The MUonE Project

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MENU2023

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Erbacher Hof, Mainz, October 15-20, 2023

Outline

- Motivations (a_μ or the muon g-2)
- Muon-electron scattering for a novel determination of a_μ^{HLO} (a space-like approach)
- Experimental status of the MUonE Project
- Theory activity
- Future plans

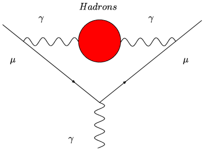
The muon g-2: experiment vs theory (in the SM)

➜ $a_\mu(\text{exp}) = 11659\mathbf{205.9}(2.2) \times 10^{-10}$ (0.19 ppm) Muon g-2 collaboration, **arXiv:2308.06230 [hep-ex]**

➜ $a_\mu(\text{SM}) = 11659\mathbf{181.0}(4.3) \times 10^{-10} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HLO}} + a_\mu^{\text{HNLO}} + a_\mu^{\text{HNNLO}} + a_\mu^{\text{HLbL,LO}} + a_\mu^{\text{HLbL,NLO}}$

↳ $693(4) \times 10^{-10}$

Muon g-2 Theory Initiative, Phys. Rept. 887 (2020) 1-166



The 5σ discrepancy reduces to $\sim 1\sigma$(ish) if using

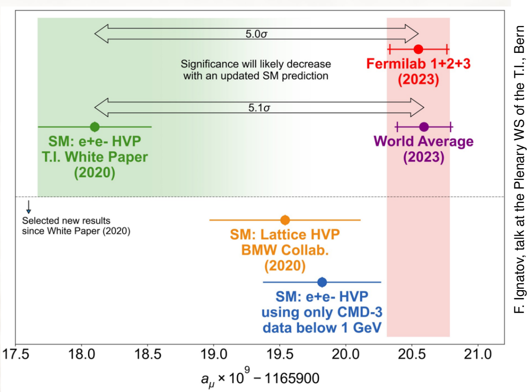
★ a_μ^{HLO} from Lattice QCD

BMW collaboration, Nature 593 (2021) 7857, 51

★ latest CMD-3 pion form-factor data in a_μ^{HLO}

CMD-3 collaboration, **arXiv:2302.08834 [hep-ex]**

✗ The scenario is cumbersome and puzzling



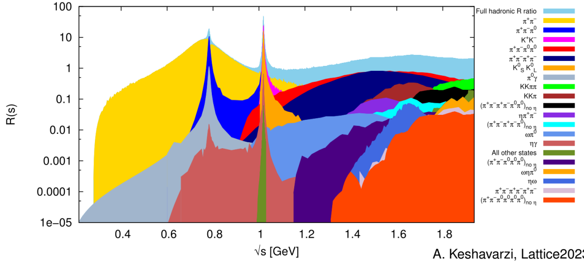
Standard approach to a_μ^{HLO}, with time-like data

- Using dispersion relations and the Optical Theorem

$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\, \sigma^0_{e^+e^-\to\text{had}}(s) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \frac{K(s) R^{\text{had}}(s)}{s} =$$

$$= \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left[\int_{m_{\pi^0}^2}^{E_{\text{cut}}^2} ds \frac{K(s) R^{\text{had}}_{\text{data}}(s)}{s} + \int_{E_{\text{cut}}^2}^{\infty} ds \frac{K(s) R^{\text{had}}_{\text{pQCD}}(s)}{s}\right]$$

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)\frac{s}{m_\mu^2}} \sim \frac{1}{s} \qquad R^{\text{had}}(s) = \sigma^0_{e^+e^-\to\text{had}}(s) \Big/ \left(\frac{4}{3}\frac{\pi\alpha^2}{s}\right)$$



A. Keshavarzi, Lattice2023

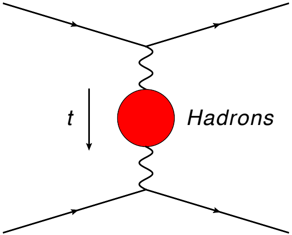
Alternatively: $a_\mu^{\rm HLO}$ with space-like data

- Alternatively (exchanging s and x integrations in $a_\mu^{\rm HLO}$)

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

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

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



⇝ $\Delta\alpha_{\rm had}(t)$ is the hadronic vacuum polarization correction to the running of the QED coupling constant, at negative momentum transfer (space-like)

★ $\Delta\alpha_{\rm had}(t)$ can be directly measured in a (single) experiment involving a space-like scattering process $\to a_\mu^{\rm HLO}$ can be independently evaluated!

