MUonE status: theory and experiment

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Second Plenary Workshop of
the Muon g-2 Theory Initiative

Helmholtz-Institut Mainz, June 18-22, 2018

Outline

- Introduction to the **MUonE project**
- QED radiative corrections to $\mu e \to \mu e$:
  NLO calculation (and phenomenology)
- Theory status and progress
- Experimental status:
  challenges, test beams at CERN
- Plans for the near future

Relevant literature:

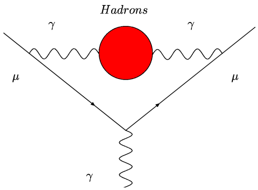
- G. Abbiendi *et al.*,
  Measuring the leading hadronic contribution to the muon g-2 via μe scattering
  Eur. Phys. J. C **77** (2017) no.3, 139 - **arXiv:1609.08987 [hep-ex]**
- C. M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni,
  A new approach to evaluate the leading hadronic corrections to the muon g-2
  Phys. Lett. B **746** (2015) 325 - **arXiv:1504.02228 [hep-ph]**

Master formula

- Standard approach

$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\; K(s)\; \sigma^0_{e^+e^-\to had}(s)$$

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

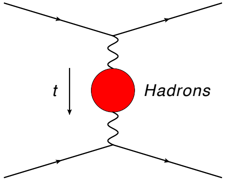


- Alternatively (exchanging s and x integrations in $a_\mu^{\rm HLO}$)

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

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

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



★ $\Delta\alpha_{\rm had}(t)$ can be directly measured in a (single) experiment involving t-channel (space-like) scattering

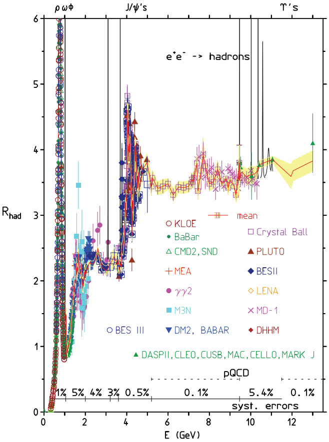
Arbuzov *et al.* EPJC 34 (2004) 267

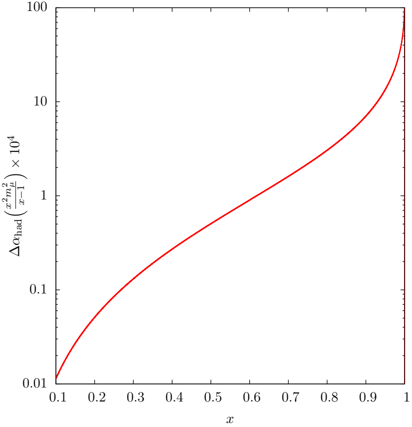
Abbiendi *et al.* (OPAL) EPJC 45 (2006) 1

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

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

F. Jegerlehner, EPJ Web Conf. 118





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

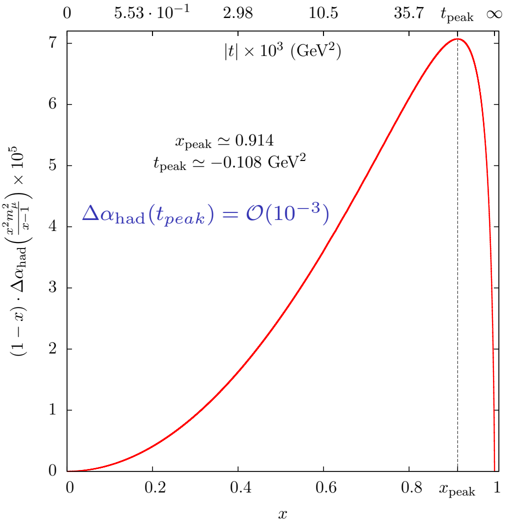
Smooth function

$\mapsto$ **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.

General considerations

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



$$x_{\rm peak} \simeq 0.914 \qquad t_{\rm peak} \simeq -0.108 \text{ GeV}^2 \simeq -(330 \text{ MeV})^2$$

General considerations

- To get $\Delta\alpha_{\rm had}(t)$, the goal is to measure the (absolute) running of $\alpha_{\rm QED}(t)$

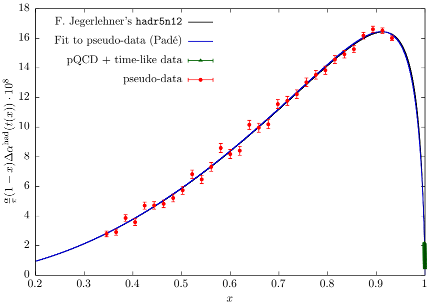
  $\rightarrow$ **The idea:** Bhabha events at e^+e^- (low-energy) colliders **[original proposal]**

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

  $\rightarrow$ or μe scattering events in a fixed target experiment **[new proposal]**

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

$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\rm other}(t) - \Delta\alpha_{\rm had}(t)} \qquad \Delta\alpha_{\rm had}(t) = 1 - \Delta\alpha_{\rm other}(t) - \frac{\alpha}{\alpha(t)}$$



Strategy:

- measure $\Delta\alpha_{\rm had}(t)$ within the exp. range
- get large $|t|$ values from elsewhere (time-like data, lattice)

  see next talk by Marina
- fit $\Delta\alpha_{\rm had}(t)$
- integrate to get $a_\mu^{\rm HLO}$

Roughly, to be competitive with the current evaluations, $\Delta\alpha_{\rm had}(t)$ needs to be know at the sub-% level

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

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

Part of the CERN *Physics Beyond Colliders* program

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

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

⋆ it is a "pure" t-channel process $\to$

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha}\right|^2 \qquad \frac{1}{2}\frac{\delta\sigma}{\sigma} \simeq \frac{\delta\alpha}{\alpha} \simeq \delta\Delta\alpha_{\rm had}, \qquad \Delta\alpha_{\rm had}(t_{peak}) = \mathcal{O}(10^{-3})$$

⋆ Assuming a 150 GeV incident muon beam we have

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

it can cover 87% of the $a_\mu^{\rm HLO}$ integral!

