The muon g-2 and the MUonE project

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Balaton Limnological Research Institute of the Hungarian Academy of Sciences

status of $a_\mu = (g-2)/2$

- E821@BNL measurement with an error of 0.54 ppm

$$a_\mu^{\rm exp} = 116592089(63) \times 10^{-11}$$

G.W. Bennet et al. (Muon (g-2)), Phys. Rev. **D73** (2006) 072003

- Experimental prospects $\Longrightarrow$ see talk by T. Mibe
- **a couple of theoretical predictions**

$$a_\mu^{\rm SM} = 116591783(35) \times 10^{-11}$$

F. Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz

$$a_\mu^{\rm SM} = 116591820(36) \times 10^{-11}$$

Keshavarzi, Nomura, Teubner, arXiv:1802.02995

- $\Delta({\rm Th} - {\rm Exp}) = -306 \pm 72$ $\sim 4\sigma$ deviation

Three possible scenarios

- New Physics?
- systematics of the measurement?
- systematics of the theoretical prediction?

Let's see what are the ingredient to make $a_\mu \neq 0 \Longrightarrow$

$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HLO} + a_\mu^{\rm HHO}$

- QED perturbative corrections known up to 4 loops plus 5 loops partial calculation:
  $a_\mu^{\rm QED} = 116584718.86(30) \times 10^{-11}$ $\sim 99.99\%$ of the total

  T. Aoyama, M. Hayakawa, T. Kinoshita; S. Laporta, E. Remiddi; M. Passera

- two loop electroweak radiative corrections: $a_\mu^{\rm EW} = 153.6(1.1) \times 10^{-11}$

  Gnendiger, Stöckinger, Stöckinger-Kim

- $a_\mu^{\rm HLO} = 6894.6(32.5) \times 10^{-11} \Longrightarrow$ largest source of uncertainty

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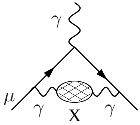

- Hadronic light-by-light: $a_\mu^{\rm LxL} = 103.4(28.8) \times 10^{-11}$

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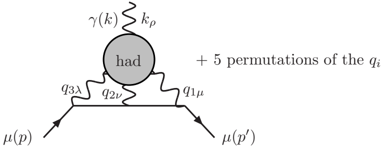


- Hadronic HO vacuum polarization: $a_\mu^{\rm HHO} = -87.0(0.6) \times 10^{-11}$

- perturbation theory (PT) reliable for leptons and $top-$quark
- **PT not reliable for light quark**

$\Rightarrow$ hadronic contribution from LQCD

$\Rightarrow$ via optical theorem, hadronic contribution from dispersion relation involving the total hadronic cross section measured experimentally at e^+e^- machines:

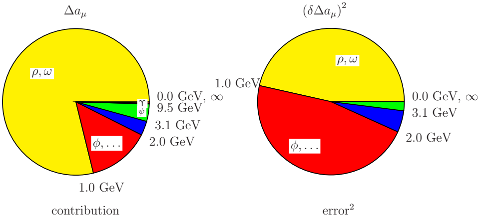
$$a_\mu^{\mathrm{HLO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{K(s)R(s)}{s^2}$$

$$= \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left(\int_{4m_\pi^2}^{E_{\mathrm{cut}}} ds \frac{K(s)R^{\mathrm{data}}(s)}{s^2} + \int_{E_{\mathrm{cut}}^2}^{\infty} ds \frac{K(s)R^{\mathrm{PQCD}}(s)}{s^2}\right)$$

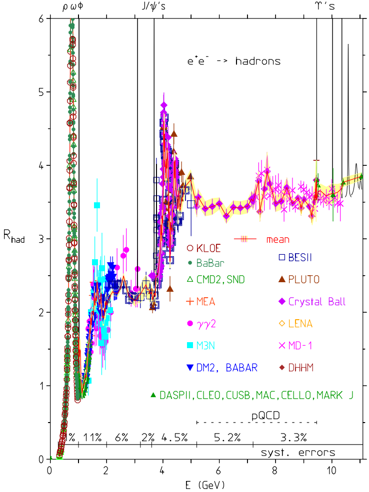
$$R(s) = \frac{\sigma^0(e^+e^- \to \gamma^* \to \mathrm{hadrons})}{\frac{4}{3}\frac{\pi\alpha^2}{s}}$$

