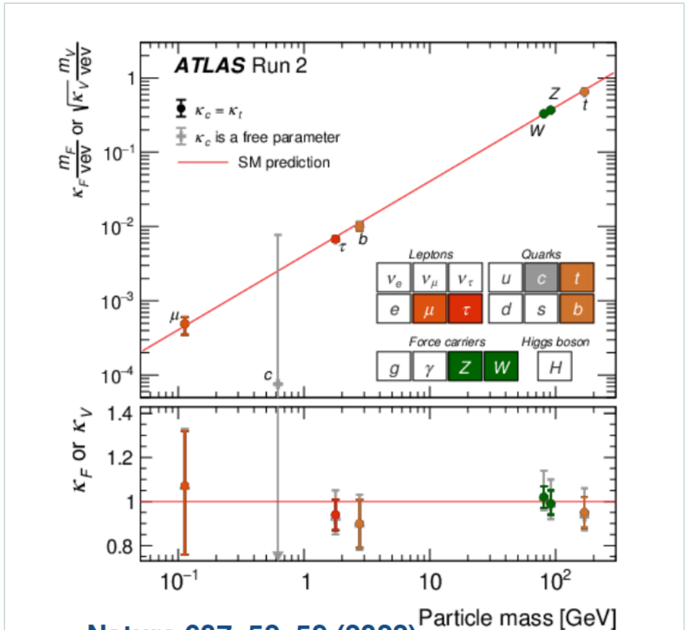
Extended Scalars and Flavor
(benefits of flavorful scalar sectors)

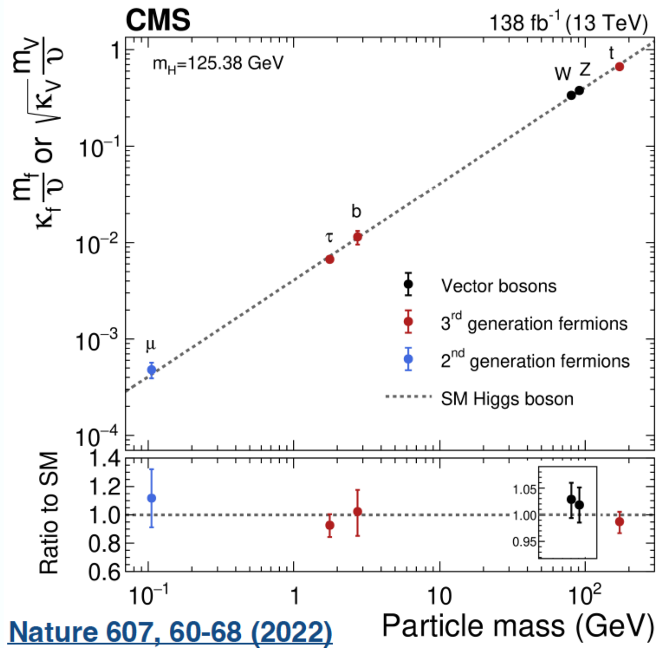
thanks to collaborators Kamila Kowalska, Daniel Litim, Martin Schmaltz, Tom Steudtner, Ivo de Medeiros Varzielas

Gudrun Hiller, TU Dortmund

SM-Higgs Yukawas $y_i \bar{\psi}_i H \psi_i$, $\quad m_i = y_i < H >= y_i v/\sqrt{2}$



Nature 607, 52–59 (2022)



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origin of mass largely open for 1st generation and strange

$y/y_{\rm SM} < 560(u), 260(d), 13(s), 260(e)$ 1905.03764, 2107.02686

Flavorful scalars– leptoquarks

Scalar leptoquarks S are flavorful: $y_{ij} \bar{q}_i S \ell_j$, $\quad q, \ell$: SM quarks and leptons

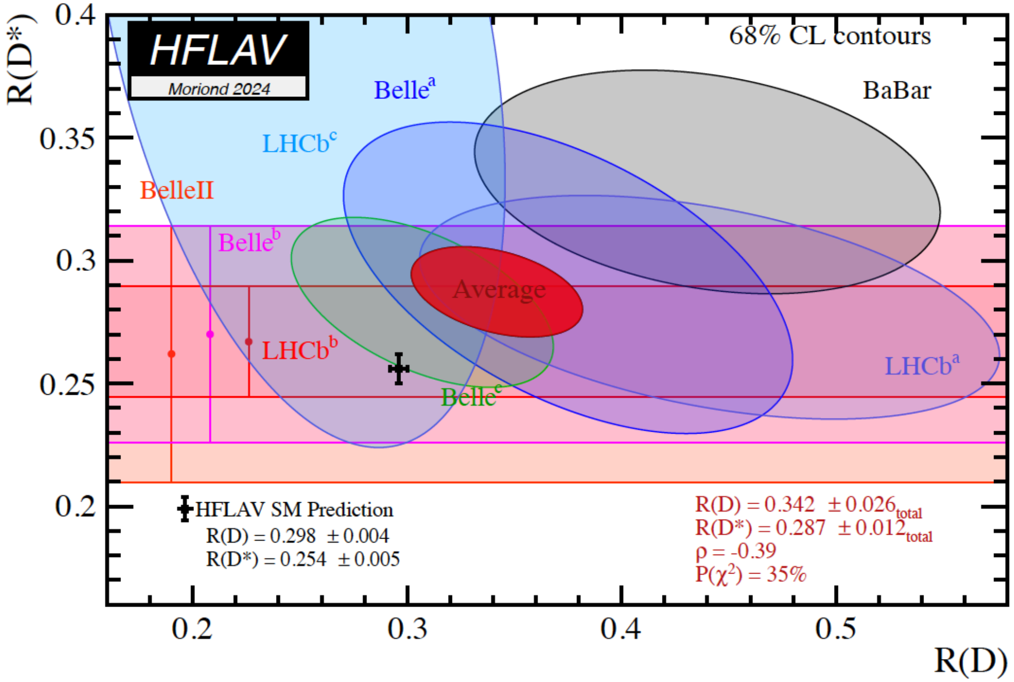
Leptoquark-Yukawa matrix: $y_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$ instrumental for tree-level explanations of B-anomalies: 1408.1627 $\begin{pmatrix} 0 & * & 0 \\ 0 & a & 0 \\ 0 & b & 0 \end{pmatrix}$

induces $b \to s\mu\mu$, (and dep. on rep, also $t \to c\mu\mu$), but not $b \to see$, can be engineered with flavor symmetries 1503.01084.

For charged current anomalies 'R_{D,D^*}': $\begin{pmatrix} 0 & * & * \\ 0 & 0 & a \\ 0 & b & 0 \end{pmatrix}$ induces $b \to c\tau\nu_\mu$

Flavorful scalars– leptoquarks

The big picture



Current status:

3.2 σ discrepancy wrt SM predictions

Even more flavorful scalars

Instead of $y_{ij}\bar{q}_i S \ell_j$, consider a matrix of scalar fields $y\bar{\psi}_i S_{ij}\psi_j$.

In the remainder of this talk I want to review the motivation, features and benefits of matrix scalars for model building and pheno.

$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \bar{\psi} i \not{D}\psi + y\bar{\psi}_i S_{ij}\psi_j - V(S)$$

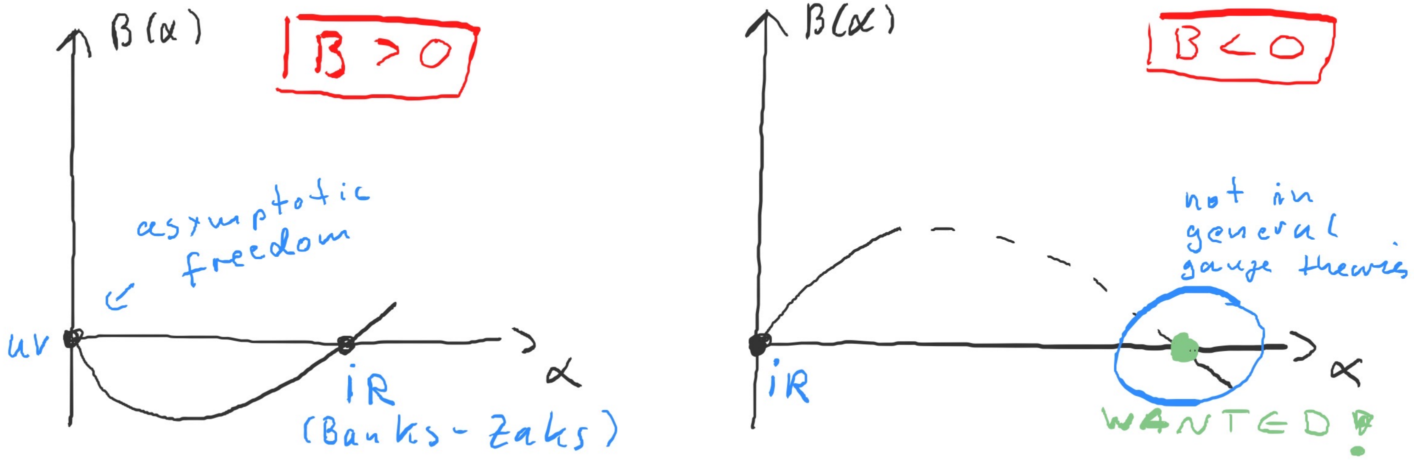
concrete CFT, with SM-features. Couplings run into UV-fixed points that are interacting – no freedom, but asymptotically safe

Template for model building.

