Collider Searches for Beyond-Standard Model Higgs bosons

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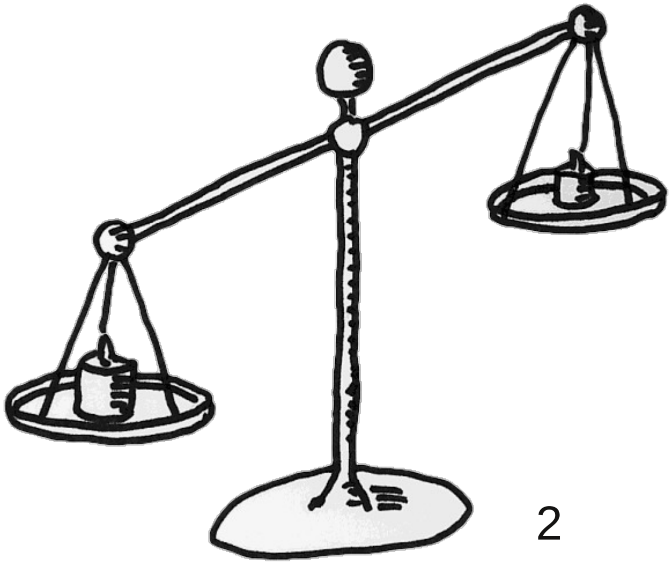
Before we start: Disclaimer

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

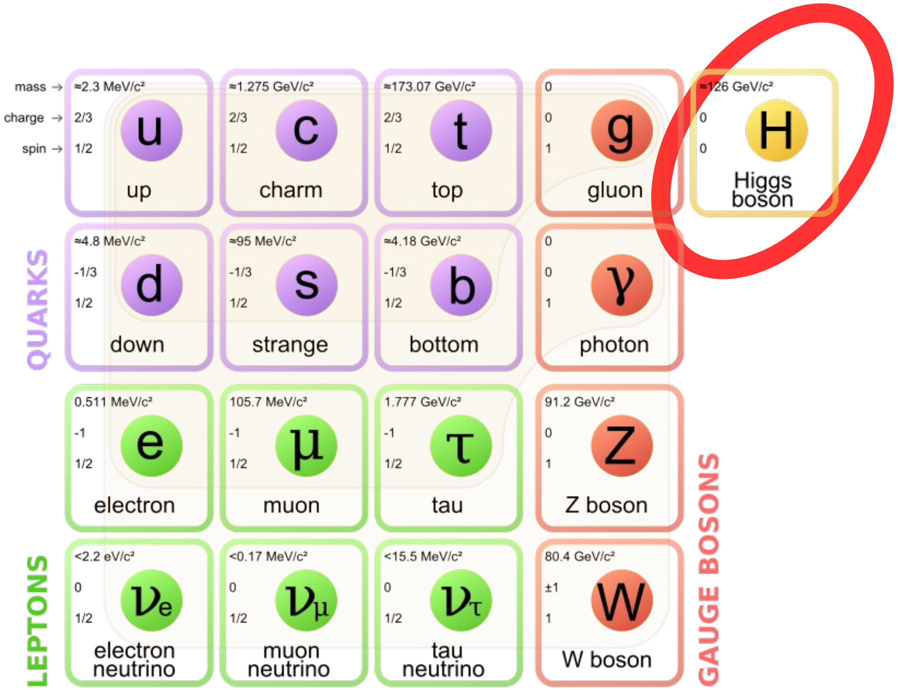
✔ The talk aims to give the "big" picture of the BSM Higgs searches to a broad experimental audience and discuss
- what is the meaning of the searches with respect to the underlying physics models?
- what does the 125-GeV Higgs discovery mean for BSM Higgs searches?
- when and how are we going to discover the BSM Higgses?

✔ Warning: Biased selection of experimental results: I will mostly show ATLAS results



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



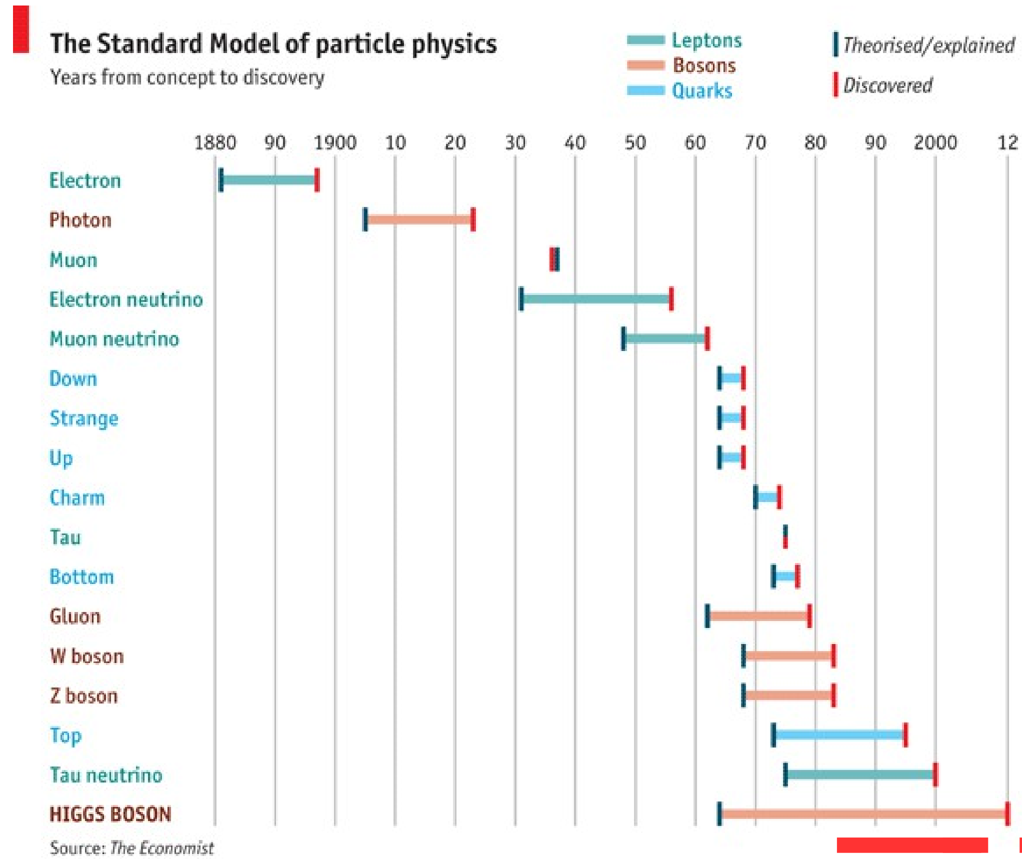


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Chart copyright “The Economist”

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
✔ direct access to a 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 may be 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 may be 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?

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.

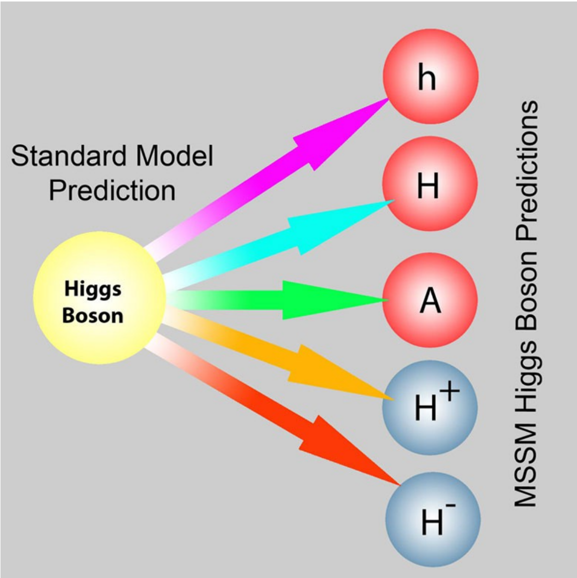
The MSSM

- 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

- One 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)
  - Driven by the top mass
    → **conspiracy** that led to the non-discovery of SUSY at LEP

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

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

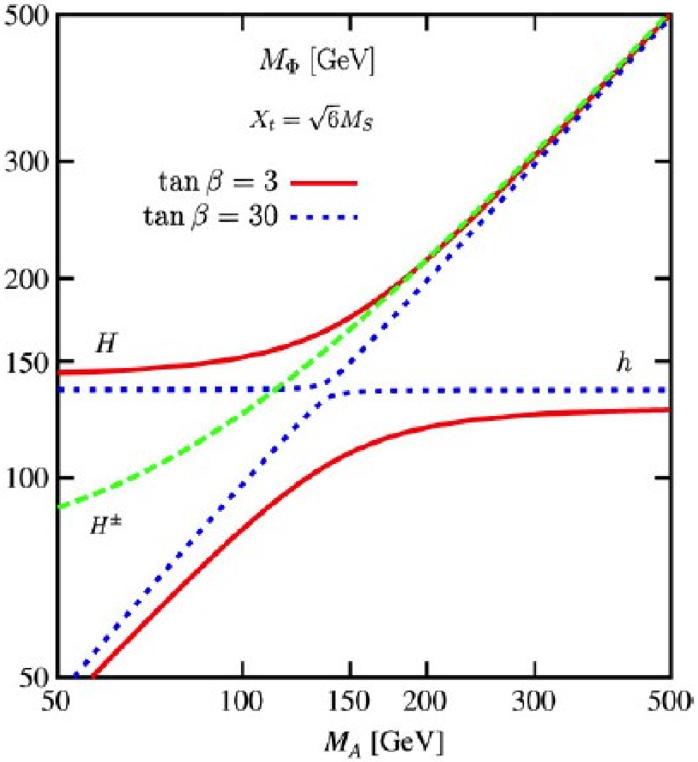
$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

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

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

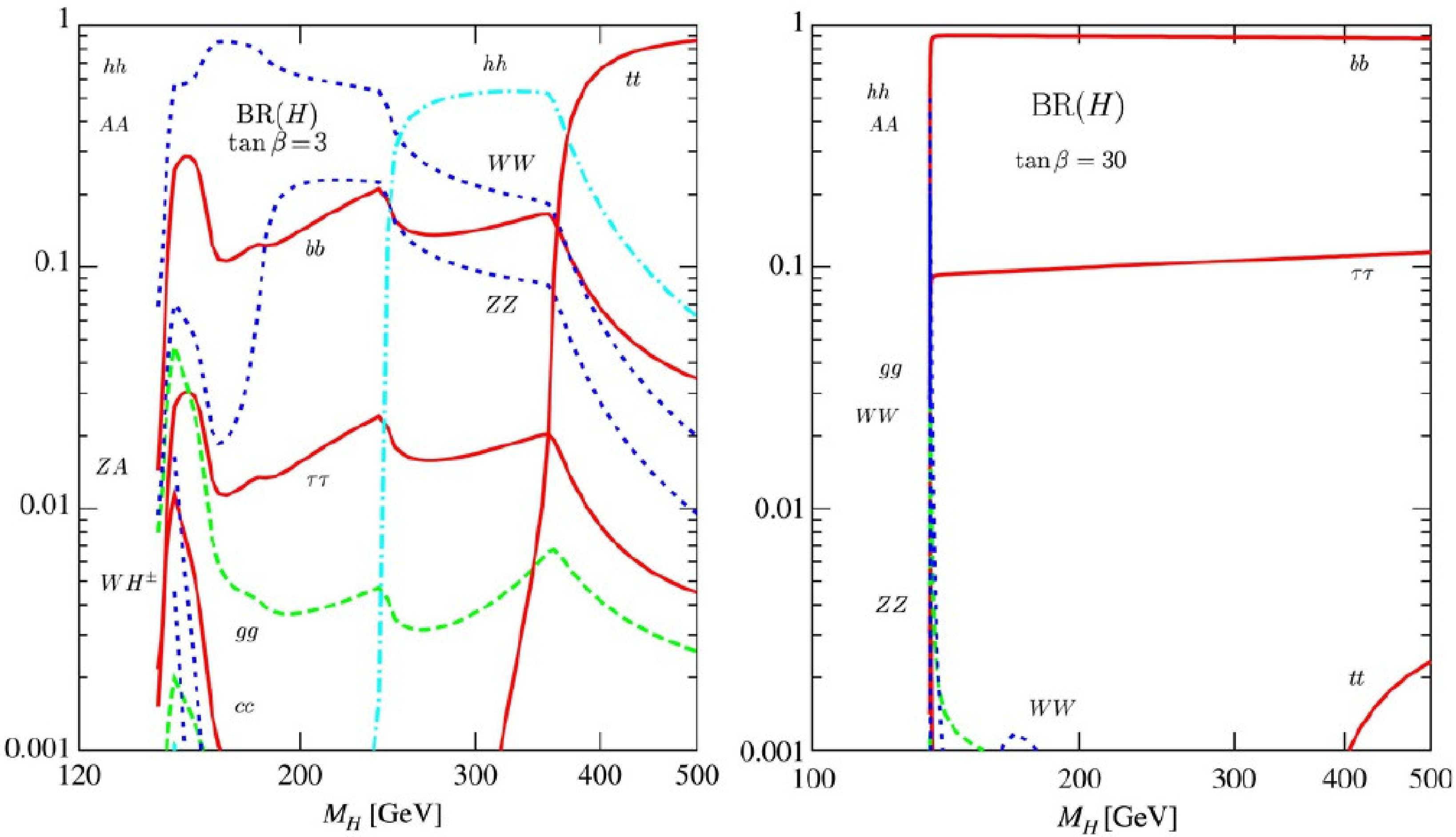
Large tanβ (>10) and small M_A (<130 GeV)

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



MSSM Higgs Properties: h/H/A Decay Modes

Neutral Higgs decays depend on the tanβ value

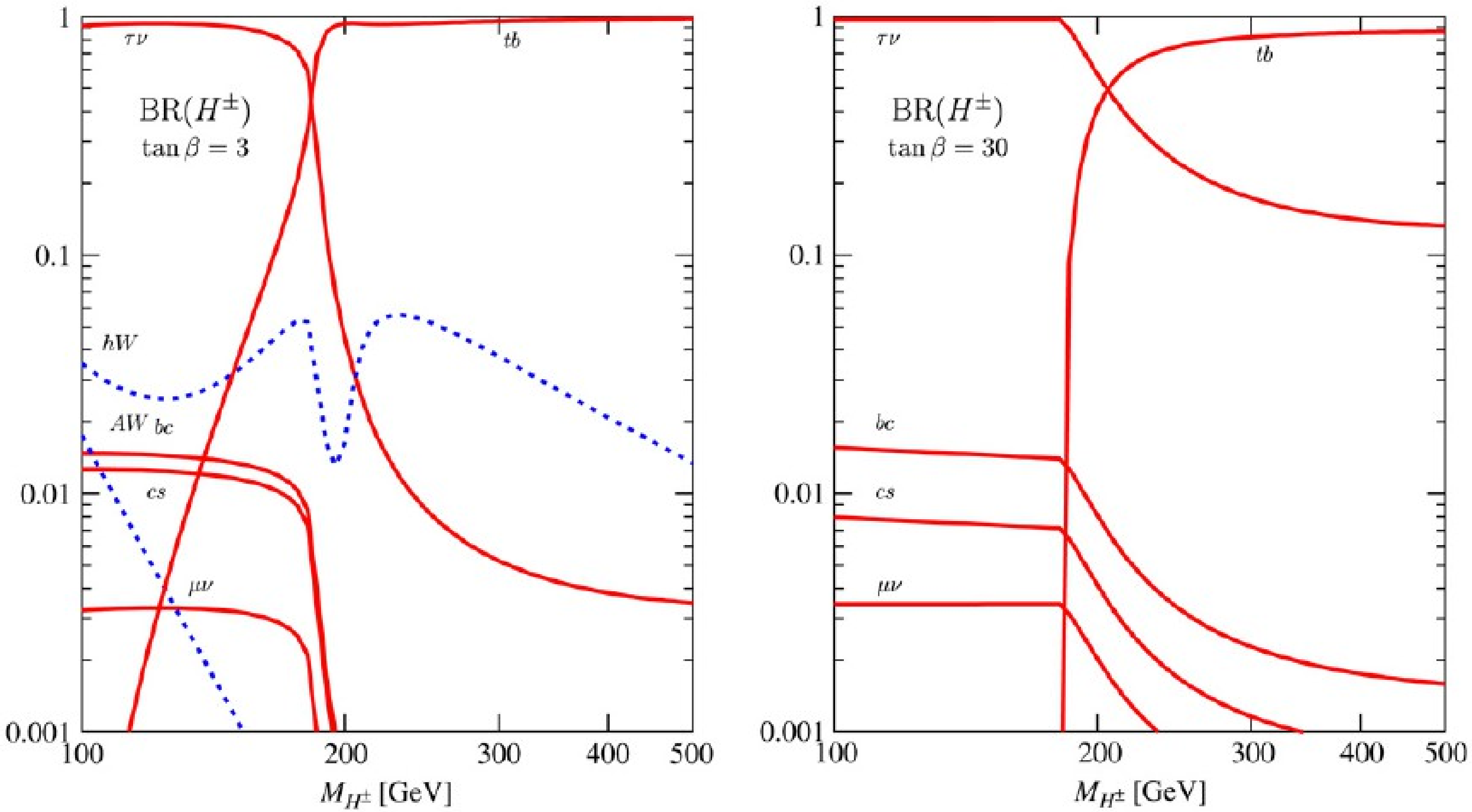


Example: Heavy CP-even Higgs decay BR for a low and high tanβ (maximal mixing)

Phys.Rept. 459 (2008) 1-241

MSSM Higgs Properties: Decay Modes

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



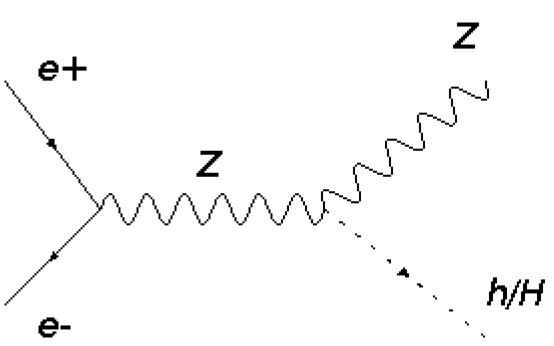
Charged Higgs decay BR for a low and high tanβ (maximal mixing)

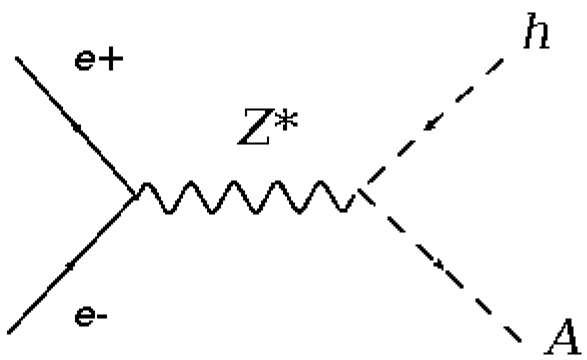
Phys.Rept. 459 (2008) 1-241

MSSM: The LEP legacy for Neutral Higgs

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

LEP was an electron-positron collider (cm energy up to 209 GeV) 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)

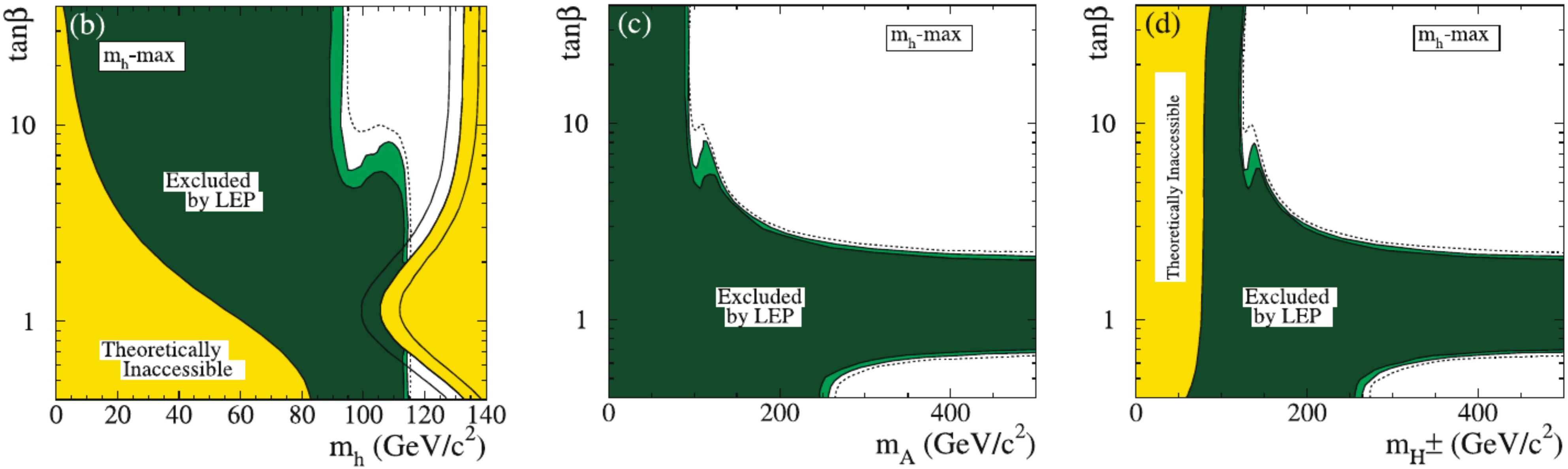




Various decay channels considered:
$h \rightarrow bb, \tau\tau, jj, AA$
$Z \rightarrow jj, ll$

