Partially Composite Higgs Models

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CP^3-Origins

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- Motivations

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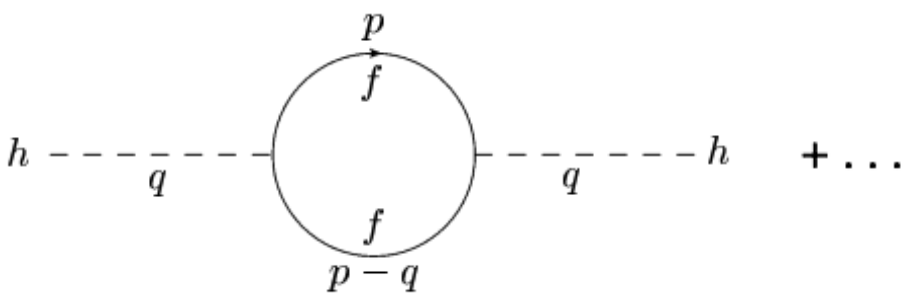
- Conclusions

The Electroweak (EW) Hierarchy Problem

- Loop corrections to the Higgs mass

$$m_h^2 = m_{h0}^2 + \delta m_{h0}^2 = m_{h0}^2 + k\Lambda^2 + \dots$$

where m_h and m_{h0} are the physical and bare mass of the Higgs boson, respectively, $k = 2.57 \cdot 10^{-2}$ and Λ is the cut-off scale above new physics happens.



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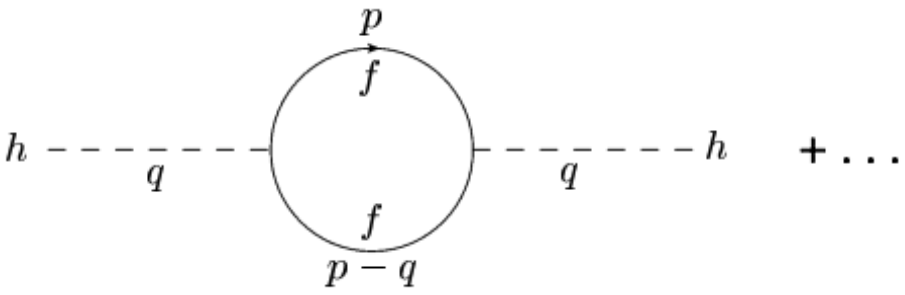
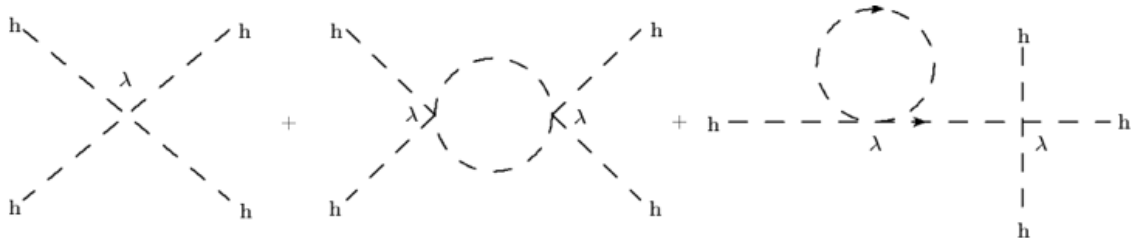


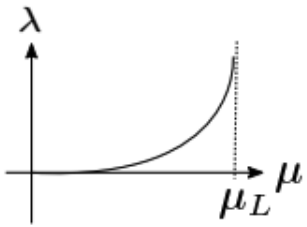
- The bare mass of the Higgs boson must be highly fine-tuned if the cut-off scale is high (e.g. Λ equals Planck scale):

$$\begin{aligned} m_{h0}^2 &= m_h^2 - k\Lambda_{Planck}^2 + \dots \\ &\approx (125\ \text{GeV})^2 - (2 \cdot 10^{18}\ \text{GeV})^2. \end{aligned}$$

The Vacuum Stability in the Standard Model

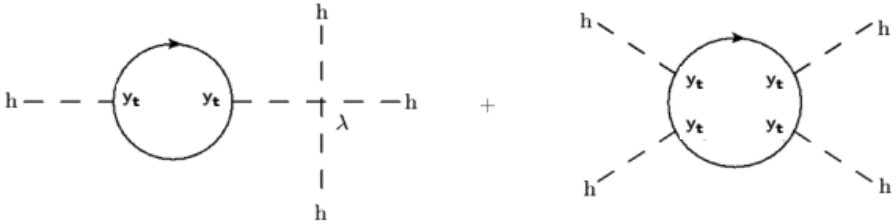
- The RG running of the quartic Higgs coupling:

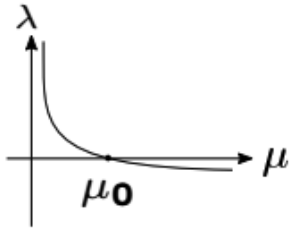




Trivial Theory

- Adding SM (top) Yukawa contributions:





Unstable Theory

- The beta function of the Higgs quartic coupling, λ,

$$\beta_\lambda \equiv \mu \frac{\partial \lambda}{\partial \mu} = \frac{1}{(4\pi)^2}\left(24\lambda^2 + 12\lambda y_t^2 - 6y_t^4 + \dots\right),$$

where y_t is the Yukawa coupling of the top quark.

Composite Dynamics for EW Symmetry Breaking (EWSB)

- New strong interactions (Farhi and Susskind, Phys.Rept. 74 (1981) 277):

$$G_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$$

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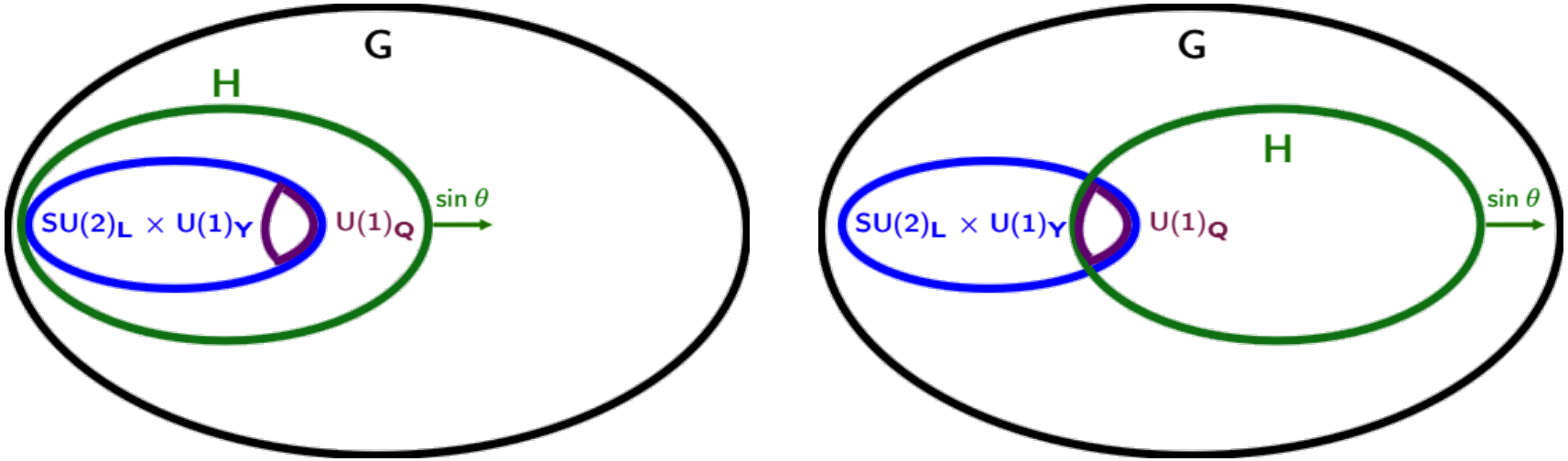
- Chiral symmetry breaking: $G \to H$
- EW unbroken vacuum Σ_{CH} ($\sin\theta = 0$): $G \to H \supset SU(2)_L \times U(1)_Y$
- Technicolor vacuum Σ_{TC} ($\sin\theta = 1$): $G \to H \supset U(1)_Q$
- Composite Higgs vacuum: $\Sigma_0 = \cos\theta \Sigma_{CH} + \sin\theta \Sigma_{TC}$



