European Strategy for Particle Physics

PARALLEL 7 / **BSM**

Higgs Compositeness

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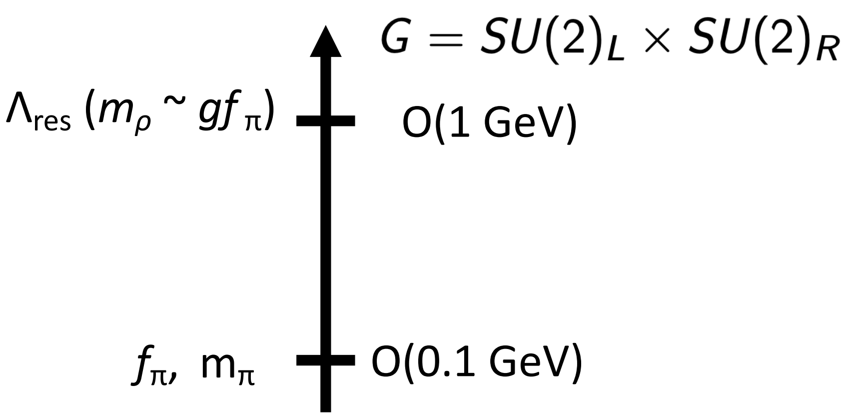
Intro & motivation

- Hierarchy Problem: Why m_H << than Planck scale?

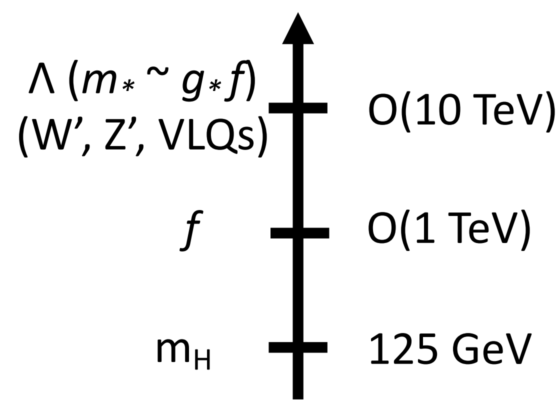
$$\delta m_H^2 \sim \frac{\Lambda^2}{16\pi^2}$$

- Possible solution: Higgs not an elementary particle
  - Instead: Pseudo-Nambu–Goldstone boson (i.e., bound state) from a new strongly interacting sector

QCD analogy



Composite Higgs



Composite Higgs

- m_H: Naturally protected by the symmetry
  - Broken explicitly by gauge and Yukawa interactions
- m_H generated via loops:

Decay constant

$$m_H^2 \propto \frac{g^2}{16\pi^2} f^2$$

$$m_H^2 \sim \frac{g^2}{16\pi^2} f^2 \ll f^2 \ll m_*^2 \sim g_* f$$

Compositeness scale

- Two approaches
  - Direct Search for resonances (e.g., W'/Z', VLQs, top partners,..)
    - (HL-)LHC limits: $m^* \lesssim O(\text{few})$ TeV
      - Small σ & large BKGs; Needs much higher E_{CM} (e.g., FCC-hh)
  - Indirect Probes
    - Precision measurements → constraints on m*~g*f

EFT in Composite Higgs

- Strongly-Interacting Light Higgs (SILH) framework
  - *L* organized via a power counting in m_* & g_*

$$\mathcal{L}_{\text{EFT}} \sim \frac{m_*^4}{g_*^2} \times \left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{g F_{\mu\nu}}{m_*^2}, \frac{\lambda_L \bar{q}_L O}{m_*^{3/2}}, \frac{\lambda_R \bar{t}_R O}{m_*^{3/2}}, \dots \right)$$

- Two approaches
  - **Non-RG:** each EFT operator is independent (à la ESPPU 2020)
  - **RG-improved:** Operators mix via RG evolution (new: PPG 2025); SILH framework

- Types considered
  - **Flavour Universal:** Tree-level (non-RG)
  - **Flavour Non-universal:** Often RG-based

Cheat sheet: Flavour universal

- All SM fermions couple *universally* to the strong sector
  - flavor-universal deviations in EW precision observables
  - Main modifications: gauge propagators & Higgs sector

