# Searches for BSM Higgs bosons in CMS at LHC

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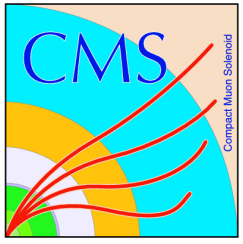
on behalf of the

CMS Collaboration

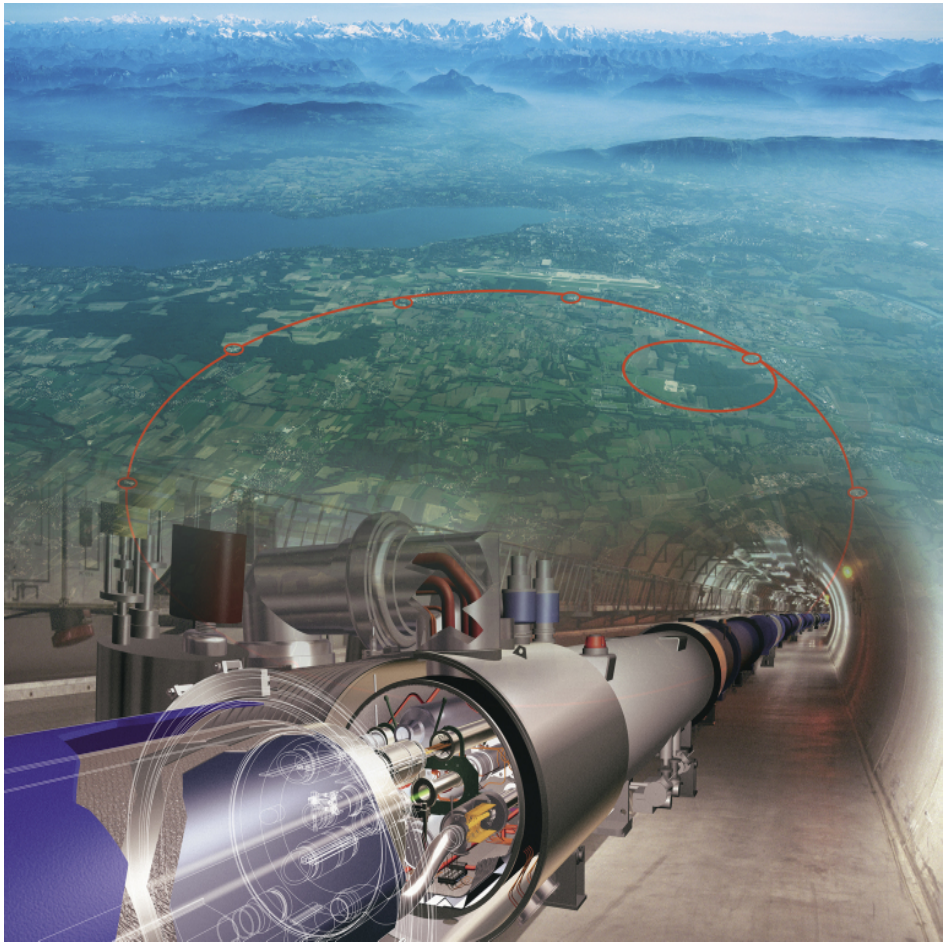




# Outline


1. LHC and CMS performance
2. Physics Beyond the SM
3. Search for BSM Higgs
4. Summary

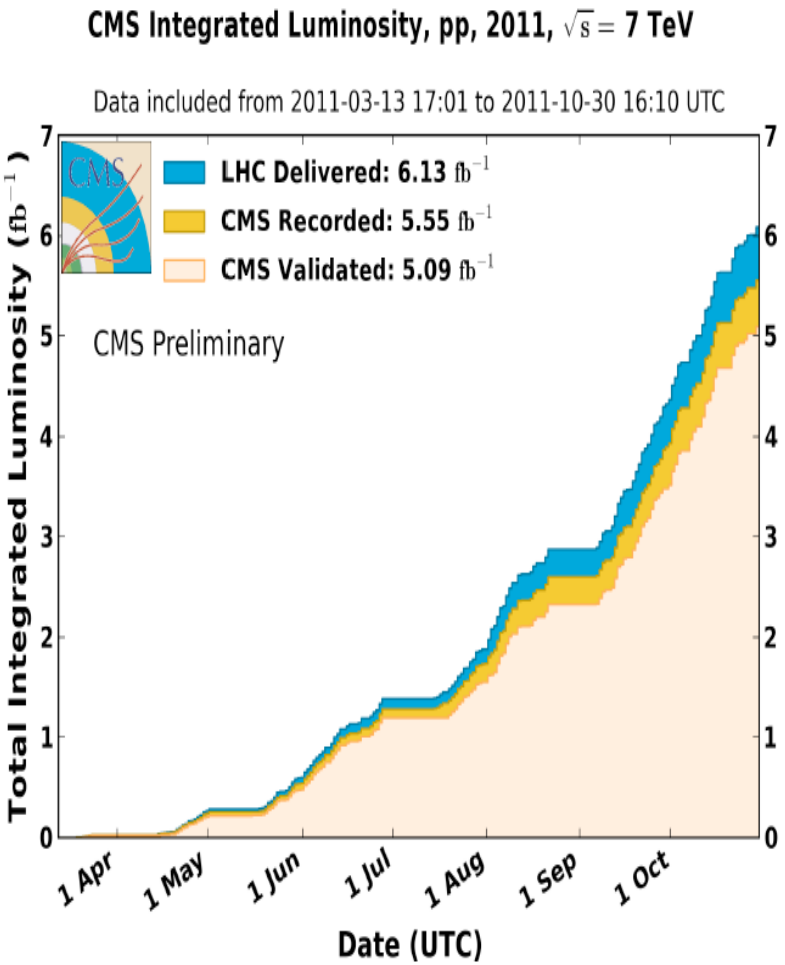
# LHC and CMS performance

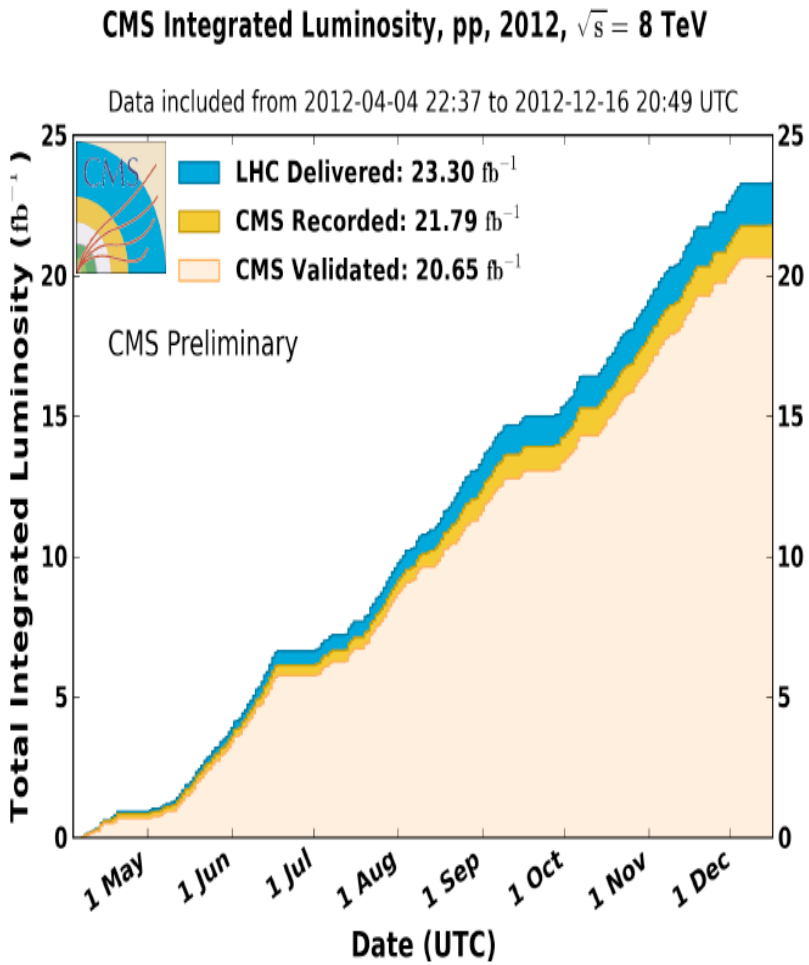


# LHC and CMS performance

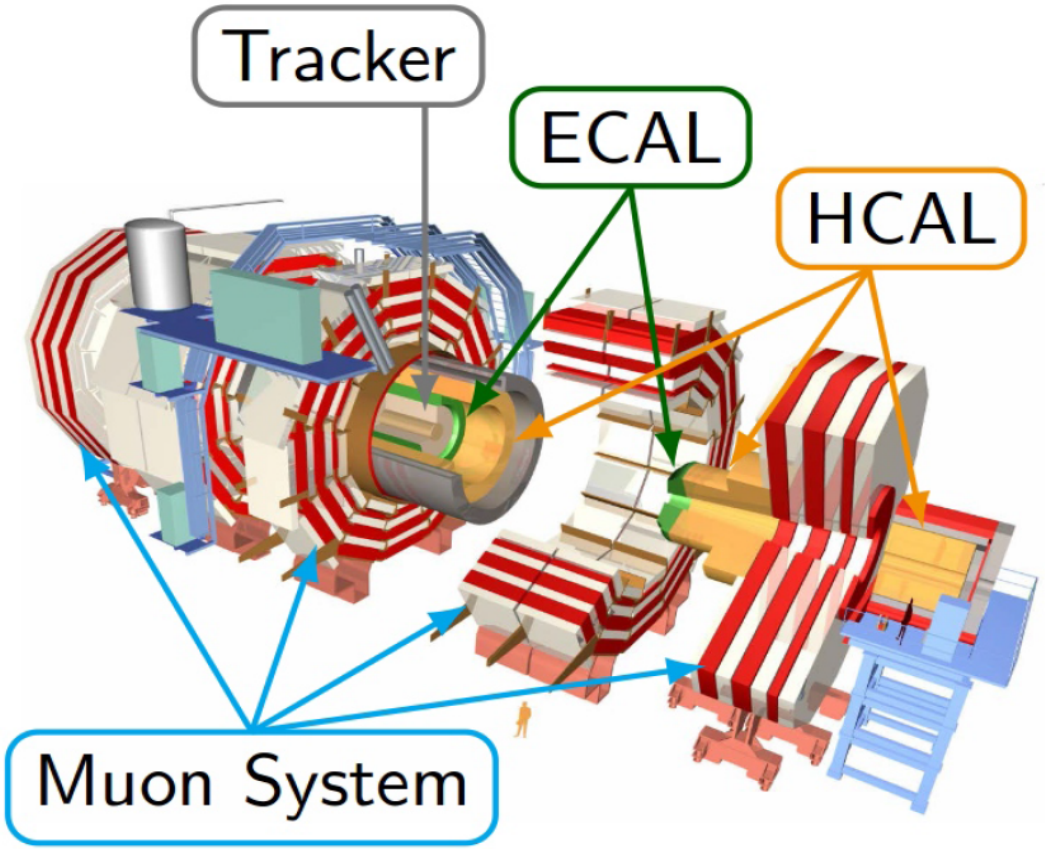
- The LHC has been performing extremely well

- CMS operation efficiency $\sim$95%
- Recorded luminosity in pp collisions of $\sim 25\ \text{fb}^{-1}$ by the end of 2012



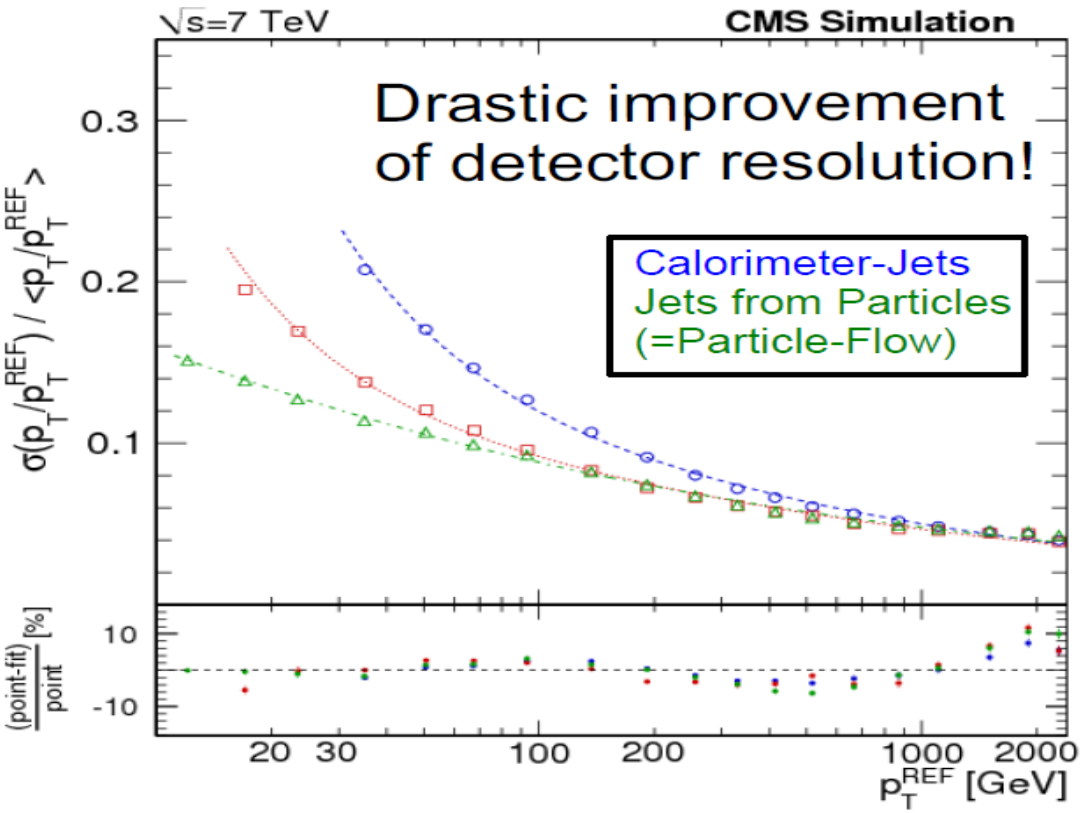
# CMS Detector Overview

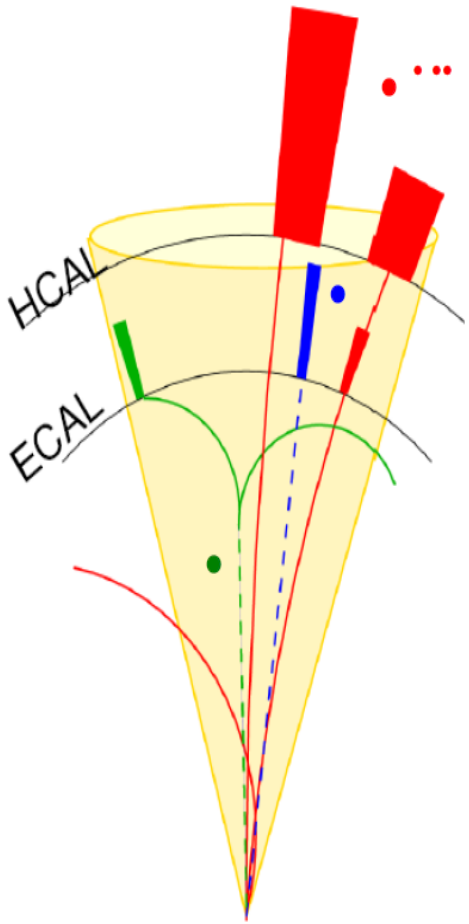



- Presented analyses extensively use in particular tracker, calorimeter and muon systems
- Application of Particle-Flow techniques for efficient reconstruction of all particles in a event