Pros:

⋆ existing μ-beam at CERN with all requirements (M2 beam line)

⋆ highly boosted kinematics

⋆ the same detector and process can be exploited for signal and normalization: for $x \lesssim 0.3$, $\Delta\alpha_{\rm had}(t) < 10^{-5} \to$ normalization region

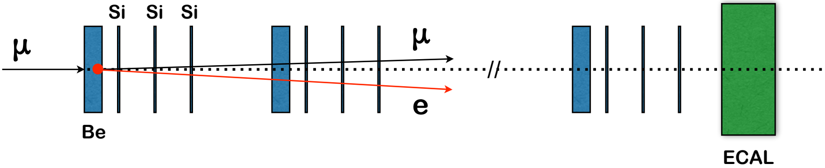
Cons:

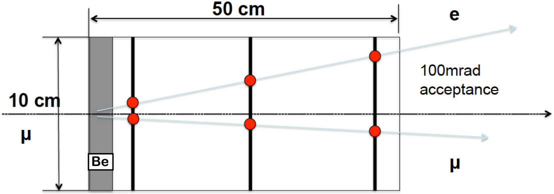
⋆ high accuracy needed: control of systematics at the 10^{-5} level

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

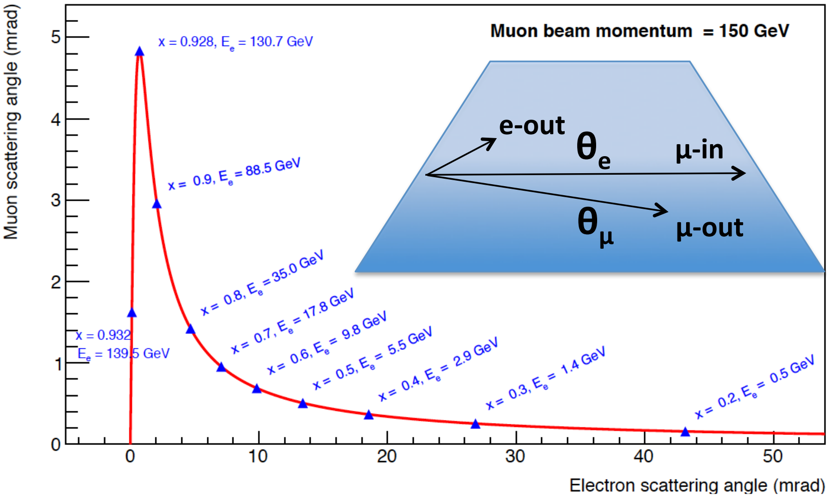
⋆ The setup is designed to measure e and μ angles with the highest accuracy

- Modular apparatus: each module has $\simeq 1$ cm Beryllium target and 3/4 Silicon strips (state-of-art) detectors (hit resolution $\simeq 10$ μm)
- $\simeq 60$ modules (distributed target)
- acceptance: $\theta_e \leq 45$ mrad (i.e. $E_e \geq 0.5$ GeV), $\theta_\mu \leq 5$ mrad. Expected angular resolution 0.02 mrad





θ_μ-θ_e correlation (elastic events)



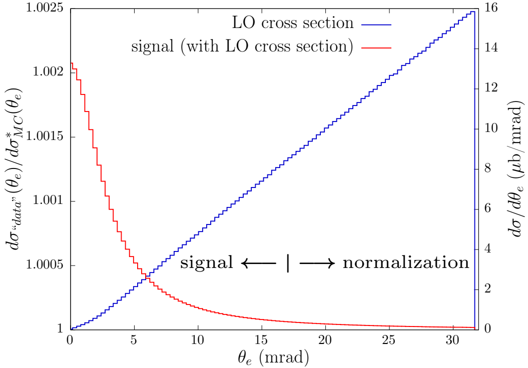
- Pure kinematics

Extracting $\Delta\alpha_{\rm had}(t)$ from $\mu e \to \mu e$ elastic data

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

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

$$\simeq 1 + 2\left[\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i)\right]$$



$\mapsto$ **A template fitting procedure needs to be designed for $\Delta\alpha_{\rm had}(t)$**

Theory: a first step, radiative corrections at NLO in QED

- The μe cross section and distributions must be known as precisely as possible
  $\mapsto$ radiative corrections (RCs) are mandatory

⋆ First step are QED $\mathcal{O}(\alpha)$ (i.e. QED NLO, next-to-leading order) RCs

The NLO cross section is split into two contributions,

$$\sigma_{NLO} = \sigma_{2\to 2} + \sigma_{2\to 3} = \sigma_{\mu e\to\mu e} + \sigma_{\mu e\to\mu e\gamma}$$

$\mapsto$ IR singularities are regularized with a vanishingly small photon mass $\boldsymbol{\lambda}$

$\mapsto$ $[2\to 2]/[2\to 3]$ phase space splitting at an arbitrarily small γ-energy cutoff $\boldsymbol{\omega_s}$

