Higgs Yukawa Coupling & Fermion Generation Puzzle

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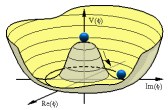
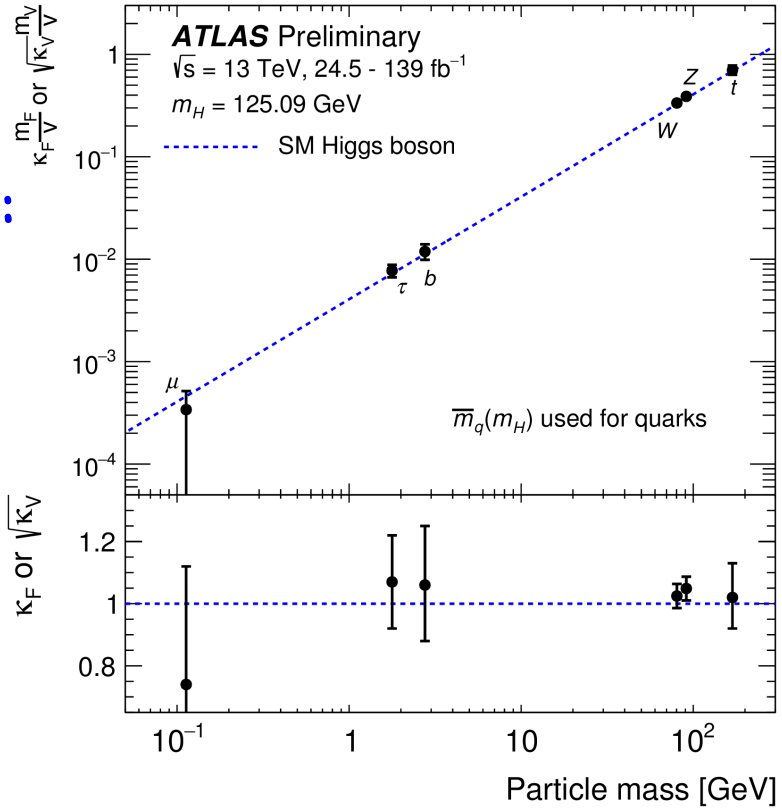
Higgs the Massenger

Higgs is 'responsible' for the masses in the SM:

- W/Z masses and Higgs self coupling:
  $|D_\mu\phi|^2 - V(\phi)$



- Fermion masses as Yukawa couplings: $y_{ij}\Psi_{iL}\phi\Psi_{jR}$ + h.c.
  but a rather ad hoc inclusion
- Present measurements follow the SM remarkably well:
  - but Yukawa coupling probes only have meaningful sensitivities for 3rd generation so far
  - Should 2nd and 1st generations also follow is a naïve SM conjecture - out of lack of understanding of the origin of 3 fermion generations



Couplings:

$hVV \sim 2M_V^2/v$

$hff \sim M_f/v$

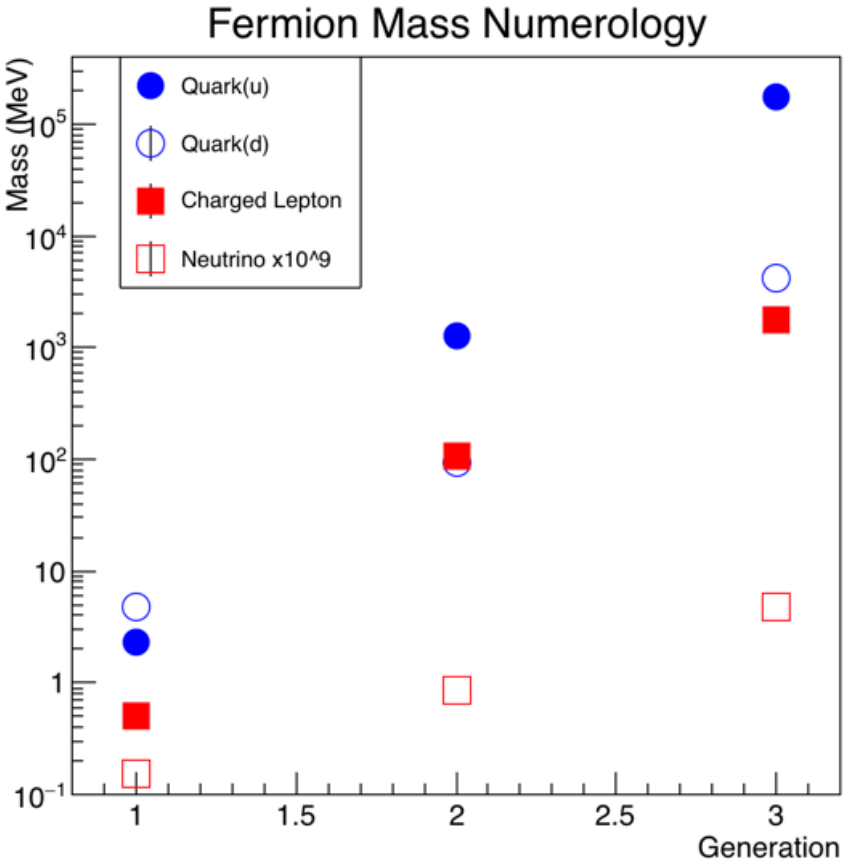
also to DM with mass ?

Non-universal Higgs Yukawa Coupling ?

- Don't be silly. Everything we know are universal between fermion families ?
  - EM force acts on only electrical charge
  - Strong interaction same strength for quarks
  - Universality of electroweak interactions
    - for charged leptons
    - for quarks and neutrinos up to some mixing matrix
- What's different between fermion families ?
  - Mass is the principle distinction
  - Higgs Yukawa coupling is special. Generation independent universality is a lazy assumption.

3 Fermion Generations

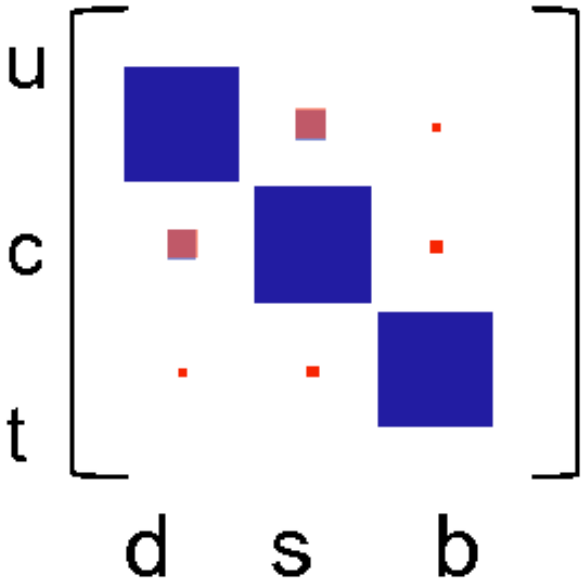
- *One of the most fundamental puzzles*
- Very little theoretical guidance. Resigned to many free parameters
  - but the masses are dropping hints we don't understand ?
- What is driving the mass hierarchy ?
  - Compositness ?
  - Generation dependent Higgs doublets ?

