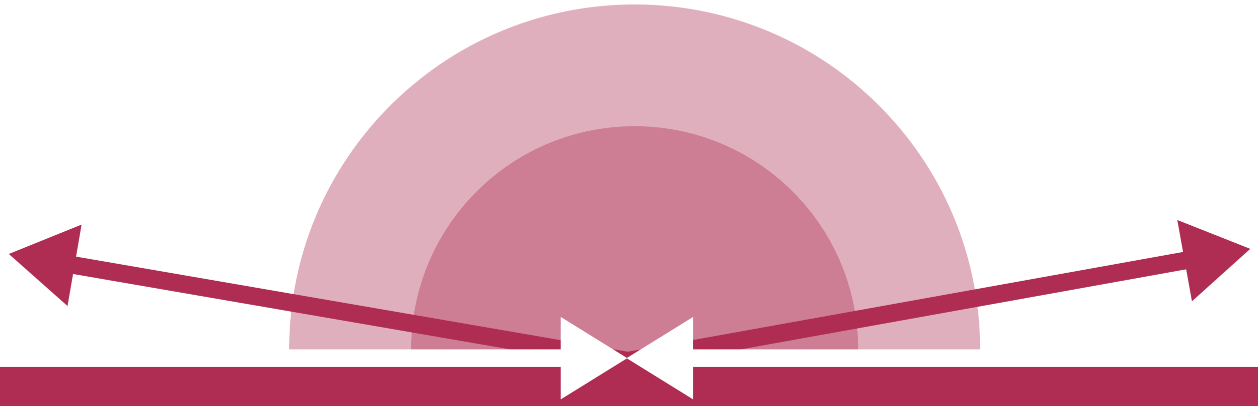
Investigating New Physics contamination in luminosity measurements at future colliders

3rd ECFA workshop on e^+e^- Higgs, Electroweak and Top Factories

Paris, 10 October 2024



Francesco P. Ucci

in collaboration with:
C. M. **Carloni Calame**, M. **Chiesa**, C. L. **Del Pio**, F. **Piccinini**

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Luminosity Measurements

Cross section measurements

$$\sigma^{\mathrm{exp}}_{e^+e^-\to X} = \frac{1}{\epsilon}\frac{N^{\mathrm{exp}}_{e^+e^-\to X}}{L}$$

$N^{\mathrm{exp}}_{e^+e^-\to X}$ | # of observed Events

L | Machine Luminosity

ϵ | Experimental Acceptance

$$\frac{\delta\sigma^{\mathrm{exp}}_{e^+e^-\to X}}{\sigma^{\mathrm{exp}}_{e^+e^-\to X}} = \frac{\delta N^{\mathrm{exp}}_{e^+e^-\to X}}{N^{\mathrm{exp}}_{e^+e^-\to X}} \oplus \frac{\delta L}{L}$$

Has to be kept small

Precision on the cross section

Statistical error

Reduced by increasing the integrated luminosity (collecting more data)

Luminosity error

Luminosity Measurements

$$L = \int \mathscr{L} \mathrm{dt} = \frac{1}{\epsilon} \frac{\mathrm{N}_0}{\sigma_0^{\mathrm{th}}}$$

At Lepton colliders the Luminosity is measured via a **benchmark process**

- High cross section so $\delta N_0 / N_0$ very small
- Cross section very well known theoretically
- Experimentally well distinguishable

Small Angle Bhabha Scattering (SABH)

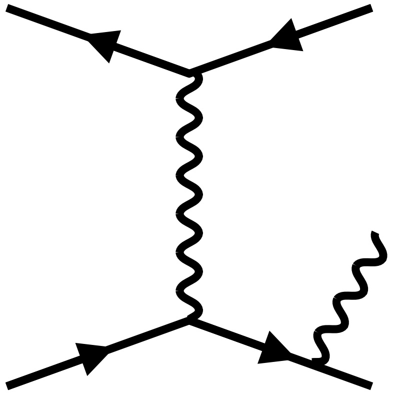
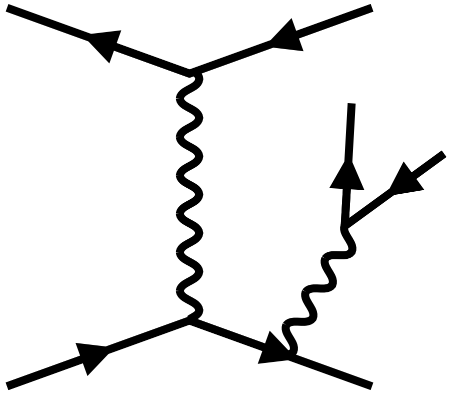
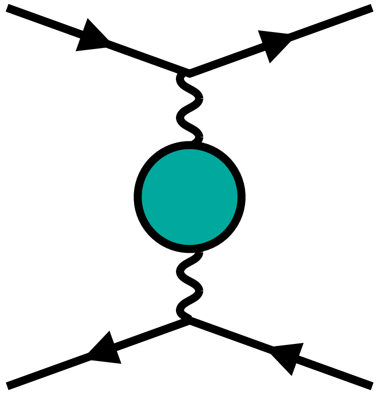
$$\sigma(e^+e^- \to e^+e^-) \sim \left(\frac{1}{\theta_{\mathrm{min}}^2} - \frac{1}{\theta_{\mathrm{max}}^2} \right) \sim \frac{1}{\theta_{\mathrm{min}}^2}$$

$$\boxed{\frac{\delta L}{L}} = 2\frac{\delta\theta_{\mathrm{min}}}{\theta_{\mathrm{min}}} \oplus \frac{\delta N_0}{N_0} \oplus \boxed{\frac{\delta\sigma_0^{\mathrm{th}}}{\sigma_0^{\mathrm{th}}}}$$

Dominant source of uncertainty

Radiative Corrections @ LEP

S. Jadach et al. Physics Letters B 790 (2019) 314–321

	Photonic	Light pairs	Vacuum Pol.	Total
				
LEP 1999 18-52 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.030%	0.040%	0.061%

Radiative Corrections @ LEP

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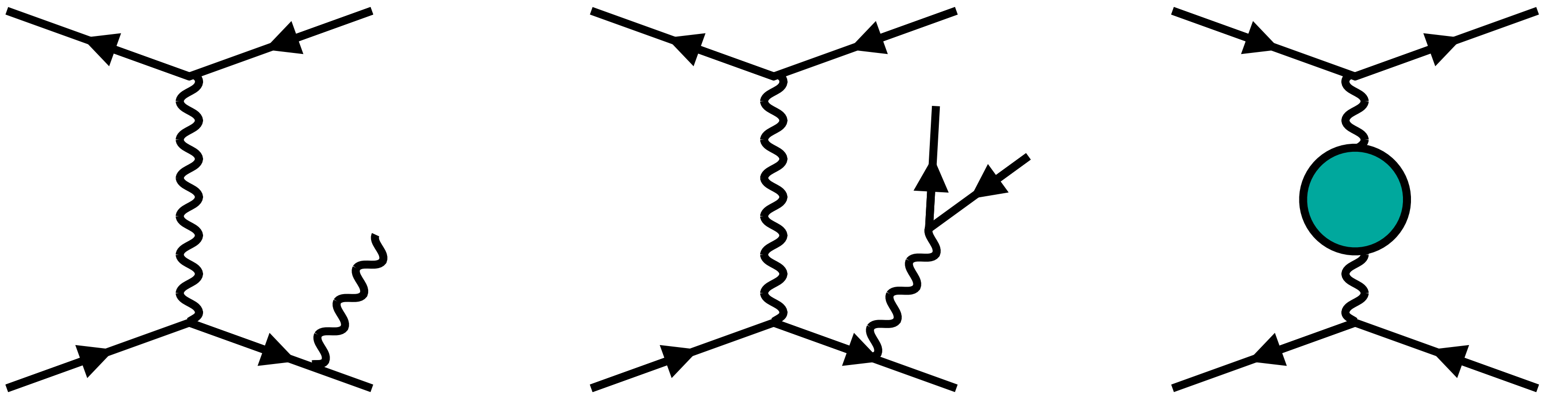

