MITP Topical Workshop

RadioMonteCarLow 2

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

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- theoretical description for $e^+ e^- \to$ hadrons at low energies $\sqrt{s} \lesssim 1 - 2\,\mathrm{GeV}$
  making also use of radiative (return) processes (some call them ISR processes)

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

- more processes
  $$e^+ e^- \to \gamma\,\gamma$$
  $$e^+ e^- \to \pi^+ \pi^- \pi^0$$
  $$e^+ e^- \to \pi^+ \pi^- \pi^0 \pi^0$$
  $$e^+ e^- \to \pi^+ \pi^- \pi^+ \pi^-$$

- there are additional processes and $(e^+ e^-)$ in final state

- Strong2020: Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in $e^+ e^-$ collisions

  WorkStop/ThinkStart in Zurich https://indico.psi.ch/event/13707/

- inspired by [0912.0749]

Eur. Phys. J. C (2010) 66: 585–686
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

- consolidate and implement the progress since 2010

  produce report and repository of MC codes and comparisons by August 2024

Team: P. Beltrame, E. Budassi, C. Carloni Calame, G. Colangelo, L. Cotrozzi, A. Driutti, T. Engel, L. Flower, A. Gurgone, M. Hoferichter, F. Ignatov, S. Kollatzsch, B. Kubis, A. Kupsc, F. Lange, A. Lusiani, G. Montagna, S. Müller, O. Nicrosini, P. Petit Rosàs, J. Paltrinieri, F. Piccinini, A. Price, L. Punzi, M. Rocco, K. Schönwald, O. Shekhovtsova, A. Signer, A. Siódmok, G. Stagnitto, P. Stoffer, T. Teubner, W. Torres Bobadilla, F. Ucci, Y. Ulrich, G. Venanzoni

WP1:	QED for leptons at NNLO
WP2:	Form factor contributions at N^3LO
WP3:	Processes with hadrons
WP4:	Parton showers
WP5:	Experimental input

AFKQED	BHWIDE
Babayaga@NLO	MadGraph
KKMC	Photos
MCGPJ	...
McMule	
Phokhara	
Sherpa	

why

- are you still using your phone of 2010 ?

  so why then should you use Monte Carlo codes of 2010 !

- preserve, further develop, and make accessible some well established codes for low-energy $e^+ e^-$
- get new (preferably young) people to join with new ideas/approaches
- cross fertilisation from huge effort made for LHC
- open science approach: what is in which generator, where can I get it

  $\Rightarrow$ a public repository of all codes and all results
- a community effort, hopefully ongoing for many years to come

it worked marvellously for the MUonE theory initiative

Eur. Phys. J. C (2020) 80:591
https://doi.org/10.1140/epjc/s10052-020-8138-9

THE EUROPEAN PHYSICAL JOURNAL C

Review

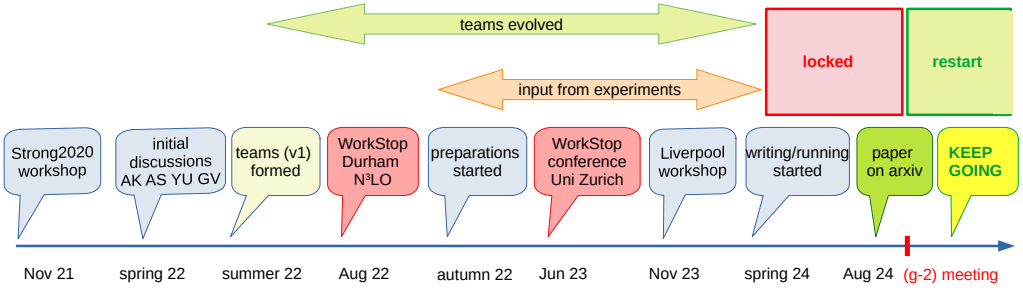
Theory for muon-electron scattering @ 10 ppm

A report of the MUonE theory initiative

P. Banerjee[1], C. M. Carloni Calame[2], M. Chiesa[3], S. Di Vita[4], T. Engel[1,5], M. Fael[6], S. Laporta[7,8], P. Mastrolia[7,8], G. Montagna[2,9], O. Nicrosini[2], G. Ossola[10], M. Passera[8], F. Piccinini[2], A. Primo[5], J. Ronca[11], A. Signer[1,5,a], W. J. Torres Bobadilla[11], L. Trentadue[12,13], Y. Ulrich[1,5], G. Venanzoni[14]

[2004.13663] was just the start of theory for MUonE !

we started just as a bunch of people, now we're in a locked phase (until Aug 2024)



09-13 September 2024 workshop of $(g-2)$ Theory Initiative $\Rightarrow$ fix point for our paper but not the end of our activities $\Rightarrow$ restart after this, anyone can join again

