Hadronic contribution to to the muon $g-2$: theoretical challenges with the MUonE experiment

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QCD@Work, Trani, 18-21 June 2024

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$$\vec{\mu}_\mu = -g_\mu \frac{e\hbar}{2m_\mu}\vec{s}$$

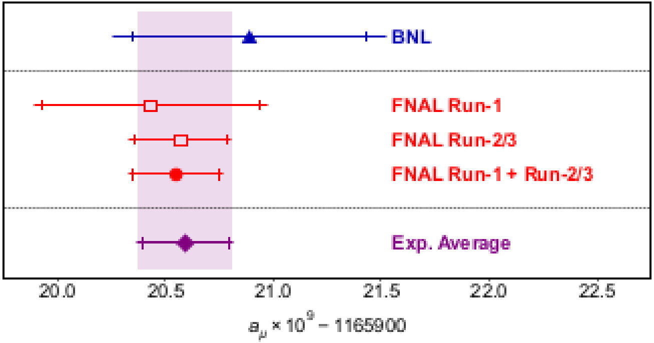
- in QED without quantum fluctuations

$$g_\mu = 2$$

- with quantum fluctuations: $g_\mu \neq 2$ at the 0.1% level

$$\mathbf{a}_\mu \equiv \frac{\mathbf{g}_\mu - \mathbf{2}}{\mathbf{2}}$$

Experimental status



Muon $g-2$ Coll., Phys. Rev. Lett. 126 (2021) 120801; Phys. Rev. Lett. 131 (2023) 161802; arXiv:2402.15410

present world average: $\mathbf{a_\mu^{exp} = 116592059(22) \cdot 10^{-11}}$ (0.19 ppm)

M. Knecht, MITP Workshop 3-7/06/2024

$\Longrightarrow \sim 0.14$ **ppm in the (very) near future**

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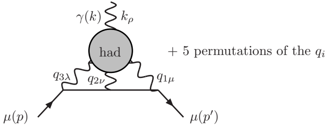
- **ElectroWeak**: calculated up to three loops, with negligible uncertainty $(\sim 153(1) \cdot 10^{-11})$
- **QCD**: the largest source of uncertainty, due to non-perturbative effects
- **possible New Physics?**

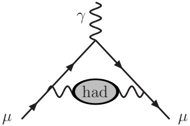
QCD contributions

- Hadronic Light-by-Light (HLxL)



F. Jegerlehner, arXiv:0902.3360

- Hadronic Vacuum Polarization (HVP)



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QCD contributions

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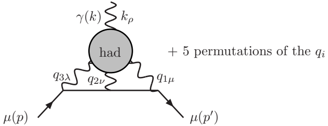

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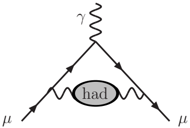
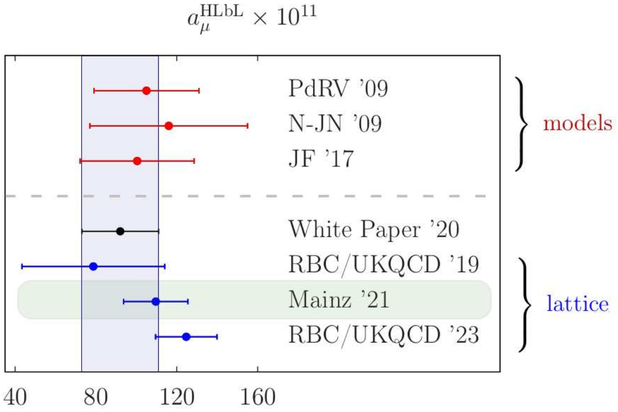


F. Jegerlehner, arXiv:0902.3360

- **two approaches for both contributions:**
  - first principle calculations with LQCD
  - dispersion relations

HLxL estimates



M. Knecht, MITP Workshop 3-7/06/2024

$\mathbf{a_\mu^{HLxL} = 91(19) \cdot 10^{-11}}$ (WP 2020) T. Aoyama et al., Phys. Rept. 887 (2020) 1

