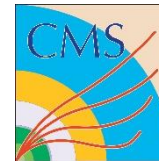


Extended Higgs sector

Alice Magnani

University of Pavia and INFN

on behalf of ATLAS and CMS collaborations



Precision theory

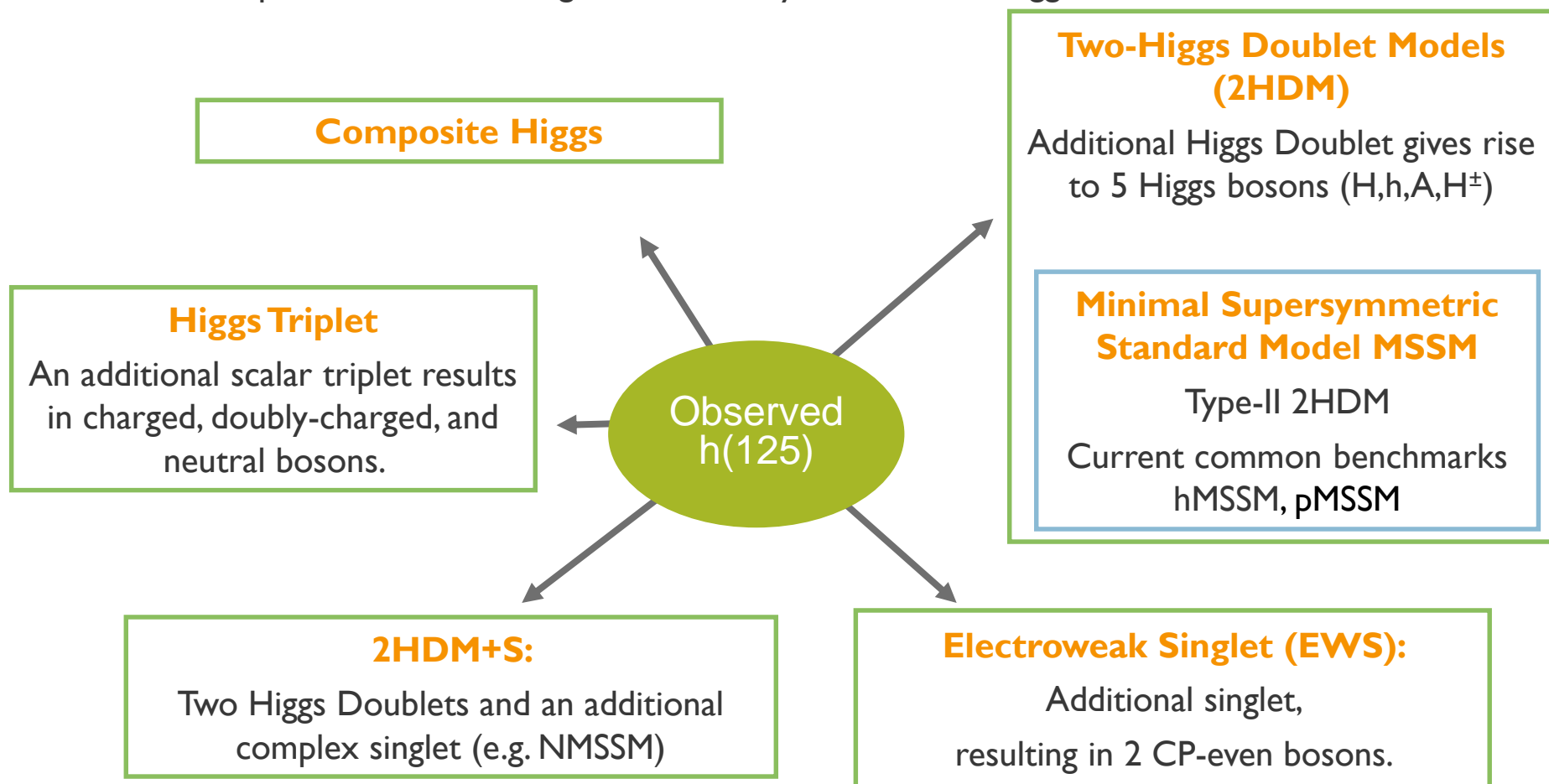
for precise measurements at the LHC and future colliders

Quy-Nhon, Vietnam

September 25-October 1, 2016

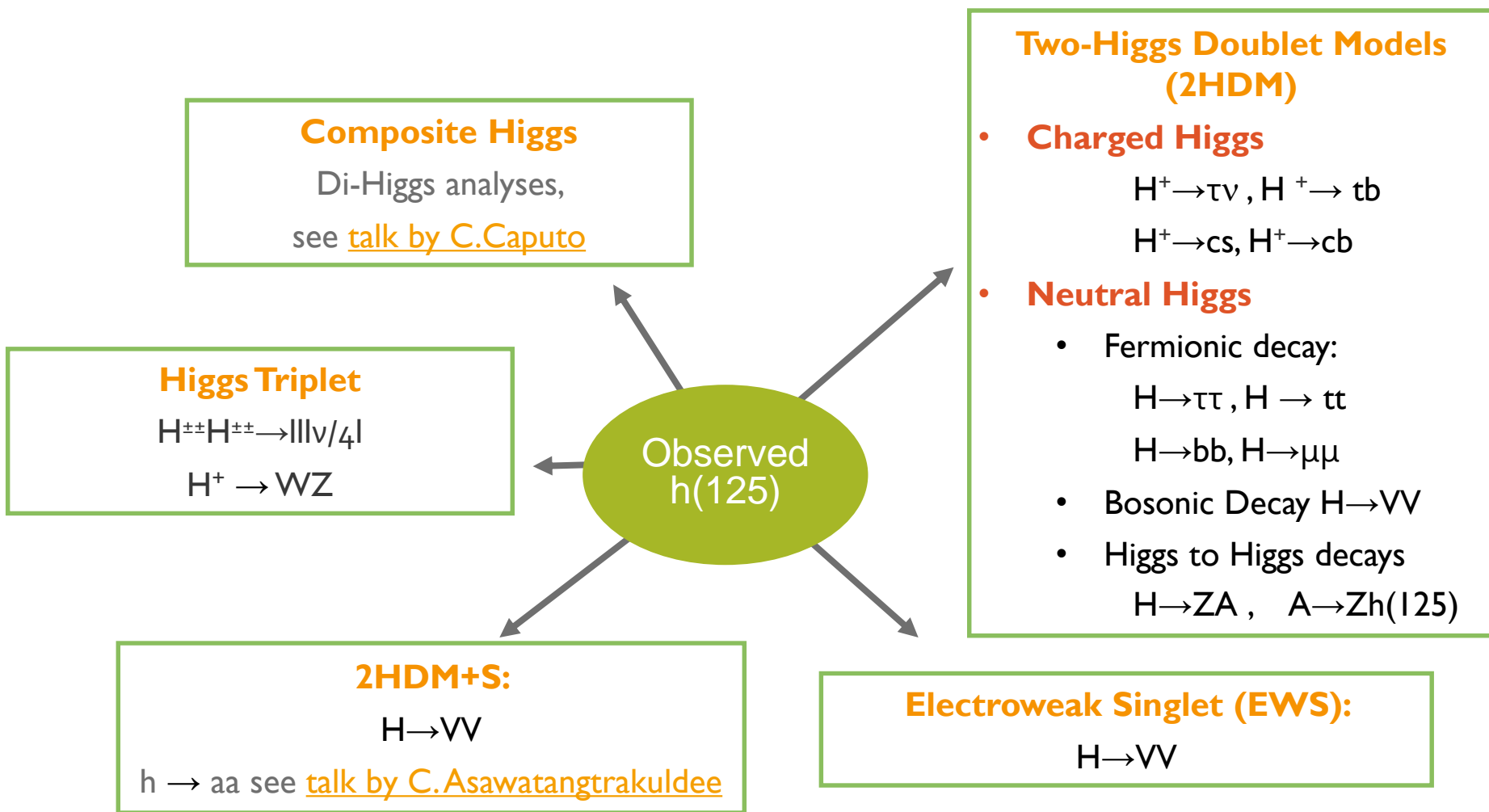
Extended Higgs sector

- Many BSM theories require for extensions of the Higgs sector.
- The observed 125 GeV Higgs boson can be part of a wider family.
- New physics in the Higgs sector can be detected either in deviations of the $h(125)$ couplings w.r.t. SM predictions, or through the discovery of additional Higgs states.



Extended Higgs searches

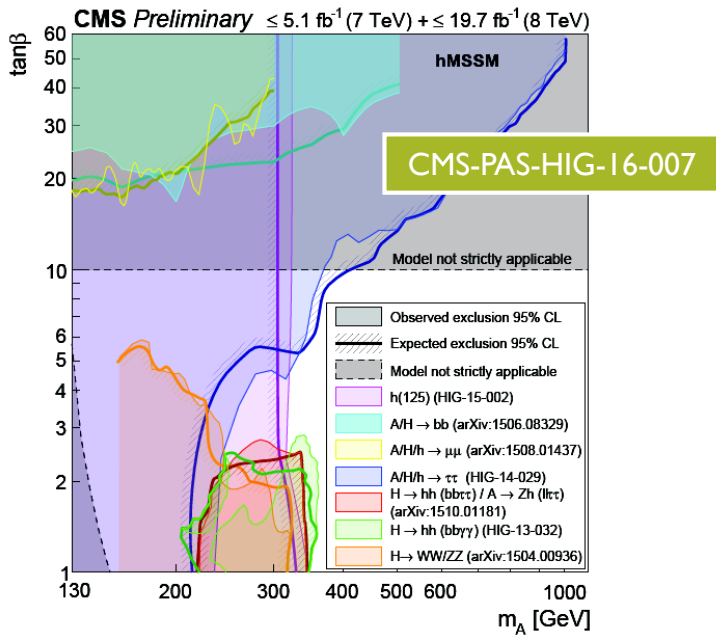
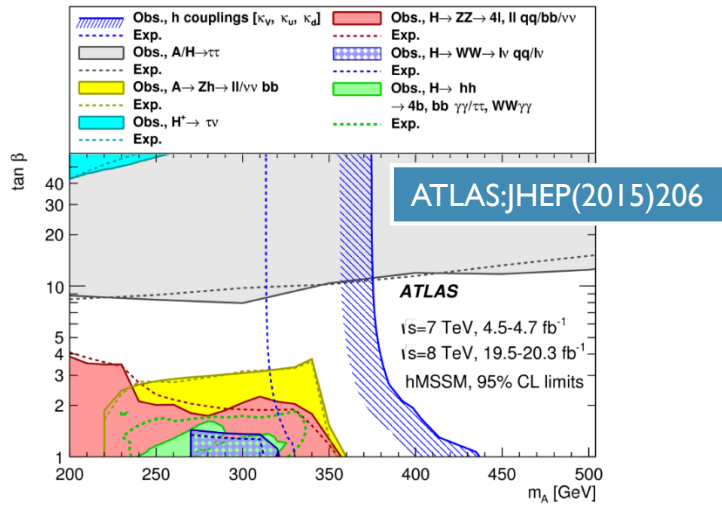
Very rich research field, with many possible signatures.



