Search for Higgs boson in models beyond SM at CMS

Aruna Kumar Nayak

IRFU, CEA, Saclay

(On behalf of CMS Collaboration)

Higgs Hunting Workshop
Orsay, France

Overview

- Higgs boson in MSSM
  - Neutral Higgs boson : bb, $\tau\tau$, $\mu\mu$
  - Charged Higgs boson : $\tau\nu$
- Higgs boson in Next-to-MSSM
  - A very light CP odd scalar boson : $a_1 \rightarrow \mu^+\mu^-$
- Doubly charged Higgs boson
  - Doubly charged Higgs boson Φ^{++} in exotic models like Type-II seesaw mechanism
- Higgs boson in SM with 4^{th} generation
  - Re-interpret searches for SM Higgs boson in the contest of SM with 4 generation of fermions

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 tanβ

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

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

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

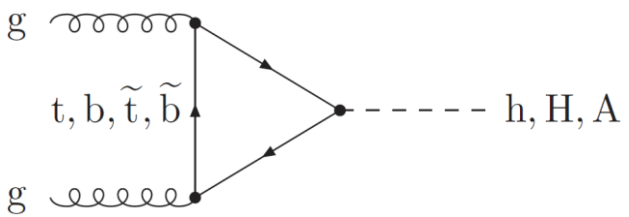
$$M_{H^+}^2 = M_A^2 + M_W^2$$

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

Other SUSY parameters are important at higher order corrections

MSSM Higgs production at LHC

- Neutral Higgs production and decay :



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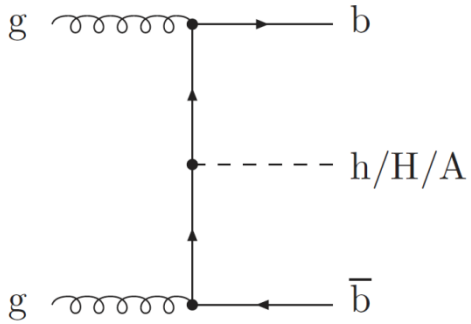
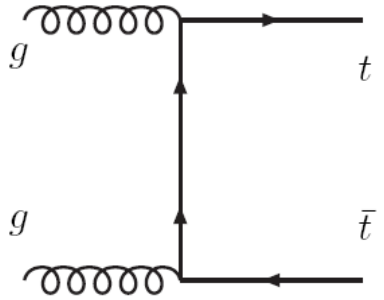


  - Dominant decay mode : bb and ττ

- Charged Higgs production and decay :

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

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



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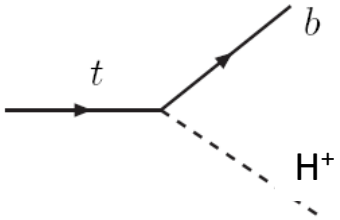


For $M_{H^+} \geq m_{top}$: $pp \to tbH^{\pm}$

(Not Yet analyzed by CMS)

MSSM Higgs search channels

- $pp \rightarrow \varphi b, \varphi \rightarrow bb$
  - Semileptonic b decays (jet containing a muon)
  - Hadronic b decays

φ : h, H, A

- $pp \rightarrow \varphi, \varphi \rightarrow \tau\tau$
  - $e+\mu$ (very clean channel, low statistics)
  - $e+\tau_{had}$ (larger background, high statistics)
  - $\mu+\tau_{had}$ (smaller background, high statistics)

τ_{had}: hadronic τ decay

- $pp \rightarrow \varphi, \varphi \rightarrow \mu\mu$
- $pp \rightarrow tt, t \rightarrow H^+b, H^+ \rightarrow \tau\nu$

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

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

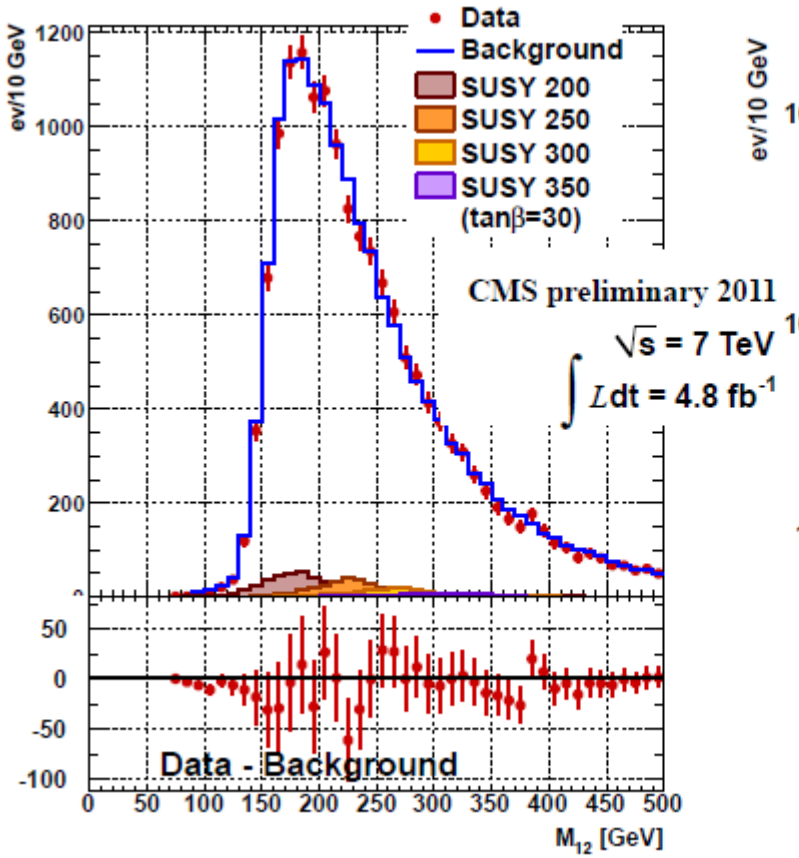
φ → bb Analysis

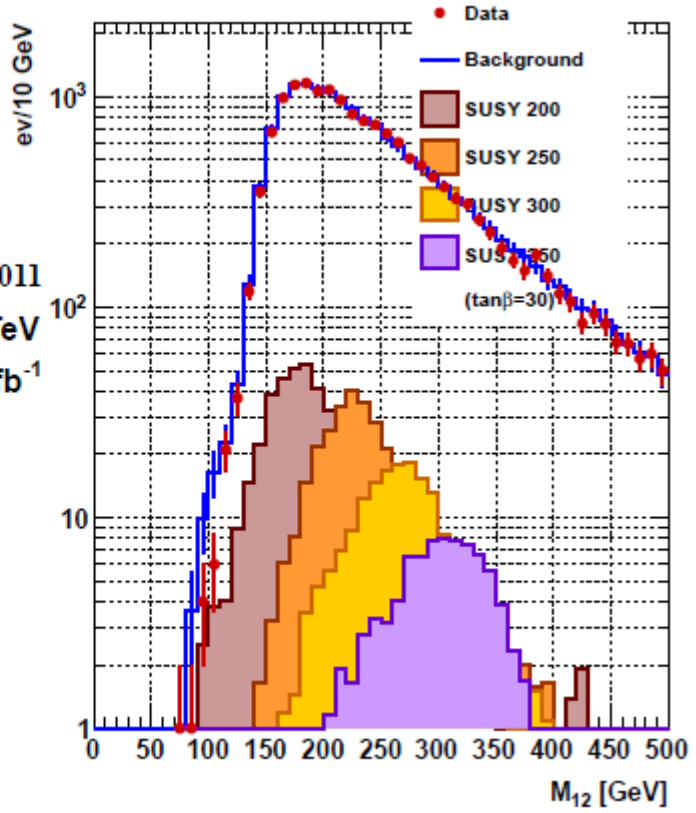
	Semileptonic	Hadronic
• **Trigger :**	Muon+1/2 Jets ≥ 1/2 b-tagged	2/3 Jets ≥ 2 b-tagged
• **Offline :**		
Muon	P_T > 15 GeV (no Isolation applied)	
Jets	≥ 2 Jets of P_T > 30 GeV + 3rd Jet of P_T > 20 GeV $\|\eta\|$(jets) < 2.6, all 3 b-tagged Muon is within one of two leading jets	≥ 3 Jets: P_T 1st > 46 (60) GeV P_T 2nd > 38 (53) GeV P_T 3rd > 20 GeV $\|\eta\|$(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 Mφ < 180 GeV (Mφ > 180 GeV), driven by Trigger Thresholds

diJet Mass (semileptonic)



