European Strategy for Particle Physics

Open Symposium
2026 Update
European Strategy for Particle Physics
June 23, 2025

Technical details of the Fits and Comparisons

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Based on the work prepared by the PPG EW WG:

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

Universidad de Granada

Introduction (Disclaimer)

- As the title indicates, **this will be mostly a technical talk**, explaining the details of the studies prepared by the Electroweak Working Group to compare the different collider projects

  (What we have so far and some things that are still in the process)

- The benchmarks follow some of the studies of the previous ESPP, but have been significantly extended in the scope, both from the theory and experimental point of view

- **Only a few results shown at the end**

Introduction

- **Two main frameworks used for the comparison of big projects:**

Kappa framework ➤ Higgs precision

EFT framework ➤ General BSM exploration

Details on the
Kappa framework comparisons

Kappa framework description of Higgs precision

- Compact description of precision of Higgs measurements taken the SM as reference:

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

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

- **PROS:** Does not require any BSM calculation per se and it is easy to interpret for several interesting NP models (e.g. CH, MSSM)
- **CONS:** Not usable beyond single-Higgs processes, does not benefit from kinematic information, polarization, …
- Two scenarios considered (naming following previous ESPP but Kappa-0 now includes HL-LHC)

$$\text{Kappa-}n = \{\kappa_Z, \kappa_W, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, \kappa_t, \kappa_b, \kappa_c, \kappa_s, \kappa_\tau, \kappa_\mu, \mathrm{BR}_{\mathrm{inv}}, \mathrm{BR}_{\mathrm{unt}}\}$$

Kappa-3 (all parameters, κ_Z through $\mathrm{BR}_{\mathrm{unt}}$)

Kappa-0 (κ_Z through κ_μ)

New physics contributions to Higgs width that are either invisible (inv) or not "tagged" by Exp. analyses ("unt")

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For HL-LHC & LHeC this fit doesn't close w/o assumptions ⇒ Add κ_V<1

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One κ_f for each $H \to f$

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BSM decays

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Projections only for e^+e^-

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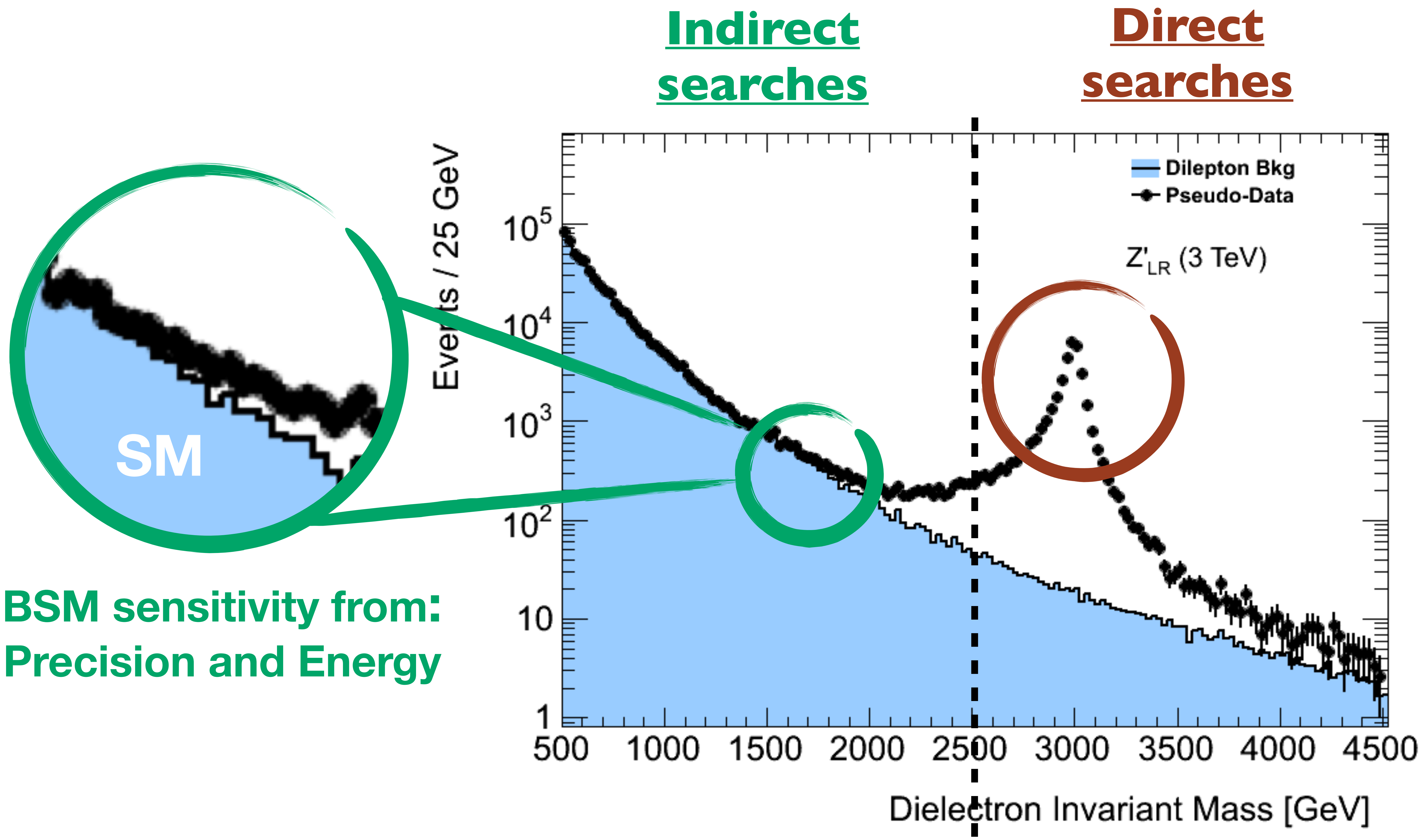
Ignores custodial symmetry works to good approximation!

But chosen to illustrate different precision of Z/W Higgs channels

Details on the
EFT framework comparisons

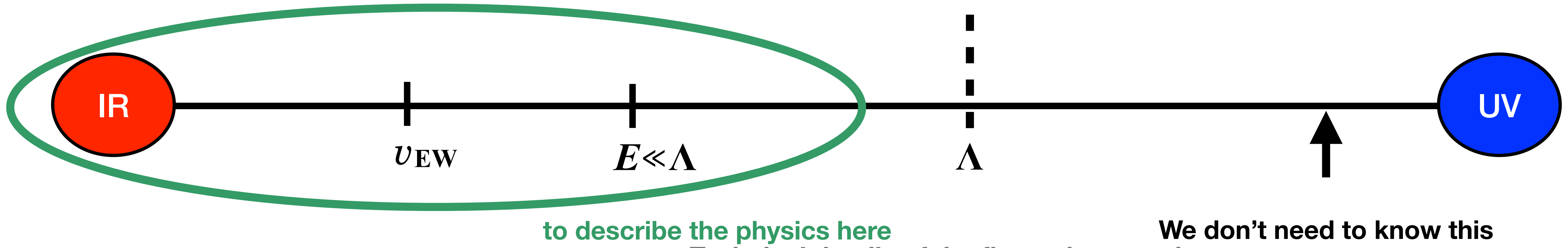
Effective Field Theories for BSM physics

- Framework used across several of the PPG Working Groups to study indirect sensitivity to BSM



$$\mathcal{L} = \mathcal{L}_{\mathrm{EFT}}(\supset \mathcal{L}_{\mathrm{SM}})$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{NP}} + \mathcal{L}_{\mathrm{NP-SM}}$$



Effective Field Theories for BSM physics

SMEFT assumptions

- With some minimal assumptions about the UV, the IR effects of new physics can be parameterized via an Effective Lagrangian

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \longleftarrow \mathcal{L}_{\rm UV}(?)$$

$$E \ll \Lambda$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

$$q = v, E < \Lambda$$

IR: SM Symmetries & Fields (H in 2~SU(2)$_L$) + Decoupling for $\Lambda \to \infty$

- Approximates the effect of any model under these assumptions
  - Even if someone's favorite model does not fit in these assumptions (e.g. light d.o.f.), the SMEFT provides a very *general* framework to explore BSM deformations, *well-motivated phenomenologically* and mature in terms of tools and techniques

