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Planck-safe BSM with Vector-like Quarks

soon on arxiv

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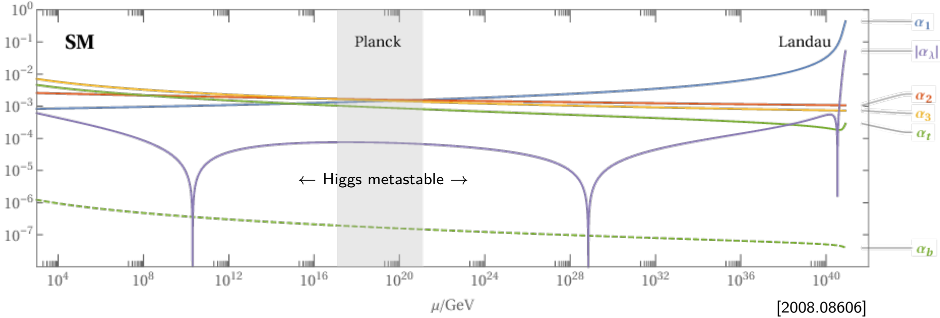
Outline

Introduction

Standard Model RG Flow (3-loop)

gauge: $\alpha_i = \frac{g_i^2}{16\pi^2}$, Yukawas: $\alpha_{t,b} = \frac{y_{t,b}^2}{16\pi^2}$, quartics: $\alpha_\lambda = \frac{\lambda}{16\pi^2}$



[2008.08606]

- Higgs potential metastable ($\alpha_\lambda < 0$) at 10^{10} - 10^{29} GeV [1307.3536]
- Hypercharge Landau pole at 10^{41} GeV

Planck Safety

RG Running of all couplings up to $M_{\mathrm{Pl}} \sim 10^{19}$ GeV without

- Landau poles
- Vacuum instabilities (especially Higgs)
- non-perturbative couplings

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very promising concept for BSM model building!

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How can Planck safety be realized?

Model

Setup

- N_F vector-like fermions ψ_i and N_F^2 uncharged scalars $\hat{S}_{ij}$ [1406.2337]
  $\Rightarrow$Avoids gauge anomalies
  $\Rightarrow$Natural Dirac mass term
  $\Rightarrow N_F = 3$ connects SM and BSM flavor
- Past: Successfull models with VLLs [2008.08606, 2011.12964]
  (→ talk by S. Bißmann)

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- Past: Successfull models with VLLs [2008.08606, 2011.12964]
  (→ talk by S. Bißmann)
- **Now:** Study models with VLQs!
  $\Rightarrow$Focus on two rep. under $U(1)_Y \times SU(2)_L \times SU(3)_C$:

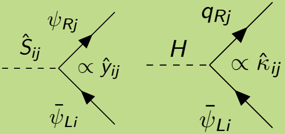
  Model I: $\psi = (-\frac{5}{6}, 2, 3)$
  Model II: $\psi = (\frac{7}{6}, 2, 3)$
- Set New Physics scale to $\mu_0 = 1$ TeV
  $\Rightarrow$Accessible at colliders (→ *talk by J. Erdmann*)

Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_F + \mathcal{L}_S + \mathcal{L}_Y^{\mathrm{BSM}} + \mathcal{L}_Y^{\mathrm{portal}} + \mathcal{L}_V$$

$$-\mathcal{L}_Y^{\mathrm{BSM}} = \hat{y}_{ij}\bar{\psi}_{Li}\hat{S}_{ij}\psi_{Rj} + \mathrm{h.c.}$$

$$-\mathcal{L}_Y^{\mathrm{portal}} = \begin{cases} \hat{\kappa}_{ij}\,\overline{\psi_L}_i H^c D_j + \mathrm{h.c.} & \text{(Modell I)} \\ \hat{\kappa}_{ij}\,\overline{\psi_L}_i H\, U_j + \mathrm{h.c.} & \text{(Model II)} \end{cases}$$



- No renormalizable Yukawa portals via $\hat{S}$

Flavor Symmetries & Splitting

A priori huge flavor symmetry

$$\mathcal{G}_F = U(3)^3_q \otimes U(3)^2_\ell \otimes U(3)^2_\psi \otimes U(3)^2_S$$

$\Rightarrow$broken by Yukawa couplings ($\rightarrow$ *Details in Backup*)

- non-negligible y_t, y_b break $U(3)^3_q \rightarrow U(2)^3_q \times U(1)^3_q$

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- 3rd gen. BSM fields & couplings separated from first two gen.