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LEP 1999 18-52 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.030%	0.040%	0.061%
2018 18-52 mrad		0.010%	0.013%	0.038%

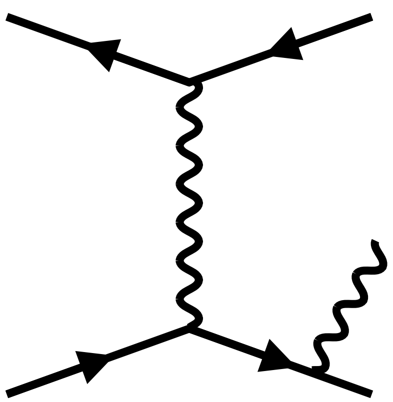
G. Montagna et al.
Nucl. Phys. B 547 (1999)
Phys. Lett. B 459 (1999)

F. Jegerlehner,
indico.cern.ch/event/469561

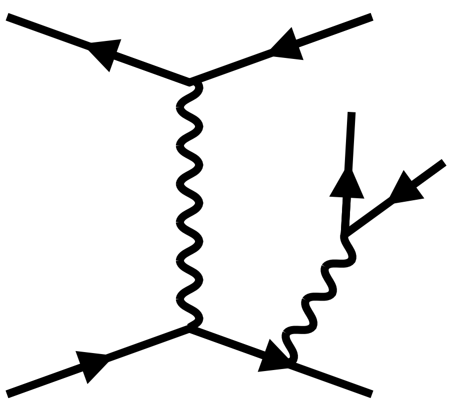
Radiative Corrections @ FCC-ee

S. Jadach et al. Physics Letters B 790 (2019) 314–321

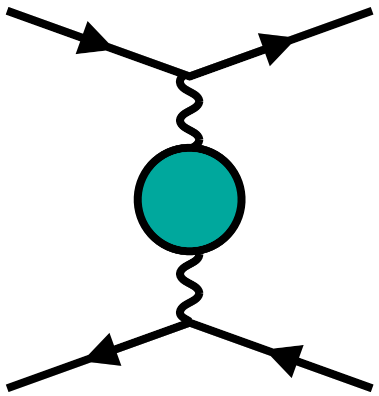
Photonic



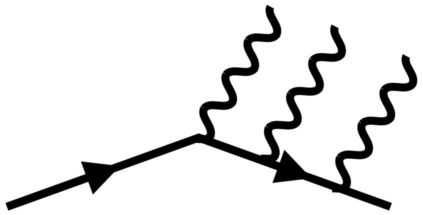
Light pairs



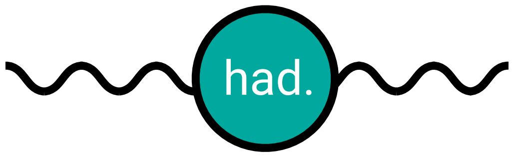
Vacuum Pol.



	Photonic	Light pairs	Vacuum Pol.	Total
2018 64-86 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.010%	0.014%	0.097%
FCC-ee Forecast	0.011% $\mathcal{O}\left(\alpha^3 L^2 \oplus \alpha^4 L^4\right)$	0.005%	0.006%	**0.01%** Goal



QED H.O. resummation is needed



$$\frac{\delta_{VP}\sigma}{\sigma} \simeq 2.4 \times 10^{-4}$$

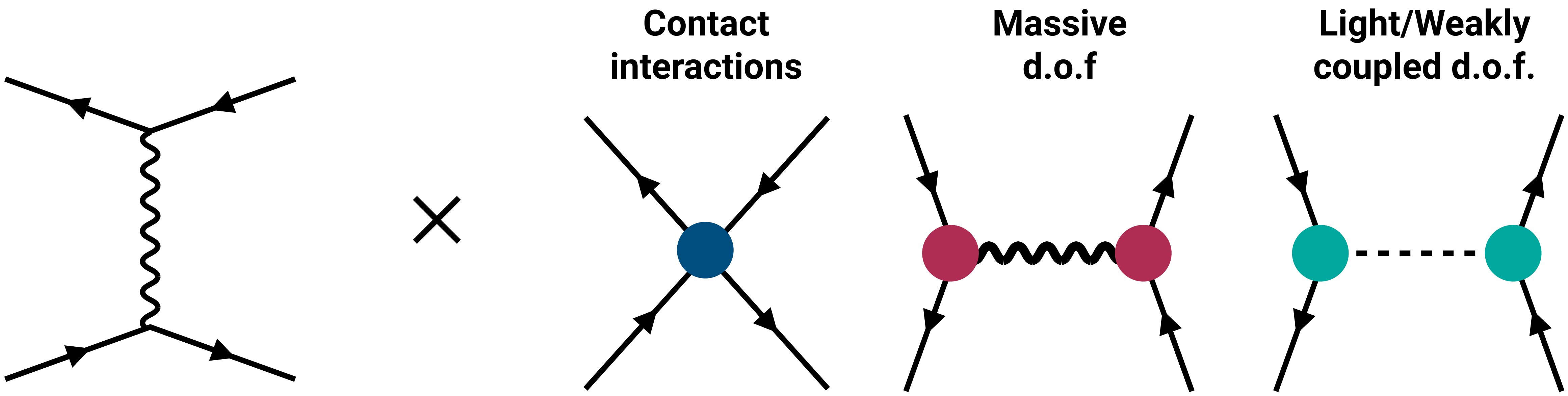
Janot, P. Direct measurement of αQED(m^2_Z) at the FCC-ee. *J. High Energ. Phys.* **2016**, 53 (2016)

New Physics Contribution

FCC-ee goal

$$\left.\frac{\delta L}{L}\right|_{\mathrm{th}} \leq 10^{-4}$$

Is the theoretical prediction of the Bhabha safe from **New Physics** contributions at **future colliders**?



Contact interactions

Massive d.o.f

Light/Weakly coupled d.o.f.

New Physics could interfere with the SM
At which level?

