Collider Searches for Beyond-SM Higgs bosons

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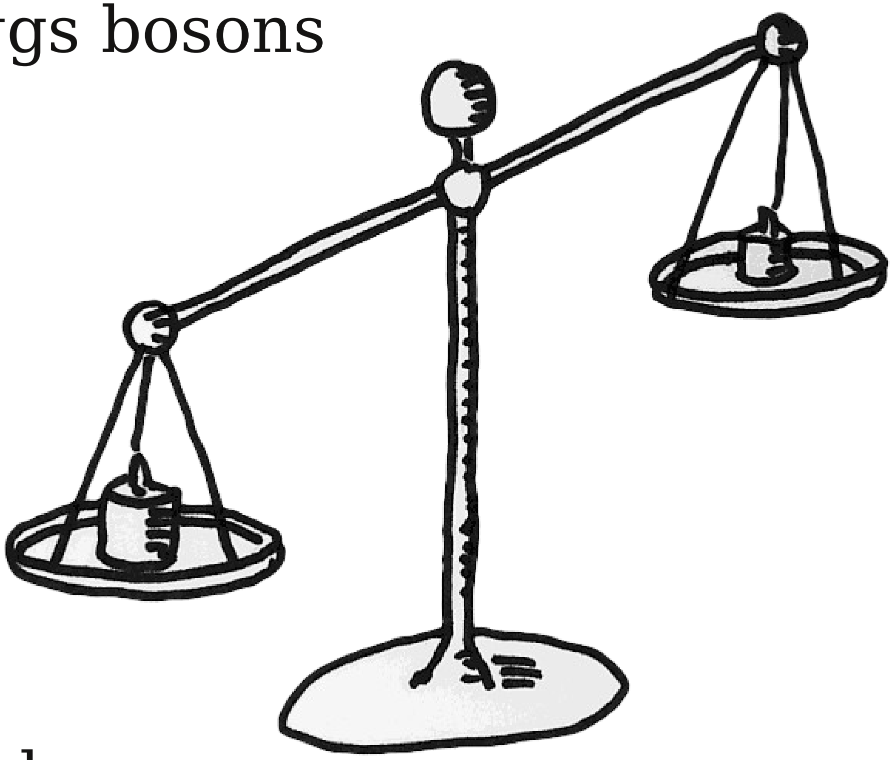
(University of Washington)

Before we start

In this talk I will be discussing only some aspects of collider searches for Beyond-SM (BSM) Higgs bosons



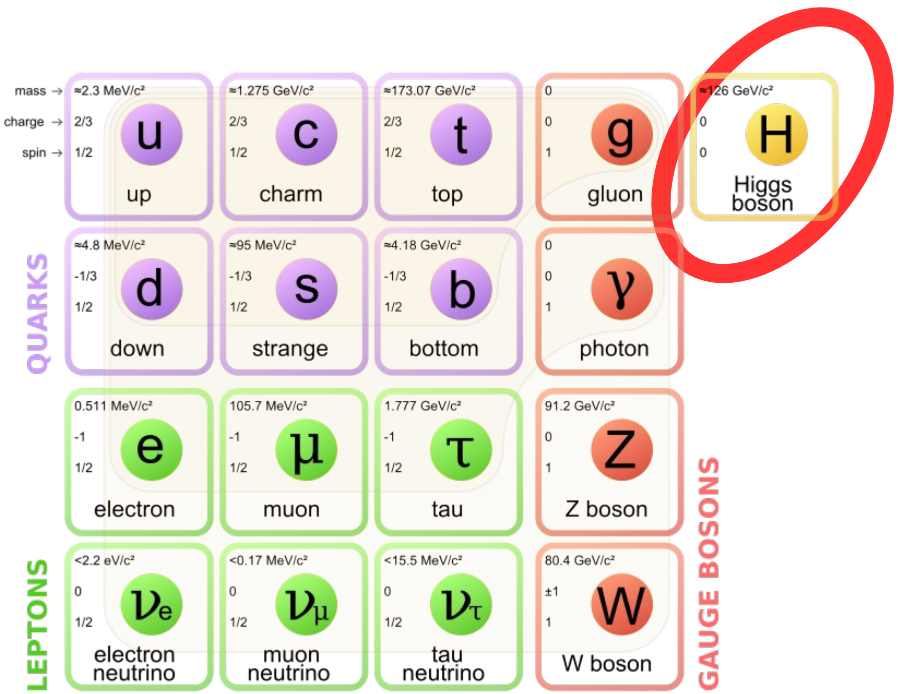
✔ Biased selection of experimental results

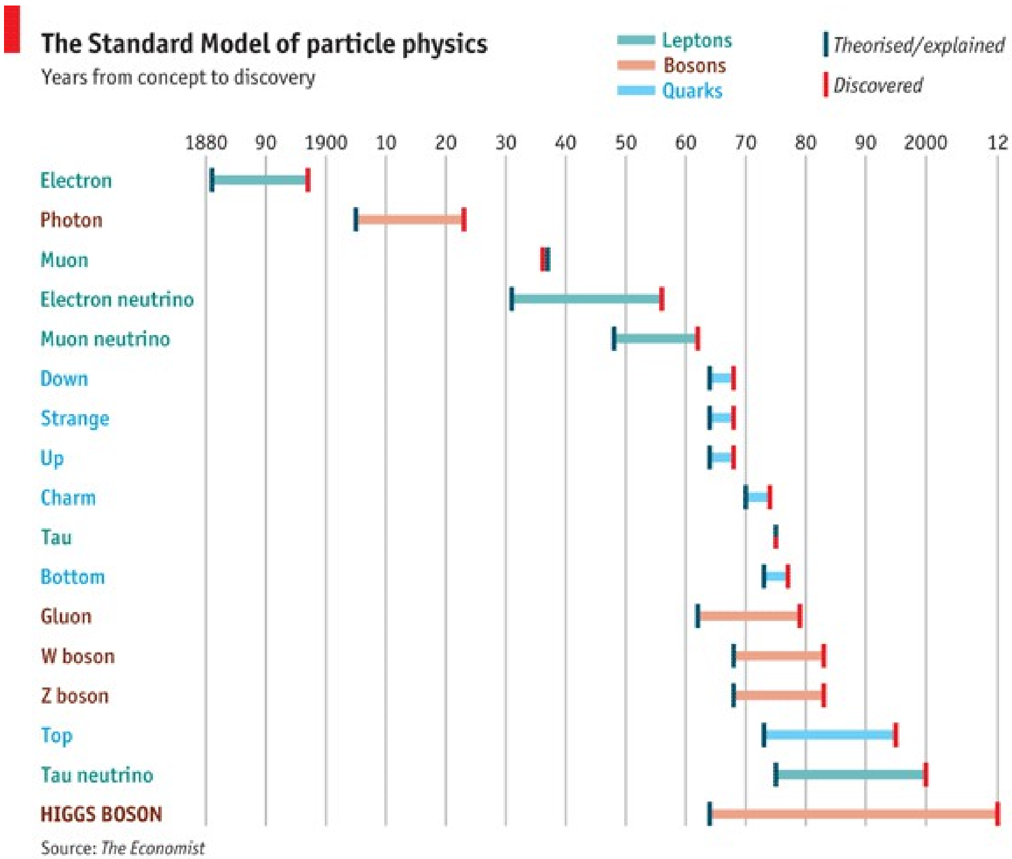
✔ Some of the opinions expressed are personal and not ATLAS statements

✔ A top-bottom approach is followed:
I will try to give the "big picture" of the experimental results and match them with the underlying phenomenology

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 put in place





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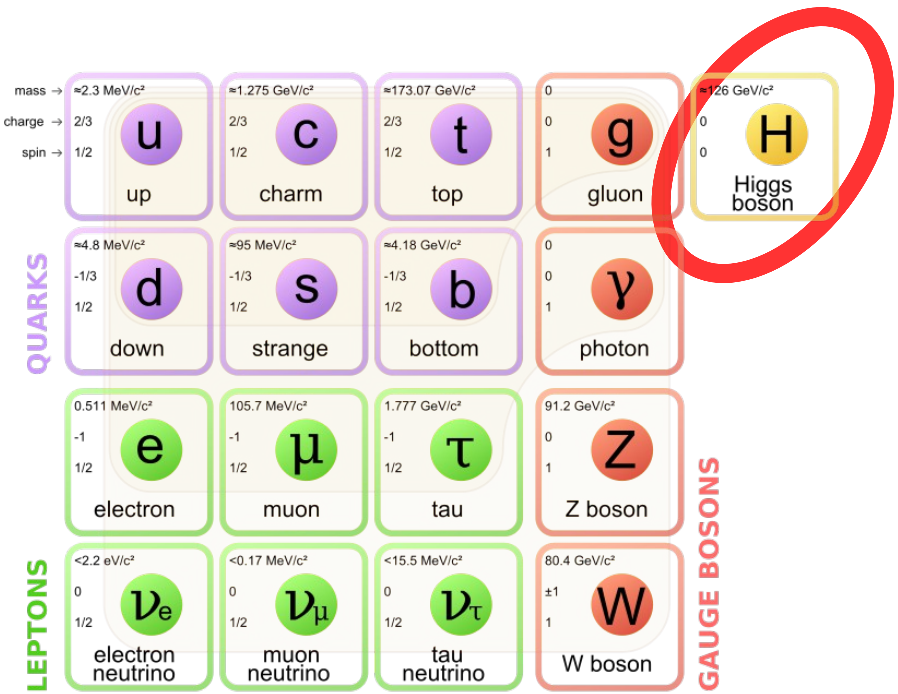
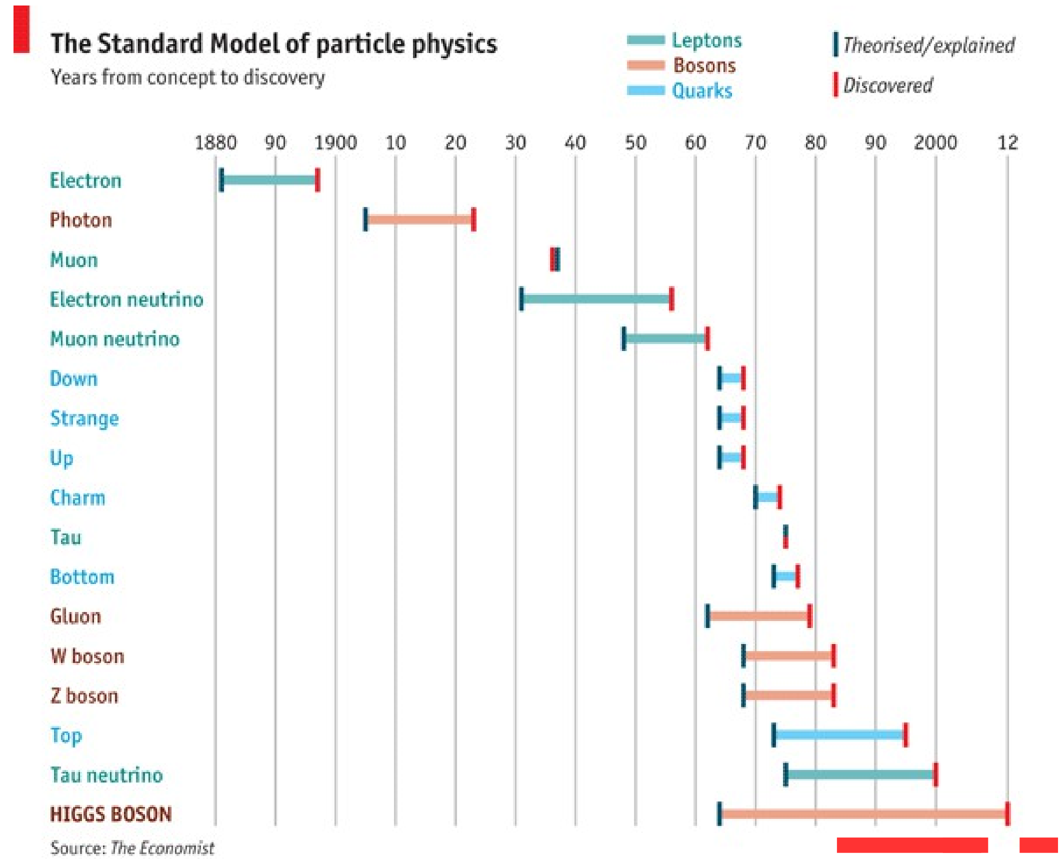




?

Chart copyright "The Economist"

Supersymmetry

The Higgs boson

The Higgs boson discovery was a great benchmark in the history of physics. Not only it provided evidence for the Brout-Englert-Higgs mechanism for the Electroweak symmetry breaking but also

✔ first fundamental (?) scalar particle found
✔ first probe of the SM sector that is less constrained by symmetry principles

The Higgs sector has such unique properties that make it an excellent probe for BSM Physics

Beyond the Standard Model

- Standard Model is not the full picture. A number of of questions that are directly related to the Higgs sector are the following
  - Where are the additional sources of CP violation in nature needed to explain the matter-antimatter asymmetry?
  - What is dark matter composed of?
  - Do interactions unify at some high energy scale?
  - What is the neutrino mass origin?
  - Can fundamental scalars exist in Nature?

Beyond the Standard Model

- Standard Model is not the full picture. A number of of questions that are directly related to the Higgs sector are the following
  - Where are the additional sources of CP violation in nature needed to explain the matter-antimatter asymmetry? **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

- In this talk only few of topics of the vast work on extended will be discussed
  - MSSM Higgs bosons
  - Beyond MSSM: generic 2HDM searches
  - Exotic 2HDMs, Exotic Higgs representations
  - Beyond MSSM: light pseudo-scalar particles (NMSSM)
  - Higgs connection to Hidden sectors
  - Comments about the current status & the future

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?

Can Higgs be 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.

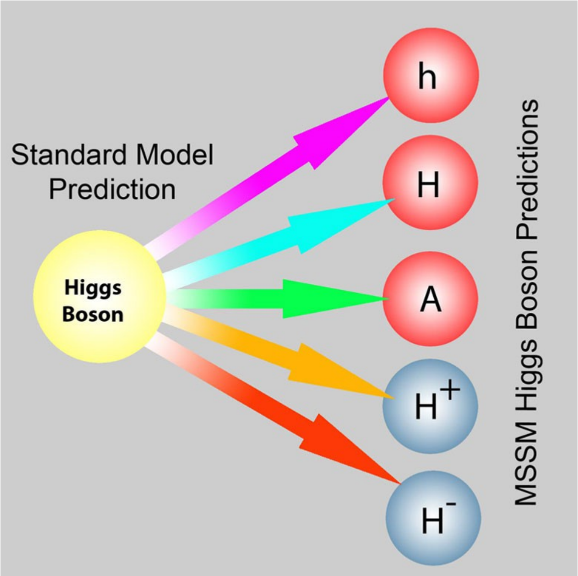
The MSSM

- The Minimal Supersymmetric Standard Model (MSSM) has been the leading idea behind the design of the BSM Higgs searches at the LHC in late 90's and up to the start of LHC
- MSSM has the following features
  - 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

In general the MSSM has about 100 parameters, which are still too many to study the phenomenological properties. Under some assumptions the number of parameters can be reduced to about 20 (pMSSM = phenomenological MSSM)

The MSSM Higgs sector

- The 1 doublet is not enough for SUSY
  - Higgs supersymmetric partner, the Higgsino, is a fermion: anomaly cancellation dictates a second doublet
  - One doublet couples to leptons & down-type quarks and the other to up-type quarks
  - This leads to 5 bosons
    → 2 CP-even bosons: h, H
    → 1 CP-odd boson: A
    → 2 charged scalars: $H^{\pm}$



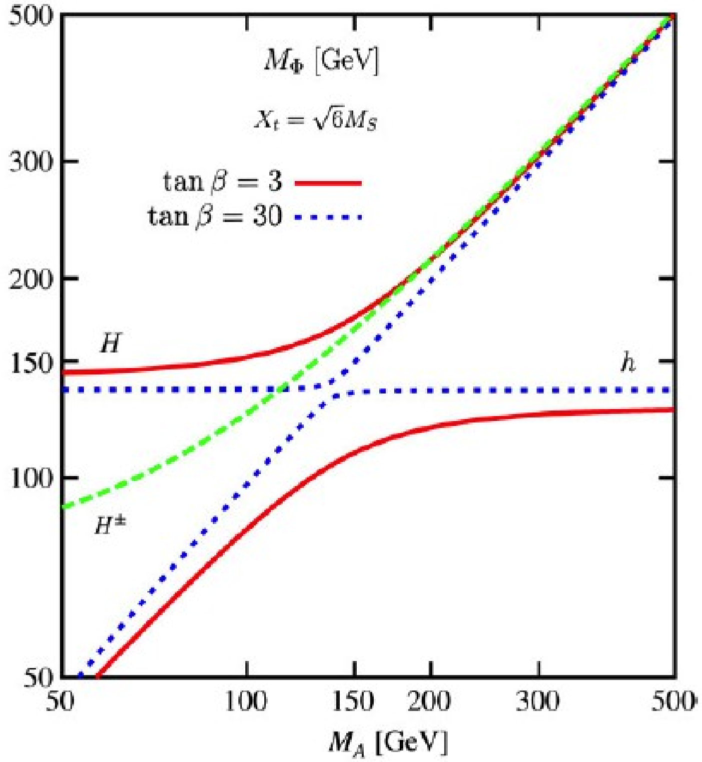
The MSSM Higgs sector depends only on 2 parameters at tree level which can be chosen to be:
→ m_A or $m_{H\pm}$
→ tanβ = ratio of the v.e.v.s of the two Higgs doublets

MSSM Higgs mass constraints

- The lightest CP-even Higgs boson, h, is light ($\lesssim$ 140 GeV)

$$\Delta M_h^2 = \frac{3G_\mu}{\sqrt{2}\pi^2} m_t^4 \log \frac{M_S^2}{m_t^2}$$

  - The effect is driven by the top mass → **conspiracy** that led to the non-discovery of SUSY at LEP



- There are also a lot of mass constraints imposed by SUSY

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

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

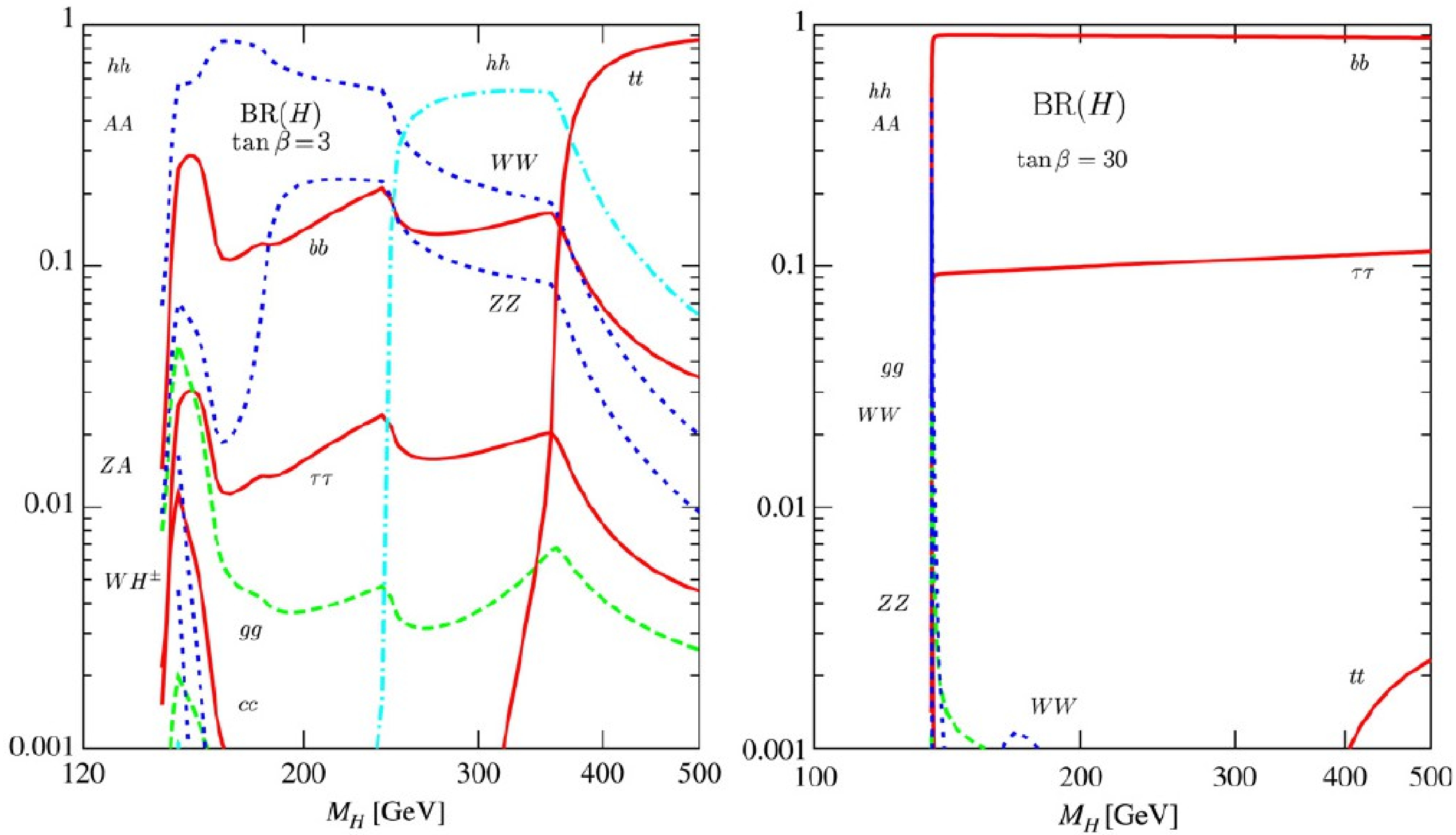
$$M_A \simeq M_H \simeq M_{H^+} \text{ and } M_h \simeq 130\,GeV$$