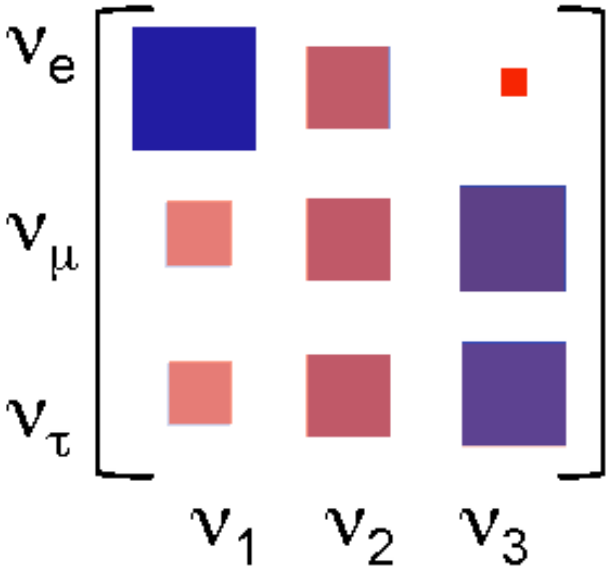


ν: 2 ΔM^2 measurements + linear logM

More Complications with Fermions

Mass eigen states are mixture of flavor eigen states





but mixing pattern look very different among quarks and among neutrinos

Fermion Mass Rotation Matrix

- Series papers from Hong-Mo Chan et al (HMC), see e.g. review paper arXiv:1103.5615
- Rank-one Rotating Mass Matrix (R2M2)

  e.g. Up type quarks $m(\mu) = m_T \alpha \alpha^\dagger$ α=eigen vector

  with only one heavy mass scale m_T to reach lighter c and u quarks by rotation.
- Also derive CKM matrix with same formalism.
- Empirical generic model – no physics origin of the rotation matrix.
- BJ also played with this: http://www.bjphysicsnotes.com

  with associated "Family of Higgs" model (but trouble with Zbb coupling measurements?)

R2M2 CKM Results

HMC/R2M2 CKM (2011)

$$\begin{pmatrix} 0.97430 & 0.2252 & 0.00357 \\ 0.2251 & 0.97345 & 0.0415 \\ 0.00879 & 0.0407 & 0.999134 \end{pmatrix},$$

which can be compared with the experimental values [18]:

$$\begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

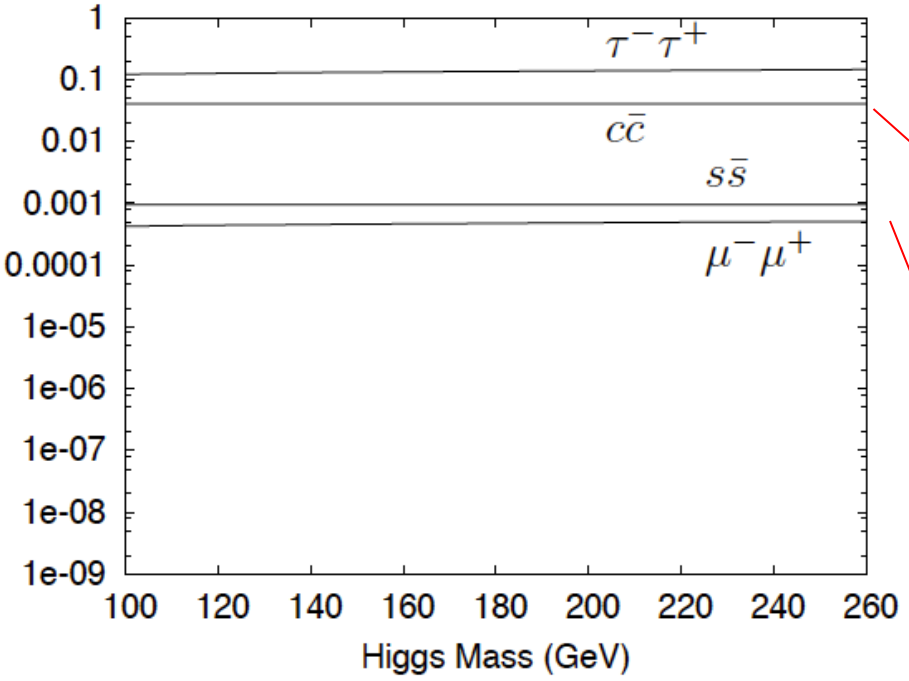
UT triangle

	PDG	R2M2
α	84.5 +5.0 -5.2	88
sin2β	0.691 +-0.017	0.691
γ	73.5 +4.2 -5.1	70

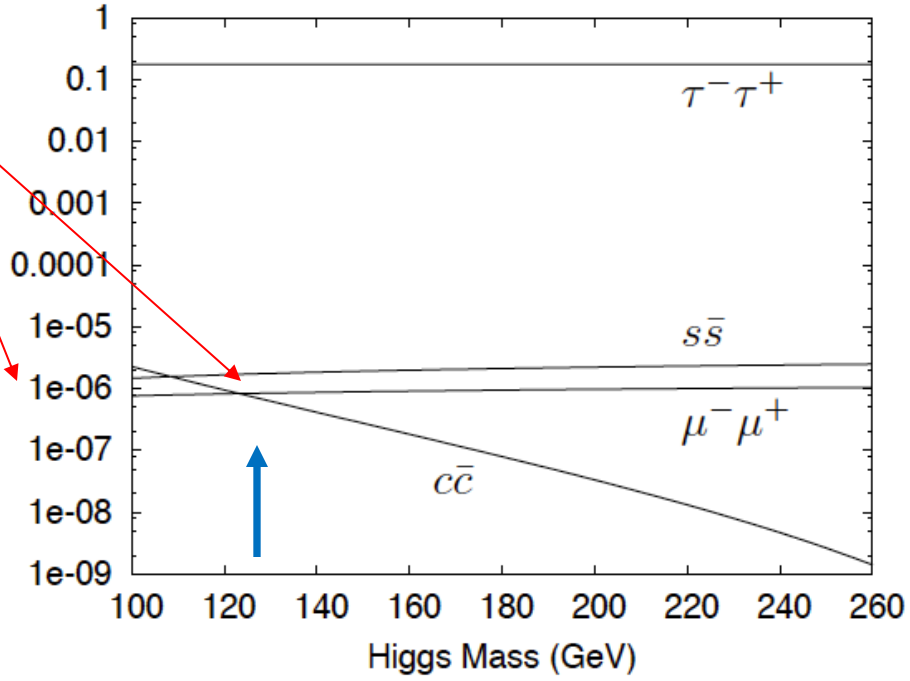
HMC/R2M2 Higgs Prediction

Γ(h->ff)/Γ(h->bb)

