VI Workshop Italiano sulla Fisica p-p a LHC
Acquario di Genova
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RICERCHE DI HIGGS ESOTICI

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OUTLINE

- Neutral Higgs Boson searches
  - Two Higgs Doublet Models (2HDM)
    - Direct heavy Higgs searches
    - Fermiophobic Higgs*
    - Minimal Supersymmetric Standard Model (MSSM)
    - Next to Minimal Supersymmetric Standard Model (NMSSM)
  - Higgs to invisible
  - Higgs in a model with a 4th generation of fermions*
  - Hidden sector*
- Charged Higgs boson searches
  - 2HDM→ MSSM : charged Higgs
  - Doubly charged Higgs
- Future Plans

* backup

NEUTRAL HIGGS BOSON SEARCHES

2 Higgs Doublet Model (2HDM)

- A simple extension of the SM is the addition of a 2nd Higgs doublet
- It gives rise to 5 Higgs Bosons: h, H, A, $H^{\pm}$
- Is the 125 GeV the lightest among the 5?
- 2HDM models are classified depending on the fermion coupling:
  - **Type I**: all quarks couple to just one of the Higgs doublets
    → fermio-phobic limit
  - **Type II**: the Q=2/3 right handed quarks couple to one Higgs doublet and the Q=-1/3 right handed quarks couple to the other
    → MSSM is a type II at tree level

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\begin{pmatrix} A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Mixing angles:
α and β

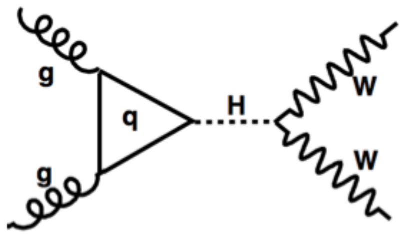
ϕ_1, ϕ_2 : CP-even fields
χ_1, χ_2 : CP-odd fields

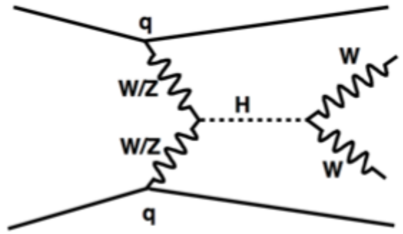
$$\tan\beta = \frac{v_2}{v_1}$$

2HDM: H→WW→eνμν NEW@Moriond

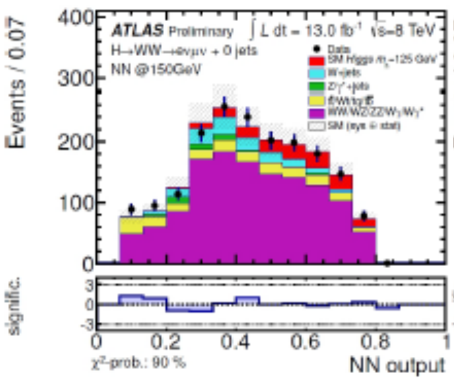
ATLAS-CONF-2013-027

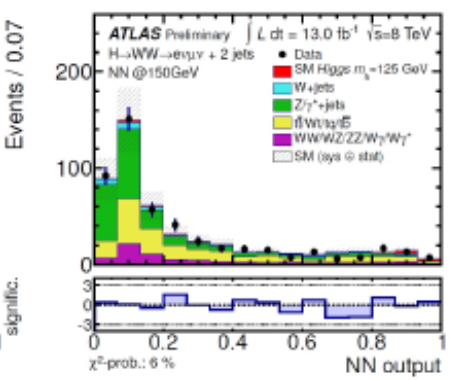
- Strategy:
  - Assume m_h = 125 GeV
  - **Direct search for the heavier neutral Higgs H between 135-300 GeV in H→WW→eνμν channel**
  - Boson A and $H^{\pm}$ assumed to be heavy → do not affect the H xsec and BR
- Selections
  - 2 leptons OS and OF
  - 0 jet and 2 jet final states



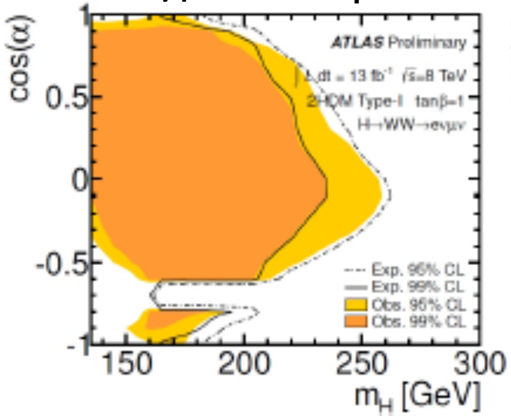


- Limits
  - Final discriminant NN output trained for mH= 150, 180, 240 GeV
  - Limits for tanβ= 1, 3, 6, 20

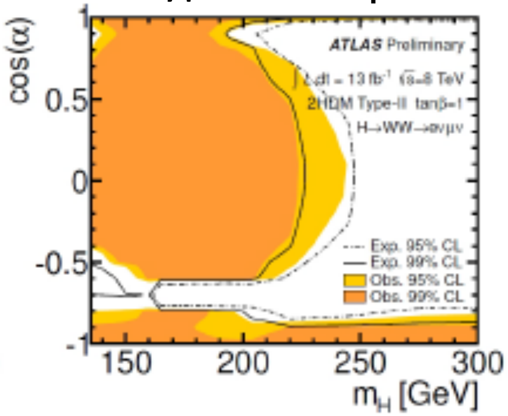




Type I - tanβ= 1

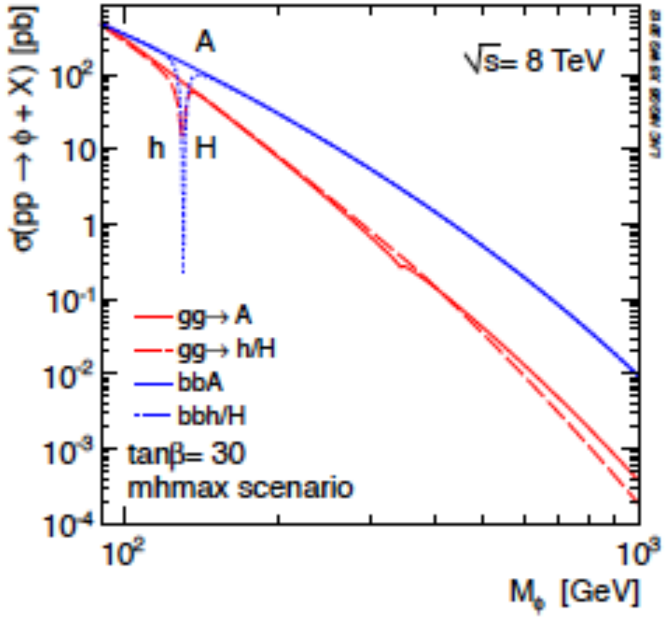


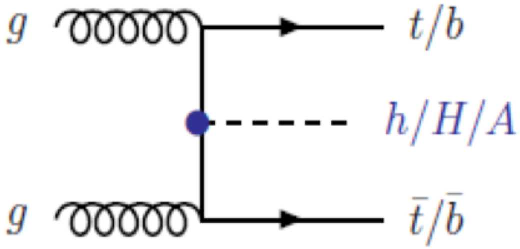
Type II - tanβ= 1

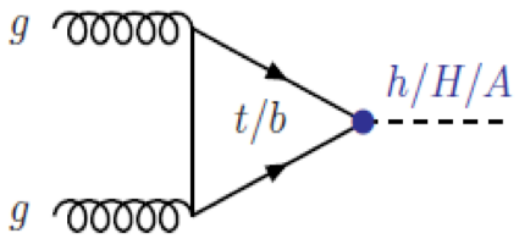


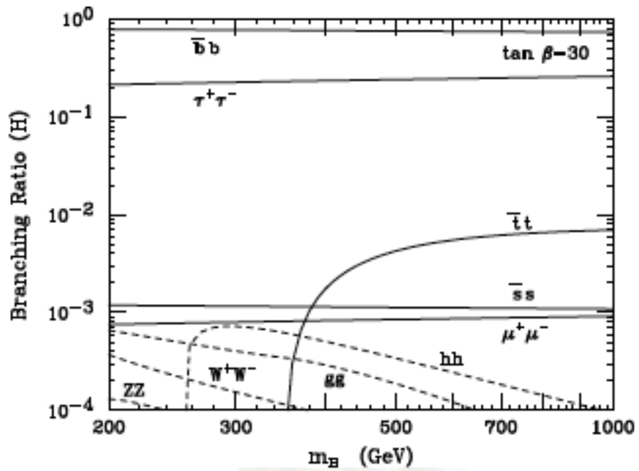
2HDM: MSSM

- Constrained 2HDM (type II)
  - MSSM can be described by tanβ and M_A
  - Coupling with down-type quarks goes with $\tan^2\beta$
- Physics Processes:
  - <u>Production</u>: Higgs couplings to b-quarks enhanced by factor ~$\tan^2\beta$ compared to SM
  - Decay:
    - H→bb (BR ~90% for Tanβ>3)
    - H→$\tau^+\tau$ (BR ~10% for Tanβ>3)
    - H→ $\mu^+\mu$ (BR ~0.04% for Tanβ>3)









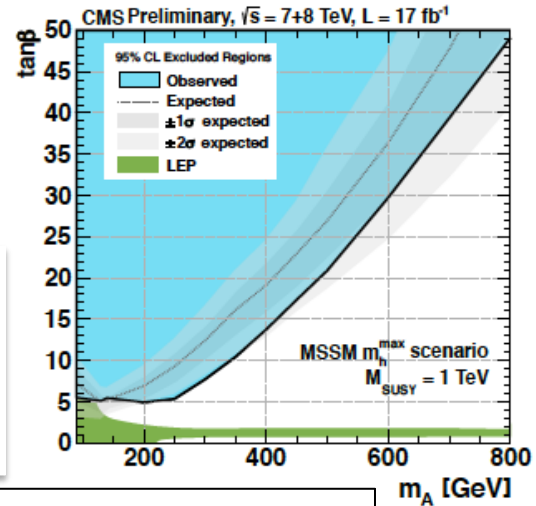
- MSSM Charged searches → see "Charged Higgs Boson searches" (slide 15)

MSSM: A/H/h→$\tau^+\tau^-$

- **Selections:** 8 final states:
  - ○ **ATLAS** 4.7-4.8 fb^{-1} @7 TeV
    - 4 channels: $\tau_{lep}\,\tau_{had}$, $\boldsymbol{\tau_{had}\,\tau_{had}}$, $\tau_e\,\tau_\mu$, $\mu\mu$
    - b-tagged/b-vetoed categories
  - ○ **CMS** 4.9 fb^{-1} @7 TeV+12.1 fb^{-1} @8 TeV
    - 4 channels: $\tau_\mu\,\tau_{had}$, $\tau_e\,\tau_{had}$, $\tau_e\,\tau_\mu$, $\tau_\mu\,\tau_\mu$
    - No b-tagged/b-tagged categories

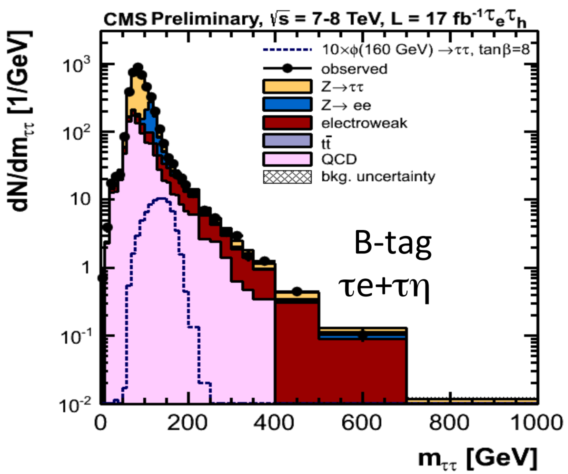
Next slide

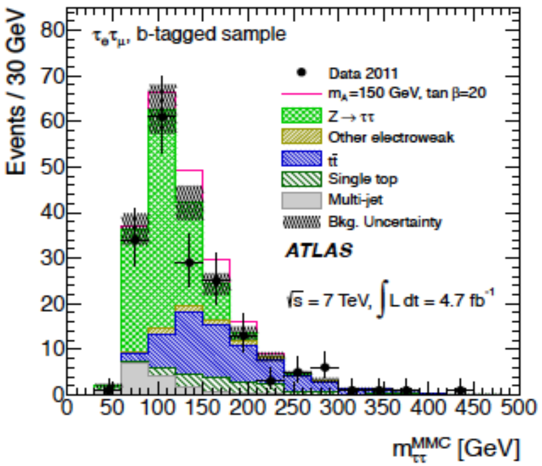
τ decay
- Lep-lep 12.4%
- Lep-Had 45.6 %
- Had-Had 42 %

