# Status of MUonE theory

F. Piccinini

INFN, Sezione di Pavia (Italy)

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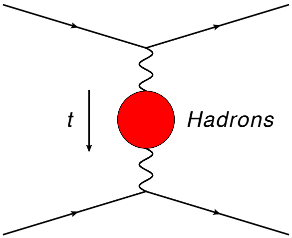
- ⋆ G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L. Trentadue, G. Venanzoni,
  *Measuring the leading hadronic contribution to the muon g-2 via* $\mu e$ *scattering*
  Eur. Phys. J. C **77** (2017) no.3, 139 - arXiv:1609.08987 [hep-ph]
- ⋆ C. M. Carloni Calame, M. Passera, L. Trentadue and G. Venanzoni,
  *A new approach to evaluate the leading hadronic corrections to the muon g-2*
  Phys. Lett. B **746** (2015) 325 - arXiv:1504.02228 [hep-ph]

# Master formula

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

*e.g.* Lautrup, Peterman, De Rafael, Phys. Rept. 3 (1972) 193




- The hadronic VP correction to the running of $\alpha$ enters
  - **$\Delta\alpha_{\rm had}(t)$ can be directly measured in a (single) experiment involving a space-like scattering process and $a_\mu^{\rm HLO}$ obtained through numerical integration**
    Carloni Calame, Passera, Trentadue, Venanzoni PLB 746 (2015) 325
  - **A data-driven evaluation of $a_\mu^{\rm HLO}$, but with space-like data**

# Kernel functions for $a_\mu^{\rm HVP}$

- LO: $\frac{\alpha}{\pi}(1-x)$

- NLO

  E. Balzani, S. Laporta, M. Passera, Phys. Lett. B834 (2022) 137462

  A.V. Nesterenko, J. Phys. G49 (2022) 5, 055001;

  J. Phys. G50 (2022) 2, 029401

- NNLO

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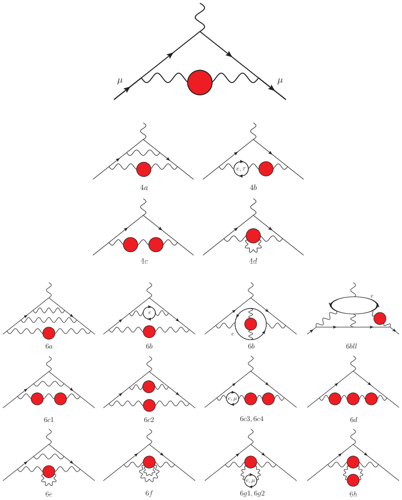


$\Longrightarrow$ talk by S. Laporta

## Main challenge: precision on shapes of differential distributions at the 10ppm level

see talks by U. Marconi and G. Abbiendi for a global update on the experimental and analysis issues

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- **Radiative corrections to the Signal, the elastic process $\mu e \to \mu e$**

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**High precision Monte Carlo simulation tools required**

# Two completely independent fixed order Monte Carlo codes under development

- **Mesmer** Pavia team
  - approximate NNLO calculation at $\mathcal{O}\left(\left[\frac{\alpha}{\pi}\ln\frac{m_\mu^2}{m_e^2}\right]^2\right)$

github.com/cm-cc/mesmer

- **McMule** PSI/Bern/Liverpool...
  - more refined approximation to NNLO: only terms of $\mathcal{O}(m_e^2/Q^2)$ neglected

gitlab.com/mule-tools/mcmule

see backup slides for details and references

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- **also next perturbative order should be estimated**

see talk by Marco Bonetti on status and prospects

# Fixed target experiment $\Longrightarrow$ bound electron effects

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R. Plestid and M.B. Wise, arXiv:2403.12184

