Measuring the Leading Order Hadronic Contribution to the *muon g-2* in the space-like region

A proposal for measuring HLO contributions from

$\mu + e \longrightarrow \mu + e$ elastic scattering

COFI workshop
Searching for Physics Beyond the Standard Model Using Charged Leptons
San Juan, 21-26 May 2018

Clara Matteuzzi *(on behalf of the proponents of the project)*

Outline

- Physics motivations
- Tools to perform the measurement
- First testbeam at CERN
- Plans and tentative timeline

★ Physics motivation

Physics motivations

$$a_\mu = \frac{g-2}{2}$$

The *muon g-2* is measured with high precision:

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

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

It shows a long standing $\approx 4\sigma$ deviations from the Standard Model prediction:

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

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

$$\boxed{\Delta a_\mu (\text{exp - SM}) = \quad 306 \pm 72}$$

The accuracy of the SM prediction $5 \cdot 10^{-10}$

is limited by **strong interactions** effects

The present error on the leading order hadronic contribution to muon $g-2$

$$\delta a_\mu^{HLO} \simeq 4 \cdot 10^{-10}$$

constitutes the main uncertainty of the SM predictions

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

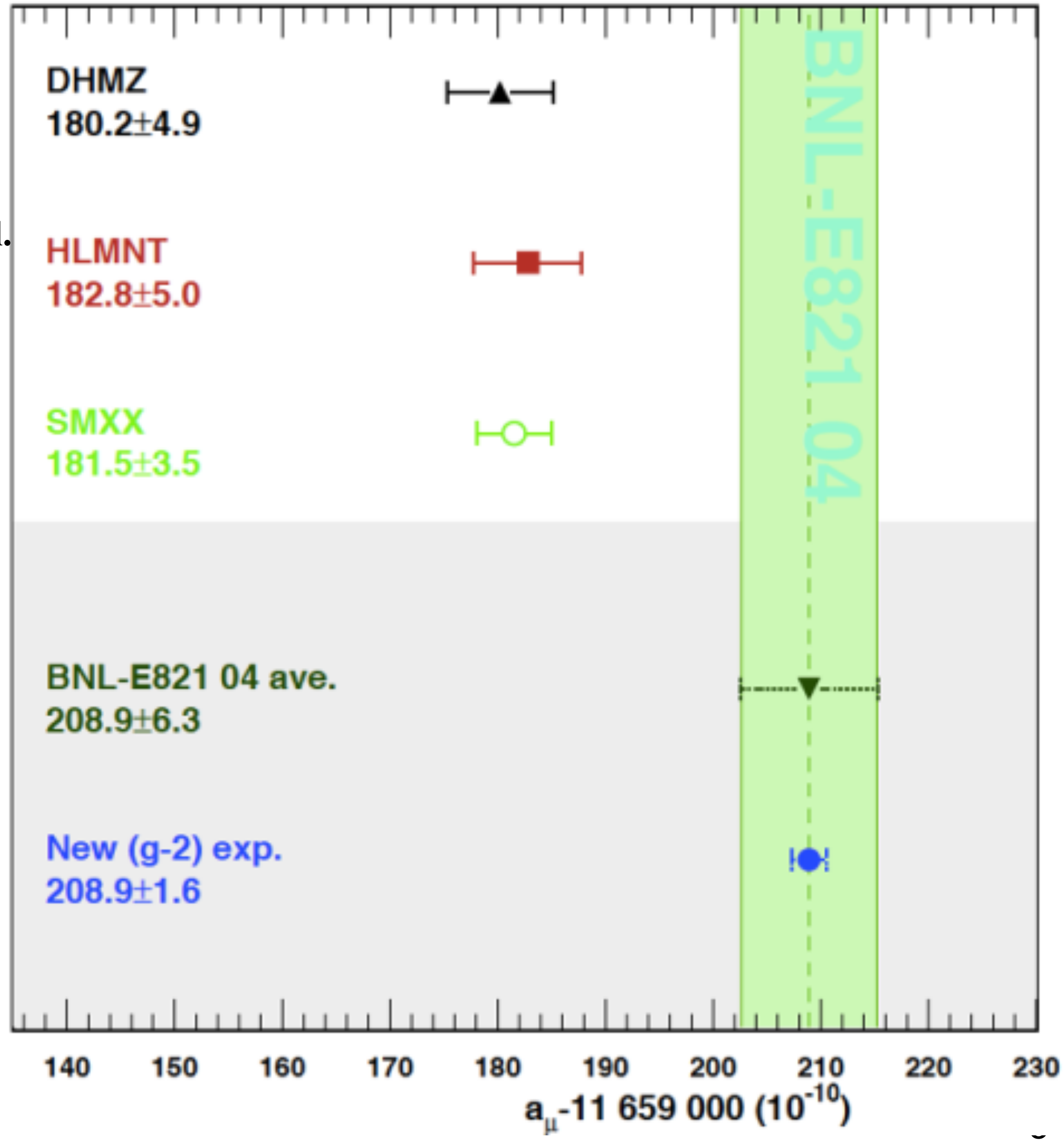
Physics motivations

T. Blum *et. al.*, "The Muon g-2 Theory Value: Present and Future"
arXiv:1311.2198 [hep-ph]

DHMZ ➔ **parametrization M.Davier et al.**
HLMNT ➔ **K. Hagiwara et al.**
SMXX ➔ **average of these two values**

Current experimental value of a_μ ➔

Assuming same central value and improved precision from Fermilab and J-PARC ➔



Physics motivations

Theory (in units of 10^{-10}) from M. Knecht talk at Capri Workshop on FCCP2015

QED	$+11658471.9$	[T. Aoyama et al. (2015)]
HVP-LO	$+692.3(4.2)$	[M. Davier et al. (2011)]
	$+694.9(4.3)$	[K. Hagiwara et al. (2011)]
HVP-NLO	$-9.84(7)$	[K. Hagiwara et al. (2011)]
HVP-NNLO	$+1.24(1)$	[A. Kurz et al. (2014)]
HLxL	$+10.5(2.6)$	[J. Prades et al. (2009)]
	$+11.5(4.0)$	[F. Jegerlehner, A. Nyffeler (2009)]
EW 1 loop	$+19.48(1)$	[(1972)]
EW 2 loops	$-4.12(10)$	[C. Gnendiger et al. (2013)]

$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (27.4 \pm 8.0) \cdot 10^{-10}$ $[3.4\sigma]$ for $a_\mu^{\text{HLxL}} = (10.5 \pm 2.6) \cdot 10^{-10}$, $a_\mu^{\text{HVP-LO}} = 692.3 \pm 4.2 \cdot 10^{-10}$

$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (23.7 \pm 8.6) \cdot 10^{-10}$ $[2.8\sigma]$ for $a_\mu^{\text{HLxL}} = (11.6 \pm 4.0) \cdot 10^{-10}$, $a_\mu^{\text{HVP-LO}} = 694.9 \pm 4.3 \cdot 10^{-10}$

Is it possible, in view of the forecoming experiments at FNAL(E989) and J-PARC(E34), to reduce the dominant theoretical uncertainties (HVP-LO and HLxL) ??

