Hunting the Flavon

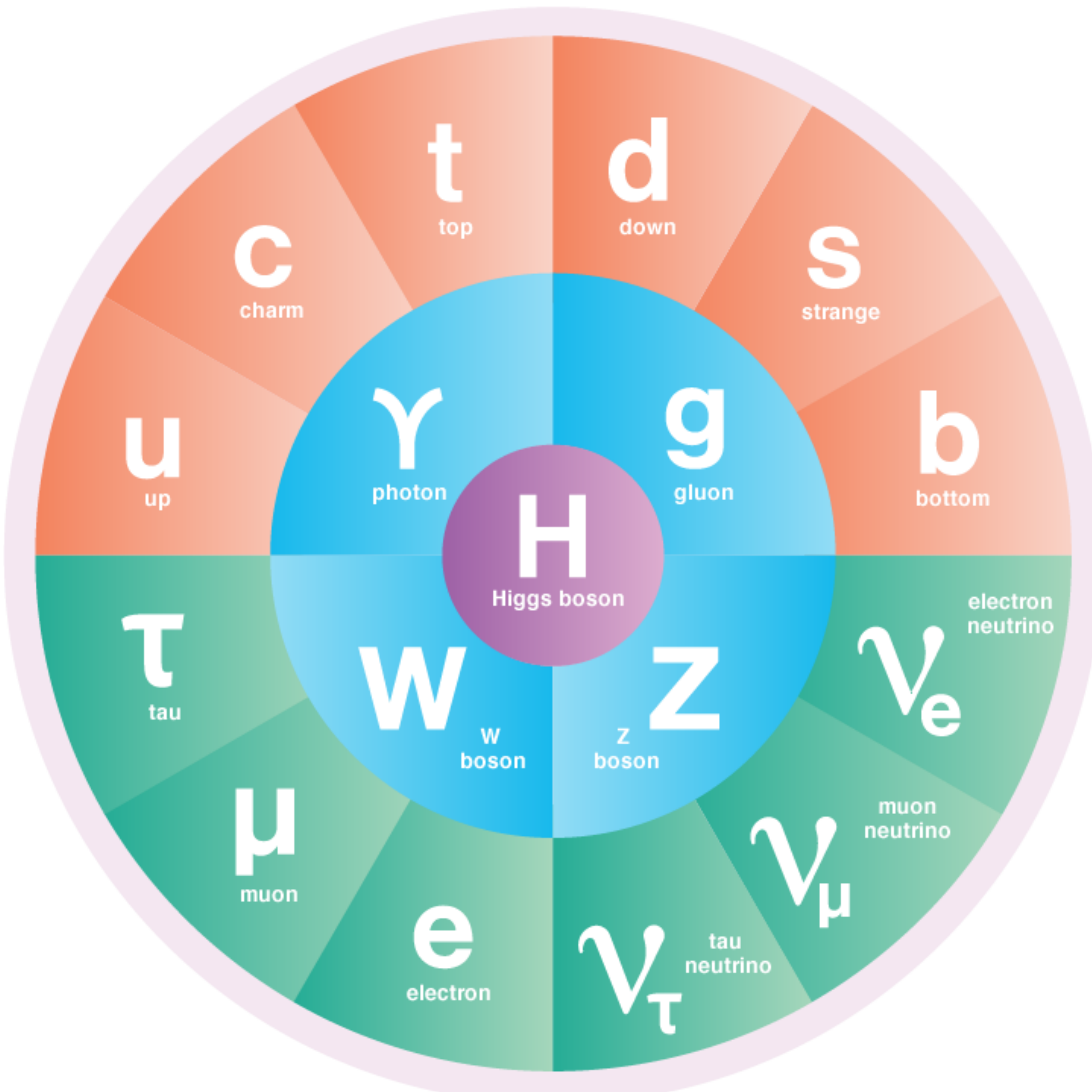
Martin Bauer

Based on

[MB, Gemmler, Carena, JHEP 1511, 016 (2015)]
[MB, Gemmler, Carena, 1512.03458]
[MB, Schell, Plehn, 1603.06950]

DESY, July 19th, 2016

The Standard Model of Particle Physics



Quarks

Spin 1/2
Charge 2/3 : Up type
Charge -1/3: Down type

Leptons

Spin 1/2
Charge -1: e, μ, τ
Charge 0: Neutrinos

Gauge Bosons

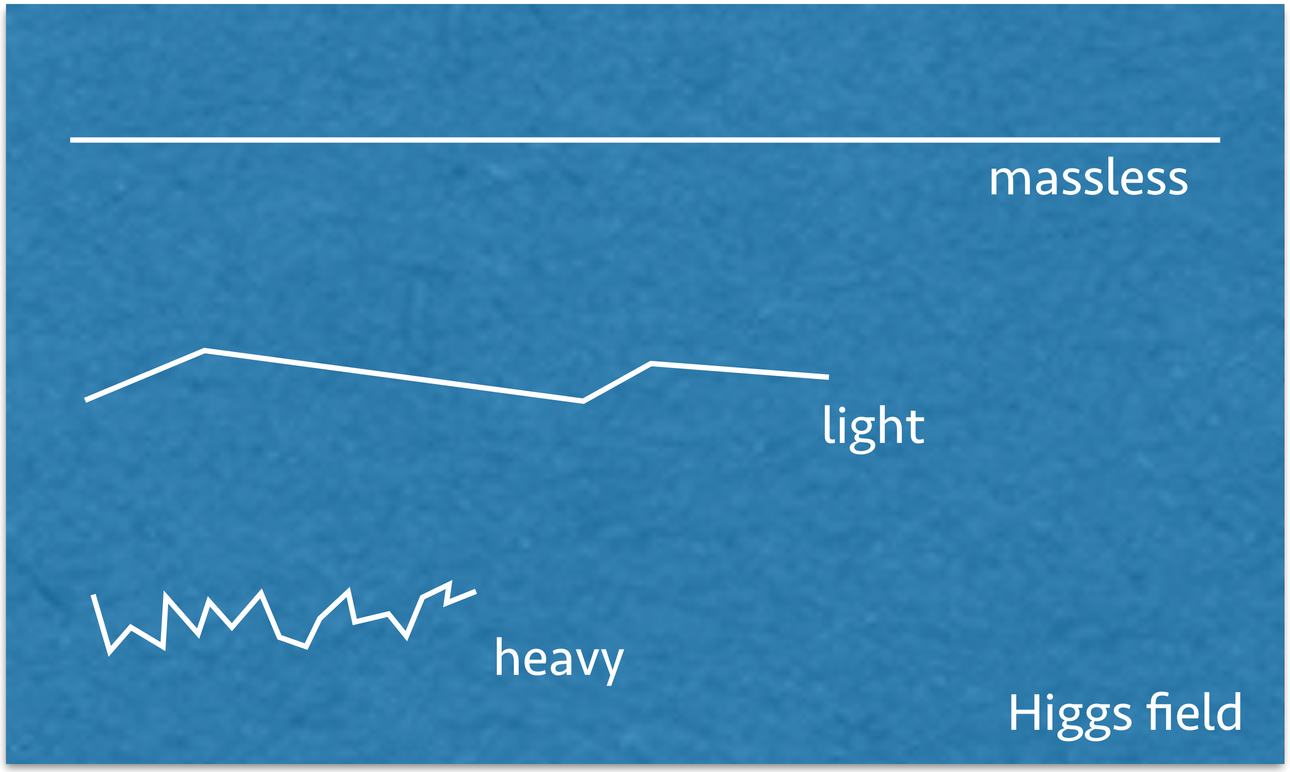
Spin 1
Charge 0 : g, γ, Z
Charge ±1: W

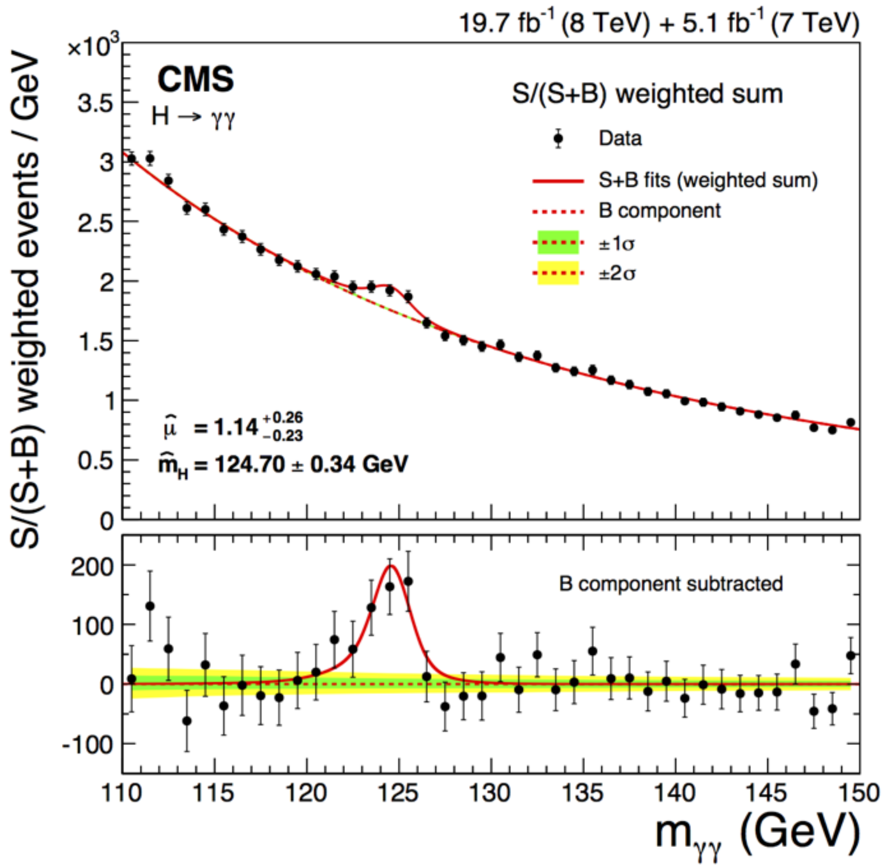
Higgs Boson

Spin 0
Charge 0

Why are elementary particles massive?

The Higgs mechanism explains why fundamental particles are massive.

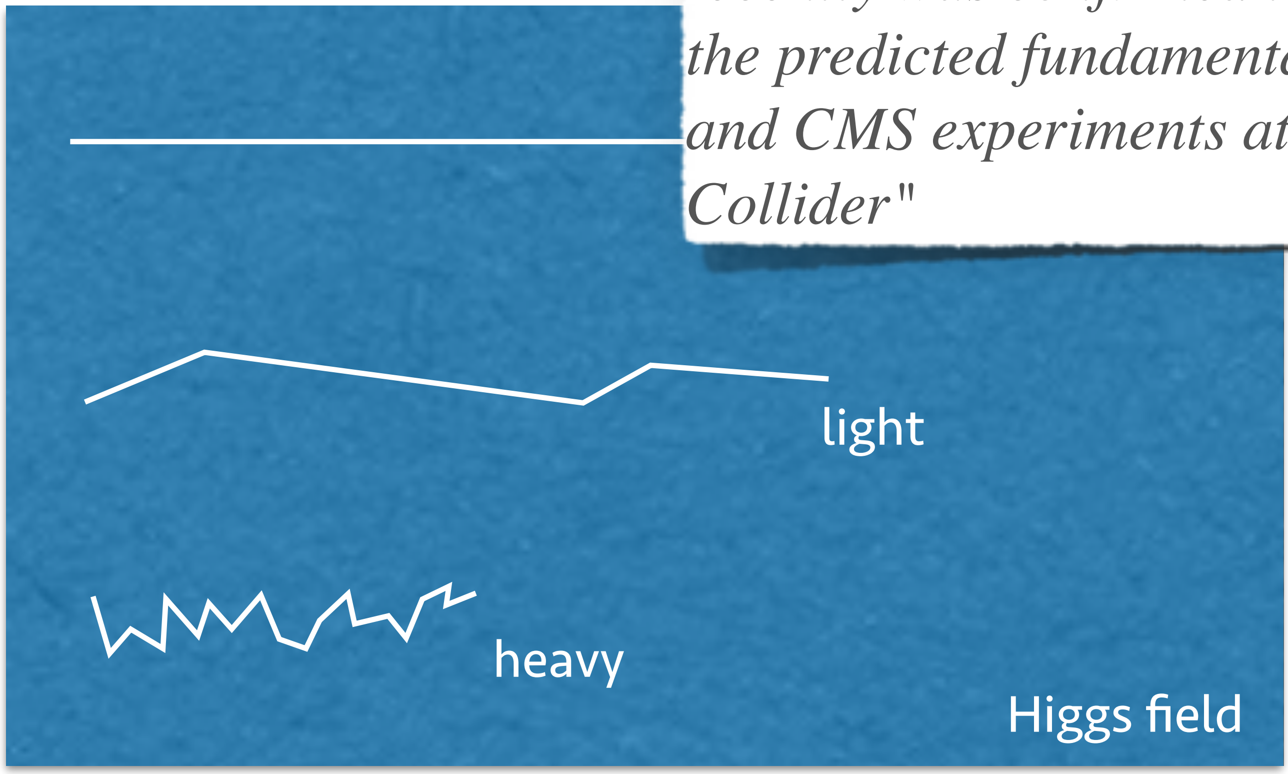


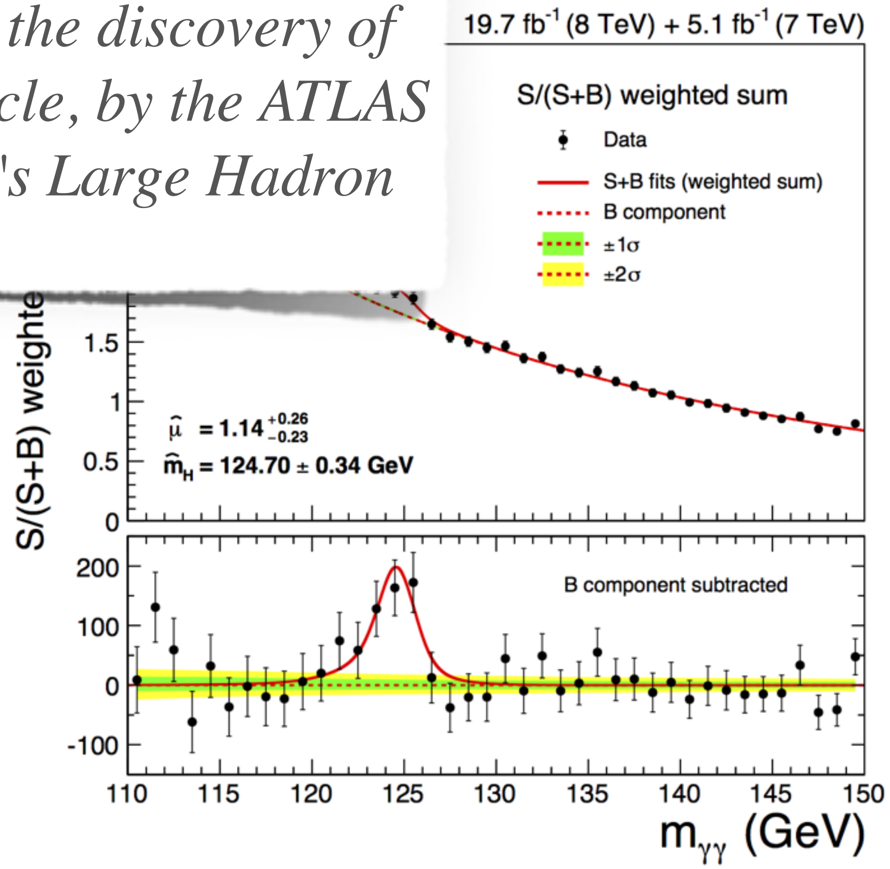


Why are elementary particles massive?

The Higgs mechanism explains why fundamental particles are massive.

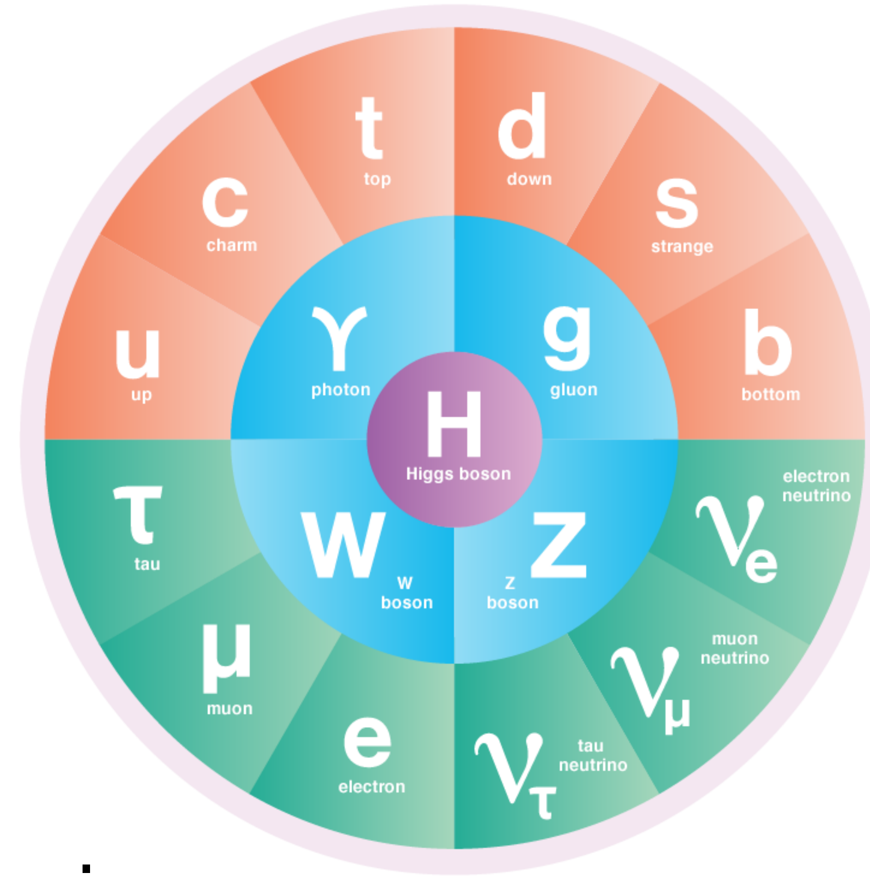
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of* ***a mechanism that contributes to our understanding of the origin of mass of subatomic particles****, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



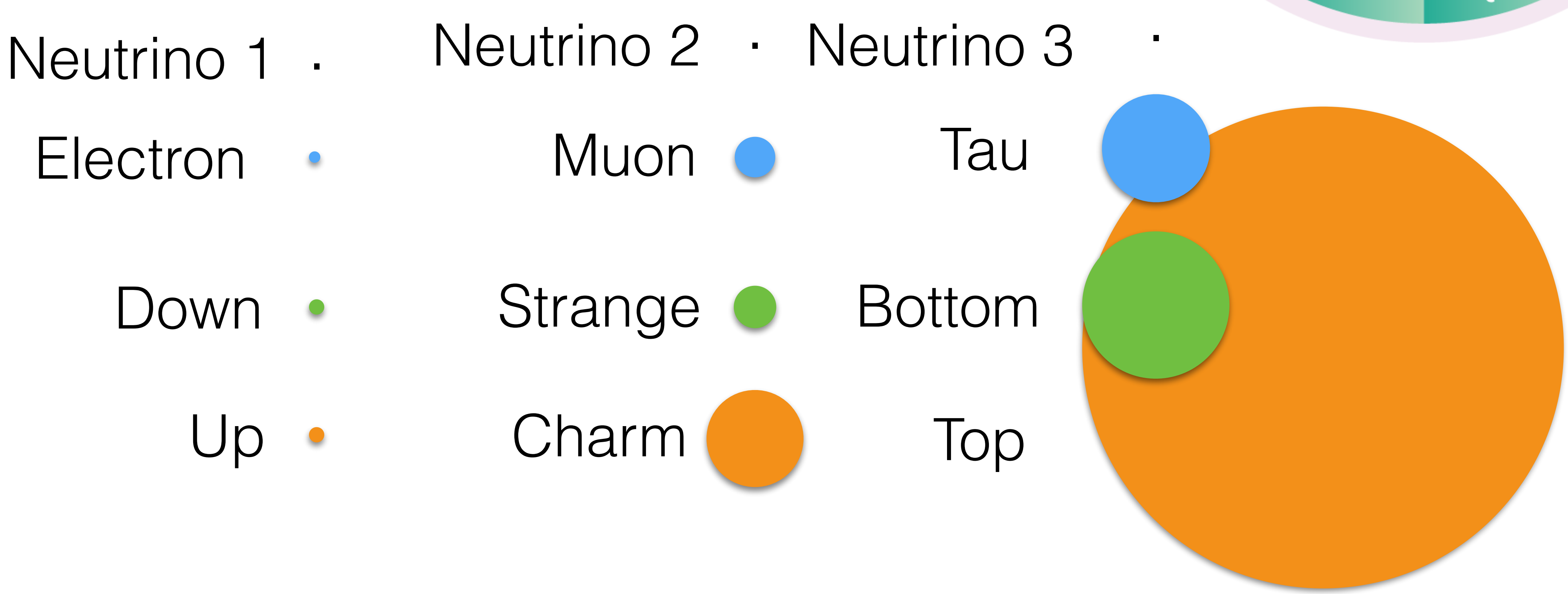


Why are fermion masses so different?