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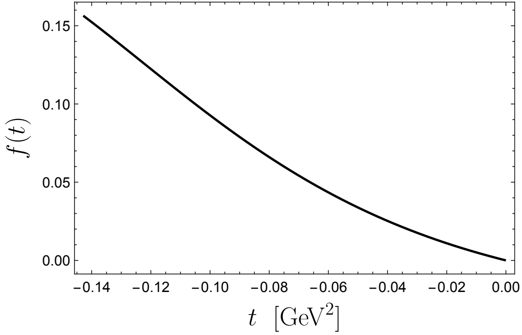
- for $C$

$$\frac{1}{\sigma}\frac{d\sigma}{dt} = \frac{1}{\sigma^0}\frac{d\sigma^0}{dt}\,(1 - K f(t))$$

  - $K = 4.5 \cdot 10^{-4}$, scaling as $1/Z_A$




- preliminary investigations of the interactions between outgoing electrons and the residual charged debris in the final state

R. Plestid and M.B. Wise, arXiv:2407.21752

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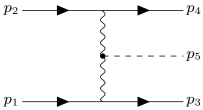


- **$\pi^0$ production** calculated and shown to be **well below $10^{-5}$** w.r.t. $\mu e \to \mu e$

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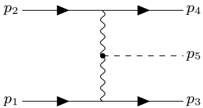


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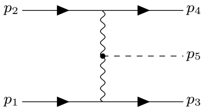


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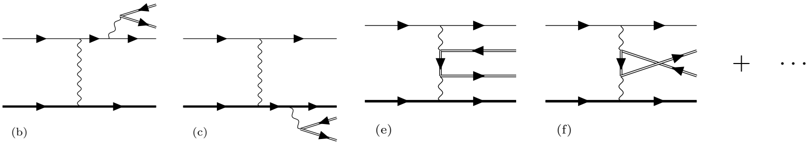
- **lepton pair production**
  - $\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$
  - $\mu^\pm N \to \mu^\pm N \ell^+ \ell^-$

# $\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$ (same pert. order as virtual pairs)

- it also contributes at NNLO accuracy w.r.t. $\mu e \to \mu e$



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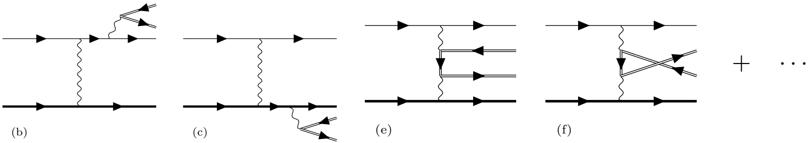


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G. Racah, Il Nuovo Cimento 14 (1937) 83-113; L.D. Landau, E.M. Lifschitz, Phys. Z. Sowjetunion 6 (1934) 244; H.J. Bhabha, Proc. Roy. Soc. Lond. A152 (1935) 559;

R.N. Lee, A.A. Lyubyakin, V.A. Smirnov, Phys. Lett. B 848 (2024) 138408

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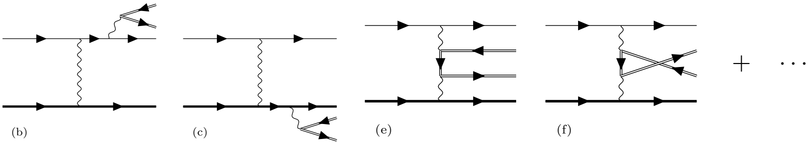


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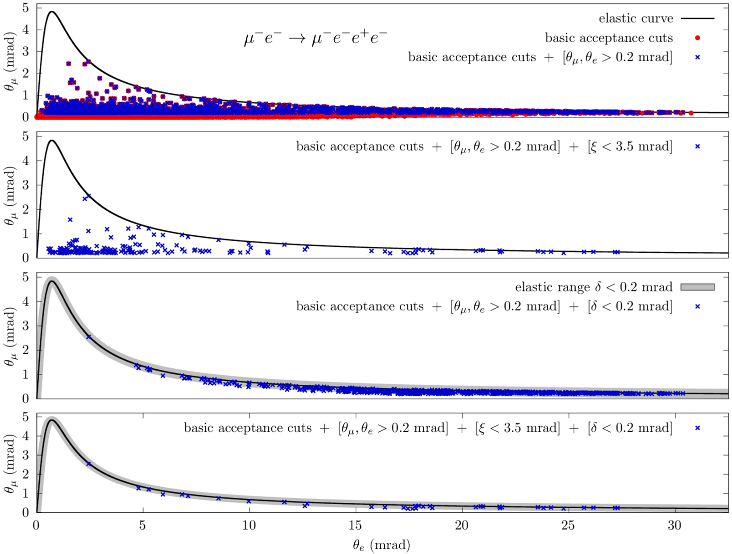
- **$\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$ calculated with finite mass effects and implemented in `Mesmer`**

