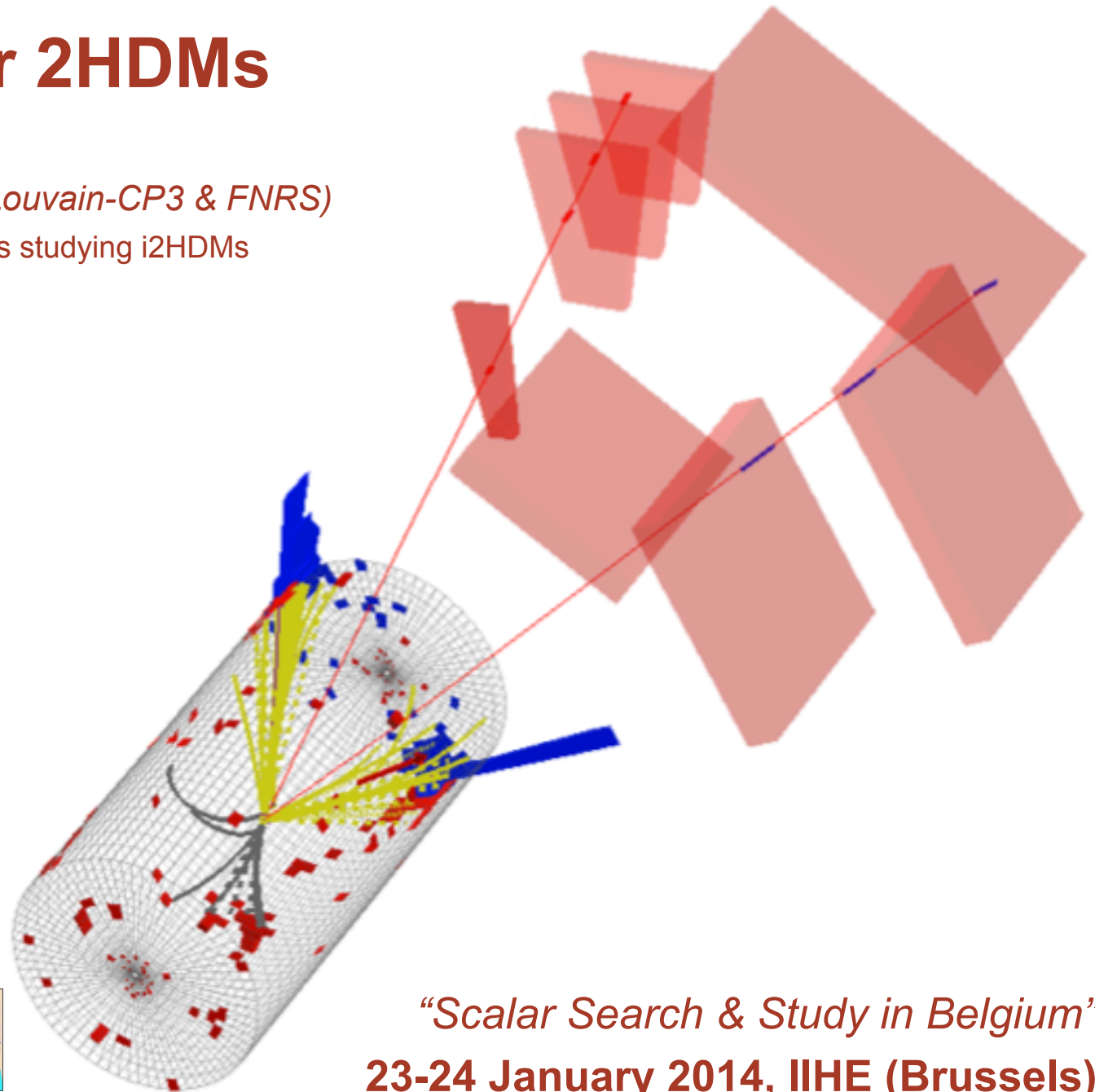


Searches for 2HDMs

Tristan du Pree (*UCLouvain-CP3 & FNRS*)

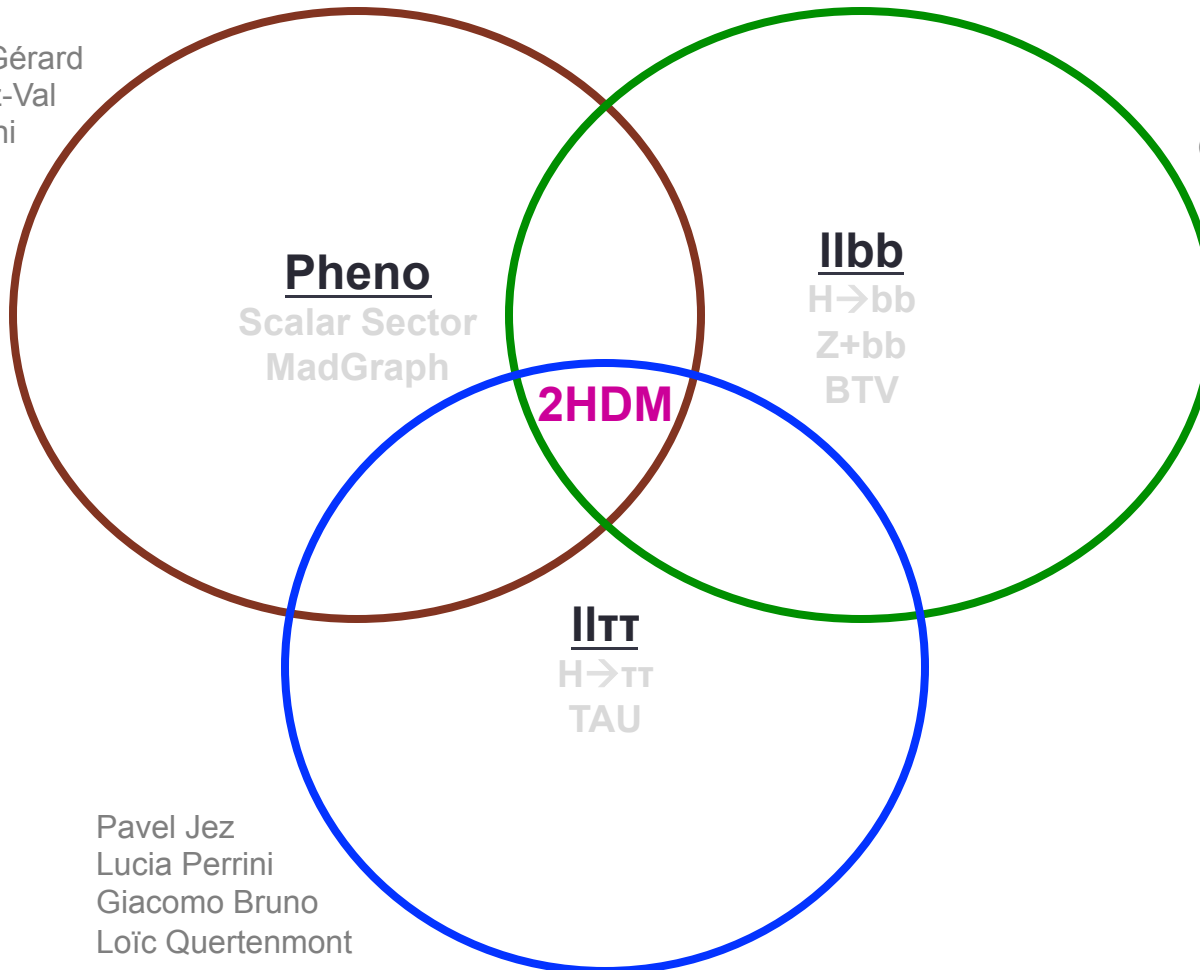
for the CP3 IIbb and IIrr groups studying i2HDMs



“Scalar Search & Study in Belgium”
23-24 January 2014, IIHE (Brussels)

2HDMs at CP3

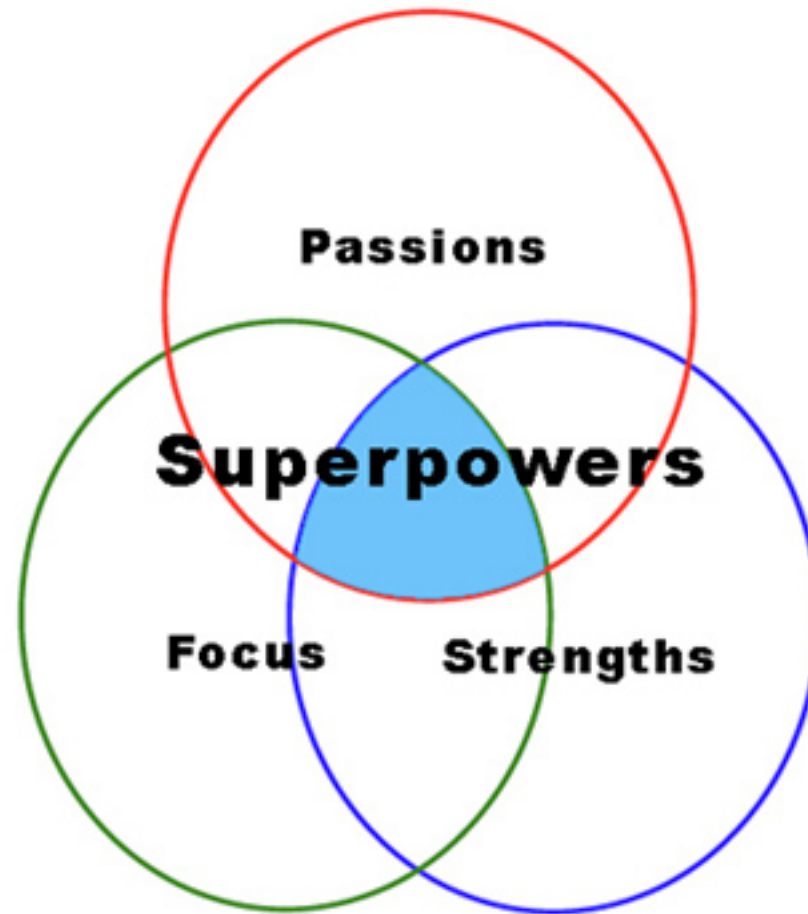
Jean-Marc Gérard
David Lopez-Val
Fabio Maltoni
...



