7^{th} $g-2$ Plenary Workshop

The Radio MonteCarLow 2 activities

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

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

$$e^+e^- \to \mu^+\mu^- + \gamma\{+\gamma\}$$
$$e^+e^- \to e^+e^- + \gamma\{+\gamma\}$$
$$e^+e^- \to \pi^+\pi^- + \gamma\{+\gamma\}$$

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

$\Rightarrow$ following successful MUonE Theory Initiative

radiomontecarlow2.gitlab.io

... 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, $2 \to 3$ NNLO & NLL is standard @ LHC
- apply this to low-energy physics

... probably the reason you're interested

but first, a disclaimer

- this is a theory exercise, any experimentally relevant conclusions you may see are purely accidental
- we want to study the importance of different contributions in realistic-ish environments
- we use different MC codes as proxies for different contributions
- for some codes, the authors are not part of the collaboration → we did our best...
- we use realistic acceptance cuts but no additional selection & detector effects
- we do not compare with experimental data
- please do not use our plots outside this very narrowly defined context!
- for more results, context, background information, etc. see `radiomontecarlow2.gitlab.io`

in Phase I

- 5 scenarios derived from community feedback:
  CMD-like, KLOE-like large angle, KLOE-like small angle, BES-like, B-like
- 3+3 channels: $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \pi^+\pi^-$
  and $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to \pi^+\pi^-\gamma$
- 7 MC codes: AfkQed, BabaYaga, KKMC, MCGPJ, McMule, Phokhara, Sherpa
- exact version and runcards will be published soon
  (more codes & scenarios welcome in Phase II)
- here: will show a very limited subset of plots
- more annotated plots online already now, more to come
  `radiomontecarlow2.gitlab.io/plots`
- agreed on HVP (NSK v2.9) and pion form factor, details online soon

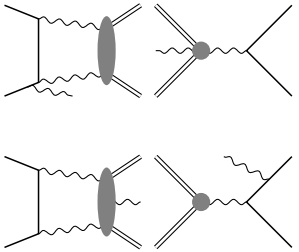
- LO, NLO, NNLO: fixed-order expansion in α
- CS: collinear structures to resum $\log m_e$ in multiphoton emission
  (may not incl. angular effects)
- PS: parton shower to resum $\log m_e$ in multiphoton emission
  (incl. angular effects)
- YFS: Monte Carlo generation of soft photons
- CEEX: coherent Monte Carlo generation of soft photons
- ISC (FSC): initial (final) state correction
  used instead of ISR and FSR because that's not really well-defined

terminology

- sQED: no form factors
- F×sQED: multiply sQED amplitude with form factor to ensure IR finiteness w/ virtual
- FsQED: include form factor in loops from pion pole (currently only in one code)
- GVMD: models pion form factor through Breit-Wigner propagators for analytic loops

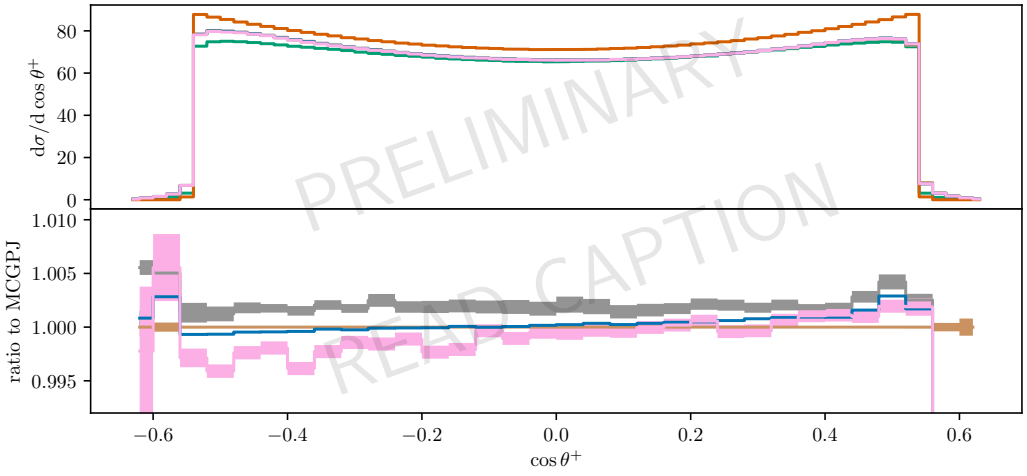
warnings

- these diagrams are C-even → contribute to σ
- not accounted for beyond F×sQED in any MC
- potentially important due to resonance enhancement (asymmetry in CMD & see below)
- future: calculate pion pole contribution in FsQED



