European Strategy for Particle Physics

Open Symposium
2026 Update
European Strategy for Particle Physics
June 25, 2025

Characterization of the Electroweak sector at Future Colliders
Comparative Assessment

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Based on the work prepared by the PPG EW WG:

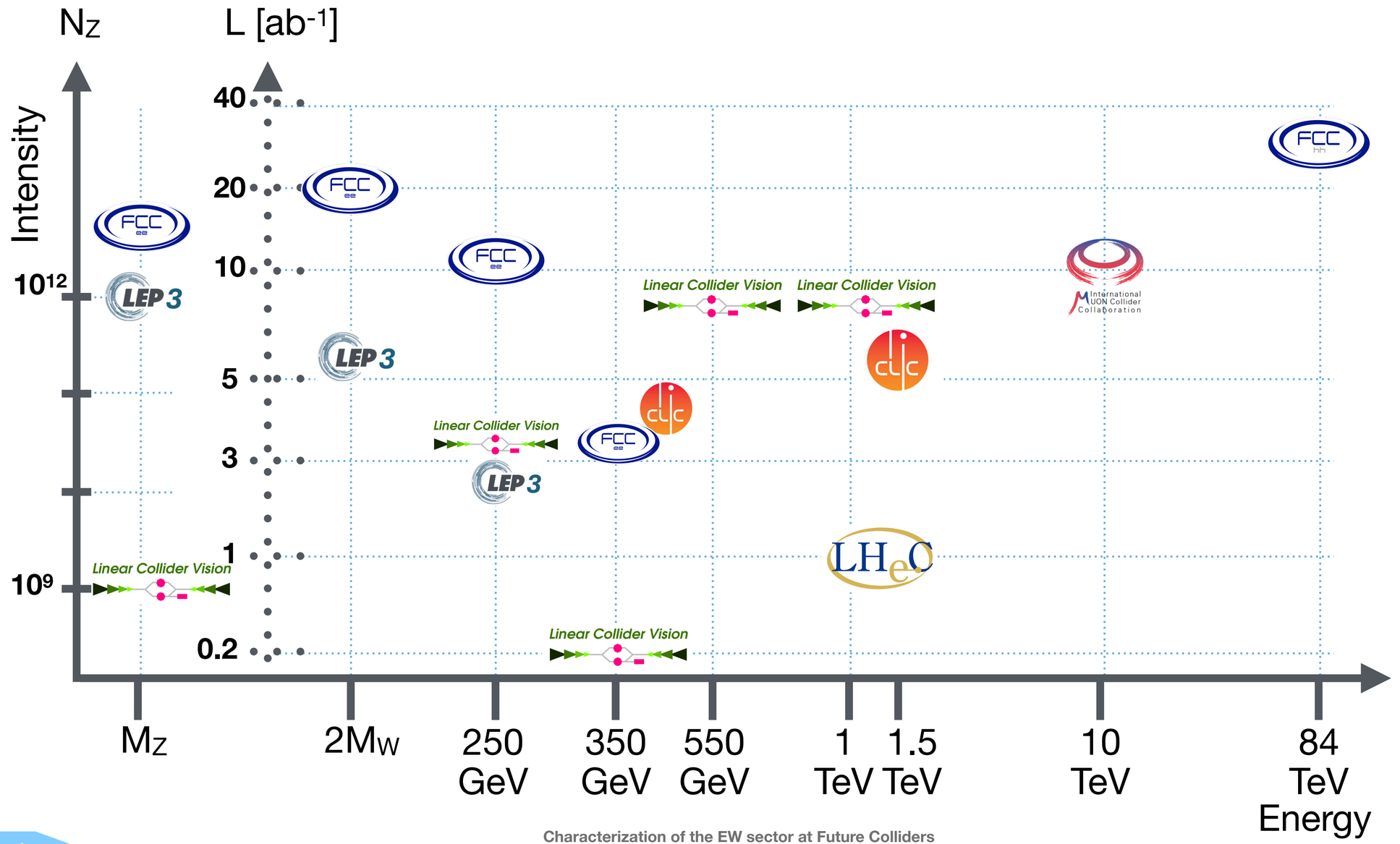
TH: E. Bagnaschi, J.B., A. Freitas, P. Giardino

EXP: M. Dunford, C. Grefe, M. Selvaggi, A. Taliercio

ugr Universidad de Granada

Comparing future collider capabilities

Very different design to address the search for new physics



Comparing future collider capabilities

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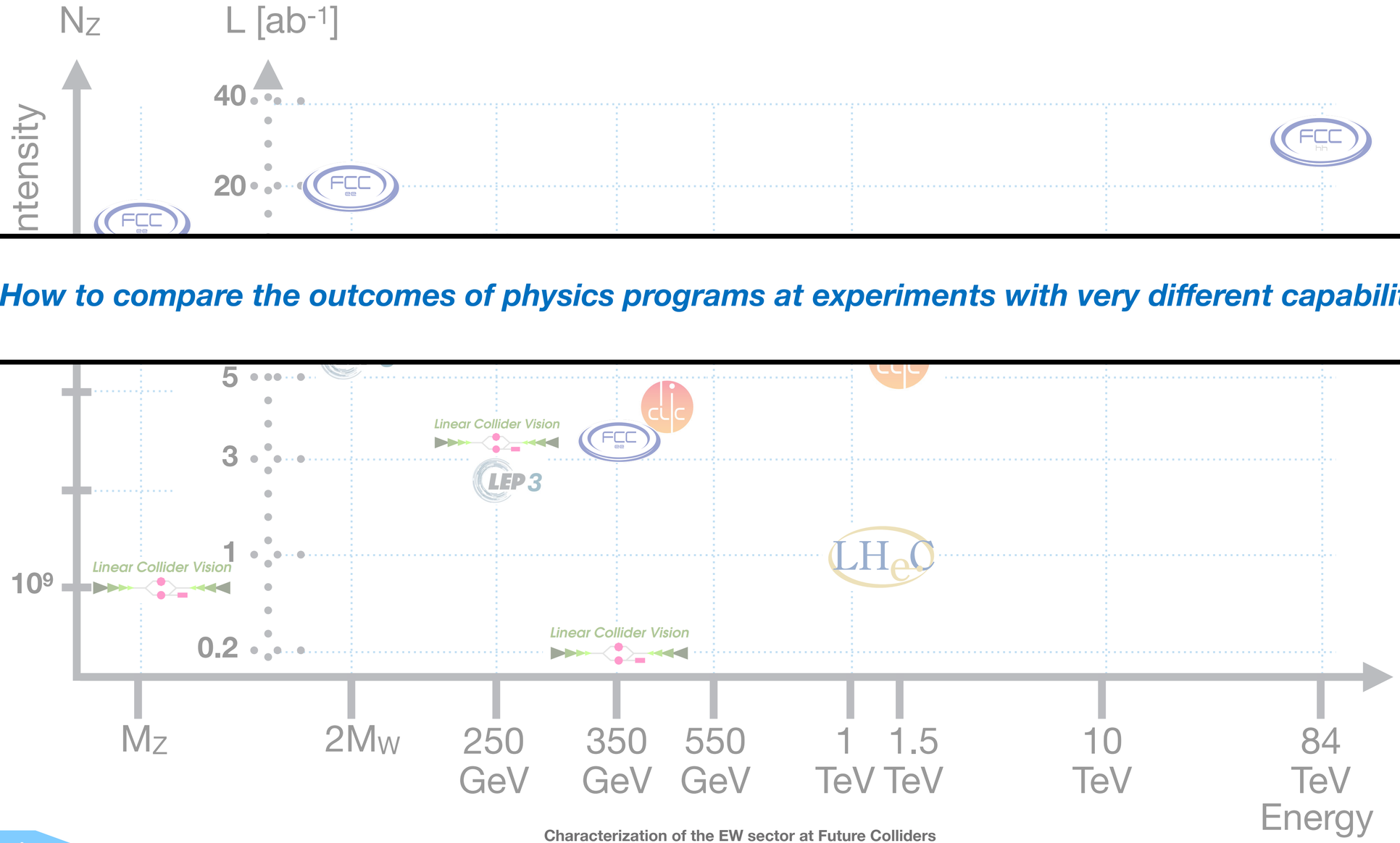
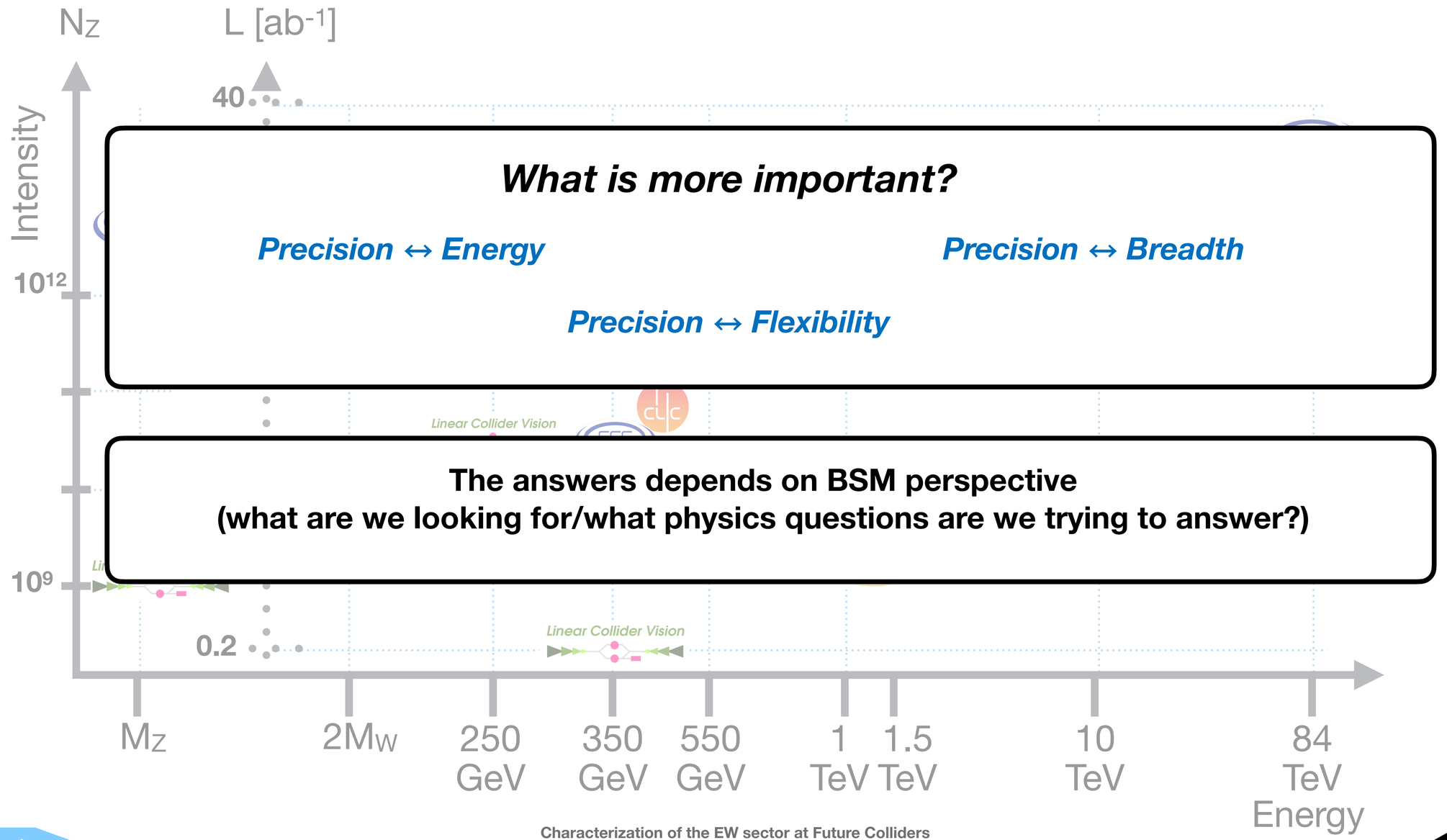


How to compare the outcomes of physics programs at experiments with very different capabilities?

Comparing future collider capabilities

Very different design to address the search for new physics

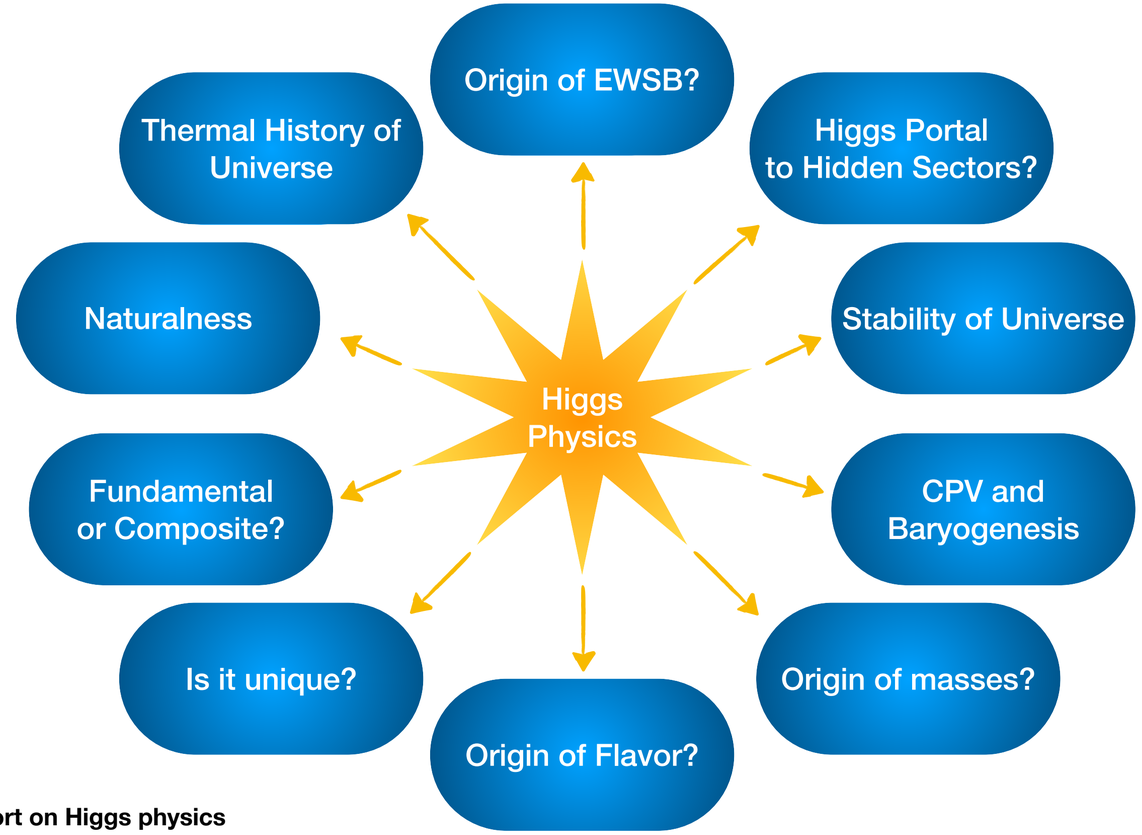


What do we need and Why†

†Title “stolen” from Section 8.3 of Higgs@FutureColliders WG report for ESPP2020

From previous ESPP2020 and 2021 Snowmass processes

- The Higgs boson may be connected to many of our BSM questions



†From Snowmass 2021 report on Higgs physics

⇒ Especial attention to capabilities for precision Higgs physics

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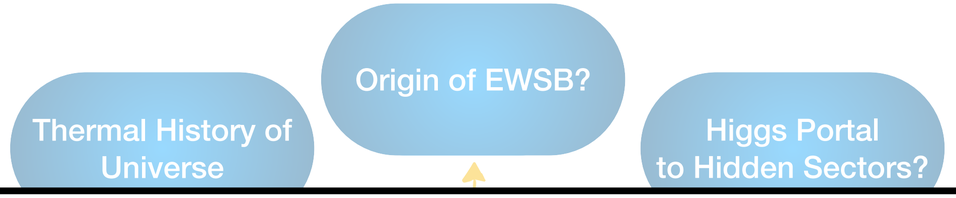
- The Higgs boson may be connected to many of our BSM questions



Capabilities for precision Higgs measurements at different machines (different production modes) can be described in a compact way via the Kappa framework

$$(\sigma \cdot \mathrm{BR})(i \to H \to f) = \kappa_i^2 \sigma^{\mathrm{SM}}(i \to H) \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}(H \to f)}{\Gamma_H}$$

One κ_f for each H→f

$$\Gamma_H = \Gamma_H^{\mathrm{SM}} \frac{\sum_i \kappa_i^2 \mathrm{BR}_i^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{inv}} - \mathrm{BR}_{\mathrm{unt}}}$$

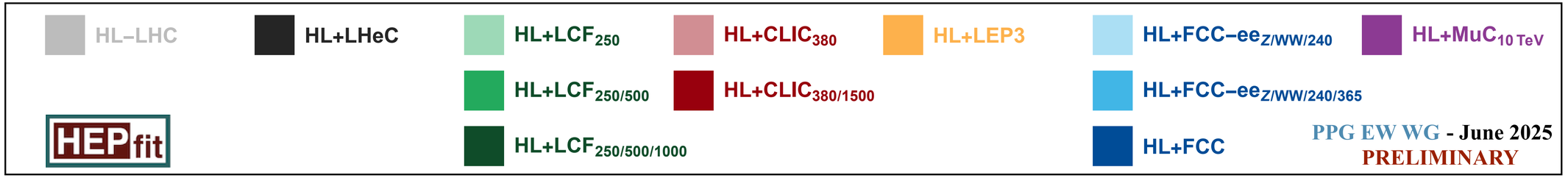
BSM decays

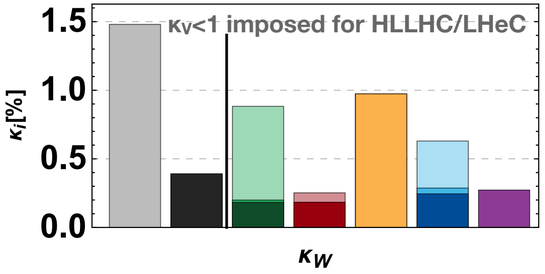
†From Snowmass 2021 report on Higgs physics

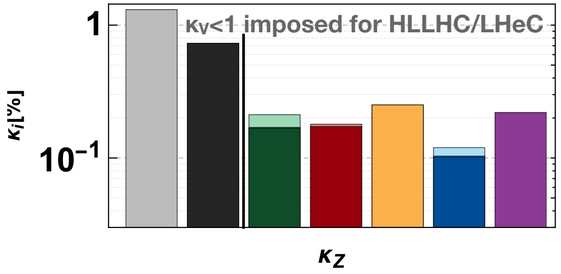
⇒ Especial attention to capabilities for precision Higgs physics

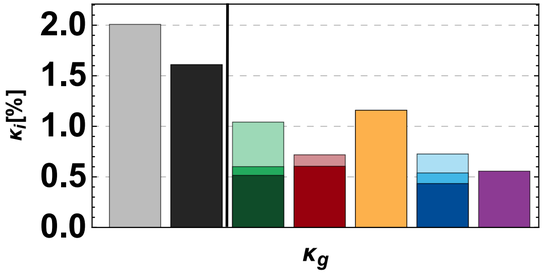
Kappa framework results
Characterizing precision of Higgs measurements

