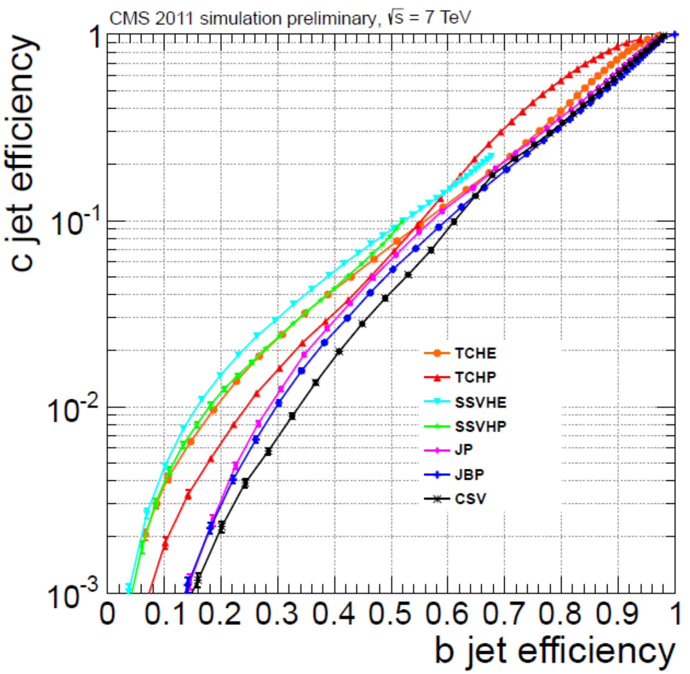
- Isolation pT summed inƒnƒ´R rings around tau
- BDT trained against jet → τ fakes

b-Jet Tagging



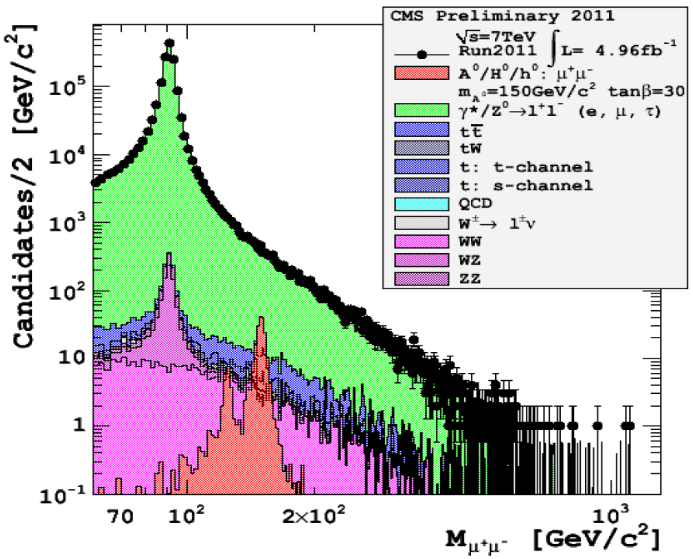
Many algorithms developed at CMS, based on track impact parameter and secondary vertex of B hadron decay
Algorithm used for most Higgs searches in 2011 : TCHE
TCHE : Simple method.
Tracks are ordered according to the impact parameter significance (IP/σ_{IP}). The IP significance of 2nd track is used as discriminator.