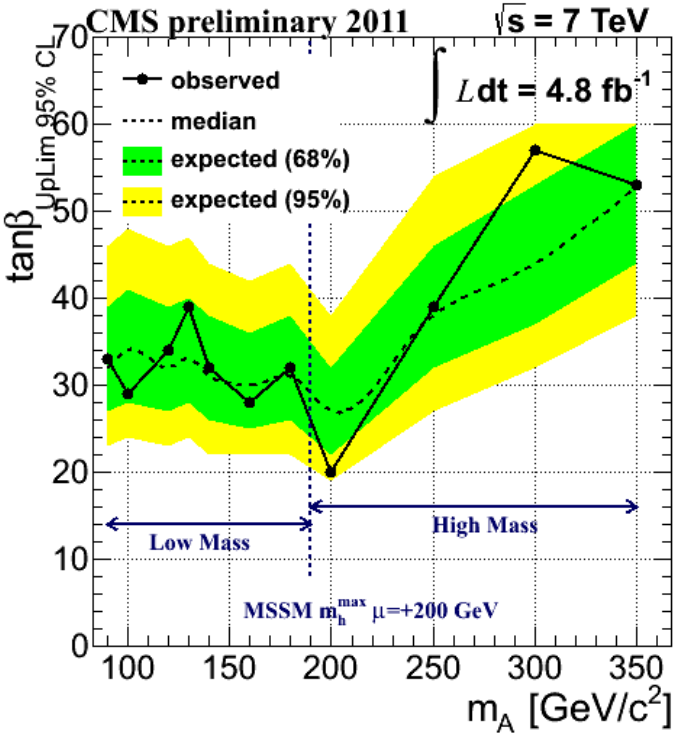


Data in Agreement with background prediction

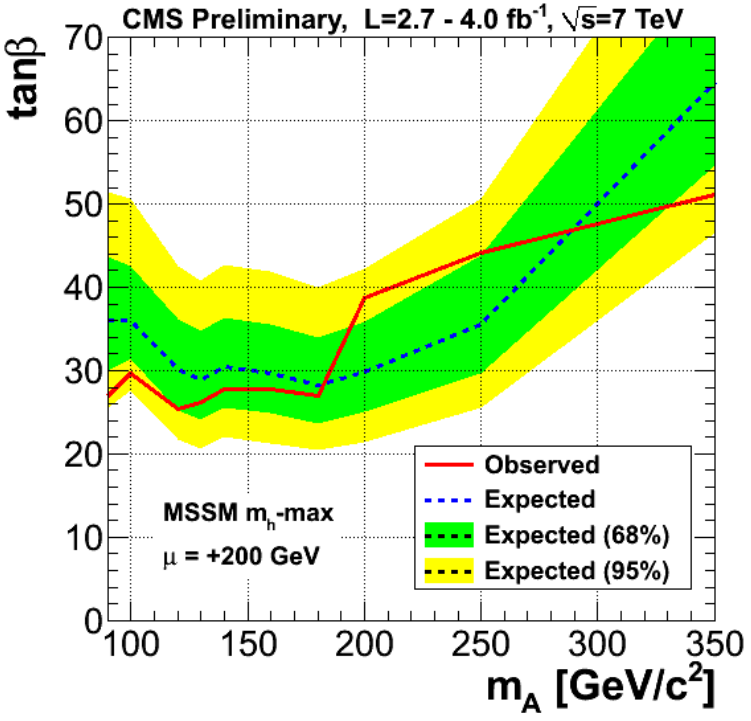
M_{12} Resolution ~15%

φ → bb Exclusion Limits

CMS PAS HIG-12-027
Semileptonic



CMS PAS HIG-12-026
Hadronic



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

$\varphi \rightarrow \tau\tau$ Analysis

Event Selection

- Trigger

Events triggered by e+μ, e+τ_{had} and μ+τ_{had} Triggers, P_T thresholds 10-20 GeV/c

- Lepton Selection

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

- Opposite Charge Lepton Pair

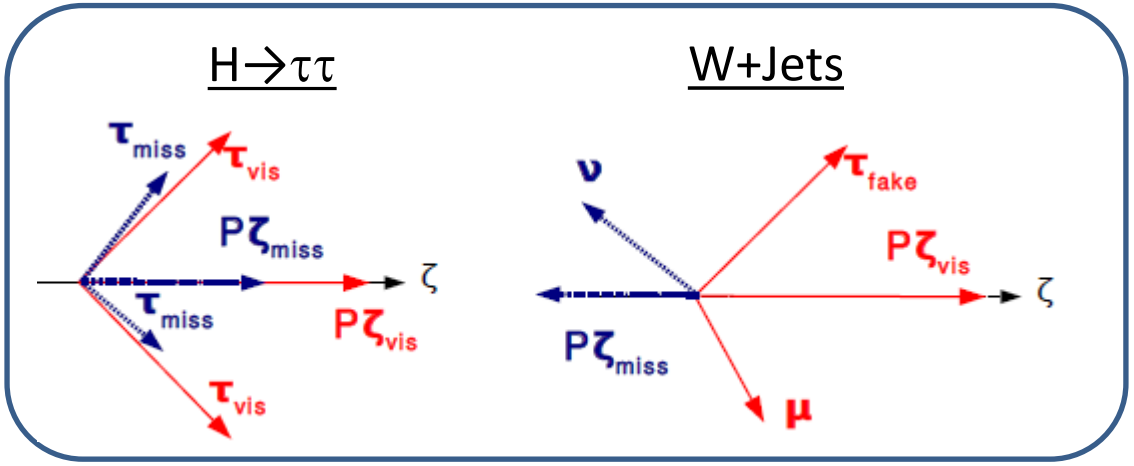
- Veto Events with additional isolated Leptons

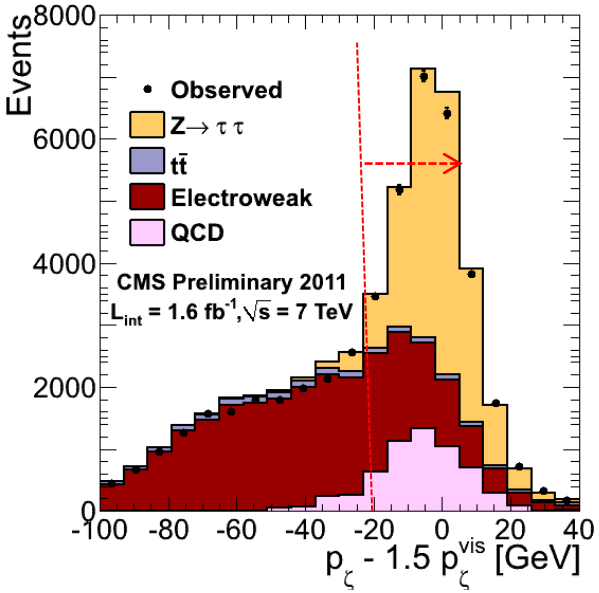
- Selected Events analyzed in 2 Categories: non-b-Tag and b-Tag
  - b-Tag : ≤ 1 jet with p_T > 30 GeV, ≥ 1 b-Tagged Jet with p_T > 20 GeV
  - Non b-Tag : ≤ 1 jet with p_T > 30 GeV, No b-Tagged Jet with p_T > 20 GeV

Background suppression

- Backgrounds : Z → ττ, Z → ee, μμ, QCD, W+Jets, ttbar, diboson.
- Taus, in signal, are produced with large p_T. Thus neutrinos produced in the tau decay are collinear with the visible products.
- Requiring E_T^{miss} to point in the direction of visible decay products suppress W+jets and top backgrounds.

$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta$$
$$P_\zeta = P_\zeta^{vis} + E_T^{miss} \cdot \zeta$$



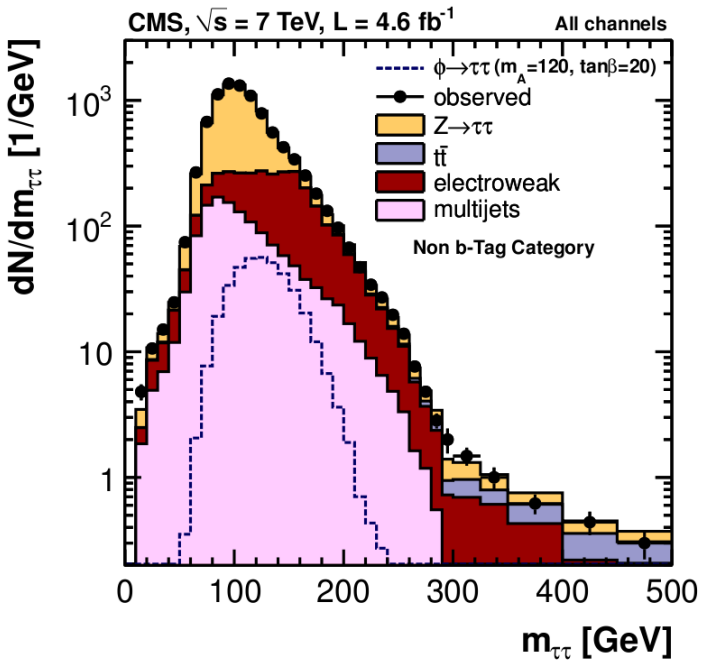


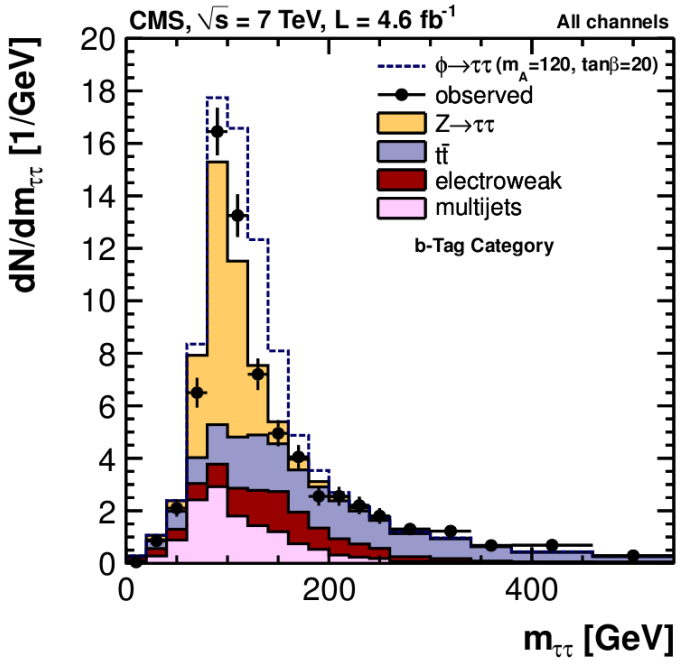
Background Estimation

- $Z \rightarrow \tau\tau$: Use observed $Z \rightarrow \mu\mu$ sample and replace muon by simulated tau ("embedding"). Normalized to the measured $Z \rightarrow \mu\mu$ cross section.
- QCD : Estimated from SS/OS data.
- W+jets : Shape from MC and normalization from P_ζ sideband.
- Top pair : Taken from MC and normalized to CMS measured cross section.
- Di-boson : Taken from MC (negligible)