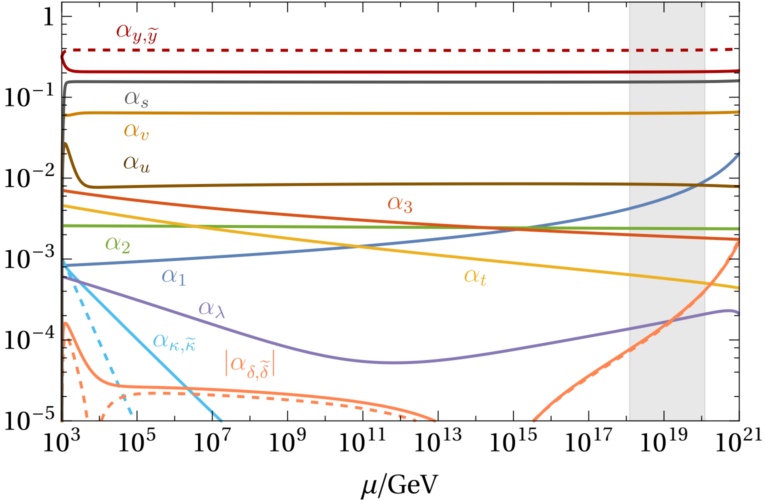
$$\hat{y} \to \begin{pmatrix} y & y & 0 \\ y & y & 0 \\ 0 & 0 & \widetilde{y} \end{pmatrix}, \qquad \hat{\kappa} \to \mathrm{diag}(\kappa, \kappa, \widetilde{\kappa})$$

- Four independent scalar fields: $\hat{S} = \begin{pmatrix} S_{2\text{x}2} & \phi_{L\,1\text{x}2} \\ \phi_{R\,2\text{x}1} & \varphi_{1\text{x}1} \end{pmatrix}$

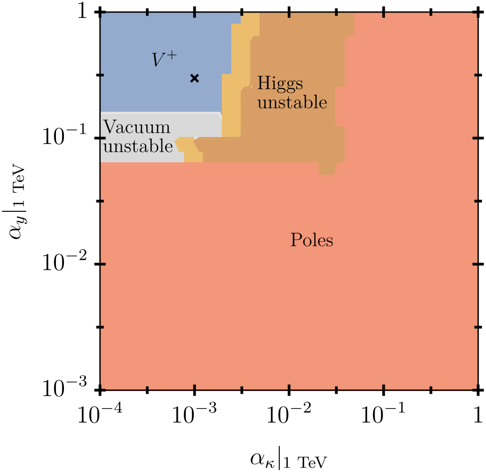
  ⇒Decouple $\phi_{L/R}$ to reduce complexity

RG Analysis

Planck-safe RG Running (Model I)



BSM Critical Surface (Model I)



Planck Safety: Results

- Subplanckian hypercharge Landau pole for feeble coupligs
  $\Rightarrow$Yukawas are unique key to tame pole [1608.00519]
  $\Rightarrow 10^{-1} \lesssim \alpha_{y,\tilde{y}}|_{1\text{ TeV}} \lesssim 1$
  $\Rightarrow$high multiplicity, little effect on α_λ
- Model II: $\alpha_{\tilde{\kappa}}|_{1\text{ TeV}} \gtrsim 1.5 \cdot 10^{-1}$
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$\Rightarrow$**Planck safety increases predictivity!**

SMEFT Analysis

Matching

Model-independent SMEFT analysis: $\mathcal{L}^{(6)}_{\text{SMEFT}} = \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$ [1008.4884]

$\Rightarrow$Compute NP Wilson coefficients C_i in our model! [1711.10391]

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We induce

$$\mathcal{O}^{ij}_{Hq} = i\left[(H^\dagger D_\mu H) - (D_\mu H)^\dagger H\right](\bar{q}^i_R\gamma^\mu q^j_R),$$

$$\mathcal{O}^{ij}_{qH} = (H^\dagger H)(\bar{Q}^i H^{[c]} q^j_R),$$

$$\mathcal{O}_{H\Box} = (H^\dagger H)\partial^\mu\partial_\mu(H^\dagger H),$$

$$\mathcal{O}_H = (H^\dagger H)^3$$

with $$\frac{C^{ij}_{Hq}}{\Lambda^2} = \xi_q\, 8\pi^2\, \frac{\alpha_{\hat{\kappa}_i}}{M^2_{F_i}}\,\delta_{ij}, \qquad \frac{C^{ij}_{qH}}{\Lambda^2} = 8\pi^2 Y^{q*}_{ji}\frac{\alpha_{\hat{\kappa}_j}}{M^2_{F_i}}$$

where $\xi_q = -1\,[+1]$ for $q = d\,[u]$ in Model I [II]