MSSM: The LEP legacy for Neutral Higgs

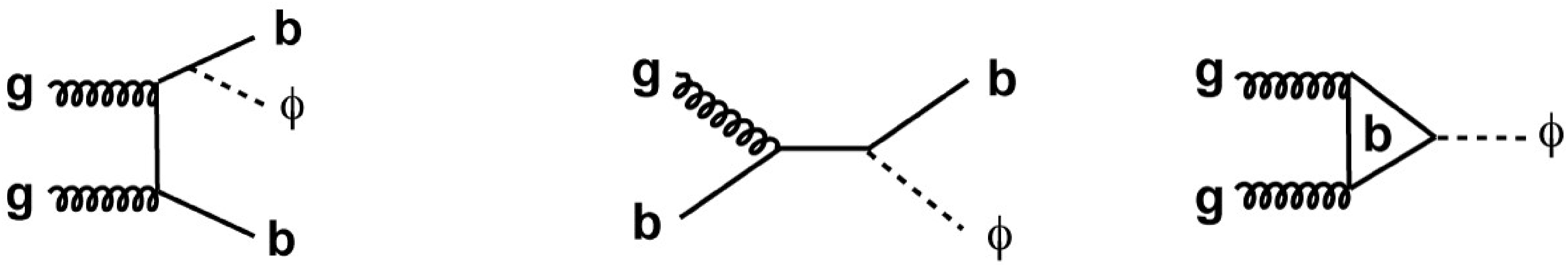
- LEP has been able to probe the MSSM very effectively disfavouring low mass Higgs bosons
  - m_A > 90 GeV is allowed



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

Neutral MSSM Higgs @ LHC

- 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**")
  - BR(H/A → ττ) ~ 10% for a large part of parameter space in the MSSM
  - Two main production mechanisms:



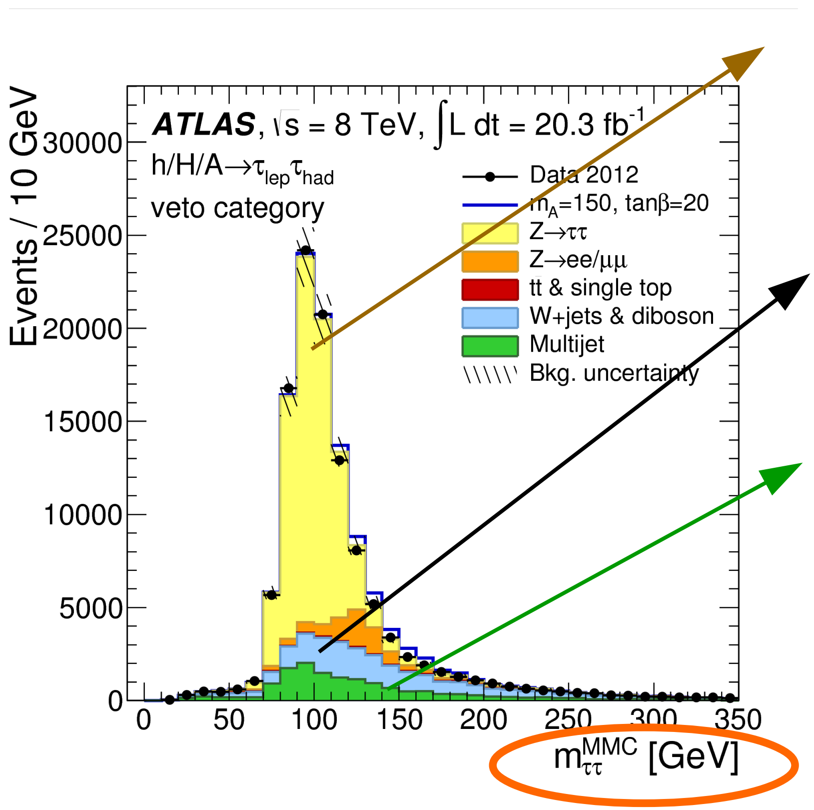
Neutral MSSM Higgs @ LHC

- Overview of channels & analysis features considered
  - Take advantage of b-associated production: categories requiring a b-tagged jet
  - "leplep": BR($\tau\ \tau \rightarrow e\mu$ + neutrinos)~6%; single & double lepton triggers; competitive sensitivity at $m_A < 200$ GeV
  - "lephad": BR($\tau\tau \rightarrow e/\mu\ \tau$(had) + neutrinos)~46%; single lepton triggers; competitive sensitivity for the whole mass range; separately optimized for low and high mass (>200 GeV)
  - "hadhad": BR($\tau\tau \rightarrow \tau$(had) τ(had) + neutrinos)~42%; single and double hadronic tau triggers; competitive sensitivity at high mass (> 200 GeV)

arXiv:1409.6064

Neutral MSSM Higgs @ LHC

- Example for the lephad channel



Z → ττ is one of the most important backgrounds: use of "tau-embedded" Z→μμ events in data

Events with a tau faked by a jet, like Z+jets, W+jets, ttbar production are normalized to control regions.

Multi-jet events with both taus faked by jets are estimated from data using a 2-dimensional sideband method based on lepton isolation and charge correlation between the tau and the lepton.

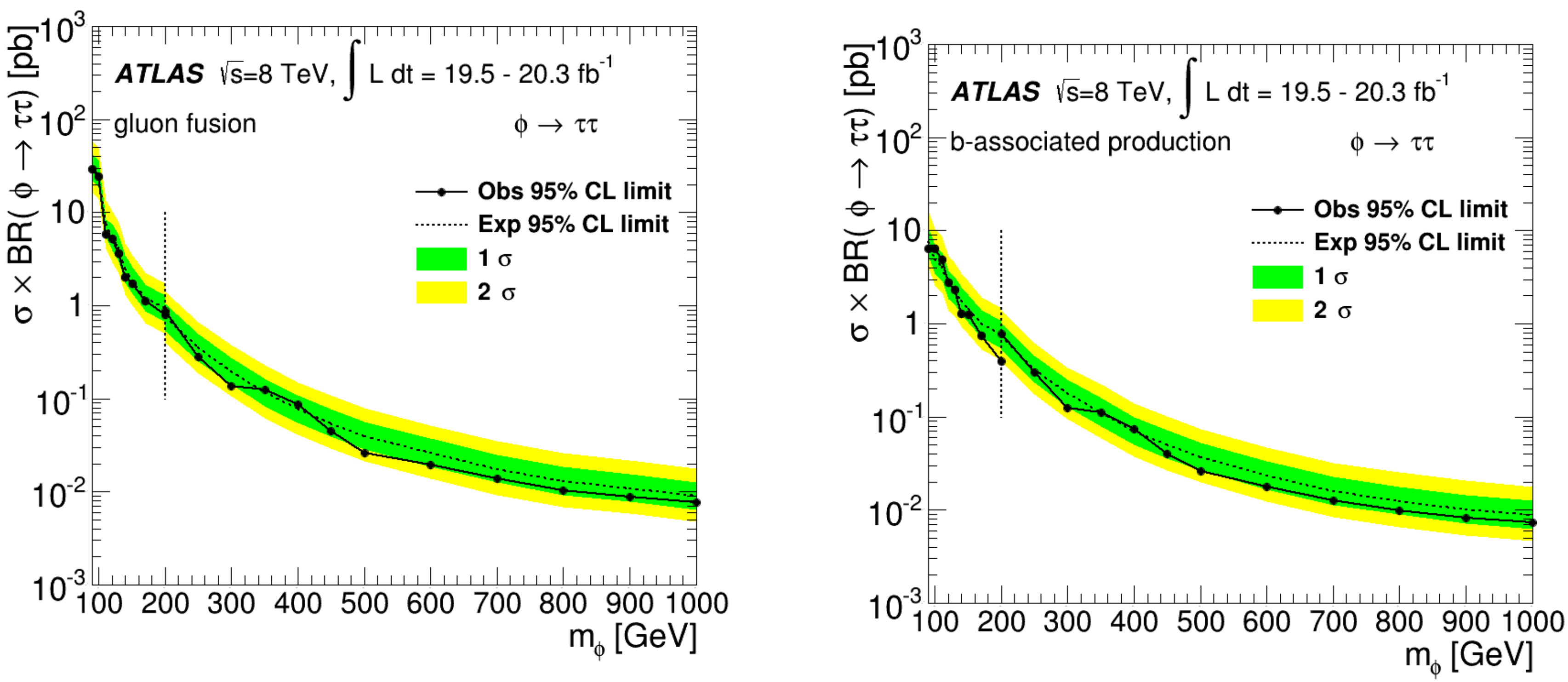
The rest of the backgrounds are taken from simulation.

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

arXiv:1409.6064

Neutral MSSM Higgs @ LHC

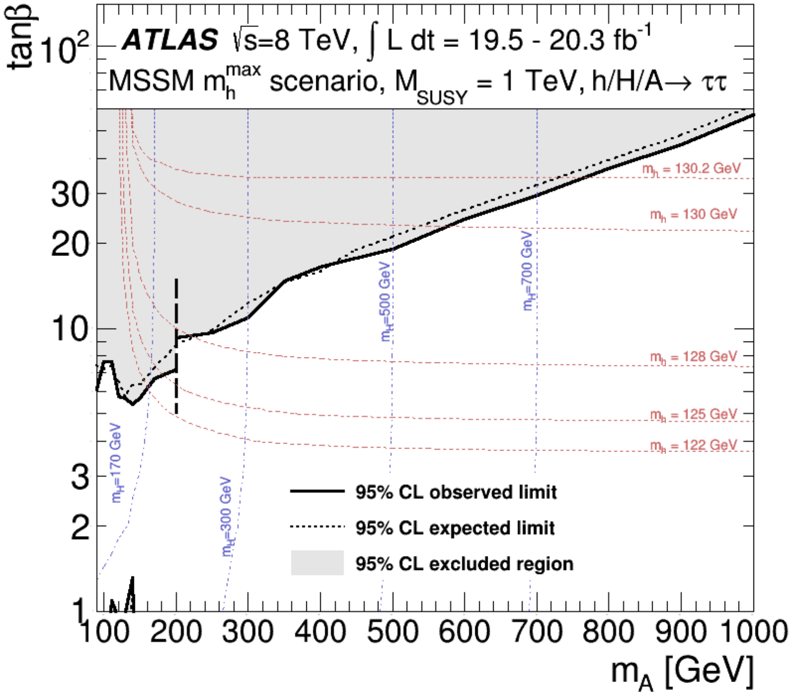
- No excess found: interpretation of the search as a search for a single tautau resonance with different production mechanisms

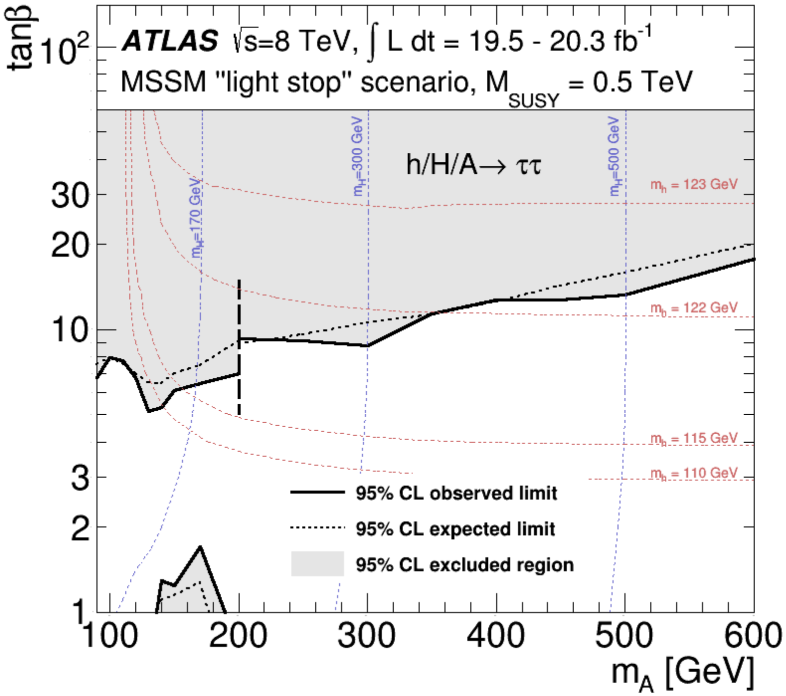


arXiv:1409.6064

Neutral MSSM Higgs @ LHC

- Model dependent interpretation: in various MSSM scenarios; just 2 examples shown here





arXiv:1409.6064

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

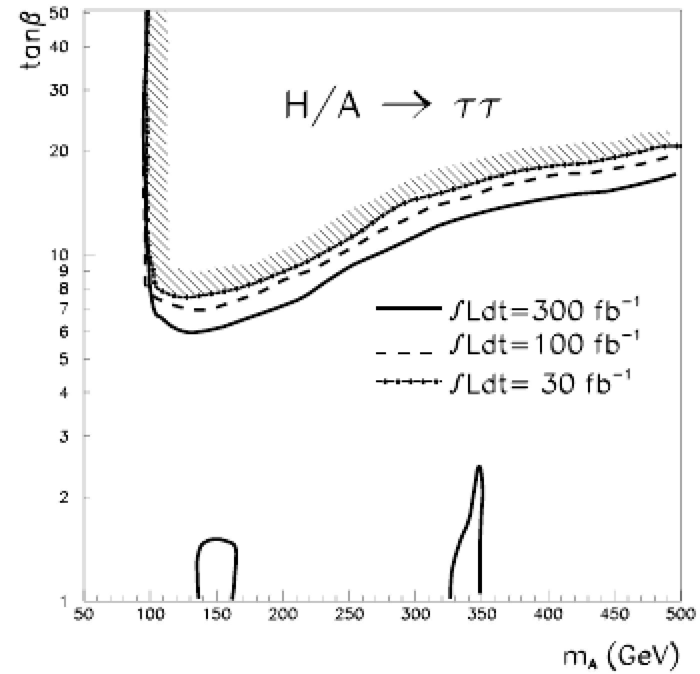


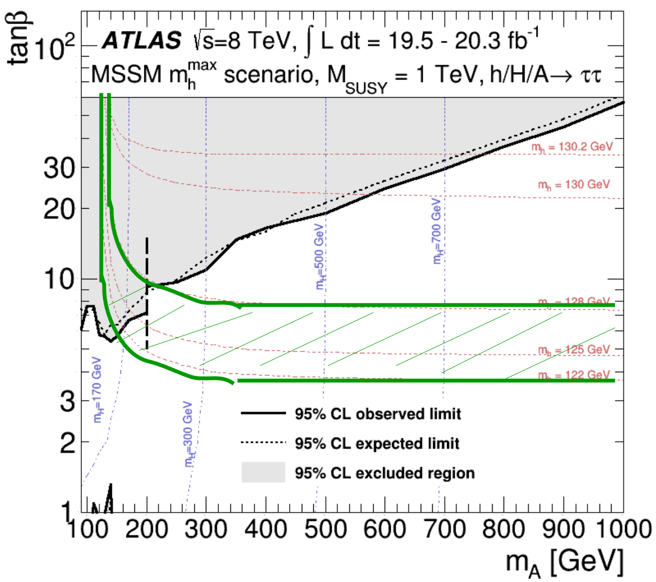
Figure 19-62 For integrated luminosities of 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1}, 5σ-discovery contour curves for the *H/A* → ττ channel in the (m_A, tanβ) plane.

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

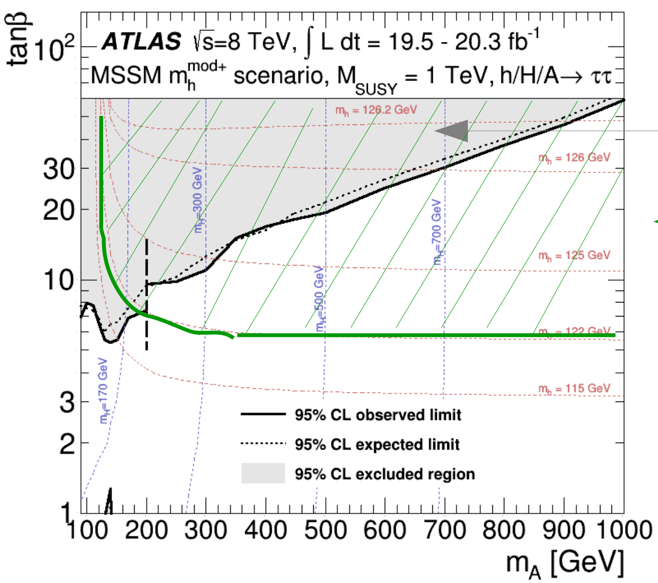
MSSM Higgs & Higgs discovery

- 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 8 TeV Run exclusion

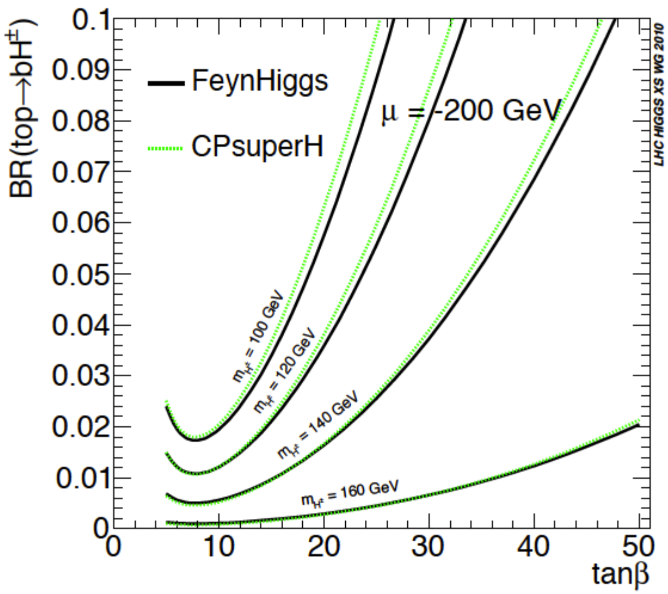
Region compatible with a 125 GeV light CP-even Higgs

Charged Scalars

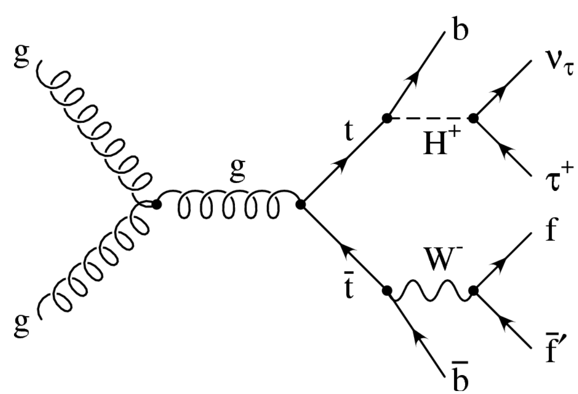
- Searches for the charged scalars of the MSSM have been performed as well

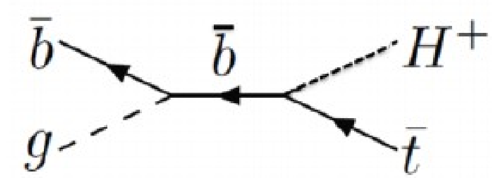
Light Charged Higgs is produced mainly in top quark decays

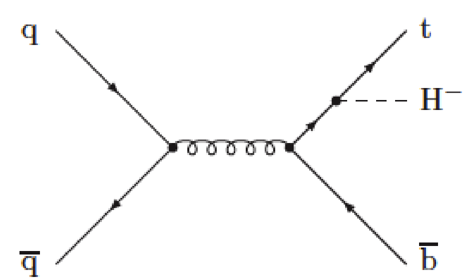
Heavy Charged Higgs is produced mainly in association with a top quark