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

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

MSSM Higgs Properties: h/H/A Decay Modes

Neutral Higgs decays depend on the tanβ value

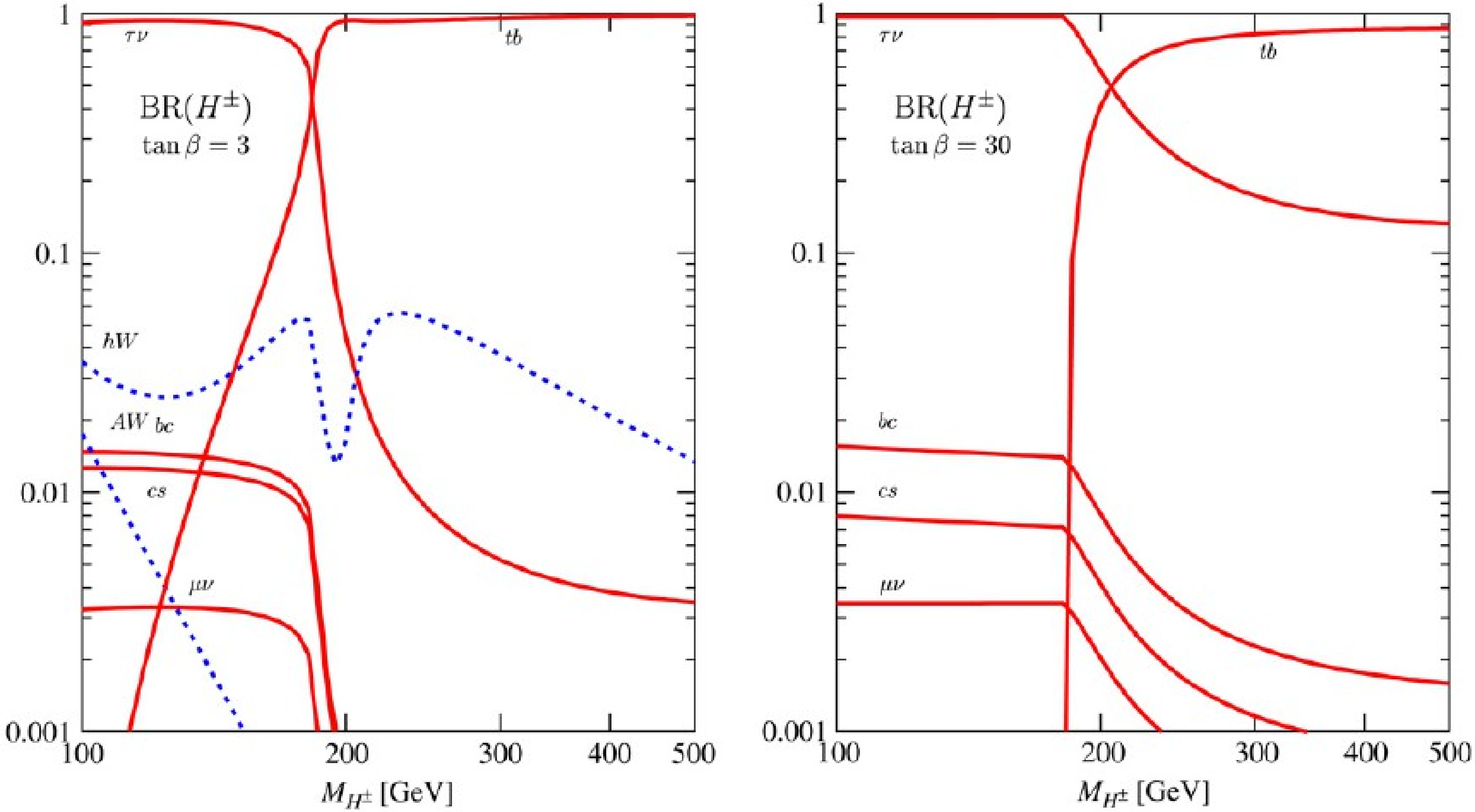


Example: Heavy CP-even Higgs decay BR for a low and high tanβ (maximal mixing)

Phys.Rept. 459 (2008) 1-241

MSSM Higgs Properties: Decay Modes

Charged Higgs decays predominantly to τν and tb depending mostly on its mass



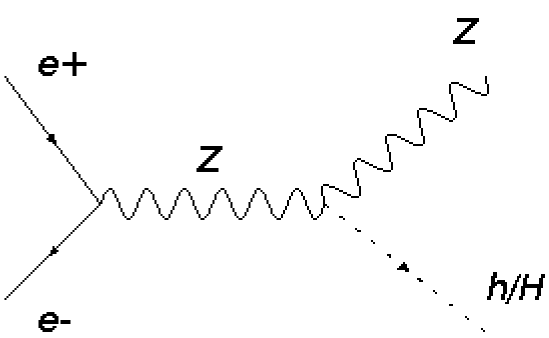
Charged Higgs decay BR for a low and high tanβ (maximal mixing)

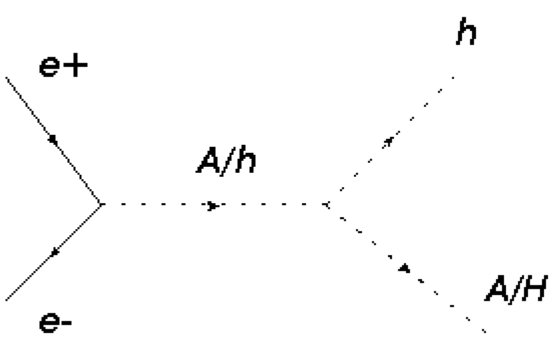
Phys.Rept. 459 (2008) 1-241

MSSM: The LEP legacy for Neutral Higgs

- LEP has left a huge legacy for MSSM Higgs searches
- The design of the LHC MSSM Higgs search has been driven by LEP results

LEP was an electron-positron collider that could produce Higgs bosons radiated off a Z boson (for the CP-even Higgs bosons) or through pair-production (the only way to access the CP-odd Higgs boson)

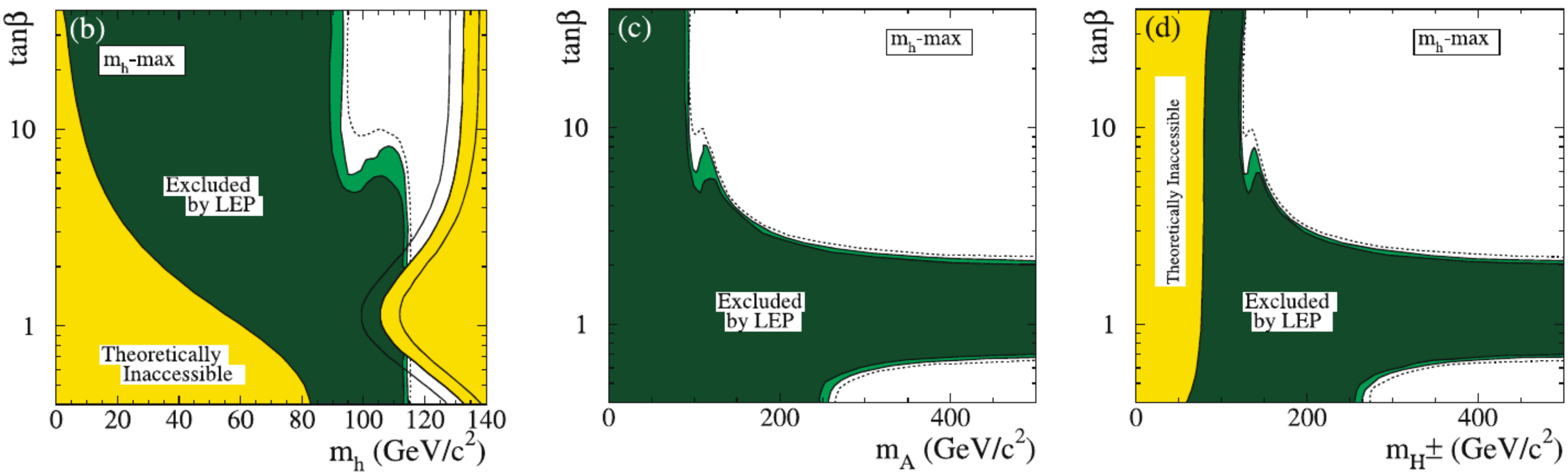




Various decay channels considered:
$h \rightarrow bb, \tau\tau, jj, AA$
$Z \rightarrow jj, ll$

MSSM: The LEP legacy for Neutral Higgs

- LEP has been able to probe the MSSM very effectively disfavouring low mass Higgs bosons
  - $m_A > 90$ GeV is allowed

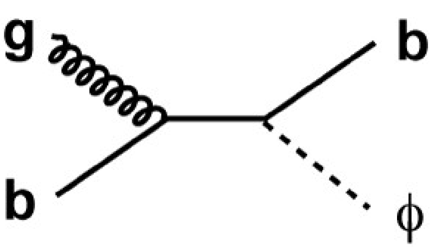


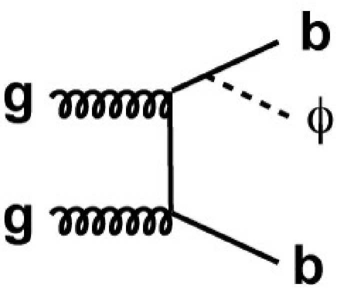
Eur.Phys.J. C47 (2006) 547-587

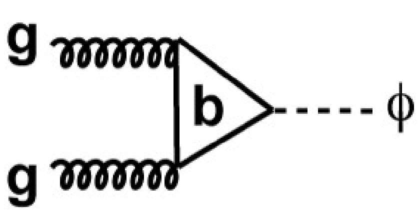
Neutral MSSM Higgs

- The search for h/H/A in the ττ channel is the best probe for MSSM Higgs at the high tanβ regime
  - Better sensitivity (wrt to other channels, e.g. bb)
  - Robustness in radiative corrections ("**ττ conspiracy**")

Two main production mechanisms





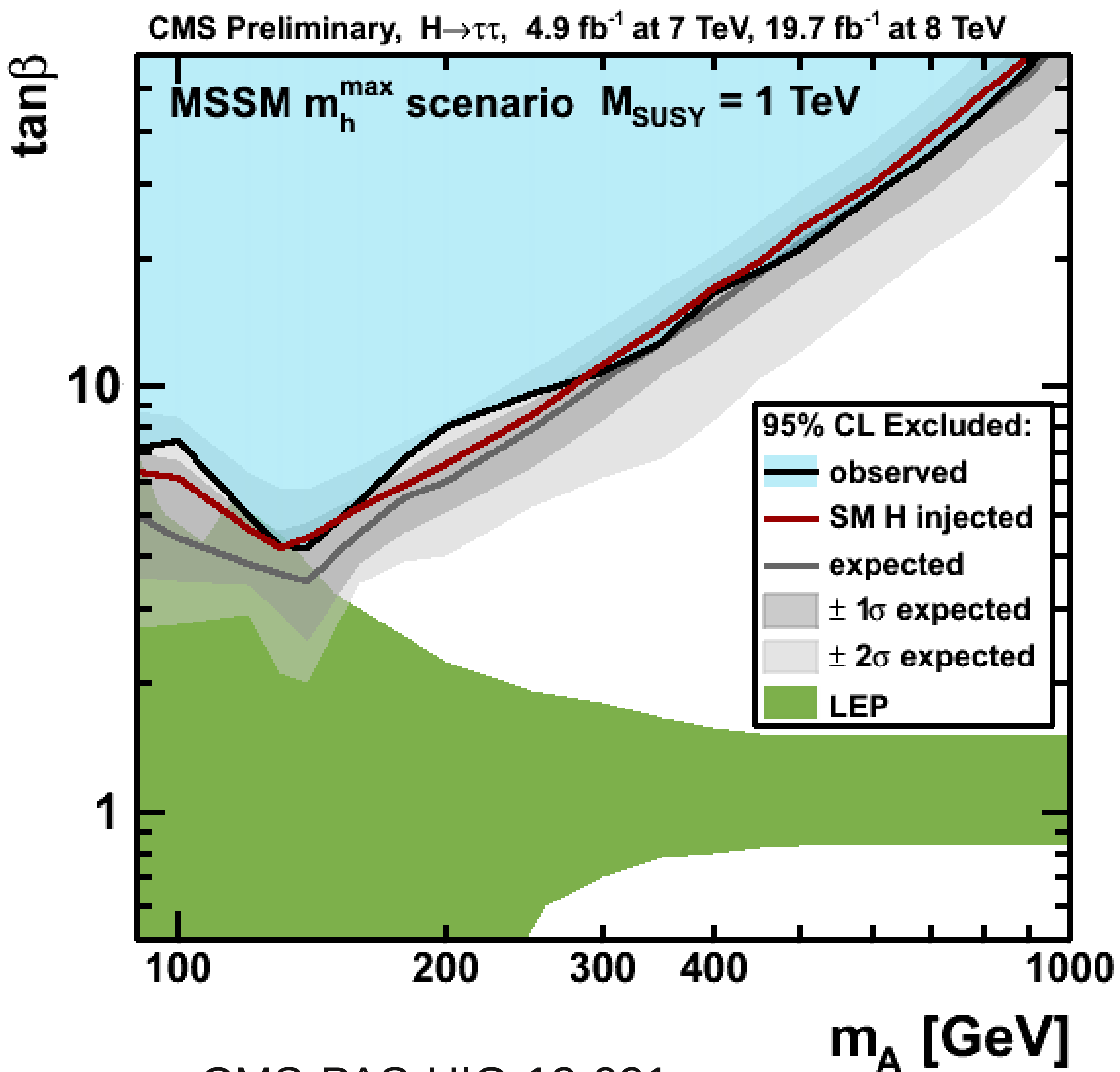


Several tau decay modes

H → τ τ	BR ~ 10%	Comment
τ(e/μ) τ(had)	BR ~ 46%	Most sensitive
τ(had) τ(had)	BR ~ 42%	Important at high mass
τ(e) τ(μ)	BR ~ 6 %	Important at low mass
τ(μ/e) τ(μ/e)	BR ~ 6 %	Low sensitivity

Neutral MSSM Higgs

- The most recent LHC MSSM ττ result

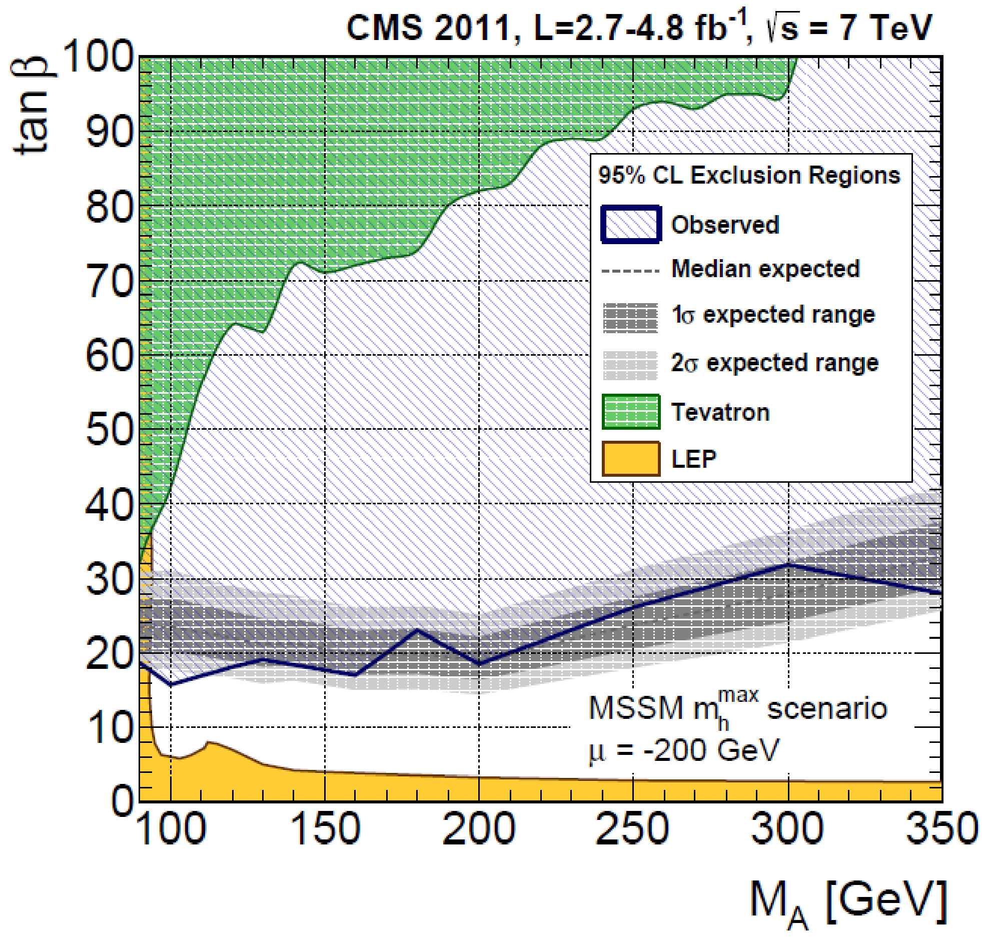


CMS-PAS-HIG-13-021

Neutral MSSM Higgs

MSSM Higgs to bb has been looked for at the Tevatron and CMS experiments.

It is less competitive than ττ (comparing results with same luminosity) and not protected by any conspiracy.



MSSM Higgs & Higgs discovery

- The ATLAS search discussed in the previous slides was essentially designed in the 90's

Technical Design Report

Issue:	1
Revision:	0
Reference:	ATLAS TDR 15, CERN/LHCC 99-15
Created:	25 May 1999
Last modified:	25 May 1999
Prepared By:	ATLAS Collaboration

Volume II

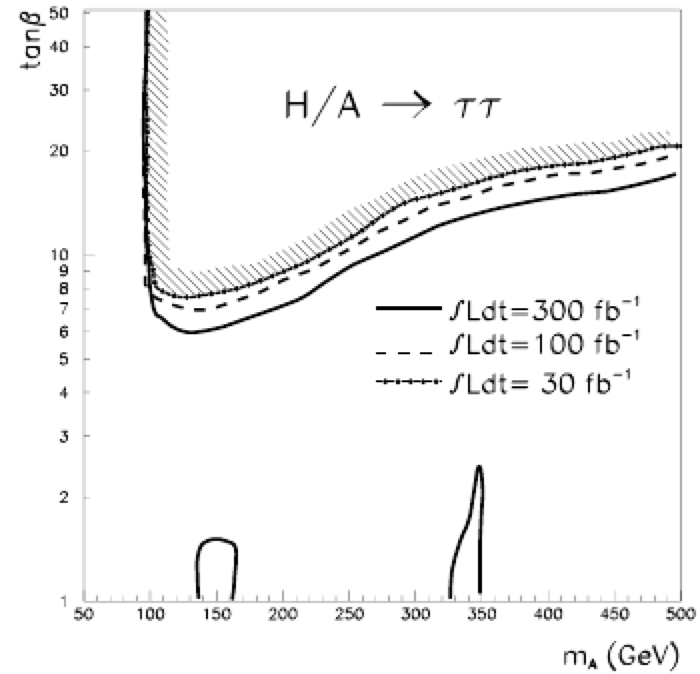


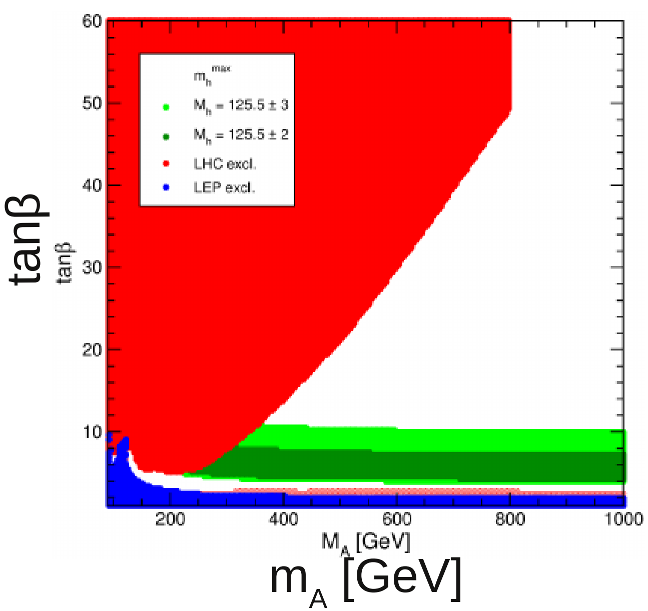
Figure 19-62 For integrated luminosities of 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1}, 5σ-discovery contour curves for the $H/A \to \tau\tau$ channel in the (m_A, tanβ) plane.

Is the way we do this search relevant after some years of LHC search results & a discovery of a 125 GeV Higgs boson?

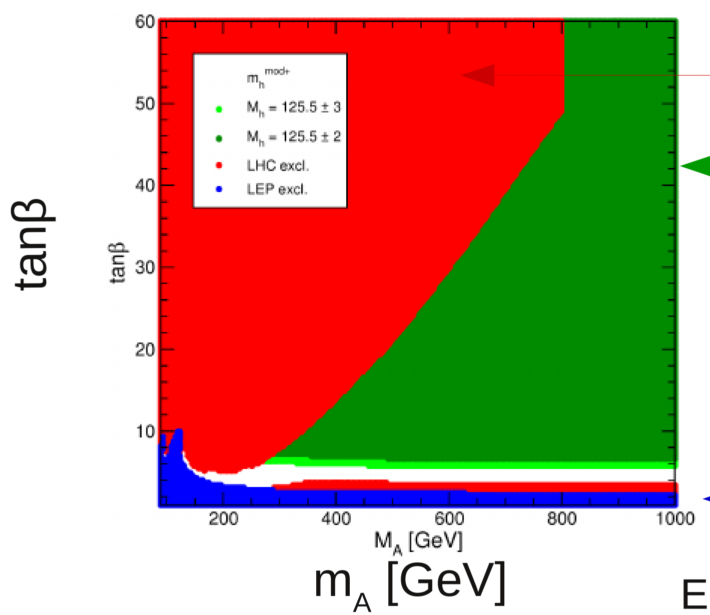
MSSM Higgs & Higgs discovery

- MSSM is compatible with a 125 GeV SM-like Higgs boson
  - Although lots of scenarios that were considered in the past are now obsolete because they cannot obtain such a high Higgs boson mass (e.g. "zero mixing" scenario)

"mh-max" scenario



"mh-mod+" scenario



LHC 7 TeV Run exclusion

Region compatible with a 125 GeV light CP-even Higgs

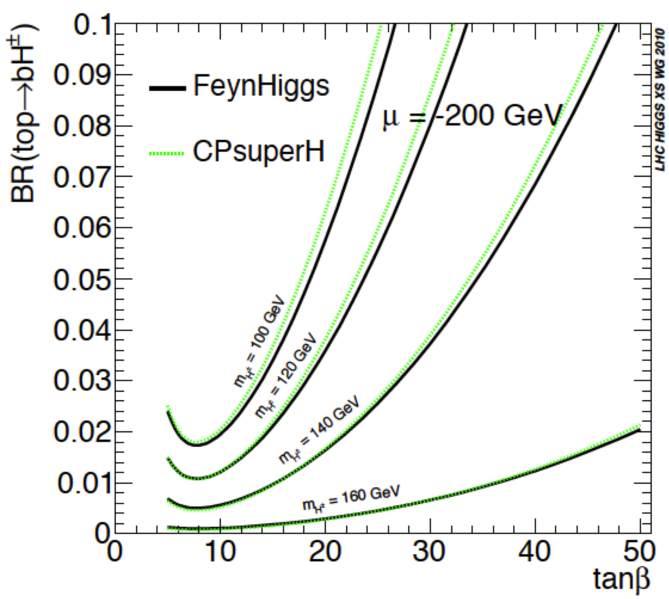
LEP exclusion

Eur.Phys.J. C73 (2013) 2552

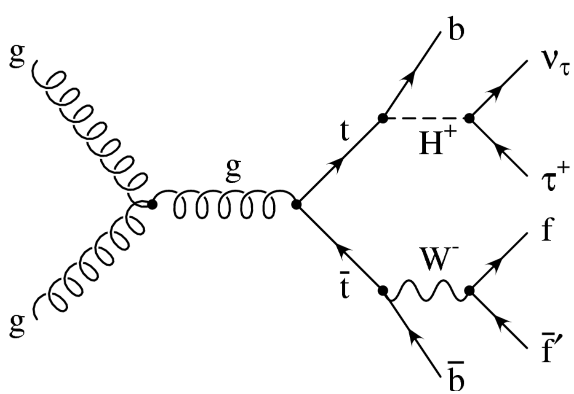
Charged Scalars

- Searches for the charged scalars of the MSSM have been performed as well

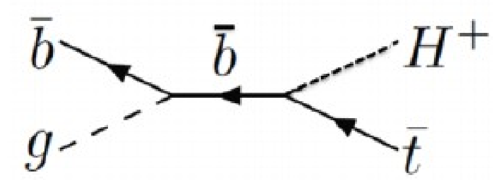
Light Charged Higgs is produced mainly in top quark decays

