PSI Universität Zürich

Monte Carlo codes overview and news for Strong2020

McMule

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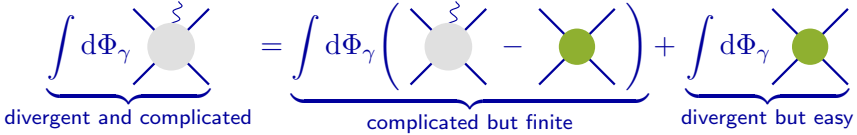
for the McMule team

06 June 2024

Monte **C**arlo for **MU**ons and other **LE**ptons (`mule-tools.gitlab.io`)

- integrator (generator WIP) for fixed-order QED up to NNLO
- use QCD methods: FKS$^\ell$ subtraction with massive fermions



- challenge virtual amplitudes with $m \neq 0 \implies$ massification
- challenge numerical instabilities $\implies$ next-to-soft stabilisation
- for details: [see talk by Marco]

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$$\mathcal{A}(m) = \left(\prod_j \sqrt{Z(m)}\right) \times S \times \mathcal{A}(m=0) + \mathcal{O}(m)$$

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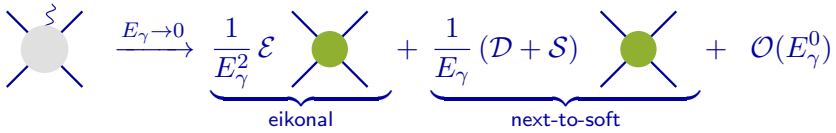
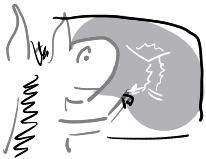


- for details: [see talk by Marco]

$$e^+e^- \to \ell^+\ell^- \quad \ell \in \{e, \mu\}$$



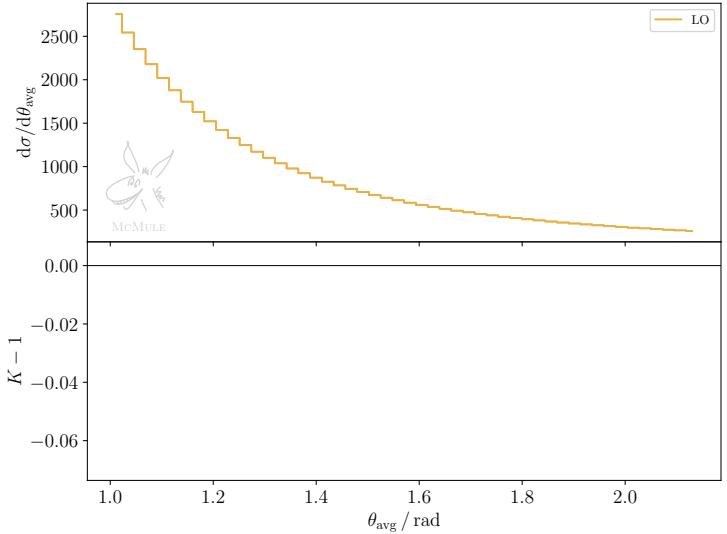
- LO, NLO with full mass dependence
- NNLO with massification & next-to-soft stabilisation
  $\ell = e$ [McMule 21] + missing fermionic corrections
  $\ell = \mu$ crossed from $e\mu \to e\mu$ [see talk by Marco]
- HVP with `alphaQED` [Jegerlehner]

radiative process is a subset: $(ee \to XX\gamma$ @ NLO$) \subset (ee \to XX$ @ NNLO)

what the mule can do – leptons

$e^+e^- \to e^+e^-$ @ CMD scenario with photonic* NNLO *fermionic underway

$\left(\sqrt{s} = 0.7\,\text{GeV};\, 1\,\text{rad} \leq \theta_{\text{avg}} \leq \pi - 1\,\text{rad};\, |\vec{p}_\pm| > 0.45\sqrt{s}/2;\, ||\phi^+ - \phi^-| - \pi| < 0.15\,\text{rad};\, |\theta^+ + \theta^- - \pi| < 0.25\,\text{rad}\right)$