- $\mu e \to \mu e$

$$\sigma_{2\to 2} = \sigma_{LO} + \sigma_{NLO}^{virtual} = \frac{1}{F}\int d\Phi_2(|\mathcal{A}_{LO}|^2 + 2\Re[\mathcal{A}_{LO}^* \times \mathcal{A}_{NLO}^{virtual}(\boldsymbol{\lambda})])$$

- $\mu e \to \mu e\gamma$

$$\sigma_{2\to 3} = \frac{1}{F}\int_{\omega>\boldsymbol{\lambda}} d\Phi_3|\mathcal{A}_{NLO}^{1\gamma}|^2 = \frac{1}{F}\left(\int_{\boldsymbol{\lambda}<\omega<\boldsymbol{\omega_s}} d\Phi_3|\mathcal{A}_{NLO}^{1\gamma}|^2 + \int_{\omega>\boldsymbol{\omega_s}} d\Phi_3|\mathcal{A}_{NLO}^{1\gamma}|^2\right)$$

$$= \Delta_s(\boldsymbol{\lambda},\boldsymbol{\omega_s})\int d\sigma_{LO} + \frac{1}{F}\int_{\omega>\boldsymbol{\omega_s}} d\Phi_3|\mathcal{A}_{NLO}^{1\gamma}|^2$$

- the integration over the 2/3-particles phase space is done with MC techniques and fully-exclusive events are generated

NLO: method and cross-checks

- Calculation performed in the on-shell renormalization scheme
- **Full mass dependency kept everywhere**, fermions' helicities kept explicit
- Diagrams manipulated with the help of **`FORM`**, independently by at least two of us [perfect agreement]

  J. Vermaseren, **`https://www.nikhef.nl/~form`**
- 1-loop tensor coefficients and scalar 2-3-4 points functions evaluated with **`LoopTools`** and **`Collier`** libraries [perfect agreement]

  T. Hahn, **`http://www.feynarts.de/looptools`**

  A. Denner, S. Dittmaier, L. Hofer, **`https://collier.hepforge.org`**
- UV finiteness and λ independence verified with high numerical accuracy
- 3 body phase-space cross-checked with 3 independent implementations [perfect agreement]
- Comparison with past/present independent results *[all good so far]*

  T. V. Kukhto, N. M. Shumeiko and S. I. Timoshin, J. Phys. G **13** (1987) 725

  D. Y. Bardin and L. Kalinovskaya, DESY-97-230, **`hep-ph/9712310`**

  N. Kaiser, J. Phys. G **37** (2010) 115005

  Fael, Passera
- Also NLO weak RCs calculated [negligible]

$\mu e \to \mu e$ at NLO, phenomenology

- The following setup is considered for $E_\mu^{beam} = 150$ GeV ($\sqrt{s} \simeq 0.4055$ GeV)

Selection criteria

- acceptance: $E_e > 200$ MeV $\theta_e, \theta_\mu < 100$ mrad

$\mapsto$ **no cuts**: only acceptance

and, **to select elastic events**,

$\mapsto$ **cut 1**: $\Delta\theta_{\rm NA7} < 0.5$ mrad

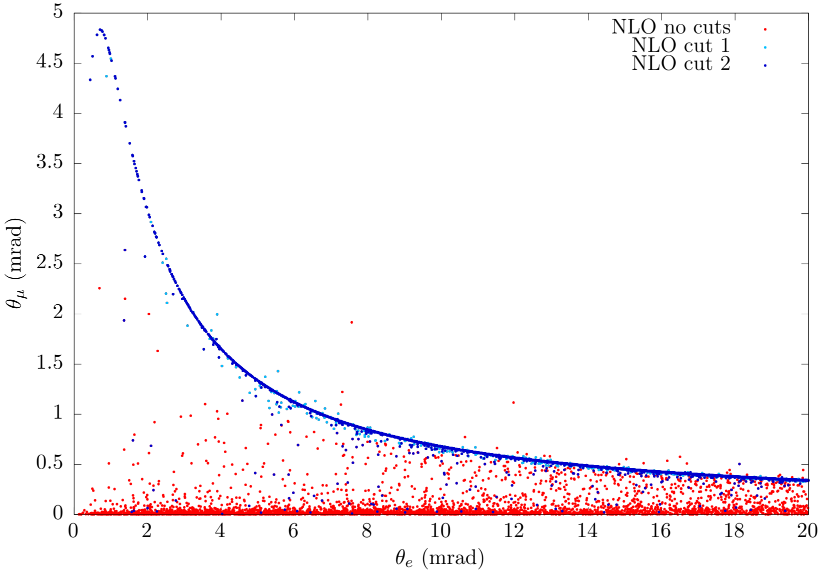
[$\Delta\theta_{\rm NA7} \simeq$ mimimum distance from the elastic curve in the θ_e-θ_μ plane]

NA7 Collaboration, NPB 277 (1986) 168

$\mapsto$ **cut 2**: acoplanarity $\equiv |\pi - (\phi_e - \phi_\mu)| < 3.5$ mrad

