MUonE

A high precision measurement of $a_{\mu}^{\text{HLO}}$ with a 150 GeV $\mu$ beam on $e^{-}$ target at CERN

G. Venanzoni,
INFN-Pisa
on behalf of the proponents

“The closer you look the more there is to see” (F. Jegerlehner)

PBC Workshop, CERN 14 June 2018
Outline

- Reminder on MUonE proposal
- Some recent progress
- Plans
- Conclusions
Optical theorem and analyticity:

\[ \sigma(s)(e^+e^\to had) = \frac{4\pi}{s} \text{Im} \Pi_{\text{hadron}}(s) \]

The high-energy tail of the integral is calculated using pQCD.

The main contribution is in the highly fluctuating low energy region.

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

The enhancement at low energy implies that the \( \rho \to \pi^\pi^- \) resonance is dominating the dispersion integral (~ 75%). Current precision ~0.5% need to be reduced by a factor ~2.

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Alternative approach: $a^\text{HLO}_\mu$ from space-like region

$$a^\text{HLO}_\mu = \frac{\alpha}{\pi} \int_0^1 dx \ (1-x) \cdot \Delta \alpha_{\text{had}} \left( -\frac{x^2 m^2_\mu}{1-x} \right)$$

$$t = \frac{x^2 m^2_\mu}{x-1} \quad 0 \leq -t < +\infty$$

$$x = \frac{t}{2 m^2_\mu} (1 - \sqrt{1 - \frac{4 m^2_\mu}{t}}); \quad 0 \leq x < 1;$$

- $a^\text{HLO}_\mu$ is given by the integral of the curve (smooth behaviour)
- It requires a measurement of the hadronic contribution to the effective electromagnetic coupling in the space-like region $\Delta \alpha_{\text{had}}(t)$ ($t=q^2<0$)
- It enhances the contribution from low $q^2$ region (below 0.11 GeV$^2$)
- Its precision is determined by the uncertainty on $\Delta \alpha_{\text{had}}(t)$ in this region

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Experimental approach

Use of a 150 GeV μ beam on Be target at CERN (elastic scattering μe → μ e)

\[ \alpha(t) \left| \frac{\alpha(t)}{\alpha_0} \right|^2 = \left| \frac{1}{1 - \Delta \alpha(t)} \right|^2 \]

\[ \Delta \alpha = \Delta \alpha_{\text{lep}} + \Delta \alpha_{\text{had}} \]


G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Statistical reach of MUonE on $a_\mu^{\text{HLO}}$

(2 years of data taking at $1.3 \times 10^7 \mu/s$)

$F. \text{Jegerlehner's hadr5n12}$
Fit to pseudo-data (Padé)
$pQCD + \text{time-like data}$
pseudo-data

$a_\mu^{\text{HLO}} = 686.9 \pm 2.3 \times 10^{-10}$ (from fit to pseudo data)

TBC with input $a_\mu^{\text{HLO}} = 688.54 \pm 5.03 \times 10^{-10}$
Detector concept

Repetition (x60) of this single module
(~ 40-45 m total length)

~50-70 cm

10 cm

μ
d

~1cm Be Target
State-of-art Silicon detectors
hit resolution ~10 μm

Angular measurement \( t = f(\theta_e; \theta_\mu) \)
Expected angular resolution \( \sim 10 \mu m / 0.5 \text{ m} = 0.02 \text{ mrad} \)
At the end ECAL and Muon Filter for PID
MUonE : signal/normalization region

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

\(a_\mu^{HLO}\) at 0.3% \(\rightarrow\) These two ratios should be known at 10^{-5}

- **Signal**: \(10^{-5} < \Delta\alpha_{had} < 10^{-3}\)
- **Normalization**: \(\Delta\alpha_{had} < 10^{-5}\)
Elastic scattering in the \((\theta_e, \theta_\mu)\) plane

Coplanarity of the momentum vectors and angular kinematical constraint

- Muon beam momentum = 150 GeV

- \(x = 0.93, E_e = 130.7\) GeV
- \(x = 0.9, E_e = 88.5\) GeV
- \(x = 0.8, E_e = 35.0\) GeV
- \(x = 0.7, E_e = 17.8\) GeV
- \(x = 0.6, E_e = 9.8\) GeV
- \(x = 0.5, E_e = 5.5\) GeV
- \(x = 0.4, E_e = 2.9\) GeV
- \(x = 0.3, E_e = 1.4\) GeV
- \(x = 0.2, E_e = 0.5\) GeV
- \(x = 0.1, E_e = 0.1\) GeV

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
(Preliminary) Analysis of Test Beam data

First $\mu$-e elastic events!

