Physics Opportunities with Heavy Flavors at the LHC

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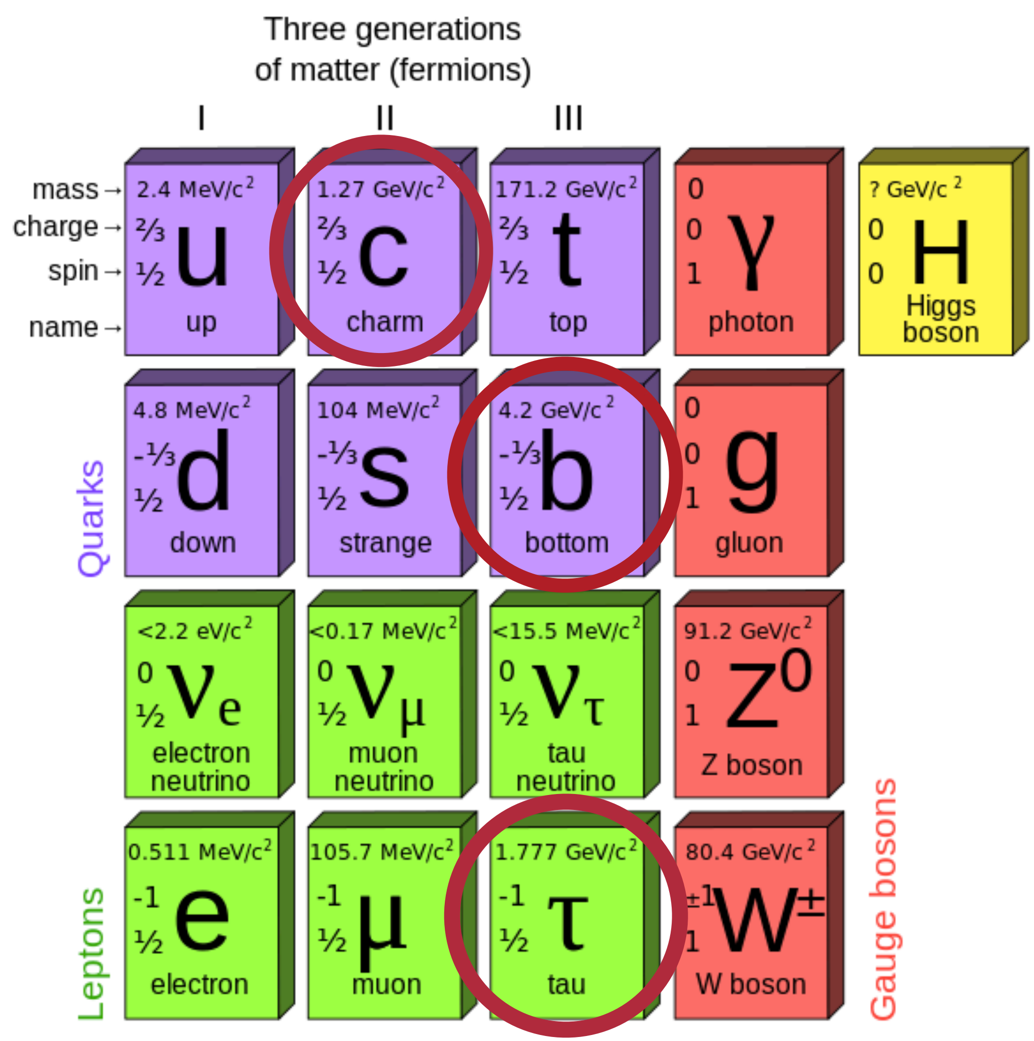
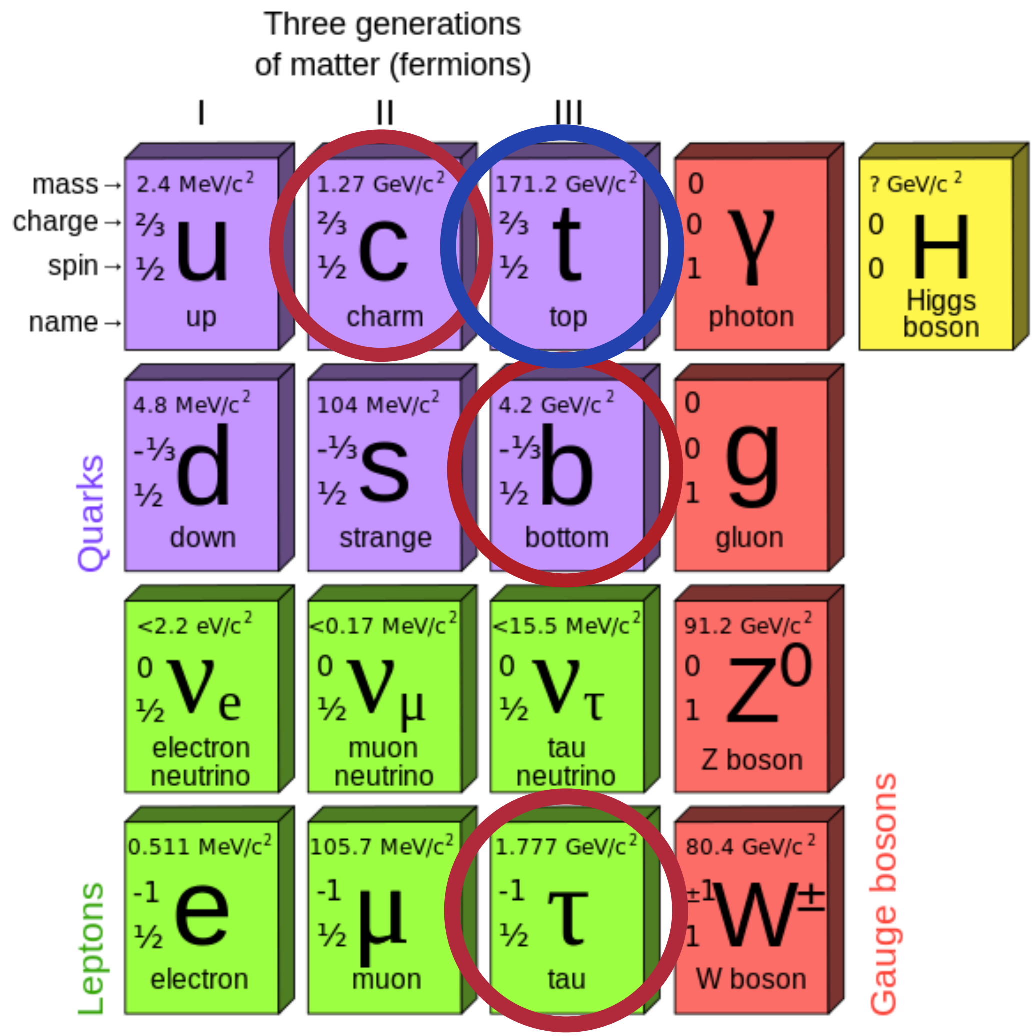
Standard Model Particles

Bottom, charm and tau masses far above all the other quark and leptons, with the exception of the top.



Standard Model Particles



Bottom, charm and tau masses far above all the other quark and leptons, with the exception of the top.

Why heavy Flavors ?

- Heavy Flavor Physics allow an efficient exploration of the dynamics related to Electroweak Symmetry Breaking

- Bottom-Quarks, Charm-Quarks and Tau-Leptons have relevant couplings to the Higgs and provide some of the most relevant decay modes in Higgs Physics

- They appear as relevant decay modes also in models with singlets, which couple to quark and leptons via the mixing with the SM Higgs

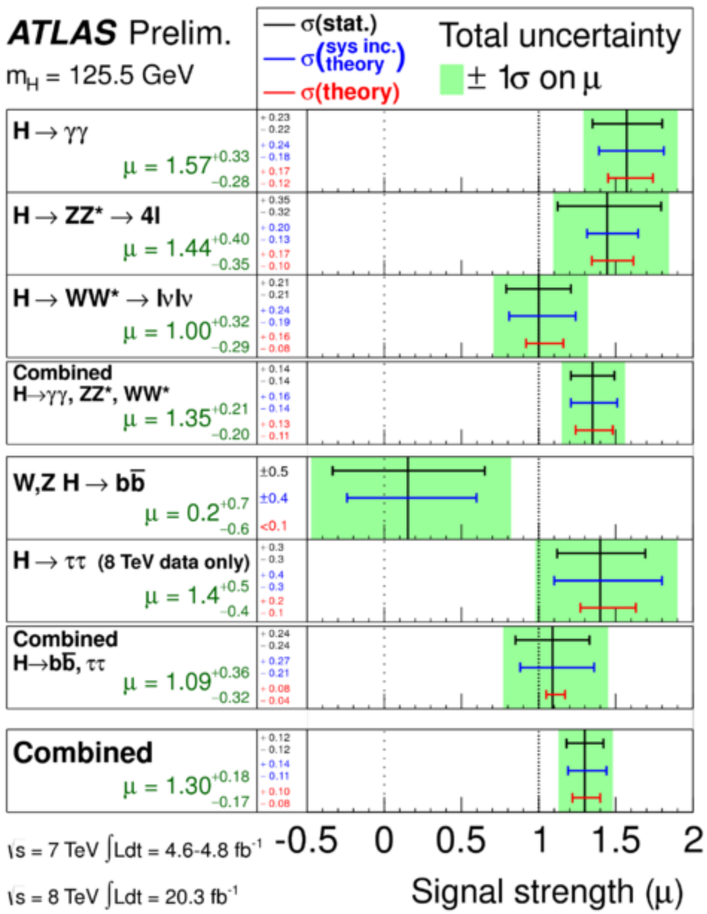
- They provide the most relevant decay modes on heavy Higgs bosons in models with two Higgs-doublets in large regions of parameter space

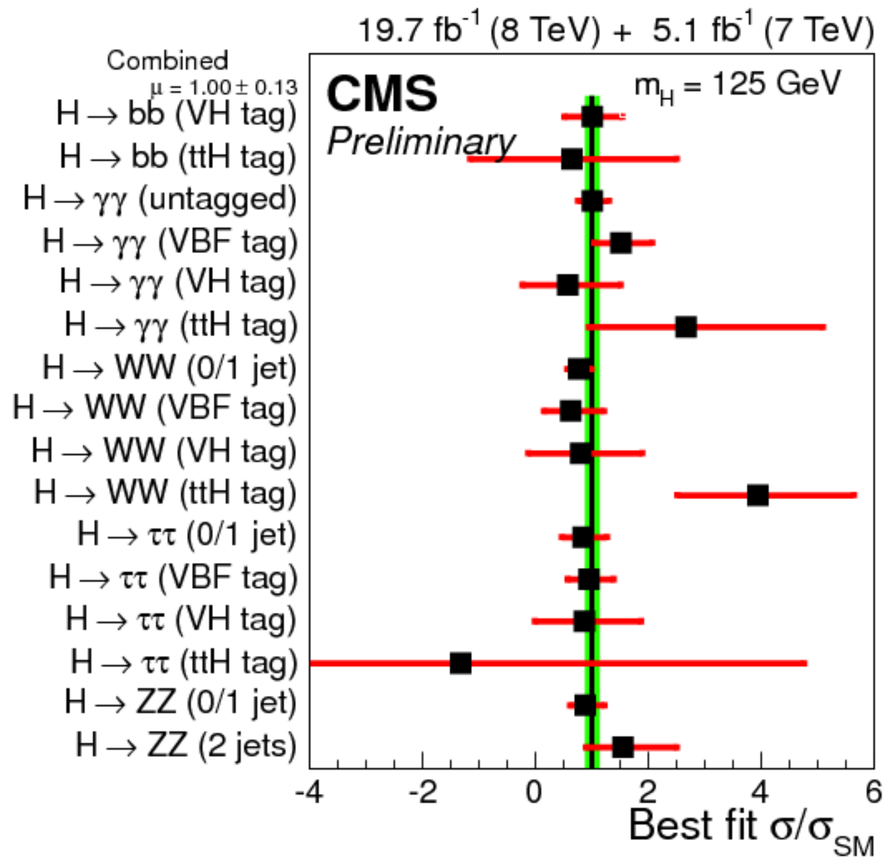
- Models with heavy vector like quarks or leptons tend to present relevant mixing with heavy SM quarks and leptons and therefore these SM particles appear in their decays

- In Supersymmetry, we expect the superpartners of the bottom and top to be among the lightest scalars and they decay in modes rich in bottom quarks and leptons.

- The mixing and rare decays of bottom and charm mesons are the most efficient way of exploring the new physics associated not only with the origin of mass but also the origin of flavor.

