The discovery potential of FCC-ee

Gino Isidori

[University of Zurich]

- Introduction
  - The SM as an effective theory
  - Higgs, EW, and Flavour physics @ FCC-ee [*highlights*]
  - Discovery reach in "motivated models" of heavy New Physics
- Conclusions

Largely based on studies done in the context of the ESPPU

European Strategy for Particle Physics

Introduction

- The Standard Model is a highly successful Theory, which describes with great success physical phenomena over a huge (*unprecedented*) range of energies. However, already in its historical name, we have a clue that is not "complete"...

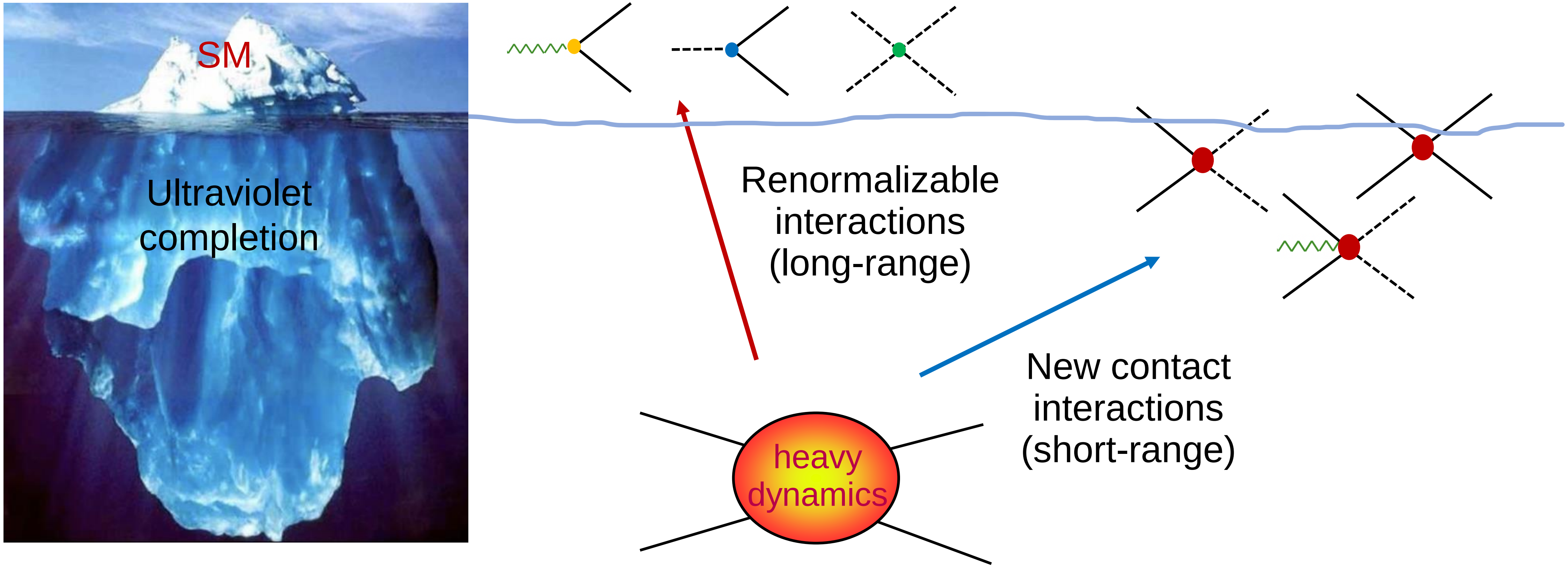
$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_i) + \mathcal{L}_{Higgs}(\phi, A_a, \psi_i)$$

- Natural [only 3 couplings, all of O(1)]
- Stable with respect to quantum corr. [largely UV in-sensitive]
- Highly symmetric

- *"Ad hoc"* [several couplings, with large hierarchies]
- Not stable with respect to quantum corr. [UV sensitive]
- Origin of all the problems of the model…

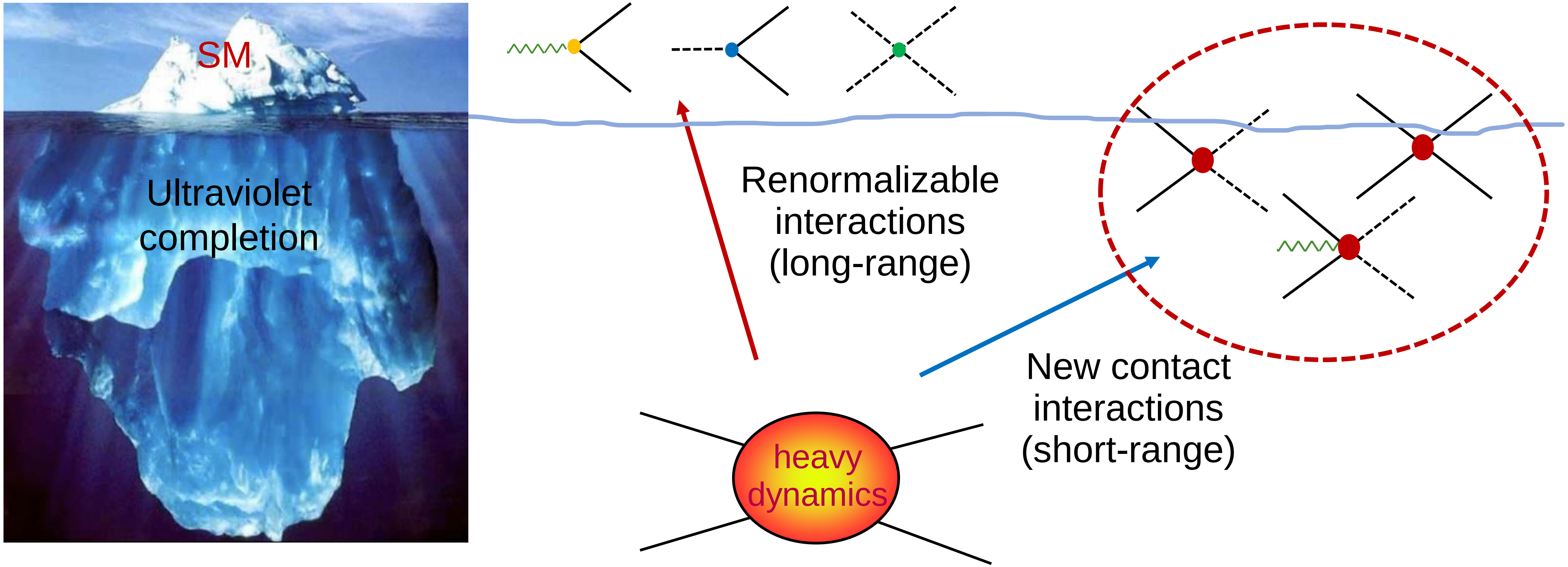
Introduction

- Natural to consider the SM Higgs sector, or better the whole SM, as the effective description of an extended, more stable sector



Introduction

- Finding clear evidences of non-standard contact interactions is (*in my opinion…*) the main objective of particle physics in the coming decades



Introduction

- Finding clear evidences of non-standard contact interactions is (*in my opinion…*) the main objective of particle physics in the coming decades

- A positive result cannot be guaranteed (*we entered a true exploration phase: no-loose theorems*), but there are very good reasons to believe this is possible @ FCC-ee.
- If this would happen, it would be a major discovery. By no means, this could be considered less relevant than what we usually call "direct discoveries"

- To this purpose, it is worth recalling that
  - Essentially the whole SM has been "built" via indirect discoveries.
  - This process was neither smooth nor extremely fast.

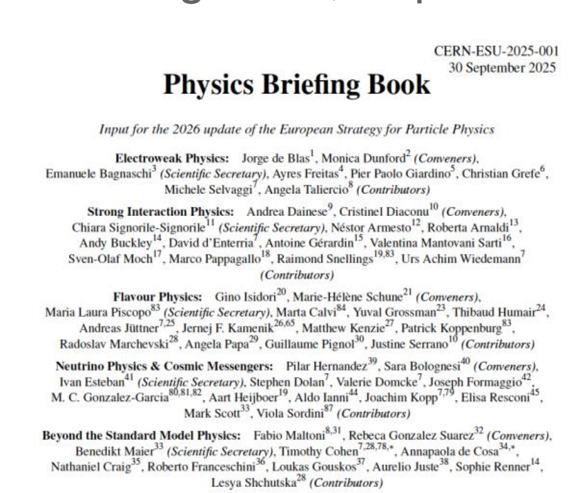
Introduction [*a few words on FCC-ee*]

FCC-ee has been identified by the particle physics community as <u>the next flagship project for CERN</u> [*intense (bottom-up) debate: Sep. 24 → May 26*]

In the following I will not discuss the technical details of the project. I will highlight the unique physics potential of FCC-ee [*focusing mainly on Higgs, EW & Flavour physics*], which is the ultimate reason why it has been (clearly) identified as the <u>best option to address our open questions</u>.

Open Symposium, June '25

Briefing Book, Sept. '25



CERN-ESU-2025-001
30 September 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

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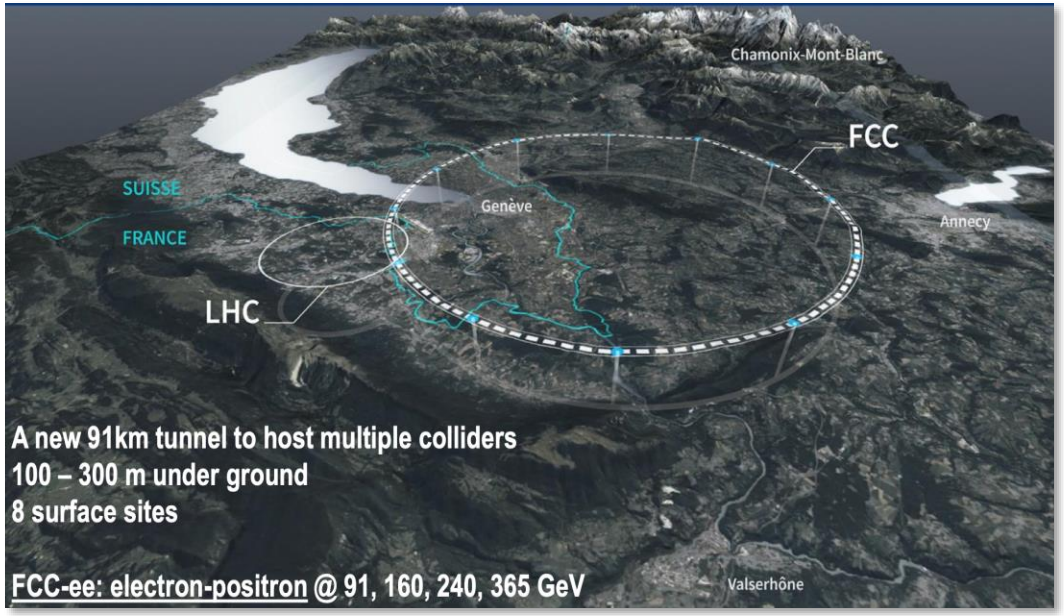
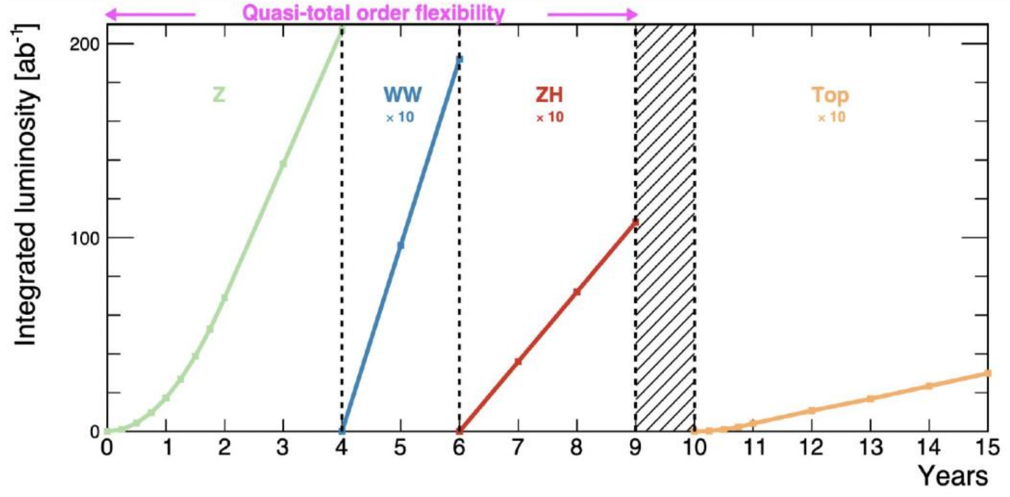
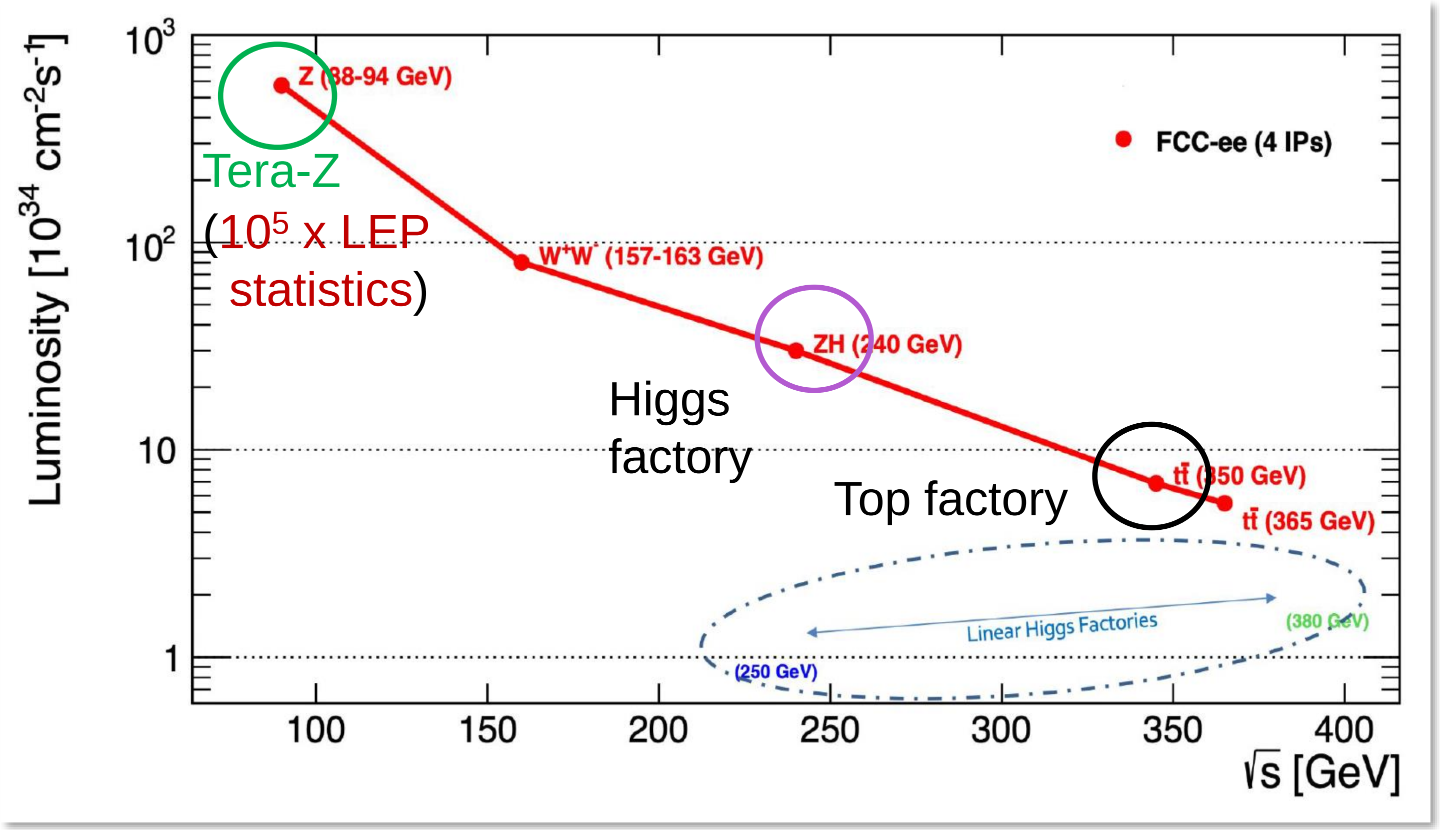
Draft. Session, Dec. '25

Introduction [*a few words on FCC-ee*]







Part I

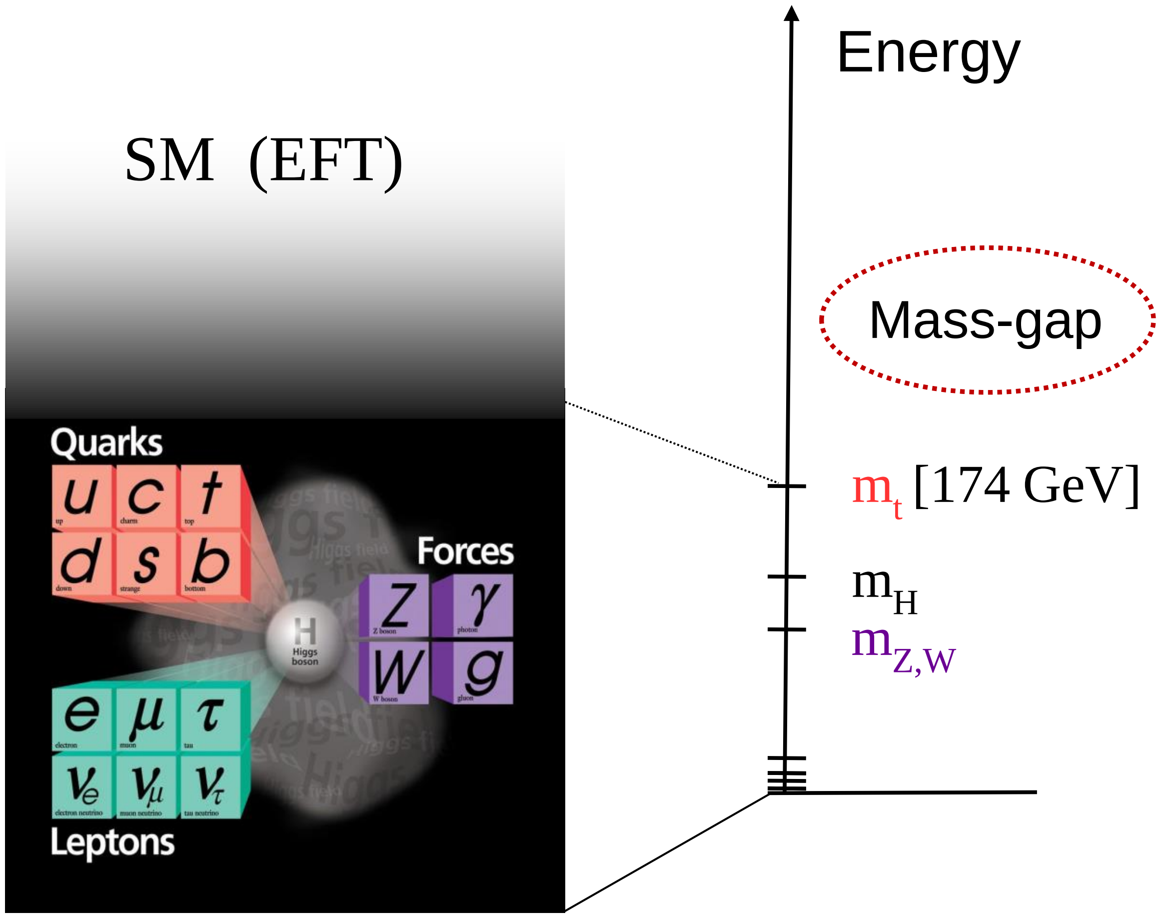
The SM as an effective theory

The SM as an effective theory

- Despite its renormalizability, the SM should be viewed (*as probably any QFT…*) as an Effective Field Theory (EFT), or the low energy limit of a more complete theory:

$$\mathcal{L}_{\text{SM-EFT}} = \underbrace{\mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}} + \ldots$$

  - We identified the long-range properties of this EFT
  - The key message following from current LHC results is that there is a mass-gap above the Fermi scale



The SM as an effective theory

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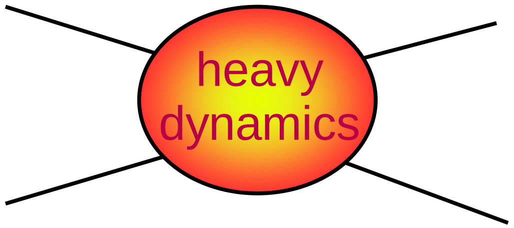
$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\phi, A_a, \psi_i)$$

What is the value of Λ
(= *lowest threshold*
for new dynamics)
is the "<u>core question</u>"
of particle physics



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What is the value of Λ
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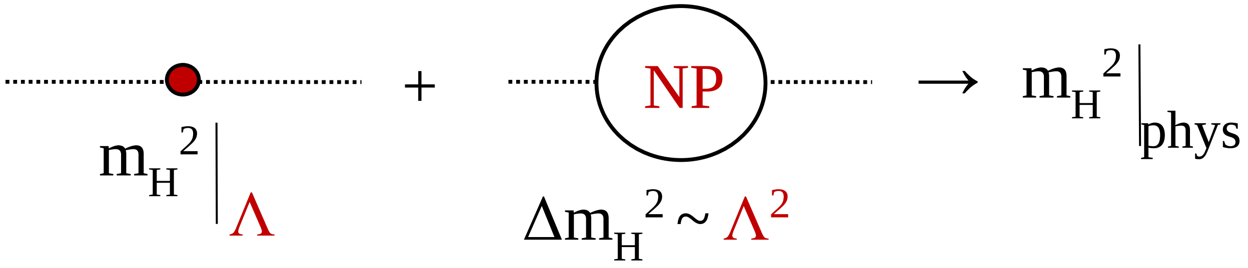
- A strong indication of a nearby energy threshold follows from the hierarchy problem:

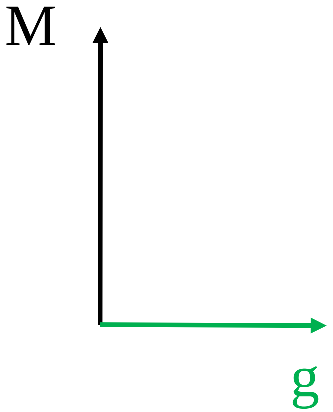


- If the Higgs mass is calculable in terms UV physics, then new degrees of freedom must show around TeV energies to "screen it" form its sensitivity to high energies.

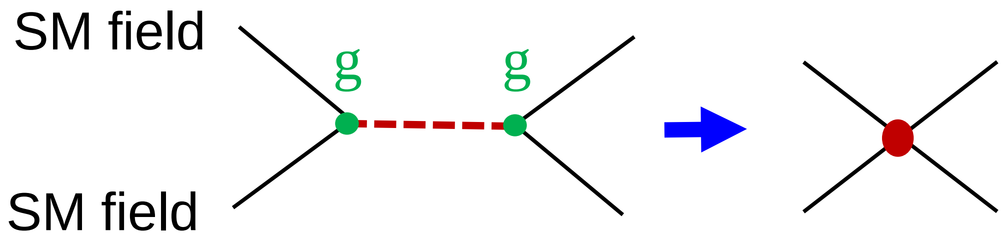
The SM as an effective theory

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\phi, A_a, \psi_i)$$

A closer look to the question of what is the value of Λ reveals many “layers”:



- What is the mass scale of the new d.o.f. ?
- New dynamics weakly or strongly coupled ?

