Beyond SM Higgs Searches at CMS

ECFA Linear Collider Workshop (LC2013),
DESY Hamburg, 2013

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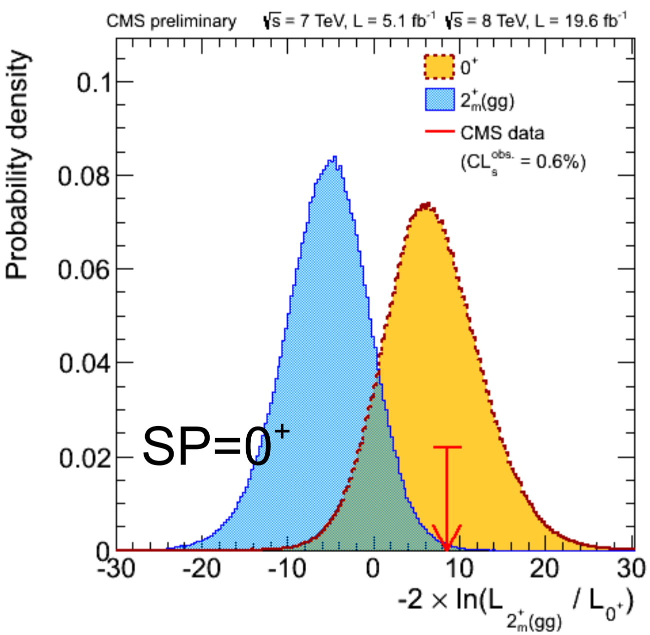
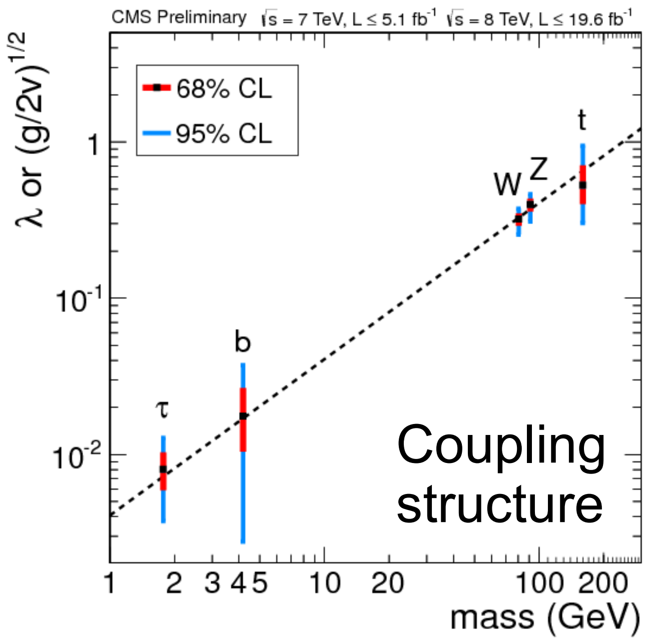
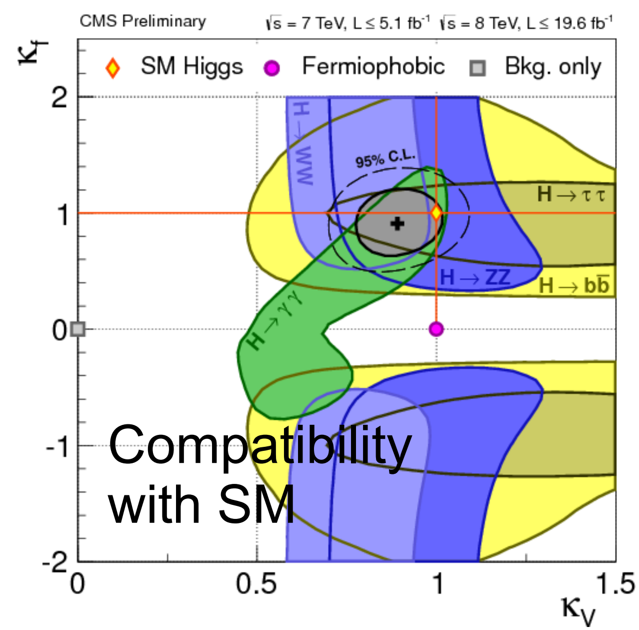
For the CMS Collaboration

The New Particle at 126 GeV (H(126))

- High confidence that new particle is a Higgs boson.
- Measured properties very close to SM expectation:



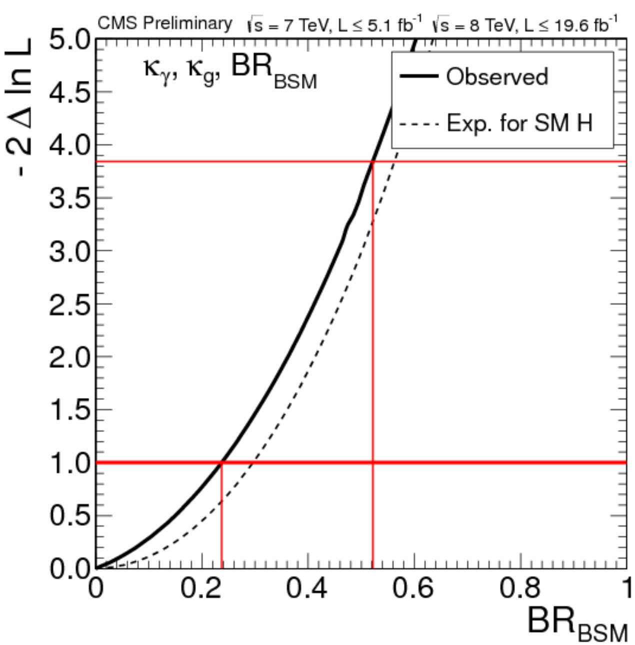




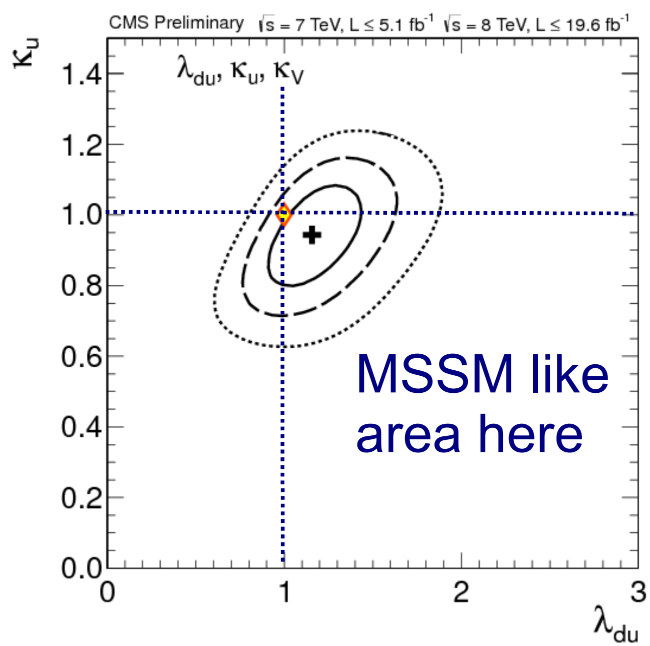
- Questions:
  - Is it THE SM Higgs boson?
  - Can we find more than one Higgs boson?

Coupling Structure of H(126)

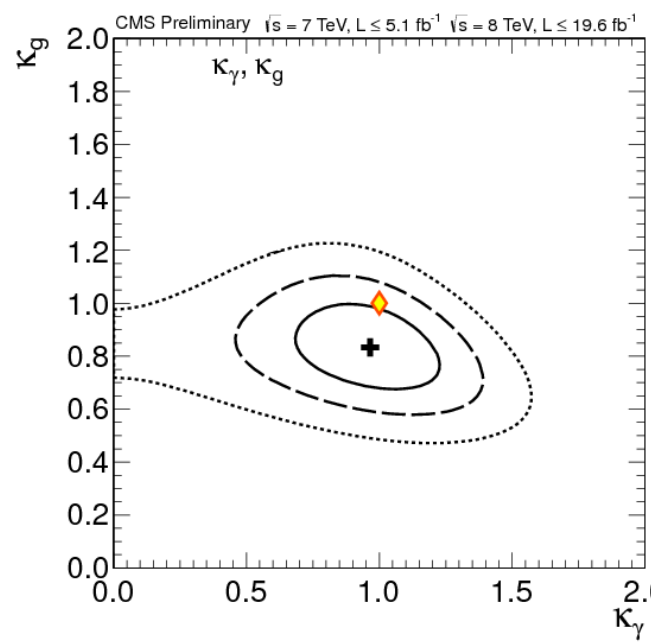
- Answers to first question: can be obtained from analysis of coupling structure of new paticle.



- Decay to untedectable/invisible particles.



- Coupling to *up*-type vs *down*-type fermions.



- New physics in loops.

- Answers to second question: by explicit searches.

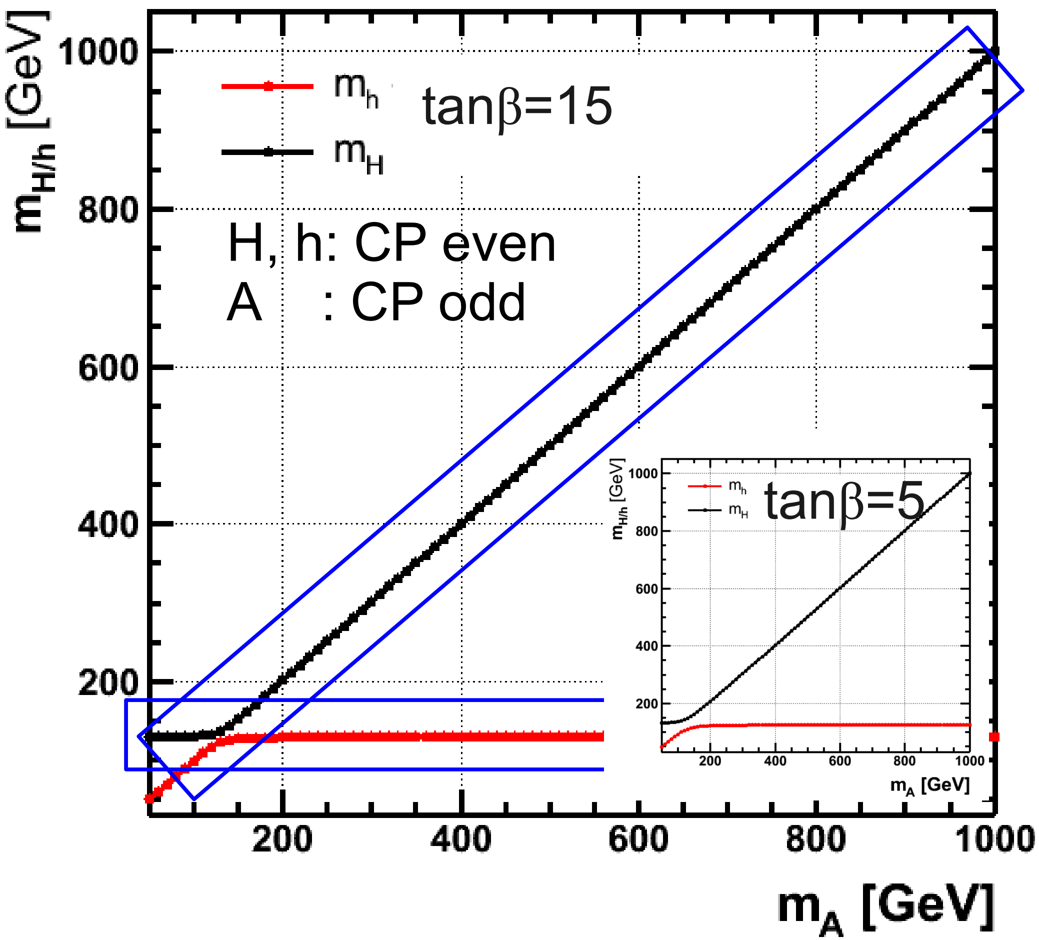
Explicit BSM Higgs Boson Searches at CMS

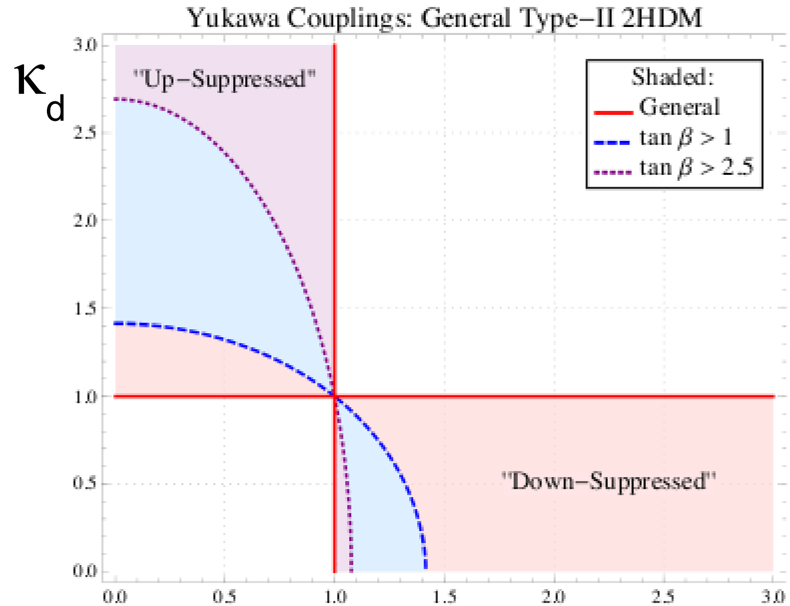
- SUSY implies presence (at least) of two Higgs doublets, leading to five observable Higgs bosons:
  - 2 charged: $H^{+/-}$:
    CERN-PH-EP/2012-123 (arXiv:1205.5736), (2.3fb^{-1} @ 7TeV).
  - 3 neutral : H, h (CP-even), A (CP-odd):
    CERN-PH-EP/2012-034 (arXiv:1202.4083) (4.6fb^{-1} @ 7TeV),
    CMS-PAS-HIG-12-033 (2.7–4.8fb^{-1} @ 7TeV),
    CMS-PAS-HIG-12-050, (17fb^{-1} @ 7+8TeV).
- „More exotic“ models (motivated by non-zero ν masses) predict doubly charged Higgs bosons $H^{++/--}$, CERN-PH-EP/2012-169 (arXiv:1207.2666), (4.6fb^{-1} @ 7TeV)

[red box] = will concentrate on the *most recent* and *most significant* result due to time constraints.