Interlude: Beyond asymptotic freedom: pure gauge

$\frac{d\alpha_s}{d\ln\mu} = \beta(\alpha_s) = \alpha_s^2(-B + C\alpha_s + ...)$, $\quad B^{\rm SM} = 14 > 0, C^{\rm SM} = 52$

Fixed points: $\alpha_s^* = 0$ or $\alpha_s^* = B/C$ (must be positive to be physical)



For $B > 0$, $\alpha_s^* = B/C$ is IR (Banks-Zaks)

For $B < 0$ in general gauge theories $C > 0$ and finite FP doesnt exist

Bond, Litim '16

Beyond asymptotic freedom: Yukawas are key

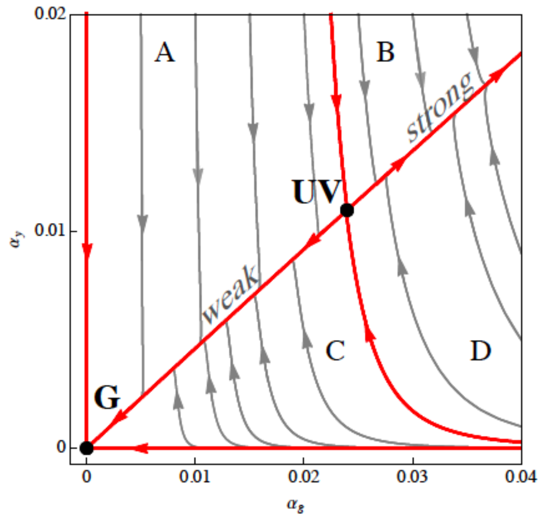
Gauge-Yukawa theory Litim, Sannino '14

$$\frac{d\alpha_s}{d\ln\mu} = \beta(\alpha_s,\alpha_y) = \alpha_s^2(-B + C\alpha_s - D\alpha_y)$$
$$\frac{d\alpha_y}{d\ln\mu} = \beta(\alpha_s,\alpha_y) = \alpha_y(E\alpha_y - F\alpha_s)$$

$B < 0$: 2 FPs: free one $\alpha^*_{s,y} = 0$ and a fully interacting one

$\alpha_y^* = \frac{F}{E}\alpha_s^*$, $\alpha_s^* = B/C'$, $\quad -B + C'\alpha_s^* = 0$, $C' = C - D\frac{F}{E}$, $C' \leq C$

Iff $C' < 0$ FP positive; needs sizable D Yukawa contribution

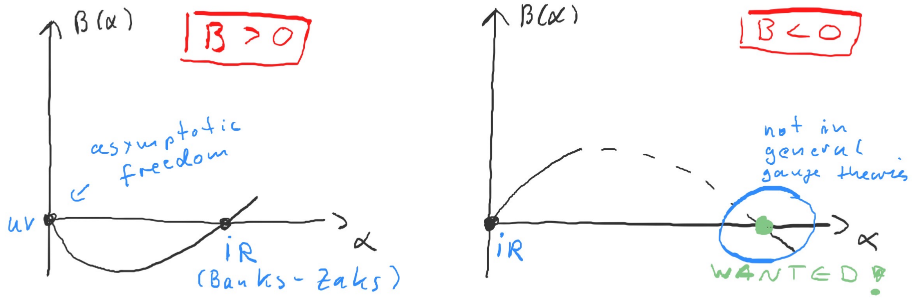


Beyond asymptotic freedom: Yukawas are key

Blue print model is flavorful Litim, Sannino '14:

N_F vector-like fermions $\psi_{L,R}$, singlet scalar matrix S_{ij}, $i, j = 1..N_F$

$$\mathcal{L}_y = y\,\psi_{Li} S_{ij} \psi_{Rj} + h.c., \quad \alpha_y = y^2/16\pi^2, \quad D \propto N_F^2,\ C' < 0$$



Gauge-Yukawa FP UV attractive (exact proof in Veneziano limes $N_F, N_C \to \infty$, N_F/N_C finite, tuneable, $N_F/N_C = \frac{11}{2} + \epsilon$, $B = -4/3\epsilon$)

Even more flavorful scalars

Instead of $y_{ij}\bar{q}_i S \ell_j$, consider a matrix of scalar fields $y\bar{\psi}_i S_{ij}\psi_j$.

In the remainder of this talk I want to review the motivation, features and benefits of matrix scalars for model building and pheno.

$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \bar{\psi} i \not{D}\psi + y\bar{\psi}_i S_{ij}\psi_j - V(S)$$

concrete CFT, with SM-features. Couplings run into UV-fixed points that are interacting – no freedom, but asymptotically safe Template for model building.

The matrix scalar S_{ij}, i.e. N_F^2 complex scalar singlets, is instrumental because it affects the gauge-coupling RG with $\propto N_F^2$.

Top-Down with UV-Safety

LiSa Litim, Sannino 1406.2337: Asymptotic Safety guaranteed in Veneziano-limit in SM-like setting (gauge-yukawa-scalar theory)

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \bar{\psi} i \not{D} \psi + y \bar{\psi}_i S_{ij} \psi_j - V(S)$$

two main catches for pheno/model building:

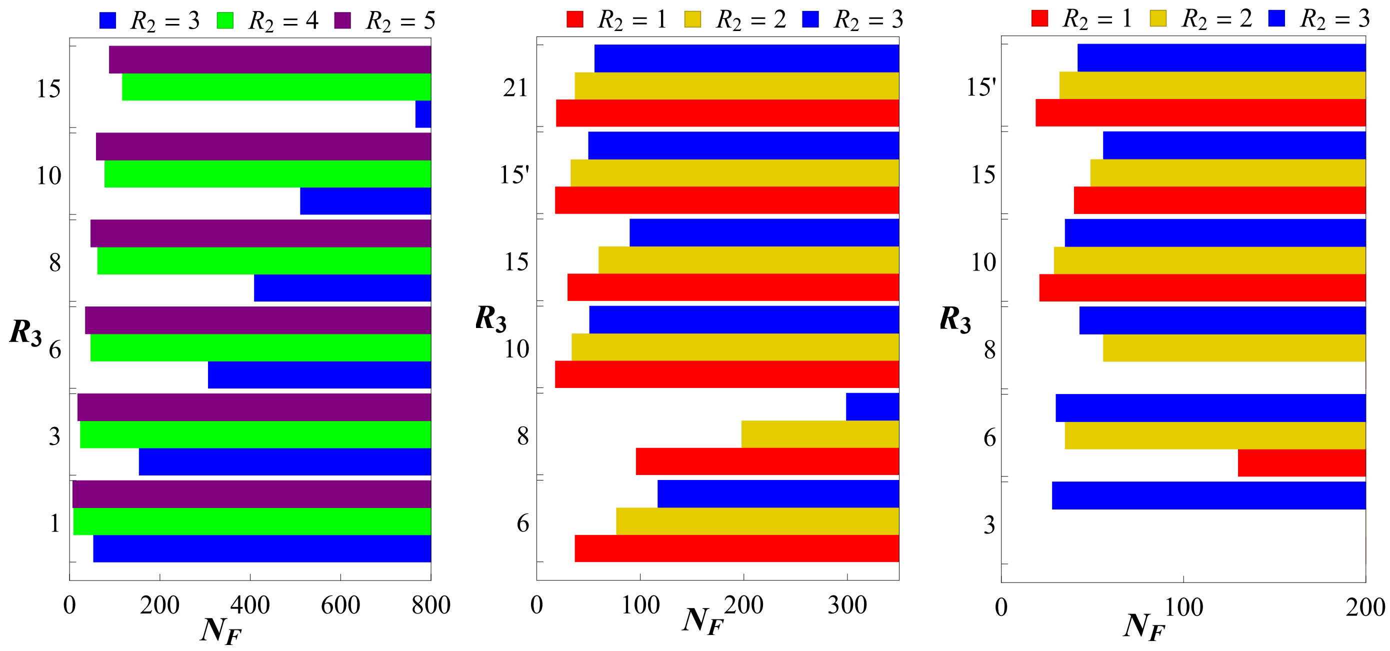
A) Can the SM emerge at low energies from a CFT? Yes. at 2-loop,