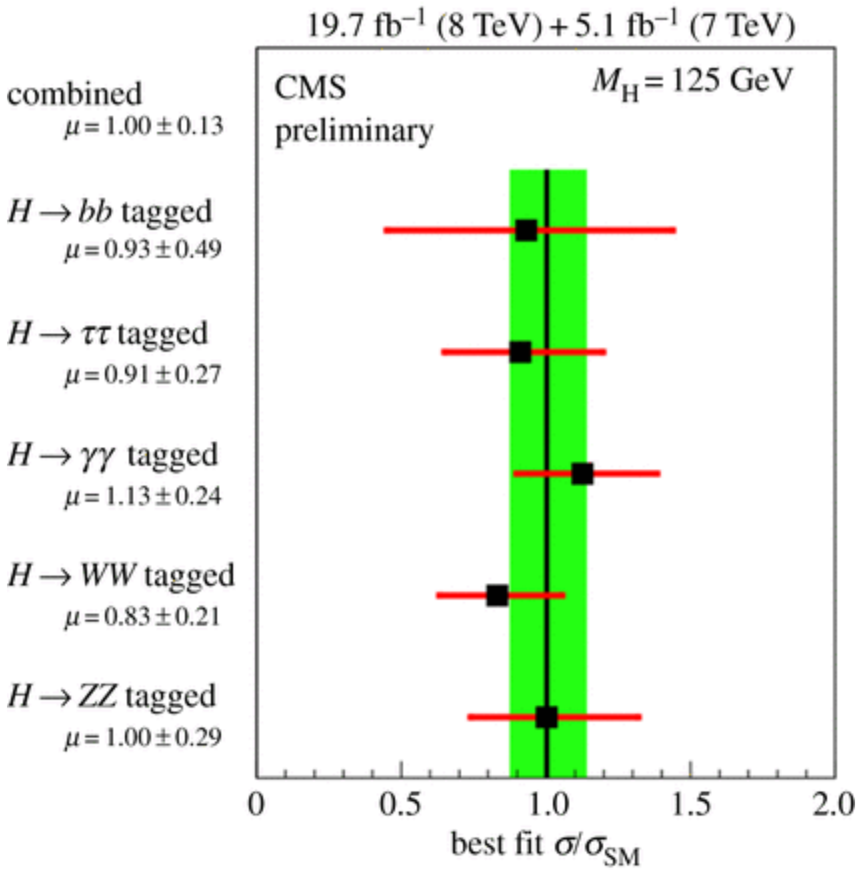
Higgs Couplings to heavy Flavor

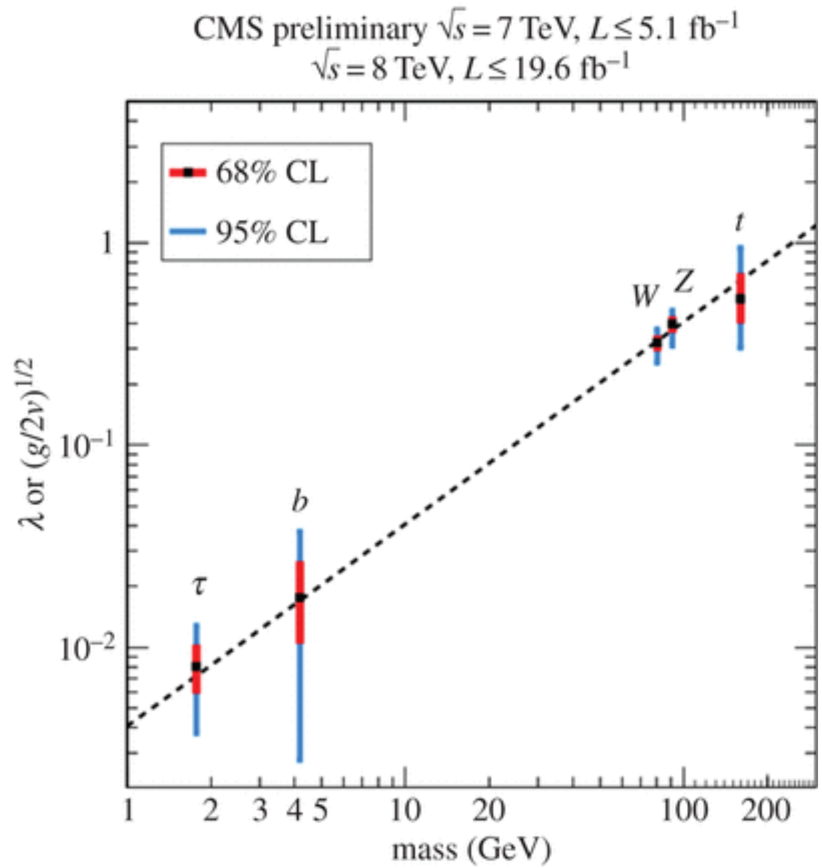




Although progress is being made, we have no information on the charm coupling and the bottom coupling remain rather uncertain, even though H to bb is the dominant decay mode

Test of SM relations





Very little is known about charm couplings

- How to obtain information on charm
- Use charm tagging !

Charm tagging at the LHC

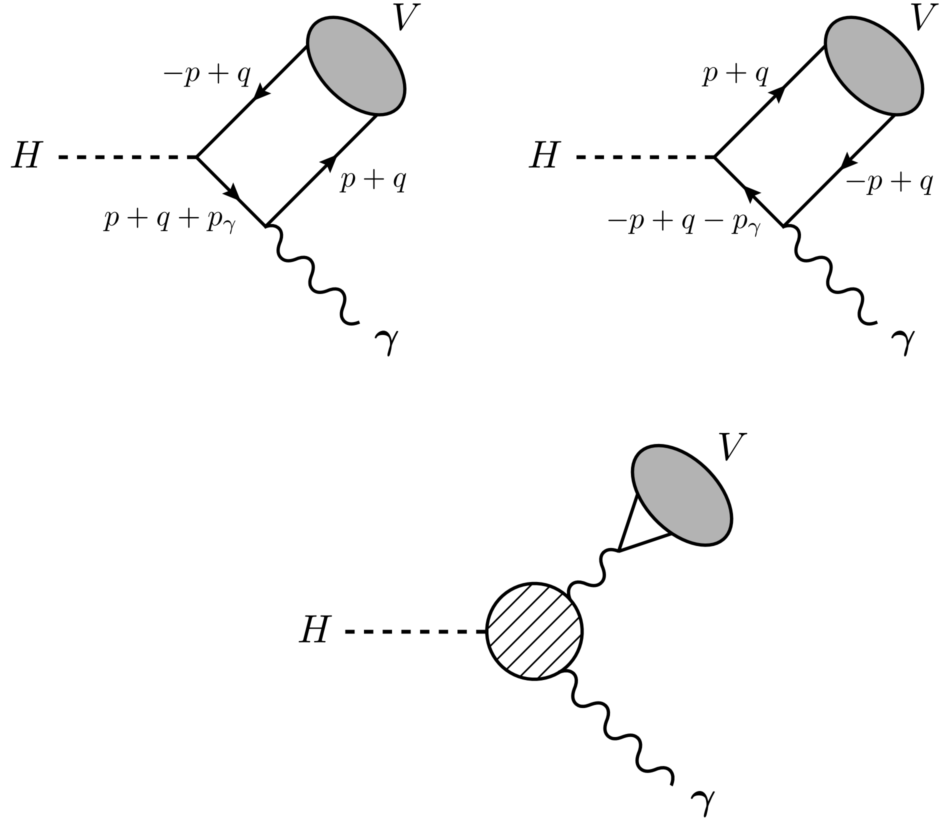
- In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \rightarrow c + \chi^0$) charm jet tagging has been employed for the first time at LHC

ATLAS-CONF-2013-068

- charm jets identified by combining "information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices" using multivariate techniques

  - 'medium' operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets.

Higgs Decay to Quarkonia



Bodwin, Chung, Ee, Lee, Petriello, Stoynev, Velasco'14

G. Perez'15

(i) Direct constraint: recast *VH(bb)*, taking advantage of 2 working point $c_c < 250$.

♦ Width bound: $\Gamma_h < 2.6\,\mathrm{GeV}$ **(ATLAS)**, $\Gamma_h < 1.7\,\mathrm{GeV}$ **(CMS) =>** $c_c < 150,\ 120$.

GP, Soreq, Stamou & Tobioka (Feb/15)

♦ Interpretation of ATLAS recent $h \to J/\psi\gamma$ (1501.03276): $\sigma(pp \to h) \times \mathrm{BR}_{h\to J\psi\gamma} < 33\,\mathrm{fb}\,,$

♦ As discussed below, this implies: $\Gamma_{h\to J/\psi\gamma} = 1.42\,(\kappa_\gamma - 0.087\kappa_c)^2 \times 10^{-8}\,\mathrm{GeV}$

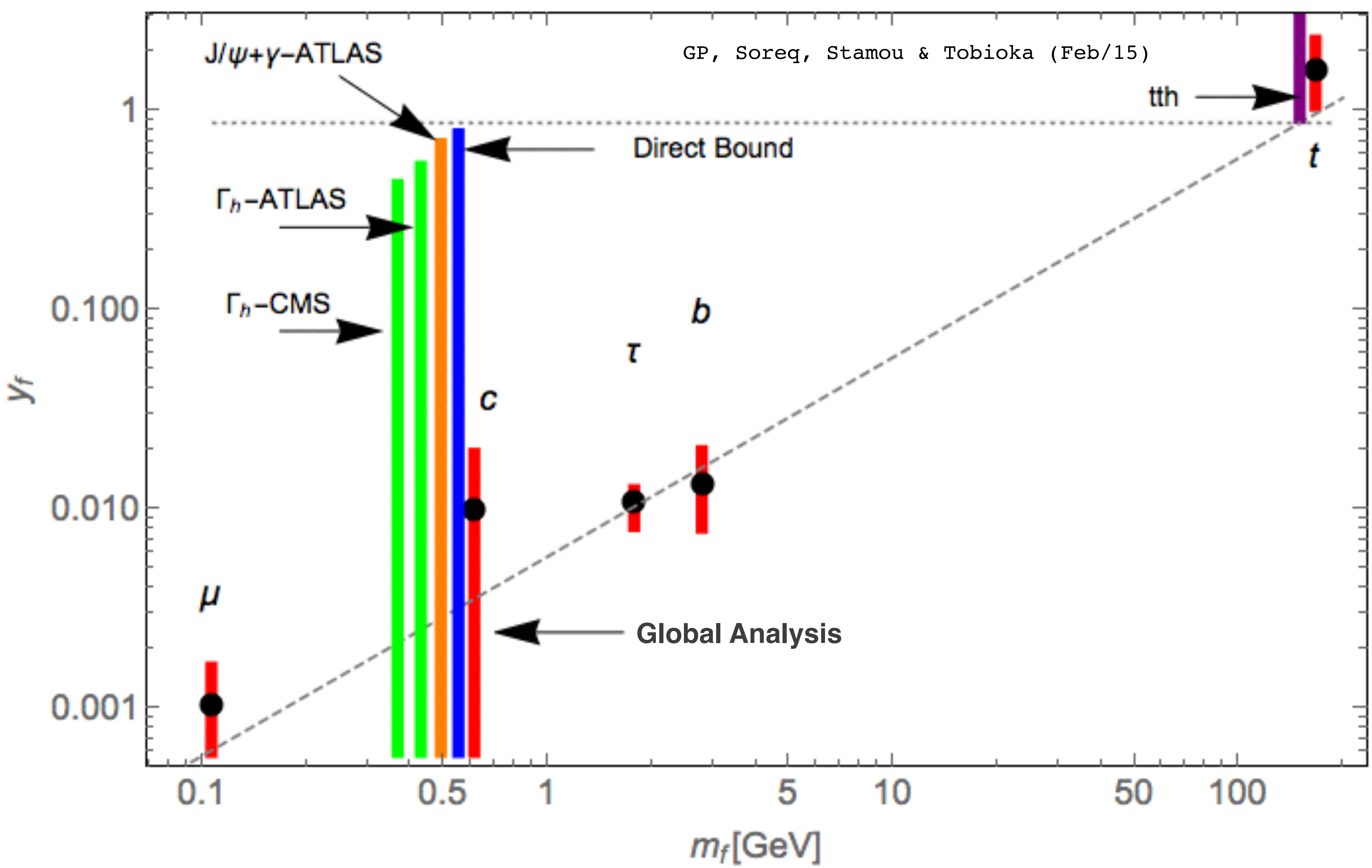
Bodwin, Petriello, Stoynev & Velasco (13); Bodwin, Chung, Ee, Lee & Petriello (14)

♦ Getting rid of production: $\mathcal{R}_{J/\psi,Z} = \frac{\sigma(pp\to h)\times \mathrm{BR}_{h\to J/\psi\gamma}}{\sigma(pp\to h)\times \mathrm{BR}_{h\to ZZ^*\to 4\ell}} = \frac{\Gamma_{h\to J/\psi\gamma}}{\Gamma_{h\to ZZ^*\to 4\ell}} = 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2} \times 10^{-2}\,,$

$$\mathcal{R}_{J/\psi,Z} = \frac{33\,\mathrm{fb}}{\mu_{ZZ^*}\sigma^{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{h\to ZZ^*\to 4\ell}} < 9.32 \quad \Longrightarrow \quad c_c < 210 c_V + 11 c_\gamma\,.$$

(LEP: $c_V = 1.08 \pm 0.07$)

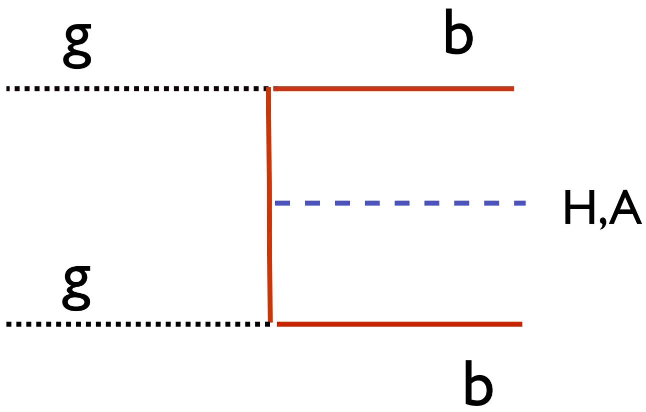
G. Perez



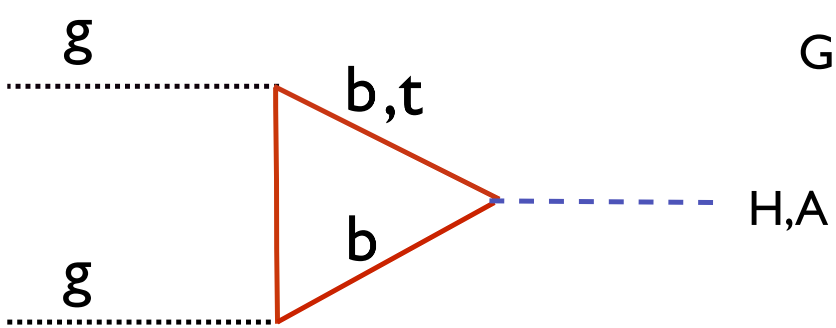
GP, Soreq, Stamou & Tobioka (Feb/15)
J/ψ+γ-ATLAS
Direct Bound
Γh-ATLAS
Γh-CMS
Global Analysis
tth
μ
c
τ
b
t
1
0.100
0.010
0.001
yf
0.1
0.5
1
5
10
50
100
mf[GeV]

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/06031



Associated Production



Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

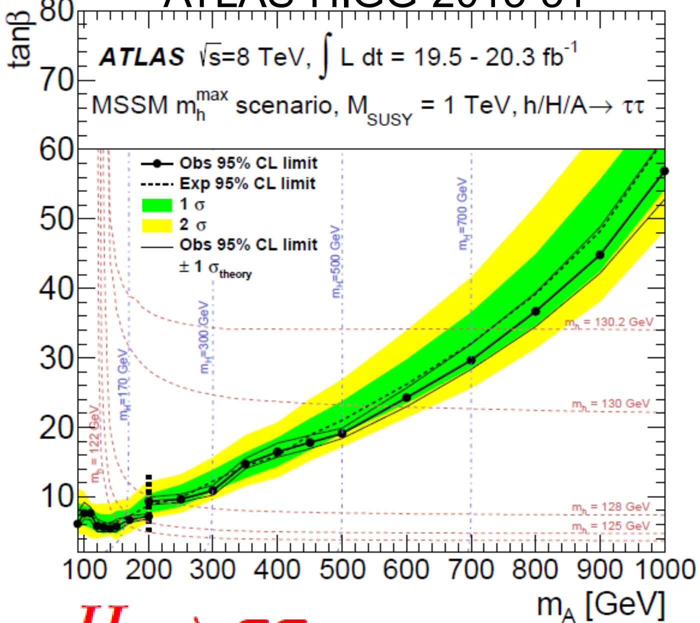
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

- If charginos are light, they contribute to the total with, suppressing the BR.

$$\sigma(pp \to H, A \to \tau\tau) \propto \frac{\tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{(M_W^2+M_Z^2)(1+\Delta_b)^2}{m_\tau^2 \tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\right]}$$