Neutral Higgs Bosons in Supersymmetry (SUSY)

- MSSM implies presence of three observable neutral Higgs bosons:
  - Masses and couplings fixed for given m_A and $\tan\beta$ (= ratio of VEV's of doublets).
  - Enhancement of coupling to down-type fermions (like τ's and b's) for $\tan\beta>1$:

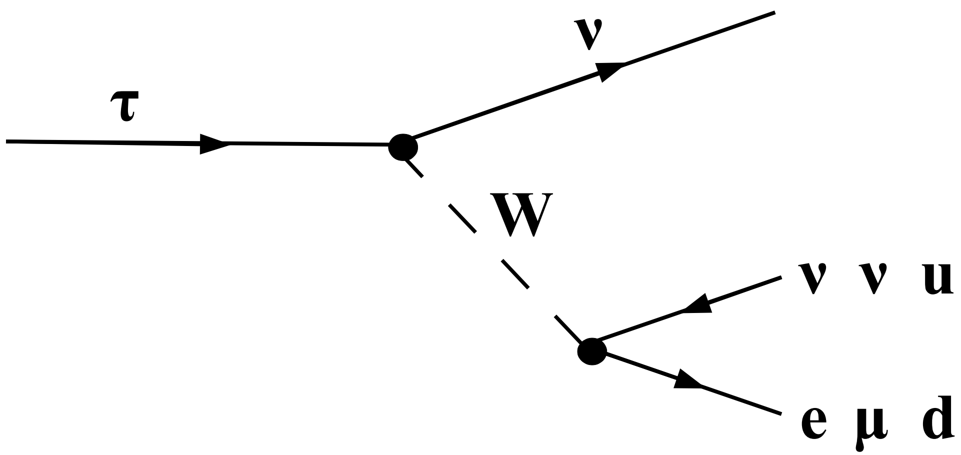




Azatov et al, PRD 86 (2012) 075033

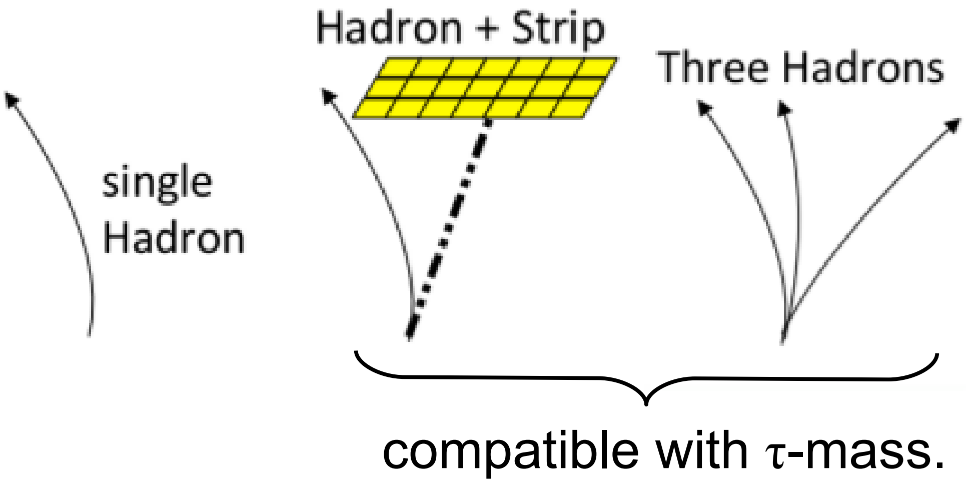
- CMS-PAS-HIG-12-033 (decay to b's).
- CMS-PAS-HIG-12-050 (decay to τ's).

Reconstruction of τ's with CMS



Decay Mode	BR
$\tau \to e\nu\nu$	17%
$\tau \to \mu\nu\nu$	18%
$\tau \to h\nu$	12%
$\tau \to hh^0\nu$	37%
$\tau \to hhh\nu$	15%

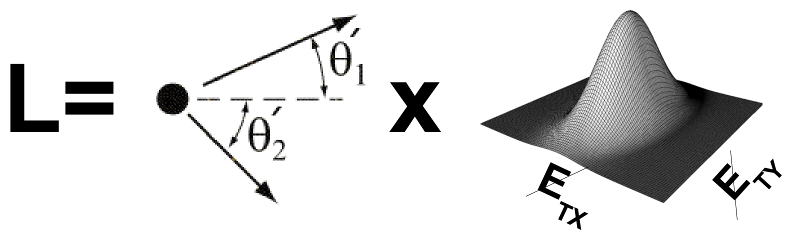
Reco of hadronic decay modes:



- Isolation (based on energy deposits in rings of $\Delta R \leq 0.5$).
- Discrimination against e's (based on shower shape info and E/p).
- Discrimination against μ's.

Reconstruction of Di-τ System

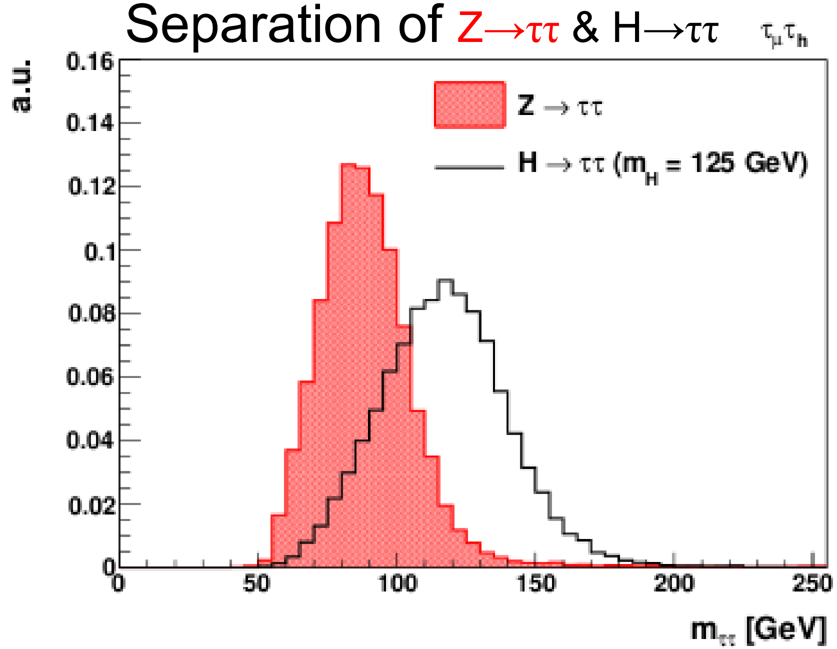
- Determine invariant mass of di-τ system with maximum likelihood method.



Phasespace of τ-decays

Expected $\not{E}_T$ Resolution

Separation of Z→ττ & H→ττ



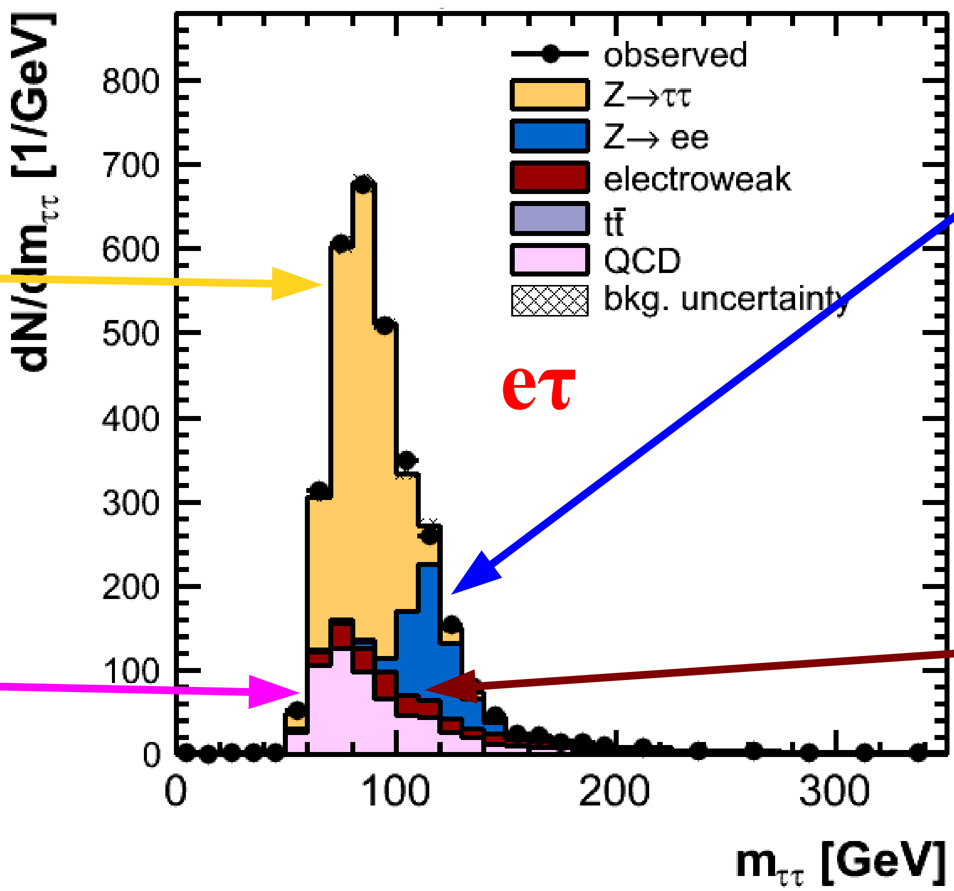
- Estimate for di-τ system, to be true for given value of $m_{\tau\tau}$.
- Inputs: four-vector information of visible leptons, x- and y- component of $\not{E}_T$ on event by event basis.
- Free parameters: φ, θ^*, ($m_{\upsilon\upsilon}$) per τ-lepton (4-6 parameters).
- Full integration of kernel. Scan of $m_{\tau\tau}$ from m_τ up to 2TeV.
- 15-20% resolution of the reconstructed $m_{\tau\tau}$ mass.

Dominant Backgrounds (example plot given for eτ)

Z→ττ:
- Embedding: in Z→μμ, replace μ by sim. τ decay.
- Normalized from Z→μμ events.

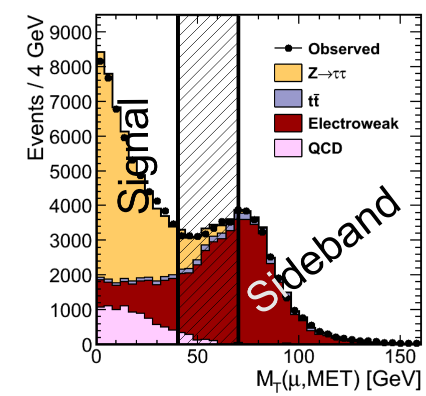
QCD:
- Normalization & shape taken from LS/OS or fakerate.

ttbar:
- From simulation.
- Normalization from sideband.



Z→ee(/μμ):
- From simulation.
- Corrected for jet→τ, e/μ→τ fakerate.

Diboson/W+jets:
- From simulation.
- Normalization from sideband.

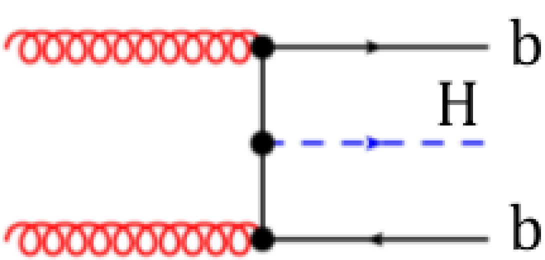


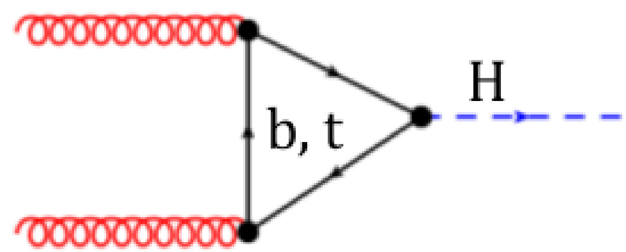
Event Selection

- Search in four decay channels: $e\mu$, $\mu\mu$, $\mu\tau_h$, $e\tau_h$.
  - Two well reconstructed, isolated leptons of opposite sign:
  - Topological event selection, based on p_ζ ($e\mu$, $\mu\mu$) or M_T ($\mu\tau_h$, $e\tau_h$).
  - Two event categories:

B-Tag:
- $N_{B\text{-}Tag}$(Jet p_T>20GeV) ≥ 1
- N_{Jet}(Jet p_T>30GeV) ≤ 1

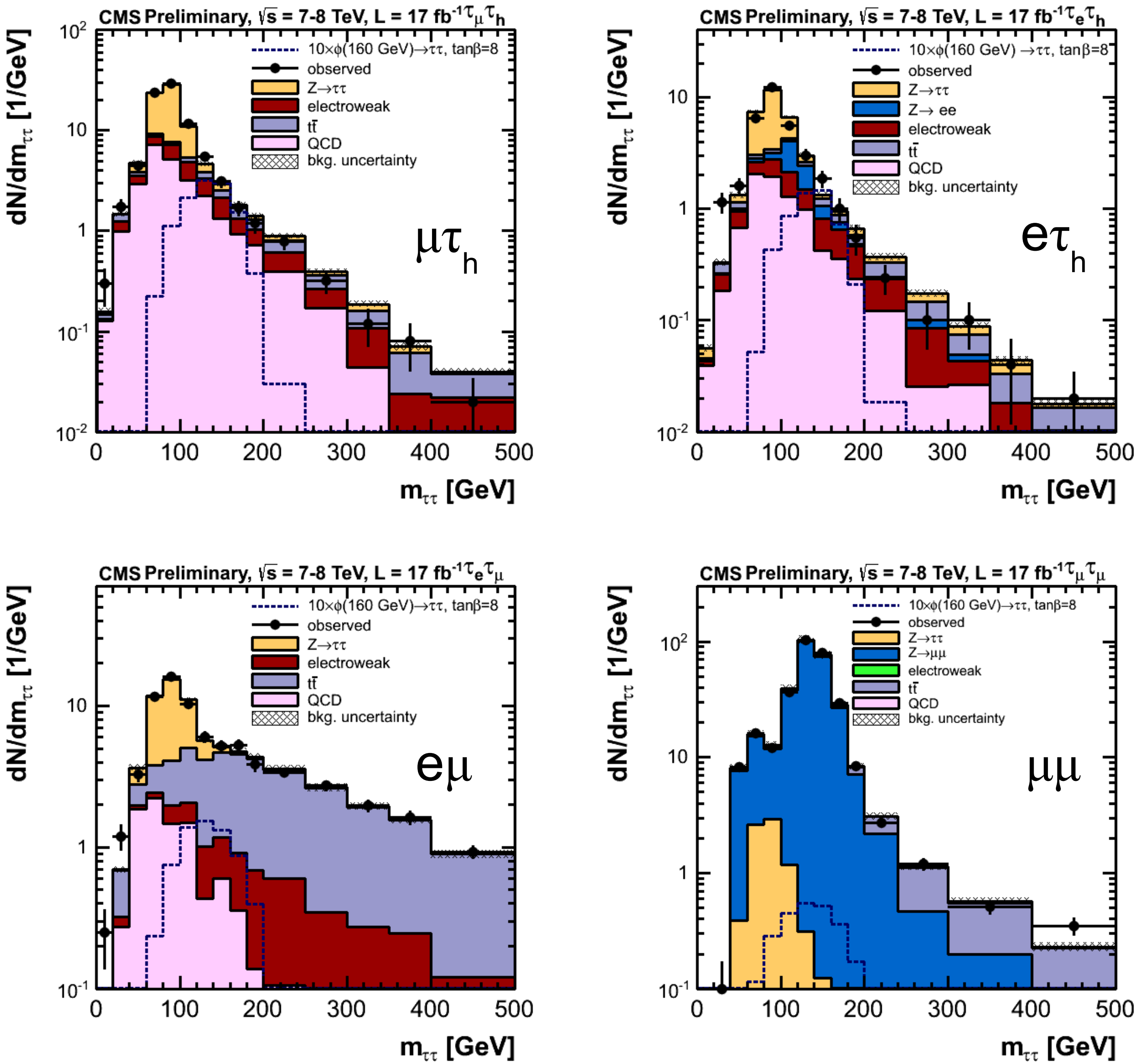
No B-Tag:
- $N_{B\text{-}Tag}$(Jet p_T>20GeV)=0





