New Physics Ideas for Run 2

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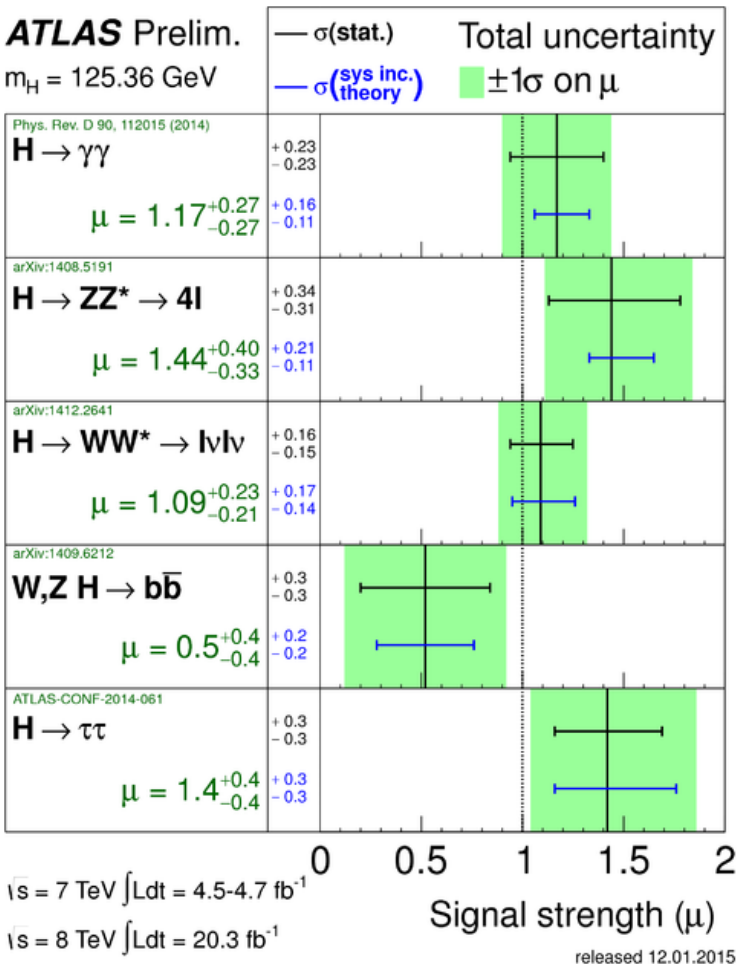
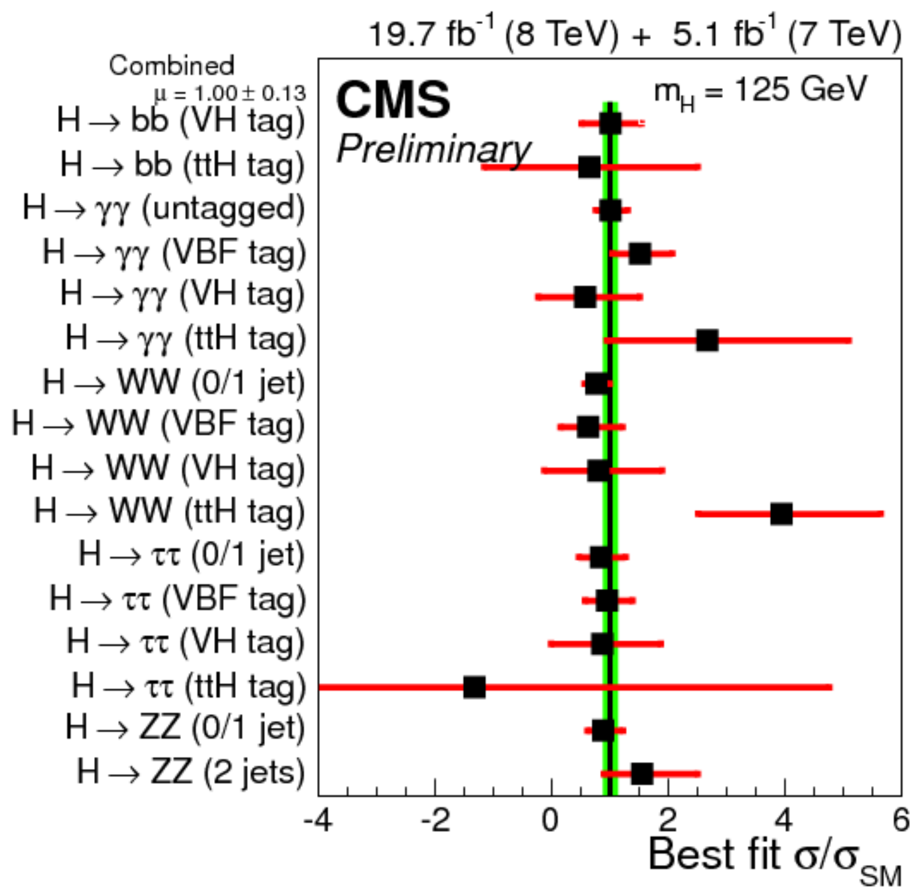
The Higgs Boson has been discovered, with very good agreement of Higgs Data and Experiment. The agreement of Higgs data with SM predictions is quite good and no compelling signal of new physics is present in 8 TeV data.






Now What?

Are we done ?

Many questions remain unanswered. Just to list some important ones :

- Why is gravity so weak or, equivalently, why is the Planck scale so high c to the weak scale ? (hierarchy problem)
- What is the origin of the matter-antimatter asymmetry
- What is the origin of Dark Matter ?
- Are neutrinos their own antiparticle ?
- Why are there three generations of fermions ?
- What is the origin of the hierarchy of fermion masses ?
- Do forces unify ? Is the proton (ordinary matter) stable ?
- What about Dark Energy ?

Some weak scale anomalies

Signals which are two to three standard deviations away from the expected SM predictions.

- LEP 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal).
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP.
- Forward-backward asymmetry of the top quark at the Tevatron.
- Apparent anomalous neutrino results, in MiniBoone, LSND and reactor fluxes.
- Anomalies observed in $B \to K^* \mu\mu$ transitions and $B \to D^* \tau \nu$
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \to p\, \mu^+ \mu^-$
- Higgs decay to $\tau\mu$, Excess in Dibosons, Anomalous events with bottoms and leptons.
- Proton radius difference measured in electron or muon hydrogen atoms ?

SUSY and Experimental Anomalies

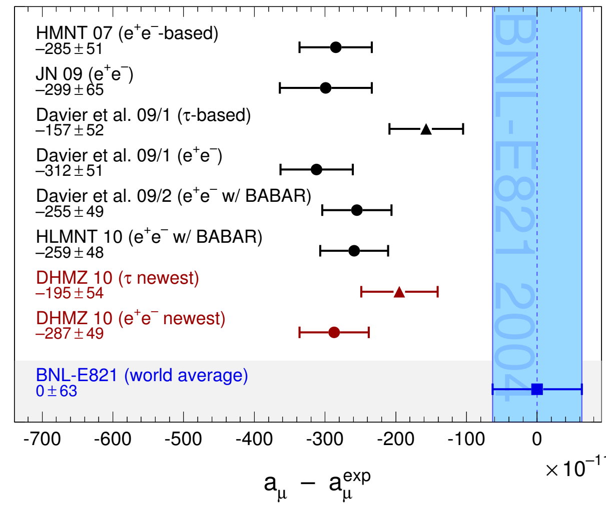
SUSY and (not very significant) Experimental Anomalies

Muon Anomalous Magnetic Moment

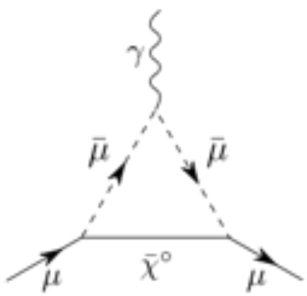
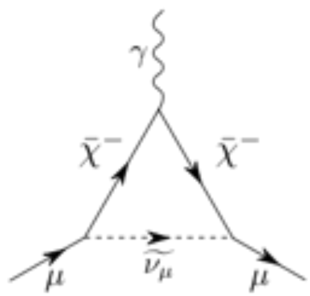
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287\ (63)(49) \times 10^{-11}$$

3.6σ Discrepancy



New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry

$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)^2 \tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10\ (50)$, values of $\tilde{m} \simeq 230\ (510)$ GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

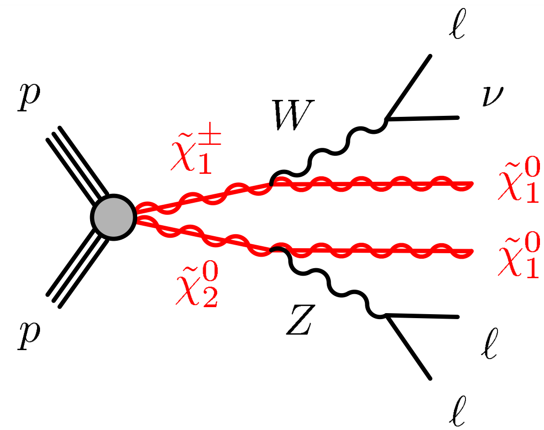
Summary of LHC Experimental Anomalies

B. Hooberman'15

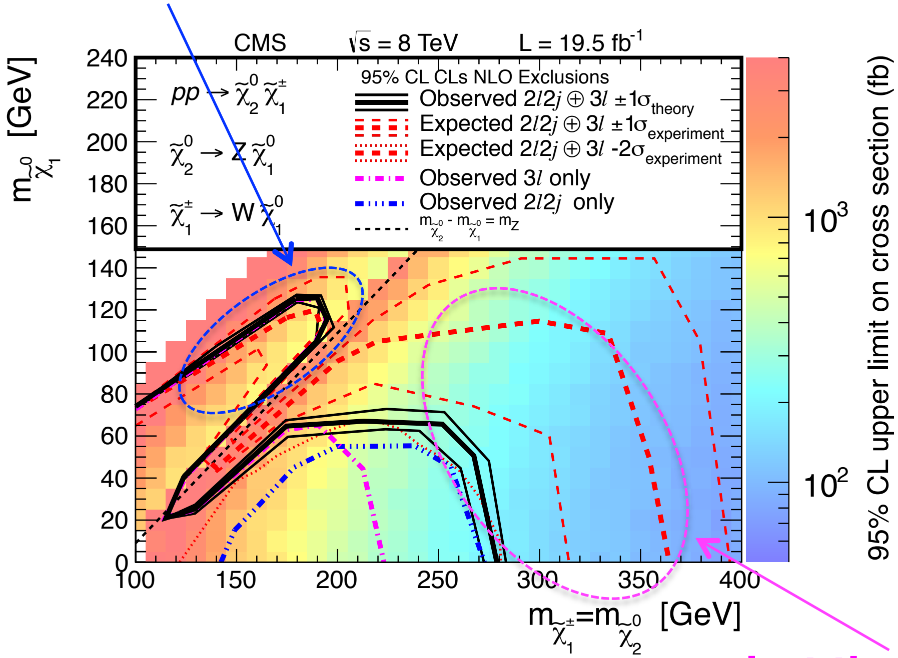
Search	Dataset	**Max Significance**	Reference
Dilepton mass edge	CMS 8 TeV	**2.6σ**	CMS-PAS-SUS-12-019
WW cross section	CMS 7 TeV	**1.0σ**	EPJC 73 2610 (2013)
WW cross section	CMS 8 TeV	**1.7σ**	PLB 721 (2013)
$3\ell+E_T^{miss}$ electroweak SUSY	CMS 8 TeV	**~2σ**	EPJC 74 (2014) 3036
$4\ell+E_T^{miss}$ electroweak SUSY (see backup)	CMS 8 TeV	**~3σ**	PRD 90, 032006 (2014)
Higgs$\longrightarrow\mu\tau$ (lepton flavor violation)	CMS 8 TeV	**2.5σ**	CMS-PAS-HIG-14-005
1st generation leptoquarks (eνjj channel)	CMS 8 TeV	**2.6σ**	CMS-PAS-EXO-12-041
ttH with same-sign muons	CMS 8 TeV	$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$	arXiv:1408.1682v1 [hep-ex]
Dijet resonance search	CMS 8 TeV	**~2σ**	arXiv:1501.04198 [hep-ex]
$3\ell+E_T^{miss}$ electroweak SUSY	ATLAS 8 TeV	**2.2σ**	PRD 90, 052001 (2014)
Soft $2\ell+E_T^{miss}$ strong SUSY	ATLAS 8 TeV	**2.3σ**	ATLAS-CONF-2013-062
WW cross section	ATLAS 7 TeV	**1.4σ**	PRD 87, 112001 (2013)
WW cross section	ATLAS 8 TeV	**2.0σ**	ATLAS-CONF-2014-033
Monojet search	ATLAS 8 TeV	**1.7σ**	arXiv:1502.01518 [hep-x]
H→h(bb)h(γγ)	ATLAS 8 TeV	**2.4σ**	arXiv:1406.5053 [hep-ex]

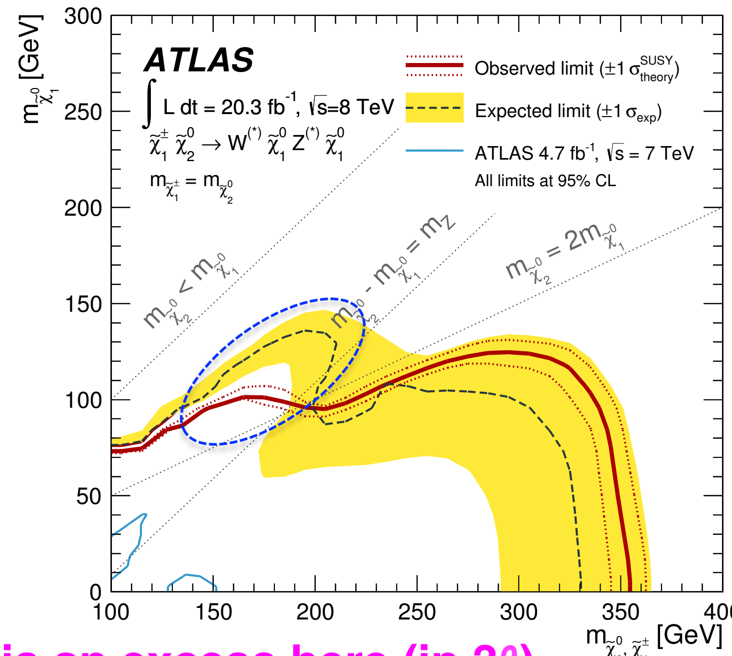
Trilepton Excess ?

- CMS search for $\chi^{+}\chi^{0} \longrightarrow WZ+E_T^{miss}$
  - Search in $WZ \longrightarrow 3\ell$ and $WZ \longrightarrow (jj)(\ell\ell)$ channels



no excess here





... but there is an excess here (in 3ℓ)

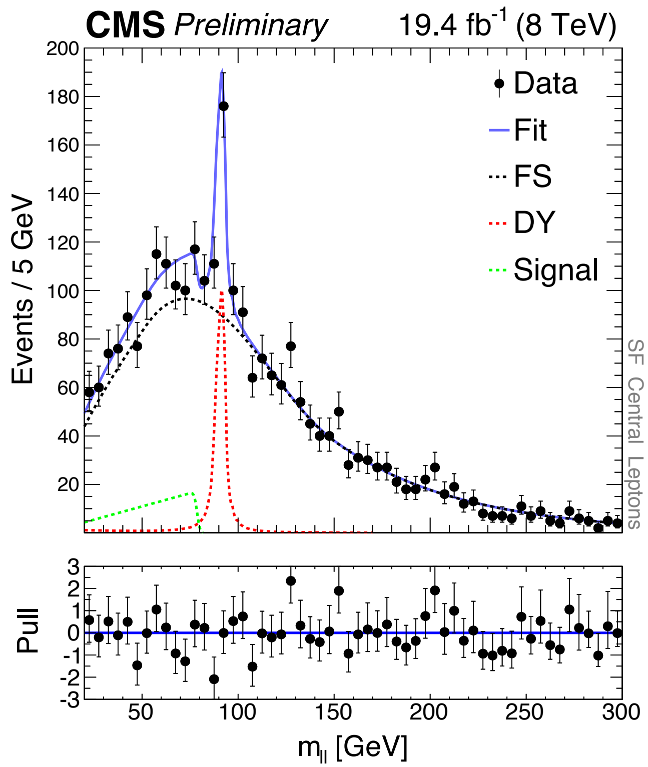
CMS, EPJC 74 (2014) 3036

B. Hooberman'15

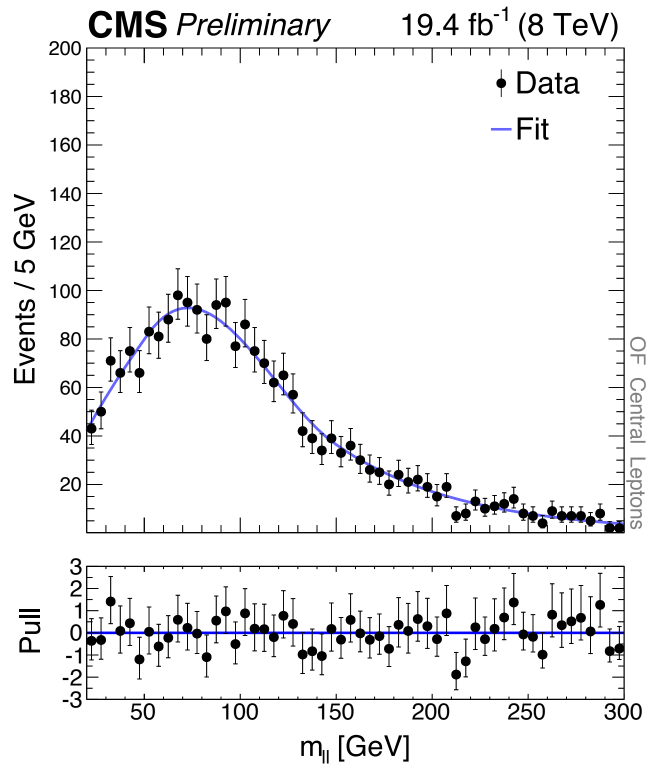
Edge in the invariant mass distribution of leptons

2 e/μ leptons with $p_T > 20$ GeV and $|\eta| < 1.4$
($n_{jets} \geq 2$ AND $E_T^{miss} > 150$ GeV) OR
($n_{jets} \geq 3$ AND $E_T^{miss} > 100$ GeV)

ee+μμ search region



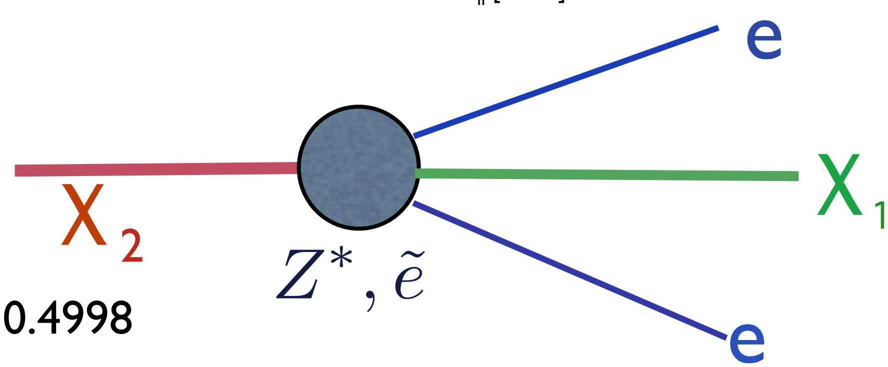
eμ control region



$$\tilde{b} \to b\ \chi_2^0$$

$$\tilde{b} \to b\ \chi_2^0 \to b\ e^+e^-\chi_1^0$$

P. Huang, C.W., arXiv:1410.4998



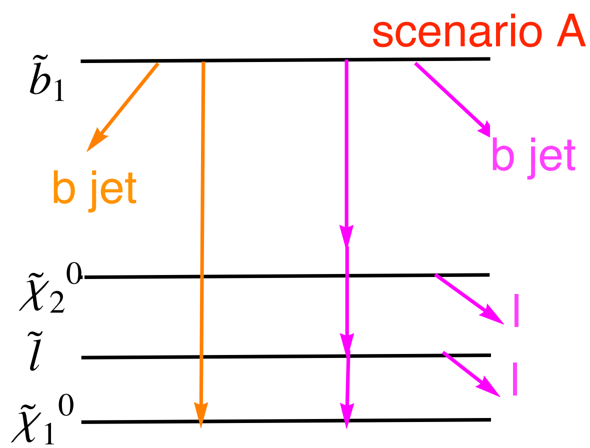
$m_{\tilde{b}} \simeq 390\mathrm{GeV}$

$m_{\tilde{\chi}_2^0} \simeq 340\mathrm{GeV}$

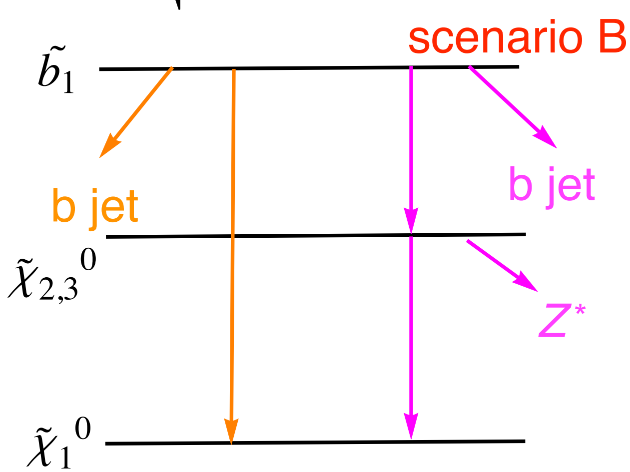
$m_{\tilde{\chi}_1^0} \simeq 260\mathrm{GeV}$

Two Possible Scenarios

P. Huang, C.W., arXiv:1410.4998



$$m_{ll}^{edge} = \sqrt{\frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}}}}$$



$$m_{ll}^{edge} = m_{\tilde{\chi}^0_2, \tilde{\chi}^0_3} - m_{\tilde{\chi}^0_1}$$