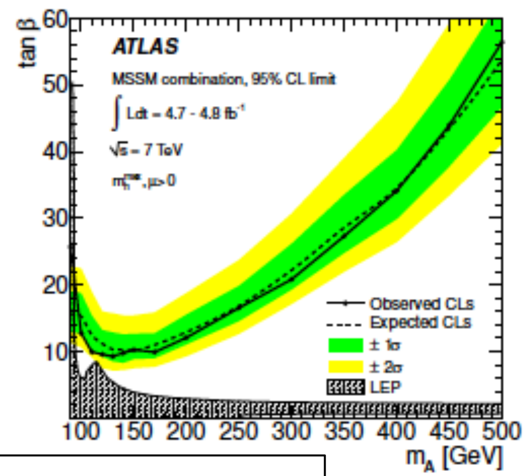


CMS-PAS-HIG-12-050

- **Limits:** final discriminant $m_{\tau\tau}$







JHEP02(2013)095

MSSM: A/H/h → $\mu^+\mu^-$

○ **ATLAS** 4.7-4.8 fb^{-1} @7 TeV

- Same analysis as H→ττ (previous slide)
- b tagged: 1 or 2 b- jets
- b vetoed

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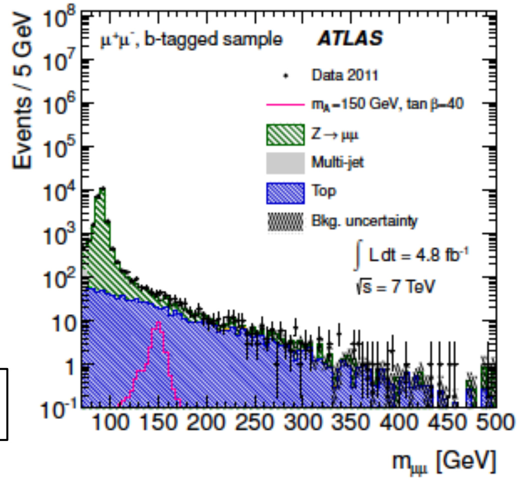
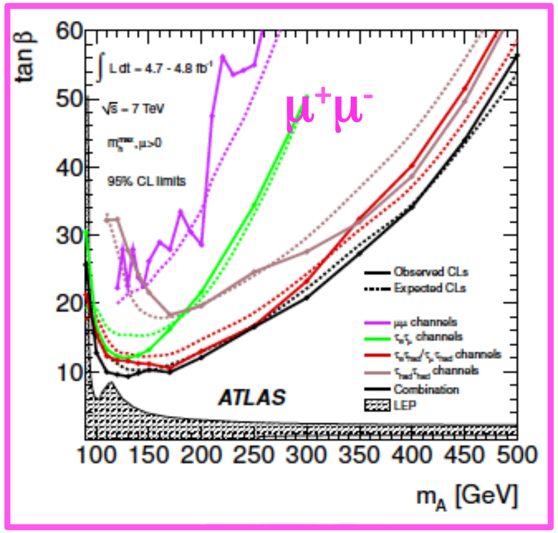
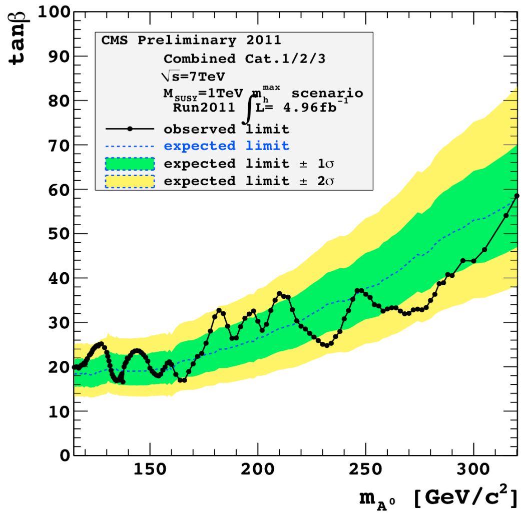
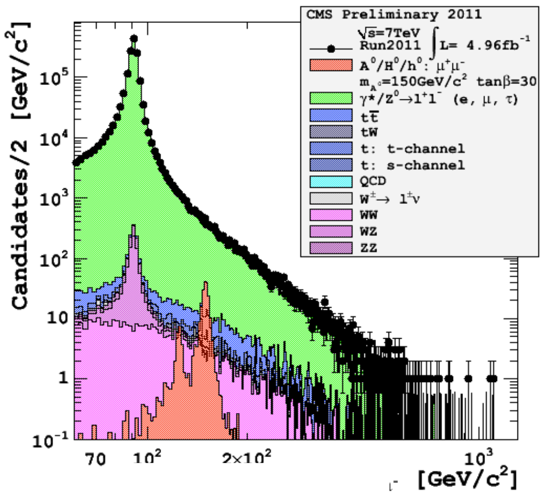




Clean signal with excellent mass resolution

Limits: final discriminant $m_{\mu\mu}$





○ **CMS** 4.96 fb^{-1} @7 TeV

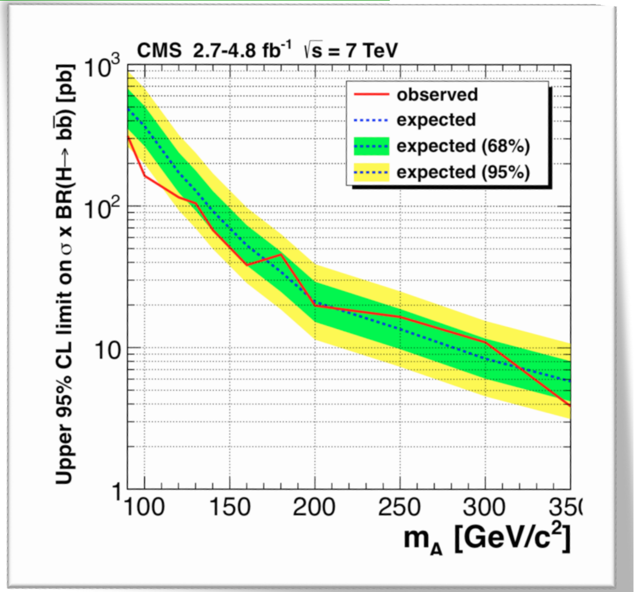
- b tagged (bH)
  - 2μ+btag
  - 2μ+third μ (from b-decay)
- b vetoed (ggF)

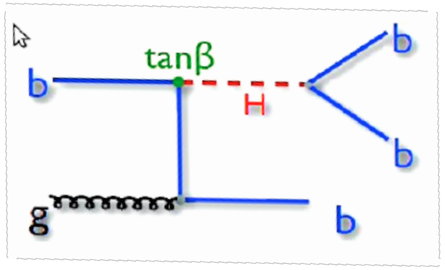
CMS-PAS-HIG-12-011

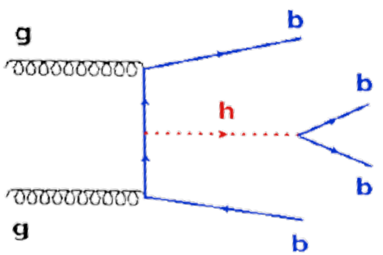
MSSM: bb A/H/h→ bb

- **CMS** 2.7- 4.8 fb^{-1} @ 7 TeV
- Search for H->bb produced in association with b-quarks
- Two approaches:
  - **All-hadronic →** exploit b-jet multiplicity
  - **Semi-leptonic →** exploit also the b→μ
- Set upper limits on σ(bbϕ) x BR(ϕ→bb)

CMS-PAS-HIG-12-033

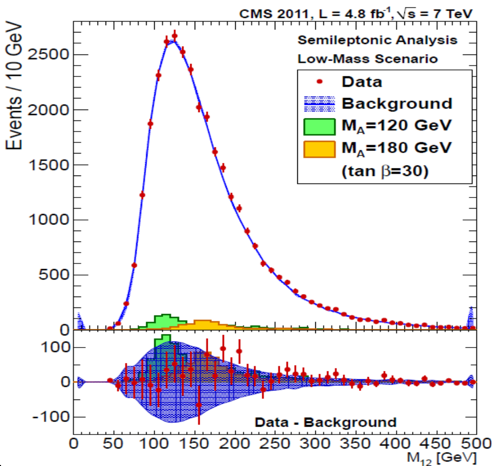






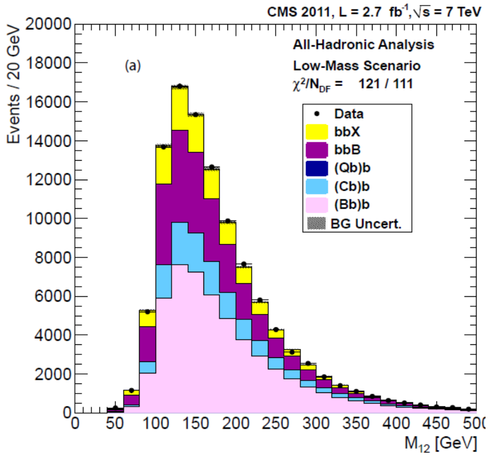
Semi- leptonic

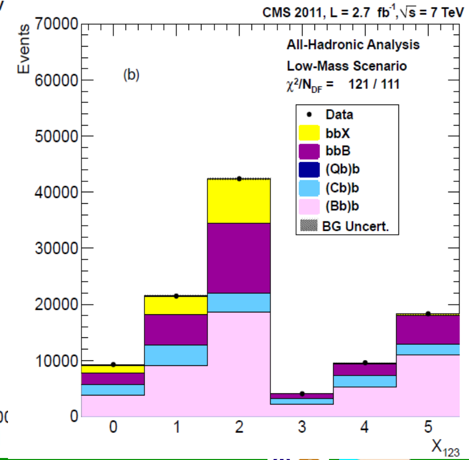
Mass of leading jets pair



Fully hadronic

Signal yields from a 2D fit on di-jet mass vs event Btag

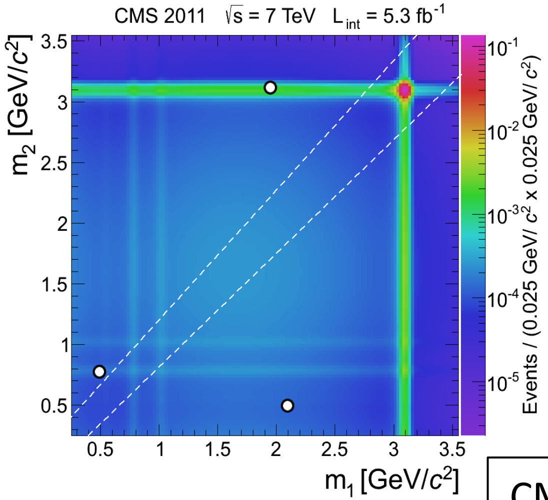


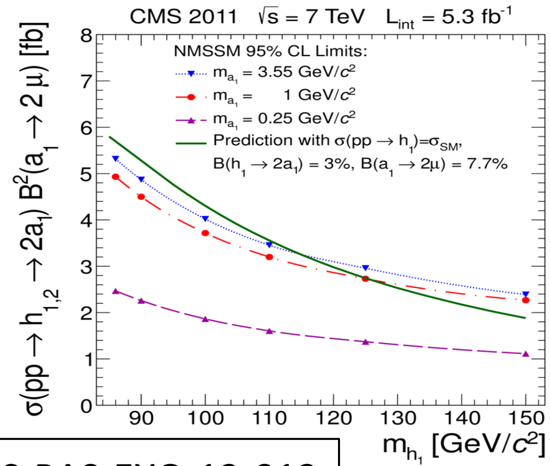


nMSSM

- nMSSM: add one scalar singlet to MSSM.
  - 3 CP-even h_1,h_2,h_3 , 2 CP-odd a_1,a_2 , charged $H^\pm$
  - one CP-odd boson (a_1) can be very light $m_{a1}<2m_b$
- Solve some problem of MSSM
  - accommodates better M_h = 125 GeV
  - no fine-tuning for μ-term (produced by VEV of singlet)
- Production via gg → (h, a) through t, b triangle loop
- Channels:
  - Neutral
    - h→aa→ $2\mu+2\mu$
    - h→aa→ $2\gamma+2\gamma$
    - a→ 2μ (backup)
  - Charged → see “Charged Higgs Boson searches” (slide 13)

NMSSM $h \to aa \to 4\mu$ / 4γ

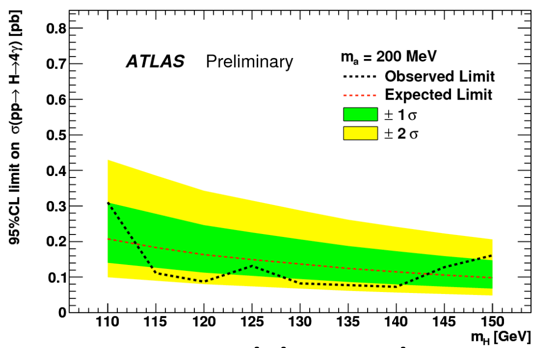


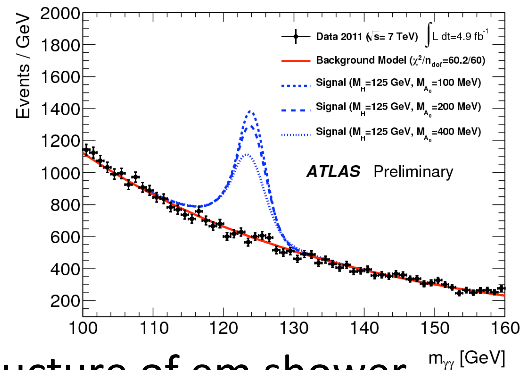


CMS-PAS-EXO-12-012

- **CMS** 5.3 fb^{-1} @ 7 TeV
- Selection:
  - ○ ≥ 4 μ, exactly 2 isolated
  - ○ Two di-muon $0.25 < m_{\mu\mu} < 3.55$ GeV
- Limit:
  - ○ A model-independent upper limit of 0.78 ± 0.05 fb for σ X BR X Acc. is set