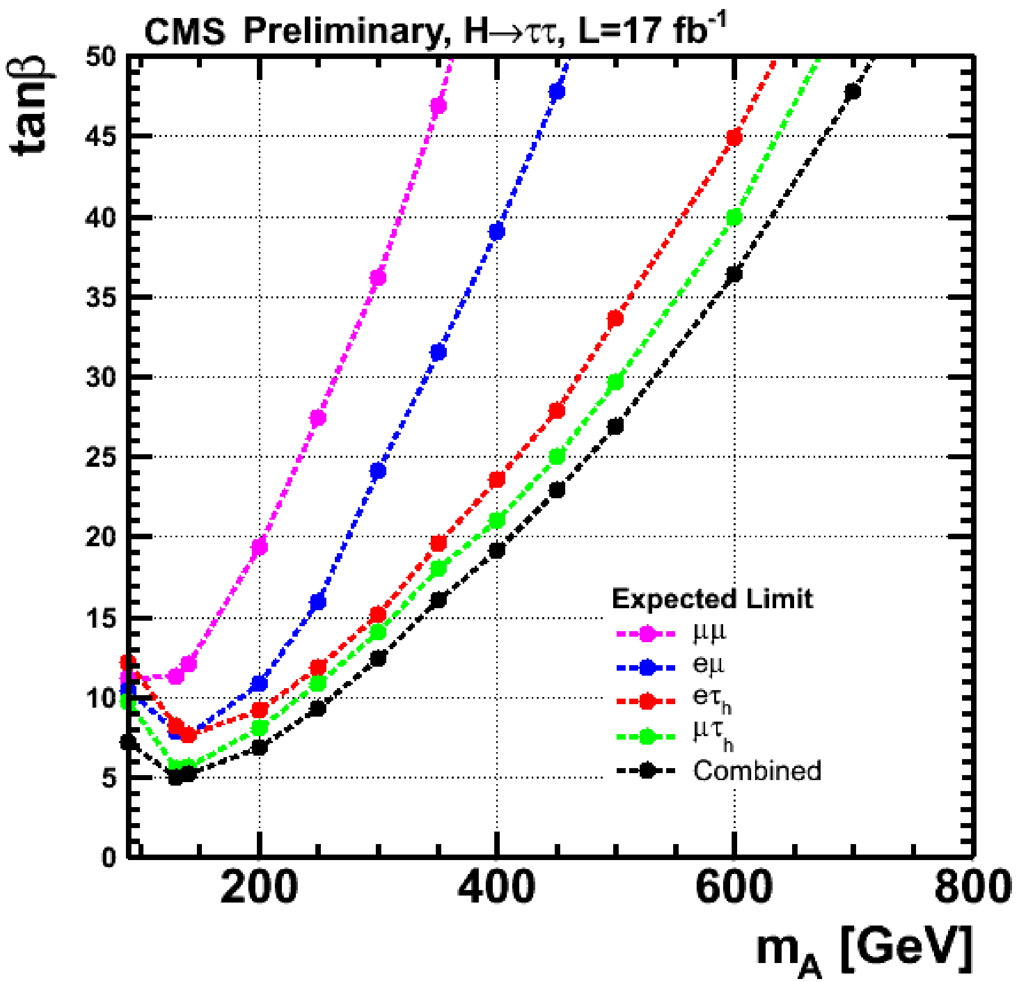
- Apply template fit to $m_{\tau\tau}$ with B and S+B model. Determine best fit value of signal strength and asymptotic CLs limit.

Reconstructed Di-τ Mass (B-Tag category)

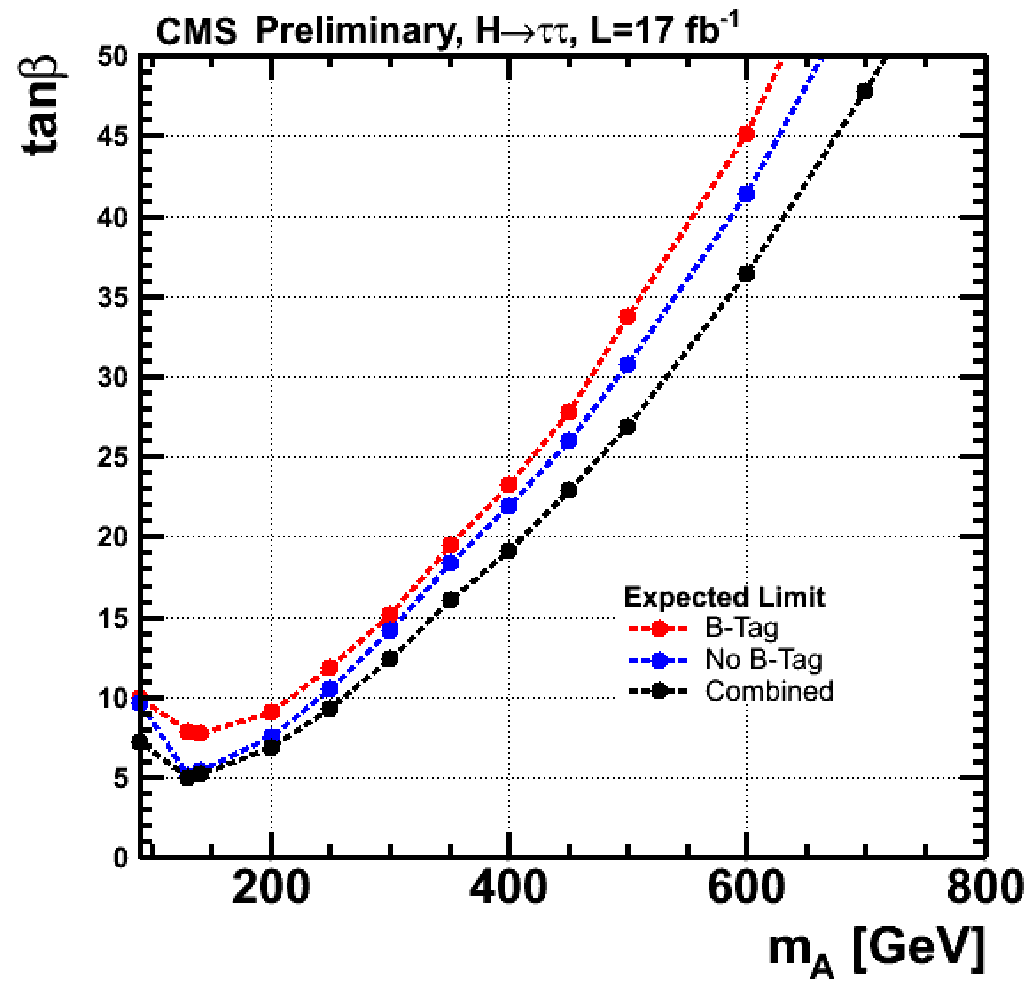


Sensitivity

Split by channels:



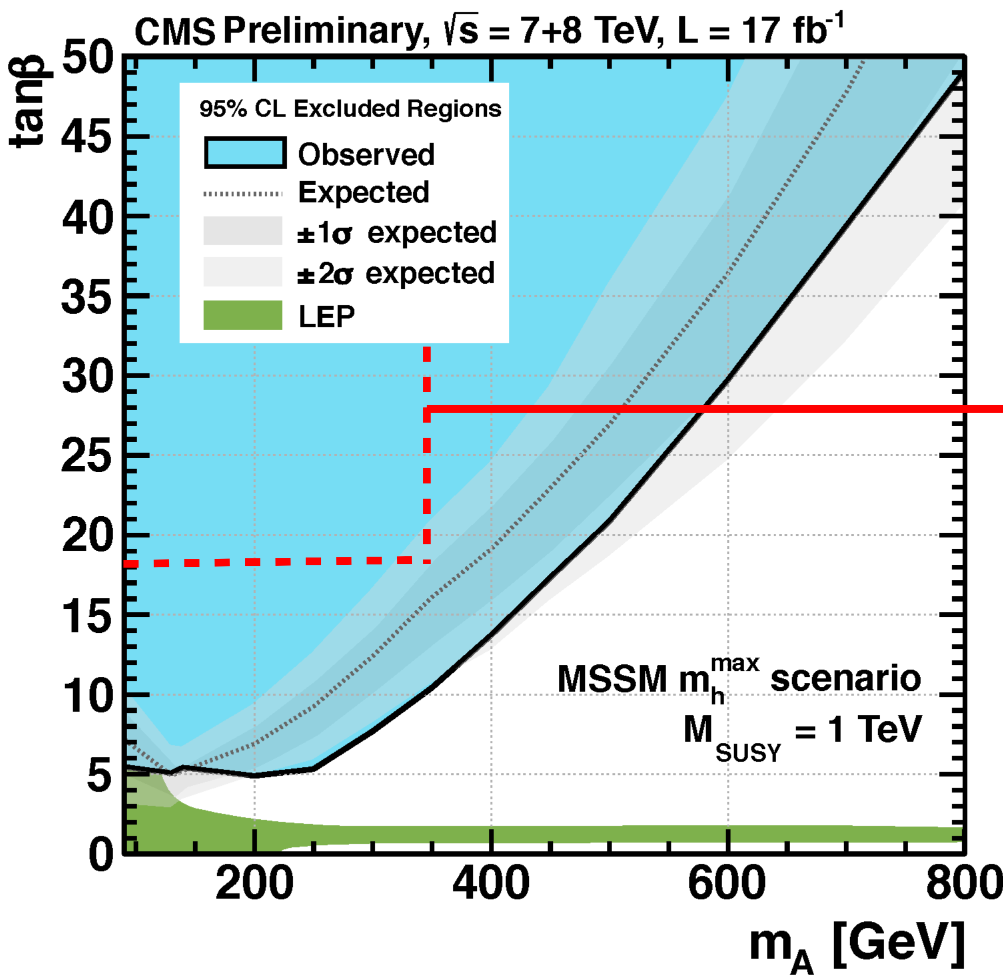
Split by category:



- Main systematics:
  τ identification (6%), τ energy scale (3%), jet energy scale (2.5% - 5%).

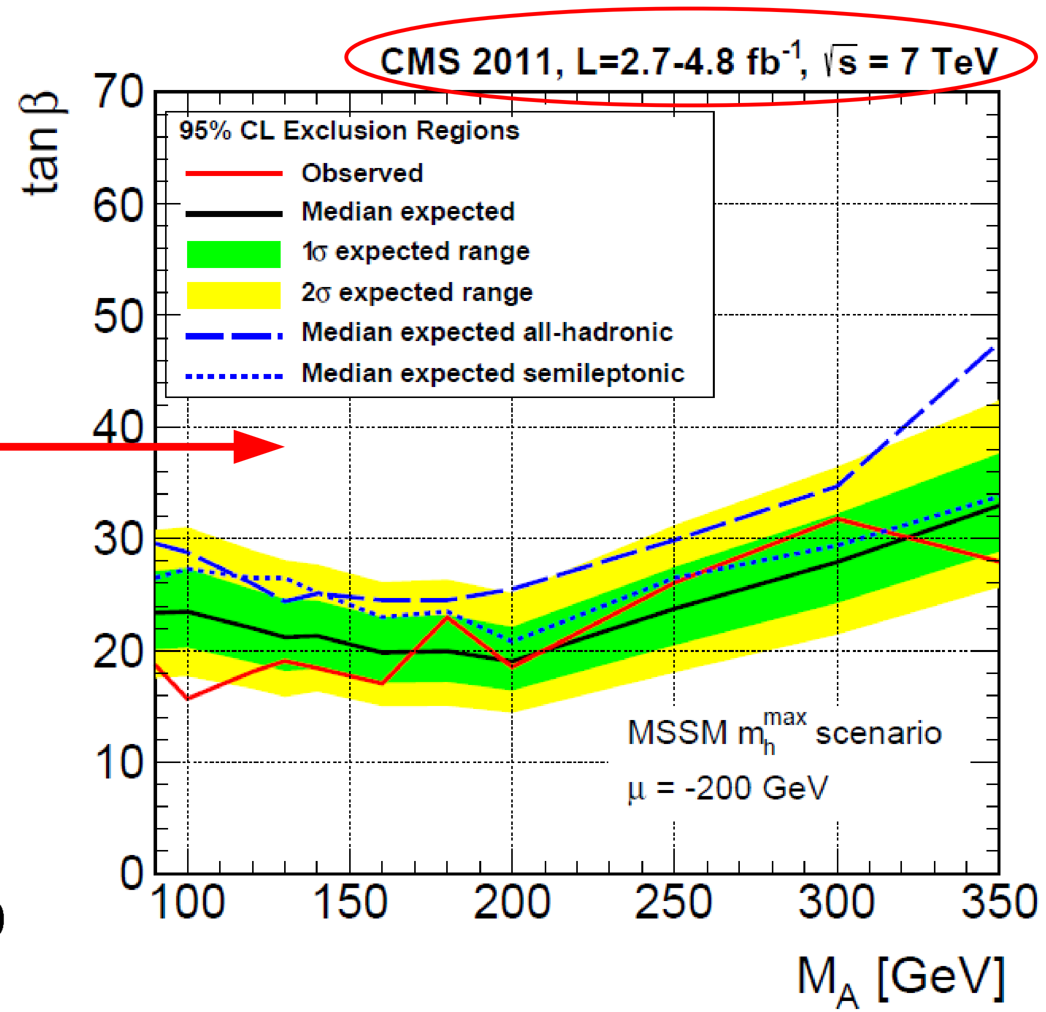
Limit in m_A-tanβ ($H\rightarrow\tau\tau$ vs. $H\rightarrow bb$)

Limits from $H\rightarrow\tau\tau$:



- CMS-PAS-HIG-12-050 (Strongest limits on additional SUSY Higgs bosons).