SM



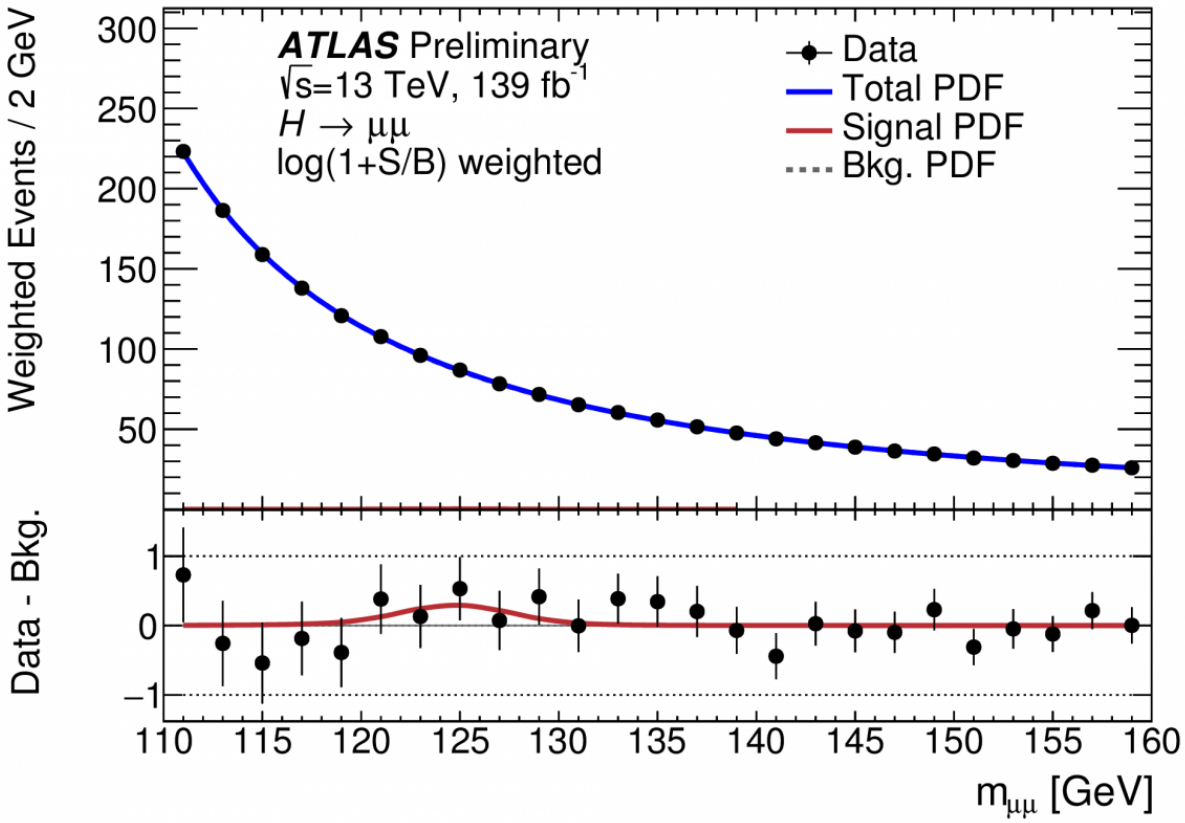
R2M2



- "charmless Higgs" – flagship measurement for e^+e^- Higgs factories. Hopeless for LHC.
- Also diminishing ss,μμ

h(125)->μμ

ATLAS-CONF-2019-028 EPS Jul/2019 139 fb^{-1}



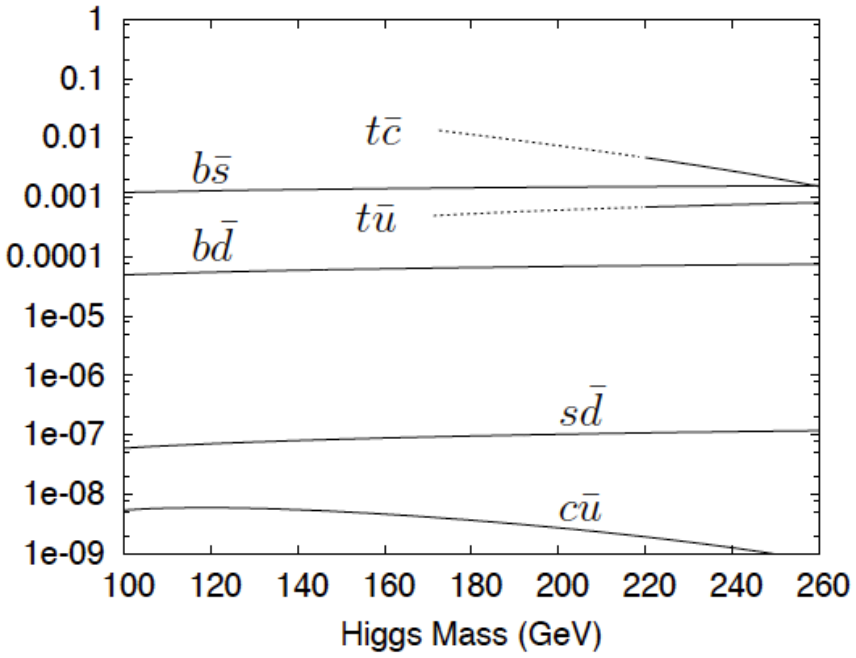
μ = 0.5 +-0.7

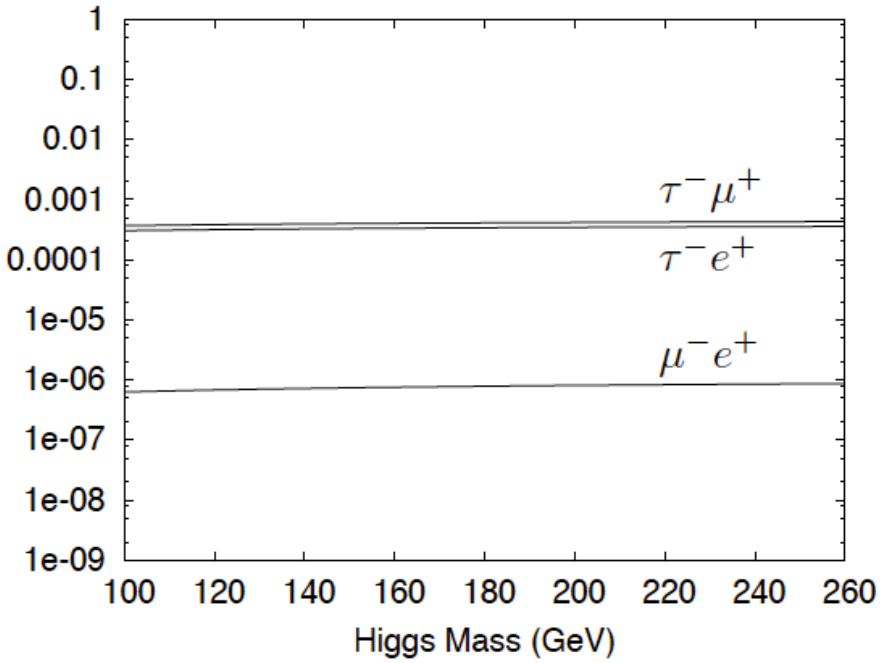
95% CL sensitivity 2.2 x SM

HL-LHC will tell if this is <<1

HMC/R2M2 Flavor Violating Higgs Decays

Γ(h->ff')/Γ(h->bb)

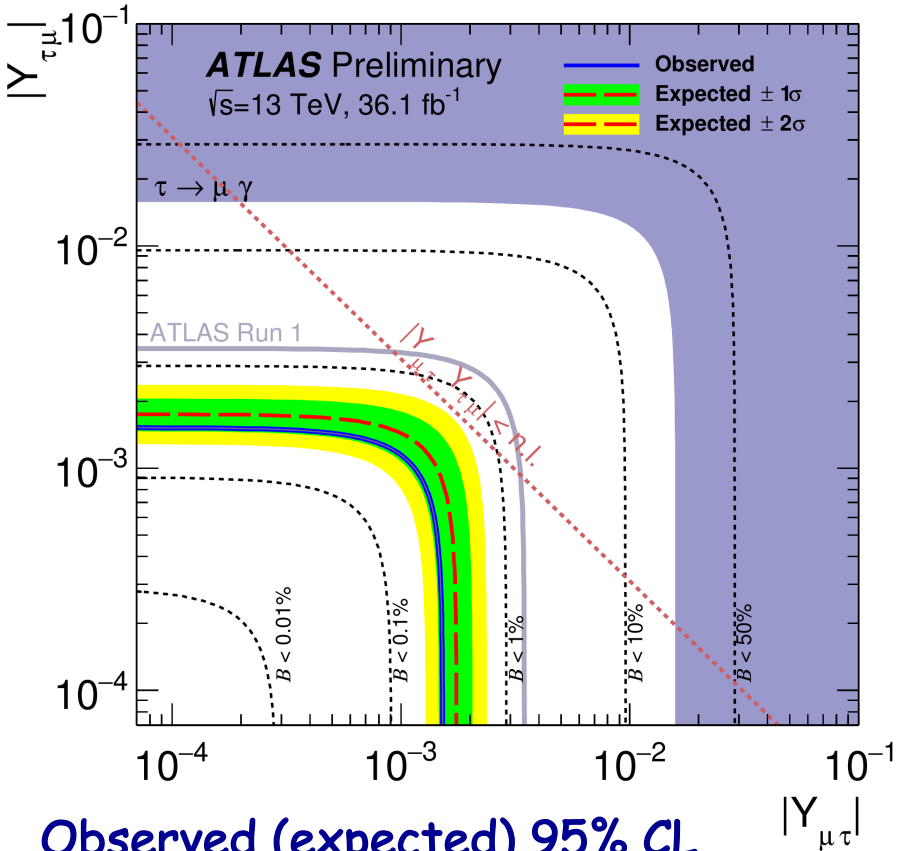




- Quark modes too difficult even for e^+e^-
- Leptonic modes BR~5×10^{-4} not far from reach ?