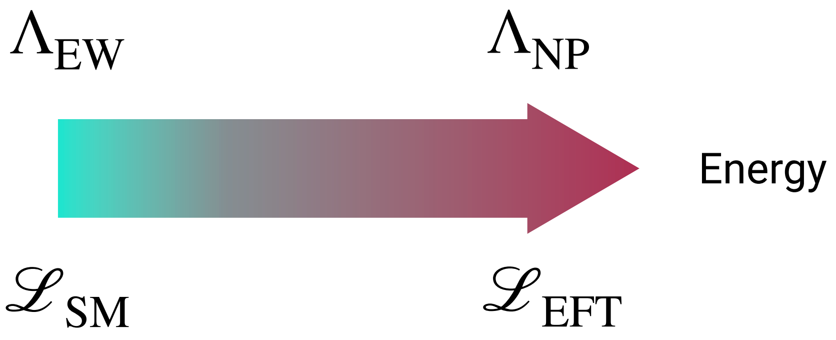
$$\frac{\delta\sigma_{\mathrm{NP}}}{\sigma_{\mathrm{SM}}} \simeq ?$$

New Physics Contribution

Workflow

$$\mathscr{L}_{\text{EFT}}$$

1. Parameterize the NP contribution in a model independent way **Effective Field Theories**

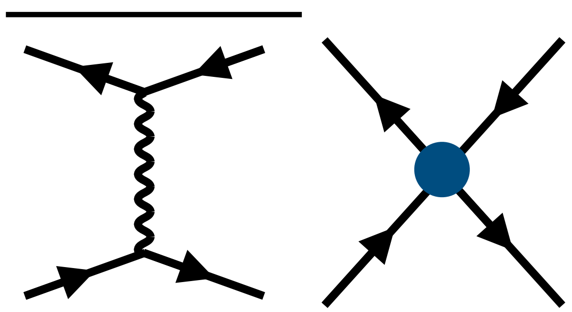


$$\leq \frac{g_i^2}{4\pi M_i^2} \leq$$

2. Find the current bounds on NP interaction from e+e- colliders

$$\frac{\delta\sigma_{\text{NP}}}{\sigma_{\text{SM}}} \simeq ?$$

3. Quantify the deviation of the Bhabha cross section from the SM



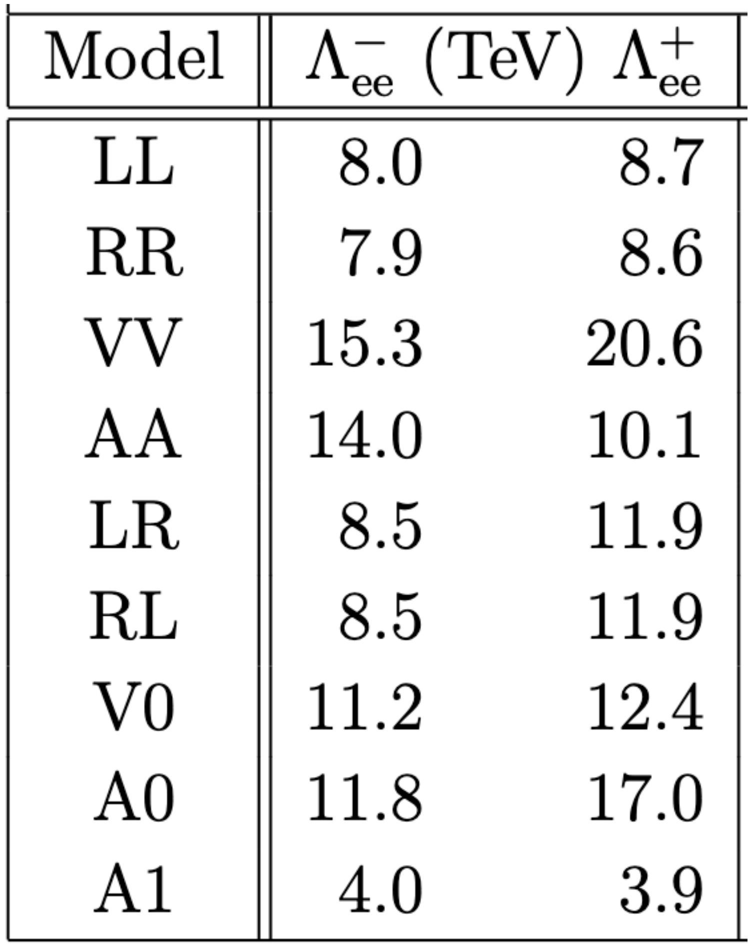
Contact Interactions

“Electroweak Measurements in Electron–Positron Collisions at W-Boson-Pair Energies at LEP.”
Physics Reports, vol. 532, no. 4, Nov. 2013, pp. 119–244. arXiv:1302.3415

In LEP analysis contact interactions were parameterized as

$$\mathscr{L}_{\text{eff}} = \frac{g^2}{(1+\delta_{ef})\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \left(\bar{e}_i \gamma_\mu e_i\right) \left(\bar{f}_j \gamma^\mu f_j\right)$$

$$\frac{g^2}{4\pi} = 1$$



Model	Λ^-_{ee} (TeV)	Λ^+_{ee}
LL	8.0	8.7
RR	7.9	8.6
VV	15.3	20.6
AA	14.0	10.1
LR	8.5	11.9
RL	8.5	11.9
V0	11.2	12.4
A0	11.8	17.0
A1	4.0	3.9

For the Bhabha scattering one has

$$\mathscr{L}^{\pm}_{\text{eff}} = \pm \frac{2\pi}{\Lambda^2_{\pm}} \sum_{ij \in \text{Models}} \eta^{\pm}_{ij} \hat{O}_{ij}$$

Bounds are obtained for the NP scale

Λ_+
Positive interference

Λ_-
Negative interference

Contact Interactions

"Electroweak Measurements in Electron–Positron Collisions at W-Boson-Pair Energies at LEP."
Physics Reports, vol. 532, no. 4, Nov. 2013, pp. 119–244. arXiv:1302.3415

First study for FCC-ee in $e^+e^- \to \gamma\gamma$:
J. A. Maestre arXiv:2206.07564

Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}
LL$^\pm$	±1	0	0	0
RR$^\pm$	0	±1	0	0
VV$^\pm$	±1	±1	±1	±1
AA$^\pm$	±1	±1	∓1	∓1
LR$^\pm$	0	0	±1	0
RL$^\pm$	0	0	0	±1
V0$^\pm$	±1	±1	0	0
A0$^\pm$	0	0	±1	±1
A1$^\pm$	±1	∓1	0	0

We consider only the linear interference with the SM as

$$|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}| \pm \frac{2\pi}{\Lambda^2_\pm} \sum_{ij\in\mathrm{Models}} \eta^\pm_{ij} 2\mathrm{Re}\{\mathscr{M}^\dagger_{\mathrm{SM}}\mathscr{M}^\pm_{ij}\}$$