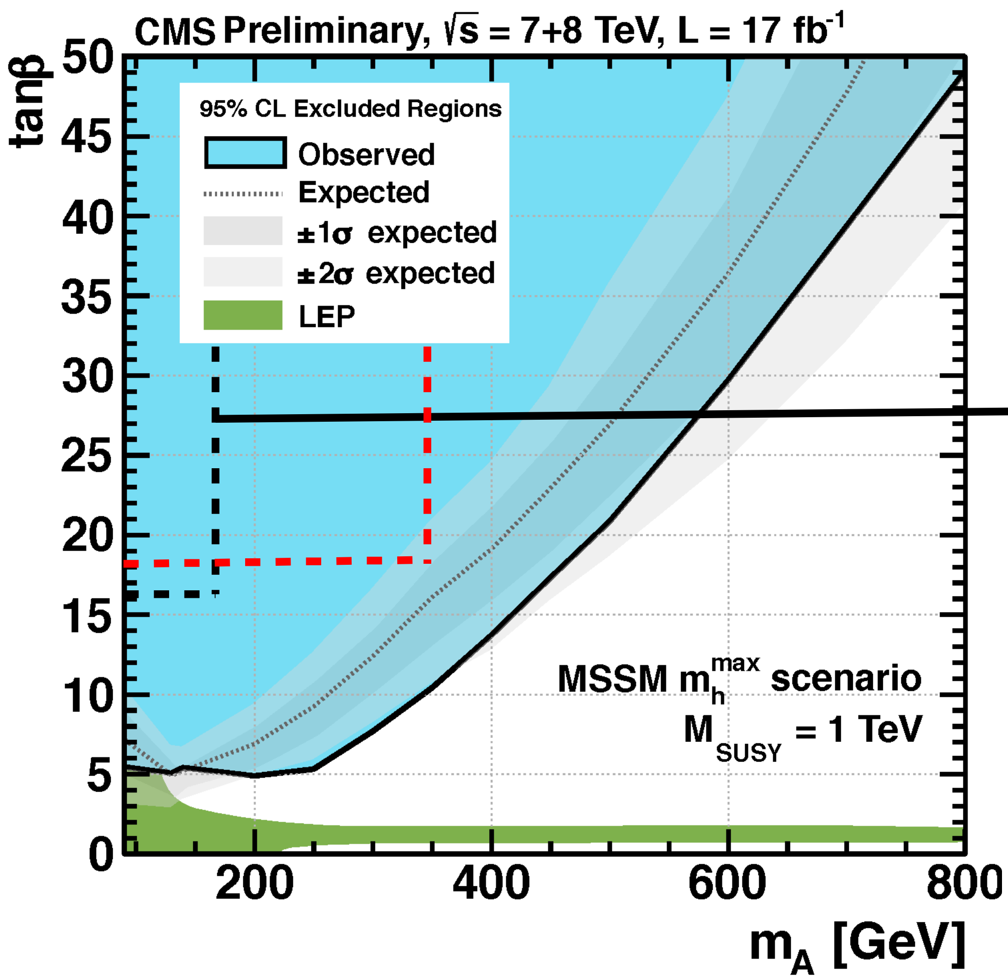
Limits from $H\rightarrow bb$:[1)]



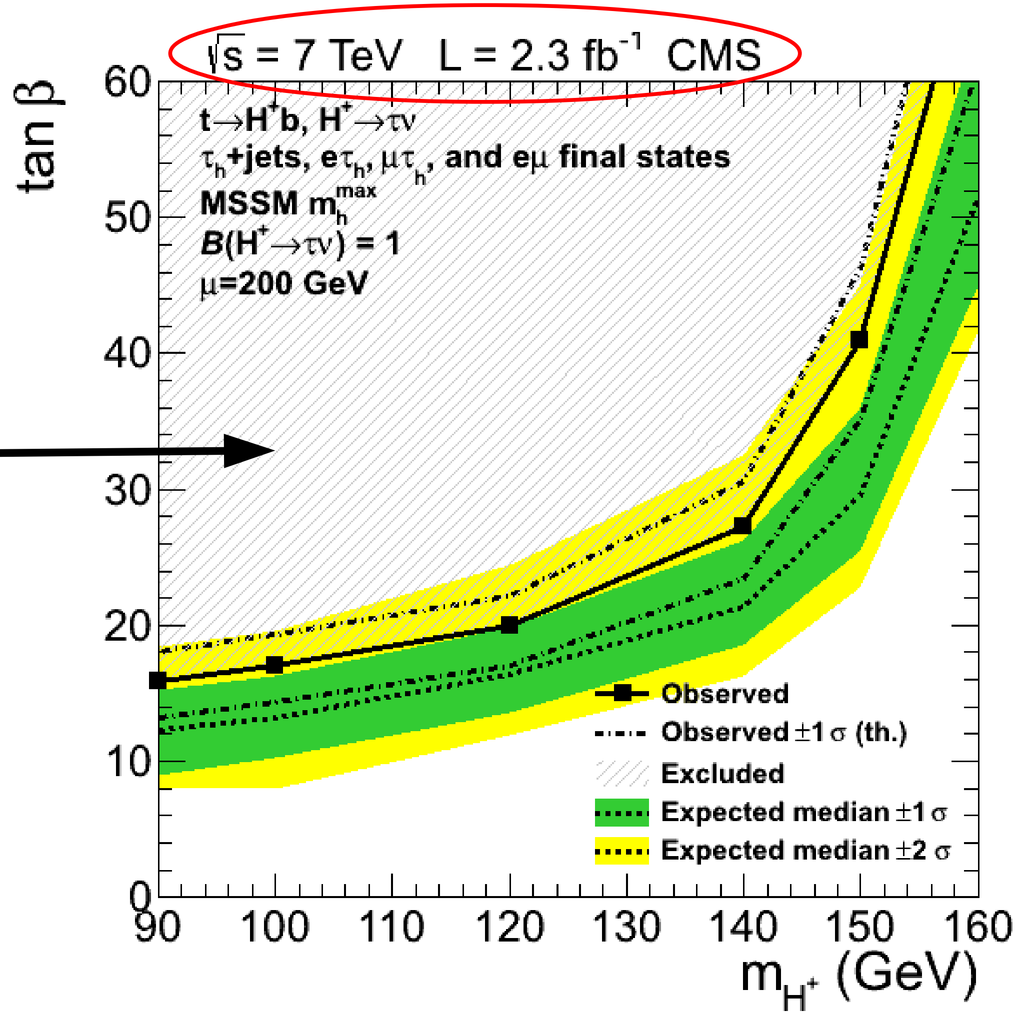
[1)] CMS-PAS-HIG-12-033 (more details in backup)

Limit in m_A-tanβ (H→ττ vs. H^+)

Limits from H→ττ:



Limits from H^+:[1)]



- CMS-PAS-HIG-12-050 (Strongest limits on additional SUSY Higgs bosons).

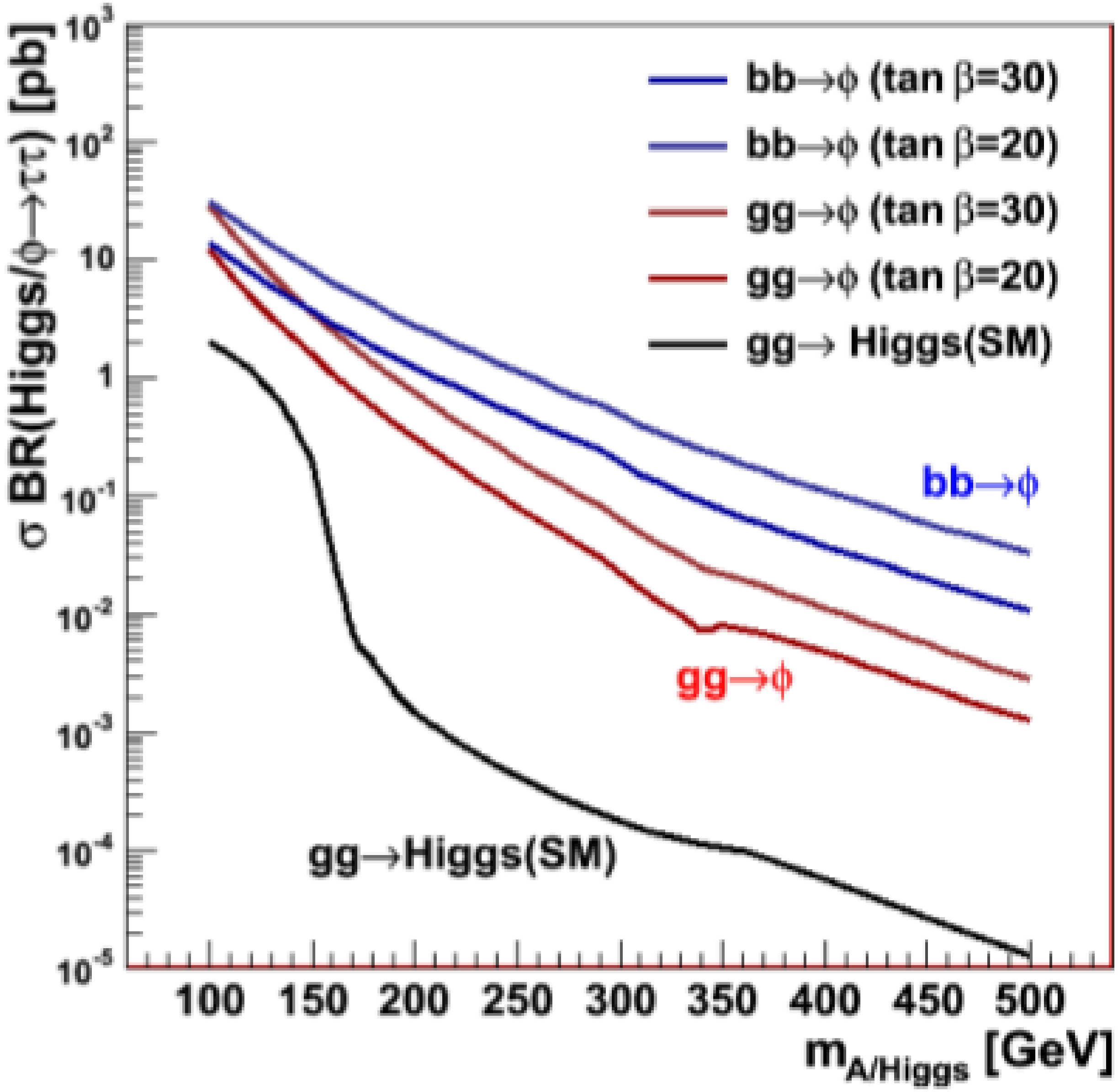
1)arXiv:1205.5736 (more details in backup)

Conclusions

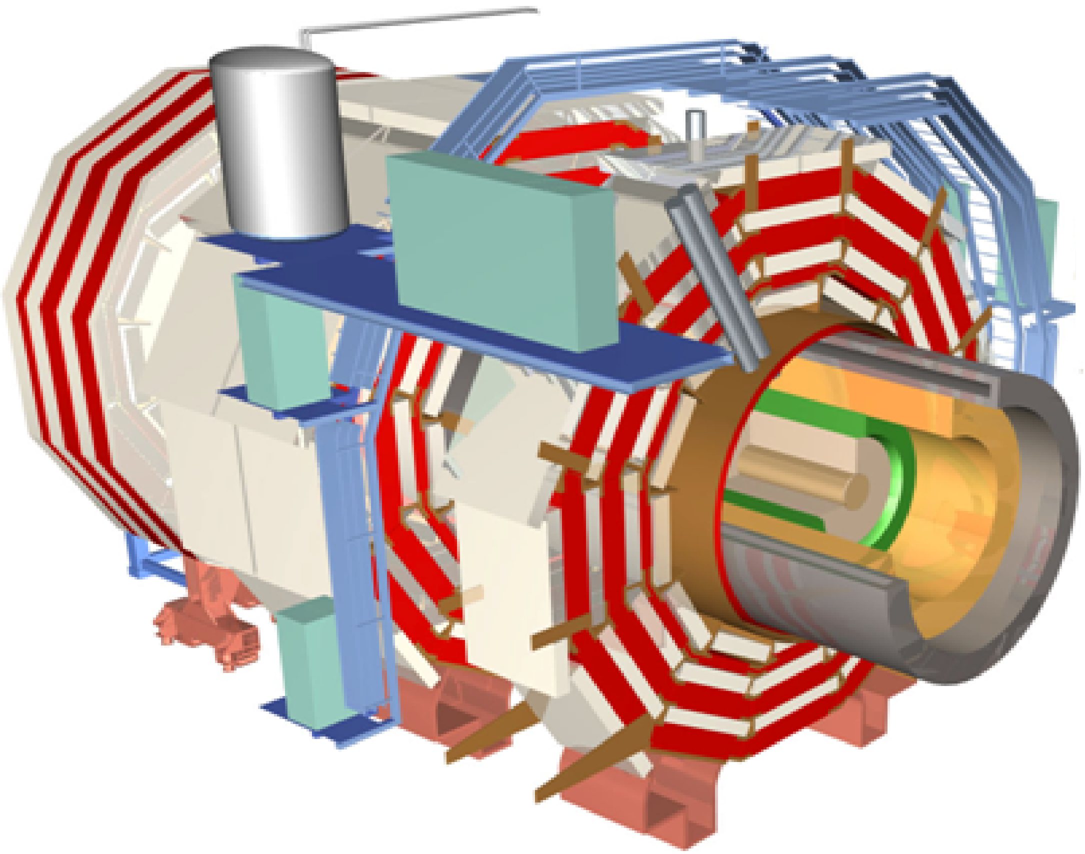
- After discovery of Higgs boson at 126 GeV, main questions:
  - Is it THE SM Higgs boson?
  - Is there more than one Higgs boson?
- Second item would give clearest hint to BSM physics.
- Most important search: additional neutral Higgs bosons in decay channel into τ's:
  - Leads to strongest limits on MSSM parameter space.
  - MSSM: example of more general 2HDM's.
- Analysis of full dataset 2011/2012 currently ongoing (plan for publication this year). Will also contain more model independent limits on $\sigma \cdot BR$ and $\sigma(gg \rightarrow H)$ vs. $\sigma(gg \rightarrow Hbb)$.

Backup

Cross Section for gg→H and Associated Production



Compact Muon Solenoid Detector (CMS)



- **Muon system:**

  →10% momentum resolution for 1 TeV muon (in muonsystem alone).

- **HCAL (Brass,Szintillator, $10\lambda_i$):**

  $$\frac{\sigma E}{E} = \frac{100\,\%}{\sqrt{E[\,\mathrm{GeV}]}} \oplus 4.5\,\%.$$

  →10% energy resolution for single 100 GeV $\mathrm{pi}^{+/-}$.

- **ECAL ($PbWO_4$, $28X_0$):**

  $$\frac{\sigma E}{E} = \frac{(2.8 \pm 0.3)\,\%}{\sqrt{E[\,\mathrm{GeV}]}} \oplus \frac{0.124\,\mathrm{GeV}}{E} \oplus 0.3\,\%.$$

  →1% energy resolution for a 30 GeV electron/photon.