h(125)->τμ,τe, μe

τμ,τe 36 fb^{-1} PLB 800 (2020) 135069

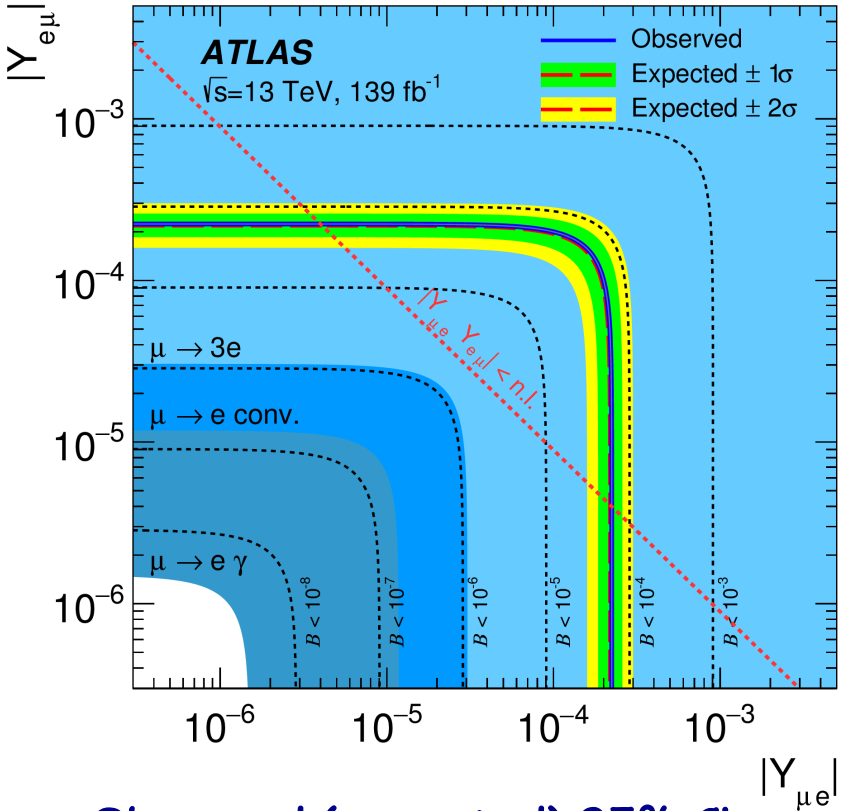


Observed (expected) 95% CL

Br(τe)<0.47% (0.34%)

Br(τμ)<0.28% (0.37%)

μe 139 fb^{-1} PLB 801 (2020) 135148



Observed (expected) 95% CL

Br(μe)<6.1x10^{-5} (5.8x10^{-5})

Br(ee)<3.6x10^{-4} (3.5x10^{-4})

Multiple Higgs Doublets

- R2M2 with a single Higgs h(125) doesn't provide physics origin for the rotation matrix.
- Multiple Higgs doublets with fermion generation dependence can be a natural source of the mass hierarchy ?
- Simplest example: Two Higgs Double Models (2HDM) with Φ_1,Φ_2 has 5 Higgs bosons: h,H^0,A,H^+,H^-

Type	I	II	Flipped	Lepton-Specific
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_1	Φ_2
L	Φ_2	Φ_1	Φ_2	Φ_1

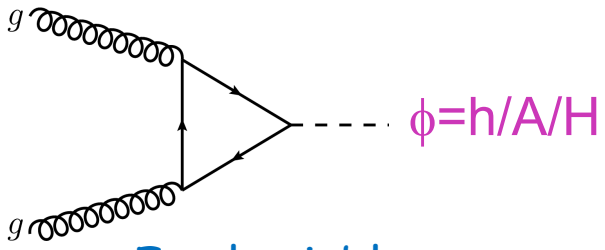
  - MSSM is a special Type II case
  - Assume Fermion universality
    - H/A -> 3rd gen dominates

Vac. Exp. Value ratio
$\tan\beta=\langle\phi_2\rangle/\langle\phi_1\rangle$

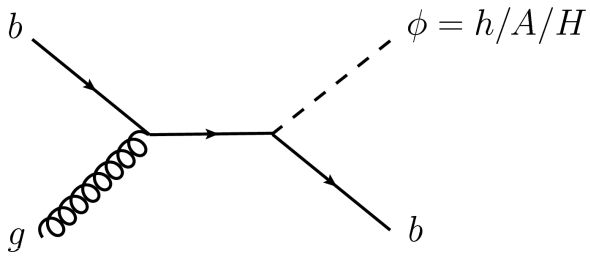
α is (h^0,H^0) mixing angle

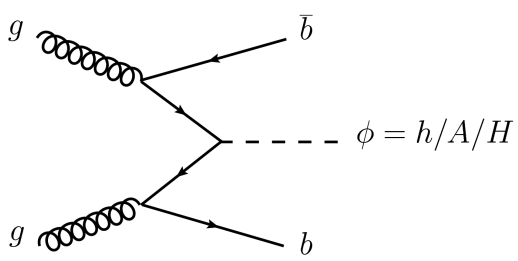
Couplings:
AVV = 0
HVV ~ $\cos(\beta-\alpha)$
(~0 is alignment limit for h to be very SM like)

Heavy H^0/A & 2HDM



ggF only viable for ττ,μμ





|~ H/A Coupling Strength|

2HDM Type	Q_U	Q_D	Lepton
I	1/tanβ	1/tanβ	1/tanβ
II (MSSM-like)	1/tanβ	tanβ	tanβ
Lepton-specific	1/tanβ	1/tanβ	tanβ
Flipped	1/tanβ	tanβ	1/tanβ