Fermion mass hierarchy:
At least 6 orders of magnitude

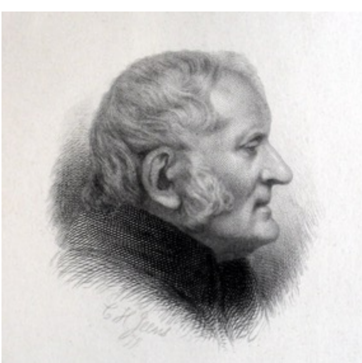


top mass = 170.000 x up mass



Take a lesson from history

Hierarchies → Fundamental Structure



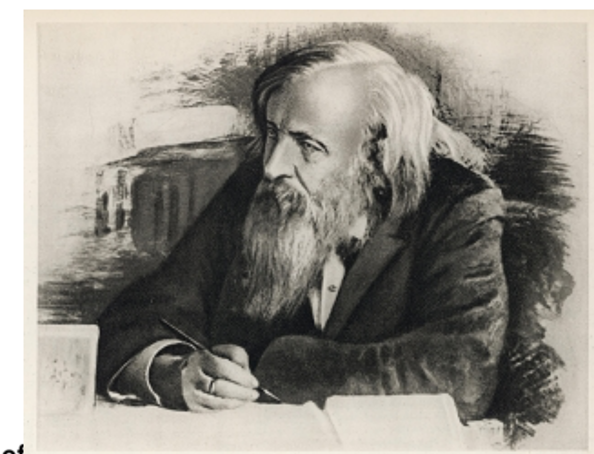
John Dalton, 1808

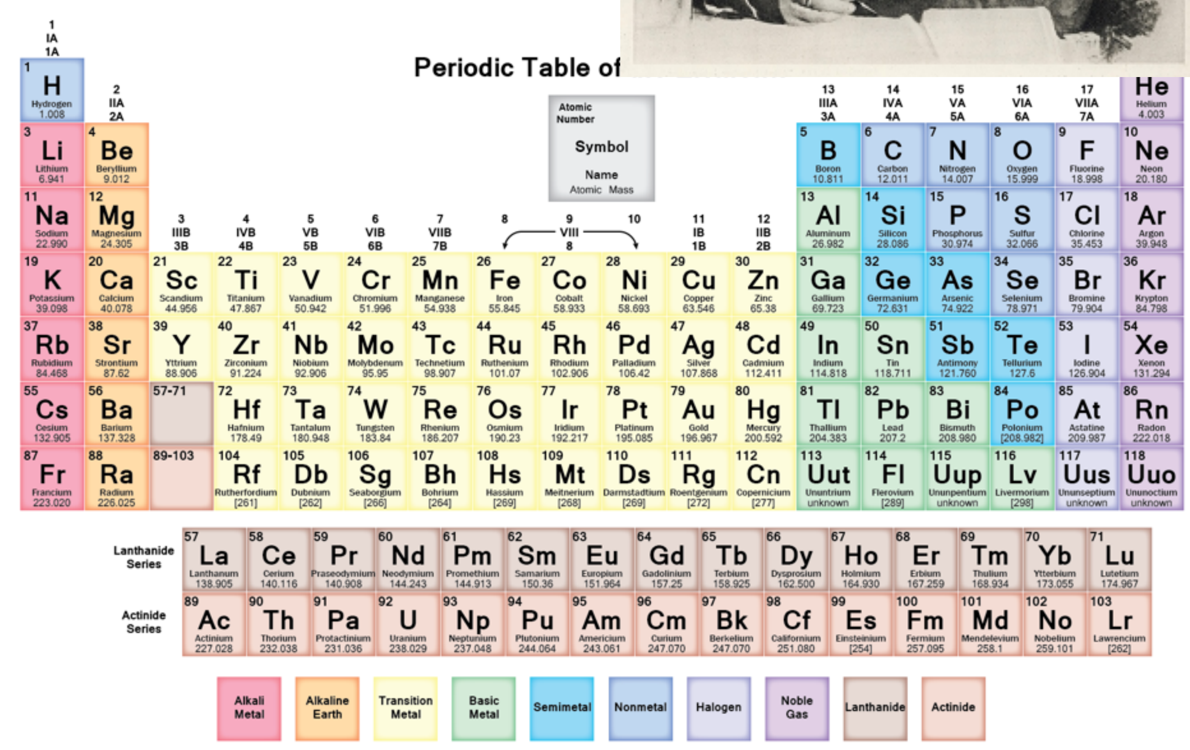
Take a lesson from history

Hierarchies → Fundamental Structure

John Dalton, 1808

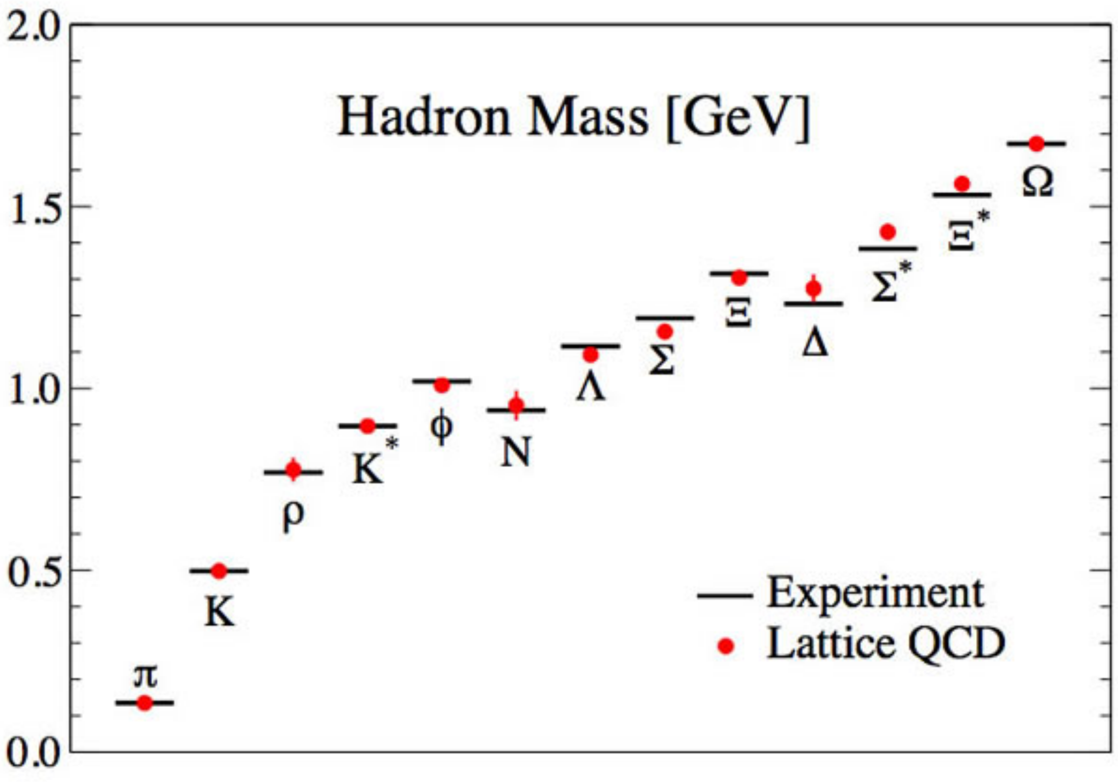
Dmitri Mendeleev, 1869





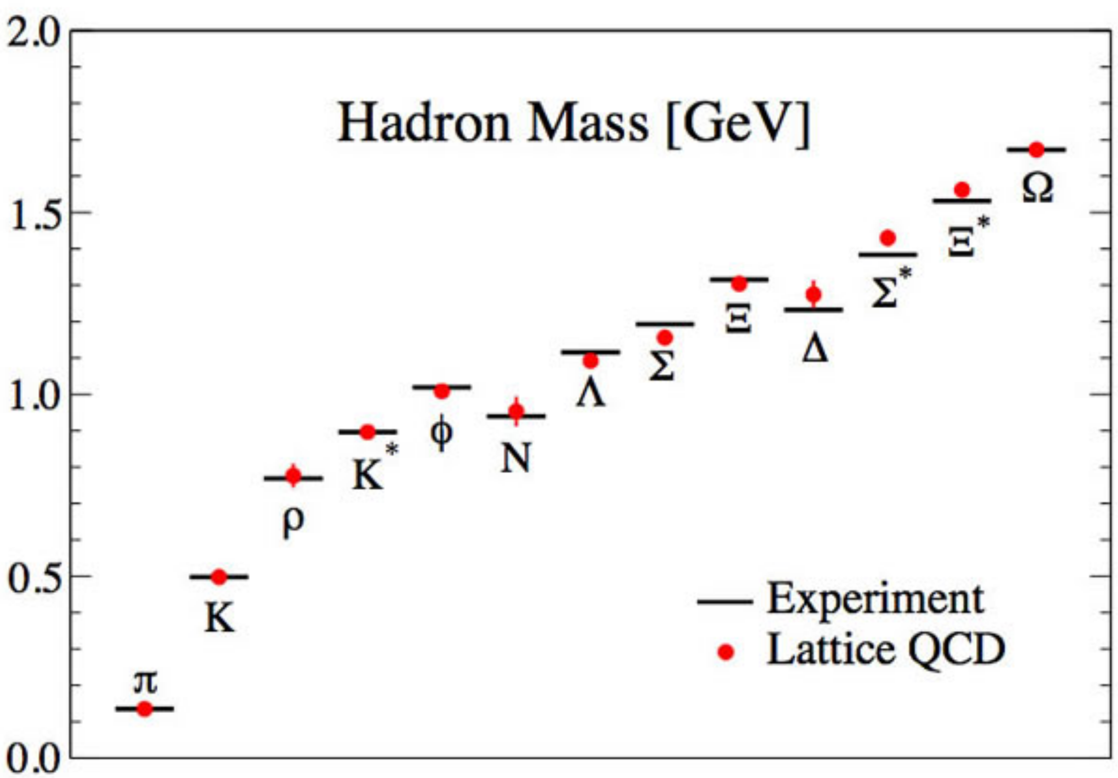
Take a lesson from history

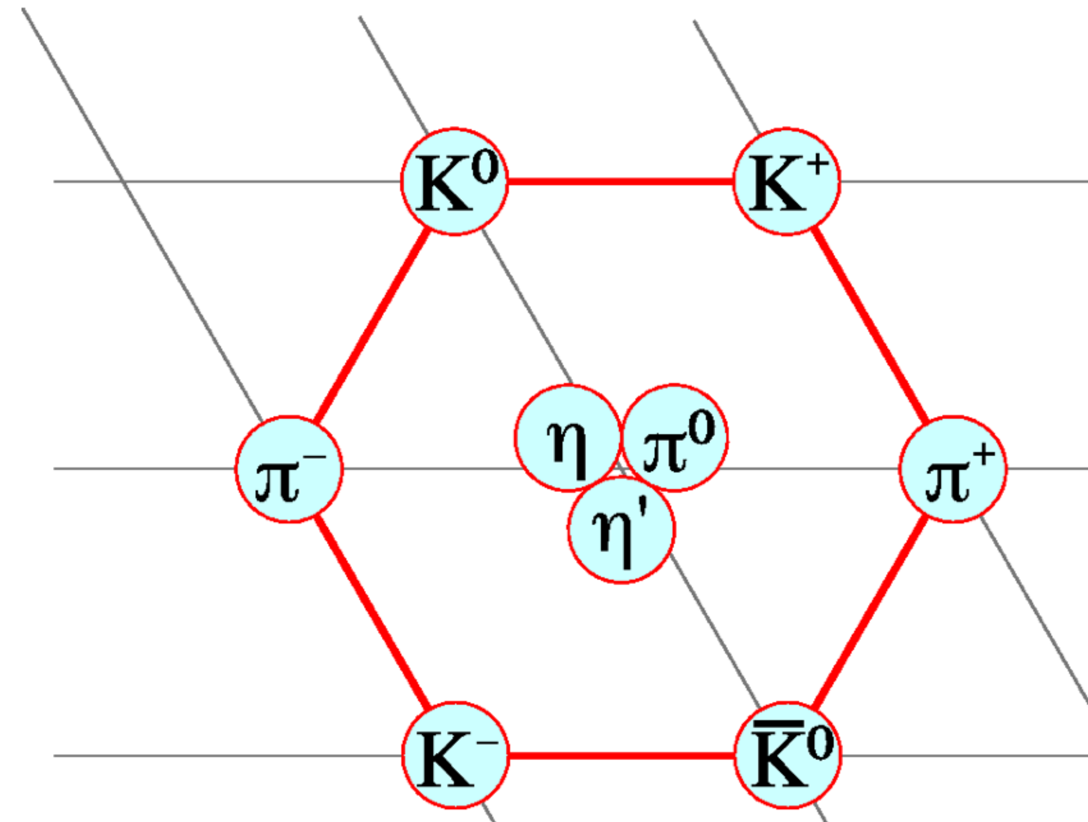
Hierarchies ⟶ Fundamental Structure



Take a lesson from history

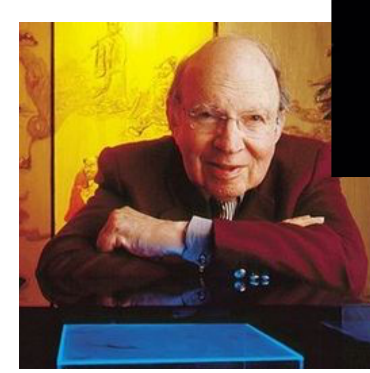
Hierarchies → Fundamental Structure





The eightfold way

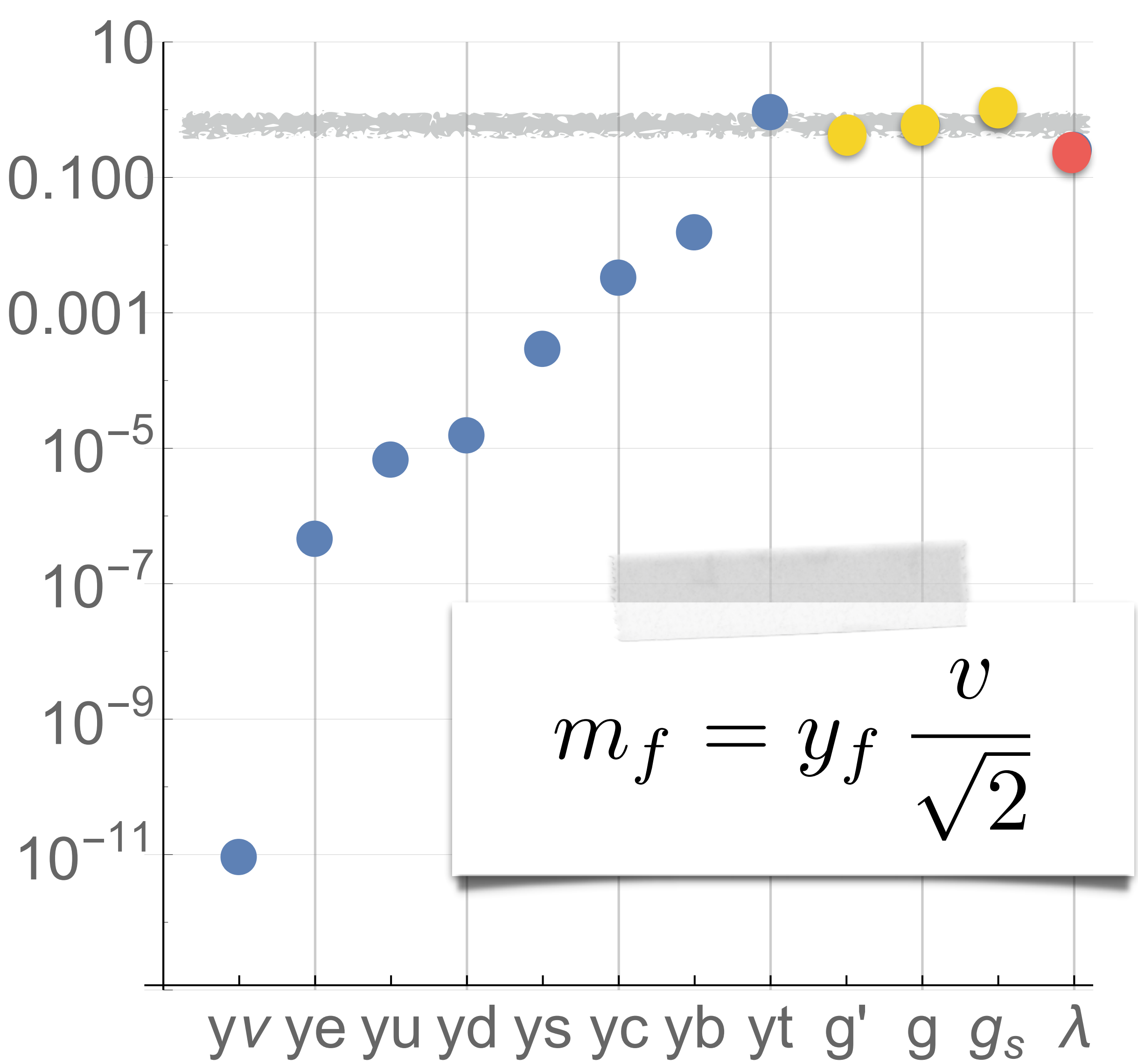
Fritzsch, Gell-Mann



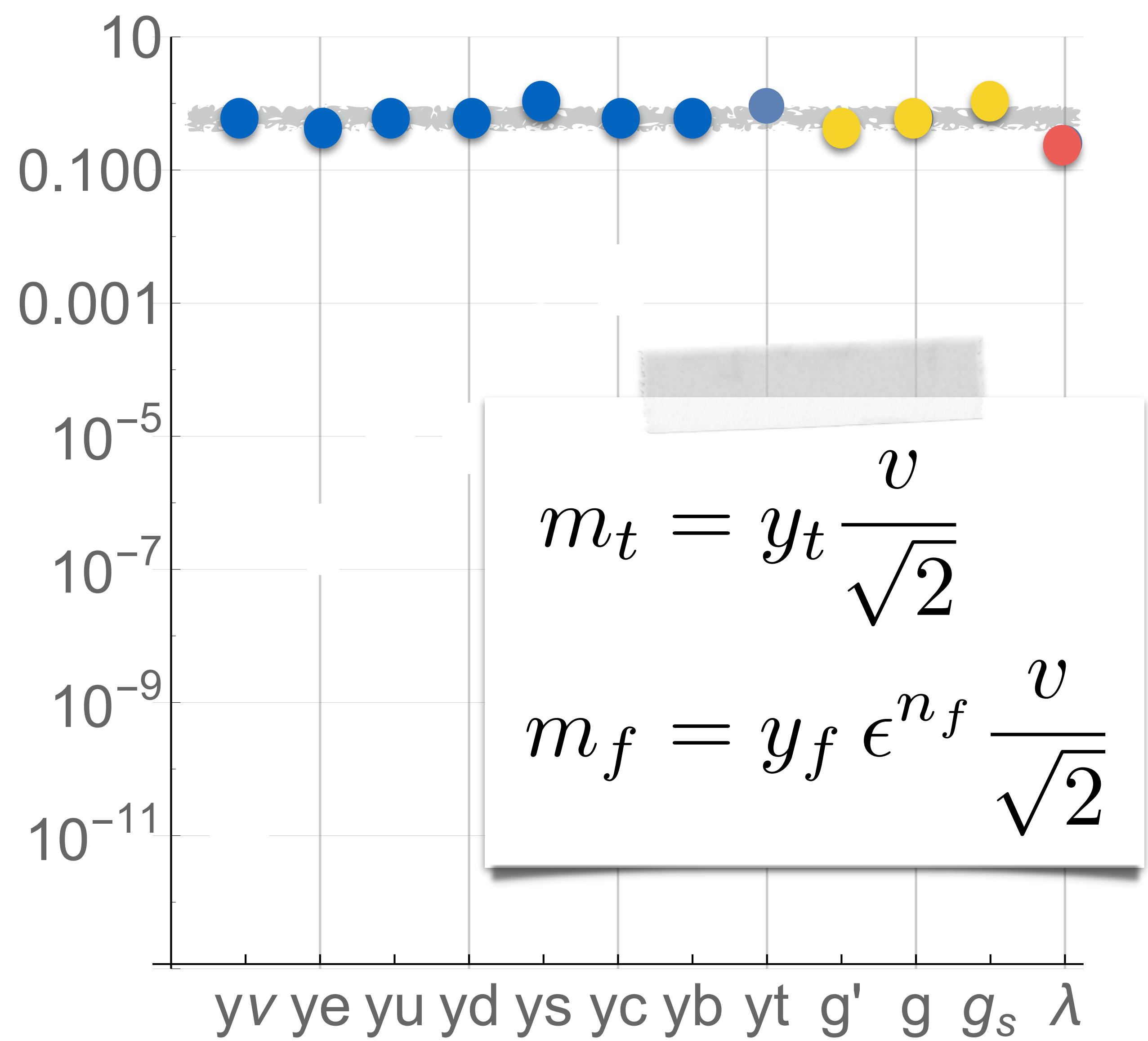
Ne'eman

Why are elementary particles so different?

$$\mathcal{L} = \mu_h^2 H^\dagger H + \lambda (H^\dagger H)^2 + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Yukawa}} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$$



$$m_f = y_f \frac{v}{\sqrt{2}}$$



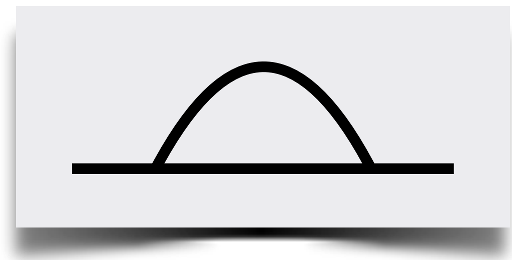
$$m_t = y_t \frac{v}{\sqrt{2}}$$

$$m_f = y_f \, \epsilon^{n_f} \frac{v}{\sqrt{2}}$$

Theories of Flavor

1. Loop Induced

[Georgi, Glashow ‘72]

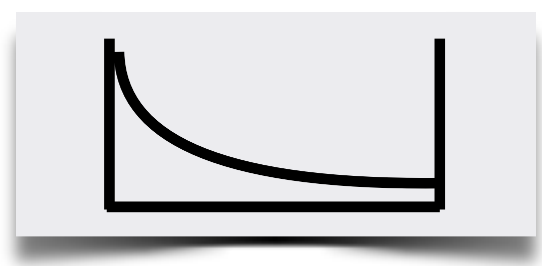


$$\epsilon \approx \frac{1}{16\pi^2} \ln\left(\frac{m_s^2}{\Lambda^2}\right)$$

2. Extra Dimensions

[Grossmann, Neubert 9912408]

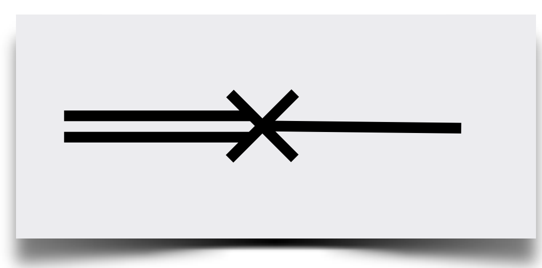
[Gherghetta, Pomarol 0003129]



$$\epsilon^n \approx e^{(c_L - c_R)\ln\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}}$$

3. Partial Compositeness

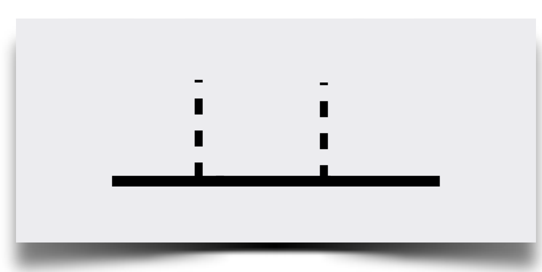
[Kaplan ‘91]



$$\epsilon^\gamma = \left(\frac{m}{M_B}\right)^\gamma$$

4. Froggatt Nielsen

[Froggatt, Nielsen ‘79]



$$\epsilon \approx \frac{f}{\Lambda}$$

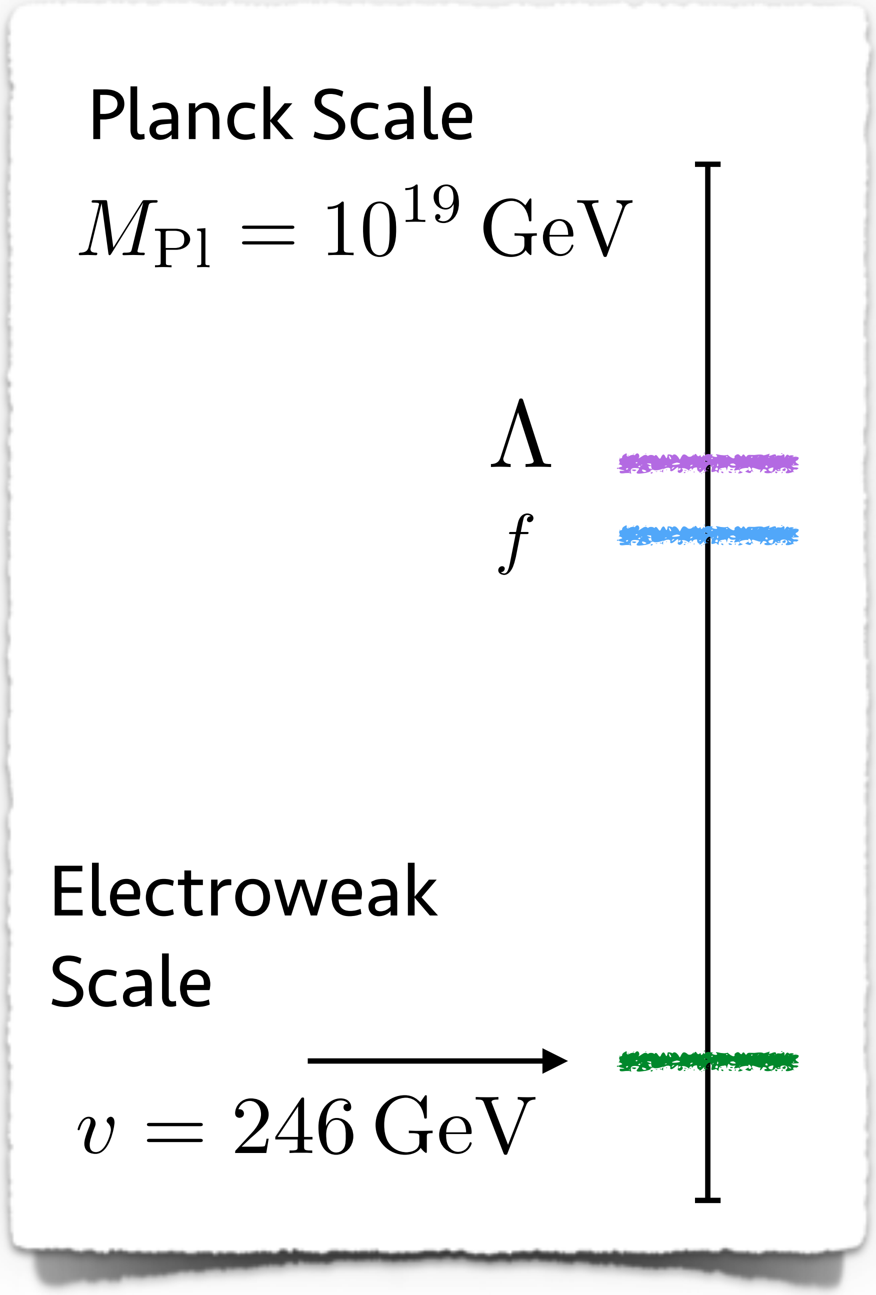
Can we discover this mechanism?

Illustration: $$y_t \bar{t} H t + y_f \left(\frac{S}{\Lambda} \right)^1 \bar{b} H b + \ldots$$

$$\langle S \rangle = f \quad \Rightarrow \quad y_b = \epsilon \, y_f$$

and $$\epsilon = \frac{f}{\Lambda} = 0.23$$

In general, the flavor scale can be arbitrarily high!



Why should the flavor scale be low?

- Why not?
- A link to Baryogenesis?
- A link to Dark Matter?
- It could be related to the electroweak scale

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Flavon Potential

Scalar potential leads to a flavor breaking minimum

$$-\mathcal{L}_{\text{potential}} = -\mu_S^2\, S^\dagger S + \lambda_S\,(S^\dagger S)^2 + b\,(S^2 + S^{\dagger 2}) + \lambda_{HS}(S^\dagger S)(H^\dagger H) + V(H)\ .$$

Breaks the flavor symmetry

Two degrees of freedom

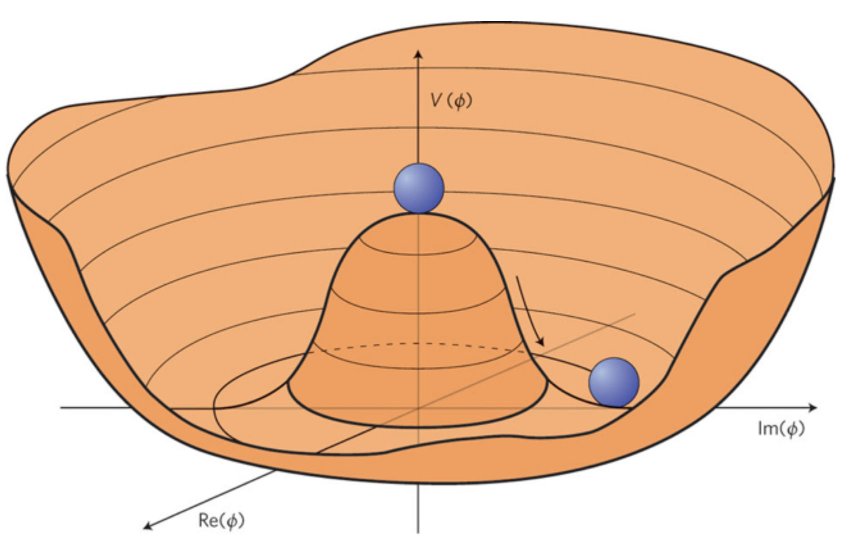
$$S(x) = \frac{f + s(x) + i\,a(x)}{\sqrt{2}}$$

With masses

$$m_s = \sqrt{2\lambda_S} f$$

$$m_a = 2\sqrt{b}$$

$$m_a < m_s \approx f < \Lambda$$



Yukawa Couplings

Yukawa couplings for quarks and leptons

$$\mathcal{L}_{\text{Yukawa}} = y^d_{ij}\left(\frac{S}{\Lambda}\right)^{n^d_{ij}} \overline{Q}_i\, H\, d_{R_j} + y^u_{ij}\left(\frac{S}{\Lambda}\right)^{n^u_{ij}} \overline{Q}_i\, \widetilde{H}\, u_{R_j}$$
$$+\, y^\ell_{ij}\left(\frac{S}{\Lambda}\right)^{n^\ell_{ij}} \overline{L}_i\, H\, \ell_{R_j} + y^\nu_{ij}\left(\frac{S}{\Lambda}\right)^{n^\nu_{ij}} \overline{L}_i\, \widetilde{H}\, \nu_{R_j} + \text{h.c.}$$

Exponents are fixed by U(1) flavor charges.

$$n^d_{ij} = a_{Q_i} - a_{d_j} - a_H$$
$$n^u_{ij} = a_{Q_i} - a_{u_j} + a_H$$

Masses and Mixings

$$\epsilon = \frac{f}{\Lambda} \equiv \frac{\langle S \rangle}{\Lambda} \equiv (V_{\mathrm{CKM}})_{12} \approx 0.23$$

Quark and Lepton Masses

$$m_t \approx \frac{v}{\sqrt{2}} \qquad \frac{m_b}{m_t} \approx \epsilon^3 \qquad \frac{m_c}{m_t} \approx \epsilon^4 \qquad \frac{m_s}{m_t} \approx \epsilon^5 \qquad \frac{m_d}{m_t} \approx \epsilon^7 \qquad \frac{m_u}{m_t} \approx \epsilon^8$$

$$\frac{m_\tau}{m_t} \approx \epsilon^3 \qquad \frac{m_\mu}{m_t} \approx \epsilon^5 \qquad \frac{m_e}{m_t} \approx \epsilon^8 \qquad \frac{m_{\nu_1}}{m_t} \approx \epsilon^{24} \qquad \frac{m_{\nu_2}}{m_t} \approx \epsilon^{21} \qquad \frac{m_{\nu_3}}{m_t} \approx \epsilon^{20}$$

and Mixings

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad U_{\mathrm{PMNS}} \approx \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

Masses and Mixings

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and Mixings

After fixing the ratio of scales there are 2 free parameters:

$$m_a \quad \text{and} \quad f$$

Flavon couplings

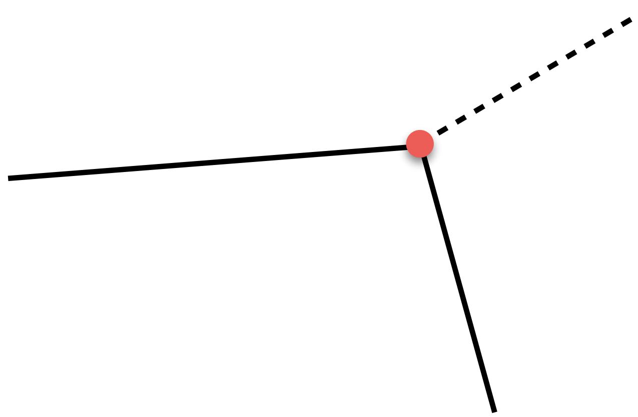
Flavon Couplings are dictated by this structure

$$S(x) = \frac{f + s(x) + i\, a(x)}{\sqrt{2}}$$

$$g^u_{aij} = \frac{1}{f} \begin{pmatrix} 8m_u & \epsilon m_c & \epsilon^3 m_t \\ \epsilon^3 m_c & 4m_c & \epsilon^2 m_t \\ \epsilon^5 m_t & \epsilon^2 m_t & 0 \end{pmatrix} \qquad g^d_{aij} = \frac{1}{f} \begin{pmatrix} 7m_d & \epsilon m_s & \epsilon^3 m_b \\ \epsilon m_s & 5m_s & \epsilon^2 m_b \\ \epsilon m_b & \epsilon^2 m_b & 3m_b \end{pmatrix}$$

$$g^\ell_{aij} = \frac{1}{f} \begin{pmatrix} 9m_e & \epsilon m_\mu & \epsilon m_\tau \\ \epsilon^3 m_\mu^3 & 5m_\mu & \epsilon^2 m_\tau \\ \epsilon^5 m_\tau & \epsilon^2 m_\tau & 3m_\tau \end{pmatrix}$$

small....potentially very small!



$$\sim \frac{m_i}{f}\epsilon$$

Flavon couplings

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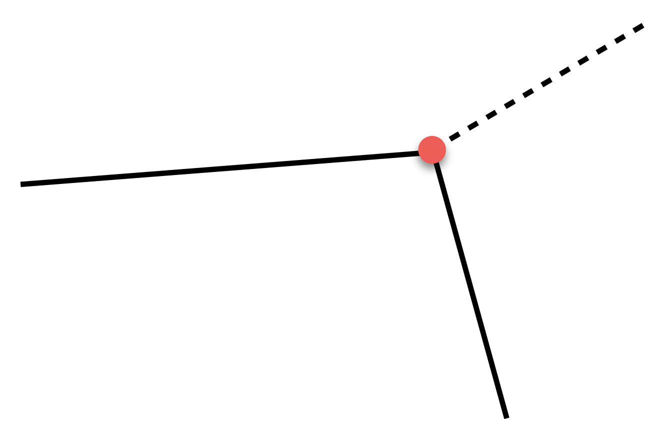
$$g_{act} = \frac{1}{3\epsilon} g_{abb}$$



$$\sim \frac{m_i}{f}\epsilon$$

Flavon couplings

Effects from flavon interactions lead to

- Quark Flavor Constraints
- Lepton Flavor Constraints
- Future Collider Constraints

Flavon couplings

Generate fundamental Yukawa couplings at the high scale and reproduce fermion masses and mixings in agreement with the SM.

$$m_{u_i} = (0.00138, 0.563, 150.1)\ \text{GeV}$$
$$m_{d_i} = (0.00342, 0.054, 2.29)\ \text{GeV}$$

$$|V_{\text{ckm}}| = \begin{pmatrix} 0.974 & 0.226 & 0.0035 \\ 0.226 & 0.974 & 0.0388 \\ 0.011 & 0.037 & 0.999 \end{pmatrix}$$

Demand $|y_{ij}| \in [0.5, 1.5]$ with arbitrary phase.

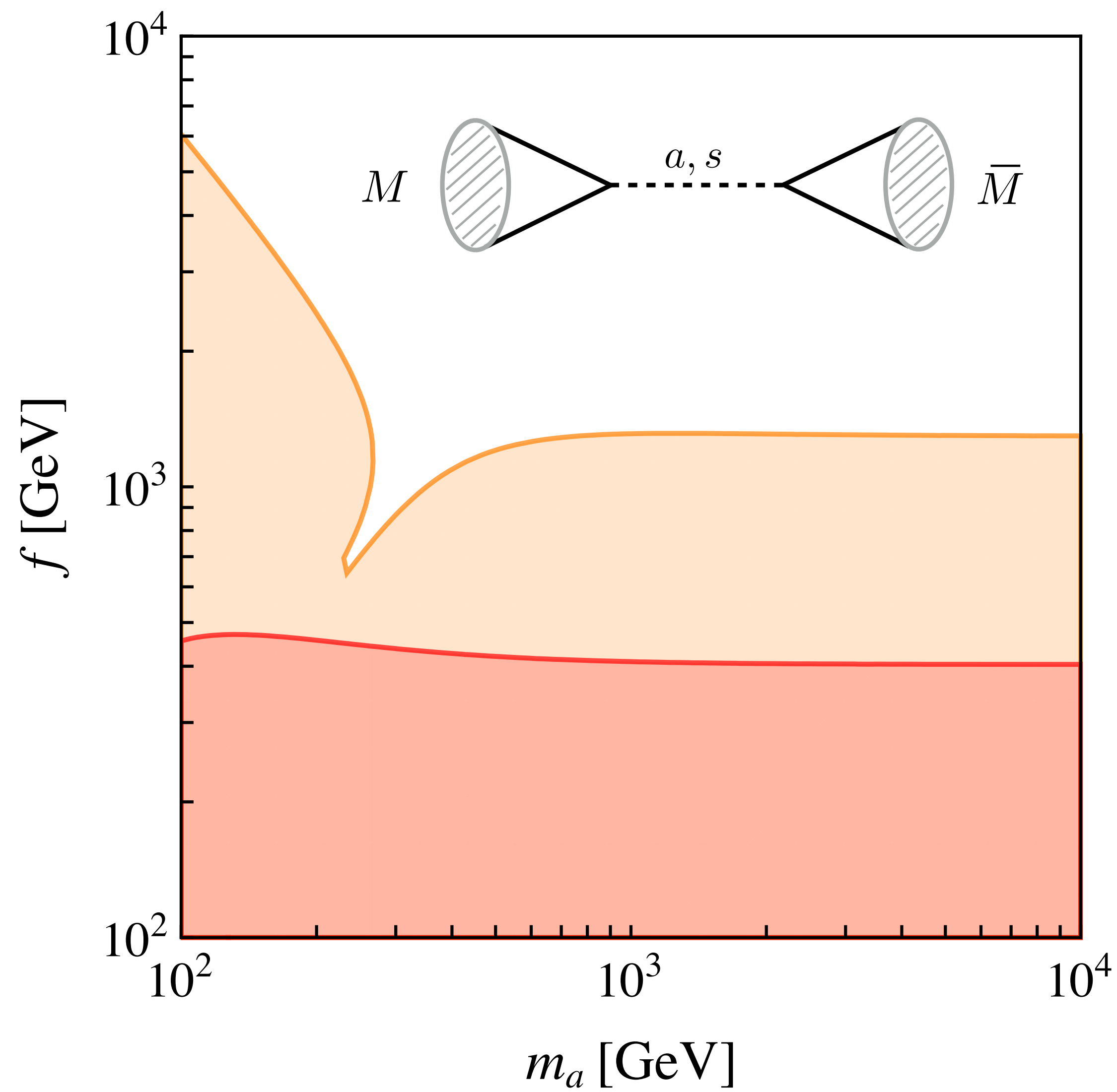
$$Y_u = \begin{pmatrix} 0.34 + 0.82i & -0.23 + 0.69i & 0.41 - 0.43i \\ -0.84 + 0.26i & -0.64 + 0.32i & 1.35 - 0.24i \\ 0.98 - 0.90i & -0.84 - 1.20i & 0.75 + 0.65i \end{pmatrix}$$

$$Y_d = \begin{pmatrix} 0.53 + 0.72i & 0.50 - 0.34i & 0.65 - 0.10i \\ 1.12 - 0.14i & 0.93 - 0.54i & -0.31 - 0.65i \\ -0.16 + 0.6i & -0.73 + 0.34i & 0.84 + 0.61i \end{pmatrix}$$

Quark Flavor constraints

$$\epsilon_K\,,\Delta m_K$$

$$\mathcal{H}_{\rm NP}^{\Delta F=2} = C_1^{ij}\,(\bar q_L^i\,\gamma_\mu\,q_L^j)^2 + \widetilde{C}_1^{ij}\,(\bar q_R^i\,\gamma_\mu\,q_R^j)^2 + C_2^{ij}\,(\bar q_R^i\,q_L^j)^2 + \widetilde{C}_2^{ij}\,(\bar q_L^i\,q_R^j)^2 + C_4^{ij}\,(\bar q_R^i\,q_L^j)\,(\bar q_L^i\,q_R^j) + C_5^{ij}\,(\bar q_L^i\,\gamma_\mu\,q_L^j)\,(\bar q_R^i\,\gamma^\mu q_R^j) + {\rm h.c.}$$



$$C_2^{sd} = -(g_{ds}^*)^2\left(\frac{1}{m_s^2} - \frac{1}{m_a^2}\right)\,,$$

$$\tilde C_2^{sd} = -g_{sd}^2\left(\frac{1}{m_s^2} - \frac{1}{m_a^2}\right)\,,$$

$$C_4^{sd} = -\frac{g_{sd}g_{ds}}{2}\left(\frac{1}{m_s^2} + \frac{1}{m_a^2}\right)\,.$$

Run down and match

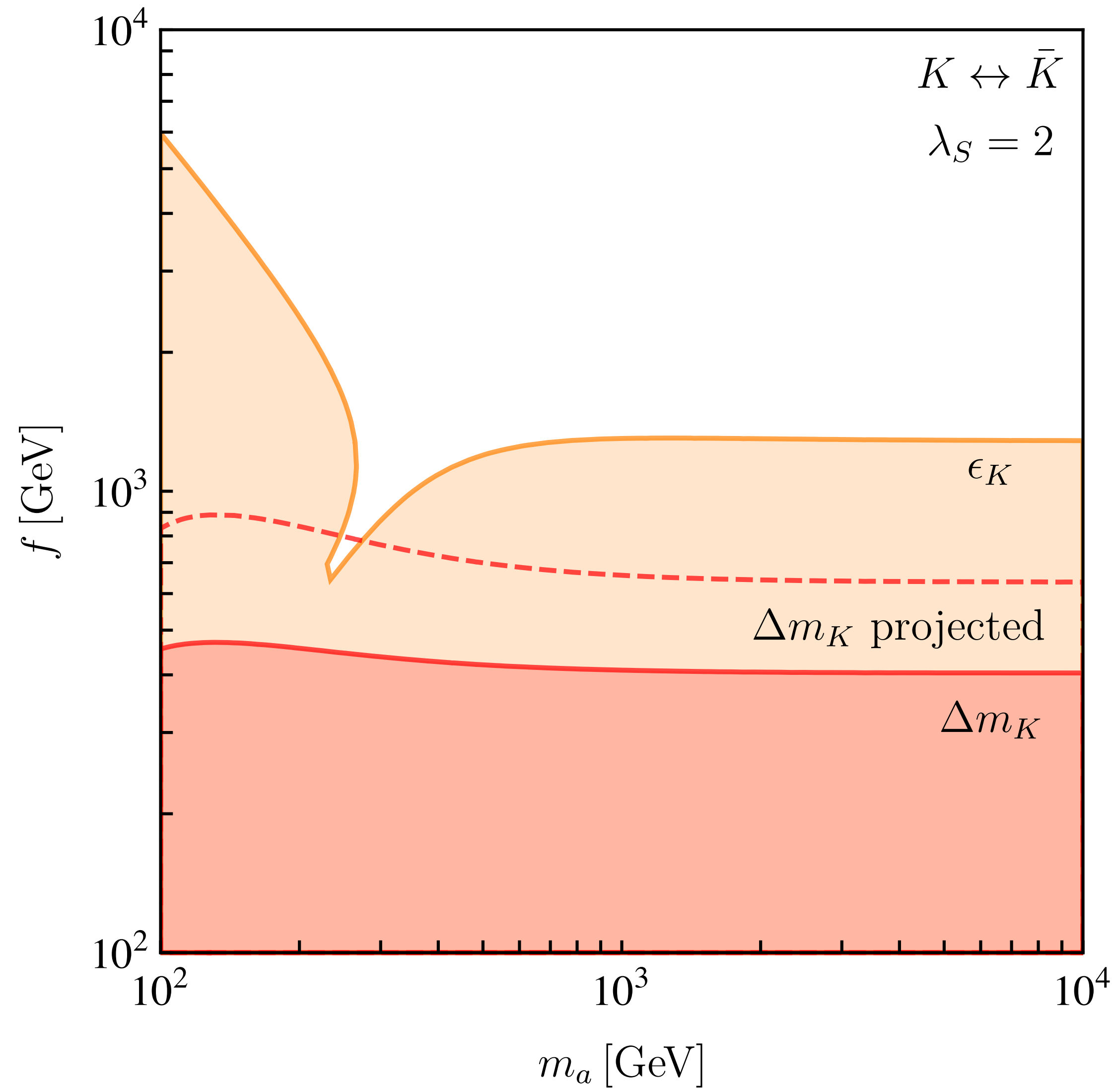
$$C_{\epsilon_K} = \frac{{\rm Im}\langle K^0|\mathcal{H}^{\Delta F=2}|\bar K^0\rangle}{{\rm Im}\langle K^0|\mathcal{H}_{\rm SM}^{\Delta F=2}|\bar K^0\rangle}$$