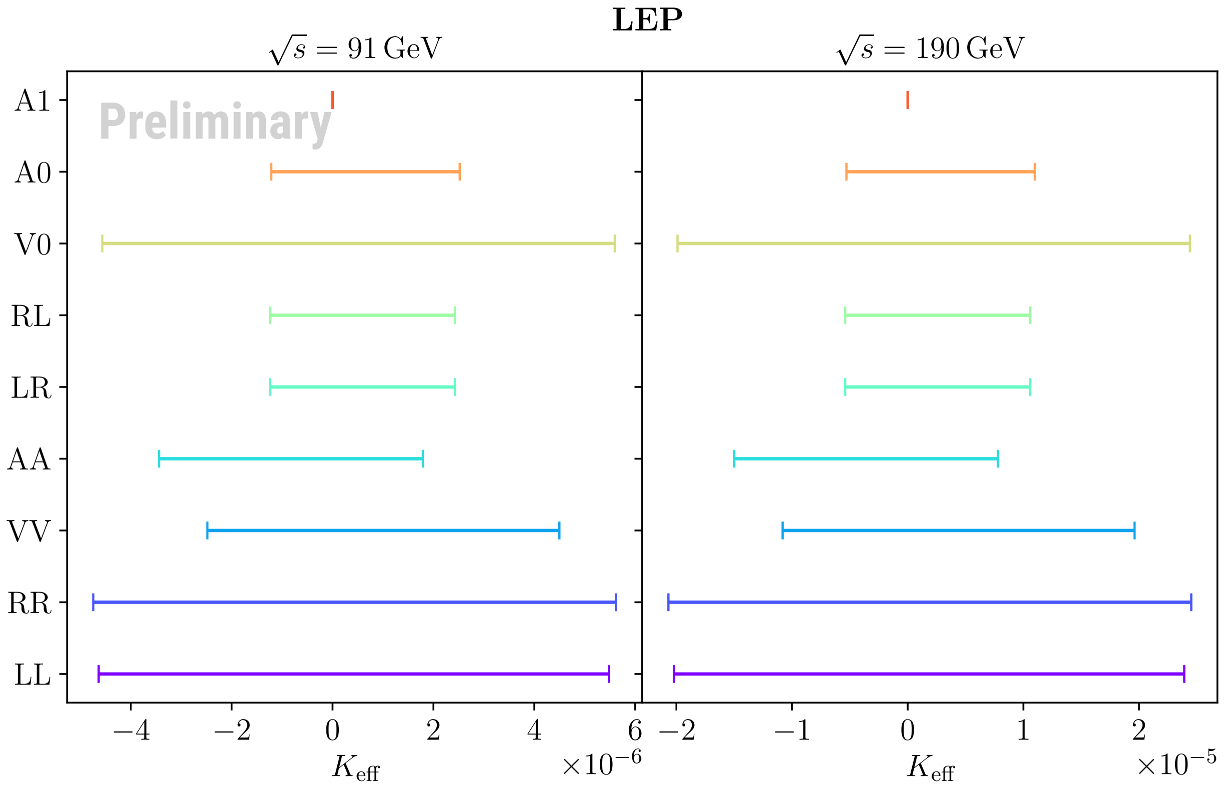
The QED t channel is the dominant contribution for SABH

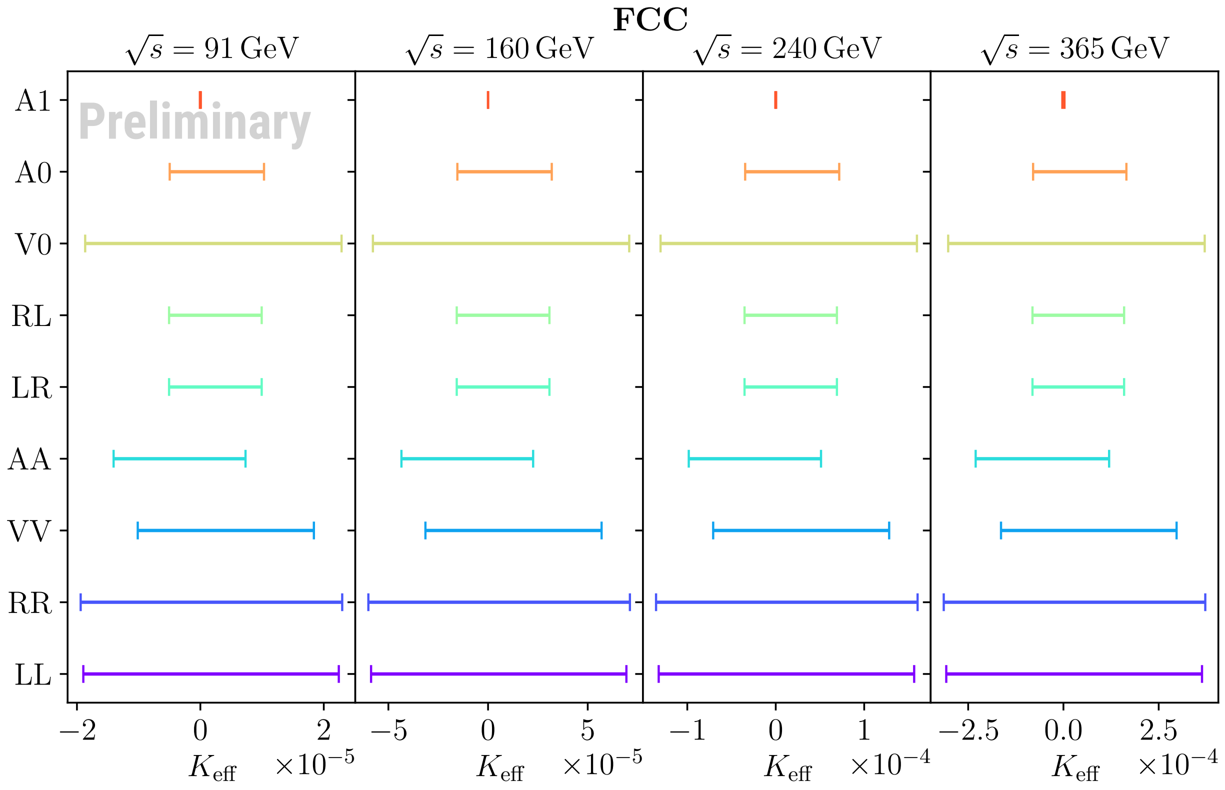
$$\mathscr{M}(t)^\dagger_\gamma \mathscr{M}_{\mathrm{LL/RR}} = -32\pi\alpha\frac{(1+\cos\theta)^2}{(1-\cos\theta)}s$$