Constraints

Global SMEFT fits [1606.06693, 1911.07866, 2012.02779]
⇒Bounds on WCs (in particular on $C^{33}_{qH,Hq}$)

- Constraints on model paramters
  ⇒In particular upper limits on $\frac{\alpha_{\tilde{\kappa}}}{M_F^2}$!
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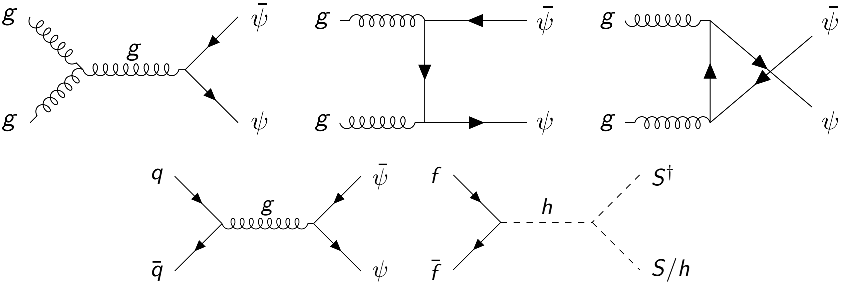
- Constraints on model paramters
  ⇒In particular upper limits on $\frac{\alpha_{\tilde{\kappa}}}{M_F^2}$!
- Complemetary to Planck safety constraints
  ⇒**Model I:** V^+ possible for $M_F \approx 1$ TeV ✓
  Model II: excluded for $M_F < 2.3\,(3.2)$ TeV! ✗
  ⇒Beyond collider limits ($M_F \lesssim 1.2 - 1.5$ TeV) [1806.01762,1807.11883]

Focus on Model I for phenomenological analysis

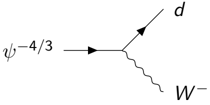
Phenomenology

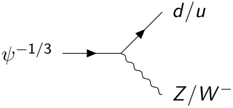
BSM Sector Production

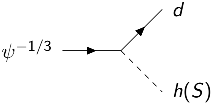


BSM Fermion Decays

- After EWSB ψ splinters into $(\psi^{-1/3}, \psi^{-4/3})^T$
- Exotic $\psi^{-4/3}$ decays exclusively via mixing as $\psi^{-4/3} \to dW^-$
- $\psi^{-1/3}$ decays to dZ, dh, uW and if $M_F > M_{\hat{S}}$ to $d\hat{S}$
- ψ decays are prompt unless $\alpha_\kappa \lesssim \mathcal{O}(10^{-14})$

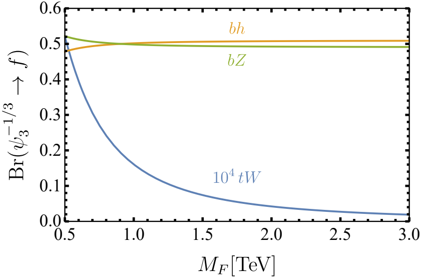




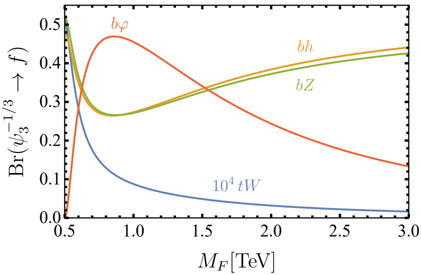


Fermionic Branching Ratios

$M_S > M_F$



$M_S < M_F$ ($M_S = 0.5$ TeV, $\alpha_y = 0.3$)