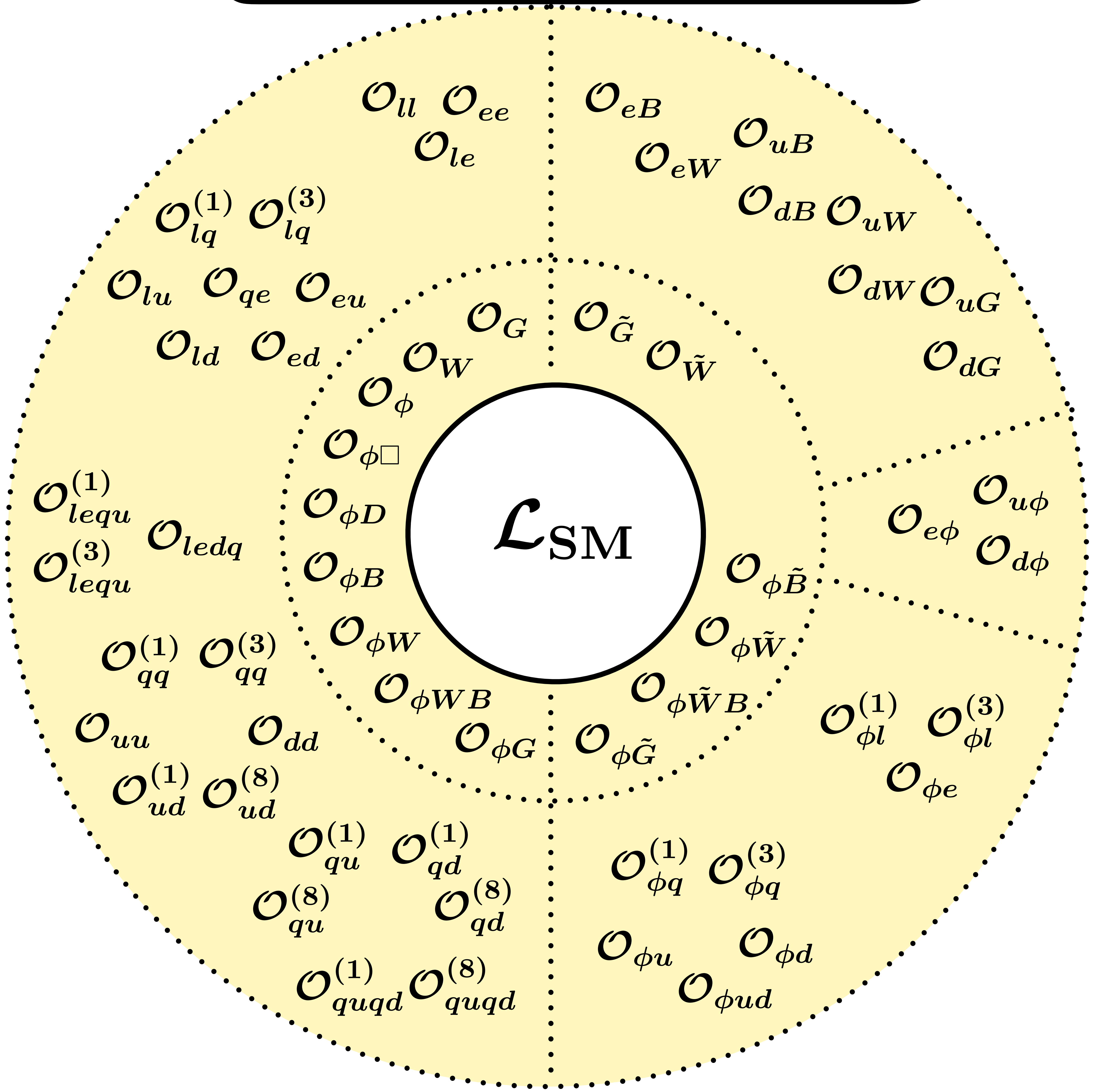
Not perfect, but it is arguably today's best choice for a comparison exercise without going directly into specific models

Effective Field Theories for BSM physics

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

The SMEFT @ d=6

59 Operator structures



Effective Field Theories for BSM physics

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

The SMEFT @ d=6

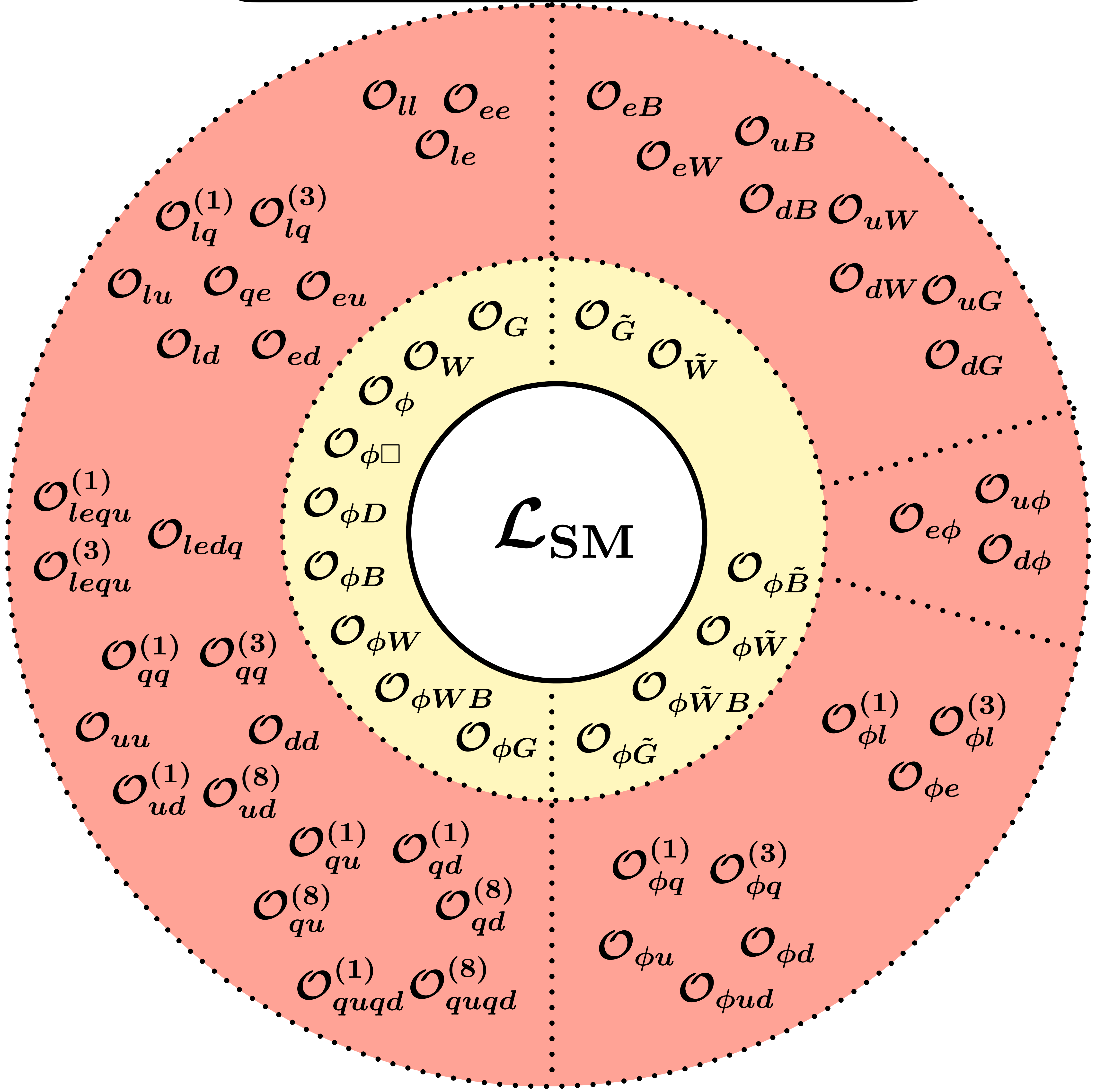
59 Operator structures

↓

2499 Operators

Most of the SMEFT is Flavor

Need reasonable assumptions to "decouple" Flavor from EW constraints



Effective Field Theories for BSM physics

Decoupling EW and Flavor

- Scale of flavor constraints typically larger than EW ⇒ Need some Flavor "protection"
  - Assume New Physics respects the approximate U(2) quark flavor symmetries of the SM