The dispersive approach for HVP in a nutshell

$$a_\mu^{\rm HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)R(s)}{s^2}$$

$$K(s) = \int_0^1 dx \, \frac{x^2(1-x)}{x^2 + (1-x)(s/m_\mu^2)}$$

$$R(s) = \frac{\sigma^0(e^+e^- \to {\rm hadrons} + \gamma))}{\sigma_{\rm pt}}$$

$$\sigma_{\rm pt} = \frac{4\pi\alpha^2}{3s}$$

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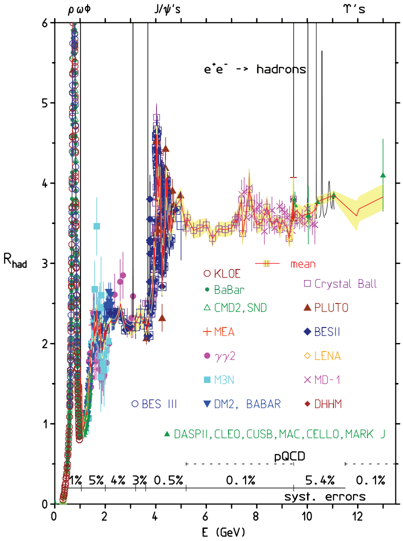
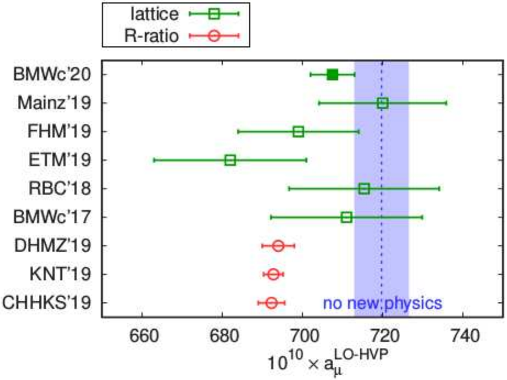


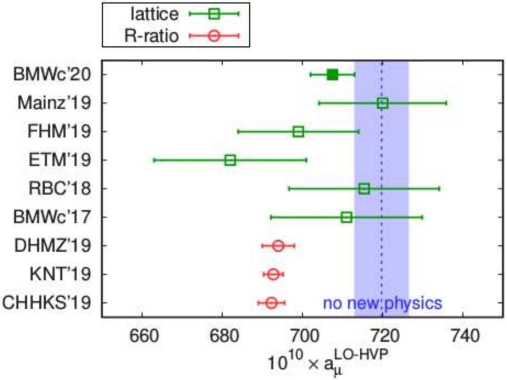
HVP-LO estimates



M. Knecht, MITP Workshop 3-7/06/2024

$\mathbf{a_\mu^{HVP-LO} = 6931(40) \cdot 10^{-11}}$ (WP 2020, without BMWc) T. Aoyama et al., Phys. Rept. 887 (2020) 1

HVP-LO estimates

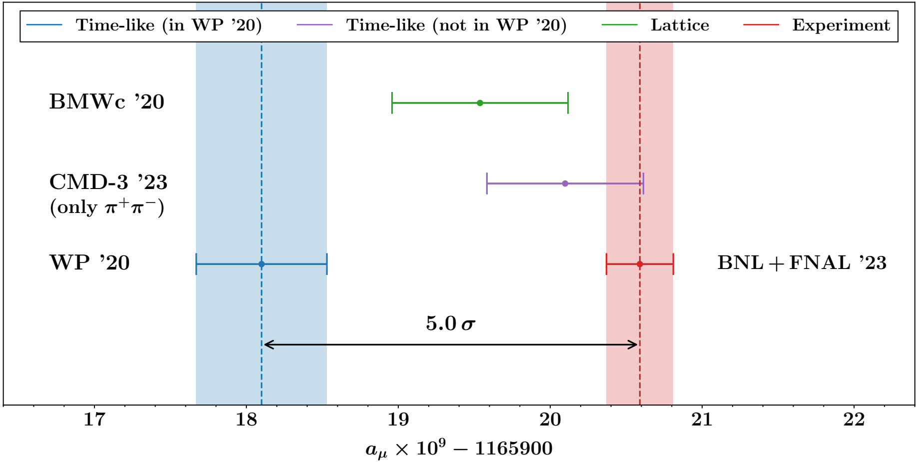


M. Knecht, MITP Workshop 3-7/06/2024

$\mathbf{a_\mu^{HVP-LO} = 6931(40) \cdot 10^{-11}}$ (WP 2020, without BMWc) T. Aoyama et al., Phys. Rept. 887 (2020) 1