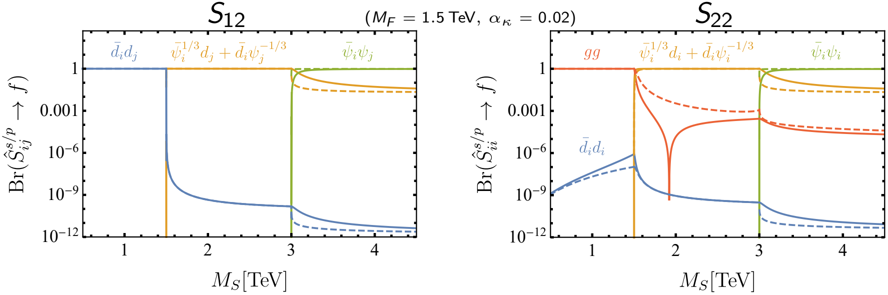
- $\psi_3^{-1/3} \to tW$ strongly suppressed by tiny LH mixing $\Rightarrow$negligible
- $\mathcal{B}(\psi_3^{-1/3} \to bH) \approx \mathcal{B}(\psi_3^{-1/3} \to bZ)$
- If open, $\psi_3^{-1/3} \to b\varphi$ dominant for $M_F \approx 1$ TeV

Collider bounds

- From running of the strong coupling constant
  $\Rightarrow M_F \gtrsim 700$ GeV (from $139\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV)[ATLAS-CONF-2020-025]
  ($\rightarrow$ *Details in Backup*)
- From pair production of exotic VLQs
  $\Rightarrow M_{F,3} \gtrsim 1350\,\mathrm{GeV}$ (from $36.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV) [1707.03347]
- Bounds on $\frac{\alpha_{\hat{\kappa}}}{M_F^2}$ from mixing (single production, $W/Z/H$-couplings)
  $\Rightarrow$Similar to SMEFT bounds
  $\Rightarrow$Compatible with Planck safety bounds

BSM Scalar Decays

- Physical d.o.f. are (pseudo-)scalar components of $\hat{S}$
- Decay as $\hat{S}_{ij} \to \bar{d}_i d_j,\ \bar{\psi}_i^{1/3} d_j,\ \bar{d}_i \psi_j^{-1/3},\ \bar{\psi}_i \psi_j$
- $\hat{S}_{ii}$ also decay via triangle loops to two gauge bosons
  $\Rightarrow \hat{S}_{ii} \to gg$ strongly dominates over $\hat{S}_{ii} \to ZZ,\ \gamma\gamma,\ WW,\ Z\gamma$



Conclusion

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SM + 3 gen. of VLQs $\psi_i = (-\frac{5}{6}/\frac{7}{6}, 2, 3)$ and flavorful singlet scalar $\hat{S}_{ij}$

- Planck safety constrains Yukawas: $\alpha_{y,\tilde{y}}|_{\mu_0} \gtrsim 10^{-1}$
  $\Rightarrow$SMEFT fit combination: Model II excluded for $M_F \lesssim 3$ TeV
- Phenomenological analysis Model I
  $\Rightarrow$Strongest VLQ mass bound (collider searches): $M_F \gtrsim 1350$ GeV
  $\Rightarrow$Mixing bounds on $\alpha_{\hat{\kappa}}$ in agreement with Planck safety bounds
  $\Rightarrow$Dominant decay channels:
  $\psi^{-4/3} \to dW^-$
  $\psi^{-1/3} \to dZ, dH[, dS]$ [if kinematically open]
  $\hat{S}_{ij(ii)} \to [\bar{\psi}\psi](, gg)$ [if kinematically open]

BACKUP

Flavor Symmetry Breaking

$$\mathcal{G}_F = U(3)_q^3 \otimes U(3)_\ell^2 \otimes U(3)_\psi^2 \otimes U(3)_S^2$$

- $\hat{y}$ identifies $U(3)_S^2$ with $U(3)_\psi^2$
- BSM fermion mass term identifies $U(3)_{\psi_L}$ with $U(3)_{\psi_R}$
- $\hat{\kappa}$ identifies $U(3)_{\psi_L}$ with $U(3)_D$ ($U(3)_U$) in Model I (II)
- y_t, y_b break $U(3)_q^3 \to U(2)_q^3 \times U(1)_q^3$

$\Rightarrow$Breaking of $U(3)_q^3$ propogates through the whole BSM sector

Vacuum Stability

$$\mathcal{L}_V = \lambda\,(H^\dagger H)^2 + s\,(\phi^\dagger\phi)^2 + u\,\mathrm{Tr}(S^\dagger S S^\dagger S) + v\,\mathrm{Tr}(S^\dagger S)\mathrm{Tr}(S^\dagger S) + \delta\,(H^\dagger H)\,\mathrm{Tr}(S^\dagger S) + \widetilde{\delta}\,(H^\dagger H)(\phi^\dagger\phi) + w\,(\phi^\dagger\phi)\,\mathrm{Tr}(S^\dagger S)\,,$$

Scalar potential has to be bounded from below!

