

SMEFT at NLO for Higgs Physics and Beyond

June 12, 2026

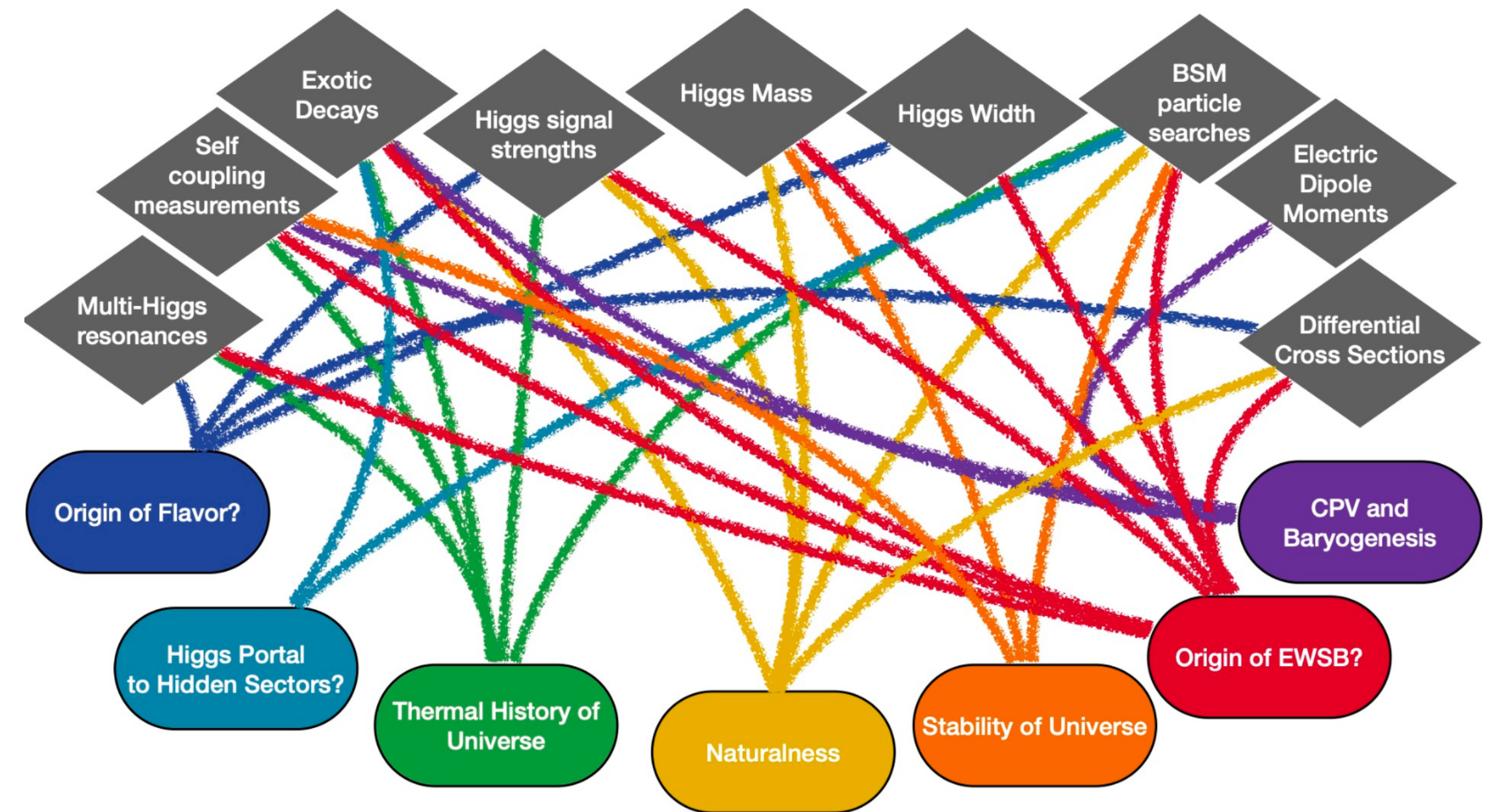
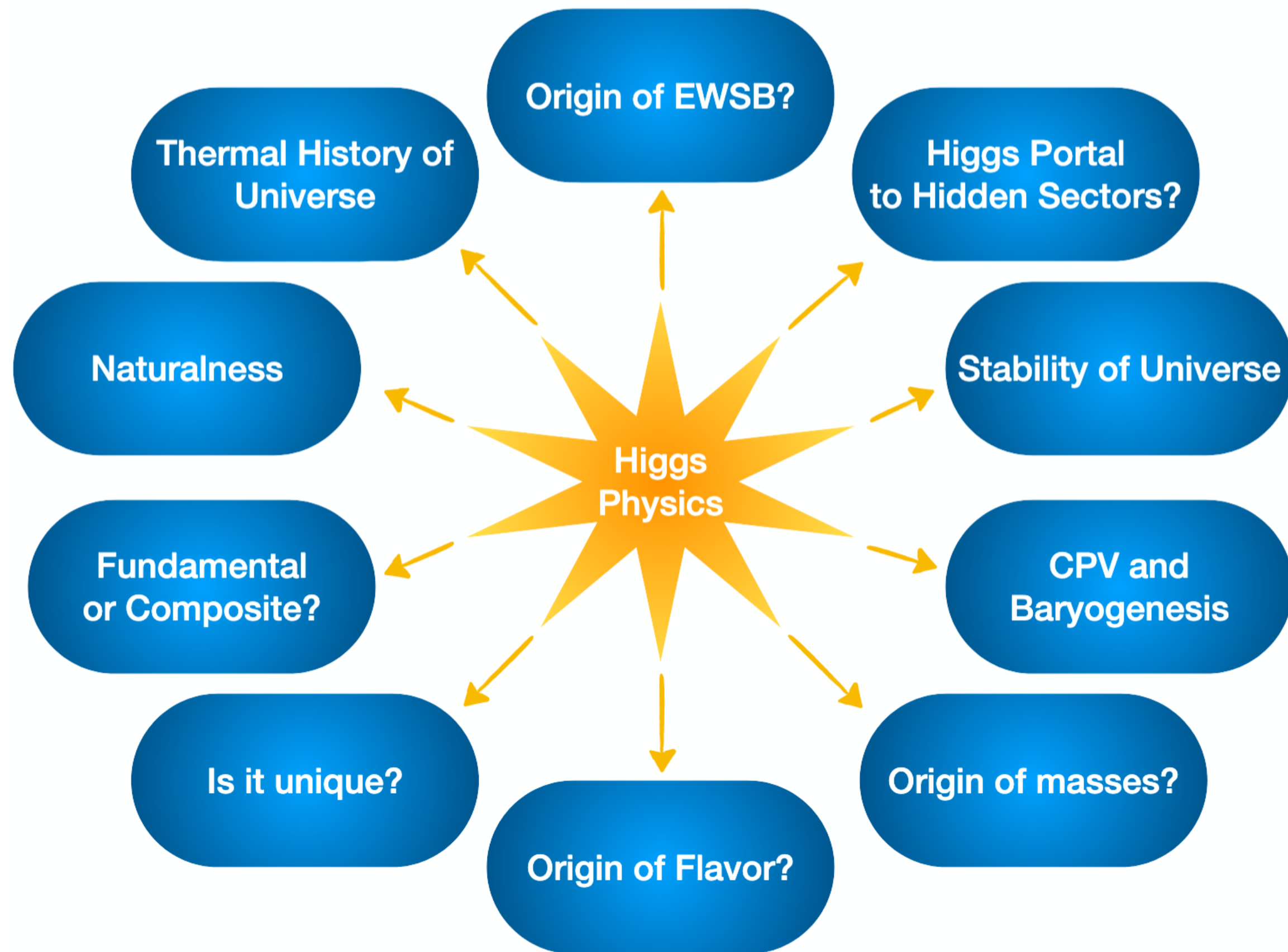
Matthew Forsslund



**PRINCETON CENTER FOR
THEORETICAL SCIENCE**

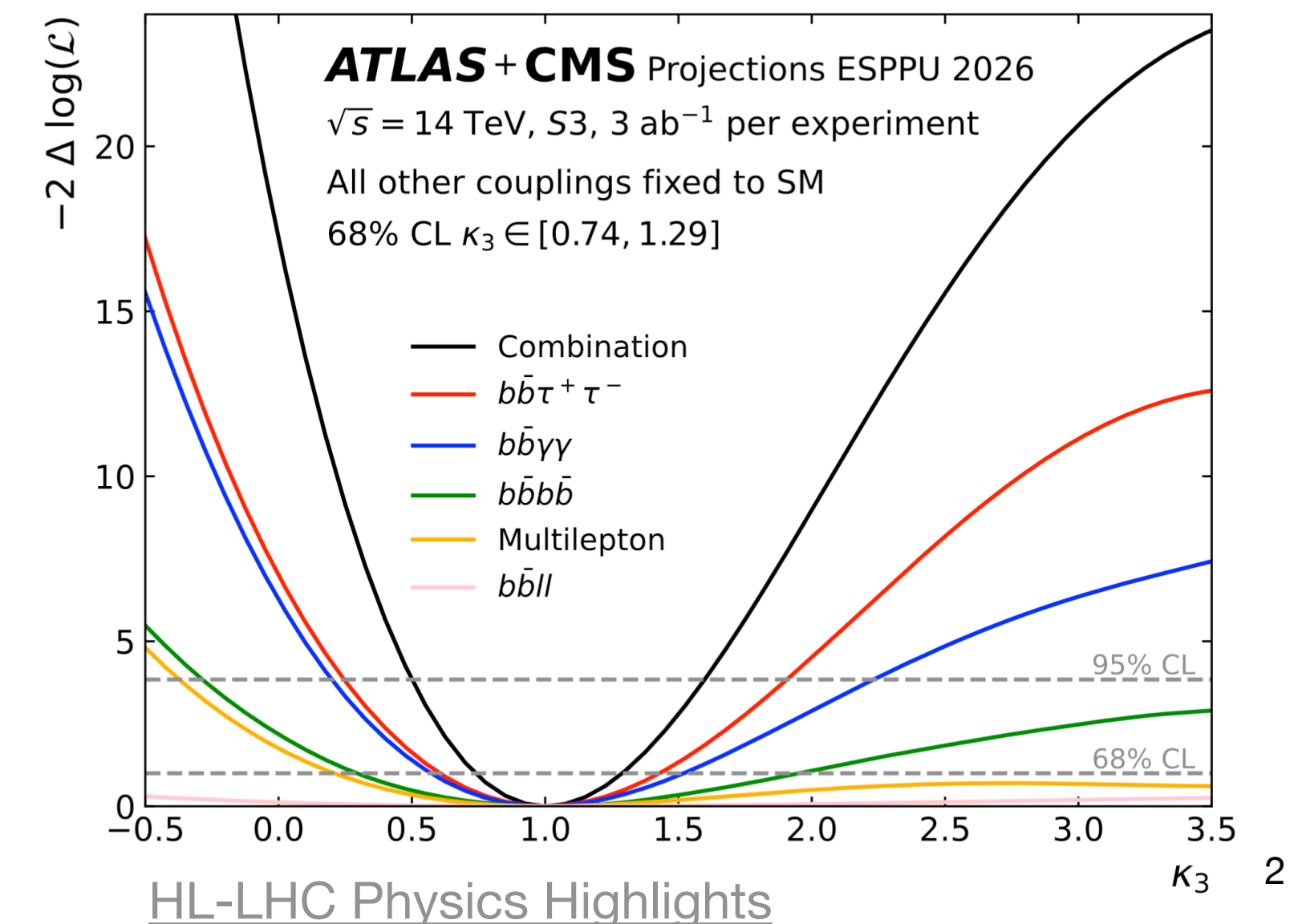
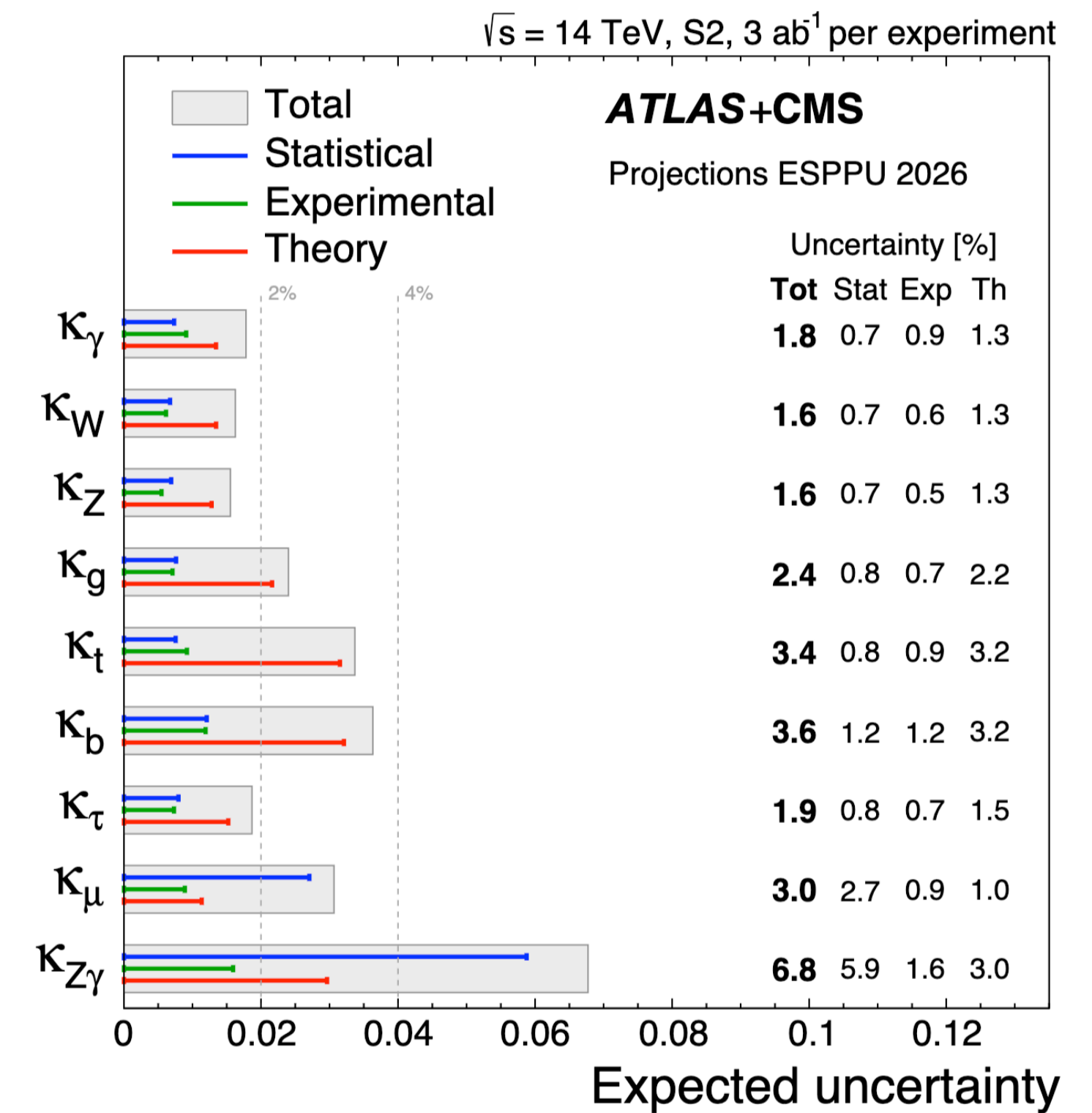
Higgs physics

- Studying the Higgs precisely is the central target of HL-LHC and future colliders

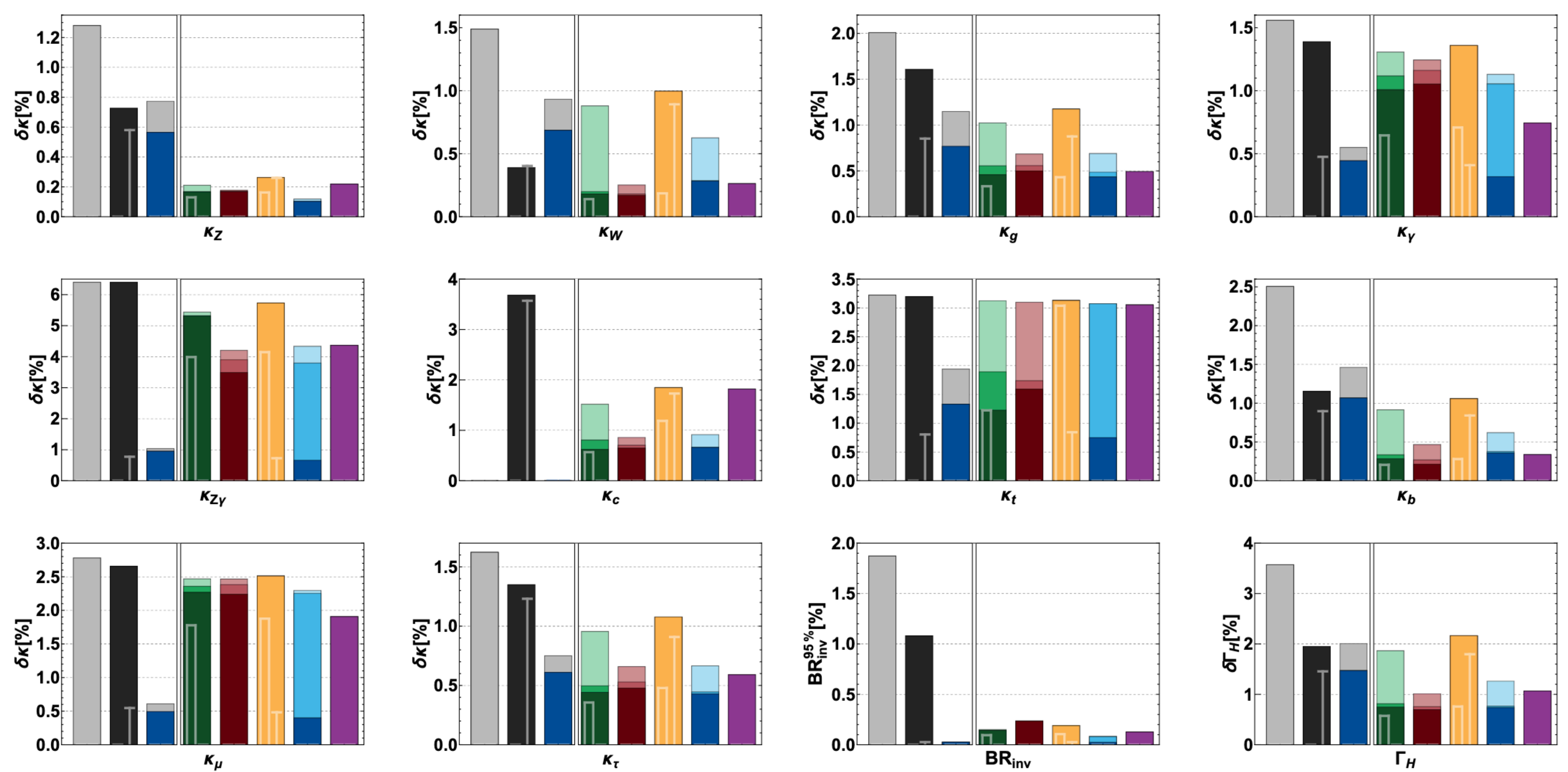
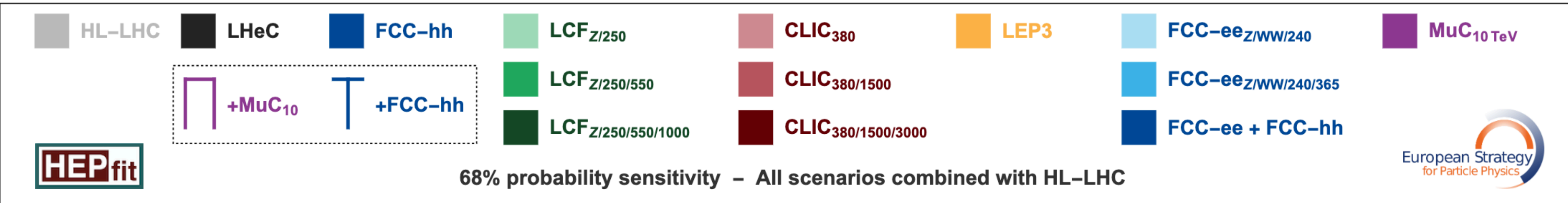


Higgs at the LHC

- LHC is already a Higgs factory: $\mathcal{O}(10^8)$ Higgs by end of HL-LHC
 - The challenge is the backgrounds
- Measurements of rare, clean decays ($4\ell, \gamma\gamma, Z\gamma, \mu\mu, \dots$) will not improve much until an eventual FCC-hh
- Other measurements will be largely theory limited (assumes factor of 2 improvement from today)



The κ picture



$$\kappa = g/g_{SM}$$

$\sim 0.1\%$ on κ_V, κ_b

$\sim 1\%$ on κ_c

Clean rare decays and κ_t : pp wins until $ee \rightarrow ttH$

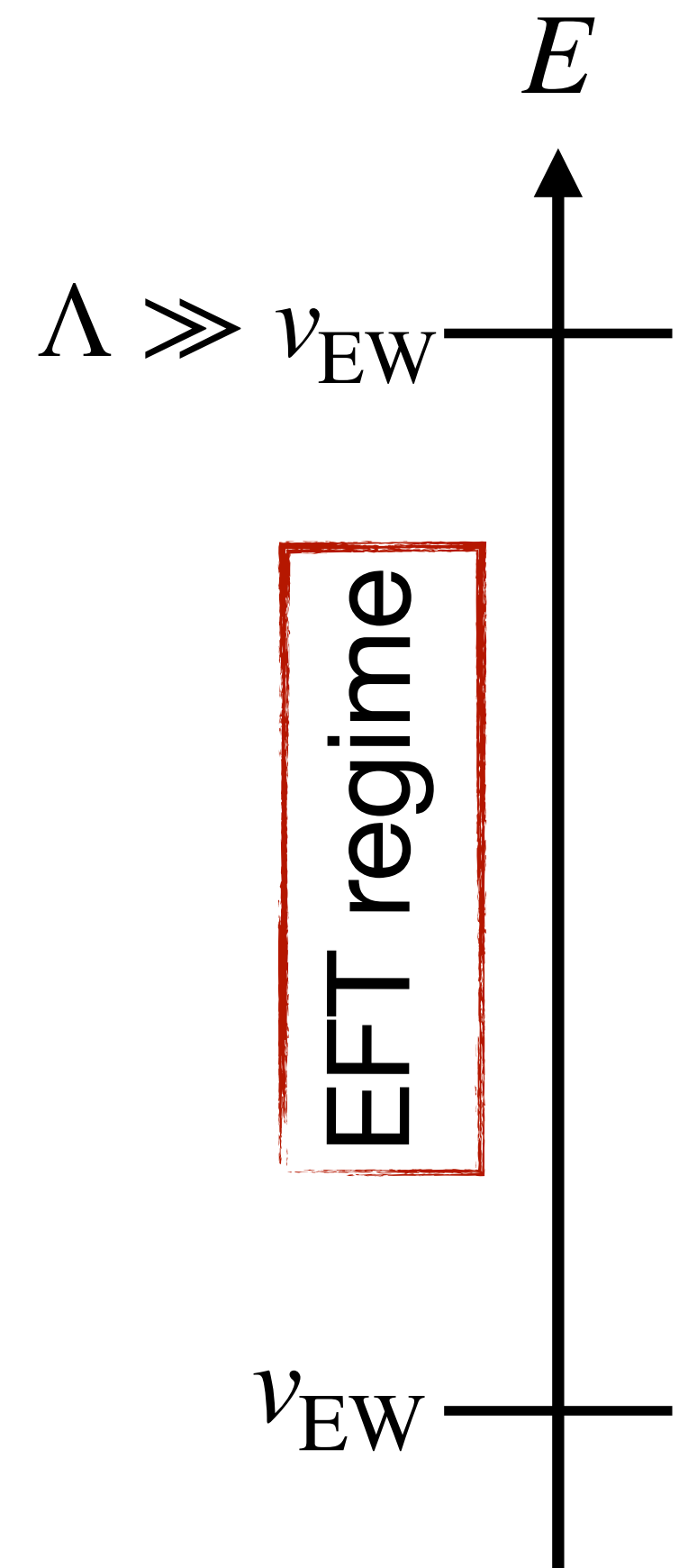
$\Gamma_H \sim 1\%$ (fewer assumptions)

Beyond Kappas

- Kappas are good first order picture but have a number of issues
 - Why should these be the only BSM deviations?
 - No systematic powercounting parameter
 - In general, gauge invariance
 - Don't capture energy dependence of all possible operators
 - Don't bake in custodial symmetry
- Not clear how to go to NLO
- SMEFT is the natural framework to handle all these issues consistently

SMEFT

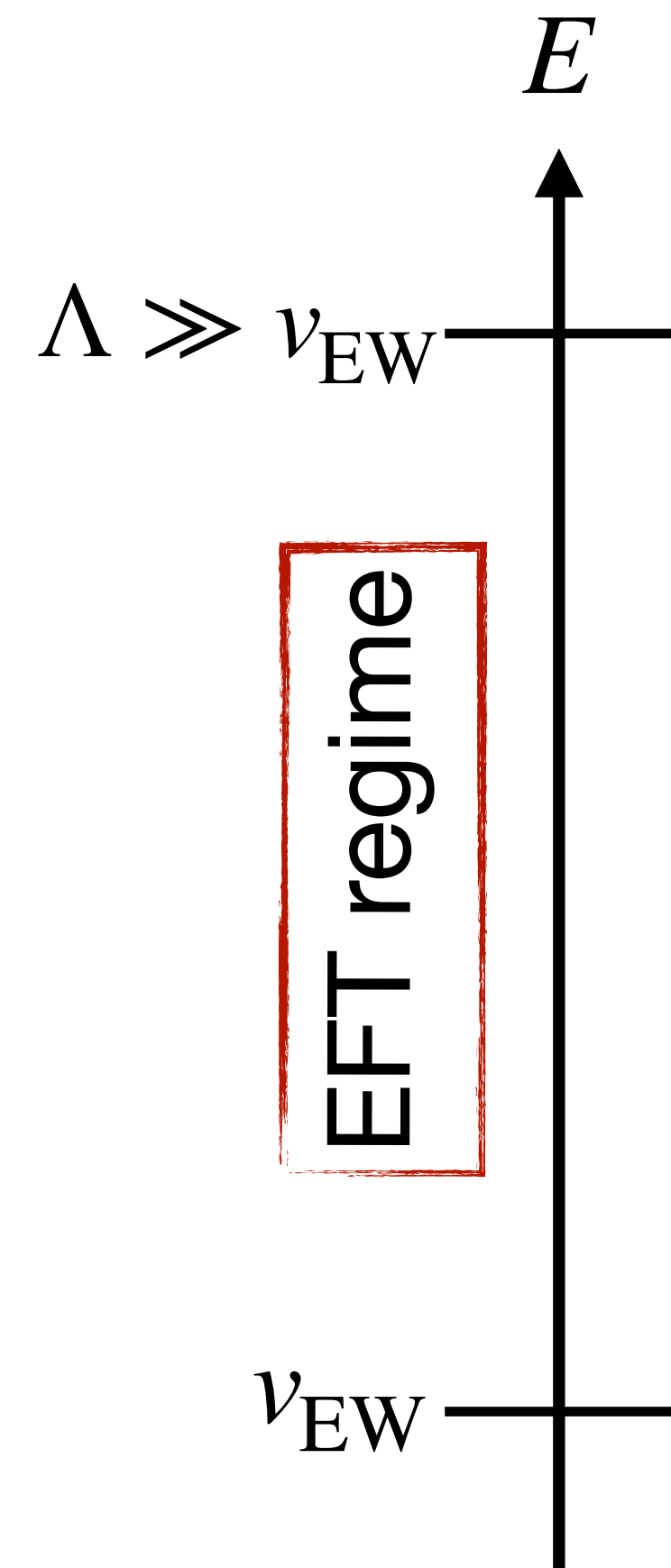
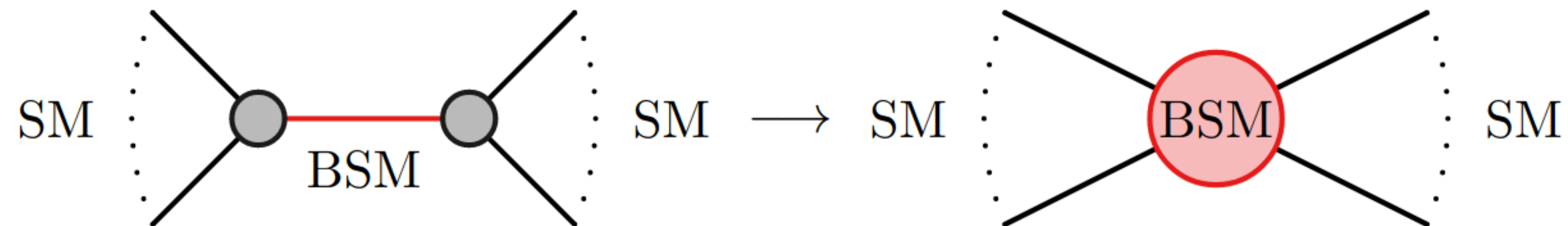
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SMEFT

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$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

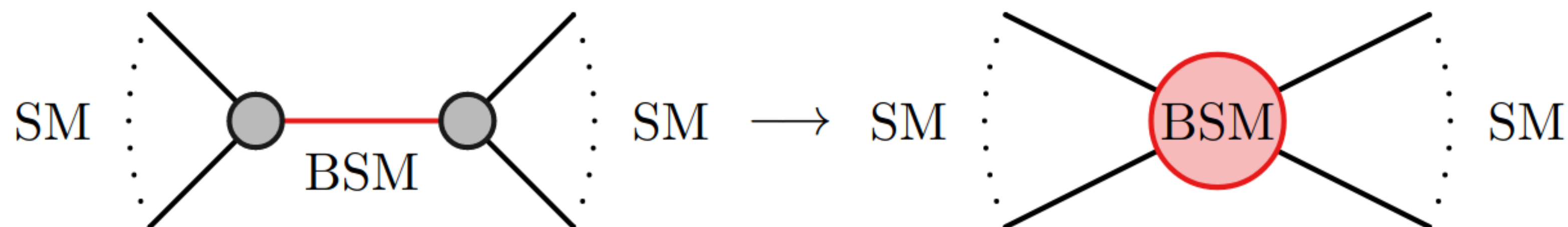
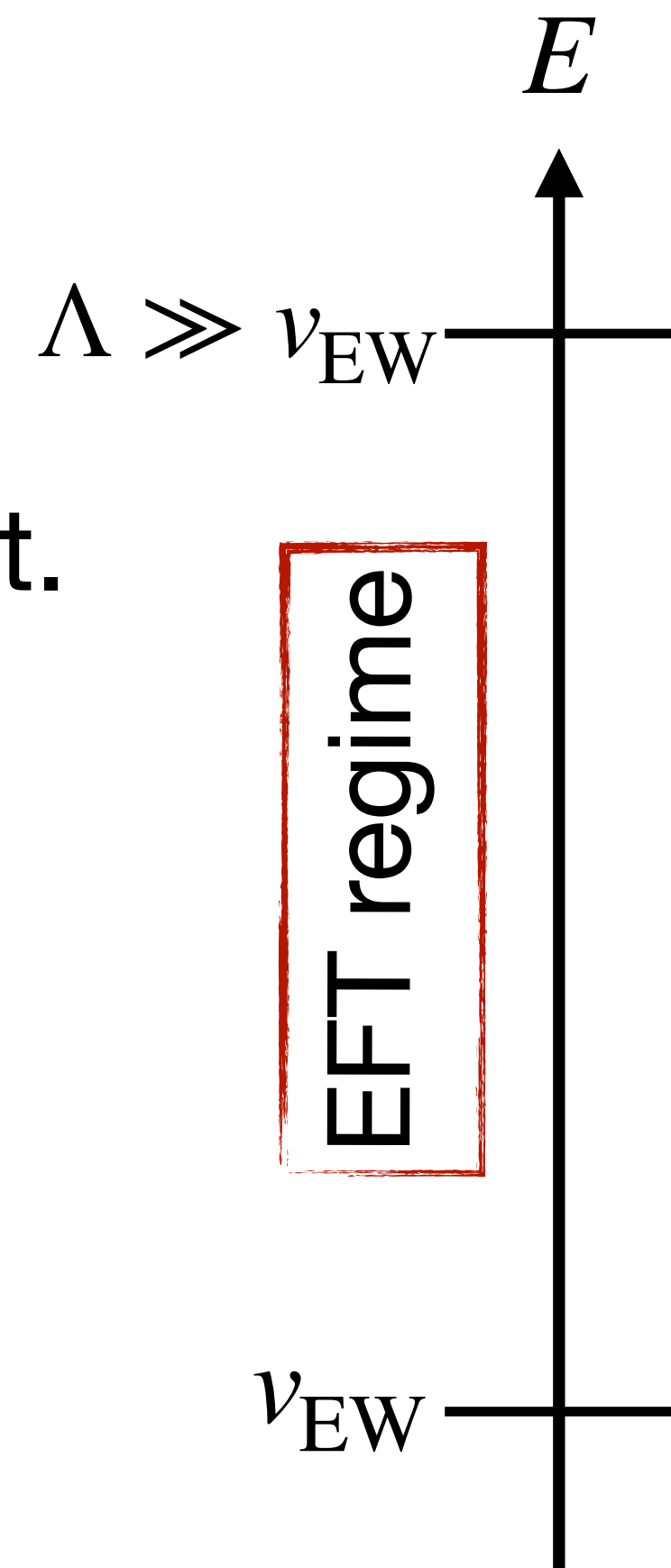