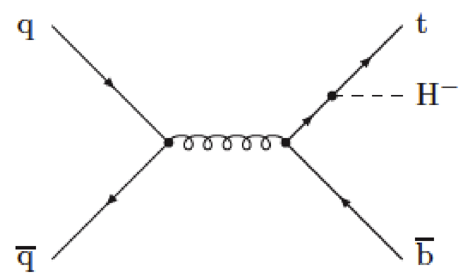


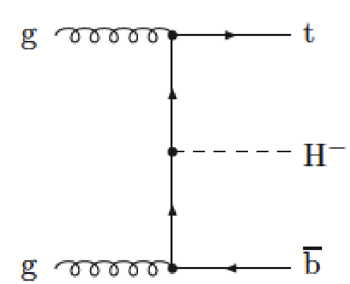
BR(Top → bH⁺) vs tanβ



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





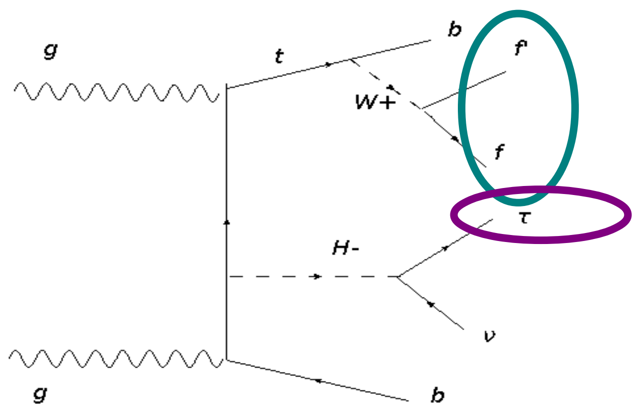


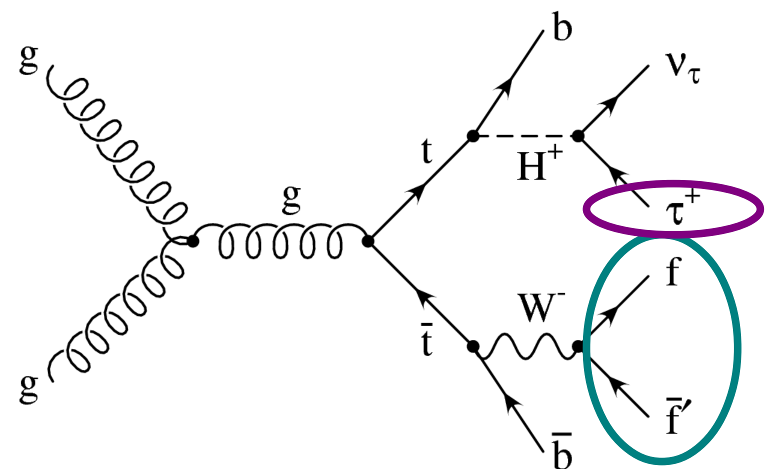
H^+ -> τν

- What we are looking for: search topology

Channel topology can be organized according to W and tau decay

$H^\pm \rightarrow \tau^\pm \nu$





τ(lep)+W(→lν):	tt → bbWH → bb (lν) (τ_{lep}ν)	BR ~ 15%
τ(had)+W(→lν):	tt → bbWH → bb (lν) (τ_{had}ν)	BR ~ 14%
τ(had)+W(→jets):	tt → bbWH → bb (qq) (τ_{had}ν)	BR ~ 46%
τ(lep)+W(→jets):	tt → bbWH → bb (qq) (τ_{lep}ν)	BR ~ 25%

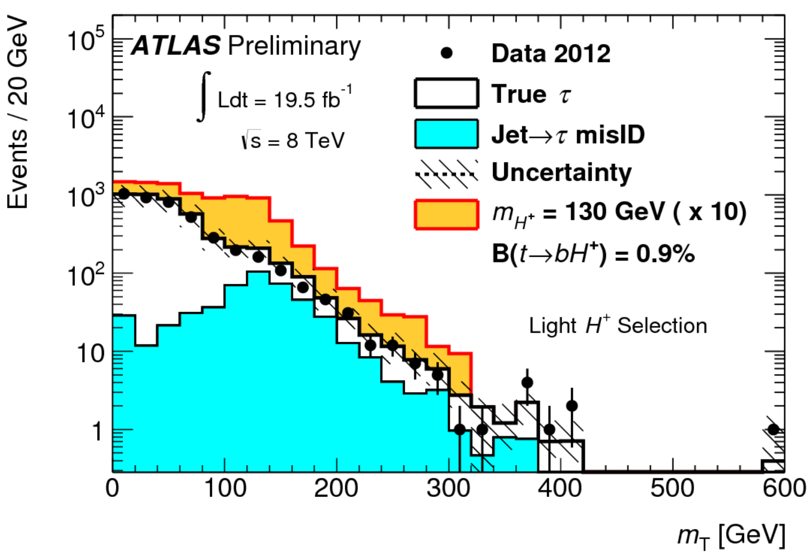
τ(lep) =
τ(e) or τ(μ)

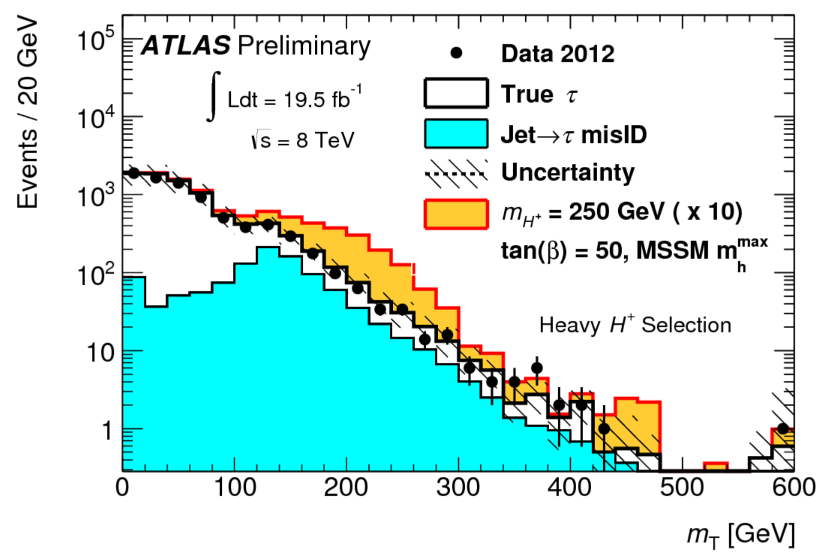
Channel of first choice: Highest BR, highest sensitivity and excellent physics potential: but all these are possible only because of the **tau(had)+MET trigger**

$H^+ \to \tau\nu$

- "Tau + jets" selection

Low mass category	High mass category
At least 4 jets; one of them b-jet	At least 3 jets; one of them b-jet
One tau(had) with pT > 40 GeV; veto additional taus, e, μ in the event	
MET > 65 GeV; MET significance > 13	MET> 80 GeV; MET significance > 12 GeV
The transverse mass of the tau and the MET is used as discriminating variable	





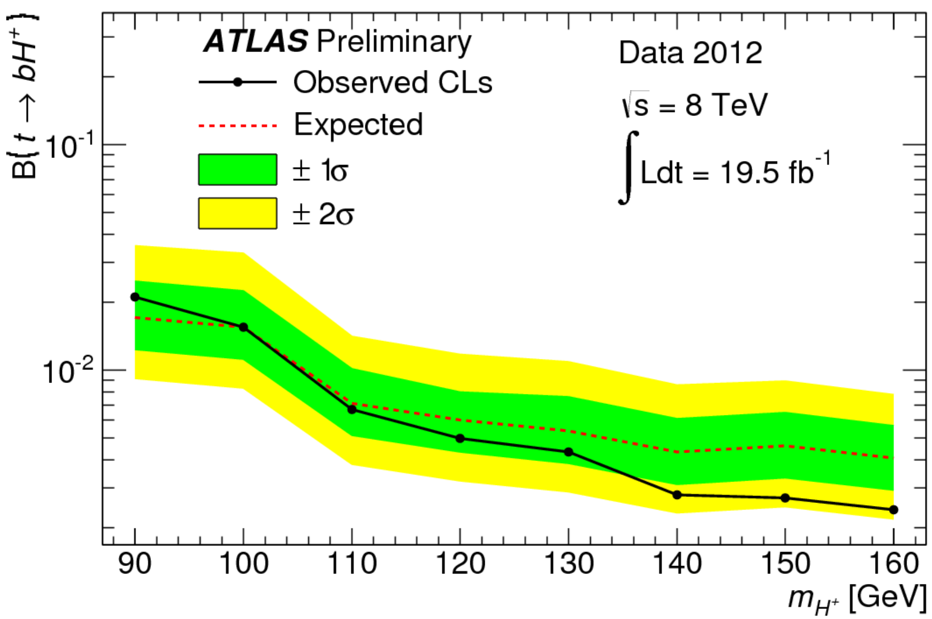
"MET signifiicance" definition:

$$\frac{E_T^{miss}}{0.5\cdot\sqrt{\sum p_T^{PV\ trk}}}$$

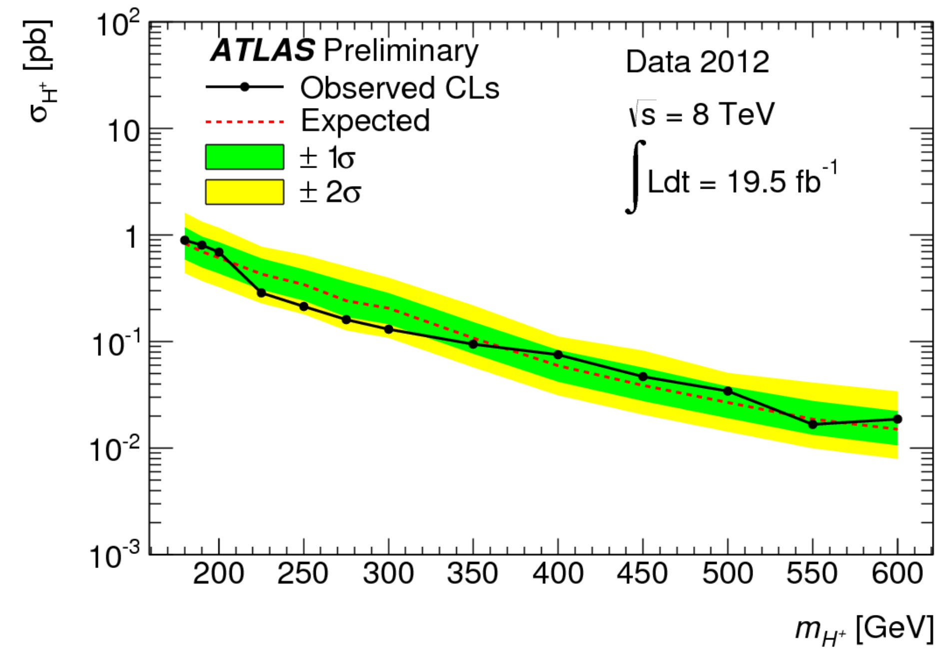
H^+ -> τν

- Constraints on charged scalars

Branching ratio of the top quark decaying to bH+ with the H+ decaying excludively to τν



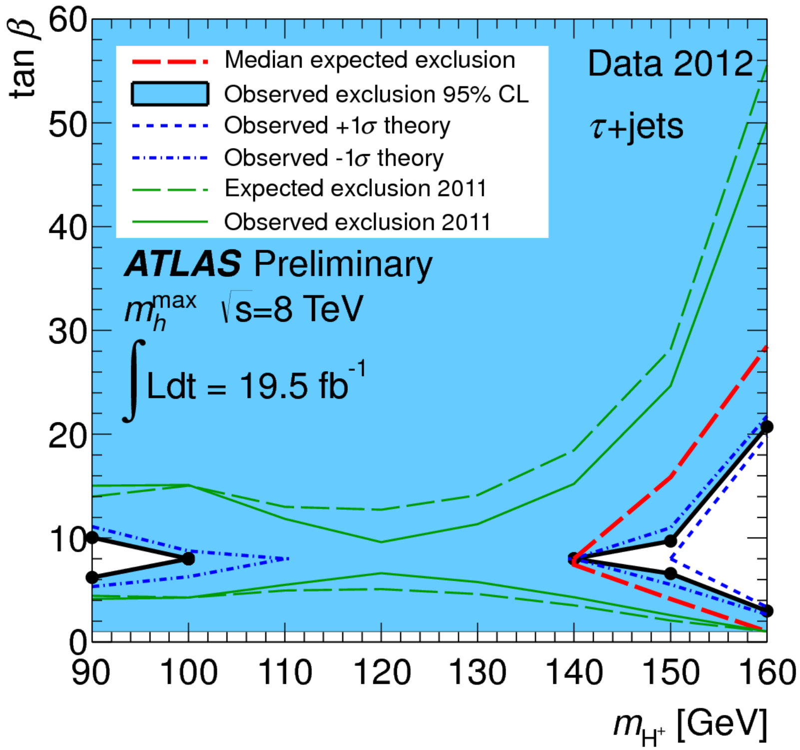
Cross section limit for a Heavy H+ (mass> top mass) assuming that H+ decays exclusively to τν

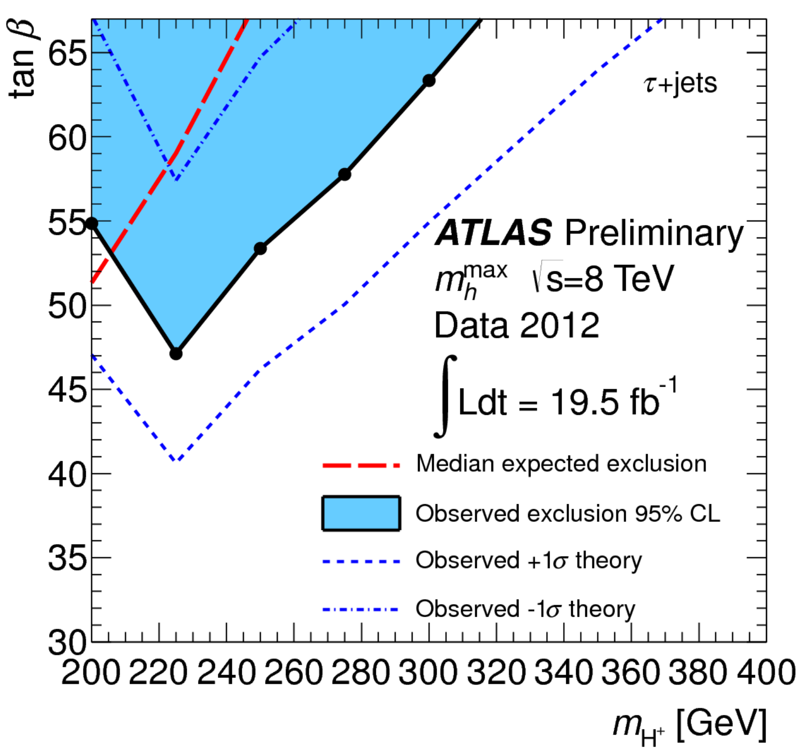


ATLAS-CONF-2013-090

$H^+ \to \tau\nu$

- Constraints on charged scalars interpreted in the MSSM parameter space





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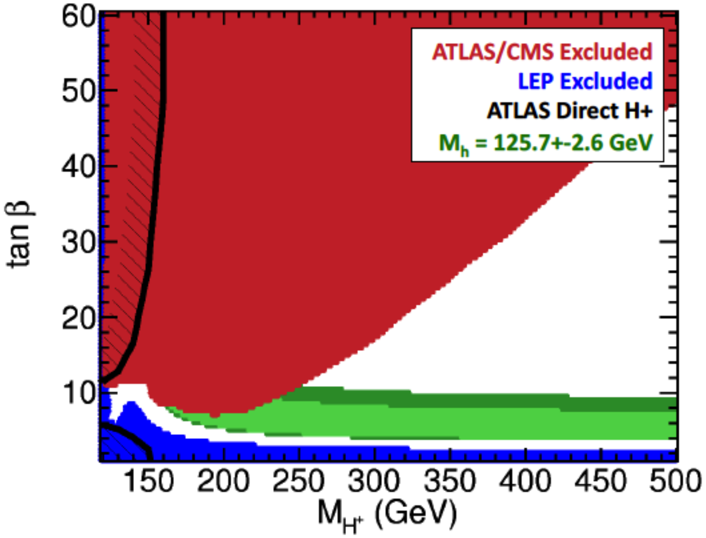
Charged Scalars and the MSSM

- The mass constrains of the MSSM imply that the MSSM charged Higgs searches face fierce competition from h/H/H -> τ τ

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



"mh-max", m(h)~126 GeV

Oscar Stöl, CHiggs2012

Comparison: 7 TeV LHC results on the MSSM plane. Black line is the contstrain from the Charged Higgs and the red area due to neutral h/H/A -> τ τ

Nevertheless, the existence of charged scalars in Nature is interesting beyond the MSSM. The simplest extensions of the Higgs sectors include them and for which none of the severe constraints of the MSSM hold

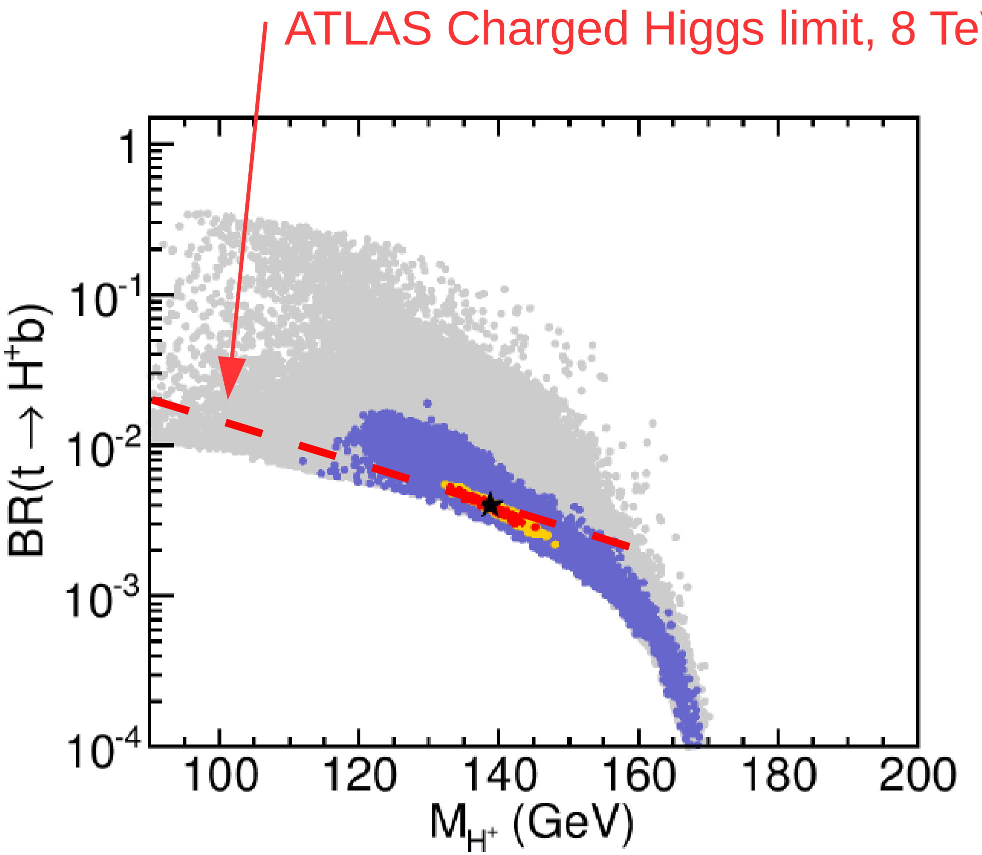
MSSM Higgses: which of them is the h125?

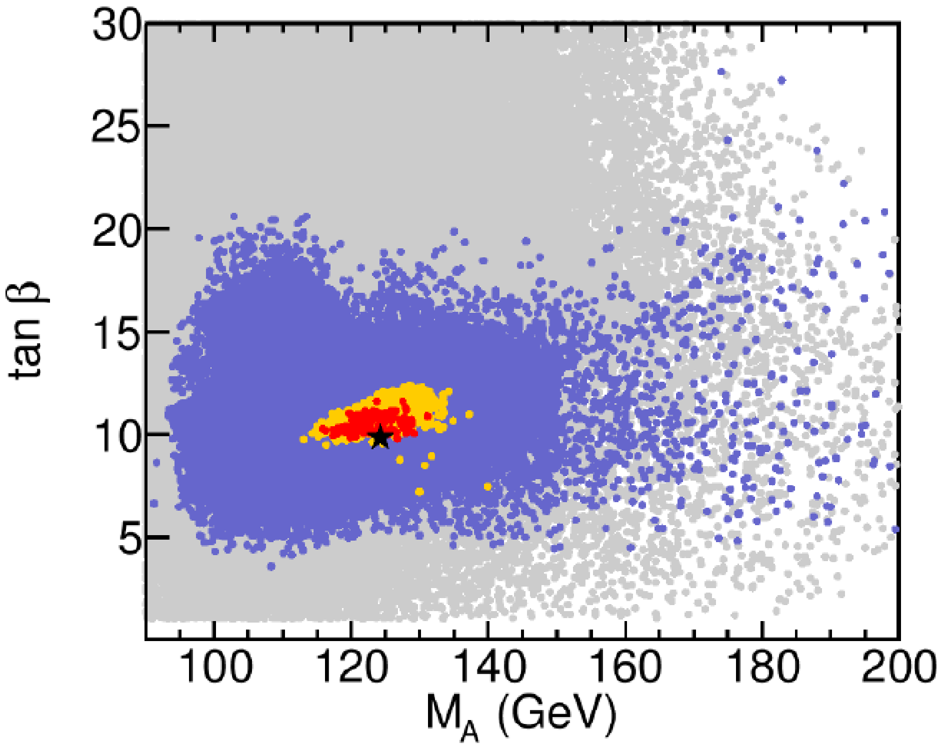
- In some of the previous slides I have assumed that the h125 Higgs boson is the lightest CP-even Higgs
  - This assumption is viable and can live in many places in the MSSM parameter space
  - The case where m_H=125 GeV is possible: we end up in a very interesting configuration
    - All Higgs bosons are light and around ~ 125 GeV
    - The lightest CP-even Higgs boson couplings to vector bosons are greatly suppressed; Charged Higgs has mass < m_{top}

As a result the mH = 125 GeV case is constrained by a number of other light mass Higgs searches and it is difficult to find much of parameter space

MSSM Higgses: which of them is the h125?

- Example of pMSSM-7 scans





Red are yellow area correspond approx. to 1 and 2 sigma bands assuming h125 measurements and few other constraints (here using mostly 2012 measurements)

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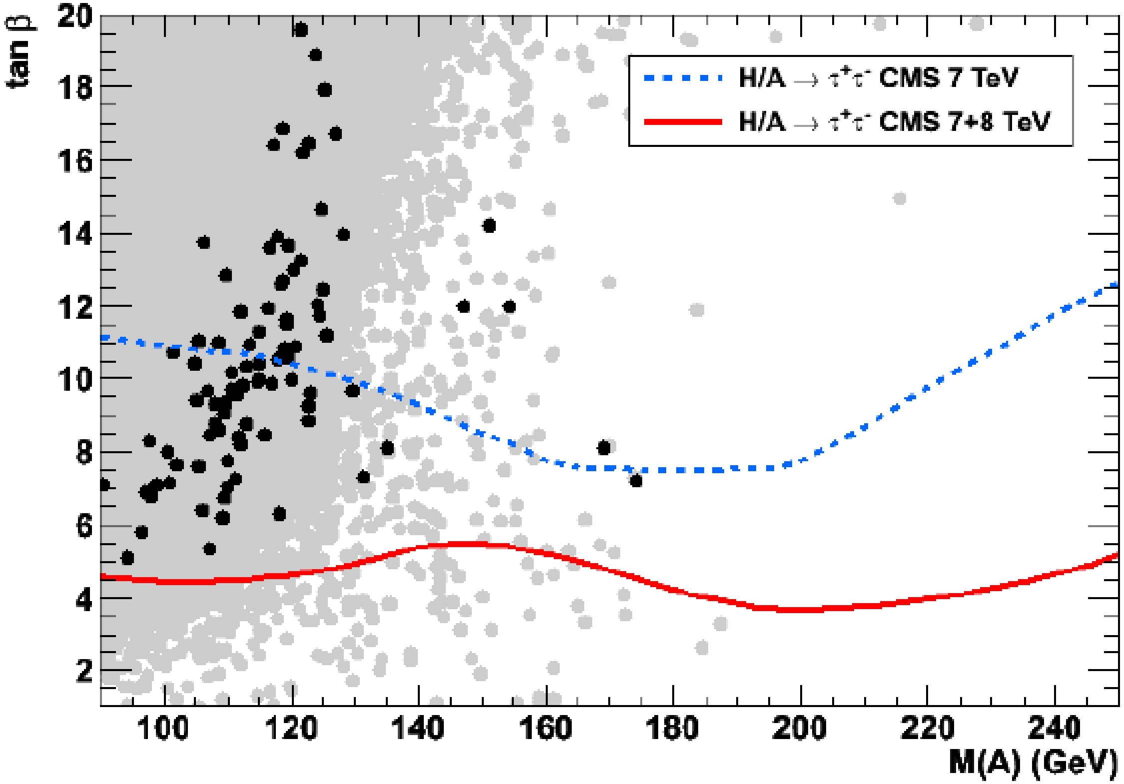
MSSM Higgses: which of them is the h125?