$\theta_{\text{avg}} = (\theta^- - \theta^+ + \pi)/2$

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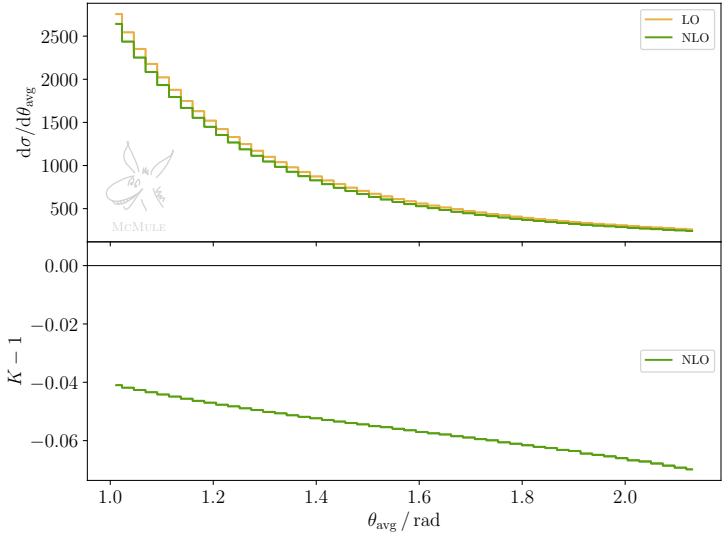

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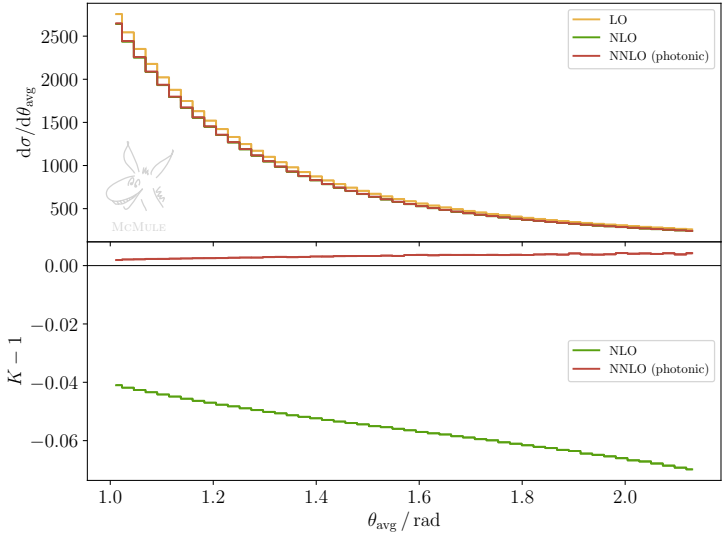

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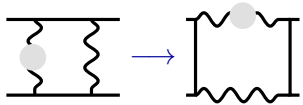
fermionic corrections



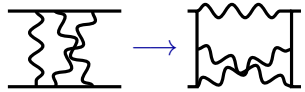
- contains HVP $\to$ numerical
- previously (t-channel): hyperspherical [Fael 18], extension to s-channel unclear

$$\sigma \sim \int_0^\infty \Pi(-Q^2) K(Q^2) \mathrm{d}Q^2$$

$\implies$ now: dispersive with threshold subtraction

$$\sigma \sim \int_{4m_\pi^2}^\infty \mathrm{Im}\left(\Pi(Q^2)\right) K'(Q^2) \mathrm{d}Q^2$$

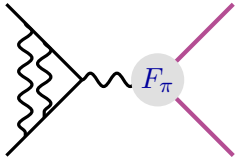
photonic corrections



- multivalued functions with non-trivial analytic continuation
- currently: hard-coded for CMD scenario
- future: include this in `handyG`