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Systematics

1. Multiple scattering
2. Tracking (alignment & misreconstructions)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the $\mu$-e cross section (see later)
7. ...

Must be precisely known to keep the error on the cross section $< 10$ppm (breakdown of these contributions to $a_\mu^{\text{HLO}}$ in progress)
Multiple Scattering studies: 
Results from Test Beam

- 27 Sep-3 October 2017 at CERN "H8 Beam Line"
- Adapted UA9 Apparatus
- Beam energy: e- of 12/20 GeV; µ of 160 GeV
- $10^7$ events with C targets of different thickness (2,4,8,-20mm)

Adapted UA9 apparatus

5 Si planes: 2 before and 3 after the target, 3.8x3.8 cm² intrinsic resolution
$\sim 100 \mu$rad

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Agreement in the core region (90% of events) ~ 1%; outside few %
Agreement in the core region (90% of events) ~ 1%; outside few %
Agreement in the core region (90% of events) ~ 1%; outside few %
Detector optimization

- Target thickness (10mm Be default)
- Silicon sensors (type, material)
- Number of tracking stations per unit (3-4)
- Dimension of apparatus
- Calorimetry/PID
- Trigger/DAQ
- …
Some numbers:

- 60 cm total Be target (2X₀) segmented in 60 stations with 1 cm target (0.03 X₀)
- ~40 m total detector length
- 10x10 cm² silicon detectors
- Resolve each μ, e track with uniform efficiency
- Best possible resolution on θμ (in the range <5 mrad), θe (in the range <50 mrad)
- μ rate: ~60 MHz (peak) → 15 MHz (averaged)
- μ separation: 17 ns (peak) → 68 ns (averaged)
- Collect 4x10¹² events with Eₑ>1GeV in ~2 years
- Scattering probability (Eₑ>1GeV): 1.7x10⁻⁴/cm
- Scattering event rate (Eₑ>1GeV): ~10 kHz per station (peak); 2.5 (avg)
- Scattering separation (Eₑ>1GeV): 100 μs per station

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
## Silicon detectors survey

<table>
<thead>
<tr>
<th>Technology</th>
<th>ALICE Upg Inner</th>
<th>ALICE Upg Outer</th>
<th>CMS Upg 2S</th>
<th>2×CMS Upg 2S</th>
<th>CMS Upg PS</th>
<th>CMS Upg Pixel</th>
<th>2×CMS Current</th>
<th>Mimosa26</th>
<th>LHCb VELO-pix</th>
</tr>
</thead>
<tbody>
<tr>
<td>active x [cm]</td>
<td>27</td>
<td>21</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>33</td>
<td>10</td>
<td>1.06</td>
<td>4.246</td>
</tr>
<tr>
<td>active y [cm]</td>
<td>1.5</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>44.2</td>
<td>10</td>
<td>2.12</td>
<td>1.408</td>
</tr>
<tr>
<td>pixel size x [µm]</td>
<td>30</td>
<td>30</td>
<td>90</td>
<td>90</td>
<td>100</td>
<td>50</td>
<td>90</td>
<td>18.4</td>
<td>55</td>
</tr>
<tr>
<td>pixel size y [µm]</td>
<td>30</td>
<td>30</td>
<td>50000</td>
<td>90</td>
<td>1400</td>
<td>50</td>
<td>50000</td>
<td>18.4</td>
<td>55</td>
</tr>
<tr>
<td>σx [µm]</td>
<td>2</td>
<td>2</td>
<td>26</td>
<td>26</td>
<td>29</td>
<td>7</td>
<td>18</td>
<td>3.2</td>
<td>12</td>
</tr>
<tr>
<td>σy [µm]</td>
<td>2</td>
<td>2</td>
<td>14434</td>
<td>26</td>
<td>404</td>
<td>7</td>
<td>18</td>
<td>3.2</td>
<td>12</td>
</tr>
<tr>
<td>Material [x/Σ₀]</td>
<td>0.3%</td>
<td>0.8%</td>
<td>2.3%</td>
<td>4.5%</td>
<td>3.8%</td>
<td>2.0%</td>
<td>4.5%</td>
<td>0.10%</td>
<td>0.94%</td>
</tr>
<tr>
<td>Sensor mat. [x/Σ₀]</td>
<td>0.3%</td>
<td>0.8%</td>
<td>0.3%</td>
<td>0.6%</td>
<td>3.8%</td>
<td>2.0%</td>
<td>0.6%</td>
<td>0.10%</td>
<td>0.94%</td>
</tr>
</tbody>
</table>
Test Beam 2018

Build up and test a full scale prototype (2 modules).

