Searches for h, H, A and $H^{\pm}$ bosons in MSSM and 2HDM in ATLAS and CMS

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EPS-HEP 2015
Universität Wien, Austria – 24/07/15

The Two-Higgs Doublet Model (2HDM)

- The 2HDM is an effective extension of the SM adding a complex scalar Higgs doublet

→ 5 physical Higgs bosons
  - 3 neutral → Φ = h (light scalar), H (heavy scalar), A (pseudoscalar)
  - 2 charged → H^+, H^-

→ 14 parameters including: m_h, m_H, m_A, $m_{H\pm}$, α = mixing between h and H, $\tan\beta = vev_u/vev_d$

- There are 4 types of 2HDM, depending on how the 2 Higgs doublet fields couple to SM particles

- Couplings of Higgs bosons also modified w.r.t. SM

Coupling scale factor	2HDM Type II
κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_{lepton}	$-\sin(\alpha)/\cos(\beta)$

→ MSSM: 2HDM type II with a SUSY sector

The Higgs sector in MSSM

- **At tree level, the MSSM is controlled by two parameters: m_A (or $m_{H\pm}$) and $\tan\beta$**

→ **Other assumptions (such as the higgsino mass parameters, the stop mass, stop mixing etc.) can be used to define MSSM benchmark scenarios**

→ **Generally, results are interpreted in the m_h^{max} and more recent m_h^{mod} scenarios** *[M. Carena et al., Eur.Phys.J. C73 (2013) 2552]*

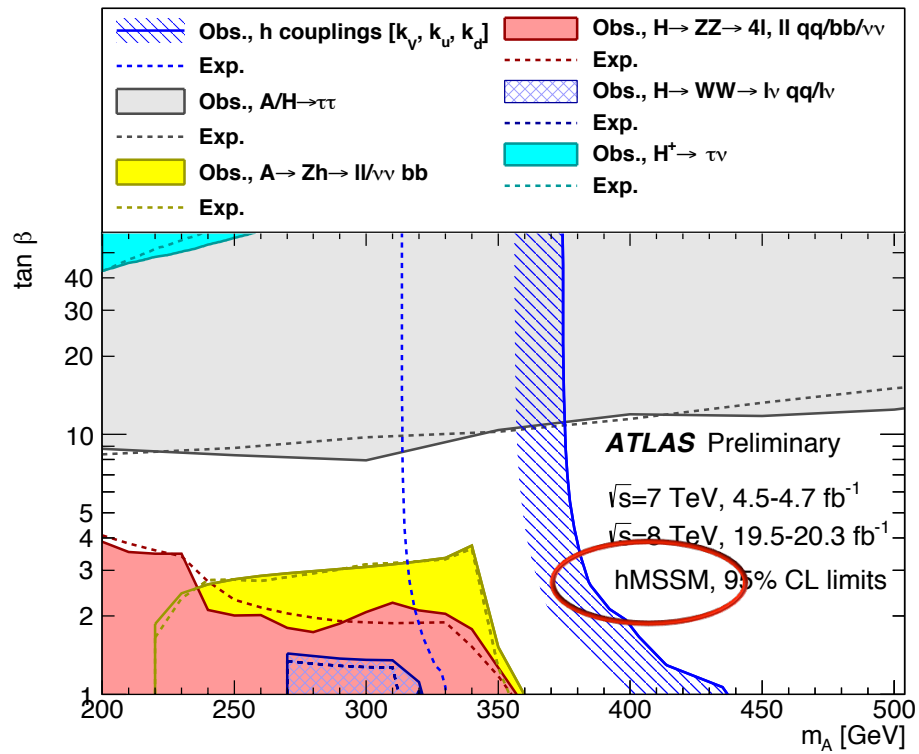
Constraints from the LHC experiments

- **Low mass region (m_A<150 GeV) excluded by $H^{\pm}\rightarrow\tau\nu$ and $\Phi\rightarrow\tau\tau$ searches**
- **Intermediate mass range allowed in tanβ 'wedge'**
- **High mass range (m_A>300 GeV) progressively covered at medium-high tanβ (mainly $\Phi\rightarrow\tau\tau$,bb) and low tanβ values (mainly di-boson final states)**

NEW RESULT!
Paper in preparation

→ **Light Higgs couplings approaching (quasi-)decoupling regime**

→ **Today, we present searches for charged Higgs and neutral Higgs bosons + new CMS Run I legacy results of $\Phi\rightarrow\tau\tau$ and $\Phi\rightarrow$bb searches**



Searches for heavy Higgses

- **During LHC Run I, the ATLAS and CMS Collaborations have been looking for additional Higgs bosons compatible with MSSM, and more generally, the 2HDM**

- **On top of m_h ~ 125 GeV, direct searches of heavy Higgses are amongst the ones putting the most stringent constraints on the MSSM phase-space**

- **<u>Two fronts are open at ATLAS and CMS</u>**

  - **Direct searches of heavy charged Higgs boson ($H^{\pm}$)**
  - → This talk reports searches in the $H^{\pm}\rightarrow\tau\nu$, cs and t(b)($H^{\pm}\rightarrow$tb) channels

  - **Direct searches of heavy neutral Higgs bosons (Φ = h, H, A)**
  - → Decays $\Phi\rightarrow$bb, $\Phi\rightarrow\tau\tau$ are covered here

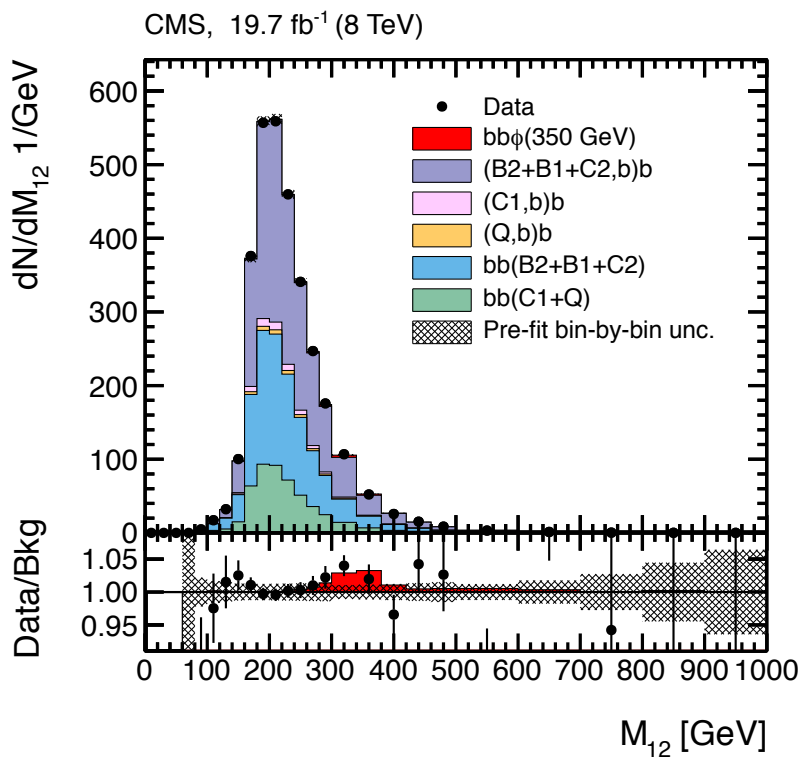
  - ***<u>Also presented at EPS-HEP 2015</u>***
  - → Searches for "cascade" decays of heavy Higgs bosons (H->hh, H->hA, A->Zh, H->ZA) at CMS – **Rebecca Lane**
  - → Searches for heavy Higgs-like resonances in di-boson decays at ATLAS and CMS – **Francesco Lo Sterzo**
  - → Search for low mass Higgs-boson like resonances at CMS – **Abdollah Mohammadi**
  - → Search for Higgs bosons beyond the Standard Model in b-quark final states at CMS – **Rainer Mankel**
  - → Constraints on new phenomena through Higgs coupling measurements with the ATLAS detector – **German Carrillo**

Φ→bb results from CMS

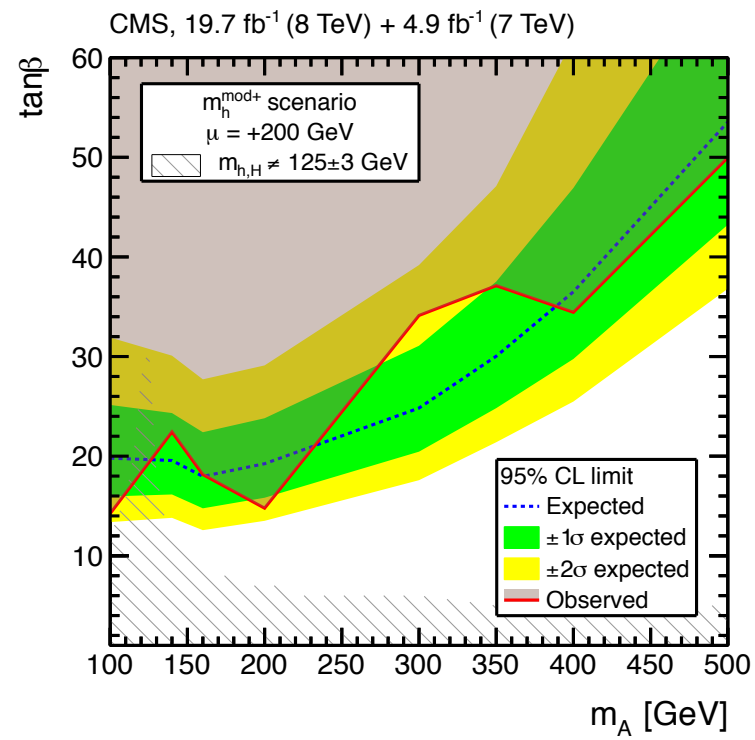
New!
arXiv:1506.08329 [hep-ex]
Submitted to JHEP

- **Already presented in Rainer Mankel's talk**
- **Couplings to down-type quarks enhanced at large tanβ → this channel is mainly sensitive at high tanβ values**
- **Signature: bΦ+X→bbb+X**

- **M_{bb} invariant mass**

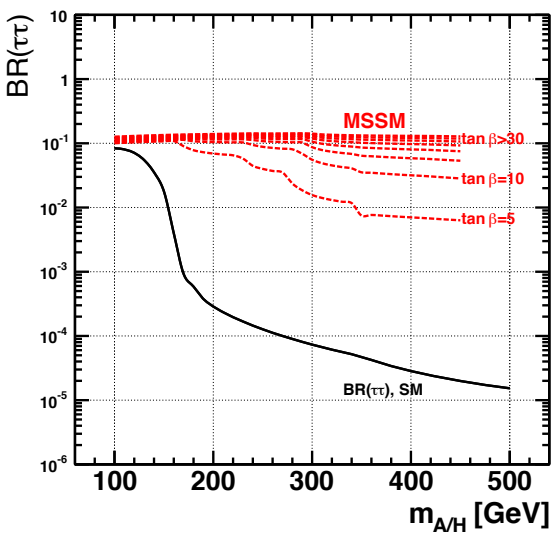


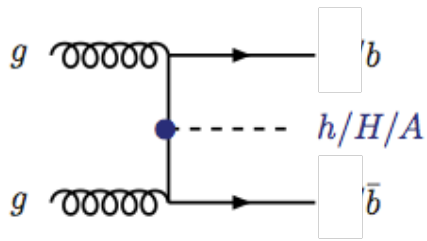
- **Limits in MSSM M_h^{mod+}**



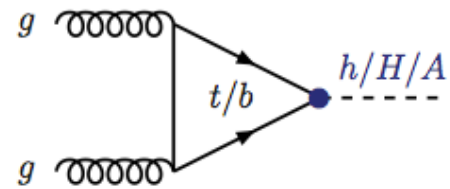
Searches for $\Phi(h,H,A) \rightarrow \tau^+\tau^-$

- ***BR($\Phi \rightarrow \tau\tau$) ~ 10^{-1}***
- ***Lower than BR(H→bb), but better S/B***





≥1 b-tagged jet



No b-tagged jet

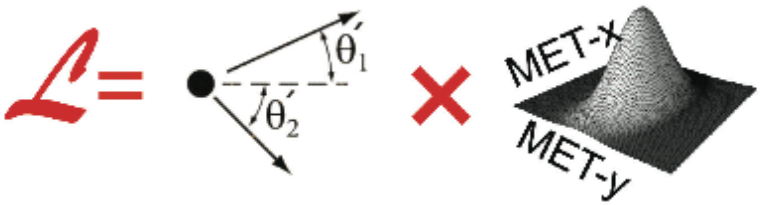
- **Probing large regions of $m_A/\tan\beta$ phase space**
- **Challenges**
  - **Large kinematic regime**
  - **$Z/\gamma^* \rightarrow \tau\tau$ background**
  - **ttbar/W+jets at high masses**
  - **QCD multijet in $\tau_h\tau_h$ channel**
  - **Presence of 2 to 4 neutrinos in final state**

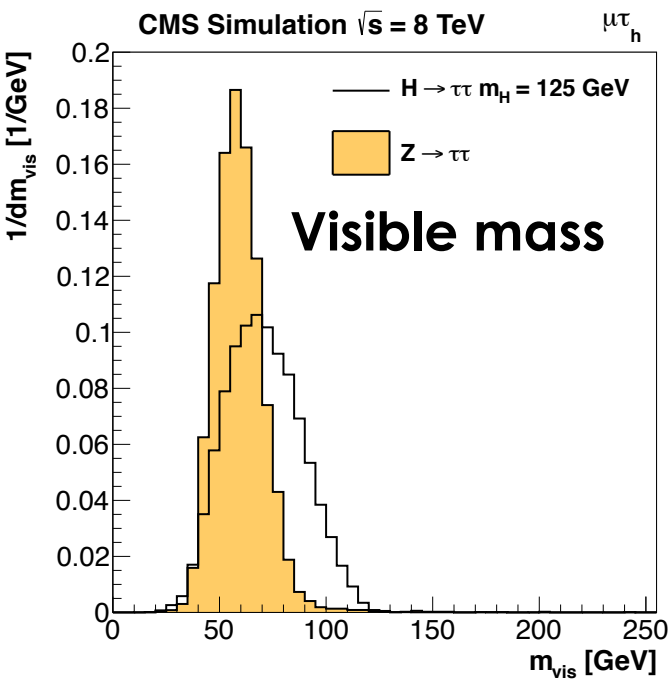
  → Challenging $M_{\tau\tau}$ reconstruction

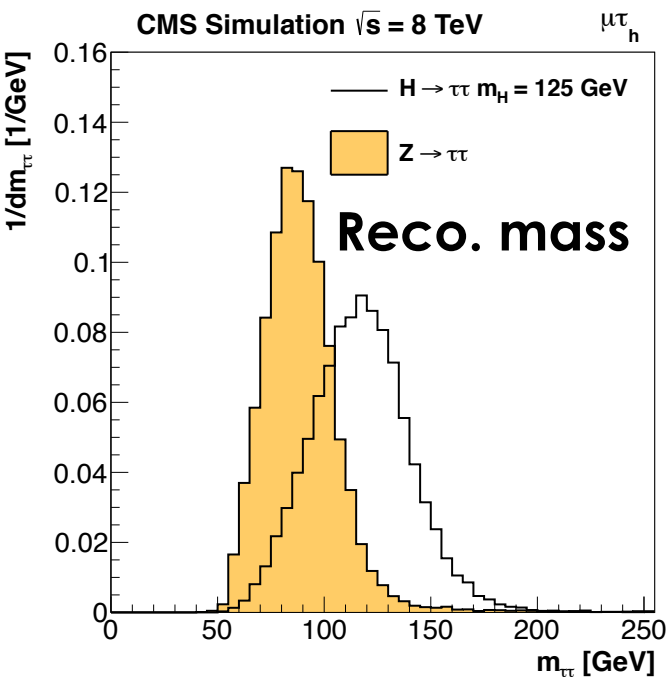
Mass reconstruction in $\Phi \rightarrow \tau^+\tau^-$