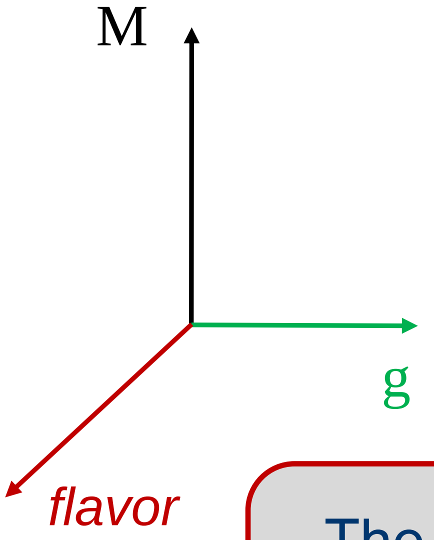


$$\frac{1}{\Lambda^2} \approx \frac{g^2}{M^2}$$

The SM as an effective theory

$$\mathcal{L}_{SM\text{-}EFT} = \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}$$

A closer look to the question of what is the value of Λ



- What is the mass scale of the new d.o
- New dynamics weakly or strongly cou
- What is the flavor structure?
  - No flavor symmetry ⟶ 2499 free couplings [@ d=6]
  - Maximal flavor symmetry ⟶ 47 free couplings [@ d=6]

The SMEFT is a very useful "map" to characterize BSM effects, especially in precision measurements; "navigating" with the SMEFT without consistent assumptions (*especially about flavor*) can be misleading…

The SM as an effective theory

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\phi, A_a, \psi_i)$$

- A useful general info is the functional dependence of precision observables (*Higgs, EW, or flavor*) from Λ:

$$A(i \to f) = A_{SM}\left[1 + k \times \frac{m_W^2}{\Lambda^2}\right]$$

SM electroweak amplitude

The sensitivity on Λ scales with $\sim N^{1/4}$ for precision measurements (*vs. linear scale with Energy for high-energy processes*)

Increasing N by 10^5 implies an increase by <u>more than a factor of 10</u> in the (indirect) energy reach

The SM as an effective theory

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}\,(\phi, A_a, \psi_i)$$

- A useful general info is the functional dependence of precision observables (*Higgs, EW, or flavor*) from Λ:

$$A(\,i \rightarrow f\,) = A_{\text{SM}} \left[1 + k \times \frac{m_W^2}{\Lambda^2} \right]$$

	$\sim 1/(16\,\pi)^2$	~ 1	$\sim (16\,\pi)^2$
$\Lambda \sim 1$ TeV $\rightarrow$	0.01%	1%	O(1)

no clear sign yet…

The SM as an effective theory

$$A(i \to f) = A_{SM}\left[1 + k\,\cancel{\frac{m_W^2}{\Lambda^2}}\right]$$

- Currently we have no clear indications of SM failures: up to which scale can we extrapolate the SM validity?

"No New Physics up to the Planck scale"

Can we agree on that?

NO !!!

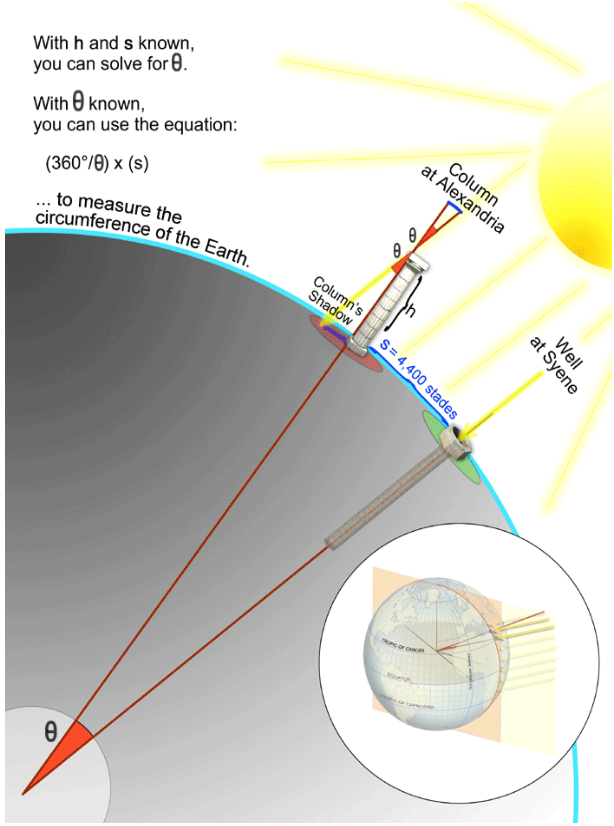
- Current bounds on Λ do not exceed 1-2 TeV in <u>motivated models</u> (*more later)* extrapolating these null results to much higher energies is neither justified nor very useful (*at least in my opinion*…)

The SM as an effective theory

$$A(i \to f) = A_{SM}\left[1 + k\,\frac{m_W^2}{\Lambda^2}\right]$$

- Current bounds on Λ do not exceed 1-2 TeV in motivated models…

- Embarking into a new high-energy effort without a clear clue of where the new energy threshold could be, is a high risk…

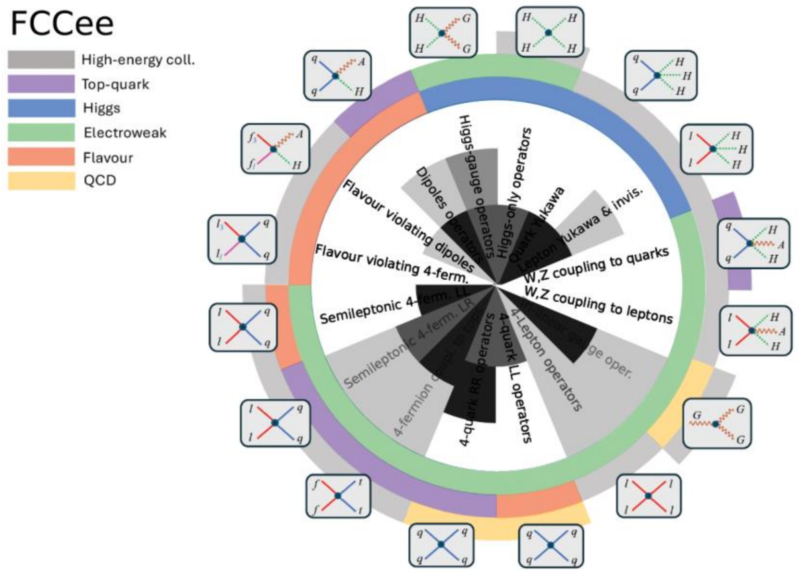


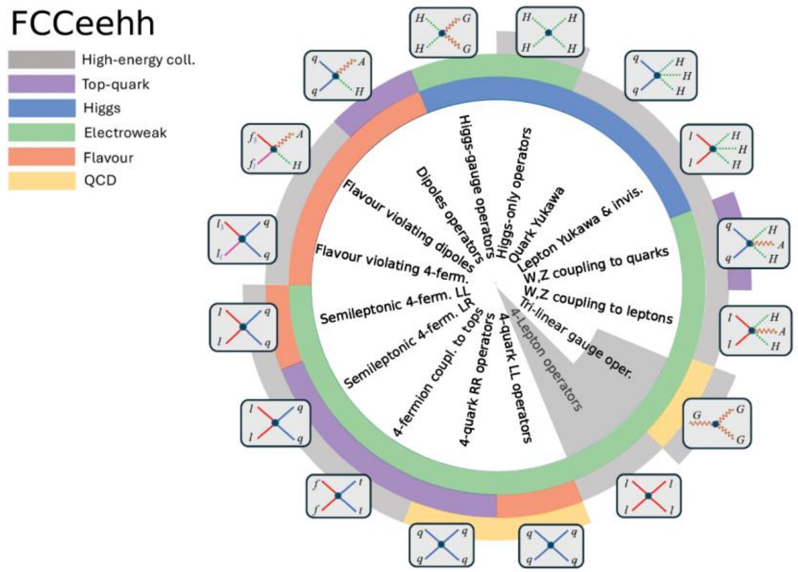
Colombo would have never started his expedition without an estimate of earth's radius...

The best strategy is to plan a significant advancement in precision measurements to obtain clear clues about the new energy threshold

Part II

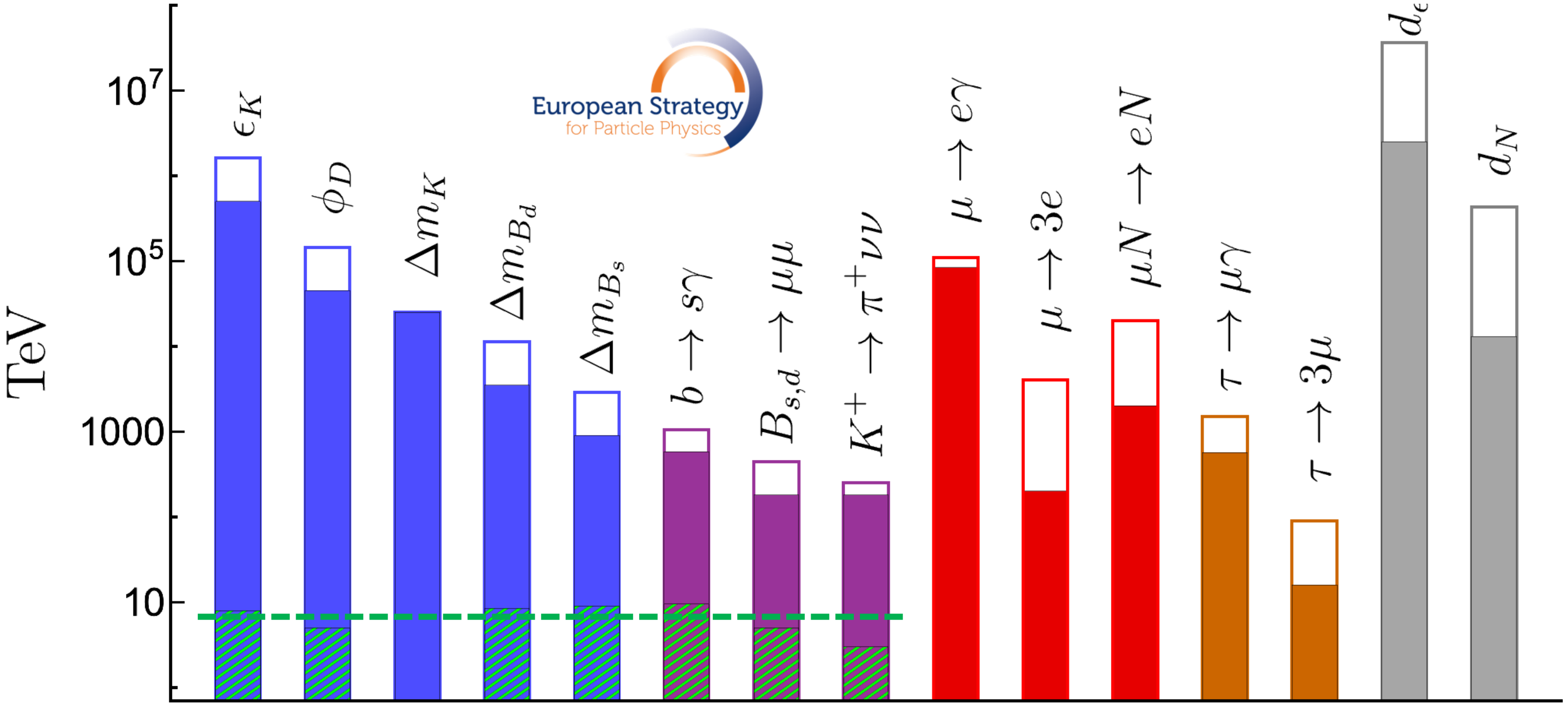
Highlights of future prospects on Higgs, EW, and Flavour





Future prospects in Higgs, EW, and Flavour

Flavour-changing processes represent the numerically largest domain of possible new contact interactions. The strong bounds currently derived by various processes imply that NP is either very heavy or, most likely, has a non-trivial flavour structure (*similarly to SM*). In both cases, improving current bounds leads to a unique & wide-range sensitivity to physics beyond the SM



$$C = \frac{1}{\Lambda^2}$$

$$C = \frac{V_{i3} V_{3j}}{\Lambda^2}$$

Future prospects in Higgs, EW, and Flavour

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}\,(e/\mu)$ $R_{bc}\,(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to$		$b \to d\,\mu\mu$ $b \to u\,\mu\nu$		$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	
$2_q \to 2_q$, 1_q	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$	$c \to u\,\mu\mu$ $c \to s\,\mu\nu$ $c \to d\,\mu\nu$	$R_{cu}\,(e/\mu)$ $R_{cs}\,(e/\mu)$ $R_{cd}\,(e/\mu)$		$c \to u\,\nu\nu$
$3_l \to 2_l$, 1_l	$\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$	$\tau \to \mu\,qq$ $\tau \to e\,qq$	$\tau \to \mu\,\mu\mu$ $\tau \to \mu\,ee$	$\tau \to \mu\,ee$ $\tau \to e\,ee$		$\tau \to \mu\,\nu\nu$ $\tau \to e\,\nu\nu$

$B(B_s \to \mu\mu)$,
$B(B \to K^*\,\mu\mu)$,
$A_{FB}(B \to K^*\mu\mu)$,
□

$R^{\tau/\mu}(D)$,
$R^{\tau/\mu}(D^*)$, …

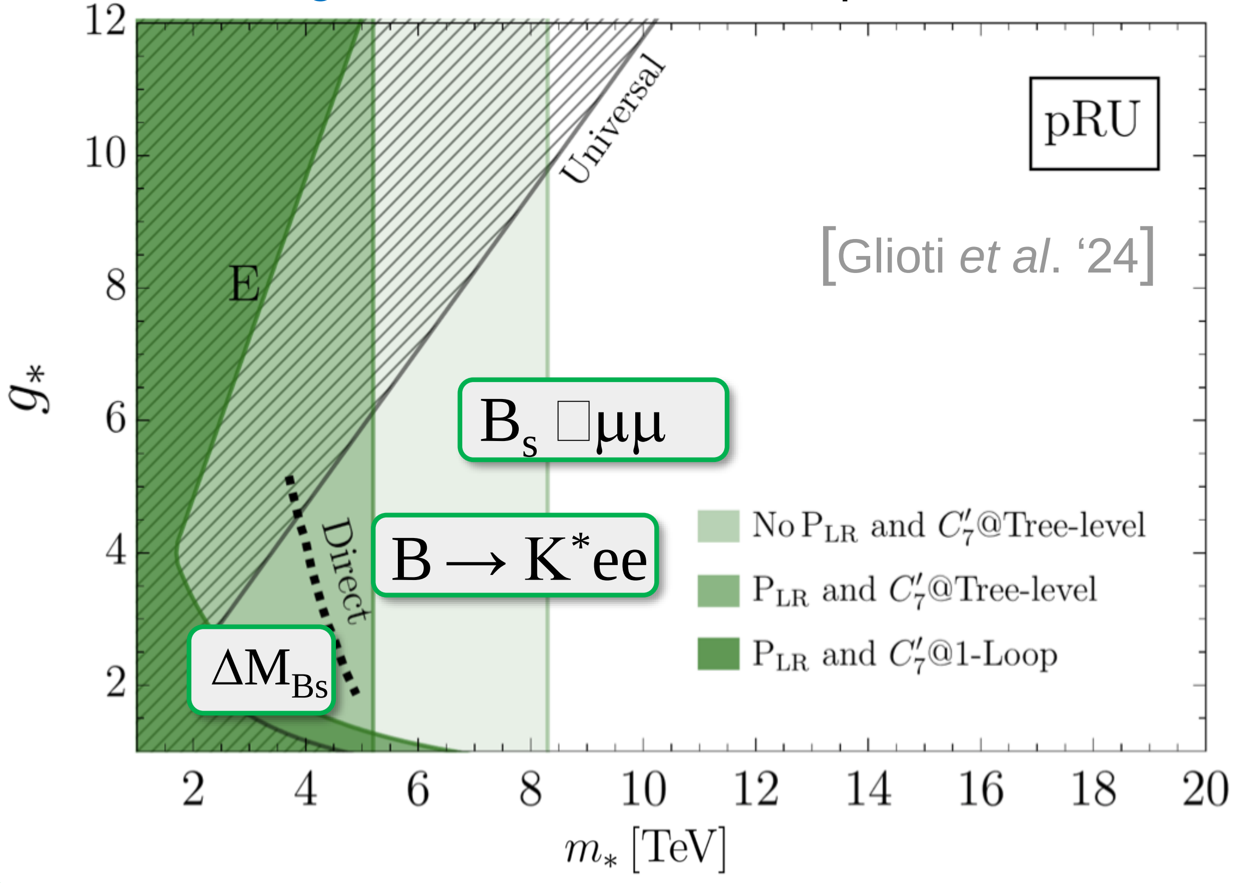
$B(B \to K\,\nu\nu)$,
$B(B \to K^*\nu\nu)$,
□

N.B.: *several observables for each transition*

Future prospects in Higgs, EW, and Flavour

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$	$R_{bs}\,(e/\mu)$	$b \to s\,\tau\tau$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$				

E.g.: Partial fermion compositeness



FCNCs currently @ 10-30%

- TeV-scale constraints in realistic models
- Current theory errors 5% - 20% → will reach 1-2%

Future prospects in Higgs, EW, and Flavour

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$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$	$b \to d\,\mu\mu$ $b \to u\,\mu\nu$	$R_{bd}\,(e/\mu)$ $R_{bu}\,(e/\mu)$	$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	$b \to d\,\nu\nu$
$2_q \to 2_q,\ 1_q$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$				$c \to u\,\nu\nu$
$3_l \to 2_l,\ 1_l$	$\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$	$\tau \to \mu\,qq$ $\tau \to e\,qq$	$\tau \to \mu\,\mu\mu$ $\tau \to \mu\,ee$	$\tau \to \mu\,ee$ $\tau \to e\,ee$		$\tau \to \mu\,\nu\nu$ $\tau \to e\,\nu\nu$

Progress from HL-LHC & Belle-II:

- (green) σ reduction by 4 – 10 times (saturating TH errors)
- (yellow) σ reduction, but still far from SM precision or ultimate NP sensitivity

Future prospects in Higgs, EW, and Flavour

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}\,(e/\mu)$ $R_{bc}\,(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to d\,\gamma$	$B_d \leftrightarrow \bar{B}_d$	$b \to d\,\mu\mu$ $b \to u\,\mu\nu$	$R_{bd}\,(e/\mu)$ $R_{bu}\,(e/\mu)$	$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	$b \to d\,\nu\nu$
$2_q \to 2_q$, 1_q	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$				$c \to u\,\nu\nu$
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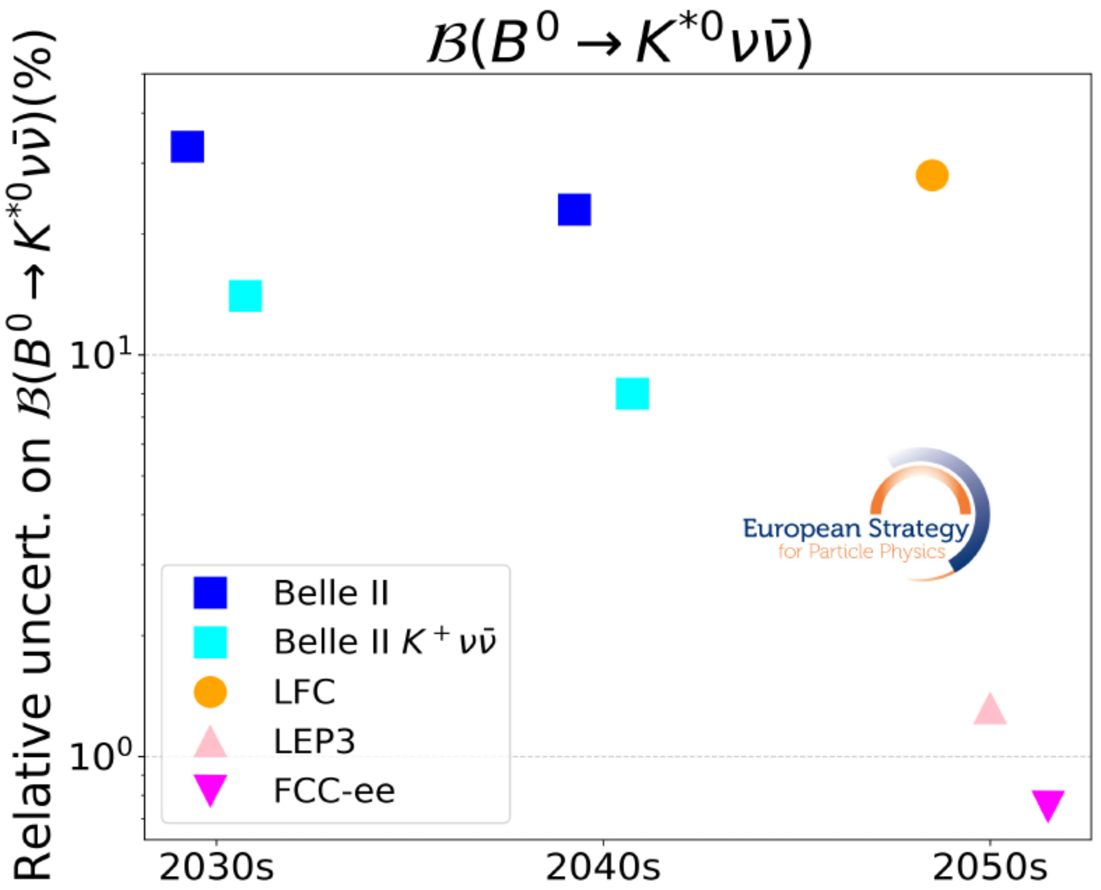
Progress from HL-LHC & Belle-II:

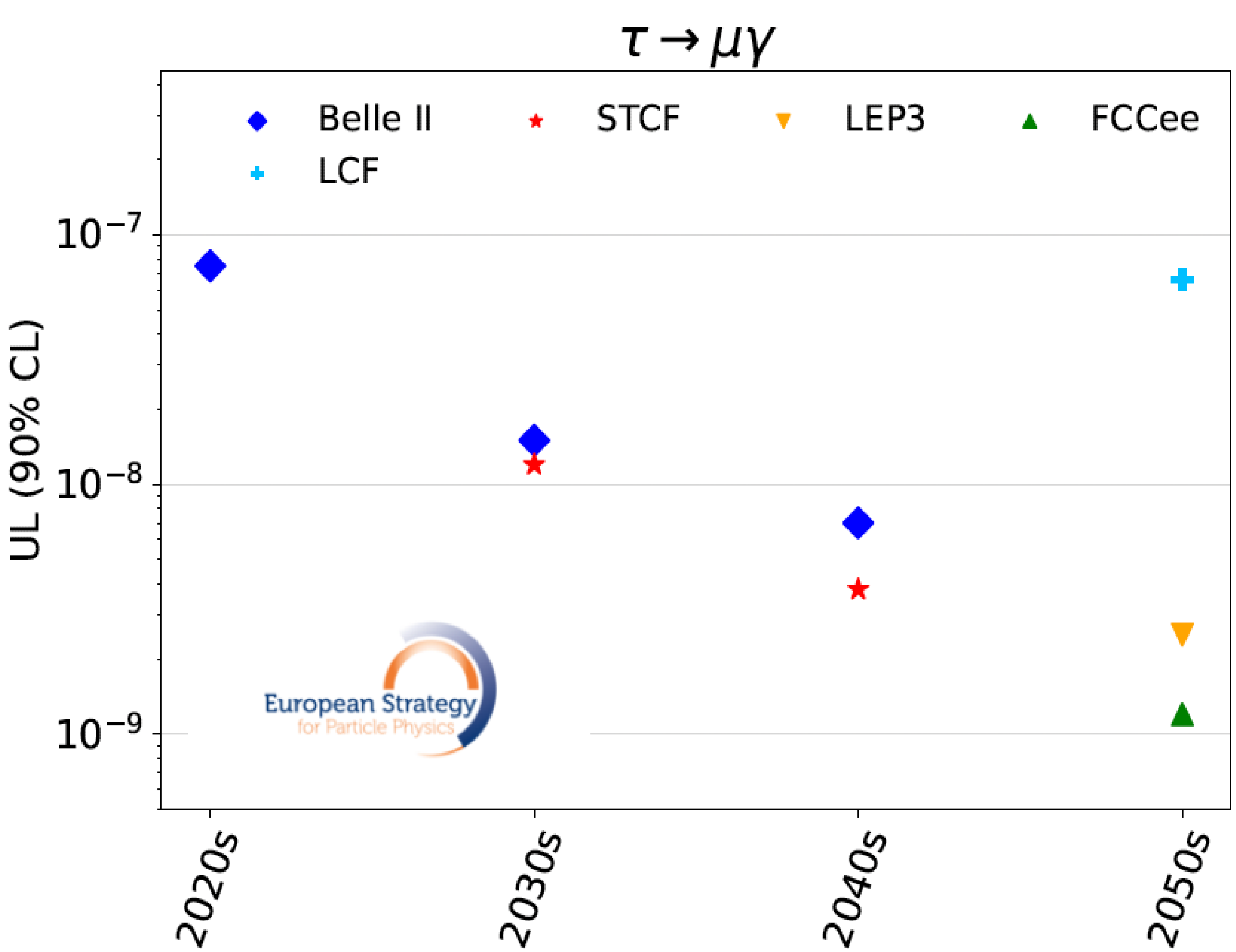
[green box] σ reduction by 4 – 10 times

Possible Tera-Z impact [6×10^{12} Z]:

[blue box] Further σ reduction by factor of ~ 10 (or more)

Future prospects in Higgs, EW, and Flavour



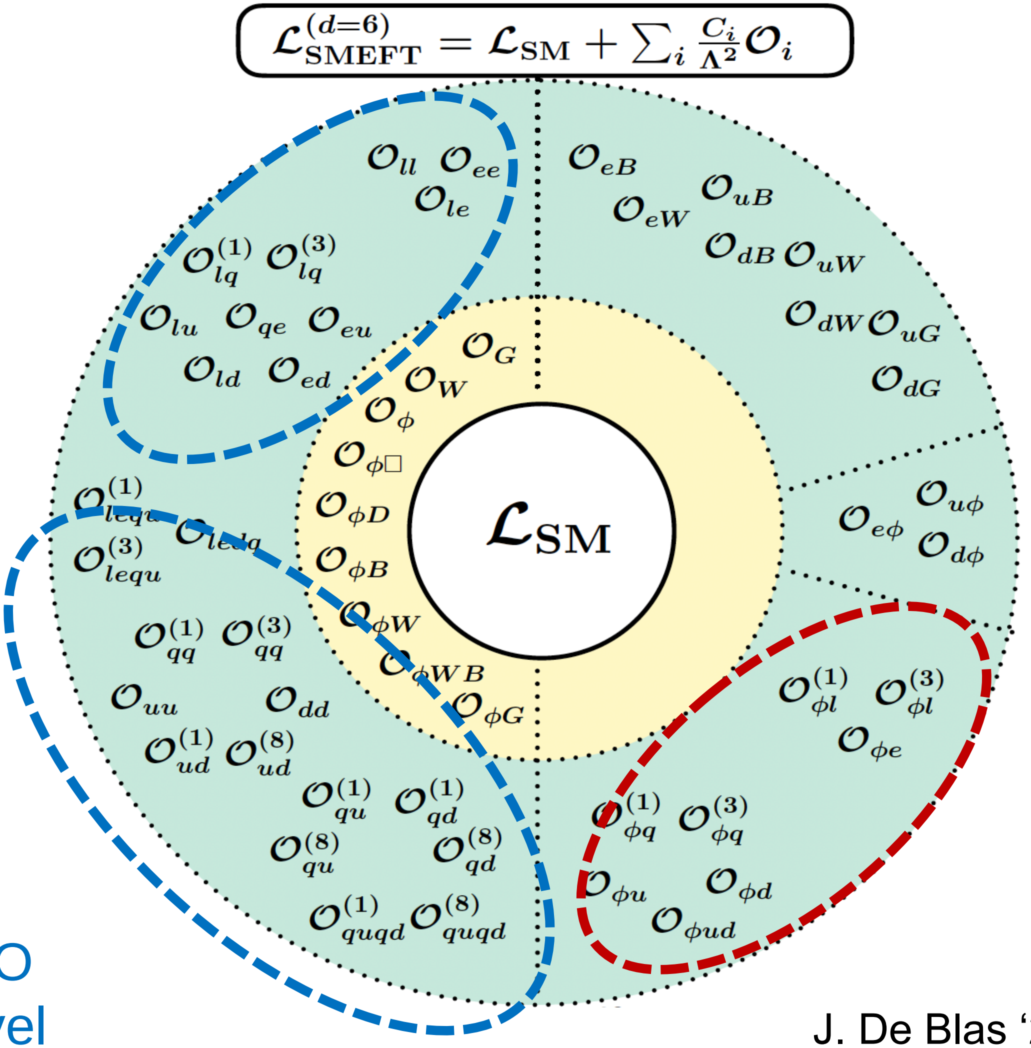


- Tera-Z [FCC-ee, LEP-3] would lead to a major improvement
- Giga-Z [LCF] is not competitive

Future prospects in Higgs, EW, and Flavour

Electroweak precision observables allow us to probe the vast majority of the flavour-conserving operators in the SMEFT

[*many constraints still dominated by LEP data*]



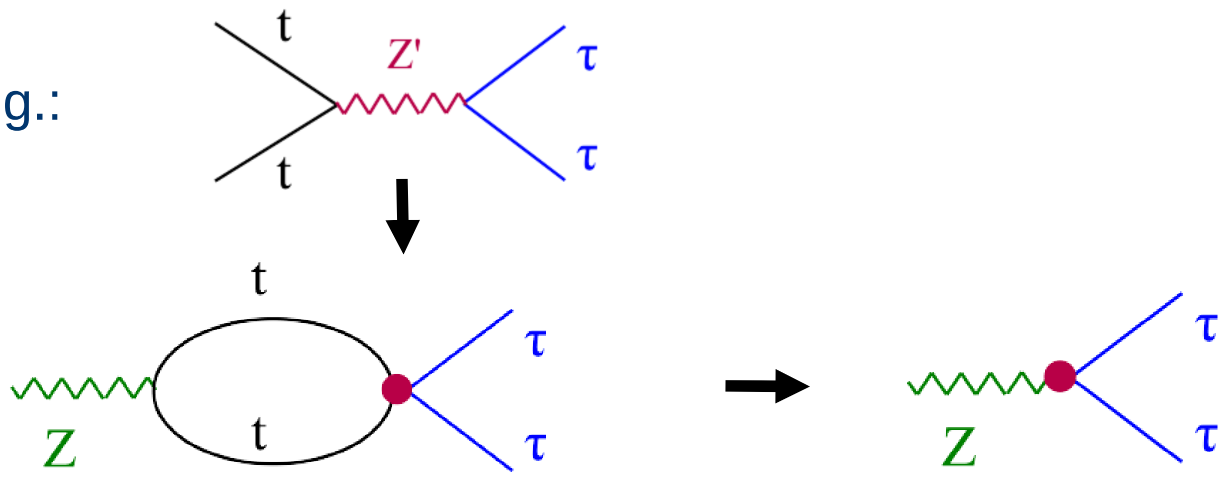
J. De Blas '25

Future prospects in Higgs, EW, and Flavour

- Unique potential of EW precision measurements @ FCC-ee:
  - The jump in precision of FCC-ee is EW physics is unprecedented:

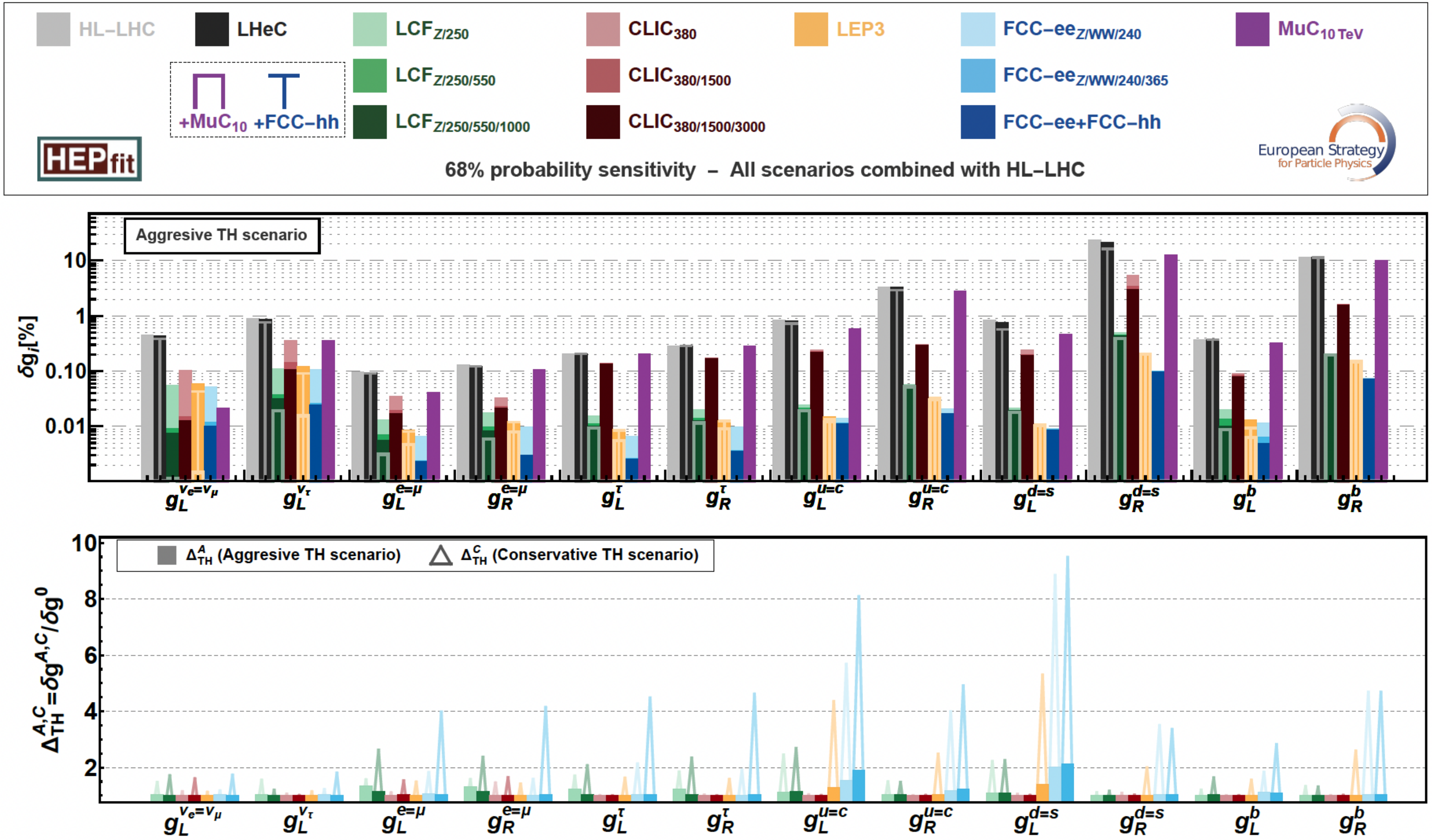
    $5\text{x}10^{12}$ Z-boson pairs ~ 10^5 LEP statistics
  - This level of precision opens the sensitivity to TeV-scale physics, even if the new states couple to EW probes only via quantum effects:

E.g.:



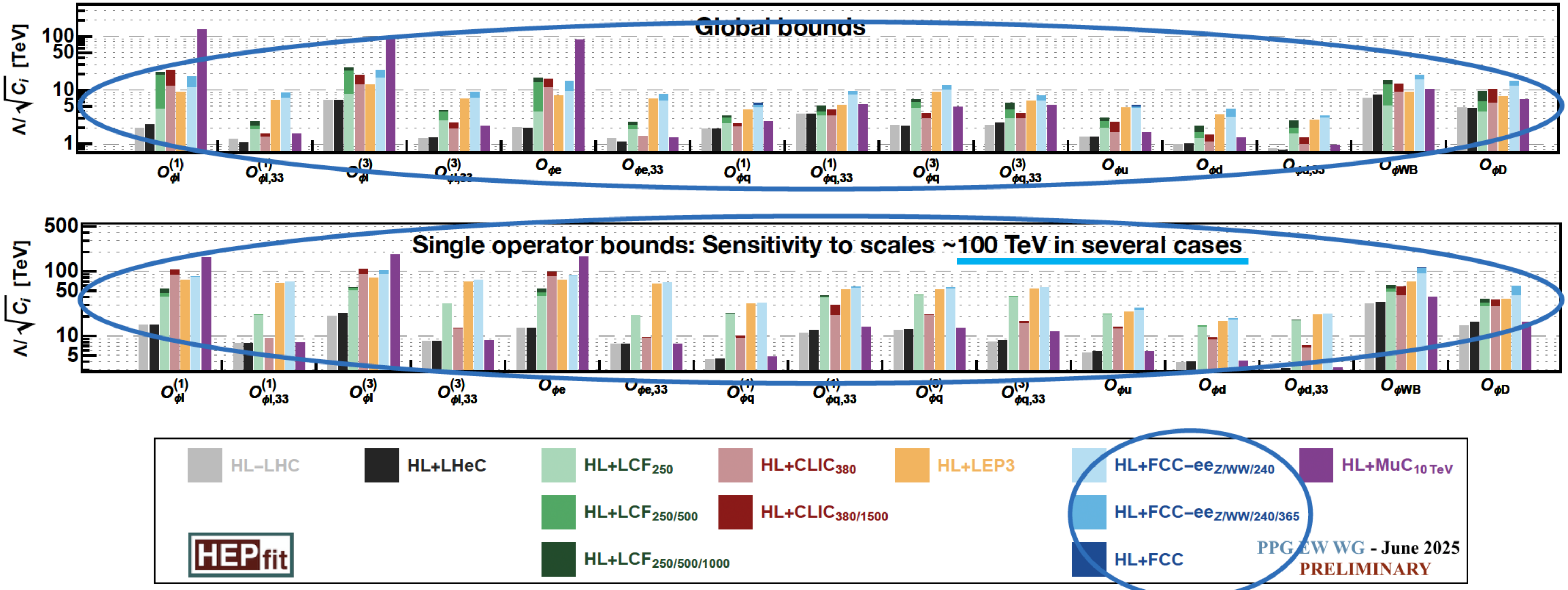
Reaching 0.01% precision overcome the (double) suppression, loop x $(m_W/\Lambda)^2$

Future prospects in Higgs, EW, and Flavour



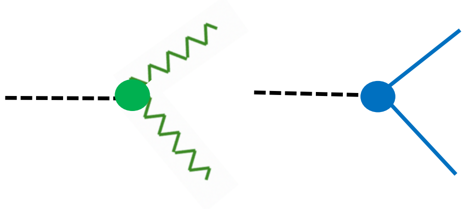
Future prospects in Higgs, EW, and Flavour

EWPO at Tera Z: Best overall sensitivity to operators modifying EW interactions



Future prospects in Higgs, EW, and Flavour

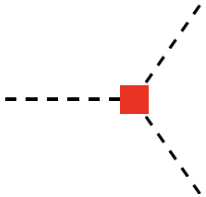
Higgs couplings



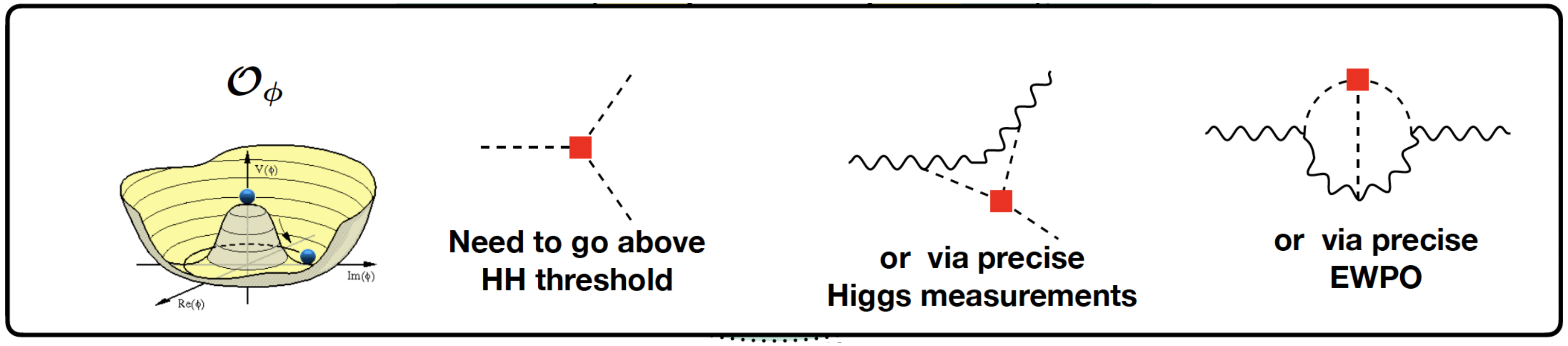
- Key ingredient: number of Higgs produced in "clean" environment [$e^+e^- \to ZH$]

Two distinct frontiers

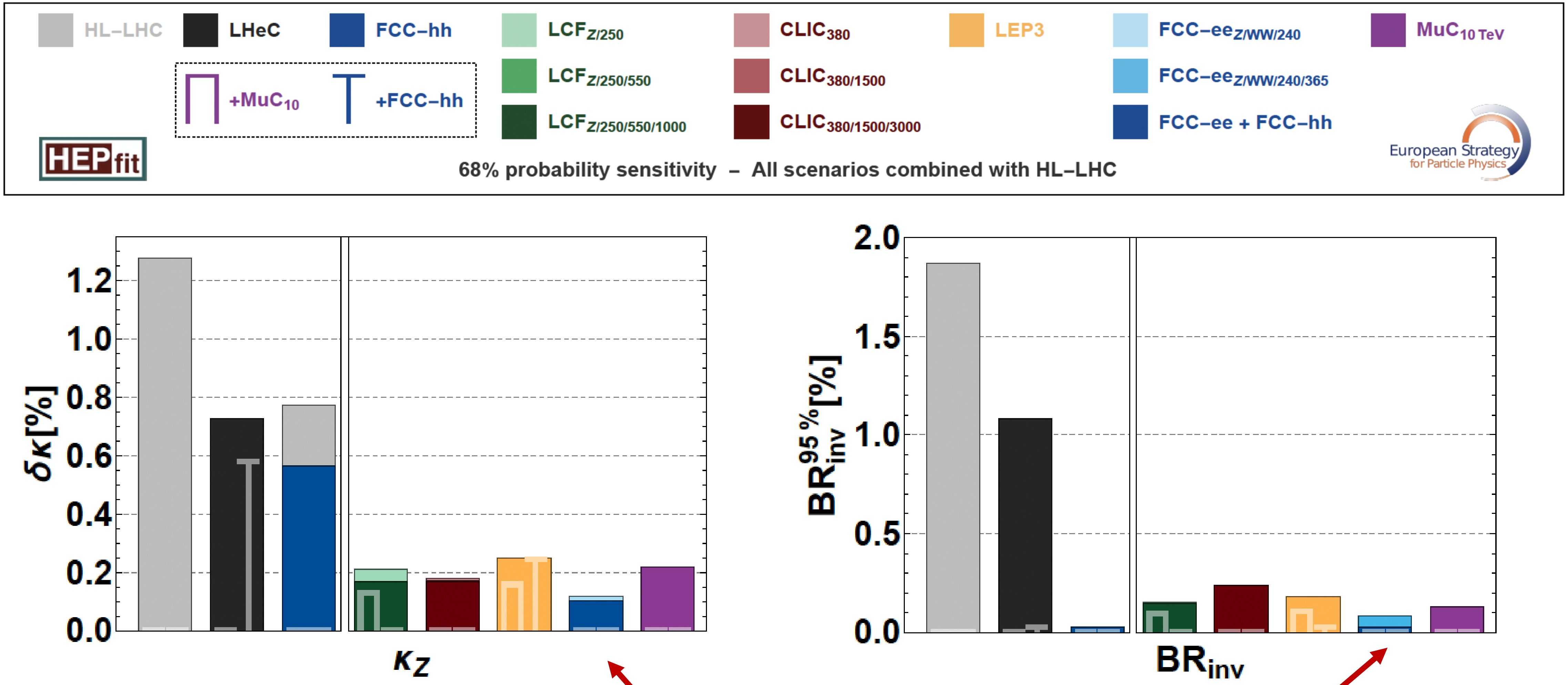
Higgs self-coupling



- Key ingredient: run at (at least) two different energies
- Ultimate precision reached by high-energy colliders

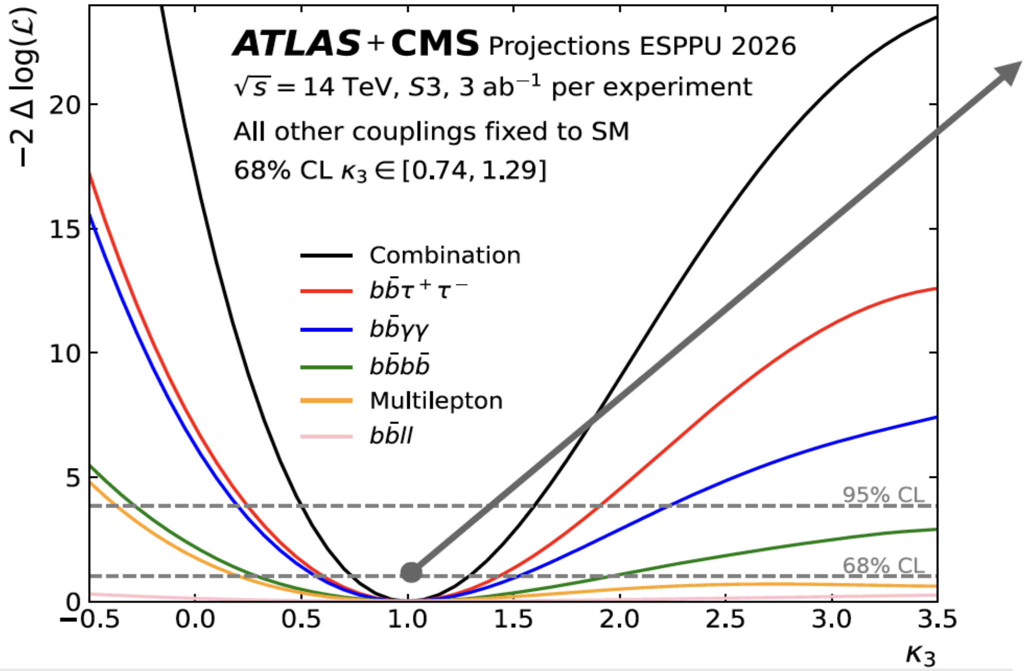


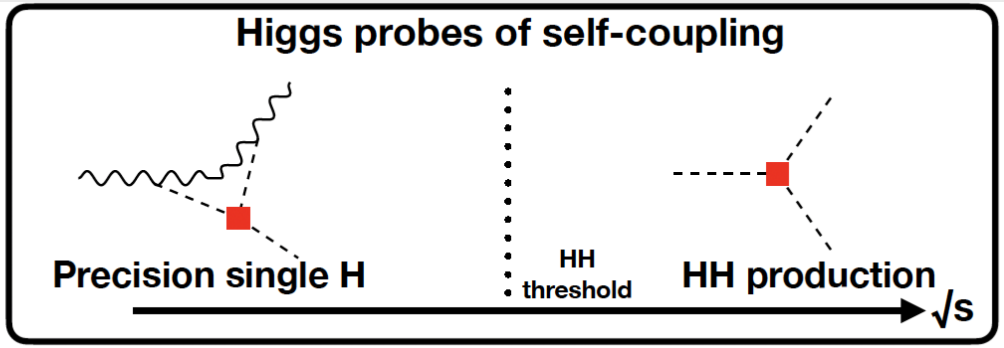
Future prospects in Higgs, EW, and Flavour