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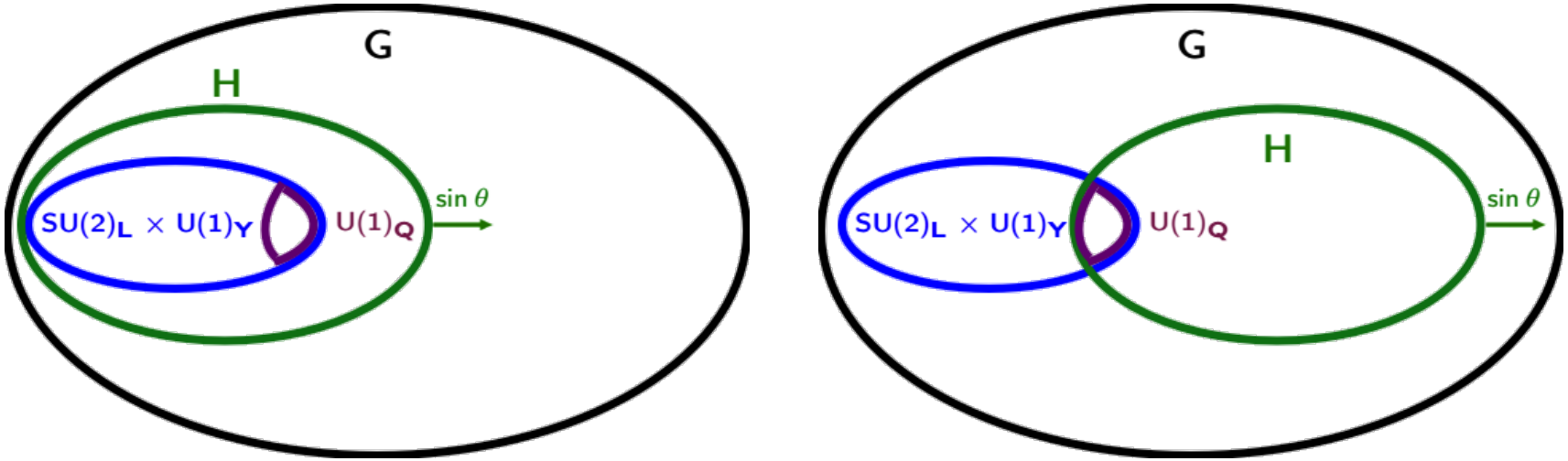
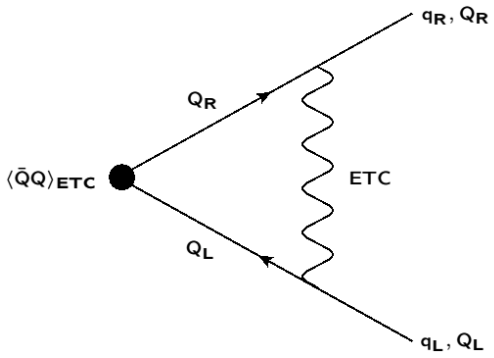


- TC and CH models (partially) generate dynamically the EWSB and therefore the masses of EW bosons and a natural the Higgs mass.

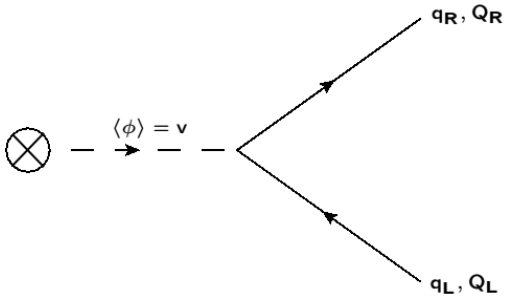
Fermion Mass Problem

i) 4 fermion operators ($\bar{q}q\bar{Q}Q$ and $\bar{Q}Q\bar{Q}Q$):



$$m_f \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2}\langle\bar{Q}Q\rangle_{ETC}$$

ii) Yukawa couplings ($\phi\bar{Q}Q$ and $\phi\bar{q}q$):



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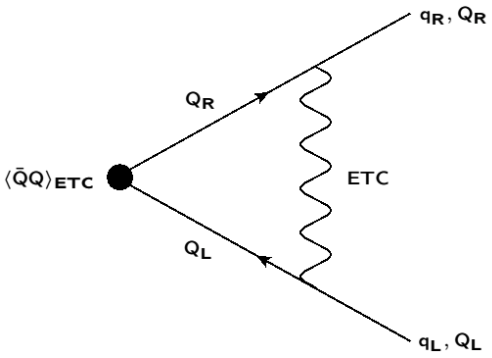

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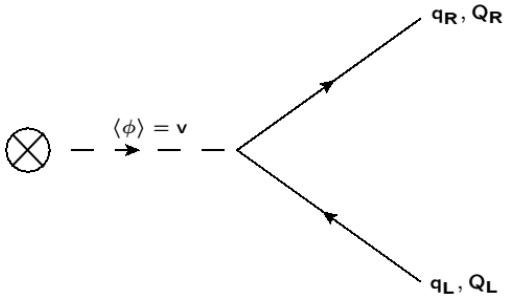

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- Models generating masses of the fermions:

Extended TC (ETC) — Bosonic TC (bTC) } Chiral symmetry breaking and EWSB simultaneous

Composite Higgs (CH) — Partially CH (pCH) } EW symmetry preserved after chiral symmetry breaking

The Higgs boson is purely composite

The Higgs boson is a mixture between a composite and a fundamental Higgs

Partially Composite Higgs (pCH) Models

- New fermion content (Galloway et al., 2017, arXiv:1609.05883 and Alanne et al., 2017, arXiv:1709.10473):

	$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
Q_L	$\square$	$\square$	0
$\widetilde{U}_L$	$\square$	1	$-1/2$
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- A SU(4) vector is defined as

$$\mathbf{Q} \equiv \left(\mathbf{U_L}, \mathbf{D_L}, \tilde{\mathbf{U}}_\mathbf{L}, \tilde{\mathbf{D}}_\mathbf{L}\right)^\mathbf{T}, \quad \text{with} \quad \tilde{\mathbf{U}}_\mathbf{L} \equiv \epsilon \mathbf{U}_\mathbf{R}^*$$

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$$\Sigma = \exp\left(i\frac{2\sqrt{2}}{f}\Pi^a X^a\right)\Sigma_0, \quad \text{with} \quad \Sigma_0 = \cos\theta\Sigma_{CH} + \sin\theta\Sigma_{TC},$$

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- The EW scale is

$$v_{EW}^2 = v^2 + f^2\sin^2\theta,$$

where $v_{EW} = 246$ GeV, f is the GB decay constant and θ is the vacuum alignment angle ($\pi/2 \leq \theta \leq \pi$).

1st term: The vev of the new fundamental Higgs boson
2nd term: The contribution to v_{EW} from the composite Higgs

Model I: Elementary Scalar Doublet

- An elementary scalar doublet and vector-like masses (Galloway et al., 2017, arXiv:1609.05883):

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sigma_h - i\pi_h^3 \\ -(\pi_h^2 + i\pi_h^1) \end{pmatrix}, \quad M = \begin{pmatrix} m_1\epsilon & 0 \\ 0 & -m_2\epsilon \end{pmatrix}$$

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- The fundamental pCH Lagrangian:

$$\begin{aligned}\mathcal{L}_{pCH} =& i\bar{Q}\not{D}Q + D_\mu H^\dagger D^\mu H - m_H^2 H^\dagger H - \lambda_H (H^\dagger H)^2 + \frac{1}{2} Q^T M Q - y_U H_\alpha (Q^T P_\alpha Q) - y_D \tilde{H}_\alpha (Q^T \tilde{P}_\alpha Q) \\ & - y_t \bar{q}_L H t_R - y_b \bar{q}_L \tilde{H} b_R + h.c.\end{aligned}$$

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- Below the condensation scale, $\Lambda_{TC} \sim 4\pi f$, the lowest-order effective potential:

$$V_{eff}^0 = 4\pi f^3 Z_2 \left(\frac{1}{2} \mathrm{Tr}[M\Sigma] + y_U H_\alpha \mathrm{Tr}[P_\alpha \Sigma] + y_D \tilde{H}_\alpha \mathrm{Tr}[\tilde{P}_\alpha \Sigma] + h.c. \right) + m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2.$$

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- The vacuum conditions:

$$\begin{aligned} 0 =& -\sqrt{2} F_0 y_{UD} f^3 s_\theta + m_\lambda^2 v, \\ 0 =& m_{12} s_\theta + y_{UD} v c_\theta / \sqrt{2} \end{aligned}$$

  where $F_0 \equiv 4\pi Z_2$, $m_\lambda^2 \equiv m_H^2 + \lambda_H v^2$ and $t_\beta \equiv v/(f s_\theta)$.

Model II: SU(4) Completion of the Scalar Sector

- We extend the scalar doublet to an SU(4) multiplet (Alanne et al., 2017, arXiv:1709.10473):

$$\Phi = \sum_{\alpha=1,2} P_\alpha H_\alpha + \tilde{P}_\alpha \tilde{H}_\alpha + P_1^S S + P_2^S S^*$$

where $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$ is the EW-singlet scalars, and $H_\alpha \equiv \mathrm{Tr}[P_\alpha \Phi]$ and $\tilde{H}_\alpha \equiv \mathrm{Tr}[\tilde{P}_\alpha \Phi]$ are the EW doublets with hypercharge $\pm 1/2$.