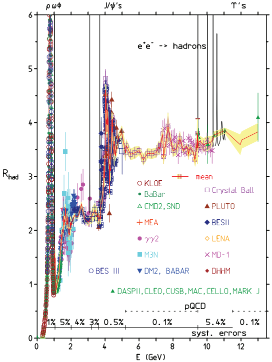
CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

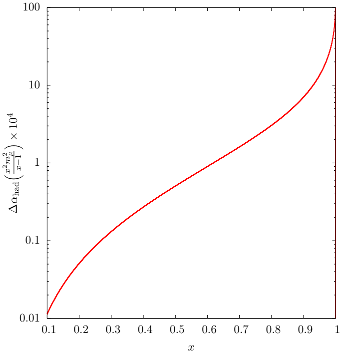
★ **Still a data-driven evaluation of $a_\mu^{\rm HLO}$, but with space-like data**

From time-like to space-like evaluation of $a_\mu^{\rm HLO}$

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

F. Jegerlehner, EPJ Web Conf. 118 (2016) 01016





CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

Smooth function

- $\mapsto$ **Time-like:** combination of many experimental data sets, control of radiative corrections 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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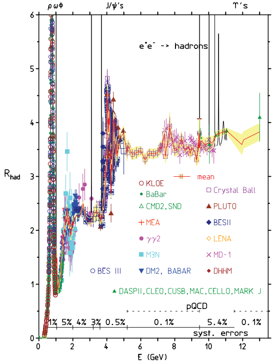

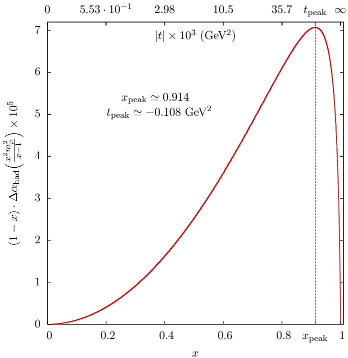

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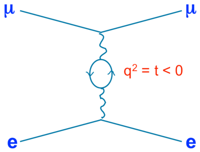
MUonE

Abbiendi *et al.* EPJC 77 (2017) no.3, 139

LoI: The MUonE Project, CERN-SPSC-2019-026; SPSC-I-252

MUonE Experiment Technical Proposal, in preparation

- $\mu e \to \mu e$ looks an ideal process. It's a "pure" t-channel process at tree-level



$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha}\right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha_{\text{lep. \& top}}(t) - \Delta\alpha_{\text{had}}(t)}$$

- 160 GeV high-intensity muon beam on atomic electrons in a low-Z target (Be/C) (CERN M2 line)
- boosted kinematics, t spans the correct range for space-like evaluation of a_μ^{HLO}

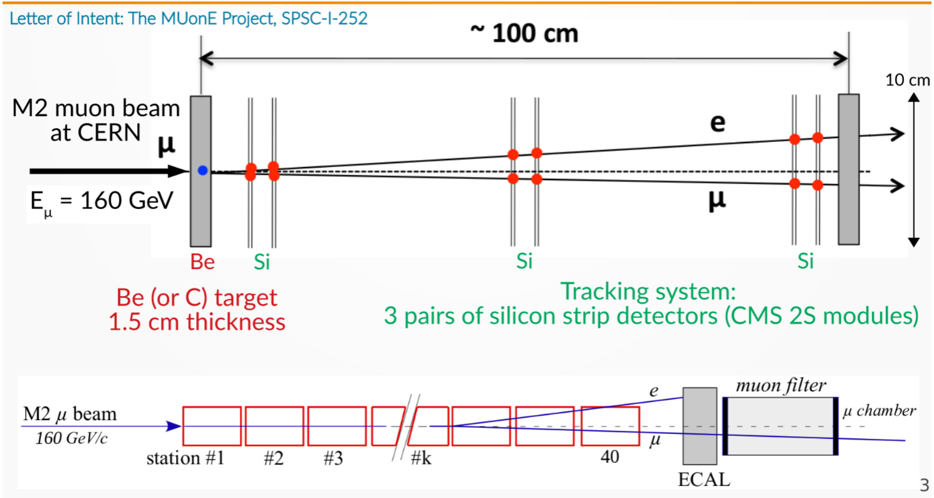
$$\sqrt{s} = 0.418 \text{ GeV} \qquad -0.153 < t < -0.001 \text{ GeV}^2$$

- with 3yr's of data taking → 0.3% statistical accuracy on a_μ^{HLO}

Main challenge: accuracy in the differential cross section(s) at the 10^{-5} level.

