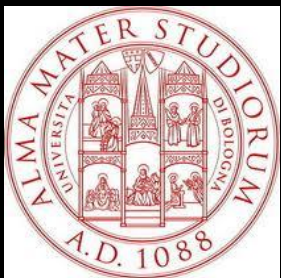




# Searches for Exotic Higgs decays in CMS



**FEDERICA PRIMAVERA**  
**UNIVERSITY OF BOLOGNA & INFN (IT)**  
**ON BEHALF OF THE CMS COLLABORATION**



**LHCP 2013 - First Large Hadron Collider Physics Conference**  
**Barcelona - 13-18 May 2013**



# Outline

- ✓ **Motivations**
- ✓ **CMS detector**
- ✓ **Search for MSSM Higgs**
- ✓ **Search for NMSSM Higgs**
- ✓ **Search for fermiophobic Higgs**
- ✓ **Search for Higgs rare decays**
- ✓ **Summary**

# SM Higgs combination

CMS-PAS-HIG-13-005

Processes induced by loop diagrams are susceptible to the presence of BSM physics:  $H \rightarrow \gamma\gamma$   $gg \rightarrow H$

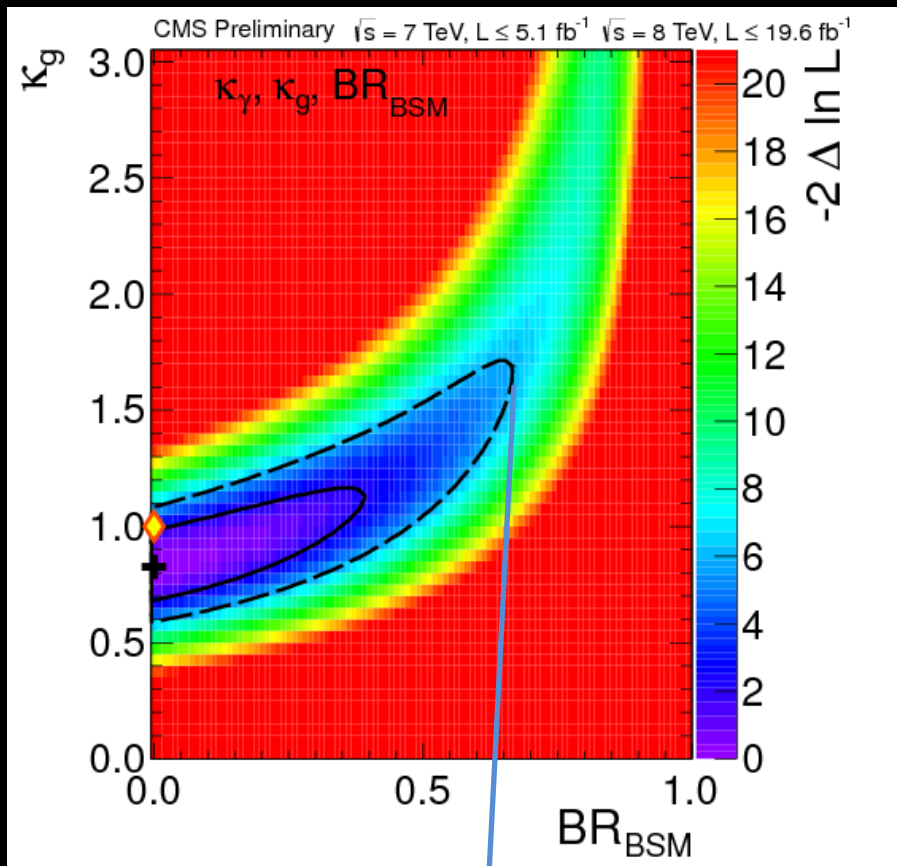
$\kappa_\gamma$

$\kappa_g$

2D test statistics  $q(\kappa_g, BR_{BSM})$  scan, profiling the modifier to the effective coupling to gluons  $\kappa_g$ .

$BR_{BSM} = \Gamma_{BSM} / \Gamma_{tot}$  assuming that couplings to the electroweak bosons are bound by the SM expectation ( $\kappa_V \leq 1$ ).

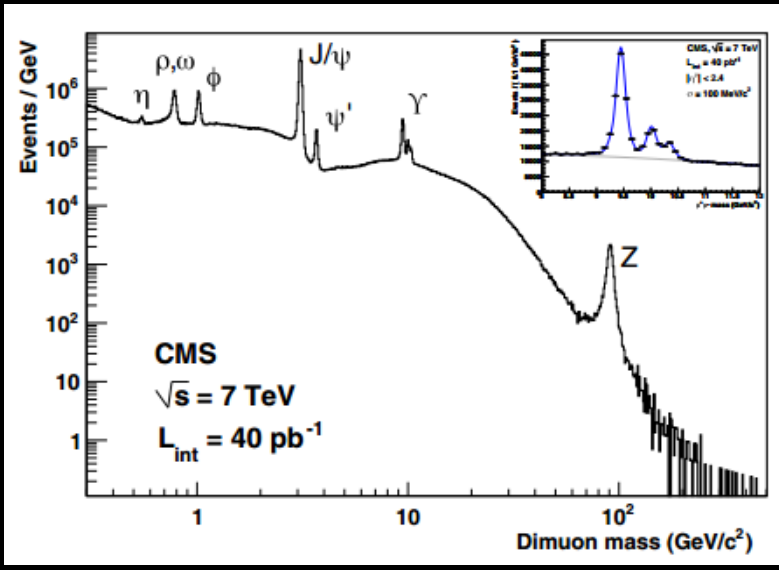
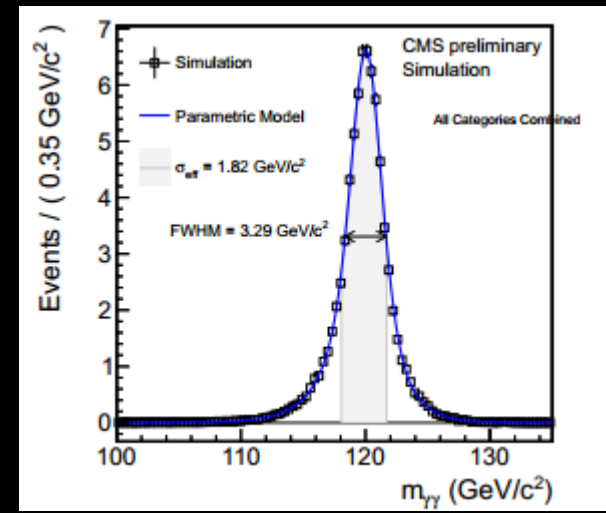
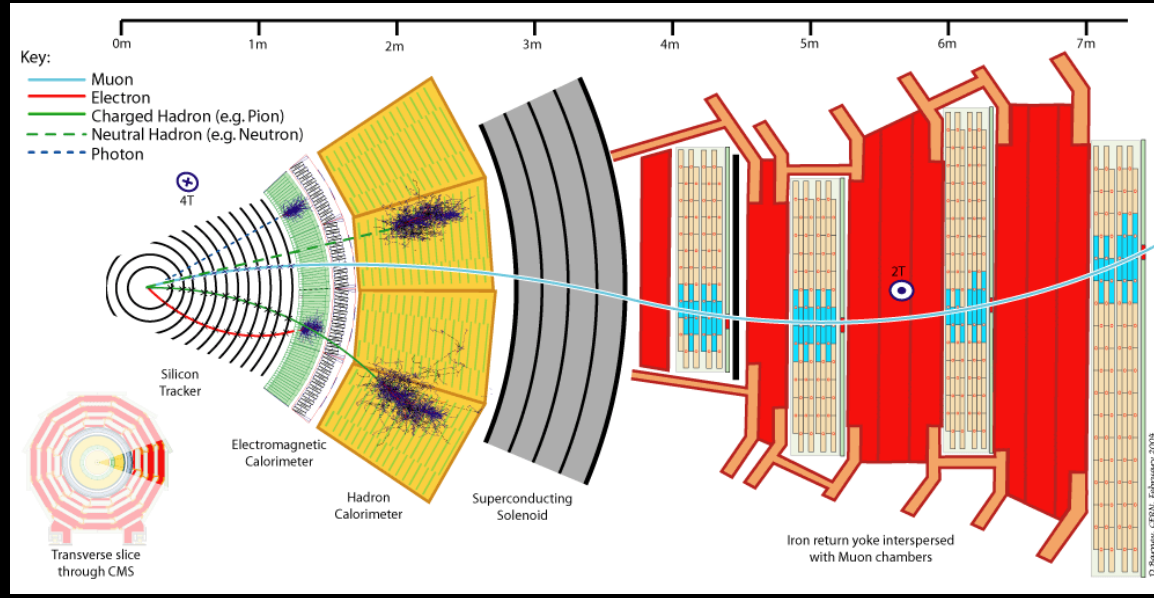
Furthermore in SM theory there are some problems that can be solved only extending the model.



$0 \leq BR_{BSM} \leq 0.64$  at 95% C.L.



# CMS detector



Photon energy resolution:  
0.2 % (barrel)  
0.5 % (endcaps)

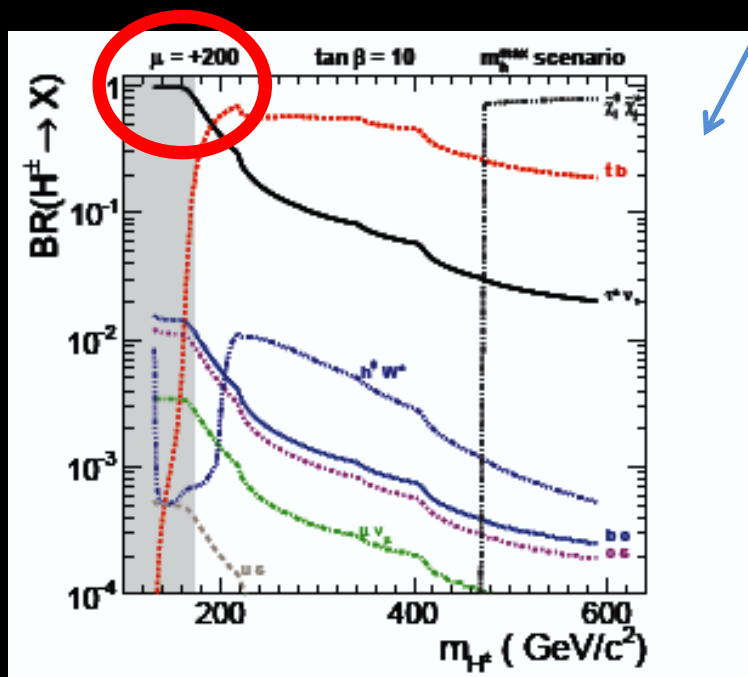
Muon  $p_T$  resolution:  
 $\sigma(p_T)/p_T = 1\%$  at 100GeV/c  
 $\sigma(p_T)/p_T = 10\%$  at 1TeV/c