# Particle-Flow Event Reconstruction in CMS

- **Reconstruct** all particles in detector volume
  - **combining** information from sub-detectors
- First, **identification** of leptons and photons
  - then the rest to cluster in **jets**

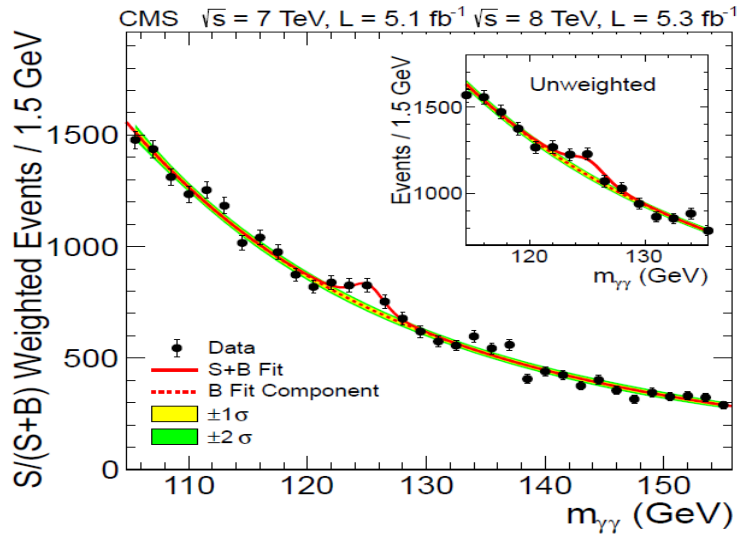


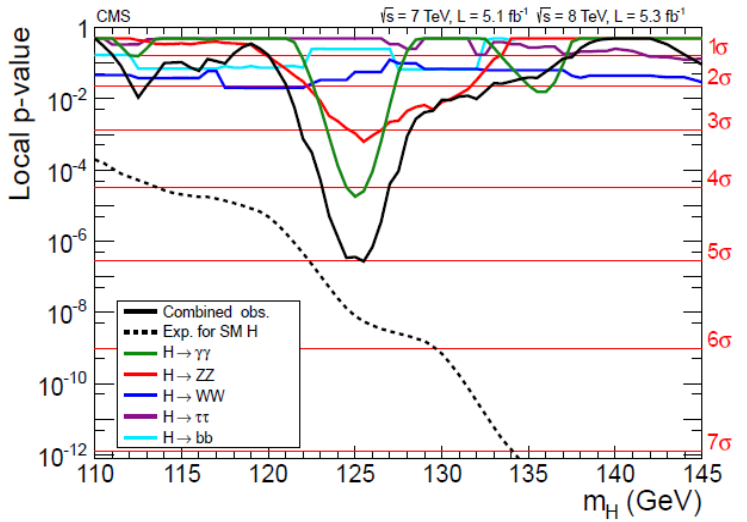



# Observation of a New Boson

# Observation of a New Boson

- Discovery of a new Boson has been announced by ATLAS and CMS
- Latest mass measurement $m_X = 125.7 \pm 0.3(stat.) \pm 0.3(syst.)$ GeV
- Consistent with a Higgs boson.
  - But which Higgs boson have we observed?
  - SM? or ... MSSM lightest $h$ ?



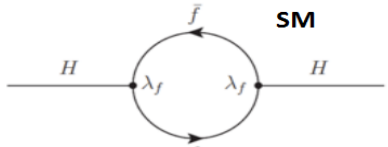



# Physics Beyond the SM

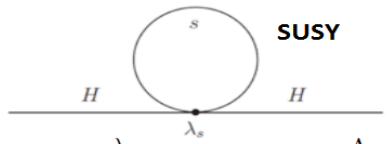
# Physics Beyond the SM

New Physics expected at TeV scale

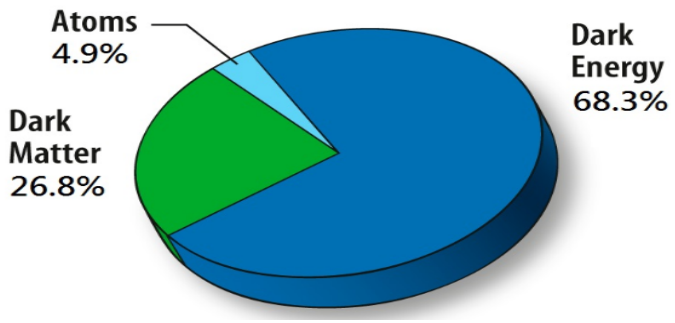
- "Fine tuning" problem: $\Delta m_H^2 \propto \Lambda_{UV}^2 \sim M_{Planck}^2$
- Hierarchy problem: $M_{W/Z}/M_{Plank(GUT)} \sim 10^{-16}$
- Dark Matter; Dark Energy
- Unifcation of gauge couplings
- SUSY as possible solution...

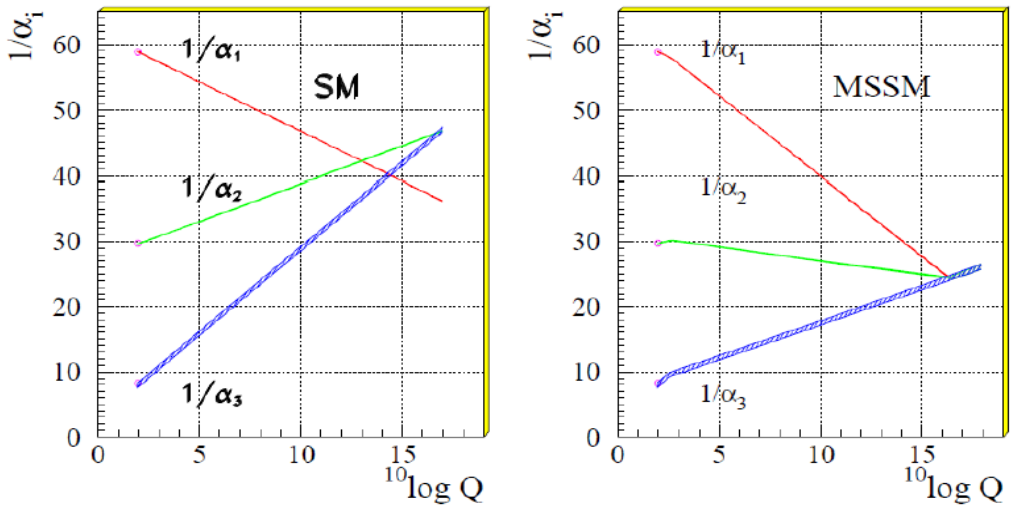



$$\Delta m_{H,f}^2 \approx -\frac{\lambda_f^2}{8\pi^2}\Lambda_{\rm UV}^2$$




$$\Delta m_{H,s}^2 \approx \frac{\lambda_s}{16\pi^2}(\Lambda_{\rm UV}^2 - 2m_s^2 \log\frac{\Lambda_{\rm UV}}{m_s})$$

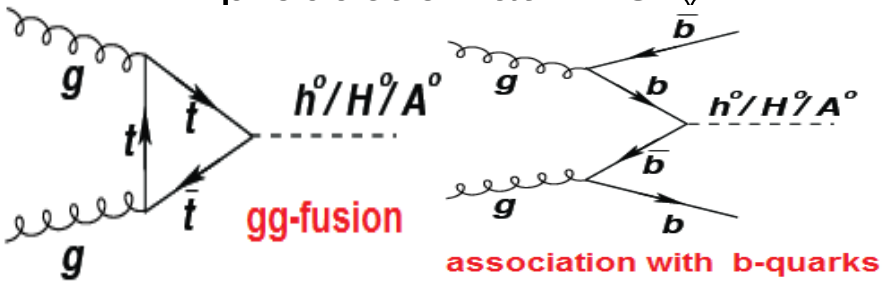


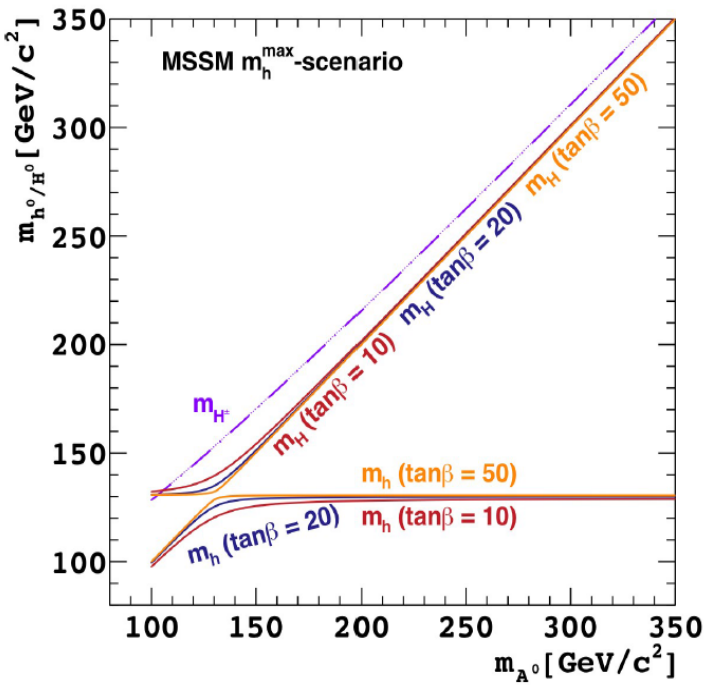



# The MSSM Higgs Sector

- Two scalar Higgs doublets, $H_u$ and $H_d$
- 5 **physical scalars**
  - 3 **neutral**
    $\Phi = h, H(CP-even)/A(CP-odd)$
  - 2 **charged** $(H^{\pm})$
- Determined by two parameters at tree level
  - $tan\beta = < H_u > / < H_d >$
  - $M_A$
- $h$ boson
  - behavior as the **SM** Higgs boson
- Decay channels of $\Phi$
  - $\Phi \to b\bar{b}$, $Br(b\bar{b}) \sim 90\%$
  - $\Phi \to \tau\bar{\tau}$, $Br(\tau\bar{\tau}) \sim 10\%$
  - $\Phi \to \mu\mu$, $Br(\mu\mu) \sim 0.03\%$

- Main channel of $\Phi$ production at LHC $\Downarrow$



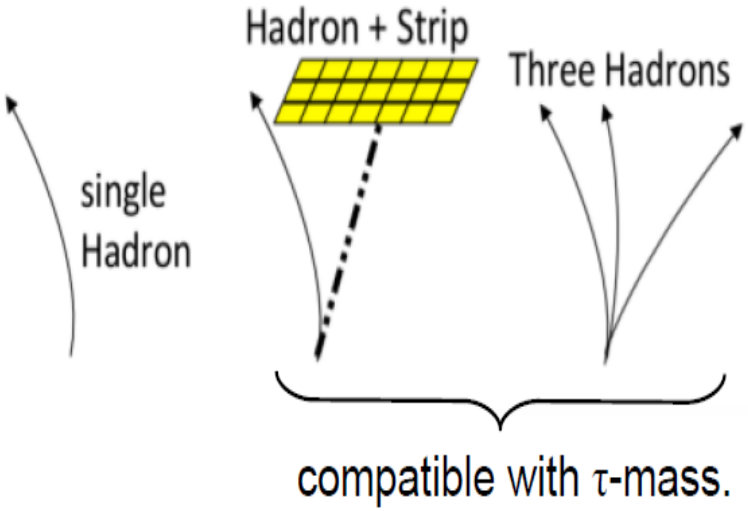
# Non-SM Higgs at CMS


- $\Phi \to \tau\tau$ : 4.9 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV
- $\Phi \to b\bar{b}$ : 4.0-4.8 fb$^{-1}$ at 7 TeV
- $\Phi \to \mu\mu$ : 4.9 fb$^{-1}$ at 7 TeV
- $H^{\pm} \to \tau\nu$ : 2.3-4.9 fb$^{-1}$ at 7 TeV

