# Searches for Beyond-Standard Model Higgs bosons

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# What it's all about

✔ What is the motivation for a BSM Higgs sector?

✔ What have we learnt from LEP and flavour physics and what does the discovery of a 125-GeV SM-like Higgs boson mean in this context?

✔ What have we learnt from LHC Run-I and what are the prospects for Run-II?

Warnings:

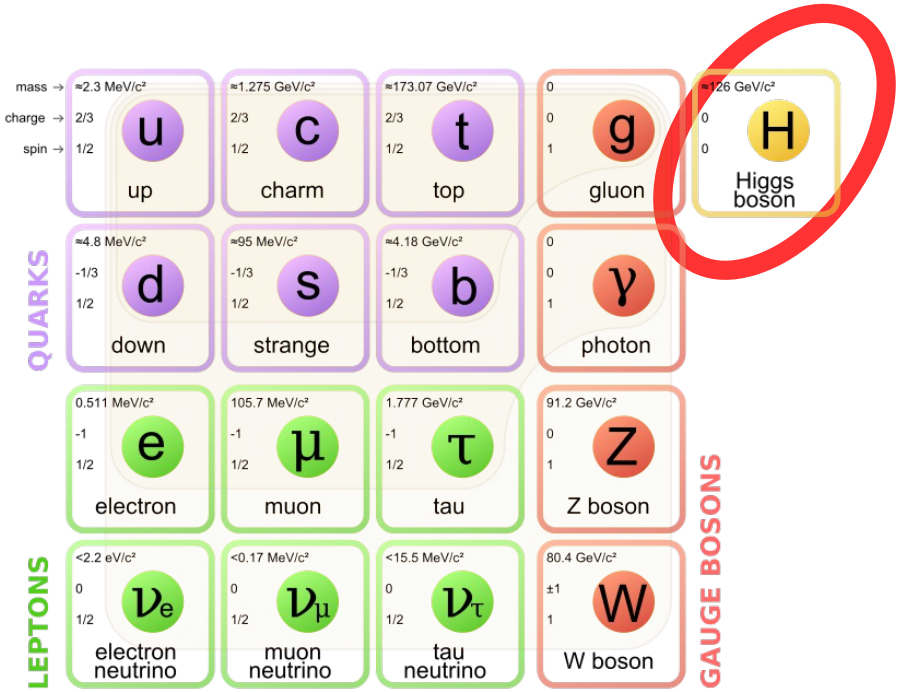
⇛ Not meant to be a comprehensive discussion of these topics: this would need much more than a seminar

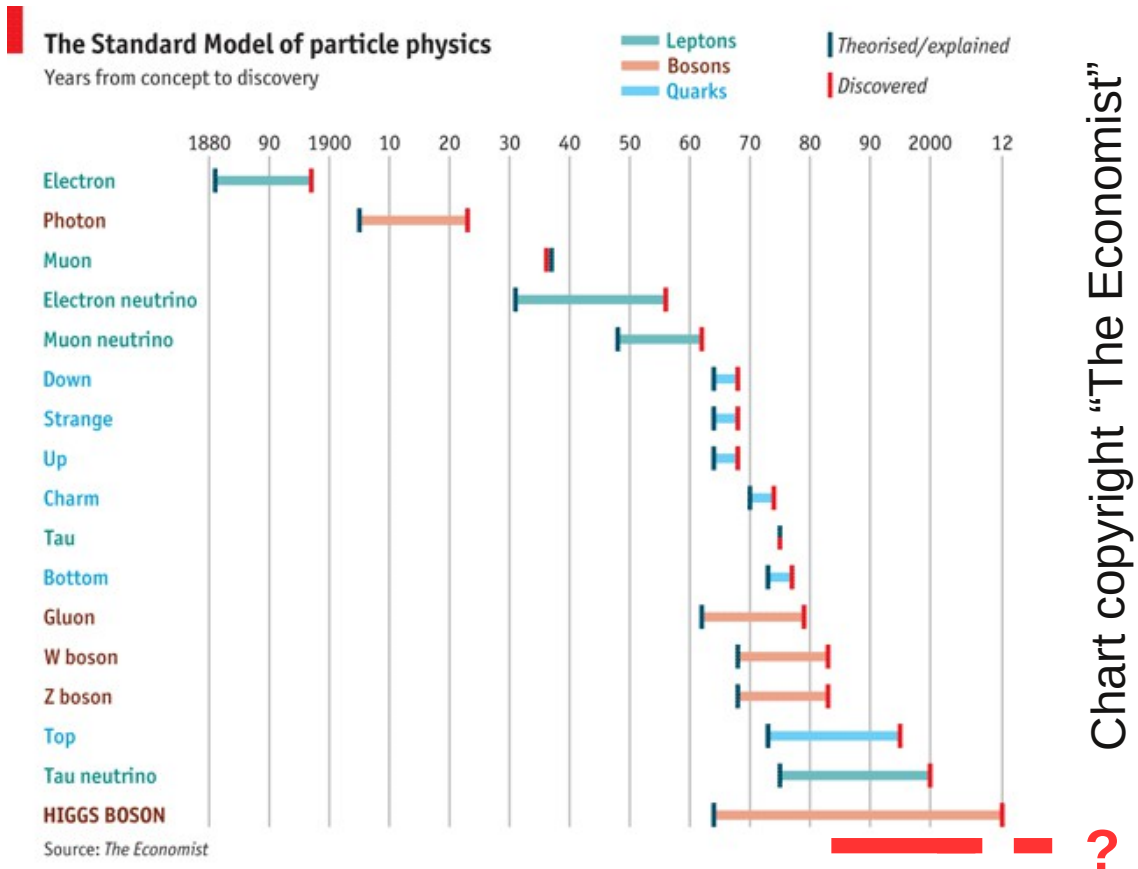
⇛ Biased selection of experimental results: I will mostly show few LEP and ATLAS results


Apologies if your favourite BSM Higgs result is missing

# The Standard Model of Particle Physics (1897 – 2012)

In summer 2012, slightly more than a century after the identification of the first elementary particle, the last piece of the Standard Model was directly observed

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**Supersymmetry**

# The Higgs boson

The Higgs boson is not only an important piece of the electroweak (EWK) symmetry breaking mechanism: it also provides access to physics beyond the SM


✔ first fundamental (?) scalar particle found
("little hierarchy" problem)

✔ a least constrained SM sector by symmetry principles ("custodial symmetry" $\rho = (m_W/m_Z \cos\theta)^2 \simeq 1$)

✔ the only dimension-2 coupling in the SM Lagrangian
("Higgs portal")

✔ the only non-gauge interaction in the SM

# Beyond the Standard Model

- Standard Model is not the full picture. A number of of questions that may be related to the Higgs sector are the following
  - CP-violation sources in nature, baryogenesis conditions
    **2HDM, SUSY, …**
  - What is dark matter composed of? **SUSY, "Higgs portal"**
  - Do interactions unify at some high energy scale? **SUSY**
  - What is the neutrino mass origin?
    **Higgs triplets & see-saw mechanism**
  - Can fundamental scalars exist in Nature? **SUSY, TC, …**

**Examples of popular topics for physics models with extended Higgs sectors**

# Talk Overview: the "big" picture

SM Higgs

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

What is the structure of the Higgs sector?

➡ 2 doublets? (2HDM; MSSM)
➡ More than 2 doublets? (e.g. NMSSM)
➡ Higher order representations?

Is Higgs a bridge to hidden sectors?

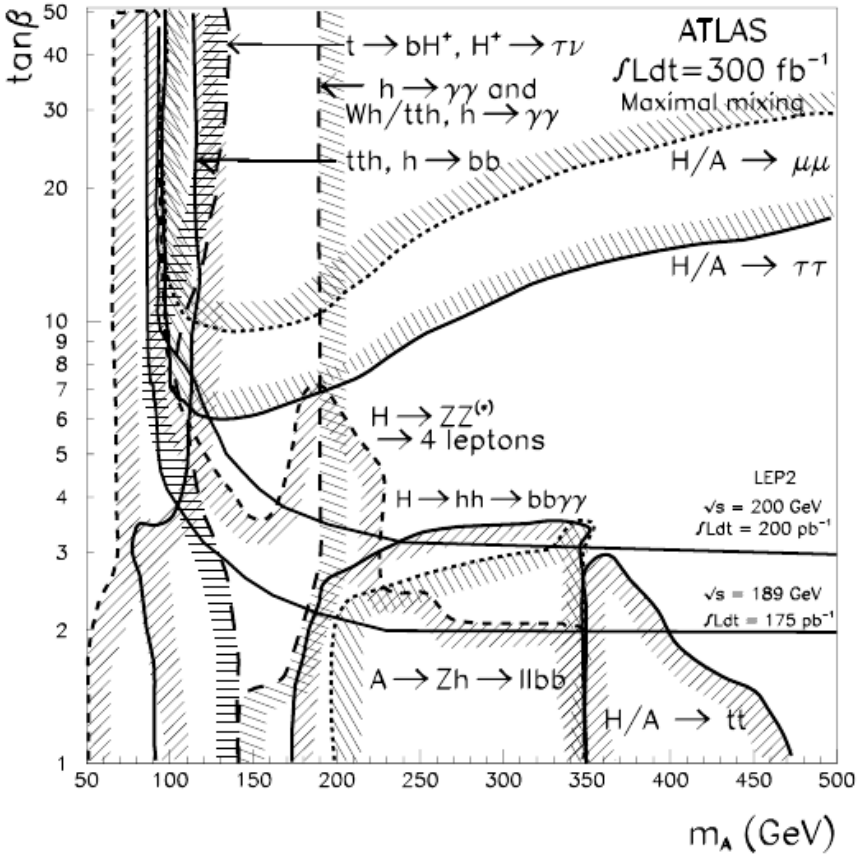
➡ hidden valley; Higgs to dark matter, ...

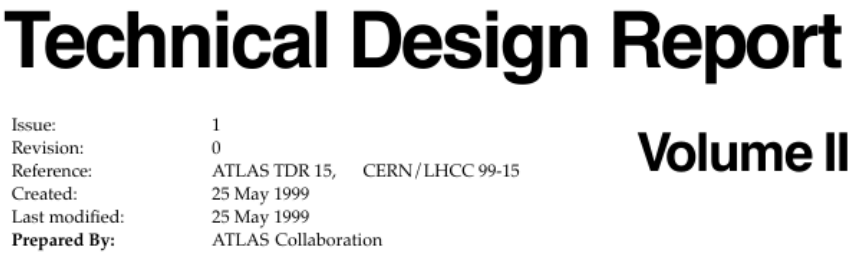
Notice: I have chosen a simple framework to place the experimental search program; I won't discuss theory models like Little Higgs, Extra Dimensions, etc.

# Supersymmetry and the MSSM

MSSM has been the basic idea behind the design of BSM Higgs searches from LEP and Tevatron till the discovery of h125.

**"There is nothing more practical than a good theory."**



# Supersymmetry and the MSSM

- MSSM = Mininal Supersymmetric Standard Model
  - An (almost ?) complete realization of low energy supersymmetry
    - Minimal gauge group, i.e. SM $SU(3)\otimes SU(2)\otimes U(1)$
    - Minimal particle content
    - R-parity conservation, i.e. dark matter candidate
    - Soft SUSY breaking

⇛ MSSM has more than 100 parameters; but fortunately it can be shown that most of the choices violate experimental bounds
⇛ Assuming reduced FCNC, no new sources of CP-violation, 1$^{st}$ & 2$^{nd}$ generation universality you are left with 19 parameters: *phenomenological MSSM* or *pMSSM*

# MSSM: Higgs at tree-level

- MSSM has 2 Higgs doublets
  - Higgsino is a fermion: anomaly cancellation needs 2nd doublet
  - One doublet for up-type fermions and the other to down-type
- CP-conserving Higgs sector (at lowest order)
  - After EWK symmetry breaking 5 Higgs bosons
  - CP-even: h and H; CP-odd A; Charged $H^+$ and $H^-$

Very economical: only two SUSY parameters needed

$\Rightarrow m_A$ or $m_{H+}$ $\Rightarrow \tan\beta = \upsilon_2/\upsilon_1$ (ratio of Higgs v.e.v.s: up / down)

Very constraining: tight restrictions in Higgs masses

$\Rightarrow$ e.g. lightest CP-even Higgs is lighter than the Z boson!

# MSSM: Higgs beyond the tree-level

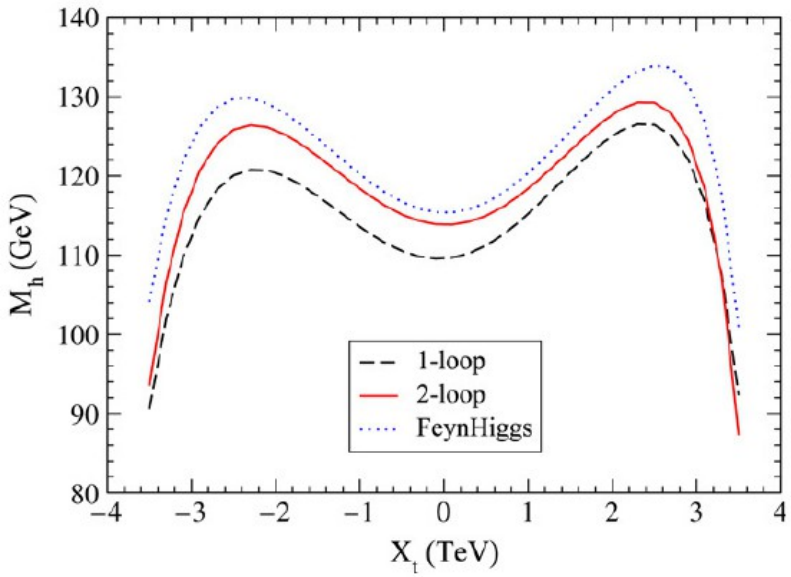
- Radiative corrections play an important role for the mass of the lightest CP-even Higgs, h

$$\Delta m_h^2 = \frac{3 m_t^4}{2\pi^2 \upsilon^2}\left[\log\frac{m_S^2}{m_t^2} + (X_t/m_S)^2\left(1 - \frac{(X_t/m_S)^2}{12}\right)\right] + \ldots$$

A. Djouadi / Physics Reports 459 (2008) 1–241

$m_S^2 = m_{\tilde{t}1} m_{\tilde{t}2}$ stop masses average

$X_t = A_t - \mu/\tan\beta$ (stop mixing)




◊ "maximal mixing scenarios" refer to fixing $m_S$ and choose $X_t$ such that $m_h$ is maximized

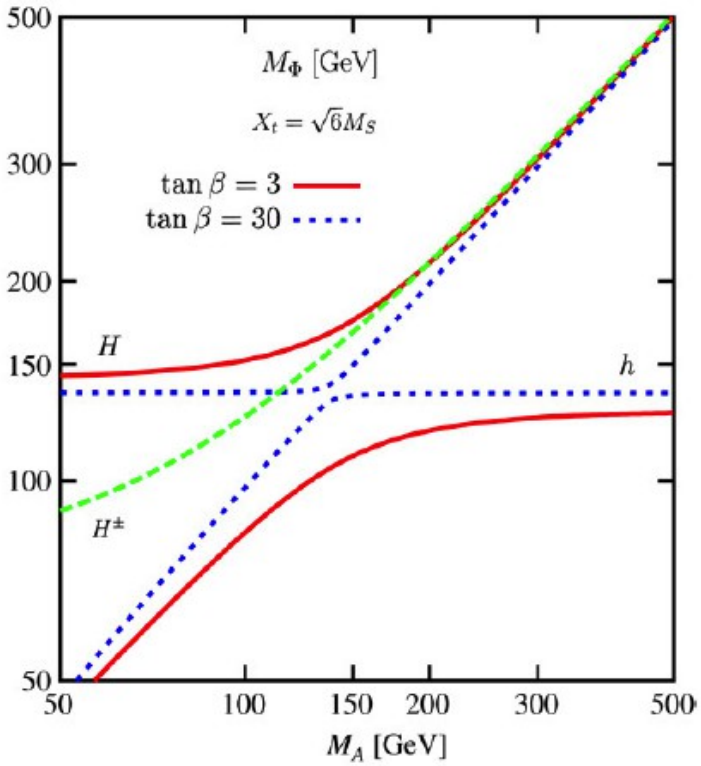
◊ you can make it up to $m_h \sim 135$ GeV

# MSSM: masses of the Heavy Higgses

- MSSM poses tight constraints on the other Higgses, especially at high mA
  - Charged Higgs mass (tree-level)

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

  - Example for other masses at a "maximal mixing" scenario




Large tanβ (>10) and large $M_A$ (>130 GeV)

$$M_A \simeq M_H \simeq M_{H^+} \text{ and } M_h \simeq 130\,GeV$$

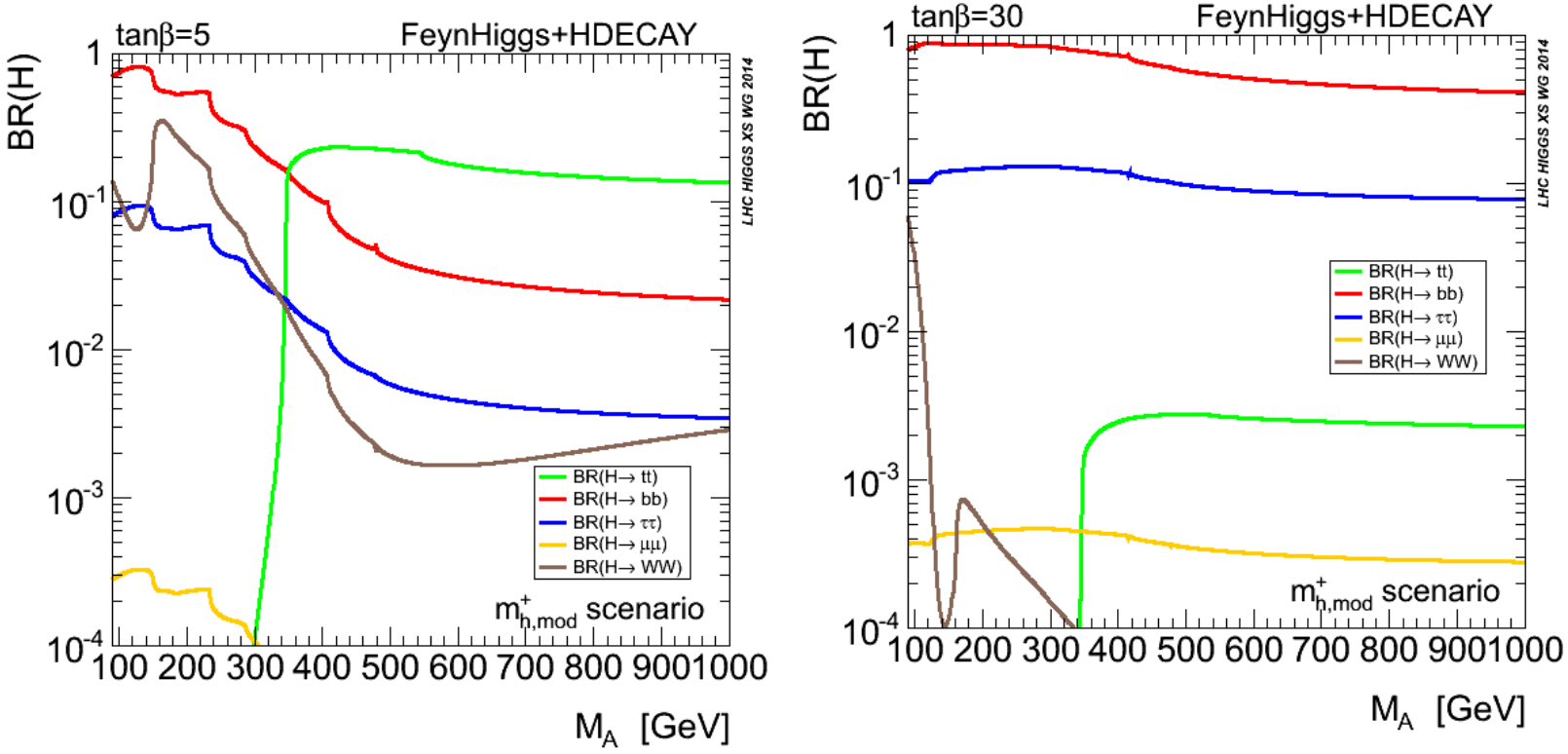
Large tanβ (>10) and small $M_A$ (<130 GeV)

$$M_A \simeq M_h \text{ and } M_H \simeq 130\,GeV$$

# MSSM Pheno: Neutral Higgs decay

- The phenomenology for neutral Higgs depends a lot on tanβ

Example for Heavy CP-even (H) Higgs decays

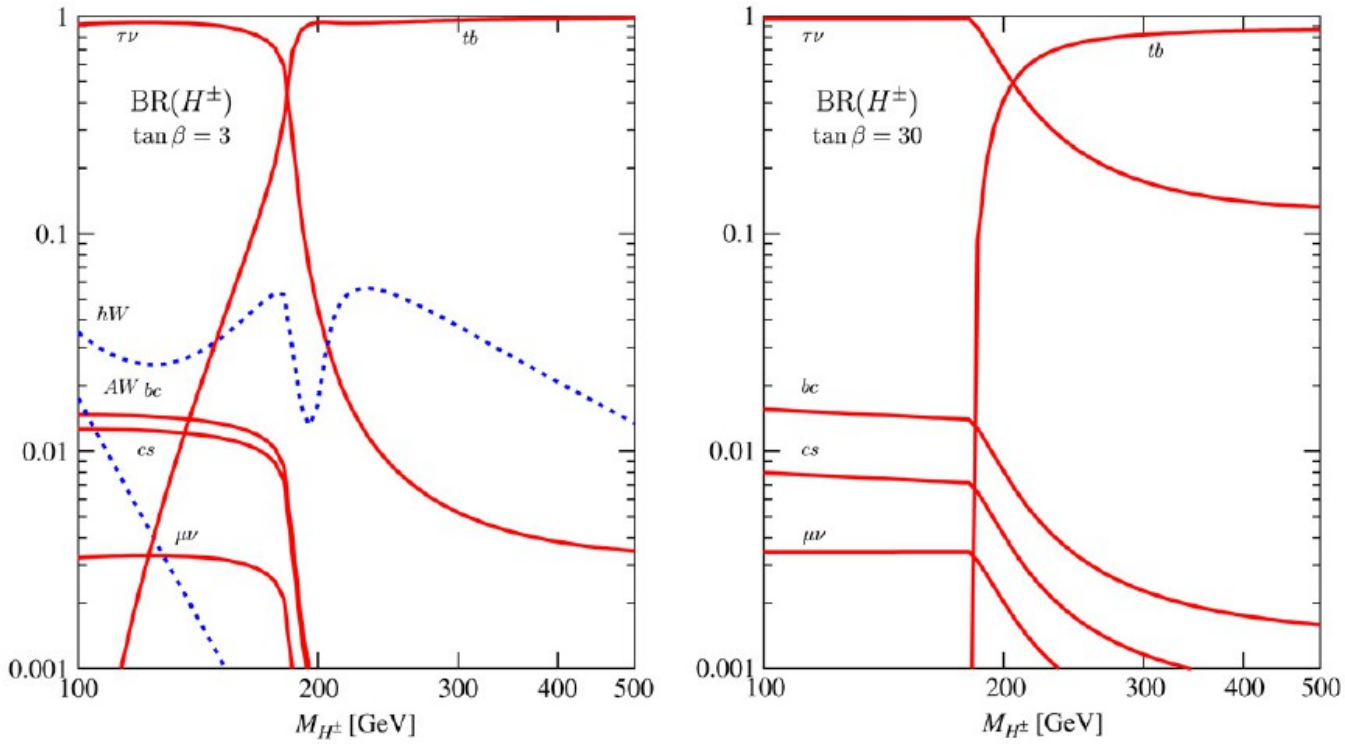



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures#MSSM_BR_plots

# MSSM Pheno: Charged Higgs decay

- The phenomenology for charged Higgs depends on tanβ, but to a smaller extend wrt neutral Higgses