UTFIT

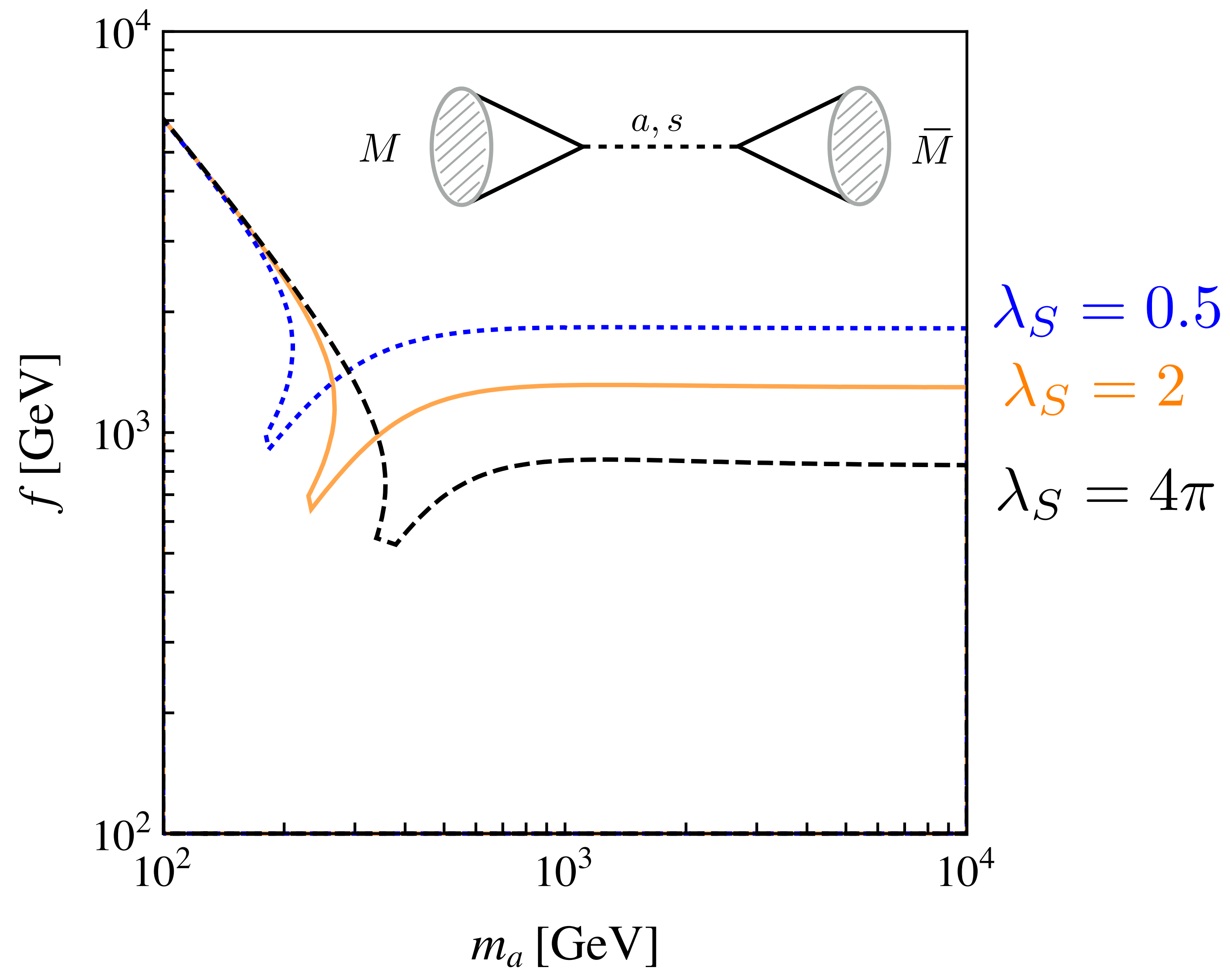
$$C_{\epsilon_K} = 1.05^{+0.36}_{-0.28} \quad @\,95\%\ CL\,, \qquad C_{\Delta_{m_K}} = 0.93^{+1.14}_{-0.42} \quad @\,95\%\ \rm CL$$

Quark Flavor constraints

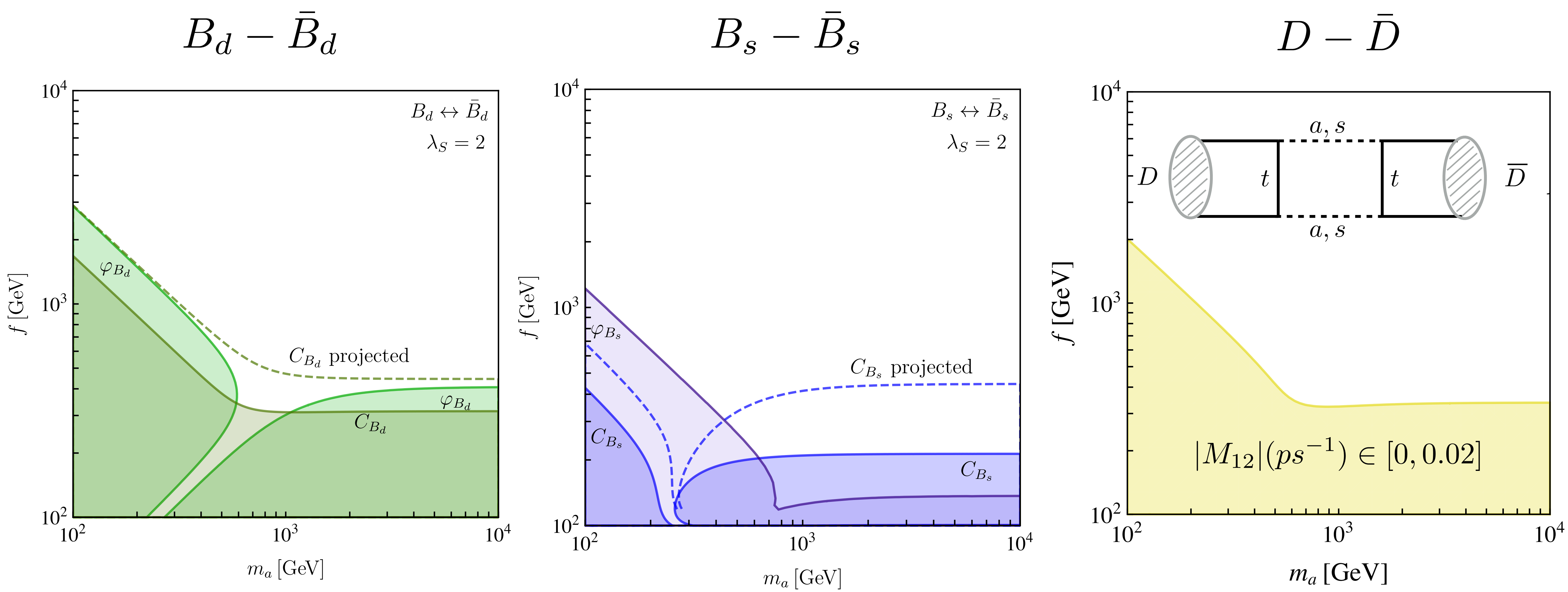
$\epsilon_K, \Delta m_K$



Varying the scalar quartic



Quark Flavor constraints



$$C_{B_q} e^{2i\varphi_{B_q}} = \frac{\langle B_q|\mathcal{H}^{\Delta F=2}|\bar{B}_q\rangle}{\langle B_q|\mathcal{H}^{\Delta F=2}_{\rm SM}|\bar{B}_q\rangle}$$

$$C_{B_d} = 1.07^{+0.36}_{-0.31} \quad @\,95\%\text{CL}\,, \qquad \varphi_{B_d} = -2.0^{+6.4}_{-6.0} \quad @\,95\%\text{CL}\,,$$

$$C_{B_s} = 1.052^{+0.178}_{-0.152} \quad @\,95\%\text{CL}\,, \qquad \varphi_{B_s} = 0.72^{+3.98}_{-2.28} \quad @\,95\%\text{CL}\,,$$

Using recent Lattice results

1602.03560 MILC & Fermilab Lattice

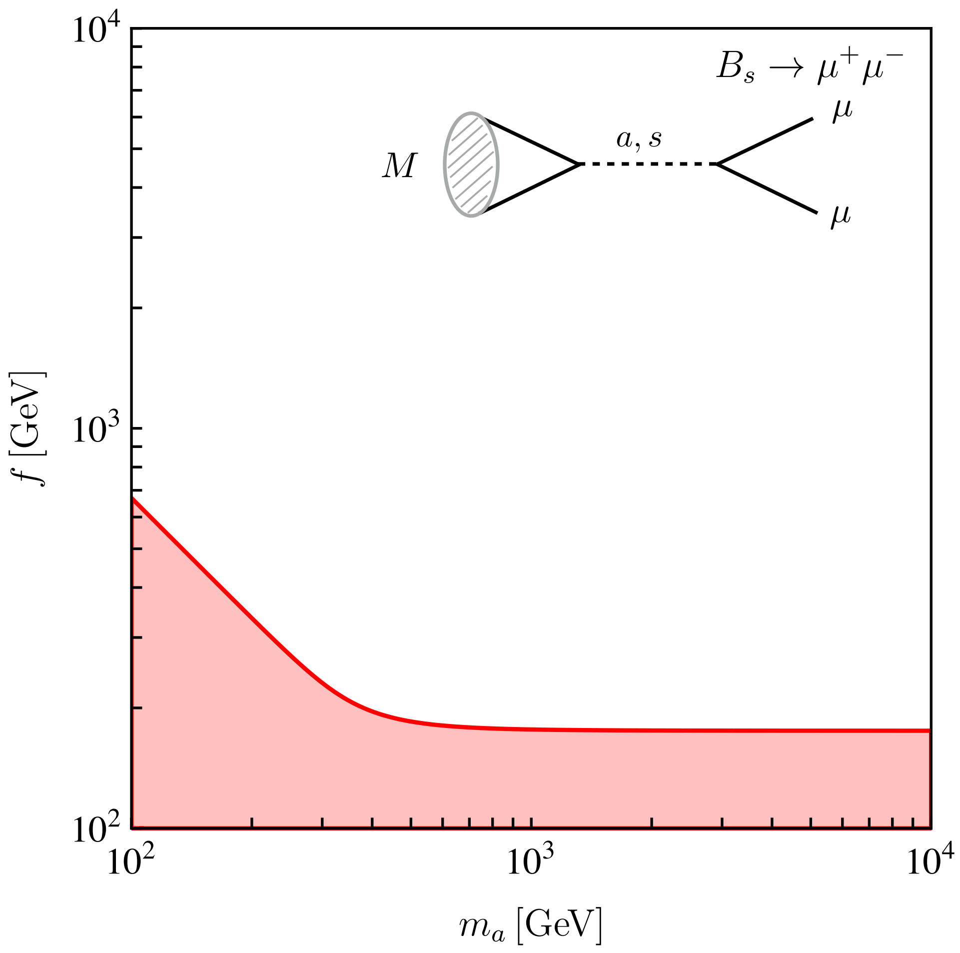
Quark Flavor constraints

$$\mathrm{BR}(M \to \ell\ell) = \frac{G_F^4 M_W^4}{8\pi^5} \beta\left(\frac{m_\ell}{M_M}\right) M_M f_M^2 m_\ell^2 \tau_M \left\{ \left| \frac{M_M^2 (C_P^{ij} - \tilde{C}_P^{ij})}{2m_\ell(m_i + m_j)} - C_A^{\mathrm{SM}} \right|^2 + \left| \frac{M_M^2 (C_S^{ij} - \tilde{C}_S^{ij})}{2m_\ell(m_i + m_j)} \right|^2 \beta^2 \left(\frac{m_\ell}{M_M}\right) \right\}$$

LHCb&CMS

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathrm{BR}(B_d \to \mu^+\mu^-) = 3.6 \pm 1.6 \times 10^{-10}$$



$$C_S^{ij} = \frac{\pi^2}{2G_F^2 M_W^2} \frac{2g_{\ell\ell} g_{ji}}{m_s^2}, \qquad \tilde{C}_S^{ij} = \frac{\pi^2}{2G_F^2 M_W^2} \frac{2g_{\ell\ell} g_{ij}}{m_s^2},$$

$$C_P^{ij} = \frac{\pi^2}{2G_F^2 M_W^2} \frac{2g_{\ell\ell} g_{ji}}{m_a^2}, \qquad \tilde{C}_P^{ij} = \frac{\pi^2}{2G_F^2 M_W^2} \frac{2g_{\ell\ell} g_{ij}}{m_a^2}.$$

Quark Flavor constraints

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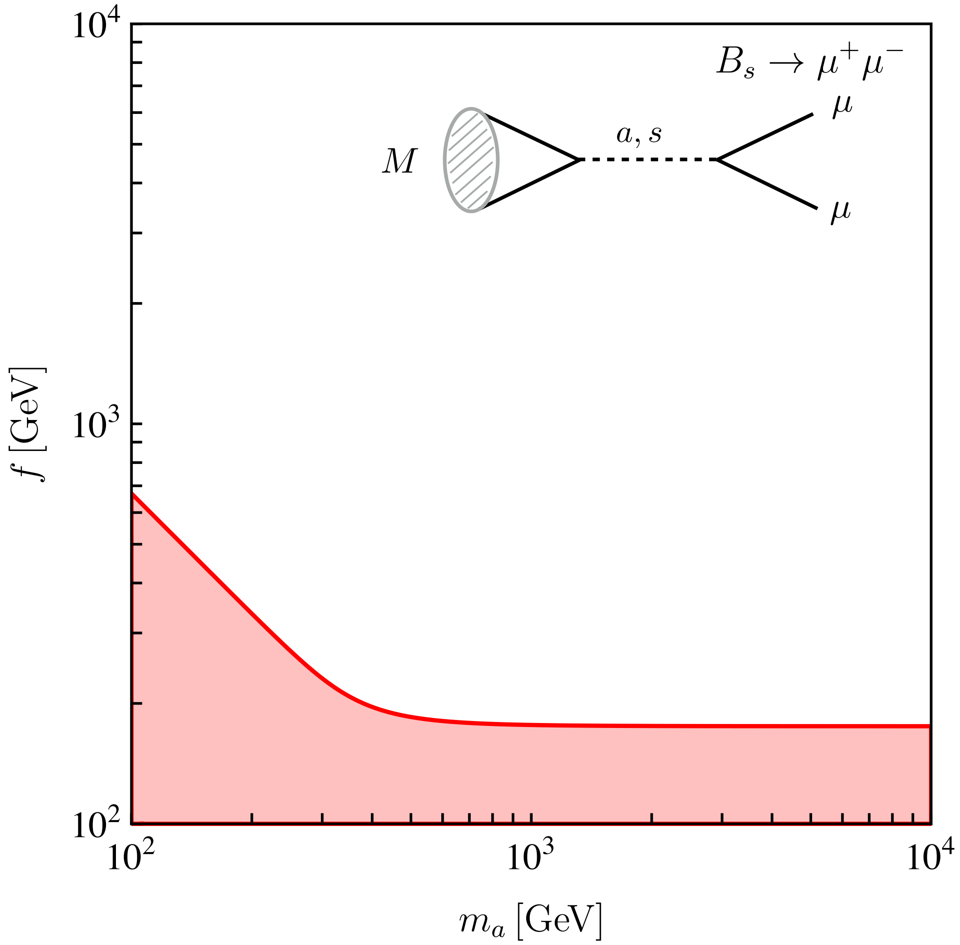
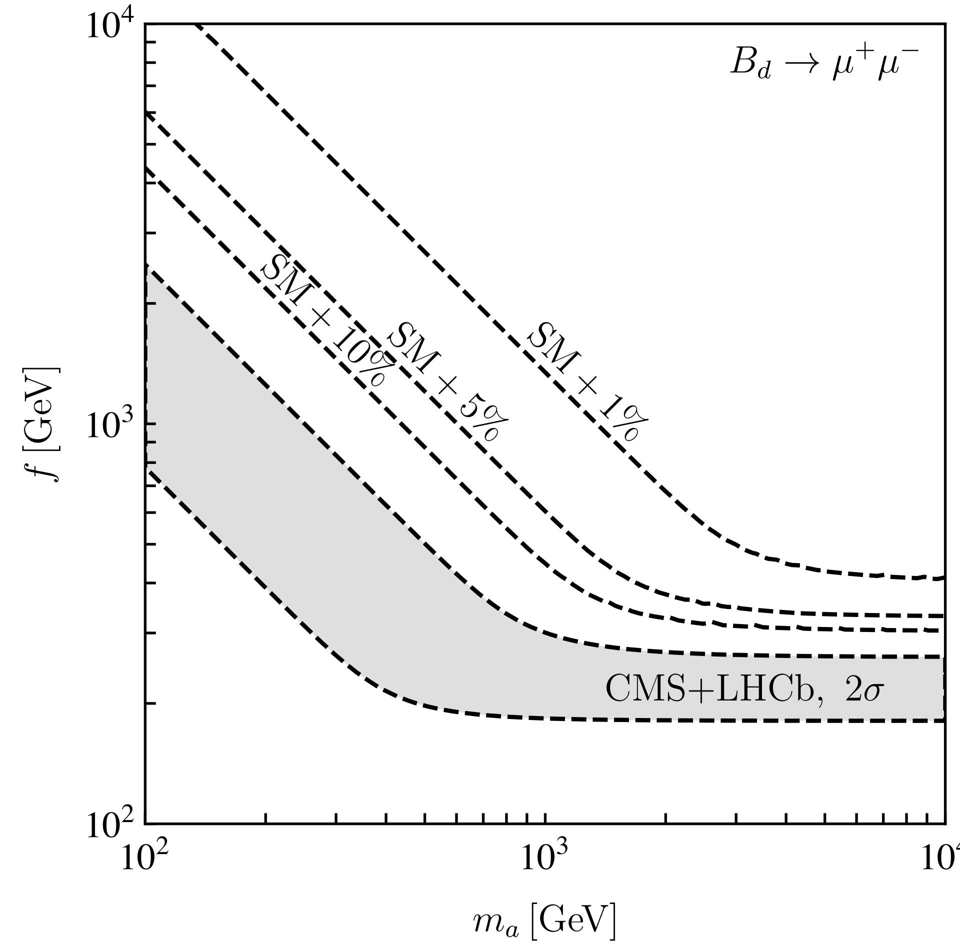


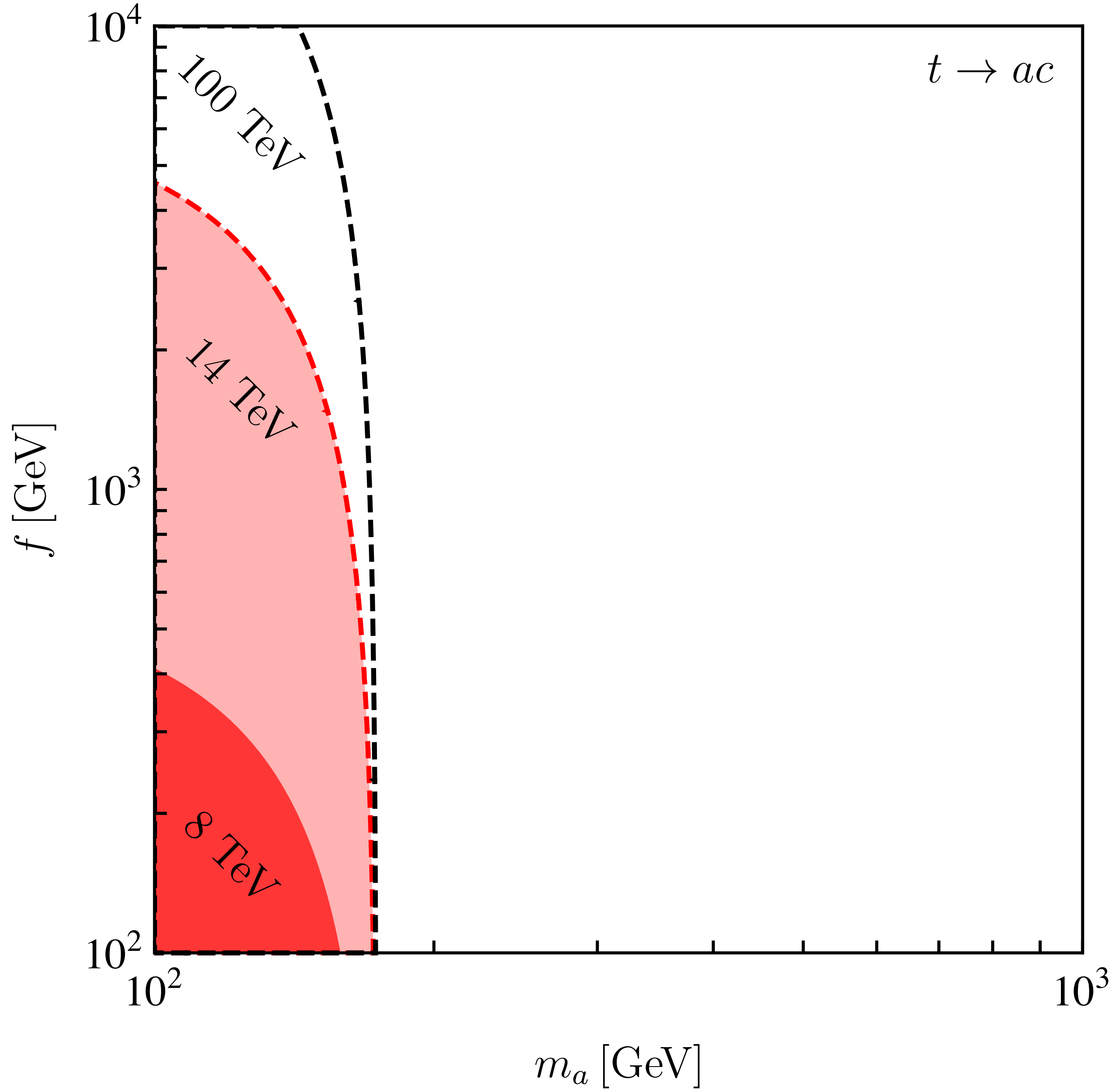


Top decays

LHC 8 $\quad \mathrm{BR}(t \to ac) < 5.6 \times 10^{-3}$

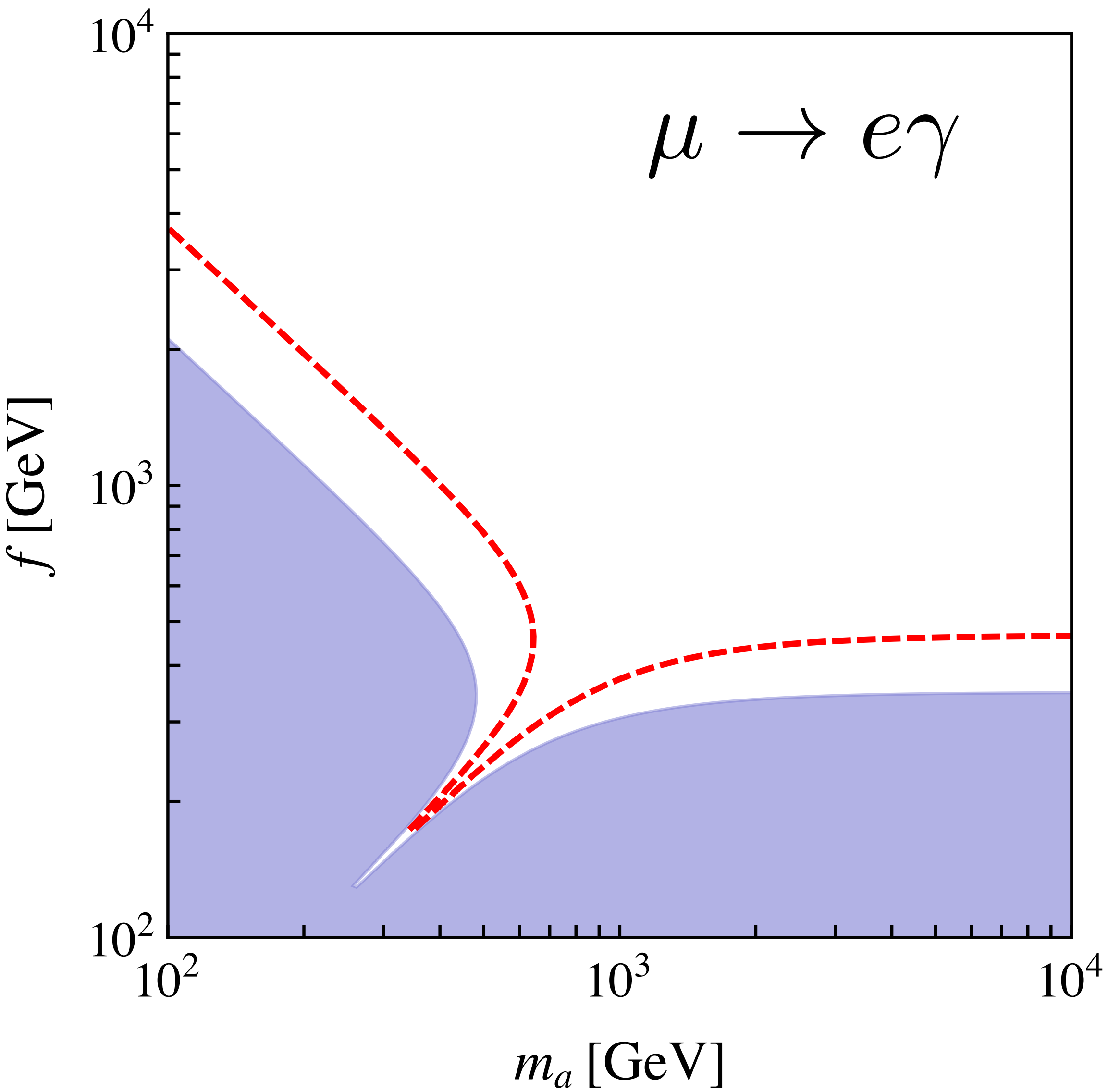
LHC 14 $\quad \mathrm{BR}(t \to ac) < 4.5 \times 10^{-5}$

100TeV $\quad \mathrm{BR}(t \to ac) < 1.5 \times 10^{-6}$



Lepton Flavor constraints

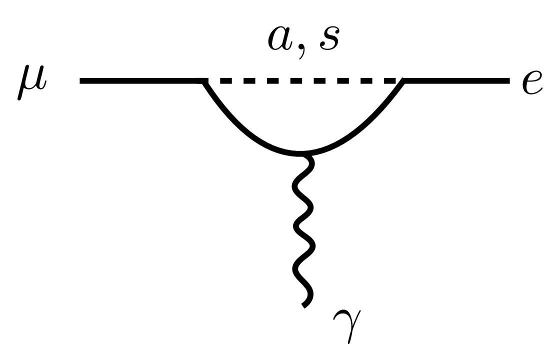
$$\mathcal{L}_{\rm eff} = m_{\ell'}\, C_T^L\, \bar{\ell}\sigma^{\rho\lambda} P_L\, \ell'\, F_{\rho\lambda} + m_{\ell'}\, C_T^R\, \bar{\ell}\sigma^{\rho\lambda} P_R\, \ell'\, F_{\rho\lambda}$$

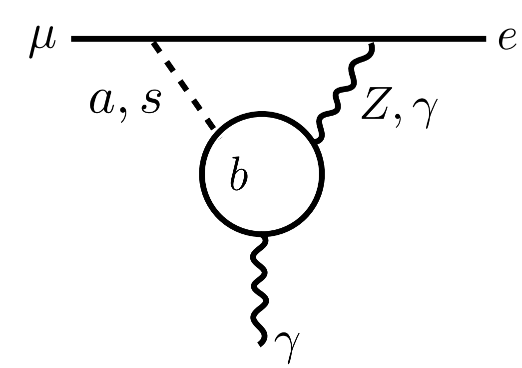


$$C_T^L = \frac{g}{32\pi^2} \sum_{k=e,\mu,\tau} \left[\frac{1}{6} \left(g^*_{\ell k} g_{\ell' k} + \frac{m_\ell}{m_k} g^*_{k\ell} g_{k\ell'} \right) \left(\frac{1}{m_s^2} - \frac{1}{m_a^2} \right) - g_{\ell k} g_{k\ell'} \frac{m_k}{m_{\ell'}} \left\{ \frac{1}{m_s^2} \left(\frac{3}{2} + \log \frac{m_{\ell'}^2}{m_s^2} \right) - \frac{1}{m_a^2} \left(\frac{3}{2} + \log \frac{m_{\ell'}^2}{m_a^2} \right) \right\} \right]$$

MEG I $\quad \mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

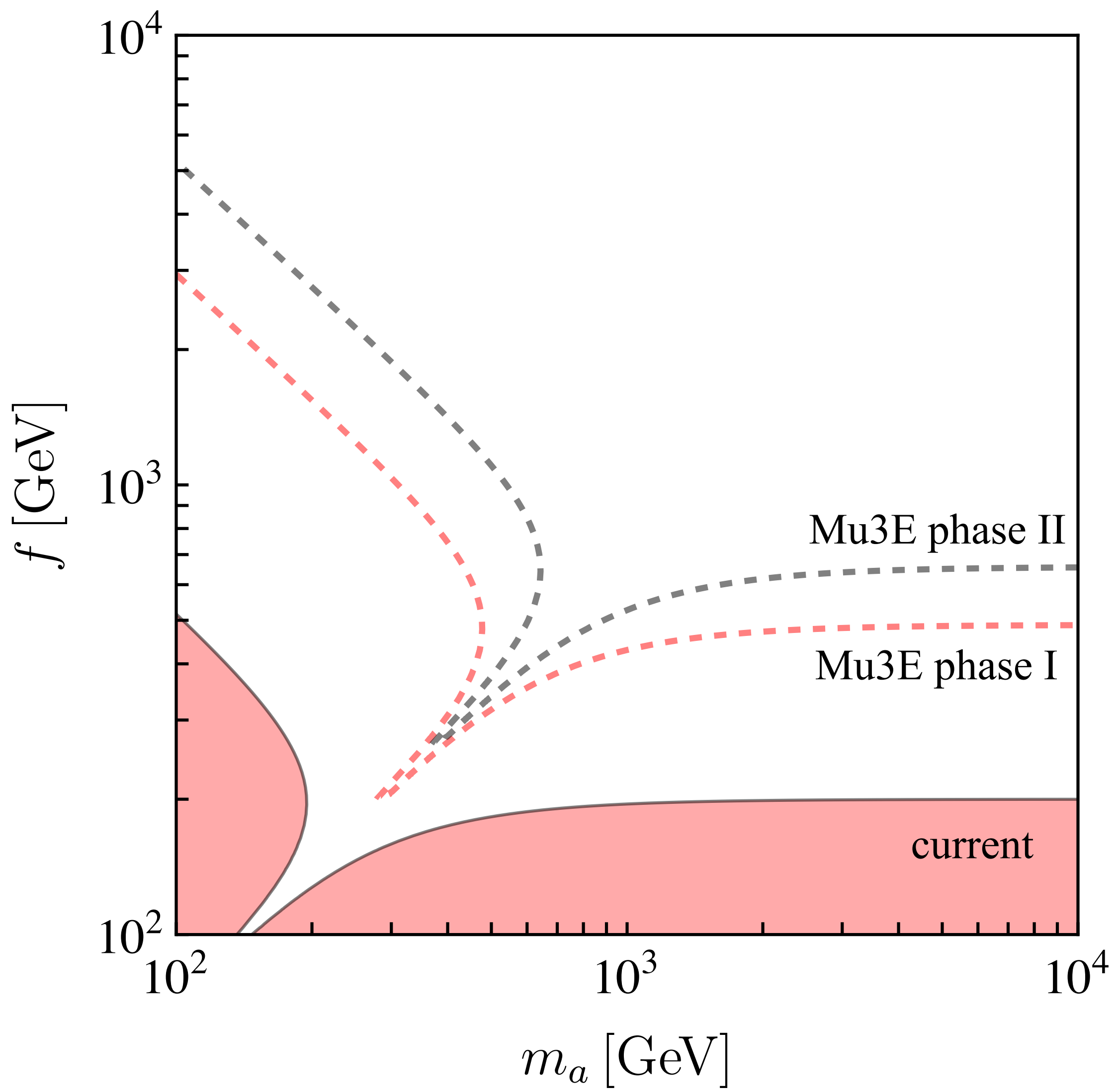
MEG II $\quad \mathrm{BR}(\mu \to e\gamma) < 6 \times 10^{-14}$





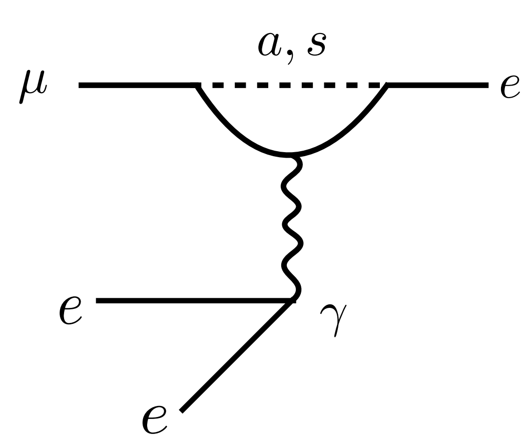
Lepton Flavor constraints

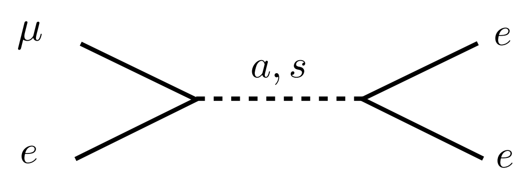
$$\mathcal{L}_{\rm eff} = m_{\ell'}\, C_T^L\, \bar{\ell}\sigma^{\rho\lambda} P_L\, \ell'\, F_{\rho\lambda} + m_{\ell'}\, C_T^R\, \bar{\ell}\sigma^{\rho\lambda} P_R\, \ell'\, F_{\rho\lambda}\,.$$



$$\mathrm{BR}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}\,,$$
$$\mathrm{BR}(\tau \to 3e) < 2.7 \cdot 10^{-8}\,,$$
$$\mathrm{BR}(\mu \to 3e) < 1.0 \cdot 10^{-12}\,.$$

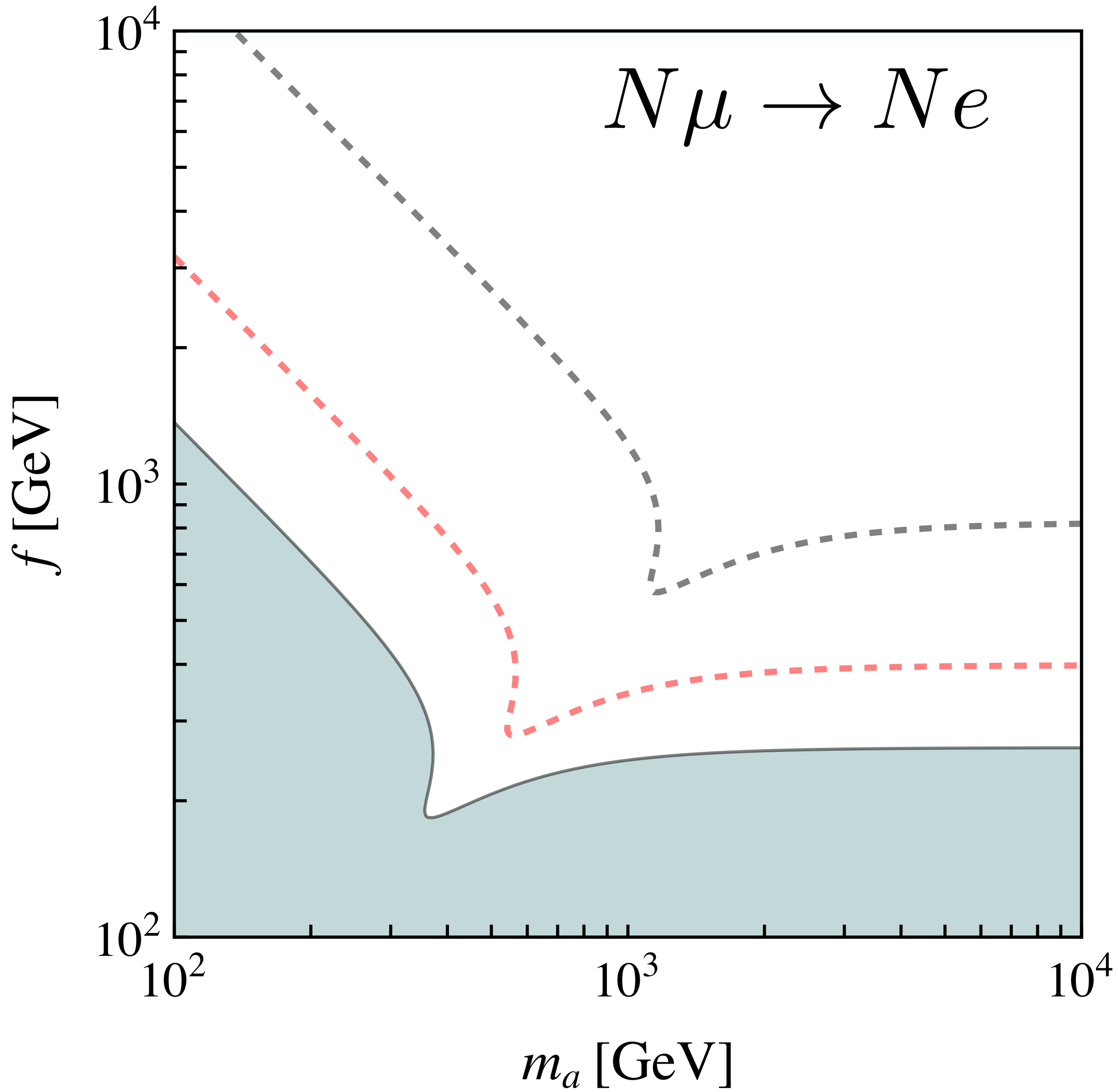
Mu3E will improve this by 3-4 orders of magnitude!