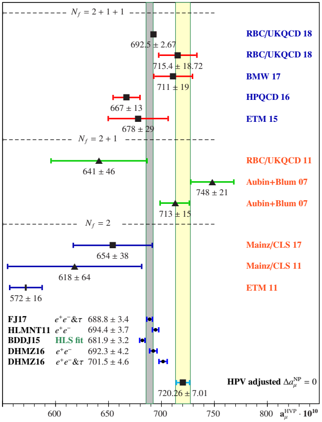
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)\frac{s}{m^2}} \sim \frac{1}{s}$$

- due to the $\frac{1}{s^2}$ in the dispersion relation,



f. Jegerlehner, in arXiv:1905.05078





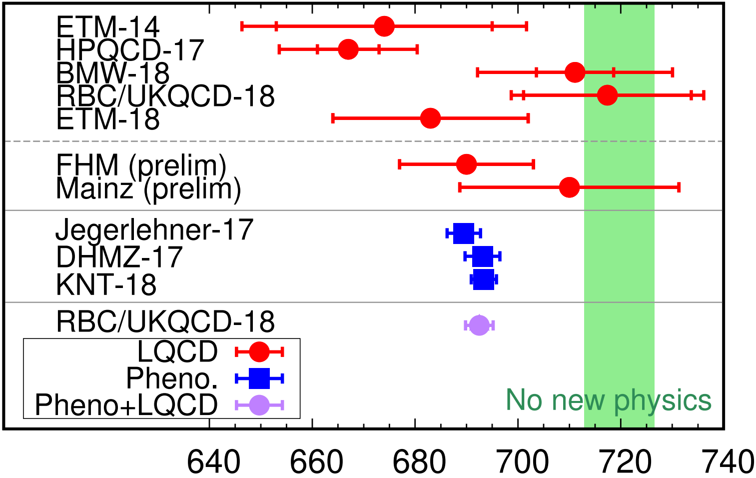
F. Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz

- Integral over time-like data extremely delicate due to combination of many (~ 40) exclusive channels

see talk by S. Eidelman

- several LQCD groups made recent progress, but not yet competitive in precision

$a_\mu^{\text{LO-HVP}} \cdot 10^{10}$



K. Miura, arXiv:1901.09052

- 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]

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

$$a_\mu^{\rm HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^\infty ds \frac{K(s)R(s)}{s^2} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\rm had}(t(x))$$

Carloni Calame, Passera, Trentadue and Venanzoni, Phys. Lett. B **746** (2015) 325

$$a_\mu^{\rm HLO} = -\frac{\alpha}{\pi}\int_{-\infty}^0 \frac{dt}{\beta t}\left(\frac{1-\beta}{1+\beta}\right)^2 \Delta\alpha_{\rm had}(t)$$