Physics motivations

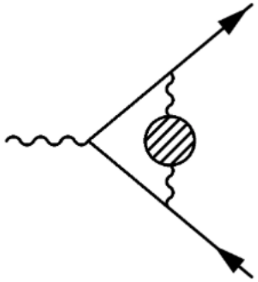
Both Fermilab and J-PARC *g-2* experiments will lower the experimental error from 0.5 ppm to ≈ 0.14 ppm in few years

Need therefore to lower the theoretical uncertainty in order to have a more precise SM prediction ➡ *more theoretical work is necessary (rad corr, lattice,..)*

The largest contribution to the theoretical uncertainty comes from the term $\Delta\alpha_{had}(t)$ **which can be measured experimentally**

★ **The standard dispersive approach**
(time-like approach)

Approach: time-like evaluation

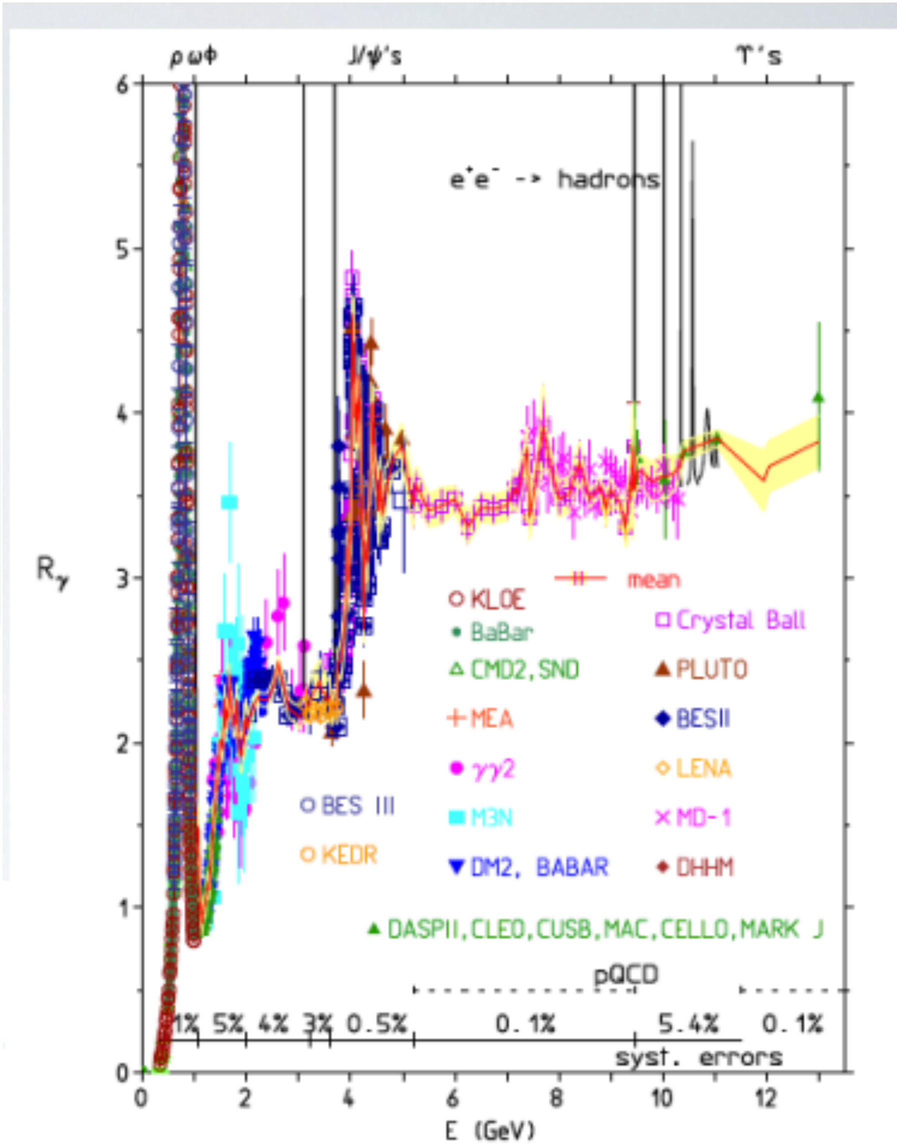


$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2}$$

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

$$R_{had}(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Combination of many exclusive channels



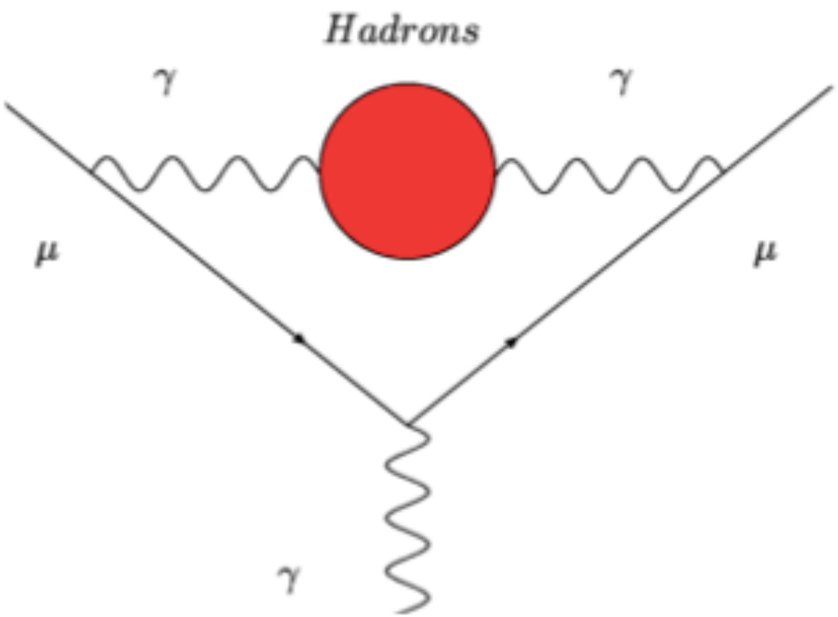
$a_\mu^{HLO} = 6870\ (42)_{tot} \times 10^{-11}$ — F. Jegerlehner, arXiv:1511.04473 (includes BESIII 2π)

$= 6923\ (42)_{tot} \times 10^{-11}$ — Davier et al, EPJ C71 (2011) 1515

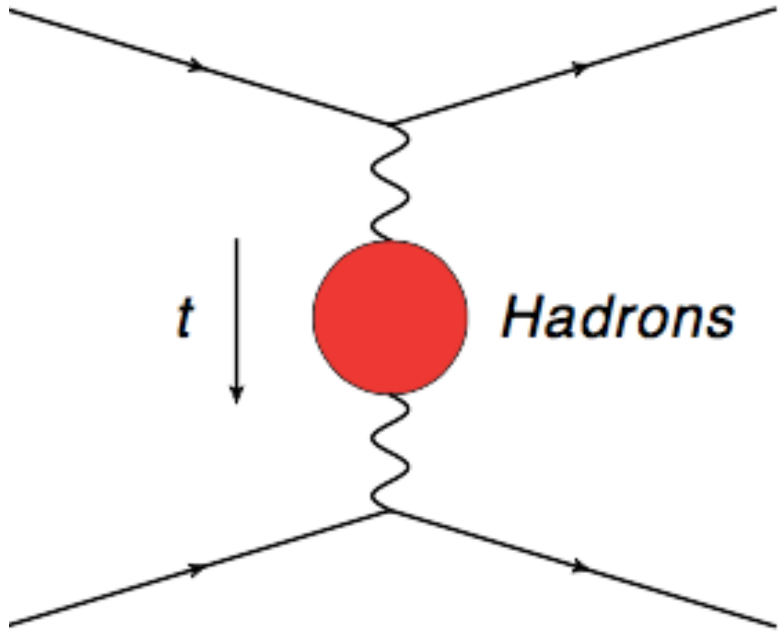
$= 6949\ (37)_{exp}\ (21)_{rad} \times 10^{-11}$ — Hagiwara et al, JPG 38 (2011) 085003

★ An alternative approach
(space-like approach)

From :



To :



Approach: space-like evaluation

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx(x-1)\bar{\Pi}_{\mathrm{had}}(t(x)) = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\mathrm{had}}(t(x))$$

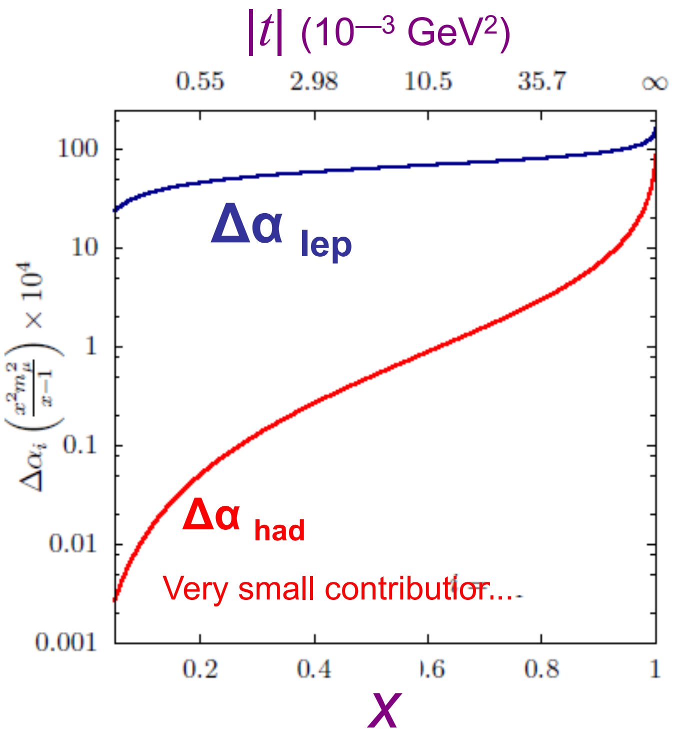
$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad t = \begin{cases} 0^- & \text{for } x \to 0^+ \\ -\infty & \text{for } x \to 1^- \end{cases}$$