Example for Heavy Charged Higgs decays



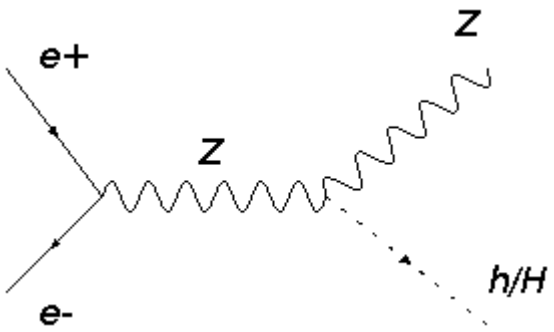

Charged Higgs decay BR for a low and high tanβ (maximal mixing)

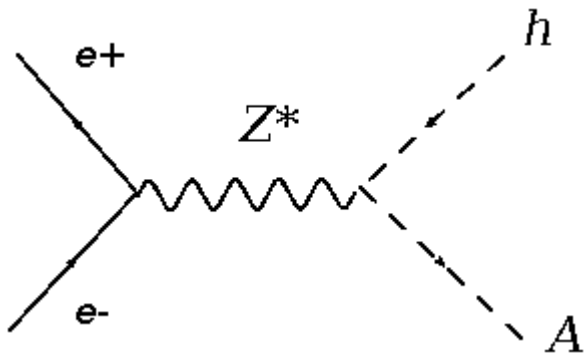


**Phys.Rept. 459 (2008) 1-241**

# MSSM Neutral Higgses at LEP

- LEP: electron – positron collisions with c.m.e. up to 209 GeV

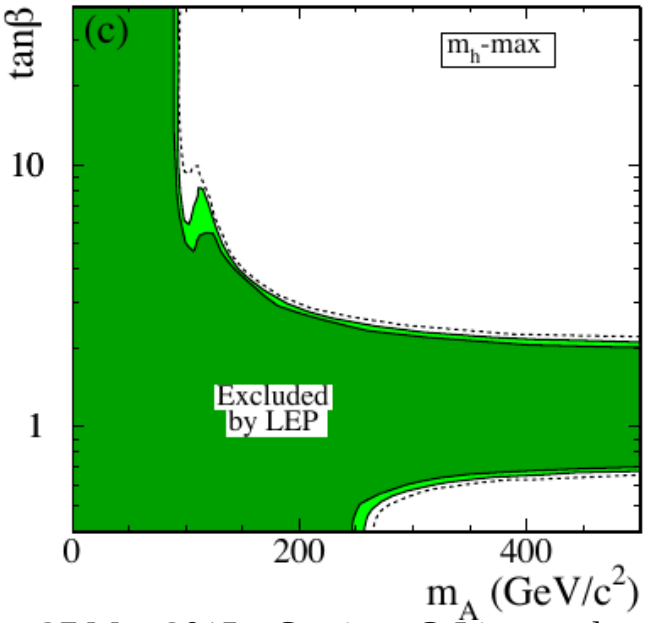


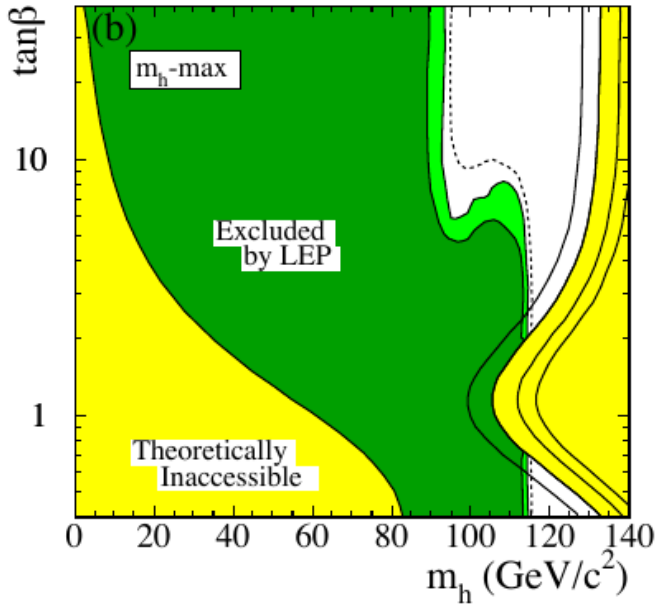




Eur.Phys.J. C47 (2006) 547-587

**Various decay channels considered:**
**h → bb, ττ, jj, AA**
**Z → jj, ll**

The basic LEP result is that
**$m_A$ < 90 GeV**
($m_{H+}$ < 120 GeV)
**is exluded**

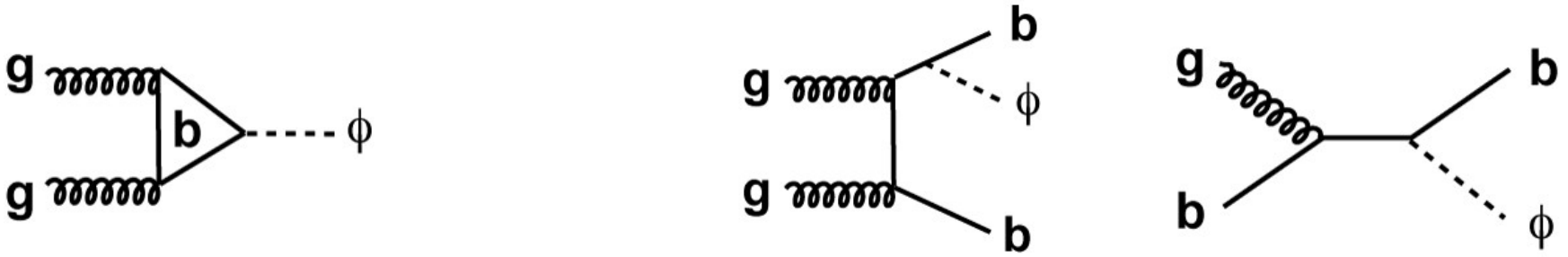


# MSSM Neutral Higgses at LHC

- Neutral Higgs production at the LHC

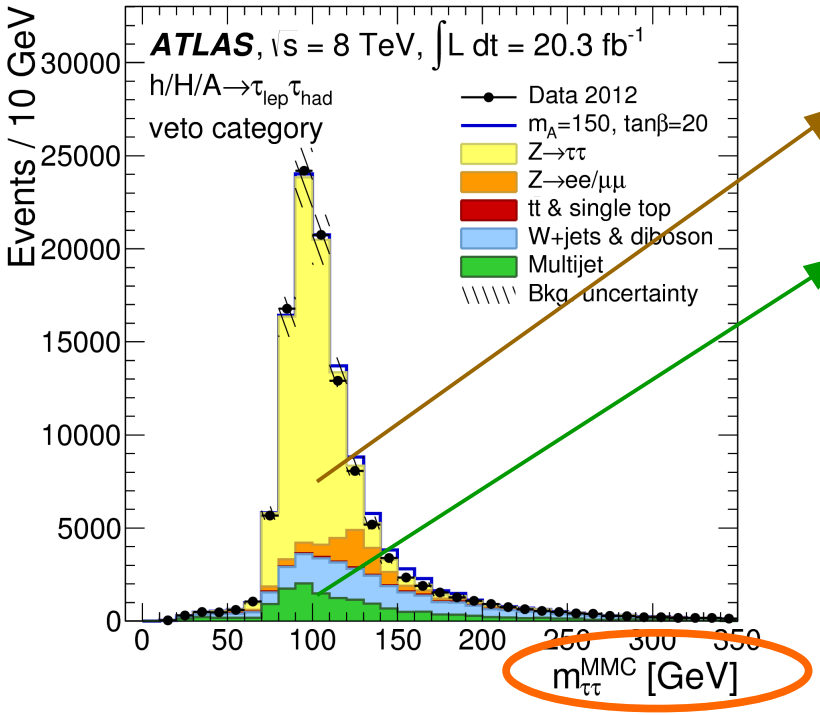
Gluon-fusion and "b-associated" production




- Preferred decays at large tanβ: h/H/A → ττ and bb
  - BR(H/A → ττ) ~ 10% for most of the parameter space
  - "ττ" modes have usually better sensitivity

# h/H/A → ττ

- Separate by τ decay mode: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ and "b-tag" / "b-veto" categories to benefit from the different production modes




Z → ττ from "tau-embedded" Z→μμ events in data

Events with a tau faked by a jet, like Z+jets, W+jets, ttbar, multi-jet production are data-driven.

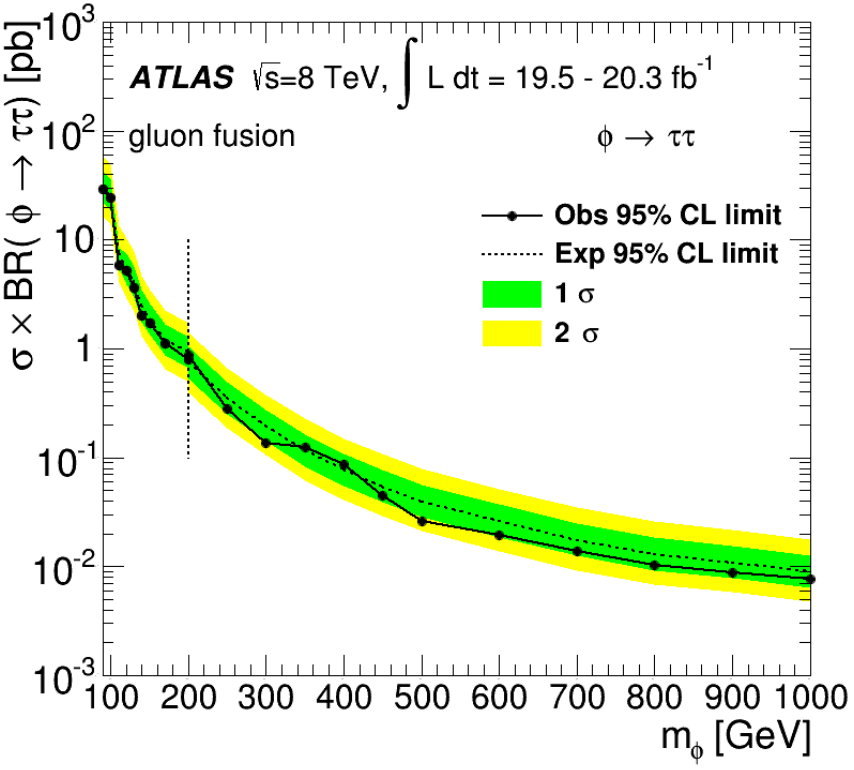
The rest of the backgrounds are taken from simulation.

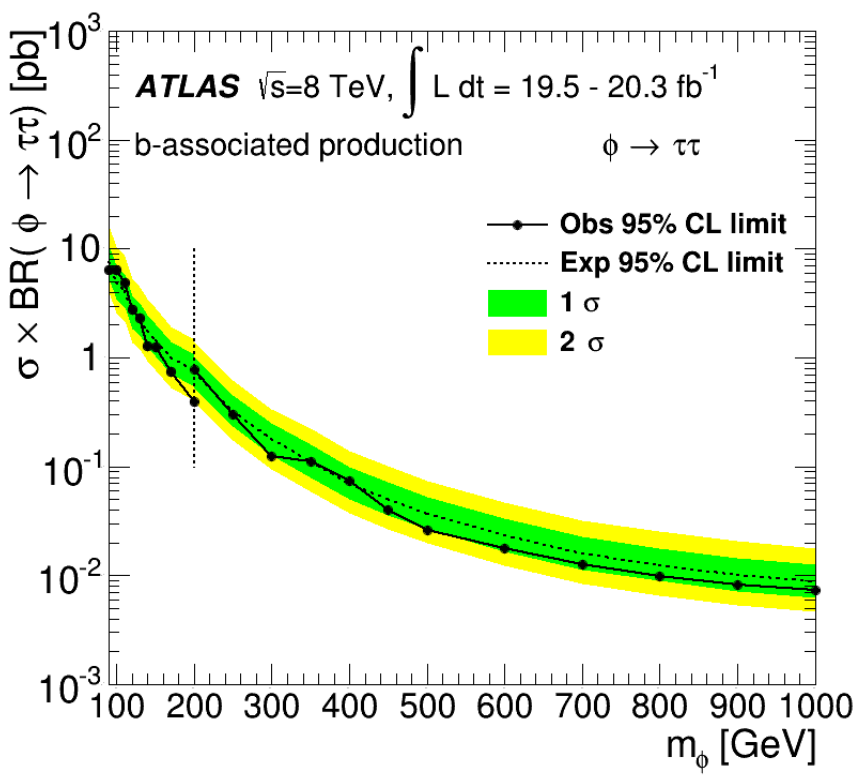
**Mass reconstruction:** MMC technique takes into account information from MET in order to predict the direction of the neutrinos

**arXiv:1409.6064**

# h/H/A → ττ

- No excess of events: cross sections limits for a narrow ττ resonance for different production mechanisms

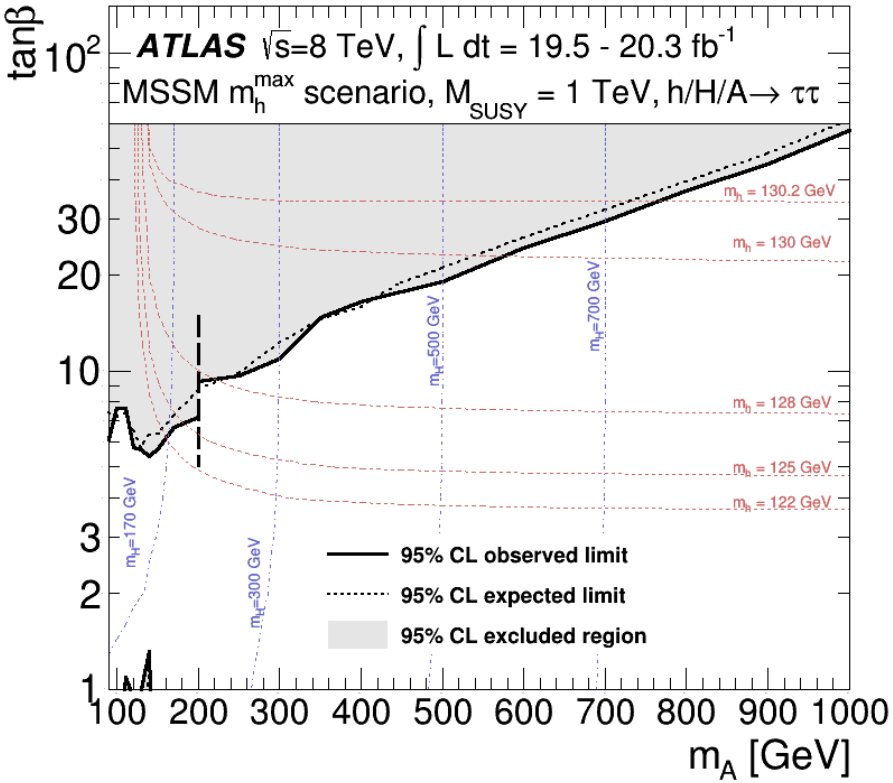


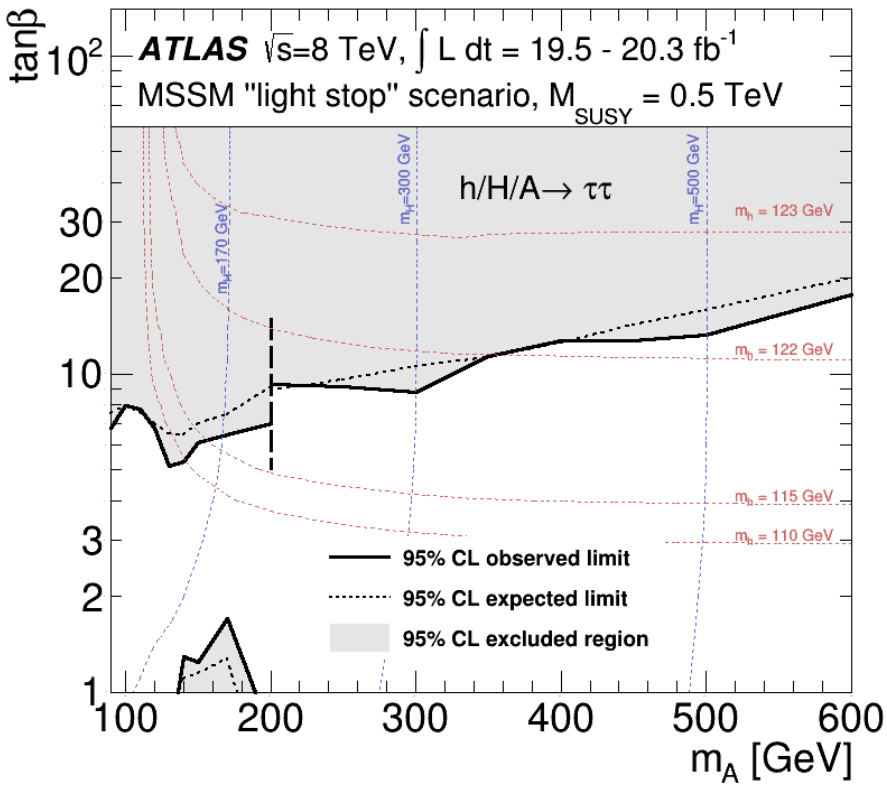




**arXiv:1409.6064**

# h/H/A → ττ

- Interpretation of the search for various MSSM scenarios

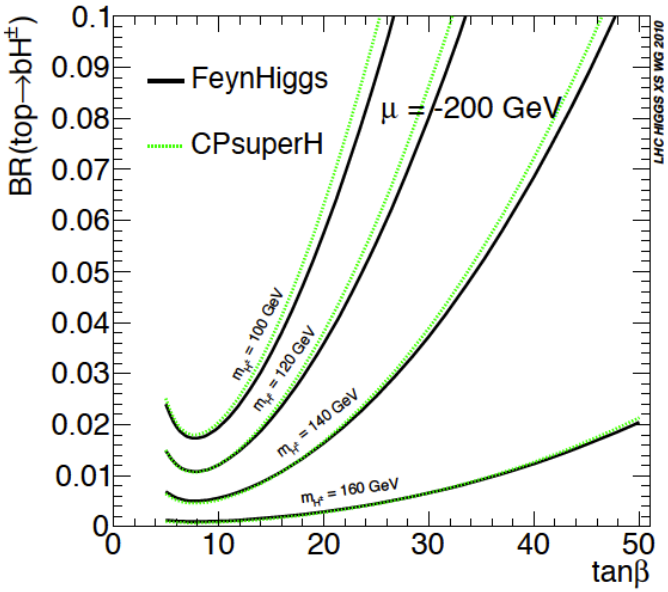



**arXiv:1409.6064**

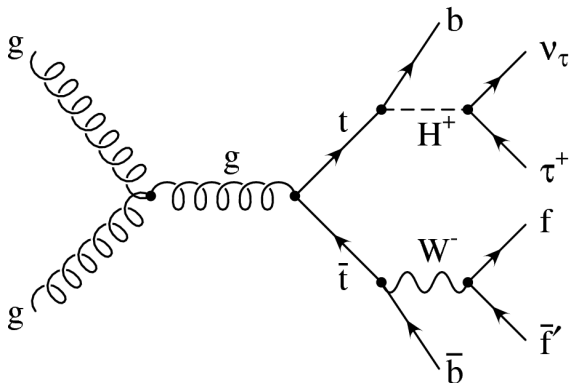
# MSSM Charged Higgs at the LHC

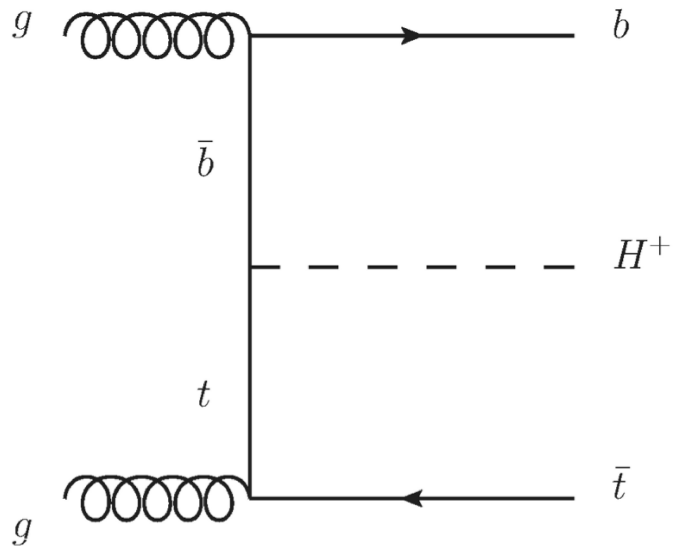
**Light Charged Higgs is produced mainly in top quark decays**




