Overview on radiative corrections and Monte Carlo codes (an update on the RadioMonteCarlow2 activities)

F. Piccinini

INFN, Pavia and GGI

Nineth Plenary Workshop of the Muon $g-2$ Theory Initiative

Department of Physics, University of Connecticut, 3-7 August 2026

Relevance of radiative corrections and MC generators for a_μ

- $\sigma^0(e^+e^- \to X)$ enters the dispersive integral for a_μ

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$\Longrightarrow$ the precision of theoretical simulations enters directly as a systematics in a_μ

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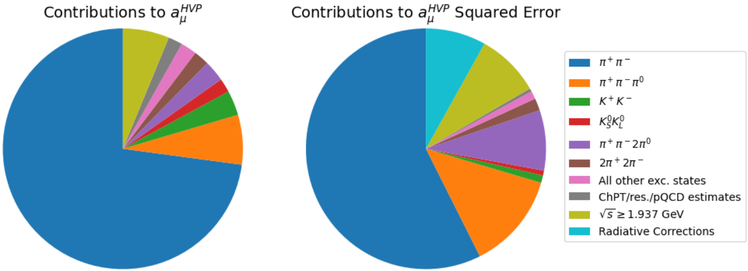
- in addition to $\pi^+\pi^-$ and $\pi^+\pi^-\gamma$ also other hadronic final states are relevant



A. Wright, FCCP2025, Capri, Italy

Classification of QED radiative corrections

- perturbative series for a $2 \to n$ cross section

$$\sigma \sim \alpha^n \sum_{m=0}^{\infty} \alpha^m \sum_{i=0}^{m} \sum_{j=0}^{m} c_m^{\{i,j\}} L^i \ell^j$$

$$L = \ln\left(\frac{Q^2}{m_e^2}\right) \quad \text{collinear log (for ISC)}$$

$$\ell = \ln\left(\frac{Q^2}{(\Delta E_\gamma)^2}\right) \quad \text{IR log}$$

- $\sqrt{Q^2}$ of the order of $1 - 10$ GeV $\Longrightarrow L \sim 10 - 15$
- ΔE_γ is an effective scale for maximum photon radiation induced by the particular event selection

$\Longrightarrow$ radiative corrections strongly dependent on the event selection and underlying physics

Order of magnitude estimates

Loosely and schematically

- referring only to collinear logs

LO	α^0		
NLO	αL	α	
NNLO	$\frac{1}{2}\alpha^2 L^2$	$\frac{1}{2}\alpha^2 L$	$\frac{1}{2}\alpha^2$
h.o.	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^n$	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^{n-1}$	$\dots$

Blue: Leading-Logs

Order of magnitude estimates

Loosely and schematically

- referring only to collinear logs

LO	90%		
NLO	10%	0.5%	
NNLO	0.5%	0.05%	0.01%
h.o.	0.01%	$\cdots$	$\cdots$

Tipically at flavour factories (on integrated Bhabha σ)

- possible additional enhancements from IR logs induced by
  - event selection
  - differential distribution under study

Different approaches to QED radiative corrections

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  - typically reliable for observables sufficiently inclusive on radiation

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Extremely important

$*$ **assess the technical precision** through tuned comparisons on differential observables between different codes with the same physics input

$*$ **estimate the residual theoretical uncertainties** through detailed comparisons between codes adopting different approaches/approximations and in collaboration with the experimental colleagues

First RadioMonteCarlow WG

Established in 2006 and coordinated by H. Czyz and G. Venanzoni

TOPIC	CONVENORS
Luminosity	G. Montagna, F. Nguyen
R Measurement	A. Arbuzov, G. Fedotovich
ISR	H. Czyz, G. Venanzoni
Tau	Z. Was, D. Epifanov
Hadronic VP, g-2 and Delta alpha	T. Teubner, S. Eidelman
Gamma-gamma physics	S. Ivashyn, D. Moricciani
FSR models	S. Gorini, A. Denig

