Precision luminosity measurements at future colliders

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Abstract

The experiments under consideration for high-energy electron-positron colliders offer a promising environment for future discoveries, by improving the current bounds on New Physics beyond the Standard Model of particle physics by several orders of magnitude. In order to carry out reliable high precision measurements, a key quantity, the collider luminosity, has to be known and theoretically calculable with unprecedented precision. In addition, it should be independent of any possible contamination from unknown New Physics. This can be achieved through the measurement of standard candle processes. For future electron-positron colliders, the reference process of main interest is small-angle Bhabha scattering, which is by far dominated by the electromagnetic interaction or diphoton production as an alternative. We quantify New Physics effects to the small-angle Bhabha process at next-generation accelerators and we discuss possible strategies to remove potential uncertainties coming from such contaminations. Moreover, we investigate such effects also in diphoton production, a proposed alternative luminosity process

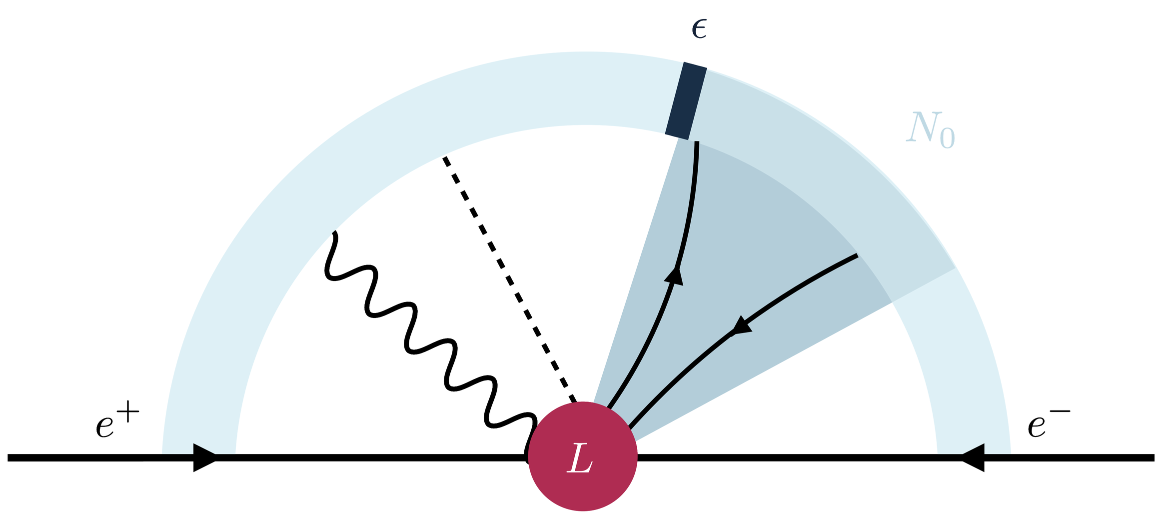
Luminosity

Luminosity *converts events into cross sections*, and it is measured as

Luminosity

$$L = \int \mathcal{L}\,\mathrm{d}t = \frac{N_0^{\mathrm{exp}}}{\epsilon\,\sigma_0^{\mathrm{th}}}$$

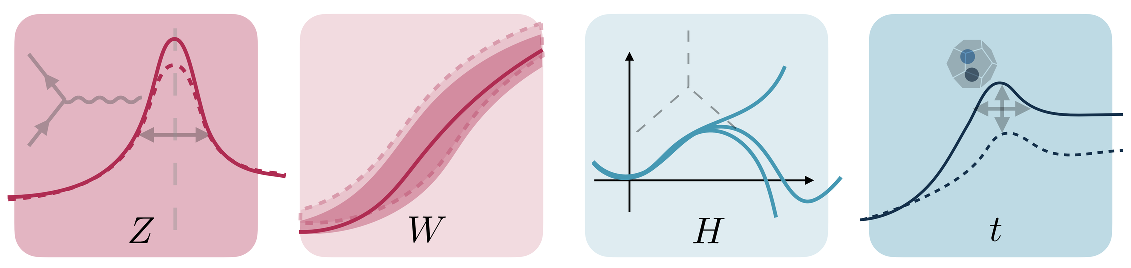
- $\mathcal{L}$ Instantaneous luminosity
- N_0^{exp} Number of events
- σ_0^{th} Reference cross-section
- ϵ Experimental acceptance