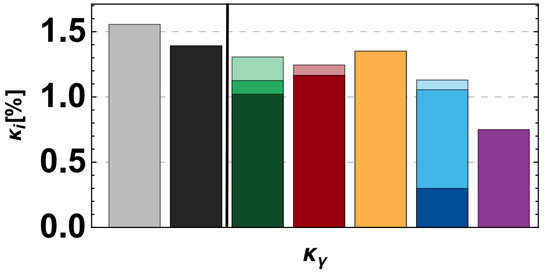
Kappa framework results

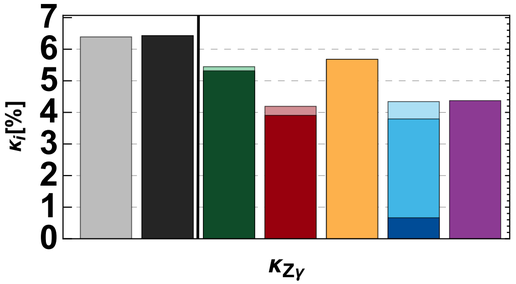


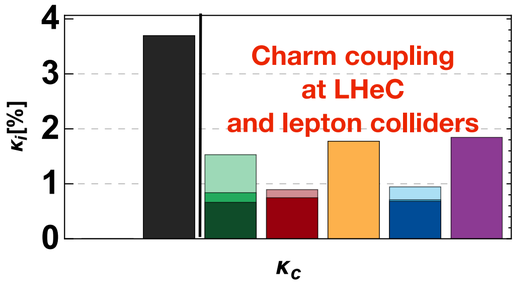


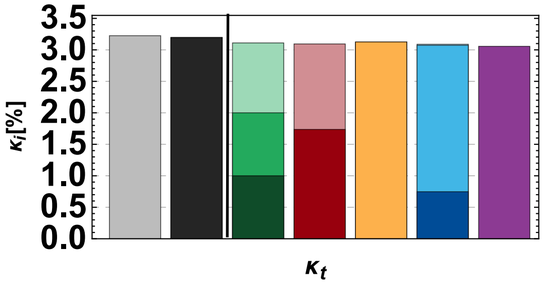


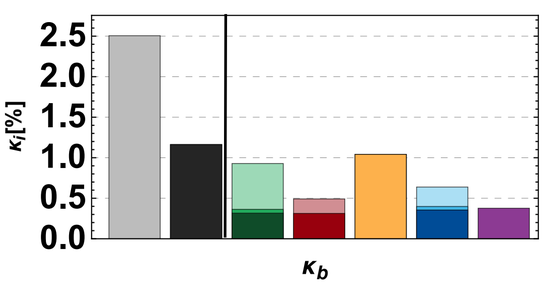


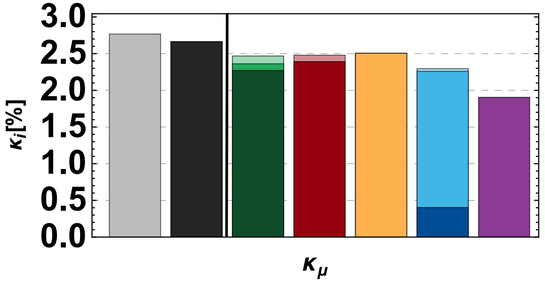


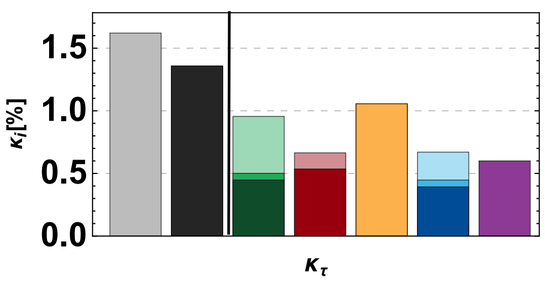


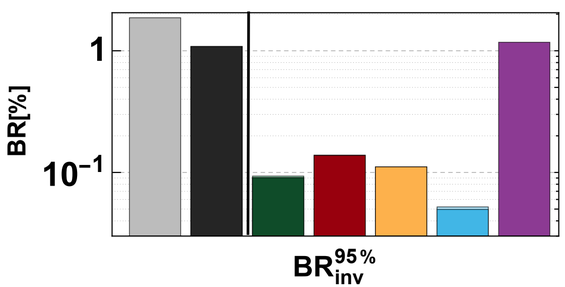


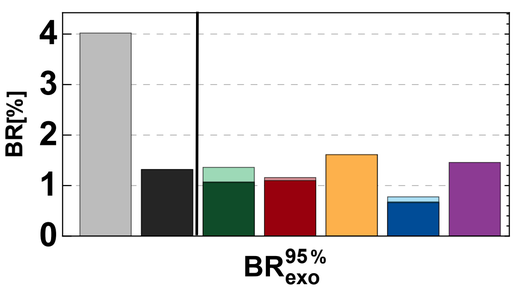










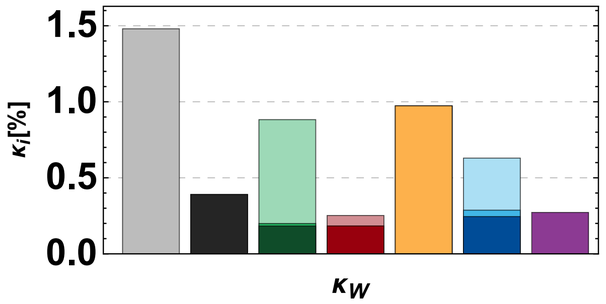


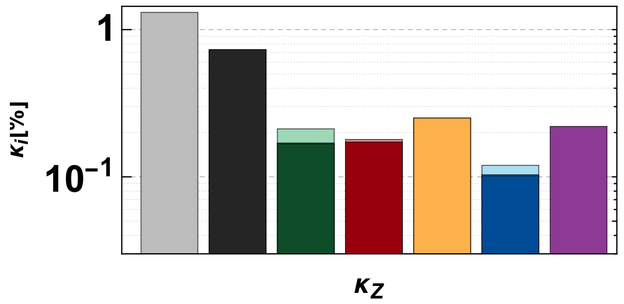
Kappa framework results

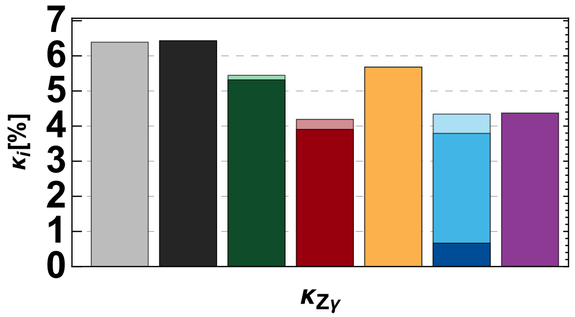
HL–LHC
HL+LHeC
HL+LCF$_{250}$
HL+LCF$_{250/500}$
HL+LCF$_{250/500/1000}$
HL+CLIC$_{380}$
HL+CLIC$_{380/1500}$
HL+LEP3
HL+FCC–ee$_{Z/WW/240}$
HL+FCC–ee$_{Z/WW/240/365}$
HL+FCC
HL+MuC$_{10\,TeV}$

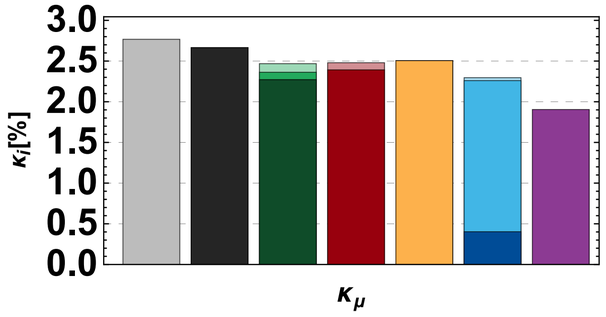
HEPfit

PPG EW WG - June 2025
PRELIMINARY









Per-mille level precision for κ_V

HL-LHC legacy (Until FCC-hh)

Also κ_t if next collider runs below ttH threshold

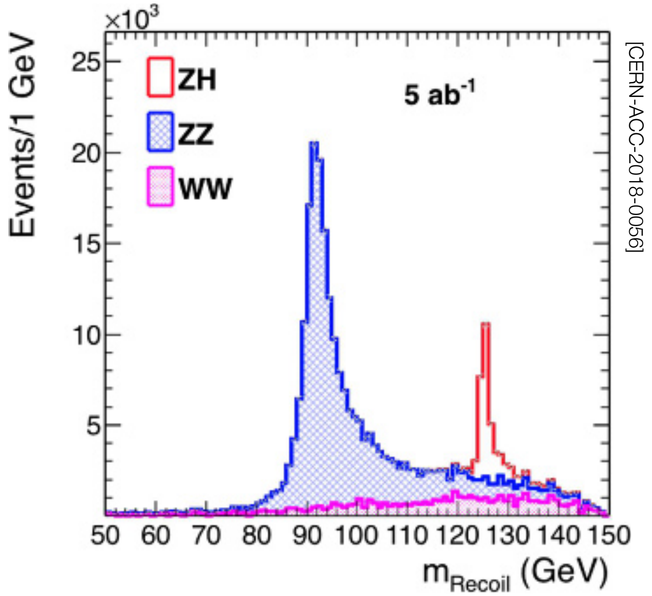
Kappa framework results

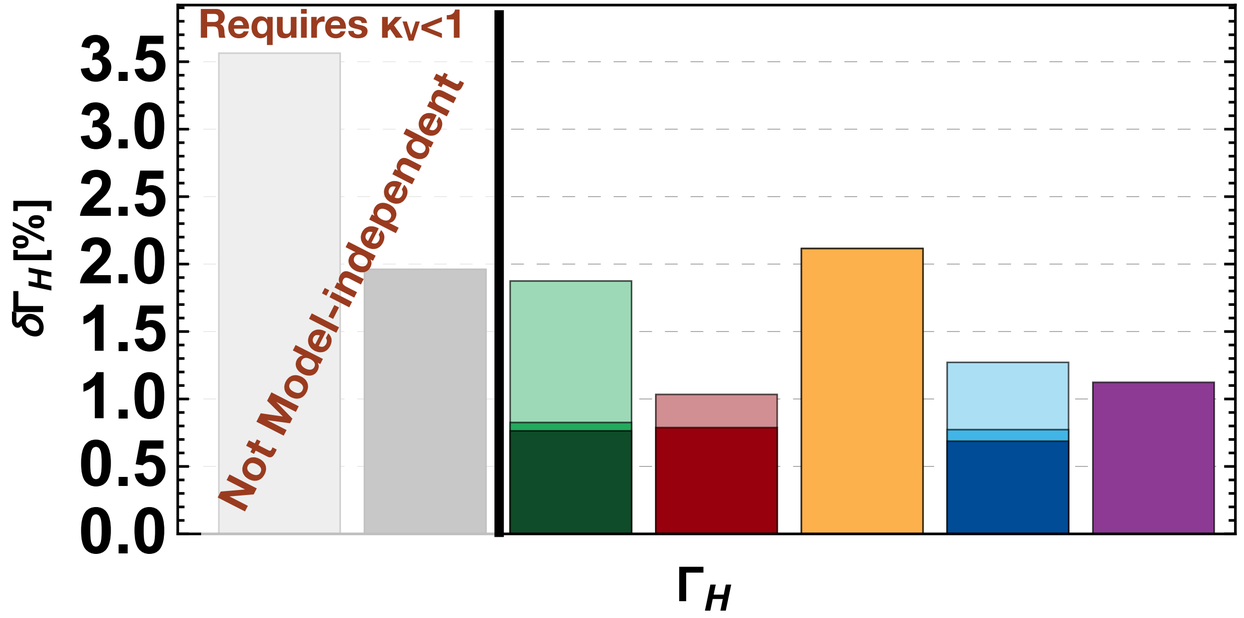
HL–LHC | HL+LHeC | HL+LCF$_{250}$ | HL+LCF$_{250/500}$ | HL+LCF$_{250/500/1000}$ | HL+CLIC$_{380}$ | HL+CLIC$_{380/1500}$ | HL+LEP3 | HL+FCC–ee$_{Z/WW/240}$ | HL+FCC–ee$_{Z/WW/240/365}$ | HL+FCC | HL+MuC$_{10\ TeV}$

HEPfit

PPG EW WG - June 2025
PRELIMINARY

Indirect determination of Higgs width





Only at l^+l^- colliders

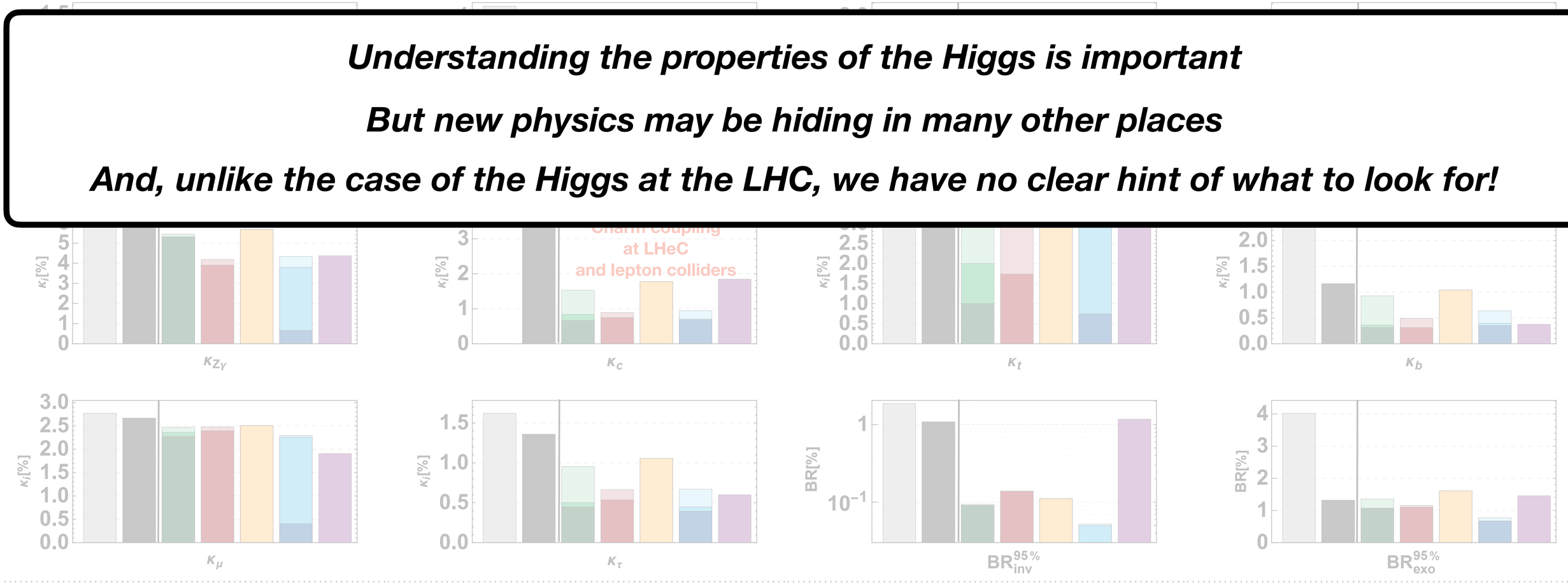
(Requires measurement providing absolute normalization of H couplings)

Kappa framework results

Understanding the properties of the Higgs is important

But new physics may be hiding in many other places

And, unlike the case of the Higgs at the LHC, we have no clear hint of what to look for!



Kappa framework results

Understanding the properties of the Higgs is important

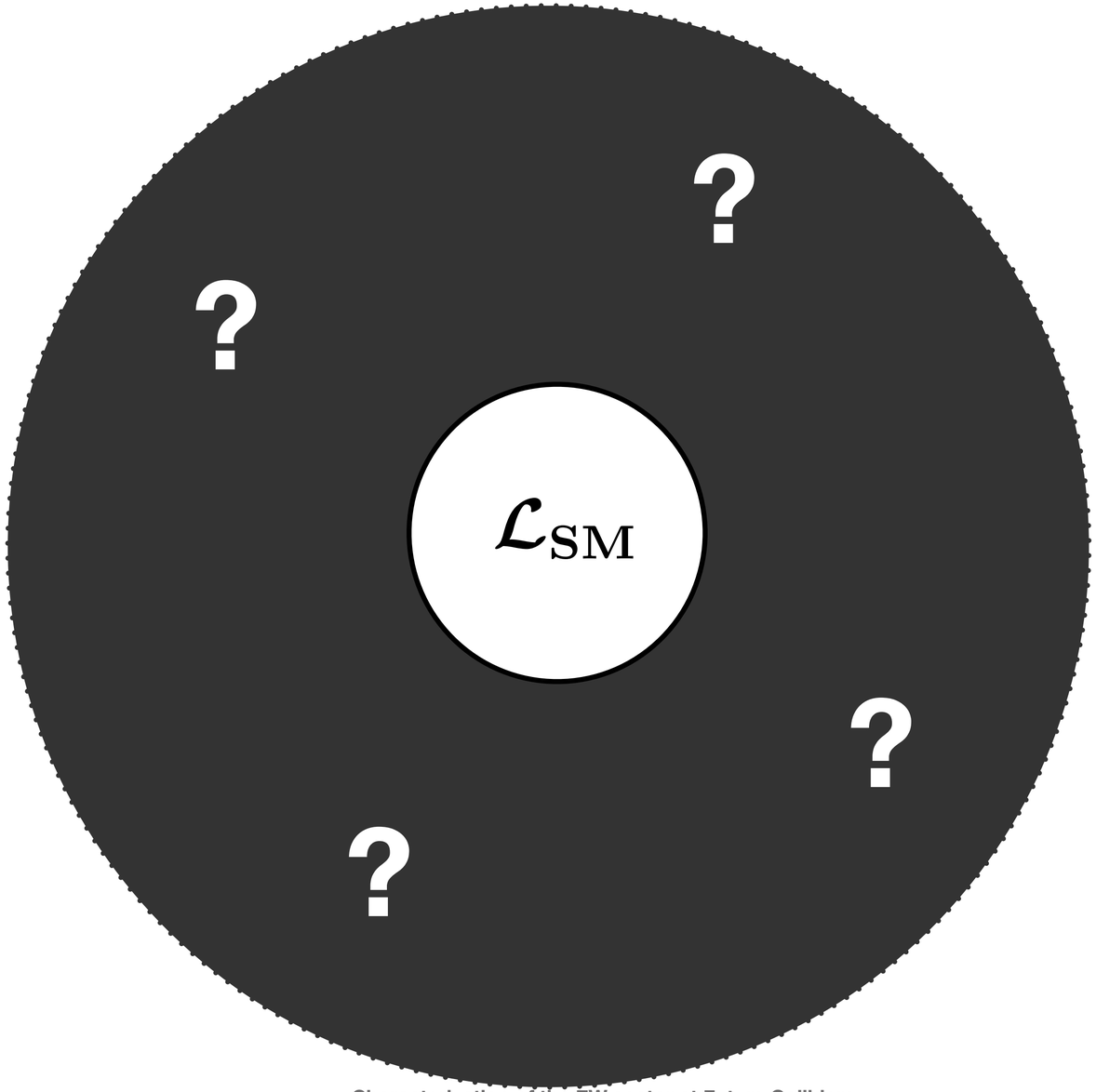
But new physics may be hiding in many other places

And, unlike the case of the Higgs at the LHC, we have no clear hint of what to look for!

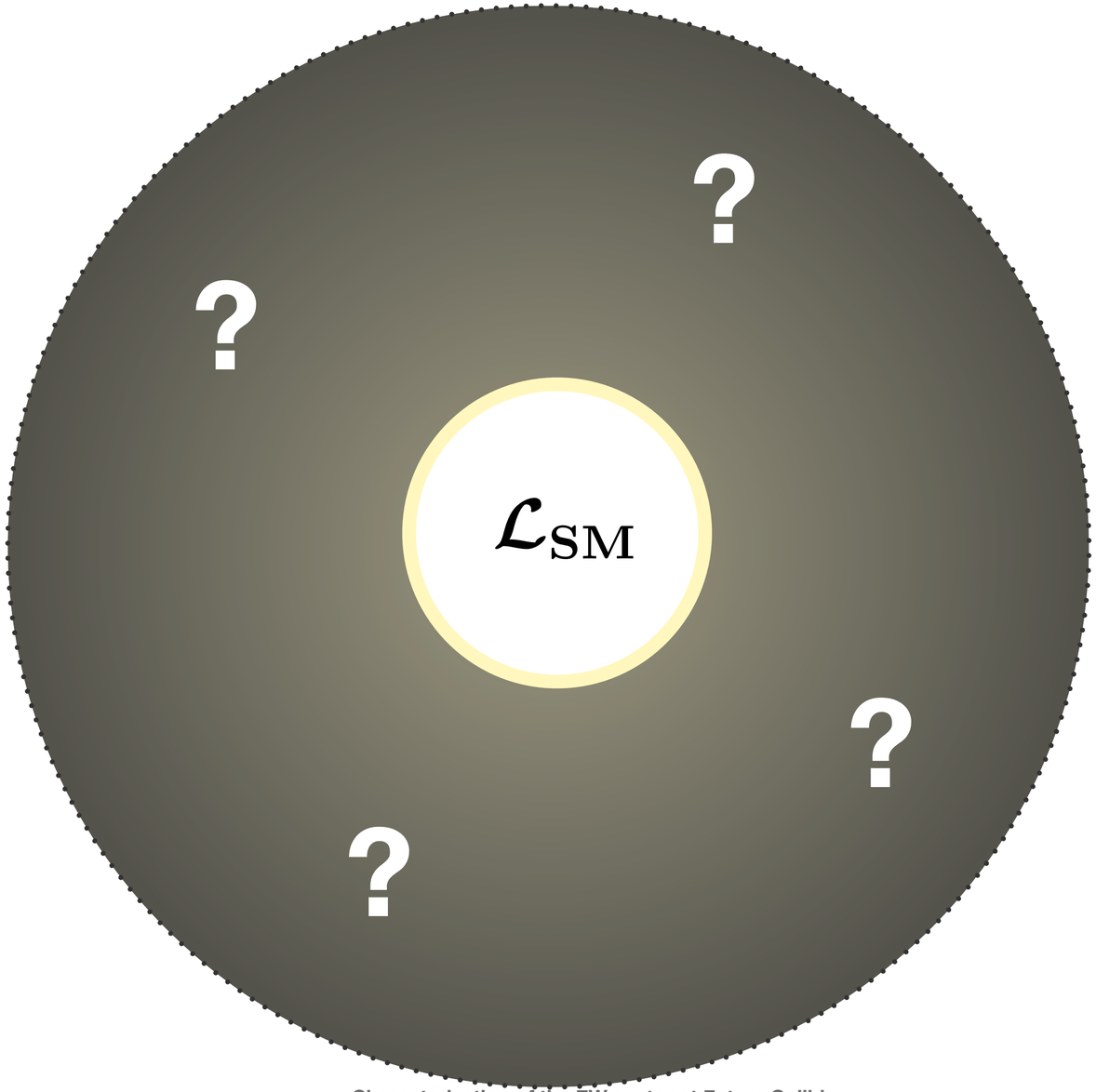
Any future collider should have the capability to explore as many BSM directions as possible

How to approach this type of exploration and compare the different projects?

