

Exploring the Terascale at Colliders

A Journey Across Energy Scales

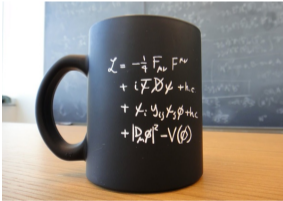
Lukas Allwicher

Seminar, SLAC, 02/23/2026

Where We Stand

The Standard Model

- > Unified description of strong, weak, and electromagnetic forces
- > $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry



		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 125.11 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
		d down	s strange	b bottom	γ photon	
LEPTONS	mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	0	$\approx 91.19 \text{ GeV}/c^2$
	charge	-1	-1	-1	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
		e electron	μ muon	τ tau	Z Z boson	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
		$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	± 1	$\approx 80.360 \text{ GeV}/c^2$

SCALAR BOSONS

GAUGE BOSONS
VECTOR BOSONS

Open Problems

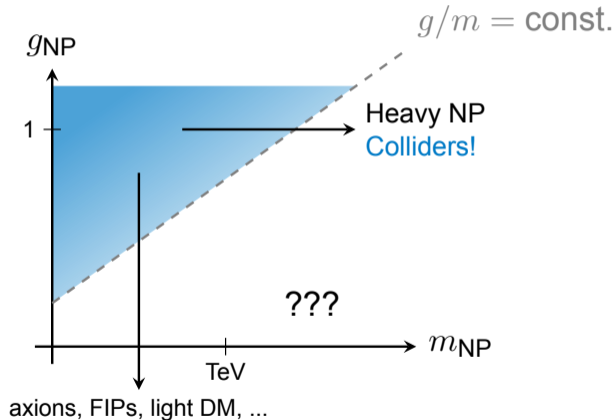
The Need for New Physics

> “Experimental” problems

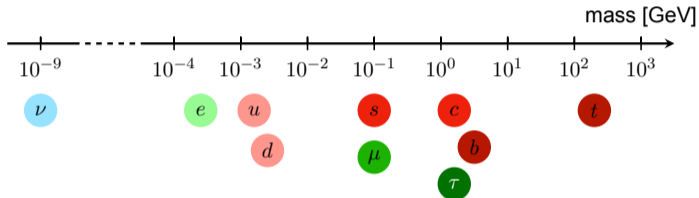
- Dark Matter
- Neutrino masses
- Matter-antimatter asymmetry
- ...

> “Theoretical” issues

- Strong-CP problem
- **Flavor puzzle**
- **Hierarchy problem**



The Flavor Puzzle



$$V_{\text{CKM}} \sim \begin{pmatrix} \blacksquare & \square & & \\ \square & \blacksquare & \square & \\ & & \square & \blacksquare \\ & & & \square & \blacksquare \end{pmatrix}$$

- > Non-trivial pattern of masses and mixings:

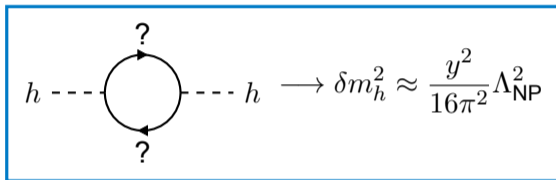
$$m_1 \ll m_2 \ll m_3 \quad V_{\text{CKM}} \sim \mathbb{1}$$

Why??

- > Dynamical explanation lies Beyond the Standard Model

The Hierarchy Problem

- > Higgs mass parameter quadratically sensitive to NP scales:



A Feynman diagram enclosed in a blue rectangular box. It shows a Higgs boson line (dashed) entering from the left, connecting to a circular loop. The loop has two arrows indicating a clockwise direction, with a question mark above and below it. The loop then connects to another Higgs boson line (dashed) exiting to the right. To the right of the diagram is an arrow pointing to the equation: $\delta m_h^2 \approx \frac{y^2}{16\pi^2} \Lambda_{\text{NP}}^2$.

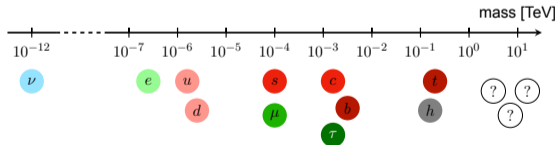
- > Calls for a mechanism to avoid “fine tuning”
- > Proposed solutions: [Composite Higgs](#), [Supersymmetry](#), ...
- > Collider searches push $\Lambda \gtrsim \text{TeV}$ (**little hierarchy**)
- > Want the NP scale **as low as possible**

The TeV Scale

Higgs \leftrightarrow Flavor

If we insist on TeV-scale New Physics, we cannot ignore flavor

- > Flavor structure must be non-trivial \rightarrow **Third-gen. New Physics**
- > "Cherries" on top (model-dependent):
 - Dark Matter \rightarrow WIMP [see e.g. 1703.07364]
 - Neutrino masses \rightarrow Inverse See-Saw [see e.g. Mohapatra '86]

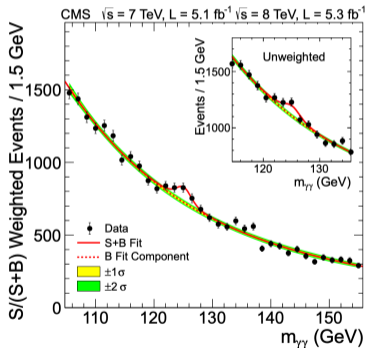


The TeV scale is an interesting place to look for New Physics!

The Hunt for New Physics

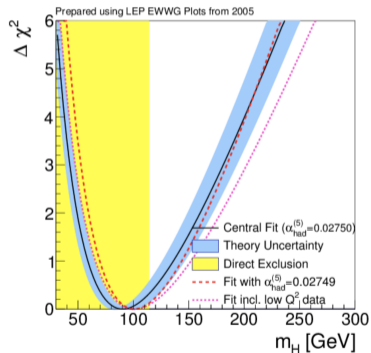
Direct searches

> High energies



Indirect searches

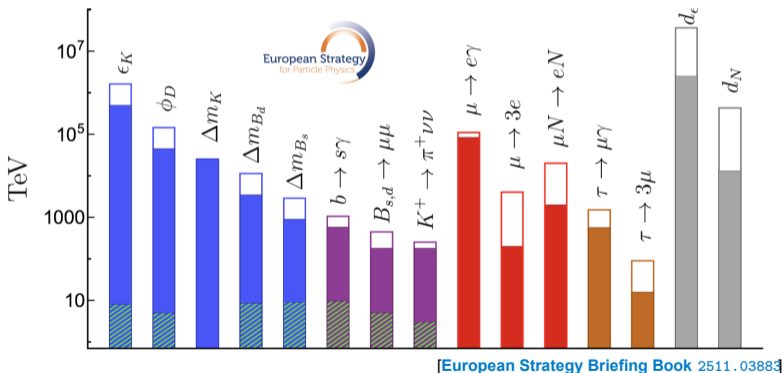
> High precision



We need both!

Low-energy Probes

- > In the absence of any BSM signals, set (lower) bounds
- > Each observable mediated by a contact interaction $\frac{1}{\Lambda^2} O_{\text{eff}}^{d=6} \rightarrow \Lambda > \dots$



What is the Scale of New Physics?

The New Physics Flavour Problem

- > Depends on the assumptions! Doesn't have to be 10^6 TeV (\leftrightarrow anarchic flavor)
- > Take e.g. $K - \bar{K}$ mixing.
After discovery, "superweak" theory

$$\frac{ce^{i\phi}}{\Lambda^2} (\bar{s}\gamma^\mu d)^2 \rightarrow \Lambda \sim 10^4 \text{ TeV} \quad [\text{Wolfenstein '79}]$$

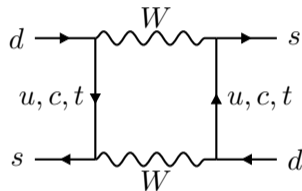
- > In the SM (GIM mechanism):

$$\frac{c}{\Lambda^2} = \frac{(V_{td}V_{ts}^*)^2 G_F^2 m_t^2}{16\pi^2}$$

What is the flavour structure of low-scale NP?

In this talk:

What do we learn from current and future collider experiments?



What is the Scale of New Physics?

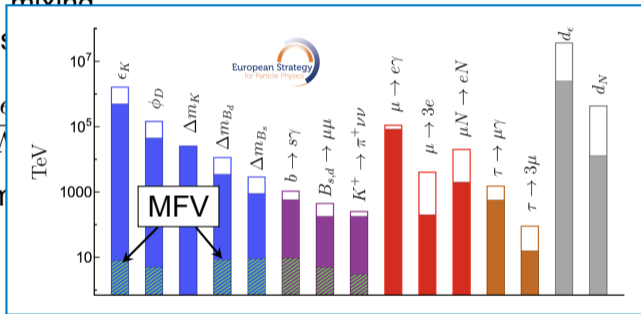
The New Physics Flavour Problem

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After discovery, “s

> In the SM (GIM m



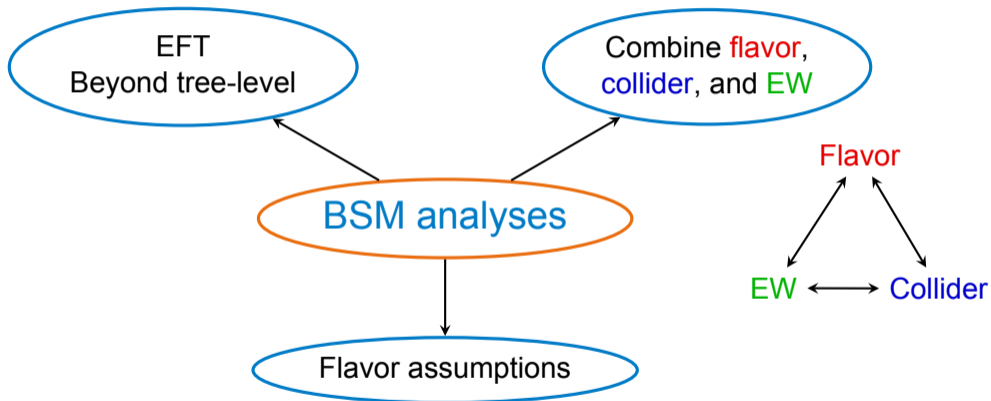
What is the flavour structure of low-scale NP?

In this talk:

What do we learn from current and future collider experiments?

What Do We Need?