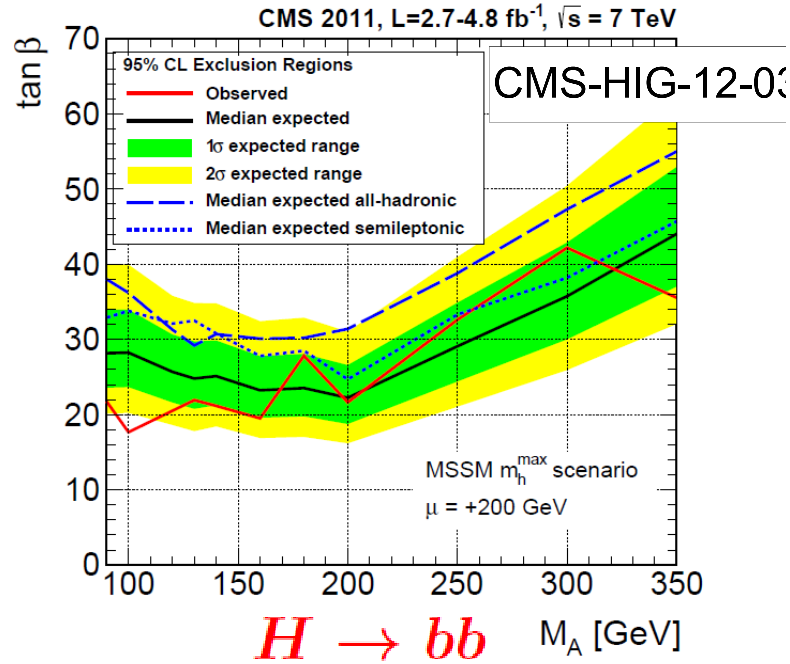
Neutral Higgs bosons

ATLAS-HIGG-2013-31



$H \to \tau\tau$

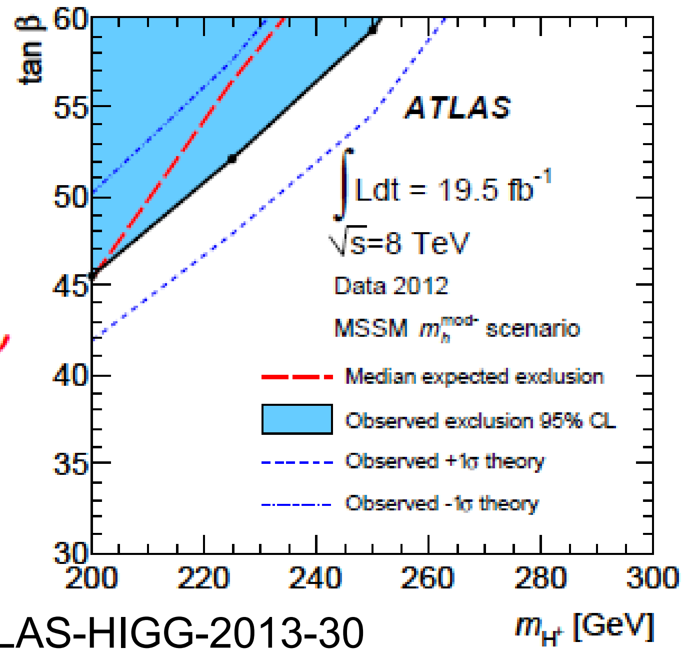
CMS-HIG-12-03



$H \to bb$

Charged Higgs bosons

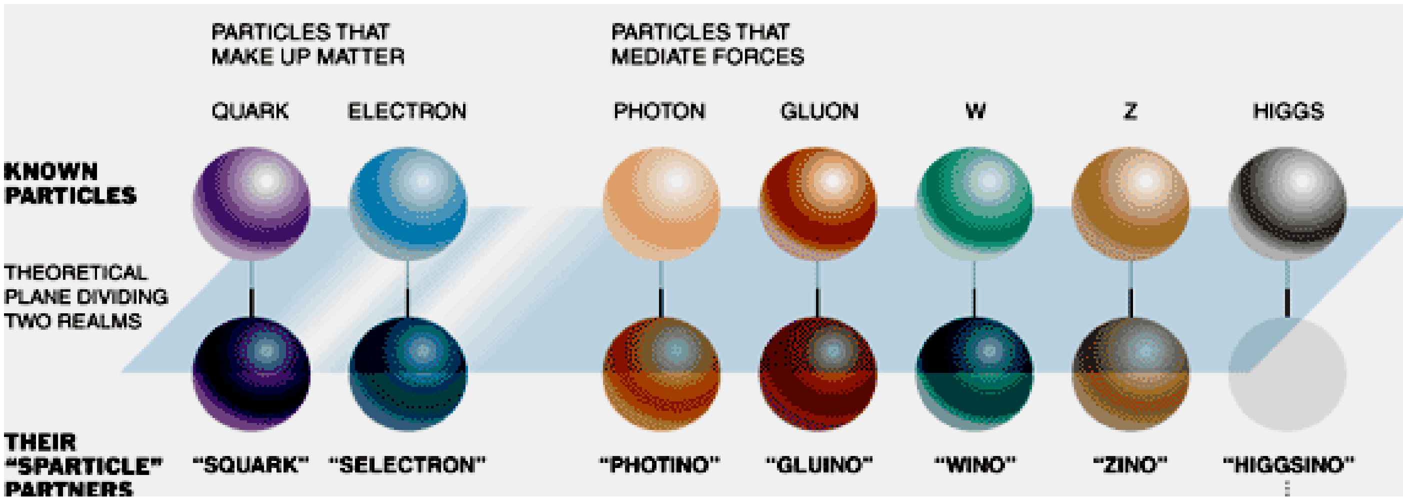
$H^{\pm} \to \tau^{\pm}\nu$



ATLAS-HIGG-2013-30

Supersymmetry

fermions **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

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)

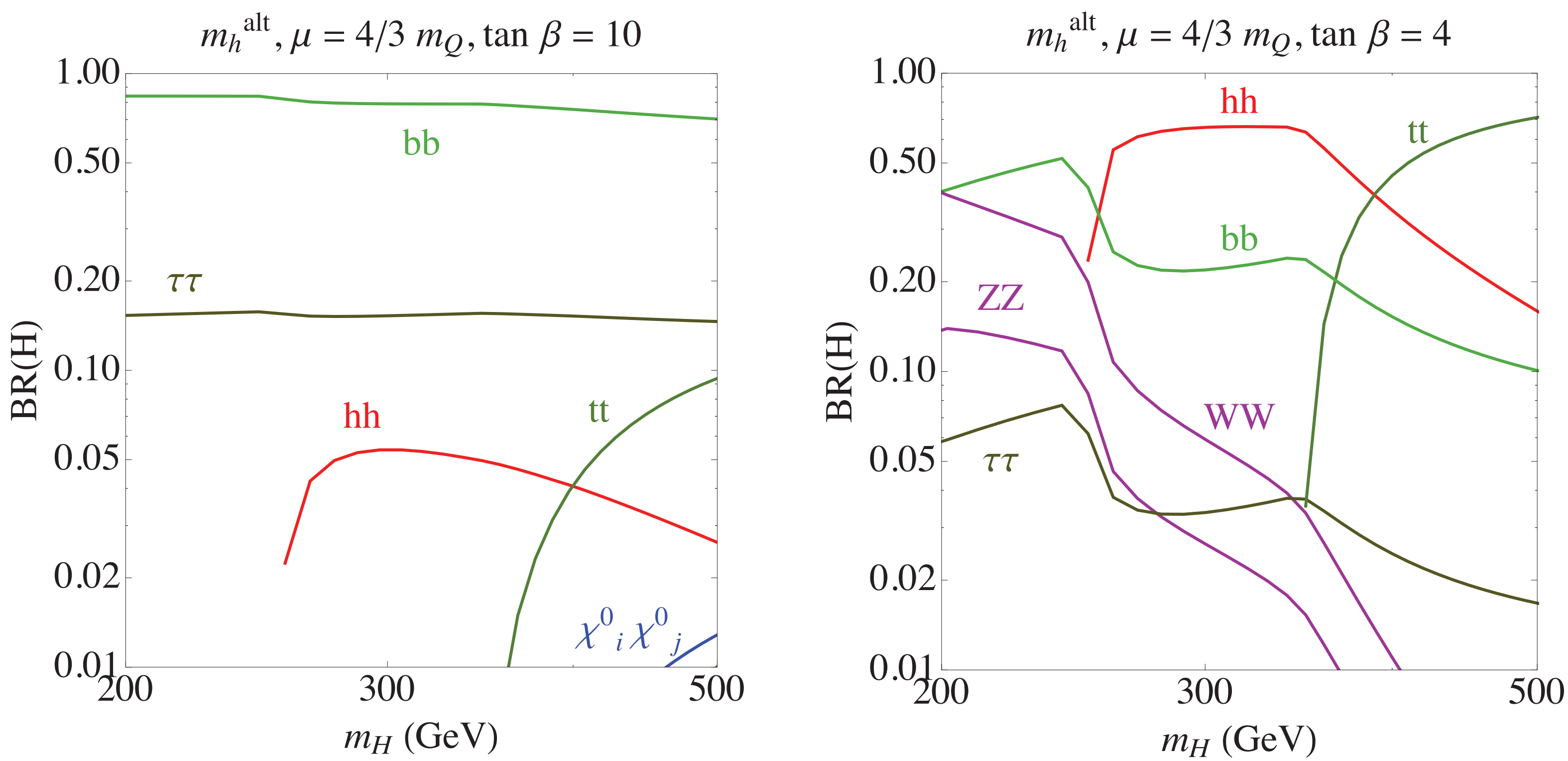
$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

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

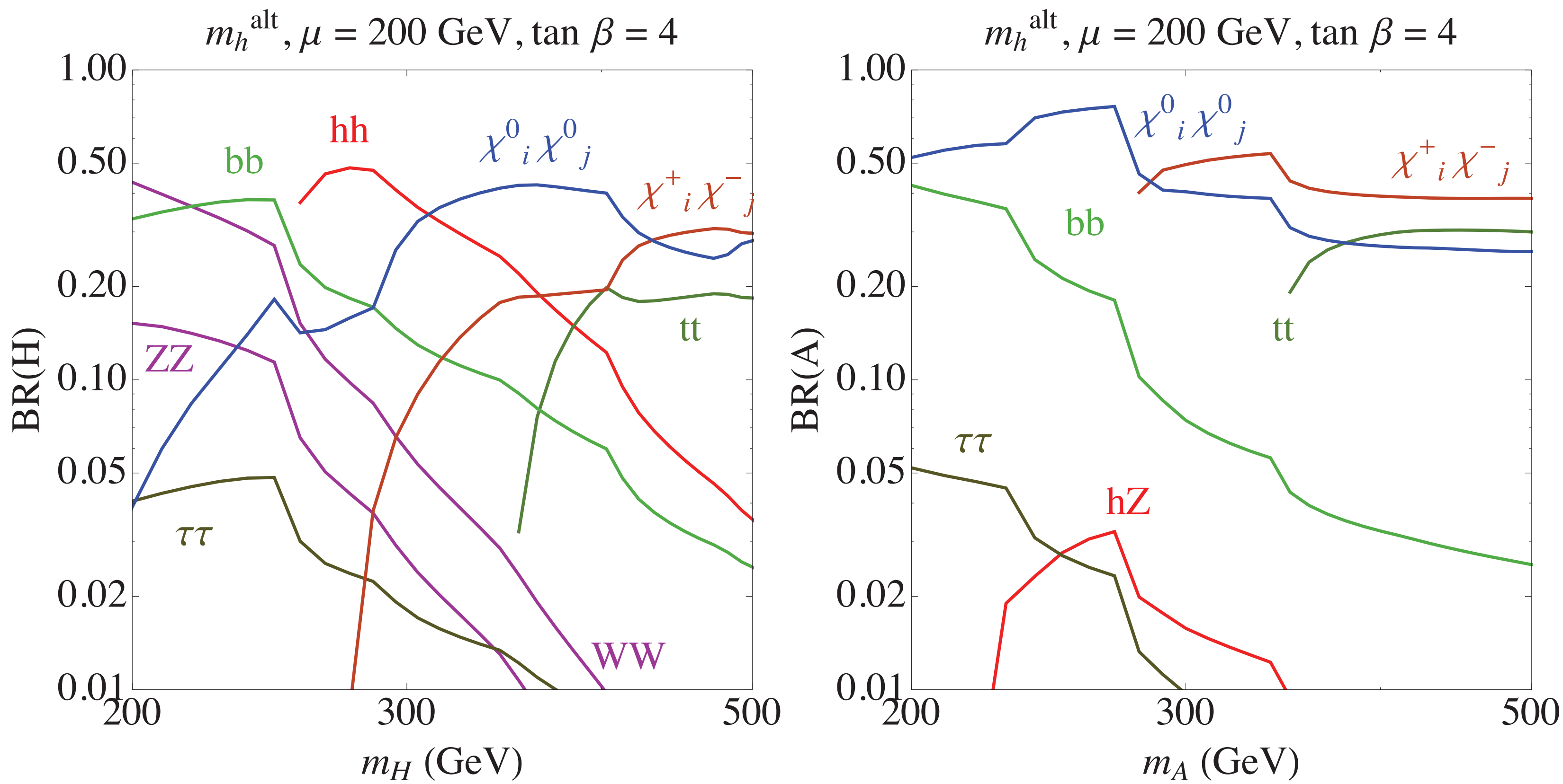
Depending on the values of μ and tanβ different search strategies must be applied.



At large tanβ, bottom and tau decay modes dominant.
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

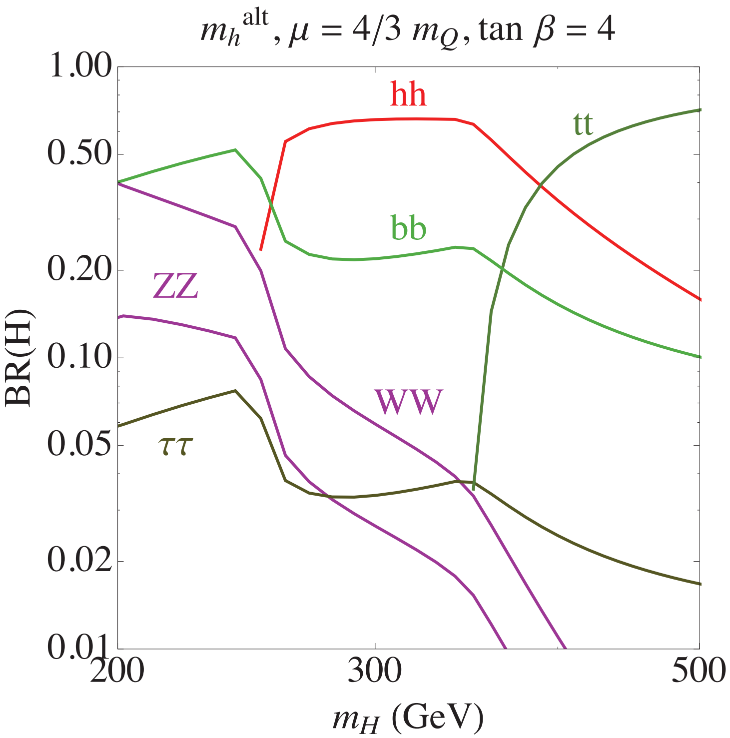
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

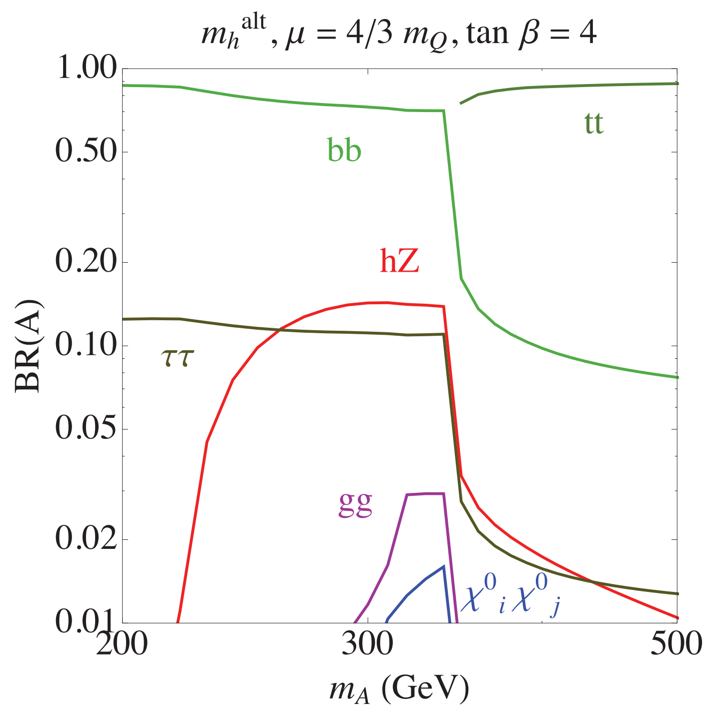
Carena, Haber, Low, Shah, C.W.'14



At small values of tanβ, and small μ, heavy Higgs decay into top quarks and electroweakinos become dominant. Still, decays into pairs of Higgs very relevant.

