

# The MUonE experiment



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

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An aerial photograph of the Fermilab Muon Campus construction site. The site features several large, modern buildings, including a tall rectangular structure and a circular building with a central tower. A large circular excavation pit is visible in the foreground. The surrounding area includes roads, parking lots, and green fields. Overlaid on the image is the text "Muon Campus in US and Europe contribution".

Muon Campus in US  
and Europe contribution

January 1, 2016 – December 31, 2019



MUSE

MUSE Network General Meeting 22 Oct 2018

# Reference papers

## A new approach to evaluate the leading hadronic corrections to the muon $g-2$ $\star$

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*Università di Parma, Parma, Italy and*

*INFN, Sezione di Milano Bicocca, Milano, Italy*

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

G. Abbiendi<sup>1</sup>, C. M. Carloni Calame<sup>2</sup>, U. Marconi<sup>1</sup>, C. Matteuzzi<sup>3</sup>, G. Montagna<sup>4,2</sup>,  
O. Nicrosini<sup>2</sup>, M. Passera<sup>5</sup>, F. Piccinini<sup>2</sup>, R. Tenchini<sup>6</sup>, L. Trentadue<sup>7,3</sup>, and G. Venanzoni<sup>8</sup>

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# Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3) \times 10^{-10} \text{ (0.54 ppm)}$$

- Tantalizing  $\sim 3\sigma$  deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659182.3(4.3) \times 10^{-10}$$

M. Davier, A. Hoecker, B. Malaescu  
and Z. Zhang, Eur. Phys. J. C77 (2017)

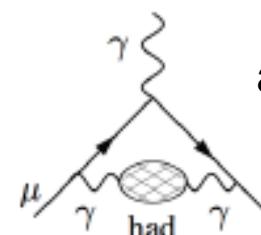
$$a_\mu^{E821} - a_\mu^{SM} \sim (26.8 \pm 7.6) \times 10^{-10} (3.5\sigma)$$

- Current discrepancy limited by:

- **Experimental** uncertainty → New experiments at FNAL and J-PARC **x4** accuracy
- **Theoretical** uncertainty → limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)



$$a_\mu^{\text{HLO}} = (693.1 \pm 3.4) 10^{-10}$$

$$\delta a_\mu / a_\mu \sim 0.5\% \rightarrow 0.2\%$$

# $a_\mu^{\text{HLO}}$ calculation, traditional way: time-like data

[C. Bouchiat, L. Michel '61; N. Cabibbo, R. Gatto 61;  
L. Durand '62-'63; M. Gourdin, E. De Rafael, '69;  
S. Eidelman F. Jegerlehner '95, . . . ]

- Optical theorem and analyticity:

$$\sigma(s)_{(e^+e^- \rightarrow \text{had})} = \frac{4\pi}{s} \text{Im } \Pi_{\text{hadron}}(s)$$