Christophe Delaere
Michele Selvaggi
Roberto Castello
Adrien Caudron
Tristan du Pree
...

Pavel Jez
Lucia Perrini
Giacomo Bruno
Loïc Quertenmont

Motivation on internet



Introduction

SM

- **BEH mechanism:**
one scalar boson
- **CP conservation**
 - Automatically
- **Custodial symmetry**
 - $M_{W^\pm} \approx M_Z$

Supersymmetry

- Two higgs doublets
➔ 5 spin-0 bosons: h, H^0, H^\pm, A
- 1. **SM-like h**
- 2. **CP-even H^0**
- 3. **Triplet: $M_{H^\pm} \approx M_A$**
 - Pseudoscalar A
 - Mass constrained
by limits on charged H^\pm
 - $M_{A, H^\pm, 0} > M_h$

Why not search for
more general 2HDMs?



Theoretical motivation

- **2HDM**

- Natural extension of SM: two doublets
- Disadvantage: no automatic CP conservation

- **Solution: impose CP invariance** in 2HDM

- Custodial symmetry: $M_{H^\pm} \approx M_{H^0}$, similar to $M_{W^\pm} \approx M_Z$

Two scenarios:

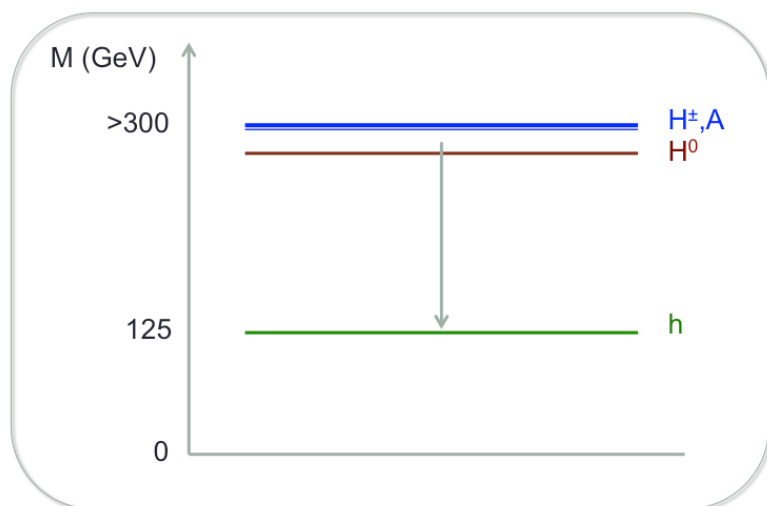
1. **Supersymmetry:** $M_{H^\pm} \approx M_A$

2. **Other possibility:** $M_{H^\pm} \approx M_{H^0}$

<http://arxiv.org/abs/hep-ph/0703051>

- CP-odd A is possibly decoupled
 - M_A unrelated to triplet: “**Inverted hierarchy**”
- Pseudoscalar A originates from breaking of U(1) symmetry
 - Pseudo-Goldstone boson (analogy with pion): **Nearly massless**

Hierarchy sketches

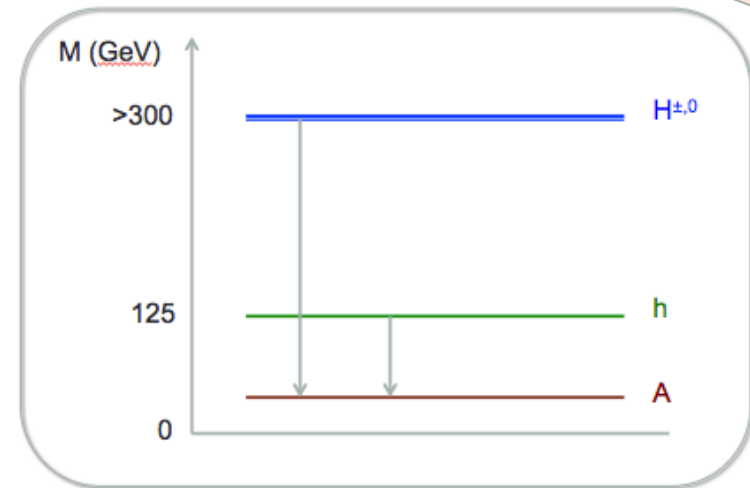
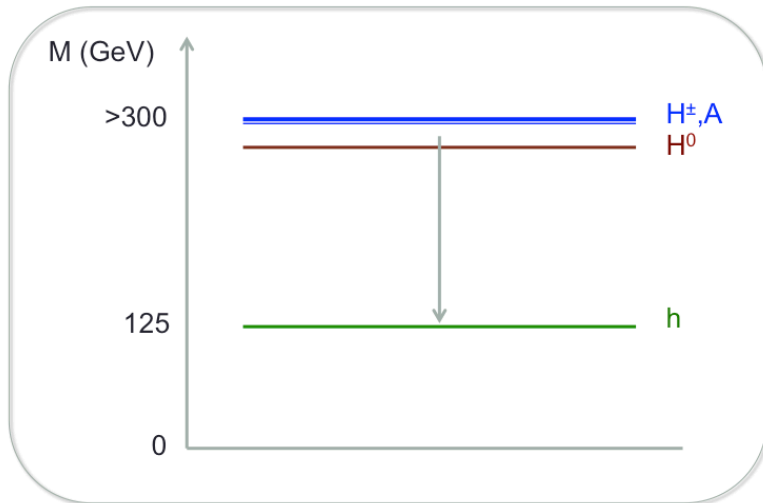


1. Usual hierarchy

- Example: **MSSM**
 - SM-like Higgs boson lightest
 - Heavy susy Higgses
 - Ongoing CMS search for $A \rightarrow Zh$
 - Final state: [A → Z\(l\)h\(bb\)](#)
with 125 GeV $h \rightarrow bb$

Hierarchy sketches

Illustrations similar to
<http://arxiv.org/abs/hep-ph/0703051>



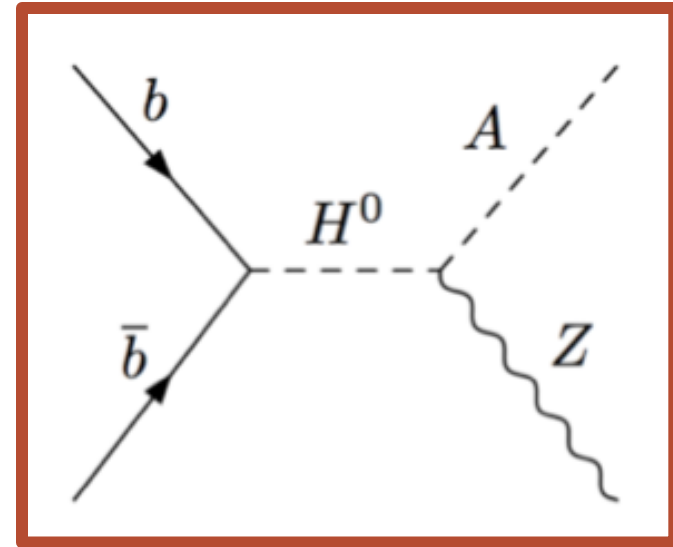
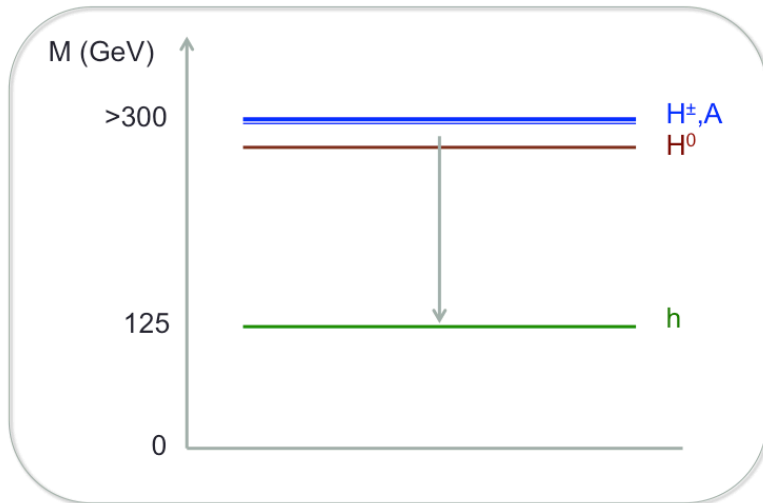
1. Usual hierarchy

- Example: MSSM
 - SM-like Higgs boson lightest
 - Heavy susy Higgses
 - Ongoing CMS search for $A \rightarrow Zh$
 - Final state: $A \rightarrow Z(\ell\ell)h(bb)$ with 125 GeV $h \rightarrow bb$

2. Alternative: inverted hierarchy

- From “A Twisted Custodial Symmetry in the Two-Higgs-Doublet Model”
 - <http://arxiv.org/abs/hep-ph/0703051>
- **Light pseudoscalar A**
 - M_A : few GeV (NMSSM) or more
 - Possibility: $H \rightarrow ZA$