Future Collider physics will be an exploration of the unknown…

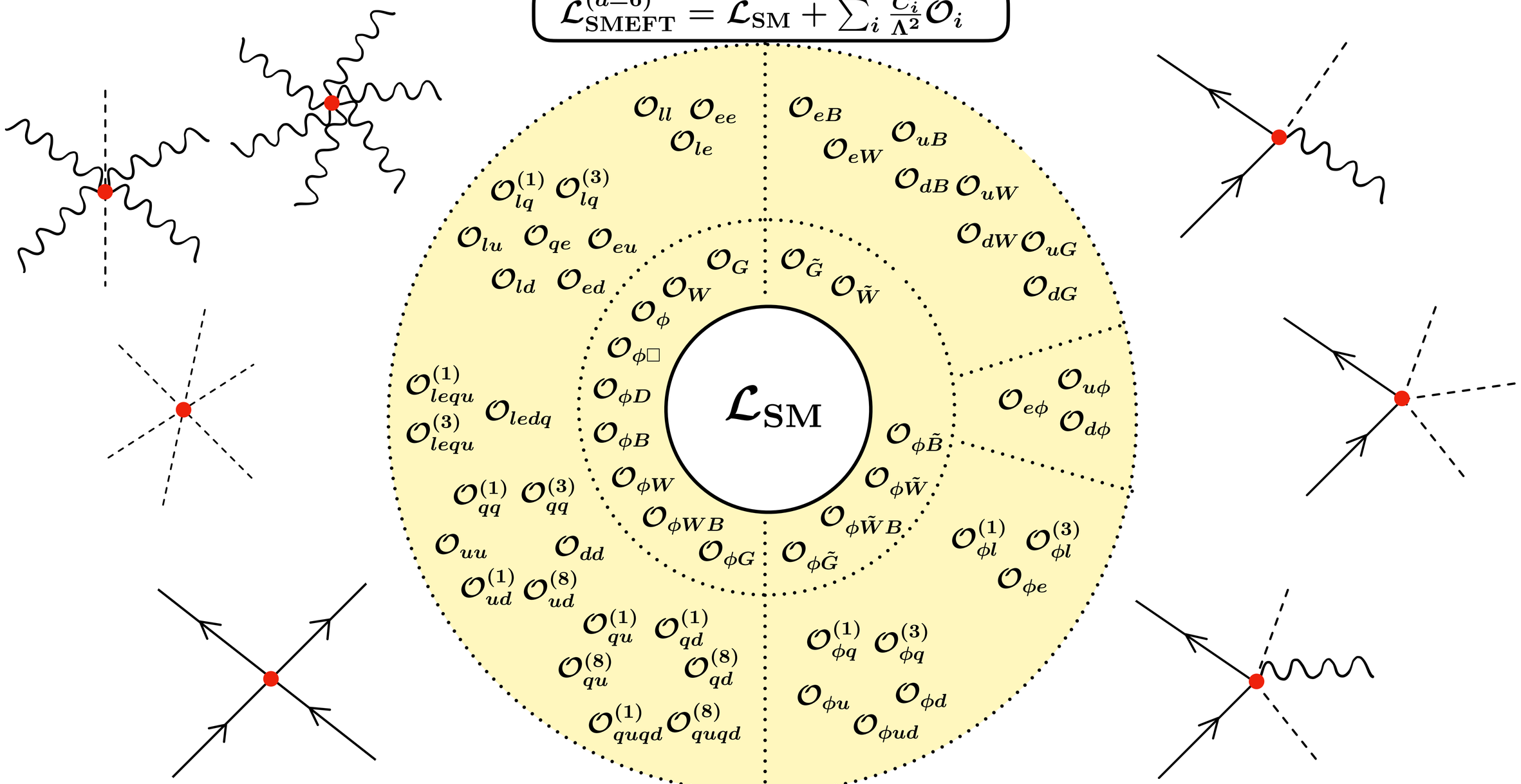


… But the structure of Standard Model can still offer some guidance



Use Effective Field Theories to parameterize BSM deformations

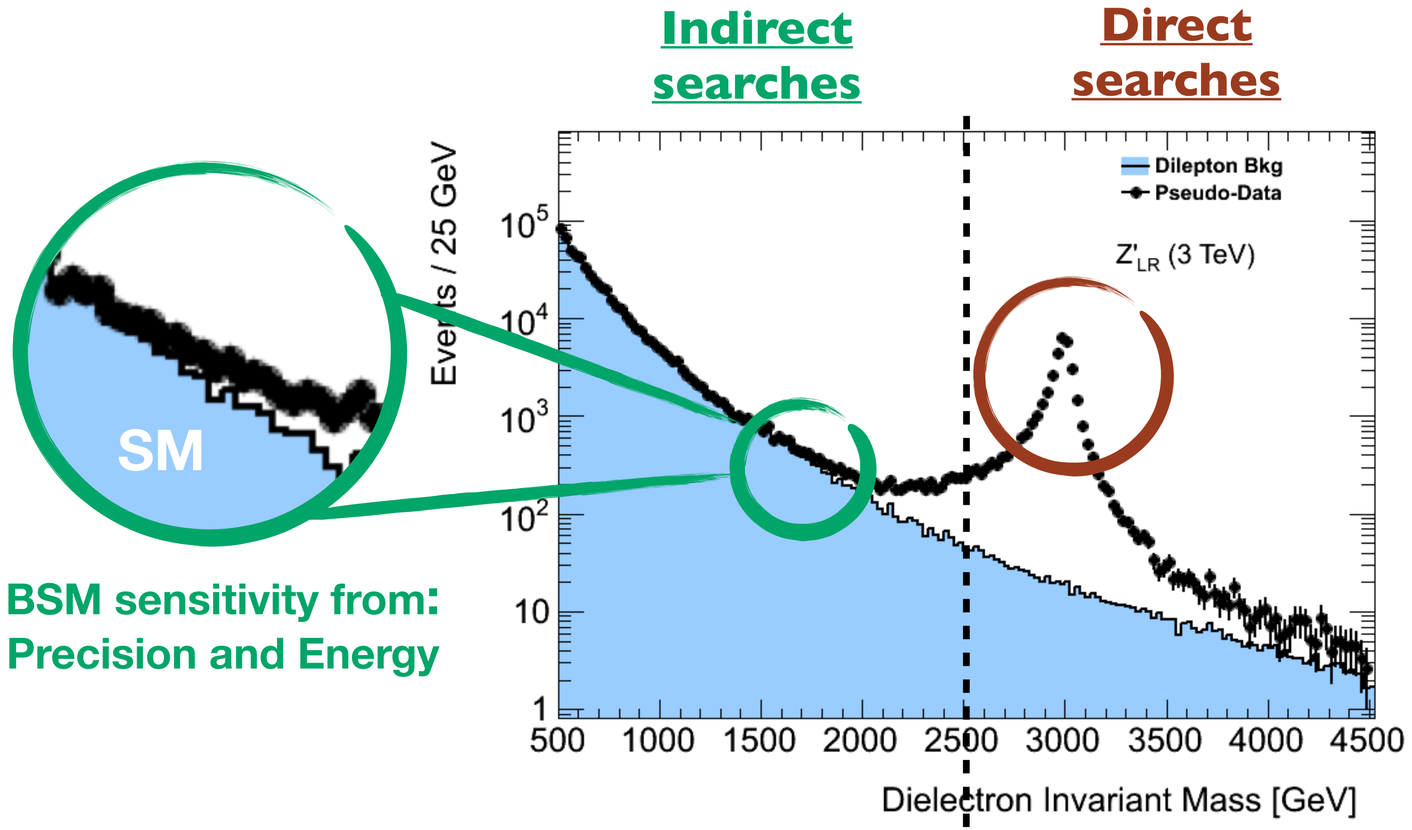
$$\mathcal{L}^{(d=6)}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$



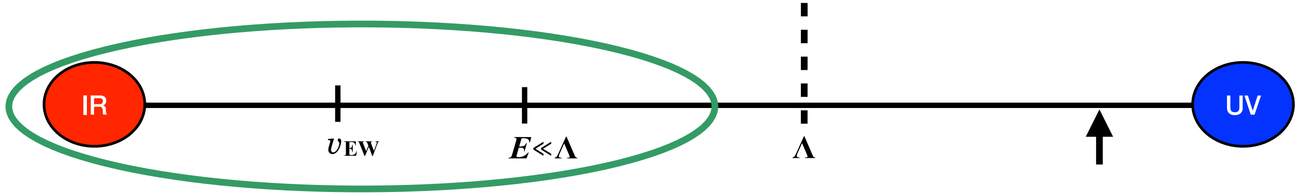
Effective Field Theories
Characterizing general BSM deformations

Effective Field Theories for BSM physics

- General framework to study indirect sensitivity to BSM without explicit reference to models



$$\mathcal{L} = \mathcal{L}_{\mathrm{EFT}}(\supset \mathcal{L}_{\mathrm{SM}}) \qquad \mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{NP}} + \mathcal{L}_{\mathrm{NP-SM}}$$

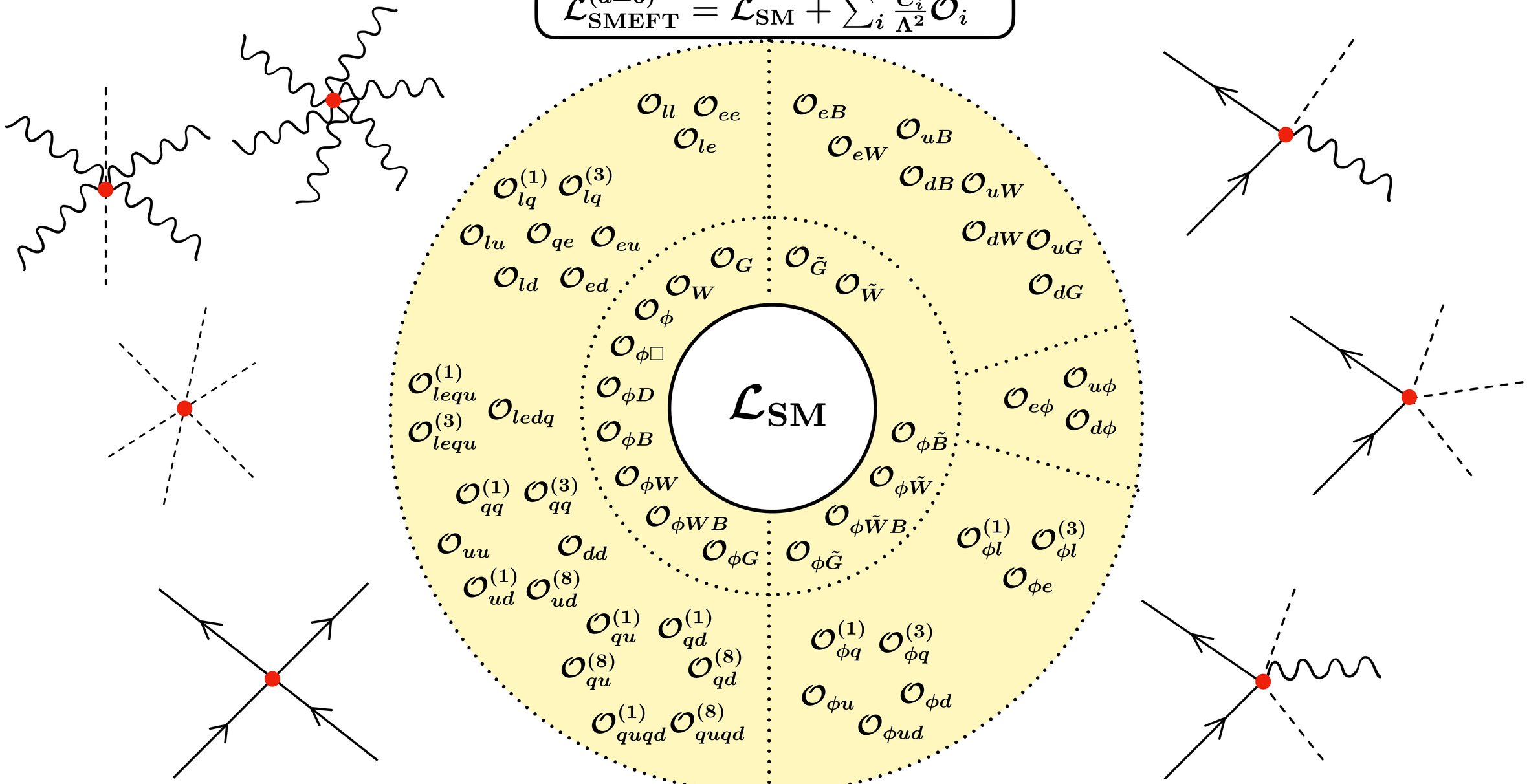


to describe the physics here

We don't need to know this

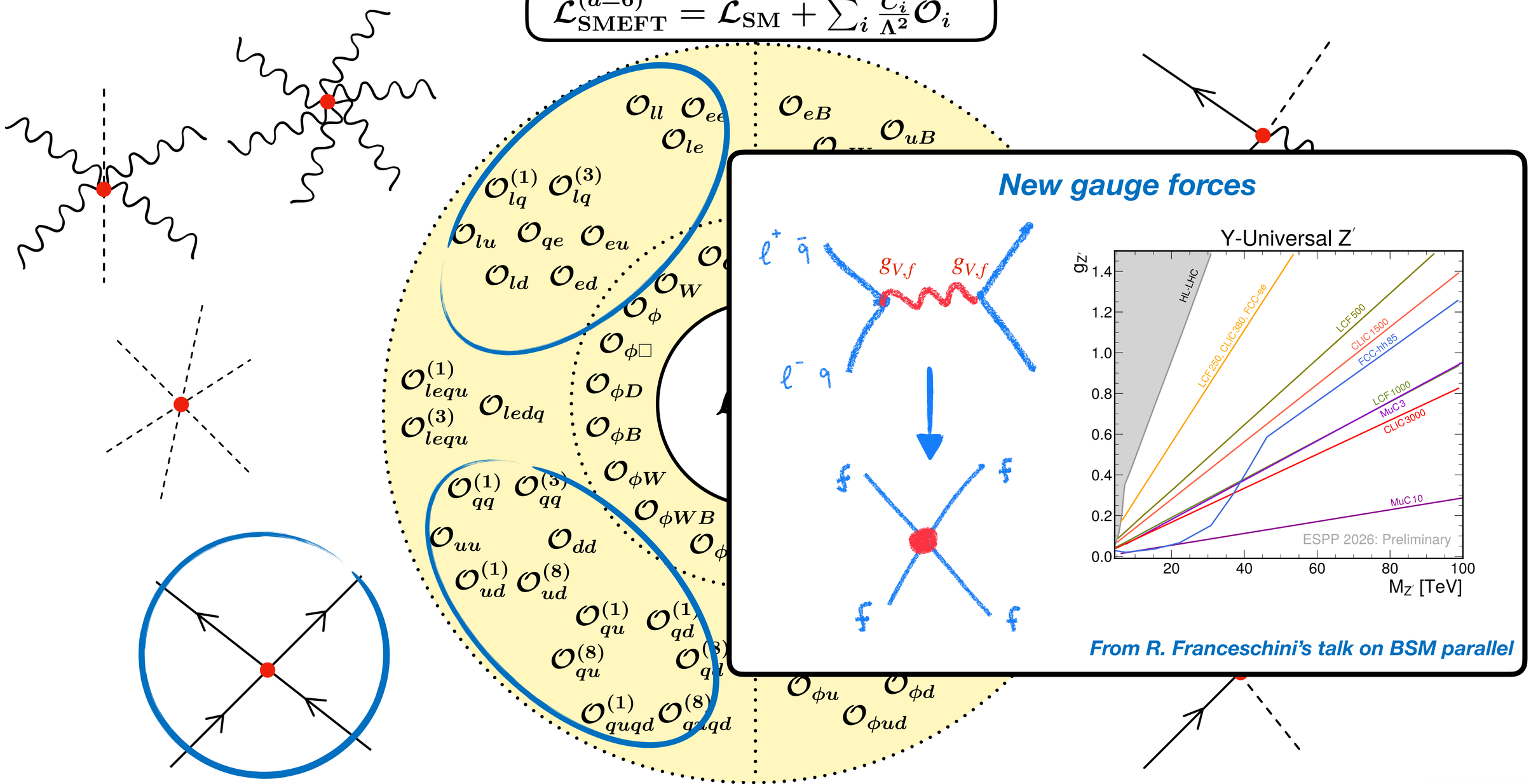
Effective Field Theories for BSM physics

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$



Effective Field Theories for BSM physics

$$\mathcal{L}^{(d=6)}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

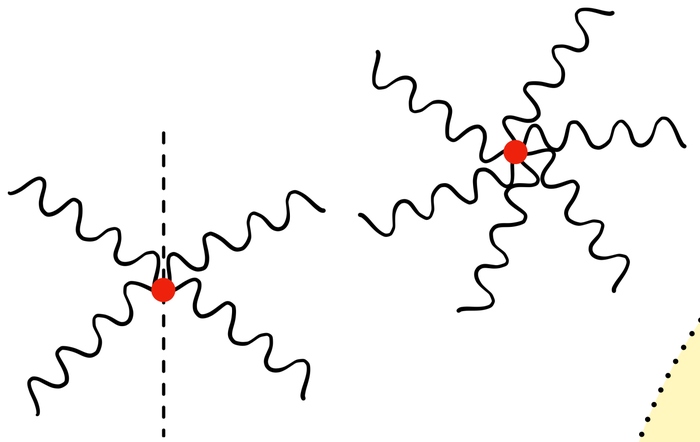


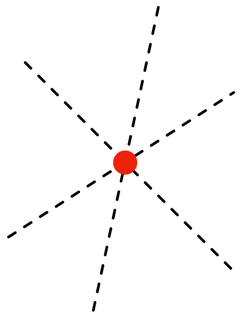
New gauge forces

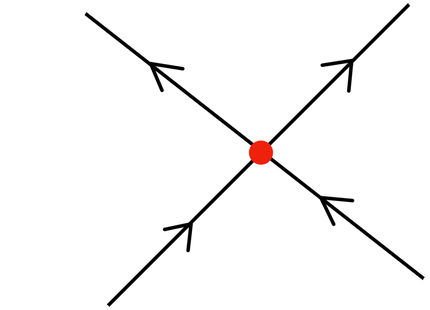
From R. Franceschini's talk on BSM parallel

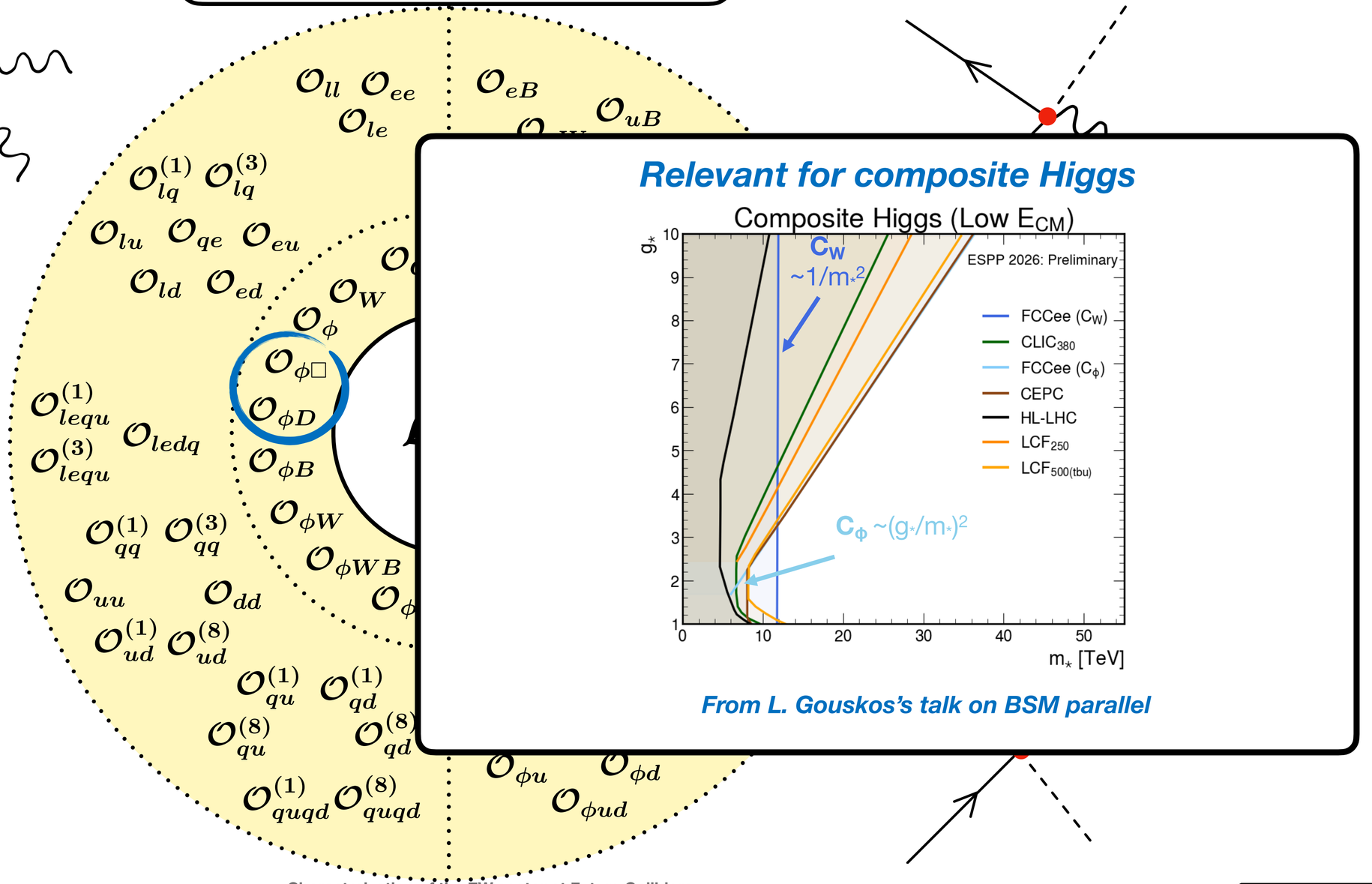
Effective Field Theories for BSM physics

$$\mathcal{L}^{(d=6)}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$









Relevant for composite Higgs

From L. Gouskos's talk on BSM parallel

Effective Field Theories for BSM physics

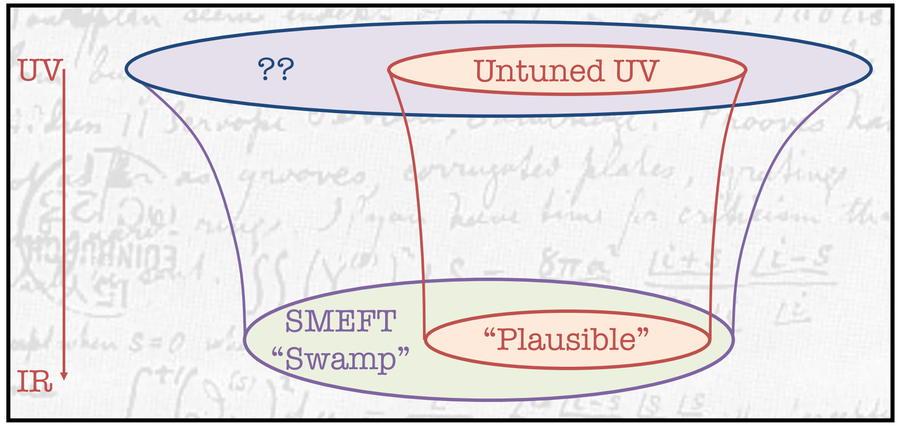
$$\mathcal{L}_{\rm SMEFT}^{(d=6)} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

$\mathcal{O}_{ll}$ $\mathcal{O}_{ee}$ $\mathcal{O}_{le}$ $\mathcal{O}_{eB}$ $\mathcal{O}_{eW}$ $\mathcal{O}_{uB}$ $\mathcal{O}_{dB}$ $\mathcal{O}_{uW}$ $\mathcal{O}_{lq}^{(1)}$ $\mathcal{O}_{lq}^{(3)}$

But if we don't know what we are looking for, we better test as many as these direction as possible

Without reference to any particular model,

What can Electroweak Physics tell us about the SMEFT "swamp"?