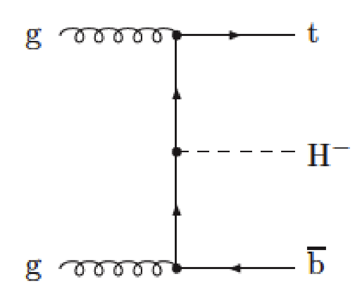


BR(Top → bH$^+$) vs tanβ







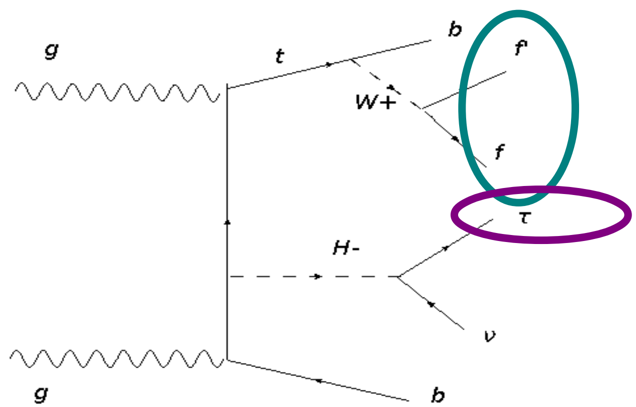


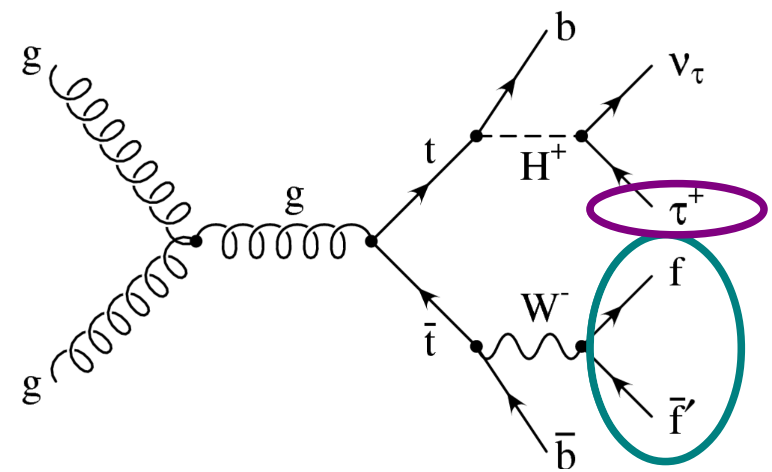
$H^+ \to \tau\nu$

- What we are looking for: search topology

Channel topology can be organized according to W and tau decay

$H^\pm \to \tau^\pm \nu$





τ(lep)+W($\to$lv): tt $\to$ bbWH $\to$ bb (lv) (τ_{lep}v) BR ~ 15%

τ(had)+W($\to$lv): tt $\to$ bbWH $\to$ bb (lv) (τ_{had}v) BR ~ 14%

τ(had)+W($\to$jets): tt $\to$ bbWH $\to$ bb (qq) (τ_{had}v) BR ~ 46%

τ(lep)+W($\to$jets): tt $\to$ bbWH $\to$ bb (qq) (τ_{lep}v) BR ~ 25%

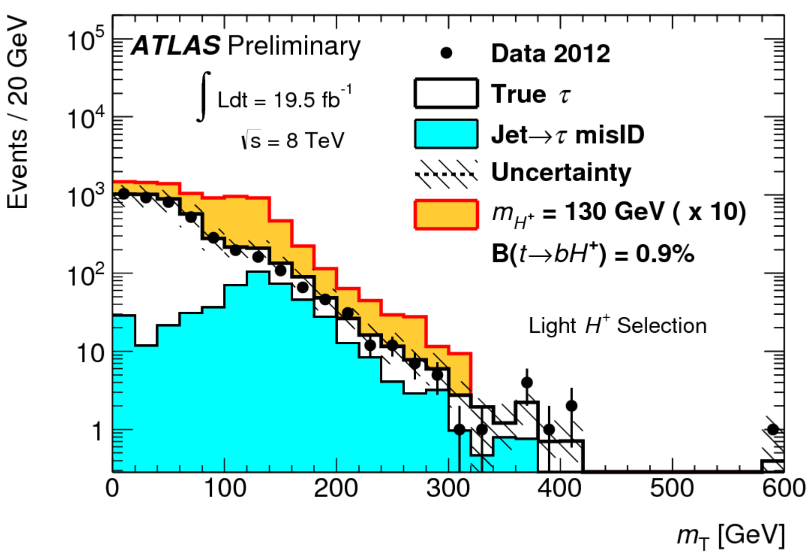
τ(lep) = τ(e) or $\tau(\mu)$

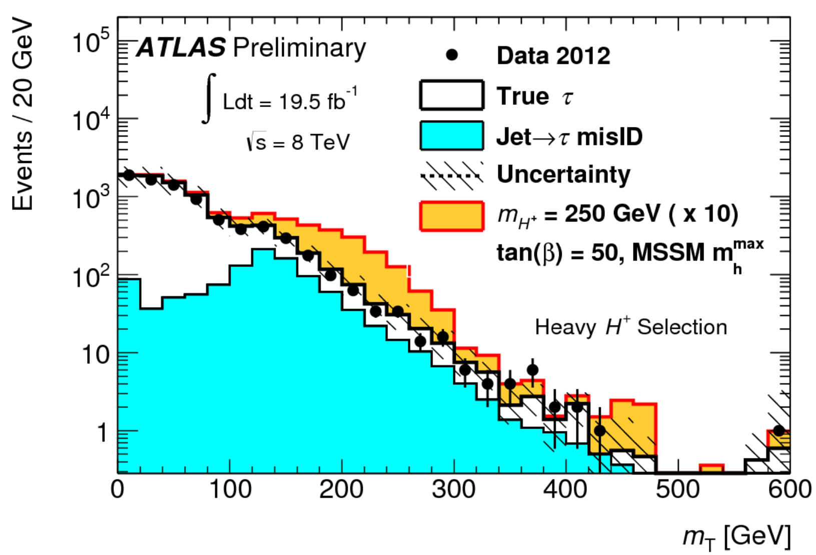
Channel of first choice: Highest BR, highest sensitivity and excellent physics potential: but all these are possible only because of the **tau(had)+MET trigger**

$H^+ \rightarrow \tau\nu$

- "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 significiance" definition:

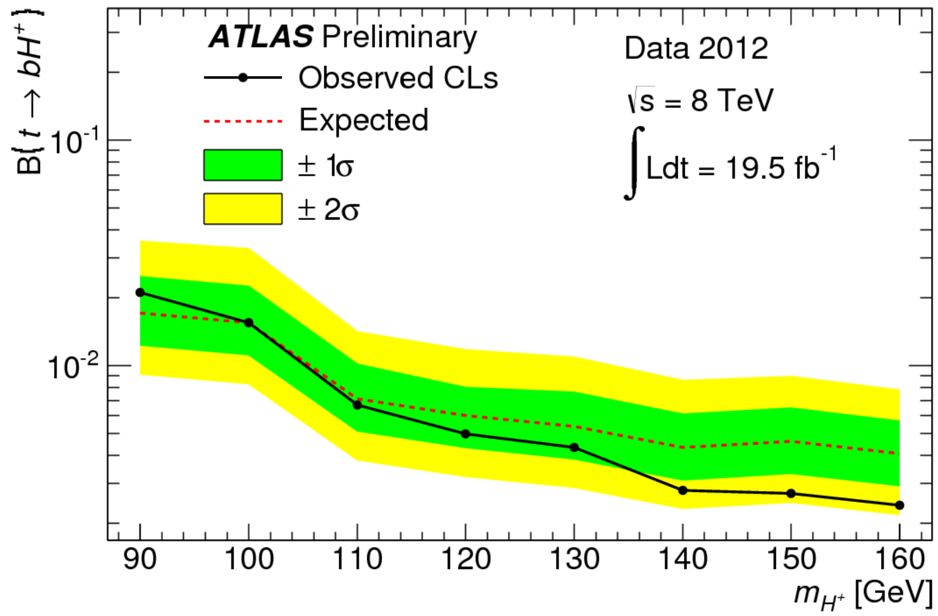
$$\frac{E_T^{miss}}{0.5 \cdot \sqrt{\sum p_T^{PV\ trk}}}$$

ATLAS-CONF-2013-090

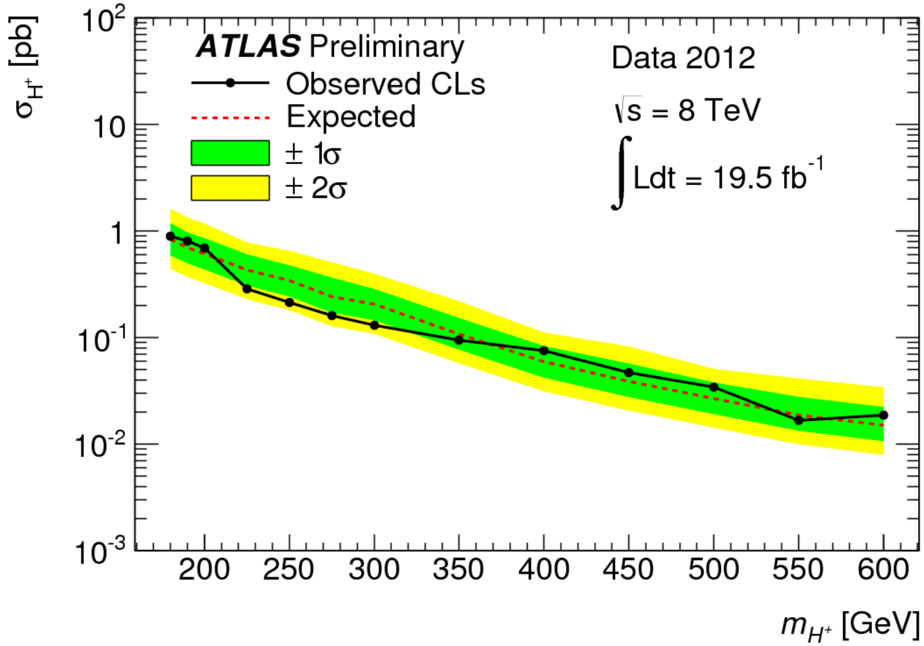
$H^+ \rightarrow \tau\nu$

- Constraints on charged scalars

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



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



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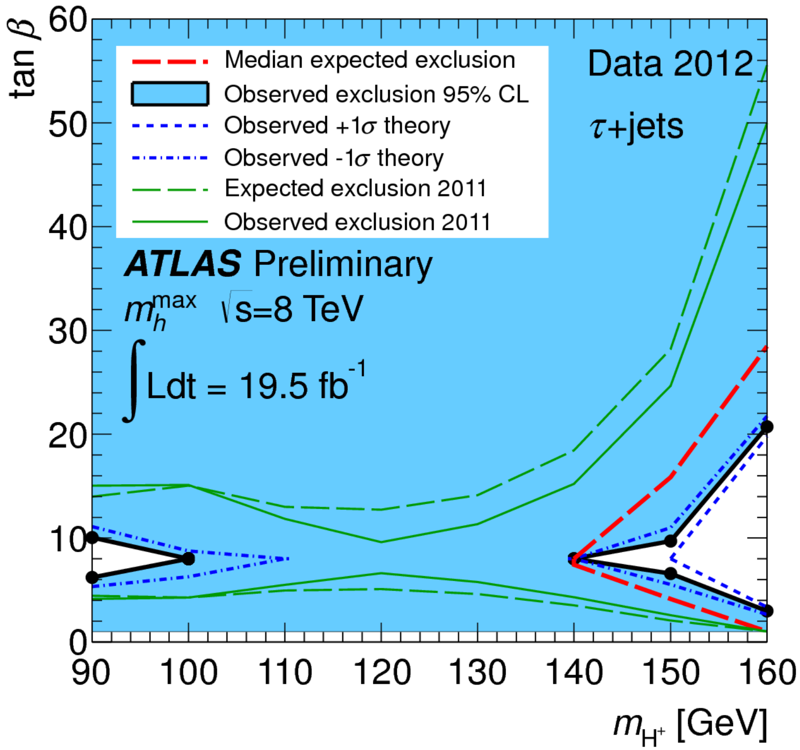
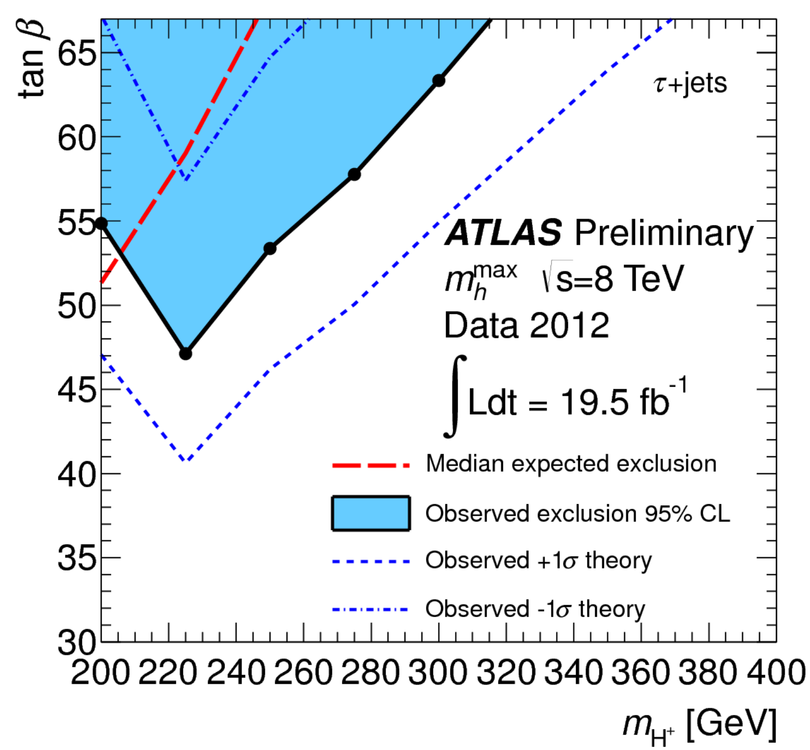
$H^+ \rightarrow \tau\nu$

- Constraints on charged scalars interpreted in the MSSM parameter space





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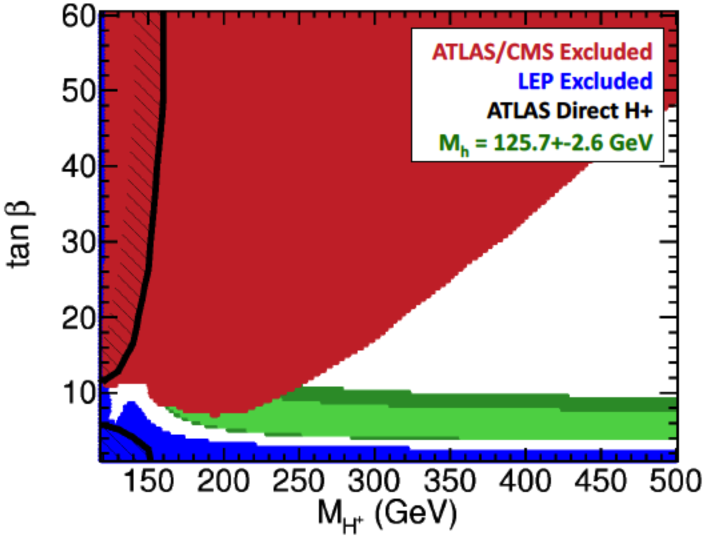
Charged Scalars and the MSSM

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

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

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



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

Oscar Stöl, CHiggs2012

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

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. Most general gauge invariant potential reads:

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

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

  - CP-conservation in the Higgs sector, softly broken Z_2 symmetry ($\Phi_1 \rightarrow -\Phi_1$) leaves us with a potential 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:
  $t_\beta = \tan\beta$;
  $c_{\beta-\alpha} = \cos(\beta-\alpha)$
  $s_{\beta-\alpha} = \sin(\beta-\alpha)$

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

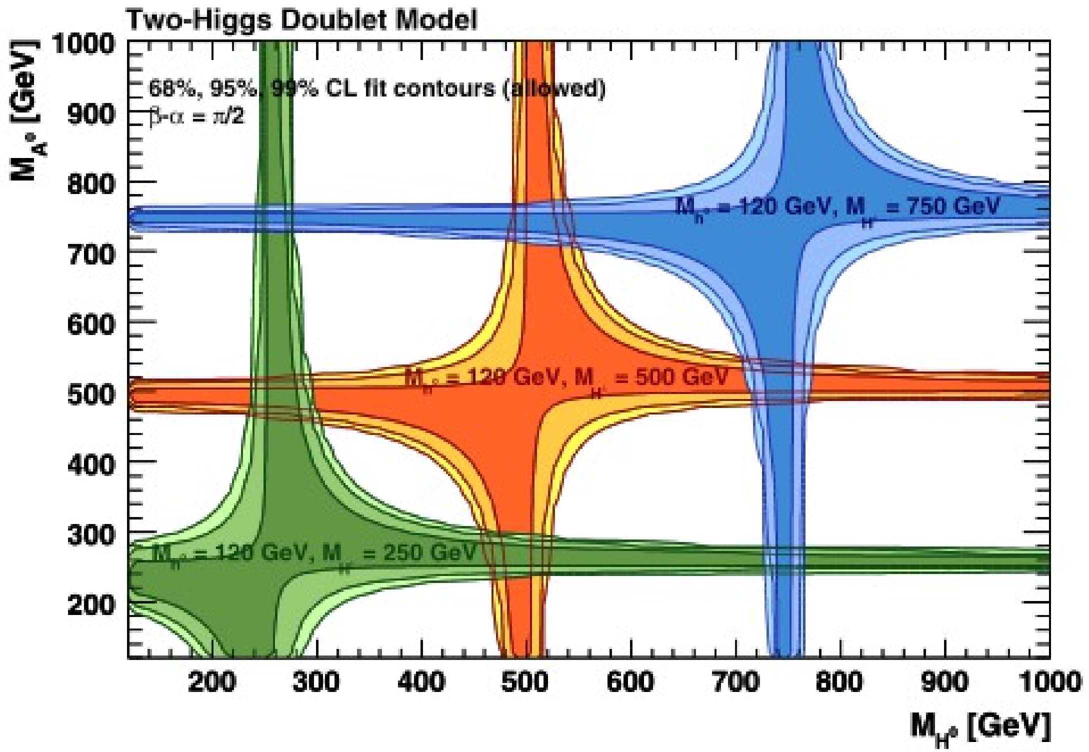
- Interesting limits:
  - Weak decoupling limit: $\sin(\beta-\alpha) \to 1$, i.e., there is a Higgs boson that can be as SM as you like but also there are light $H/A/H^+$ bosons
  - (strong) Decoupling limit: $\sin(\beta-\alpha)=1$ and two mass scales i.e. all additional particles heavy. For a more formal 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.

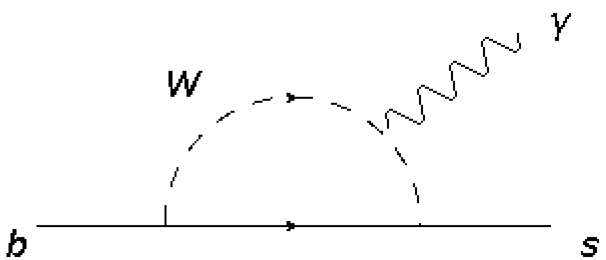


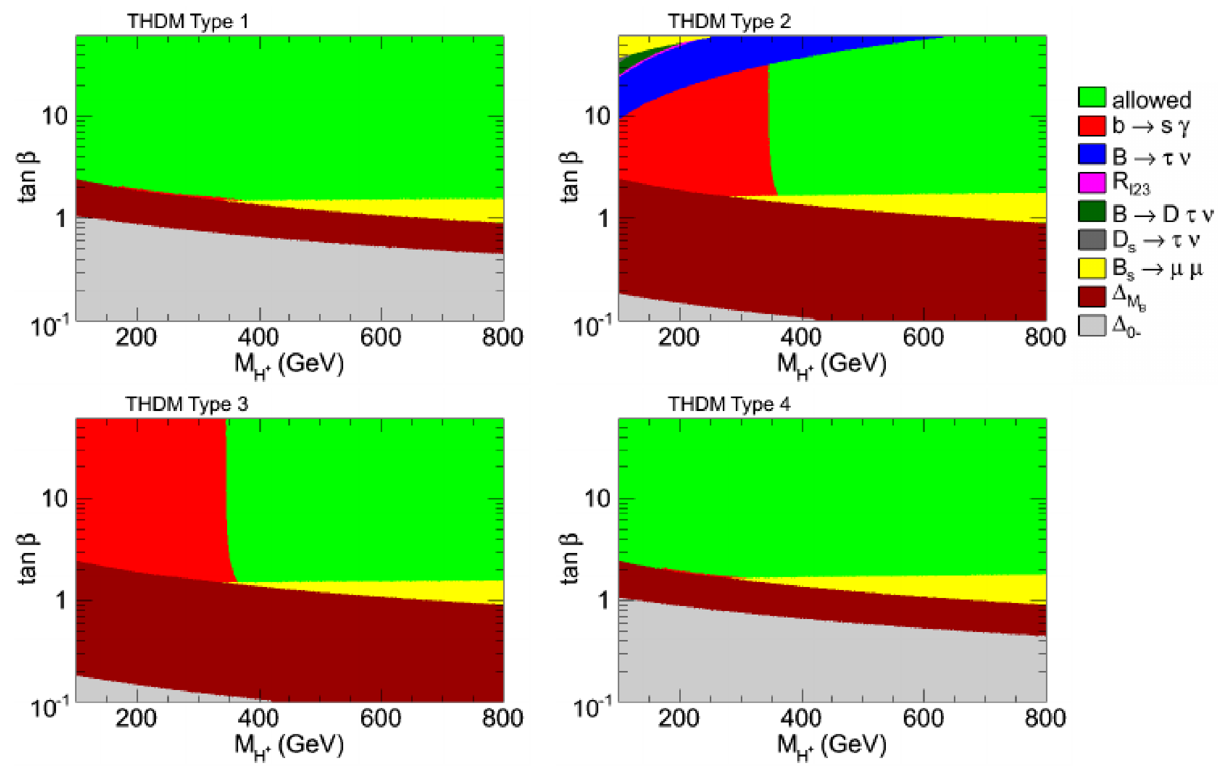
Eur. Phys. J. C (2012) 72:2003

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

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

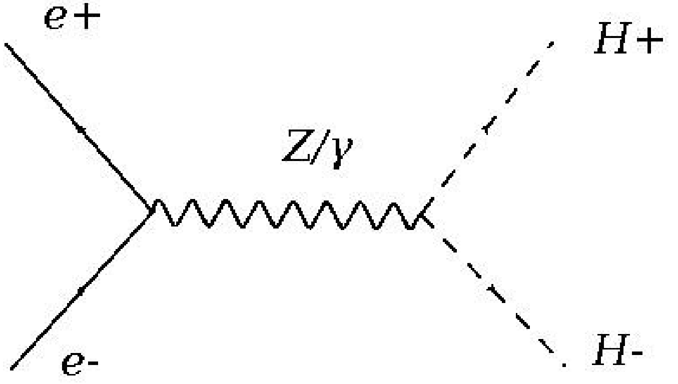
N. Mahmoudi & O. Stall, SuperIso v.3.4

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
- 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