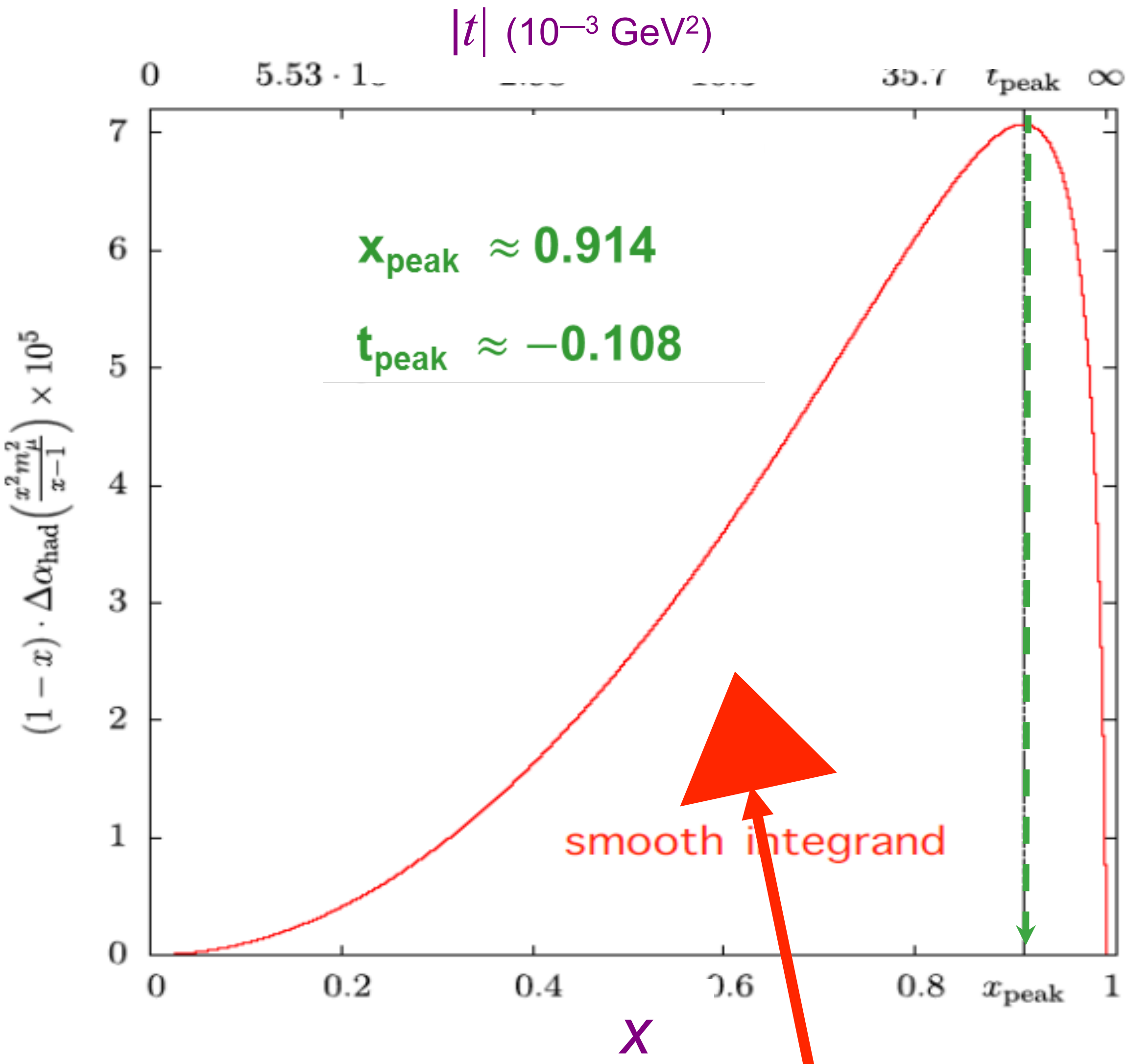
$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\mathrm{other}}(t) - \Delta\alpha_{\mathrm{had}}(t)}$$

★ **Strategy:**

- measure $\Delta\alpha_{\mathrm{had}}(t)$ in the reachable experimental kinematic range
- fit $\Delta\alpha_{\mathrm{had}}(t)$
- get large |t| values from theory
- get the integrand function and the value of a_μ^{HLO}

Approach: space-like evaluation





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

a_{HAD} is the total area under this curve

★ **Why $\mu + e^- \rightarrow \mu + e^-$**

Which strategy ??

1. Running of $\alpha_{e.m.}$ with Bhabha scattering

The running of the electromagnetic coupling α in small-angle Bhabha scattering

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A new approach to evaluate the leading hadronic corrections to the muon g-2 ☆

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2. Extract HLO from the running of $\alpha_{e.m}$

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

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Received: date / Accepted: date

3. measure HLO from the $\mu + e \rightarrow \mu + e$ elastic scattering

Why $\mu + e \rightarrow \mu + e$?

Muon scattering on atomic electrons looks an ideal process:

- It is a pure t-channel process

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

- A high intensity (1.3 x 107 μ/s) muon beam is available in the North area at CERN. With Ebeam ~ 150 GeV:

$$-0.143 \lesssim t < 0 \text{ GeV}^2 \qquad 0 < x \lesssim 0.93$$ *spans the peak)*

- The highly boosted kinematics allows to access the full kinematic range

- The same detector can cover signal (x > 0.4 – 0.5) and normalization (x≤ 0.3) regions

The kinematics

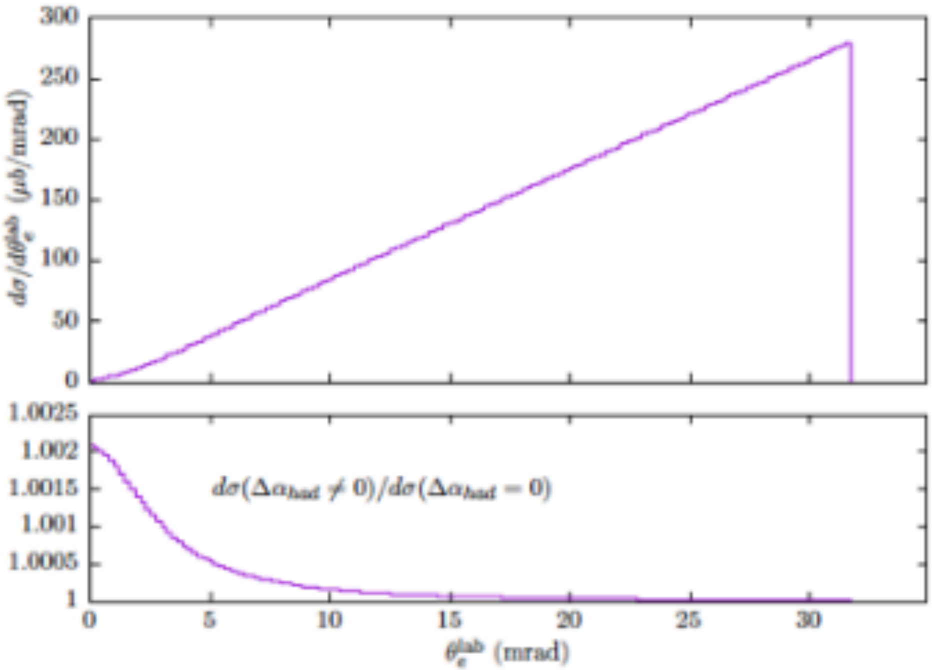
(from C.Calame)

- the $2 \to 2$ kinematics reads

$$t = 2m_e^2 - 2m_e E_e, \qquad s = m_\mu^2 + m_e^2 + 2m_e E_\mu^i \qquad r \equiv \frac{\sqrt{(E_\mu^i)^2 - m_\mu^2}}{E_\mu^i + m_e}$$

$$E_e = m_e \frac{1 + r^2 c_e^2}{1 - r^2 c_e^2}, \qquad \theta_e = \arccos\left(\frac{1}{r}\sqrt{\frac{E_e - m_e}{E_e + m_e}}\right) \qquad c_e \equiv \cos\theta_e$$