    ⇒ No new sources of flavor mixing but separate 3rd and light generations

$$U(2)_{q_L} \times U(2)_{u_R} \times U(2)_{d_R}$$

- For this symposium, adopted full $U(2)^5$ flavor symmetry (+ CP conservation) ⇒124 operators

$$U(2)^5 = U(2)_{q_L} \times U(2)_{u_R} \times U(2)_{d_R} \times U(2)_{l_L} \times U(2)_{e_R}$$

Selects 124 operators of the general SMEFT

(Leptonic U(2) symmetries may be lifted for Briefing Book - less restrictive)

Effective Field Theories for BSM physics

Decoupling EW and Flavor

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⇒ No r

- For this sy

Implications of Flavor assumptions

- New physics cannot modify, independently, light-quark Yukawa (e.g. charm)

  ⇒ Covered in Kappa framework anyway

- Electron and Muon go together: facilitates comparison of e^+e^- and $\mu^+\mu^-$, but misses information from universality tests
  - Can be recovered, if relevant, lifting the leptonic U(2)

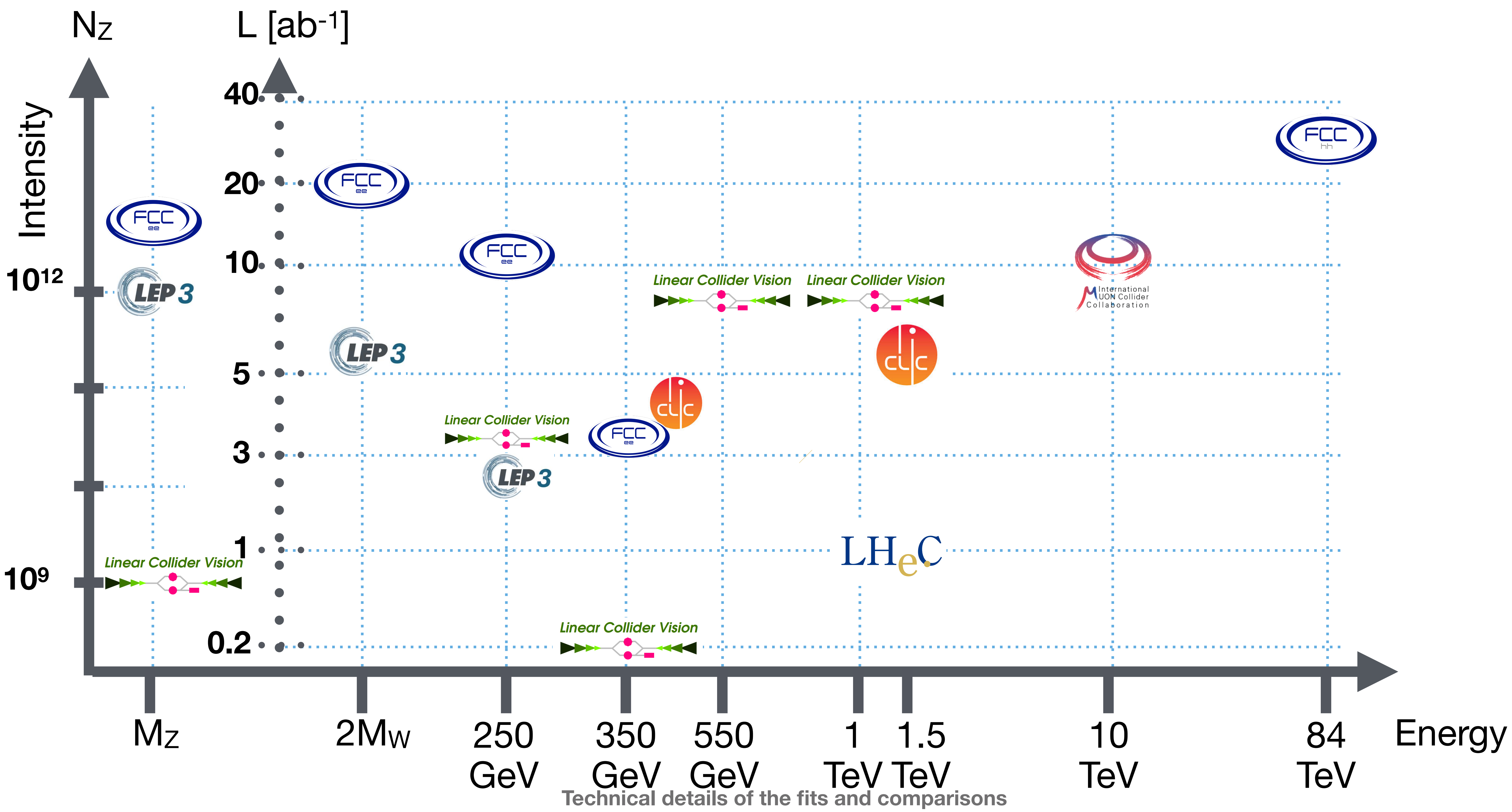
(Leptonic U(2) symmetries may be lifted for Briefing Book - less restrictive)

Effective Field Theories for BSM physics

Setting the scale

- EFTs should only be used at energies below the cut-off scale Λ, but each collider have different energy reach…
- In general, flavor assumptions on NP are technically scale dependent
  (though for the previous assumptions, respecting SM approximate symmetries, the dependence should be small)

⇒ For consistency, set the same scale Λ in the comparison. Which one?



Effective Field Theories for BSM physics

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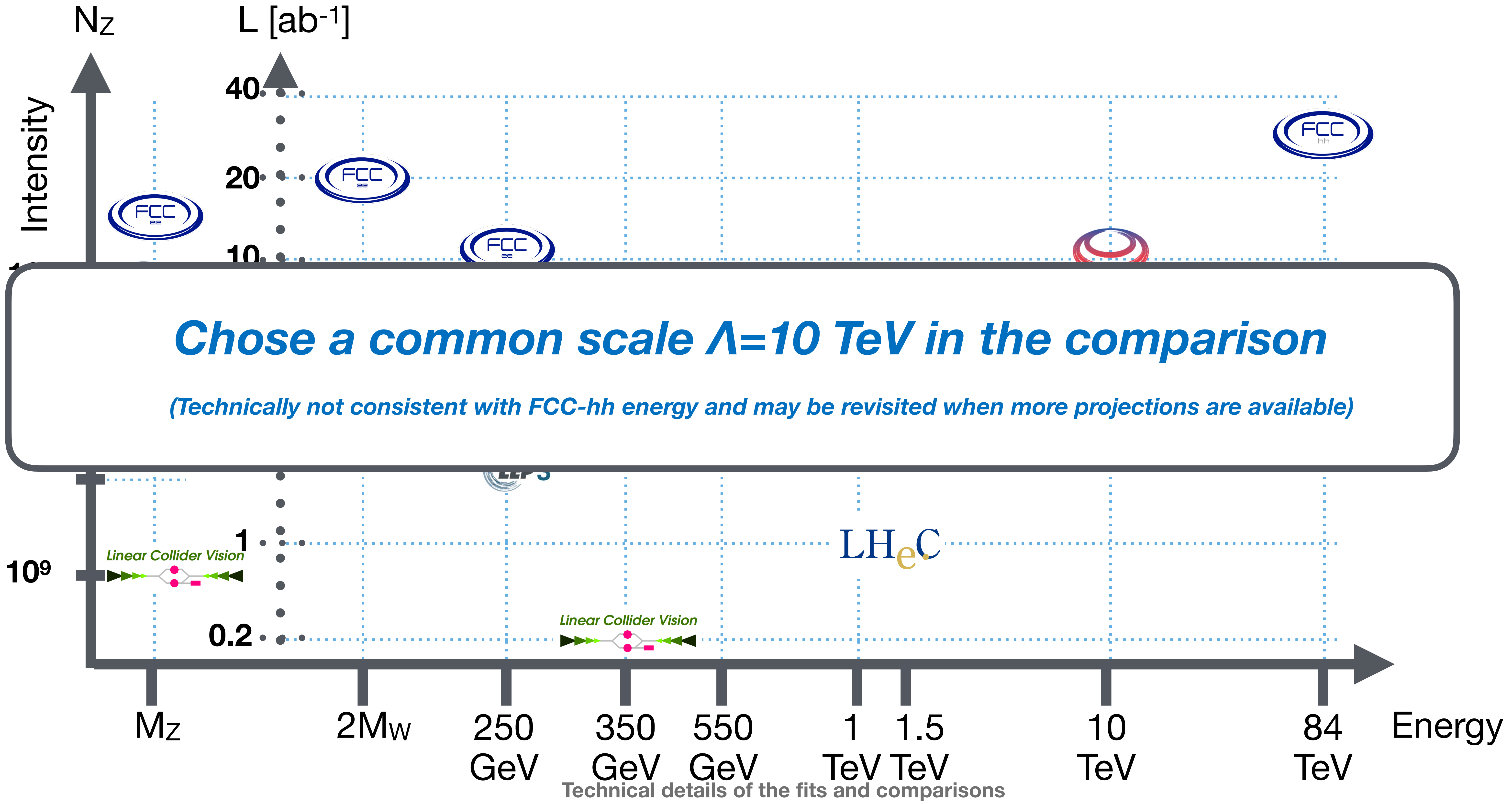