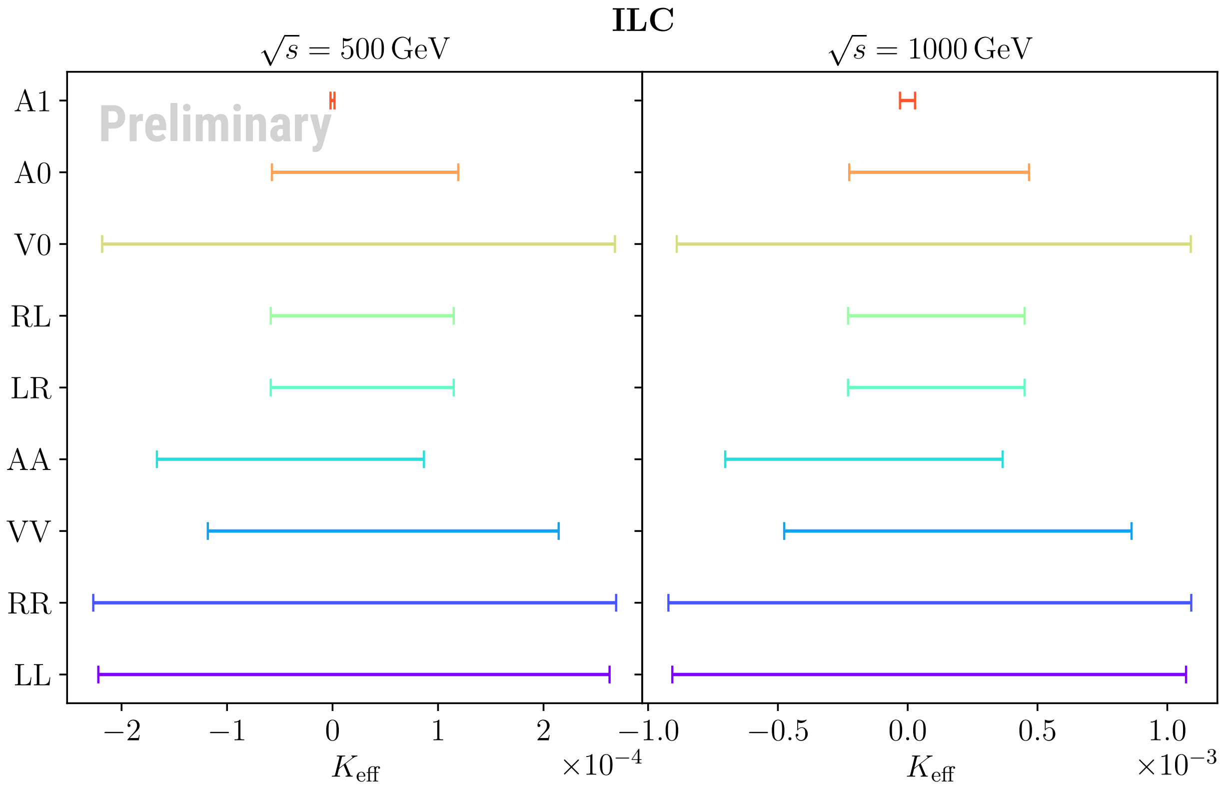
$$\mathscr{M}(t)^\dagger_\gamma \mathscr{M}_{\mathrm{RL/LR}} = -64\pi\alpha\frac{s}{(1-\cos\theta)}$$

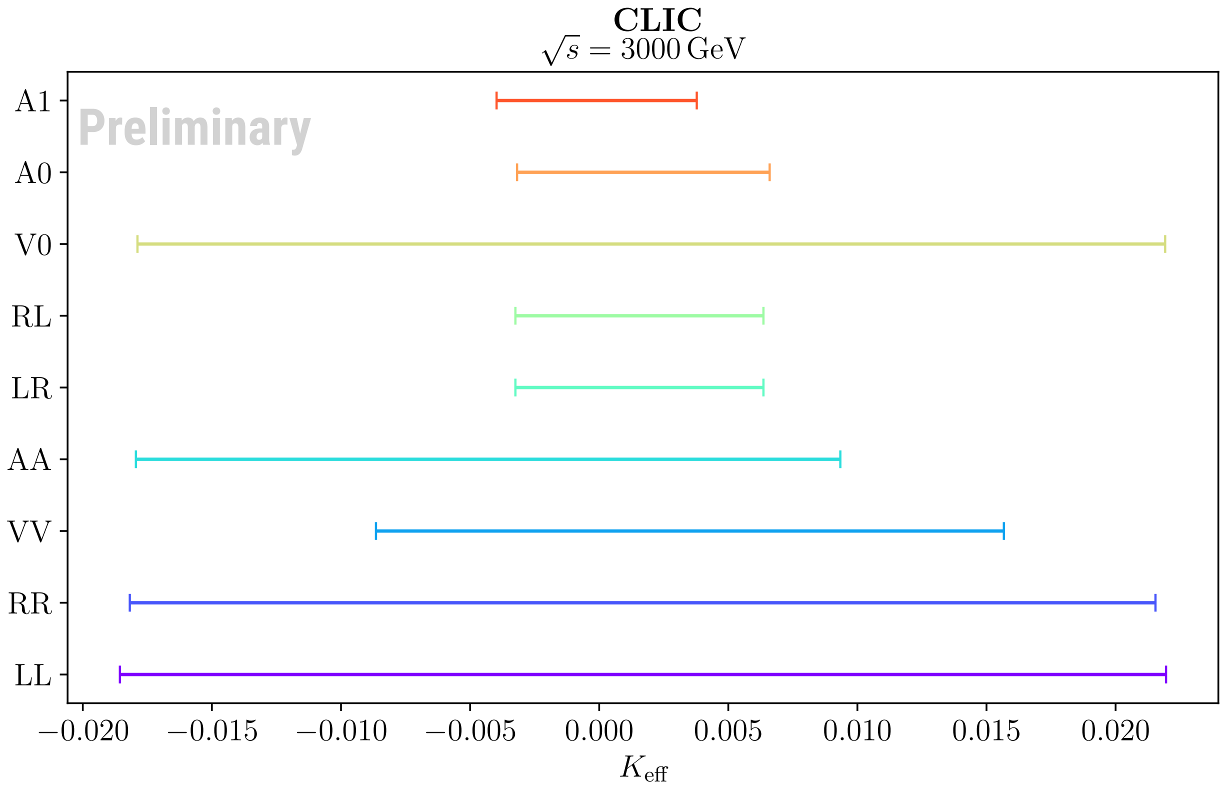
Collider	**Acceptance [mrad]**	**Energies [GeV]**
LEP	25-60 ~ Wide acceptance	90,190
FCC	64-86	91,160,240,365
ILC	31-77	500,1000
CLIC	39-134	3000

Contact Interactions: results







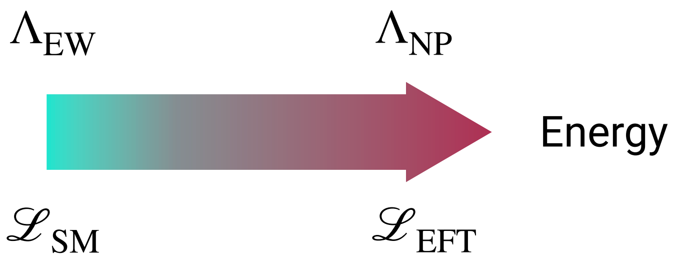


SMEFT

The most comprehensive way to parameterise NP is to treat the SM as low-energy limit of an EFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda_{\text{NP}}^2} Q_i^{(6)} + \mathcal{O}(\Lambda_{\text{NP}}^{-4})$$

Useful tool for indirect searches



Assumes a large mass gap between the electroweak scale and NP scale

Shift of input parameters

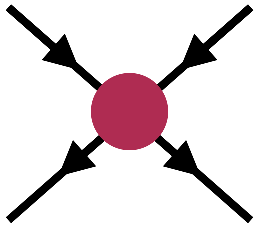
$$g = g_{\text{SM}} + \Delta g$$

$$G_\mu = \frac{1}{\sqrt{2} v_T^2}\left(1 + \frac{1}{\sqrt{2} G_\mu}\left(C_{Hl}^{(3)11} + C_{Hl}^{(3)22} - C_{ll}^{1221}\right)\right.$$

$$\alpha_{\text{em}} = \frac{1}{4\pi} \frac{g_W^2 g_1^2}{g_W^2 + g_1^2}(1 + \Delta\alpha_{\text{em}})$$

I. Brivio, "SMEFTsim3.0 - a practical guide"
arXiv:2012.11343

New vertices



$$\mathscr{L}_{\text{eff}} \in \mathscr{L}_{\text{SMEFT}}^{4f} = \frac{C_{ij}}{\Lambda_{\text{NP}}^2} Q_{ij}^{(6)}$$