# MSSM extention

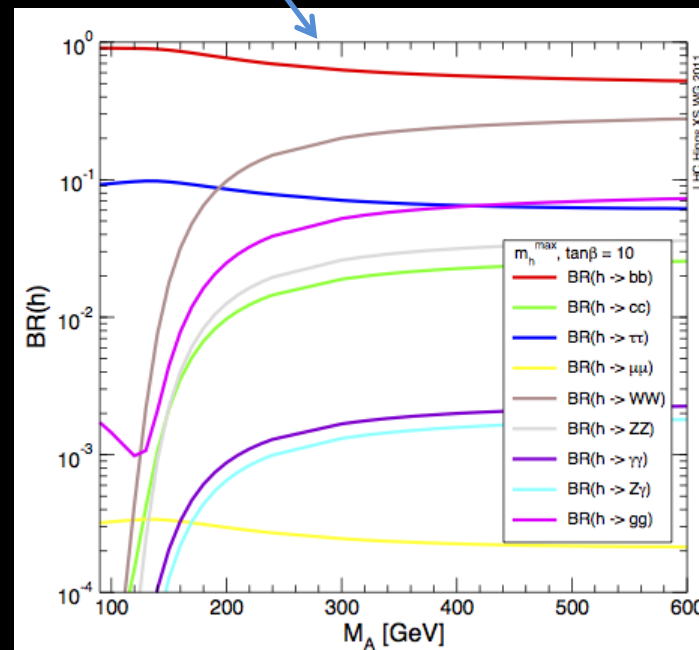
The minimal supersymmetric standard model (MSSM) contains two Higgs doublets, giving rise to five physical states:

- ✓ a light neutral CP-even state ( $h$ ),
- ✓ a heavy neutral CP-even state ( $H$ ),
- ✓ a neutral CP-odd state ( $A$ ),
- ✓ and a pair of charged states ( $H^+, H^-$ ).

}  $\Phi$



Charged Higgs BR



Neutral Higgs BR

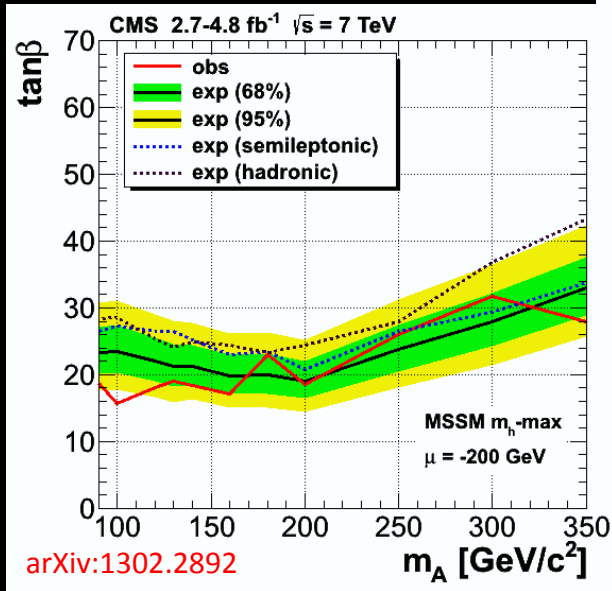
$m_h^{\max}$  scenario  $\tan\beta = 10$



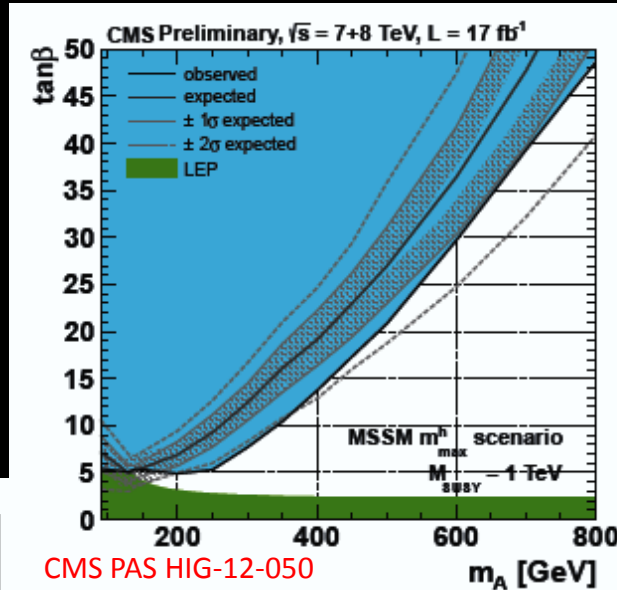
# MSSM neutral Higgs

$$\phi^0 \rightarrow bb$$

- ✓ Highest BR.
- ✓ Search for associated production with a b-pair.
- ✓ Challenging background.
- ✓ 2 analyses at CMS with data at 7 TeV.



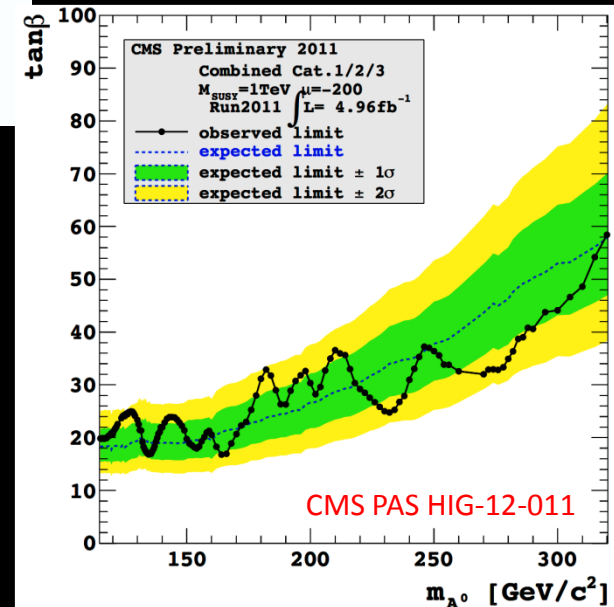
$$\phi^0 \rightarrow \tau^+\tau^-$$



- ✓ Best significance thanks to better control of the QCD background and di- $\tau$  mass parametrization.
- ✓ Search for associated production and gluon fusion.
- ✓ Combination of 7 and 8 TeV data.

$$\phi^0 \rightarrow \mu^+\mu^-$$

- ✓ Low BR but good sensitivity.
- ✓ Search for associated production and gluon fusion.
- ✓ Best channel for measurement of  $\tan\beta$  (mass resolution at Z-peak is  $\approx 3\%$ )
- ✓ Results for data at 7 TeV.





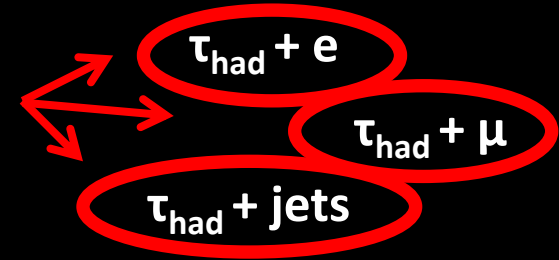
# MSSM charged Higgs

Hypothesis:

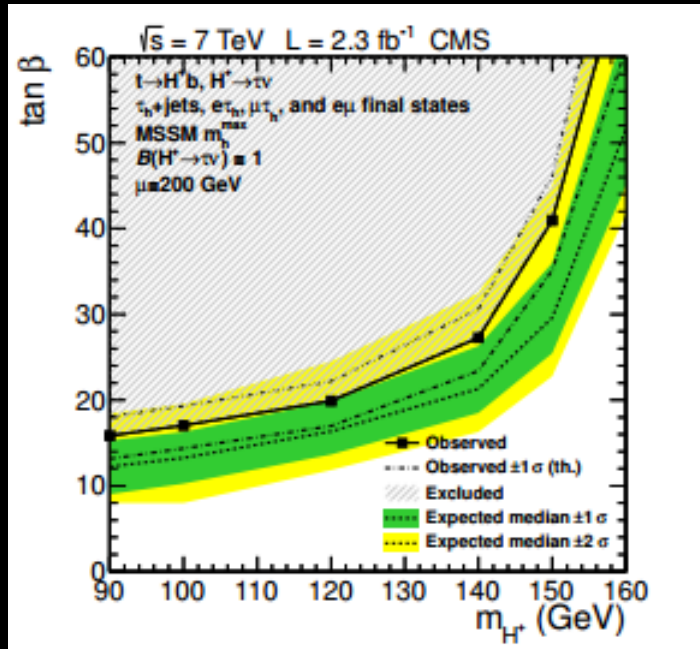
✓ **Low Higgs mass:**  $H^+$  production in top decays;  
kinematic acceptance  $M_H < m_t + m_b$  ( $\approx 160$  GeV).

CMS-PAS-HIG-12-052  
JHEP07(2012)143

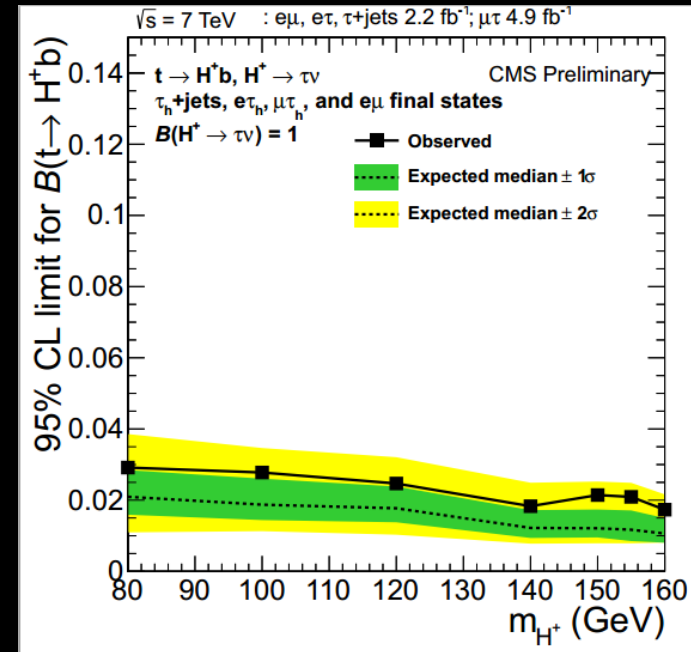
✓ Searches for  $pp \rightarrow HbHb$  &  $pp \rightarrow HbWb$  in  $\tau\nu$  decays



✓  $BR(H \rightarrow \tau\nu) = 1$  Significant for  $\tan\beta > 2$ .