- the new CMD-3 result on pion form-factor introduced an additional puzzle F.V. Ignatov et al, arXiv:2302.08834

Summary of the comparison data-theory



courtesy of A. Gurgone

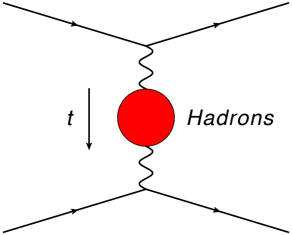
- G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L. Trentadue, G. Venanzoni,
  Measuring the leading hadronic contribution to the muon g-2 via μe *scattering*
  Eur. Phys. J. C **77** (2017) no.3, 139 - arXiv:1609.08987 [hep-ph]
- 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



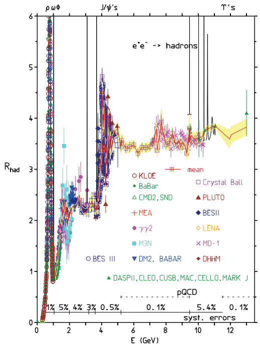
- ⋆ **$\Delta\alpha_{\rm had}(t)$ can be directly measured in a (single) experiment involving a space-like scattering process and $a_\mu^{\rm HLO}$ obtained through numerical integration**

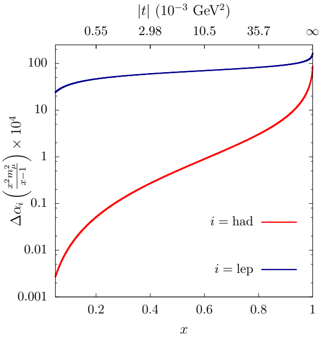
  Carloni Calame, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

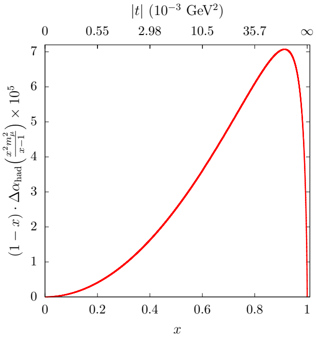
- ⋆ **A data-driven, inclusive evaluation of $a_\mu^{\rm HLO}$, but with space-like data**

From time-like to space-like evaluation of a_μ^{HLO}

Time-like $\mapsto$ **Space-like**







Smooth function

- $\mapsto$ **Time-like:** combination of many experimental data sets, control of RCs better than $\mathcal{O}(1\%)$ on hadronic channels required
- $\mapsto$ **Space-like:** in principle, one single experiment, *it's a one-loop effect, very high accuracy needed*

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- **Radiative corrections to the signal**

- **Predictions for Background processes**

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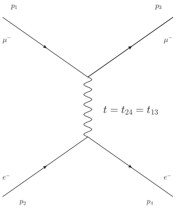
High precision Monte Carlo simulation tools required

First step towards precision: QED NLO and MC (2018)

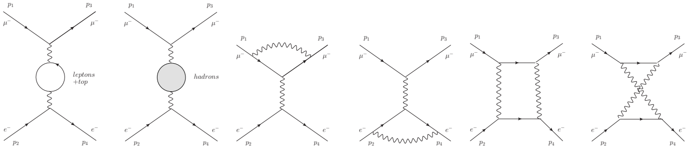


- analytical expression for tree level

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{\lambda(s, m_\mu^2, m_e^2)} \left[\frac{(s - m_\mu^2 - m_e^2)^2}{t^2} + \frac{s}{t} + \frac{1}{2} \right]$$