- Example of a pMSSM-19 scan

Grey points compatible with mH = 123 – 129 GeV
Black points with Higgs couplings & flavour physics constraints



Phys.Lett. B720 (2013) 153-160

The 2-Higgs-Doublet Model

- The 2-Higgs-Doublet-Model (2HDM) is conceptually one of the most straightforward extensions of the SM
  - Simply add another SU(2) scalar doublet in the model and you get after electroweak symmetry breaking 5 Higgs bosons: h, H, A, H^+, H^-
  - There is some physics motivation, e.g. non-minimal Susy, opens options for more sources of CP violation
    - But it doesn't address at all naturalness, unification etc: addressing these issues means that the 2HDM won't come by itself, but with some company (e.g. like in the case of SUSY)

2HDM basics

- Some assumptions are made to reduce the number of free parameters
  - None of them is compulsory, you can make viable models without them
  - CP-conservation in the Higgs sector, softly broken Z2 symmetry ($\Phi_1 \rightarrow -\Phi_1$) leaves us with a potential

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \mathrm{h.c}\}$$

that has 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: type-I, type-II, “lepton-specific” and”flipped”

2HDM features

- Yukawa couplings

  In this notation:
  t_β = tanβ;
  $c_{\beta-\alpha}$ = cos(β-α)
  $s_{\beta-\alpha}$ = sin(β-α)

- Interesting limits:

	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_β	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β	t_β	$-1/t_\beta$

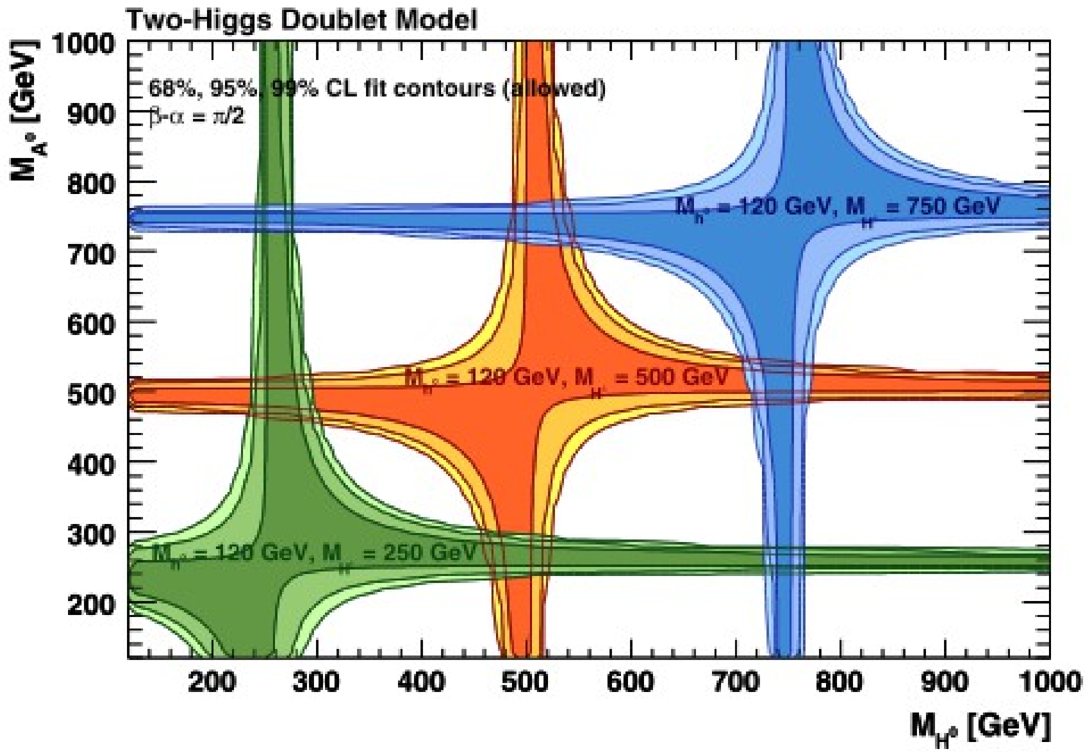
  - Weak decoupling limit: sin(β-α) → 1, i.e., there is a Higgs boson that can be as SM as you like but also there are light $H/A/H^+$ bosons
  - (strong) Decoupling limit: sin(β-α)=1 and two mass scales i.e. all additional particles heavy. For a more formal definition see PhysRevD 67, 075019

2HDM (and also MSSM) has a decoupling limit which means that you cannot kill it, unless you kill first SM

Constrains to 2HDM

- Precision EWK: measurement of $\rho = m_W/(m_Z \cos\theta_W) \simeq 1$

For large mass splitting radiative corrections affect ρ hence it seems that 2 of the heavy bosons tend to be approximately mass degenerate.

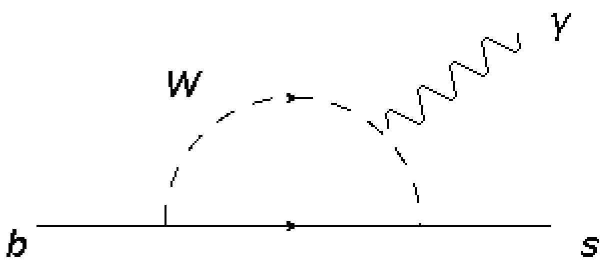


Eur. Phys. J. C (2012) 72:2003

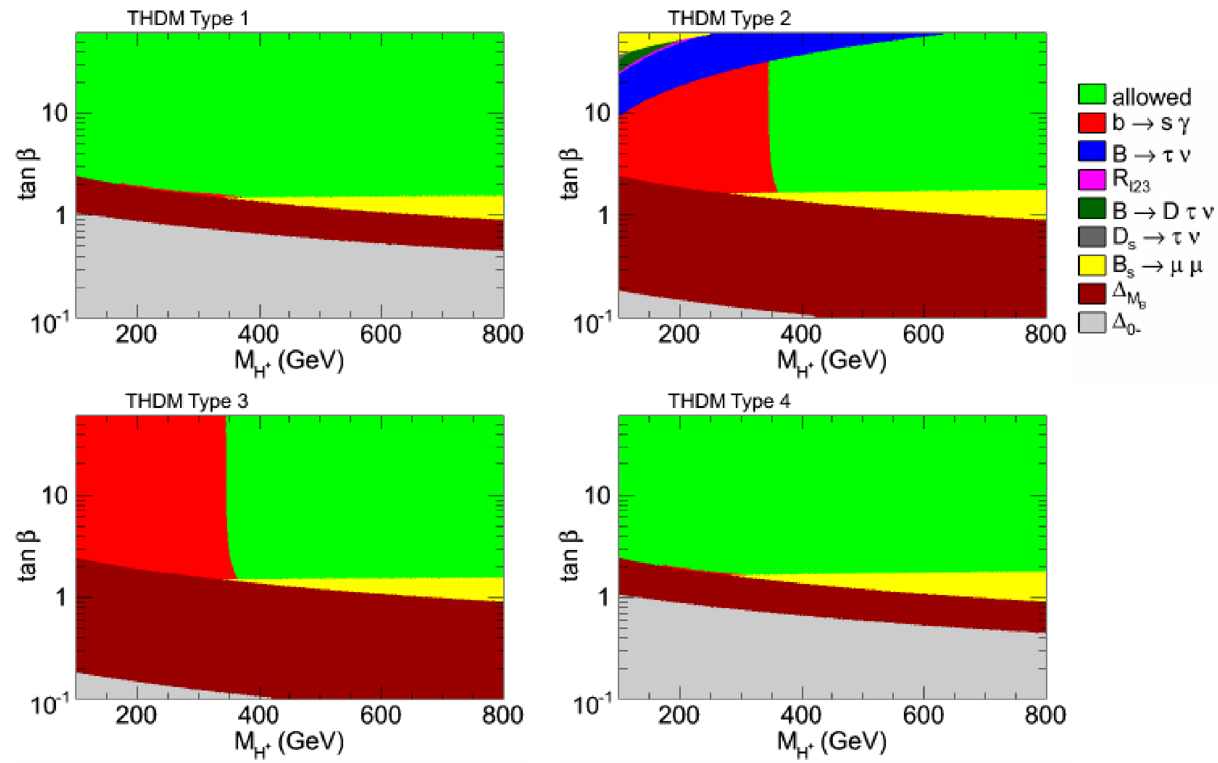
Constrains to 2HDM

- Charged scalar mass constraints from flavour physics

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	$\cot\beta$	$-\tan\beta$



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

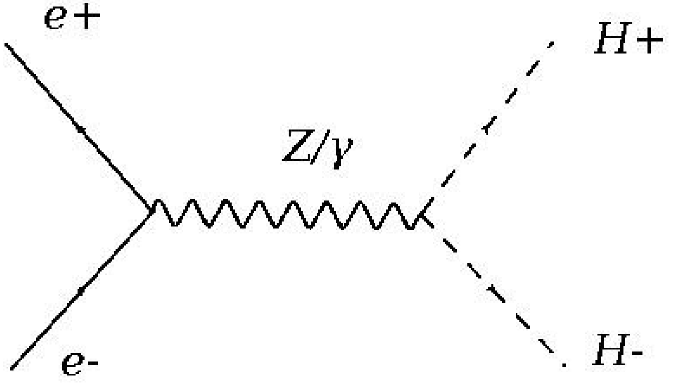
N. Mahmoudi & O. Stall, SuperIso v.3.4

Here and in the following I won't consider the BaBar B->D(*)τν measurement

The Charged Higgs LEP legacy

- LEP results can indirectly constrain charged scalars (e.g. through the Rb measurement that can constrain low tanβ)
- But also LEP has made the most comprehensive search for charged scalars in the 2HDM for m_{H+}< 100 GeV. LEP was in an advantageous position
  - Simple production mechanism and few decay patterns

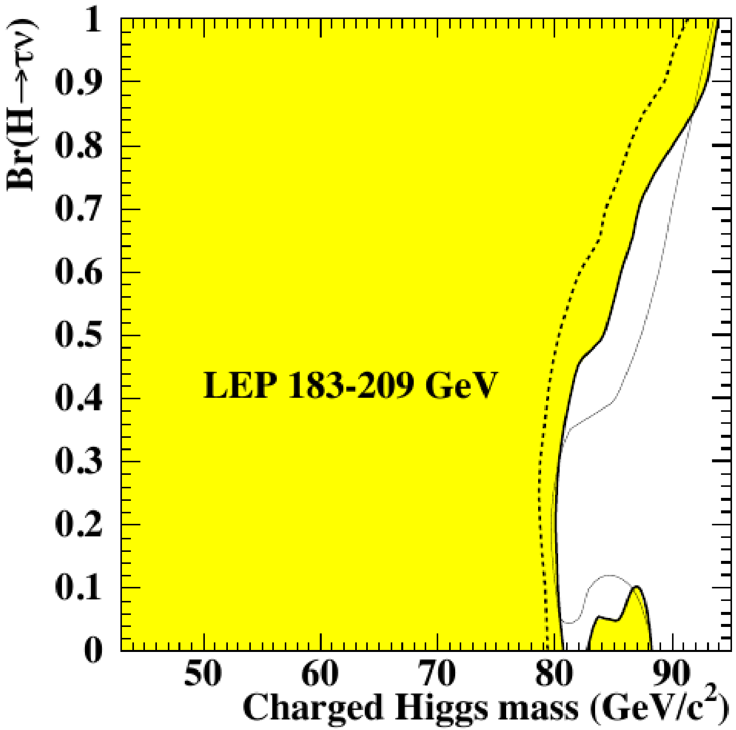
Charged Higgs production at LEP is through pair production

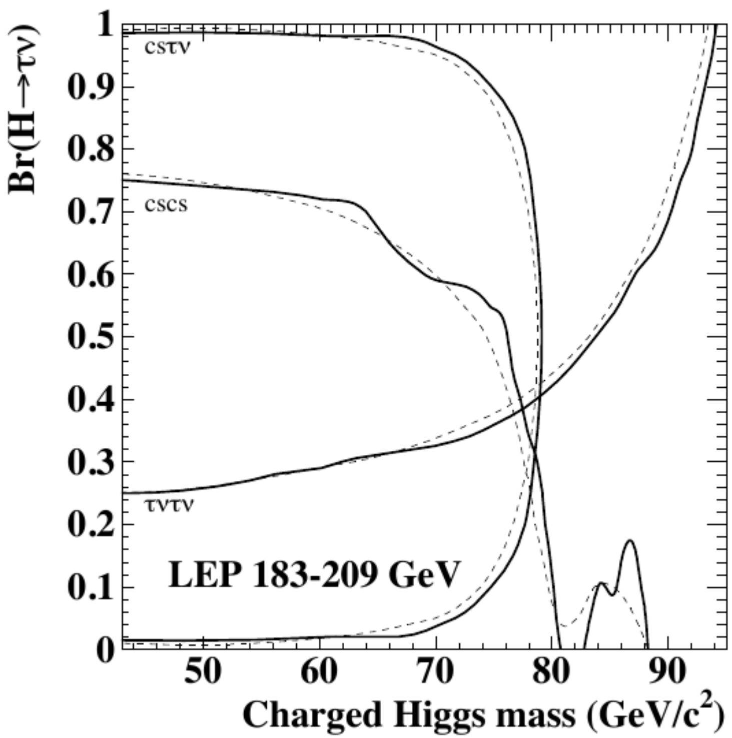


The Charged Higgs LEP legacy

Type-II 2HDM at LEP: in the relevant mass range there are essentially 2 decay patterns $H^+ \to \tau\nu$ and $H^+ \to cs$

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

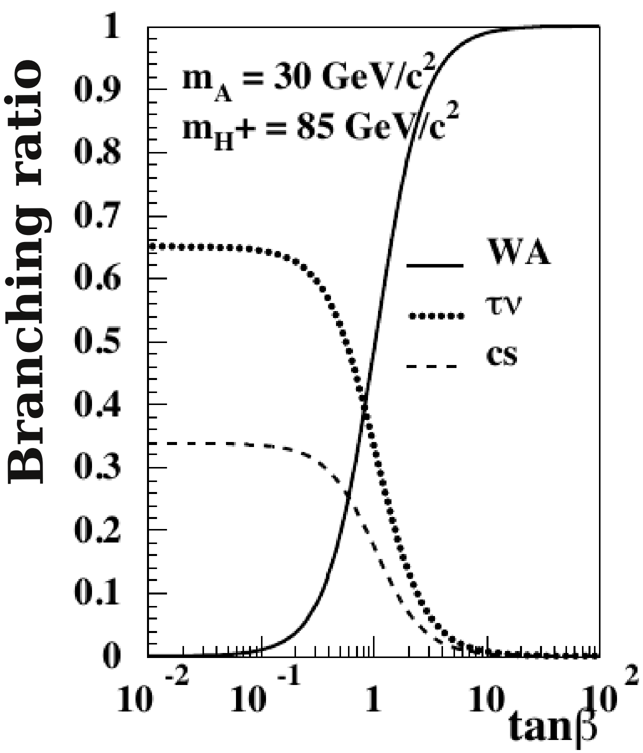


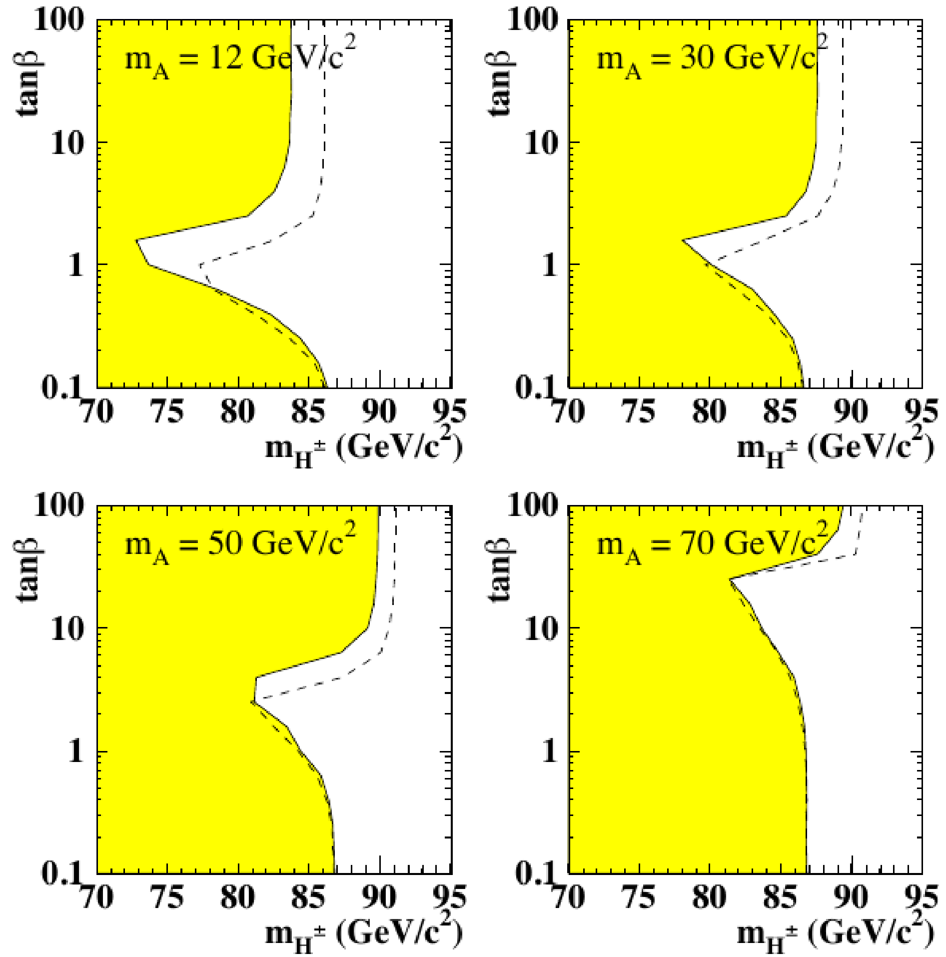


The Charged Higgs LEP legacy

Type-I 2HDM at LEP: here there are 3 decay patterns $H^+ \rightarrow \tau\nu/cs/AW$ and hence there is some dependence on A mass

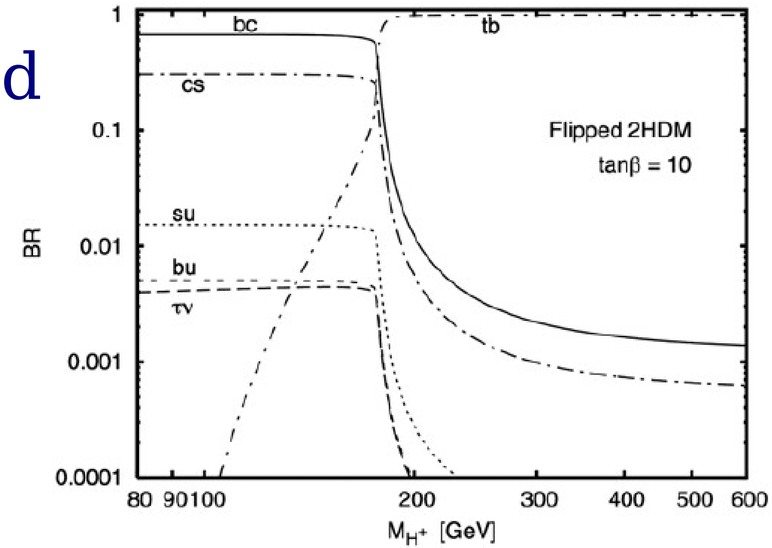
Weaker constrain than type-II

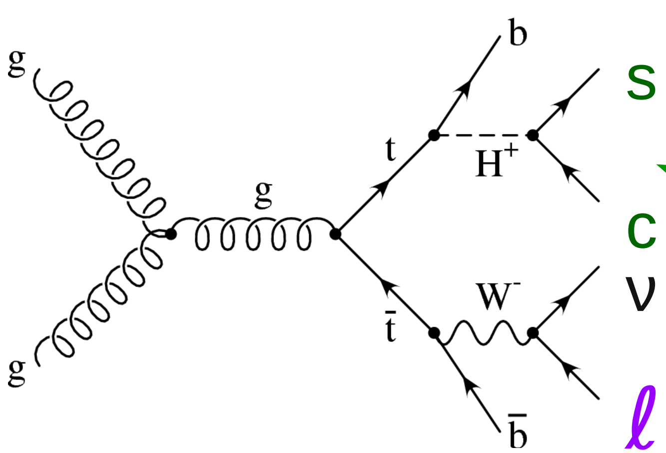




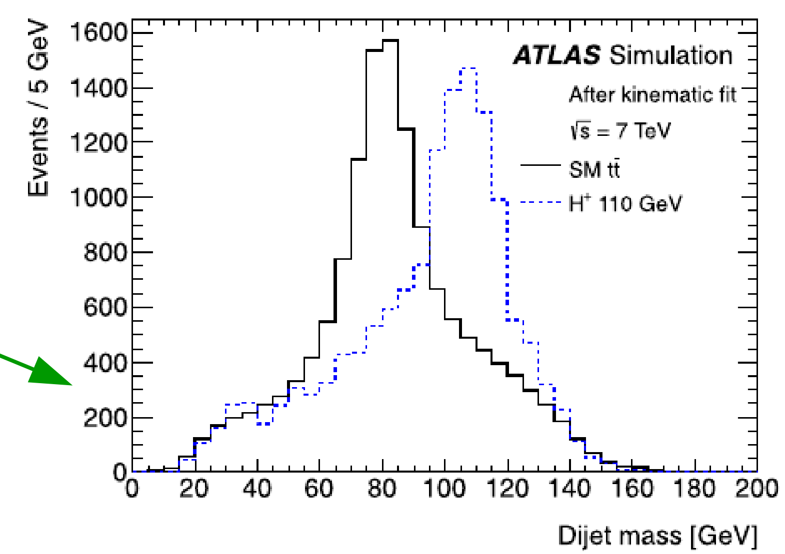
$H^+ \rightarrow cs$ from ATLAS

- Charged Higgs to quarks is favoured in considerable parts of the 2HDM parameter space (and not only)
- The ATLAS search looks for H+ in semileptonic ttbar production