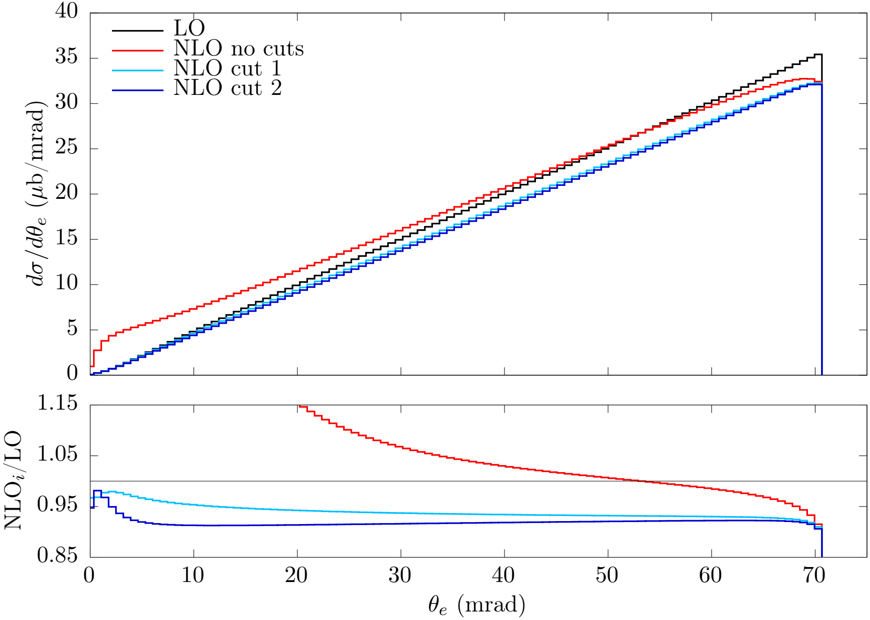
$\mapsto$ Only angular cuts are applied, besides acceptance

μ^--e^- angles correlation in the lab

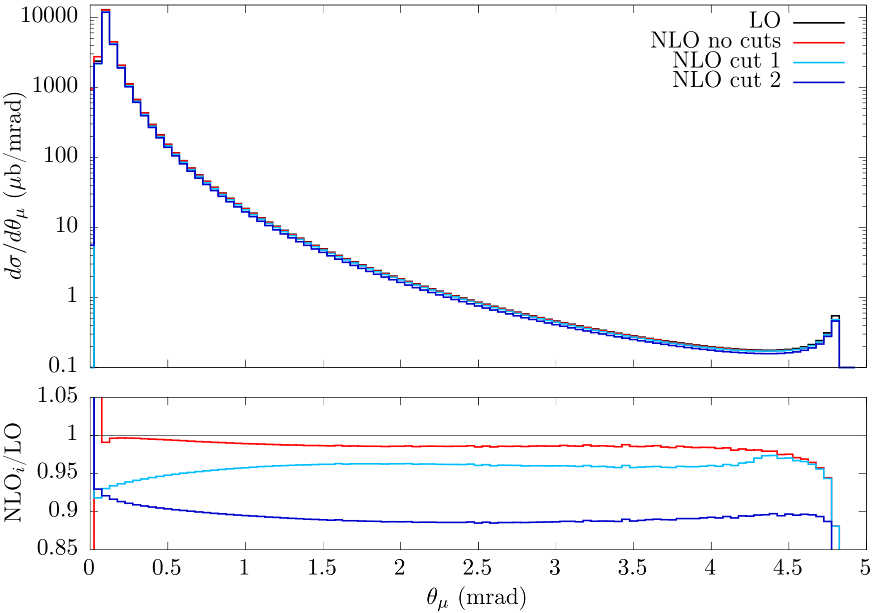


- Sample of $\simeq 1$M events at NLO

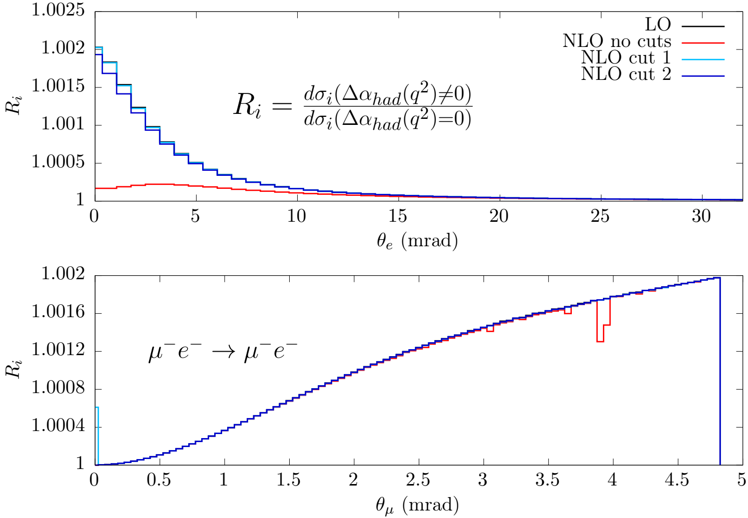
θ_e distribution, $\mu^- e^- \to \mu^- e^-$



θ_μ distribution, $\mu^- e^- \to \mu^- e^-$



Signal on θ_e and θ_μ distributions, $\mu^- e^- \to \mu^- e^-$



same conclusion for $\mu^+ e^- \to \mu^+ e^-$

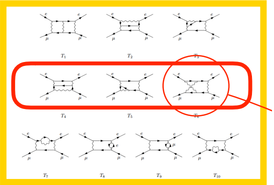
↦ without cuts, NLO RCs destroy the sensitivity to $\Delta\alpha_{had}(q^2)$ on θ_e distribution

↦ θ_μ distribution is much more robust under RCs and applied cuts

Theory: towards NNLO

- full NNLO QED corrections mandatory

- **NNLO: Missing MI for the planar 2-loop box diagrams computed.**



Mastrolia et al. JHEP 11 (2017) 198

Non-planar: not yet!