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 hypotheses
- $m_{\tau\tau}$ Resolution ~20% (almost Gaussian)



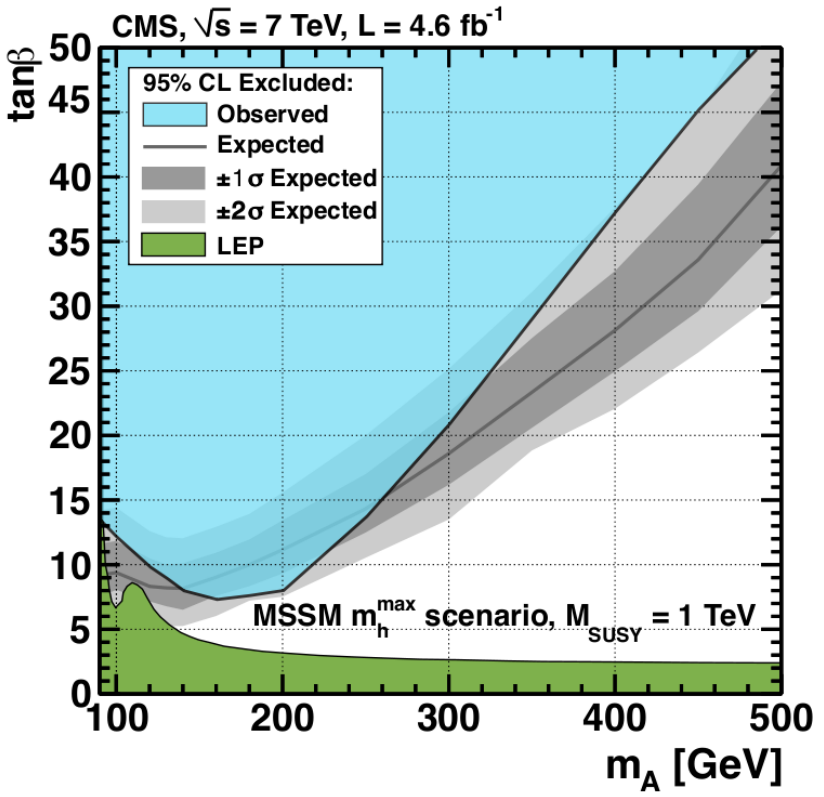


- Distribution observed in Data in agreement with background expectation

φ → ττ Exclusion Limit

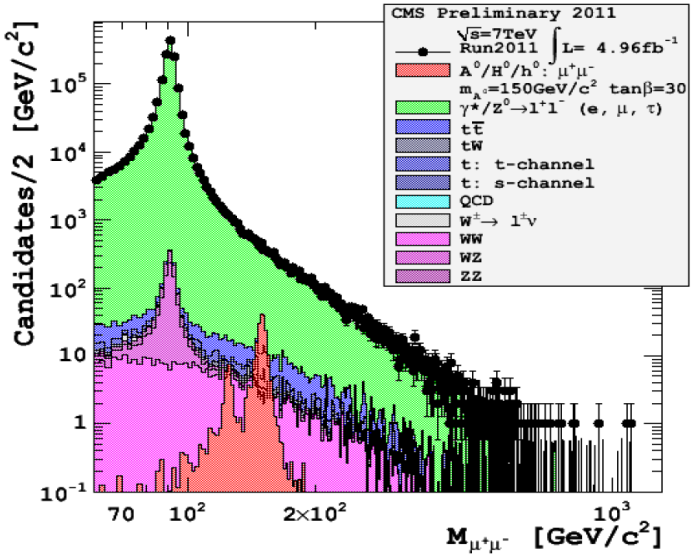
arXiv:1202.4083

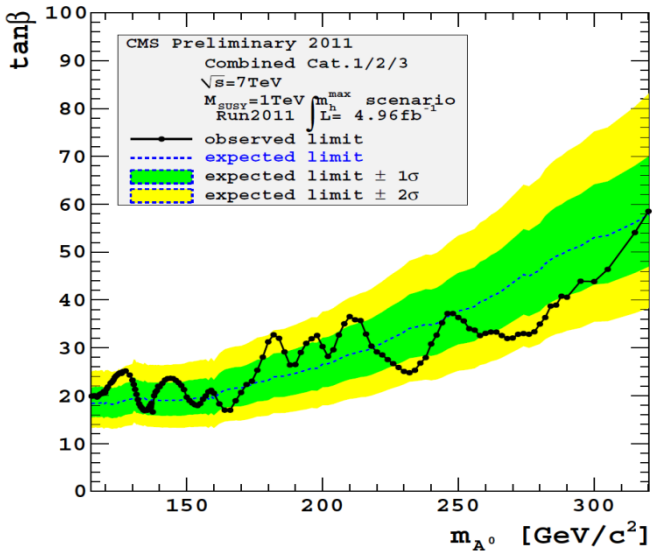
- Limit obtained by scanning tanβ for each mass hypothesis M_A:
- Cross-section × BR for gg → φ and bb → φ computed as function of M_A, tan(β)
- Dependence of M_h and M_H on tanβ taken into account



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^+ Event Selection

	τ_{had}+Jets	e/μ+τ_{had}	e+μ
➢ Trigger	τ_{had}+E_T^{miss}	Electron+2 Jets+missing H_T / single Muon	Electron+Muon
➢ Lepton Selection	$P_T^{\tau} > 40$ GeV tight Tau Id.	$P_T^{e} > 35$ GeV $P_T^{\mu} > 30$ GeV isolated $P_T^{\tau} > 20$ GeV	$P_T^{e} > 20$ GeV $P_T^{\mu} > 20$ GeV isolated
➢ Jets	3 Jets of $P_T > 30$ GeV 1 b-tagged	2 Jets of $P_T > 35$ (30) GeV 1 b-tagged	2 Jets of $P_T > 20$ GeV
➢ E_T^{miss}	> 50 GeV $\Delta\phi(\tau_{had}, E_T^{miss}) < 160^o$	> 45 GeV for e+τ_{had} > 40 GeV for μ+τ_{had}	