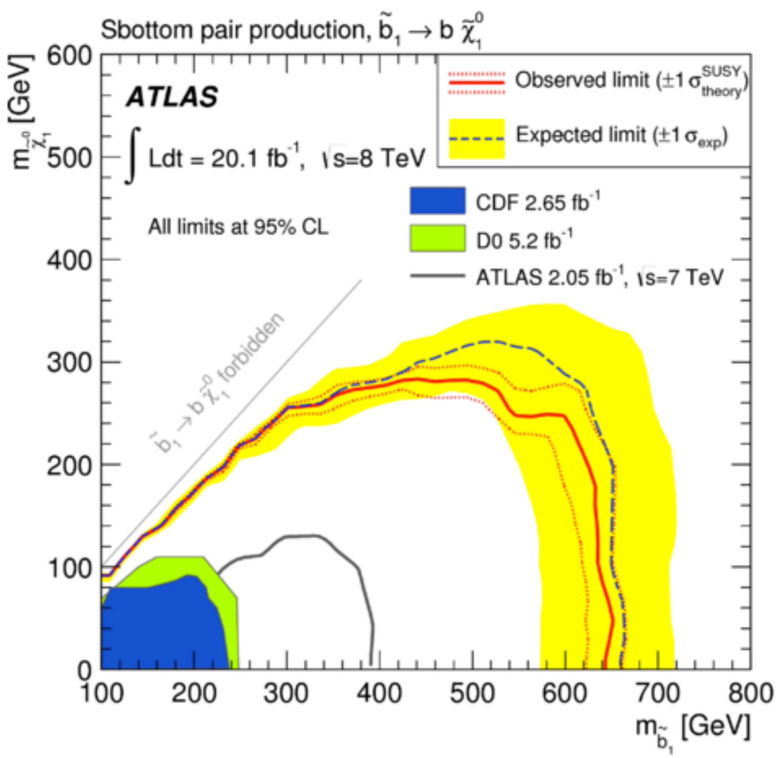
parameter	scenario A	scenario B
$m_{\tilde{b}_1}$ (GeV)	390	330
$m_{\tilde{\chi}^0_1}$ (GeV)	260	212
$m_{\tilde{\chi}^0_2}$ (GeV)	340	288
$m_{\tilde{\chi}^0_3}$ (GeV)	$\sim$ 500	290
$m_{\tilde{l}}$ (GeV)	297	500
$\tan\beta$	25	50
$\sigma(pp \to \tilde{b}_1 \tilde{b}_1)$ (pb)	0.42	1.14
$\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}^0_1)$	0.93	0.56
$\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}^0_2)$	0.07	0.25
$\mathrm{BF}(\tilde{b}_1 \to b\tilde{\chi}^0_3)$	0	019
Δa_μ	2.0×10^{-9}	2.7×10^{-9}
Ωh^2	0.11	0.11

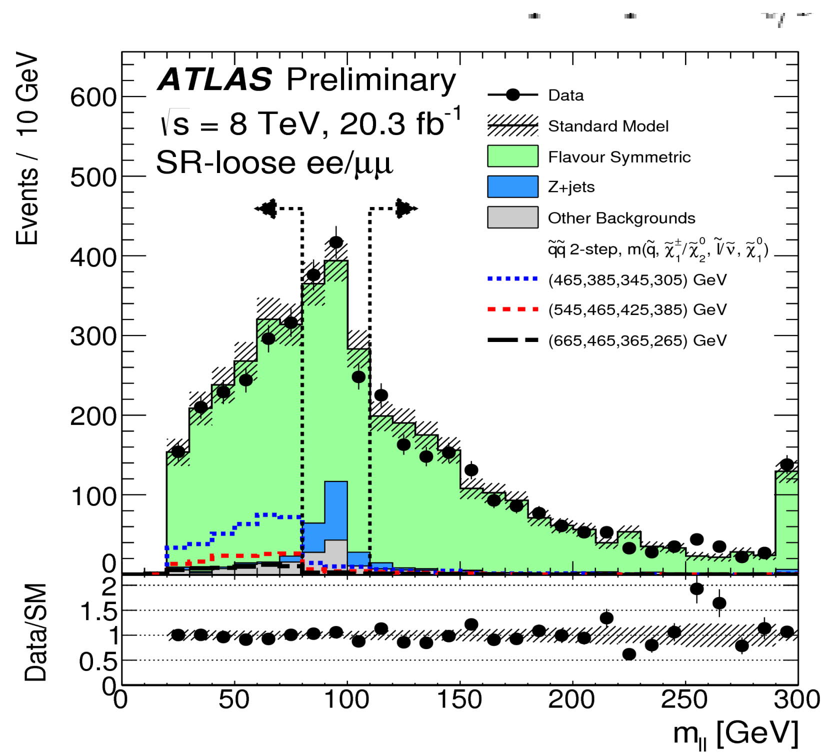
Constraints from ATLAS :

1) Sbottom Searches in events with bottoms and Missing Energy

2) Searches for a similar edge in the invariant mass distribution of leptons

No excess found !

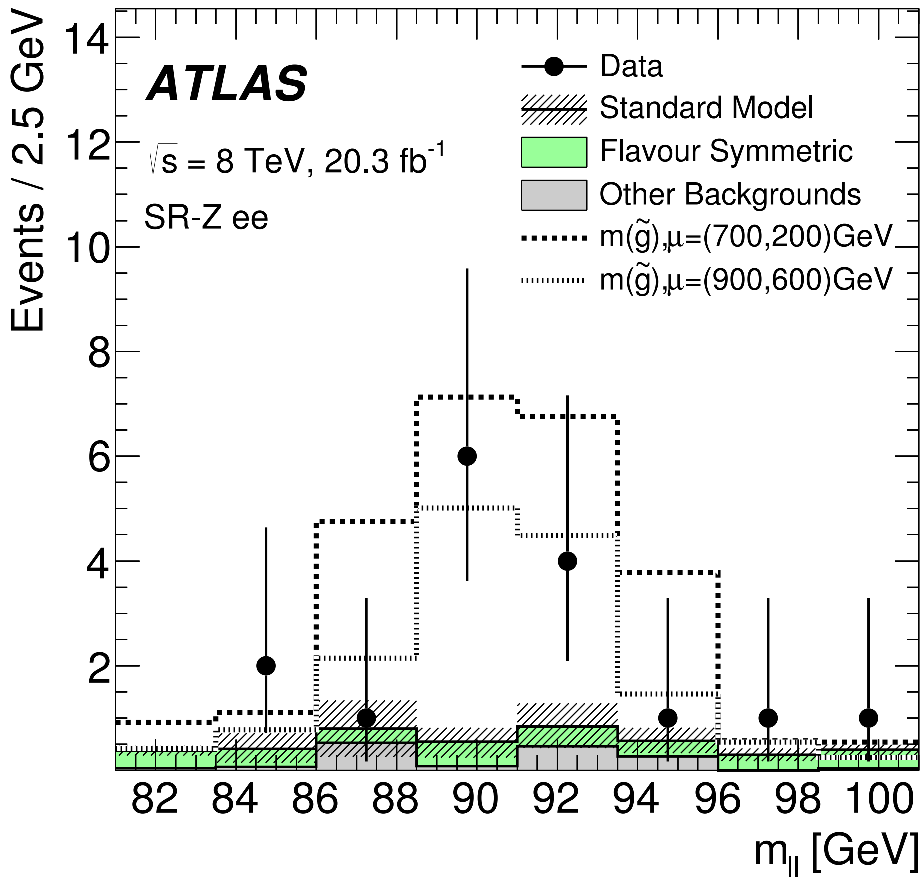


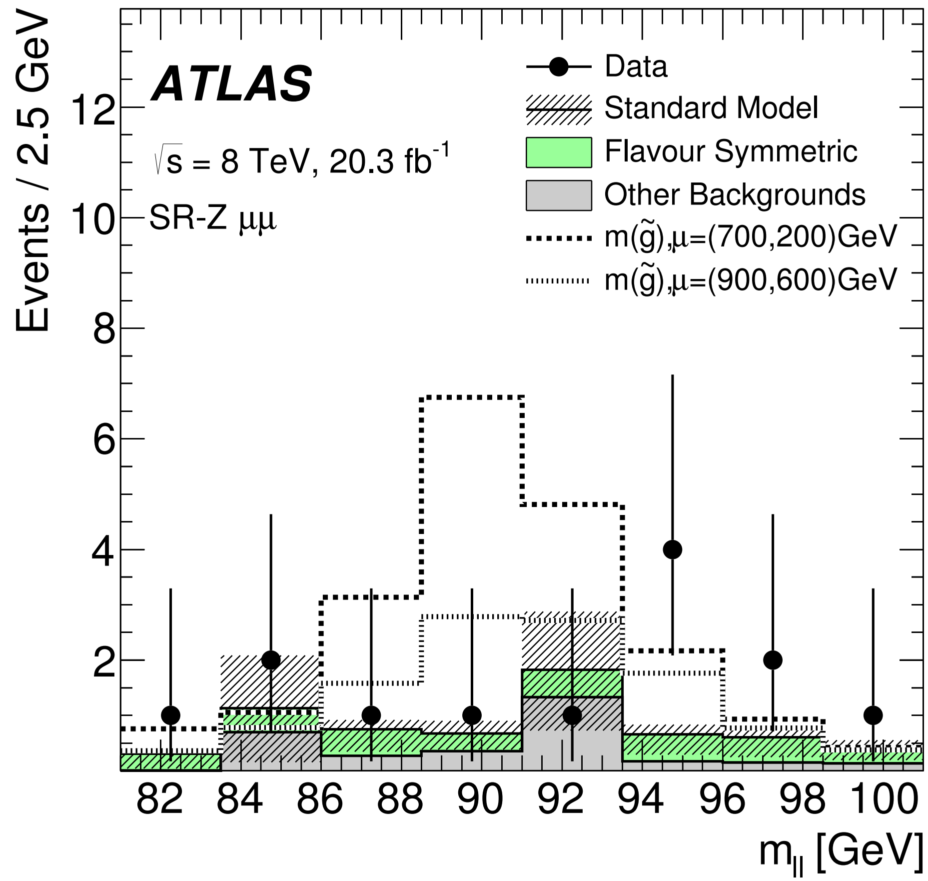


	Dilepton edge	Z+MET
ATLAS	No excess	3.0σ
CMS	2.6σ	No excess

The ATLAS and CMS edge selections are the same (by design) but the Z+MET are different, only ~30% of our events enter the CMS selection

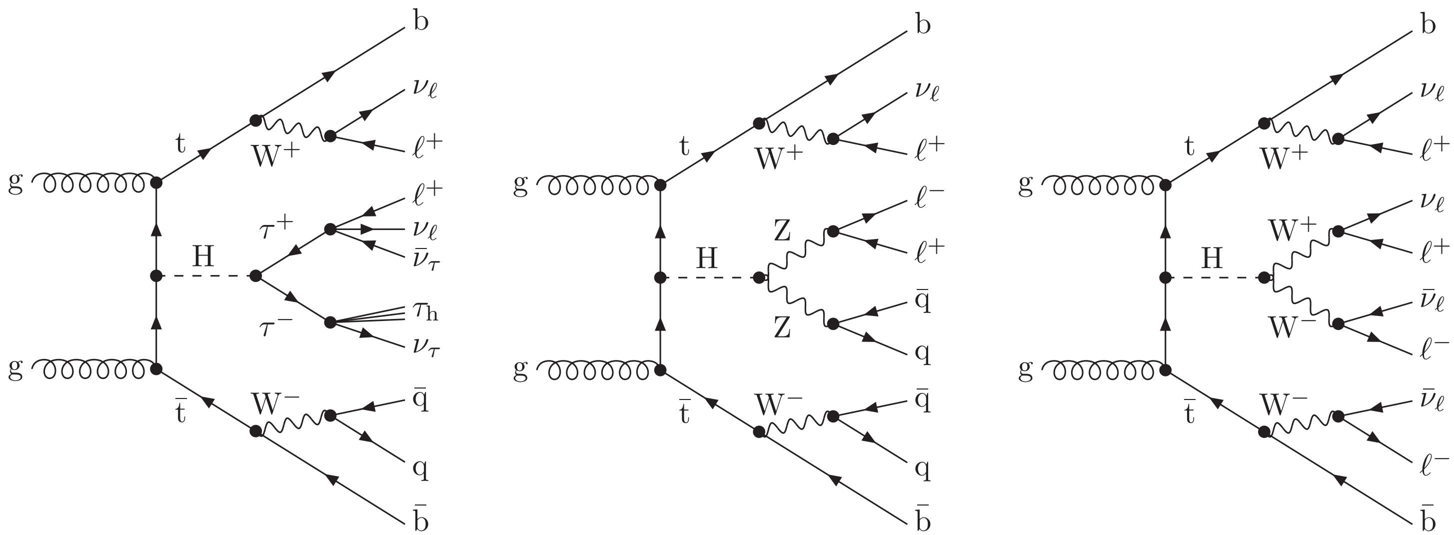
Same Flavor, Opposite Sign lepton Excess





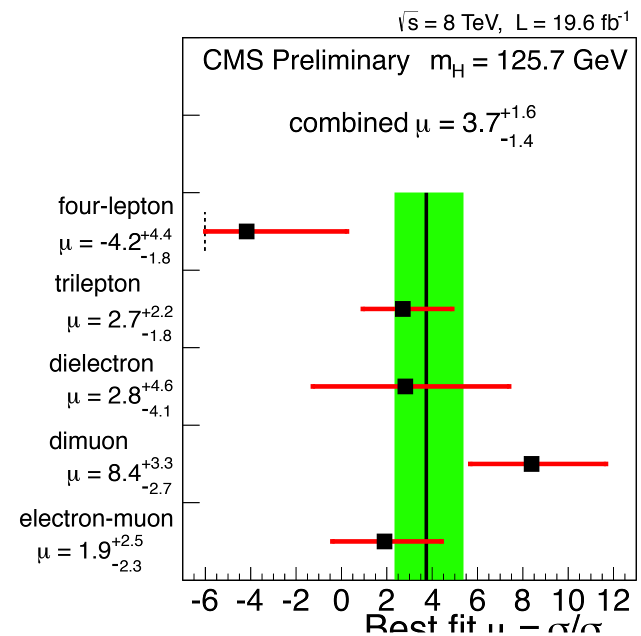
$ttH, H \to WW$

CMS-Hig13-020



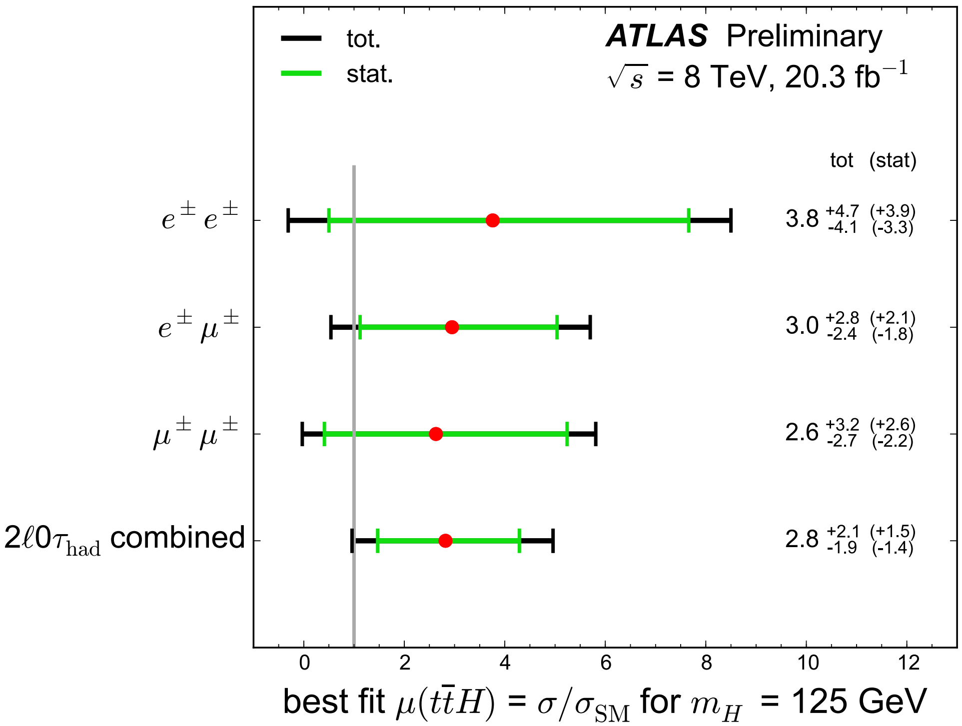
Most relevant channels : 2 bottom-quarks and equal sign leptons/trileptons

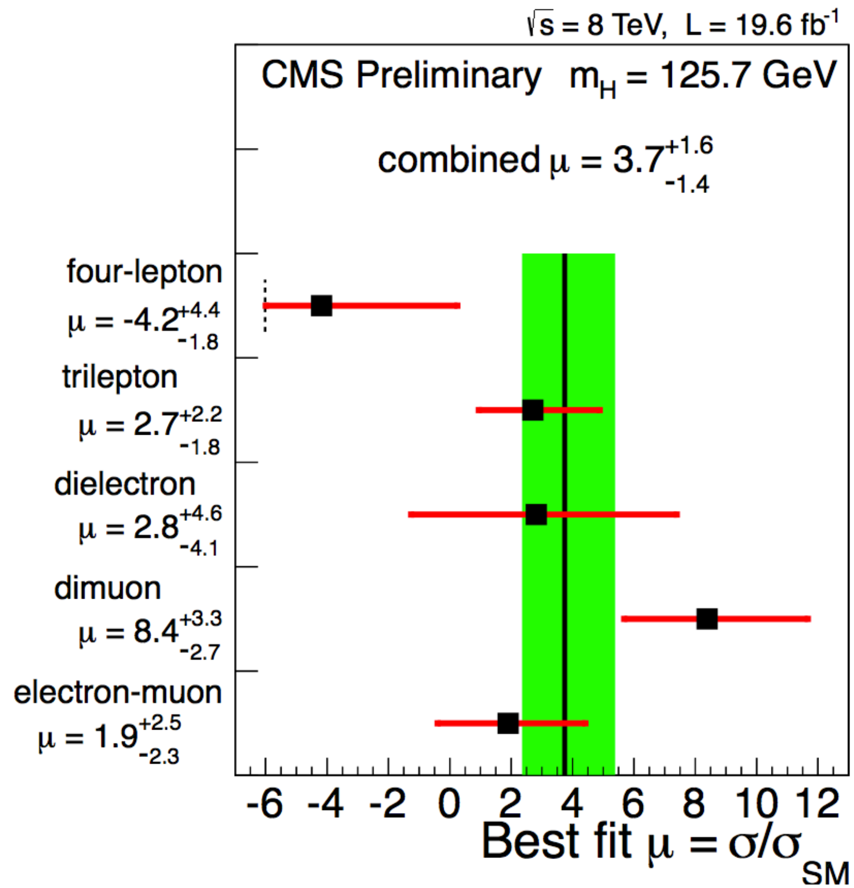
	$\mu\mu$	ee	$e\mu$	3ℓ	4ℓ
$t\bar{t}H, H \to WW$	2.0 ± 0.3	0.9 ± 0.1	2.7 ± 0.4	3.2 ± 0.6	0.28 ± 0.05
$t\bar{t}H, H \to ZZ$	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \to \tau\tau$	0.6 ± 0.1	0.3 ± 0.0	0.9 ± 0.1	1.0 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	8.2 ± 1.5	3.4 ± 0.6	13.0 ± 2.2	9.2 ± 1.9	-
$t\bar{t}Z/\gamma^*$	2.5 ± 0.5	1.6 ± 0.3	4.2 ± 0.9	7.9 ± 1.7	1.25 ± 0.88
$t\bar{t}WW$	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	-	1.3 ± 0.3	1.9 ± 0.5	2.9 ± 0.8	-
WZ	0.8 ± 0.9	0.5 ± 0.5	1.2 ± 1.3	4.2 ± 0.9	-
ZZ	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.4 ± 0.1	0.45 ± 0.09
rare SM bkg.	1.1 ± 0.0	0.4 ± 0.0	1.5 ± 0.0	0.8 ± 0.0	0.01 ± 0.00
non-prompt	10.8 ± 4.8	8.9 ± 4.5	21.2 ± 8.1	33.2 ± 12.3	0.53 ± 0.32
charge flip	-	1.9 ± 0.6	2.4 ± 0.8	-	-
all signals	2.7 ± 0.4	1.2 ± 0.2	3.7 ± 0.6	4.4 ± 0.8	0.52 ± 0.09
all backgrounds	23.7 ± 5.2	18.0 ± 4.7	45.9 ± 8.6	58.9 ± 12.7	2.28 ± 0.94
data	41	19	51	68	1



Work correlating these signals in progress :
A. Ismail, P. Huang, I.Low, C.W.'15

ATLAS and CMS results





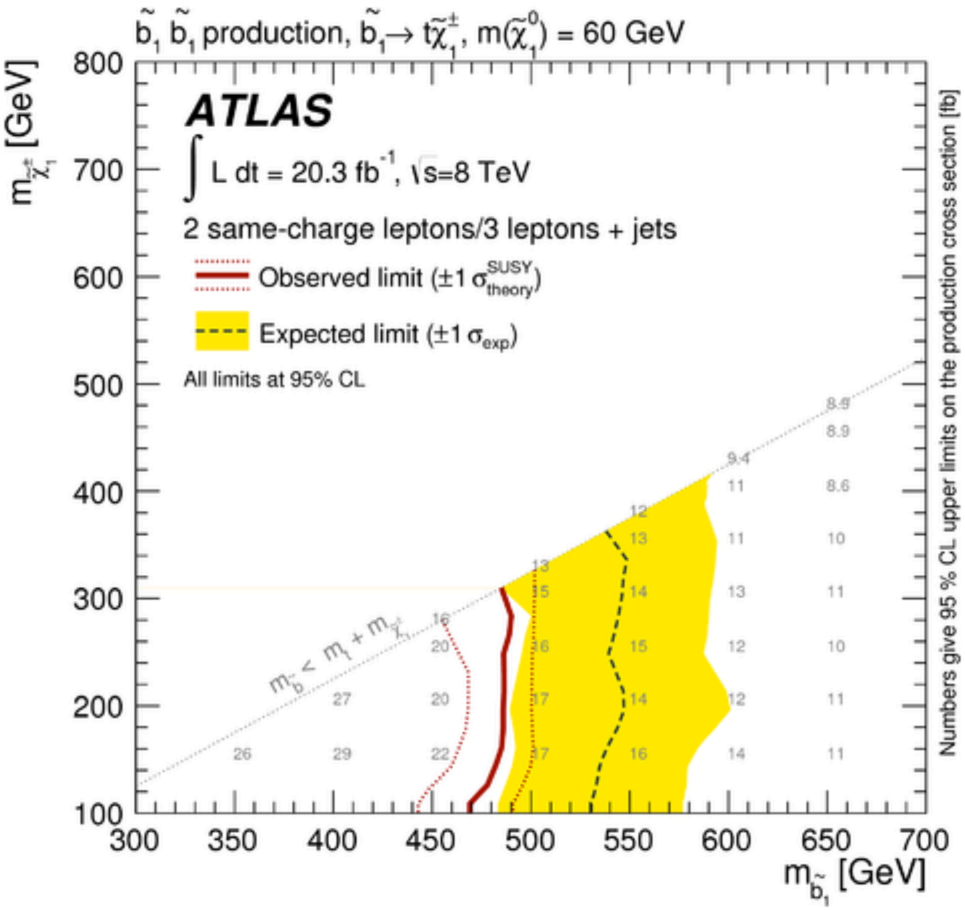
What is here called tth, with h decaying to WW
is really a search for 2b + 4W, leading to