- **NNLO amplitudes: virtual 2-loop, real-virtual, double real, automation, subtractions...** Mastrolia, Ossola, MP, Primo, Schubert, Torres
- **NNLO hadronic contributions** Fael, MP
- **Fixed-order NNLO + Resummation** Broggio, Signer, Ulrich
- **Towards a MC at NNLO** Pavia group, Czyz
- **Interplay with lattice calculations** Marinković

from M. Passera's talk at Legnaro Labs, May 24 2018

- Also resummation will be needed and implemented into a MC generator

Theory: towards NNLO

- full NNLO QED corrections mandatory

Master integrals for the NNLO virtual corrections to μe scattering in QED: the planar graphs

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JHEP 11 (2017) 198

- Also resummation will be needed and implemented into a MC generator

- full NNLO QED corrections mandatory

Master integrals for the NNLO virtual corrections to μe scattering in QED: the non-planar graphs

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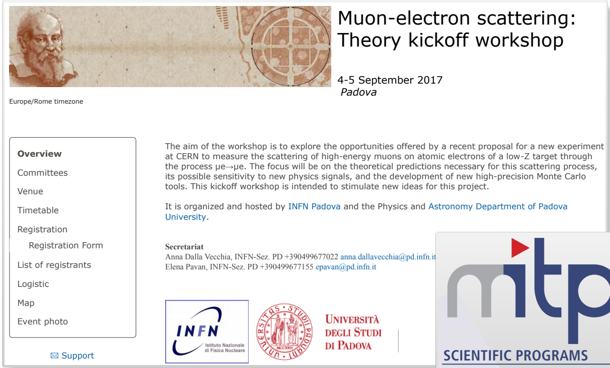
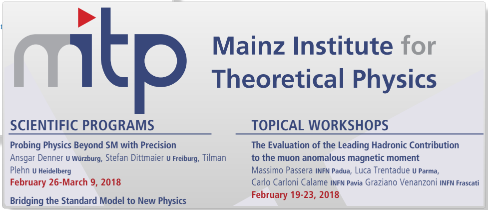
on the arXiv soon, likely tomorrow

- Also resummation will be needed and implemented into a MC generator





- growing community, give a look at the talks on the agendas

↦ link to the **Padova Theory Kickoff Workshop**

↦ link to the **MITP Topical Workshop**

- next *hands-on* **workstop/thinkstart** strongly focussed on NNLO & theory MCs

  Physik-Institut, University of Zurich, February 2019

Status of the experiment

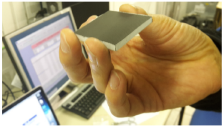
$\mapsto$ Systematics challenges

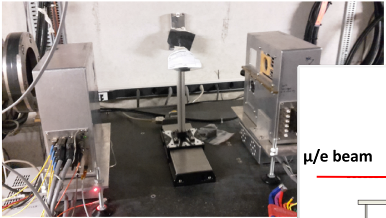
- ⋆ Multiple scattering
- ⋆ Tracking (alignment & mis-reconstruction)
- ⋆ Knowledge of incoming μ momentum distribution
- ⋆ Background
- ⋆ GEANT4 accuracy

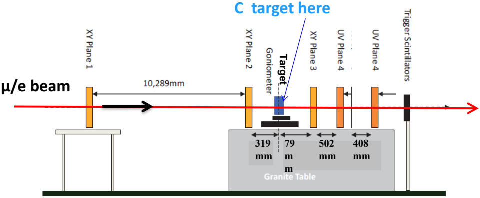
$\mapsto$ Test beams at CERN

- ⋆ 1$^{\rm st}$ TB on H8 beam line, September 27-October 3 2017
  - performed with an adapted UA9 apparatus
  - Beam energies: e^- at 12 & 20 GeV, μ at 160 GeV
  - collected $\simeq 10^8$ events with Carbon targets at different thickness $(2, 4, 8, 20\text{ mm})$
  - Check GEANT4 MSC predictions and populate the 2D $[\theta_e, \theta_\mu]$ plane
- ⋆ 2$^{\rm nd}$ TB on M2 line, after COMPASS detector, April-October 2018, on-going. Main goals:
  - collect a large sample of elastic events
  - study the effect of μ beam momentum mean and resolution
  - study uniformity of tracking eff. vs scattering angles
  - measure θ_e vs E_e

Thanks to the UA9 Collaboration
(particularly M. Garattini, R. Iaconageli,
M. Pesaresi), J. Bernhard