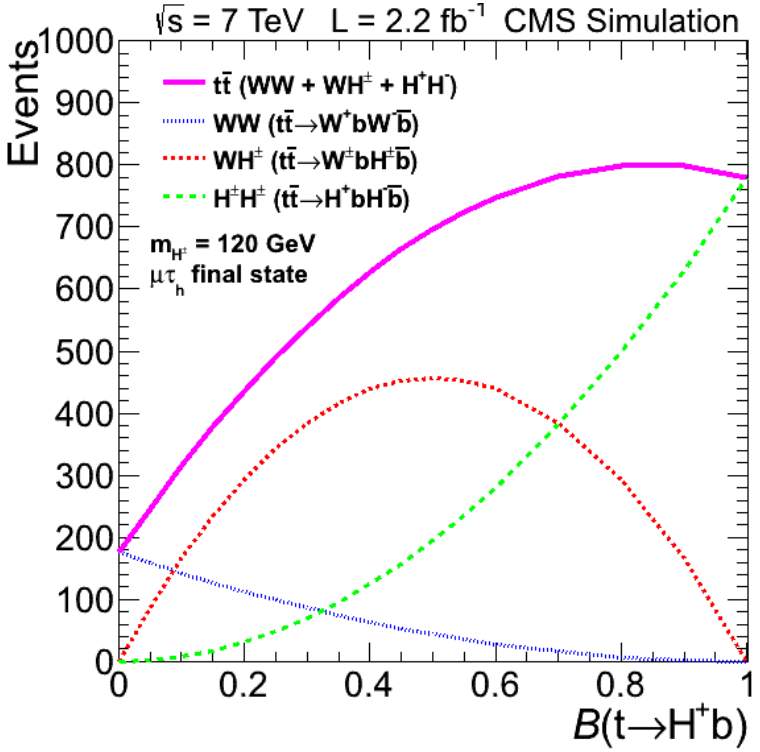
➢ Opposite Charge Lepton Pair

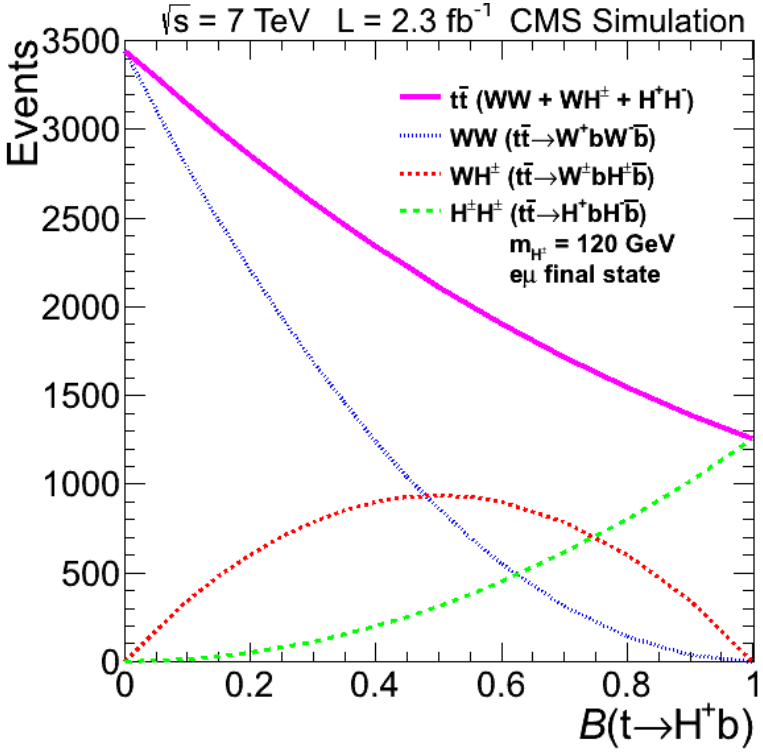
➢ Veto Events with additional isolated Electrons or Muons

Major backgrounds have been estimated from data

H^+ signal interpretation

Excess (deficit) of events expected in the channels with hadronic (leptonic) tau decay

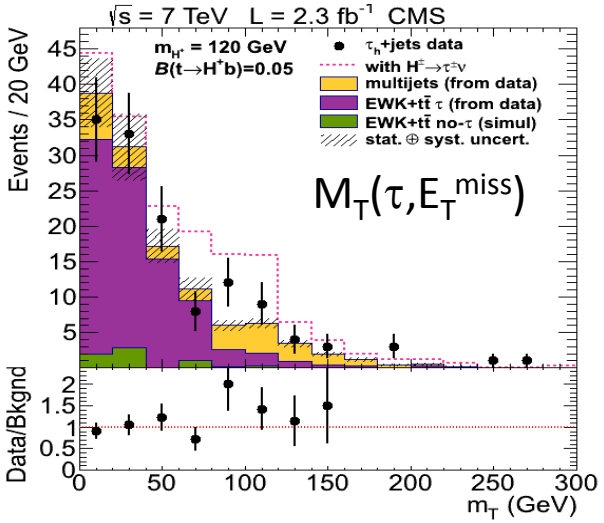




$x = BR(t \rightarrow bH^+)$

N_{tt} (in presence of H^+) = $N_{WH}\, 2(1-x)x + N_{HH}\, x^2 + N_{tt}^{SM}\, (1-x)^2$

H^+ Signal Extraction



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

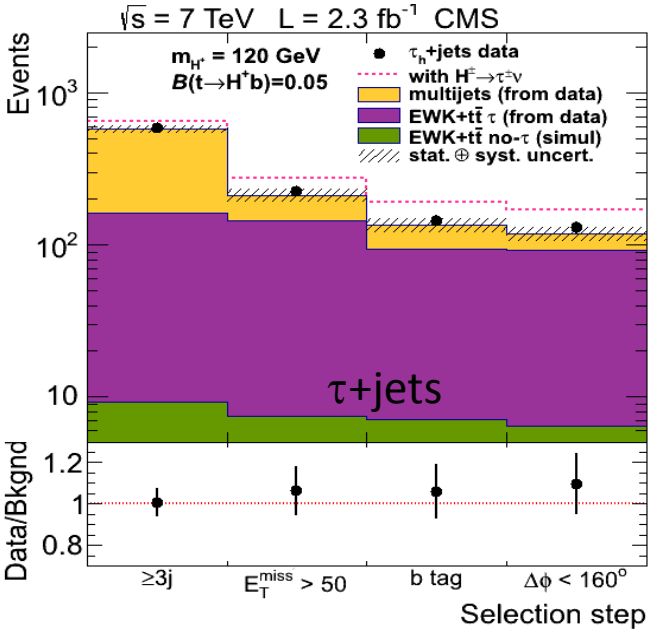
N_{excess} =

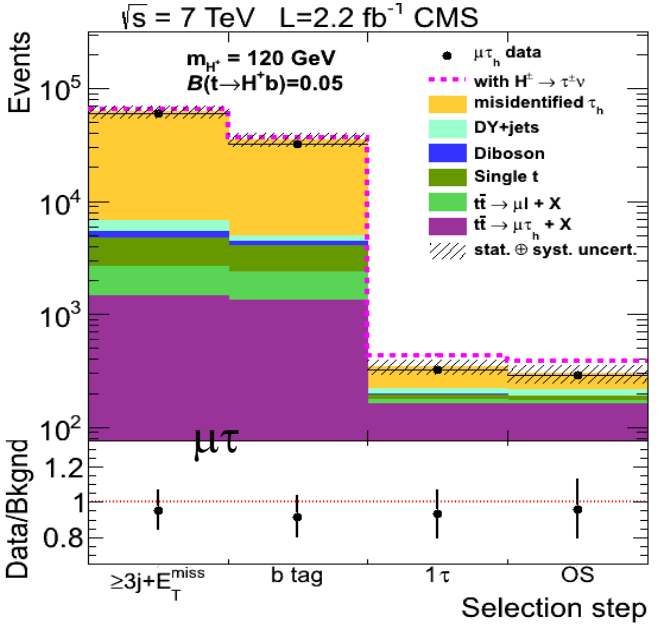
$N_{tt}^{MSSM} - N_{tt}^{SM} = N_{WH}\, 2(1-x)x + N_{HH}\, x^2 + N_{tt}^{SM}\, ((1-x)^2 - 1)$,

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

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

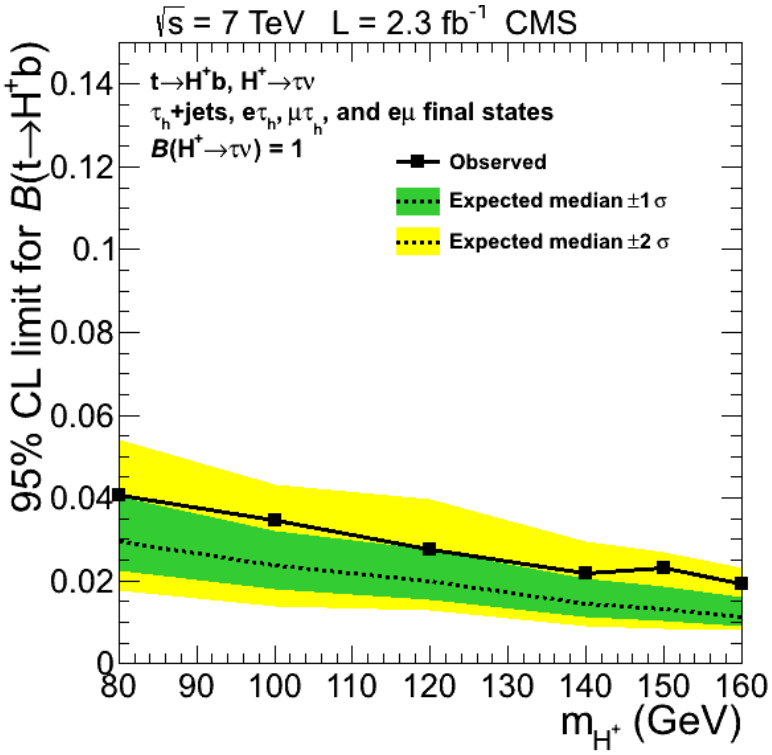
Major backgrounds are estimated from data.

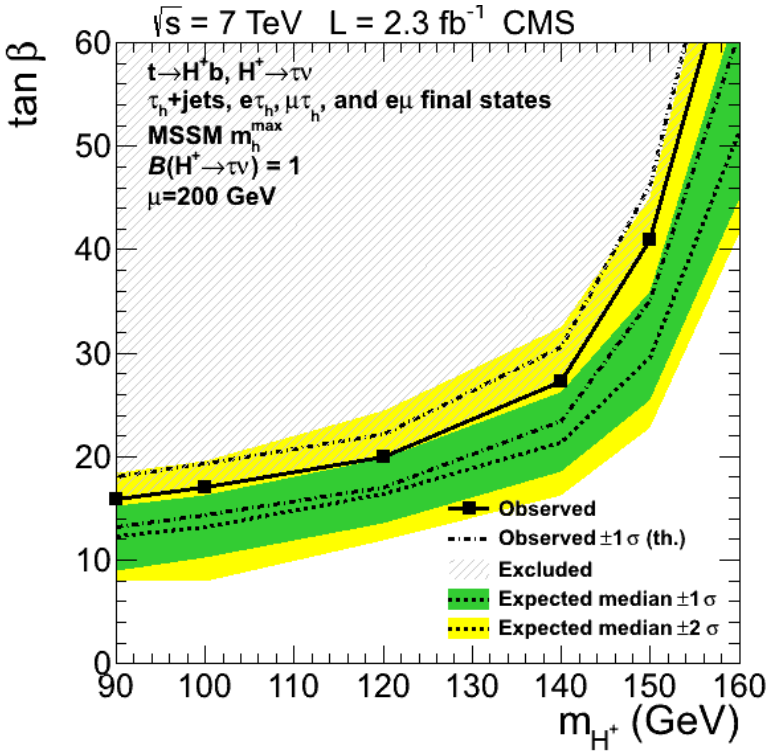




H^+ Exclusion Limit

arXiv:1205.5736





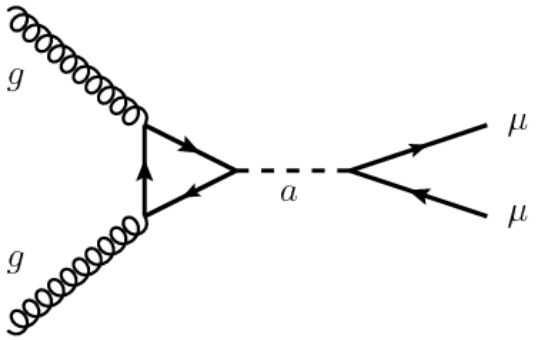
Upper limit on BR(t → H^+b) excludes region of large tanβ in MSSM Parameter space for $M_{H+} / M_A \leq M_{top}$

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.