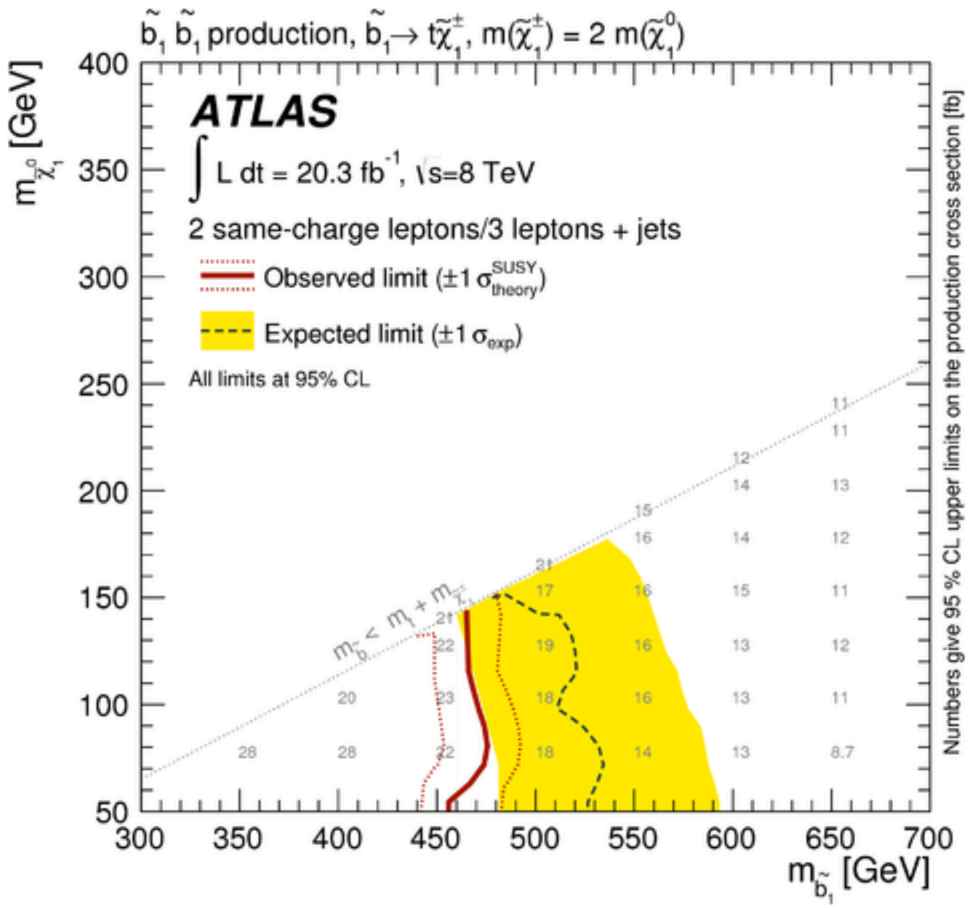
2b + 2l + MET
2b + 3l + MET

Appears in many
new physics searches

Sbottom Searches

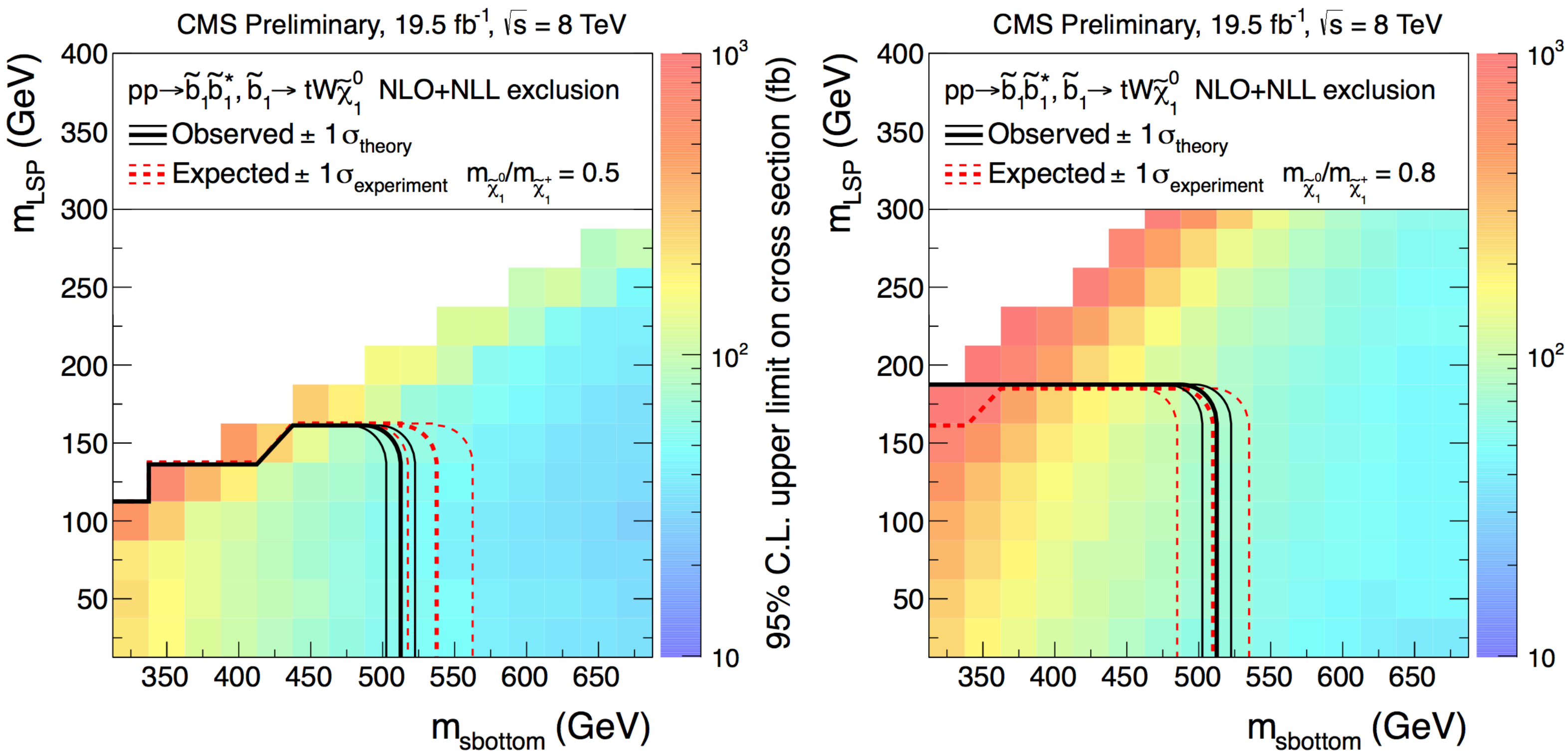
Small excess observed in 2 bottoms plus
equal sign leptons or tripleptons





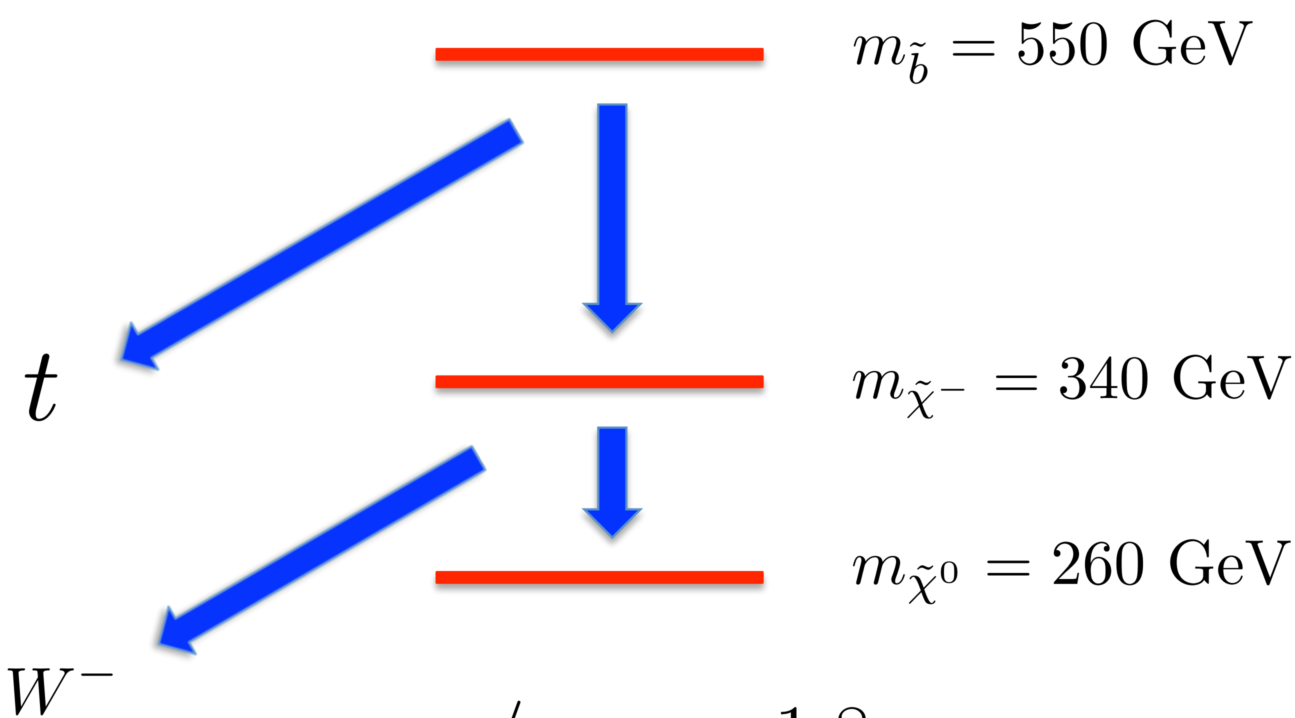
2 b + 4 W + Missing ET

Similar results at CMS, showing the dependence on the mass splitting of charginos and neutralinos



Interpretation of results easier in a stop scenario

One of our benchmarks has the following spectrum:

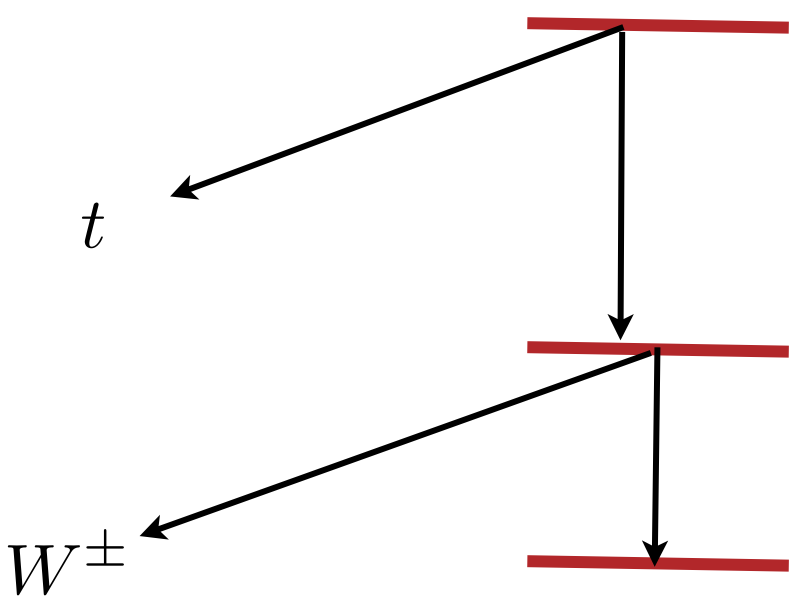


$$\mu_{\tilde{b}}/\mu_{ttH} = 1.8$$

$$\mu_{tot} = 2.8$$

Interpretation in terms of Stop scenario is easier due to larger branching ratios and brings new interesting signals

Stop mainly right-handed and second lightest neutralino mainly Bino



$$m_{\tilde{t}} = 550 \text{ GeV}$$

$$m_{\chi^0} = 340 \text{ GeV}$$

$$m_{\chi^\pm} = 260 \text{ GeV}$$

Similar to the sbottom case, but with two signs of W's

$$\mu_{\tilde{t}}/\mu_{tth} = 1.8$$

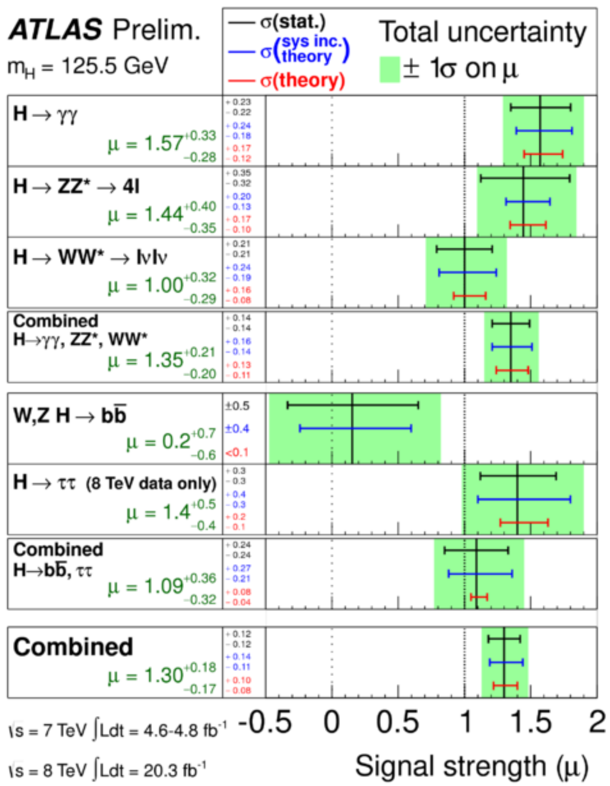
$$\mu_{tot} = 2.8$$

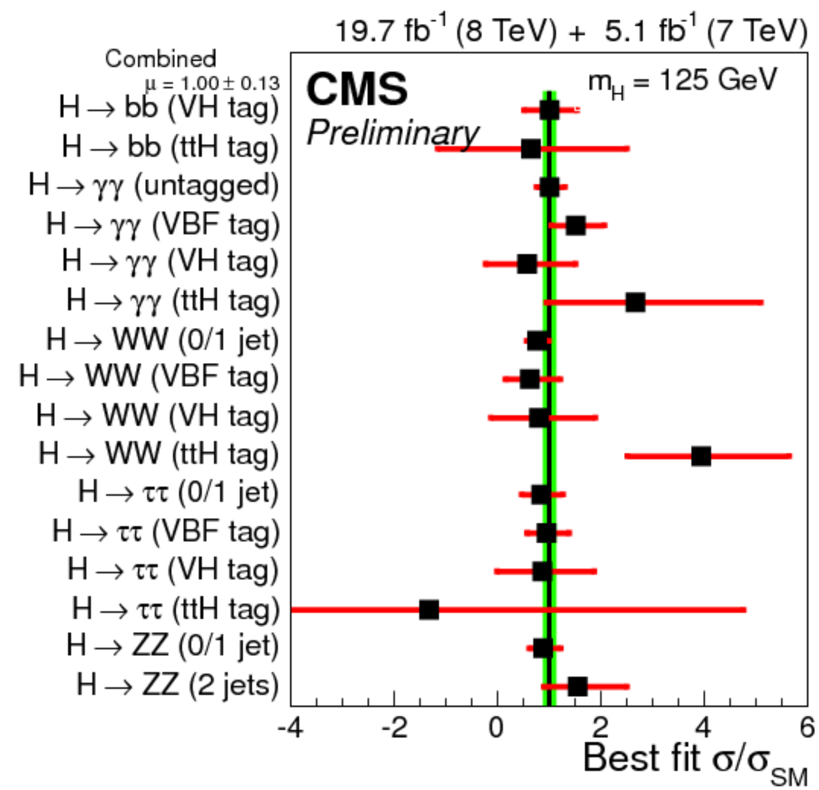
Stop Signatures

- Similar equal sign dilepton signal as in the sbottom case.
- We estimated that for a stop describing the tth excess, 40 inverse fb at 13 TeV will lead to a discovery signal. Observe that for this search tth is a background, so we assume it to be SM-like !
- In addition, there are suddenly equal sign trileptons apart from equal sign dileptons
- The signal is lower, since demands three W's decaying leptonically and with equal signs (about 1/15 of the equal sign dileptons signal)
- The background is small, coming mainly from ttbar and ttV. To see 5 events one needs about 40 inverse fb, so you could discover the stops and differentiate it from sbottoms at the same time

The properties of the recently discovered Higgs boson are close to the SM ones

Variations of Higgs couplings are still possible





As these measurements become more precise, they constrain possible extensions of the SM, and they could lead to the evidence of new physics.

It is worth studying what kind of effects one could obtain in well motivated extensions of the Standard Model, like SUSY.

(for an extensive review, see Christensen, Han and Su'13)

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{(-\sin\alpha)}{\cos\beta}, \qquad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{\cos\alpha}{\cos\beta}$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{(\cos\alpha)}{\sin\beta}, \qquad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{\sin\alpha}{\sin\beta}$$

- If the mixing is such that

$$\sin\alpha = -\cos\beta, \qquad \sin(\beta-\alpha) \simeq 1$$

$$\cos\alpha = \sin\beta \qquad (\cos(\beta-\alpha) = 0)$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

- Observe that close to the decoupling limit, the lightest Higgs couplings are SM-like, while the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor. We shall concentrate on this case.

- It is important to stress that the coupling of the CP-odd Higgs boson

$$g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\rm diag}^{\rm dd}}{v} \tan\beta, \qquad g_{Aff}^{uu} = \frac{\mathcal{M}_{\rm diag}^{\rm uu}}{v\tan\beta}$$

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta \ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2} t_\beta^{-2}\eta^2\right) g_V \ , \qquad g_{HVV} \approx t_\beta^{-1}\eta \ g_V \ ,$$

$$g_{hdd} \approx (1-\eta)\, g_f \ , \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \ , \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

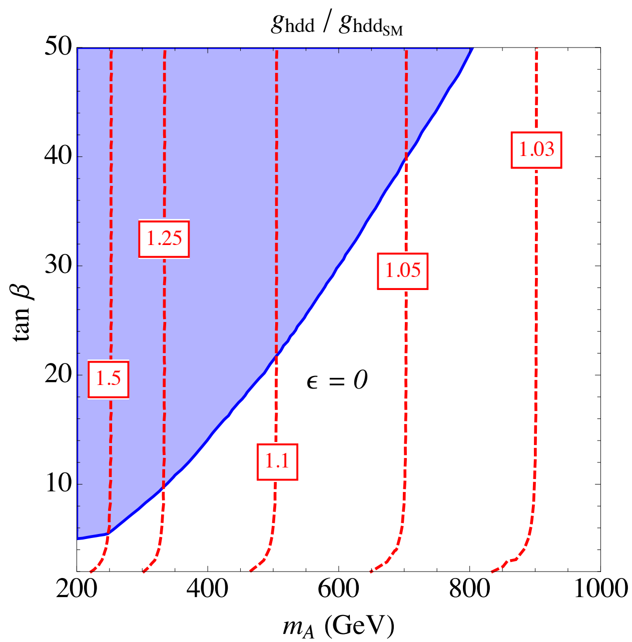
At moderate or large values of $\tan\beta$, it is clear that the only relevant deviations will be in the bottom coupling

Down Couplings in the MSSM for low values of μ

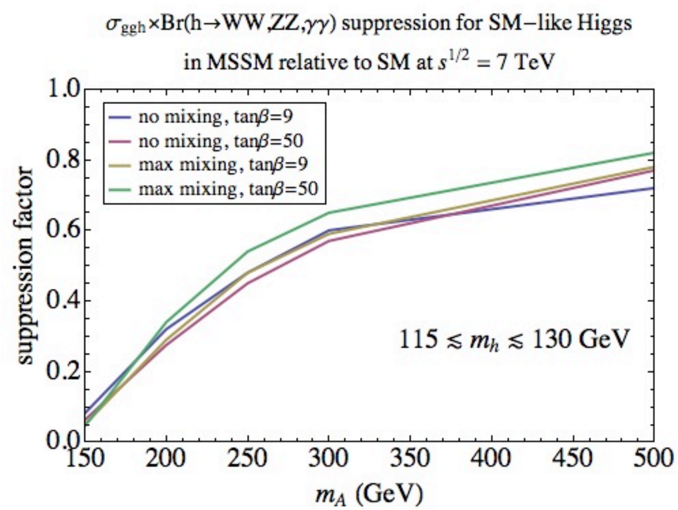
- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26$$

$$\lambda_2 \simeq \frac{M_Z^2}{v^2} + \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{A_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



Carena, Low, Shah, C.W.'13



All vector boson branching ratios suppressed by enhancement of the bottom decay width

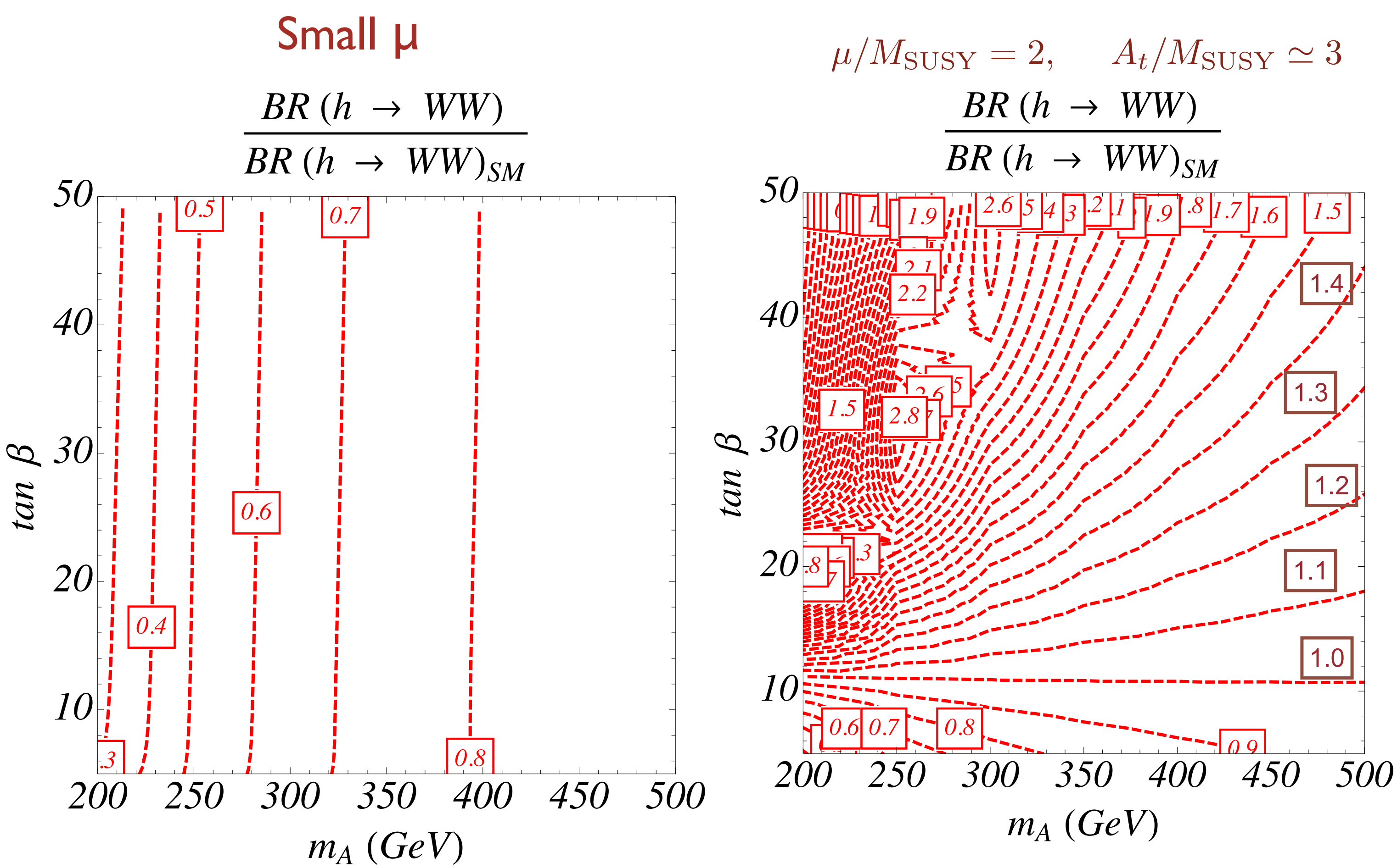
$$t_\beta\, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3 m_t^4}{4\pi^2 v^2 M_S^2}\left\{ A_t \mu t_\beta \left(1 - \frac{A_t^2}{6 M_S^2}\right) - \mu^2 \left(1 - \frac{A_t^2}{2 M_S^2}\right)\right\}\right]$$