Operator	Physical Effect	Scaling
$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$	Kinetic term renormalization	$\frac{g_*^2}{m_*^2} \sim \frac{1}{f^2}$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	Custodial symmetry violation (T param.)	
$\mathcal{O}_W = i\frac{g_2}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\mu\nu}$	Triple gauge couplings (TGC)	$\frac{1}{m_*^2}$
$\mathcal{O}_B = i\frac{g_1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$	Hypercharge mixing (S param.)	
$\mathcal{O}_{2W} = -\frac{g_2^2}{2}(D^\mu W_{\mu\nu})(D_\rho W^{\rho\nu})$	Gauge propagator corrections	$\frac{1}{g_*^2 m_*^2}$
$\mathcal{O}_{2B} = -\frac{g_1^2}{2}(\partial^\mu B_{\mu\nu})(\partial^\rho B^{\rho\nu})$		

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Higgs Rates/couplings: κ_V, κ_f

WW threshold: m_W
Z-pole: Γ_Z, $\sin\theta$

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WW threshold: m_W
Multi-V: direct
Z-pole: Γ_Z, $\sin\theta$

Z-pole: $\sin\theta$,
A_{FB}, A_L asymmetries
$A_{FB} \sim A_e A_f$, $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$

DY processes:
direct searches

Cheat sheet: Flavour non-universal

- SM fermions partially composite & generation-dependent coupling strengths to the strong sector
  - EW vertex corrections scale often suppressed
  - Flavour non-universal deviations in V couplings

w/o top-compositeness

Operator	Physical Effect	Scaling
$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L)$	EW vertex: $Z\bar{q}_L q_L$	$\frac{\epsilon^2}{f^2}$
$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{q}_L \gamma^\mu \tau^a q_L)$	EW vertex: W couplings	
$\mathcal{O}_{qD}^{(1)} = (\bar{q}_L \gamma^\mu q_L)(\partial^\nu B_{\mu\nu})$	Zff vector corrections	$\frac{\epsilon^2}{m_*^2}$
$\mathcal{O}_{qD}^{(3)} = (\bar{q}_L \gamma^\mu \tau^a q_L)(D^\nu W^a_{\mu\nu})$	W vertex corr., TGCs	

($\epsilon = \lambda / g_*$)

top-compositeness

$\mathcal{O}_{Ht} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R)$	$Z\bar{t}t$ vertex correction	$\frac{\epsilon_t^2}{f^2}$
$\mathcal{O}_{tD} = (\bar{t}_R \gamma^\mu t_R)(\partial^\nu B_{\mu\nu})$	Vectorial BSM shift	$\frac{\epsilon_t^2}{m_*^2}$
$\mathcal{O}_{tB} = (\bar{t}_R \gamma^\mu t_R) B_{\mu\nu}$	Dipole-type vertex	

($\epsilon_t^2 / f^2 \sim y_t^2 / m_*^2$)

Cheat sheet: Flavour non-universal

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Z-pole

$R_b = \frac{\Gamma_b}{\Gamma_{had}} \quad R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$

WW threshold: m_W, Γ_W

Z-pole: m_Z, Γ_Z, σ_0^{had}, R_L

WW threshold, Multi-V (direct)

top-compositeness

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ttbar threshold, tt dif. distributions

