LEVERHULME TRUST

The RadioMonteCarLow2 Effort

Radiative Corrections and Monte Carlo Generators for low-energy e^+e^- into leptons and hadrons final states

Jérémy Paltrinieri on behalf of RMCL2

8th July 2025

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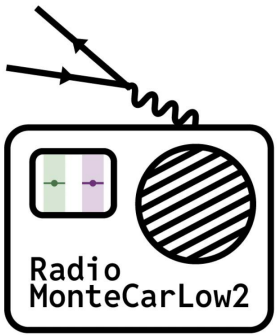

Introduction

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RadioMonteCarlow2 is a community effort aimed at improving the description of electron-positron collisions at low energy ($\sqrt{s} \leq$ few GeV). Phase I culminated in [SciPost 10.21468] and Phase II was launched in November 2024.

Goal

The goal is to provide state-of-the-art predictions for:

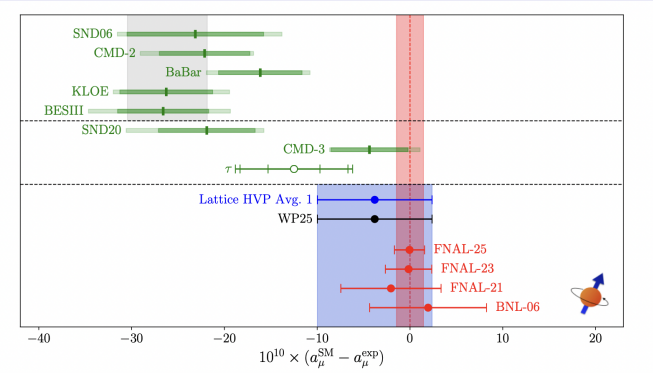
- $e^+e^- \to \mu^+\mu^-(\gamma)$
- $e^+e^- \to e^+e^-(\gamma)$
- $e^+e^- \to \pi^+\pi^-(\gamma)$

radiomontecarlow2.gitlab.io

PRECISIONSM: anotated database for $e^+e^- \to$ hadrons L. Cotrozzi talk.

Motivation

$(g-2)_\mu$



Tensions between e^+e^- experiments motivate the need for scrutiny over the Monte Carlo tools used for these data analyses: [2505.21476] (Updated White Paper).

S. Charity plenary talk.

Motivation

$(g-2)_\mu$

Tensions between e^+e^- experiments motivate the need for scrutiny over the Monte Carlo tools which are available for the relevant data analyses: updated White Paper [2505.21476].

Beyond $(g-2)_\mu$

- Testing the SM at low energy with high precision is important regardless of $(g-2)_\mu$ and predates the RMCL2 effort: [0912.0749].
- Applying tools developed by high-energy LHC community to low energy physics must be investigated.

The comparison: a foreword

Different codes provide different predictions: how important / relevant are they in different experimental setups?

Setup

- Study different contributions in "realistic" experimental setups.
- Acceptance cuts of the experiments are included, but *not* detector effects.
- No comparison with experimental data.

Disclaimer

This is a study on Monte Carlo tools and the effects modeled by them, we do not claim to provide experimentally relevant conclusions.

Despite this, our analysis allows us to have a lot of insights on the codes and on the physics they model.

The comparison: why so many codes?

The calculations

- Fixed-order calculations beyond NLO are extremely difficult, even for purely leptonic processes. Pions complicate the picture even more.
- Radiative effects beyond fixed-order are interesting and can be calculated (although in some approximation).
- We aim to understand what effects are sizeable, relevant and calculable for each experimental setup.

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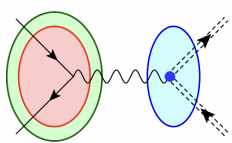
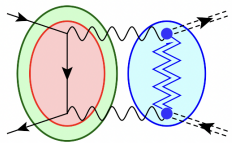
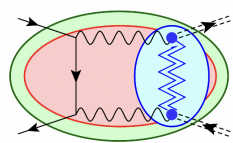
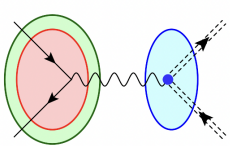
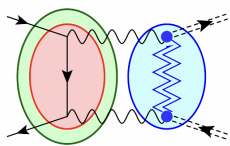




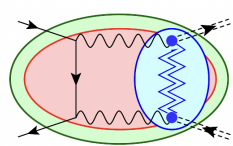
The comparison: why so many codes?

The calculations

- Red blob: fixed-order QED.
- Blue blob: Techniques beyond fixed-order to incorporate pions in a standard perturbative framework (they are models, however complicated they are).
- Green blob: approximations which capture leading contributions at all orders in the QED coupling.