- Run of a 2 full scale modules on a muon beam on M2 (behind COMPASS) from April/May
- Study of the detector performance: signal/background; tracking efficiency; understand the systematics
- Data taking is going on!

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
EXPERIMENTAL SETUP

Picture taken on 8/4/18

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Test Beam 2018

- Setup mounted in April 3-9;
- It take data since April 9
- 220M events already collected (~700GB);
- Rate: 7Mev/day (20GB/day)
- QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group)

- First results obtained for the NNLO box diagrams contributing to mu-e scattering in QED (Padova group)

Master integrals for the NNLO virtual corrections to $\mu e$ scattering in QED: the planar graphs

An unprecedented precision challenge for theory: a full NNLO MC generator for $\mu$-e scattering ($10^{-5}$ accuracy)
Theory: international community!


- 2018, Feb 19-23: A Topical workshop at MIPT, Mainz https://indico.mitp.uni-mainz.de/event/128/

- 2019, Feb 4-7: Workshop on “Theory for muon-electron scattering @ 10ppm” in Zurich

G. Venanzoni, PBC Workshop, CERN, 14 Jun 2018
Status of the Collaboration

• Collaboration is growing and interest from International groups from CERN, Poland (Kracow), Russia (Novosibirsk), UK (Liverpool, UCL), USA (Virginia) has been expressed.

• Results so far encouraging; we are working hard toward a formal LoI (2019).

Report of A. Magnon, PBC meet, 2 March 18

- Concerning the final project for High precision measurement of $a_{\mu}^{\text{HLO}}$
  
  Certainly very challenging
  
  I (Alain Magnon) DO NOT SEE a priori showstopper(s)
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
Beam considerations

Requirements for the experiment:

1. The beam must be:
   - “Parallel” (divergence <0.5 mrad) and “large” (σ~2-2.5 cm)
   - Highest energy/intensity as possible (~150 GeV) and O(10⁸ µ/spill)
   - Pure (π contamination < 10⁻⁶)
   - Need to know the incoming p_µ at <1%

2. The final apparatus is small in transverse dimension but long along the beam axis (~40m for trackers+targets, 0.8 m for calo, ~3m for µ filter (passive material)+ a couple of active chambers) \(\rightarrow\) needs a space of ~ 40-45 m (total extension)

Final detector should go wherever these conditions can be satisfied (and in agreement with all the users!)
Conclusion

- Exciting times for the muon g-2!
- **Alternative/competitive determinations of** $a_{\mu}^{HLO}$ **are essential**:  
  - Time-like (dispersive) approach  
  - Lattice  
  - Space-like approach (MUonE)

- **Progress on MUonE:**  
  - Analysis of MS 2017 TB data  
  - Detector optimization, Si sensors survey  
  - Compatibility studies/implementation in EHN2  
  - Progress on the Theory side  
  - Test run in 2018; planned tests for 2019 (MS)  
  - Growing interest from both experiment and theory community  
  - Lol planned for 2019
MUonE Collaboration
(in progress...)

THE END

(Thanks to J. Berhnard, L. Gatignon and A. Magnon for many useful discussions)
SPARE
Report of A. Magnon (MUonE referee in PBC) 2 March 2018

- Expect a lot of physics Input from these tests
  Hope we can run at (close) to nominal $\mu$ Flux

- Concerning the final project for High precision measurement of $a_\mu^{HLO}$
  Certainly very challenging
  I (Alain Magnon) DO NOT SEE a priori showstopper(s)
Detector optimization

Diagrams showing the interaction of particles with target and Si detectors.
Reference papers

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

C. M. Carloni Calame$^a$, M. Passera$^b$, L. Trentadue$^c$, G. Venanzoni$^d$

$^a$Dipartimento di Fisica, Università di Pavia, Pavia, Italy
$^b$INFN, Sezione di Padova, Padova, Italy
$^c$Dipartimento di Fisica e Scienze della Terra “M. Melloni” Università di Parma, Parma, Italy and INFN, Sezione di Milano Bicocca, Milano, Italy
$^d$INFN, Laboratori Nazionali di Frascati, Frascati, Italy