Large μ and small tanβ

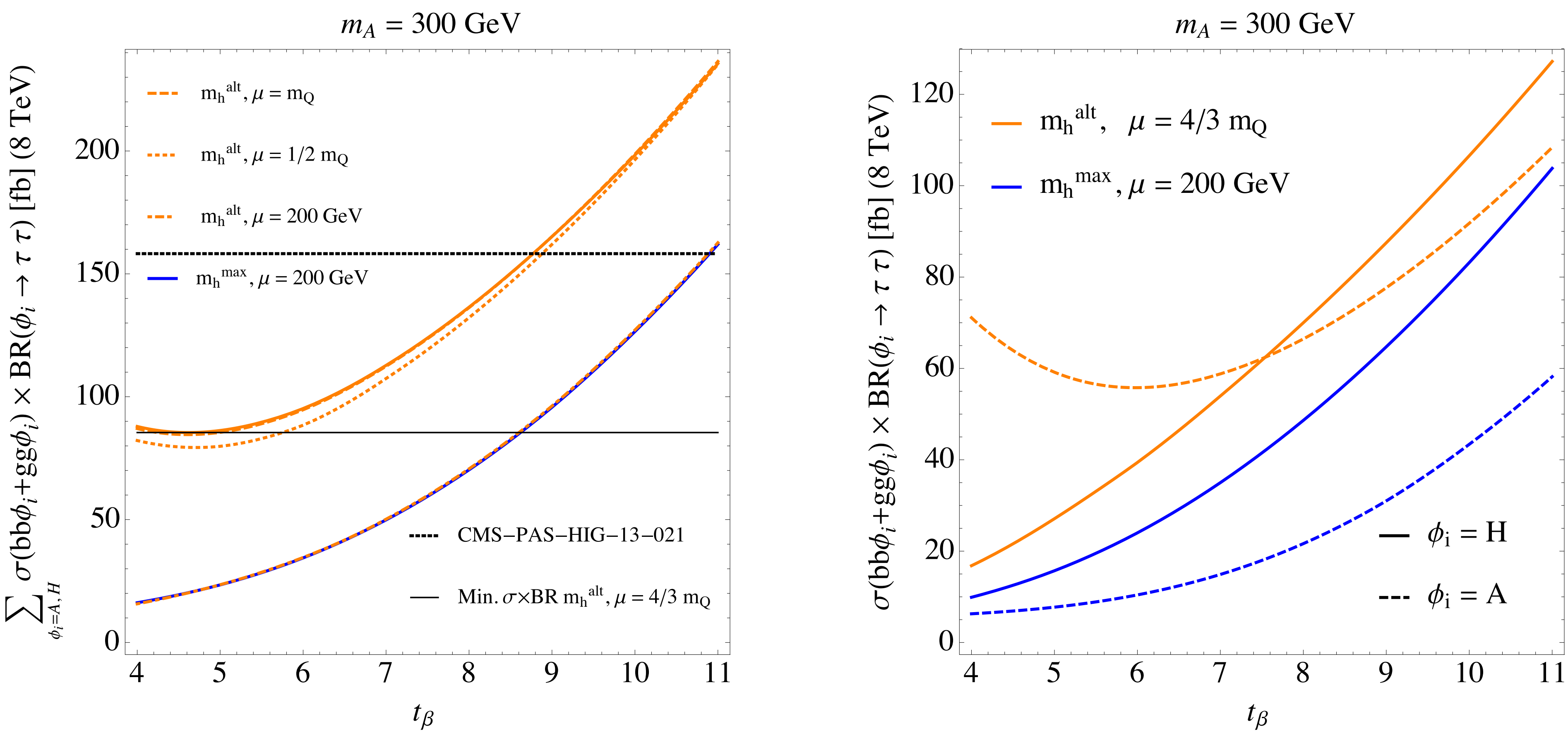




Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

Change in bound of tan β due to variation of μ

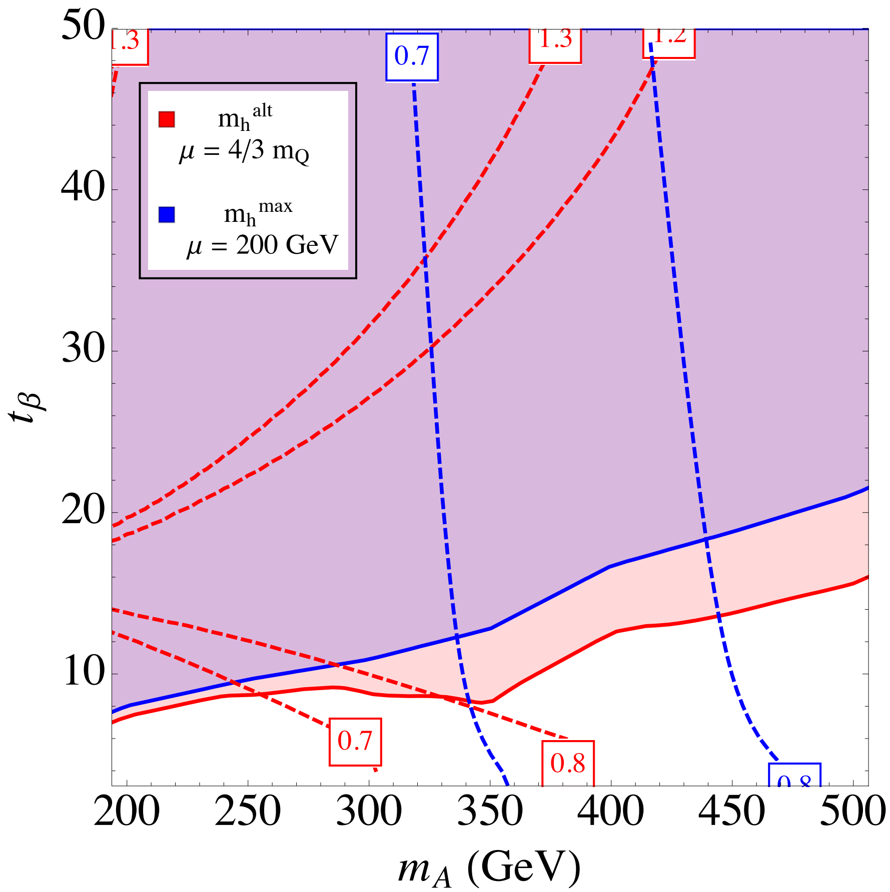
Carena, Haber, Low, Shah, C.W.'14



The CP-odd Higgs contribution is unsuppressed at low values of tanβ

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)

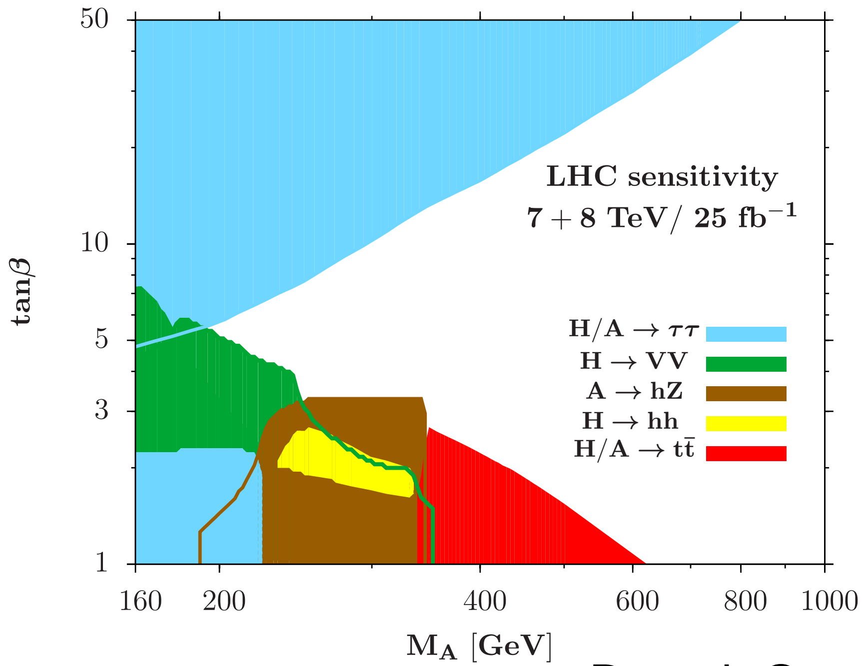
--- $\sigma(bbh+ggh)\times BR(h\to VV)/SM$

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

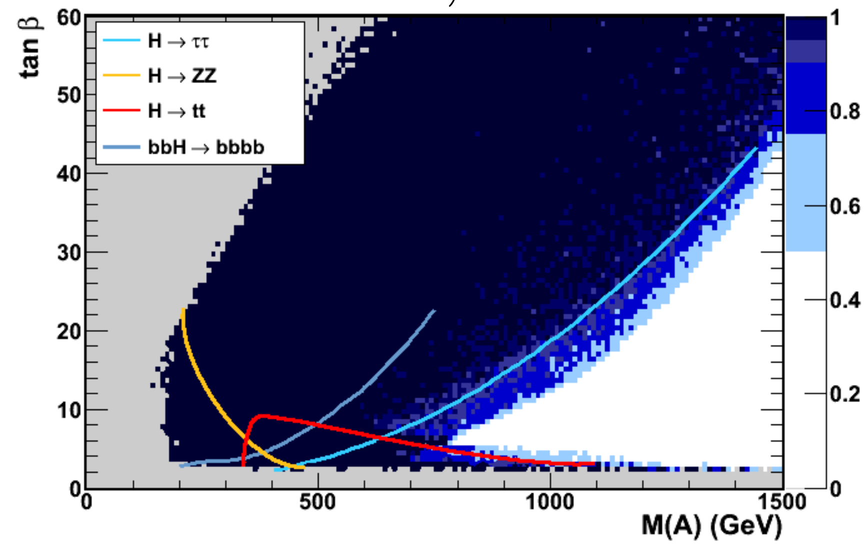
With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

Reach in different channels. Energy Dependence

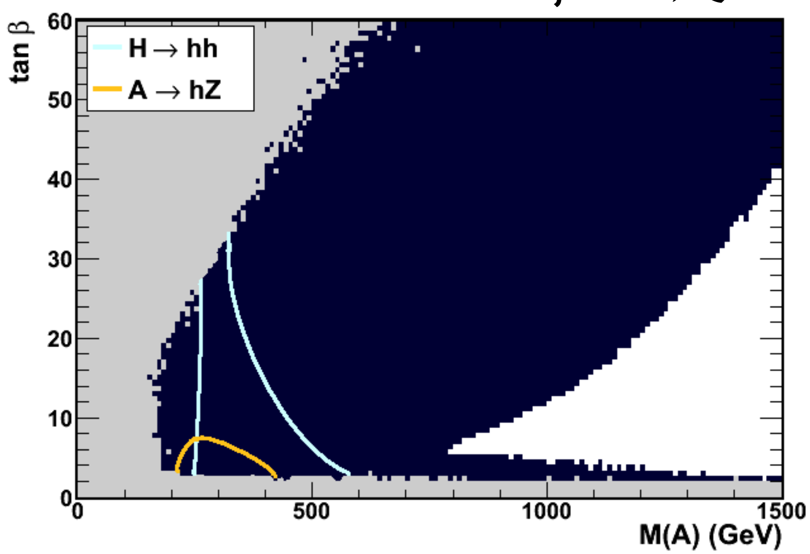


Djouadi, Quevillon'13

14 TeV, 150 fb^{-1}



Arbey, Battaglia, Mahmoudi'13

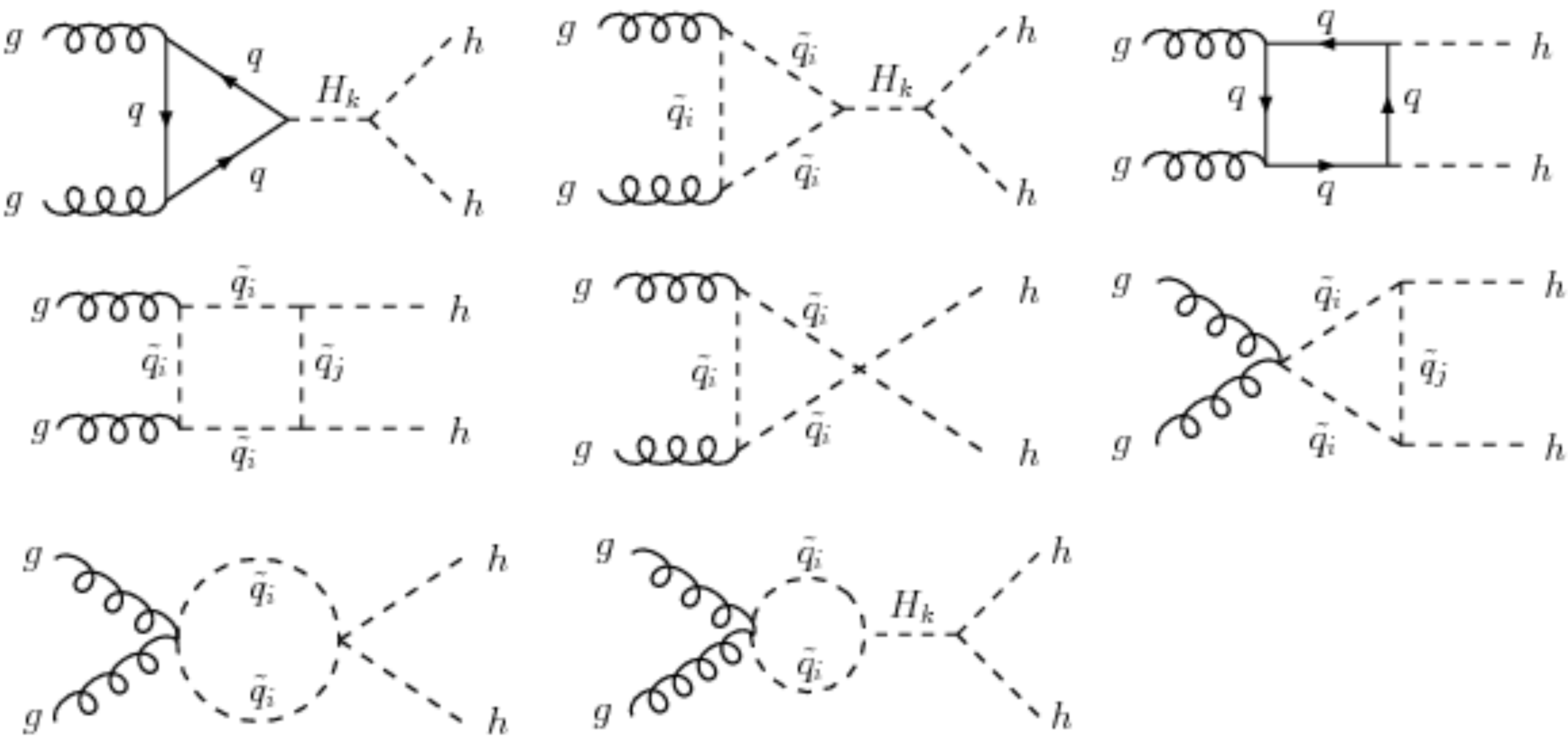


14 TeV, 150 fb^{-1}

These latest channels are only open away from the Alignment region. Here μ is mostly sizable, but sufficiently small so alignment not obtained