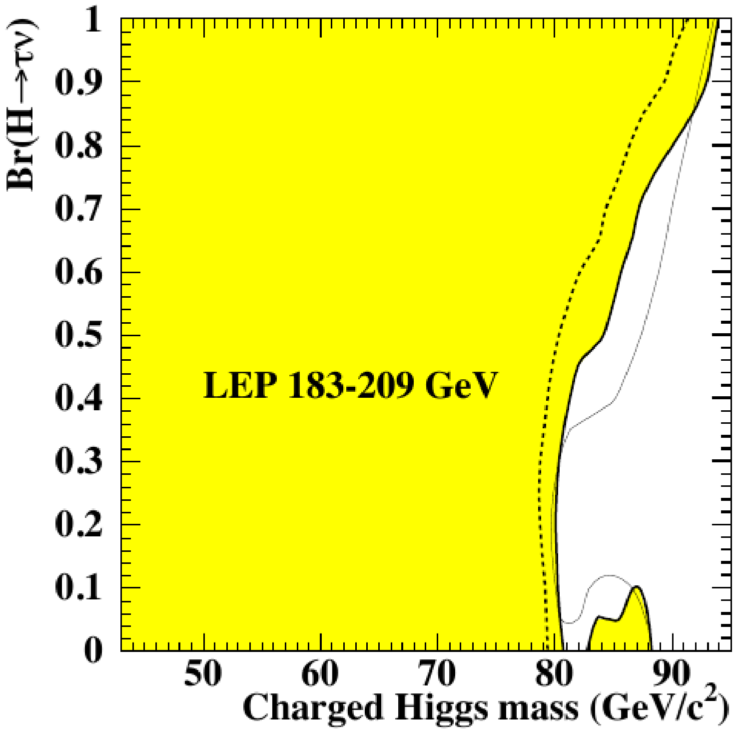
Charged Higgs production at LEP is through pair production

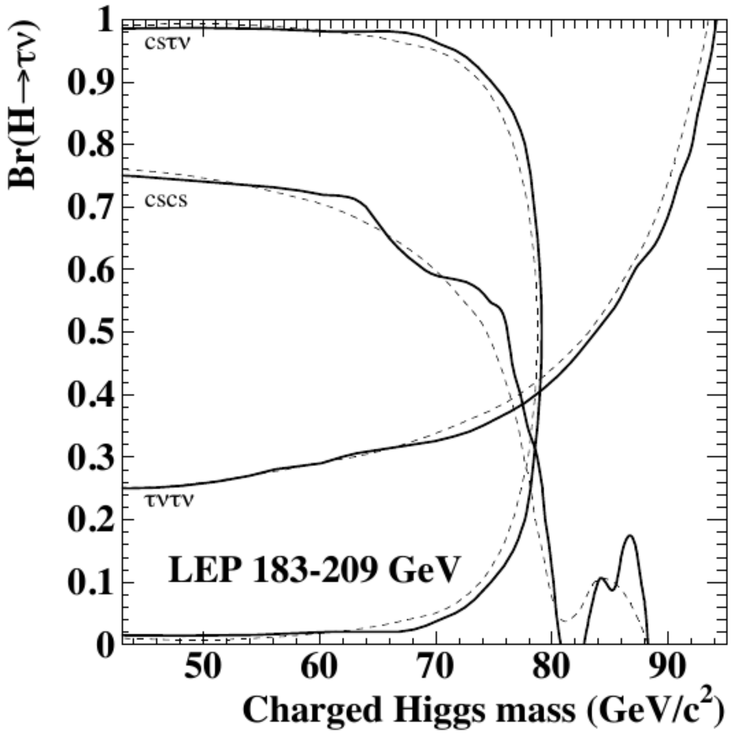


The Charged Higgs LEP legacy

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

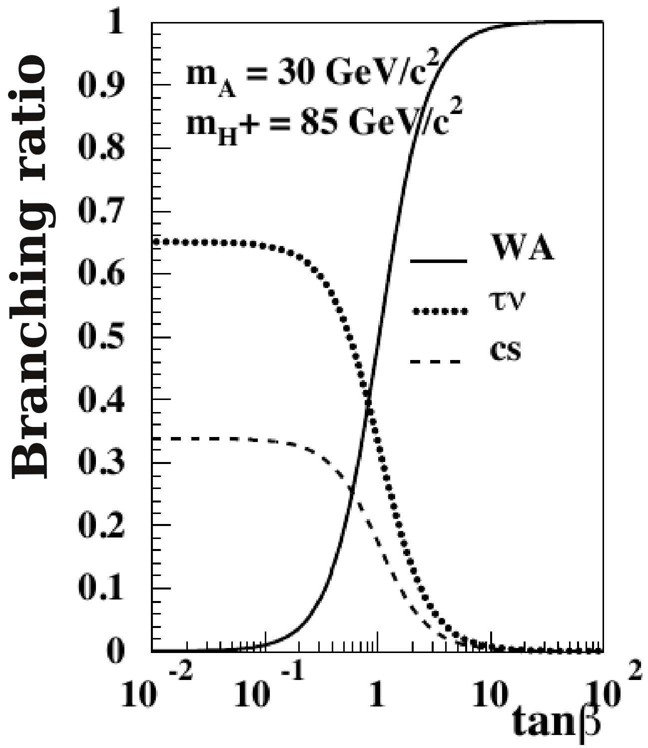


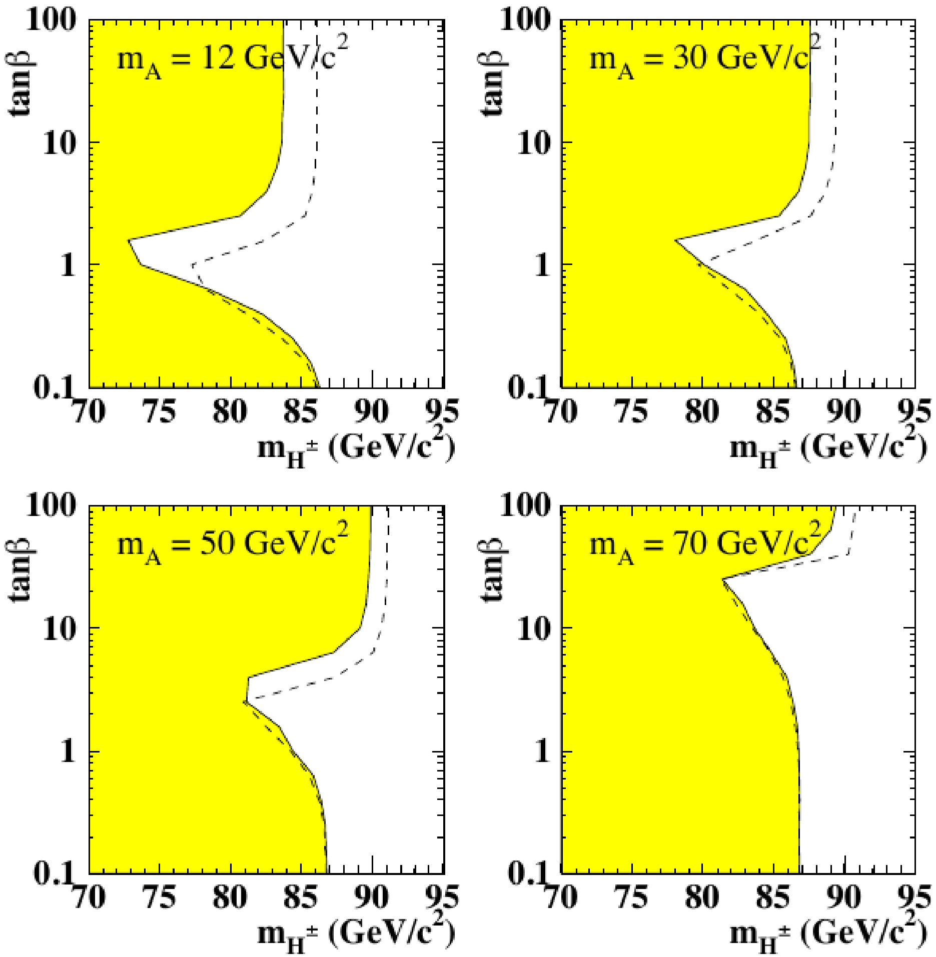


The Charged Higgs LEP legacy

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

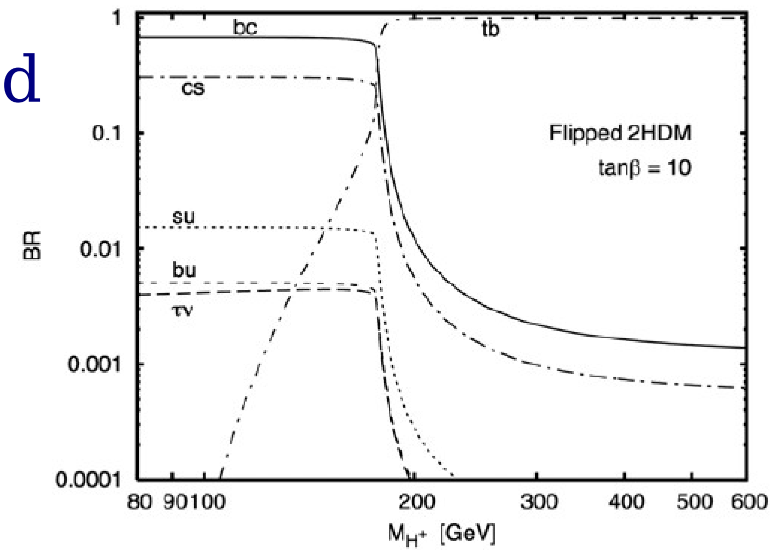
Weaker constrain than type-II

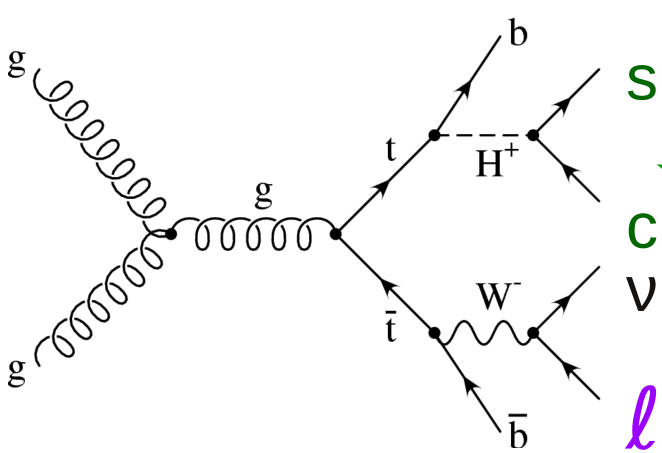




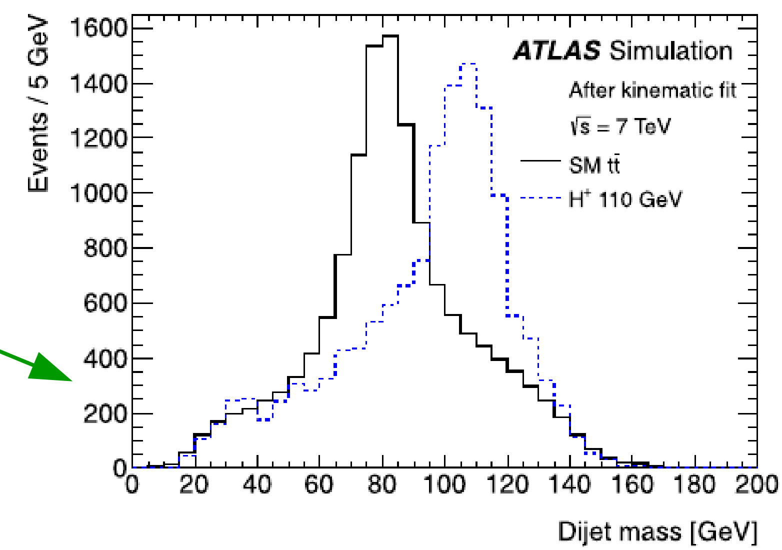
$H^+ \rightarrow cs$

- 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

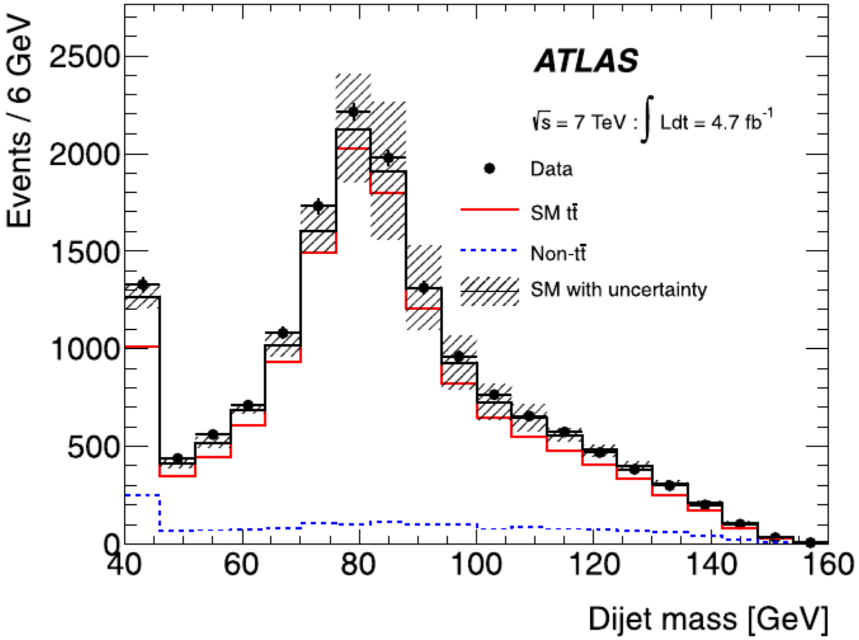


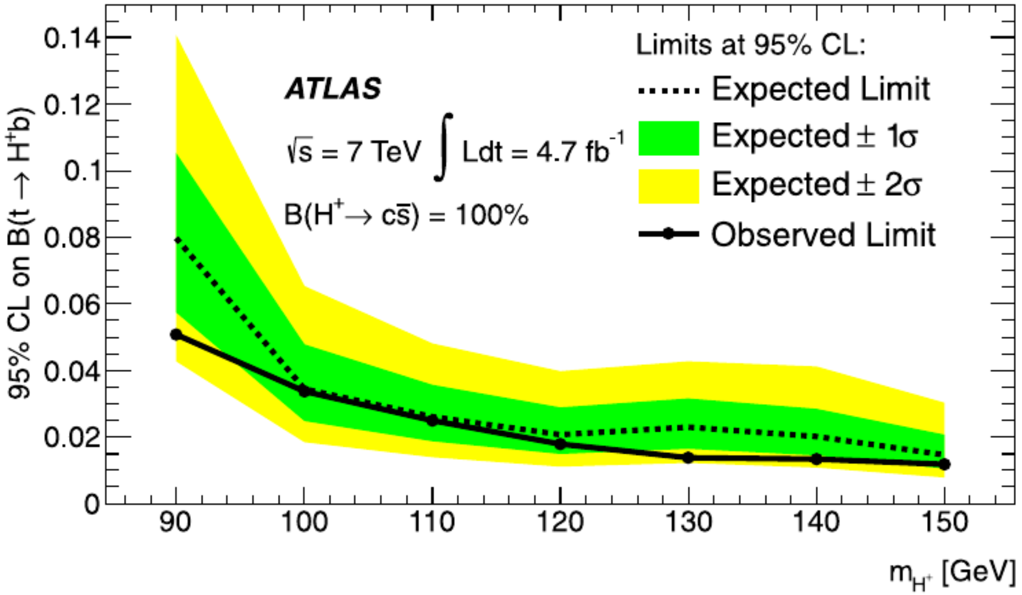
Electron or muon to trigger the event

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

$H^+ \rightarrow cs$

The invariant mass of the Higgs decay candidate system



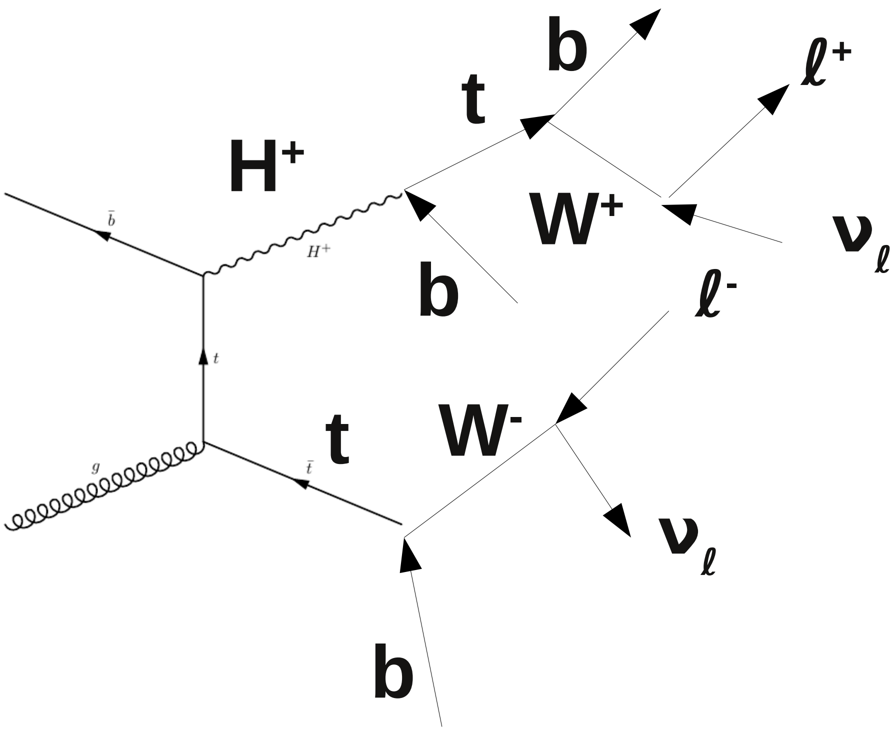


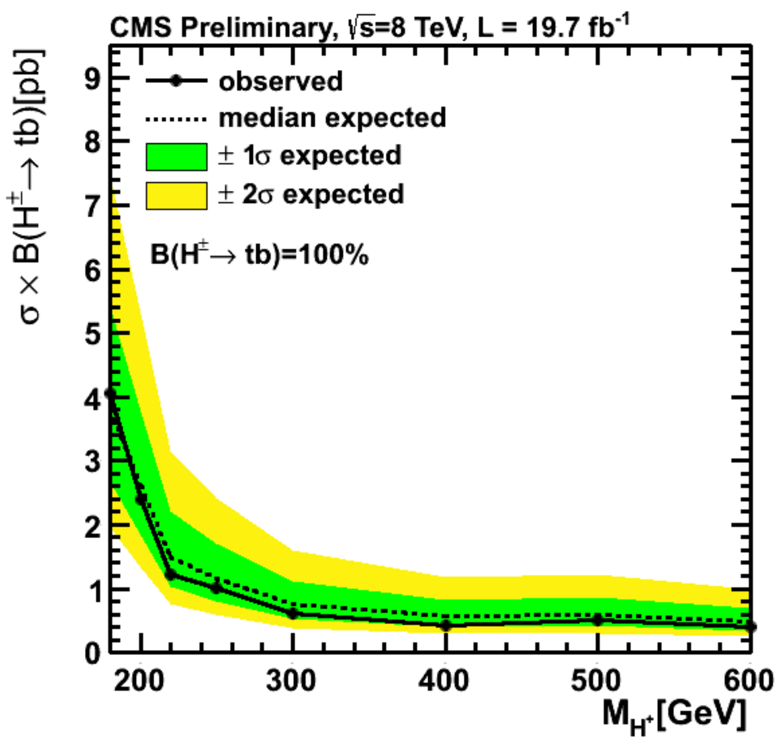
Limits for the Branching Ratio of top to charged Higgs assuming charged Higgs decays only to cs