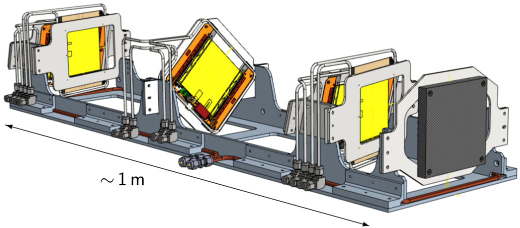
$a_\mu^{\text{HLO}} < 1\%$ implies 10^{-5} on $\mu e \to \mu e$ differential cross-sections

MUonE apparatus



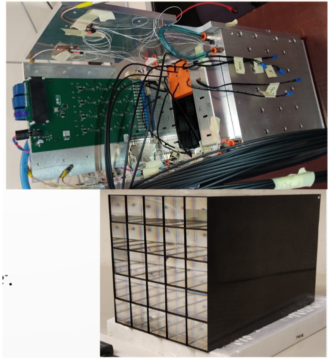
R. Pilato, EPS 2023

MUonE tracking station & ECAL



- 3 pairs of LHC 2S silicon strip modules
- modules may be tilted to reduce effective pitch; effect on alignment under study,
- frames made from Invar Fe/Ni alloy to maintain dimensional stability within 10 μm,
- monitored by holographic laser system (see below),
- temperature controlled environment.

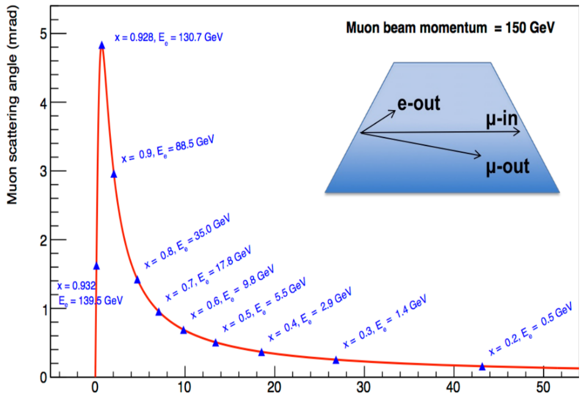
D. Počanić, MUon4Future Workshop, 2023



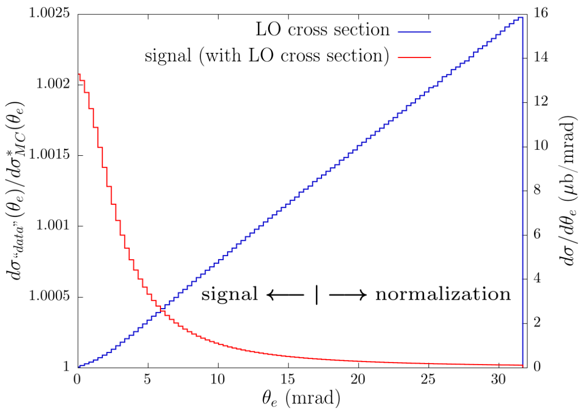
R. Pilato, Plenary WS T.I., Bern

- 5×5 $PbWO_4$ crystals,
  $A = 2.85 \times 2.85$ cm^2, $L = 22$ cm $(\sim 25X_0)$
- total area: $\sim 14 \times 14$ cm^2

Kinematics & “signal”



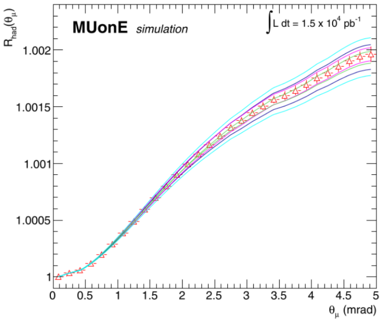
Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