Measuring the leading hadronic contribution to the muon $g-2$ via $\mu e$ scattering

G. Abbiendi$^1$, C. M. Carloni Calame$^2$, U. Marconi$^1$, C. Matteuzzi$^3$, G. Montagna$^{4,2}$, O. Nicrosini$^2$, M. Passera$^5$, F. Piccinini$^2$, R. Tenchini$^6$, L. Trentadue$^{7,3}$, and G. Venanzoni$^8$

$^1$INFN, Sezione di Bologna, Bologna, Italy
$^2$INFN, Sezione di Pavia, Pavia, Italy
$^3$INFN, Sezione di Milano Bicocca, Milano, Italy
$^4$Dipartimento di Fisica, Università di Pavia, Pavia, Italy
$^5$INFN, Sezione di Padova, Padova, Italy
$^6$INFN, Sezione di Pisa, Pisa, Italy
$^7$Dipartimento di Fisica e Scienze della Terra “M. Melloni”, Università di Parma, Parma, Italy
$^8$INFN, Laboratori Nazionali di Frascati, Frascati, Italy
Plans: detector considerations

Final detector is a sequence of 60 modules, each acting as a stand-alone detector to measure the outcoming angles of $\mu$ and $\epsilon$

Plan to use state of the art silicon detectors developed for the HL-LHC or Belle2 (possibly already funded by INFN)

Calorimeter and muon filter at the end of the 60 elements
The setup was mounted during: April 3 - 9

It has been running since: April 9

Calorimeters installed:
- Shashlik from April 9th to May 1st
- Replaced with PbWO crystal from May 1st to May 23rd
- Replaced with BGO crystal (calibrated in EA)
  *(installed in the setup on the 5th June 2018)*

9 x BGO (~7x7 cm², 22 X₀)

3x3 array (no dead zones)
Calibrated in the 1-15 GeV range at the East Hall (T9) May 2018
PMT readout
Running behind COMPASS
Take $\mu$ 's from M2 when requested by COMPASS
Take $\mu$ 's from $\pi$ decays when COMPASS use $\pi$ 's beam

Muon Distribution Downstream (D)

- Muon Position Distribution

Flux for $10^{17}$ pot $\sim 10^3$ spill within 10 cm x 10 cm of beam axis
$\sigma_x = 100.2$ mm, $\sigma_y = 84.23$ mm
Note: Change in scale

From D. Banerjee EHN2 meeting

Muon Distribution Downstream (D)

- Muon Momentum

Beam Divergence, $X' \sim 2$ mrad
Beam Divergence, $Y' \sim 1.6$ mrad
Beam Momentum = 186 GeV/c with tail

$\mu$ momentum 186 GeV/c
9 x PbWO (CMS) \([25 \times \bar{X}_0]\) \([9 \times 9 \text{ cm}^2]\)

3x3 array (small air gap between crystals), 2017 calibration
SiPM readout, already integrated in the DAQ, self
equalization (leds on the SiPM board)
Not available in August (will be re-calibrated)
Test Beam setup and target

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

G. Venanzoni, g-2 Coll Meeting 22 March 2018
Resolution dominated by MS up to 10~100 GeV/c

- Resolution on scattering angle assumptions:
  - 2 measurement plane 0.5 m apart
  - Scattering on:
    - No plane (ideal resolution)
    - First detector plane (pure tracker resolution)
    - First plane + ½ Be target (includes “average” MS in target)
  - Core of MS only considered (no tails)

Angle resolution:
\[ \Delta \theta^2 = \Delta \theta_T^2 + \Delta \theta_{MS}^2 \]

Angle intrinsic resolution:
\[ \Delta \theta_T = \frac{\Delta x \sqrt{2}}{0.5 \text{ m}} \]

MS angle:
\[ \Delta \theta_{MS} = \frac{13.6}{p/\text{MeV}} \sqrt{m \times (1 + 0.038 \ln m)} \]

Scattering material: first layer only
\[ m = \left( \frac{X}{X_0} \right)_{\text{det}} \]
Detector integration time

- Hybrid pixels & strips for (HL-)LHC: 25 ns
- ALPIDE: 1 µs
- Mimosa26: 112 µs

\[
N_\mu = r \times \tau \\
e.g. \quad N_\mu = 40 \text{ MHz} \times 25 \text{ ns} = 1 \\
e.g. \quad N_\mu = 40 \text{ MHz} \times 1 \mu\text{s} = 40
\]

Expected pile-up events (per 40MHz)

G. Venanzoni, Pisa, 5 June 2018
Why measuring \( \Delta \alpha_{\text{had}}(t) \) with a 150 GeV \( \mu \) beam on e\(^-\) target?