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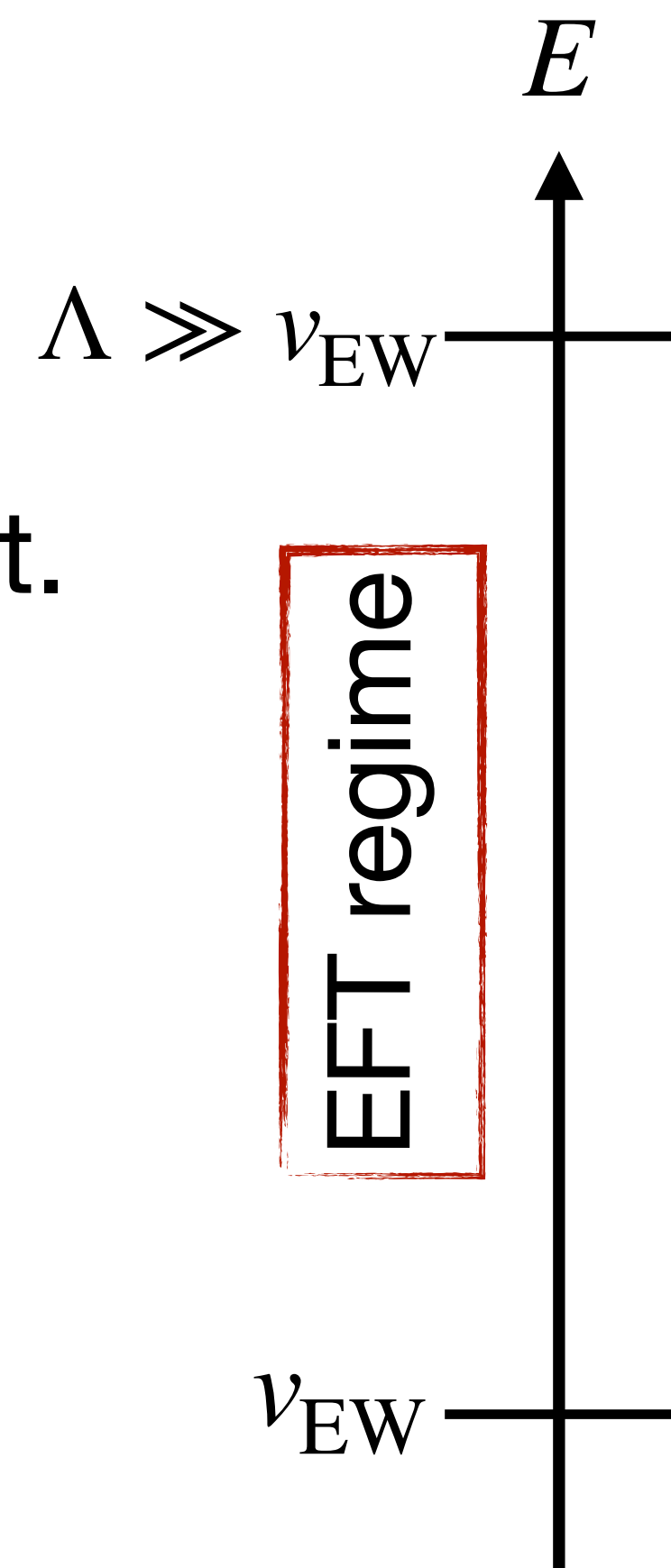
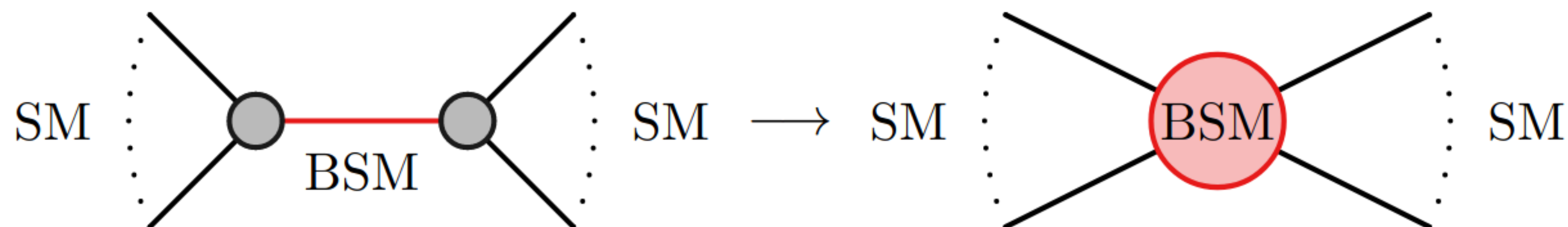
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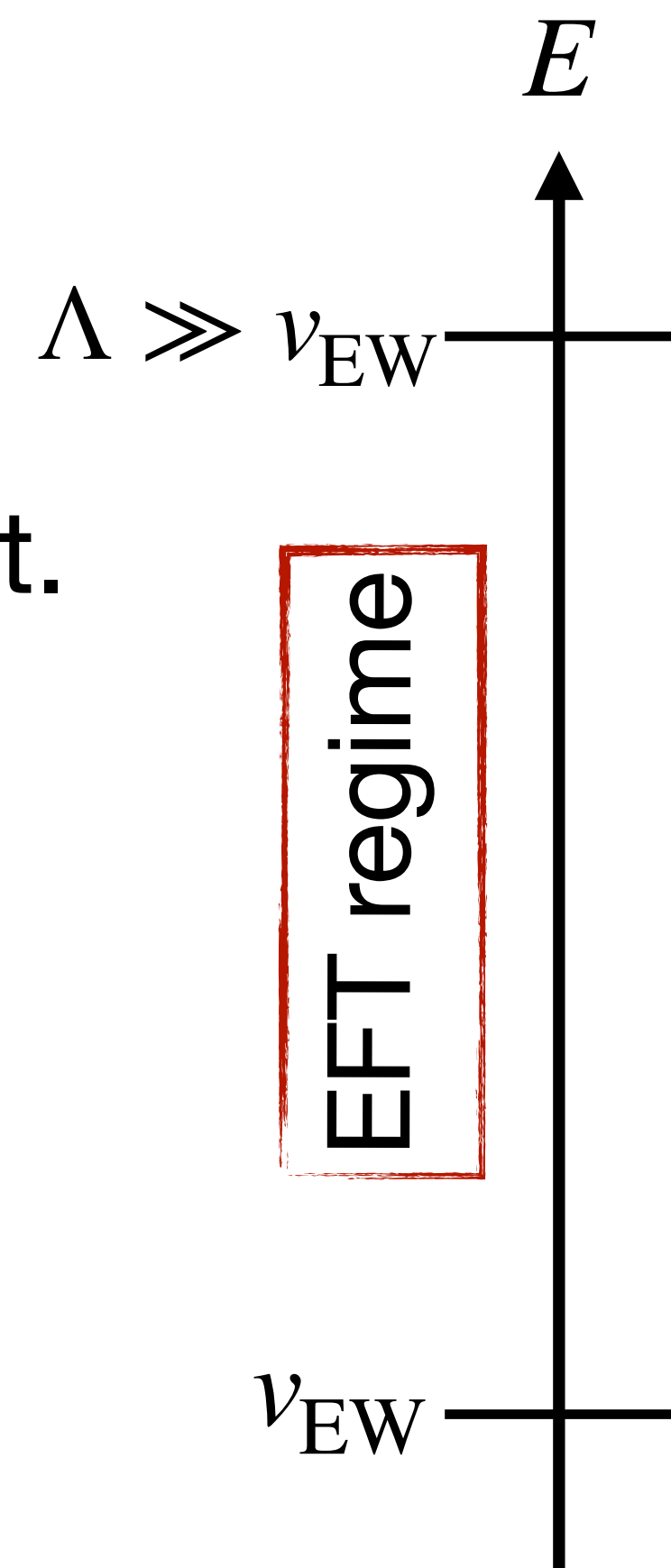
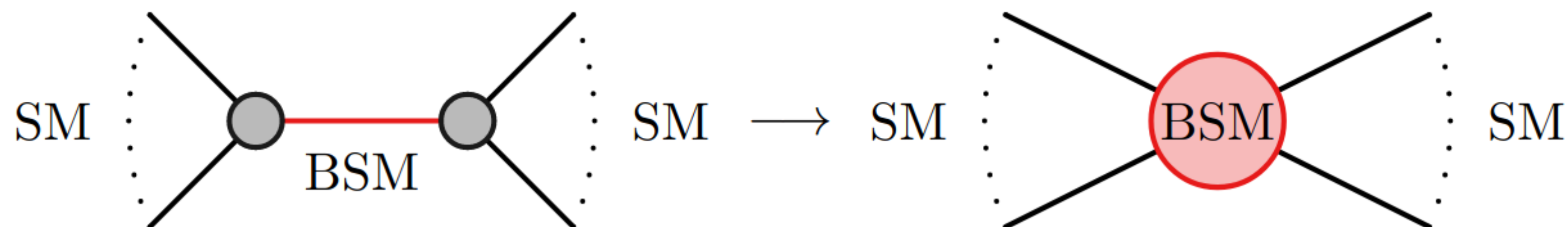
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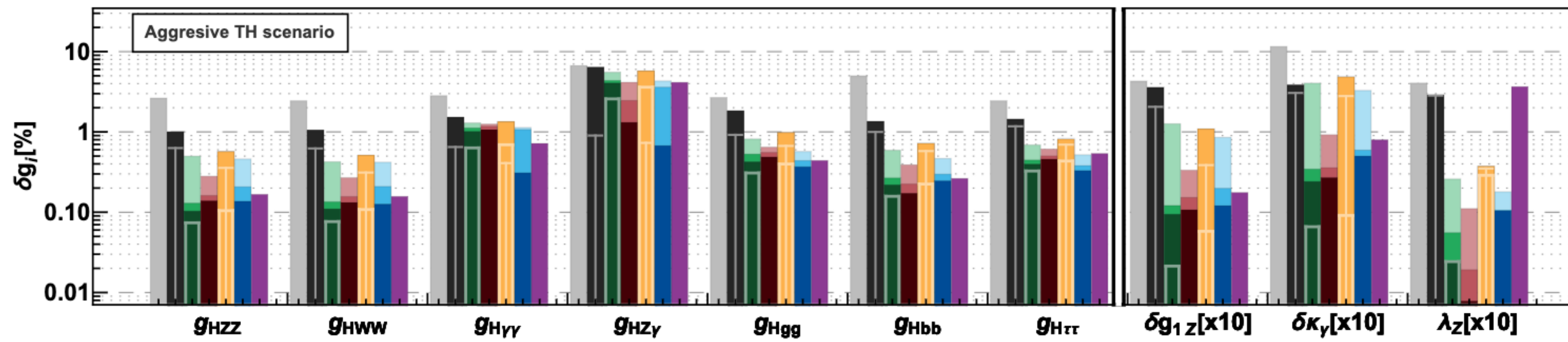
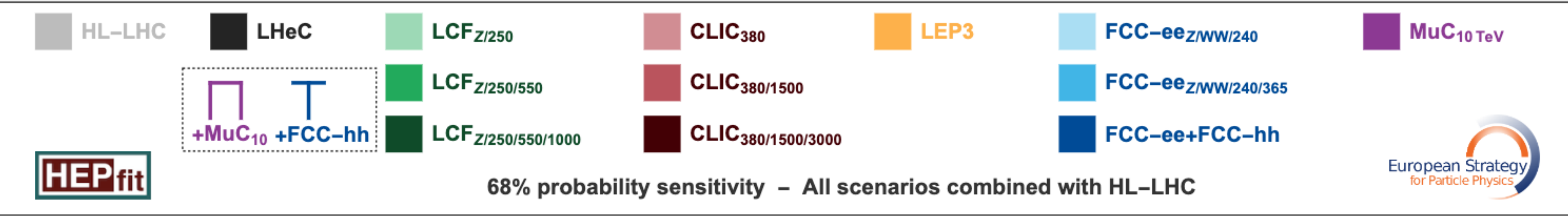
- For this talk: truncate at $\mathcal{O}(1/\Lambda^2)$, Warsaw basis SMEFT

Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 10 (2010) 085



Beyond Kappas

From 2026 European Strategy



- For the most part, SMEFT approach not much more complicated than kappas at tree-level, after adding EWPO
- However, this depends on symmetry assumptions

Symmetry assumptions

- ~2500 operators appear at dimension-6, overwhelmingly from flavour sector.
- Typically reduce with some assumptions:
 - $U(3)^5$, Minimal Flavour Violation, $U(2)^3 \times U(3)^2$, or $U(2)^3 \times U(1)_{l+e}^3$

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- B and L violating are dropped
- CPV operators typically drop out at tree-level for inclusive observables, but at NLO they can contribute!

Why NLO?

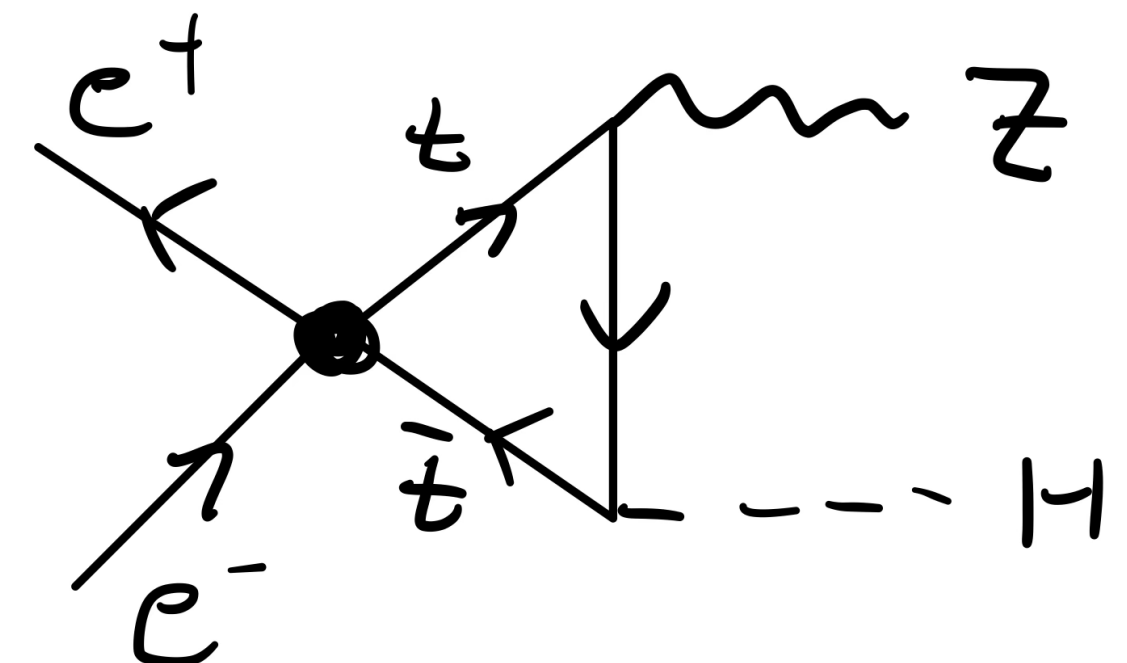
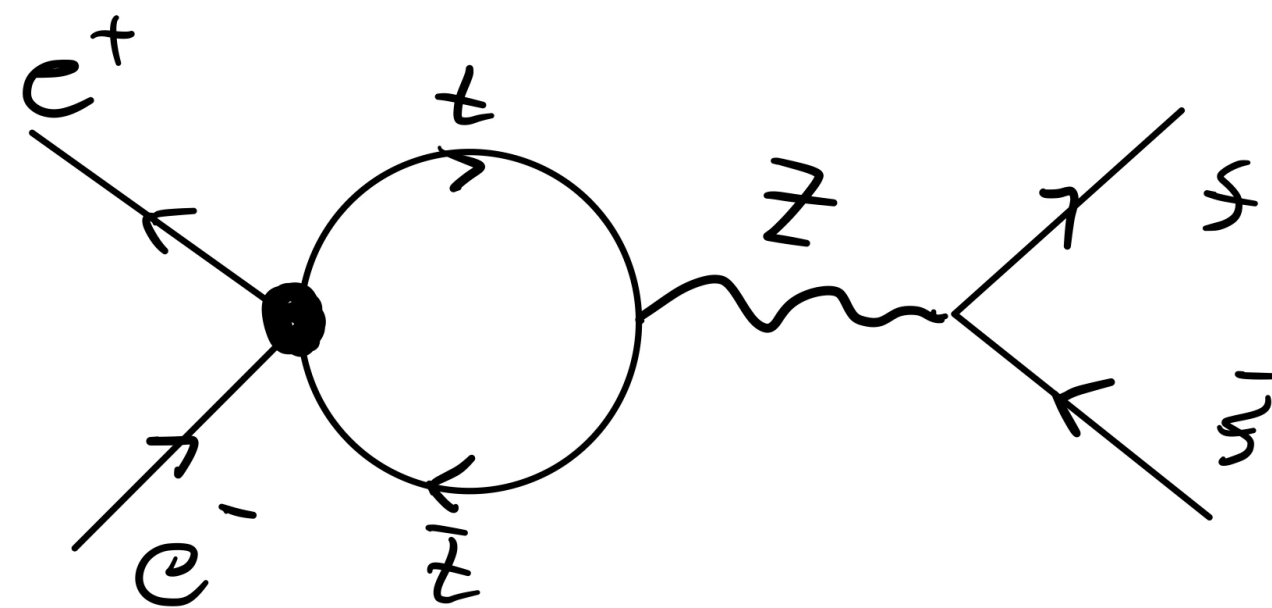
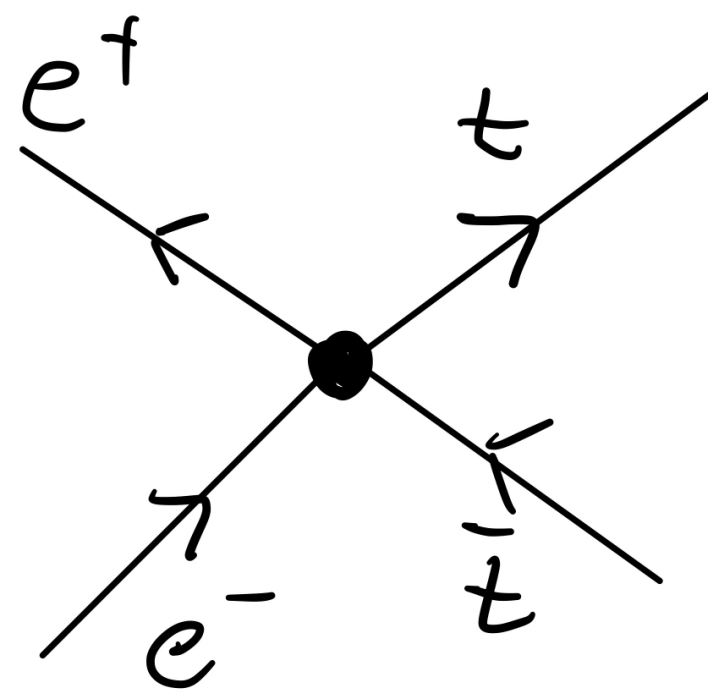
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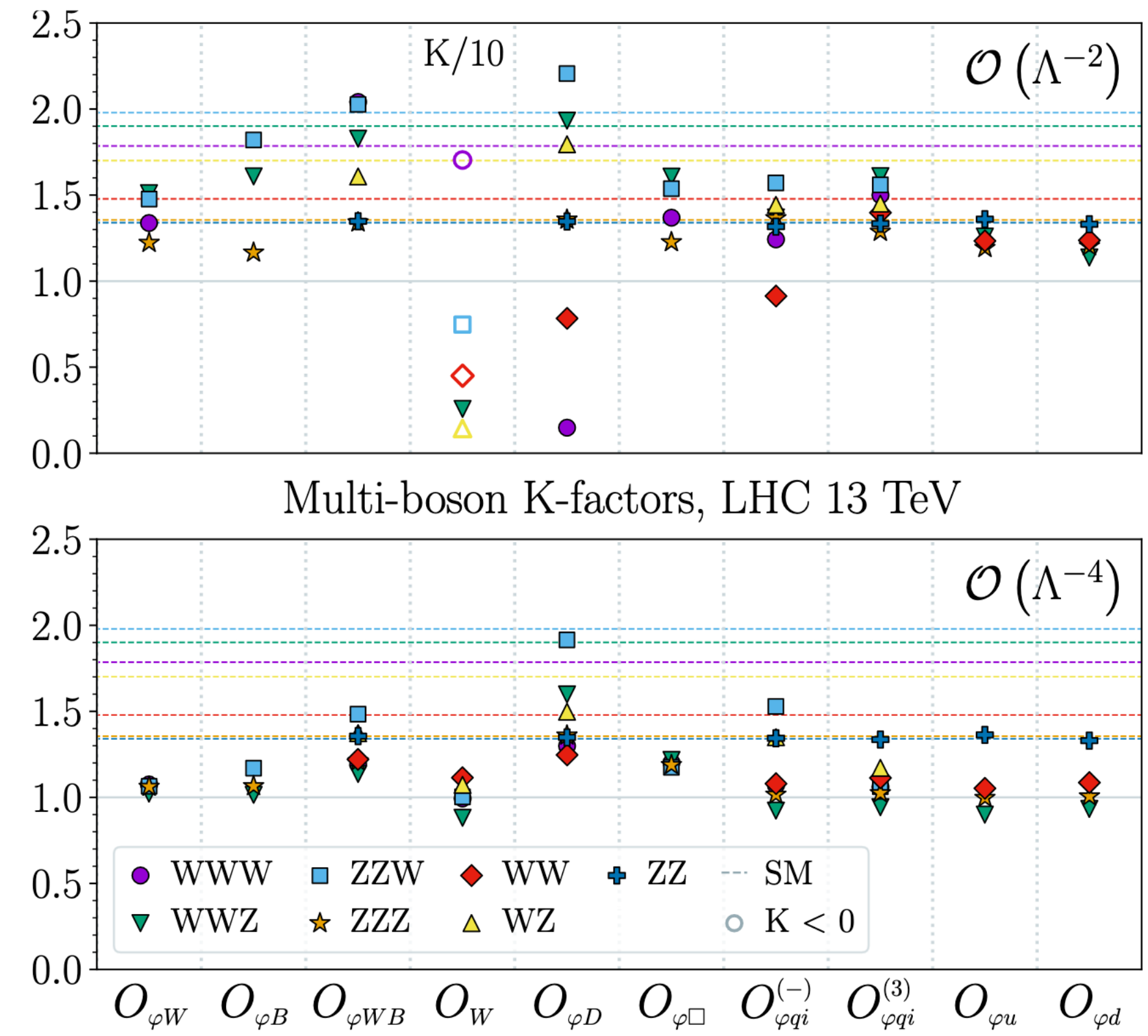
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3. Complementarity between observables at NLO. Measuring a deviation in i.e. $e^+e^- \rightarrow t\bar{t}$ should also alter Z -pole (and Higgs) through top-quark loops.



SMEFT at NLO

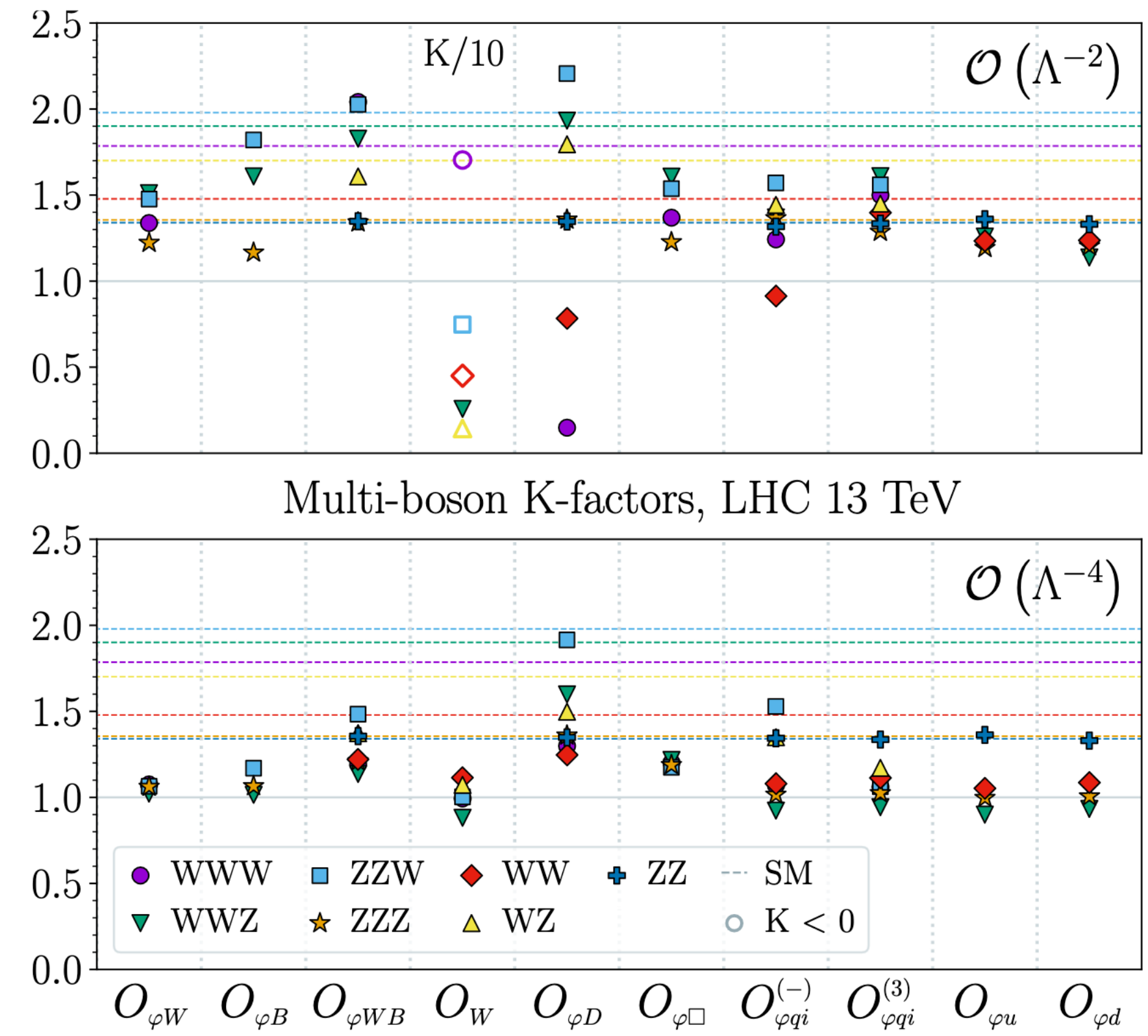
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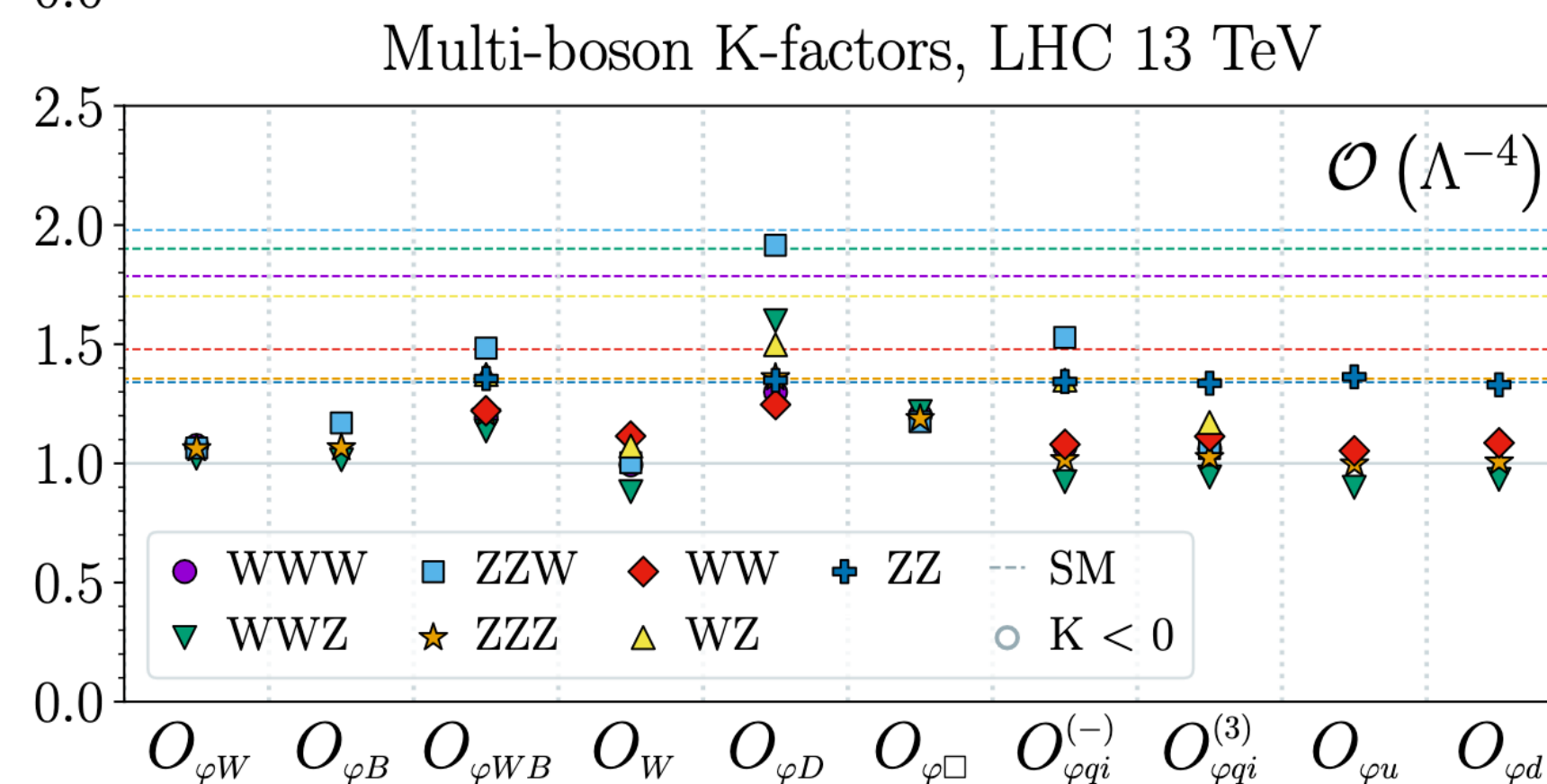
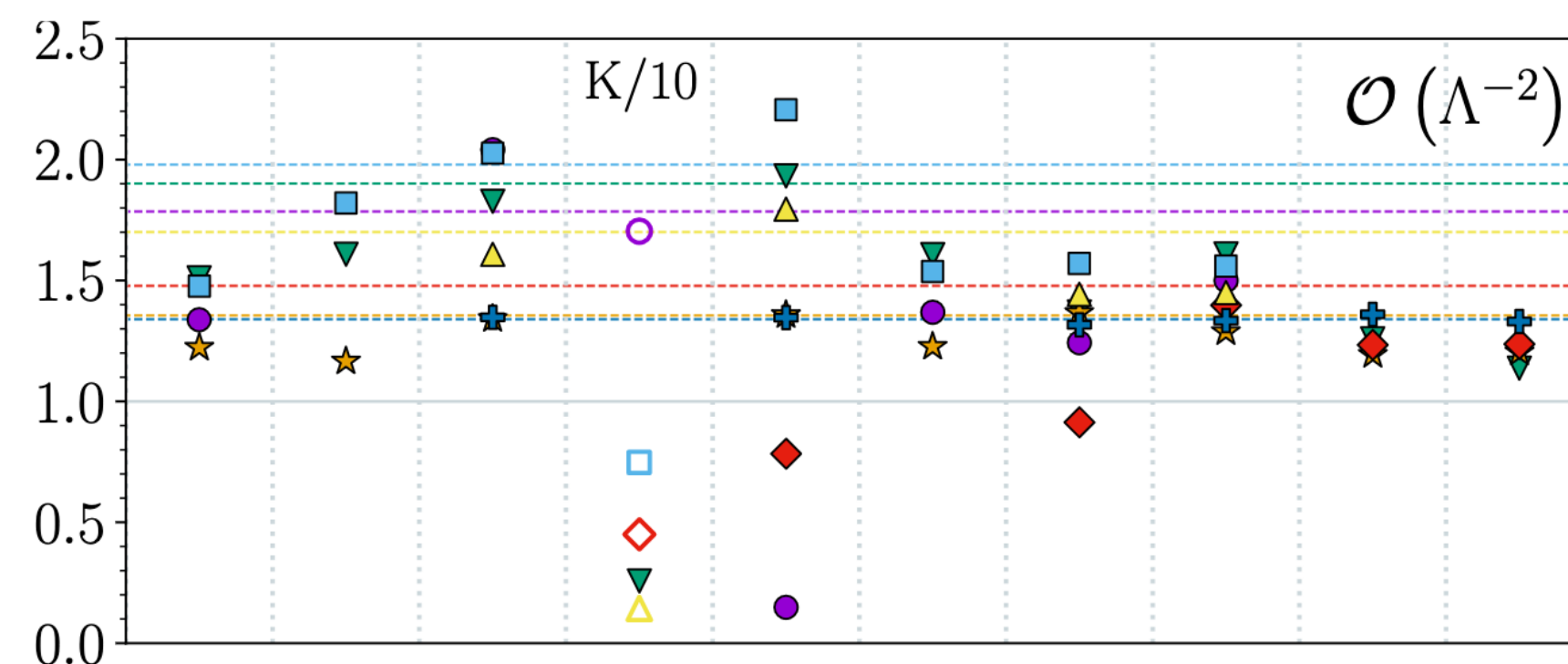
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- Electroweak corrections still must be done process-by-process
- EWPO already known at NLO EW [Dawson, Giardino 2019](#)
- Many interesting new operators appear first at NLO electroweak: i.e. C_ϕ