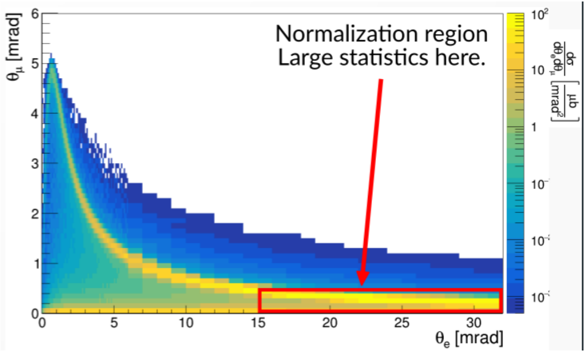


Theory

- The challenge of 10^{-5} accuracy requires the inclusion of **QED** Radiative Corrections at Next-to-Next-to-LO (NNLO) (and beyond) to $\mu e \to \mu e$. *Also backgrounds need to be precisely simulated!*
- Differential cross-sections must be simulated as precisely as possible, calculations must be provided as fully-exclusive Monte Carlo event generators for meaningful data analysis
- $\Delta\alpha_{\rm had}(t)$ will be extracted with a template fit method

Expected signal size:





Theory work

- Carloni Calame et al., PLB 746 (2015), 325
- 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
- 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
- Broggio et al., JHEP 01 (2023) 112
- T. Ahmed et al., **arXiv:2308.05028 [hep-ph]**
- F. Ignatov et al., **arXiv:2309.14205 [hep-ph]**

➜ New Physics studies
(NP contamination excluded in the signal region)

↦ A lively theory community is active to provide state-of-the-art calculations to match the required accuracy for meaningful data analysis

↦ We meet at "regular" theory workshops:
Padua '17, Zurich '19 & '23, Durham '22, MITP '18, '22, **MITP June '24**

↦ Independent numerical codes (Monte Carlo generators and/or integrators) are developed and cross-checked to validate high-precision calculations. Chiefly

✓ **Mesmer** in Pavia

github.com/cm-cc/mesmer

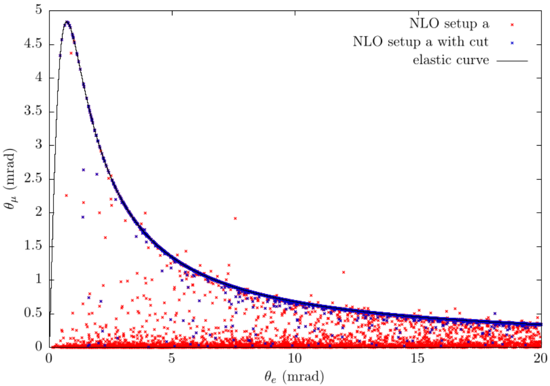
✓ **McMule** at PSI/IPPP

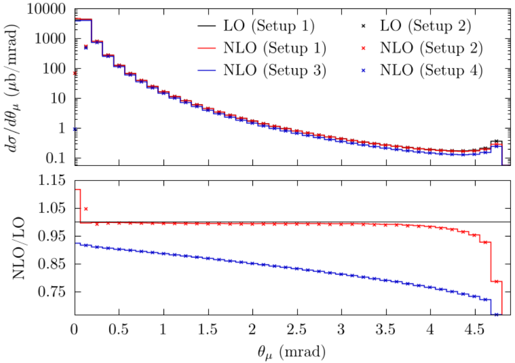
gitlab.com/mule-tools/mcmule

Radiative Corrections to $\mu e \to \mu e$ in **Mesmer**

- ➜ **Mesmer** is already used for feasibility studies and current simulations of the elementary processes. It includes:
- ✓ Next-to-Leading order corrections, *i.e.* with one extra real or virtual photon (exact)
  Alacevich et al., JHEP 02 (2019) 155
- ✓ photonic NNLO, with up to two extra real or virtual photons (the subset of virtual double-boxes are approximated)
  Carloni Calame et al., JHEP 11 (2020) 028

  Exact NNLO photonic corrections available in **McMule**. Differences of order $\frac{\alpha^2}{\pi^2} \log^2 \left(m_\mu^2/m_e^2\right)$
  Broggio et al., JHEP 01 (2023) 112
- ✓ NNLO virtual leptonic and hadronic vacuum polarization corrections (exact)
  Budassi et al., JHEP 11 (2021) 098
- ✓ real pair corrections ($\mu^\pm e^- \to \mu^\pm e^- \; e^+ e^-$): can mimic the signal, *potentially a dangerous background* (exact)
  ibidem
- ✓ π^0 production ($\mu e \to \mu e \pi^0, \pi^0 \to \gamma\gamma$), *a negligible background*
  Budassi et al., PLB 829 (2022) 137138
- ➜ "Nuclear" background $\mu N \to \mu N \; e^+ e^-$ available soon, work in progress (GEANT4 too crude!)