Similar technique in ATLAS and CMS

- **CMS' di-τ mass reconstruction**
  - **Maximum likelihood method**
  - **Tau kinematics x MET resol. (x phase space constraints)**







Improved separation with Z→ττ background
15-20% resolution on $M_{\tau\tau}$

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

JHEP 11 (2014) 056

- Analysis of 8 TeV data (19.5 – 20.3 fb^{-1})
  - Channels: $e\mu/\mu\tau_h/e\tau_h/\tau_h\tau_h$
  - Two variables are used as final discriminators:

① Missing Mass Calculator (MMC) in $e\mu$, $e\tau_h$, $\mu\tau_h$

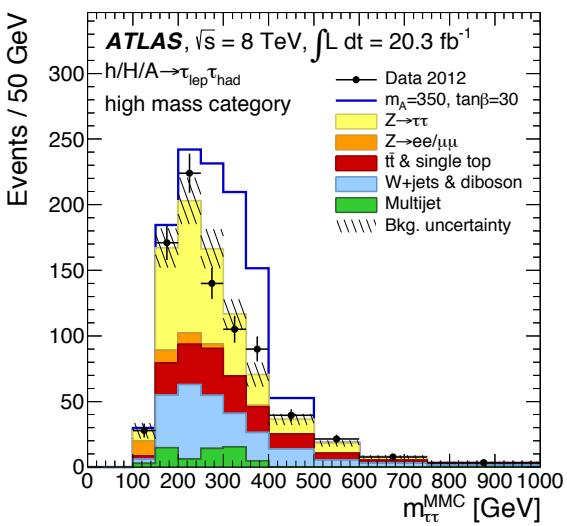
② Total transverse mass in $\tau_h\tau_h$ channel

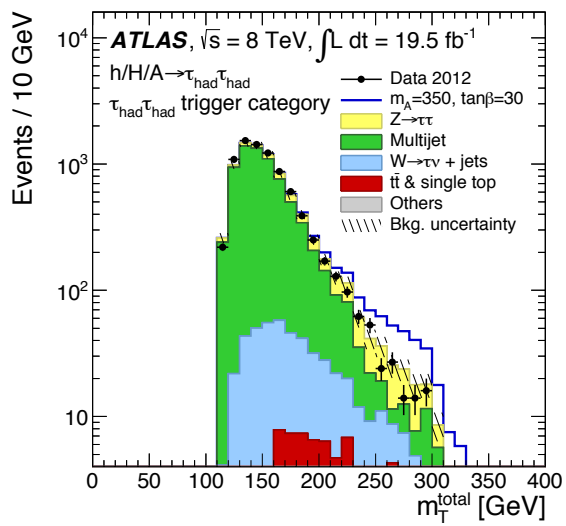
- Categories based on:

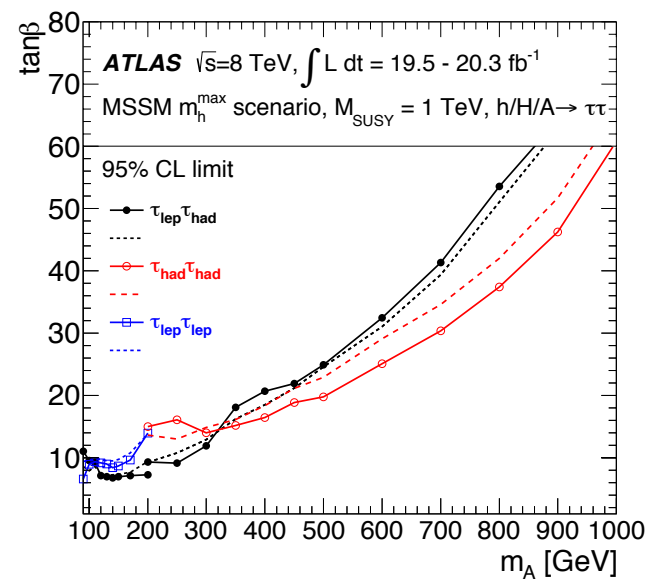
① number of b-tagged jets for $e\mu$, $e\tau_h$, $\mu\tau_h$ channels

② low m_A / high m_A specific cuts for $e\tau_h$ and $\mu\tau_h$ channels

③ Trigger used in $\tau_h\tau_h$ channel







- each channel is used in the mass range for which it is most sensitive

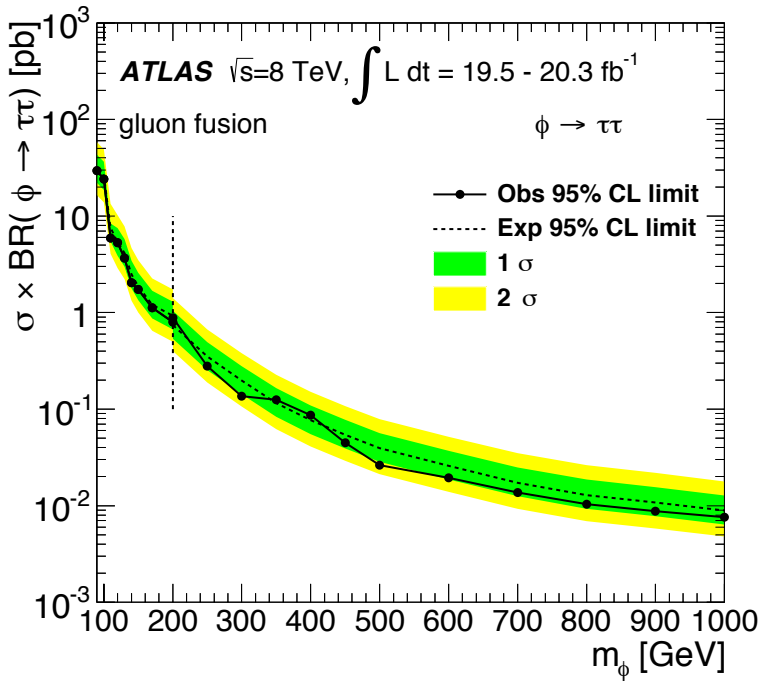
(e.g. $\tau_h\tau_h$ only used at high masses)

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

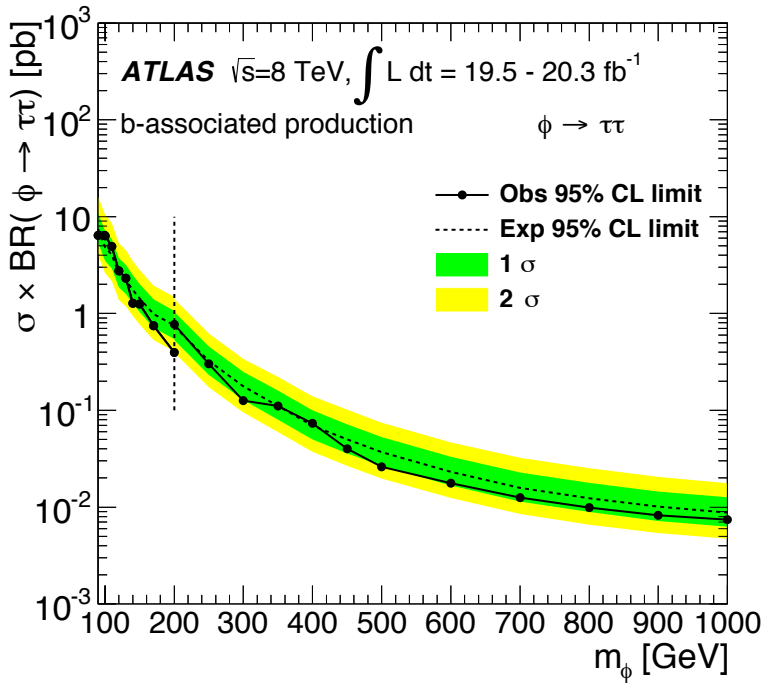
JHEP 11 (2014) 056

- **95% CL limits on ggΦ and bbΦ production cross section x BR**

ggΦ



bbΦ

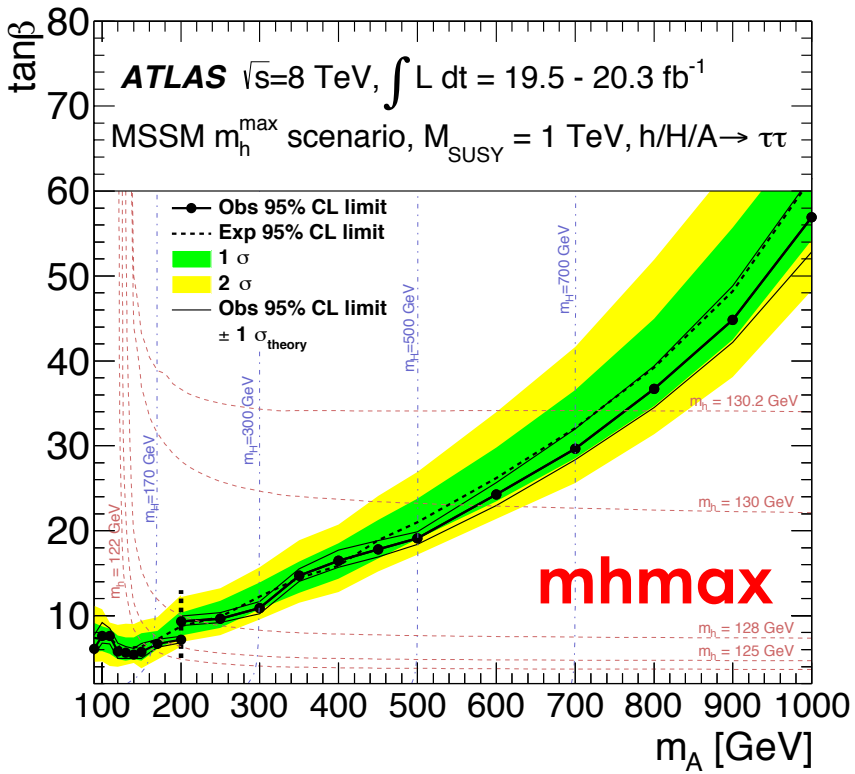


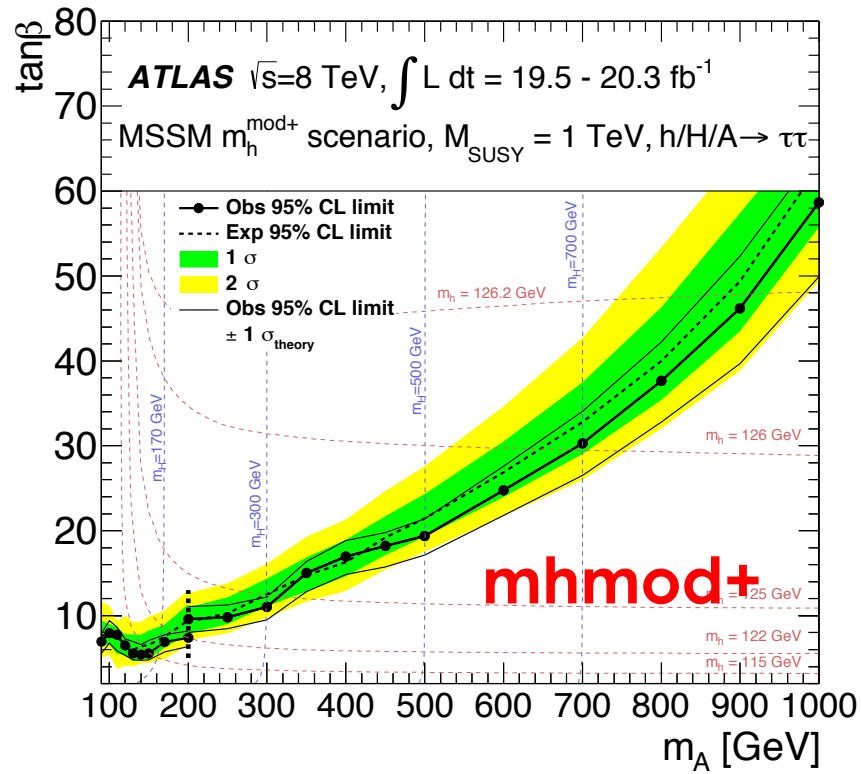
- **No excess found**
- **Limits range**
  - **O(10) pb for m_Φ~100 GeV**
  - **O(10^{-2}) pb for m_Φ~1000 GeV**

$\Phi \rightarrow \tau^+\tau^-$ results from ATLAS

JHEP 11 (2014) 056

- **Model dependent 95% CL limits in (m_A,tanβ) plane**





- **Search excludes low m_A region except for low tanβ (<10-20)**
- **Larger masses and moderate tanβ (<20-50) still allowed**

Updated CMS $\Phi \rightarrow \tau\tau$ search

New!
CMS PAS HIG-14-029

- **Previous published CMS $\Phi \rightarrow \tau\tau$ search is HIG-13-021 [JHEP 10 (2014) 160]**

- **Today, we present a new analysis [CMS PAS HIG-14-029] that brings two improvements along:**

  ① **Use of MVA "boosted" identification of the hadronic taus (τ_h)**
  [will be documented in Run I Legacy (τ_h) paper **TAU-14-001**, out soon]

  ② **Refined event categorization which allows for a better sensitivity to the MSSM-specific kinematics**

- **Analysis of 7+8 TeV data (4.9+19.7 fb^{-1})**

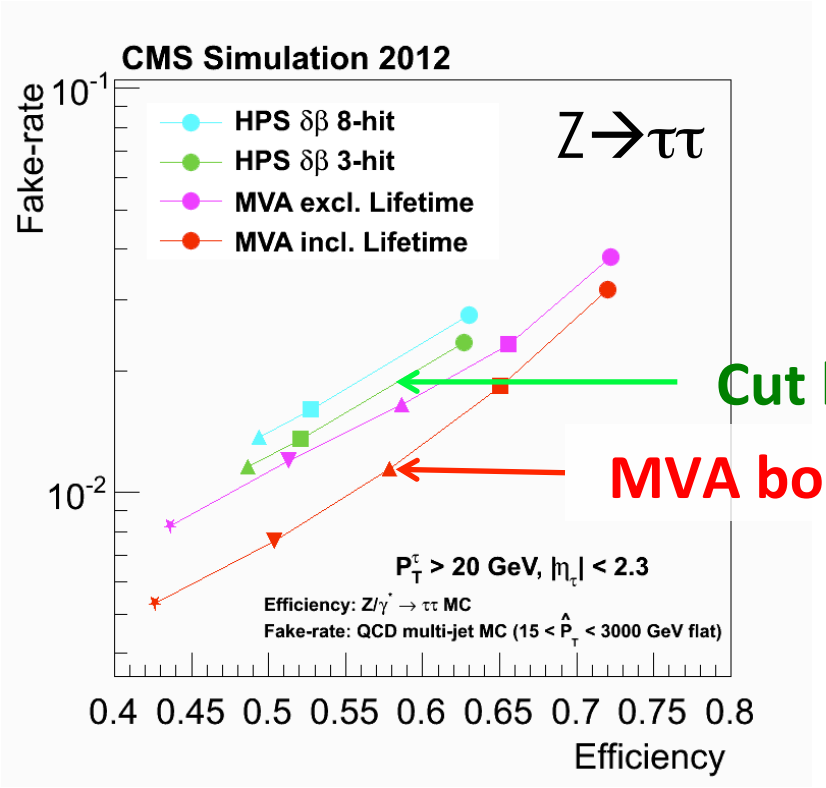
  - **Channels: $\mu\mu/e\mu/\mu\tau_h/e\tau_h/\tau_h\tau_h$**