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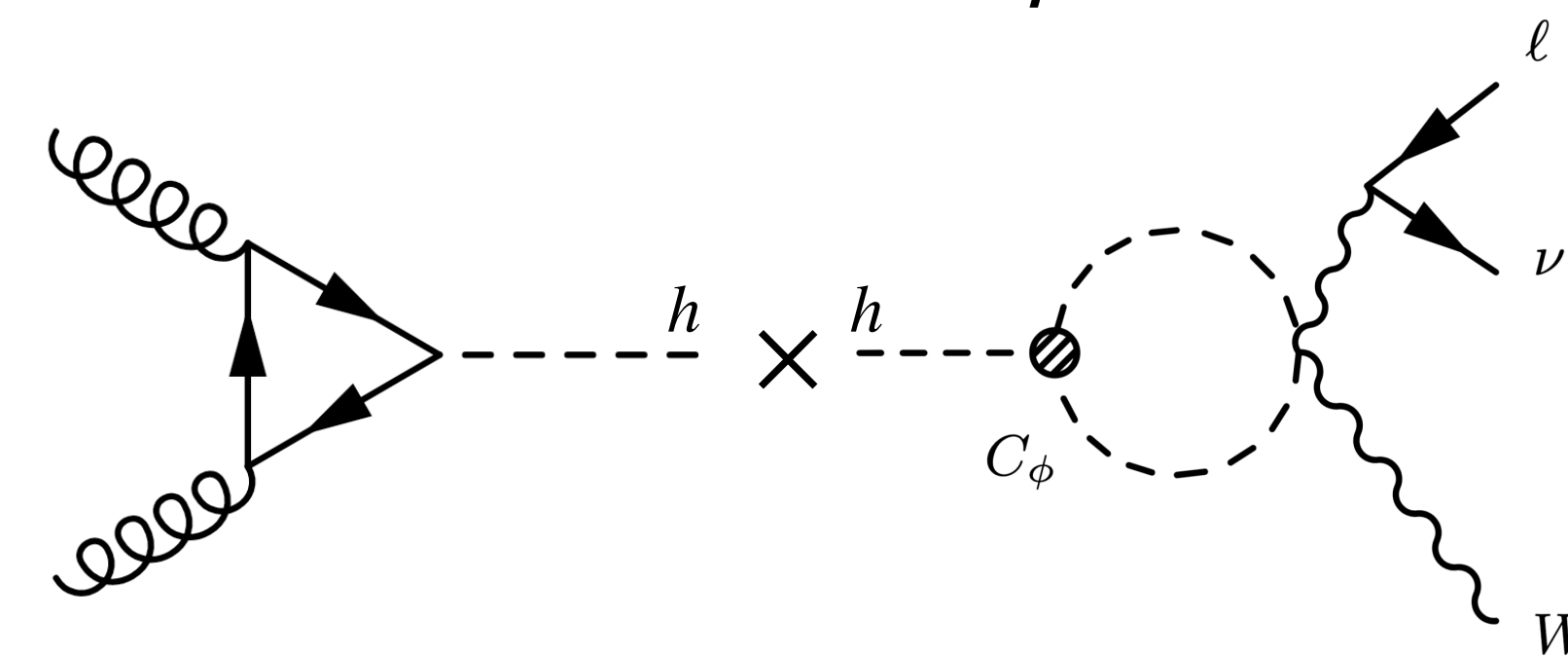
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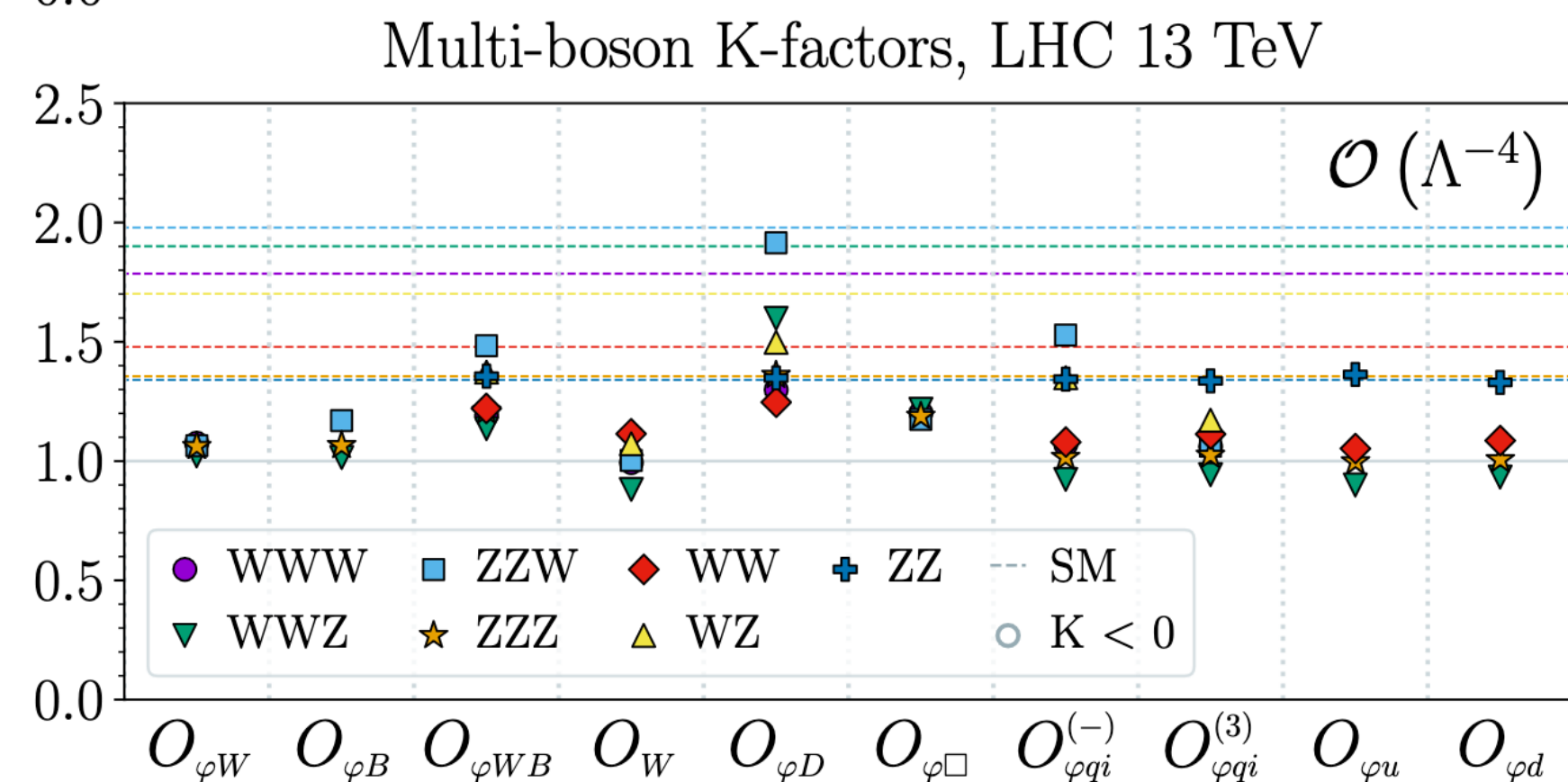
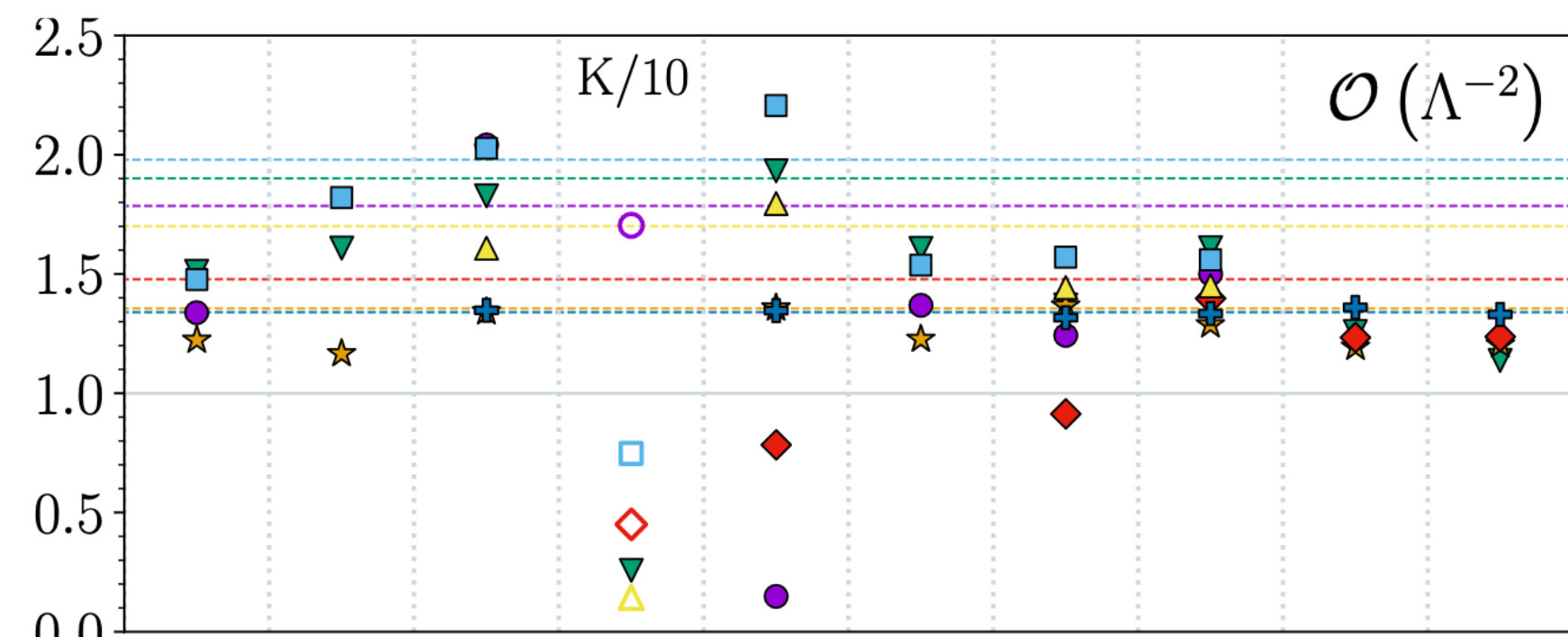
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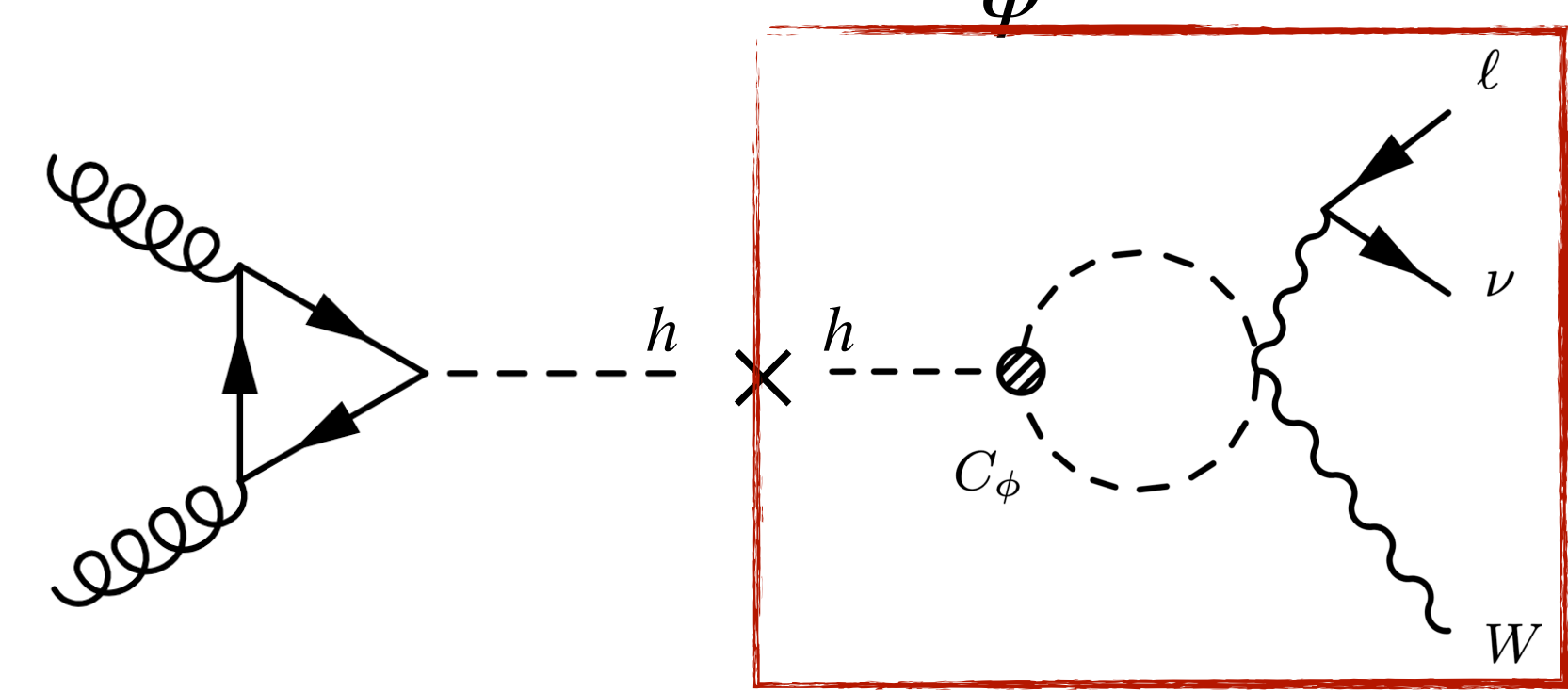
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H decays at NLO over the last 10 years

- $H \rightarrow b\bar{b}$ [Gauld, Pecjak, Scott, PRD 94 \(2016\) 7, 074045](#) [Cullen, Pecjak, Scott, JHEP 08 \(2019\) 173](#) [Cullen, Pecjak, JHEP 11 \(2020\) 079](#)
- $H \rightarrow \tau^+\tau^-, \mu^+\mu^-, c\bar{c}$ [Gauld, Pecjak, Scott, JHEP 05 \(2016\) 080](#) [Cullen, Pecjak, JHEP 11 \(2020\) 079](#)
- $H \rightarrow gg$ [Deutschmann, Duhr, Maltoni, Vryonidou, JHEP 12 \(2017\) 063](#) [Corbett, Martin, Trott JHEP 12 \(2021\) 147](#) [Martin, Trott JHEP 01 \(2024\) 170](#)
- $H \rightarrow \gamma\gamma$ [Hartmann, Trott, PRL 115 \(2015\) 19, 191801](#) [Dawson, Giardino, PRD 98 \(2018\) 9, 095005](#)
 [Hartmann, Trott, JHEP 07 \(2015\) 151](#) [Dedes, Paraskevas, Rosiek, Suxho, Trifyllis JHEP 08 \(2018\) 103](#)
- $H \rightarrow Z\gamma$ [Dawson, Giardino, PRD 97 \(2018\) 9, 093003](#) [Dedes, Suxho, Trifyllis JHEP 06 \(2019\) 115](#)
- $H \rightarrow ggZ$ [Rossia, Thomas, Vryonidou JHEP 11 \(2023\) 132](#)
- $H \rightarrow \ell^+\ell^-Z$ [Dawson, Forsslund, Giardino, PRD 111 \(2025\) 1, 015016](#)
- $H \rightarrow q\bar{q}Z$ [Bellafronte, Dawson, Del Pio, Forsslund, Giardino, PRL 136 \(2026\) 5, 051801](#)
 [Bellafronte, Dawson, Del Pio, Forsslund, Giardino, \[2601.09599\]](#)
- $H \rightarrow f\bar{f}W^\pm$ New! Gives access to all $H \rightarrow 4f$ decays at NLO in the narrow width approximation

NEWiSH

- Fixed-order Monte Carlo code written in Fortran
- Consistent implementation of all major H partial widths at NLO QCD and EW in the SMEFT
- Exact $H \rightarrow 4f$ at LO, NWA at NLO
- Publicly available! (Along with numerical results)

<https://gitlab.com/mforslund/newish>

NLO
Electro-
Weak
in the
SMEFT for
Higgs widths

NEWiSH

- Easy to use config files
- Coefficients in standard WCxF format (same as DsixTools)
- Some limited differential distributions ($d\sigma/dm_{\ell\ell}$ for $H \rightarrow 4\ell$)
- Coefficients defined at the scale $\mu = m_H$. Running not implemented!

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  "nlo_flag": 0,  
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  "MZ": 91.1535,  
  "MT": 172.76,  
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  "mc": 1.51,  
  "ms": 0.1,  
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}
```

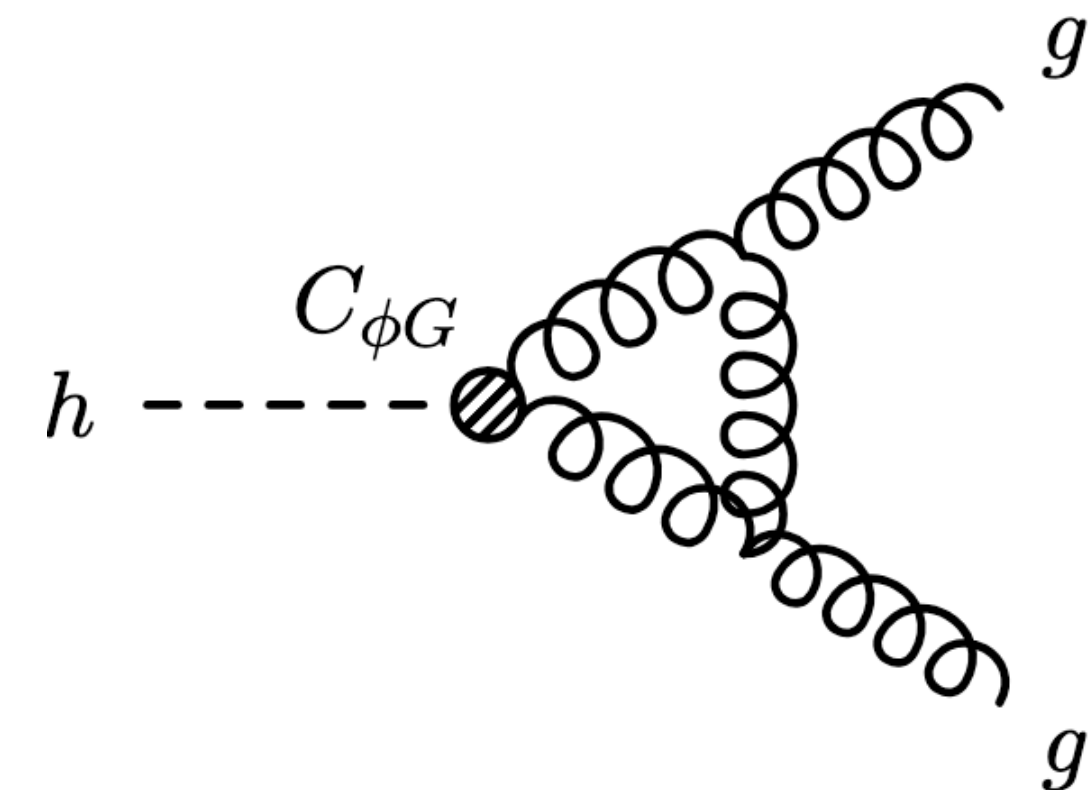
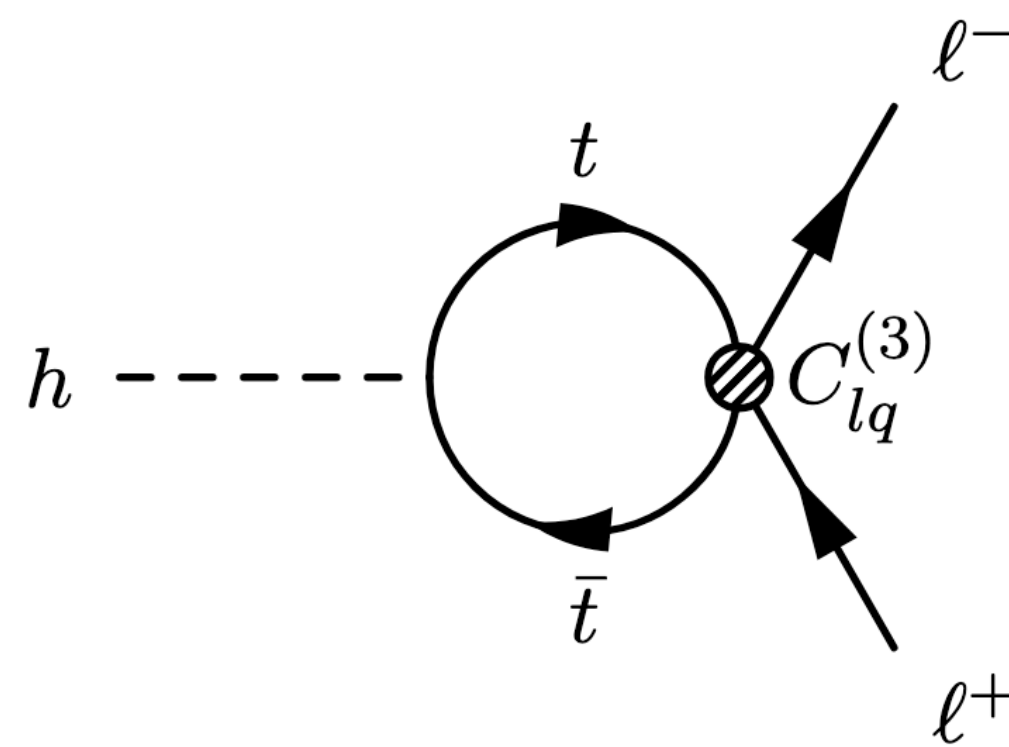
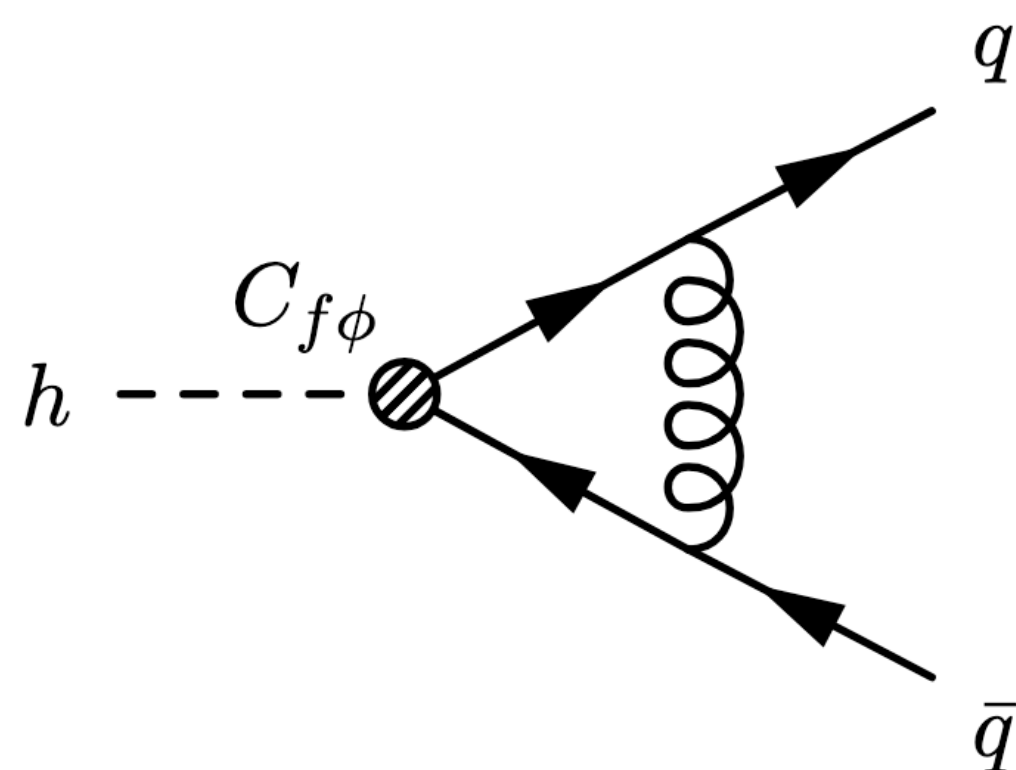
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      "Im": 0  
    },  
  },  
}
```

Virtual

- FeynRules \rightarrow FeynArts \rightarrow FeynCalc to obtain amplitudes
- Inputs: G_F , m_W , m_Z , α_S , m_h , m_t , and additional m_f for $H \rightarrow f\bar{f}$
- On-shell renormalization for SM params, $\overline{\text{MS}}$ for SMEFT coefficients

$$C_i(\mu) = C_{0,i} - \frac{1}{2} \left[\frac{1}{\epsilon} \bar{\mu}^{2\epsilon} \right] \frac{1}{16\pi^2} \gamma_{ij} C_j(\mu)$$

$$\frac{dC_i(\mu)}{d \ln \mu} = \frac{1}{16\pi^2} \gamma_{ij} C_j(\mu)$$



Real Emission

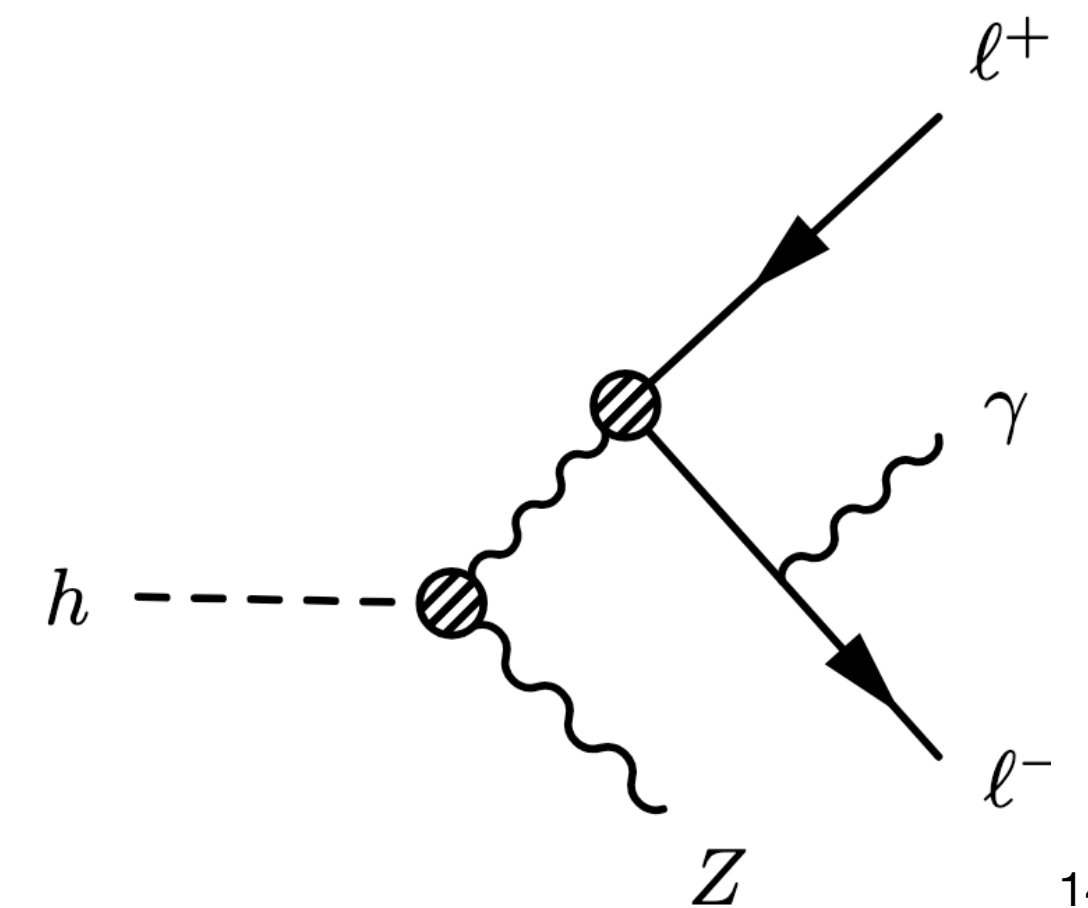
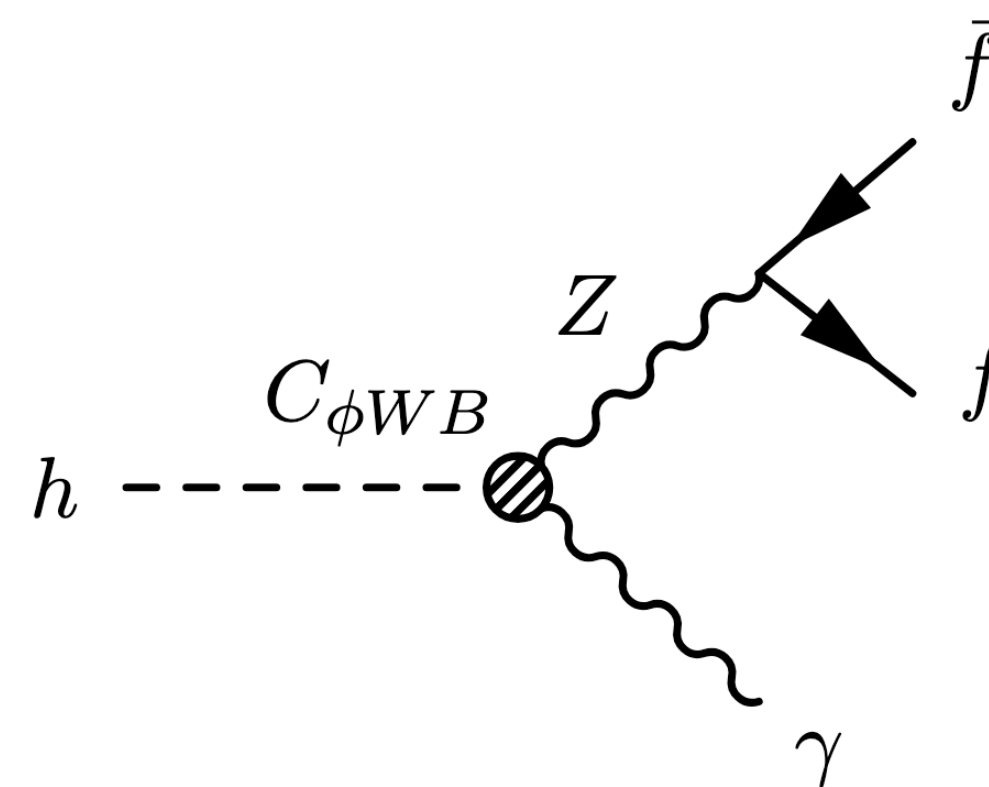
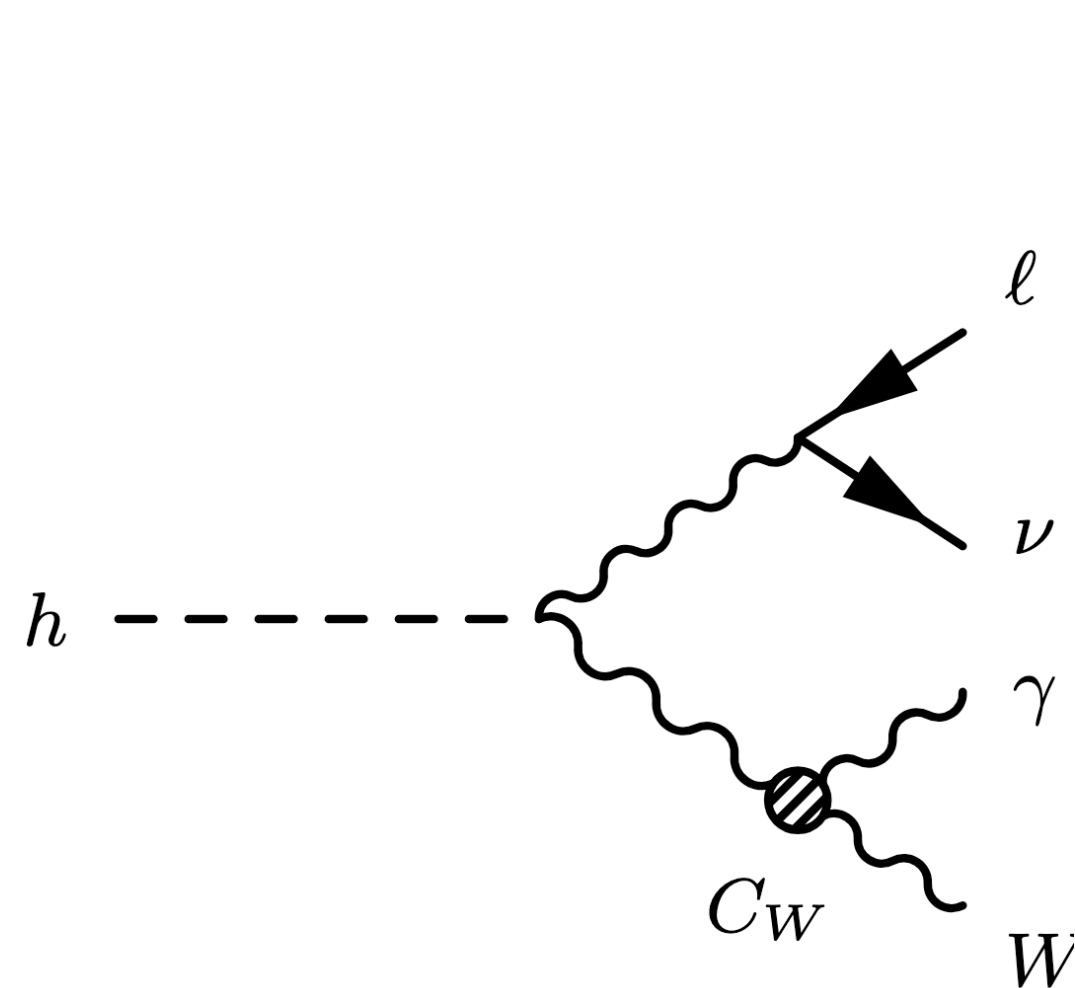
- IR singularities from the virtual $H \rightarrow X$ cancel with $H \rightarrow X + (\gamma, g)$
- Handle IR singularities with standard massive and massless dipole subtraction

$$\Gamma_R = \frac{1}{2m_H} \int d\text{PS}_n \left(|\mathcal{A}_R|^2 - |\mathcal{A}_{\text{sub}}|^2 \right) + \int d\Gamma_{\text{sub}}$$

Catani, Seymour, Nucl. Phys. B 485 (1997) 291–419

Dittmaier, Nucl. Phys. B 565 (2000) 69–122

Catani et al., Nucl. Phys. B 627 (2002) 189–265



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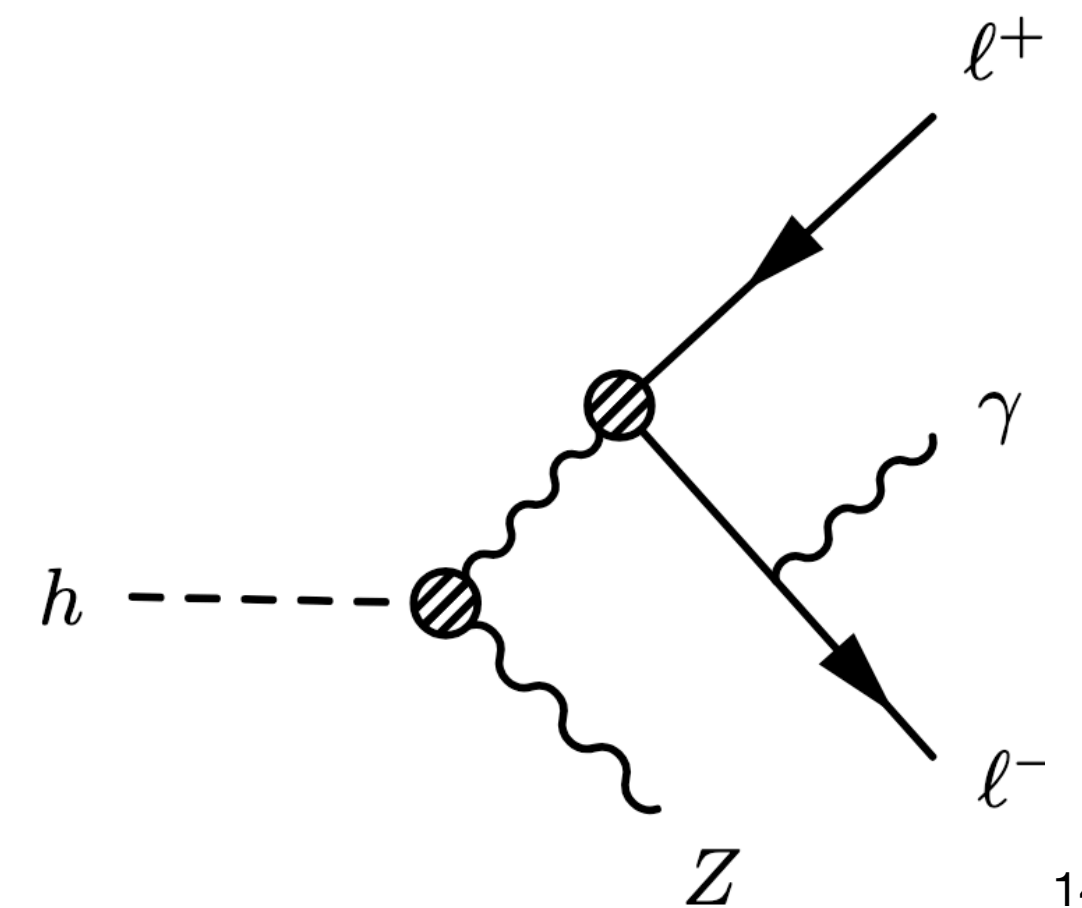
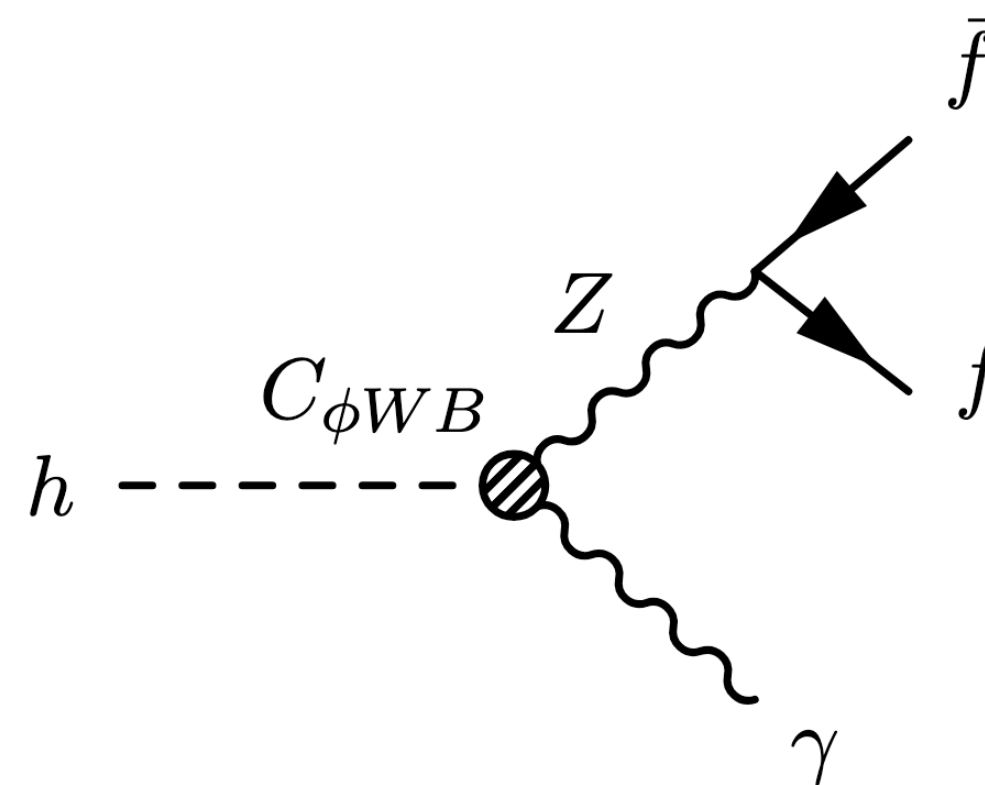
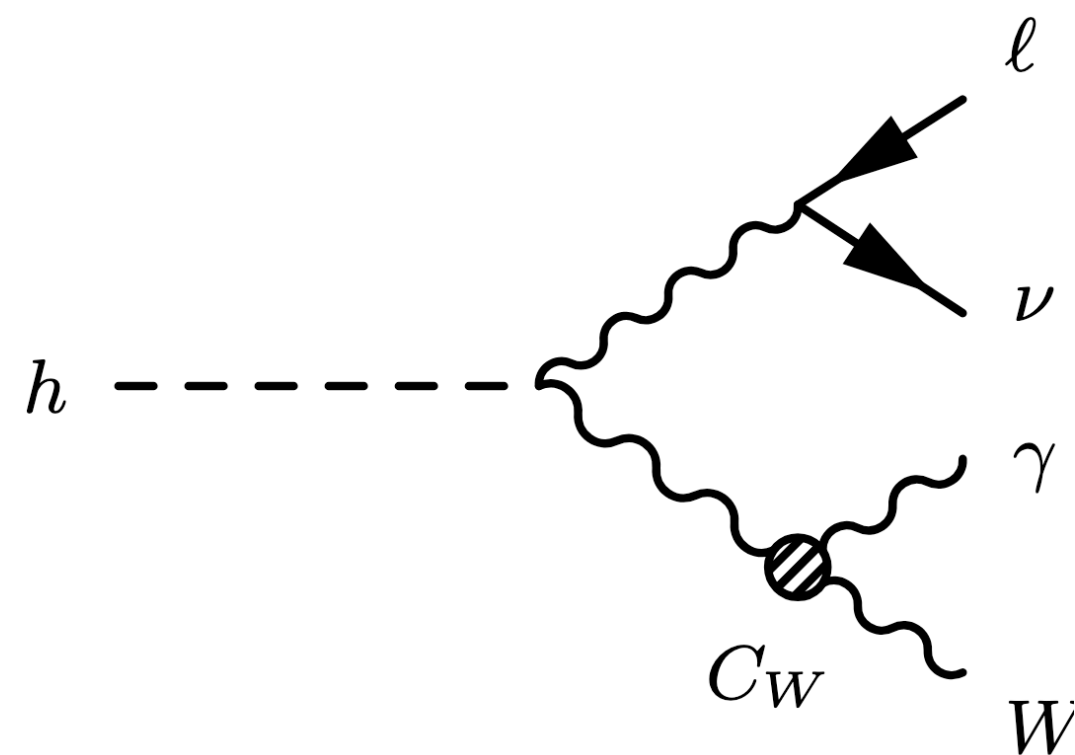
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- For $H \rightarrow 4\ell$, experimental cuts introduce additional pieces $\sim \log Q^2/m_\ell^2$



$$H \rightarrow 4f$$

- Massless light fermions, flavour general* *But with a diagonal CKM matrix
- Partial widths always truncated to $\mathcal{O}(1/\Lambda^2)$
- At LO, use complex mass scheme to include width effects
 - (This is a source of scheme dependence)