Kinematic fitter to reconstruct the H+ mass

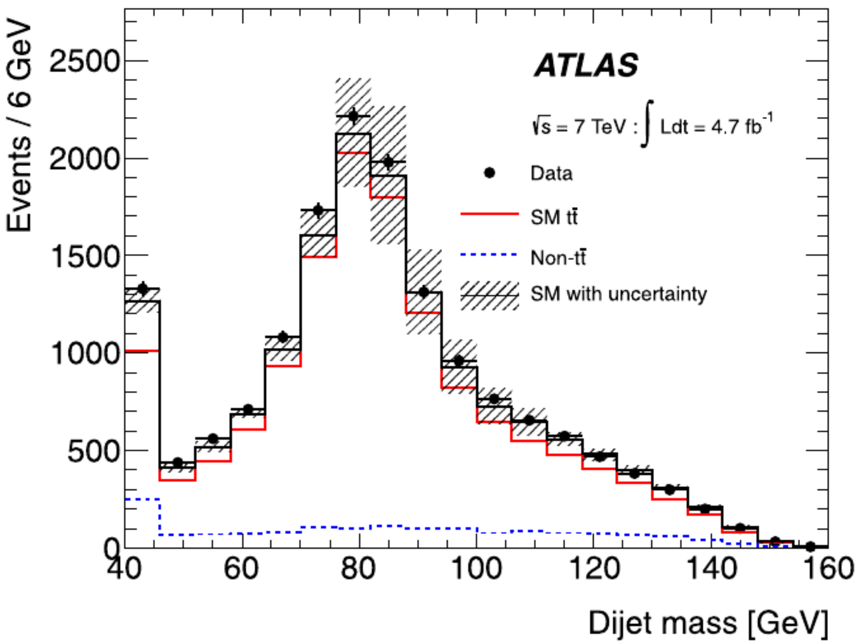


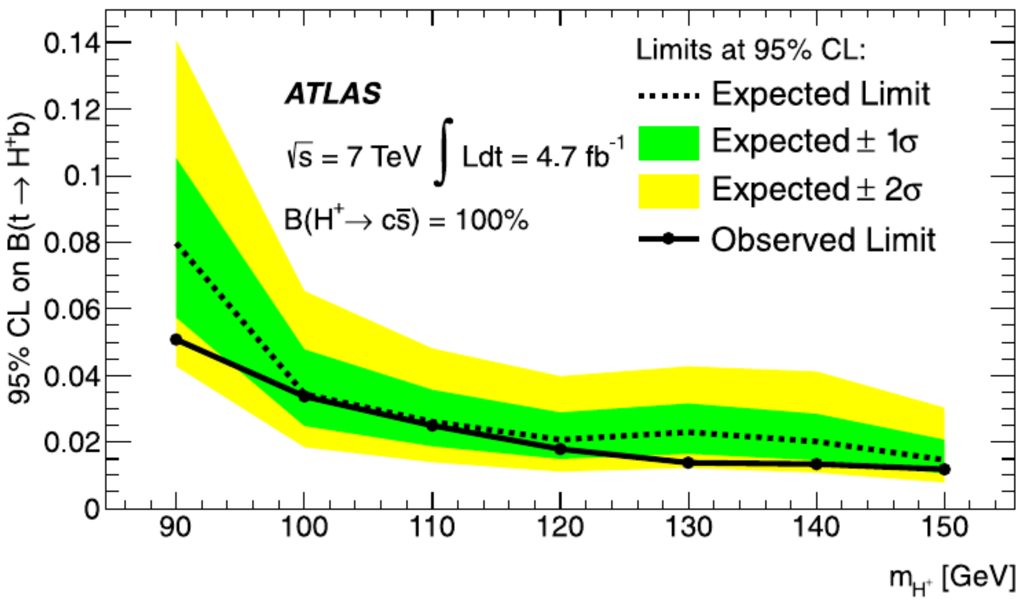
Electron or muon to trigger the event

Eur. Phys. J. C (2013) 73:2465

$H^+ \rightarrow cs$ from ATLAS

The invariant mass of the Higgs decay candidate system





Limits for the Branching Ratio of top to charged Higgs assuming charged Higgs decays only to cs

Eur. Phys. J. C (2013) 73:2465

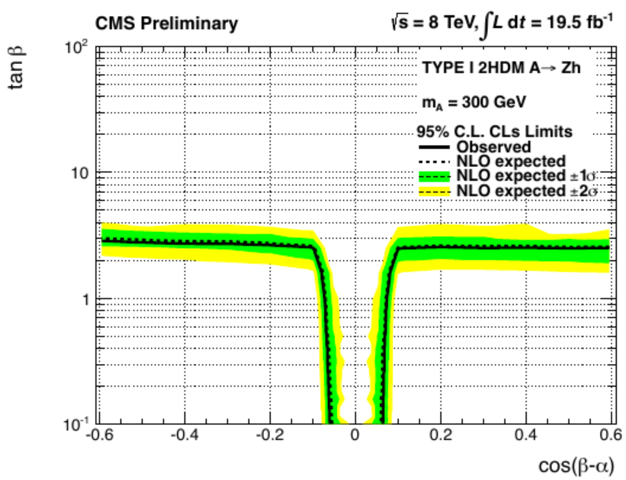
Heavy Higgs search: **Higgs** to Higgs

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

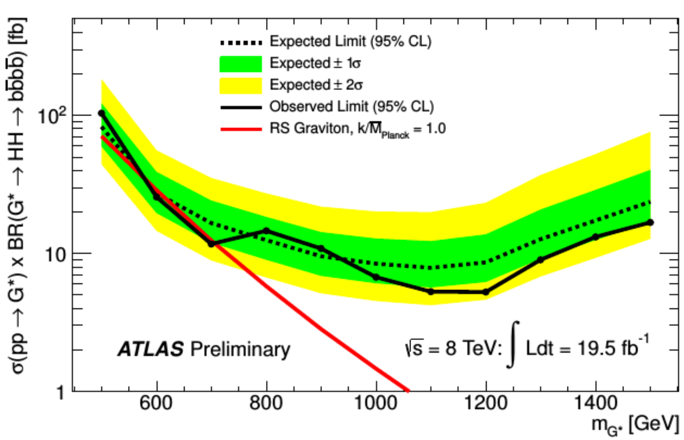
H → hh and A → Zh

- I will just mention few results
  - CMS dedicated search for 2HDM H → hh and A → Zh including a large variety of final states
  - A resonant hh → bbbb search from ATLAS
  - A resonant hh → bbγγ search from CMS

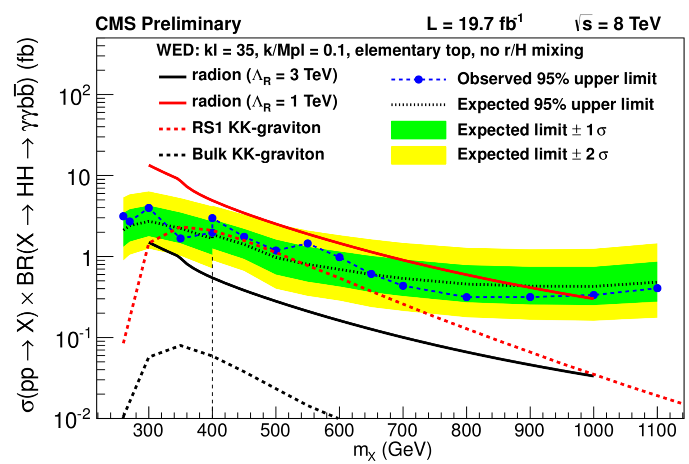
CMS PAS HIG-13-025



ATLAS-CONF-2014-005

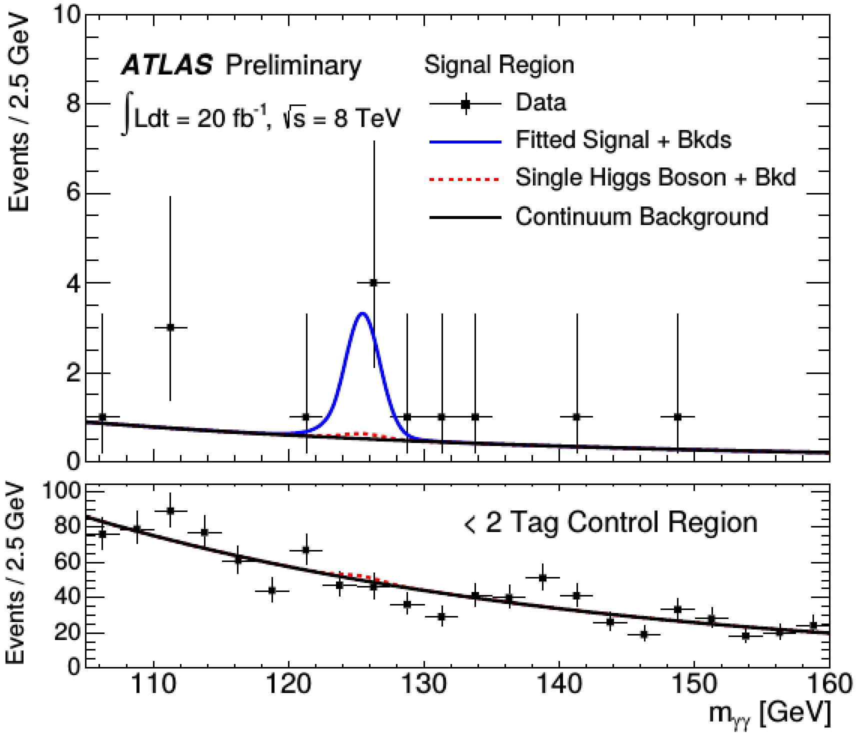


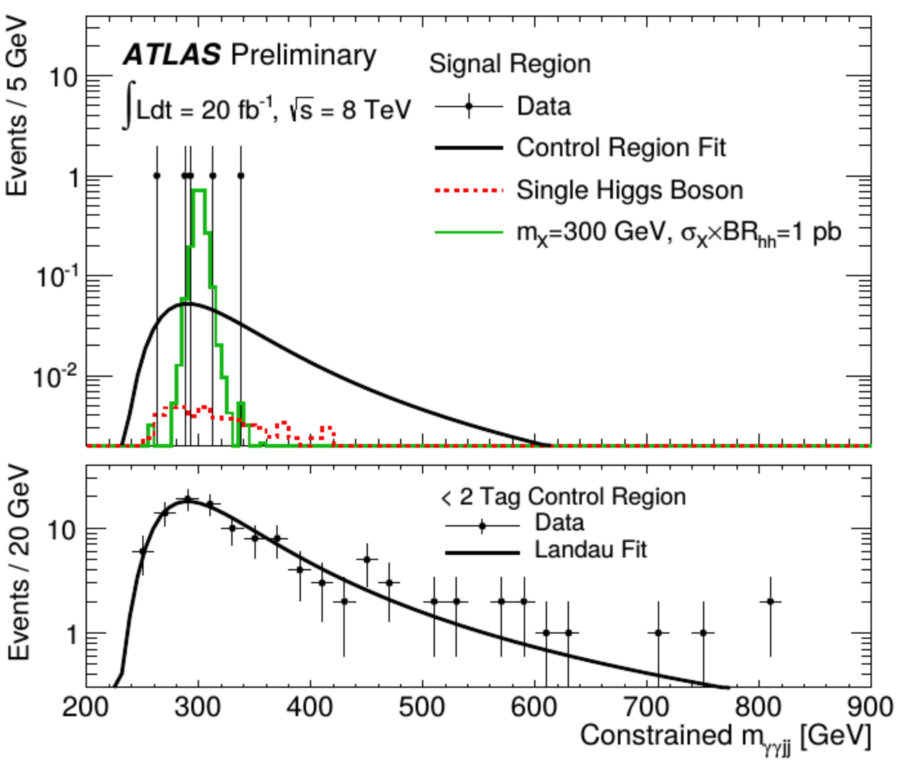
CMS PAS HIG-13-032



Di-Higgs production: hh → bbγγ

- Search for **non-resonant** and **resonant** hh → bbγγ production

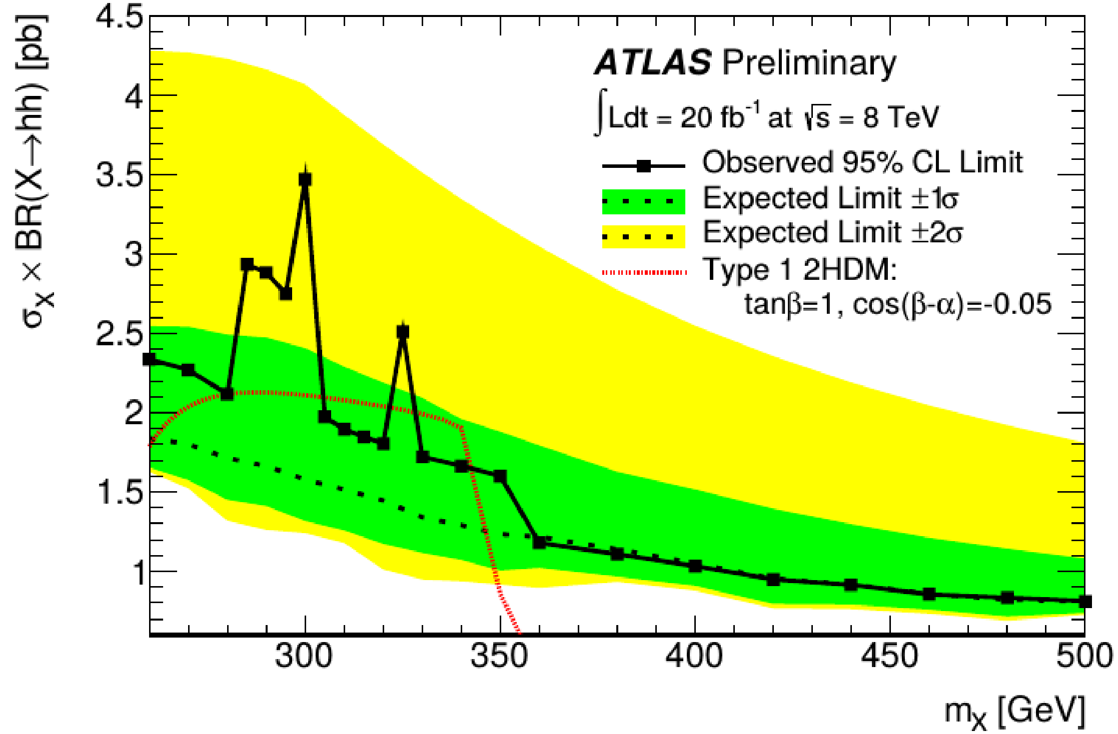




ATLAS result, shown in LHCP last week

Di-Higgs production: hh → bbγγ

Observed upper limit for anomalous non-resonant hh production:
2.2 pb (expected: 1.0 pb)
(c.f. **SM hh production ~ 10 fb**)



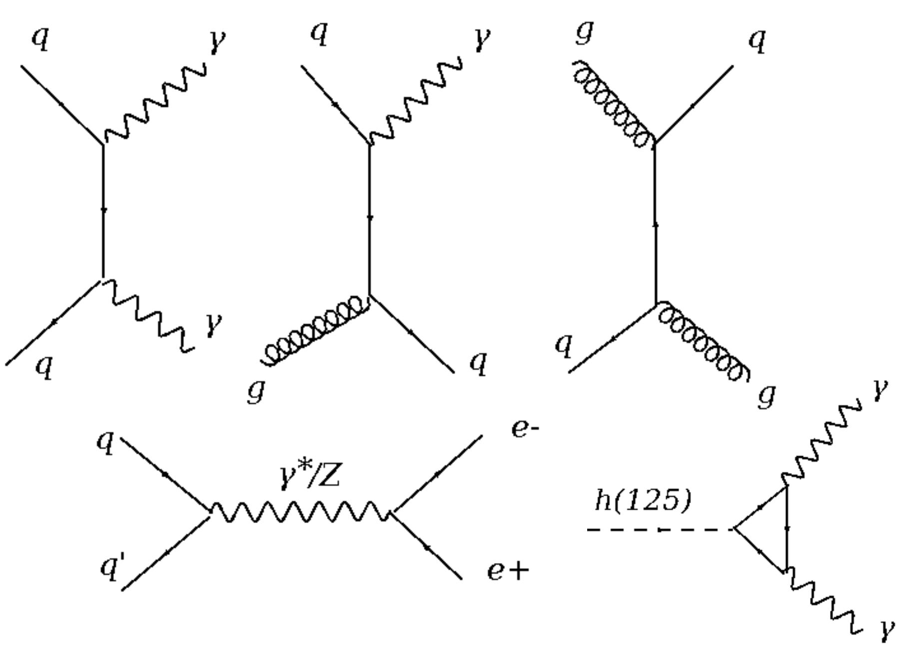
Cross section X BR limits for a **narrow scalar resonance** decaying to hh → bbγγ

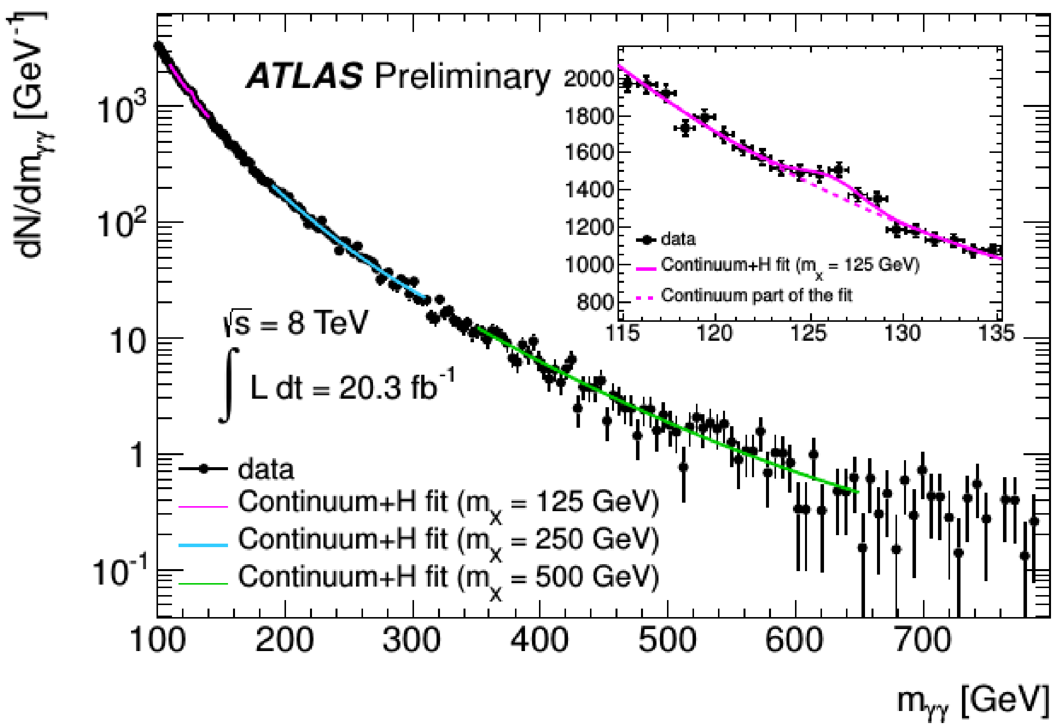
ATLAS result, shown in LHCP last week

Scalar resonances to di-photon pairs

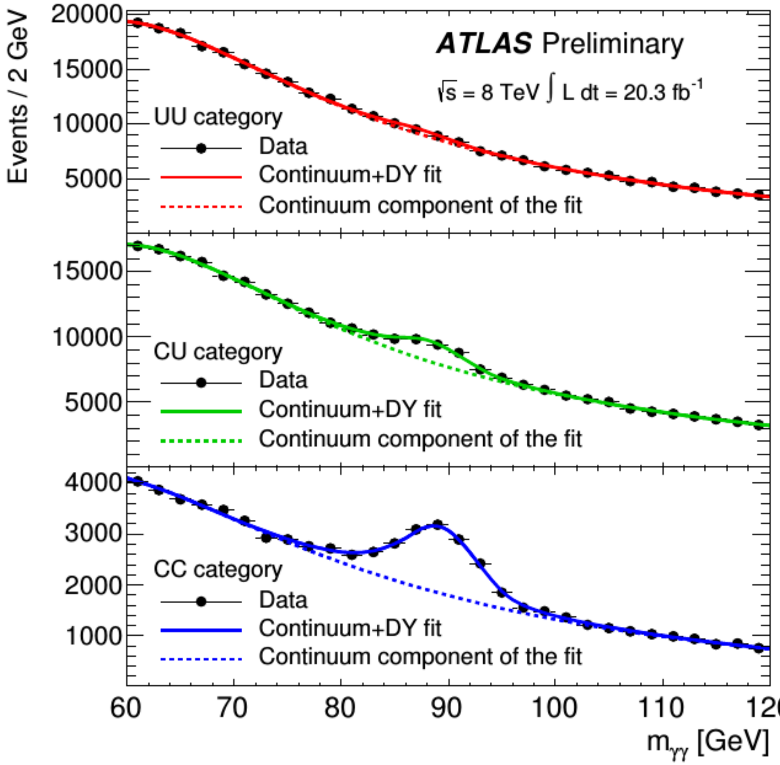
- ATLAS has looked for A/H → γγ at a mass range from 65–600 GeV extending the techniques mastered in the SM Higgs → γγ search

ATLAS-CONF-2014-031





Scalar resonances to di-photon pairs

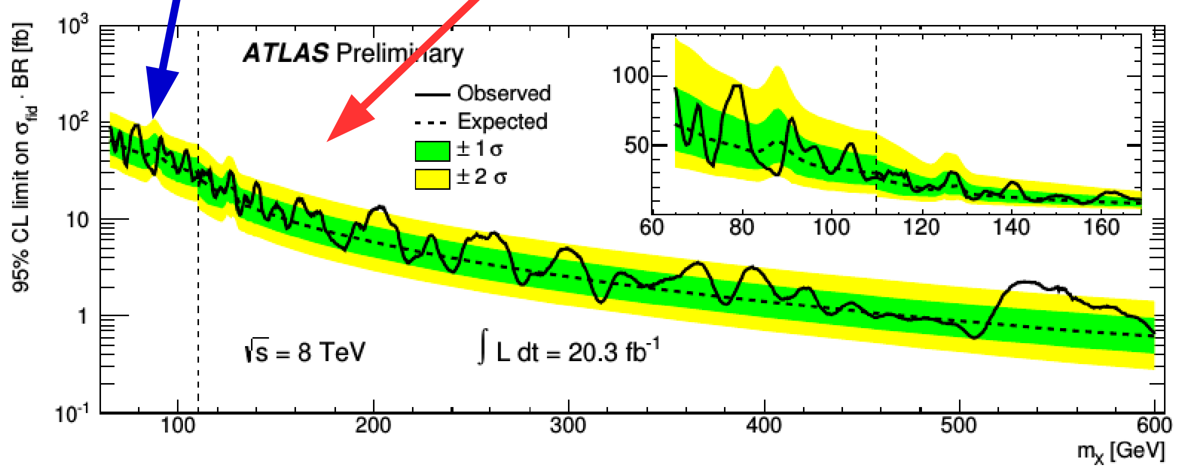


UU: unconverted-unconverted
UC: unconverted-converted
CC: converted-converted

Background estimation from $m_{\gamma\gamma}$ sidebands interpolation
Analytical functions used for shapes of signals and backgrounds