**BR(Top → bH⁺) vs tanβ**

**Heavy Charged Higgs is produced mainly in association with a top quark**

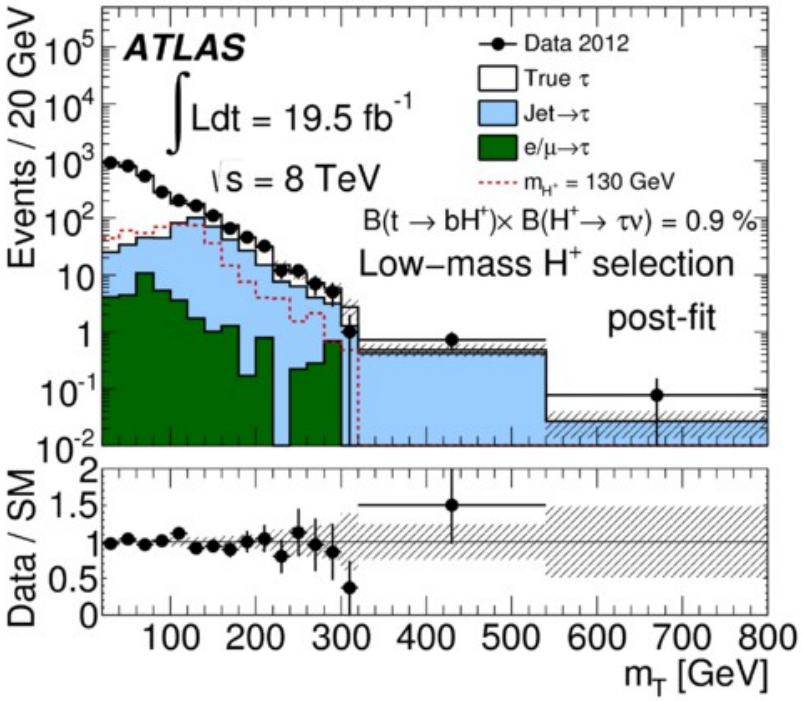


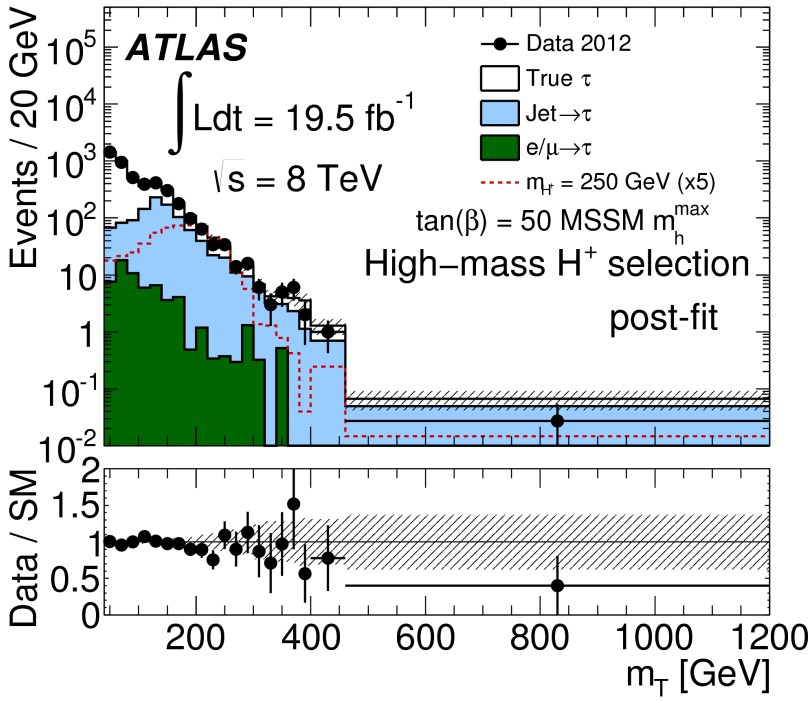



# $H^+ \to \tau\nu$

- Final state: one tau(had) from $H^+$, MET (from $\nu$), jets from the full hadronic top decay
- Trigger: tau(had)+MET;  Separate analysis for low and high mass

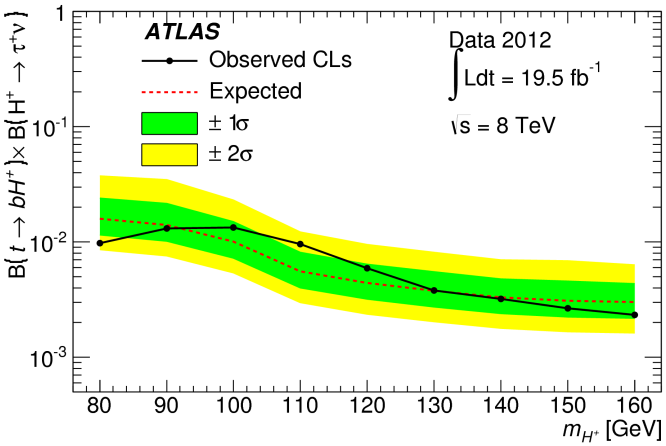
$$m_T = \sqrt{2 p_T(\tau) E_T^{miss} (1 - \cos\Delta\phi(E_T^{miss}, \tau))}$$

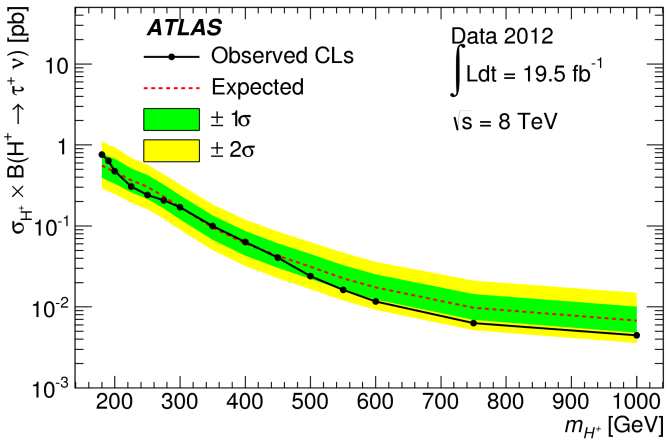


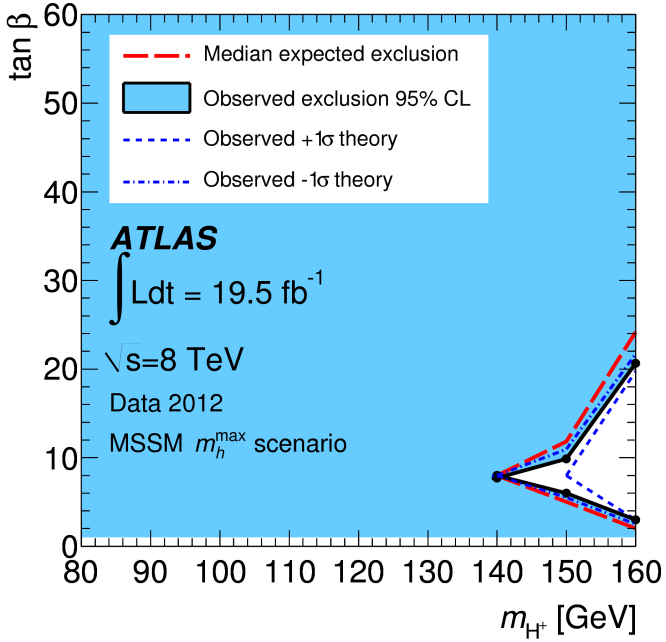



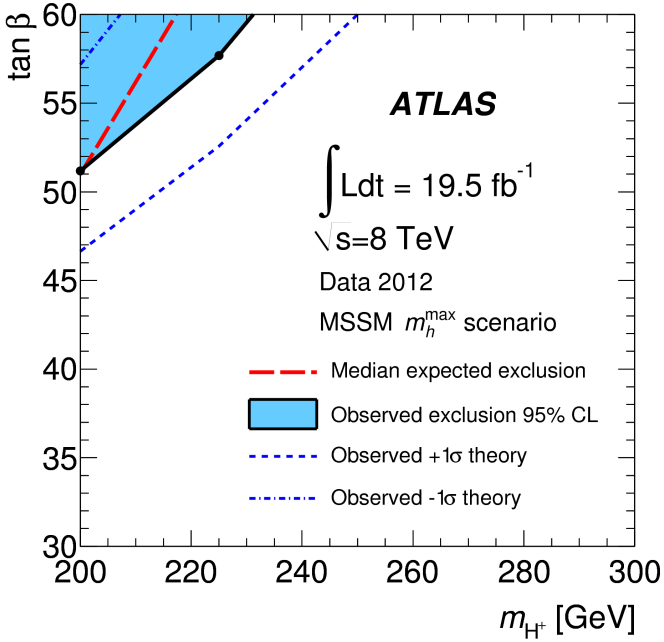
# $H^+ \to \tau\nu$

- BR($t \to bH^+$) x BR($H^+ \to \tau\nu$) and cross section limits translated to MSSM parameter space limits



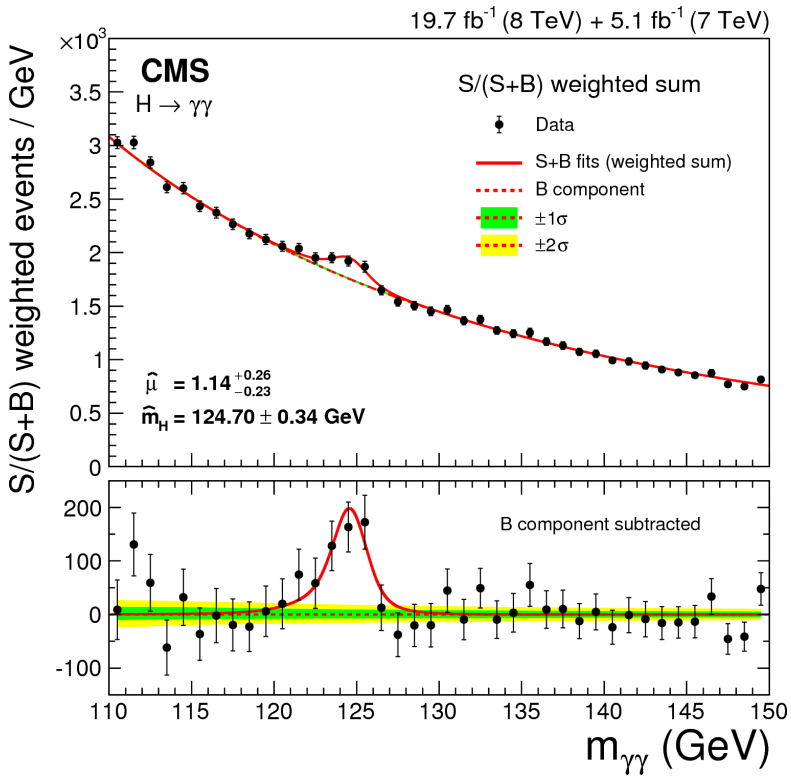



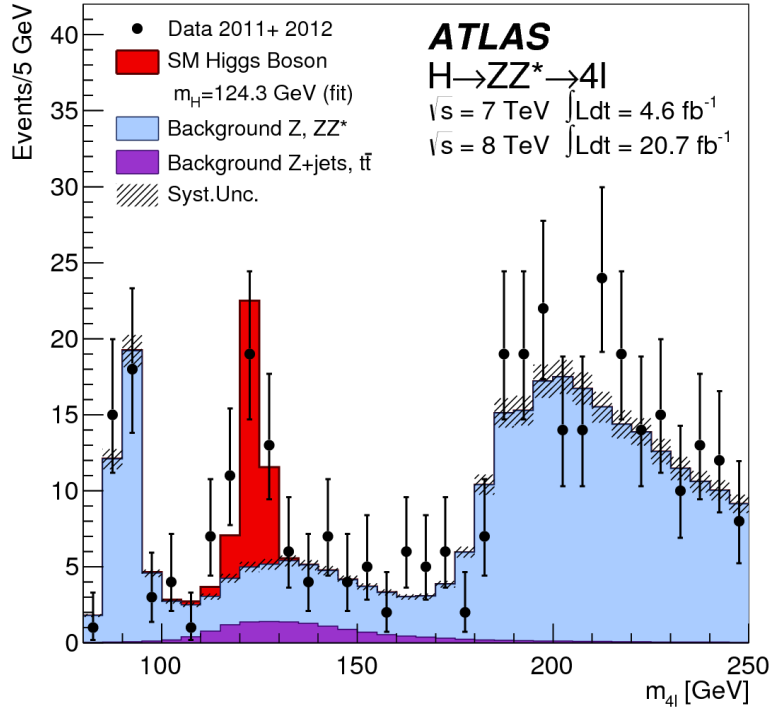



# The discovery of a Higgs boson at the LHC

- The LHC has already discovered a Higgs boson!




# Which MSSM Higgs is the "h125"?

- The MSSM is fully compatible with a SM-like Higgs at 125 GeV
  - This can be identified with one of the MSSM Higgs bosons

Which Higgs boson is the one at 125 GeV?

Eur.Phys.J. C73 (2013) 2354

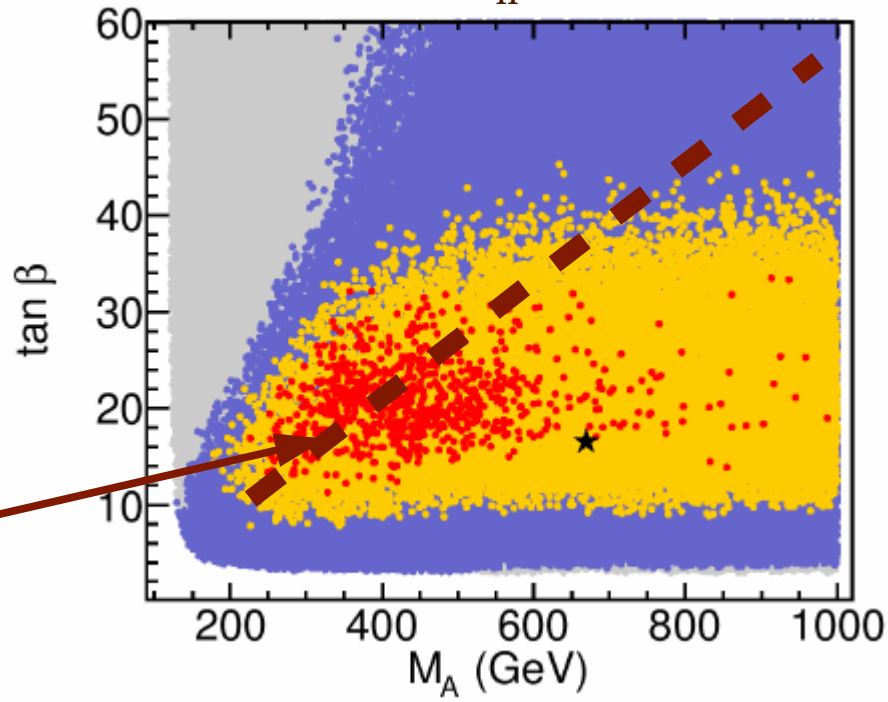
"pMSSM-7" assuming stops up to 1.5 TeV among few other assumptions; fits Higgs measurements, flavour observables etc

→ yellow points ~ 95% CL

→ red points ~68% CL

→ grey points: excluded at the time of the study by direct MSSM Higgs searches

Assuming $m_h$ = 125 GeV




LHC Run-I h/A/H → ττ search limit

# Which MSSM Higgs is the "h125"?

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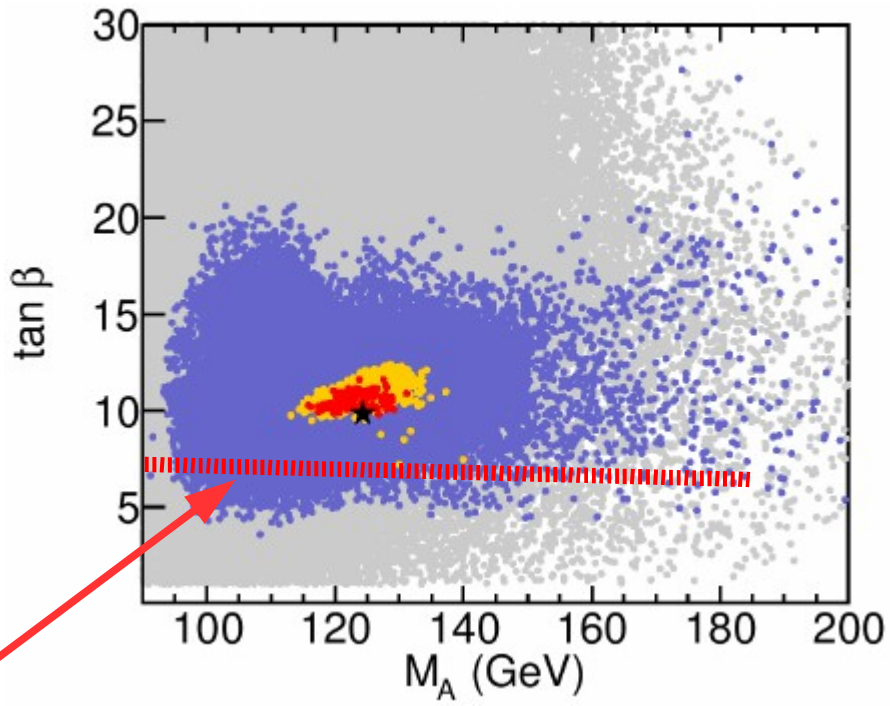
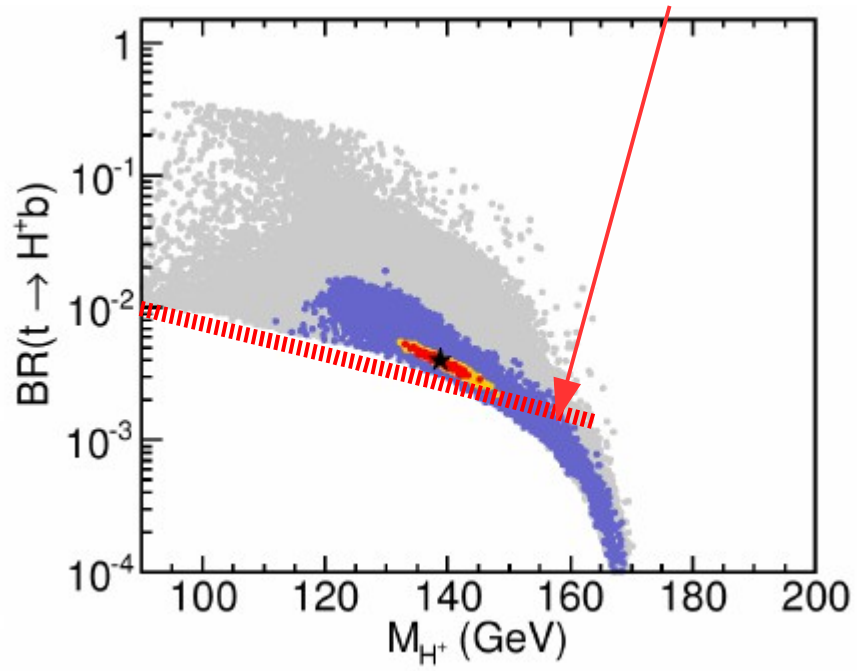
Assuming $m_H = 125$ GeV

LHC Run-I $H^+ \to \tau\nu$ search limit



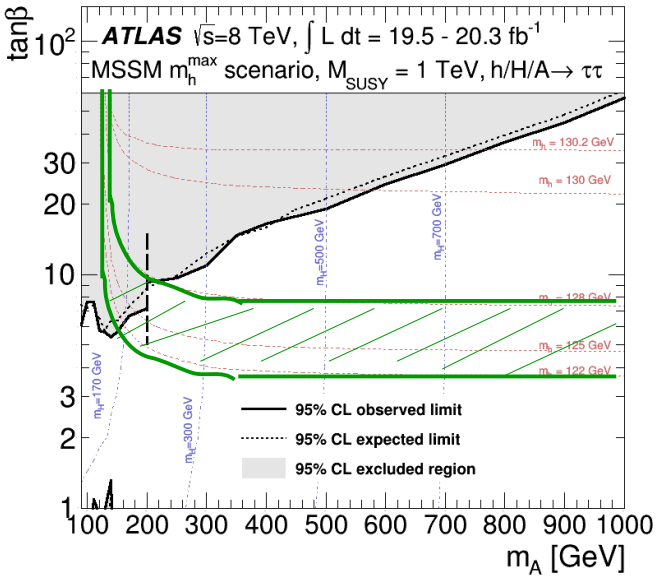




LHC Run-I $h/A/H \to \tau\tau$ search limit

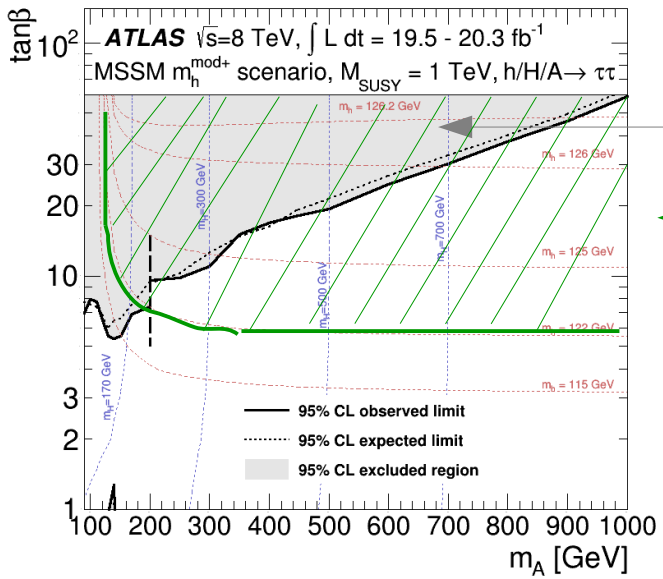
# MSSM scenarios after the discovery

Update of MSSM scenarios in order to include a light CP-even Higgs with mass ~ 125 GeV