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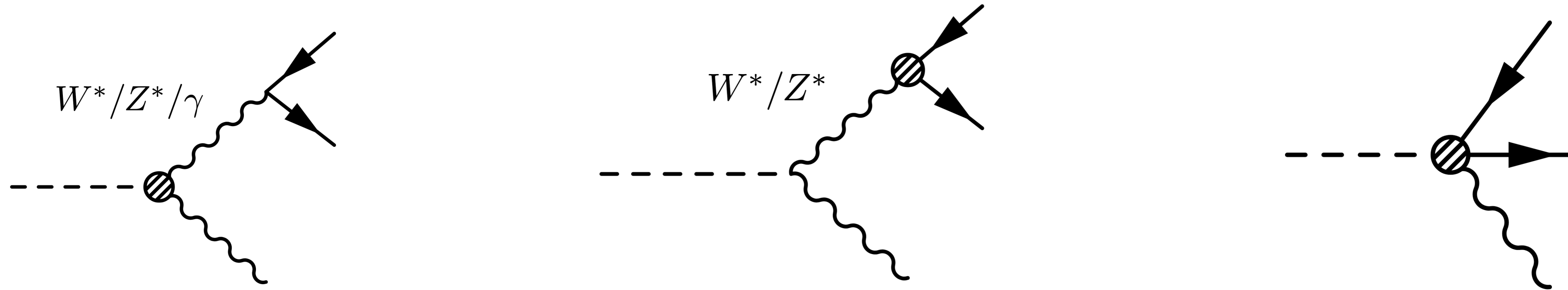
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See also [Brivio, Corbett, Trott, JHEP 10 \(2019\) 056](#)

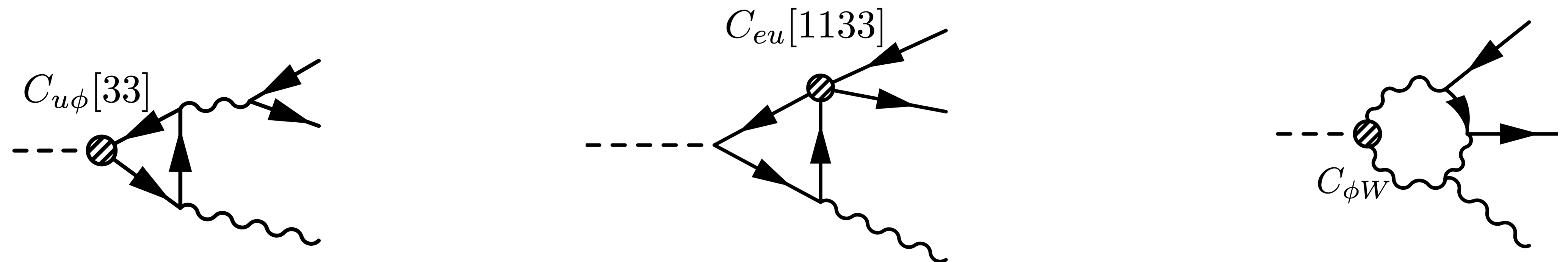
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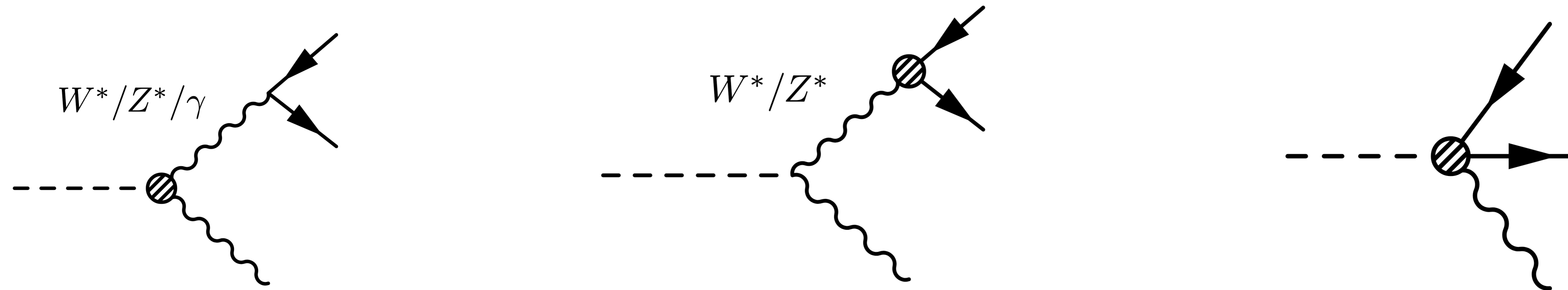


- At NLO, 184 operators contribute without flavour assumptions, or 92 assuming a $U(2)^5$ symmetry

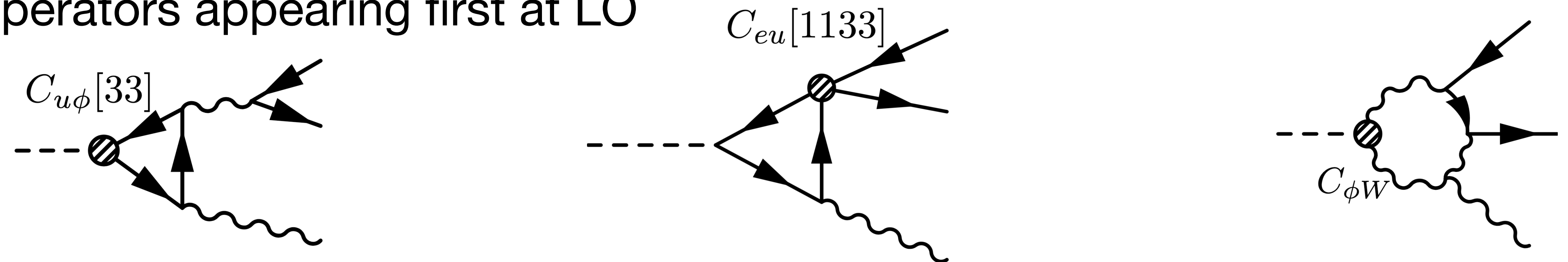


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- At LO, 26 operators contribute to $H \rightarrow ffV$ through 3 diagrams

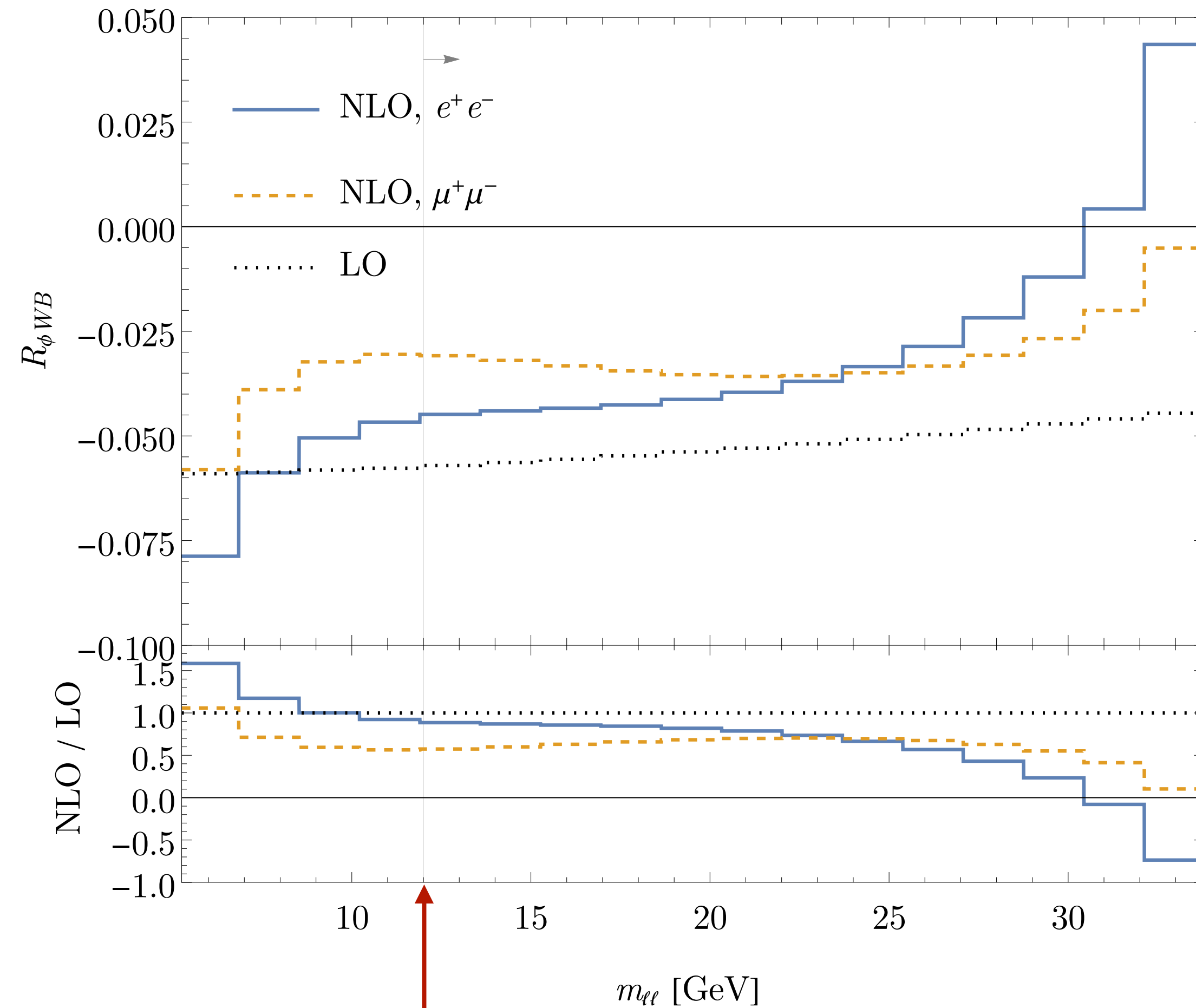


- At NLO, 184 operators contribute without flavour assumptions, or 92 assuming a $U(2)^5$ symmetry
- Many negligible — dominant pieces: top-quark operators, sizable corrections to operators appearing first at LO



$H \rightarrow \ell^+ \ell^- Z$ corrections

$C_{\phi WB}, 1/\Lambda^2, \Lambda = 1 \text{ TeV}$



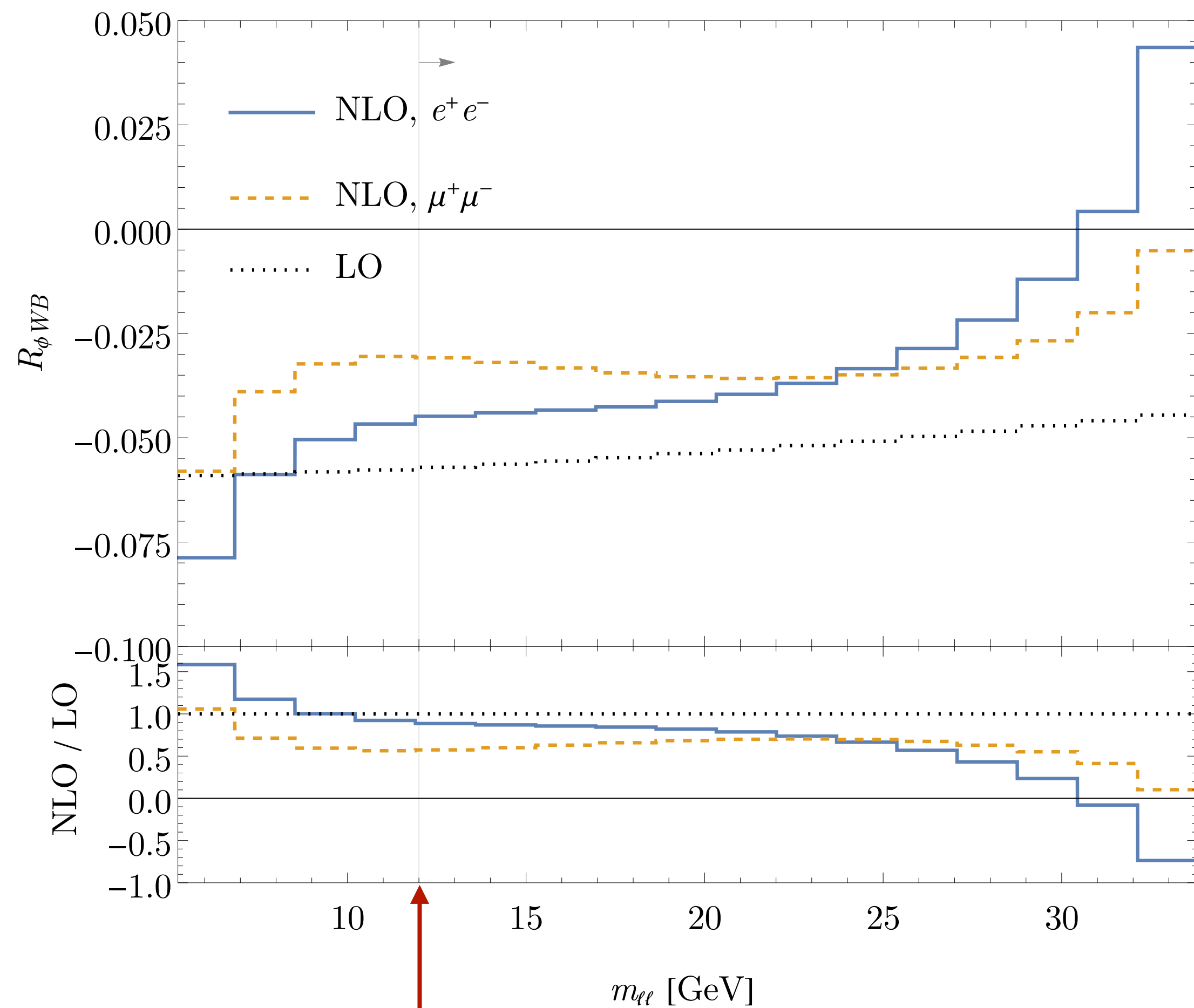
$R_i = \text{EFT/SM}$

$m_{\ell\ell} > 12 \text{ GeV} - \text{Typical exp. cut}$

- Up to 40% corrections to some LO operators at NLO

$H \rightarrow \ell^+ \ell^- Z$ corrections

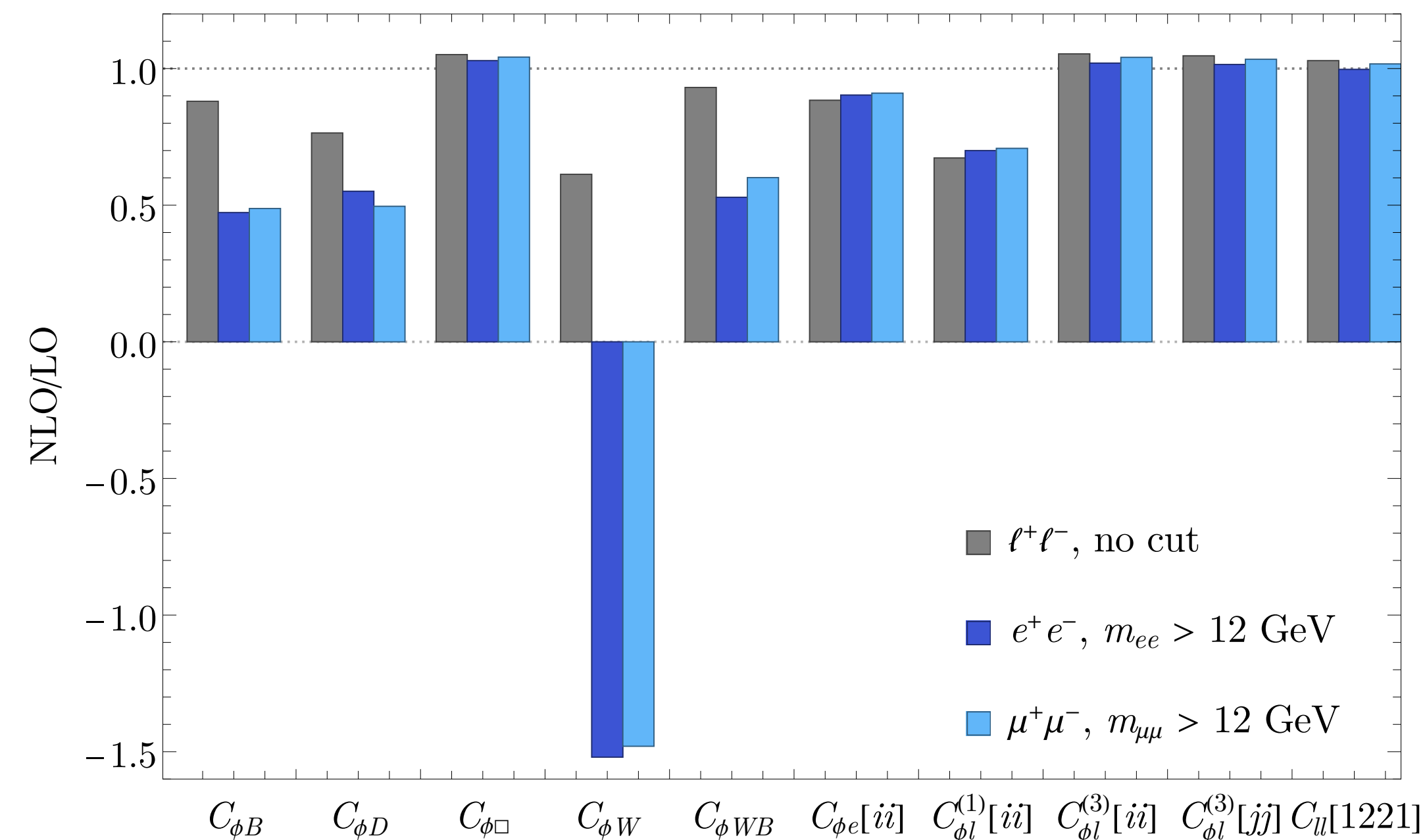
$C_{\phi WB}, 1/\Lambda^2, \Lambda = 1 \text{ TeV}$



$R_i = \text{EFT/SM}$

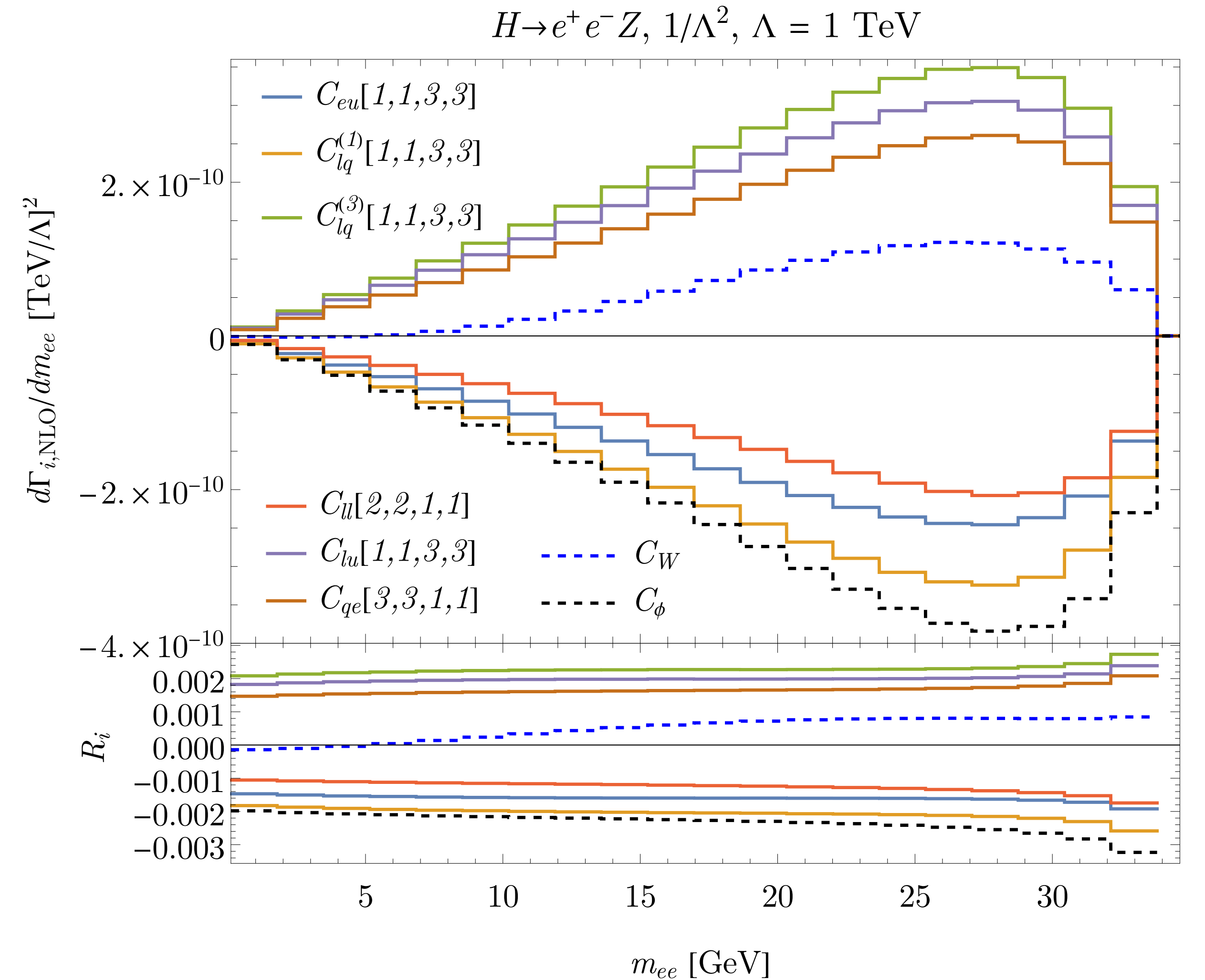
$m_{\ell\ell} > 12 \text{ GeV}$ - Typical exp. cut

- Up to 40% corrections to some LO operators at NLO
- With realistic experimental cuts, corrections become even larger



$H \rightarrow \ell^+ \ell^- Z$ corrections

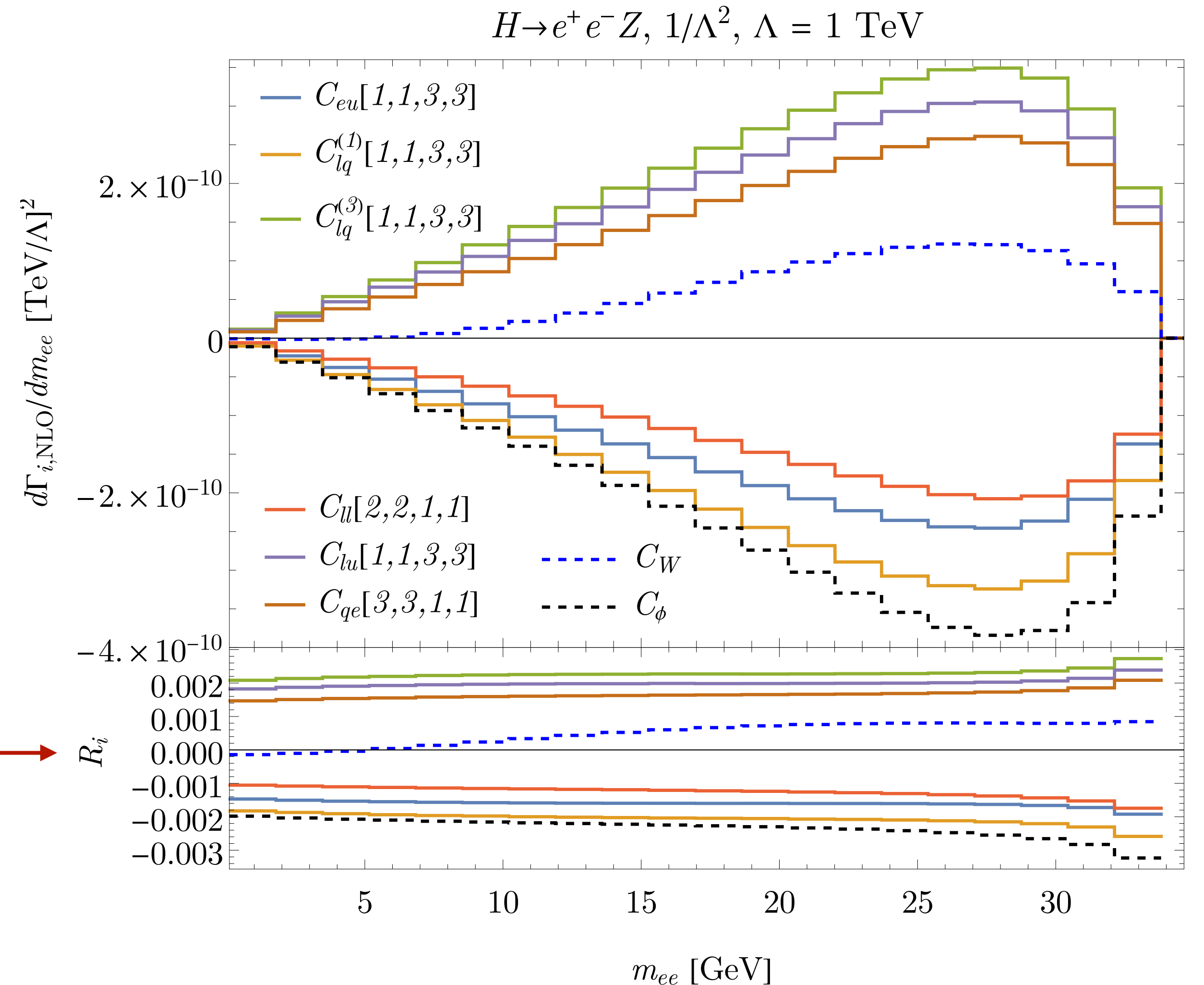
- All operators appearing first at NLO have very SM-like $m_{\ell\ell}$ distributions
- Biggest exception: C_W



$H \rightarrow \ell^+ \ell^- Z$ corrections

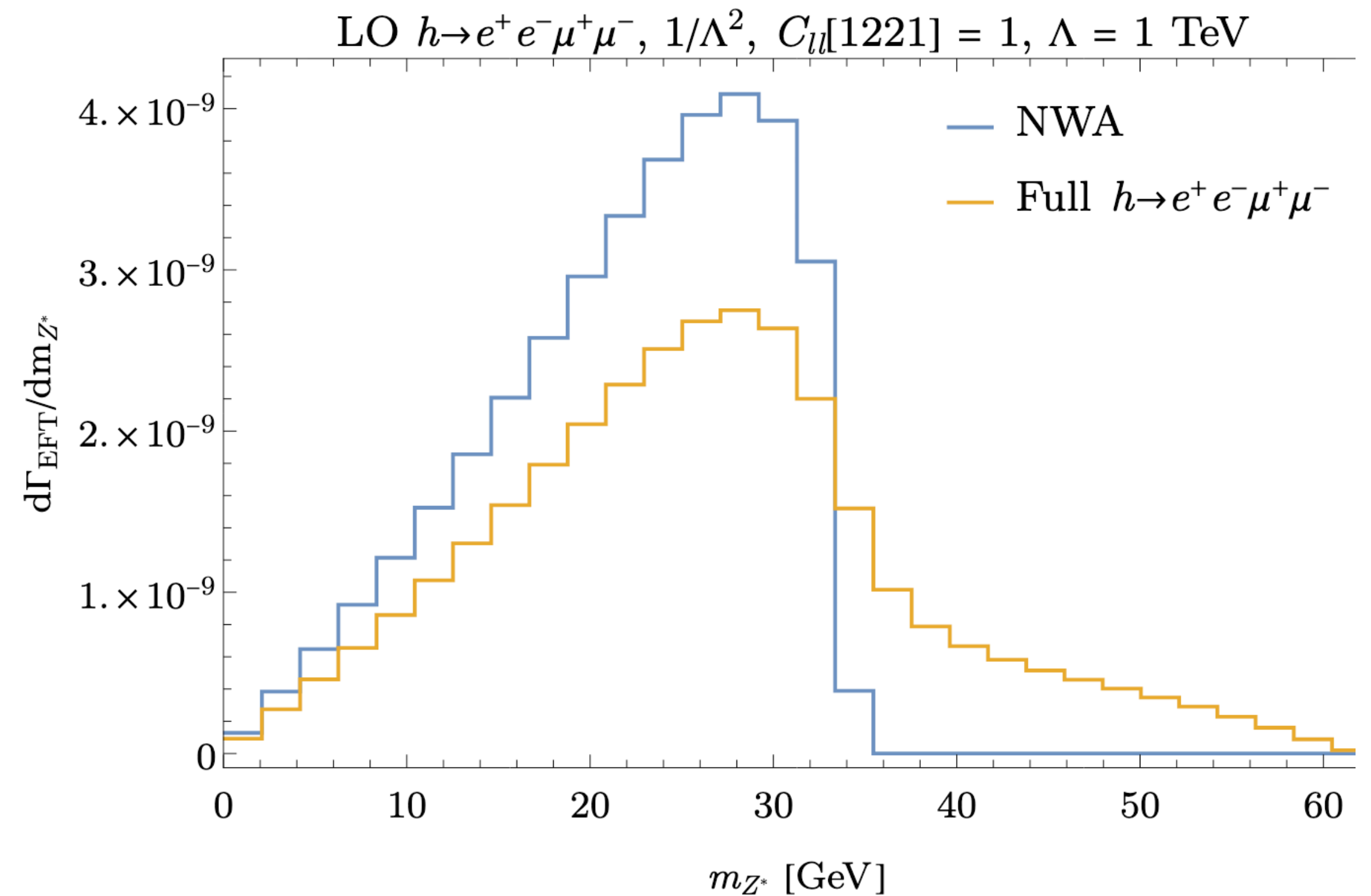
- All operators appearing first at NLO have very SM-like $m_{\ell\ell}$ distributions
- Biggest exception: C_W

Flat = SM-like \longrightarrow



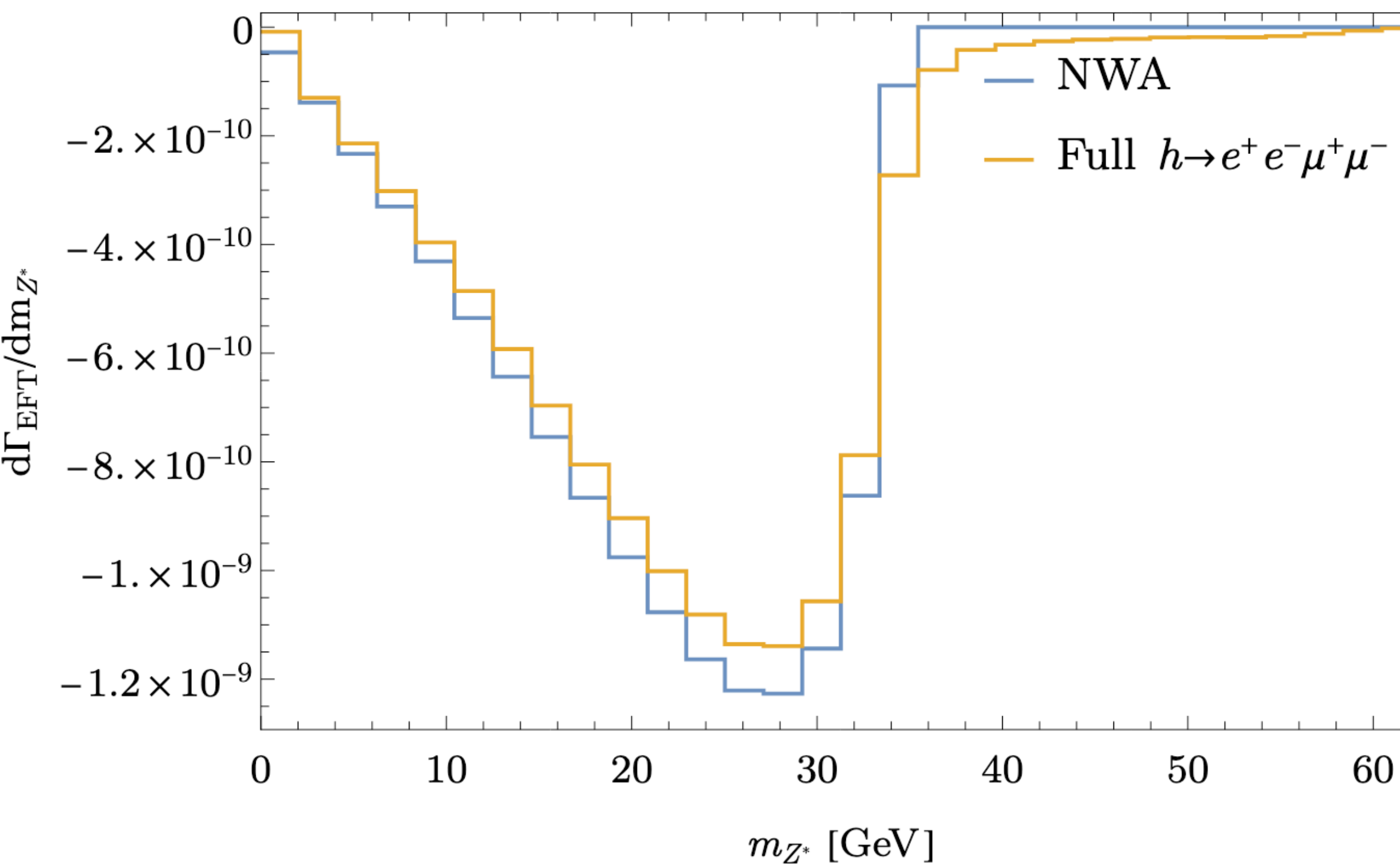
How good is the NWA?

- Can compare our full $H \rightarrow 4f$ and NWA at LO
- For individual $H \rightarrow f_1 f_2 f_3 f_4$ channels, inclusive agree within 10% for almost all operators
- For differential distributions, agreement depends significantly on process and operator

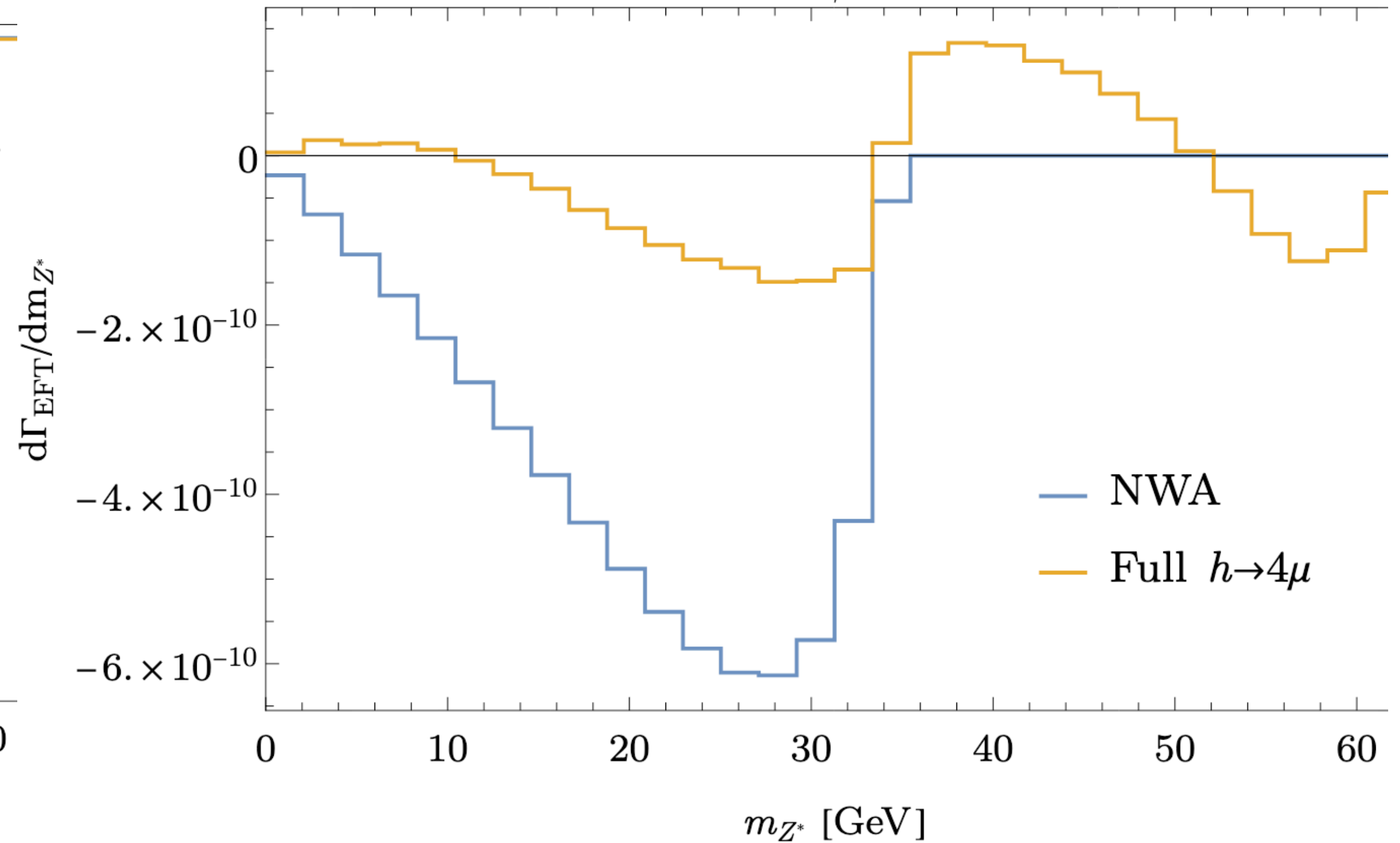


How good is the NWA?