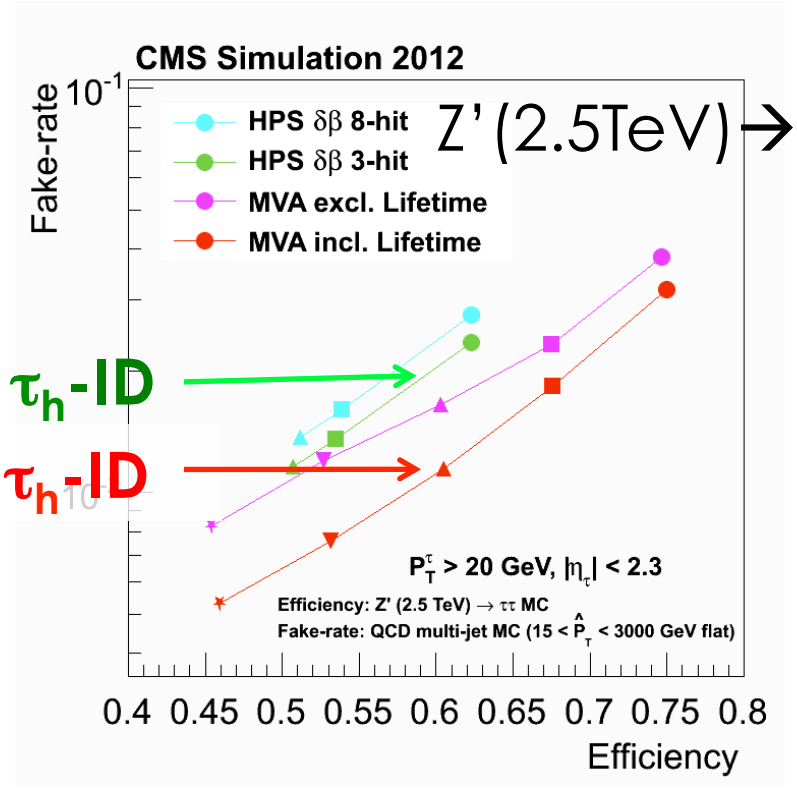
  - **Discriminant variable: SVfit mass (CMS' reconstruced $M_{\tau\tau}$)**

Boosted τ_h-ID

New!
CMS PAS HIG-14-029

Use of MVA boosted τ_h-ID: combines isolation energy and τ lifetime information





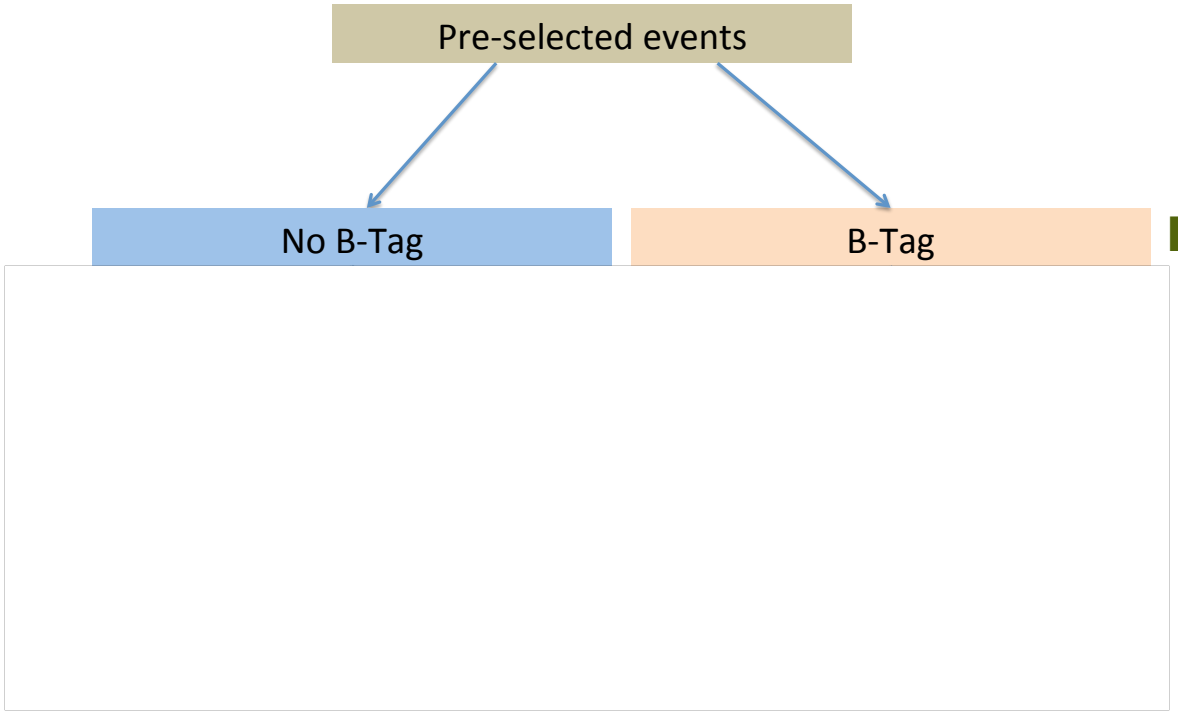
Cut based τ_h-ID

MVA boosted τ_h-ID

Reduction of jet→τ_h fake rate by 40 to 50% at constant efficiency, for low p_T as well as for high p_T τ_h(s)

Refined event categories

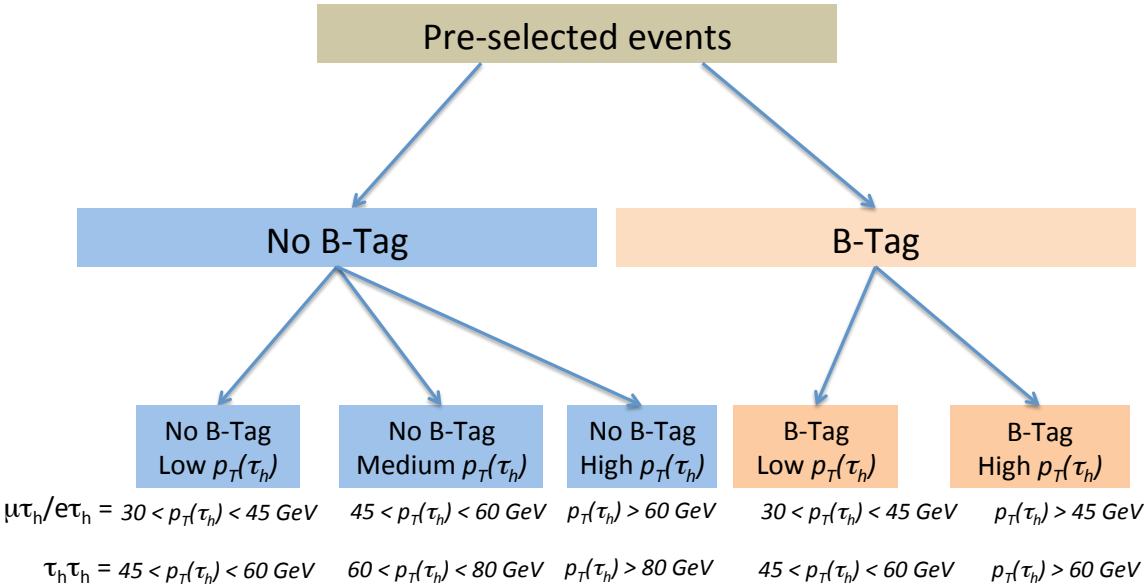
New!
CMS PAS HIG-14-029



- **Previous categorization based on presence or not of b-tagged jet**

Refined event categories

New!
CMS PAS HIG-14-029



→ 5 exclusive categories for each decay channel

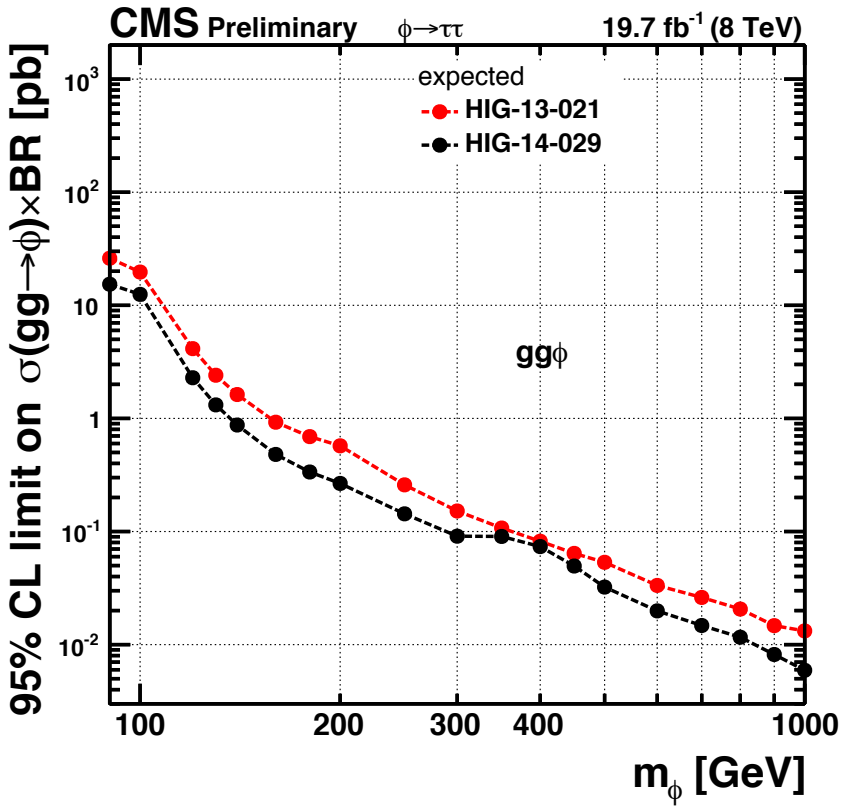
- **Further splitting using $p_T(\tau_h)$ and applied to 8 TeV most sensitive channels: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$**

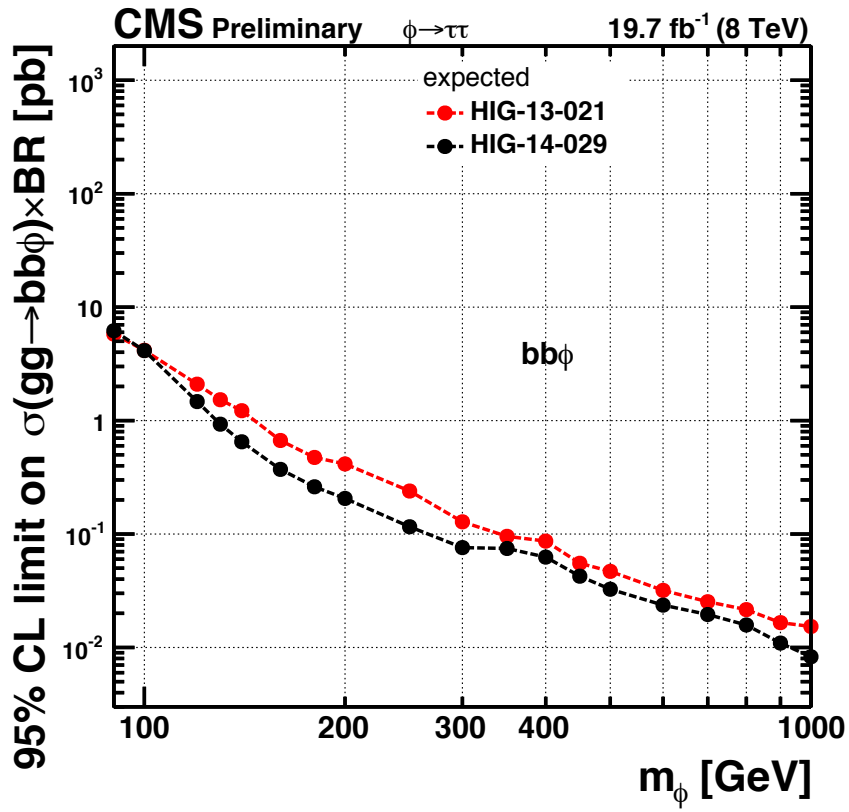
- **Improved sensitivity as different kinematic regimes have different S/B ratios**
- **High-mass Higgs signals expected to contribute mostly to no-b-tag high and b-tag high categories**

$\Phi \rightarrow \tau^+\tau^-$ results from CMS

New!
CMS PAS HIG-14-029

- **Comparison with previous published CMS analysis (HIG-13-021)**



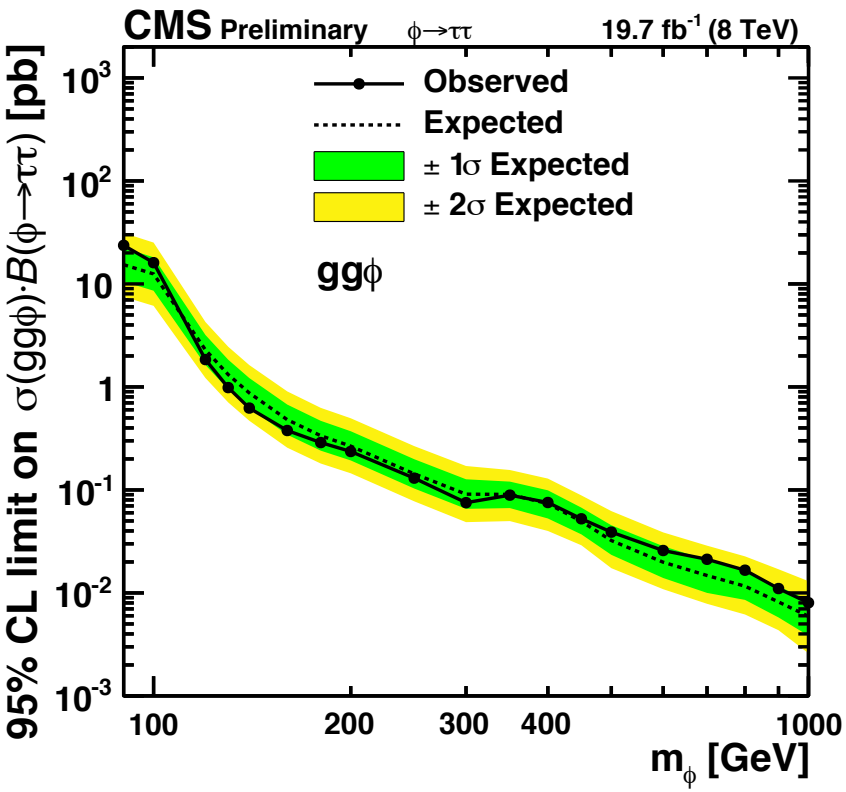


For most of the mass points, the improvement in expected sensitivity is > 20% and up to 50%

