Searches for beyond the Standard Model Higgs bosons in ATLAS & CMS

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On behalf of the ATLAS & CMS collaborations

ASTROPARTICLE PHYSICS 2014
A joint TeVPA/IDM conference

After the discovery of 125 GeV EBH boson

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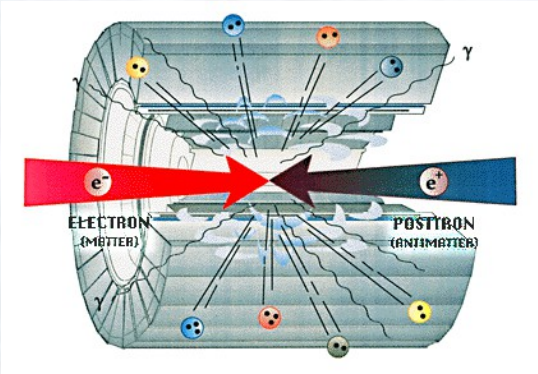
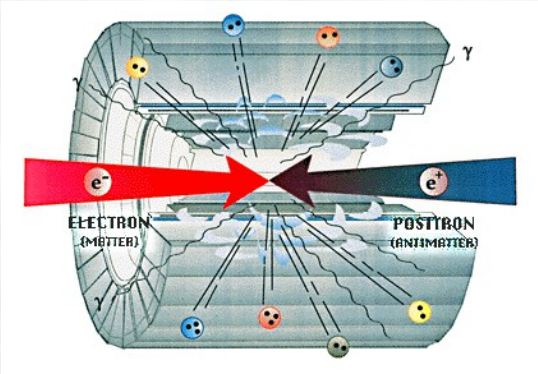


Collider physics : all Standard Model consistent
A marvellous & much acclaimed achievement of modern science

After the discovery of 125 GeV EBH boson



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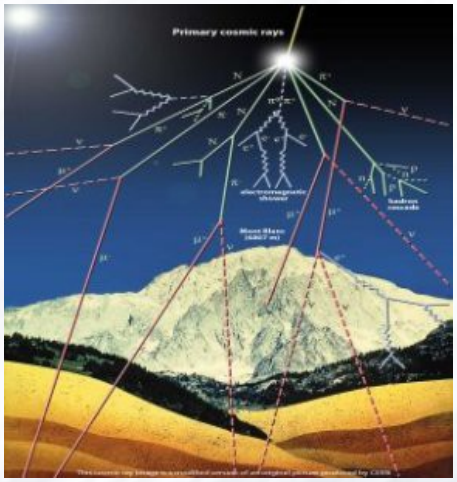
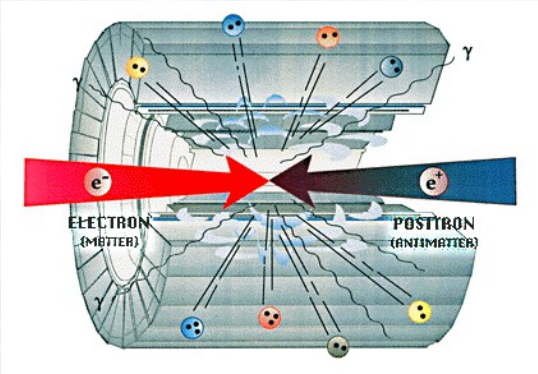


Cosmology, astrophysics & : many long-lasting puzzles
astroparticle

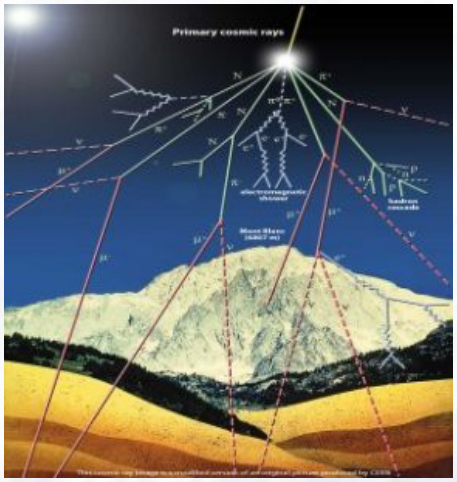
- matter-antimatter asymmetry
- dark matter
- dark energy
- cosmic inflation
- neutrino masses & oscillations

After the discovery of 125 GeV EBH boson



Collider physics : all Standard Model consistent
A marvellous & much acclaimed achievement of modern science

Can the physics of fundamental scalar field(s) help to bridge these two domains ?



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- matter-antimatter asymmetry
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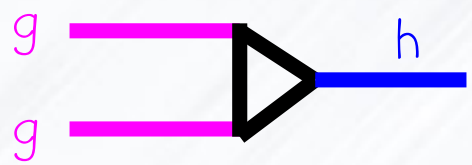
Many theorists say yes

- In general, any extension of SM comes with extra scalar fields and Higgses
- Extra scalar singlets
- More scalar doublets like in 2 Higgs Doublet Models (2HDM)
- Supersymmetry : MSSM, NMSSM...
- Extra scalar triplets
- Inflaton
- ....

Search strategies

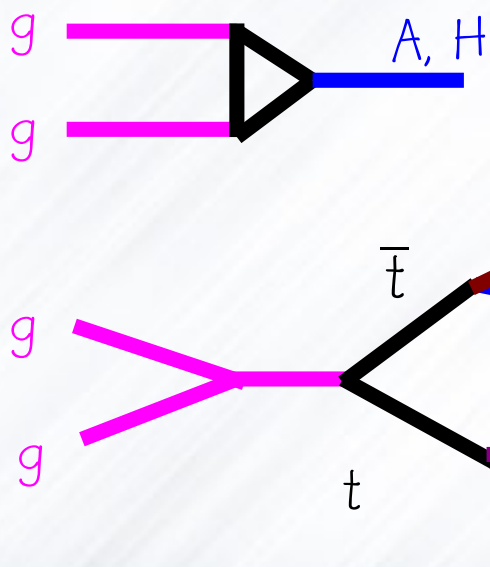
- Indirect search through careful studies of 125 GeV EBH boson properties & decays



+ sub-dominant production channels : VBF, VH, ttH...

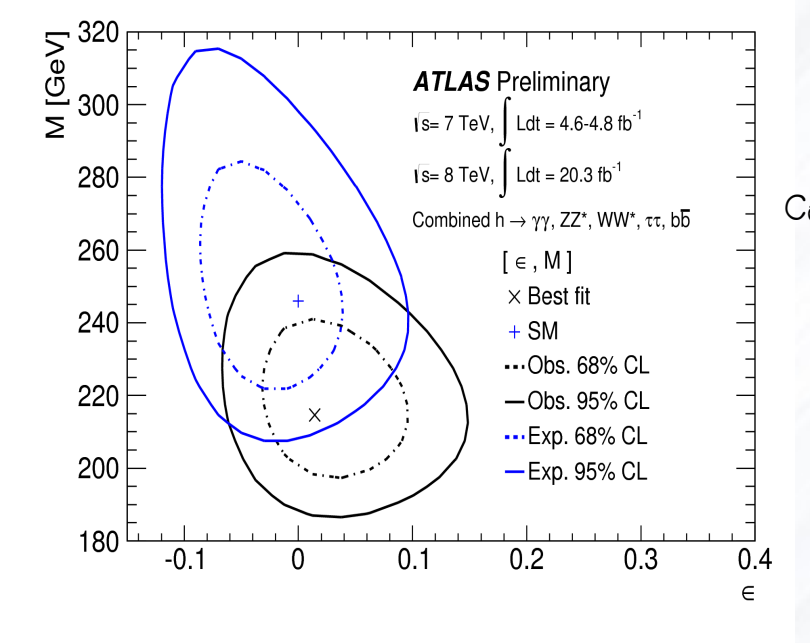
- Direct search from decays of extra neutral or charged Higgs(es)

(associated production may also significantly contribute)



$m_{H^+} < m_t$

Probe mass scaling of observed h couplings



- General consistency test of observed h decay rates in all channels with respect to SM

Couplings to fermions (f) and vector bosons (v) scale like :

$$k_{f,i} = v \frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$ linear mass dependence

$$k_{V,j} = v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$ quadratic mass dependence

SM $\Rightarrow$ $\epsilon = 0, M = v = 246$ GeV

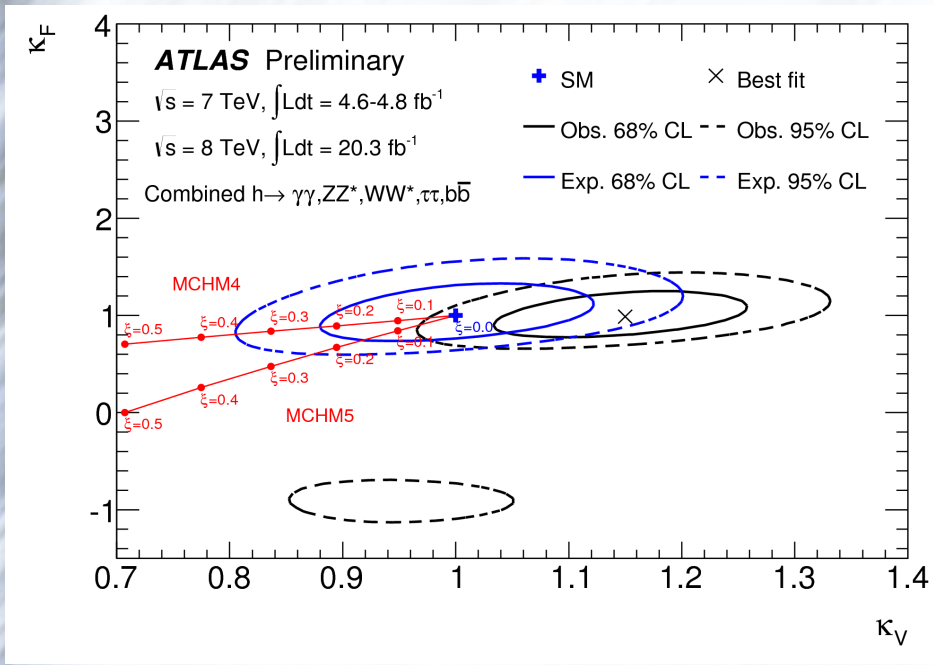
Best fit agrees with SM at 1.5 σ

ATLAS-CONF-2014-010

Ellis & You, JHEP 1306 (2013) 103

Could observed h be composite ?