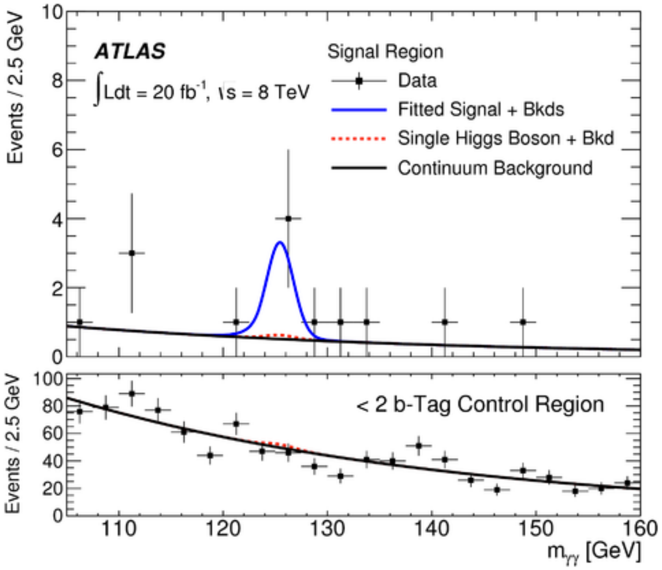
Double Higgs Production in SUSY Models

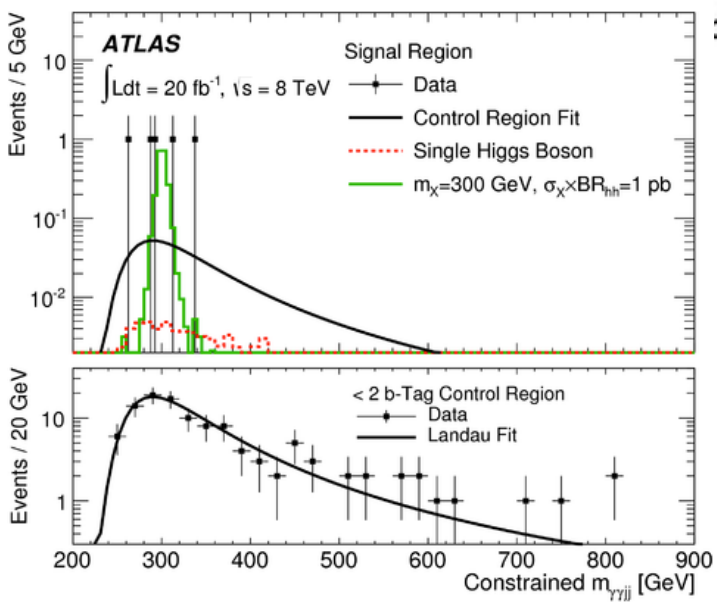
Squark Mediated Diagrams suppressed if stops are heavy

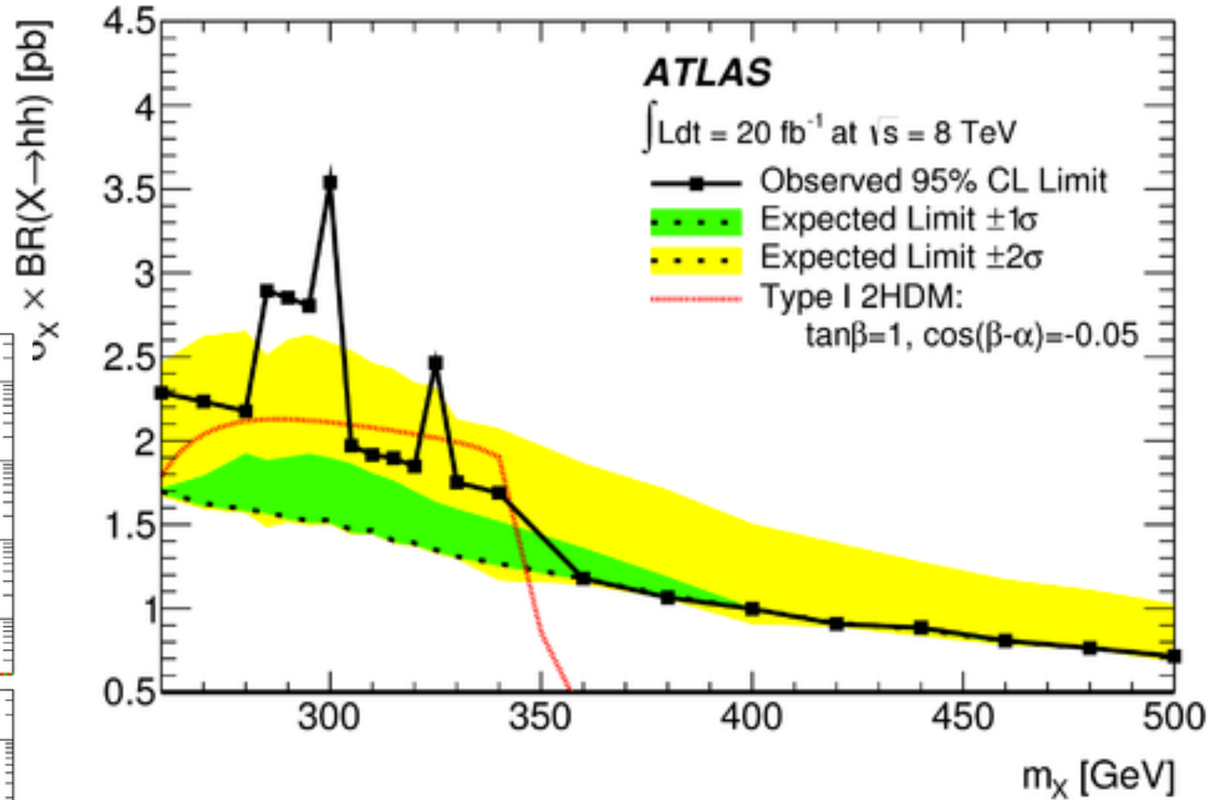


$H \to hh$

$H \to hh, \quad h \to b\bar{b}, \quad h \to \gamma\gamma$







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 $\tan\beta$

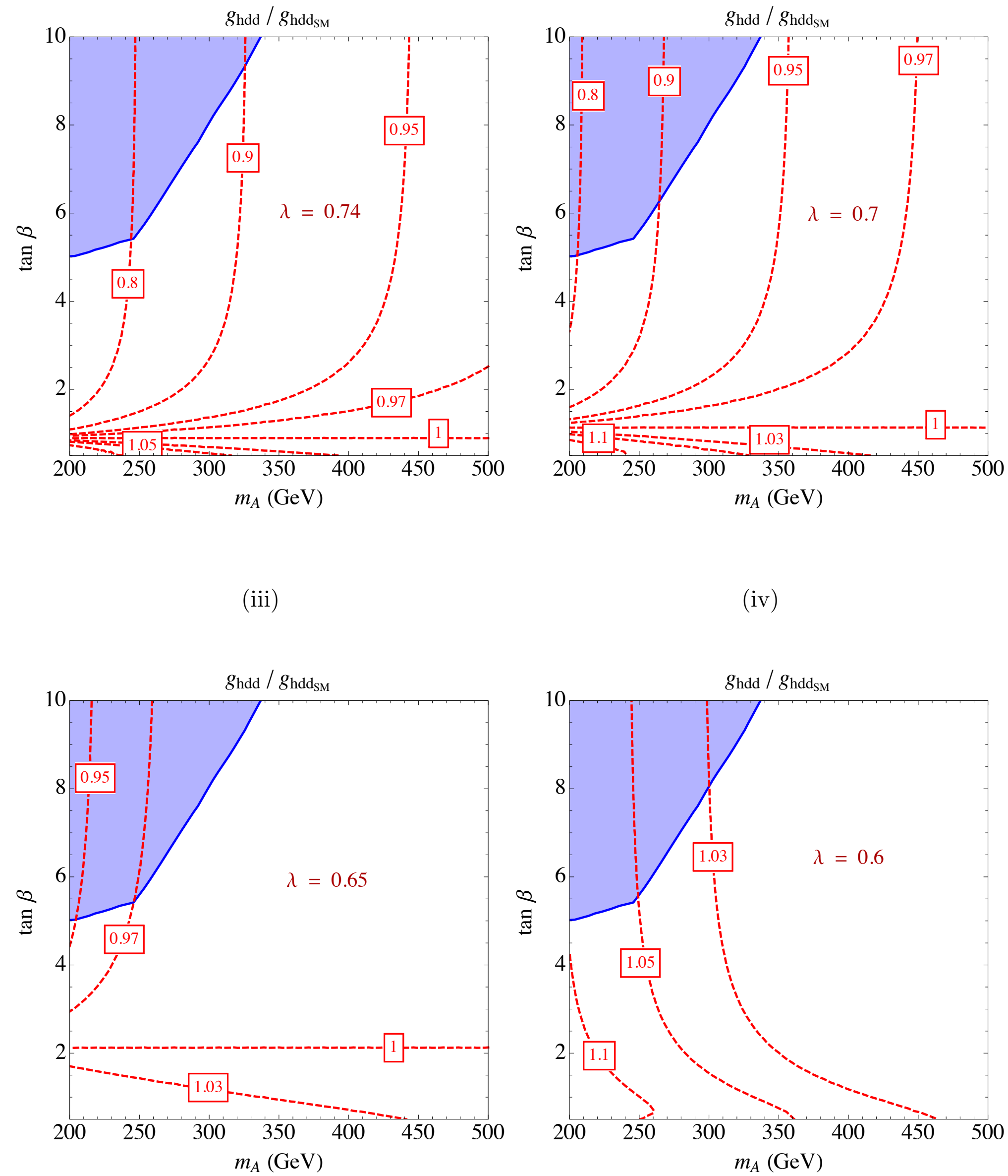
- So, alignment leads to a determination of lambda,

- 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)