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- Sources that align the vacuum explicitly

$$V_{gauge} = -C_g \left[g_2^2 f^4 \sum_{i=1}^{4} \mathrm{Tr}\left(T_L^i \Sigma (T_L^i \Sigma)^*\right) + g_1^2 f^4 \mathrm{Tr}\left(T_R^3 \Sigma (T_R^3 \Sigma)^*\right) \right] \rightarrow \text{ Align towards EW unbroken limit}$$

$$V_{\delta m^2} = 2\delta m^2 \mathrm{Tr}[P_i^S \Phi] \mathrm{Tr}[P_i^S \Phi]^* = \frac{1}{2}\delta m^2 (S_R^2 + S_I^2) \rightarrow \text{ Align towards technicolor limit}$$

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- The fundamental pCH Lagrangian:

$$\mathcal{L}_{pCH_2} = i\bar{Q}\not{D}Q + \mathrm{Tr}[D_\mu \Phi^\dagger D^\mu \Phi] - m_\Phi^2 \mathrm{Tr}[\Phi^\dagger \Phi] - \lambda_\Phi \mathrm{Tr}[\Phi^\dagger \Phi]^2 - y_Q Q^T \Phi Q - y_t \bar{q}_L H t_R - y_b \bar{q}_L \tilde{H} b_R + \mathrm{h.c.}$$

- The lowest-order effective potential:

$$V_{eff}^0 = 4\pi f^3 Z_2 \left(y_Q \mathrm{Tr}[\Phi\Sigma] + \mathrm{h.c.}\right) + m_\Phi^2 \mathrm{Tr}[\Phi^\dagger \Phi] + \lambda_\Phi \mathrm{Tr}[\Phi^\dagger \Phi]^2 .$$

- Sources that align the vacuum explicitly

$$V_{gauge} = -C_g \left[g_2^2 f^4 \sum_{i=1}^{4} \mathrm{Tr}\left(T_L^i \Sigma (T_L^i \Sigma)^*\right) + g_1^2 f^4 \mathrm{Tr}\left(T_R^3 \Sigma (T_R^3 \Sigma)^*\right) \right] \rightarrow \text{ Align towards EW unbroken limit}$$

$$V_{\delta m^2} = 2\delta m^2 \mathrm{Tr}[P_i^S \Phi]\mathrm{Tr}[P_i^S \Phi]^* = \frac{1}{2}\delta m^2 (S_R^2 + S_I^2) \rightarrow \text{ Align towards technicolor limit}$$

- From the vacuum conditions we obtain

$$y_Q = \frac{m_\lambda^2 v}{8\sqrt{2} Z_2 f^3 s_\theta}, \quad v_S = \frac{\tilde{C}_g Z_2^2 f^4 s_\theta^2 - v^2 m_\lambda^2}{t_\theta v m_\lambda^2}, \quad \delta m^2 = \frac{\tilde{C}_g Z_2^2 f^4 s_\theta^2 m_\lambda^2}{v^2 m_\lambda^2 - \tilde{C}_g Z_2^2 f^4 s_\theta^2}.$$

RG Running Analyses of pCH Models (Model I)

- Motivation to make RG running analyses of the models is because of an enhancement of top Yukawa compared to the SM:

$$y_t = y_t^{SM}/s_\beta\,,$$

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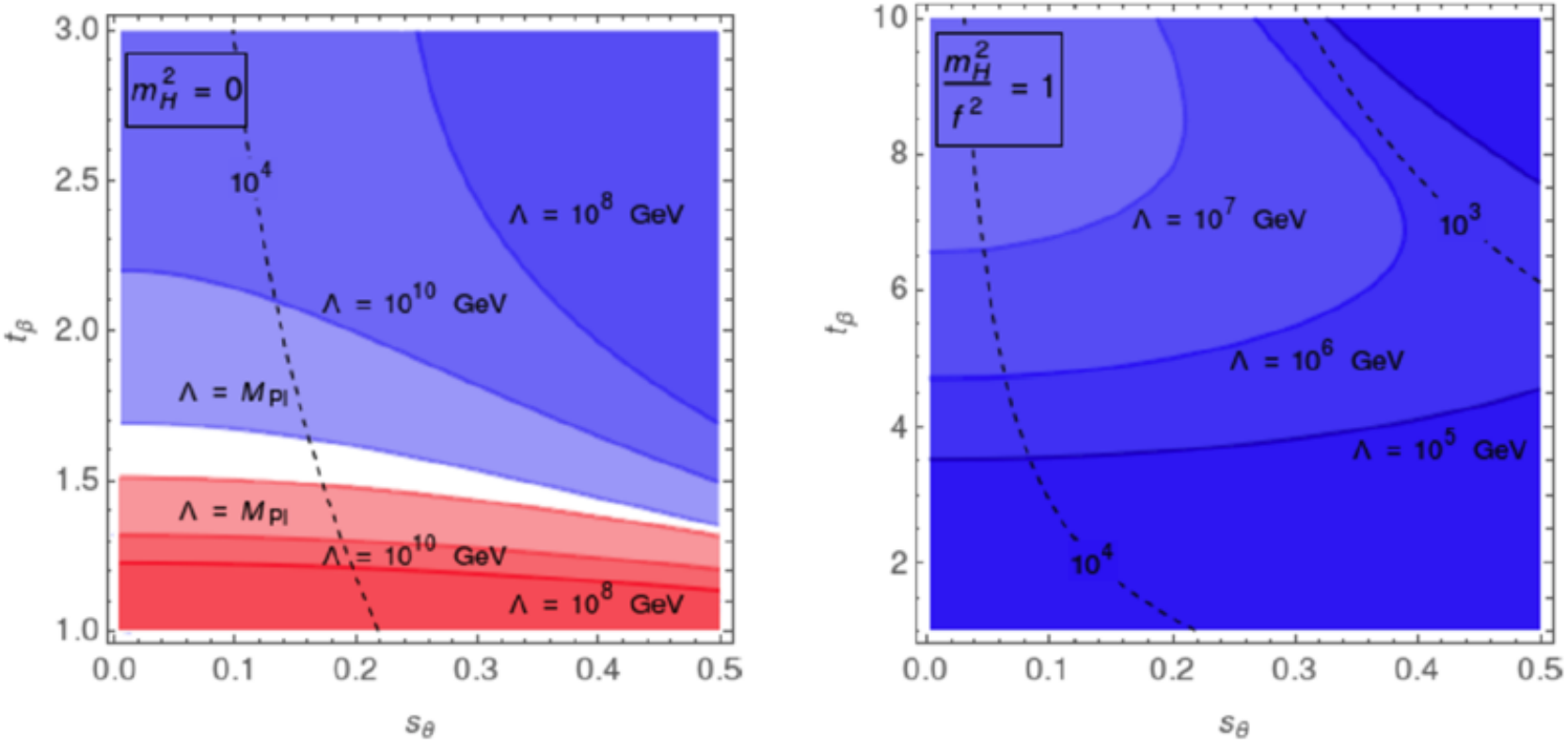
- RG running analysis of Model I (Elementary scalar doublet):



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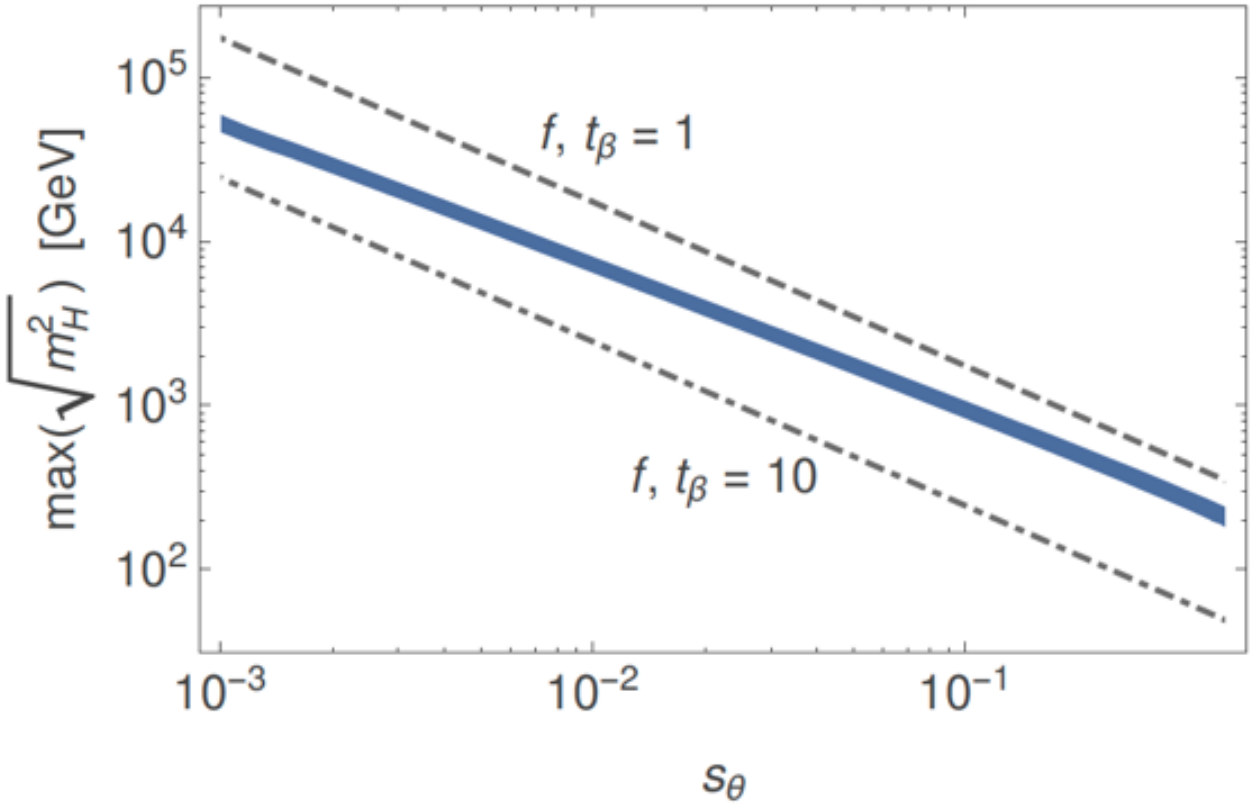
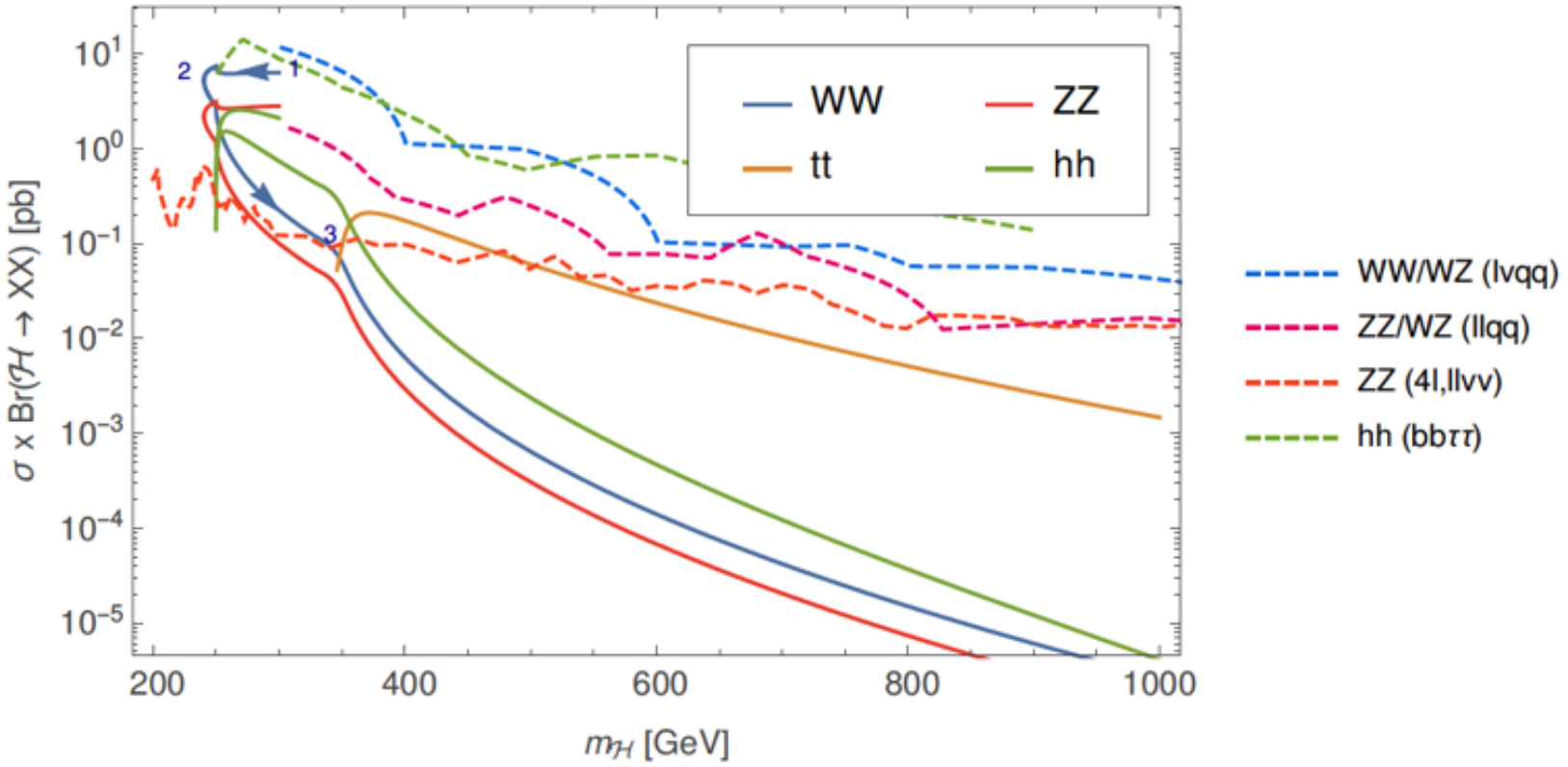