Exclusion limit for  $m_h^{max}$  scenario



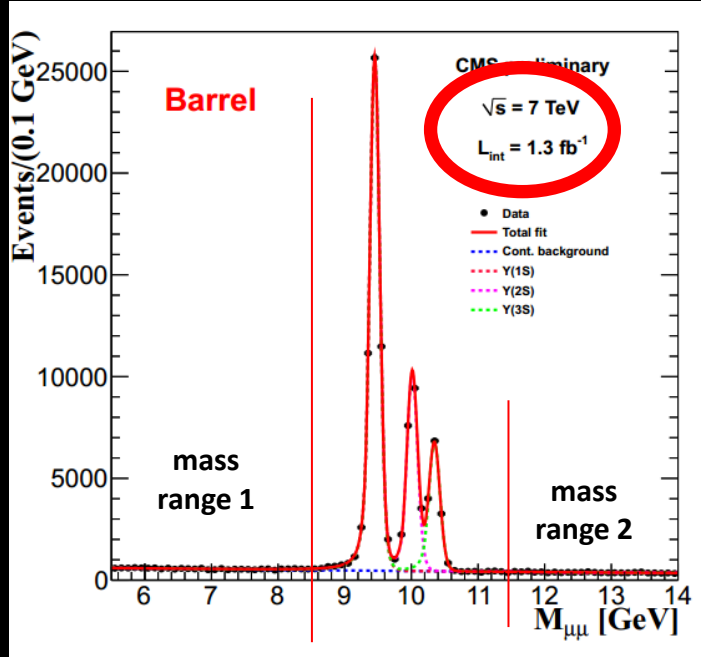
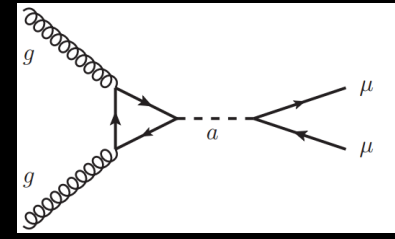
Limit on the  $BR(t \rightarrow H^+ b)$



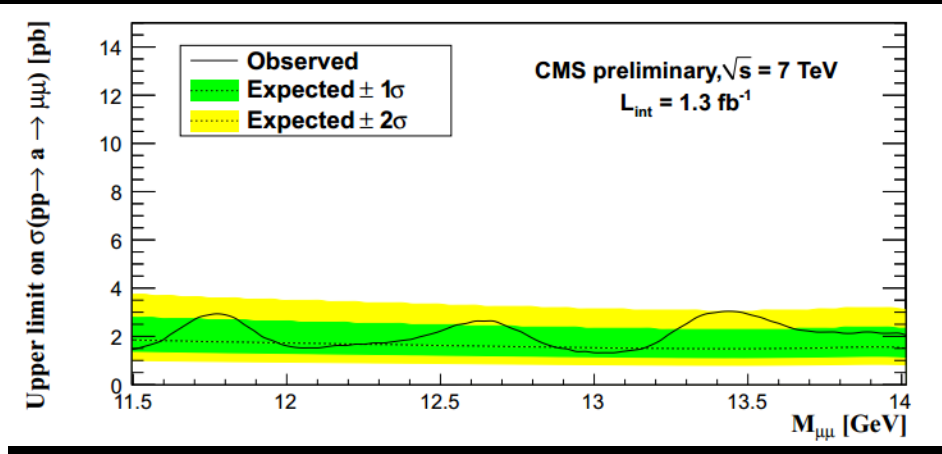
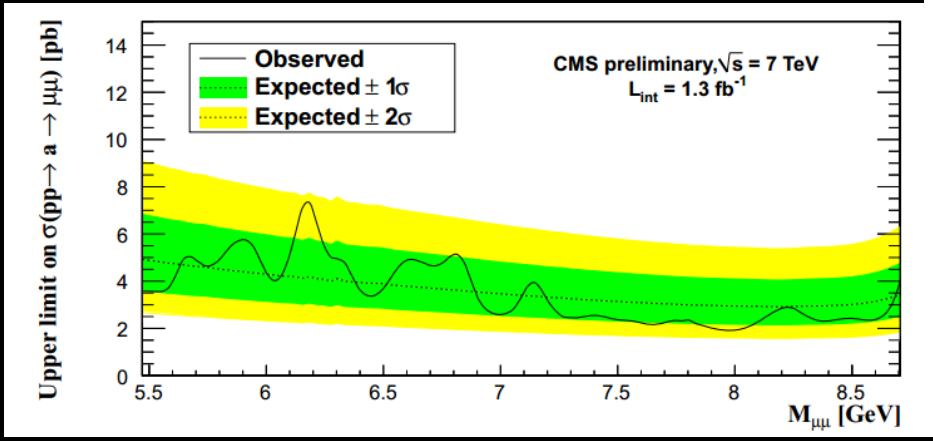


# Next-to-MSSM extension

✓ NMSSM adds one scalar singlet to MSSM: 3 CP-even  $h_1, h_2, h_3$ ,  
2 CP-odd  $a_1, a_2$   
2 charged  $H^\pm$



- ✓ Cross section strongly dependent from  $\tan\beta$  and  $m_{a1}$ .
- ✓ BR changes very little.
- ✓  $m_{a1}$  can be very light  $m_{a1} \ll 2m_b$ .
- ✓ Data driven estimation of bkg (QCD and Y(1S) tail).



arXiv:1206.6326

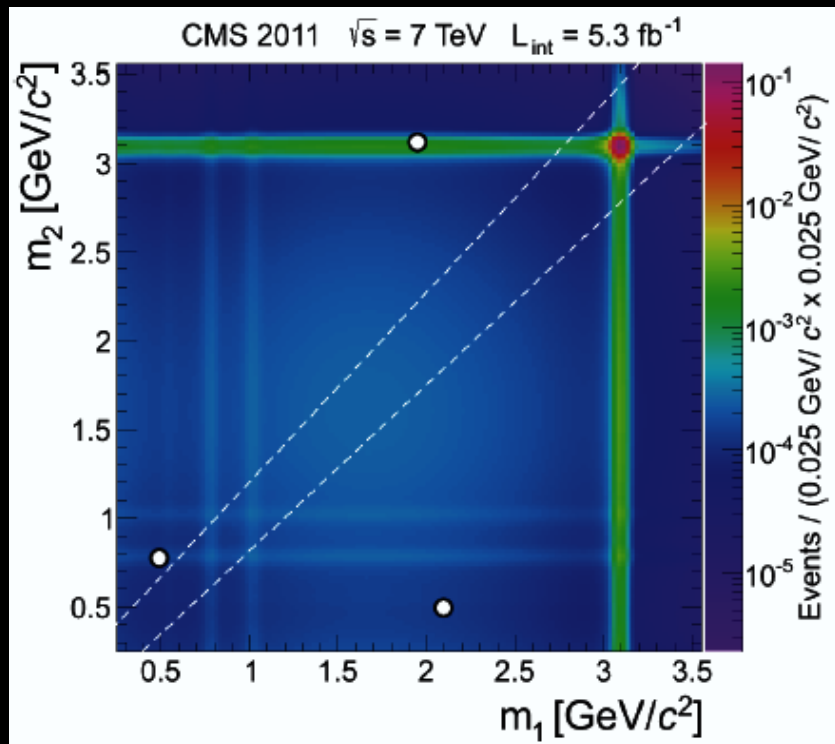




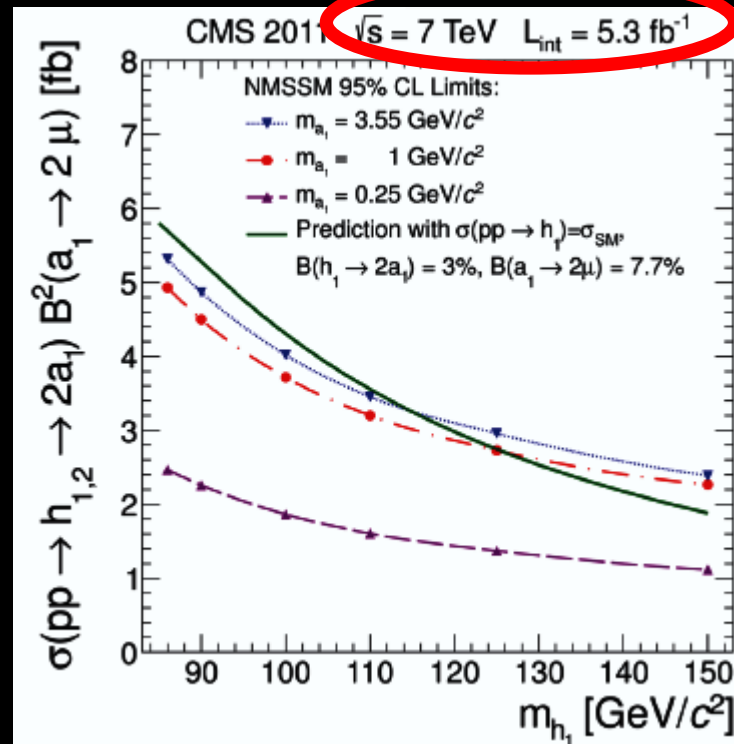
# NMSSM Higgs $h$ to $4\mu$

arXiv:1210.7619

- ✓ Several models beyond the SM predict  $h \rightarrow 2a + X \rightarrow 4\mu + X$ .
- ✓ In the NMSSM  $h_{1,2} \rightarrow 2a_1$  sensitive for  $2m_\mu < m_{a_1} < 2m_\tau$ .
- ✓ Background from  $bb$  pair and  $J/\psi$  prompt.