Low mass category

High mass category



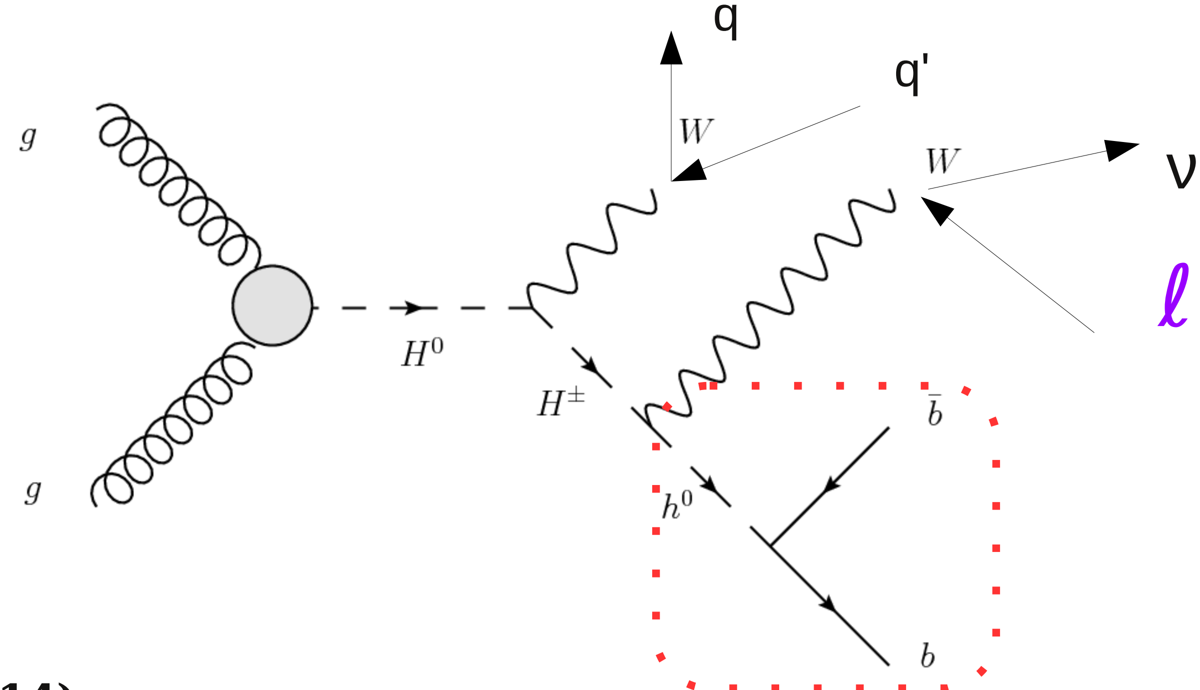
Limit on the fiducial cross section as a function of the assumed resonance mass

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

Electron or muon to trigger the event

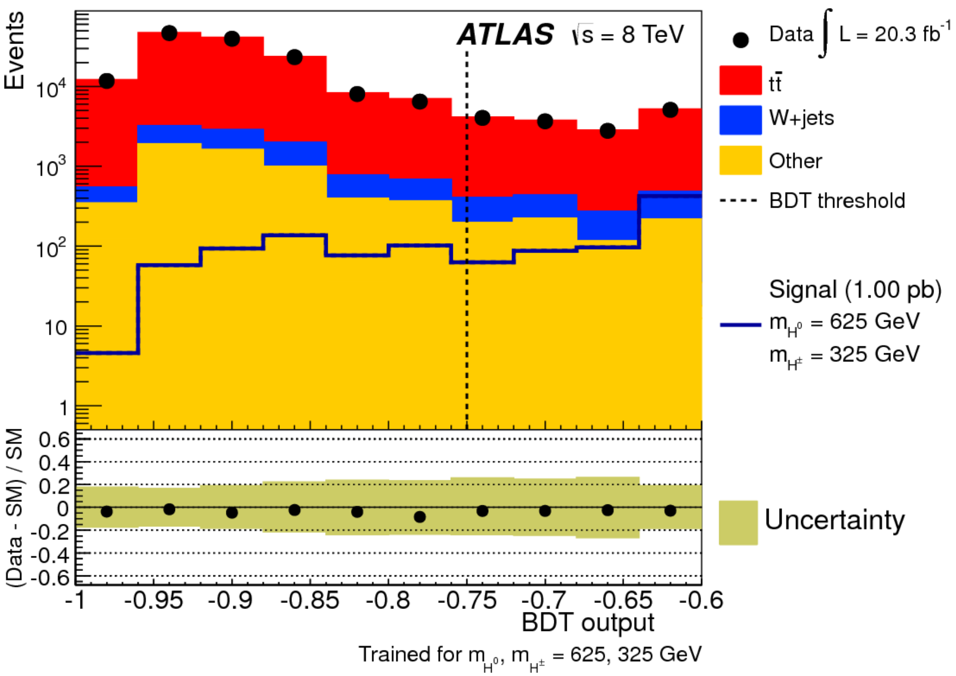
Example of a cascade decay: this final state may be simply hidden in ttbar events!

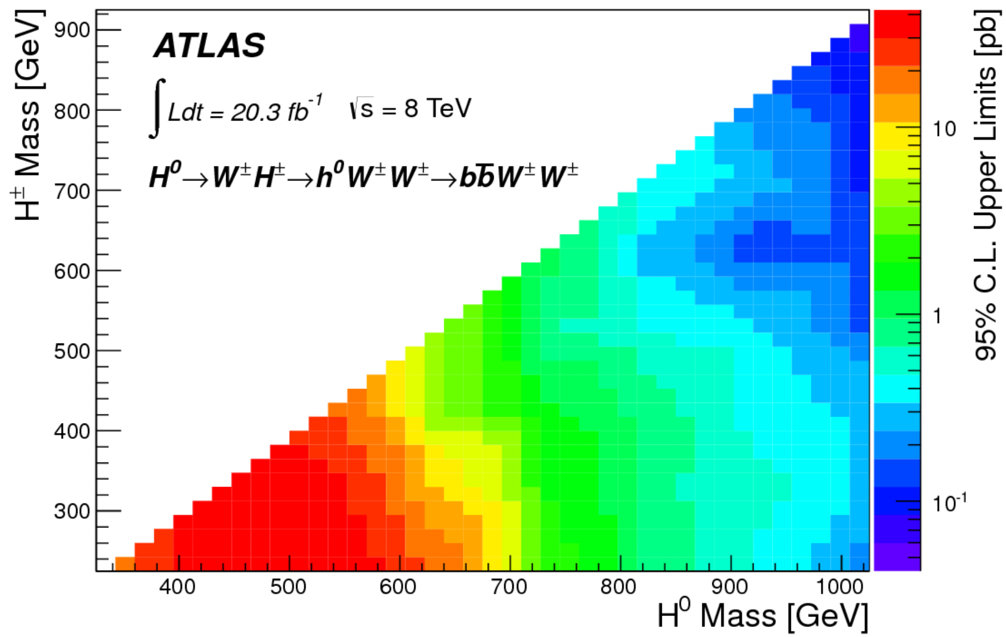


125-GeV SM-like Higgs decaying to bb

Phys. Rev. D 89, 032002 (2014)

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





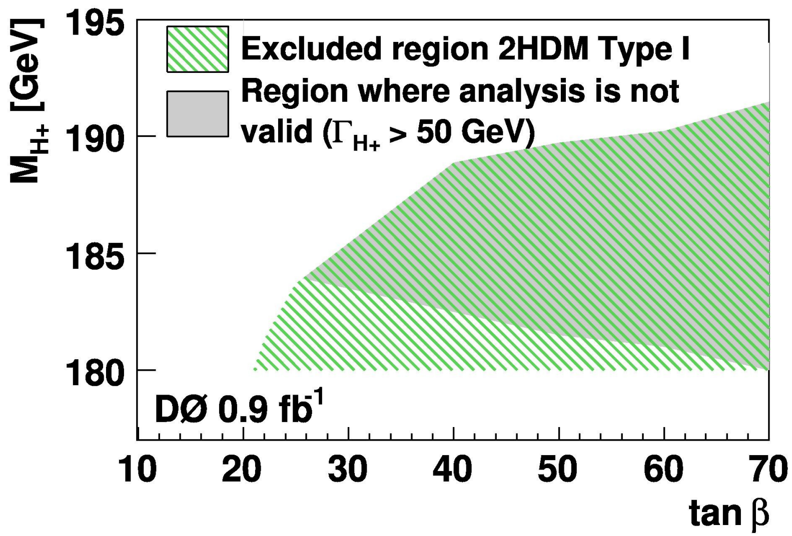
Example of a BDT output: the kinematic differences between a Higgs cascade and top pair production is exploited to improve sensitivity

Phys. Rev. D 89, 032002 (2014)

High-BR high mass Higgs channels

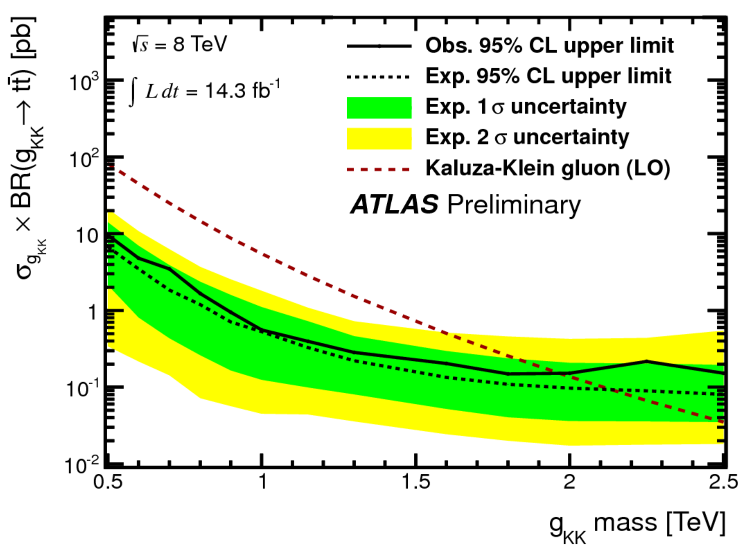
- There are some high mass decay channels in which a generic 2HDM heavy boson will prefer to decay to, nevertheless, due to their difficulty the LHC searches are still behind

Charged Higgs to tb



Phys. Rev. Lett. 102 , 191802 (2009)

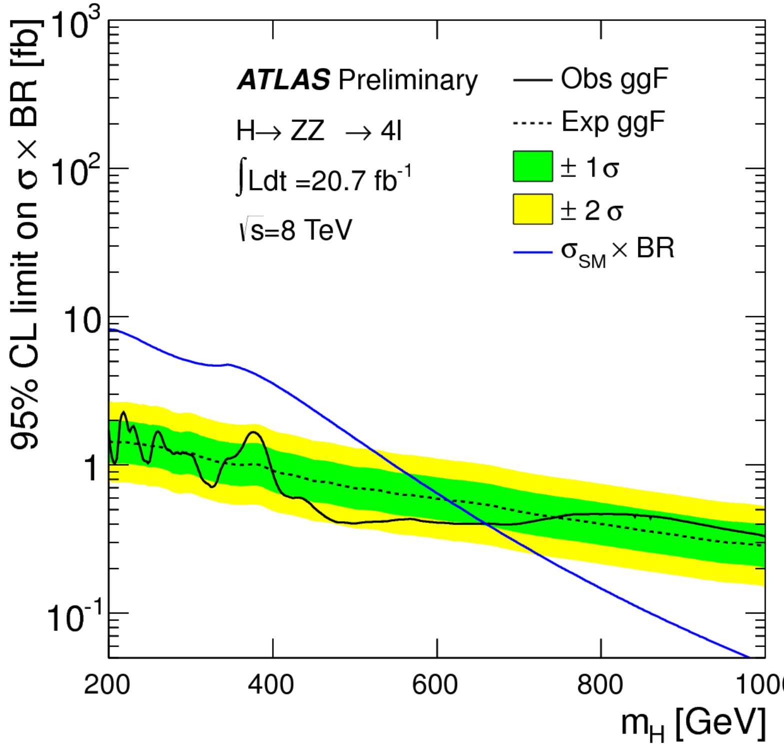
Heavy Higgs to top pair



LHC results are available, but no direct interpretation to Higgs can be made due to width and interference issues

Heavy Higgs search: WW/ZZ final states

- Extension of the old SM Higgs searches to WW/ZZ that were covering a large mass range up to 1 TeV is relatively cheap
- There is relevance to 2HDM, also relevant for a simpler extension in which a singlet is added on top of the SM doublet



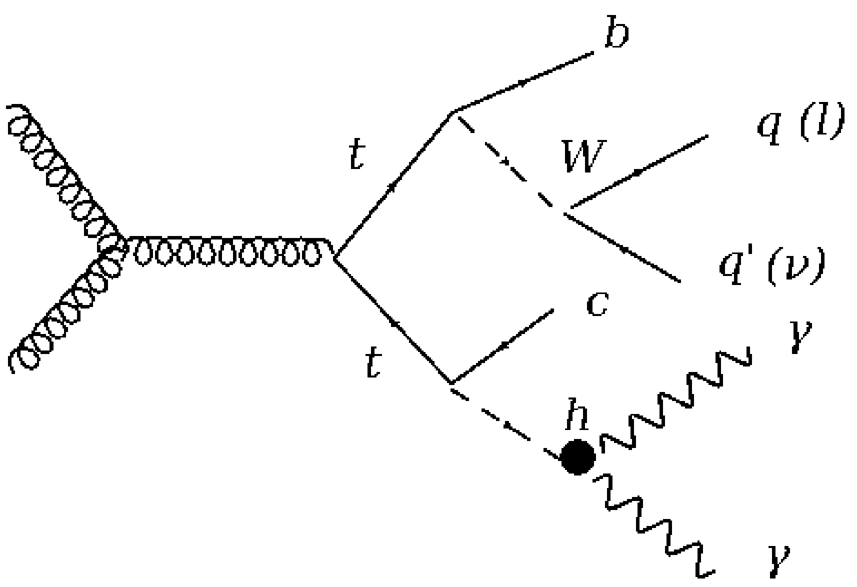
Some examples from ATLAS:
Higgs to WW, ATLAS-CONF-2013-027

High mass $h \rightarrow ZZ \rightarrow 4l$ from ATLAS-CONF-2013-013

Exotic 2HDMs: Flavour Violation

- 2HDM benchmarks have usually a built-in flavour changing (FC) neutral currents suppression, but this is not necessary
  - In type-III 2HDM, for instance, FC couplings tch and tuh exist
  - With a 125-GeV Higgs boson, h, the BR(t → ch/uh) can be sizeable and within the LHC reach
- ATLAS has looked explicitly for FC decay t → ch/uh in ttbar events with h → γγ

◇ 2 isolated photons, ET>40, 30 GeV to form a Higgs boson candidate
◇ Two channels: the other top decays hadronically or leptonically
◇ The analysis uses finally a sidebands data-driven technique around the Higgs boson resonance to estimate the background

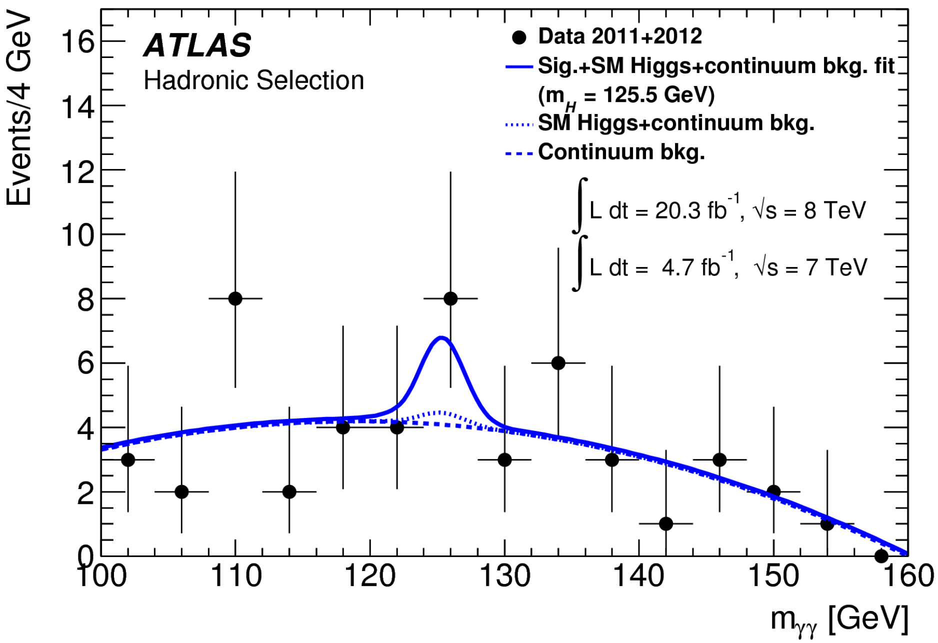


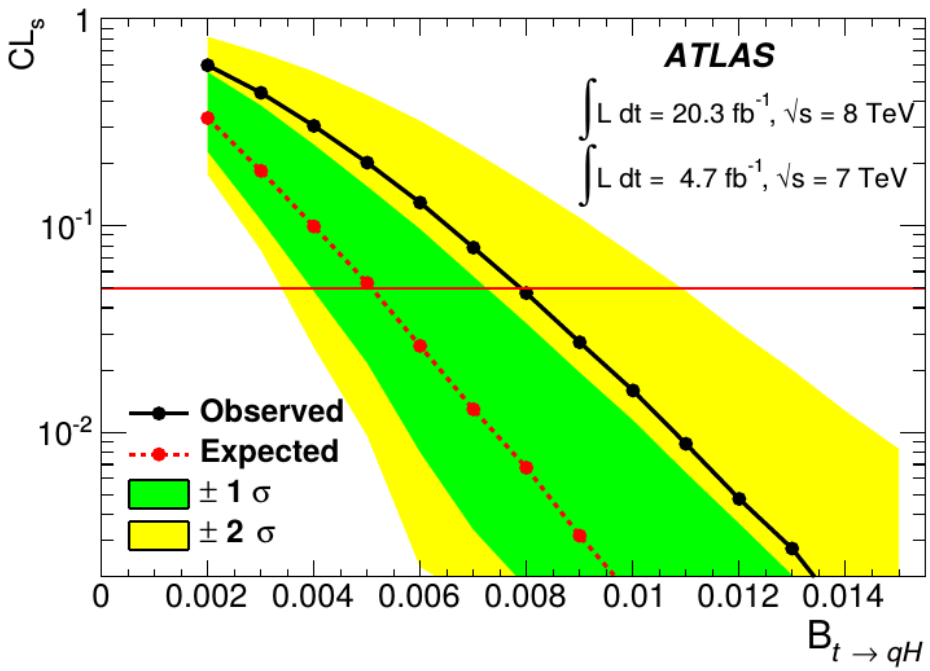
arXiv:1403.6293

Flavour violating top decays: t → ch

Example from the “hadronic top quark” channel: final distribution of events.

The CLs as a function of the FC branching ratio





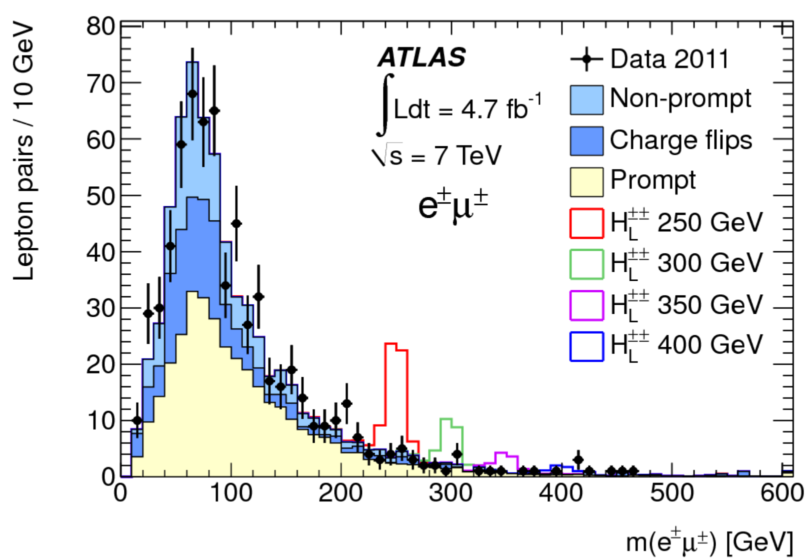
Final constrain on the FC branching ratio:
BR(t → qh) < 0.79 (0.51) % observed (expected) @ 95% CL

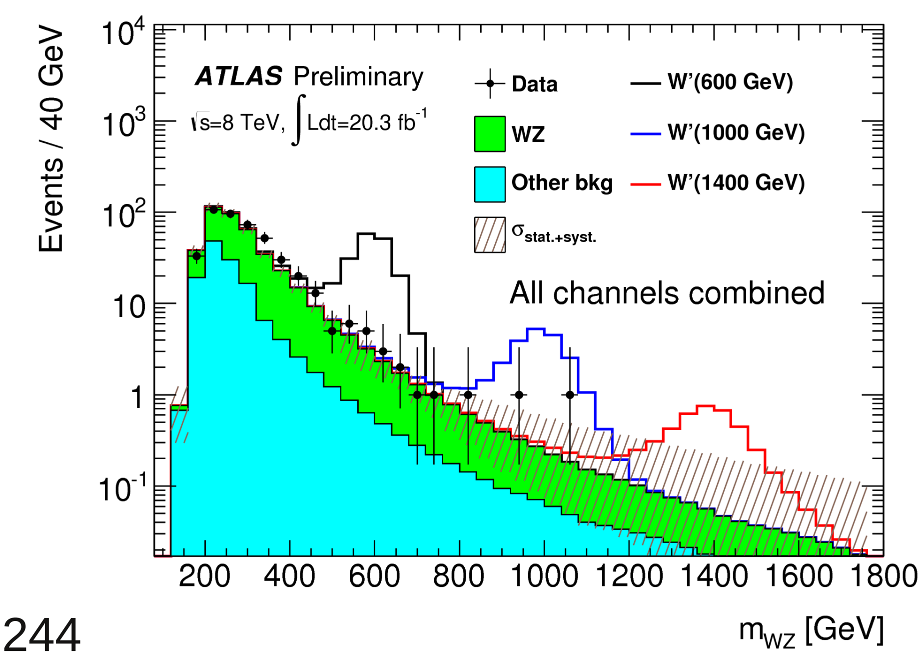
arXiv:1403.6293

Exotic Higgs sectors: Higher order representations

- It is also conceivable that the Higgs sector is extended with exotic representation, e.g. Higgs triplets (but not only)
- Signature examples (just examples)
  - Doubly charged Higgs
  - Exotic vertex $H^{+}WZ$

Example from ATLAS resonant WZ production search ATLAS-CONF-2014-015





ATLAS H++ Higgs search Eur.Phys.J. C72 (2012) 2244

Higgs Singlets: the NMSSM

- Extending the MSSM Higgs sector is another way to get more freedom from the severe constraints of the MSSM
  - Simplest way is to include a singlet: next-to-MSSM = NMSSM
  - Two additional Higgs bosons and one more neutralino wrt MSSM
  - It also solves the so-called μ-problem of the MSSM (that was actually the main motivation for introducing NMSSM)