Rosenlyst et al., 2018, arXiv:1711.10410

- The blue band shows the maximum allowed value of $\sqrt{m_H^2}$ as a function of s_θ if stability at least up to the compositeness scale, $\Lambda_{TC} = 4\pi f$, is required and t_β is varied within the range $1 \ldots 10$.
- The dashed (dot-dashed) line shows f as a function of s_θ for constant value of $t_\beta = 1$ ($t_\beta = 10$).

Collider Phenomenology (Model I)



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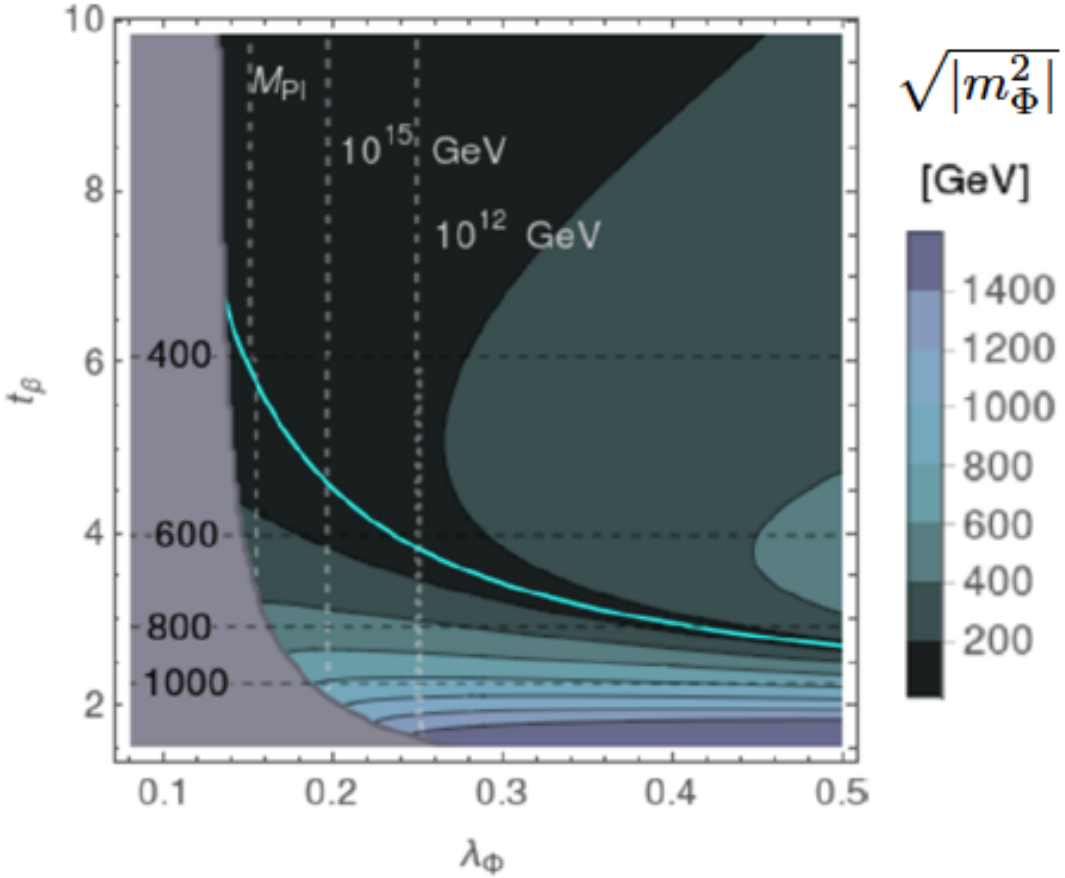
- $\sigma \times \mathrm{Br}(\mathcal{H} \to \mathrm{XX}$ for the benchmark scenario with fixed $s_\theta = 0.1$ and $m_H^2 = 0$.
- The arrow shows the growing t_β, and the points 1, 2, and 3 represent $t_\beta = 1.0, 1.7, 3.6$, respectively.
- The LHC limits are shown in dashed lines

RG Running Analyses of pCH Models (Model II)

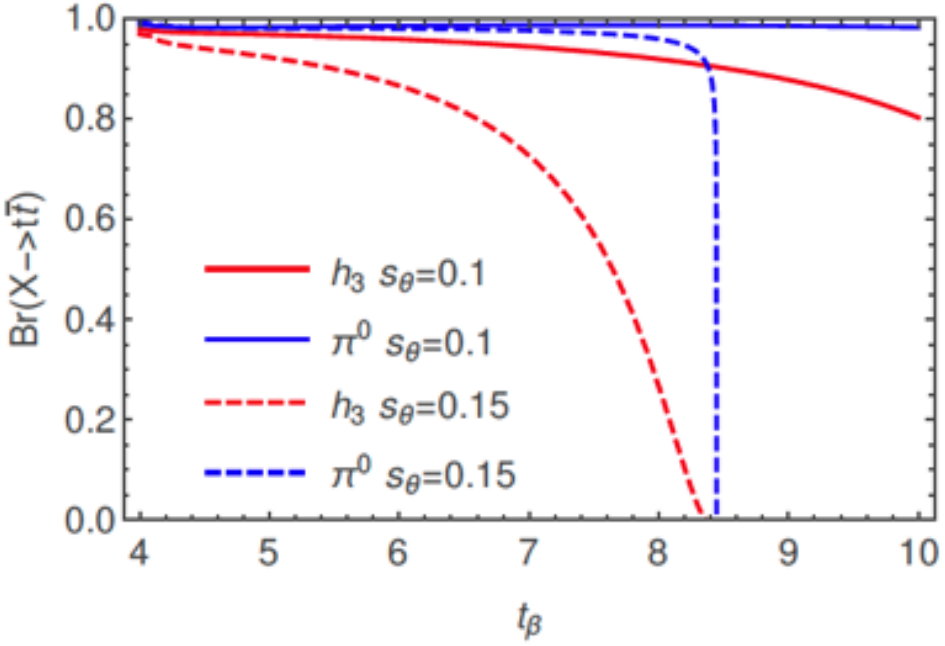
- RG running analysis of Model II (SU(4) completion of the scalar sector):



Rosenlyst et al., 2018, arXiv:1711.10410

- The values of mass parameter $\sqrt{|m_\Phi^2|}$ when mass is imposed for fixed $s_\theta = 0.1$.
- The dashed vertical lines show the parameter values where the maximum scale up to which the perturbativity of the couplings can be attained is 10^{12} GeV, 10^{15} GeV or M_{Pl}.
- Below the cyan line $m_\Phi^2 > 0$.