# simulation of $5 \cdot 10^5$ points of $\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$



# Real pair emission from scattering on nucleus: $\mu^{\pm}N \to \mu^{\pm}N\ell^{+}\ell^{-}$

G. Abbiendi et al., Phys. Lett B854 (2024) 138720

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$\Longrightarrow$ **a dedicated calculation implemented in the Monte Carlo generator `Mesmer`**

- **approximation: scattering on the external nucleus field**
- **finite extension of the nucleus through a form factor**

$$F_Z(q) = \frac{1}{Ze} \int_0^\infty dr\, r^2 \rho_Z(r) \frac{\sin(qr)}{qr}$$

  - $q$ : momentum transferred to the nucleus
  - $\rho_Z$ : nuclear charged density

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- **different models for charge density**

J. Heeck, R. Szafron, Y. Uesaka, PRD 105 (2022) 053006

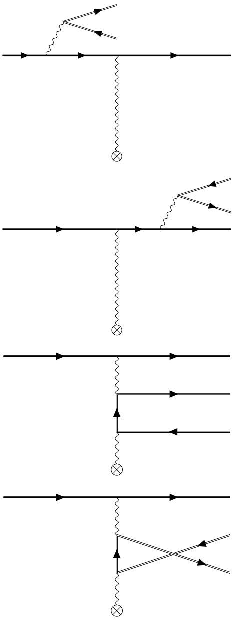
  - $F_Z(q) = 1$ (conservative)
  - 1 parameter Fermi model (1pF)

$$\rho_Z(r) = \frac{\rho_0}{1 + \exp\frac{r-c}{z}}$$

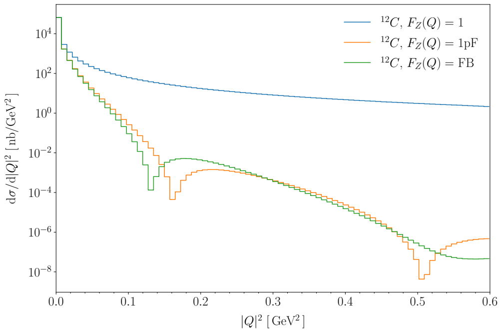
  - Fourier Bessel expansion (FB)

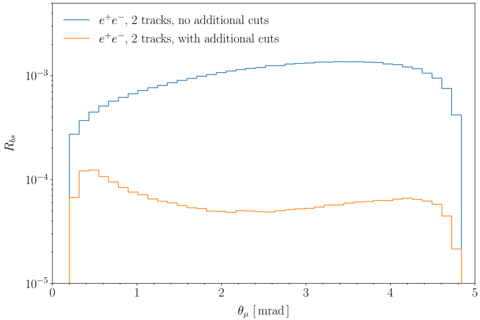
$$\begin{aligned} \rho_Z(r) &= \sum_k^n a_k\, j_0\left(\frac{k\pi r}{R}\right), \quad r \geq R \\ &= 0 \qquad\qquad\qquad\qquad > R \end{aligned}$$

  - modified-harmonic oscillator model



# Background/signal ratio




G. Abbiendi, E. Budassi, C.M. Carloni Calame, A. Gurgone, F.P., Phys.Lett.B 854 (2024) 138720

# For a safe background subtraction

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- **QED corrections to lepton pair production will be important**

- **Interaction with an additional nucleus is of the same order, enhanced by $Z$**