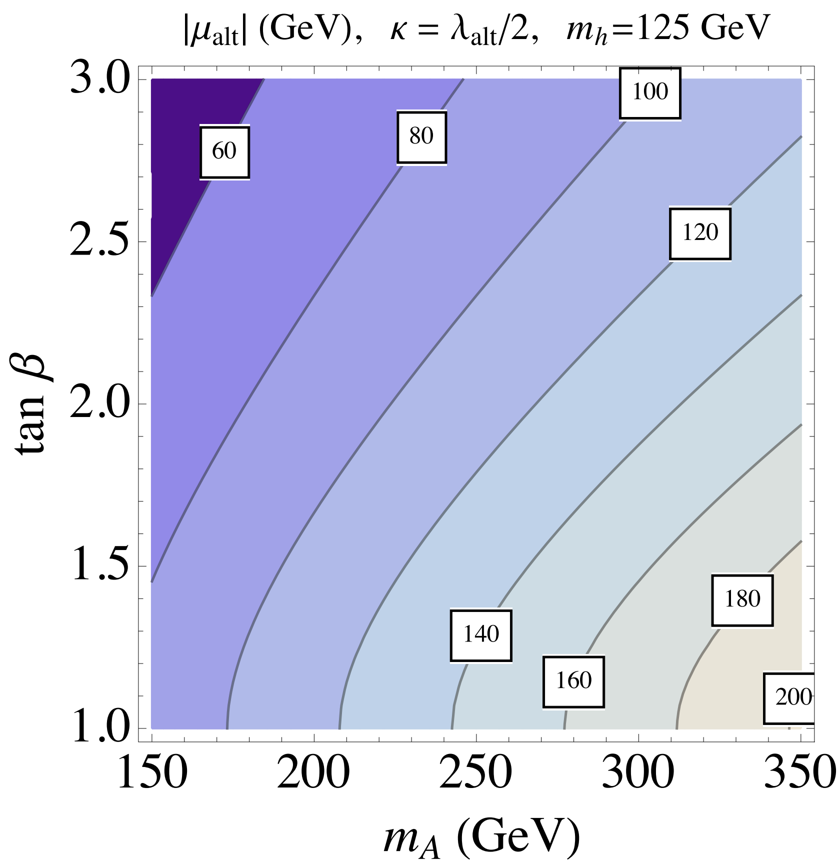
Carena, Low, Shah, C.W.'13

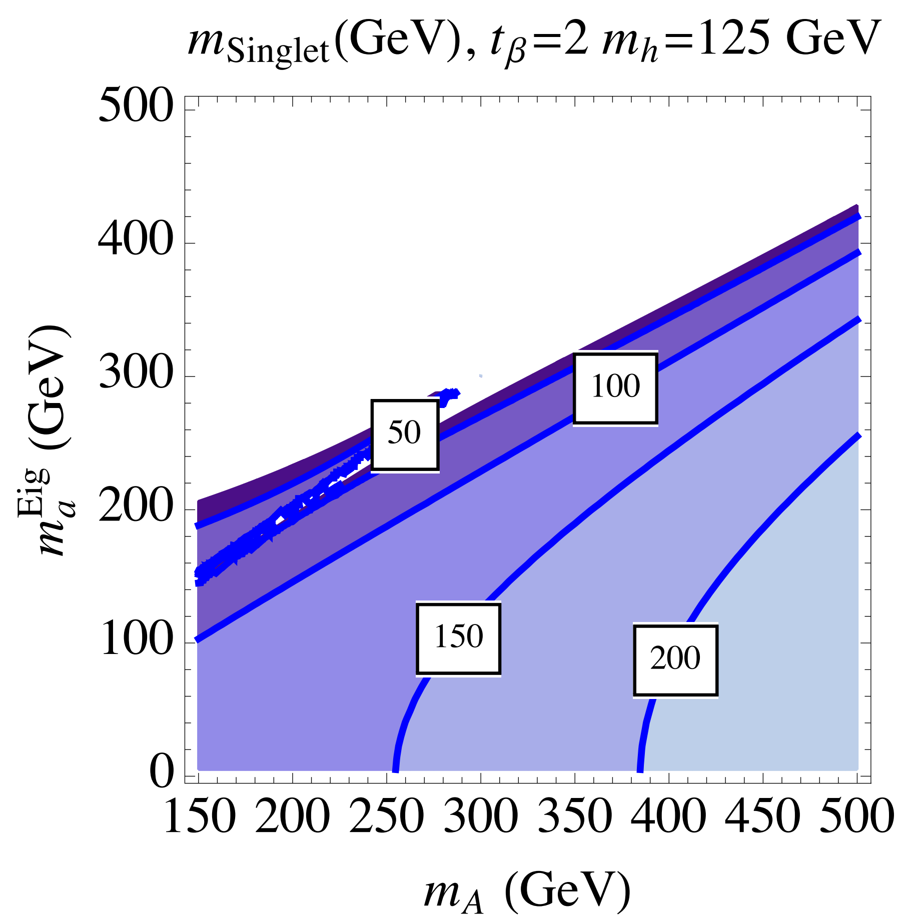


It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

Values of the Singlet, Higgsino and Singlino Masses

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



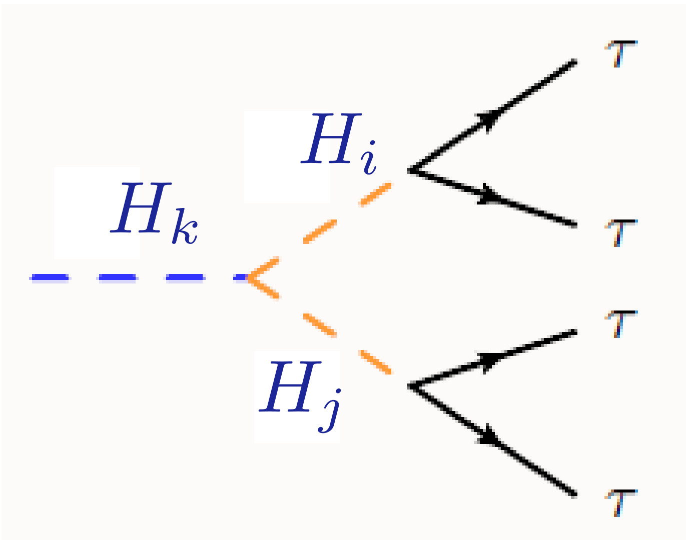


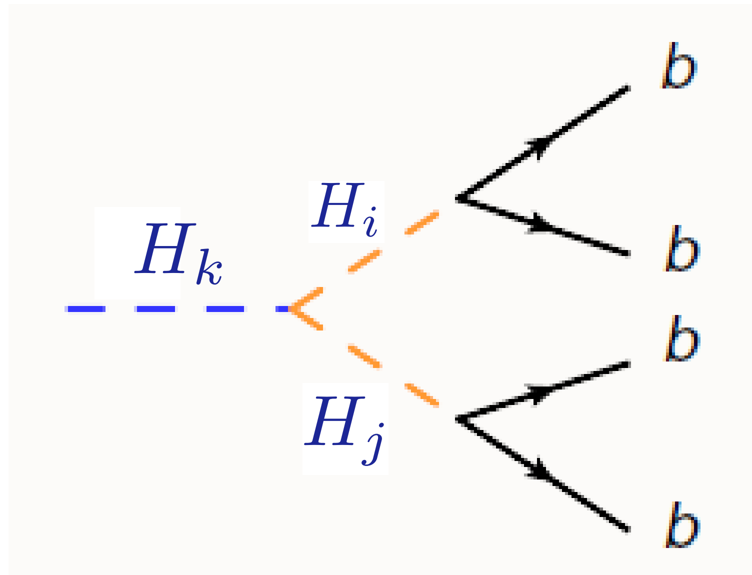
In this limit, the singlino mass is equal to the Higgsino mass.

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

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

Decays of SM and Heavy Higgs Bosons into Higgses

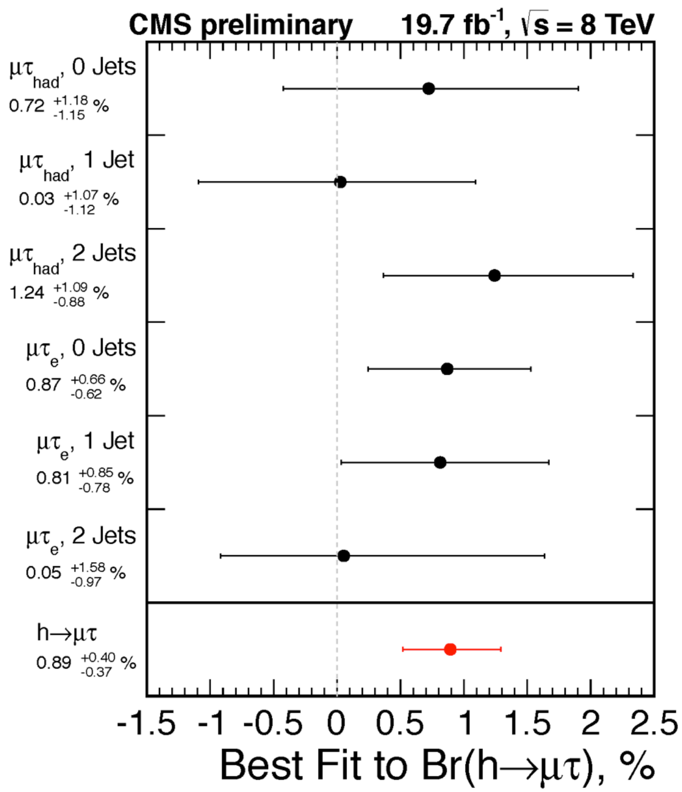


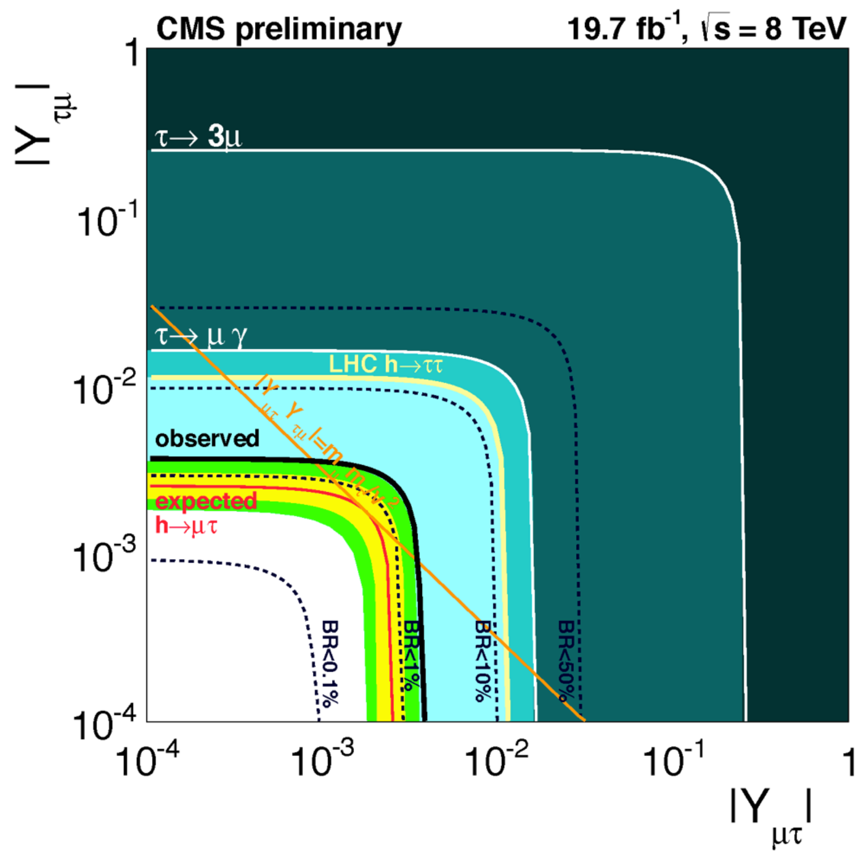


A modified J. Shelton's Original

Heavier Higgs Bosons can Decay into Lighter Ones
Decays into Charginos and Neutralinos also allowed.
Rich Higgs Signatures.

Flavor Violating Higgs Decays (tau mu) and CP-odd Component





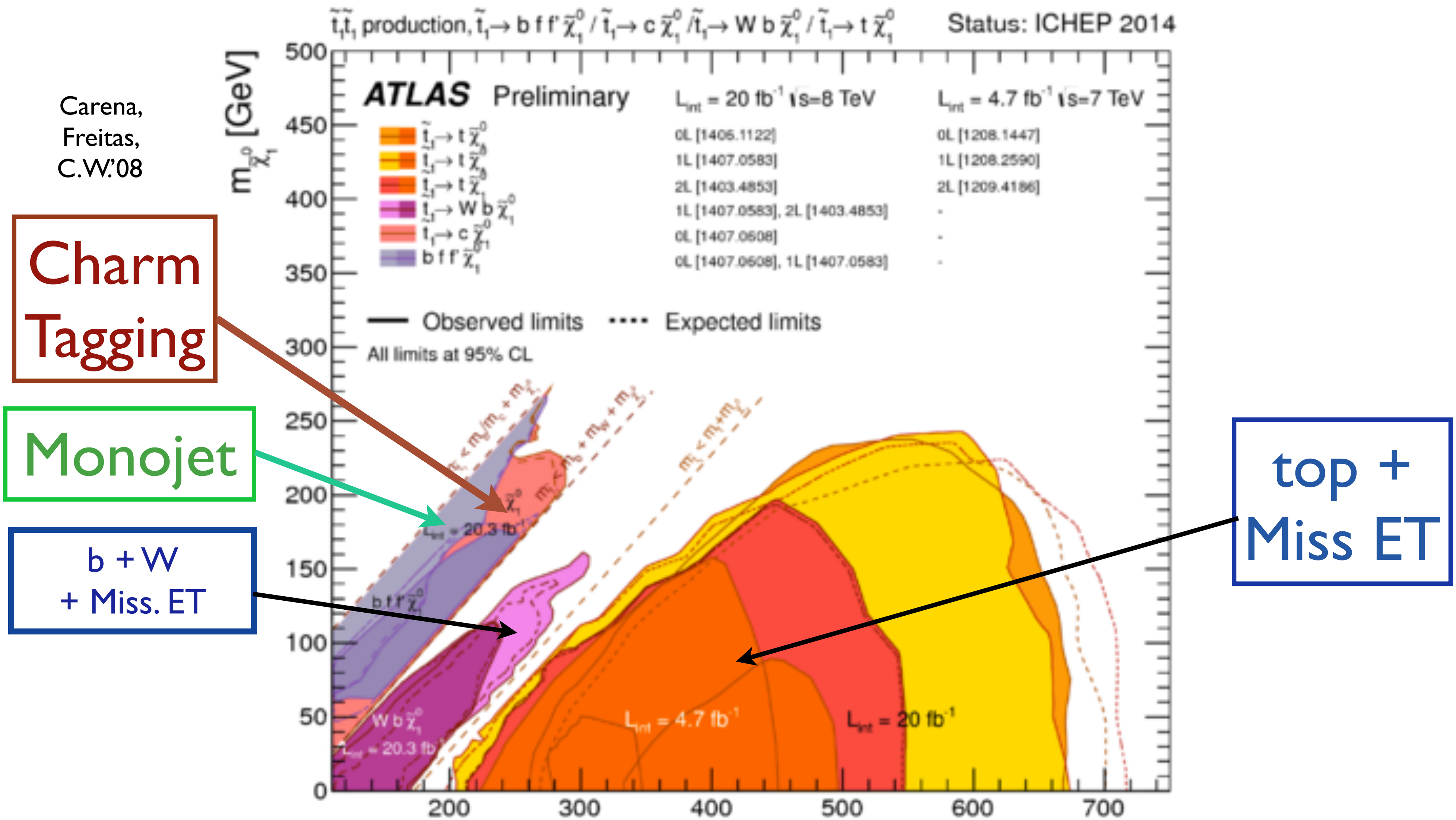
Check of CP-odd Component may be done in the h to tau tau mode

Harnik et al, Bernreuther et al'14

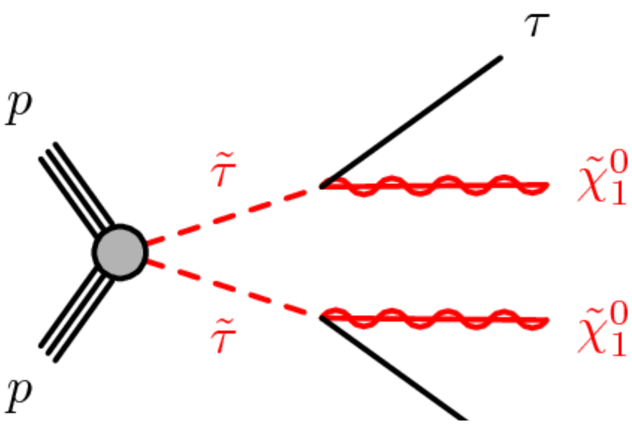
Testable CP-odd Components may appear, for instance, in the MSSM