Lepton Flavor constraints

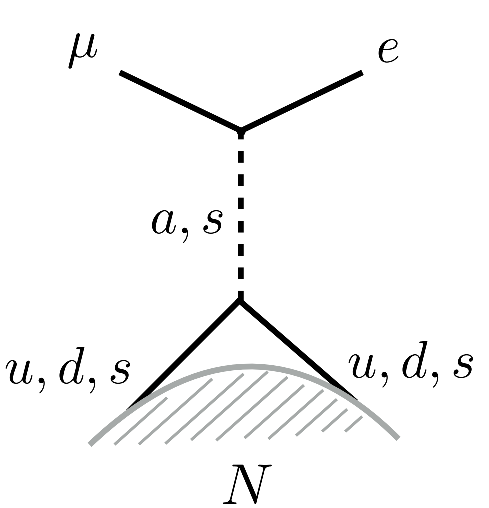
$$\mathcal{L}_{\rm eff} = C_{qq}^{VL}\,\bar{e}\gamma^{\nu}P_L\mu\,\bar{q}\gamma_{\nu}q + m_\mu m_q\,C_{qq}^{SL}\bar{e}P_R\mu\,\bar{q}q + m_\mu\alpha_s C_{gg}^{L}\,\bar{e}P_R\mu\,G_{\rho\nu}G^{\rho\nu} + R\leftrightarrow L,$$

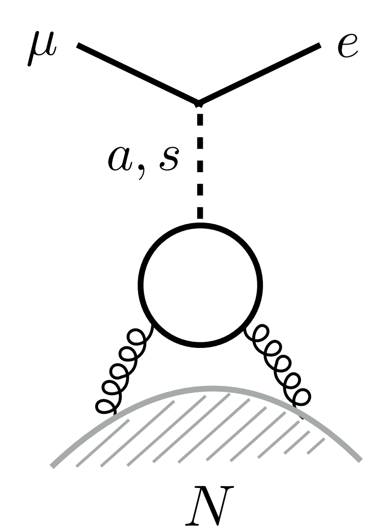


Sindrum II $\quad \mathrm{BR}(\mu\to e)^{\mathrm{Au}} < 7\times 10^{-13}$

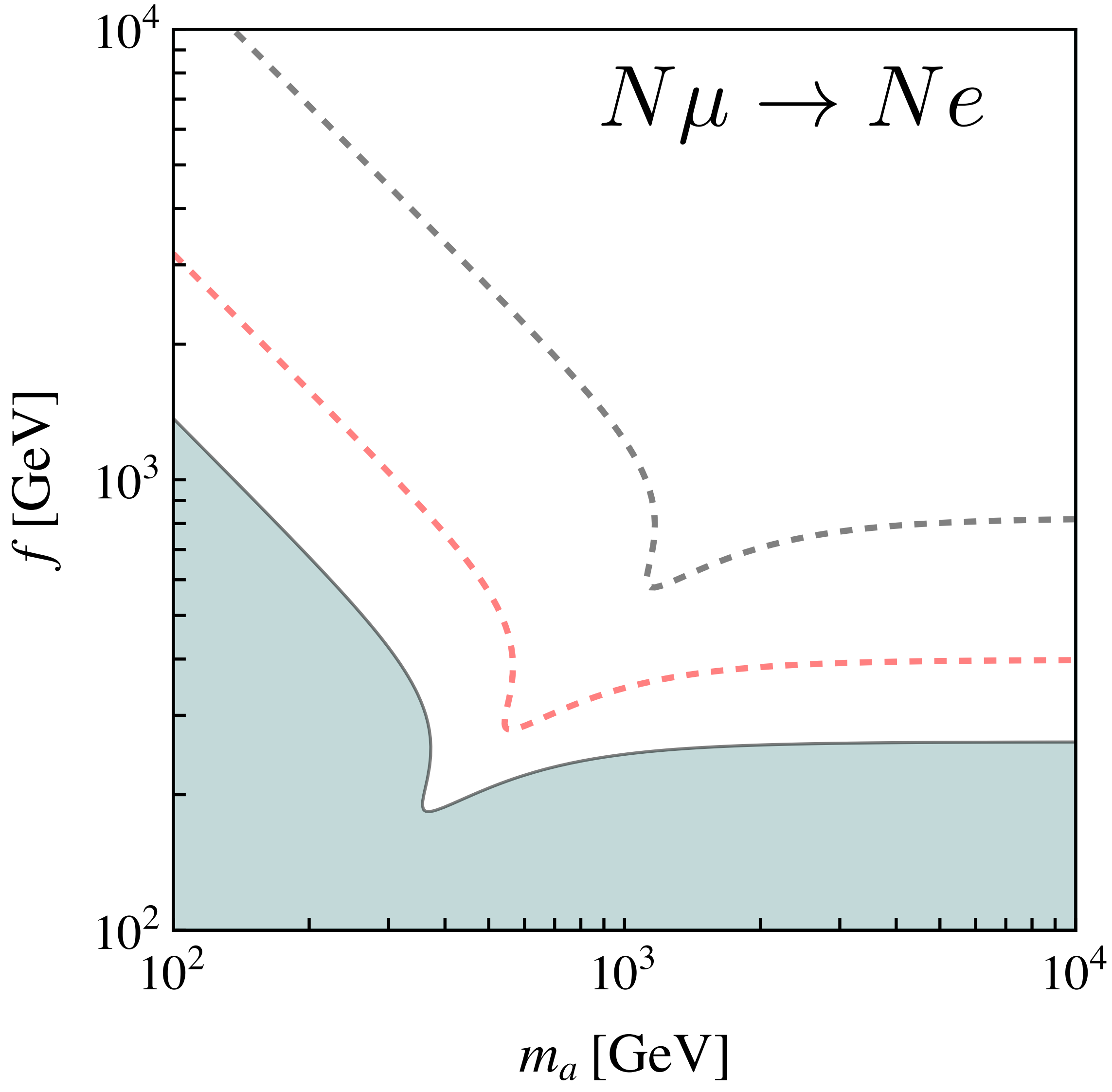
DeeMe $\quad \mathrm{BR}(\mu\to e)^{\mathrm{Si}} < 2\times 10^{-14}$

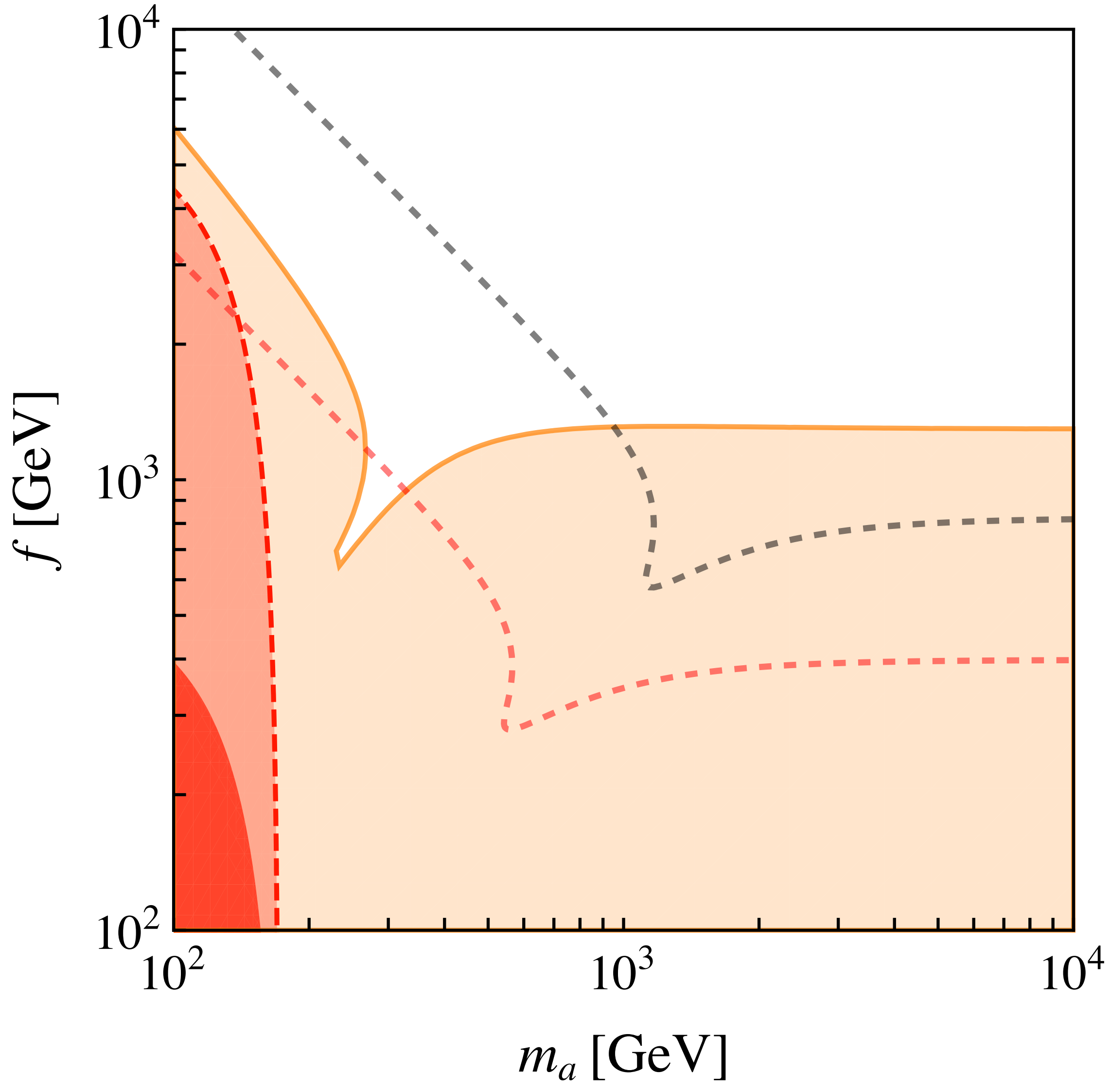
COMET $\quad \mathrm{BR}(\mu\to e)^{\mathrm{Al}} < 6\times 10^{-17}$





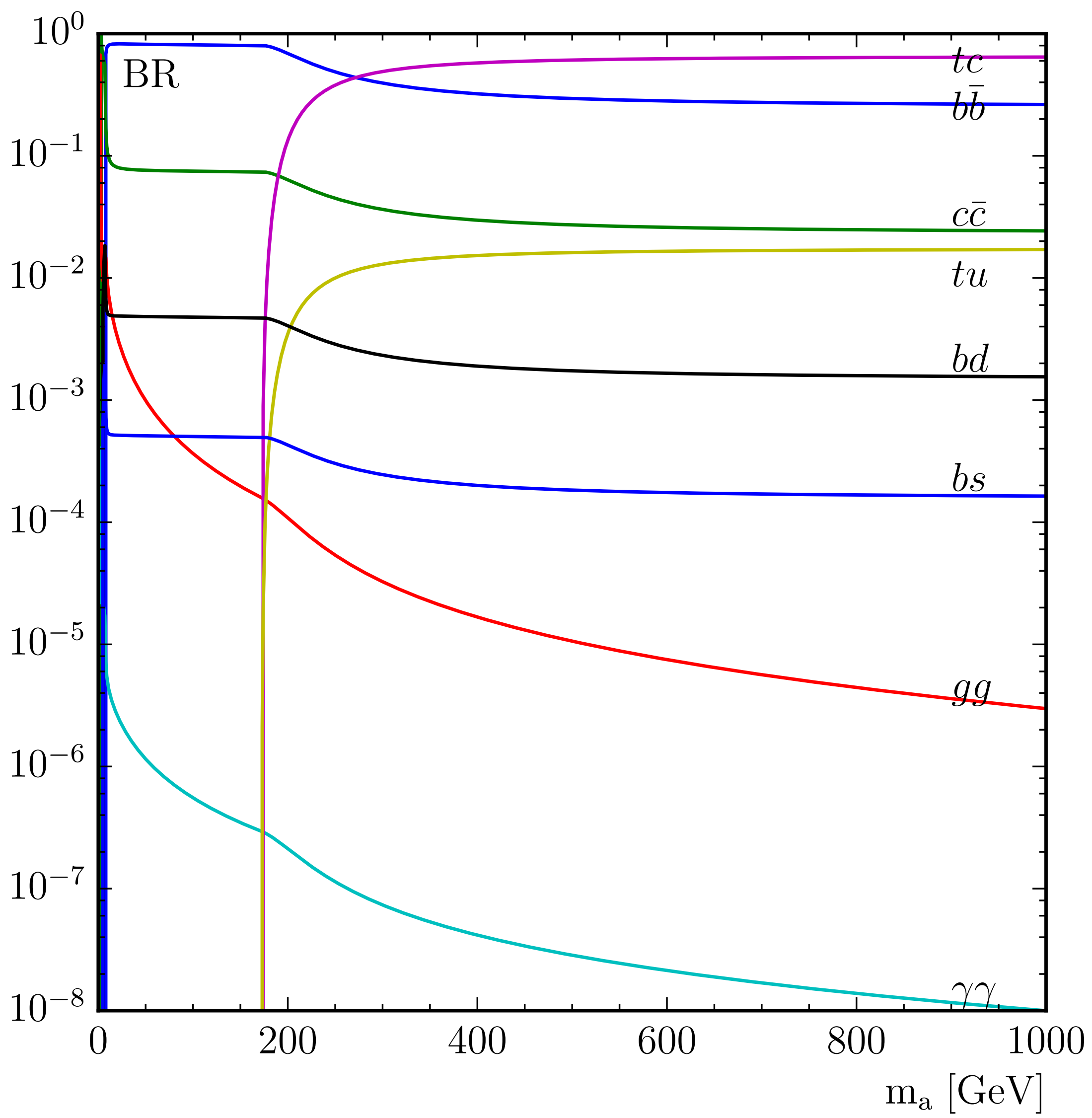
Lepton Flavor constraints

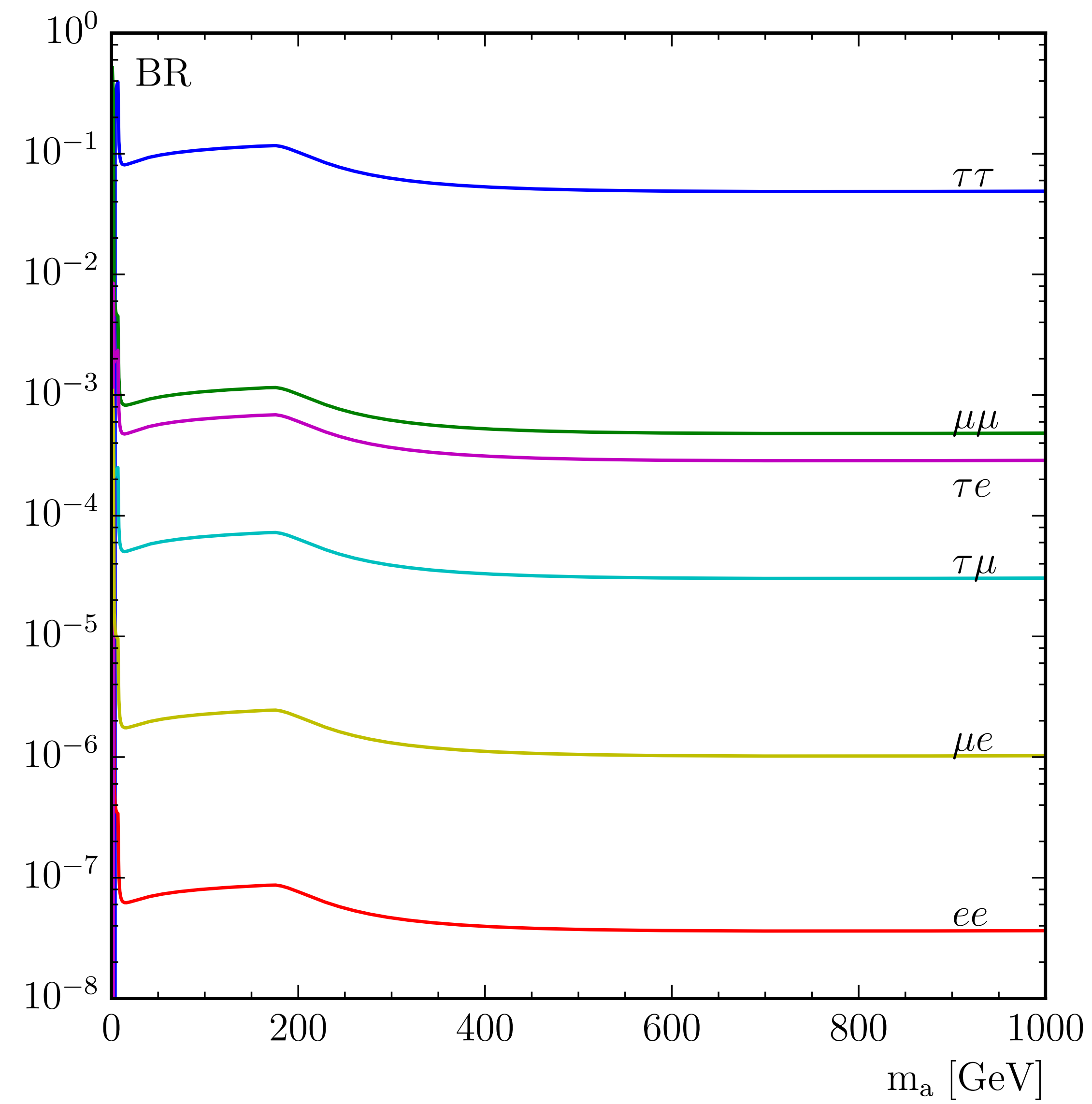




Future Collider Searches

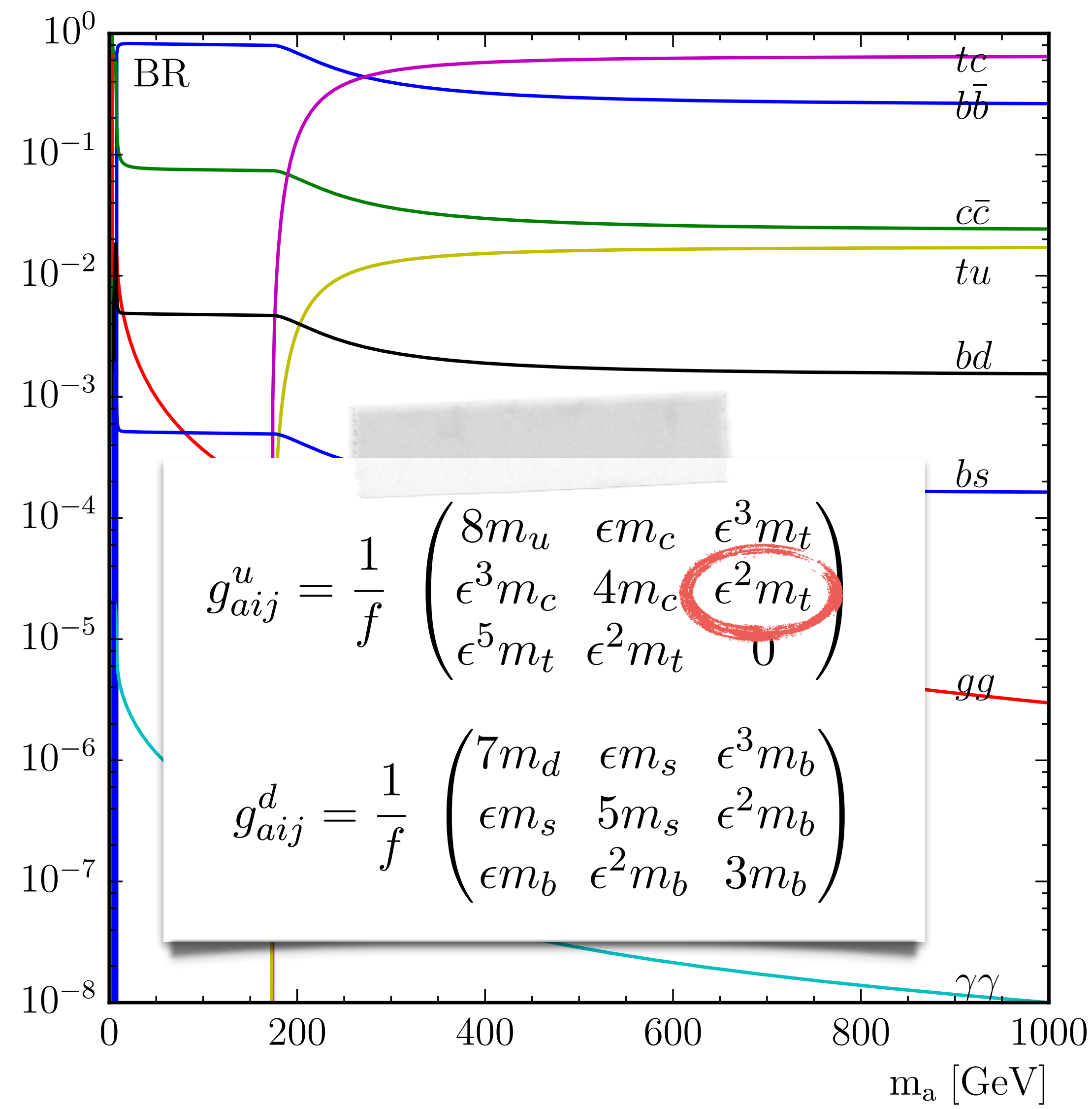
Branching Ratios





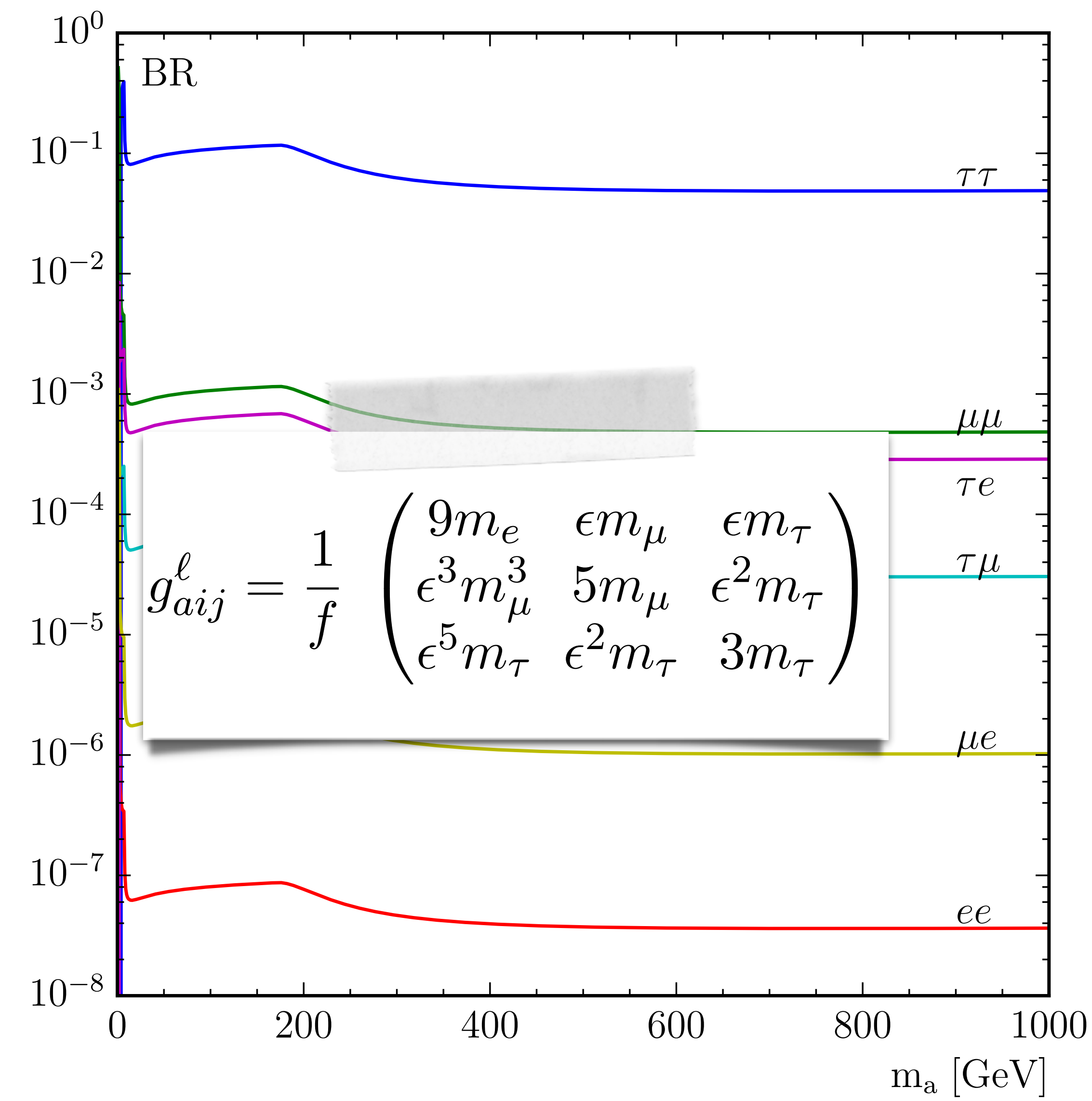
Future Collider Searches

Branching Ratios



$$g^u_{aij} = \frac{1}{f}\begin{pmatrix} 8m_u & \epsilon m_c & \epsilon^3 m_t \\ \epsilon^3 m_c & 4m_c & \epsilon^2 m_t \\ \epsilon^5 m_t & \epsilon^2 m_t & 0 \end{pmatrix}$$

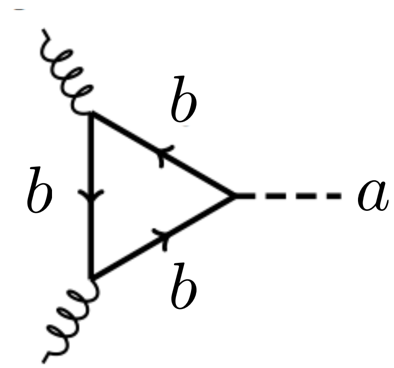
$$g^d_{aij} = \frac{1}{f}\begin{pmatrix} 7m_d & \epsilon m_s & \epsilon^3 m_b \\ \epsilon m_s & 5m_s & \epsilon^2 m_b \\ \epsilon m_b & \epsilon^2 m_b & 3m_b \end{pmatrix}$$

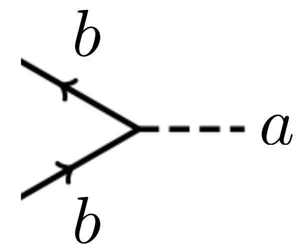


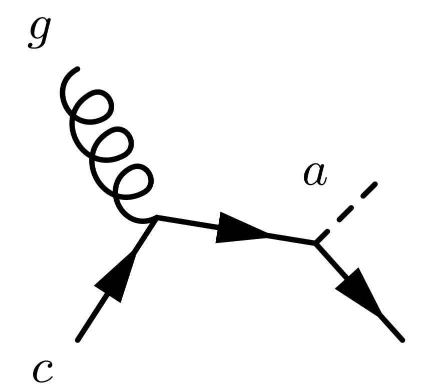
$$g^\ell_{aij} = \frac{1}{f}\begin{pmatrix} 9m_e & \epsilon m_\mu & \epsilon m_\tau \\ \epsilon^3 m_\mu^3 & 5m_\mu & \epsilon^2 m_\tau \\ \epsilon^5 m_\tau & \epsilon^2 m_\tau & 3m_\tau \end{pmatrix}$$