- Minimal Composite Higgs Models – Scaling factors times SM couplings



ATLAS-CONF-2014-010

K. Agashe et al., Nucl.Phys. B719 (2005) 165

R. Contino, Phys. Rev. D75 (2007) 055014

M.S. Carena et al. Phys. Rev. D76 (2007) 035006

MCHM4 : $k = k_v = k_f = \sqrt{1-\epsilon}$, with $\epsilon = v^2/f^2$

f is the h compositeness scale

SM : $f \rightarrow \infty$, $\epsilon = 0$

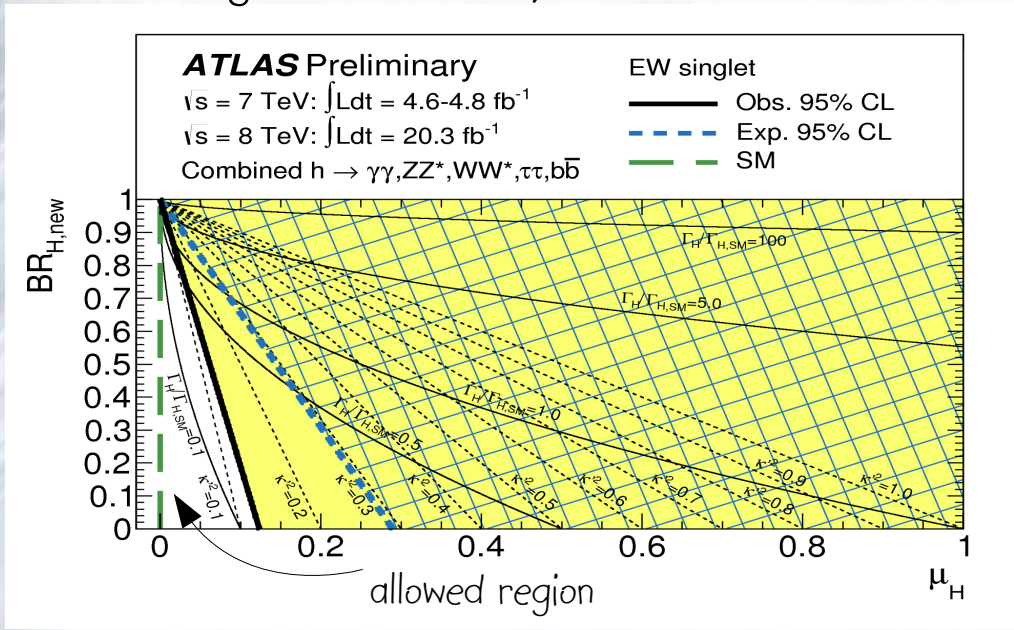
$f > 710\,\mathrm{GeV}$ or $0 \leqslant \epsilon < 0.12$ @ 95 CL

MCHM5 : $k_v = \sqrt{1-\epsilon}$, and $k_f = \frac{1-2\epsilon}{\sqrt{1-\epsilon}}$

$f > 640\,\mathrm{GeV}$ or $0 \leqslant \epsilon < 0.15$ @ 95 CL

Extra EW scalar singlet in data ?

- Assume the addition of a scalar singlet that mixes with doublet state after SSB to produce two neutral Higgses : h & H
- Assume both couple to f and V in a similar way as SM but with a strength reduced by k & k' scale factors, for h & H respectively



$k^2 + k'^2 = 1$

$k^2 = \mu_h$ signal strength of h

$k'^2 = 1 - \mu_h$

$\mu_H = k'^2 (1 - BR_{H,new})$ signal strength of H

branching ratio of all new non-SM kinematically-allowed channels that open when m_H increases

SM: $k' = 0 = \mu_H$

ATLAS-CONF-2014-010

LHC Higgs XS WG, arxiv : 1307.1347[hep-ph]

A. Hill & J van der Bij, Phys. Rev. D36

M. Veltman & F. Yndurain, Nucl. Phys. B325 (1989) 1

T. Binoth & J. van der Bij, Z. Phys. C75 (1997) 17

R. Schabinger & J.D. Wells, Phys. Rev. D 72 (2005) 093007

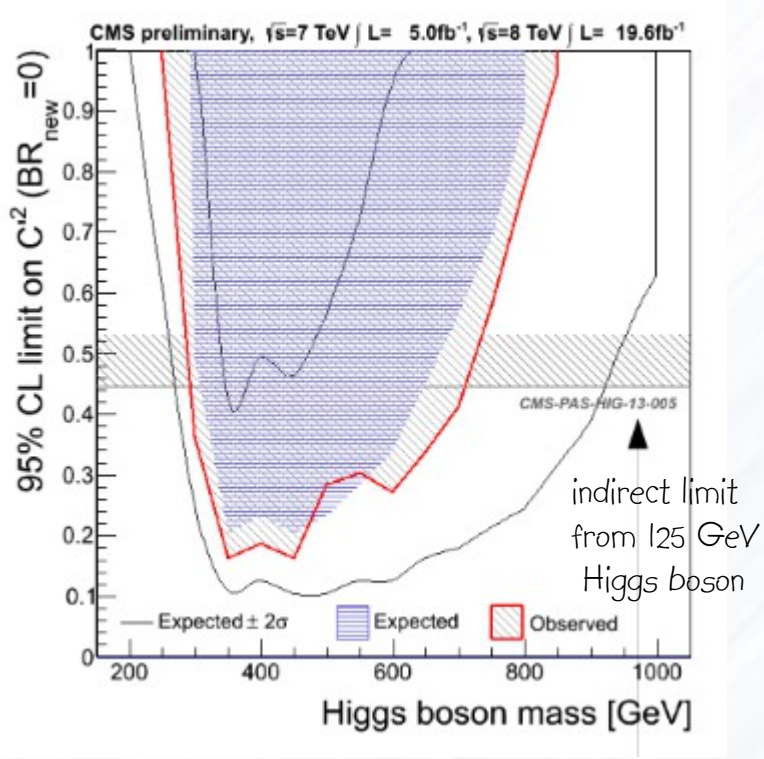
B. Patt & F. Wilczek, arxiv : hep-ph/0605188

G.M. Pruna & T. Robeus, arxiv : 1303.1150 [hep-ph]

Extra EW scalar singlet in data ?

Similar limits were obtained with CMS in direct & indirect searches

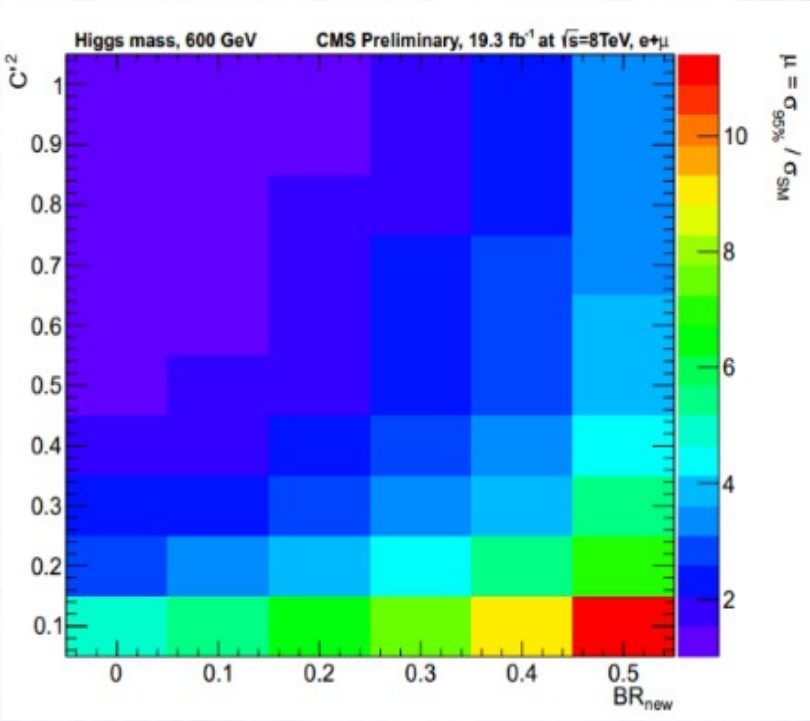
H-> ZZ -> 2 l 2 ν



$C'^2 = K'^2$

CMS-PAS-HIG-13-014

H-> WW -> lν qq'