**"mh-max" scenario**




**"mh-mod+" scenario**

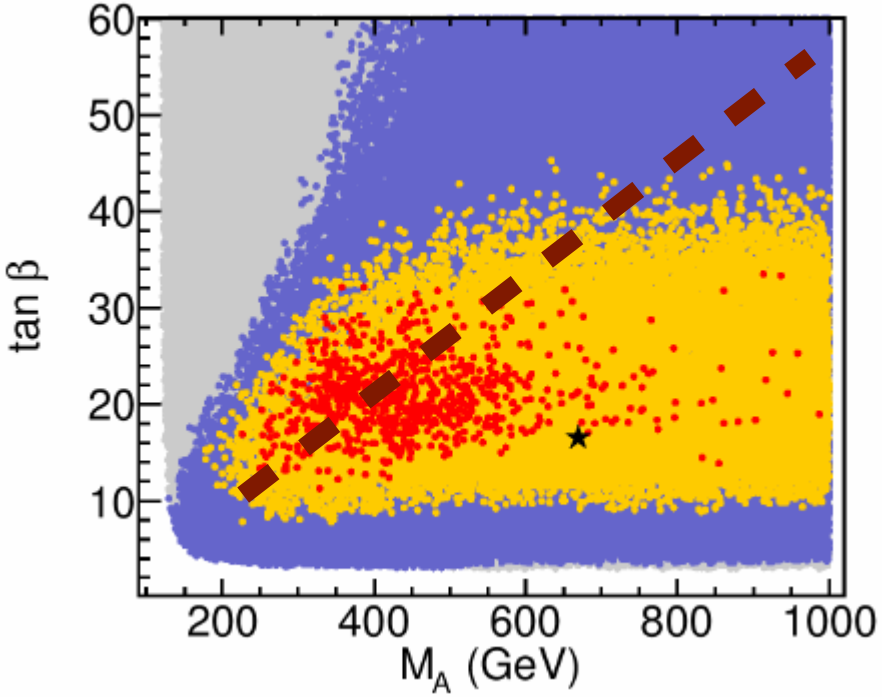


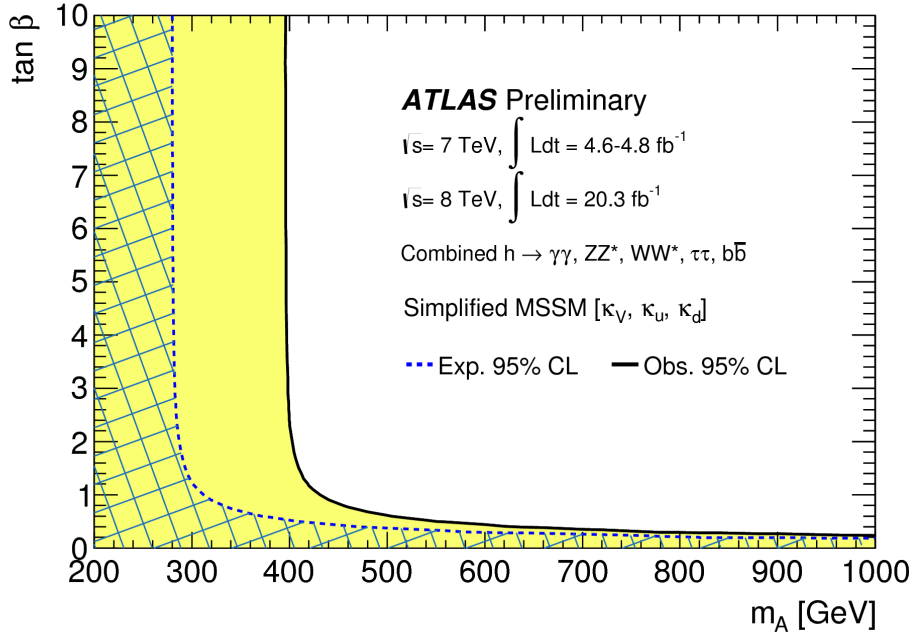

**LHC 8 TeV Run exclusion**

**Region compatible with a 125 GeV light CP-even Higgs**

# The effect of the Higgs measurement

- 125 GeV is ok, but what about the h125 properties?
  - The decoupling regime is ok with h125 measurements
  - Low tanβ needs very high mass Susy scale to accommodate the mass and even in that case doesn't survive the Higgs measurements




**Plot to be handled with care**

# Beyond the MSSM Higgs sector structure

- Going beyond the MSSM
  - LHC Run-I showed two major outcomes:
    - 125-GeV Higgs boson and no evidence for supersymmetry
- The discovery it opens the way to
  - Define searches without the MSSM pheno prejudice
  - Use the mass of the Higgs and its SM-like properties to choose among possible models

I will only mention here very few simple cases related to modifying the Higgs sector structure:

→ **Two-Higgs-Doublet models** (2HDMs)

→ **next-to-MSSM** (NMSSM)

→ **Higher order representations**

# 2HDM: Two-Higgs-Doublet model

- The 2-Higgs-Doublet-Model (2HDM) is conceptually one of the most straightforward extensions of the SM
  - Add another SU(2) doublet in the model and you get after EWK symmetry breaking 5 Higgs bosons: $h_1$, $h_2$, $h_3$, $H^+$, $H^-$

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \text{h.c}\}$$

→ Opens the phasespace for more decays
→ Decouples the mass of the neutral and charged Higgses
→ More options for CP-violation
→ …
But it doesn't address naturalness: most probably it will come with company

# 2HDM basics (I)

- CP-conserving 2HDM with a (softly broken) $Z_2$ symmetry ($\Phi_1 \rightarrow -\Phi_1$) leaves us with
  7 free parameters: masses ($m_h$, $m_H$, $m_A$, $m_{H+}$) angles (tan β, cos(β-α))
  and a potential parameter $m_{12}$
  and 4 ways to arrange the yukawa couplings to fermions:

In this notation:
$t_\beta = \tan\beta$;
$c_{\beta-\alpha} = \cos(\beta-\alpha)$
$s_{\beta-\alpha} = \sin(\beta-\alpha)$

| | Type-I | Type-II | lepton specific | flipped |
|---|---|---|---|---|
| $hVV$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ |
| $hQu$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ |
| $hQd$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ |
| $hLe$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ |
| $HVV$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ |
| $HQu$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ |
| $HQd$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ |
| $HLe$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ |
| $AVV$ | 0 | 0 | 0 | 0 |
| $AQu$ | $1/t_\beta$ | $1/t_\beta$ | $1/t_\beta$ | $1/t_\beta$ |
| $AQd$ | $-1/t_\beta$ | $t_\beta$ | $-1/t_\beta$ | $t_\beta$ |
| $ALe$ | $-1/t_\beta$ | $t_\beta$ | $t_\beta$ | $-1/t_\beta$ |

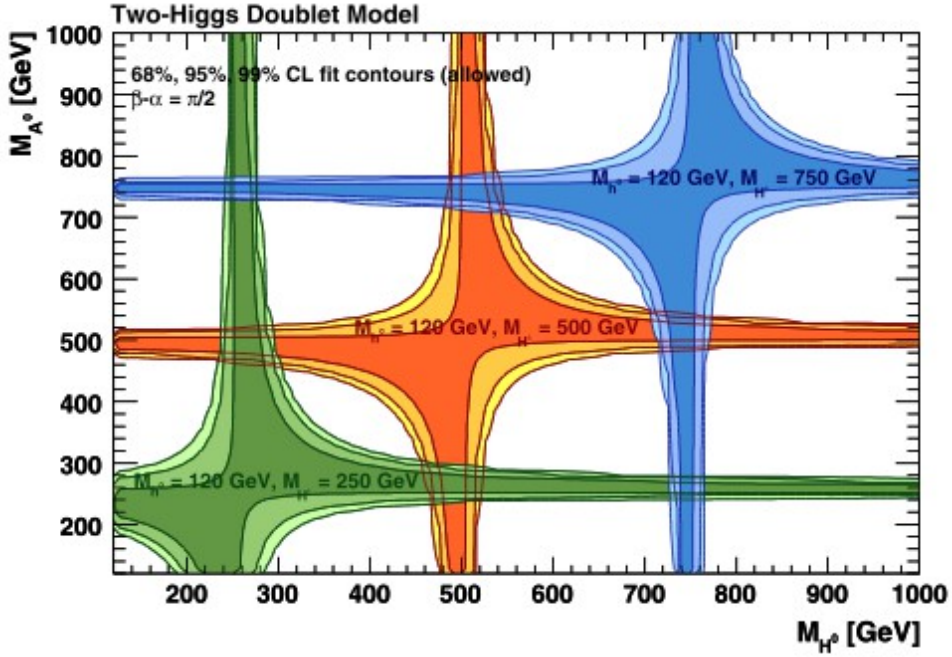
# 2HDM basics (II)

- Interesting limits:
  - Weak decoupling limit: sin(β-α) → 1, i.e., there is a Higgs boson that can be as SM as you like but also there are light H/A/H$^+$ bosons
  - (strong) Decoupling limit: sin(β-α)=1 and two mass scales i.e. all additional particles heavy. For a more formal definition see PhysRevD 67, 075019
- Constraints from EWK precision measurements

$$\rho = (m_W/(m_Z \cos\theta_W))^2 \simeq 1$$

2HDM has ρ = 1 at tree level, but radiative corrections affect this number a lot!

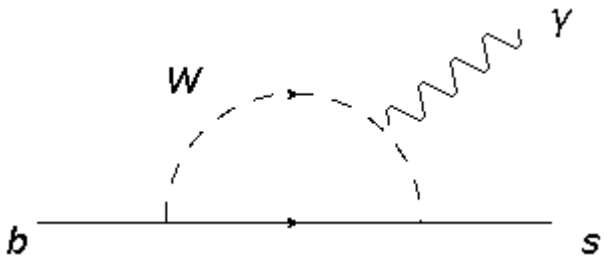
Eur. Phys. J. C (2012) 72:2003



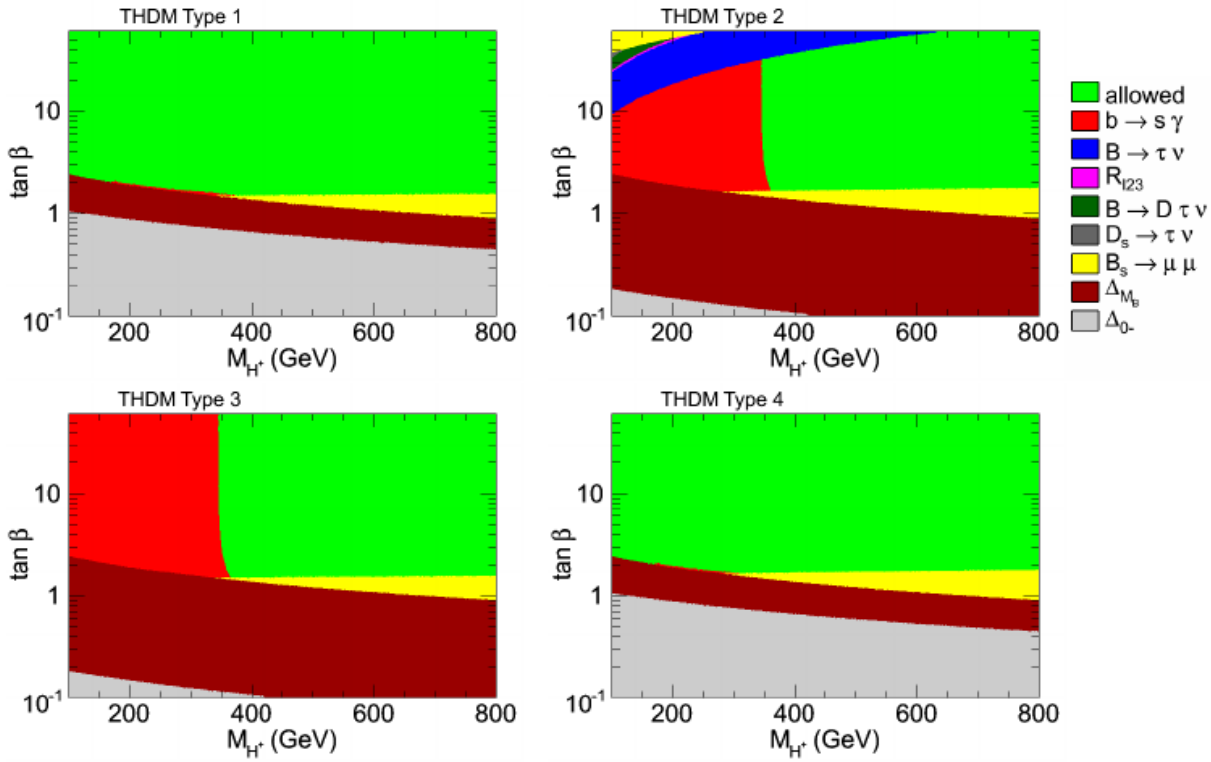
# 2HDM basics (III)

- Flavour physics constraints to 2HDM

Flavor constrains heavily type-II, but low masses, even below 100 GeV are allowed for type-I




| | Type I | Type II |
|---|---|---|
| $X$ | $\cot\beta$ | $\cot\beta$ |
| $Y$ | $\cot\beta$ | $-\tan\beta$ |
| $Z$ | $\cot\beta$ | $-\tan\beta$ |

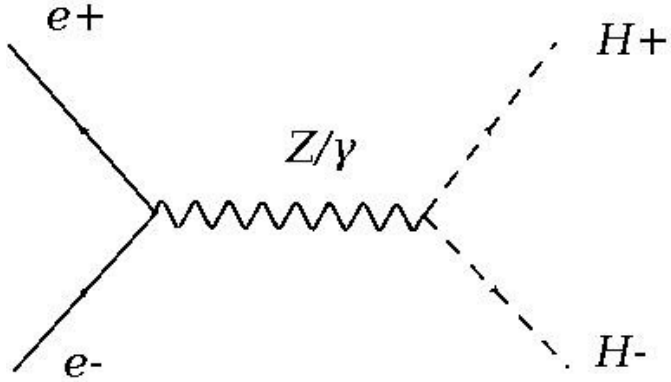



$$\mathcal{L}_{H^\pm} = -H^+\left(\frac{\sqrt{2}\,V_{ud}}{v}\,\bar{u}\,(m_u X P_L + m_d Y P_R)\,d + \frac{\sqrt{2}\,m_\ell}{v}\,Z\,\bar{\nu}_L \ell_R\right) + \text{H.c.}$$

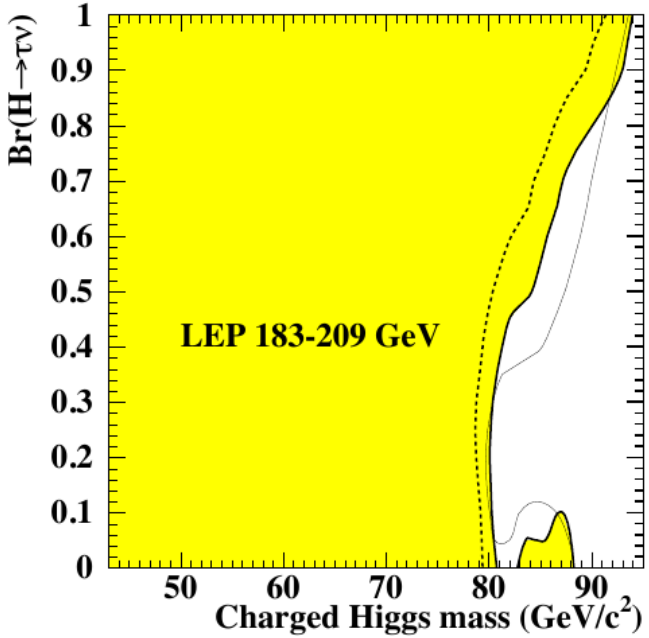
N. Mahmoudi & O. Stall, SuperIso v.3.4

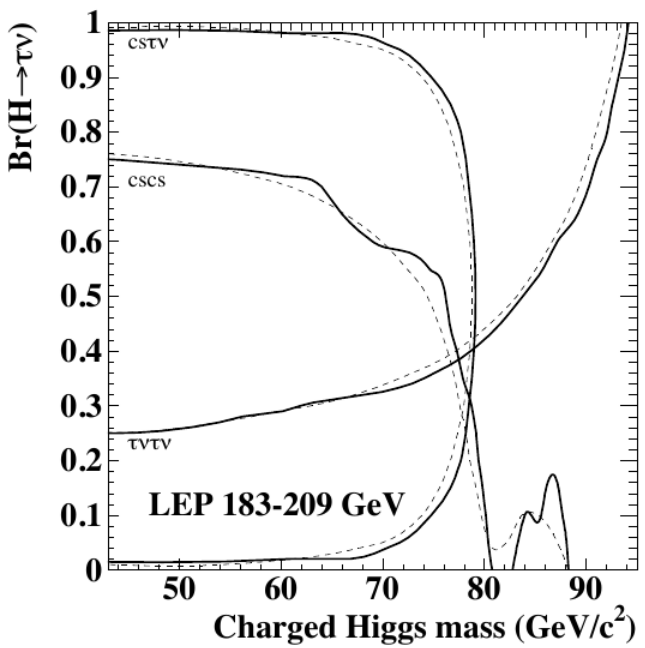
# Charged Higgs at LEP

- Charged Higgs at LEP: simple production, limited decay channels = perfect 2HDM case!




2HDM Type-II has just $H^+ \to \tau\nu$ and $H^+ \to cs$

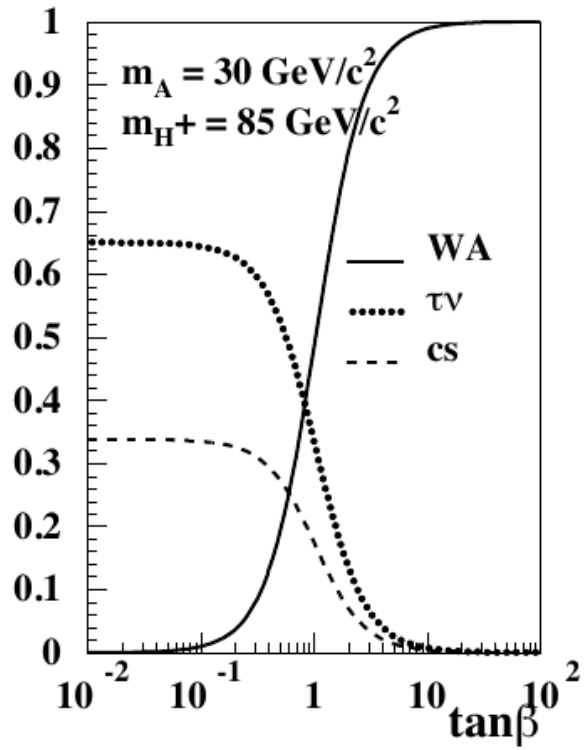


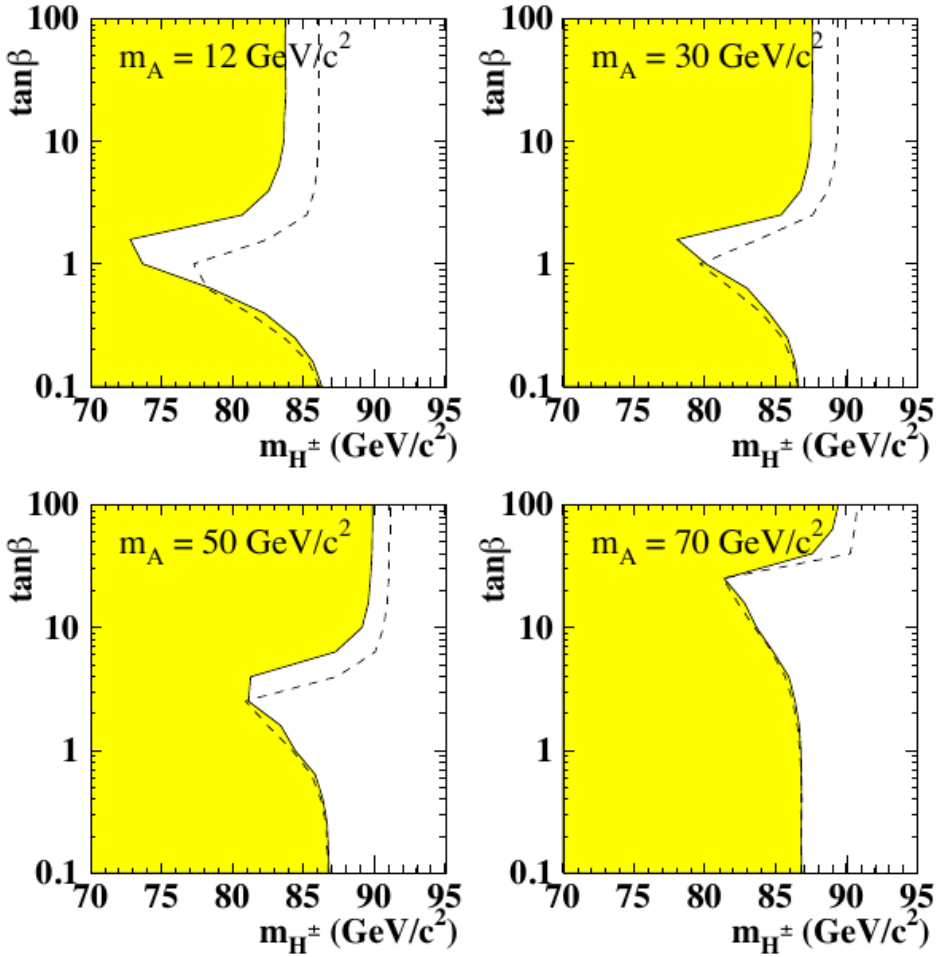




**LEP excludes a type-II 2HDM Charged Higgs with mass < 80 GeV**

# Charged Higgs at LEP

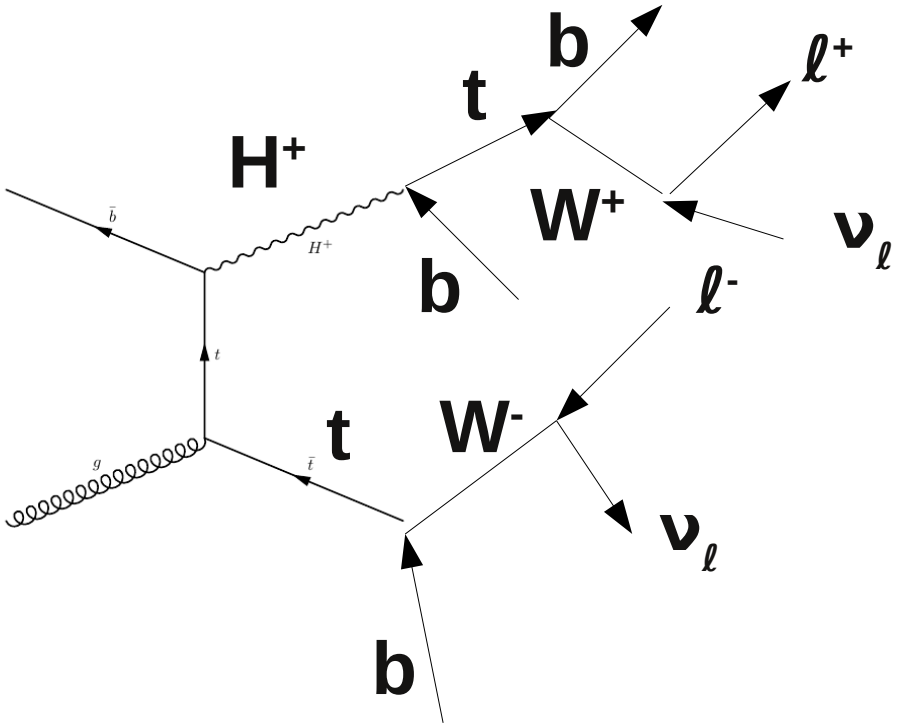
2HDM Type-I is more complicated: it has one more decay:
**$H^+ \to \tau\nu$, $H^+ \to cs$** and **$H^+ \to W^+A$**