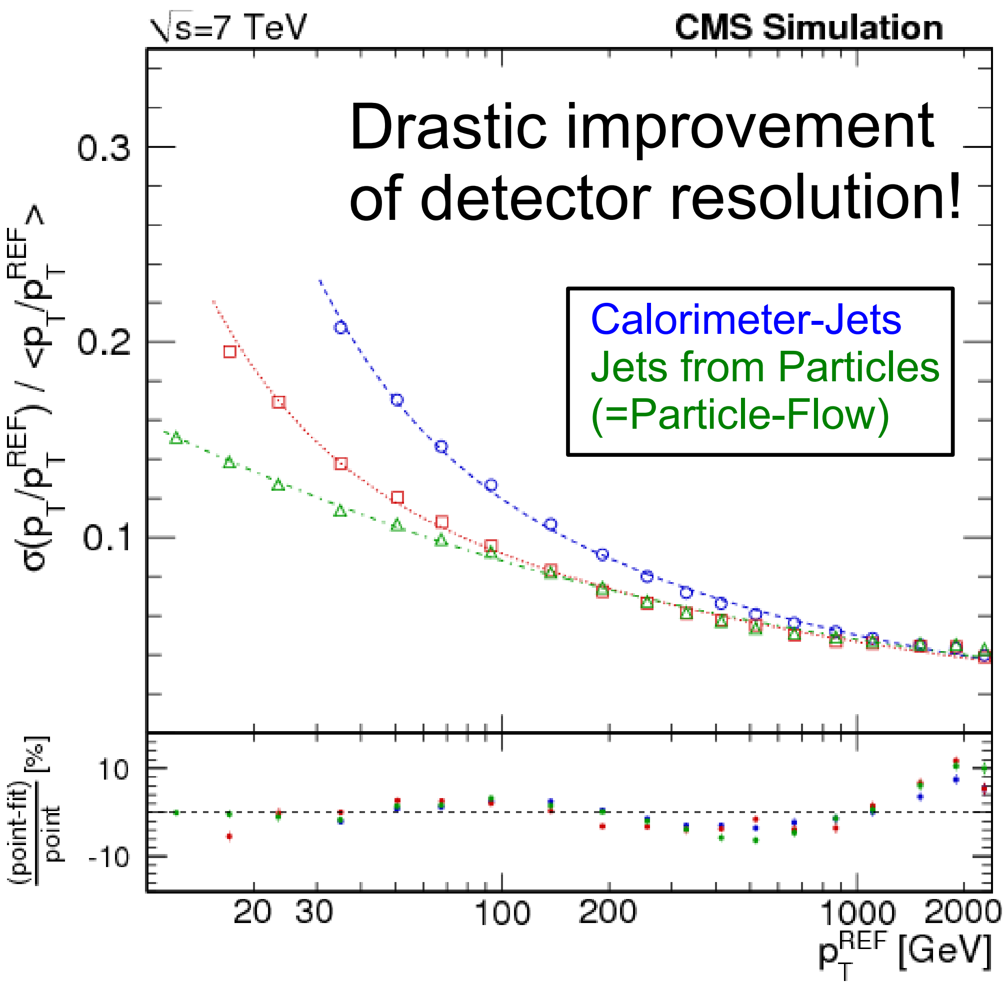
- **Tracker(Pixel/Strips):**

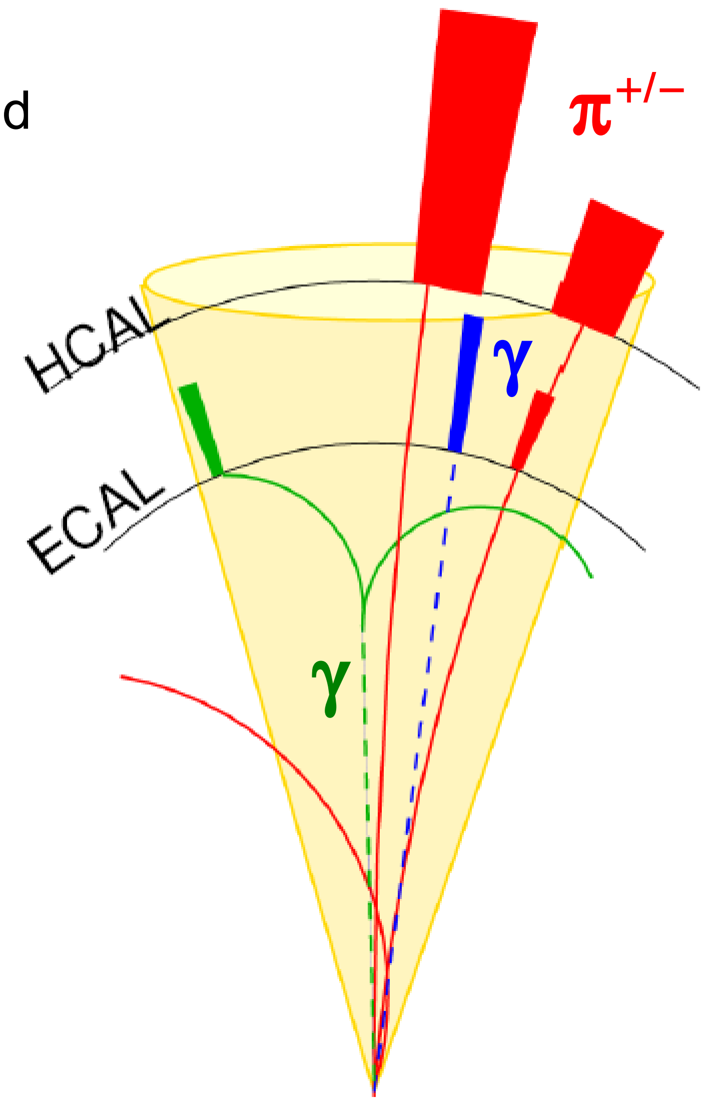
  $$\frac{\sigma p_T}{p_T} \simeq (15 \cdot p_T[\,\mathrm{TeV}] \oplus 0.5)\%$$

  →0.5% momentum resolution for 10 GeV track of a charged particle.

Particle-Flow Event Reconstruction

- Fully reconstruct all particles in detector volume making best use of all possible detector information (esp. tracker & ECAL).
- Special particles (i.e. isolated leptons) are identified and others clustered to jets.

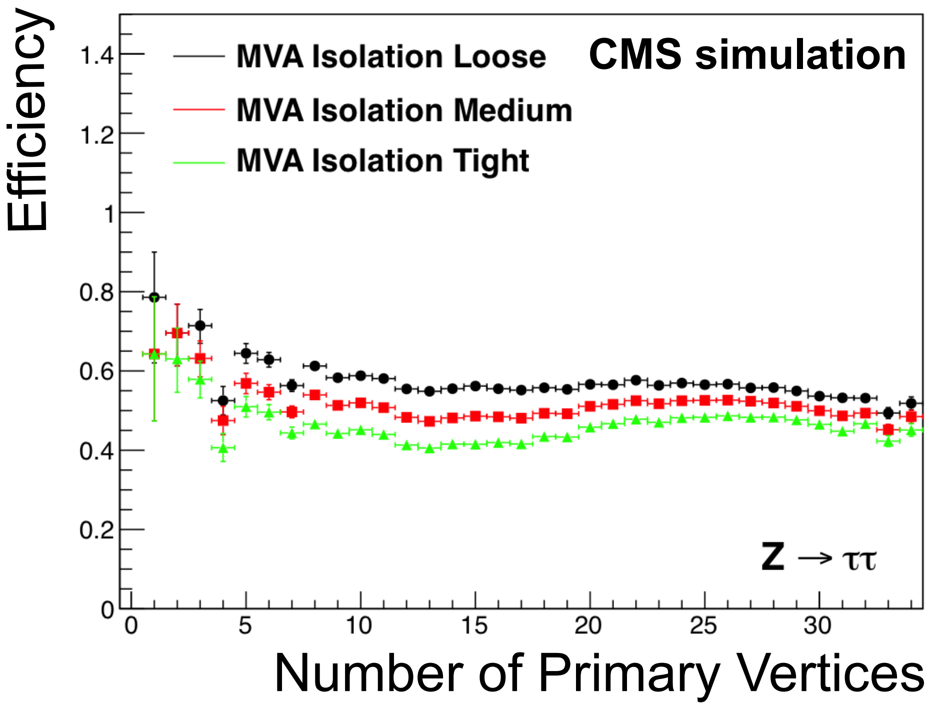




Performance of τ Reconstruction

- Efficiency >60% (flat for p_T>30GeV). Fakerate 1–3%.
- Efficiency and momentum resolution (nearly) independent from pileup.
- Control efficiency to 7% from data (from tag&probe and from incl. Z cross section measurement).

Isolation efficiency:



- Control energy scale to 3% from data (reco. of τ-mass in 3-hadrons and hadron+strip, further constraint in combined fit used for Higgs analysis).

$H\rightarrow\tau\tau$ Event Selection (extended information)

- Search in four decay channels: $e\mu$, $\mu\mu$, $\mu\tau_h$, $e\tau_h$.
  - Two well reconstructed, isolated leptons of opposite sign:

$\mu\mu$ / $e\mu$

- e $p_T>10(20)$ GeV, $|\eta|<2.3$
- μ $p_T>20(10)$ GeV, $|\eta|<2.1$

$e\tau_h$ / $\mu\tau_h$

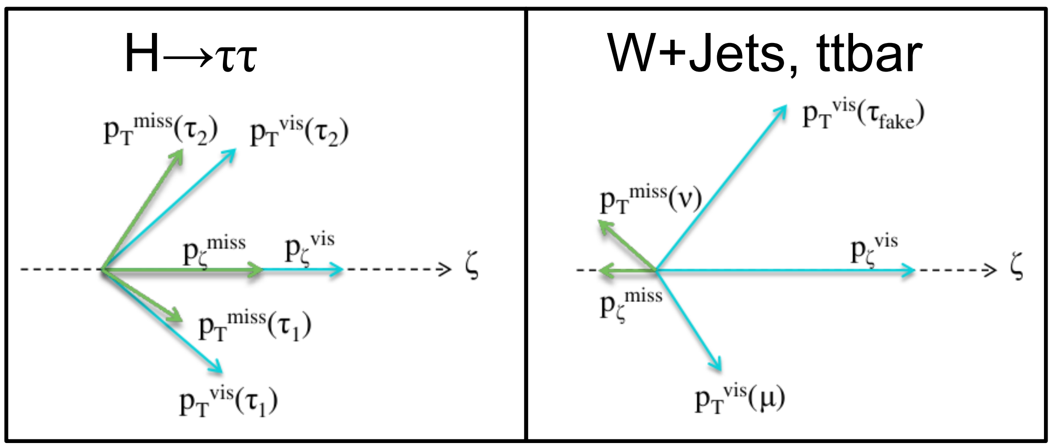
- e $p_T>20$ (24) GeV, $|\eta|<2.1$
- μ $p_T>17$ (20) GeV, $|\eta|<2.1$
- τ_h $p_T>20$ GeV, $|\eta|<2.3$

  - Topological event selection:
    - $p_\zeta^{cut}=(p_\zeta-1.85\cdot p_\zeta^{vis})>-25$ GeV
    - $M_T<40$ GeV

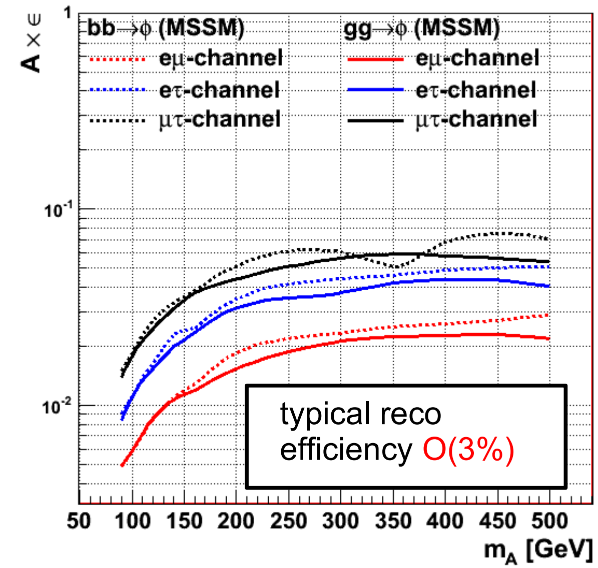
Definition of p_ζ^{cut} and Event Selection Efficiency

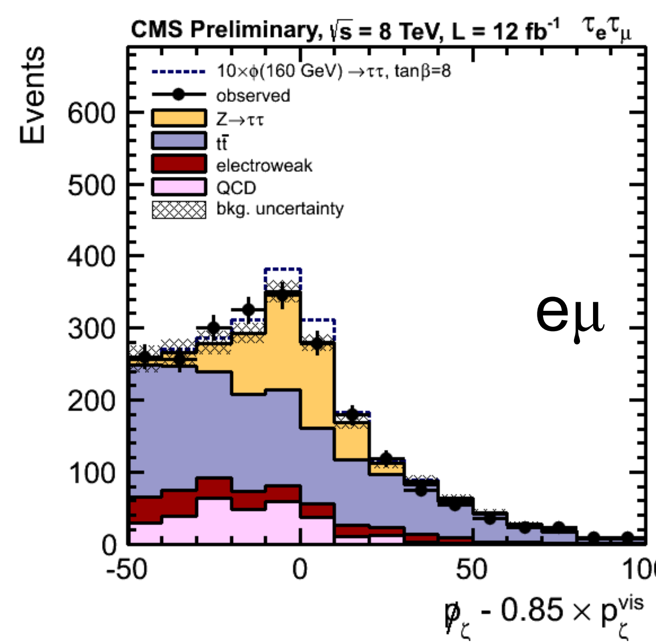
- Topological event selection (eμ, μμ):

$$p_\zeta^{cut} = (p_\zeta - 0.85 \cdot p_\zeta^{vis}) > -25 \text{ GeV}$$

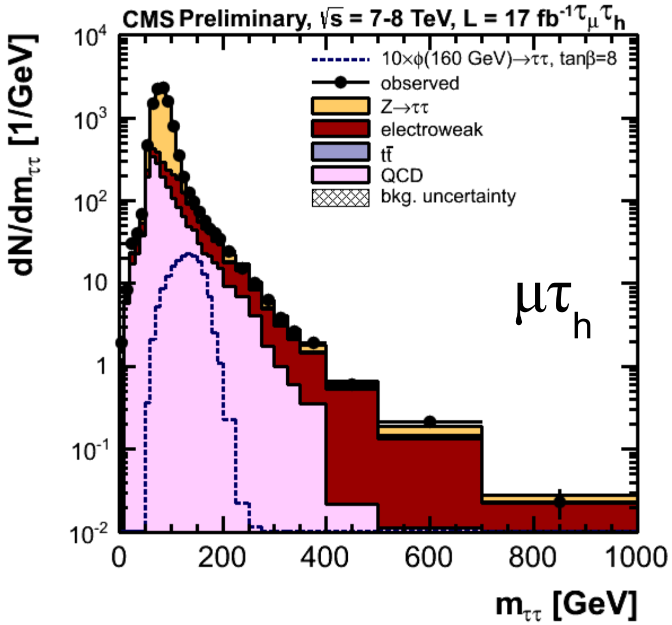


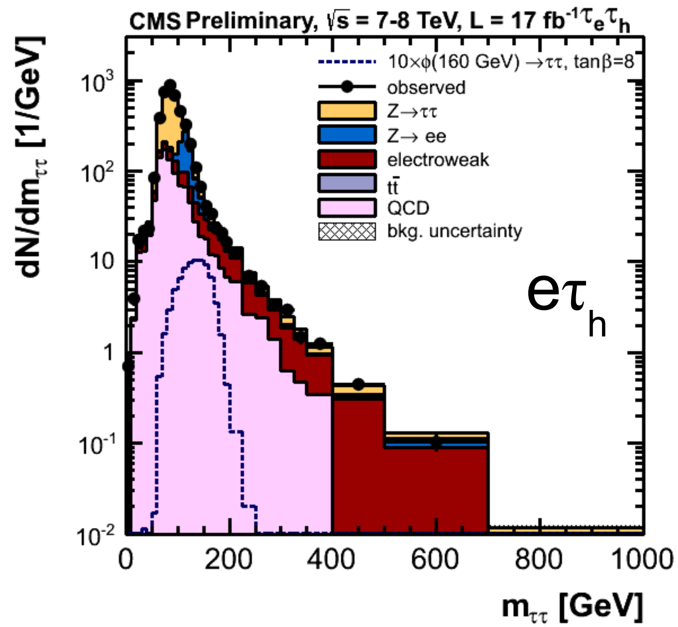
Tends towards zero | Tends negative values