Bond et al 1702.01727 $\mathcal{L} = \mathcal{L}_{\rm SM} + y \bar{\psi}_i S_{ij} \psi_j - V(S)$

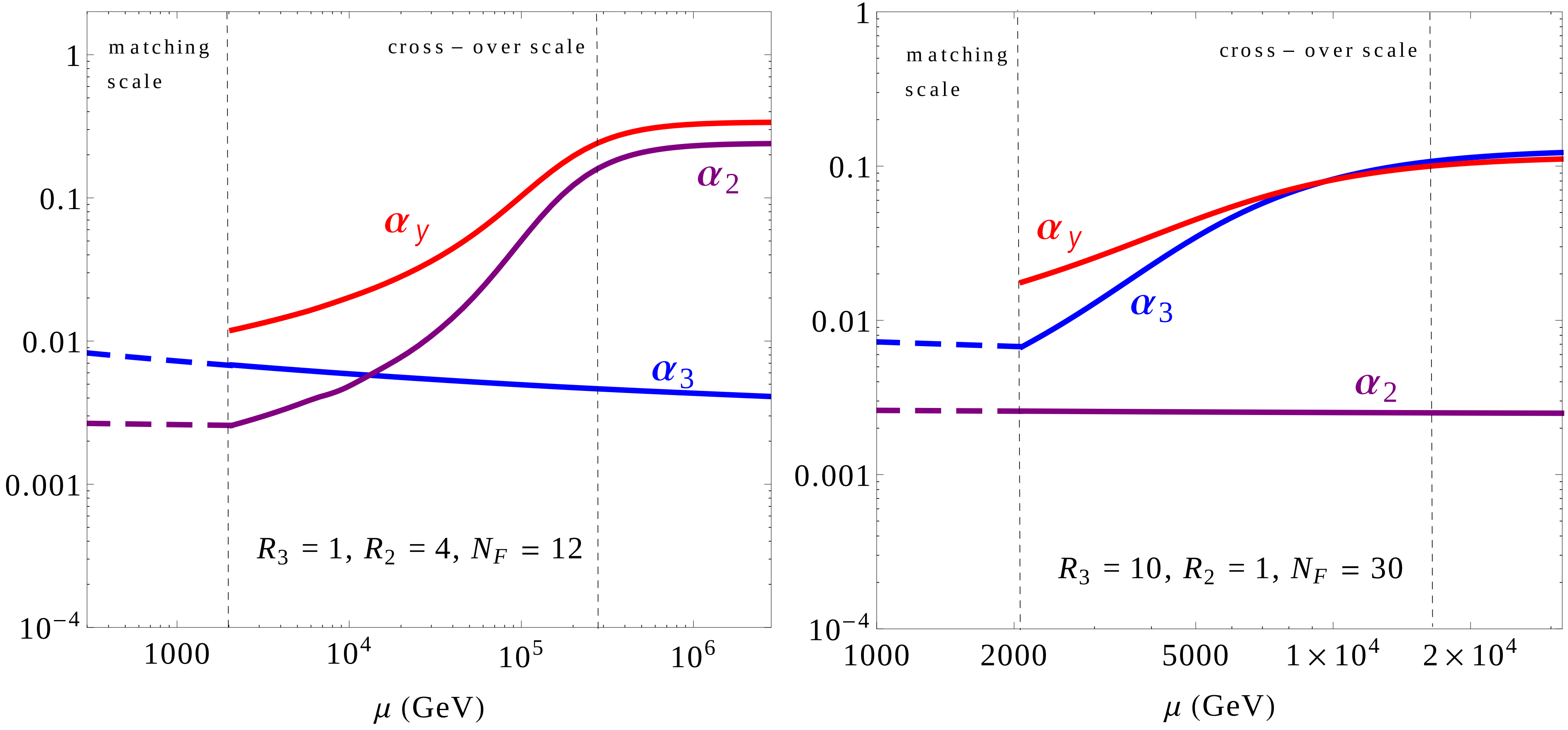
framework has predictivity, stability, no poles (from the electroweak scale upwards) "UV complete"

Concrete SM-extensions obtained and analyzed by Bond et al '17 1702.01727 Demand for higher-order beta-functions with analytical dependence on N_F and reps. $\rightarrow$ ARGES tool 2012.12955

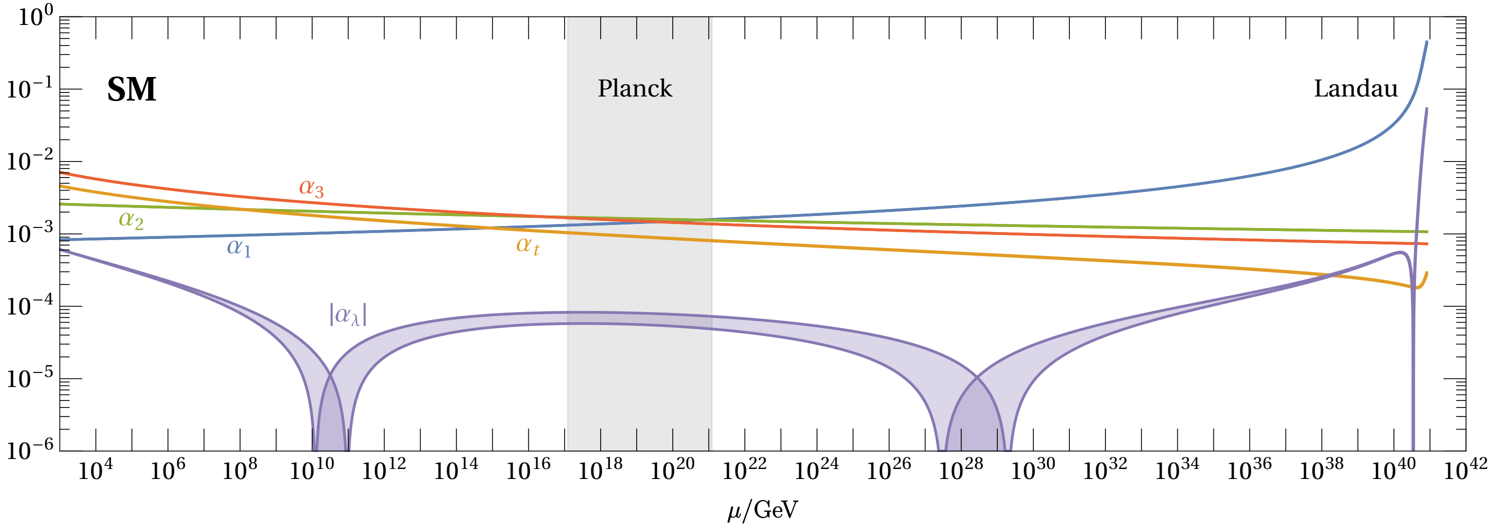
Availability of weakly interacting UV fixed points $\alpha_3^* = 0$ (left), $\alpha_2^* = 0$ (mid), fully interacting (right) with VLFs $\psi(R_3, R_2, 0)$ 1702.01727



Due to flavor symmetry, they are long-lived; LHC: dijet searches, R-hadrons, LLP searches