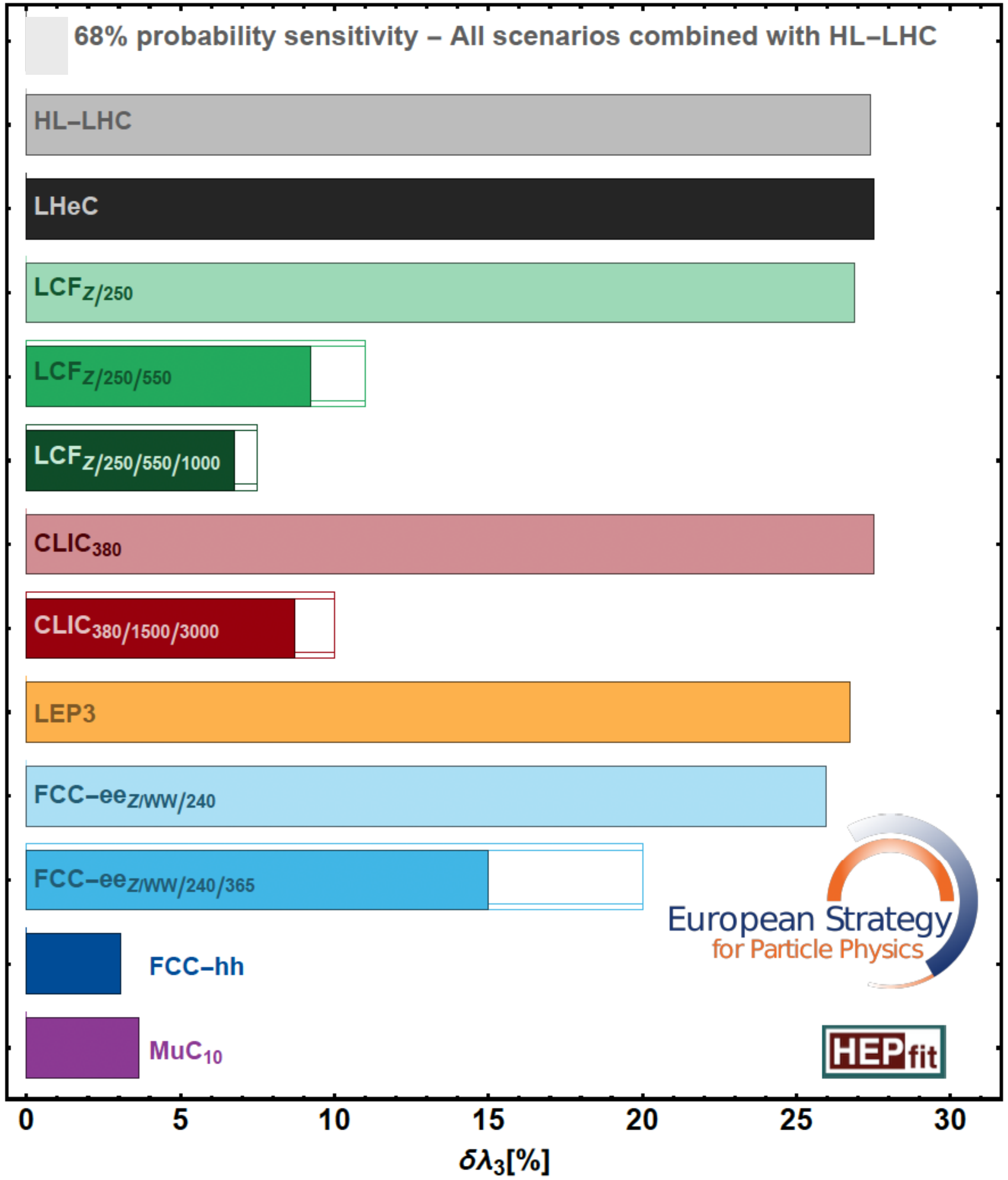


0.1% precision [unique BSM sensitivity]

Future prospects in Higgs, EW, and Flavour





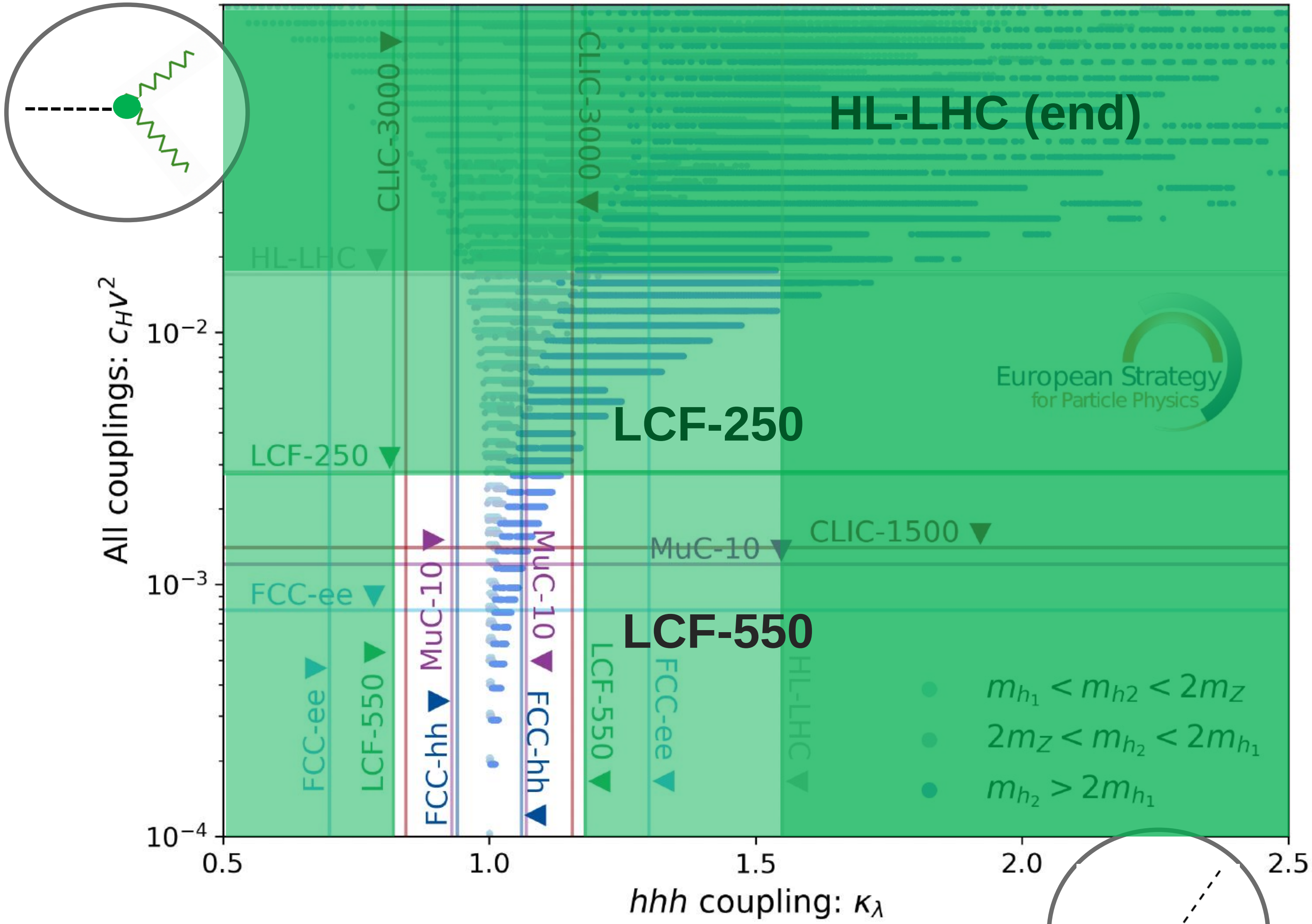


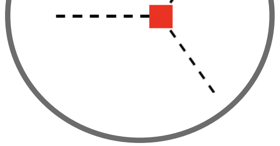
Future prospects in Higgs, EW, and Flavour

The relative role of couplings vs. self-couplings is a (BSM)-dependent question

As general rule: it is hard (*if not impossible...*), having a large impact on the self-coupling without touching the other couplings

Explicit example in a concrete (minimal) model: mixing of the SM Higgs with a scalar singlet (*parameter space leading to first-order EWPT*)





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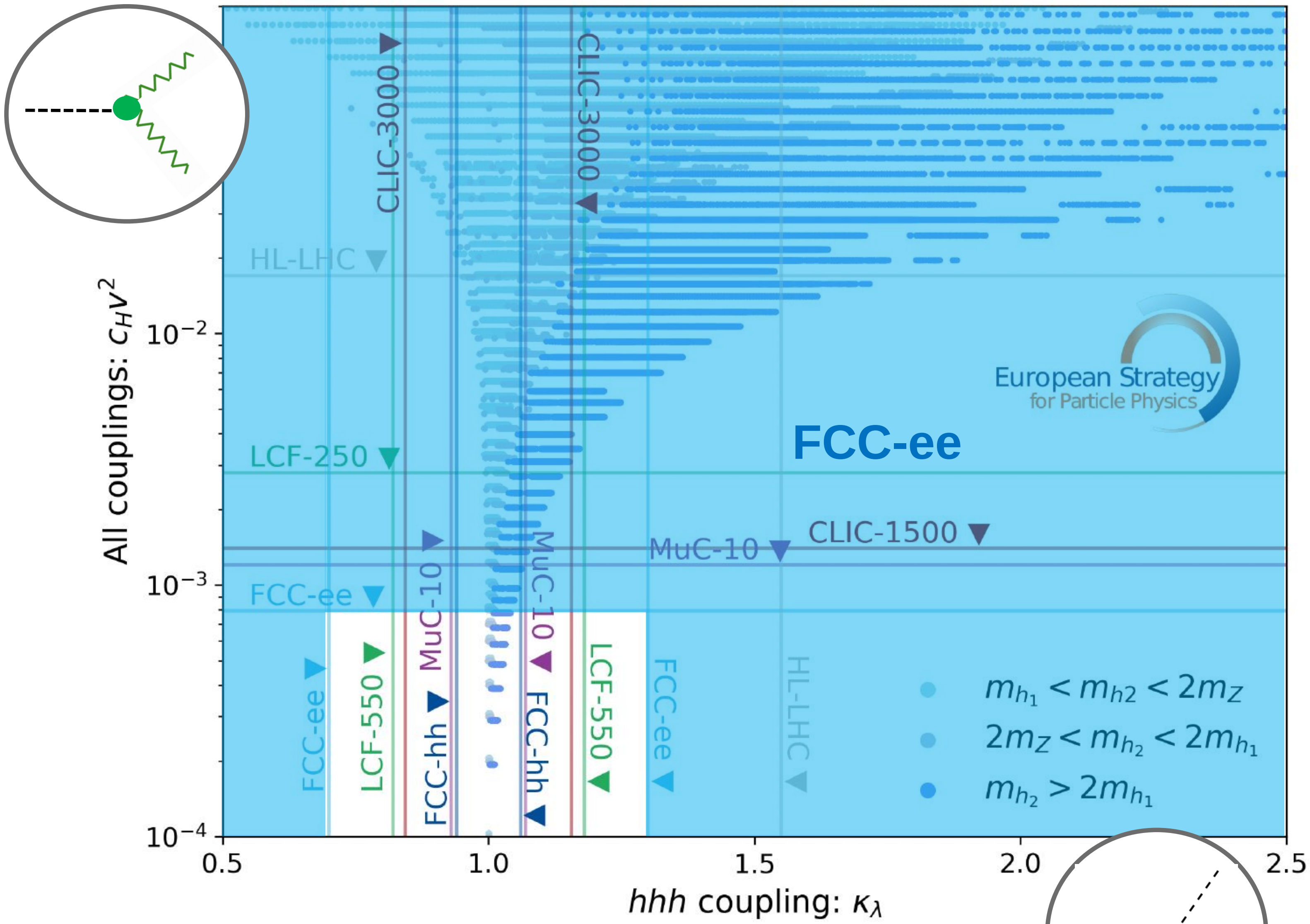
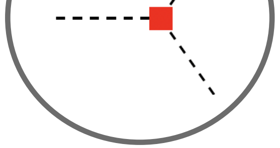
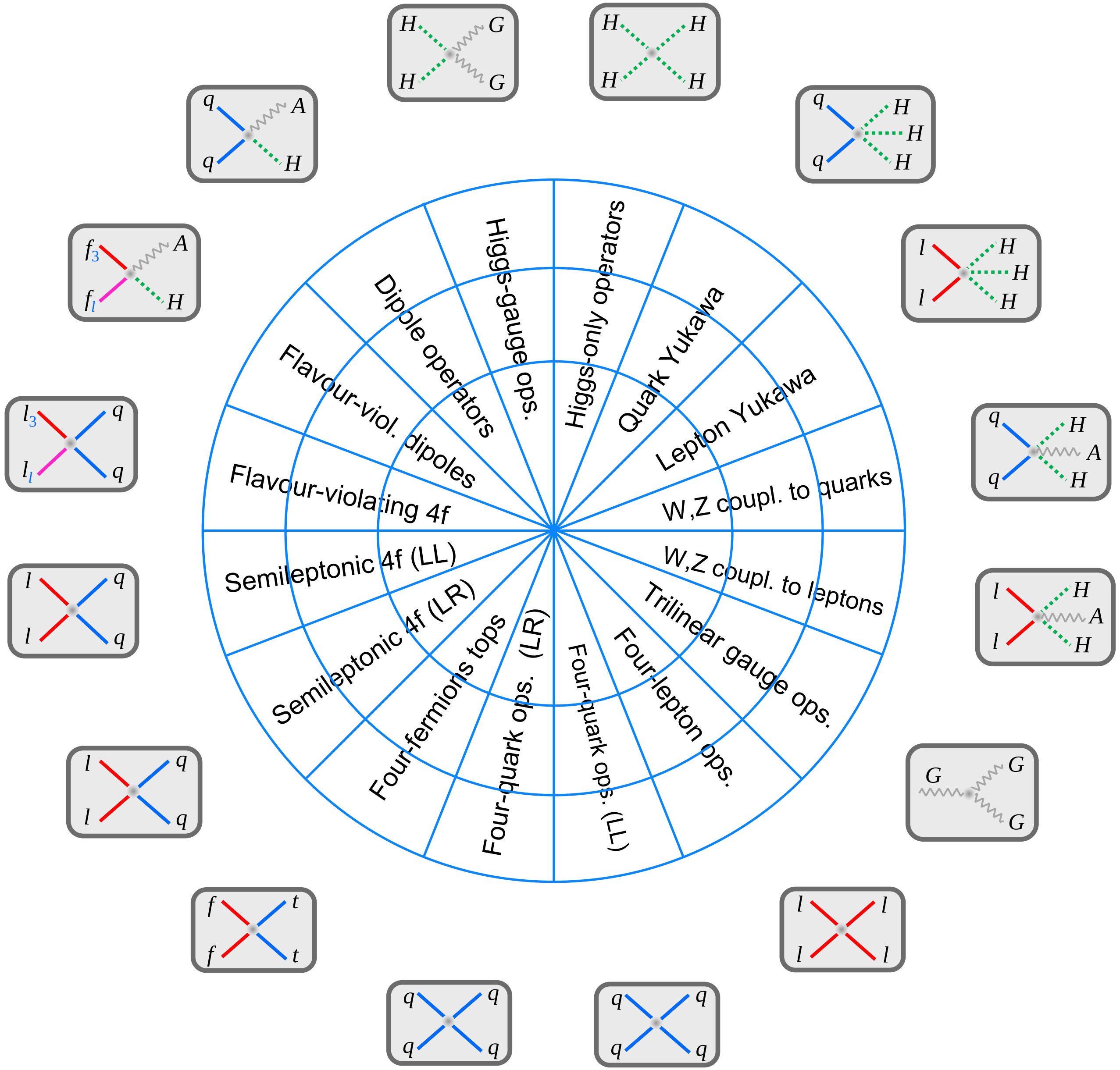




More about future prospects…

- The large number of SMEFT coupl. is not a problem, but an opportunity [*these couplings are <u>not independent</u> model parameters, rather independent <u>observables</u>*]



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High-energy coll.
Top-quark
Higgs
Electroweak
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European Strategy for Particle Physics

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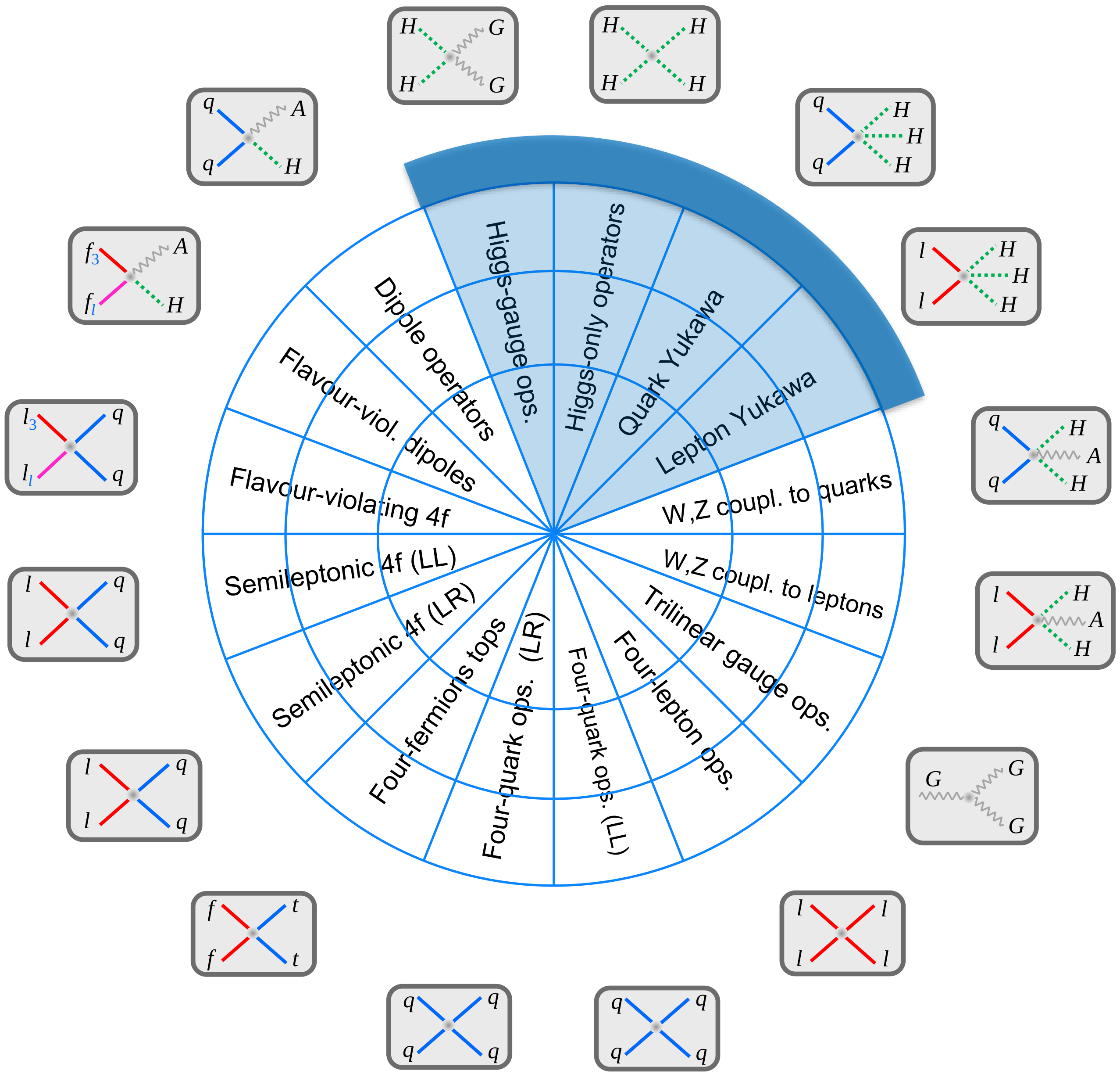

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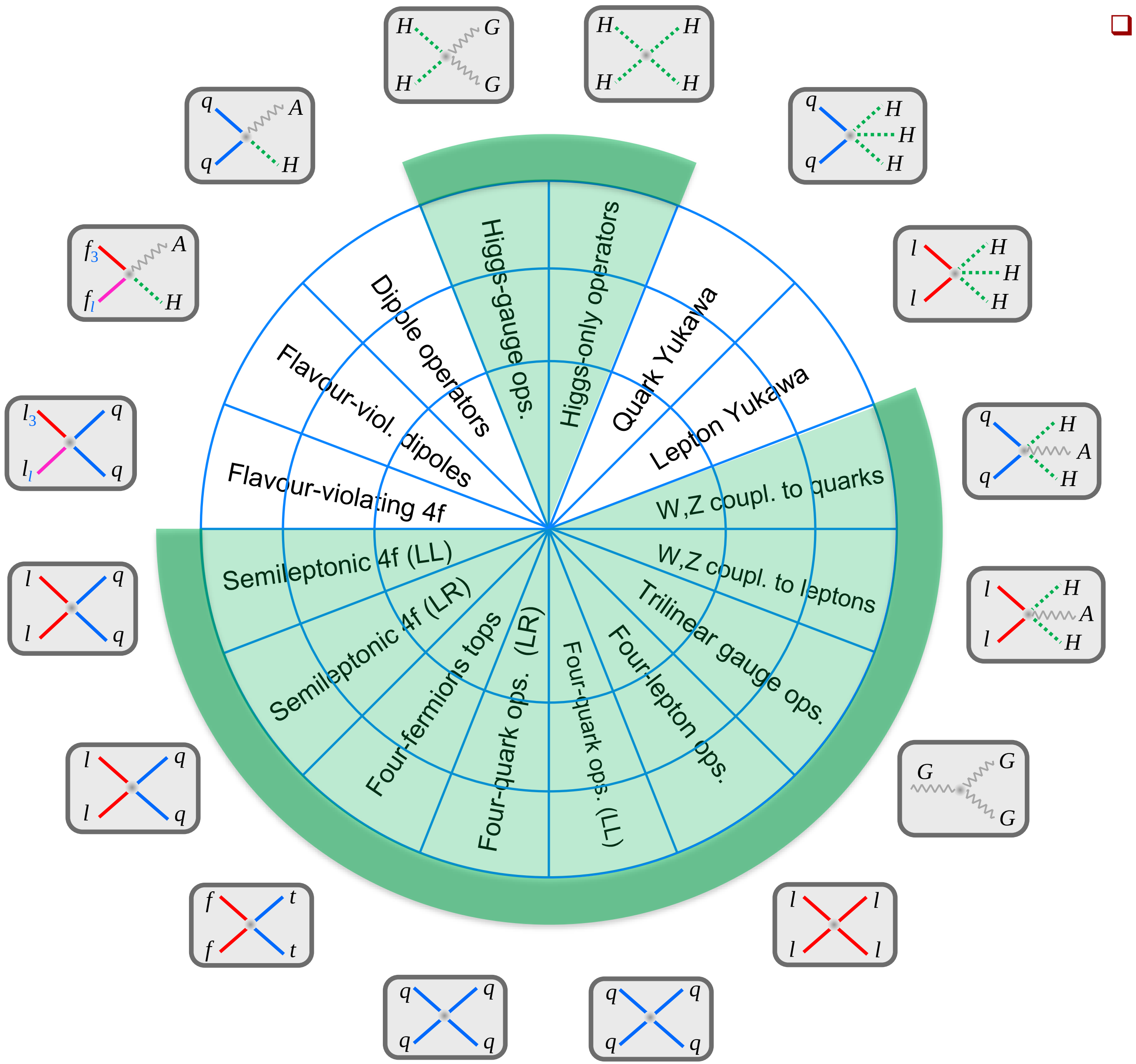