Towards Consistent BSM Analyses



Outline

I EFT Analyses

- The EFT Approach: SMEFT
- Collider and Flavor: Drell-Yan
- Loops in the EFT: RGE effects
- Flavor Assumptions: TeV-scale New Physics

II FCC-ee

- Electroweak Precision Observables
- Flavor Prospects
- Above the Z -pole: Higgs Self-coupling

EFT Analyses



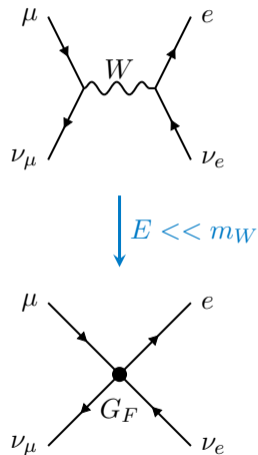
The EFT Approach

- > At a given scale, use only the relevant degrees of freedom
- > Many examples, take e.g. **muon decay**

$$\mu \rightarrow e \nu_\mu \bar{\nu}_e$$

$$\mathcal{L}_{\text{weak}} \supset -\frac{G_F}{\sqrt{2}} (\bar{\mu} \gamma_\alpha (1 - \gamma_5) \nu_\mu) (\bar{\nu}_e \gamma^\alpha (1 - \gamma_5) e)$$

- > **No need to know the UV** to describe the data well
- > $m_\mu \ll m_W$, W boson “integrated out”
- > Can take the same bottom-up approach for BSM effects



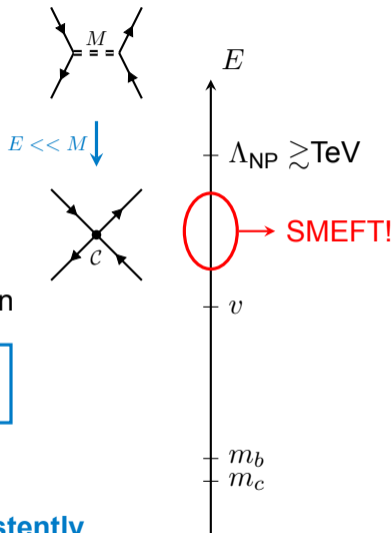
SMEFT

Standard Model Effective Field Theory

- > Heavy ($\Lambda \gg v$), decoupling New Physics
- > Relevant ingredients:
 - **SM fields:** $q, \ell, u, d, e, H, G_{\mu\nu}, W_{\mu\nu}, B_{\mu\nu}$
 - **Symmetry:** $SU(3) \times SU(2) \times U(1)$
 - **Power counting:** E/Λ
- > Add higher-dimensional structures to the SM Lagrangian

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} c_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} c_i^{(6)} \mathcal{O}_i^{(6)} + \dots$$

- > Systematic way of describing deviations from the SM
- > **Study connections between different sectors consistently**



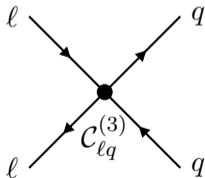
Examples of SMEFT operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{C}_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} \mathcal{C}_i^{(6)} \mathcal{O}_i^{(6)} + \dots$$

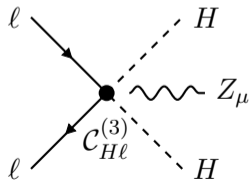
> At dimension six: 59 operators, 2499 parameters

[Warsaw basis 1008.4884]

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{\ell}_i \gamma_\mu \sigma^I \ell_j) (\bar{q}_k \gamma^\mu \sigma^I q_l)$$



$$[\mathcal{O}_{Hl}^{(3)}]_{ij} = (H^\dagger \overleftrightarrow{D}_\mu^I H) (\bar{\ell}_i \gamma^\mu \sigma^I \ell_j)$$



Bounds on SMEFT coefficients

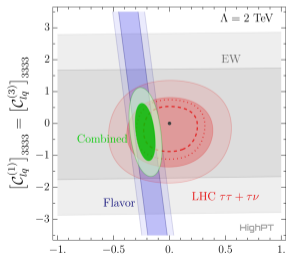
- > $C_i = 0$ is the SM point
- > In the absence of New Physics signals, expect C_i compatible with zero \rightarrow **bounds**

Fix Λ

Fix C ($C = 1$)

- > Single coefficient: $C \in [-a, b]$
- > Multi-dimensional fits:

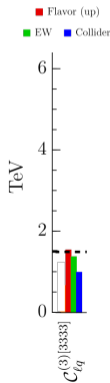
[LA, Cornella, Isidori, Stefaneke 2311.00020]



[LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714]

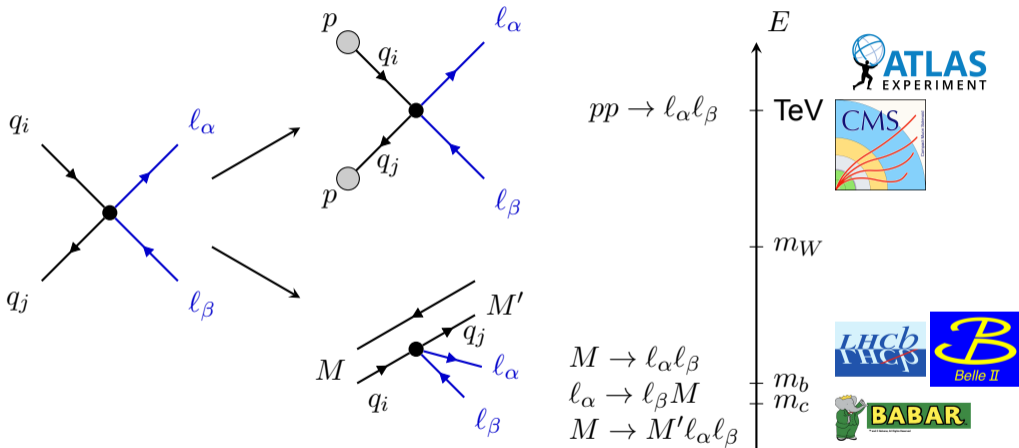
- > Lower bound on Λ
- > At $d = 6$:

$$\Lambda > \min \left(\frac{1}{\sqrt{a}}, \frac{1}{\sqrt{b}} \right)$$



Probes at Different Energy Scales

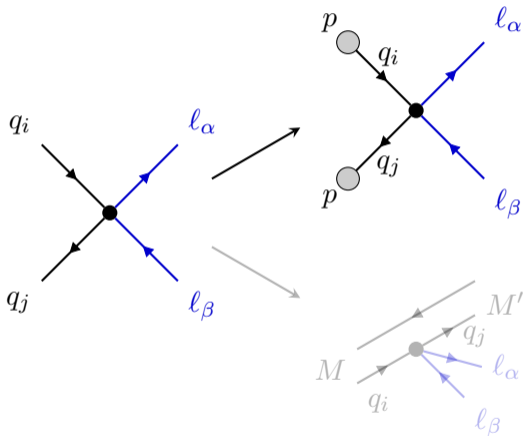
Semileptonic interactions



High- p_T searches can probe the same operators directly constrained by flavor-physics experiments (and more)

Probes at Different Energy Scales

Semileptonic interactions

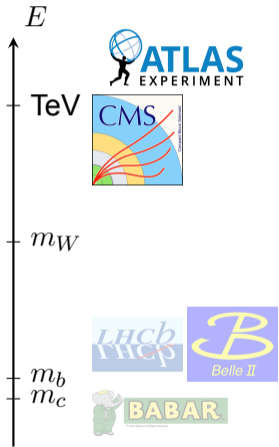


$$pp \rightarrow l_\alpha \bar{l}_\beta$$

$$M \rightarrow l_\alpha \bar{l}_\beta$$

$$l_\alpha \rightarrow l_\beta M$$

$$M \rightarrow M' l_\alpha \bar{l}_\beta$$



Energy-enhancements in the EFT

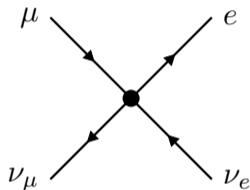
- > Take again muon decay:

$$\mathcal{L}_{\text{weak}} \supset -\frac{G_F}{\sqrt{2}}(\bar{\mu}\gamma_\alpha(1-\gamma_5)\nu_\mu)(\bar{\nu}_e\gamma^\alpha(1-\gamma_5)e)$$

- > $2 \rightarrow 2$ scattering amplitudes grow with c.o.m. energy

$$\mathcal{A}(e^+\mu^- \rightarrow \bar{\nu}_e\nu_\mu) \propto E^2$$

- > Breakdown of perturbativity at $E \sim \text{TeV}$
→ regulated by W boson



Use the same feature to look for New Physics in high-energy tails of distributions

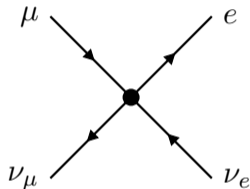
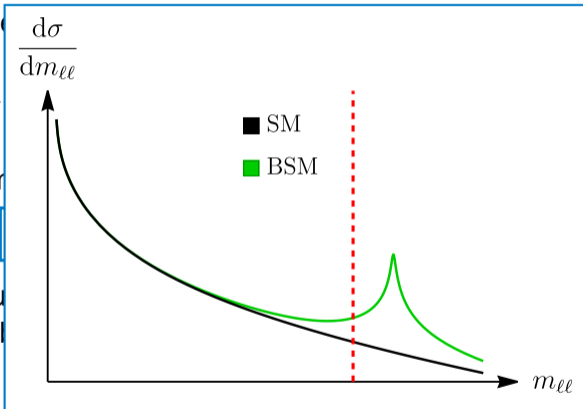
Energy-enhancements in the EFT

> Take again muon d

$\mathcal{L}_{\text{weak}} \supset -$

> $2 \rightarrow 2$ scattering am

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Use the same feature to look for New Physics in high-energy tails of distributions

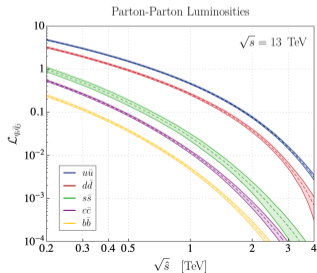
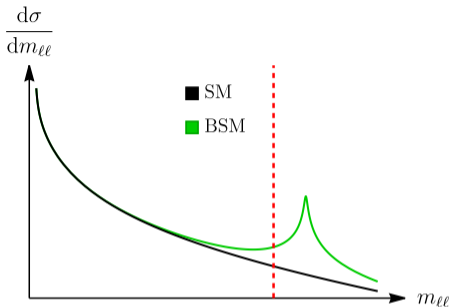
Drell-Yan Tails as Flavor Probes

- > 5 active flavors in the proton
- > Drell-Yan at LHC: $pp \rightarrow l_\alpha^+ l_\beta^-, l_\alpha^+ \nu_\beta$
- > Hadronic cross-section:

$$\sigma(pp \rightarrow l_\alpha l_\beta) = \mathcal{L}_{ij} \times \hat{\sigma}_{ij}^{\alpha\beta}$$

- > $\hat{\sigma}_{ij}^{\alpha\beta} = \hat{\sigma}(q_i \bar{q}_j \rightarrow l_\alpha l_\beta)$ partonic cross-section
→ energy-enhanced in the EFT.
- > Heavy flavours suppressed by parton luminosities
- > Energy enhancement can (partially) overcome PDF suppression

[Angelescu, Faroughy, Sumensari 2002.05684]



HighPT

LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10756

- > Run-2 LHC Drell-Yan searches
- > Large variety of NP scenarios:
 - SMEFT $d = 6, d = 8$ (up to $\mathcal{O}(\Lambda^{-4})$)
 - Tree-level mediators
- > Allows to compute:
 - Hadronic cross-sections
 - Event yields \rightarrow bin-by-bin in the exp. searches
 - χ^2 likelihood as function of Wilson coefficients/coupling constants

\rightarrow Extract bounds on Wilson coefficients/couplings

- > Work in progress for version 2!