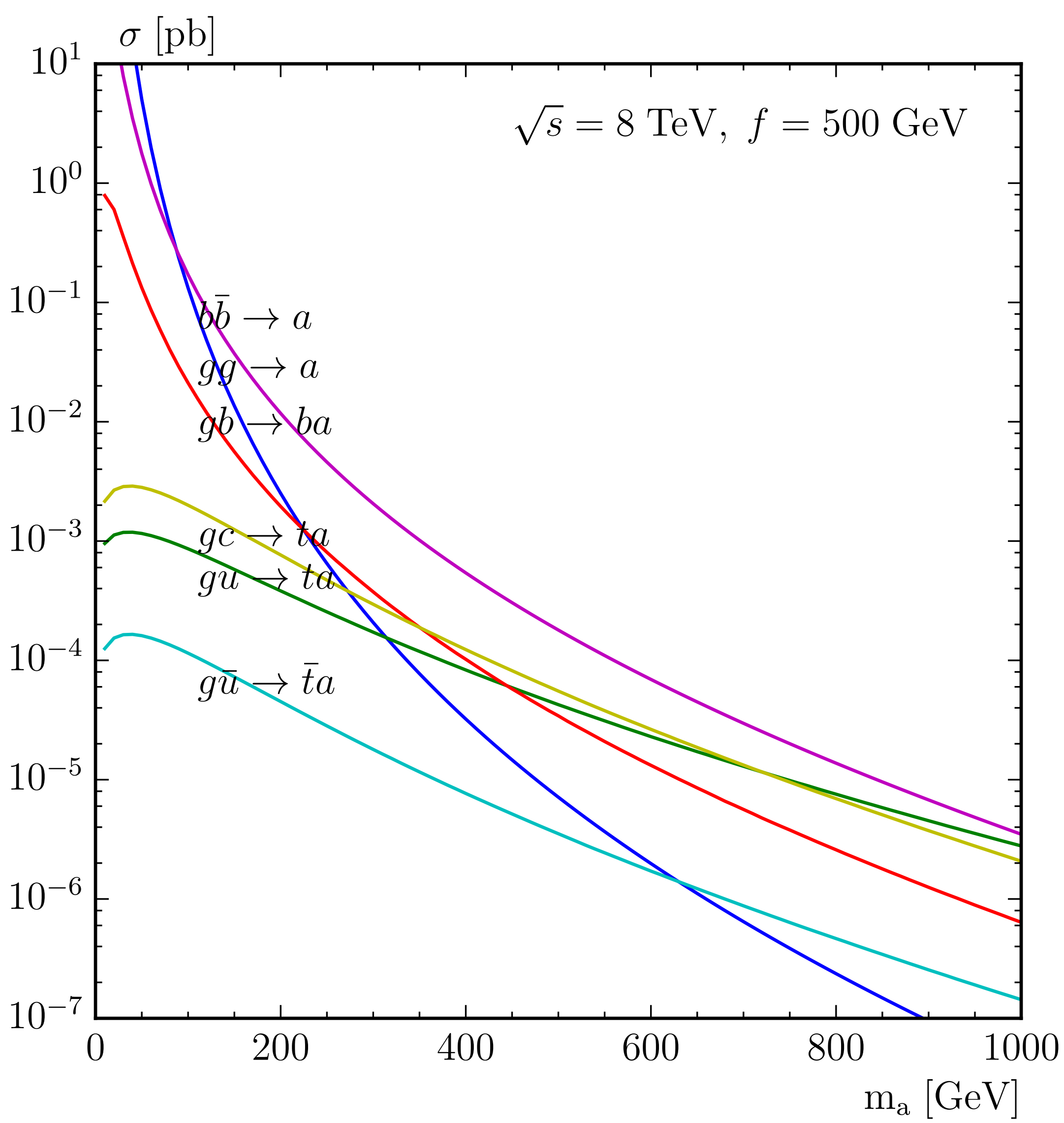
(Future) Collider Searches

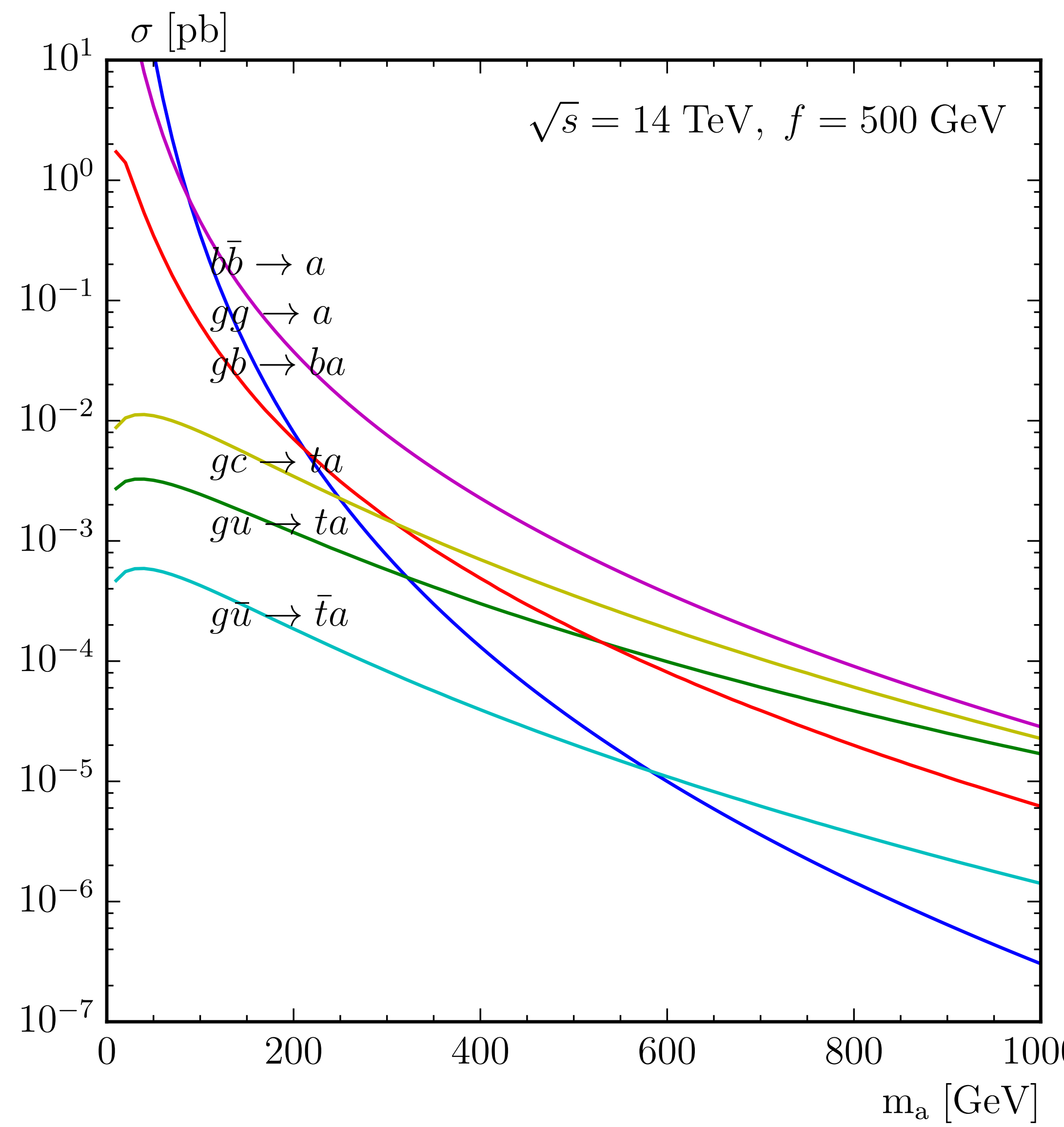
Production Cross Sections at LHC





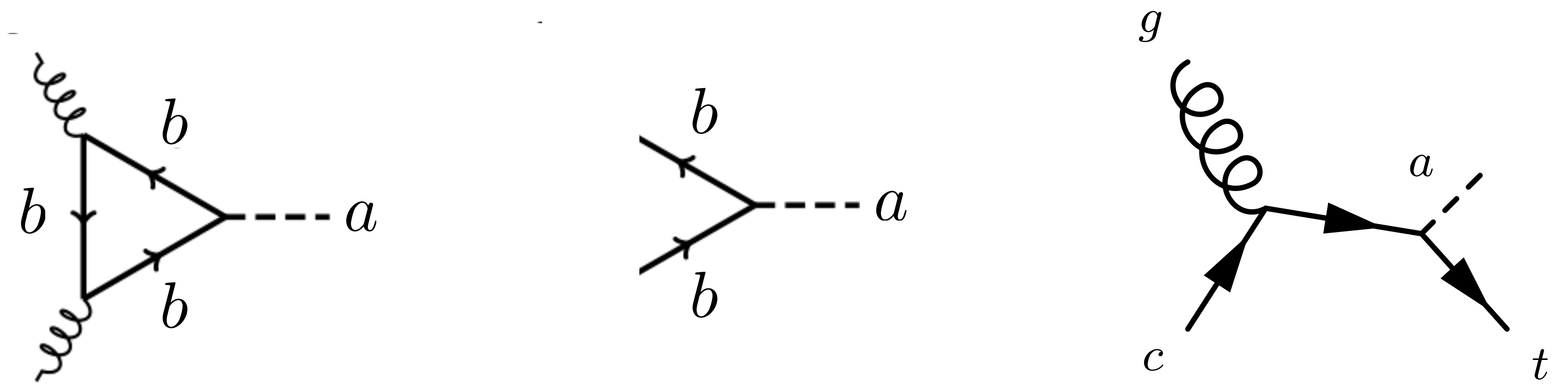




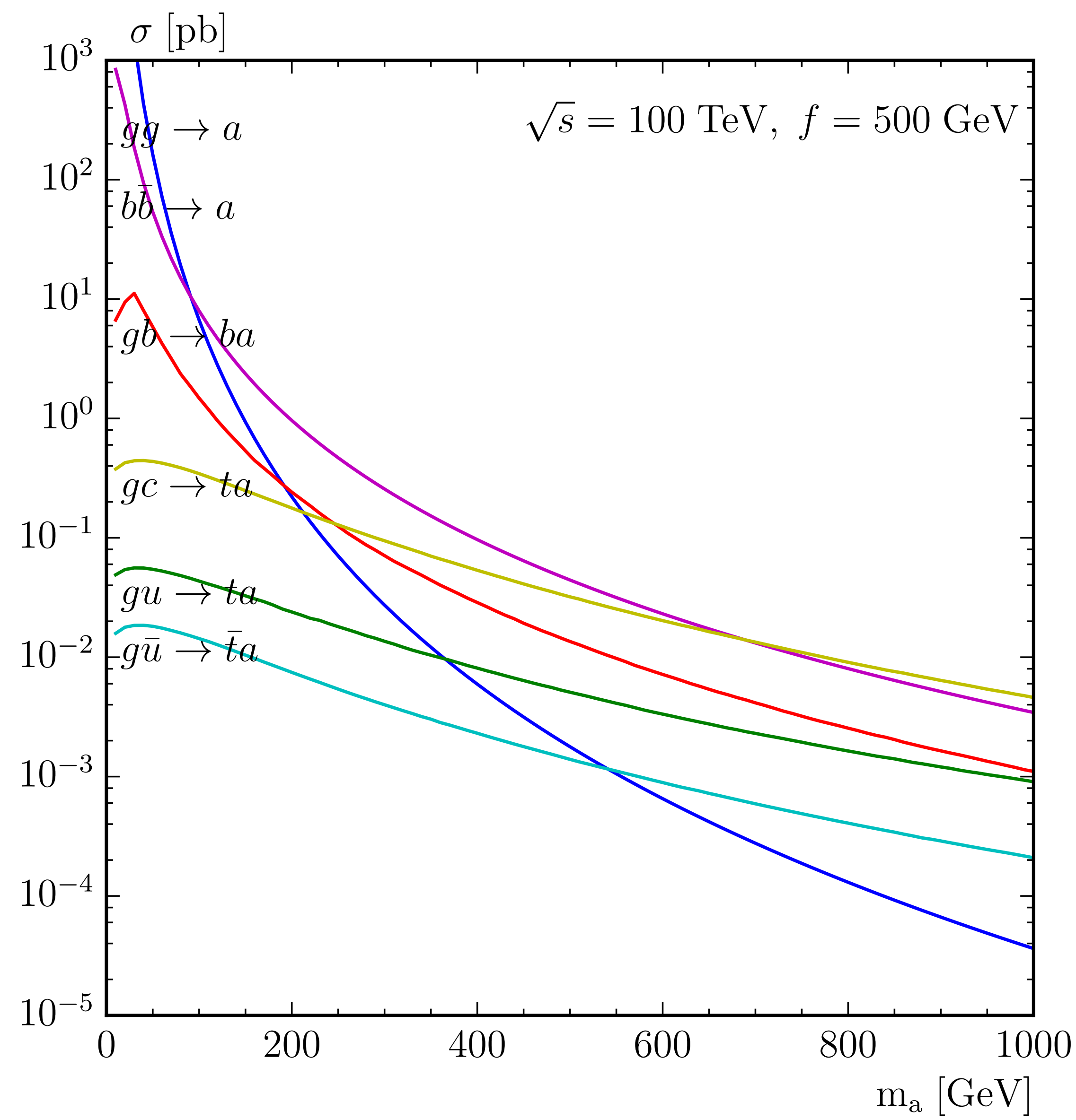


Future Collider Searches

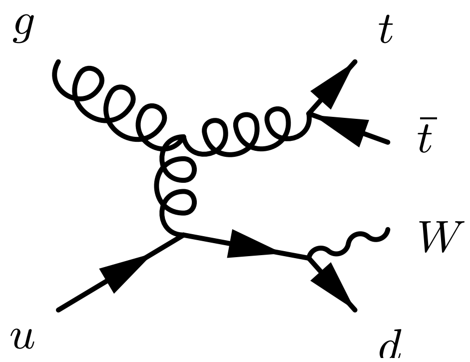
Production Cross Sections at 100 TeV

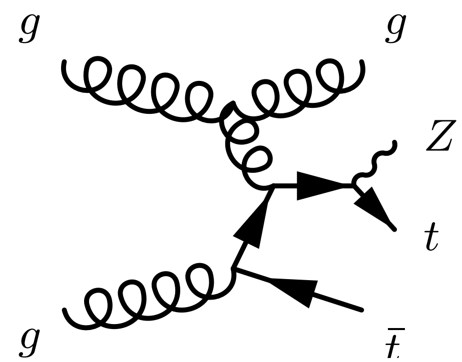


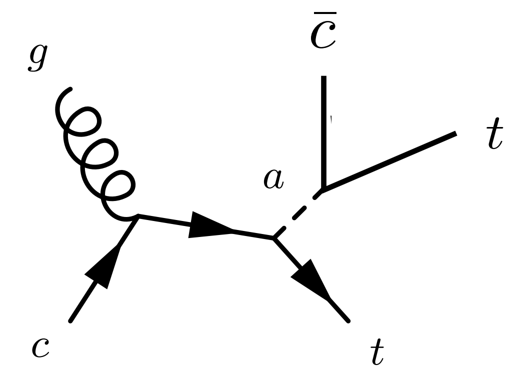
The huge background and the BRs make decays into taus and bs hopeless!



Future Collider Searches



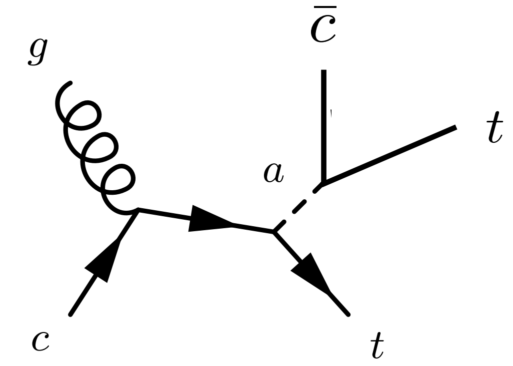




- 2 same-sign leptons(+) (2 hardest ones) with $p_T > 10$ GeV, $|\eta| < 2.5$ $R_{\rm iso} = 0.2$
- if there is a 3rd lepton of different sign, veto events with $|m_{\ell_i^{(\rm ss)}\ell^{(\rm ds)}} - m_Z| < 15$ GeV
- require for hardest jet $p_T > 100$ GeV
- b-tagging: partonlevel b within $R < 0.3$, assumed efficiency 50 %
- require for the remaining jets $N_b \geq 2$
- $\not{p}_T > 50$ GeV
- minimize $R_{\ell_1 b_i} + R_{\ell_2 b_j}$ to define $(\ell b)_1$ and $(\ell b)_2$
- minimize $\Delta y((\ell b)_i, j)$ to define $(\ell b j)$ and (ℓb)
- calculate m_{T2}

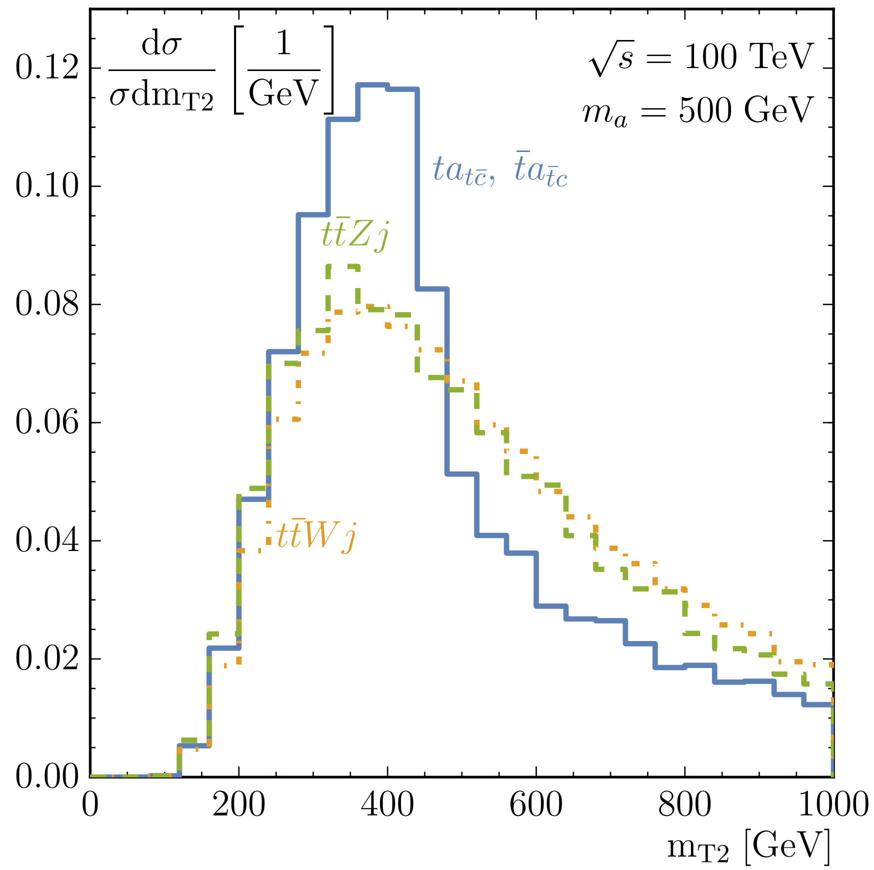
Future Collider Searches

- b-$\bar{b}$ distinction

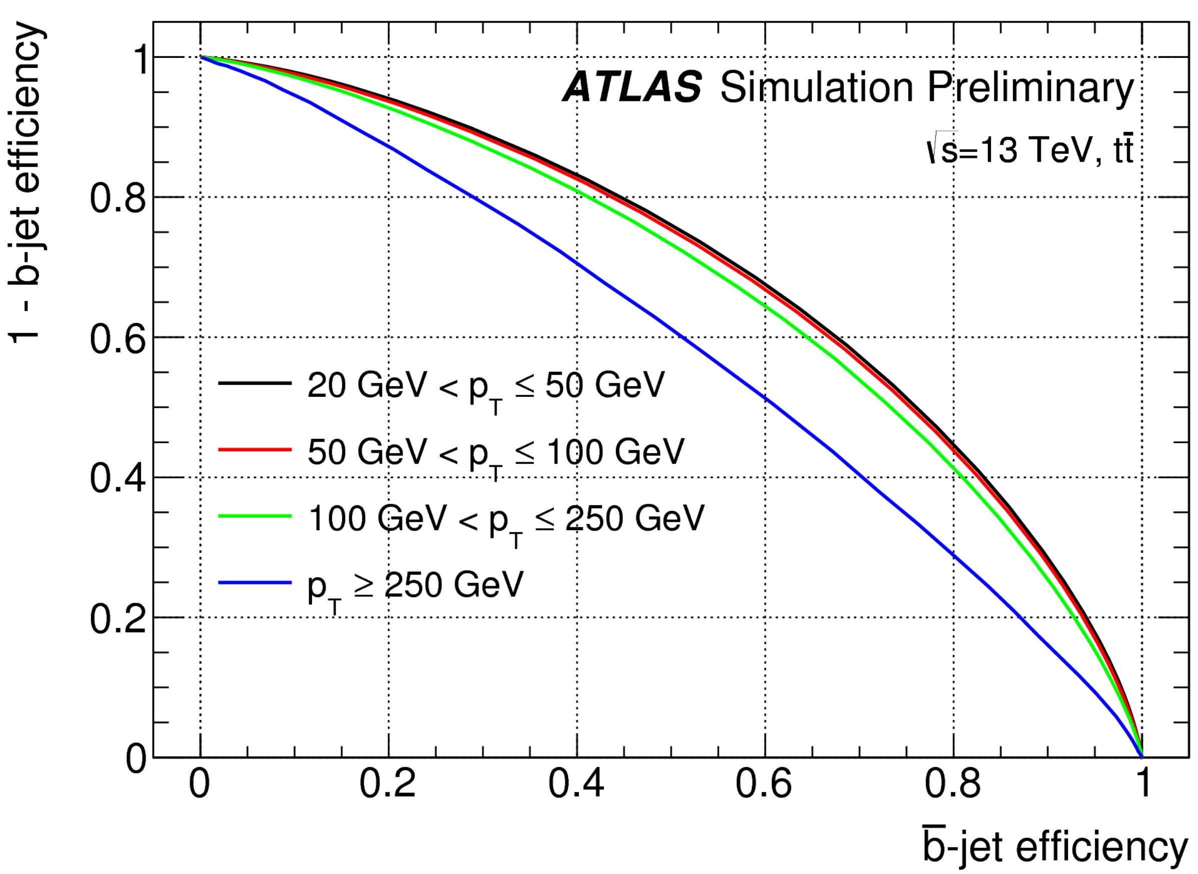


conservative $\quad \epsilon_b = 0.2\,, \epsilon_{\bar{b}} = 0.06$

optimistic $\quad \epsilon_b = 0.2\,, \epsilon_{\bar{b}} = 0.01$



ATL-PHYS-PUB-2015-040

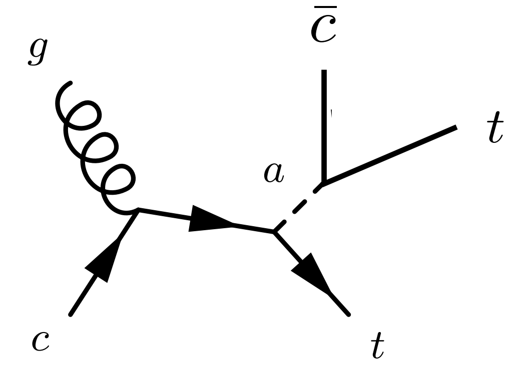


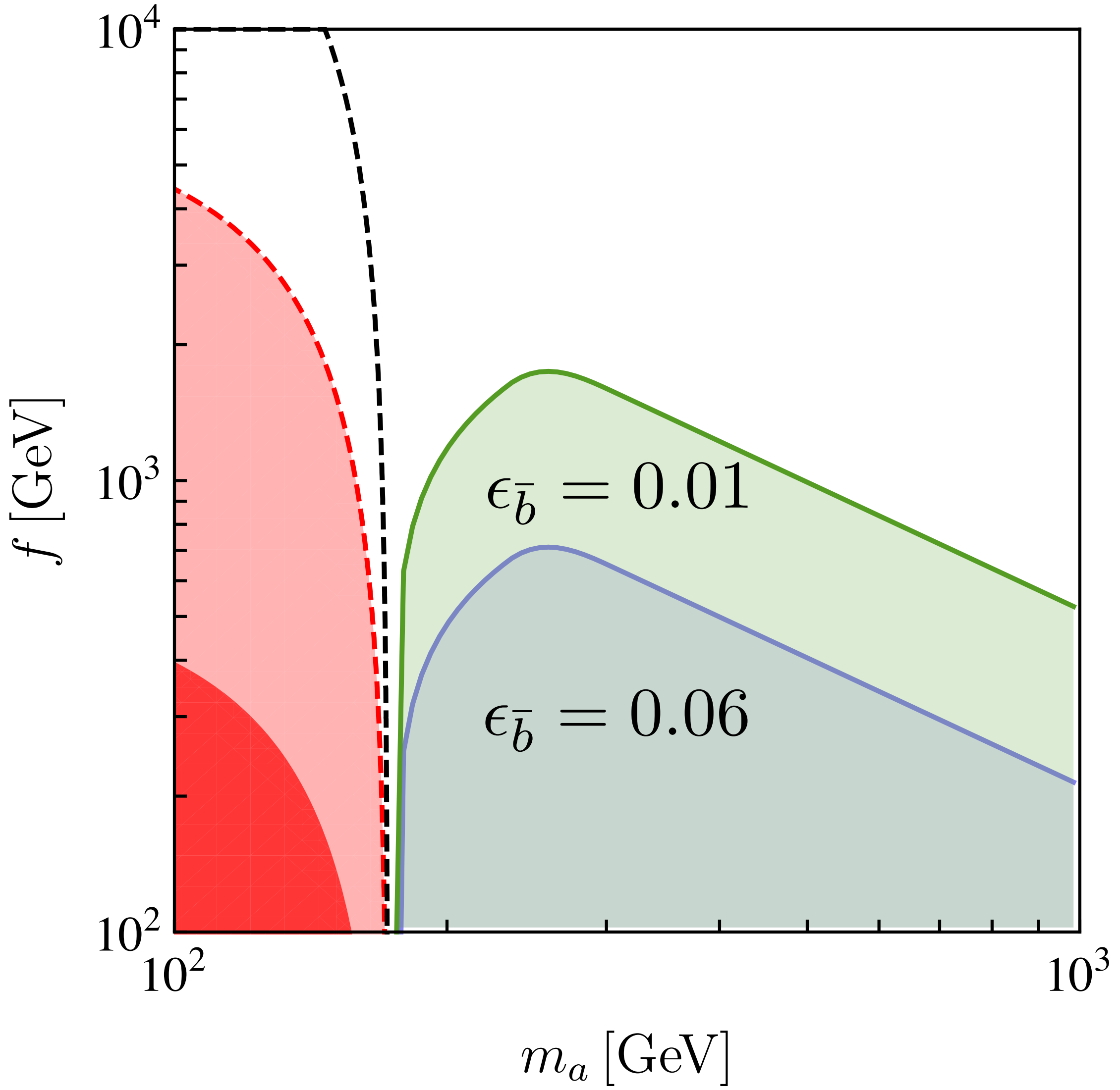
Future Collider Searches

- b-$\bar{b}$ distinction

conservative $\epsilon_b = 0.2\,, \epsilon_{\bar{b}} = 0.06$

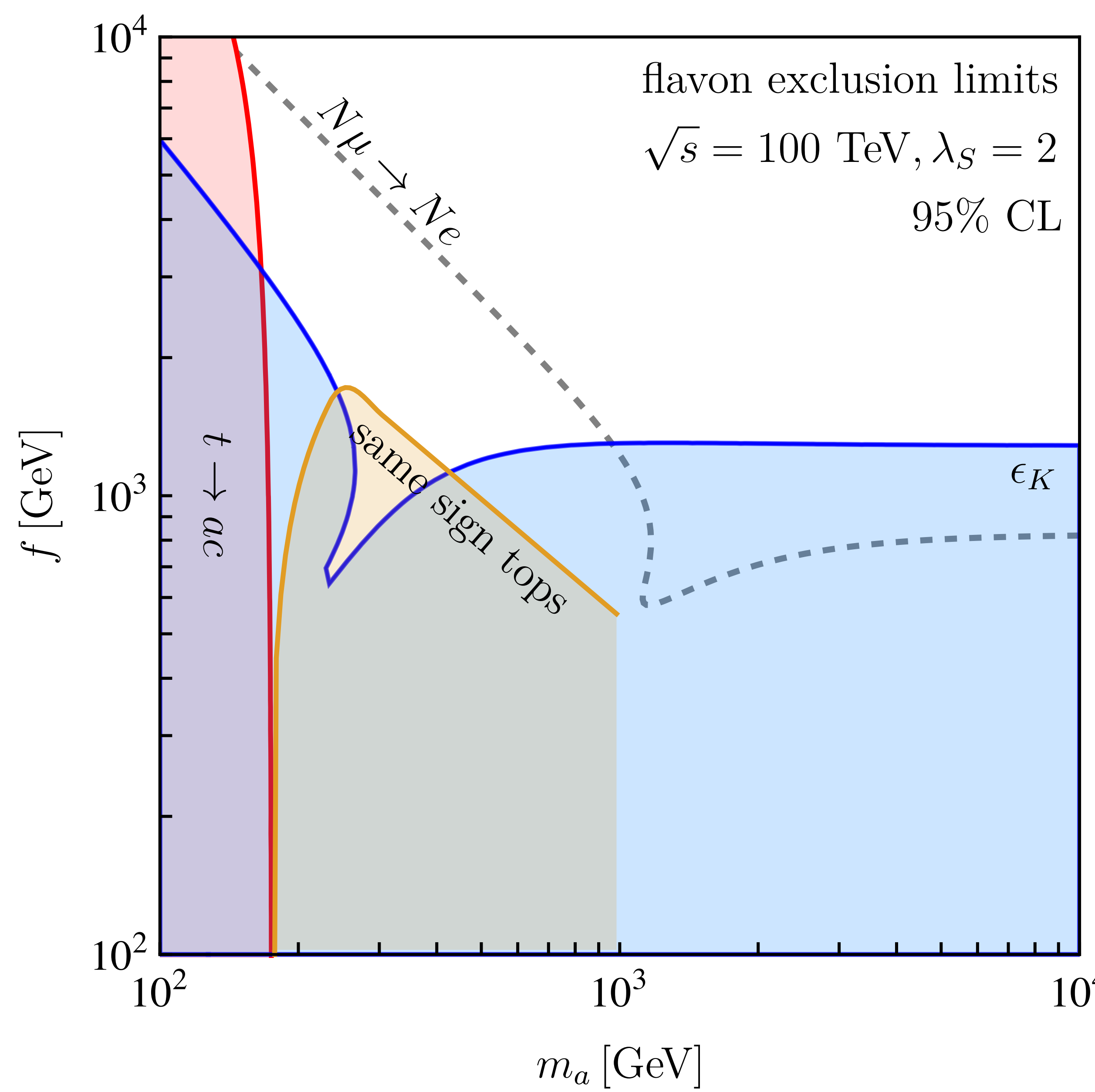
optimistic $\epsilon_b = 0.2\,, \epsilon_{\bar{b}} = 0.01$





Future Collider Searches

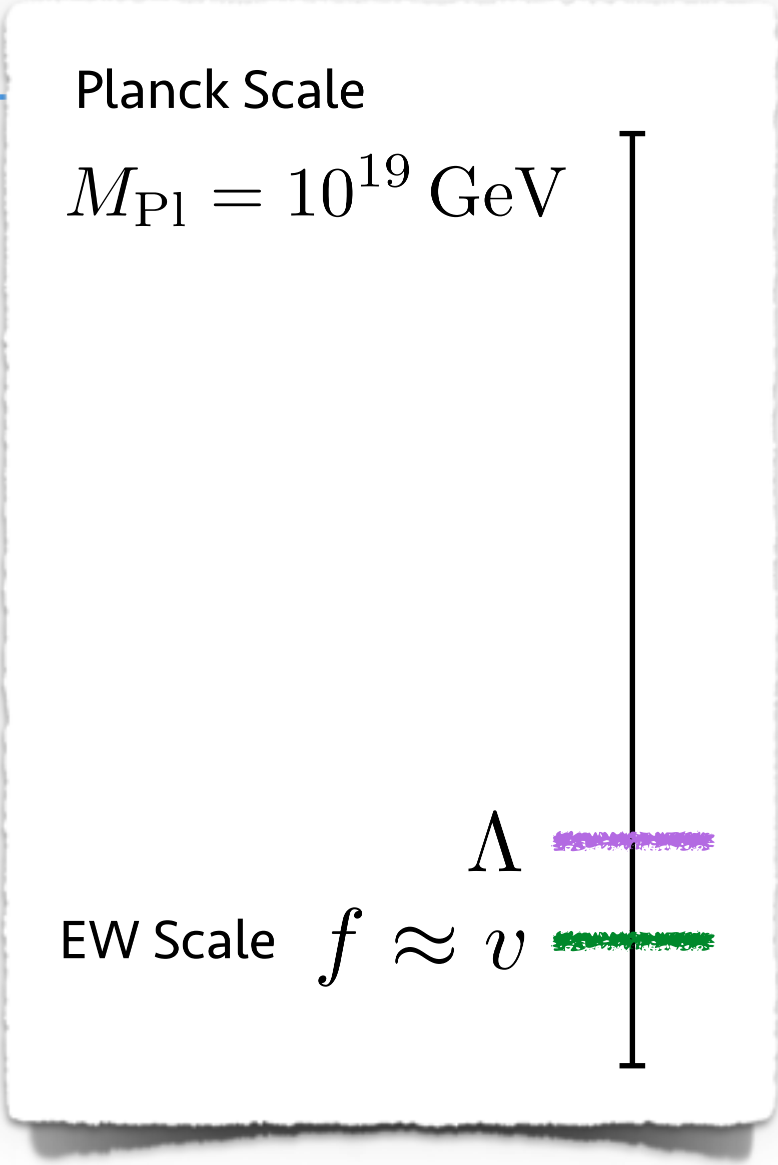
- Next generation lepton flavor experiments will cut deep into the parameter space
- A 100 TeV collider is our first semi-realistic shot at discovering a flavon



Why should the flavor scale be low?

- Why not?
- A link to Baryogenesis?
- A link to Dark Matter?
- It could be related to the electroweak scale

Why should the flavor scale be low?



- Why not?
- A link to Baryogenesis?
- A link to Dark Matter?
- It could be related to the electroweak scale

Flavor from the Electroweak Scale?