The precision of observed absolute cross sections $\sigma = (1/\epsilon)N/L$ is limited by the error on luminosity

$$\frac{\Delta\sigma^{\mathrm{exp}}}{\sigma^{\mathrm{exp}}} = \frac{\Delta N^{\mathrm{exp}}}{N^{\mathrm{exp}}} \oplus \frac{\Delta L}{L} \qquad \frac{\Delta L}{L} \leq 10^{-4}$$

The error on luminosity affects the precision measurements of the main parameters at future Higgs/ Top/Electroweak factories, such as the Future Circular Collider (FCC-ee)

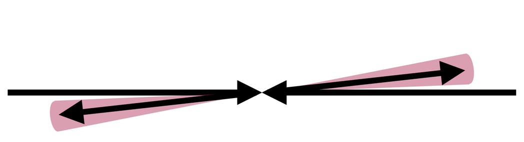


In the most recent LEP analysis, the most precise estimate $\Delta L/L = 0.037\%$ removed a long-standing tension on the number of light neutrino species N_ν.

Alternative processes

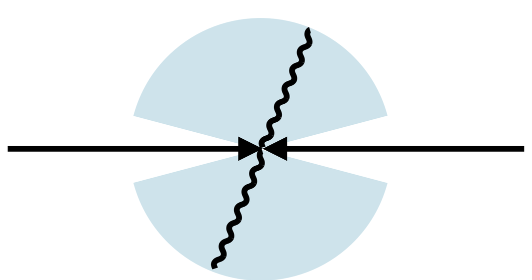
Luminosity is measured through benchmark processes. At e^+e^- colliders, the alternatives are

Small-angle Bhabha



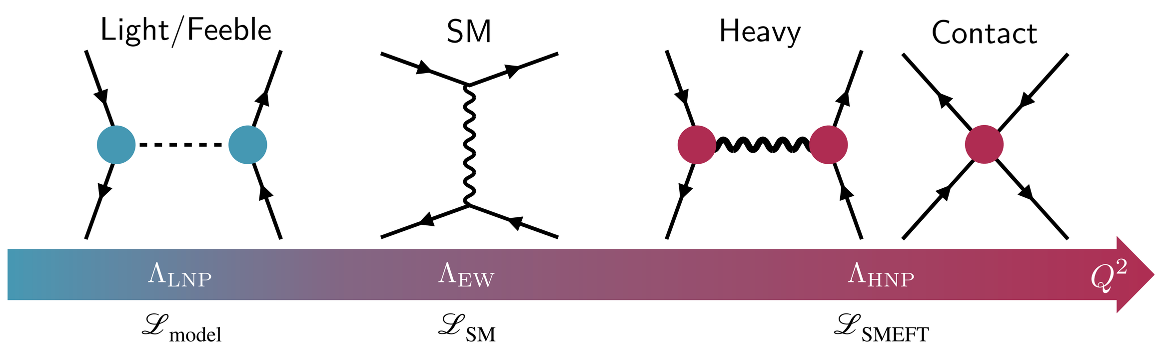
Essentially a QED process for $t = -\frac{s}{2}(1-\cos\theta),\ \cos\theta \ll 1$

Diphoton



Pure QED, EW effects at NLO and hadronic uncertainty starts at NNLO

In order to have the luminosity process under control, one should investigate, other than SM radiative corrections, also hypothetical new heavy and light degrees of freedom that could mediate the process