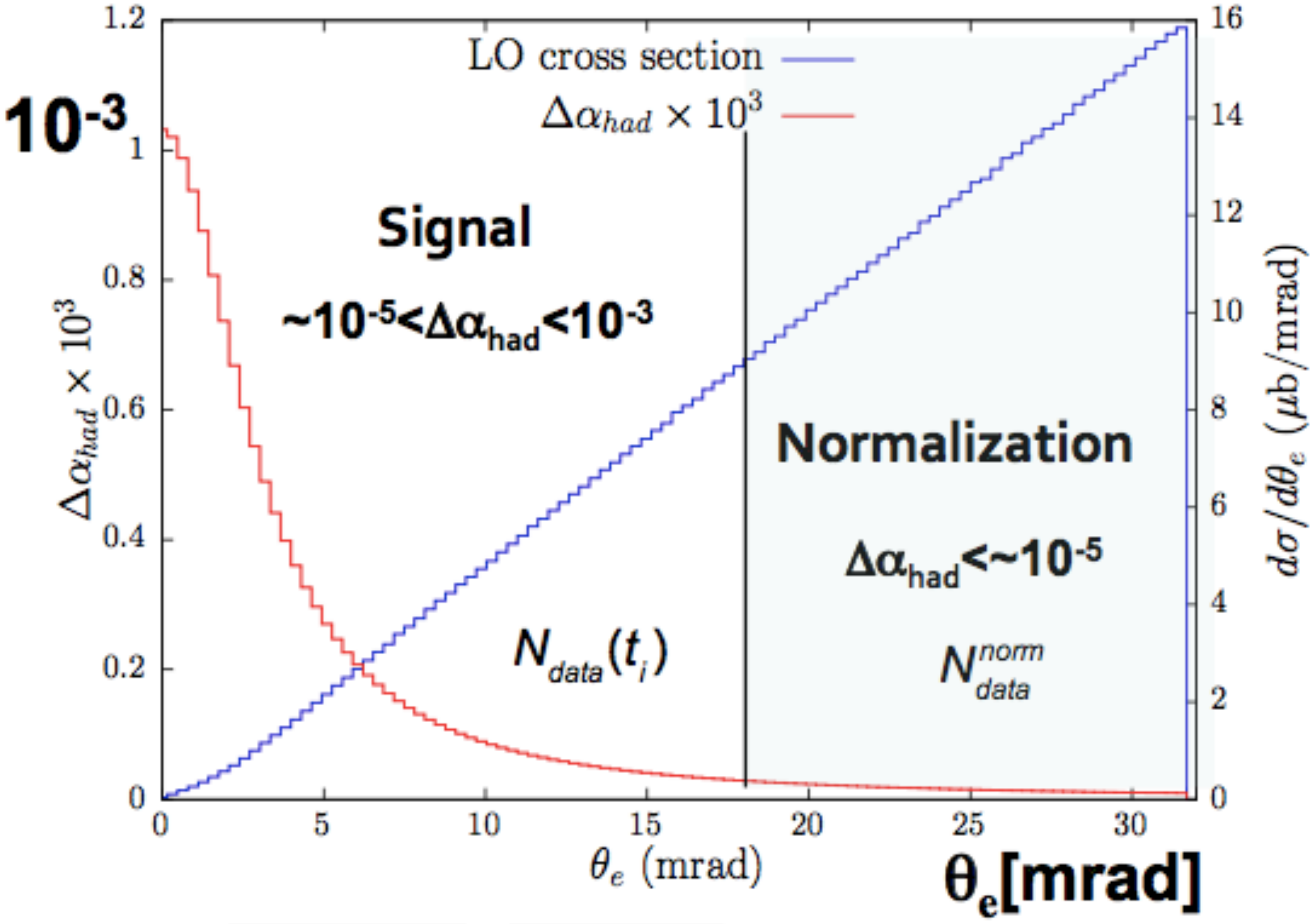
- $0 < \theta_e < 31.85$ mrad $\longleftrightarrow$ $139.8 > E_e > 1$ GeV $\longleftrightarrow$ $-0.143 < t < -10^{-3}$ GeV^2



→ differential cross-section at LO (including vacuum polarization) as a function of θ_e

→ effect due to $\Delta\alpha_{\rm had}(t)$

→ for instance the region $\theta_e > 20 \div 25$ mrad can be used as normalization



10-3
LO cross section
$\Delta\alpha_{had} \times 10^3$
Signal
$\sim 10^{-5} < \Delta\alpha_{had} < 10^{-3}$
Normalization
$\Delta\alpha_{had} < \sim 10^{-5}$
$N_{data}(t_i)$
N_{data}^{norm}
θ_e (mrad)
θ_e[mrad]
$d\sigma/d\theta_e$ (μb/mrad)

Tools to do the measurement

A high energy muon beam *(must cover the t range needed)*

the beam **M2 at CERN** has the characteristics **($E_\mu \approx 150$ GeV, 1.3×10^7 μ/s)** adequate for such a measurement.

The target : atomic electrons must be provided by a light material,

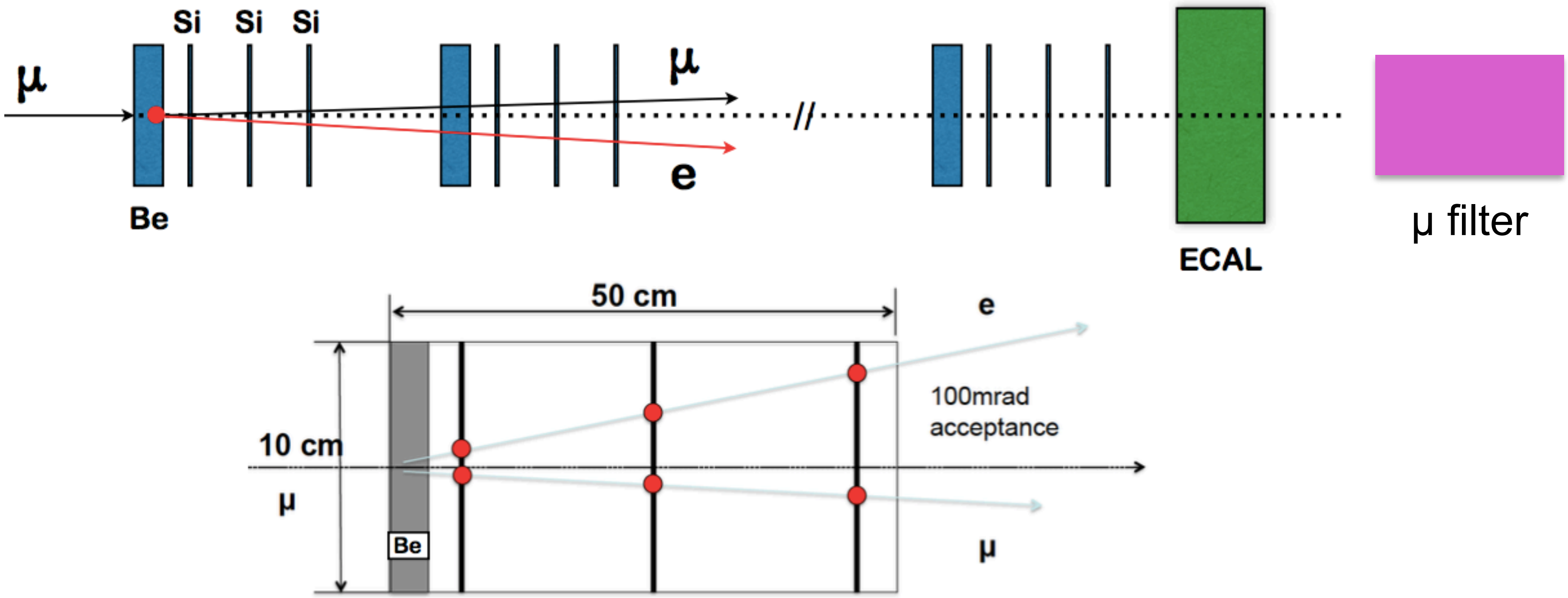
to minimize the e.m. interactions inside the target, but at the same time must provide a high enough number of target electrons
Berillium (or eventually Carbon)