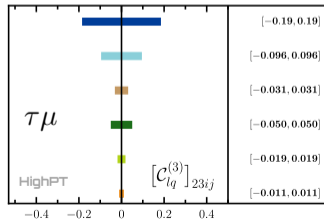
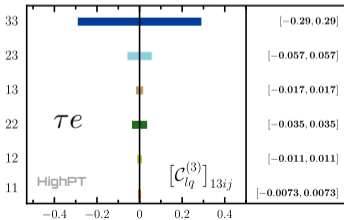
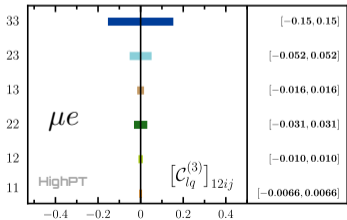
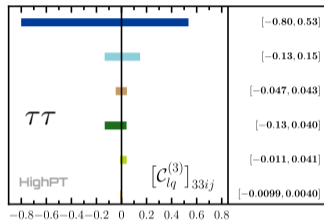
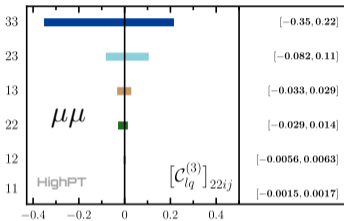
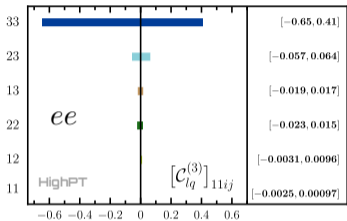


SMEFT Constraints from Drell-Yan

$$[\mathcal{O}_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \gamma^\mu \sigma^I \ell_L^\beta) (\bar{q}_L^i \gamma^\mu \sigma^I q_L^j)$$

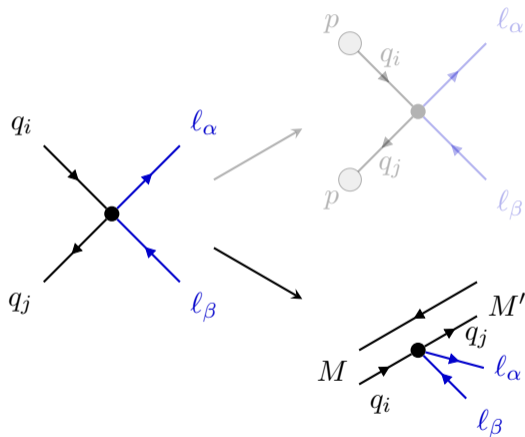
- > Switch on one operator at a time
- > $\Lambda = 1$ TeV

[LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714]



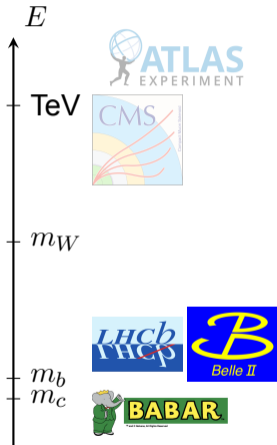
Probes at Different Energy Scales

Semileptonic interactions



$$pp \rightarrow l_\alpha l_\beta$$

$$\begin{aligned}
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 \end{aligned}$$



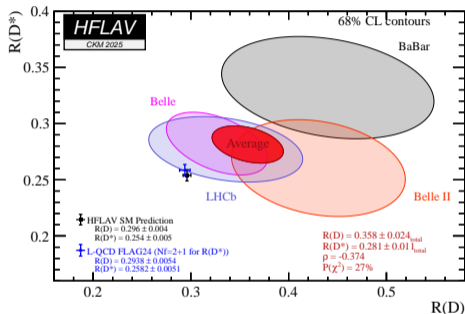
Complementarity with Low Energy

LFU tests in B decays

> LFU ratios:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)} \ell \bar{\nu})} \quad \ell = \mu, e$$

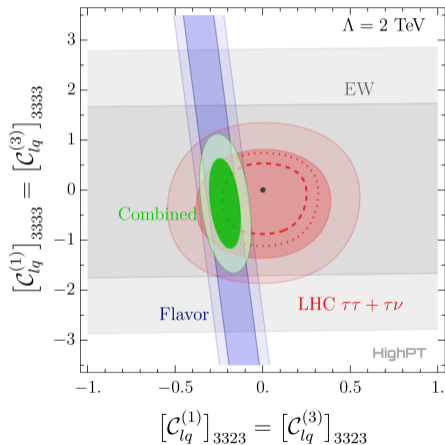
> Currently $\sim 3\sigma$ tension
→ good illustrative example



Is it compatible with high-energy data?

Combined Fit

LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714



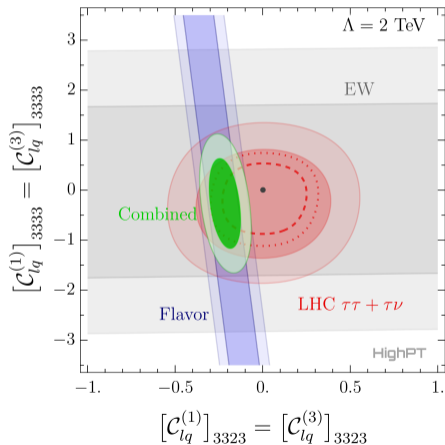
$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\bar{\ell}_i \gamma_\mu \ell_j) (\bar{q}_k \gamma^\mu q_l)$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{\ell}_i \gamma_\mu \sigma^I \ell_j) (\bar{q}_k \gamma^\mu \sigma^I q_l)$$

- > Flavor: R_D, R_{D^*}
- > **LHC already constrains the parameter space**
- > Dashed (dotted) lines: HL-LHC (3 ab^{-1}) projections

Combined Fit

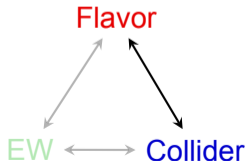
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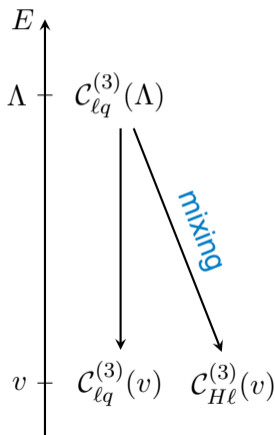
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Operator mixing



- > **Everything is scale-dependent!**

$$\alpha_{\text{em}}(0) \simeq \frac{1}{137} \quad \alpha_{\text{em}}(m_Z) \simeq \frac{1}{128}$$

- > The same is true for EFT coefficients
→ self-renormalization + mixing
- > The scale at which a coefficient is defined is a crucial piece of information

SMEFT RGE

- > Operators mix under Renormalization Group Evolution

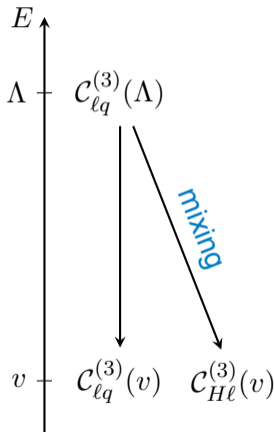
$$\mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij}(\vec{g}(\mu)) C_j(\mu)$$

- > γ_{ij} **anomalous dimension** matrix
- > At one-loop, in Leading-Log approximation,

$$C_i(\mu) = \frac{1}{16\pi^2} \log \frac{\mu}{\Lambda} \gamma_{ij}^{(0)} C_j(\Lambda)$$

- > **Connect effects at a scale Λ with others at scale μ**
- > One- and two-loop anomalous dimensions known

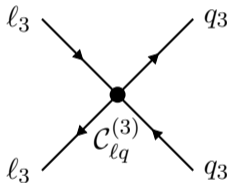
1308.2627, 1310.4838, 1312.2014, 2601.19974



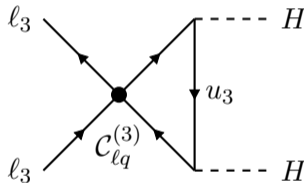
SMEFT RGE

Example: Semileptonic Interactions in Z Decays

$$[\mathcal{O}_{lq}^{(3)}]_{3333} = (\bar{l}_3 \gamma_\mu \sigma^I l_3)(\bar{q}_3 \gamma^\mu \sigma^I q_3)$$



$$[\mathcal{O}_{Hl}^{(3)}]_{33} = (H^\dagger \overleftrightarrow{D}_\mu^I H)(\bar{l}_3 \gamma^\mu \sigma^I l_3)$$



$$\mu \frac{d}{d\mu} [\mathcal{C}_{Hl}^{(3)}]_{33} \supset \frac{1}{16\pi^2} 2N_c y_t^2 [\mathcal{C}_{lq}^{(3)}]_{3333}$$

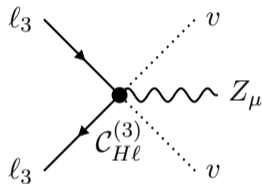
SMEFT RGE

Example: Semileptonic Interactions in Z Decays

- > A closer look at $\mathcal{O}_{H\ell}^{(3)} = (H^\dagger \overleftrightarrow{D}_\mu^I H)(\bar{\ell}_3 \gamma^\mu \sigma^I \ell_3)$
- > Focus again on third-gen. couplings

$$H^\dagger \overleftrightarrow{D}_\mu H \xrightarrow{H \rightarrow \langle H \rangle} \frac{v^2}{2} Z_\mu$$

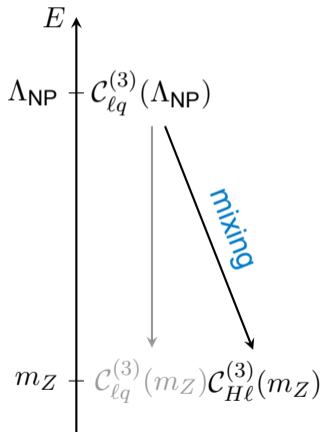
- > **Modify the $Z\tau\tau$ coupling**



How do Z decays compare to collider and flavor data?