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

$H^+ \rightarrow tb$

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

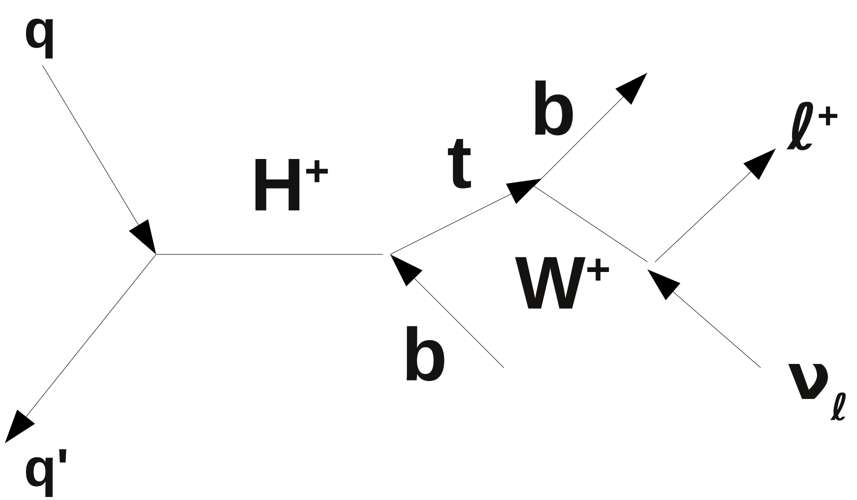


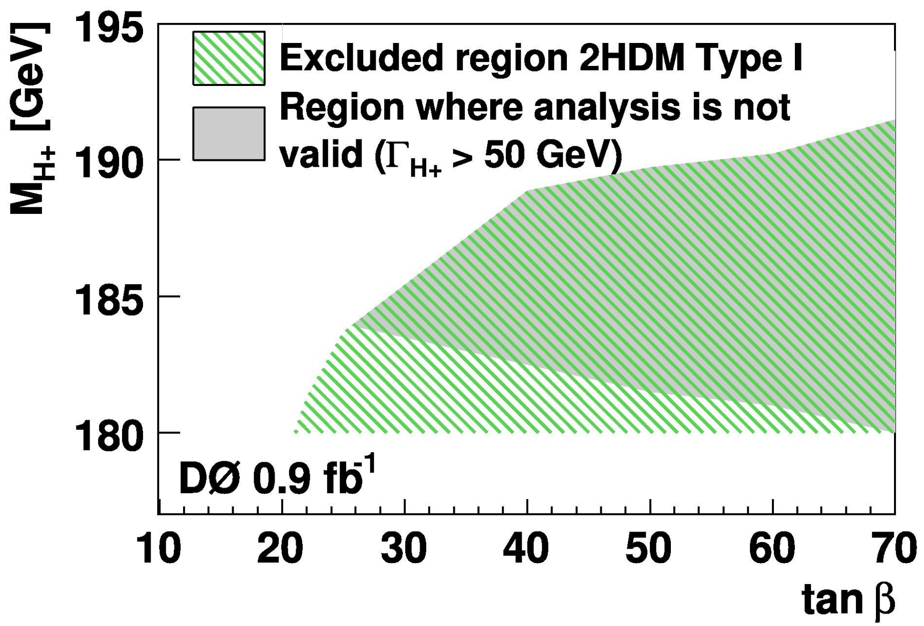


CMS-PAS-HIG-13-026

$H^+ \rightarrow tb$

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



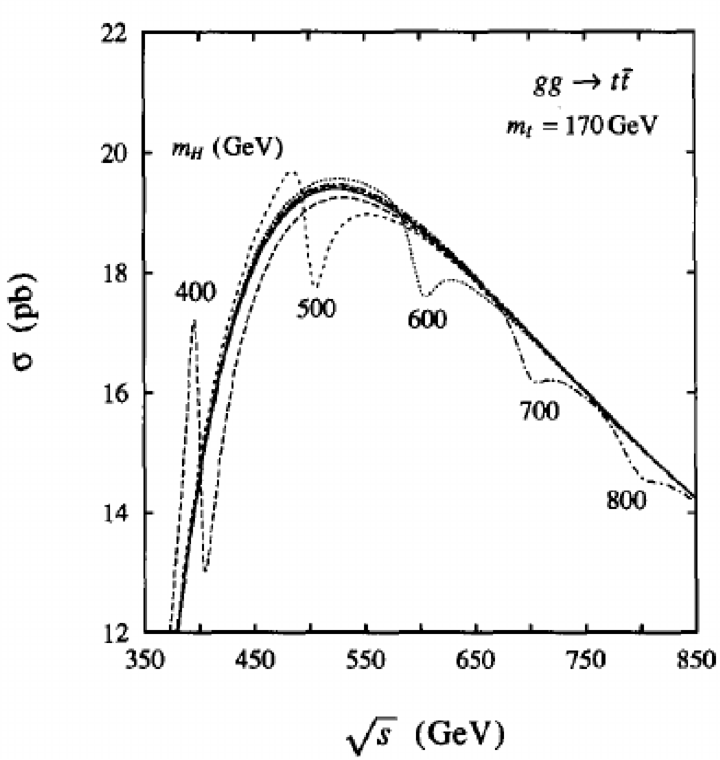


Phys. Rev. Lett. 102 , 191802 (2009)

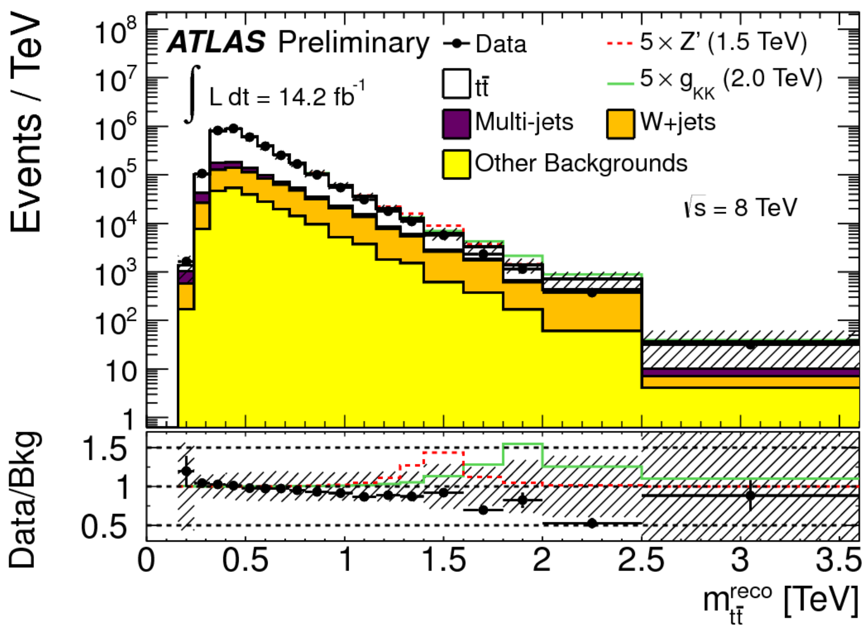
A/H → tt

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

Despite the fact that this is a highly motivated channel to look at, it is extremely difficult due to the fact that the interference with a ttbar background changes the shape of the peak: essentially you need a shape analysis



PLB 333 (1994) 126-131

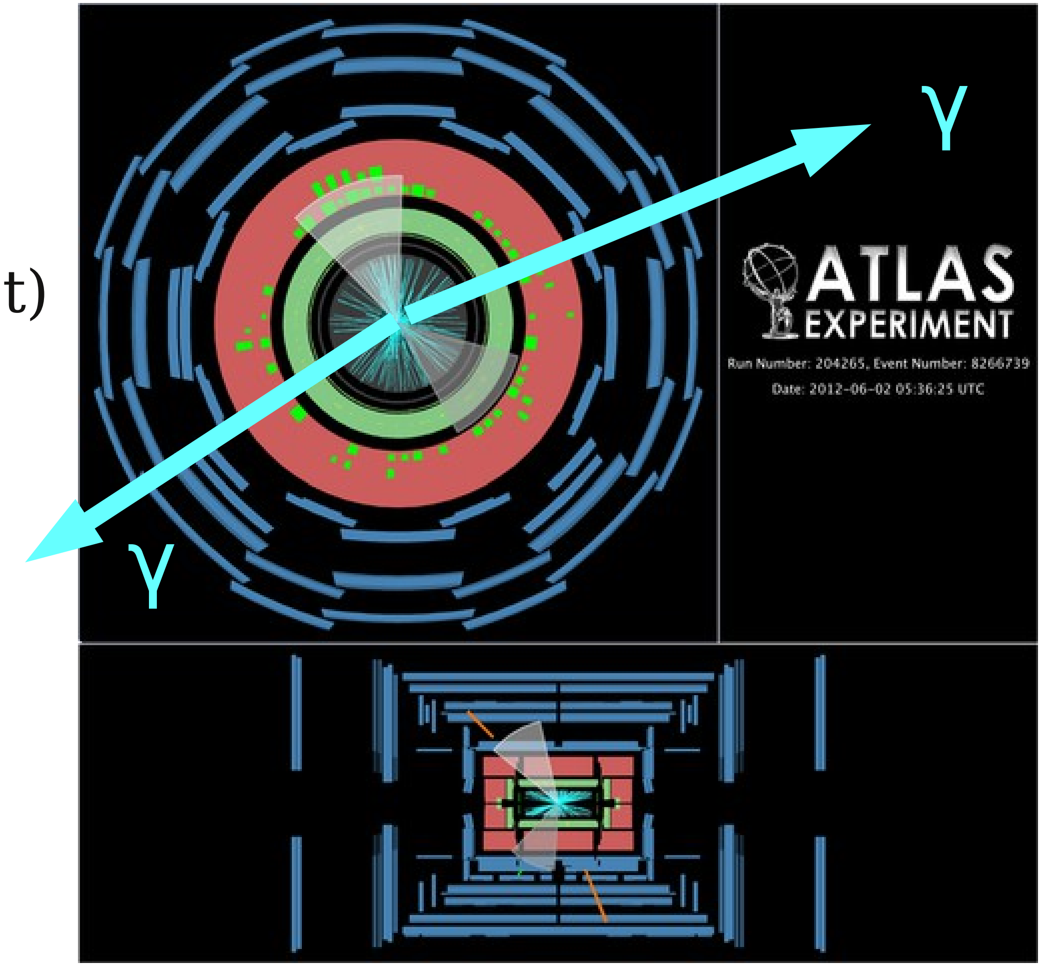


Heavy Higgs search: **Higgs** to Higgs

- 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

Di-Higgs production: hh → bbγγ

- Collect events with a loose di-photon trigger
- Event contains 2 b-jets (p_T > 55 GeV for leading, 35 GeV for the rest)
- 105 < m(γγ) < 160 GeV
- 95 < m(bb) < 135 GeV
- Use of techniques from the ATLAS SM h → γγ search



Example of a bb γγ event as recorded by the ATLAS detector.

This event has m(γγ) = 125 GeV and m(γγbb) = 265 GeV

Di-Higgs production: hh → bbγγ

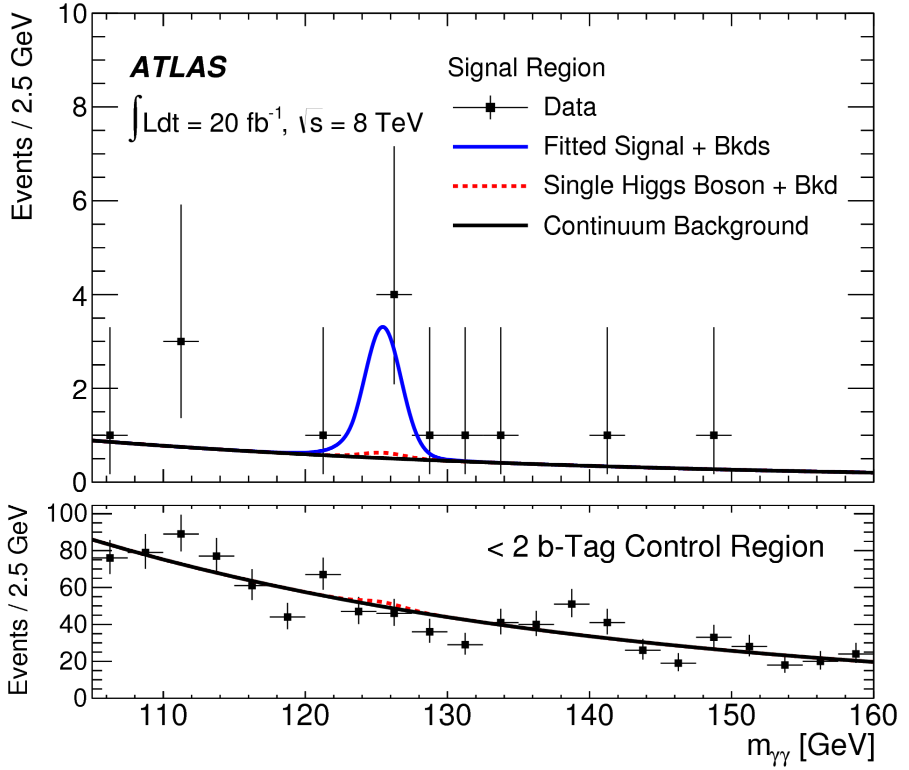
- Search for anomalous, non-resonant hh production

⎔ Fit the m(γγ) distribution: exponential for background and Crystal Ball+Gaussian for signal

⎔ Constrain the fit from a control region that contains less than 2 b-jets

⎔ **Obtained limit for anomalous non-resonant hh production: < 2.2 pb (Exp: 1.0 pb)**

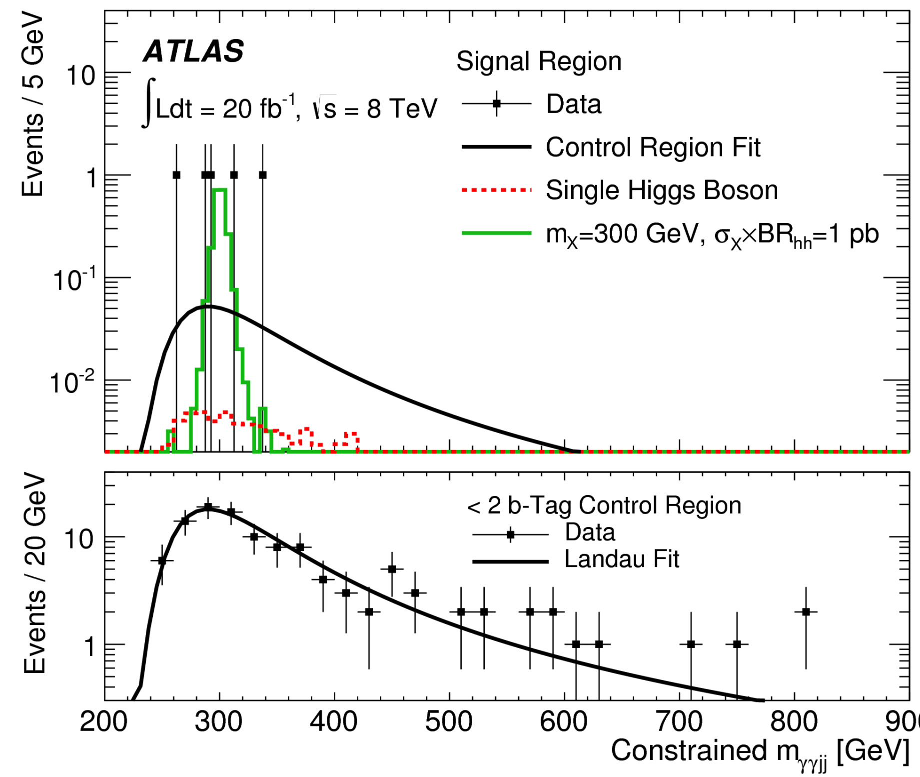
(c.f. SM hh production ~ 10 fb)

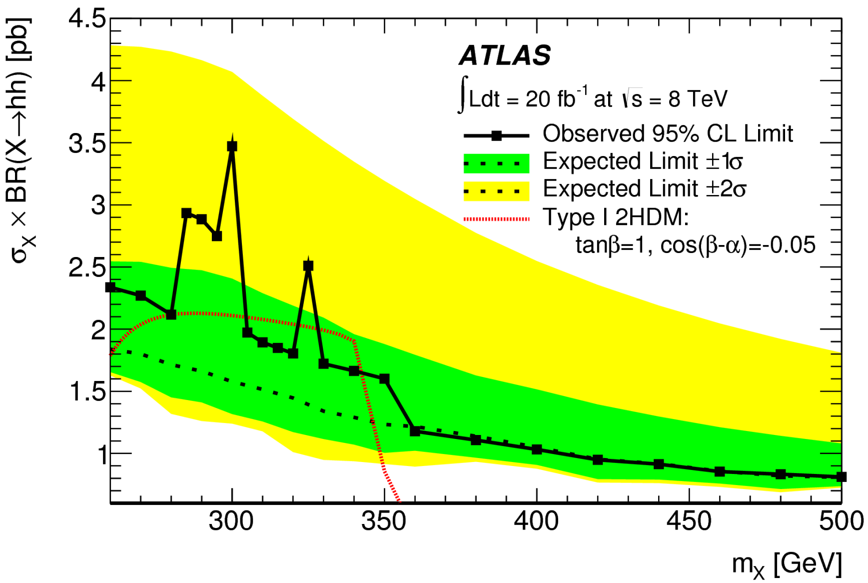


Di-Higgs production: hh → bbγγ

- Search for resonant hh production

⎔ Use of the same event as in the non-resonant search, but in addition a constraint in m(γγbb) mass is imposed
⎔ Simple event counting experiment





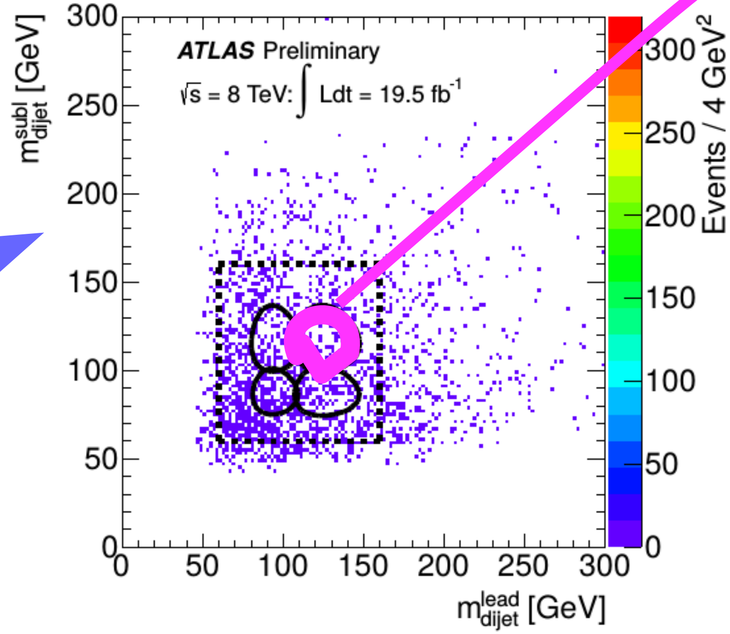
Cross section X BR limits for a **narrow scalar resonance** decaying to hh → bbγγ

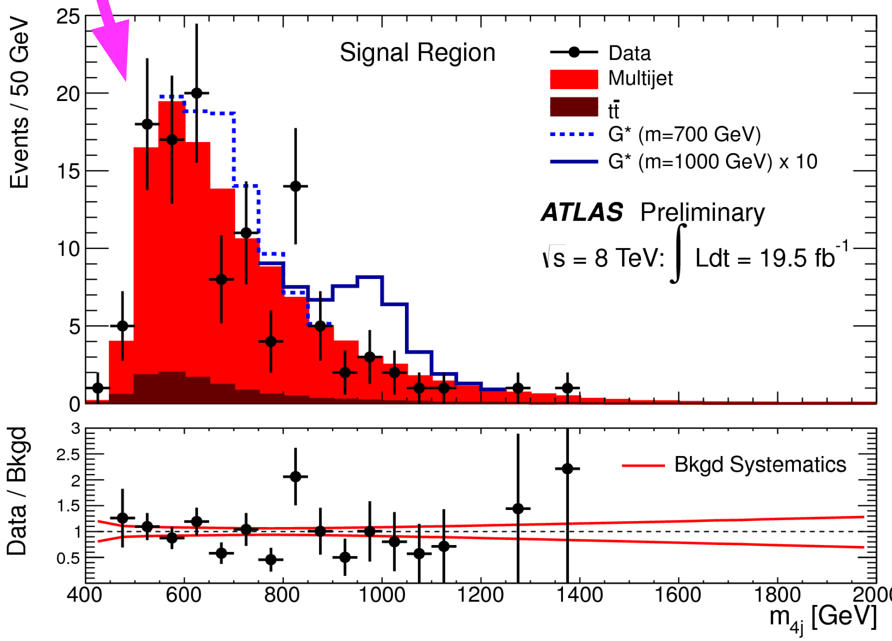
Di-Higgs production: hh → bbbb

- Search for resonant hh production

⎔ Events are selected by a set of jet triggers some of which trigger on b-jets
⎔ ≥ 4 b-jets (p_T > 40 GeV) forming two di-jet systems with $p_T(bb)$ > 200 GeV
⎔ Dedicated tt veto
⎔ Constrain on di-jet mass system