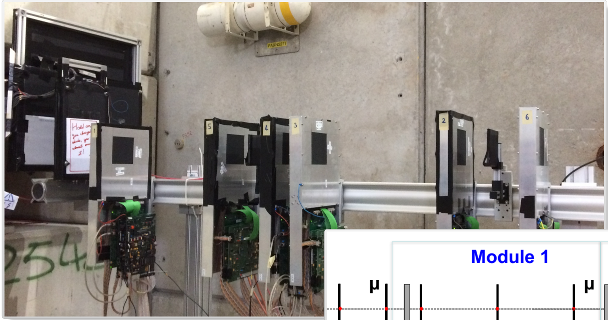


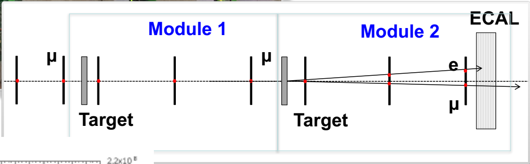


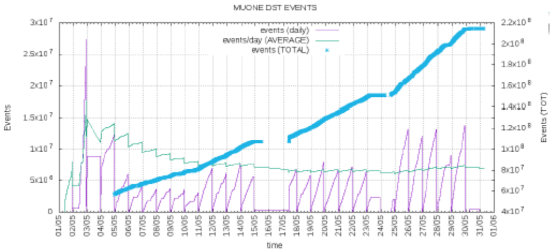
Adapted UA9 apparatus

5 Si planes: 2 before and 3 after the target, 3.8x3.8 cm2 intrinsic resolution ~**100**μrad

2018 test beam



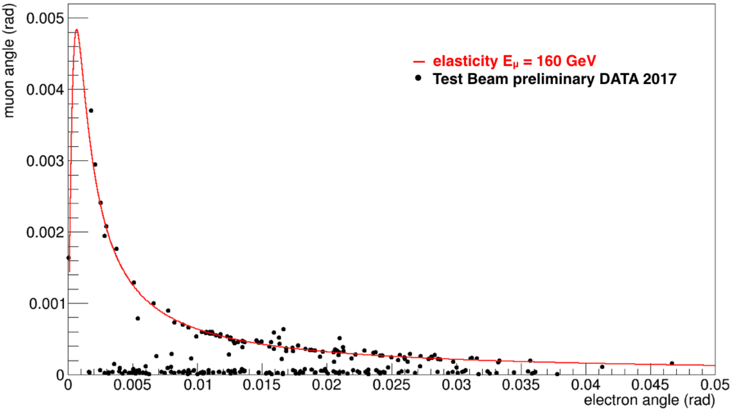




- 2-modules prototipe installed in April 2018
- up to now, 220M collected
- rate: $7 \cdot 10^6$ evts/day

$\mu e \to \mu e$ events in 2017 test beam data

- 160 GeV muon beam, 8 mm Carbon target
- $\simeq 250$ events
- events are spread due to MS, beam spread and radiative events, no acoplanarity cut applied

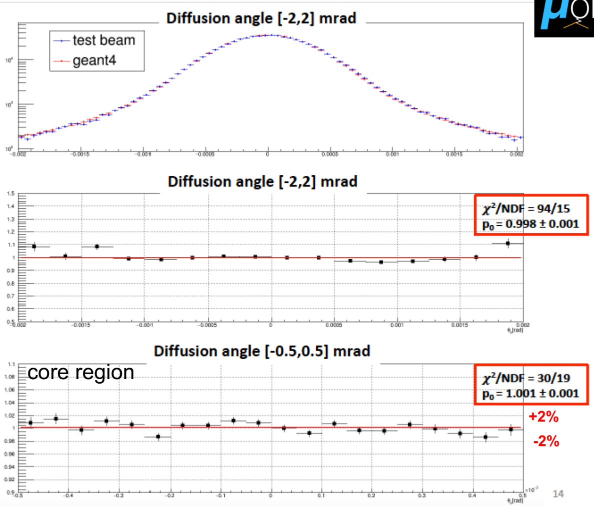


courtesy of A. Principe

- Analysis of TB data keeps going-on
- Encouraging comparisons of data vs GEANT4

2017 TB data vs Geant4

20mm, 12 GeV



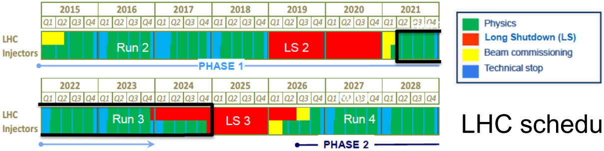
Agreement in the core region (90% of events) ~ 1%; outside few %

from G. Venanzoni's talk at Physics Beyond Colliders WG meeting, June 13-14 2018

Plans

- **2018-2019**
  - Detector optimization studies: simulation; Test Run at CERN (2018); Mainz/Desy with few GeV e- (2019); Fermilab with 60 GeV μ (TBC)
  - Theoretical studies
  - Set up a collaboration
  - Letter of Intent to the SPSC
- **2020-2021**
  - Detector construction and installation

  2021–2024
  - Data taking: staged detector for a first (pilot) run +2 years with full detector



LHC schedule

from G. Venanzoni's talk at Physics Beyond Colliders WG meeting, June 13-14 2018

Conclusions and outlook

- The MUonE project is part of the CERN Physics Beyond Colliders workshop
- The aim is measuring $\Delta\alpha_{\rm had}(t)$ in the space-like region with high-accuracy
- The goal is to provide a new independent evaluation of $a_\mu^{\rm HLO}$ with 0.3% statistical accuracy and a competitive systematic one in two years data taking on CERN M2 μ beam line
- We will the use $\mu e \to \mu e$ process, scattering $\mu^\pm$ on e^- on a low-Z fixed target
- The CERN M2 muon beam provides the necessary energy $(150$ GeV) and intensity ($\simeq 10^7$ muons/s)
- A lot of work is going on, both on the experimental and theory side
- The collaboration and interest are growing:

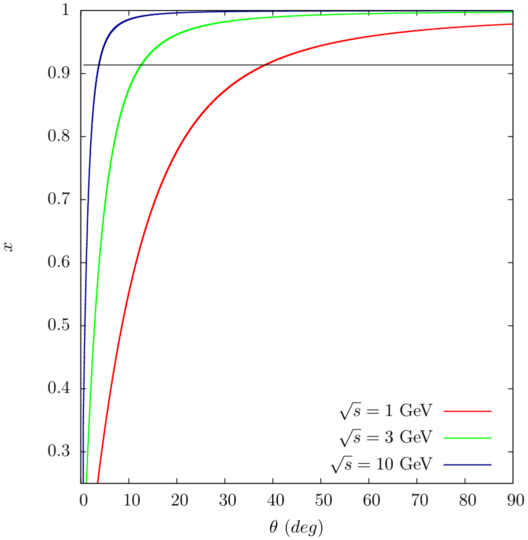
  CERN, Krakow, Novosibirsk, Liverpool, Manchester, UCL, Virginia