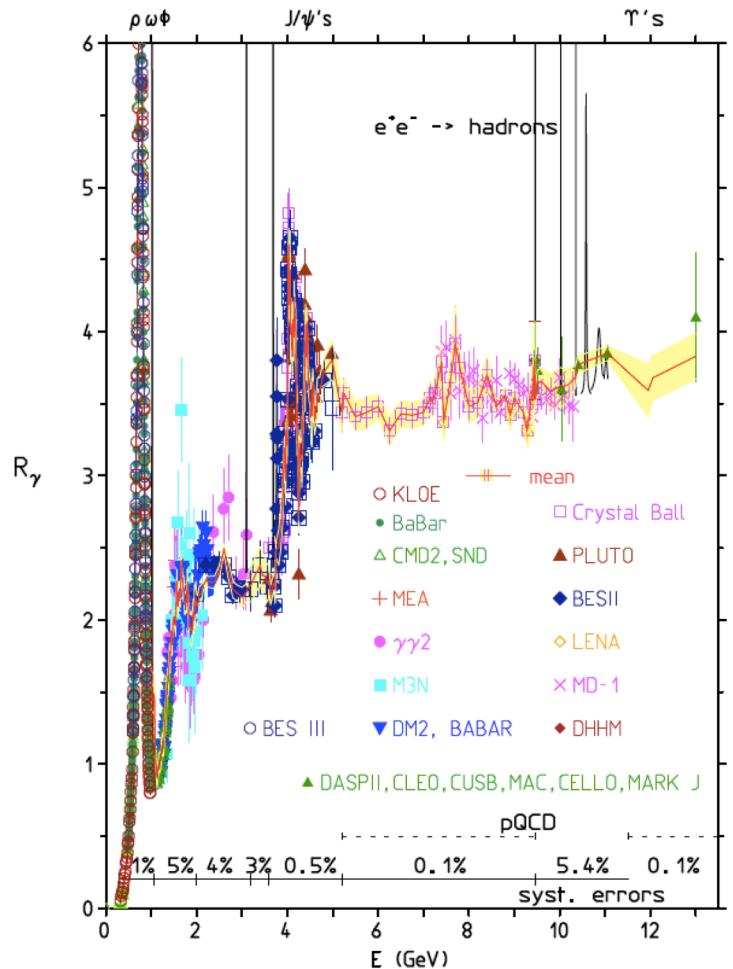
$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^\infty ds K(s) \cdot \sigma(s)_{(e^+e^- \rightarrow \text{had})}$$

- The main contribution is in the highly fluctuating low energy

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

The enhancement at low energy implies that the  $\rho \rightarrow \pi^+\pi^-$  resonance is dominating the dispersion integral ( $\sim 75\%$ ). Current precision at 0.6%  $\rightarrow$  need to be reduced by a factor  $\sim 2$

Collection of many experimental results



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

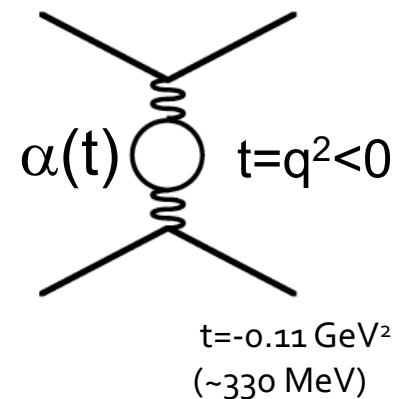
# Alternative approach: $a_\mu^{\text{HLO}}$ from space-like region

[C.M. C. Calame et al, Phys. Lett. B 746 (2015) 325]

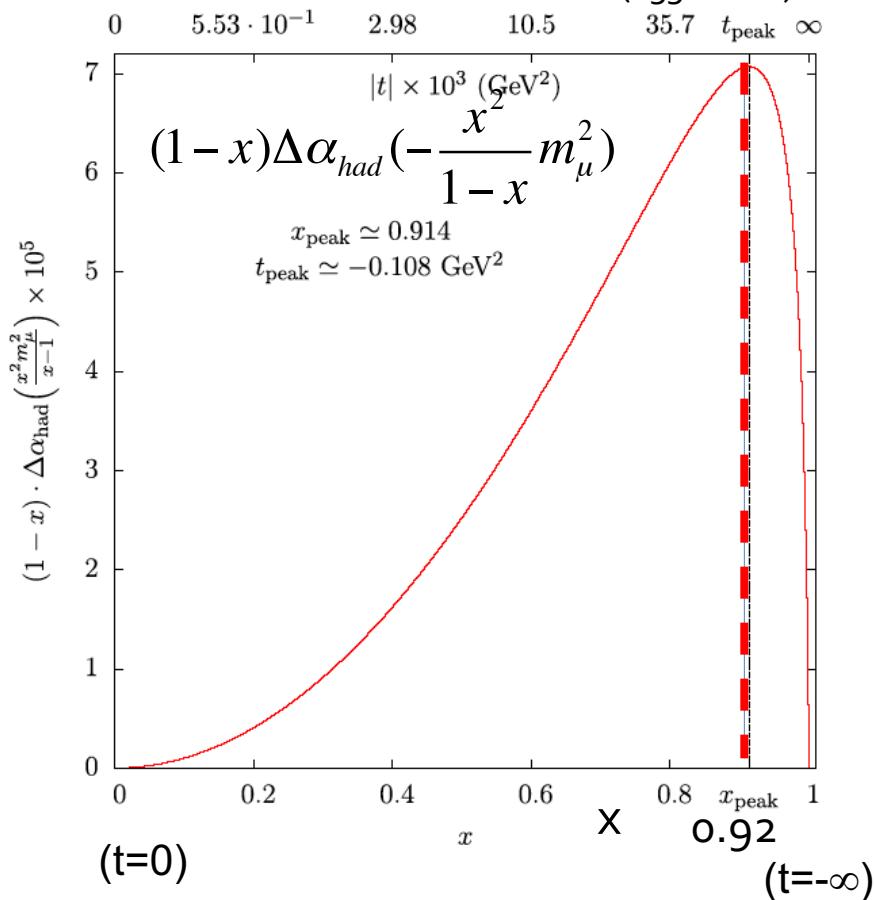
$$a_\mu^{\text{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \cdot \Delta\alpha_{\text{had}} \left( -\frac{x^2 m_\mu^2}{1-x} \right)$$