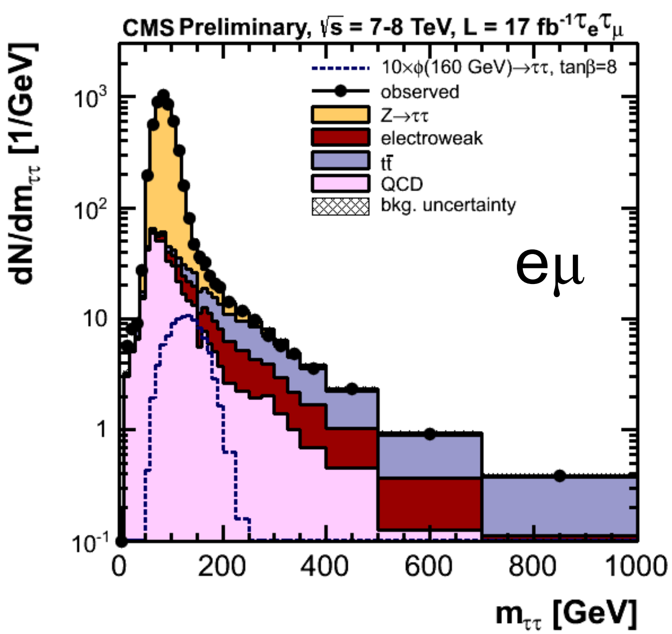


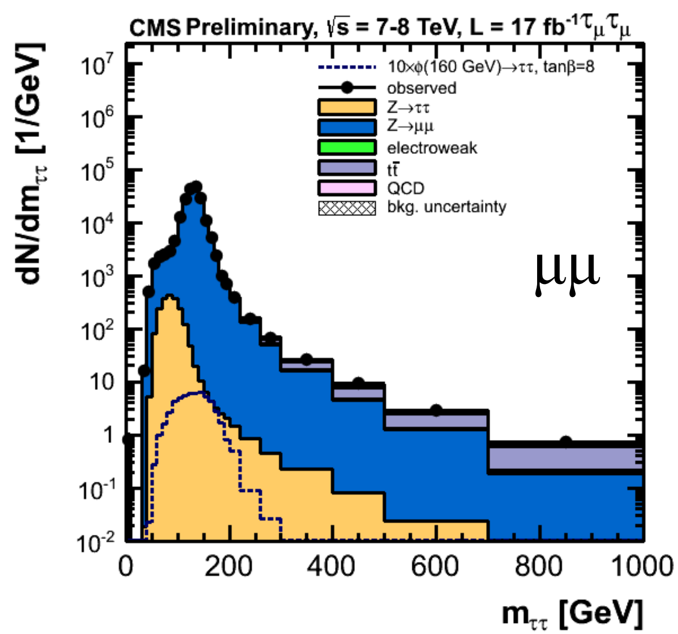


Reconstructed Di-τ Mass (No B-Tag category - log)

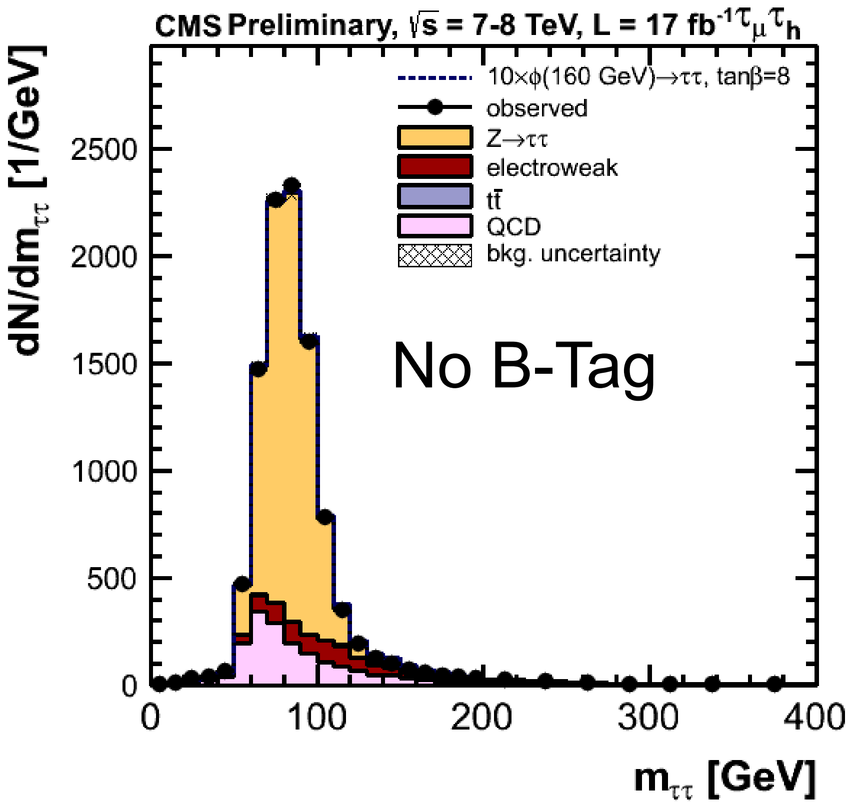


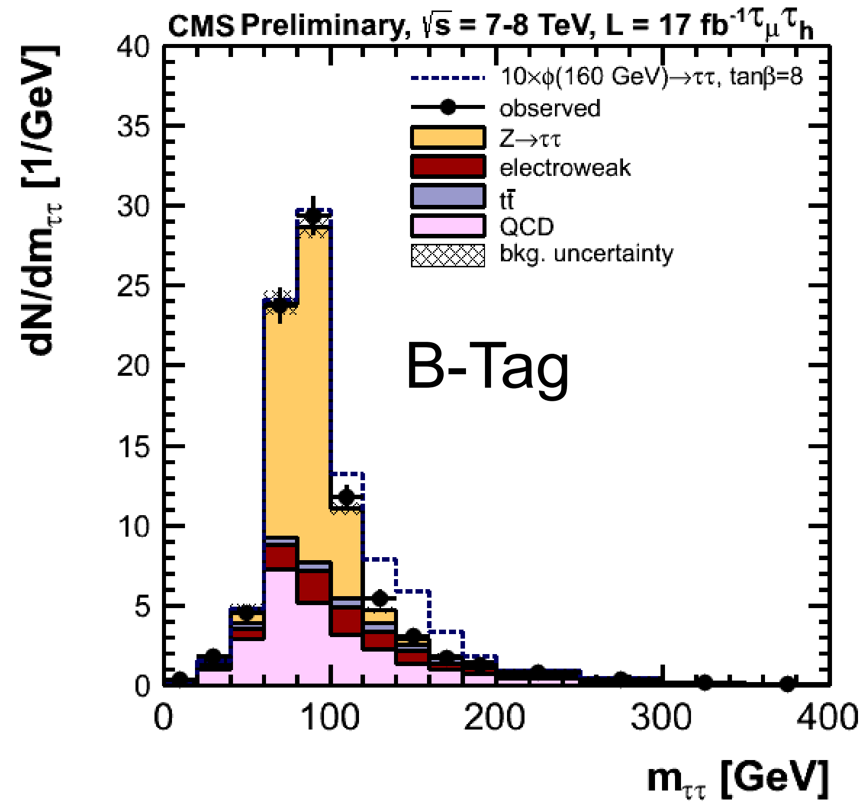






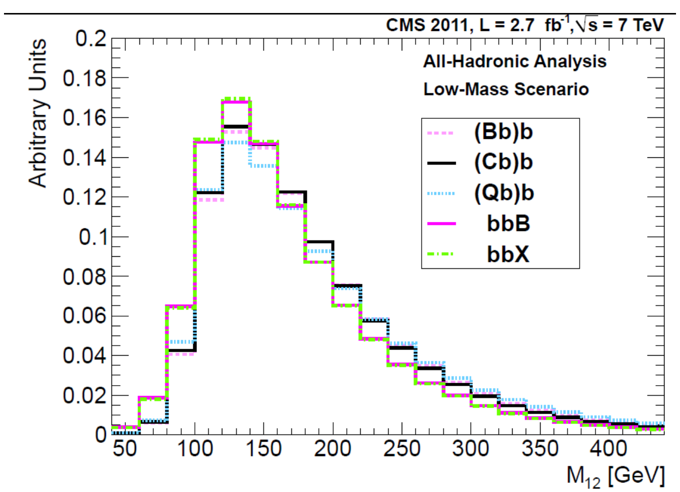
Reconstructed Di-τ Mass (linear plots, $\mu\tau_h$ channel)

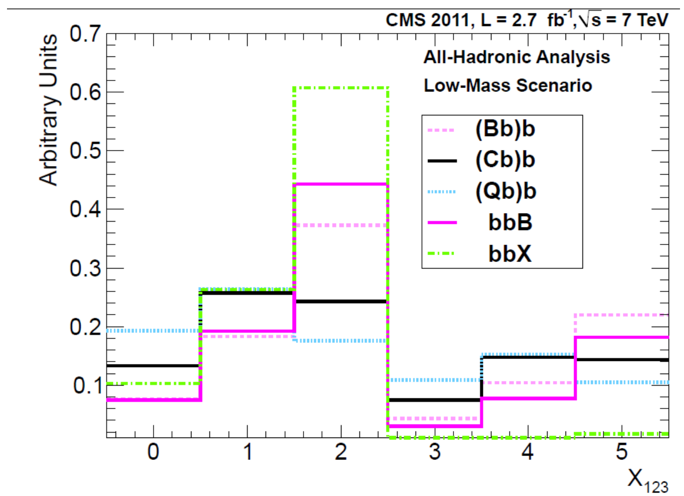




H→bb Search (2.7 - 4.8 fb^{-1} @ 7TeV)

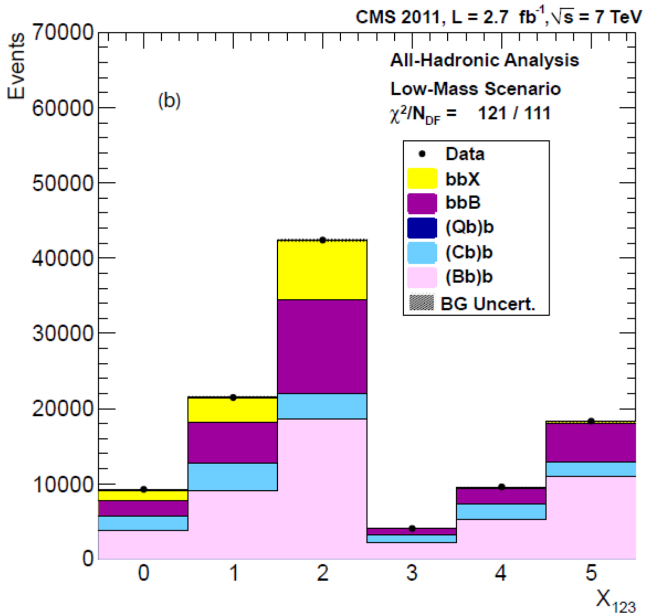
- Select events with N(Jet)≥3 (|η|<2.1, varying cuts on p_T) & N(B-Tag)≥3.
- B-Tag working point with f(Fake)≈0.1%, ε(B-Tag)≈55%.
- Check M_{jj} of 2 leading jets and variable X_{123} based on secondary vertex mass of the three tagged jets.



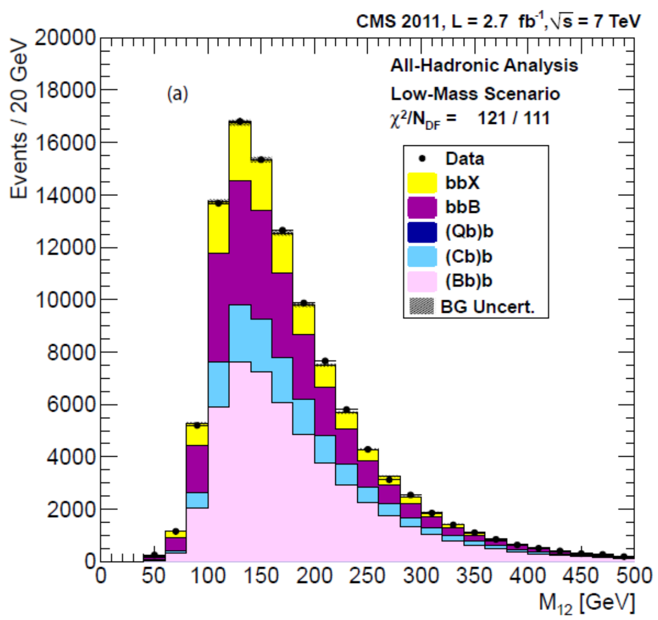


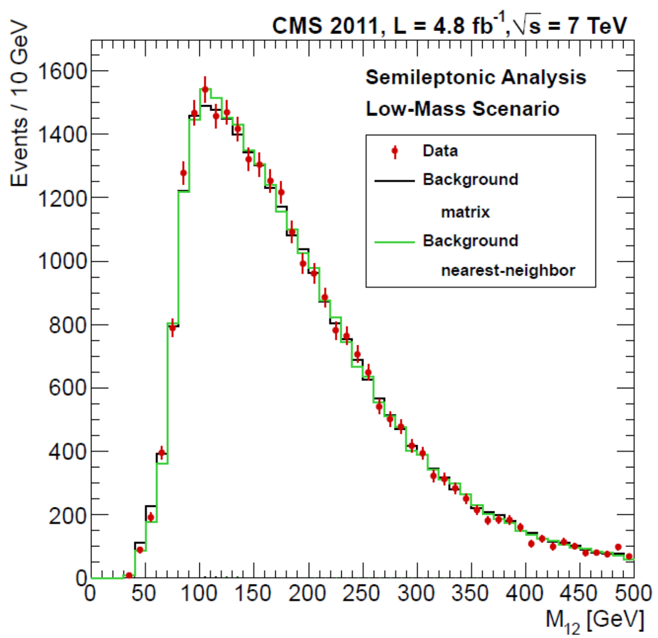
- Determine background from QCD events from N(B-Tag)=2, where non tagged jet is weighted according to hypothesis for Q, C, B.