  INFN, Bologna, Ferrara, Milano Bicocca, Padova, Parma, Pavia, SNS Pisa

- Next year, (at least) one post-doc position at INFN (Pavia) will be open, mainly dedicated to the MUonE project

SPARES

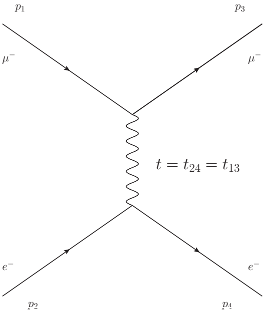
Bhabha scattering: x vs θ_{e^-}



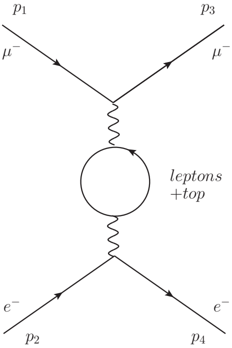
↦ x vs θ_{e^-} in Bhabha scattering

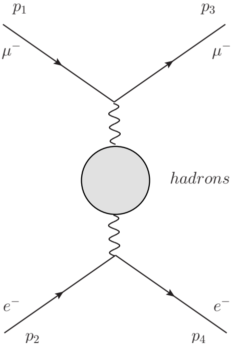
LO and NLO vacuum polarization diagrams

- $\mathcal{A}_{LO}$

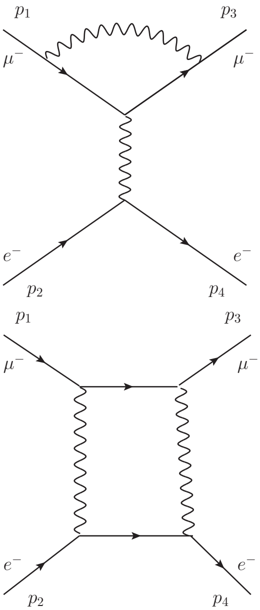


- $\mathcal{A}_{NLO}^{virtual}$



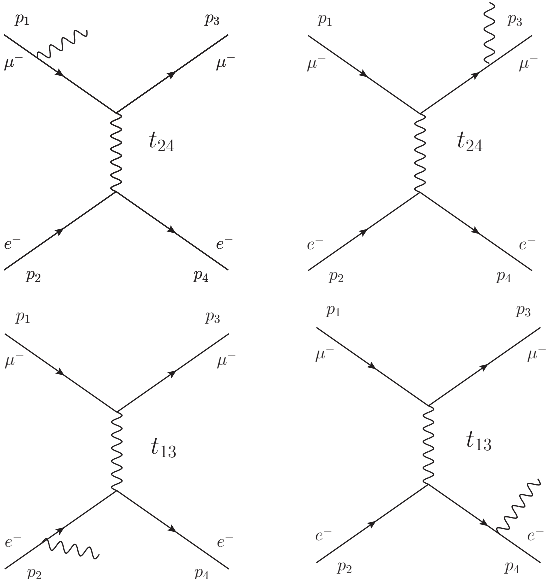


NLO virtual diagrams $\mathcal{A}_{NLO}^{virtual}$ (dependent on λ)