SMEFT RGE

Example: Semileptonic Interactions in Z Decays

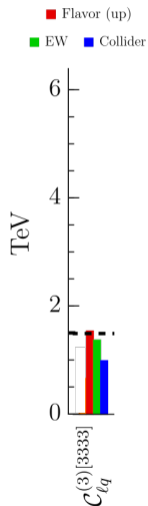
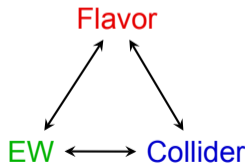


> $\Lambda_{\text{NP}} = 2 \text{ TeV} \rightarrow \text{at } \mu = m_Z$

$$[C_{H\ell}^{(3)}]_{33}(m_Z) \simeq \frac{1}{16\pi^2} 2N_c y_t^2 \log \frac{m_Z}{\Lambda_{\text{NP}}} [C_{\ell q}^{(3)}]_{3333}(\Lambda_{\text{NP}})$$

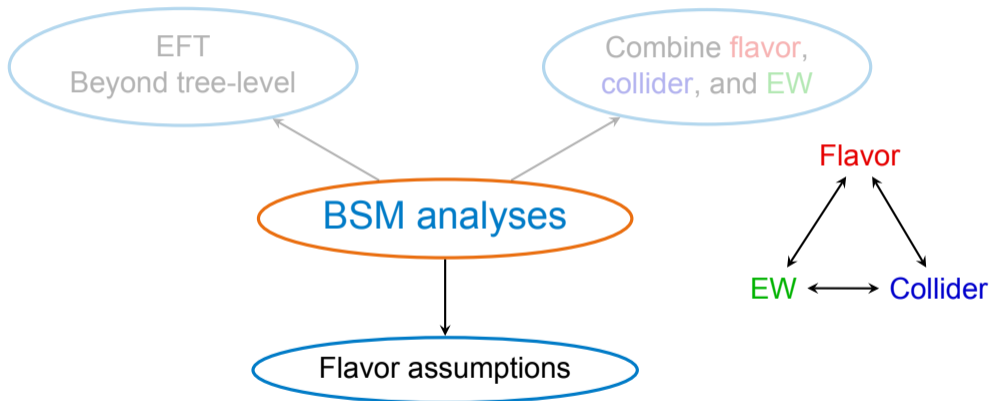
$$\simeq -0.1 [C_{\ell q}^{(3)}]_{3333}(\Lambda_{\text{NP}})$$

> Depends on the precision!



What Do We Need?

Towards Consistent BSM Analyses



Flavor assumptions

Some guidance from the Standard Model

> Need to address the flavor structure of NP

> SM gauge sector:

$$U(3)^5 \equiv U(3)_q \times U(3)_\ell \times U(3)_u \times U(3)_d \times U(3)_e$$

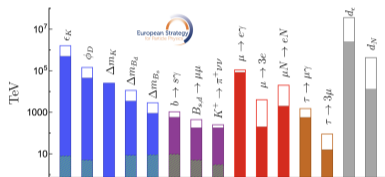
> Yukawas:

$$Y \simeq y_3 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Approximate (accidental) $U(2)^5$ symmetry!

> What if New Physics follows the same structure?

> Starting point to address the SM flavour puzzle



$U(2)$ in SMEFT

Taming flavor constraints

- > $U(2)$ imposes flavor conservation for New Physics:

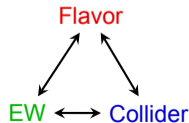
$$\bar{q}_i \gamma_\mu q_j \xrightarrow{U(2)_q} a \bar{q}_3 \gamma_\mu q_3 + b \sum_{i=1}^2 \bar{q}_i \gamma_\mu q_i$$

- > But it is already broken at dimension-four ($y \lesssim 10^{-2}$)
→ flavor-changing processes follow CKM-like (GIM) suppression

$$Y = y_3 \begin{pmatrix} \Delta & V \\ 0 & 1 \end{pmatrix}$$

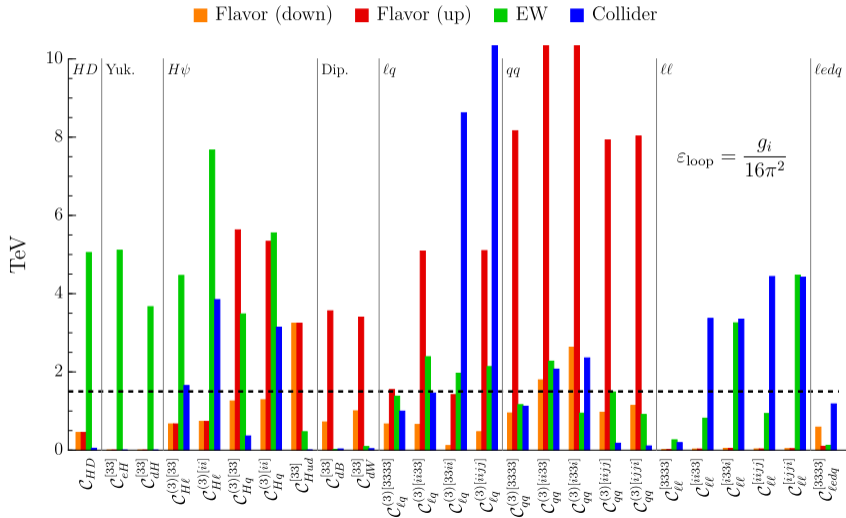
We can impose a $U(2)^5$ symmetry on the SMEFT and study the implications

- > Combine **flavor**, **collider**, and **EW** observables



SMEFT Fits to $U(2)$ Operators

$\Lambda = 3$ TeV, individual fits

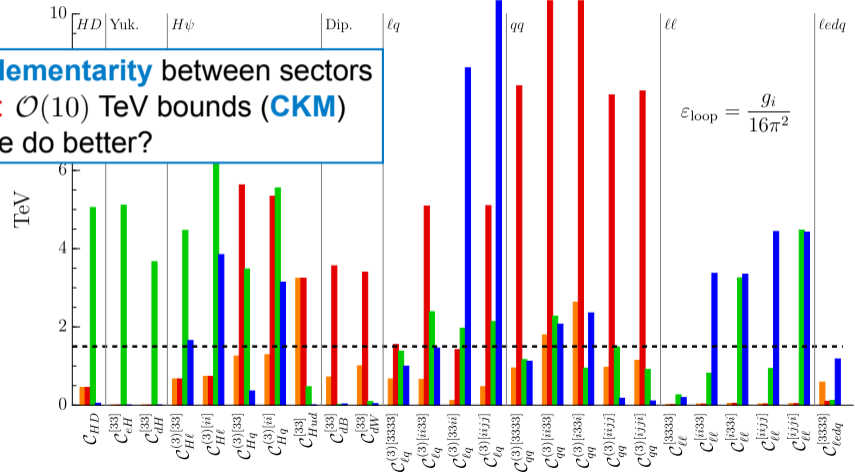


SMEFT Fits to $U(2)$ Operators

$\Lambda = 3 \text{ TeV}$, individual fits

■ Flavor (down)
 ■ Flavor (up)
 ■ EW
 ■ Collider

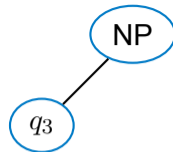
- **Complementarity** between sectors
- **Flavor:** $\mathcal{O}(10)$ TeV bounds (**CKM**)
- Can we do better?



New Physics in the Third Generation?

- > $U(2)$ naturally singles out the third generation

$$\bar{q}_i \gamma_\mu q_j \xrightarrow{U(2)_q} a \bar{q}_3 \gamma_\mu q_3 + b \sum_{i=1}^2 \bar{q}_i \gamma_\mu q_i$$



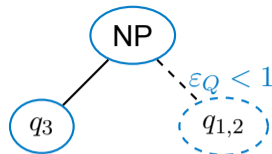
- > If New Physics couples to the third gen. \rightarrow accidental $U(2)$ symmetry
 \rightarrow take e.g. a Z'

$$\mathcal{L}_{Z'} \supset g Z'_\mu (\bar{q}_1 \quad \bar{q}_2 \quad \bar{q}_3) \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

New Physics in the Third Generation?

- > $U(2)$ naturally singles out the third generation

$$\bar{q}_i \gamma_\mu q_j \xrightarrow{U(2)_q} a \bar{q}_3 \gamma_\mu q_3 + b \sum_{i=1}^2 \bar{q}_i \gamma_\mu q_i$$



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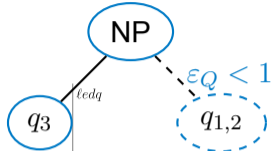
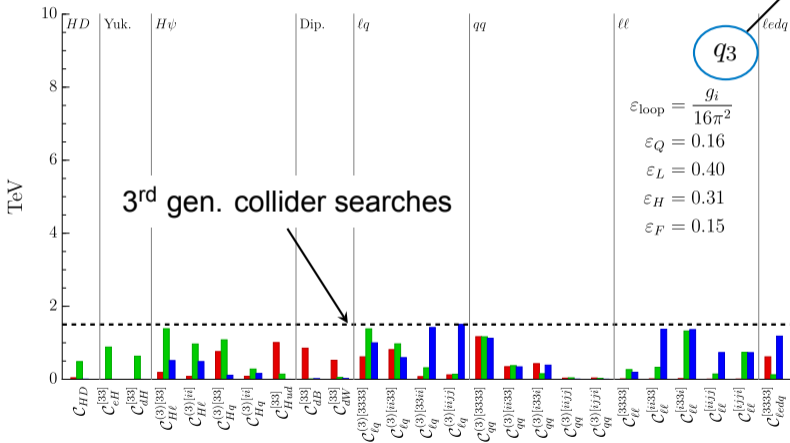
- > How much do we need to suppress the light generations?

$$\mathcal{L}_{Z'} \supset g Z'_\mu (\bar{q}_1 \quad \bar{q}_2 \quad \bar{q}_3) \gamma^\mu \begin{pmatrix} \epsilon_Q^2 & 0 & 0 \\ 0 & \epsilon_Q^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

New Physics in the Third Generation?