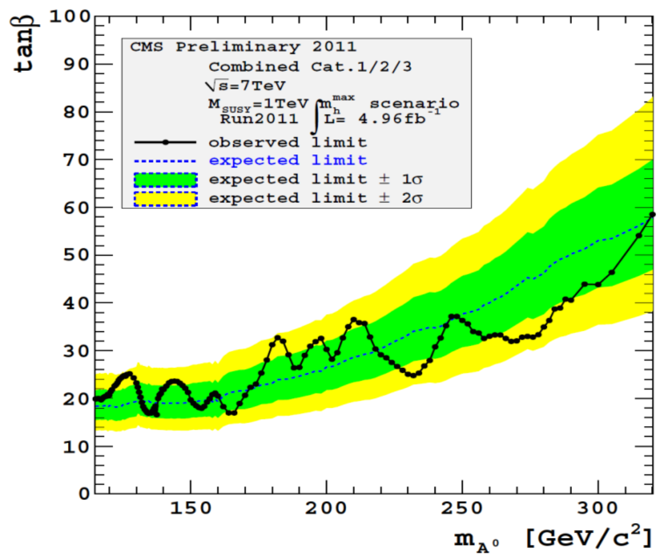




φ→μμ Search

CMS PAS HIG-12-011





Small Branching ratio (few times 10^{-4}), However, Muons are reconstructed very efficiently in CMS and with very good Mass Resolution (almost comparable to Higgs width)

Event Selection

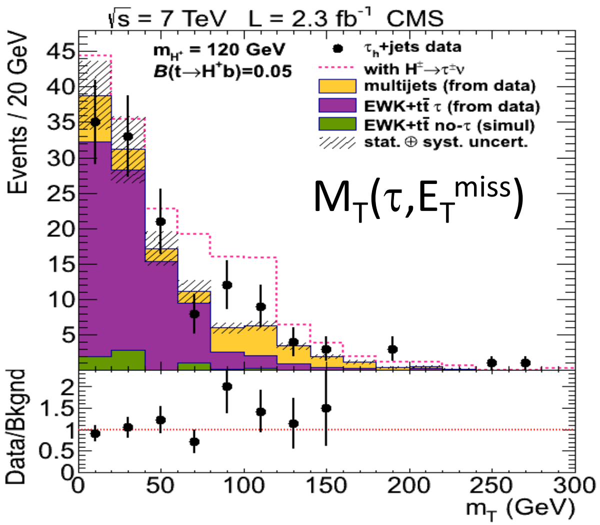
Single Muon trigger
2 Muons P_T 1st > 30 GeV P_T 2nd > 20 GeV
$|\eta| < 2.1$, isolated

Opposite Charge Muon Pair
Suppression of tt Background $E_T^{miss} < 30$ GeV

Selected Events analyzed in 3 Categories: b-Tag, 3rd Muon and neither

- Observed diMuon mass spectrum is well in agreement with background expectations.