Future colliders

Many projects have been proposed, like CEPC, CLIC, ILC, MuCol, etc, but the European Strategy for Particle Physics chose FCC-ee as the preferred option. FCC will run at centre-of-mass energies

$$\sqrt{s} = 91,\ 160,\ 240,\ 365\,\mathrm{GeV}$$

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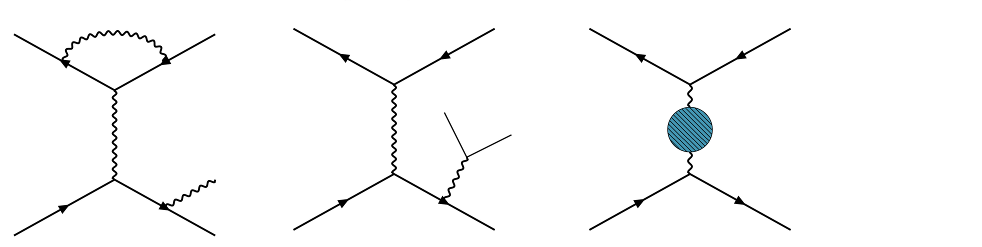
arXiv:2501.05256

New Physics in SABS

Standard Model

The main challenge for the Standard Model calculations is to compute Electroweak radiative corrections at 10^{-4} level. Below, the actual state-of-the-art precision



$$0.011\% \oplus 0.005\% \oplus 0.006\% \simeq 0.01\%$$

From the SM side, the photonic corrections have to be calculated at NNLO QED + NLO EW + PS accuracy to meet this goal.

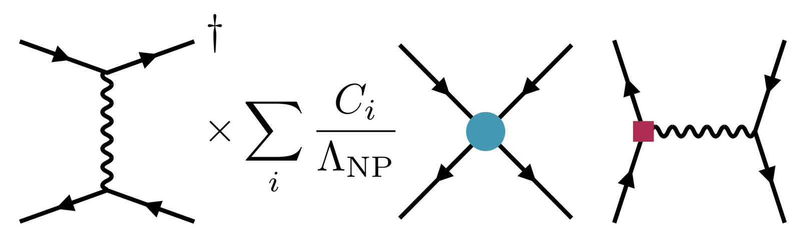
Heavy New Physics scenarios

The ambitious luminosity precision goals at future colliders could be compromised if contributions from New Physics are of similar magnitude. We focus on a model-independent parameterisation of **heavy** NP via an effective Lagrangian expanded about the SM

SMEFT Lagrangian

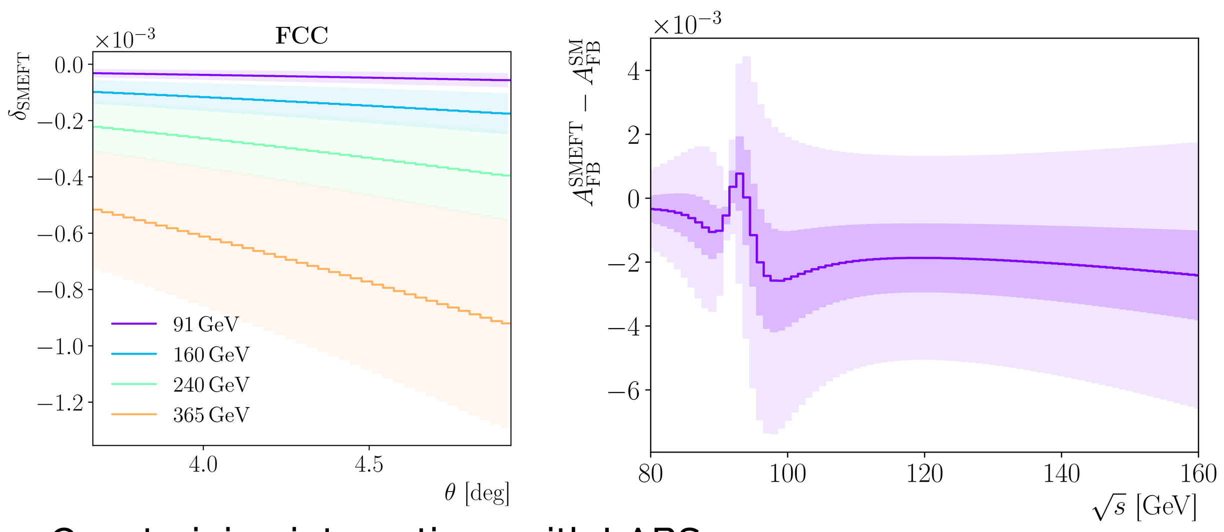
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{C_i \hat{O}_i^{(6)}}{\Lambda_{\mathrm{NP}}^2} + \mathcal{O}\left(\frac{1}{\Lambda_{\mathrm{NP}}^4}\right)$$