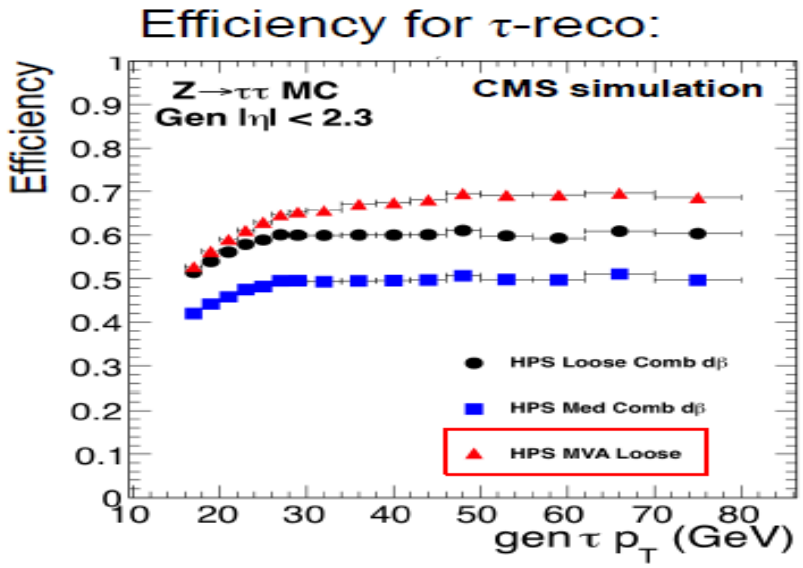
# MSSM $\Phi \rightarrow \tau\tau$

# $\tau$ and $Di-\tau$ reconstructions

## Identification of $\tau \rightarrow$

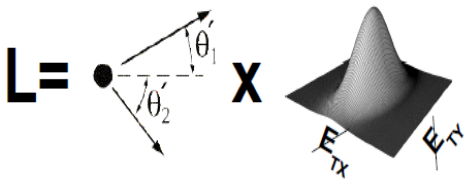


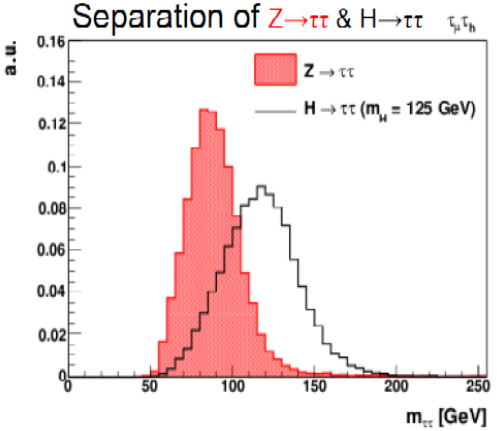

- $\tau-$ *reconstruction efficiency* $\sim 70\%$




## $Di-\tau$ system $\rightarrow$

- $M_{\tau\tau}$ with maximum likelihood method
- 4-vectors of visible leptons, $\not{E}_T$ as input
- 15-20% resolution of $M_{\tau\tau}$



# $\Phi \to \tau\tau$ triggering and event selection

**(CMS-HIG-12-050)**

- **Trigger** : selection based on $e/\mu$ and $\tau$ objects
  - four channels: $e+\tau_h$, $\mu+\tau_h$, $e+\mu$, $\mu+\mu$
- **Event selection**
  - lepton selection: $p_T > 20$ GeV; $|\eta| < 2.1$; isolated
  - $\not{E}_T > 25$ GeV; $M_T$<40 GeV (to supp. W+jet, $t\bar{t}$)
- **2 categories** to increase the sensitivity of the analysis:

**b-tag** (sensitive for $gg \to bb\Phi$ )
$\leq 1$ jet of $p_T > 30$ GeV
$\geq 1$ b-tagged jet of $p_T > 20$ GeV

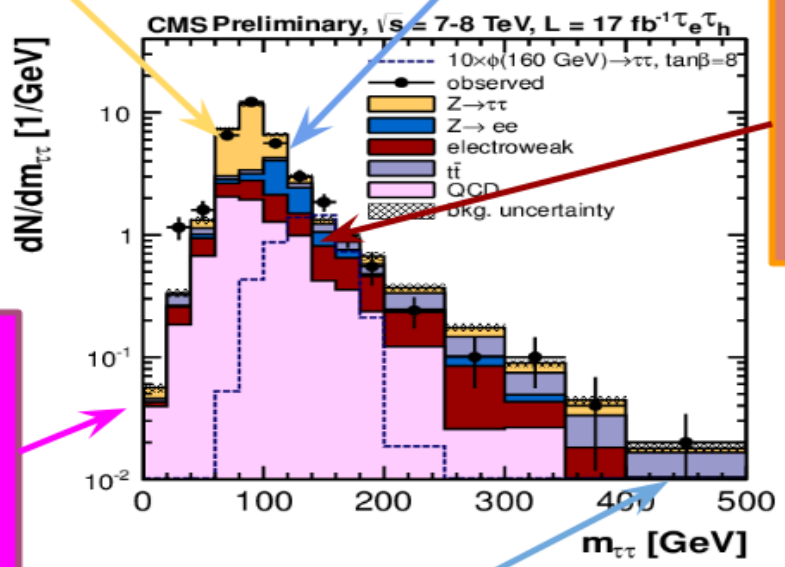
**non b-tag** (sensitive for $gg \to \Phi$ )
$\leq 1$ jet of $p_T > 30$ GeV
$\geq 1$ no b-tagged jet of $p_T > 20$ GeV

- **Signal extraction**: by the shape analysis of $M_{\tau\tau}$
- $\to$ **binned maximum likelihood fit** to reconstruced $\tau\tau$ invariant mass spectrum

# $\Phi \rightarrow \tau\tau$ background estimation

**Z→ ττ**
1. Embedding: Z→μμ, replace μ by sim. τ decay.
2. Normalized from Z→μμ events.

**Z→ee (Z→μμ)**
1. From simulation
2. Corrected for jet -> tau
3. e/mu fakerate

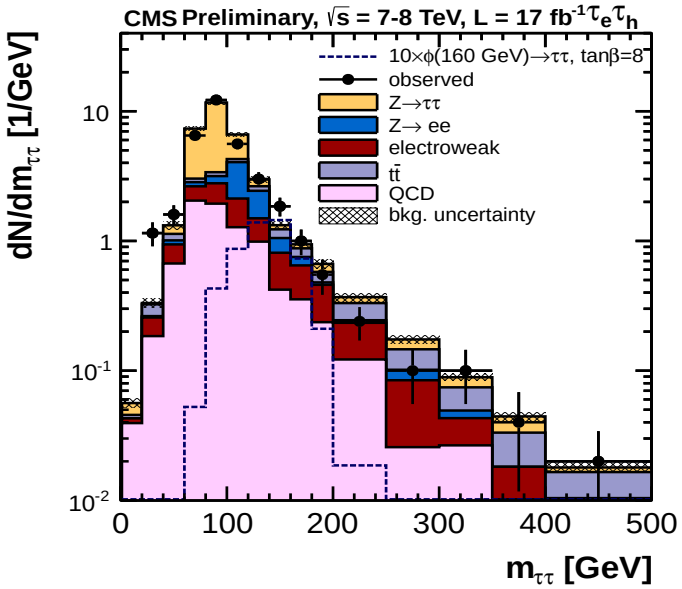


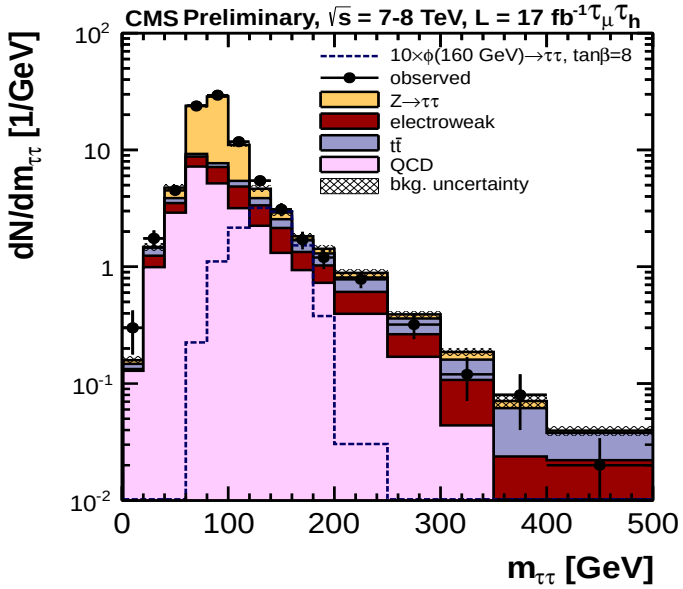

**Diboson**
1. From simulation
2. Normalization from sideband

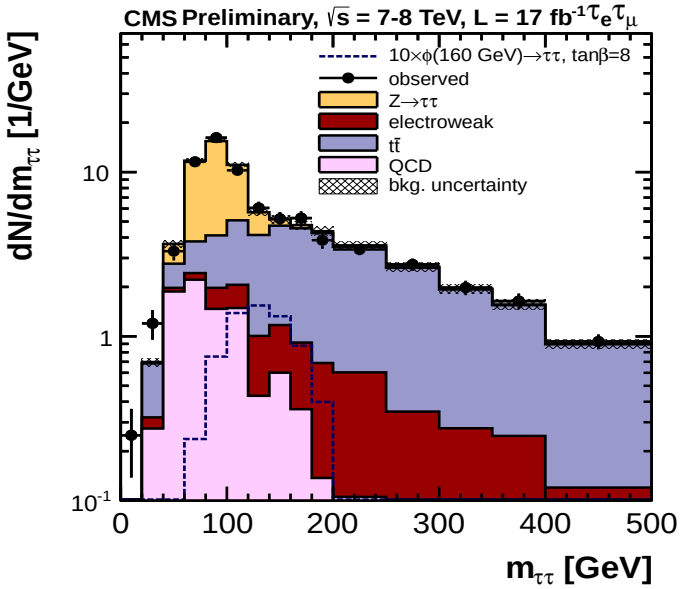
**QCD**
**Normalization & shape from LS/OS or fakerate**

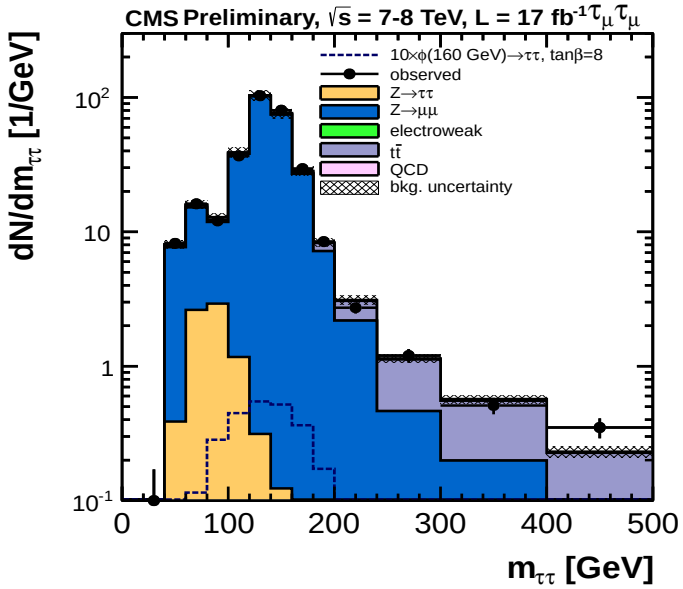
**ttbar**
**From simulation**
**Normalization from sideband**

# $\Phi \to \tau\tau$ results in the b-tag category



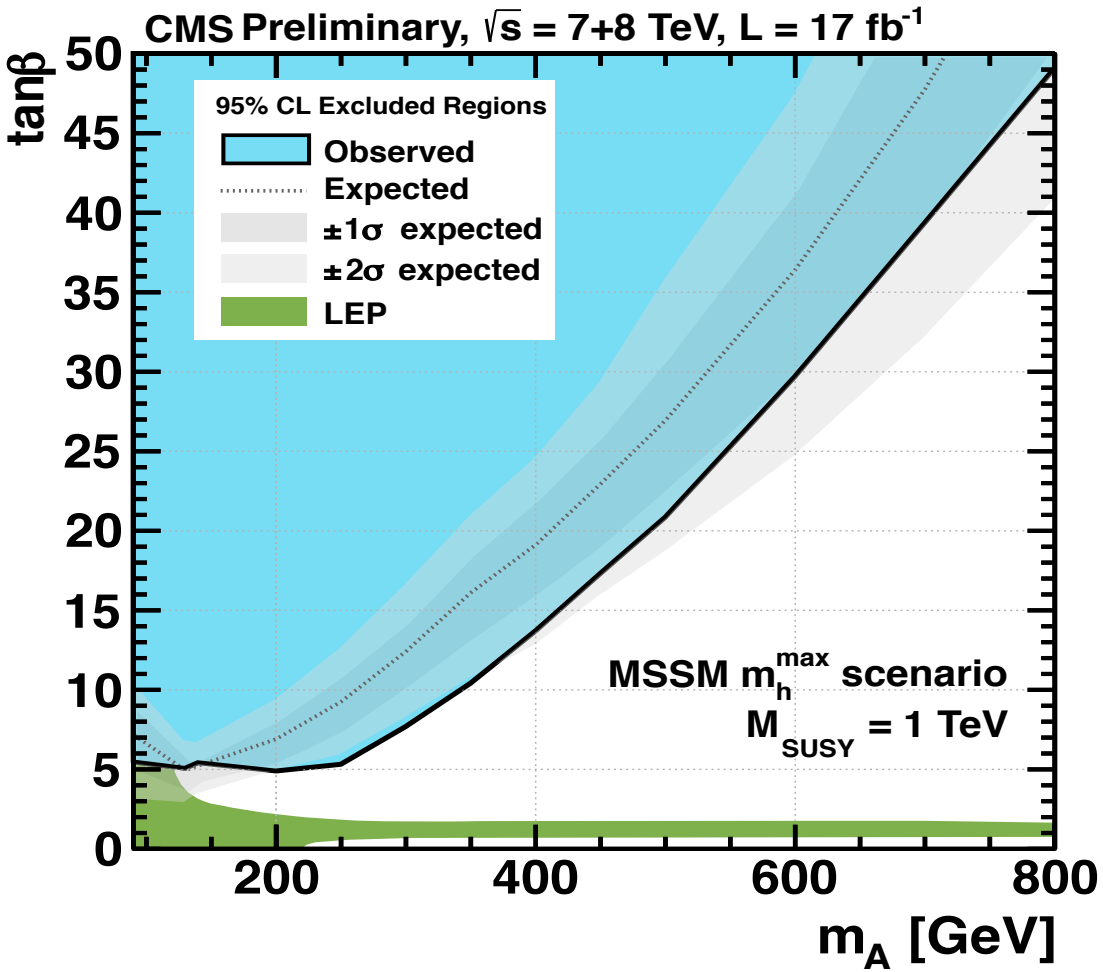




- Templates fitting **S+B** hypothesis.
- Shaded bands: uncert's after fit.