- **ATLAS** 4.9 fb^{-1} @ 7 TeV
- a $\to\gamma\gamma$ decays very collimated
  - ○ mimic di-photon events
- Selection:
  - ○ di-photon selection
  - ○ γ -ID cuts with loosened shower-shape cuts sensitive to inner structure of em shower
  - ○ acceptance selection efficiency: 16-30 %
- Limit:
  - ○ exclude σ (pp $\to$ h $\to$aa$\to$ 4γ) > 0.1 pb (0.2 pb) for m_a = 100, 200 (400) MeV



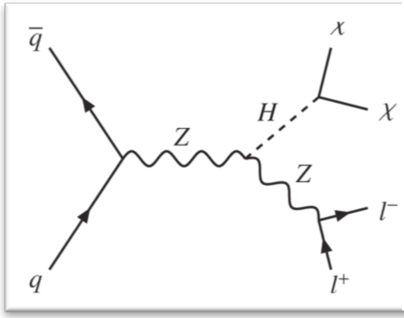


ATLAS-CONF-2012-079

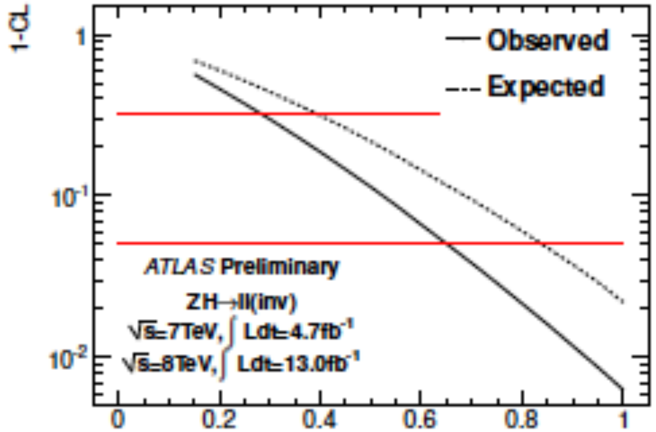
HIGGS TO INVISIBLE

NEW @ Moriond

- **ATLAS**: 4.97 fb^{-1} @ 7 TeV + 13 fb^{-1} @ 8 TeV
- **Direct search** for the invisible decays of Higgs
- Selection:
  - e or μ pair compatible with m_Z
  - no additional lepton or jet



- Limits:
  1. assume SM ZH production for m_h = 125 GeV, BR(H→inv)<0.65@95% CL obs.
  2. set upper limit on additional Higgs-like state: σ_{ZH} * BR(Z → ll) * BR(H → inv)



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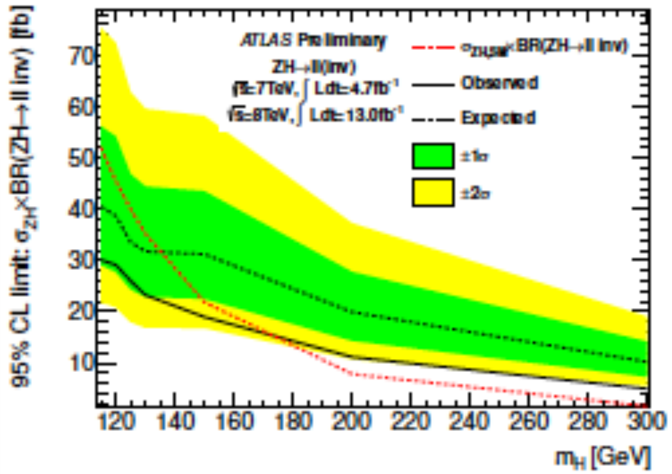
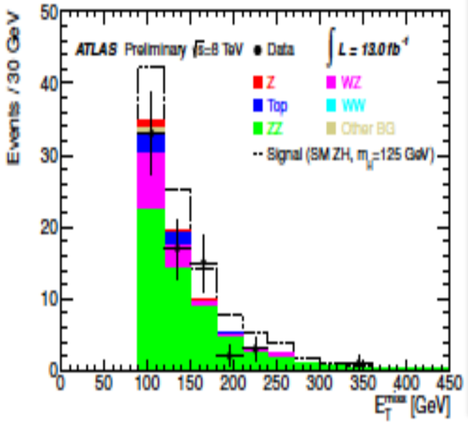
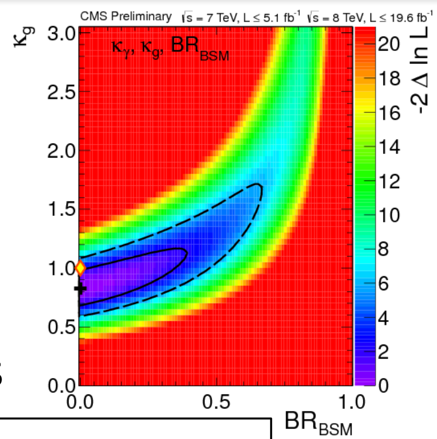


Previous Limits: Combined LEP results exclude H → invisible up to m_h < 114.4 GeV, assuming BR(H → inv) = 100%

E^t_{miss} Final discriminant



- **CMS**
- Indirect searches
- Reinterpretation of SM results to set BR limits in BSM



CMS-PAS-HIG-13-005

CHARGED HIGGS BOSON SEARCHES

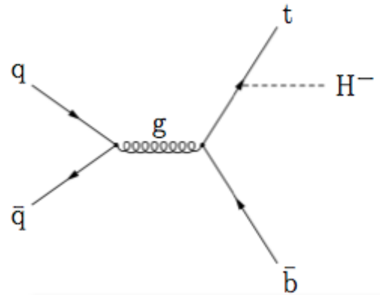
- 2HDM→ MSSM : charged Higgs
  - $H^+ \rightarrow \tau^+\nu$
  - $H^+ \rightarrow cs$
- Doubly charged Higgs boson H^{++}

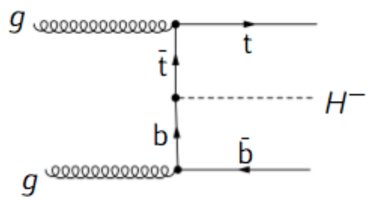
CHARGED HIGGS

Charged Higgs searches can also offer limits on 2HDM

$m_{H+} < m_{top}$

- Main H^+ **production** mode $t \rightarrow bH^+$
- **Decay** channels
  - $H^+ \rightarrow \tau^+\nu$: large tanβ
  - $H^+ \rightarrow cs$: tanβ < 1



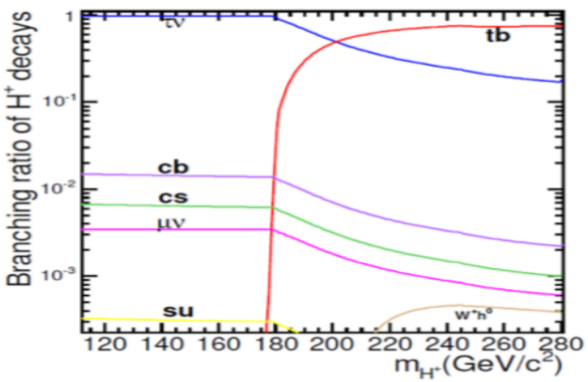


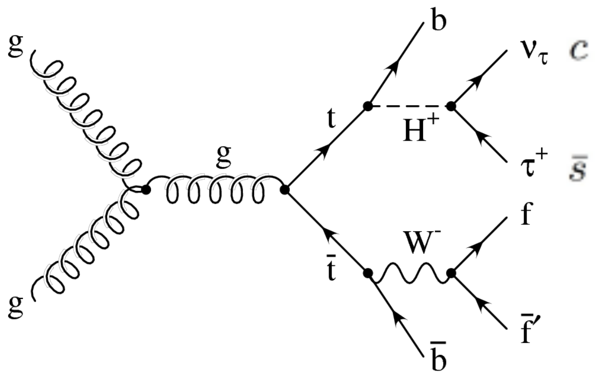
The cross section for **H⁺** production from single top quark events is much smaller than from tt

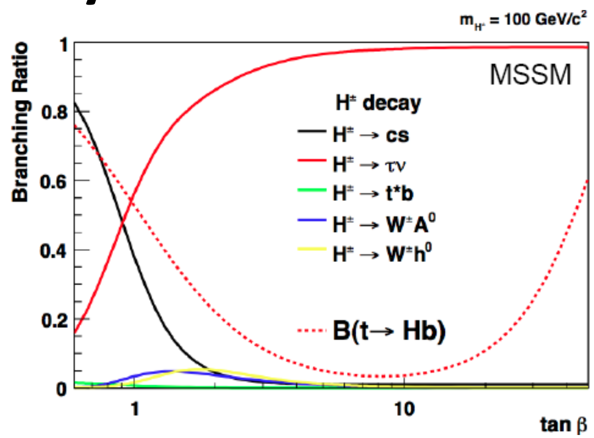
$m_{H+} > m_{top}$

- Main **production** mode gluon gluon tbH^+
- **Decay** channels
  - $H^+ \rightarrow tb$
  - $H^+ \rightarrow \tau^+\nu$

Charged Higgs in top quark decays







CHARGED HIGGS: $H^+ \rightarrow \tau\nu$ / c s

$H^+ \rightarrow \tau\nu$

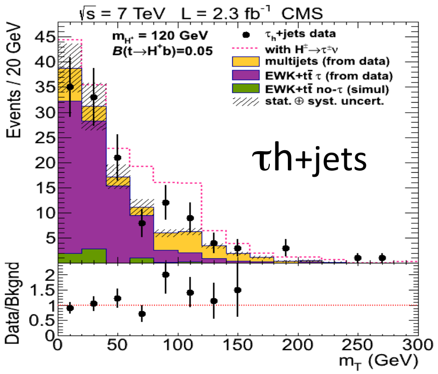
$B(H+ \rightarrow \tau\nu)$ = 100% assumed

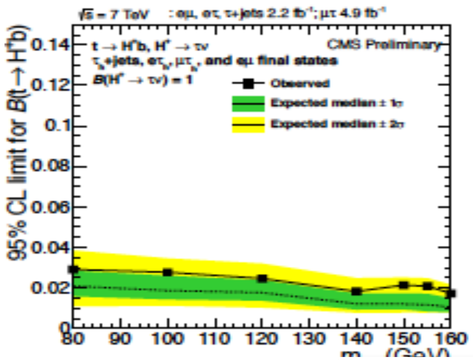
CMS-PAS-HIG-12-052

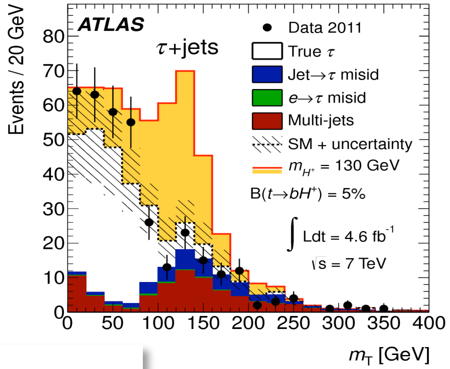
JHEP 1206 (2012) 039

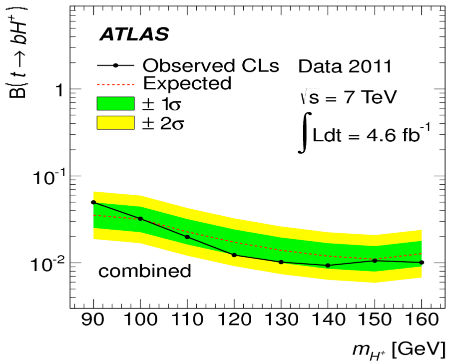
- **CMS**: 2.2-4.9 fb^{-1} @ 7 TeV
- 3 final states
  - Di-lepton ($\tau \rightarrow l\nu\nu$; $W \rightarrow l\nu$)
  - τh+lepton (τh + $W \rightarrow l\nu$)
  - Fully hadronic (τh+$W \rightarrow$jets)

- **ATLAS**: 4.6 fb^{-1} @ 7 TeV
- 3 final states
  - Semi-lepton ($\tau \rightarrow l\nu\nu$; $W \rightarrow$jets)
  - τh+lepton (τh + $W \rightarrow l\nu$)
  - Fully hadronic (τh+$W \rightarrow$jets)





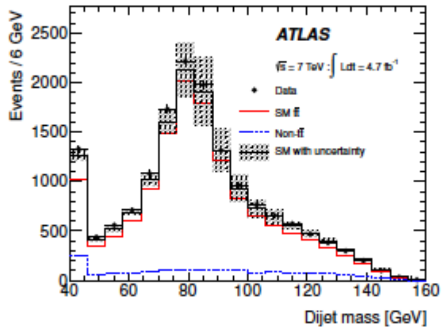


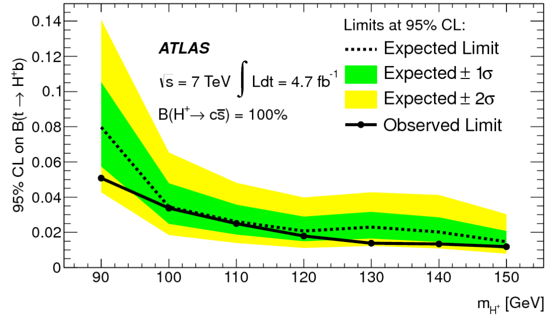


$H^+ \rightarrow$ c s

arXiv:1302.3694

- **ATLAS**: 4.7 fb^{-1} @ 7 TeV
- Selection
  - Single lepton trigger
  - At least 4 jets pT>25 GeV
- Limits
  - Final discriminat di-jet mass
  - Limits on BR($t \rightarrow H^+b$) = 1%-5% assuming BR ($H^+ \rightarrow cs$)=100%