Hierarchy sketches



1. Usual hierarchy

- Example: MSSM
 - SM-like Higgs boson lightest
 - Heavy susy Higgses
 - Ongoing CMS search for $A \rightarrow Zh$
 - Final state: $A \rightarrow Z(\ell\ell)h(bb)$ with 125 GeV $h \rightarrow bb$

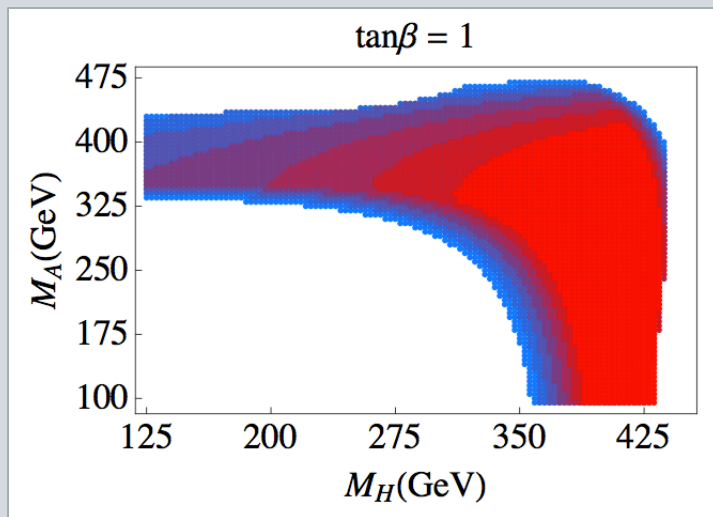
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 - M_A : few GeV (NMSSM) or more
 - Possibility: $H \rightarrow ZA$

Limits & couplings

<http://arxiv.org/pdf/1304.0028v1.pdf>

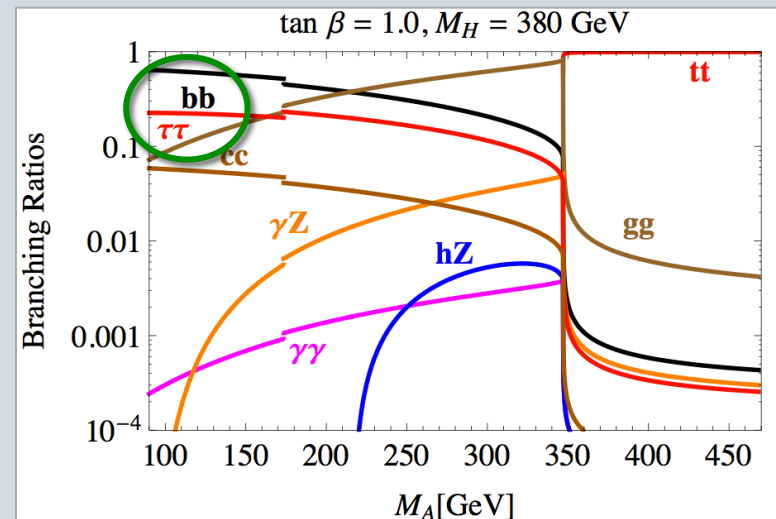
Recent limits



This plot ($\tan\beta=1$) favors

- **Heavy M_H** (~ 400 GeV)
- **Lighter M_A** (95-400 GeV)

BRs

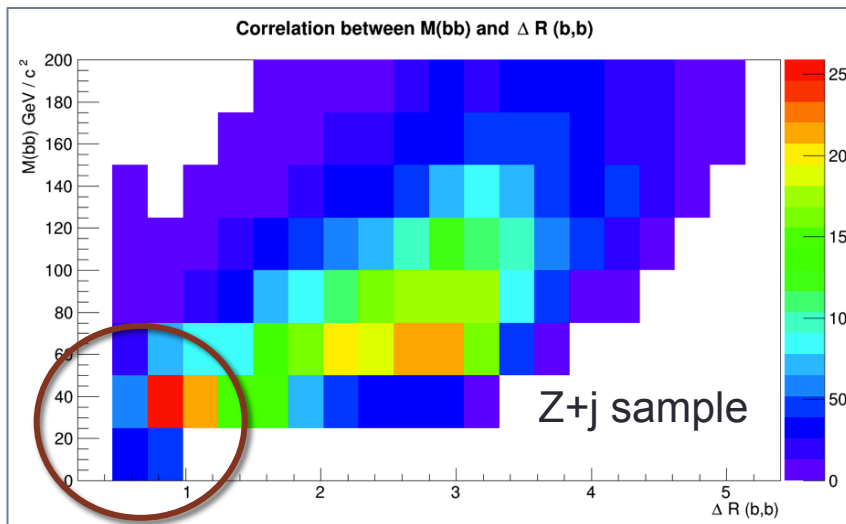


If M_A small \rightarrow dominant decays:

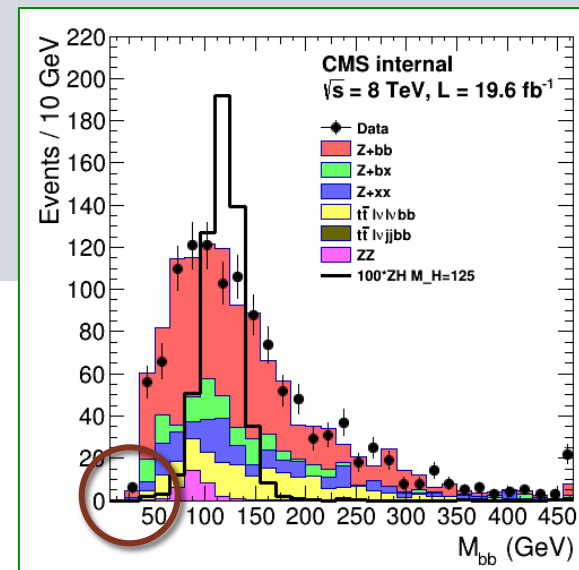
- **$A \rightarrow bb$**
- **$A \rightarrow \tau\tau$**
 - $H \rightarrow Z(\text{II})A(bb)$ and $H \rightarrow Z(\text{II})A(\tau\tau)$

Kinematics

- M_{bb} after $h \rightarrow bb$ selection
 - See Adrien Caudron
 - **No events at small M_{bb}**
 - **Both b's in a single jet?**



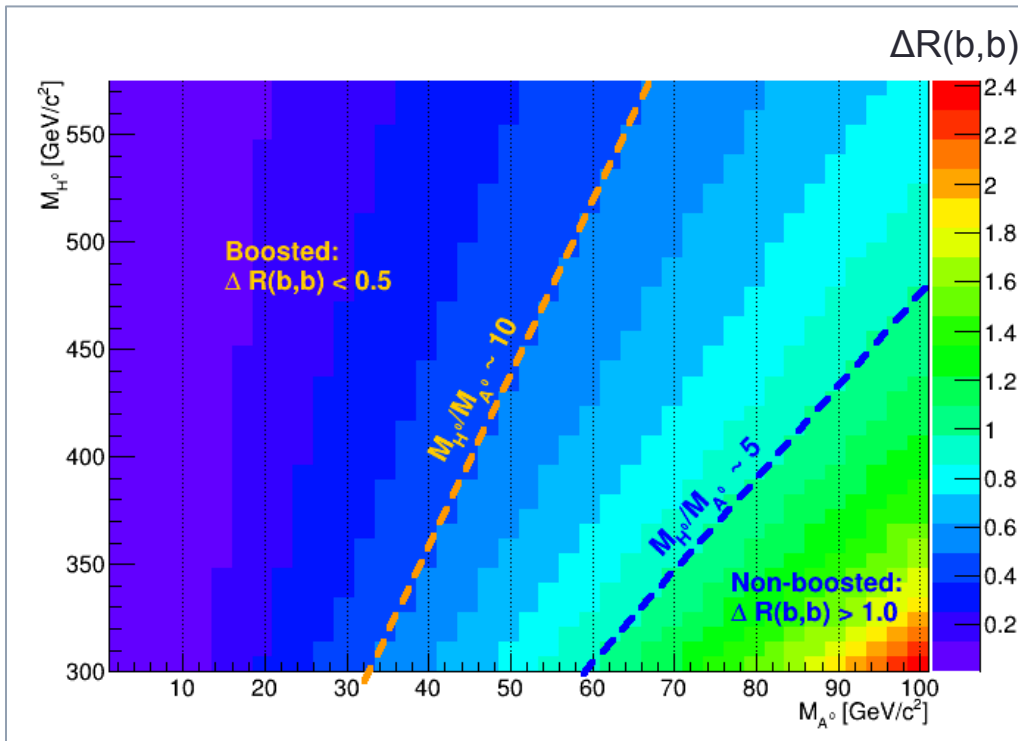
NB: background Z+bb sample, without $A \rightarrow bb$



- ΔR vs M_{bb}
 - Large M_{bb} : non-boosted regime
 - **Small $M_{bb} \rightarrow$ small ΔR**
 - **Collinear b's!**

Boosted topologies

- $\Delta R(b,b)$: $M_{A \rightarrow bb}$ vs $M_{H \rightarrow ZA}$
 - Light A, boosted topology: $\Delta R < 1$
 - Typical mass ratio of $M_A : M_H = 1 : (5-10)$
 - $A \rightarrow \tau\tau$: very similar