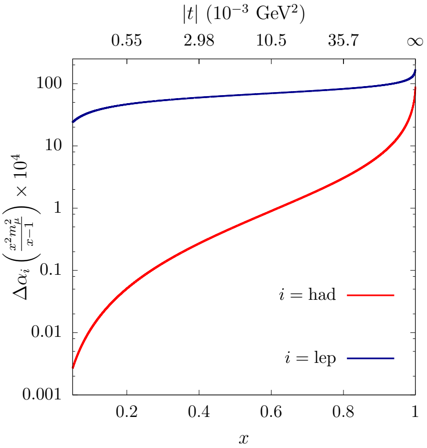
where

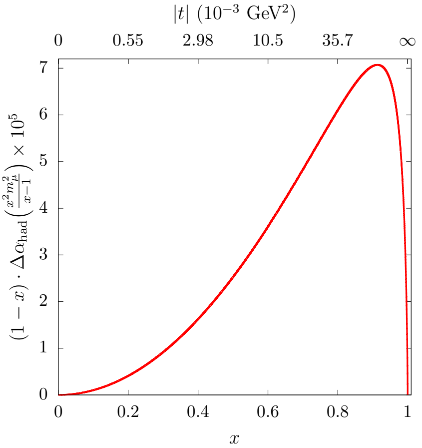
$$t(x) = \frac{x^2 m_\mu^2}{x-1} \quad \beta(t) = \sqrt{1-\frac{4m_\mu^2}{t}} \quad x(t) = \frac{t\,(1-\beta(t))}{2m_\mu^2} \quad t = \begin{cases} 0^- & \text{for } x\to 0^+ \\ -\infty & \text{for } x \to 1^- \end{cases}$$

$\Delta\alpha_{\rm had}(t)$ is the hadronic contribution to the running of $\alpha_{\rm QED}(q^2) = \frac{\alpha}{1-\Delta\alpha(q^2)}$

- ⋆ $a_\mu^{\rm HLO}$ can be obtained by measuring the running of $\alpha_{\rm QED}$ in a space-like process
- ⋆ $\Delta\alpha_{\rm had}(t)$ in the integrand is evaluated in the space-like region (negative transfer momenta) where it is a smooth function
- ⋆ Roughly, to be competitive with current time-like evaluations, $\Delta\alpha_{\rm had}(t)$ needs to be known at some $\%$ level

General considerations





- $\Delta\alpha_{\mathrm{had}}(t(x))$ (red) as a function of x
- $\Delta\alpha_{\mathrm{lep}}(t(x))$ (blue) as a function of x

- integrand function $(1-x)\Delta\alpha_{\mathrm{had}}(t(x))$

$$x_{\mathrm{peak}} \simeq 0.914$$
$$t_{\mathrm{peak}} \simeq -0.108\ \mathrm{GeV}^2$$

$\mu e \to \mu e$ elastic scattering in a fixed target experiment

G. Abbiendi *et al.*, Eur. Phys. J. C **77** (2017) no.3, 139

↦ A ∼150 GeV high-intensity (∼1.3×10^7 μ's/s) muon beam available at CERN North Area

↦ Muon scattering on a low-Z target ($\mu e \to \mu e$) looks an ideal process

- ⋆ it is a pure t–channel process →

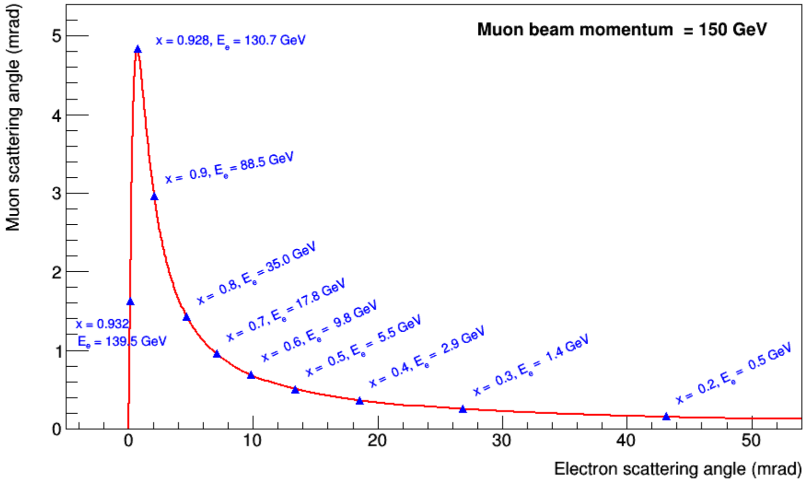
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha} \right|^2$$

- ⋆ Assuming a 150 GeV incident μ beam we have

$s \simeq 0.164\ \mathrm{GeV}^2$ $\quad -0.143 \lesssim t < 0\ \mathrm{GeV}^2$ $\quad 0 < x \lesssim 0.93$ **it spans the peak!**