- one/two meetings/year

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DOI 10.1140/epjc/s10052-010-1251-4

THE EUROPEAN PHYSICAL JOURNAL C

Review

Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[38], A. Arbuzov[9,e], G. Balossini[32,33], P. Beltrame[13], C. Bignamini[32,33], R. Bonciani[15], C.M. Carloni Calame[35], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[19,a,f,i], A. Denig[22], S. Eidelman[25,26,g], G.V. Fedotovich[25,26,e], A. Ferroglia[23], J. Gluza[19], A. Grzelińska[8], M. Gunia[19], A. Hafner[22], F. Ignatov[25], S. Jadach[8], F. Jegerlehner[3,19,41], A. Kalinowski[29], W. Kluge[17], A. Korchin[20], J.H. Kühn[18], E.A. Kuraev[9], P. Lukin[25], P. Mastrolia[14], G. Montagna[32,33,b,d], S.E. Müller[22,f], F. Nguyen[34,d], O. Nicrosini[33], D. Nomura[36,h], G. Pakhlova[24], G. Pancheri[11], M. Passera[28], A. Penin[10], F. Piccinini[33], W. Płaczek[7], T. Przedzinski[6], E. Remiddi[4,5], T. Riemann[41], G. Rodrigo[37], P. Roig[27], O. Shekhovtsova[11], C.P. Shen[16], A.L. Sibidanov[25], T. Teubner[21,h], L. Trentadue[30,31], G. Venanzoni[11,c,i], J.J. van der Bij[12], P. Wang[2], B.F.L. Ward[39], Z. Was[8,g], M. Worek[40,19], C.Z. Yuan[2]

RadioMonteCarLow2 WG

Coordinated by A. Kupsc, A. Signer, Y. Ulrich, G. Venanzoni

- 1^{st} Meeting, Zürich, 5-9 June 2023
- 1^{st} Satellite Meeting, Liverpool, 15 Nov. 2024
- 2^{nd} Meeting, Pisa, 7-9 May 2025
- 2^{nd} Satell. Meeting, Liverpool, 14 Nov. 2025
- 3^{rd} Meeting, Torino, 3-5 June 2026

The RadioMonteCarLow 2 Effort

https://radiomontecarlow2.gitlab.io/

- main output of phase I
  - a repository of benchmark results obtained through **tuned comparisons** for a set of standardized event selections and input parameters
  - a repository of the corresponding versions of the MC codes
  - in order to have a gauge of the impact of different physical effects/approximations, collect comparisons among the “best” predictions of the MC codes (**without any attempt to give estimates of theoretical uncertainties**)

SciPost

SciPost Phys. Comm. Rep. 9 (2025)

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Riccardo Aliberti[1], Paolo Beltrame[2], Ettore Budassi[3,4], Carlo M. Carloni Calame[4], Gilberto Colangelo[5], Lorenzo Cotrozzi[2], Achim Denig[1], Anna Driutti[6,7], Tim Engel[8], Lois Flower[2,9], Andrea Gurgone[3,6,7], Martin Hoferichter[5], Fedor Ignatov[2], Sophie Kollatzsch[10,11], Bastian Kubis[12], Andrzej Kupść[13,14⋆], Fabian Lange[10,11], Alberto Lusiani[7,15], Stefan E. Müller[16], Jérémy Paltrinieri[2], Pau Petit Rosàs[2], Fulvio Piccinini[4], Alan Price[17], Lorenzo Punzi[7,15], Marco Rocco[10,18], Olga Shekhovtsova[19,20], Andrzej Siódmok[17], Adrian Signer[10,11⋆], Giovanni Stagnitto[21], Peter Stoffer[10,11], Thomas Teubner[2], William J. Torres Bobadilla[2], Francesco P. Ucci[3,4], Yannick Ulrich[2,5⋆] and Graziano Venanzoni[2,7⋆]
(RadioMonteCarLow 2 working group)