# $\Phi \rightarrow \tau\tau$ exclusion limits

- Signal cross section and uncertainties from LHC Higgs Cross Section Group
- **No excess** over predicted SM background in any event categroy
- **Rules out a significant part of the parameter space previously unexplored**: $\tan\beta$ reaching as low as 5 for $M_A < 250$ GeV in $m_h^{max}$ scenario



$$\text{MSSM } \Phi \rightarrow b\bar{b}$$

# $\Phi \to b\bar{b}$ triggering and event selection

**(CMS-HIG-12-033)**

- Two event categories considered: **all-hadronic** (3 b-jets) and **semi-leptonic** (2 b-jets with an non-isolated muon)
  - challenging triggers at the LHC
  - almost independent samples (2-3% overlap)

| **all-hadronic** | **semi-leptonic** |
|---|---|
| **Trigger** | |
| 2 or 3 jets, $\geq$ 2 b-tagged | 1 muon + 2 jets, $\geq$ 1 b-tagged |
| **Jet selection** | |
| $\geq$ 3 high-$p_T$ jets in $\lvert\eta\rvert < 2.2$ | $\geq$ 3 high-$p_T$ jets in $\lvert\eta\rvert < 2.6$ |
| 3 leading offline 'tight' b-tags | 2 'tight' b-tags, 1 loose b-tag |
| $\Delta R_{12} > 1$ | $\Delta R_{ij} > 1$ |
| | **1 muon with $p_T > 15$ GeV in a jet** |

- **Signal extraction**
  - as a peak in the di-jet mass distribution $M_{12}$ in triple-btag sample

# $\Phi \rightarrow b\bar{b}$ data-driven estimation of background

- Background:
  - **QCD multi-jets** events with **3** b-jets (**2** b-jets **+ 1** misidentifed c- or udsg-jet)
  - Other backgrounds such as $t\bar{t}$ **or Z+jets** found to be small
  - **2-b-tagged data samples** to be utilized

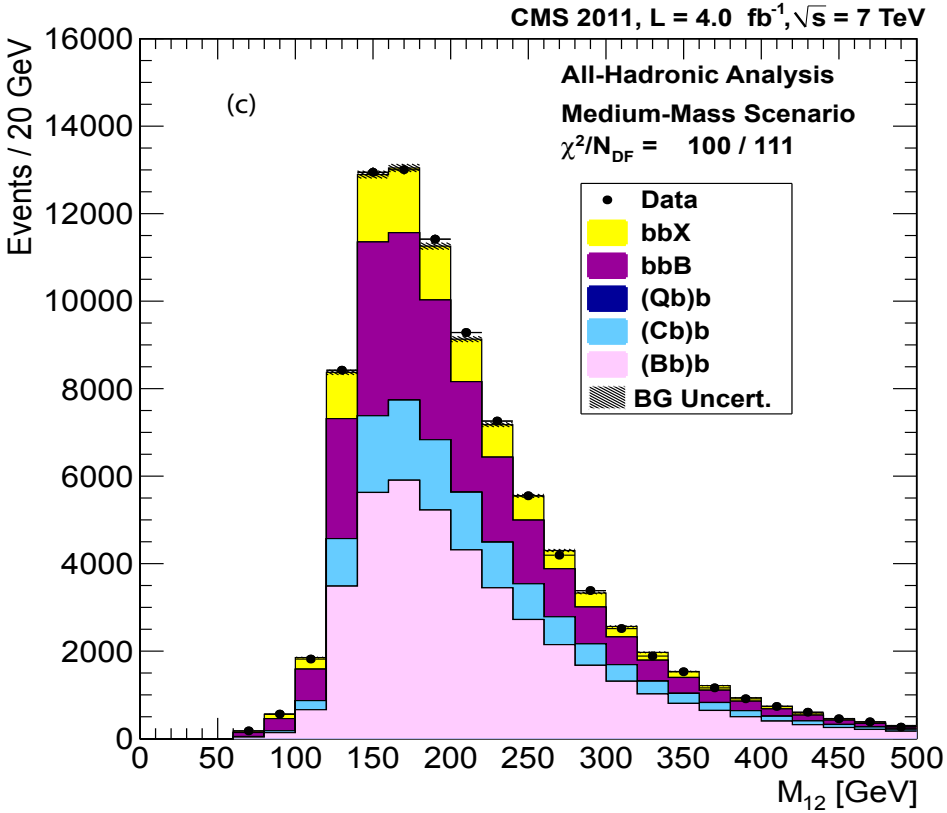
## all-hadronic

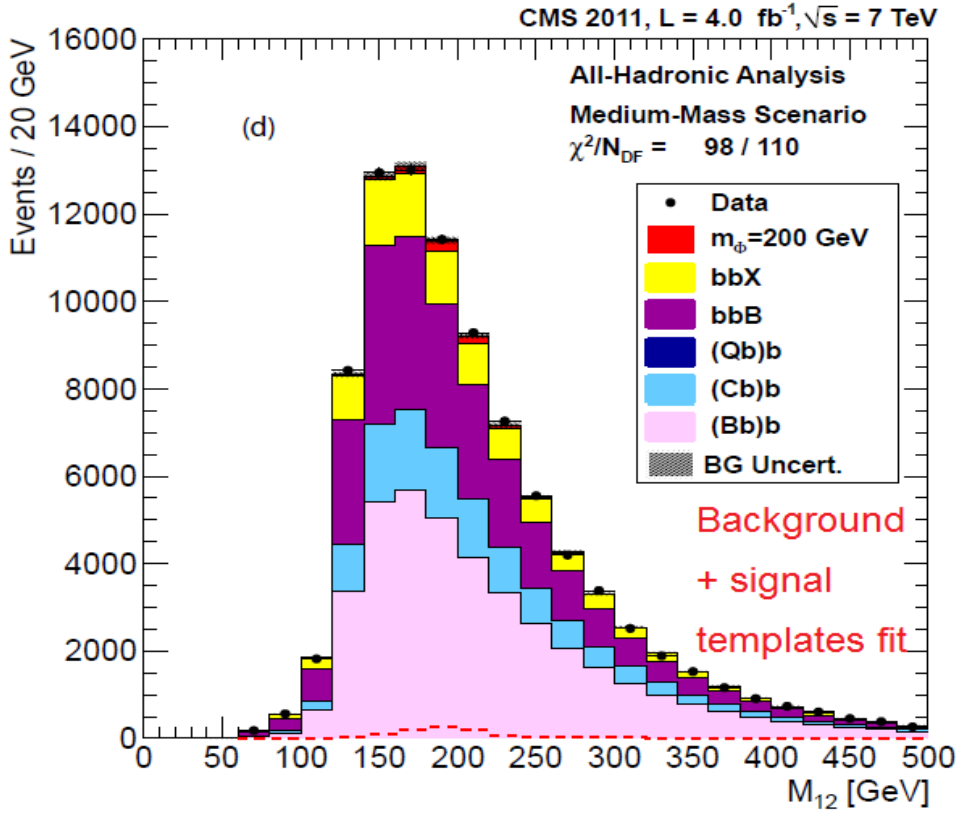
- 2-b-tagged data; $\geq 3$ jets (sorted in $p_T$)
- **b,c,udsg** flavour assumptions to untagged jet **X**: **bbX**, **bXb**, **Xbb**
- **2D templates** on $M_{12}$ and $X_{123}$ (predicts flavor content)
- 5 templates

## semi-leptonic

- **Probability of 3$^{rd}$ b-tagged jet**:
  - $P_b = \varepsilon_b \cdot f_b + \varepsilon_c \cdot f_c + \varepsilon_q \cdot f_q$
- $\varepsilon$ **taken from MC** (sclaled by data/MC)
- $f$ **- data-driven estimated** via a template fit

# $\Phi \rightarrow b\bar{b}$ results in the all-hadronic category

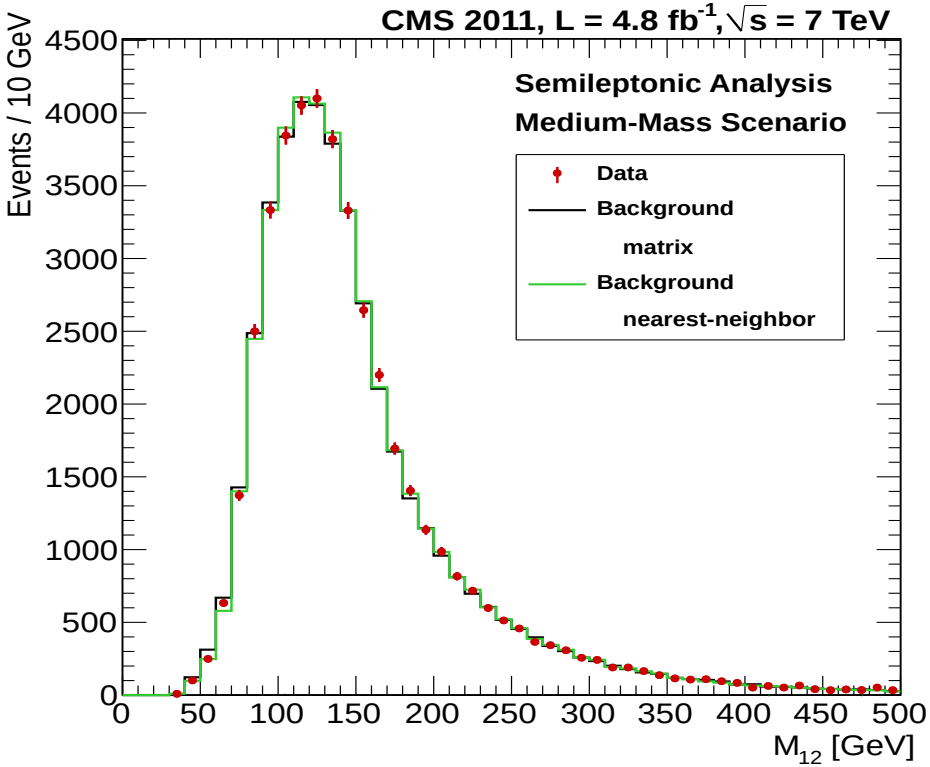


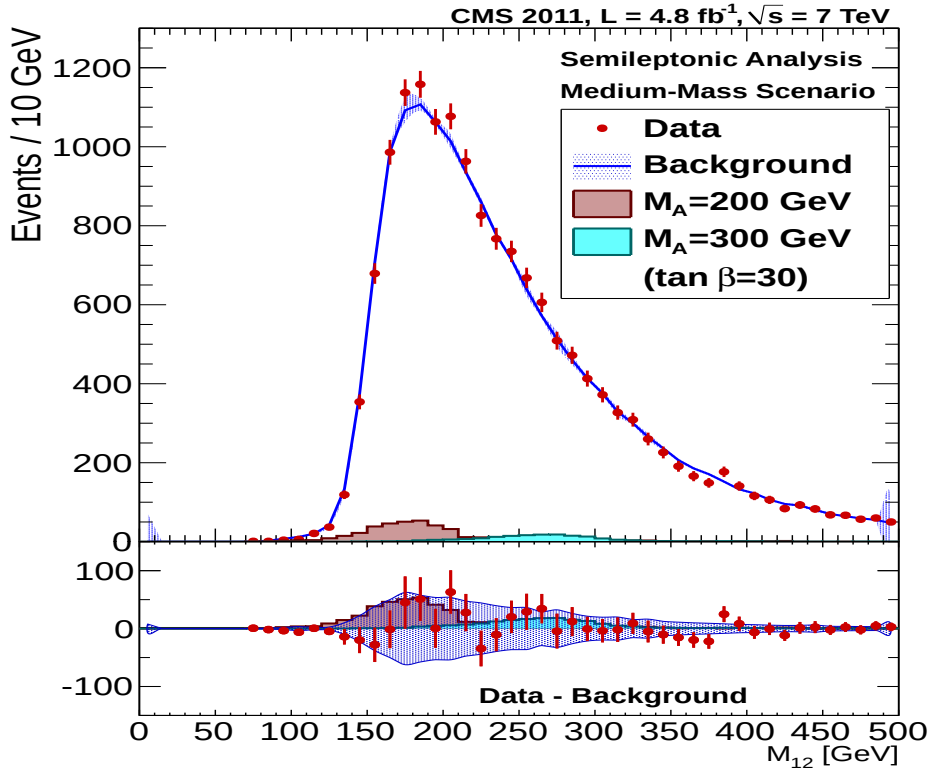




- No significant deviation from background
- Background mainly ($\sim$ 70%) composed of three b jets