H→bb (input distributions)

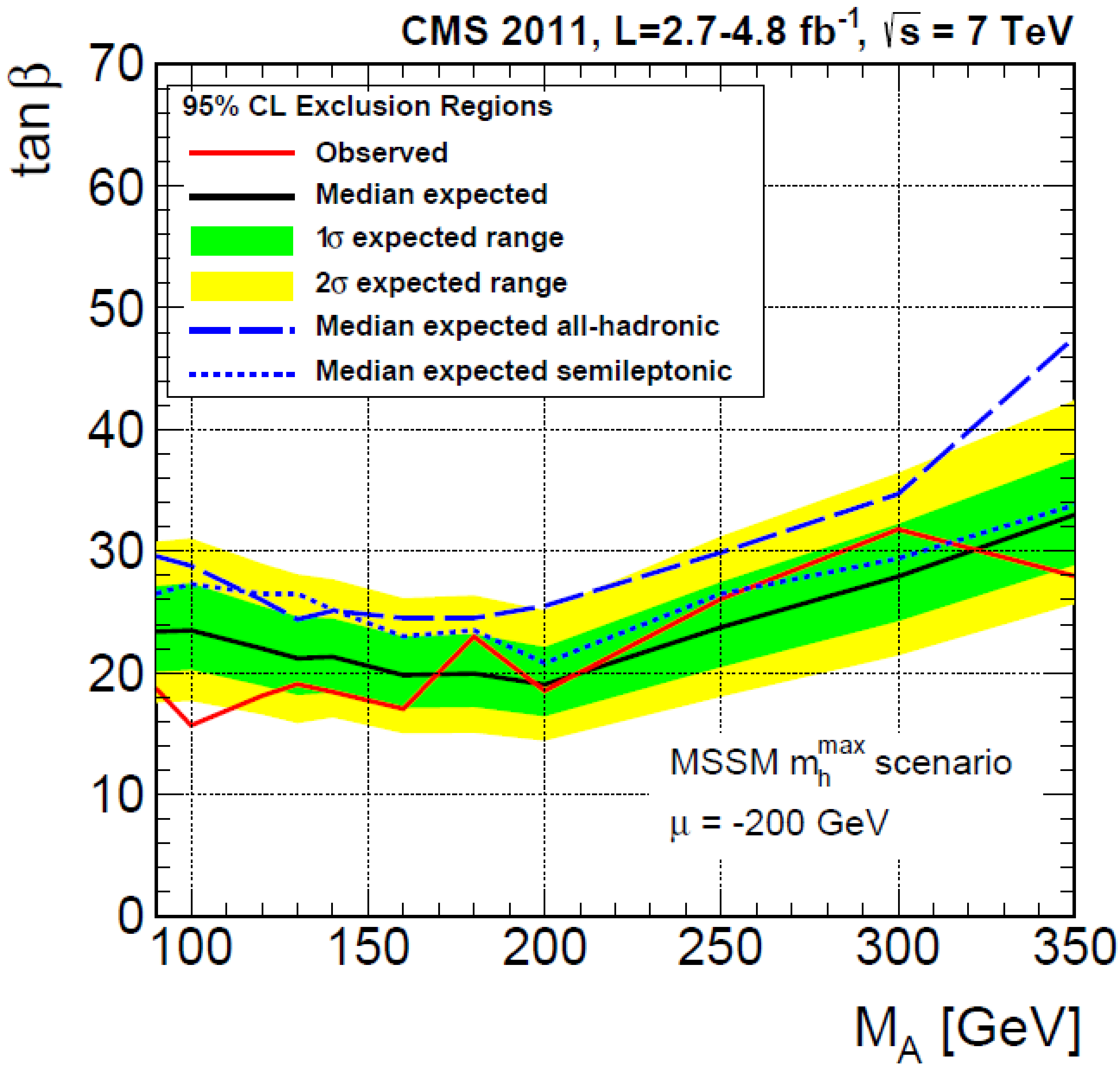


- All hadronic analysis (left).
- Analysis with one isolated μ (semi-leptonic, bottom), based on on M_{jj} only.
- Two methods to estimate background from QCD.





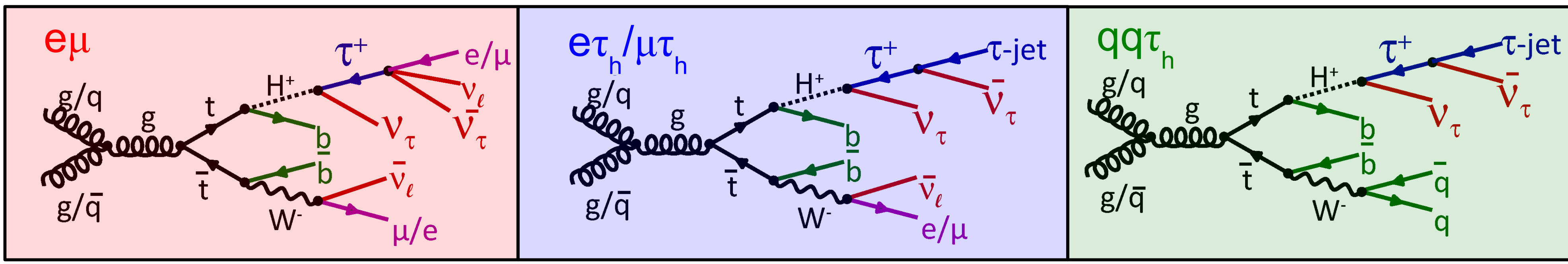
H→bb Limit (2.7 - 4.8 fb^{-1} @ 7TeV)



Singly Charged Higgs Bosons (2.3 fb^{-1} @ 7TeV)

- If $m_{H+/-} < m_{top}$, $H^{+/-}$ can be produced via top quarks ($t \rightarrow H^{+/-}b$)
  - Under the assumption $BR(H^+ \rightarrow \tau^+\nu)=1$ limits can be derived on $BR(t \rightarrow H^+b)$.

- Search in three decay channels:

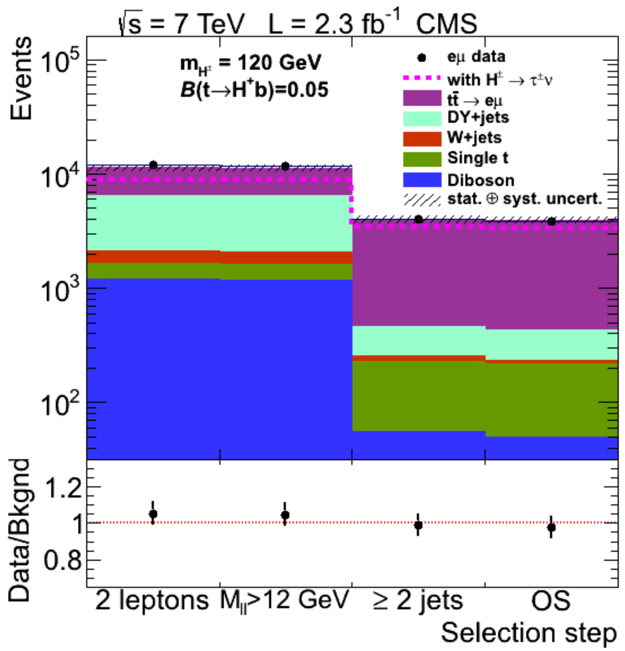


- Consider single ($tt \rightarrow W^{+/-}H^{-/+}bb$) and double ($tt \rightarrow H^{+/-}H^{-/+}bb$) $H^{+/-}$ production

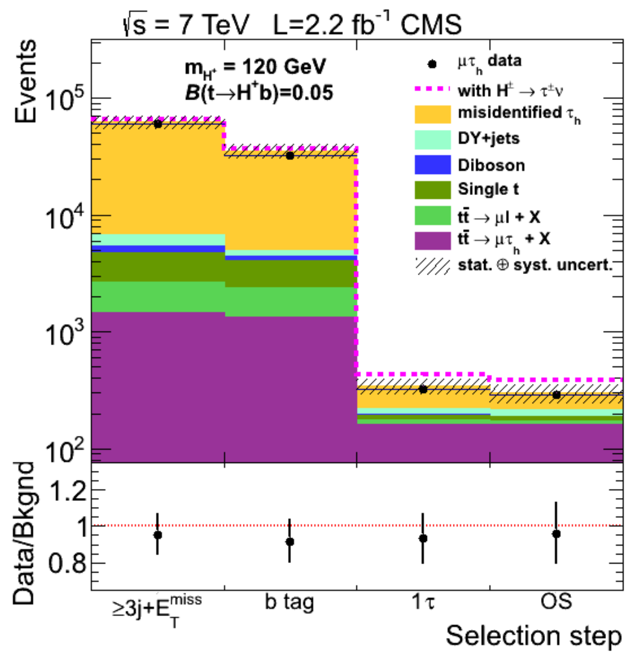
- Use typical selection for top quark pairs
- Isolated e/μ, jets, b-jets, MET
- Expect $H^{+/-}$ signal as deviation from SM expectation for tt

Event Selection

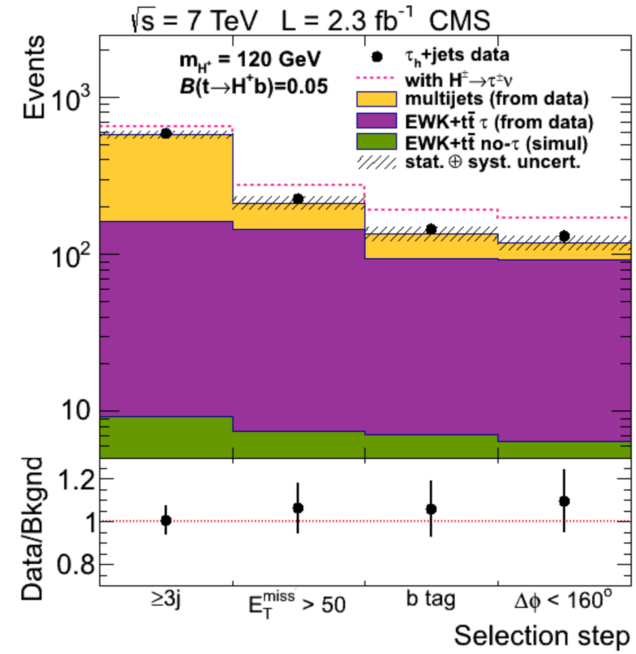
- $e\mu$:



- $e\tau_h/\mu\tau_h$:



- $qq\tau_h$:



$e\mu$		stat.		syst.
Exp:	3866	± 38	±	406
Obs:	3875			

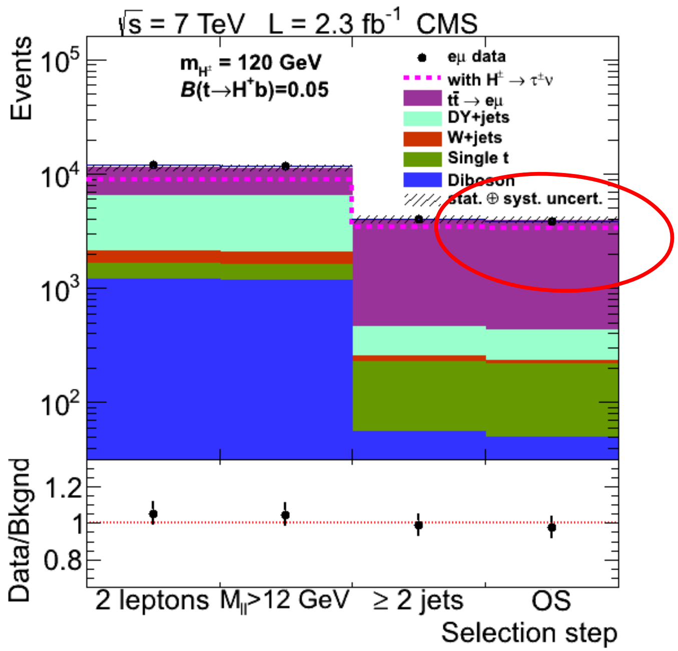
$\mu\tau_h$		stat.		syst.
Exp:	306	± 11	±	32
Obs:	288			

$qq\tau_h$		stat.		syst.
Exp:	119	± 5	±	12
Obs:	130			

$e\tau_h$		stat.		syst.
Exp:	194	± 8	±	20
Obs:	176			

Event Selection

- $e\mu$:

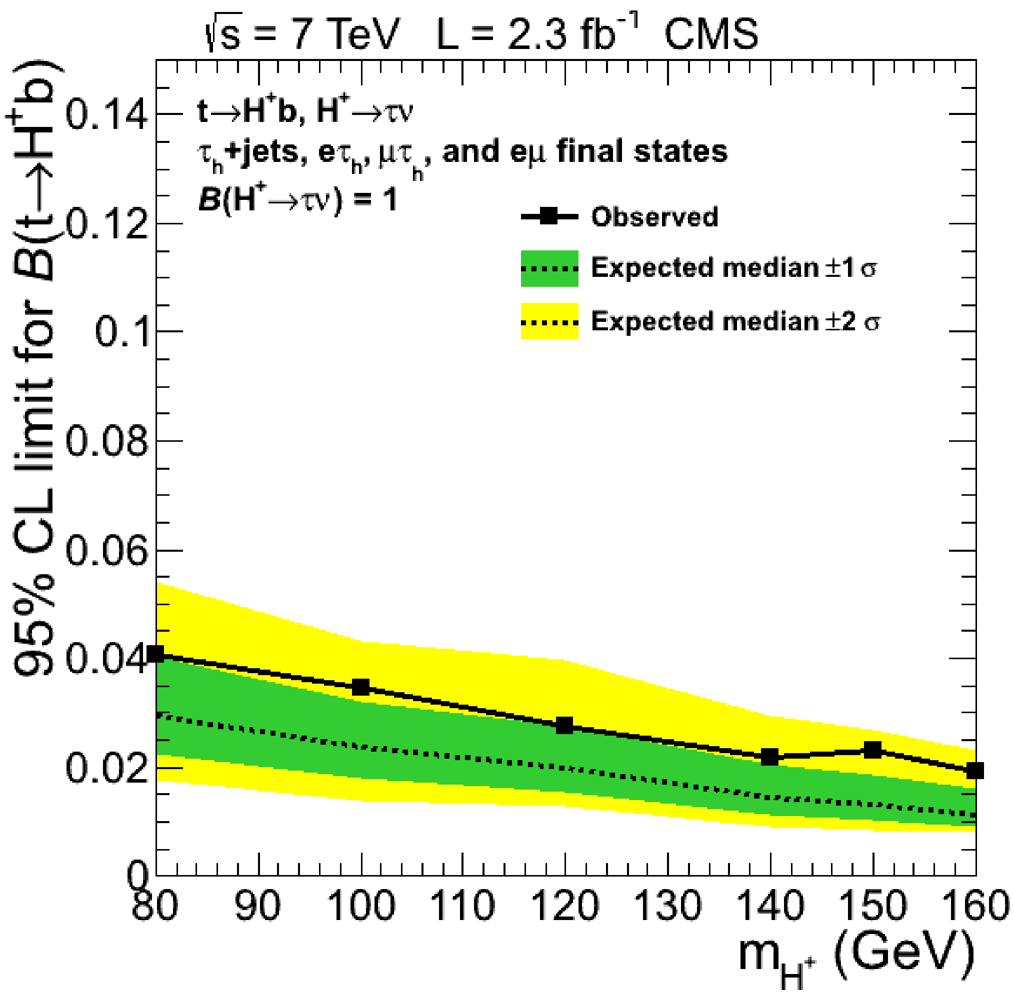


$e\mu$	stat.	syst.
Exp: 3866	± 38	± 406
Obs: 3875		

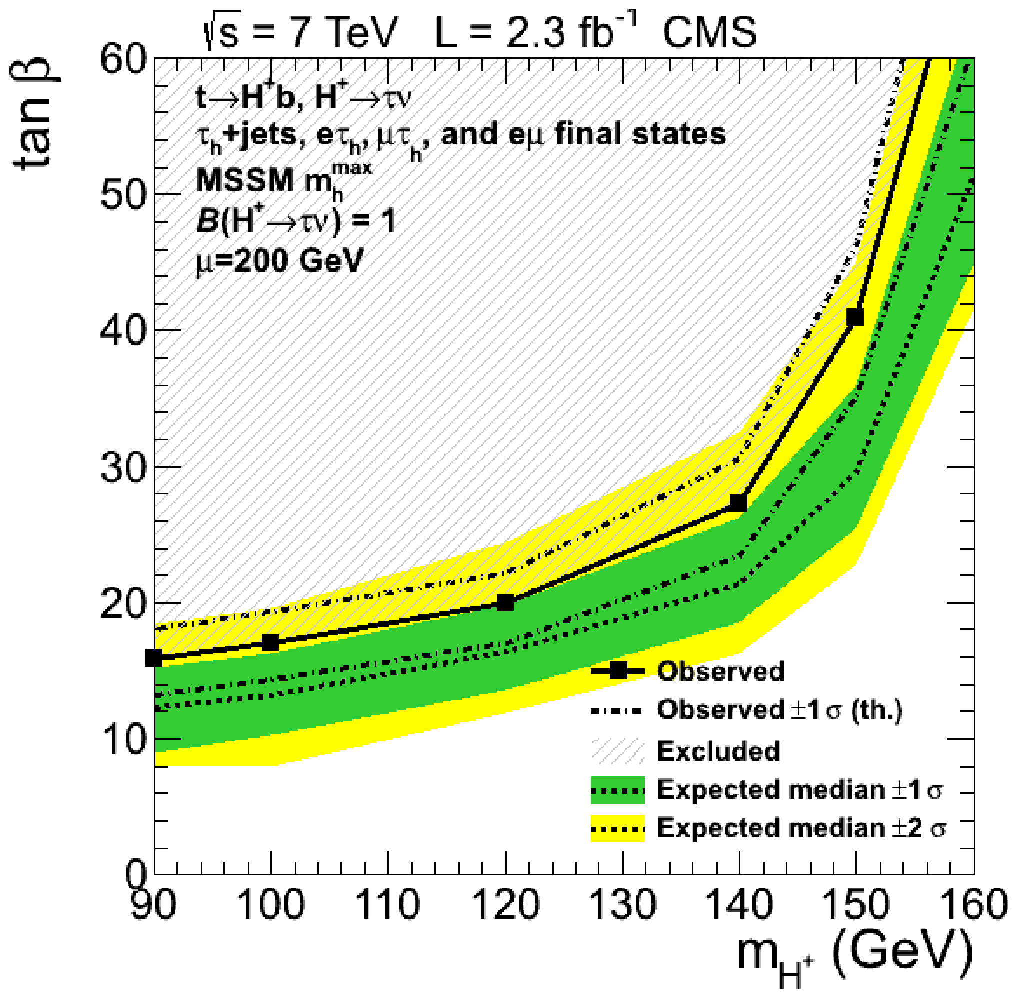
- The major contribution to the event yield comes from $tt \rightarrow e\mu X$.
- The signal has a softer $p_T(e/\mu)$ spectrum wrt. prompt e/μ from tt decays due to the $\tau \rightarrow l\nu\nu$ decay.
- Therefore a larger contribution of signal would lead to a lower yield of reconstructed events.