From M. McCullough. "Swamp" term by G. Giudice

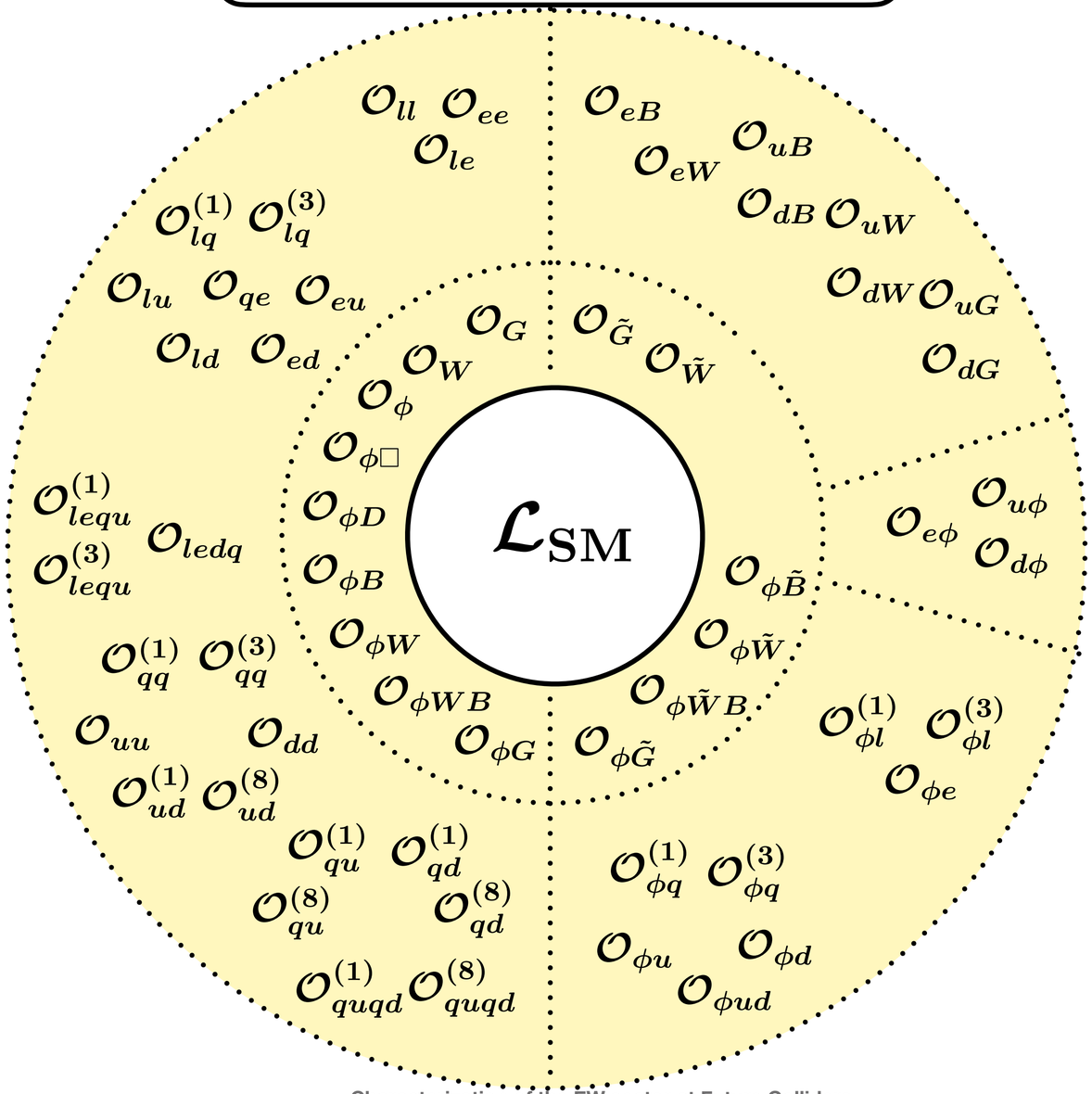
$\mathcal{O}_{quqd}$ $\mathcal{O}_{quqd}$ $\mathcal{O}_{\phi ud}$

Effective Field Theories for BSM physics

$$\mathcal{L}_{\rm SMEFT}^{(d=6)} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

SMEFT @ d=6

59 Operator structures



Effective Field Theories for BSM physics

$$\mathcal{L}_{\rm SMEFT}^{(d=6)} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

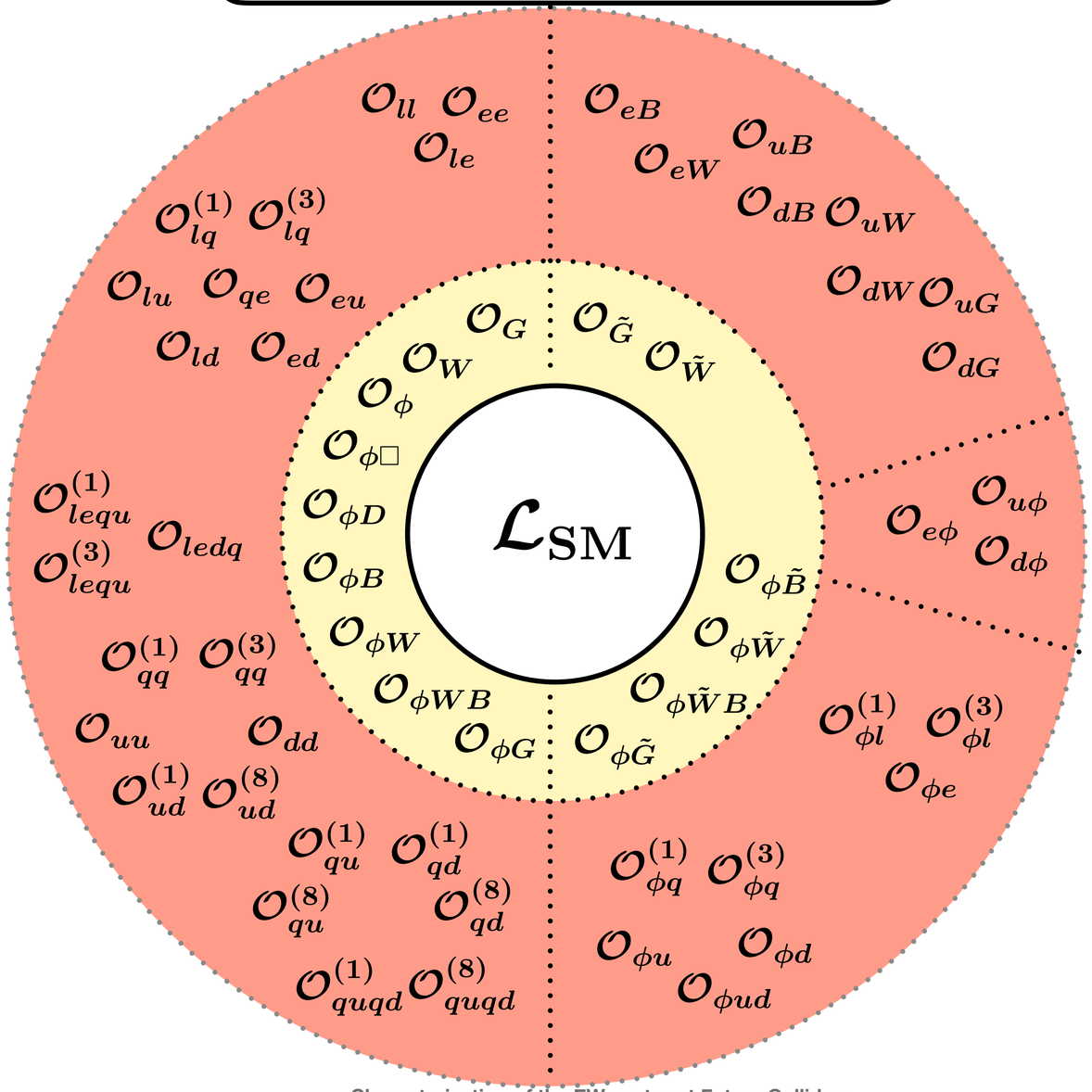
SMEFT @ d=6

59 Operator structures

2499 Operators

Most of the SMEFT is Flavor

Need reasonable assumptions to "decouple" Flavor from EW constraints



$$\mathcal{O}_{ud}^{(1)} \equiv (\mathcal{O}_{ud}^{(1)})_{ijkl}$$

$$\left(\bar{u}^i\gamma_\mu u^j\right)\left(\bar{d}^k\gamma_\mu d^l\right)$$

81 operators

Effective Field Theories for BSM physics

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

SMEFT @ d=6

59 Operator structures

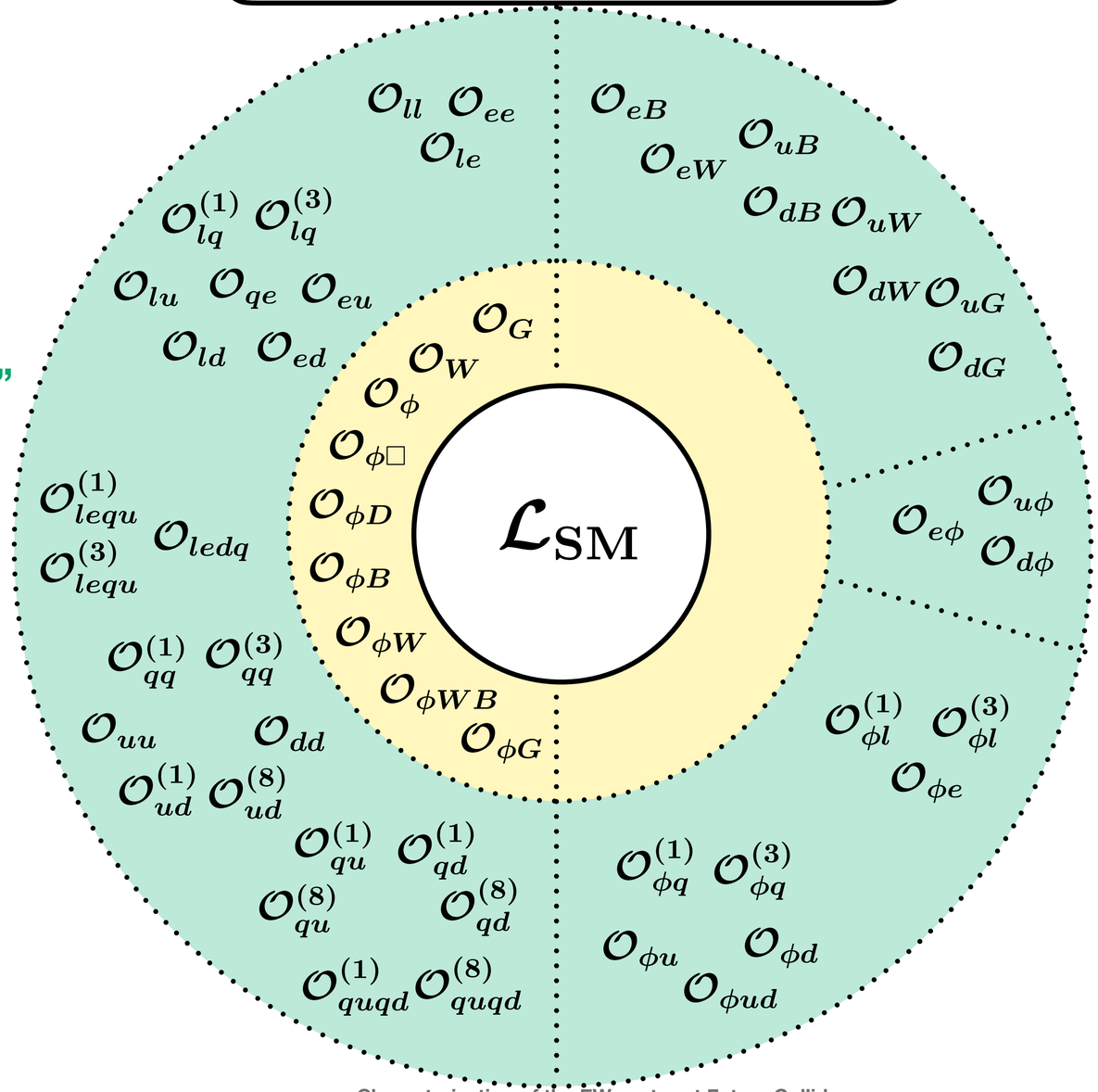
Assume some flavor "protection" e.g. U(2)^5

(and CP-even)

~~2499 Operators~~

124 Operators

Now we can discuss what EW physics gets us



$$\mathcal{O}_{ud}^{(1)} \equiv (\mathcal{O}_{ud}^{(1)})_{ijkl}$$

$$(\bar{u}^i\gamma_\mu u^j)\,(\bar{d}^k\gamma_\mu d^l)$$

81 operators

U(2)^5

$$(\bar{u}^a\gamma_\mu u^a)\,(\bar{d}^b\gamma_\mu d^b)$$
$$(\bar{u}^3\gamma_\mu u^3)\,(\bar{d}^b\gamma_\mu d^b)$$
$$(\bar{u}^a\gamma_\mu u^3)\,(\bar{d}^3\gamma_\mu d^3)$$
$$(\bar{u}^3\gamma_\mu u^3)\,(\bar{d}^3\gamma_\mu d^3)$$

4 operators (& flavor diagonal)

Effective Field Theories for BSM physics

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

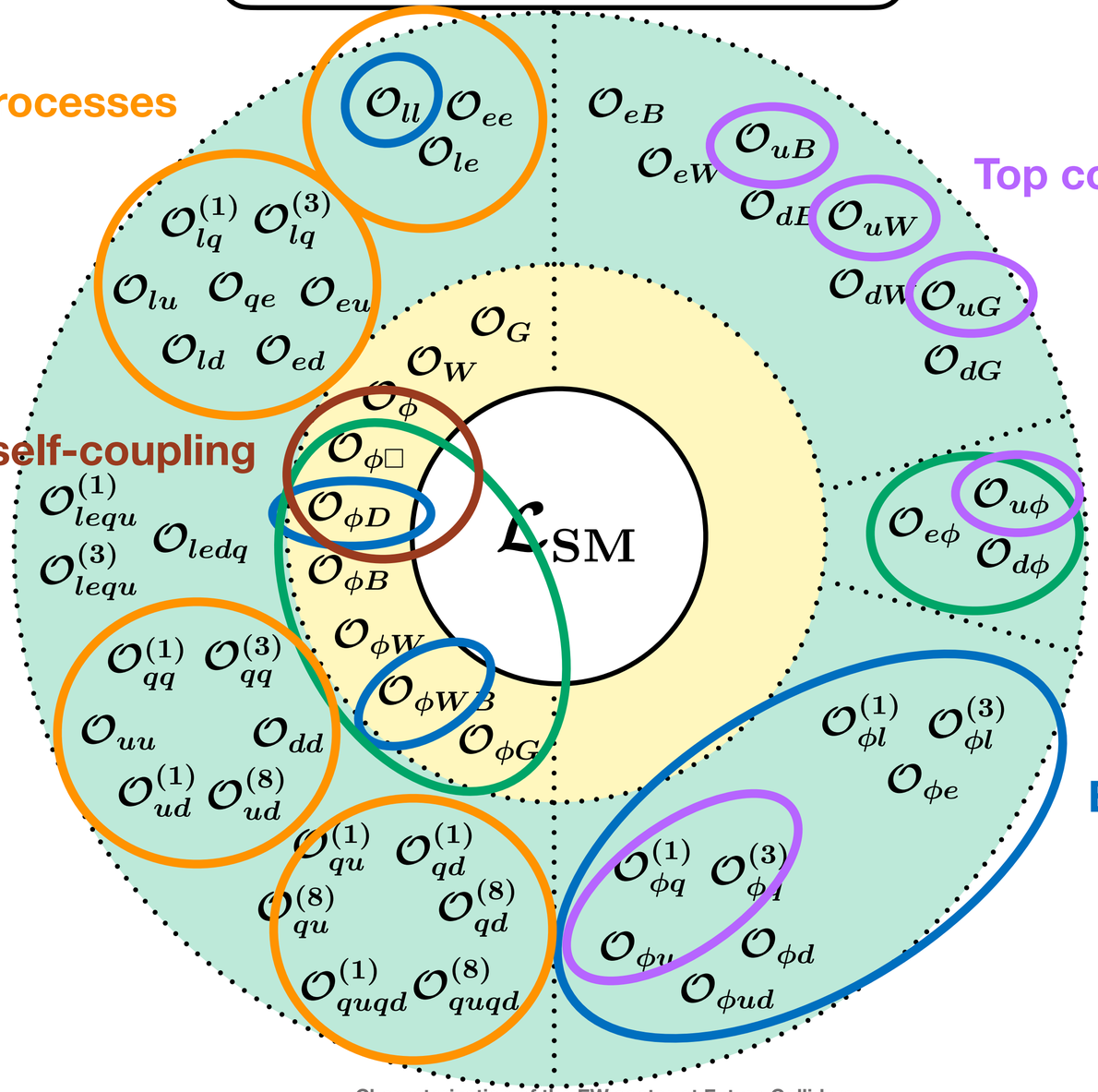
2 to 2 fermion processes

Higgs self-coupling

Top couplings

Higgs “couplings"

EWPO: Z-pole, W obs.