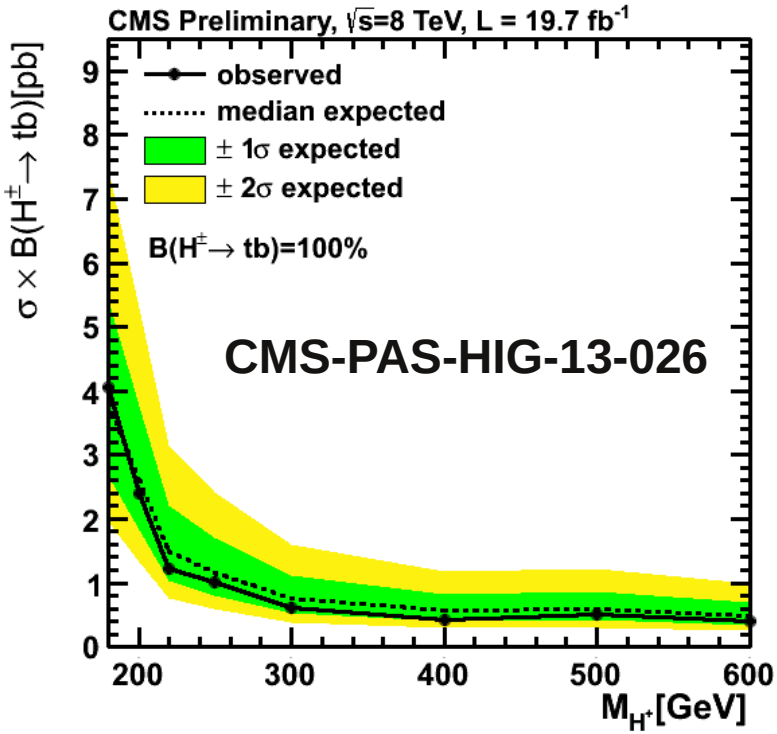


# $H^+ \rightarrow tb$

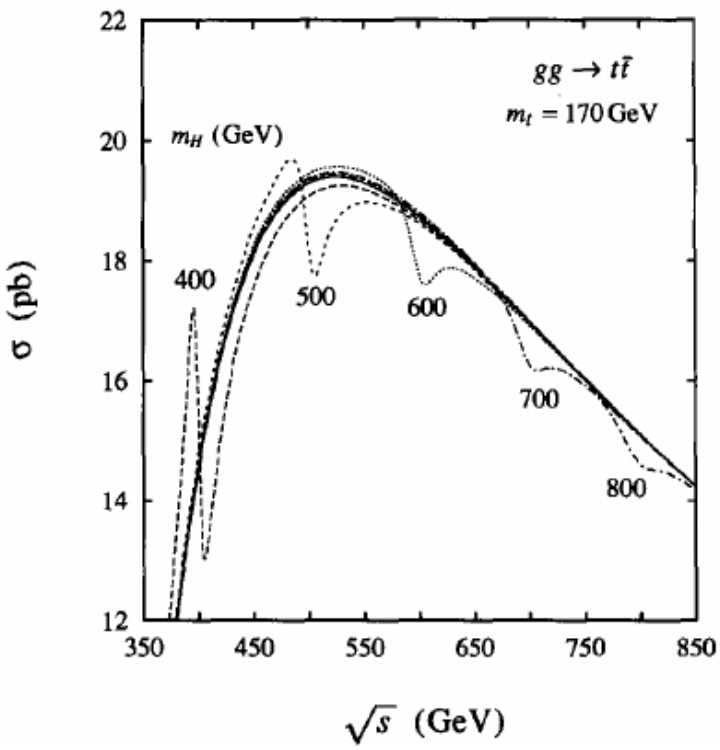
- This is the most typical decay mode of a high mass Charged Higgs
- The LHC has just started exploring that!



# A/H → tt

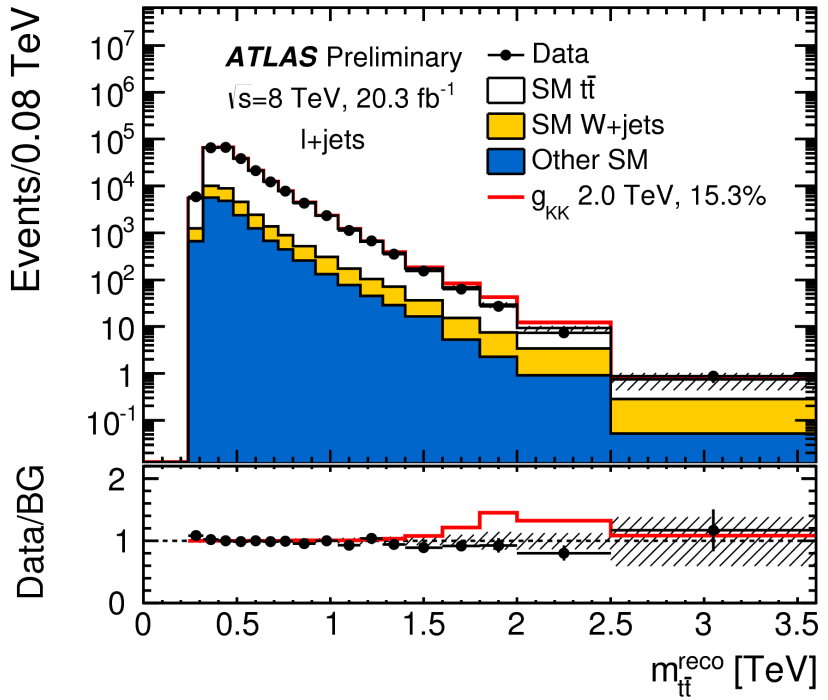
- This is typically one of the most dominant decay modes of a heavy neutral Higgs (m> 2 $m_{top}$)




**PLB 333 (1994) 126-131**

Highly motivated, but very difficult due to interference

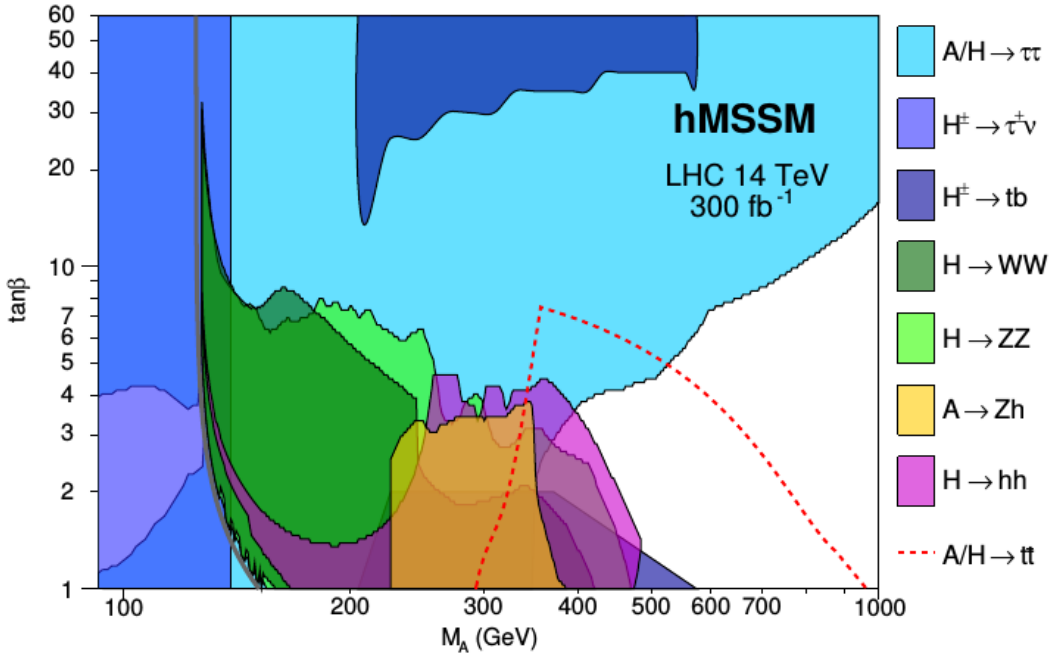
ATLAS-CONF-2015-009



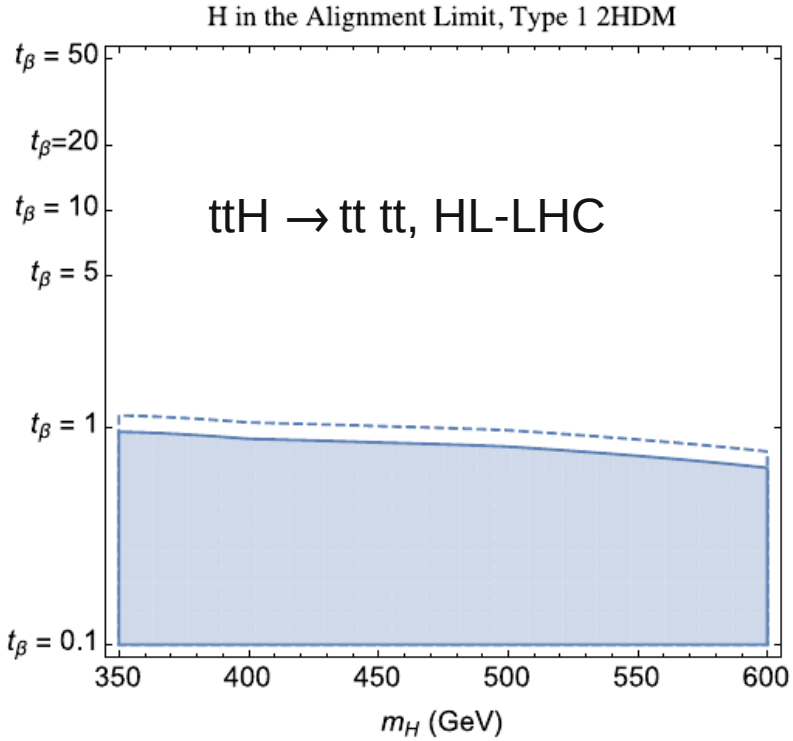
# A/H → tt

- Recently there has been a lot of interest from the pheno community on whether there is any sensitivity to H/A → tt

Djuadi et al arXiv:1502.05653




Craig et al arXiv:1504.04630

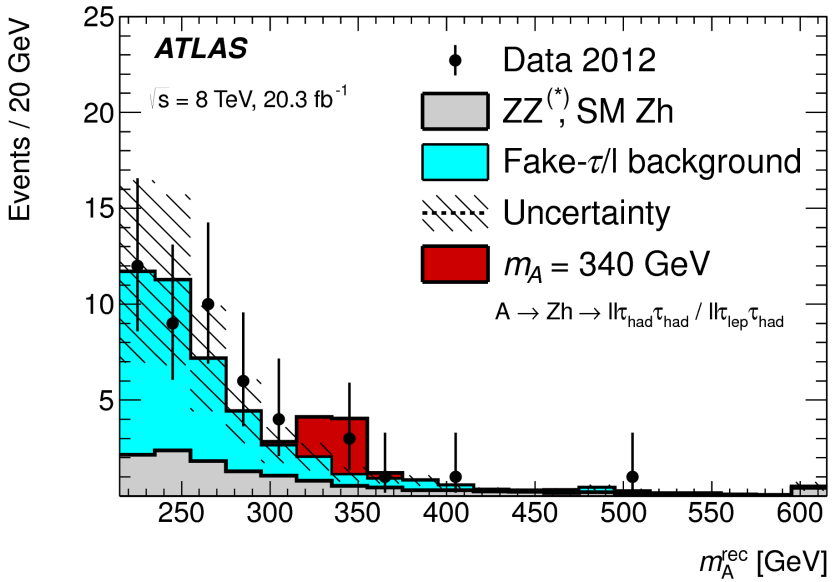


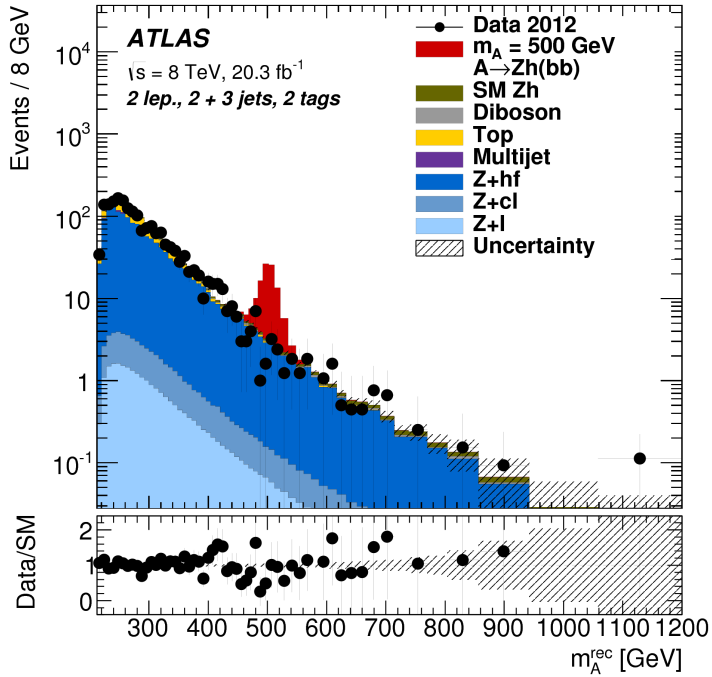
# Heavy Higgs search: (heavy) Higgs to (light) Higgs

- Very interesting signatures that are very important in generic 2HDMs:
  - $H \rightarrow hh$, $A \rightarrow Zh$, $H^+ \rightarrow Wh$
  - $A \rightarrow ZH$, $H^+ \rightarrow WH$
  - Conspiracy victims: The very nicely defined $H \rightarrow hh$, $A \rightarrow Zh$, $H^+ \rightarrow Wh$ suffer from vanishing couplings in the weak decoupling limit; $A \rightarrow ZH$, $H^+ \rightarrow WH$ have maximal couplings there, but they may be constrained kinematically
  - The LHC has just started exploring these final states

# A → Zh

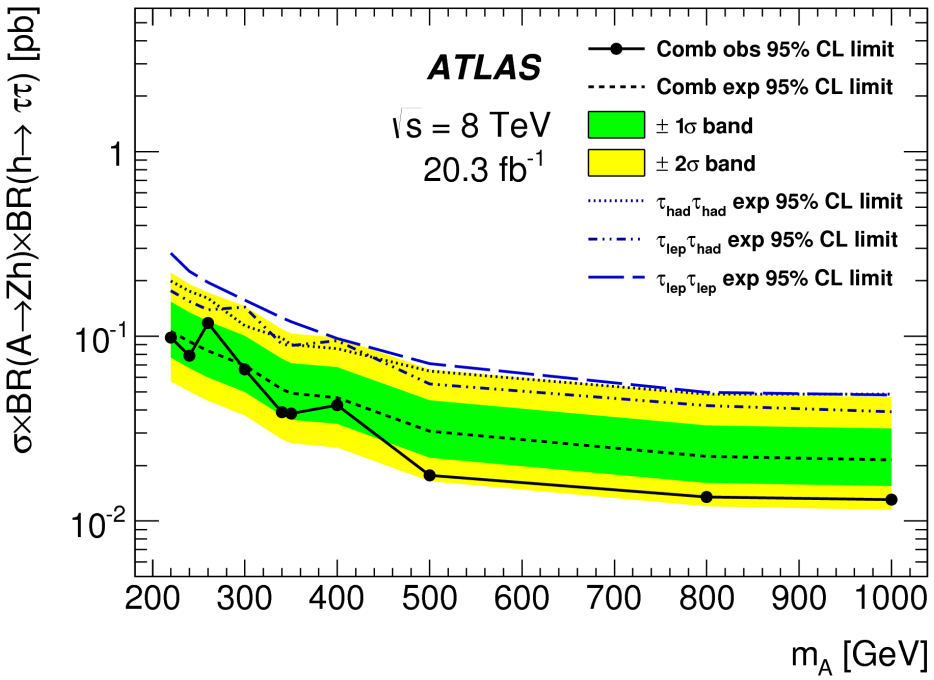
- Very interesting channel, mostly in $m_A$ ~ 220 – 350 GeV
- ATLAS search looked for Zh → llττ, llbb and ννbb final states

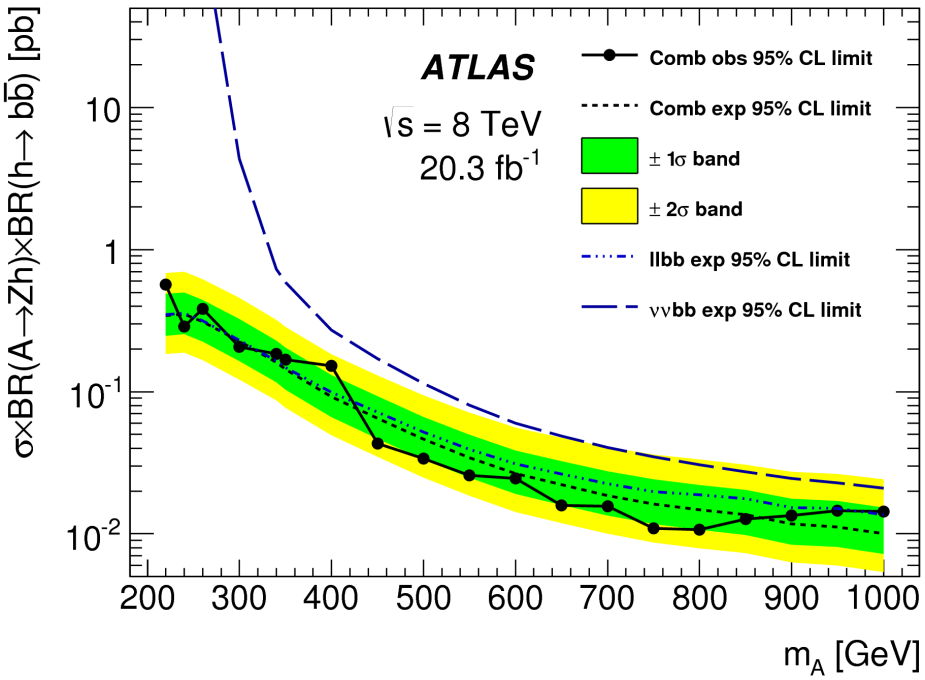


# A → Zh

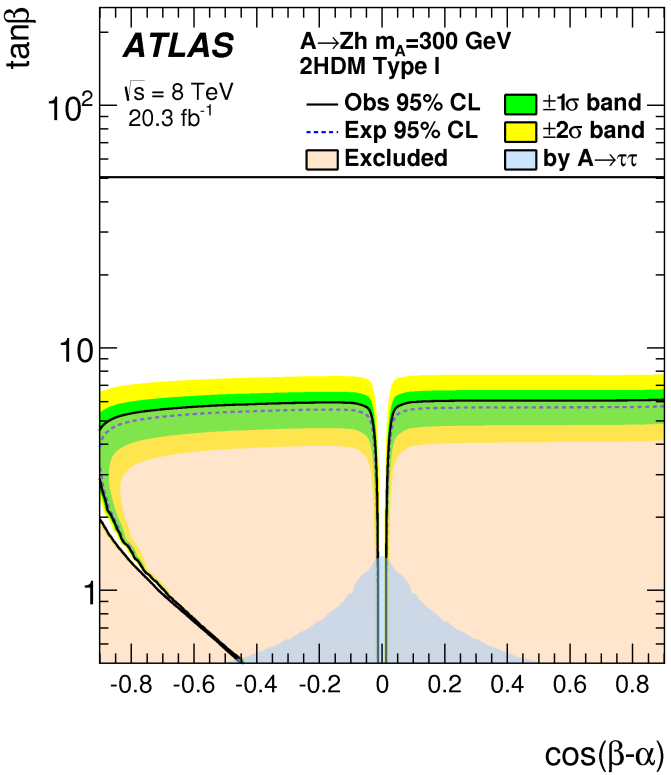
Cross section limits for heavy, narrow width, CP-odd Higgs produced via gluon fusion