WP1: QED for leptons at NNLO

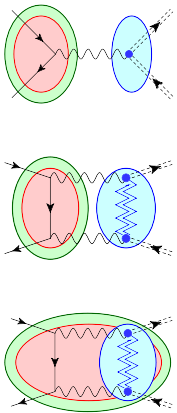
WP2: Form factor contributions at N^3LO

WP3: Processes with hadrons

WP4: Parton showers / YFS

WP5: Experimental input

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



Contents

Sec 2: experimental input

summary, reference

Sec 3: computational set up

set up 'language' to define
various contributions

Sec 4: precise description of MC codes

what is included and what not

Sec 5: MC comparison for scenarios

NOT an analysis, a realistic estimate
of importance of various contributions

?? Sec 6 ?? luminosity processes

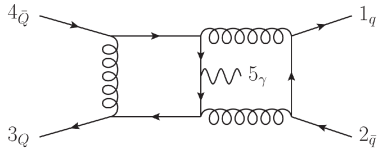
outline

remainder of this talk / discussion

- everything I know (i.e. nothing) about Section 2, experimental input ⇒ Achim's talk
- some remarks about Section 3, computational set up
  - pure QED contributions McMule / Mesmer / Matteo talks
  - flag Section 3.4, pions in the final state ⇒ Peter's talk
- flag Section 4, description of codes ⇒ Thursday's talks
- flag Section 5, Monte Carlo comparisons ⇒ Yannick's talk
- nothing about Section 6, processes for luminosity, ⇒ likely to disappear
- timeline for completion of phase I by August 2024

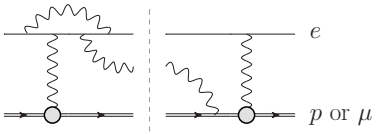
QCD@LHC

- e.g. [2304.06682] NNLO cross section for $p\,p \to j\,j\,\gamma$ (i.e. $2 \to 3$ massless)

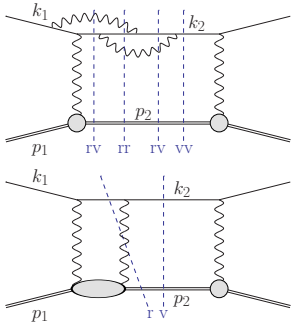


- automated one-loop codes, e.g. OpenLoops
- high-energy event generators e.g. Sherpa
- match NNLO to shower e.g. MiNNLO$_{PS}$

and, of course, MUonE



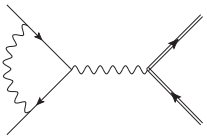
lepton-proton
(similar situation / issues)



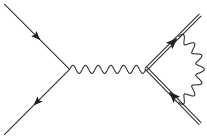
pure QED

example: $e^+\,e^- \to \mu^+\,\mu^-$ at NLO, split into gauge invariant parts

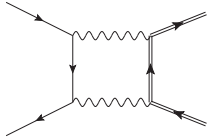
for computational and conceptual reasons



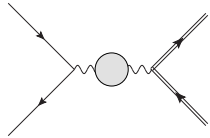
initial-state (ISC)



final-state (FSC)



mixed corrections



(H)VP corrections

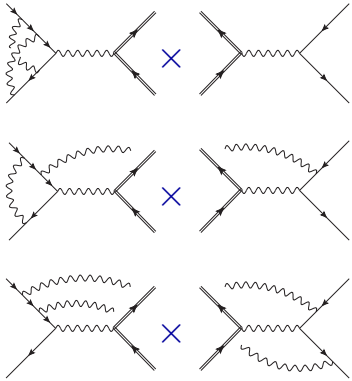
$$\mathcal{A}^{(1)}_{mm}(q_e\,q_m\,q_\ell^2) = \mathcal{A}^{(1)}_{mm}(q_e^3\,q_m) + \mathcal{A}^{(1)}_{mm}(q_e\,q_m^3) + \mathcal{A}^{(1)}_{mm}(q_e^2\,q_m^2) + \mathcal{A}^{(1)}_{mm}(q_e\,q_m\,\Pi^{(1)})$$

$$\mathrm{d}\sigma^{(1)}_{mm}(q_e^2\,q_m^2\,q_\ell^2) = \underbrace{\mathrm{d}\sigma^{(1)}_{mm}(q_e^4\,q_m^2)}_{\text{ISC}} + \underbrace{\mathrm{d}\sigma^{(1)}_{mm}(q_e^2\,q_m^4)}_{\text{FSC}} + \underbrace{\mathrm{d}\sigma^{(1)}_{mm}(q_e^3\,q_m^3)}_{\text{mixed}} + \underbrace{\mathrm{d}\sigma^{(1)}_{mm}(q_e^2\,q_m^2\,\Pi^{(1)})}_{\text{VPC}}$$