At LO SMEFT, the prediction for the Bhabha cross section is given by the interference of the SM with dim-6 effective operators



The results come mostly from 4-fermions operators

Exp.	$[\theta_{\min}, \theta_{\max}]$	$\sqrt{s}$ [GeV]	$(\delta \pm \Delta\delta)_{\mathrm{SMEFT}}$	$\Delta L/L$
FCC	$[3.7^\circ, 4.9^\circ]$	91	$(-4.2 \pm 1.7) \times 10^{-5}$	$< 10^{-4}$
		160	$(-1.3 \pm 0.5) \times 10^{-4}$	
		240	$(-2.9 \pm 1.2) \times 10^{-4}$	10^{-4}
		365	$(-6.7 \pm 2.7) \times 10^{-4}$	



Constraining interactions with LABS

In order to reduce the uncertainty coming from three coefficients $C_{4f} = \{C_{le}, C_{ll}, C_{ee}\}$ we can fit the forward-backward asymmetry pseudo data $A_{\mathrm{FB}}(\sqrt{s_\alpha})$

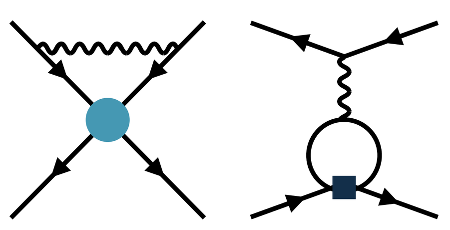
Forward-backward asymmetry fit

$$\sum_{i\in 4f} \frac{C_i}{\Lambda_{\mathrm{NP}}^2}\left[\frac{(\sigma_{\mathrm{F}}-\sigma_{\mathrm{B}})_i^{(6)}}{(\sigma_{\mathrm{F}}-\sigma_{\mathrm{B}})_{\mathrm{SM}}} - \frac{(\sigma_{\mathrm{F}}+\sigma_{\mathrm{B}})_i^{(6)}}{(\sigma_{\mathrm{F}}+\sigma_{\mathrm{B}})_{\mathrm{SM}}}\right]_\alpha = \frac{\Delta A_{\mathrm{FB},\alpha}^0}{A_{\mathrm{FB},\alpha}^0},$$

The three measured points are chosen to be the ones that **maximise** the difference $A_{\mathrm{FB}}^{\mathrm{SMEFT}} - A_{\mathrm{FB}}^{\mathrm{SM}}$ based on current bounds.

The 1σ uncertainty on four-electrons coefficients is reduced to $\Delta C_{ll/ee} \lesssim 10^{-2}$ and $\Delta C_{le} \lesssim 10^{-3}$ yielding to $\delta_{\mathrm{SMEFT}} \sim 5 \times 10^{-6}$ on the Z-peak luminosity at FCC.

$$\sum_j \frac{C_j(\mu)}{16\pi^2\Lambda_{\mathrm{NP}}^2}$$



The NLO SMEFT corrections are $\mathcal{O}(1-10\%)$ over the LO, thus negligible.