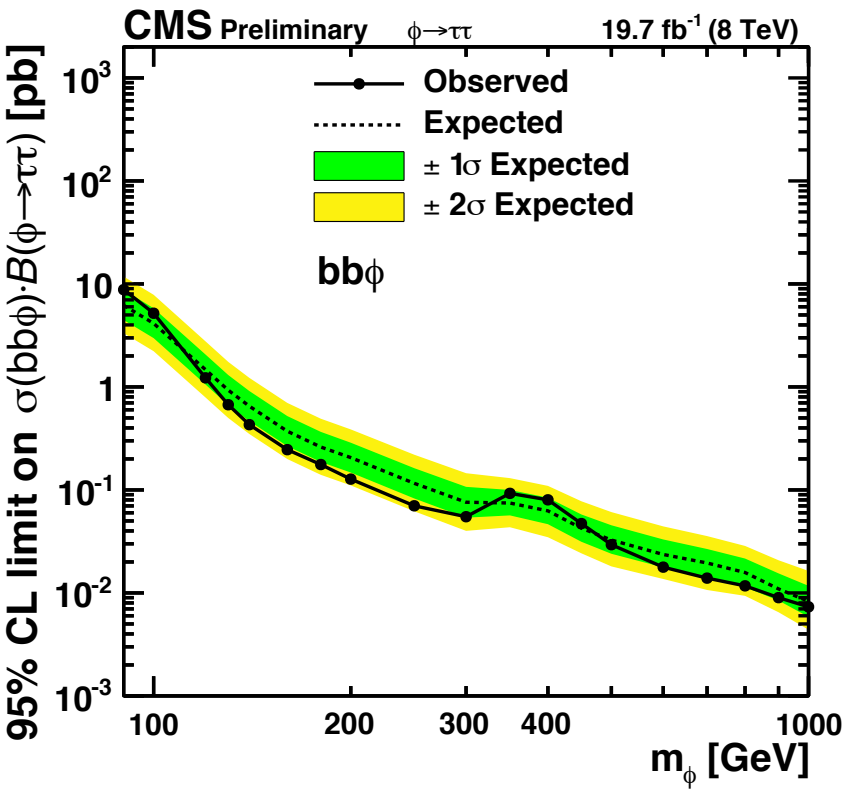
$\Phi \rightarrow \tau^+\tau^-$ results from CMS

New!
CMS PAS HIG-14-029

ggΦ



bbΦ

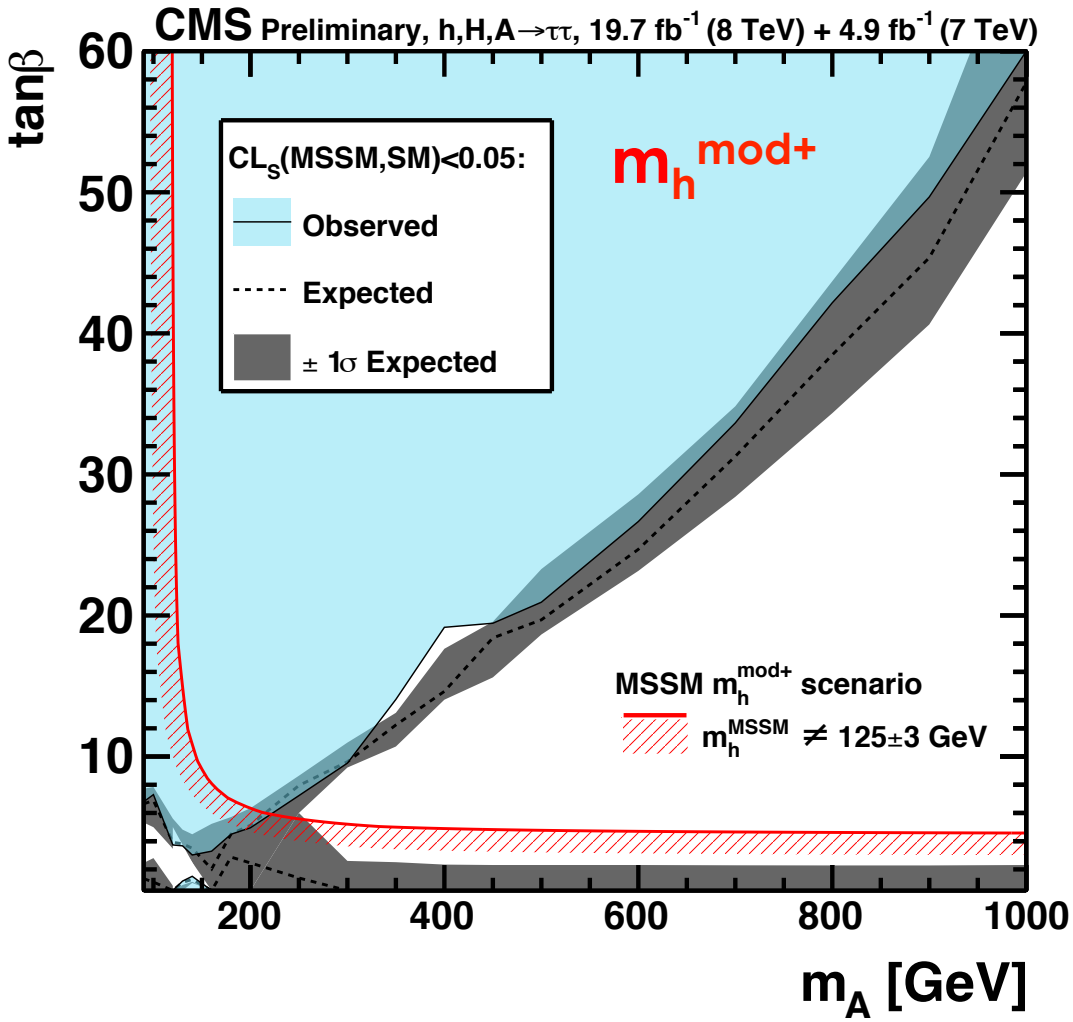


- No significant excess found
- Limits range
  - O(10) pb for m_Φ~100 GeV
  - O(10^{-2}) pb for m_Φ~1000 GeV

$\Phi \rightarrow \tau^+\tau^-$ results from CMS

New!
CMS PAS HIG-14-029

- **Model dependent 95% CL limits in (m_A,tanβ) plane**



- **Search excludes low m_A region except tanβ <10-20**
- **Larger masses and tanβ ~ 20-50 still allowed**
- **Run II will extend search to masses beyond 1 TeV**

Searches for $H^{\pm}\rightarrow\tau\nu$

- $H^{\pm}\rightarrow\tau\nu$: BR dominant for $m_{H\pm}$ <~ 200 GeV
- → Makes this search favorable at low masses

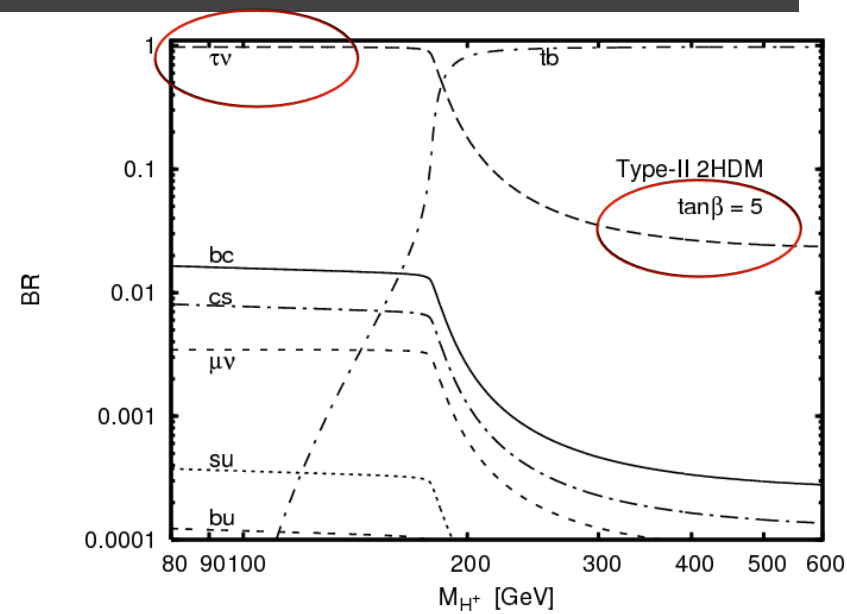
- Two kinematic regimes

① *Light*: $m_{H\pm} < m_t - m_b$

→ *Search for increase in $t\rightarrow b\tau\nu$ decays due to $H^{\pm}$*
Relevant measurement: $BR(t\rightarrow H^{\pm}b)xBR(H^{\pm}\rightarrow\tau\nu)$

② *Heavy*: $m_{H\pm} > m_t - m_b$

→ *Search for associate production with a top (+bottom)*
Relevant measurement: $\sigma(pp\rightarrow t(b)H^{\pm})xBR(H^{\pm}\rightarrow\tau\nu)$

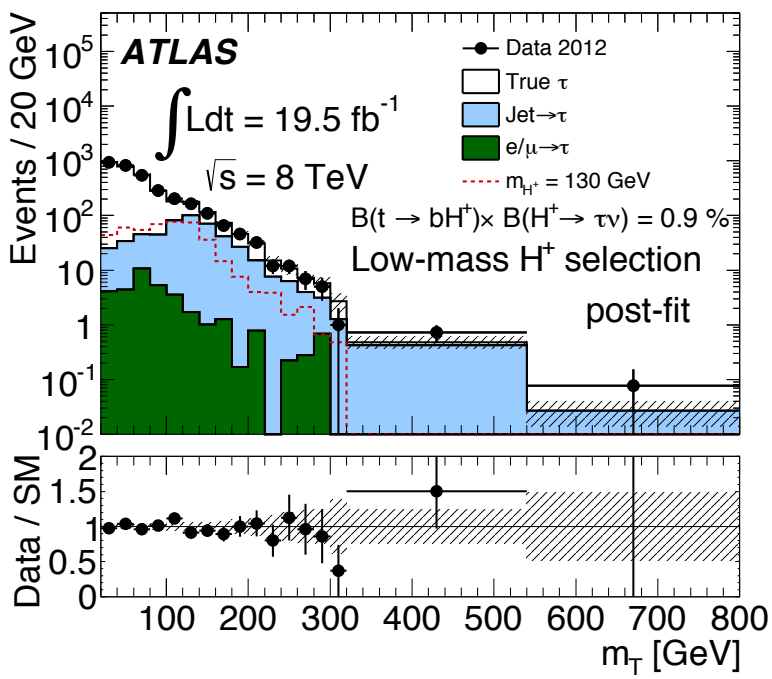


- Final states: hadronic τ, ≥3 jets (≥1 b-jet), large MET, no leptons
- Complex τ_h+MET cross trigger used
- Control of dominant SM backgrounds: ttbar (~irreducible) + QCD multijets
- Look for excess in tranverse mass distribution

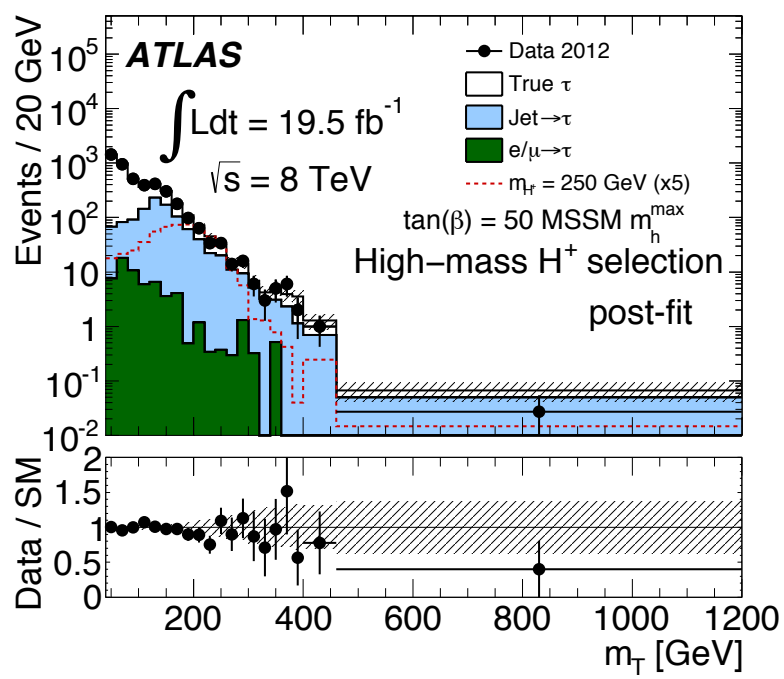
$H^{\pm} \rightarrow \tau\nu$ results from ATLAS

JHEP03 (2015) 088

- **Background prediction**
  - **Processes with a true τ_h: 'embedding' (μ+jets data events where the μ is replaced by a simulated τ_h)**
  - **Multi-jet background: sideband method (loose/tight τ-ID)**
  - **$e/\mu \rightarrow \tau_h$ fakes: simulation (fake rate corrected using data-driven techniques)**