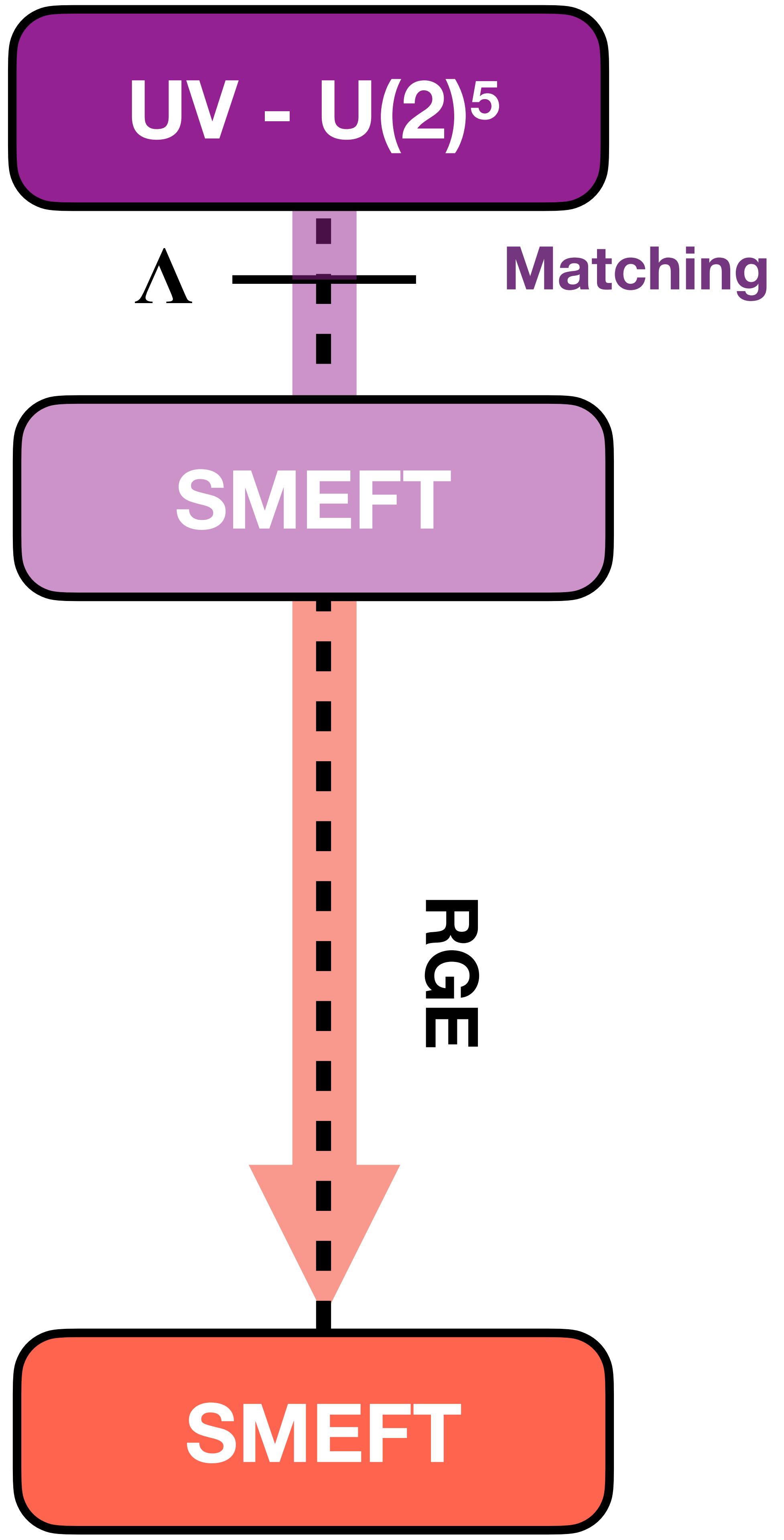
Chose a common scale Λ=10 TeV in the comparison

(Technically not consistent with FCC-hh energy and may be revisited when more projections are available)

The SMEFT setup

- Working at dimension 6 in the *Warsaw basis*
- Assume NP respects $U(2)^5$ flavor symmetry (+ CP conservation) at Λ=10 TeV
  - Flavor basis aligned with up-quark basis
- Include RGE evolution from 10 TeV down to the relevant scales
  - For the moment ignoring a few operators that only mix very weakly with the ones tested at low energy

    ⇒ 100 operators (all active for all colliders)
- Compute new physics contributions to observables:
  - Calculations in "{M_Z ,M_W,G_F}" Electroweak input scheme
  - Finite NLO effects included for some of the most precise observables (EWPO, $e^+e^- \to ZH$)

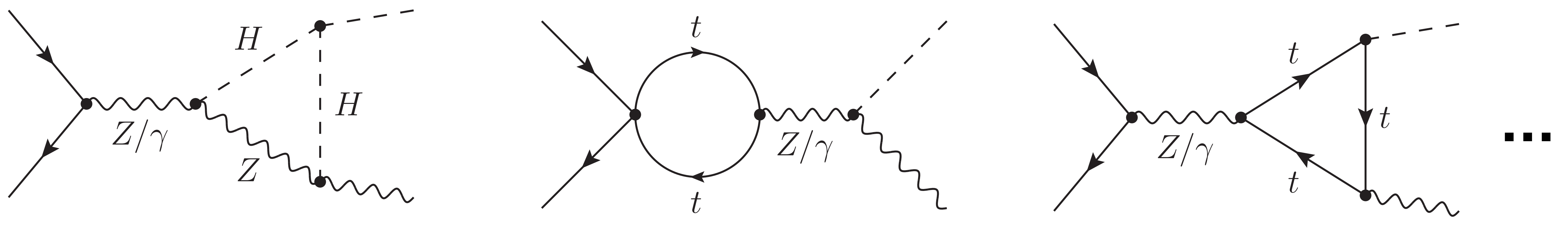


The SMEFT setup

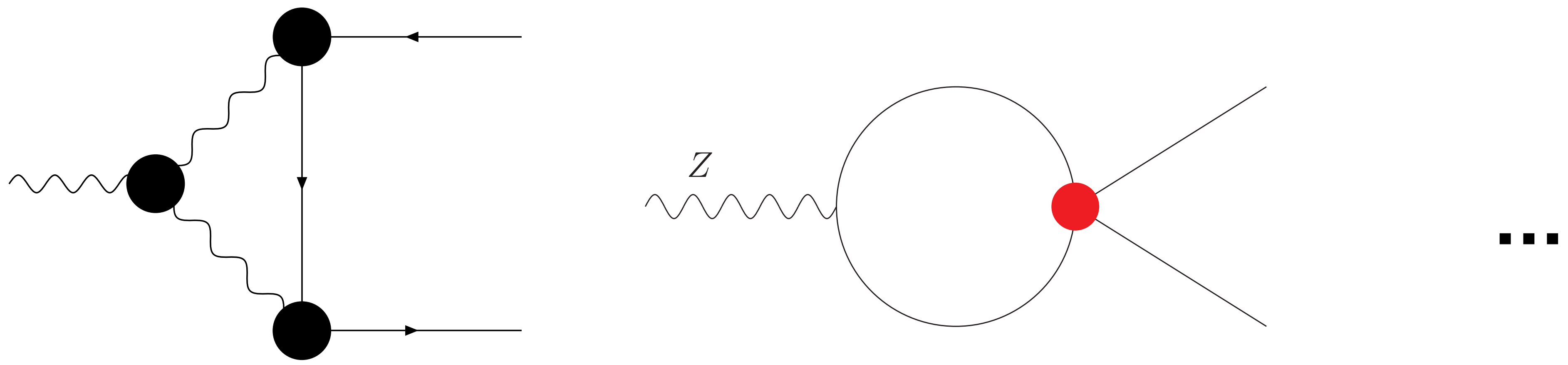
- Worki
- Assum (+ CP
  - Flav
- Include
  - For weal
- Comp
  - Calc
  - Finit obse

NLO effects introduces dependence on multiple interactions not present at LO

$e^+e^- \to ZH$:



EWPO:



New opportunities to use precision measurements as probe of these effects, but could be challenging to disentangle the source of a signal?