Carena, Haber, Low, Shah, C.W.'14

M. Carena, I. Low, N. Shah, C.W.'13

Higgs Decay into Gauge Bosons

Mostly determined by the change of width

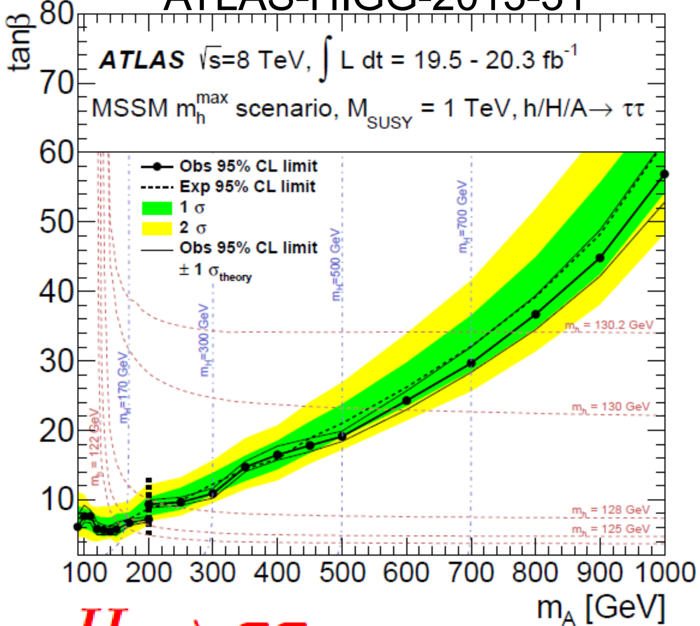


CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Non-Standard Higgs Searches

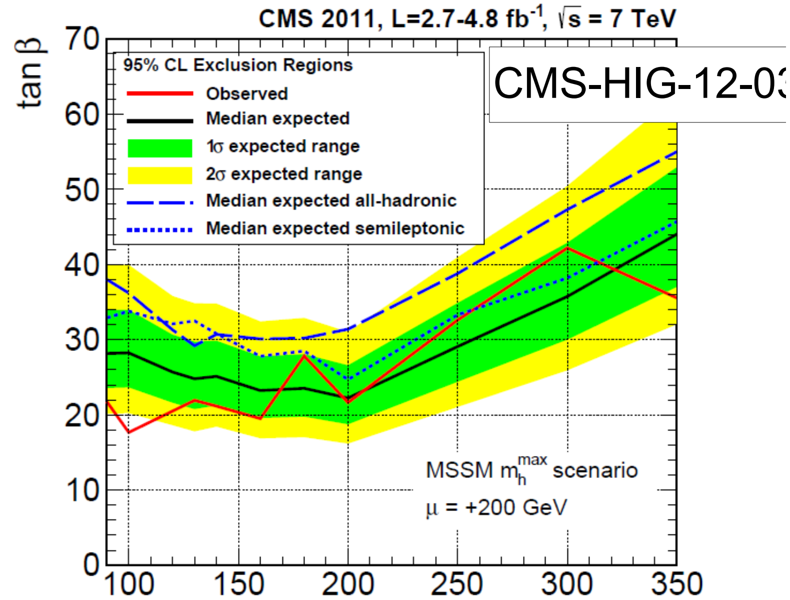
Neutral Higgs bosons

ATLAS-HIGG-2013-31



$H \to \tau\tau$

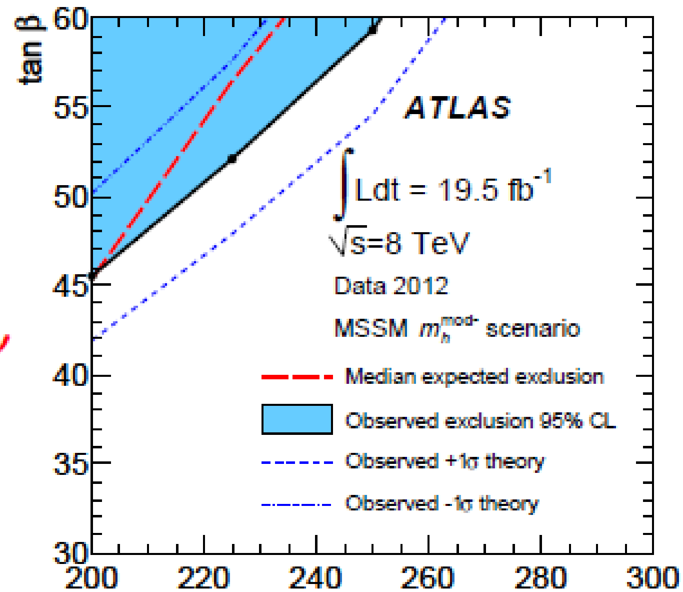
CMS-HIG-12-03



$H \to bb$

Charged Higgs bosons

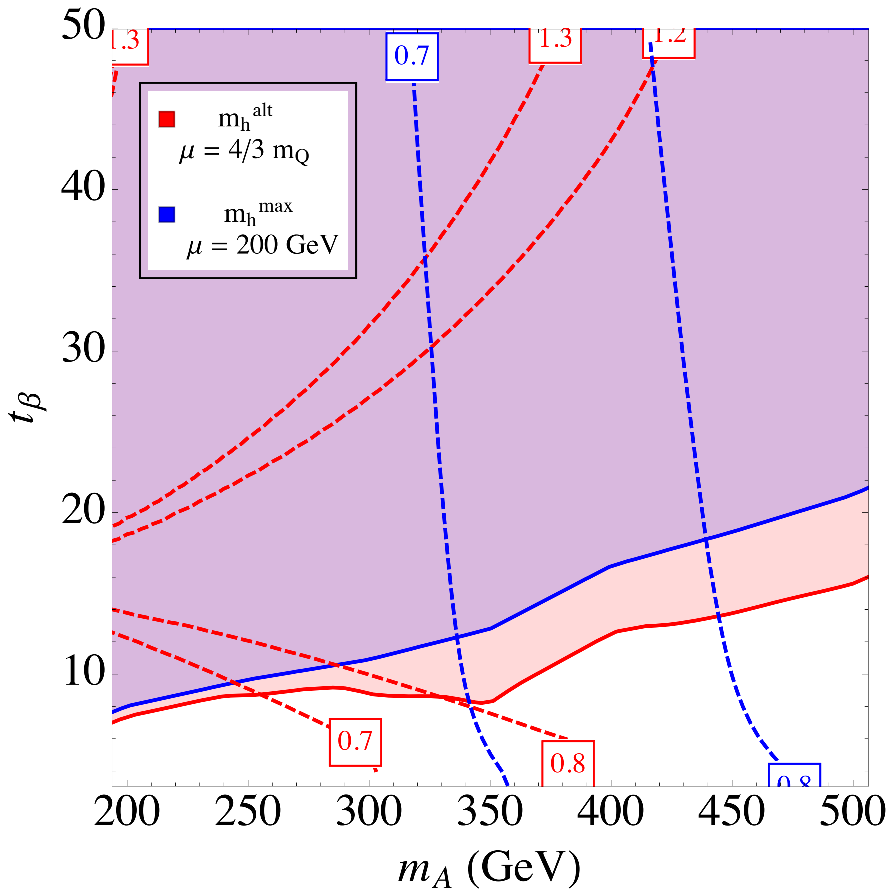
$H^\pm \to \tau^\pm \nu$



ATLAS-HIGG-2013-30

Complementarity between different search channels

Carena, Haber, Low, Shah, C.W.'14



Limits coming from measurements of h couplings become weaker for larger values of μ

— $\sum_{\phi_i = A, H} \sigma(bb\phi_i + gg\phi_i) \times BR(\phi_i \to \tau\,\tau)$ (8 TeV)

--- $\sigma(bbh+ggh) \times BR(h \to VV)/SM$

Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

Carena, Haber, Low, Shah, C.W.'15

Naturalness and Alignment in the NMSSM

see also Kang, Li, Li,Liu, Shu'13,   Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis,

$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}} \right)$$

- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

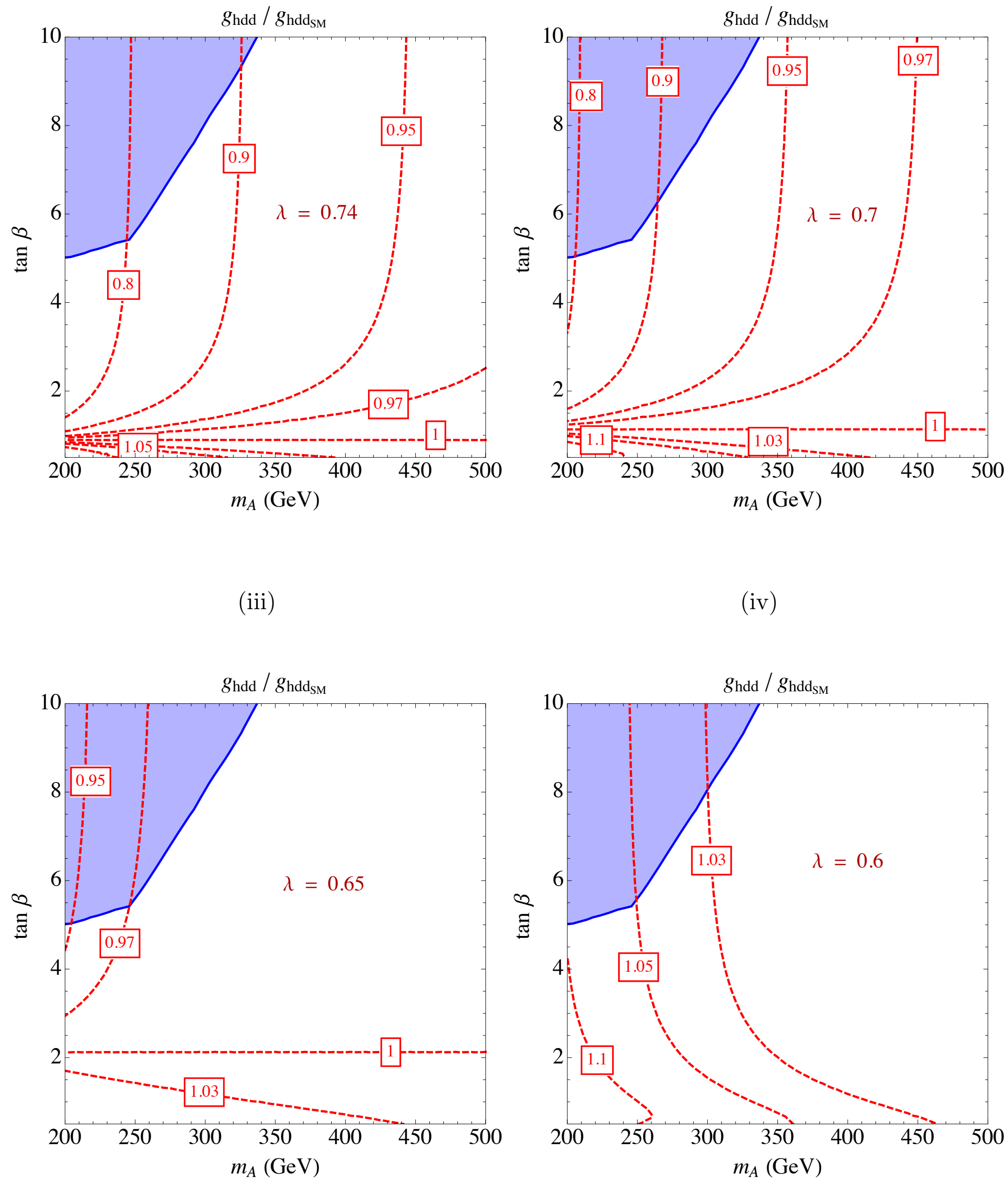
- So, alignment leads to a determination of lambda,

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for allvalues of tanbeta, that are the values that lead to naturalness with perturbativity up to the GUT scale

$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Alignment in the NMSSM (heavy or aligned singlets)

Carena, Low, Shah, C.W.'13



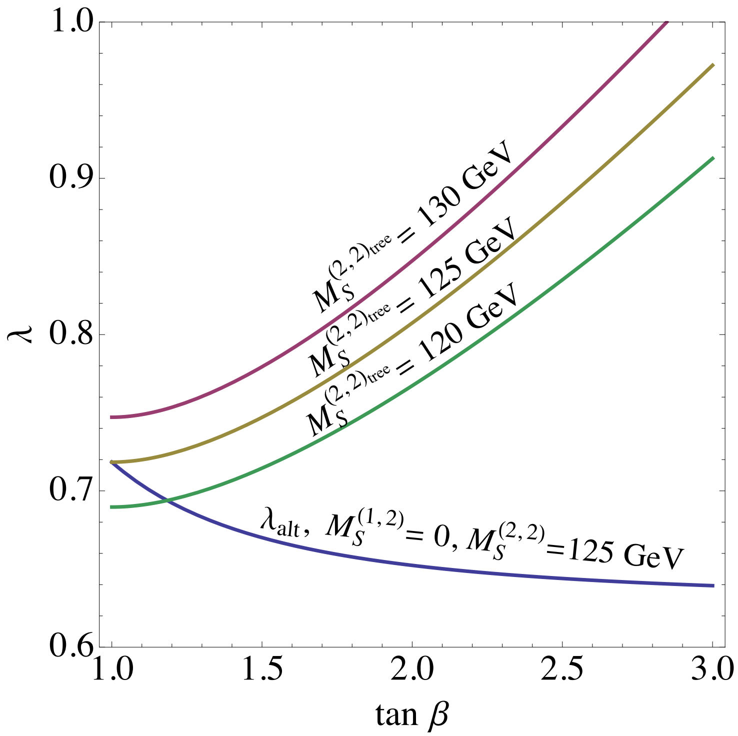
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

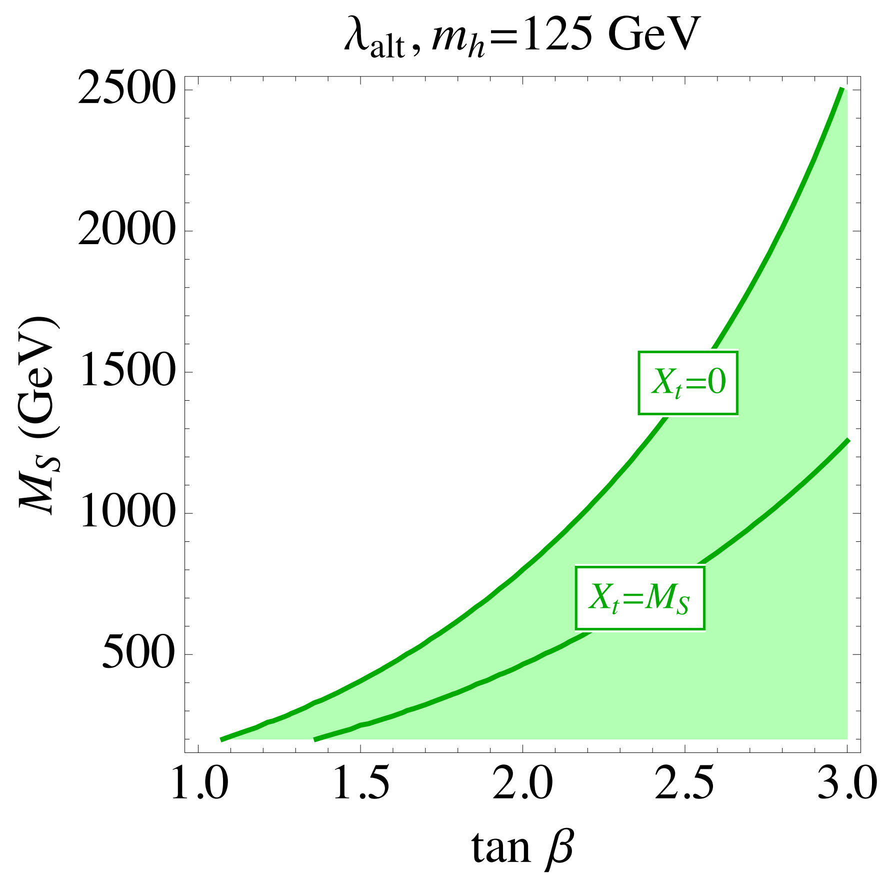
Stop Contribution at alignment

Carena, Haber, Low, Shah, C.W.'15

Interesting, after some simple algebra, one can show that

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$





For moderate mixing, It is clear that low values of $\tan\beta < 3$
lead to lower corrections to the Higgs mass parameter at the alignment values

Aligning the singlets

Carena, Haber, Low, Shah, C.W.'15

- The previous formulae assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states

- The mixing mass matrix element between the singlets and the SM-like Higgs is approximately given by

$$M_S^2(1,3) \simeq 2\lambda v \mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

- If one assumes alignment, the expression inside the bracket must cancel

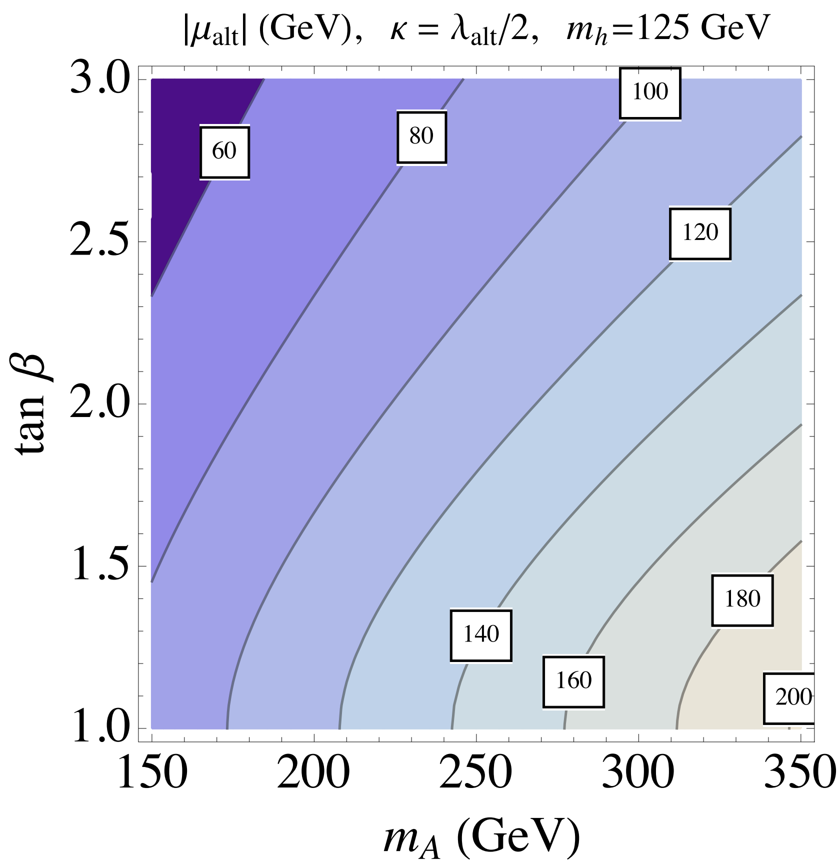
- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one inmediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated in mass with the parameter mu, namely

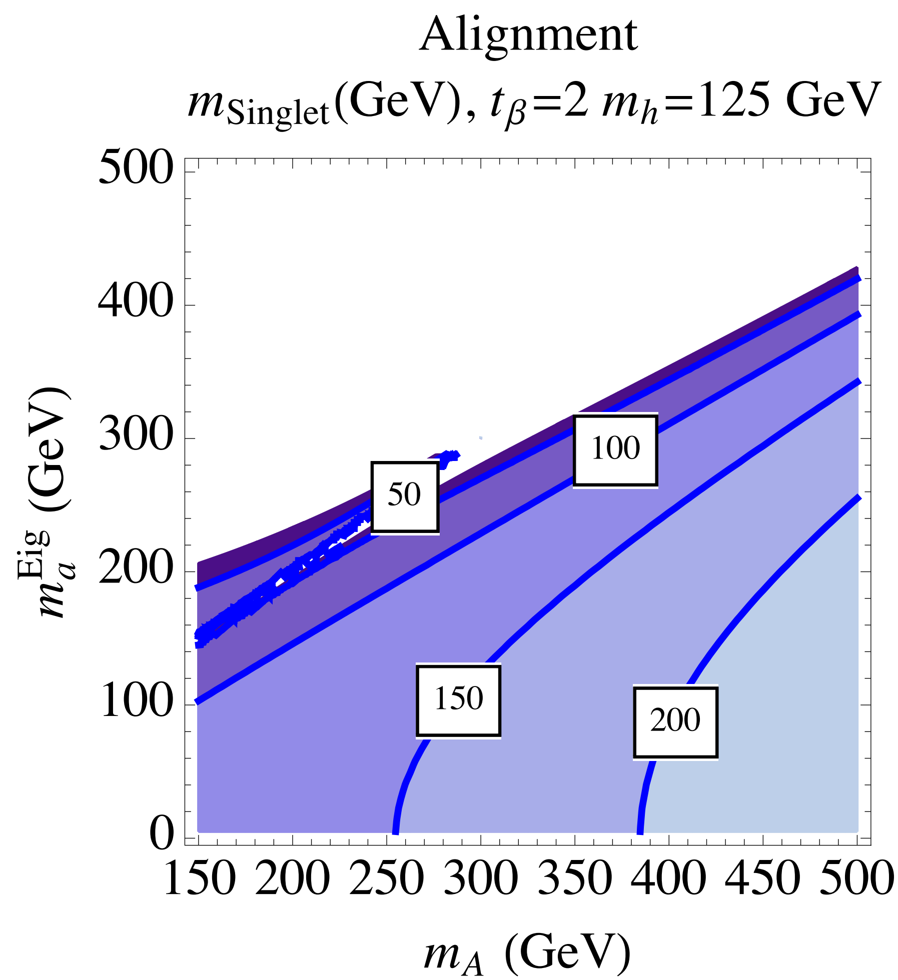
- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

- Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets (and singlino) become self consistently light