If fermion universality: b and τ searches have complementary roles

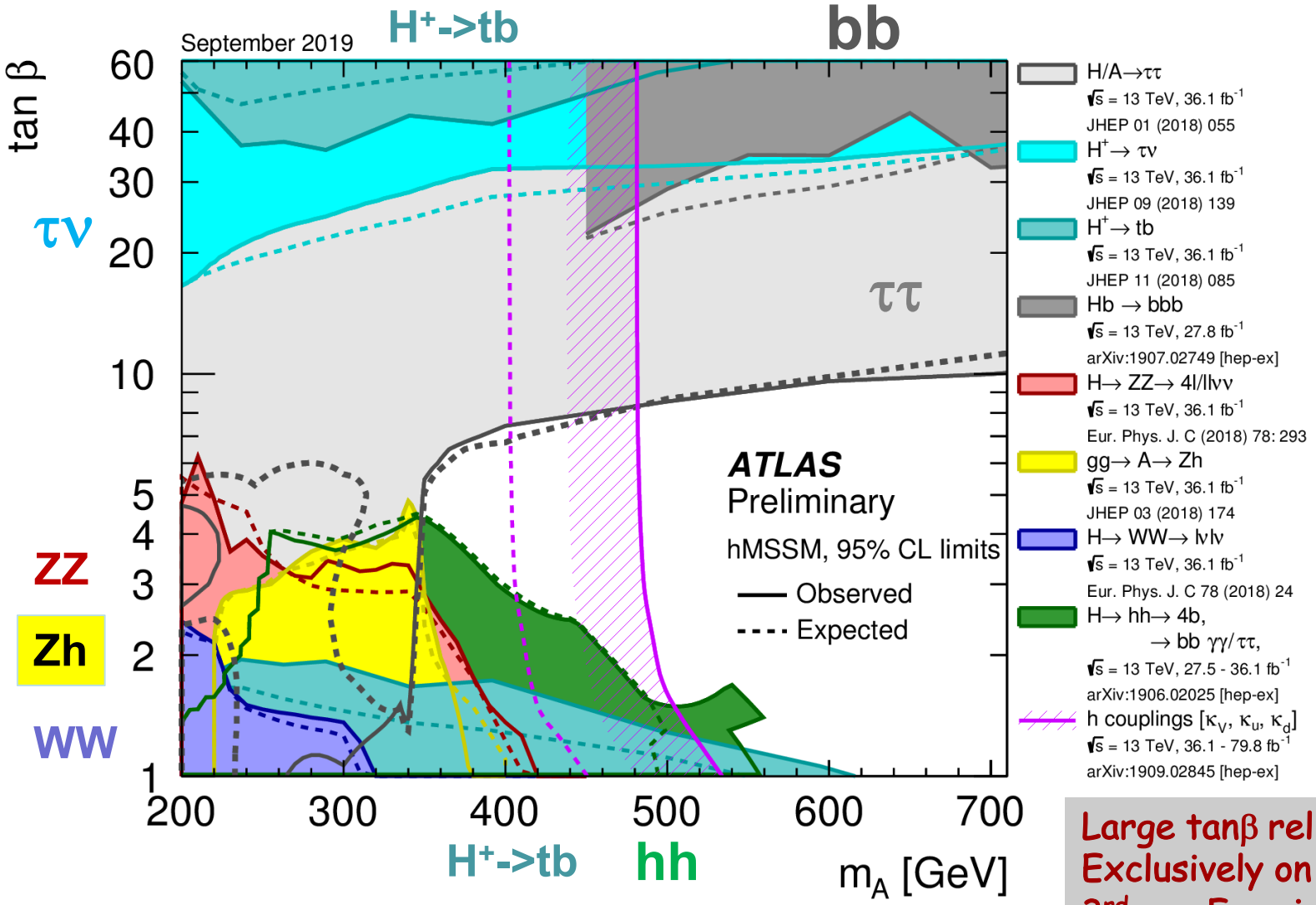
Opposite dependence between b and τ

(b)bH/A production enhanced by ~ $\tan^2\beta$ for Type II & Flipped

If h is 3rd gen centric / H/A 2nd gen centric:

(c)cH/A production becomes more important and H/A->cc, μμ BR become much larger

hMSSM Higgs Summary



Large tanβ relies Exclusively on 3rd gen Fermion modes

Info Hunting @ SUSY2019

SUSY 2019:

Corpus Christi, Texas

May/25 BSM Flavor Physics session:

Doug Tuckler (UCSC) Student of W.Altmannshofer and S. Gori
"Flavorful Higgs bosons at LHC"

Roman Pasechnik (Lund), Antonio Morais (Aveiro)
"Phenomenology of family-nonuniversal 3HDM"

=> Held special session with UCSC theorists Jul/2019
Talk by Wolfgang at West Coast LHC Forum, Oct/2019

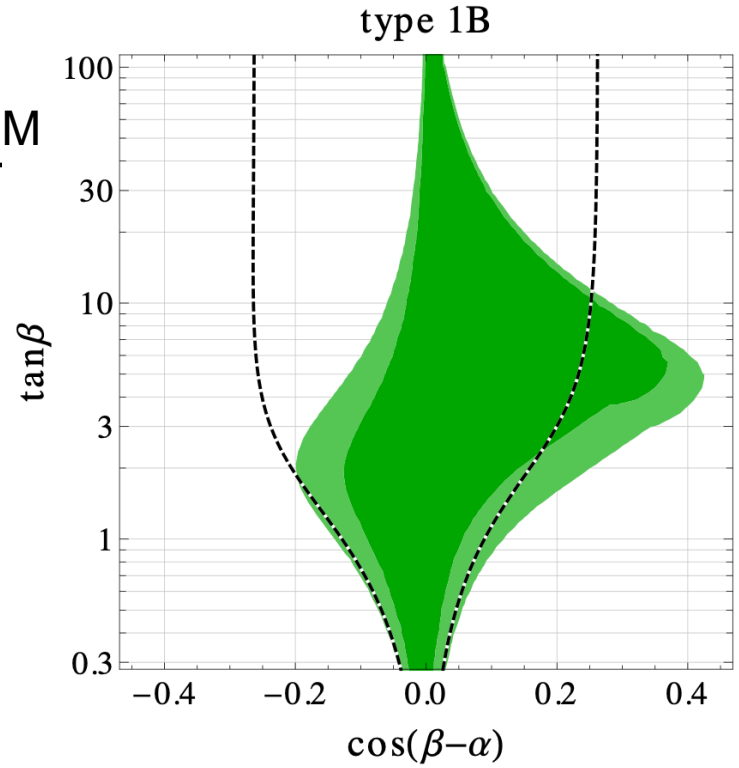
"Flavorful Higgs"