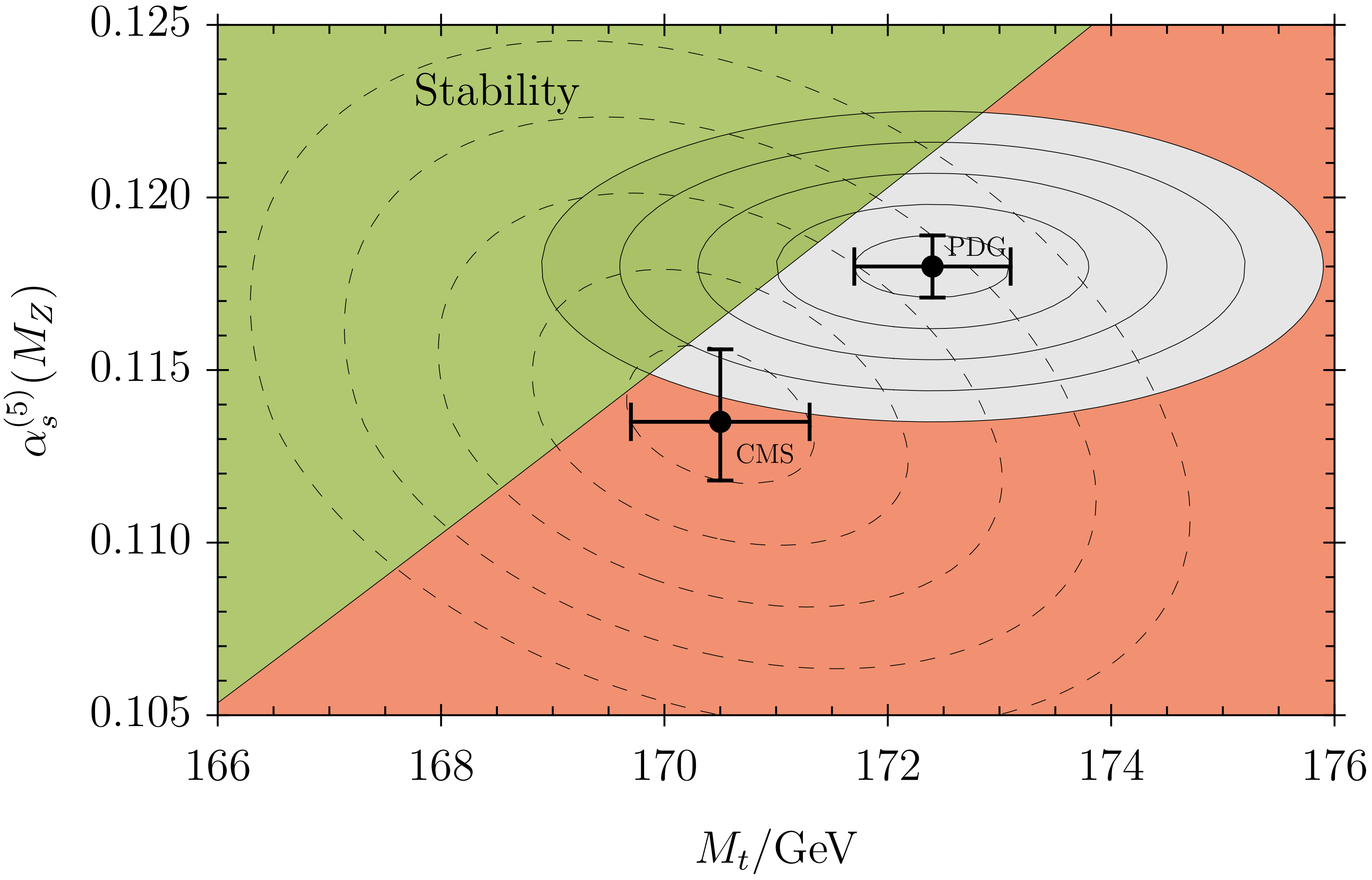

matching scale
cross – over scale
1
0.1
0.01
0.001
10^{-4}
1000
10^4
10^5
10^6
μ (GeV)
α_y
α_2
α_3
$R_3 = 1, R_2 = 4, N_F = 12$
matching scale
cross – over scale
1
0.1
0.01
0.001
10^{-4}
1000
2000
5000
1×10^4
2×10^4
μ (GeV)
α_y
α_3
α_2
$R_3 = 10, R_2 = 1, N_F = 30$

all the way up to the Planck scale



Its intruiging that the SM is so near-critical when it comes to vacuum stability.

Vacuum Stability



2401.08811

Obs.	Value	$\alpha_\lambda > 0$		$\alpha_{\lambda,\text{eff}} > 0$	
PDG 2024 :					
M_h/GeV	$125.20(11)$	127.97	$+25.2\sigma$	127.85	$+24.0\sigma$
M_t^σ/GeV	$172.4(7)$	171.04	$-\ 1.9\sigma$	171.10	$-\ 1.9\sigma$
M_t^{MC}/GeV	$172.57(29)$		$-\ 5.3\sigma$		$-\ 5.1\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.3	$-\ 0.8\sigma$	161.4	$-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1180(9)$	0.1215	$+\ 3.9\sigma$	0.1213	$+\ 3.7\sigma$
CMS [**?**]:					
M_t/GeV	$170.5(8)$	169.25	$-\ 1.6\sigma$	169.31	$-\ 1.5\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1135(^{+21}_{-17})$	0.1167	$+\ 1.5\sigma$	0.1165	$+\ 1.4\sigma$

$M_t - \alpha_s$ correlations matter. M_h not relevant currently to decide fate of SM. More precise M_t needed (factor $\gtrsim 2$ ($\lesssim 300$ MeV) great)

LiSa Litim, Sannino 1406.2337: Asymptotic Safety guaranteed in SM-like setting (gauge-yukawa-scalar theory)

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \bar{\psi} i \not{D} \psi + y \bar{\psi}_i S_{ij} \psi_j - V(S)$$

two main catches for pheno/model building:

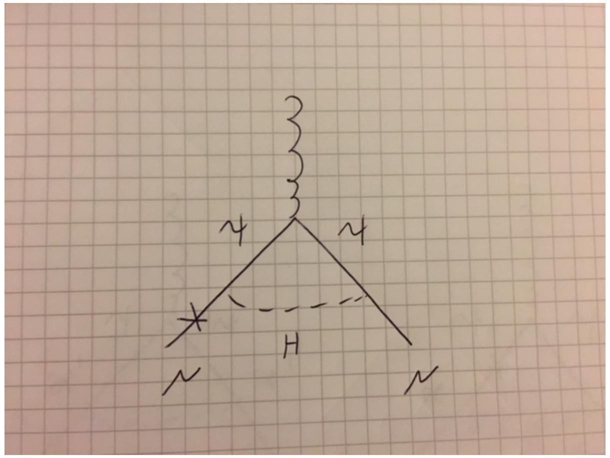
B) new tool for flavorful model building: S_{ij} matrix scalar

application: $g-2$ of electron and muon 1910.14062 ; flavor-protection ”no LFV”, nor flavor non-universality needed (unique explanation)

novel multi-lepton signatures at LHC: $\psi\bar{\psi}$-production,
$\psi_e^- \to S_{e\mu}\mu^- \to e^-\mu^+\mu^-$ looks LFV but isnt 2011.12964

Consider vector-like leptons with mixed Yukawas for Δa_μ: $\kappa \bar{L} H \psi$

Giudice, Wise, Ligeti, ..

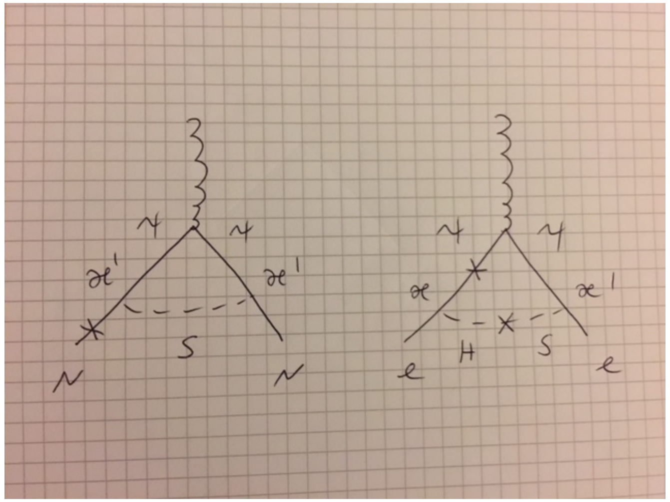


problems: Δa_e unaccounted, $Z\ell\ell$ bounds and LFV (fermions mix)

does not work

Straight-forward explanation with enlarged BSM-flavor sector: VLLs and scalar singlets with Higgs portal as in Planck-safe frameworks:

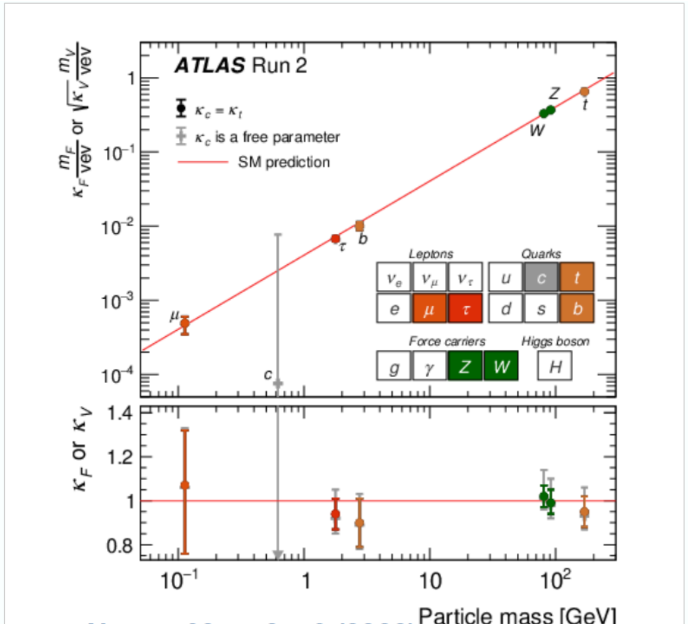
$$\kappa \bar{L} H \psi + \kappa' E S \psi + \delta S^\dagger S H^\dagger H, \quad \Delta a_\mu \sim \frac{m_\mu^2}{M_\psi^2} \frac{\kappa'^2}{16\pi^2}, \quad \Delta a_e \sim \frac{m_e}{M_\psi} \frac{\kappa \kappa' \delta}{16\pi^2}$$



Flavorful scalar sector from asymptotic safety instrumental – $\kappa' E_i S_{ij} \psi_j$ no LFV constraints due to flavor symmetry $SU(3) \times SU(3)$.