Processes, reference “simplified” event selections and MC tools

- Processes
  - $e^+e^- \to \pi^+\pi^-(\gamma)$
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to e^+e^-(\gamma)$
  - $e^+e^- \to \pi^+\pi^-\gamma(\gamma)$
  - $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$
  - $e^+e^- \to e^+e^-\gamma(\gamma)$
- Reference event selections
  - energy scan
    - CMD-like
  - radiative return
    - KLOE-LA (tagged)
    - KLOE-SA (untagged)
    - BES III
    - B factories
- Monte Carlo codes
  - AFKQED
  - BABAYAGA@NLO
  - KKMC
  - MCGPJ
  - McMULE
  - PHOKHARA
  - SHERPA

Luminosity

Not discussed within RMCL2 up to now because it is not an issue at the 0.1% level

by comparing NNLO (McMule) with NLOPS (BabaYaga@NLO) photonic corrections

$$e^+e^- \to e^+e^-$$

$$\sqrt{s} = 1020\ \text{MeV}$$
$$20^\circ < \vartheta_\pm < 160^\circ$$
$$E_e > 408\ \text{MeV}$$
$$\zeta < 10^\circ$$

	σ/μb McMule	σ/μb BABAYAGA	$\delta K^{(i)}/\%$ McMule
$\sigma^{(0)}$	6.8557	6.8557	
$\sigma^{(1)}$	-0.7957	-0.7957	-11.606
$\sigma^{(2)}$	0.0312	0.0267	0.515
σ_2	6.0912	6.0868	

Banerjee, Engel, Schalch, Signer, Ulrich, arXiv:2106.07469

$$e^+e^- \to \gamma\gamma$$

$$45^\circ < \vartheta_\gamma < 135^\circ$$
$$E_\gamma > 0.3\sqrt{s}$$
$$\zeta < 10^\circ$$

$\sqrt{s}$	1 GeV		3 GeV		10 GeV	
	McMule [nb]	[12] [nb]	McMule [nb]	[12] [nb]	McMule [nb]	[12] [nb]
σ_0	137.531	137.53	15.2812	15.281	1.37531	1.3753
σ_1	129.444	129.45	14.2099	14.211	1.26185	1.2620
σ_2	129.760		14.2570		1.26738	
σ_{exp}		129.77		14.263		1.2685
$\sigma^{(2,\gamma)}$	0.383		0.0598		0.00738	
$\sigma_{\text{exp}} - \sigma_1$		0.32		0.053		0.0065
$\sigma^{(2,\text{VP}e)}$	-0.069		-0.0128		-0.00186	
$\sigma^{(2,\text{LbL}e)}$	-0.0014		-0.00016		-0.000014	
$\sigma^{(2,\text{rLbL}e)}$	0.0030		0.00033		0.000030	
$\sigma^{(2,\text{VP}\mu\tau)}$	-0.000077		-0.00018		-0.000080	
$\sigma^{(2,\text{VPh})}$	0.000090		-0.00010		-0.000097	

T. Engel, M. Rocco, A. Signer, Y. Ulrich, arXiv:2512.22929

Some recent activities/focus:

- **improvement of radiative corrections for QED $2 \to 3$ radiative processes in different directions**

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E. Budassi et al., JHEP 05 (2026) 221

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    E. Budassi et al., JHEP 05 (2026) 221

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  - towards NNLO accuracy in fixed order calculations

    T. Dave, J. Paltrinieri, P.P.Rosàs, W.J. Torres Bobadilla, arXiv:2604.16251; M. Pozzoli and W.J. Torres Bobadilla, arXiv:2607.03343

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- **improvements on the simulation/theoretical description of the pion final states**

  up to know the simulations for radiative processes with hadronic final states have been based on the NLO calculation of PHOKHARA