> Suppress operators with light fermion indices

■ Flavor ■ EW ■ Collider



$$\epsilon_{\text{loop}} = \frac{g_i}{16\pi^2}$$

$$\epsilon_Q = 0.16$$

$$\epsilon_L = 0.40$$

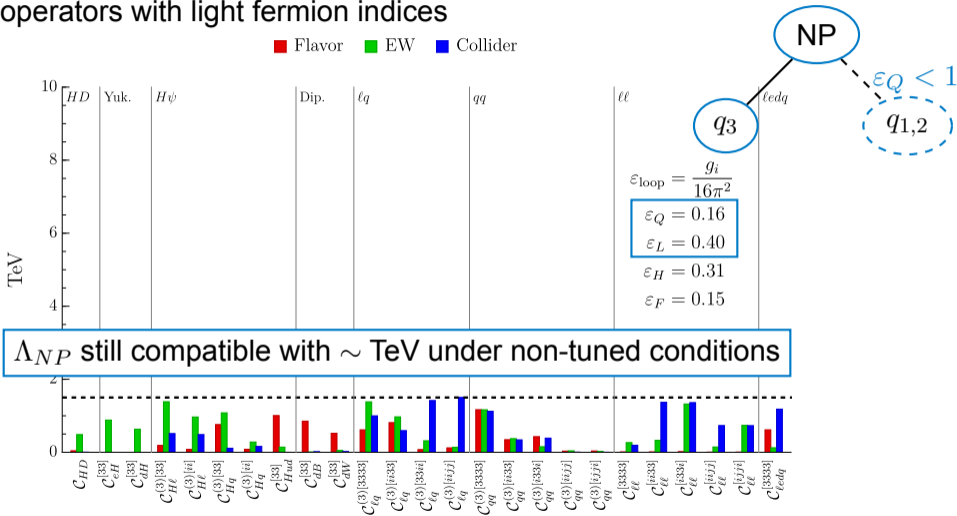
$$\epsilon_H = 0.31$$

$$\epsilon_F = 0.15$$

New Physics in the Third Generation?

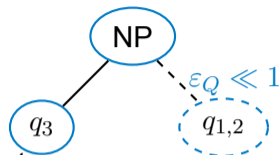
> Suppress operators with light fermion indices

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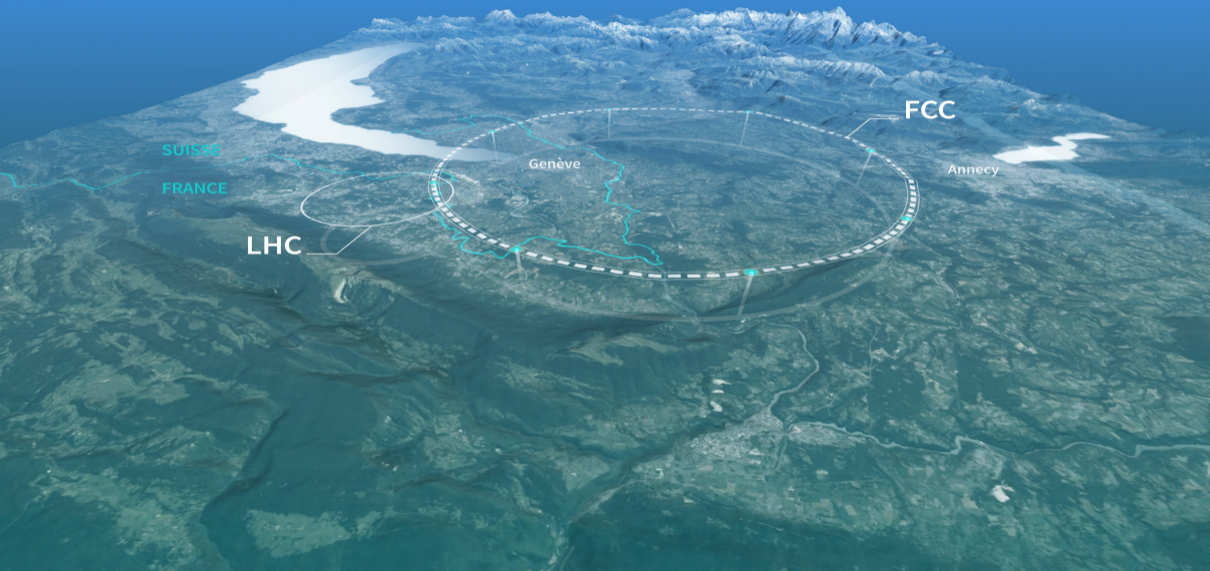
What Have We Learned?

- > $U(2)^5$ is a good symmetry:
 - suppress flavor-violating NP effects
 - single out the third generation
- > Flavor, collider and EW data conspire in constraining the parameter space
- > **We are only now starting to explore the TeV scale**
 - third-generation New Physics
- > It is **not a model**
 - EFT parametrizes classes of models with specific features



Given our framework with comparably weak constraints, how will improvements in experimental precision impact the results?

FCC-ee



The Future Circular Collider

[Table from FCC FSR 2505.0027]



Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
\sqrt{s} (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH	2×10^6 $t\bar{t}$	
			+ 65k WW \rightarrow H	+ 370k ZH	+ 92k WW \rightarrow H

EWPOs

- > Focus on Z - and W -pole obs.
- > Constrain flavour-conserving NP

Flavor

- > Large number of $b\bar{b}$ and $\tau^+\tau^-$ pairs from Z decays
- > Constrain flavour-violating NP

Higgs

- > Yukawas, hVV couplings
- > Self-coupling

→ overall great potential for cornering NP indirectly

Electroweak Precision Observables

- > Measure Z - and W boson couplings to fermions through partial decay widths
- > Current measurements largely from LEP, $\mathcal{O}(1\text{‰})$ precision
- > Expect an improvement by 10-100 at FCC-ee

[Table from FCC FSR 2505.00272]

	Observable	Definition
Z-pole	Γ_Z	$\sum_f \Gamma(Z \rightarrow f\bar{f})$
	σ_{had}	$\frac{12\pi}{m_Z} \frac{\Gamma(Z \rightarrow e^+e^-)\Gamma(Z \rightarrow q\bar{q})}{\Gamma_Z^2}$
	$R_f (f = e, \mu, \tau, c, b)$	$\frac{\Gamma(Z \rightarrow f\bar{f})}{\sum_q \Gamma(Z \rightarrow q\bar{q})}$
	$A_f (f = e, \mu, \tau, s, c, b)$	$\frac{\Gamma(Z \rightarrow f_L f_L) - \Gamma(Z \rightarrow f_R \bar{f}_R)}{\Gamma(Z \rightarrow f\bar{f})}$
	$A_{\text{FB}}^{0,\ell} (\ell = e, \mu, \tau)$	$\frac{3}{4} A_e A_\ell$
	$A_q^{\text{FB}} (q = c, b)$	$\frac{3}{4} A_e A_q$
W-pole	m_W	
	Γ_W	$\sum_{f_1, f_2} \Gamma(W \rightarrow f_1 f_2)$
	$\text{Br}(W \rightarrow \ell\nu) (\ell = e, \mu, \tau)$	

Observable	present		FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
	value	± uncertainty			
m_Z (keV)	91 187 600	± 2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	± 2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_{\text{eff}}^e (\times 10^6)$	231,480	± 160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	± 14	3.9	small	From $A_{\text{FB}}^{\mu\mu}$ off peak
			0.8	tb	From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	± 25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	± 30	0.1	1	Combined $R_\ell^Z, \Gamma_{\text{tot}}^Z, \sigma_{\text{had}}^0$ fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	± 32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	± 7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	± 660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	± 16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	± 49	0.07	0.2	τ polarisation asymmetry τ decay physics

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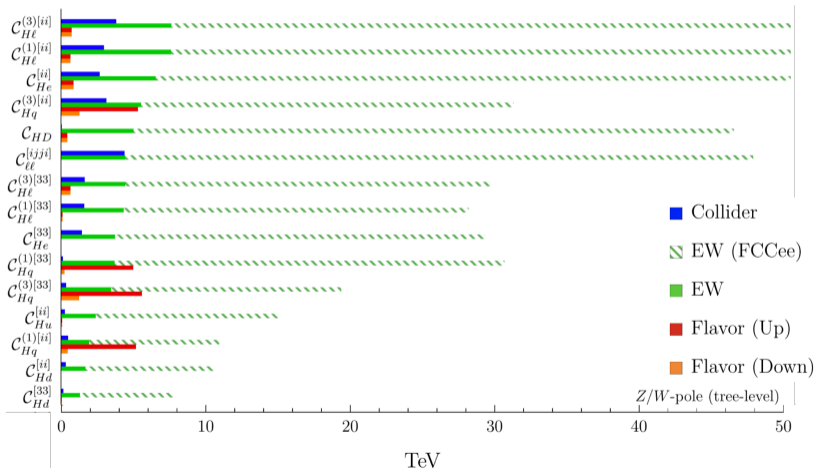
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Prospects from EWPOs

[LA, Cornella, Isidori, Stefaneke 2311.0002]

Tree-level effects

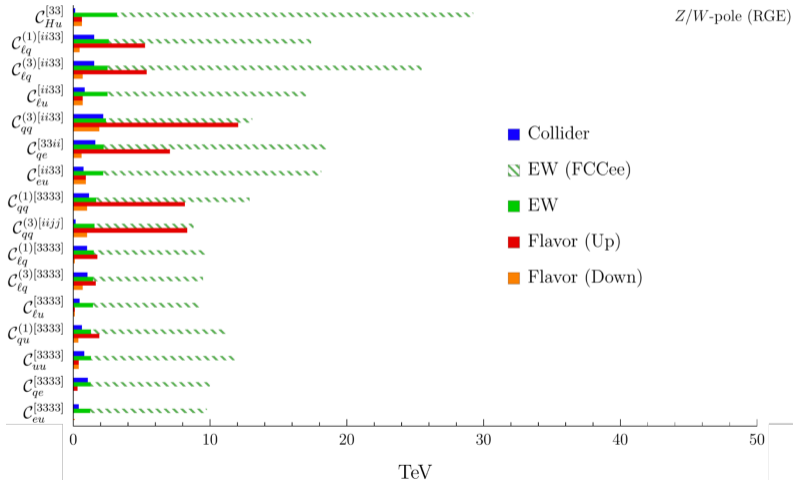
> From current $\mathcal{O}(\text{few})\text{TeV}$ to 30 TeV range at FCC-ee



