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Lepton pair production at NNLO in QED with EW effects

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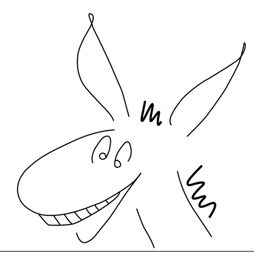
τ physics at the high-intensity frontier

Low-energy precision experiments with leptons require a precise knowledge of the SM background.
The Belle II experiment at the SuperKEKB facility will provide a world-leading precision for measurements of τ properties. Together with the proposed beam polarisation upgrade it will even be possible to probe the SM prediction of $(g-2)_\tau$. At Belle II's CMS energy of $\sqrt{s} \approx 10.5\,\text{GeV}$ QED effects still dominate even though EW effects start to become relevant.

What is McMule?

McMule is a framework for fully-differential higher-order calculations for low-energy processes dominated by QED. We use modern methods adapted from QCD:

- dimensional regularisation for UV- and IR-divergences
- subtraction for phase-space integration
- master integrals, automated tools, EFT methods



In particular, McMule is based on:

- FKS$^\ell$ – infrared structure
- massification – multi-scale integrals
- next-to-soft stabilisation – numerics

$\mu \to e\bar\nu\nu$	NNLO + resumm.
$\mu \to e\bar\nu\nu\gamma$	NLO
$\mu \to e\bar\nu\nu ee$	NLO
$e\mu \to e\mu$	NNLO
$\ell p \to \ell p$	dom. NNLO
$ee \to ee$	NNLO
$e^+e^- \to e^+e^-$	NNLO
$e^+e^- \to \gamma\gamma$	NNLO
$e^+e^- \to \ell^+\ell^-$	dom. NNLO + NLO EW

The FKS$^\ell$ subtraction scheme

We use the simple structure of soft singularities in QED

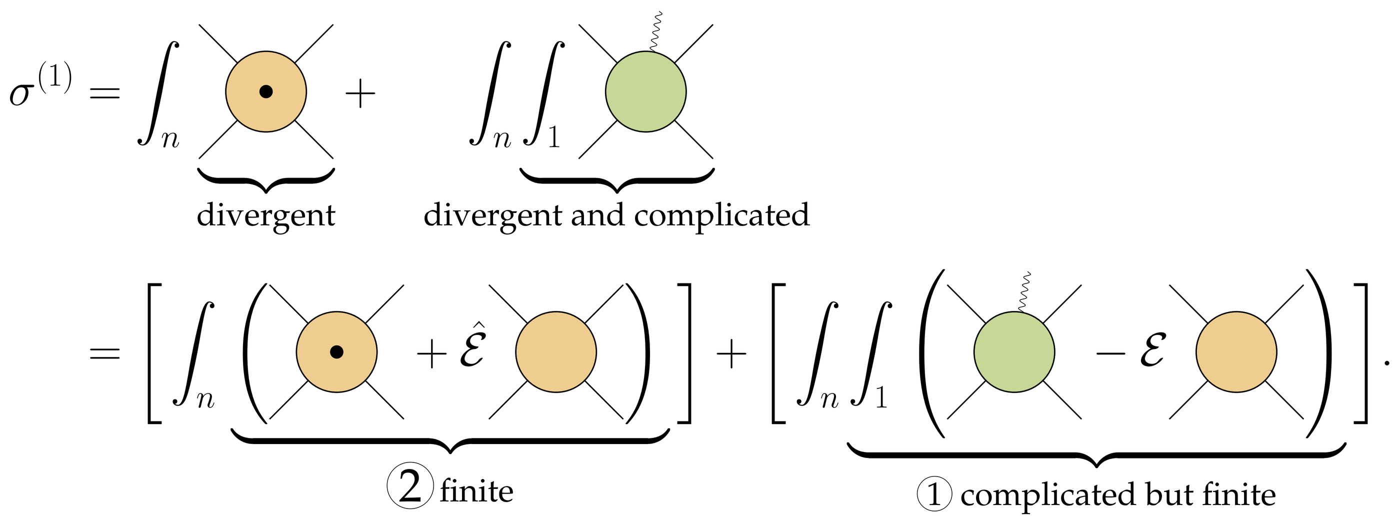
① universal (leading) soft limit

$$\mathcal{M}^{(\ell)}_{n+1} = \mathcal{E}\mathcal{M}^{(\ell)}_n + \mathcal{O}(E_\gamma^{-1})$$