CMS-PAS-HIG-13-008

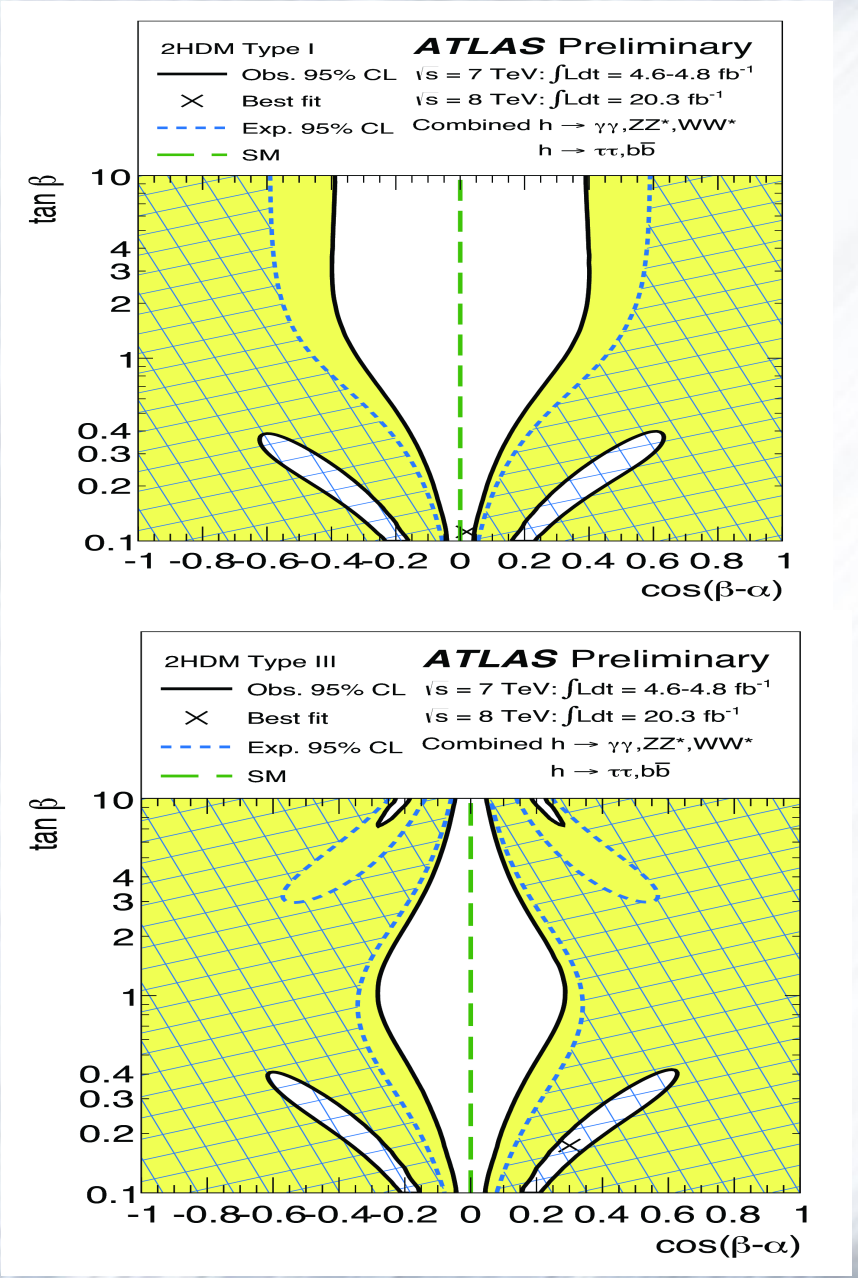
2HDM reminder

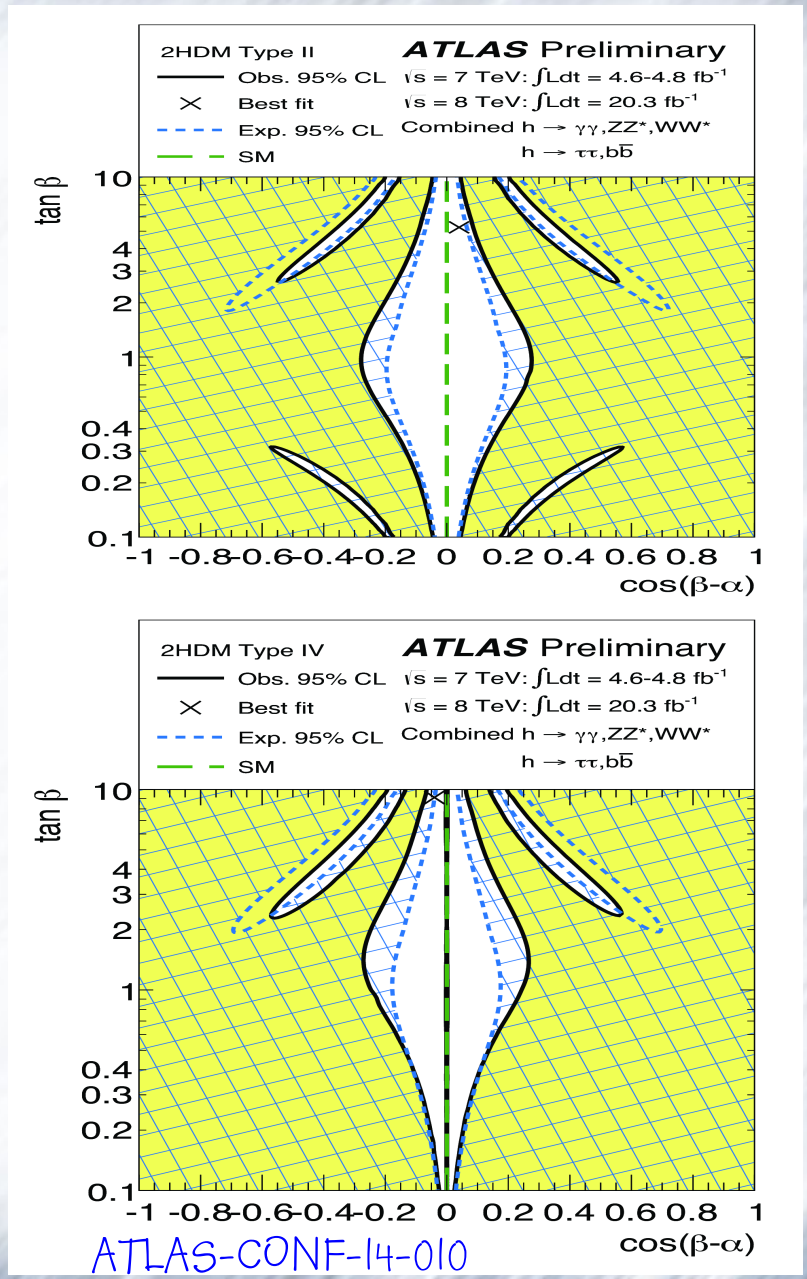
- 8 initial degrees of freedom
  - 3 eaten by W_L's and Z_L
  - 3 neutral Higgses and 2 charged ones (H^+, H^-)
- CP conservation and Paschos-Glashow-Weinberg condition :
  - 2 CP-even neutrals : h & H, 1 CP-odd neutral A, H^+, H^-
  - 4 Higgs masses, $\tan\beta = v_u/v_d$, α : h & H mixing angle
  - $v_u^2 + v_d^2 = v^2 = (246\ \text{GeV})^2$

	coupling scale factor of h /SM	type I fermiophobic	type II MSSM like	type III lepton-specific	type IV flipped
gauge bosons	k_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
up quarks	k_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
down quarks	k_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
charged leptons	k_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

G. Branco et al :arXiv:1106.0034 [hep-ph].

Additional scalar doublet in data ?





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Simplified MSSM

- In such a model, coupling scale factors are expressed as functions of m_A and $\tan\beta$.

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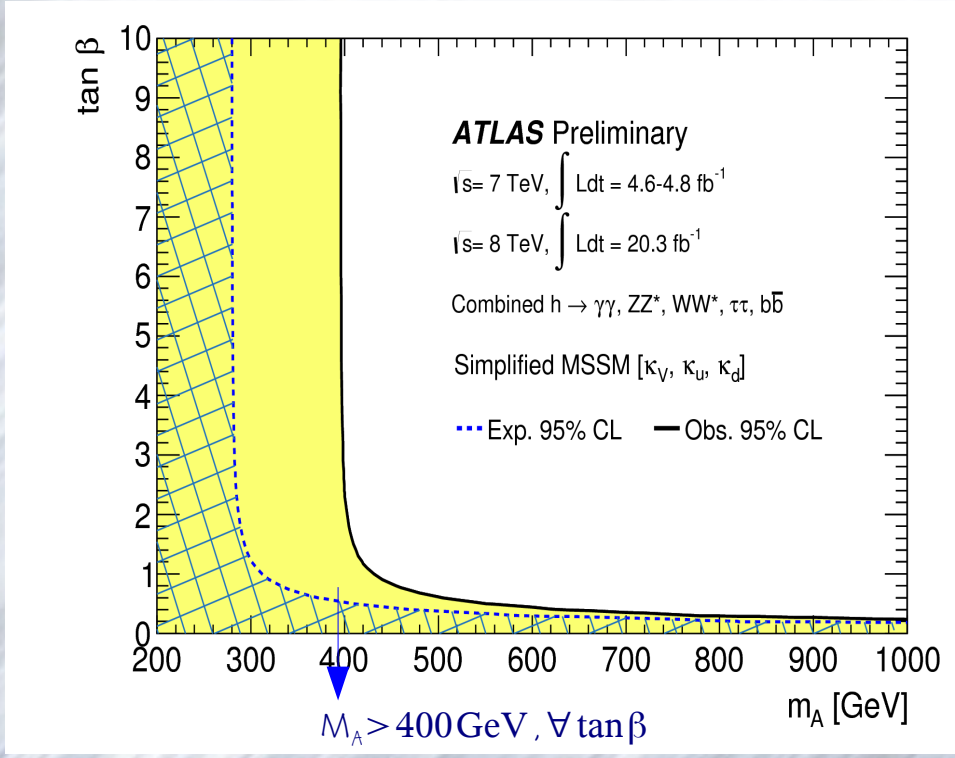


$$\kappa_V = \frac{s_d(m_A, \tan\beta) + \tan\beta \; s_u(m_A, \tan\beta)}{\sqrt{1+\tan^2\beta}}$$

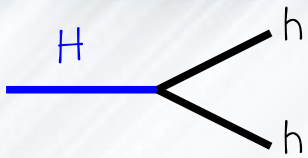
$$\kappa_u = s_u(m_A, \tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

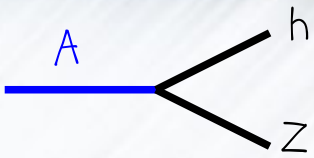
$$\kappa_d = \kappa_l = s_d(m_A, \tan\beta)\sqrt{1+\tan^2\beta}$$

$$s_u = \left(1 + \left(\frac{(m_Z^2 + m_A^2)\tan\beta}{m_Z^2 + m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)}\right)^2\right)^{-1/2}$$

$$s_d = \frac{(m_Z^2 + m_A^2)\tan\beta}{m_Z^2 + m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)} \; s_u$$

direct search for H->hh & A->Zh



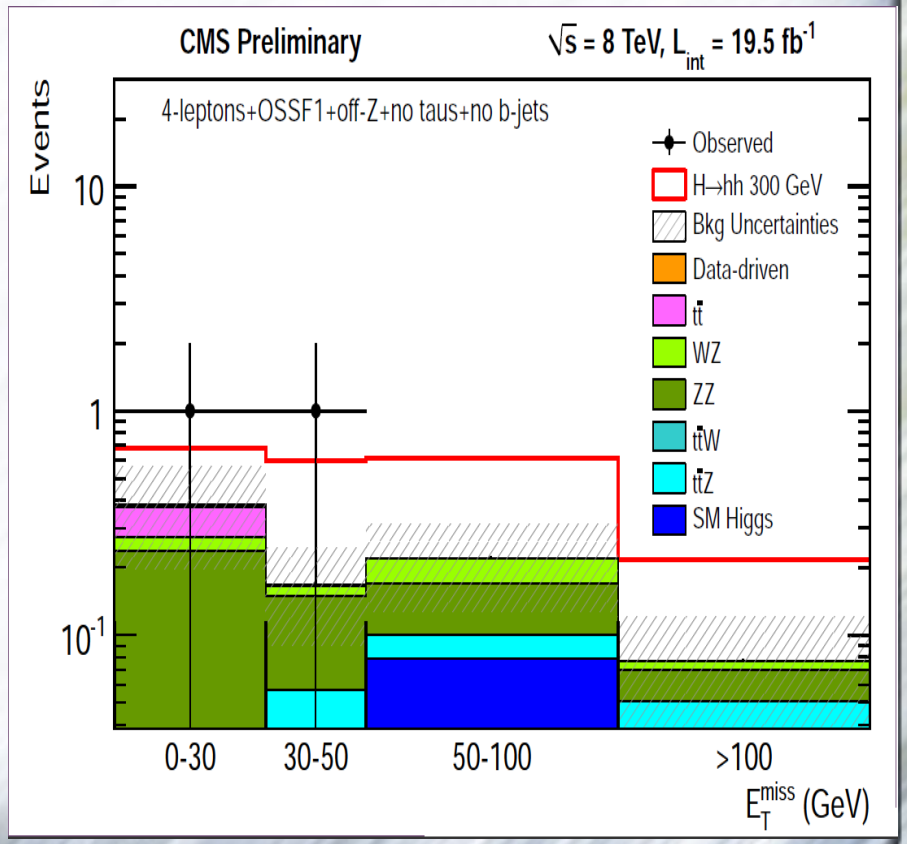


- for $m_H > 2\ m_h$ and $2\ m_h < m_A < 2\ m_t$, these decays are predominant
- h decays like in SM, leads to multilepton and diphoton signatures further categorized as in table below