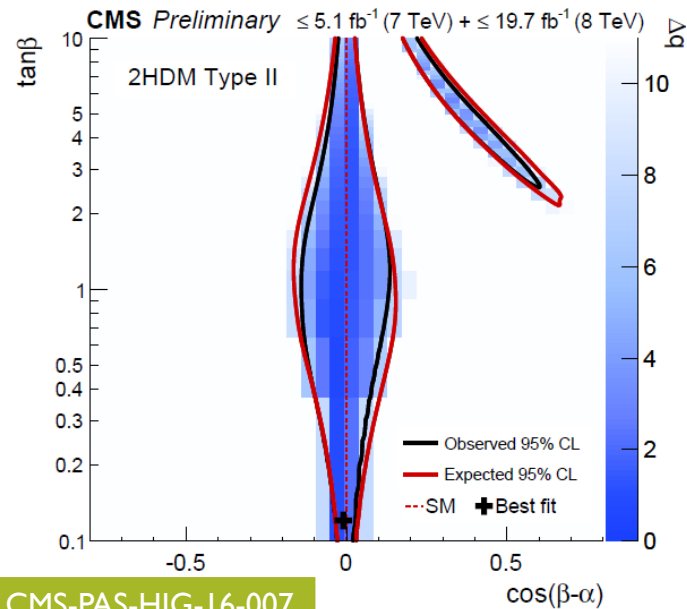
Neutral Higgs

Fermionic decays

The MSSM after Run I

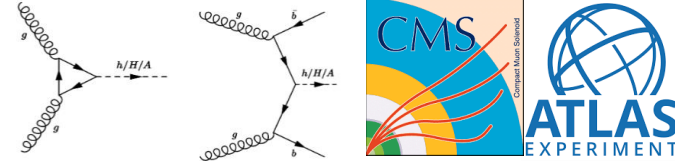


- Many searches were performed in **run-I** at the LHC, **no evidence** of BSM physics
- Much parameter space is excluded, but there is still room for high mass BSM Higgs
- In MSSM coupling $HVV \propto \cos(\beta - \alpha) < 0.1$ given the observed h125 coupling. This makes **fermionic channels** particularly interesting. **$\tau\tau$ final state is the most sensitive.**



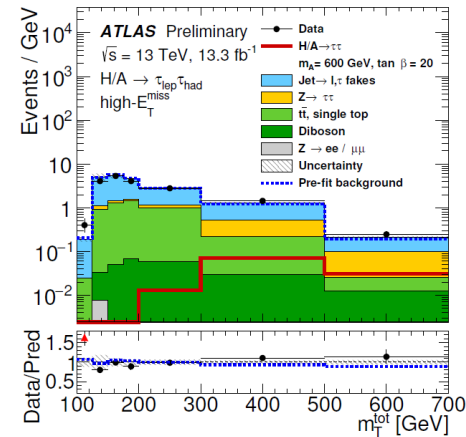
CMS-PAS-HIG-16-007

Search for $A/H \rightarrow \tau\tau$

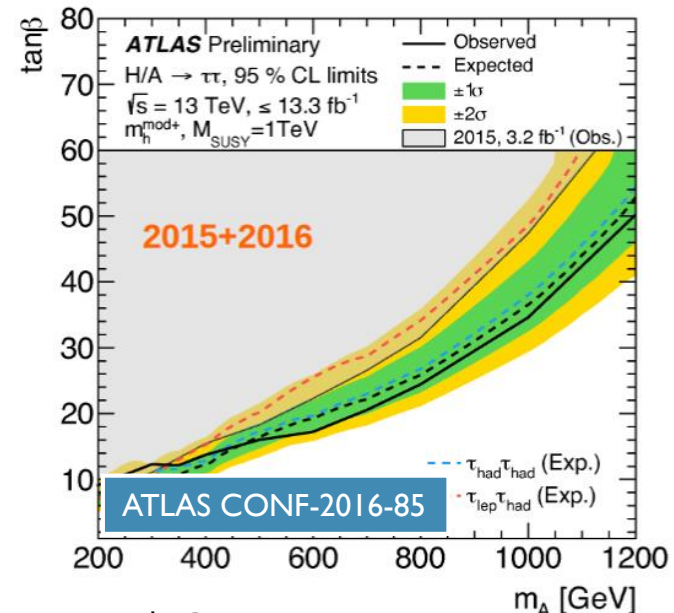
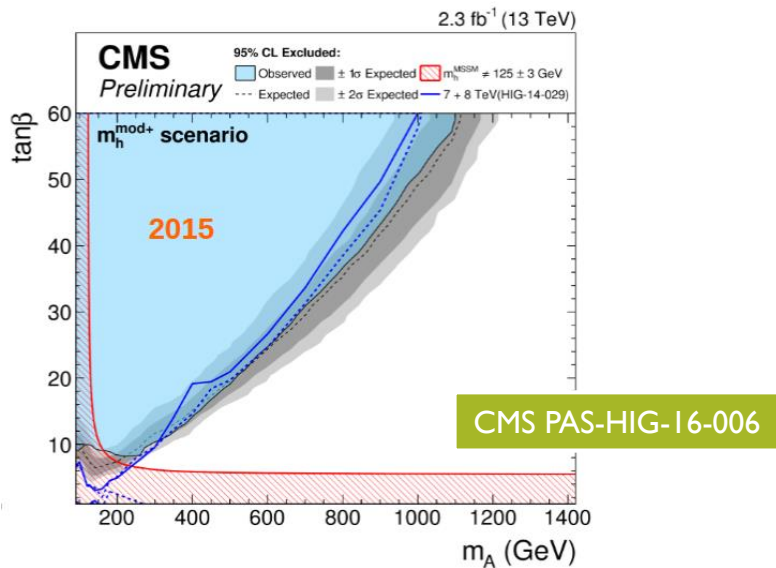


- Gluon fusion and b-associated production.
- **Discriminating variable:**
CMS transverse mass of the di-tau system
ATLAS total transverse mass
- Non-observation interpreted as limit in $(m_A, \tan\beta)$ plane for **various MSSM scenarios**

Final state	Categories
$\tau_{lep}\tau_{had}$	b-tag , b veto, high E_t^{miss} [ATLAS]
$\tau_{had}\tau_{had}$	b tag, b veto
[CMS: $e\mu$]	b tag, b veto



$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)},$$



Exclusion limit competitive already with few fb^{-1} @ 13 TeV with Run I

Search for $A/H \rightarrow \mu\mu$

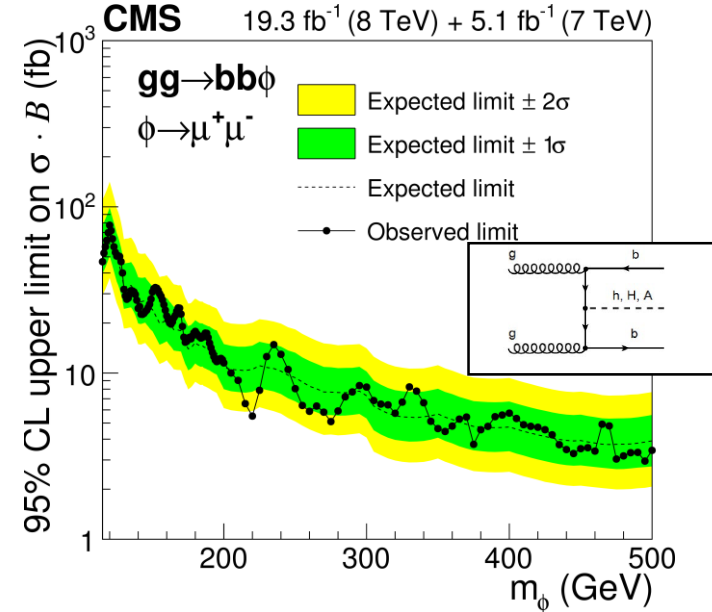
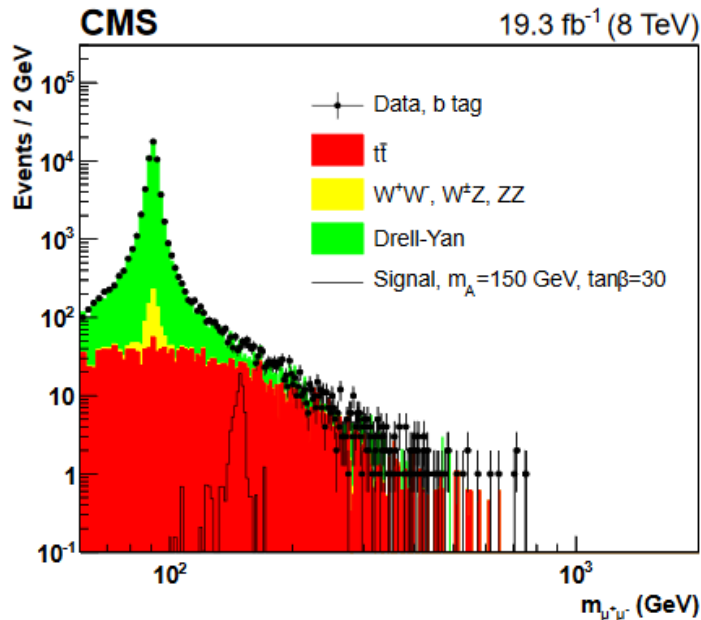
CMS | 508.0 | 437v2



- Expected BR $O(10^3)$ smaller than $\tau\tau$ but **experimentally cleaner**
- efficient reconstruction and excellent mass resolution
- Also split in gluon-fusion and b-associated production

CMS results with 8 TeV, ATLAS search only at 7 TeV

Common selection	
Single muon trigger	$p_T > 24 \text{ GeV} + \text{isolation} + \eta < 2.1$
Event primary vertex	$ z_{PV} < 24 \text{ cm}$
Muon selection	2 opposite-charged muons, $p_T > 24 \text{ GeV}, \eta < 2.1,$ track quality cuts, $ d_{xy} < 0.02 \text{ cm}, d_z < 0.1 \text{ cm},$ angular matching with trigger, isolation $E_T^{\text{miss}} < 35 \text{ GeV}$
Category C1	
b tag	1 or 2 b-tagged jets, $p_T^{\text{jet}} > 20 \text{ GeV}, \eta^{\text{jet}} < 2.4$
Category C2	
No b tag	Events with no b-tagged jets



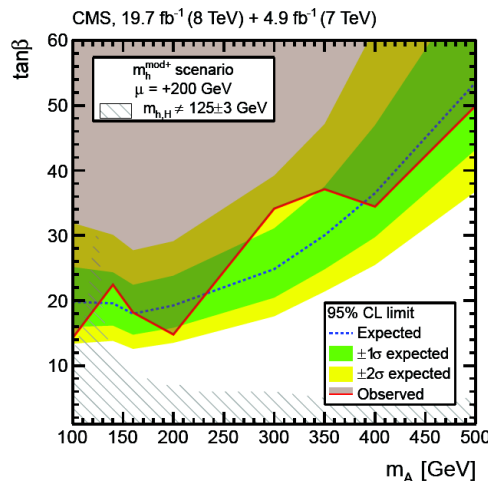
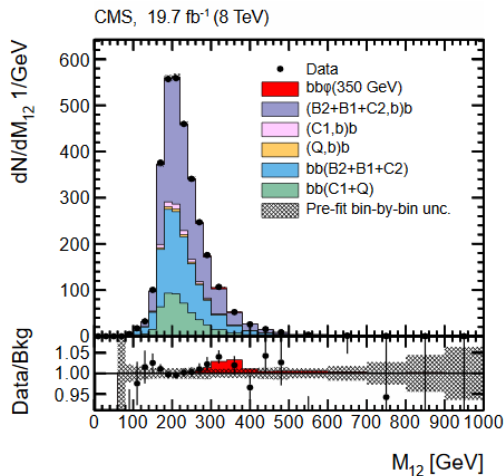
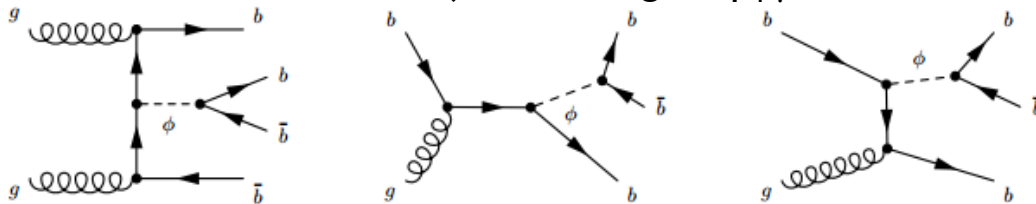
Search for $A/H \rightarrow bb$

8 TeV CMS 1506.08329v2

ϕ produced in association with at least one b quark and decaying to bb .

Final state with ≥ 3 b-jets. Signature sensitive to MSSM Higgs at high $\tan\beta$.

Search for a peak in the invariant mass distribution of the two b jets with higher p_T .