② universal pole structure

$$e^{\hat{\mathcal{E}}} \sum_{\ell=0}^{\infty} \mathcal{M}^{(\ell)}_n = \text{finite}$$

and combine them into an all-order subtraction scheme FKS$^\ell$



Further information: mule-tools.gitlab.io

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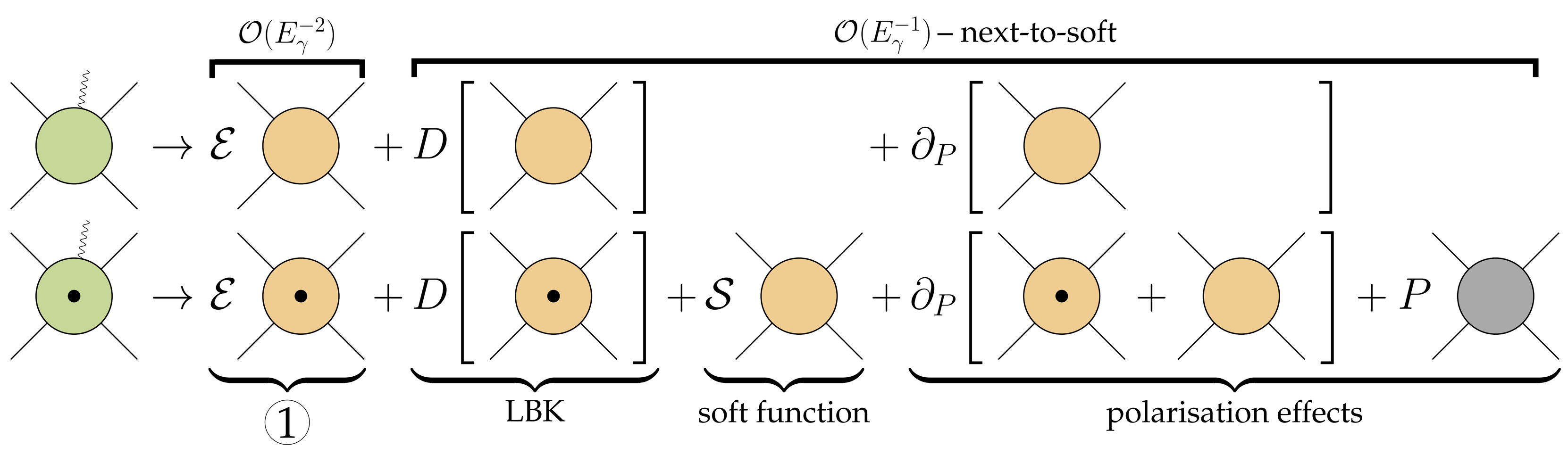
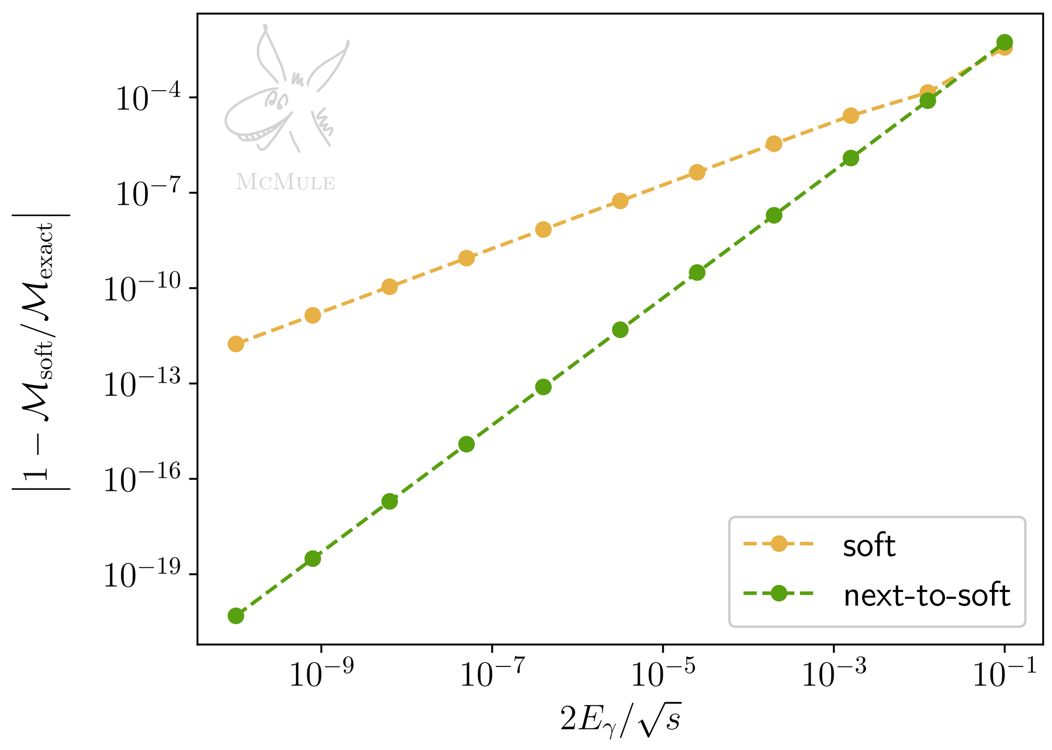
Next-to-soft stabilisation