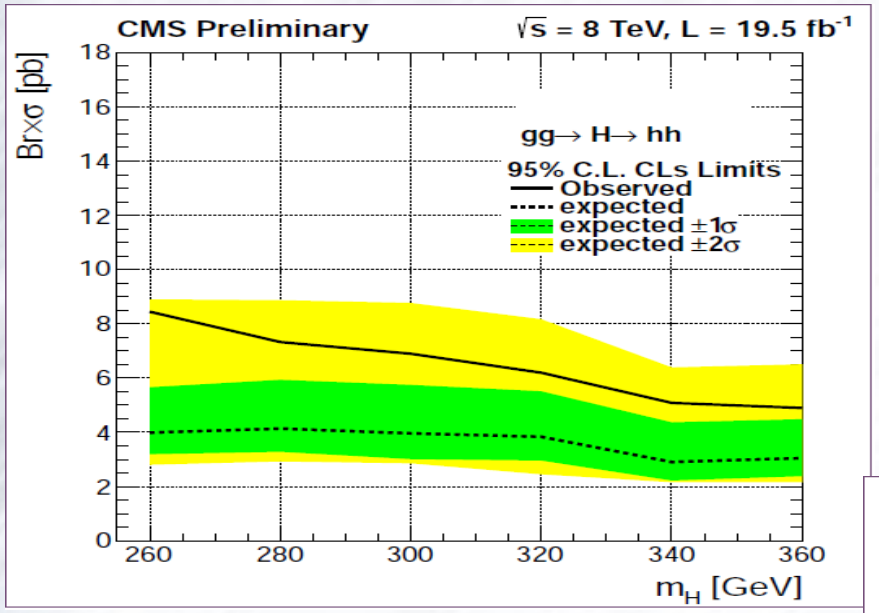
leptons	photons	opposite side same flavor pairs	hadronic tau	b-tag
4	0	0,1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

each channel further divided in bins of E_T^{miss}

CMS-PAS-HIG-13-025



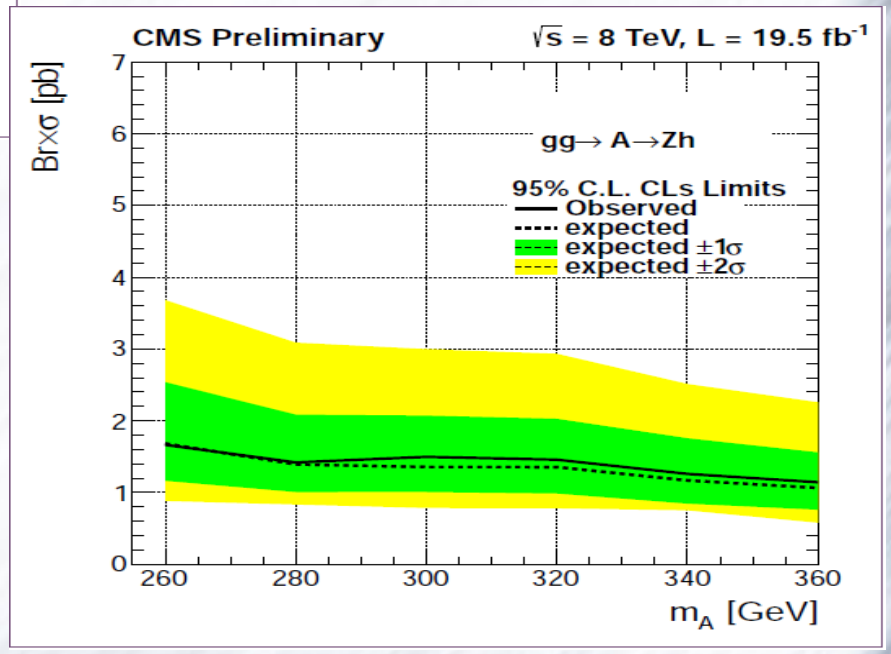
direct search for H->hh & A->Zh



CMS-PAS-HIG-13-025

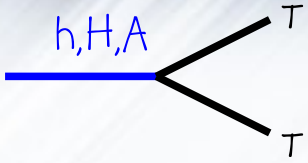
model-independent limits

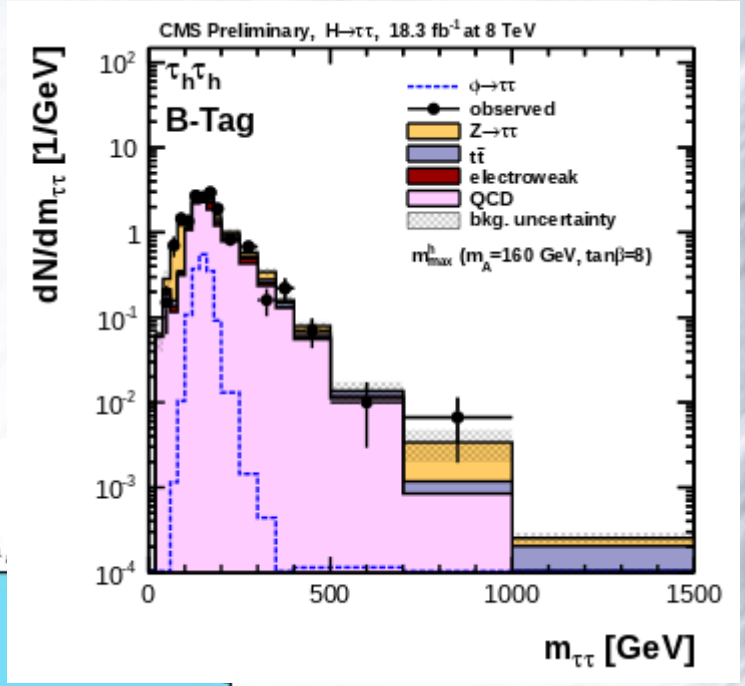
Bxσ H (A) production probed down to 4 (1.5) pb.

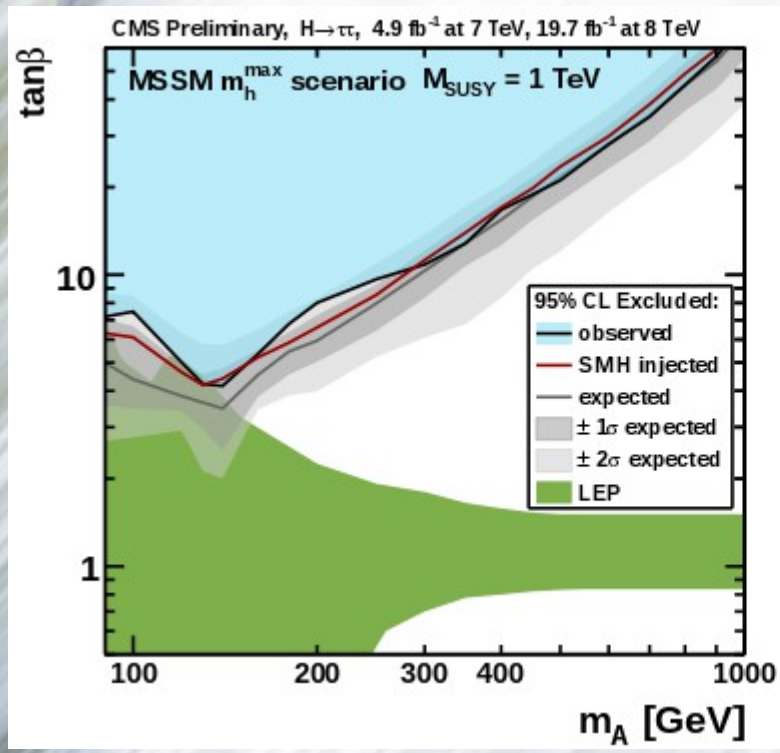


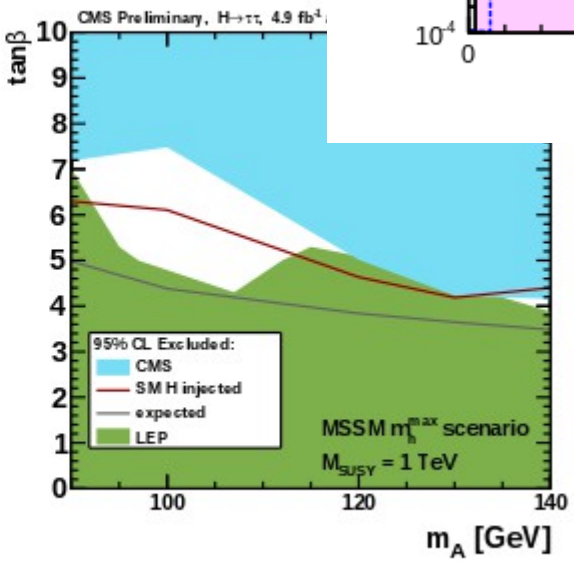
Direct search for MSSM h,H,A-> 2 taus

- h is 125 GeV SM Higgs
- 0 or 1 b-tag for ggF or bbH production
- MSSM m_h^{max} scenario (to push m_h to 125 GeV)









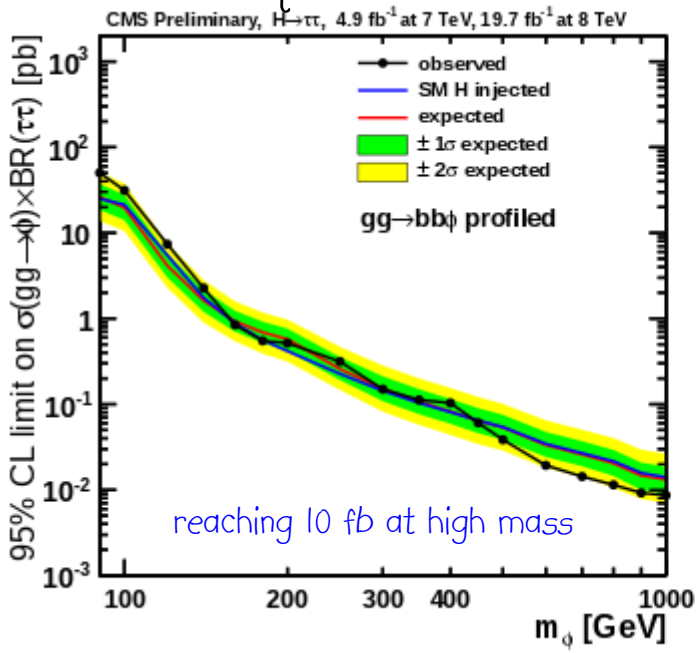
CMS-PAS-HIG-13-021

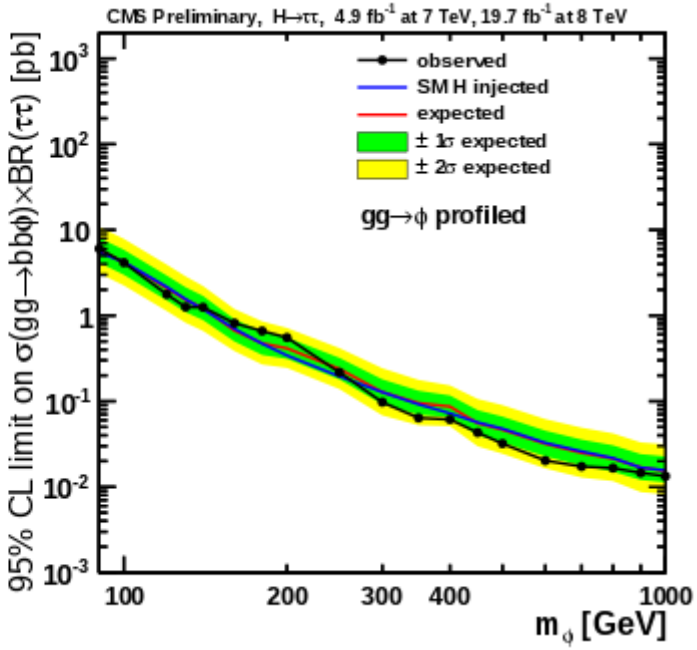
MS. Carena et al.
Eur. Phys. J.C. 45 (2006) 797
Eur. Phys. J.C. 26 (2003) 601

Complementary to ATLAS indirect search limits especially at high m_A

Direct search for ϕ-> 2 taus

- same analyzed data interpreted in a model independent way
- search for a unique scalar resonance : ϕ