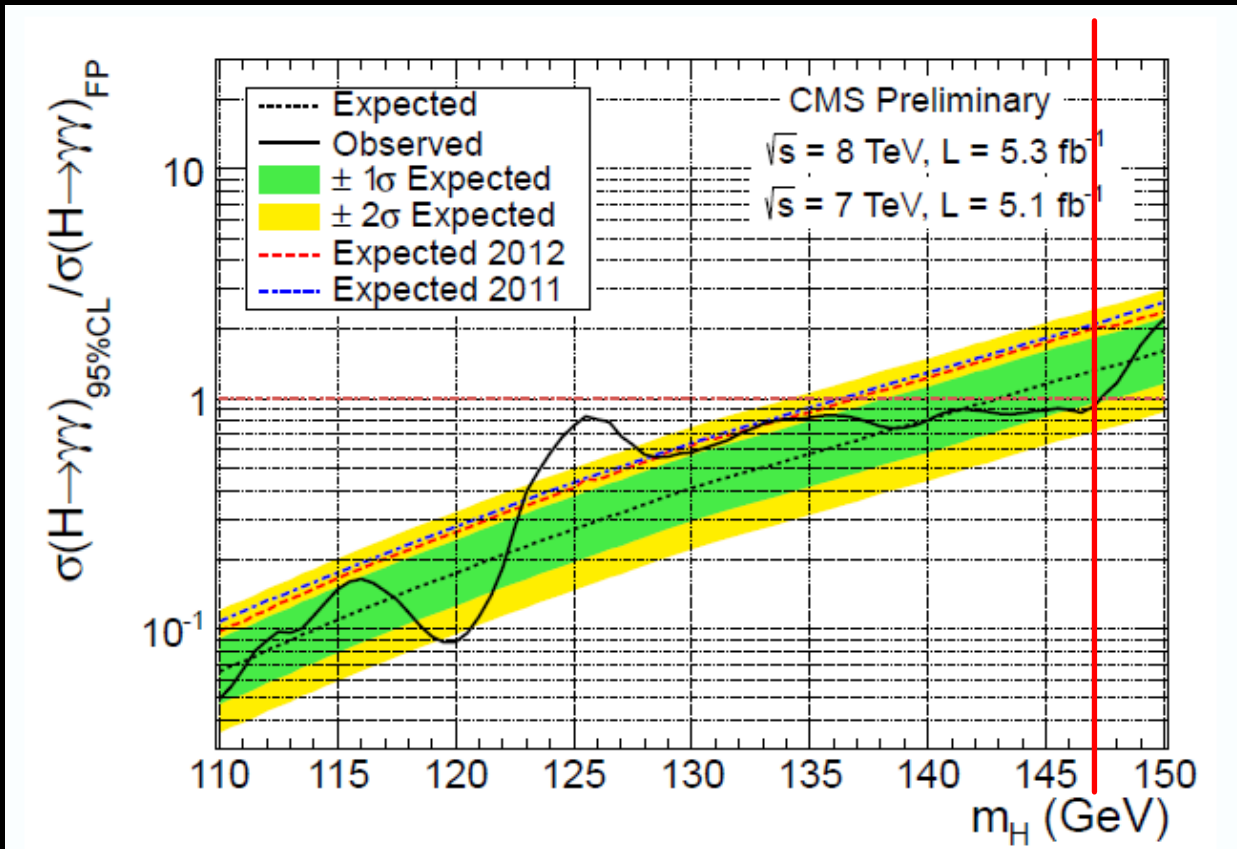
Signal Region: zero events  
measured and  $1.0 \pm 0.5$  expected



95% CL upper limit for  
NMSSM case

# Fermiophobic Higgs

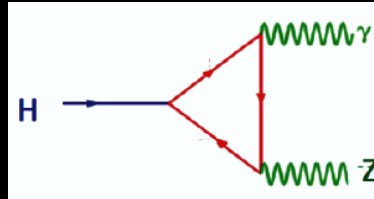
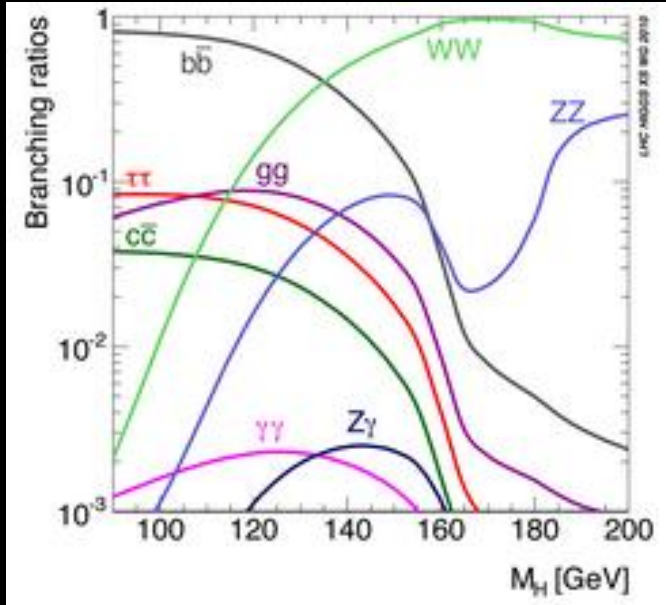
- ✓ Several extension of SM where Higgs boson couples only to the vector bosons.
- ✓ Search for VBF and associated VH production in  $\gamma\gamma$  final state.
- ✓ Resolution of 1 GeV at Higgs mass peak.



- Combination of  $5.1 \text{ fb}^{-1}$  at 7 TeV with  $5.3 \text{ fb}^{-1}$  at 8 TeV data.
- Data driven estimation of the bkg: misidentified electrons and photons in jets .
- Excluded at 95 % CL between 110-147 GeV.

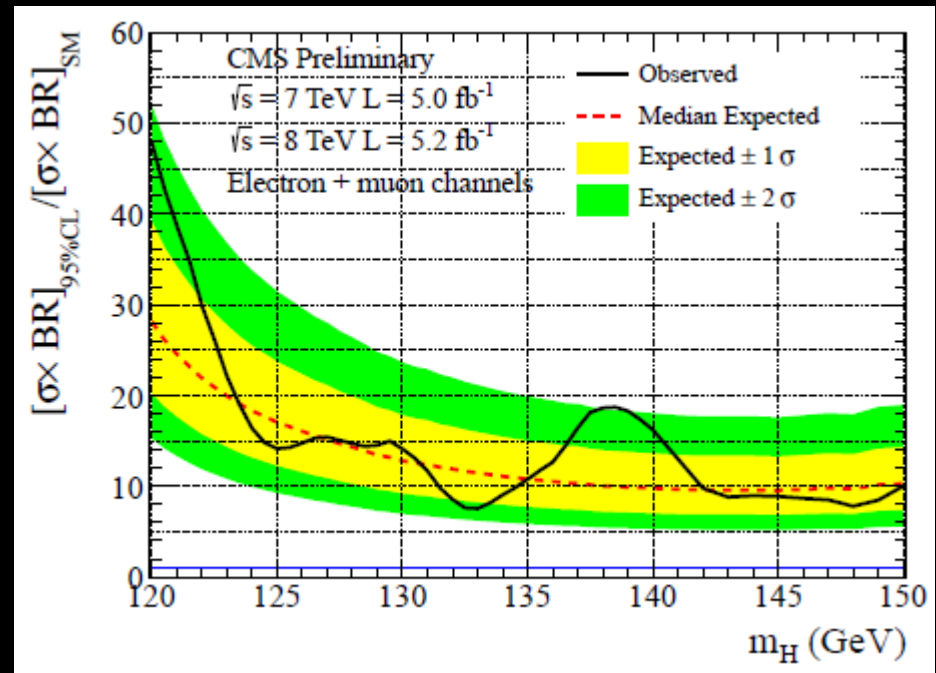
# Rare Higgs decays

CMS-PAS-HIG-13-006



- ✓  $BR(h \rightarrow Z\gamma) = 1.6 \times 10^{-3}$
- ✓ Z decays in electrons or muons.
- ✓ Data driven estimation of the bkg:  
70%  $pp \rightarrow Z\gamma$  and 30% Drell-Yan.

Upper cross-section limits  
are about an order of  
magnitude larger  
than the SM expectation.





# Summary

- ✓ **Combination of the CMS results sets the limits at  $0 \leq BR_{\text{BSM}} \leq 0.64$  at 95% C.L.**
  
- ✓ **No signal was observed in Higgs exotic decays, but:**
  - **MSSM -  $\tan\beta$  vs.  $m_A$  allowed plane is becoming smaller and smaller.**
  - **MSSM - charged Higgs from  $t \rightarrow bH^+$  observes the limit within one standard deviation consistent with the expected limit.**
  - **For the additional bosons, e.g.  $a_1$ , predicted in NMSSM, upper limit for  $\sigma \times B^2 \times \text{Acc.}$  is set, and it is excluded in the mass ranges between [5.5 - 8.8] and [11.5 - 14] GeV.**
  - **Fermiophobic Higgs in  $\gamma\gamma$  is excluded at 95% CL in the mass range 110-147 GeV.**
  
- ✓ **Also for rare decays as  $Z^0\gamma$  we could set only upper limit.**

# Back-up

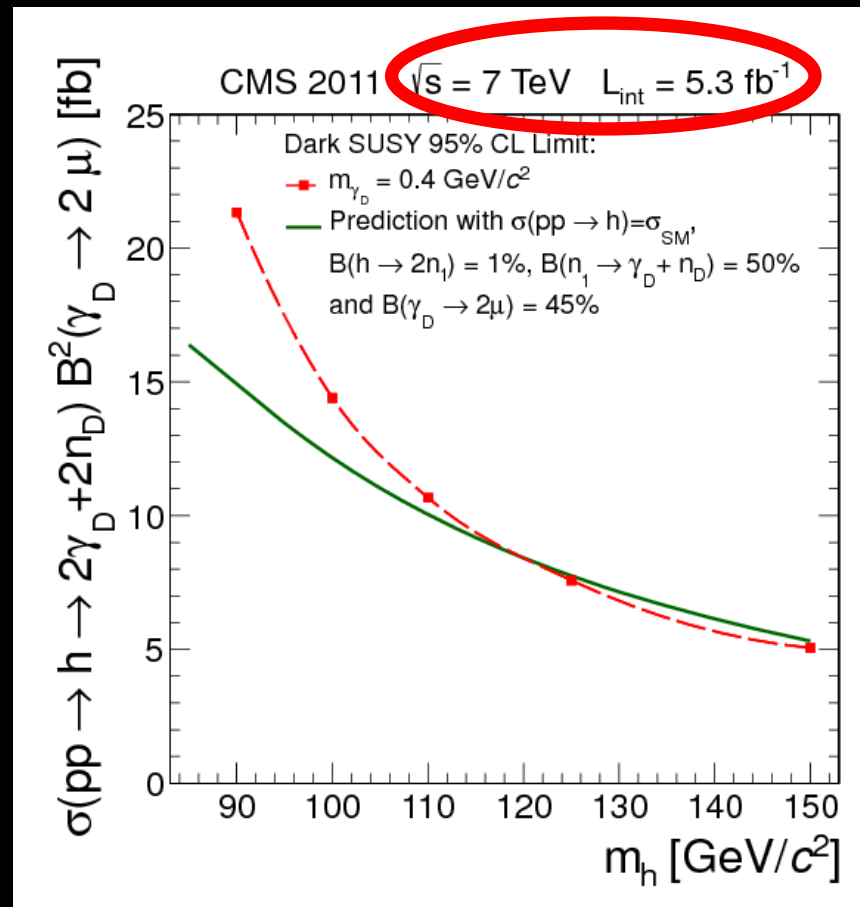


# NMSSM Higgs $h$ to $4\mu$ dark-susy

arXiv:1210.7619

## DARK SUSY:

- ✓ Lightest neutralino  $n_1$  no longer stable:  $n_1 \rightarrow \gamma_D n_D$
- ✓  $\gamma_D$  – dark photon,  $n_D$  – dark fermion
- ✓ assumption  $\gamma_D$  decays only in SM particles:  $\gamma_D \rightarrow \mu^+\mu^-$  with BR.  $\approx 45\%$