Ingredients

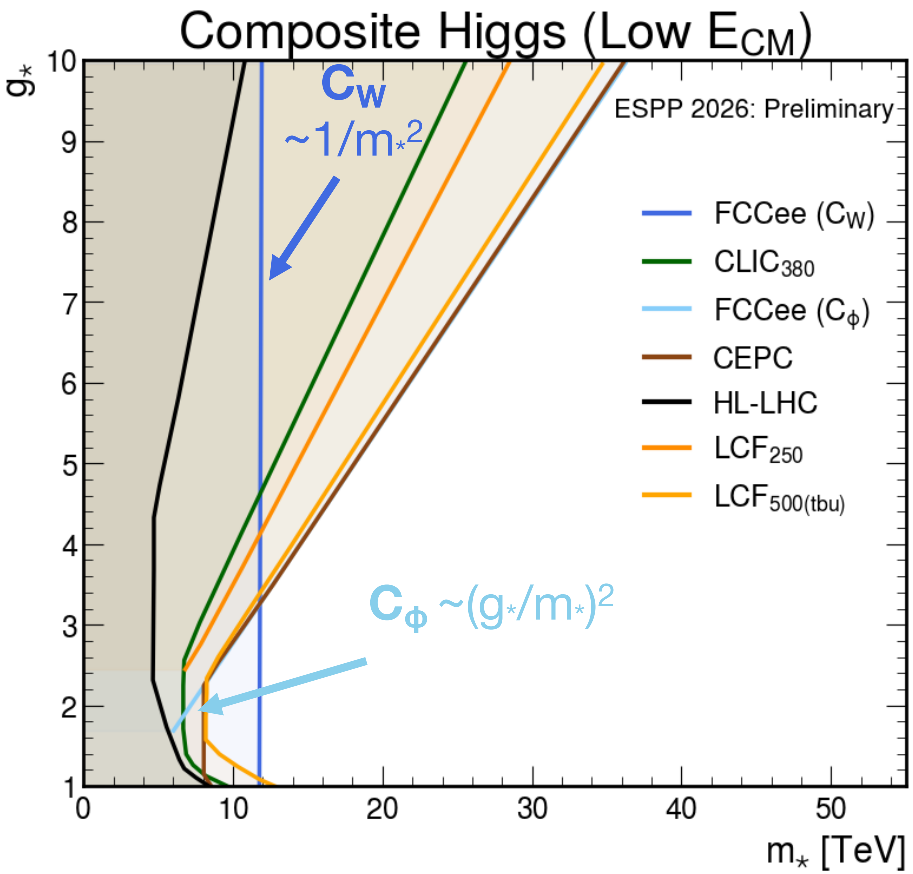
- **Theory** uncertainties (from EW WG; preliminary)
  - Uncertainties in translating EXP data to pseudo-observables (PO), BKG processes @Z-pole, ..
  - Missing higher-orders in TH predictions (loop-level EW, QCD, Higgs prod./decay)
    - Two projection scenarios: Aggressive & Conservative

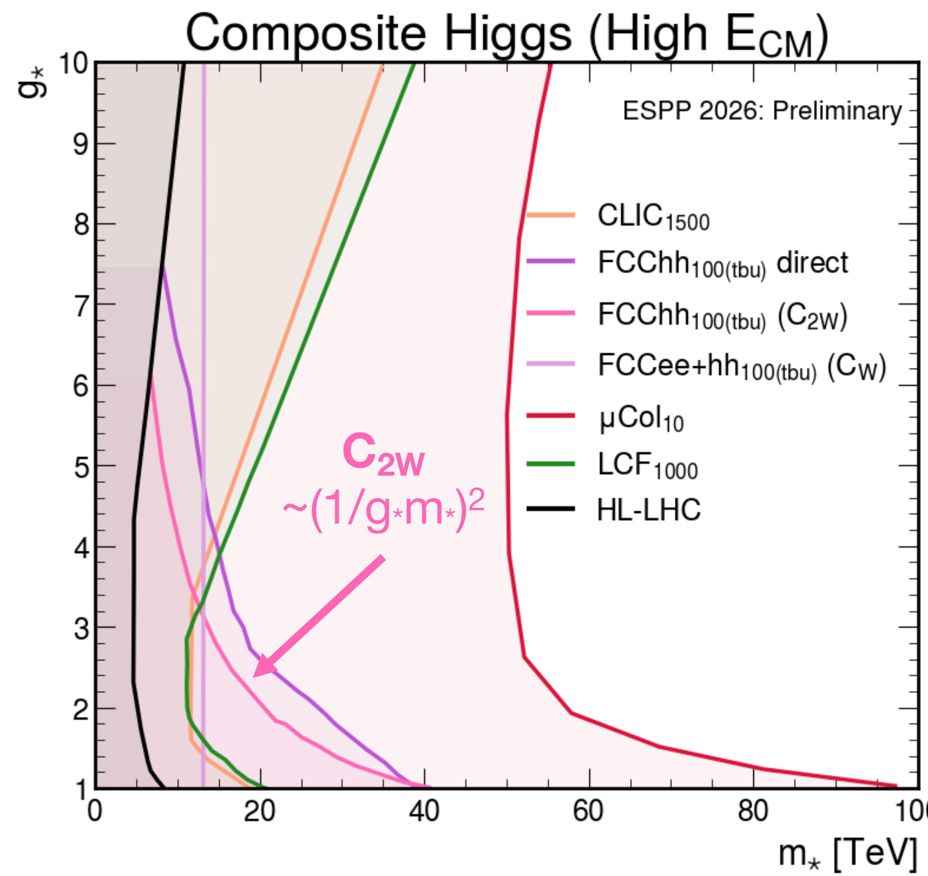
- **Experimental** projections (stat. & syst. errors)
  - FCC-ee & LEP 3: A. Blondel, M. Selvaggi
  - LCVision/LCF: J. List, M. Peskin, R. Pöschl, G. Wilson