WARNING:* *Complete NLO calculations only available for EW precision observables

Higgs: only for ZH, but full NLO corrections missing in WBF, Higgs decays

Thanks to P. P. Giardino and K. Asteriadis for providing updated results of their calculations

The SMEFT setup

- Working at dimension 6 in the *Warsaw basis*
- Assume NP respects U(2)^5 flavor symmetry
  (+ CP conser
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    weakly wit

    ⇒
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  - Calculation
  - Finite NLO effects included for some of the most precise observables (EWPO, $e^+e^- \to ZH$)

UV - U(2)^5

tching

On the Higgs width in the SMEFT approach

- In the SMEFT, by definition, there are no contributions to the Higgs width from non-SM final states
- In previous studies, this possibility was modeled phenomenologically introducing extra parameters to describe such effects:
  - Technically, not consistent with SMEFT approach (even more when starting to introduce NLO effects) ⇒ Not considered here
  - Higgs width determination covered by Kappa framework anyway

Computational Framework
and Fit details

Statistical analysis

Strategy for estimation of future sensitivity to New Physics

- Fit to POI in each of the frameworks using HEPfit http://hepfit.roma1.infn.it

Special thanks to Luca Silvestrini for his constant support working with the code and Victor Miralles for help with Top-quark studies

Statistical analysis

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- Other tools available for this purpose, with many future colliders studies appearing recently. Thanks to:
  - ✓ Jiayin Gu
  - ✓ Michael Peskin and Junping Tian
  - ✓ The members of the SMEFiT collaboration, especially Eugenia Celada, Simone Tentori and Alejo Rossia
- All of which have helped in the validation and cross check of the different tools, since the previous ESPP, during the 2021 Snowmass and until now
- Their studies (and others, e.g. L. Allwicher, V. Maura, B. Stefanek, T. You, …) have greatly helped understand better the global SMEFT picture at future colliders

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- General considerations
- **Bayesian** statistical framework

➡ Sensitivity obtained from posterior information (NP parameters/Observables statistical errors/limits [68% prob.])

- **Likelihood:** SM predictions as central values for future "experimental" measurements (Level-0 pseudodata). Uncertainties from projected experimental errors.
- **Theory** uncertainties in SM predictions included where available, modeled by extra nuisance parameters
  - Following prescriptions in previous talk (Not all scenarios available yet)

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- ***Kappa framework*** **considerations:**
  - **Flat priors** for all κ parameters
  - New (non-SM) contributions to the Higgs BR constrained to the physical region ($BR_{inv/unt} \geq 0$)

Statistical analysis

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- ***SMEFT framework*** **considerations**
  - SM dependence included to current knowledge for most precise observables
  - New physics effects: SMEFT dependence included consistently to dimension 6

$$O = O_{\mathrm{SM}} + \delta O_{\mathrm{NP}} \frac{1}{\Lambda^2}$$

  - RGE evolution included via **RGESolver** S. Di Noi, L. Silvestrini, Eur. Phys.J.C 83 (2023) 3, 200
  - Currently including **100** of the124 $U(2)^5$ operators simultaneously (ignoring those that enter in observables only via weak RG mixing)

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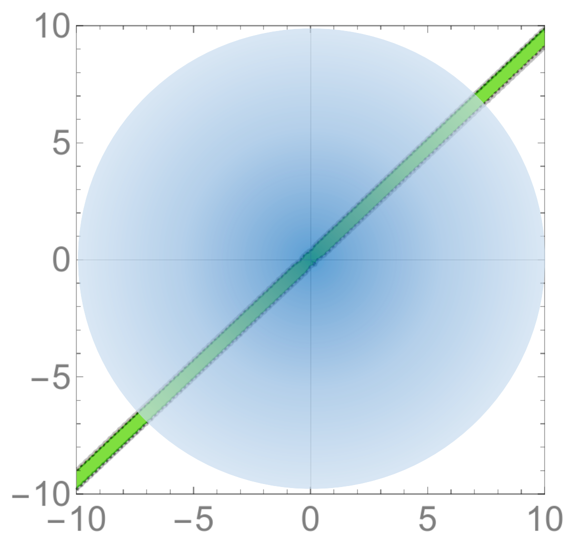
- ***SMEFT framework*** **considerations**
  - **Flat priors** for most parameters
  - Flat directions cans still be present, depending on the observables available at each collider project

    ⇒ Impose theory constrain: perturbative TeV scale new physics

$$\frac{C_i}{\Lambda^2} \sim \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \Rightarrow g_{\rm NP}^2 \leq 4\pi \text{ for } M_{\rm NP} \sim 1 \text{ TeV}$$



⇒ Via Gaussian prior of the Wilson coefficients at 68% probability (conservative)

Statistical analysis

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- **SMEFT framework** considerations
  - **Flat priors** for most parameters
  - Flat di... ...llider
    projec...

    ⇒ I...

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⇒ Via Gaussian prior of the Wilson coefficients at 68% probability (conservative)

Final version of the code used for Briefing Book results will be made available via a container (Thanks to E. Bagnaschi)

Presentation of results

Kappa framework

- 68% prob. uncertainties on κ parameter / 95% prob. upper limit on $BR_{inv/unt}$
- Higgs width precision for Kappa-3 (prediction)

SMEFT framework

- Results expressed in terms of 68% prob. uncertainty on predictions for effective SM couplings (on-shell, defined from observable physical quantities)

$$g_{HX}^{\text{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{SM}}\ , \quad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}(|g_L^e|^2+|g_R^e|^2), \qquad A_e = \frac{|g_L^e|^2-|g_R^e|^2}{|g_L^e|^2+|g_R^e|^2}$$

- Exceptions: *Ztt, ttH, H* self coupling:
  - Defined in terms of their SMEFT LO expressions, evaluated at $\mu=M_Z$ and M_H, respectively
  - Or presented in terms of the relevant Wilson coefficients modifying their SM values

Inputs included:
Electroweak, Higgs and Top

Inputs included for EFT studies

See talks in the previous EW parallel session for details

		Higgs	EW	Top
pp (Baseline)	HL-LHC	H, HH	LEP/SLD EWPO HL-LHC M_W	m_t, CMS extrap.
ep	LHeC	H	DIS, aTGC	-
e^+e^-	LEP3 M_Z/161/230 GeV	H	EWPO, $e^+e^-\to ff$, $e^+e^-\to W^+W^-$	No
e^+e^-	LCF M_Z/250/350/550/1000 GeV	H, HH	EWPO, $e^+e^-\to ff$, $e^+e^-\to W^+W^-$	m_t, $e^+e^-\to tt$
e^+e^-	CLIC 380/1500 GeV	H, HH	EWPO via Rad. Return, $e^+e^-\to ff$, $e^+e^-\to W^+W^-$	m_t, $e^+e^-\to tt$
e^+e^-	FCC-ee M_Z/161/240/345-365 GeV	H	EWPO, $e^+e^-\to ff$, $e^+e^-\to W^+W^-$	m_t, $e^+e^-\to tt$
pp	FCC-hh 85 TeV	H, HH	- WW WiP for Brief. Book	ttH/ttZ tt, 4t WiP for Brief. Book
$\mu^+\mu^-$	MuC 10 TeV	H, HH	$\mu^+\mu^-\to ff$, VV *VBF (differential)*	$\mu^+\mu^-\to tt$, *VBF*