# References

- **Search for a light charged Higgs boson in top quark decays in pp collisions at  $\sqrt{s} = 7\text{TeV}$**   
[http://dx.doi.org/10.1007/JHEP07\(2012\)143](http://dx.doi.org/10.1007/JHEP07(2012)143)    <http://arxiv.org/abs/1205.5736>
- **Search for a Higgs boson produced in association with b quarks and decaying into a b-quark pair**  
<http://arxiv.org/abs/1302.2892>  
<http://cdsweb.cern.ch/record/1460104/files/HIG-12-026-pas.pdf>
- **Search for SuperSymmetric Higgs boson states decaying into bb and produced in association with b-quarks in events collected by semi-leptonic triggers in pp collisions at  $\sqrt{s} = 7\text{TeV}$**   
<http://cdsweb.cern.ch/record/1460105/files/HIG-12-027-pas.pdf>
- **3. Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions**  
<http://cdsweb.cern.ch/record/1493521/files/HIG-12-050-pas.pdf>
- **4. Search for Neutral MSSM Higgs Bosons in the  $\mu^+\mu^-$  final state with the CMS experiment in pp Collisions at  $\sqrt{s}=7\text{TeV}$**   
<http://cdsweb.cern.ch/record/1453716/files/HIG-12-011-pas.pdf>
- **Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at  $\sqrt{s} = 7\text{TeV}$**   
<http://arxiv.org/abs/1206.6326>
- **Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at  $\sqrt{s} = 7$  and  $8\sqrt{\text{TeV}}$**   
<http://cds.cern.ch/record/1523674?ln=en>
- **Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states**  
<http://arxiv.org/abs/1210.7619>
- **Higgs to gamma gamma, Fermiophobic**  
<http://cds.cern.ch/record/1461937?ln=en>





# MSSM extention

The minimal supersymmetric standard model (MSSM) contains two Higgs doublets, giving rise to five physical states:

- a light neutral CP-even state (h),
- a heavy neutral CP-even state (H),
- a neutral CP-odd state (A),
- and a pair of charged states (H<sup>+</sup>,H<sup>-</sup>).

}  $\Phi^0$

For  $m_h^{\max}$  scenario, the model can be described by two free parameters:  $m_A$  and  $\tan\beta$  :

$$m_{H^\pm} = (m_W^2 + m_{A^0}^2)^{1/2}$$

$$m_{h^0} = \left\{ \frac{1}{2} \{ m_{A^0}^2 + m_{Z^0}^2 - [(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{A^0}^2 m_{Z^0}^2 \cos^2 2\beta]^{1/2} \} \right\}^{1/2}$$

$$m_{H^0} = \left\{ \frac{1}{2} \{ m_{A^0}^2 + m_{Z^0}^2 + [(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{A^0}^2 m_{Z^0}^2 \cos^2 2\beta]^{1/2} \} \right\}^{1/2}$$

# Charged Higgs: $H^\pm \rightarrow \tau\nu$

Hypothesis:

## 1. low Higgs mass

$H^+$  production in top decays

kinematic acceptance  $M_H < m_t + m_b$  ( $\approx 160$  GeV)

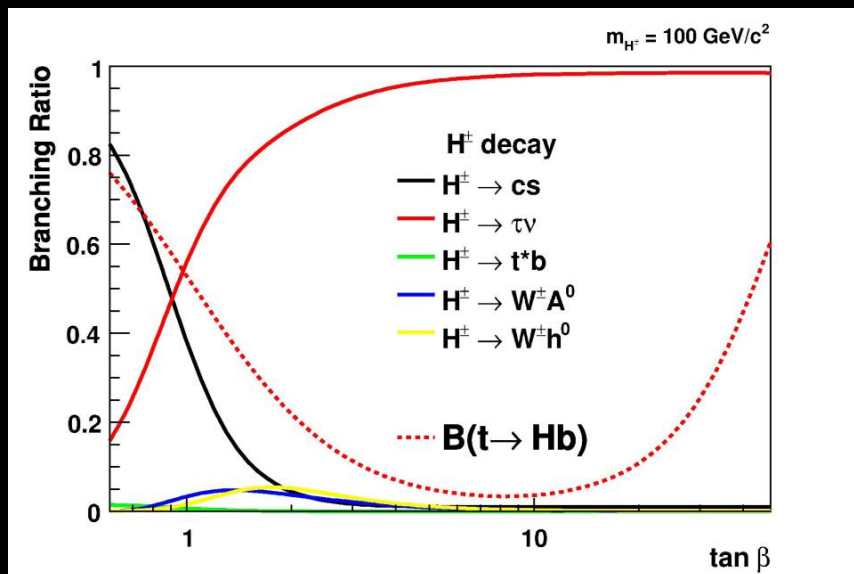
## 2. MSSM Signal contribution

$pp \rightarrow HbHb$

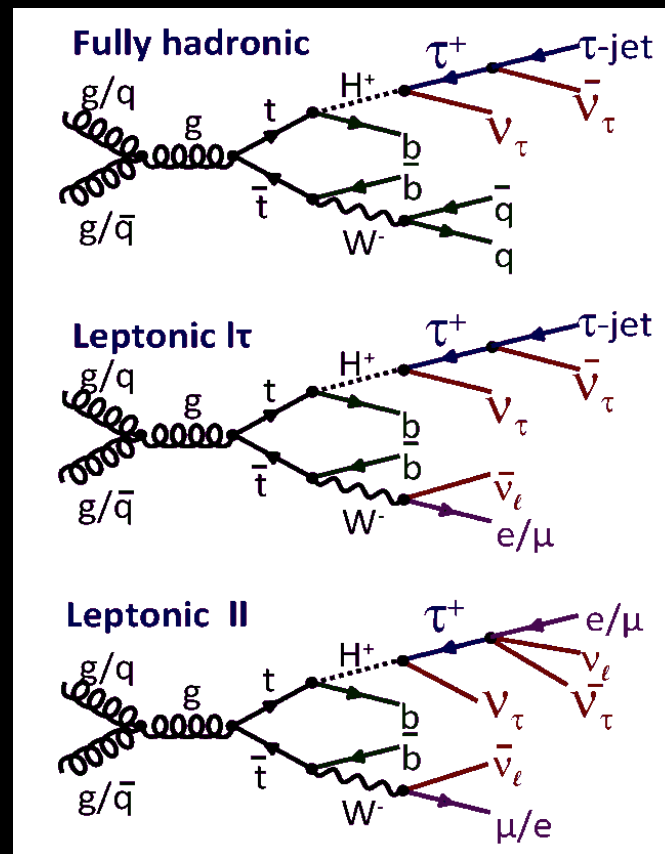
$pp \rightarrow HbWb$

## 3. $BR(H \rightarrow \tau\nu) = 1$

Dominant for  $\tan\beta > 5$



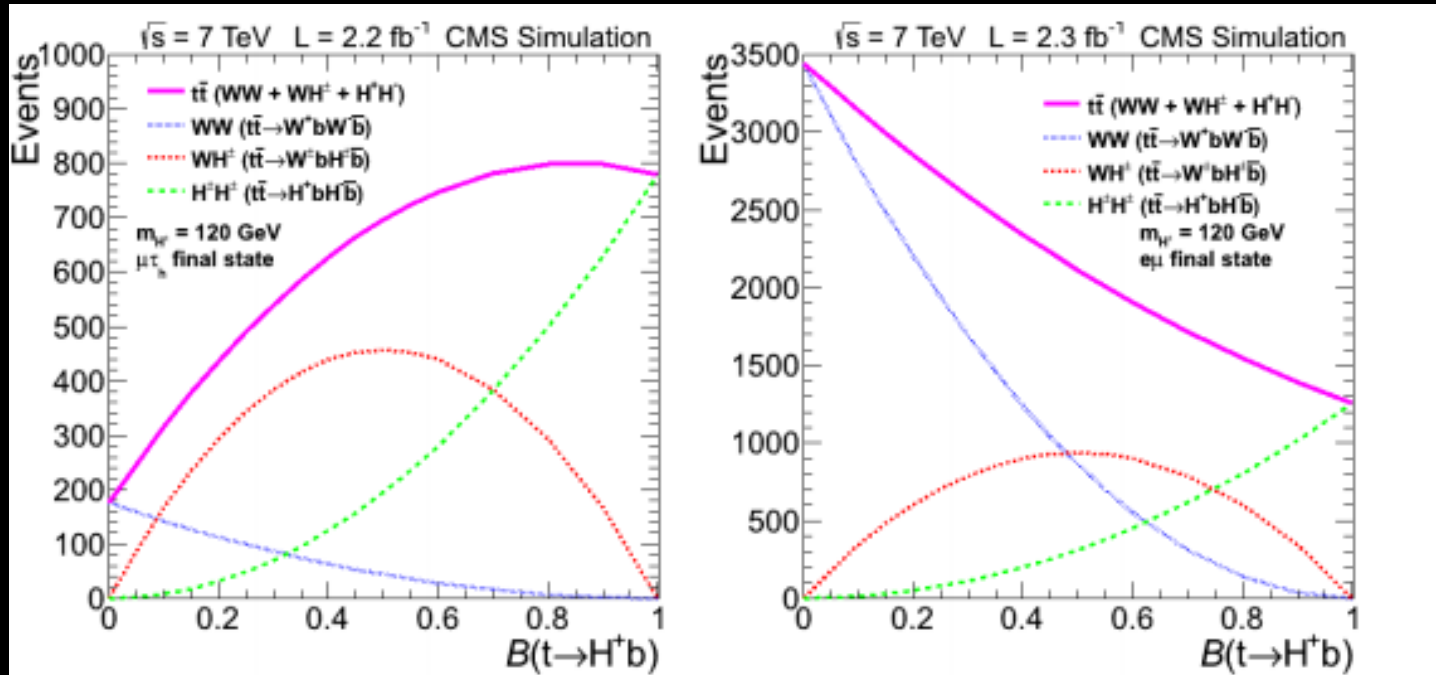
Signal:



3 mutually exclusive final states

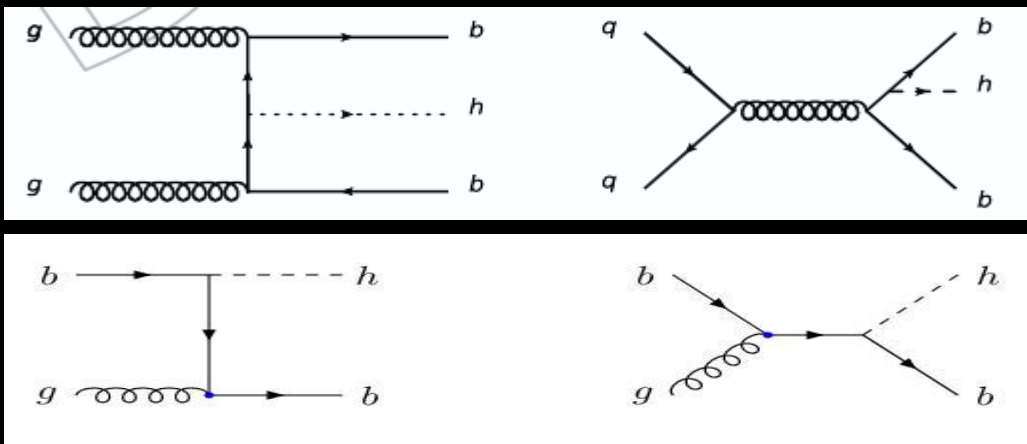


# Charged Higgs: expected BR



# MSSM Neutral Higgs : $\Phi^0 \rightarrow bb$

**Production mechanism:  
associated production with at least one b**



**Decay:  
bb**

**two analyzes are performed**

## **Selection:**

hadronic b-decay:

**CMS PAS-HIG-12-026**

**4.0 fb<sup>-1</sup> in collision at  $\sqrt{s} = 7$  TeV**

at least 3 b-tagged leading jets

semileptonic b-decay:

**CMS PAS-HIG-12-027**

**4.8 fb<sup>-1</sup> in collision at  $\sqrt{s} = 7$  TeV**

at least 3 b-tagged leading jets

not-isolated  $\mu$  used to reconstruct  
one of the leading jet



# MSSM Neutral Higgs: $\Phi^0 \rightarrow |^+|^-$

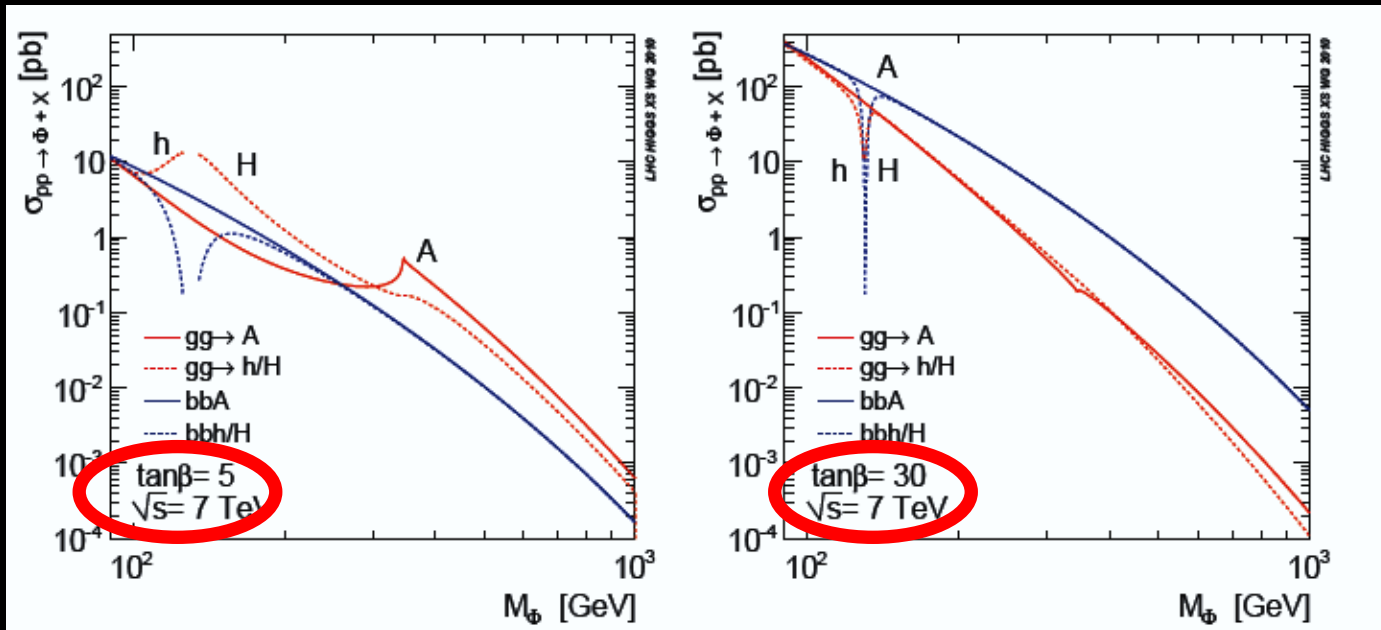
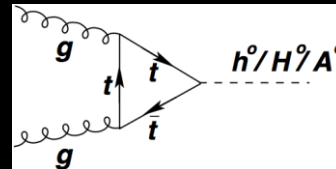
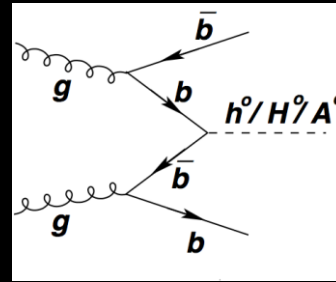
Production mechanism:

associated production  
b-tag Category in the analysis

gluon fusion  
No b-tag Category in the analysis

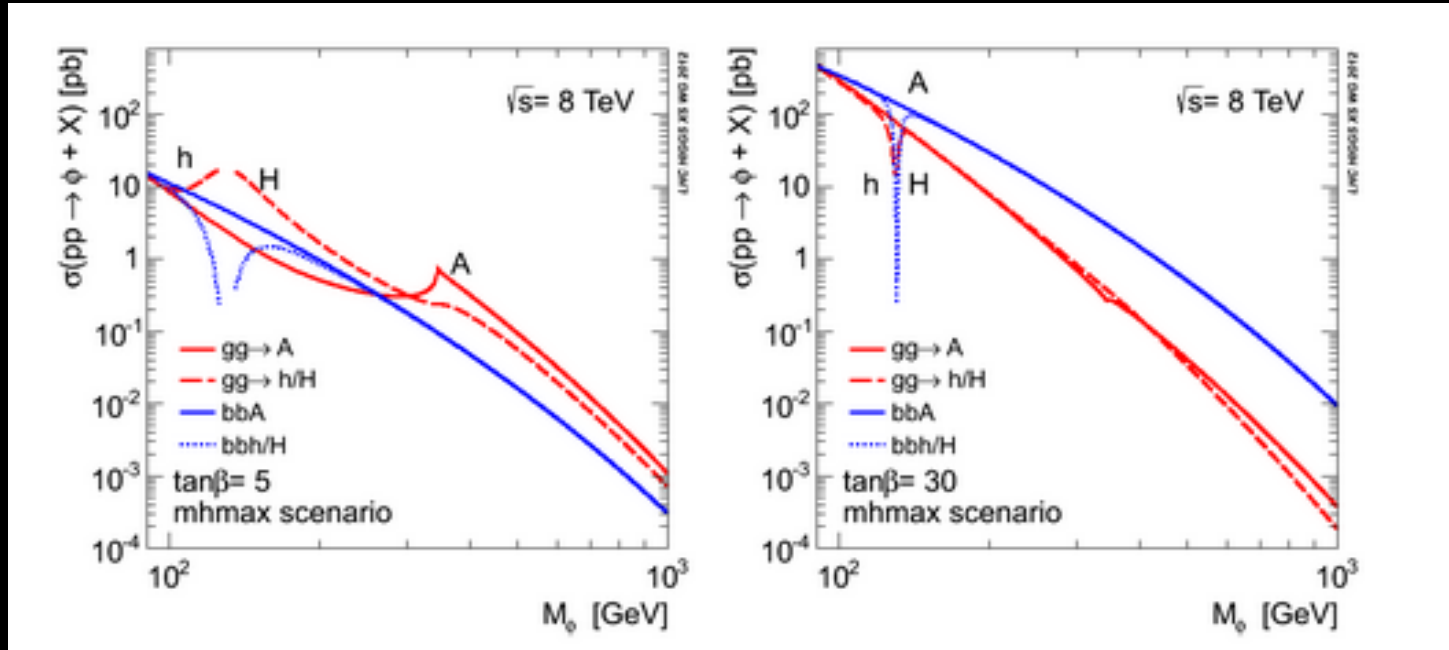
Decay modes:

$\tau^+\tau^- / \mu^+\mu^-$



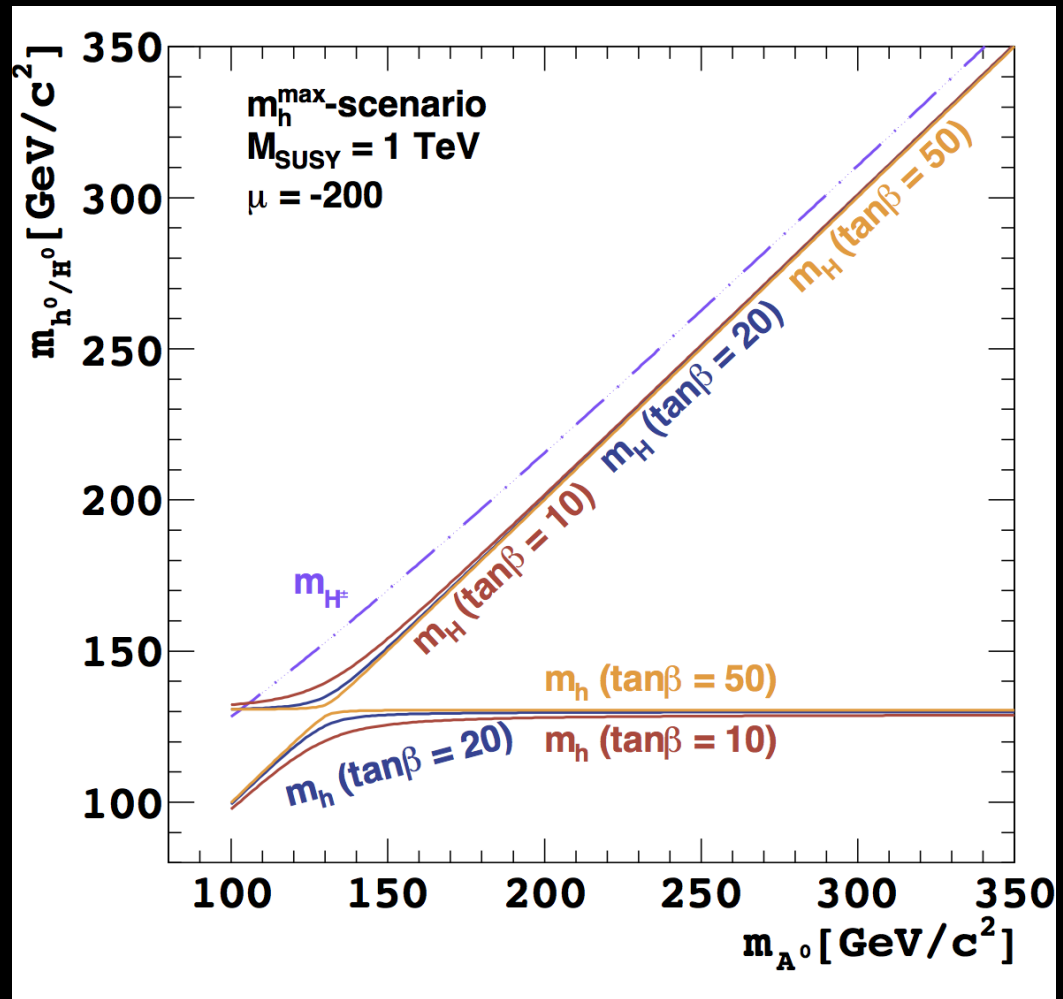
# MSSM Neutral Higgs

Cross section  $pp$  at LHC at 8 TeV



# MSSM Neutral Higgs

The Higgs bosons masses in the MSSM  $m_h^{\max}$  scenario.