Low mass analysis

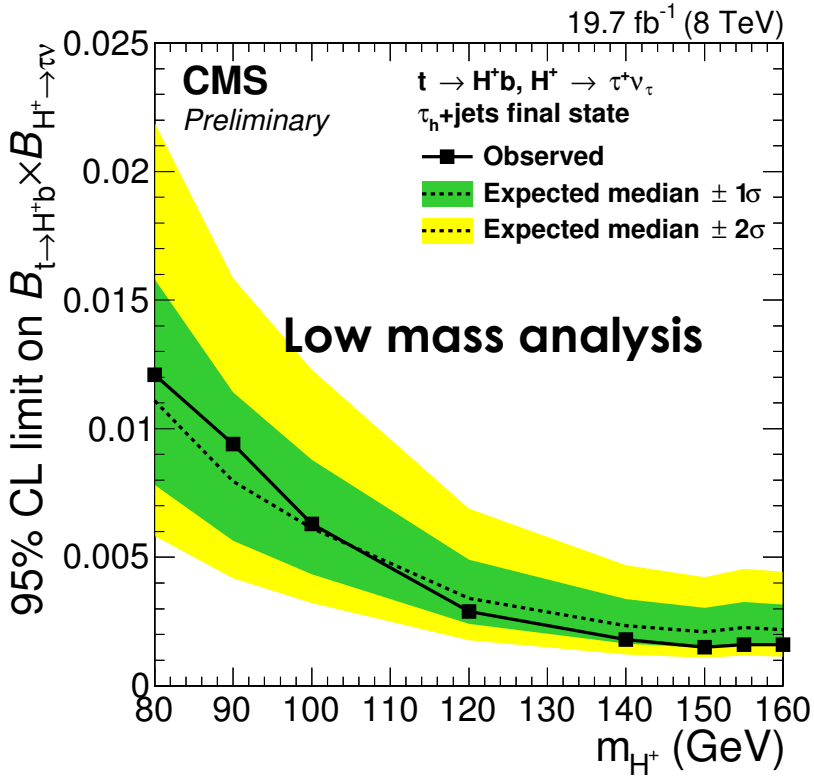


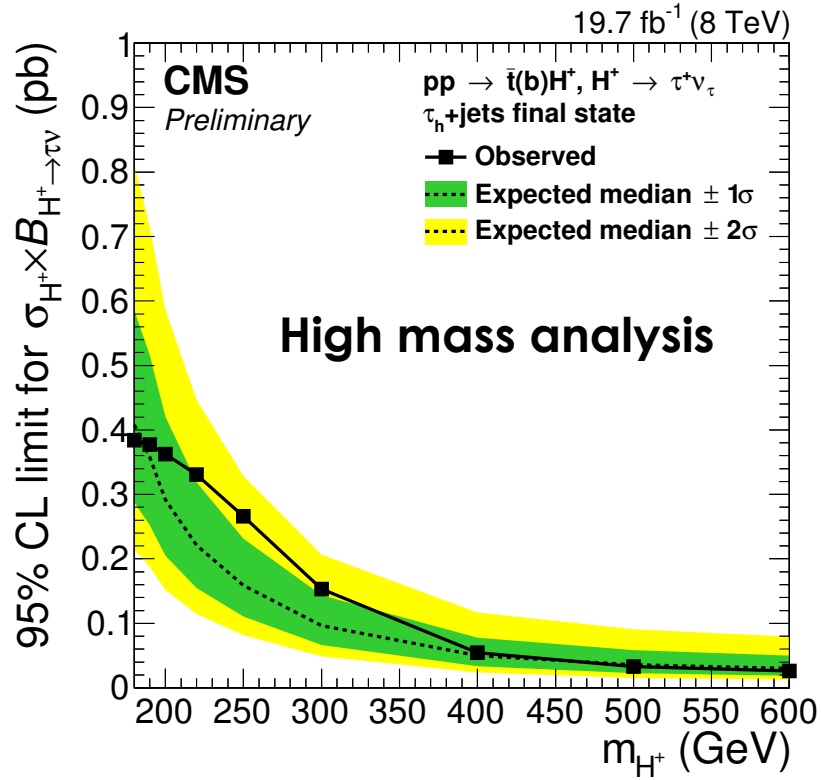
High mass analysis

$H^{\pm}\rightarrow\tau\nu$ results from CMS

CMS PAS HIG-14-020

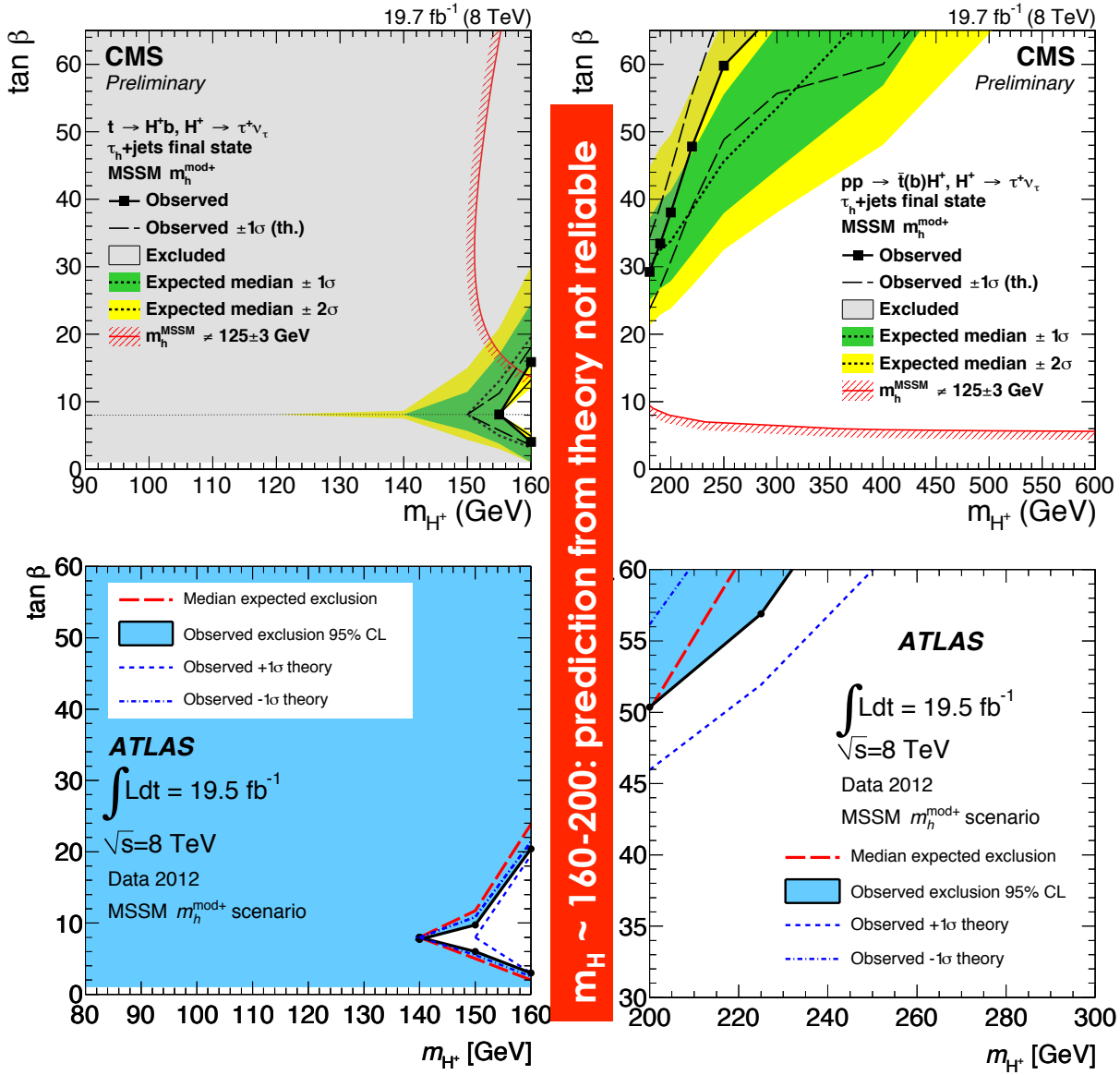
- **Background prediction (similar to ATLAS)**
  - **True τ_h: 'embedding'**
  - **Multi-jet background: fake-rate technique**
  - **$e/\mu\rightarrow\tau_h$ fakes: simulation reweighting**





Similar results from ATLAS & CMS

$H^{\pm} \rightarrow \tau\nu$ limits in m_h^{mod+} scenario

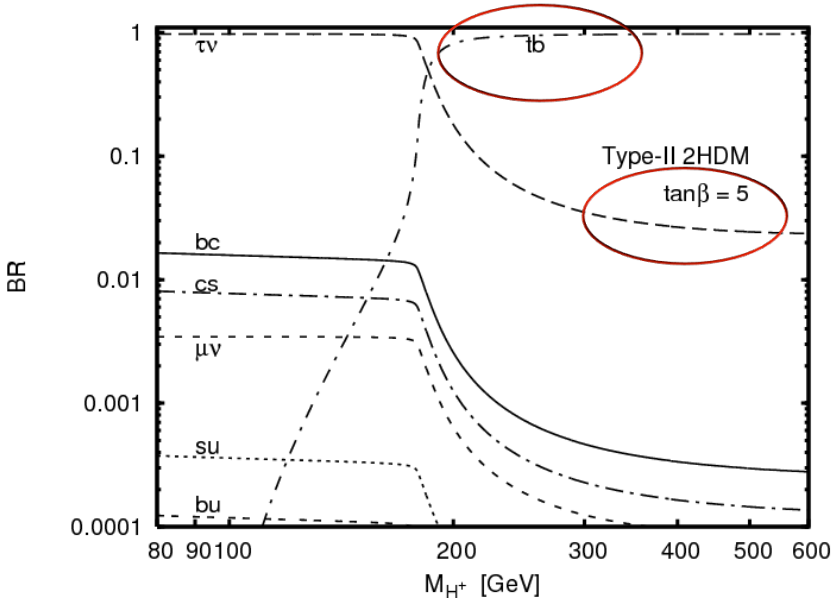


ATLAS: JHEP03 (2015) 088
CMS: CMS PAS HIG-14-020

- ATLAS and CMS essentially carry the same message: all tanβ regions excluded for $m_{H\pm} < 140$ GeV
- Also excludes the low-m_H MSSM scenario in which we have the heavy CP even Higgs of the MSSM being SM-Higgs like
- Higher masses limited due to small BR($H \rightarrow \tau\nu$)
- Other benchmark scenarios available, same conclusions reached

Combined searches of $H^{\pm}\rightarrow tb/\tau\nu$

- $H^{\pm}\rightarrow tb$: BR dominant for $m_{H\pm}$ >~ 200 GeV
- → Makes this search favorable at high masses



- Search strategy & challenges
  - Discriminant variable = b-jet multiplicity
  - Final states in $H^{\pm}\rightarrow tb/\tau\nu$ search
    $gg\rightarrow H^{\pm}tb\rightarrow(l\nu_l bb)(l'\nu_{l'}b)b = ee/e\mu/\mu\mu$ + jets
    $gg\rightarrow H^{\pm}tb\rightarrow(\tau_h\nu_\tau)(\mu\nu_\mu b)b = \mu\tau_h$ + jets
  - → Combinatorics in b-jet association

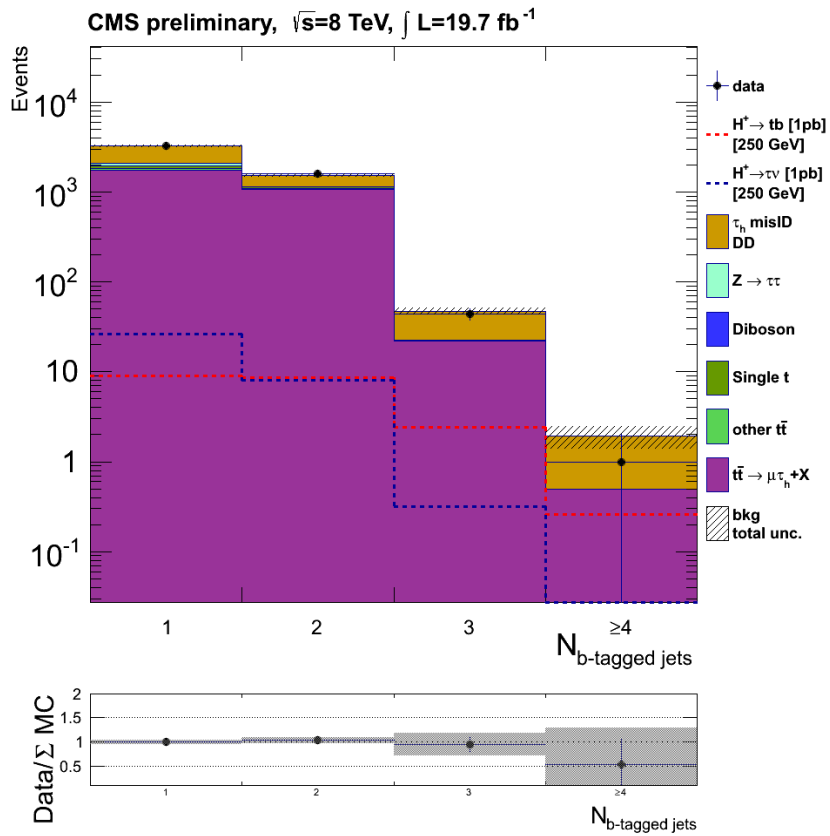
- Background prediction
  - With genuine τ_h predicted from simulation
  - With fake τ_h predicted using fake-rate method: probability for a jet to mimic a τ_h applied to μ+≥3jets data events
  - Other backgrounds (e.g. DY,ttbar→ee/$\mu\mu$) from simulation

$H^{\pm}\rightarrow tb/\tau\nu$ results from CMS

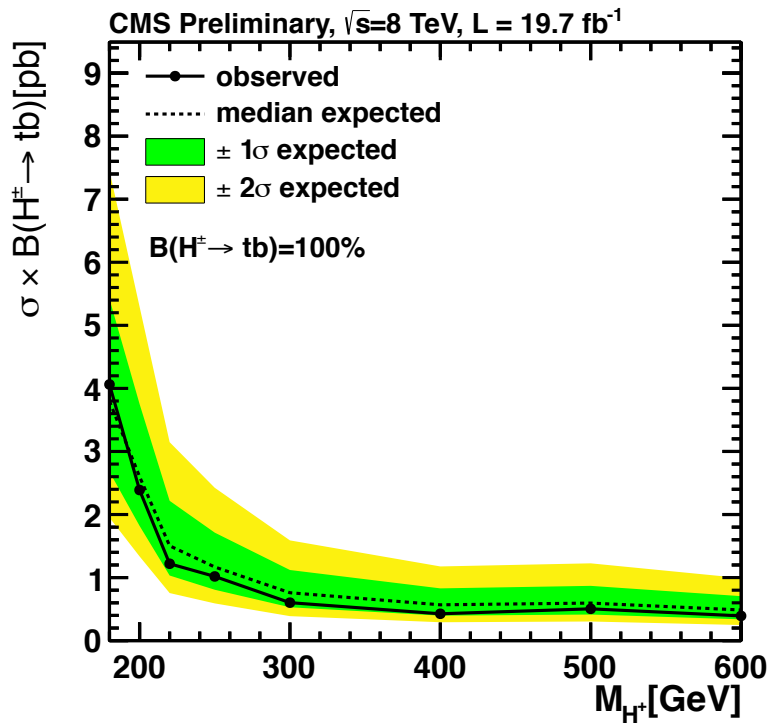
CMS PAS HIG-13-026

- For most masses, the search is more sensitive to $H^{\pm}\rightarrow tb$ than to $H^{\pm}\rightarrow\tau\nu$

$\mu\tau_h$ channel



Assuming $BR(H^{\pm}\rightarrow tb)=100\%$

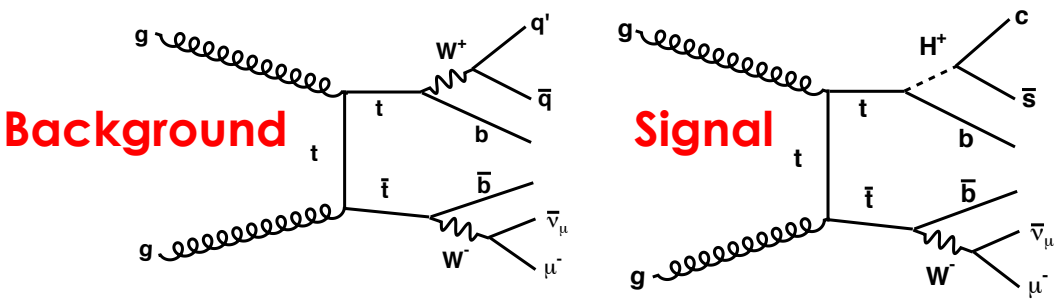


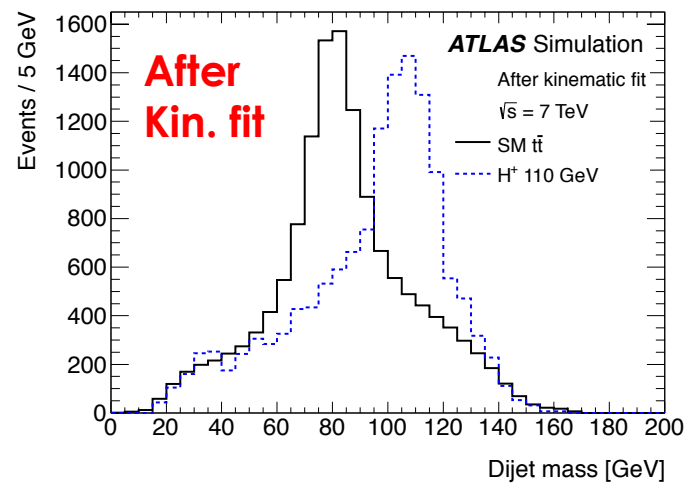
Limit on σ x $BR(H^{\pm}\rightarrow tb)$ is ~1 pb for $180 < m_{H\pm} < 600$ GeV

Searches for $H^{\pm}\rightarrow cs$

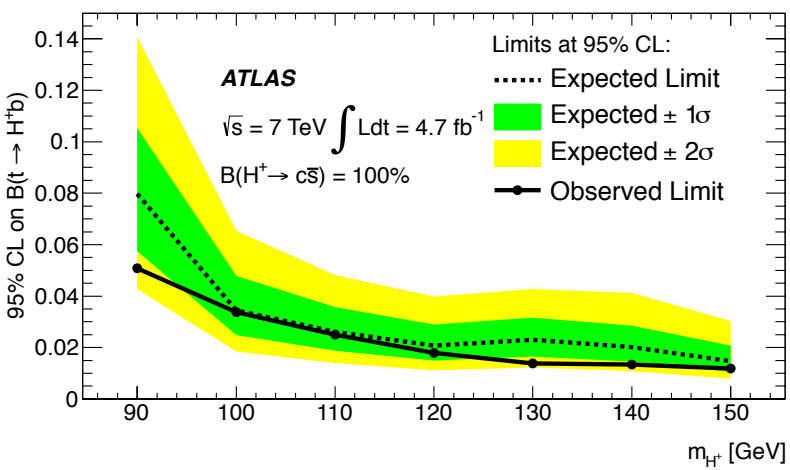
ATLAS: Eur. Phys. J. C, 73 6 (2013) 2465
CMS: CMS PAS HIG-13-035