The detector setup:

- a modular target made by 60 layers of Be (C) 1 (0.8) cm thick, sandwiched in layers of Si tracking planes.
- Need to measure very precisely the angles of the outcoming muons and electrons (to exploit kinematical correlation of the μ-e collision)
- Need to measure energy and direction of the incoming muon (a la COMPASS or NA62 GTRK)
- a simple PID (e.m. calorimeter and muon system) will be necessary

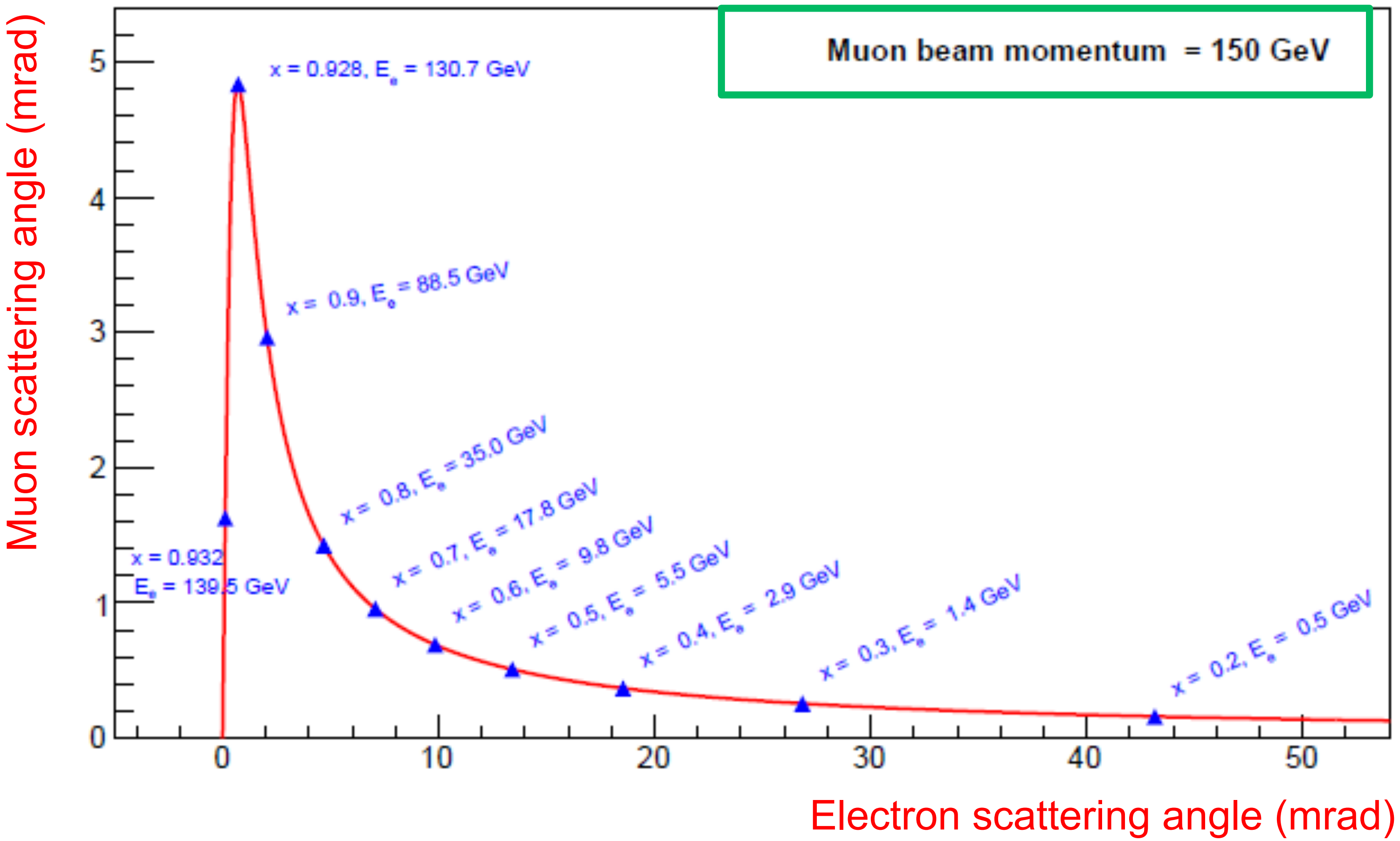
Tools to do the measurement

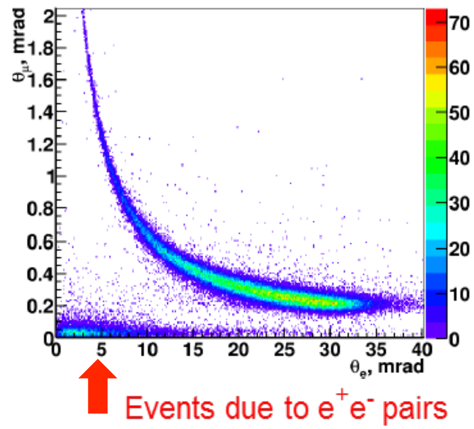
Target elements are sandwiched between Si planes and spaced by ~ 50 cm air



The kinematics: *correlation curve*

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





The constraint is useful to select elastic events, reject background and reduce systematics in *t* determination

Below 2-3 mrad *μ* and *e* overlap, to be resolved by *μ/e* identification

Multiple scattering breaks the correlation: simulation and data will help to optimize the detector and reduce the systematics

Tools to do the measurement

Statistics

Expected statistics achievable assuming:

the μ beam **M2** with 1.3×10^{7} μ/s , running time 2×10^{7} s/yr

60 layers of 10 mm Be target → 60 cm Be

Lumi ~ 0.8×10^{7} nb^{-1} /yr

→ ~ **2×10^{12}** events /yr (will allow to have a statistical precision of 0.3 % on a_{μ}^{HLO} in two years running)

Systematics

many effects will have to be under control:

efficiencies (uniformity,acceptance, tracking, trigger, PID)

alignment of the Si planes

uncertainties in vertex location, incoming muon momentum,

effect of multiple scattering *(different in "control" and "signal" regions)*

……………………….*(many others, can be studied with data themselves).*

Theory

to extract $\Delta\alpha(t)$ from this measurement, the SM prediction must be known at the NNLO

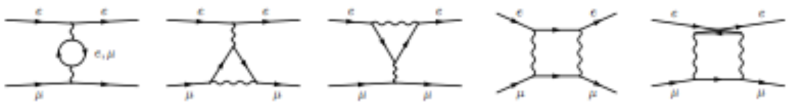
Tools to do the measurement

Theory *(From M. Passera)*

Our final TH goal: a running MC for the ratio of the SM cross sections in the signal and normalization regions below, at the level, of 10ppm

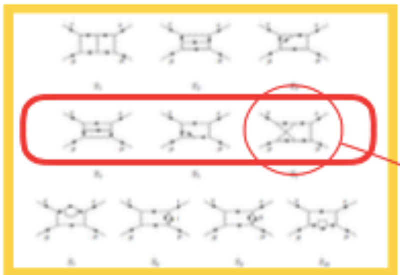
Muon-electron scattering: theory progress

- NLO QED corrections known & checked. MC @ NLO ready and tailored to the fixed target kinematics.