Effective Field Theories for BSM physics

$$\mathcal{L}^{(d=6)}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

And this is just the simple picture at LO

2 to 2 fermion processes

Top/Higgs/EW physics @ e+e-

Higgs self-coupling

Top/Higgs/EW physics @ pp

Top couplings

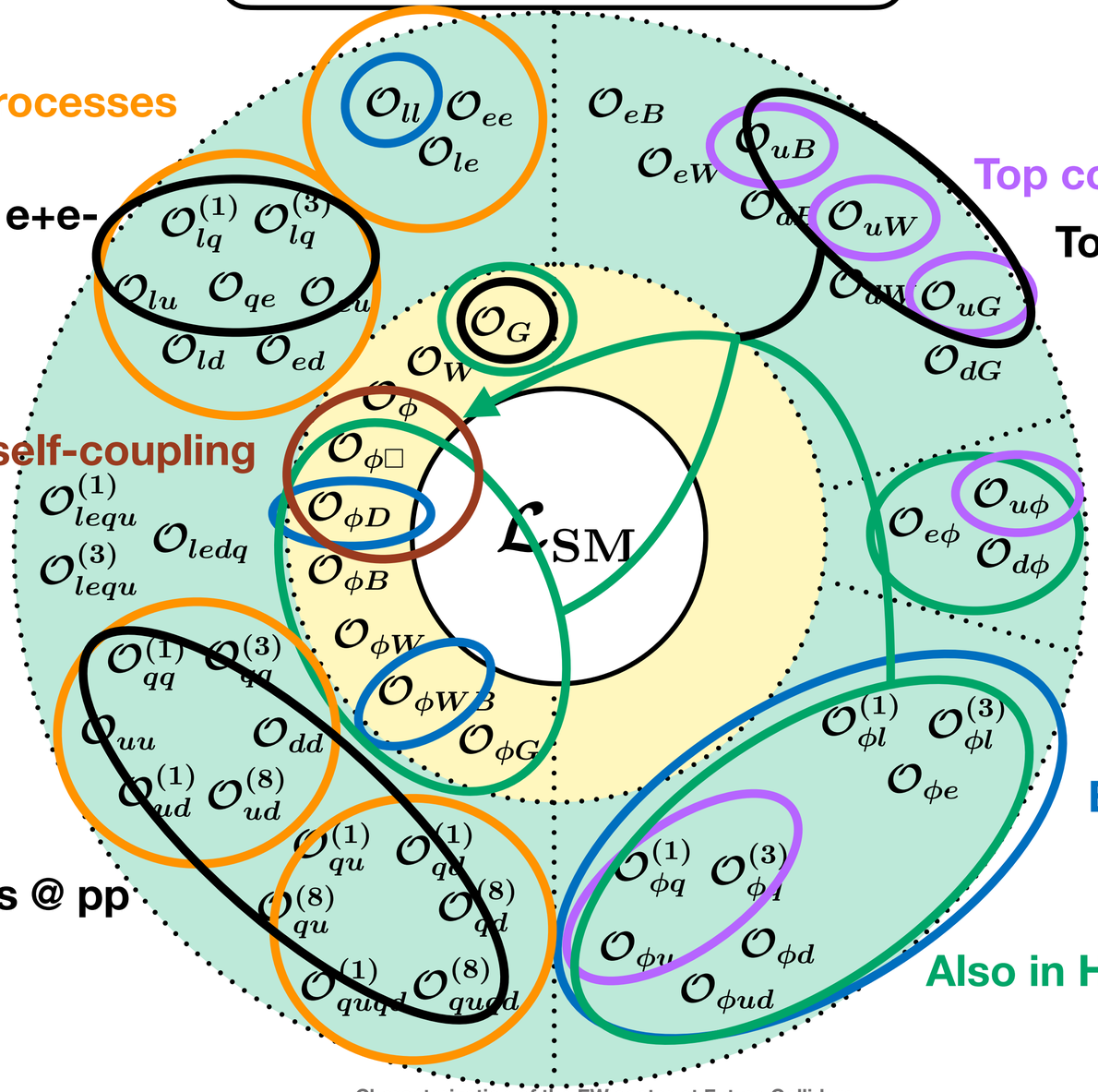
Top/Higgs/EW physics

Higgs “couplings"

EWPO: Z-pole, W obs.

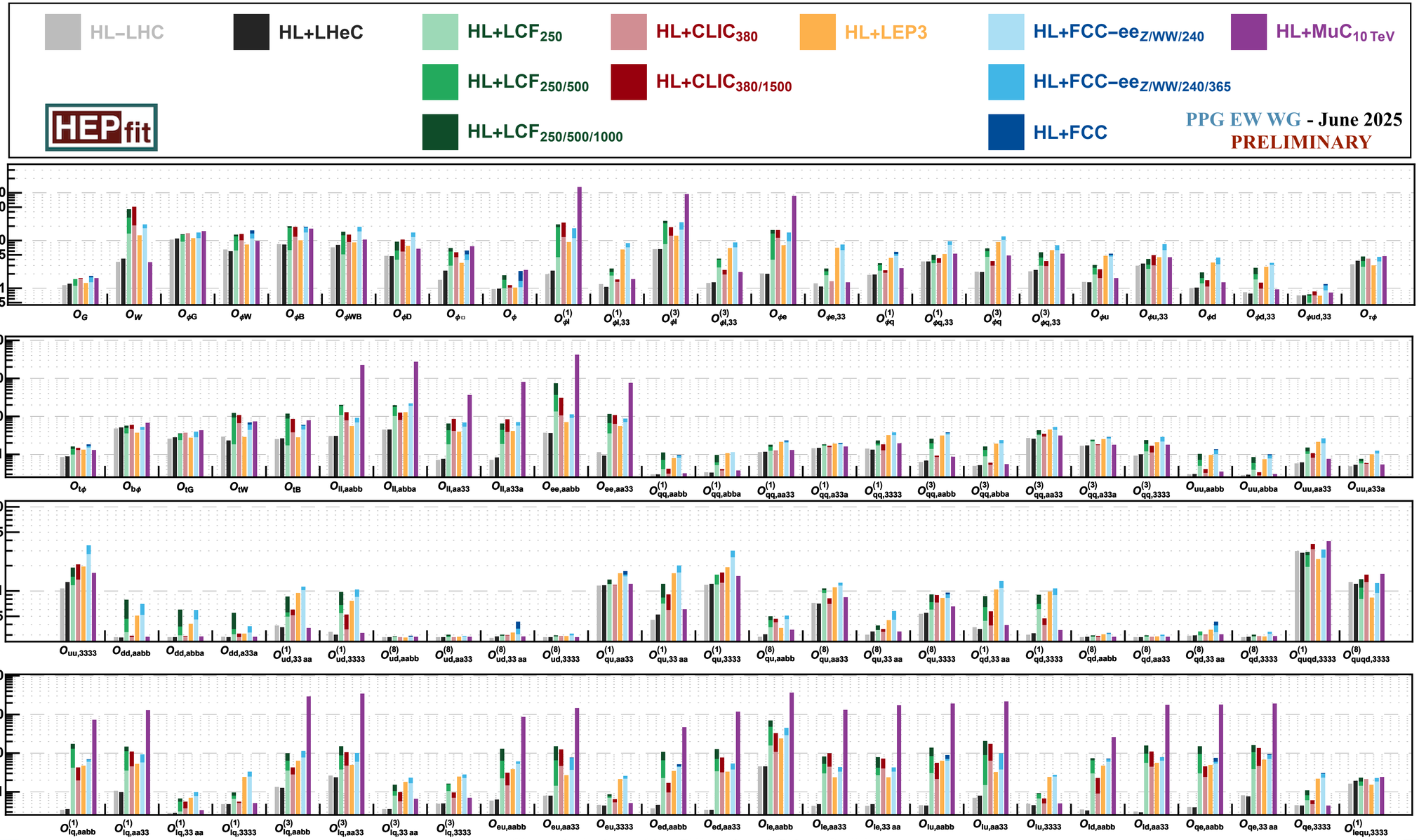
EW precision/Higgs precision

Also in Higgs physics (VBF, VH)



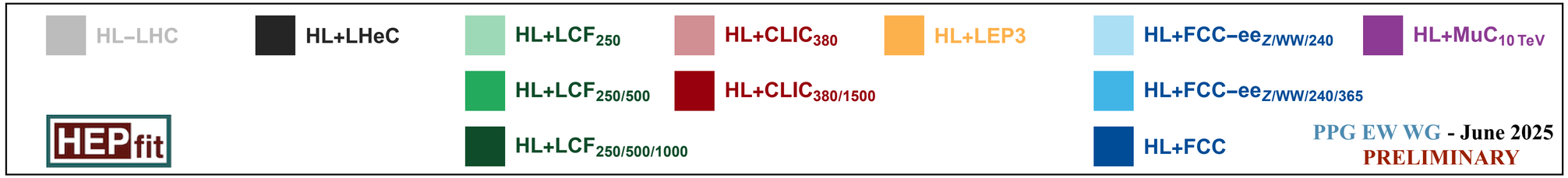
Effective Field Theories for BSM physics

A simple fit to 100 of these operators



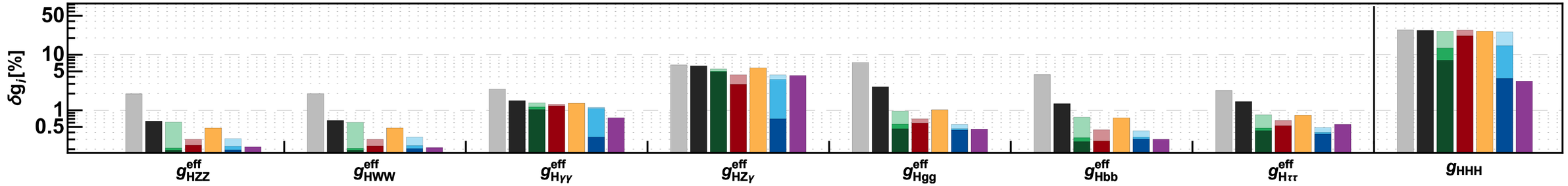
Effective Field Theories for BSM physics

A simple fit to 100 of these operators



Many of these affect directly the properties of the Higgs boson

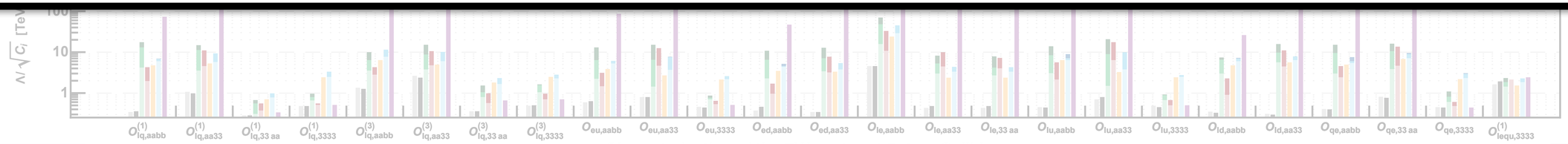
⇒ Predicted Higgs (effective) couplings



hZZ ~hWW

up to custodial symmetry breaking effects

Similar conclusions than in Kappa analysis



Effective Field Theories for BSM physics

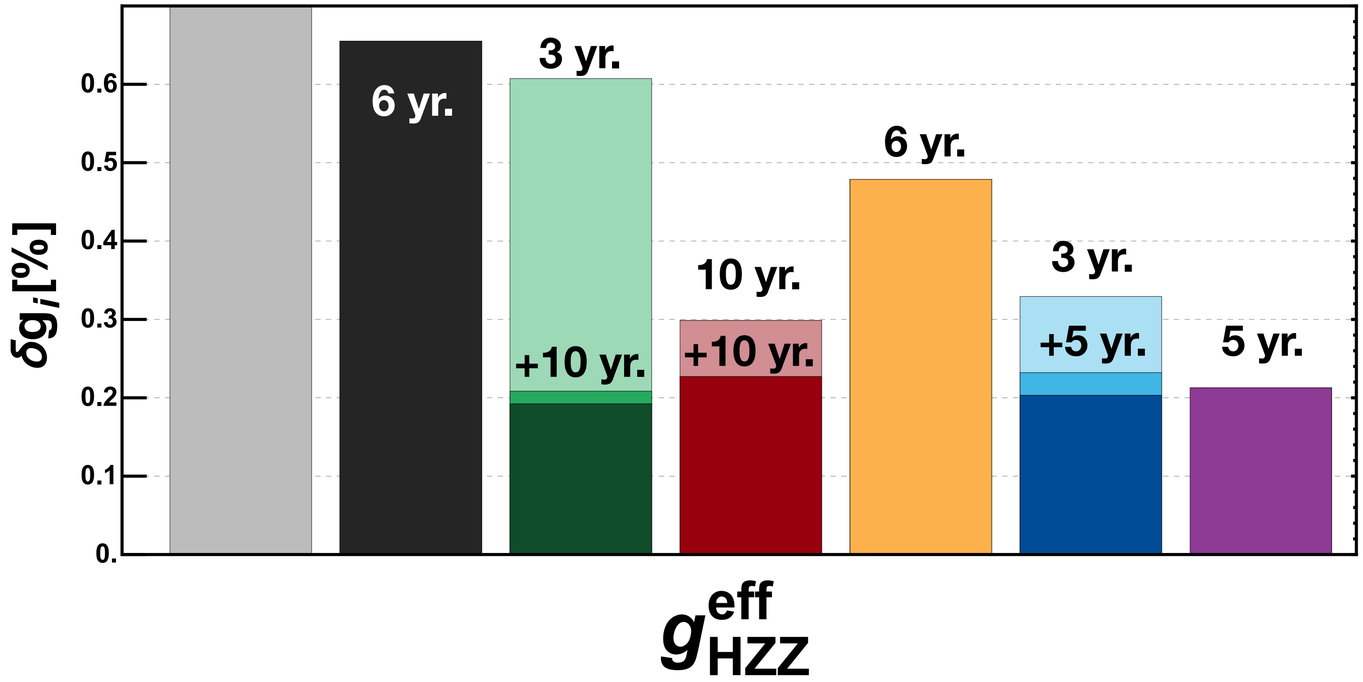
A simple fit to 100 of these operators

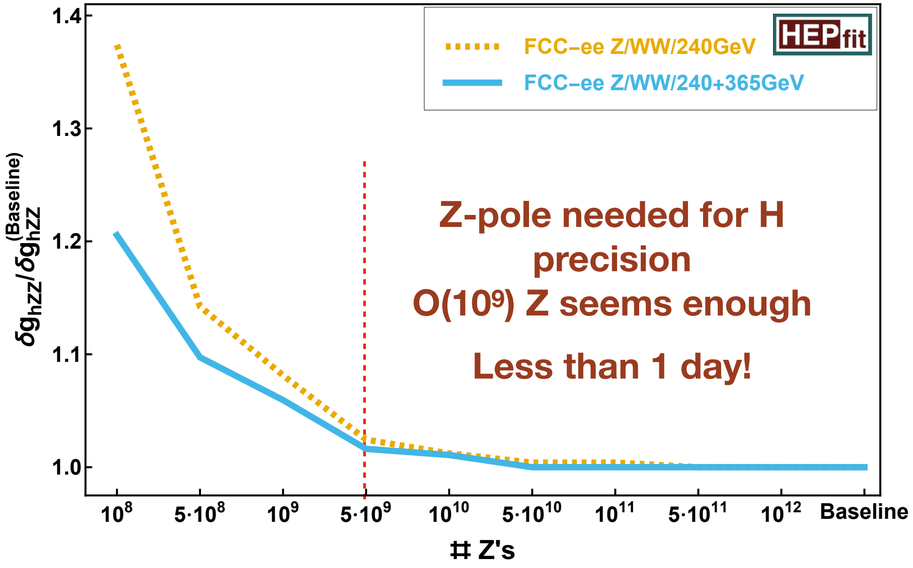
HL–LHC
HL+LHeC
HL+LCF$_{250}$
HL+LCF$_{250/500}$
HL+LCF$_{250/500/1000}$
HL+CLIC$_{380}$
HL+CLIC$_{380/1500}$
HL+LEP3
HL+FCC–ee$_{Z/WW/240}$
HL+FCC–ee$_{Z/WW/240/365}$
HL+FCC
HL+MuC$_{10\ TeV}$

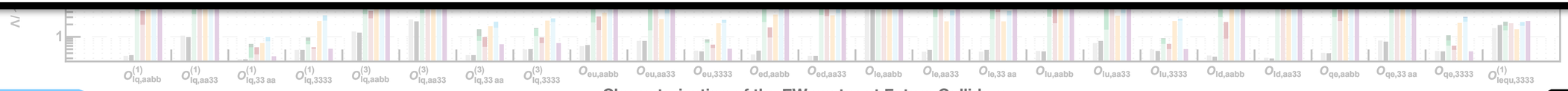
HEPfit

PPG EW WG - June 2025
PRELIMINARY

Precision and time







Effective Field Theories for BSM physics

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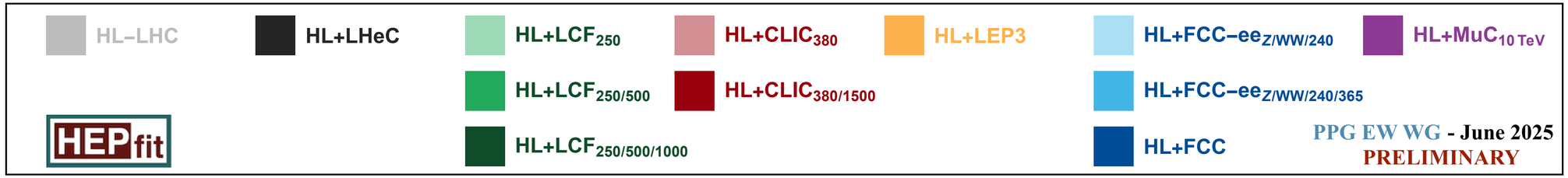
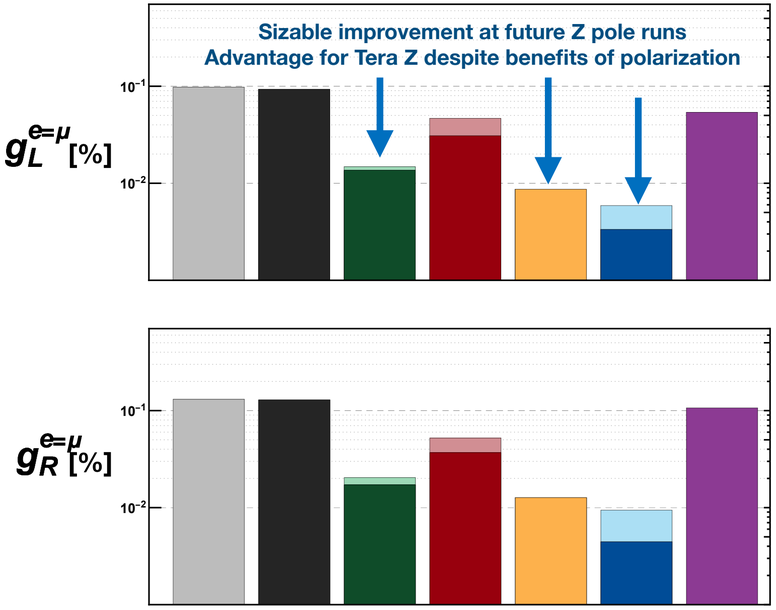
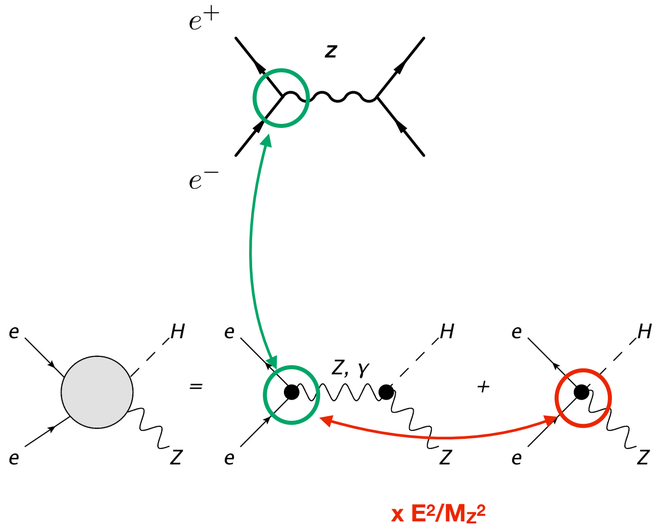
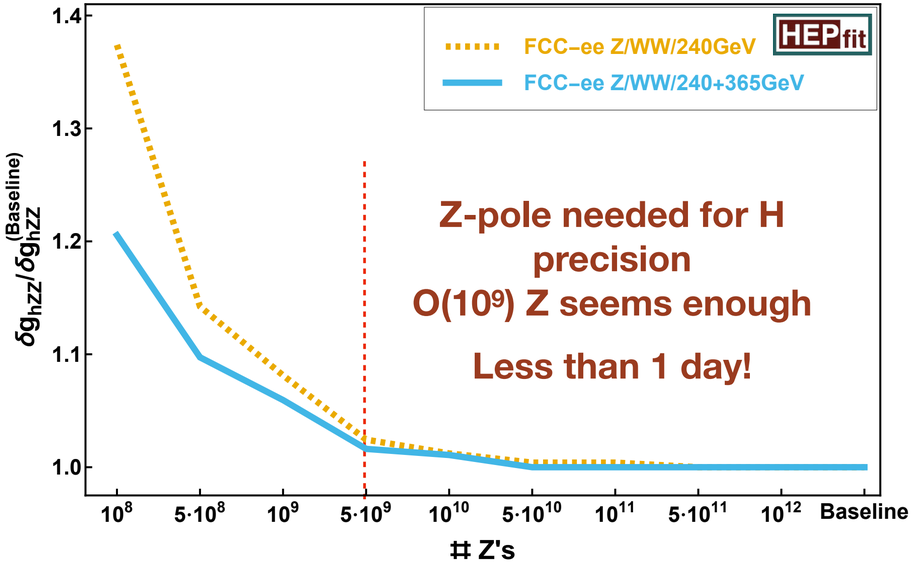