H^+ Signal Extraction



The signal is defined as the excess of ttbar event yields in presence of H^+

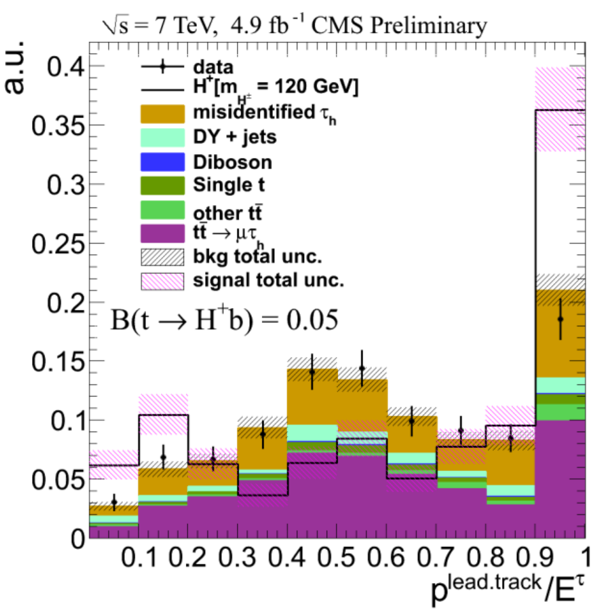
N_{excess} =

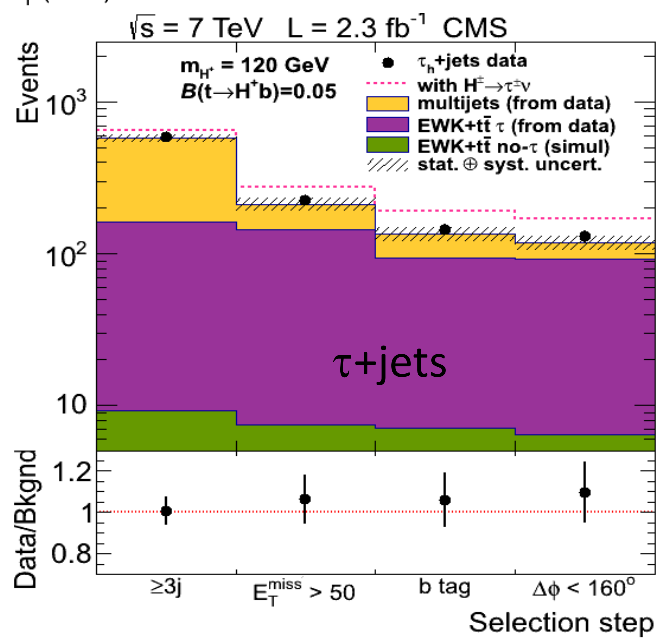
$N_{tt}^{MSSM} - N_{tt}^{SM} = N_{WH}\, 2(1-x)x + N_{HH}\, x^2 + N_{tt}^{SM}\, ((1-x)^2 - 1)$,

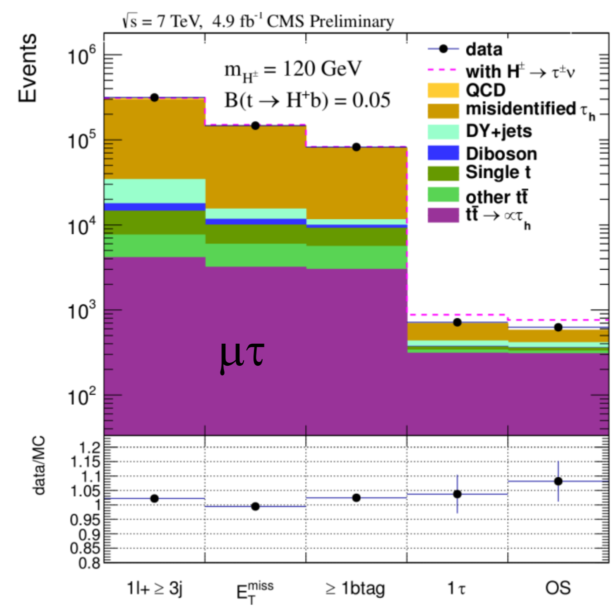
$x = BR(t \to H^+ b)$

No Excess of events observed. Data is agrees well with SM backgrounds

Major backgrounds are estimated from data.