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

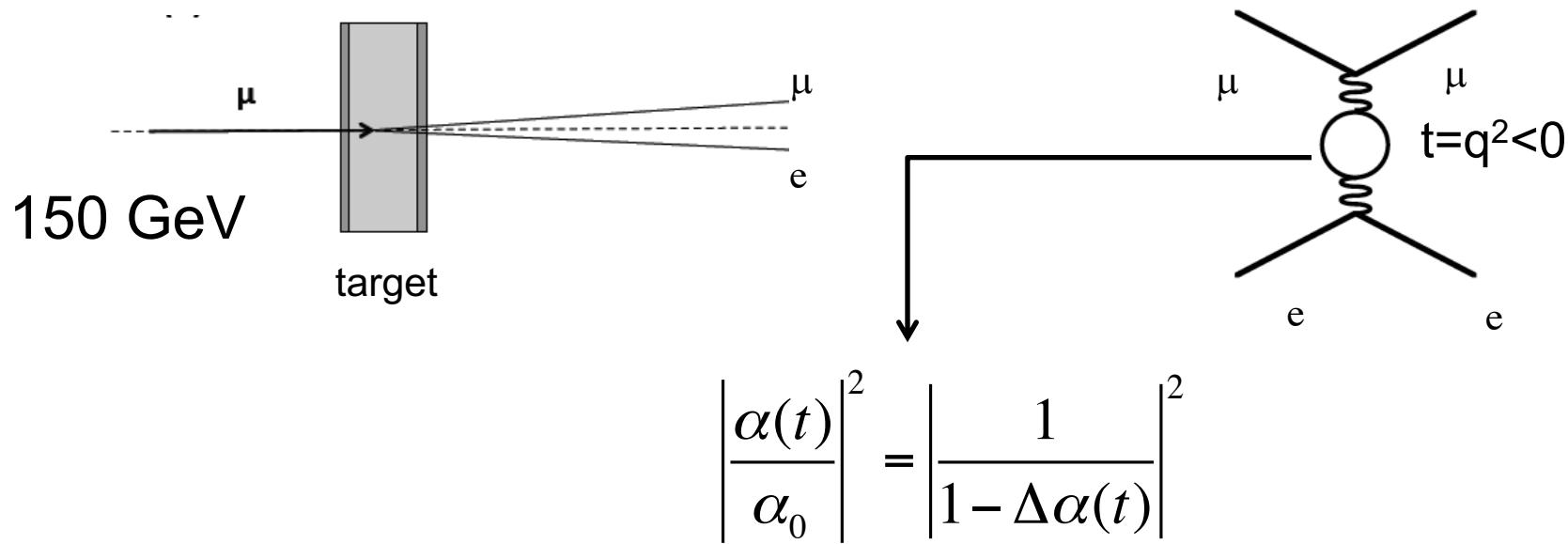
$$x = \frac{t}{2m_\mu^2} \left( 1 - \sqrt{1 - \frac{4m_\mu^2}{t}} \right); \quad 0 \leq x < 1;$$