# Summary

- **Given its precision requirements, MUonE represents a challenge (on the theory side) for**
  - **QED corrections**
  - **background calculation**

- **at present we have two independent Monte Carlo tools, `Mesmer` and `McMule` featuring**
  - NLO QED corrections
  - NNLO QED corections from single lepton legs
  - YFS inspired approximation to the full NNLO QED in **`Mesmer`**
  - full NNLO QED with electron "massification" in **`McMule`**
  - pair production in **`Mesmer`**
    - $\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$
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- **enough to study the pre- LHC LS data**

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- **towards N$^3$LO** $\to$ next talk

# Theoretical progress since 2017, thanks to expanding collaborative effort

- MUonE theory workshops
  - Theory Kickoff Workshop, Padova, 4-5 September 2017
  - MITP Workshop, Mainz 19-23 February 2018
  - $2^{\mathrm{nd}}$ Workstop/ThinkStart, Zürich, 4-7 February 2019
  - N$^3$LO kick-off workstop/thinkstart IPPP Durham, 3-5 August 2022
  - MITP Workshop, Mainz 14-18 November 2022
  - MITP Workshop, Mainz 3-7 June 2024
- Five General MUonE Collaboration Meetings

# A collection of references on calculation developments


- Carloni Calame et al., PLB 746 (2015), 325
- Abbiendi et al., EPJ C77 (2017), 139
- Mastrolia et al., JHEP 11 (2017) 198
- Di Vita et al., JHEP 09 (2018) 016
- Alacevich et al., JHEP 02 (2019) 155
- Fael and Passera, PRL 122 (2019) 19, 192001
- Fael, JHEP 02 (2019) 027
- Engel et al., JHEP 02 (2019) 118
- Engel et al., JHEP 01 (2020) 085
- Carloni Calame et al., JHEP 11 (2020) 028
- Banerjee et al., SciPost Phys. 9 (2020), 027
- Banerjee et al., EPJC 80 (2020) 6, 591
- Budassi et al., JHEP 11 (2021) 098
- Balzani et al., PLB 834 (2022) 137462
- Bonciani et al., PRL 128 (2022) 2, 022002
- Budassi et al., PLB 829 (2022) 137138
- Engel et al., JHEP 04 (2022) 097
- Fael et al., PRL 128 (2022) 172003
- Fael et al., PRD 106 (2022) 034029
- Broggio et al., JHEP 01 (2023) 112
- Fael et al., PRD 107 (2023) 094017
- Engel, JHEP 07 (2023) 177
- Badger et al., JHEP 11 (2023) 041
- Fadin and Lee., JHEP 11 (2023) 148
- Ahmed et al., JHEP 01 (2024) 010
- Engel, JHEP 03 (2024) 004
- Abbiendi et al., PLB 854 (2024) 138720
- Plestid and Wise, arXiv:2403.12184;arXiv:2407.21752

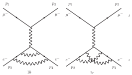
**THANK YOU**

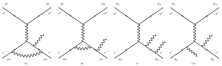
**BACKUP**

# Details about radiative corrections for signal

# First approximate *photonic* radiative corrections at **NNLO**

- **exact calculation of corrections along one lepton line with all finite mass effects**





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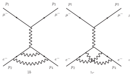

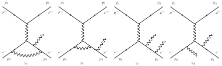

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    Carloni Calame et al., JHEP 11 (2020) 028,

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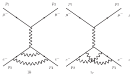

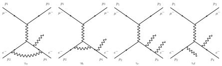

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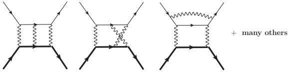
  - implemented in **`Mesmer`** and **`McMule`**, perfect numerical agreement

- **NNLO with finite mass effects and approximate up-down interference in `Mesmer`**
  - interference of LO $\mu e \to \mu e$ amplitude with




⇝ NNLO double-virtual amplitudes where at least 2 photons connect the $e$ and $\mu$ lines are approximated according to the Yennie-Frautschi-Suura ('61) formalism to catch the IR divergent structure

