MUonE project

F. Piccinini

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La Thuile, February 27th, 2018

- 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]

- 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

- Error reduction by about a factor of 4 in few years with E989@FNAL

R.M. Carey et al., (2009), Fermilab-Proposal-0989

- E34@JPARC can later cross-check the E989 result with a completely independent method

J. Imazato, Nucl. Phys. Proc. Suppl. 129 (2004) 81, J-PARC Proposal

- Theoretical prediction

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

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

- $\Delta({\rm Th} - {\rm Exp}) = -306 \pm 72$ $\sim 4\sigma$ deviation
  - New Physics?
  - systematics of the measurement?
  - systematics of the theoretical prediction? $\Longrightarrow$

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

- 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

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

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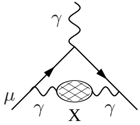

- Hadronic light-by-light: $a_\mu^{\rm LxL} = 103.4(28.8) \times 10^{-11}$

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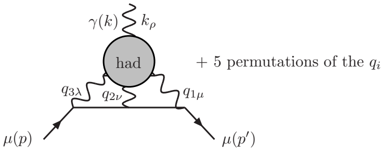


- Hadronic HO vacuum polarization: $a_\mu^{\rm HHO} = -87.0(0.6) \times 10^{-11}$
- two loop electroweak radiative corrections: $a_\mu^{\rm EW} = 153.6(1.1) \times 10^{-11}$

Gnendiger, Stöckinger, Stöckinger-Kim

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

$\Rightarrow$ hadronic contribution from LQCD

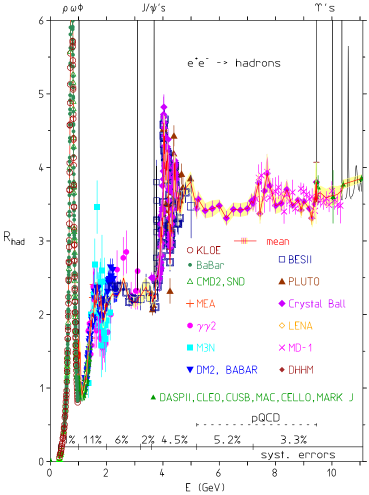
$\Rightarrow$ via optical theorem, hadronic contribution from dispersion relation involving the total hadronic cross section measured experimentally at e^+e^- machines:

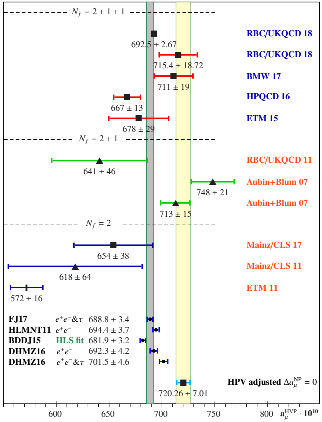
$$a_\mu^{\mathrm{HLO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{K(s)R(s)}{s^2}$$

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

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

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





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- LQCD not yet competitive in precision
- Integral over time-like data extremely delicate due to combination of many exclusive channels

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

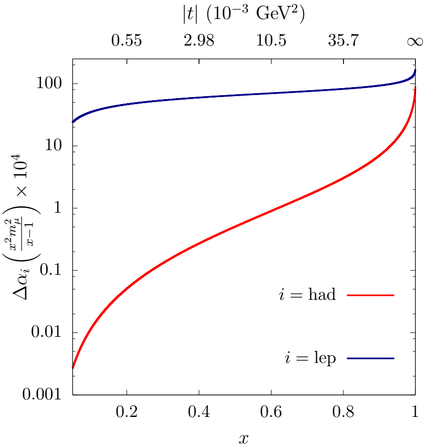
$$a_\mu^{\rm HLO} = -\frac{\alpha}{\pi}\int_{-\infty}^{0} \frac{dt}{\beta t}\left(\frac{1-\beta}{1+\beta}\right)^2 \Delta\alpha_{\rm had}(t)$$