ATLAS-CONF-2014-005

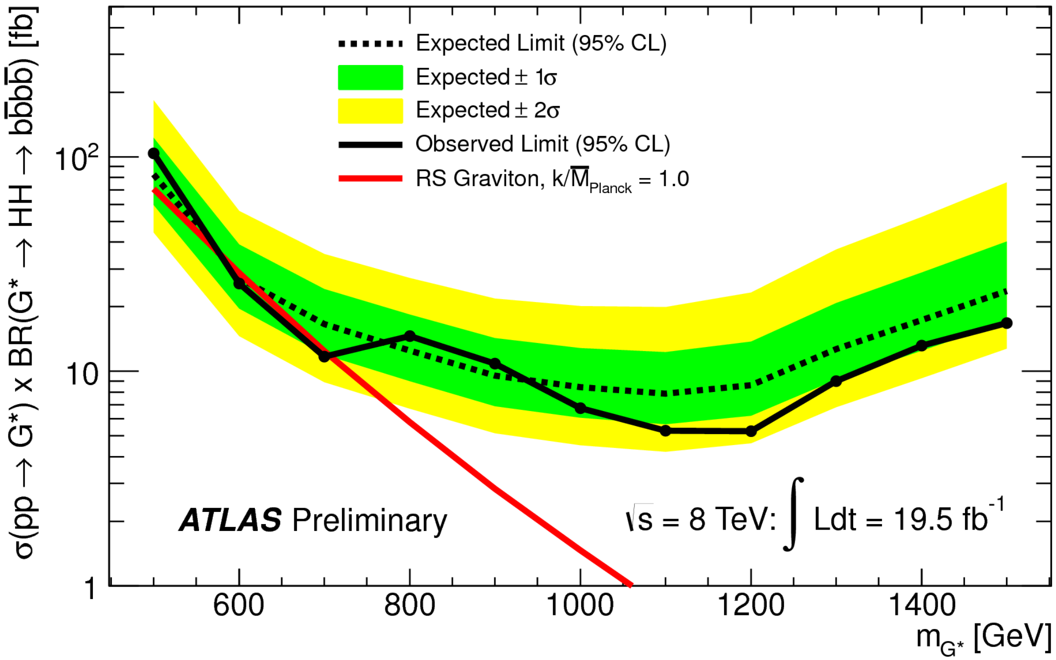




Di-Higgs production: hh → bbbb

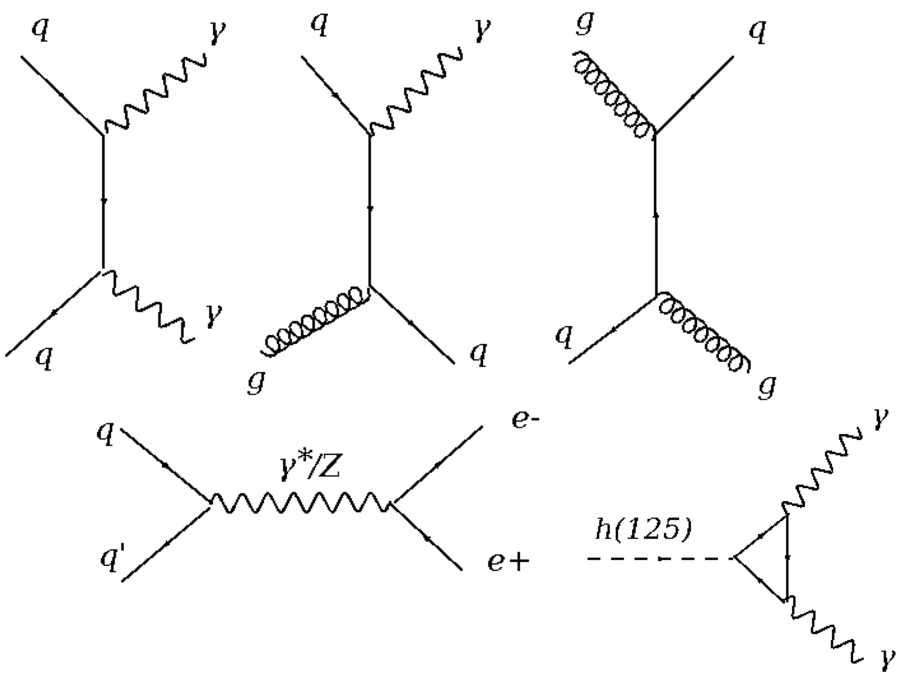
⬡ Interpretation of the result of this search using a Graviton model, but you can also get an idea what the limit would be on heavy Higgs production

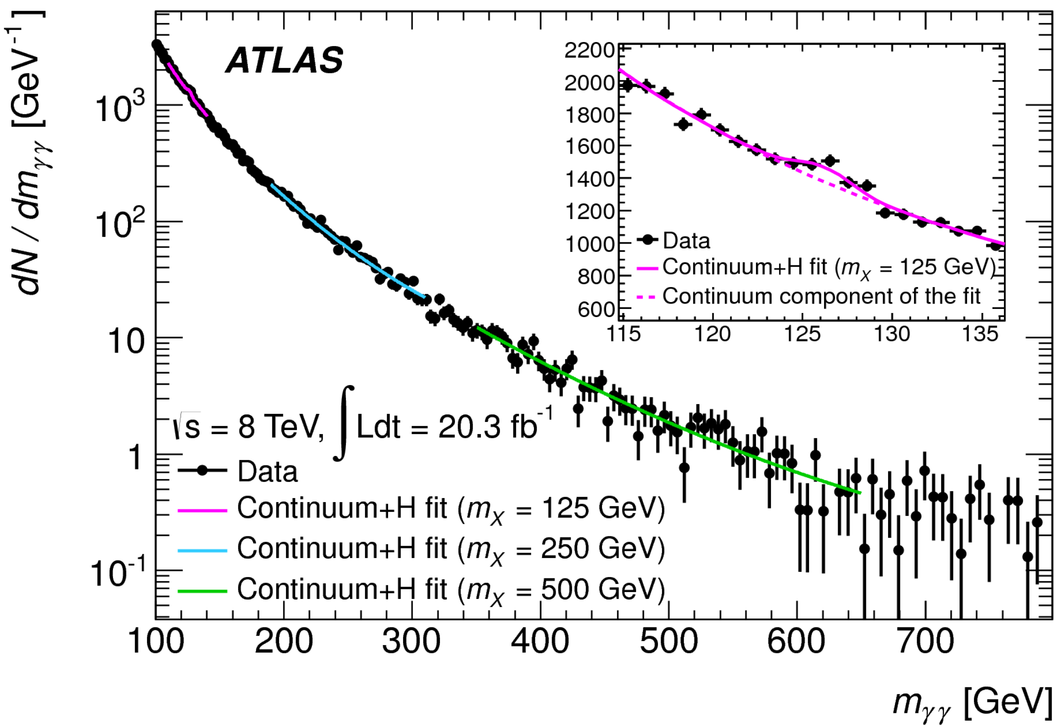
ATLAS-CONF-2014-005



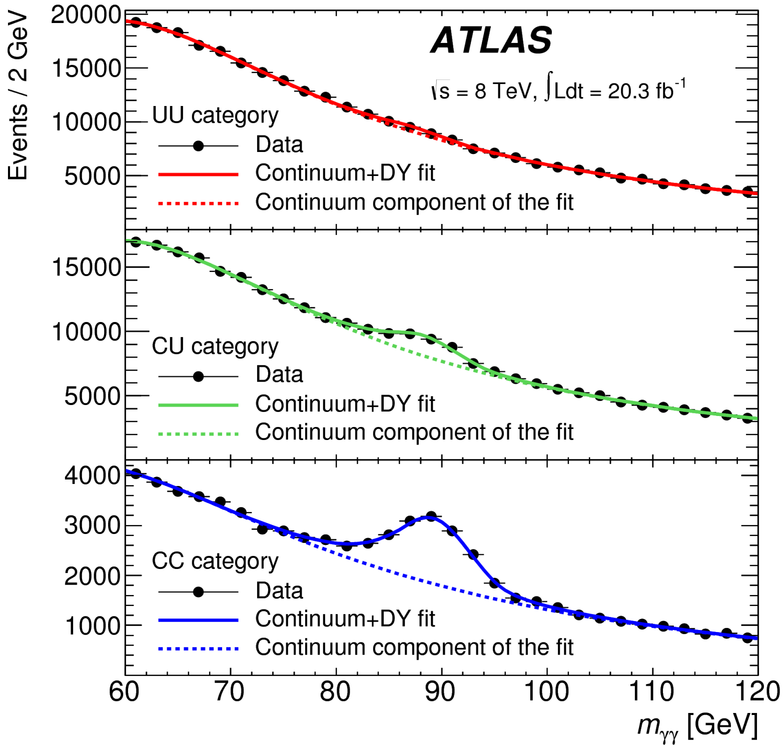
Scalar resonances to di-photon pairs

- 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





Scalar resonances to di-photon pairs

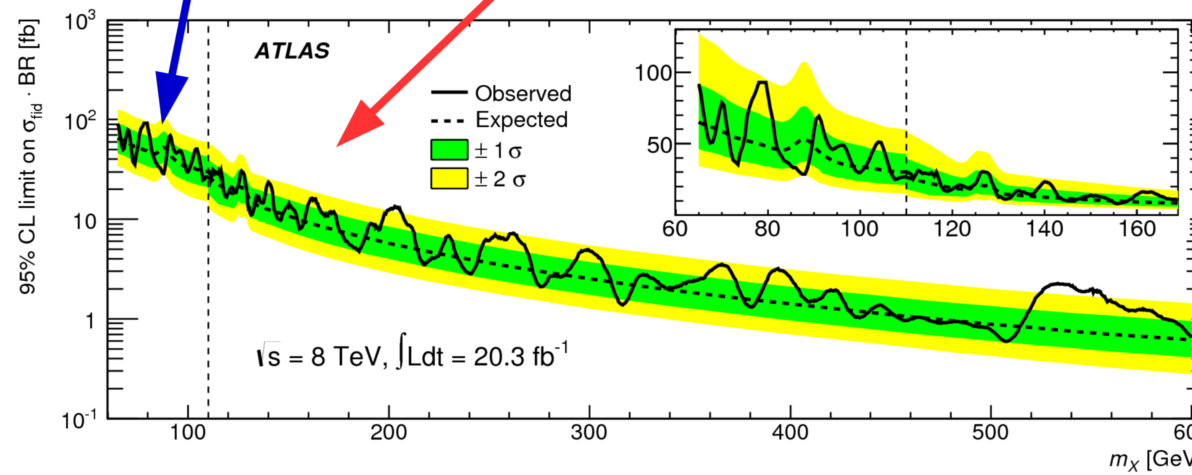


UU: unconverted-unconverted
UC: unconverted-converted
CC: converted-converted

Background estimation from m(γγ) sidebands interpolation
Analytical functions used for shapes of signals and backgrounds

Low mass category

High mass category



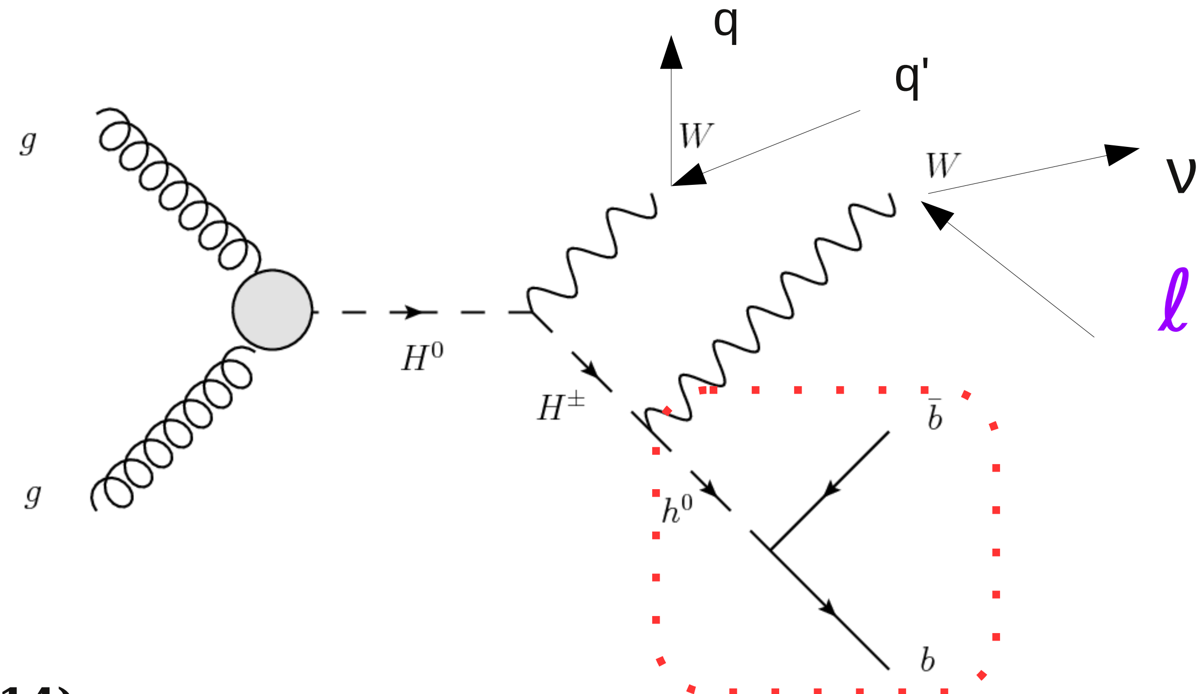
Limit on the fiducial cross section as a function of the assumed resonance mass

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

- 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

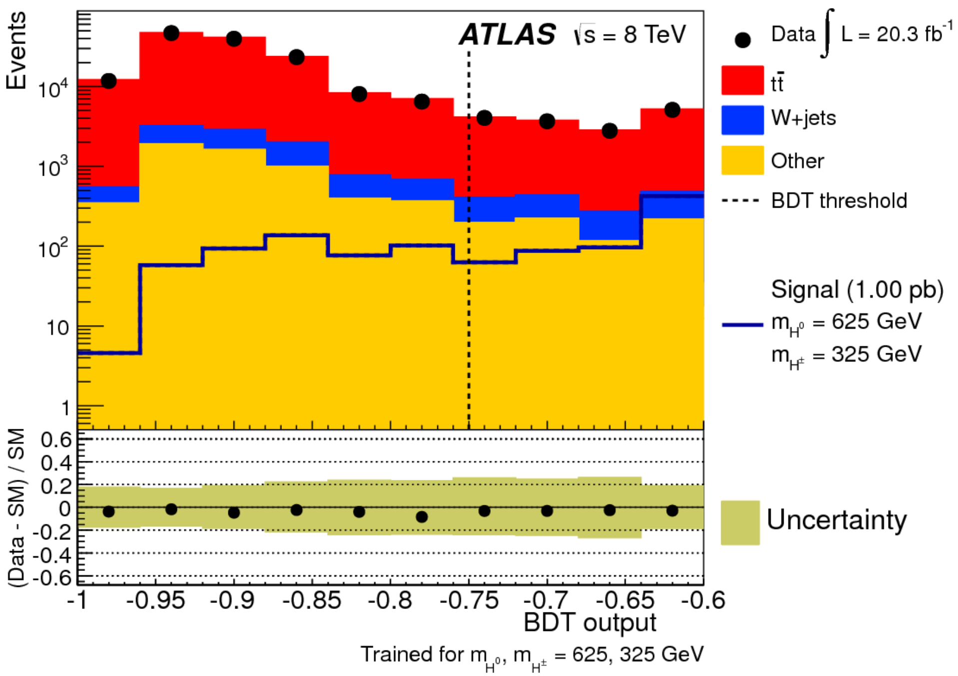
Example of a cascade decay: this final state may be simply hidden in ttbar events!

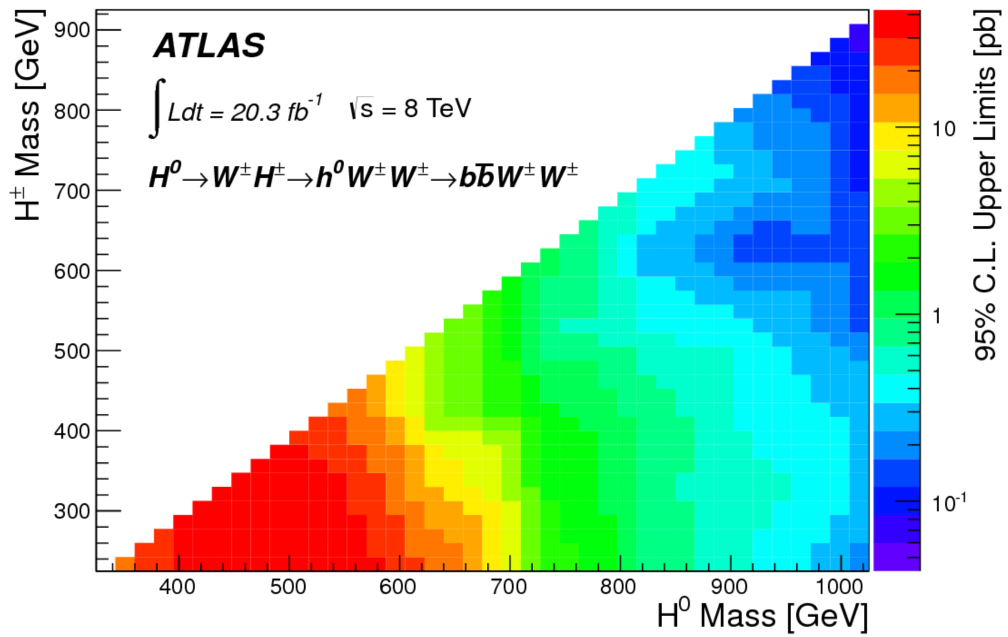


125-GeV SM-like Higgs decaying to bb

Phys. Rev. D 89, 032002 (2014)

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



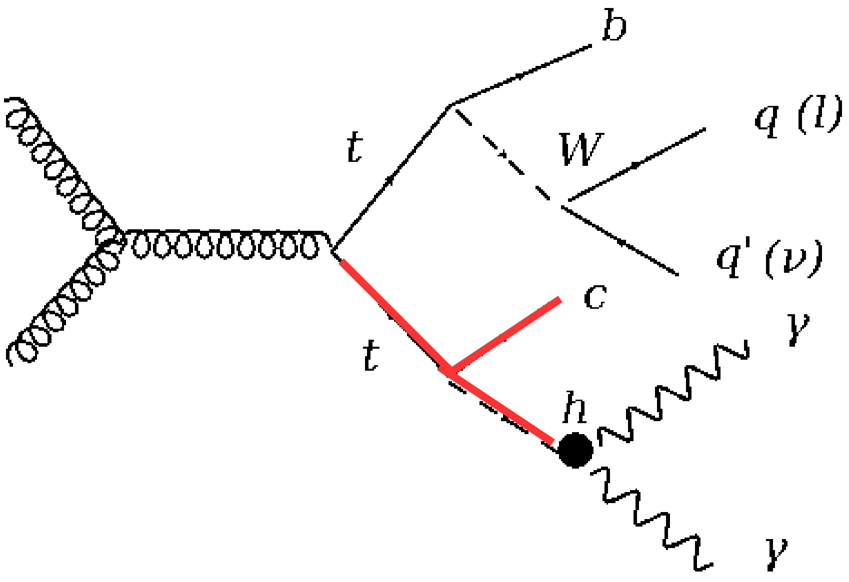


Example of a BDT output: the kinematic differences between a Higgs cascade and top pair production is exploited to improve sensitivity

Phys. Rev. D 89, 032002 (2014)

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
- ATLAS has looked for FC decay **t → ch**/uh in ttbar events with h → γγ

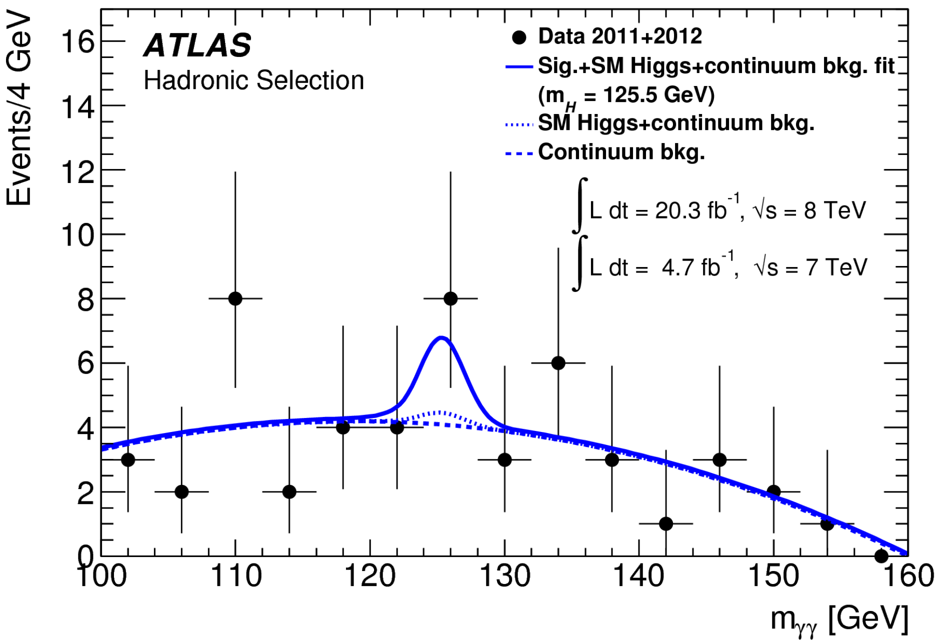


◇ 2 isolated photons, ET>40, 30 GeV to form a Higgs boson candidate
◇ Two channels: the other top decays hadronically or leptonically