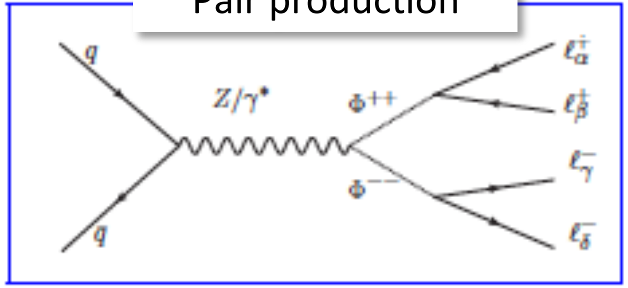




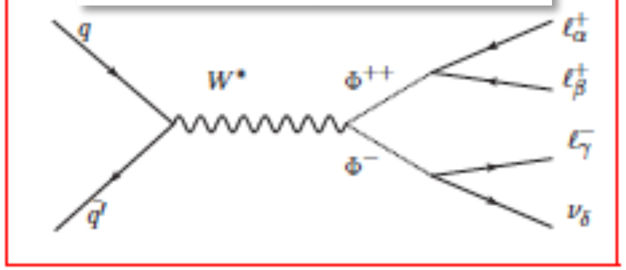
DOUBLY CHARGED HIGGS : $H^{\pm\pm}$

- Minimal See-Saw Type II
  - Higgs sector extended to a triplet: Φ, $\Phi^{\pm}$, $\Phi^{\pm\pm}$
  - Responsible for low neutrino masses
- Search for $\Phi^{\pm\pm}$ and $\Phi^{\pm}$ produced from W/Z
- 3 or 4 leptons in the final state
- $\Phi^{\pm\pm}$: narrow resonance
- Search for pairs of same sign leptons
- $\Phi^{\pm\pm}$ couples to left- or right-handed fermions

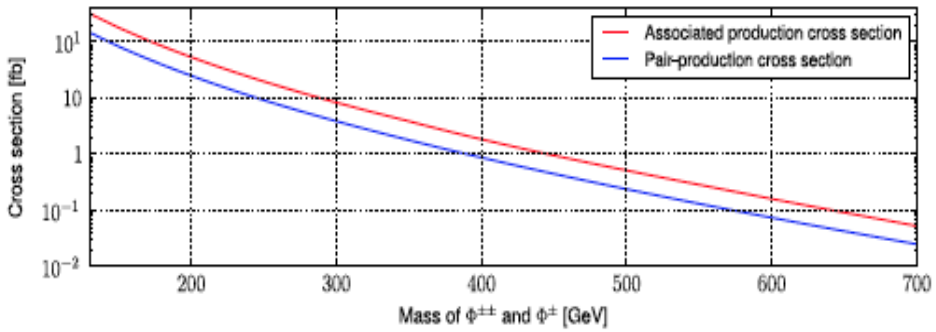
Pair production



Associate production



- Variety of models
  - Higgs Triplet
  - Little Higgs
  - Left-Right Symmetric Models



DOUBLY CHARGED HIGGS : $H^{\pm\pm}$

- **ATLAS**: 4.7 fb^{-1} @ 7 TeV
- Final states: $e^{\pm}, \mu^{\pm}$

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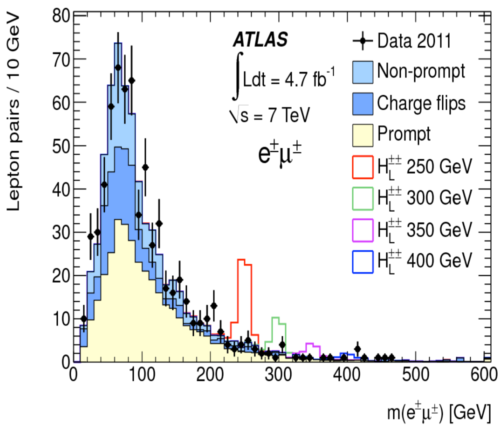
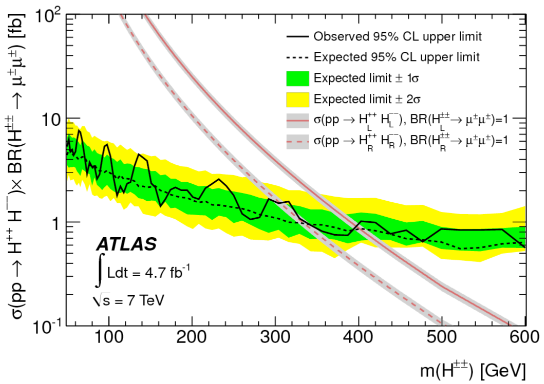
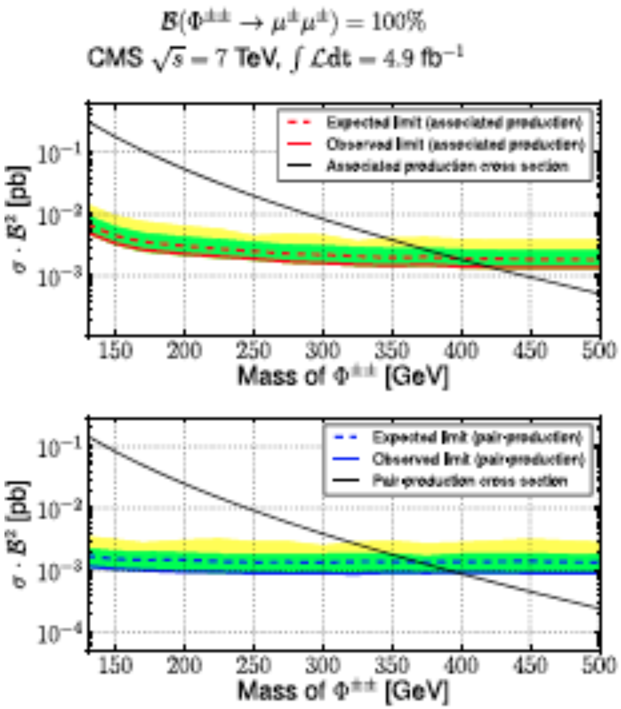




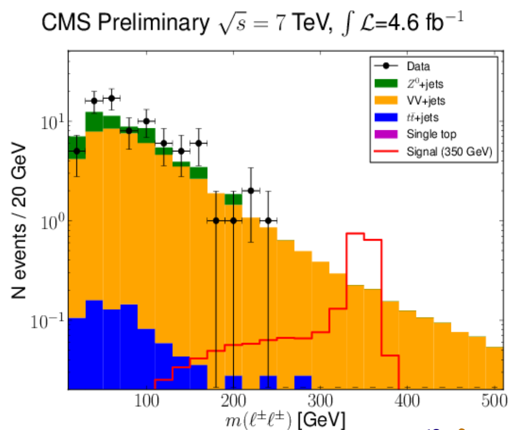
As we don't know ν mass matrix, we don't know BRs Search for BR(Φ++→l+l+)=100% (l=e,μ,τ)

Final State	pair prod.		combined
	ATLAS[1]	CMS	
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\%$	409	382	444
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\%$	409	391	453
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\%$	398	395	459
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\%$	-	293	373
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\%$	-	300	375
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\%$	-	169	204



- **CMS**: 4.9 fb^{-1} @ 7 TeV
- Final states: $e^{\pm}, \mu^{\pm} \tau^{\pm}$

CMS-PAS-HIG-12-005



FUTURE PLANS

FUTURE PLANS

Where theory drives both experiments...

... discussions and strategy plans ongoing within the

BSM LHC Cross Section Working Group *

a joint effort among **ATLAS**, **CMS** and *theory community* whose main goals are:

- Select/define **general benchmarks** for BSM searches
- Reinterpret SM searches/signatures in BSM scenarios

Plan for the future

- **Complete presented analysis with full available statistics**
- **Investigate more generic models for Heavier Higgs partner searches** :
  - neutral and charged,
  - Including H→hh decays
  - more final states for heavy Higgs
    - **EW-singlet mixed with SM-like Higgs**
    - 2HDM → (type II discussed yesterday by R.Contino)
- **Investigate further final states**

* https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSM

CONCLUSIONS

- The present
  - Several BSM Higgs bosons searches in ATLAS and CMS:
    - Neutral
    - Charged
  - No BSM/exotic Higgs observed
  - Set limits on the presented scenarios
- The Future
  - Finalize some of the presented analysis with the whole available statistic
  - Explore new final states driven by theory
  - Approach more generic benchmark models

BACKUP

OTHER CHANNELS

SM HIGGS + REAL SINGLET

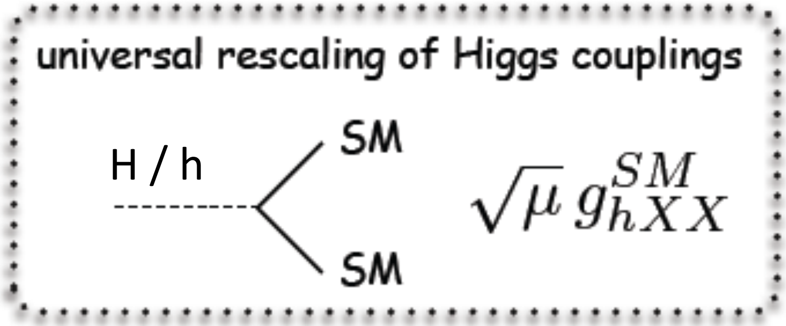
Two resonances with couplings rescaled wrt to SM

- h125 (h) coupling = C × SM
- Heavy Higgs (H) coupling= C' × SM

2 free parameters:
M_H and θ mixing angle

- **Unitarization**

  $C'^2 + C^2 = 1$, ie $C' = \cos\theta$, $C = \sin\theta$



- Heavy Higgs **width and cross-section directly rescaled with $\cos^2\theta$**
  - $\mu_H' = \cos^2\theta \times n_H^{SM}$
  - $\Gamma_H' = \cos^2\theta \times C_H^{SM}$

$$c_V = c_F = \sqrt{\mu} \qquad c_V^2 + c_V'^2 = 1$$

- **H coupling** constrained by the measured **h**

  Signal strength (July2012):
  - μ_{HATLAS} = **1.4±0.3**
  - μ_{HCMS} = **0.87±0.23**

Taking the uncertainty to be Gaussian, these correspond to a **2σ** lower bound on μ and hence an upper bound of C'^2 of

$\mu_{HATLAS} > 0.8 \rightarrow$ **$C'^2 < 0.2$**

$\mu_{HCMS} > 0.41 \rightarrow$ **$C'^2 < 0.59$**

SM HIGGS + REAL SINGLET (II)

What if H→h h decay (+ new unknown decays) ?

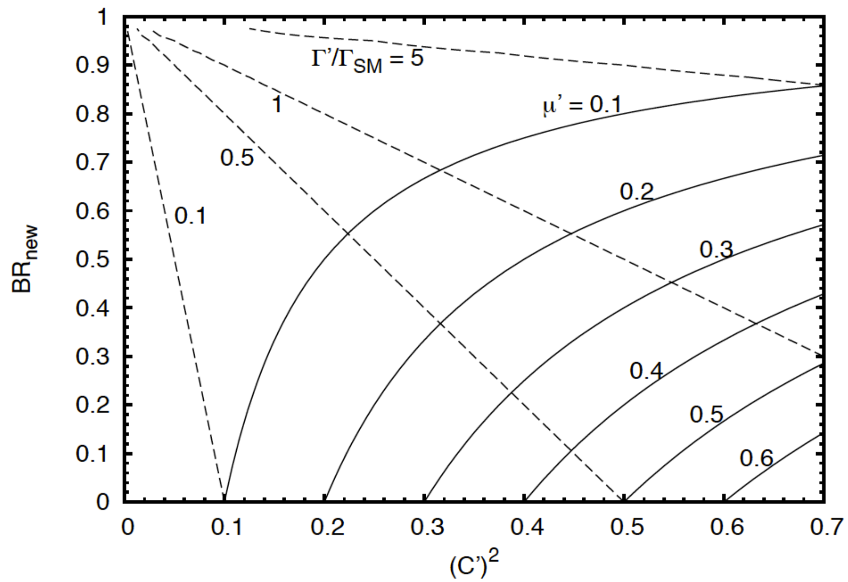
- Considering **H→ h h decay**
  (+ new unknown decays)

→1 additional free parameter (BR_{new})

3 free parameters:
M_H, θ mixing angle, BR_{new}

- Heavy Higgs search in **2 parameters space for each mH hypotesis**

$$\mu' = C'^2(1 - \mathrm{BR}_{new})$$
$$\Gamma'_{tot} = \frac{C'^2}{(1 - \mathrm{BR}_{new})}\Gamma_{\mathrm{SM}}.$$