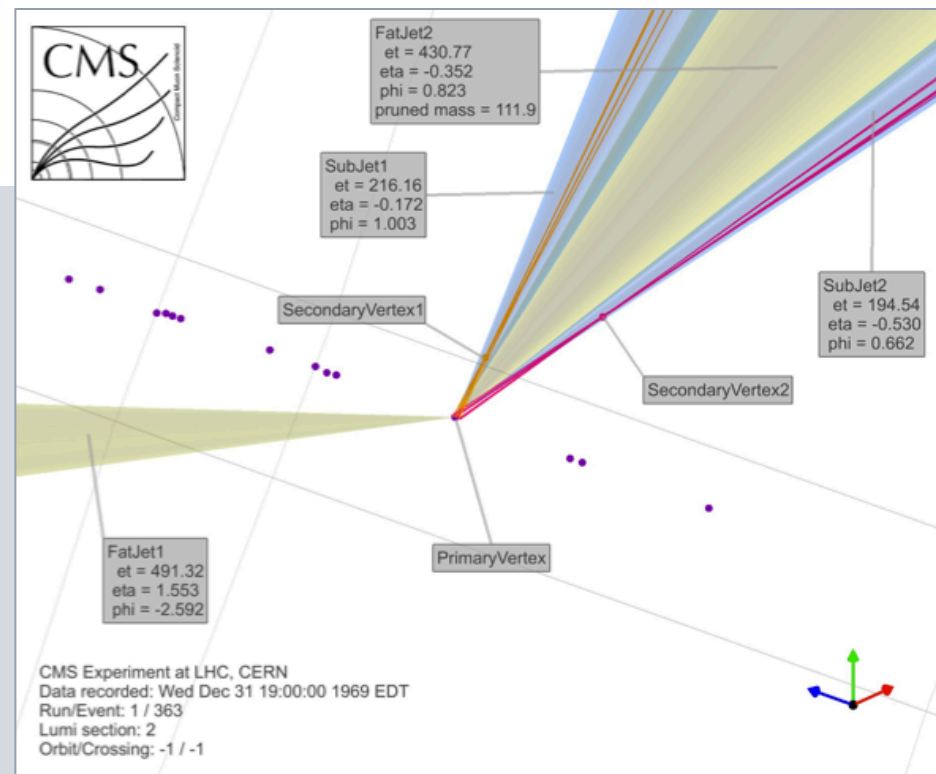


NB: axes flipped wrt plots on previous slide

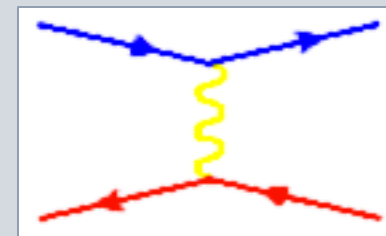
Developments

Reconstruction of bb & $\tau\tau$

1. **Heavy A**: non-boosted
 - Usual b & τ reconstruction
2. **Light A**: boosted topologies
 - Dedicated reconstruction
 1. **Subjet b-tagging**
 - See [BTV-13-001](#)
 2. **Taus**: similar activities
 - See presentation by Pavel Jez

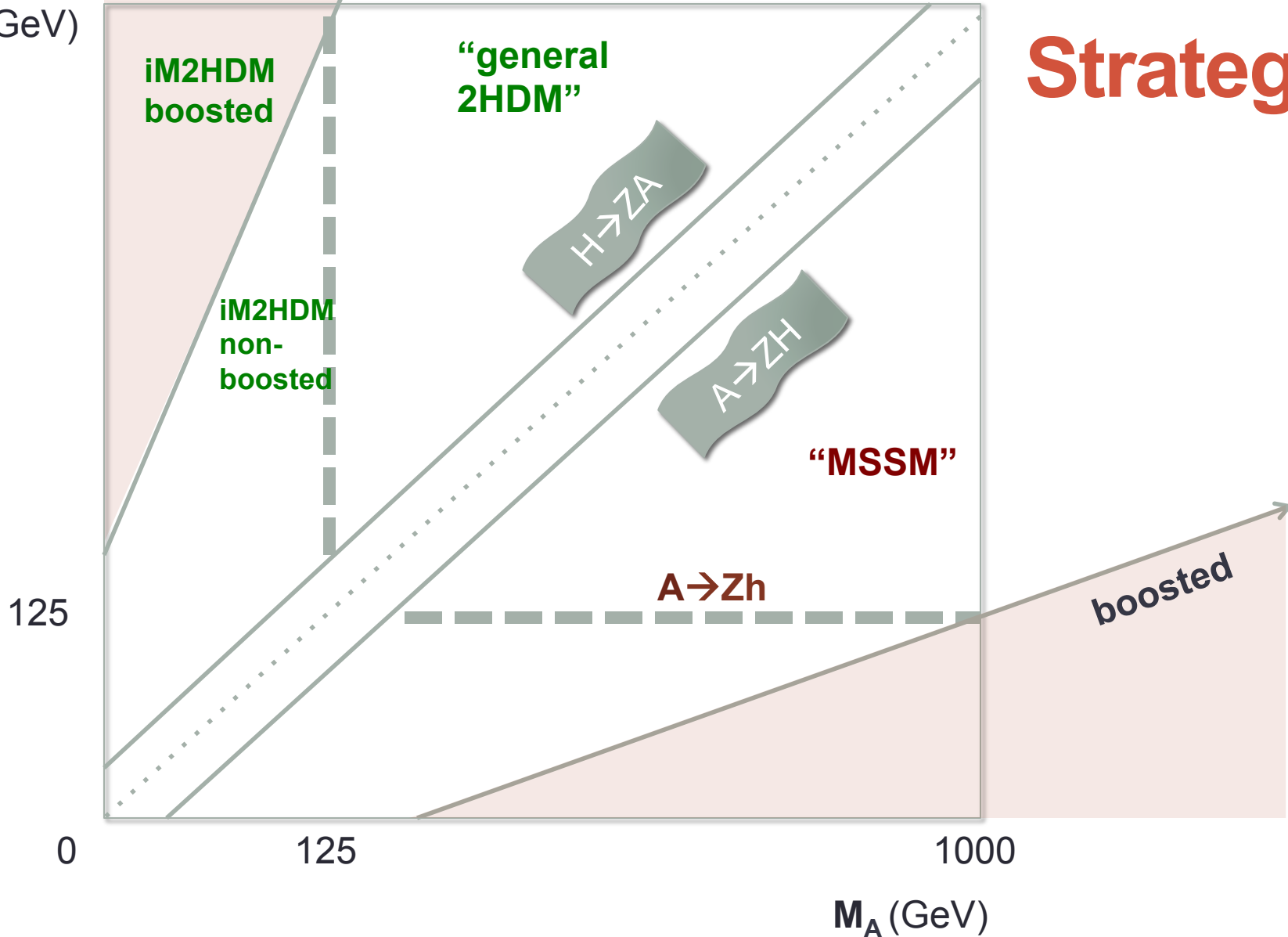


- **Simulation of signal samples**
 - Central simulation by CMS?
 - First version now in **MadGraph 5**
 - FeynRules improvements

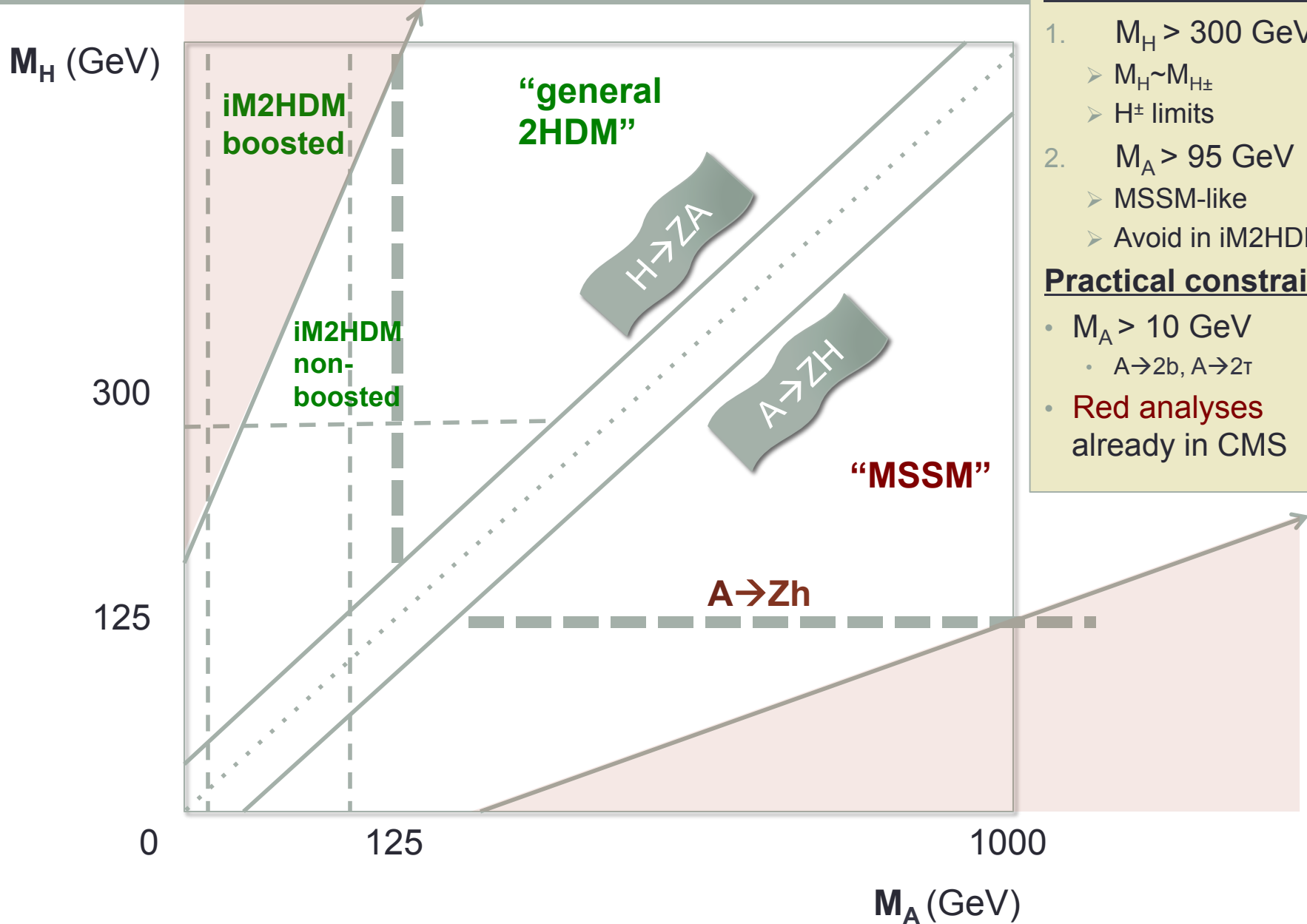


M_H (GeV)