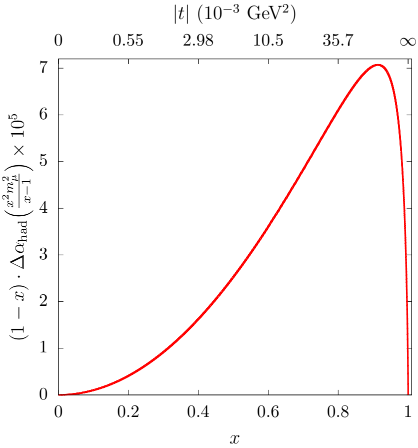
where

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

$\Delta\alpha_{\rm had}(t)$ 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





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

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

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

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

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

$\mapsto$ A 150 GeV high-intensity ($\sim$1.3$\times 10^7$ μ's/s) muon beam available at CERN North Area

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

⋆ it is a pure t–channel process $\to$

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

⋆ Assuming a 150 GeV incident μ beam we have

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

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

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

μe scattering kinematics for leading order ($2 \to 2$, elastic process)

p_1, p_2 initial state μ and e $\quad$ p_3, p_4 final state μ and e

In the lab

$$\begin{aligned} p_1 &= (E_\mu^{beam}, 0, 0, p) \\ p_2 &= (m_e, 0, 0, 0) \\ p_3 &= p_1 + p_2 - p_4 \\ p_4 &= (E_e, p_e \sin\theta_e, 0, p_e \cos\theta_e) \end{aligned}$$

In the center of mass

$$\begin{aligned} p_1 &= (E^\mu_{CM}, 0, 0, p_{CM}) \\ p_2 &= (E^e_{CM}, 0, 0, -p_{CM}) \\ p_3 &= (E^\mu_{CM}, p_{CM}\sin\theta, 0, p_{CM}\cos\theta) \\ p_4 &= (E^e_{CM}, -p_{CM}\sin\theta, 0, -p_{CM}\cos\theta) \end{aligned}$$

Invariants:

$$\begin{aligned} s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\ &= m_e^2 + m_\mu^2 + 2E^\mu_{CM} E^e_{CM} + 2p^2_{CM} \\ &= m_e^2 + m_\mu^2 + 2E_\mu^{beam} m_e \end{aligned}$$

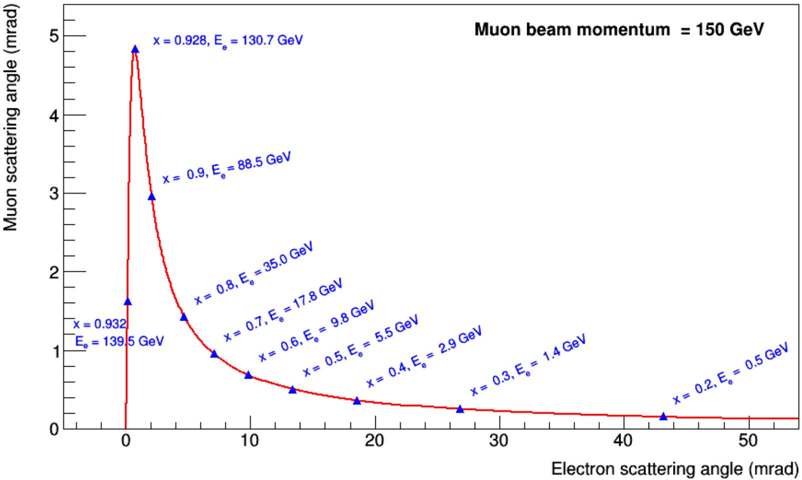
$$\begin{aligned} t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\ &= -2p^2_{CM}(1 - \cos\theta) \\ &= 2m_e^2 - 2E_e m_e \end{aligned}$$