Additional inputs considered for all colliders: $\alpha_S(M_Z)$, $\Delta\alpha_{had}^{(5)}(M_Z)$, m_b, m_c **(from LatticeQCD)**

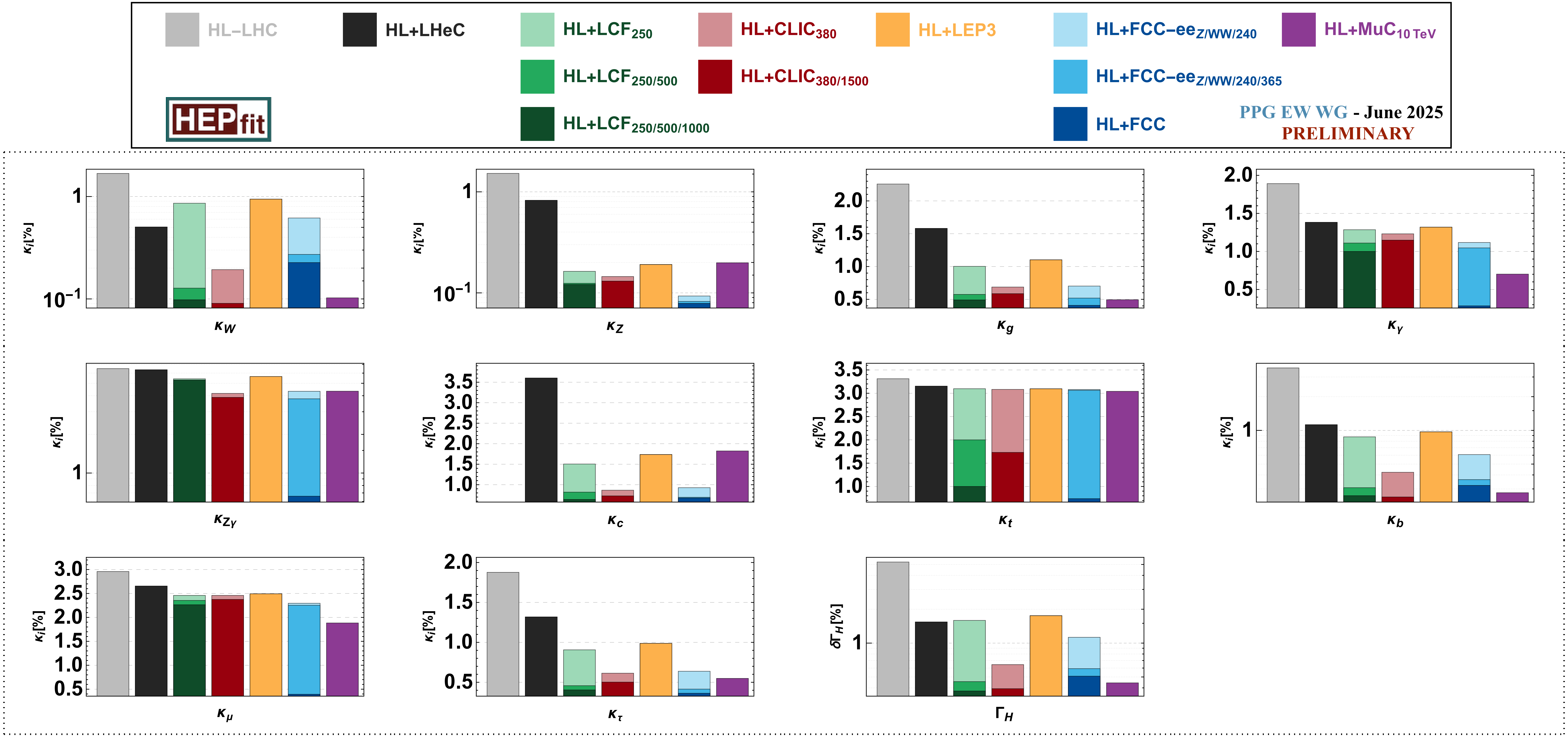
Theory uncertainties

Theory uncertainty scenario	No Theory Uncertainty	Agressive TH estimates	Agressive TH estimates
Kappa framework	Baseline for this symposium	For comparison	
SMEFT framework	For comparison	Baseline for this symposium	N/A yet (For comparison in Briefing Book)

See previous talk for details.
TH systematics folded into input EXP projections & TH prediction uncertainties directly in the SM calculations