- VP gauge invariant subset of NLO rad. corr.
- factorized over tree-level: $\alpha \to \alpha(t)$

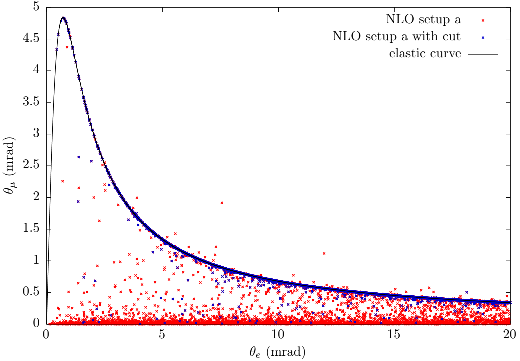
- QED NLO virtual diagrams and real emission diagrams with exact finite m_e and m_μ effects

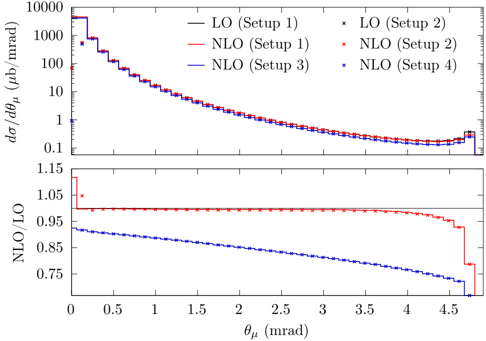


- **tree-level Z-exchange important** at the 10^{-5} level ($\sim tG_\mu/4\pi\alpha\sqrt{2}$ in the Fermi theory)
- SM weak RCs at most at a few 10^{-6} level, negligible

Alacevich et al. JHEP 02 (2019) 155

First realistic description of scattering events

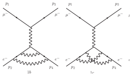


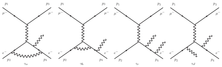


- many points fall out of the $2 \to 2$ correlation curve $\theta_\mu - \theta_e$ because of the radiative events
- NLO QED radiative corrections at the % level, enhanced by exclusive event selections

Second step, towards *photonic* radiative corrections at **NNLO** (2020)

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





  - two independent calculations, with different IR singularities handling procedures (slicing and subtraction)

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

P. Banerjee, T. Engel, A. Signer, Y. Ulrich, SciPost Phys. 9 (2020) 027

  - 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

+ many others

⇝ NNLO double-virtual amplitudes where at least 2 photons connect the e and μ 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)
- **"massification" to recover the leading m_e terms**, i.e. neglecting powers of m_e^2/Q^2

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

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

- **FKS$^\ell$ subtraction scheme**

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

- **Next-to-soft stabilisation**, to obtain numerical stability in real-virtual corrections with soft and/or collinear photon configurations

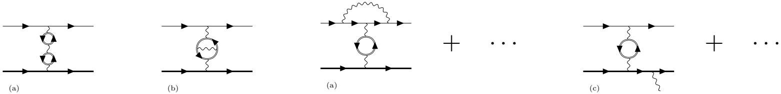
T. Engel, A. Signer, Y. Ulrich, JHEP 04 (2022) 097; T. Engel, JHEP 07 (2023) 177

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

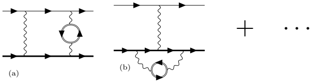
A. Broggio et al., JHEP 01 (2023) 112

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`**

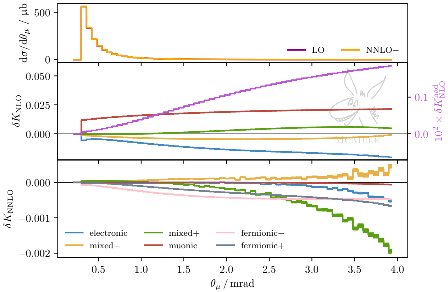
used e.g. in the past for Bhabha: Actis et al., Phys. Rev. Lett. 100 (2008) 131602; Carloni Calame et al., JHEP 07 (2011) 126