Collider Phenomenology (Model II)



Rosenlyst et al., 2018, arXiv:1711.10410

- In the case where the top decay channel prevails, we can have a situation in which the LHC might be able to observe these states.
- These states are nearly degenerate in mass
- Therefore, they would be seen as a single summed peak at the LHC detectors.

Conclusions

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- Dynamical generation of the vector-like masses of the new fermions.
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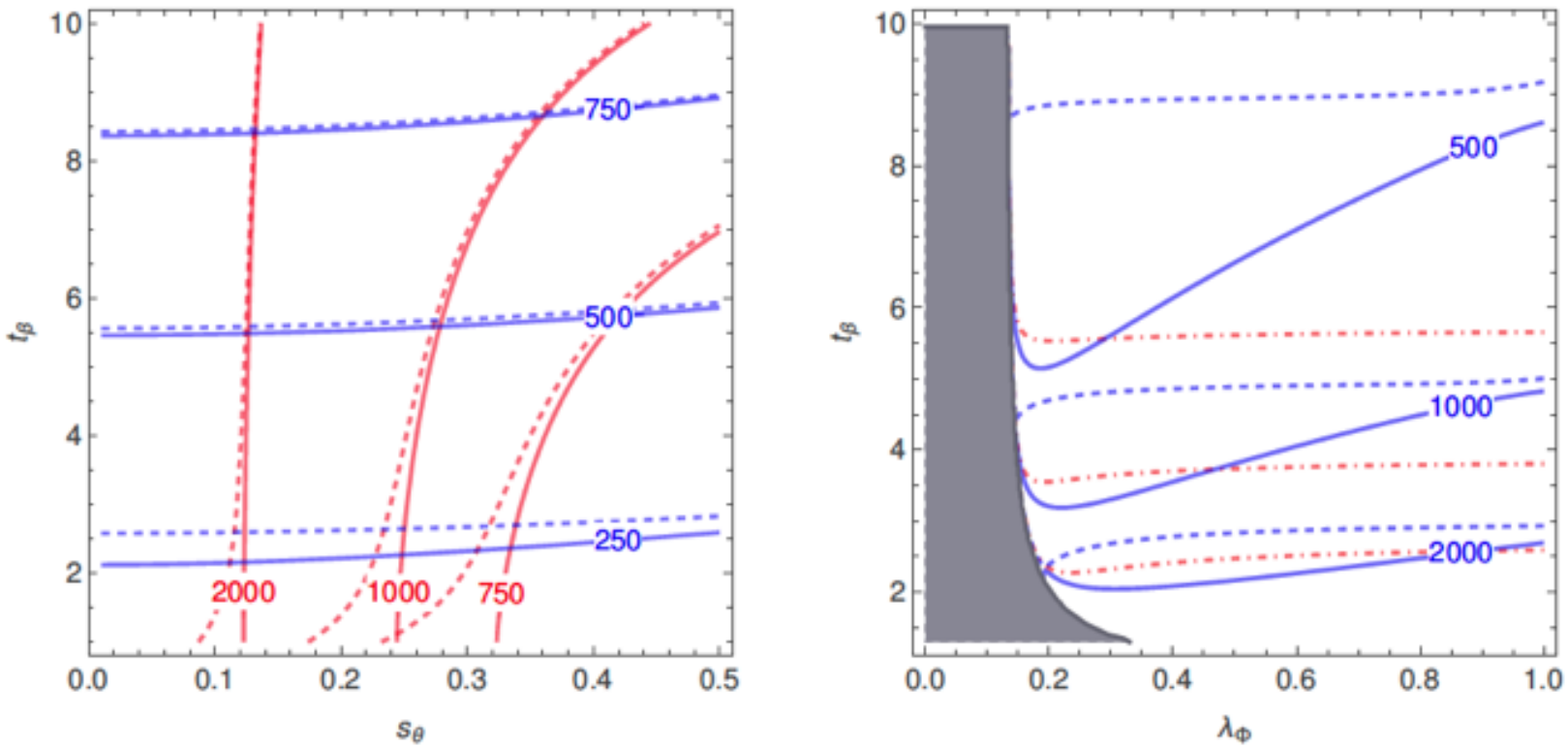
SU(4) Completion of the Scalar Sector (Model II):

- Dynamical generation of the vector-like masses of the new fermions.
- A stable vacuum and the mass parameter, respectively, up to the Planck scale and TeV scale.
- There is an interesting possibility to observe the heavier scalar states of the model at the LHC in the future.

Additional Slides

Additional Slides



Rosenlyst et al., 2018, arXiv:1711.10410

Figure 1. *Left panel:* model I spectrum. The blue (red) solid contours show the mass of the heavier CP-even state, $\mathcal{H}$, in GeV for fixed $m_H^2/f^2 = 0$ ($m_H^2/f^2 = 1$). The dashed curves show the mass of the pseudoscalar Π_5 for the same scenarios. *Right panel:* model II spectrum. The solid (dashed) blue lines show the mass contours (500 GeV, 1000 GeV, 2000 GeV) of m_{h_2} (m_{h_3}). The mass of the heavy pion triplet follows closely the contours of m_{h_3} , and we have omitted those for clarity. The dot-dashed red lines show the same mass contours for the non-pGB mass eigenstate of the two mixing pseudoscalar states, Π_5 and $S_{\rm I}$. We have fixed $s_\theta = 0.1$.

Additional Slides

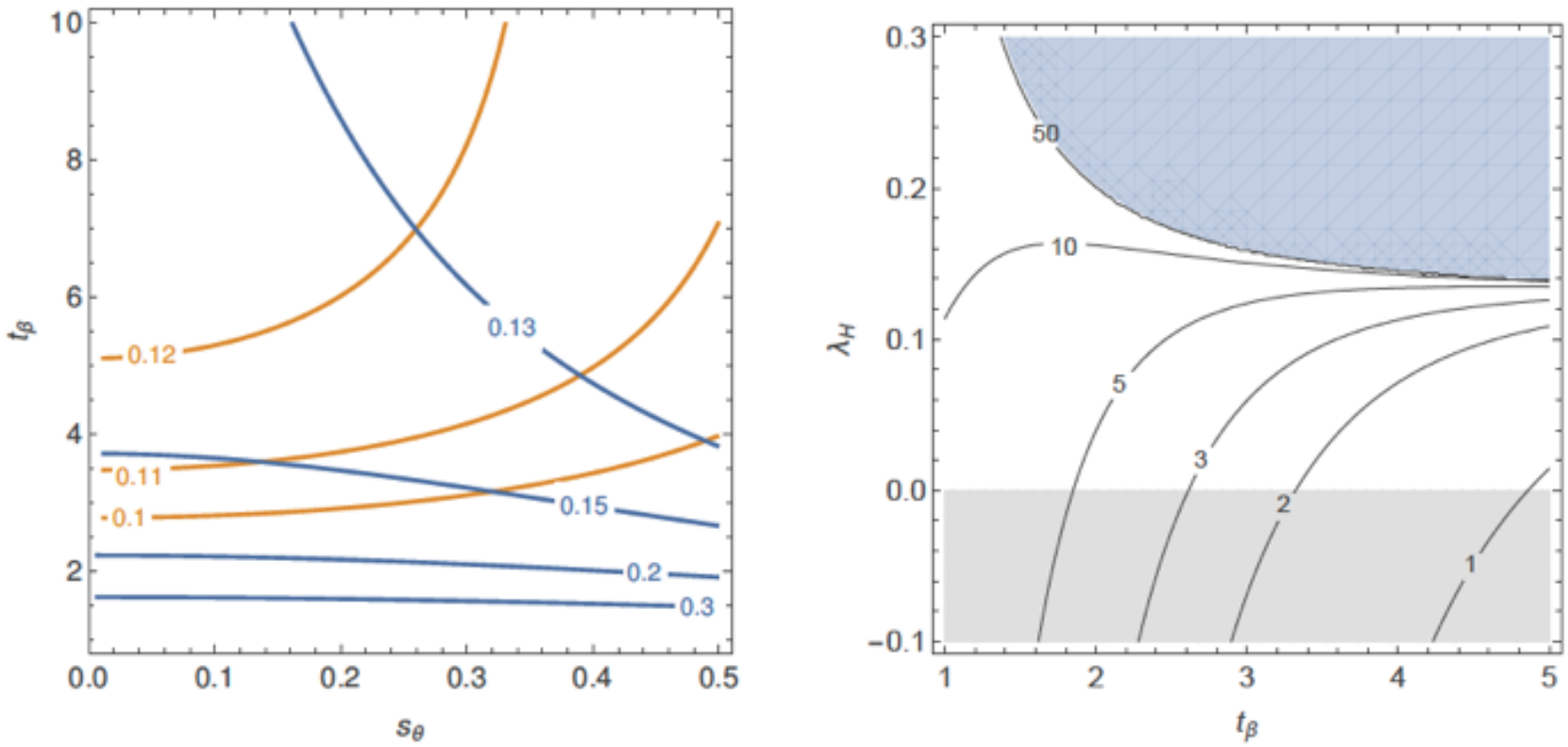


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Figure 2. *Left panel:* values of λ_H. Blue (yellow) contours represent the case $m_H^2/f^2 = 0$ ($m_H^2/f^2 = 1$). *Right panel:* the contours show the value of $\Lambda_{\rm TC} = 4\pi f$ in TeV corresponding to a 1 TeV heavy Higgs mass. The region $\lambda_H < 0$ is excluded by the requirement of stability of the potential. For $\Lambda_{\rm TC} \to \infty$ the curves lie on top of the $\Lambda_{\rm TC} = 50$ TeV contour so the shaded area results in no viable solutions. More details in the text.