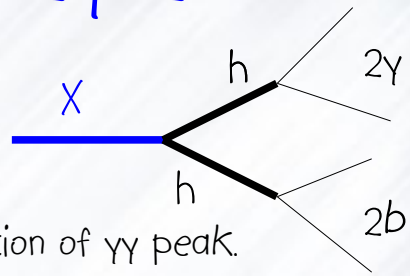


b-associated (bbH) production mode

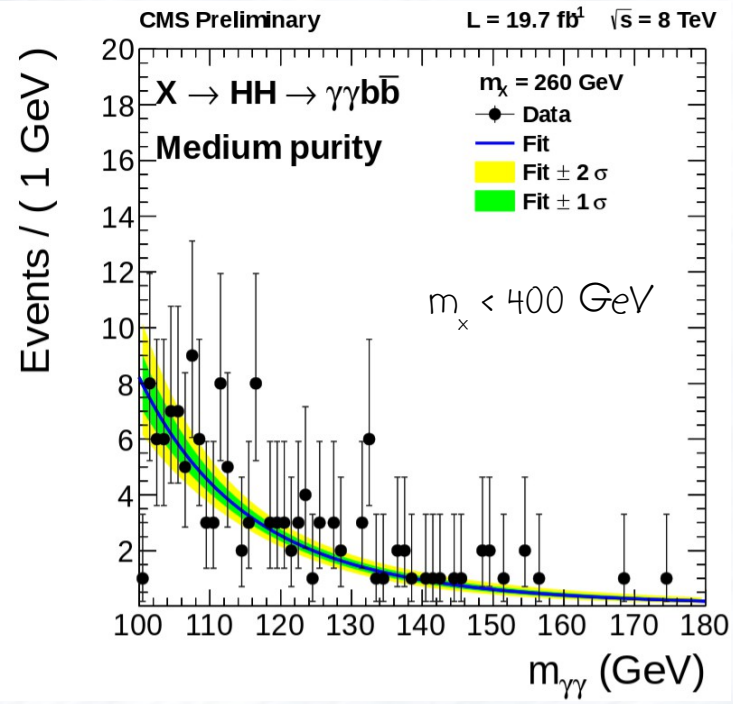
gg fusion production mode

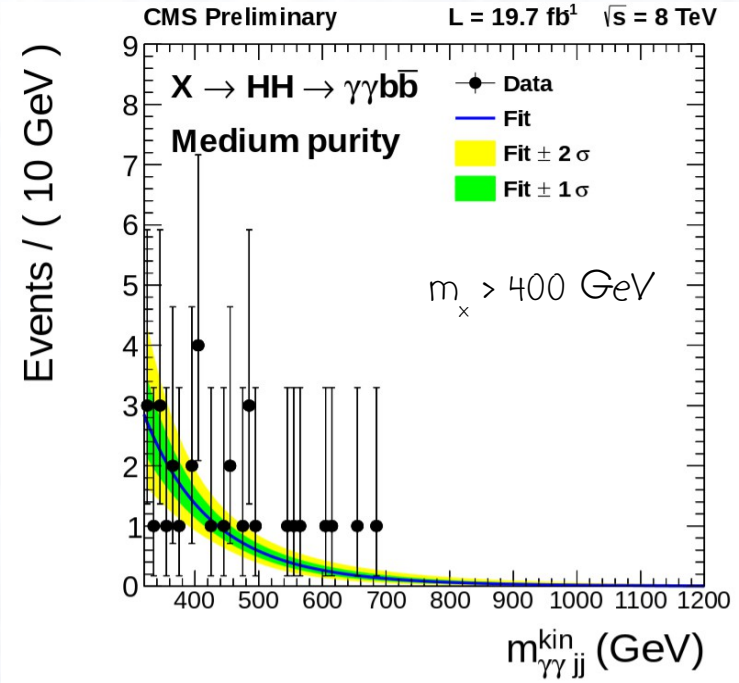
CMS-PAS-13-021

direct search of X -> hh -> 2γ 2b



- search for a new hh resonance in the m_X region 260-1100 GeV
- combines high bb BR with better background rejection capability & resolution of γγ peak.
- search in the $m_{\gamma\gamma}$ spectrum for m_X < 400 GeV and in $m_{\gamma\gamma jj}$ spectrum for m_X > 400 GeV

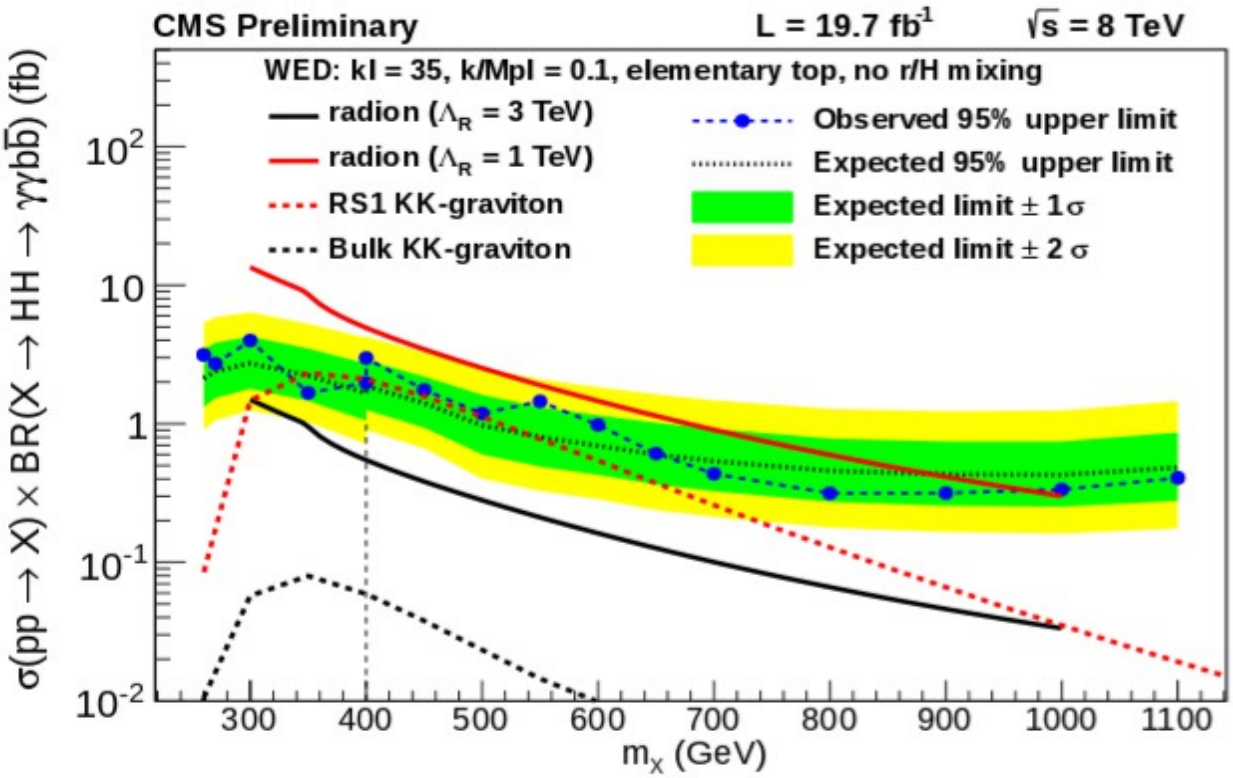




CMS-PAS-13-032

direct search of X -> hh -> 2γ 2b

- Model-independent upper limit
- Prediction lines of several Wrapped Extra Dimension models also shown



CMS-PAS-13-032

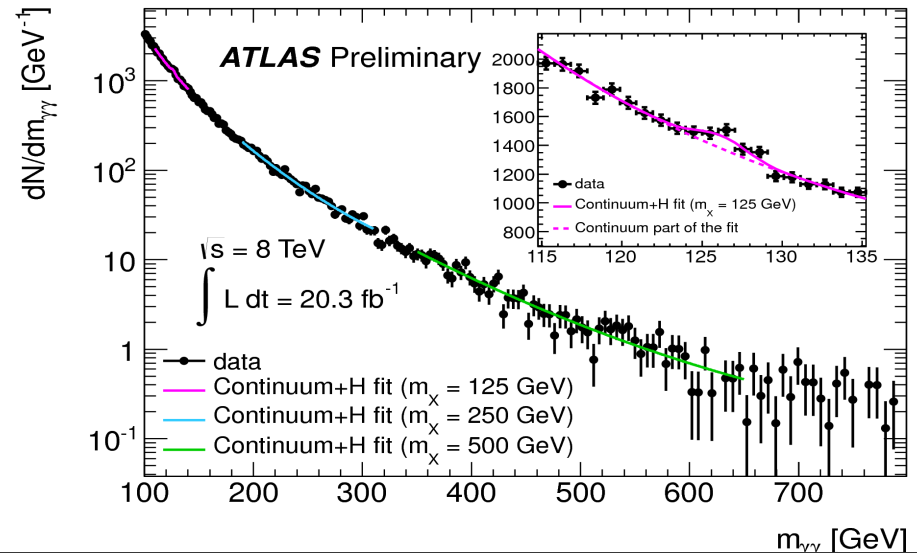
C. Csaki et al. : arXiv hep-th/0008151
L. Randall & R. Sundrum : arXiv hep-ph/9905221
T. Hapola and O. Antipin : http://cp3-origins.dk/research/units/ed-tools
P. Aquino : http://feynrules.irmp.ucl.ac.be/wiki/RSmodel
A. L. Fitzpatrick et al. : arXiv hep-ph/0701150
G. F. Giudice et al. : arXiv hep-ph/0002178