Numerical stability during the phase-space integration of the emitted photon is one of the main challenges.

Idea	Use expanded radiative matrix element including next-to-soft contribution for small E_γ.
Realisation	Subleading term is related to non-radiative matrix elements through: • LBK operator $D \to \partial/\partial p_i$ • universal soft function $\mathcal{S}$ • polarisation effects $P \to$ new object

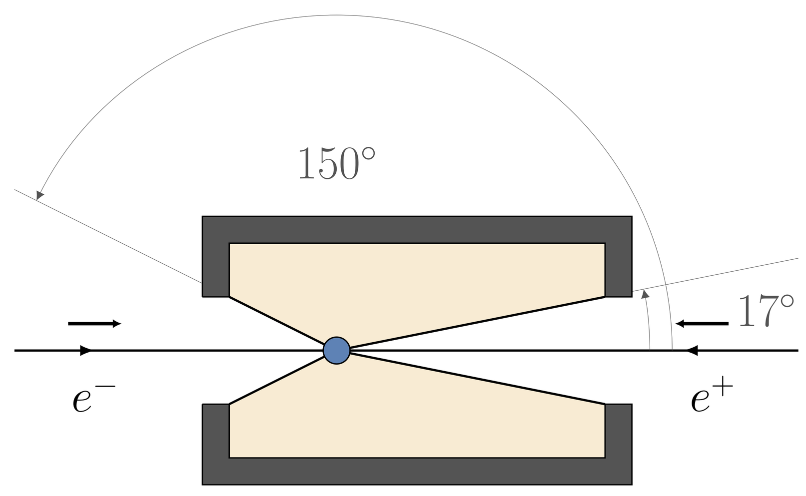


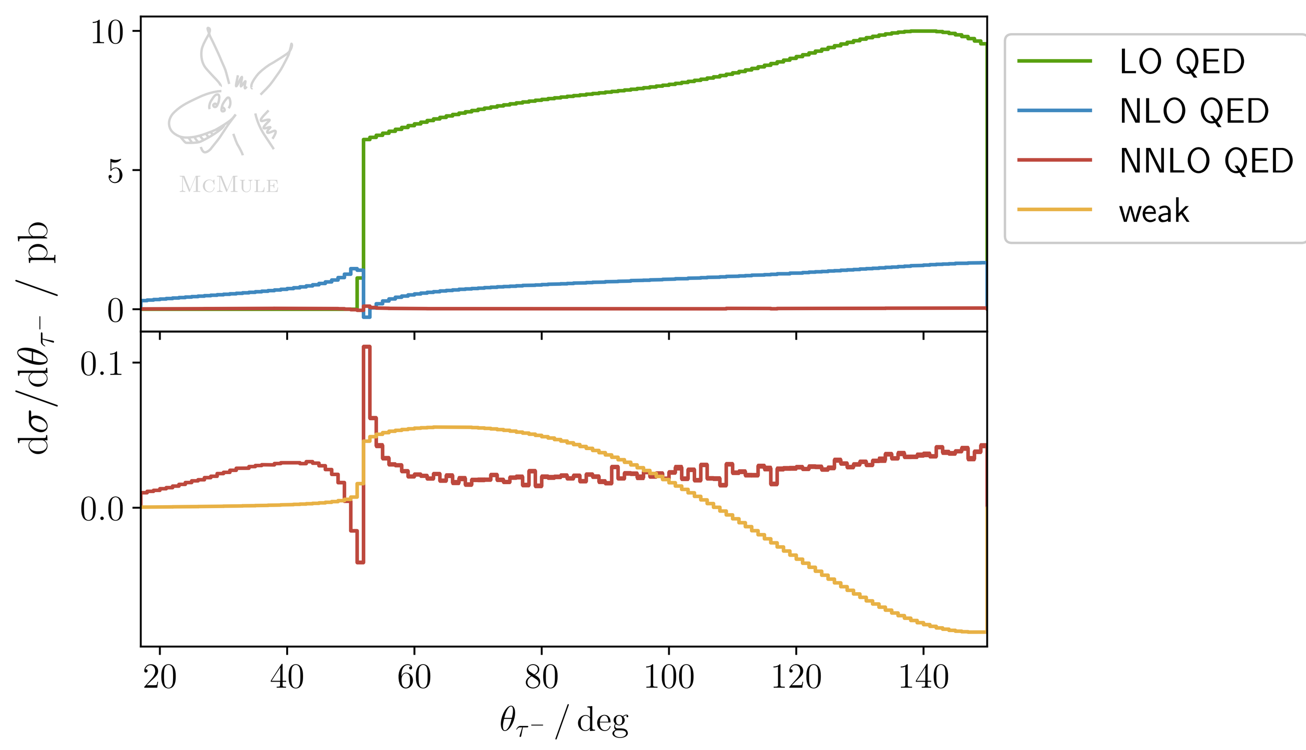
Numerical verification: dominant one-loop corrections to $ee \to \ell\ell\gamma$ against $\mathcal{M}_\text{exact}$ calculated with arbitrary precision in Mathematica



First Results

We present results for the process $e^+e^- \to \gamma/Z \to \tau^+\tau^-\{\gamma\gamma\}$ including dominant NNLO QED and NLO EW effects tailored to the Belle II detector with 70% longitudinal initial beam polarisation ($E^\text{(in)}_{e^+} = 4\,\text{GeV}$ and $E^\text{(in)}_{e^-} = 7\,\text{GeV}$).





Cross sections & forward-backward asym. (w/o cuts on θ_i & unpolarised)

	$\sigma^{(0)}_\text{QED}$	$\sigma^{(1)}_\text{QED}$	$\sigma^{(2)}_\text{QED}$	$\sigma^{(0+1)}_\text{weak}$
σ/pb	771.641(3)	139.28(1)	2.393(6)	0.14013(6)
δK^i/%		18.05(1)	0.4567(7)	0.015314(6)
$A_\text{FB}(\theta_{\tau^-})$	0	0.07573(8)	n.a.	72.94(3)