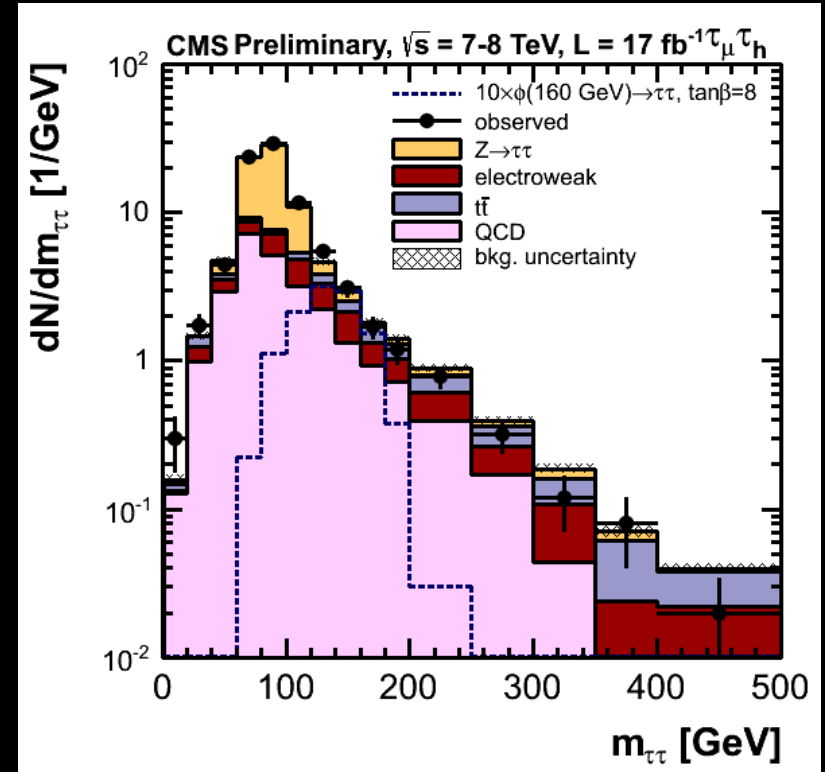
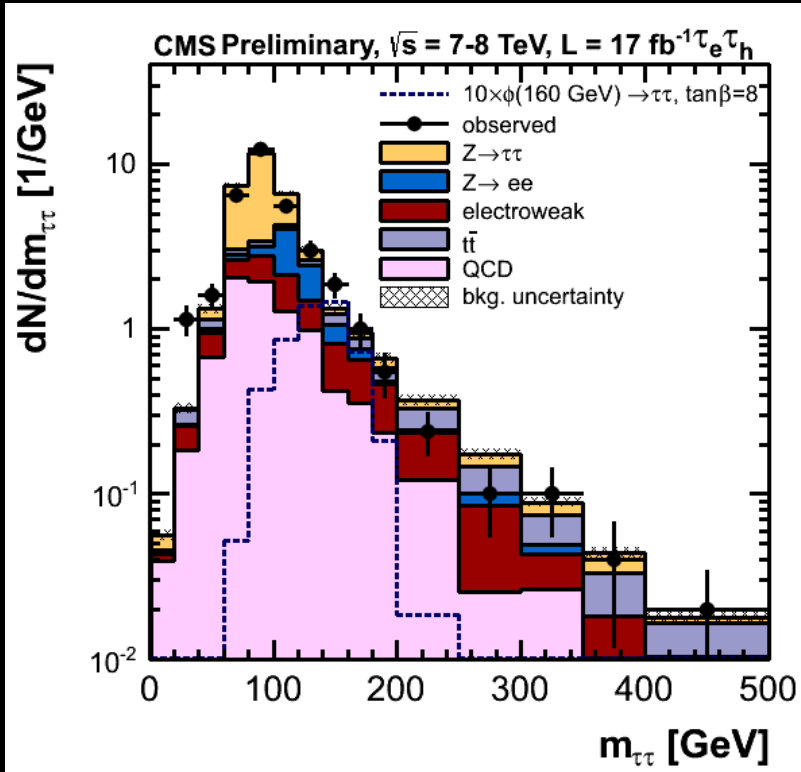




# MSSM Neutral Higgs: $\Phi^0 \rightarrow \tau^+\tau^-$

$$\phi^0 \rightarrow \tau^+\tau^- \rightarrow e\tau^h + 2\nu$$

$$\phi^0 \rightarrow \tau^+\tau^- \rightarrow \mu\tau^h + 2\nu$$



Main backgrounds: irreducible  $Z \rightarrow \tau\tau$   
 QCD (jet-misidentification)  
 W + jets

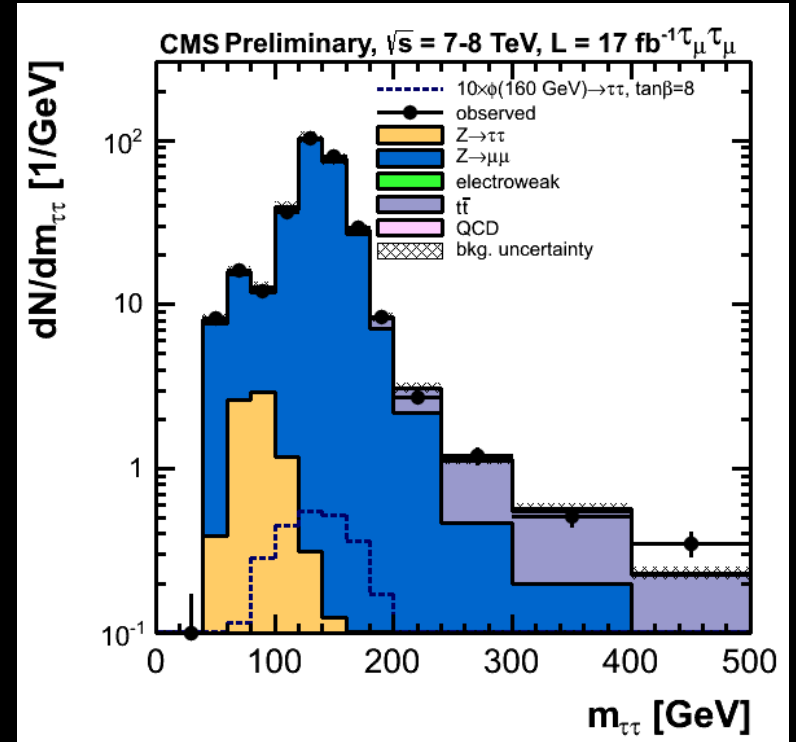
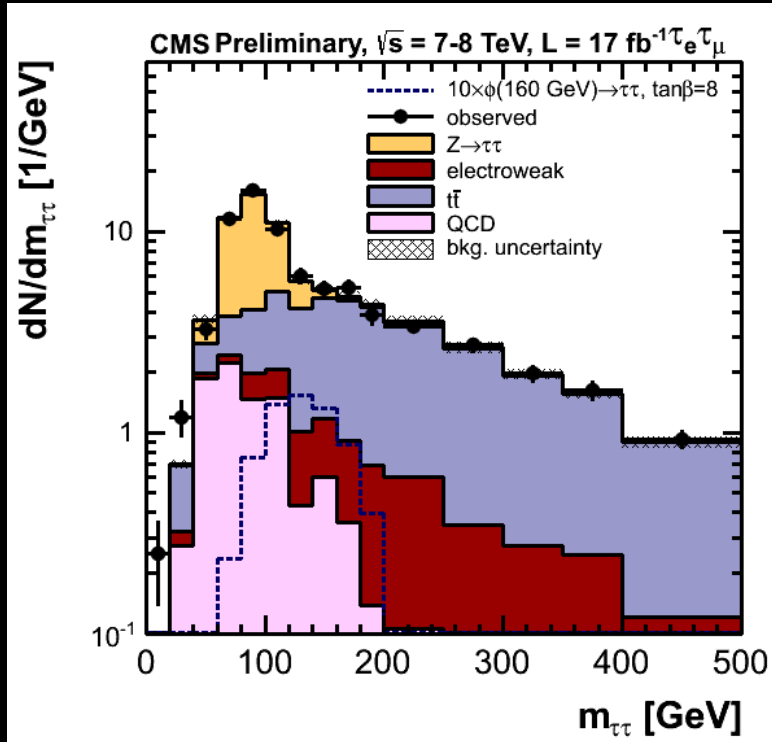
Mass resolution  $\approx 15 - 20\%$



# MSSM Neutral Higgs: $\Phi^0 \rightarrow \tau^+ \tau^-$

$$\phi^0 \rightarrow \tau^+ \tau^- \rightarrow e\mu + 4\nu$$

$$\phi^0 \rightarrow \tau^+ \tau^- \rightarrow \mu^+ \mu^- + 4\nu$$





# Neutral Higgs: $\Phi^0 \rightarrow \mu^+ \mu^-$

Trigger selection: isolated muon

5 fb<sup>-1</sup> at  $\sqrt{s} = 7$  TeV

Selection:

2 isolated & high  $p_t$  muons

$E_t^{\text{miss}}$  veto [to reject  $t\bar{t}$  bkg]