Pavia Group

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

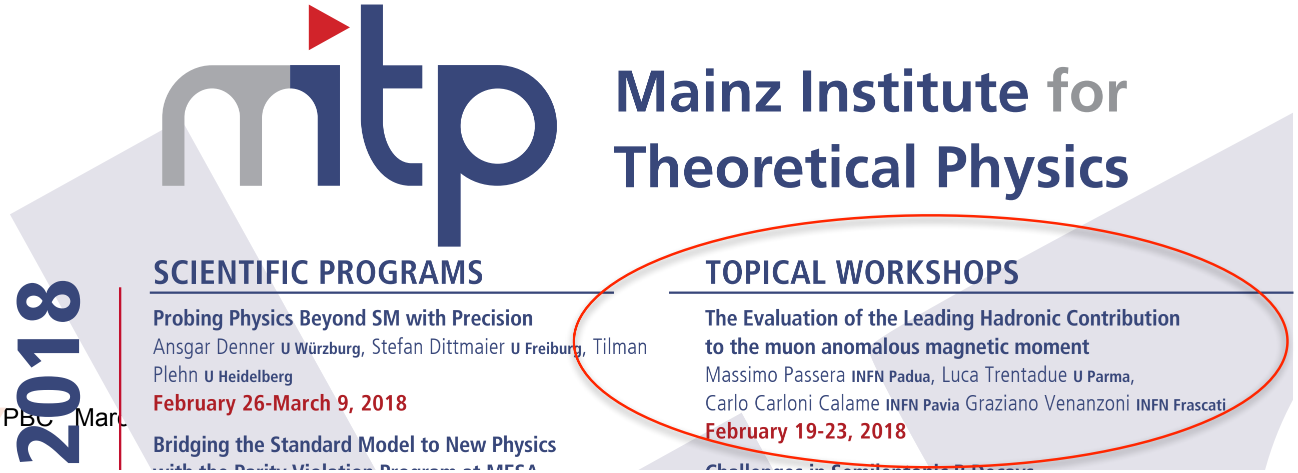


Mastrolia, MP, Primo & Schubert, arXiv:1709.07435.

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

2nd MUonE theory workshop: Mainz - Feb 2018



Mainz Institute for Theoretical Physics

2018

SCIENTIFIC PROGRAMS

Probing Physics Beyond SM with Precision
Ansgar Denner U Würzburg, Stefan Dittmaier U Freiburg, Tilman Plehn U Heidelberg
February 26-March 9, 2018

Bridging the Standard Model to New Physics

TOPICAL WORKSHOPS

The Evaluation of the Leading Hadronic Contribution to the muon anomalous magnetic moment
Massimo Passera INFN Padua, Luca Trentadue U Parma, Carlo Carloni Calame INFN Pavia Graziano Venanzoni INFN Frascati
February 19-23, 2018

This is an experiment where the main issue is to control the systematic error at the same level as the statistical one

Important contribution identified is the multiple scattering of low energy electrons ($E_e \approx$ few GeV)

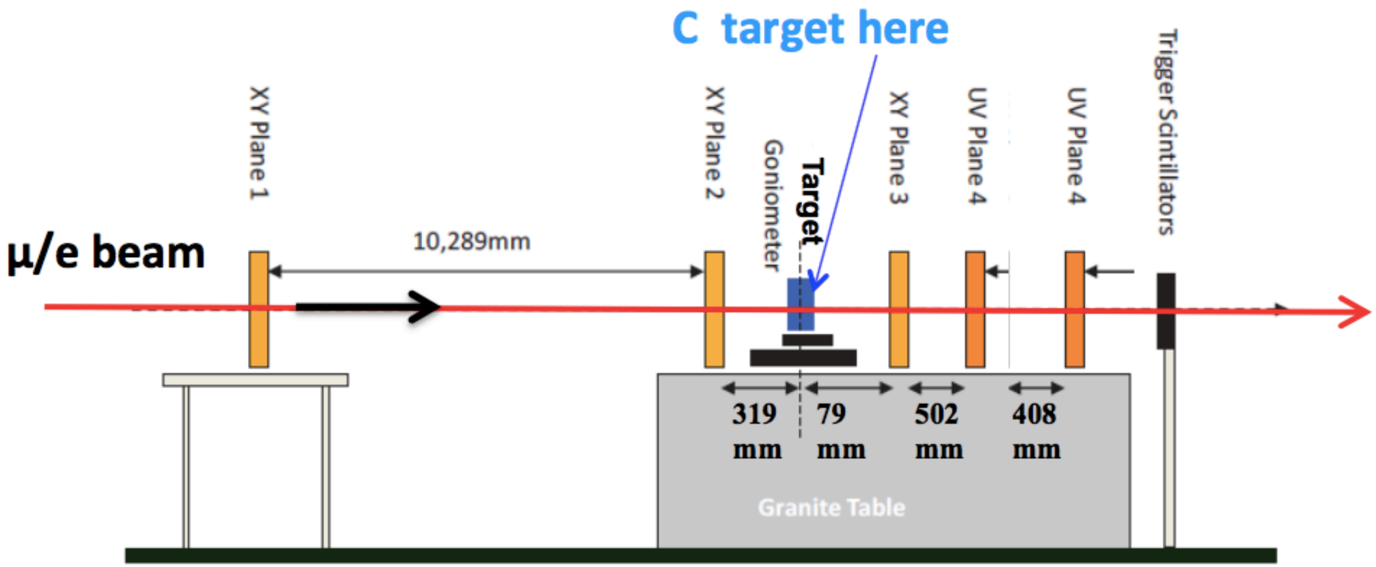
★ **Testbeams results**

Testbeam in 2017

TB in 2017

Used existing setup from Imperial College :

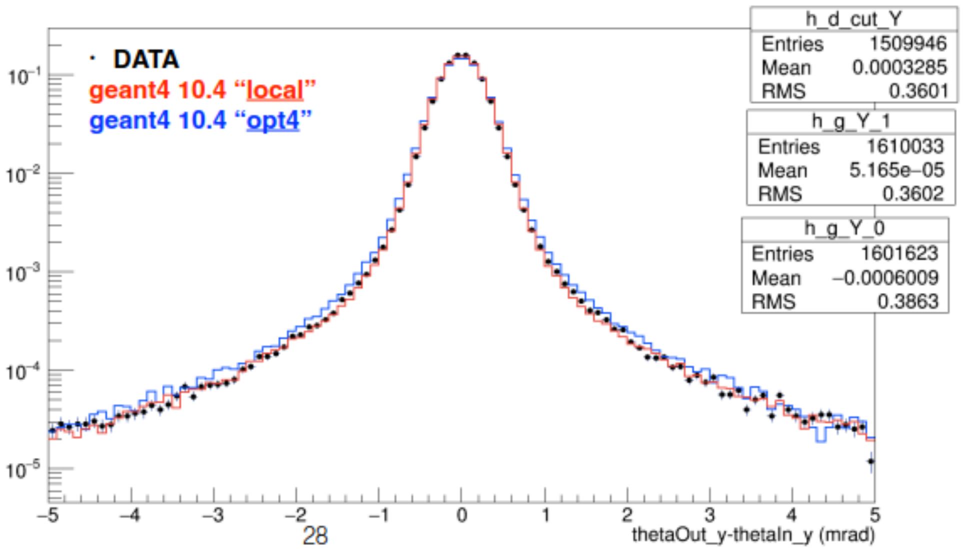
5 Si planes, 2 before and 3 after the target, 3.8x3.8 cm2
as is it the setup achieves 5.2 μrad, limited by the MS in the Si



Data taken with electrons and muons and with different targets thicknesses
Aim: study MS of electrons and first look at elastic events

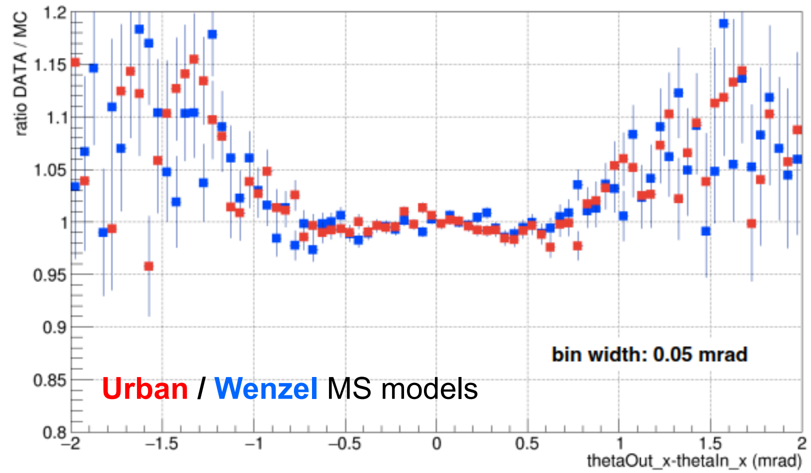
Testbeam in 2017 *(Multiple Scattering study)*

Data taken with
- **Graphite targets of 4, 8, 20 mm**
- **Electron energies 12 and 20 GeV**
- **Muons of 160 GeV**