VLFs affect the link between fermion mass and Higgs (125)-Yukawa:

$y/y_{\rm SM} < 560(u), 260(d), 13(s), 260(e)$ 2008.08606, 2410.08272 1905.03764, 2107.02686



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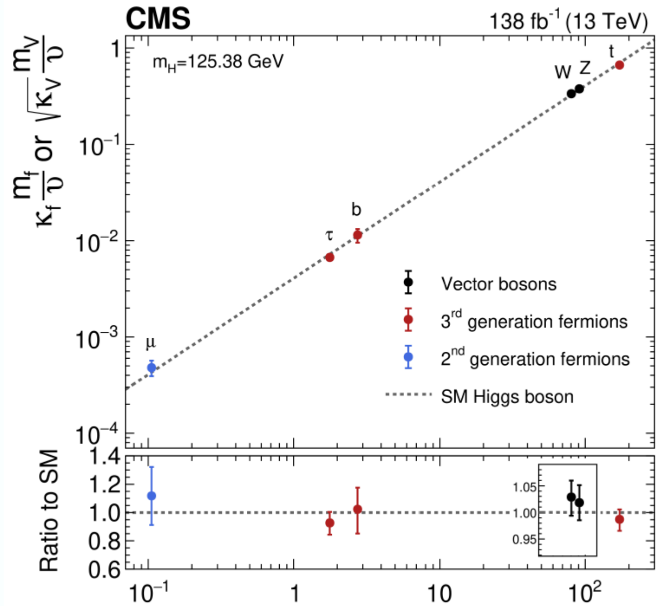

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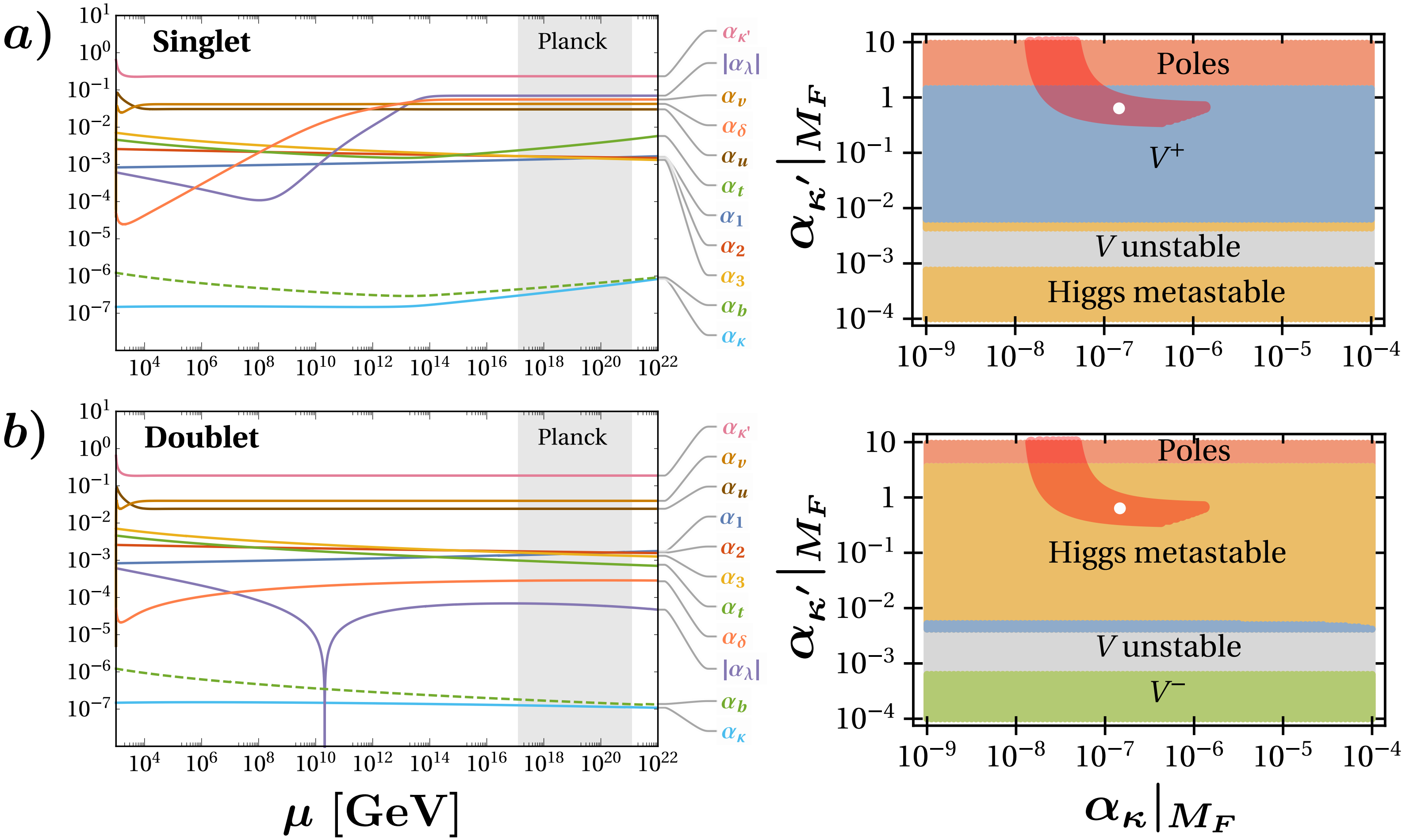
origin of mass largely open for 1st generation and strange

model building with Planck safety



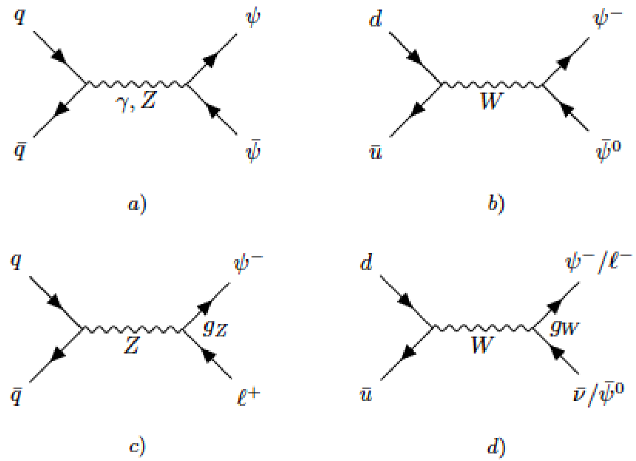
right plots: TeV-BSM parameters with Planck features and red banana: $g-2$, V^+: universal groundstate, V^-: vacuum singles out electrons– spontaneous breakdown of universality 1910.14062

Lagrangian encodes flavor symmetry-links between SM and BSM

$\kappa \bar{L} H \psi + \kappa' E S \psi + \delta S^\dagger S H^\dagger H$

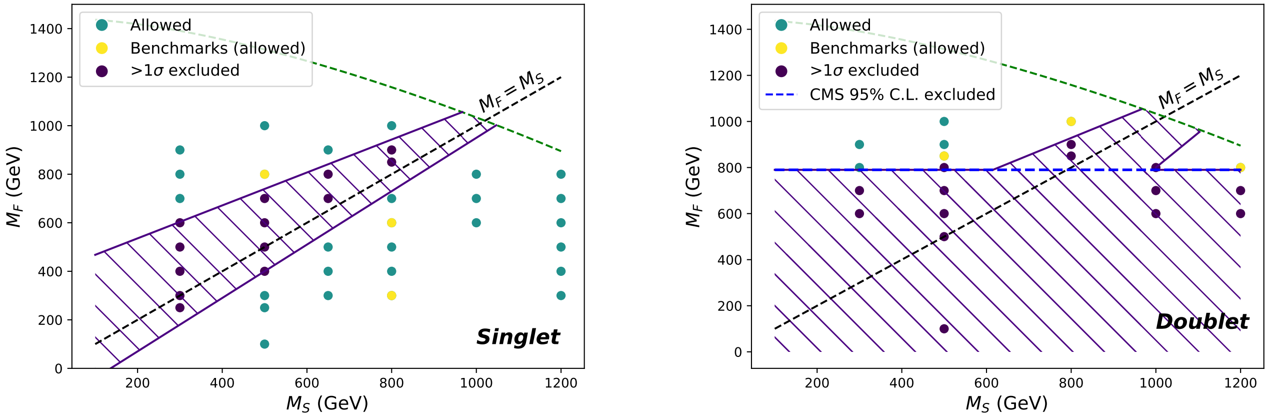
$\kappa \bar{L} H \psi = \kappa \bar{L}_i H \psi_i$, $\kappa' E S \psi = \kappa' E_i S_{ij} \psi_j$ lepton flavor is conserved!