Additional Slides

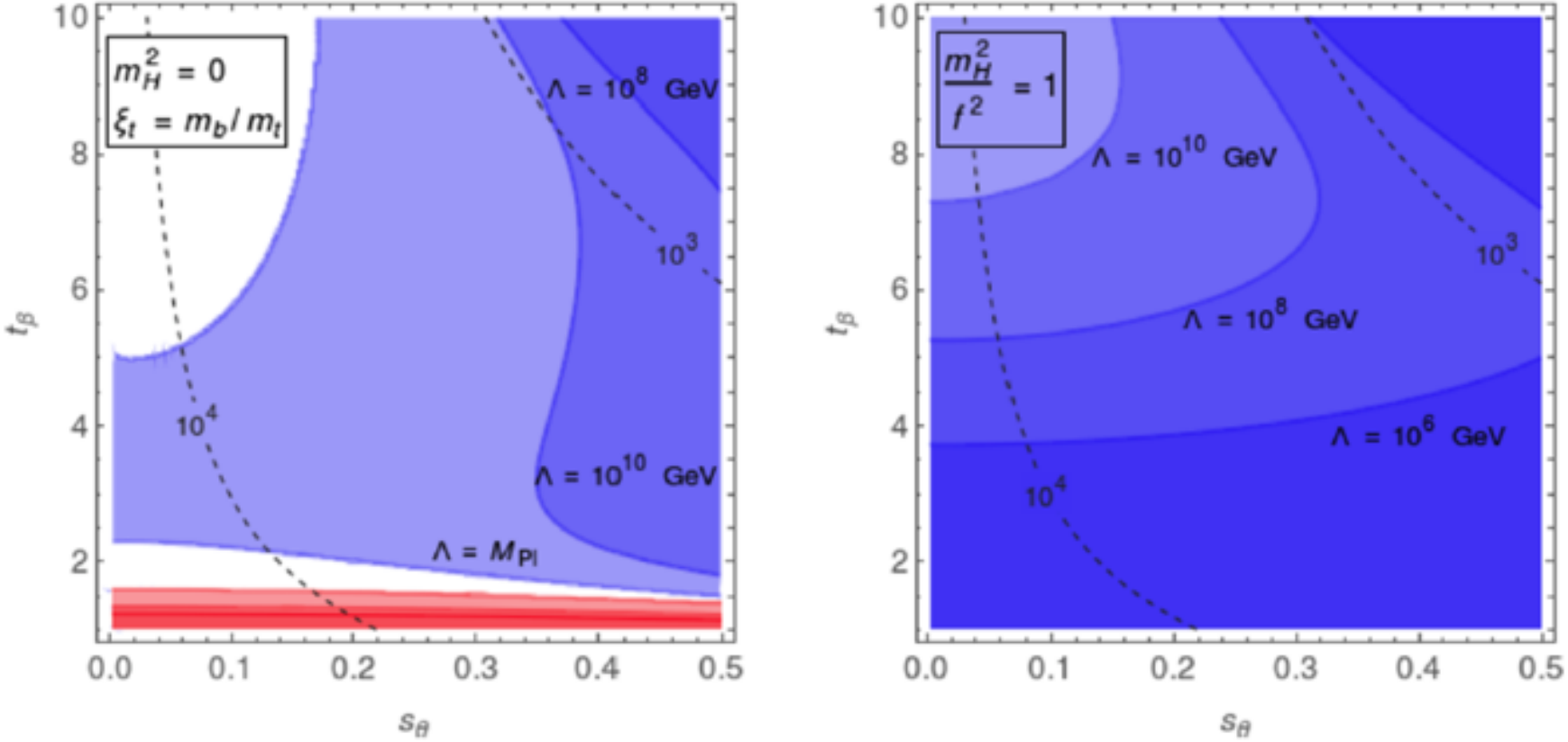

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Figure 5. Corresponding plots to figure 3 with $\xi_t = m_b/m_t$. On the unshaded area $\Lambda \geq M_{\rm Pl}$. The dashed lines show the values of $4\pi f$ in GeV.

Additional source for the top-quark mass:

$$\mathcal{L}_{4f} \sim -\frac{Y_t Y_U}{\Lambda_t^2}(\bar{q}_L t_R)^\dagger_\alpha (Q^T P_\alpha Q) + \text{ h.c.}$$

$$\mathcal{L}_{4f} \sim -4\pi f^3 Z_2 \frac{Y_t Y_U}{\Lambda_t^2}\mathrm{Tr}[P_1\Sigma]\bar{t}t = -y_t' f s_\theta\, \bar{t}t + \ldots,$$

$$y_t' \equiv \frac{4\pi f^2 Y_t Y_U Z_2}{\Lambda_t^2}.$$

$$V_{\text{top}} = -C_t y_t'^2 f^4 \left|\mathrm{Tr}[P_\alpha \Sigma]\right|^2 = -C_t y_t'^2 f^4 s_\theta^2 + \ldots$$

$$V_{\text{eff,top}} = V_{\text{eff}} + V_{\text{top}}$$

$$\kappa_t = -\xi_t \frac{s_\alpha c_\theta}{c_\beta} + (1-\xi_t)\frac{c_\alpha}{s_\beta}.$$

$$y_t' f s_\theta \equiv \xi_t m_t,$$

$$0 = \left.\frac{\partial V_{\text{eff,top}}}{\partial \theta}\right|_{\text{vac}} = \left.\frac{\partial V_{\text{eff}}}{\partial \theta}\right|_{\text{vac}} - \frac{2 f^2 C_t \xi_t^2 m_t^2}{t_\theta}.$$

$$M^2_{h,\text{top}} = m_\lambda^2 \begin{pmatrix} 1+\delta & -c_\theta t_\beta \\ -c_\theta t_\beta & t_\beta^2 + 2C_t \xi_t^2 m_t^2/m_\lambda^2 \end{pmatrix}$$

$$y_t = y_t^{\text{SM}}(1-\xi_t)/s_\beta.$$

$$\kappa_b = -\frac{s_\alpha c_\theta}{c_\beta}.$$

Additional Slides

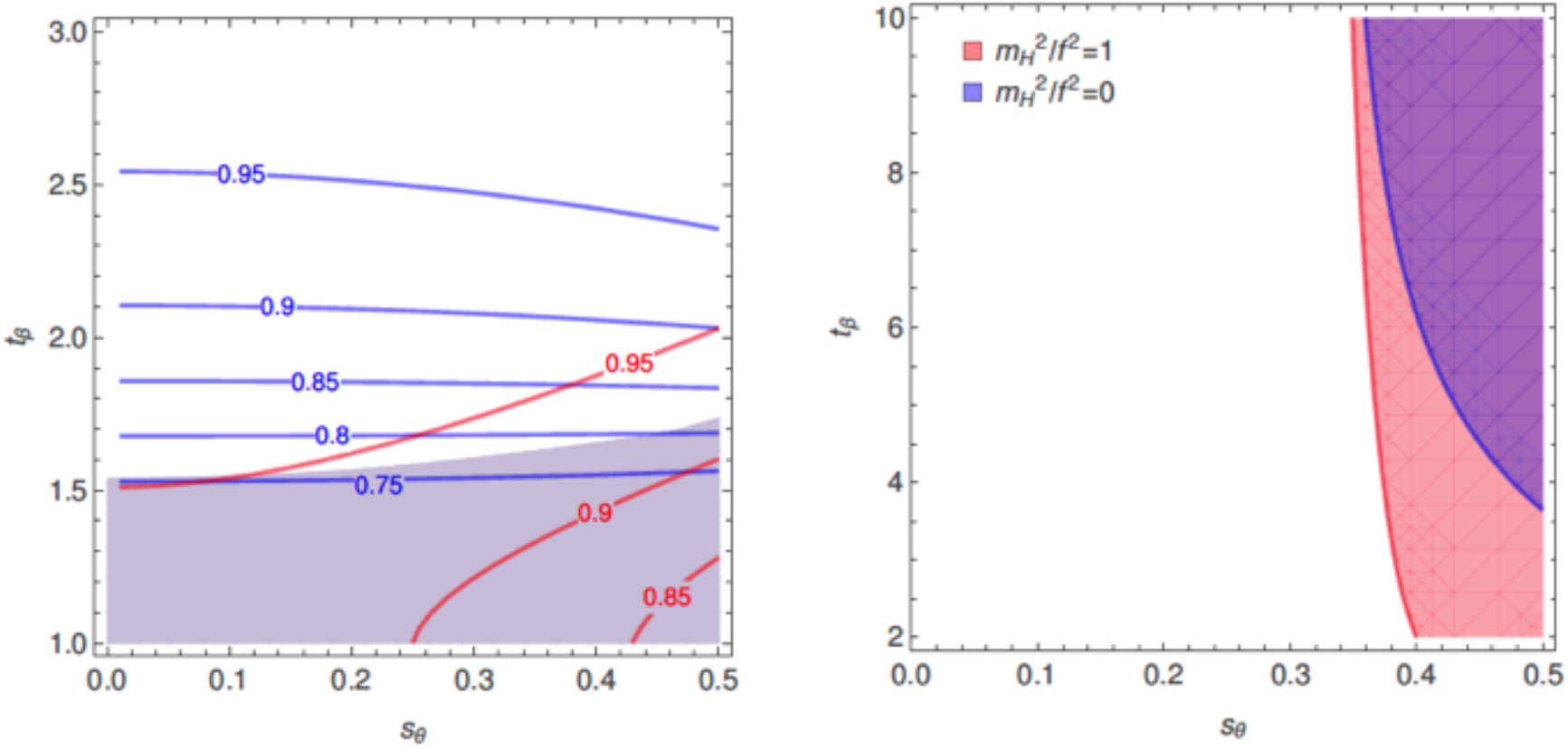

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Figure 6. *Left panel:* the blue (red) curves show $|\kappa_t|$ ($|\kappa_V|$) for $m_H^2 = 0$ case. The shaded region shows the 2σ exclusion from the two-parameter κ_f, κ_V fit [28]. *Right panel:* region in which κ_b is within 2σ of the measured value $|\kappa_b| = 0.57 \pm 0.16$, improved w.r.t. the SM prediction.