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

with $$\epsilon = \frac{v^2}{2\Lambda^2} = \frac{m_b}{m_t} \quad \Rightarrow \quad \Lambda \approx (5-6)\, v$$

Two drawbacks:

[Babu 033002]

[Giudice, Lebedev 0804.1753]

- The flavon is a flavor singlet
- The coupling to b quarks is

$$g_{hbb} \propto 3\frac{m_b}{v} \qquad \Gamma(h \to b\bar{b}) \approx 9 \times \Gamma(h \to b\bar{b})_{\rm SM}$$

Flavor from the Electroweak Scale

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

with $\epsilon = \frac{v_u v_d}{\Lambda^2} = \frac{m_b}{m_t} \quad \Rightarrow \quad \Lambda \approx (5-6)\, v \sqrt{\frac{\tan\beta}{1+\tan^2\beta}}$

$$\tan\beta = \mathcal{O}(1), \quad \Lambda \approx 1\text{TeV}$$

Flavor from the Electroweak Scale

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

11 Flavour charges, 8 + 2 conditions

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

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

$$m_t = 172\,\text{GeV}$$
$$m_b \approx m_c \approx 2.9\,\text{GeV}$$
$$m_s = 50\,\text{MeV}$$
$$m_u = m_d \approx 1\,\text{MeV}$$

A rescaling freedom remains

$$a_{H_u} = 1\,, \quad a_{H_d} = 0\,,$$

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

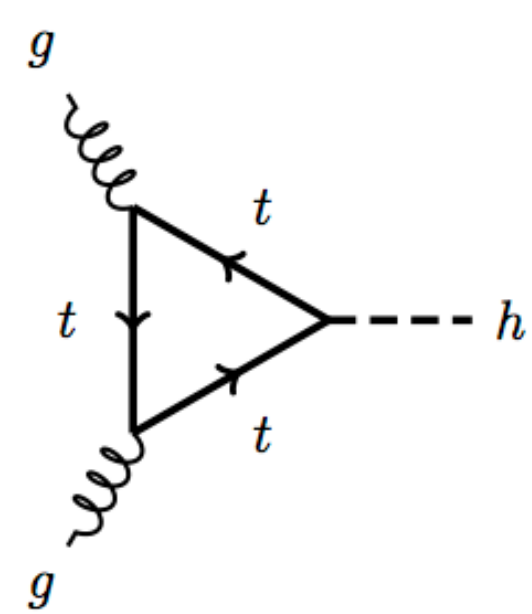
Higgs Couplings

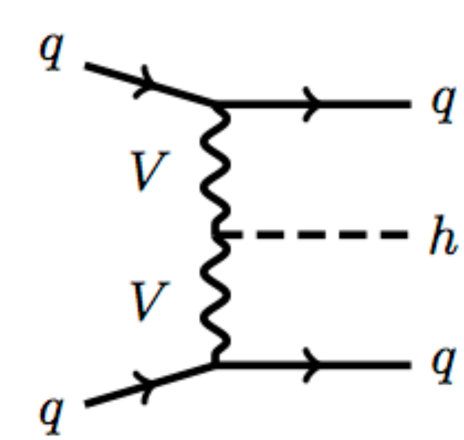
- Couplings are rescaled $g_{hVV} = \kappa_V \, g_{hVV}^{\mathrm{SM}} \quad g_{hff} = \kappa_f \, g_{hff}^{\mathrm{SM}}$
- To $W^{\pm}, Z$ fixed by gauge symmetry:

$$\kappa_V = \sin(\beta - \alpha)$$

- To the top: $\kappa_t = \kappa_t^{\mathrm{II\,HDM}} = \dfrac{\cos\alpha}{\sin\beta}$

Higgs Production like in a 2HDM of type II

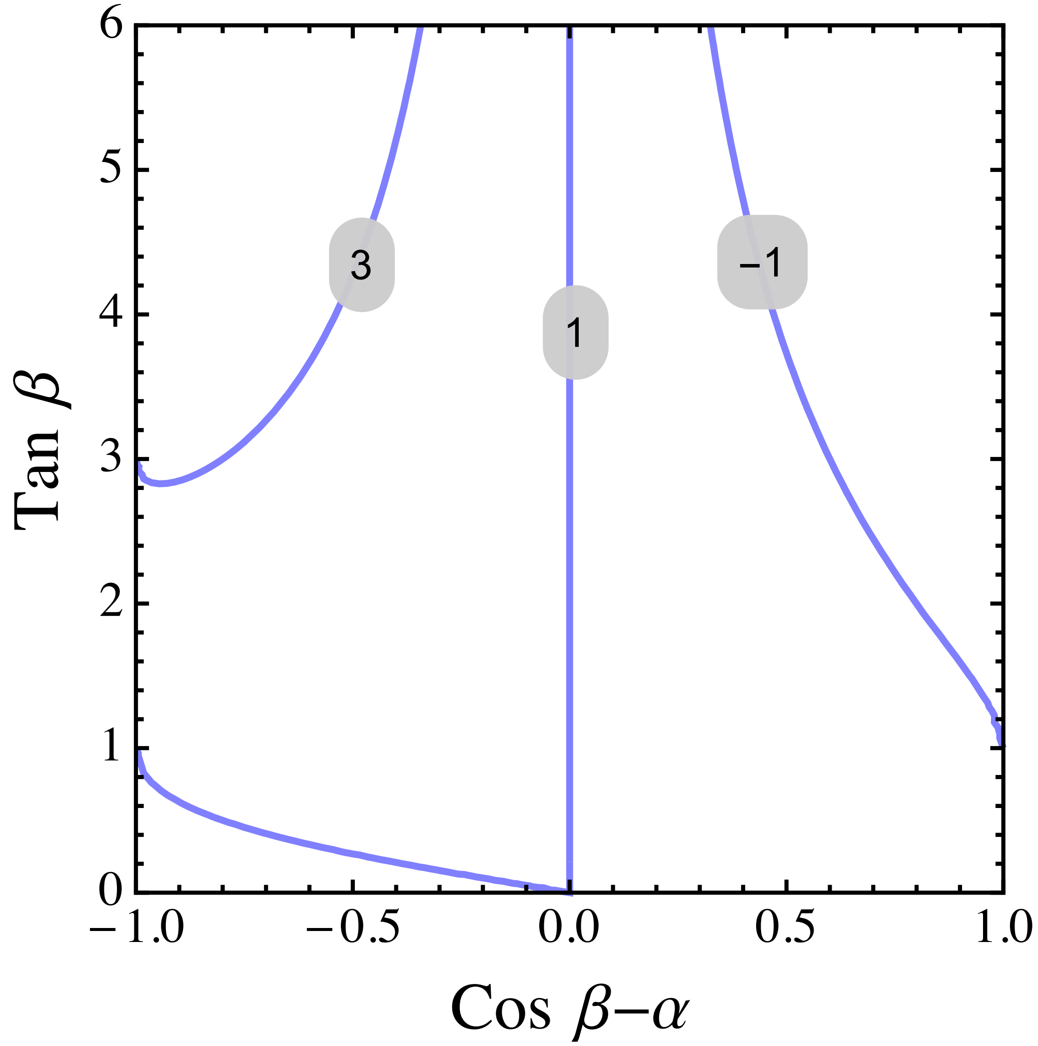




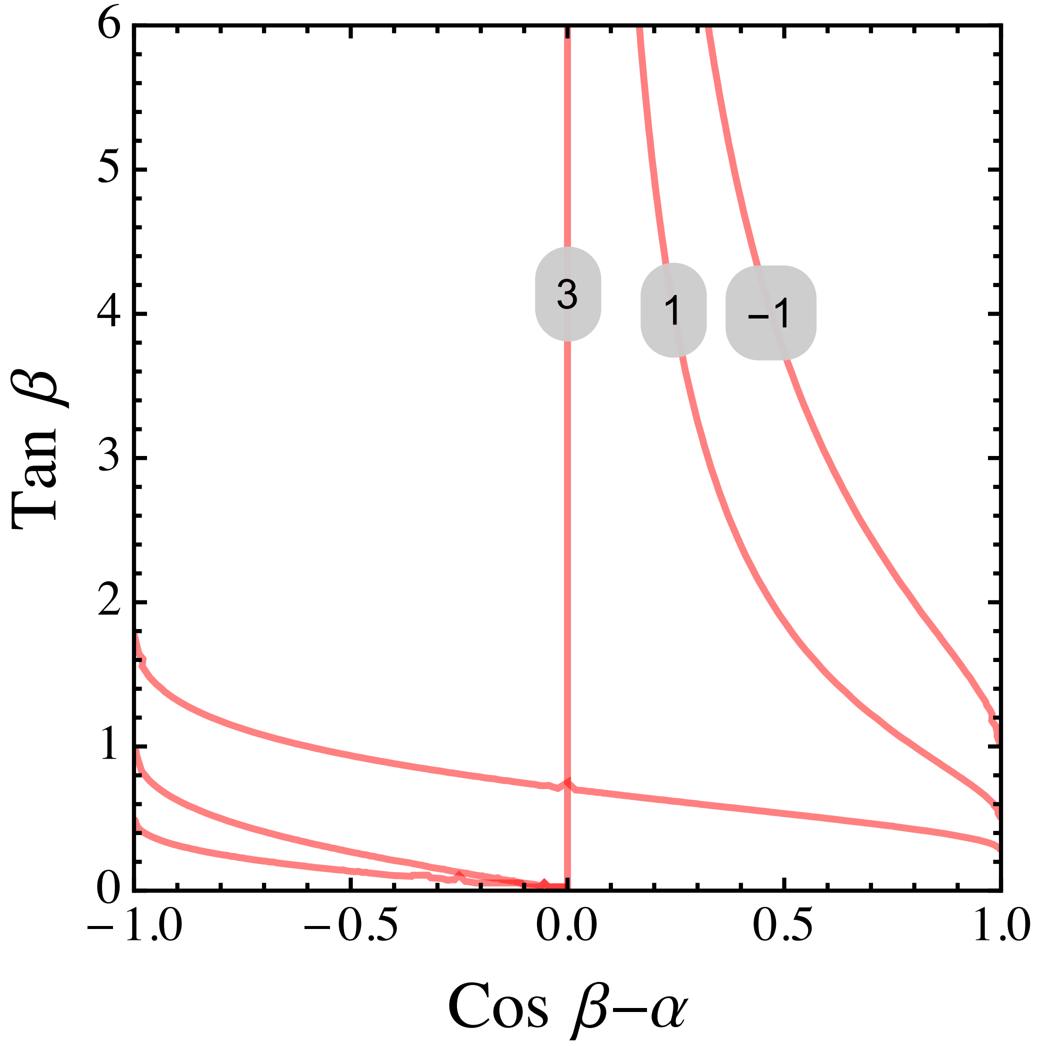
Higgs Couplings

- To the bottom:

$$\kappa_b^{\mathrm{II\,HDM}} = -\frac{\sin\alpha}{\cos\beta}$$



$$\kappa_b = -2\frac{\sin\alpha}{\cos\beta} + \frac{\cos\alpha}{\sin\beta}$$



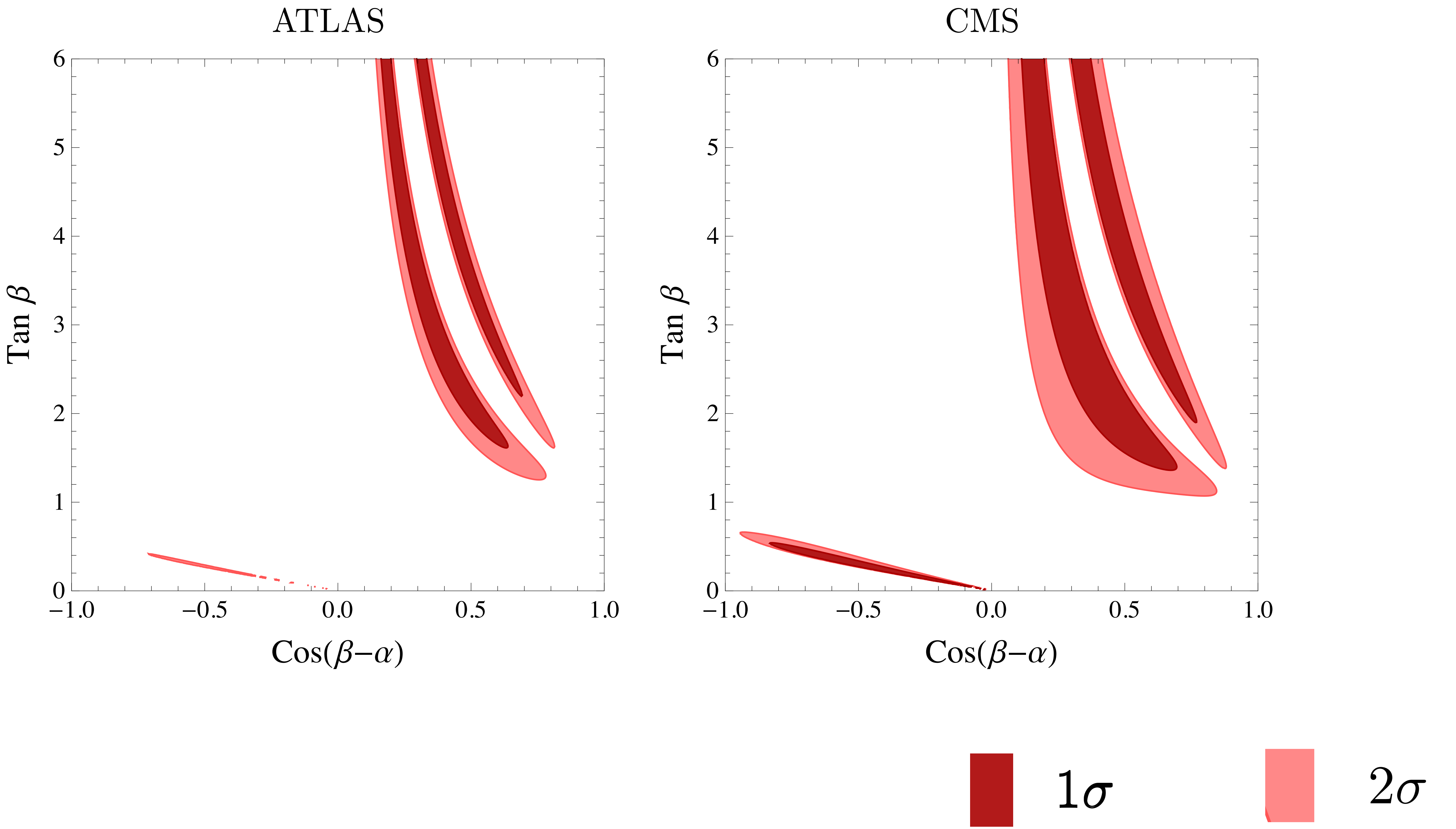
Global Higgs Fit

We performed a global Higgs fit to 8 different channels at ATLAS & CMS

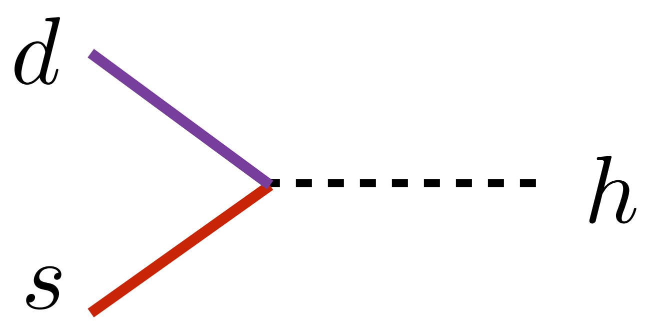
$$\mu_X = \frac{\sigma_{\text{prod}}}{\sigma^{\text{SM}}_{\text{prod}}} \frac{\Gamma_{h\to X}}{\Gamma^{\text{SM}}_{h\to X}} \frac{\Gamma^{\text{SM}}_{h,\,\text{tot}}}{\Gamma_h}$$

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 Higgs Fit



Flavor from the Electroweak Scale



$$\sim g_{hsd}$$

Universal function

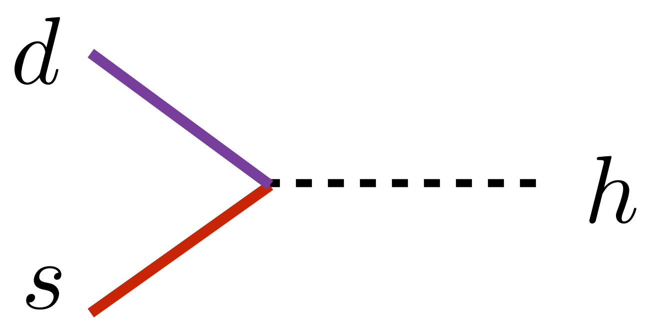
$$f^h(\alpha,\beta) = \frac{c_\alpha}{s_\beta} - \frac{s_\alpha}{c_\beta}$$

$$g_{hd_id_i} = \left(\frac{c_\alpha}{s_\alpha} + n_{d_i} f^h(\alpha,\beta)\right)\frac{m_{d_i}}{v}$$

$$g_{hd_id_j} = \left(\mathcal{Q}_{ij}\frac{m_{d_j}}{v} - \frac{m_{d_i}}{v}\mathcal{D}_{ij}\right) f^h(\alpha,\beta)$$

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

Flavor from the Electroweak Scale



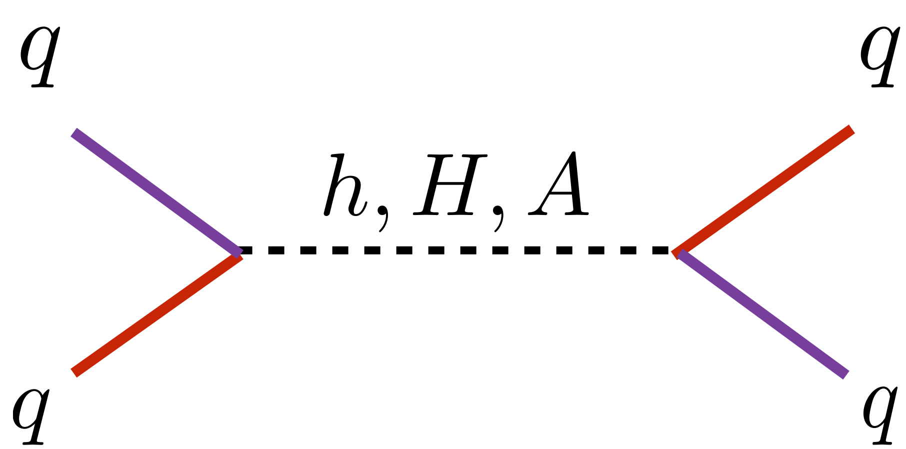
$$\sim \quad \frac{m_s}{v}\,\epsilon\, f^h(\alpha,\beta) \approx 3 \times 10^{-6} \times f^h(\alpha,\beta)$$

$$g_{hd_id_i} = \left(\frac{c_\alpha}{s_\alpha} + n_{d_i} f^h(\alpha,\beta)\right)\frac{m_{d_i}}{v}$$

$$g_{hd_id_j} = \left(\mathcal{Q}_{ij}\frac{m_{d_j}}{v} - \frac{m_{d_i}}{v}\mathcal{D}_{ij}\right) f^h(\alpha,\beta)$$

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

Flavor from the Electroweak Scale

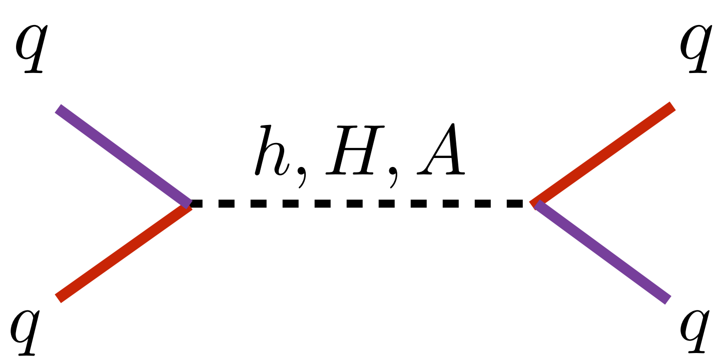


$$g_{hd_id_j} = g^h(\alpha,\beta)\left(\frac{m_d}{v}\right)_{ij} + f^h(\alpha,\beta)\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii}\mathcal{D}_{ij}\right]$$

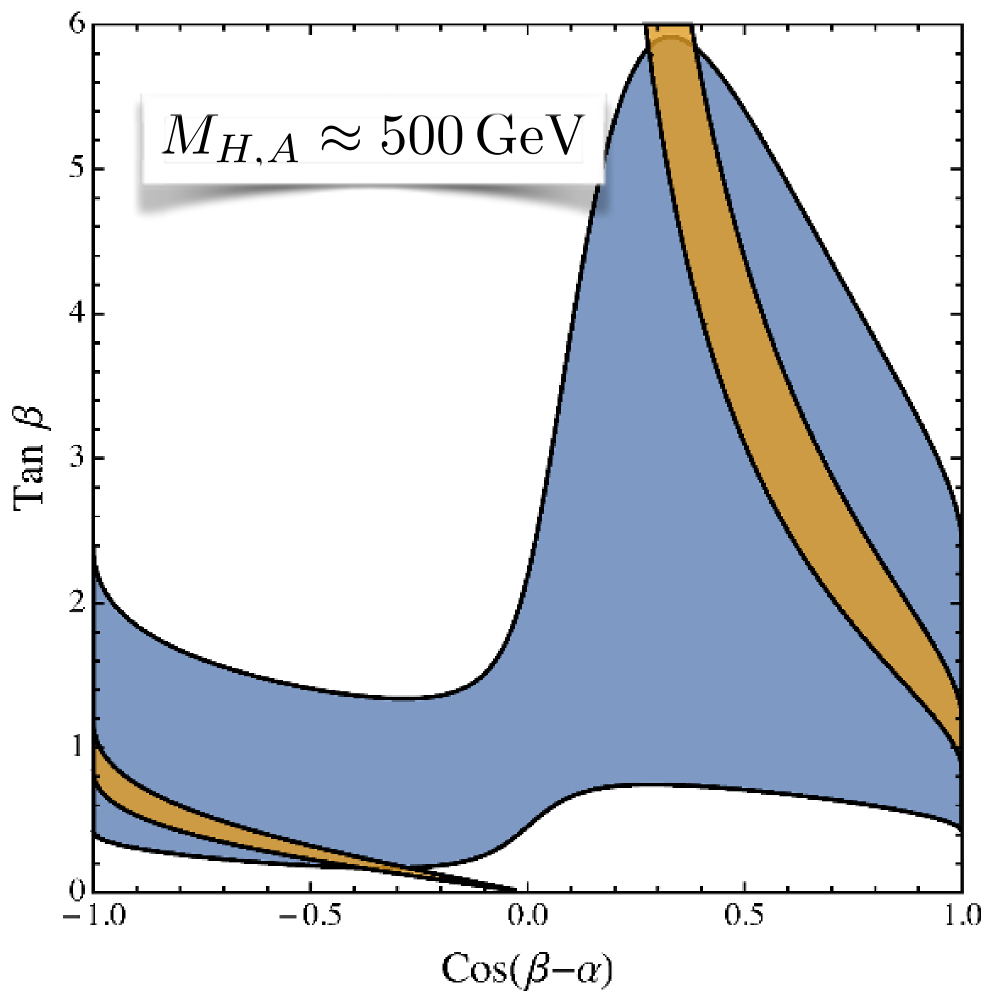
$$g_{Hd_id_j} = G^H(\alpha,\beta)\left(\frac{m_d}{v}\right)_{ij} + F^H(\alpha,\beta)\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii}\mathcal{D}^d_{ij}\right]$$

$$g_{Ad_id_j} = G^A(\alpha,\beta)\left(\frac{m_d}{v}\right)_{ij} + F^A(\alpha,\beta)\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii}\mathcal{D}^d_{ij}\right]$$

Constraints from Meson Mixing

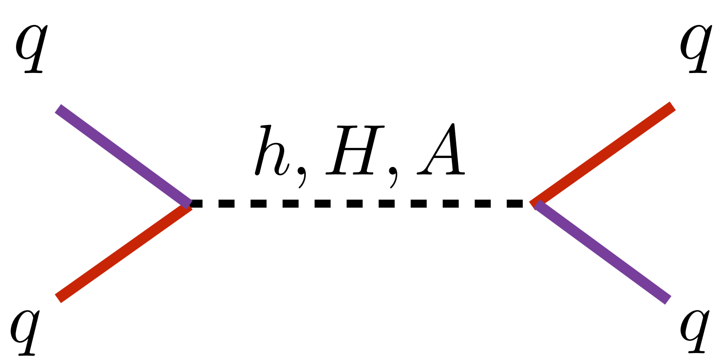


$$\approx \varepsilon^X \frac{m_q^2}{v^2} \left\{ \frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_H^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2} \right\}$$

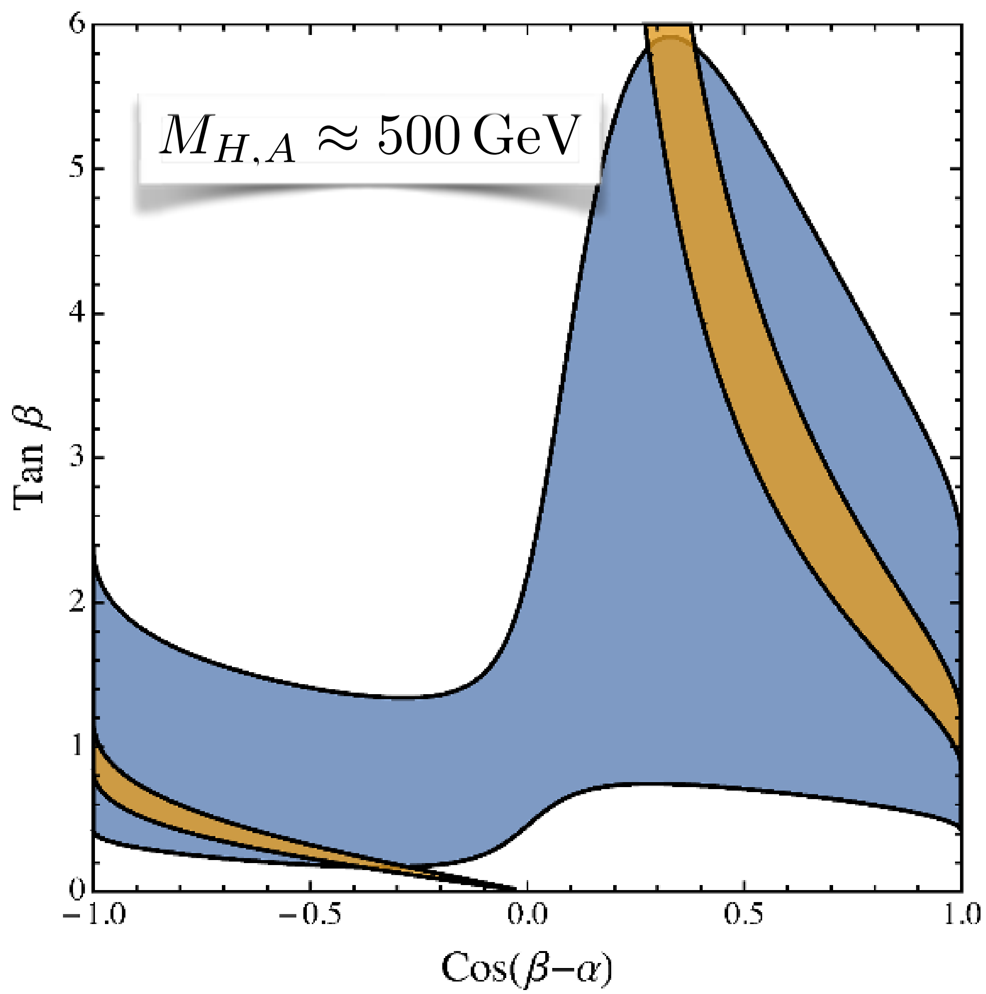


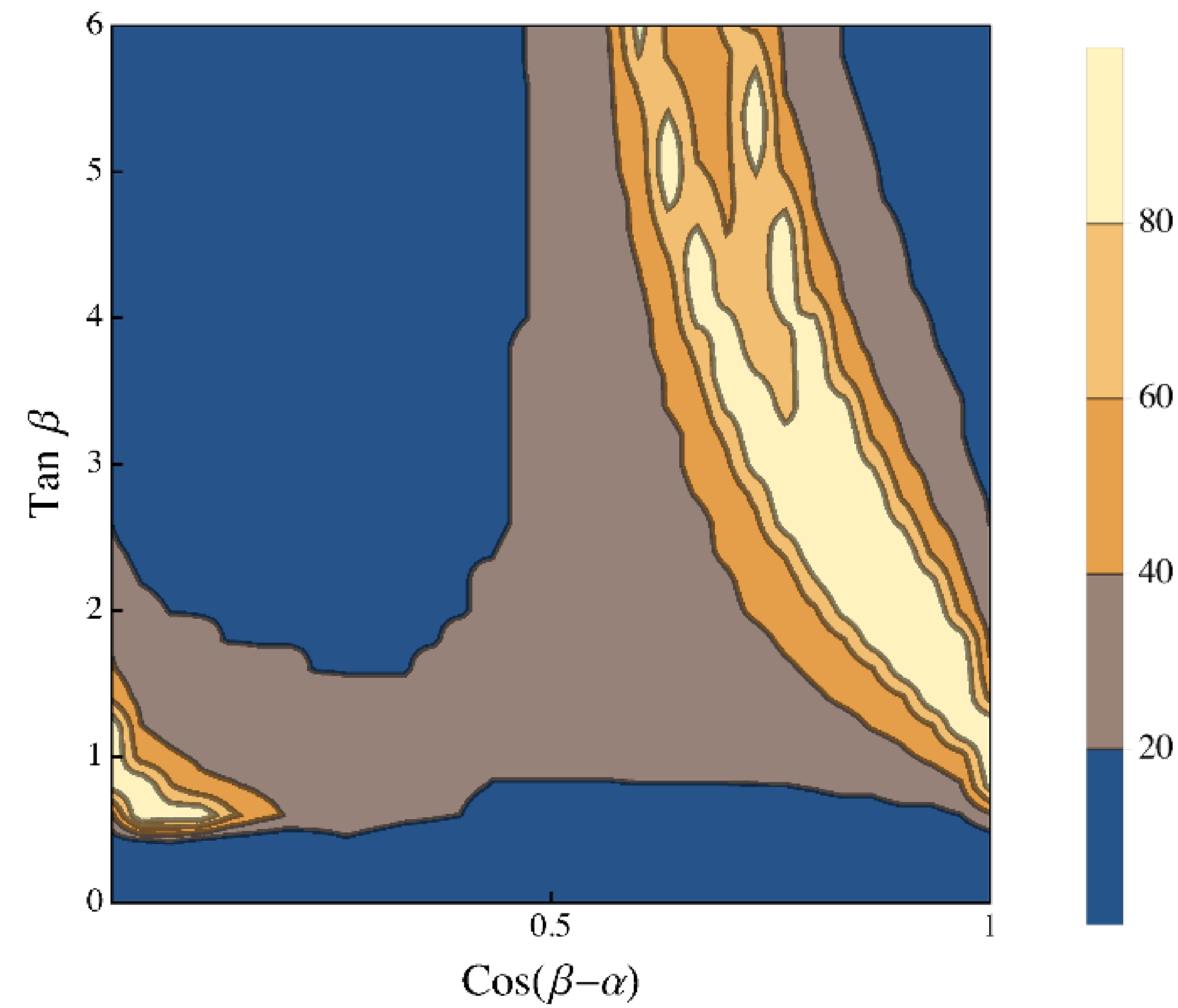
$$\begin{aligned}\mathcal{H}_{\text{eff}}^{\Delta S=2} &= C_1^{sd}\,(\bar{s}_L\,\gamma_\mu\,d_L)^2 + \tilde{C}_1^{sd}\,(\bar{s}_R\,\gamma_\mu\,d_R)^2 \\ &+ C_2^{sd}\,(\bar{s}_R\,d_L)^2 + \tilde{C}_2^{sd}\,(\bar{s}_L\,d_R)^2 \\ &+ C_4^{sd}\,(\bar{s}_R\,d_L)\,(\bar{s}_L\,d_R) \\ &+ C_5^{sd}\,(\bar{s}_L\,\gamma_\mu\,d_L)\,(\bar{s}_R\,\gamma^\mu d_R) + h.c.\end{aligned}$$

$K^0 - \bar{K}^0$ Mixing

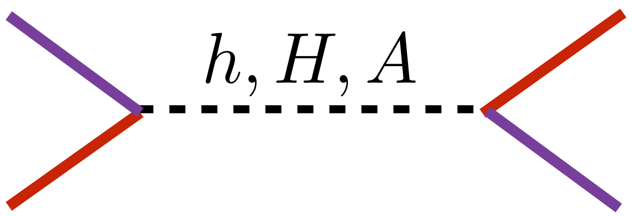


$$\approx \varepsilon^X \frac{m_q^2}{v^2} \left\{ \frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_H^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2} \right\}$$