Gives rise to quasi -LFV signatures – low SM background 2011.12964

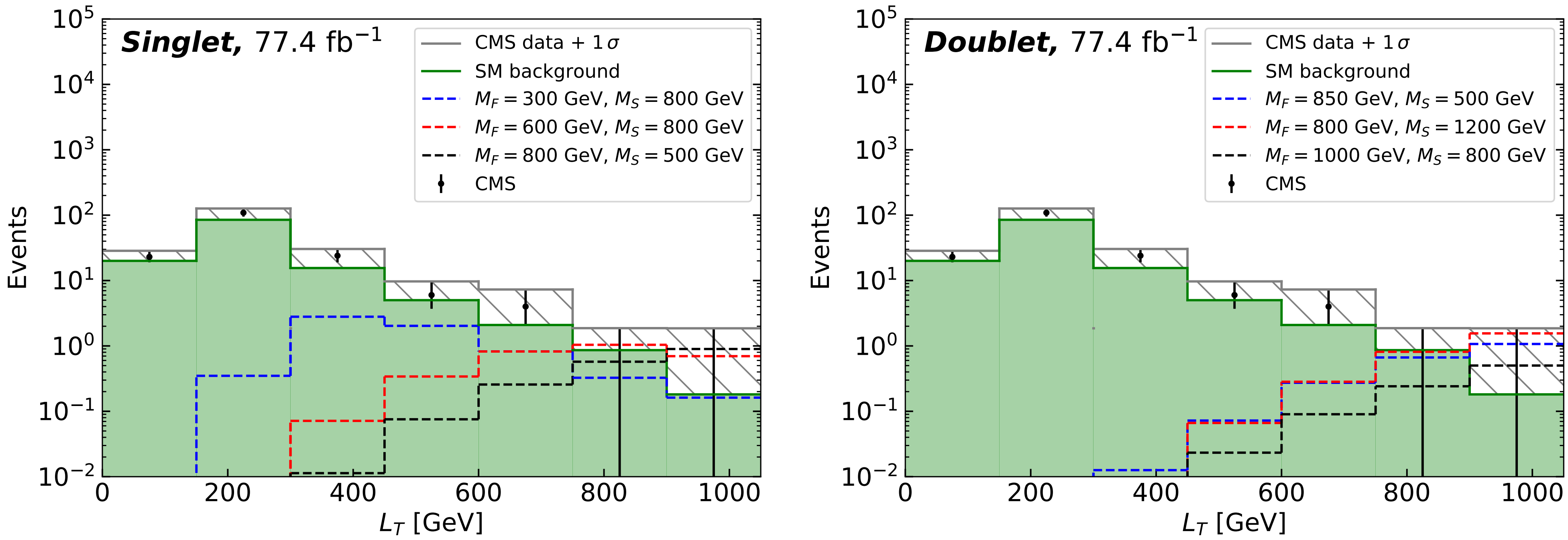


VLL pair-production, the cascade decays $\psi_i \to S^*_{ij}\, \ell^-_j \to \ell^-_i\, \ell^+_j\, \ell^-_j$.

e.g. $\psi_e \to S^*_{ej}\, \ell^-_j \to \ell^-_i\, \ell^+_j\, e^-$.



confronting models to re-interpreted CMS search with at least 4 light leptons (4L) 1905.10853

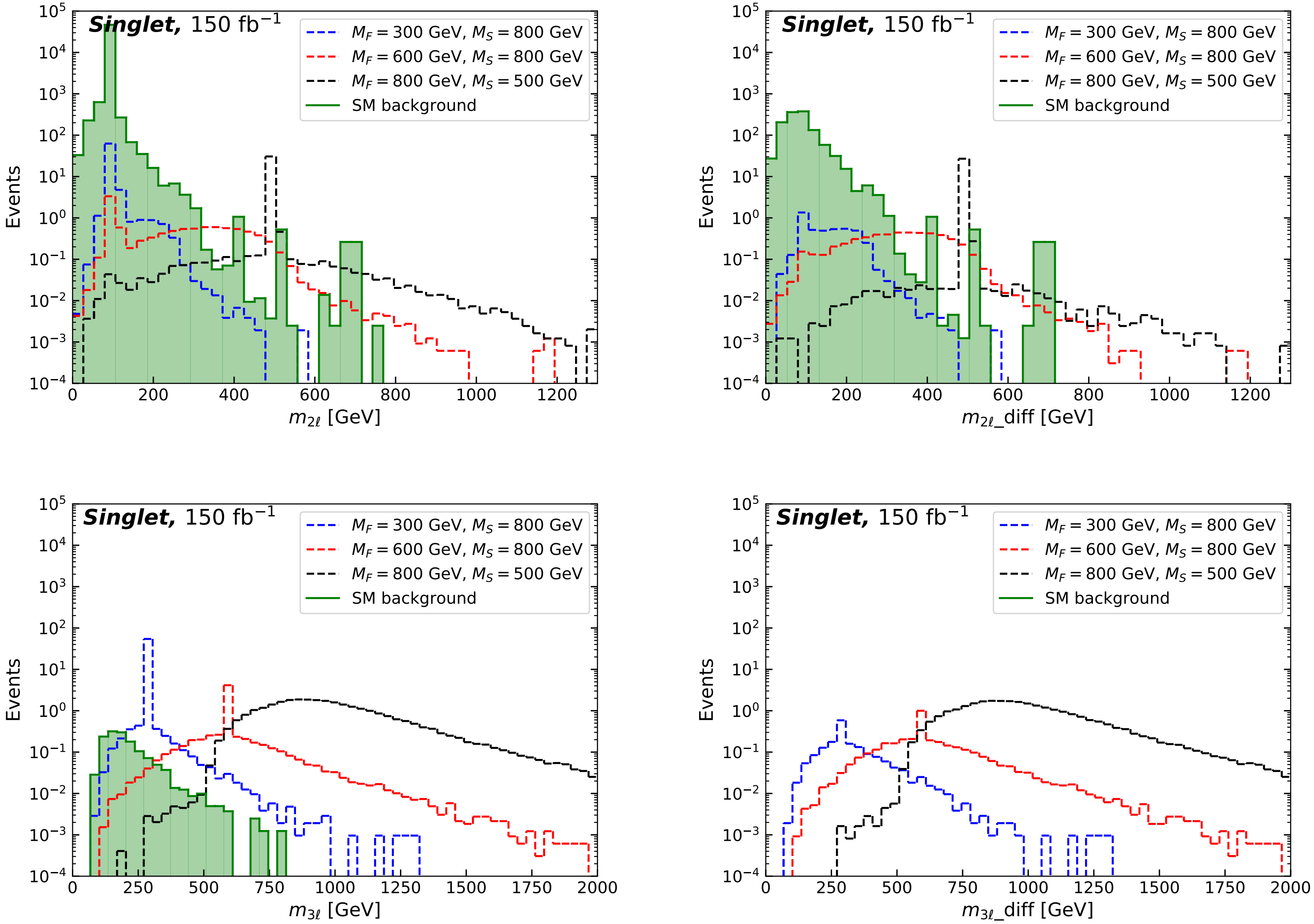


L_T distributions in the singlet (left) and the doublet model (right) for SM background processes in our simulation (green shaded area) and for the different benchmark masses of vector-like fermions and new scalars (yellow circles in Fig. **??**). The observables are shown for an integrated luminosity of 77.4 fb^{-1} and subsequent detector simulation. Also shown are CMS data [**?**] (black points), including the range covered up to 1σ (hatched area), see text for details.

