

# McMULE & RadioMonteCarLow 2

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a community effort for theory improvement of  $e^+e^- \rightarrow \text{stuff}$  at  $\sqrt{s} \lesssim \text{few GeV}$

- started in spring 2022, largely independently of  $(g-2)_\mu$
- goal: state-of-the-art predictions (ie. NNLO+ for leptonic processes) for

$$e^+e^- \rightarrow \mu^+\mu^- + \gamma\{+\gamma\}$$

$$e^+e^- \rightarrow e^+e^- + \gamma\{+\gamma\}$$

$$e^+e^- \rightarrow \pi^+\pi^- + \gamma\{+\gamma\}$$

- other processes to remember  
 $e^+e^- \rightarrow \gamma\gamma, 3\pi, 4\pi, \dots$



[radiomontecarlow2.gitlab.io](https://radiomontecarlow2.gitlab.io)

⇒ following successful MUonE Theory Initiative

... not (just) because of  $(g - 2)_\mu$

- inspired by [\[0912.0749\]](#)

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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

- improve SM precision tests at low energy
- ... but of course also provide input for  $(g - 2)$
- a lot has happened since 2009,  $2 \rightarrow 3$  NNLO & NLL is standard @ LHC
- apply this to low-energy physics

fixed-order NNLO QED framework Monte Carlo for MUons and other LEptons

- provided: matrix elements by us or others
- output: **physical cross section** for any physical observable
- McMULE: phase space generation, subtraction, stabilisation, integration, event generation, etc.
- all leptonic  $2 \rightarrow 2$  processes in QED at NNLO (+ a few others)
- stable public version is an integrator
- generator on development branch

Get the code here: <https://mule-tools.gitlab.io>

Read the docs here: <https://mcmule.readthedocs.io>



McMULE

process	experiment	physics motivation	order
$e\mu \rightarrow e\mu$	MUonE	HVP to $(g-2)_\mu$	NNLO+
$lp \rightarrow lp$	P2, Muse, Prad, QWeak, ...	proton radius and weak charge	NNLO
$eN \rightarrow eN$	PRad, ULQ2	background	+
$e^-e^- \rightarrow e^-e^-$	Prad 2	normalisation	NNLO
	MOLLER, ...	$\sin^2 \theta_W$ at low $Q^2$	
$e^+e^- \rightarrow e^+e^-$	any $e^+e^-$ collider	luminosity measurement	NNLO
$ee \rightarrow ll$	VEPP, BES, Daphne, ...	$R$ -ratio	NNLO±
	Belle	$\tau$ properties	
$ee \rightarrow \gamma\gamma$	Daphne	dark searches	NNLO-
	any $e^+e^-$ collider	luminosity measurement	
$e\nu \rightarrow e\nu$	DUNE	flux & $\sin^2 \theta_W$	NNLO-
$\mu \rightarrow \nu\bar{\nu}e$	MEG	ALP searches	NNLO+
	DUNE	beam-line profiling	
$\mu \rightarrow \nu\bar{\nu}e\gamma$	MEG, Mu3e, Pioneer	background	NLO
$\mu \rightarrow \nu\bar{\nu}eee$	MEG, Mu3e	background	NLO
$ee \rightarrow \pi\pi$	VEPP, BES, Daphne, ...	$R$ -ratio	+
$ee \rightarrow ll\gamma$	VEPP, BES, Daphne, ...	$R$ -ratio	+

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$e\mu \rightarrow e\mu$	MUonE	HVP to $(g-2)_\mu$	NNLO+
$lp \rightarrow lp$	P2, Muse, Prad. QWeak. ...	proton radius and weak charge	NNLO
$eN \rightarrow eN$	PRad, ULQ2		+
$e^-e^- \rightarrow e^-e^-$	Prad 2	on	NNLO
$e^+e^- \rightarrow e^+e^-$	MOLLER, ...	low $Q^2$	NNLO
$ee \rightarrow ll$	any $e^+e^-$ col	measurement	NNLO±
$ee \rightarrow \gamma\gamma$	VEPP, BES, Belle	s	NNLO-
$ee \rightarrow \gamma\gamma$	Daphne	es	NNLO-
$e\nu \rightarrow e\nu$	any $e^+e^-$ col	measurement	NNLO-
$\mu \rightarrow \nu\bar{\nu}e$	DUNE	$\theta_W$	NNLO-
$\mu \rightarrow \nu\bar{\nu}e\gamma$	MEG	goal: world domination	NNLO+
$\mu \rightarrow \nu\bar{\nu}eee$	DUNE	filing	
$\mu \rightarrow \nu\bar{\nu}e\gamma$	MEG, Mu3e, Pioneer	background	NLO
$\mu \rightarrow \nu\bar{\nu}eee$	MEG, Mu3e	background	NLO
$ee \rightarrow \pi\pi$	VEPP, BES, Daphne, ...	R-ratio	+
$ee \rightarrow ll\gamma$	VEPP, BES, Daphne, ...	R-ratio	+



on release



amplitude: OpenLoops, LHC, William, ...



massification ( $m_e^2 \ll s$ ), NTS stabilisation,  
FKS<sup>l</sup> subtraction



Monte Carlo integration

work in progress



event generation



shower resummation



electro-weak physics

## customer support



manual: <https://mcmule.readthedocs.io>



library of published results



happy to meet & talk

## examples



MUonE



MUSE

mule not found

RadioMonteCarLow 2 (esp. **KLOE**)



	MC integrator	MC generator
what does it do?	calculates observable	generates events
measurement function	as part of the generation	in post
	assumed to be very fast	can be slow
weights are	just numbers	probabilities
weights vary	over many orders of magnitude	very little
efficient for	theory	experiment



f.l.t.r.: S.Kollatzsch (Zurich & PSI), A.Signer (Zurich & PSI), V.Sharkovska (Zurich & PSI), S.Gündogdu (Zurich & PSI), D. Moreno (PSI), A.Coutinho (IFIC), Y.Ulrich (Liverpool), D. Radic (Zurich & PSI), L.Naterop (Zurich & PSI), M.Rocco (Turin)  
not shown: F.Hagelstein (Mainz), N.Schalch (Oxford), T.Engel (Freiburg), A.Gurgone (Pavia), P.Banerjee (Cosenza)



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