Prospects from EWPOs

One-loop (RGE) effects

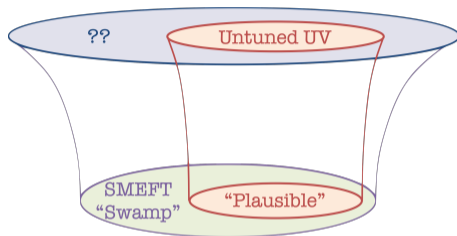
> $\mathcal{O}(10)$ TeV constraints for four-fermion operators (3rd gen. quarks)



From EFT to Models

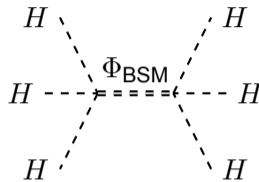
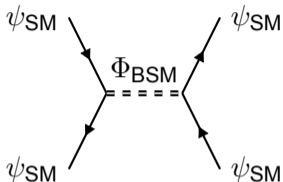
- > The operator basis is **arbitrary**
→ physics is independent of the choice of basis
- > Explicit models will correlate different coefficients
→ only some directions get populated
- > Go beyond the EFT

[Figure by M. McCullough]



How will explicit models be probed by EWPOs at FCC-ee?

Linear Extensions of the SM



- > Finite number of representations \rightarrow **Granada dictionary**
- > Everything that matches onto dimension-six SMEFT
- > E.g. for scalars

Name	\mathcal{S}	\mathcal{S}_1	\mathcal{S}_2	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1, 1)_0$	$(1, 1)_1$	$(1, 1)_2$	$(1, 2)_{\frac{1}{2}}$	$(1, 3)_0$	$(1, 3)_1$	$(1, 4)_{\frac{1}{2}}$	$(1, 4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3, 1)_{-\frac{1}{3}}$	$(3, 1)_{\frac{2}{3}}$	$(3, 1)_{-\frac{4}{3}}$	$(3, 2)_{\frac{1}{6}}$	$(3, 2)_{\frac{7}{6}}$	$(3, 3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6, 1)_{\frac{1}{3}}$	$(6, 1)_{-\frac{2}{3}}$	$(6, 1)_{\frac{4}{3}}$	$(6, 3)_{\frac{1}{3}}$	$(8, 2)_{\frac{1}{2}}$			

[1711.10391]

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

Prospects from EWPOs

(*) = special choice of couplings to avoid tree-level EWPO

BSM scalars

■ Universal couplings
 ■ Third-gen. only
 ■ Flavourless couplings
 ■ Antisymm. couplings

= no running

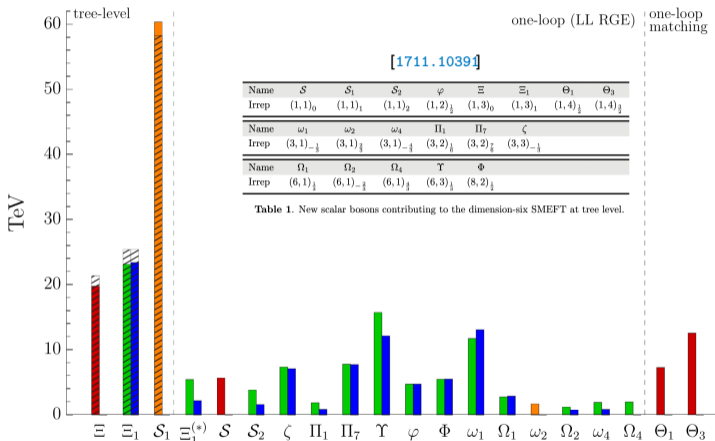


Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

[LA, Mccullough, Renner 2408.03992]

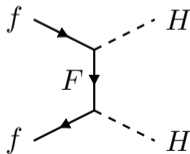
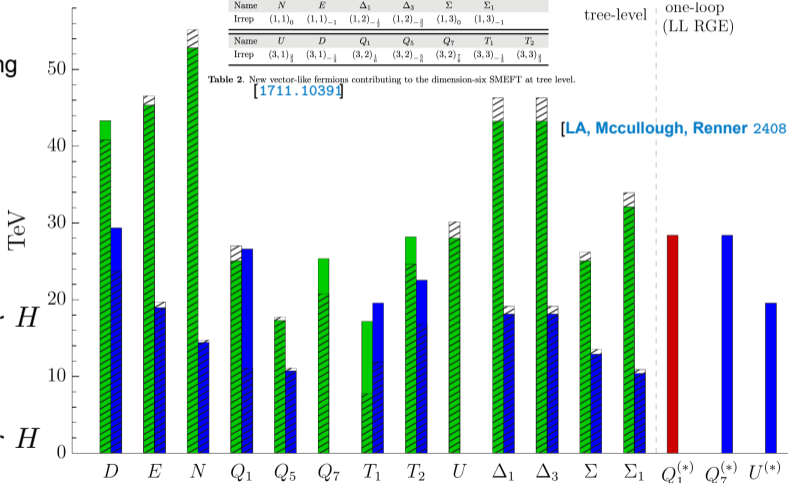
Prospects from EWPOs

BSM fermions

(*) = special choice of couplings to avoid tree-level EWPO

■ Universal couplings ■ Third-gen. only ■ Other

▨ = no running




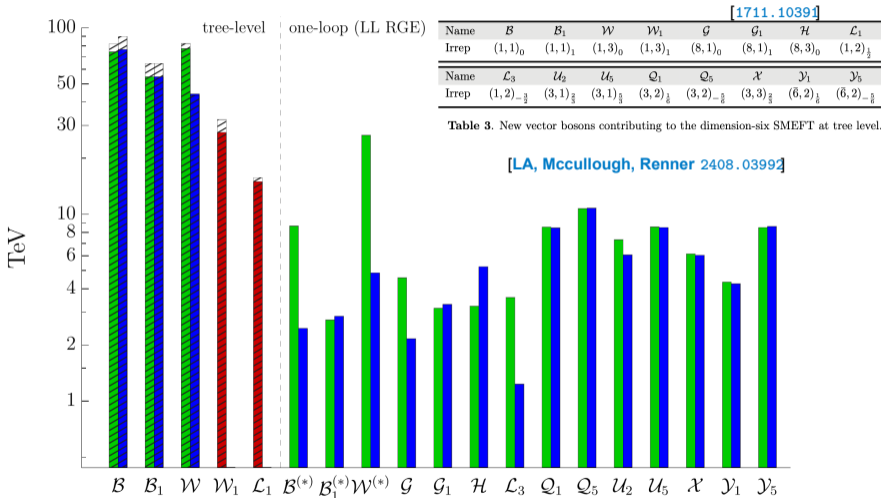
Prospects from EWPOs

BSM vectors

(*) = special choice of couplings to avoid tree-level EWPO

■ Universal couplings
 ■ Third-gen. only
 ■ Flavourless couplings

 = no running



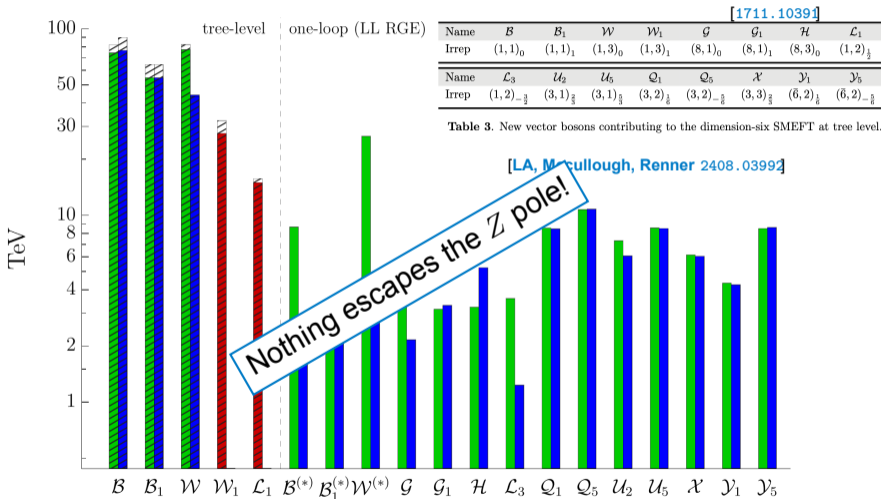
Prospects from EWPOs

BSM vectors

(*) = special choice of couplings to avoid tree-level EWPO

■ Universal couplings ■ Third-gen. only ■ Flavourless couplings

▨ = no running



Flavor Prospects at FCC-ee

Table 6: Yields of heavy-flavoured particles produced at FCC-ee for 6×10^{12} Z decays [190].