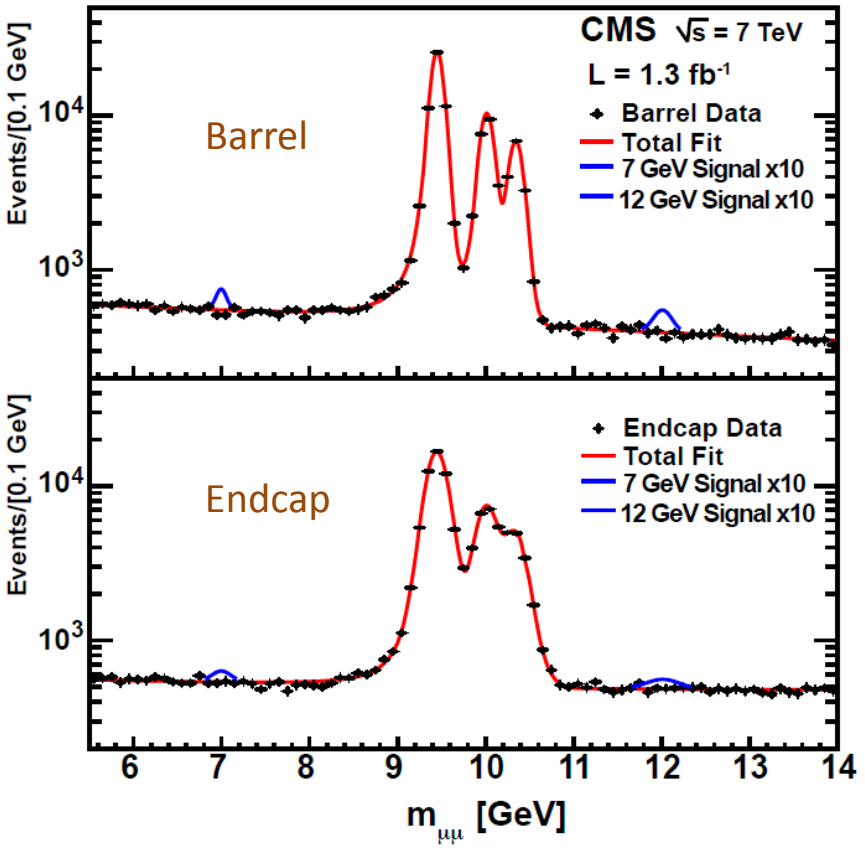
Search mass ranges
5.5-8.8 GeV and 11.5-14 GeV

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

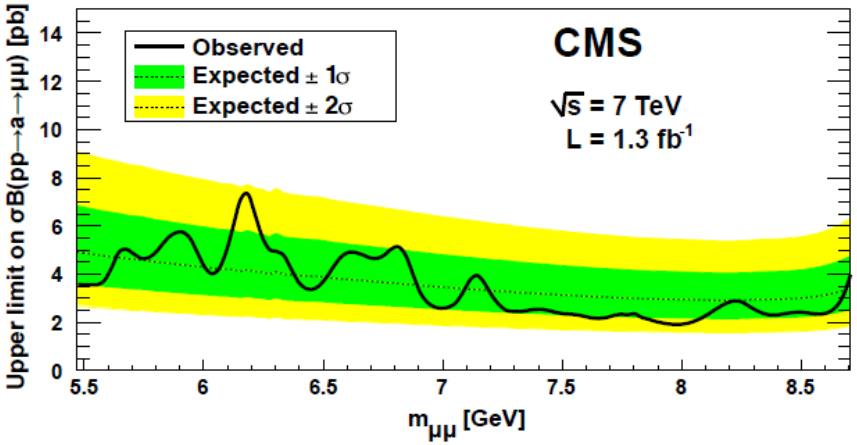
Search Strategy

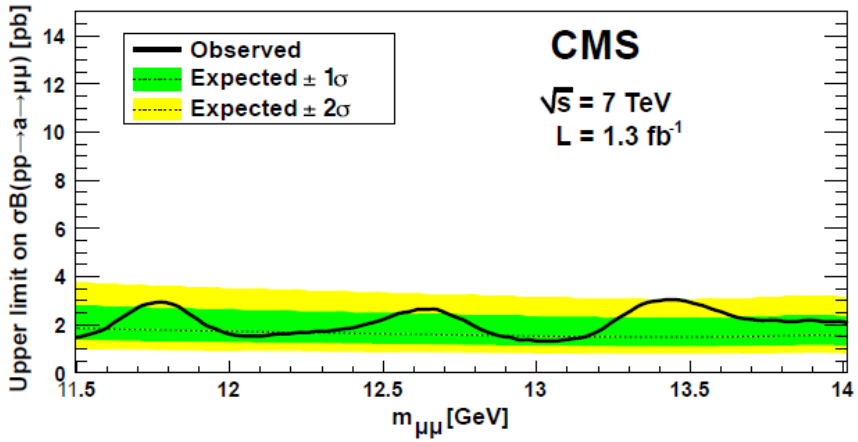
- Signal extraction
  - Binned ML fit over 5.5 – 14 GeV
  - Mass scan in 30 MeV steps
- Background model
  - QCD: 1st-order polynomial
  - Y(NS): double crystal ball
- Signal model
  - Single Gaussian
  - Mean fixed to center of step
  - Width fixed to detector resolution (by fitting the inv. mass spectrum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



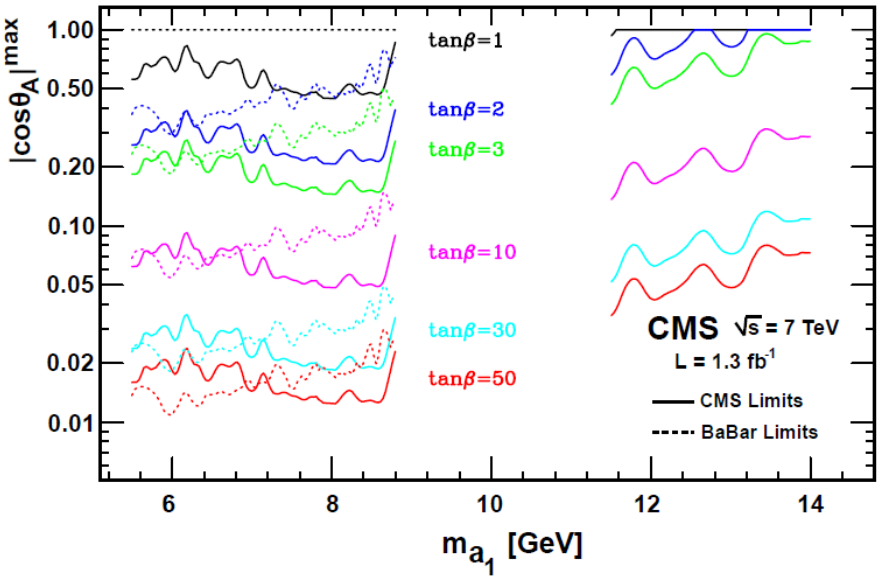
Exclusion Limits

arXiv:1206.6326



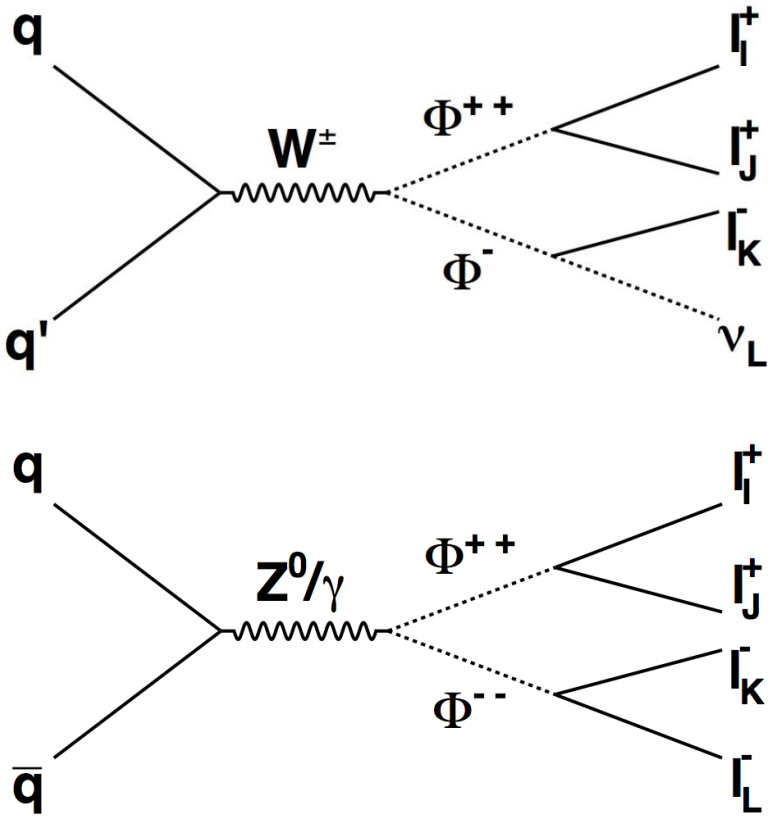


No significant excess of events observed in 1.3fb-1 @ 7 TeV, exclusion limits set at the level of 2 – 6 pb for σ x B