$K^0 - \bar{K}^0$ Mixing



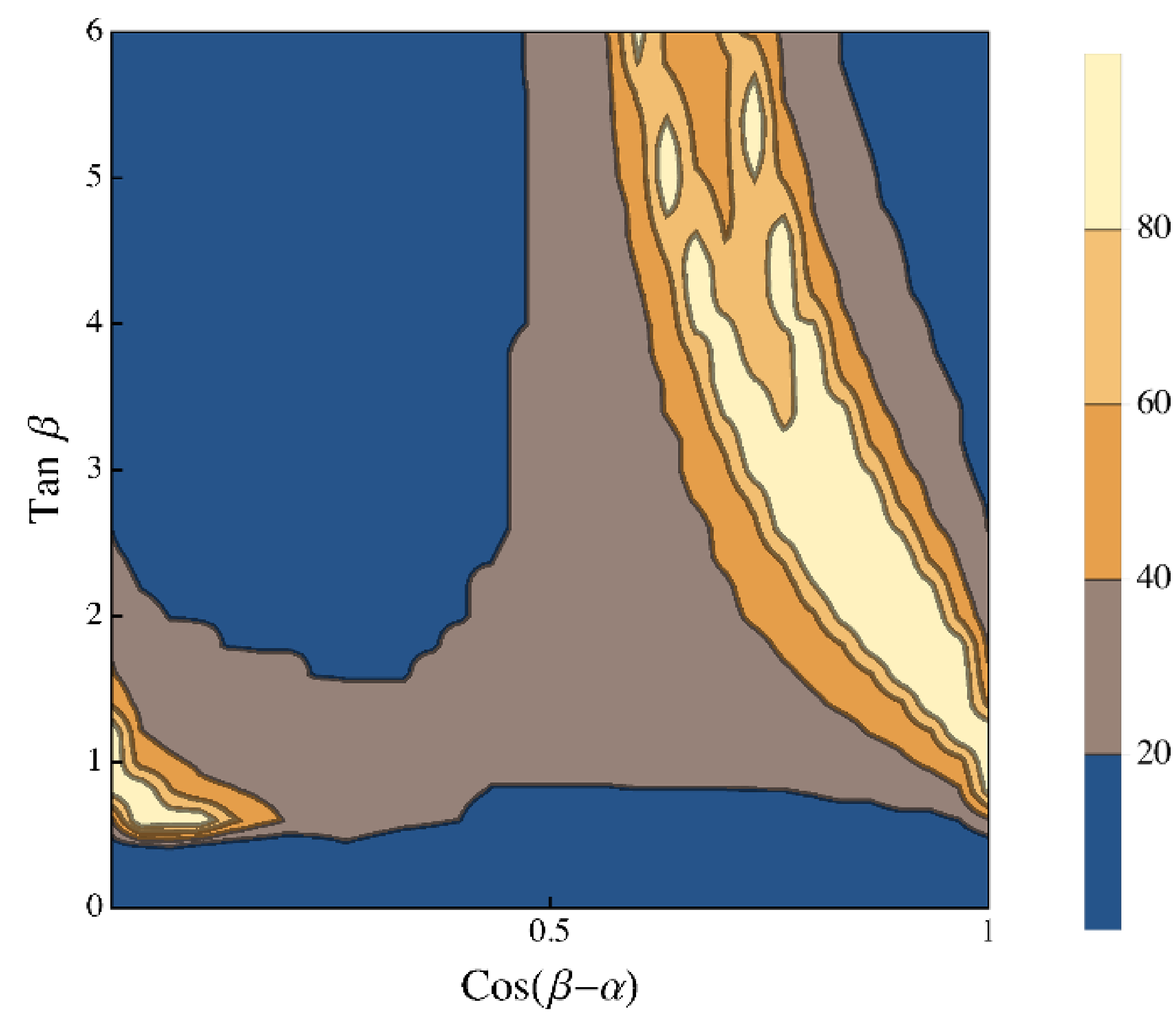
$$\approx \frac{c_i}{v^2}\left\{\frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_h^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2}\right\}$$

Flavor dependent Wilson Coefficient

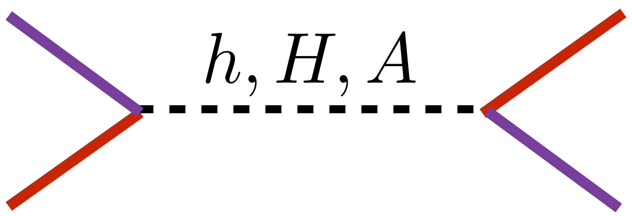
$$\mathcal{Q}^d \sim \begin{pmatrix} 2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & 2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \qquad \mathcal{D} \sim \begin{pmatrix} -1 & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 &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

$$c_2^{sd} = \varepsilon^4 m_s^2$$
$$\tilde{c}_2^{sd} = \varepsilon^2 m_s^2$$
$$c_4^{sd} = \varepsilon^3 m_s^2$$

$M_{H,A} \approx 500\,\mathrm{GeV}$



$B_s^0 - \bar{B}_s^0$ Mixing



$$\approx \frac{c_i}{v^2}\left\{\frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_h^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2}\right\}$$

Flavor dependent Wilson Coefficient

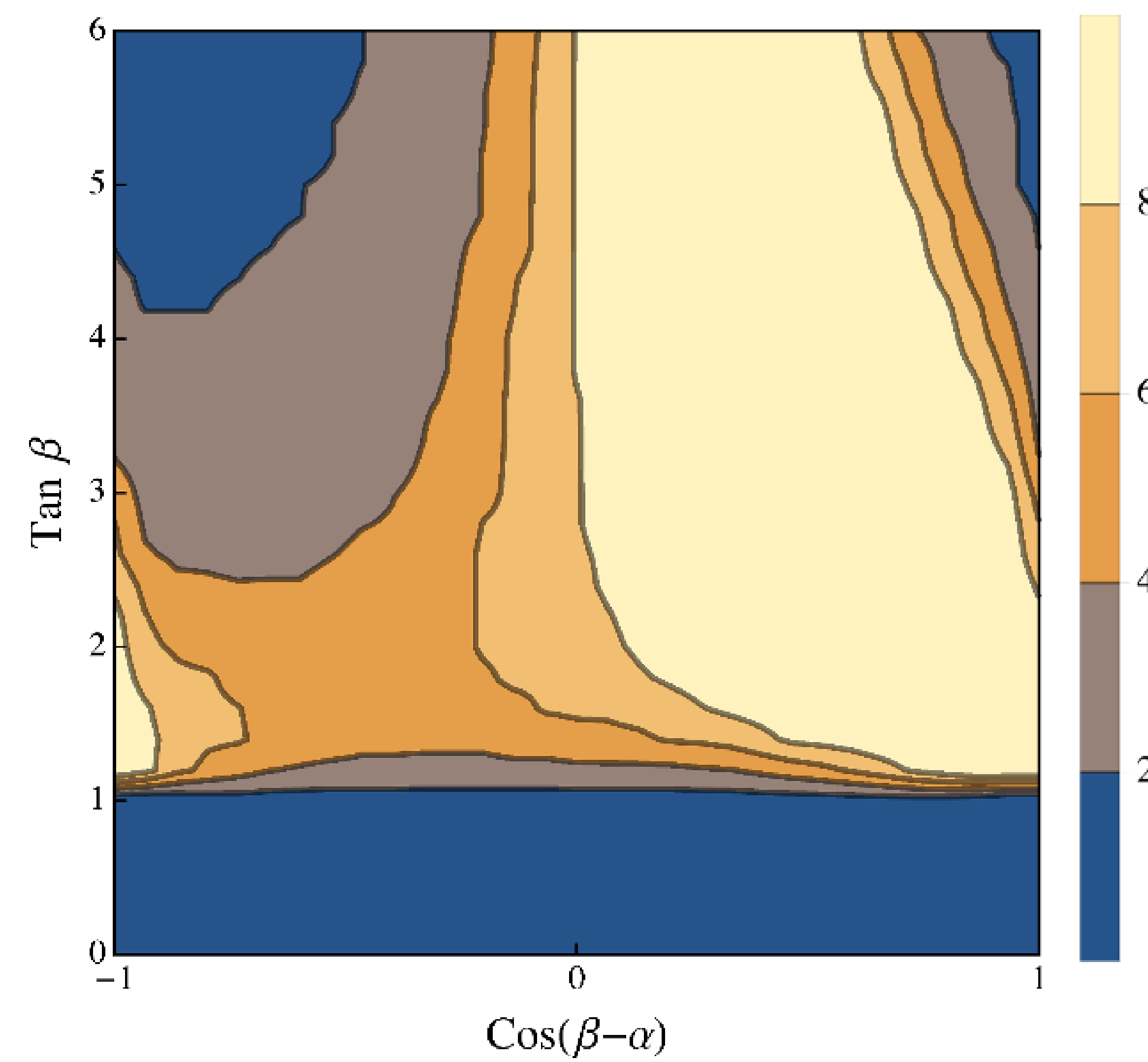
$$\mathcal{Q}^d \sim \begin{pmatrix} 2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & 2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \qquad \mathcal{D} \sim \begin{pmatrix} -1 & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 &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

$M_{H,A} \approx 500\,\mathrm{GeV}$

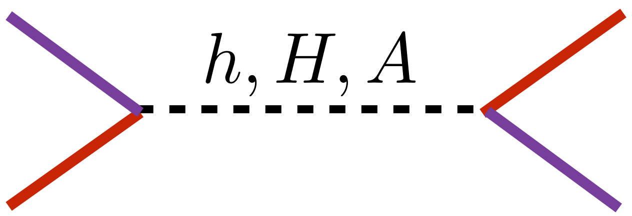
$$c_2^{bs} = \varepsilon^2 m_b^2$$

$$\tilde{c}_2^{bs} = \varepsilon^4 m_b^2$$

$$c_4^{bs} = \varepsilon^3 m_b^2$$



$B_d^0 - \bar{B}_d^0$ Mixing



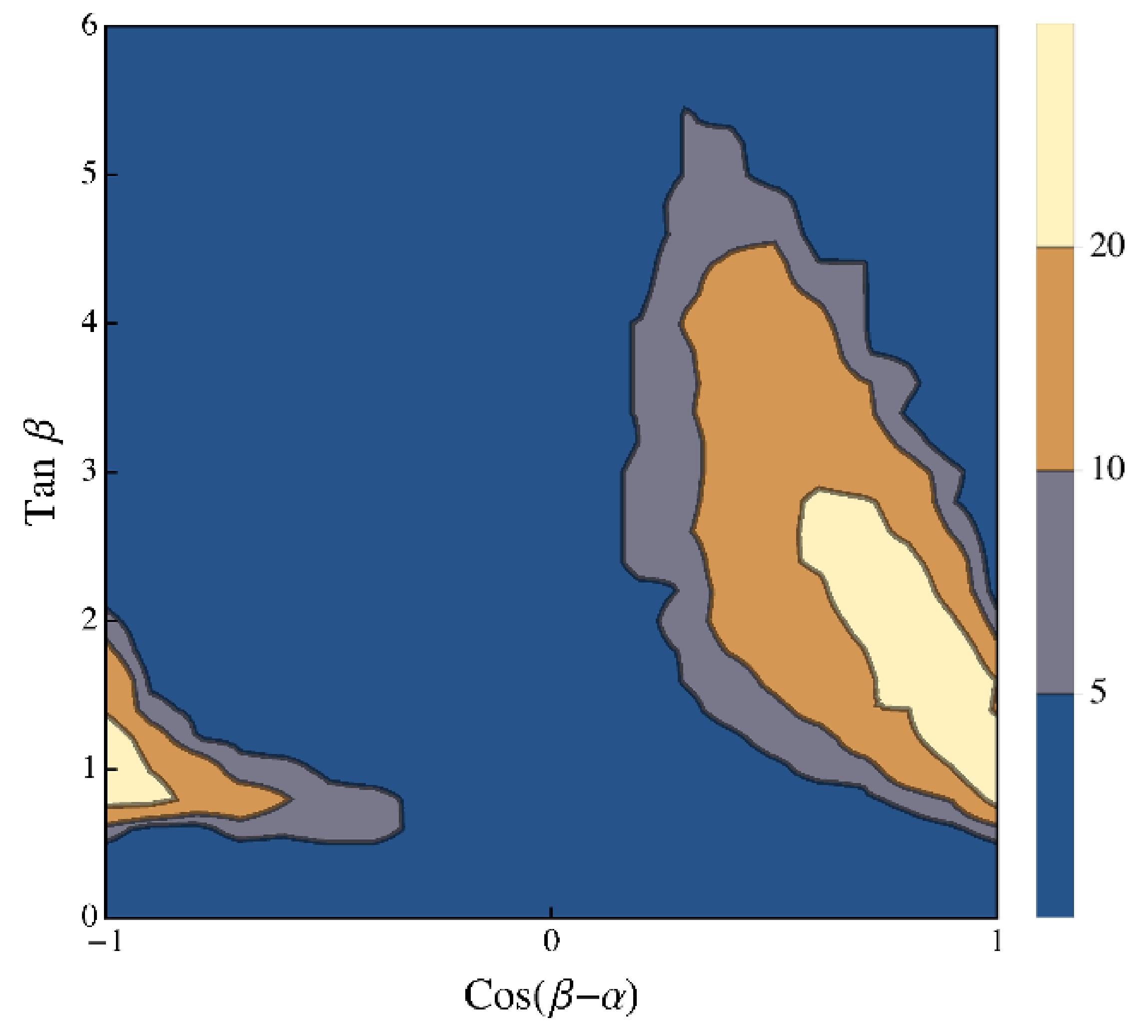
$$\approx \frac{c_i}{v^2}\left\{\frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_h^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2}\right\}$$

Flavor dependent Wilson Coefficient

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

$M_{H,A} \approx 500\,\mathrm{GeV}$

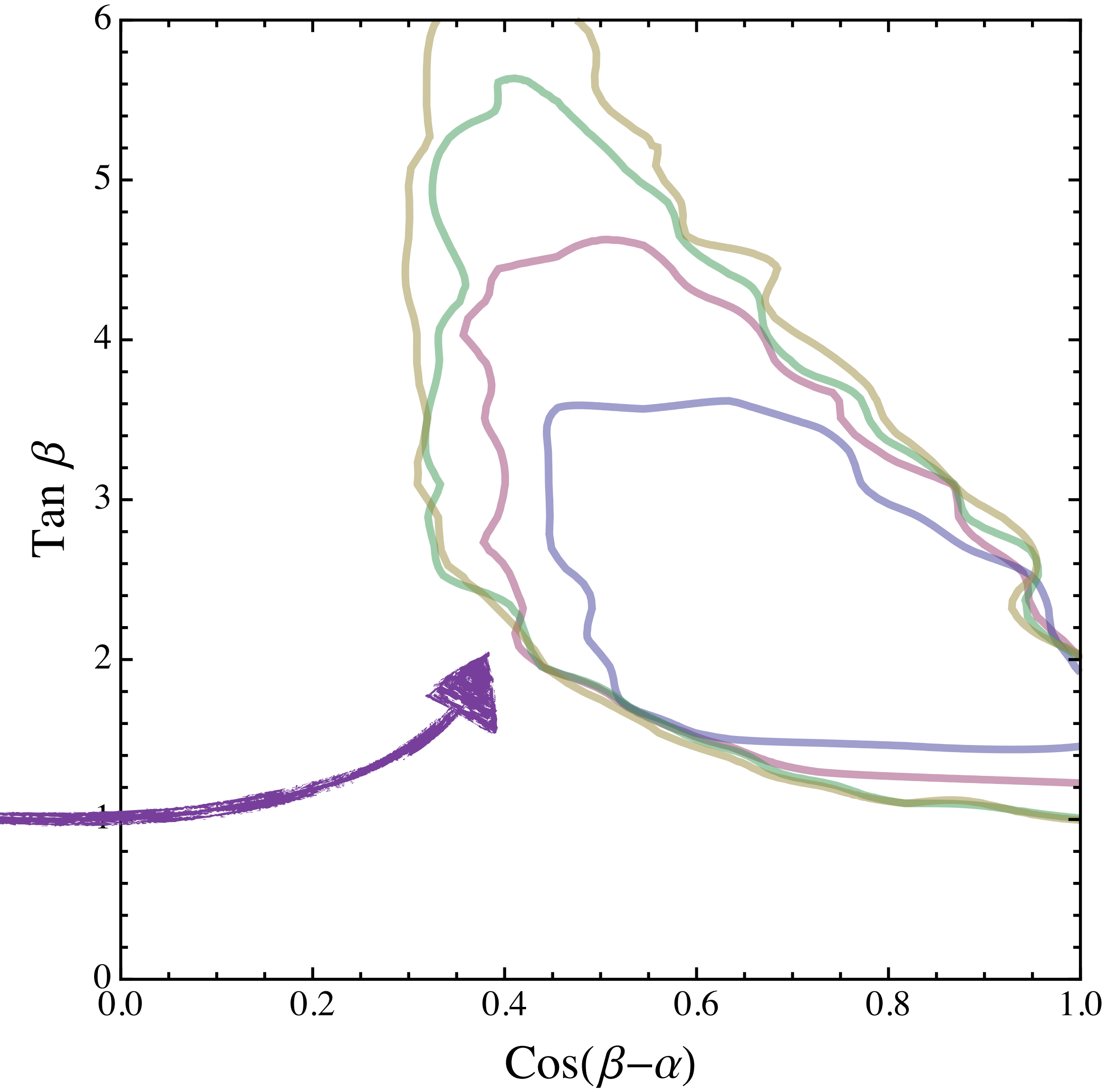
$$c_2^{bd} = \varepsilon^2 m_b^2$$
$$\tilde{c}_2^{bd} = \varepsilon^2 m_b^2$$
$$c_4^{bd} = \varepsilon^2 m_b^2$$



Flavor Bounds

$$M \equiv M_H = M_A = M_{H^+}$$

- $M = 700\,\mathrm{GeV}$
- $M = 600\,\mathrm{GeV}$
- $M = 500\,\mathrm{GeV}$
- $M = 400\,\mathrm{GeV}$



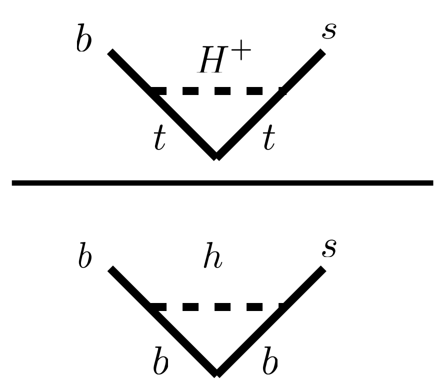
10% Contours

Flavor Bounds

- Contributions to rare leptonic decays depend on the lepton flavor sector
- Bounds from Loop induced processes like $b \to s\gamma$ put constraints on the mass of the charged scalar

$$M_{H^\pm} \gtrsim 358\,(480)\,\text{GeV} \quad @\,99\%(95\%)\ \text{CL}$$ [Misiak et al. 1503.01789]

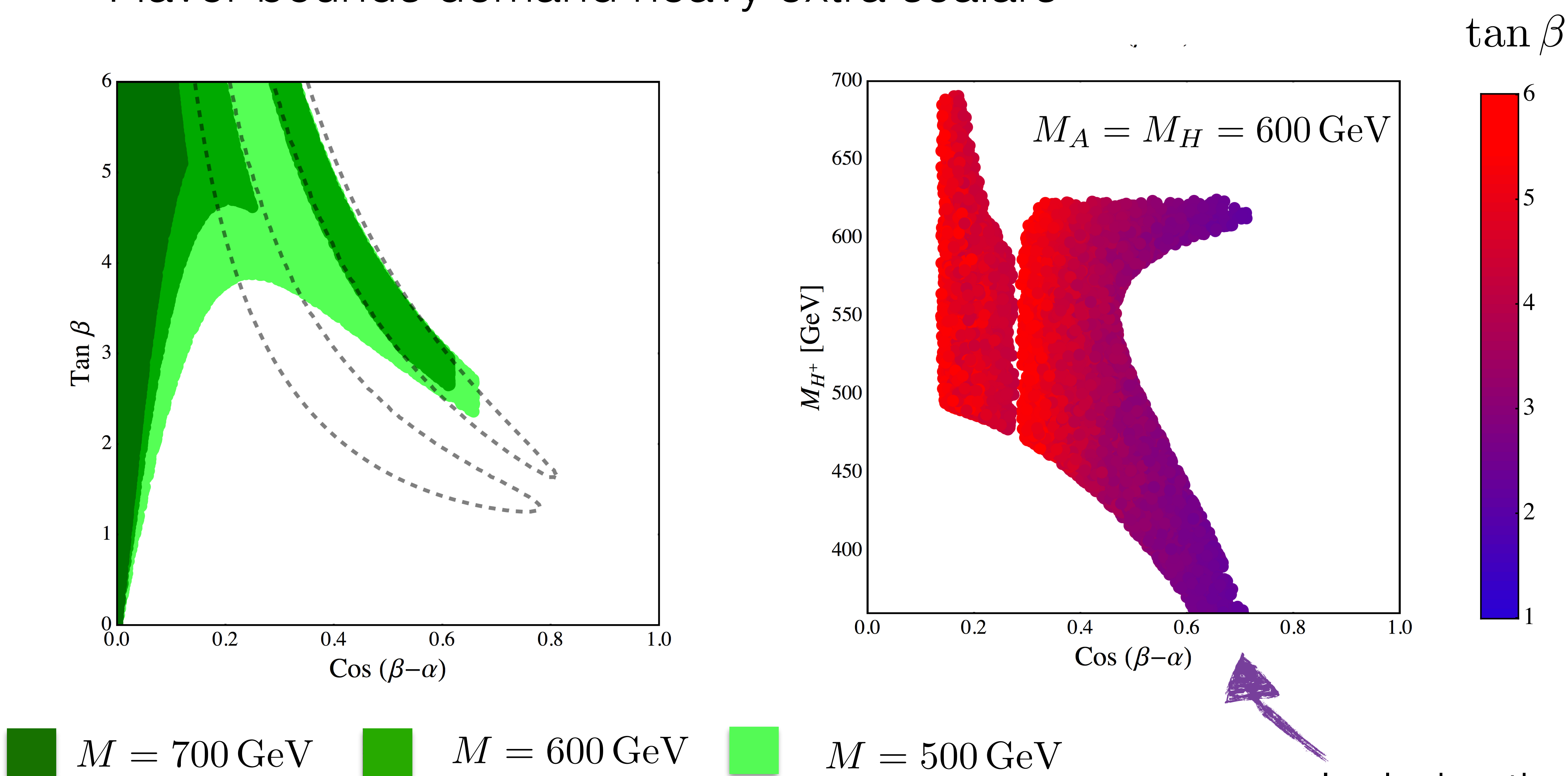
- Neutral Scalar contributions are typically much smaller



$$\frac{m_t\, V_{tb}\, V_{ts}^*}{m_b\, f(\alpha,\beta)\,\varepsilon} \approx \mathcal{O}(10^2 - 10^3)$$

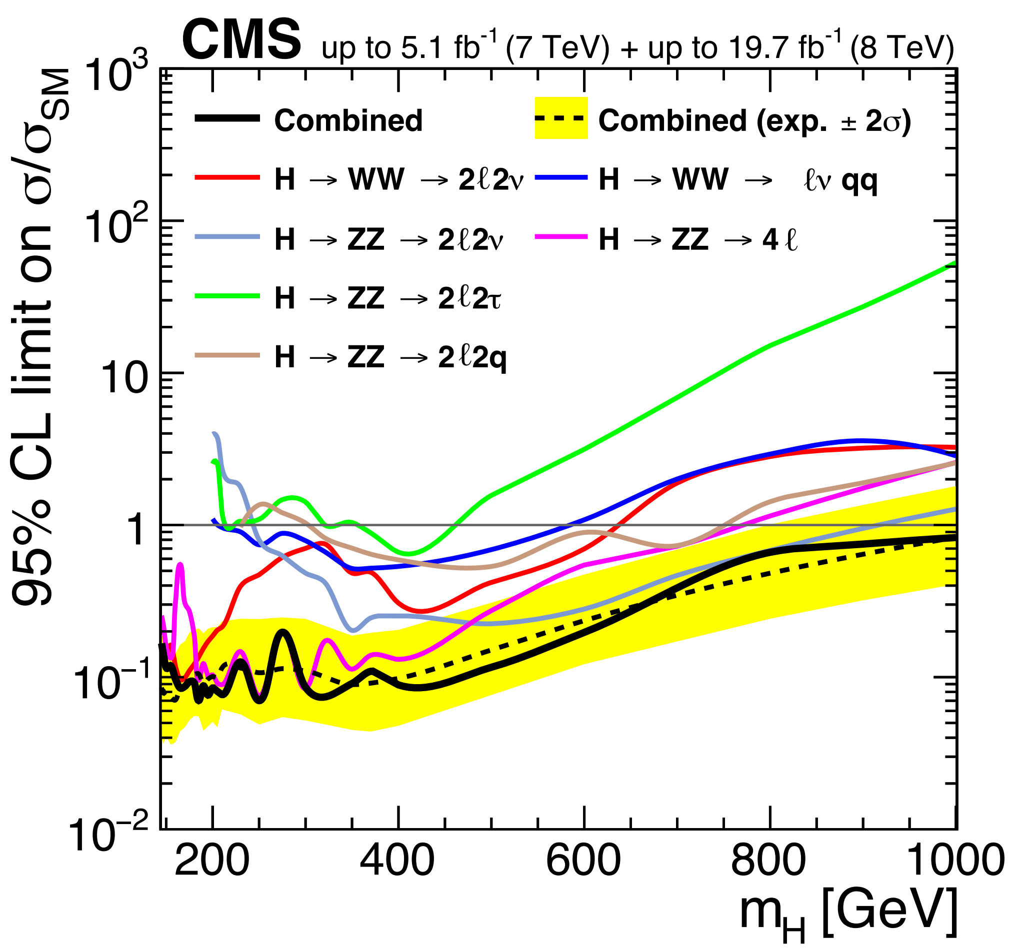
Decoupling and EWPM

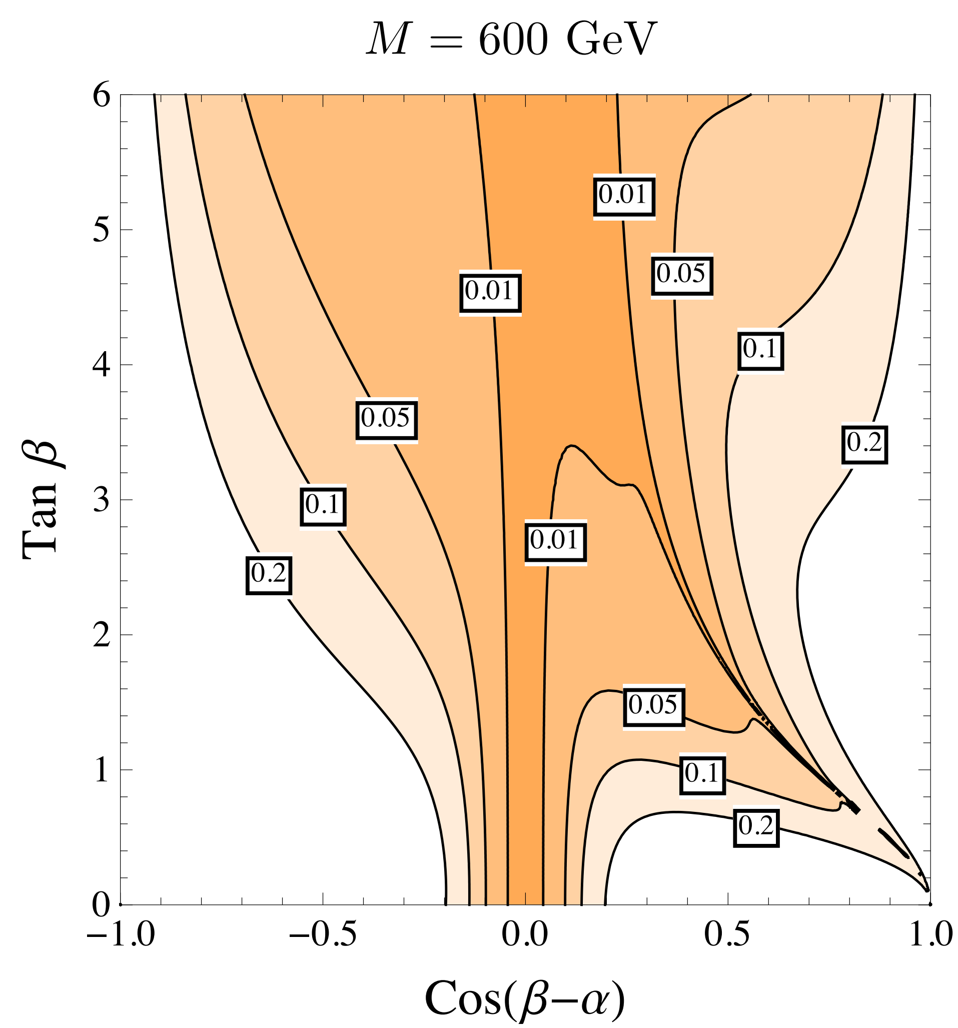
- The global Higgs fit (and Flavor bounds) demand sizable $\cos(\beta-\alpha)$
- Flavor bounds demand heavy extra scalars



Includes the Higgs fit

Collider Searches for Heavy Higgses



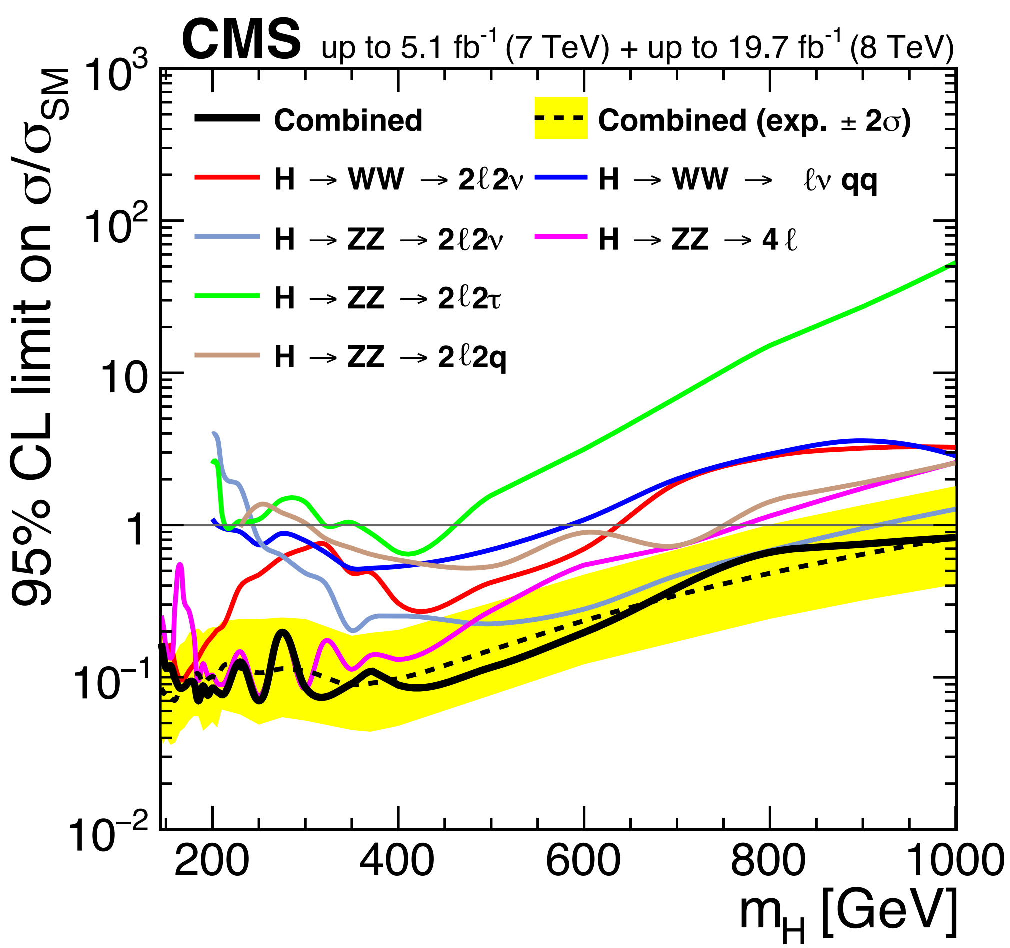


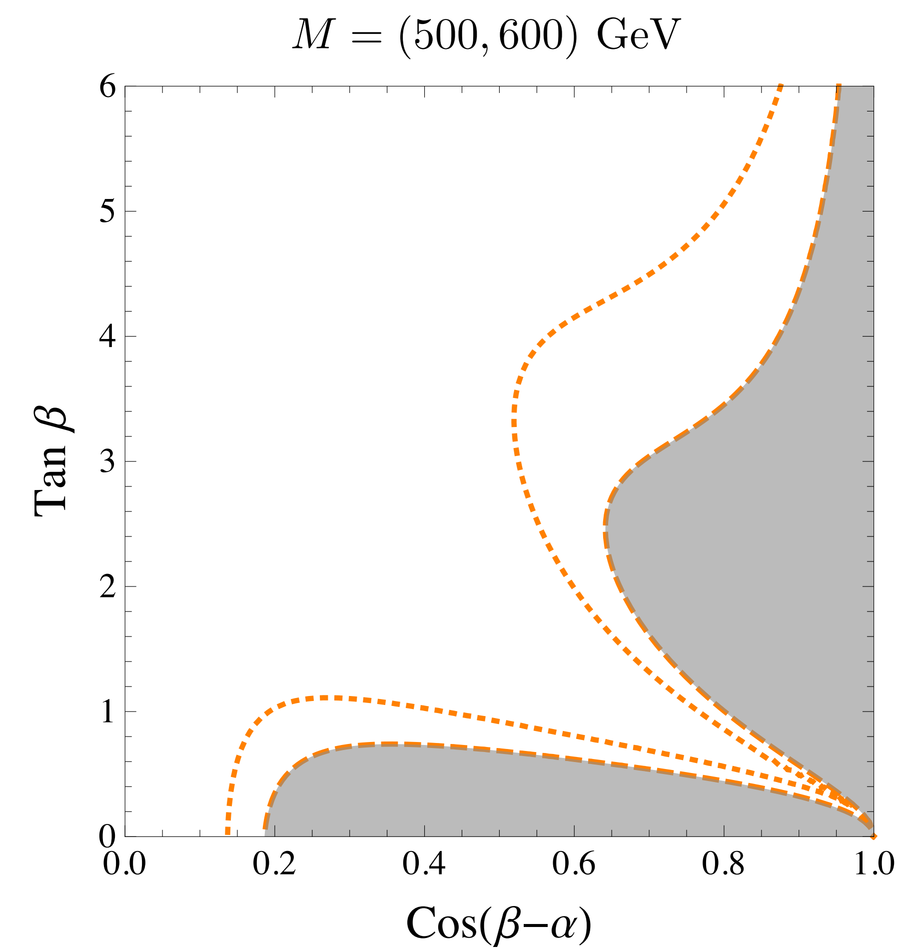
$$\frac{\sigma(gg \to H) \times \mathrm{Br}(H \to VV)}{(\sigma(gg \to H) \times \mathrm{Br}(H \to VV))_{\mathrm{SM}}} = (\kappa_t^H)^2 \left(1 + \xi_b^H \frac{\kappa_b^H}{\kappa_t^H}\right)^2 (\kappa_V^H)^2 \frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H},$$

$$\frac{\sigma(pp \to qqH) \times \mathrm{Br}(H \to VV)}{(\sigma(pp \to qqH) \times \mathrm{Br}(H \to VV))_{\mathrm{SM}}} = (\kappa_V^H)^4 \frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H},$$