Results: Flavour universal

- Non-RG-improved (à la PPG 2019)
  - Select individual experimental constraints (e.g., C_ϕ, C_W,..)
  - Translate into bounds on specific operators (m_*, g_*)

Results: Flavour universal





NB: Digitization of ESPPU 2020 (added μ-Col10 TeV; LEP 3 pending)
Machinery in place to produce it when EFT inputs available

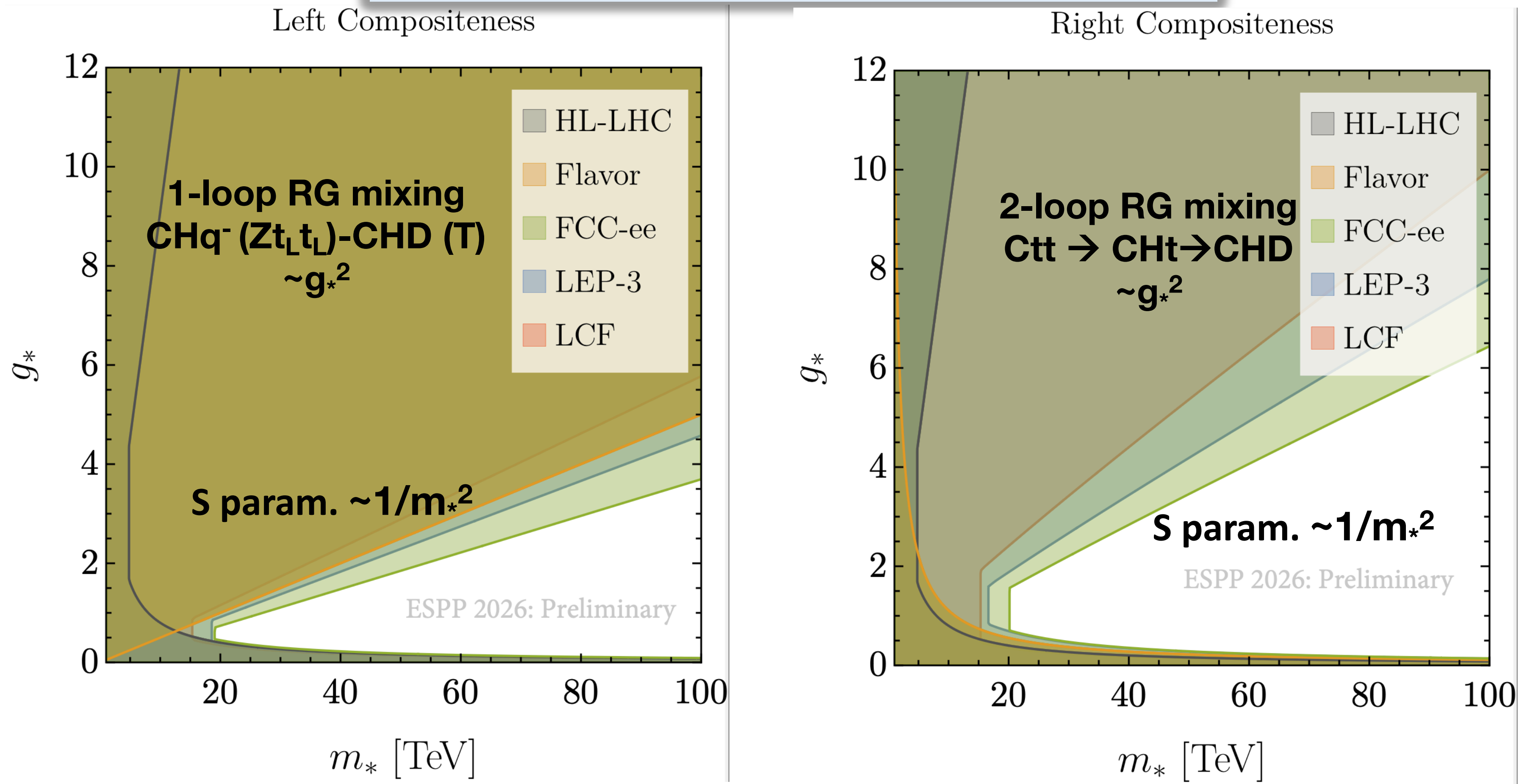
Results: RG-improved

- **RG-improved** (based on 2407.09593; B. Stefanek et al.)
  - Operators evolve from high scale (25-50 TeV) → EW scale
