

IPPP Steering Committee meeting

QED calculations at NNLO (and beyond)

Yannick Ulrich

for the `MCMULE` collaboration

IPPP, University of Durham

27 SEPTEMBER 2022

non-exhaustive list of experiments as implemented in McMULE

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

$$\begin{aligned}
 \sigma = & \int d\Phi_2 \left| \begin{array}{c} \text{tree} \\ + \text{loop} \\ + \text{loop} \\ + \dots \end{array} \right|^2 \\
 & + \int d\Phi_3 \left| \begin{array}{c} \text{loop} \\ + \text{loop} \\ + \dots \end{array} \right|^2 \\
 & + \int d\Phi_4 \left| \begin{array}{c} \text{loop} \\ + \dots \end{array} \right|^2 \\
 & + \dots
 \end{aligned}$$

challenges

- fully differential phase-space integration
- ⇒ FKS^ℓ
- virtual amplitudes with massive particles
- ⇒ one-loop: OpenLoops
- ⇒ two-loop: massification
- numerical instabilities due to pseudo-singularities
- ⇒ next-to-soft stabilisation

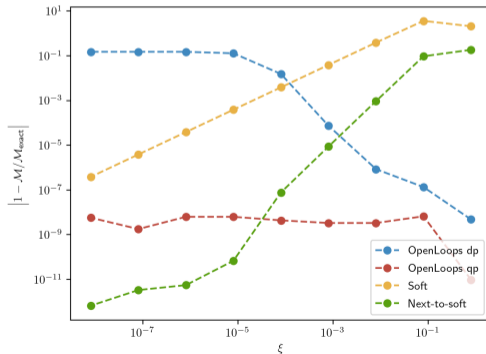
real-virtual corrections trivial in principle, extremely delicate numerically



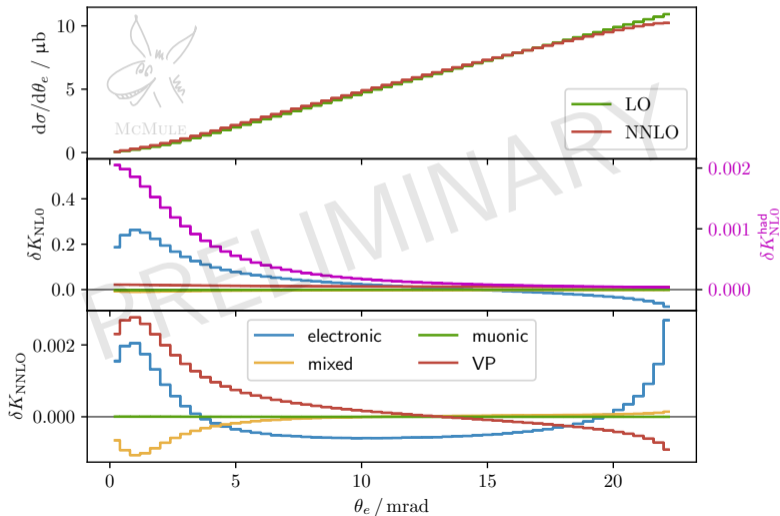
example $ee \rightarrow ee\gamma$

[Banerjee, Engel, Schalch, Signer, YU 21]

- soft limit (of collinear emission)
 $E_\gamma = \xi \sqrt{s}/2$
- arbitrary prec. calculation vs **dp**, **qp**, **eikonal**, **NTS**
- stability problem solved & speed-up



$E_{\text{beam}}^\mu = 150 \text{ GeV}$, $E_e > 1 \text{ GeV}$, $\theta_\mu > 0.3 \text{ mrad}$ [Broggio, Engel, Ferroglia, Mandal, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Zoller, YU 2?]

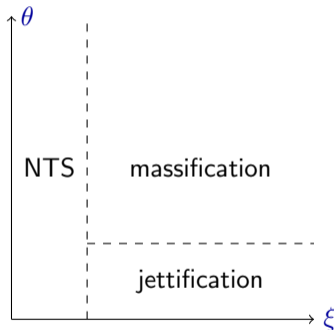


$ee \rightarrow \gamma^*$ can be taken to N^3 LO

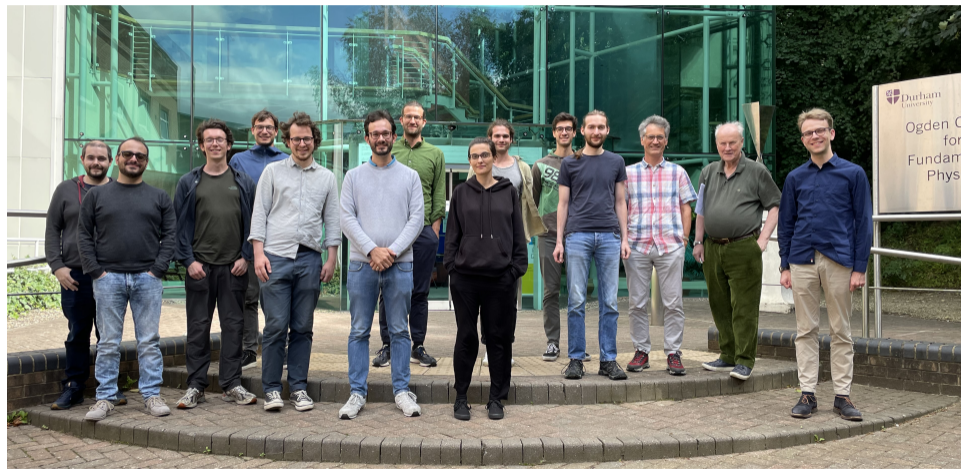
- VVV: known
[Fael, Lange, Schönwald, Steinhauser 22]
 - RRR: “trivial”
 - RRV: OpenLoops + NTS stabilisation
 - RVV: massless known (three-jet @ NNLO), massive (DiffExp?)
- ⇒ LBK + jettification at two-loop

jettification

- expand for small emission angles



N^3 LO workstop in Durham





McMULE

mule-tools.gitlab.io

f.l.t.r.: F.Hagelstein (Mainz), A.Coutinho (PSI), 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 (Durham), A.Gurgone (Pavia)