- ⋆ the region $0.9 \le x < 1$ can be covered with LQCD + PQCD

M. Marinkovic, MITP Workshop, 19-23 February 2018, Mainz

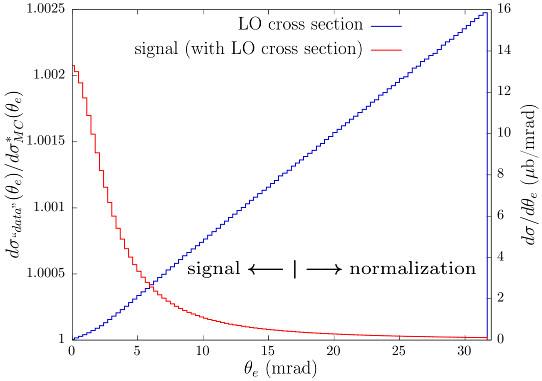


- **where is the challenge?**

$$\text{Our signal} \equiv \frac{dN_{data}(O_i)}{dN_{MC}(O_i)|_{\Delta\alpha_{had}(t)=0}} \equiv \frac{dN_{data}(O_i)}{dN^*_{MC}(O_i)} =$$

$$= \frac{d\sigma_{data}(O_i)}{d\sigma^*_{MC}(O_i)} = \frac{dN_{data}(O_i)}{N^{norm}_{data}} \times \frac{\sigma^{norm}_{MC}}{d\sigma^*_{MC}(O_i)} \simeq$$

$$\simeq 1 + 2\left[\Delta\alpha_{\text{lep}}(O_i) + \Delta\alpha_{\text{had}}(O_i)\right] \qquad \text{(at LO)}$$



$$\boldsymbol{\delta(\Delta\alpha_{\text{had}}(t)) \sim 0.3\% \Longrightarrow \sigma^{\text{norm}}_{\text{MC}}/d\sigma^*_{\text{MC}} \sim 10^{-5}}$$

statistics and (main) systematic uncertainties

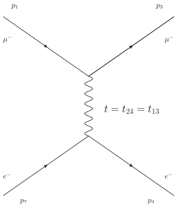
- **statistics**: CERN muon beam M2 ($E = 150$ GeV), $1.3 \cdot 10^7\ \mu/s$ with a target of Be layers (total thickness 60 cm) $\Longrightarrow L \sim 1.5 \cdot 10^7$nb^{-1} $\Longrightarrow$ statistical sensitivity ~ 0.3% on $a_\mu^{HLO} (\sim 20 \cdot 10^{-11})$

Sistematics

- theoretical: higher order radiative corrections modify the shapes
  - order of magnitude estimate, barring infrared logs and setting $c_{i,j} \sim 10$
  - $c_{1,1} \left(\frac{\alpha}{\pi}\right) L \sim 0.2$ $\quad c_{1,0} \left(\frac{\alpha}{\pi}\right) \sim 2.5 \cdot 10^{-2}$
  - $c_{2,2} \left(\frac{\alpha}{\pi}\right)^2 L^2 \sim 5 \cdot 10^{-3}$ $\quad c_{2,1} \left(\frac{\alpha}{\pi}\right)^2 L \sim 5 \cdot 10^{-4}$ $\quad c_{2,0} \left(\frac{\alpha}{\pi}\right)^2 \sim 5 \cdot 10^{-5}$
  - $c_{3,3} \left(\frac{\alpha}{\pi}\right)^3 L^3 \sim 1.5 \cdot 10^{-4}$ $\quad c_{3,1} \left(\frac{\alpha}{\pi}\right)^3 L^2 \sim 1.5 \cdot 10^{-5}$ $\quad c_{3,0} \left(\frac{\alpha}{\pi}\right)^3 L \sim 1.5 \cdot 10^{-6}$
  - the most advanced technologies for NNLO calculations and higher order resummation are needed

- (main) experimental sources
  - multiple scattering: E_e in normalization region much lower than in signal region Effect $\sim 1/E \Longrightarrow$ it affects signal and normalization in different way
  - absolute μ beam energy scale, 5 MeV $\Longrightarrow 10^{-5}$ effect
  - electron pair production
  - bremsstrahlung