It looks an ideal process!

- \( \mu \ e \rightarrow \mu \ e \) is pure t-channel (at LO)

- **Simple** kinematics (2 body process, \( t = -2m_eE_e < 0 \)) allows to span the region \( 0 < t < 0.143 \) GeV\(^2\) (\( 0 < x < 0.93 \)); 87\% of total \( \alpha_{\mu}^{\text{HLO}} \) (the rest can be computed by pQCD/time-like data)

- Angular measurement: high boosted system gives access to all angles (\( t \)) in the cms region \( \theta_e^{\text{LAB}} < 32 \) mrad (\( E_e > 1 \) GeV) \( \theta_{\mu}^{\text{LAB}} < 5 \) mrad

- It allows using the same detector for signal and normalization (\( x < 0.3, \Delta \alpha_{\text{had}}(t) < 10^{-5} \)) \( \rightarrow \) cancellation of detector effects at first order

G. Venanzoni, Pisa, 5 June 2018
Muon beam M2 at CERN

“Forty years ago, on 7 May 1977, CERN inaugurated the world’s largest accelerator at the time – the Super Proton Synchrotron”.

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum ((p_\mu)/(p_\pi))</td>
<td>((160 \text{ GeV/c})/(172 \text{ GeV/c}))</td>
</tr>
<tr>
<td>Proton flux on T6 per SPS cycle</td>
<td>(1.2 \cdot 10^{13})</td>
</tr>
<tr>
<td>Focussed muon flux per SPS cycle</td>
<td>(2 \cdot 10^{8})</td>
</tr>
<tr>
<td>Beam polarisation</td>
<td>((-80 \pm 4))%</td>
</tr>
<tr>
<td>Spot size at COMPASS target ((\sigma_x \times \sigma_y))</td>
<td>(8 \times 8 \text{ mm}^2)</td>
</tr>
<tr>
<td>Divergence at COMPASS target ((\sigma_x \times \sigma_y))</td>
<td>(0.4 \times 0.8 \text{ mrad})</td>
</tr>
<tr>
<td>Muon halo within 15 cm from beam axis</td>
<td>16%</td>
</tr>
<tr>
<td>Halo in experiment ((3.2 \times 2.5 \text{ m}^2)) at (</td>
<td>x, y</td>
</tr>
</tbody>
</table>

\[ I_{\text{beam}} > 10^7 \text{ muon/s}, \ E_\mu = 150 \text{ GeV} \]

G. Venanzoni, Pisa, 5 June 2018
Detector considerations

- Modular apparatus: 60 layers of \(~1\) cm Be (target), each coupled to \(~0.5\) m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle.

- The \(t=q^2\) of the interaction is determined by the electron (or muon) scattering angle (à la NA7).

- ECAL and \(\mu\) Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID.

- It provides uniform full acceptance, with the potential to keep the systematic errors at \(10^{-5}\) (main effect is the multiple scattering for normalization which can be studied by data).

- Statistical considerations show that a 0.3\% error can be achieved on \(a_{\mu}^{\text{HLO}}\) in 2 years of data taking with \(~10^7\) \(\mu\)/s (4x10^{14}\mu\) total).
Last module of the detector

Measure both the electron angle and $E_e$ to define the reference, calibration curve. Detailed check of GEANT predictions.
Fraction of $a_{\mu}^{\text{HLO}}$ covered

87% of $a_{\mu}^{\text{HLO}}$ covered with $P_{\mu}=150$ GeV

G. Venanzoni, Pisa, 5 June 2018
Fraction of $a_\mu^{HLO}$ covered

$P_\mu = 150$ GeV/c

$\Delta \alpha_{\text{HAD}} \times 10^4$

$x_{\text{MAX}} = 0.932$

$a_{\text{HAD}} = 87\%$

87% of $a_\mu^{HLO}$ covered with $P_\mu=150$ GeV

(courtesy of M. Incagli)