[CMS 1504.00936]

Collider Searches for Heavy Higgses



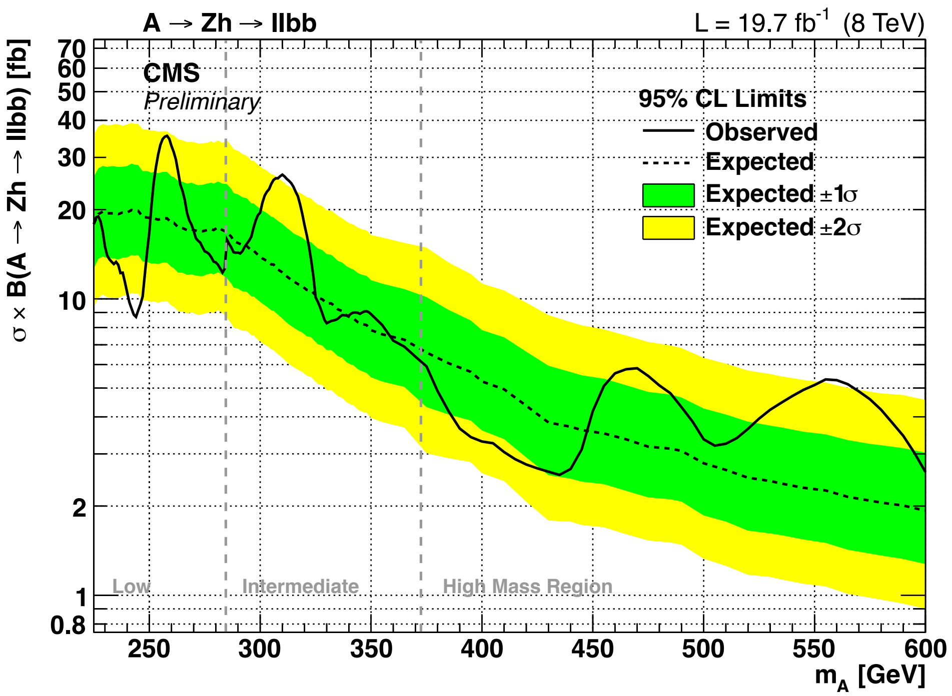


$$\frac{\sigma(gg\to H)\times \mathrm{Br}(H\to VV)}{(\sigma(gg\to H)\times \mathrm{Br}(H\to VV))_{\mathrm{SM}}} = (\kappa_t^H)^2\left(1+\xi_b^H\frac{\kappa_b^H}{\kappa_t^H}\right)^2(\kappa_V^H)^2\,\frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H}\,,$$

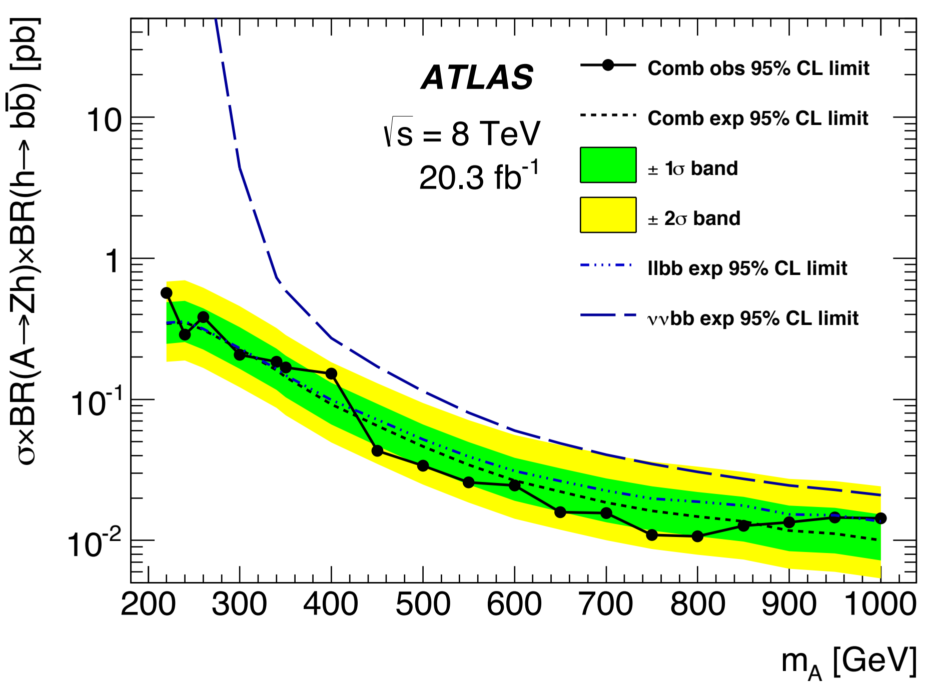
$$\frac{\sigma(pp\to qqH)\times \mathrm{Br}(H\to VV)}{(\sigma(pp\to qqH)\times \mathrm{Br}(H\to VV))_{\mathrm{SM}}} = (\kappa_V^H)^4\,\frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H}\,,$$

[CMS 1504.00936]

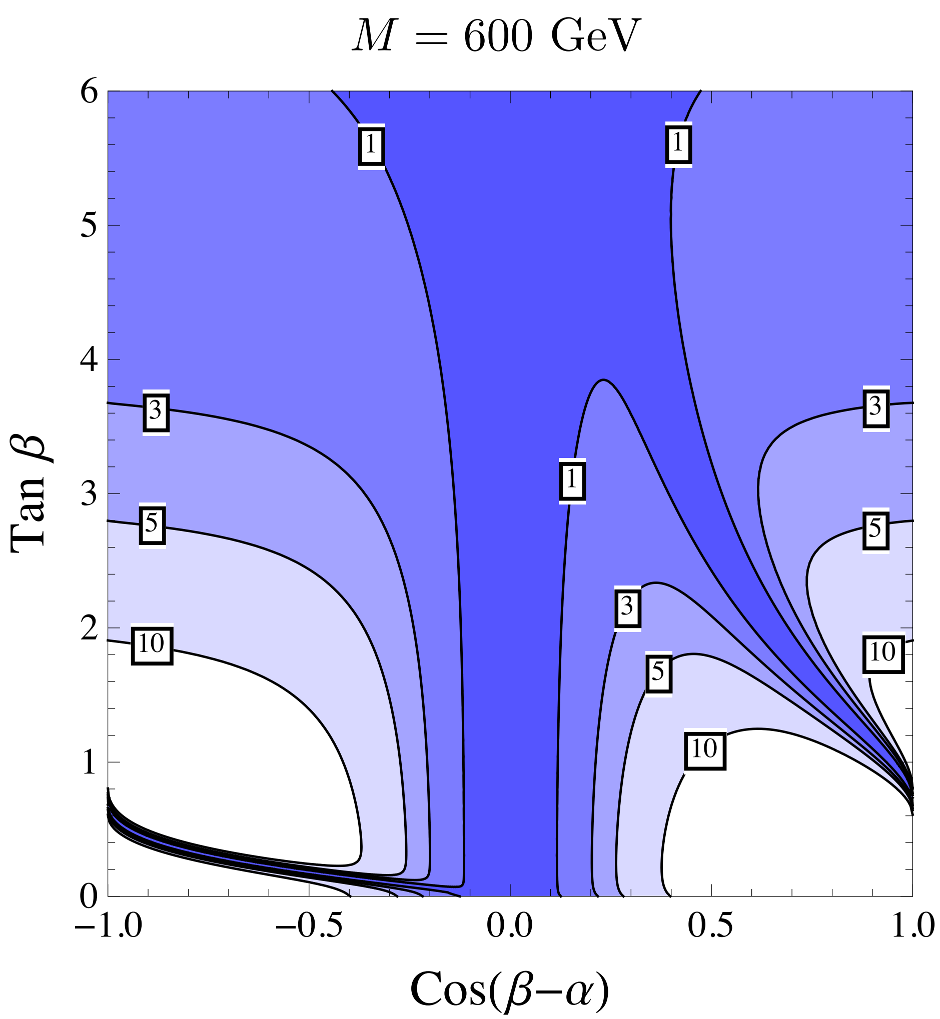
Collider Searches for Heavy Higgses



CMS PAS HIG-14-011

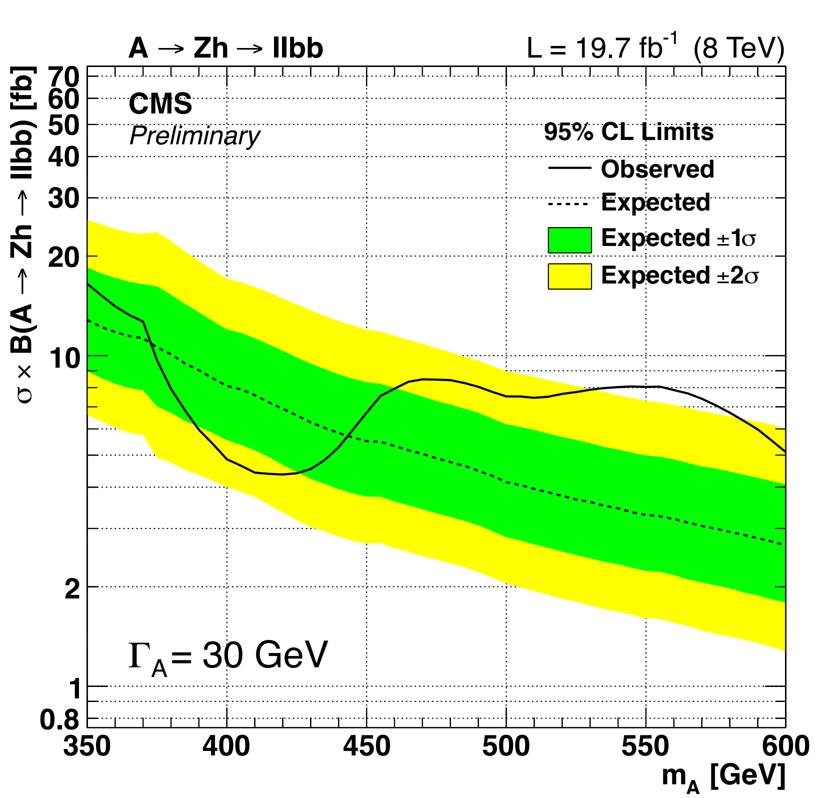


[ATLAS 1502.04478]

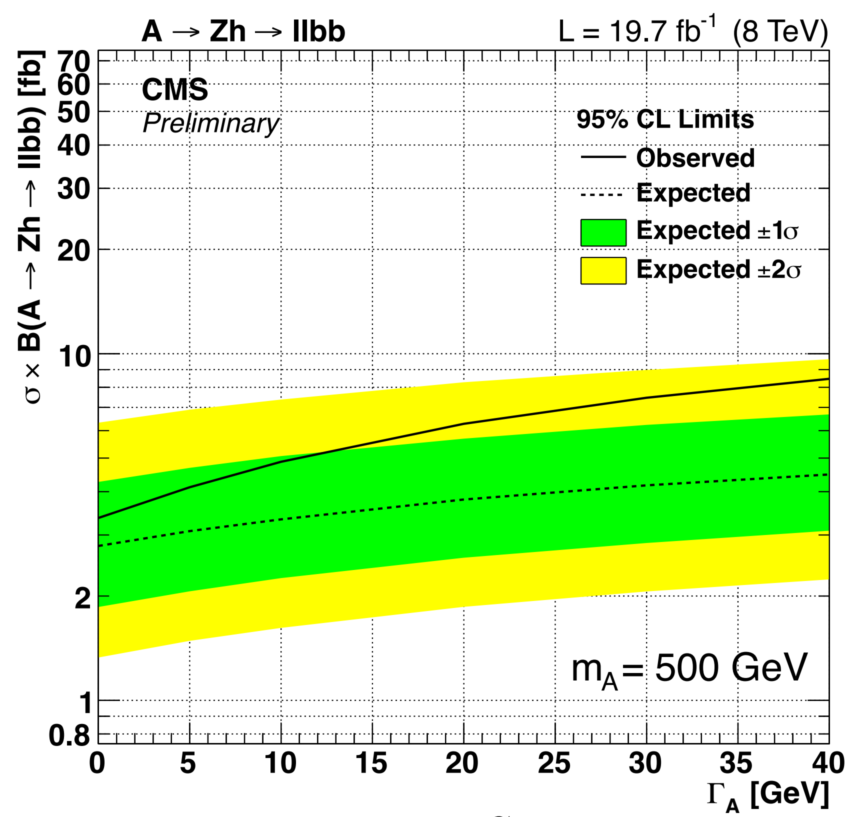


$$\sigma(gg \to A) \times \text{Br}(A \to hZ \to \ell^+\ell^- b\bar{b})$$

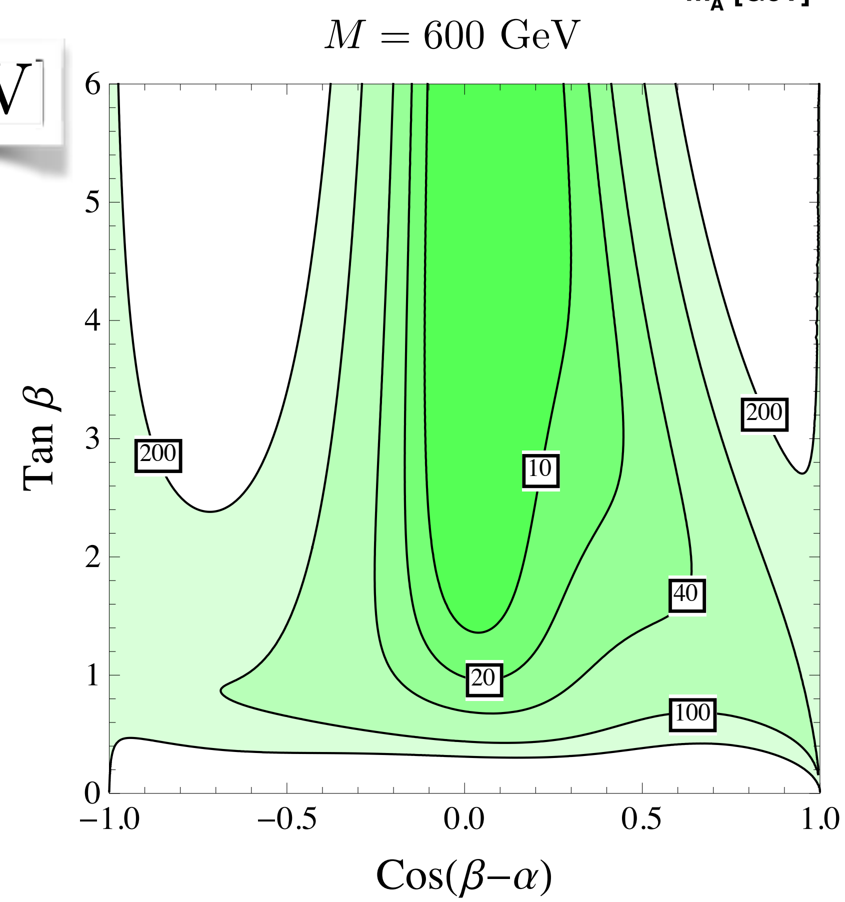
Finite Width Effects



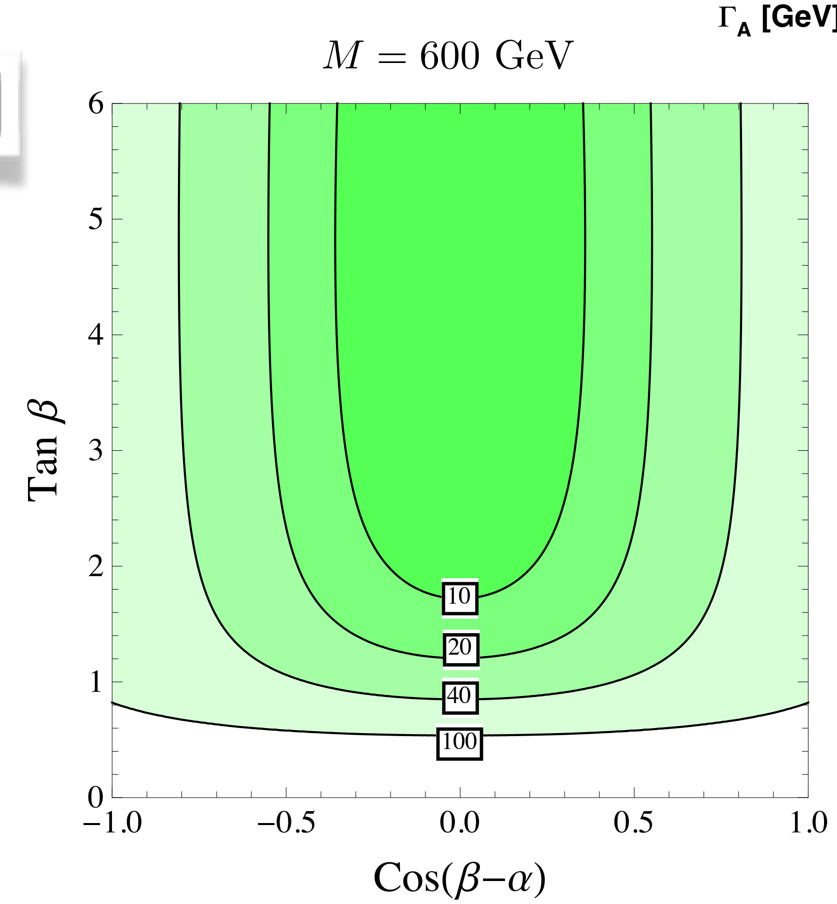
CMS PAS HIG-14-011



Γ_A[GeV]

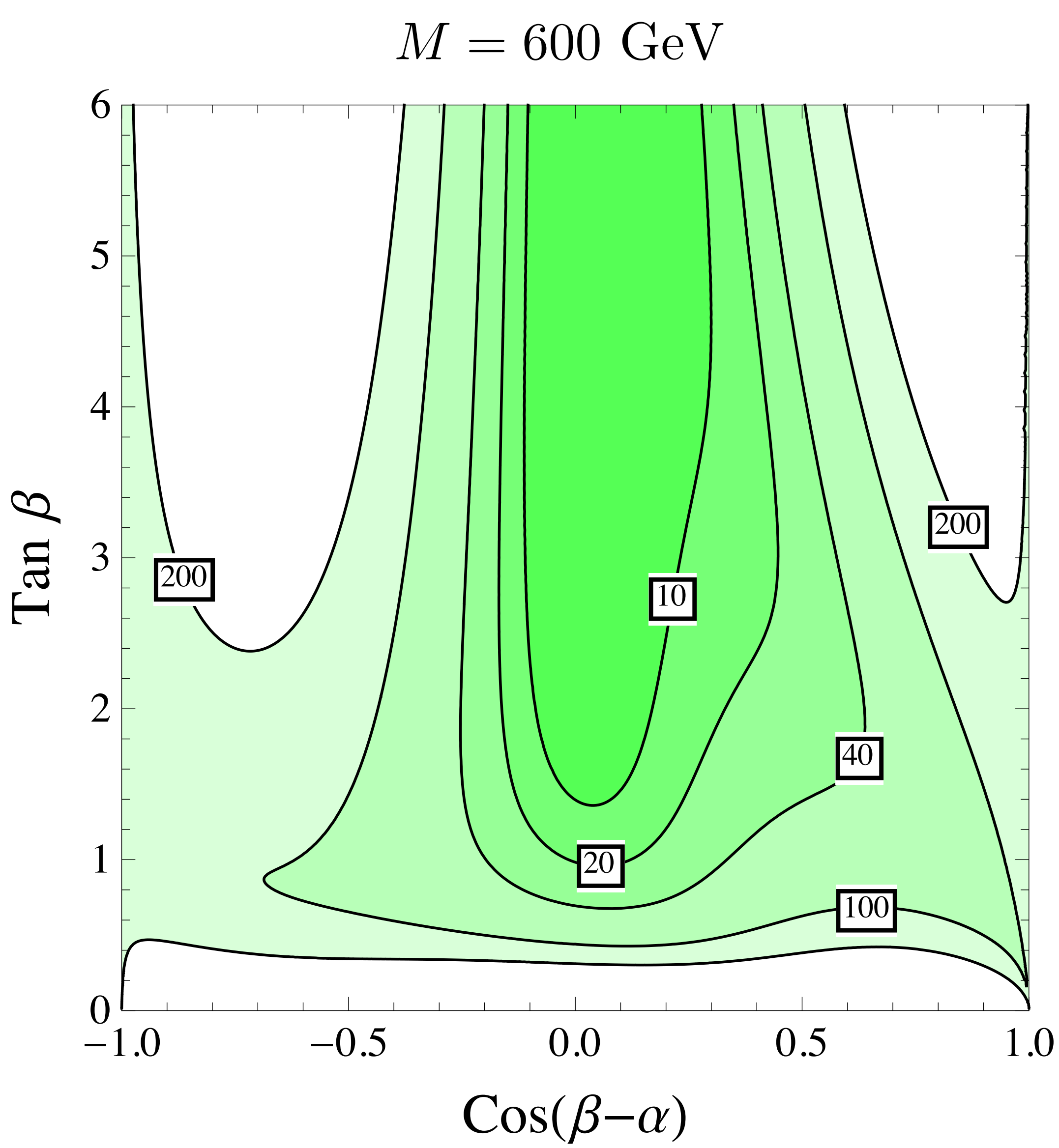


Γ_H[GeV]

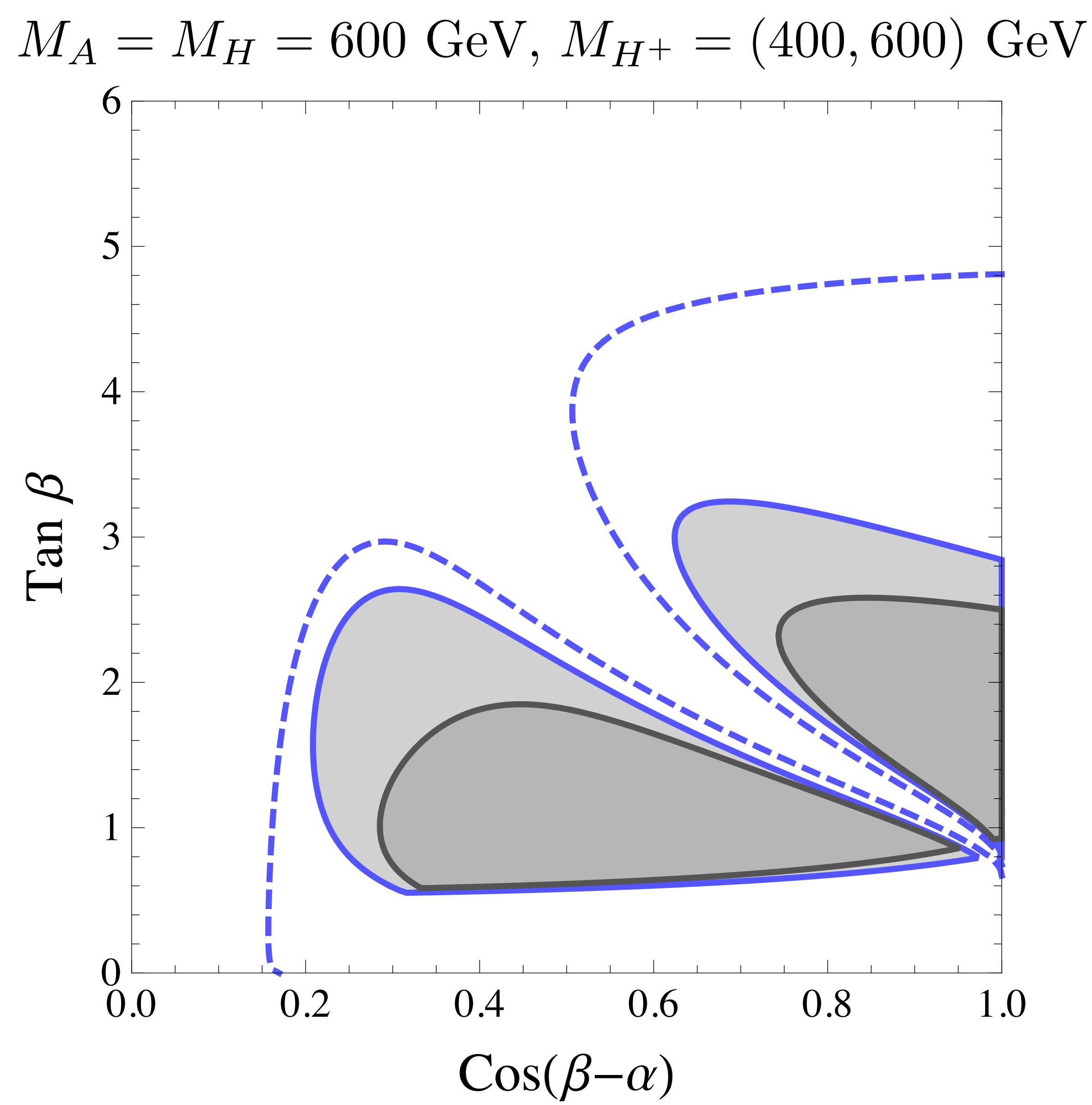


Finite Width Effects

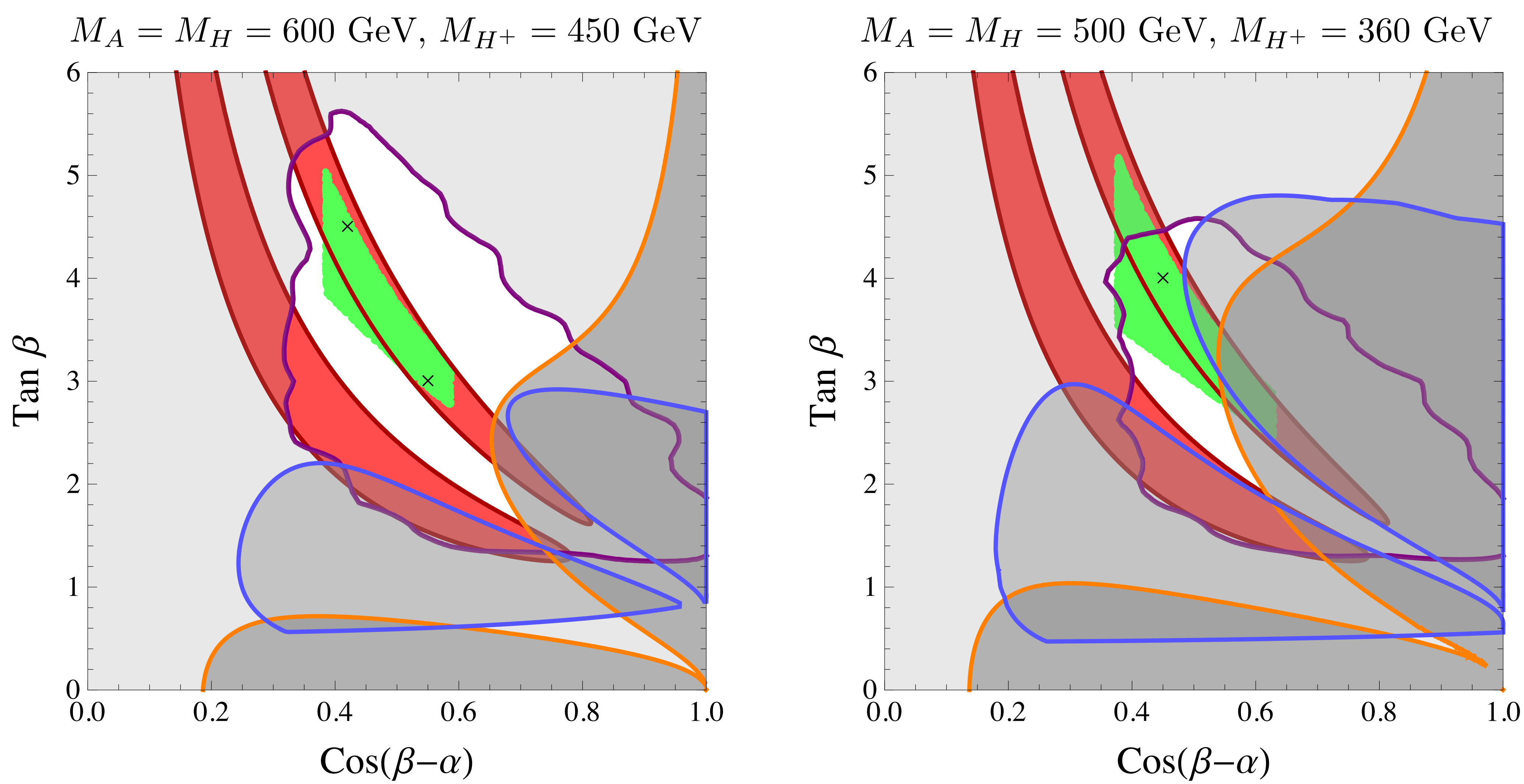
$\Gamma_A[\text{GeV}]$



$\sigma(gg \to A) \times \text{Br}(A \to hZ \to \ell^+\ell^- b\bar{b})$



Final Plots



Flavour constraint

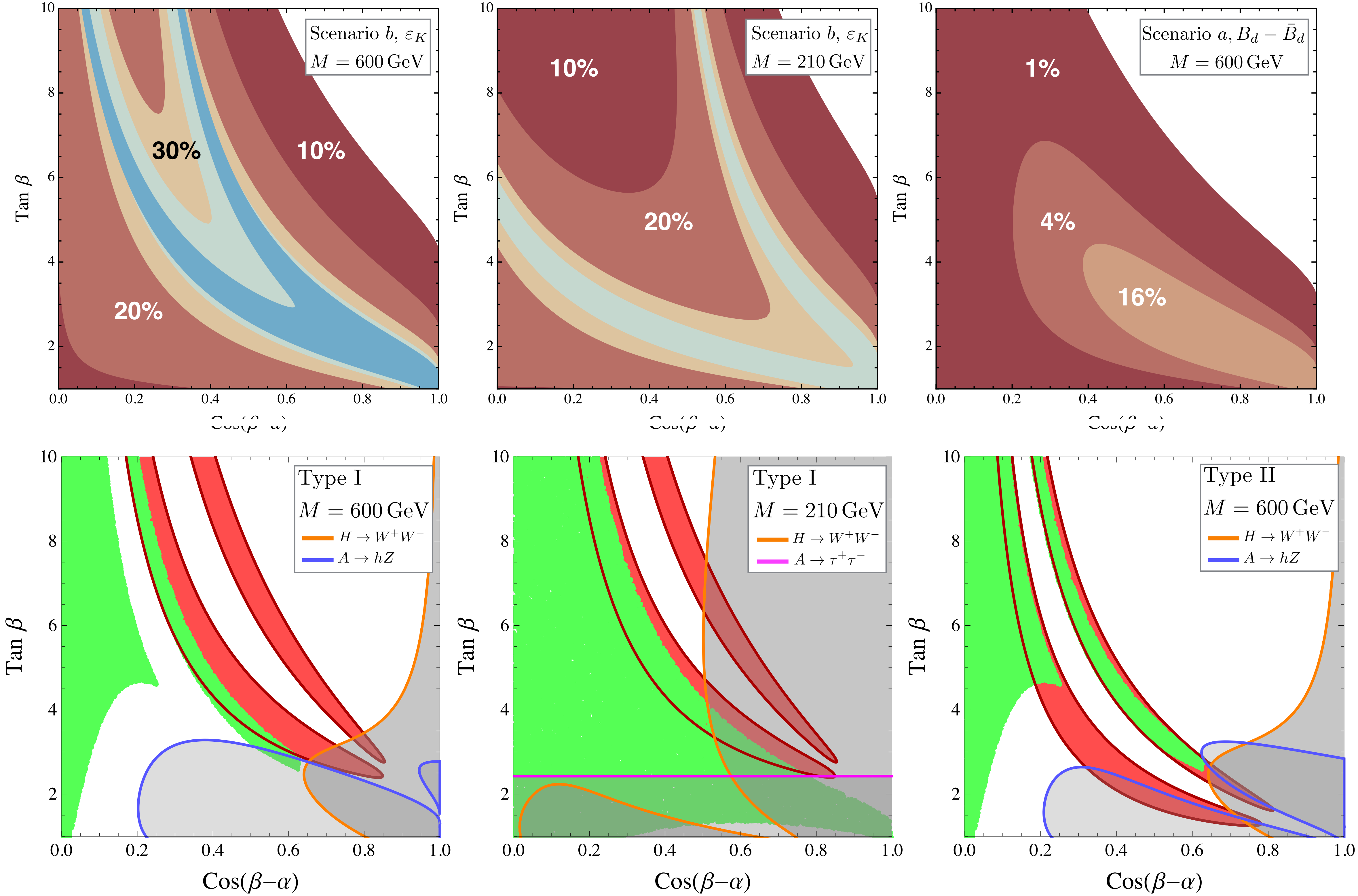
Pseudoscalar into

Heavy scalar into gauge bosons

Global Higgs fit

EWPB

Type I vs Type II



Conclusions

- Electroweak scale flavor symmetries will be discovered or excluded by the LHC.

- A generic flavon is very hard to discover. A 100 TeV collider would be the first machine in history with a realistic shot.

- The upcoming golden age of Lepton flavor will test the flavor structure in the lepton sector and improve on the bounds in the quark sector