LO $h \rightarrow e^+ e^- \mu^+ \mu^-$, $1/\Lambda^2$, $C_{\phi\text{WB}} = 1$, $\Lambda = 1$ TeV



LO $h \rightarrow 4\mu$, $1/\Lambda^2$, $C_{\phi\text{WB}} = 1$, $\Lambda = 1$ TeV



- Neglected cross terms can become important for $H \rightarrow 4\mu$, $4e$
- Not clear how much carries over at NLO. Eventually would like full NLO $H \rightarrow 4f$

Scheme dependence

- Have to choose an input scheme for calculations. Typical (OS) choices:
- G_F scheme (G_F, M_W, M_Z) , LEP scheme (G_F, α, M_Z) , α scheme (α, M_W, M_Z)
- In SMEFT, whatever isn't chosen as an input gets LO SMEFT corrections.
 - Can lead to very large scheme dependence for specific coefficients.
- At NLO, G_F and α schemes are most natural to avoid having to expand propagators
- Quark masses (m_b) demand another choice between $\overline{\text{MS}}$ and on-shell
- For $H \rightarrow 4f$, complex mass scheme introduces another choice

Scheme dependence

Some ($C_{\phi D}$, $C_{\phi WB}$) well constrained so scheme dependence is not as important, but not always guaranteed

		C_{HD}	C_{HWB}	C_{He}_{33}	C_{Hu}_{33}	$C_{Hq}^{(3)}_{33}$
v_{μ}^{eff}	LO	$-0.500^{+0.033}_{-0.033}$	$0.000^{+0.000}_{-0.000}$	$-1.843^{+0.048}_{-0.048}$	$0.000^{+0.052}_{-0.052}$	$0.000^{+0.000}_{-0.000}$
	NLO	$-0.527^{+0.005}_{-0.000}$	$0.004^{+0.000}_{-0.000}$	$-1.905^{+0.004}_{-0.000}$	$0.048^{+0.000}_{-0.013}$	$0.022^{+0.000}_{-0.004}$
v_{α}^{eff}	LO	$0.000^{+0.000}_{-0.000}$	$2.370^{+0.081}_{-0.081}$	$-1.843^{+0.050}_{-0.050}$	$0.000^{+0.003}_{-0.003}$	$0.000^{+0.005}_{-0.005}$
	NLO	$-0.001^{+0.000}_{-0.000}$	$2.439^{+0.000}_{-0.006}$	$-1.903^{+0.004}_{-0.000}$	$0.005^{+0.000}_{-0.001}$	$0.002^{+0.000}_{-0.000}$
α_{μ}	LO	$-0.169^{+0.011}_{-0.011}$	$0.355^{+0.012}_{-0.012}$	$-1.764^{+0.046}_{-0.046}$	$0.000^{+0.018}_{-0.018}$	$0.000^{+0.001}_{-0.001}$
	NLO	$-0.289^{+0.009}_{-0.007}$	$0.258^{+0.003}_{-0.004}$	$-1.897^{+0.006}_{-0.002}$	$0.018^{+0.011}_{-0.016}$	$0.006^{+0.000}_{-0.002}$
α	LO	$1.573^{+0.108}_{-0.108}$	$4.088^{+0.143}_{-0.143}$	$-1.764^{+0.050}_{-0.050}$	$0.000^{+0.162}_{-0.162}$	$0.000^{+0.008}_{-0.008}$
	NLO	$1.408^{+0.002}_{-0.019}$	$3.869^{+0.002}_{-0.013}$	$-1.898^{+0.006}_{-0.002}$	$-0.142^{+0.030}_{-0.000}$	$-0.073^{+0.014}_{-0.000}$
LEP	LO	$-0.600^{+0.040}_{-0.040}$	$-0.474^{+0.016}_{-0.016}$	$-1.837^{+0.048}_{-0.048}$	$0.000^{+0.062}_{-0.062}$	$0.000^{+0.001}_{-0.001}$
	NLO	$-0.631^{+0.005}_{-0.000}$	$-0.475^{+0.001}_{-0.000}$	$-1.899^{+0.004}_{-0.000}$	$0.057^{+0.000}_{-0.015}$	$0.025^{+0.000}_{-0.005}$

	SM	$C_{H\Box}$	C_{HD}	C_{dH}_{33}	C_{HWB}	$C_{Hl}^{(3)}_{jj}$	C_{ll}_{1221}
	20.3%	20.3%	20.3%	20.3%	20.3%	-	-
	-5.2 %	2.1%	-11.0%	4.2%	-6.7%	-	-
	15.1%	22.4%	9.3%	24.5%	13.6%	-	-
	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	-0.8 %	2.1%	2.0%	1.9%	-	0.9%	-0.8%
	19.5%	22.4%	22.3%	22.2%	-	21.2%	19.5%
	20.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
	-0.7 %	2.1%	1.6%	1.9%	-	0.7%	-0.9%
	19.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

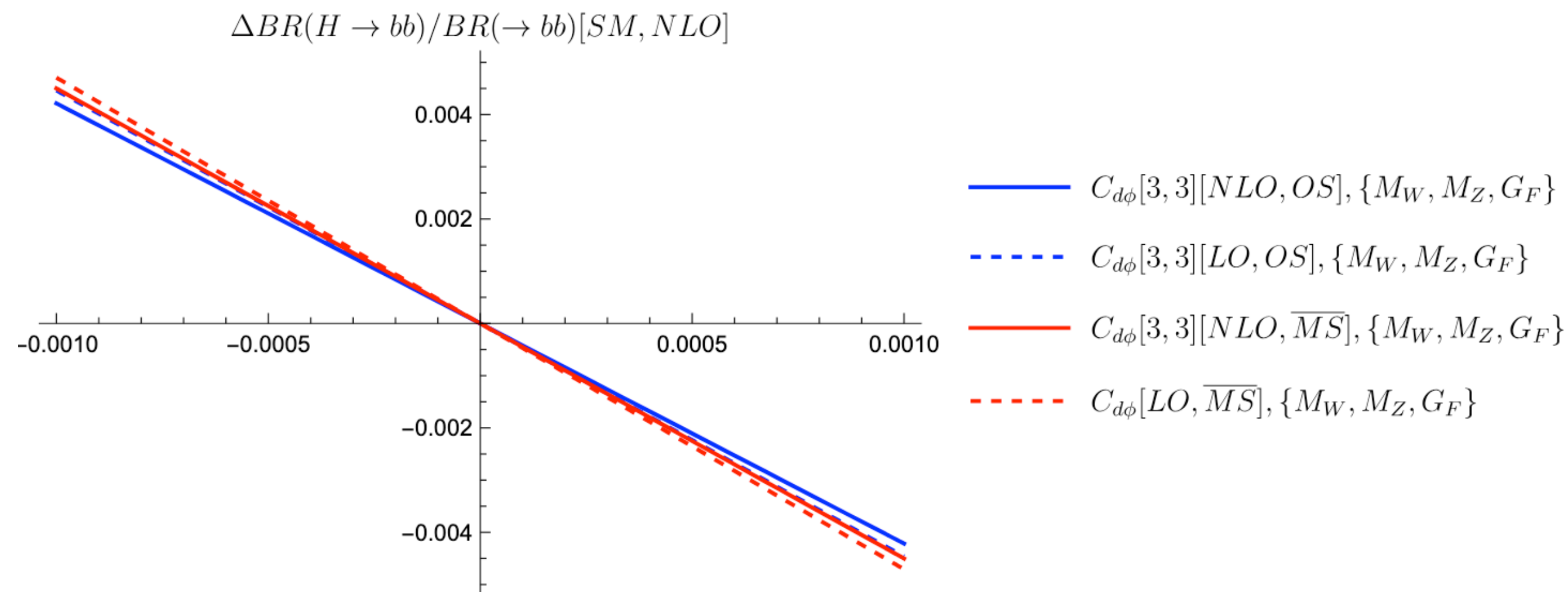
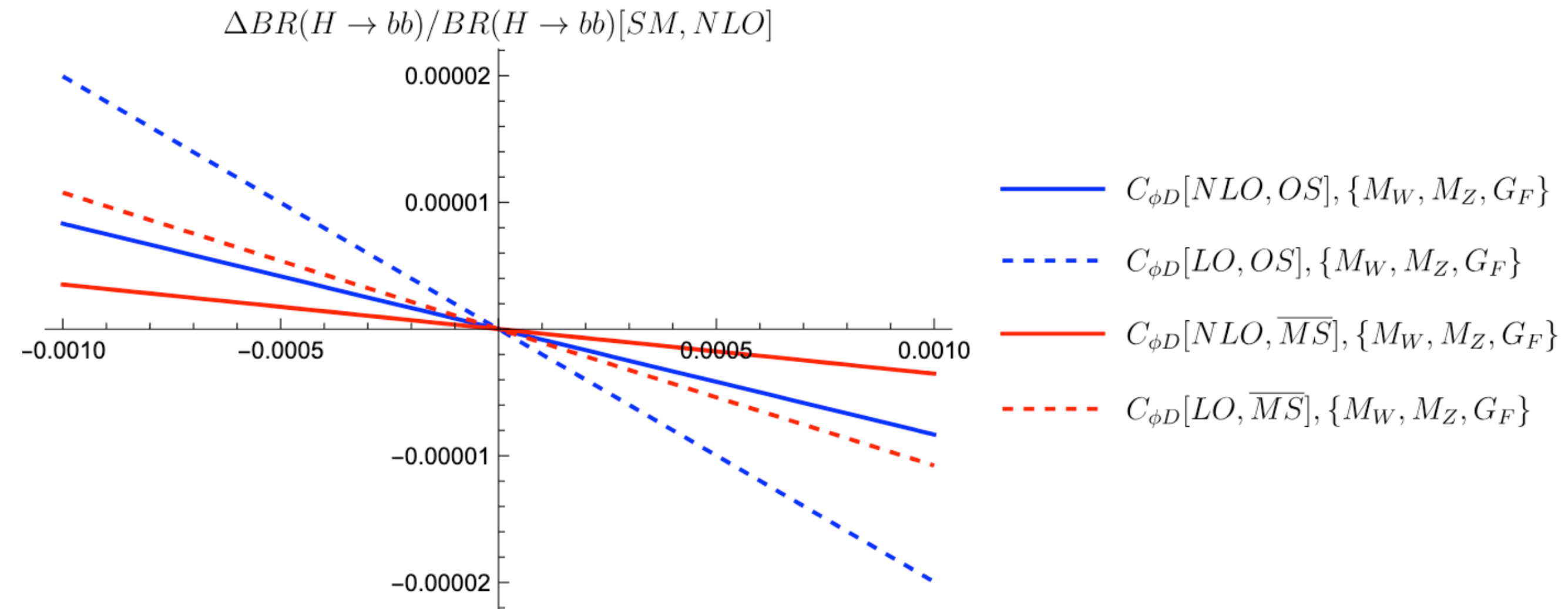
Biekötter, Pecjak, Scott, Smith

Figure 6: Selected SMEFT contributions to the $Z \rightarrow \tau\tau$ decay rate including scale variation in the five schemes.

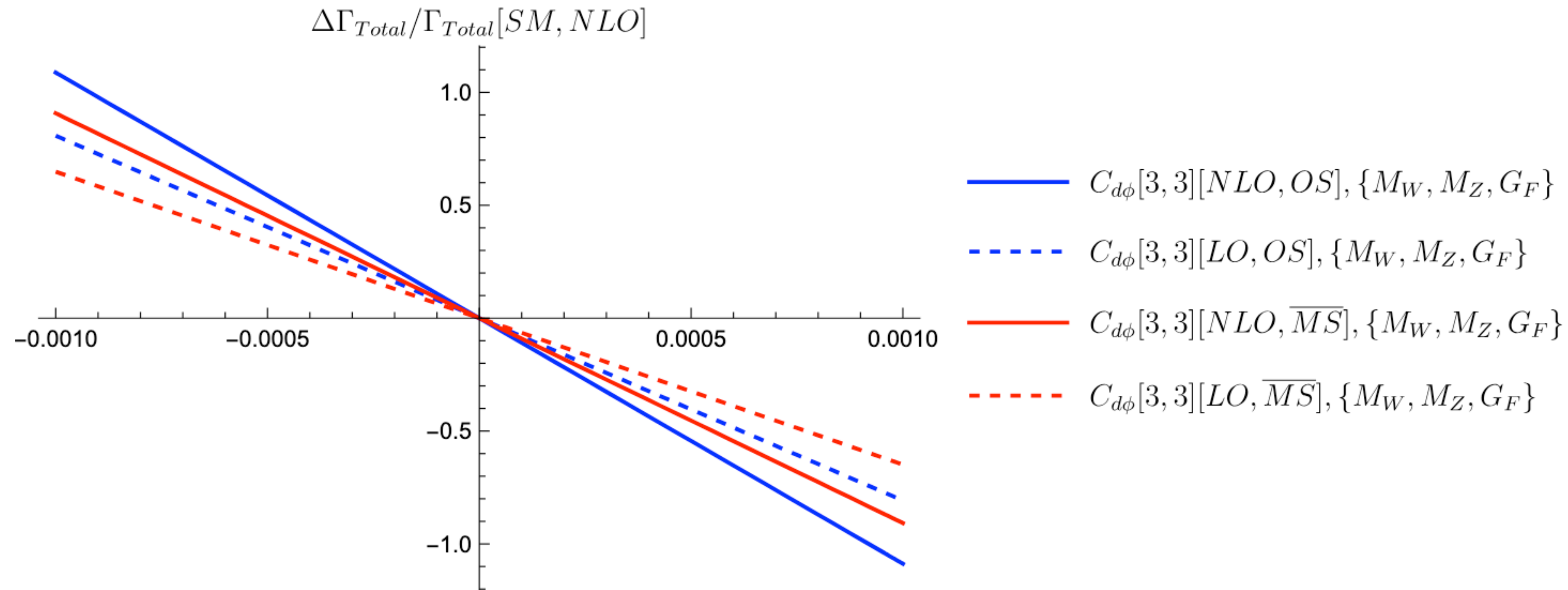
Biekötter, Pecjak, Smith

Scheme dependence: \overline{MS} vs on-shell quark masses

- \overline{MS} vs on-shell m_b scheme can matter for some coefficients
- We've implemented both in NEWiSH



Scheme dependence: \overline{MS} vs on-shell quark masses



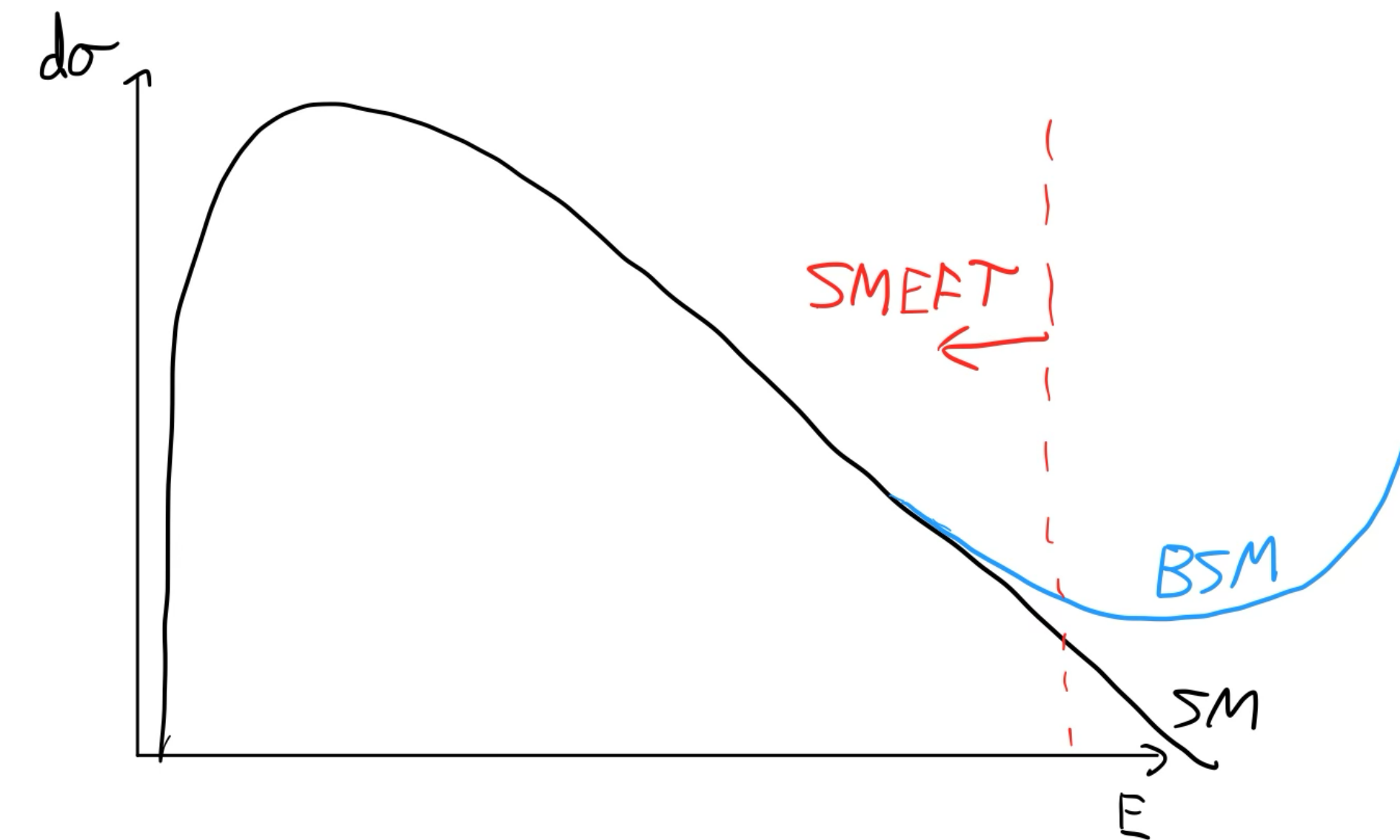
- Since bb is the largest channel, this impacts all channels through the total width

Results in POPxf format

- To make our results maximally useful, we compiled a repository for YR5 with numerical results in the POPxf format [Brivio, Mimasu, Stangl et al. \[2511.17348\]](#)
- New standardization of SMEFT results to ease sharing and comparison
- Included:
 - Higgs decays, both Γ 's and BR's, with both on-shell and $\overline{\text{MS}}$ quark masses
[Bellafronte, Dawson, Del Pio, Forslund, Giardino, PRL 136 \(2026\) 5, 051801](#) , [Bellafronte, Dawson, Del Pio, Forslund, Giardino, \[2601.09599\]](#)
 - $H \rightarrow 4e, 4\mu, 2e2\mu$ with experimental $m_{\ell\ell} > 12$ GeV cut
[Dawson, Forslund, Giardino, PRD 111 \(2025\) 1, 015016](#), [Bellafronte, Dawson, Del Pio, Forslund, Giardino, \[2601.09599\]](#)
 - Differential $d\Gamma/dm_{Z^*}$ distributions for $H \rightarrow 4e, 4\mu, 2e2\mu$
 - EWPO in (M_W, M_Z, G_F) and (α, M_Z, G_F) schemes
[Dawson, Giardino, Phys.Rev.D 101 \(2020\) 1, 013001](#), [Bellafronte, Dawson, Giardino, JHEP 05 \(2023\) 208](#)
 - $e^+e^- \rightarrow ZH$ at 240 and 365 GeV, polarized and unpolarized
[Asteriadis, Dawson, Giardino, Szafron PRL 133 \(2024\) 23, 231801](#) , [Asteriadis, Dawson, Giardino, Szafron JHEP 02 \(2025\) 162](#)

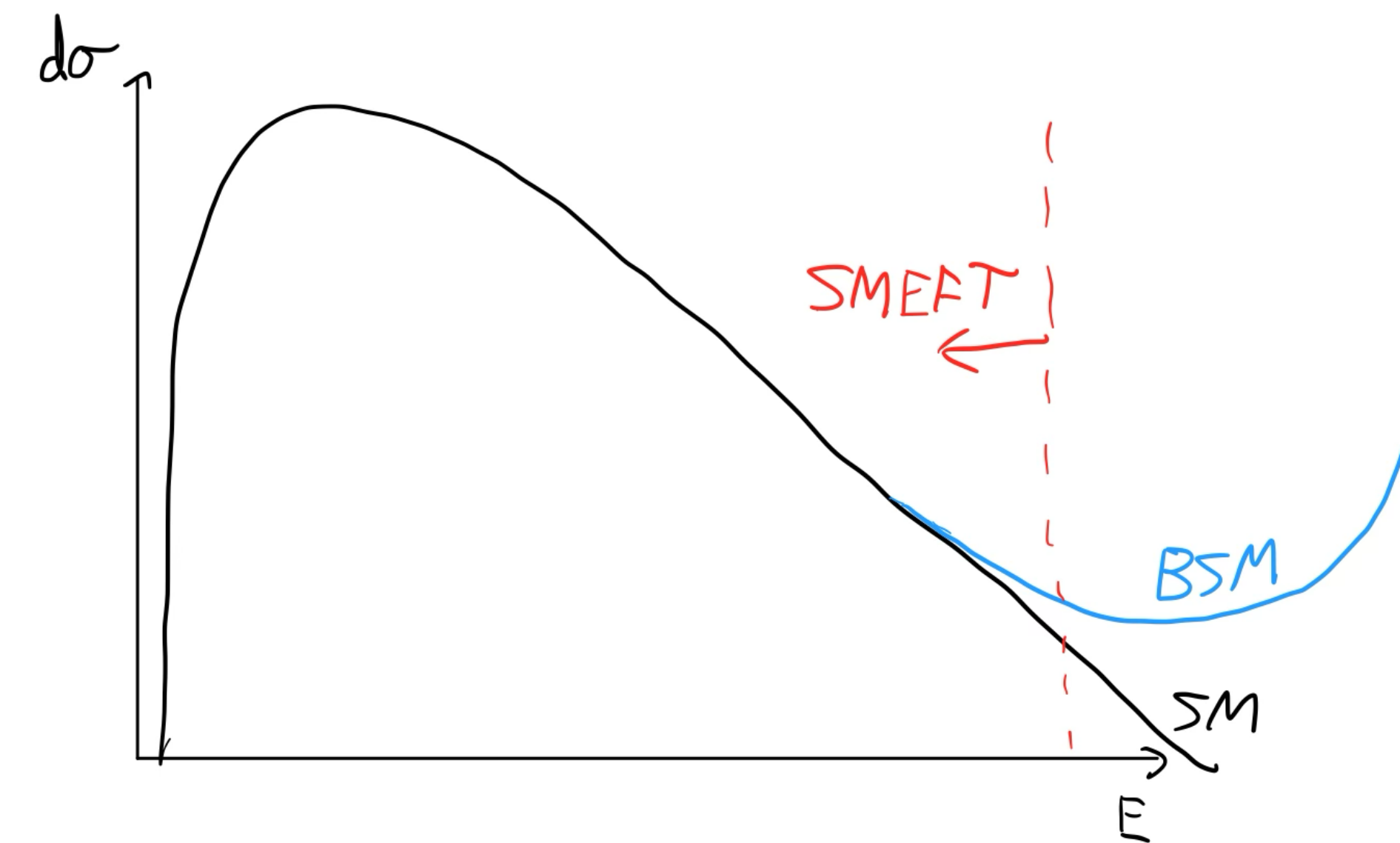
An aside on EFT validity

- For EFT to be valid, $\Lambda \gg E$ for your observable at energy E .
- Bounds on C_i 's only meaningful if this is satisfied.
- (Nearly) automatic at FCCee. For LHC SMEFT analyses, not always guaranteed!



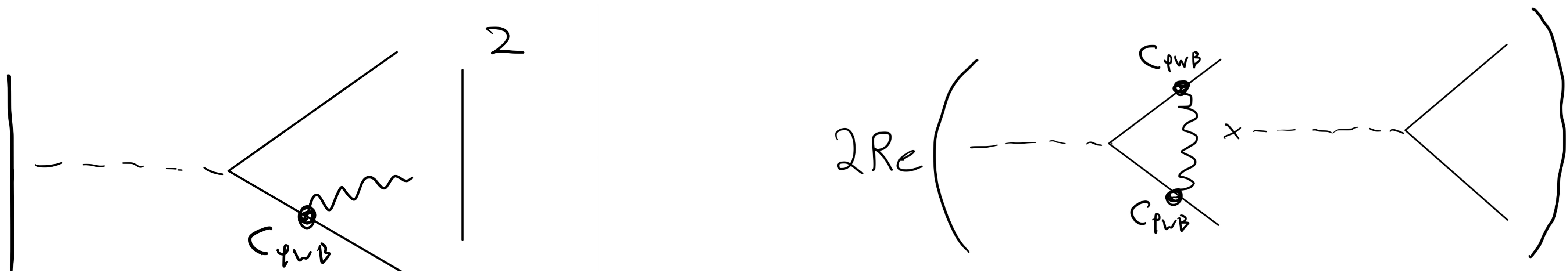
An aside on EFT validity

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- Bounds on C_i 's only meaningful if this is satisfied.
- (Nearly) automatic at FCCee. For LHC SMEFT analyses, not always guaranteed!
- One diagnostic: check relative sizes of dim-6 squared and dim-6 pieces
 - If dim-6 squared is small, probably valid
 - (But dim-6 squared constraints are unphysical!)
 - Usually ignores double insertions
- SMEFT results often include dim-6 squared



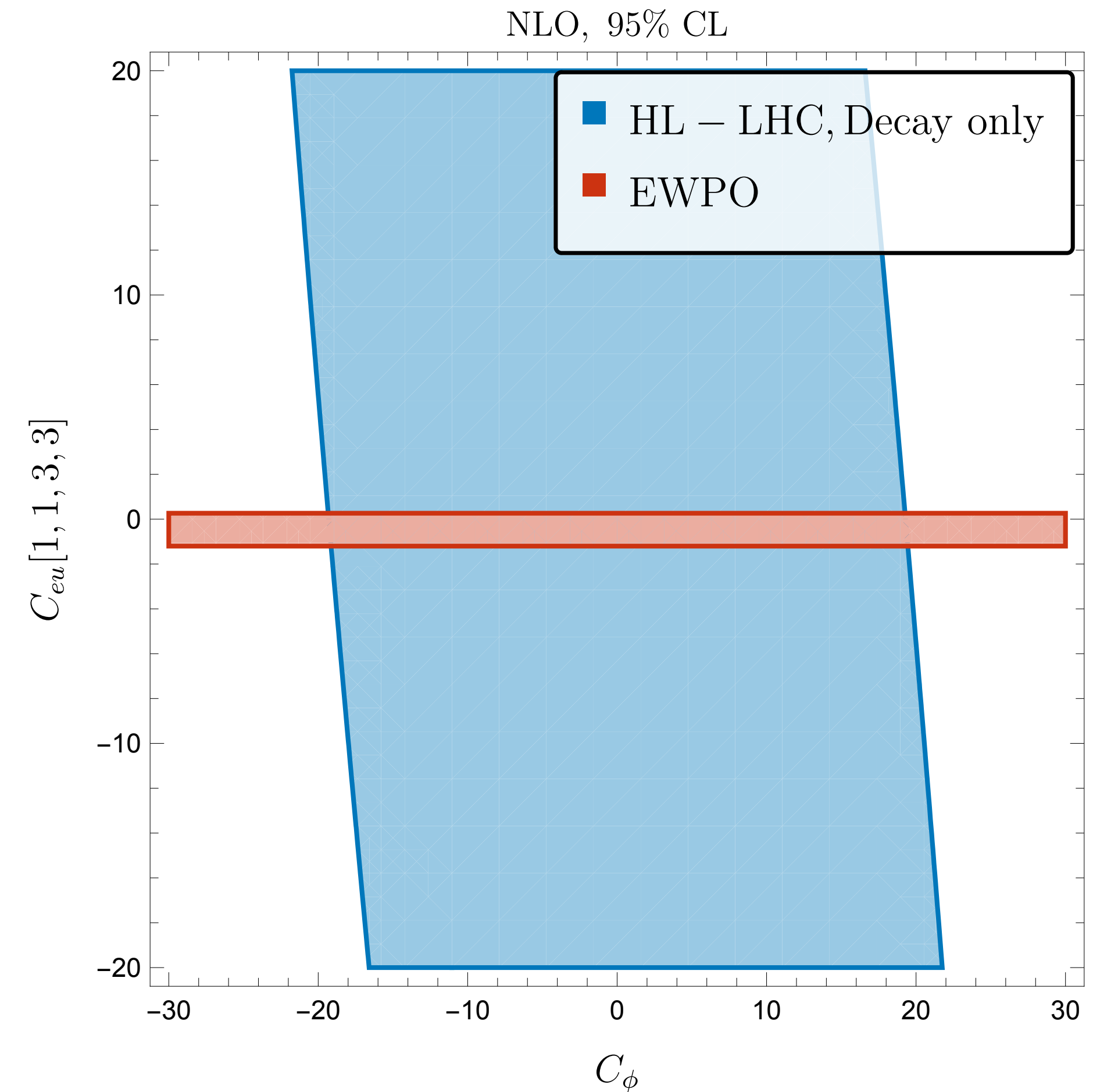
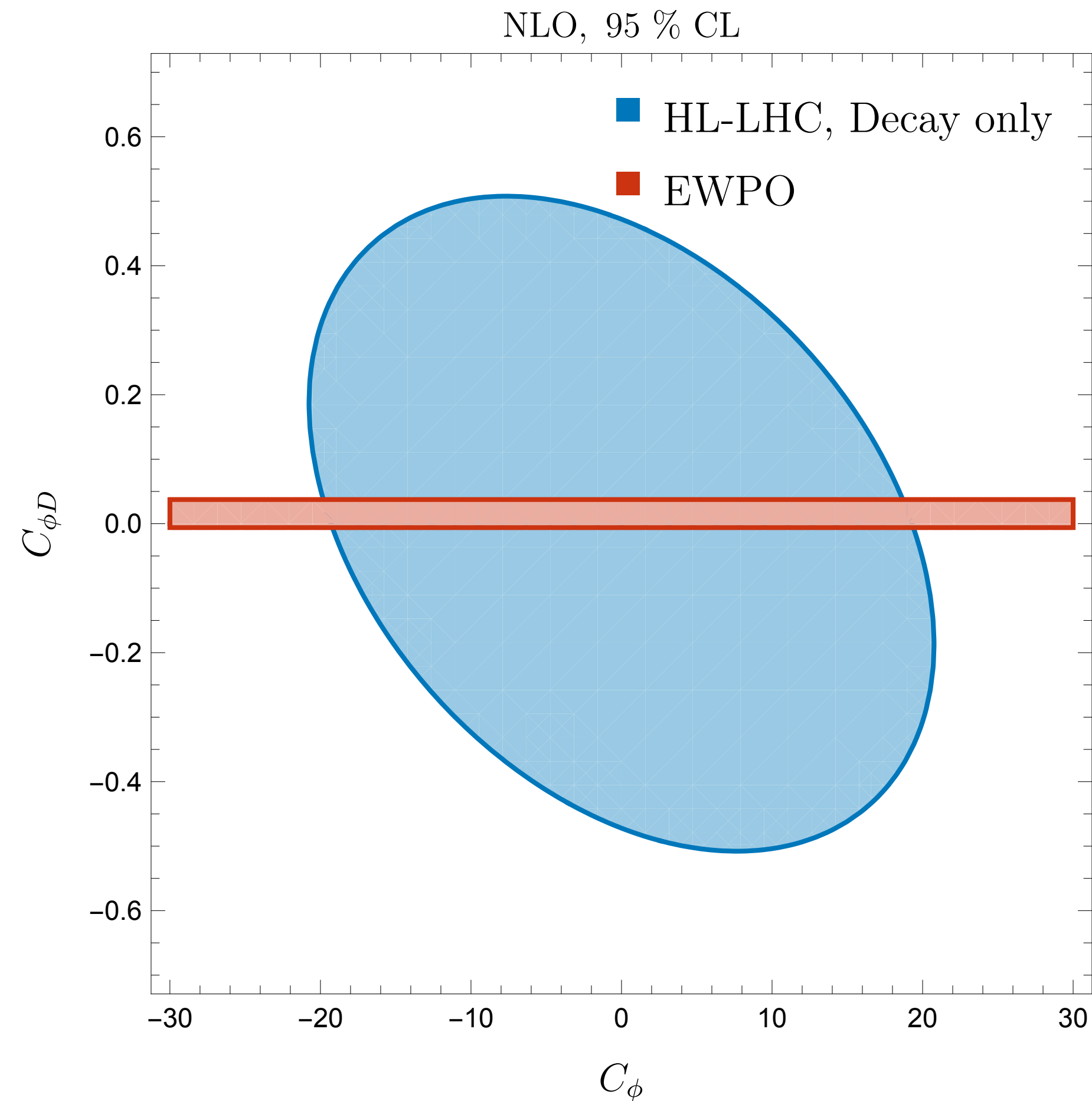
An aside on EFT validity

- At NLO: can't do quadratic dim-6 in usual G_F scheme
- Including dim-6 squared means real emission squared.
 - But α redefinitions lead to IR divergences for $C_{\phi WB}$, $C_{\phi D}$, $C_{\phi l}^{(3)}$, C_{ll} !
- These cancel with a double insertion diagram that would be usually be neglected
- (Not a problem if α is used as an input instead of G_F , but is a consequence of inconsistent powercounting)



Bounds and projections

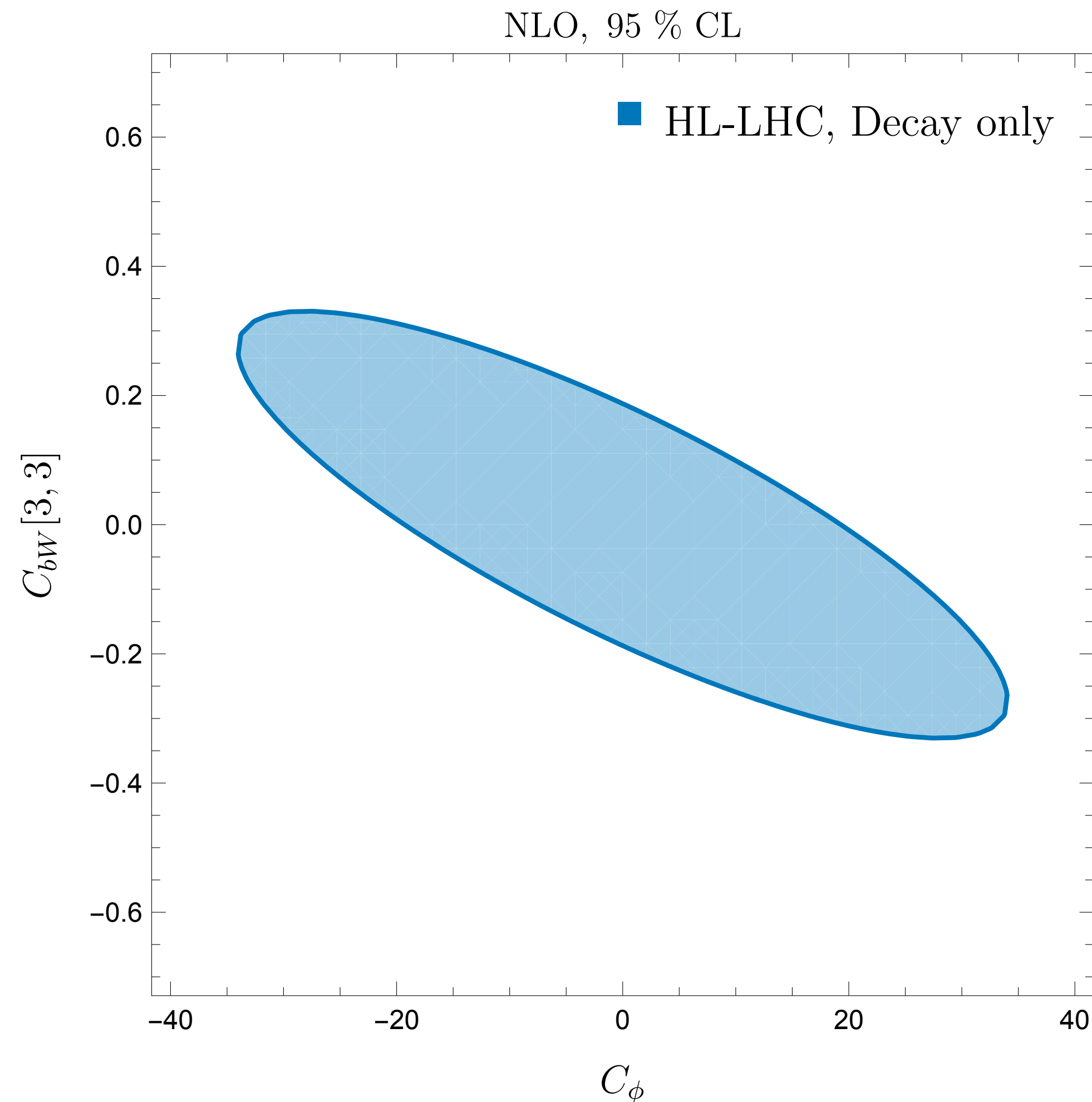
Extracting C_ϕ at the LHC



Bounds on C_ϕ sensitive to other operators at NLO, but EWPO can sometimes save you