# Second step, *photonic* radiative corrections at **NNLO** (2023)

- **complete calculation of the amplitude $f^+f^- \to F^+F^-$ with $m_f = 0$, $m_F \neq 0$** R. Bonciani *et al.*, PRL 128 (2022)

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T. Engel, C. Gnendiger, A. Signer and Y. Ulrich, JHEP 02 (2019) 118

Y. Ulrich, *PoS* RADCOR2023 (2024) 077

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T. Engel, A. Signer, Y. Ulrich, JHEP 01 (2020) 085

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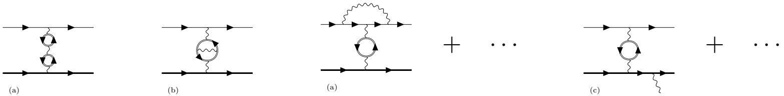
- with the above ingredients
  - **NNLO calculation neglecting terms of $\mathcal{O}(m_e^2/Q^2)$ in `McMule`**

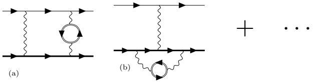
A. Broggio et al., JHEP 01 (2023) 112

# NNLO virtual leptonic pairs (vacuum polarization insertion) (2021)

- any lepton (and hadron) in the VP blobs
- interfered with $\mu e \to \mu e$ or $\mu e \to \mu e \gamma$ amplitudes




- interfered with $\mu e \to \mu e$ amplitude




- 2-loop integral evaluated with dispersion relation techniques in **Mesmer**

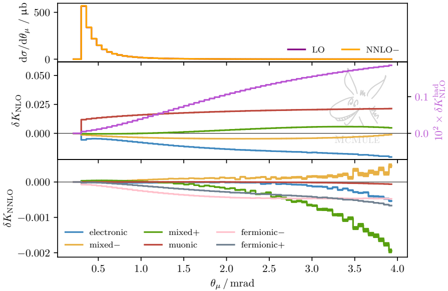
used e.g. in the past for Bhabha: Actis et al., Phys. Rev. Lett. 100 (2008) 131602; Carloni Calame et al., JHEP 07 (2011) 126

$$\frac{g_{\mu\nu}}{q^2 + i\epsilon} \to g_{\mu\nu} \frac{\alpha}{3\pi} \int_{4m_\ell^2}^{\infty} \frac{dz}{z} \frac{R_\ell(z)}{q^2 - z + i\epsilon} = g_{\mu\nu} \frac{\alpha}{3\pi} \int_{4m_\ell^2}^{\infty} \frac{dz}{z} \frac{1}{q^2 - z + i\epsilon} \left(1 + \frac{4m_\ell^2}{2z}\right) \sqrt{1 - \frac{4m_\ell^2}{z}}$$