what the mule can do – pions

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



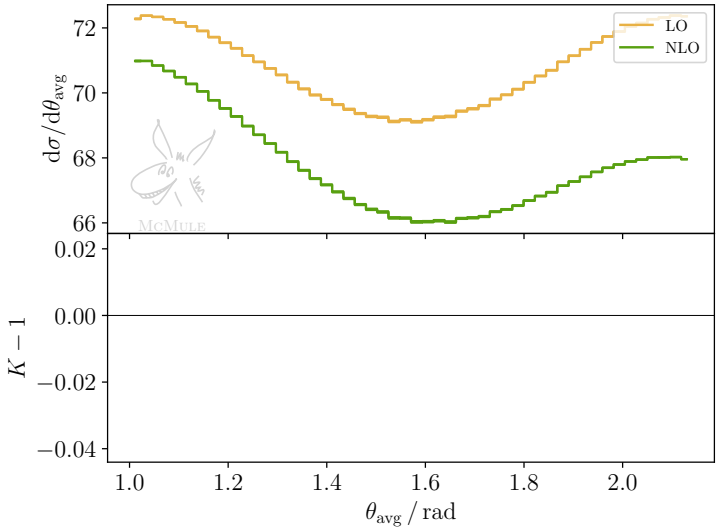
- we have electronic (ISC) NNLO for $ep \to ep$ with proton described by F_1 & F_2 [McMule 23]
  $\implies$ π can be obtained with $F_1, F_2 \sim f(F_\pi)$ & crossing
- soon: generic framework for NNLO $e^+e^- \to \gamma^* \to$ arbitrary nucleons

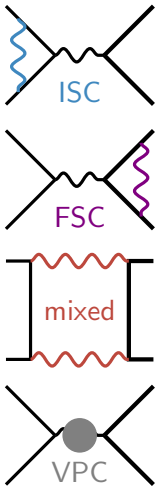
$$|\mathcal{A}|^2 \sim L^{\text{NNLO}}_{\mu\nu} \left(\sum_h j^\mu_X j^{*\nu}_X \right) \qquad X \in \{\pi, {}^{12}C, p, {}^2H, \dots\}$$

gauge-invariant split [see talk by Marco]

$e^+e^- \to \mu^+\mu^-$ @ CMD scenario *NNLO underway

$\left(\sqrt{s} = 0.7\,\text{GeV}; 1\,\text{rad} \leq \theta_{\text{avg}} \leq \pi - 1\,\text{rad}; |\vec{p}_\pm| > 0.45\sqrt{s}/2; ||\phi^+ - \phi^-| - \pi| < 0.15\,\text{rad}; |\theta^+ + \theta^- - \pi| < 0.25\,\text{rad}\right)$





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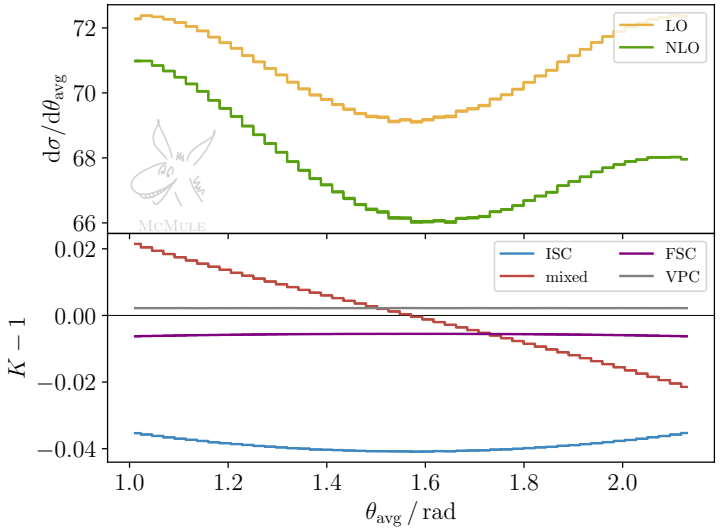
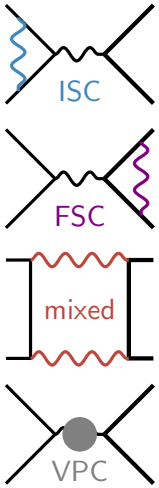




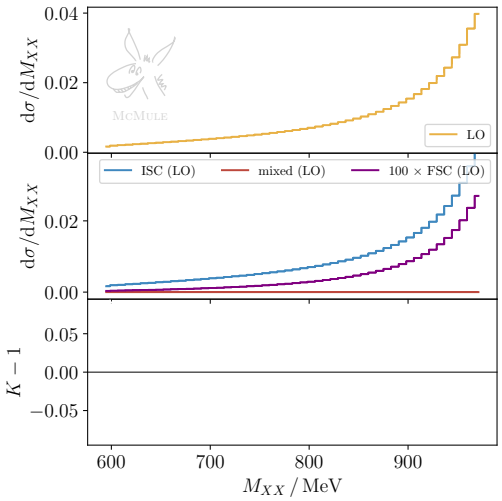
gauge-invariant split @ KLOE scenarios ($ee \to \mu\mu\gamma$)