Some results:
Kappa framework

Kappa-0 result summary



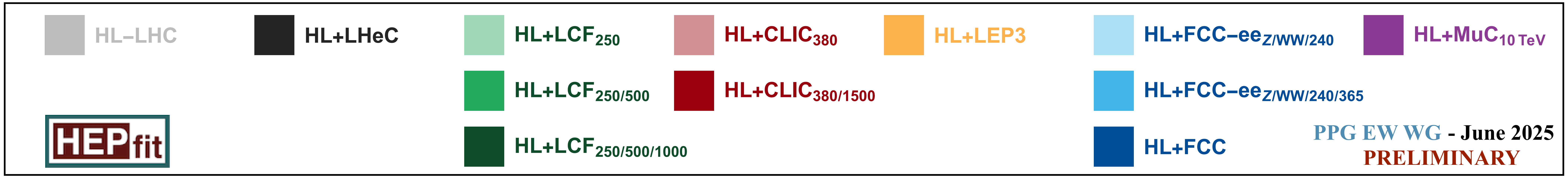
Kappa-3 result summary

Kappa-3 result summary

Parametrizing non-SM Higgs decay modes

Kappa-3 result summary

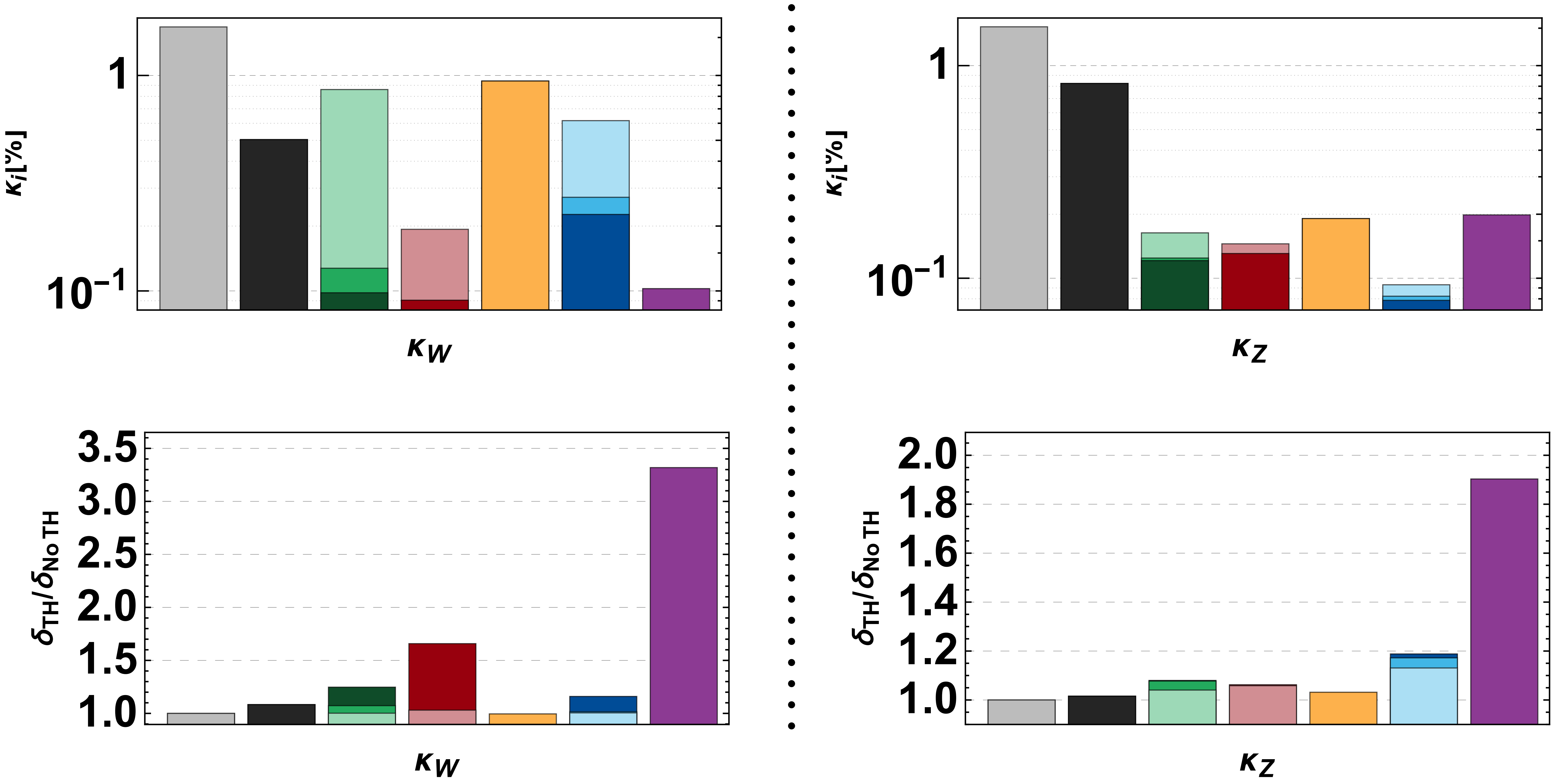
On Theory uncertainties: Kappa-0



Theory uncertainty in production

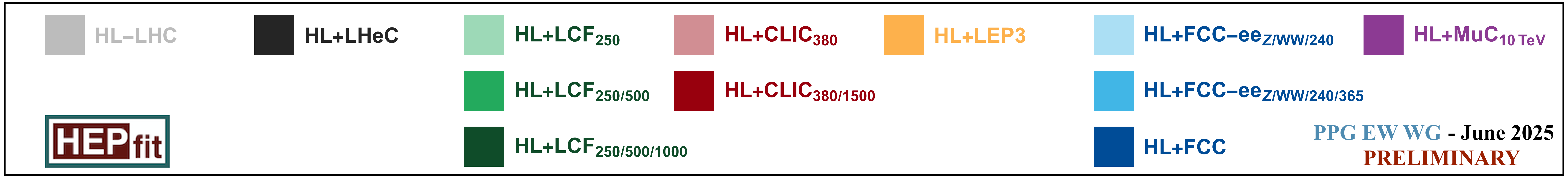
Kappa-0 baseline:

Kappa-0 + TH unc. / Kappa-0 baseline



High-E lepton colliders more affected when precision comes from VBF

On Theory uncertainties: Kappa-0

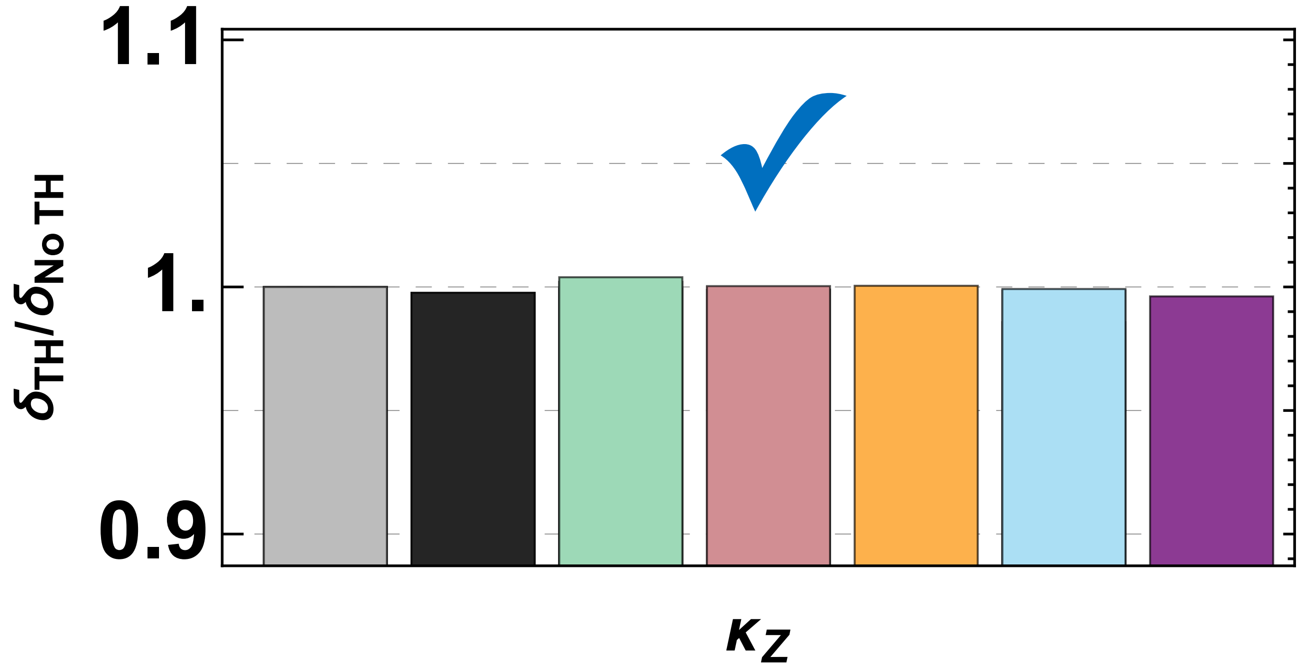


Parametric uncertainties

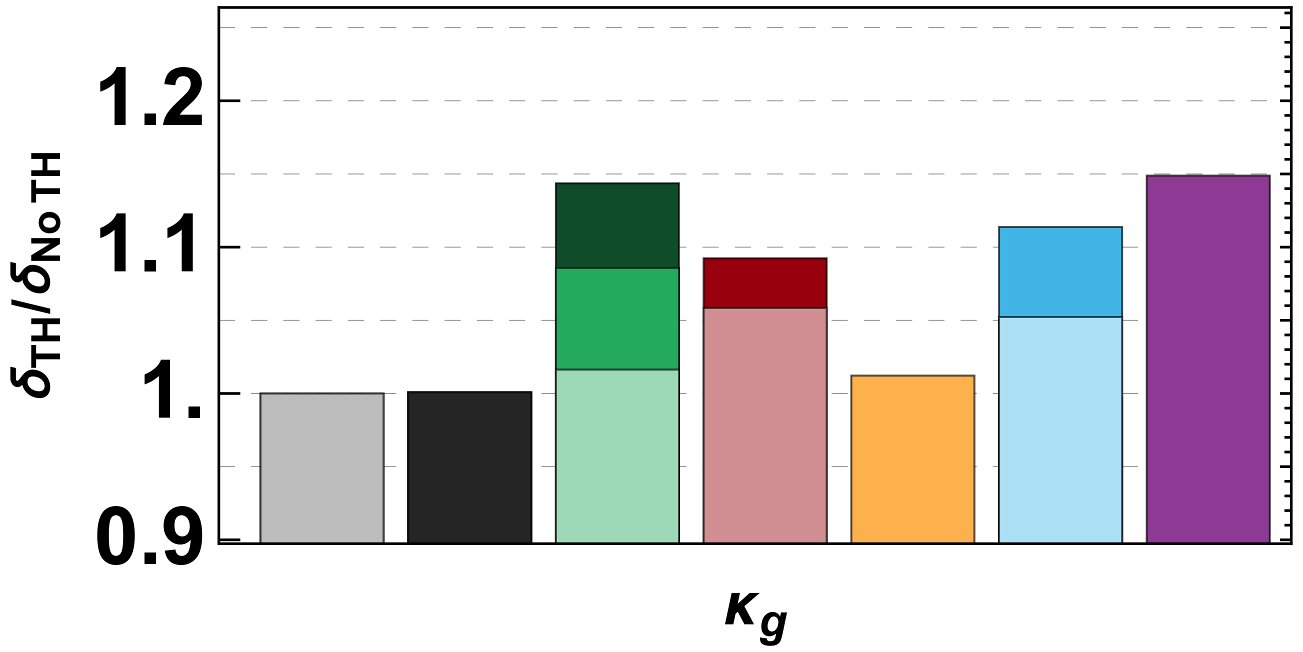
Kappa-0 baseline

Kappa-0 No par unc.