$$p_{CM} = \frac{1}{2}\sqrt{\frac{\lambda(s, m_\mu^2, m_e^2)}{s}}$$

$$t = m_\mu^2 \frac{x^2}{x-1} \propto E_e$$

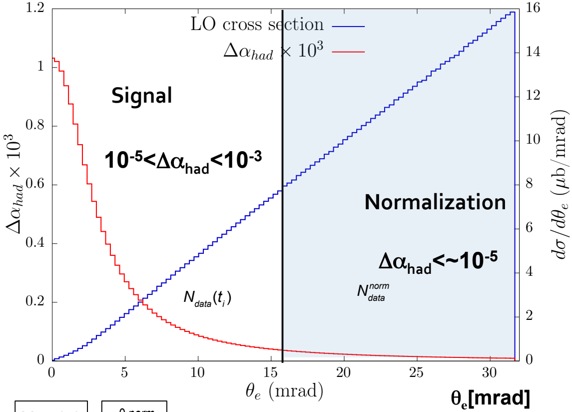
$$E_e = m_e \frac{1 + r^2\cos^2\theta_e}{1 - r^2\cos^2\theta_e}$$

$$r \equiv \frac{\sqrt{\left(E_\mu^{beam}\right)^2 - m_\mu^2}}{E_\mu^{beam} + m_e}$$



- **where is the challenge?**

MUonE : signal/normalization region



$$\frac{N_{data}(t_i)}{N_{MC}^0(t_i)} = \boxed{\frac{N_{data}(t_i)}{N_{data}^{norm}}} \times \boxed{\frac{\sigma_{MC}^{0,norm}}{\sigma_{MC}^0(t_i)}} \sim 1 - 2(\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

Ratio of data $N_{signal}(t)/N_{normalization}$

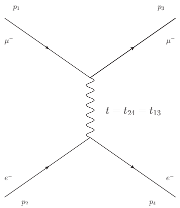
a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

G. Venanzoni, MUonE @MITP, Mainz 19 February 2018

(main) systematic uncertainties

- theoretical: higher order radiative corrections modify the shapes
  - 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
  - electron pair production
  - bremsstrahlung

Theoretical status



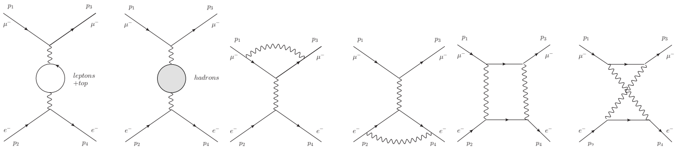
- analytical expression for tree level

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

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

- NLO virtual diagrams

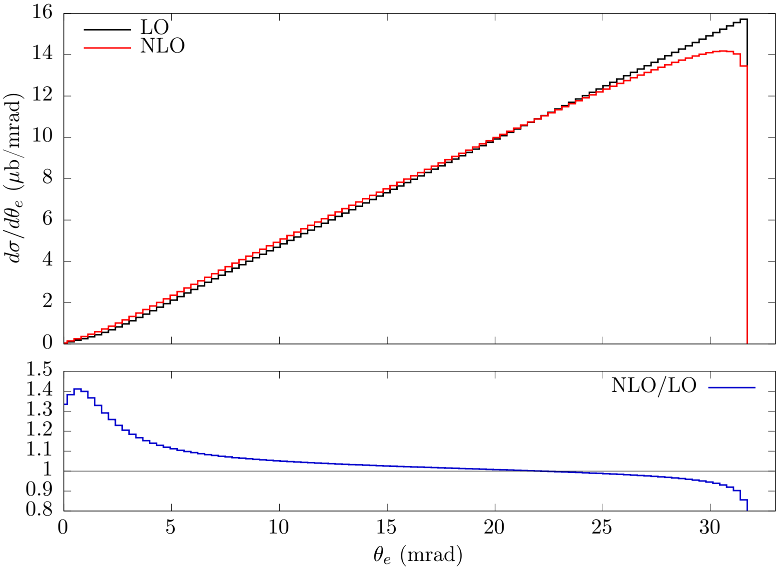
(Van Nieuwenhuizen 1971, D'Ambrosio 1983, Kukhto et al. 1987, Bardin, Kalinovskaya 1997)