G. Venanzoni, Pisa, 5 June 2018
Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:
  \[ a_\mu^{E821} = 11659208.9(6.3) \times 10^{-10} \, (0.54 \, \text{ppm}) \]

- Tantalizing \(\sim 3\sigma\) deviation with SM (persistent since >10 years):
  \[ a_\mu^{SM} = 11659180.2(4.9) \times 10^{-10} \, (DHMZ) \]
  \[ a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8) \times 10^{-10} \]

- Current discrepancy limited by:
  - **Experimental** uncertainty \(\rightarrow\) New experiments at FNAL and J-PARC \(\times 4\) accuracy
  - **Theoretical** uncertainty \(\rightarrow\) limited by hadronic effects

\[ a_\mu^{SM} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} \]

Hadronic Vacuum polarization (HLO)

\[ a_\mu^{HLO} = (692.3 \pm 4.2) \times 10^{-10} \]

\[ \delta a_\mu^{HLO}/a_\mu^{HLO} \sim 0.6\% \]
The silicon detectors
Sensors developed for AGILE, being used by LEMMA

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (cm²)</td>
<td>9.5 × 9.5</td>
</tr>
<tr>
<td>Thickness (µm)</td>
<td>410</td>
</tr>
<tr>
<td>Readout strips</td>
<td>384</td>
</tr>
<tr>
<td>Readout pitch (µm)</td>
<td>242</td>
</tr>
<tr>
<td>Physical pitch (µm)</td>
<td>121</td>
</tr>
<tr>
<td>Bias resistor (MΩ)</td>
<td>40</td>
</tr>
<tr>
<td>AC coupling Al resistance (Ω/cm)</td>
<td>4.5</td>
</tr>
<tr>
<td>Coupling capacitance (pF)</td>
<td>527</td>
</tr>
<tr>
<td>Leakage current (nA/cm²)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Daniela Lietti, PhD thesis. VISION: a Versatile and Innovative Silicon tracking system


G. Venanzoni, Fermilab, 10 April 2018
Experimental setup location

Site inspection in COMPASS on 11/10/2017
Counting room quite far from experimental site: DAQ PC near setup → “short” optical fiber from crate VME to DAQ PC, then ethernet cable from DAQ PC to counting room

G. Venanzoni, g-2 Coll Meeting 22 March 2018
Timelike data aiming at 0.2% on $a^\text{HLO}_\mu$?

- Not an easy task!
  - $>30$ channels to keep under control (at (sub)percent level)
  - Local discrepancies in main channels ($2\pi$ (KLOE/Babar), $K^+K^-$ CMD2/Babar)
  - Isospin corrections for not measured channels
  - Treatment of narrow resonances? (See F. Jegerlehner, ArXiv:1511.04473)

An independent/complementary approach is highly desirable!

M. Davier, TAU16 WS

G. Venanzoni, $\mu$-e Theory Workshop, Padova, 4 September 2017
Lattice-QCD progress on $a_\mu^{\text{HVP}}$

- Can calculate nonperturbative vacuum polarization function $\Pi(Q^2)$ directly in lattice QCD from simple 2-point correlation function of EM quark current [Blum, PRL 91 (2003) 052001]

- Several ongoing lattice efforts yielding new results since ICHEP 2014 including:

  (1) First calculation of quark-disconnected contribution [RBC/UKQCD, PRL 116, 232002 (2016)]

  (2) Second complete calculation of leading-order $a_\mu^{\text{HVP}}$ [HPQCD, arXiv:1601.03071]

  - First to reach precision needed to observe significant deviation from experiment

- ~1% total uncertainty by 2018 possible
- Sub-percent precision will require inclusion of isospin breaking & QED, and hence take longer
**However**: Recent Lattice evaluation

Hadronic vacuum polarization contribution to the anomalous magnetic moments of leptons from first principles

Sz. Borsanyi,1 Z. Fodor,1,2,3 C. Hoelbling,1 T. Kawanai,3 S. Krieg,1,3 L. Lellouch,4 R. Malak,4,5 K. Miura,4 K.K. Szabo,1,3 C. Torrero,4 and B.C. Toth1

(Budapest-Marseille-Wuppertal collaboration)

\[ a_{\mu}^{LO-HVP} \cdot 10^{10} \]

**This work**

HPQCD 16

ETM 14

Jegerlehner 17

Davier 16

Hagiwara 16

LQCD Pheno.