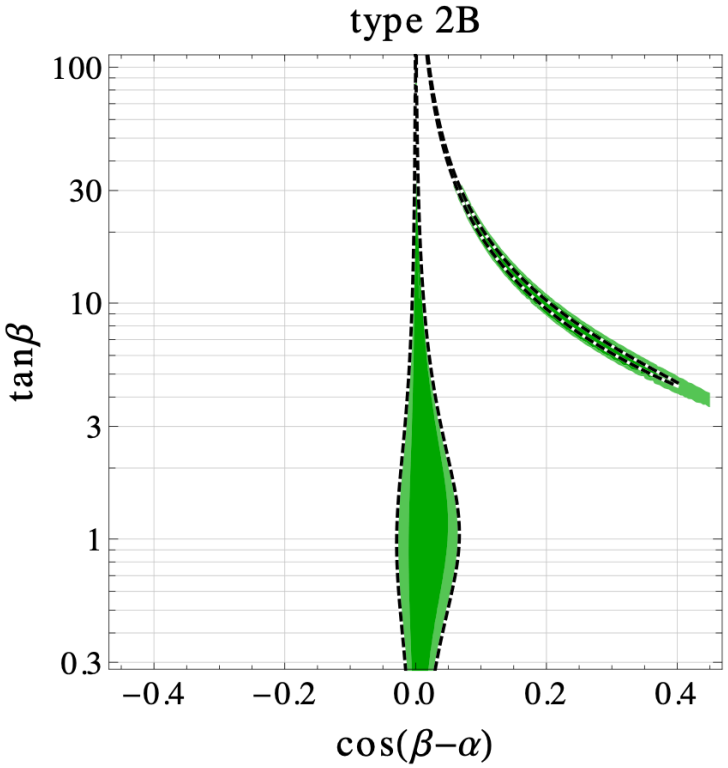
h(125) coupling

Altmannshofer,Maddock 1805.08659

Std 2HDM

F2HDM





3rd gen t,b,τ $c_\alpha/s_\beta \sim 1$

2nd gen c,s,μ $s_\alpha/c_\beta \sim 0.5$–4

t: $c_\alpha/s_\beta \sim 1$, b,τ: $s_\alpha/c_\beta \sim 0.5$–3

c: $s_\alpha/c_\beta \sim 0.5$–3, s,μ: $c_\alpha/s_\beta \sim 1$

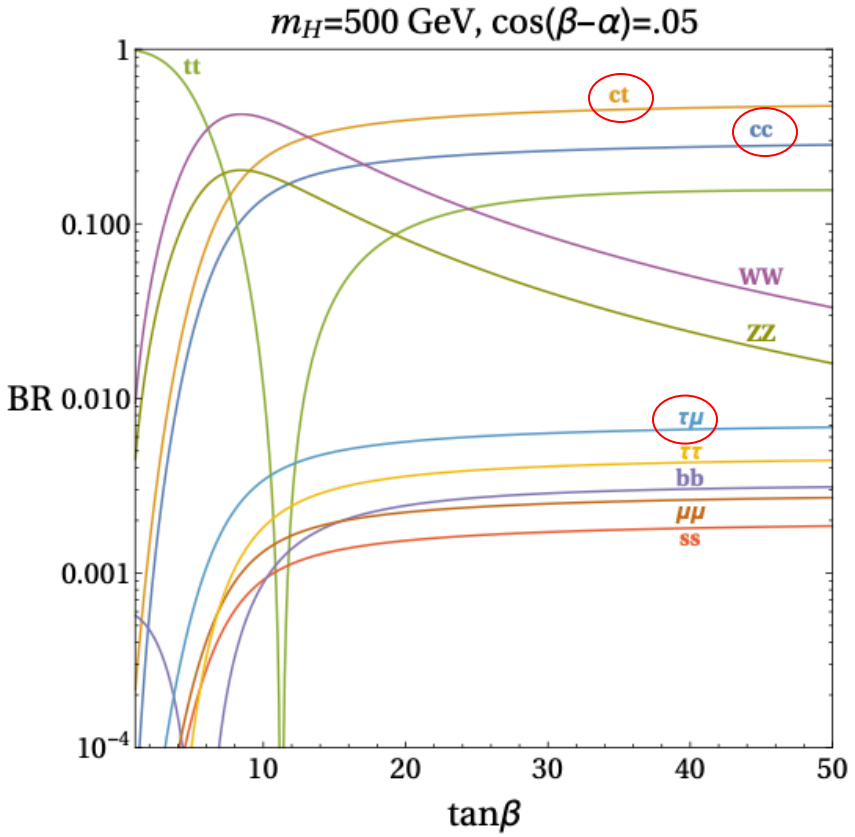
Flavorful Higgs

Heavy H/A	W,Z κ_V	up quarks $\kappa_t, \kappa_c, \kappa_u$	down quarks $\kappa_b, \kappa_s, \kappa_d$	leptons $\kappa_\tau, \kappa_\mu, \kappa_e$
mixing with singlet	s_α	s_α	s_α	s_α
2HDM type 1	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
2HDM type 2	0	$\frac{1}{t_\beta}$	t_β	t_β
flavorful 2HDM	0	$\frac{1}{t_\beta}, t_\beta, t_\beta$	$\frac{1}{t_\beta}, t_\beta, t_\beta$	$\frac{1}{t_\beta}, t_\beta, t_\beta$

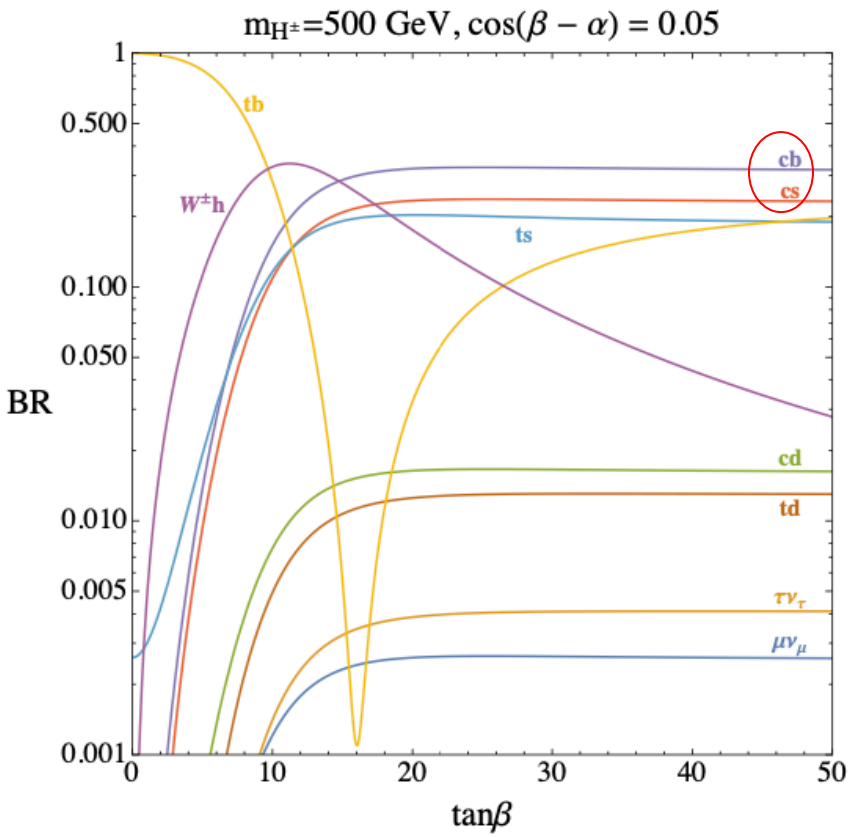
- Heavy H/A couplings to c,μ dominates at large tanβ
- Usual search via t,b,τ suppressed by 1/tanβ
- Needs search for cH/A production instead of bH/A

"Flavorful Higgs"