$\left(50^\circ \le \theta^\pm \le 130^\circ; |p_\pm^z| > 90\,\text{MeV} \vee |\mathrm{p}_\pm^\perp| > 160\,\text{MeV}\right)$

small angle (untagged)

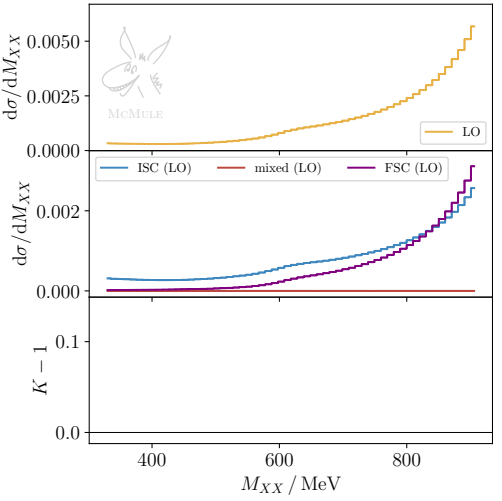
$\left(\vec{p}_{\tilde{\gamma}} = -(\vec{p_+} + \vec{p_-})\right)$

$\left(\theta_{\tilde{\gamma}} \le 15^\circ \vee \theta_{\tilde{\gamma}} > 165^\circ; 0.35\,\text{GeV}^2 \le M_{XX}^2 \le 0.95\,\text{GeV}^2\right)$



large angle (tagged)

$\left(50^\circ \le \theta_\gamma \le 130^\circ \wedge E_\gamma > 20\,\text{MeV}; 0.1\,\text{GeV}^2 \le M_{XX}^2 \le 0.85\,\text{GeV}^2\right)$



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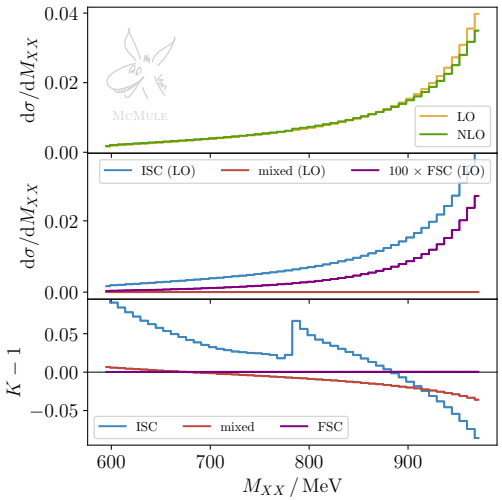

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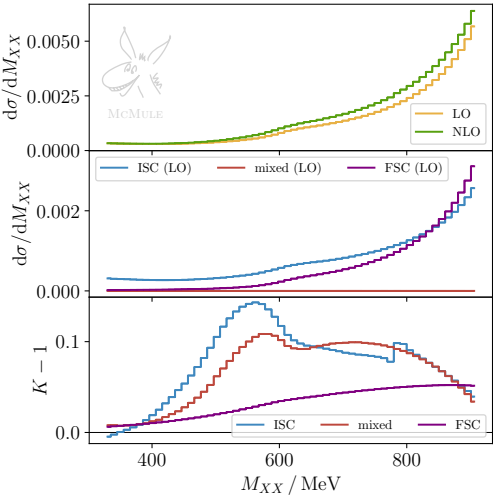
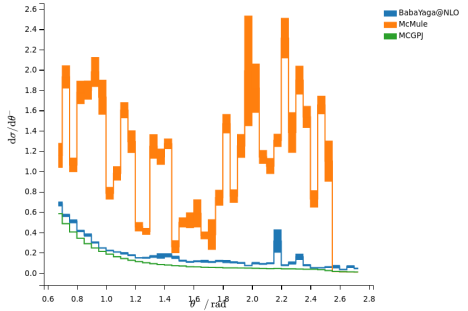
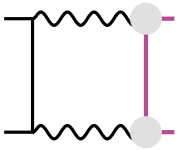


to be investigated numerical instabilities for $ee \to ee\gamma$ in the B scenario

Observable θ^-



future include FSC/mixed for pions [Colangelo, Hoferichter, Monnard, Ruiz de Elvira 22]



future NNLO $ee \to \mu\mu\gamma$ from $pp \to 2j + \gamma$ [Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia 23]

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

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