- 2-loop integral evaluated (also) with hyperspherical method in **McMule**

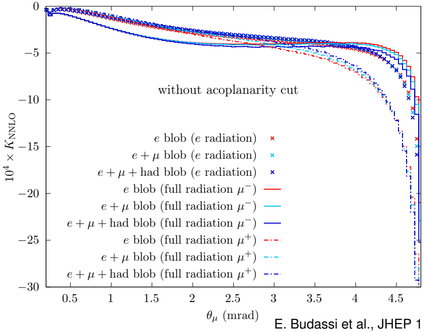
M. Fael, JHEP02 (2019) 027

**McMule**




A. Broggio et al., JHEP 01 (2023) 112

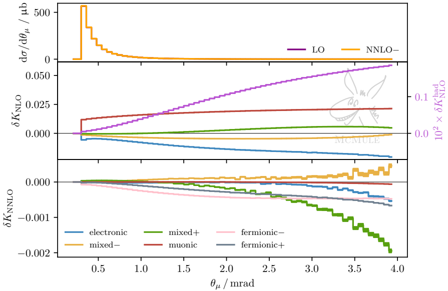
**Mesmer**




E. Budassi et al., JHEP 11 (2021) 098

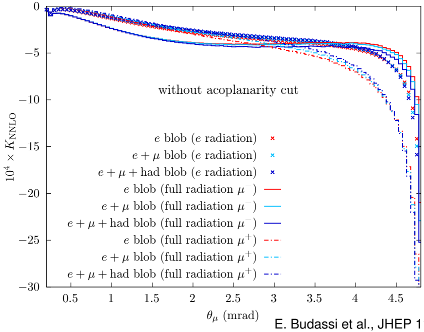
# NNLO order of magnitude

**McMule**




A. Broggio et al., JHEP 01 (2023) 112

**Mesmer**

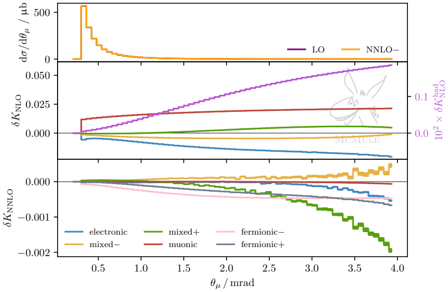



E. Budassi et al., JHEP 11 (2021) 098

- **NNLO corrections at the $10^{-4} - 10^{-3}$ level**

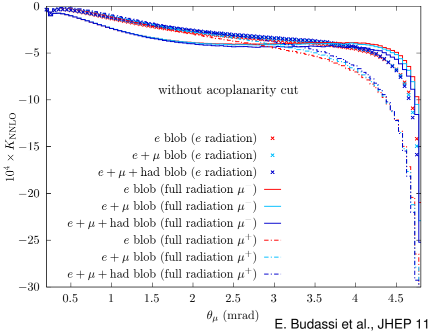
# NNLO order of magnitude

**McMule**




A. Broggio et al., JHEP 01 (2023) 112

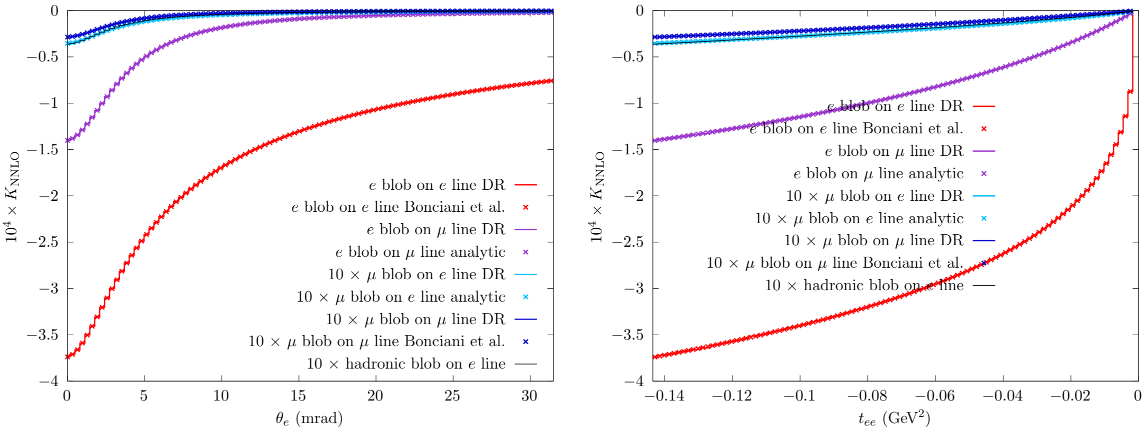
**Mesmer**



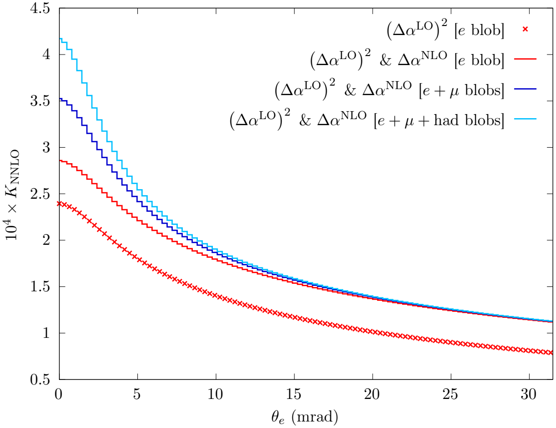

E. Budassi et al., JHEP 11 (2021) 098

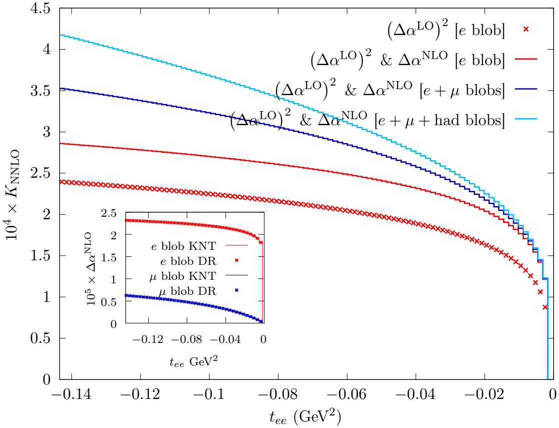
- **NNLO corrections at the $10^{-4} - 10^{-3}$ level**
- **eventually fixed order calculations need to be matched to resummation of higher order corrections, through PS techniques (e.g. BaBayaga) or YFS techniques (e.g. KKMC/SHERPA)**

# Virtual leptonic (and hadronic NNLO) vertex corrections

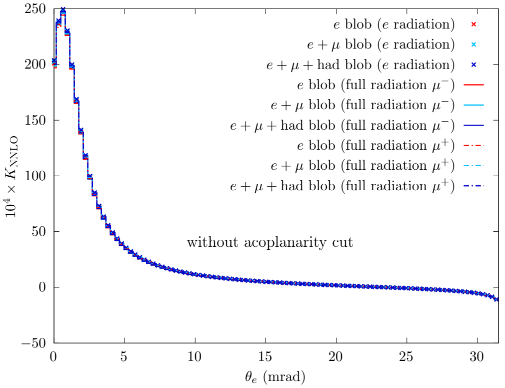