Doubly charged Higgs boson (Φ^{++})

- Standard model extension by a scalar triplet adding three new particles
  - $\Phi^{++}, \Phi^{+}, \Phi^{0}$ (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^{++} analysis strategy

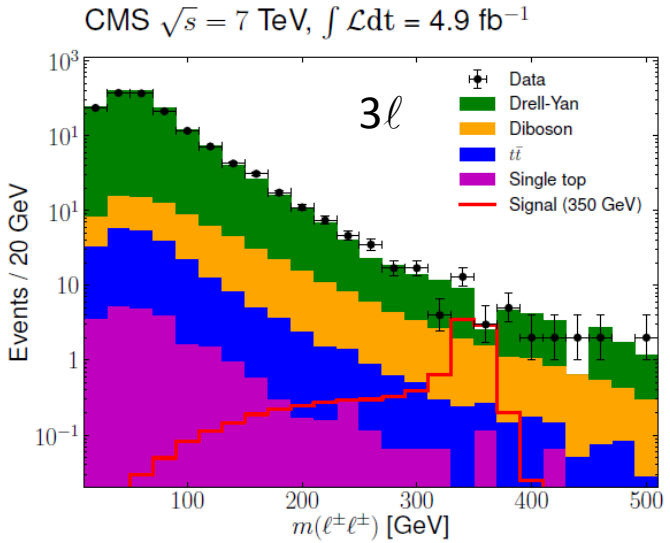
- Signatures: **3 or 4 leptons** in the final state, dilepton made by same sign lepton

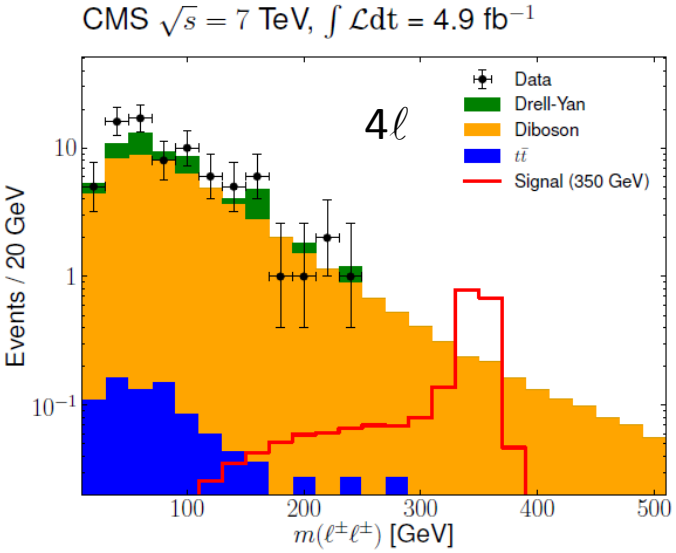
- Selection strategy:
  - dilepton triggers : 17/8 GeV for ee, eμ; varying for μμ
  - lepton id and charge matching
  - At least two leptons with pT > 20 / 10 GeV
  - Loose isolation requirement
  - Veto of low invariant mass resonances (< 12 GeV)

  pre-selection

  - Σp_T cuts on leptons (depend on m_ϕ)
  - tight isolation of leptons
  - Z veto, E_T^{miss}
  - cut on $\Delta\phi$ between leptons

  Topological cuts on leptons depending on final states (3 OR 4 leptons) and m_ϕ



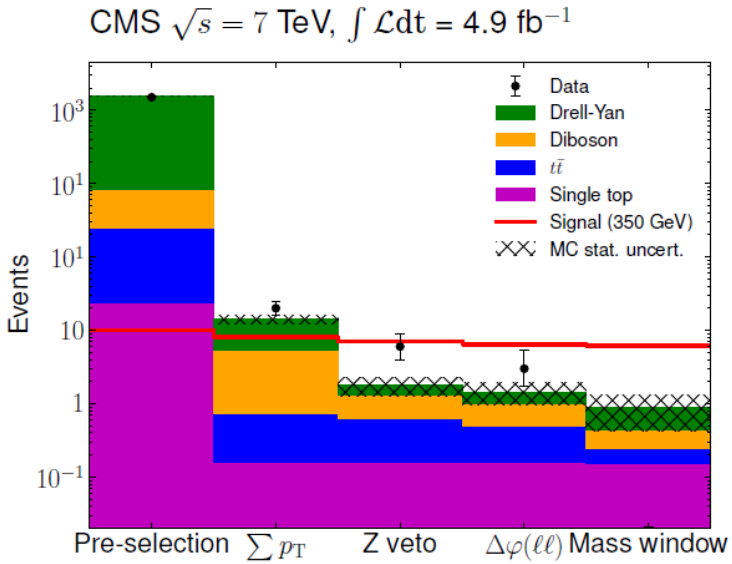


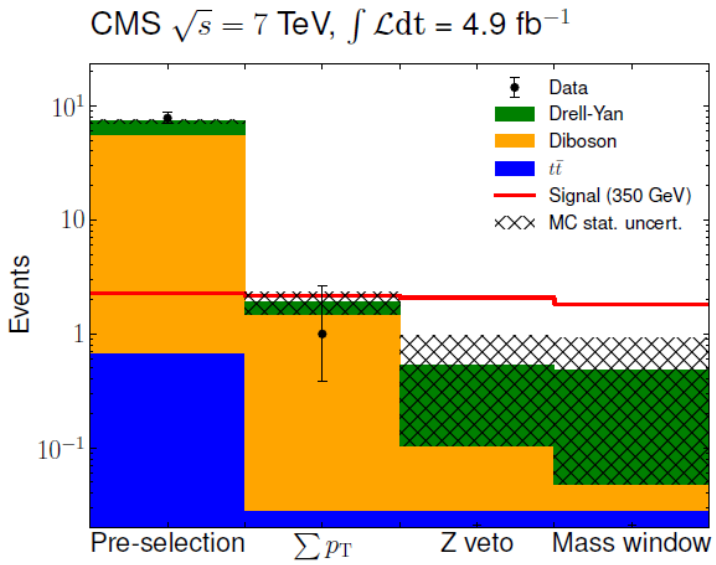
- Events are counted in the mass window depending on the Higgs boson mass considered

- Selections are optimized as a function of m_Φ separately for $\ell\ell$, $\ell\tau_h$, and $\tau_h\tau_h$ events, where ℓ = e, m