- Shown $M_\Phi = 200$GeV:
  - Good fit quality
  - Largest upward fluctuation of $\sim 1.4\sigma$
  - No signal observed at any mass from [90-350] GeV

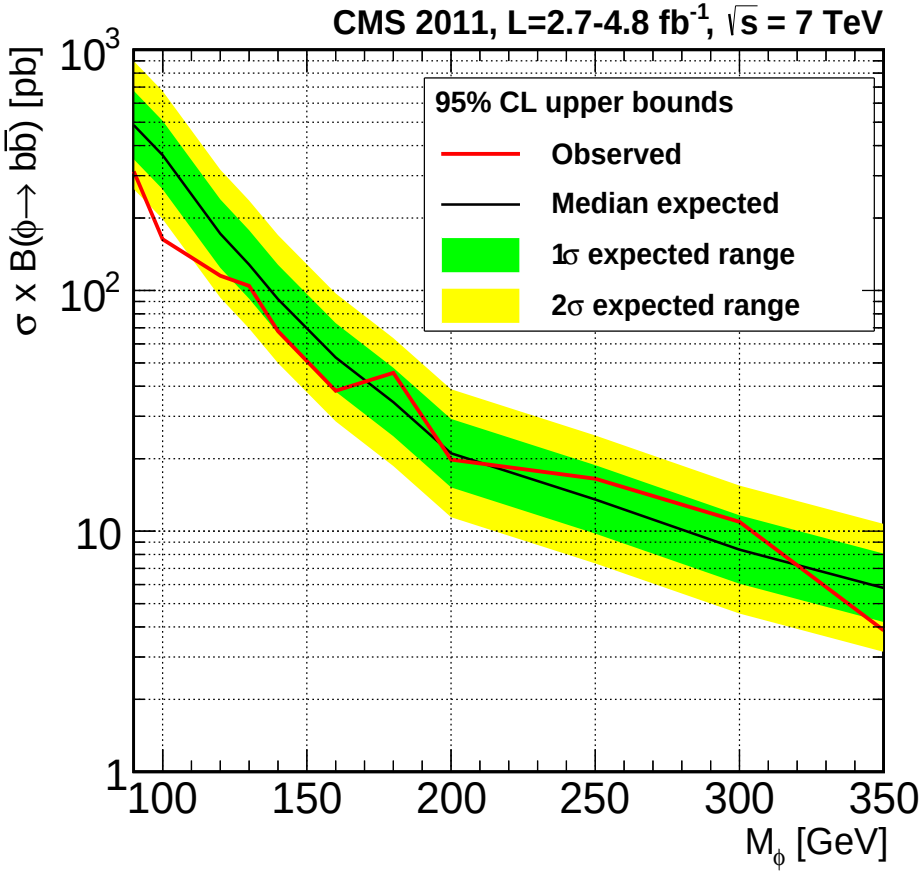
# $\Phi \rightarrow b\bar{b}$ results in the semileptonic category

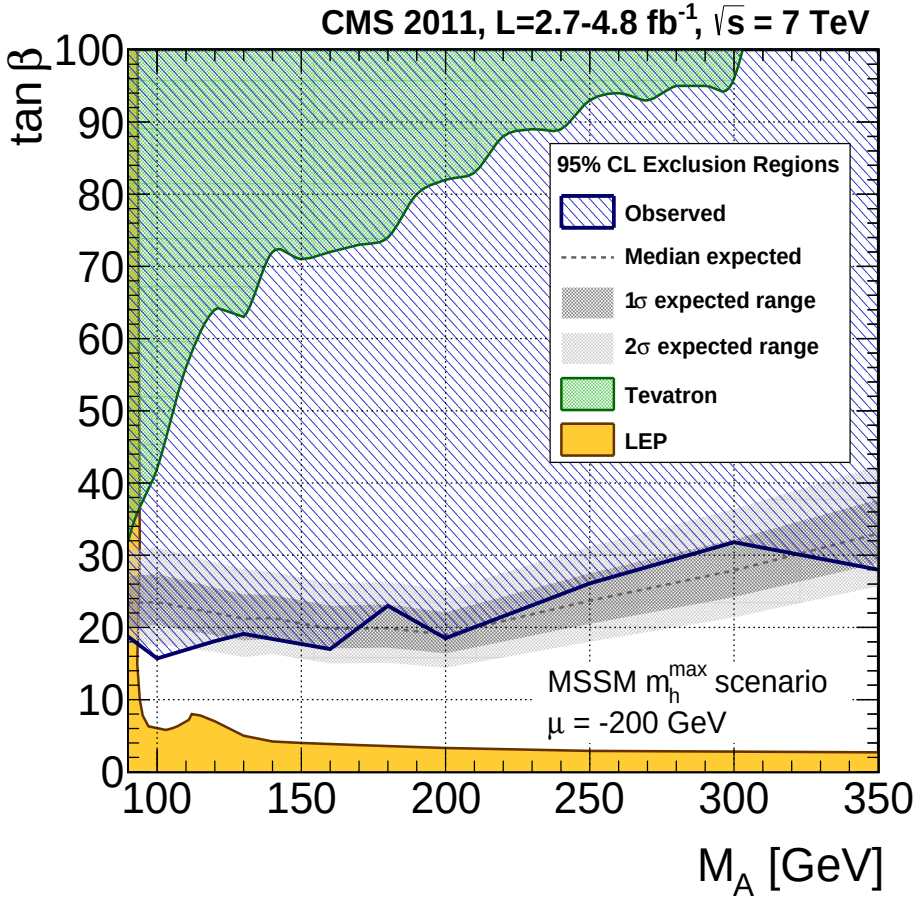



- Two independent data-driven estimations of background agree well
- No indication of signal excess

# $\Phi \rightarrow b\bar{b}$ combined results




- Stringent limits (model-independent) on the cross section for $\Phi \rightarrow b\bar{b}$
- **World's best sensitivity in MSSM searches in the $b\bar{b}$ channel**

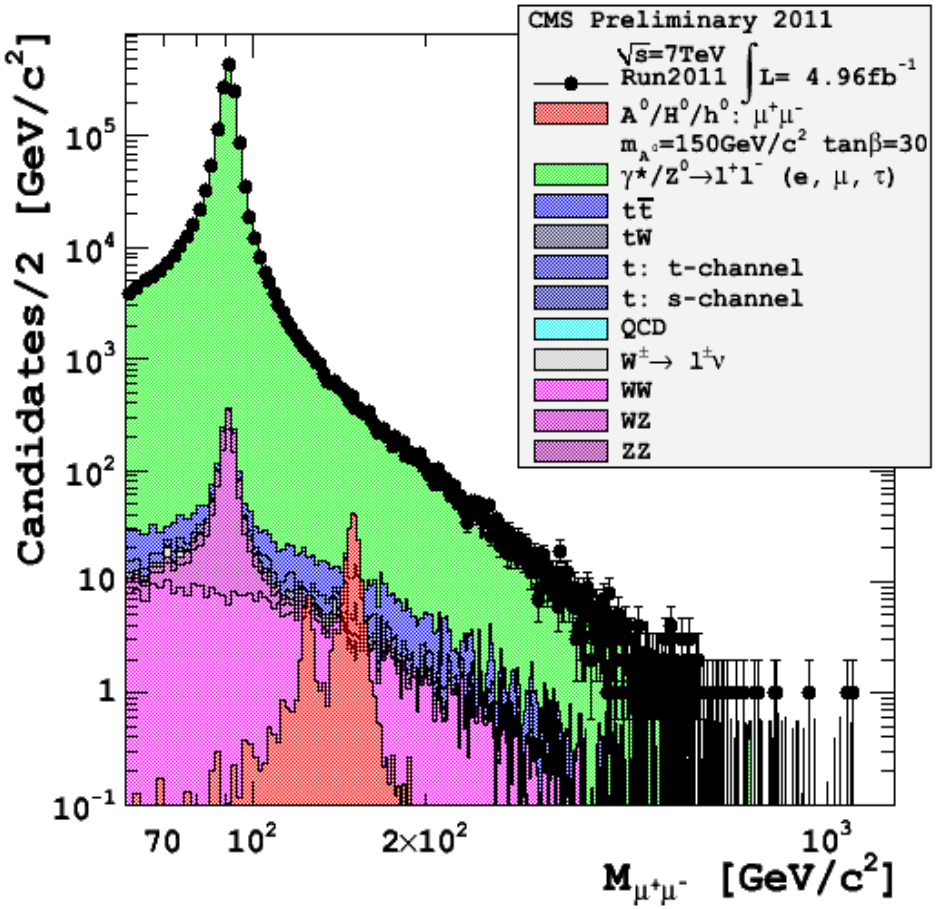
$$\text{MSSM } \Phi \rightarrow \mu^+\mu^-$$

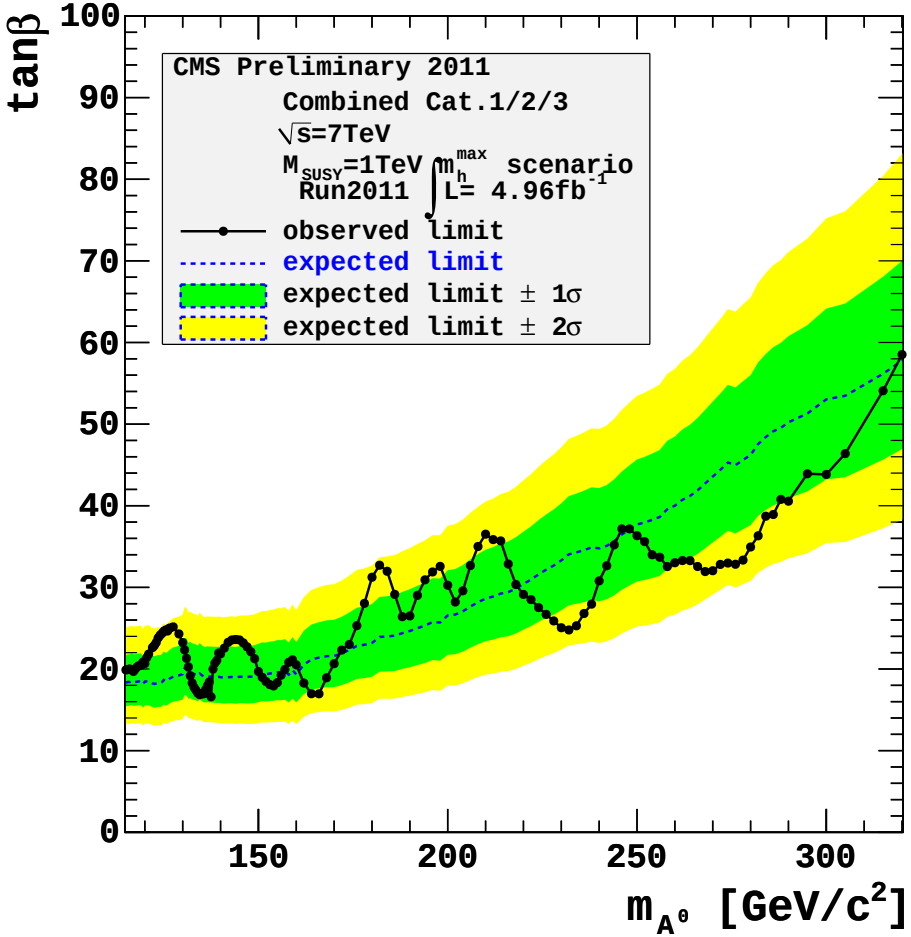
# $\Phi \to \mu^+\mu^-$ triggering and event selection

**(CMS-HIG-12-011)**

- Excellent mass resolution and manageable backgrounds, but low **BR**
- Signature: two oppositely charged, isolated muons with $p_{T1(2)} > 30(20)$GeV, $|\eta| < 2.1$ and $\not{E}_T < 30$GeV
- **Category 1** ($gg \to b\bar{b}\Phi$)
  - $\geq 1$ b-tagged jet: $p_T > 20$ GeV, $|\eta| < 2.4$, $\Delta R(\mu, j) > 0.5$
- **Category 2** ($gg \to b\bar{b}\Phi$)
  - veto on b-tagged jets, but a $3^{rd}$ $\mu$: $p_T > 3$ GeV, $|\eta| < 2.4$, $\Delta R(\mu, \mu) > 0.5$
- **Category 3** ($gg \to \Phi$)
  - all events $\notin$ **Categories 1,2**
- **Background**from data: mostly Drell-Yan (Zbb), $t\bar{t}$, $W^+W^-$, MC Breit-Wigner on $M^2_{\mu\mu}$ around Z-peak
- **Signal extraction**: a **unbinned maximum likelihood fit** of 3 signal $M_{\mu\mu}$ + background Breit-Wigners hypotheses to data