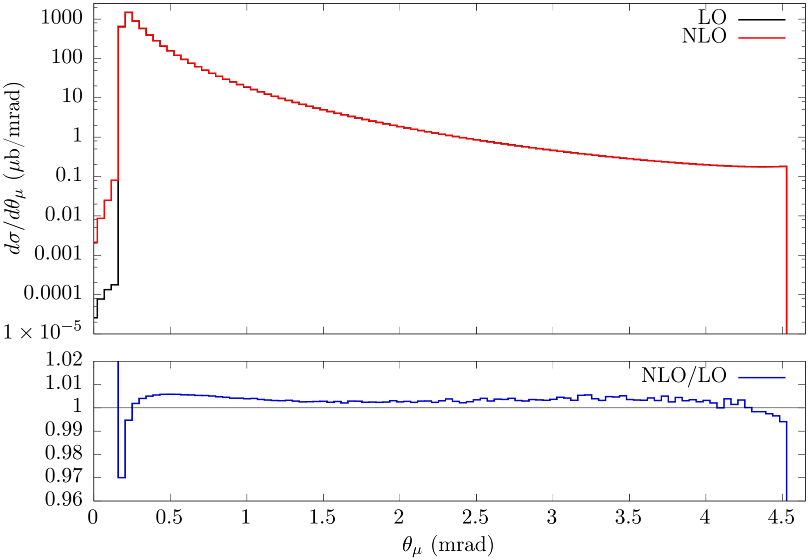
- and corresponding real emission diagrams
- NLO matrix elements calculated with finite m_μ and m_e mass effects and a Monte Carlo program has been developed and taylored to the fixed target kinematics

M. Alacevich et al., in progress

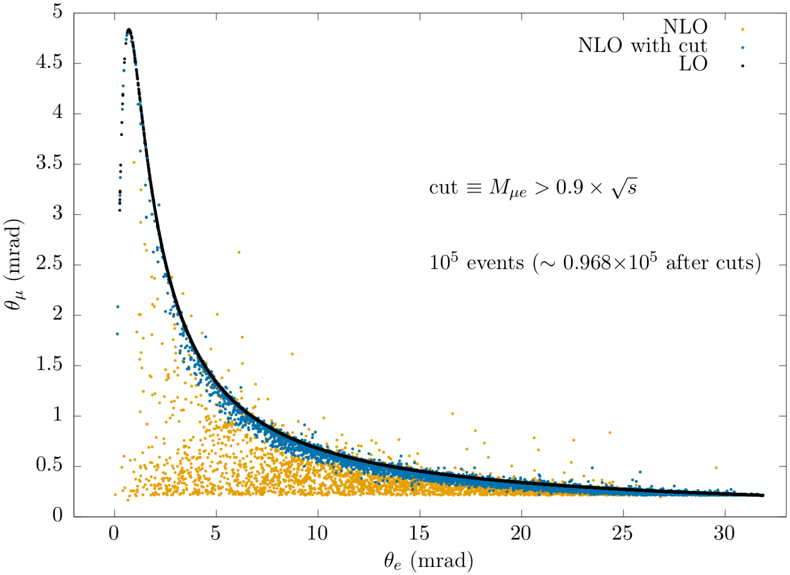
θ_e distribution and corrections in the lab



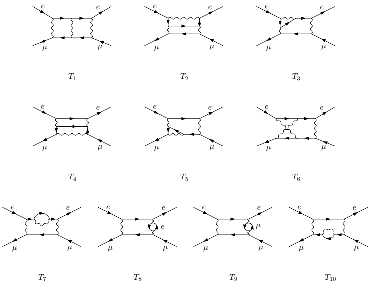
θ_μ distribution and corrections in the lab