pure QED

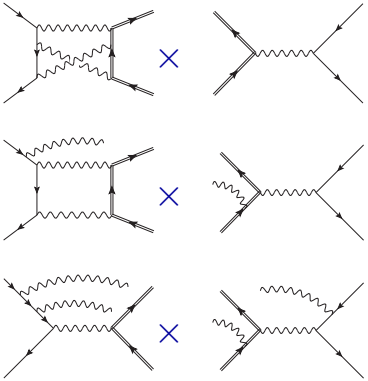
split for NNLO corrections to cross section

initial-state corrections



$\mathrm{d}\sigma^{(2)}_{mm}(q_e^6 q_m^2)$

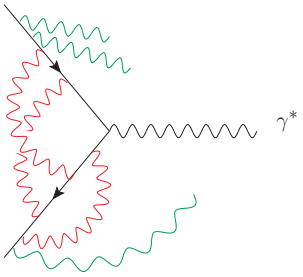
mixed corrections



$\mathrm{d}\sigma^{(2)}_{mm}(q_e^4 q_m^6)$ and $\mathrm{d}\sigma_{mm}(q_e^5 q_m^3)\ldots$

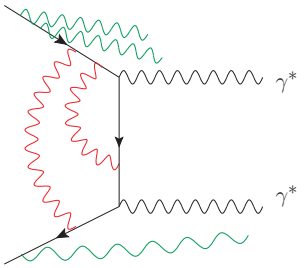
pure QED

Buliding block $e^+ e^- \to \gamma^*$



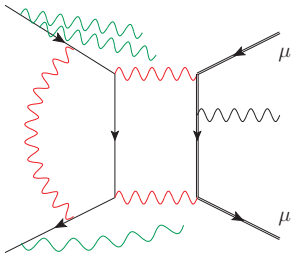
- NNLO available (used for $e\,\mu \to e\,\mu$ and $\ell\,p \to \ell\,p$) including real and vitual, no approximation
- moving towards NNNLO, $\exists$ open questions
  - 3-loop known [2202.05276]
  - 2-loop $e^+ e^- \to \gamma^*\gamma$ bottleneck, need $m_e \neq 0$
  - 1-loop $e^+ e^- \to \gamma^*\gamma\gamma$ use tools, numerics?
  - 0-loop $e^+ e^- \to \gamma^*\gamma\gamma\gamma$ trivial but dangerous
- playground for combination with shower/YFS
- (dominant??) subset of N^{3}LO for MUonE
- can we use next-to-soft LBK to improve YFS ??

Buliding block $e^+ e^- \to \gamma^* \gamma^*$



- doubly virtual Compton scattering (gauge invariant)
- NLO doable, including real and vitual
- NNLO painful, would it be useful ?
  - if one $\gamma^* \to \gamma$ it is desperately wanted
  - combine with $\pi^+\pi^-$ final state (??)
  - a (gauge-invariant) subset of N^{3}LO for MUonE
- playground for combination with shower/YFS

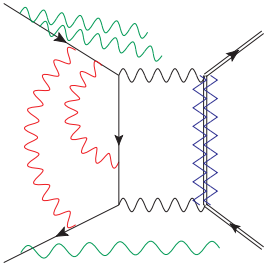
Process $e^+ e^- \to \mu^+ \mu^- \gamma$



- NLO done as part of NNLO MUonE (+ crossing)
- NNLO no show stoppers, but approximations
  - two-loop amplitude use 'massification' (drop m_e^2/Q^2 and m_μ^2/Q^2 effects)
  - one-loop available with full mass dependence
  - phase-space integration tricky but doable
- massification ok'ish for tagged well-isolated photon
- some subsets (OPE) can be done with full mass dependence, very useful for δ_{th} determination
- ??? full m_μ mass dependence for two-loop ???

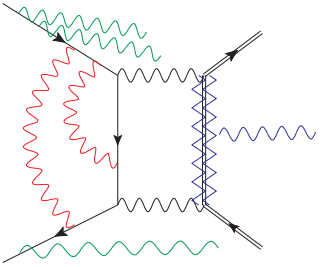
sewing together building blocks for $e^+ e^- \to \pi^+ \pi^-$

"ISC"



FsQED ok'ish if $F_\pi(q^2)$ in (!!) the loop

"FSC/mixed"



just adding form factors = (bad) fudge

the magnificent seven

- AFKQED: LO $2 \to 3$ + ISR "collinear structures", FSR with Photos for $X \in \{\mu, \pi\}$
- Babayaga@NLO: NLO $2 \to 2$ + parton shower + "pions"
- KKMC: LO + YFS (CEEX) with $X = \mu$
- MCGPJ: NLO $2 \to 2$ + "collinear structures" for $X \in \{e, \mu, \pi\}$
- McMule: NNLO QED for $2 \to 2$ with $X \in \{e, \mu\}$, ISR for $X = \pi$
- Phokhara: NLO for $2 \to 3$ with $X \in \{\mu, \pi\}$, sQED for π
- Sherpa: (automated) YFS for $X \in \{\mu, \pi\}$ with matched NLO $2 \to 2$, sQED for π