Higgs Singlets: the NMSSM

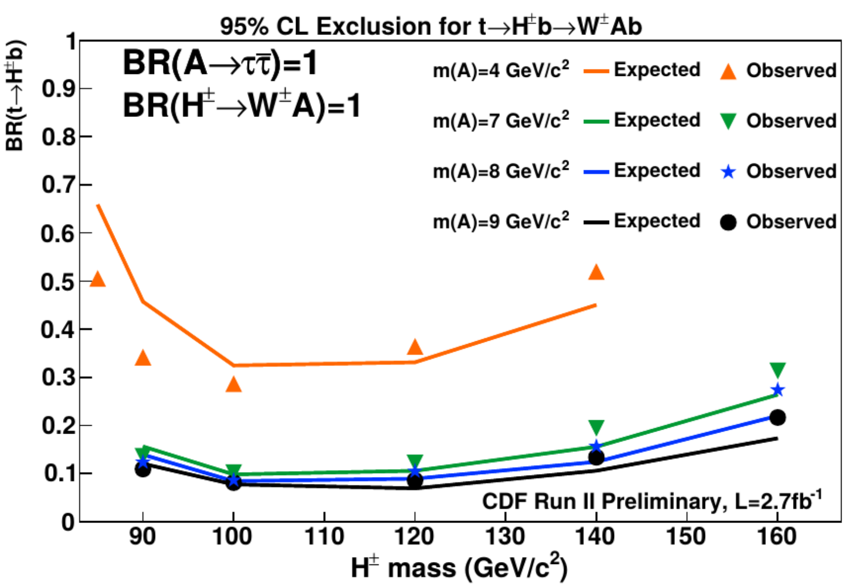
- The NMSSM is not simply about introducing more particles
  - The Higgs sector is not necessarily CP-conserving at tree level (c.f. MSSM)
    - Although many pheno studies assume CP-conservation
  - The lightest Higgs boson can be heavier than the MSSM: the tree-level "$m_h < m_Z$" relation is modified
  - The MSSM LEP constraints don't hold
    - In general, ultra-light Higgses, even few GeV in mass are allowed
    - Even in the CP-conserving case the decay $h_1 \rightarrow a_1 a_1$ opens up weakening the LEP limit

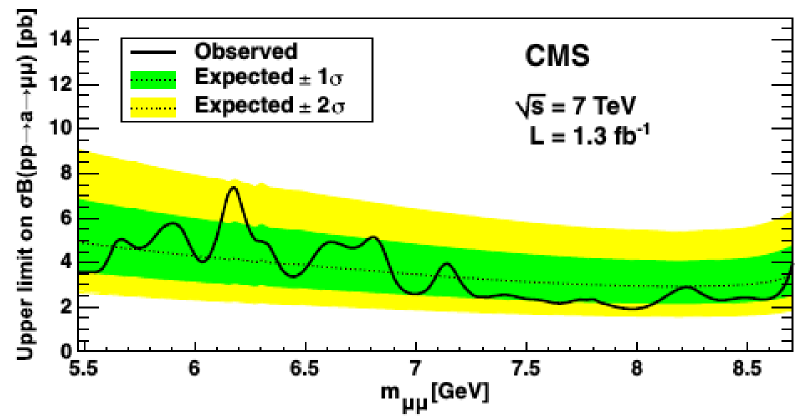
NMSSM motivated searches

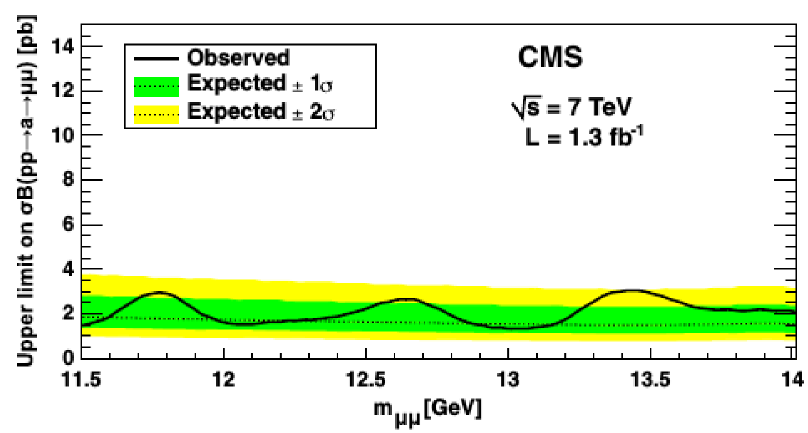
- The basic feature of CP-conserving NMSSM is the addition of potentially light CP-odd particles which can be looked for
  - Direct decays: $a_1 \rightarrow \mu\mu/\tau\tau/bb$;
    decays to $\gamma\gamma$ and ee also possible, though more constrained from fixed target experiments and axion searches
  - Through Higgs decays: $h_1 \rightarrow a_1 \, a_1$

Few NMSSM motivated searches

- Light CP-odd Higgs a1 → μμ CMS PRL 109 (2012) 121801
- Charged Higgs
  h+ → W a1 (→ μμ/ττ)
  CDF note 10104



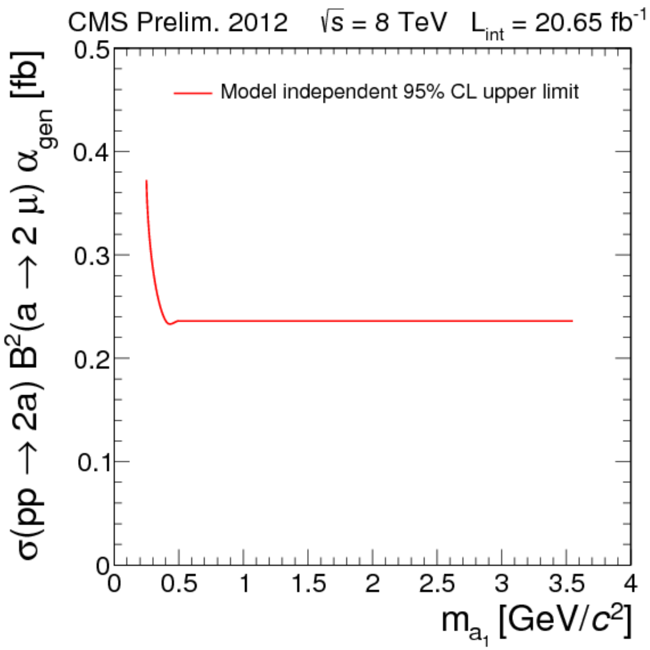


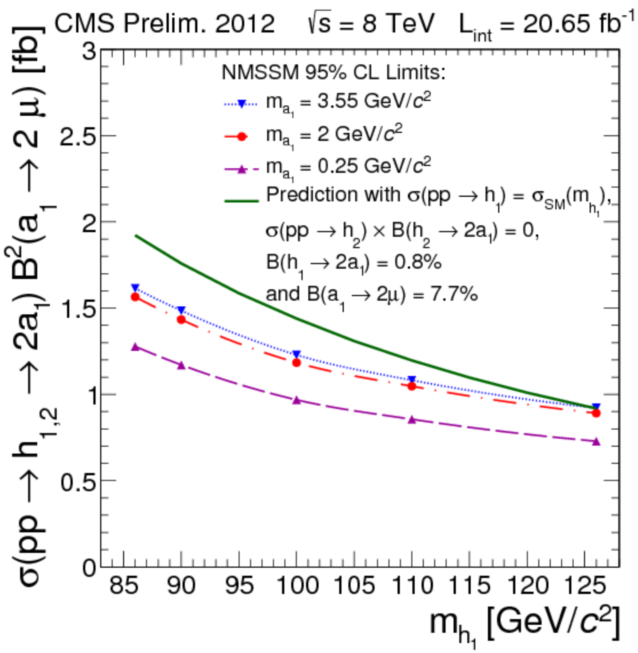


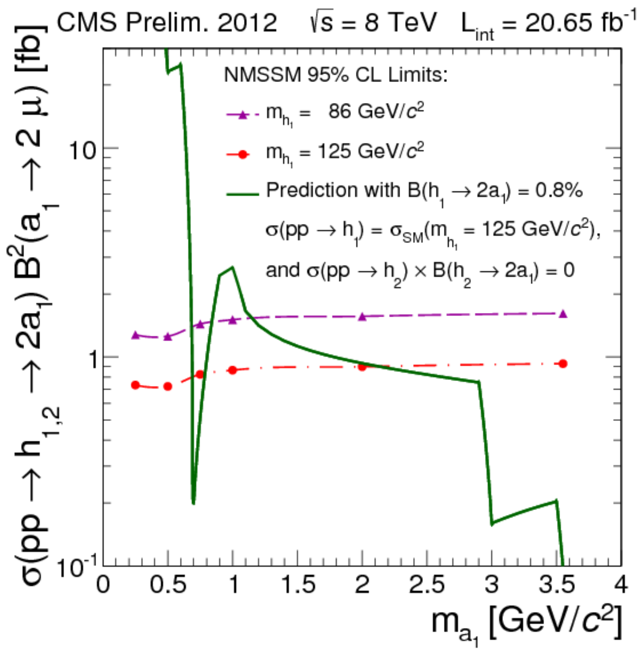
Few NMSSM motivated searches

- Higgs → a1 a1 with
  - a1 a1 → μμ μμ CMS-PAS-HIG-13-010
  - a1 a1 → γγ γγ ATLAS-CONF-2012-079

Some limit example plots from CMS-PAS-HIGG-13-010

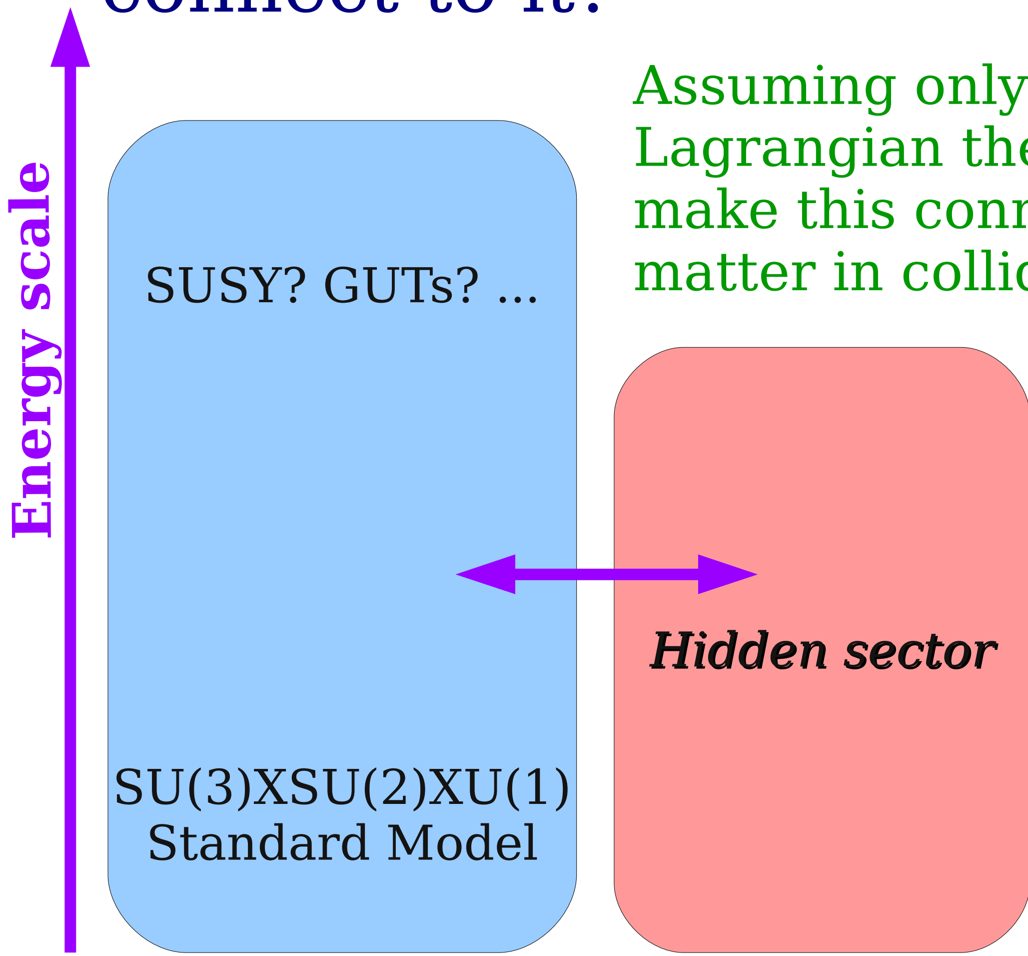






Portals to Hidden Sectors

- Assuming a hidden sector in nature: how to connect to it?



Assuming only renormalizeable terms in the Lagrangian there are only a handful of ways to make this connection! Potential access to Dark matter in colliders

$\phi \phi S S$ — **Higgs portal**

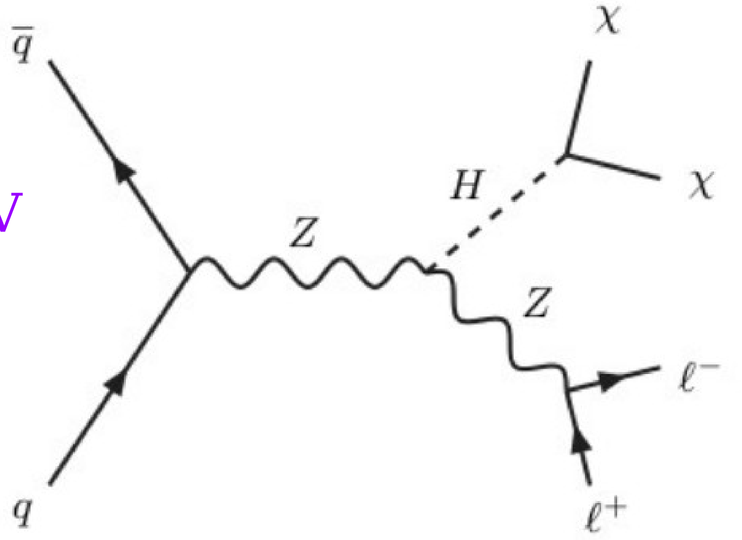
$\phi L \psi$ — Neutrino portal

$F_{\mu\nu} F'^{\mu\nu}$ — Vector and Axion portal

Higgs to invisible

- LEP legacy: LEP had also looked for Higgs to invisible and the LHC example discussed in the following is a continuation of this trend (see arXiv:hep-ex/0107032)
- An LHC example: Zh production with Higgs decaying to invisible particles

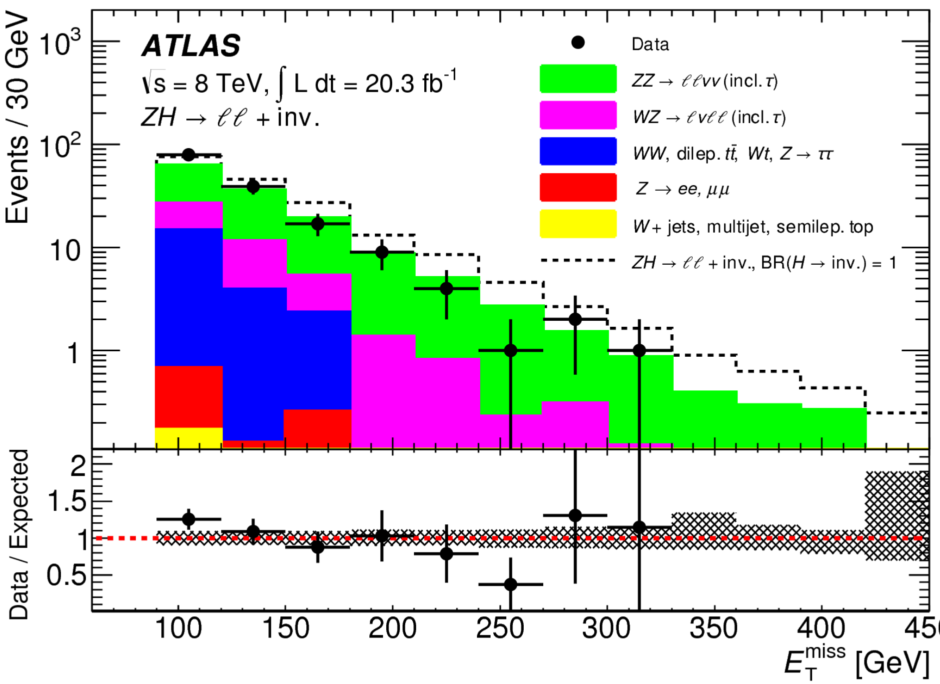
Zh → ll invisible: event selection
◇ single or double lepton trigger;
◇ ee or μμ (p_T > 20 GeV) & m(ll): 76 – 106 GeV
◇ MET > 90 GeV; Δφ(MET, p_T^{miss}) < 0.2
(p_T^{miss} : track-based missing p_T)
◇ Δφ(MET,Δp_T^{ll}) > 2.6; Δφ(l,l) < 1.7
◇ |MET-p_T^{ll}|/p_T^{ll} < 0.2
◇ no jets pT>25 GeV and |η|<2.5



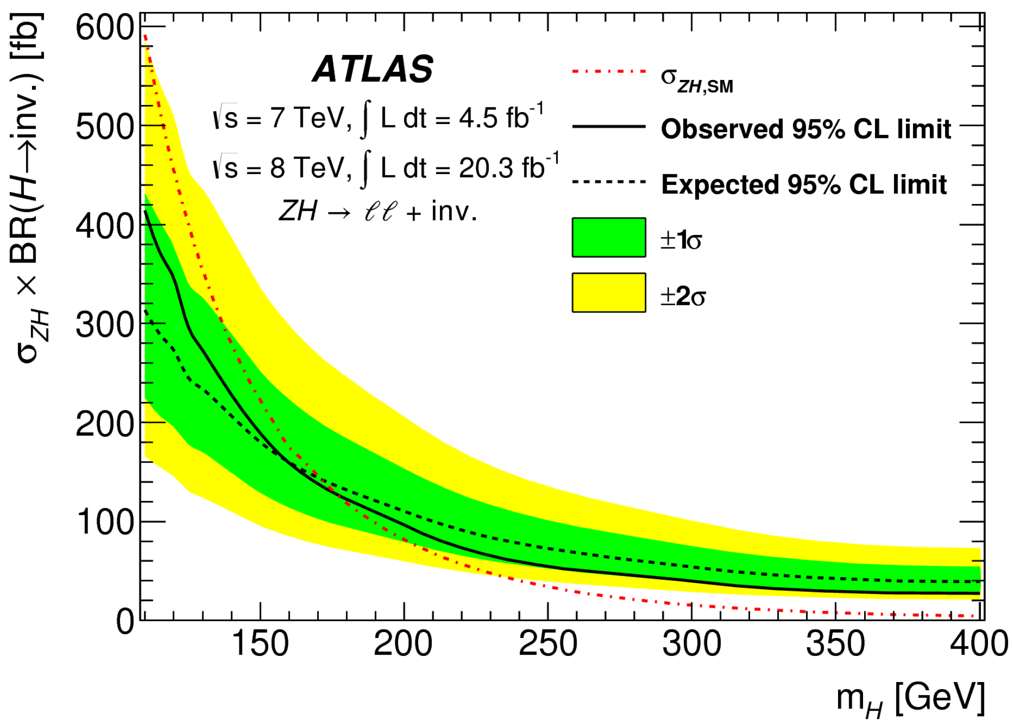
arXiv:1402.3244

Higgs to Invisible

arXiv:1402.3244



MET after full selection: this is the discriminating variable of this analysis

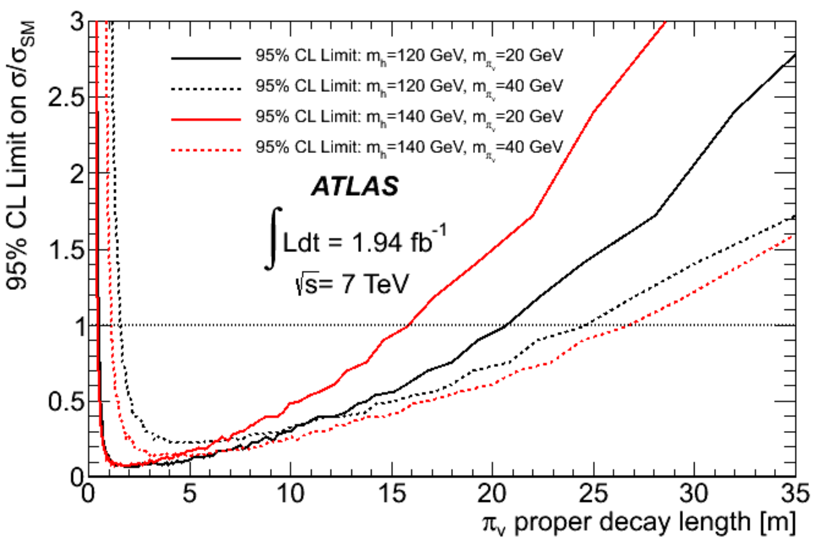


The limit on σ(pp -> Zh) X BR(h->inv) compared to the SM σ(pp -> Zh)

Higgs to hidden sector

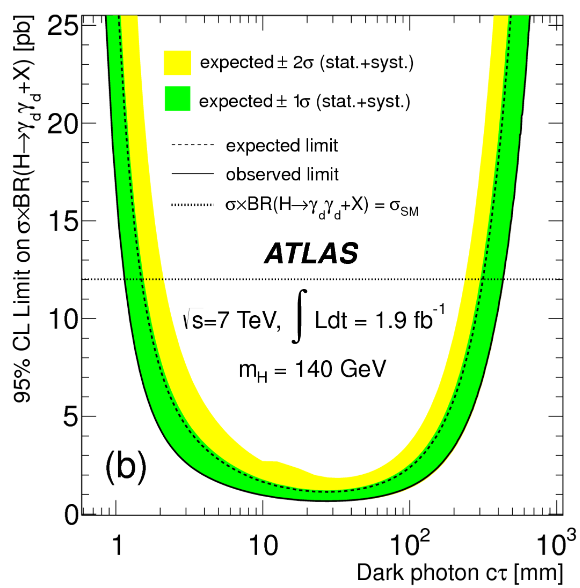
- Higgs doesn't have to decay to dark matter particles, it can simply connect a hidden sector with exotics particles
- Various results have been obtained

Higgs to hidden valley particles



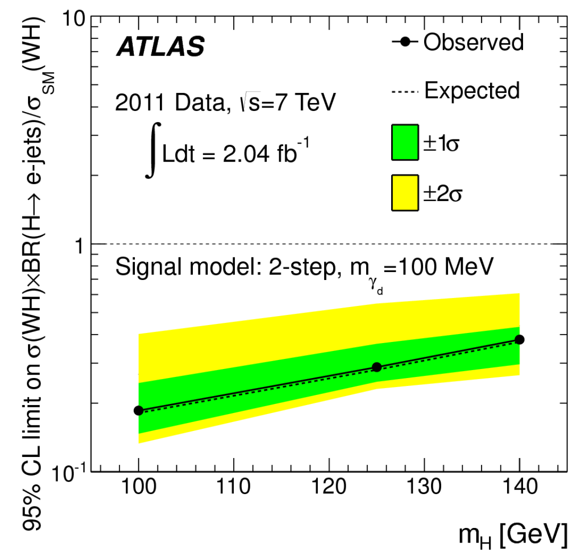
PRL 108 (2012) 251801

Higgs to muon jets



Phys.Lett. B721 (2013) 32-50

Higgs to electron jets

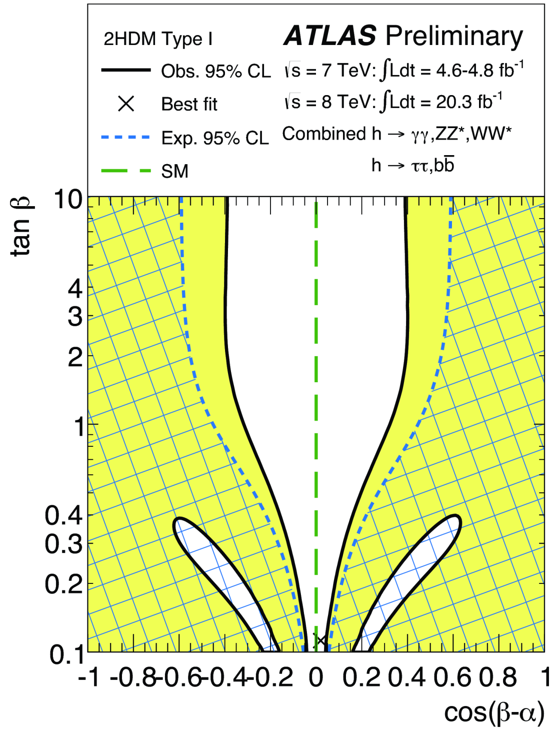


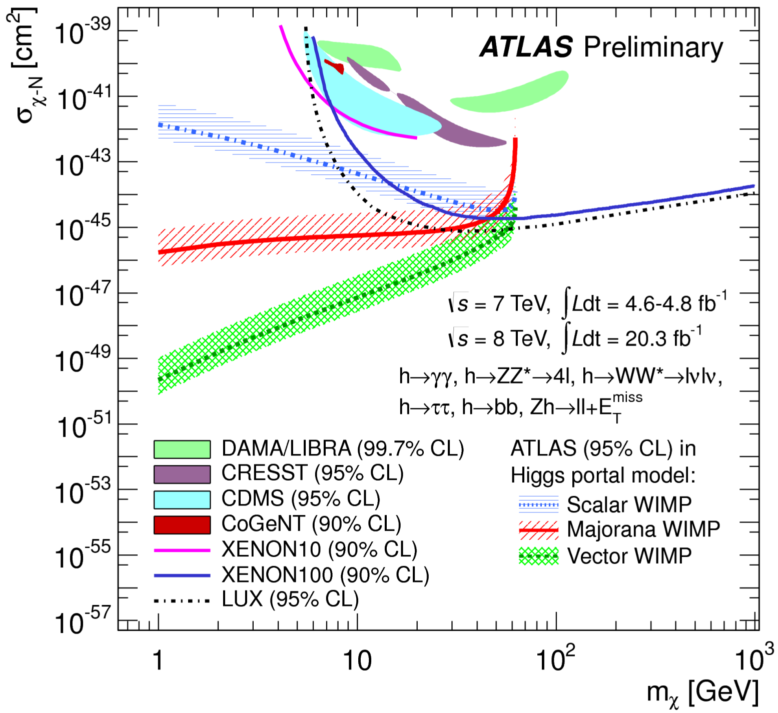
New J. Phys. 15 (2013) 043009

Higgs couplings re-interpretation

- The measurement of the couplings of the discovered Higgs boson can be used to set constraints on BSM physics
- Dedicated ATLAS conference note ATLAS-CONF-2014-010 with lots of results

Just two examples here:
→ 2HDM parameter space constraints
→ interpretation of the Higgs to invisible and the indirect Higgs boson BR measurements as a limit of the nucleon-dark matter scattering cross section





Where we stand: hints for the future

- There is definitely a high motivation for an extended Higgs sector
  - MSSM starts becoming more and more constrained, nevertheless, it is still a viable model
  - More generic models can help us extend our searches beyond the MSSM, e.g. generic 2HDMs, NMSSM etc
  - Besides, exotic ideas like Higgs portal, composite Higgs, etc are also possible
  - Keep in mind that width & interference issues may degrade our sensitivity in a lot of these searches

Warning: this slide may be incomplete and biased by personal opinions and interests!