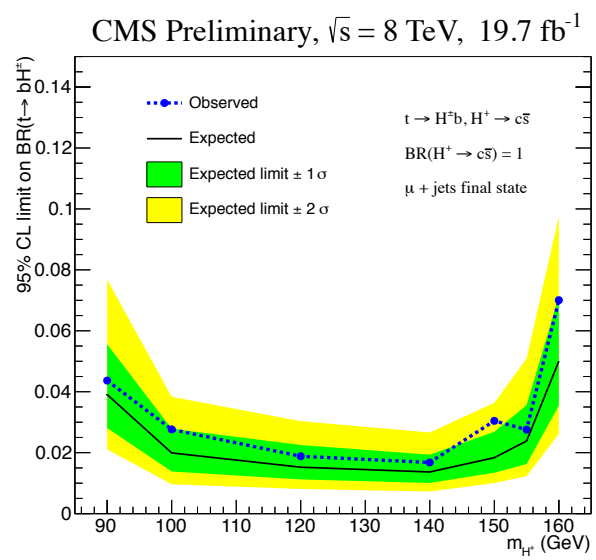
- If $\tan\beta < 1$ and $m_{H\pm}<m_t-m_b$, **BR($H^{\pm}\rightarrow cs$) becomes sizeable and can reach ~70-100%** for 2HDM Type II
- Search for $t\rightarrow Hb$ decays in ttbar production





- **Final state looked for is: $tt\rightarrow WbH^{\pm}b\rightarrow \mu/e$ + jets**
  (require 2 b-tags)





Conclusions

- Using LHC Run I data, ATLAS and CMS have searched for heavy Higgs bosons
  - Neutral Higgs bosons in $\Phi \rightarrow bb$ and $\Phi \rightarrow \tau^+\tau^-$ (inc. new results from CMS)
  - → Limits are set. For example: $m_A < 400$ GeV + $\tan\beta > 12$ is excluded
  - Charged Higgs bosons in the $H^\pm \rightarrow \tau\nu_\tau$, $H^\pm \rightarrow tb$ (CMS) and $H^\pm \rightarrow cs$ decay modes
  - → $H^\pm$ are excluded below 140 GeV, with $H^\pm \rightarrow \tau\nu$ ($H^\pm \rightarrow tb$) dominating at low (high) mass
  - New ATLAS result (from 2 days ago): search for heavy $H \rightarrow ZZ$ in the 2HDM context
  - → Briefly presented by Francesco Lo Sterzo yesterday
  - → See backup
- No evidence of extra Higgs bosons found just yet
- Stringent limits on extra resonances and MSSM parameter space were set
- LHC Run II data will extend the reach of the analyses
  - → Highest center-of-mass energy
  - → Increased luminosity
  - → New experimental techniques

Stay tuned for fresh results soon! ☺

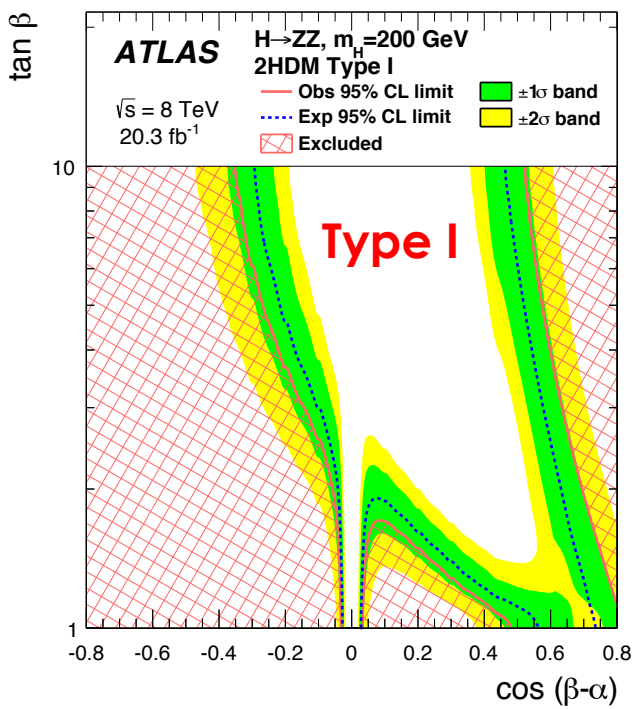
Backup

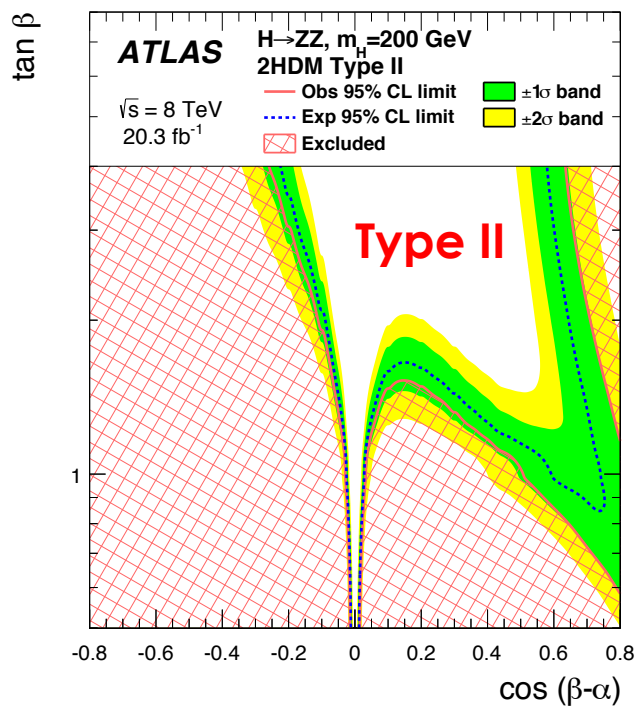
Search for heavy H→ZZ

New!
arXiv:1507.05930v1

- Analysis of 8 TeV data (20.3 fb^{-1})
- Assumes production through ggF and VBF
- No significant excess found
- → Limits are set on σ x BR for ggF and VBF
- → Interpretation in Type I and type II 2HDMs

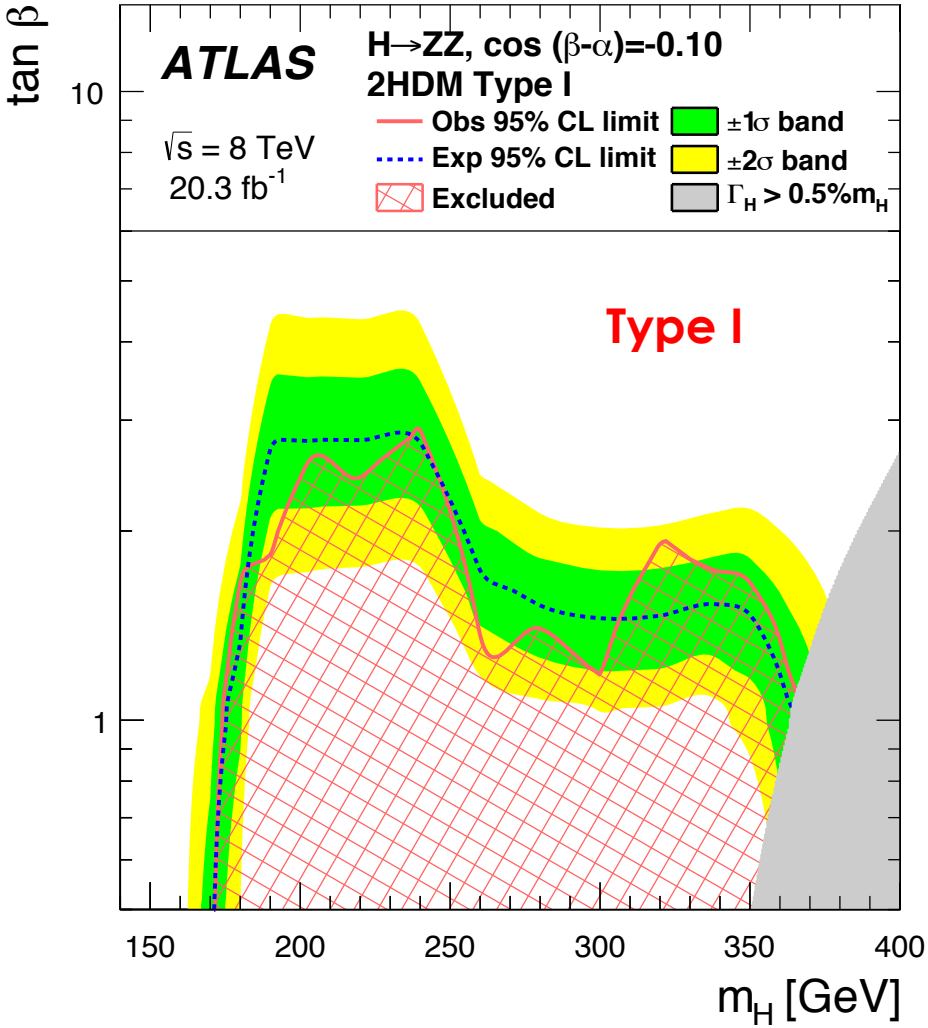
4 channels:	Discriminant variable
4 leptons	M_{4l}
2 leptons + 2 neutrinos	m_T^{ZZ}
2 leptons + 2 quarks	M_{lljj}
2 neutrinos + 2 quarks	m_T