Aim: for each code, make a precise statement what is included and how $\Rightarrow$ Thursday's talks

possible further codes to be included in the future: BHWIDE, MadGraph, ????

scenarios: $e^+ e^- \to X^+ X^-(+\gamma)$ for $X \in \{e, \mu, \pi\}$, many observables $\Rightarrow$ Yannick's talk

always cut on $p_\pm >$ something, selection of further cuts:

- CMD: $e^+ e^- \to X^+(p_+)\, X^-(p_-)$ with $\sqrt{s} = 0.7\,\text{GeV}$

  cuts: $\supset \; \big||\phi^+ - \phi^-| - \pi\big| < 0.15\,\text{rad}; \quad |\theta^+ + \theta^- - \pi| < 0.25\,\text{rad};$

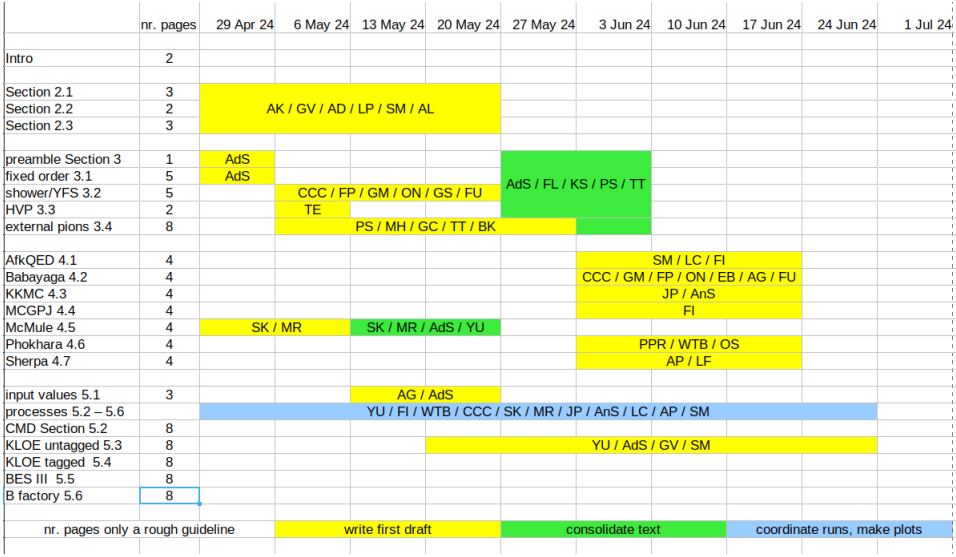
- KLOE small angle (untagged): $e^+ e^- \to X^+ X^- \gamma$ with $\sqrt{s} = 1.02\,\text{GeV}$

  cuts: $\supset$ range of $\theta_\pm$ and M_{XX}; set $\vec{p}_{\tilde{\gamma}} \equiv -(\vec{p}_+ + \vec{p}_-)$ and $\theta_{\tilde{\gamma}} \leq 15^\circ$ or $\theta_{\tilde{\gamma}} > 165^\circ$

- KLOE large angle (tagged): $e^+ e^- \to X^+ X^- \gamma$ with $\sqrt{s} = 1.02\,\text{GeV}$
- BES III: $e^+ e^- \to X^+ X^- \gamma$ with $\sqrt{s} = 4\,\text{GeV}$
- B: $e^+ e^- \to X^+ X^- \gamma$ with $\sqrt{s} = 10\,\text{GeV}$

  cuts: $\supset$ range of $\theta_\pm$ and $\exists\gamma$ within range of θ_γ and $E_\gamma >$ something

timeline


nr. pages
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6 May 24
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27 May 24
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Babayaga 4.2 4
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AG / AdS
YU / FI / WTB / CCC / SK / MR / JP / AnS / LC / AP / SM
YU / AdS / GV / SM
nr. pages only a rough guideline
write first draft
consolidate text
coordinate runs, make plots

most urgent tasks for MC responsible

- produce all observables for all possible scenarios for all MC codes by yesterday and check whether the results make sense !!
- convert the talks about the MC codes given on Thursday into a text on overleaf (roughly 4 pages) by 20 June

other urgent tasks

- finish Section 2
- finish Section 3

we will produce

- an updated on Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in $e^+ e^-$ collisions by August 2024