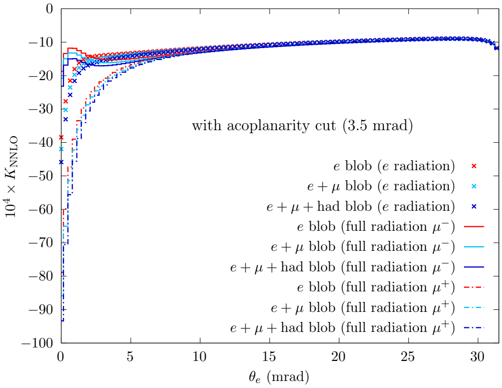
# Virtual leptonic (and hadronic) NNLO VP corrections



# Virtual pair effects



# Possible New Physics contamination in the $\Delta\alpha(t)$ determination?

A. Masiero, P. Paradisi and M. Passera, Phys. Rev. D102 (2020) 075013

P.S.B. Dev, W. Rodejohann, X.-J. Xu and Y. Zhang, JHEP 05 (2020) 053

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**HVP determination with MUonE data will be robust against New Physics**

# Possible New Physics studies with MUonE (in complementary regions to $\Delta\alpha_h$)

- **interesting proposals for NP searches at MUonE (new light mediators) in $2 \to 3$ processes**
  - invisibly decaying light $Z'$ in $\mu e \to \mu e Z'$

    Asai et al., Phys. Rev. D106 (2022) 5
    - a relevant background can be $\mu e \to \mu e \pi^0$, in addition to $\mu e \to \mu e \gamma$
  - long-lived mediators with displaced vertex signatures $\mu e \to \mu e A' \to \mu e e^+ e^-$

    Galon et al., Phys.Rev.D 107 (2023) 095003
  - through scattering off the target nuclei $\mu N \to \mu N X \to \mu N e^+ e^-$

    Grilli di Cortona and E. Nardi, Phys. Rev. D105 (2022) L111701