Strategy



M_A (GeV)



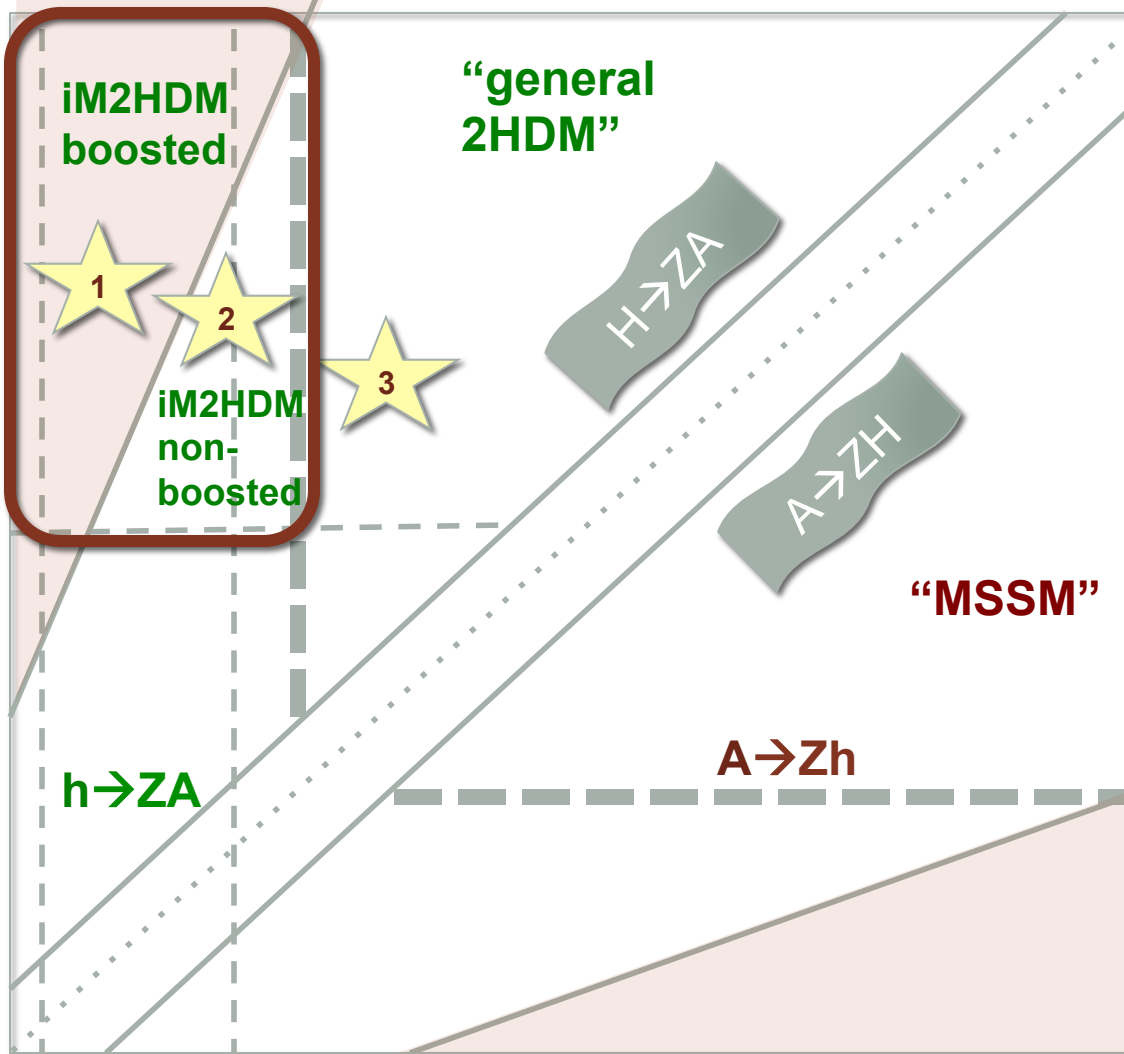
i2HDM constraints:

1. $M_H > 300$ GeV
 - $M_H \sim M_{H^\pm}$
 - H^\pm limits
2. $M_A > 95$ GeV
 - MSSM-like
 - Avoid in iM2HDM

Practical constraints:

- $M_A > 10$ GeV
 - $A \rightarrow 2b, A \rightarrow 2\tau$
- **Red analyses** already in CMS

M_H (GeV)



- Benchmarks:**
1. Boosted i2HDM
 2. Non-boosted i2HDM
 3. General 2HDM

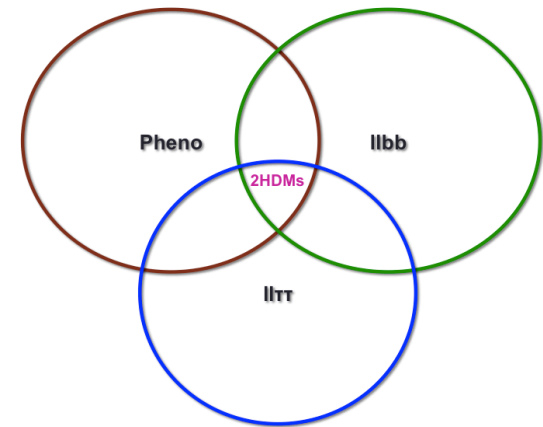
M_A (GeV)

Conclusions

- **2HDMs** are gaining interest
 - Logical extension of SM scalar sector
- **Light pseudoscalar A** possible
 - Often overlooked
 - “Inverted” hierarchy
- Final states: **Z+bb and Z+ $\tau\tau$**
 - Boosted bb and $\tau\tau$ tagging
- Possibly probe **large parameter space**
 - Sensitive to various models

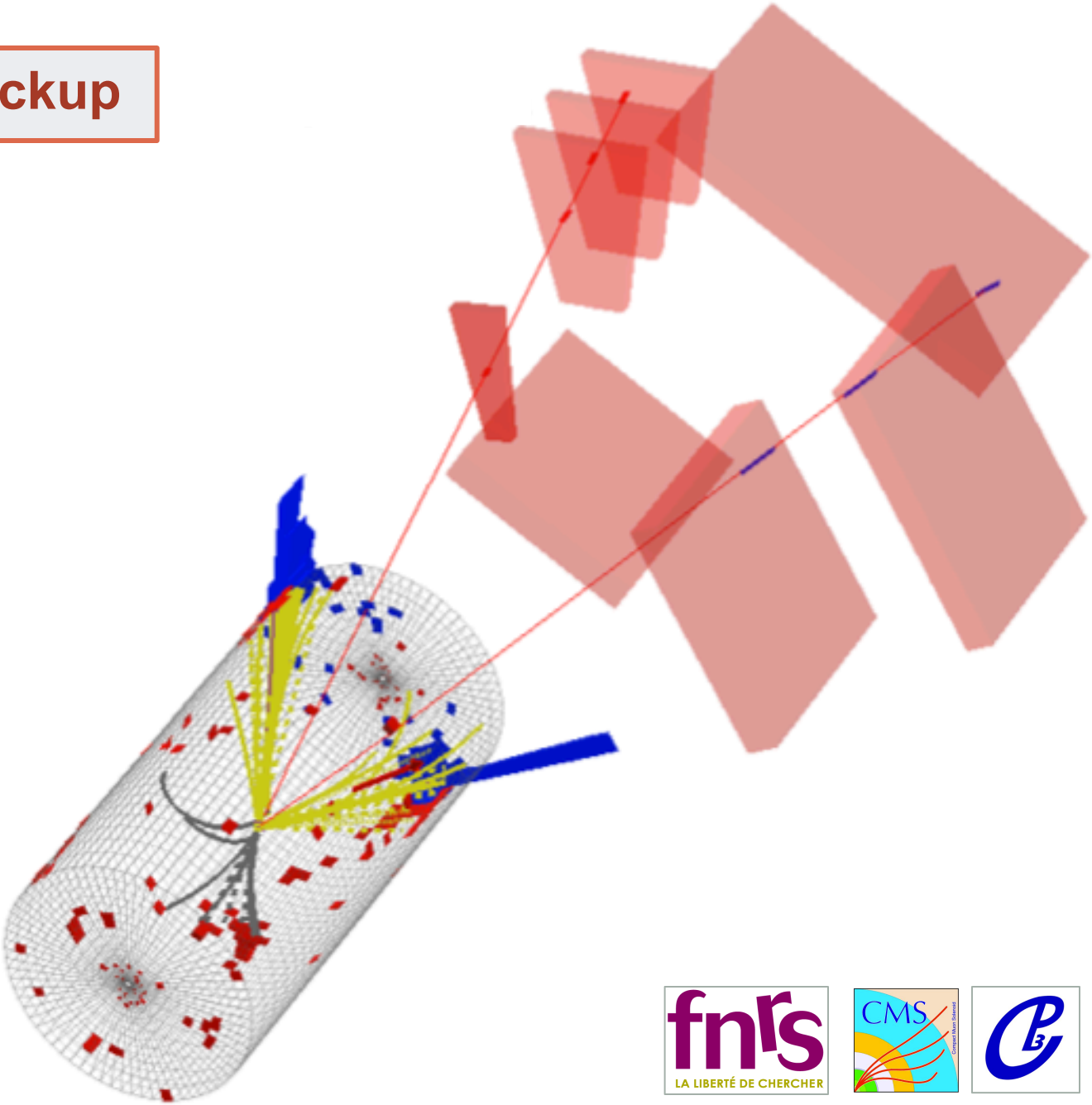
Conclusions

- **2HDMs** are gaining interest
 - Logical extension of SM scalar sector
- **Light pseudoscalar A** possible
 - Often overlooked
 - “Inverted” hierarchy
- Final states: **Z+bb** and **Z+ττ**
 - Boosted bb and ττ tagging
- Possibly probe **large parameter space**
 - Sensitive to various models