μ-e angle correlation in the lab



towards NNLO amplitudes



Mastrolia, Passera, Primo, Schubert, arXiv:1709.07435

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

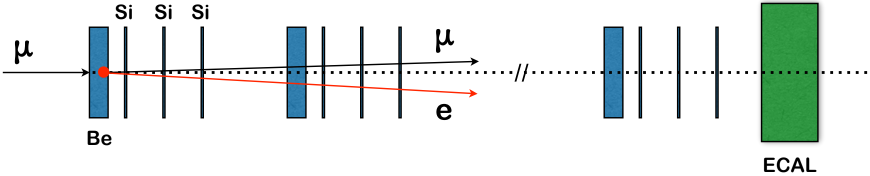
Fael, Passera, in progress

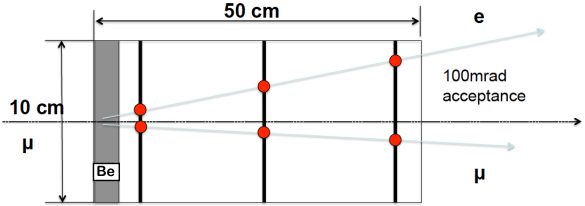
- NLO vacuum polarization corrections

On the experimental side

- a modular apparatus has been proposed

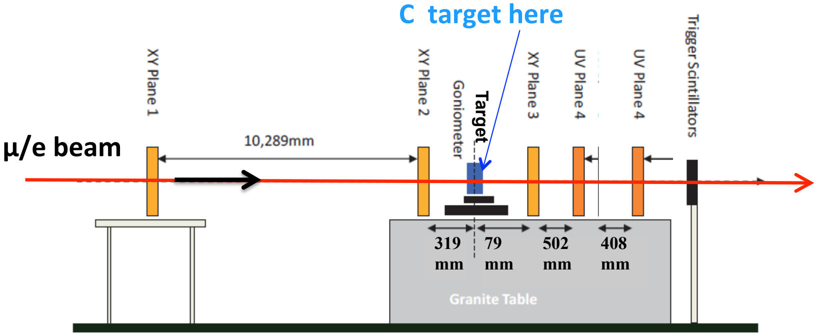
G. Abbiendi *et al.*, Eur. Phys. J. C **77** (2017) no.3, 139



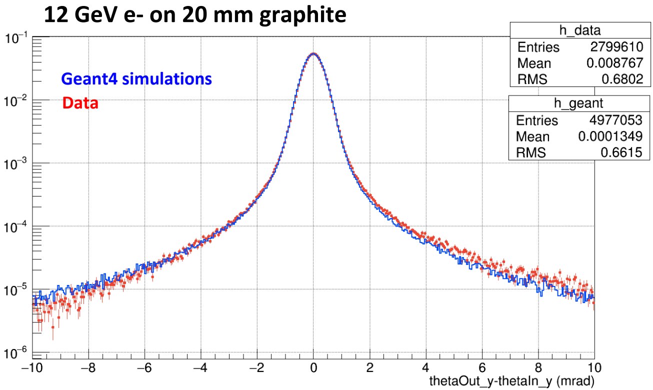


First Test Beam in 2017 to study multiple scattering

- 27 September - 3 October 2017, CERN, H8 Beam Line
- adapted UA9 apparatus
- electron beams of 12 GeV and 20 GeV; μ of 160 GeV
- 10^7 events with graphite targets of thickness 2, 4, 8, 20 mm



Test Beam results



Agreement of the gaussian core of the distributions better than 1 %

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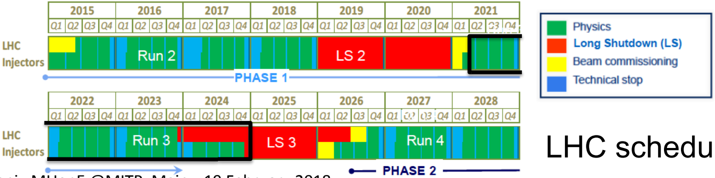
U. Marconi, MITP Workshop, 19-23 February 2018, Mainz

Plans

- **2018-2019**
  - Detector optimization studies: Simulation and Test Beam
  - Theoretical studies
  - Set up a collaboration
  - Letter of Intent to the SPSC
- **2020-2021**
  - Detector construction and installation
    (a staged version of the detector may be)
- **2022–2024**
  - Start the data taking after LS2 to measure $\mathbf{a_\mu^{HLO}}$
    (not necessarily the ultimate precision)



LHC schedule

G. Venanzoni, MUonE @MITP, Mainz 19 February 2018

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 $10^{-4}/10^{-5}$
        - progress on the theory side and on the optimization studies related to the experiment
        - synergic collaboration between theorists and experimentalists