- Backgrounds are estimated from sidebands

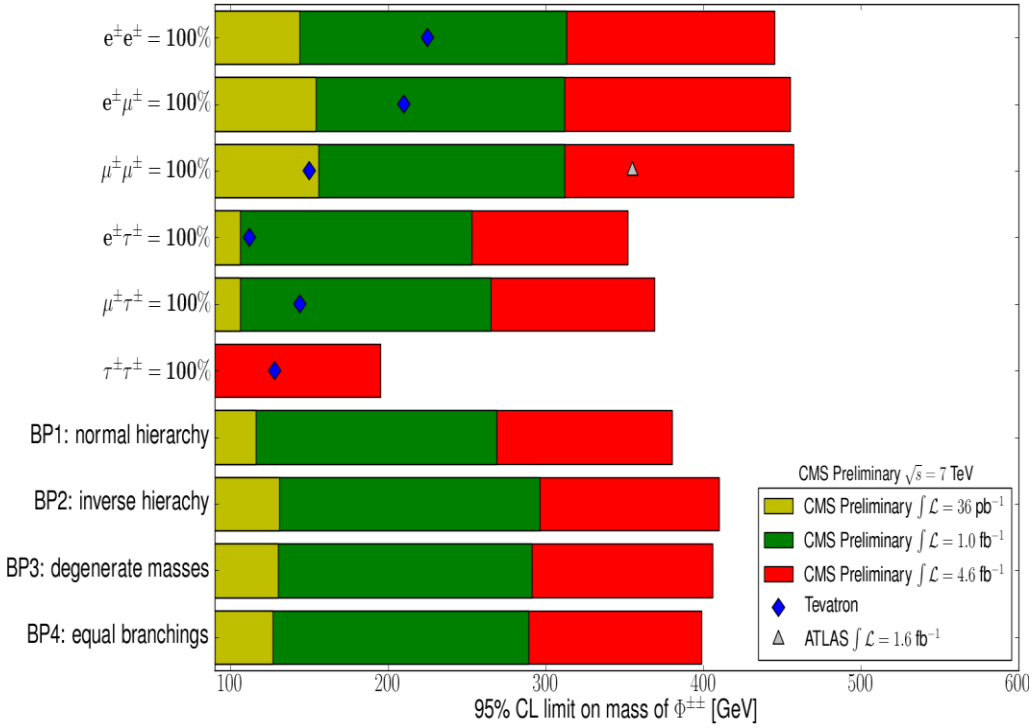
Φ^{++} Exclusion Limits





arXiv:1207.2666

The best Limit ever



Higgs in a SM with 4 Generations

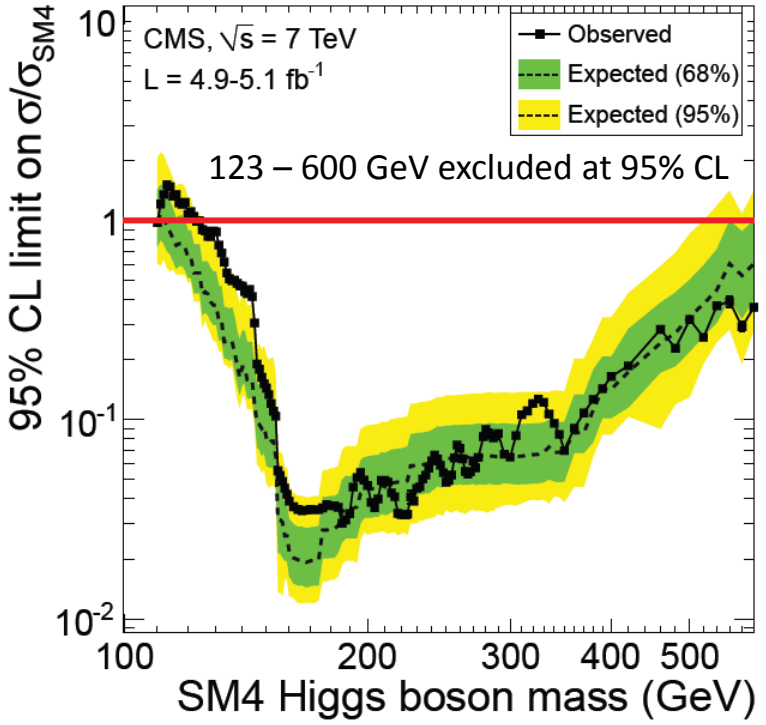
- **Reinterpret SM Higgs search in the context of 4th generation of fermions**
- **Large impact on production and decay rates**
  - Gluon fusion enhanced up to ~ x10
  - Decay BFs modified significantly

Model parameters
– LHC XS WG benchmark:

$$m_{d4} = m_{L4} = m_{\nu} = 600\ \text{GeV}$$

$$m_{u4} - m_{d4} = \left[1 + \frac{1}{5}\ln\left(\frac{m_H}{115}\right)\right] \cdot 50\ \text{GeV}$$

- Use existing SM search results @ 7 TeV
  gg fusion dominates, neglect VBF and VH production
- Channels contributing:
  - H → γγ
  - H → ττ
  - H → WW(2l2ν)
  - H → ZZ(4l, 2l2ν, 2l2q, 2l2τ)
  - (W/Z)H, H→bb



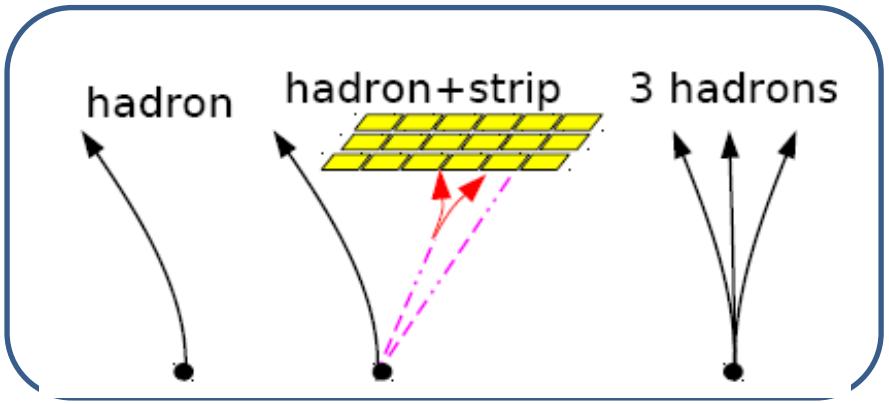
Summary

- CMS explored the search for Higgs boson in many promising models beyond SM.
- Most of the results presented today are from 7 TeV data.
- No evidence of any excess above backgrounds.
- Stringent limit set on the production of Higgs boson in most of the models beyond SM.
- More BSM Higgs search results from 2012 LHC runs are expected soon.

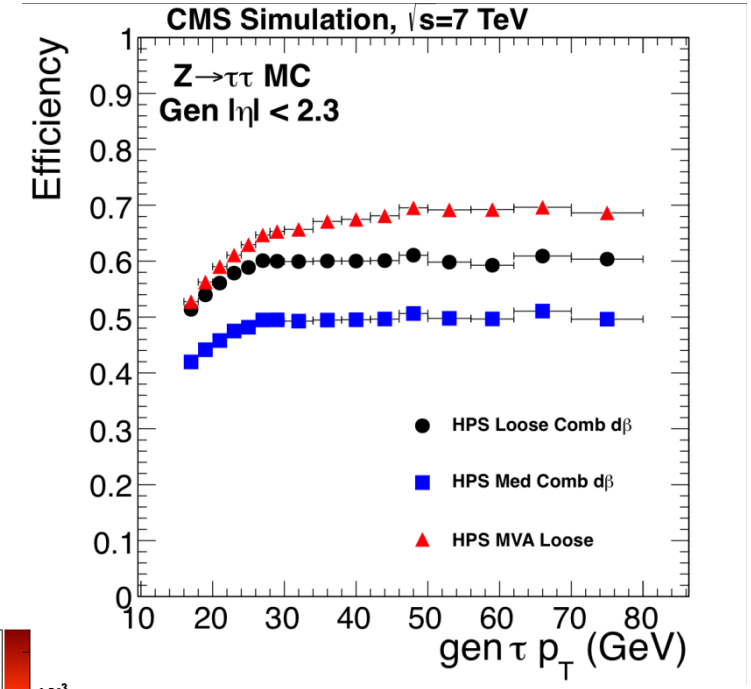
backup

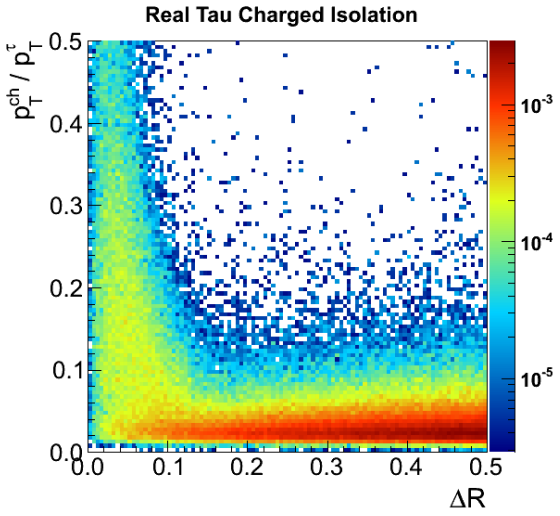
Tau Identification @ CMS

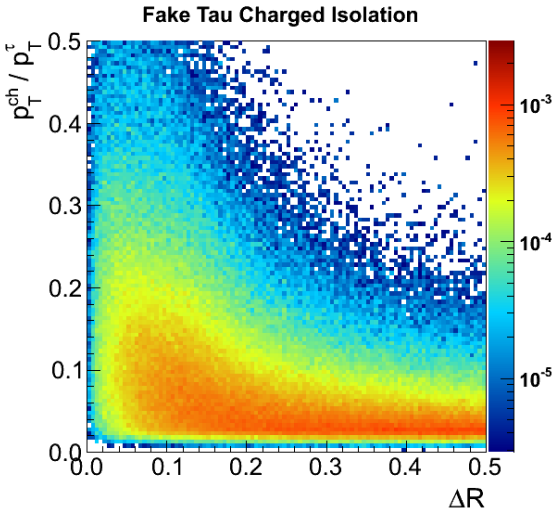
Hadron + Strips Algorithm



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



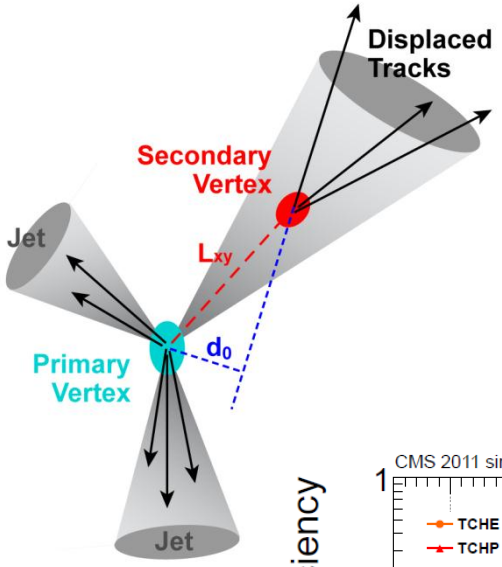




Ring-Based Isolation :