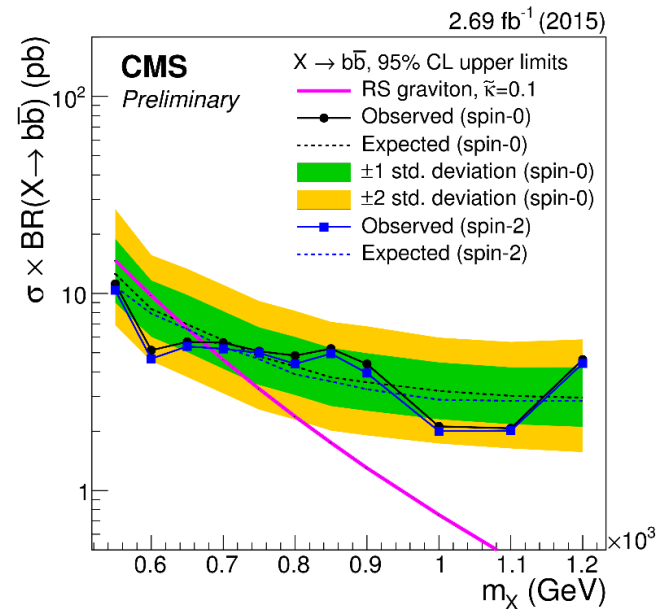


13 TeV CMS PAS-HIG-14-017

Search for a neutral boson resonance decaying to b quarks with a mass in the range 650-1200 GeV.

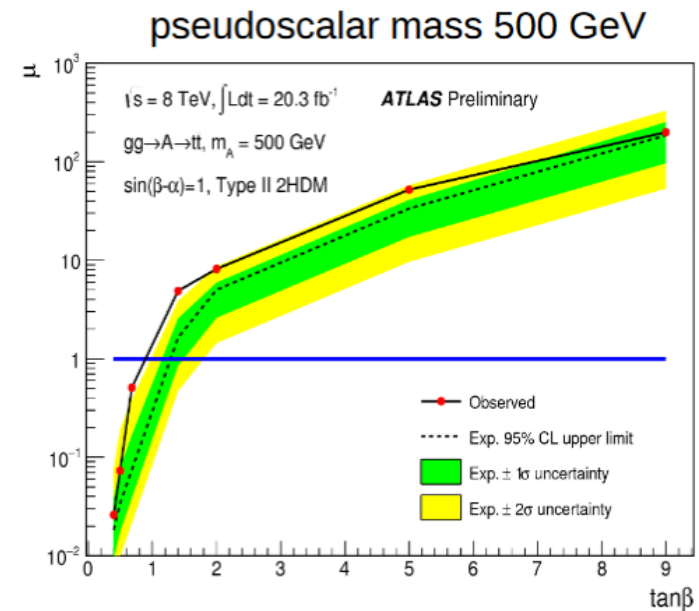
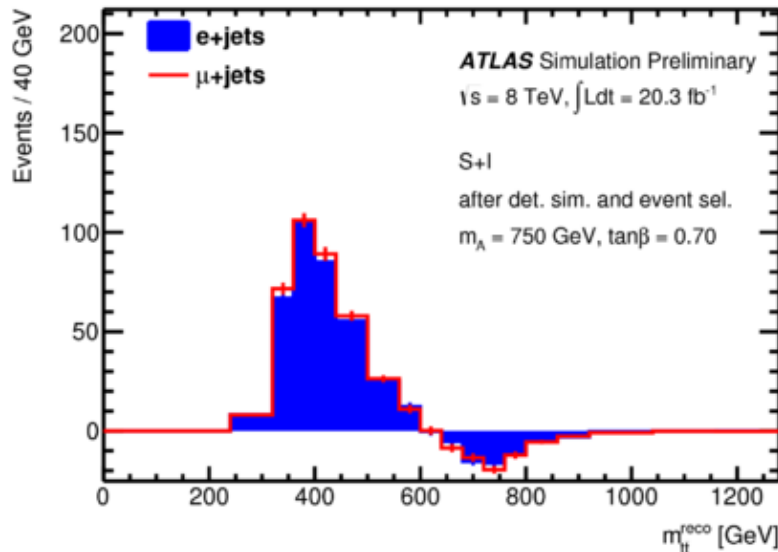
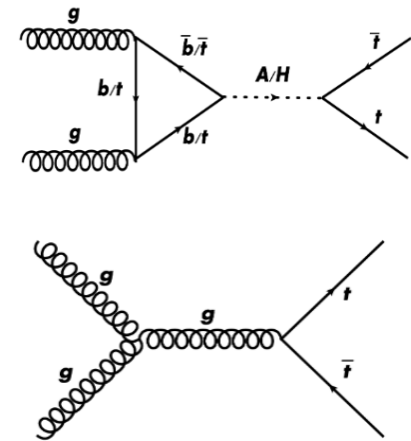
≥ 2 b-jets selections.

2 benchmark models, spin-0/spin-2



Search for $A/H \rightarrow t\bar{t}$ @8 TeV

- If the new boson mass is above $2 m_t$, decay to top pair is allowed.
- Particularly competitive in 2HDM for high masses and **small/intermediate tan beta**.
- **Invariant mass spectrum of the $t\bar{t}$ pair** in semileptonic final states is reconstructed via a **kinematic fit** technique.
- **Interference effects** between the signal process and $gg \rightarrow t\bar{t}$ production in the Standard Model, **heavily distorts the signal shape to a peak-dip structure**,
- **Exclusion limits** for two masses (500 and 750 GeV), and for scalar and pseudoscalar hypotheses, as a function of $\tan\beta$ in MSSM. **The 500 GeV limit excludes $\tan\beta < 0.85$ (0.45) for A(H) hypothesis**



Neutral Higgs

Higgs to Higgs decays

Search for $A \rightarrow Zh, h \rightarrow bb$

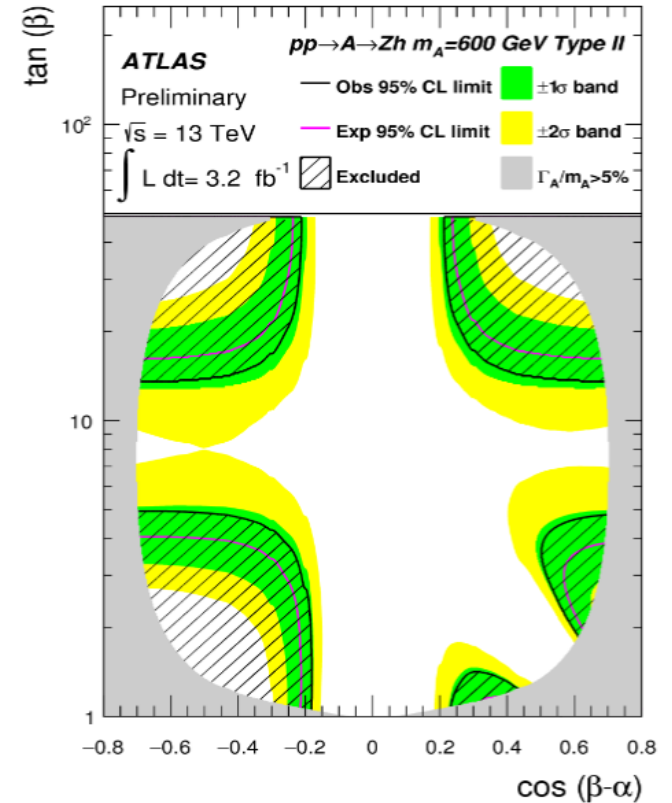
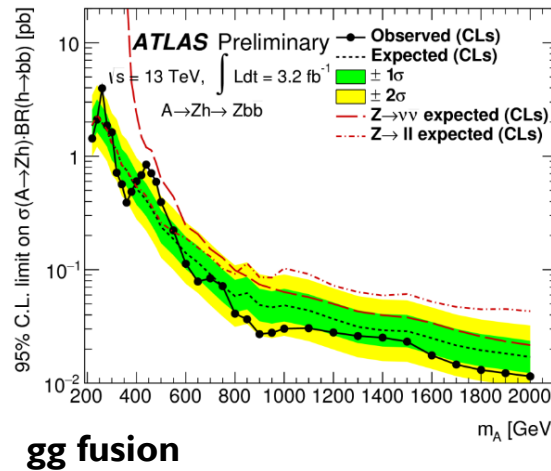
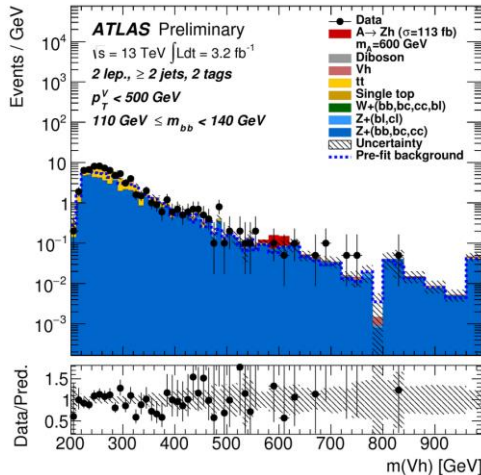
- Search for a pseudoscalar state in the mass range 200 – 2000 GeV
- Decay mode: Z boson to $\nu\nu$ or ll and a SM Higgs to bb .
- Useful to probe a complementary region of the parameter space with respect to fermionic decays in MSSM.

Categories according to

- 0/2 leptons
- p_T of Z candidate (low < 500 GeV, high ≥ 500 GeV)
- # b-tagged jets (gg fusion or b associated production)

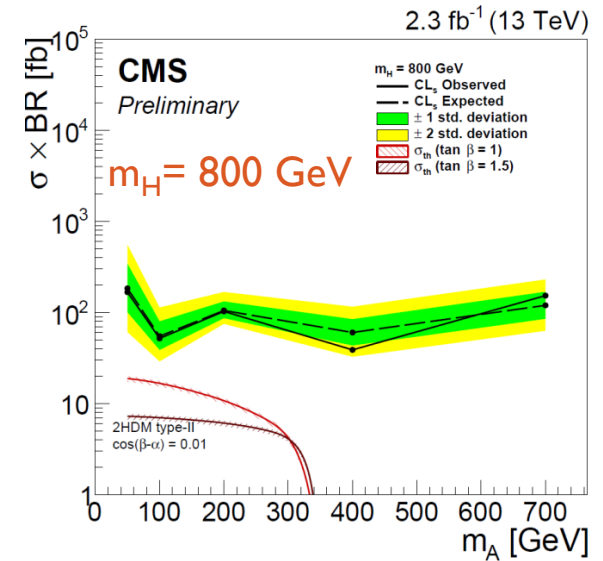
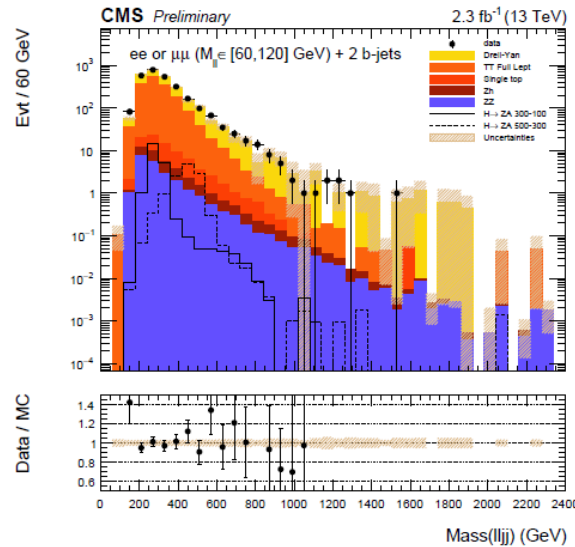
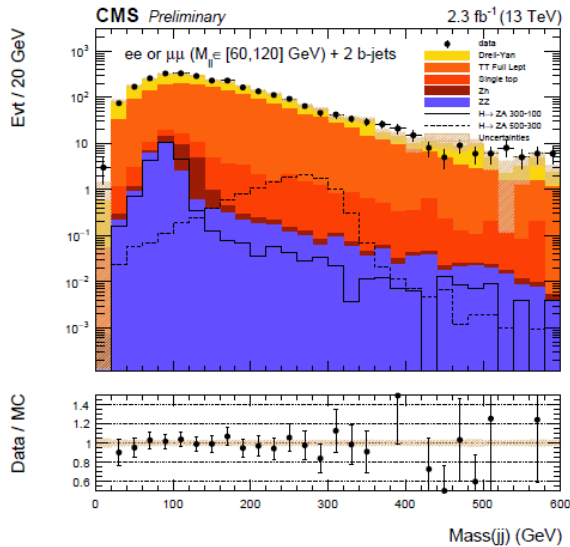
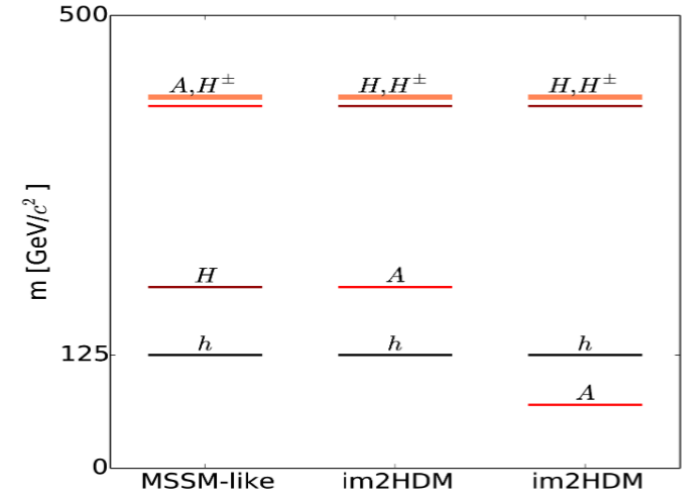
Final discriminant:

$m(Zh)$ in 2-lep category, $m_T(Zh)$ transverse mass in 0-lep category



Search for $H \rightarrow ZA, Z \rightarrow ll, A \rightarrow bb$

- Motivated in 2HDM with **twisted custodial symmetry** which gives a heavier scalar H and a lighter pseudoscalar A boson.
- **2 l + 2 b selection**
- Depending on $(m_H - m_A)$ hypothesis, a rectangular signal region is defined in the (m_{llbb}, m_{bb}) plane. The inverse is used as control region.
- **Limits for three m_H hypotheses, as a function of m_A**



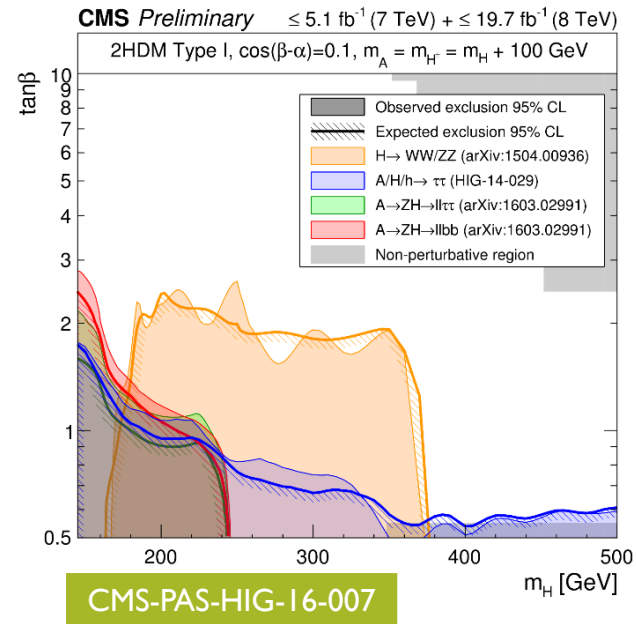
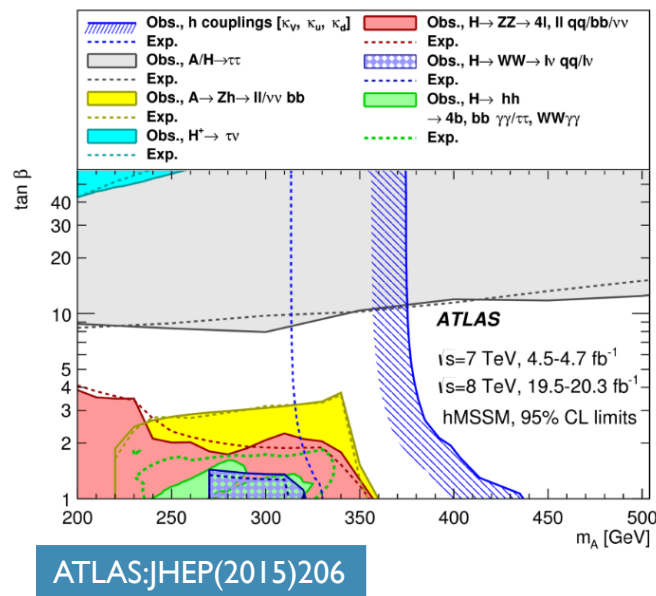
Diboson searches

	CMS	ATLAS
$H \rightarrow ZZ \rightarrow 4l$	CMS-PAS-HIG-15-004	ATLAS-CONF-2015-059
$H \rightarrow ZZ \rightarrow 2l2\nu$	CMS-PAS-HIG-16-001	ATLAS-CONF-2016-012
$H \rightarrow ZZ/ZW \rightarrow 2l2q/2\nu2q$	CMS-PAS-B2G-16-010	ATLAS-CONF-2016-082
$H \rightarrow WW/WZ \rightarrow l\nu2q$	CMS-PAS-B2G-16-020	ATLAS-CONF-2016-062
$H \rightarrow WW \rightarrow l\nu l\nu$	-	ATLAS-CONF-2016-021

Searches for $H \rightarrow VV$

- VV resonances important in **several models**, including extra-dimensions (e.g. $G \rightarrow VV$ in Randall-Sundrum models). Typically scalar searches limited in the range up to 1 TeV.
- In the **MSSM** they cover **low/int region in $\tan\beta$** in the mass range $2m_W \lesssim m_H \lesssim 2m_t$.
- For run I they provided **complementary information with respect to fermionic searches**.
- Projections for run II show limited improvement of the phase space that will be covered by fermionic decays.
- Di Boson searches are instead useful in **type I 2HDM**, and they are a good probe for **Singlet (+Doublet) Models**.

No evidence for new physics has been found.



Charged Higgs Bosons

Charged Higgs searches

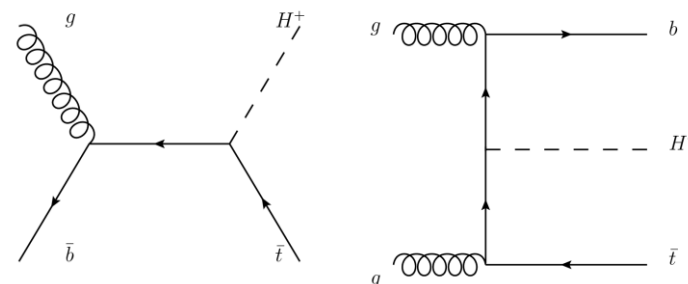
Wide range of final states allow to probe different regions of the parameter space in a variety of SM extensions: MSSM, 2HDM, Higgs triplet models...

	Model	H^+ mass range
$H^+ \rightarrow \tau \nu$	MSSM , 2HDM	both low and high
$H^+ \rightarrow tb$	MSSM , 2HDM	High mass
$H^+ \rightarrow cb$	MSSM, 2HDM	Low mass
$H^+ \rightarrow cs$	MSSM, 2HDM	Low mass
VBF $qqH^+ \rightarrow qqWZ$	Higgs triplet	High mass
H^{++} to leptons	Higgs triplet	High mass

In 2HDM a charged Higgs production modes depend on m_{H^+} .

- At **low mass** ($m_{H^+} < m_t - m_b$) charged Higgs can be looked for in top quark decays.
- At **high mass** ($m_{H^+} > m_t - m_b$) the charged Higgs is produced in association with a top quark

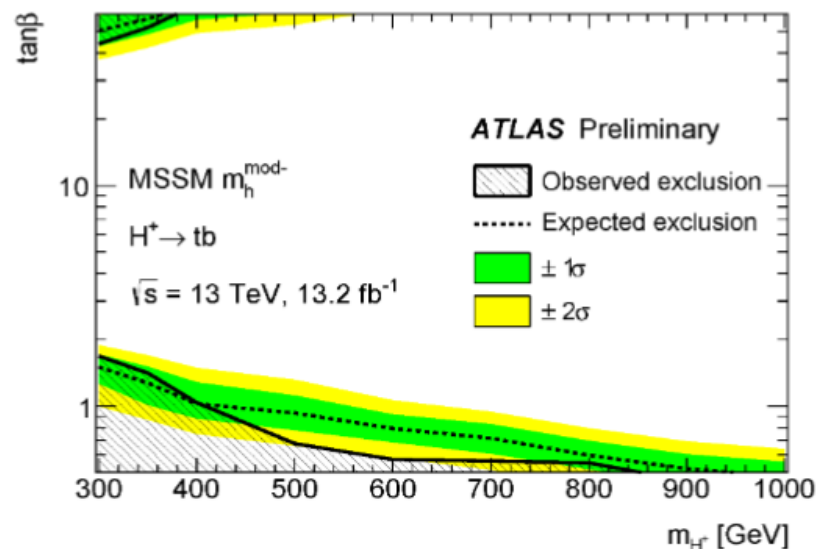
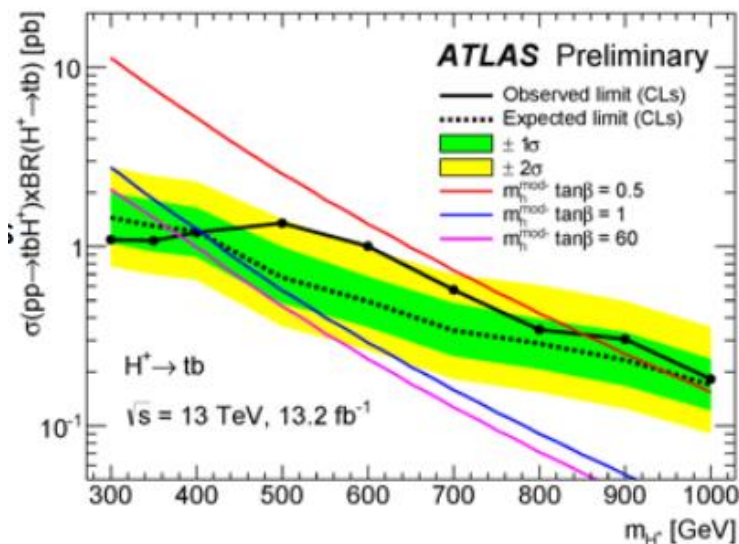
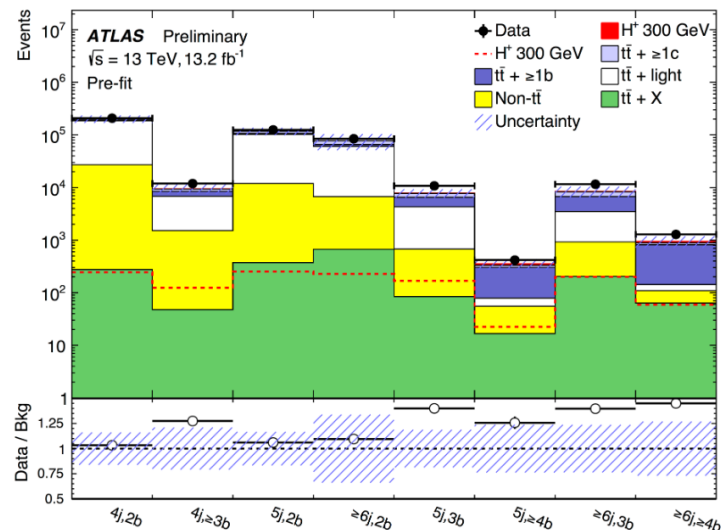
$$m_{H^+} > m_t - m_b$$



High mass searches $H^+ \rightarrow tb$

ATLAS analysis on 2015+2016 dataset

- 1 lepton, > 4 jets, >2 btag, τ_{had} veto
- 4 control region and 4 signal region based on the **number of jets and of b-jets**
- **Discriminating variable** in signal region is the output of a **Boosted Decision Tree**



CMS result @8 TeV. Upper limit on the $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow tb)$ between 1.99 and 0.13 pb in the mass range 180-600 GeV [CMS: 1508.07774v2]