**Thank you for
your attention!**

Backup



Status of CP3 studies in $l\bar{l}b\bar{b}$

Being finalized

- **Z+b-jets** cross-section measurements
 - **SMP-13-004** in post-FR
- **H→bb** search
 - Novel multivariate matrix element technique
 - MadWeight-based search in Z(l)H(bb) final state
 - Sensitivity comparable to baseline CMS H→bb result
 - **AN-12-476** being completed
 - See CMS PhD thesis Arnaud Pin: [defense at UCLouvain, 7 Oct]

➤ Next step: $l\bar{l}b\bar{b}$ in 2HDM

- With **inverted mass hierarchy**
- Project description:
 - https://twiki.cern.ch/twiki/bin/viewauth/CMS/HiggsExotics?skin=drupal#2HDM_heavy_H_ZA_l\bar{l}b\bar{b}

i2HDM characteristics

- **SM-like scalar boson h**

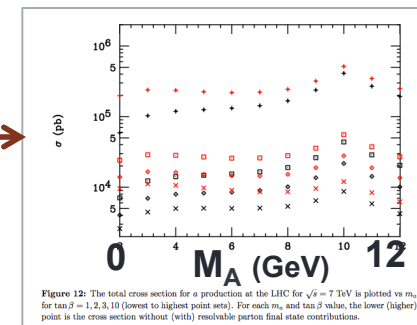
- We now know $M_h \approx 125 \text{ GeV}$

- **Triplet $H^{\pm,0}$**

- Charged H^{\pm} and CP-even H^0
- Constrained by searches for charged Higgs boson: $M_{H^{\pm}} \approx M_{H^0}$
- $M_{H^0} \approx M_{H^{\pm}} > 300 \text{ GeV}$

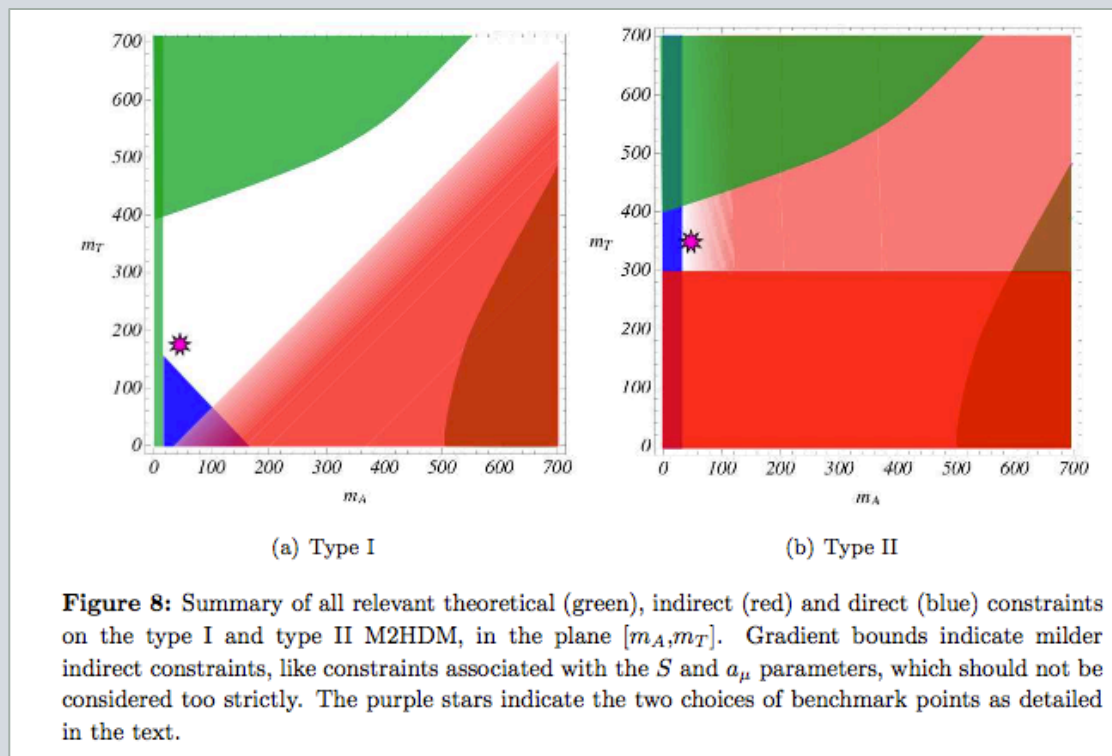
- **Pseudoscalar A**

- Possibly light CP-odd A: $M_A > 0 \text{ GeV}$
 - Even few GeV, see e.g.: <http://arxiv.org/pdf/0911.2460.pdf>
- LEP: Since A is CP-odd \rightarrow no ZZA coupling
- LEP limit: $M_A > 95 \text{ GeV}$, in MSSM-like models



Constraints specific for iM2HDM

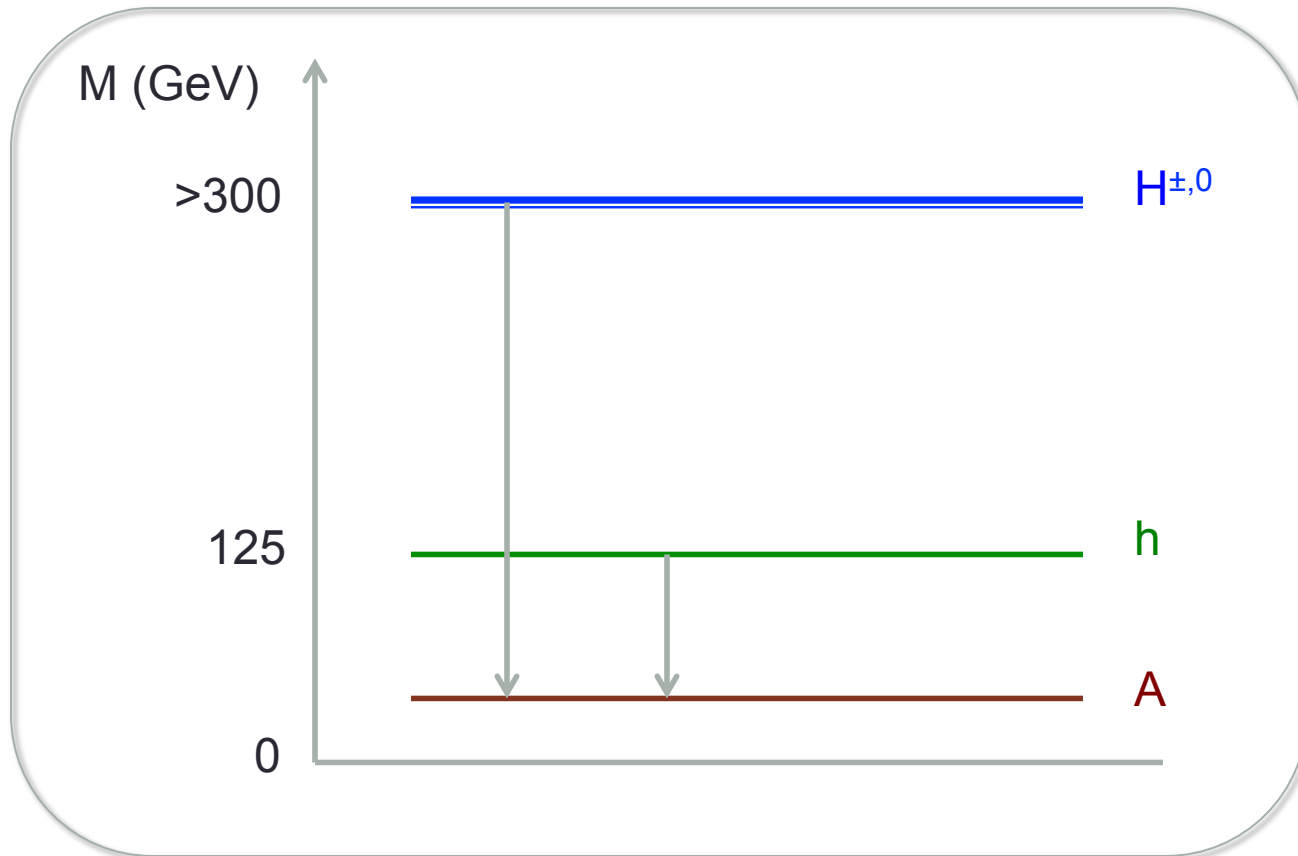
pre-LHC, from <http://arxiv.org/pdf/0904.0705v2.pdf>:



- Shows room for **heavy H & light A**
 - Constraints depend on details of the model

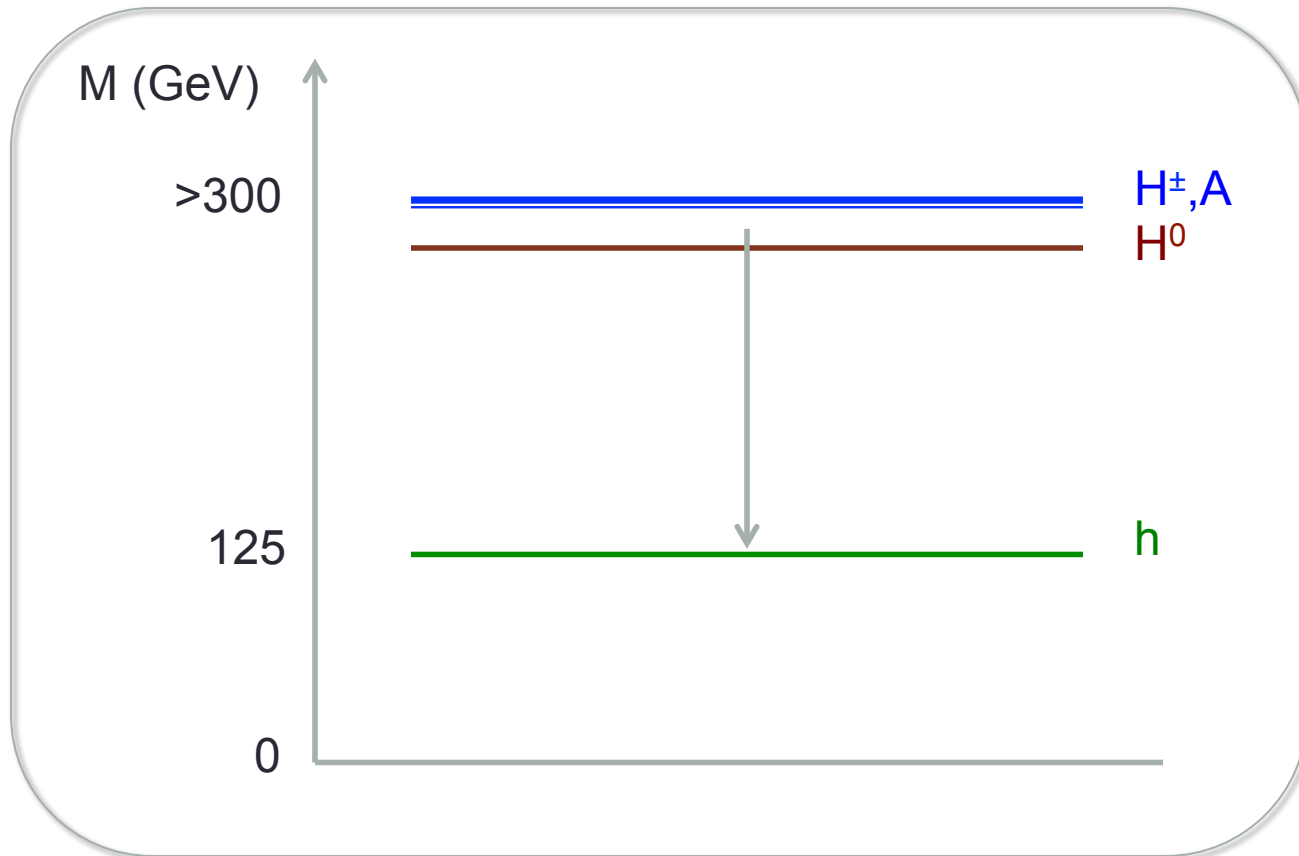
2HDM graph

- The i2HDM model we plan to search for:



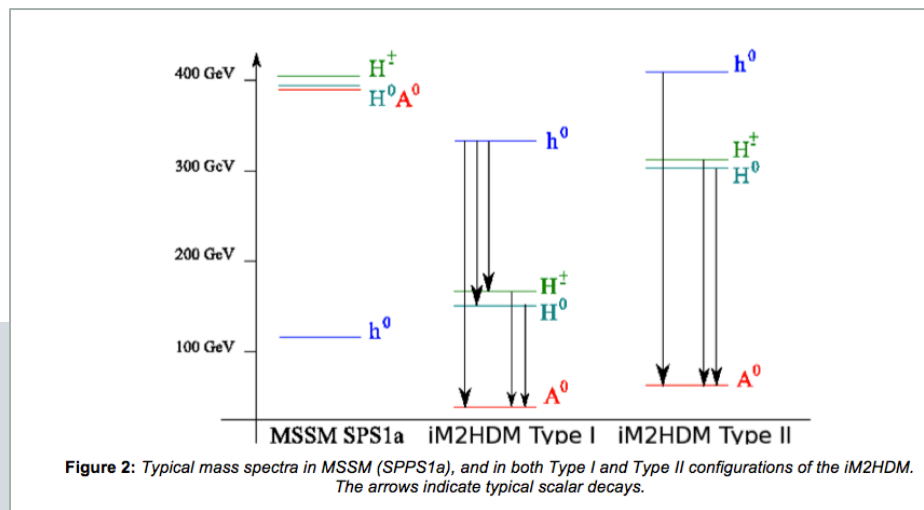
i2HDM graph

- The susy 2HDM model



Inverted hierarchy

iM2HDM example:



References:

- [11] S. Davidson and H.E. Haber, "Basis-independent methods for the two-Higgs doublet model", Phys. Rev. D72 (2005) 035004 [hep-ph/0504050].
- [12] J.M. Gerard and M. Herquet, "A twisted custodial symmetry in the two-Higgs-doublet model", Phys. Rev. Lett. 98 (2007) 251802.
- [13] S. de Visscher et al., "Unconventional phenomenology of a minimal two-Higgs-doublet model", JHEP 0908:042 (arXiv:0904.0705), 2009.
- [14] M. Herquet, "A twisted two-Higgs-doublet model: motivation and phenomenology", PhD thesis, UCL, 2007.
- [15] S. de Visscher, "Observability of an unconventional two-Higgs-doublet model at the LHC", PhD thesis, UCL, 2009.

More recent publication: arXiv:1308.1979

- a.o. David Lopez-Val (now UCL-CP3)
- Several two-Higgs doublet benchmarks

Constraints

Example: how phenomenologists retrieve them

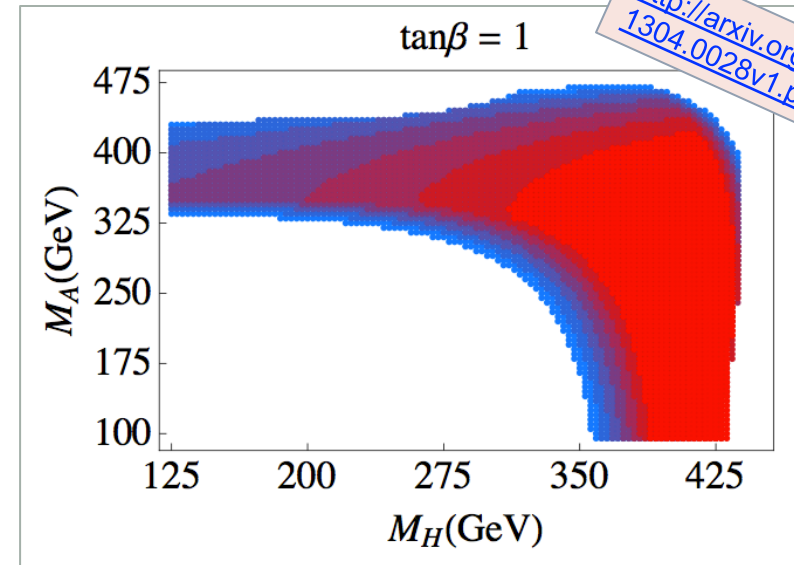
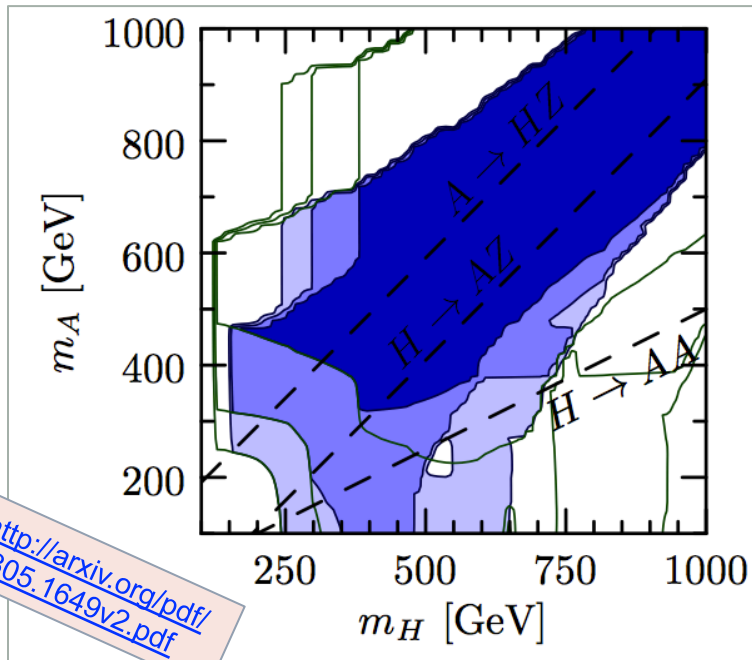
- **Possibilities remaining for 2HDMs**, example of recent overview: <http://arxiv.org/abs/1308.1979>
 - a.o. David Lopez-Val (now UCL-CP3)
 - Several two-Higgs doublet benchmark scenarios
 - Implements (indirect) constraints on α/β with few theoretical assumptions
 - Still susy-like scenarios