Values of the Singlet, Higgsino and Singlino Masses

Carena, Haber, Low, Shah, C.W.'15





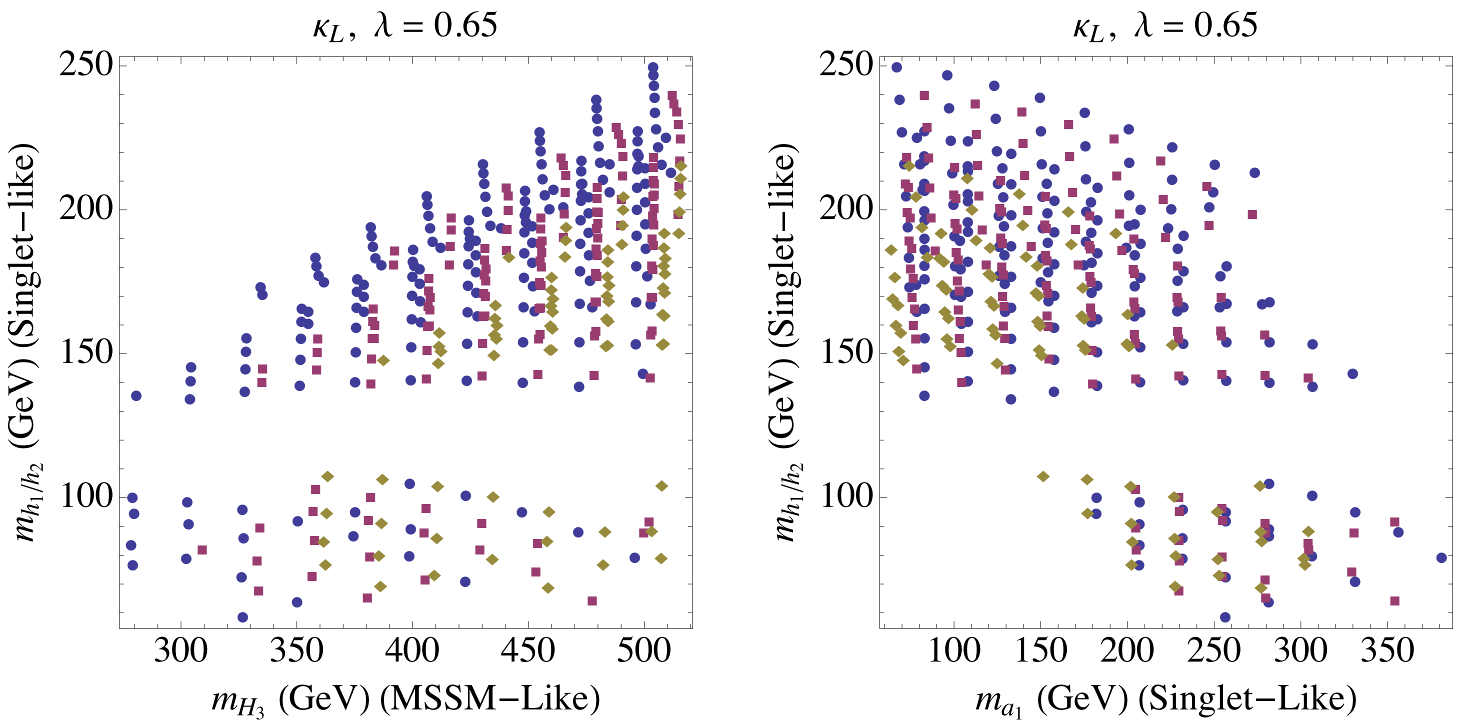
In this limit, the singlino mass is equal to the Higgsino mass.

$$m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}$$

So, the whole Higgs and Higgsino spectrum remains light, as anticipated

Resulting Higgs Masses

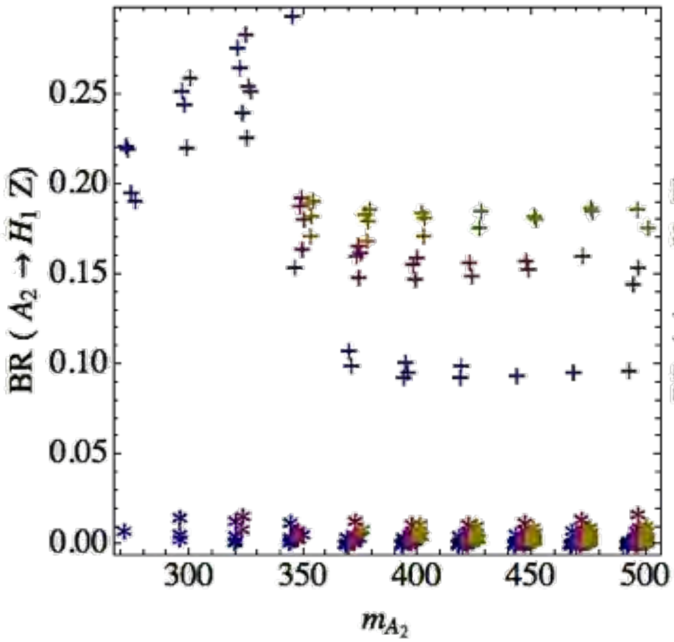
Carena, Haber, Low, Shah, C.W.'15

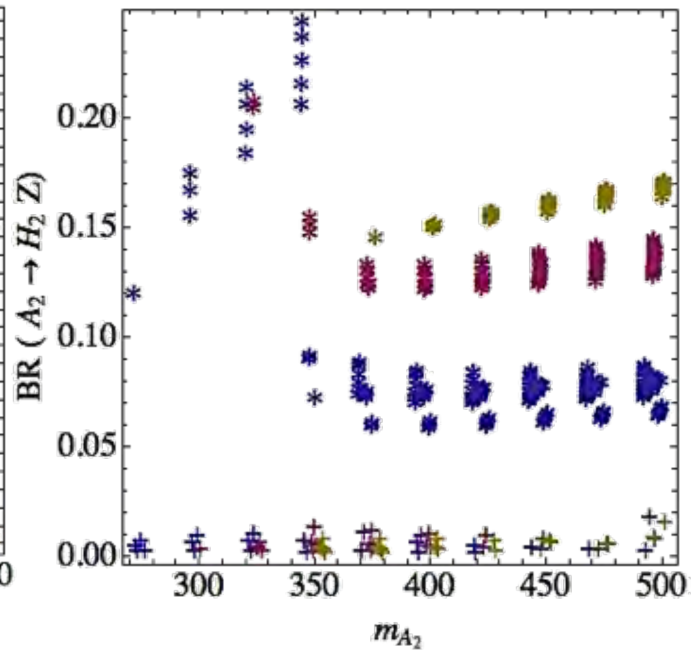


The whole Higgs spectrum is light, with heavy Higgs bosons with masses of the order of a few hundred GeV and the lighter ones below the weak scale

Searches for decays into Higgs plus Z bosons

Carena, Haber, Low, Shah, C.W.'15





The production cross section is of the order of a few pb, so this produces a visible signature at 8 and 13 TeV runs, with the lighter Higgs not being identified with the SM one.

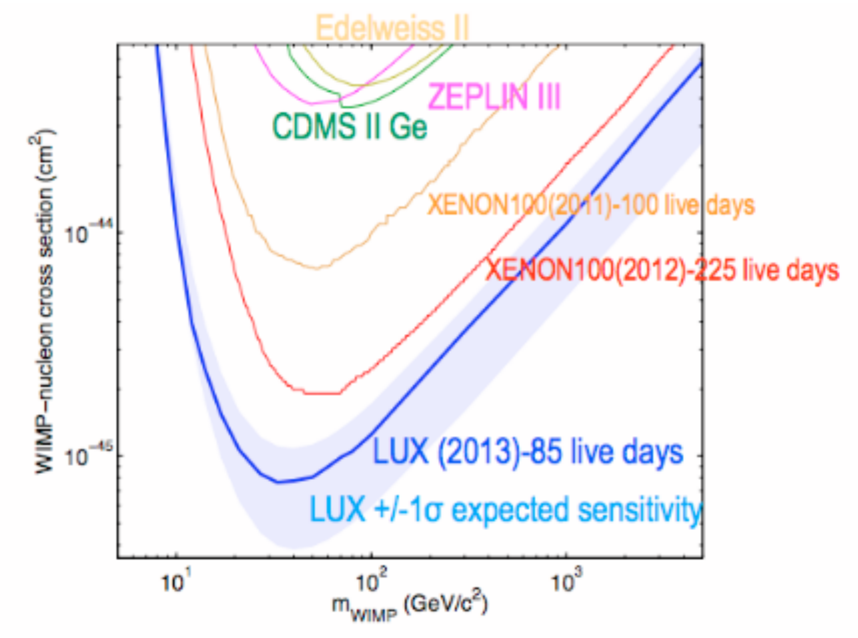
Interesting excess at CMS at heavy Higgs mass close to 285 GeV and lighter Higgs mass of order 95 GeV may be explained by these models (and also the LEP anomaly)

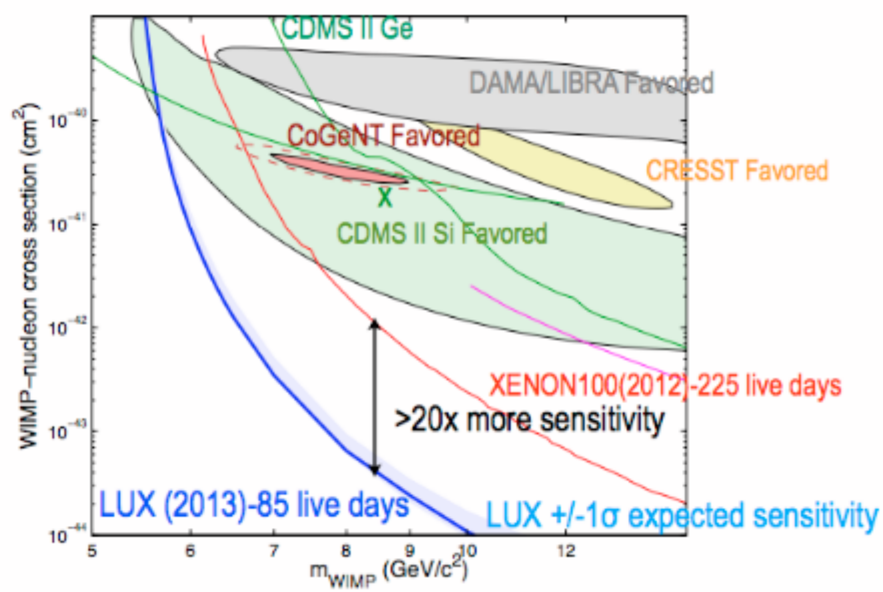
CMS analysis : arXiv:1504.04710

Stops and Dark Matter

- Light Higgsinos and light stops are naturally present in the theory.
- Gaugino masses are not fixed in this scenario, but if light, of the order of the Higgsino mass scale, the correct relic density may be obtained
- Direct Dark Matter detection signatures increase in such a case, but regions of parameters space, blind spots, exist, where Direct Dark Matter detection is reduced, (much) below the present bounds.
- Winos could be heavier, so Higgsino production should be considered, with a rich number of decays into lighter electroweakinos and Higgs bosons
- Stops are naturally close to the current bounds and present a rich patern of decays into neutralinos and charginos

Direct Dark Matter Detection





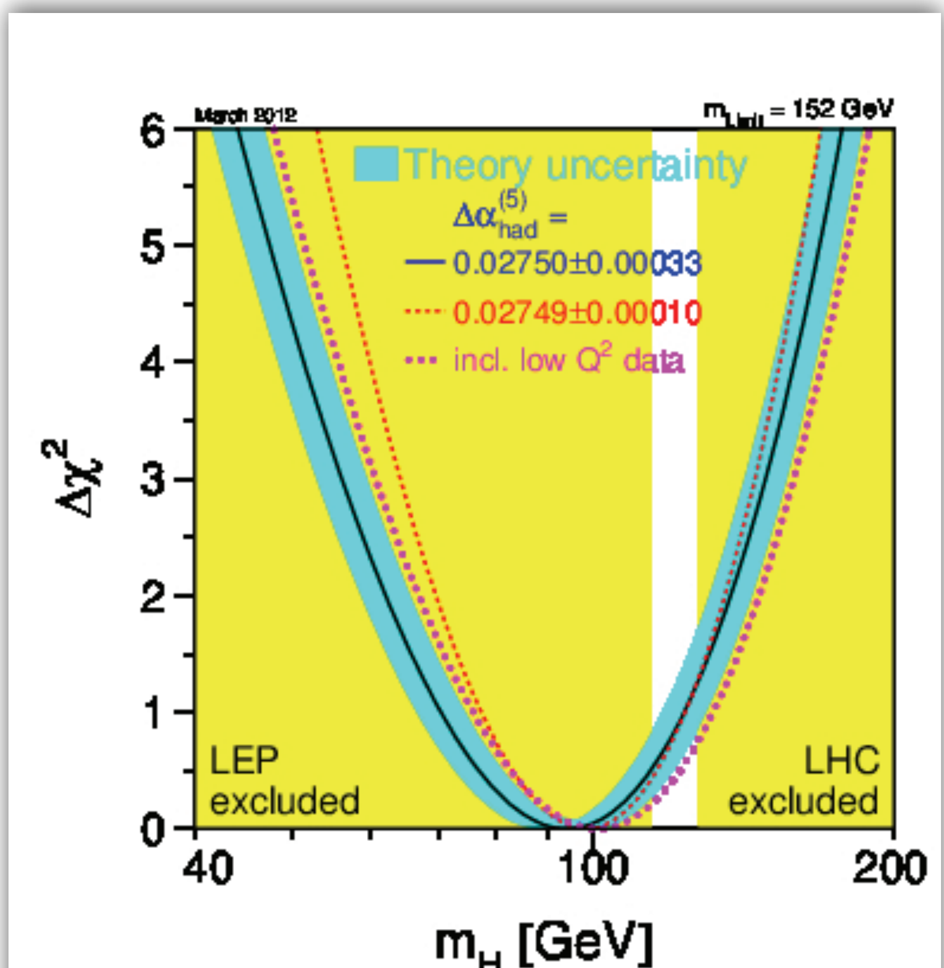
Non-observation of any Spin Independent Signal

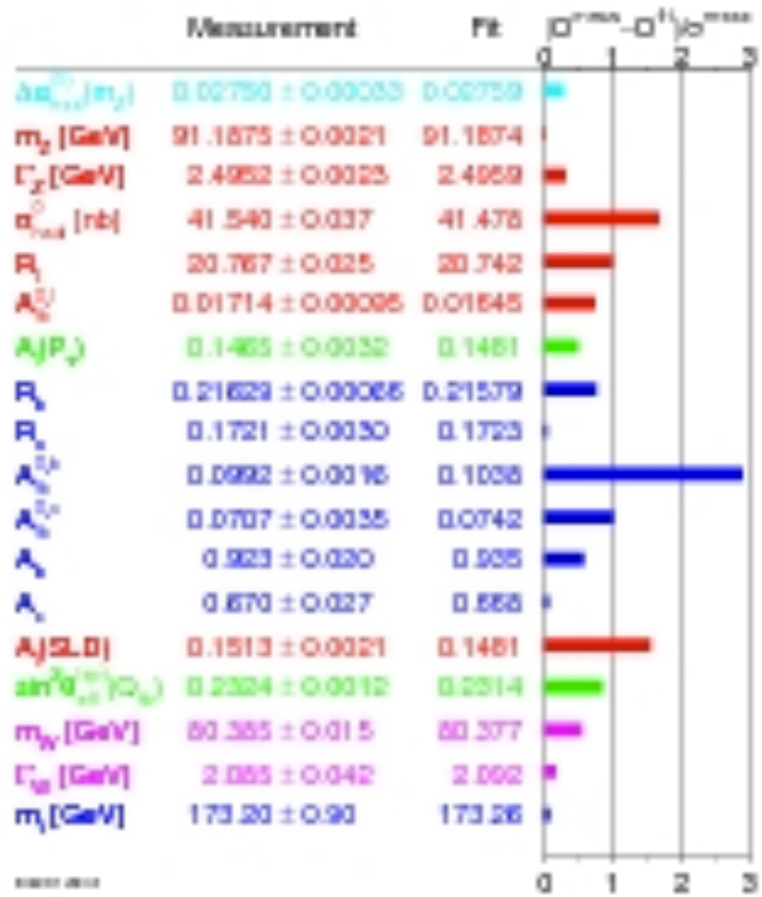
Ellis, Ferstl, Olive'00, Ellis et al'05, Baer et al'07
Cheung, Hall, Pinner, Rudermann '13
Huang, C.W. '14

Blind Spots for Gaugino--Higgsino Mixed Dark Matter

$$2\ (m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq -\ \mu \tan\beta \frac{1}{m_H^2}$$

Precision Electroweak Data





[LEP EWWG]

Modify $Zb_R\bar{b}_R$ coupling

[Haber, Logan '99]
[Choudhury, Tait, Wagner '01]

$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu \bar{b}(g_{Lb}P_L + g_{Rb}P_R)b$$

$$g_{Lb} = -\frac{1}{2} + \frac{1}{3}s_w^2 \approx -0.43$$
$$g_{Rb} = \frac{1}{3}s_w^2 \approx 0.0771$$

Goal: shift A_{FB}^b and R_b

$$A_{FB} = \frac{3}{4}\frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}\frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2}$$

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \frac{g_{Lb}^2 + g_{Rb}^2}{\sum_q [g_{Lq}^2 + g_{Rq}^2]}$$

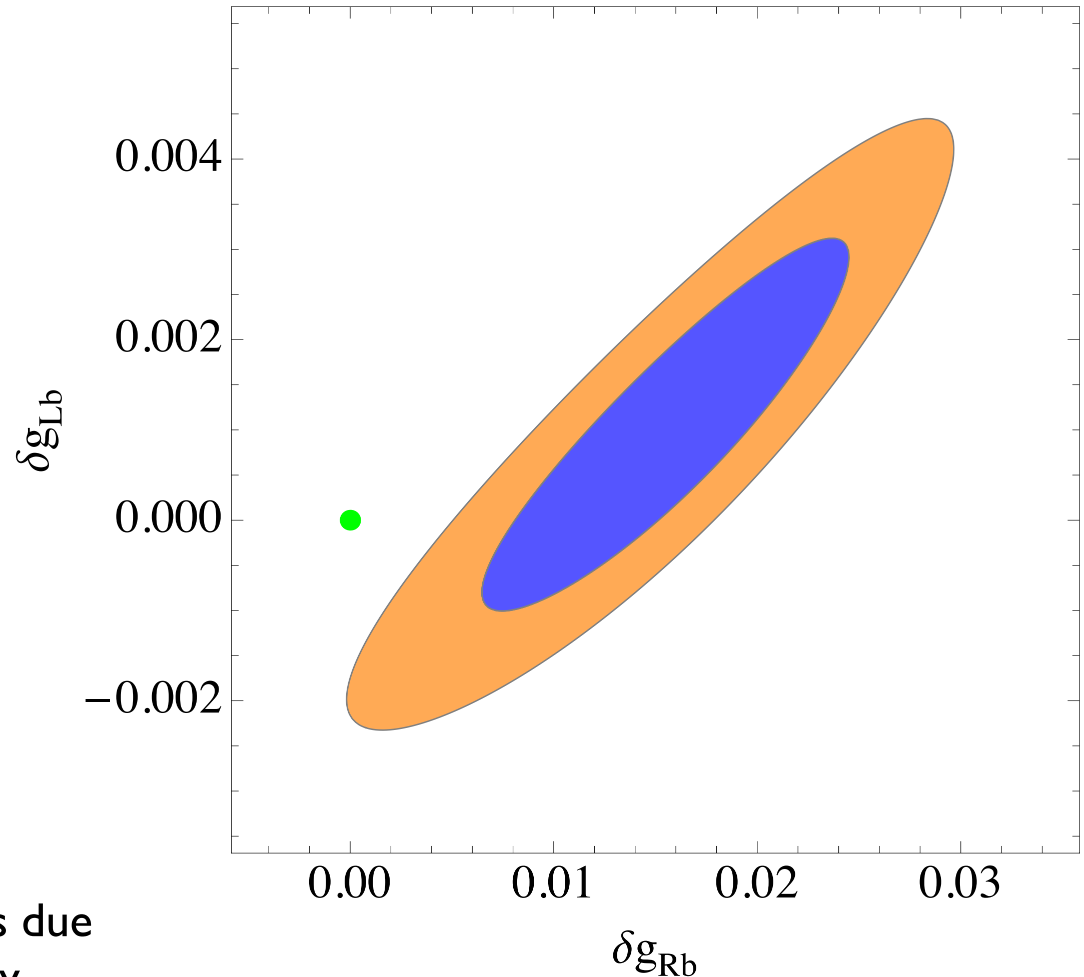
Z-pole data allows 4 solutions in $(\delta g_{Lb}, \delta g_{Rb})$, off-peak data for A_{FB}^b eliminate 2 possible solutions

Data prefers a bigger shift in δg_{Rb}, smaller shift in δg_{Lb}

Best-fit region:

$$\delta g_{Lb} \sim 0.001 \pm 0.001$$

$$\delta g_{Rb} \sim 0.015 \pm 0.005$$



Batell, Gori, Wang'12

(They consider Rb anomaly which was due to incorrect theoretical analysis by other authors. Slight shift in right- and left-handed coupling)

See also: [Choudhury, Tait, Wagner '01]
[Kumar, Shepard, Tait, Vega-Morales '10]

Beautiful Mirrors [Choudhury, Tait, Wagner '01]

Basic idea: Mix new vector-like quark with bottom quark

$$\mathcal{L} \supset -\left(\bar{b}'_L \quad \bar{B}'_L\right) \left(\begin{array}{cc} M_{11} & M_{12} \\ M_{21} & M_{22} \end{array} \right) \left(\begin{array}{c} b'_R \\ B'_R \end{array} \right) + \text{h.c.}$$

Diagonalize mass matrix via rotations of $b_{i(L,R)}$, with angles $\theta_{L,R}$

Z boson interactions: $\mathcal{L} \supset \frac{g}{c_w} Z_\mu \sum_{ij} \bar{b}_i \gamma^\mu (L_{ij} P_L + R_{ij} P_R) b_j$

Shifts in $Z\bar{b}b$ couplings:

$$\delta g_{Lb} = \left(t_{3L} + \frac{1}{2}\right) s_L^2, \qquad \delta g_{Rb} = t_{3R} s_R^2,$$

Singles out 3 vector-like representations:

$$\Psi_{L,R} \sim (3,2,1/6), (3,2,-5/6), (3,3,2/3)$$

Focus on $\Psi \sim (3, 2, -5/6) \sim \begin{pmatrix} B \\ X \end{pmatrix}$ $Q_X = -4/3$

$$t_{3R}^B = \frac{1}{2} \quad \Rightarrow \quad \delta g_{Rb} = \frac{1}{2} s_R^2 = 0.015 \quad \Rightarrow \quad s_R \sim 0.17$$

(small mixing)

Minimal model:

$$-\mathcal{L} \supset y_1 \bar{Q} H b_R + y_2 \bar{\Psi}_L H^\dagger b_R + M \bar{\Psi}_L \Psi_R + \text{h.c.}\ .$$

$$= (\bar{b}_L \ B_L) \left[\begin{pmatrix} Y_1 & 0 \\ Y_2 & M \end{pmatrix} + \frac{h}{v} \begin{pmatrix} Y_1 & 0 \\ Y_2 & 0 \end{pmatrix} \right] \begin{pmatrix} b_R \\ B_R \end{pmatrix}, \qquad Y_i \equiv \frac{y_i v}{\sqrt{2}}$$

shifts: $\delta g_{Rb} \simeq \frac{Y_2^2}{2M^2} \quad \Rightarrow \quad Y_2 \sim 0.17 M$