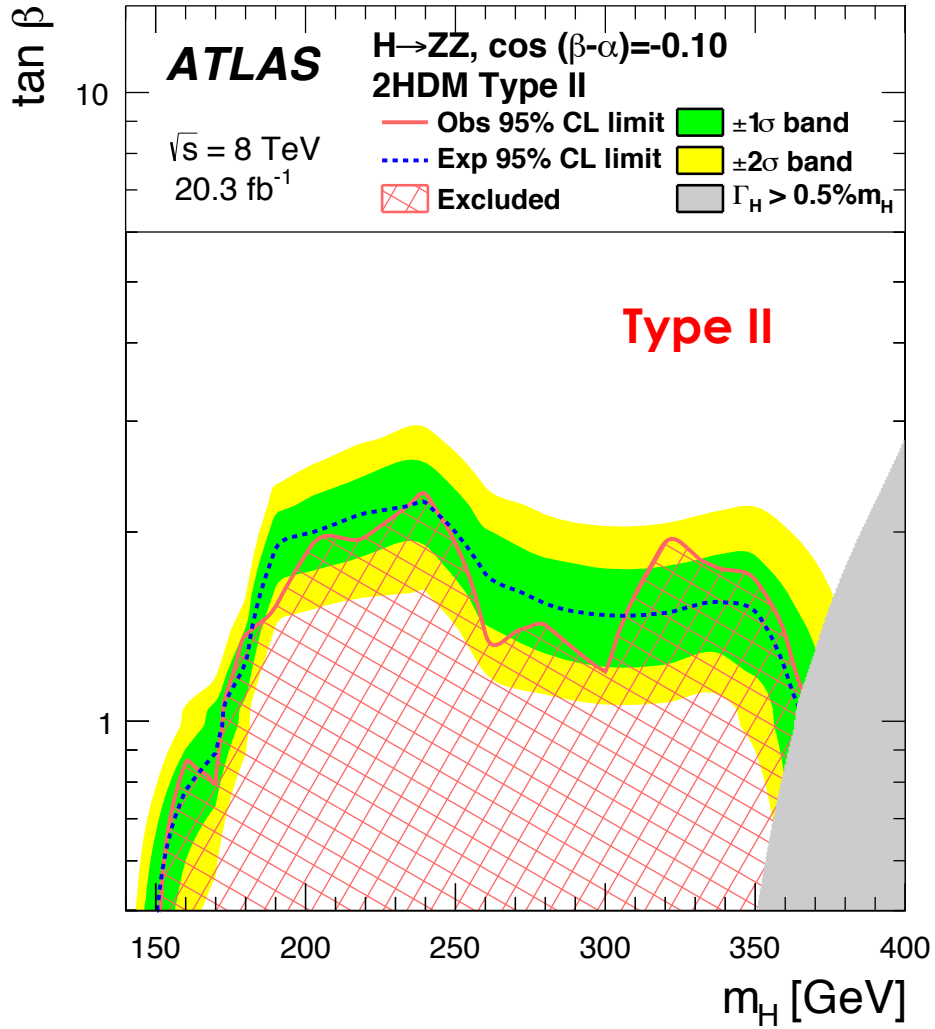




Search for heavy H→ZZ

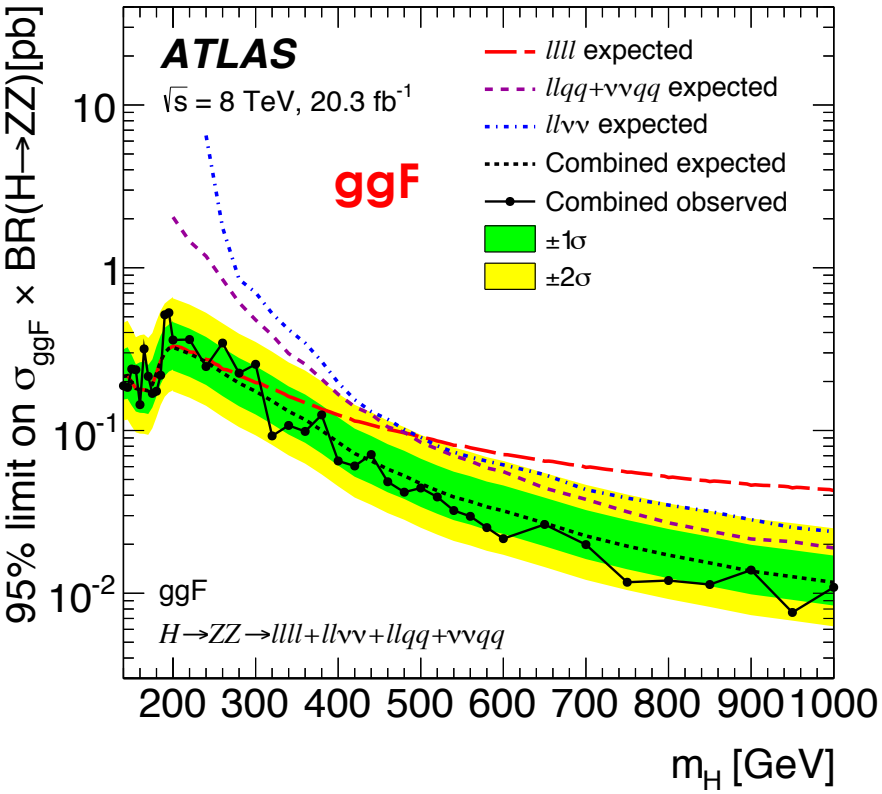
New!
arXiv:1507.05930v1

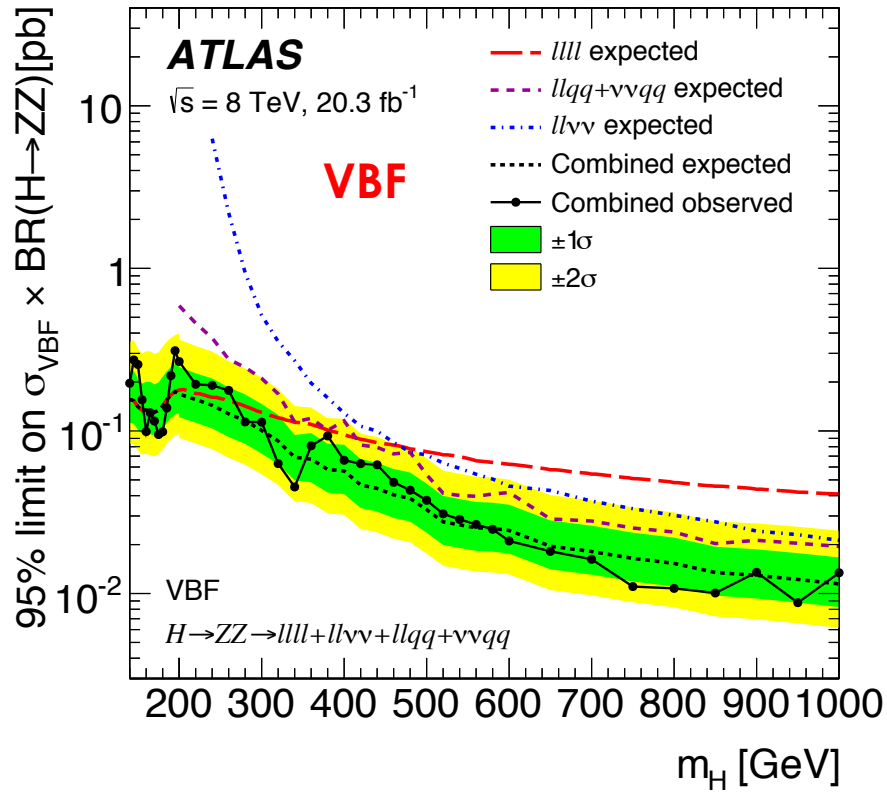




Search for heavy H→ZZ

New!
arXiv:1507.05930v1





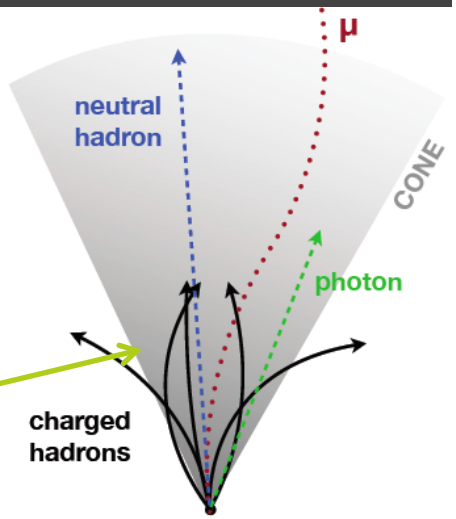
Missing transverse energy (MET)

- **Presence of 2 to 4 neutrinos in the final state**
  → **Challenging $M_{\tau\tau}$ reconstruction**

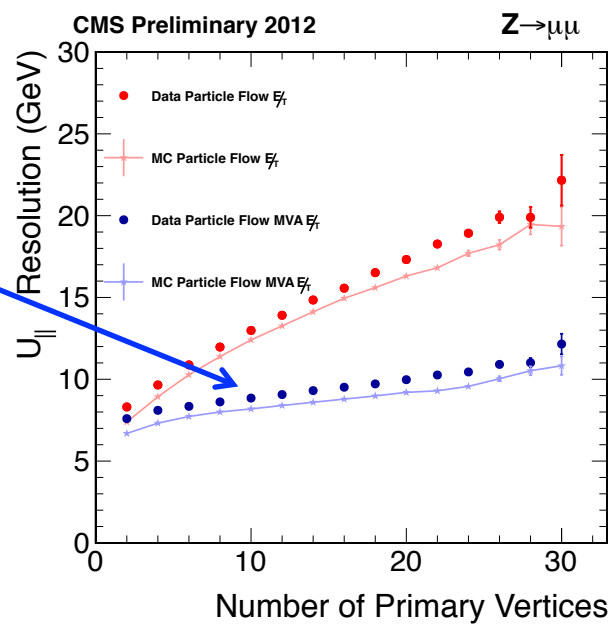
- **MET = fundamental ingredient in $M_{\tau\tau}$ reconstruction**

$$\overrightarrow{MET} = -\sum_{\text{PF particles}} \vec{p}_T$$

Jet subconstituent contribution taken into account using Particle Flow

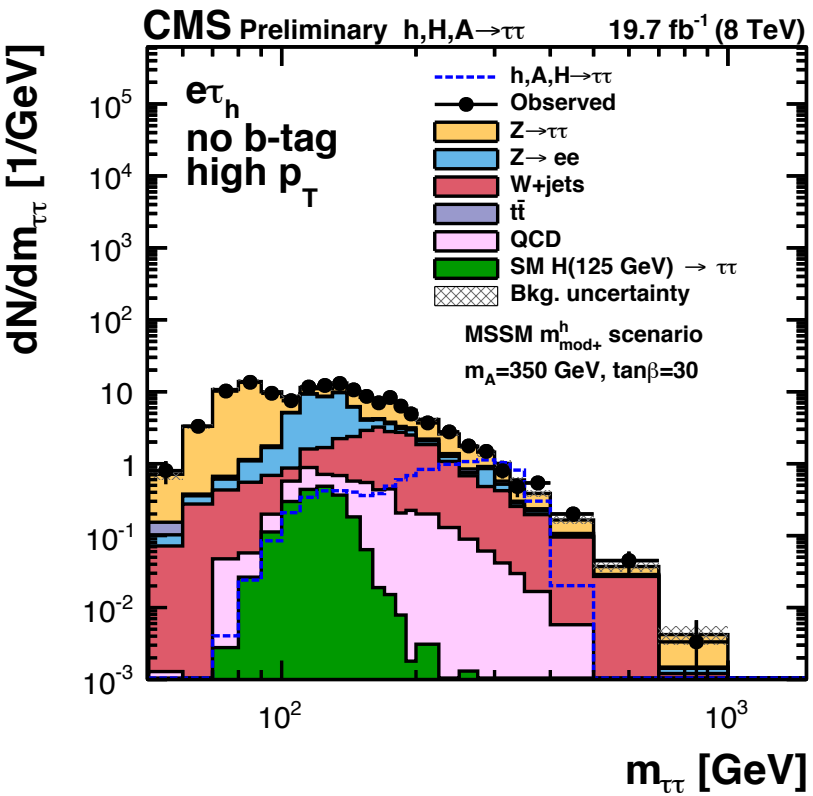


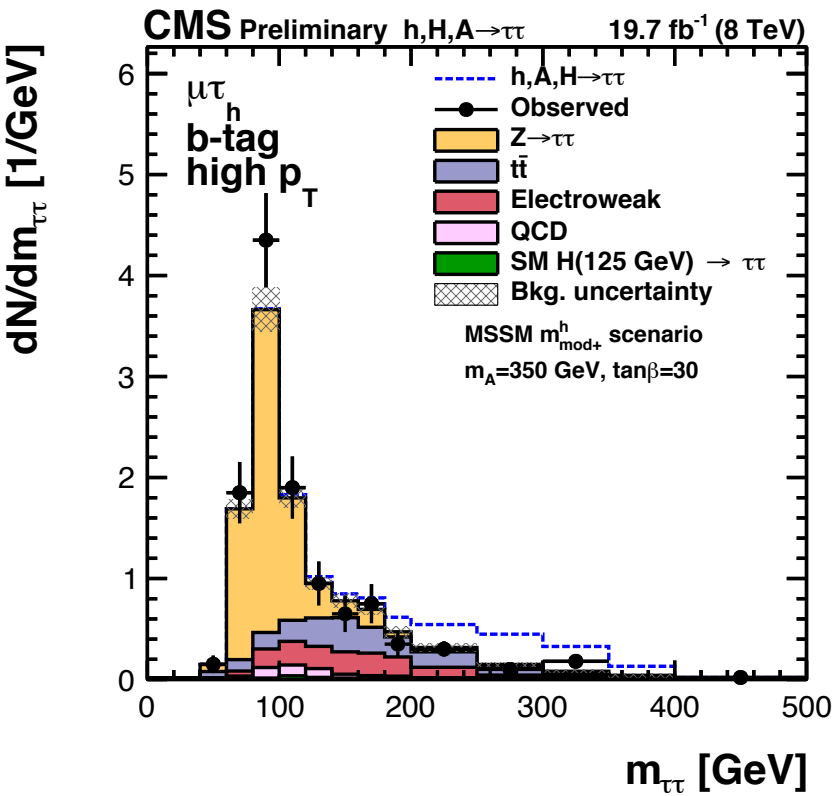
Build MVA MET to reduce degradation of resolution with pile-up



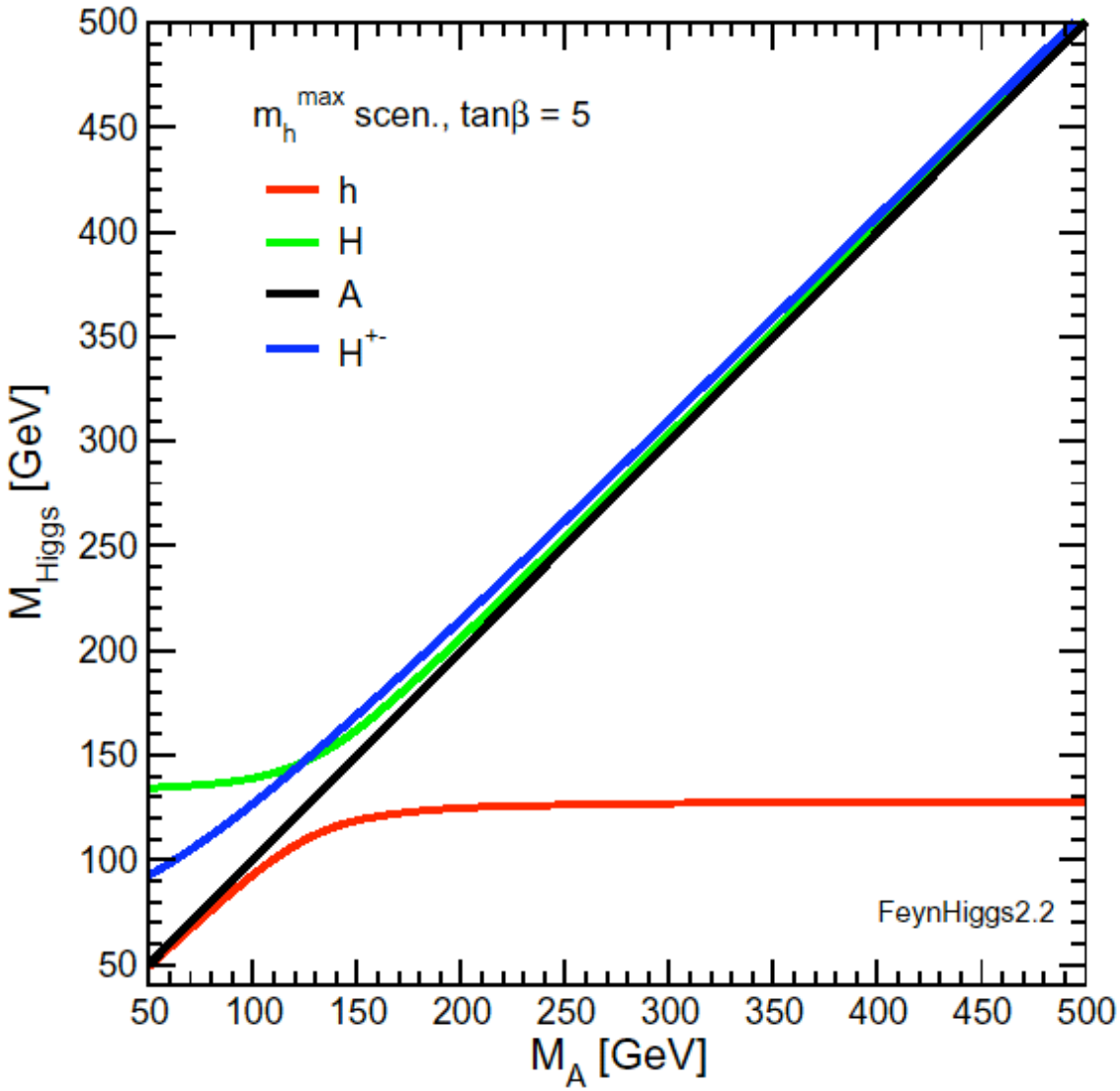
$\Phi \rightarrow \tau^+\tau^-$ results from CMS

New!
CMS PAS HIG-14-029





Mass of Higgs bosons in SUSY



MSSM benchmark scenarios

Scenario	Description
m_h^{max}	Value of X_t chosen as to maximize mass of light scalar h
m_h^{mod}	Reduced amount of mixing in the top sector, in order to relax the effect of the constraint from the 125 GeV measurement on parameter space (mod+ and mod- are specific choices of the parameters)
Light stop	Large value of $\|X_t\|$ leads to light stop which has a rather large impact on light h production rate in ggF
Light stau	A light stau leads to modified $H \rightarrow \gamma\gamma$ rate
Tau-phobic	Large values of m, tanβ and $A_{t,b,\tau}$: modified couplings to down-type fermions (+ light staus)
Low m_H	125 GeV boson identified with heavy scalar H (scenario excluded)

hMSSM scenario

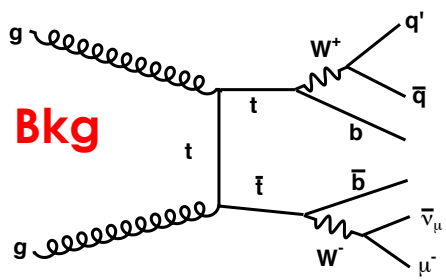
[A. Djouadi et al., JHEP06 (2015)168]

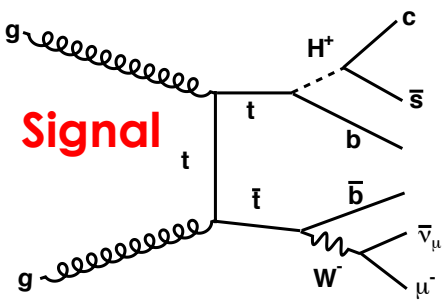
A straightforward and easily implementable solution to this problem has been proposed in Refs. [10–12]: if the experimental constraint $M_h \approx 125$ GeV is enforced, one in fact removes the dependence of the Higgs sector on the dominant radiative correction and, hence, on the additional SUSY parameters, in particular M_S and X_t. One can again parametrise the MSSM Higgs sector using only the two basic inputs $\tan\beta$ and M_A, exactly like it was the case at tree–level. The masses of the heavier H and $H^\pm$ states as well as the mixing angle α in the CP–even sector are given by very simple expressions in terms of $\tan\beta$ and M_A with the constraint $M_h = 125$ GeV. It was shown that this approximation is very good in most of the MSSM parameter space that is currently accessible at the LHC, even when subleading radiative corrections are also considered [10].