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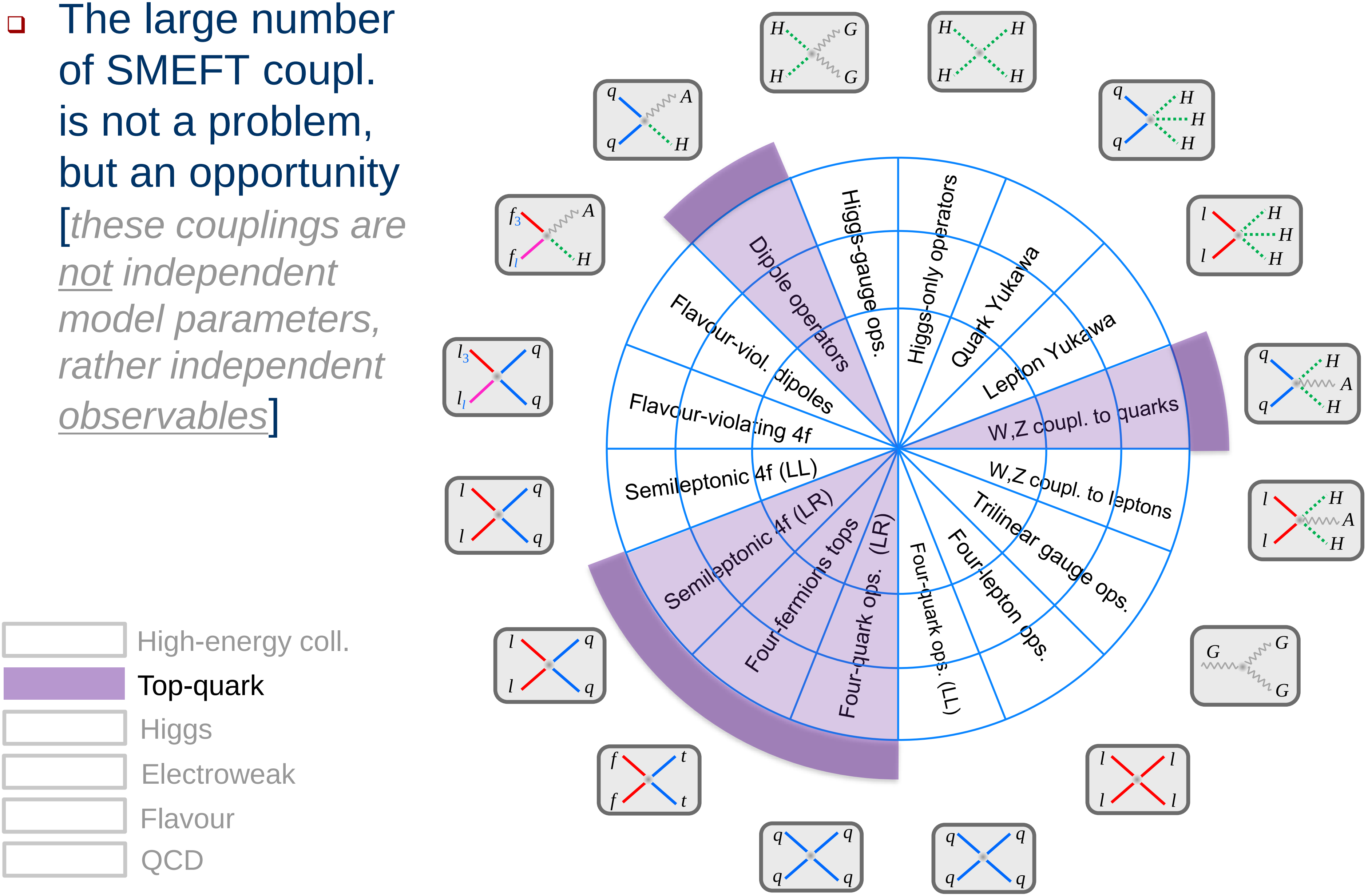

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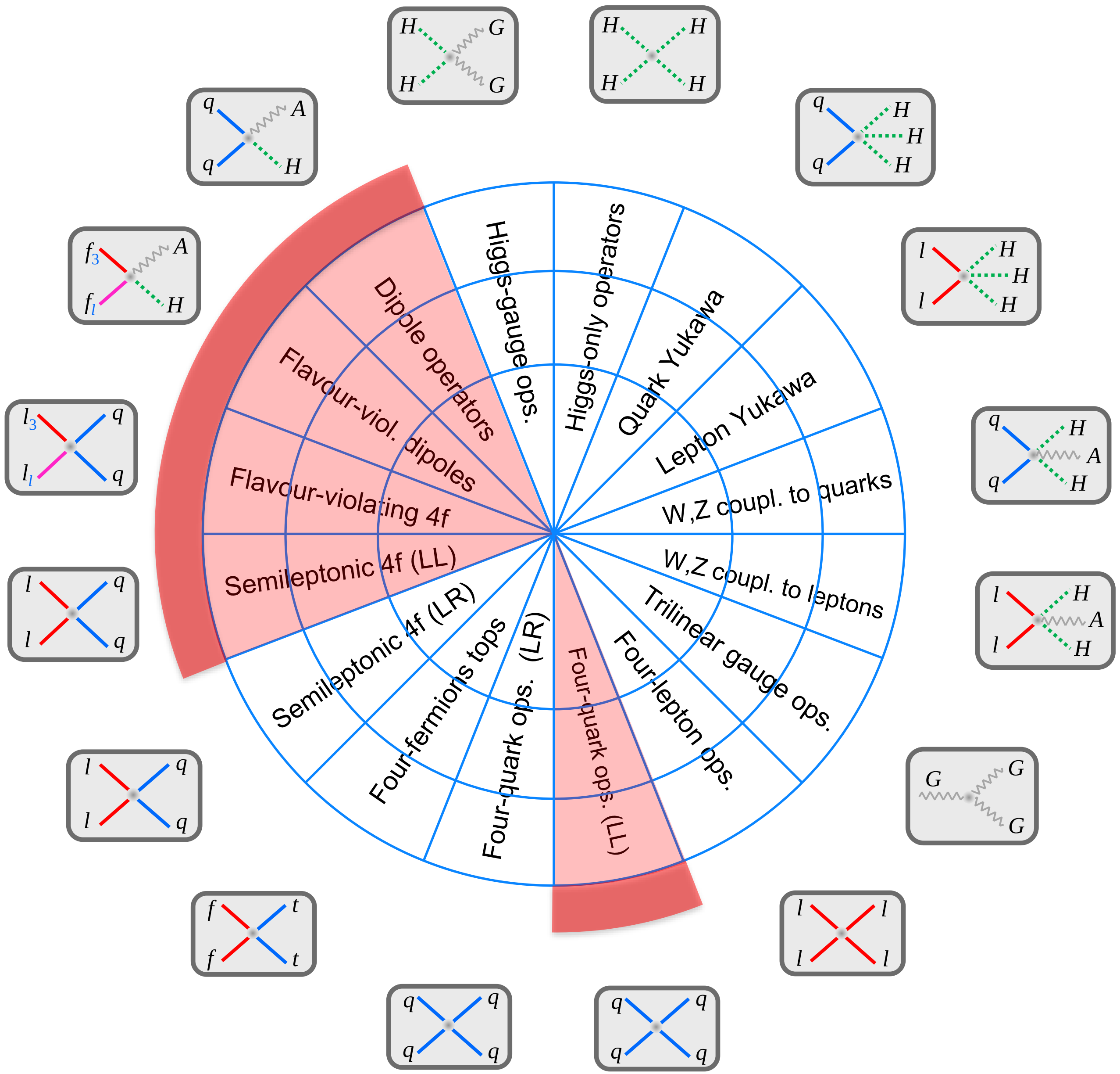

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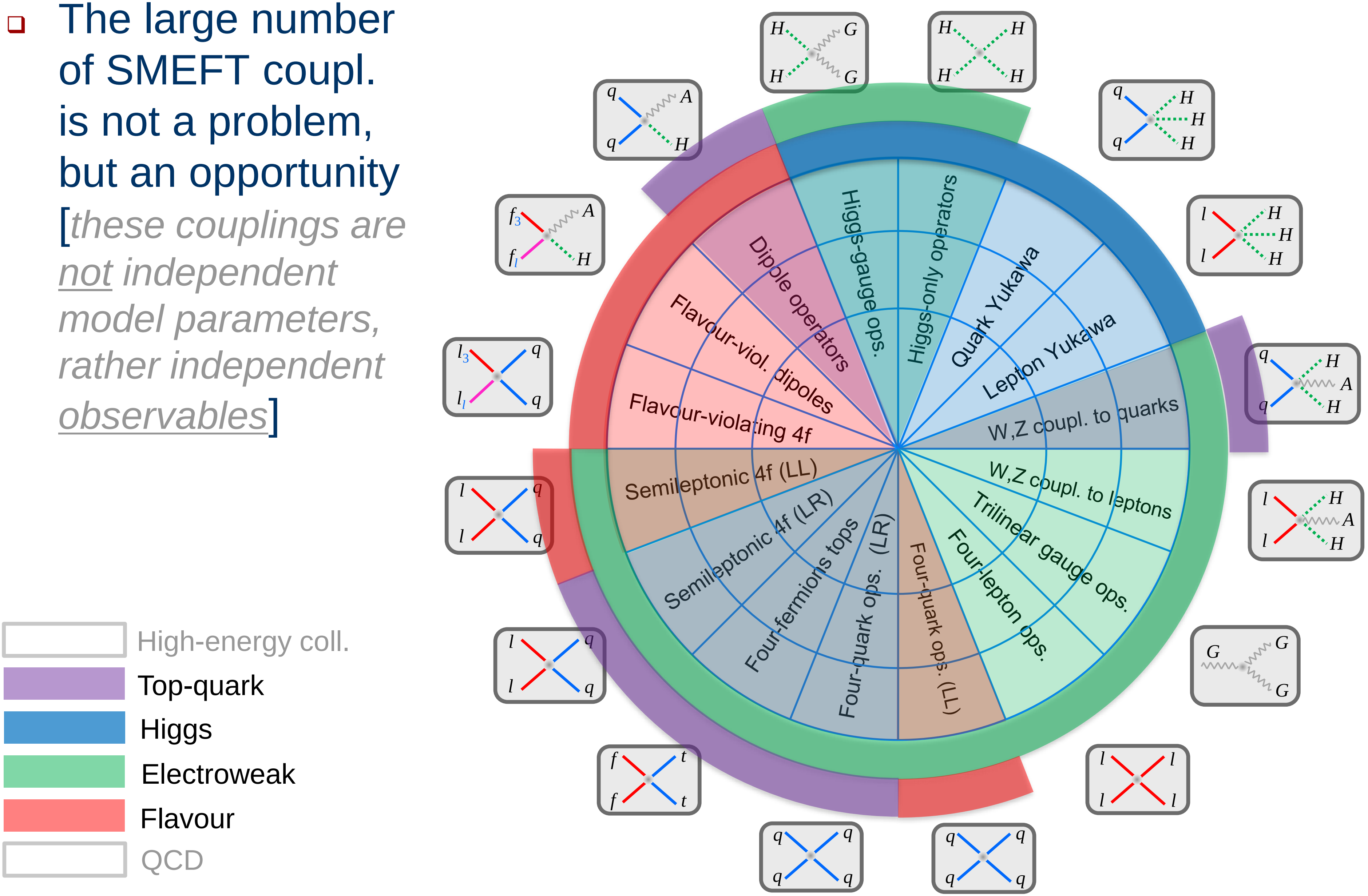

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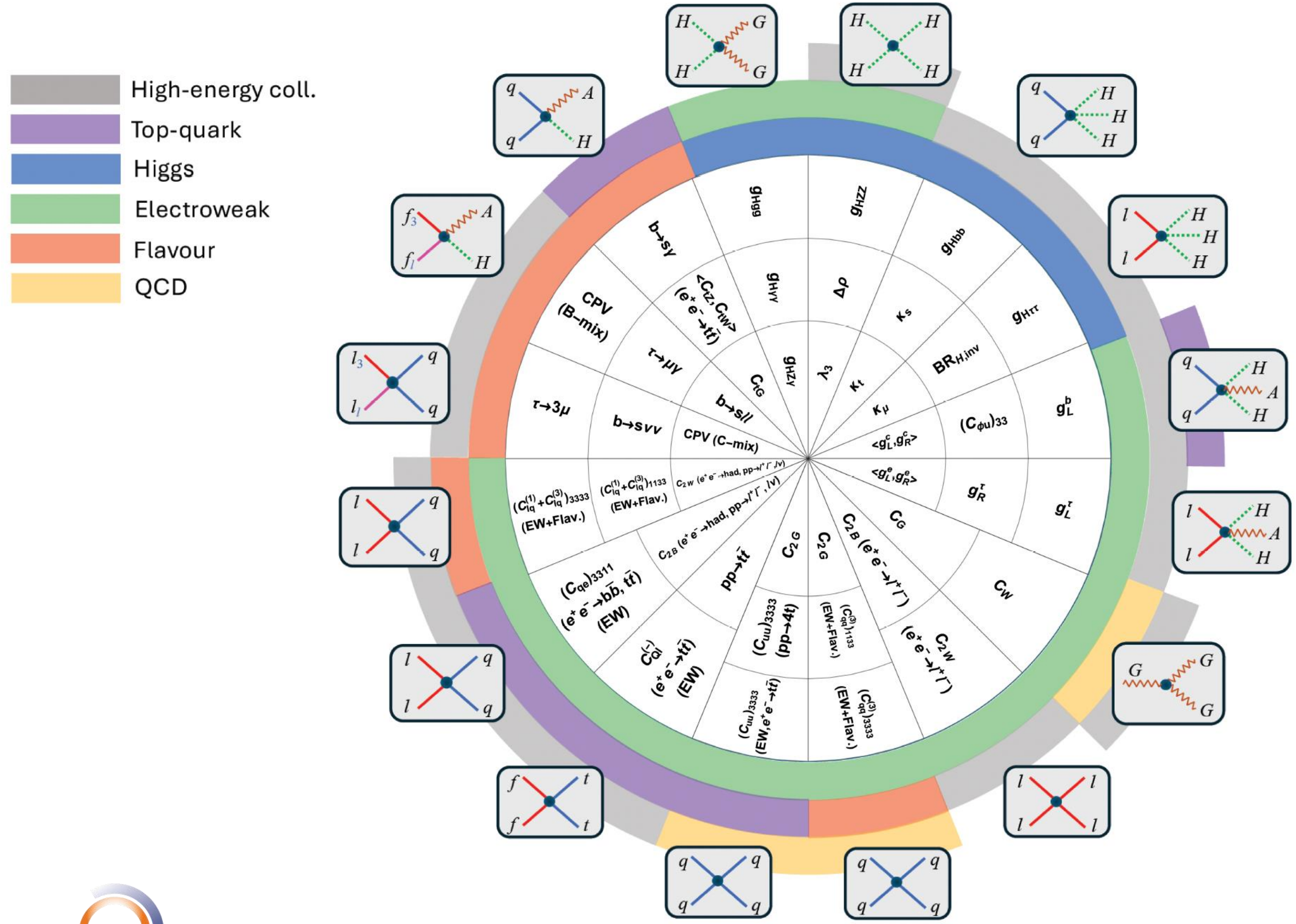
The unique <u>discovery potential</u> of FCC-ee lies in the ability to cover all these sectors with <u>precision</u> & <u>redundancy</u>

More about future prospects…



Quantitative comparison of the potential of future colliders:

- 16 sectors [classes of contact interactions]
- 3 layers of observables in each sector [characterized by growing difficulty, need for high E]

- Improvement factors in log scale [gray scale]:
- HL-LHC defines the initial benchmark
- The best reach of any future collider defines the maximal value

European Strategy for Particle Physics

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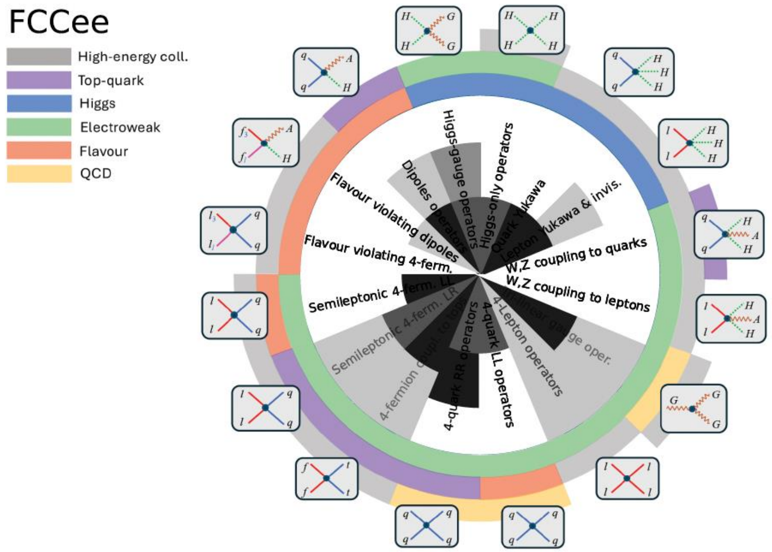

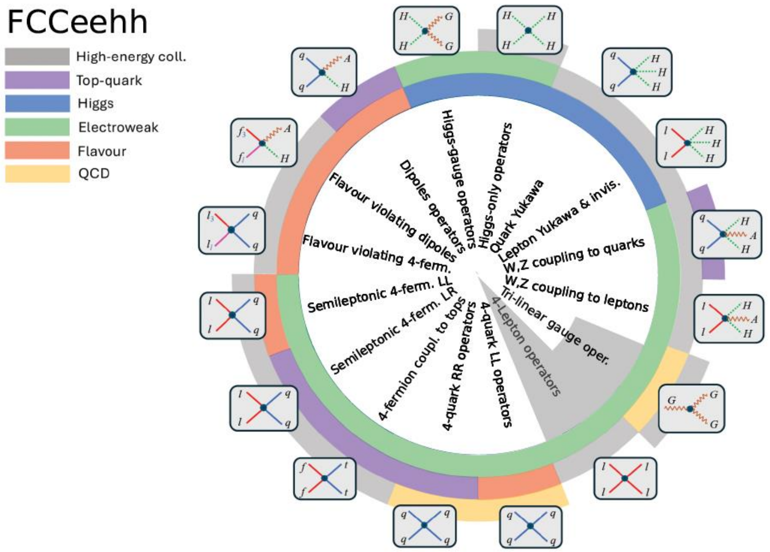

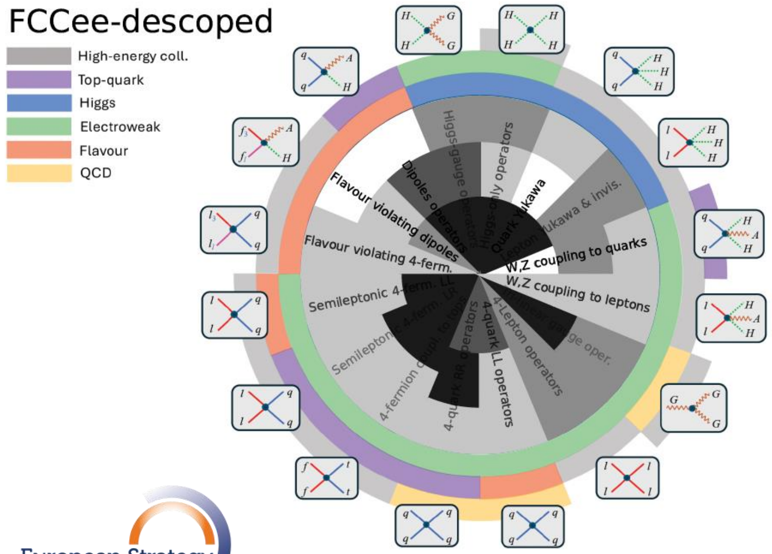

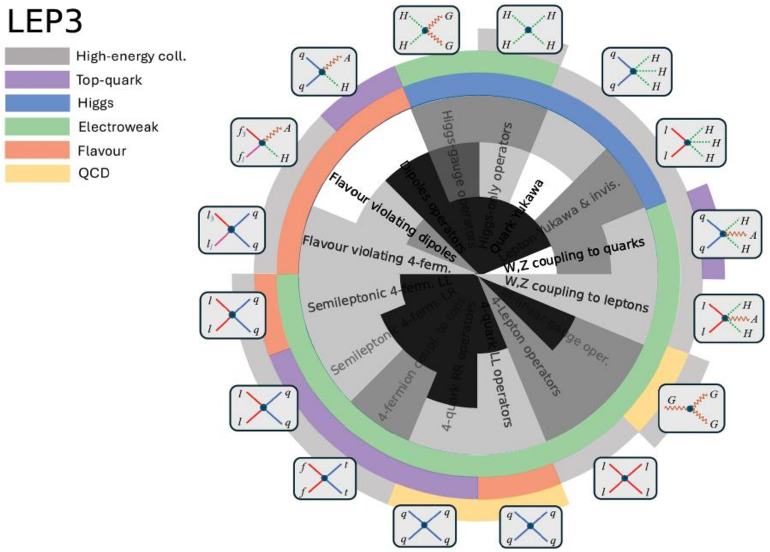

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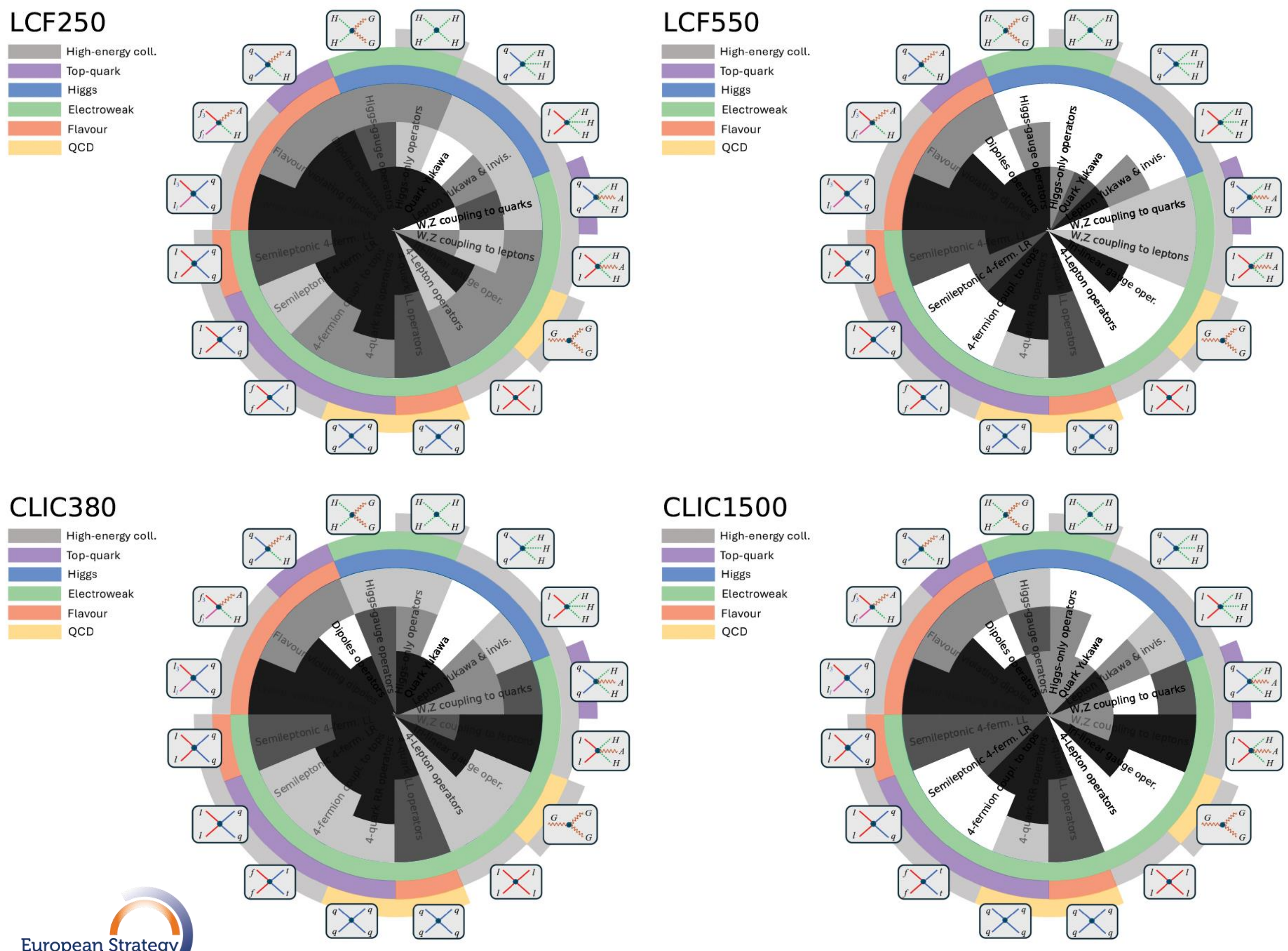