The comparison: technicalities

Setup

- 5 experimental setups inspired by:
  - KLOE small/large angle-like (DAΦNE, Italy),
  - CMD-like (VEPP-2000, Russia),
  - BES-like (BEPCII, China),
  - B-like (BaBar, SLAC PEP-II, US and Belle-II, SuperKEKB, Japan).
- 6 channels to study both radiative return and scan modes:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$,
  - $e^+e^- \to \pi^+\pi^-(\gamma)$,
  - $e^+e^- \to e^+e^-(\gamma)$.
- 7 codes: AfkQed, BabaYaga@NLO, KKMC, MCGPJ, McMule, Phokhara (P. Petit Rosàs talk.), and Sherpa.

The comparison: terminology

Fixed-order vs all orders

- LO, NLO, NNLO: fixed order as exact expansion in α_{QED}.
- ISC, FSC: Initial, Final state Contributions.
- PS: Parton Shower, resummation of $\log m_e$ with angular effects.
- CS: Collinear Structures: resummation of $\log m_e$ without angular effects.
- YFS / CEEX: resummation of soft photon logs: [YFS] / [CEEX].
- VPC: Vacuum Polarisation Contribution.

Pion treatment

- sQED: Scalar QED.
- F $\times$ sQED: Pion Form Factor times Scalar QED.
- GVMD: Generalised Vector-Meson Dominance (allows for analytical loop calculations).

Phase I

The codes

Code \ Process	$\mu^+\mu^-$	$\mu^+\mu^-\gamma$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
AfkQed	–	LO+CS	–	LO+CS no FSC
BabaYaga@NLO	NLO+PS	LO+PS	NLO+PS F×sQED	LO+PS F×sQED
KKMC	CEEX	CEEX	–	–
MCGPJ	NLO+CS	LO+CS	LO+CS GVMD	LO+CS GVMD
McMule	NNLO	NLO	NNLO ISC	NLO ISC
Phokhara	–	NLO	–	NLO F×sQED
Sherpa	NLO+YFS	NLO	YFS sQED	YFS sQED

Results

CMD-like $e^+e^- \to \mu^+\mu^-$

For the CMD-like scenario, we consider the scan-mode process:

$$e^+e^- \to \mu^+\mu^-,$$

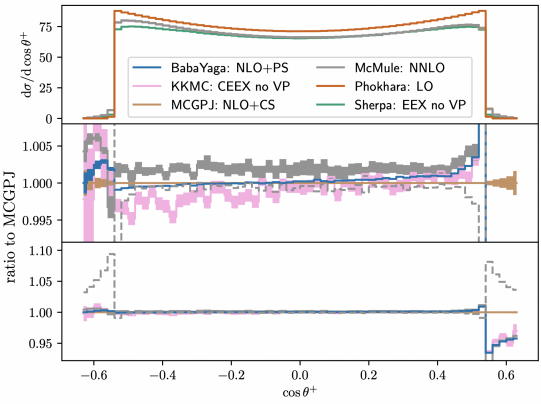
at a center-of-mass energy of $\sqrt{s} = 0.7$ GeV, and apply the kinematic selection cuts:

CMD-like cuts

$$1 \text{ rad} \leq \theta_{\text{avg}} \leq \pi - 1 \text{ rad},$$
$$p_\pm > 0.45 \cdot \frac{\sqrt{s}}{2},$$
$$|\delta\phi| \equiv ||\phi_+ - \phi_-| - \pi| < 0.15 \text{ rad},$$
$$\xi \equiv |\theta_+ + \theta_- - \pi| < 0.25 \text{ rad}.$$

CMD-like $e^+e^- \to \mu^+\mu^-$

CMD-like



- No VPC here for KKMC and SHERPA, but present for all other codes.
- BABAYAGA close to KKMC despite two resummation procedures.
- PHOKHARA: it is designed for radiative return, only LO for scan setups.
- Dashed MCMULE line: NLO.

KLOE-like $e^+e^- \to \pi^+\pi^-\gamma$ at small angle

The angle θ_γ associated with the 'untagged' photon momentum $\vec{p}_\gamma \equiv -(\vec{p}_+ + \vec{p}_-)$ is assumed to be small with respect to the beam direction. The energy is set to $\sqrt{s} = 1.02$ GeV.
The cuts we apply are:

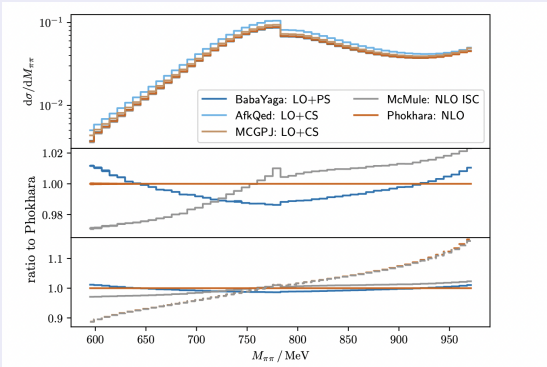
KLOE-SA-like cuts

$$\theta_\gamma \leq 15^\circ \quad \text{or} \quad \theta_\gamma > 165^\circ,$$
$$0.35 \text{ GeV}^2 \leq M_{XX}^2 \leq 0.95 \text{ GeV}^2,$$
$$50^\circ \leq \theta_\pm \leq 130^\circ,$$
$$|p_z^\pm| > 90 \text{ MeV} \quad \text{or} \quad p_\perp^\pm > 160 \text{ MeV},$$

where $p_z^\pm$ and $p_\perp^\pm$ denote the longitudinal and transverse components of the charged final-state momenta, respectively.