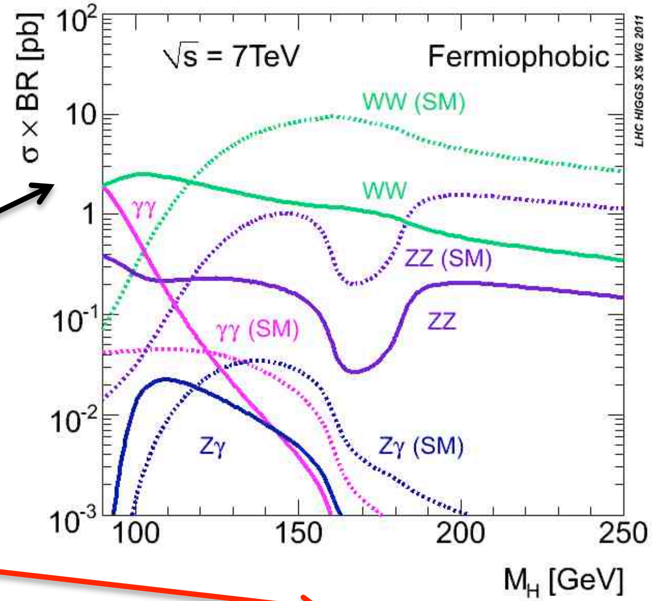


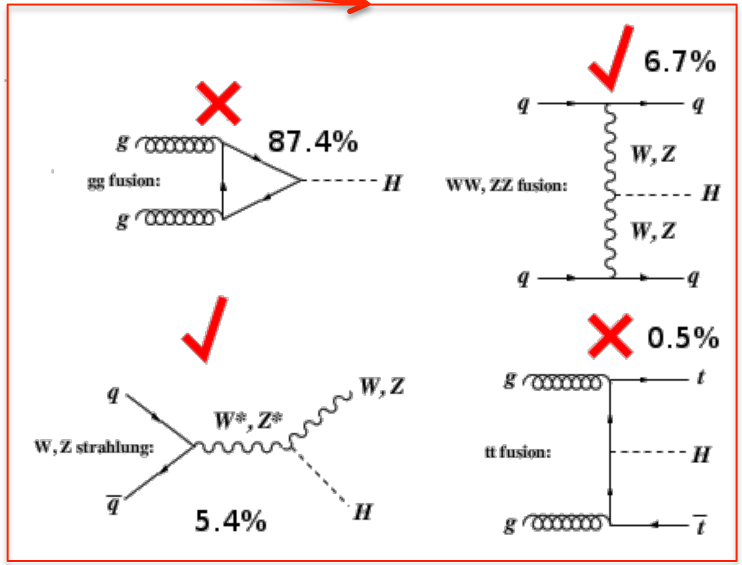
- Very narrow width possible

Direct heavy Higgs search can be reinterpreted in this BSM scenarios as limit on mixing angle and H mass

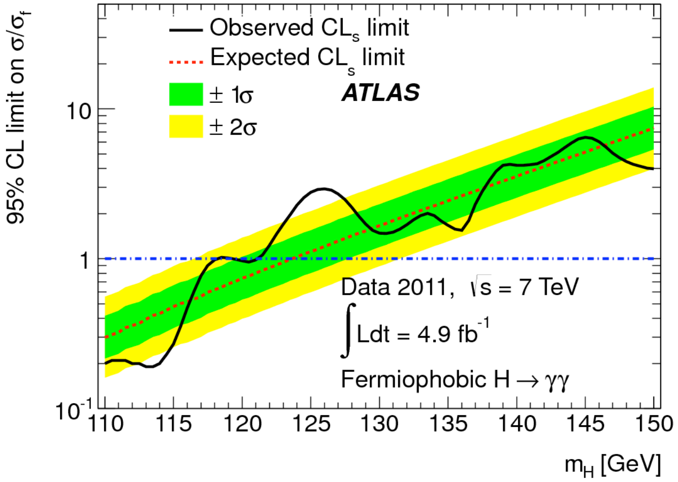
2HDM: FERMIOPHOBIC HIGGS

- Possible with extended Higgs sector (2HDM Type I)
- SM-like but no coupling to fermions
  - decay H → WW / ZZ , $\gamma\gamma$ only
    - $\gamma\gamma$ enanched (no negative interference between W and t loops)
  - Production only via VBF and VH
  - no gg → H nor ttH production
  - Total yield comparable to SM at 125 GeV
  - Higgs is boosted due to production mode
  - additional signatures due to associate production: di-jet, lepton, MET
- LEP excluded M_{Hfp} < 108.2 GeV





2HDM: Fermiophobic Higgs

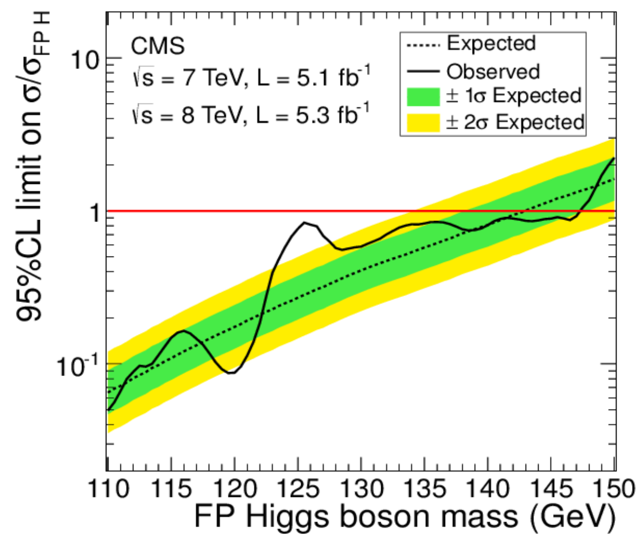


Eur. Phys. J. C (2012) 72:2157

- **ATLAS**: 4.9 fb^{-1} @ 7 TeV
- H→ γγ: SM-like selections
- Largest excess M_H=125.5 GeV 1.6 σ
- Exclusion for 110 ≤ M_{Hfp}≤118 GeV and 119.5 ≤ M_{Hfp}≤121 GeV @95% CL

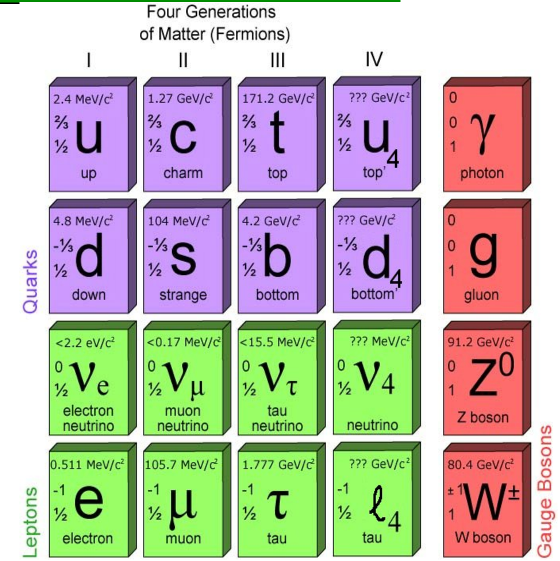
- **CMS**: 5.1 fb^{-1} @ 7 TeV + 5.3 fb^{-1} @ 8 TeV
- H→ WW/ZZ
- H→ γγ in association with
  - Di-jets
  - Isolated lepton
  - Boosted Higgs
- Excess at M_H=125 GeV is the SM Higgs → not compatible with FB Higgs
- Exclusion for 110 ≤ M_{Hfp}≤147 GeV @95% CL

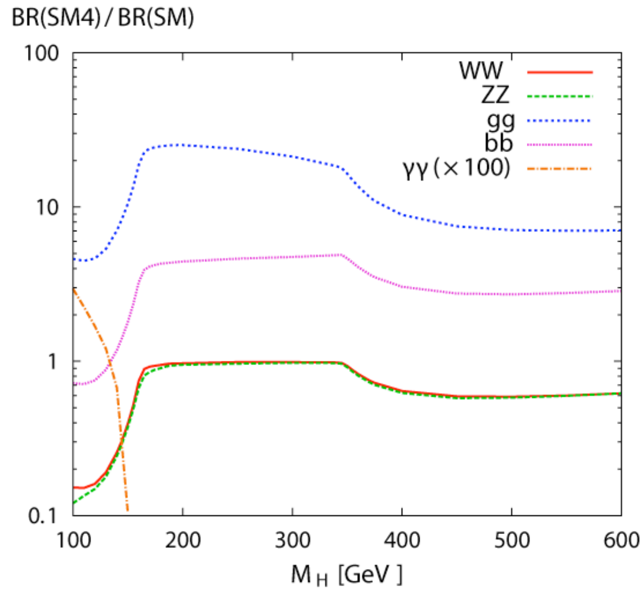
CMS-PAS-HIG-12-013



HIGGS IN STANDARD MODEL WITH 4TH GENERATION

- Standard Model with a fourth generation of fermions u_4, d_4, l_4,ν_4
- **4**th gen. masses not excluded by direct searches
- Large impact on production and decay rates
  - $\sigma(gg \rightarrow H)$ enhanced
  - VBF and VH negligible
  - BR(H→WW/ZZ) smaller
  - H→γγ suppressed
  - H→fermions larger
- Need re-interpretation of SM(3) results in the context of SM4

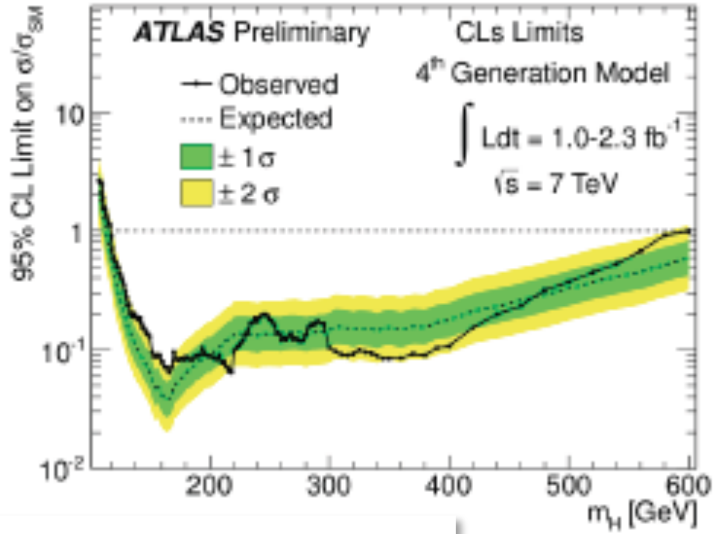




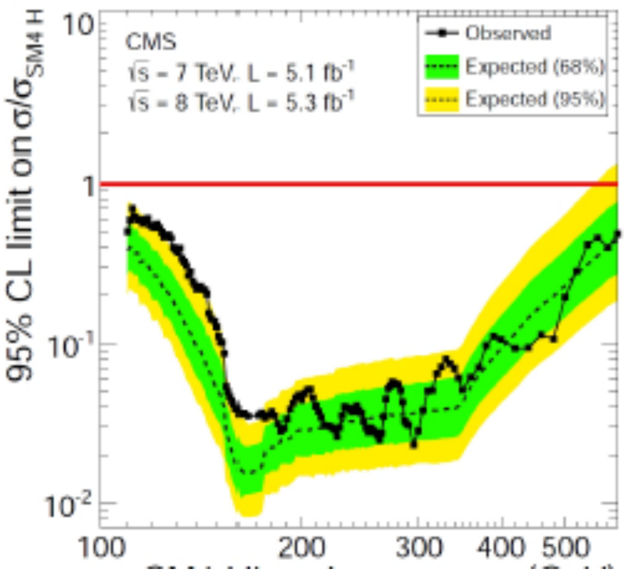
HIGGS IN STANDARD MODEL WITH 4TH GENERATION

- **ATLAS**: 1.0-2.3 fb^{-1} @ 7 TeV
- Channels:
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4l$ / $ll\nu\nu$ / $llqq$
  - $H \rightarrow WW \rightarrow l\nu l\nu$
  - $H \rightarrow \tau\tau \rightarrow l\tau_h\, 3\nu$ / $ll\, 4\nu$
  - $H \rightarrow bb$
- Exclusion: 95% CL 119 ≤ mH ≤593 GeV

ATLAS-CONF-2011-135



$\mathbf{m_{l4} = m_{\nu 4} = m_{d4}} = 600$ **GeV**
$\mathbf{m_{u4} - m_{d4}} = (50 + 10\ \ln(\mathbf{m_H}=115))$ **GeV**



- **CMS**: 5.1 fb^{-1} @ 7 TeV + 5.3 fb^{-1} @ 8 TeV
- Channels:
  - $H \rightarrow ZZ \rightarrow 4l$ / $ll\nu\nu$ / $llqq$
  - $H \rightarrow WW \rightarrow l\nu l\nu$
  - $H \rightarrow \tau\tau \rightarrow l\tau_h\, 3\nu$ / $\mu\mu\, 4\nu$ / $e\mu\, 4\nu$
- Exclusion: 99% CL 110 ≤ mH ≤600 GeV

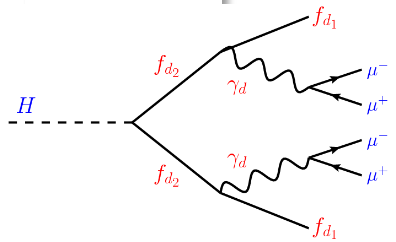
CMS-PAS-HIG-12-013

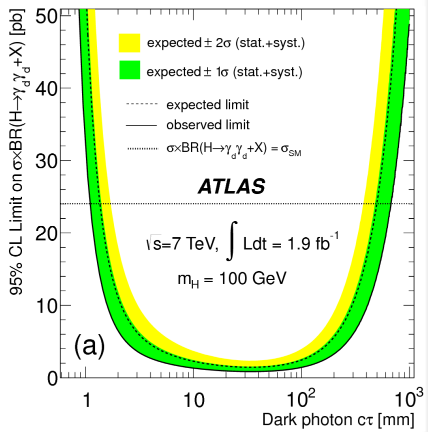
HIDDEN SECTOR

- **ATLAS**: 1.9-2.04 fb^{-1} @ 7 TeV
- Search for rare H decay into hidden-sector particles
- New particles assumed very light → decays are boosted → jet of muons/electrons with high impact parameters

- Assume
  - heavier γ_d: 400MeV, with cτ~(40mm)
  - $m(f_{d2})$=5GeV, $m(f_{d1})$=2GeV
  - $\gamma_d \to \mu\mu$: 45%
- Trigger with the muon spectrometer, large IP prevent the use of inner tracker
- 2 isolated muon jets, back-to-back (Δϕ>2)