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

- 2-loop integral evaluated (also) with hypherspherical method in **`McMule`** M. Fael, JHEP02 (2019) 027

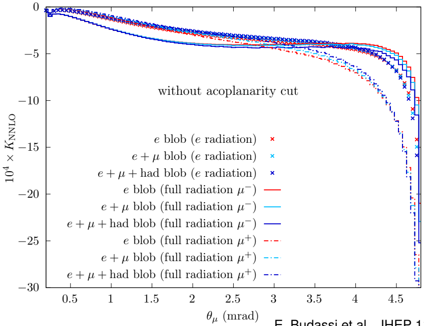
NNLO order of magnitude

McMule



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

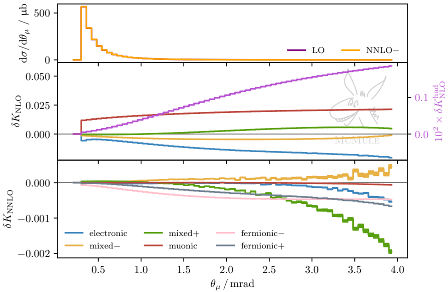
Mesmer



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

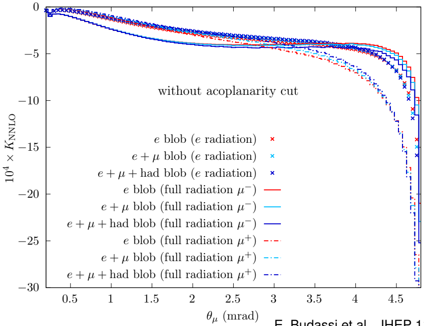
- **NNLO corrections at the $10^{-4} - 10^{-3}$ level**

McMule



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

Mesmer

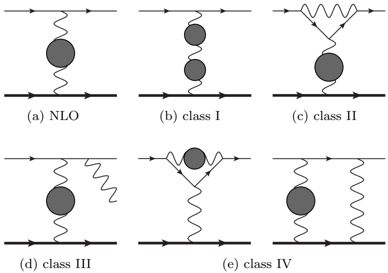


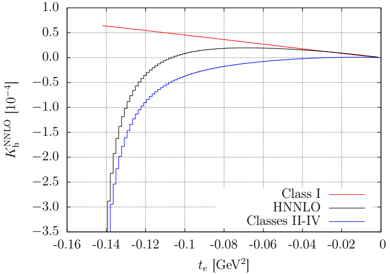
E. Budassi et al., JHEP 11 (2021) 098

- **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)**

NNLO hadronic contributions (2019)

- using the dispersion relation approach





Fael, Passera, Phys. Rev. Lett. 122 (2019) 192001

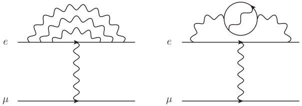
- corrections of the order of 10^{-4}
- hyperspherical integration method to calculate hadronic NNLO corrections, where the hadronic vacuum polarization is employed in the space-like region (used in **McMule**)

M. Fael, JHEP02 (2019) 027

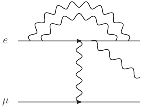
Towards N^3LO on the electron line

Y. Ulrich, N^3LO kick-off workstop/thinkstart, Durham, 3-5 August 2022

- All virtual (three loops)



- Single real emission (two loops)



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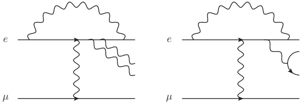
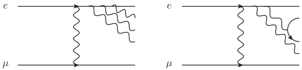


- Triple real



M. Fael, MUonE Collaboration Meeting, 16/05/2023, CERN

- **this contribution will allow improved perturbative predictions and more reliable theoretical uncertainty estimates**

Recent progress

- **the three-loop form factor with finite fermion mass is now available**

M. Fael, F. Lange, K. Schönwald, M. Steinhauser, Phys. Rev. Lett 128 (2022) 172003

M. Fael, F. Lange, K. Schönwald, M. Steinhauser, Phys. Rev.D 106 (2022) 034029

M. Fael, F. Lange, K. Schönwald, M. Steinhauser, Phys. Rev.D 107 (2023) 094017

- **All order subtraction scheme FKS$^\ell$ availale**

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

- **very recent generalisation of the LBK theorem to multi-photon emission** $\Longrightarrow$ extension of next-to-soft stabilisation to multiple radiation