code		$ee \to \mu\mu$	$ee \to \pi\pi$
AfkQed	$+\gamma$	LO+CS	no FSC, only YFS
BabaYaga@NLO		NLO+PS	NLO+PS, F×sQED*
	$+\gamma$	LO+PS	LO+PS, F×sQED
KKMC		CEEX	CEEX
	$+\gamma$	CEEX	CEEX
MCGPJ		NLO+CS	NLO+CS GVMD*
	$+\gamma$	LO+CS	LO+CS GVMD
McMule		NNLO	NNLO ISC, no FSC
	$+\gamma$	NLO	NLO ISC, no FSC
Phokhara	$+\gamma$	NLO	NLO, F×sQED
Sherpa		NLO+YFS	YFS, sQED
	$+\gamma$	NLO	YFS, sQED

* FsQED & GVMD available but not used for this

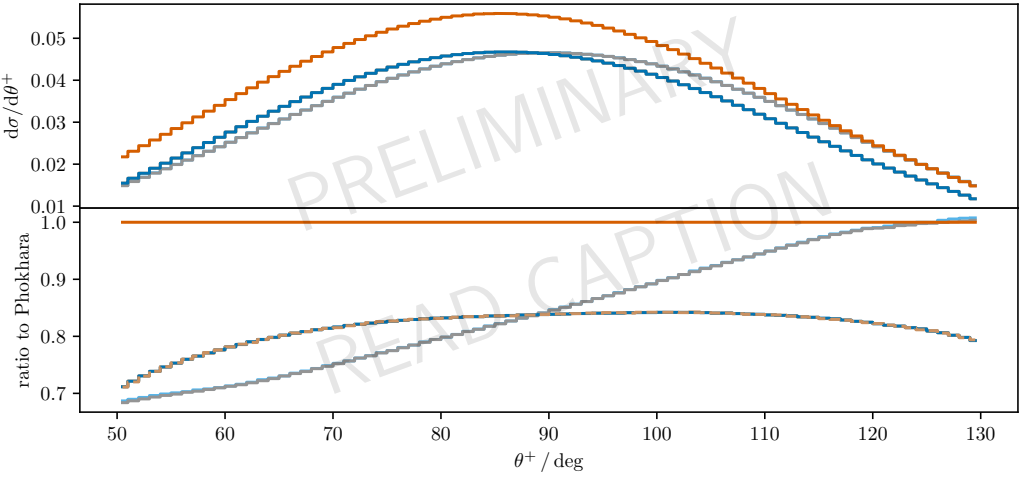


(for more results and commentary, see `radiomontecarlow2.gitlab.io/plots/CMD/mm`)

- all codes except KKMC: VP active but small so comparison still possible
- McMule: exact NNLO, BabaYaga@NLO: NLO+PS (w/ angl. distr.), MCGPJ: NLO+PS (w/o angl. distr.), KKMC: CEEX

$\Rightarrow$ BabaYaga@NLO probably slightly more reliable

- BabaYaga@NLO $\approx$ KKMC despite very different methods used
- Phokhara adapted for scan $\rightarrow$ only LO
- from $M_{\mu\mu}$ (see online) & tail: shower is dominated by one extra radiation