*Fitting only to BR's

Extracting C_ϕ at the LHC



- EWPO can't save you for every coefficient
- In general, conclusions depend on assumptions
- Fits shown ignore production — more work needed for complete picture

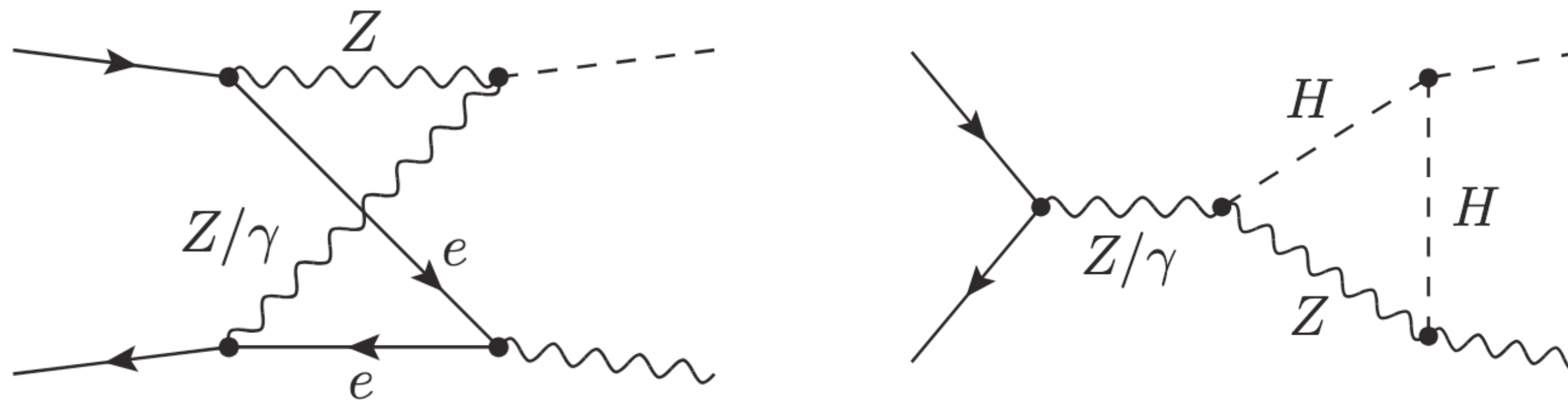
*Fitting only to BR's

Looking forward: FCC-ee

- NLO SMEFT corrections to $e^+e^- \rightarrow Zh$ known
- Depends on 10 coeffs at LO, ~ 70 at NLO

[Asteriadis, Dawson, Giardino, Szafron PRL 133 \(2024\) 23, 231801](#)

[Asteriadis, Dawson, Giardino, Szafron JHEP 02 \(2025\) 162](#)

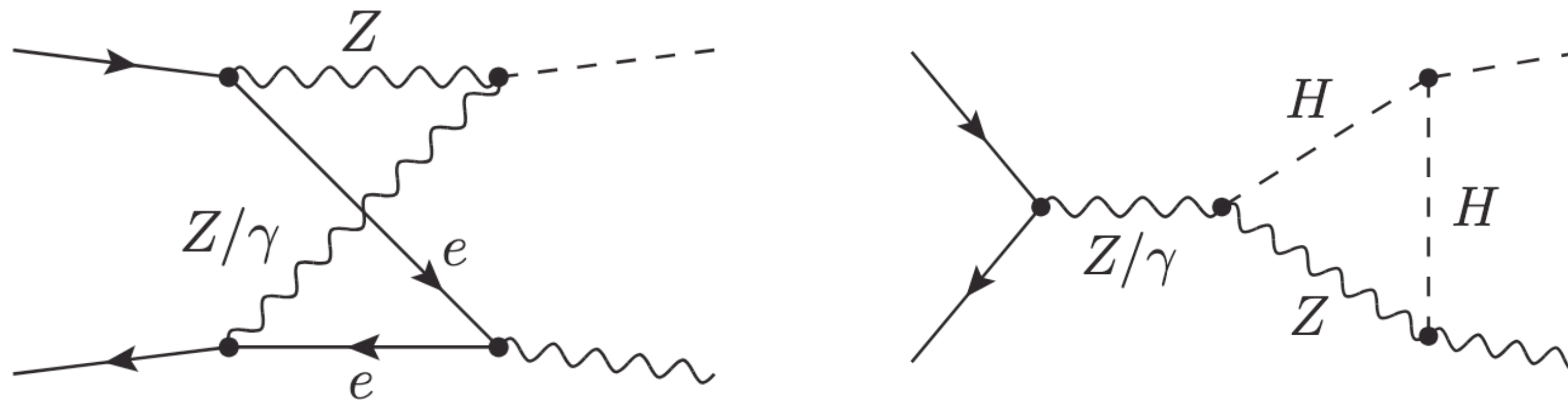


Looking forward: FCC-ee

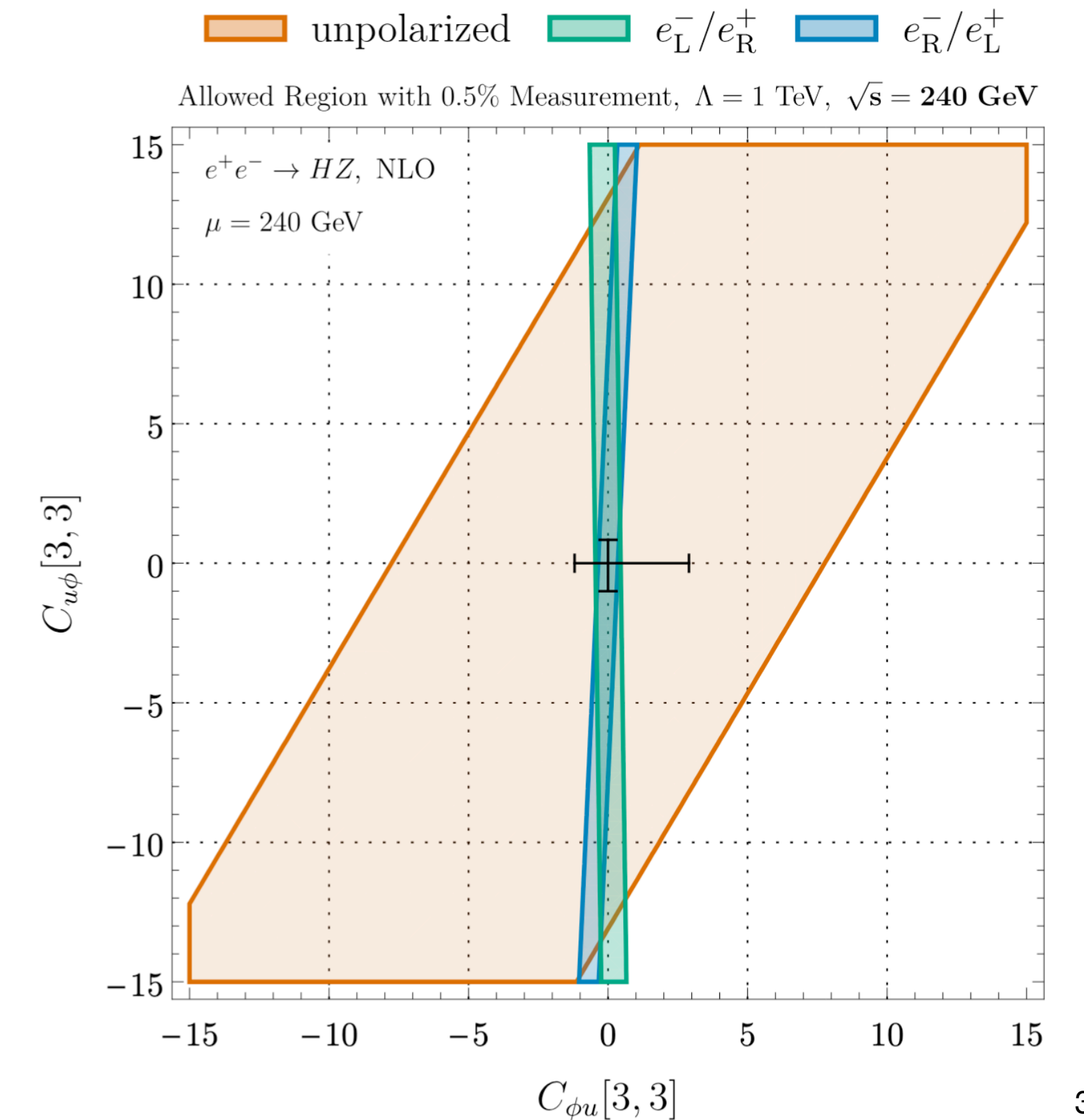
- NLO SMEFT corrections to $e^+e^- \rightarrow Zh$ known
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[Asteriadis, Dawson, Giardino, Szafron PRL 133 \(2024\) 23, 231801](#)

[Asteriadis, Dawson, Giardino, Szafron JHEP 02 \(2025\) 162](#)

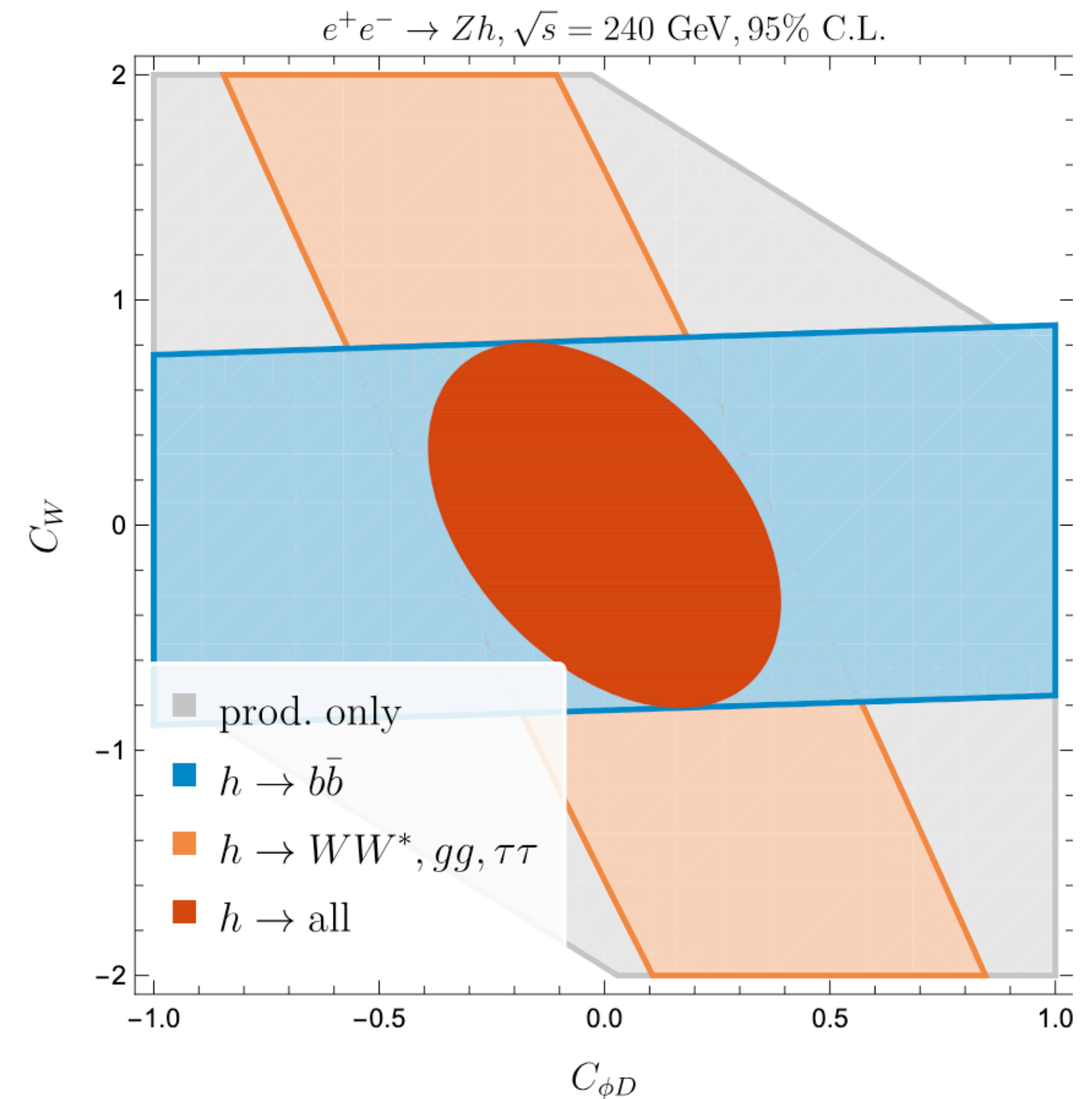
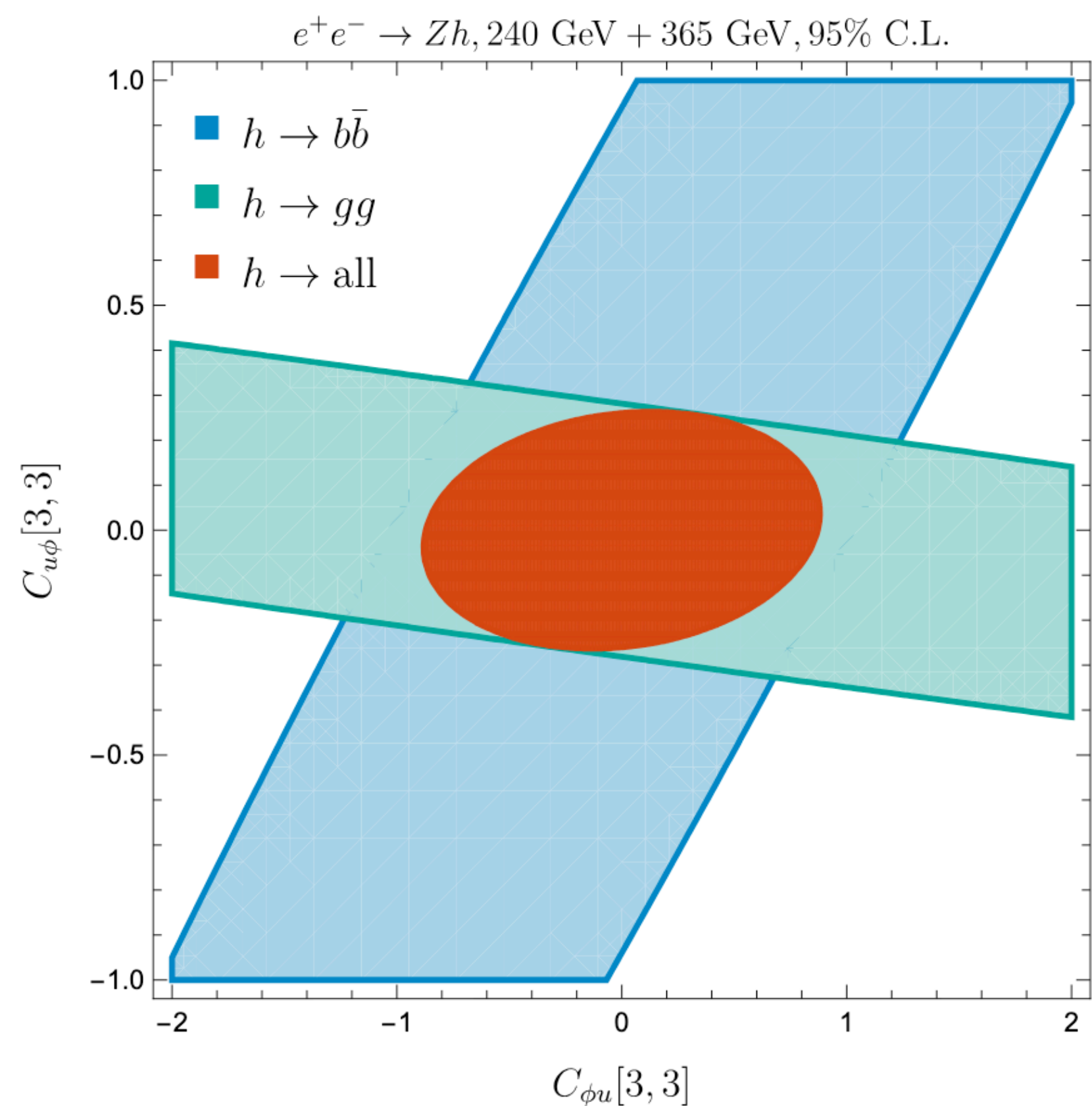


- For inclusive $e^+e^- \rightarrow Zh$, polarization and energy variations were needed to break degeneracies



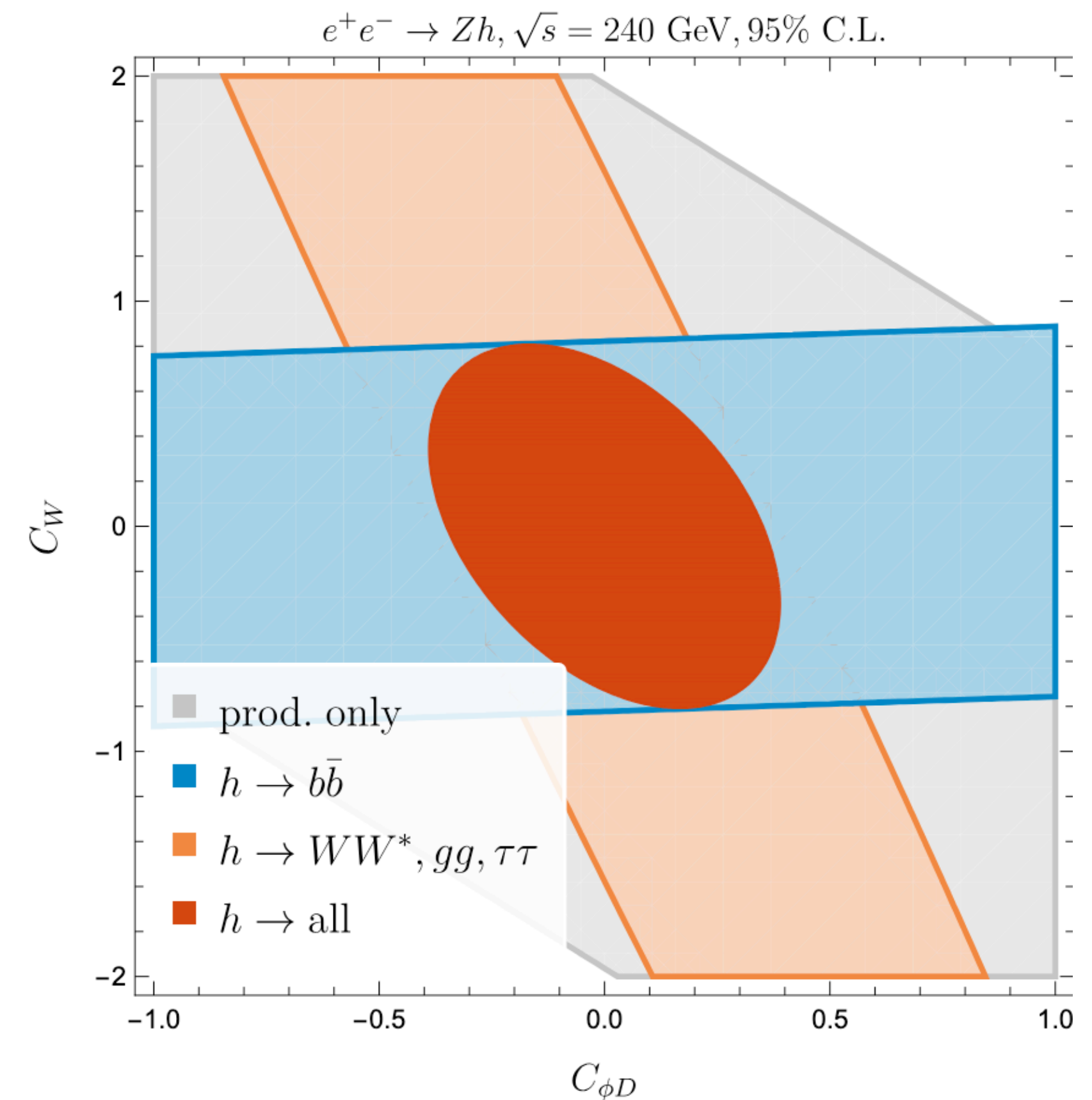
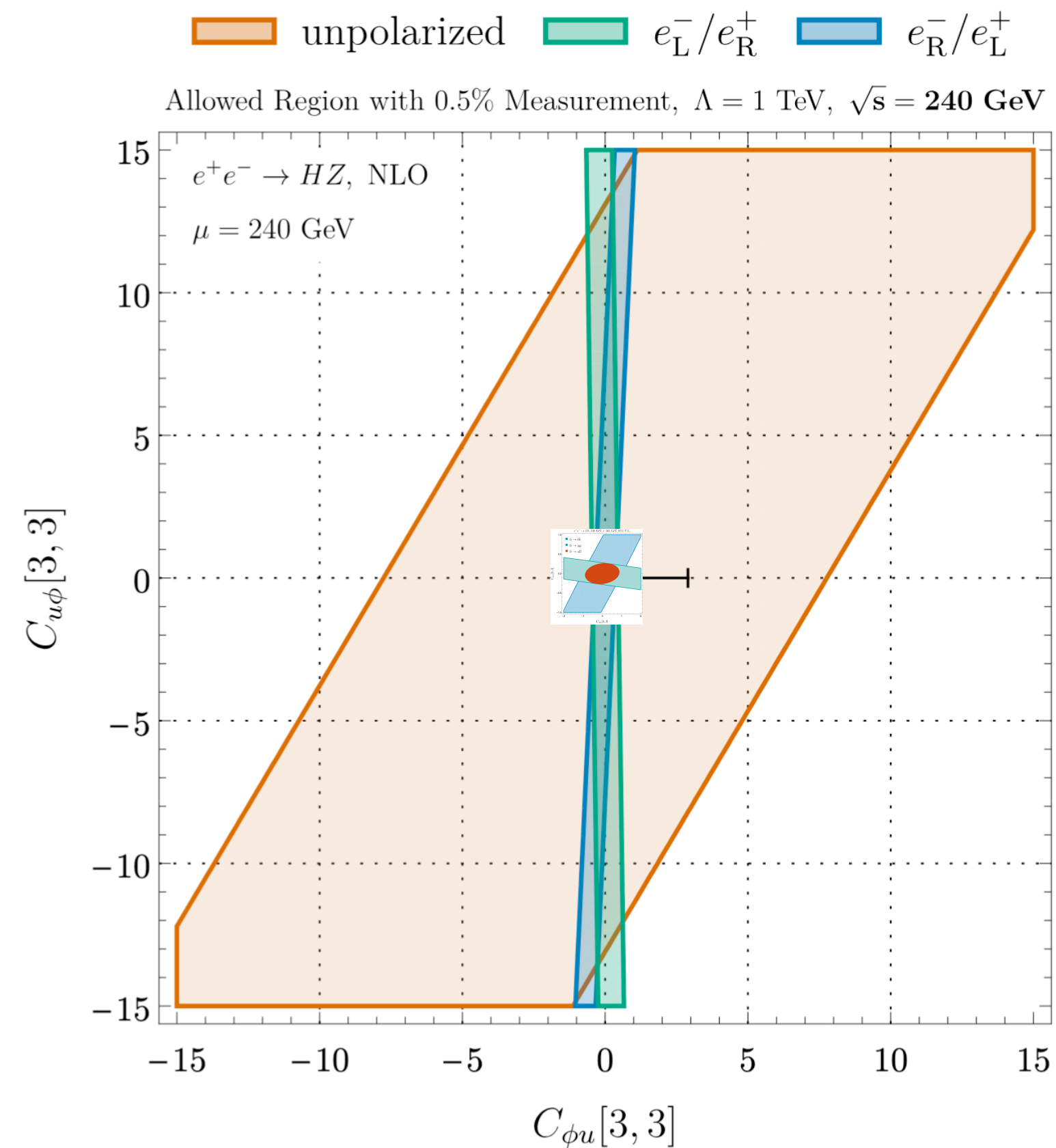
Adding decays

- Much more information available when adding decays
 - Degeneracies are lifted



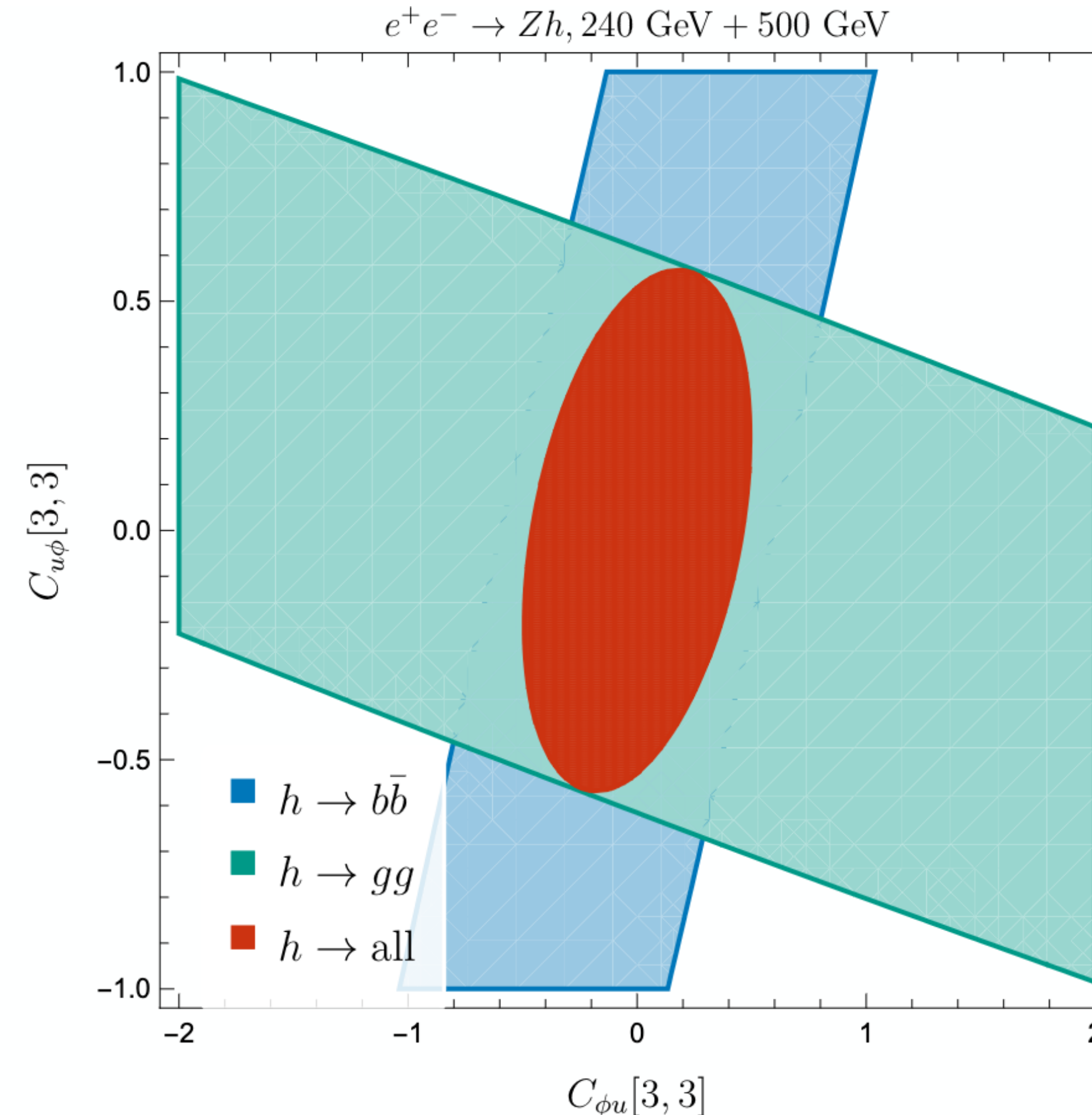
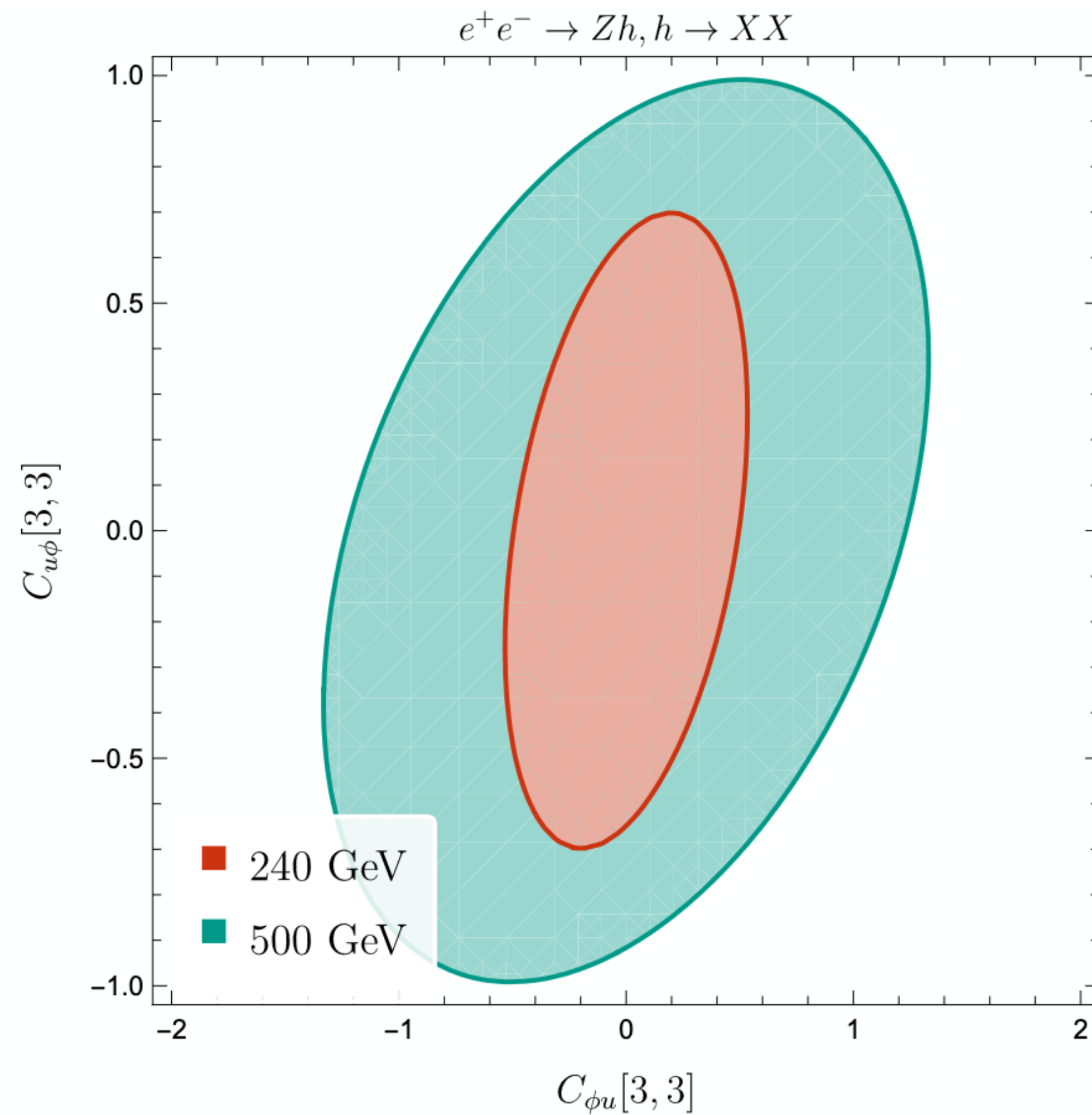
Adding decays

- Much more information available when adding decays
 - Degeneracies are lifted



Effects of multiple energies

- Degeneracies can be further mitigated by using production at different energies

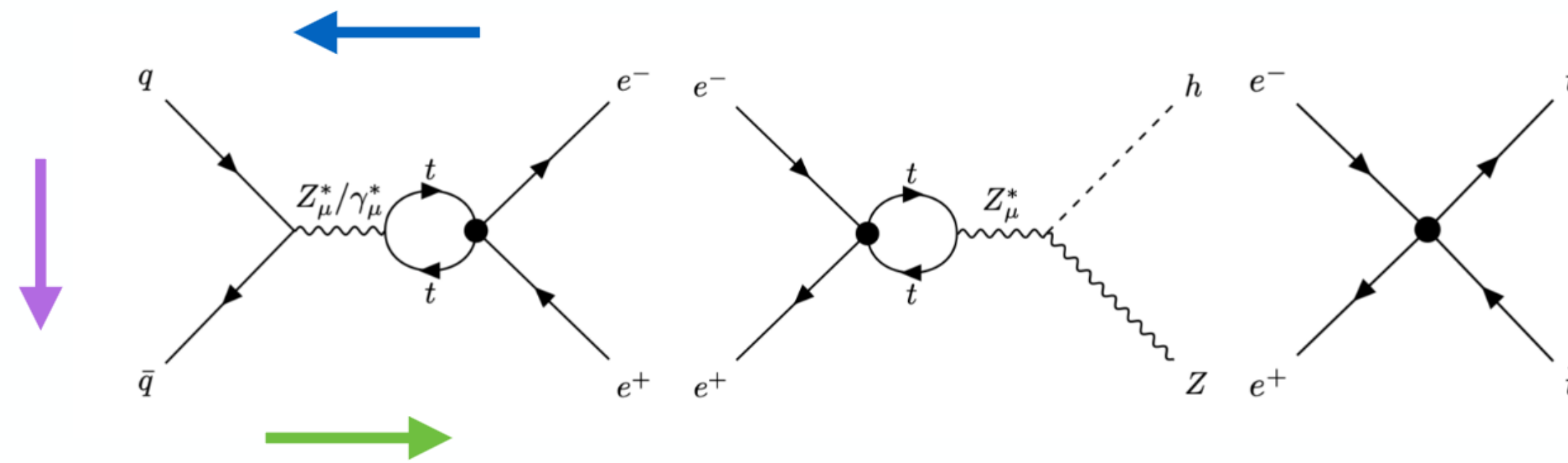


*Using ILC numbers

Complementarity

- Mitigating flat directions requires multiple observables, energies, experiments

$$\mathcal{O}_{lq}^{(3),1133}, \mathcal{O}_{lq}^{(1),1133}, \mathcal{O}_{qe}^{3311}, \mathcal{O}_{lu}^{1133}, \mathcal{O}_{eu}^{1133},$$