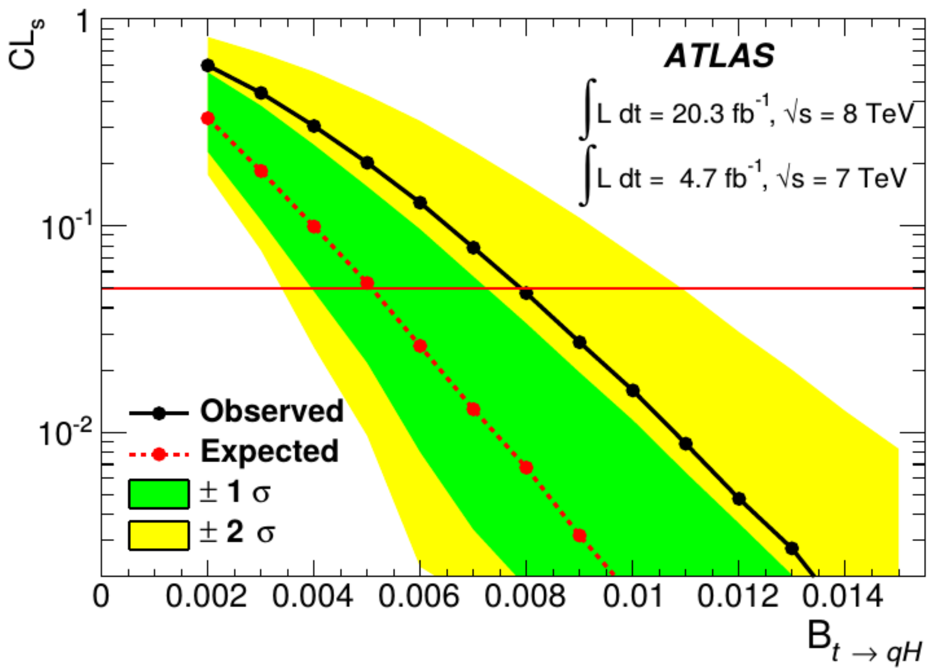
arXiv:1403.6293

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

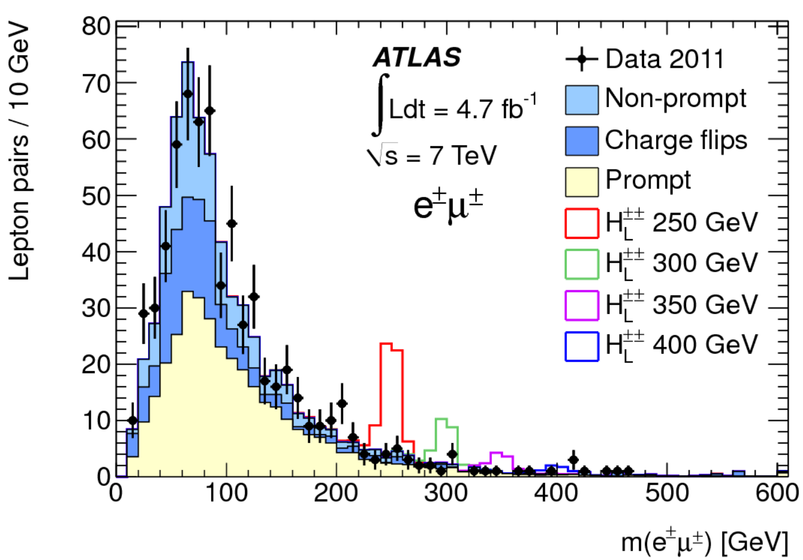
Higher order representations

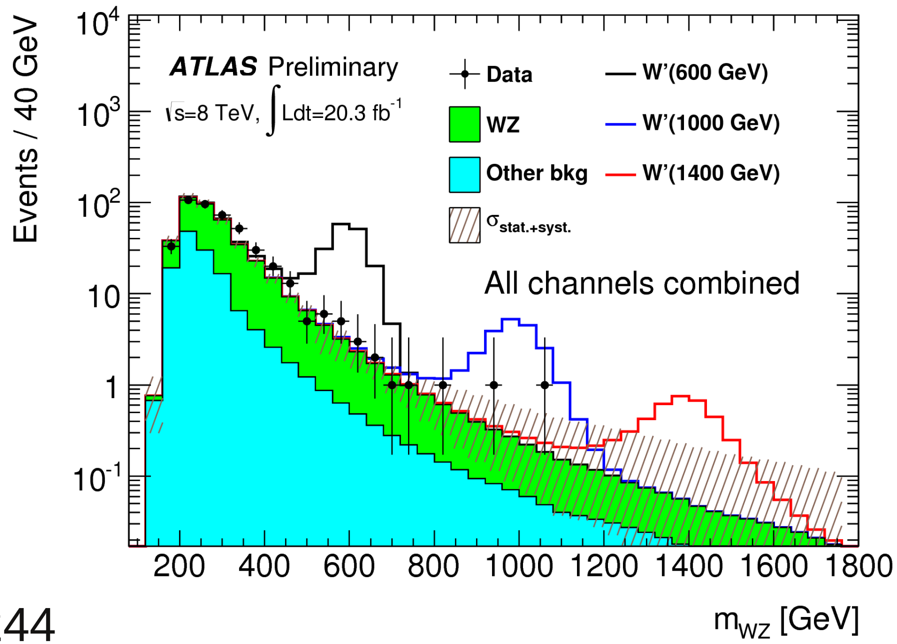
- The addition of multiplets with weak isospin higher than ½ can give very interesting phenomenology
  - Also one can envision a connection with neutrino mass when one considers T = 1 (i.e. Higgs triplet)
- The big problem here is that these models generically have to be fine tuned such that they do not contradict precision electroweak measurements mentioned previously
- However, it is possible to make models which suffer less from fine tuning
  - For instance Georgi & Machacek (Nucl. Phys. B 262, 463 (1985)) had noticed that if you introduce 2 triplets: one real (Y=0) and one complex (Y=2) the ρ parameter is still one at tree level

Higgs Triplets motivated signatures

- Doubly charged Higgs and exotic charged Higgs decays like $H^+ \rightarrow WZ$ are examples of signatures that cannot be found in (tree level) 2HDM, but they come from a Higgs triplet

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

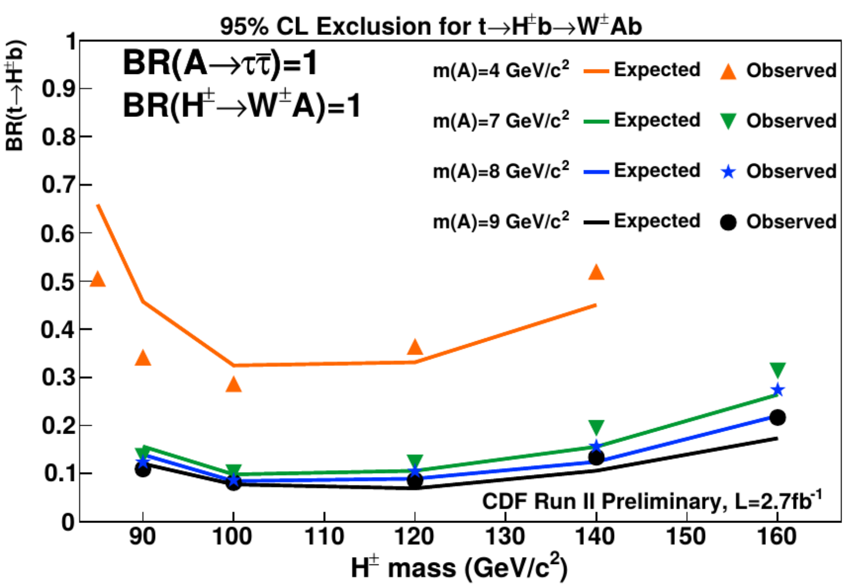
- The NMSSM is not simply about introducing more particles
  - The Higgs sector is not necessarily CP-conserving at tree level (c.f. MSSM)
    - Although many pheno studies assume CP-conservation
  - The tree-level "$m_h < m_Z$" relation is modified: no constrain for a light SM-like Higgs boson
  - The MSSM LEP constraints don't hold
    - In general, ultra-light Higgses, even few GeV in mass are allowed
    - The decay $h_1 \rightarrow a_1 a_1$ opens up weakening the LEP limit

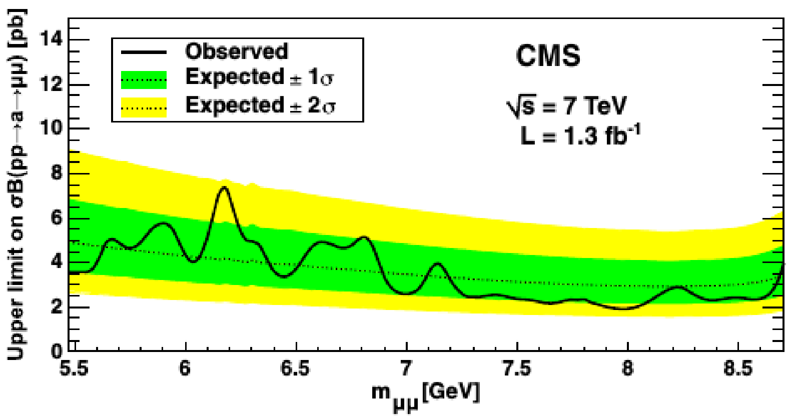
NMSSM motivated searches

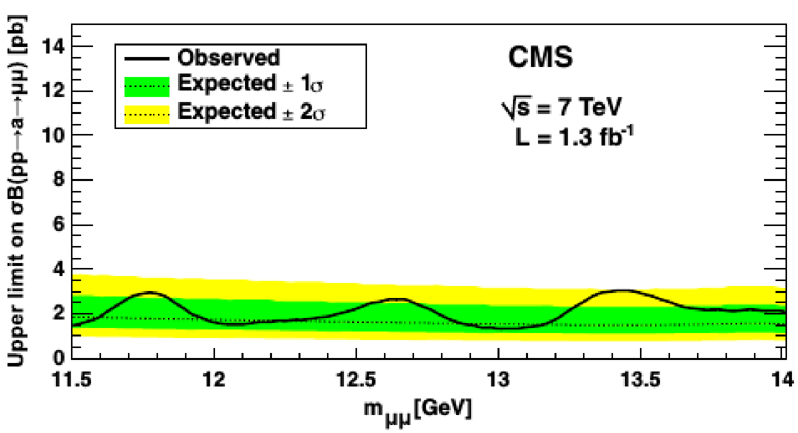
- The basic feature of CP-conserving NMSSM is the addition of potentially light CP-odd particles which can be looked for
  - Direct decays: $a_1 \rightarrow \mu\mu/\tau\tau/bb$;
    decays to γγ and ee also possible, though more constrained from fixed target experiments and axion searches; Charged Higgs decays: $h^+ \rightarrow Wa_1$
  - 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



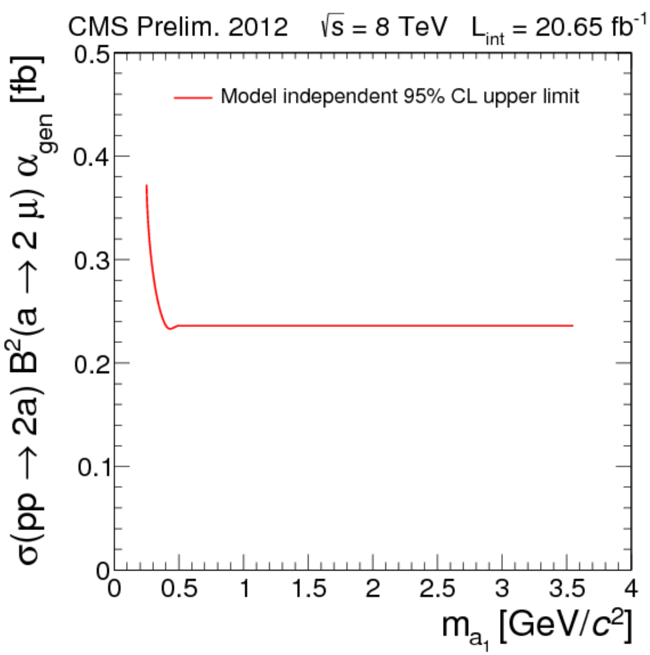


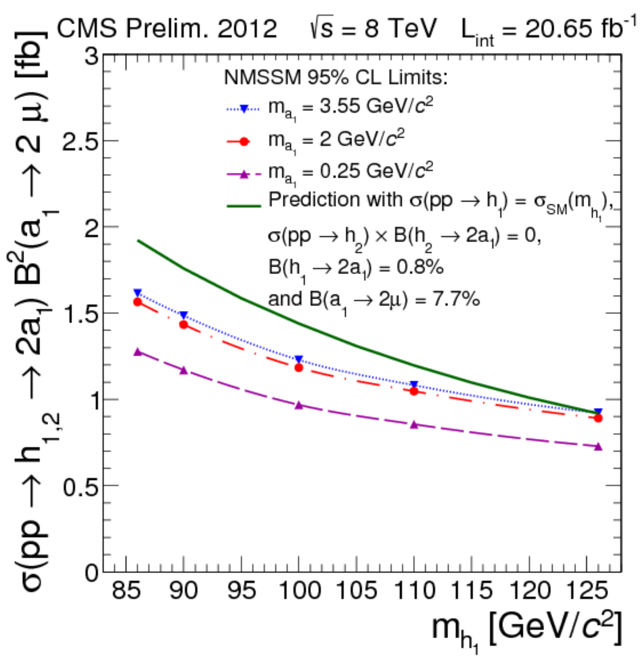


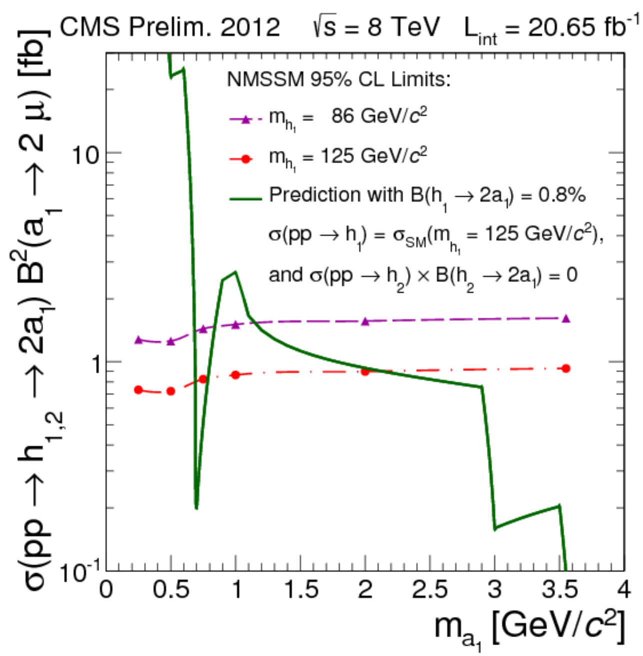
Few NMSSM motivated searches

- 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

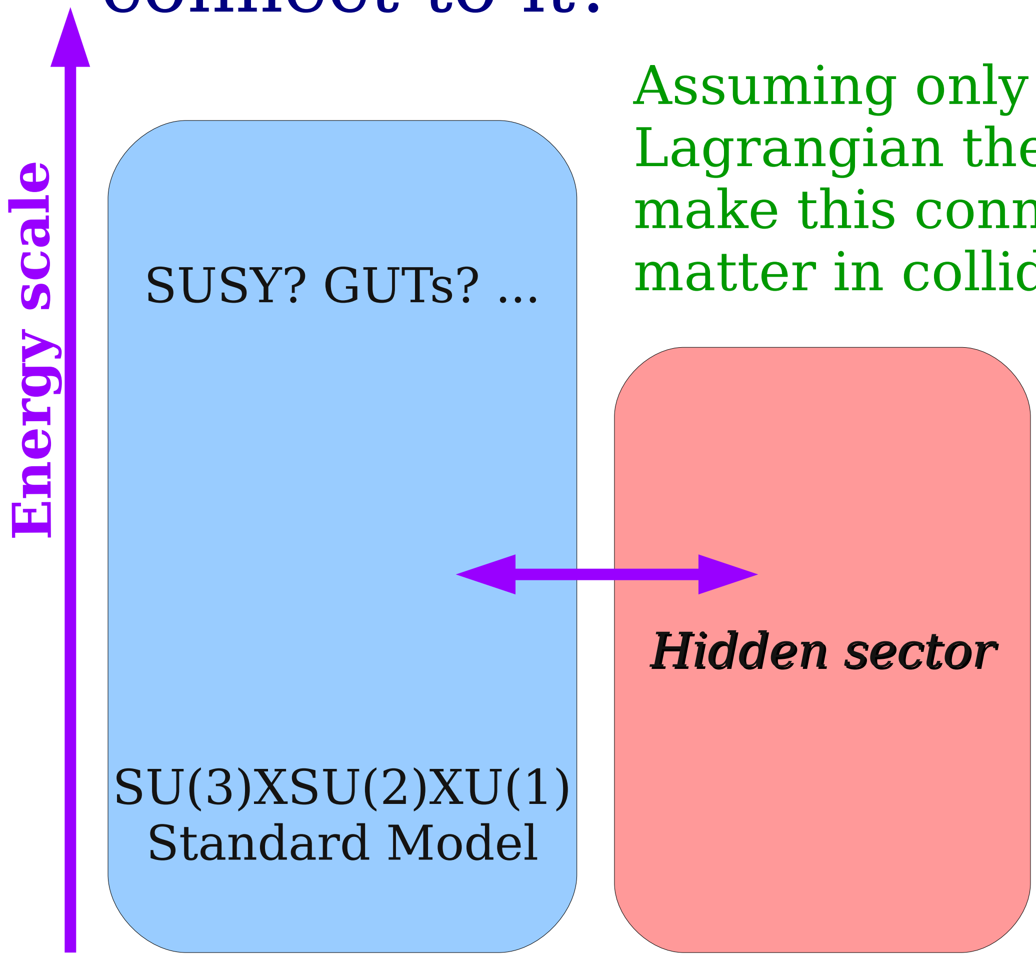






Portals to Hidden Sectors

- If there is 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

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

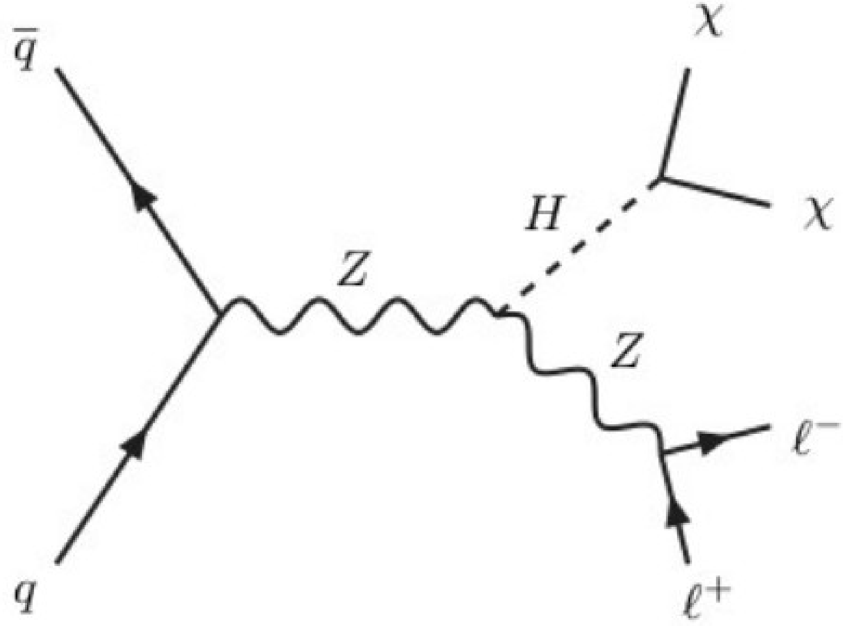
$\phi L \psi$ Neutrino portal

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

Higgs to Invisible

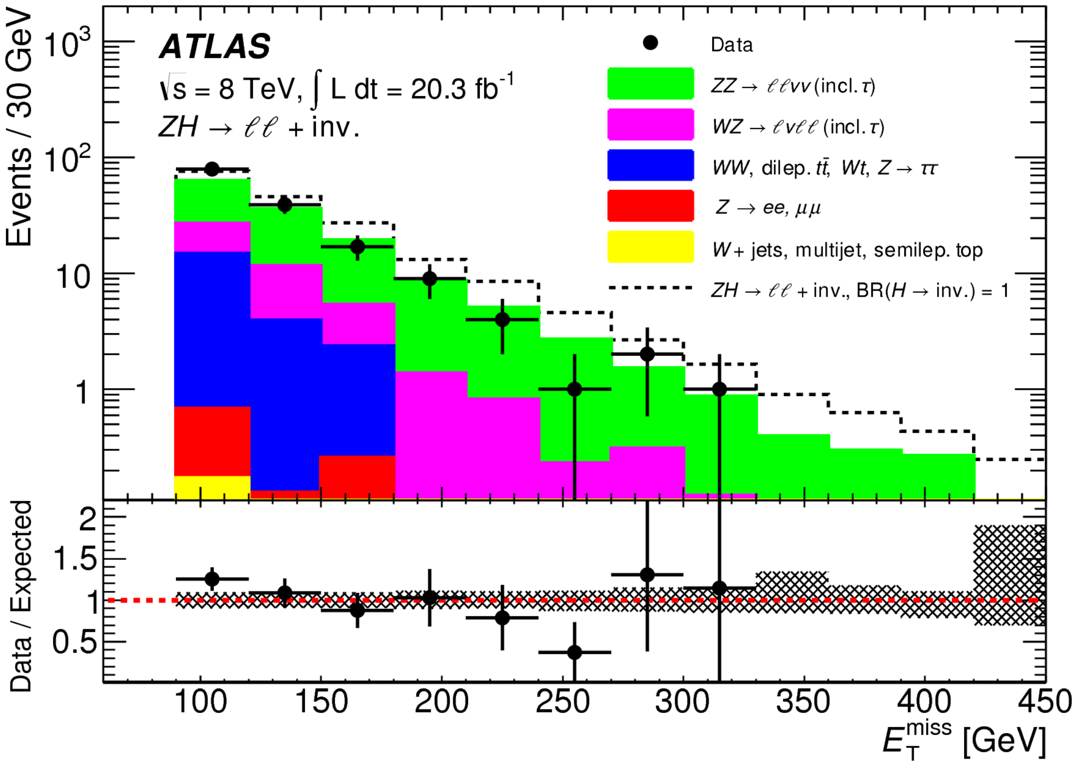
- The SM Higgs boson has decays to (LHC detector) invisible particles, e.g., **$h \rightarrow ZZ \rightarrow \nu\nu\nu\nu$**, which has **BR ~ 1/1000** and hence it is beyond our current sensitivity.
- So, we can use invisible Higgs decays to probe Higgs portal
- ATLAS has looked for $Zh \rightarrow \ell\ell$ inv

arXiv:1402.3244



Higgs to Invisible

- Data collected with single lepton and di-lepton triggers
- $76 < m(\ell\ell) < 106$ GeV
- MET > 90 GeV
- $\Delta\varphi(\mathrm{MET}, p_T\mathrm{miss}) < 0.2$,
- $\Delta\varphi(\mathrm{MET}, p_T^{\ell\ell}) > 2.6$
- $\Delta\varphi(\ell\ell) < 1.7$
- $|\mathrm{MET} - p_T^{\ell\ell}| / p_T^{\ell\ell} < 0.2$
- veto of additional jets