Where we stand: hints for the future

- Neutral Higgs boson searches
  - The neutral MSSM Higgs search to ττ and bb will continue be relevant for the next run and will dominate the high tan β high mA search
    - Flavour constraints e.g. from Bs → μμ will help in constraining or clarifying the situation in case of a discovery
  - 2HDM (and not only) motivated signatures will be very relevant as well:
    - Higgs-to-Higgs decays: A → Zh, H → hh will be very promising
    - A/H → tt **may be the only way** to access the extended Higgs sector
    - H → WW and ZZ are easy to maintain and certainly deserve attention
    - The possibility of cascades and decays like A → ZH should not be underestimated
  - We must not forget low mass searches (e.g. NMSSM)

Warning: this slide may be incomplete and biased by personal opinions and interests!

Where we stand: hints for the future

- Charged Higgs bosons
  - Light charged Higgs (mass < m_{top}) is heavily constrained in the MSSM/type II
    - Nevertheless Type-I is much less restricted and viable decays to di-jet, bbW etc should be pursued as well
  - High mass charged Higgs (> m_{top}) is largely unexplored and the searches in the tb and also in the τν final state are critical to continue
  - Alternative channels like $H^+ \rightarrow$ Wh/WH should be pursued as well
  - Exotic channels like WZ are also possible

Warning: this slide may be incomplete and biased by personal opinions and interests!

Where we stand: hints for the future

- Higgs properties
  - It is very important to measure as precisely as possible Higgs couplings, BR and production cross section
  - Keep in mind that ("weak" or "strong") decoupling limits exist in many theories, hence direct searches are indispensable
- Rare decays
  - Haven't talked about these at all in this talk, but there are BSM scenarios in which several relatively rare modes are enhanced
  - e.g. exotic top decays to hc which in the near future will become sensitive to type-III 2HDM, etc
  - Also have a look to the "Exotic Higgs decay bible": **arXiv:1312.4992**

Warning: this slide may be incomplete and biased by personal opinions and interests!

Where we stand: hints for the future

- Flavour physics
  - In many cases complementary to the direct searches at ATLAS/CMS and will provide key info for identifying the details of the new physics when discovered
  - But also keep an eye: there is a good chance that BSM Higgs appears there first (e.g. if Babar $B \rightarrow D^*\tau\nu$ result is confirmed)
- Last but most important point:
  - The search for BSM Higgs has just started. Only now we are starting being sensitive to realistic Higgs sector extensions

Warning: this slide may be incomplete and biased by personal opinions and interests!

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

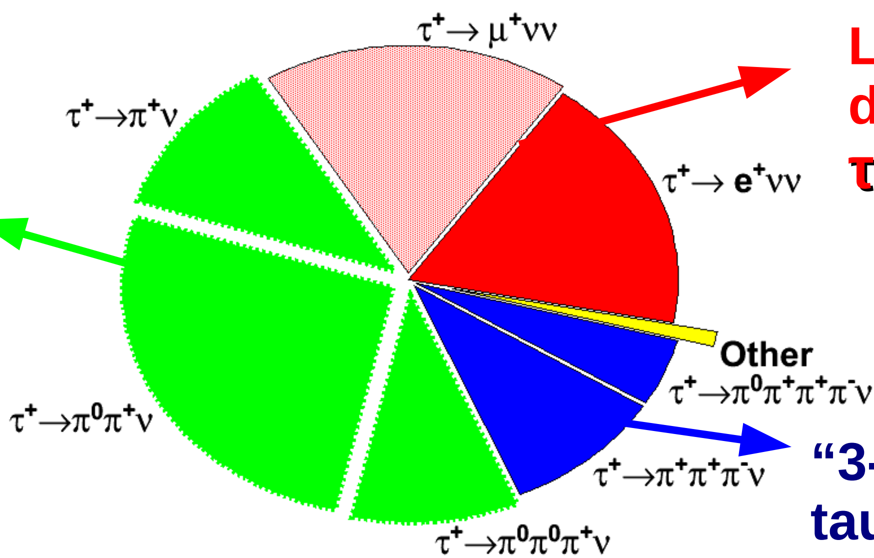
From the theory summary talk in LHCP 2014 by J. Ellis

Additional Slides

Taus

- "Golden" MSSM Higgs search channels: **H→ττ, H$^{\pm}$→τ$^{\pm}$ν**
- Taus: the only leptons that can decay hadronically

"1-prong" hadronic tau decays (~50%)



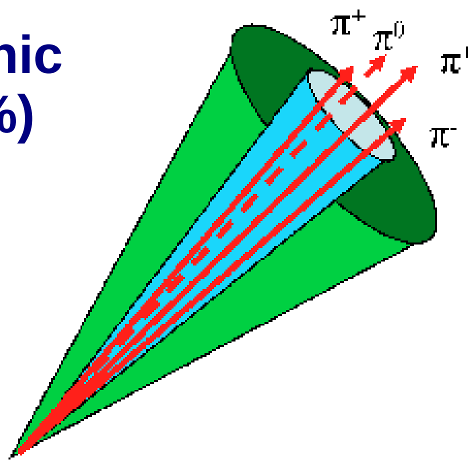
Leptonic tau decays (~35%)
τ(lep)

τ(had)

"3-prong" hadronic tau decays (~15%)

Studies with taus are involved:

- pions in τ(had): large fake rates from multi-jet production
- neutrinos in the final state: degraded di-tau mass resolution

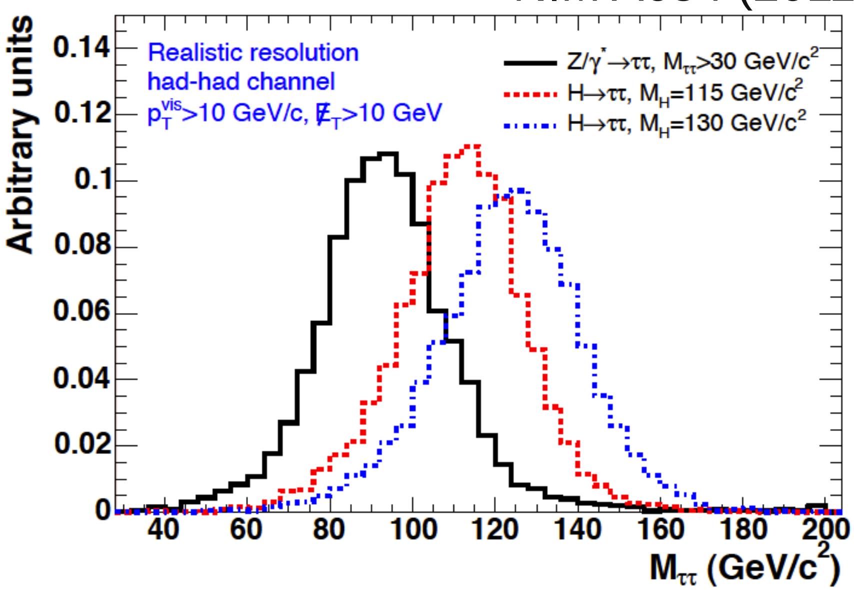


Neutral MSSM Higgs

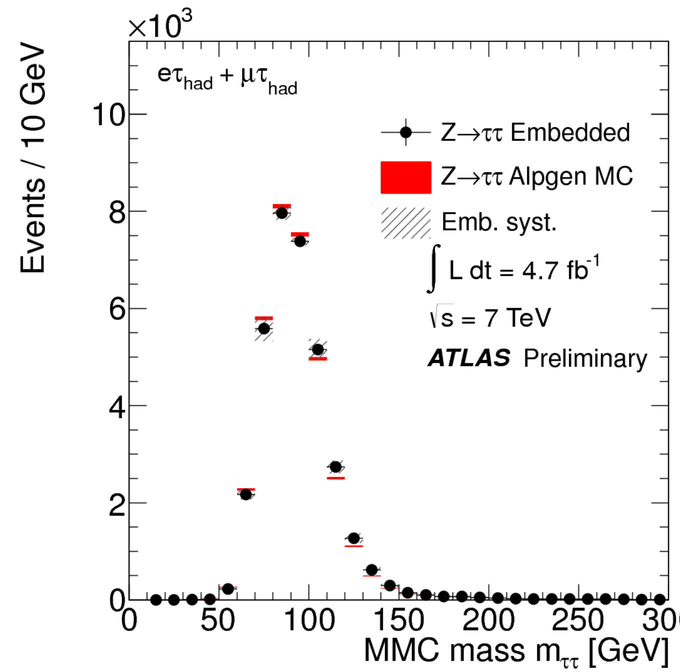
- Di-tau mass resolution: very poor due to the presence of neutrinos in the final state
  - Visible mass (mass of visible objects)
  - "Missing Mass Calculator" (MMC):

Constrain unknown neutrino momenta using τ decay kinematics

NIM A654 (2011) 481



- Z → τ τ : very important background source



"τ-embedded" Z → μμ data events: select Z→μμ events from data and replace μ with a simulated τ

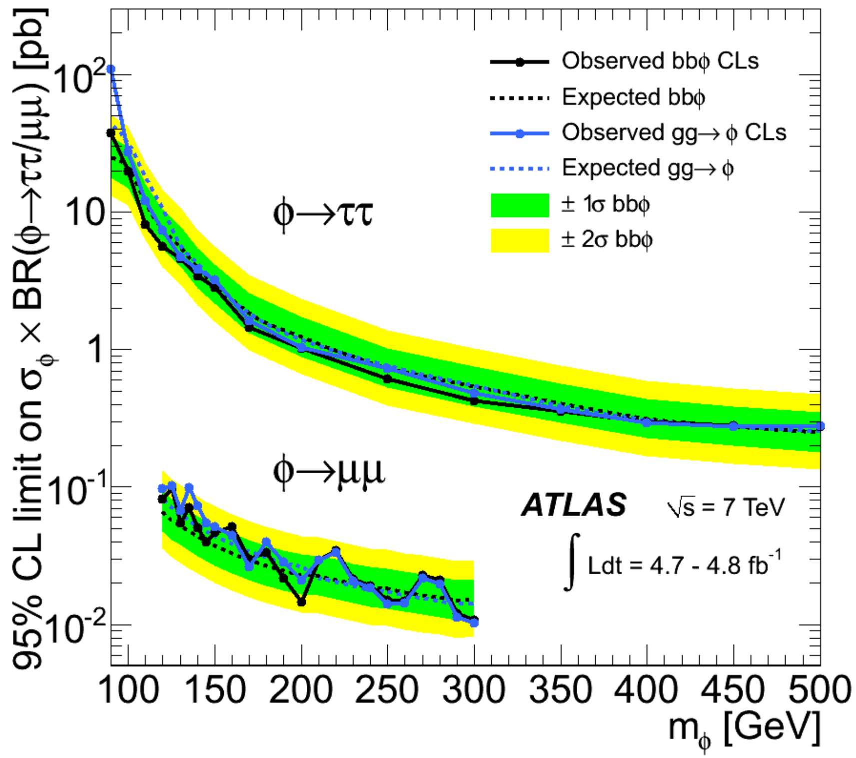
Neutral MSSM Higgs

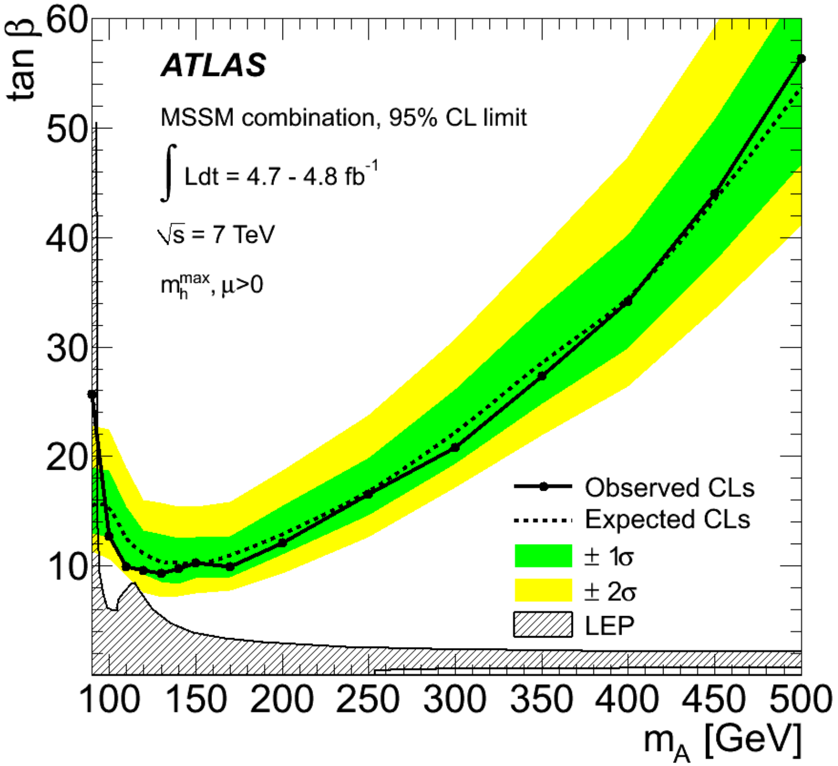
arXiv:1211.6956

- Exclusion Limits: all channels combined

Limit on σ BR(φ → ττ)

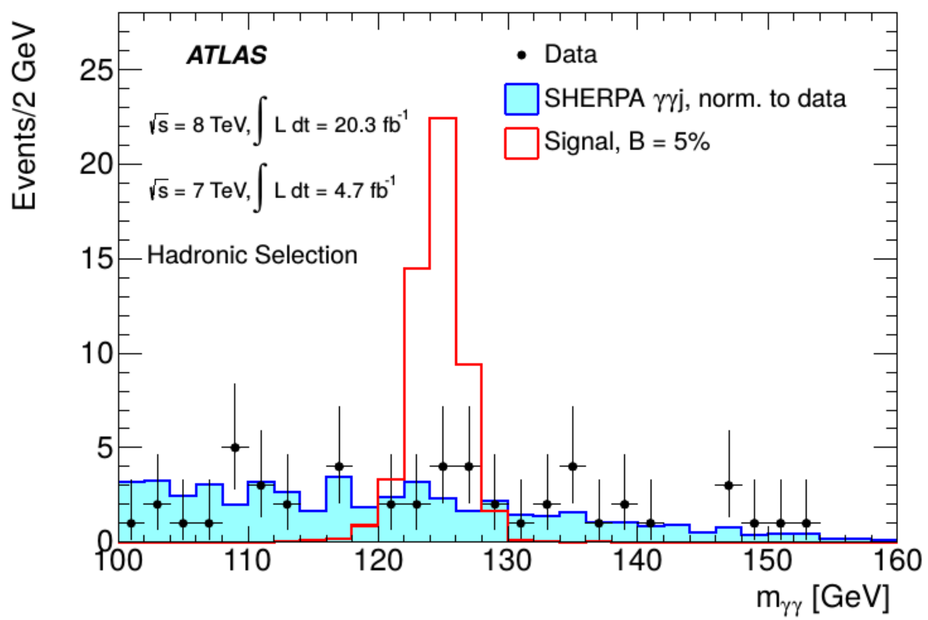
"m_A-tanβ" space limit m_h^{max}

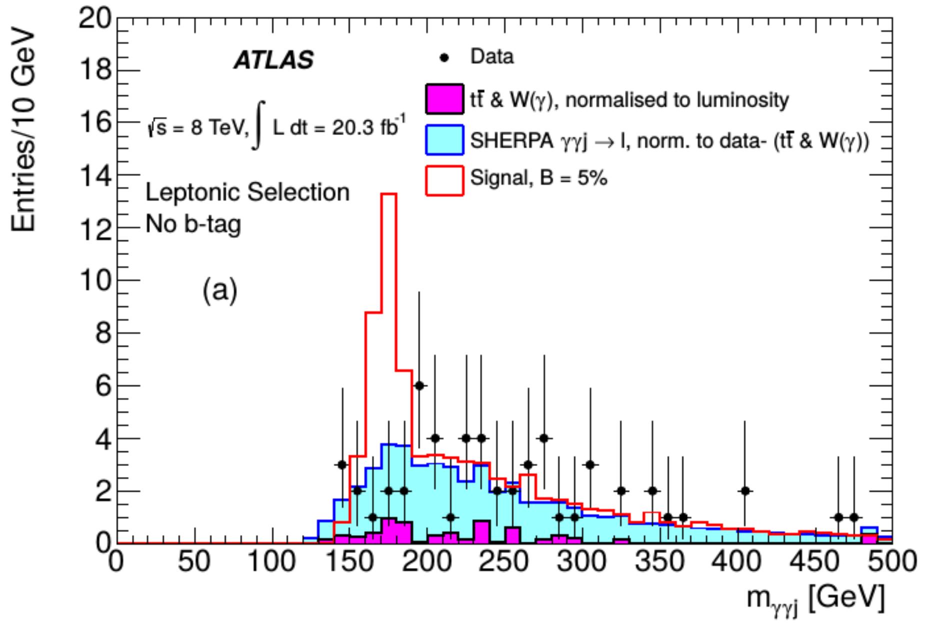




Flavour violating top decays: t → ch

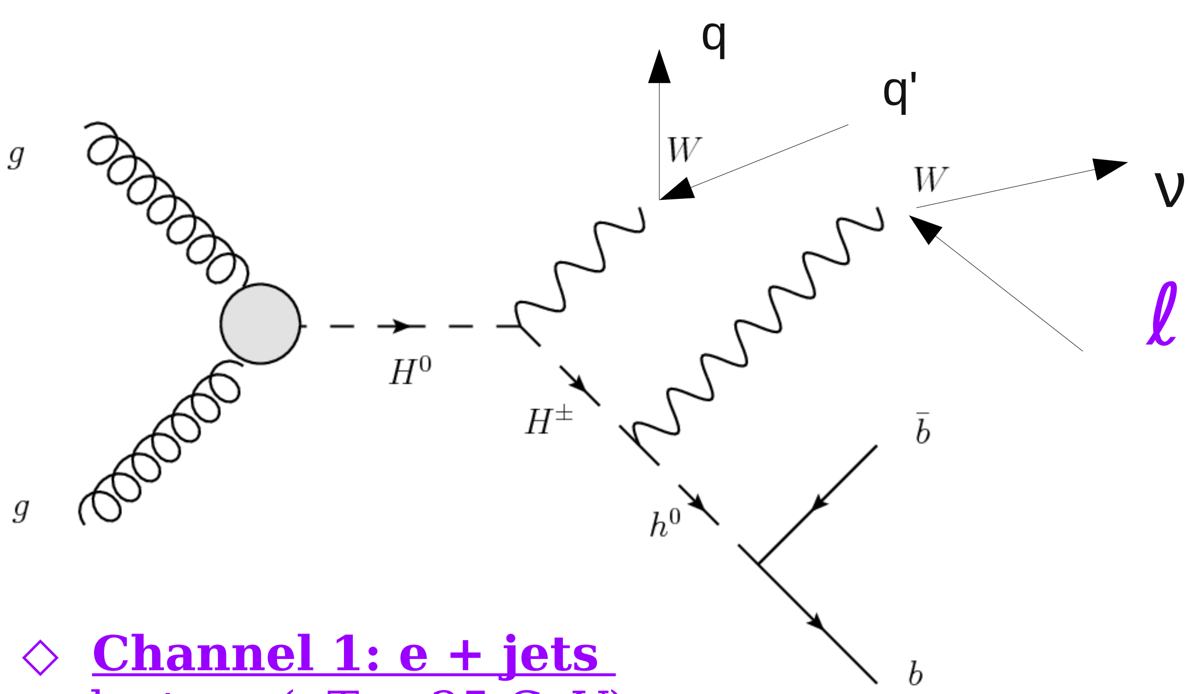
◇ **Channel 1: Hadronically decaying top quark**
– at least 4 jets with at least one of them a b-jet
– (γγ + jet), (3 jets) form the two top candidates
◇ **Channel 2: Leptonically decaying top quark**
– exactly one e (p_T>15 GeV) or μ (p_T>10 GeV)
– mT(lepton,MET) > 30 GeV; at least 2 jets, one of them is a b-jet
– (γγ + jet), (jet+lepton+MET) form the two top quark candidates





arXiv:1403.6293

Higgs Cascade



◇ **Channel 1: e + jets**
– electron (pT > 25 GeV)
– m_T(e,MET) > 30 GeV

◇ **Channel 2: μ + jets**
– muon pT > 25 GeV
– m_T(μ,MET)+MET > 60 GeV

◇ both channels:
– at least 4 jets, and at least two of them are b-jets

Variables used in the BDT against top background:
1. mass(b,b)
2. mass(b,b,W,W)
3. mass(b,b,W) using W candidate that gives the largest bbW mass
4. m_{t1} =mass(W (→ lv),b)
5. m_{t2} = mass(W(→ jj),b)
6. $|m_{t1} – m_{t2}|$
7. ΔR(b,b)