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200



- > $\sim 10^3$ more $b\bar{b}$ and $\tau^+\tau^-$ w.r.to Belle
- > $\sim \times 5$ improvement in Λ_{NP} reach
- > Access to B_s and B_c - not produced at b factories
- > Great advantage due to **clean environment** and **boosted final states**

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	(✓)
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

[Kamenik et al. '25]



Projections for Flavor Observables

[LA, Isidori, Pešut 2503.17019]

Observable	SM	Current value [14]	Pre-FCC projection	FCC-ee expected
$ g_\tau/g_\mu $	1	1.0009 ± 0.0014	–	± 0.0001 [15]
$ g_\tau/g_e $	1	1.0027 ± 0.0014	–	± 0.0001 [15]
corr.		0.51		
$\mathcal{B}(\tau \rightarrow \mu \bar{\mu} \mu)$	0	$< 2.1 \times 10^{-8}$	$< 0.37 \times 10^{-8}$ [*] [16]	$< 1.5 \times 10^{-11}$ [*] [15]
R_D	0.298 ± 0.004	0.342 ± 0.026 [17]	$\pm 3.0\%$ [16]	
R_{D^*}	0.254 ± 0.005	0.287 ± 0.012 [17]	$\pm 1.8\%$ [16]	
corr.		-0.39		
$\mathcal{B}(B_c \rightarrow \tau \bar{\nu})$	$(1.95 \pm 0.09) \times 10^{-2}$	< 0.3 (68%C.L.)	–	$\pm 1.6\%$ [8]
$\mathcal{B}(B \rightarrow K \nu \bar{\nu})$	$(4.44 \pm 0.30) \times 10^{-6}$	$(1.3 \pm 0.4) \times 10^{-5}$	$\pm 14\%$ [16]	$\pm 3\%$ [7]
$\mathcal{B}(B \rightarrow K^* \nu \bar{\nu})$	$(9.8 \pm 1.4) \times 10^{-6}$	$< 1.2 \times 10^{-5}$ (68%C.L.)	$\pm 33\%$ [16]	$\pm 3\%$ [7]
$\mathcal{B}(B \rightarrow K \tau \bar{\tau})$	$(1.42 \pm 0.14) \times 10^{-7}$	$< 1.5 \times 10^{-3}$ (68%C.L.)	$< 2.7 \times 10^{-4}$	$\pm 20\%$ [**] [18]
$\mathcal{B}(B \rightarrow K^* \tau \bar{\tau})$	$(1.64 \pm 0.06) \times 10^{-7}$	$< 2.1 \times 10^{-3}$ (68%C.L.)	$< 6.5 \times 10^{-4}$ [*] [16]	$\pm 20\%$ [**] [18]
$\mathcal{B}(B_s \rightarrow \tau \bar{\tau})$	$(7.45 \pm 0.26) \times 10^{-7}$	$< 3.4 \times 10^{-3}$ (68%C.L.)	$< 4.0 \times 10^{-4}$ [*] [16]	$\pm 10\%$ [**] [18]
$\Delta M_{B_s}/\Delta M_{B_s}^{\text{SM}}$	1	$\pm 7.6\%$	$\pm 3.3\%$ [19]	$\pm 1.5\%$ [19]
$\mathcal{B}(B \rightarrow K \tau \bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	
$\mathcal{B}(B_s \rightarrow \tau \bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	

> Subset of observables, relevant for our example study

Projections for Flavor Observables

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> Subset of observables, relevant for our example study

Projections for Flavor Observables

[LA, Isidori, Pešut 2503.17019]

Observable	SM	Current value [14]	Pre-FCC projection	FCC-ee expected
$ g_\tau/g_\mu $	1	1.0009 ± 0.0014	–	± 0.0001 [15]
$ g_\tau/g_e $	1	1.0027 ± 0.0014	–	± 0.0001 [15]
corr.		0.51		
$\mathcal{B}(\tau \rightarrow \mu \bar{\mu} \mu)$	0	$< 2.1 \times 10^{-8}$	$< 0.37 \times 10^{-8}$ [*] [16]	$< 1.5 \times 10^{-11}$ [*] [15]
R_D	0.298 ± 0.004	0.342 ± 0.026 [17]	$\pm 3.0\%$ [16]	
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Third-gen. Semileptonics: Future Prospects

SMEFT Analysis

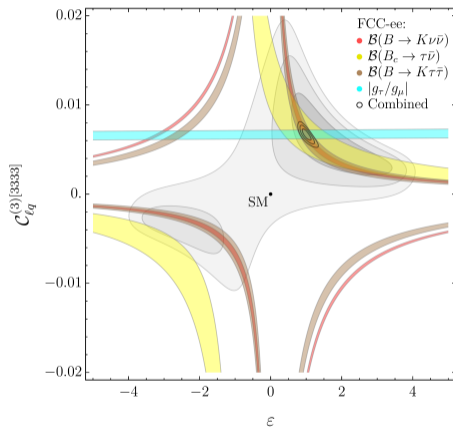
> $[\mathcal{O}_{lq}^{(3)}]_{3333} = (\bar{l}_3 \gamma_\mu \sigma^I l_3)(\bar{q}_3 \gamma^\mu \sigma^I q_3)$

> Flavor-violating effects:

$$\tilde{V} = -\varepsilon V_{ts} \begin{pmatrix} V_{td}/V_{ts} \\ 1 \end{pmatrix} \quad \varepsilon \sim \mathcal{O}(1)$$

> Assume a signal compatible with current measurements (gray region), and project for FCC-ee expected errors

[LA, Isidori, Pešut 2503.17019]



$$q_L^3 \rightarrow q_L^3 - \varepsilon V_{ti} q_L^i$$

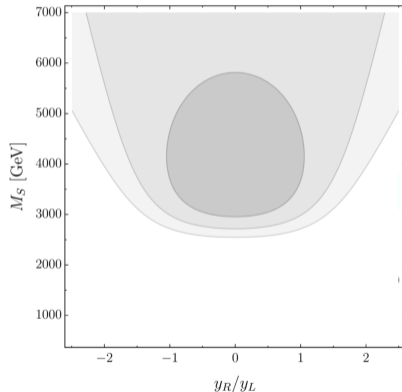
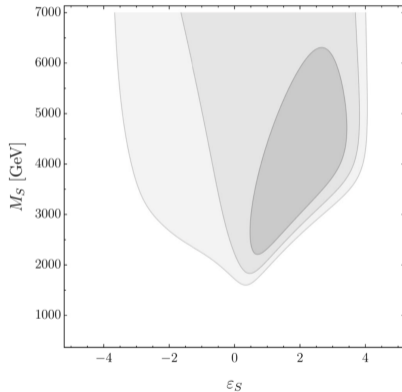
An Explicit (Simplified) Model: S_1 Scalar Leptoquark

Synergies Between Higgs/EW/Flavour

$$\mathcal{L}_{S_1} \supset iy_L S_1 (\bar{q}_L^c \sigma_2 \ell_L^3) + y_R S_1 (\bar{u}^{3c} e_R^3) + \text{h.c.} \quad S_1 \sim (\mathbf{3}, \mathbf{1}, 1/3)$$



- > Third-generation couplings only
- > Current data



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[LA, Isidori, Pešut 2503.17019]

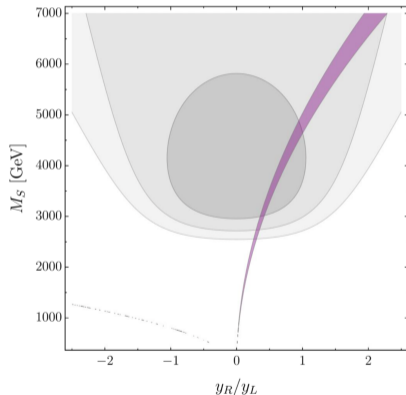
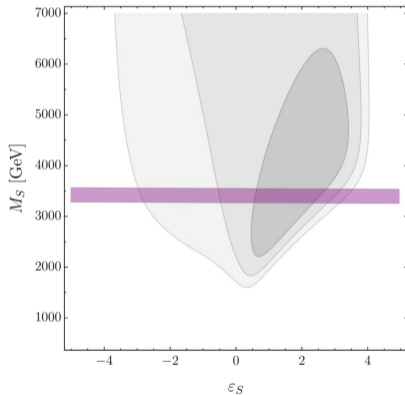
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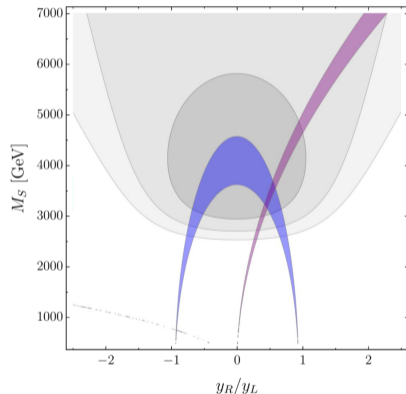
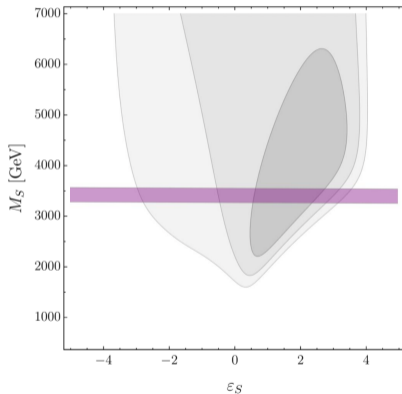
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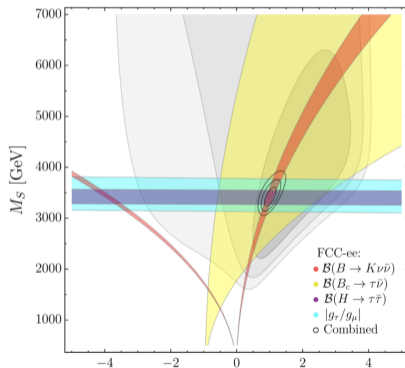
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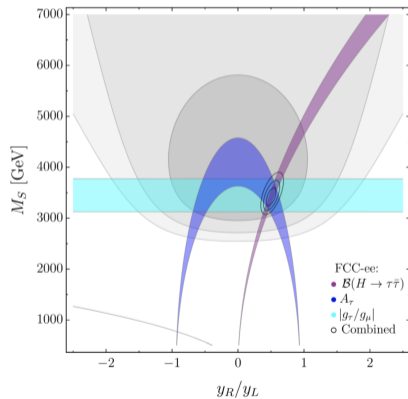
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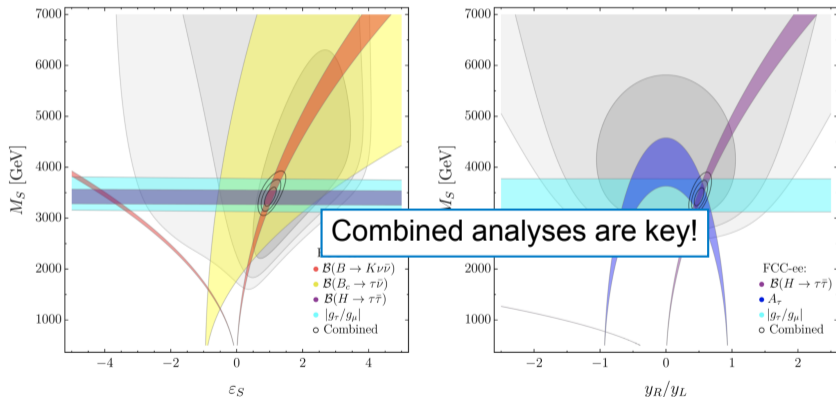
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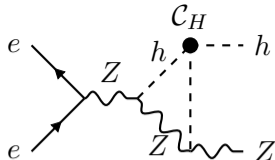
The Higgs Trilinear at FCC-ee