⇒Vacuum stability conditions: [1501.03061, 1205.3781]

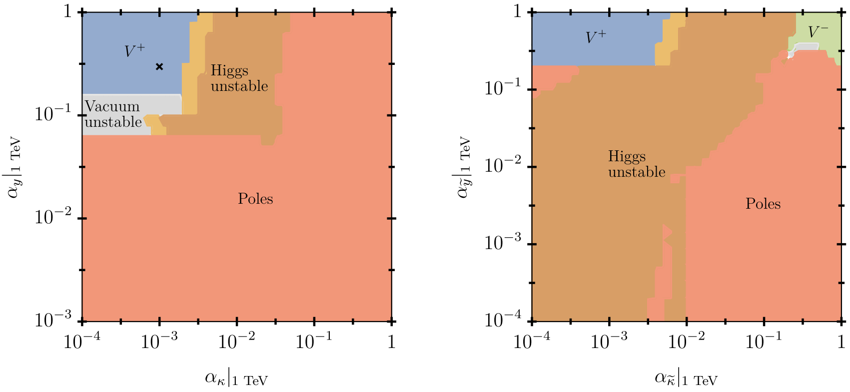
$$\lambda > 0, \qquad \Delta > 0, \qquad s > 0,$$

$$\delta' = \delta + 2\sqrt{\lambda\Delta} > 0, \quad \widetilde{\delta}' = \widetilde{\delta} + 2\sqrt{\lambda s} > 0, \quad w' = w + 2\sqrt{s\Delta} > 0,$$

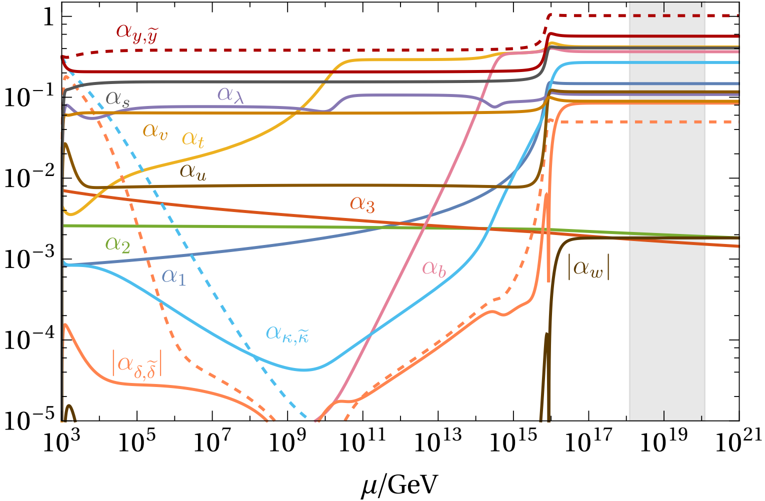
$$2\sqrt{\lambda\Delta s} + \delta\sqrt{s} + \widetilde{\delta}\sqrt{\Delta} + w\sqrt{\lambda} + \sqrt{\delta'\widetilde{\delta}'w'} > 0$$

$$\text{where} \quad \Delta = \begin{cases} \frac{u}{2} + v > 0 & \text{for } u > 0 \quad (V^+) \\ u + v > 0 & \text{for } u < 0 \quad (V^-) \end{cases},$$

BSM Critical Surface (Model I)



Planck-safe RG Running (Model II)



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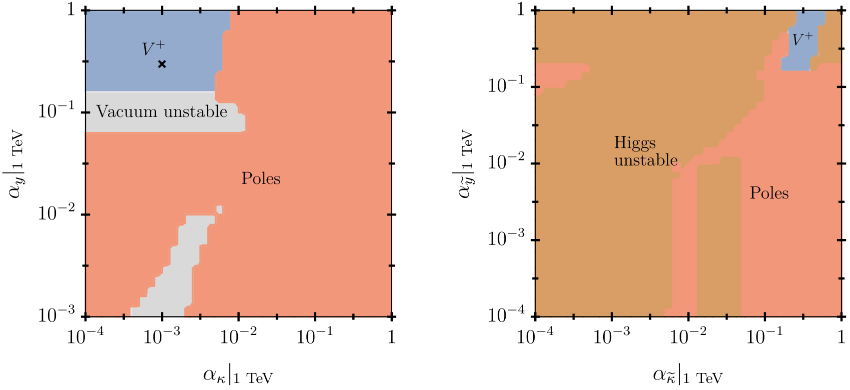