- points fall out of the elastic curve in the θ_μ-θ_e plane because of radiative events
- NLO QED radiative corrections at the % level, depend on event selection criteria

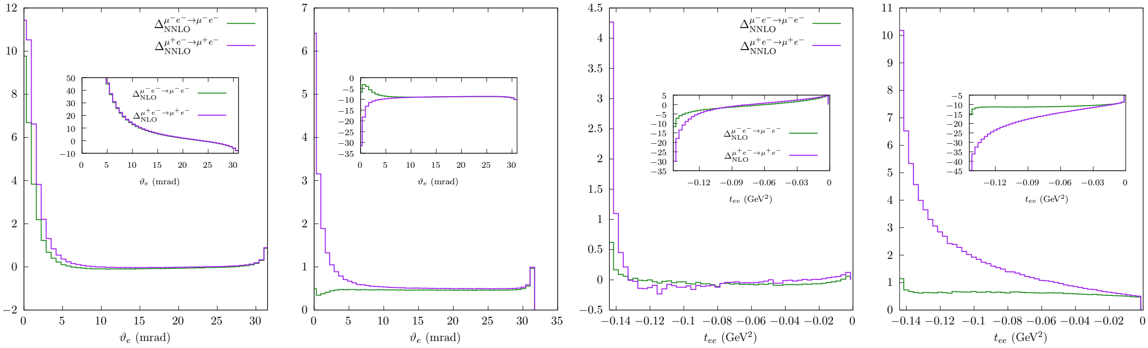
NNLO results

JHEP 11 (2020) 028

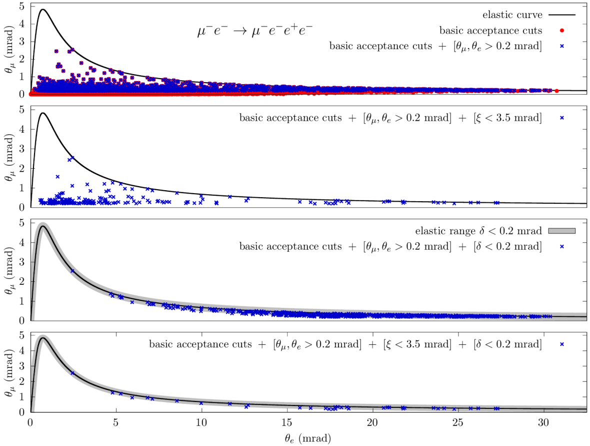
- Showing

$$\Delta^i_{\text{NNLO}} \equiv 100 \times \frac{d\sigma^i_{\text{NNLO}} - d\sigma^i_{\text{NLO}}}{d\sigma_{\text{LO}}}$$

⇝ full NNLO radiation for incoming μ^+ or μ^-, with or without acoplanarity cut

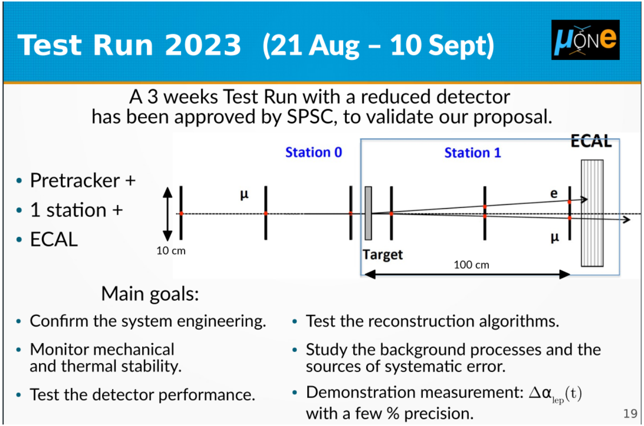


- $\mu e \to \mu e\ e^+e^-$ events with 2 visible tracks ("mimicking" $\mu e \to \mu e$)



⇝ only 0.007% of $\mu e \to \mu e\ e^+e^-$ events survives the combination of the three cuts

- A number of Test-Beams performed in ’17/’18/’21/’22
- **A 3-weeks Test Run with reduced apparatus performed last summer!**