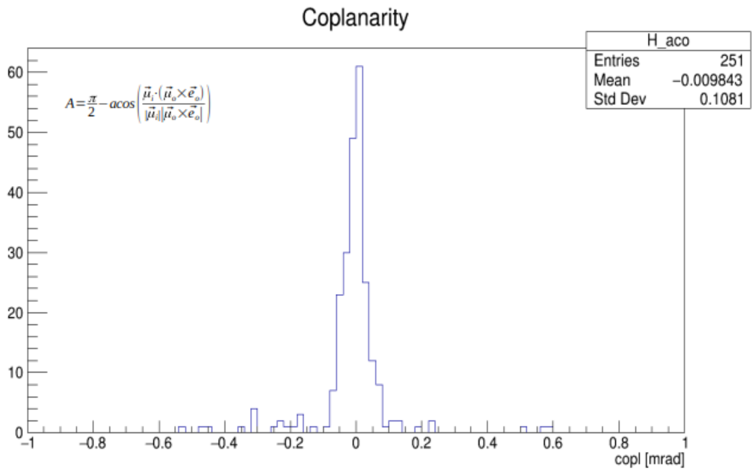
12 GeV electrons, 8 mm graphite
Comparison GEANT/DATA

12 GeV electrons, 20 mm graphite
GEANT/DATA

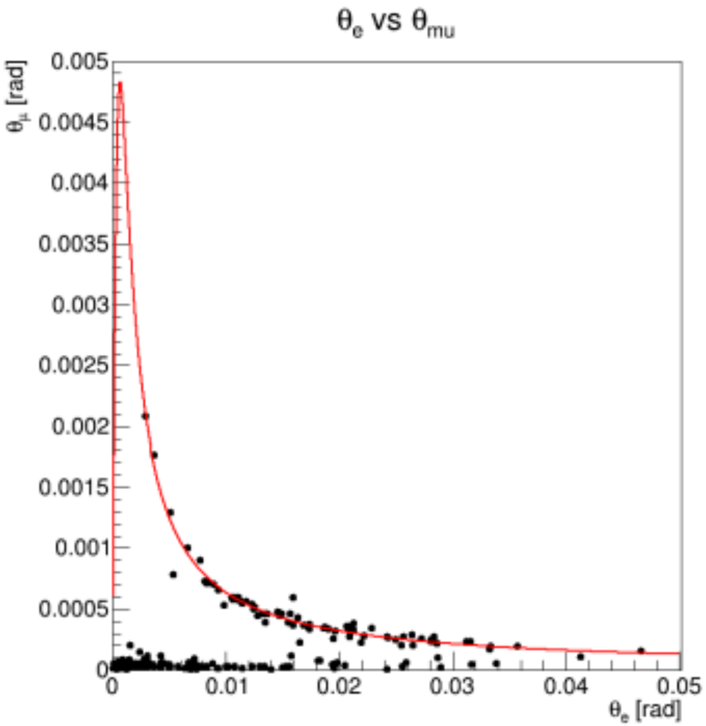


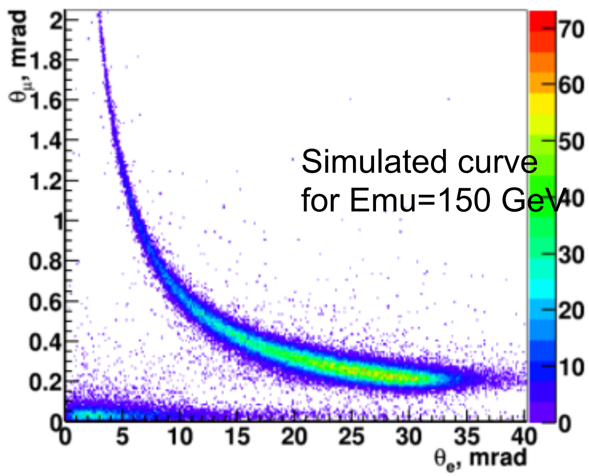
Testbeam in 2017

TB in 2017



2017 DATA



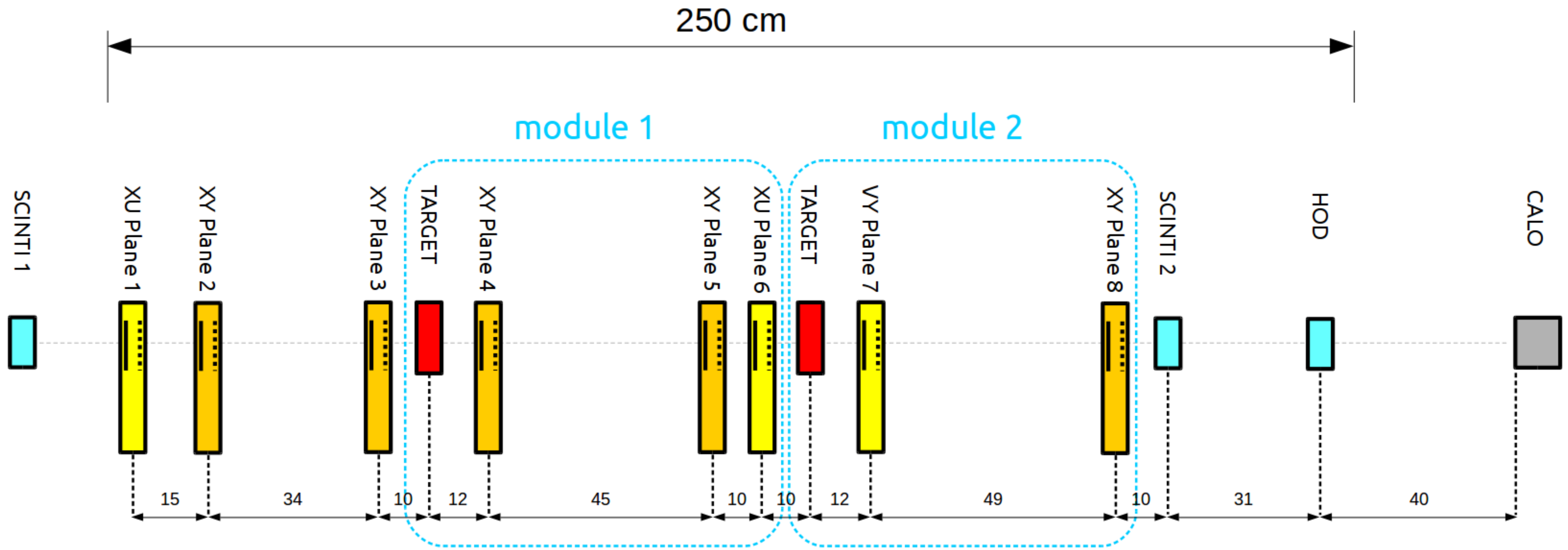


Simulated curve
for Emu=150 GeV

Testbeam in 2018

Two 'modules' :

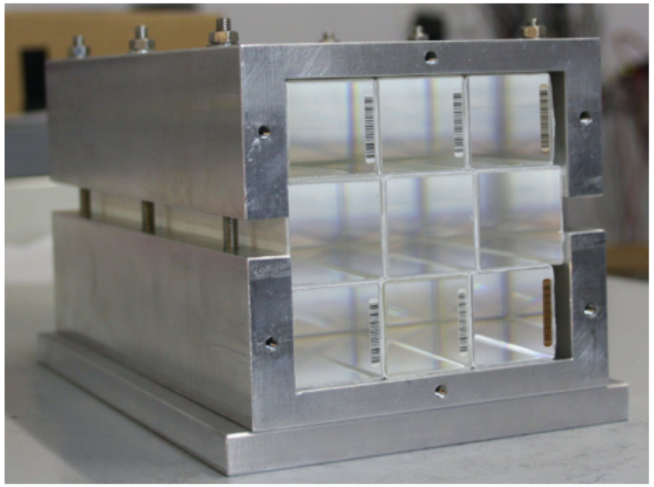
8 Si planes 9.5 x 9.5 cm , 2 C targets (8 mm thick)
e.m. calorimeter (CMS crystals)



Running with muons behind COMPASS detector

Testbeam in 2018

Setup located in the North Area behind COMPASS detector



Array of 3 x 3 crystals from CMS
$PbWO$, $25X_o$, $9.9\ cm^2$

Tentative timeline of the project:

Studies with GEANT 4 under way

geometrical configuration
target modularity and thickness
number of tracking Si planes
need to have particle identification (calorimeter, muon filter)

~ 1 year

Plan to have exploratory beam tests:

first one in 2017, one ongoing in 2018 with muons, planned tests with electron beams in 2019 *(using "existing" setups)*

~ 2 years

Once the geometry optimization is made:

detector elements: Hamamatsu sensors, existing r/o electronics,
explore if existing calorimeters&muon system can be re-used,

~ 2 – 3 years

Mount whatever part of the detector will be ready in 2021 to start taking data

Summary

We propose to measure $\mu\, e \rightarrow \mu\, e$ scattering in the space-like region with the existing CERN North Area μ beam and a detector which should not require R&D for new technologies

We are convinced that the physics case is extremely important (and timely!). The experiment is very challenging from the experimental point of view considering the systematic uncertainty which must be achieved, and hopefully it is doable in a relative short timescale

Quote from F. Jegerlehner (MITP workshop, Mainz 21-23 feb 2018)

- This experiment G. Abbiendi et al. is absolutely important also as it allows for for direct crosschecks with lattice QCD results and is has completely different systematics. Even a 5% crosscheck would be very helpful to scrutinize the HVP issue, and last bu not least whether the observed deviation is a real BSM effect.