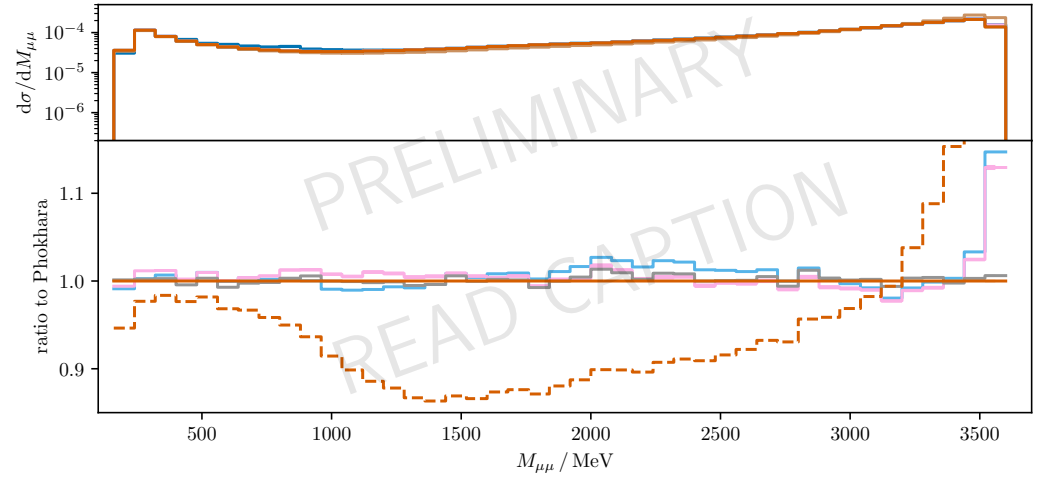


(for more results and commentary, see `radiomontecarlow2.gitlab.io/plots/KLOE-LA/pp`)

- important cut: $50^\circ < \theta_\gamma < 130^\circ$
- Phokhara: full NLO with F×sQED
- AfkQed = McMule: only ISC (Photos is switched off)

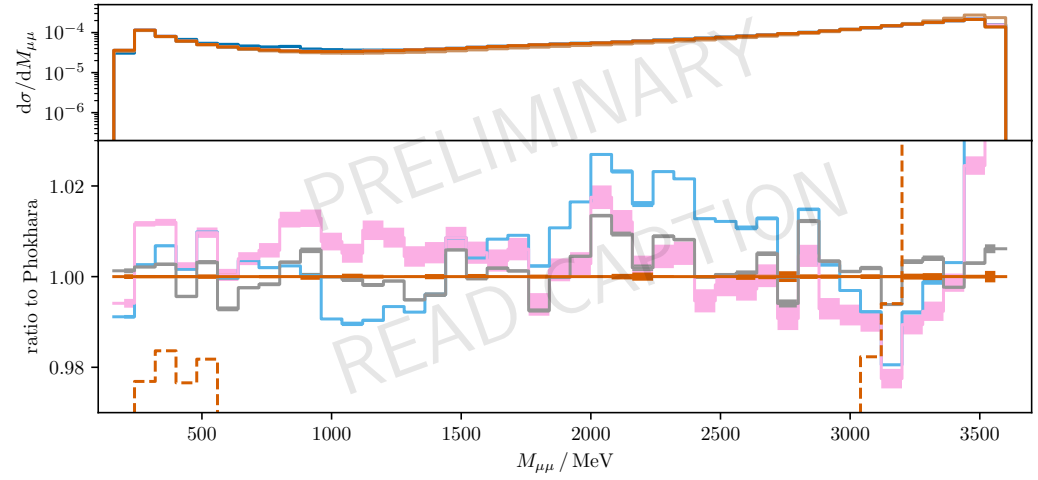
$\Rightarrow$ FSC are very large because photon is at large angle

- BabaYaga: only LO provided, agrees with MCGPJ's LO
- all errors are statistical as reported by the MC