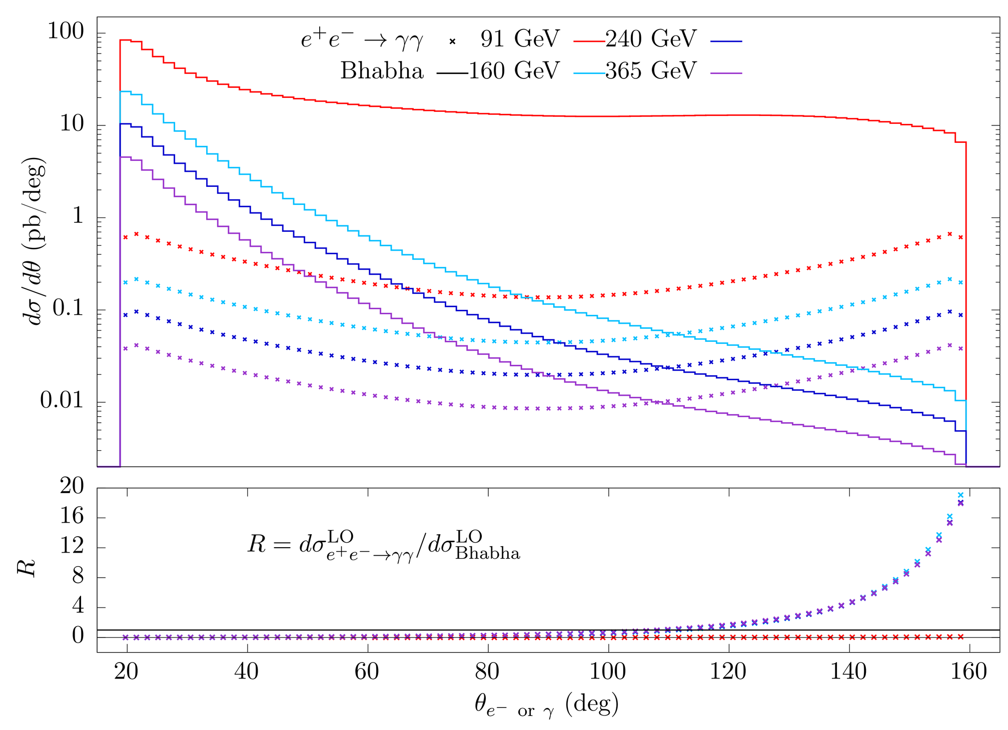
NLO EW corrections to $\gamma\gamma$ in the SM(EFT)

Standard Model EW corrections + PS

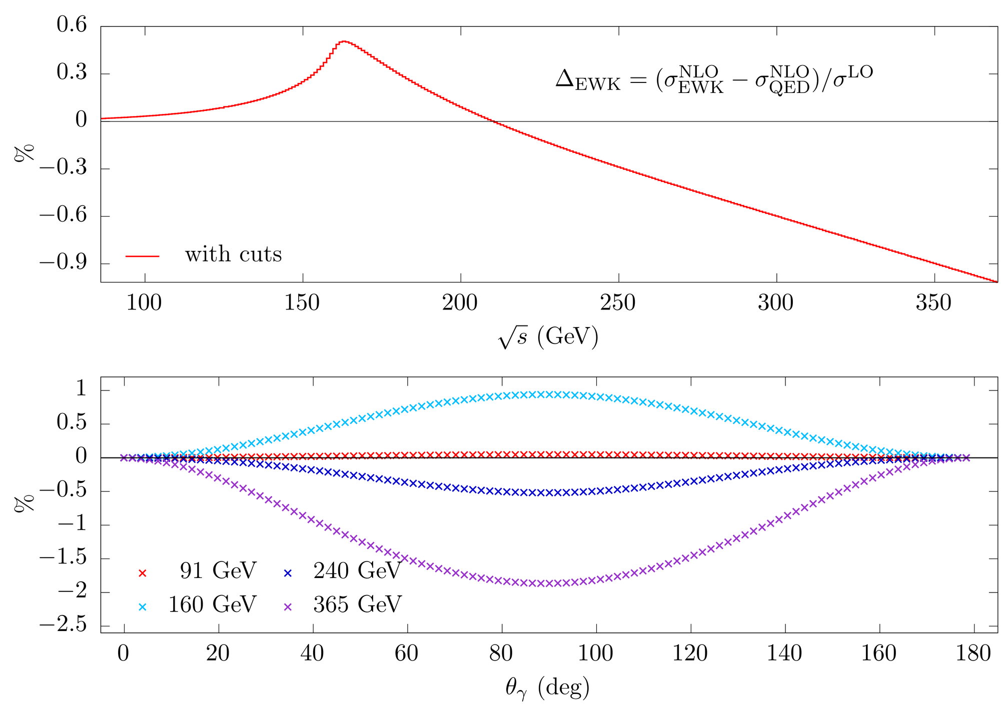
The cross section, as computed by BabaYaga@NLO, is given by the photon-resummed formula