MUONS

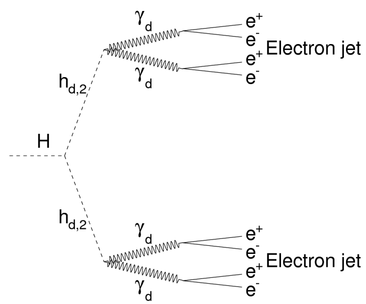


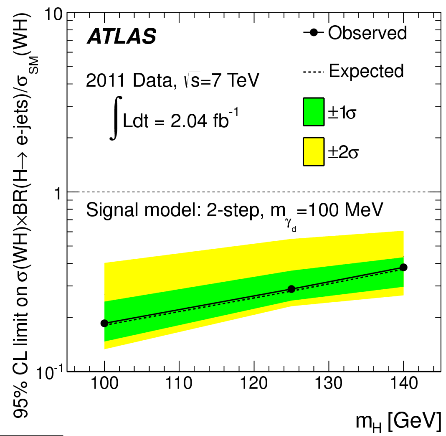


Phys. Lett. B 721 (2013) 32-50

- Search using the HW(→e/μ ν) production
- Single lepton trigger, one isolated lepton, MET>25GeV
- at least 2 electron-jets
- 3 step decay chain model also studied

ELECTRONS

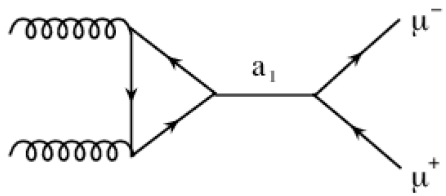


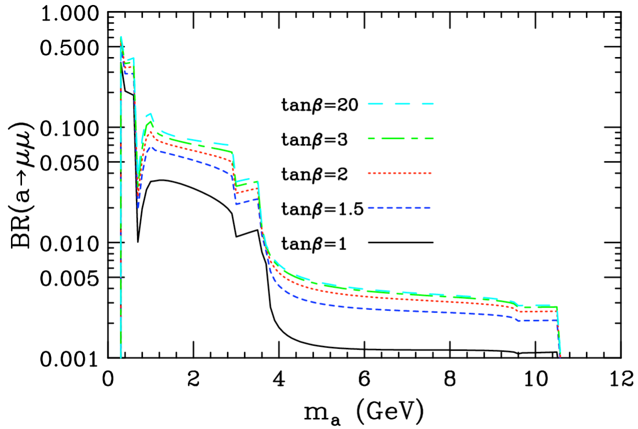


New J. Phys. 15 (2013) 043009

NMSSM: a $\rightarrow \mu\mu$

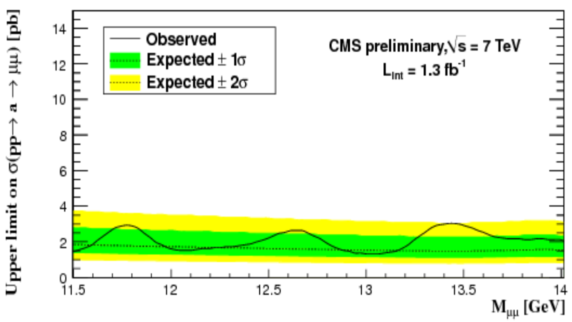
- Search below and above Υ resonances
- Substantial BR($a_1 \rightarrow \mu\mu$) for $2m_\mu < m_{a1} < 2m_\tau$
- Dedicated exclusive Trigger
  - 2μ, low pt, same vtx
  - selection in Mμμ

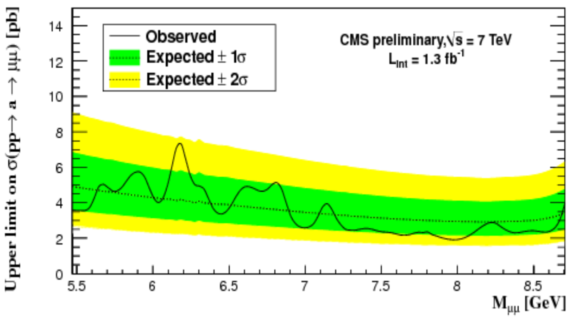


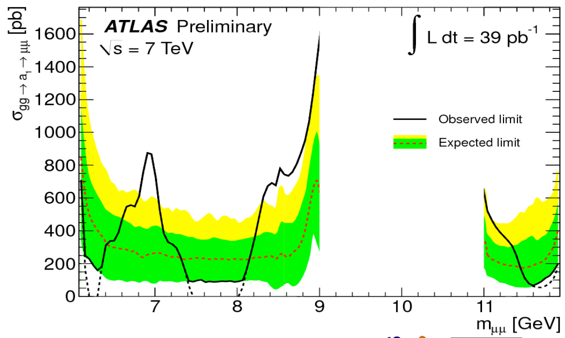


- **CMS** 1.3 fb^{-1} @ 7 TeV
- Selection: CMS-PAS-HIG-12-004
  - 2 isolated, prompt μ
- Limit:
  - Mμμ∈ [5.5 – 8.8] ∪ [11.5 – 14] GeV excluded

- **ATLAS** 39 pb^{-1} @ 7 TeV
- Selection: ATLAS-CONF-2011-020
  - 2 isolated μ coming from the same particle
  - likelihood-based discriminant

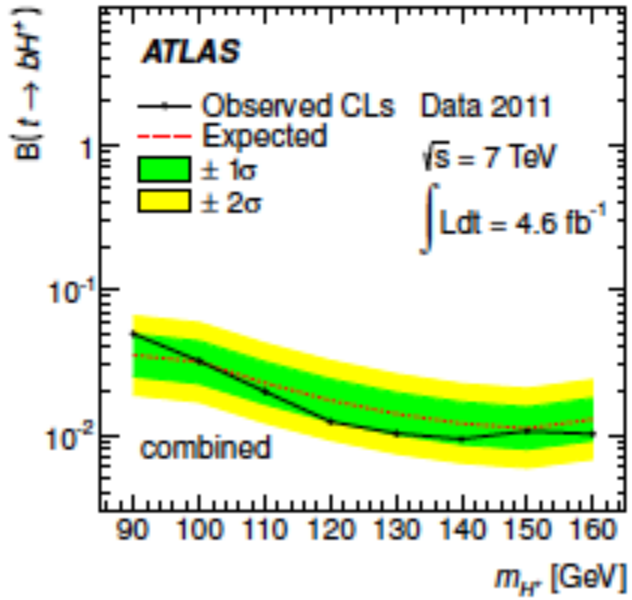




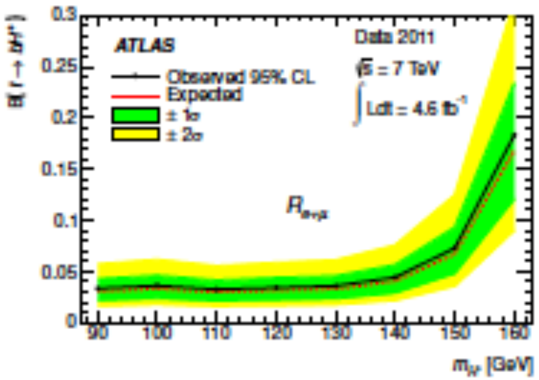


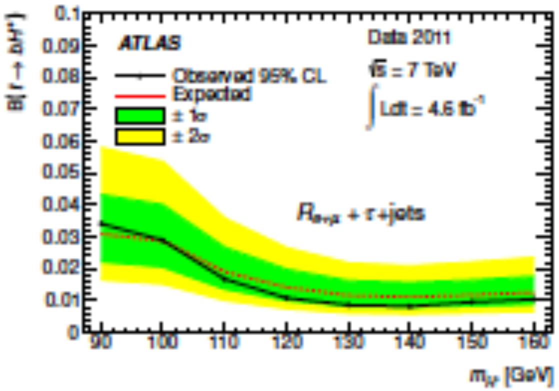
CHARGED HIGGS: $H^+ \to \tau\nu$

Search for **H+** $\to$ **$\tau\nu$** in **tt** $\to$ **bbWH+** $\to$ **bb(lν)($\tau\nu$)**



- **ATLAS**: 4.6 fb^{-1} @ 7 TeV
- Search through violation of lepton universality in **tt**
- **Method:**
  - **R_e = N(e+τ_{had})/ N(e+μ)** **$R_{e,SM}$** ~0.11
  - in **tt** decays with **H^+** - decays **R_{MSSM}** differs from **R_{SM}** due to enhanced **$H^+ \to \tau^+ \nu$** coupling
- **Limit**
  - event yield ratio **$R_{e+\mu}$** = **[N(e+τ_{had})+N(μ+τ_{had})]/ [N(e+μ)+N_{OR}(μ+e)**



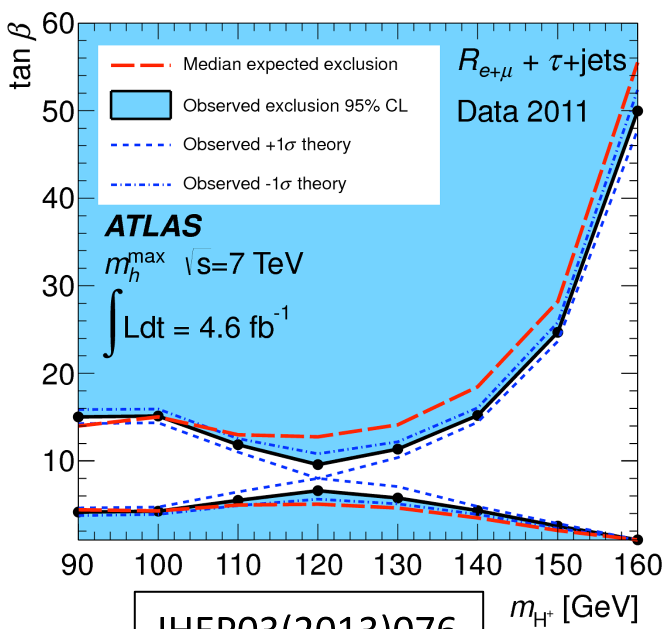


- combined limits from direct searches for **H^+** $\to \tau\nu$ (all channels)
- **$R_{e,\mu}$** limit derived with ratio-method
- combination of limits from **tt** $\to$ **bb (qq')(τ_{had} ν)** and ratio-method

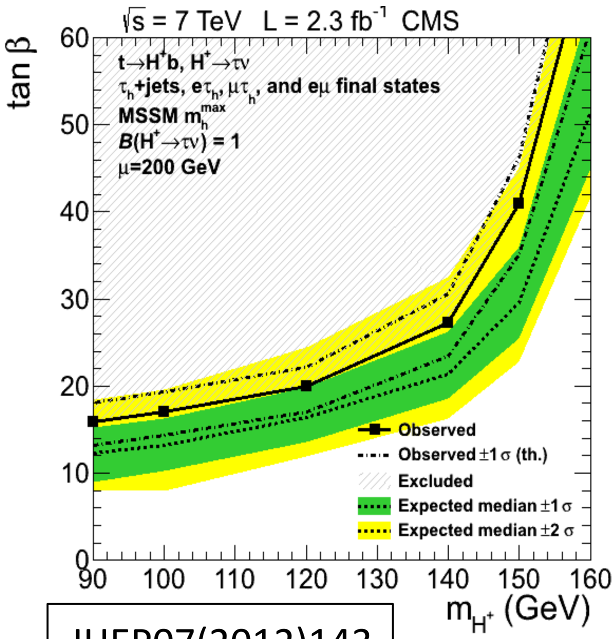
CHARGED HIGGS: $H^+ \to \tau\nu$ – m_h^{max}

m_h^{max} -scenario: [hep-ph/9912223]

- parameters chosen such that maximum possible Higgs-boson mass $\mathbf{m_h}$ is obtained



JHEP03(2013)076



JHEP07(2012)143

- **M**SUSY = 1 TeV; the common soft-SUSY-breaking squark mass of the third generation
- **X**t = 2**M**SUSY ;
  Xt = **A**t -μ **=** tanβ is the stop mixing parameter
- μ = 200 GeV;
  the Higgsino mass parameter
- **M~**g = 800 GeV;
  the gluino mass
- **M2** = 200 GeV;
  the SU(2)-gaugino mass
- **A**b = **A**t;
  At and **A**b are the stop and sbottom trilinear couplings
- The value of $\mathbf{M_1}$ is xed via the unication relation $\mathbf{M_1}$ = (5/3)$\mathbf{M_2}$ $\sin\theta_W$= $\cos\theta_W$

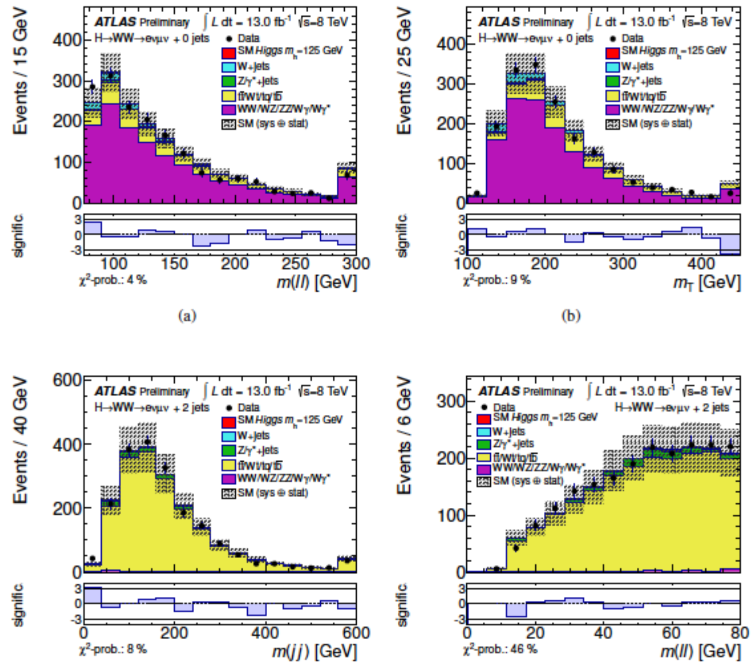
- Large regions of parameter space excluded
- unexcluded regions still compatible with 126 GeV SM-like Higgs boson

2HDM: H→WW→eνμν NEW@Moriond

Variables used in the 0-jet channel and the 2-jet channel	
$\lvert\eta(\ell_1)\rvert$	The absolute value of the pseudorapidity of the leading lepton.
m_T	The transverse mass of the lepton-E_T^{miss} system, as defined in Equation 2.
$m(\ell_1\ell_2)$	The invariant mass of the dilepton system.