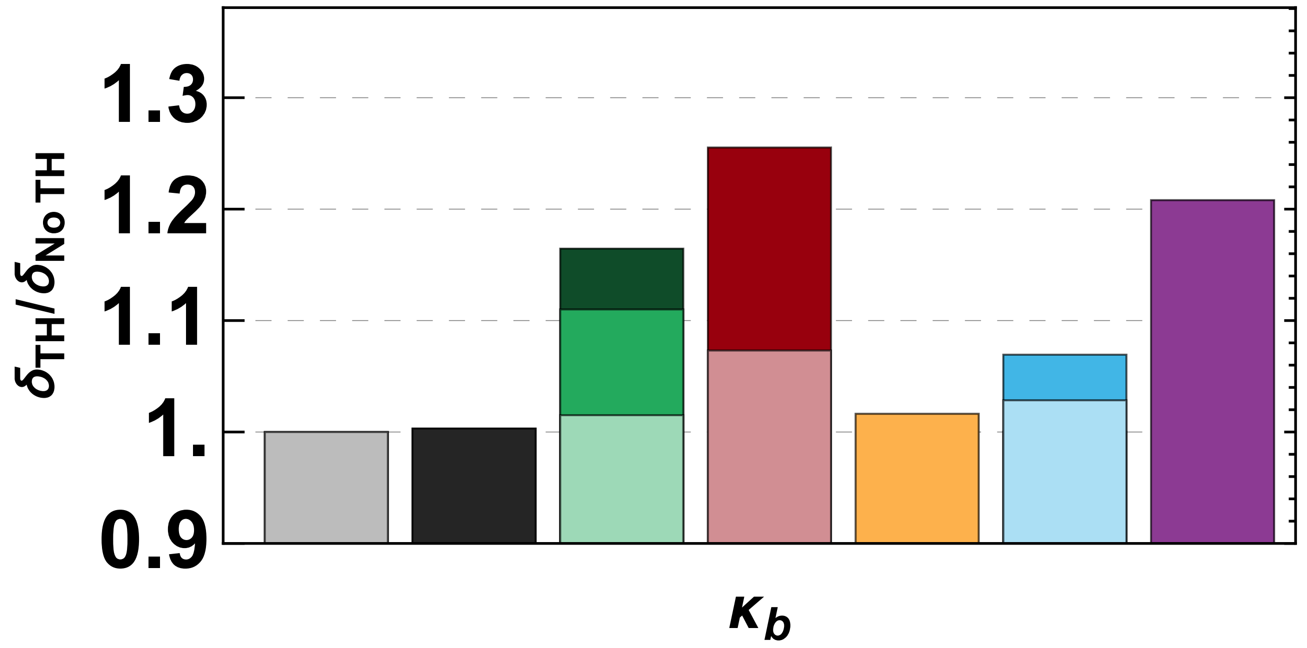
Key parameter: M_H



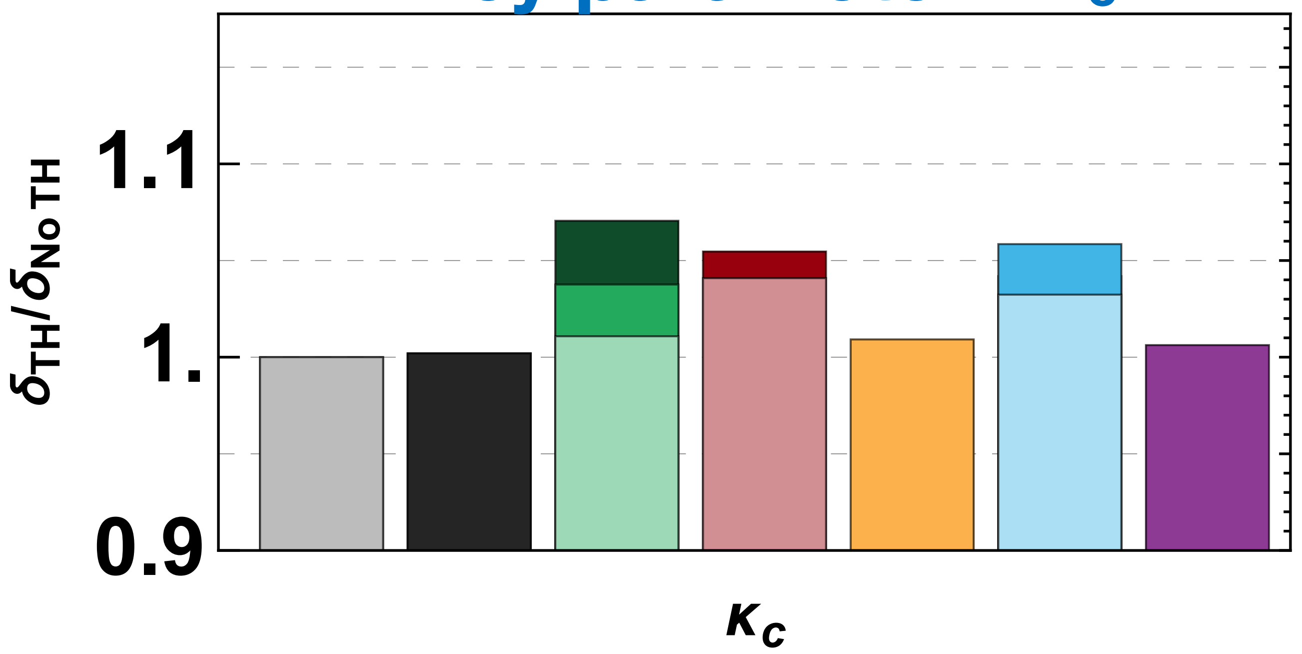
Key parameter: α_S



Key parameter: m_b



Key parameter: m_c



Parametric uncertainties generally under control

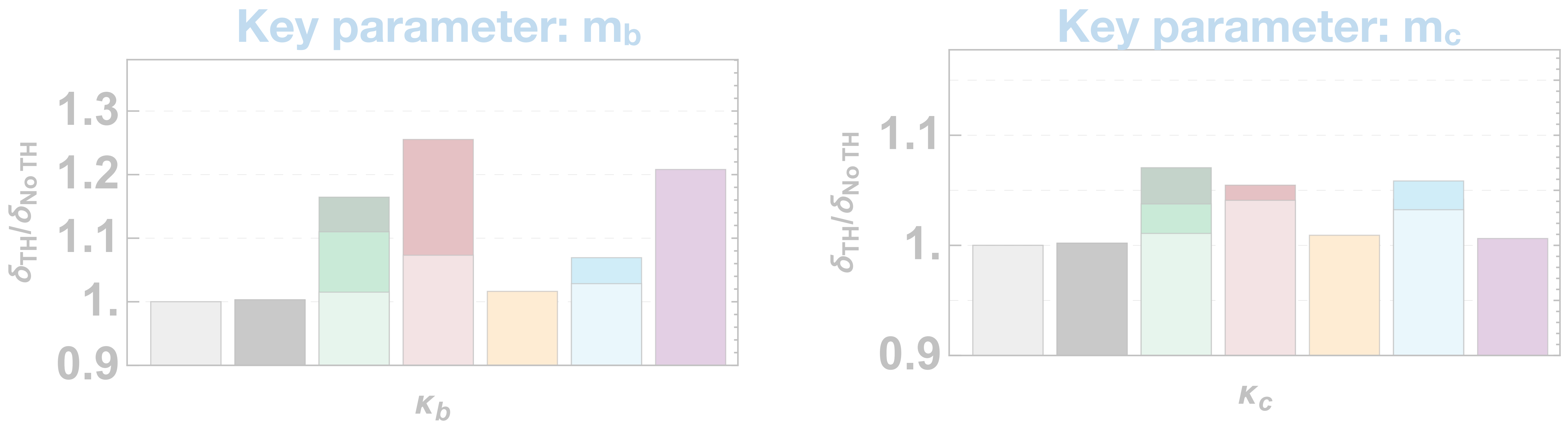
On Theory uncertainties: Kappa-0

Parametric uncertainties

These results, to be discussed in more detail on Wednesday, together with what is presented then must be considered PRELIMINARY

Kappa-0 baseline

Kappa-0 No par unc.



Parametric uncertainties generally under control

Conclusions

See you on Wednesday for the discussion of Results