$$\mathrm{d}\sigma_{\mathrm{NLOPS}} = F_{\mathrm{SV}}\Pi(\epsilon, Q^2)\sum_{n=0}^{\infty}\frac{1}{n!}\left(\prod_{i=0}^{n} F_{H,i}\right)\left|\mathcal{M}_n^{\mathrm{LL}}\right|^2 \mathrm{d}\Phi_n$$

Here we show a comparison of the $\gamma\gamma$ and Bhabha cross sections at LO. Angular distribution can be used to separate the background.



The relative impact of the complete NLO EW corrections w.r.t. the QED ones is at the level of $1-2\%$.



NNLO Pair corrections

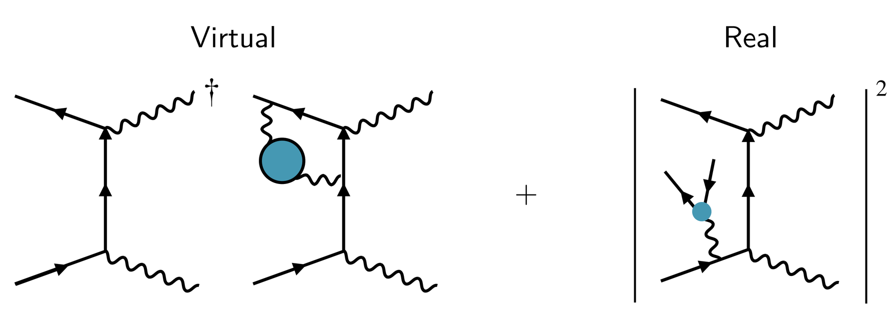
An approximate way to estimate hadronic pair corrections is through the expansion of the cross section with the running of α

$$\sigma_{\mathrm{NNLO}}^{\Delta\alpha} \pm \delta\sigma_{\mathrm{had}} \simeq (\sigma_{\mathrm{NLO}}^{\mathrm{QED}} - \sigma_{\mathrm{LO}}) \times [\Delta\alpha(s) \pm \Delta\alpha_{\mathrm{had}}]$$

$\sqrt{s}$ (GeV)	$\sigma^{\mathrm{NNLO}}_{\Delta\alpha\ \mathrm{lep+top}}/\sigma_{\mathrm{LO}}$	$\sigma^{\mathrm{NNLO}}_{\Delta\alpha\ \mathrm{had}}/\sigma_{\mathrm{LO}}$	$\delta\sigma_{\mathrm{had}}/\sigma_{\mathrm{LO}}$
91	0.096%	0.085%	$3.7\cdot 10^{-6}$
160	0.108%	0.098%	$3.8\cdot 10^{-6}$
240	0.115%	0.108%	$3.9\cdot 10^{-6}$
365	0.119%	0.120%	$4.0\cdot 10^{-6}$

However, the full calculation (Work in progress) has to include both virtual and real, as well both hadronic and leptonic pairs, in order to estimate the background to 10^{-4} level

$$\frac{-ig_{\mu\nu}}{q^2+i\epsilon} \to ig_{\mu\nu}\left(\frac{-q^2}{\pi}\right)\int_{4m_l^2}^{\infty}\frac{\mathrm{d}z}{z}\frac{\Pi(q^2)}{q^2-z+i\epsilon}$$



SMEFT NLO corrections

In the SMEFT, the first contributions to this process appear at next-to-leading order

$$\sigma_{\mathrm{SMEFT}} = \sigma_{\mathrm{SM}} + \sum_i \frac{C_i}{16\pi^2\Lambda_{\mathrm{NP}}^2}\sigma_i^{(6,1)}$$