Fermionic Mixing

- Mixed Higgs Yukawa coupling κ induces off-diagonal mass term

$$-\mathcal{L}_{\text{mass}} = \begin{pmatrix} d_L \\ \psi_L^{-1/3} \end{pmatrix}_i^\dagger \begin{pmatrix} \frac{v}{\sqrt{2}} Y_d & 0 \\ \frac{v}{\sqrt{2}} \hat{\kappa} & M_F \end{pmatrix}_{ij} \begin{pmatrix} d_R \\ \psi_R^{-1/3} \end{pmatrix}_j + \text{h.c.}$$

- Mass eigenstates $(d', \psi'^{-1/3})$ are admixtures of gauge eigenstates $\Rightarrow \theta_R = \frac{\kappa}{\sqrt{2}} \frac{v}{M_F}$, $\theta_L = \frac{\kappa}{2} Y_d \frac{v^2}{M_F^2} \Rightarrow \theta_L \ll \theta_R$
- Modified and new mixed couplings of $(d', \psi'^{-1/3})$ to h, Z, W

Mixing bounds

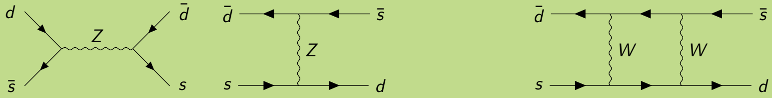
- Single production collider searches (for $M_F = 1400$ GeV)[1812.07343]

$$\alpha_{\tilde{\kappa}} \lesssim 2.4 * 10^{-2}$$

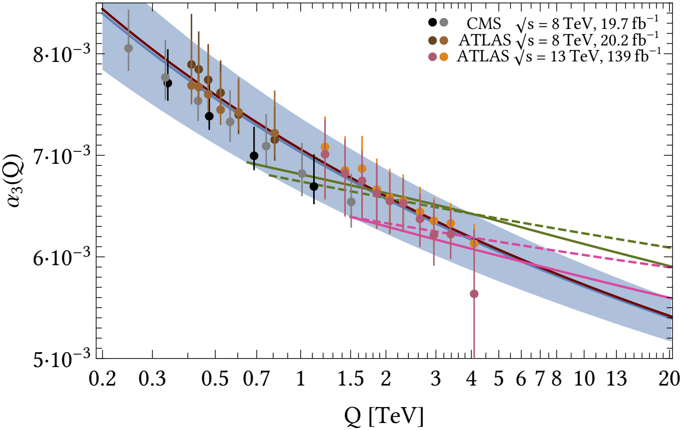
- Shift in down-type quark Z-couplings due to mixing [PDG 2020]

$$\alpha_{\hat{\kappa}} \lesssim 1.6 * 10^{-2} \left(\frac{M_F}{\text{TeV}}\right)^2$$

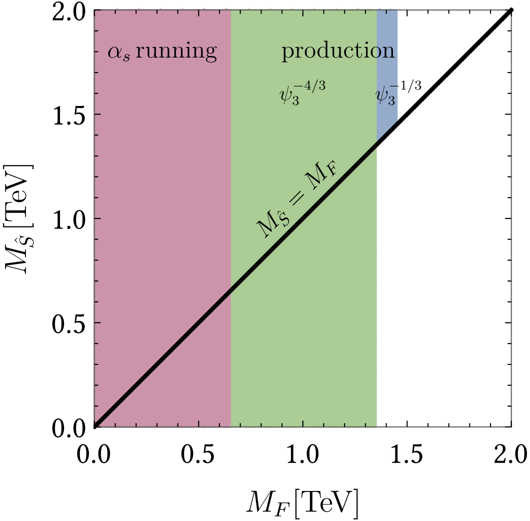
- Off-diagonal mixing causes tree-level FCNCs
  ⇒very strong bounds from neutral kaon oscillations



α_s Running



Mass bounds


α_s running
production
$\psi_3^{-4/3}$
$\psi_3^{-1/3}$
$M_{\hat{S}} = M_F$
$M_{\hat{S}}$ [TeV]
M_F [TeV]
0.0
0.5
1.0
1.5
2.0