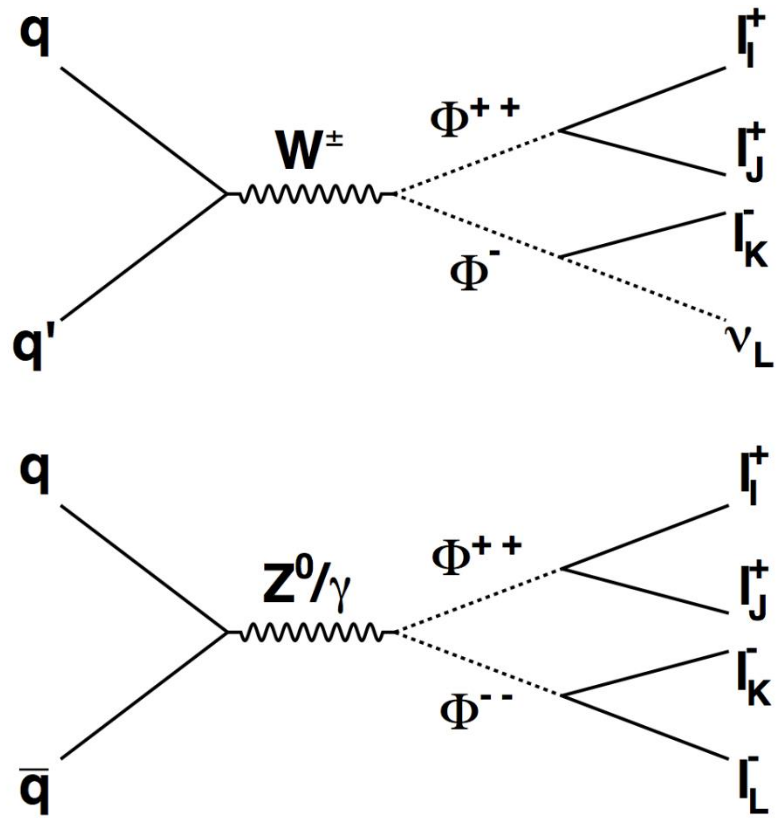






Doubly charged Higgs boson (Φ^{++})

- Standard model extension by a scalar triplet adding three new particles
  - Φ^{++}, Φ^{+}, Φ^{0} (e.g. Type-|| seesaw model)
- The triplet is responsible for neutrino masses, the couplings being directly linked to the mass matrix
  - $M_{ij} = k\, Y_{ij}$
- Unknown neutrino mass matrix
  → unknown branching ratios
- assume branching ratios to leptons only

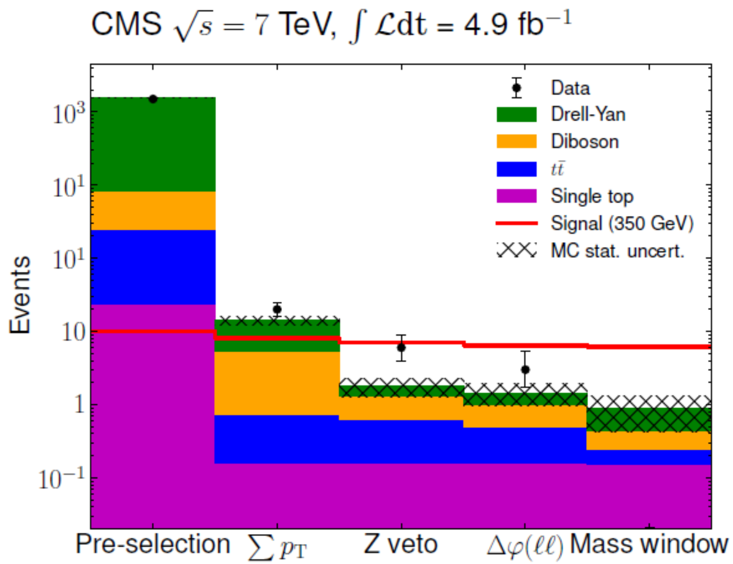


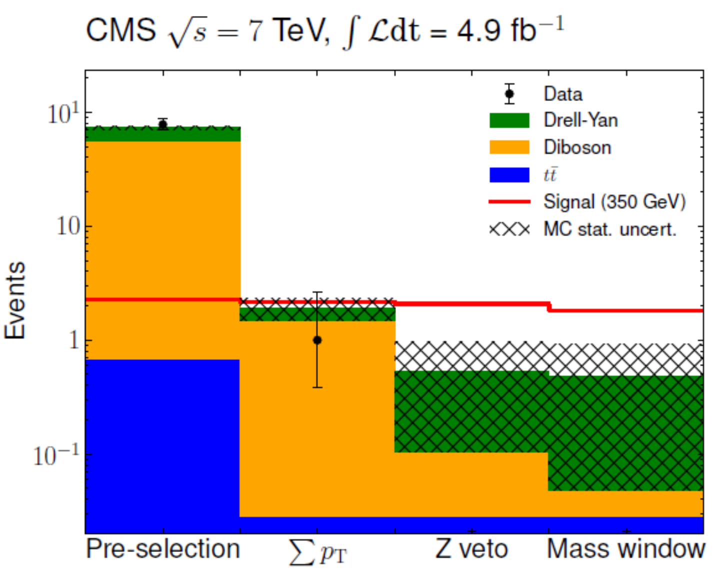
➢ Six standard searches covered, where **$BR(\Phi^{++} \rightarrow l^{+}l^{+}) = 100\%$**