Ruling out one radion model up to m_x = 1 TeV

Model-independent search for H -> 2 photons

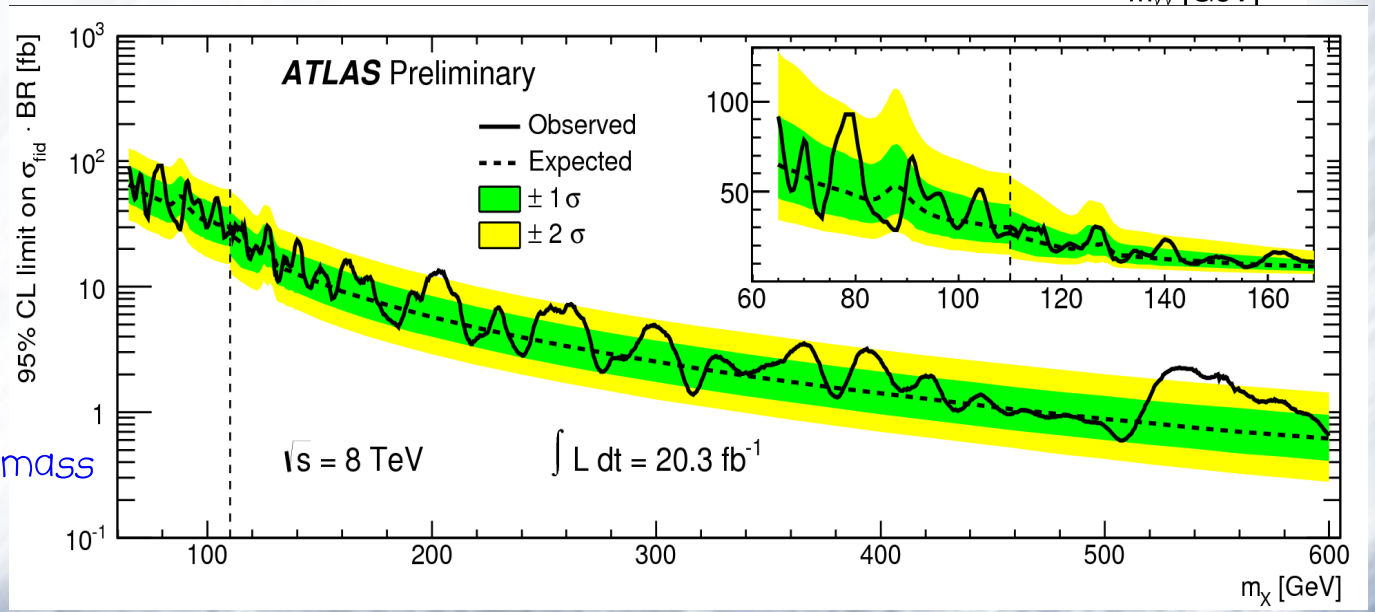
ATLAS-CONF-2014-031

Searching for another scalar resonance that would decay into 2 photons



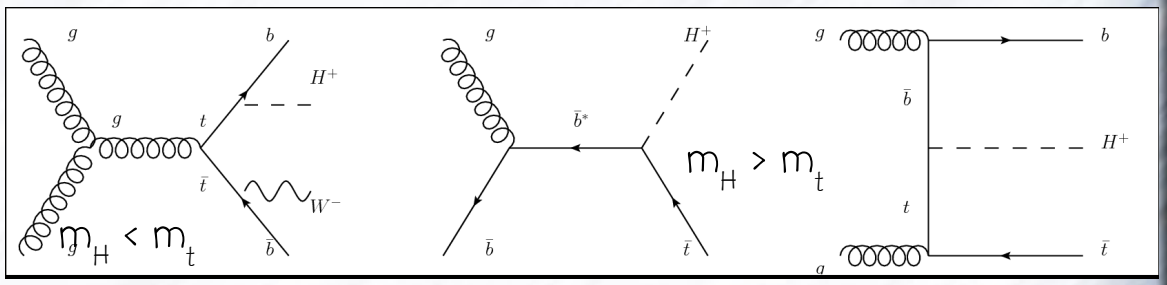
Model independent interpretation

reaching 1 fb at high-mass



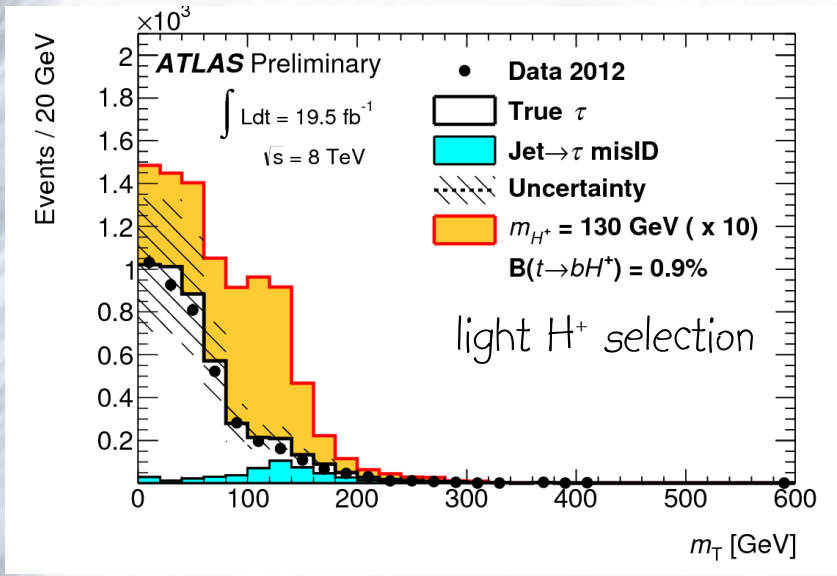
Direct search for charged Higgs

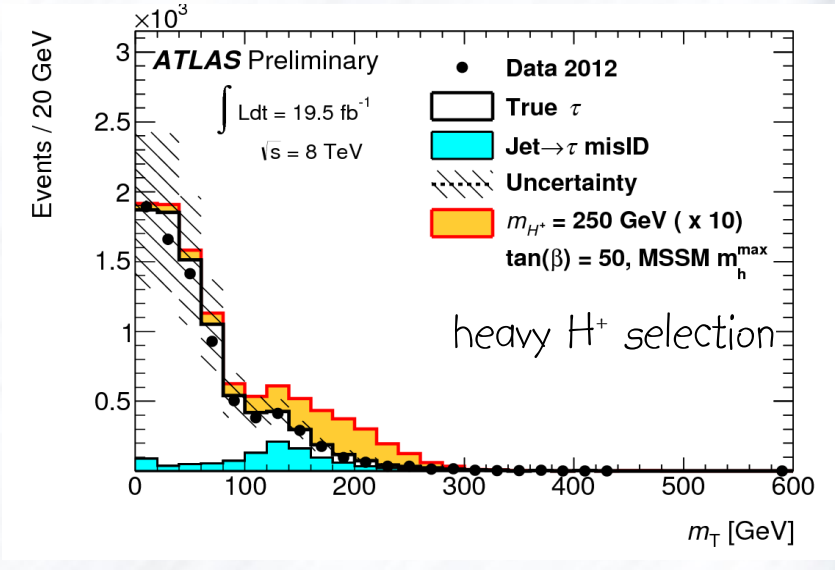
- $H^+ \to \tau^+ \nu_\tau$
- tau (had) +jets channel



Measure : $BR(t \to b H^+)$ σ_{H^+}(production cross section)

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

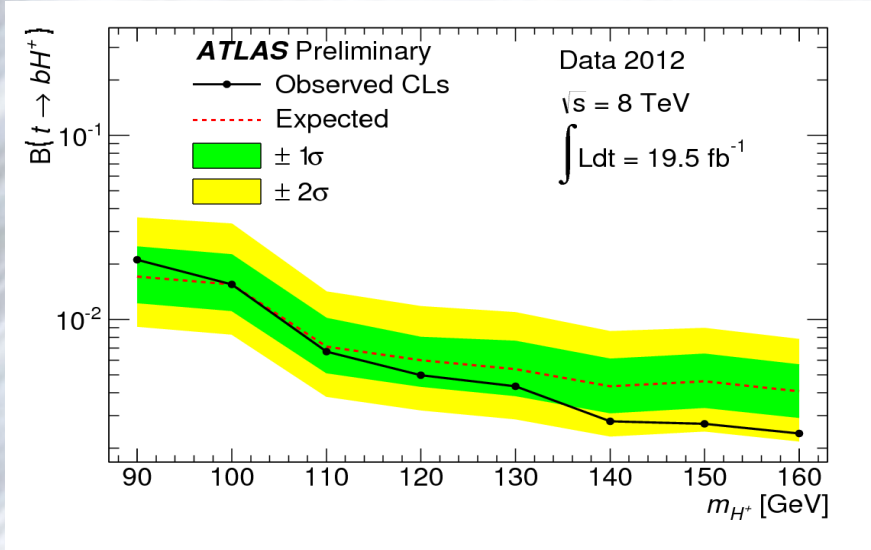




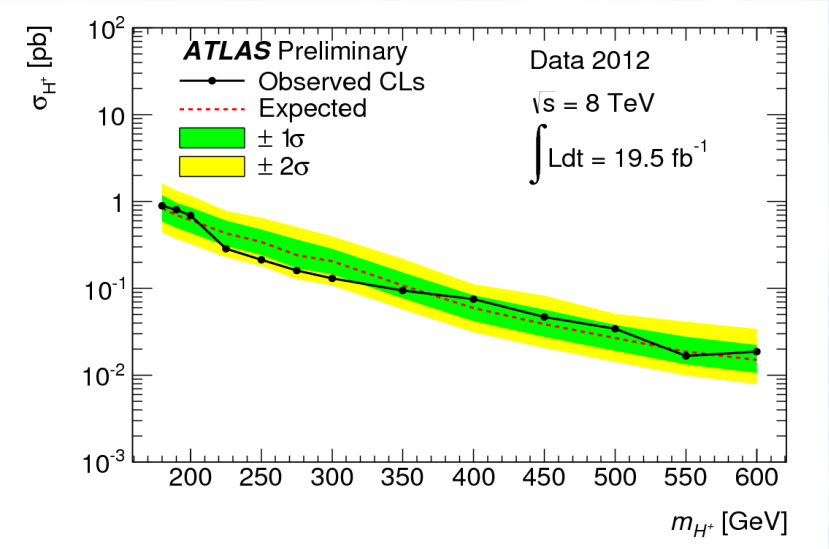
ATLAS-CONF-2013-090

Direct search for charged Higgs

- interpreted in a model-independent way



BR(t->bH⁺) < 1% for a light charged Higgs



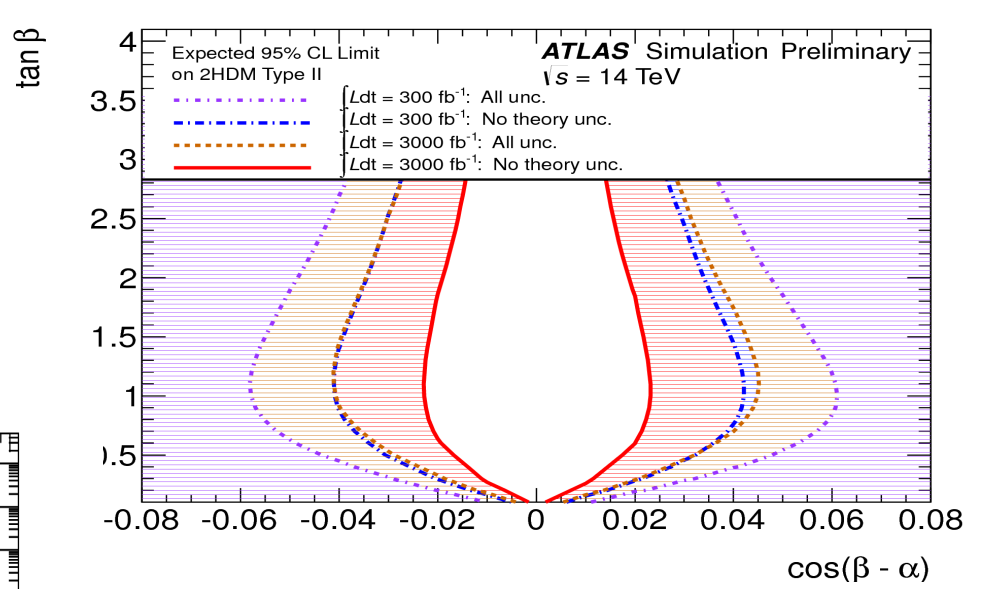
Production cross section of heavy charged Higgs < 1 pb