error \approx 2.7%
\[ a_\mu^{\text{LO-HVP}} = 711.0(7.5)(17.3) \times 10^{-10} \]

(NP). Using the SM contributions summarized in [8], we find 
\[ a_\mu^{\text{LO-HVP}} = (720.0 \pm 6.8) \times 10^{-10} \]. The errors on 
the lattice results, which are in the range of 2.0 to 4.1% 
are substantially larger than those of the phenomenological approach. Our result for 
\[ a_\mu^{\text{LO-HVP}} \] is larger than 
those of the other lattice calculations and in slight tension with the one from HPQCD [33] which is 1.9 \sigma away. 
A more detailed flavor-by-flavor comparison is given in [45]. However, our result is consistent with those from 
phenomenology within about one standard deviation, as 
well as with \[ a_\mu^{\text{LO-HVP}} \]. Thus, one will have to wait for 
the next generation of lattice QCD calculations to confirm or 
infirm the larger than 3 \sigma deviation between the 
measurement of \[ a_\mu \] and the prediction of the SM based 
on phenomenology.
Experimental Setup

Scintillators: 2 100 x 100 mm²

Silicon detectors: 12 XY planes
2 UV plane ±45°

Need 3 stereo views to resolve ambiguities
Multiple scattering angle

Multiple scattering, \( p=140 \text{ GeV/c} \)

- Mimosa26 chip
- ALICE Upg Inner
- CMS Upg 2S
- 2×CMS current
- 2×CMS upg 2S
- ALICE Upg Outer
- LHCb VELOpix
- Be target [0.5cm]
- CMS Upg Pixel
- CMS Upg PS
- Be target [1.5cm]

Scattering angle [mrad]

mrad

G. Venanzoni, PBC QCD-WG Meeting 2 March 2018
τ and trigger rate define operation mode

![Graph showing the relationship between max trigger rate and integration time τ.](image)

G. Venanzoni, PBC QCD-WG Meeting 2 March 2018
DAQ program (C + Tk/Tk GUI)
- trigger selection (AND, OR, VETO, ...)
- calibration routines (silicon strips)
- pedestal run

online data processing
- "dst" production
- monitoring tools

Software

idle
- SPS spill start
- Triggers ON, events stored on local memories
- SPS spill stop
- Triggers OFF, data written on hard drives
The multiple scattering resolution is shown with various angular resolutions.

- The detector effects (mostly MS in the target) modify the theoretical spectrum ($N(\theta_e)$).
- We assume a 1% miscalibration on the GEANT model for $\sigma_{\theta_e}$ MS ($N_{\text{mis}}$).
- $N_{\text{mis}}$ quadratically in $\theta_e$ respect to NO bias ($N_i$).
- By correcting $N_{\text{mis}}/N_i$ in the normalization region $\rightarrow$ residual effects $<10^{-5}$ in the signal region.

$\rho_0 = (4.2 \pm 1) \times 10^{-6}$

G. Venanzoni, PBC Workshop, CERN, 21 November 2017
Low energy electrons should be tagged

These do not even cross 300 µm Si

Events to be tagged in some way
Not only the track angle

The tracker provides more information on the track than just its angle. These three parameters can be used as input to a global track quality parameter. Usually $dE/dx$ is another discriminator, but unfortunately it is not significant in our range of energies.
Il readout

**Readout electronics**
- Zero suppression mode
- 1 ADC board per 4 moduli single side
- 1 VME Readout Board per leggere gli ADC e immagazzinare i dati durante la spill
- Readout speed → 6 kHz → questo numero può salire a 15 kHz se ognuno dei 3 ASIC che leggono una vista è letto in modo indipendente (e non in una daisy chain a 3 come succede adesso)
- è possibile solo costruendo moduli nuovi

Abbiamo materiale per costruire ulteriori 10 viste x-y
Prospect for 2018 run

**Silicon beam chambers:**
- 4 moduli X-Y con i rivelatori single side di AGILE → 9.5x9.5 cm² con strip a passo 242 μm – 1 strip floating → risoluzione spaziale di 30 μm
- 4 moduli X-Y richiedibili a INFN Bari (gruppo Fermi) → rivelatori single side di 8.75x8.75 cm² con strip a passo 228 μm
- In costruzione: 5 moduli X-Y per LEMMA con i rivelatori single side di AGILE


Daniela Lietti, PhD thesis. VISION: a Versatile and Innovative SIlicON tracking system