➢ Four additional model dependent points to describe the neutrino sector

Φ^{++} and Φ^{+} are assumed to be degenerate in mass

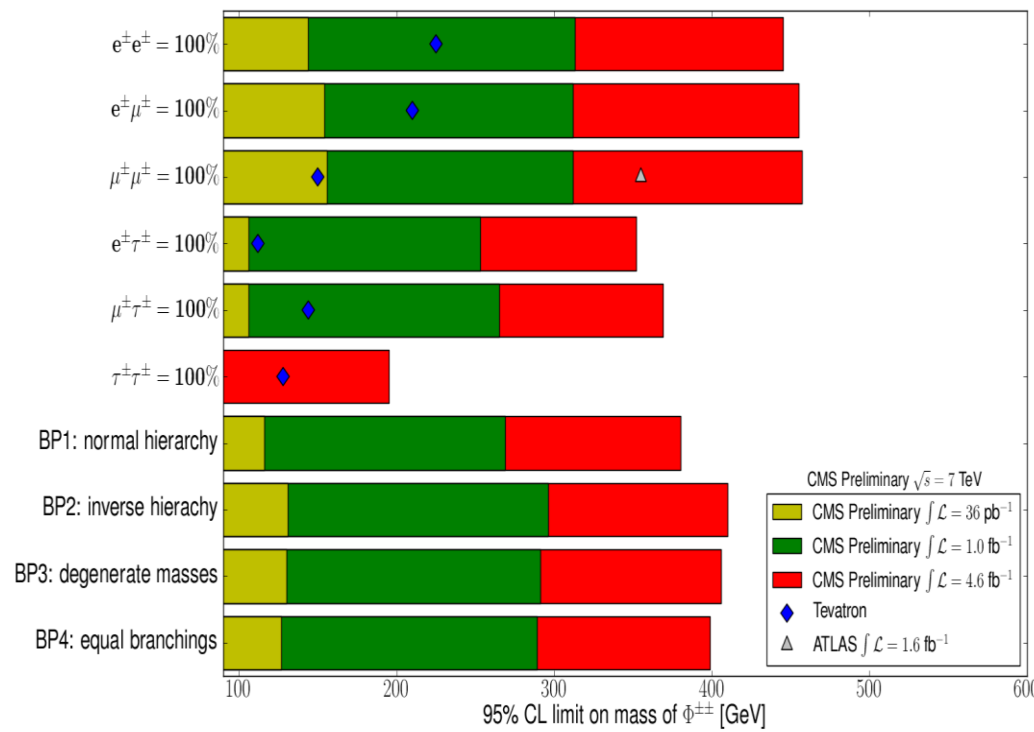
Φ^{++} Exclusion Limits





Signatures: 3 or 4 leptons in the final state, dilepton made by same sign lepton

arXiv:1207.2666



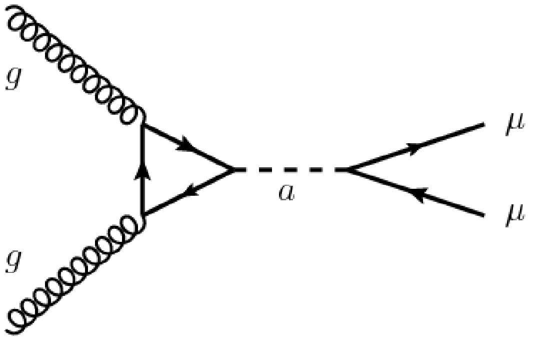
NMSSM: $a_1 \rightarrow \mu^+\mu^-$

- Add a scalar singlet to MSSM Higgs family
  - 3 CP even (h1, h2, h3) , 2 CP odd (a1, a2), and H±
  - One of the CP odd Higgs boson can be very light

    $a1 = a_{mssm} \cos\theta_A + a_s \sin\theta_A$

    (superposition of MSSM CP odd doublet scalar

    And the additional CP odd singlet scalar)
- At CMS: search above and below the Upsilon family
  - Larger production rate relative to Tevatron
  - Extended search relative to BaBar.