Z pole physics for Higgs physics

Effective EW couplings





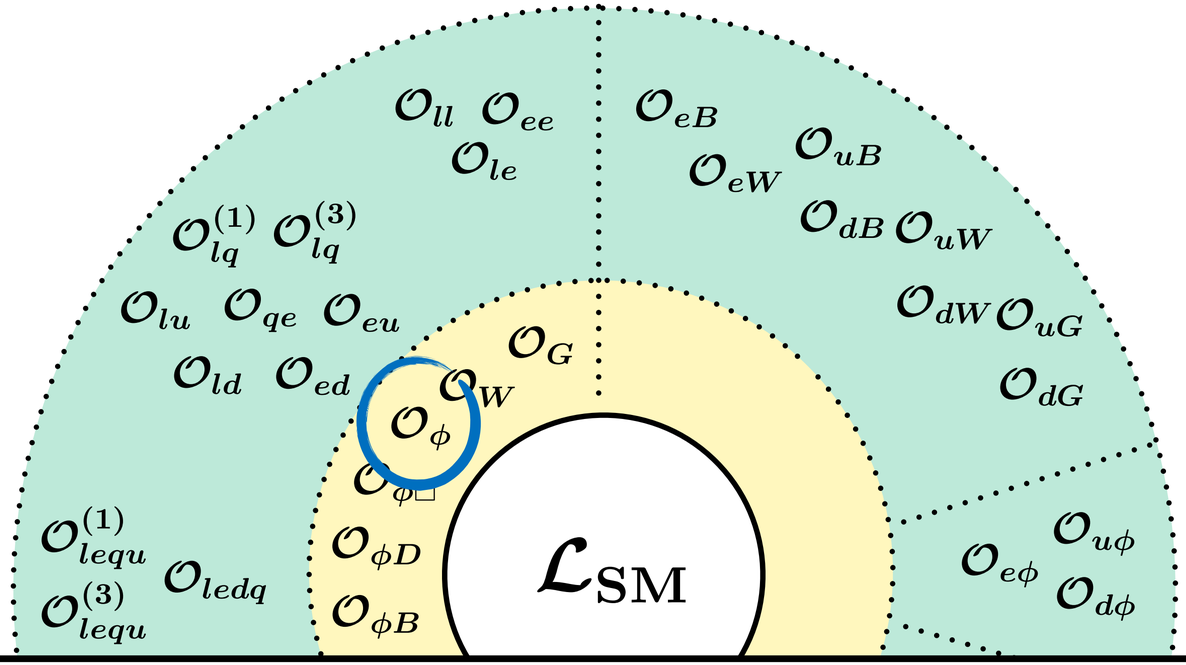


Effect mitigated at linear colliders thanks to polarization

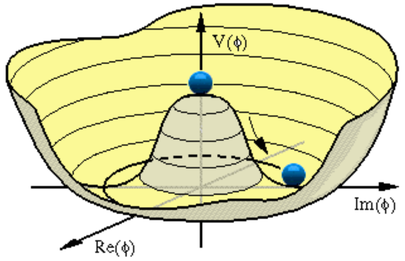
Precision vs. Energy

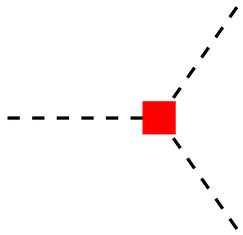
Precision from Energy

Precision vs. Energy: 2 relevant (and related) examples

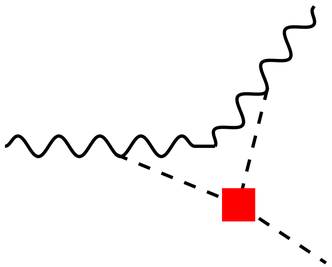


$\mathcal{O}_{\phi}$

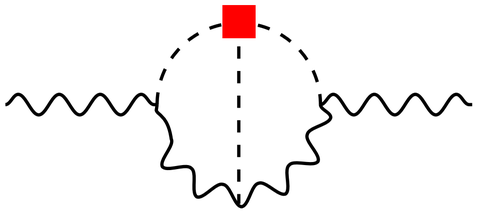




Need to go above HH threshold



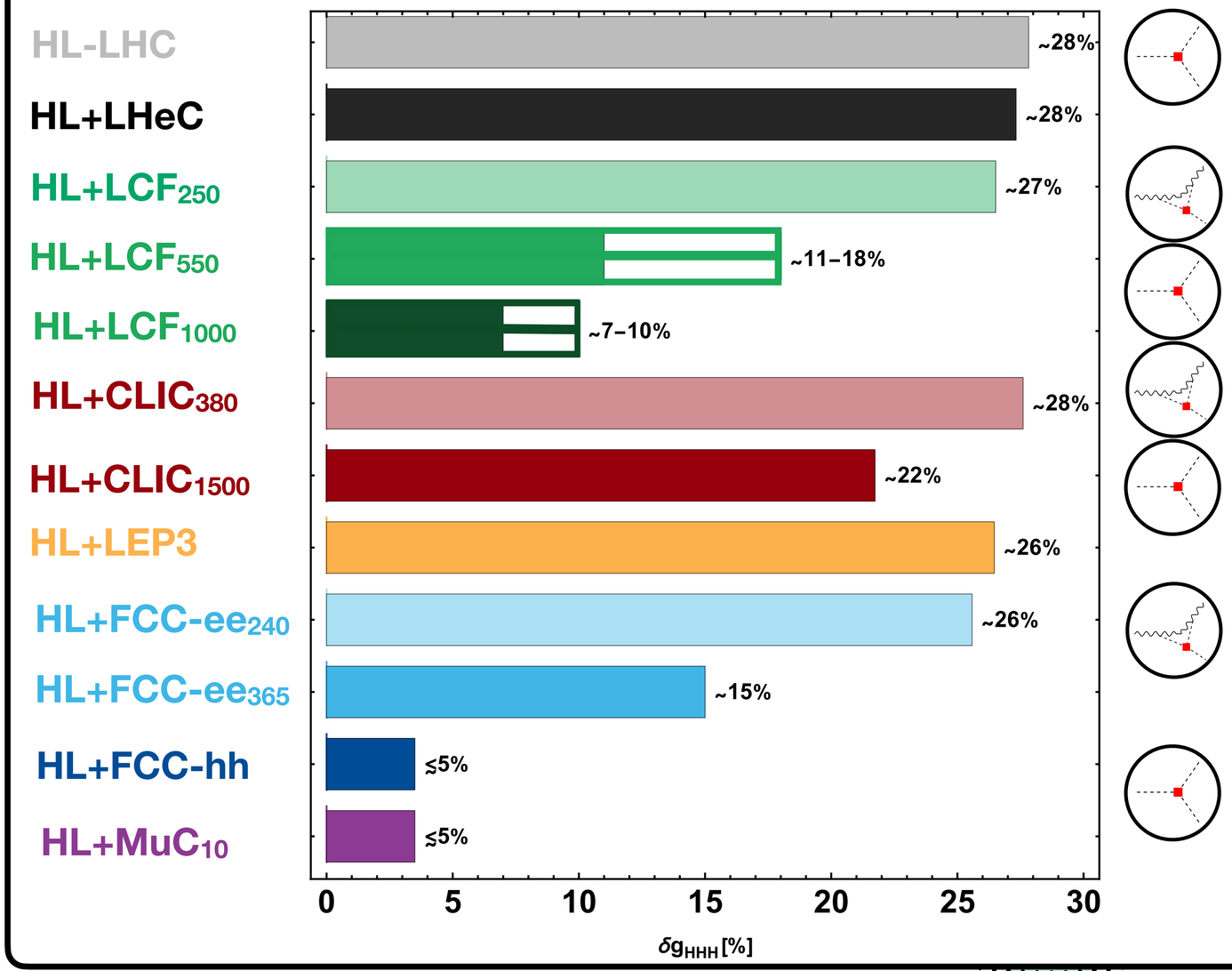
or via precise Higgs measurements

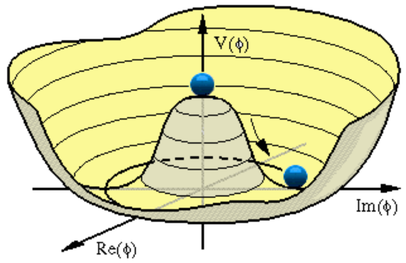


or via precise EWPO

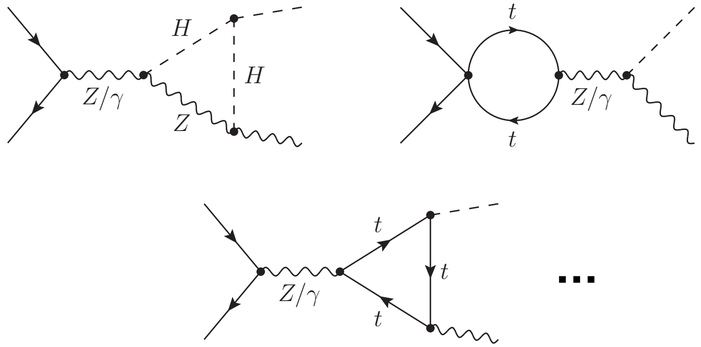
Precision vs. Energy: 2 relevant (and related) examples

On the Higgs self-coupling (Higgs potential)

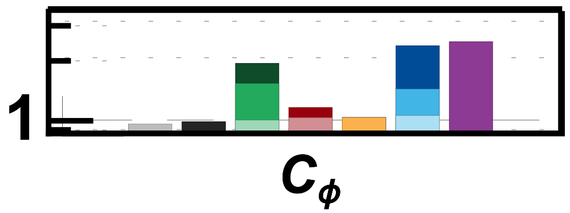




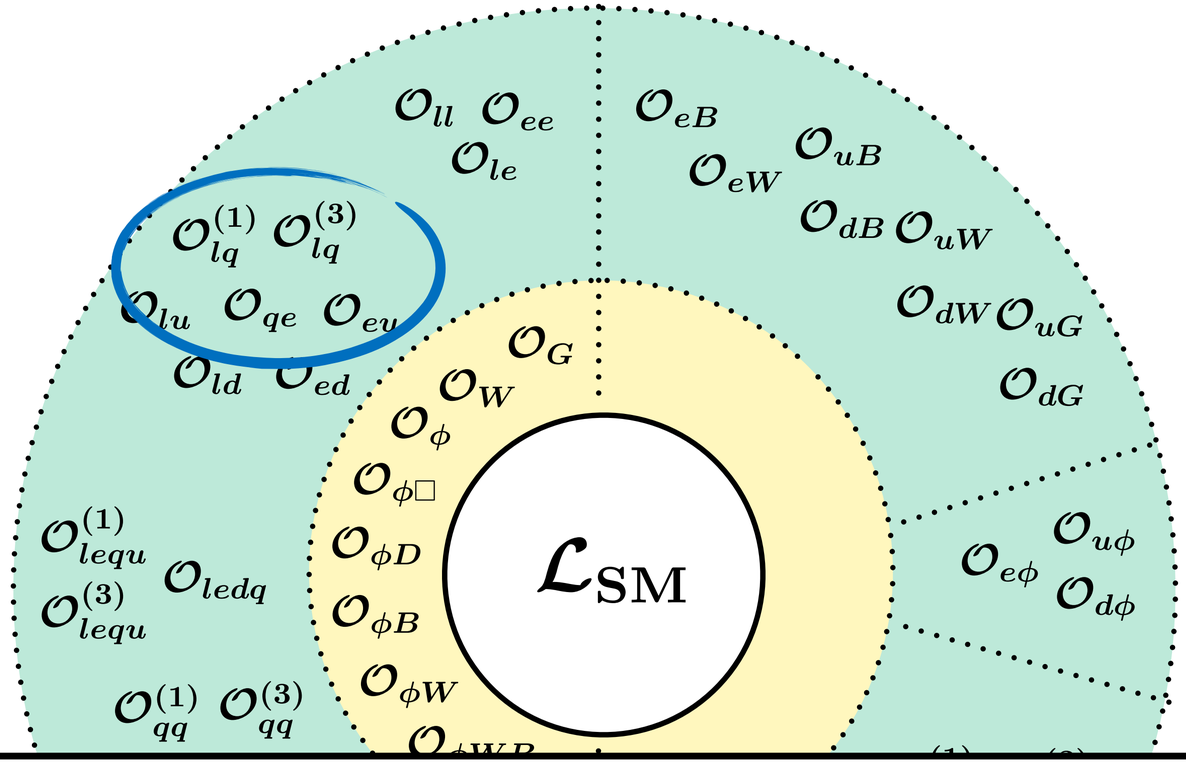
Single-Higgs determination requires constraining other contributions in the loops



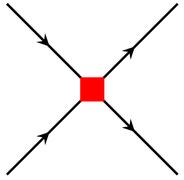
Sizable contributions from Top operators!



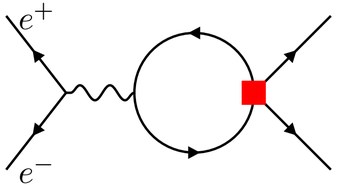
Precision vs. Energy: 2 relevant (and related) examples



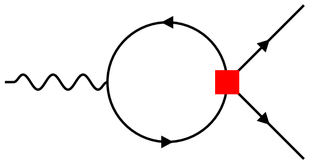
***e⁺e⁻ tt* operators**



Need to go above *tt* threshold

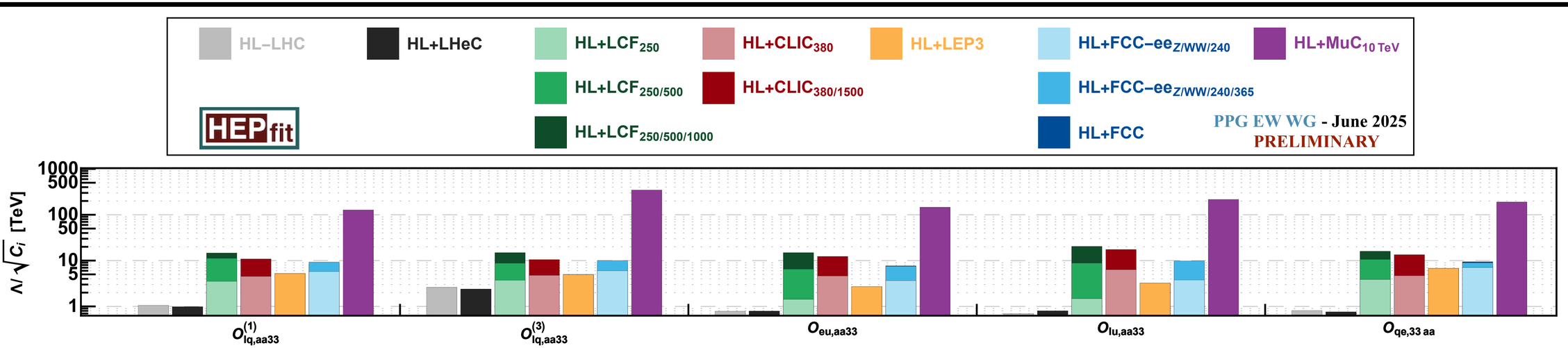


or via precise *e⁺e⁻* →*ff*



or via precise Z-pole

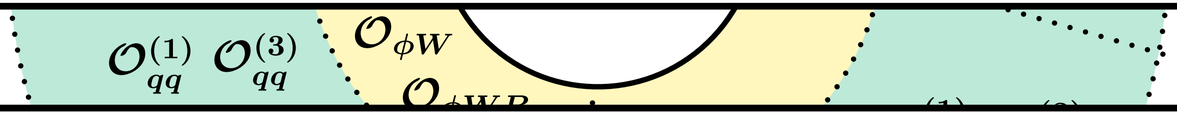
Precision vs. Energy: 2 relevant (and related) examples



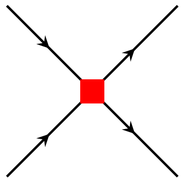
Very high precision can mitigate (to some extent) the lack of top runs at different energies

Still, access to higher and higher energies gives a clear advantage for contact interactions the higher we go in energy

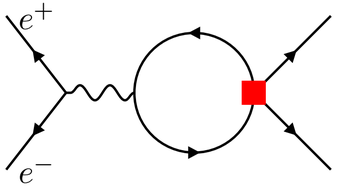
⇒ Precision from energy



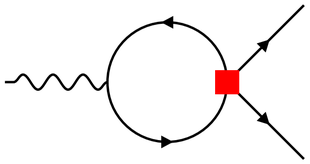
***e⁺e⁻ tt* operators**



Need to go above *tt* threshold



or via precise *e⁺e⁻* → *ff*



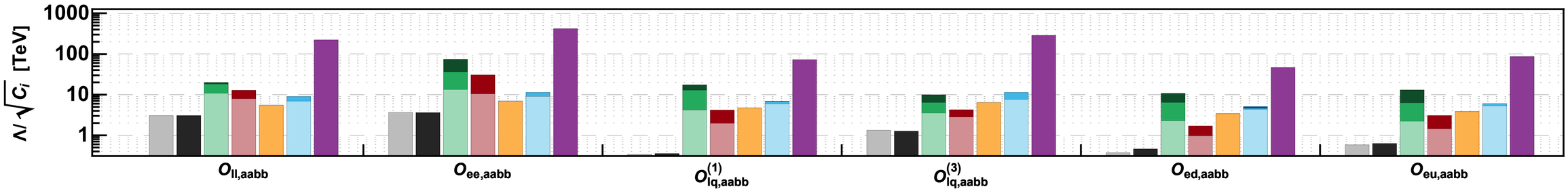
or via precise Z-pole

Precision FROM Energy

Access to higher and higher energies gives a clear advantage for contact interactions the higher we go in energy

⇒ Precision from energy

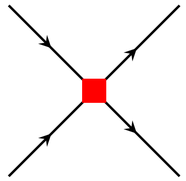
Light 4-fermion interactions in 2 to 2 fermion processes



Lepton collider specific

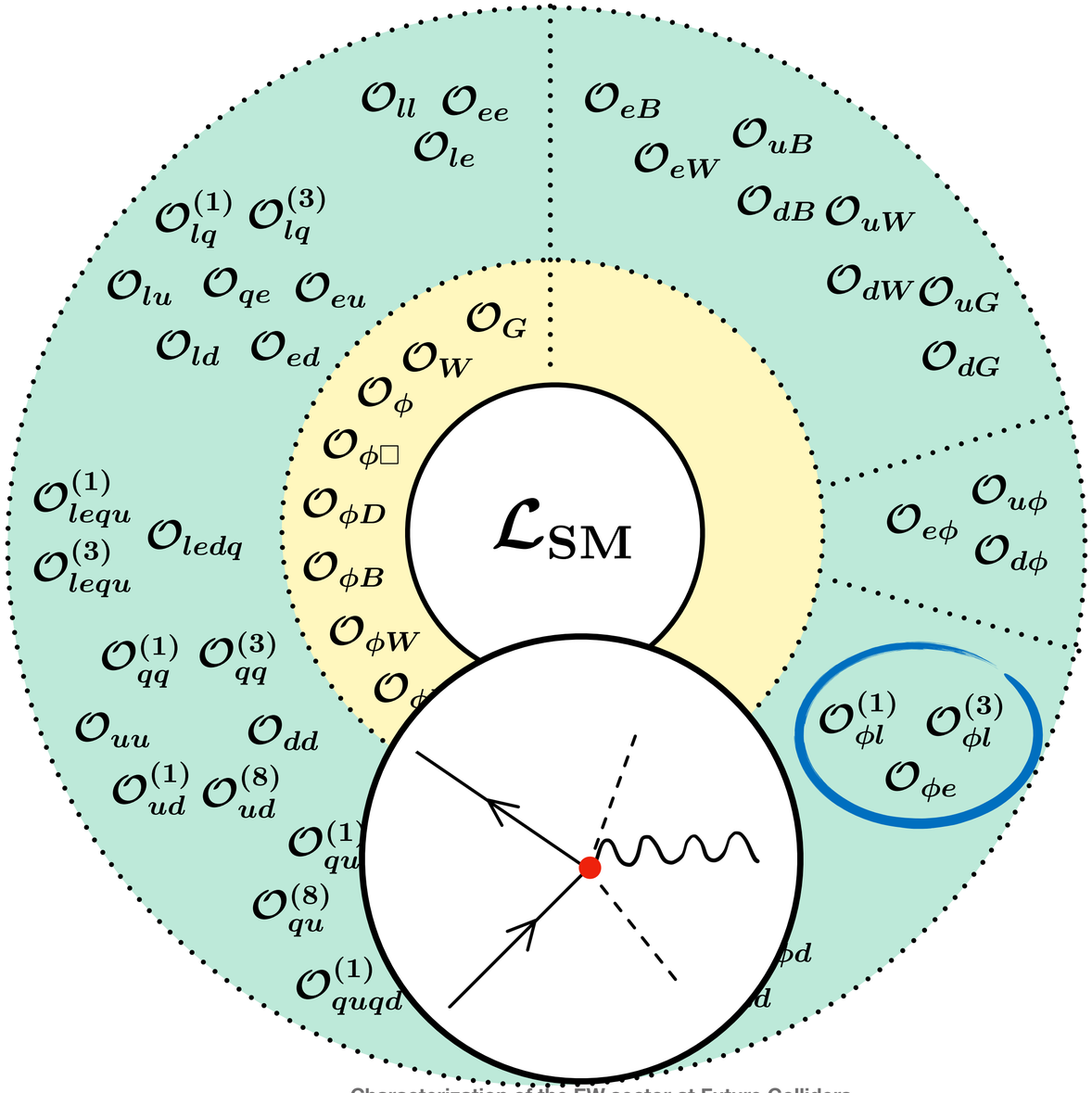
Lepton collider but also FCC-hh (Drell-Yan, WiP)

(FCC-hh also brings access to similar effects for 4q operators via dijet)