- Small oblique parameters S, T [Peskin, Takeuchi `90, `92]
- Light Higgs, heavy mirror quarks preferred by EW data

Extension of the minimal model:

[Choudhury, Tait, Wagner '01]

- One can further improve the EW fit by adding an SU(2) singlet quark $\hat{B} \sim (3, 1, -1/3)$ that mixes with the bottom

- This causes a shift $\delta g_{Lb} \sim 0.001$

- Mass matrix:

$$\mathcal{M}_B = \begin{pmatrix} Y_1 & 0 & Y_2 \\ Y_3 & M_1 & Y_4 \\ 0 & Y_5 & M_2 \end{pmatrix},$$

δg_{Lb} (Y_2)

δg_{Rb} (Y_3)

Higgs properties (Y_4, Y_5)

- Large Y_4, Y_5 can alter Higgs rates, but also cause large custodial symmetry breaking; ⇨ custodial extension

Non-universal $Zb\bar{b}$ shifts: $\delta g_{Lb} = \frac{Y_2^2}{2M_2^2}, \quad \delta g_{Rb} = \frac{Y_3^2}{2M_1^2}$

Recall $\delta g_{Rb} \sim 0.015, \quad \delta g_{Lb} \sim 0.001,$

$$\Rightarrow \quad Y_2 \simeq \pm 0.04\, M_2 \quad Y_3 \simeq \pm 0.17\, M_1$$

b - quark mass &

$h - b - \bar{b}$ coupling

$$m_b = Y_1 \left(1 - \frac{Y_2^2}{2M_2^2} - \frac{Y_3^2}{2M_1^2}\right) + \frac{Y_2 Y_3 Y_5}{M_1 M_2}$$

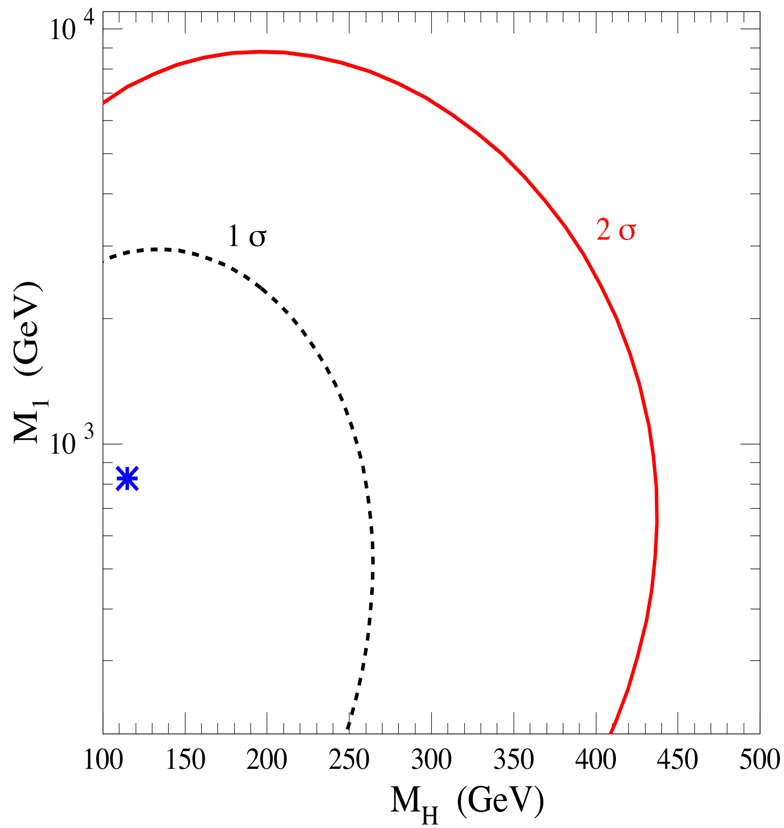
$$y_{hbb} = \frac{1}{v}\left[Y_1 \left(1 - \frac{3Y_2^2}{2M_2^2} - \frac{3Y_3^2}{2M_1^2}\right) + \frac{3Y_2 Y_3 Y_5}{M_1 M_2}\right]$$

$$r_b = \left(\frac{y_{hbb}}{m_b/v}\right)^2 \approx 1 + 8\sqrt{\delta g_{Rb}\delta g_{Rb}}\frac{Y_5}{m_b}$$

Large corrections to $h \to b\bar{b}$ possible only if Y_5 large

Choudhury, Tait, Wagner'01

Best Fit values for the ω Mass



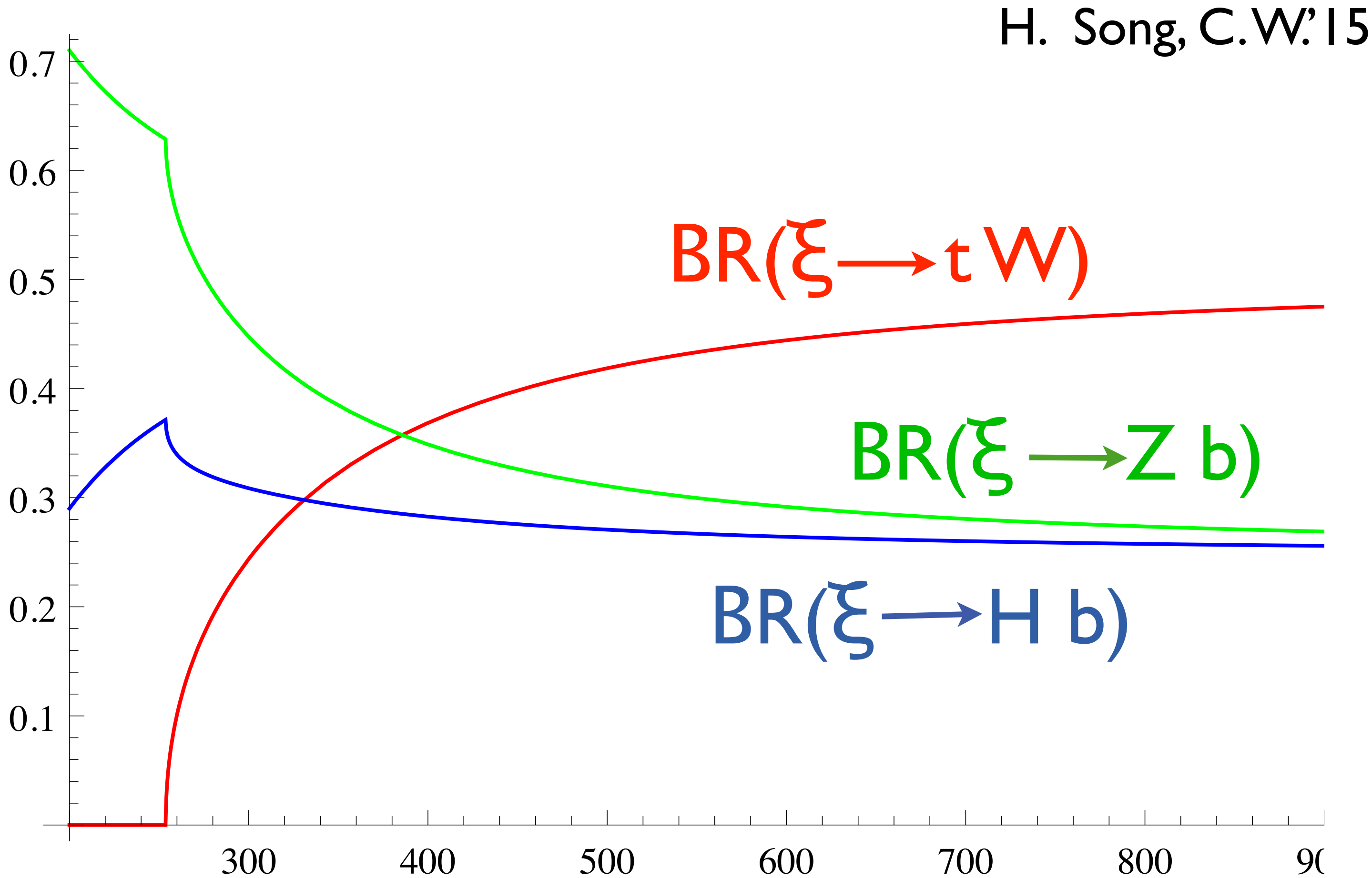
Mixing angles small unless particles heavy. Somewhat heavier particles preferred, inducing T-parameter corrections that improve lepton asymmetries and W mass fit

H. Song, C.W.'15

Weak Eigenstates
Particle Content

Field		T_3	Y	$Q = T_3 + Y$
$Q_L^{'}$	t_L	1/2	1/6	2/3
	$b_L^{'}$	−1/2	1/6	−1/3
	t_R	0	2/3	2/3
	$b_R^{'}$	0	−1/3	−1/3
$\psi_L^{'}$	$\omega_L^{'}$	1/2	−5/6	−1/3
	χ_L	−1/2	−5/6	−4/3
$\psi_R^{'}$	$\omega_R^{'}$	1/2	−5/6	−1/3
	χ_R	−1/2	−5/6	−4/3
	$\xi_L^{'}$	0	−1/3	−1/3
	$\xi_R^{'}$	0	−1/3	−1/3
ϕ	ϕ^+	1/2	1/2	1
	ϕ^0	−1/2	1/2	0

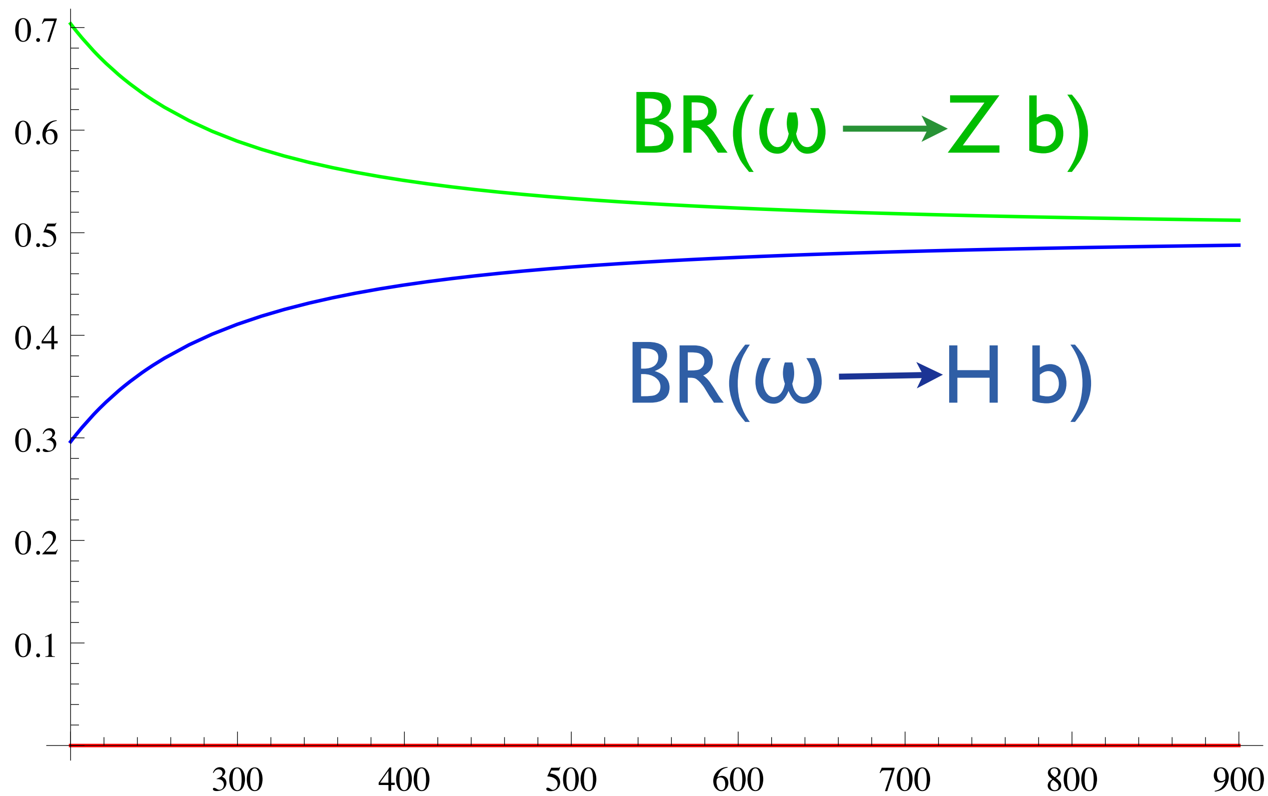
Decay Rates of ξ-particle



No $\omega - \xi$ Mixing (Y4 = Y5 = 0)

Decays of the ω-particle

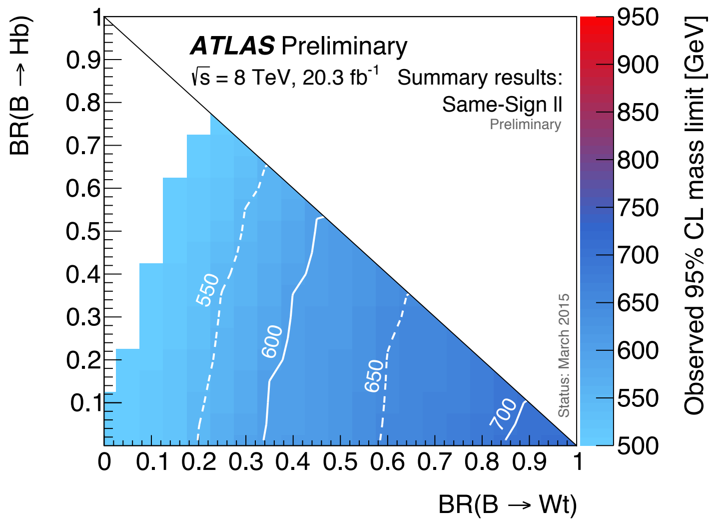
H. Song, C.W.'15



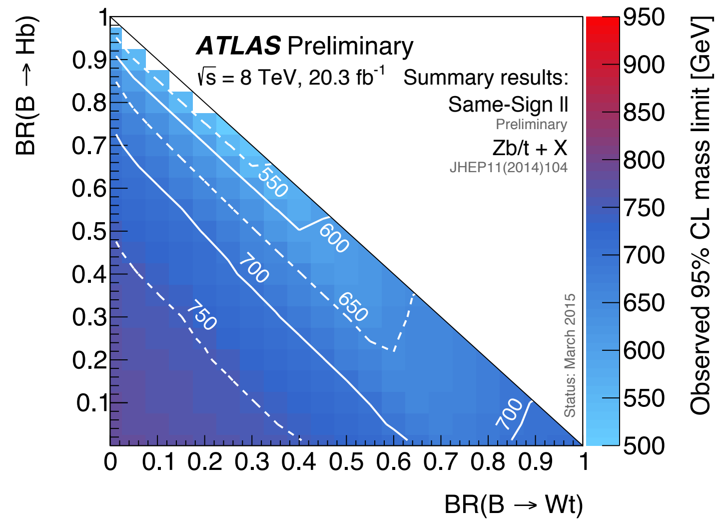
Decay Branching Ratios of Omega (SU(2) doublet) Particle

(Y4 = Y5 =0)

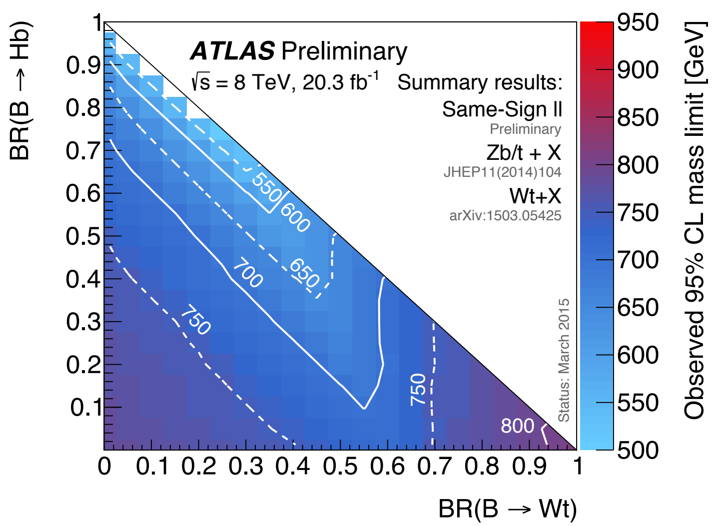
ATLAS Search Channels



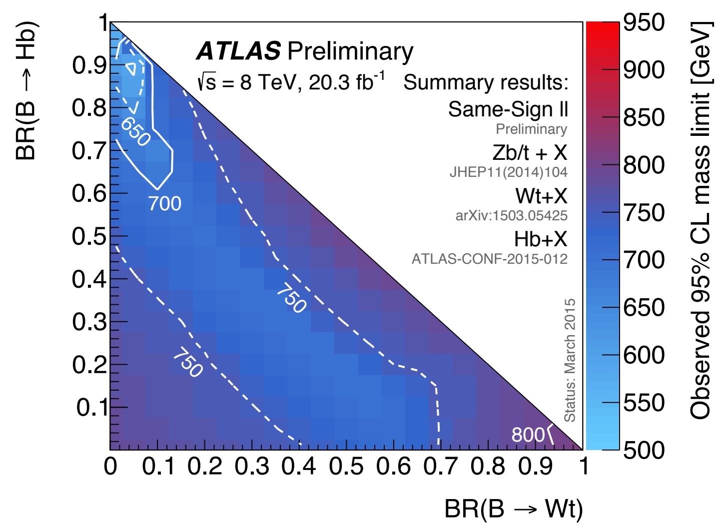
Hb+X



Hb+X / Same-Sign II

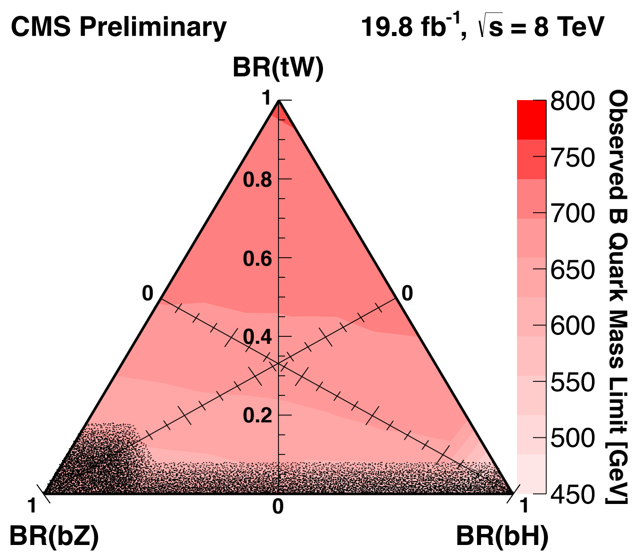


Hb+X / Same-Sign II
Zb/t+X

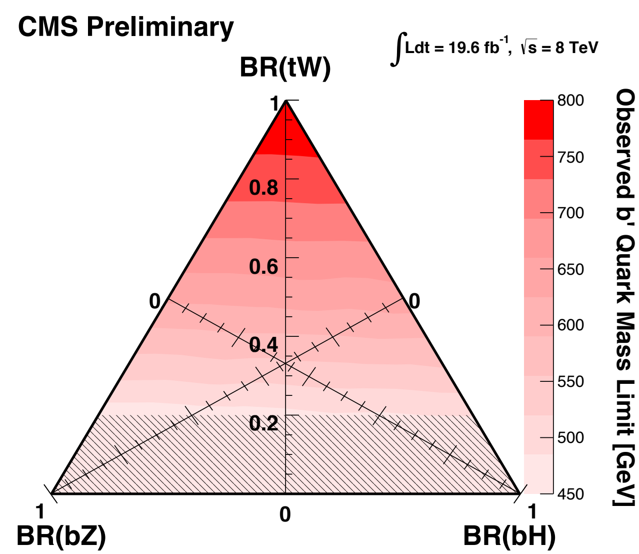


Hb+X / Same-Sign II
Zb/t+X / Wt+X

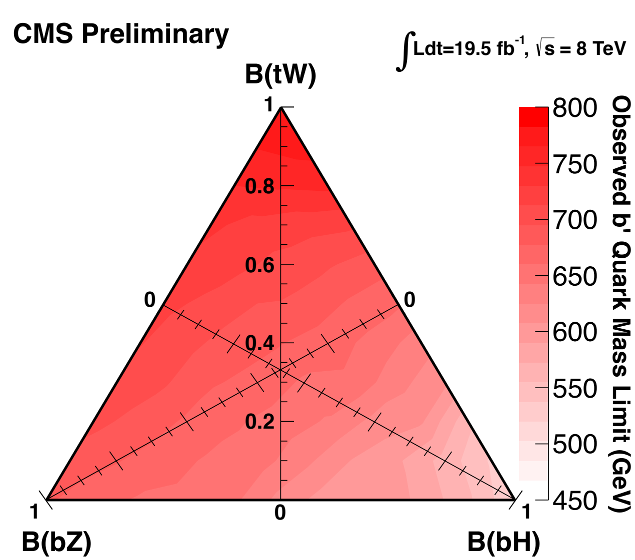
CMS Search Channels



(a) B2G-12-019(2013/09/10) lepton+jets



(b) B2G-12-020(2014/08/07) same-sign dilepton



(c) B2G-13-003(2013/11/18) multilepton

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

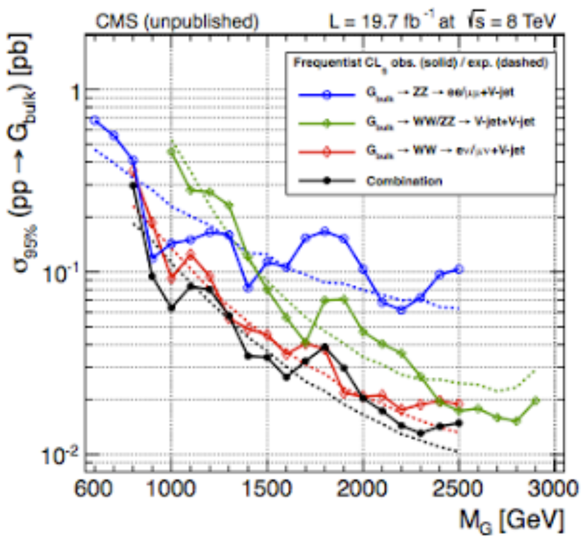
ATLAS Preliminary

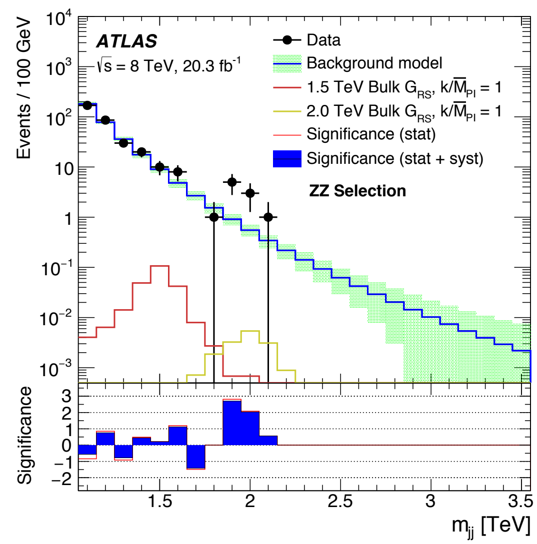
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