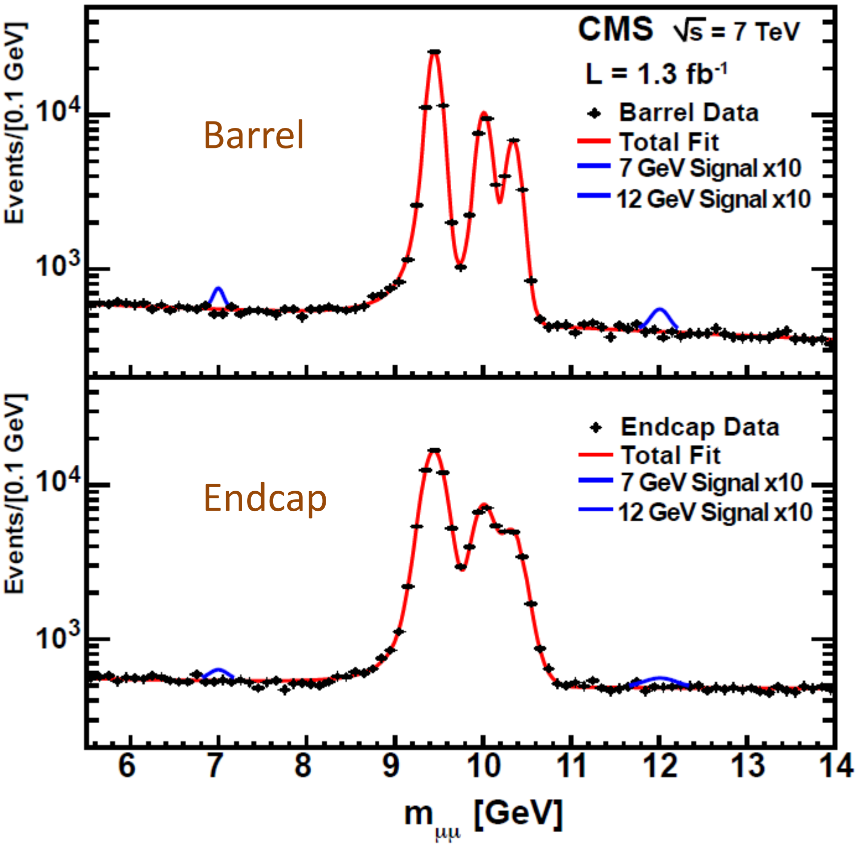
Search mass ranges
5.5-8.8 GeV and 11.5-14 GeV

Event Selection

- Trigger (Prescaled) :
  - OS dimuon, $p_T^{\mu} > 3.5$ GeV, $p_T^{\mu\mu} > 6.0$ GeV
  - $5.5 < m_{\mu\mu} < 14$ GeV
  - Impact parameter compatible with prompt muon
- Offline Muon Selection : $p_T^{\mu} > 5.5$ GeV, $|\eta| < 2.4$, isolated