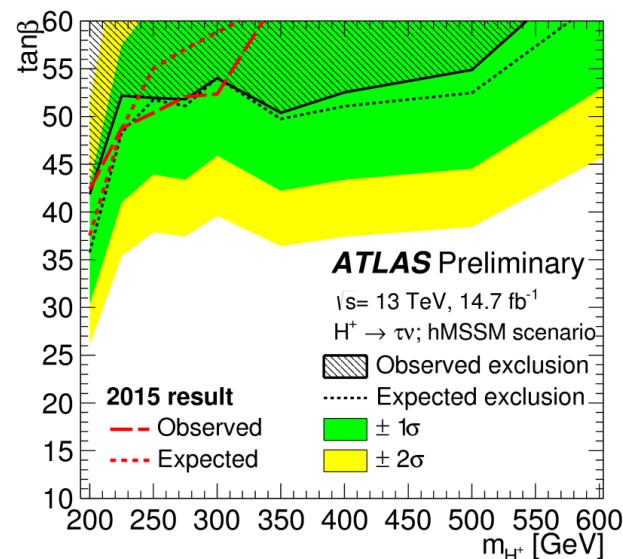
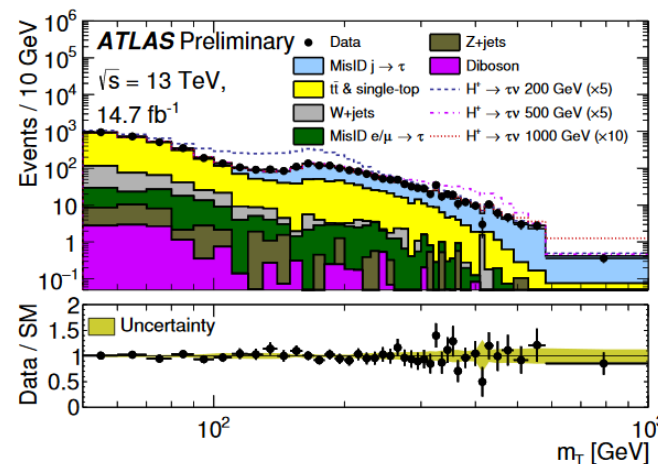
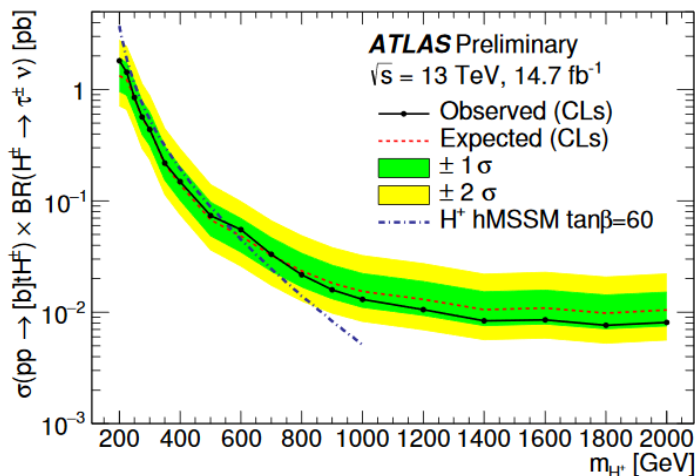
ATLAS analysis on 2015+2016 dataset

Event Selection

- ≥ 3 jets including ≥ 1 b-tagged jet
- 1 τ and no e or μ
- $E_{T\text{miss}} > 150$ GeV
- $m_T > 50$ GeV

final discriminant variable

$$m_T = \sqrt{2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta\phi_{\tau\text{had-vis,miss}})}$$



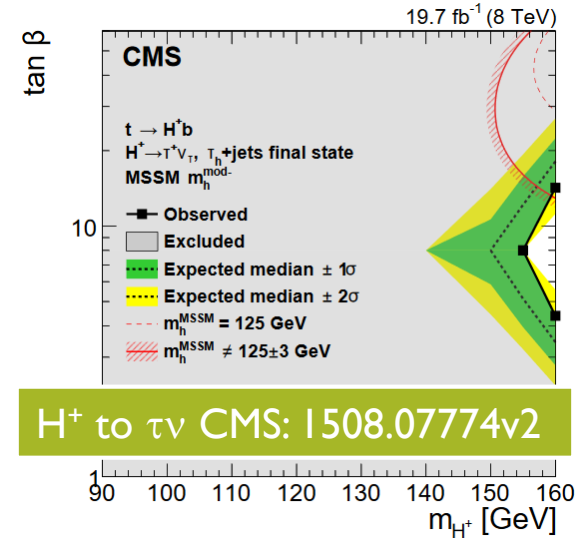
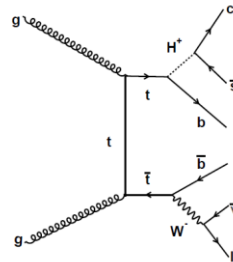
CMS result @8 TeV. Upper limit on the $\sigma(\text{pp} \rightarrow \text{tb}H^+) \times \text{BR}(H^+ \rightarrow \text{tb})$ between 0.38 and 0.025 pb in the mass range 180-600 GeV [CMS: 1508.07774v2]

Low mass searches @ 8 TeV

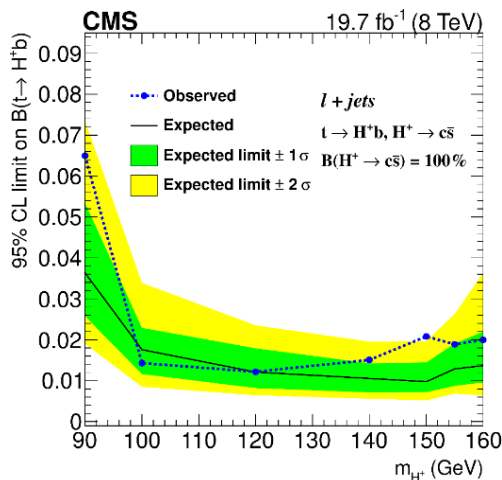
- In the **MSSM** $\tau\nu$ is the most sensitive final state, excluding completely $m_{H^+} < m_{top}$, also in the low $\tan\beta$ region, where decays such as $t \rightarrow H^+ \rightarrow cs$ become prominent.

- Still room for a light H^+ in other 2HDM. **Decays to quarks** are particularly enhanced in **Flipped-2HDM**

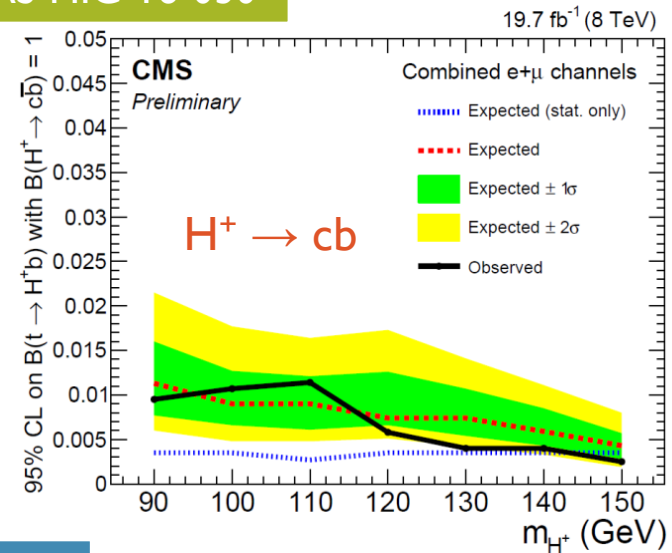
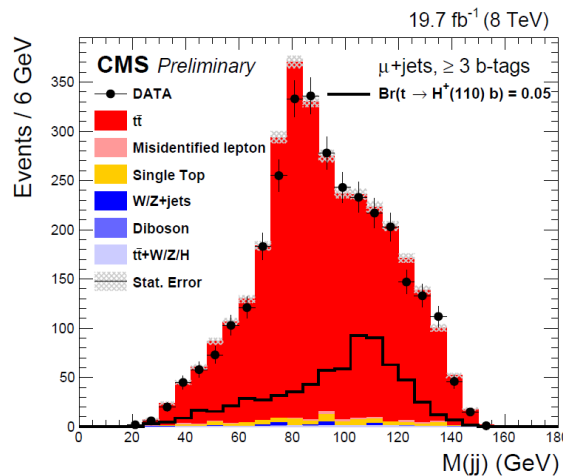
Search for **semilep tt pair events**. The H^+ can be looked for reconstructing the dijet mass from the **W decay** with a **kinematic fit** technique and looking for a **secondary peak**.



$H^+ \rightarrow cs$ CMS: 1510.04252



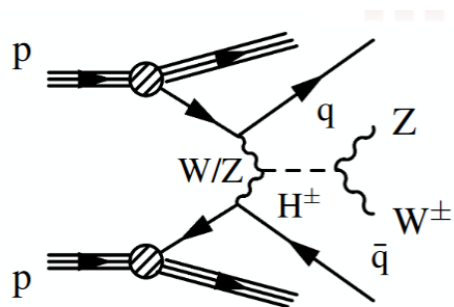
$H^+ \rightarrow cb$ CMS: PAS-HIG-16-030



ATLAS result @ 7 TeV for H^+ to cs . Eur. Phys. J. C (2013) 73:2465
Observed limit on BR ($t \rightarrow H^+ b$) **5.1%-1.2%**

Higgs Triplet - $H^\pm \rightarrow WZ$

Georgi-Machacek Nucl. Phys. B 262(1985)



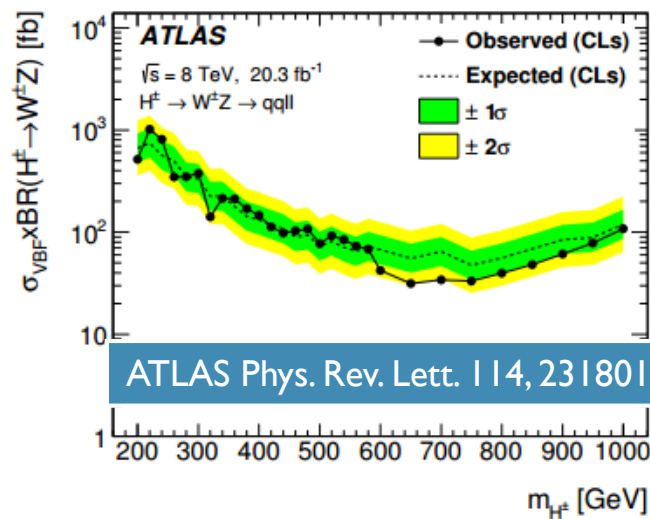
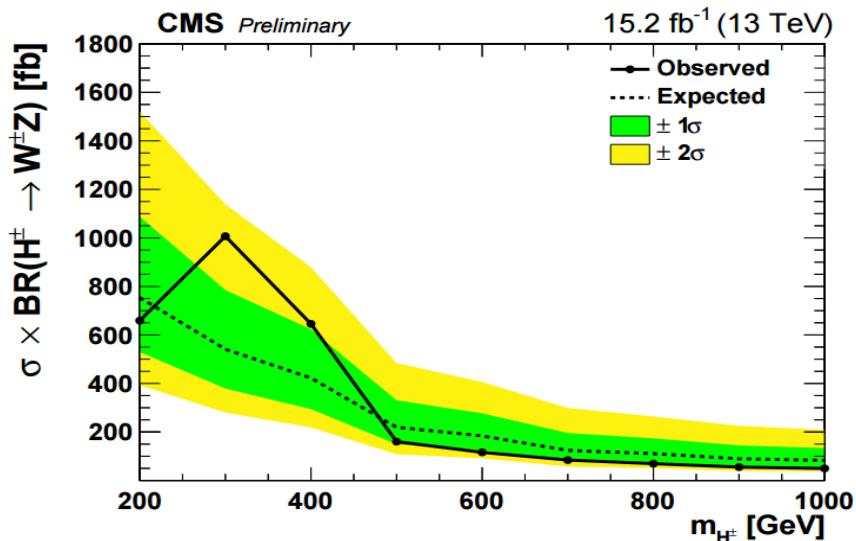
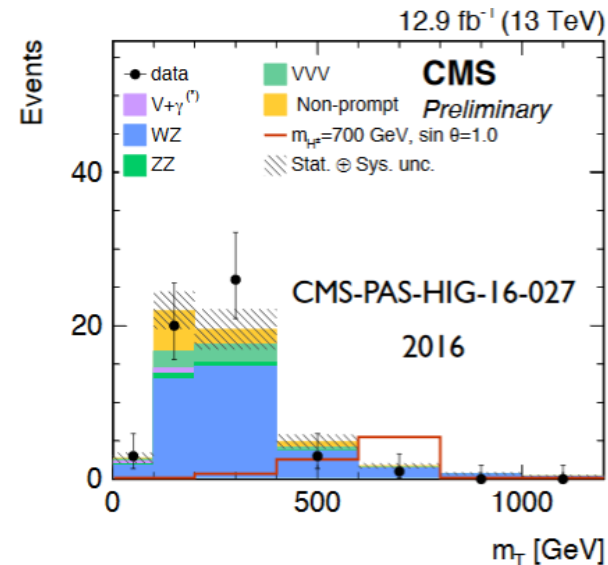
Event Selection:

3l, 2 jets, 1 Z (opposite sign lepton pair within 15 GeV from the Z mass), MET

Data-driven non-prompt background estimation

final discriminant variable

$$M_T(WZ) = \sqrt{(E_T^Z + E_T^W)^2 - (\vec{p}_T^Z + \vec{p}_T^W)^2}$$

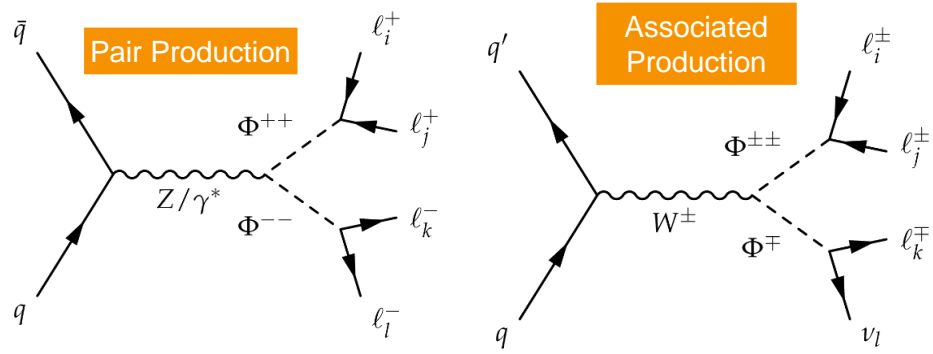


ATLAS Phys. Rev. Lett. | 14, 23 | 80 |

Higgs Triplet: Search for $H^{\pm\pm}$

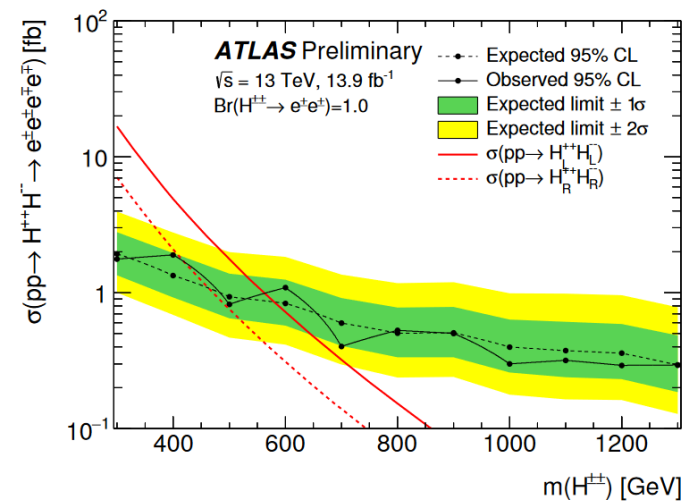
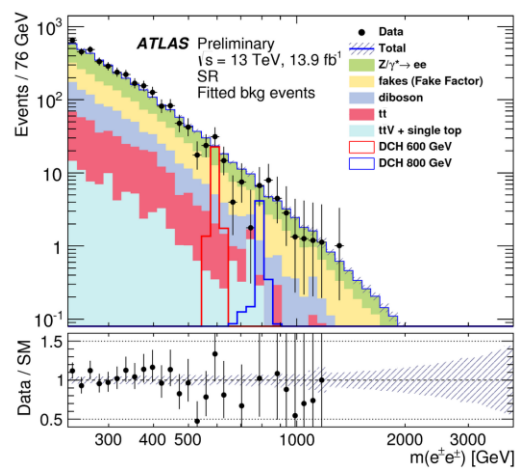
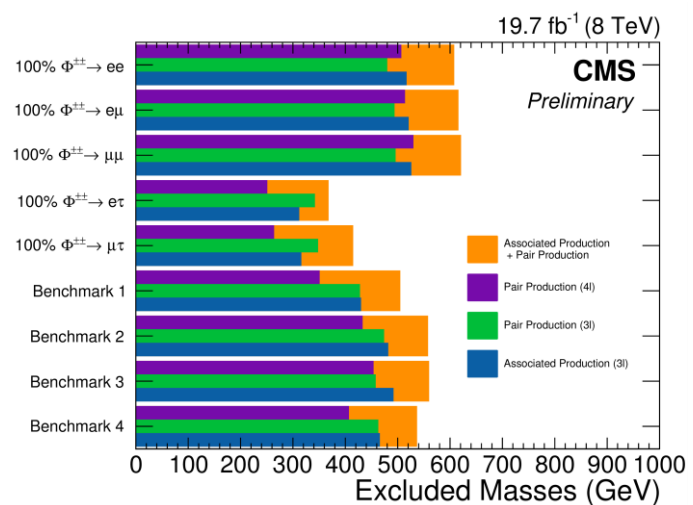
13 TeV - ATLAS-CONF-2016-051

Electron channel only, pair production only
Signal region: at least 1 same signed pair with $m_{ee} > 300$ GeV



8 TeV - CMS-PAS-HIG-14-039

Both electron and muon final states both pair production and associated production

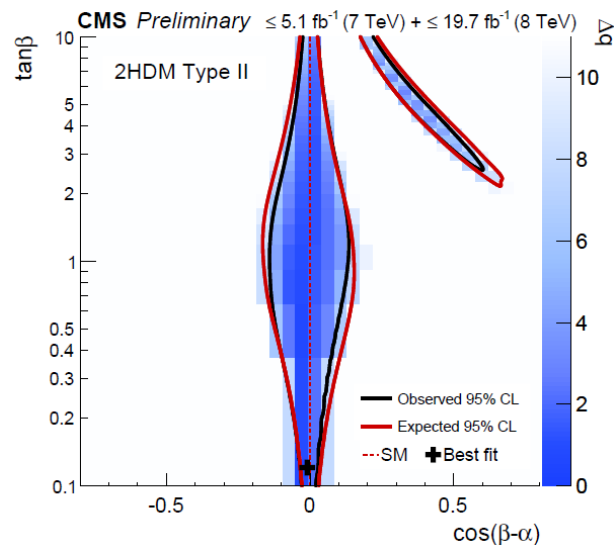
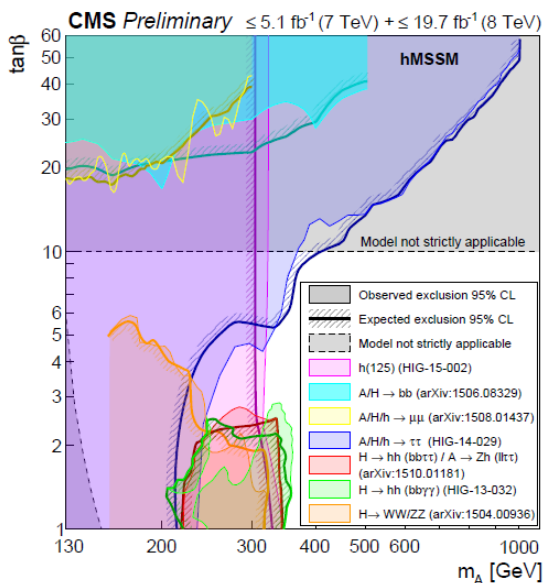
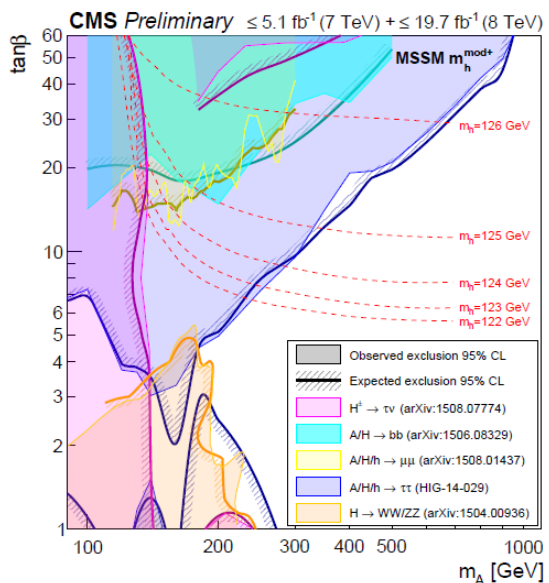
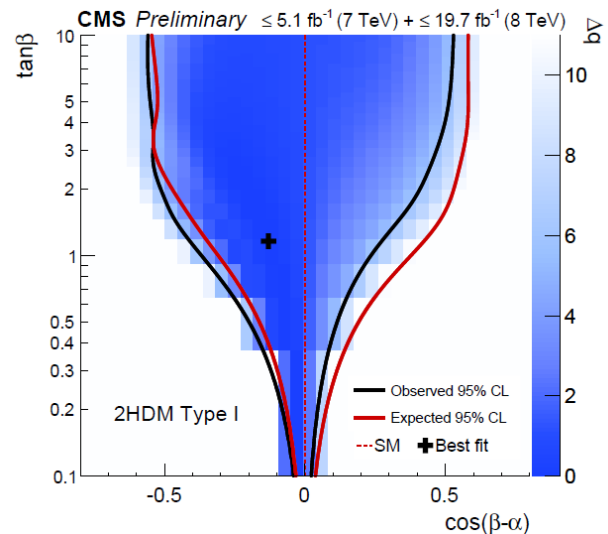
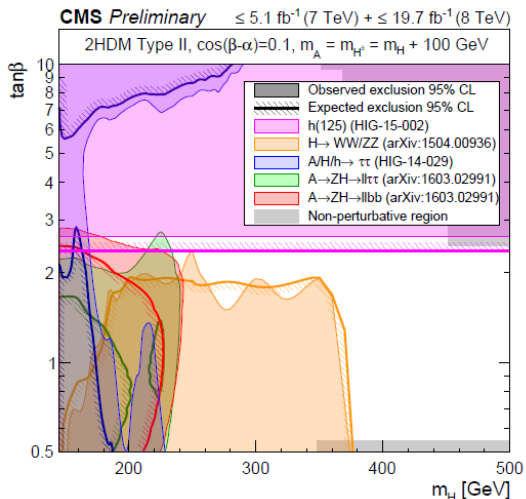
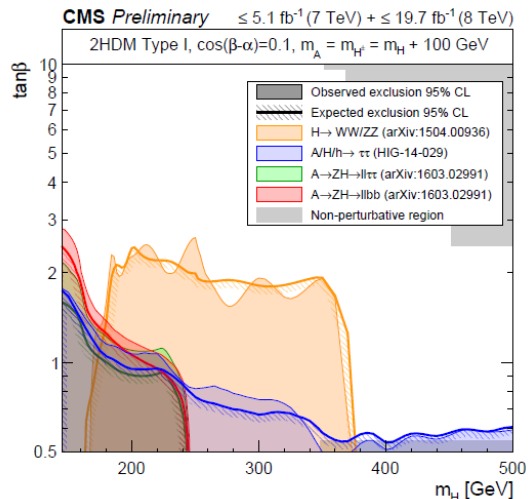


- The observed Higgs boson at mass 125 GeV may be part of an extended Higgs sector
- **BSM** models predict **new scalar, pseudoscalar and charged Higgs** states. **Extensive experimental program** at ATLAS and CMS to probe a very rich phenomenology
- No evidence found so far. Results are allowing to set more and more stringent **constraints in the parameter space of different BSM models.**
- **Stay tuned!** Many interesting results expected in the near future