  - Leading 1-loop RGEs resummed; incl. operator mixing effects
- Mixing Scenarios:
  - Left-(Right-) compositeness: q_L (q_R) couples to strong sector
  - Mixed compositeness: both q_L (q_R) partially composite
- Systematics Scenarios:

	Scenario	Exp. unc.	Theor. unc.
"pessimistic"	S0	✓	conservative
	S1	✓	aggressive
	S2	✓	"Data-driven" PO unc. constrained from data
"dream scenario"	S3	✓	-

Results: RG-improved

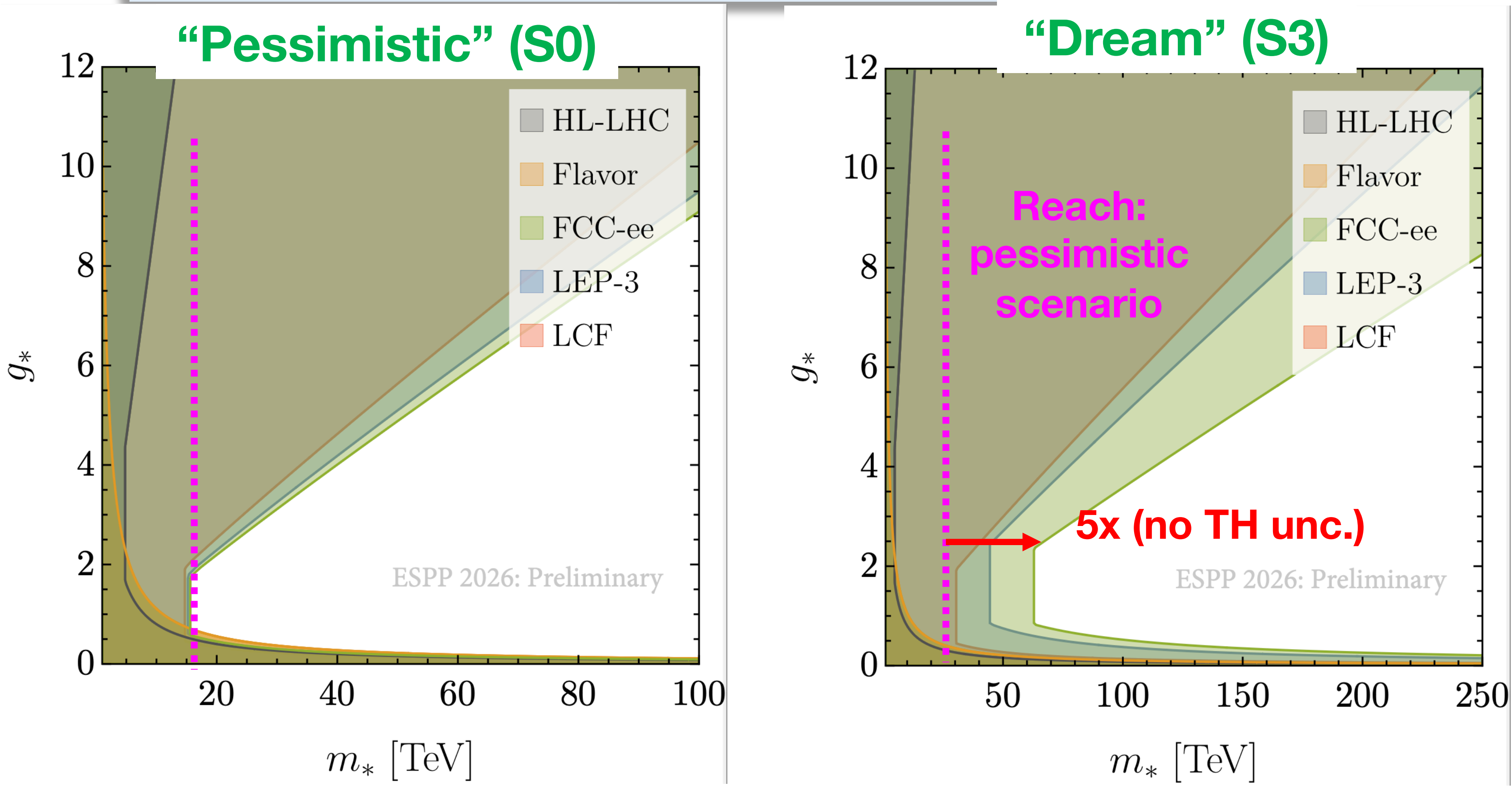
Different mixing scenarios (for “S1”)