Neutral H/A



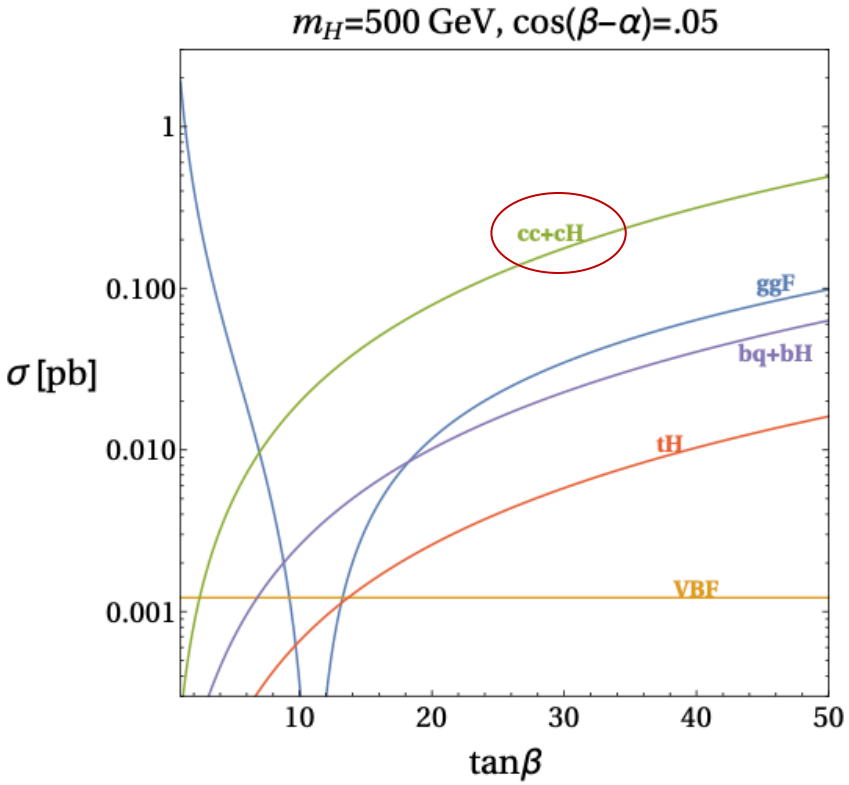
Charged H^{+-}



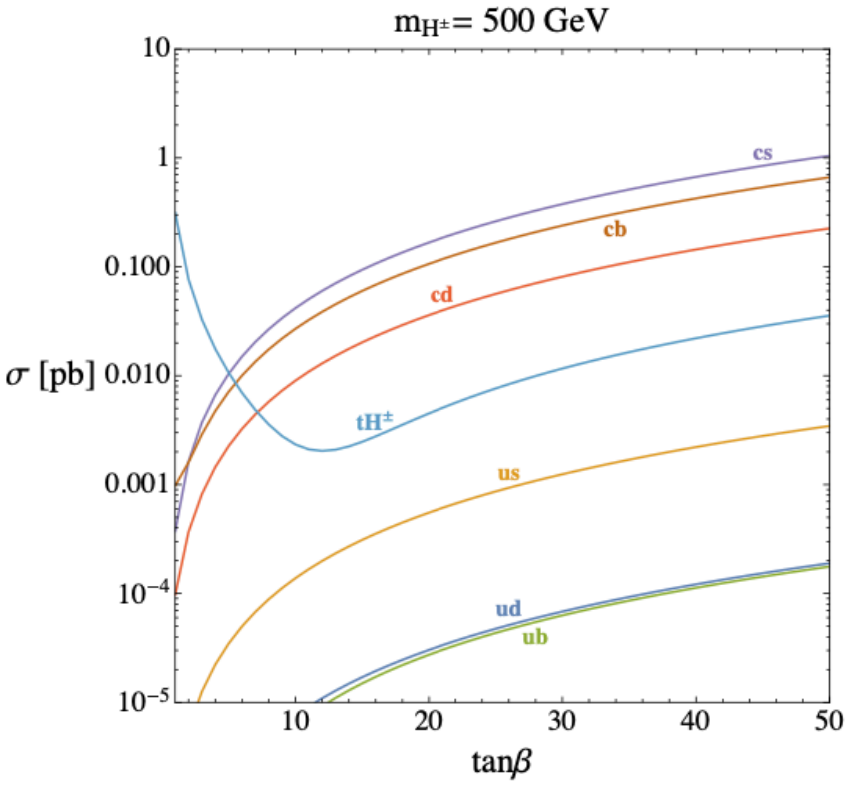
Also flavor violating modes ct, τμ !

"Flavorful Higgs"

Neutral H/A



Charged H^{+-}



Altmannshofer, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

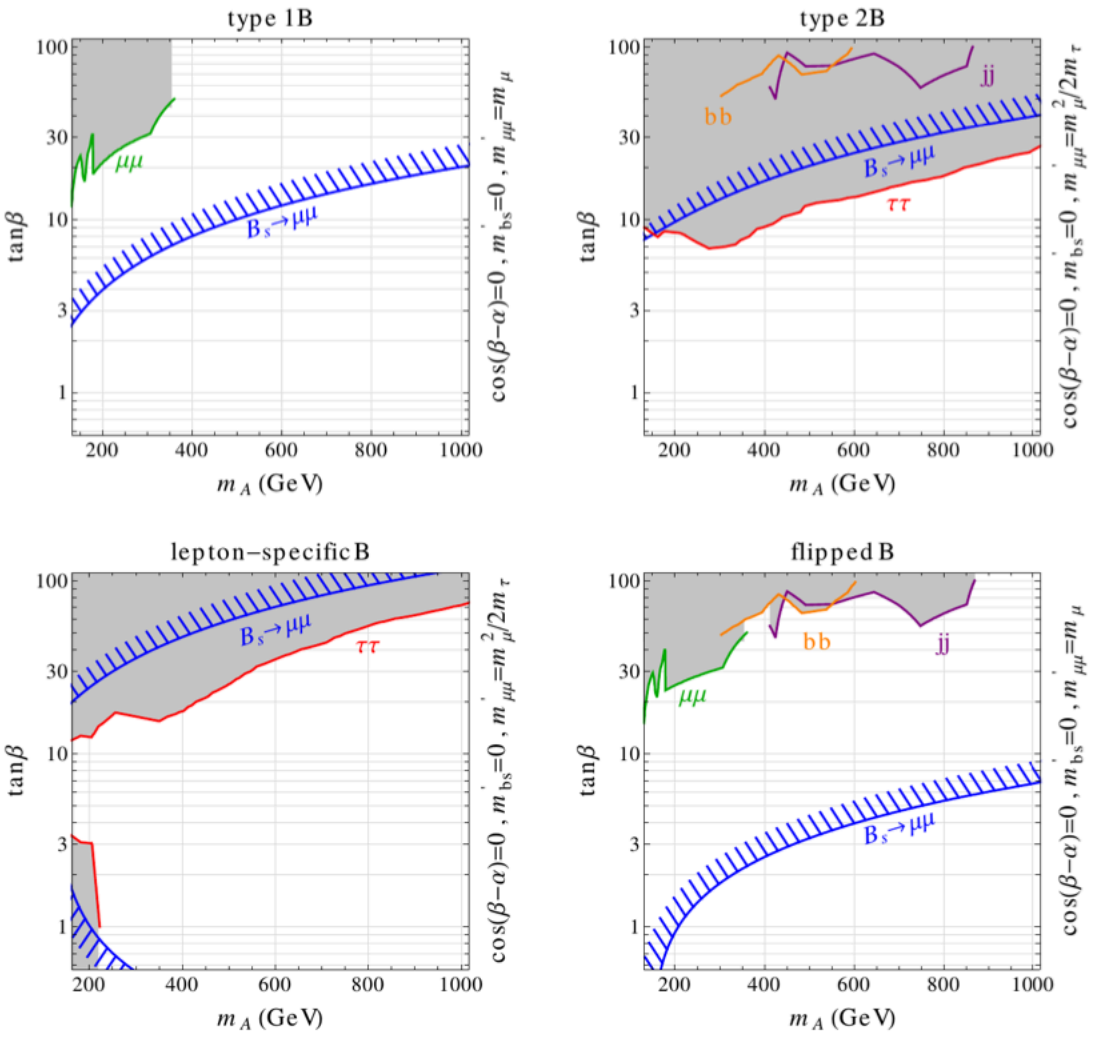
"Flavorful Higgs"

Altmannshofer,Maddock 1805.08659

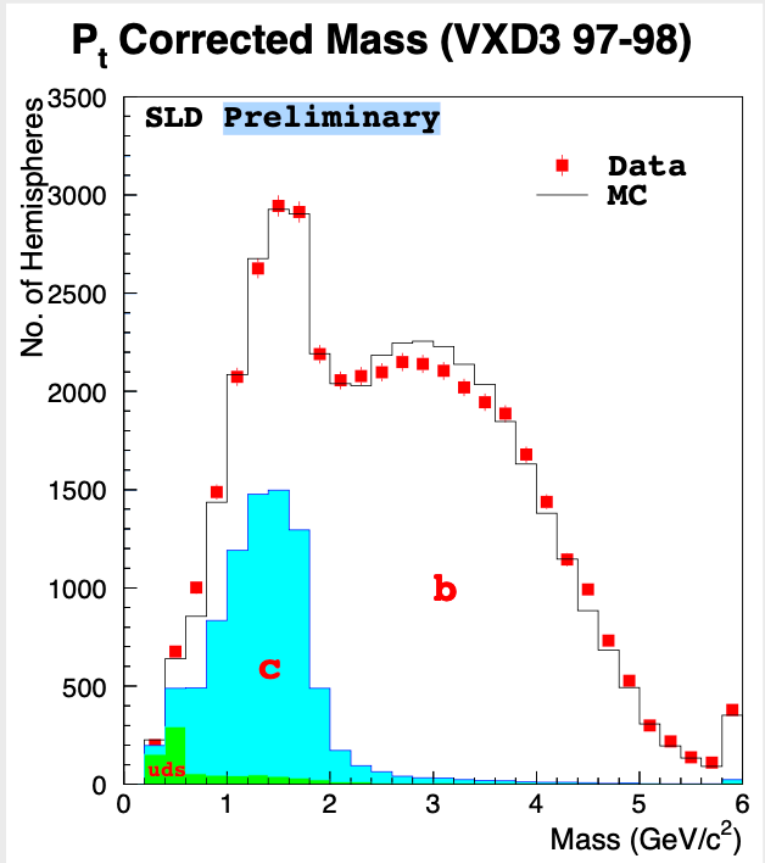
Where would the yet searched ct, cc modes land ?