Spares

Measure the Hadronic Leading Order contribution (HLO) to the muon g-2 in the space-like region

Proposed by:
G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G.Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L.Trentadue, G.Venanzoni

Reference:
G. Abbiendi et al., Eur. Phys. J. C (2017) 77:139. doi :10.1140/epjc/s10052-017-4633-z.

Physics motivations

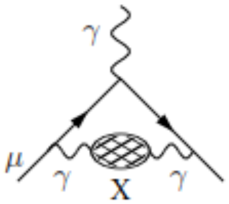
From F. Piccinini La Thuile 2018

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

- 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

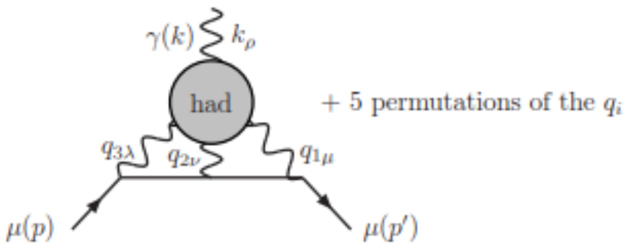
  T. Aoyama, M. Hayakawa, T. Kinoshita; S. Laporta, E. Remiddi; M. Passera
- $a_\mu^{\rm HLO} = 6894.6(32.5) \times 10^{-11} \Longrightarrow$ largest source of uncertainty

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



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

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

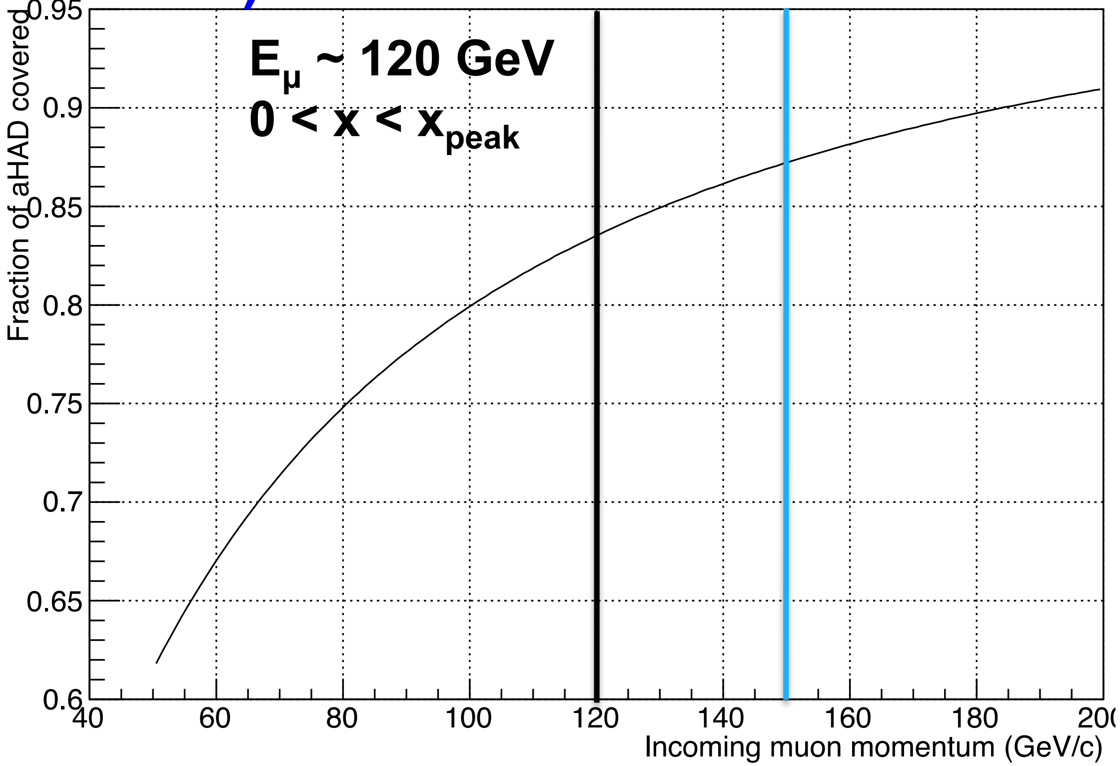


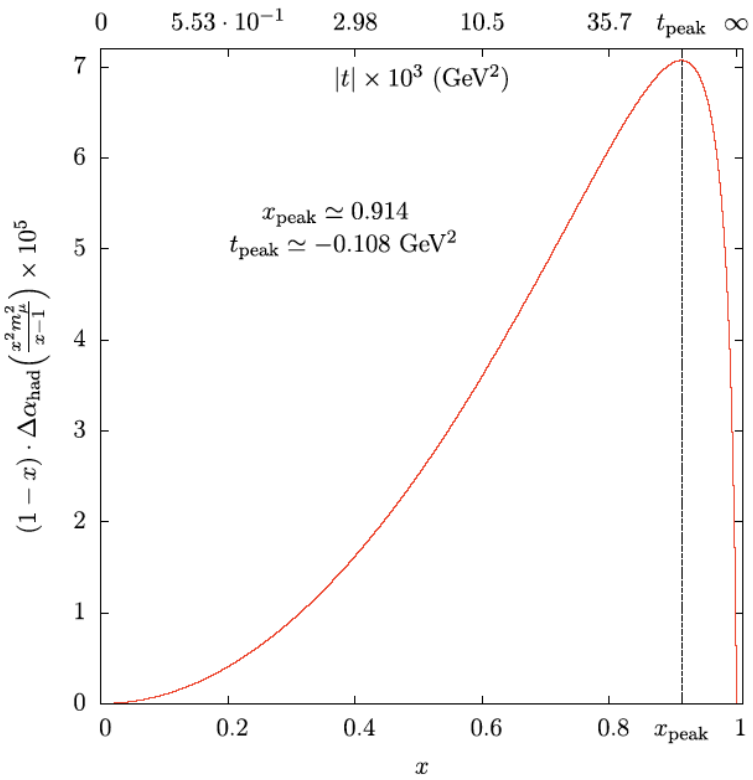
- Hadronic HO vacuum polarization: $a_\mu^{\rm HHO} = -87.0(0.6) \times 10^{-11}$
- two loop electroweak radiative corrections: $a_\mu^{\rm EW} = 153.6(1.1) \times 10^{-11}$

  Gnendiger, Stöckinger, Stöckinger-Kim

Optimal Muon Beam Momentum

Fraction of the a_μ^{HLO} integral as a function of the muon beam momentum: p_μ = 150 GeV → 87% of the integral ($0 < x < 0.93$).





Beyond the kinematic limit the integral can be determined using pQCD & time-like data, and/or lattice QCD results.

Activity on the theory side

1. QED NLO corrections. Easy.

2. Resummation of dominant corrections up to all orders, matched with NLO corrections. Non-trivial issue: mass effects in this case are important

3. NNLO corrections: some classes of NNLO re-usable from existing Bhabha calculations, some new due to different mass scales ($\mathbf{m}_{\mu}$ and $\mathbf{m}_{e}$). In any case, NNLO must be matched with 1. and 2. [references: Eur. Phys. J. C 66 (2010) 585 and references therein]

4. Development of dedicated MC tools including all the above ingredients

5. Detailed study of all the mentioned corrections, comparison among independent calculations, estimate of further-missing higher-order corrections