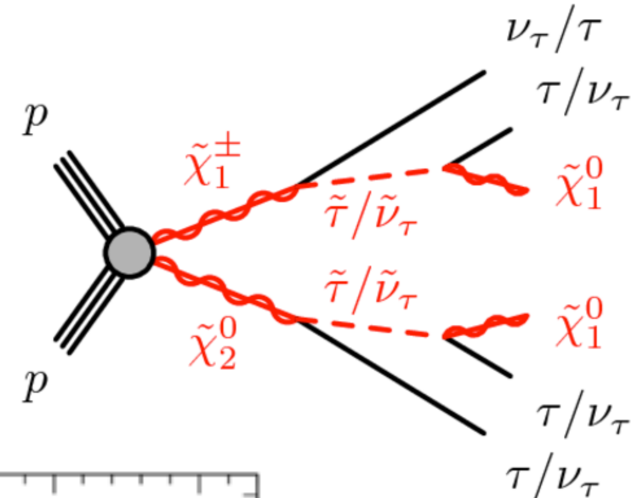
Bing Li, C.W.'15

Stop Searches

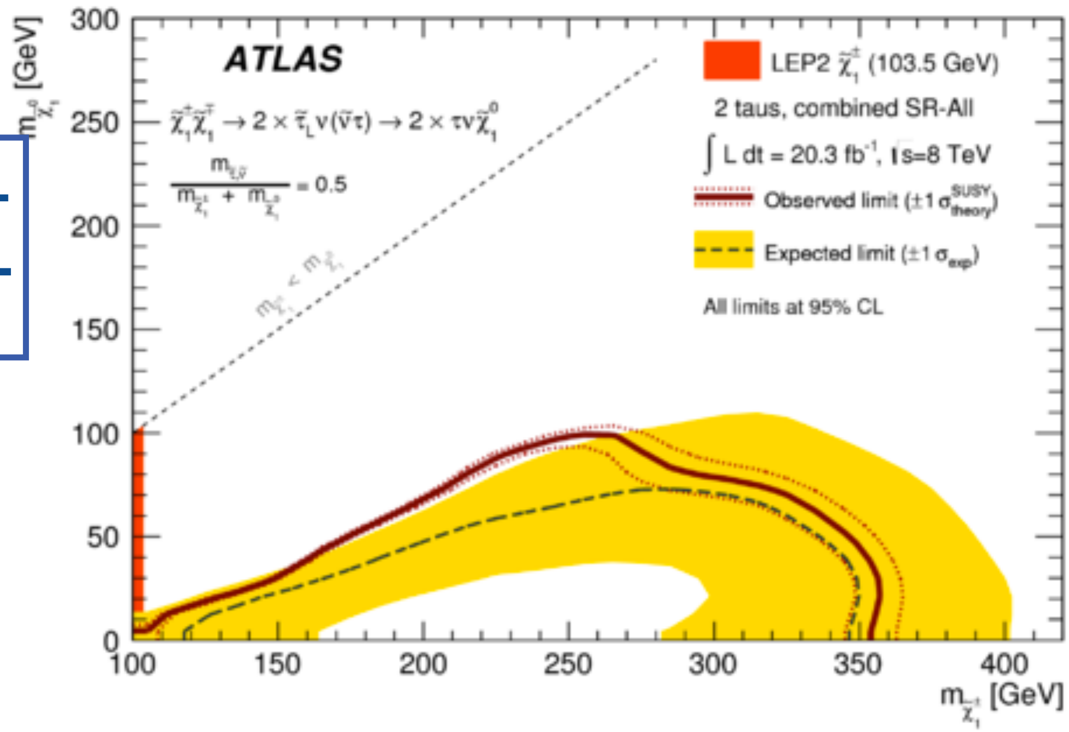


Stau Searches





2 taus + Miss. ET



Direct stau decay into taus quite difficult. No bounds

Alternative :

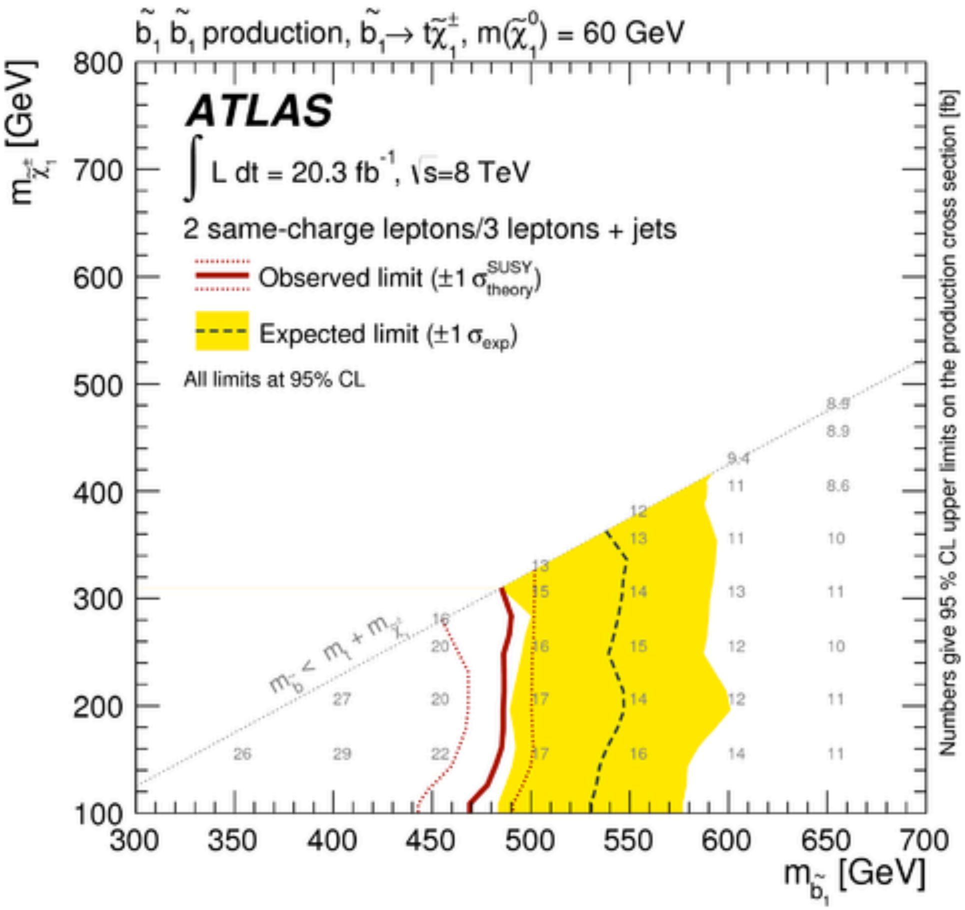
Stau-sneutrino production

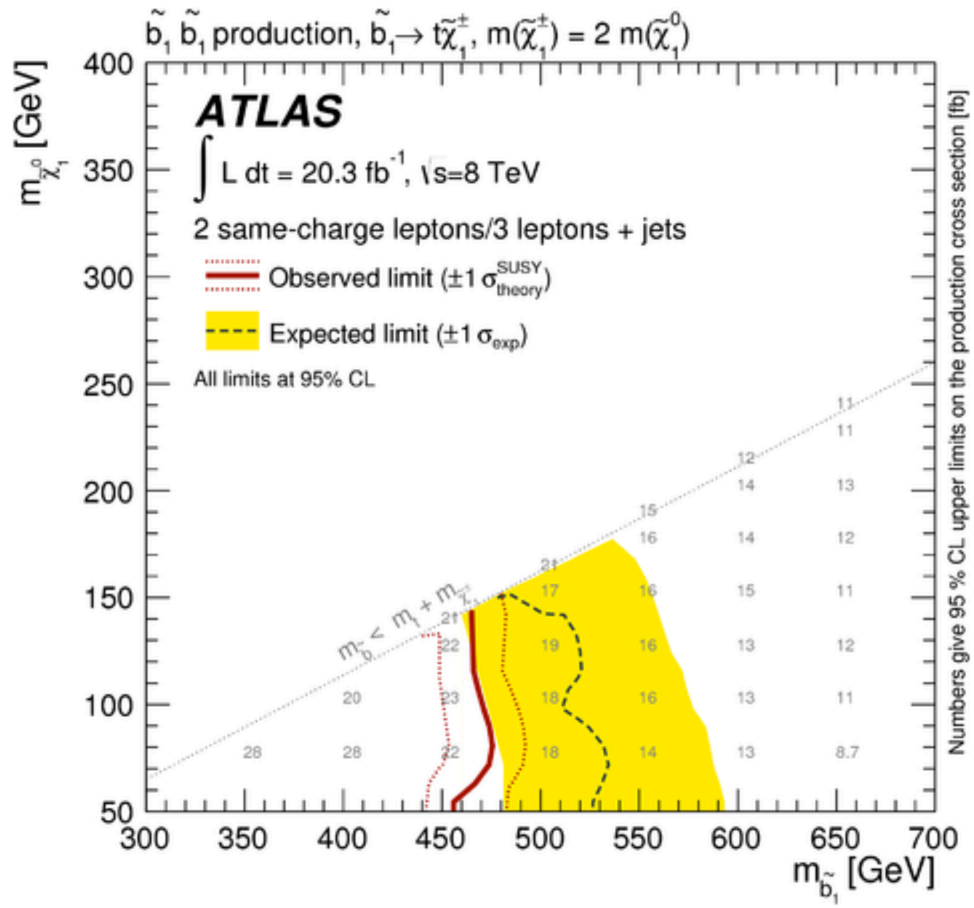
2 taus + W + Miss. ET

Carena, Gori, Sha, Wang, C.W'13

Sbottom Searches

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

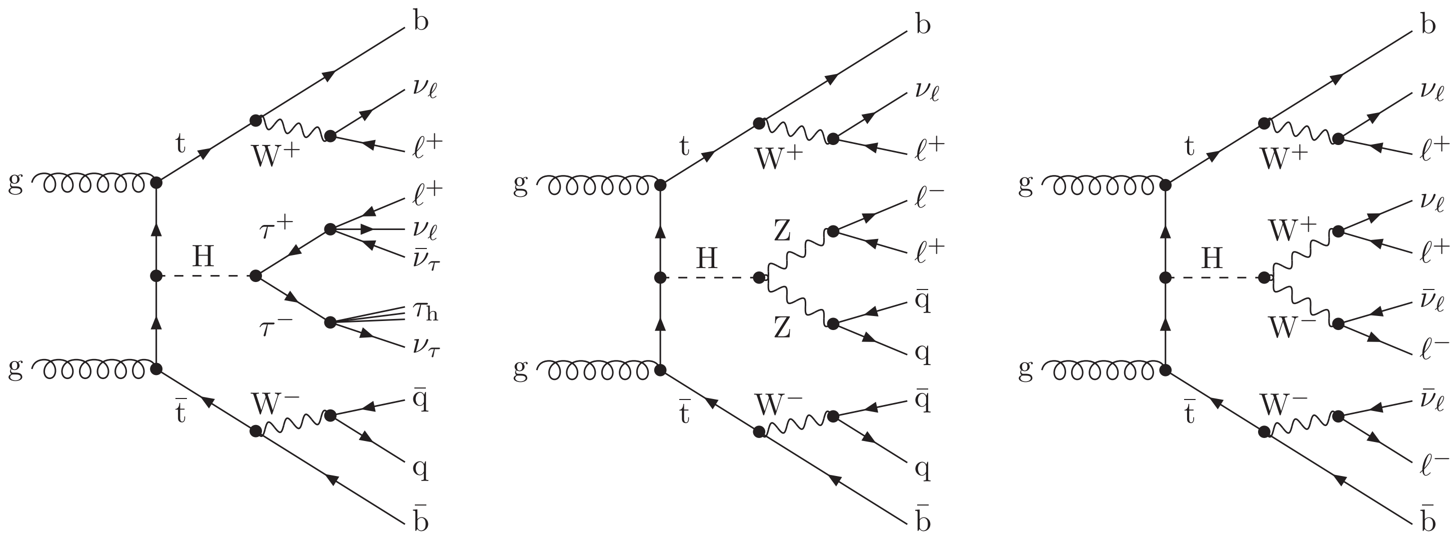




2 b + 4 W + Missing ET

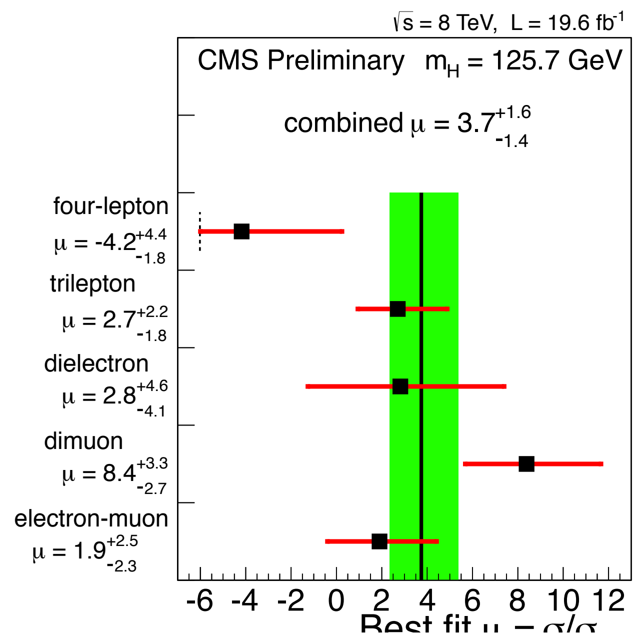
$ttH, H \to WW$

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 :
S. Gori, A. Ismail, P. Huang, I.Low, C.W.'15

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- Not any convincing hints.
- But imagine we go back in time and you only new about the electron, the positron and the photon.
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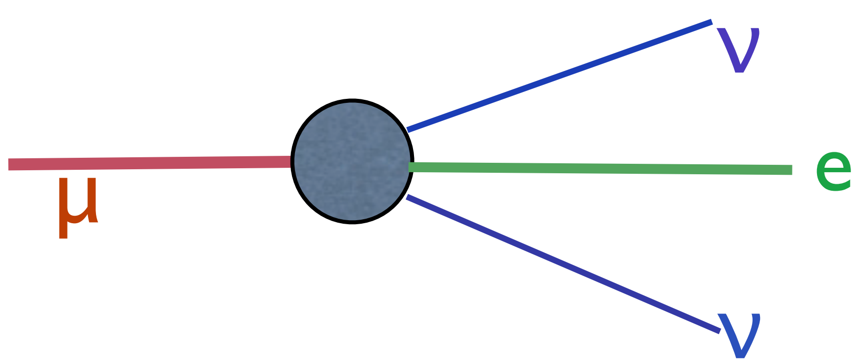