Can jj improve with c,s tags ?

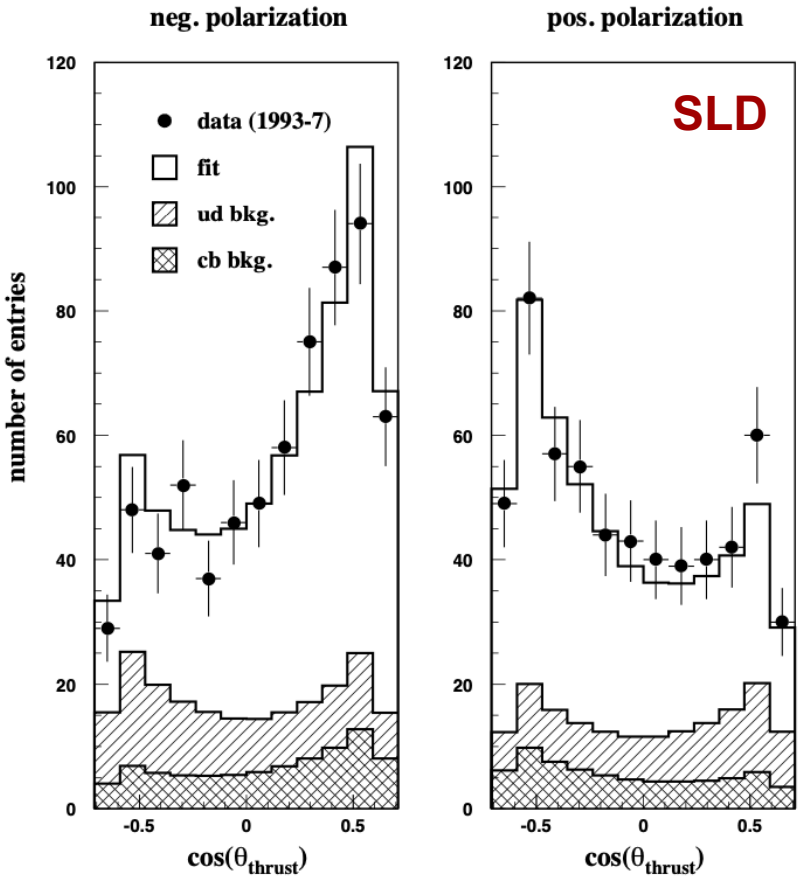
What about other types of models such as 3HDM ?



Charm/strange tagging ?



b/c separation with vertex mass tag

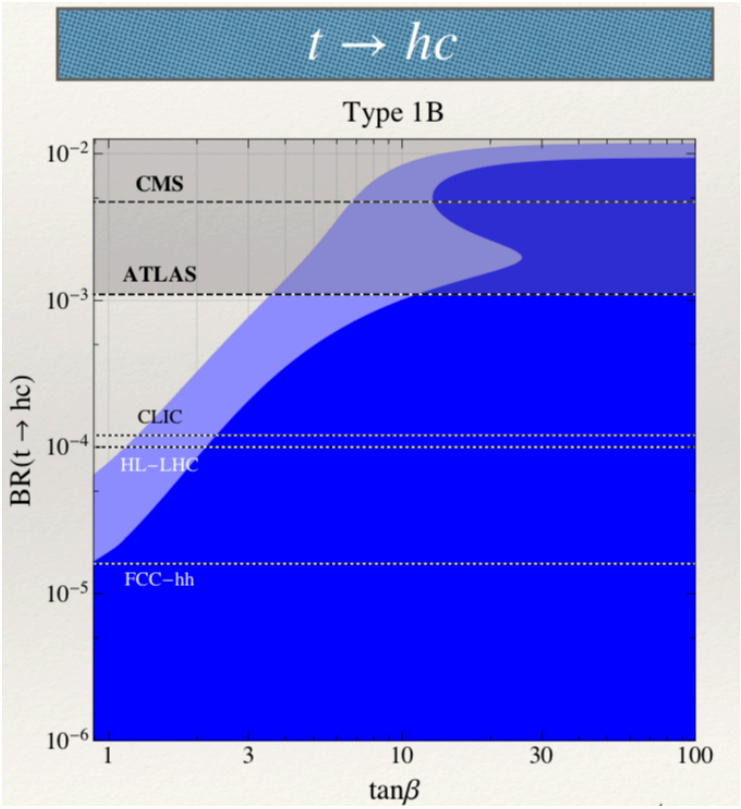


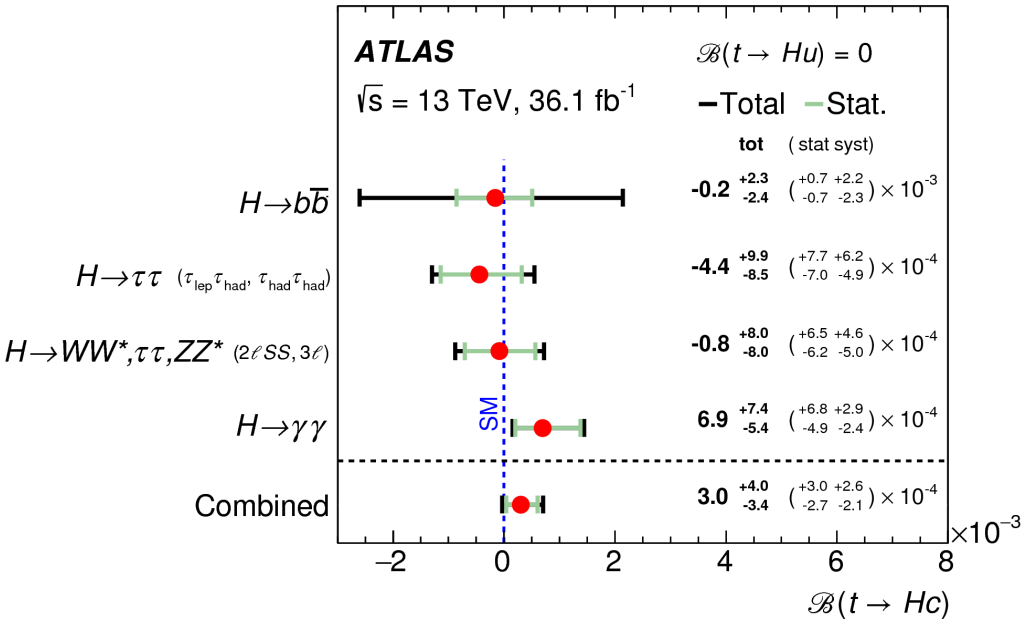
SLD s-tag with fast K,Λ used to measure polarized Z->ss asymmetry

h mediated FCNC: t->hq

arXiv: 1812.11568 Dec/2018

Flavorful Higgs





95% CL Observed (expected) limits:
Br(t->hc) < 0.11% (0.083%)
Br(t->hu) < 0.12% (0.083%)

Collider Complementarity

Needs a suite of measurements to map out the possible fermion generation dependent extended Higgs sector

- LHC and future hadron colliders
  - h(125)->μμ, μτ
  - Flavor violating decays of t->hc
  - First detection of heavy H/A through flavor conserving and flavor violating modes involving charm tag
- e^+e^- Higgs factories
  - Best sensitivity for h(125)->cc. Unique e^+e^- strength.
- Higher energy e^+e^- linear collider
  - Clean measurements of varieties of H/A (if reachable) production and decays to illuminate the Higgs/fermion generation hierachy

Conclusions

- Rare opportunity to shed light on the fundamental puzzle of 3 fermion generations, by challenging a weak spot of the SM on Higgs Yukawa couplings.
- New phenomenology with a whole suite of searches and many being first of its kind, including intriguing signatures such as flavor violating decays.
- New experimental approaches to develop to capitalize on distinctive production and decays.
- Future colliders offer complementary capabilities for mapping out the Higgs-flavor puzzle.