Constraints from:

- **2HDMC**: “T” & “S”, EWK precision
- **HiggsBounds**: bounds on Higgs masses
 - E.g.:
 - $\tan\beta > 1$ (B-Bbar mixing)
 - $\tan\beta < 10$ ($b \rightarrow s\gamma$, etc)
 - Direct constraint $M_{H_{\pm}} > 300$ GeV

Recent constraints

- **Examples.** NB: these papers use the MSSM-like constraint from LEP
 - $M_A > 95$ GeV
- Even then still **much room remaining**
 - Also with inverted hierarchy



Top plot ($\tan\beta=1$) favors

- **Heavy M_H** (~ 400 GeV)
- **Lighter M_A** (95-400 GeV)

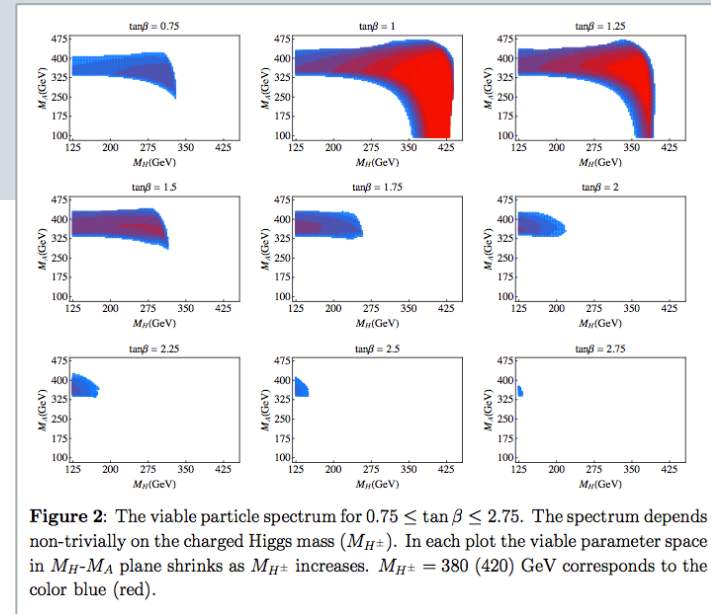
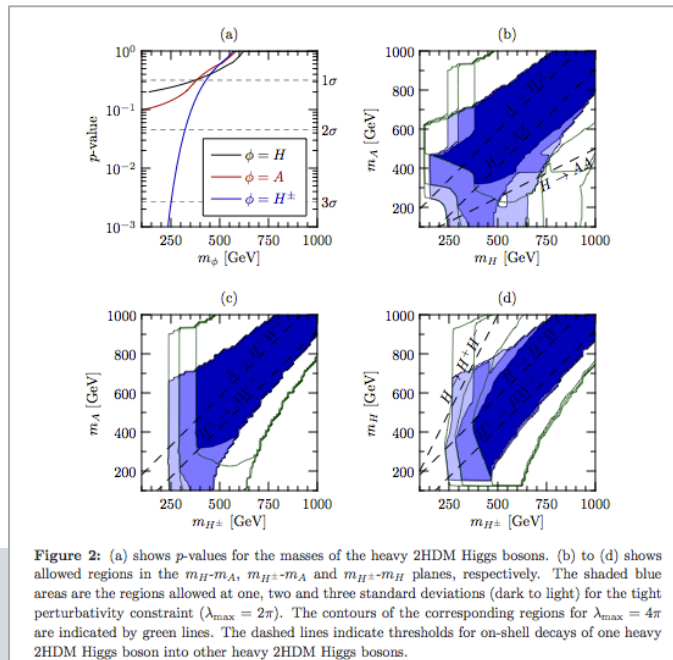
- Next pages:
schematic overview of possibilities
from point-of-view of **experimentalist!**

References

Examples: recent constraints

- Figure 2

- From <http://arxiv.org/pdf/1304.0028v1.pdf>
- See also the discussion in section 5.2



- Figure 2

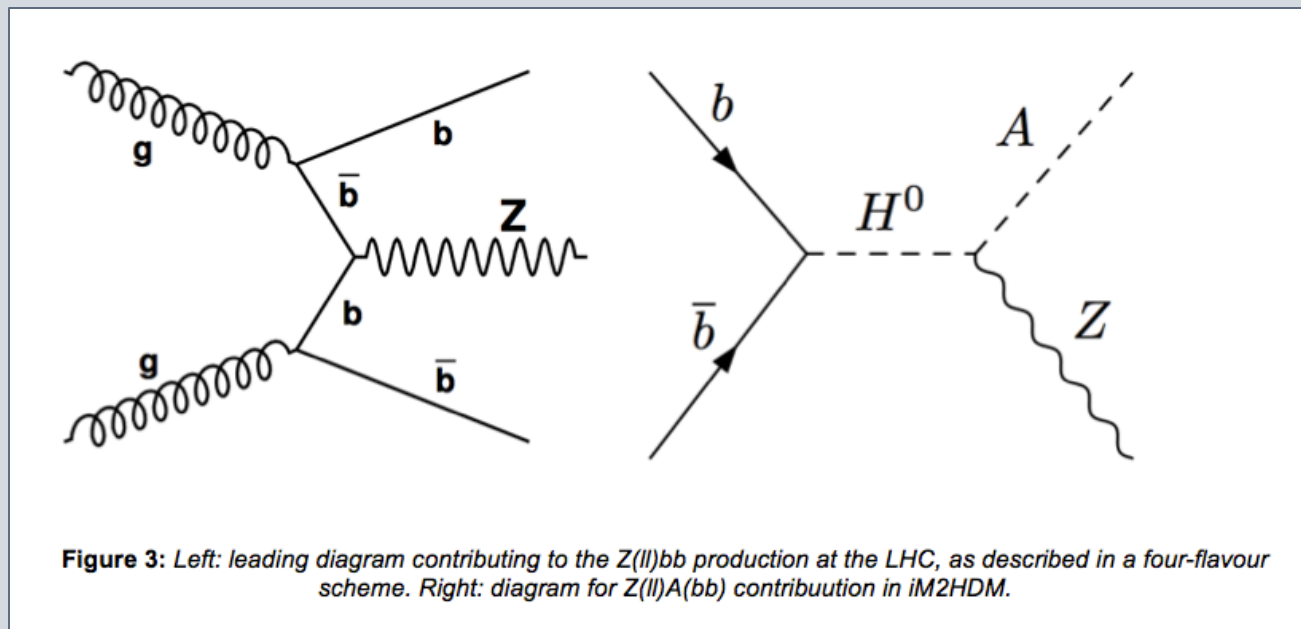
- From <http://arxiv.org/pdf/1305.1649v2.pdf>

Workplan

- Scan the **two free observable parameters**:
 - $M_A > 10 \text{ GeV}$
 - $M_H > 300 \text{ GeV}$
- Use benchmarks in previous slide
 - Avoid overlaps with existing CMS searches
- Put limit on (or observe) **cross section of $H \rightarrow Z(\ell)A(bb)$**
 - Model-independent limits
 - Can be interpreted depending on couplings
 - Couplings different for different 2HDMs

Boosted $X \rightarrow bb$ tagging

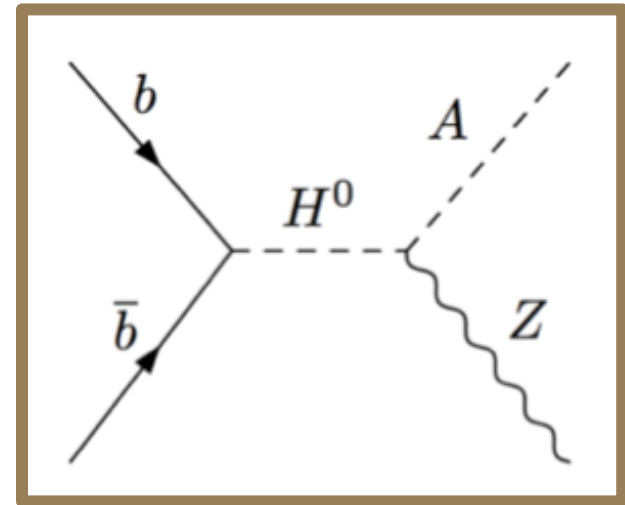
- Existing documented studies of collinear $bb\bar{b}$ production are the following:
 - **Standalone IVF**
 - used for $bb\bar{b}$ angular correlations in events with jets:
 - BPH-10-010 (journal publication in JHEP03(2011)136)
 - for $bb\bar{b}$ angular correlations in associated Z boson production
 - EWK-11-015 (final reading finished, submitted to journal)
 - **b-tagging in subjets**
 - Specific development for boosted $H \rightarrow bb$ (no use of IVF):
 - BTV-13-001 (paper draft in preparation)



In summary

We plan to search for

- i2HDM
- $H^0 \rightarrow Z(\ell\ell)A(bb)$
- Light A: $M_A > 10 \text{ GeV}$
- Heavy H: $M_H > 300 \text{ GeV}$
- Possibly boosted topologies



“I am suspicious about no-go theorems.
One often forgets to mention the smallprint,
which withholds us from further investigating interesting possibilities”

- Gerard 't Hooft (from “In search of the ultimate building blocks”)

“We should never have told you experimentalists about $\tan\beta$ ”

- Anonymous phenomenologist