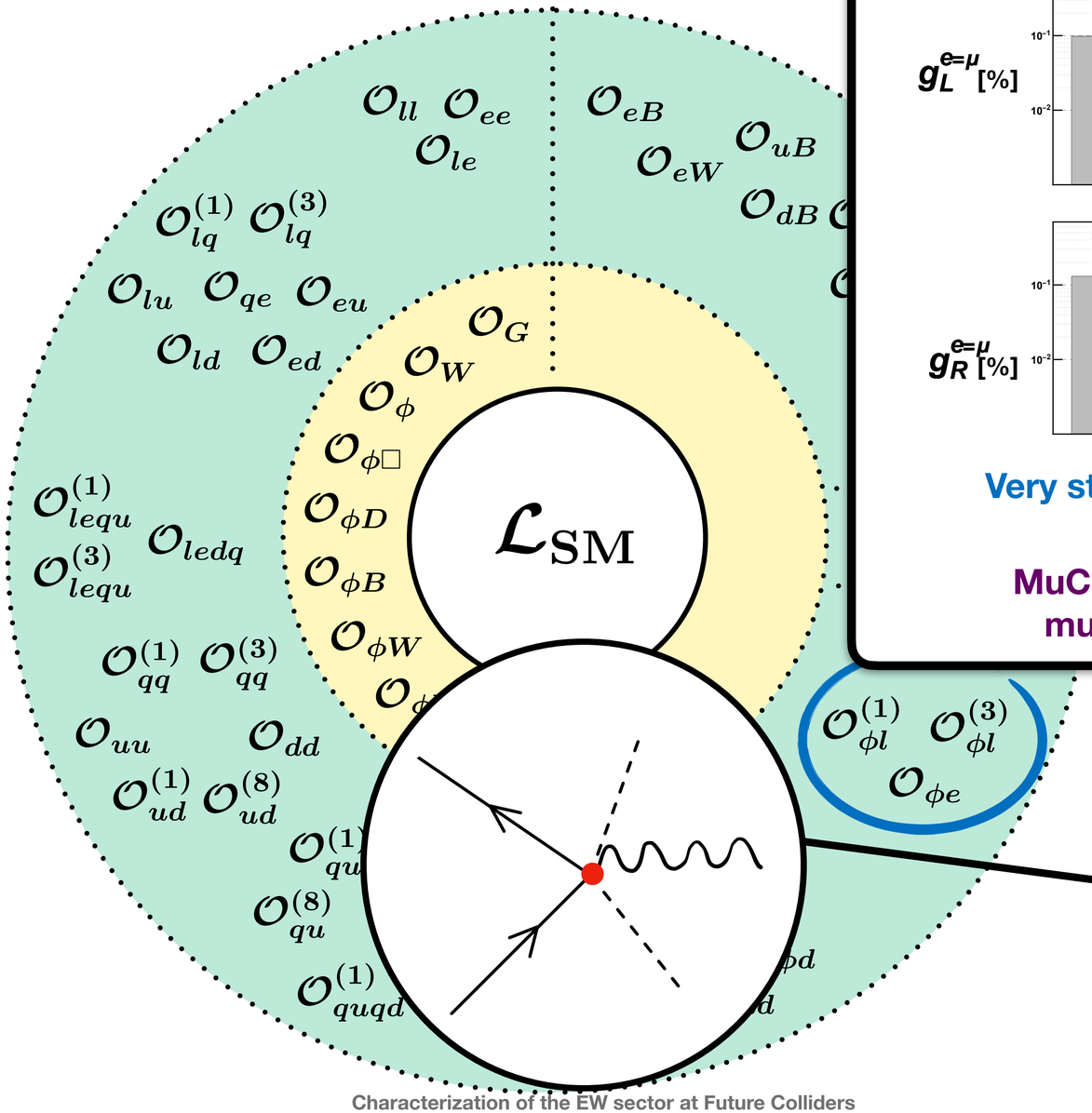


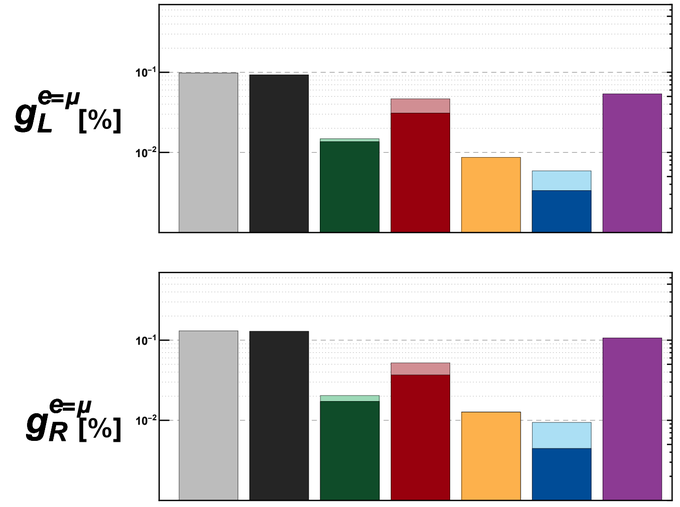
$$\frac{\Delta O}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

Precision FROM Energy: EW physics at high-E machines



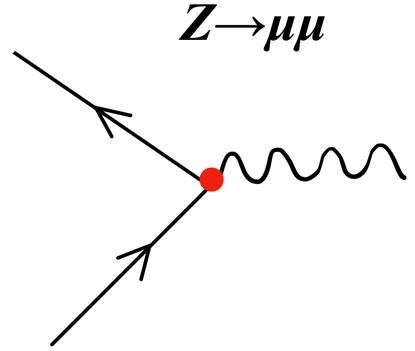
Precision FROM Energy: EW physics at high-E machines





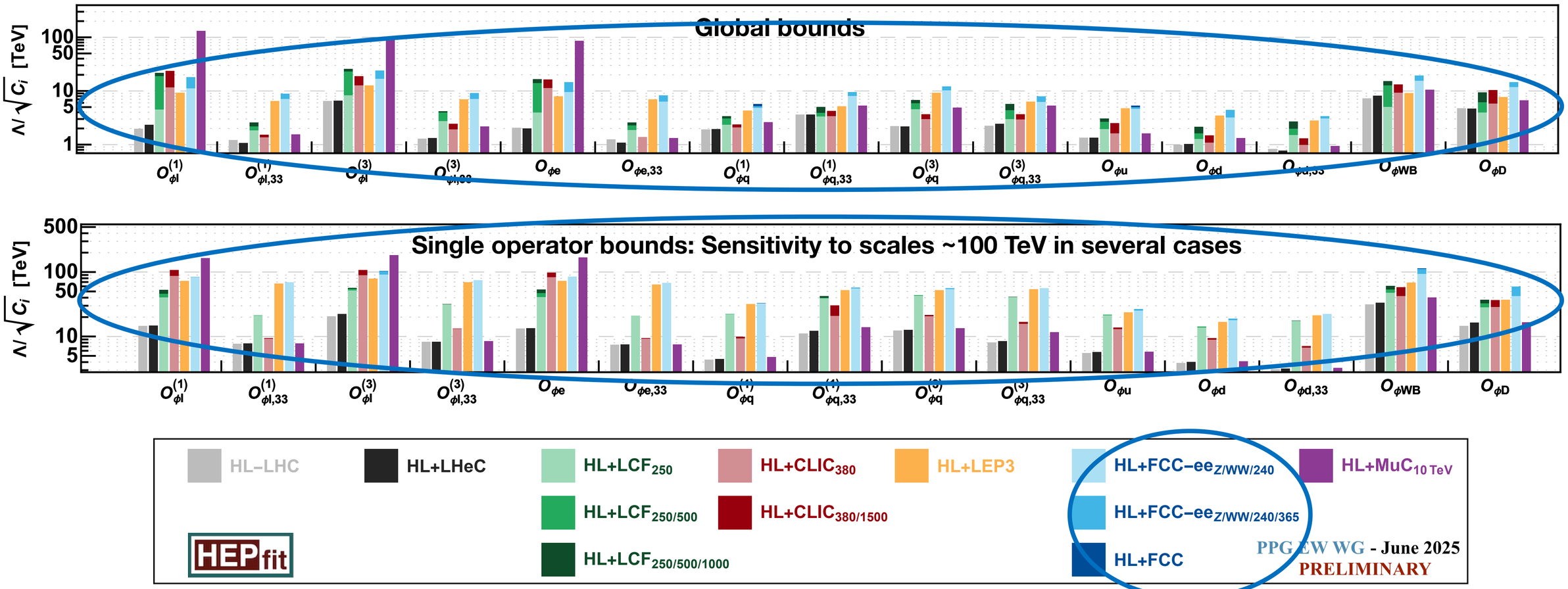
Very strong constraints from EWPO (Z-pole)

MuC, without Z-pole run, seems much worse in comparison?



Precision FROM Energy: EW physics at high-E machines

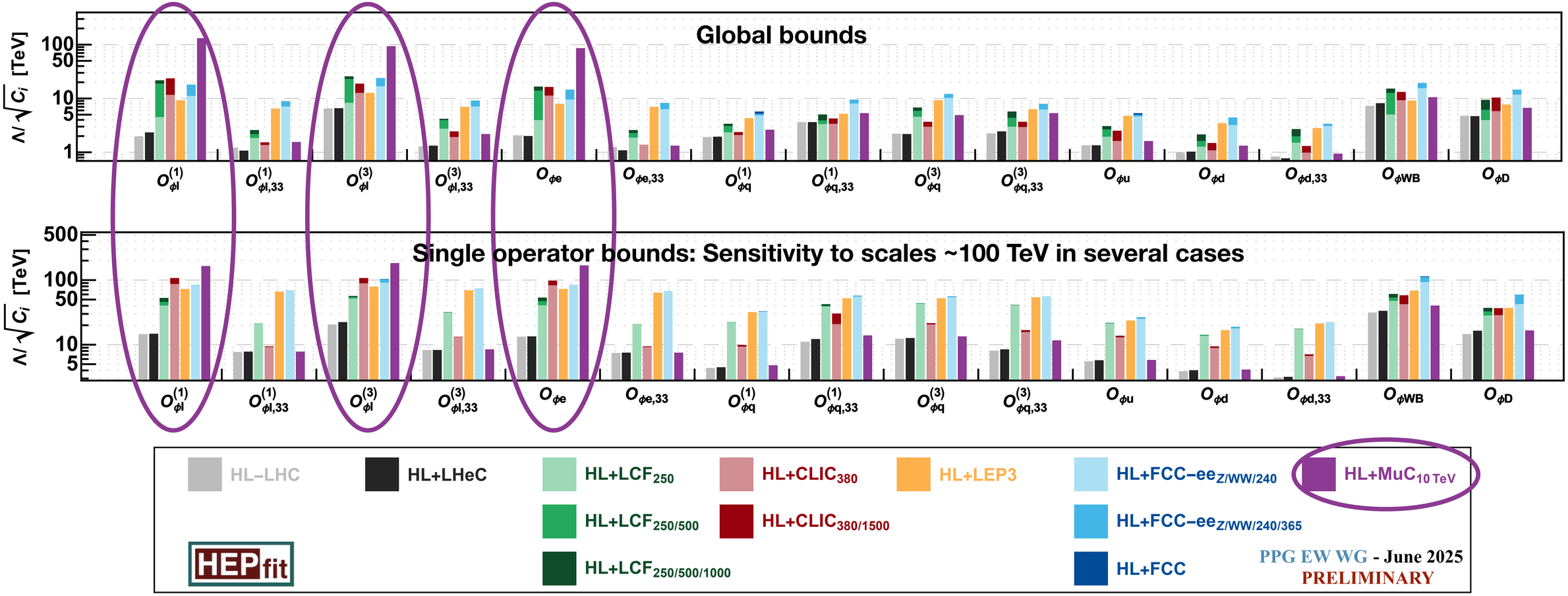
EWPO at Tera Z: Best overall sensitivity to operators modifying EW interactions



Precision FROM Energy: EW physics at high-E machines

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

But muon collider provides stronger sensitivity if NP couples via 2nd family (or universally)



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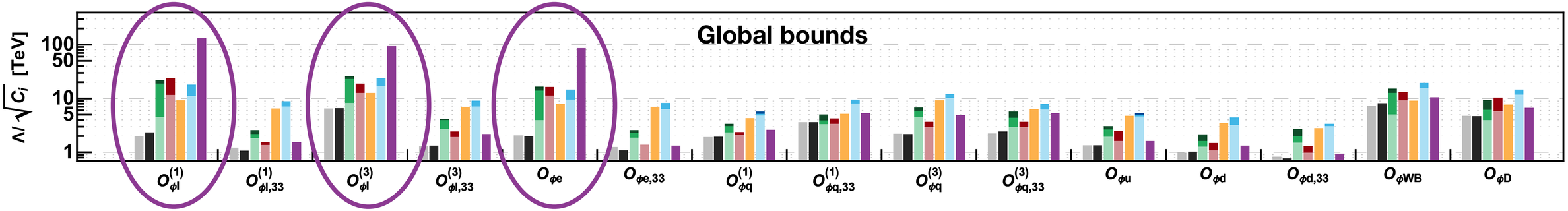
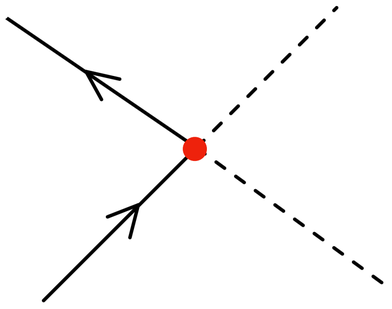
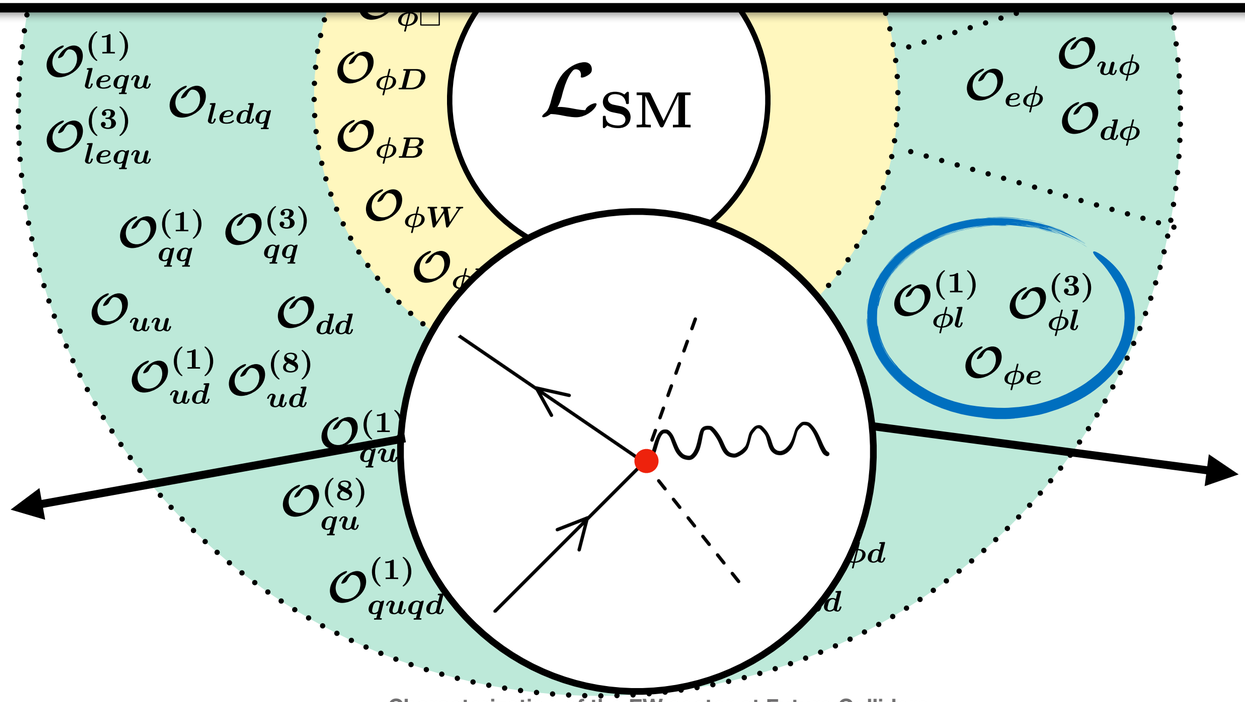


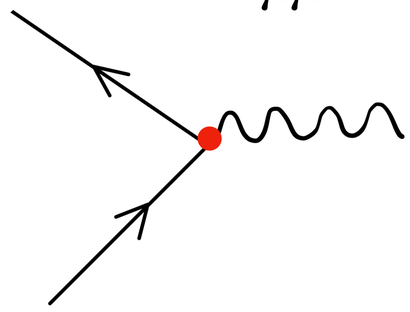
Growing with E effects in diBoson

$\mu\mu \to VV$





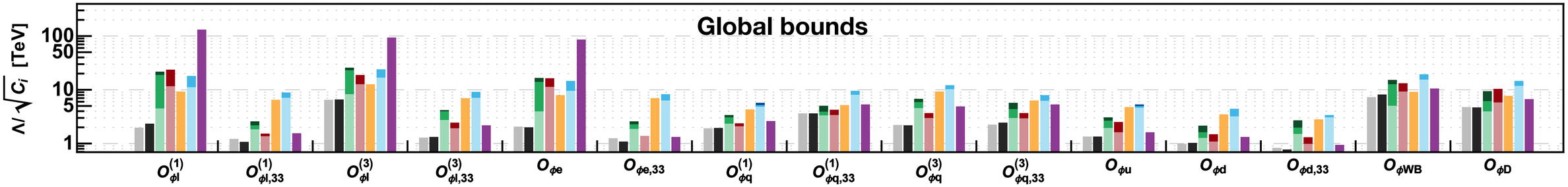
$Z \to \mu\mu$

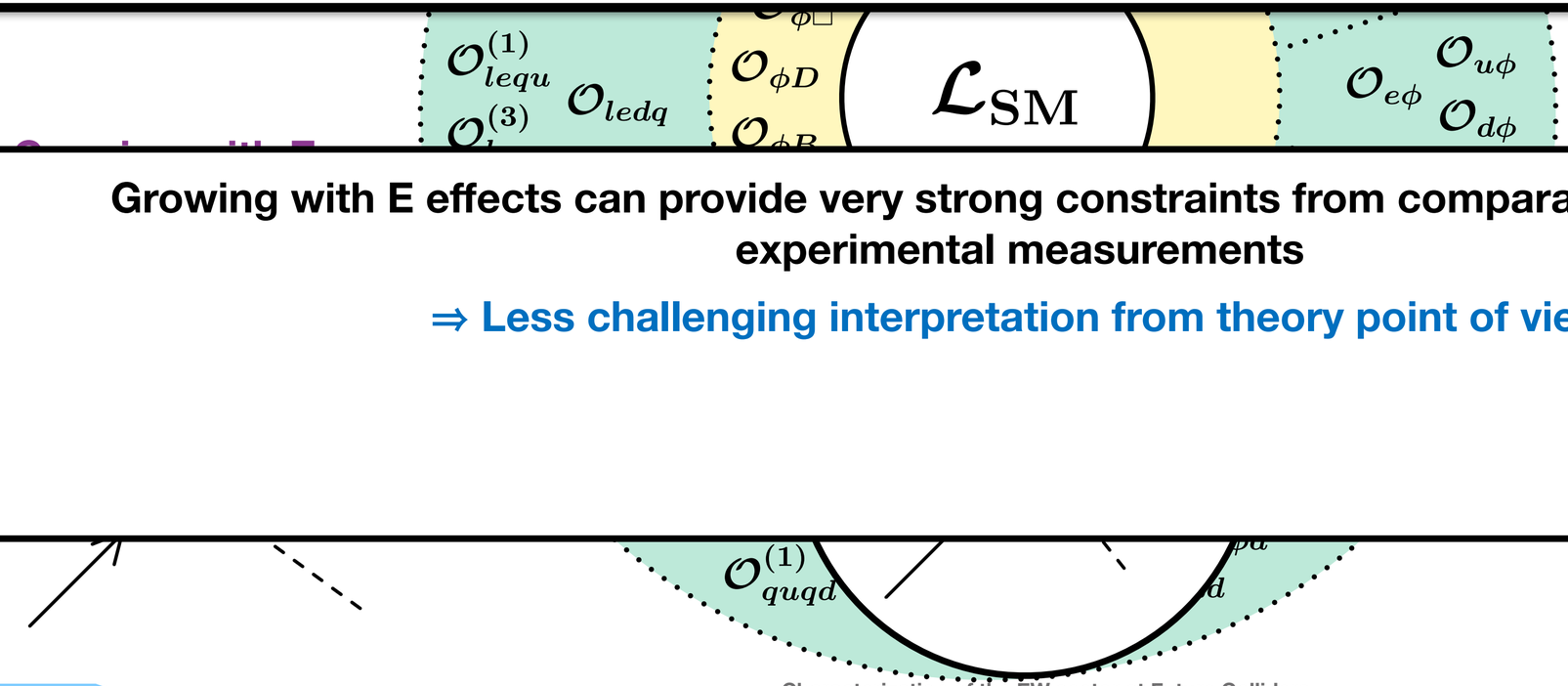


Precision FROM Energy: EW physics at high-E machines

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

But muon collider provides stronger sensitivity if NP couples via 2nd family (or universally)