- > Higgs potential unprobed beyond the mass term

$$V(h) = m_h^2 + \kappa_3 \lambda_3^{\text{SM}} h^3 + \kappa_4 \lambda_4^{\text{SM}} h^4 + \dots$$

- > At (circular) e^+e^- , λ_3 enters at one-loop in Zh production
- > If only κ_3 is allowed to vary, expect $\sim 20\%$ precision
- > Many New Physics effects can modify the cross-section

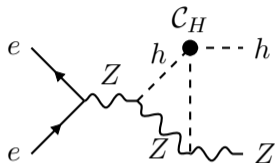
[Asteriadis, Dawson, Giardino, Szafron 2409.11466]



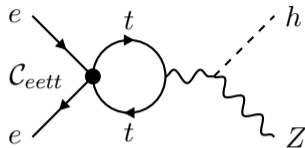
Tree-level	One-loop
$\mathcal{O}_{HD}, \mathcal{O}_{H\Box}, \mathcal{O}_{HWB}, \mathcal{O}_{HW}, \mathcal{O}_{HB},$ $[\mathcal{O}_{He}]_{11}, [\mathcal{O}_{HI}^{(1)}]_{11} + [\mathcal{O}_{HI}^{(3)}]_{11}$	$[\mathcal{O}_{He}]_{ii}, [\mathcal{O}_{HI}^{(1)}]_{ii}, [\mathcal{O}_{HI}^{(3)}]_{ii}, [\mathcal{O}_{Hu}]_{ii}, [\mathcal{O}_{Hd}]_{ii}$ $[\mathcal{O}_{uH}]_{ii}, [\mathcal{O}_{Hq}^{(1)}]_{ii}, [\mathcal{O}_{Hq}^{(3)}]_{ii}, [\mathcal{O}_{uW}]_{33}, [\mathcal{O}_{uB}]_{33}, [\mathcal{O}_{uH}]_{33},$ $\mathcal{O}_W, \mathcal{O}_H[\mathcal{O}_{eu}]_{11ii}, [\mathcal{O}_{qe}]_{ii11}, [\mathcal{O}_{lu}]_{11ii}, [\mathcal{O}_{lq}^{(1)}]_{11ii}$ $[\mathcal{O}_{lq}^{(3)}]_{11ii}, [\mathcal{O}_{lq}^{(3)}]_{2233}, [\mathcal{O}_{ed}]_{11ii}, [\mathcal{O}_{ld}]_{11ii}$ $[\mathcal{O}_{le}]_{11ii}, [\mathcal{O}_{ll}]_{ii jj}, [\mathcal{O}_{ll}]_{1ii1}, [\mathcal{O}_{ee}]_{ii jj}, [\mathcal{O}_{ee}]_{1ii1}$

Will we be able to disentangle the different effects?

Trilinear v. Electron-top Interactions



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



$$[\mathcal{O}_{lq}^{(1)}]_{1133} = (\bar{l}_1 \gamma_\mu l_1) (\bar{q}_3 \gamma^\mu q_3),$$

$$[\mathcal{O}_{lq}^{(3)}]_{1133} = (\bar{l}_1 \gamma_\mu \sigma^I l_1) (\bar{q}_3 \gamma^\mu \sigma^I q_3),$$

$$[\mathcal{O}_{qe}]_{3311} = (\bar{q}_3 \gamma^\mu q_3) (\bar{e}_1 \gamma_\mu e_1),$$

$$[\mathcal{O}_{lu}]_{1133} = (\bar{l}_1 \gamma_\mu l_1) (\bar{u}_3 \gamma^\mu u_3),$$

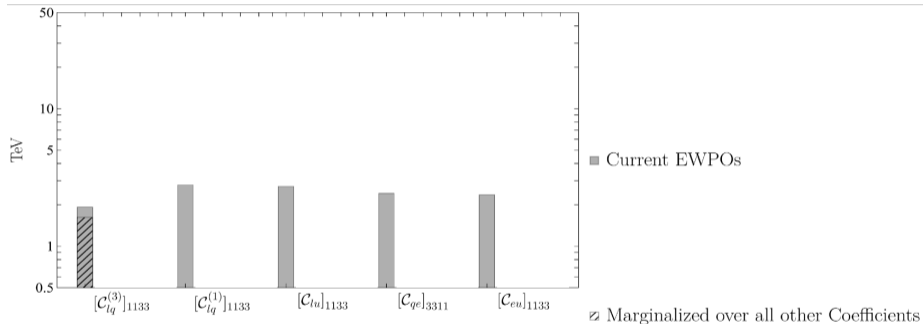
$$[\mathcal{O}_{eu}]_{1133} = (\bar{e}_1 \gamma_\mu e_1) (\bar{u}_3 \gamma^\mu u_3),$$

> C_H and $eett$ interactions enter at the same order in $e^+e^- \rightarrow Zh$

> **Can we independently constrain $eett$ operators?**
What's the impact on the trilinear?

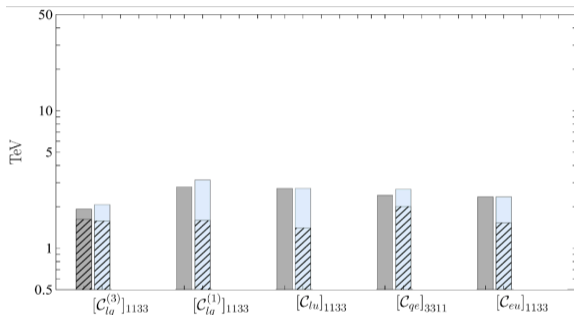
Trilinear v. electron-top interactions

LA, Grojean, Tabatt 2512.06916



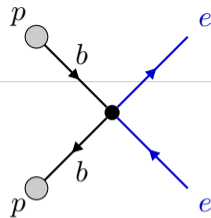
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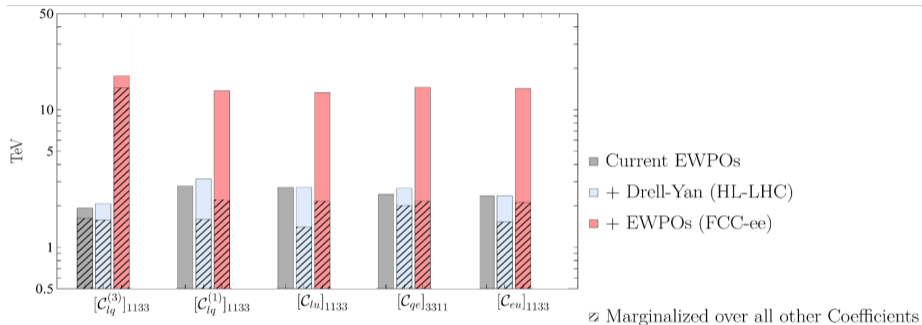
■ Current EWPOs
▨ + Drell-Yan (HL-LHC)

⊗ Marginalized over all other Coefficients



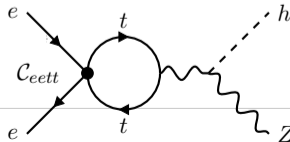
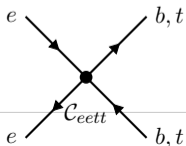
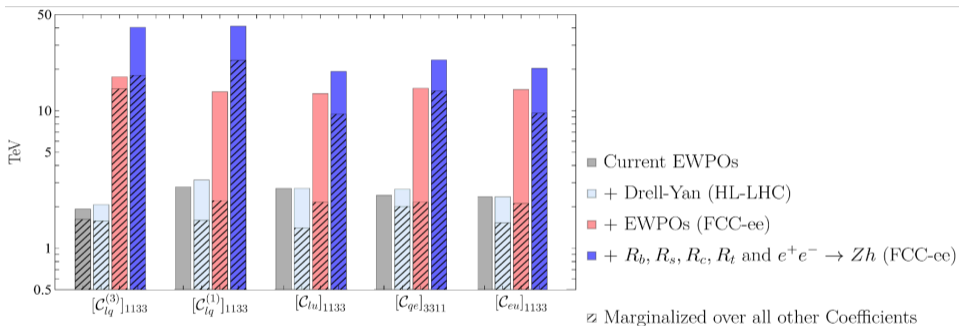
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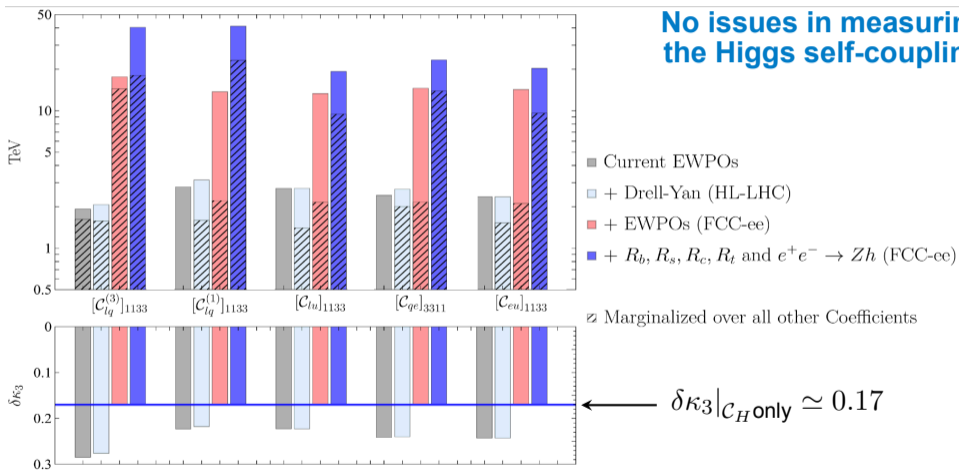
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 - Complementarities between high- p_T and flavor
 - Connection between scales through renormalization effects (EFT)
- iii) Precision physics plays a crucial role, both now and in the future**
 - FCC-ee as a machine for unprecedented precision in Electroweak, Flavor, and Higgs physics
 - Indirect reach way into the 10 TeV range
 - Just the beginning...

Outlook

High- p_T :

- HL-LHC will push the high-energy frontier
- Not only Drell-Yan, but also 4-quark operators, $pp \rightarrow$ missing E , direct searches...
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Other:

- More tools available: matching, RGE, ...
- HighPT 2.0: include flavor, EW, Higgs observables
- Towards consistent SMEFT likelihoods
- More model building

Thank you!

lukas.allwicher@desy.de