Additional Slides

$$(m_\pi^{\pm,0})^2 = \frac{8\sqrt{2}\pi Z_2 v_{\rm w}^2 y_Q}{t_\beta s_\theta^2}.$$

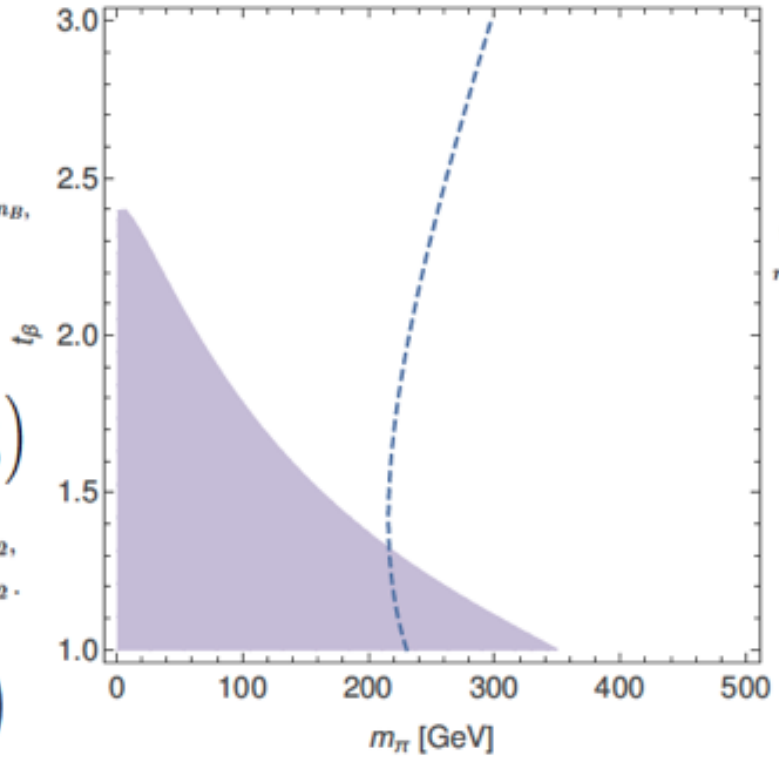
$$\Delta m_B = \frac{G_F^2}{6\pi^2} m_W^2 |V_{td}V_{tb}^*|^2 S(x_W, x_\pi)\eta(x_W, x_\pi) B_B f_B^2 m_B,$$

$$E = \cos\theta E_- + \sin\theta E_{\rm B}.$$

$$E_\pm = \begin{pmatrix} {\rm i}\sigma_2 & 0 \\ 0 & \pm{\rm i}\sigma_2 \end{pmatrix}, \qquad E_B = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$2P_1 = \delta_{i1}\delta_{j3} - \delta_{i3}\delta_{j1},\ 2P_2 = \delta_{i2}\delta_{j3} - \delta_{i3}\delta_{j2},$$
$$2\widetilde{P}_1 = \delta_{i1}\delta_{j4} - \delta_{i4}\delta_{j1},\ 2\widetilde{P}_2 = \delta_{i2}\delta_{j4} - \delta_{i4}\delta_{j2}.$$

$$P_1^{\rm S} = \frac{1}{2}\begin{pmatrix} -{\rm i}\sigma_2 & 0 \\ 0 & 0 \end{pmatrix},\ P_2^{\rm S} = \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 0 & {\rm i}\sigma_2 \end{pmatrix}$$



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$$h_1 = c_\alpha \sigma_h - s_\alpha \Pi^4, \quad h_2 = s_\alpha \sigma_h + c_\alpha \Pi^4,$$

$$t_{2\alpha} = \frac{2t_\beta c_\theta}{1 - t_\beta^2 + \delta}.$$

$$m_{h_{1,2}}^2 = \frac{m_\lambda^2}{2}\left[1 + t_\beta^2 + \delta \pm \left(2c_\theta t_\beta s_{2\alpha} + (1 - t_\beta^2 + \delta)c_{2\alpha}\right)\right]$$
$$m_{\pi^{\pm,0}}^2 = m_\lambda^2/c_\beta^2, \quad m_{\Pi_5}^2 = t_\beta^2 m_\lambda^2.$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \equiv R \begin{pmatrix} \sigma_h \\ \Pi_4 \\ S_{\rm R} \end{pmatrix}.$$

$$\kappa_{f,i} \equiv \frac{g_{h_i \bar{f} f}}{g_{\bar{h} f f}^{\rm SM}}, \quad \kappa_{V,i} \equiv \frac{g_{h_i VV}}{g_{hVV}^{\rm SM}}, \quad i = 1, 2.$$

$$\kappa_{f,i} = \frac{R_{i1}}{s_\beta}, \quad \kappa_{V,i} = R_{i1} s_\beta + R_{i2} c_\beta c_\theta$$

Figure 8. Excluded region by $B^0 - \overline{B^0}$ mixing. The dashed curve shows the value of m_π calculated for the benchmark scenario with $m_H^2 = 0$.