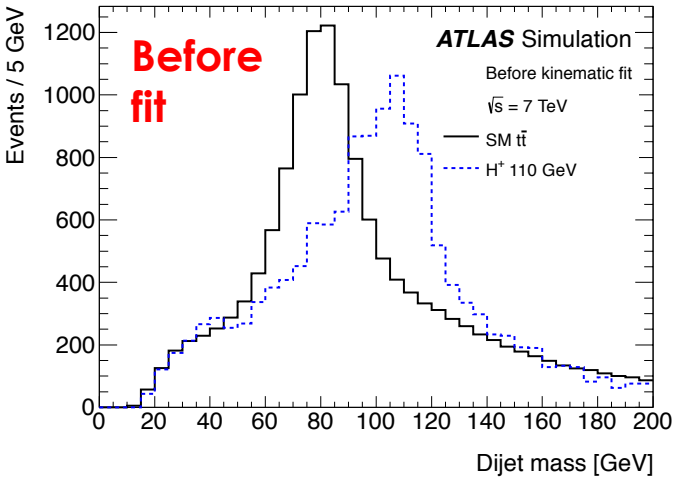
In this minimal and almost model independent approach, called the hMSSM in Ref. [10], one has access to the entire $[\tan\beta, M_A]$ parameter space without being in conflict with the LHC data, as the information $M_h = 125$ GeV is taken into account from the very beginning (this is not always the case for the Higgs couplings which conflict with the measured ones at low M_A). In particular, the low $\tan\beta$ region can naturally be accessed, but at the expense of assuming a very high SUSY scale M_S. The reason is that at $\tan\beta$ values too

Searches for $H^{\pm}\rightarrow cs$

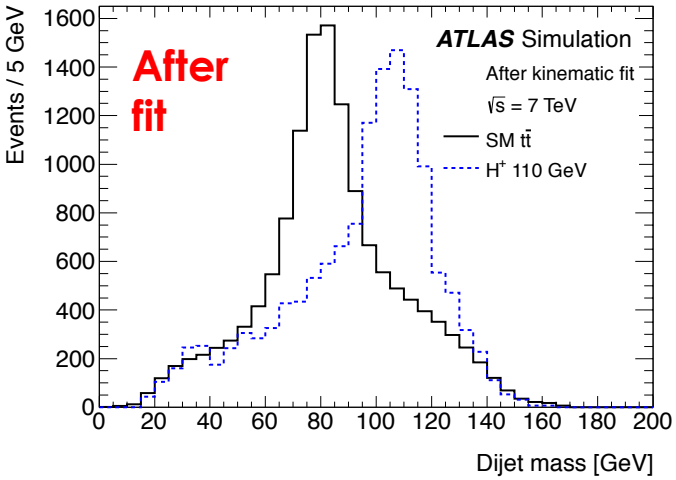
- If $\tan\beta < 1$ and $m_{H\pm}<m_t$, $BR(H^{\pm}\rightarrow cs)$ becomes sizeable and can reach ~70-100% for 2HDM Type II
- Search for $t\rightarrow Hb$ decays in ttbar production
- → search is probing low $H^{\pm}$ masses ($< m_t - m_b$)







- Final state looked for is: $tt\rightarrow WbH^{\pm}b\rightarrow \mu/e$ + jets
  (require 2 b-tags)

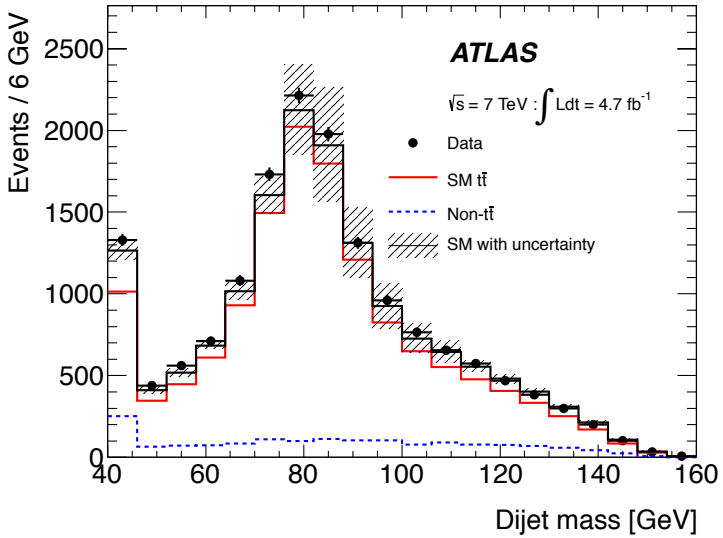


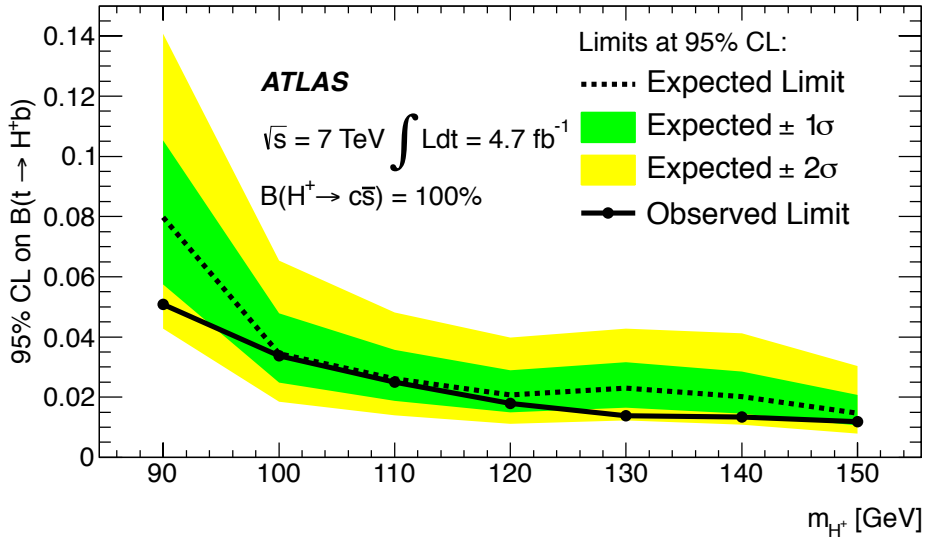
- Challenges of the search
  - Using the muon/electron from W to trigger
  - Large background from ttbar and W+jets
  - Separation between $W^{\pm}/H^{\pm}$ → reconstruction of $m_W(m_H)$ through kinematic fit using μ and jet kinematics, MET (+ resolutions + constraints on top mass)
  - → Discriminant variable is M_{jj} ($\sim M_{cs}$)
  - → Limits are set on $BR(t\rightarrow H^{\pm}b)$, assuming $BR(H^{\pm}\rightarrow cs)=100\%$

$H^{\pm} \rightarrow cs$ results from ATLAS

Eur. Phys. J. C, 73 6 (2013) 2465

- Search is performed on the 7 TeV dataset only (4.7 fb^{-1})
- Background estimation
  - ttbar/single top: simulation
  - QCD multijets: yield estimated using likelihood fit on MET distribution / shape from sideband using relaxed lepton isolation sideband
  - W+jets: yield from data driven method / shape from simulation
- Dominant systematic uncertainty is from Jet Energy Scale / Resolution





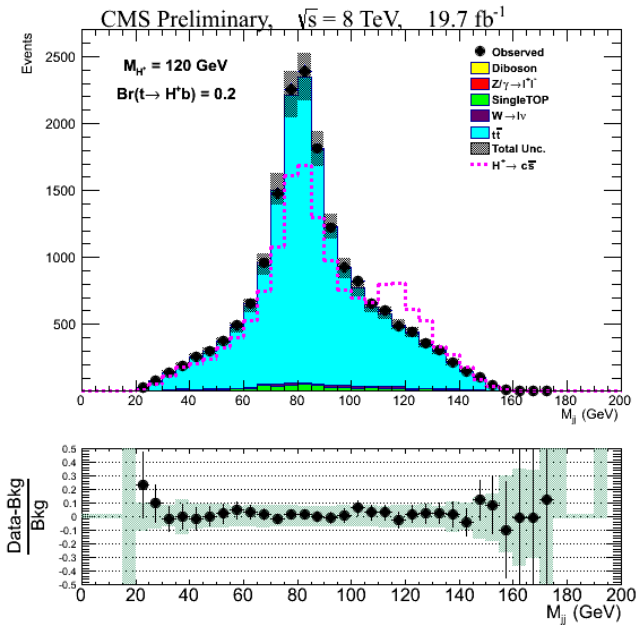
- Observed limits on BR($t \rightarrow H^{\pm}b$) ranges between 5% (90 GeV) and 1% (150 GeV), assuming BR($H^{\pm} \rightarrow cs$=100%)

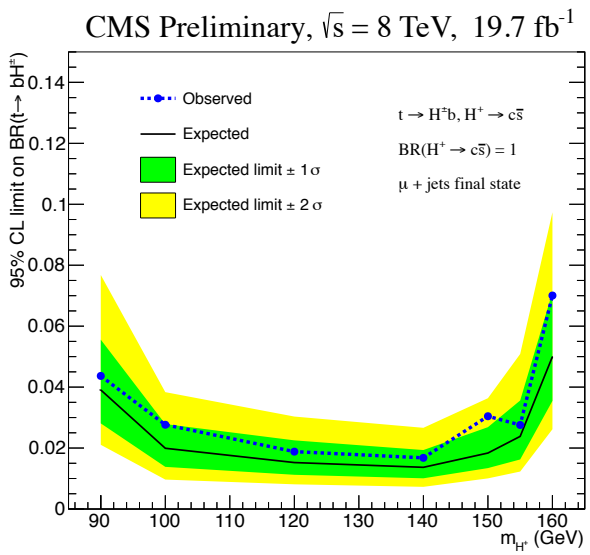
$H^{\pm}\rightarrow cs$ results from CMS

CMS PAS HIG-13-035

- **Search is focused on the μ+jets final state only (8 TeV)**
- **Background estimation (ttbar/W+jets/etc.) taken from simulation**
- **Dominant systematic uncertainty is from Jet Energy Scale / Resolution**

	WH	$t\bar{t}_{\mu+\text{jets}}$	W+jets	Z+jets	Single top	Dibosons
JES+JER+MET	7.8	6.5	18.5	14.2	6.9	15.8
b-jet tagging	4.2	4.6	-	-	4.2	-
Jet→b mis-id	-	-	5.8	6.5	-	8.6
Lepton selections	2.0	2.0	2.0	2.0	2.0	2.0
Cross-section	6.0	6.0	5.0	4.0	6.0	10.0
MC Statistics	3.1	0.7	7.8	6.0	3.8	10.1
Top-Pt reweighting	1.8	1.9	-	-	-	-
Luminosity	2.6	2.6	2.6	2.6	2.6	2.6



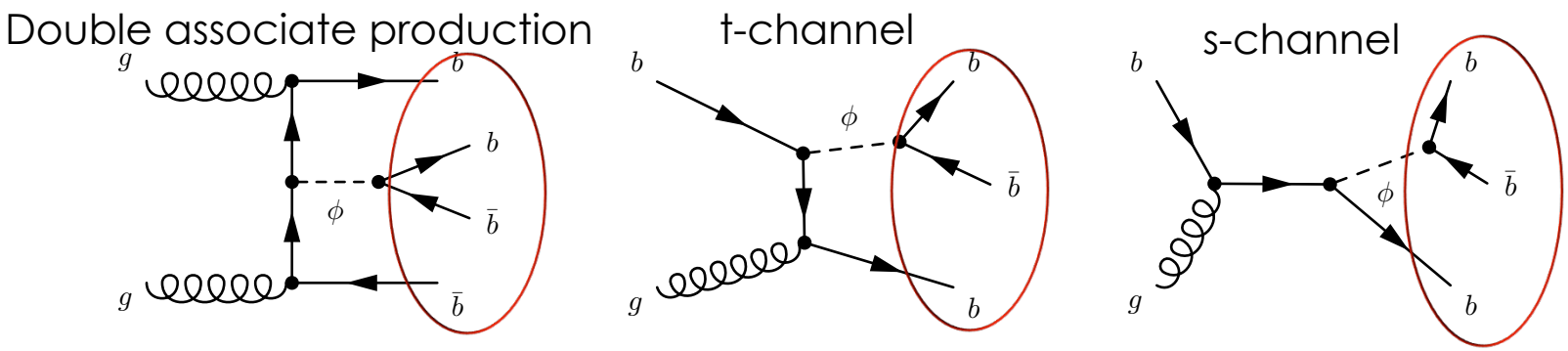


- **Observed limits on BR(t→H±b) ranges between 4% (90 GeV) and 2% (150 GeV), assuming BR(H±→cs=100%)**

Searches for Φ(h,H,A)→bb

- **Branching ratio Φ→bb is ~90% and relatively stable with m_A**
- **Due to dependence of couplings to down-type quarks, this channel is mainly sensitive at high tanβ values**
- **Searches performed in the m_Φ = 100-900 GeV range**

- **Signature: bΦ+X→bbb+X**



Analyses look for 2 to 3 b-tagged jets

- **Key challenges**
  1. **Triggering on b-jets of high p_T (thresholds 70-80 GeV)**
  2. **Rejection of very large QCD background – through $\Delta R(b_i,b_j)$**
  3. **Control of b-tagging mis-tag rate**
  4. **Combinatorics in jet association to form reconstructed m_Φ**

Φ→bb results from CMS

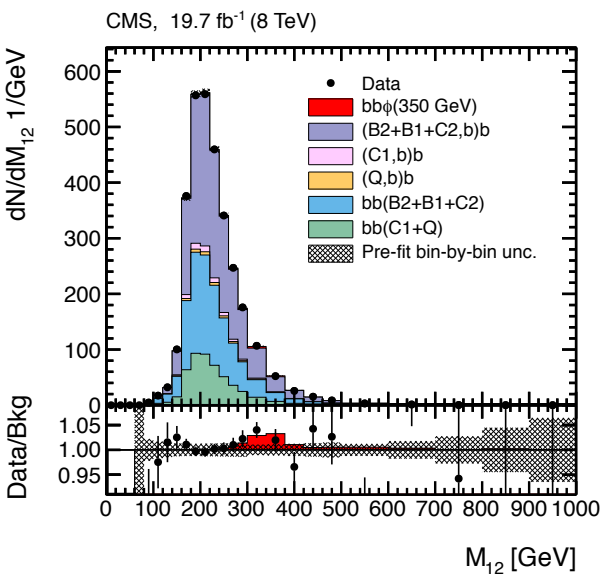
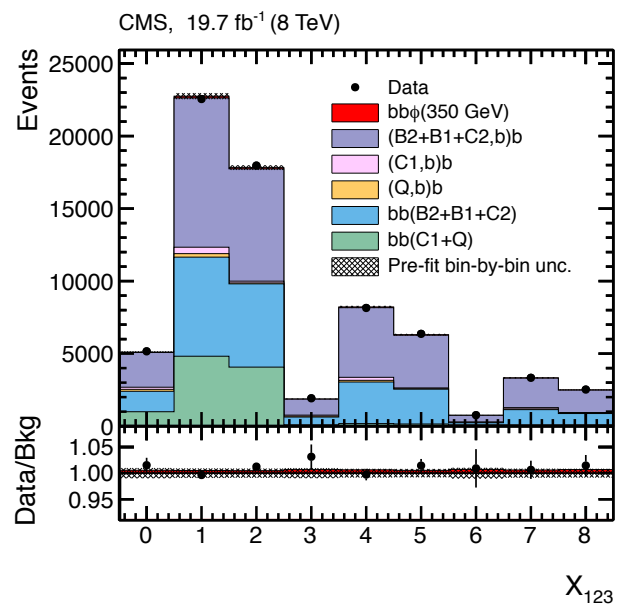
New!
arXiv:1506.08329 [hep-ex]
Submitted to JHEP

- **Selection of 2 (3) b-tagged jets with p_T>80, 70 (25) GeV**
- **The candiate events are categorized based on a combination of the secondary vertex masses of the jets in the event: $\Sigma M_{SV,j}$**

→ **9 categories defined on simultaneous values of $\Sigma M_{SV,j}$ for the 2 (3) jets in the event**

$\Sigma M_{SV,j}$ [GeV]	B_j
0–1	0
1–2	1
2–3	2
>3	3

B_3	B_1+B_2 0–1	2–3	4–6
0–1	0	1	2
2	3	4	5
3	6	7	8

→ **X_{123} value is 0..9**

- **2D (M_{12}, X_{123}) signal and background templates (here showing projections)**