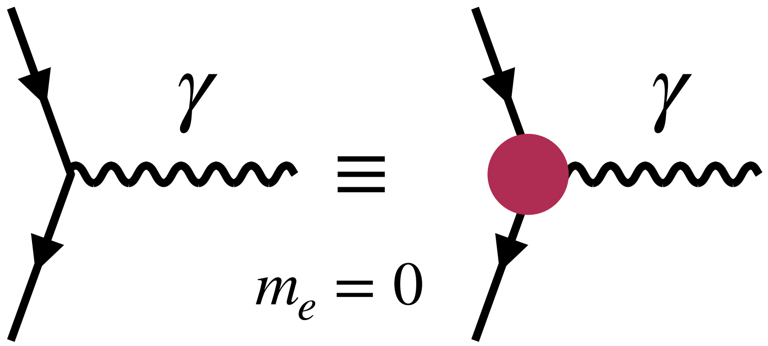
The Lagrangian used in LEP studies is a linear combination of SMEFT operators

SMEFT: Electroweak Sector

We use the $\{\alpha, M_Z, G_\mu\}$ scheme to compute the SMEFT prediction

$U(3)^5$ flavour assumption

QED



$$\Delta\alpha_{\text{em}} = 0$$

Weak NC

$$\mathscr{L}^{\text{NC}}_{\text{SMEFT}} = 2^{\frac{5}{4}}\sqrt{\hat{G}_\mu}\hat{M}_Z\ \bar{e}\left(\gamma_\mu \bar{g}_V - \bar{g}_A\gamma_5\right) e\ Z^\mu$$

$$\delta g_V = \delta g_Z \bar{g}_V - \delta s_\theta^2 + \Delta_V$$

$$\delta g_A = \delta g_Z \bar{g}_A + \Delta_A$$

● Shift of Z coupling

● Axial/Vector coupling

$$\delta \bar{g}_Z = -\frac{1}{4\sqrt{2}G_\mu}\left(C_{HD} + 2C_{\phi l}^{(3),1} + 2C_{\phi l}^{(3),2} - 2C_{ll}^{1221}\right)$$

$$\Delta^e_{V/A} = -\frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{He}^{(1)} + C_{He}^{(3)} + C_{He}\right)$$

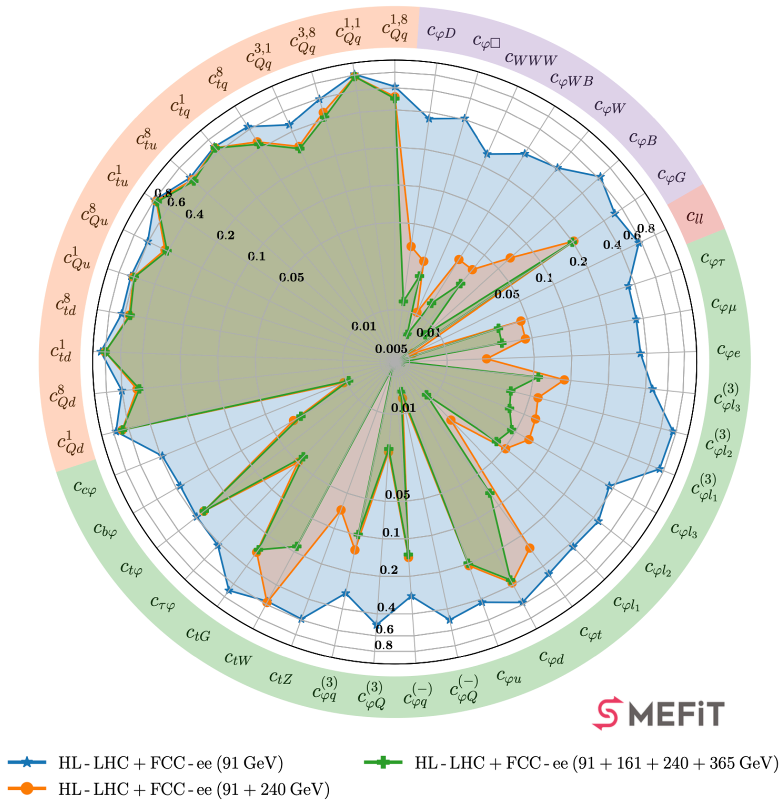
Global Fits

Fitting LEP and LHC data to constrain SMEFT coefficients.
Some (**not comprehensive, sorry**) Global fits we are studying

SMEFIT 3.0

E. Celada et al. SMEFiT 3.0
arXiv:2404.12809

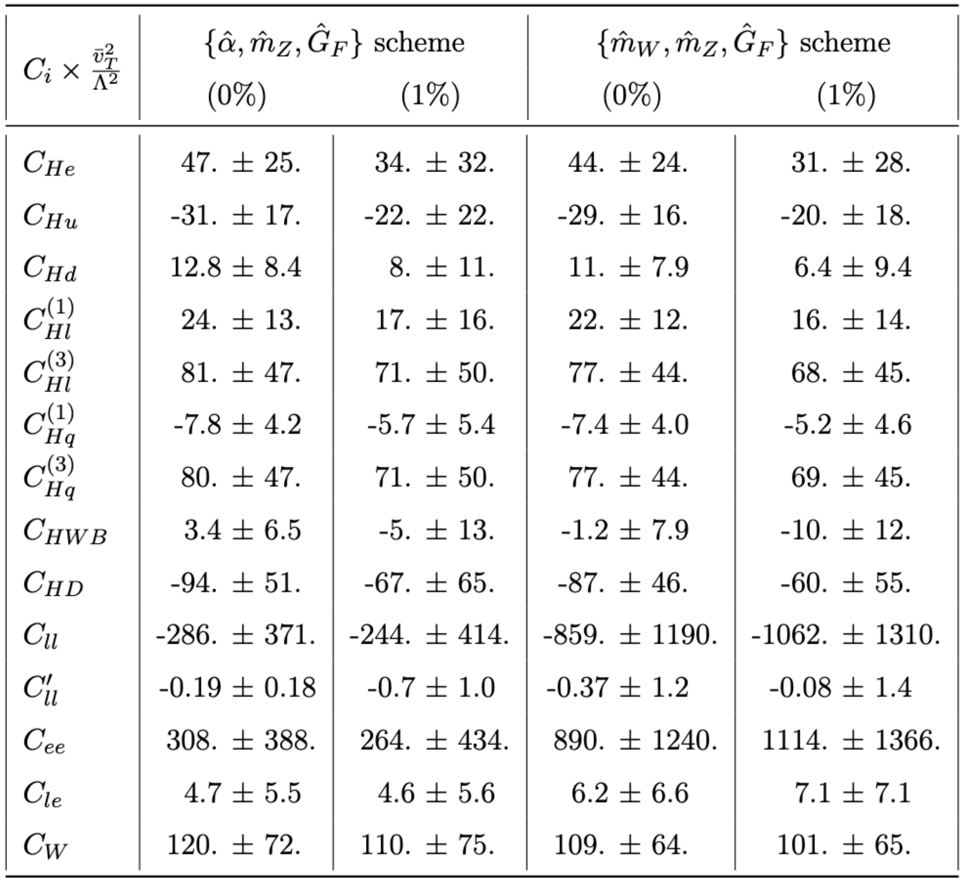
>>>See Jaco's talk from yesterday



- Projections for HL-LHC and FCC-ee precision reach
- Comprehensive fit (both data and # of WCs)
- Does not include C_{le}, C_{ee}