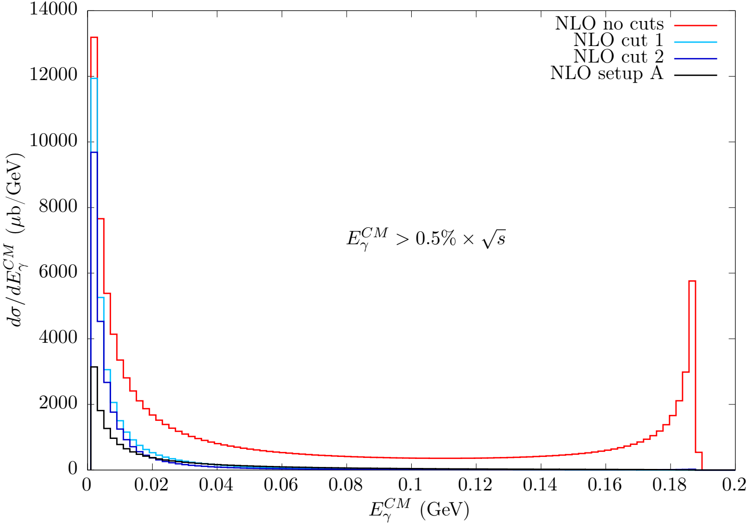


+ counterterms

NLO real diagrams $\mathcal{A}^{1\gamma}_{NLO}$

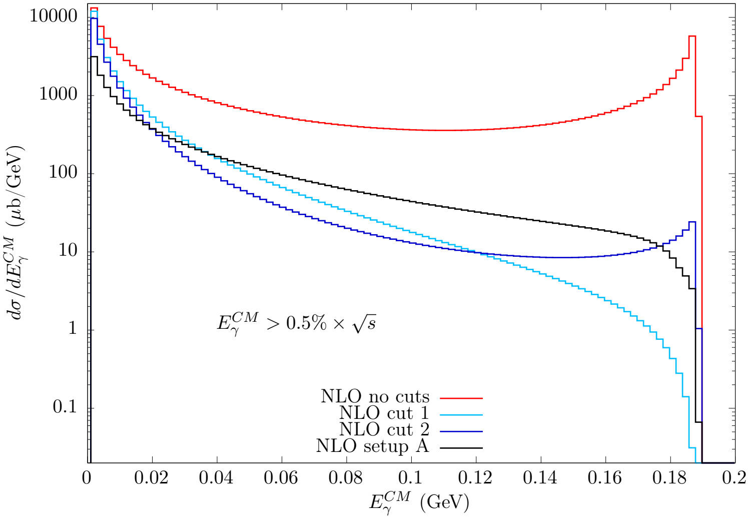


Photon energy **in the center of mass**, incoming μ^-

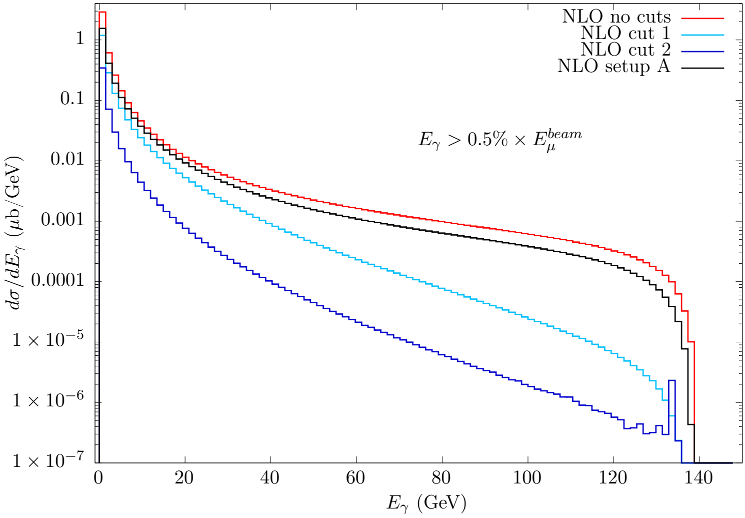


- a peak at large photon energy is present with no cuts
- it is cut off by applying cuts

Photon energy **in the center of mass**, incoming μ^-



Photon energy **in the lab**, incoming μ^-

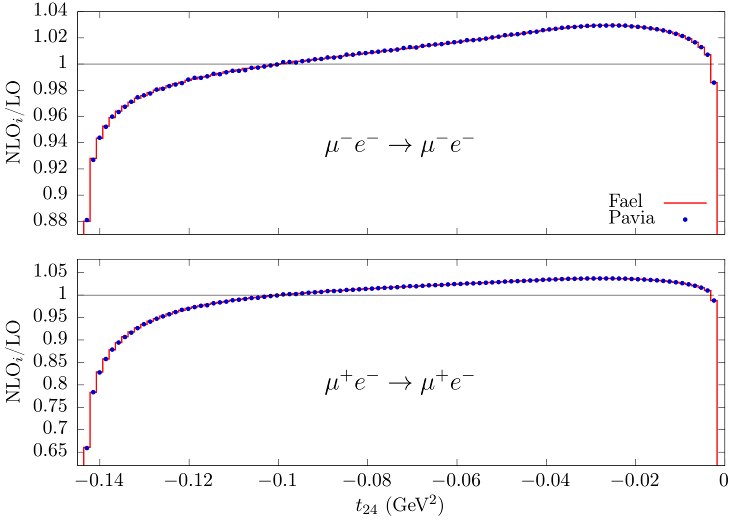


$\mu^\pm e^- \to \mu^\pm e^-$ cross sections at NLO

- Any vacuum polarization effect is switched off, to quantify only NLO photonic RCs

$\mapsto$	$\mu^\pm$ LO	$=$	$1265.06\ \mu$b	
$\mapsto$	μ^- NLO no cuts	$=$	$1323.48\ \mu$b	$(+4.62\%)$
$\mapsto$	μ^- NLO cut 1	$=$	$1179.22\ \mu$b	(-6.79%)
$\mapsto$	μ^- NLO cut 2	$=$	$1161.89\ \mu$b	(-8.16%)
$\mapsto$	μ^+ NLO no cuts	$=$	$1325.23\ \mu$b	$(+4.76\%)$
$\mapsto$	μ^+ NLO cut 1	$=$	$1180.71\ \mu$b	(-6.67%)
$\mapsto$	μ^+ NLO cut 2	$=$	$1162.45\ \mu$b	(-8.11%)

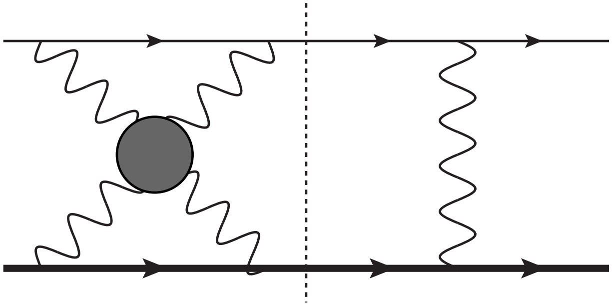
Tuned comparison with independent calculation (Fael)



$\mapsto$ Fael's calculation uses FKS subtraction for IR and collinear singularities

$\mapsto$ same level of agreement on t_{13} distribution

No LbL up to N^{3}LO in μe scattering



M. Fael, talk at MITP topical workshop, February 2018

is of $O(\alpha^5)$.

[i.e. $\mathcal{O}(\alpha^3)$ w.r.t. LO]