  C.M. Carloni Calame et al., Phys. Lett. B879 (2026) 140666; arXiv:2607.24642; P. Petit Rosàs, O. Shekhovtsova and W.J. Torres Bobadilla, arXiv:2603.13171; Y. Fang et al., arXiv:2512.10709

  see talks by M. Ghilardi, S. Kollatzsch and W.J. Torre Bobabilla

$\pi^+\pi^-$ final states in Monte Carlo simulations

The typical model for calculating matrix elements $e^+e^- \to \pi^+\pi^- + n\gamma \, (n = 0, 1, ...)$ is sQED, with pion form factors at the $\gamma\pi^+\pi^-$ vertices, in various levels of approximation

the simplest approach:

- **F$\times$sQED**: gauge-invariant subamplitudes are multiplied by $F(q^2)$ where $q^2 = s$ or $q^2 = m^2_{\pi\pi}$

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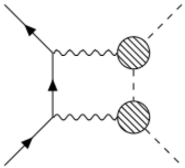
  cons

  - ambiguities in virtual corrections involving pions in the loop diagrams



Inserting pion momenta in loop integrals

- **GVMD**: the form factor approximated by a sum of Breit-Wigner functions

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- the form factor does not respect the necessary requirements (the imaginary part beloww threshold different from zero)

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- **FsQED**: the form factor is represented dispersively:

$$\frac{F_\pi(q^2)}{q^2} = \frac{1}{q^2 - \lambda^2} - \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'}{s'} \frac{\mathrm{Im}F(s')}{s'(q^2 - s')}$$

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cons

- the loop integration has to be organized partially numerically

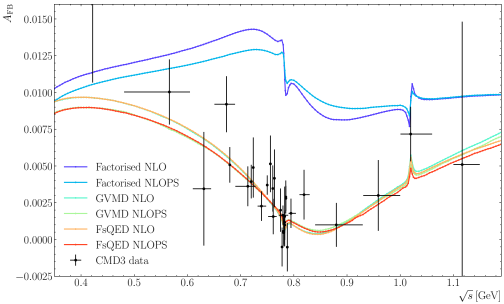
pros

- for the process $e^+e^- \to \pi^+\pi^-$ it has been shown that FsQED is equivalent to the pion pole contribution to a model-independent dispersive

G. Colangelo, M. Hoferichter, M. Procura and P. Stoffer, JHEP 09 (2015) 074

di-pion final state: charge asymmetry

$$A_{\mathrm{FB}}\left(\sqrt{s}\right) = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



E. Budassi et al., JHEP05 (2025) 196 [arXiv:2409.03469]

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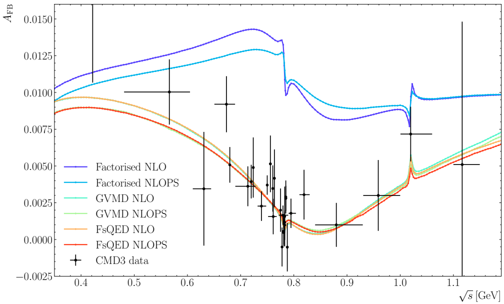

E. Budassi et al., JHEP05 (2025) 196 [arXiv:2409.03469]

- **can we adopt the same treatment of the structure dependent corrections for the radiative process $e^+e^- \to \pi^+\pi^-\gamma$?** C.M. Carloni Calame et al., arXiv:2607.24642; arXiv:2603.28621; P. Petit Rosàs O. Shekhovtsova, W.J. Torres Bobadilla, arXiv:2603.13171

see talks by M. Ghilardi and M. Hoferichter

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- continuous efforts (and progress) aimed at reaching NNLO perturbative precision in the radiative $2 \to 3$ processes
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- very recent progress in the treatment of pion structure dependent radiative corrections
- with the above building blocks, more reliable estimates of theoretical uncertainties become viable
- possible future evolution within RMCL2
  - additional hadronic final states w.r.t. pions
  - More realistic event selections
  - additional background procceses (e.g. additional e^+e^- pairs)