2 high- $p_t$  jets

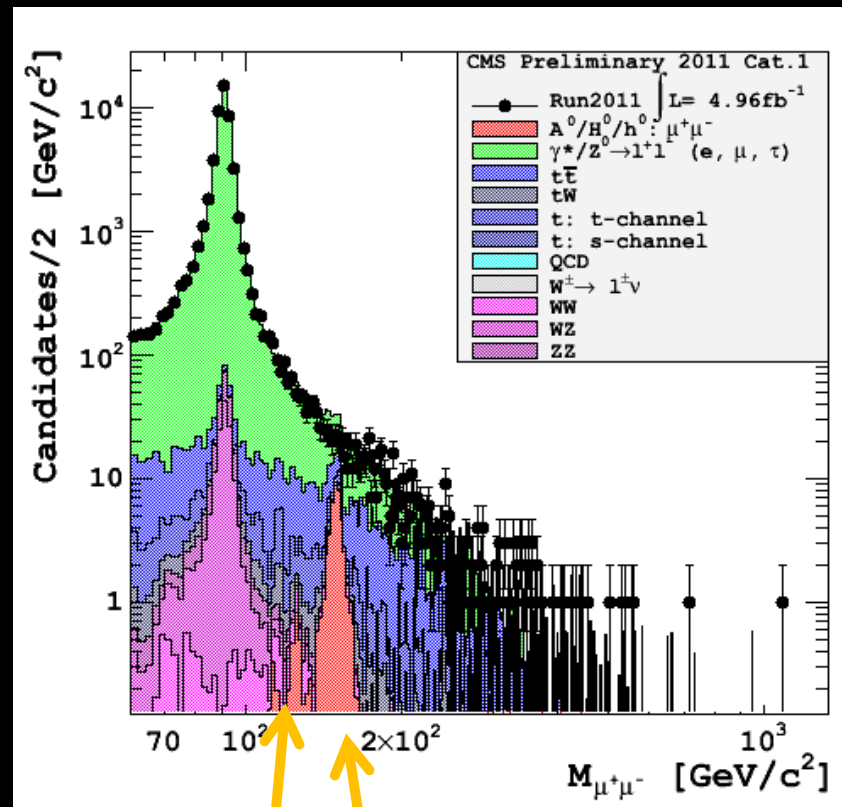
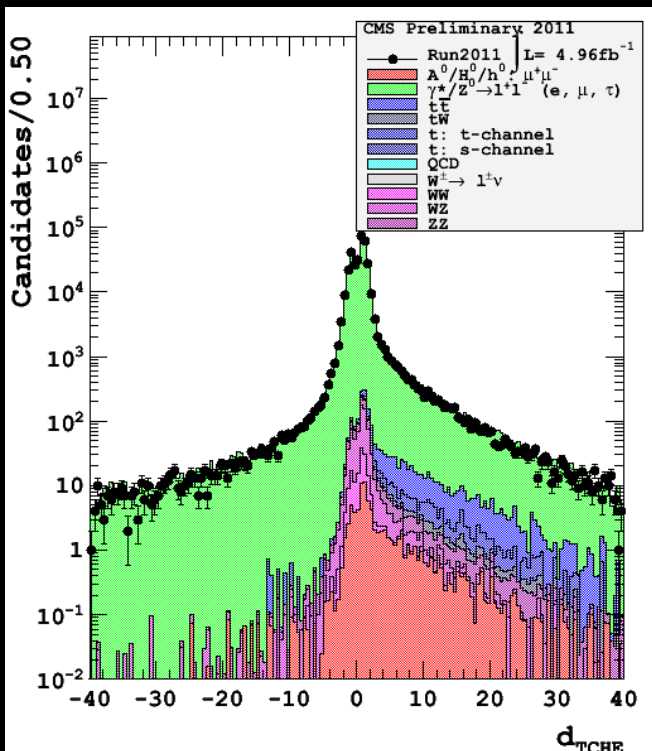
split the events in 2 categories:

with one b-tagged jet

[to reject DY bkg]

with no

b-tagged jet



Mass resolution at Z-peak is  $\approx 3\%$

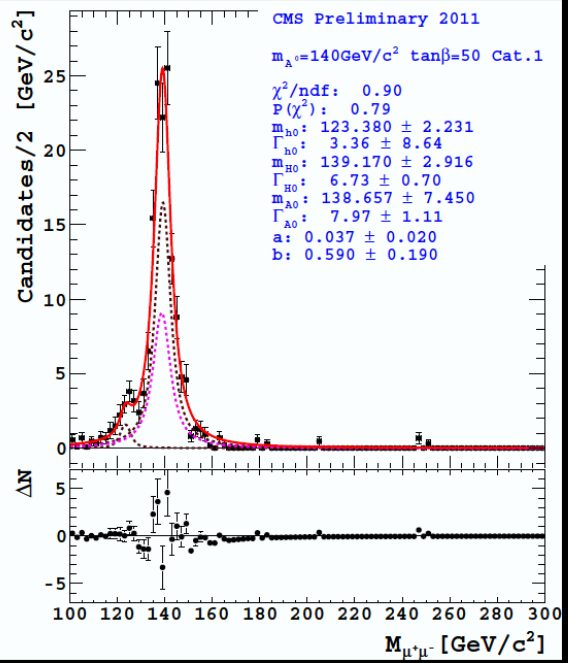


# bkg estimation for $\Phi^0 \rightarrow \mu^+ \mu^-$

The MC di-muon invariant mass distribution, for each signal hypothesis ( $m_A, \tan \beta$ ), is fitted by:

$$F_{sig} = a \cdot F_{BW h^0} + b \cdot F_{BW H^0} + (1 - a - b) \cdot F_{BW A^0}$$

Each **F** is a convolution of Breit-Wigner (BW) and Gaussian functions, and contains 2 free parameters (mass and width) computed in the fit.



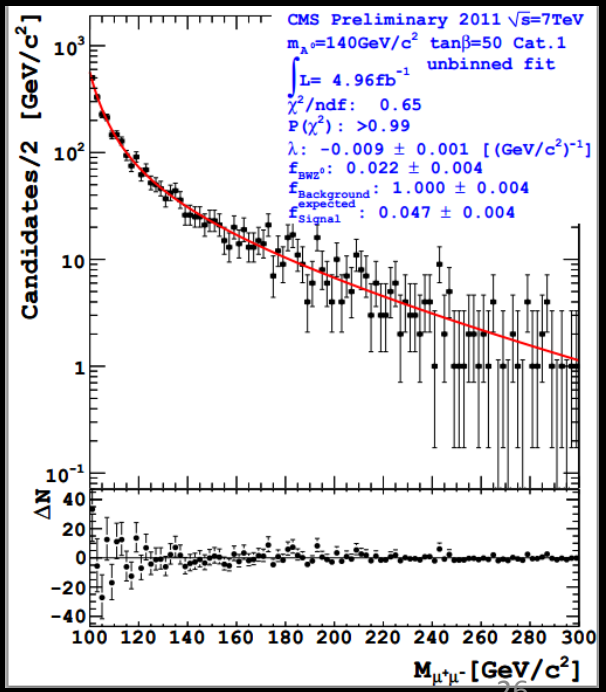
The data di-muon invariant mass distribution is fitted by

$$F = (1 - f_{Background}) \cdot F_{sig} + f_{Background} \cdot F_{bkg}$$

where the background is described by:

$$F_{bkg} = e^{\lambda x} \left[ \frac{f_{BW} Z^0 \cdot \Gamma_{Z^0}}{(x - M_{Z^0})^2 + \frac{\Gamma_{Z^0}^2}{4}} + \frac{1 - f_{BW} Z^0}{x^2} \right]$$

the free parameter “ $f_{Background}$ ” computes the amount of observed signal in the data. It’s computed in the by the final fit.



# NMSSM $a_1 \rightarrow \mu\mu$

## $a_1 \rightarrow \mu\mu$

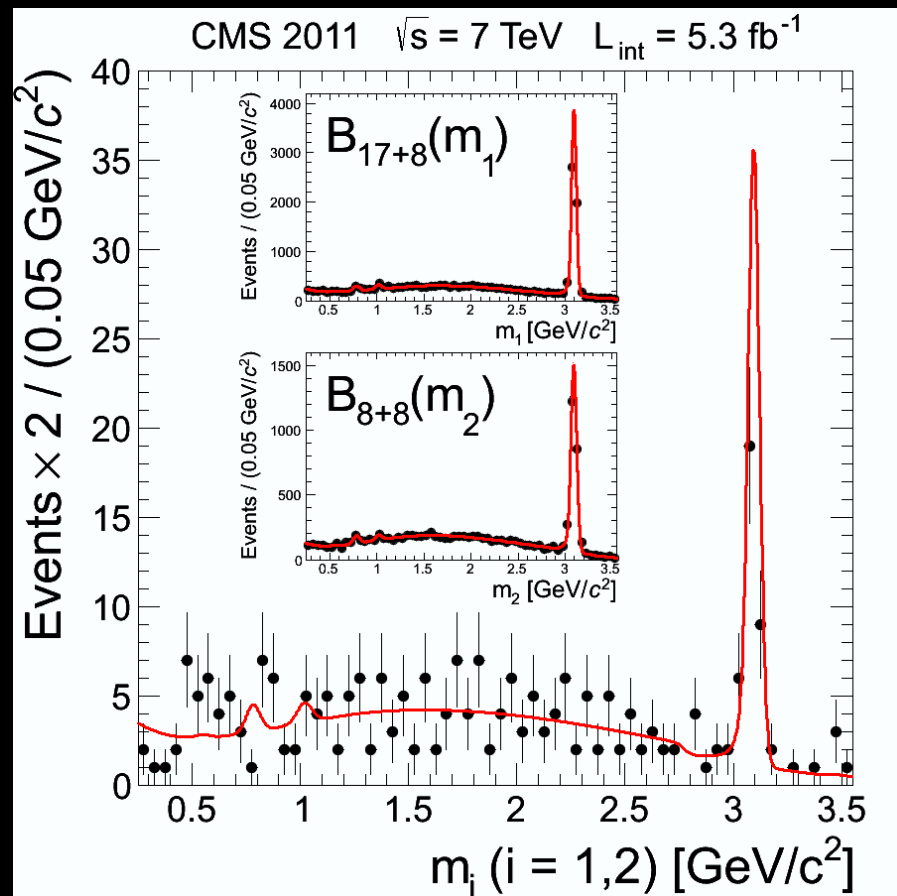
selection:

- ✓ dimuon trigger with muon  $p_T > 3.5$  GeV,  
 $p_T(\mu\mu) > 6$  GeV,  
 $5.5 \leq M_{\mu\mu} \leq 14$  GeV,
- ✓ two isolated and opposite charged,
- ✓ offline muon  $p_T > 5.5$  GeV.

## $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$

selection:

- ✓ dimuon trigger ( $p_T > 8$  GeV &  $p_T > 17$  GeV)
- ✓ at least 4 isolated  $\mu$  with  $p_T > 8$  GeV,  
 $|\eta| < 2.4$ ,
- ✓ one of them with  $p_T > 17$  GeV,  
 $|\eta| < 0.9$





# Fermiophobic $H \rightarrow \gamma\gamma$

Trigger selection:

- ✓ 2 isolated (loose) photons with
  - $p_T > 26$  (18) GeV;
  - $|\eta| < 2.5$

Offline selections of 2 isolated and high  $p_T$  photons splitted in 4 classes:

- ✓ Dijet tag event classes (VBF production);
- ✓ Lepton tag event classes (VH production);
- ✓  $E_T^{\text{miss}}$  tag class event (VH production  $Z \rightarrow \nu\nu$ );
- ✓ Untagged classes.

# SM rare decay $H \rightarrow Z\gamma$

selection:

- ✓ dilepton triggers;
- ✓ two opposite charge, same flavor and isolated leptons with  $p_T > 20$  (10) GeV and  $|\eta| < 2.4$  (2.5) for  $\mu$  (e);
- ✓ isolated photon  $p_T > 15$  GeV &  $|\eta| < 2.5$