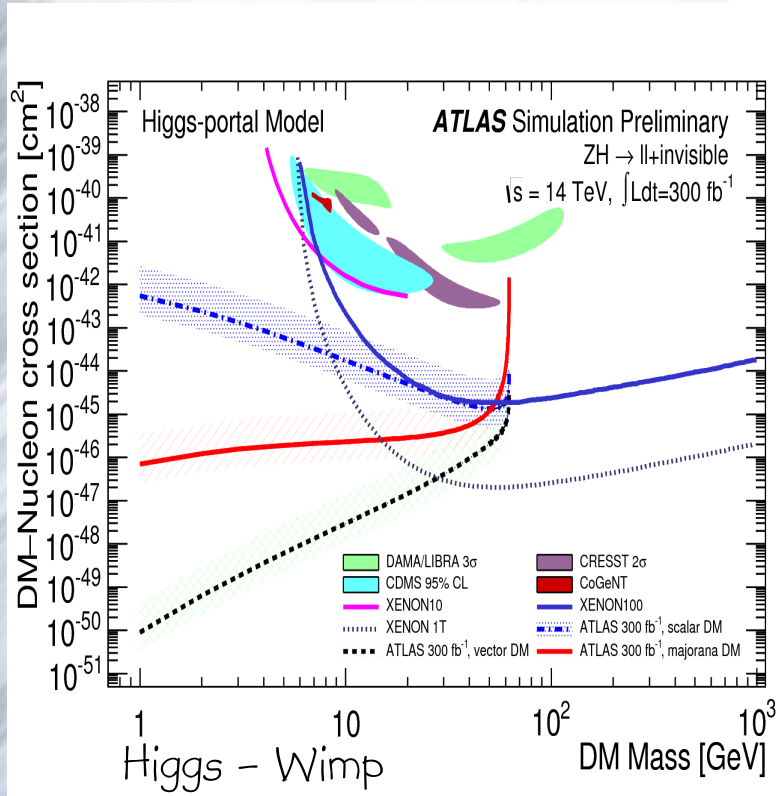
ATLAS-CONF-2013-090

Run II prospects

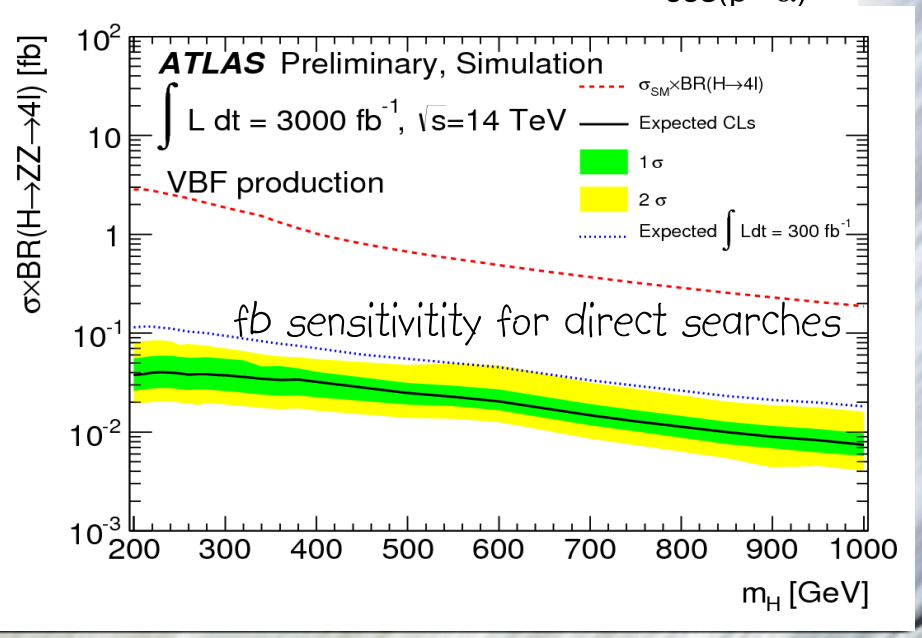
ATLAS-PHYS-PUB-2013-016
ATLAS-PHYS-PUB-2013-015
ATLAS-PHYS-PUB-2013-014

"Precision" coupling measurements





Higgs – Wimp interaction ?

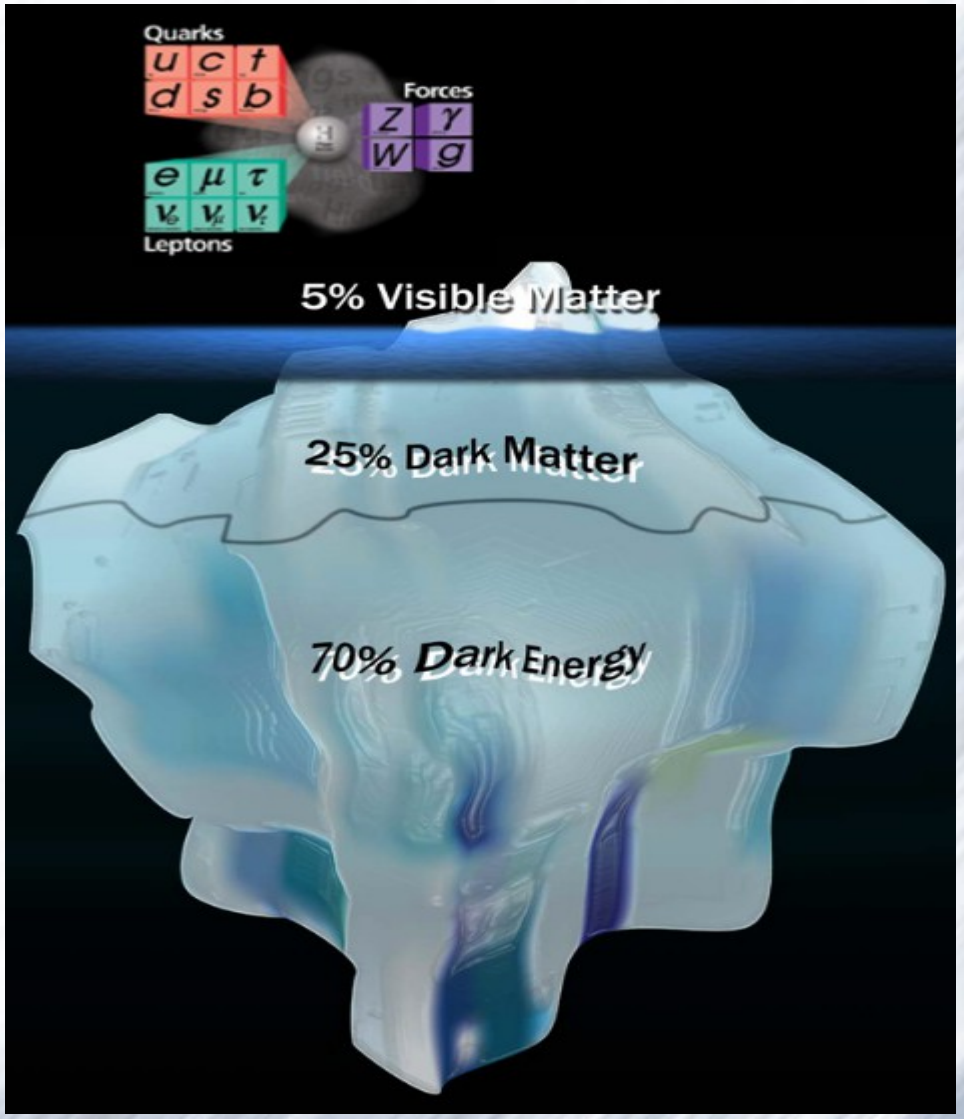


fb sensitivity for direct searches

Conclusion

- LHC Run I has promoted fundamental scalar fields to credible physical entities. It would be strange that nature has made the Higgs boson a unique child !

- Run II has the potential to help us bridge micro & macro physics.



Backup slides

Bibliography

- Limits on new phenomena via coupling measurements : ATLAS-CONF-2014-010 , CMS-PAS-HIG-13-005
- Direct searches :
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  - CMS-PAS-HIG-13-032 , CMS-PAS-HIG-13-024 , CMS-PAS-HIG-13-010
  - ATLAS-CONF-2014-005 , ATLAS-CONF-2013-027 , ATLAS-CONF-2013-090
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  - PRL 108 (2012) 251801 , Phys. Lett. B721 (2013) 32, New J. Phys. 15(2013) 043009
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direct search for H->hh & A->Zh

- $m_H > 2\ m_h$ then H->hh ; $2\ m_h < m_A < 2\ m_t$ then A-> Zh predominantly
- h decays like in SM ; multilepton and diphoton signatures

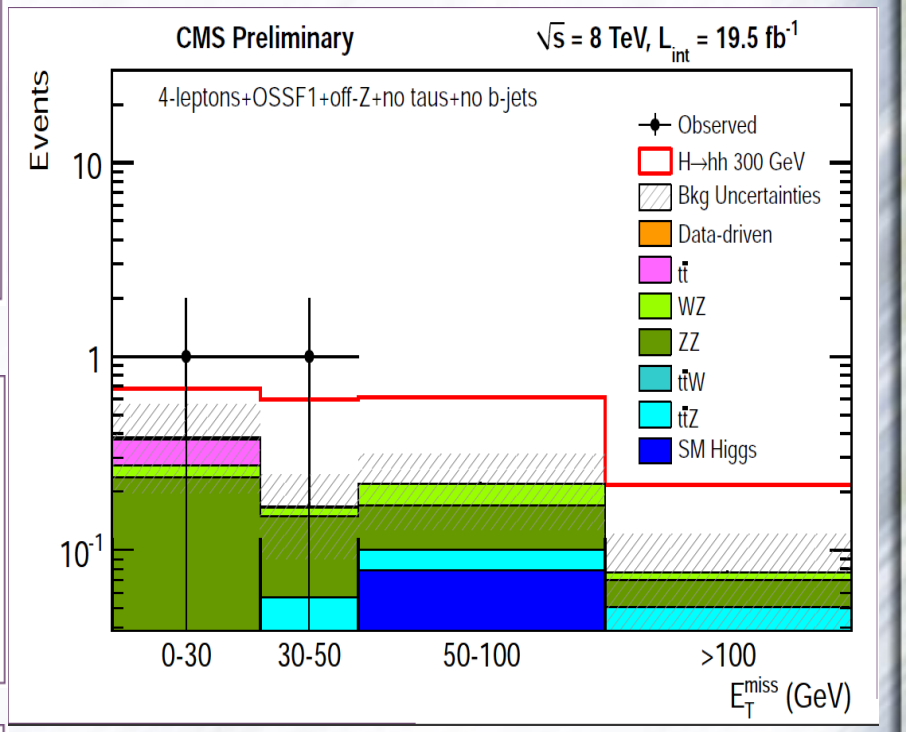
Leptons	Photons	OSSF pairs	Hadronic τ	b-tag
4	0	0, 1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

each channel further divided in bins of E_T^{miss}

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	X	✓
$h \to ZZ^*$	-	✓	✓	✓	✓
$h \to \tau\tau$	-	-	✓	X	✓
$h \to bb$	-	-	-	X	X
$h \to \gamma\gamma$	-	-	-	-	X