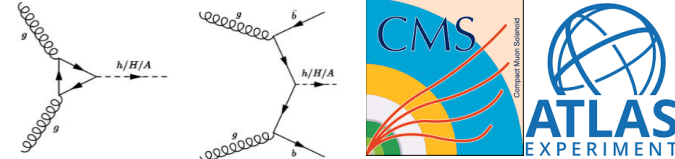
Backup

CMS Run I summary plots

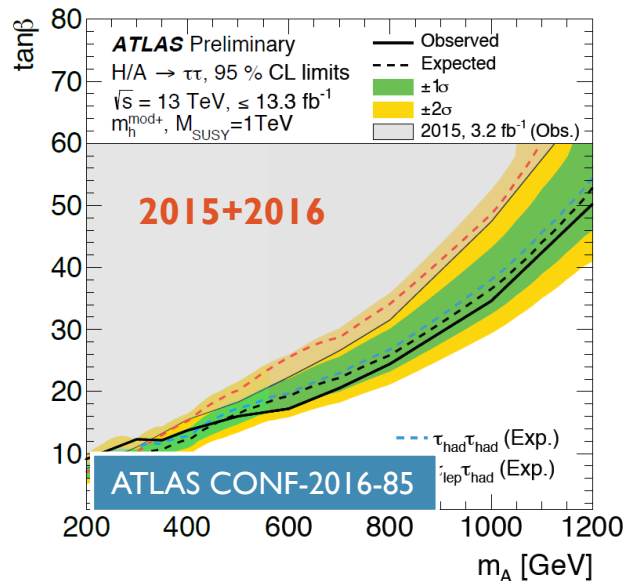
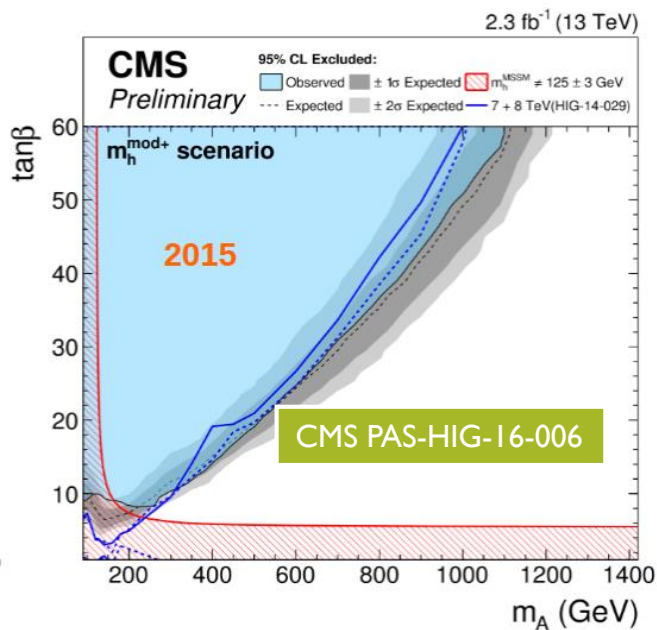
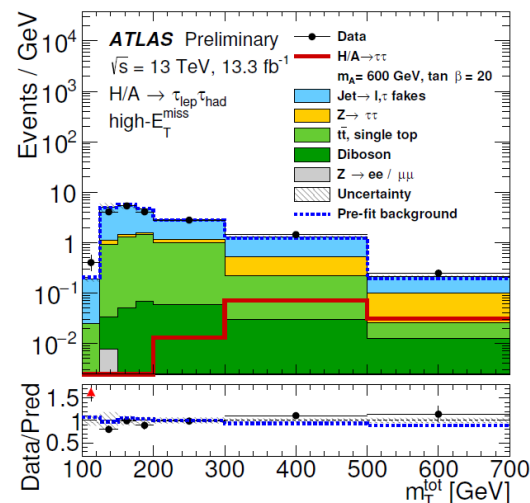
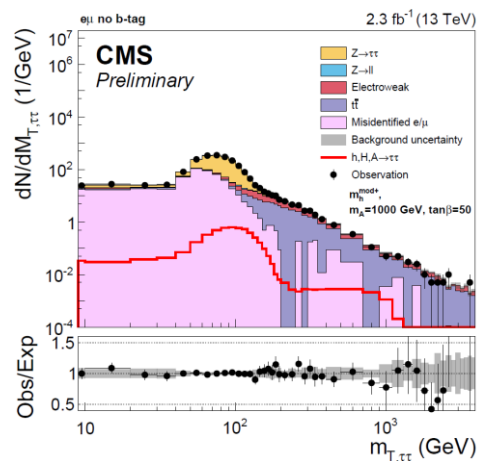
CMS-PAS-HIG-16-007



Search for $A/H \rightarrow \tau\tau$



$$m_T^{\text{tot}} = \sqrt{m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)}$$



Search for $A/H \rightarrow \tau\tau$

$\tau_{lep} \tau_{had}$ signal region	$\Delta\phi(\tau_{had-vis}, \ell) > 2.4$, $m_T(\ell, E_T^{miss}) < 40$ GeV, Veto $80 < m_{e,\tau} < 110$ GeV for $\tau_e \tau_{had}$. high- E_T^{miss} category: $E_T^{miss} (\vec{p}_T(\mu) + \vec{E}_T^{miss}) > 150$ GeV for $\tau_e \tau_{had}$ ($\tau_\mu \tau_{had}$), b-tag/b-veto categories: fail high- E_T^{miss} category requirements, $N_{b-tag} \geq 1$ (b-tag category), $N_{b-tag} = 0$ (b-veto category)
b-veto/ $t\bar{t}$ fake-factor control region	$m_T(\ell, E_T^{miss}) > 70$ (60) GeV for $\tau_e \tau_{had}$ ($\tau_\mu \tau_{had}$), $N_{b-tag} = 0$ different $\tau_{had-vis}$ identification for the anti- τ_{had} region
b-tag control region	$N_{b-tag} \geq 1$, $m_T(\ell, E_T^{miss}) > 100$ GeV
Multi-jet fake-factor control region	invert e, μ isolation requirement, $N_{b-tag} \geq 1$ (b-tag category), $N_{b-tag} = 0$ (b-veto and high- E_T^{miss} categories) different $\tau_{had-vis}$ identification for the anti- τ_{had} multi-jet control region
Multi-jet control region for r_{MJ} estimation	$m_T(\ell, E_T^{miss}) < 30$ GeV, no e, μ isolation requirement, no $\tau_{had-vis}$ passing loose identification, $N_{jet} \geq 1$ and $N_{b-tag} = 0$ (b-veto category), $N_{jet} \geq 2$ and $N_{b-tag} \geq 1$ (b-tag category), $N_{jet} \geq 1$, $N_{b-tag} = 0$ and $E_T^{miss} (\vec{p}_T(\mu) + \vec{E}_T^{miss}) > 150$ GeV for $\tau_e \tau_{had}$ ($\tau_\mu \tau_{had}$) (high- E_T^{miss} category)
$\tau_{had} \tau_{had}$ signal region	$\Delta\phi(\tau_{had-vis,1}, \tau_{had-vis,2}) > 2.7$, $N_{b-tag} \geq 1$ and $p_T > 65$ GeV for the sub-leading $\tau_{had-vis}$ (b-tag category), $N_{b-tag} = 0$ (b-veto category)
Multi-jet fake-factor control region	pass single-jet trigger, leading $\tau_{had-vis}$ with $p_T > 100$ GeV that fails medium identification, no charge requirements and for leading $\tau_{had-vis}$ $n_{tracks} \leq 7$ (b-tag category), $n_{tracks} = 1, 3$ (b-veto category), $\frac{p_T^{\tau_{had-vis,2}}}{p_T^{\tau_{had-vis,1}}} > 0.3$
Fake rate control region	pass single-muon trigger, isolated muon with $p_T > 55$ GeV, $\tau_{had-vis}$ with $p_T > 50$ GeV, $\Delta\phi(\mu, \tau_{had-vis}) > 2.4$, $m_T(\mu, E_T^{miss}) > 40$ GeV $N_{b-tag} \geq 1$ (b-tag category), $N_{b-tag} = 0$ (b-veto category)
Same-sign validation region	The two $\tau_{had-vis}$ objects are required to have the same electric charge

Search for $A/H \rightarrow \mu\mu$

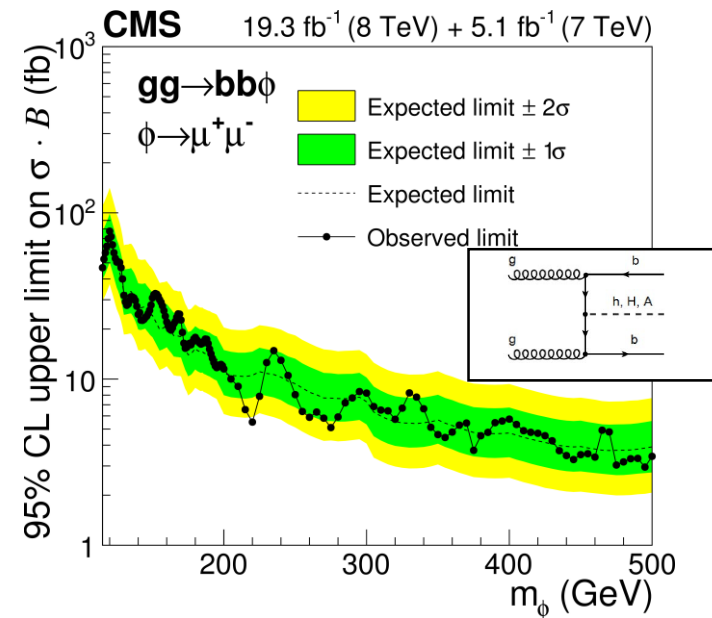
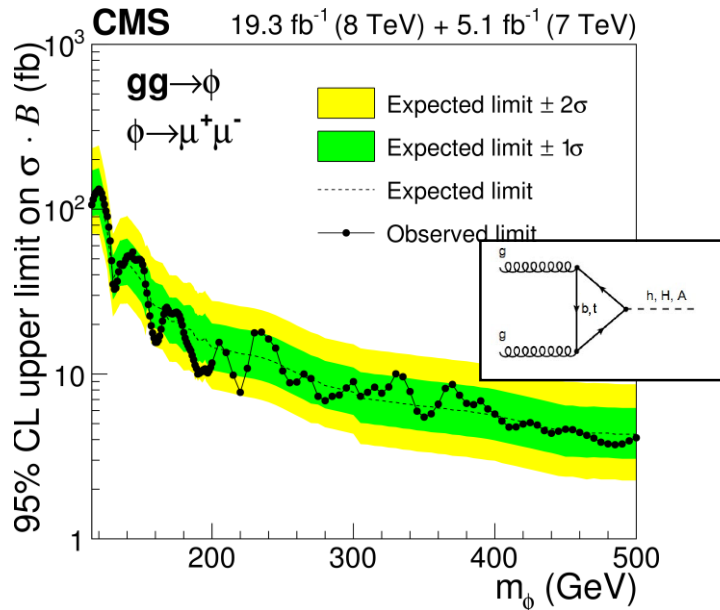
CMS | 508.0 | 437v2



- Expected BR $O(10^3)$ smaller than $\tau\tau$ but **experimentally cleaner**
- efficient reconstruction and excellent mass resolution
- Also split in gluon-fusion and b-associated production

CMS results with 8 TeV ATLAS search only at 7 TeV

Common selection	
Single muon trigger	$p_T > 24 \text{ GeV} + \text{isolation} + \eta < 2.1$
Event primary vertex	$ z_{PV} < 24 \text{ cm}$
Muon selection	2 opposite-charged muons, $p_T > 24 \text{ GeV}, \eta < 2.1,$ track quality cuts, $ d_{xy} < 0.02 \text{ cm}, d_z < 0.1 \text{ cm},$ angular matching with trigger, isolation
E_T^{miss}	$E_T^{\text{miss}} < 35 \text{ GeV}$
Category C1	
b tag	1 or 2 b-tagged jets, $p_T^{\text{jet}} > 20 \text{ GeV}, \eta^{\text{jet}} < 2.4$
Category C2	
No b tag	Events with no b-tagged jets



Search for $A \rightarrow Zh, h \rightarrow bb$

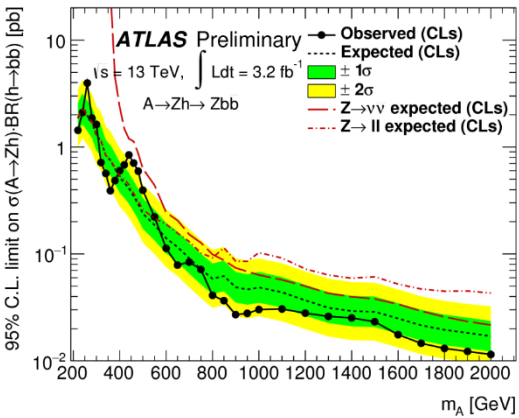
Search for a pseudoscalar state in the mass range 200 – 2000 GeV and decaying to a Z boson to $\nu\nu$ or ll and a SM Higgs going to bb . In the 2HDM type II, it is useful to probe a complementary region of the parameter space with respect to fermionic decays.