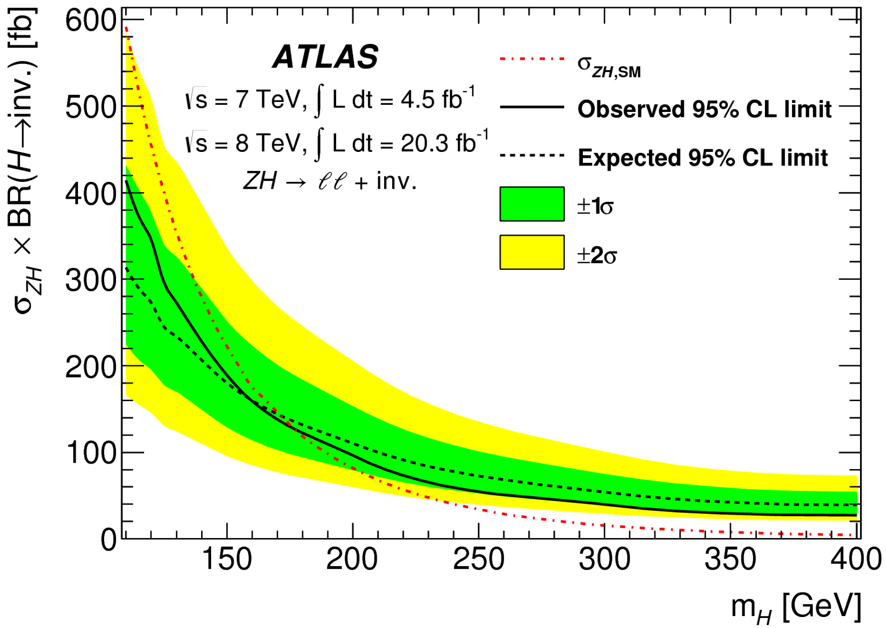


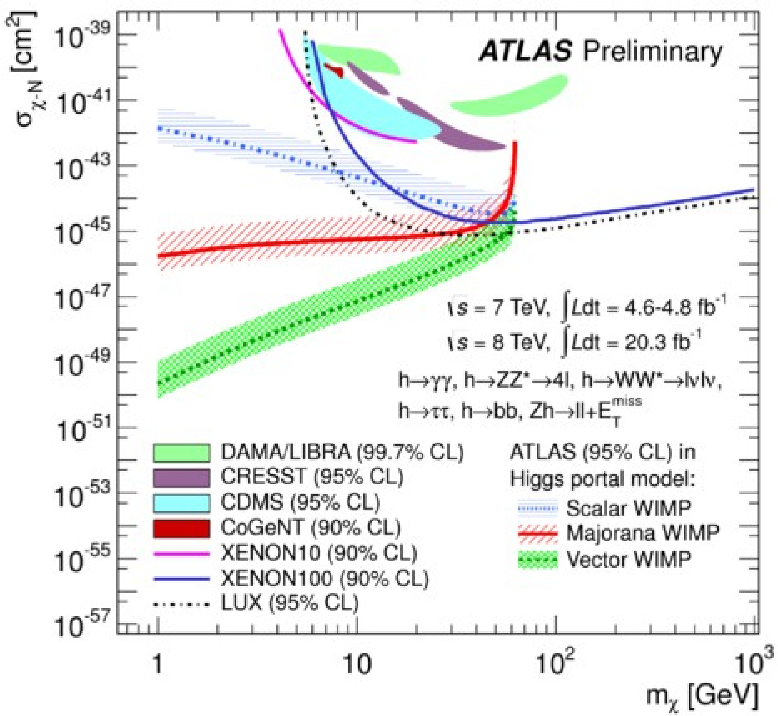
Examine the MET distribution for discrepancies

Higgs to Invisible

arXiv:1402.3244

ATLAS-CONF-2014-010





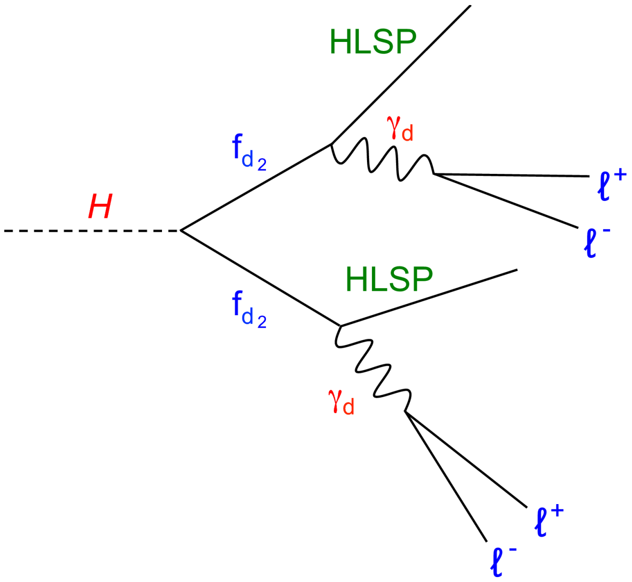
Constrains for the discovered Higgs boson:
BR(h → inv) < 75% (observed) (62% expected)

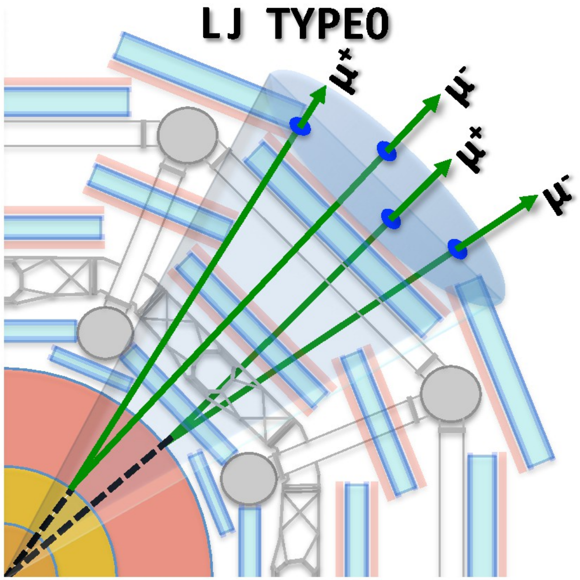
- The Zh → ll inv constrain on the BR(h→ inv) can be combined with the direct measurements of the Higgs couplings giving a combined result
  - BR(h→ inv) < 37 % (observed) (39% expected); the result can also be interpreted in terms of the dark matter-nucleon scattering cross section

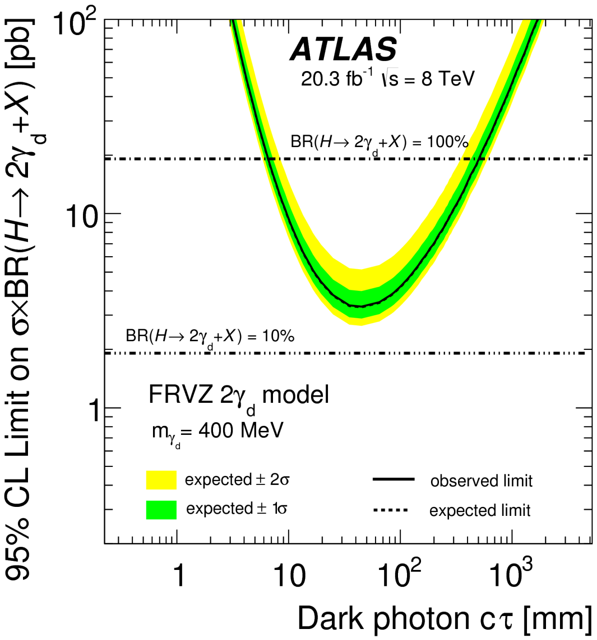
Higgs to hidden sector

- 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 lepton jets and long-lived particles





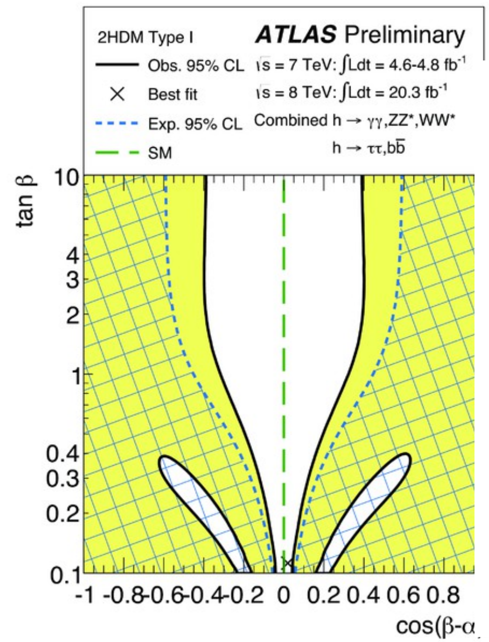


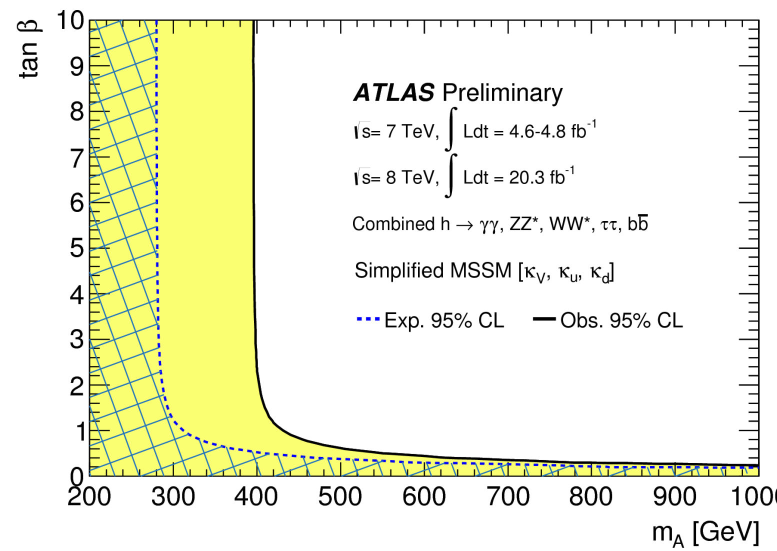
arXiv:1409.0746

Constraints from Higgs measurements

- I have already mentioned that Higgs to invisible decays can be constrained by Higgs coupling measurements
- We can use Higgs couplings also to constrain several other BSM Higgs scenarios, like 2HDM, MSSM, etc

See for instance several examples in ATLAS-CONF-2014-010





Where we stand: hints for the future

- There is high motivation to look for an extended Higgs sector
  - Higgs sector is little constrained by SM symmetries & precision measurements
  - Many BSM theories include either an extended Higgs sector or more Higgses (e.g. Susy, Extra dimensions);
    others include exotic Higgs properties (e.g. composite Higgs, Higgs portal)
- A lot of BSM theories include a (weak) decoupling limit
  - In other words it is possible that you have exactly a SM Higgs boson and a 200 GeV additional Higgs boson
  - **i.e. the direct search for Higgs bosons is indispensable!**

Where we stand: hints for the future

- We have just started probing the relevant parameter space for most models
  - MSSM Higgs searches are mature and they have constrained the high tanβ region
  - MSSM is still relevant and MSSM Higgs searches will continue playing a major role in the search for BSM physics
  - More generic models than the MSSM help us in extending the list of signatures; e.g. NMSSM inspired $h \rightarrow a_1 a_1$ searches

Where we stand: hints for the future

- A very important point:
  a generic signature for a heavy neutral Higgs is its decay to tt (for m > $2m_{top}$)
  a generic signature for a heavy charged Higgs is its decay to tb
  - None of these decays has been studied in detail yet at the LHC!!!
  - This is because these are very difficult channels and require a lot of advanced techniques and integrated luminosity
- Also remember that Higgs production is not like SUSY: the cross sections are generically small

Concluding remarks

- BSM Higgs search program is still in its early years, but we have learnt a lot!
- The road to discovery is difficult:
  - most of the highly motivated signatures are difficult
  - Cross sections are usually low: unlike SUSY, Higgs is less likely to be discovered with few pb^{-1} of data from a high energy machine
- So, it is not unreasonable that BSM Higgses exist but we haven't discovered them yet
- Be tuned for the next LHC Run:
  Run-I was Higgs, Run-II could be Higgses!

Concluding remarks

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

MSSM Higgses: which of them is the h125?

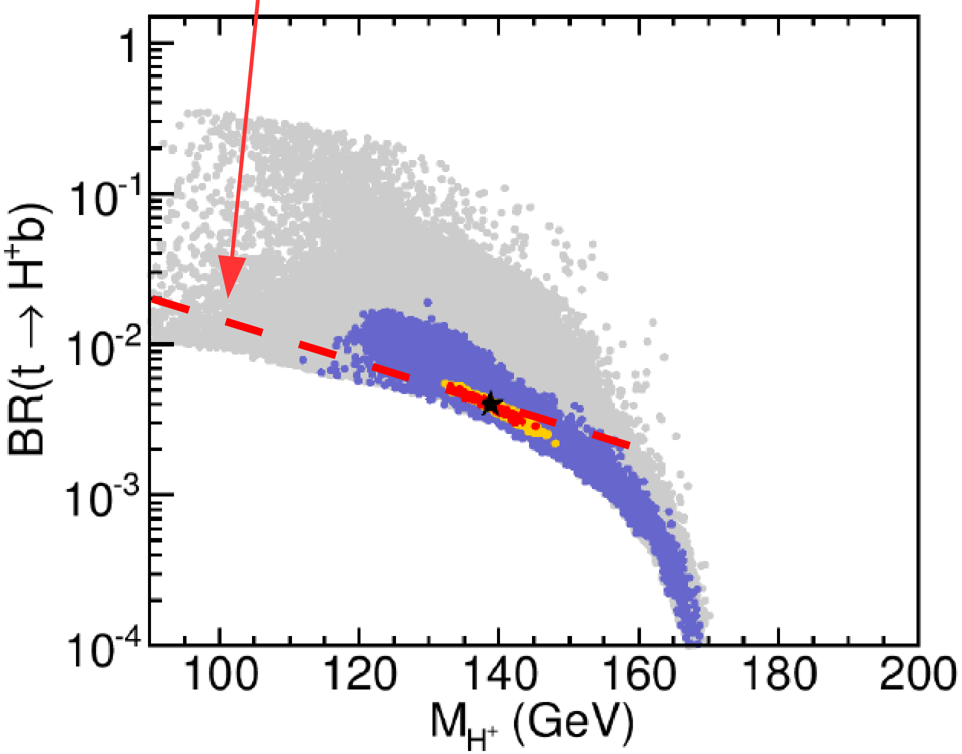
- In some of the previous slides I have assumed that the h125 Higgs boson is the lightest CP-even Higgs
  - This assumption is viable and can live in many places in the MSSM parameter space
  - The case where m_H=125 GeV is possible: we end up in a very interesting configuration
    - All Higgs bosons 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}

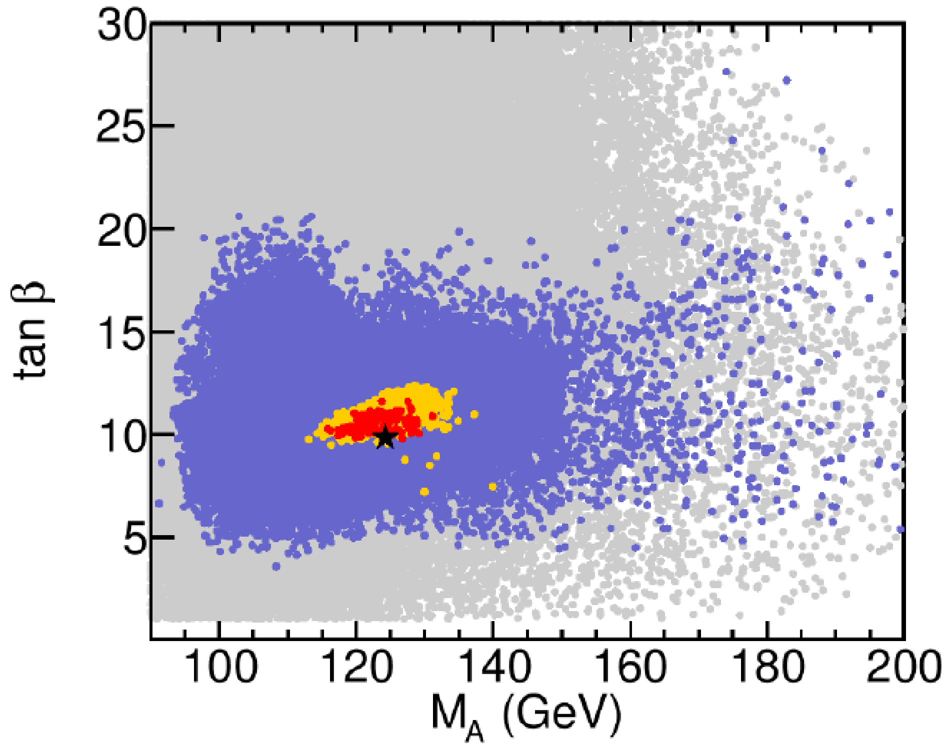
As a result the mH = 125 GeV case is constrained by a number of other light mass Higgs searches and it is difficult to find much of parameter space

MSSM Higgses: which of them is the h125?

- Example of pMSSM-7 scans

ATLAS Charged Higgs limit, 8 TeV



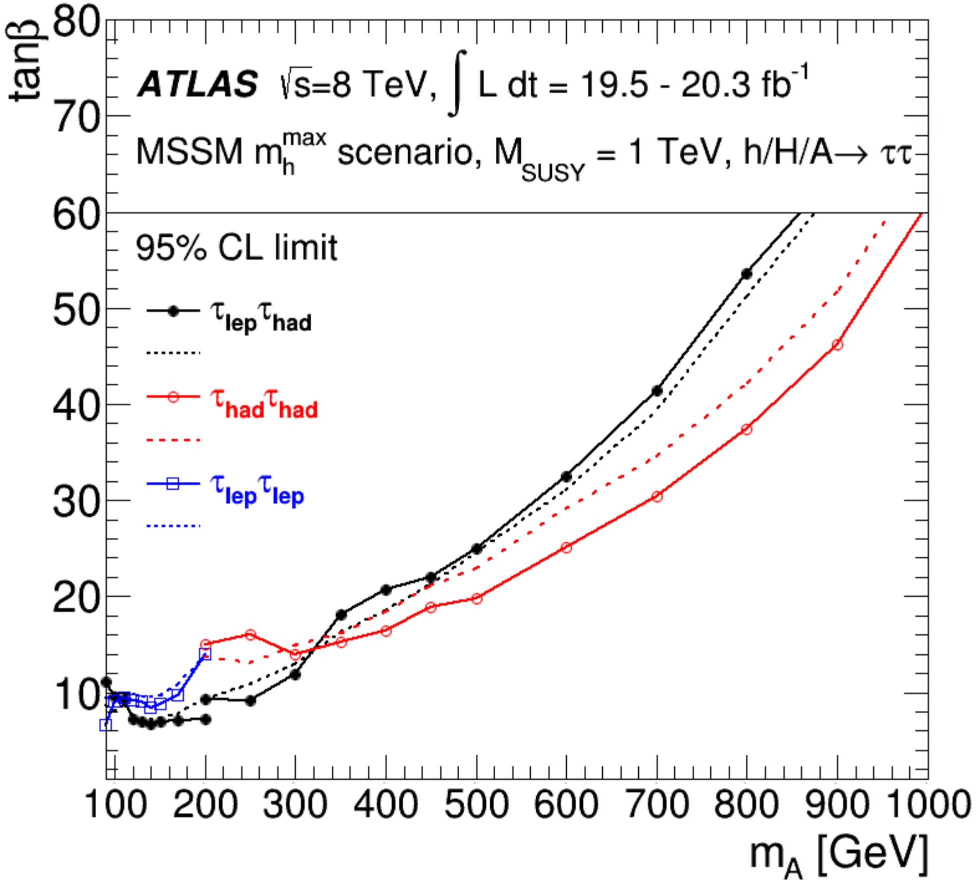


Red are yellow area correspond approx. to 1 and 2 sigma bands assuming h125 measurements and few other constraints (here using mostly 2012 measurements)

Eur.Phys.J. C73 (2013) 2354

Neutral MSSM Higgs

- Comparison of the sensitivity of each channel



arXiv:1409.6064