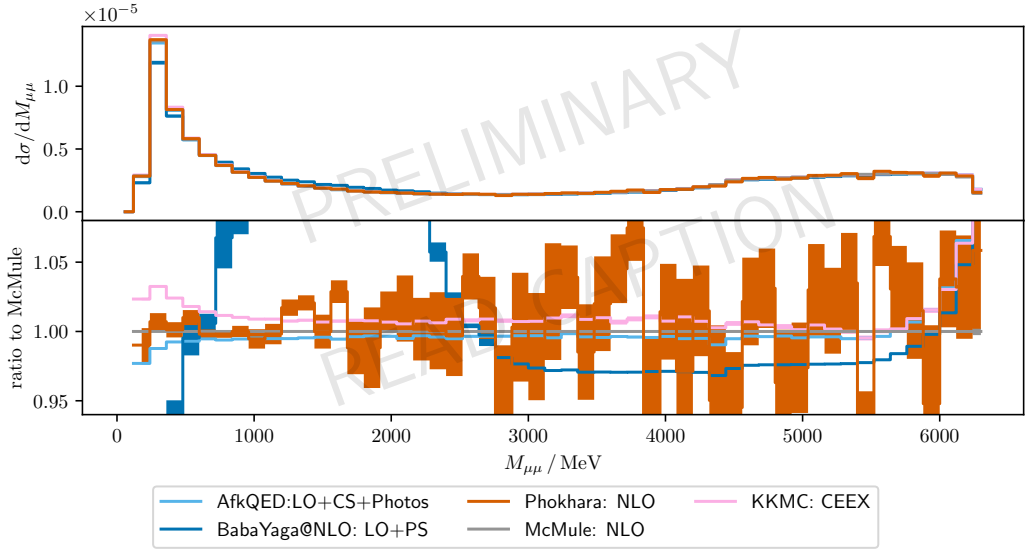
(for more results and commentary, see radiomontecarlow2.gitlab.io/plots/BES/mm)

BES-like $ee \to \mu\mu\gamma$ w/ photon at large angle in detector, no VP

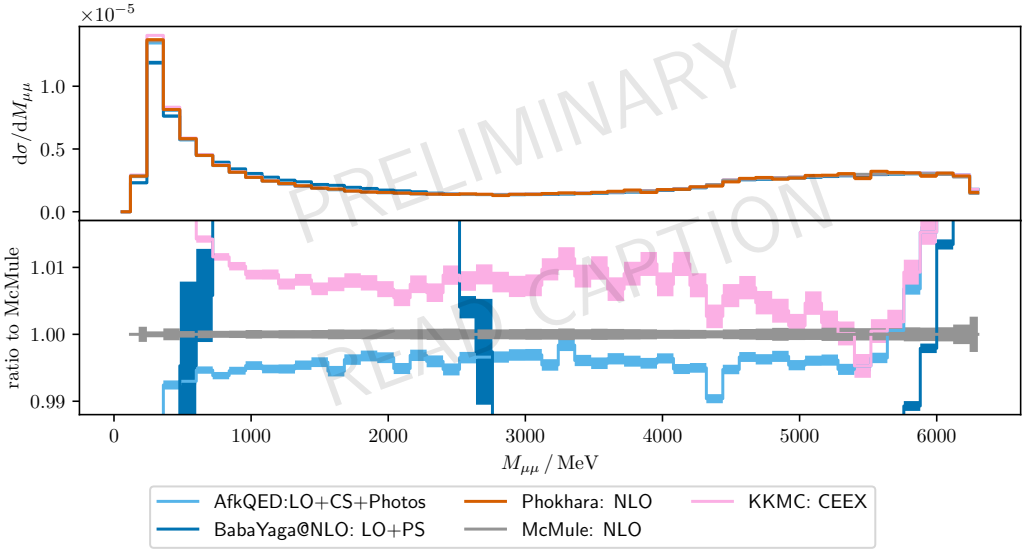


(for more results and commentary, see radiomontecarlow2.gitlab.io/plots/BES/mm)

- no VP included $\Rightarrow$ comparison is somewhat unphysical but avoids some issues
- two full NLO calculations: McMule = Phokhara within bin-to-bin variation
- AfkQED & MCGPJ: LO and (different) collinear structures
- AfkQED: FSC with Photos
- BabaYaga@NLO: only in upper panel, not tailored for radiative processes and improvements of numerics are WIP
- KKMC: CEEX
- all errors are statistical as reported by the MC