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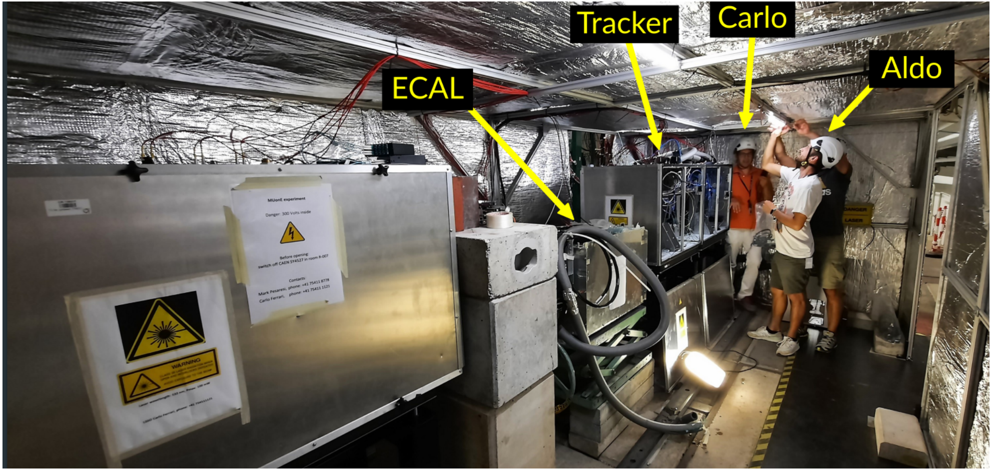
2023 Test Run



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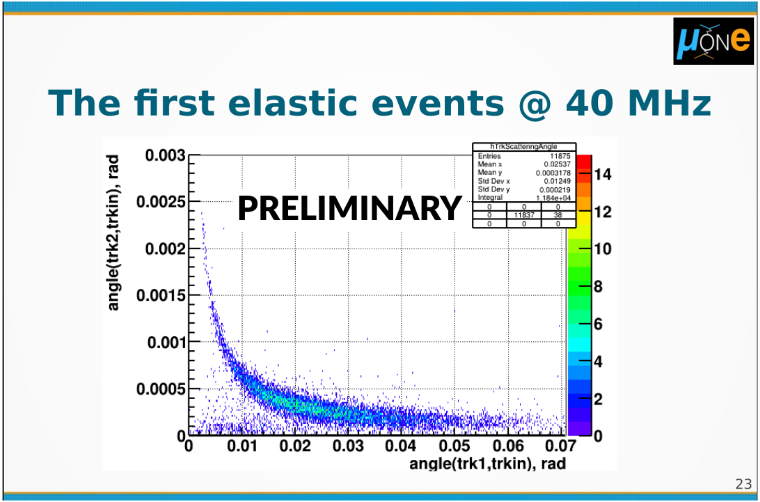
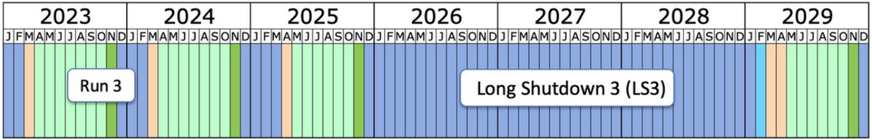


R. Pilato, Plenary WS T.I., Bern

Future



✓ **Experiment:**

- ➜ MUonE Technical Proposal in 2024 based on the results of 2023 Test Run.
  A measurement of $\Delta\alpha_{\text{leptonic}}(t)$ $[> 10 \times \Delta\alpha_{\text{had}}(t)]$ is feasible.
- ➜ Before CERN LS3 in 2026: 5-10 stations with 2-4 months of data taking,
  first evaluation of a_μ^{HLO} with MUonE data (few $\%$ precision)
- ➜ Full apparatus (40 stations) after LS3 to achieve the target precision (0.3% stat. and similar syst.)

✓ **Theory:**

- ➜ Include in MCs QED radiative corrections beyond NNLO
  (QED Parton Shower, YFS exponentiation, N^{3}LO on the electron line)
- ➜ Careful and tuned comparisons of results: independent implementations and cross-validation are extremely important to achieve the required precision on the theoretical side

MUonE (growing) collaboration: new collaborators always welcome!

New collaborators, especially on the experimental side, needed!