Additional Slides

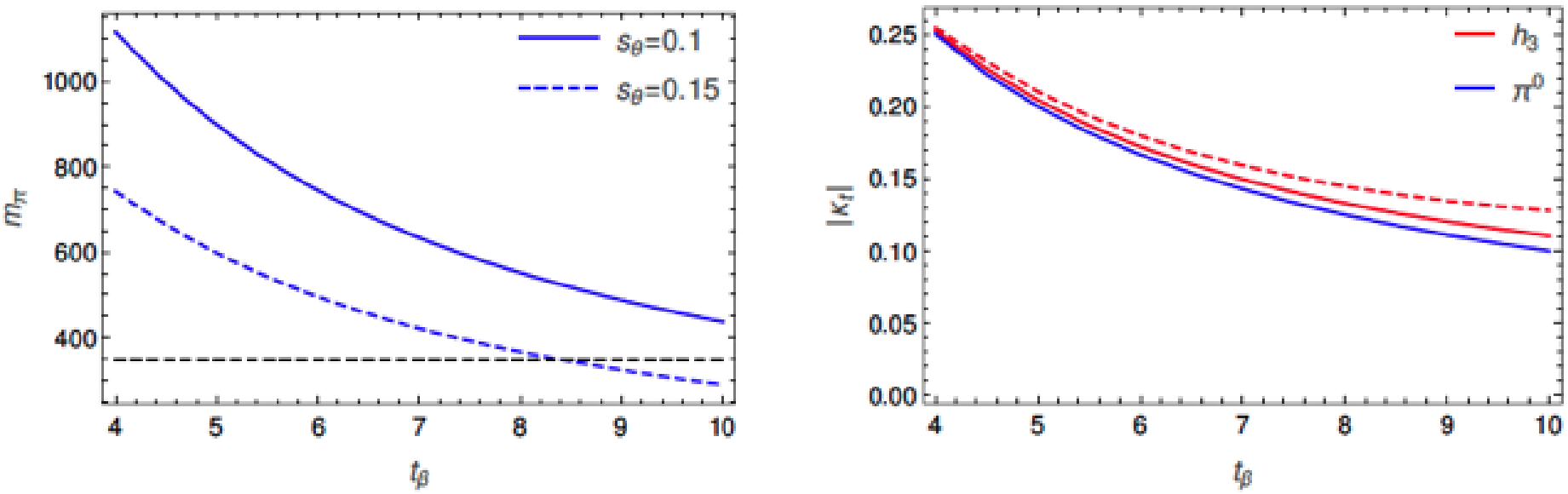

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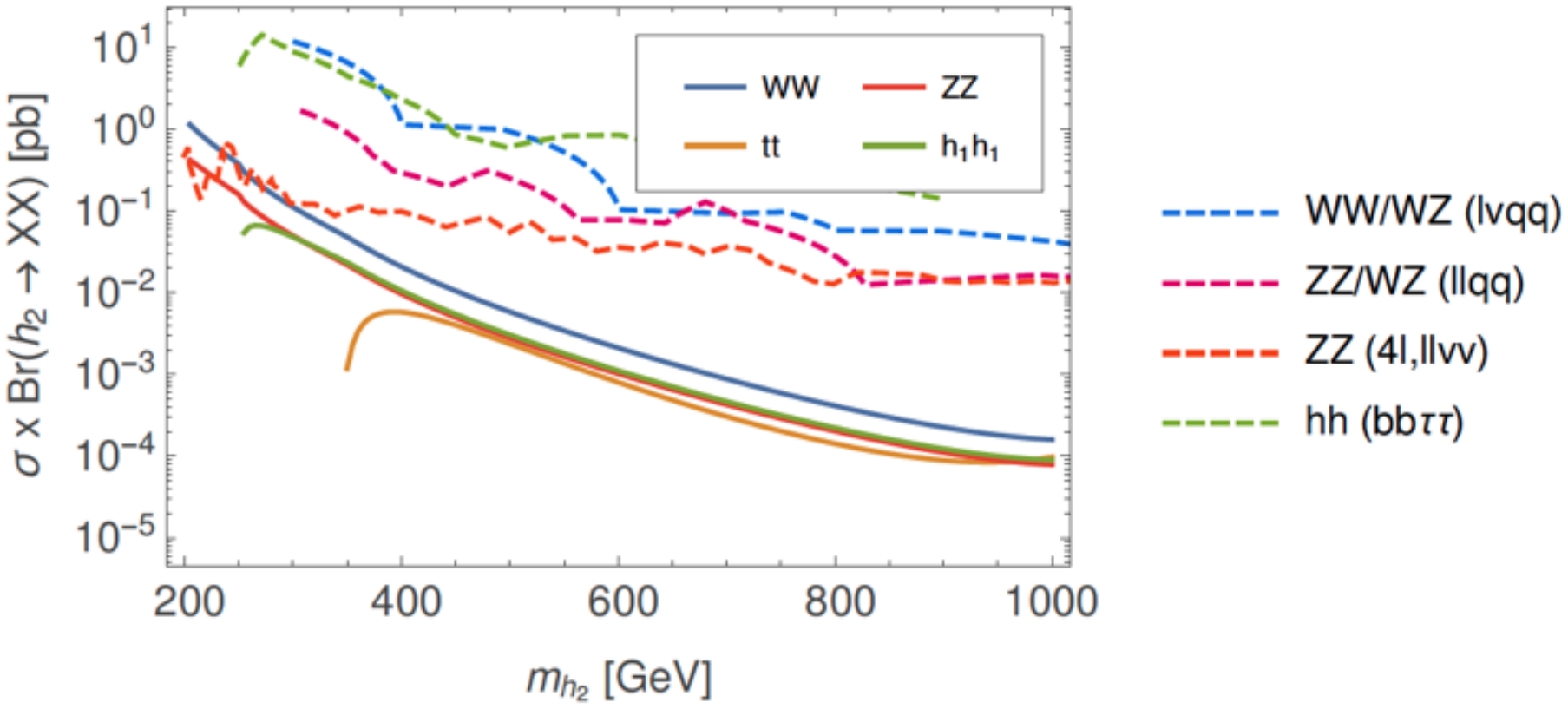
Figure 11. (a) Mass of the π^0. The dashed horizontal line shows the $t\bar{t}$ threshold. (b) Reduced coupling to top quarks.

Additional Slides



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- $\sigma \times \mathrm{Br}(h_2 \to XX)$ in different channels with corresponding LHC limits.
- We have fixed $\lambda_\Phi = 0.15$ and $s_\theta = 0.10$.

A RG equations: elementary doublet

We consider a rather generic bTC framework featuring $N_{\rm F}$ new $\mathrm{SU}(2)_{\rm L}$-doublet fermionic fields, $Q_{\rm L} = (U_{\rm L}, D_{\rm L})$, transforming under the representation $R_{\rm F}$ under the new strong gauge group, and coupling to the elementary Higgs doublet via Yukawa interactions. The one-loop evolution of the relevant couplings above the condensation scale, $\Lambda_{\rm TC}$, is given by

$$
\begin{aligned}
16\pi^2\beta_{g_c} &= -7g_c^3,\\
16\pi^2\beta_{g_{\rm TC}} &= -\left(\frac{11}{3}C_2(A) - \frac{8}{3}\cdot N_{\rm F}T(R_{\rm F})\right)g_{\rm TC}^3\,,\\
16\pi^2\beta_{g_{\rm L}} &= -\left(\frac{19}{6} - \frac{2}{3}N_{\rm F}d(R_{\rm F})T(R_{\rm F})\right)g_{\rm L}^3,\\
16\pi^2\beta_{g_Y} &= \left(\frac{41}{6} + \frac{4}{3}N_{\rm F}d(R_{\rm F})\left(4Y(Q_{\rm L})^2 + \frac{1}{2}\right)\right)g_Y^3,\\
16\pi^2\beta_{y_t} &= \left(-8g_c^2 - \frac{9}{4}g_{\rm L}^2 - \frac{17}{12}g_Y^2 + \frac{9}{2}y_t^2 + d(R_{\rm F})(y_U^2 + y_D^2)\right)y_t,\\
16\pi^2\beta_{y_U} &= \left(-6C_2(R_{\rm F})g_{\rm TC}^2 - \frac{9}{4}g_{\rm L}^2 - \frac{17}{12}g_Y^2 + 3y_t^2 + \left(d(R_{\rm F}) + \frac{3}{2}\right)y_U^2 + d(R_{\rm F})y_D^2\right)y_U,\\
16\pi^2\beta_{y_D} &= \left(-6C_2(R_{\rm F})g_{\rm TC}^2 - \frac{9}{4}g_{\rm L}^2 - \frac{5}{12}g_Y^2 + 3y_t^2 + \left(d(R_{\rm F}) + \frac{3}{2}\right)y_D^2 + d(R_{\rm F})y_U^2\right)y_D,\\
16\pi^2\beta_\lambda &= 24\lambda^2 + \lambda\left(-3\left(3g_{\rm L}^2 + g_Y^2\right) + 12y_t^2 + 4d(R_{\rm F})\left(y_U^2 + y_D^2\right)\right)\\
&\quad + \frac{3}{8}\left(2g_{\rm L}^4 + \left(g_{\rm L}^2 + g_Y^2\right)^2\right)\Big) - 6y_t^4 - 2d(R_{\rm F})(y_U^4 + y_D^4),
\end{aligned}
$$

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B RG equations: SU(4) multiplet of elementary scalars

$$V^{(4)} = \lambda_H (H^\dagger H)^2 + \frac{\lambda_{S_R}}{4} S_R^4 + \frac{\lambda_{S_I}}{4} S_I^4 + \lambda_{HS_R} (H^\dagger H) S_R^2 + \lambda_{HS_I} (H^\dagger H) S_I^2 + \frac{\lambda_{S_R S_I}}{2} S_R^2 S_I^2,$$

$$16\pi^2 \beta_{g_{\rm TC}} = -6 g_{\rm TC}^3, \quad 16\pi^2 \beta_{g_{\rm L}} = -\frac{5}{2} g_{\rm L}^3, \quad 16\pi^2 \beta_{g_Y} = \frac{15}{2} g_Y^3,$$

$$16\pi^2 \beta_{y_t} = \left(-8 g_c^2 - \frac{9}{4} g_{\rm L}^2 - \frac{17}{12} g_Y^2 + \frac{9}{2} y_t^2 \right) y_t,$$

$$\begin{aligned} 16\pi^2 \beta_{\lambda_H} &= 24 \lambda_H^2 + 2(\lambda_{HS_R}^2 + \lambda_{HS_I}^2) + \lambda_H \left(-3 \left(3 g_{\rm L}^2 + g_Y^2 \right) + 12 y_t^2 \right) \\ &\quad + \frac{3}{8} \left(2 g_{\rm L}^4 + \left(g_{\rm L}^2 + g_Y^2 \right)^2 \right) \Big) - 6 y_t^4, \end{aligned}$$

$$\begin{aligned} 16\pi^2 \beta_{\lambda_{HS_R}} &= 8 \lambda_{HS_R}^2 + 6 \left(2\lambda_H + \lambda_{S_R} \right) \lambda_{HS_R} + 2 \lambda_{HS_I} \lambda_{S_R S_I} \\ &\quad + \lambda_{HS_R} \left(-\frac{3}{2} \left(3 g_{\rm L}^2 + g_Y^2 \right) + 6 y_t^2 \right), \end{aligned}$$

$$\begin{aligned} 16\pi^2 \beta_{\lambda_{HS_I}} &= 8 \lambda_{HS_I}^2 + 6 \left(2\lambda_H + \lambda_{S_I} \right) \lambda_{HS_I} + 2 \lambda_{HS_R} \lambda_{S_R S_I} \\ &\quad + \lambda_{HS_I} \left(-\frac{3}{2} \left(3 g_{\rm L}^2 + g_Y^2 \right) + 6 y_t^2 \right), \end{aligned}$$

$$\begin{aligned} 16\pi^2 \beta_{\lambda_{S_R}} &= 18 \lambda_{S_R}^2 + 8 \lambda_{HS_R}^2 + 2 \lambda_{S_R S_I}^2, \\ 16\pi^2 \beta_{\lambda_{S_I}} &= 18 \lambda_{S_I}^2 + 8 \lambda_{HS_I}^2 + 2 \lambda_{S_R S_I}^2, \\ 16\pi^2 \beta_{\lambda_{S_R S_I}} &= 8 \lambda_{S_R S_I}^2 + 6 \lambda_{S_R S_I} (\lambda_{S_R} + \lambda_{S_I}) + 8 \lambda_{HS_R} \lambda_{HS_I}. \end{aligned}$$