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

b-Jet Tagging

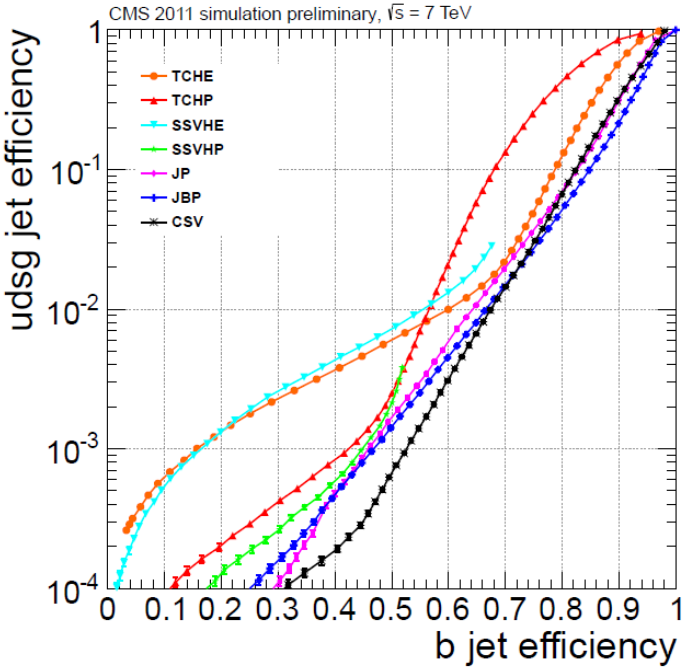


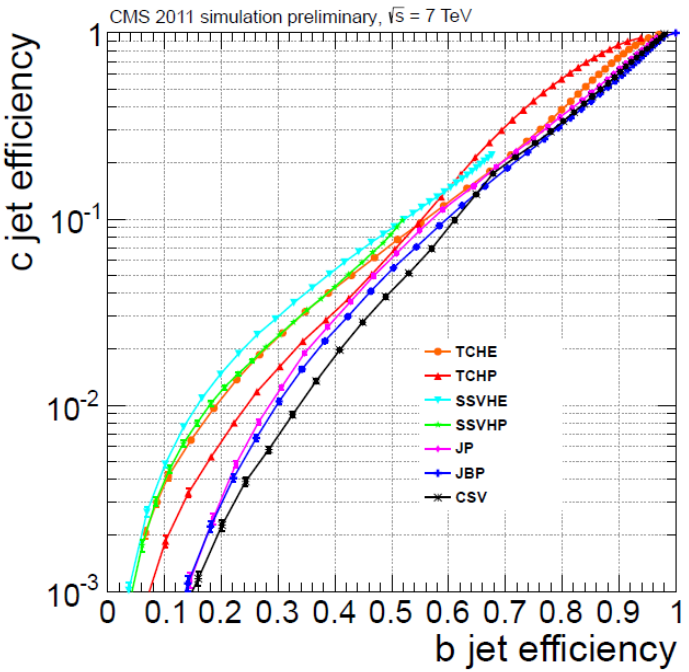
Many algorithms developed at CMS, based on track impact parameter and secondary vertex of B hadron decay

Algorithm used for most Higgs searches in 2011 : TCHE

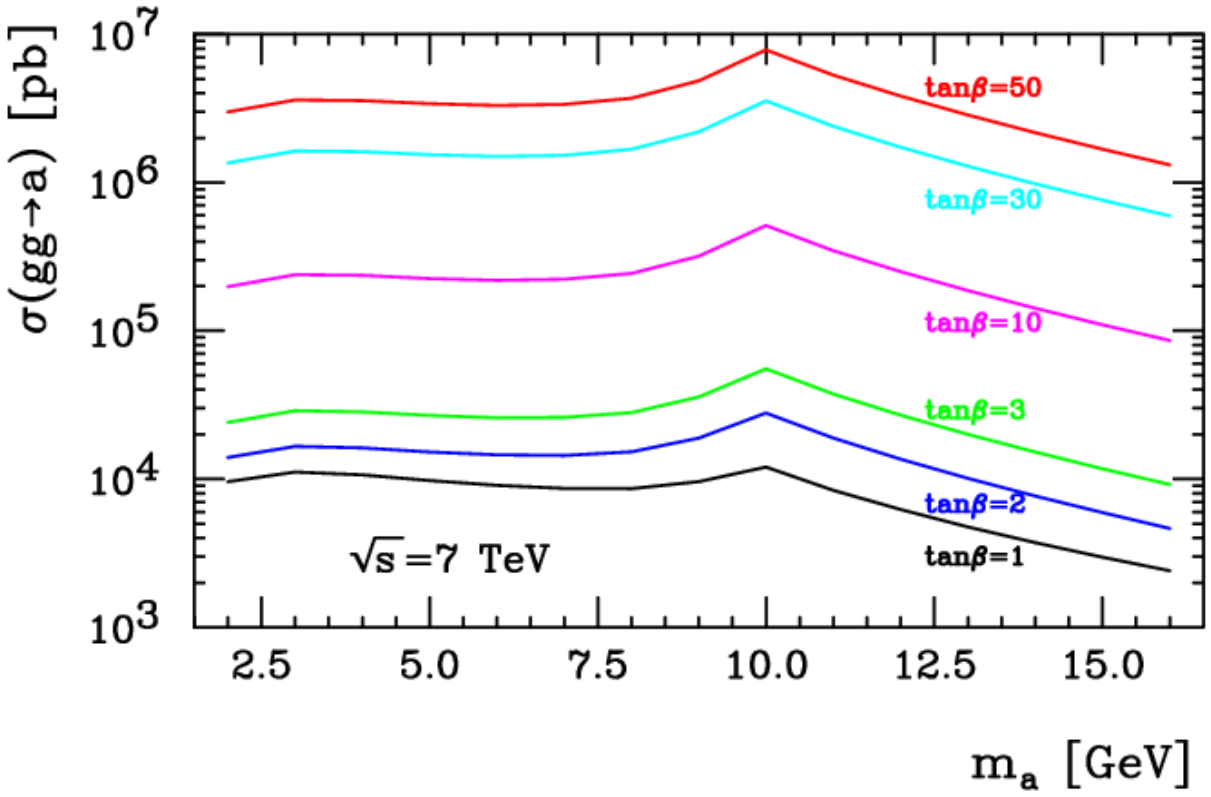
TCHE : Simple method.

Tracks are ordered according to the impact parameter significance (IP/σ_{IP}). The IP significance of 2nd track is used as discriminator.





production of a_1

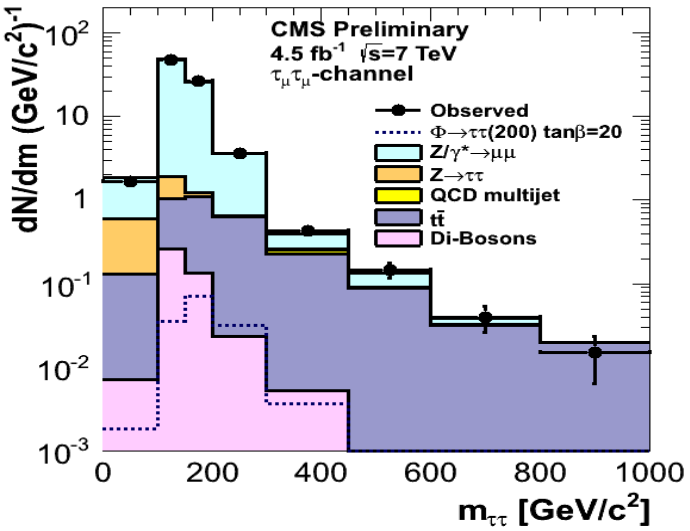


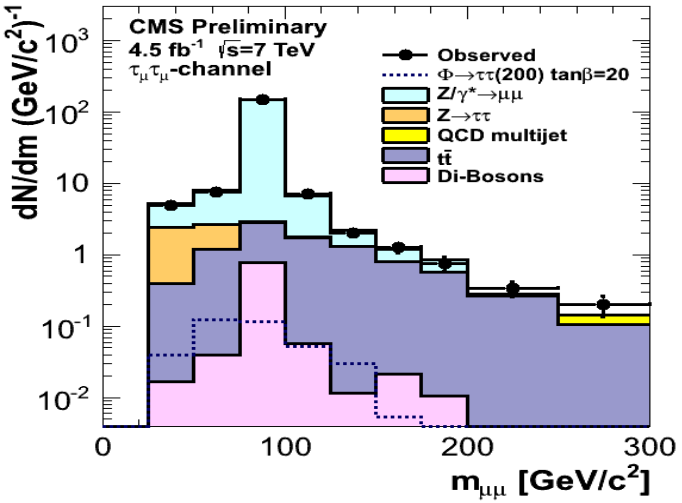
H^{++} Benchmark Points

Table 1: Branching fractions of Φ^{++} at the four benchmark points.

Benchmark point	ee	eμ	eτ	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

$\varphi \rightarrow \tau\tau \rightarrow \mu\mu$ Search





Analysis category similar as other $H \rightarrow \tau\tau$ channels : b-Tag & Non b-Tag

Additional MVA (Likelihood) discriminant to suppress $Z/\gamma^* \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$ w.r.t. signal

Signal extraction based on a binned likelihood function constructed from the 2D distribution of ($m_{\tau\tau}$, $m_{\mu\mu}$)