Credits: B. Stefanek

Results: RG-improved (FCC-ee)

Right Compositeness: “S0” vs. “S3” syst scenarios



Credits: B. Stefanek

Theory improvements key to unlock “dream” potential of future experiments

Summary and outlook

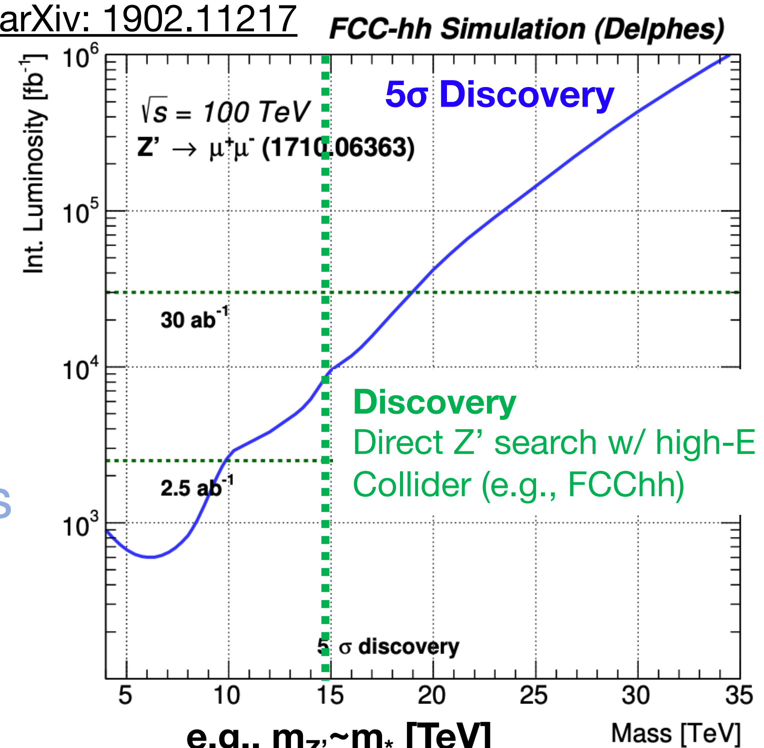
- EFT interpretations categorized by:
  - **Flavor assumptions**: Universal vs. non-universal
  - **Methodology**: Direct interpretation (no RG) vs. RG-improved