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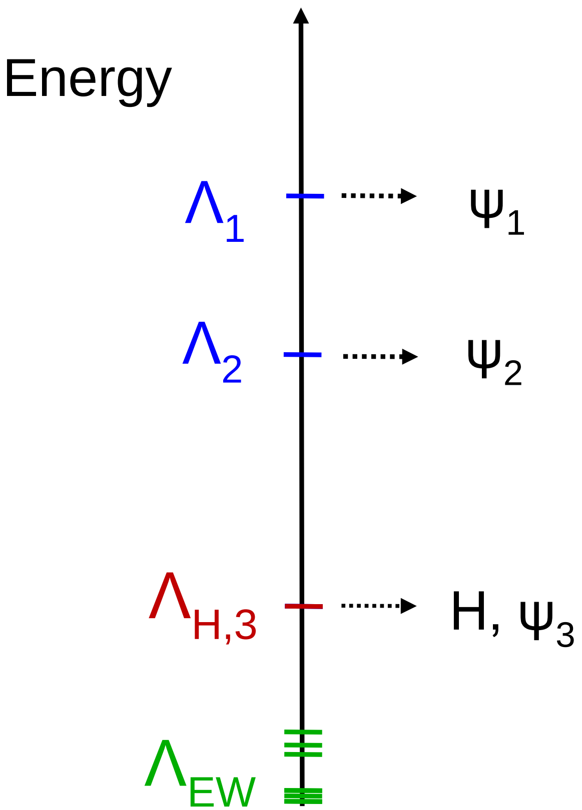
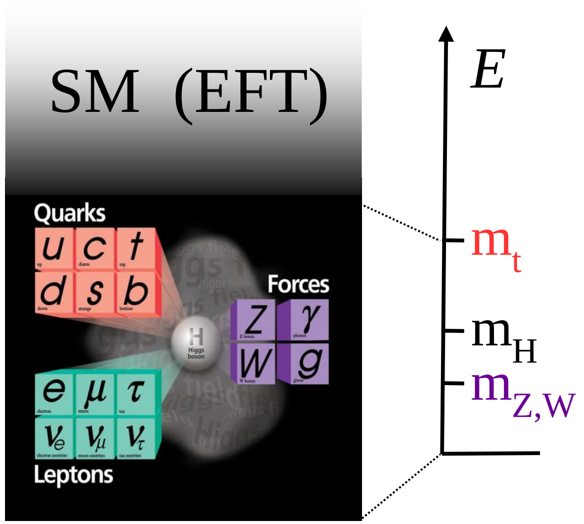
European Strategy for Particle Physics

Discovery reach in “motivated models” of heavy NP



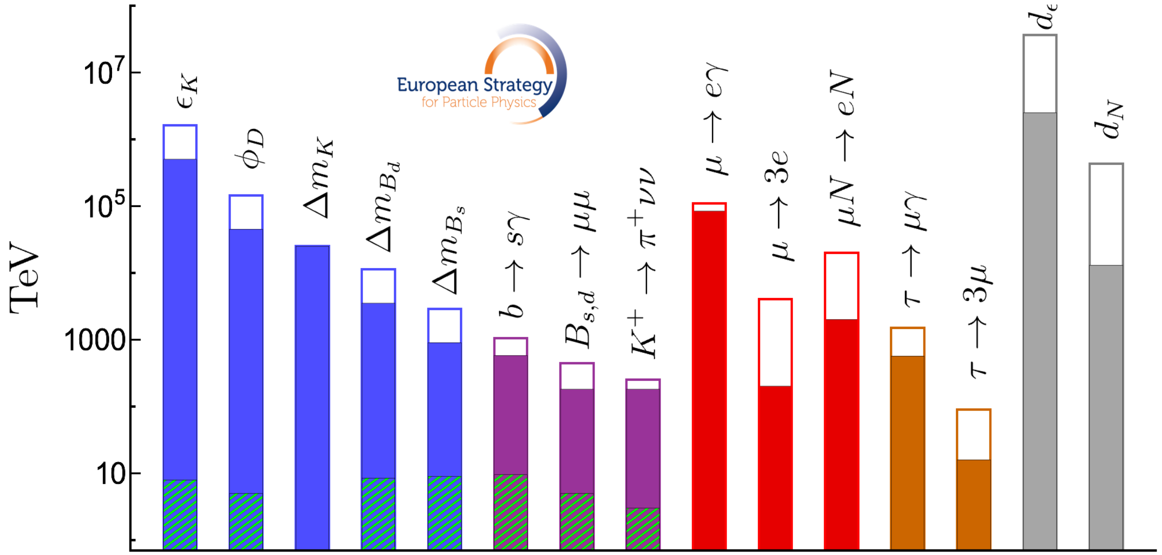
NP reach in "motivated models"

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \boxed{\mathcal{L}_{\text{Higgs}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\phi, A_a, \psi_i)}$$

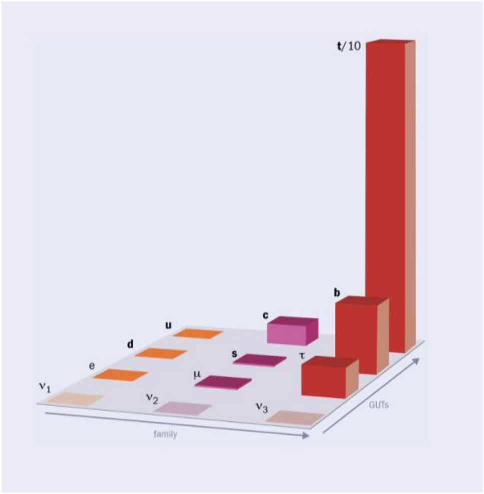


What do we know so far about the SMEFT and its cut-off?

- Hierarchy problem $\rightarrow$ $\Lambda \sim 1$ TeV [*at least for Higgs & top*]
- EWPO $\rightarrow$ $\Lambda > 1$ TeV - 10 TeV
- Flavour-violating [d=6]:



- Flavour-violating [d=4]:

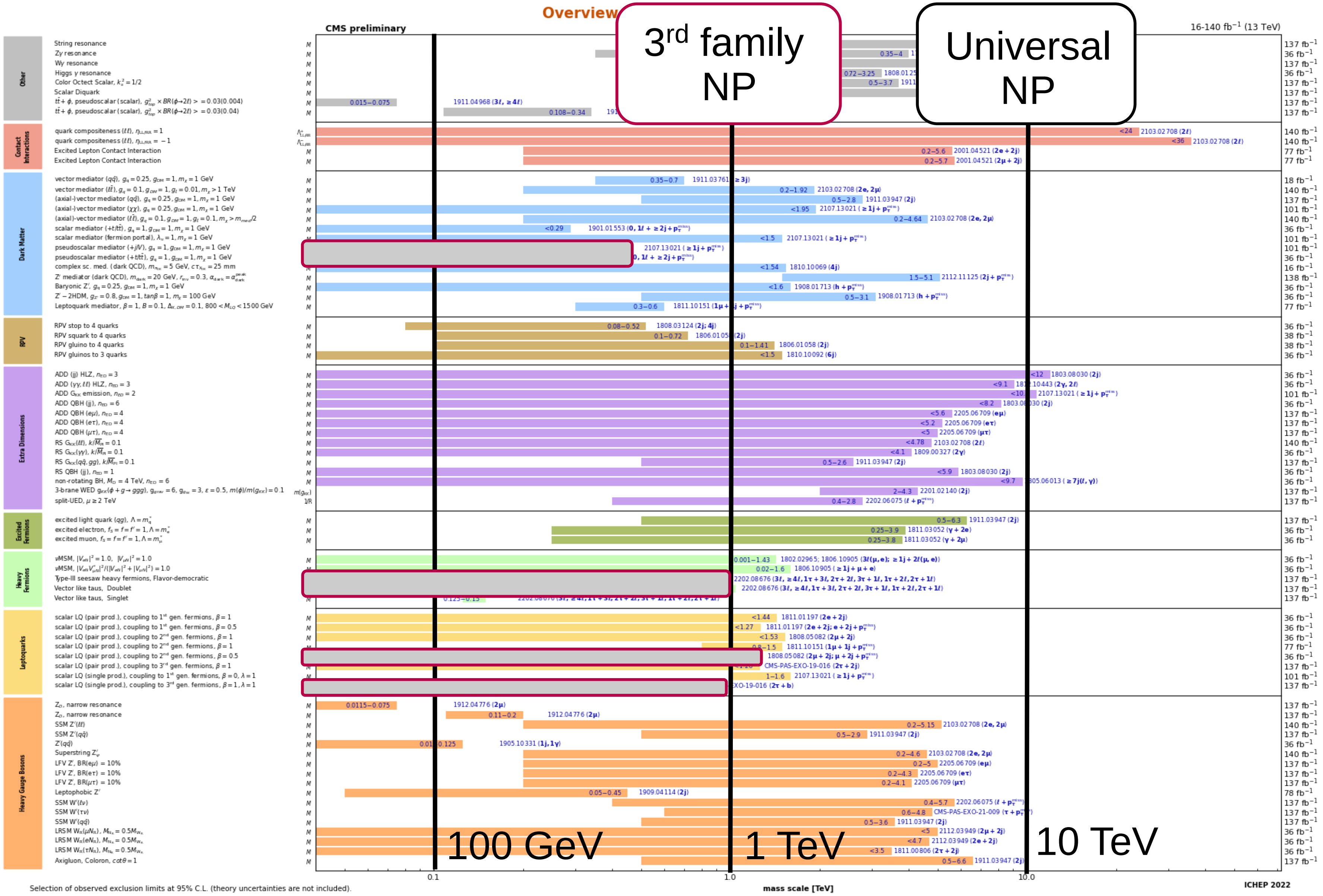


highly non-trivial flavour structure

NP reach in “motivated models”

- High-energy searches:

- Also in this case flavour hypotheses play an important role…



NP reach in "motivated models"

- If New Physics is there to solve the shortcomings of the Higgs sector, it is natural to assume that it couples in a flavor non-universal manner, mainly to the third generation
  - The Yukawa couplings are strongly hierarchal
  - The electroweak hierarchy problem and the Higgs instability problem are both related to the large top-quark Yukawa coupling (*light quarks play no role…)*

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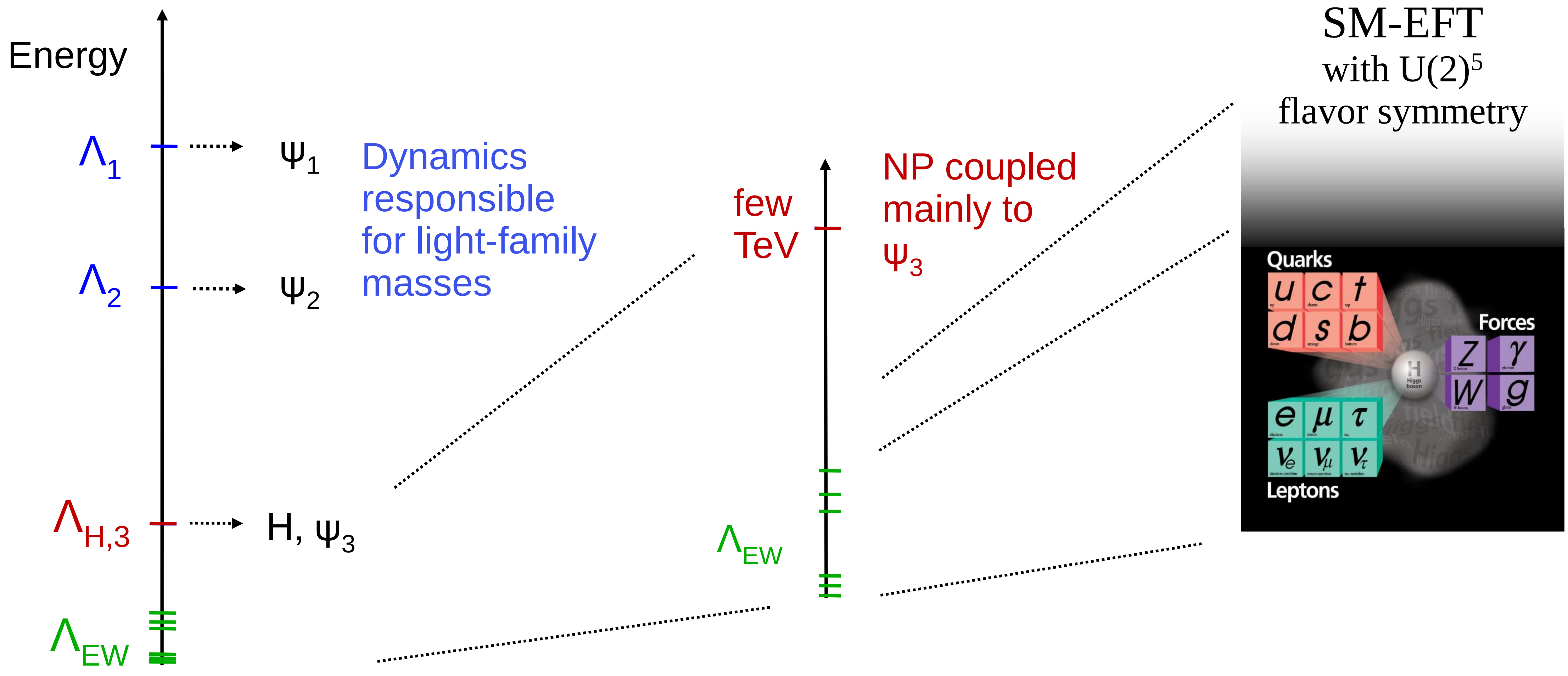
$$\mathcal{L}_{\rm Higgs} = D\phi^+ D\phi - [\, -\mu^2\, \phi^+\phi + \lambda\, (\phi^+\phi)^2 + Y^{ij}\, \psi_L{}^i\, \psi_R{}^j\, \phi \,]$$

$$Y_U \sim \begin{array}{c} \overbrace{\hphantom{<0.01\quad}}^{U(2)_u} \\ \left(\begin{array}{cc|c} \multicolumn{2}{c|}{<0.01} & 0.003 \\ & & 0.04 \\ \hline & & 1 \end{array}\right) \end{array} \; U(2)_q$$

NP reach in “motivated models”

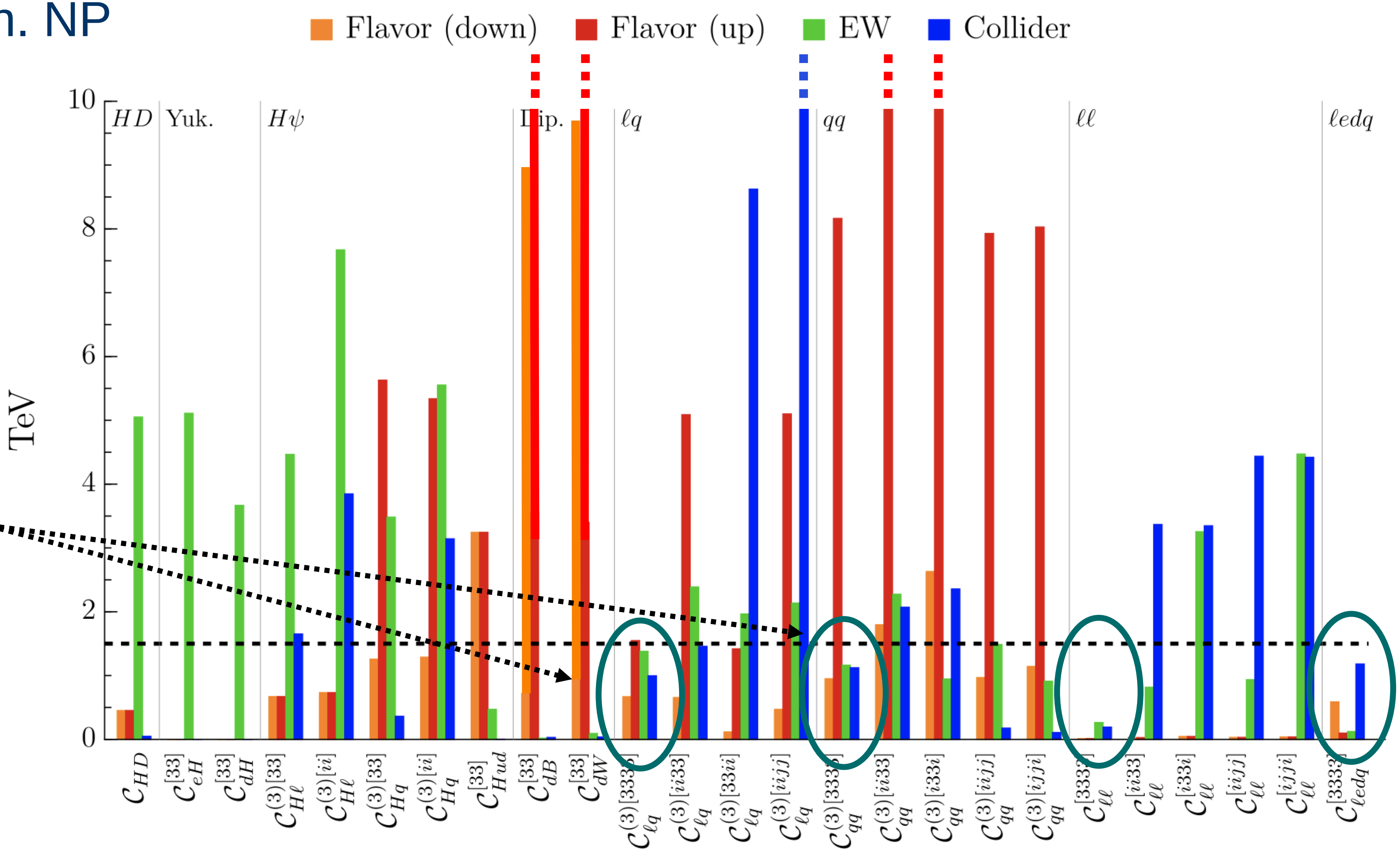
- A possible multi-scale completion of the SM:



NP reach in “motivated models”

- SMEFT for 3rd gen. NP
  - Assume NP couples differently to the 3rd family and universally 1st & 2nd [120 ops.]

Operators involving only 3rd family fields → collider bounds below 1.5 TeV

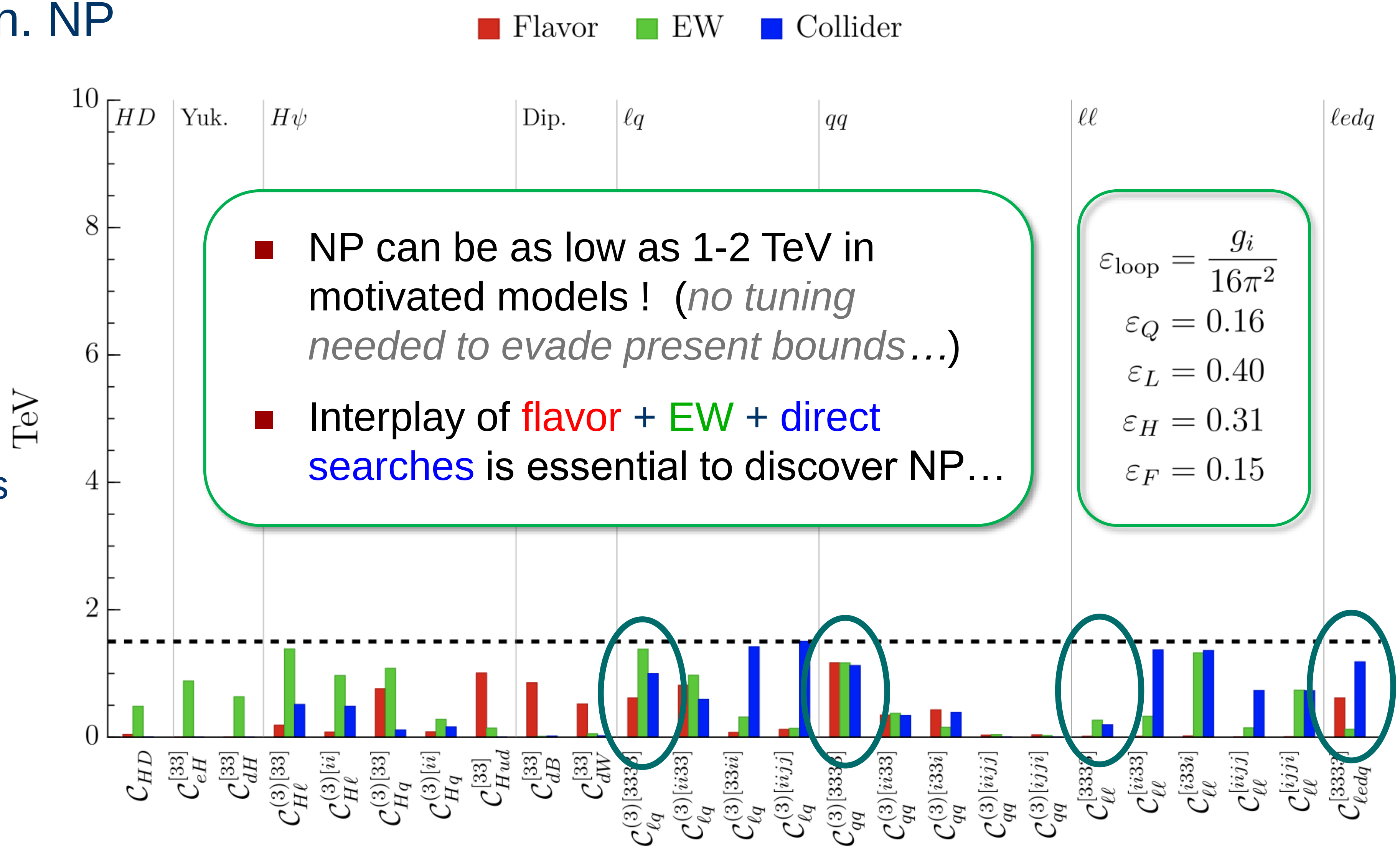


Allwicher, Cornella, GI, Stefanek ‘24

NP reach in “motivated models”

- SMEFT for 3rd gen. NP
  - Assume NP couples differently to the 3rd family and universally 1st & 2nd [120 ops.]
  - Modified bounds implementing the dynamical hypothesis of NP coupled manly to the 3rd generation [*mild suppression factors for light families*]