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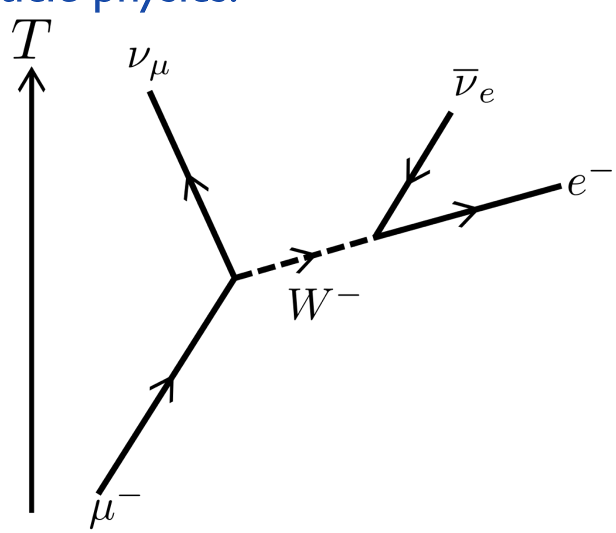
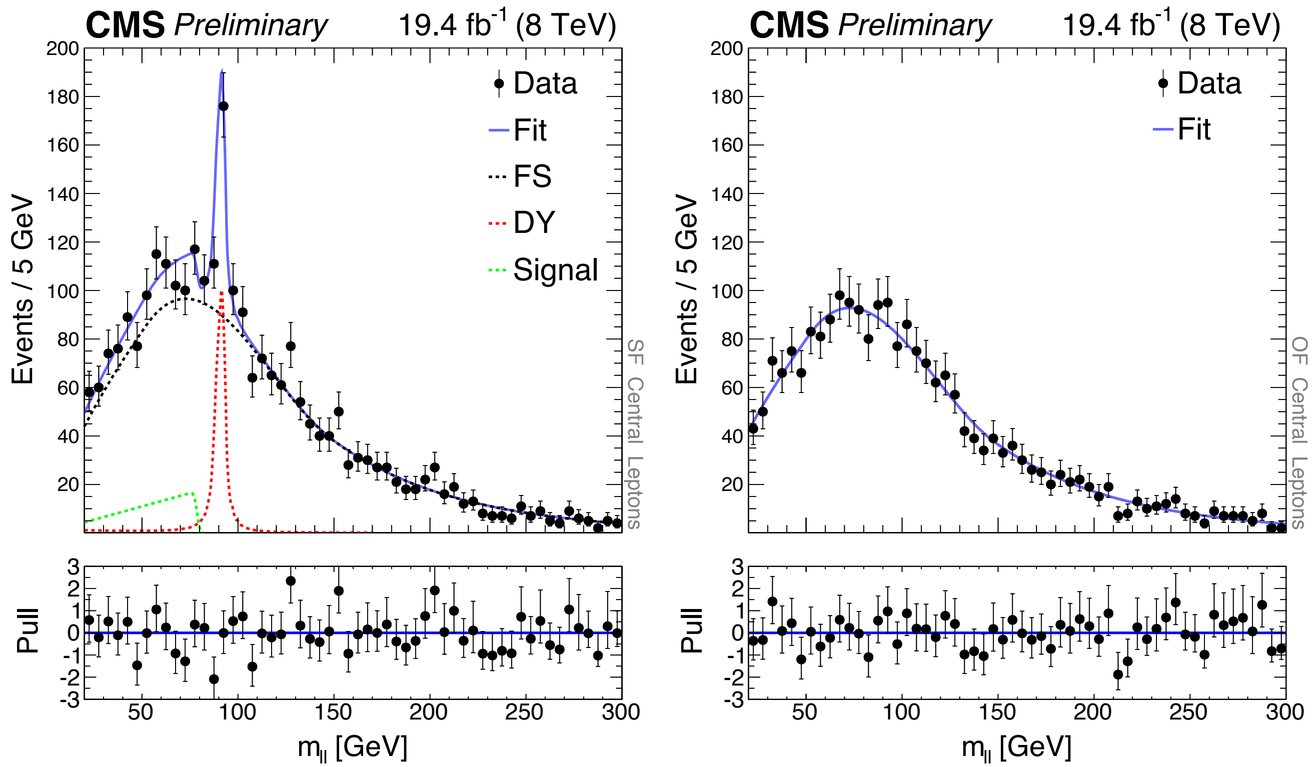
- You also realize that there must be some massive particle mediating the decay. If you are at Chicago, you call it W, after the last name of the guy who taught you particle physics.



You discovered three particles at once ! (actually four)

Edge in the invariant mass distribution of leptons

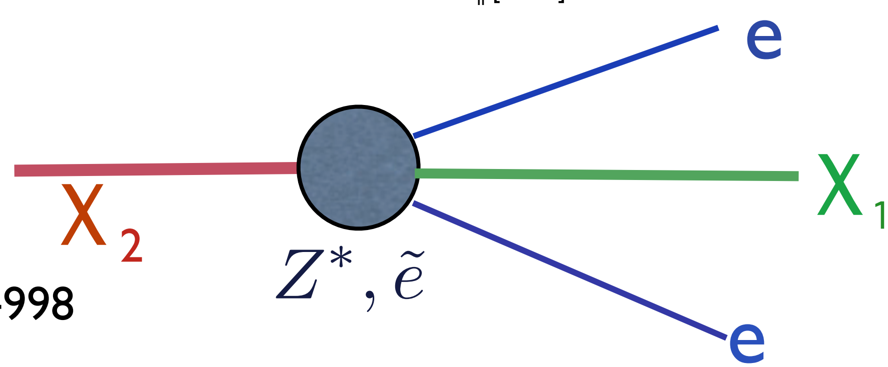
2 jets with $p_T > 40$ GeV
2 leptons with $p_T > 20$ GeV
Missing $E_T > 150$ GeV
(or $N_{\text{jets}} > 3$ and Miss. $E_T > 100$ GeV)



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

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

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



$m_{\tilde{b}} \simeq 390\text{GeV}$
$m_{\tilde{\chi}_2^0} \simeq 340\text{GeV}$
$m_{\tilde{\chi}_1^0} \simeq 260\text{GeV}$

Event Counting

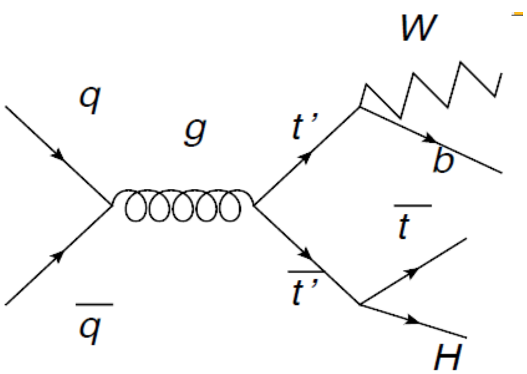
SUS-12-019

2 jets with $p_T > 40$ GeV
2 leptons with $p_T > 20$ GeV
Missing $E_T > 150$ GeV
(or $N_{\text{jets}} > 3$ and Miss. $E_T > 100$ GeV)

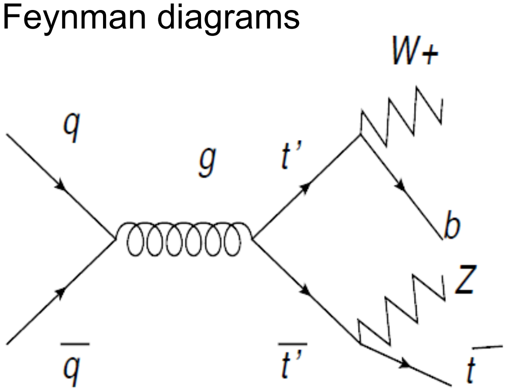
	Central	Forward
Observed [SF]	860	163
Flav. Sym. [OF]	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$
Drell–Yan	8.2 ± 2.6	1.7 ± 1.4
Total estimates	730 ± 40	157 ± 16
Observed – Estimated	130^{+48}_{-49}	6^{+20}_{-21}
Significance [σ]	2.6	0.3

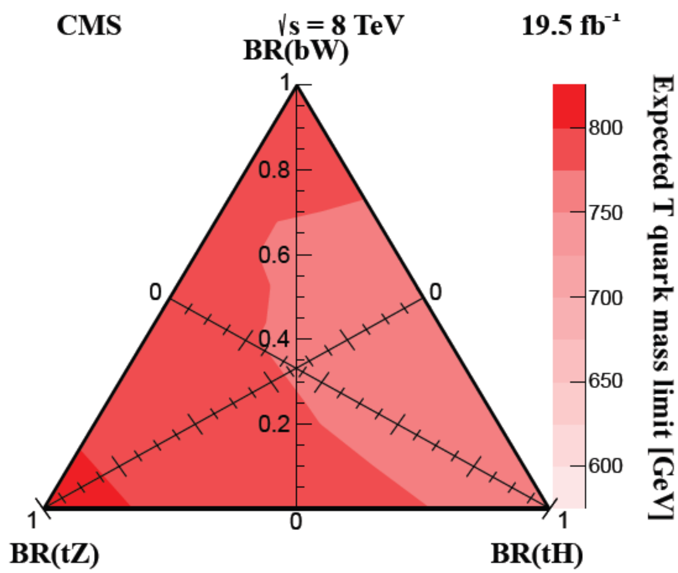
Heavy Top Quarks

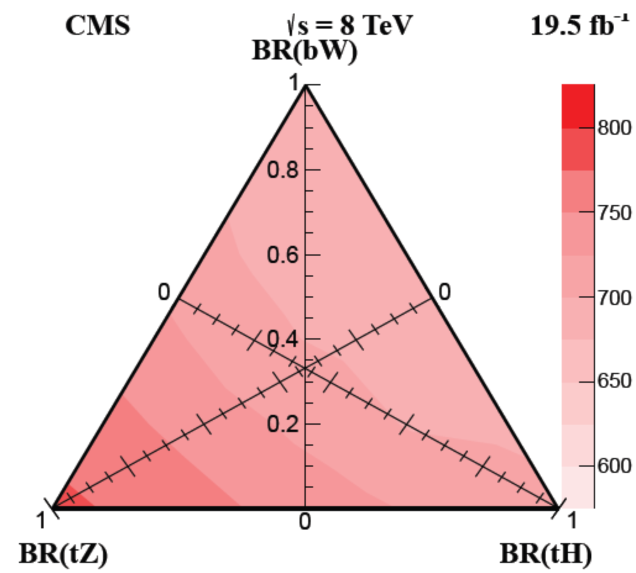
$$\mathcal{Q} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (\mathbf{2},\mathbf{2})_{2/3} \ , \ \tilde{T} = (\mathbf{1},\mathbf{1})_{2/3}$$



There are many more Feynman diagrams



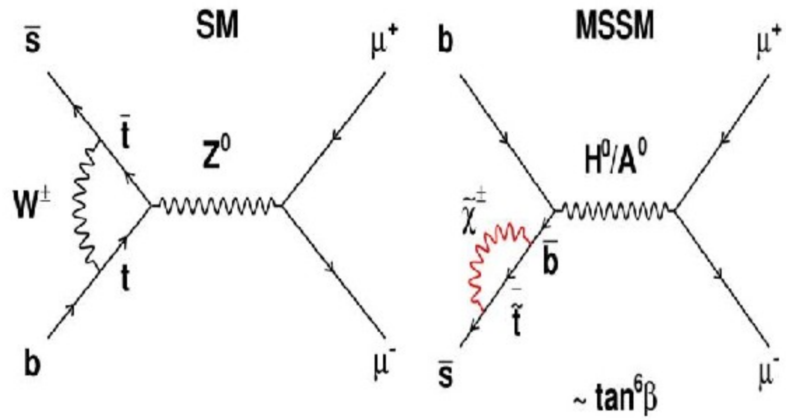




- Exclude T masses between 687 and 782 GeV
  - Inclusive analysis allows a novel interpretation
    - BR(bW) + BR(tH) + BR(tZ) = 1 → Triangle
    - Results available for any branching fraction
- Similar results from ATLAS (Phys.Lett., B718:1284–1302, 2012; Phys.Lett. B718 (2013) 1284-1302)

Rare B Decays

$$B_s \to \mu\mu$$

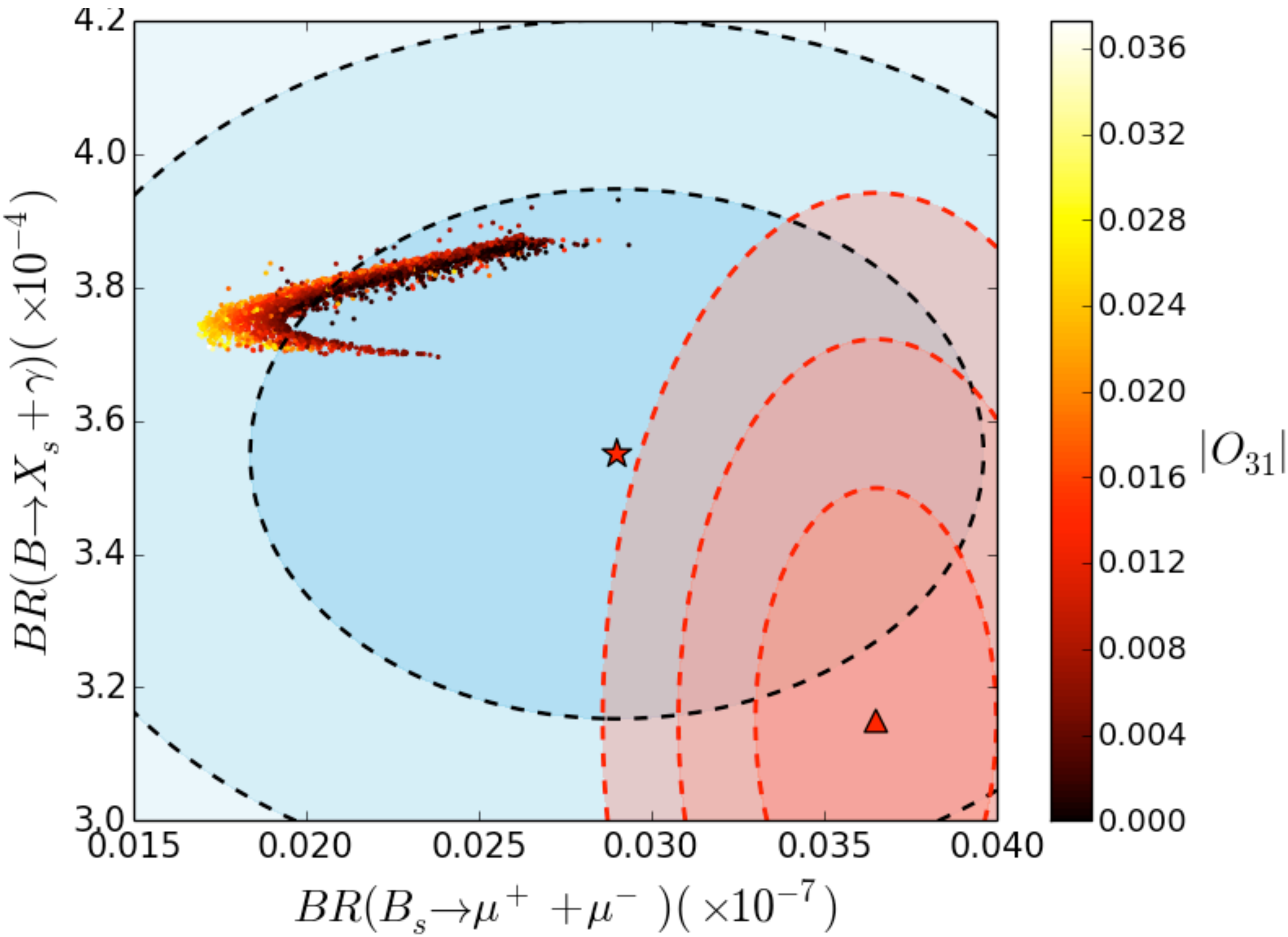


$$BR(B_s \to \mu^+ + \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$(B_s \to \mu\mu)^{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$$B(B_s \to \mu^+\mu^-)^{\mathrm{MSSM}} \sim \tan^6\beta / M^4_{A0}$$

Higher Precision may probe new physics contributions



4.2
4.0
3.8
3.6
3.4
3.2
3.0
0.015
0.020
0.025
0.030
0.035
0.040
$BR(B_s \to \mu^+ + \mu^-)(\times 10^{-7})$
$BR(B \to X_s + \gamma)(\times 10^{-4})$
0.036
0.032
0.028
0.024
0.020
0.016
0.012
0.008
0.004
0.000
$|O_{31}|$

Bing Li, C.W.'15

Conclusions

- Heavy Flavor Physics is exciting and must be pursued at the LHC