Categories according to

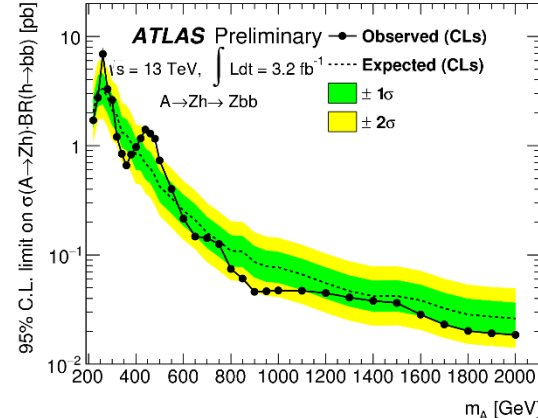
- 0/2 leptons
- p_T of Z candidate (low < 500 GeV, high \geq 500 GeV)
- # b-tagged jets (gg fusion or b associated production)

Final discriminant:

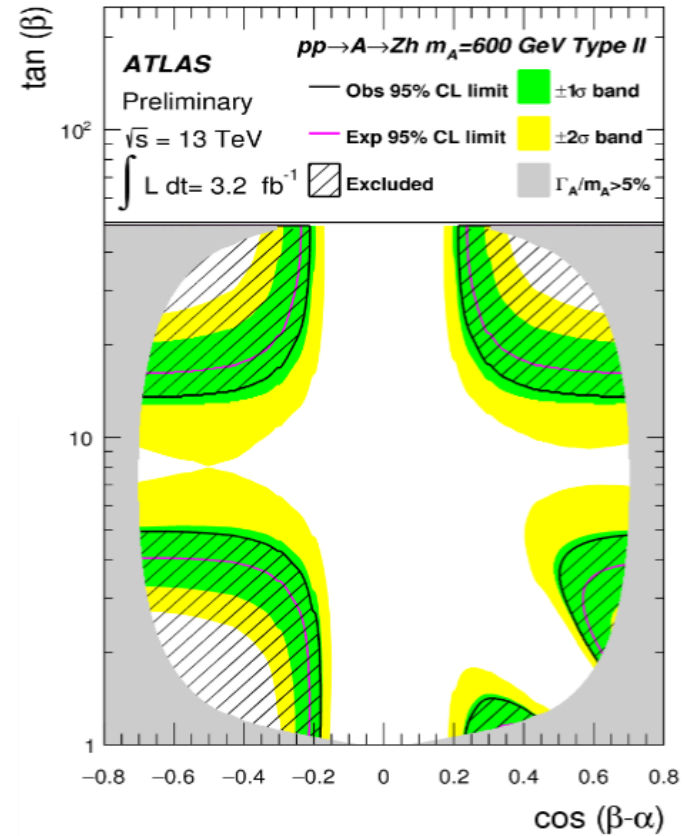
m_{ll} in 2-lep category, transverse mass in 0-lep category



gg fusion



b associated production



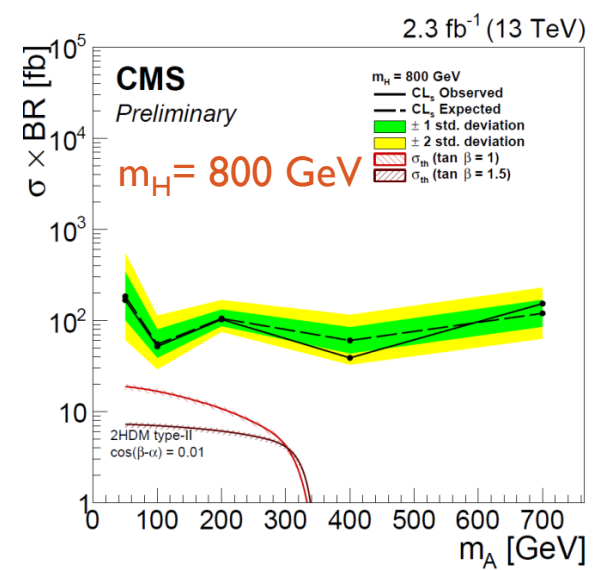
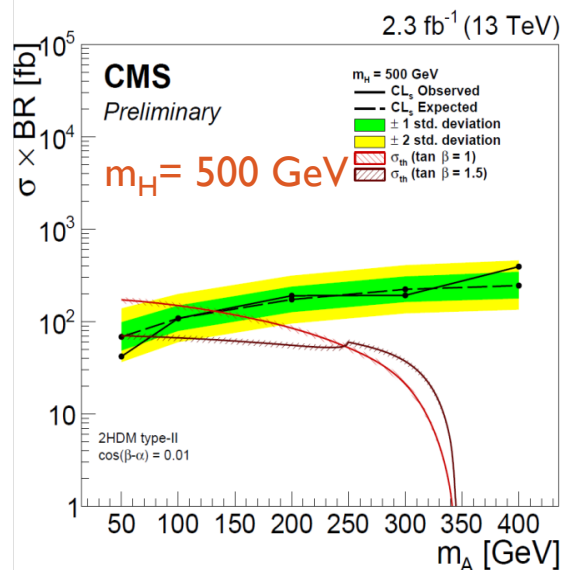
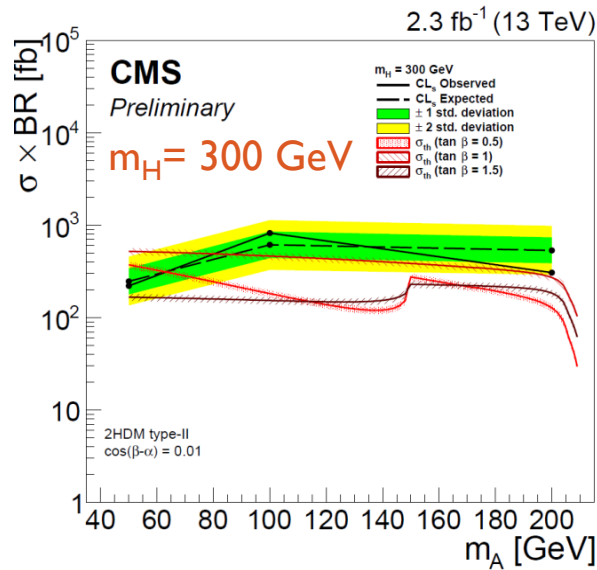
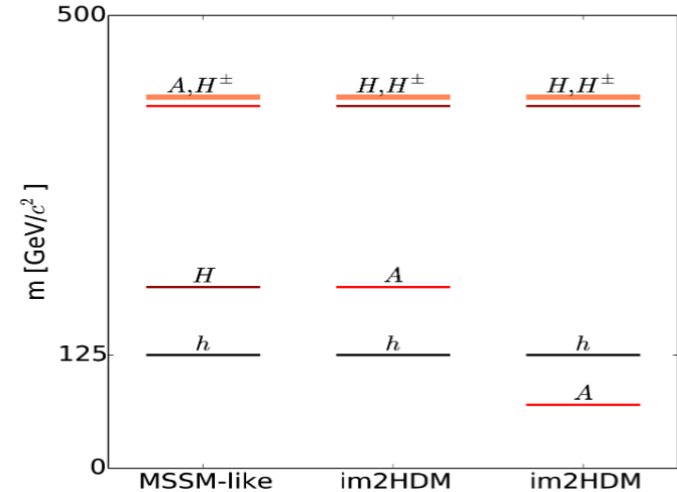
Search for $H \rightarrow ZA, Z \rightarrow ll, A \rightarrow bb$

Motivated in 2HDM with twisted custodial symmetry which gives a heavier scalar H and a lighter pseudoscalar A boson.

2 l + 2 b selections

Depending on $(m_H - m_A)$ hypothesis, a rectangular signal region is defined in the (m_{llbb}, m_{bb}) plane. The inverse is used as control region.

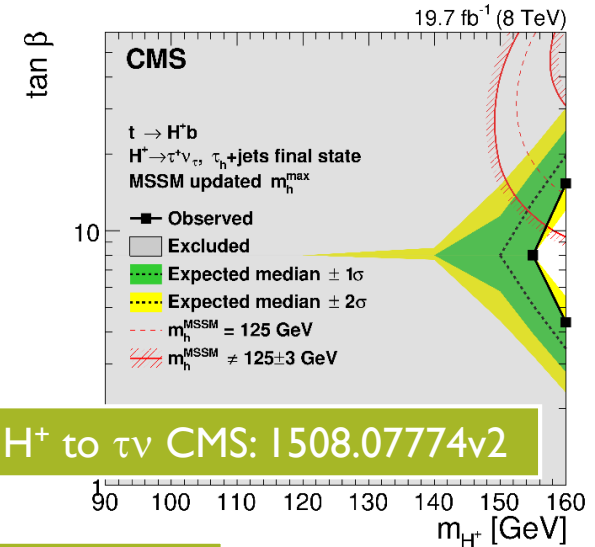
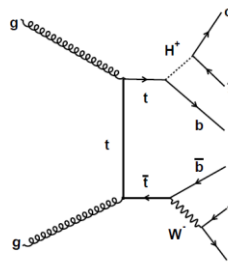
Limits for three m_H hypotheses, as a function of m_A



Low mass searches @ 8 TeV

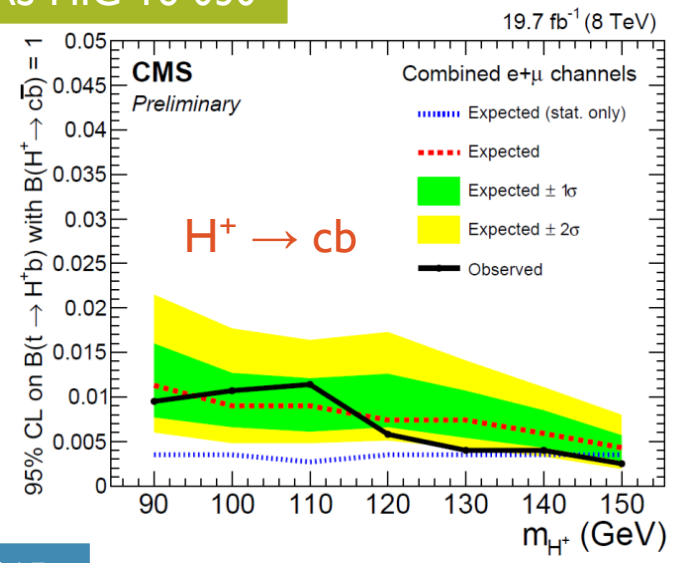
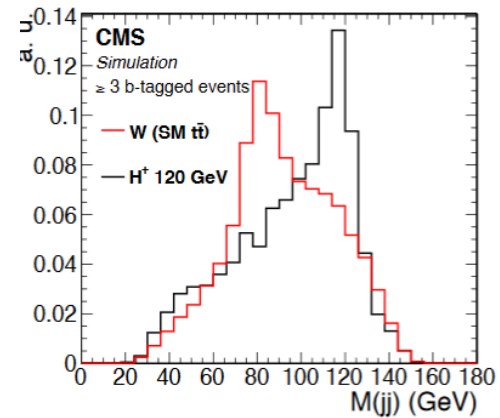
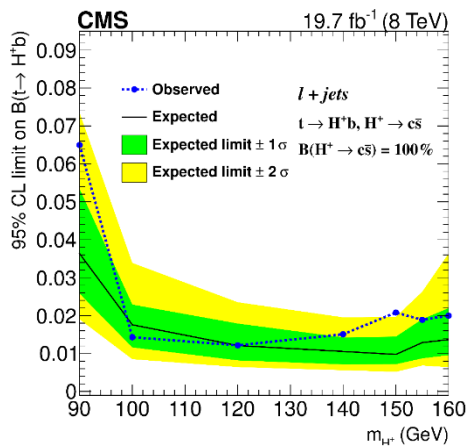
- In the MSSM $\tau\nu$ is the most sensitive final state, excluding completely the low $\tan\beta$ region for masses $m_{H^+} < m_{top}$.
- Still room for a light H^+ in other 2HDM. **Decays to quarks** are particularly enhanced in **Flipped-2HDM**

Search for **semilep tt pair events**. The H^+ can be looked for reconstructing the dijet mass from the **W decay** with a **kinematic fit** technique and looking for a **secondary peak**.



H^+ to cb CMS: PAS-HIG-16-030

H^+ to cs CMS: 1510.04252



ATLAS result @ 7 TeV for H^+ to cs . Eur. Phys. J. C (2013) 73:2465
 Observed limit on BR ($t \rightarrow H^+ b$) **5.1%-1.2%**