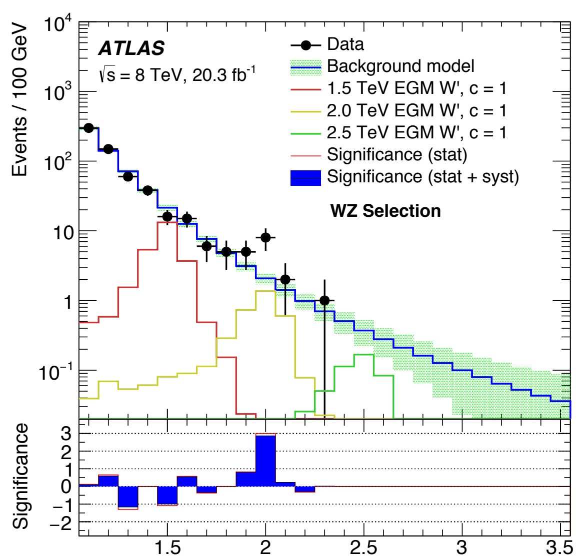
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	2 j / 1 J	Yes	20.3	W′ mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z′ mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z′ mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W′ mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W′ mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W′ mass 1.59 TeV		1409.6190
	HVT $W' \to WH \to \ell\nu bb$	$1\ e, \mu$	2 b	Yes	20.3	W′ mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W′ mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W′ mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	Preliminary
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.35 TeV	$\lvert C_{LL} \rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1^{st} gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2^{nd} gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3^{rd} gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \to Ht + X, Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \to Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary
	$T_{5/3} \to Wt$	$1\ e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		Preliminary

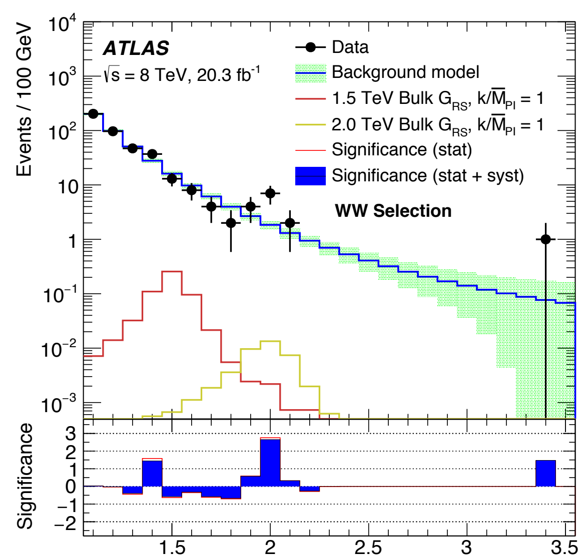
Searches for Beautiful Mirrors lead to limits of about 750 GeV, independently of decay channels which are close to the preferred values for their masses

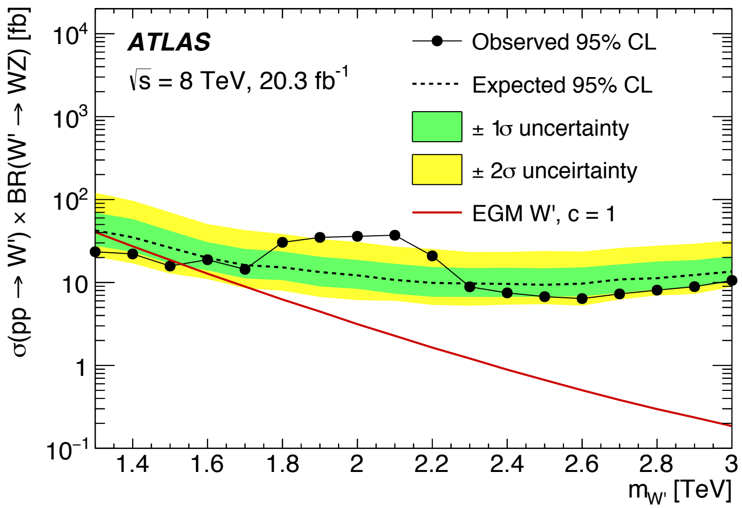
Diboson Signals



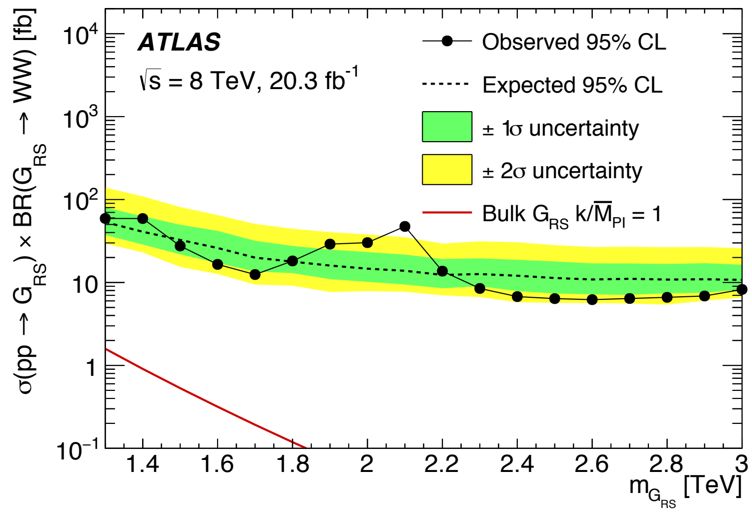




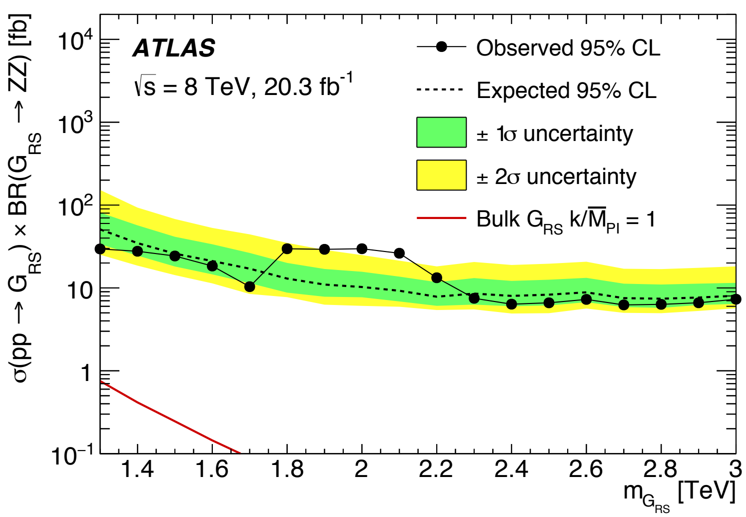



ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ unceirtainty
EGM W', c = 1
σ(pp → W') × BR(W' → WZ) [fb]
m_W' [TeV]

(a)


ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_RS k/M̄_Pl = 1
σ(pp → G_RS) × BR(G_RS → WW) [fb]
m_G_RS [TeV]

(b)

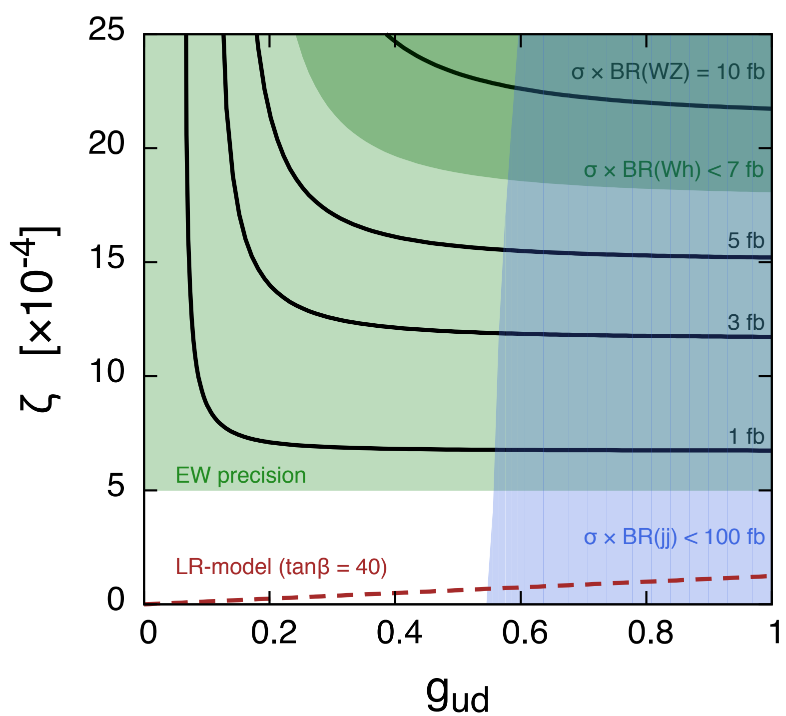

ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_RS k/M̄_Pl = 1
σ(pp → G_RS) × BR(G_RS → ZZ) [fb]
m_G_RS [TeV]

Hisano et al'15

Simple Explanations
Charged W' boson mixing with the SM W

$$\begin{pmatrix} W^+ \\ W'^+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} \hat{W}^+ \\ \hat{W}'^+ \end{pmatrix}$$

$$\Gamma(W'^+ \to W^+ Z) \simeq \frac{\alpha_2 \sin^2 2\zeta}{192} \frac{M_{W'}^5}{M_W^4}$$



Strong constraints from dijet resonance, precision measurements and Wh searches

Hisano et al'15

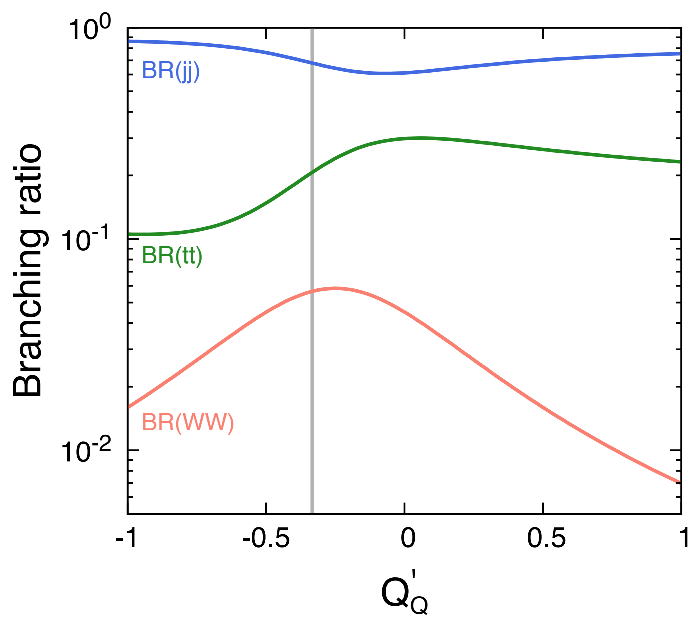
Leptophobic Z'

Similar constraints as in the charged W' case, although larger cross section may be accommodated

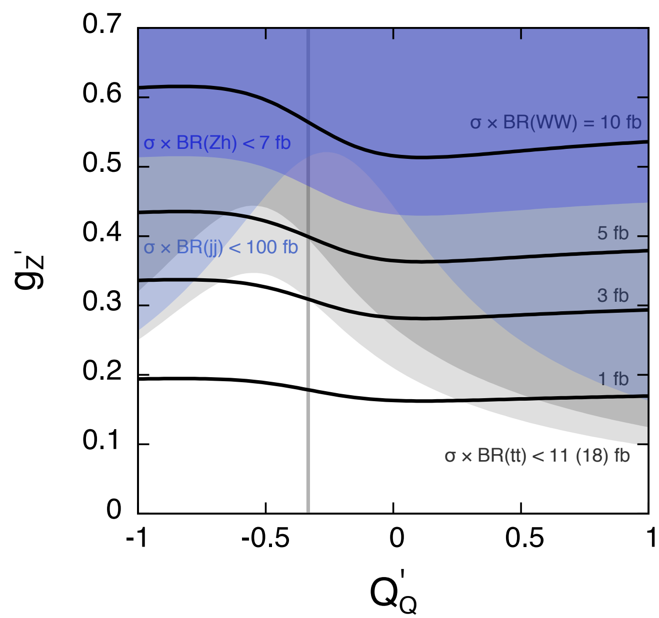
$$\mathcal{L}_{\rm int} = g_{Z'} \overline{f} \hat{\not{Z}}' (Q'_{f_L} P_L + Q'_{f_R} P_R) f$$

$$\Gamma(Z' \to q\bar{q}) = \frac{g_{Z'}^2 N_C}{24\pi} M_{Z'} \left[Q'^2_{qL} + Q'^2_{qR} - (Q'_{qL} - Q'_{qR})^2 \frac{m_q^2}{M_{Z'}^2} \right] \sqrt{1 - \frac{4m_q^2}{M_{Z'}^2}}$$

$$\Gamma(Z' \to W^+W^-) = \frac{g_{Z'}^2}{48\pi} Q'^2_{H_u} \sin^4\beta M_{Z'}$$



(a) Branching ratios

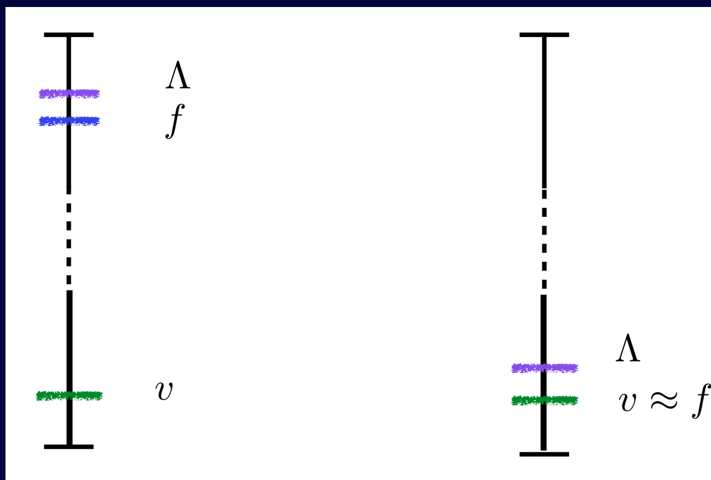


(b) $\sigma(pp \to Z') \times {\rm BR}(Z' \to WW)$

How to define the scales? Can the Higgs play the role of the Flavon?

$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \to y_b \left(\frac{H^\dagger H}{\Lambda^2}\right)^{n_b} \bar{Q}_L H b_R$$

Babu, Nandi ‘00, Giudice-Lebedev ‘08



Effective Yukawa coupling:

$$y_i^{eff} = \left(\frac{v^2}{2\Lambda^2}\right)^{n_i} y_i$$

Suppression factor:

$$\epsilon = v^2/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v$$

Flavor Scale is fixed by electroweak scale

Two Main Problems

- **The flavon is a flavor singlet**
- **The Higgs coupling to Bottom quarks is too large**

$$g_{hbb} \propto 3\, m_b/v \longrightarrow \frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to b\bar{b})_{SM}} = 9$$

Bauer, Carena, Gemmler'15

Two Higgs Doublet Flavor Model

$$\mathcal{L}_{\rm Yuk} = y^u_{ij}\left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{u_j} - a_{H_u}} \bar{Q}_i H_u u_{Rj} + y^d_{ij}\left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{d_j} - a_{H_d}} \bar{Q}_i H_d d_{Rj} + h.c.$$

After rotation to mass eigenstates, we obtain the flavor structure from fixing the flavor charges

$$\begin{aligned} a_{H_u} &= 1\,, & a_1 &= 2\,, & a_u &= -2\,, & a_d &= -1\,,\\ a_{H_d} &= 0\,, & a_2 &= 2\,, & a_c &= 0\,, & a_s &= 0\\ & & a_3 &= 1\,, & a_t &= 0\,, & a_b &= 0 \end{aligned}$$

→

$$m_t \approx \frac{v_u}{\sqrt{2}}\,, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1\,, \quad \frac{m_s}{m_t} \approx \varepsilon^2\,, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

$$(V_{\rm CKM})_{12} \approx \varepsilon^0\,, \qquad (V_{\rm CKM})_{13} \approx (V_{\rm CKM})_{23} \approx \varepsilon^1$$

The Higgs-quark couplings can then be computed: e.g. for the light (SM-like) Higgs

$$g_{hu_iu_j} = \left(\frac{m_u}{v}\right)_{ij}\delta_{ij}\left[\frac{c_\alpha}{s_\beta} - a_{H_u} f(\alpha,\beta)\right] + f(\alpha,\beta)\left[\mathcal{Q}^u_{ij}\left(\frac{m_u}{v}\right)_{jj} - \left(\frac{m_u}{v}\right)_{ii}\mathcal{U}_{ij}\right]$$

$$g_{hd_id_j} = \left(\frac{m_d}{v}\right)_{ij}\delta_{ij}\left[-\frac{s_\alpha}{c_\beta} - a_{H_d} f(\alpha,\beta)\right] + f(\alpha,\beta)\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii}\mathcal{D}_{ij}\right]$$

Process Dependent factors

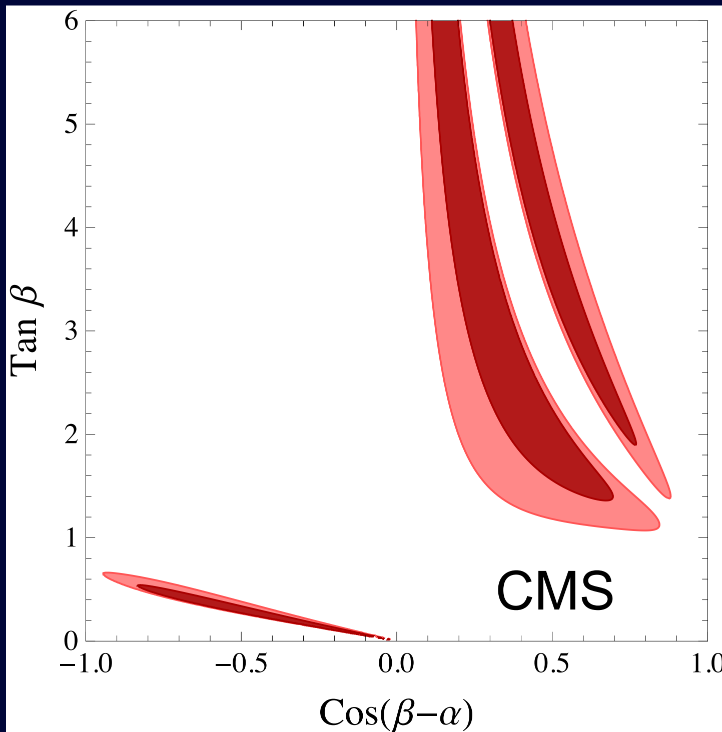
$$\mathcal{Q}^u \sim \mathcal{Q}^d \sim \begin{pmatrix} 2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & 2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \qquad \mathcal{U} \sim \begin{pmatrix} -2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^4 \\ \varepsilon^2 & \varepsilon^4 & \varepsilon^4 \end{pmatrix} \qquad \mathcal{D} \sim \begin{pmatrix} -1 & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \end{pmatrix}$$

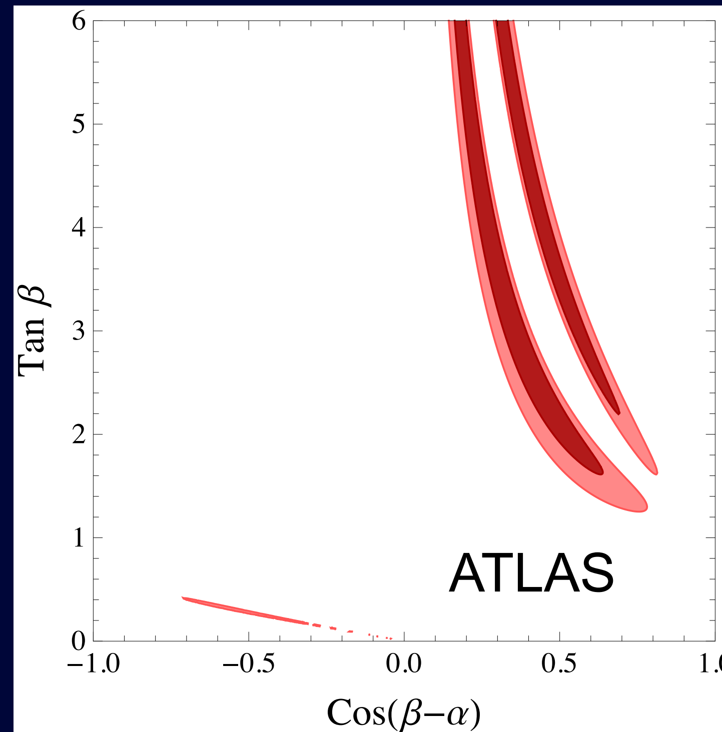
Universal function

$$f(\alpha,\beta) = \frac{c_\alpha}{s_\beta} - \frac{s_\alpha}{c_\beta} = c_{\beta-\alpha}\left(\frac{1}{t_\beta} - t_\beta\right) + 2 s_{\beta-\alpha}$$

Similar functions for 1) for the Heavy CP-even Higgs replacing cα → sα & -sα → cα
2) for the CP-odd Higgs by subsequently multiplying by i and replacing cα → sβ & sα → cβ
3) Charged Higgs boson couplings are independent of flavor charges; Same as in Type II

Lightest Higgs Global Fit to ATLAS and CMS data





Decay Mode	Production Channels $\sigma_{gg\to h}$, $\sigma_{t\bar{t}\to h}$	Production Channels σ_{VBF}, σ_{VH}	Experiment
$h \to WW^*$	$\mu_W = 1.02^{+0.29}_{-0.26}$ [17]	$\mu_W = 1.27^{+0.53}_{-0.45}$ [17]	ATLAS
	$\mu_W \simeq 0.75 \pm 0.35$ [18]	$\mu_W \simeq 0.7 \pm 0.85$ [18]	CMS
$h \to ZZ^*$	$\mu_Z = 1.7^{+0.5}_{-0.4}$ [19]	$\mu_Z = 0.3^{+1.6}_{-0.9}$ [19]	ATLAS
	$\mu_Z = 0.8^{+0.46}_{-0.36}$ [20]	$\mu_Z = 1.7^{+2.2}_{-2.1}$ [20]	CMS
$h \to \gamma\gamma$	$\mu_\gamma = 1.32 \pm 0.38$ [21]	$\mu_\gamma = 0.8 \pm 0.7$ [21]	ATLAS
	$\mu_\gamma = 1.13^{+0.37}_{-0.31}$ [22]	$\mu_\gamma = 1.16^{+0.63}_{-0.58}$ [22]	CMS
$h \to \bar{b}b$	$\mu_b = 1.5 \pm 1.1$ [23]	$\mu_b = 0.52 \pm 0.32 \pm 0.24$ [24]	ATLAS
	$\mu_b = 0.67^{+1.35}_{-1.33}$ [25]	$\mu_b = 1.0 \pm 0.5$ [26]	CMS
$h \to \tau\tau$	$\mu_\tau = 2.0 \pm 0.8^{+1.2}_{-0.8} \pm 0.3$ [27]	$\mu_\tau = 1.24^{+0.49}_{-0.45}{}^{+0.31}_{-0.29} \pm 0.08$ [27]	ATLAS
	$\mu_\tau \simeq 0.5^{+0.8}_{-0.7}$ [28]	$\mu_\tau \simeq 1.1^{+0.7}_{-0.5}$ [28]	CMS