Allwicher, Cornella, GI, Stefanek ‘24



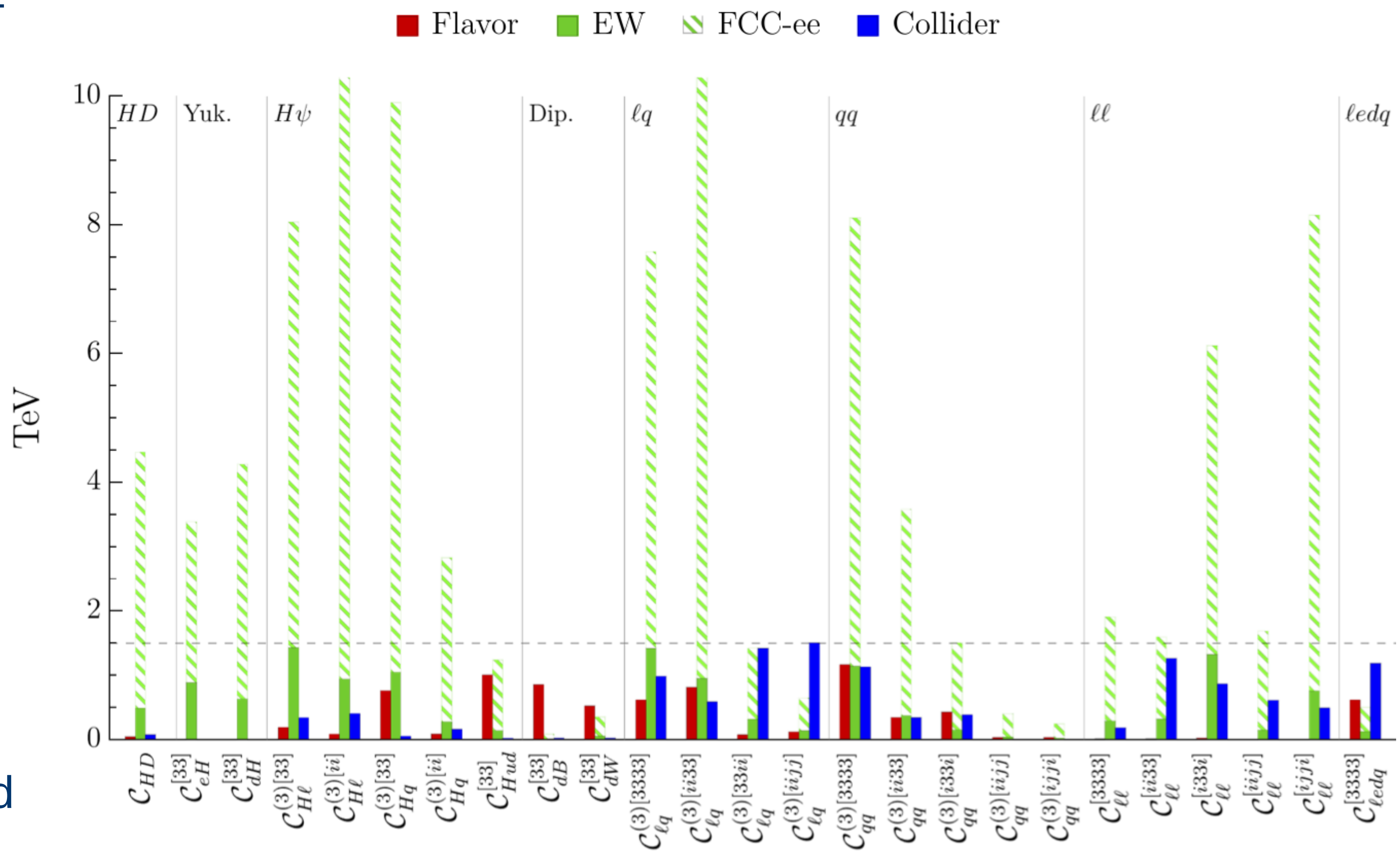
- NP can be as low as 1-2 TeV in motivated models ! (*no tuning needed to evade present bounds…*)
- Interplay of flavor + EW + direct searches is essential to discover NP…

$$\varepsilon_{\rm loop} = \frac{g_i}{16\pi^2}$$
$$\varepsilon_Q = 0.16$$
$$\varepsilon_L = 0.40$$
$$\varepsilon_H = 0.31$$
$$\varepsilon_F = 0.15$$

NP reach in "motivated models"

- Potential reach of FCC-ee from EW and Higgs measurements

The natural range for Λ dictated by the hierarchy problem (i.e. few TeV) would be completely covered

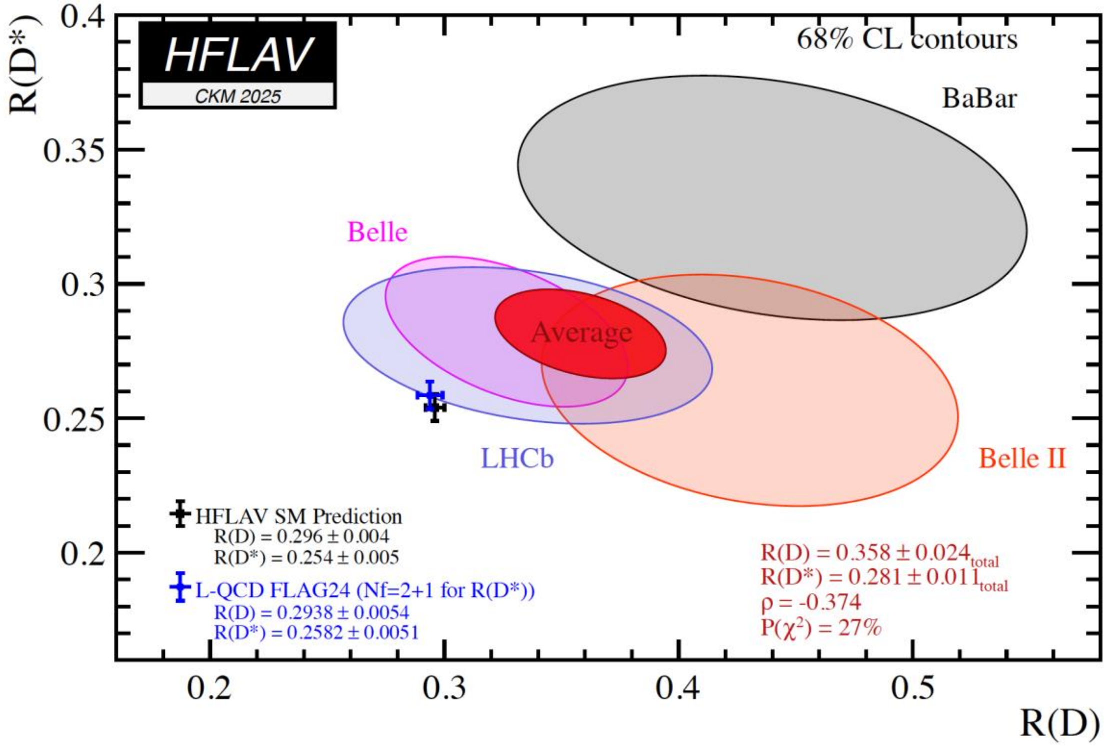


Examples of interplay in indirect NP searches

Looking at bounds from individual observables misses one of the key the main point of indirect NP searches: the interplay of a large number of observables in “decoding” the underlying theory

To illustrate this point, we need to consider an explicit example assuming a NP signal

$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\mu\nu)}$$



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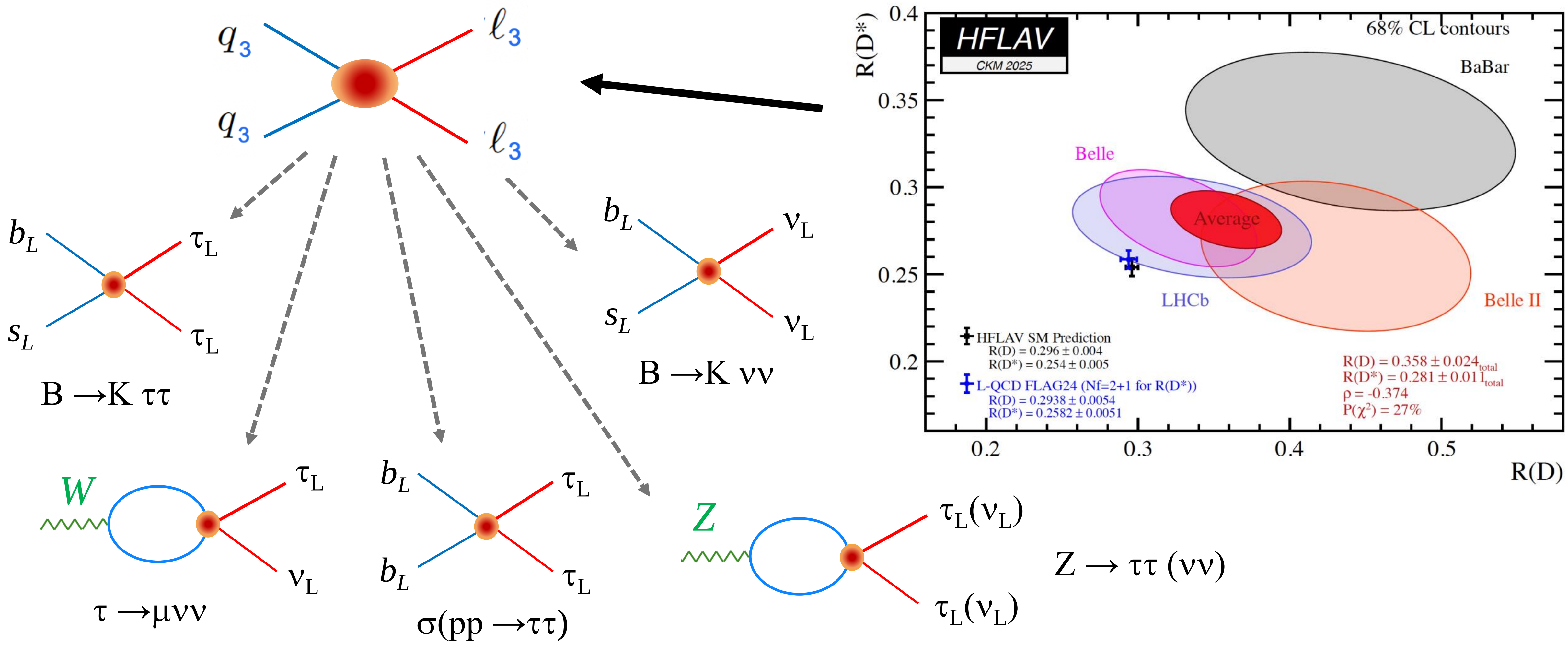

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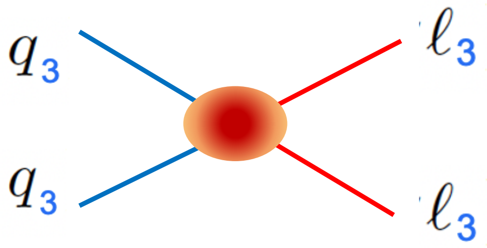
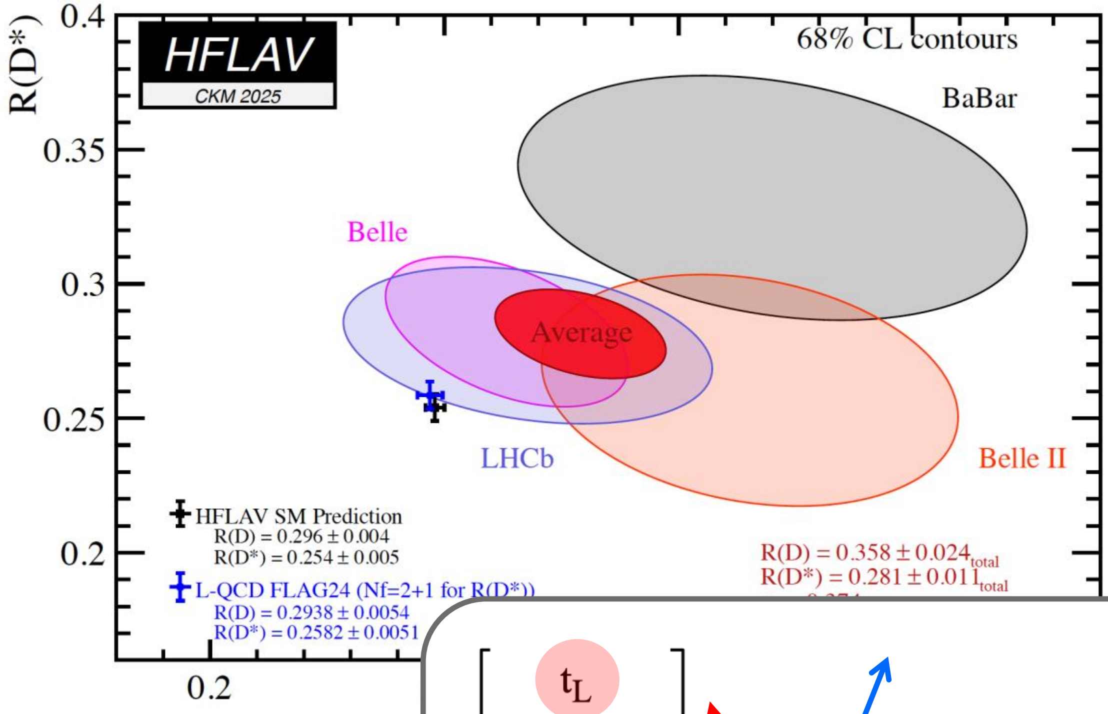
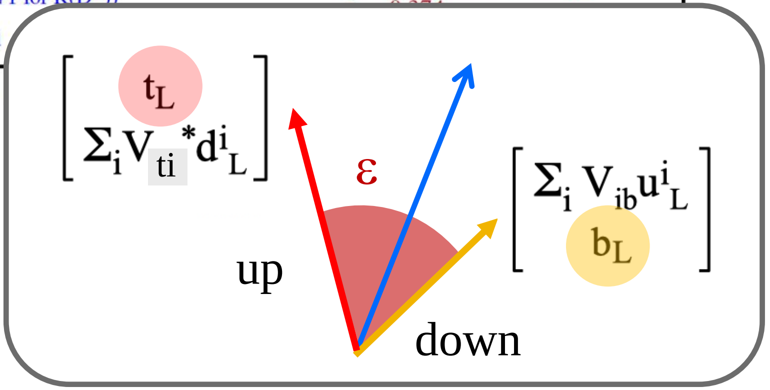


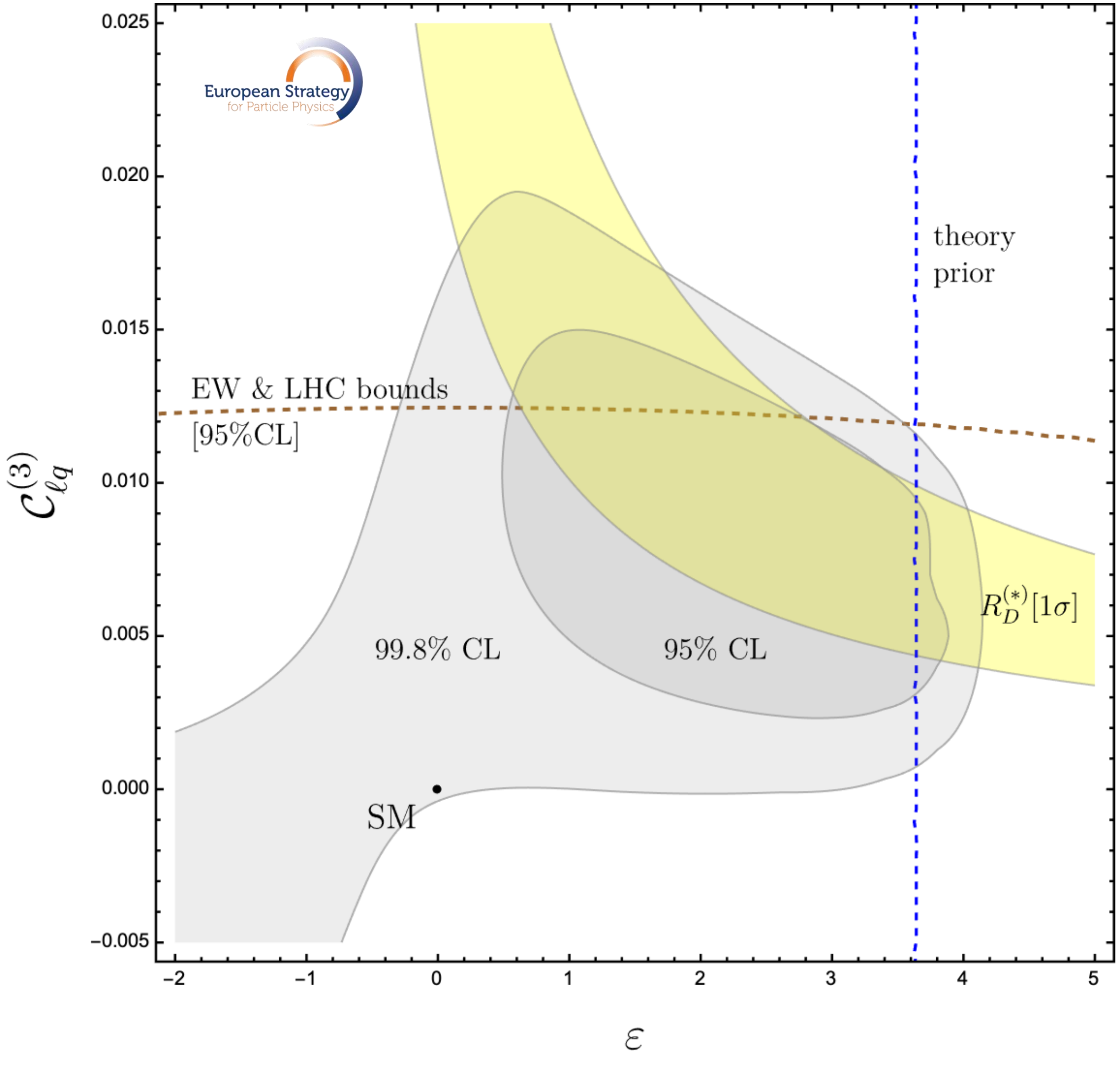


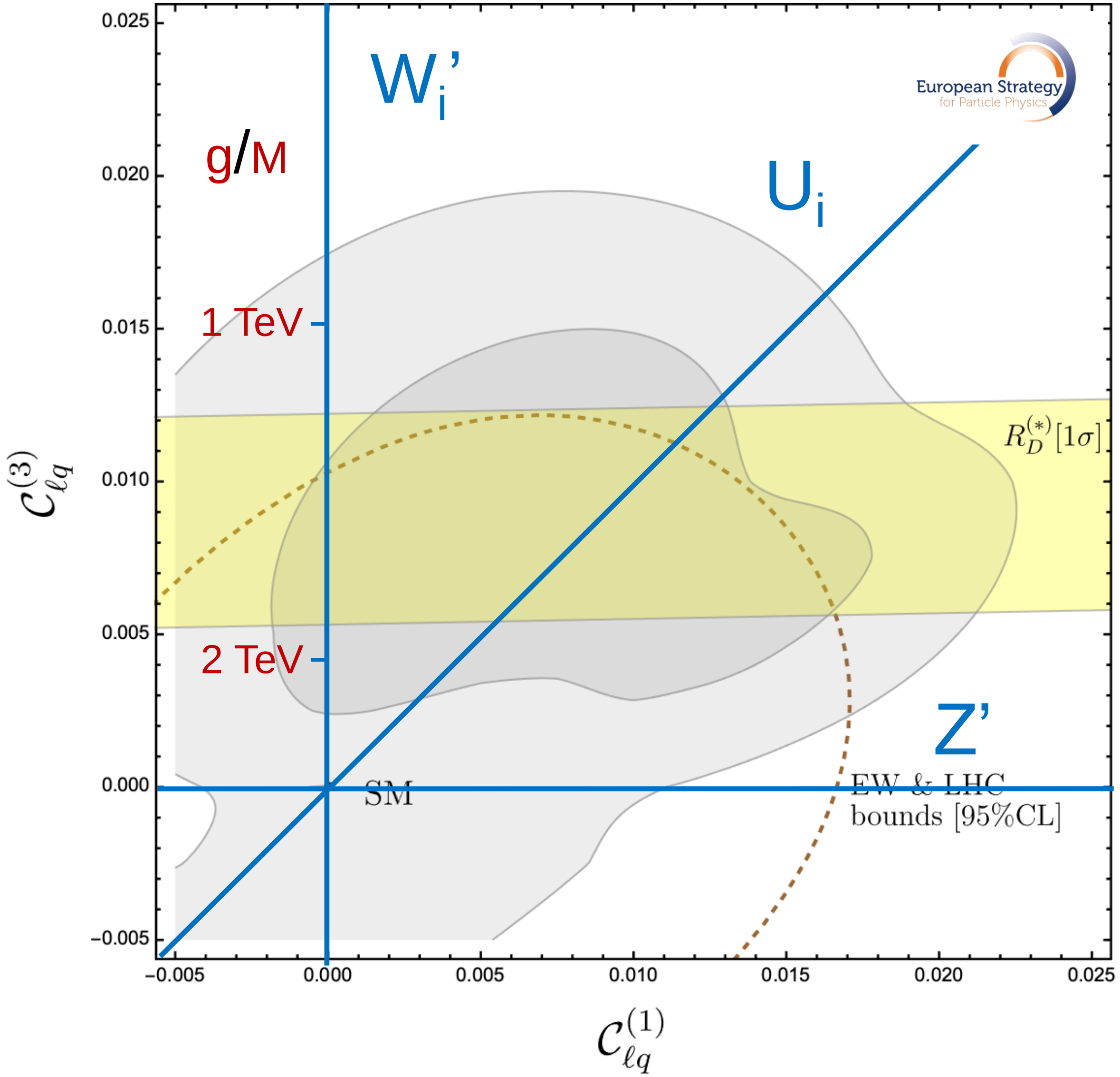


A simple, consistent, description of the system involves (*at least*) 3 parameters:

- 2 Wilson coefficients $\mathcal{C}_{\ell q}^{(1)}$ $\mathcal{C}_{\ell q}^{(3)}$
- 1 flavour-mixing parameter, $\varepsilon = O(1)$: $q_3 = b_L + \varepsilon\, |V_{ts}|\, s_L$

Examples of interplay in indirect NP searches





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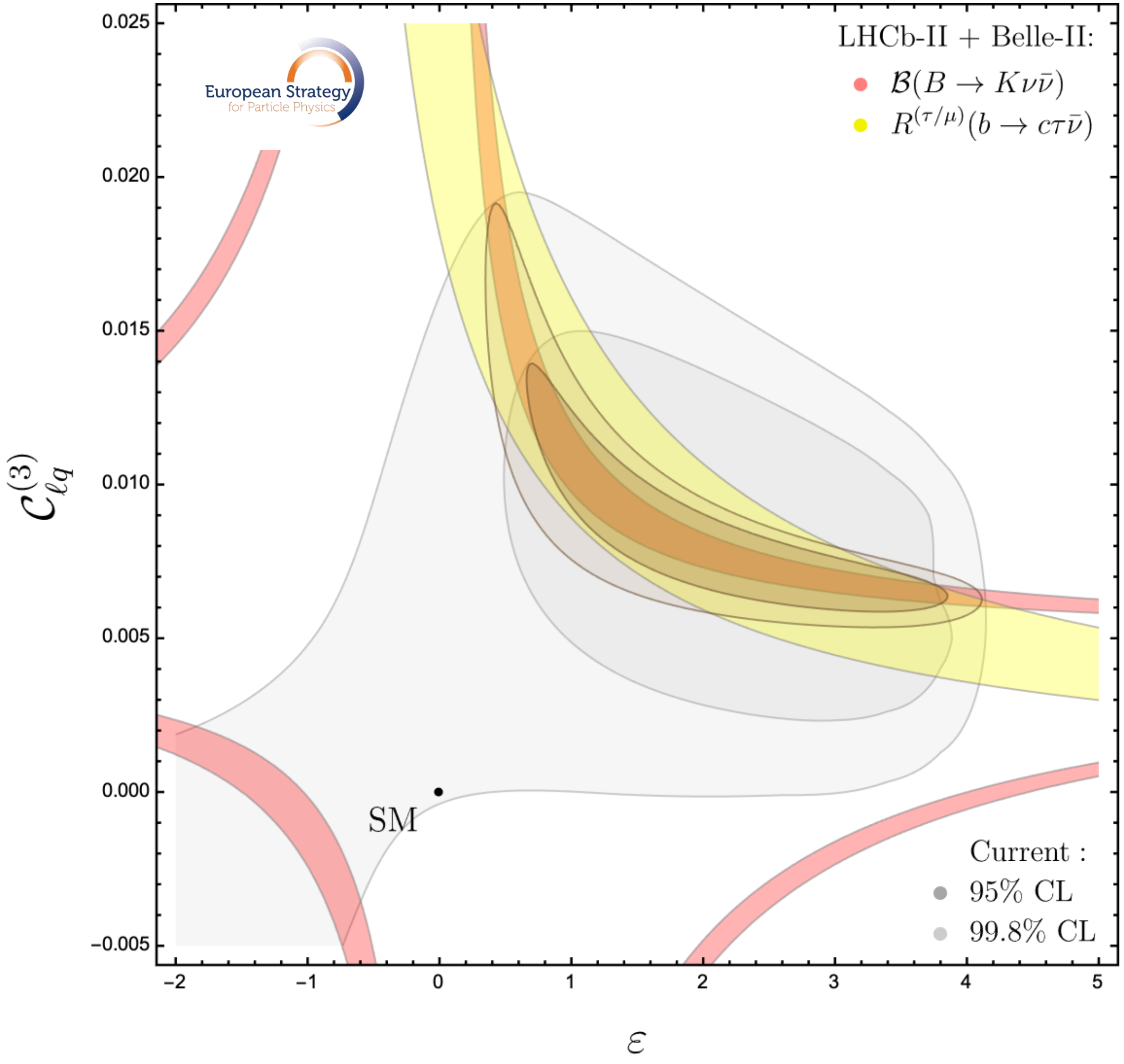