# $\Phi \to \mu^+\mu^-$ combined result from 3 categories



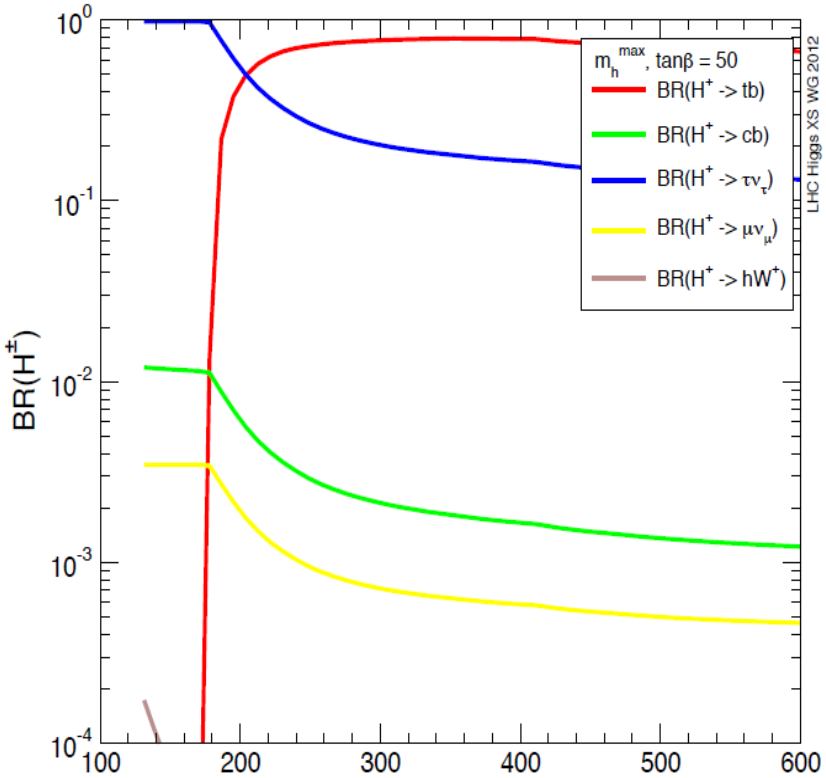

- No excess seen over predicted SM background in the combination
- 95 % CL upper limit on $\sigma \times Br(\mu\mu) < 40 - 20$fb for $M_A = 150 - 300$ GeV

# MSSM $t \to bH^{\pm}$, $H^{\pm} \to \tau\nu$

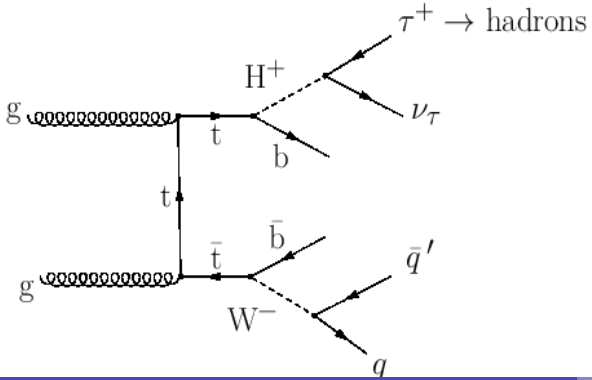
# MSSM $H^{\pm}$ production and decays

**(CMS-HIG-12-019, CMS-HIG-12-052)**

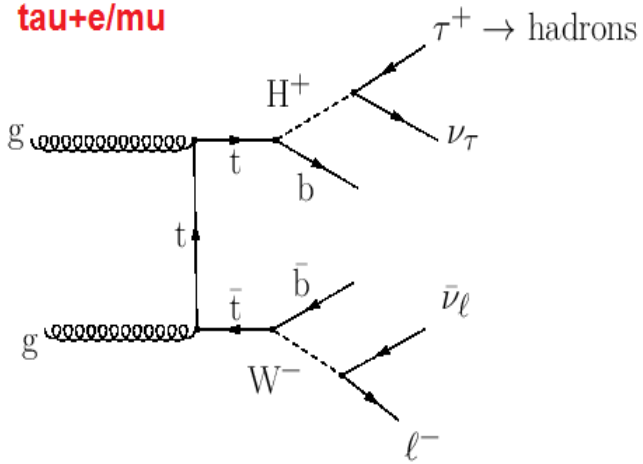
- Charged Higgs of low masses, $m_{H^{\pm}} < m_{top} - m_b$
  - in $t\bar{t}$ decays $t\bar{t} \to H^{\pm} W^{\mp} b\bar{b}$
- at large $\tan\beta > 5$
  - $\mathrm{Br}(H^{\pm} \to \tau^{\pm}\nu) \simeq 1$
- channels to study:
  - $e + \tau$, $e + \mu$, $\tau + jets$ (2.0-2.3 fb$^{-1}$)
  - $\mu + \tau$(4.9 fb$^{-1}$)



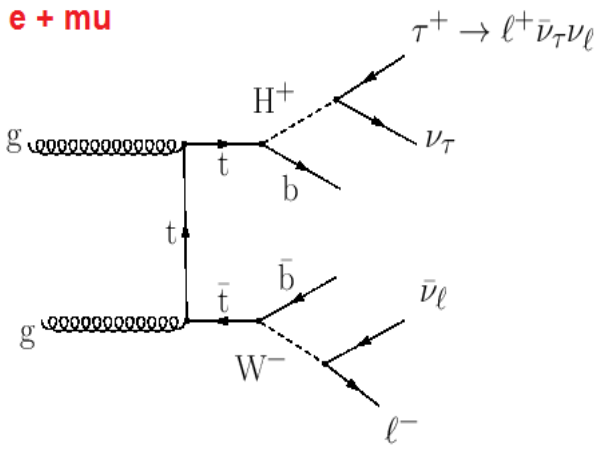

**tau + jets**



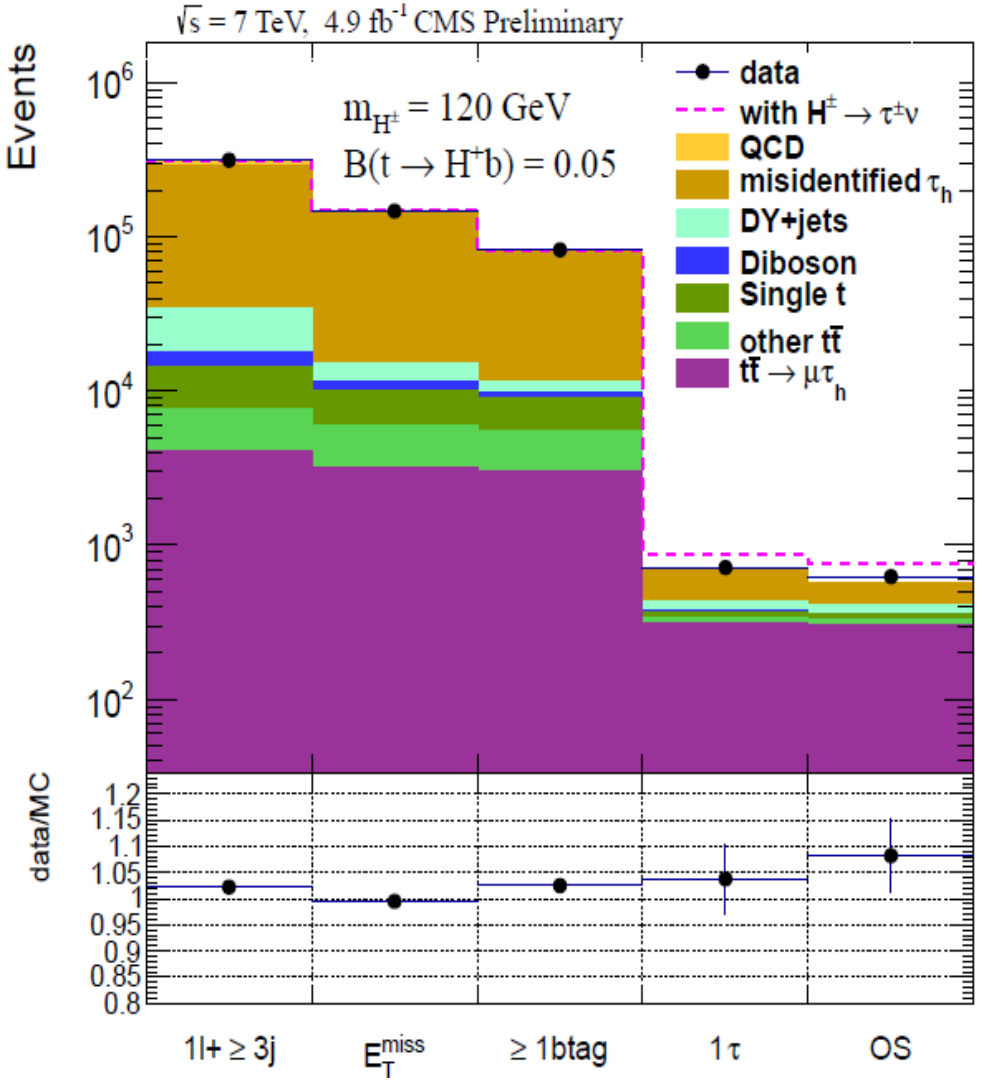

**tau+e/mu**




**e + mu**

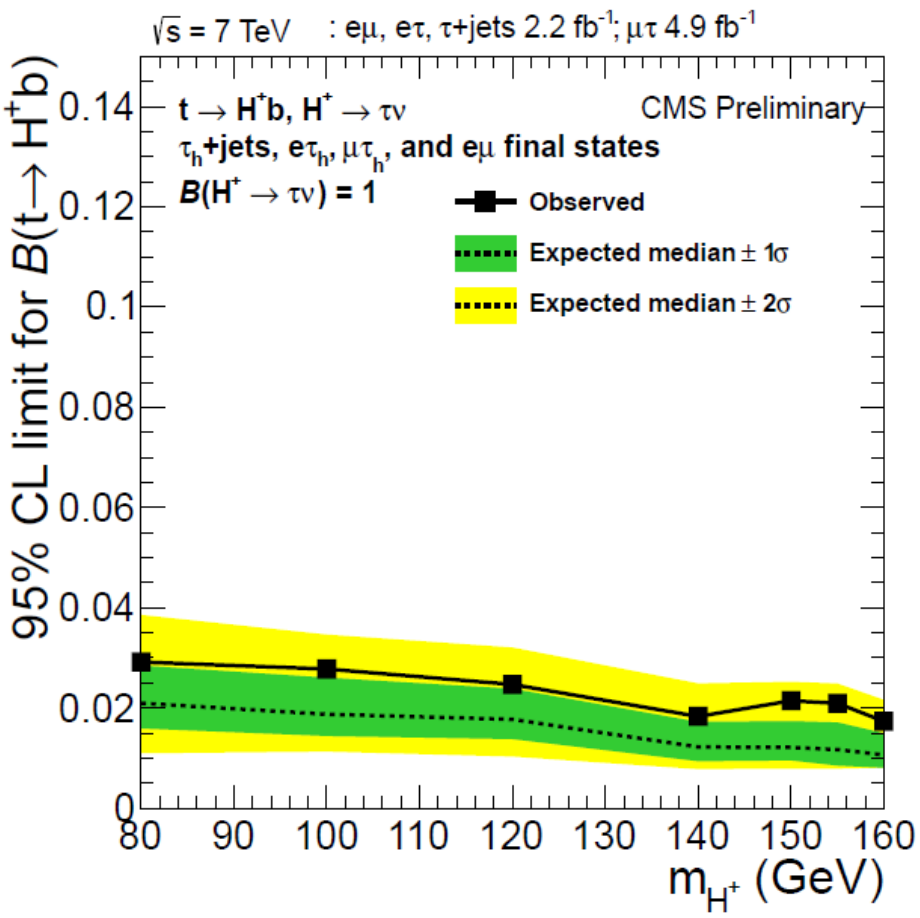


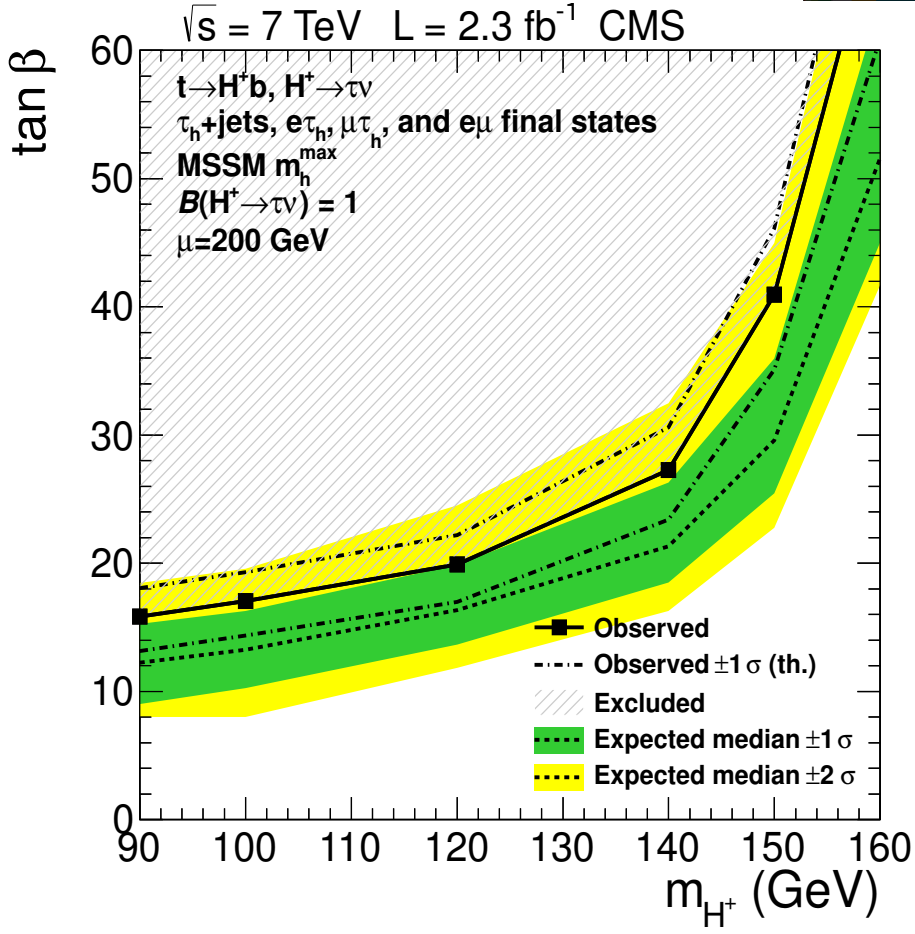
# Light $H^{\pm}$ : Results




- Signal extraction:
  - $\tau + jets$ : fit of $M_T$ for $\tau, \not{E}_T$ pair
  - $\mu + \tau$ : fit of $R = p_T^{lead.track} / E_\tau$
  - Other channels: event counting
- No signal observed