T. Engel, JHEP 03 (2024) 004

- **real-virtual-virtual corrections recently recalculated with** $m_e \to 0$

S. Badger, J. Krys, R. Moodle, S. Zoia, JHEP 11 (2023) 041

V.S. Fadin, R.N. Lee, JHEP 11 (2023) 148

Fixed target experiment $\Longrightarrow$ bound electron effects

Fixed target experiment $\Longrightarrow$ bound electron effects

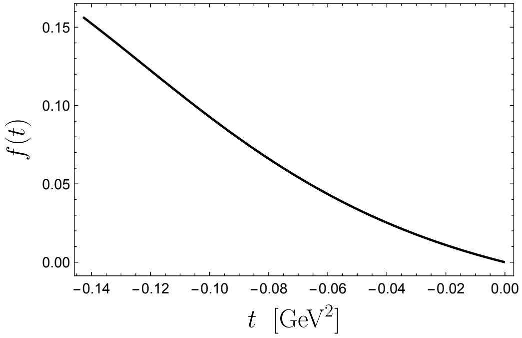
- **very recently estimated**

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

- for C

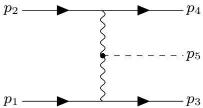
$$\frac{1}{\sigma}\frac{d\sigma}{dt} = \frac{1}{\sigma^0}\frac{d\sigma^0}{dt}\,(1 - K f(t))$$

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



Backgrounds

- **pion pair production forbidden** kinematically with the available $\sqrt{s}$
- **single π^0 production possible**



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

E. Budassi et al., PLB 829 (2022) 137138

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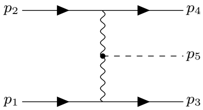
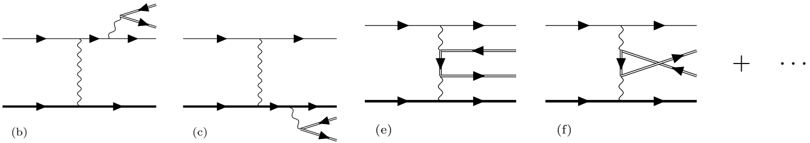


- **π^0 production** calculated and shown to be **well below 10^{-5}** w.r.t. $\mu e \to \mu e$

E. Budassi et al., PLB 829 (2022) 137138

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

- it also contributes at NNLO accuracy



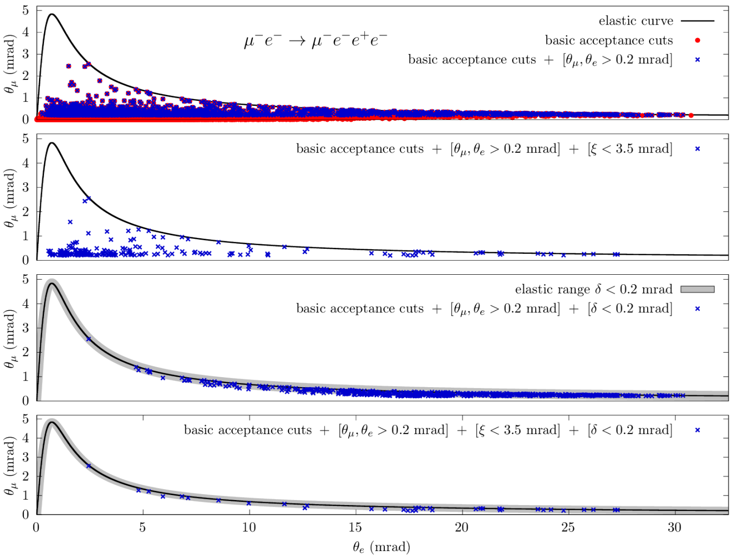
- the emission of an extra electron pair $\mu e \to \mu e\, e^+ e^-$ is potentially a dramatically large background, because of the presence of "peripheral" diagrams which develop powers of collinear logarithms upon integration