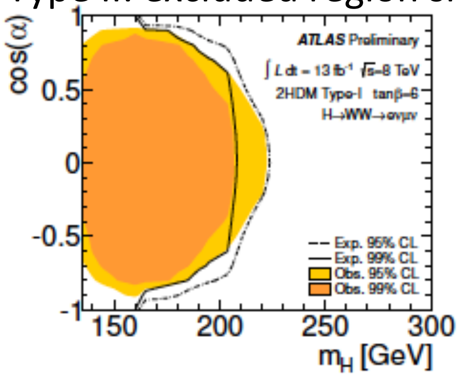
Variables used in the 0-jet channel only	
$p_T(\ell_1\ell_2)$	The transverse momentum of the dilepton system.
$E_{T,rel}^{miss}$	The projection of the calorimeter-based missing transverse momentum.
$\lvert\Delta Y(\ell_1\ell_2)\rvert$	The absolute value of the rapidity differences of the two charged leptons.

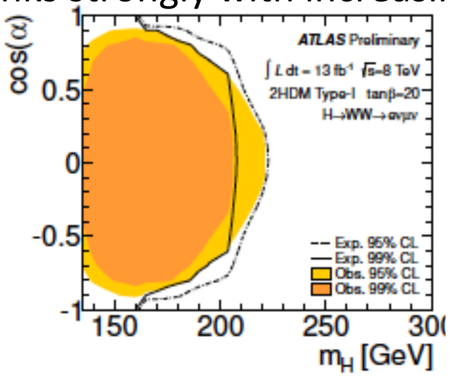
Variables used in the 2-jet channel only	
$p_T(\ell_2)$	The transverse momentum of the second-leading lepton.
$p_T(j_1)$	The transverse momentum of the leading jet.
$m(j_1)$	The mass of the leading jet.
$\cos\theta(\ell_1,\ell_2)$	The cosine of the angle between the two charged leptons.
$m(j_1 j_2)$	The invariant mass of the dijet system.
p_T^{tot}	The total transverse momentum, defined as the magnitude of the vector sum of the transverse momenta of the two jets, the two leptons and the missing transverse momentum: $p_T^{tot} = \lvert\mathbf{p}_T^{tot}\rvert = \lvert\mathbf{p}_T^{\ell 1} + \mathbf{p}_T^{\ell 2} + \mathbf{p}_T^{j1} + \mathbf{p}_T^{j2} + \mathbf{p}_T^{miss}\rvert$.

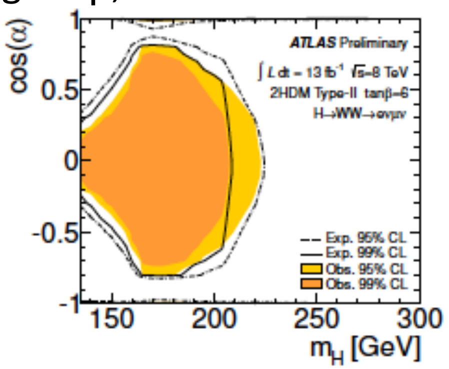


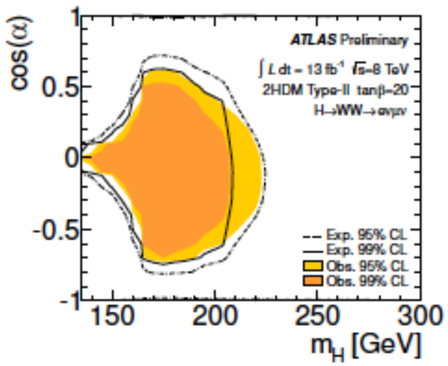
(a) (b) (c) (d)

Type II: excluded region shrinks strongly with increasing tanβ, since the BR to the WW final state decreases

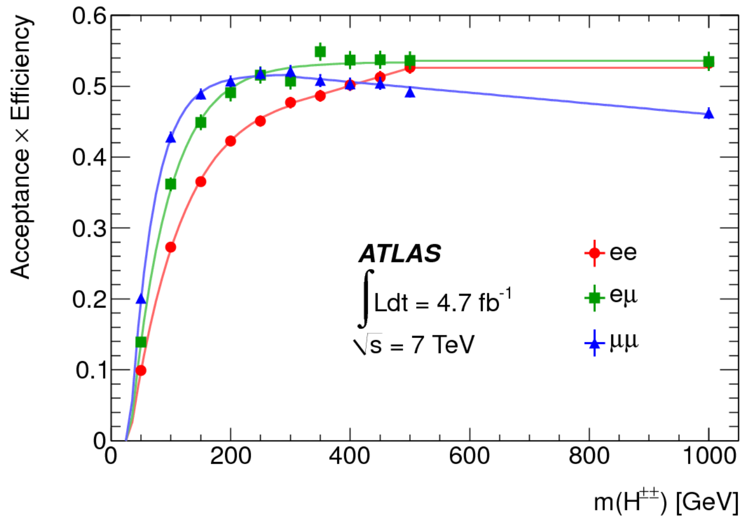








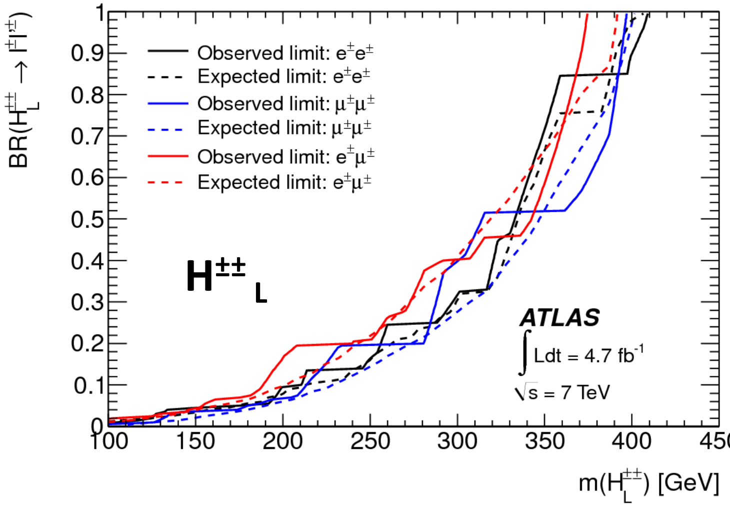
Doubly charged Higgs boson

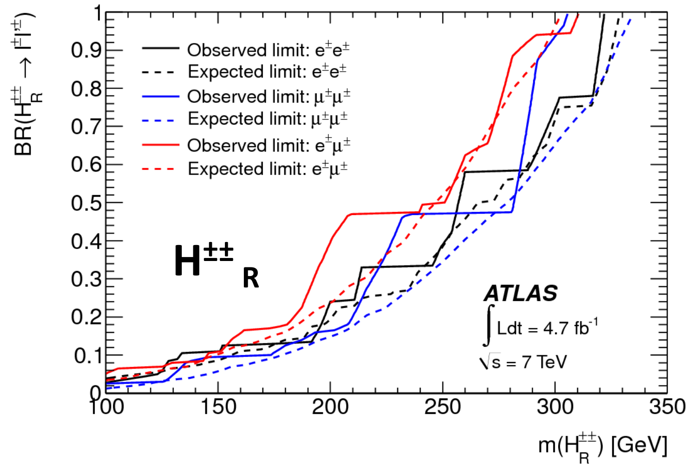


Dominant uncertainties:

- ±12% for WZ/ZZ cross-sections
- ±40% for non-prompt and charge flips
- Limited by the statistics at high mass

Limits depend on if the $H^{\pm\pm}$ couples to left- or right-handed fermions





BSM HIGH MASS REGION –MOTIVATION-

We want to determine if the ~125 GeV Higgs-like particle (h) is fully responsible for the generation of the masses of the other SM particles

- Does h fully unitarizes the high-energy scattering amplitudes for $V_L V_L \to V_L V_L$ (V=W,Z) and $V_L V_L \to f\bar{f}$?
- **If h is NOT fully responsible for the unitarization of the scattering amplitudes, then additional new physics must be present to play this role**
- There are **BSM 'SM-like' models** in which a **second heavier scalar particle (H)** completes the unitarization of scattering amplitudes

BSM HIGH MASS REGION –STRATEGY-

Is a completely model independent analysis possible?

→ **NOT enough data yet to have a model independent conclusion**

Even with a few reasonable assumptions

- spin-0 + CP-even
- custodial W/Z symmetry
- No FCNC

still the parameter space is large

Relations imposed by unitarity

$V_L V_L \to V_L V_L$	$c_V^2 + c_V'^2 = 1$
$V_L V_L \to f\bar{f}$	$c_V c_F + c_V' c_F' = 1$

→**need to consider benchmark models** that…

- **… are consistent with ~125 GeV observation**
- … contain an heavy Higgs-like state
- … compatible with EW precision data:
  - h VV couplings to be less than 15-20% deviated from the SM

Two proposed benchmarks:

1. **SM Higgs + Real Singlet**
2. **2HDM (Type I and Type II)**

FIRST STUDIES: SM+REAL SINGLET

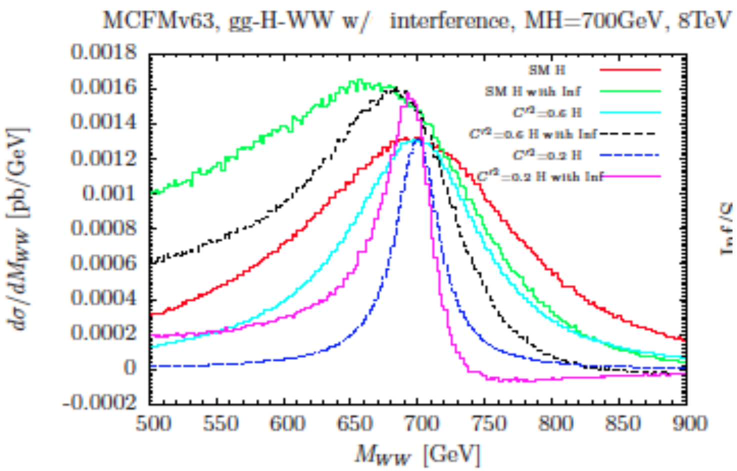
- Goal: reweight the heavy Higgs lineshape width by some factor $\Gamma' = (C'^2/(1-BR_{new}))*\Gamma_{SM}$
- How to devise a reasonable reweighting scheme

Presented by **CMS** at the BSM LHCXSWG

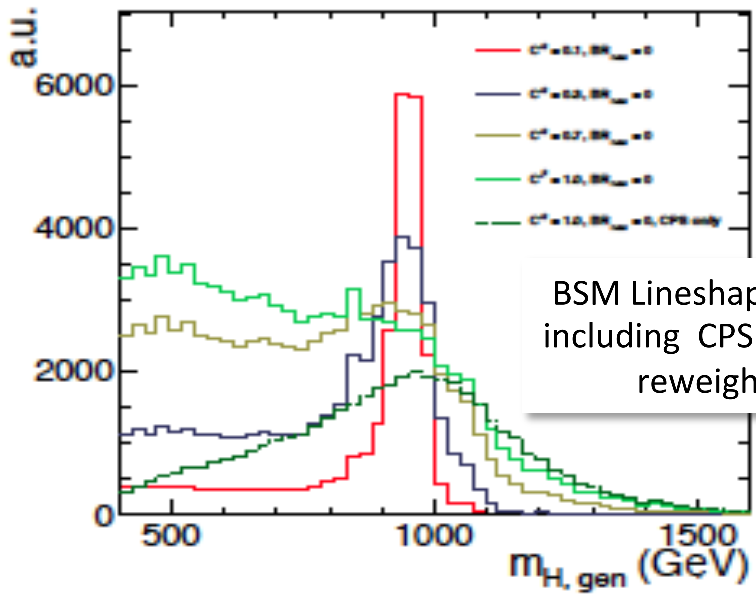
- ○ Re-weighting the CPS lineshape:

  Ad-hoc scaling proposed by fitting the CPS lineshape to a BW (fixed width) and scaling the fitted width by the BSM factor $(C'^2/(1-BR_{new}))$

- ○ Scaling interference effects to the BSM case



Distributions of mass with and without interference for different values of C'