Brivio&Trott

I.B. and M.T. "Scheming in the SMEFT… and a reparameterization invariance!"
arXiv:1701.06424



$C_i \times \frac{\bar{v}_T^2}{\Lambda^2}$	$\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	$\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme (1%)	$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme (1%)
C_{He}	47. ± 25.	34. ± 32.	44. ± 24.	31. ± 28.
C_{Hu}	-31. ± 17.	-22. ± 22.	-29. ± 16.	-20. ± 18.
C_{Hd}	12.8 ± 8.4	8. ± 11.	11. ± 7.9	6.4 ± 9.4
$C_{Hl}^{(1)}$	24. ± 13.	17. ± 16.	22. ± 12.	16. ± 14.
$C_{Hl}^{(3)}$	81. ± 47.	71. ± 50.	77. ± 44.	68. ± 45.
$C_{Hq}^{(1)}$	-7.8 ± 4.2	-5.7 ± 5.4	-7.4 ± 4.0	-5.2 ± 4.6
$C_{Hq}^{(3)}$	80. ± 47.	71. ± 50.	77. ± 44.	69. ± 45.
C_{HWB}	3.4 ± 6.5	-5. ± 13.	-1.2 ± 7.9	-10. ± 12.
C_{HD}	-94. ± 51.	-67. ± 65.	-87. ± 46.	-60. ± 55.
C_{ll}	-286. ± 371.	-244. ± 414.	-859. ± 1190.	-1062. ± 1310.
C'_{ll}	-0.19 ± 0.18	-0.7 ± 1.0	-0.37 ± 1.2	-0.08 ± 1.4
C_{ee}	308. ± 388.	264. ± 434.	890. ± 1240.	1114. ± 1366.
C_{le}	4.7 ± 5.5	4.6 ± 5.6	6.2 ± 6.6	7.1 ± 7.1
C_W	120. ± 72.	110. ± 75.	109. ± 64.	101. ± 65.

- Predictions in both schemes with central values
- Loose bounds on Four fermion operators

Others:

De Blas et al. "Global SMEFT Fits at Future Colliders"
arXiv:2206.08326

Falkowski, Adam, et al. "Compilation of Low-Energy Constraints on 4-Fermion Operators in the SMEFT."
arXiv:1706.03783

SMEFT: Results

Results obtained with:

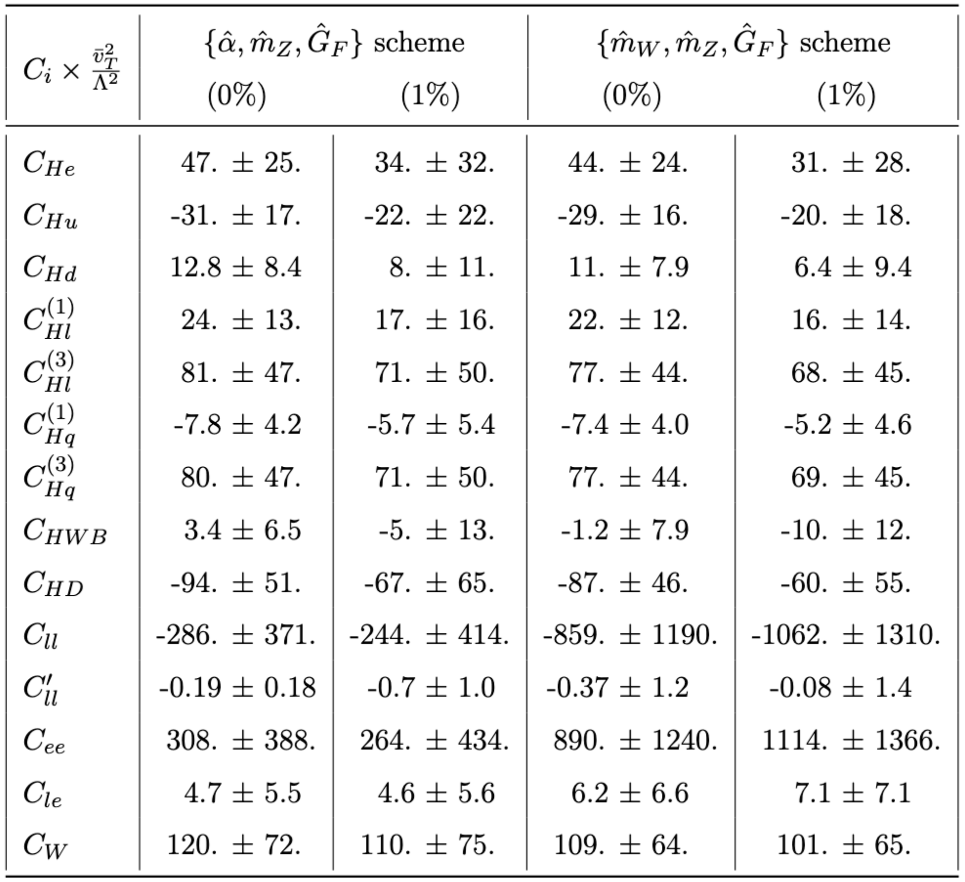
- **BabaYaga** MC generator
- **MG5@NLO** to compute the Matrix element
- **SMEFTsim** for the UFO

Collider	√s [GeV]	K
LEP	91	-2.3×10^{-4}
	190	-1×10^{-3}
FCC	91	-9.7×10^{-4}
	160	-2.8×10^{-3}
	240	-6.4×10^{-3}
	365	-1.4%
ILC	500	-1%
	1000	-4%
CLIC	300	-38%

$$K_{\text{SMEFT}} = \frac{\sigma_{\text{SMEFT}}}{\sigma_{\text{SM}}} - 1$$

Brivio&Trott

I.B. and M.T. “Scheming in the SMEFT… and a reparameterization invariance!”
arXiv:1701.06424