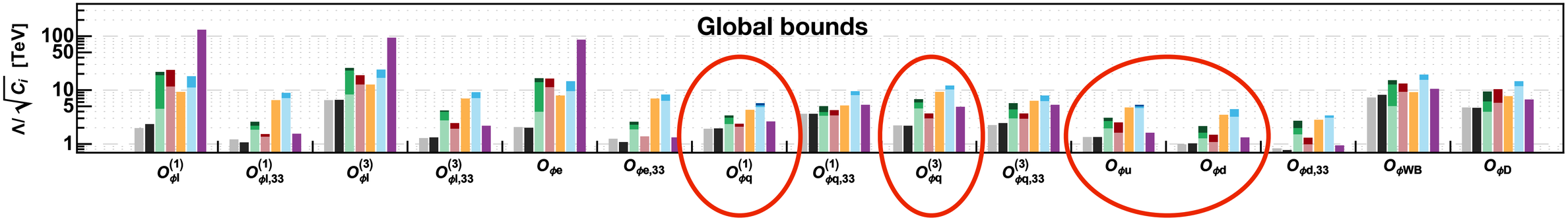
Growing with E effects can provide very strong constraints from comparatively less precise experimental measurements

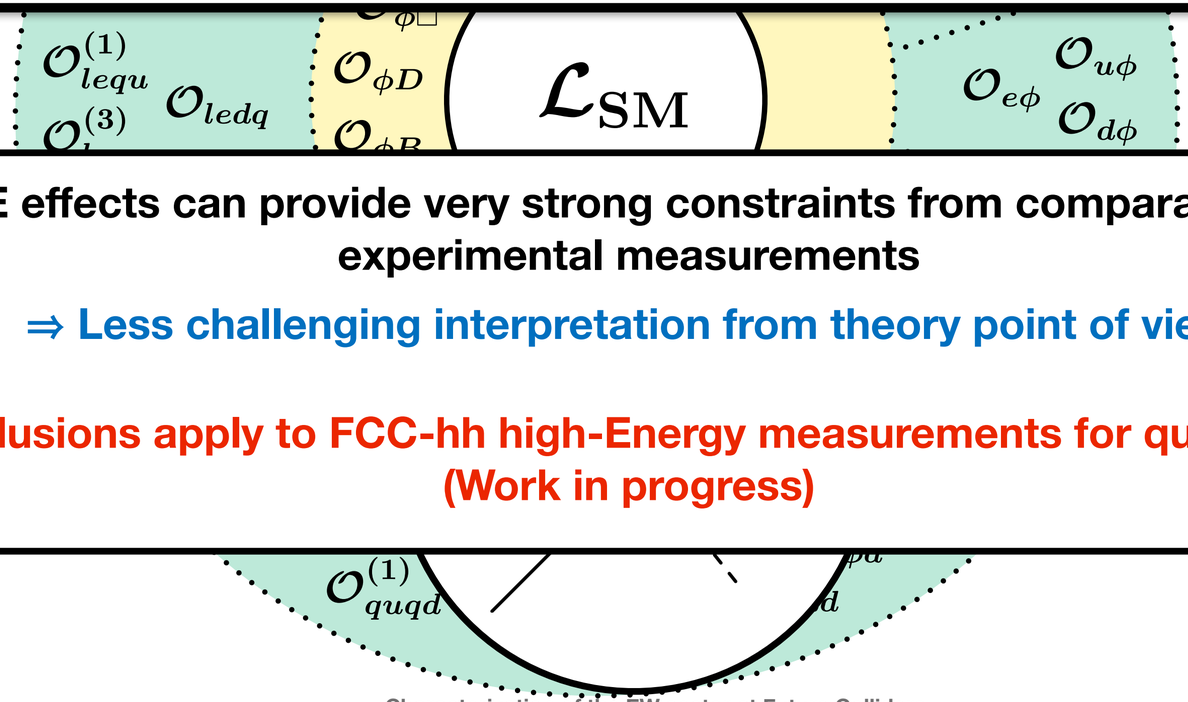
⇒ Less challenging interpretation from theory point of view

Precision FROM Energy: EW physics at high-E machines

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

But muon collider provides stronger sensitivity if NP couples via 2nd family (or universally)





Growing with E effects can provide very strong constraints from comparatively less precise experimental measurements

⇒ Less challenging interpretation from theory point of view

Similar conclusions apply to FCC-hh high-Energy measurements for quark interactions (Work in progress)

EXP Precision

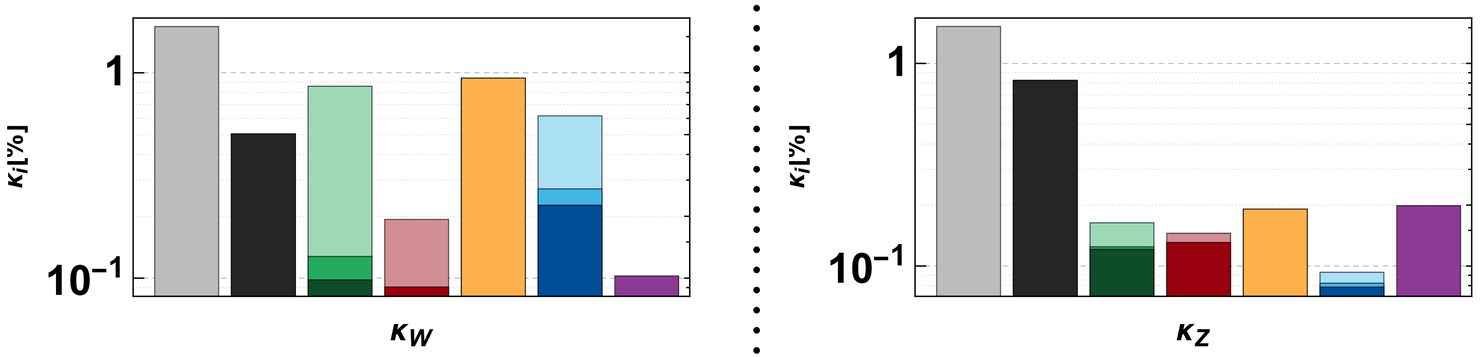
TH Precision

A few words on the impact of theory uncertainties

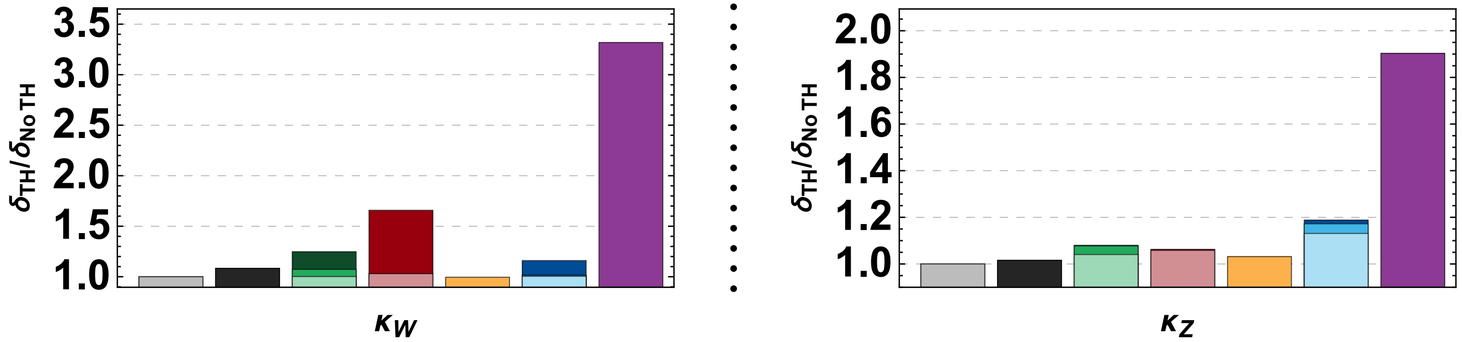
- *Theory precision is fundamental to extract all the information from experimental precision tests*
  - SM theory precision (for interpretation) is likely not going to be a bottleneck in Higgs physics at lepton colliders, unless one goes to very high energies

Impact of Future projected theory uncertainties in production

Kappa-0 baseline:



$$\frac{\textit{Kappa-0 + TH unc.}}{\textit{Kappa-0 baseline}}$$

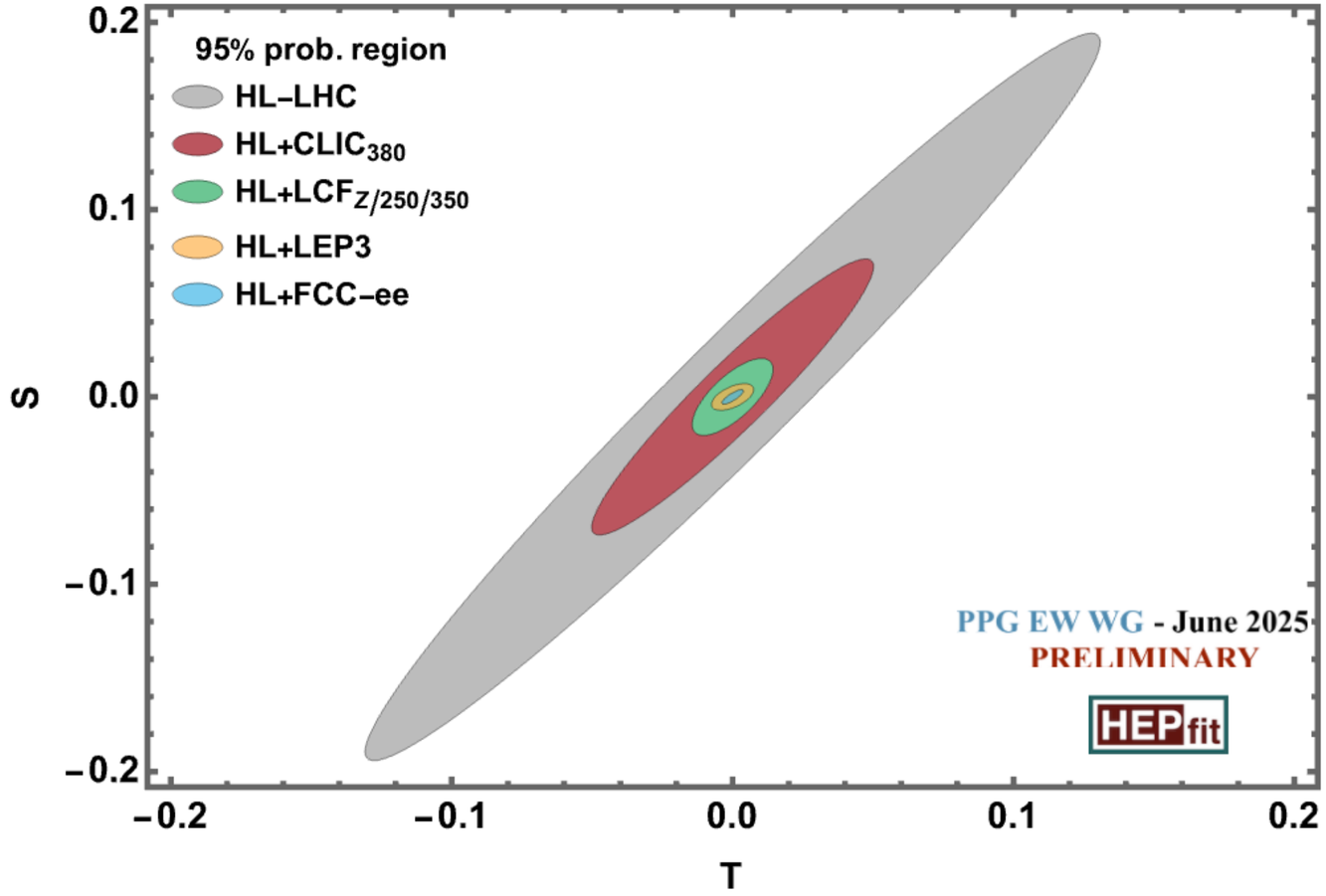


High-E lepton colliders more affected when precision comes from VBF
(log- enhanced EW correction major source of TH uncertainty)

A few words on the impact of theory uncertainties

- *Theory precision is fundamental to extract all the information from experimental precision tests*
  - But the impact may be much larger Electroweak precision measurements (+ rethinking of EWPO needed!)

Impact of projected theory uncertainties in EWPO: ST oblique parameters



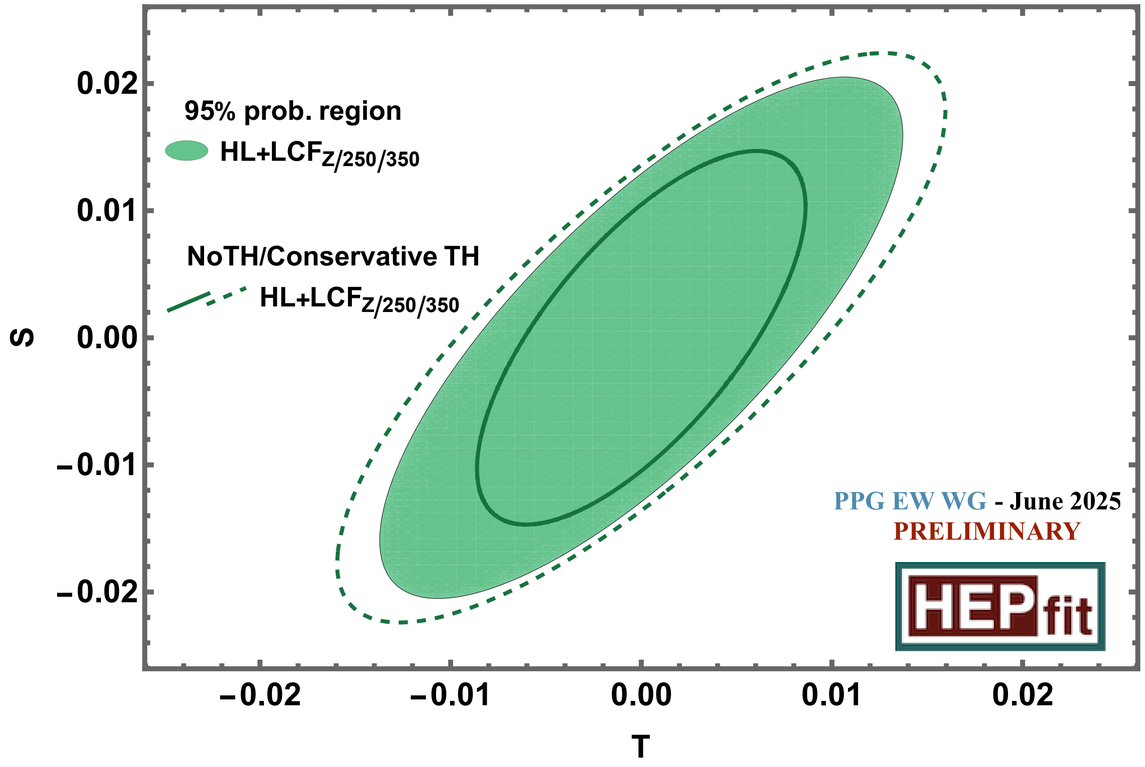
Baseline assuming the "Aggressive" theory uncertainty scenario discussed in A. Freitas talk on Monday

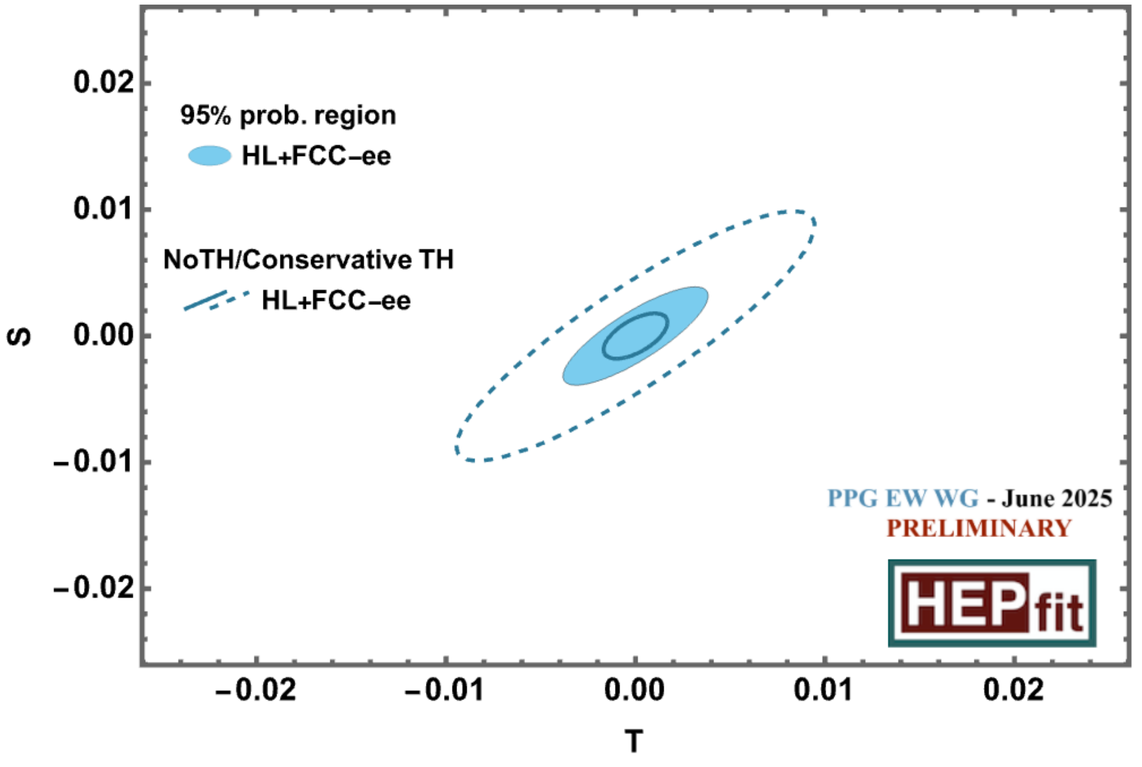
A few words on the impact of theory uncertainties

- *Theory precision is fundamental to extract all the information from experimental precision tests*
  - But the impact may be much larger Electroweak precision measurements (+ rethinking of EWPO needed!)

Impact of Theory uncertainties in EWPO: ST oblique parameters

Comparing the "Aggressive"/"Conservative" Theory uncertainty scenarios discussed in A. Freitas talk on Monday





Large impact on assumptions about the size of theory uncertainties

The road forward

What is left to be done for the Briefing Book

What is missing?

- *The results presented in this talk must be considered as* ***PRELIMINARY***

- *Several things still missing:*
  - Inputs:
    - Information from FCC-hh high-Energy measurements (di-Boson, Top)
    - Updates on some of the inputs still under discussion
  - Outputs: Top couplings

- *A container with the fitting tools used in the study will be made available after the Briefing Book*

Concluding...
Back to the important questions

What do we need?

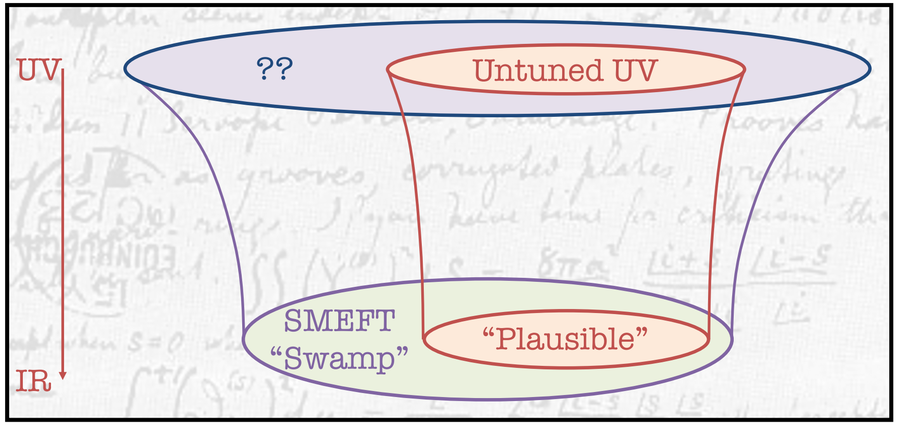
- *Having the highest precision in a single set of measurements vs. less precision over a wider set of measurements?*
  - If we knew what we are looking for, probably the former…
  - We don't know ⇒ We need the most precision we can get over the widest set of measurement possible

- Precision vs. Energy?
  - Both can give access to similar new physics effects in the SMEFT interpretation
  - The key word is complementarity: consistency of high-energy results with low-energy precision measurements can bring extra information
  - Caution: part of the complementarity is lost if some of the SMEFT assumptions are not valid (e.g. HEFT)…

What do we need?

- How much experimental precision? Short answer would be "as much as possible" but…
  - Challenges: Theory precision/Detector designs capable of matching target precision. Not an easy task

- If we can overcome these challenges, what still matters most it to have a large array of measurements that can be used to characterize the origin of an eventual NP signal
  - Not only Electroweak measurements ⇒ Flavour, Neutrino, QCD, … Inputs from all WGs are needed to get a global picture of what is the best collider option and…
  - BSM WG: Where everything comes together to get answers to the open questions of particle physics



Not all SMEFT directions are equal

SMEFT tells you about what measurement can do
BUT some BSM perspective should be taken into consideration to decide what is most important

What do we need?

- How much experimental precision? Short answer would be "as much as possible" but…
  - Challenges: Theory precision/Detector designs capable of matching target precision. Not an easy task

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- Finally, we should keep in mind that we can still find something at the LHC! What's next?
  - Many models could be consistent with a given signal
  - Consistency with much higher precision tests of the EW sector would be crucial in guiding future direct searches and to uncover the new sector