Theoretical status



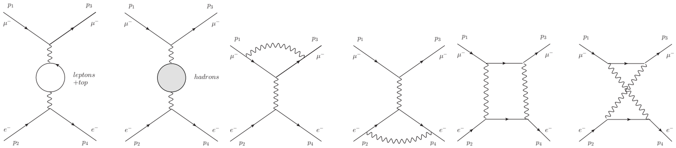
- analytical expression for tree level

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

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

(Van Nieuwenhuizen 1971, D'Ambrosio 1983, Kukhto et al. 1987, Bardin, Kalinovskaya 1997)

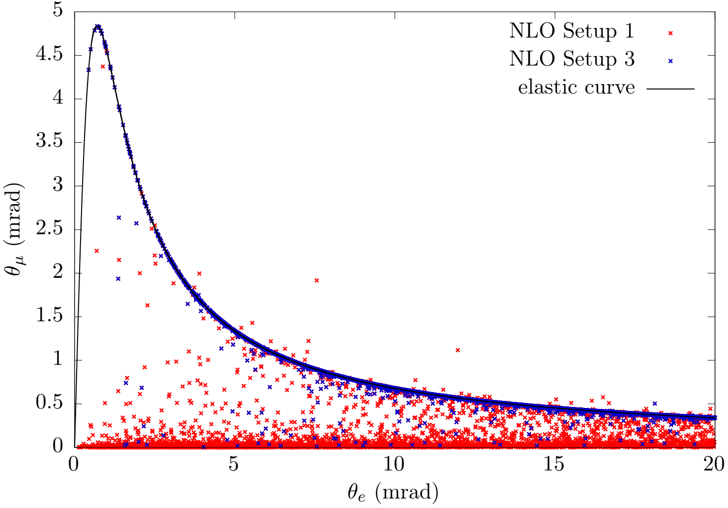
- NLO virtual diagrams



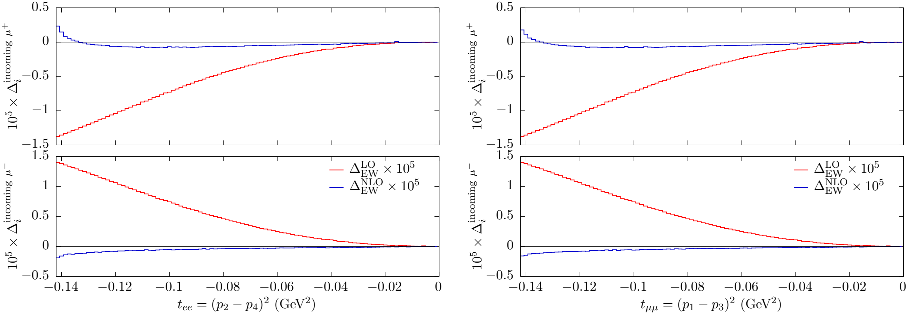
- and corresponding real emission diagrams
- **NLO matrix elements** calculated with finite m_μ and m_e mass effects and a **Monte Carlo** program has been developed and taylored to the fixed target kinematics

Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini, arXiv:1811.06743

θ_e-θ_μ correlation **(in the lab. frame)**



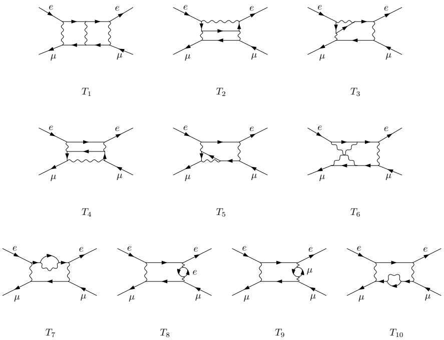
EWKology on t_{ee} & $t_{\mu\mu}$



Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini, arXiv:1811.06743

- tree-level Z-exchange important at the 10^{-5} level
- purely weak RCs (in QED NLO units) at a few 10^{-6} level