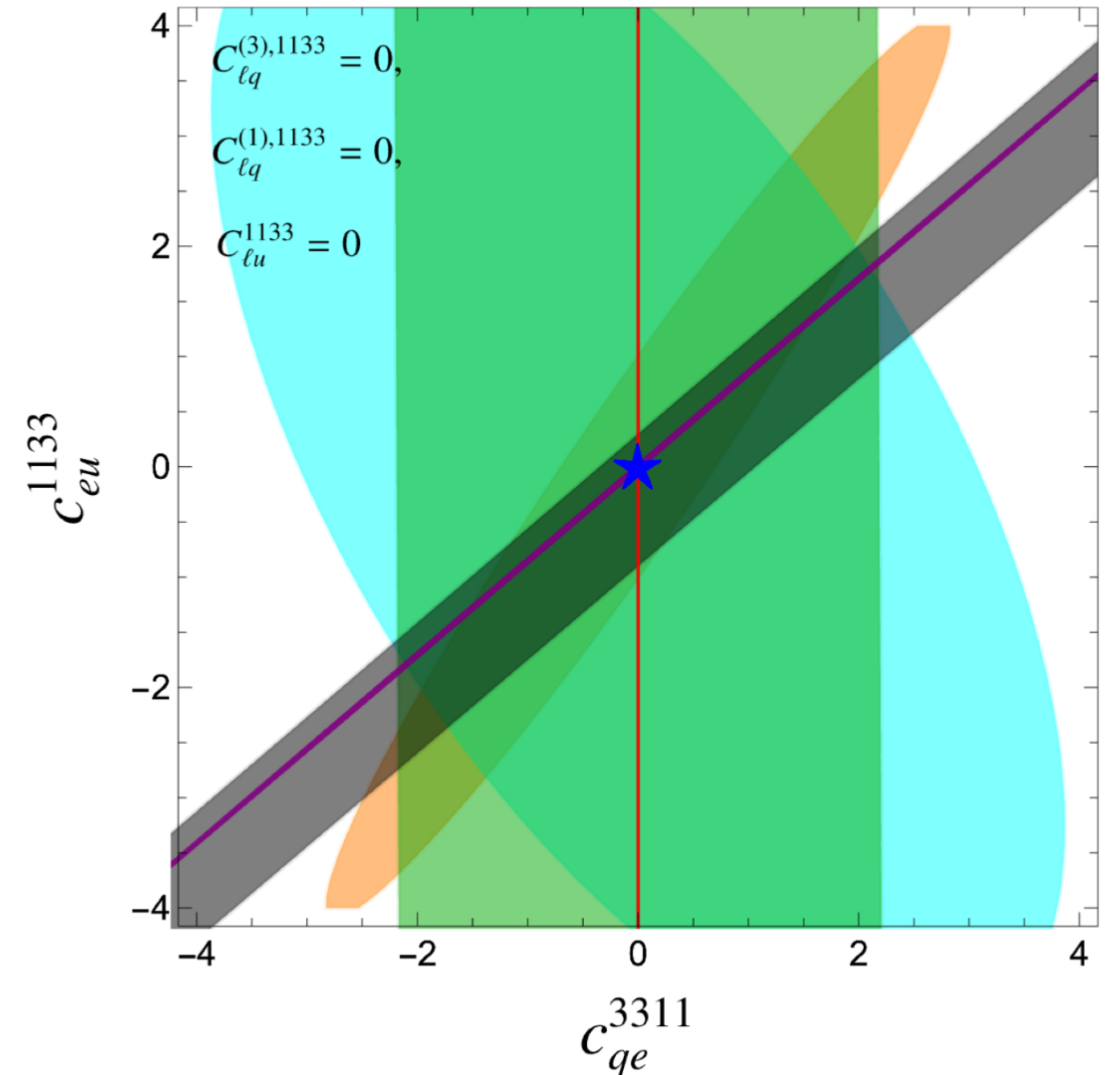
Hadron collider

Lepton collider

Lepton-Hadron collider

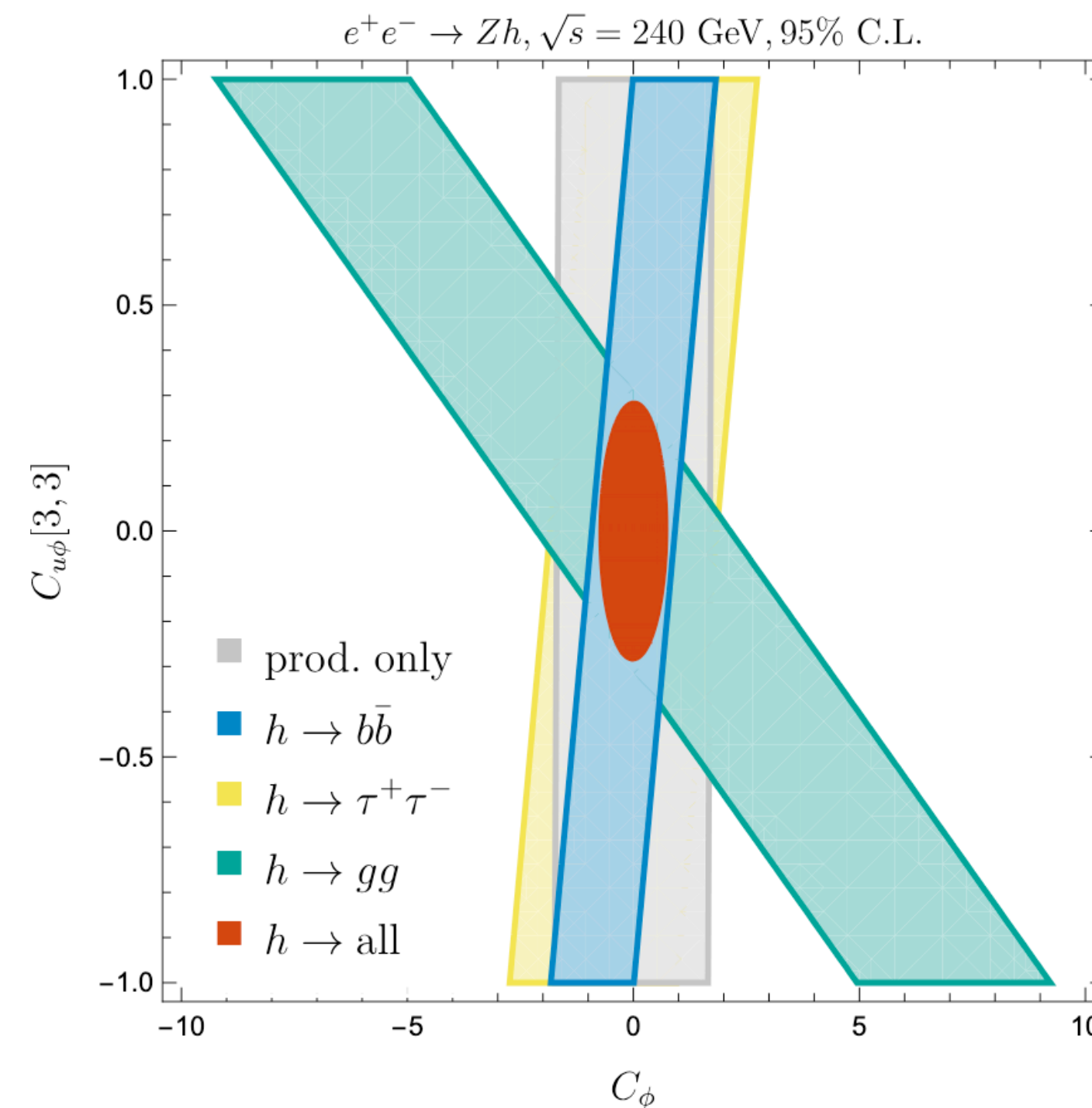
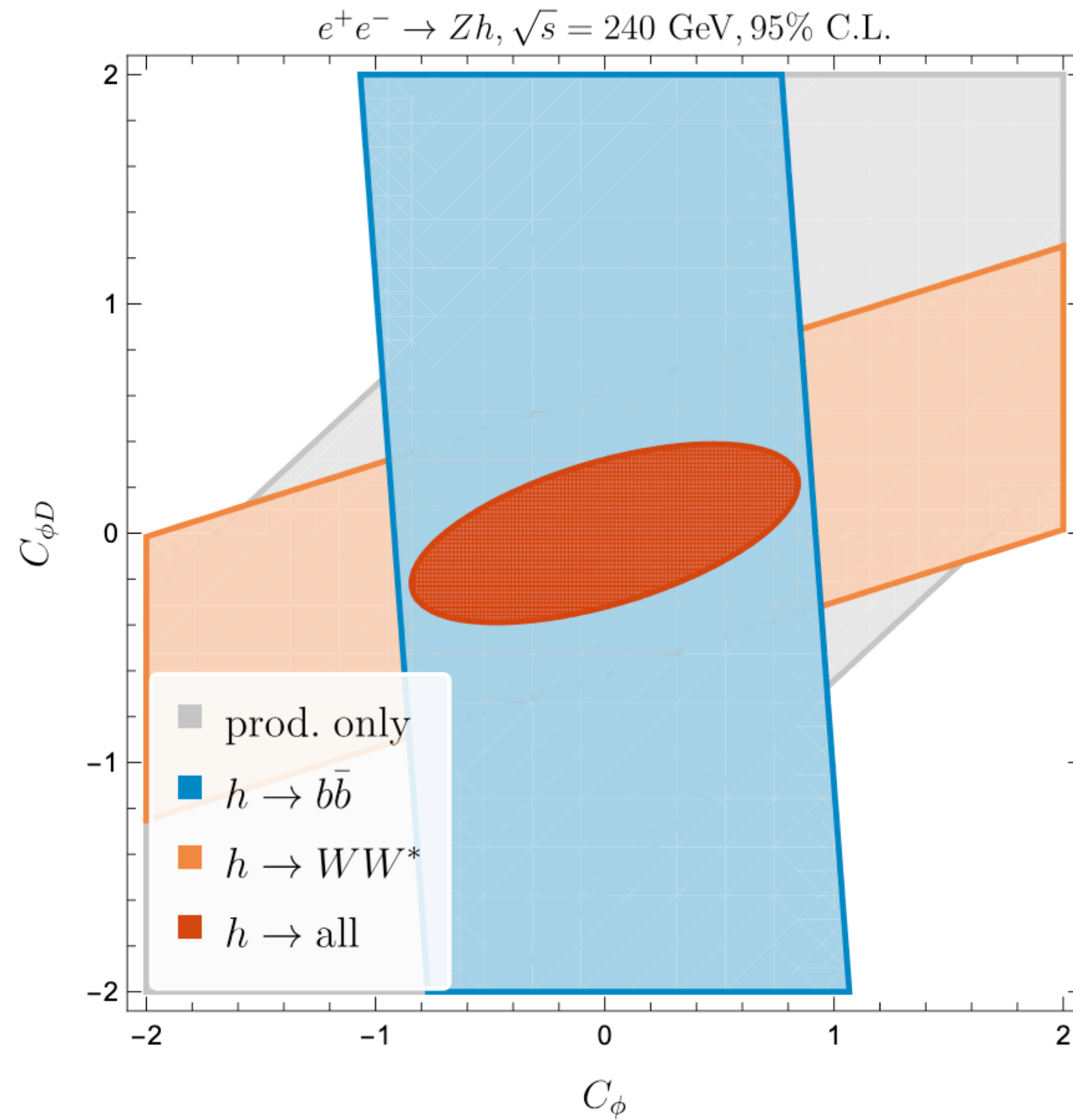
(Tree-level $e^+e^- \rightarrow t\bar{t}$)

Current Z-pole
 HL-LHC
 EIC
 FCC-ee (Z-pole)
 FCC-ee (162 GeV)
 FCC-ee (240 GeV)
 FCC-ee (365 GeV)



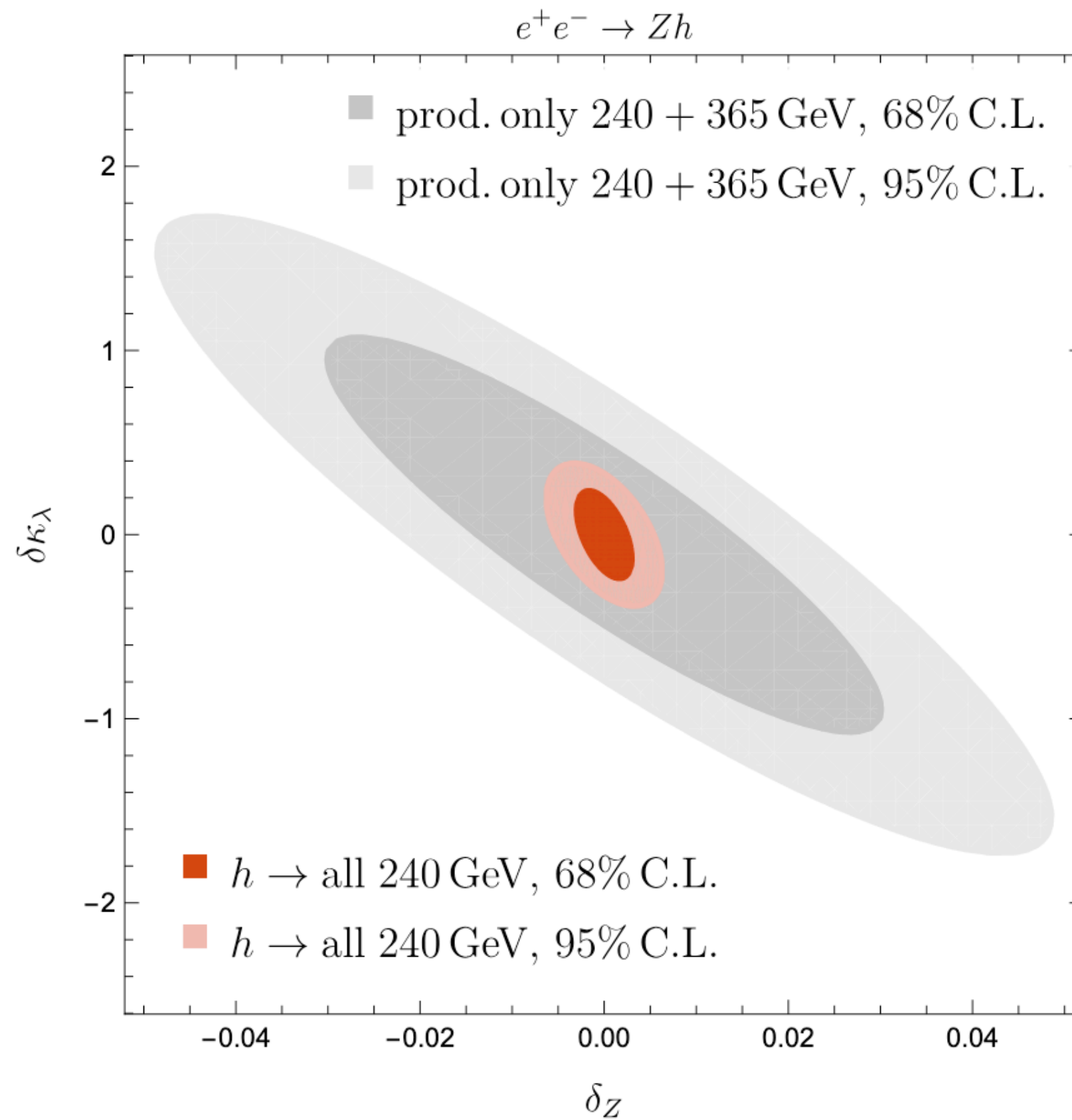
Higgs self-coupling at FCC-ee

- We now have complete calculation at NLO for consistent C_ϕ extraction at FCC-ee
- Decays are crucial for breaking degeneracies in inclusive $e^+e^- \rightarrow Zh$



Higgs self-coupling at FCC-ee

- Equivalently, written as κ 's*
- Only linear pieces, consistent with $\mathcal{O}(1/\Lambda^2)$ truncation



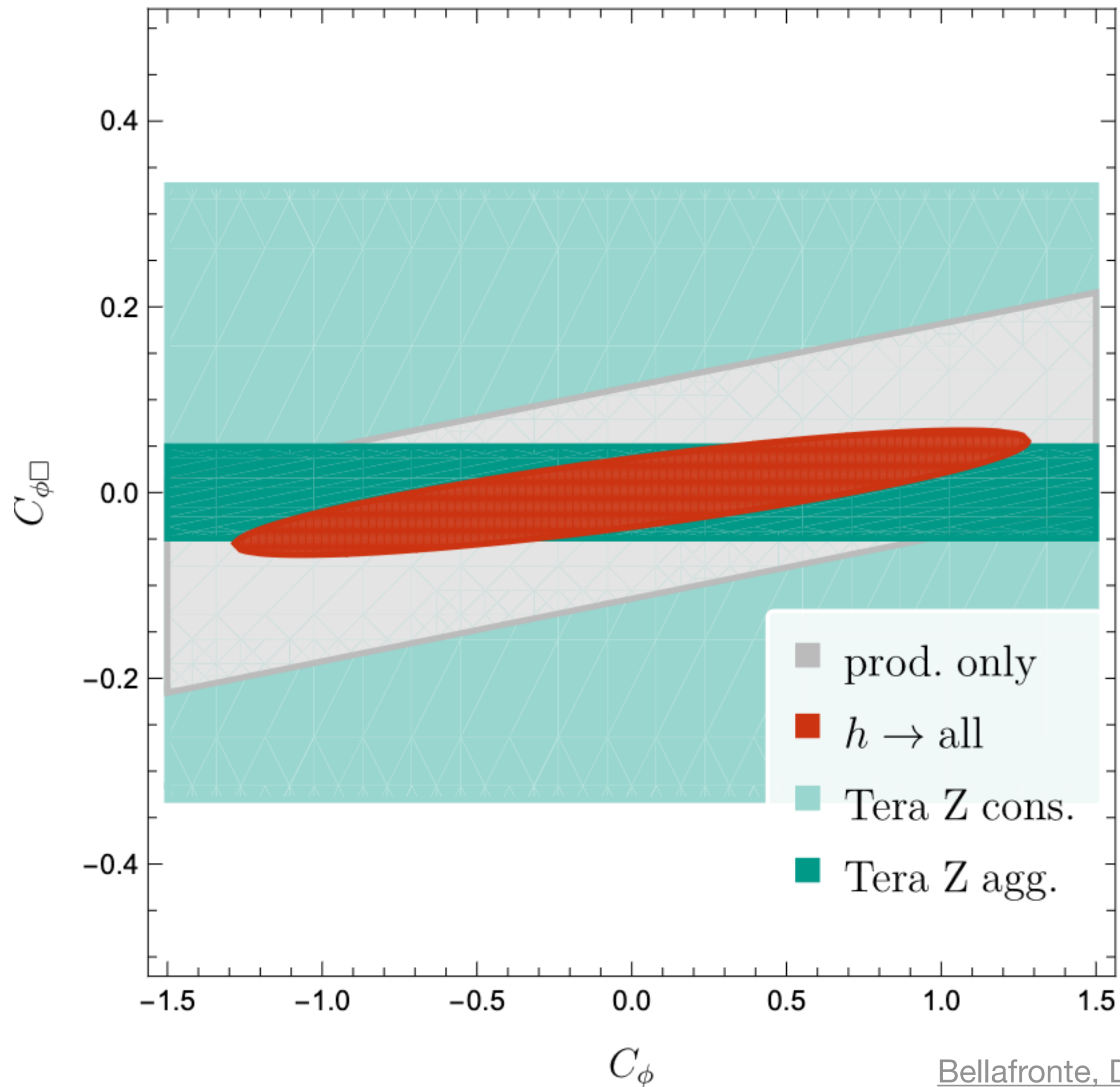
$$\delta_Z = \frac{1}{4} \frac{v^2}{\Lambda^2} \left(C_{\phi D} + 4C_{\phi \square} \right)$$

$$\kappa_\lambda = 1 + \frac{v^2}{\Lambda^2} \left(\frac{3}{4} \left[C_{\phi D} - 4C_{\phi \square} \right] - 2 \frac{v^2}{m_H^2} C_\phi \right)$$

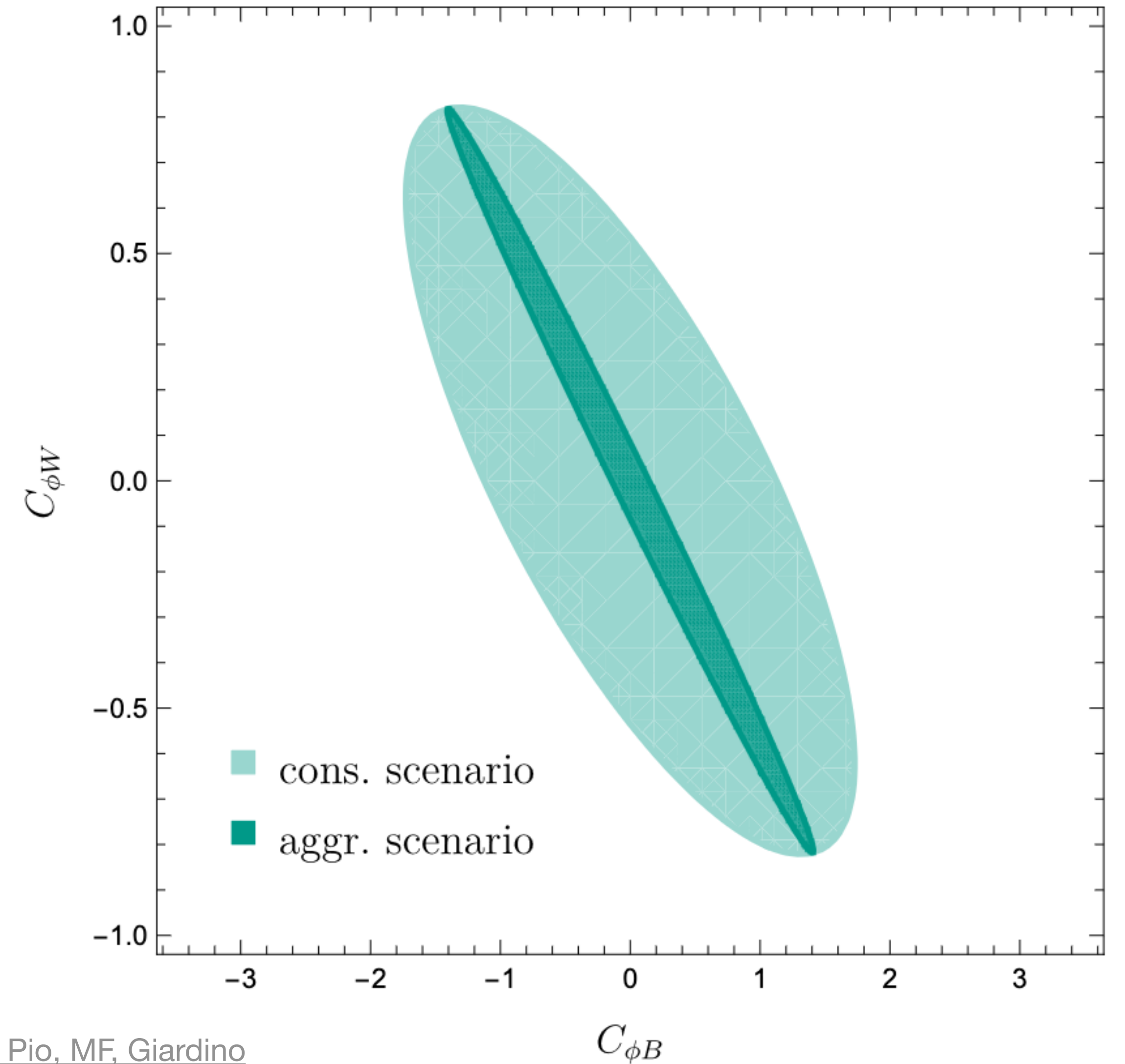
*Depends on 3 coeffs — we took $C_{\phi \square} = 0$ here

Electroweak Precision is also Higgs Physics

95% C.L., $\Lambda = 1$ TeV



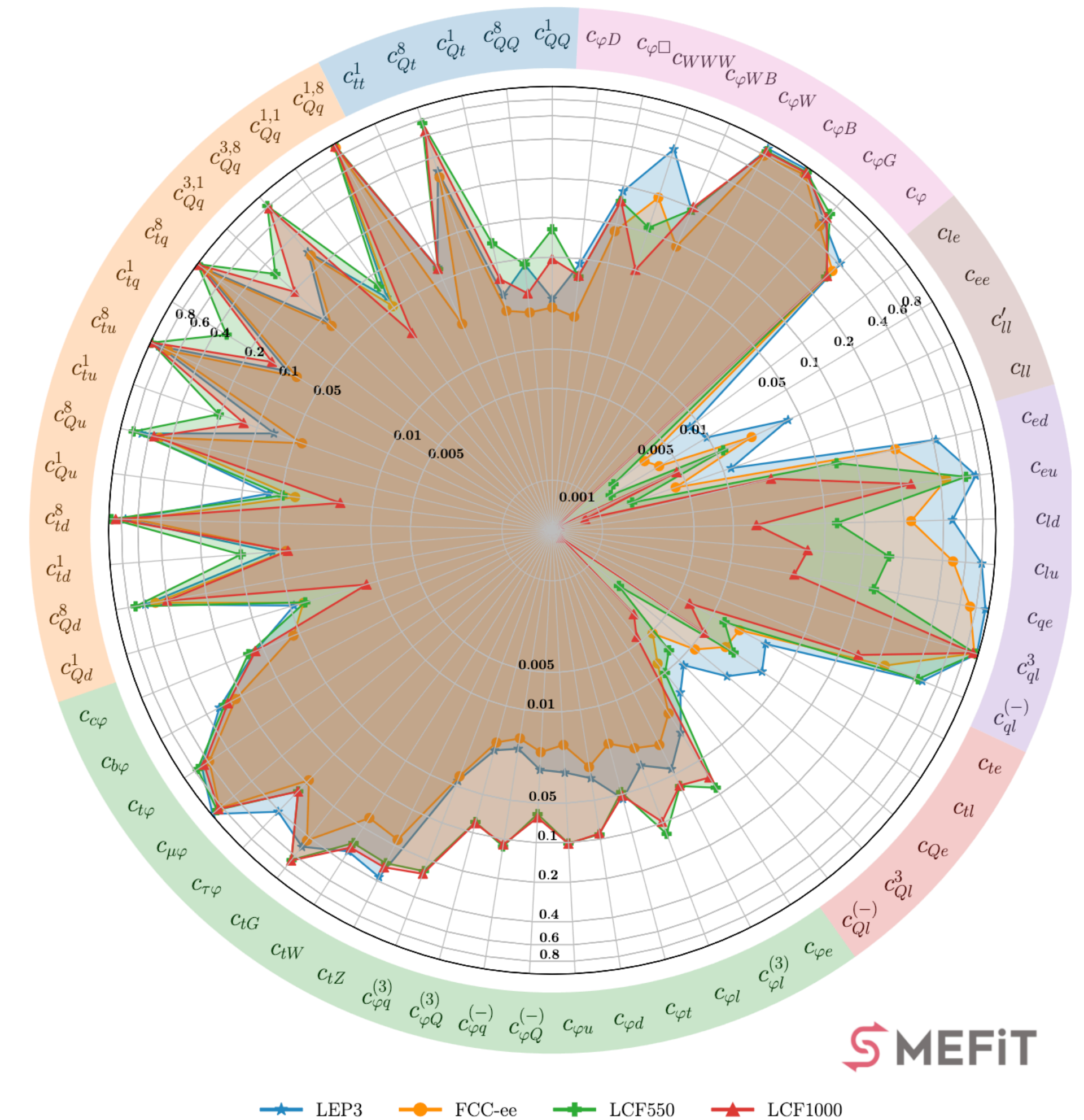
Tera Z run, 95% C.L., $\Lambda = 1$ TeV



At 1-loop, operators contribute to many observables

- Global fits including NLO Higgs eventually for better picture
- Least conservative: one operator at a time

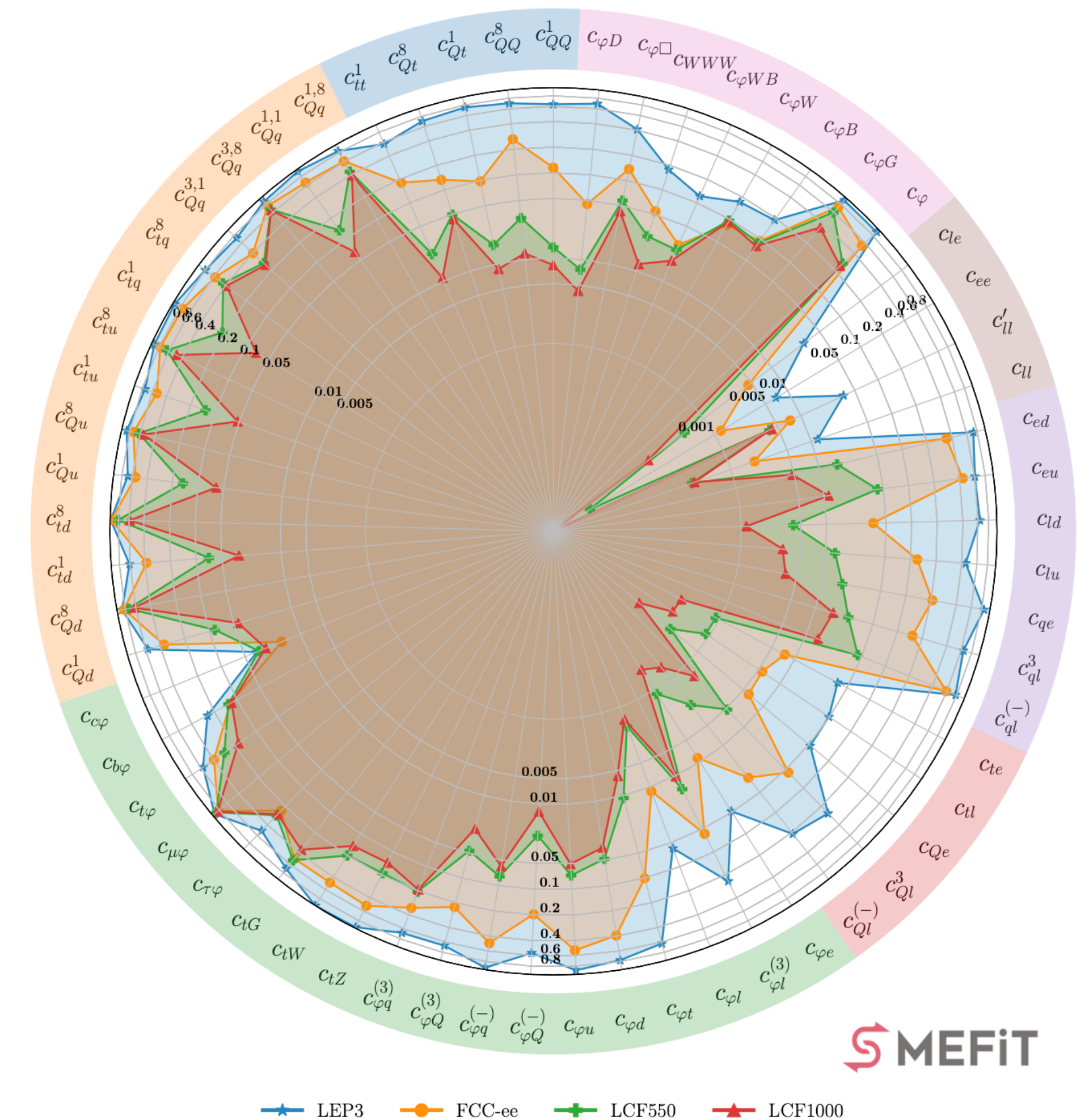
Ratio of Uncertainties to HL-LHC Baseline $\mathcal{O}(\Lambda^{-2})$, Individual



At 1-loop, operators contribute to many observables

- Global fits including NLO Higgs eventually for better picture
- Least conservative: one operator at a time
- Most conservative: fully marginalized
 - Many approximate flat directions

Ratio of Uncertainties to HL-LHC Baseline $\mathcal{O}(\Lambda^{-2})$, Marginalised



MEFIT

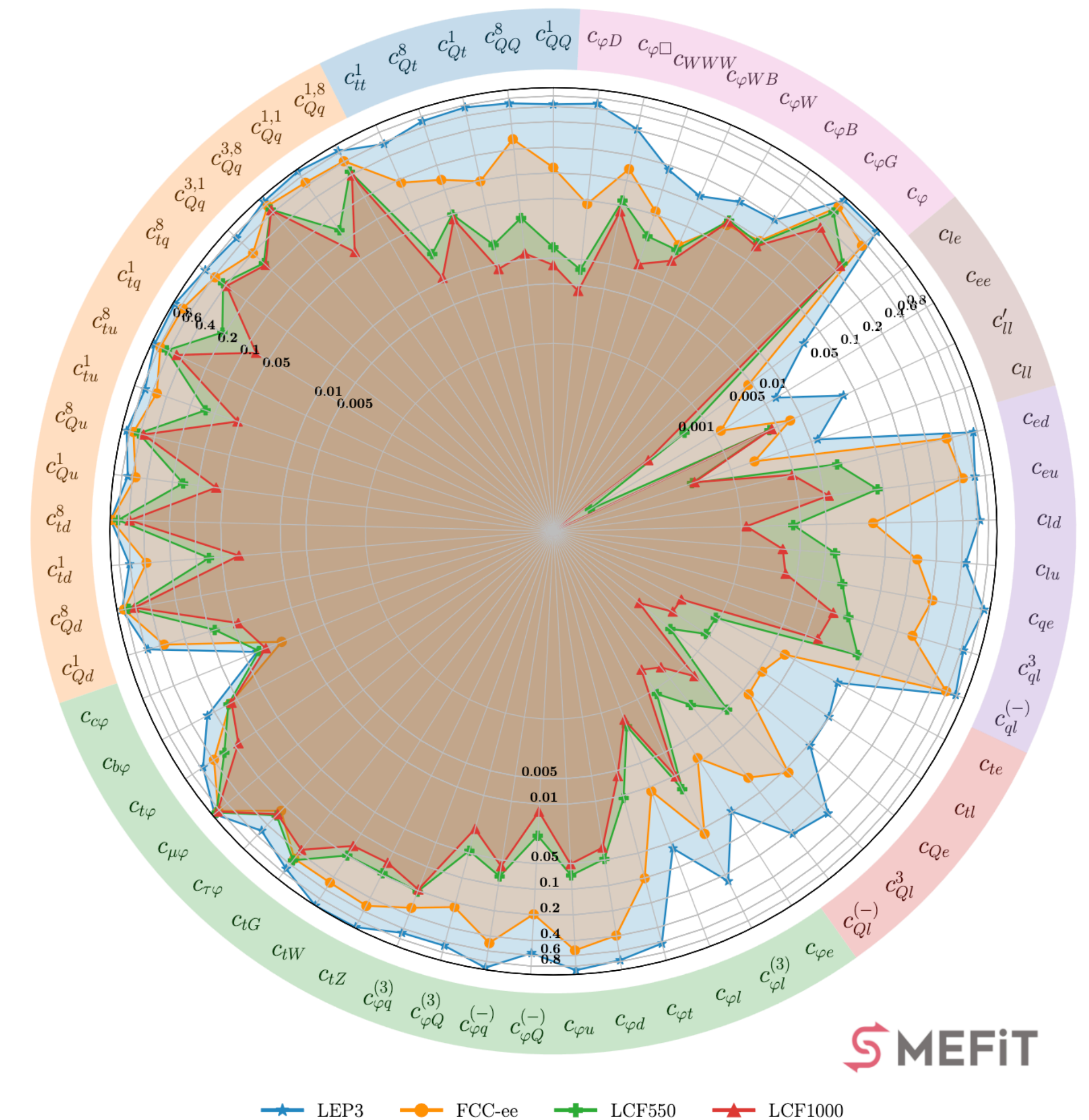
Armadillo et al

*Not using our NLO results

At 1-loop, operators contribute to many observables

- Global fits including NLO Higgs eventually for better picture
- Least conservative: one operator at a time
- Most conservative: fully marginalized
 - Many approximate flat directions
- Any actual UV model will have patterns: neither of these are