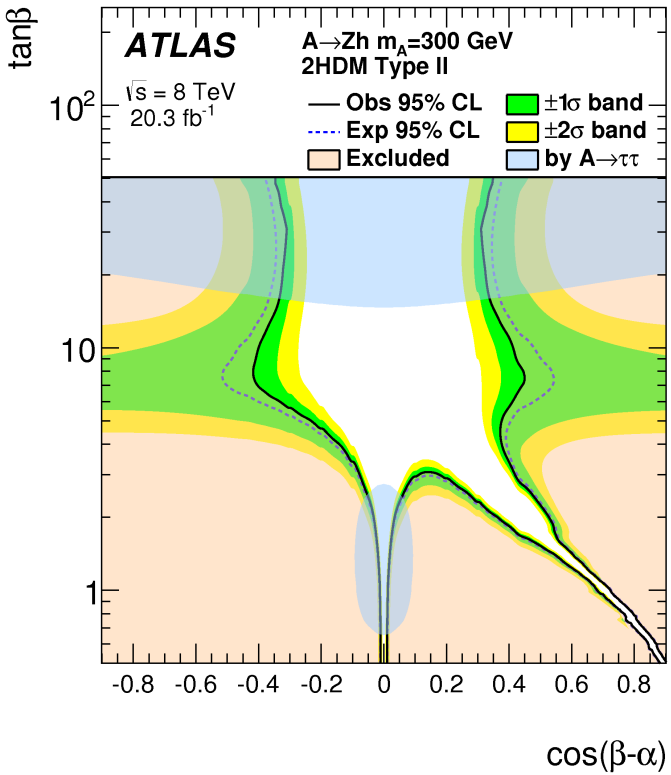


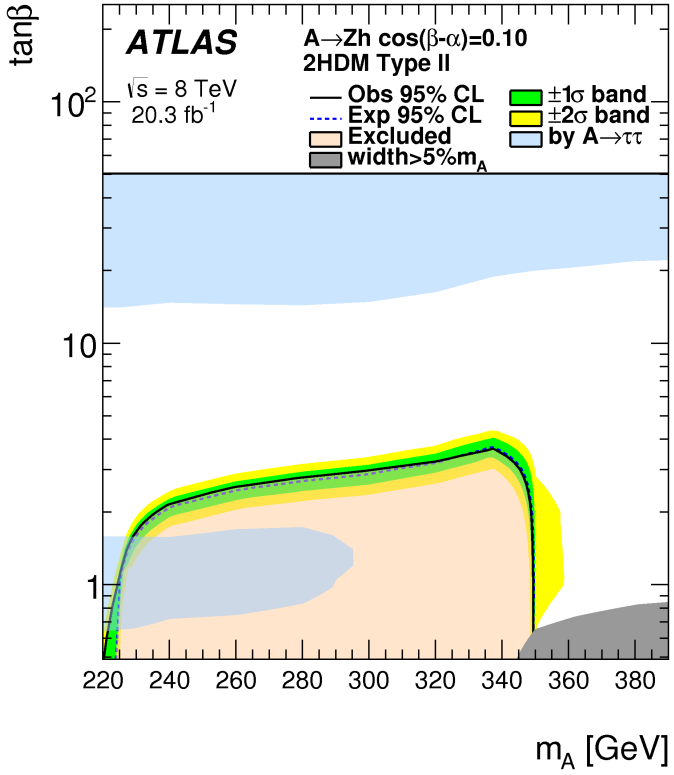



# A → Zh

Examples of the interpretation of the search in the CP-conserving 2HDM (also on the plots the constraint from A → ττ)



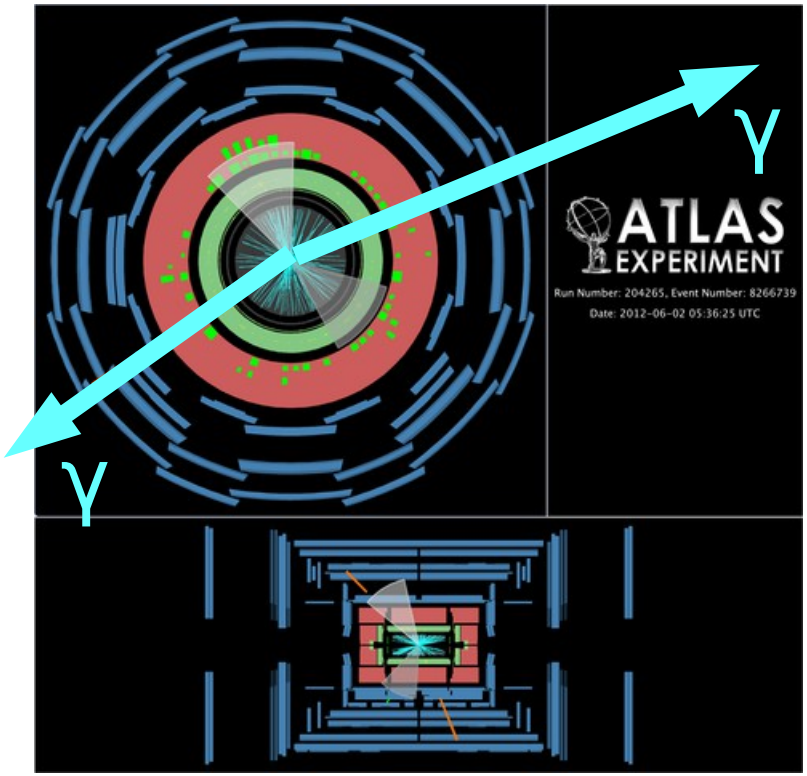



# Di-Higgs production: hh → bbγγ

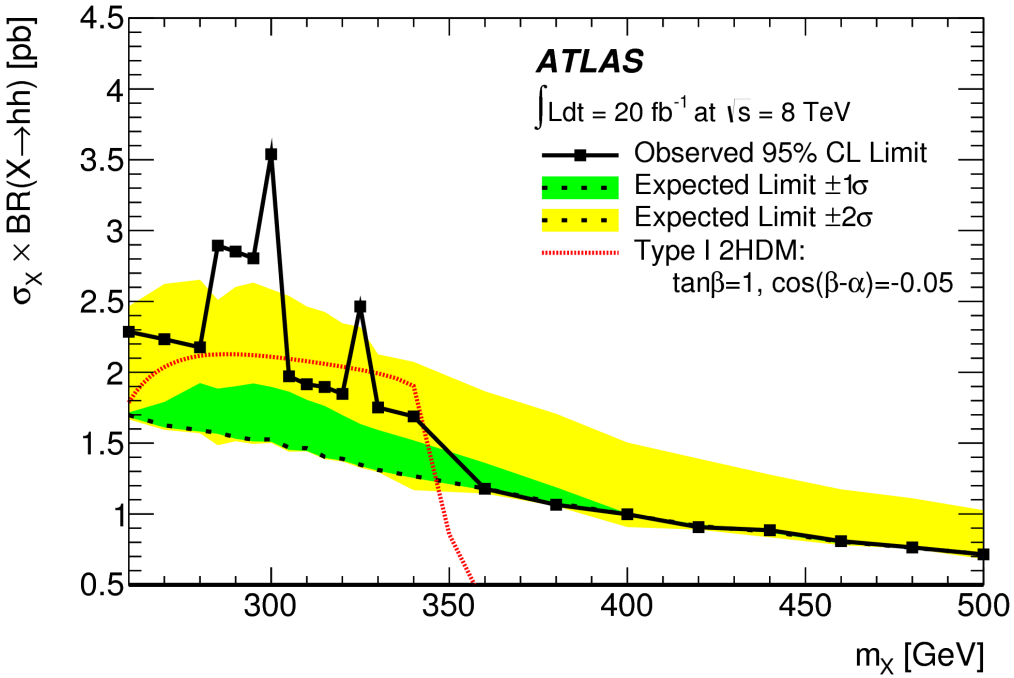
Obtained limit for anomalous non-resonant hh production:

σ < 2.2 pb (Exp: 1.0 pb)

→ Compare SM hh production ~10fb

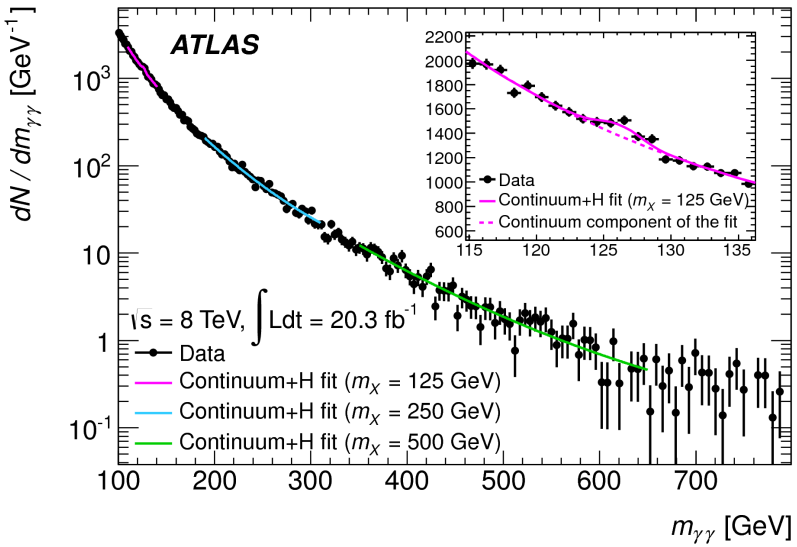



Limit for resonant hh production (assuming narrow width)



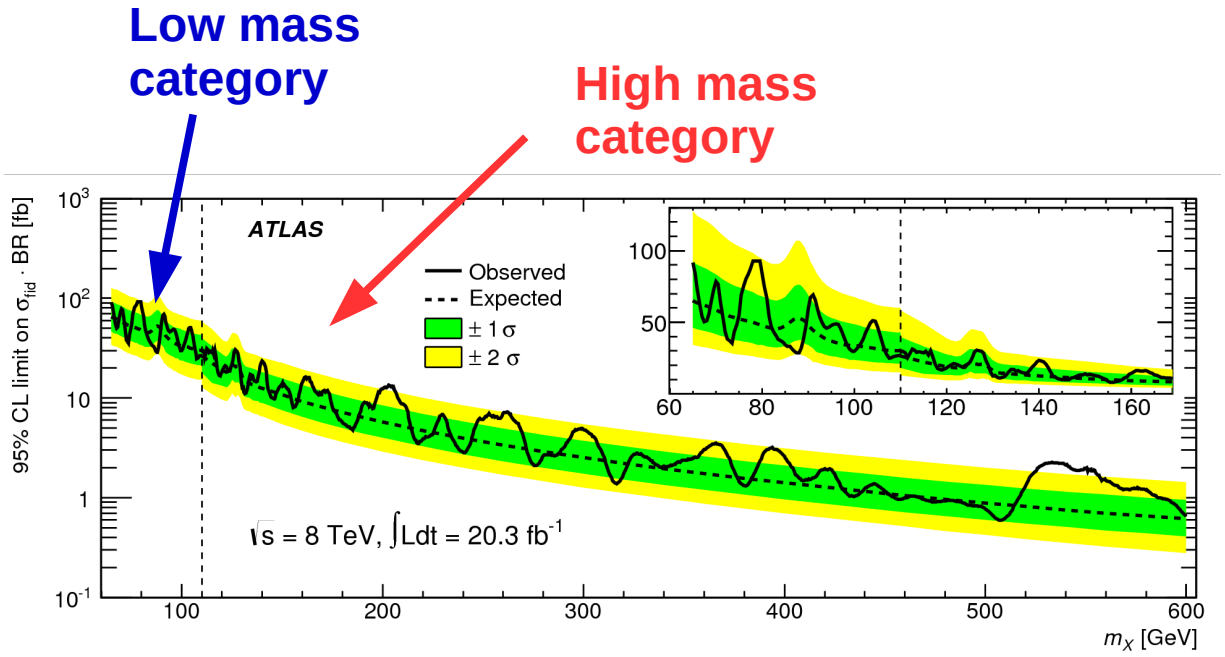
# Scalar resonances to di-photon pairs

- ATLAS has looked for A/H → γγ at a mass range from 65–600 GeV extending the techniques mastered in the SM Higgs → γγ search




Low mass category

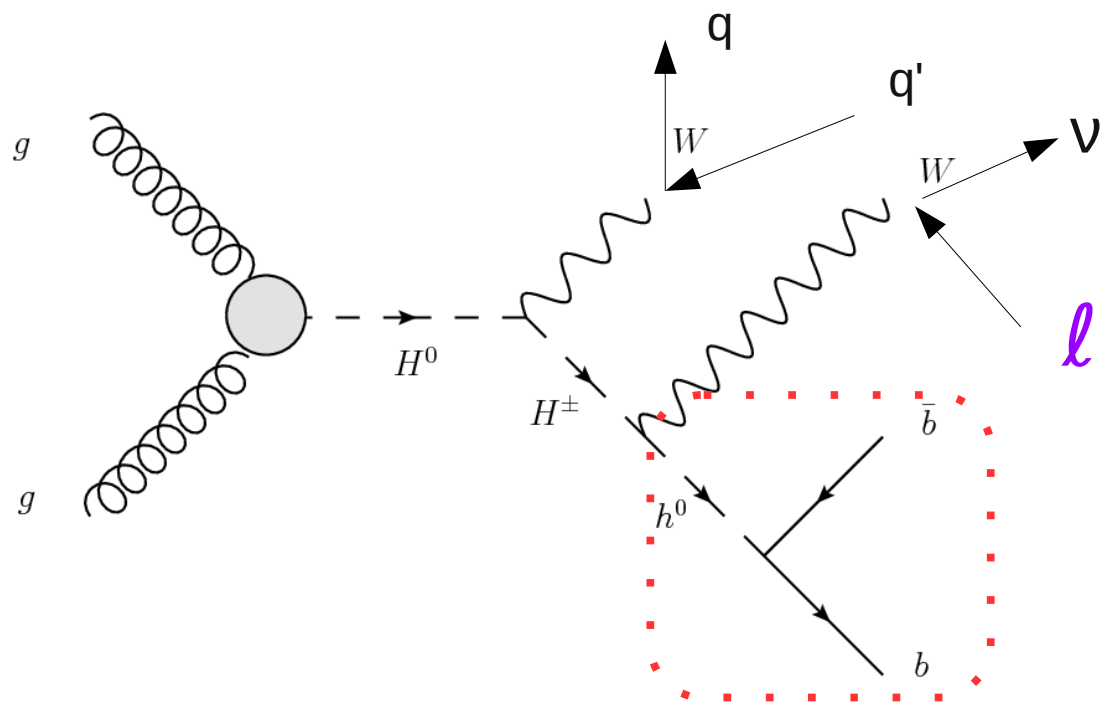
High mass category



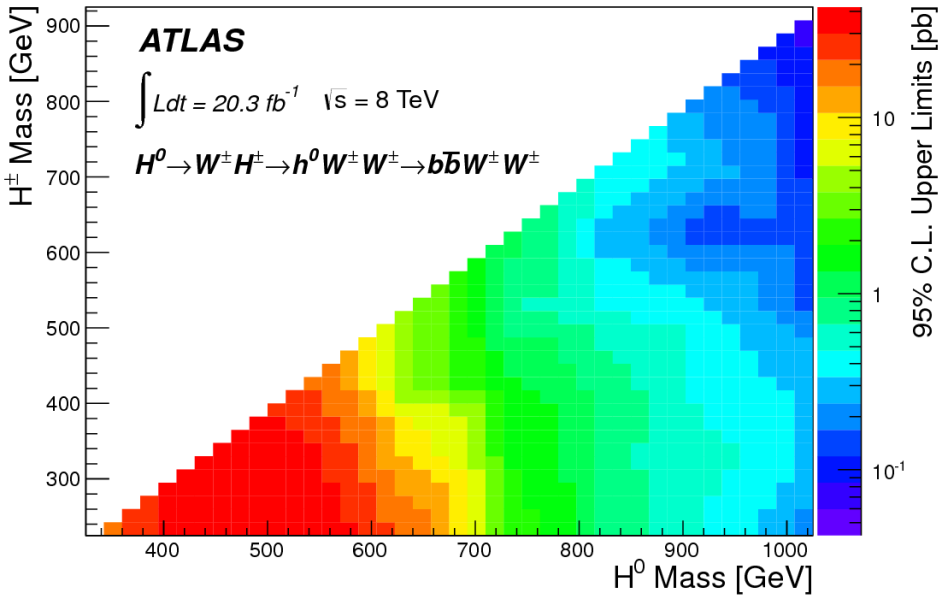

Limit on the fiducial cross section as a function of the assumed resonance mass

# Higgs cascades: $H^0/A \to H^+ W^- \to W^+ W^- h$

- An interesting possibility when more than one Higgs bosons appear in the model includes decays of Heavy Higgses into lighter ones



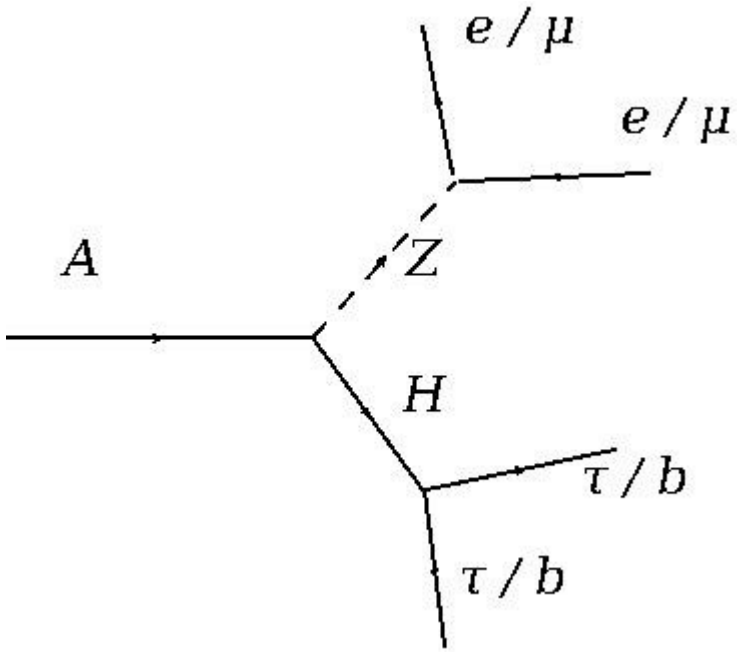

**125-GeV SM-like Higgs decaying to bb**



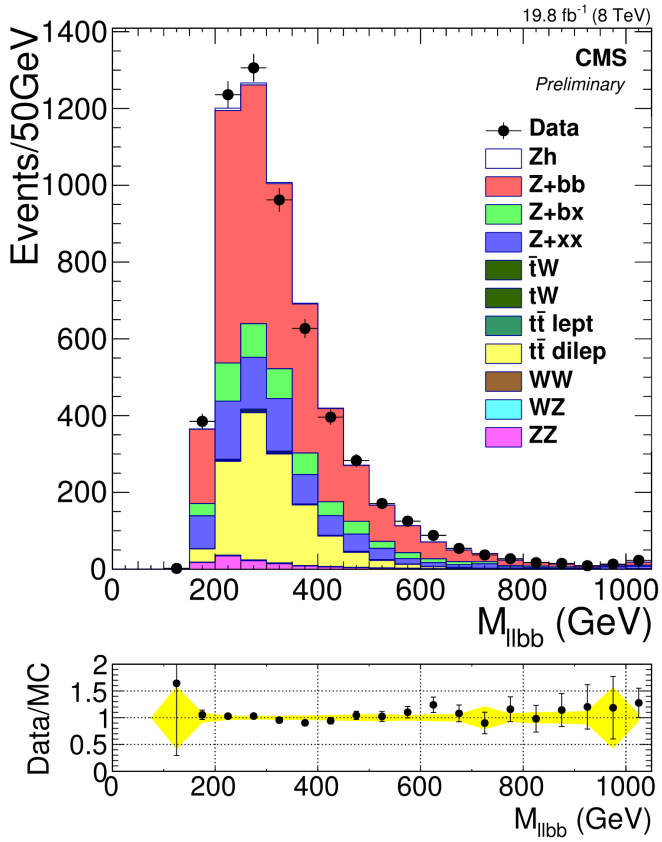

**Phys. Rev. D 89, 032002 (2014)**

# Heavy Higgs to Heavy Higgs

- CMS was bold enough to proceed to analysis that doesn't vanish in the 2HDM weak decoupling limit