- Key Takeaways
  - Systematic uncertainties are critical to sensitivity projections
    - Significant loss in reach: "dream" (EXP-only) vs. "cons" scenarios
    - Observables such as R_b can dominate sensitivity IF $\Delta(R_b)$ ~10^{-6}
  - RG improvement exposes loop-induced operator mixing
  - **μ-Col@10 TeV**: strongest constraints on operators like O_ϕ ~$(g_*/m_*)^2$ → boost in reach
    - less dependent on TH uncertainties

Summary and outlook

- Pending / Ongoing Work
  - Finalize TH uncertainty recommendations (EW WG)
    - Machinery in place to translate EFT inputs to constraints on $g_* - m_*$
  - Quantify relative importance of different EFT inputs
  - RG-improved: LEP3, LCF, μ-Col
- Main Topics for discussion:
  - Uncertainty on the inputs
  - How to incorporate direct limits from e.g., FCC-hh
    - Synergy direct-indirect measurements
    - Direct searches: Model-dependence?

arXiv: 1902.11217



Example:
e^+e^- (indirect): deviation @ (m_*, g_*)=(15 TeV, 5)

Additional material

Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
$\mathcal{C}_T$	A_b^{FB}	8.17
$\mathcal{C}_{Hq}^{(1)}$	R_τ	3.98
$\mathcal{C}_{Hq}^{(3)}$	R_b	3.94
$\mathcal{C}_{Ht}$	A_b^{FB}	3.00
$\mathcal{C}_{Hq}^{(-)}$	A_b^{FB}	2.98
$\mathcal{C}_B$	A_b^{FB}	2.48
$\mathcal{C}_W$	A_b^{FB}	2.41
$\mathcal{C}_{tW}$	A_b^{FB}	1.86
$\mathcal{C}_{qD}^{(3)}$	R_τ	1.83
$\mathcal{C}_{qq}^{(1)}$	R_τ	1.50
$\mathcal{C}_{tB}$	A_b^{FB}	1.44
$\mathcal{C}_{2W}$	A_b^{FB}	1.29
$\mathcal{C}_{qt}^{(1)}$	R_τ	1.14
$\mathcal{C}_{qD}^{(1)}$	A_b^{FB}	1.12
$\mathcal{C}_{tt}$	A_b^{FB}	1.05
$\mathcal{C}_{qq}^{(3)}$	R_b	0.94
$\mathcal{C}_{tD}$	A_b^{FB}	0.93
$\mathcal{C}_{2B}$	A_b^{FB}	0.77
$\mathcal{C}_H$	A_b^{FB}	0.47
$\mathcal{C}_{tG}$	A_b^{FB}	0.46
$\mathcal{C}_{tH}$	$H \to \mu\mu$	0.18
$\mathcal{C}_{qt}^{(8)}$	R_τ	0.11

(a) Current bounds

Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
$\mathcal{C}_T$	m_W	74.24
$\mathcal{C}_{Hq}^{(1)}$	m_W	39.82
$\mathcal{C}_{Hq}^{(3)}$	R_μ	24.81
$\mathcal{C}_{Ht}$	m_W	35.92
$\mathcal{C}_{Hq}^{(-)}$	m_W	33.97
$\mathcal{C}_B$	A_e	26.15
$\mathcal{C}_W$	A_e	24.67
$\mathcal{C}_{tW}$	A_e	26.19
$\mathcal{C}_{qD}^{(3)}$	R_μ	11.73
$\mathcal{C}_{qq}^{(1)}$	m_W	16.59
$\mathcal{C}_{tB}$	A_e	20.24
$\mathcal{C}_{2W}$	A_e	12.48
$\mathcal{C}_{qt}^{(1)}$	m_W	14.61
$\mathcal{C}_{qD}^{(1)}$	A_e	13.73
$\mathcal{C}_{tt}$	m_W	14.64
$\mathcal{C}_{qq}^{(3)}$	R_μ	7.95
$\mathcal{C}_{tD}$	A_e	12.90
$\mathcal{C}_{2B}$	A_e	8.58
$\mathcal{C}_H$	m_W	6.03
$\mathcal{C}_{tG}$	A_e	7.91
$\mathcal{C}_{tH}$	$H \to \tau\tau$	0.95
$\mathcal{C}_{qt}^{(8)}$	m_W	1.61

(b) FCC-ee projection