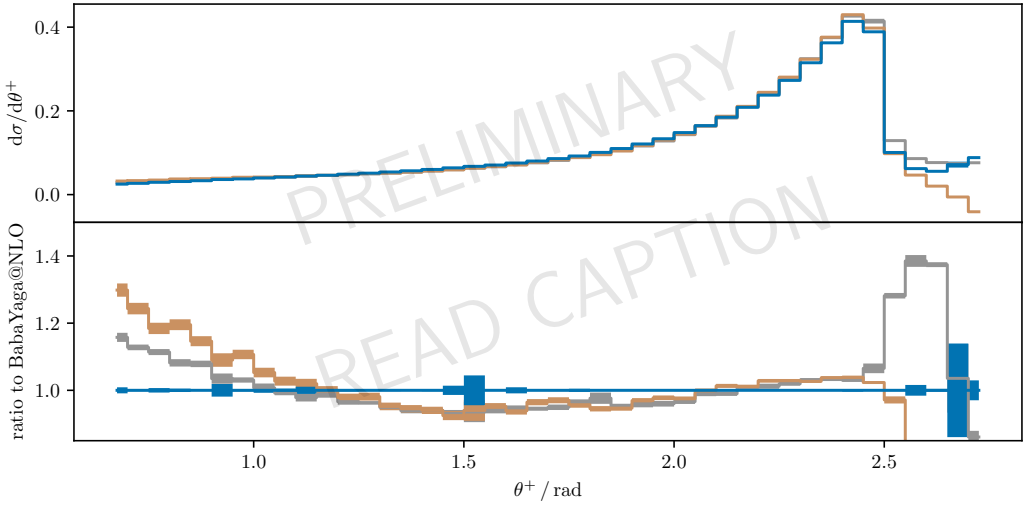
(for more results and commentary, see radiomontecarlow2.gitlab.io/plots/B/mm)



(for more results and commentary, see radiomontecarlow2.gitlab.io/plots/B/mm)

- no VP included to compare to KKMC
- NLO codes Phokhara = McMule up to numerical noise in Phokhara (problem identified, fix online soon)
- BabaYaga@NLO: LS+PS w. angular distribution but not designed for radiative processes $\rightarrow$ breakdown at low $M_{\mu\mu}$
- AfkQed: LO+CS & Photos
- all errors are statistical as reported by the MC

B-like, $ee \to ee\gamma$ w/ photon at large angle in detector



(for more results and commentary, see `radiomontecarlow2.gitlab.io/plots/B/ee`)

- NLO: McMule
- LO+PS: BabaYaga@NLO, MCGPJ (both w/ ang. distr.)
- BabaYaga@NLO & MCGPJ not designed for radiative process!
- good agreement in bulk but problems towards ends
- could be improved with tailored sampling at end points
- all errors are statistical as reported by the MC

- no code has better fixed-order than NNLO for $ee \to XX$ and NLO for $ee \to XX\gamma$
- multiphoton effects are important but dominated by one extra radiation
- FsQED available in some codes but not used here
- it is not clear what NNLO would mean for $ee \to \pi\pi$
- FSC can be very large and then needs to be modelled carefully

$\Rightarrow$ error from F$\times$sQED is not obviously small

- we can derive physics insight from our comparison
- (partially) new codes: BabaYaga@NLO (for pions), McMule, Sherpa

better comparisons

- add more codes & make use of all features
- improve cuts & better mock analysis
- compare with data

better codes

- FsQED treatment for $ee \to \pi\pi$ by more codes
- FsQED treatment for evil diagrams in $ee \to \pi\pi\gamma$
- investigations beyond FsQED
- NNLO / NLO+PS for $ee \to \mu\mu\gamma$, NNLO ISC for $ee \to \pi\pi\gamma$
- new codes: (try to) reach feature parity with exisiting codes

Phase II

Phase II will be launched in November as a satellite meeting to the 3rd Liverpool Workshop on Muon Precision Physics (`https://indico.ph.liv.ac.uk/event/1666`)

Please contact Andrzej Kupsc, Adrian Signer, Yannick Ulrich, and Graziano Venanzoni, if you are interested in joining the RadioMonteCarLow2 effort or have questions or feedback.

Members during 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, Guido Montagna, Stefan E. Müller, Oreste Nicrosini, Jérémy Paltrinieri, Pau Petit Rosàs, Fulvio Piccinini, Alan Price, Lorenzo Punzi, Marco Rocco, Kay Schönwald, Olga Shekhovtsova, Andrzej Siódmok, Adrian Signer, Giovanni Stagnitto, Peter Stoffer, Thomas Teubner, William J. Torres Bobadilla, Francesco P. Ucci, Yannick Ulrich, Graziano Venanzoni