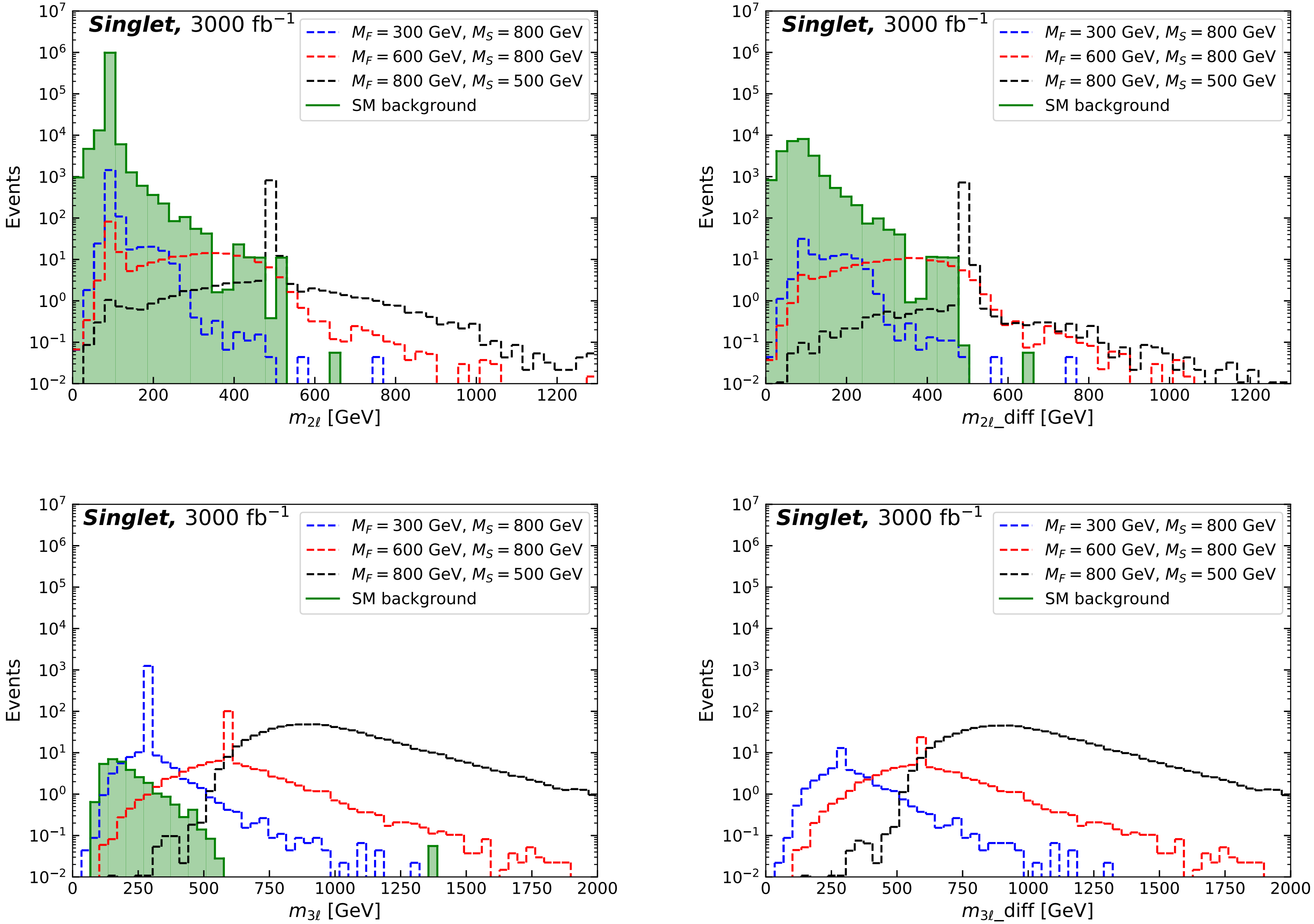
New SM null test observables emply flavor features

$\psi_i \to S^*_{ij}\, \ell^-_j \to \ell^-_i\, \ell^+_j\, \ell^-_j$. to suppress BGD. Best for HL-LHC

Di- and trilepton invariant mass distributions $m_{2\ell}$, $m_{2\ell}$_diff, $m_{3\ell}$, and $m_{3\ell}$_diff for the singlet model for different benchmark masses of the VLLs and the BSM scalars at a luminosity of 150 fb^{-1} and $\sqrt{s} = 13$ TeV and 3000 fb^{-1} and $\sqrt{s} = 14$ TeV.


Singlet, 150 fb^{-1}
$M_F = 300$ GeV, $M_S = 800$ GeV
$M_F = 600$ GeV, $M_S = 800$ GeV
$M_F = 800$ GeV, $M_S = 500$ GeV
SM background
Events
$m_{2\ell}$ [GeV]
$m_{2\ell}$_diff [GeV]
$m_{3\ell}$ [GeV]
$m_{3\ell}$_diff [GeV]

Multi-leptons at the LHC

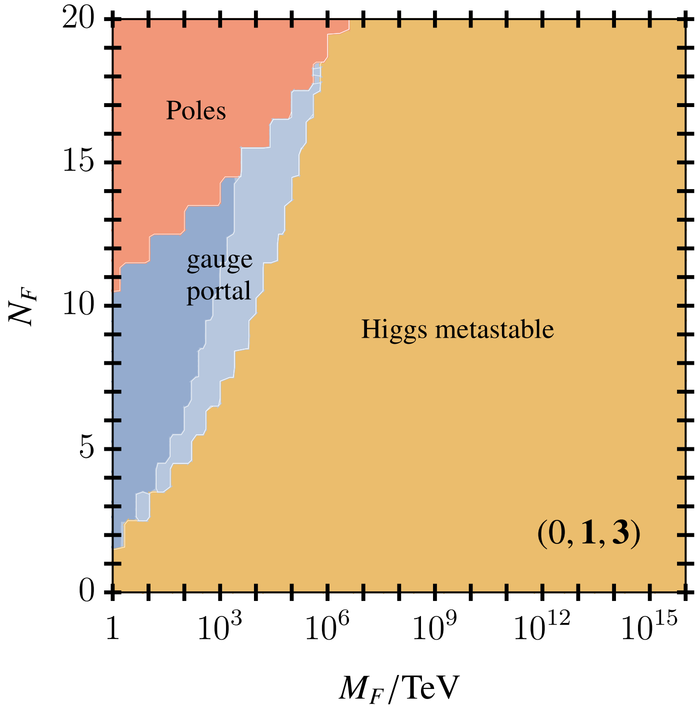


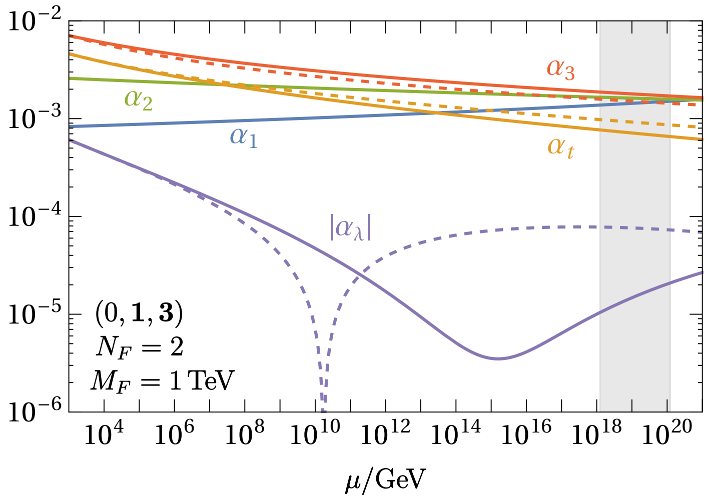
Summary

- Take home message: new, concrete & testable directions from formal QFT for BSM model building beyond EFTs.
- Genuine new scalar sector: the S_{ij} matrix field; offers different ground states 2008.08606 and leads to novel flavorful signatures at the LHC "only LFV-like" 2011.12964
- Can explain $g-2$, flavor anomalies in beauty and charm 1910.14062, 2109.06201, 2210.16330, and stabilize the SM vaccum 2207.07737, 2305.18520 , 2401.08811
- Planck safety requires "no poles, no instabilities" up to Planck scale; works with or without 2207.07737 the new wonder tool S_{ij}
- Stay tuned

What does it take to achieve stability in SM?

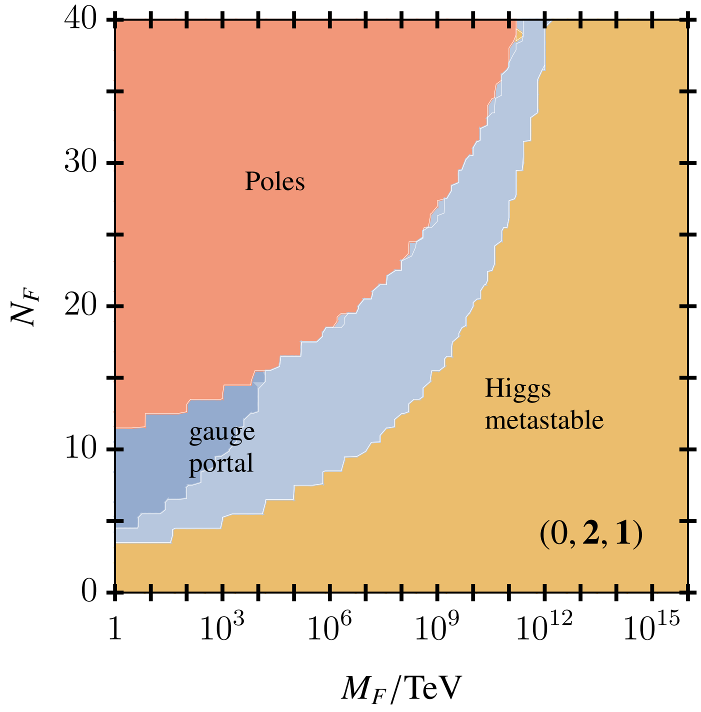
Minimal fix: the gauge portal: add VLFs. It works with charged under only QCD, $SU(2)_L$ and $U(1)_Y$ 2207.07737 Dont add too little too late