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

- **$\mu^\pm e^- \to \mu^\pm e^- \ell^+ \ell^-$ 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

- **it can mimic the signal if one particle is not reconstructed or two tracks overlap within resolution**
- **cross section scaling $\sim Z^2$**

- **GEANT4: “for the process of e^+e^- pair production the muon deflection is neglected”**

A.G. Bogdanov et al., IEEE transactions on nuclear science, 53, n. 2, April 2006

$\Longrightarrow$ **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
  - ρ_Z : nuclear charged density

- **different models for charge density**

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

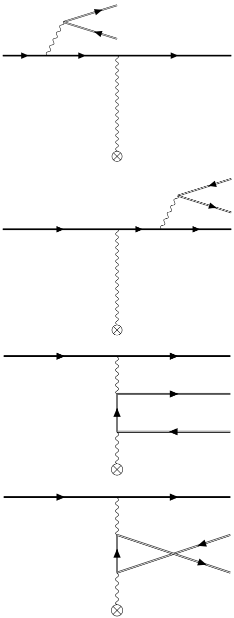
  - $F_Z(q) = 1$ (conservative)
  - 1 parameter Fermi model (1pF)

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

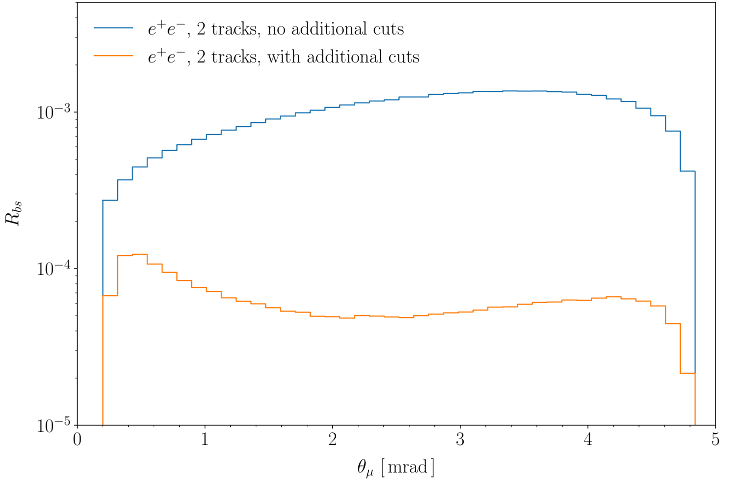
  - Fourier Bessel expansion (FB)

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

  - 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

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

- Effects of **heavy** $(M_{NP} \gg 1$ GeV$)$ NP mediators investigated through EFT with dim-6 operators
  - excluded (at the 10^{-5} level) by existing data
- Effects of **light** $(M_{NP} \leq 1$ GeV$)$ NP mediators investigated with spin-dependent general models
  - spin-0 NP mediators (ALPs)
  - spin-1 NP mediators (Dark Photons, light Z' vector bosons)
  - excluded (at the 10^{-5} level) by existing data

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

Summary

- **Given its precision requirements, MUonE represents a challenge 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`**
    - $\mu^{\pm} e^{-} \to \mu^{\pm} e^{-} \ell^{+} \ell^{-}$
    - $\mu^{\pm} N \to \mu^{\pm} N \ell^{+} \ell^{-}$

- **efforts for N^{3}LO started**

- **work in progress for matching with higher order QED corrections**

Past MUonE topical meetings

- MUonE theory workshops
  - Theory Kickoff Workshop, Padova, 4-5 September 2017
  - MITP Workshop, Mainz 19-23 February 2018
  - 2^{nd} Workstop/ThinkStart, Zürich, 4-7 February 2019
  - N^3LO kick-off workstop/thinkstart IPPP Durham, 3-5 August 2022
  - MITP Workshop, Mainz 14-18 November 2022
  - MITP Workshop, Mainz 03-07 June 2024
- Five General MUonE Collaboration Meetings