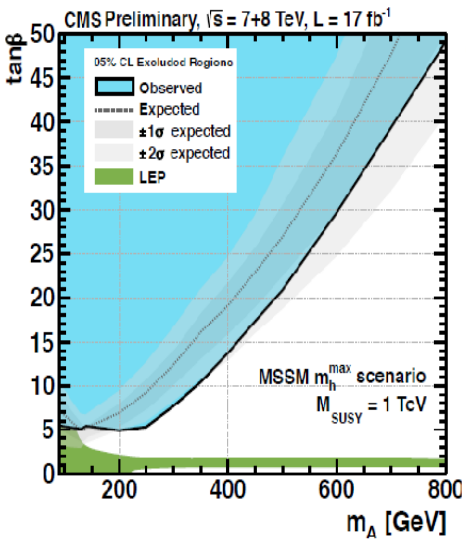
# Light $H^{\pm}$ : Exclusion limits of the combination

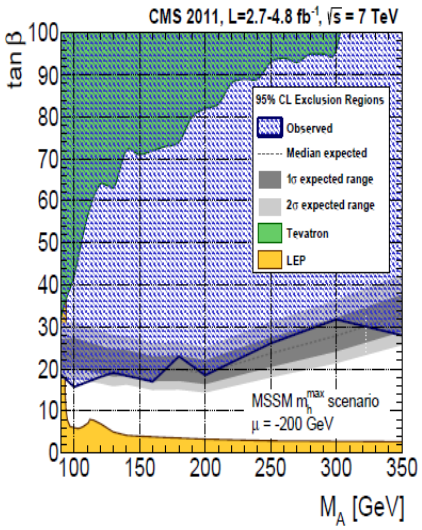


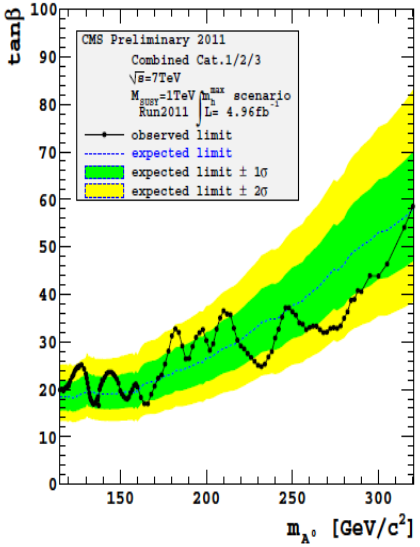



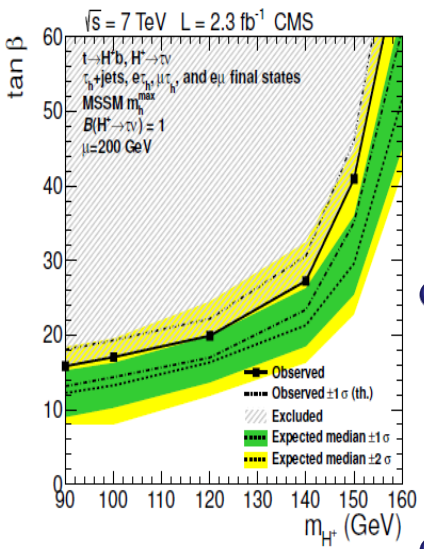

- Significant constraint on $Br(t \to H^+ b) < 3 - 2\%$

# Summary



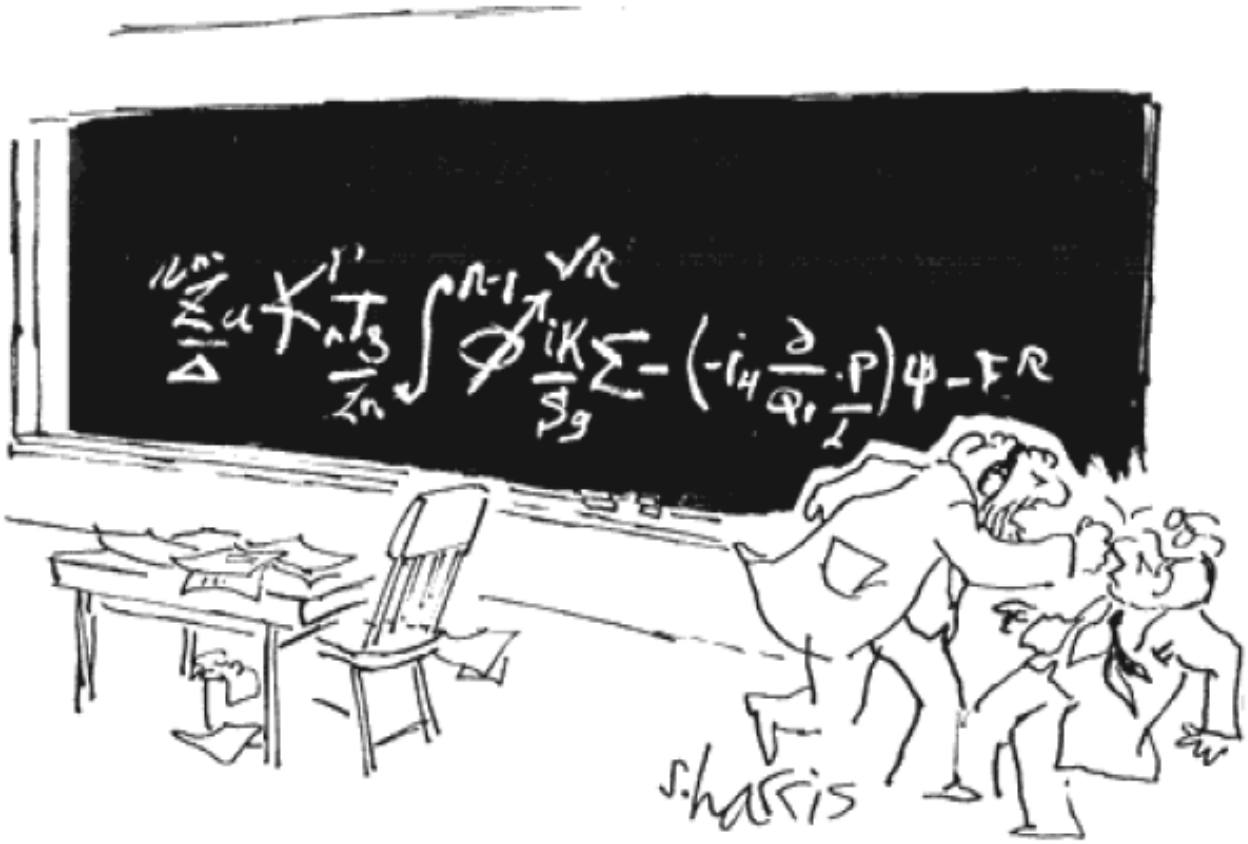




- There is no evidence of a BSM Higgs boson.
- Limits in the MSSM parameters have been set by the CMS
  - $\Phi \to \tau\tau$ : **the most stringent** limits on the MSSM $(\tan\beta, M_A)$ parameter space
  - $\Phi \to b\bar{b}$ : **First time at LHC! World's best limit in this channel**
  - $\Phi \to \mu\mu$ : best mass resolution; high sensitivity even with low BR
  - Light $H^{\pm}$ : **new stringent** exclusion limits in the $BR \times \sigma$
- **MORE 8 TeV** searches are being updated and developed
- **Stay tuned!**

# Backup slides



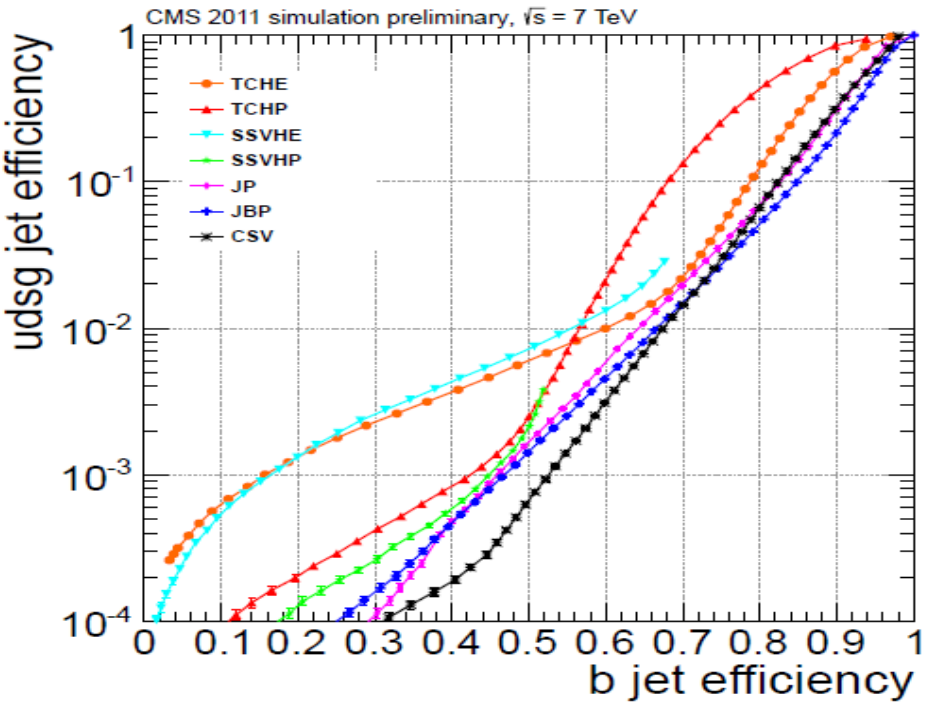

*"You want proof? I'll give you proof!"*

# MSSM $m_h^{max}$ scenario

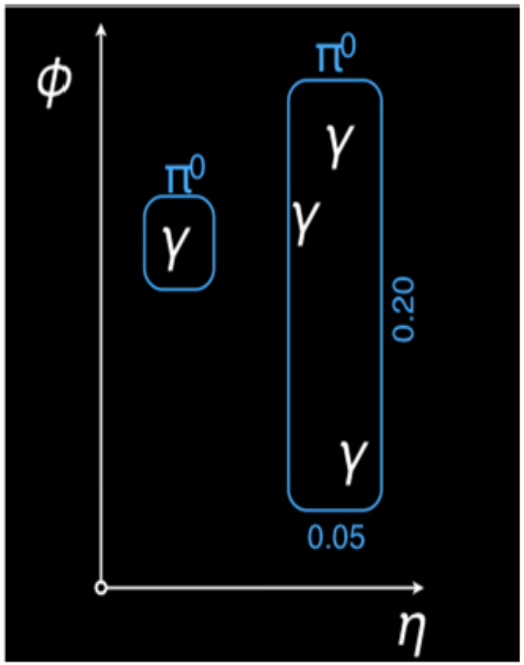
- $M_{SUSY} = 1\,TeV$, $X_{t(b)} = 2M_{SUSY}$, $\mu = \pm 200\,GeV$, $M_{\tilde{g}} = 800\,GeV$, $M_2 = 200\,GeV$, $M_3 = 800\,GeV$

# b-jet identification

- b-tagging:
  - Combined Secondary Vertex (CSV) algorithm -- reconstruction of secondary vertices together with track-based lifetime in a jet for a maximum likelihood
  - 3-D impact parameter (IP) of tracks; IP significance $(IP/\sigma)$ of $2^{nd}$ or $3^{rd}$ jet used as b-tagging discriminator
  - CMS-PAS-BTV-11-004



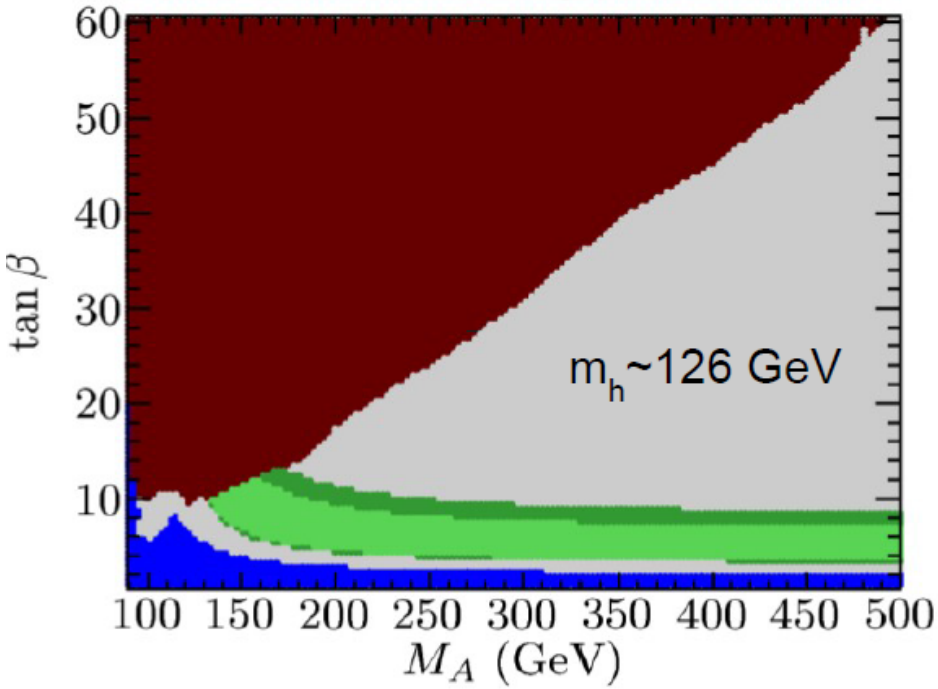
# $\tau-$ id with the "Hadron Plus Strips" algorithm