Limits on BR($t \to H^+ b$) & tanβ-m_{H+} (2.3 fb^{-1} @ 7TeV)

- Limit on BR($t \to H^+ b$):



Limit in m_{H+}-tanβ:

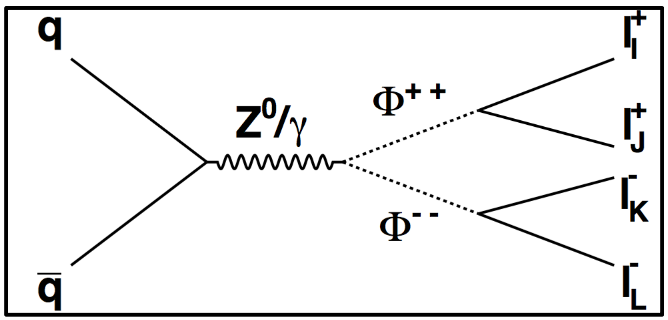


- Main systematics:
  τ (miss-)id 6% (15%), jet energy scale (2.5%-5%), b-jet (miss-)tagging (10%)

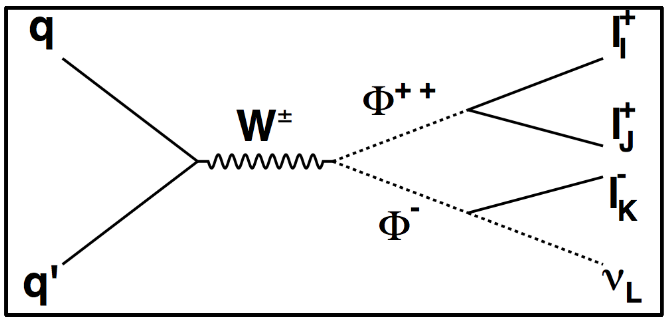
Doubly Charged Higgs Bosons (4.6 fb^{-1} @ 7TeV)

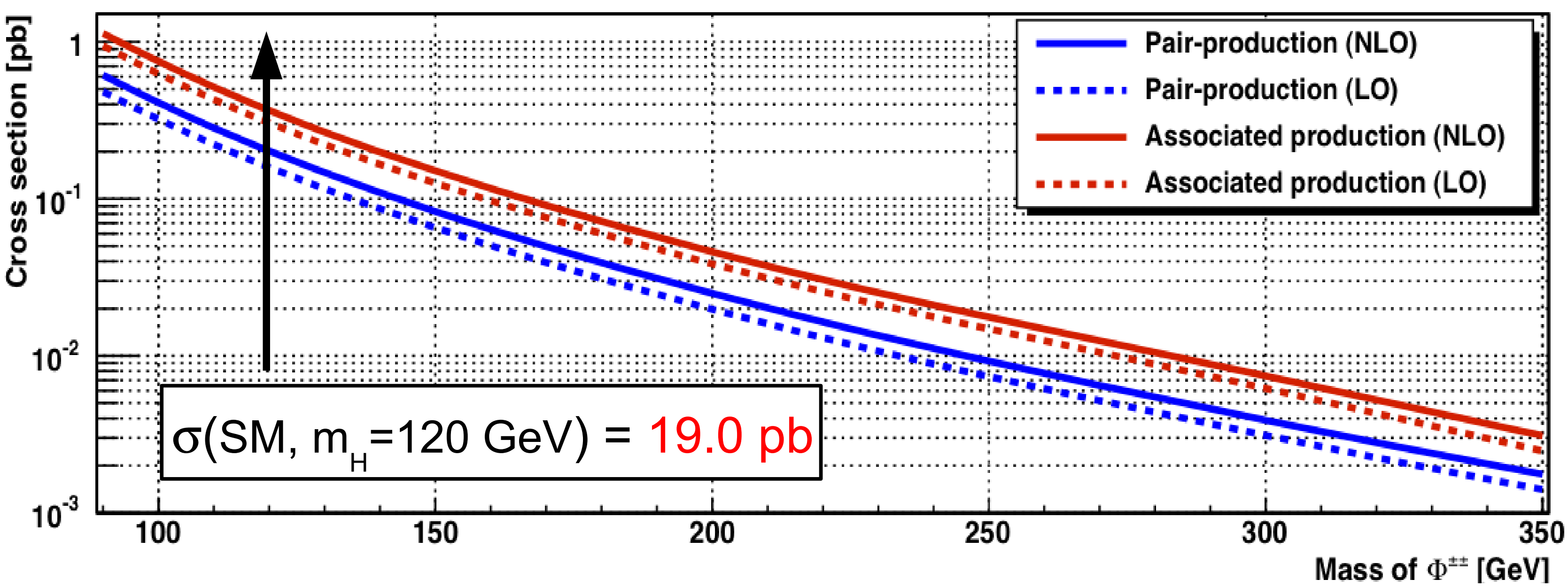
- Minimal seasaw models of type II, introduced to explain non-zero ν masses are realized with a triplet scalar field which introduces a doubly charged $H^{++/--}$ state:

Pair Production:



Associated Production:

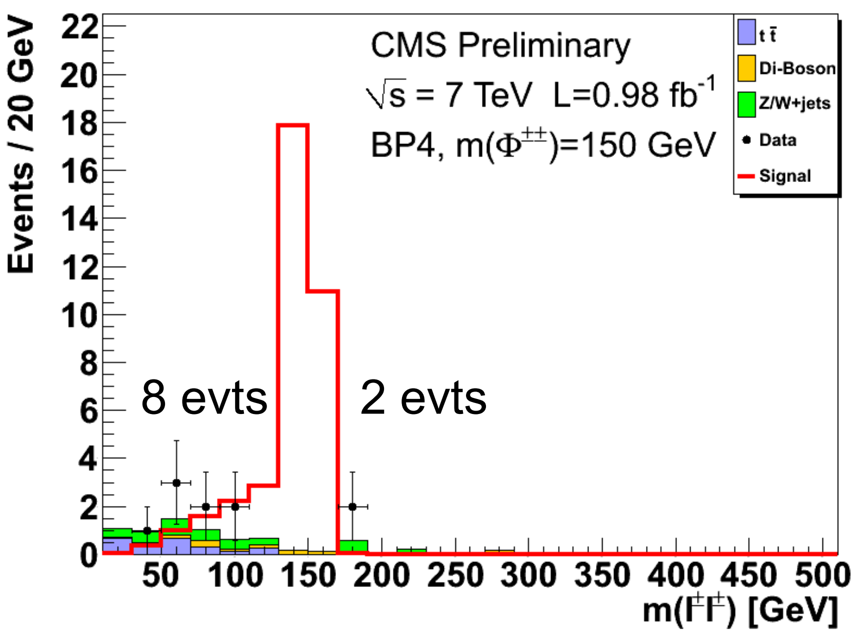


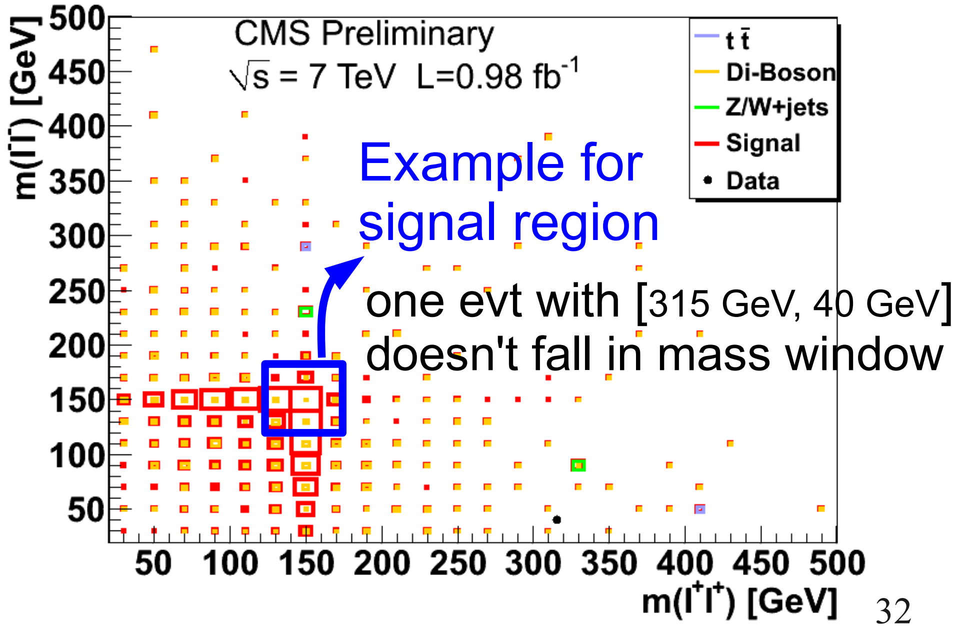


Event Selection (example plots from prel. results)

- Search for 3 or 4 isolated leptons in mass dependent like-sign(!) resonance mass windows (search in 2-channels)
- Allow for lepton flavour violation (i.e. combine all kinds of flavours, include τ leptons)
- Exotic signature - basically free of SM backgrounds

Three Leptons:	Four Leptons:
$\Sigma p_T(3l's) > m(\phi) + 80GeV$	$\Sigma p_T(4l's) > m(\phi) + 80GeV$
$m(ll)$ $[m_{lower}(flav), m(\phi)+10GeV]$	$m(ll)$ $[m_{lower}(flav), m(\phi)+10GeV]$

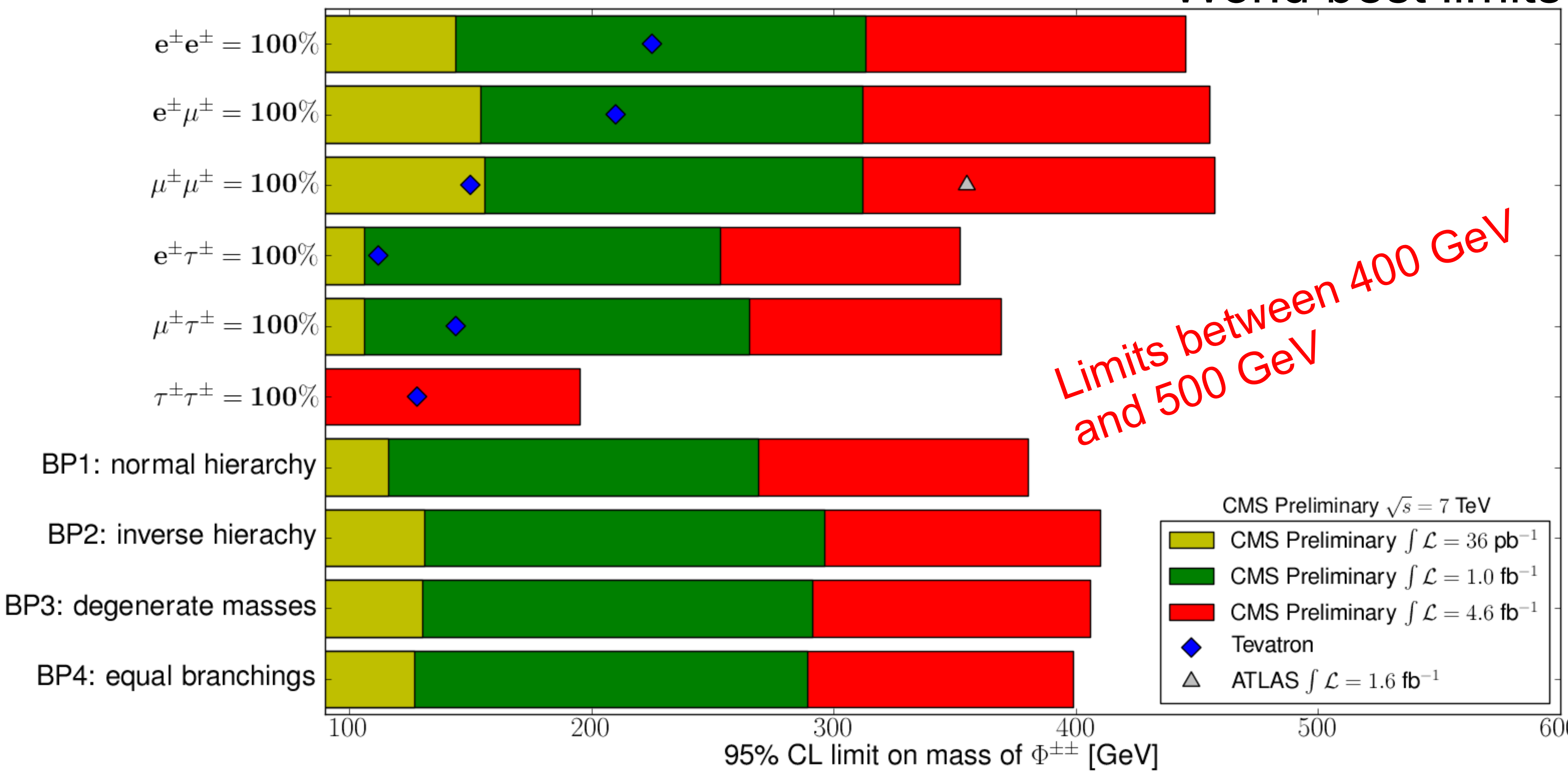




Exclusion Limits (4.6 fb^{-1} @ 7TeV)

- Absence of events allows to set limits:

World best limits



Main uncertainties:
τ identification (8%), signal cross section (10%), stat. limitations in sidebands for background determination (10-100%)