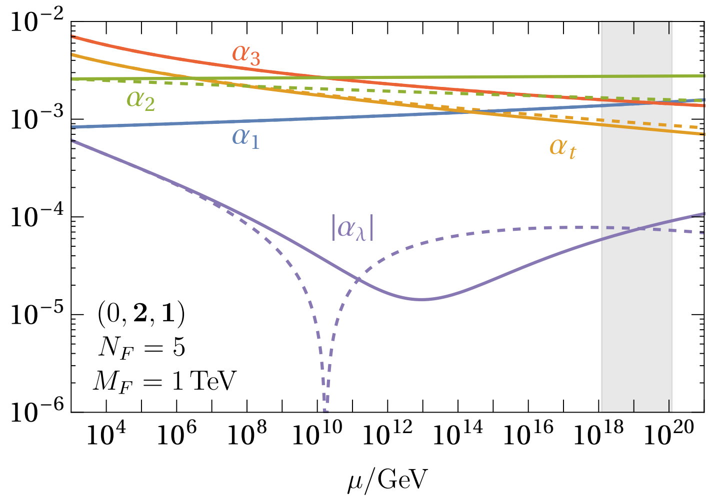




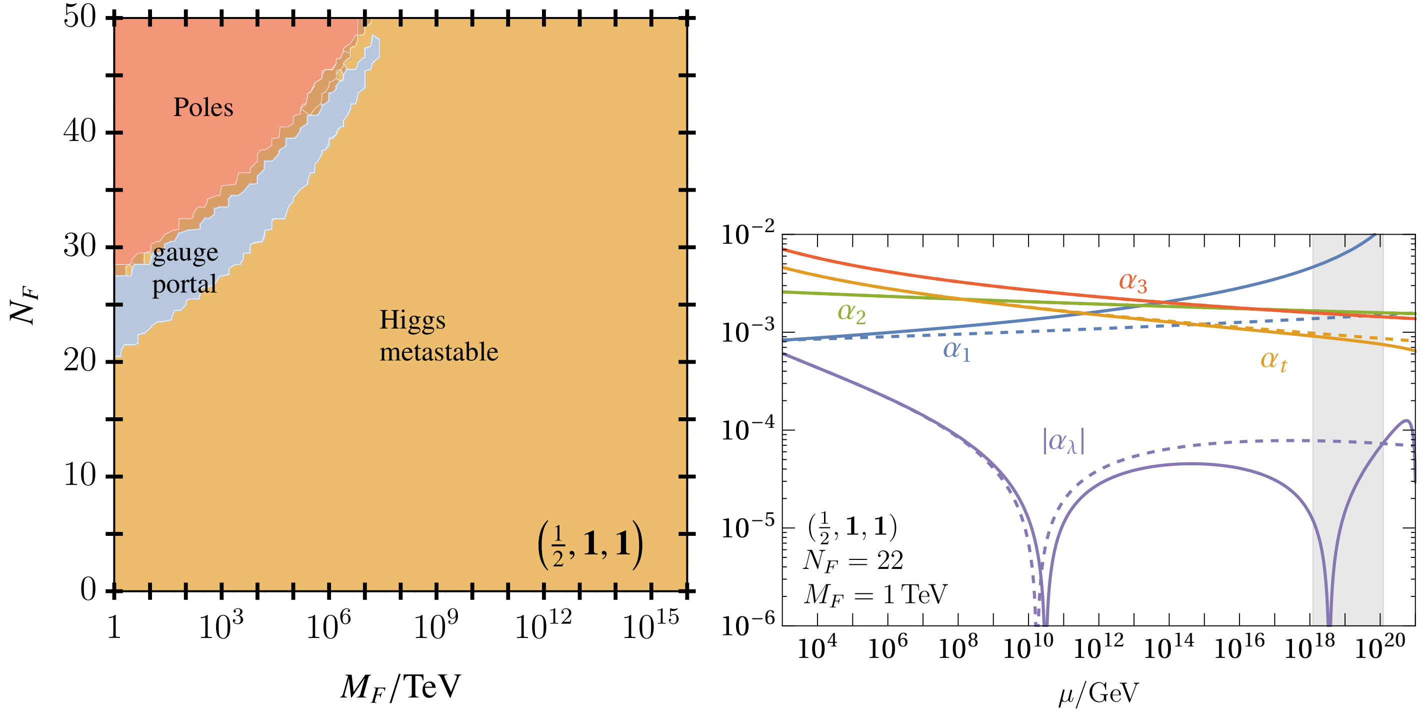
VLQs

Bottom-Up with UV-Safety





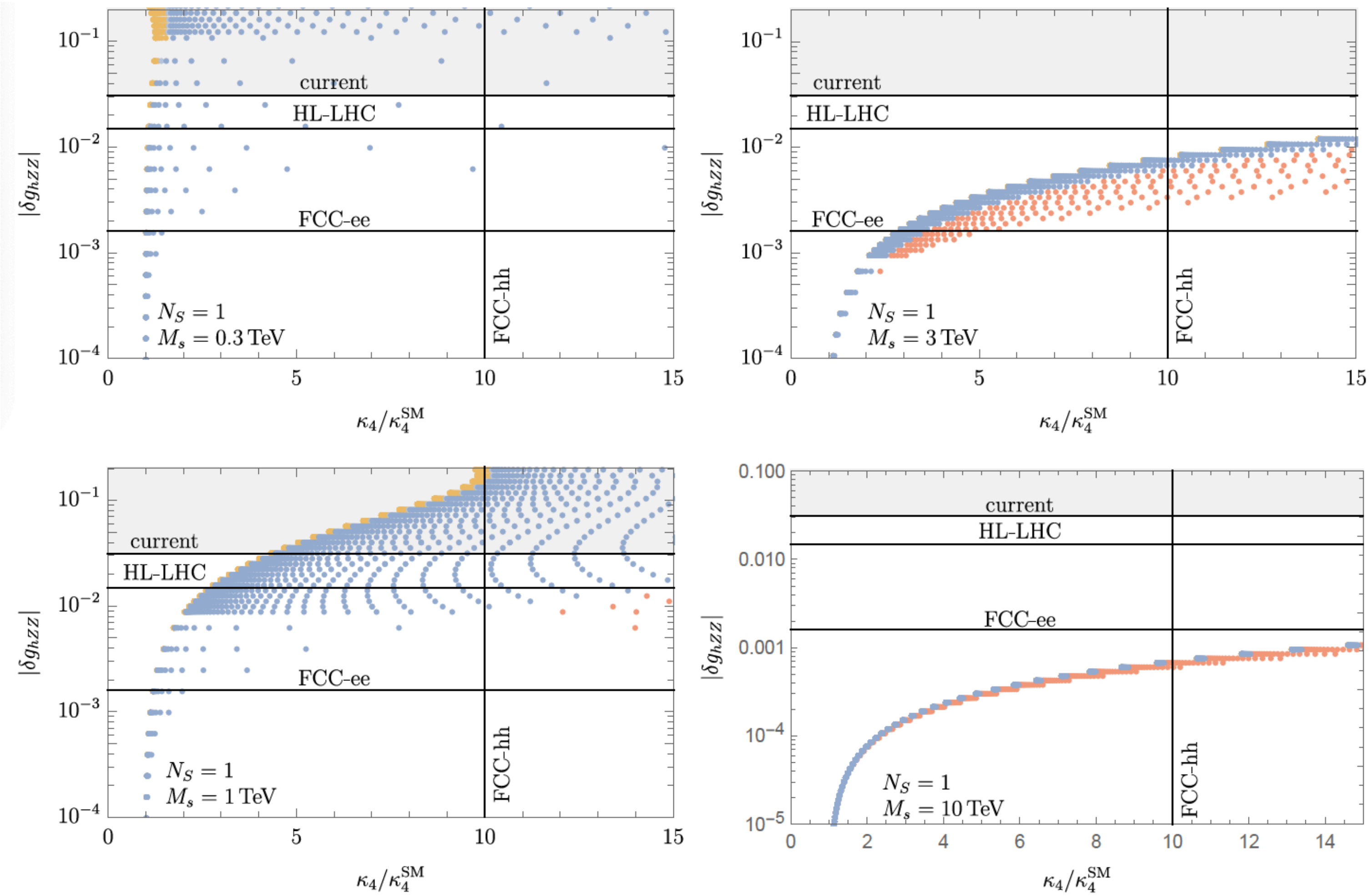
VLLs



Hypercharged

Systematic study of Higgs-portal $\delta H^\dagger H S^\dagger S$ with Higgs coupling predictions for HL-LHC and FCC 2401.08811

Bottom-Up with UV-Safety



red: poles, blue: stable