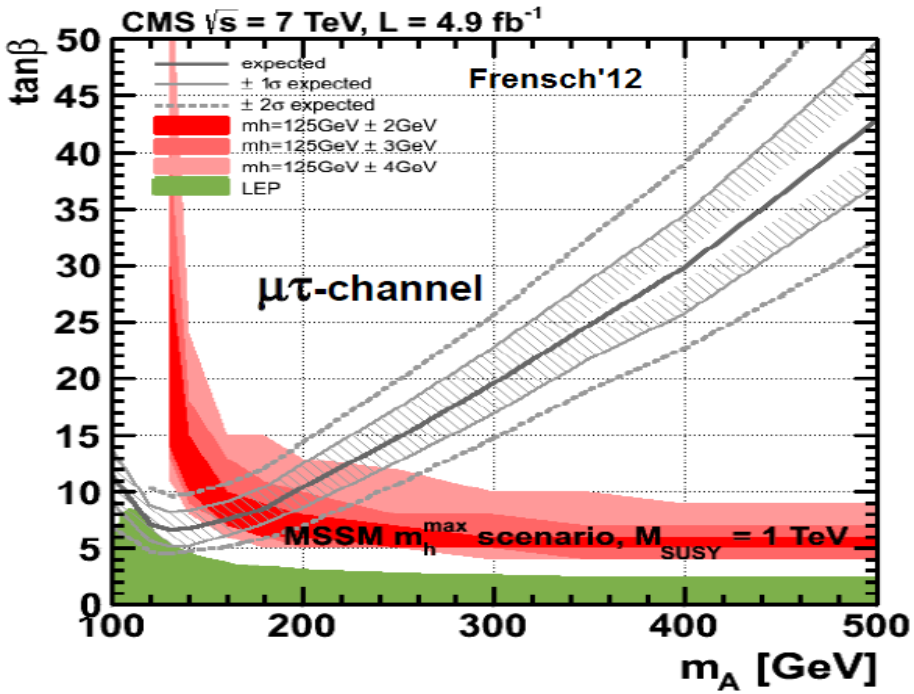



- HPS : $\pi^0$'s candidates are formed from any PF-photon or PF-electron found inside "strips" which account for possible broadening of the calorimeter signature by photon conversions. The mass of the composite system must be compatible with a $\rho$ or $a_1$ hypothesis.

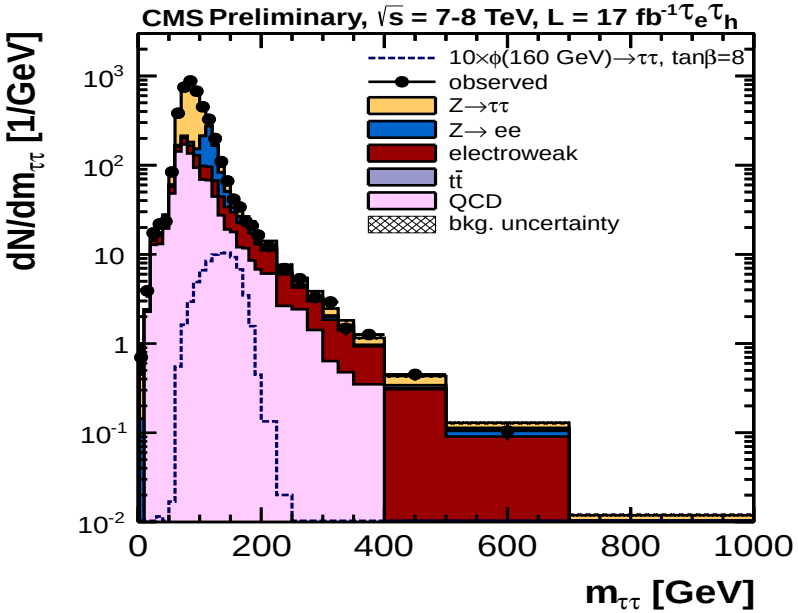
# MSSM implication of 126 GeV Resonance

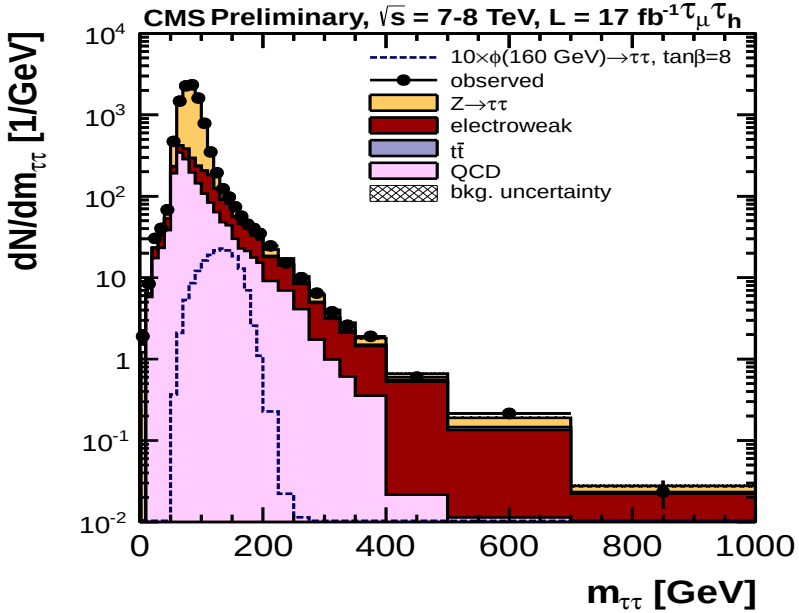
- some MSSM scenarios are compatible with $M_h = 126$ GeV
  - in decoupling regime with $M_A, M_H, M_{H^\pm} > 150$ GeV
  - possible $m_h^{max}$ interpretation
- Heinemeyer et al., **arXiv:1112.3026**, Arbey et al., **arXiv:1207.1348**
- $\Phi \to \tau\tau$ excludes $M_h = 126$ at $M_A < 200$ GeV

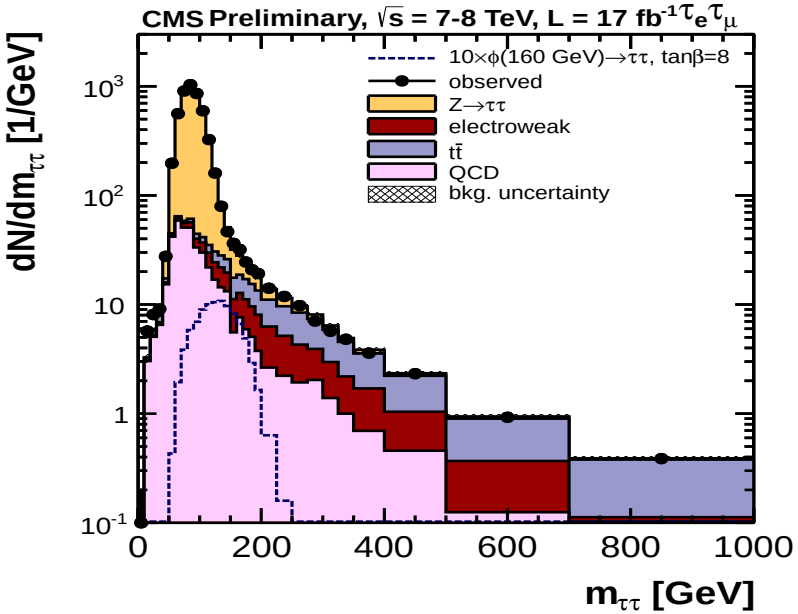


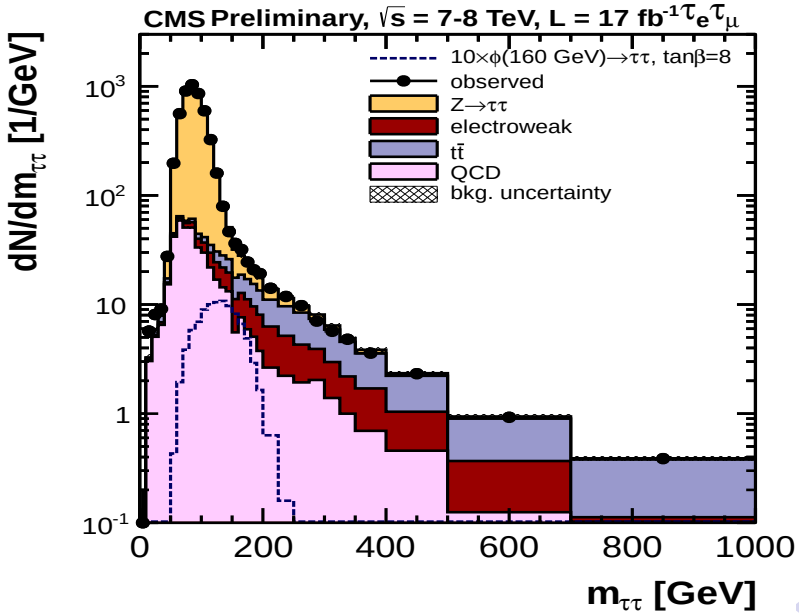



# $\Phi \rightarrow \tau\tau$ results in the non-b-tag category



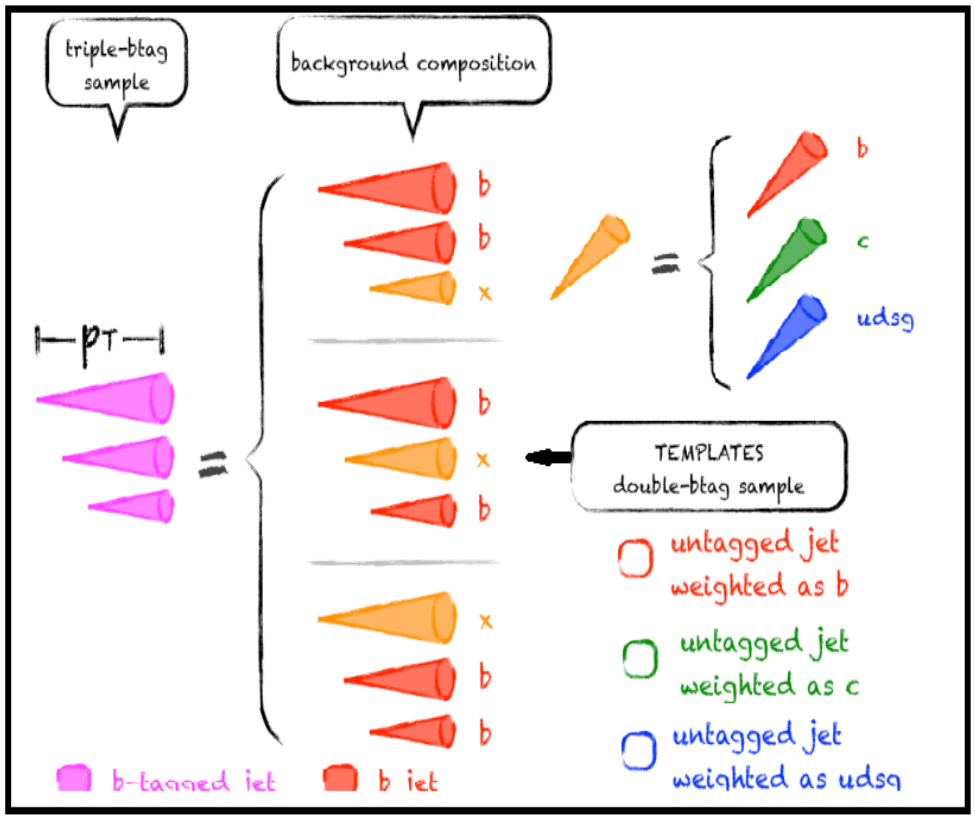



# $\Phi \rightarrow b\bar{b}$ data-driven estimation of background

- Background:
  - QCD multi-jets events with 3 b-jets and 2 b-jets + 1 misidentifed c or udsg-flavour jet
  - Other backgrounds such as $t\bar{t}$ or Z+jets found to be small
  - **2-b-tagged data samples** to be utilized

## all-hadronic



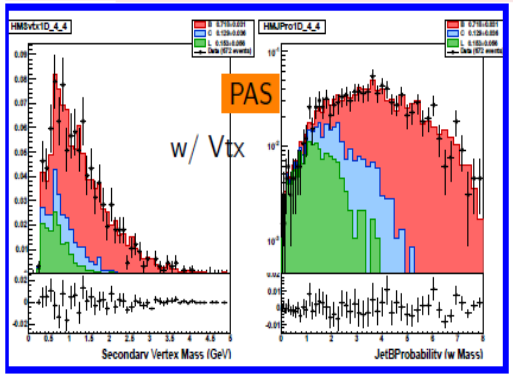

## semi-leptonic

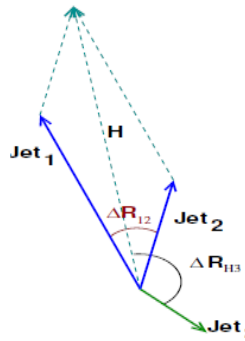
B-tagging probability matrices $P^{3^{rd}jet}_{b-tag}(\ldots)$ in control region

$$P^{3^{rd}jet}_{b-tag}(\ldots) = \epsilon_b \cdot f_b + \epsilon_c \cdot f_c + \epsilon_l \cdot f_l$$

any $bbb$ distribution $F(x; bbb)$ for variable $x$ in signalregion

$$F(x; bbb) = F(x; bbj) \otimes P^{3^{rd}jet}_{b-tag}(\ldots)$$




$$F_B = F_{B,C}\left(E_T^{(j_3)}, |\eta^{(j_3)}|\right) \times F_{B,C}(\Delta R_{H,j_3}, \Delta R_{j_1,j_2})$$