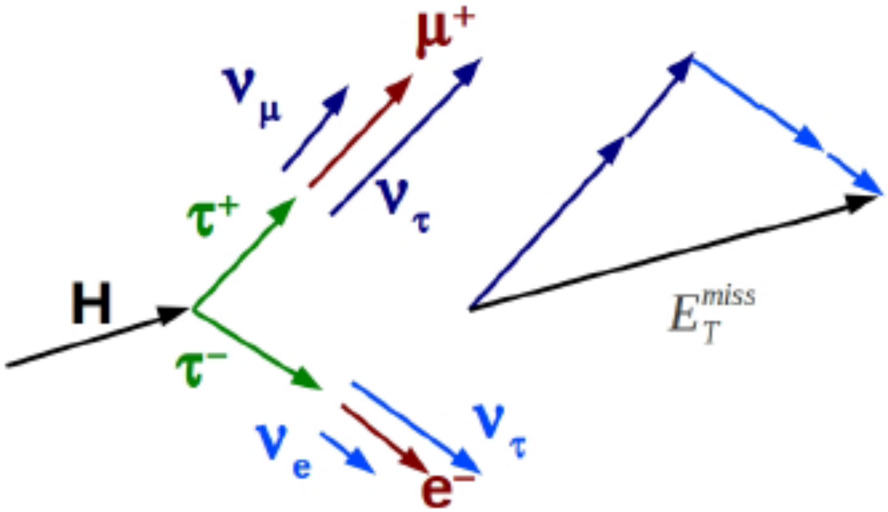
2HDM APPROACH

- Particular focus on the "low mass" region (neutral Higgs < 400 GeV)
- The 2HDM parameter space is large
  - Free parameters: **mh, mH, mH+, mA, tanβ, α** (or m_{12} and potential parameters $\lambda_1,\ldots,\lambda_5$) for the CP-conserving 2HDM
  - Different possible scan: cos(β - α) , tanβ and 3 self-coupling combinations λ , λ_A and λ_F (mh is fixed to 125, so 5 parameters remain)
  - Some simplifications have to be done (e.g. mh=125 GeV, some parameters neglected for specific searches, etc)
- Tools:
  - For the experimental search we need (σ X BR)(m_h,m_H,m_{H+},m_A, α, β, m_{12}, …)
  - **BR and width**
    - 2HDMC calculates all 2HDM BR and width for any parameter (yukawa type, mass or potential term) at tree level
    - HDECAY/EDECAY: can calculate BR and width taking into account higher order corrections; in the latest version we have to include the couplings by hand in order to get the 2HDM
  - **Production cross sections**
    - SusHi : can calculate ggh and bbh production
    - VBF/VH: one can get adequate estimates by running VBF@NNLO and VH@NNLO and NLO and apply the 2HDM ouplings to the Higgs to these cross sections
    - Charged Higgs? There is a calculation by M. Dittmaier et al for MSSM; can it be modified to implement 2HDM?

ANALYSIS CUTS

$M_{\tau\tau}$ MASS DISTRIBUTION

Fully leptonic H→ττ decay



- Invariant mass not fully constrained by reconstructed objects
  - $M_{\mu e}$ would underestimate m_H
  - Undetected neutrinos → E^T_{miss}

ATLAS

Missing Mass Calculator (MMC)

Scans neutrino direction and keep Most probable value for mass reconstruction

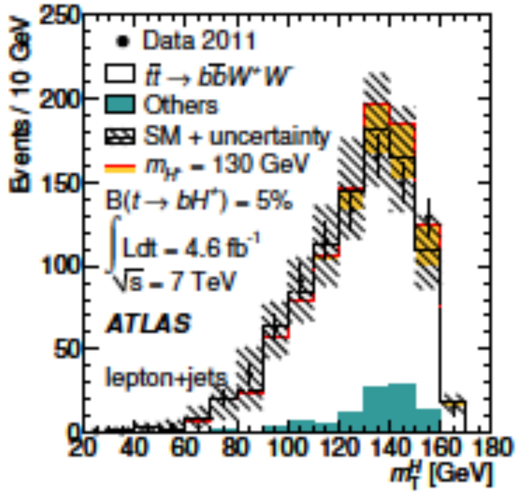
CMS

Maximum Likelihood Mass

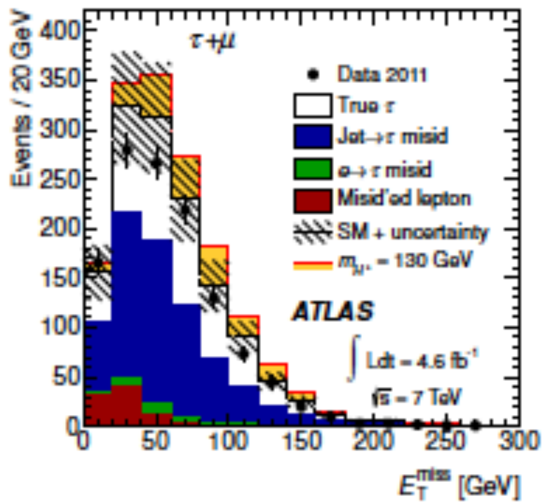
Likelihood for free parameters maximized wrt kinematic constraints

ATLAS $H^+ \rightarrow \tau\nu$

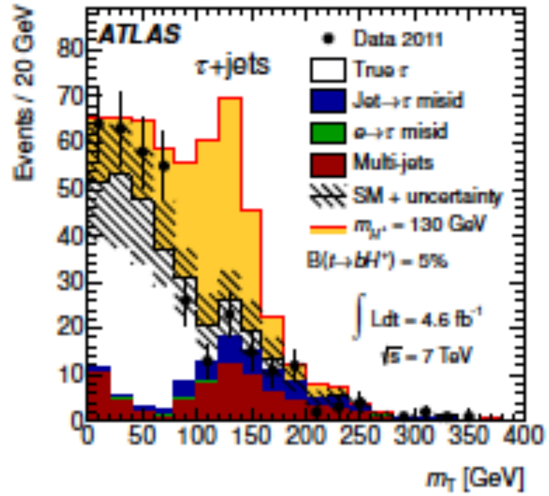
$t\bar{t} \rightarrow b\bar{b}(qq')(\tau_{lep}\nu)$



$t\bar{t} \rightarrow b\bar{b}(\tau_{lep}\nu)(\tau_{had}\nu)$



$t\bar{t} \rightarrow b\bar{b}(q\bar{q}')(\tau_{had}\nu)$



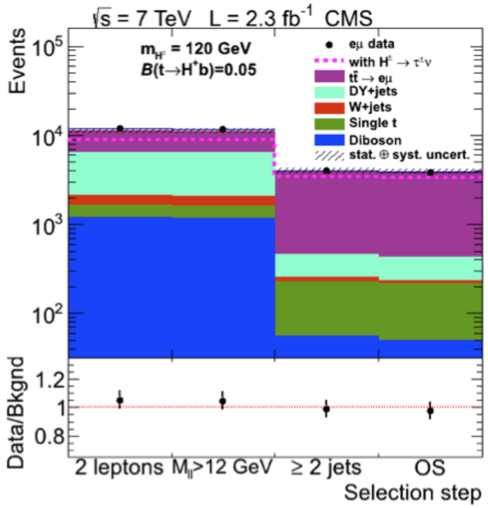
- Single μ or e trigger
- P^t_e> 25 or P^t_μ> 20 GeV
- 2 b-tagged jets
- E^t_{miss}> 40 GeV
- Top pair kinematics
- Fake leptons bkg estimated in loose control samples

- Single μ or e trigger
- P^t_e> 25 or P^t_μ> 20 GeV
- Tau: P^t_τ> 20 GeV
- ≥1 b-tagged jets
- tau lepton fake from e and jets estimated from data

- τ + E^t_{miss} trigger
- ≥4 jets, ≥1 b-tagged
- Tau: P^t_τ> 40 GeV
- E^t_{miss}> 65 GeV
- Top pair kinematics
- Multi jet bkg estimated from E^t_{miss} template fit

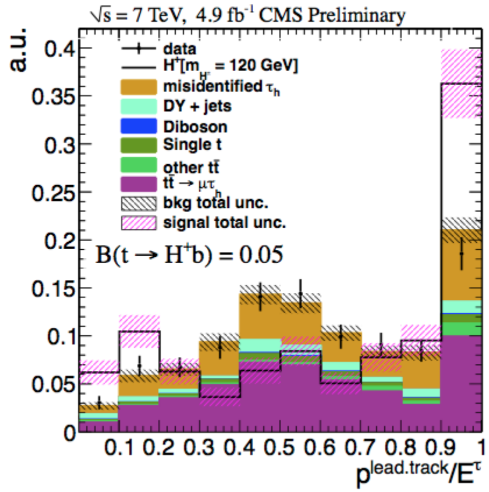
CMS: $H^+ \rightarrow \tau\nu$

Di-leptons ($e\mu$)



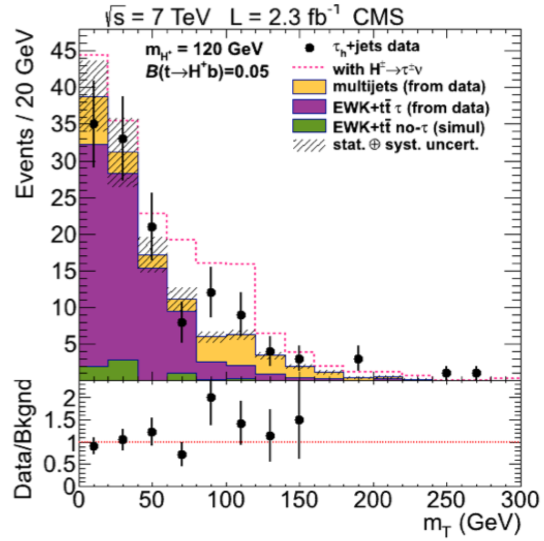
- $e\mu$ trigger
- P^t> 20 GeV
- ≥2 jets, P^t_{jet}> 30 GeV
- Main bkg: tt

τ + leptons



- Single μ (or e) trigger
- One isolated e/μ
- ≥2 jets, P^t_{jet}> 35(30) GeV, ≥1 b-tagged
- E^t_{miss}> 45(40) GeV
- 1 Tau: P^t_{τ}> 20 GeV
- OS τ-lepton

τ + jets



- τ + E^t_{miss} trigger
- ≥3 jets, P^t_{jet}> 30 GeV, ≥1 b-tagged
- 1 Tau: P^t_{τ}> 40 GeV
- E^t_{miss}> 50 GeV
- $\Delta\phi(\tau + E^t_{miss})$ <160
- Reconstruct $M_T(\tau + E^t_{miss})$

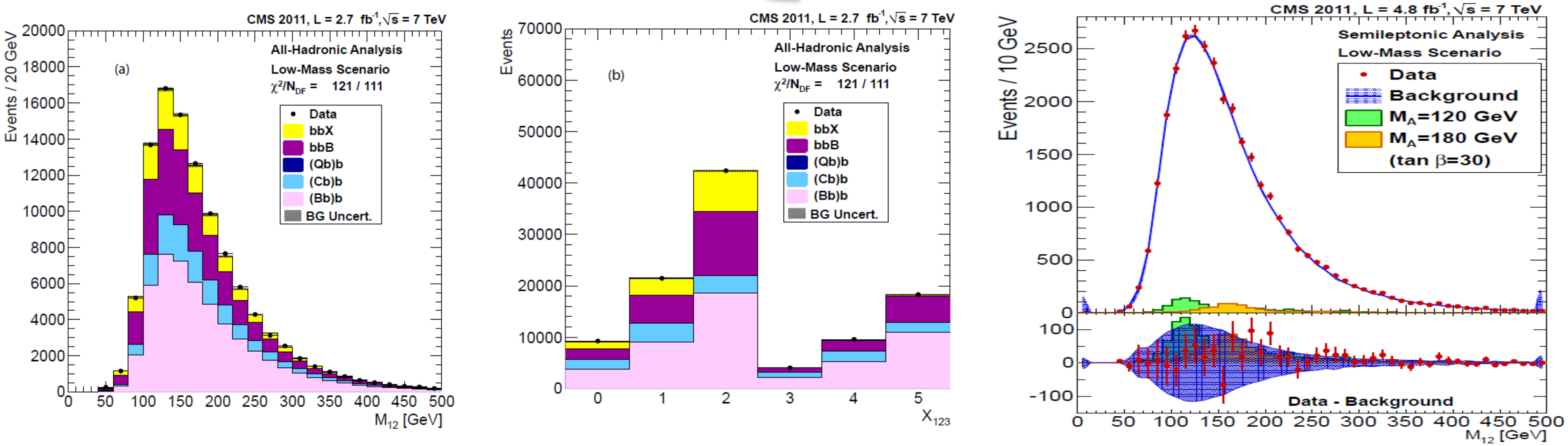
MSSM: bb A/H/h→ bb

- **CMS** 2.7- 4.8 fb^{-1} @ 7 TeV
- Search for H->bb produced in association with b-quarks
- Two approaches:
  - **All-hadronic**
  - **Semi-leptonic**
- Two dedicated triggers path, small overlap

All-hadronic:
- Use di-b-jets mass and Event-BTag, a
- dedicated variable that combines the
- b-tag info of the 3 jets
- Get 2D data-driven templates
- Fit 2D templates to observed data.

Semi-leptonic:
- Use di-b-jets mass
- Two data driven QCD background estimates
  - from single and double b-tag samples

CMS-PAS-HIG-12-033



FUTURE PLANS

Upgrade issues

- Trigger object definitions
  - H^+ physics relies on τ+MET triggers currently → these challenge the trigger bandwidth
- Level-1 Topological
  - What can be gained by having access to η, ϕ, and E_T at Level-1 for τ, jet, bjet topologies?
  - Study topological triggers to avoid the threshold creep