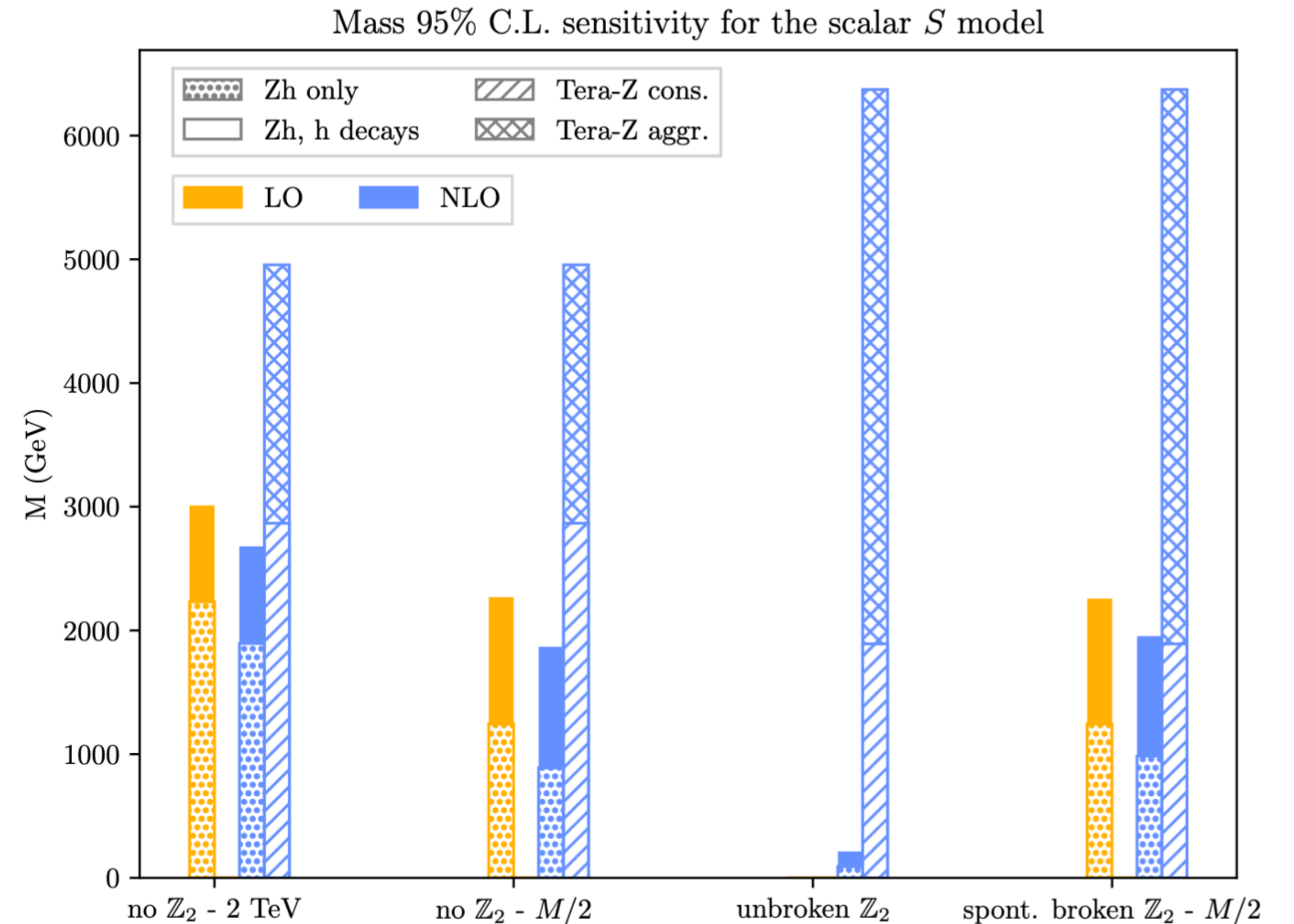
Ratio of Uncertainties to HL-LHC Baseline $\mathcal{O}(\Lambda^{-2})$, Marginalised



Electroweak Precision is also Higgs Physics

- For actual models: loops + RG can make EWPO as important
- Even a scalar singlet can be probed at Tera-Z as well as with Higgstrahlung
- Depends crucially on theory uncertainties at Tera-Z

$$V(\Phi, S) = -\mu_H^2 \Phi^\dagger \Phi + \lambda_H (\Phi^\dagger \Phi)^2 + \frac{m_\xi}{2} \Phi^\dagger \Phi S + \frac{\kappa}{2} \Phi^\dagger \Phi S^2 + t_S S + \frac{M^2}{2} S^2 + \frac{m_\zeta}{3} S^3 + \frac{\lambda_S}{4} S^4.$$



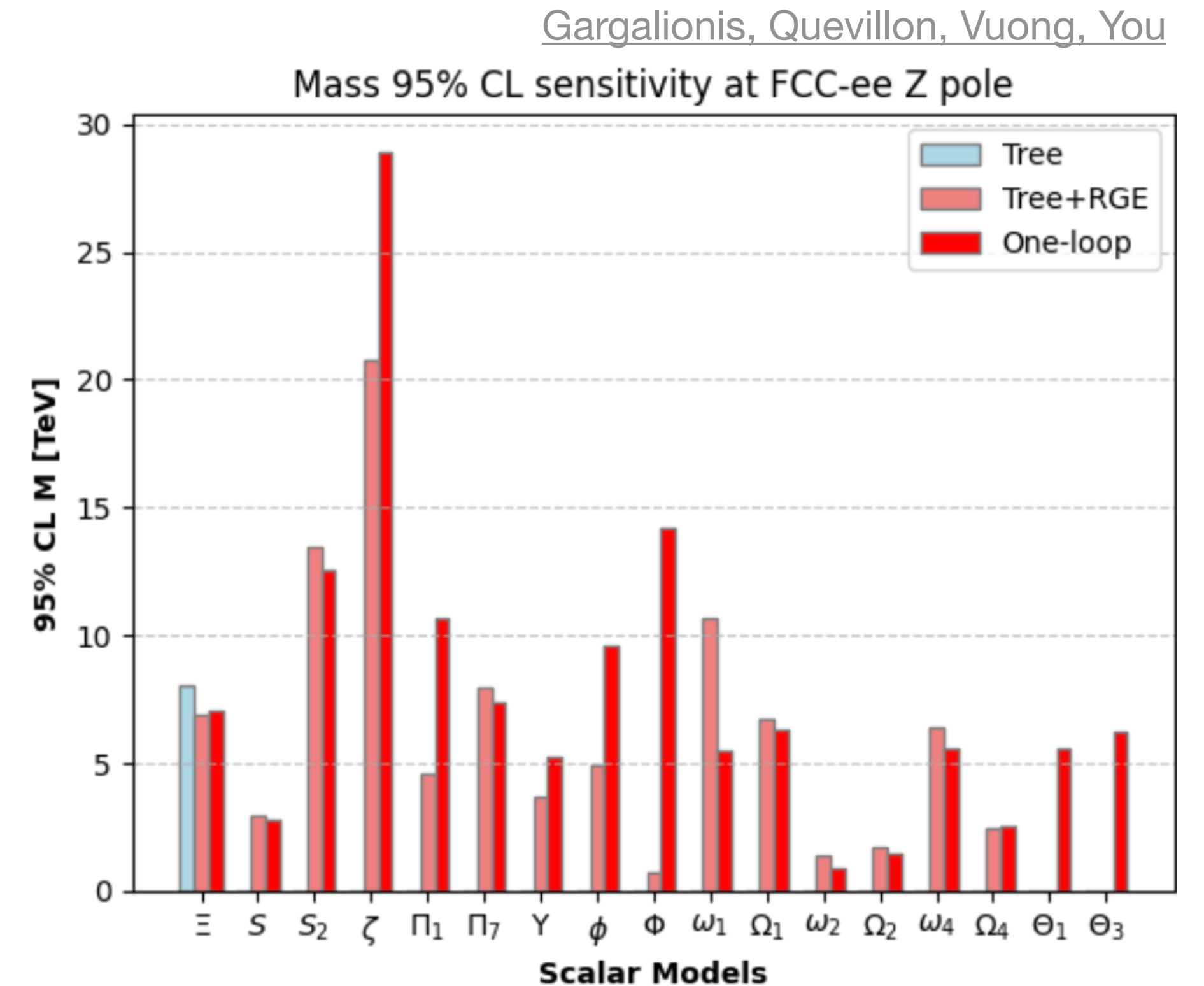
Bellafronte, Dawson, Del Pio, MF, Giardino

*Used 1-loop RGEs, 2-loop available now

Born, Fuentes-Martín, Thomsen, also Banik, Crivellin, Naterop, Stoffer for B violating

Electroweak Precision is also Higgs Physics

- A similar thing has been noticed before for all scalar models - but not comparing with ZH
- This is just the start of a more systematic approach. Need to play with UV couplings, include Higgs observables, etc
- Out of the box - need something special for Tera-Z to not win!
- (All super sensitive to achievable theory uncertainties)

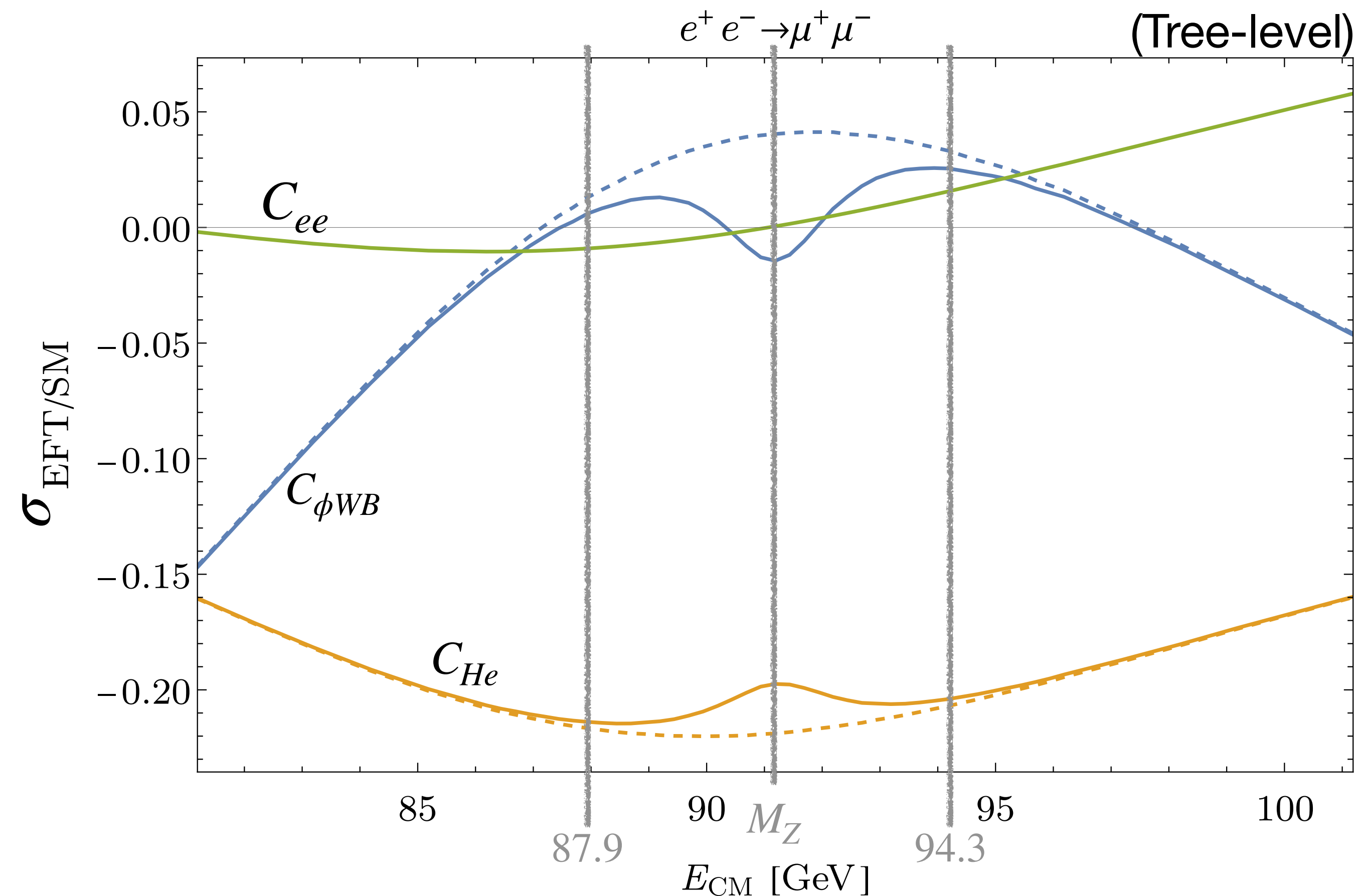


*Only EWPO, no Higgs

Ongoing work and future plans

$e^+e^- \rightarrow f\bar{f}$ Beyond the NWA

- Even around the Z -pole, there is a lot more than just $Z \rightarrow f\bar{f}$!
- Full $e^+e^- \rightarrow f\bar{f}$ gives access to observables used to measure $\alpha(m_Z^2)$, which could have SMEFT contamination
- Also $4f$ operators that are not captured usually
- Amplitudes done, will hopefully appear this summer. Stay tuned!



$$e^+ e^- \rightarrow t \bar{t}$$

- 365 GeV is one of the 4 primary run targets for FCC-ee
- At tree-level, already important for constraining top-sector operators
 - (Generically the dangerous ones when extracting κ_λ robustly)
- At NLO -- massive final states complicate amplitudes and subtraction
- Toponium!
- Top-quark CPV
- Entanglement, quantum observables, etc. Lots of interesting things to do!

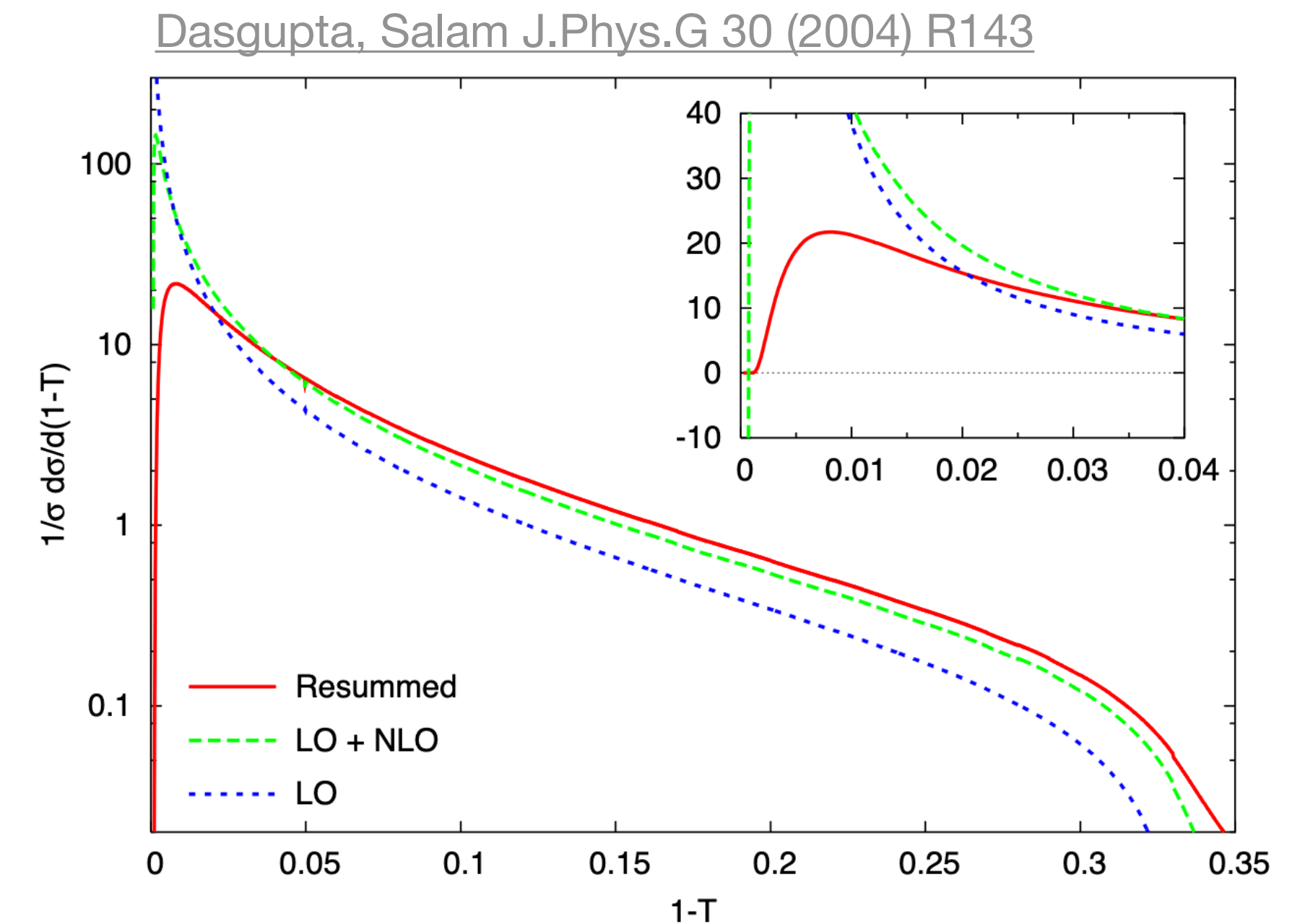
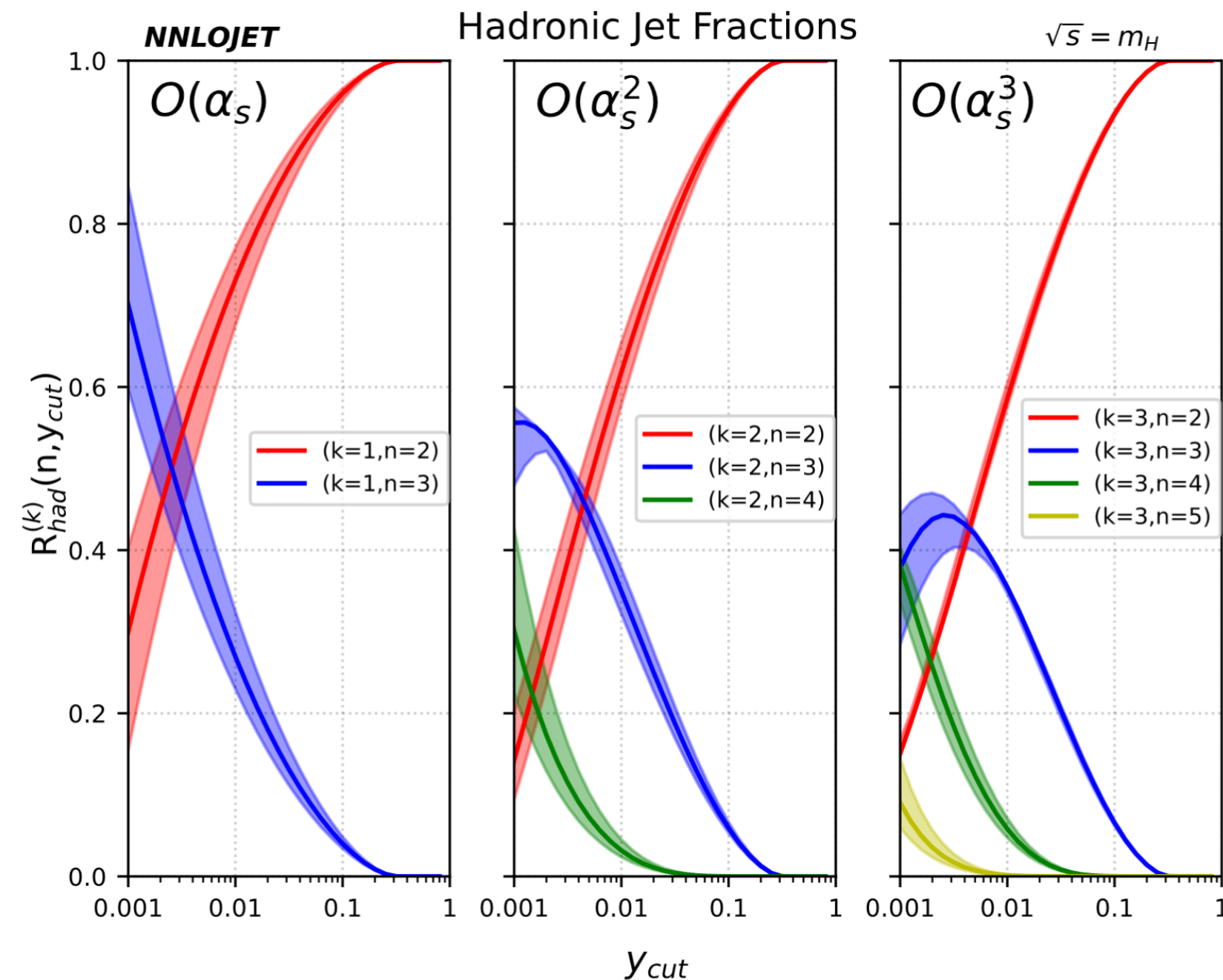
Wishlist

- Core processes we would like to compute for a fully NLO accurate fits:
 - $H \rightarrow 4f$ beyond the NWA
 - e^+e^- colliders:
 - $e^+e^- \rightarrow f\bar{f}, e^+e^- \rightarrow t\bar{t}$ (in progress)
 - $e^+e^- \rightarrow W^+W^-$ (subset in [Celada, Miralles, Vryonidou](#) appearing yesterday)
 - VBF $e^+e^- \rightarrow (\nu\bar{\nu}, e^+e^-)H$
 - LHC:
 - $pp \rightarrow VH$ (POWHEG implementation in progress)
 - VBF $pp \rightarrow jjH$
 - $pp \rightarrow t\bar{t}H$

Other future directions

- Primarily for FCC-ee: would like to go differential
 - Full event generation for SMEFT NLO corrections?
 - Other observables? $e^+e^- \rightarrow 3j$, event shapes, fragmentation functions, etc
 - Simultaneous m_b, y_b measurement through $H \rightarrow 3j$?

Fox et al, PRL 134 (2025) 25, 251905

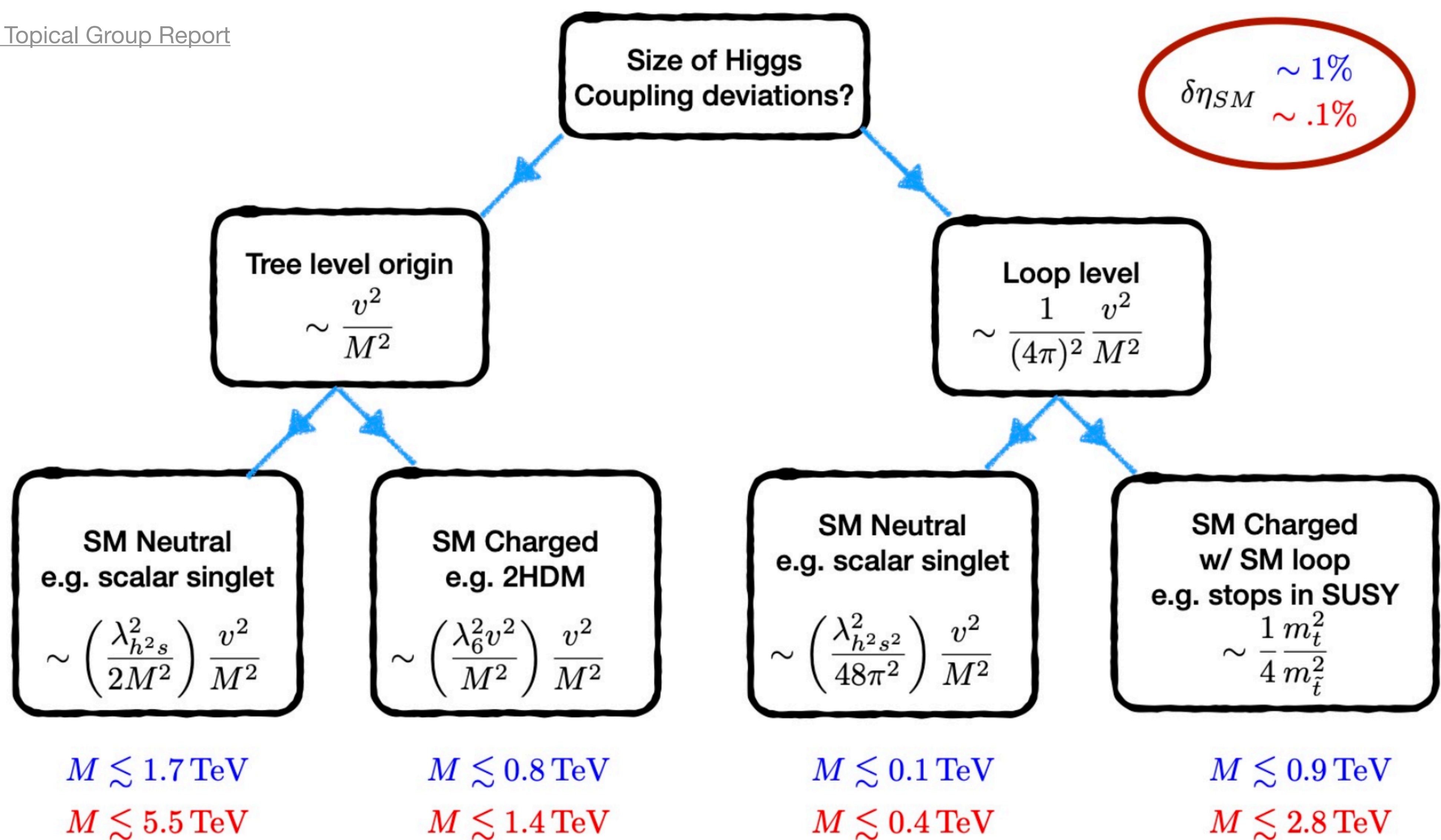


Closing thoughts

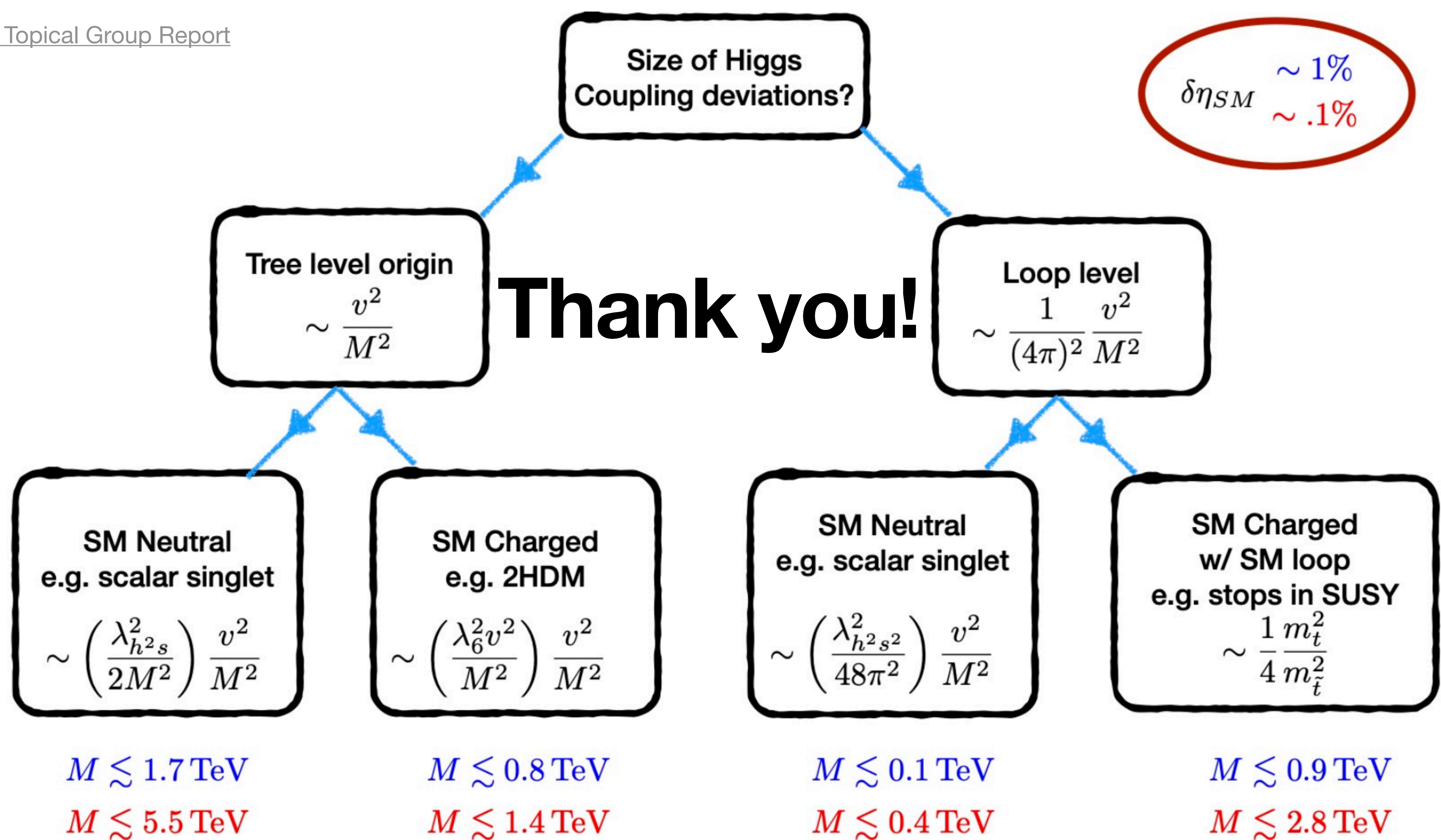
- SMEFT is a natural framework for constraining new physics in low energy, high precision measurements
 - At future lepton colliders, loop effects start to matter!
 - Processes must be computed at NLO for full picture -- clear separation between sectors goes away.
 - Fully NLO accurate SMEFT fits (and matched onto explicit UV models) becoming a reality.

Closing thoughts

- SMEFT is a natural framework for constraining new physics in low energy, high precision measurements
 - At future lepton colliders, loop effects start to matter!
 - Processes must be computed at NLO for full picture -- clear separation between sectors goes away.
 - Fully NLO accurate SMEFT fits (and matched onto explicit UV models) becoming a reality.
- On the other hand, our goal is discovery, and precision only gets us so far
 - Unless we are very lucky, it will be difficult to unambiguously connect a signal to the UV. Looking at many observables maximises our chances
 - Eventually we need to produce the BSM particle directly!



- Higgs precision reach for simple UV complete models gets you to $\mathcal{O}(10 \text{ TeV})$
- High energy pp or $\ell^+ \ell^-$ must remain the (eventual) goal. Precision is just the first step to get there!



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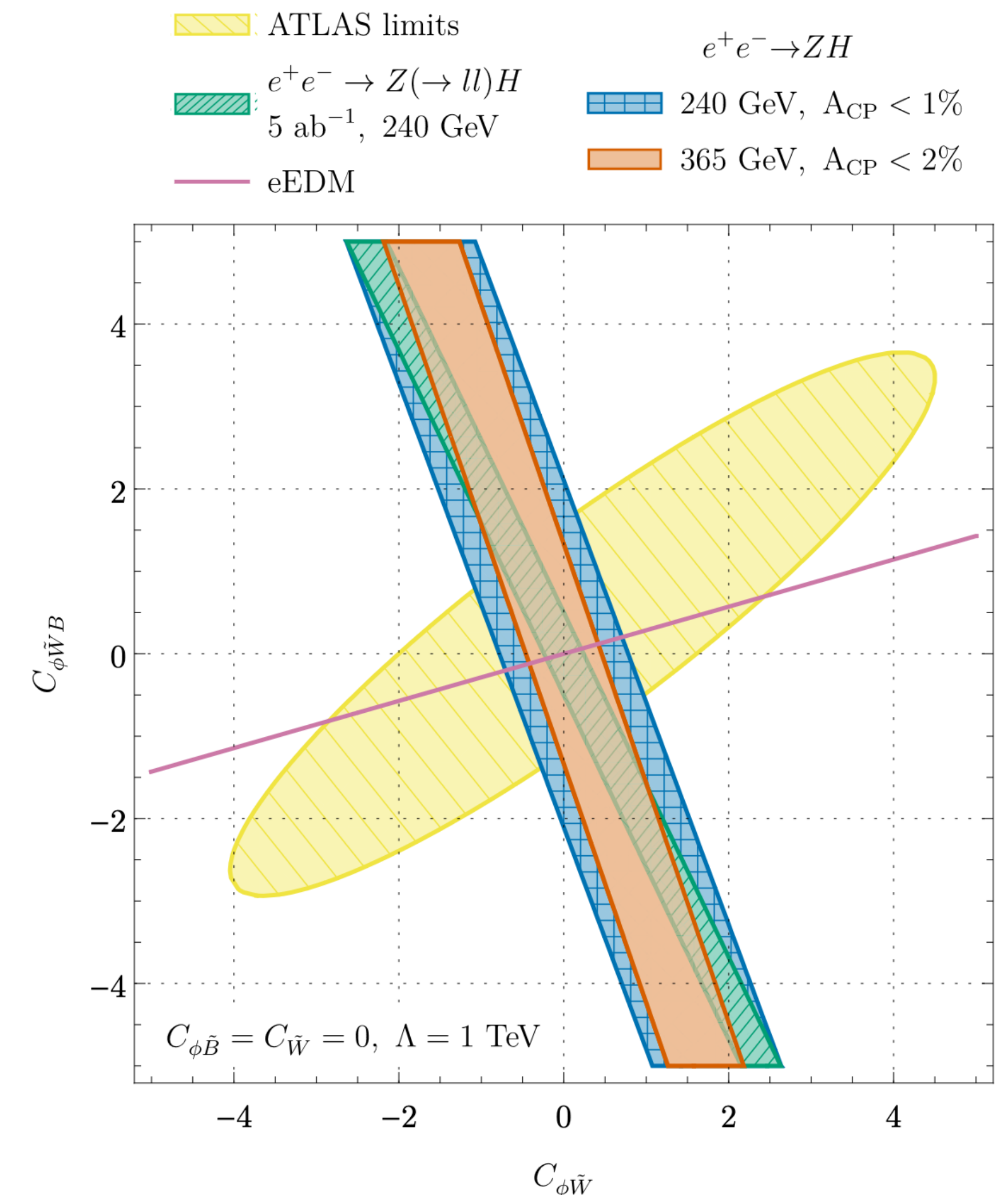
Backups

CPV in $e^+e^- \rightarrow ZH$

- At one-loop, amplitudes become imaginary
- CP-violating operators can now contribute
- Negligible for decays -- need on-shell particles in the loop. For ZH , WW , can contribute!
- Different combination than EDMs.
- Decays are always below threshold, so they add no information here.

Asteriadis, Dawson, Giardino, Szafron PRL 133 (2024) 23, 231801

Asteriadis, Dawson, Giardino, Szafron JHEP 02 (2025) 162



Tera-Z Theory Uncertainties

FCC-ee Uncertainties	Stat	Syst	PO(C)	PO(A)	Theory (C)	Theory (A)
$\Delta\Gamma_Z(\text{KeV})$	4	12	35	–	80	16
δR_e	3.4×10^{-6} [143]	2.3×10^{-6} [143]	4×10^{-4}	–	1.2×10^{-3}	2×10^{-4}
δR_μ	2.4×10^{-6}	2.3×10^{-6}	4×10^{-4}	–	1.2×10^{-3}	2×10^{-4}
δR_τ	2.7×10^{-6} [143]	2.3×10^{-6} [143]	4×10^{-4}	–	1.2×10^{-3}	2×10^{-4}
δR_b	1.2×10^{-6}	1.6×10^{-6}	4.4×10^{-5}	9×10^{-6}	2×10^{-5}	3.5×10^{-6}
δR_c	1.4×10^{-6} [143]	2.2×10^{-6} [143]	1.7×10^{-4}	3.4×10^{-5}	1×10^{-5}	2×10^{-6}
$\Delta\sigma_h(pb)$	0.03[143]	0.8[143]	1.7	–	1.6	0.3
ΔA_e	14×10^{-6} [143]	11×10^{-6} [143]	19.5×10^{-5} [*]	–	5.3×10^{-5} [*]	4.5×10^{-6} [*]
ΔA_μ	32×10^{-6} [143]		19.5×10^{-5} [*]	–	5.3×10^{-5} [*]	4.5×10^{-6} [*]
ΔA_τ	34×10^{-6} [143]		19.5×10^{-5} [*]	–	5.3×10^{-5} [*]	4.5×10^{-6} [*]
ΔA_c	60×10^{-6} [143]		91×10^{-5} [*]	–	2.3×10^{-5} [*]	2×10^{-6} [*]
ΔA_b	98×10^{-6} [143]		126×10^{-5} [*]	–	4.3×10^{-6} [*]	3.7×10^{-7} [*]
$\Delta A_{e,FB}$	3.3×10^{-6} [143]	2.4×10^{-6} [143]	4.3×10^{-5}	–	1.2×10^{-5} [*]	1×10^{-6} [*]
$\Delta A_{\mu,FB}$	2.3×10^{-6} [143]	2.4×10^{-6} [143]	4.3×10^{-5}	–	1.2×10^{-5} [*]	1×10^{-6} [*]
$\Delta A_{\tau,FB}$	2.8×10^{-6} [143]	2.4×10^{-6} [143]	4.3×10^{-5}	–	1.2×10^{-5} [*]	1×10^{-6} [*]
$\Delta A_{b,FB}$	4×10^{-6} [143]	4×10^{-6} [143]	3.2×10^{-5}	2.8×10^{-6}	3.8×10^{-5} [*]	3.2×10^{-6} [*]
$\Delta A_{c,FB}$	5×10^{-6} [143]	5×10^{-6} [143]	2.3×10^{-5}	2.1×10^{-6}	2.9×10^{-5} [*]	2.5×10^{-6} [*]
$\Delta\Gamma_W(\text{KeV})$	270	200			1000	100
$\Delta\alpha(M_Z)^{-1}$	8×10^{-4}	3.8×10^{-3}			5×10^{-5}	2×10^{-5}

Scheme dependence

- Scheme dependence is large in EWPO for coeffs appearing in M_W