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- Predictions in both schemes with central values
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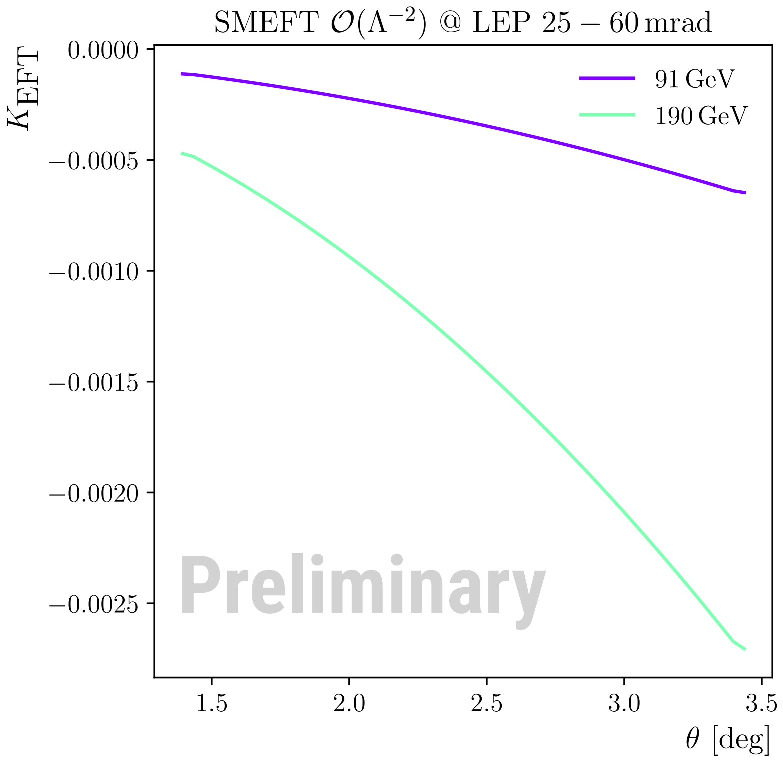
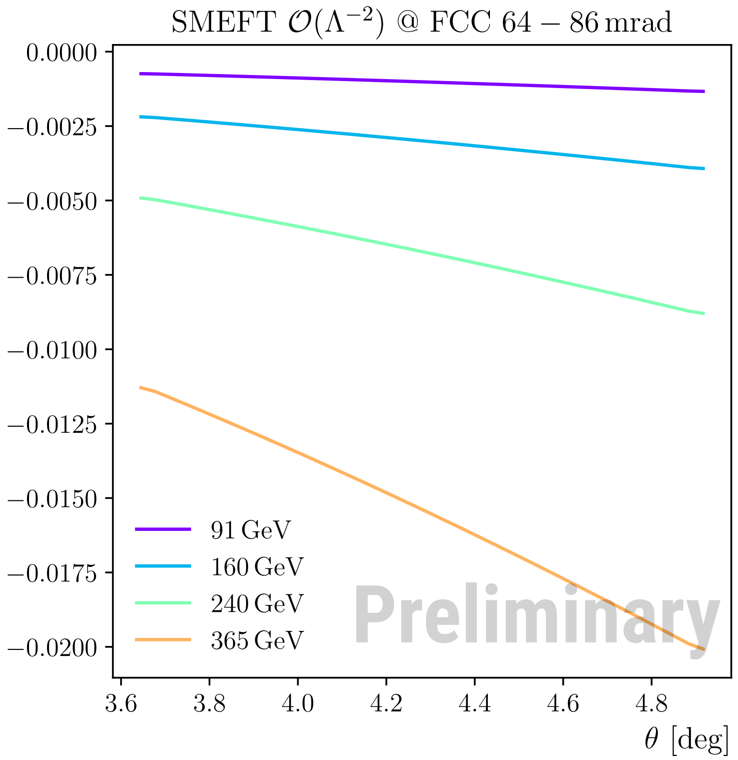
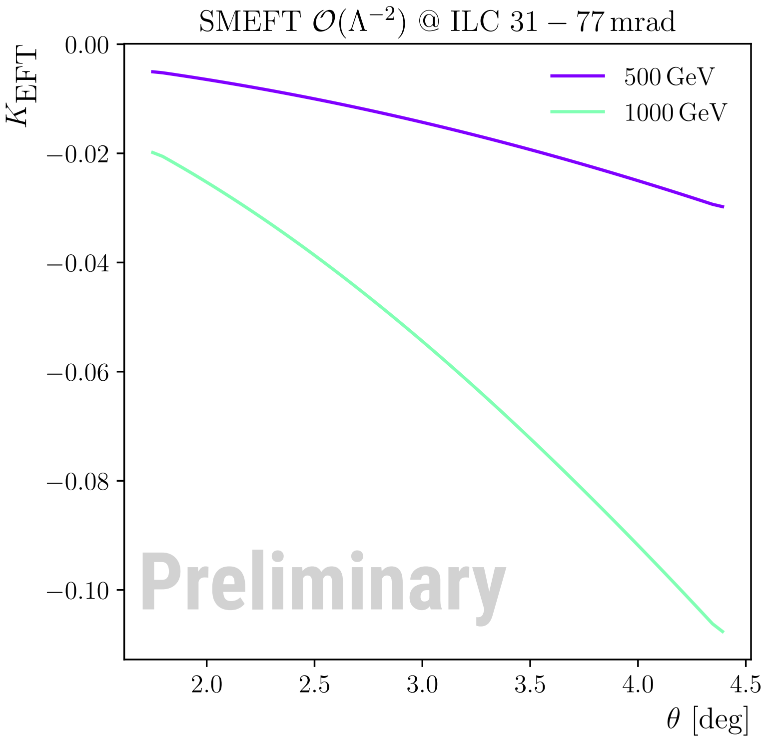
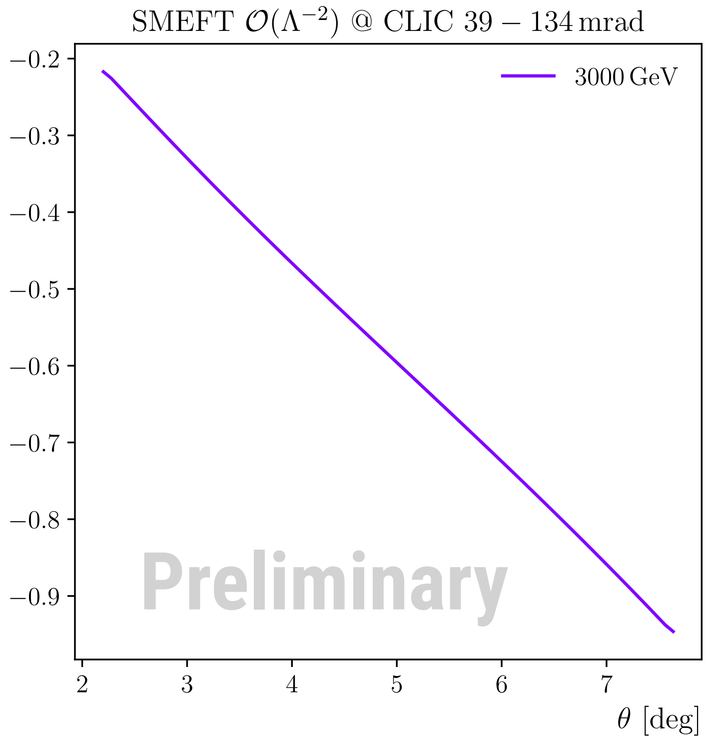
SMEFT: results


SMEFT $\mathcal{O}(\Lambda^{-2})$ @ LEP 25 – 60 mrad


SMEFT $\mathcal{O}(\Lambda^{-2})$ @ FCC 64 – 86 mrad


SMEFT $\mathcal{O}(\Lambda^{-2})$ @ ILC 31 – 77 mrad


SMEFT $\mathcal{O}(\Lambda^{-2})$ @ CLIC 39 – 134 mrad

Summary&Outlook

Conclusions:

It is crucial to estimate the NP contribution to assign a proper theory error to the Luminosity at future collider

Preliminary result show that the effects are small with LEP bounds but not under control using a Global Fit

Ongoing:

Estimating the SMEFT error on cross section

Considering other Fits (e.g. SMEFiT)

In addition to the SMEFT, also consider weakly coupled/light NP