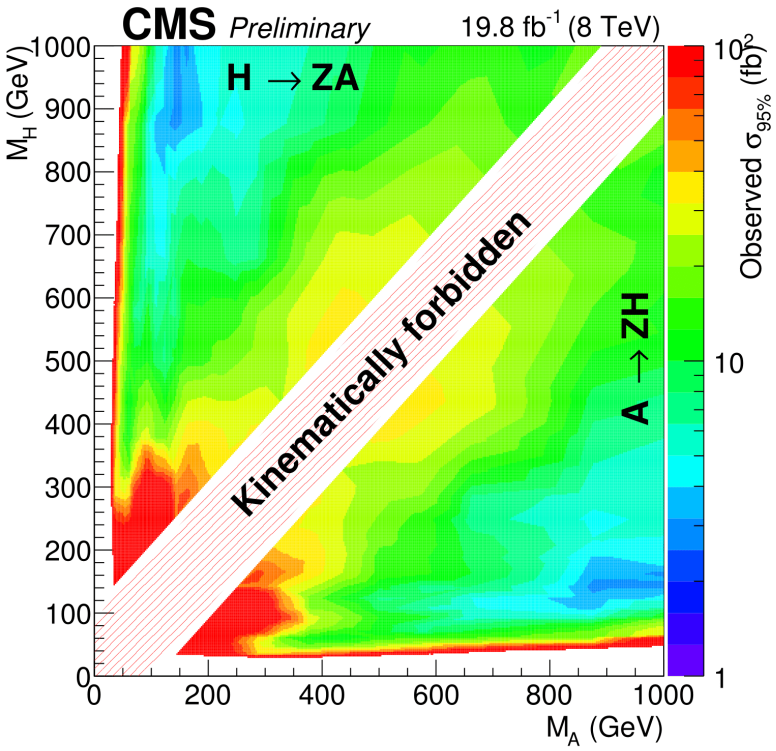

CMS-PAS-HIG-15-001



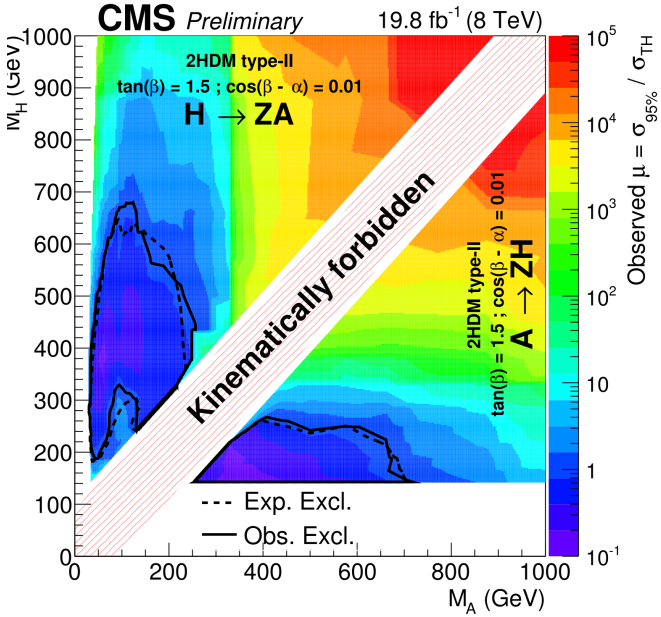
# Heavy Higgs to Heavy Higgs

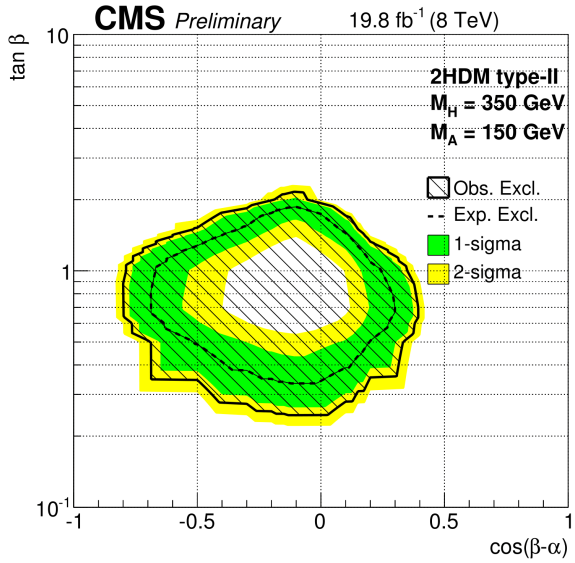
- Interpretation is more complicated than the previous searches

Cross section limit in the $m_A - m_H$ plane



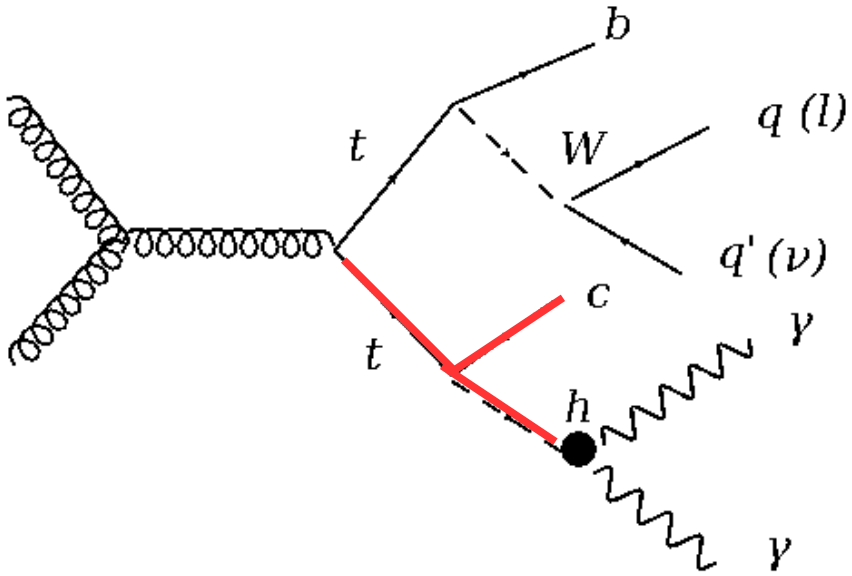

Attempt to show constraints on a type-II 2HDM configuration

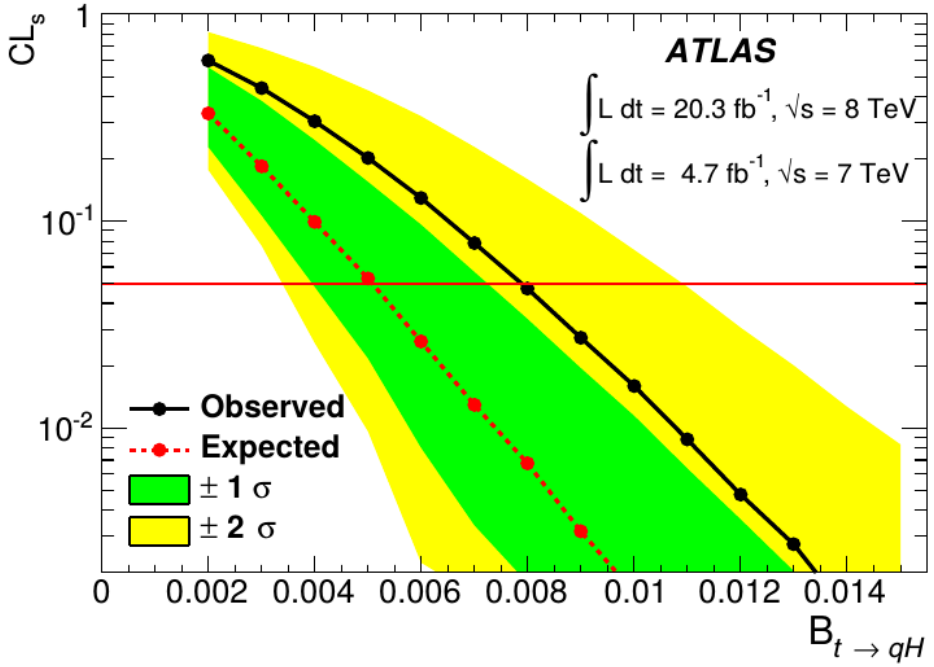


# Exotic Higgs sectors: Flavour violation

- Flavour changing (FC) neutral currents appear in many BSM theories
  - In type-III 2HDM, for instance, FC couplings **tch** (and tuh) exist and can have sizeable effects for LHC searches




Final constrain on the FC branching ratio:
BR(t → qh) < 0.79 (0.51) % observed (expected) @ 95% CL

# Higgs singlets: NMSSM

- Criticism of the 2HDM

The only solution is to follow the teachings of Wess and Zumino!

2HDM gives you **more freedom**
→ no severe mass constraints
→ options for more searches for CP-violation
→ more signatures

But you have to trade the physics motivation of the MSSM or expect that it will come with some company:
NMSSM keeps the SUSY physics motivation and allows for more freedom!

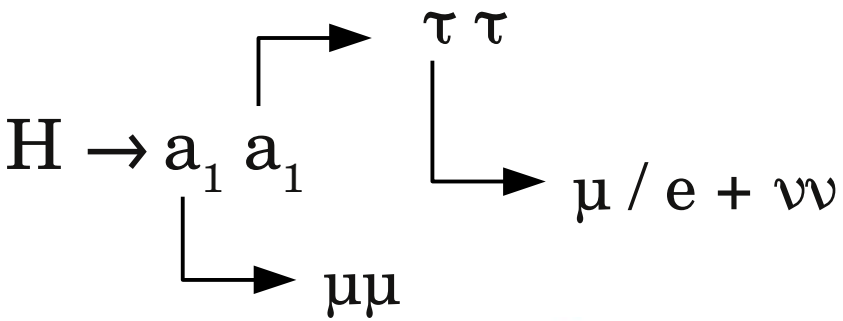
# Higgs singlets: NMSSM

- NMSSM = next-to-minimal supersymmetric SM
  - Adds a singlet to the 2 Higgs Doublets of the MSSM: two additional Higgs bosons and one more neutralino (wrt MSSM)
  - Solves also the MSSM μ problem
  - Higgs sector not CP-conserving at tree-level!
  - The tree-level MSSM relation "$m_h < m_Z$" is not valid!
  - LEP and MSSM ττ limits showed previously are not valid!

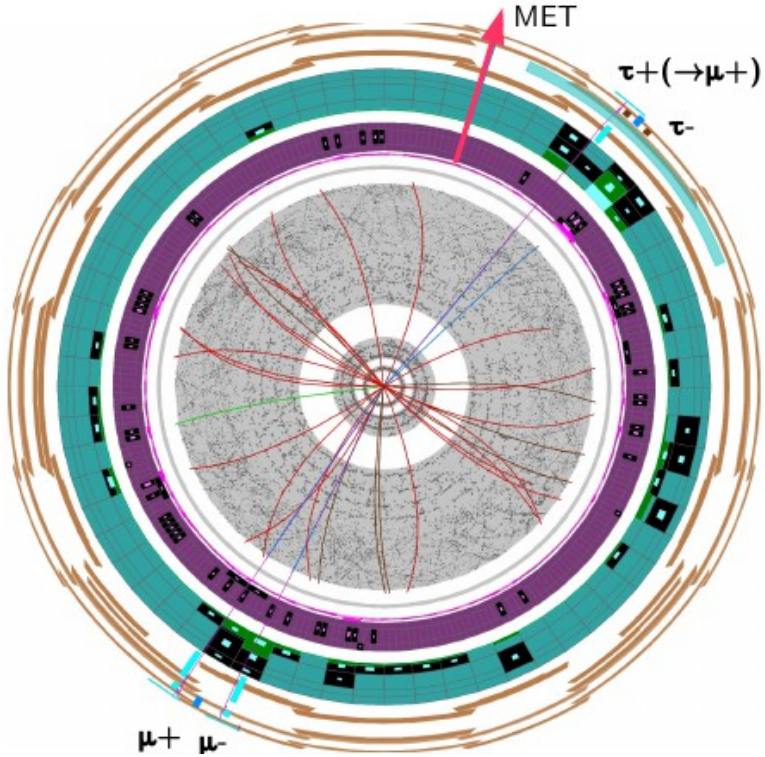
Typical phenomenological signature of NMSSM: existence of ultra-low mass Higgses, $a_1$, opening up decays like $h_1 \rightarrow a_1 a_1$, $H^+ \rightarrow a_1 W$

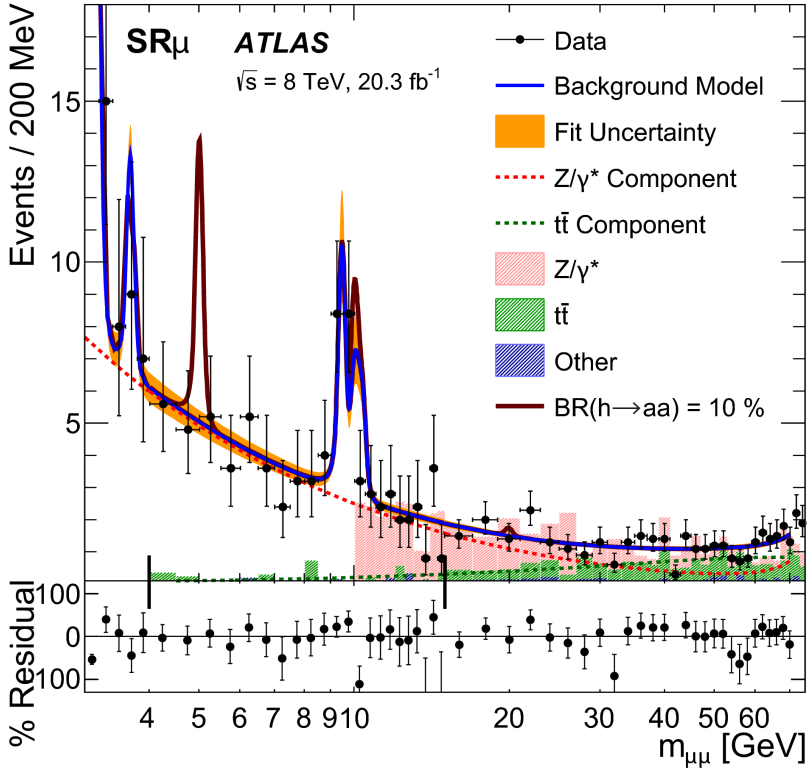
# $h \rightarrow a_1 a_1 \rightarrow \mu\,\mu\,\tau\,\tau$

**arXiv:1505.01609**



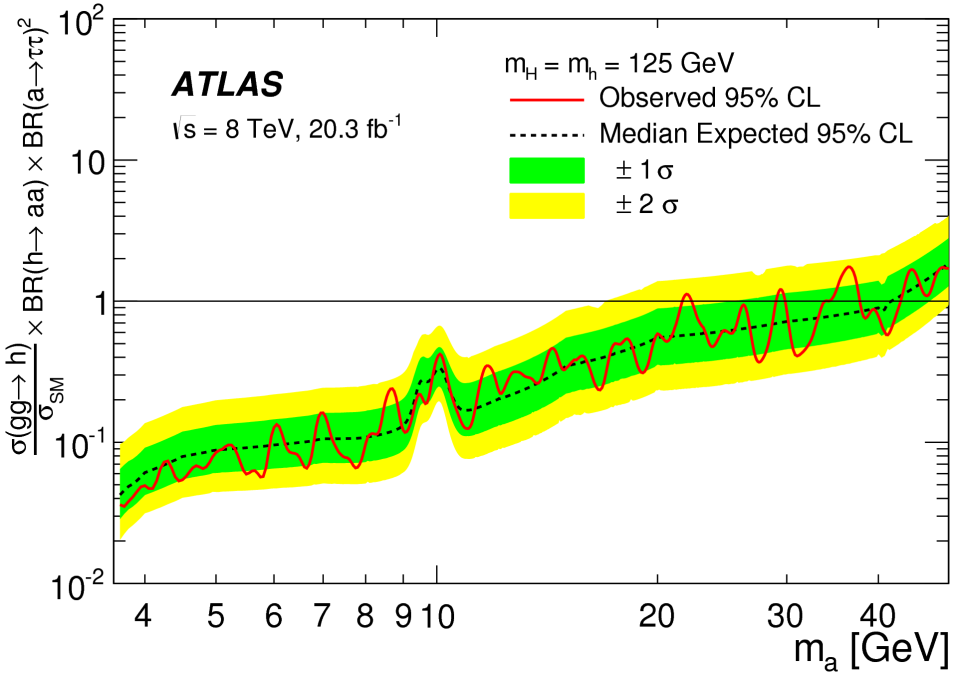

Searching for a bump in the μμ spectrum:

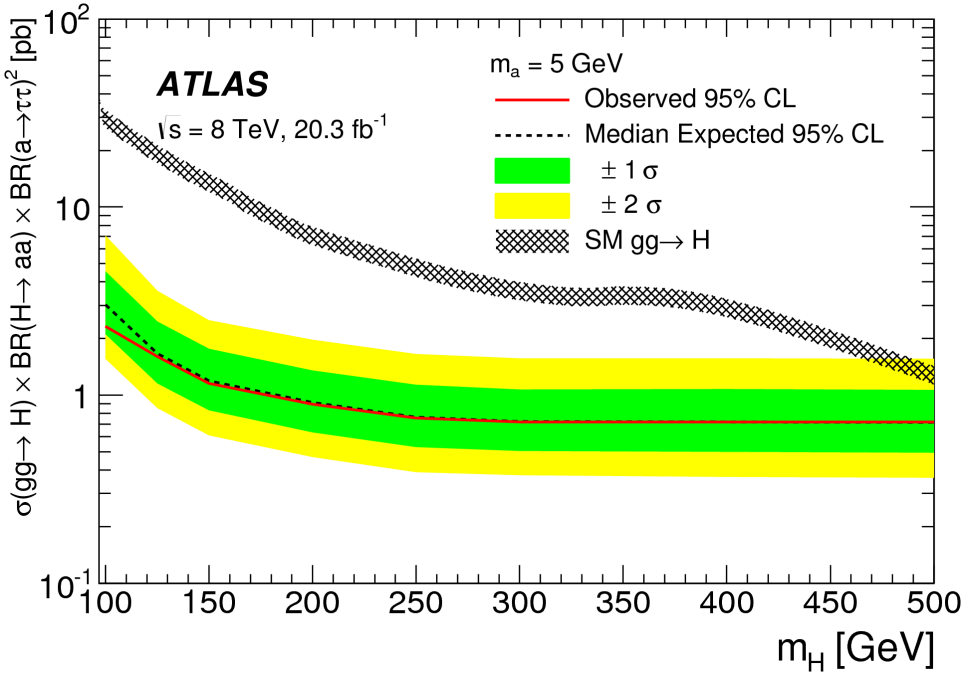


# $h \to a_1 a_1 \to \mu\,\mu\,\tau\,\tau$

Look for $m_a$ in the mass range: 3.7 – 50 GeV and for a heavy Higgs decaying to aa in the range 100 – 500 GeV



# Higher Order Representations

- There are arguments why one would be interested in higher order representations (i.e. isospin > ½)
  - triplets (isospin=1) may be connected to neutrino masses
  - there are reasonable phenomenological possibilities that are not covered by 2HDM/MSSM due to their restricted Higgs sector structure
    ✔ absence of vertices like $H^+ZW$ (although they violate no basic symmetry)
    ✔ Higgs couplings to W/Z must be less than their SM values
  - But they also suffer from a fundamental problem
    ✗ $\rho \neq 1$ at tree-level

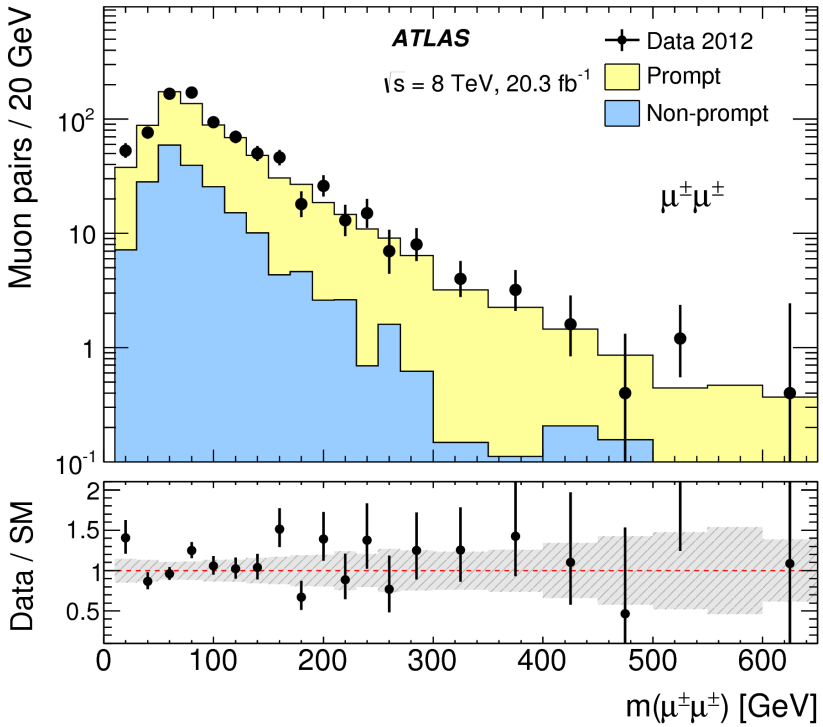
# Higher Order Representations

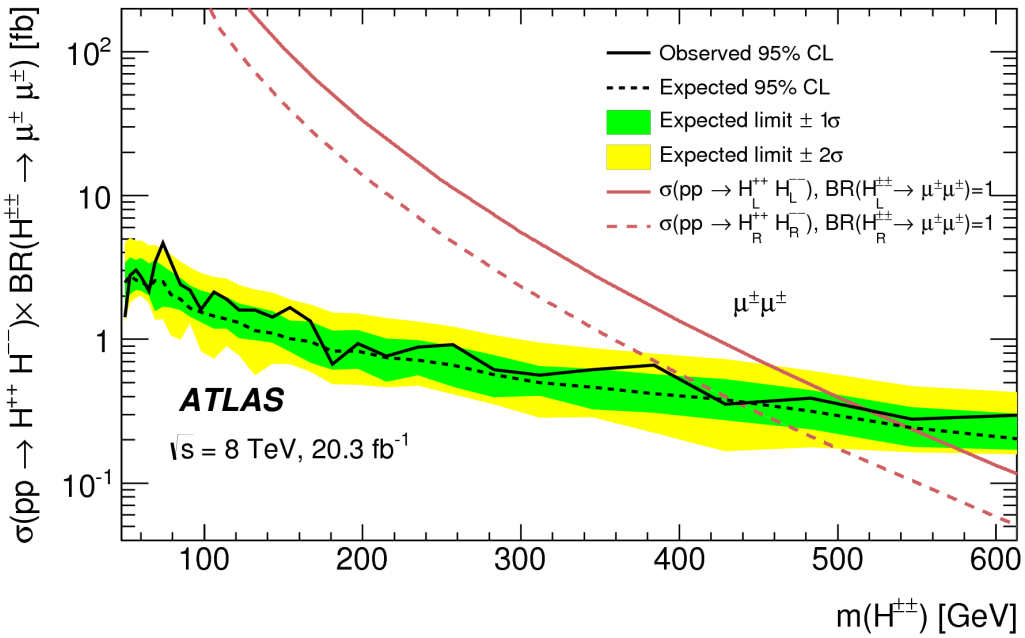
- There are ways to solve the tree-level $\rho \neq 1$ issue
  - Fine tune the value of the triplet v.e.v. (up to GeV)
  - Fine tune the Higgs potential, such that it has the custodial $SU(2)_V$ symmetry after EWSB (e.g. Georgi-Machacek model)
- Typical signatures
  - Doubly charged Higgs
  - $H^+ \to WZ$