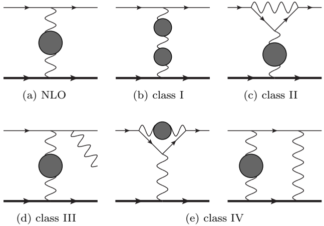
towards NNLO amplitudes

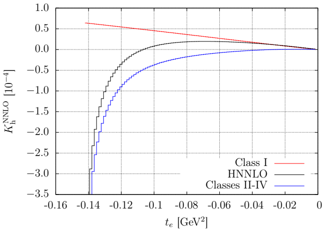


Mastrolia, Passera, Primo, Schubert, arXiv:1709.07435

Di Vita, Laporta, Mastrolia, Primo, Schubert, arXiv:1806.08241

- same diagrams needed for NNLO QCD $t\bar{t}$ production at the LHC





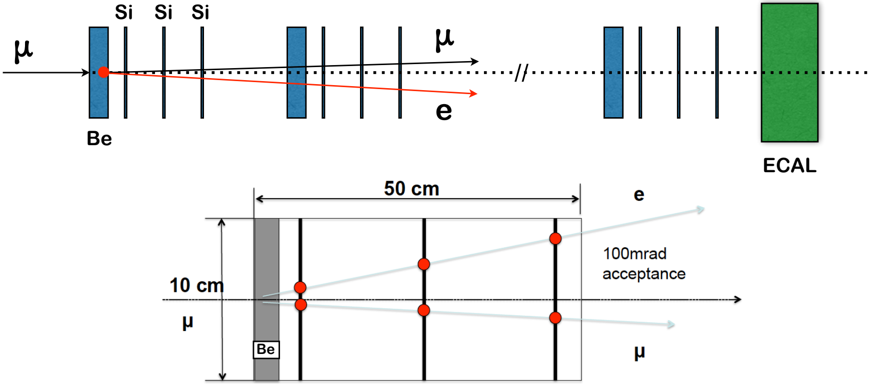
Fael, Passera, arXiv:1901.03106

- relevant on the target precision scale
- even larger contributions from lepton (mainly electron) loops
  - expected larger cancellation with real part (lepton pair emission)

work in progress

- a modular apparatus has been proposed

G. Abbiendi *et al.*, Eur. Phys. J. C **77** (2017) no.3, 139

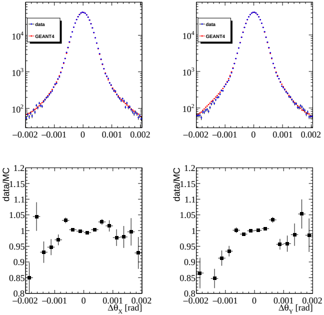


First Test Beam in 2017 to study multiple scattering

- 27 September - 3 October 2017, CERN, H8 Beam Line
- adapted UA9 apparatus

Beam	Target Type	N events$\times 10^6$
12 GeV e^-	8 mm C	15
20 GeV e^-	8 mm C	12
12 GeV e^-	20 mm C	15

G. Abbiendi et al., arXiv:1905.11677



- data well described by GEANT in the core region
- some disagreement on the tails but too low statistics
- **second testbeam in 2018** analysis in progress

- International Collaboration has been setup

- Letter of Intent just submitted to CERN SPSC

- schedule
    - three week Pilot run towards the end of 2021
    - detector assembled during 2022
    - run during LHC Run 3

Summary

- $(g-2)_\mu$ discrepancy between E821 result and SM predictions reached the 4σ level
- HLO vacuum polarization contribution is the dominant source of th. uncertainty
- different methods required to allow independent cross-checks
  - time-like dispersive approach: the most precise up to now
  - LQCD calculations: not yet competitive but improving
  - space-like dispersive approach and MUonE experiment proposal: promising, provided theoretical and experimental systematics are kept under control at the level of 10^{-5}
    - synergic collaboration between theorists and experimentalists