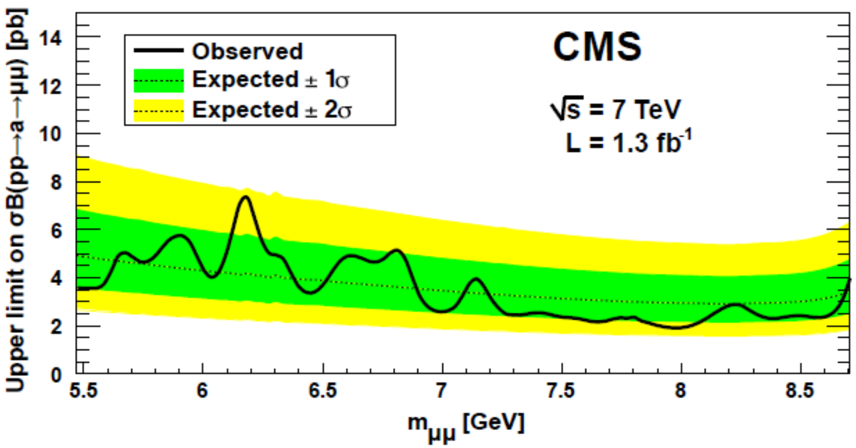
Search Strategy

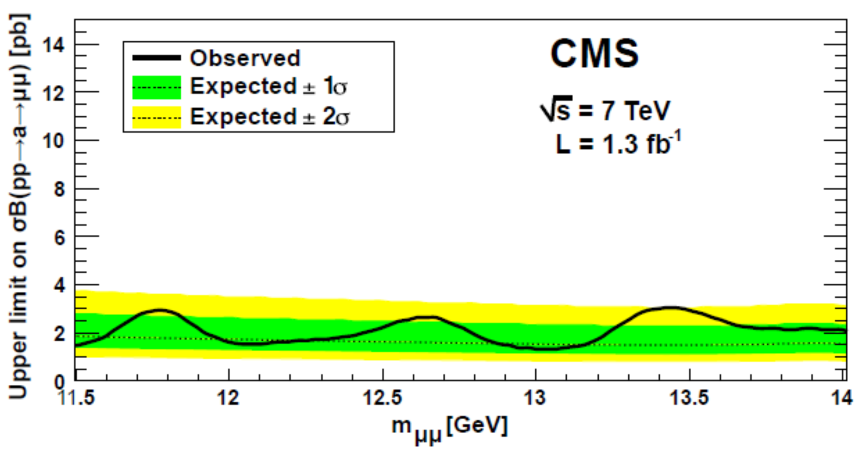
- Signal extraction
  - Binned ML fit over 5.5 – 14 GeV
  - Mass scan in 30 MeV steps
- Background model
  - QCD: 1st-order polynomial
  - Y(NS): double crystal ball
- Signal model
  - Single Gaussian
  - Mean fixed to center of step
  - Width fixed to detector resolution (by fitting the inv. mass spectrum with two CB functions)
    - Barrel : 50 – 120 MeV
    - Endcap : 90 – 190 MeV



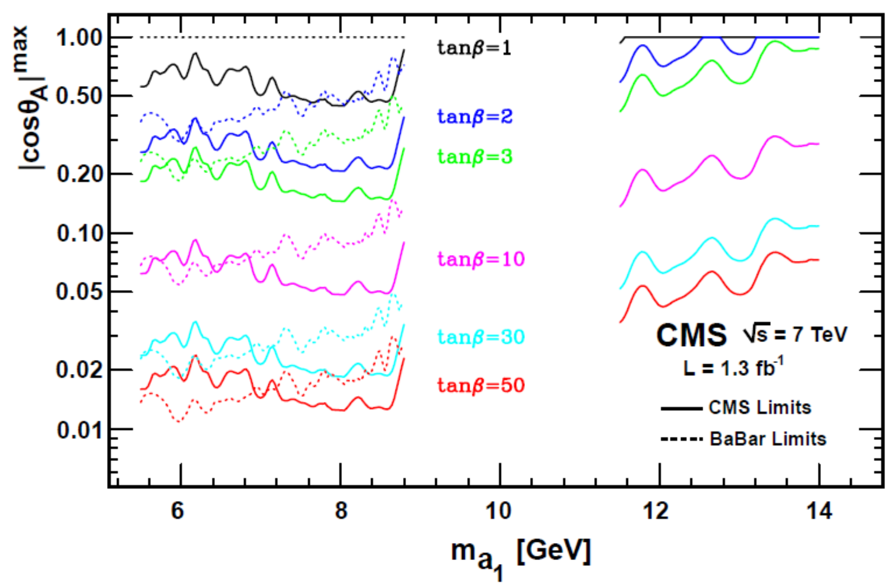
Exclusion Limits

arXiv:1206.6326





No significant excess of events observed in 1.3fb-1 @ 7 TeV, exclusion limits set at the level of 2 – 6 pb for σ x B



production of a_1