√ considered , X not considered

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X



CMS-PAS-HIG-13-025

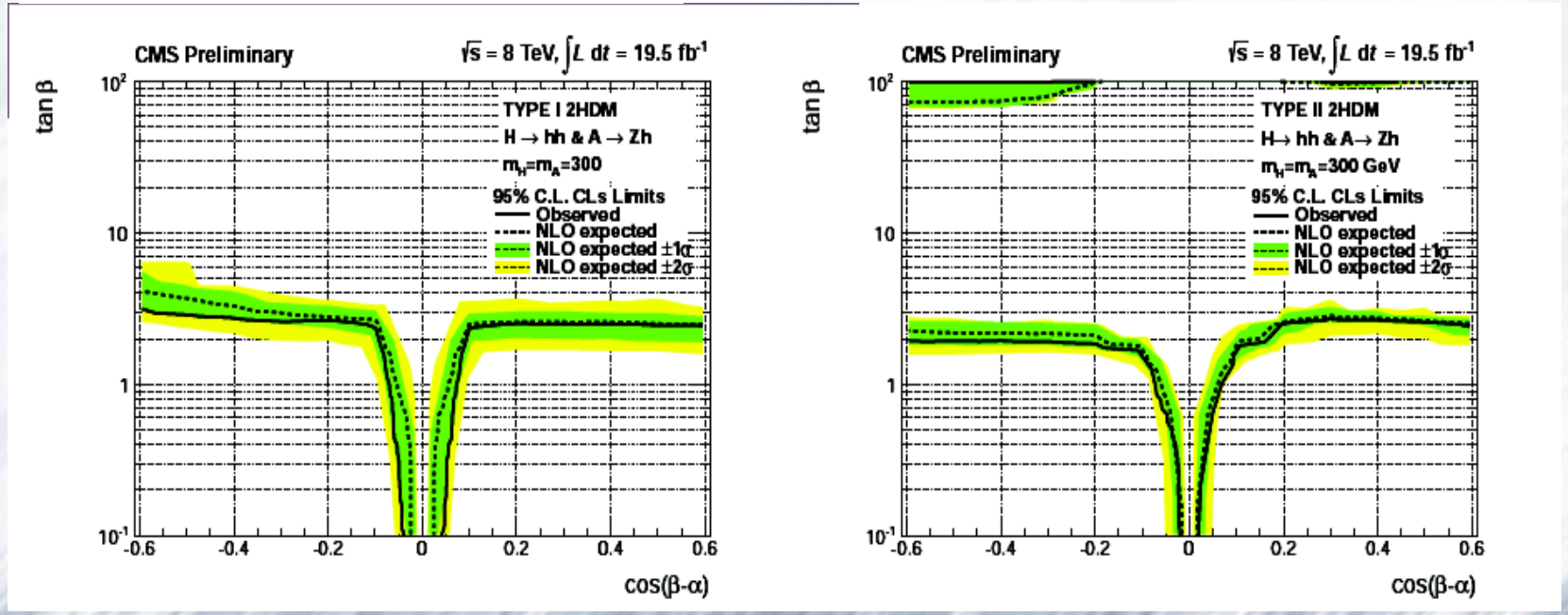
direct search for H->hh & A->Zh

y_{2HDM}/y_{SM}	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$

CMS-PAS-HIG-13-025

N. Craig et al. : arXiv:1210.0559.

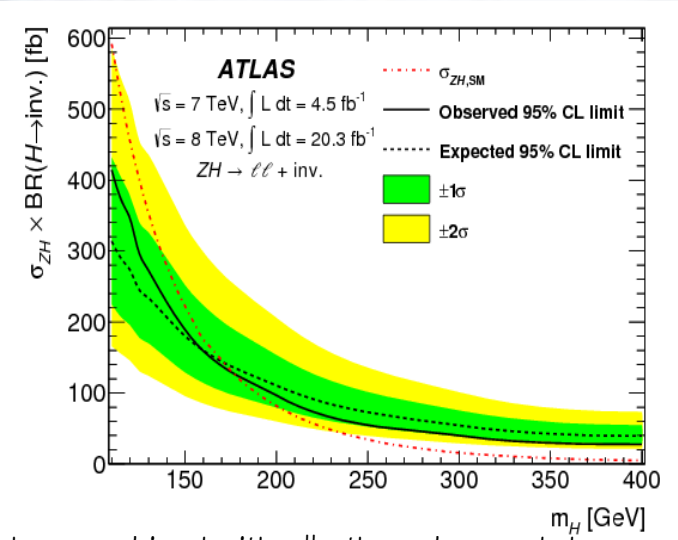
for $m_H = m_A = 300$ GeV and type I & II 2HDMs



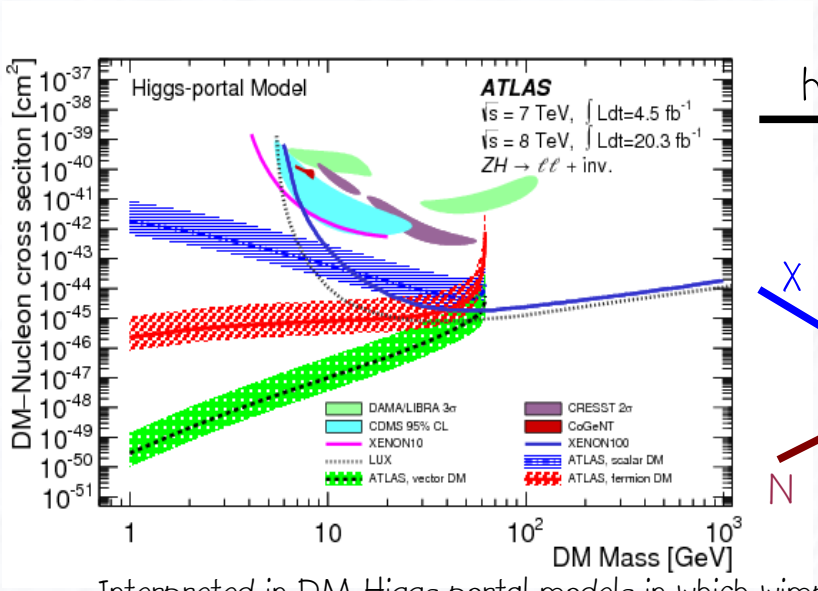
Invisible decays of a BSM Higgs

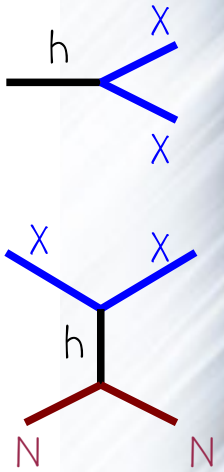
Predicted branching ratio of SM Higgs invisible decay = 1.3 10^{-3} (h-> Z Z^* -> 4 ν)

Probing production of a Higgs boson produced in association with a Z that would predominantly decay into invisible particles : Z H -> 2 charged leptons + E_T^{miss}



when combined with all other observed decay channels : inv. BR of SM Higgs < 37% @ 95% CL





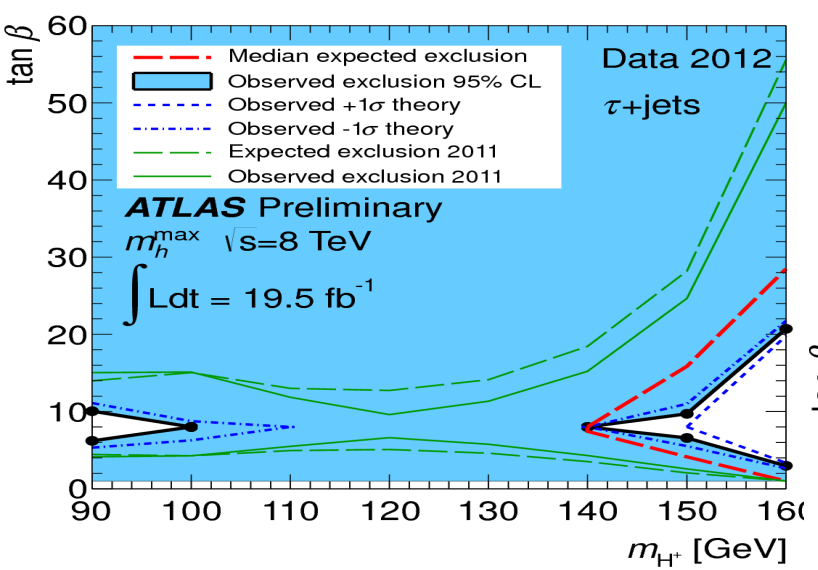
Interpreted in DM Higgs portal models in which wimps very weakly interact with SM particles except for the Higgs boson. In these models, wimps would predominantly interact with matter by Higgs boson exchange.

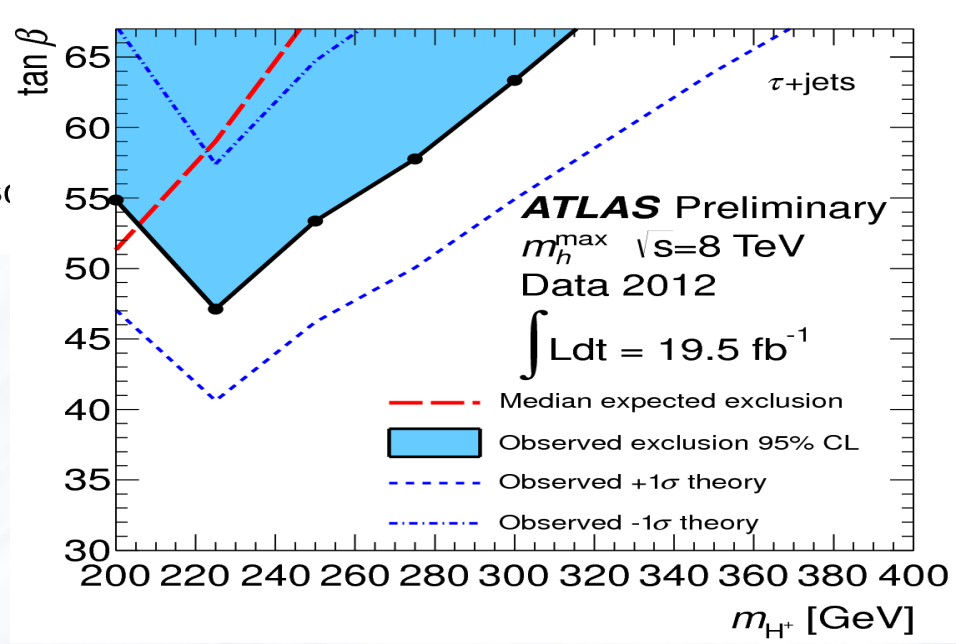
ATLAS-CONF-14-010 , arXiv : 1402.3244v2 , PRL 112(2014) 201802

B. Patt & F. Wilczek : arXiv : hep-ph/0605188
S. Kanemura et al. : Phys.Rev. D82 (2010) 055026, arXiv : 1005.5661 [hep-ph]
P.J. Fox et al. : Phys. ReV. D85 (2012) 056011, arXiv : 1109.4398 [hep-ph]
A. Djouadi et al. : Phys. Lett. B709 (2012) 65, arXiv:1112.3288 [hep-ph)
L. Lopez-Honorez et al. : Phys. Lett. B716 (2012) 179, arXiv:1203.2064 [hep-ph]

Direct search for charged Higgs

- interpreted in MSSM m_h^{max} scenario





Existence of a MSSM light charged Higgs almost ruled out, but still plenty of room for a heavy one (run II).

ATLAS-CONF-2013-090

M. Carena et al., arXiv : 1302.7033