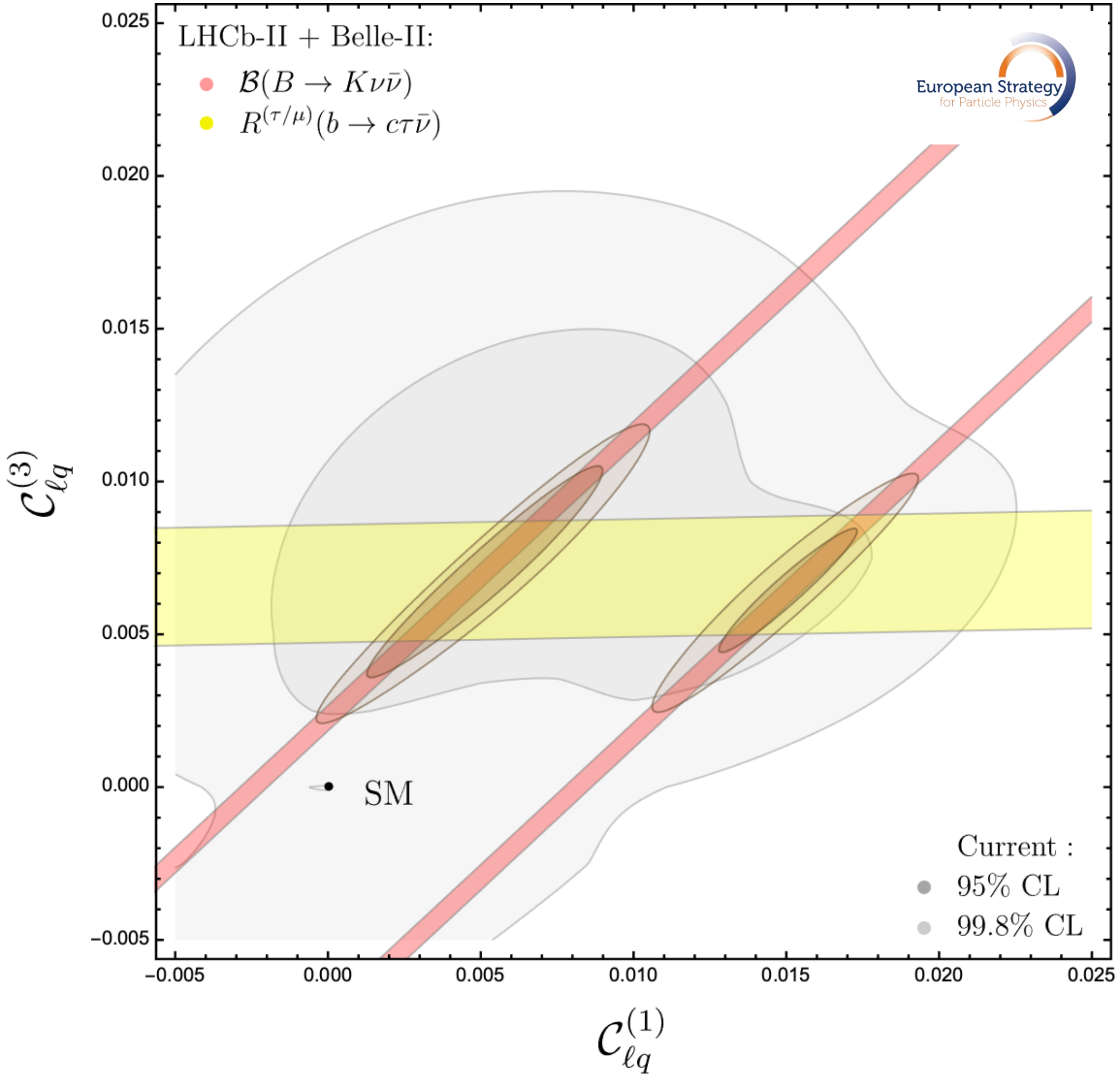

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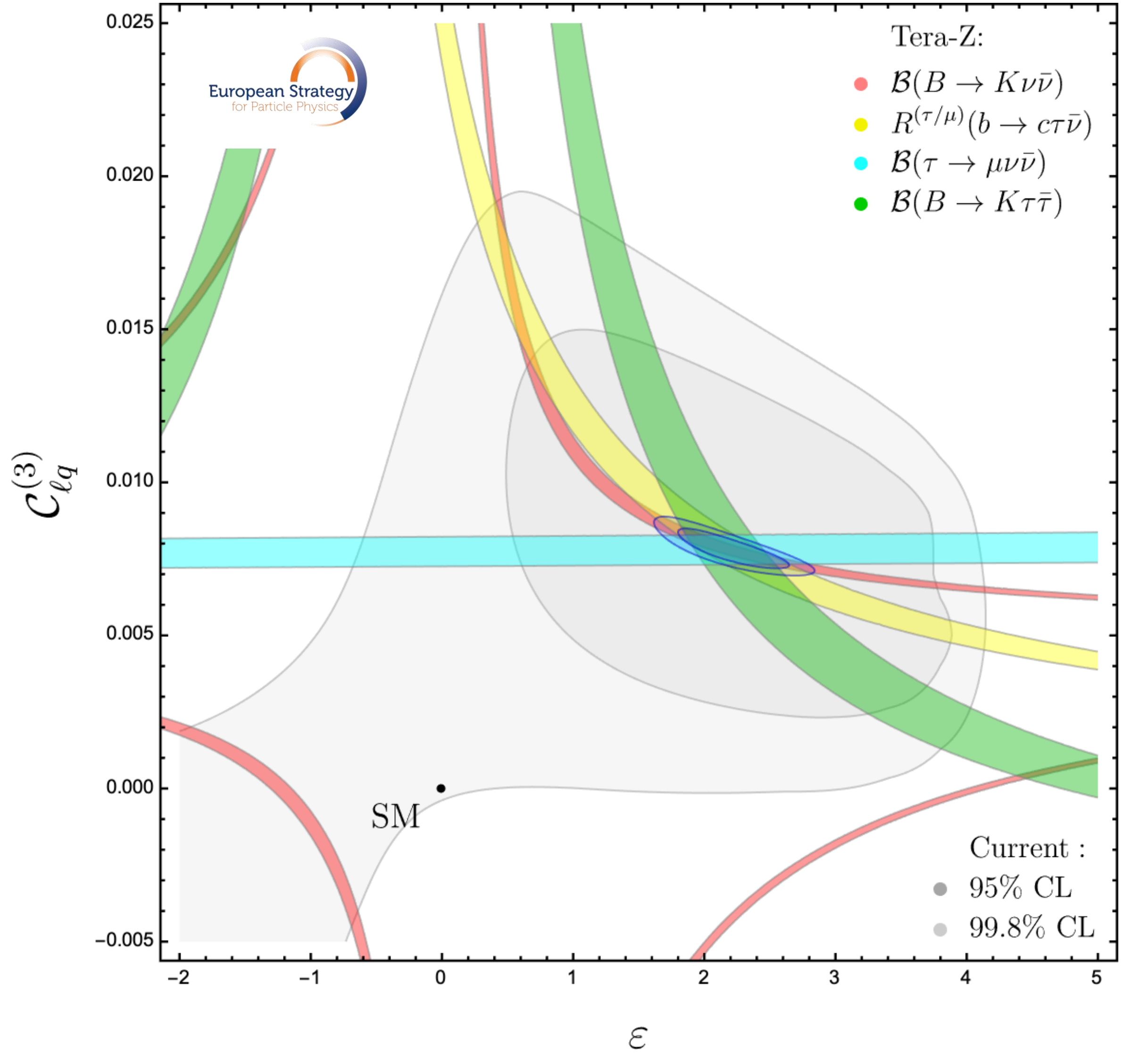
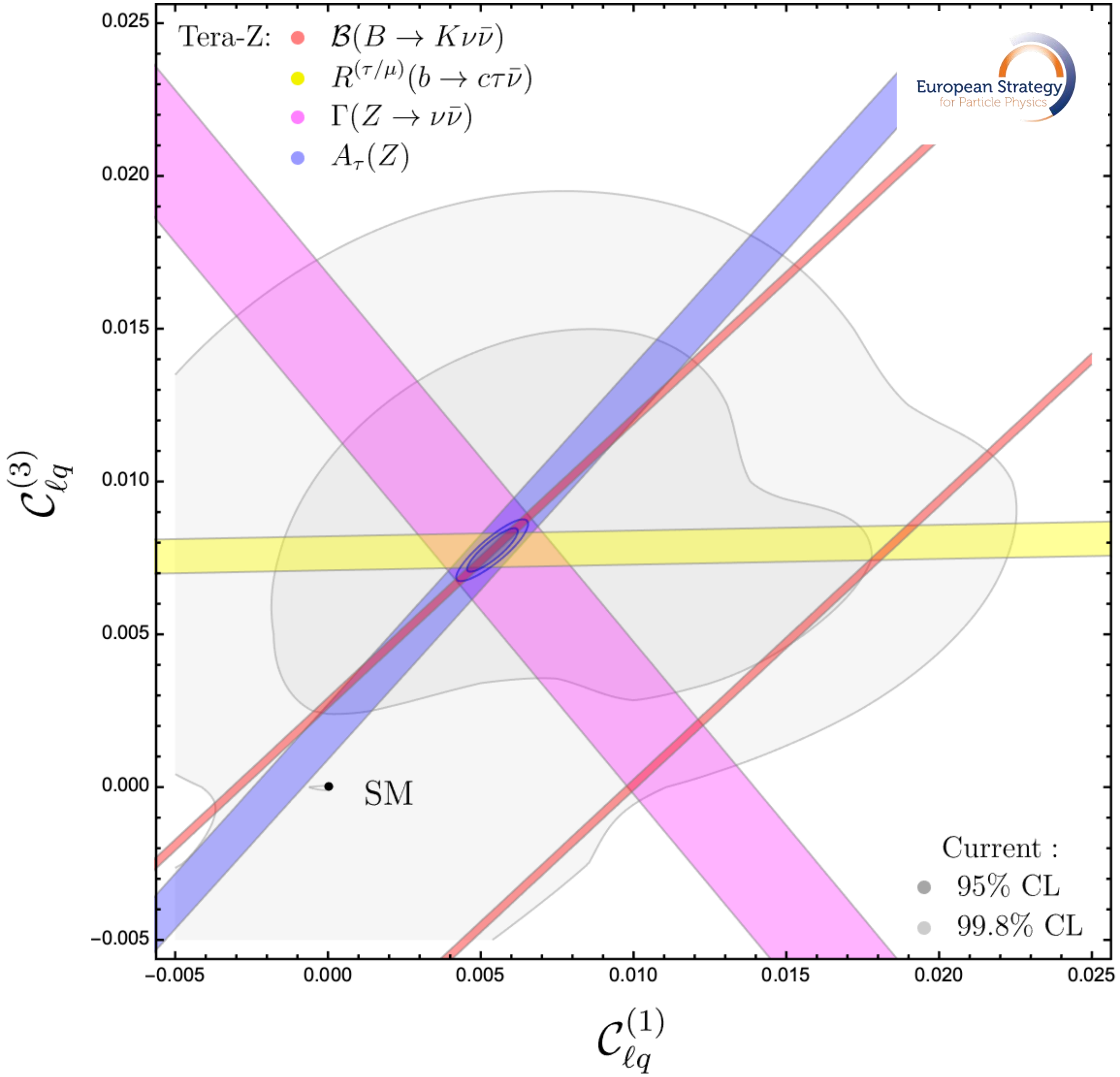
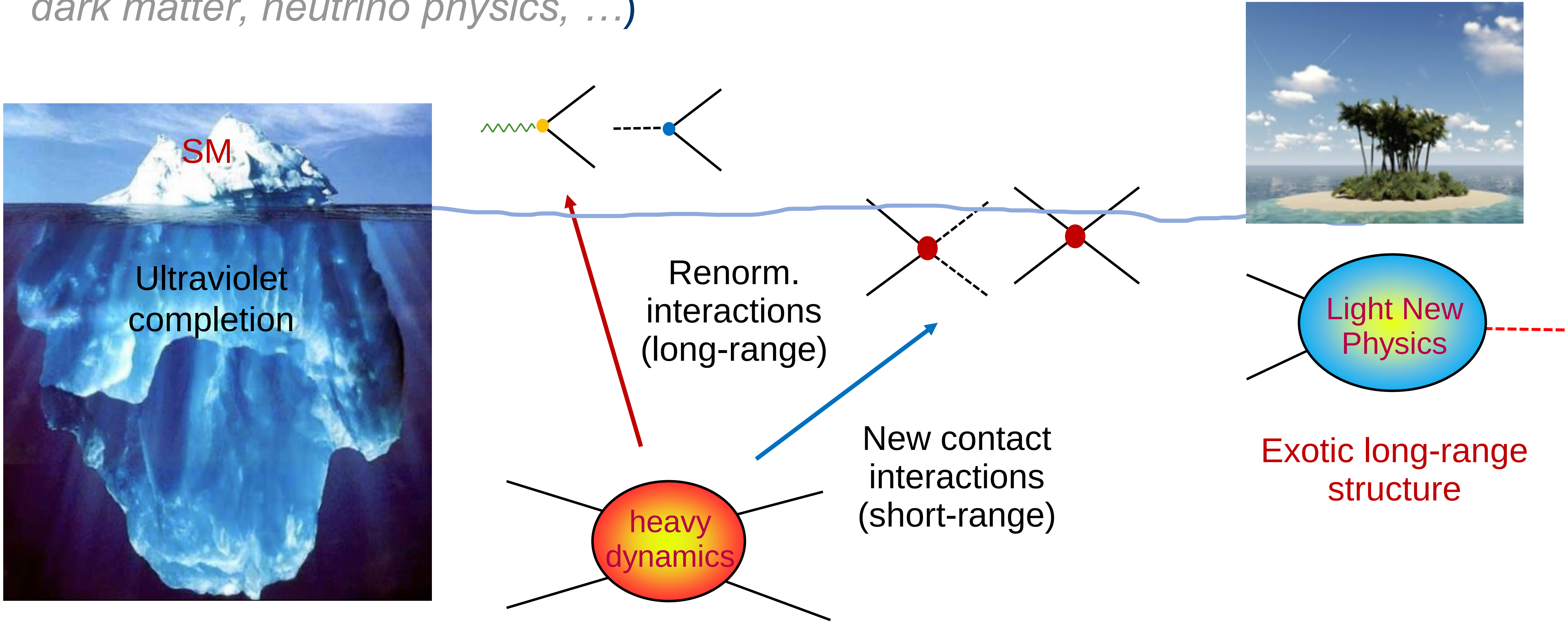




Last but not least…[beyond indirect searches]

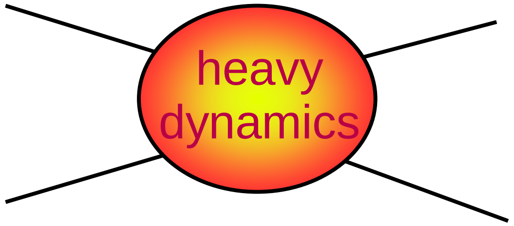
- While heavy NP leads to contact interactions among SM fields, other classes of NP could lead to to new light states with tiny interactions to the SM fields (*motivated by dark matter, neutrino physics, …*)

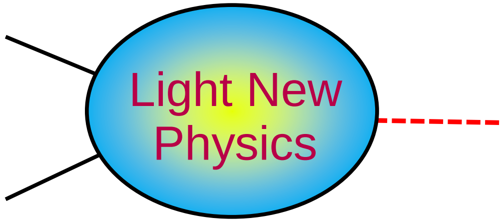


Last but not least…[beyond indirect searches]

- While heavy NP leads to contact interactions among SM fields, other classes of NP could lead to to new light states with tiny interactions to the SM fields (*motivated by dark matter, neutrino physics, …*)
- The smallness of such interactions (forced by data) naturally leads to consider the so-called portals [= lowest-dim. operators involving the exotic fields]

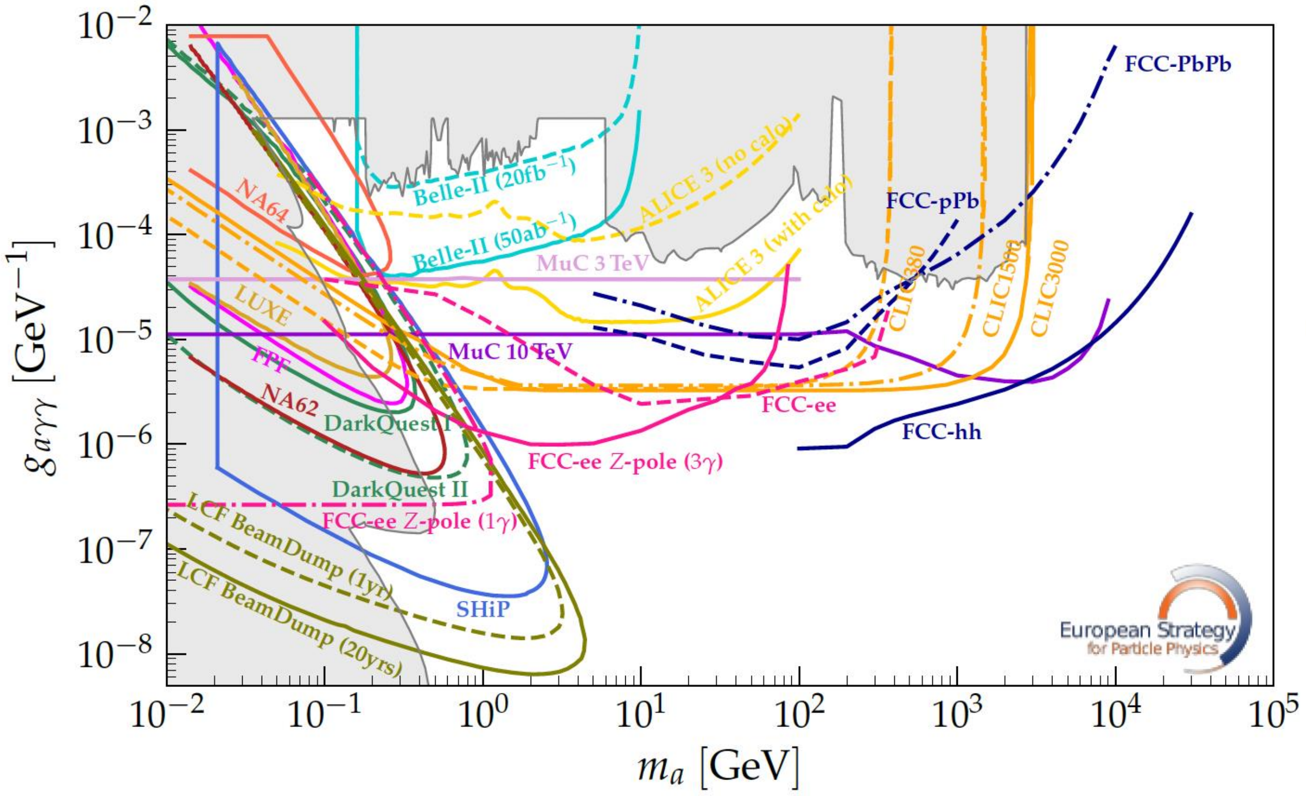
$$\mathcal{L}_{NP} = \overbrace{\mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\psi_{SM})}^{\text{SMEFT}} + \overbrace{\frac{1}{f} a F_{\mu\nu}F^{\mu\nu} + y_N L\phi N + \delta_\chi(\phi^+\phi)\chi^+\chi + \dots}^{\text{Portals}}$$

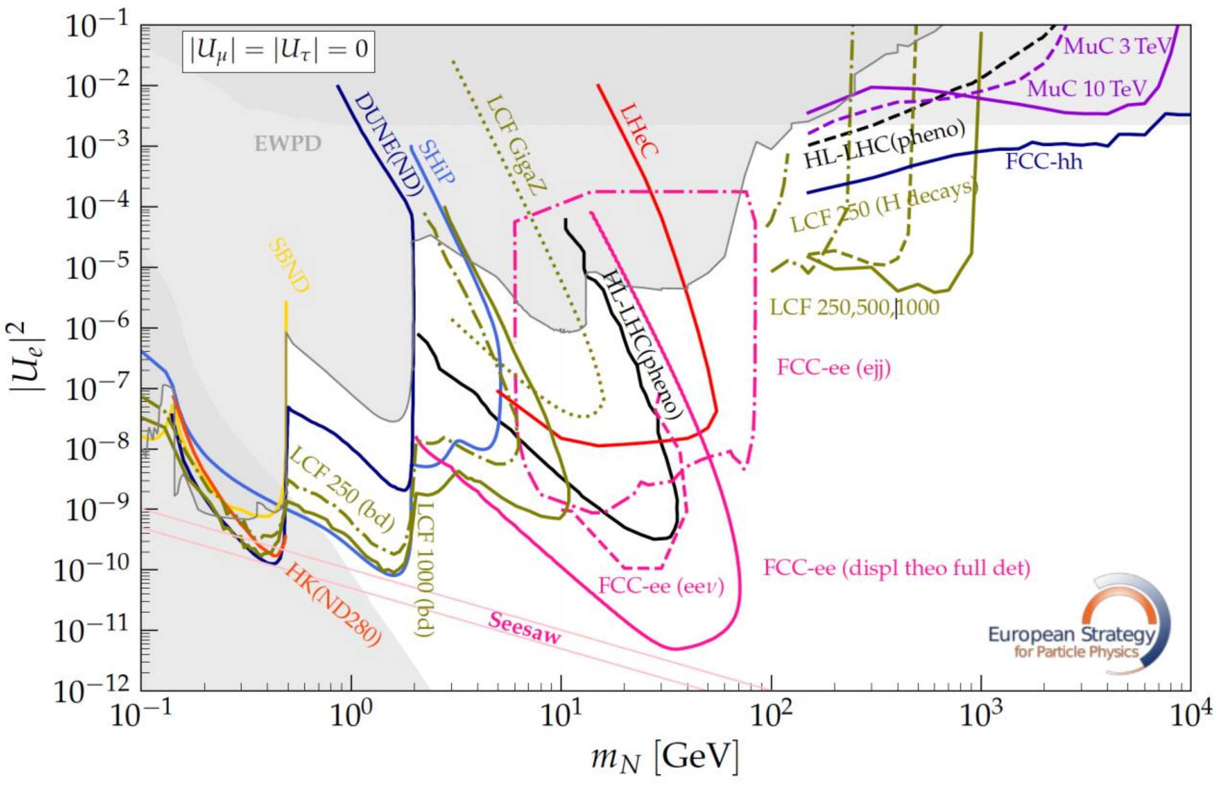




Last but not least…[beyond indirect searches]

In this case the NP parameter range is much wider → no hope for complete coverage with a single set-up. However, the high statistics & clean environment provided by FCC-ee would allow us to probe large unexplored regions, e.g.:





Conclusions

What I have illustrated at the end of this talk are specific examples, but the conclusions that can be drawn are very general:

- In motivated classes of SM extensions NP can still be around few TeV.
  To discover it, the interplay of a large number of observables is a key ingredient, both to "decode" the underlying theory & to "validate" possible discoveries
- Precision Higgs, electroweak, and flavour physics are three faces of the same strategy: their primary objective are indirect discoveries, and in realistic model with TeV-scale NP, they provide very complementary information
- Natural synergy of the precision frontier with the data-driven searches for "exotic" NP models with light weakly-coupled new particles [*high intensity is the driving factor*]

In view of all these considerations, the FCC-ee program is very exciting !

Conclusions