KLOE-like $e^+e^- \to \pi^+\pi^-\gamma$ at small angle

KLOE-SA-like



- AfkQed, MCGPJ: for illustration only (not suitable for selection cuts / radiative return).
- McMule: ISC only, no radiation off pions. At LO, the effect is small (see overlapping dashed lines), but is of order 2% at NLO.

B-like $e^+e^- \to \mu^+\mu^-\gamma$

This scenario is inspired by B factories. In order to be detected, we require for the charged particles and photons:

B-like cuts

$$0.65 \text{ rad} \leq \theta^{\pm} \leq 2.75 \text{ rad}, \qquad p^{\pm} > 1 \text{ GeV}$$
$$0.6 \text{ rad} \leq \theta^{\gamma} \leq 2.7 \text{ rad}, \qquad E_{\gamma} > 3 \text{ GeV}$$

Furthermore, denoting the most energetic photon passing the above cut by $\gamma^{(h)}$ and introducing

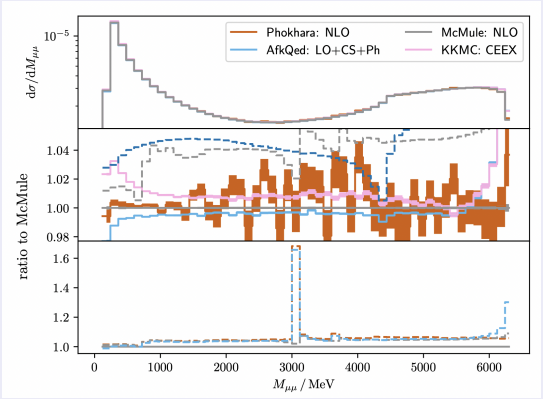
$$M^2_{XX\gamma} \equiv (p^+ + p^- + p_{\gamma^{(h)}})^2,$$

we require

$$\theta_{\gamma^{(h)},\gamma} \equiv \angle(\vec{p}_{\gamma^{(h)}}, \vec{p}_{\gamma}) < 0.3 \text{ rad}, \quad M_{XX\gamma} > 8 \text{ GeV}.$$

B-like $e^+e^- \to \mu^+\mu^-\gamma$

B-like



- PHOKHARA and MCMULE agree up to stat. instabilities.
- no VPC to allow for comparison with KKMC.
- middle panel: dashed blue line: LO, dashed gray line: MCMULE at NLO with VPC not resummed.
- lower panel: dashed: including VPC (note the effect of the VPC at 3 GeV).

Conclusions

Summary and outlook

State-of-the-art

- Current status for fixed-order: XX at NNLO and $XX\gamma$ at NLO.
- Multiphoton effects are important but largely dominated by one extra photon.
- Differences between the codes are understood and under control.
- Check out [SciPost 10.21468].

Future

- Better modeling of experimental setups.
- Better codes:
  - achieving higher precision: NNLO for $XX\gamma$ at the amplitude level and MC implementation.
  - achieving better accuracy in resummation procedures: YFS / CEEX / PS.
  - improving the efficiency of the Monte-Carlos, their usability, their documentation and reproducability: open-science mindset.

The people

List of people in Phase-I

Riccardo Aliberti, Paolo Beltrame, Ettore Budassi, Carlo M. Carloni Calame, Gilberto Colangelo, Lorenzo Cotrozzi, Achim Denig, Anna Driutti, Tim Engel, Lois Flower, Andrea Gurgone, Martin Hoferichter, Fedor Ignatov, Sophie Kollatzsch, Bastian Kubis, Andrzej Kupsc, Fabian Lange, Alberto Lusiani, Stefan E. Müller, Jérémy Paltrinieri, Pau Petit Rosàs, Fulvio Piccinini, Alan Price, Lorenzo Punzi, Marco Rocco, Olga Shekhovtsova, Andrzej Siódmok, Adrian Signer, Giovanni Stagnitto, Peter Stoffer, Thomas Teubner, William J. Torres Bobadilla, Francesco P. Ucci, Yannick Ulrich, Graziano Venanzoni.

Want to join?

✉ Andrzej Kupsc, Adrian Signer, Yannick Ulrich, or Graziano Venanzoni if you are interested in joining the RadioMonteCarLow2 effort, have feedback or want to discuss.

Thank you for your attention!

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