Global Fit:

Higgs - b-quark couplings with $\kappa_b^2 \sim$ or $<$ 1 are preferred

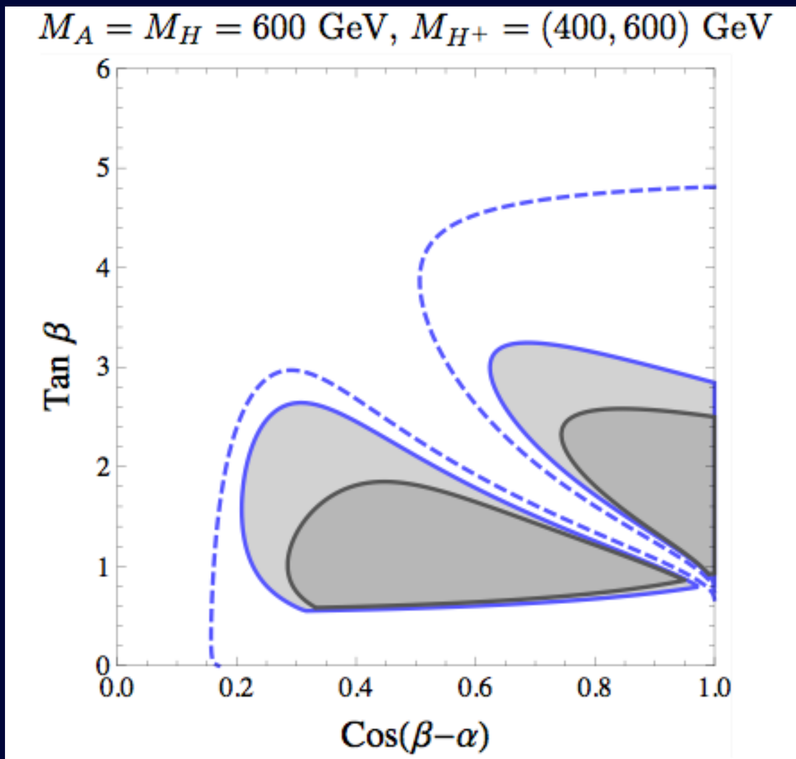
We assumed $\kappa_b \sim \kappa_\tau$

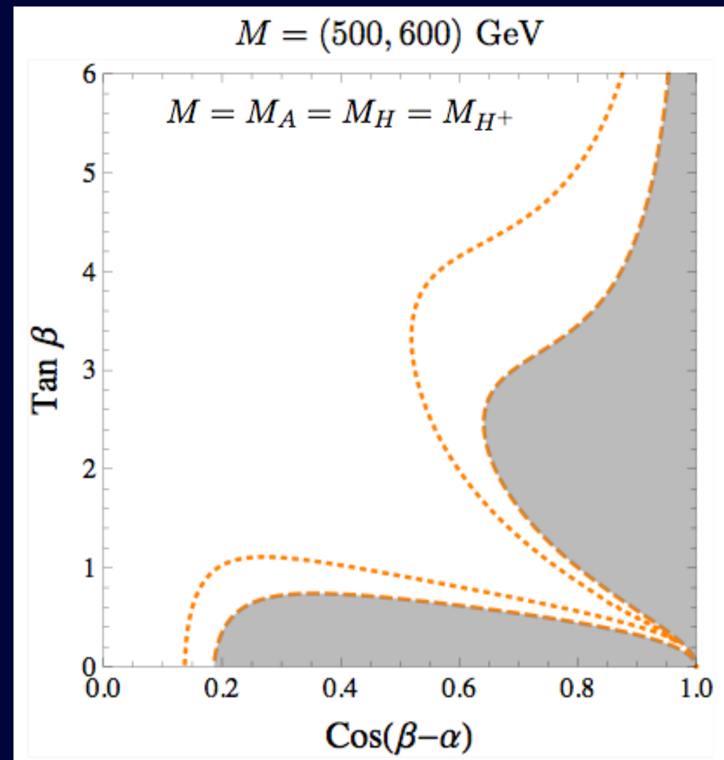
$$\mu_X = \frac{\sigma_{\rm prod}}{\sigma_{\rm prod}^{\rm SM}} \frac{\Gamma_{h\to X}}{\Gamma_{h\to X}^{\rm SM}} \frac{\Gamma_{h,\,{\rm tot}}^{\rm SM}}{\Gamma_h}.$$

Most promising LHC Discovery channels for A and H

$\sigma(gg \to A) \times \mathrm{Br}(A \to hZ) \times \mathrm{Br}(h \to b\bar{b})$

$\sigma(pp \to H + X) \times \mathrm{Br}(H \to VV) / (\sigma(pp \to H + X) \times \mathrm{Br}(H \to VV))_{SM}$





Exclusion bound from ATLAS data for M = 600 GeV in the narrow width approximation, and after considering finite width effects (with and without splitting)

Increasing relevance of VBF channels due to strong gluon fusion suppression in relevant regions of parameter space ~ Very small κ_t^H ~

Conclusions

- Although there are good reasons to expect new physics at the LHC, guidance from experiments is essential at this point
- I tried to discuss some theoretically wwell motivated ideas as well as some motivated by data (or both)
- Looking forward to the results of the current run and to the new physics signatures associated with it.

Backup

Higgs physics

see also Wagner, Morrissey '03

Main effects in Higgs production and decay:

1. Rotations shift in the $hb\bar{b}$ vertex: $\mathcal{L}_{hbb} \simeq -c_R^2 \frac{m_b}{v} h\bar{b}b$

⇨ Partial width $h \to b\bar{b}$ suppressed by c_R^4

2. Heavy quark B contributes to $h \to gg$ and $h \to \gamma\gamma$

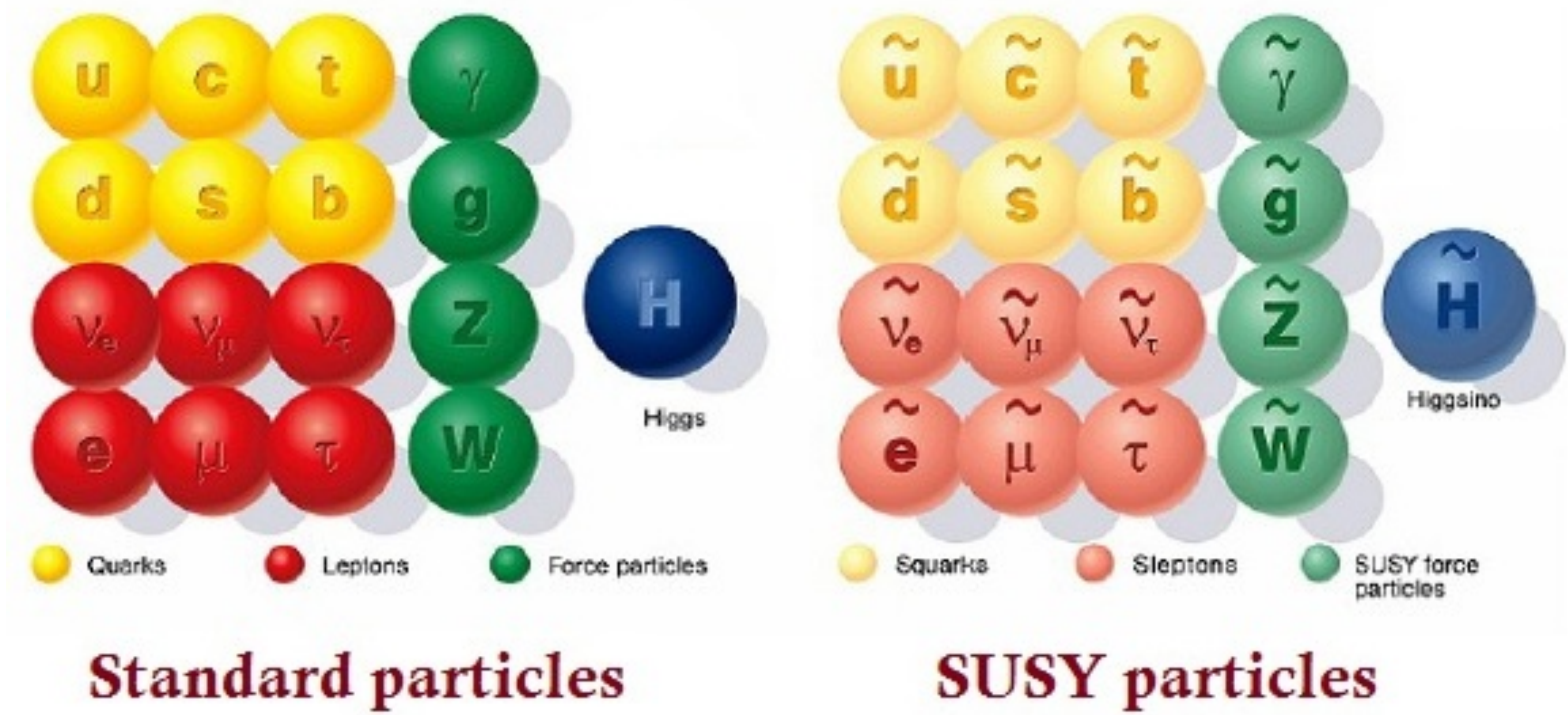
can be characterized
in terms of ratios

$$r_b, r_g, r_\gamma, \qquad r_i \equiv \frac{\Gamma(h \to i)}{\Gamma(h \to i)_{\rm SM}}$$

But, mixing angle and Yukawas are small in the minimal model

⇨ Higgs boson is SM-like (10% shifts at most)

SUPERSYMMETRY



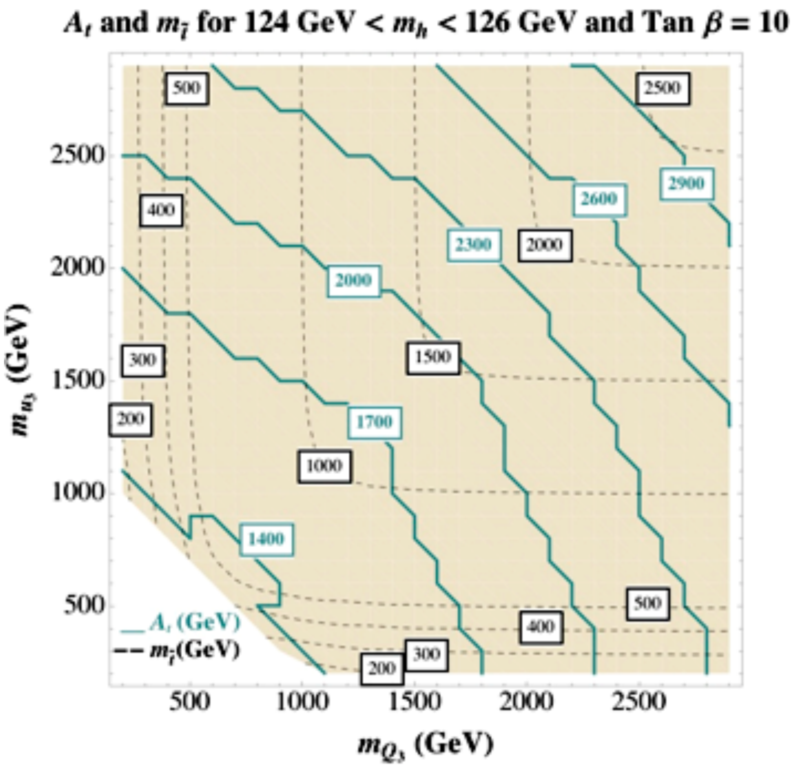
Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

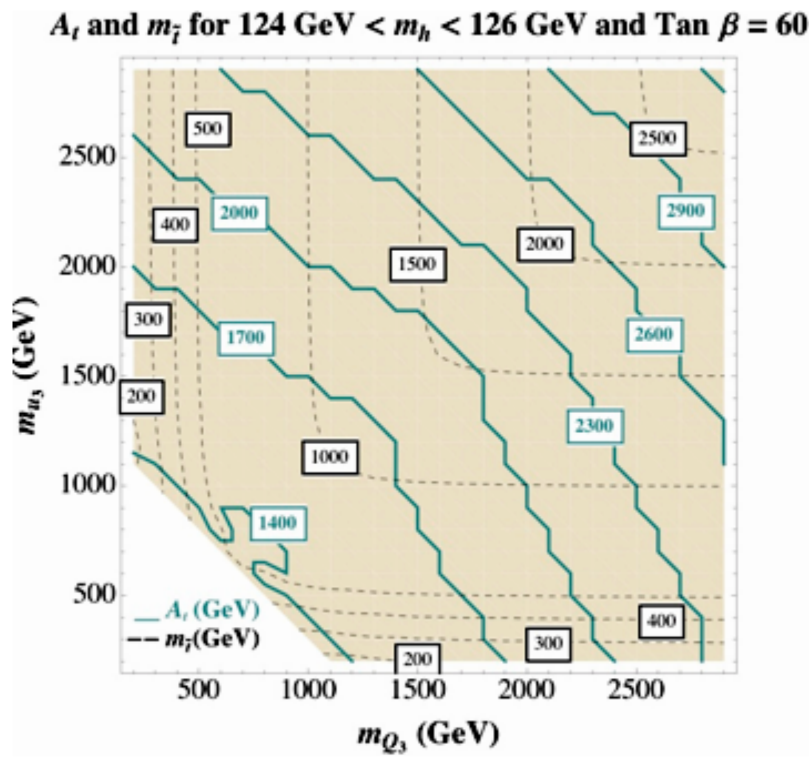
Two Higgs doublets necessary $\rightarrow \tan\beta = \frac{v_2}{v_1}$

Splitting the Two Stop Masses

Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842





Large stop sector mixing

A_t > 1 TeV

No lower bound on the lightest stop

Intermediate values of tan beta lead to the largest values of m_h for the same values of stop mass parameters

Light stop coupling to the Higgs

$$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

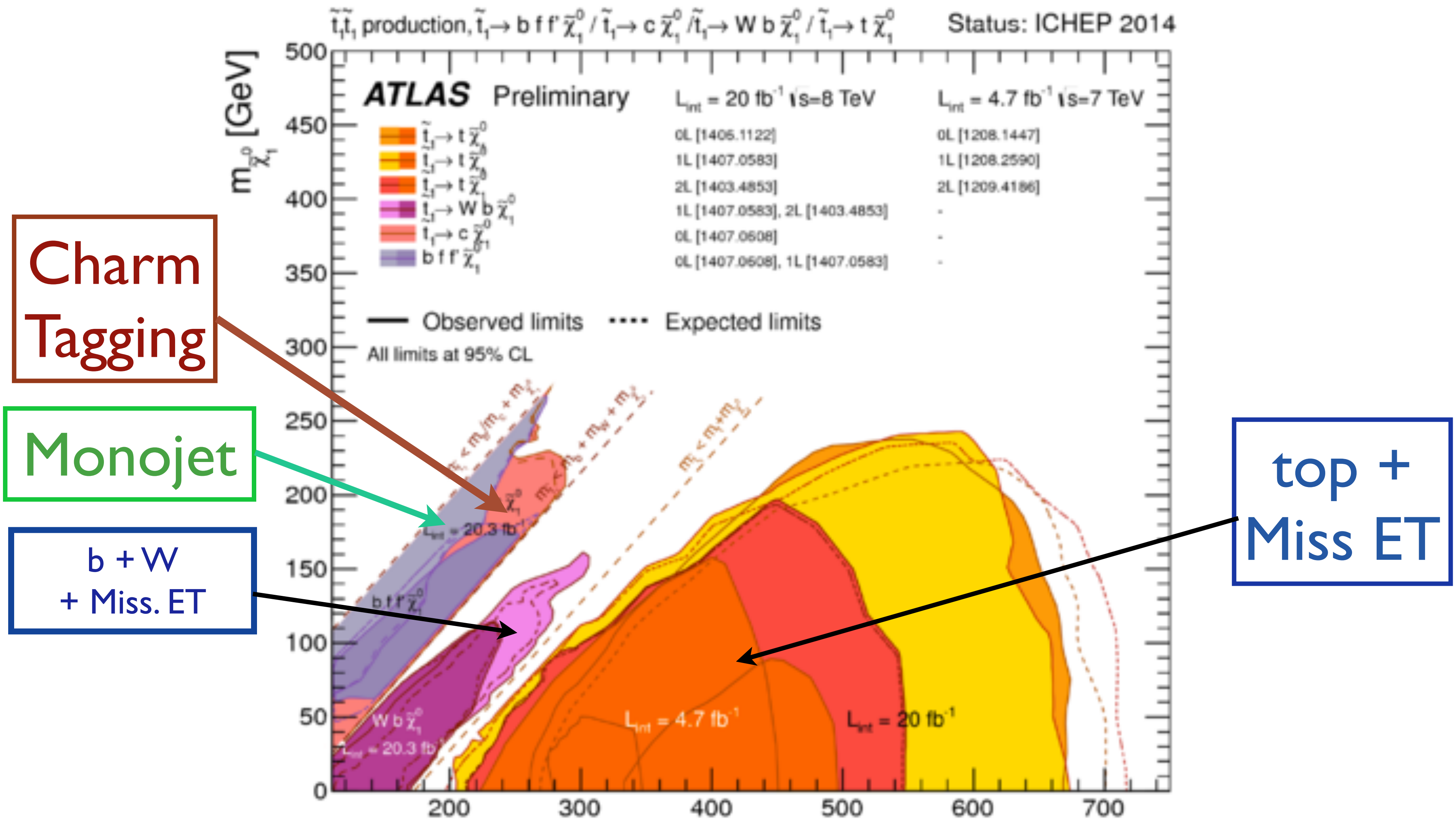
Lightest stop coupling to the Higgs approximately vanishes for $X_t \simeq m_Q$

Higgs mass pushes us in that direction

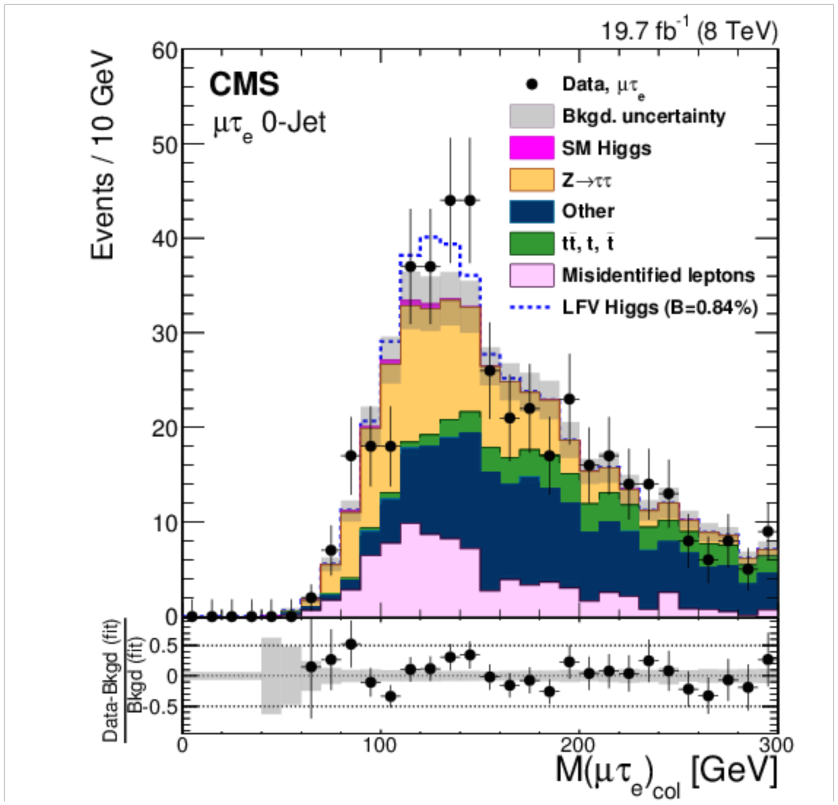
Modification of the gluon fusion rate milder due to this reason.

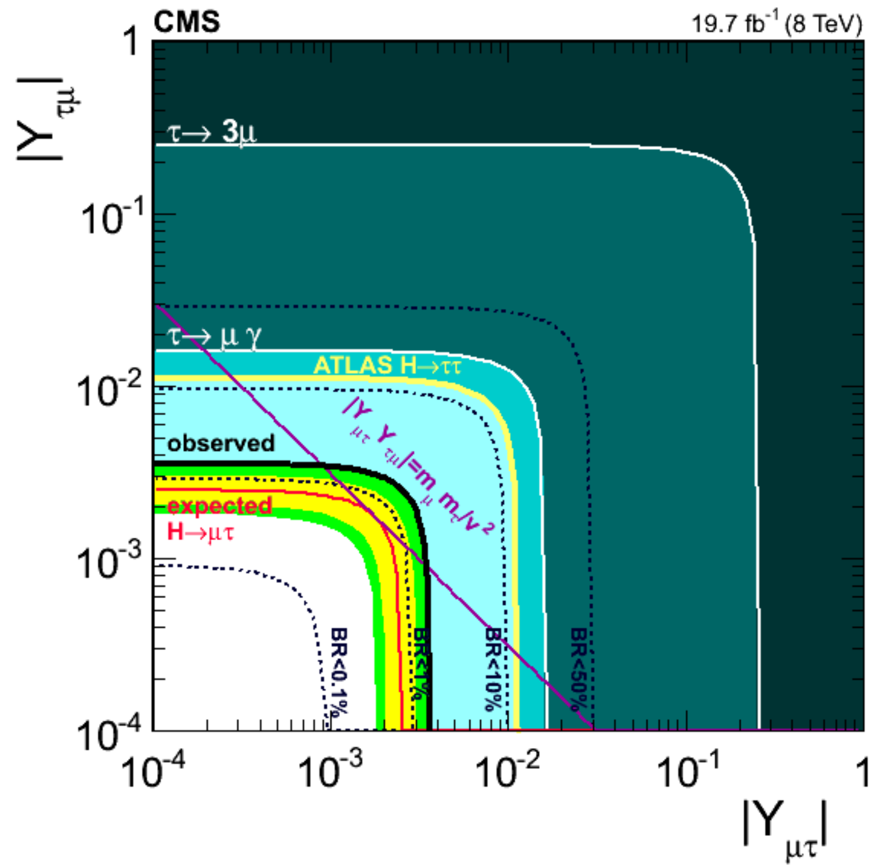
Stop Searches

Provided the lightest neutralino (DM) is heavier than about 250 GeV, there are no limits on stops. Even for lighter neutralinos, there are big holes.



Flavor Violating Leptonic Higgs Decays





Possible in generic 2 Higgs doublet models