# $H^{++} \rightarrow \ell^+\ell^+$

JHEP03(2015)041

- Doubly charged Higgs to same sign leptons
  - Pair production of $H^{++}$ via Z/γ*

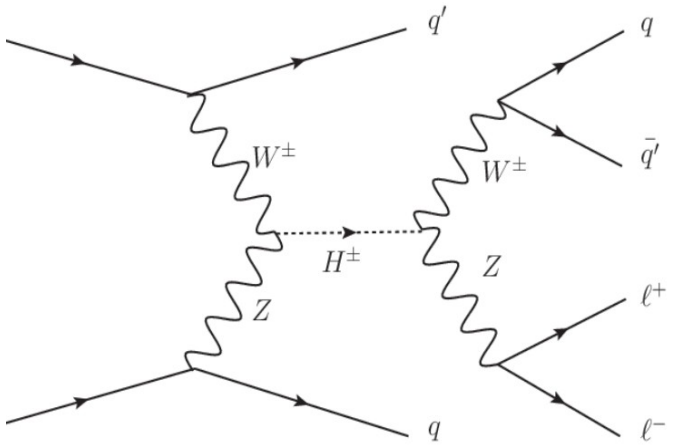


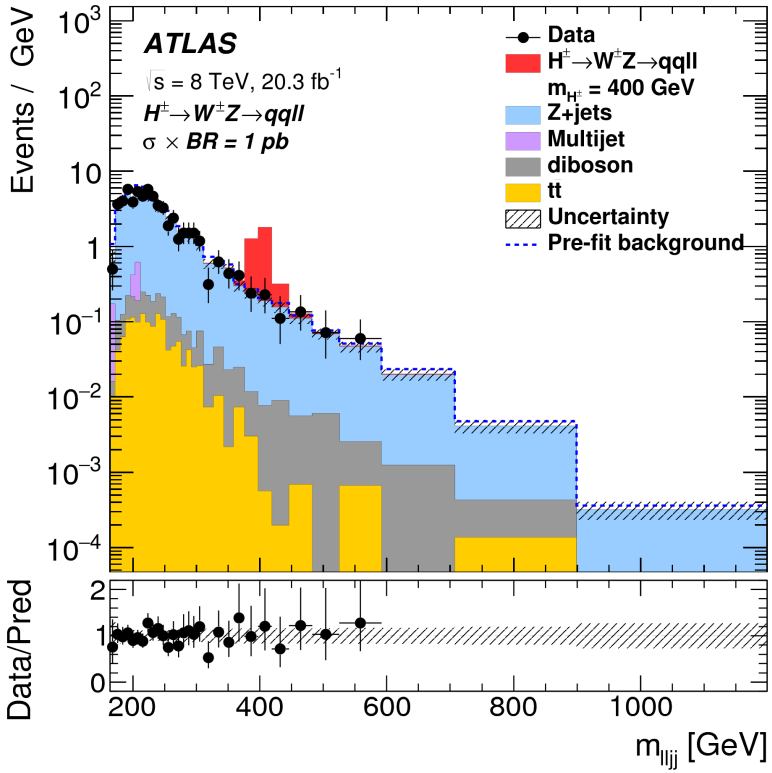

Example from the μμ channel. Other channels are also in the paper: eμ, ee

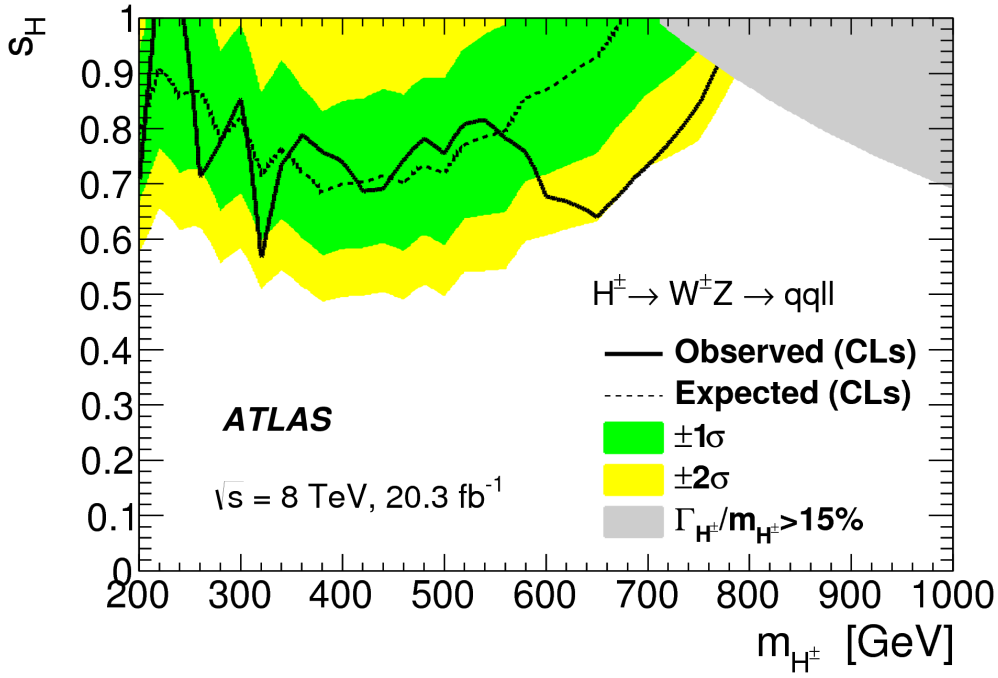
# $H^+ \rightarrow WZ$

- VBF Production of a charged scalar that decays to ZW



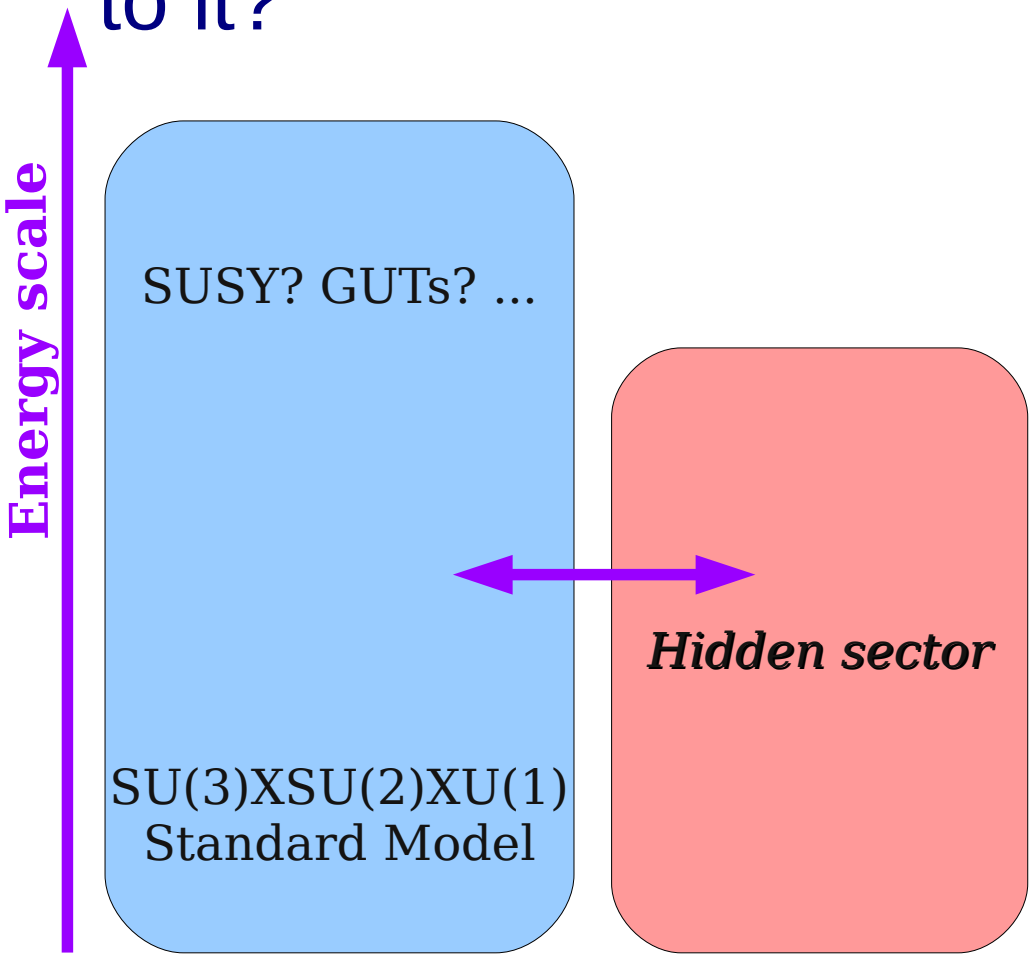

**arXiv:1503.04233**



# Portals to Hidden Sectors

- If there is a hidden sector in nature: how to connect to it?




The Higgs sector provides a connection with a singlet S under the SM group using renormalizable operators:

$\phi\phi SS$ **Higgs portal**

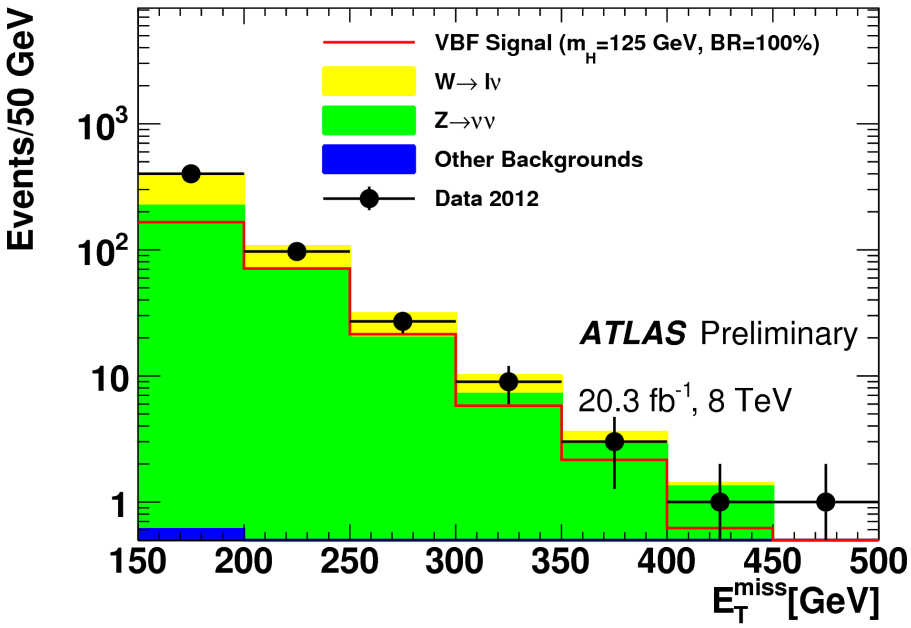
# Portals to Hidden Sectors

- A variety of signatures is motivated by such a connection
  - Couplings of Higgs to light (pseudo)scalars, ie. similar to the signatures of the NMSSM, see also **arXiv:1312.4992**
  - Higgs to dark matter (invisible) or long lived particles

# Higgs to invisible

- The SM Higgs boson has decays to (LHC detector) invisible particles, e.g., $h \to ZZ \to \nu\nu\nu\nu$, which has BR ~ 1/1000 and hence it is beyond our current sensitivity.
- Some ATLAS searches looking for "h125" → invisible

VBF Higgs to invisible: BR(inv) < 29%



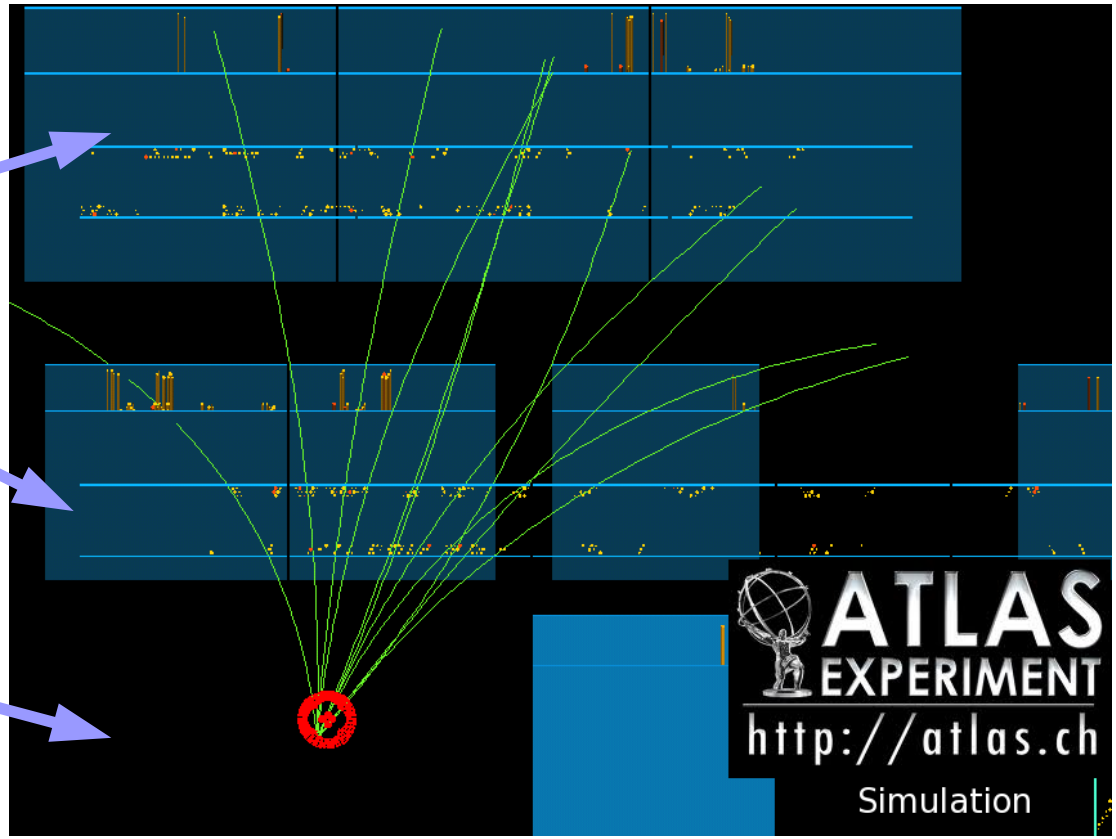

V( → jj)H Higgs to invisible: BR(inv) < 78%

Z(→ll)H Higgs to invisible: BR(inv) < 75%

# Higgs to Long Lived particles

- Higgs decaying to invisible, long-lived "hidden valley" pions $\pi_v$, which decay to jets in the outer calorimeter and are detected in the muon system

**$h \rightarrow \pi_v \pi_v$; $\pi_v \rightarrow bb/cc/\tau\tau$**

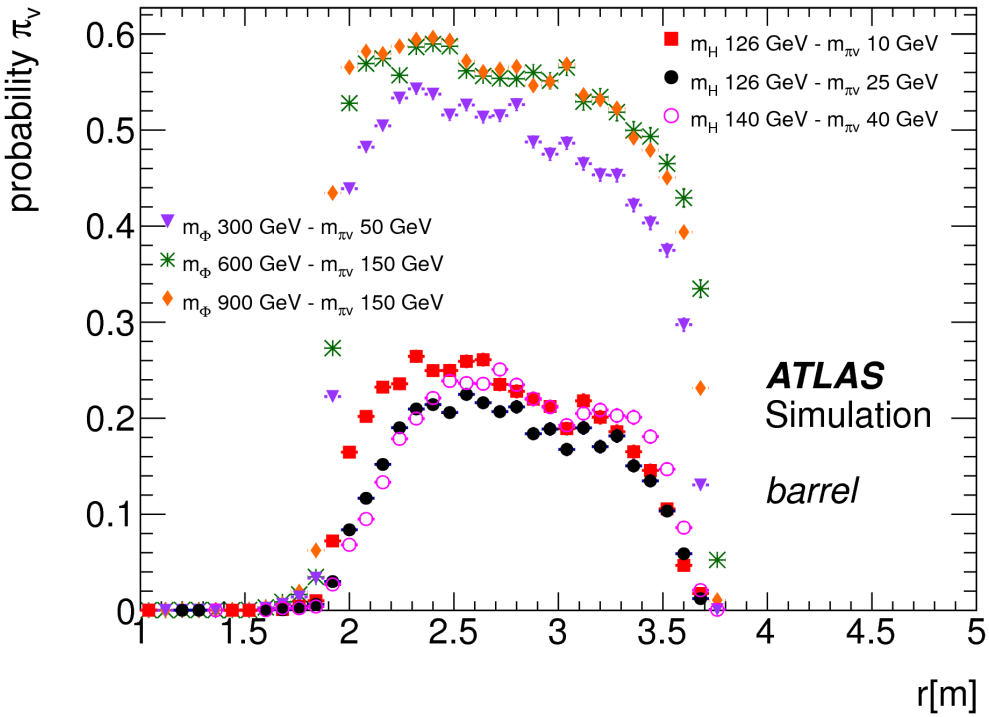


# Higgs to Long Lived particles

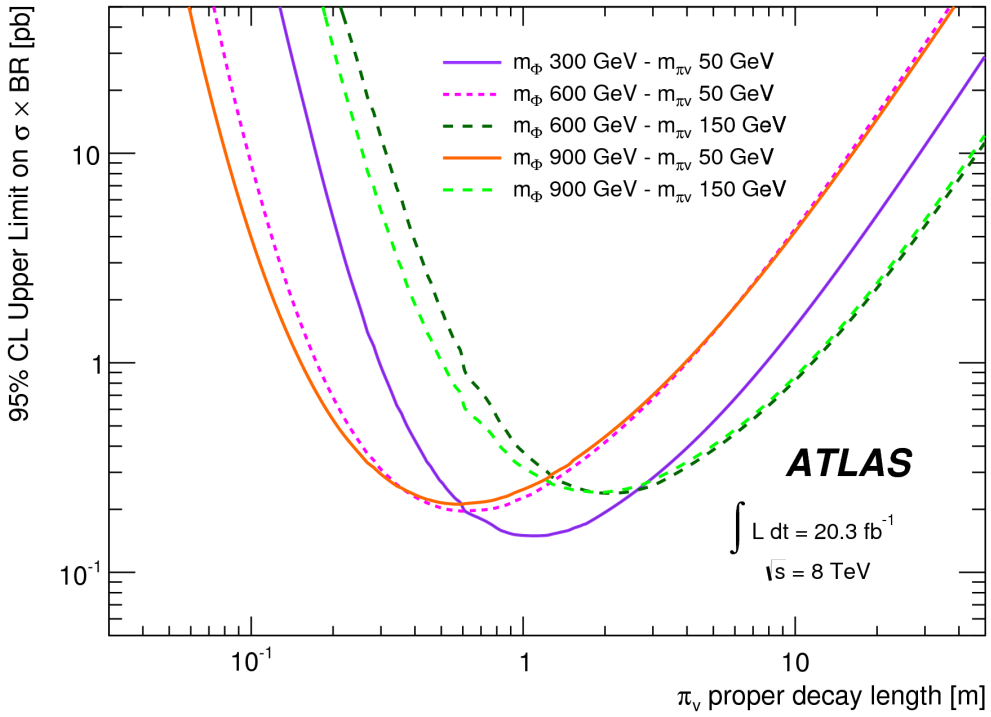
- Dedicated trigger development

Phys. Lett. B 743 (2015) 15-34

Trigger efficiency for a signle $\pi_v$ as a function of the radial decay length in the barrel




Observed limit for various mass assumptions



# Run-I results and hints for the future

- The search for BSM Higgs has just started!
- There is significant physics motivation

Supersymmetry, composite Higgs, baryogenesis, neutrino mass, dark matter, …

- Only now we are start being sensitivity to most of the models

# Run-I results and hints for the future

- In Run-I we discovered what is most probably the lightest CP-even SUSY Higgs
  - We have disfavoured additional light MSSM Higgses, as well as the possibility that the heavy CP-even Higgs is the one at 125 GeV
  - There is still a lot of space for MSSM Higgses at high mA
    - H/A->tautau will continue being the workhorse at high tanβ
- In Run-I also we started exploring lots of signatures without the SUSY bias: Some of them have just started and are not yet sensitive to any realistic model
  - $H^+ \rightarrow tb$ has just started; $H/A \rightarrow tt$ is very difficult
  - Triplets, exotic decays etc are just in their infancy

# Run-I results and hints for the future

- Do not forget flavour physics:
  - I didn't have time to talk a lot, but many channels, including $B_s \to \mu\mu$, $B \to \tau\nu$, etc have very high BSM Higgs interest
- We have to keep in mind looking for a Higgs boson means that we are looking for “a Higgs boson”
  - Higgs couples to mass, so disfavouring your exotic Higgs model doesn't mean that you disfavoured BSM Higgs
  - This essentially means that life may be more difficult than we would want and we should not be surprised if we have to wait for a discovery till the later stages of Run-II

# Concluding remark

## No BSM? Beware Historical Hubris

- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"*** **- Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

From the theory summary talk in LHCP 2014 by J. Ellis

# Even more results

- Not all results were able to be shown
- All public results from ATLAS here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

# Exotic Higgs sectors: Flavour violation

- Flavour changing neutral currents may also appear in Higgs decays as well

**arXiv:1502.07400**

  - $H \rightarrow \tau\mu$

$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c.$$