A collection of references on calculation developments

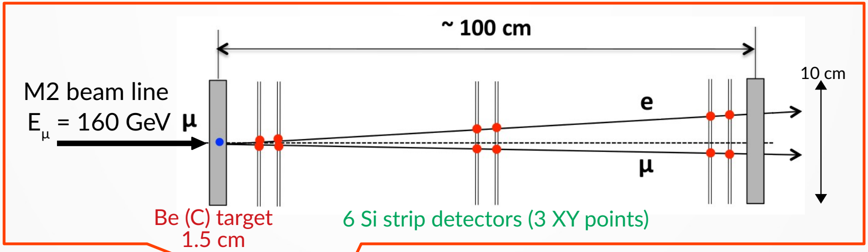
- Carloni Calame et al., PLB 746 (2015), 325
- Abbiendi et al., EPJ C77 (2017), 139
- Mastrolia et al., JHEP 11 (2017) 198
- Di Vita et al., JHEP 09 (2018) 016
- Alacevich et al., JHEP 02 (2019) 155
- Fael and Passera, PRL 122 (2019) 19, 192001
- Fael, JHEP 02 (2019) 027
- Engel et al., JHEP 02 (2019) 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

THANK YOU!

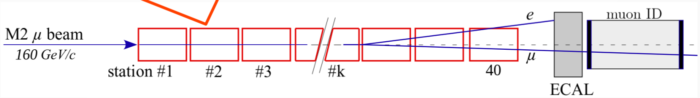
Few slides from R. Pilato for an exp. update

MITP Workshop, 03-07/06/2024, Mainz, Germany

The experimental apparatus



BMS ....



After LS3:
full apparatus with 40 stations

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R. Pilato, MITP Workshop, 3-7 June 2024

Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking = ~0.3% statistical accuracy on a^{HLO}

(~4x10^{12} events E_e > 1 GeV)

Competitive with the latest theoretical predictions

Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm in the signal region

Main systematic effects:

- Longitudinal alignment (<10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (<1%)
- Angular intrinsic resolution
- Non-uniform detector response

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Staged approach towards the full experiment

- 2017: dedicated test beam to study multiple scattering.
- 2018: test beam to study elastic scattering properties and event selection.
- 2021: first joint test CMS-MUonE
  with a few 2S modules prototypes (parasitic).
- 2022:
  - test with 1 tracking station.
  - test the calorimeter.
- 2023: test with 2 tracking stations + calorimeter.
- 2025: run with a scaled version of the complete apparatus:
  - 3 tracking stations;
  - Calorimeter;
  - Muon ID;
  - Beam Momentum Spectrometer (BMS).

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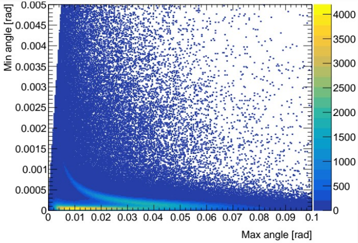
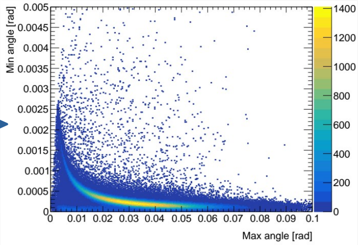
TB 2023
μ-e elastic scattering event selection

- Single μ_{in} candidate.
- μ_{out}, e_{out} pair candidate.



Initial selection

- Loose χ^2_{vtx} cut.
- $|z_{vtx} - z_{target}| < 3$ cm.
- Acoplanarity cut (elastic events are planar).



Work in progress:

- Exploit dedicated MC generators to study the backgrounds.
- Study the main sources of systematic error using tracker data:
  - Angular intrinsic resolution;
  - Beam energy scale.

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Run 2025

- MUonE recently submitted a proposal for a phase 1 of the experiment to the SPSC, concerning a small scale version of the final apparatus.
- If approved, MUonE will request 4 weeks of data taking in 2025.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

MUonE Phase 1 Experiment Proposal

April 25, 2024

Proposal for phase 1 of the MUonE Experiment

The MUonE Collaboration