- $a_\mu^{\text{HLO}}$  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  $0.11 \text{ GeV}^2$ )
- Its precision is determined by the uncertainty on  $\Delta\alpha_{\text{had}}(t)$  in this region



Use of a 150 GeV  $\mu$  beam on Be target at CERN (elastic scattering  $\mu e \rightarrow \mu e$ ) to get  $\Delta\alpha_{\text{had}}(t < 0)$



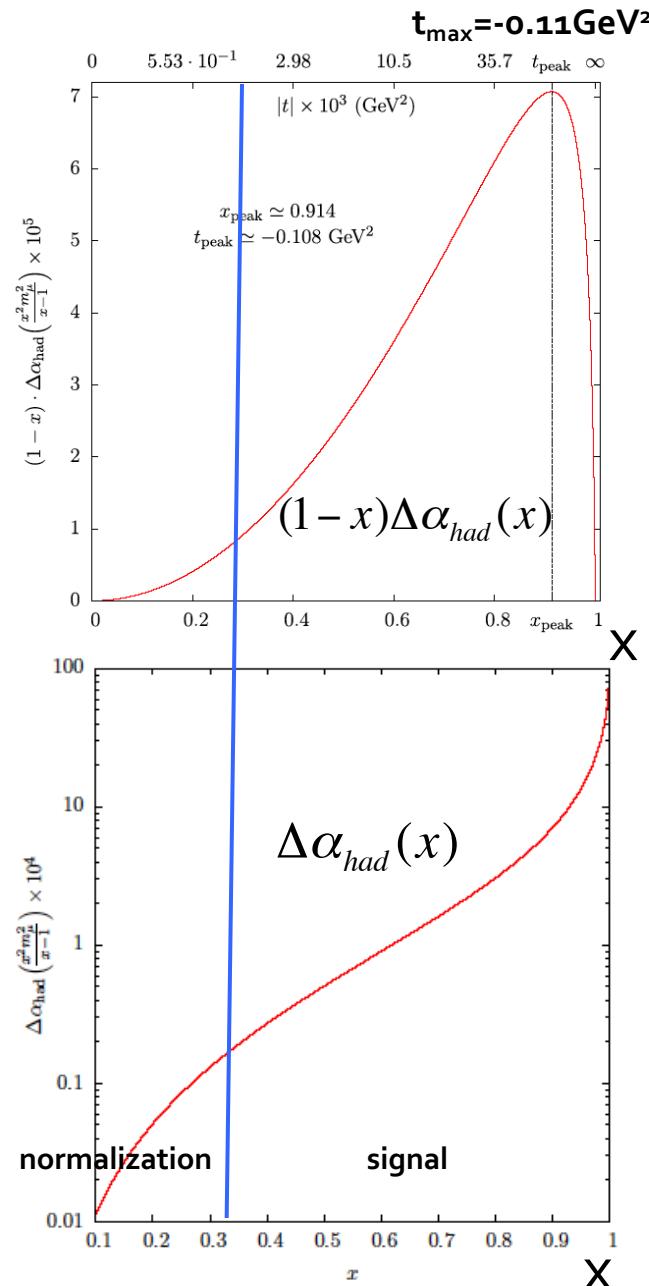
**Measuring the leading hadronic contribution to the muon g-2 via  $\mu e$  scattering,**  
G. Abbiendi *et al*, Eur.Phys.J. C77 (2017) no.3, 139

# Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV $\mu$ beam on $e^-$ target ?

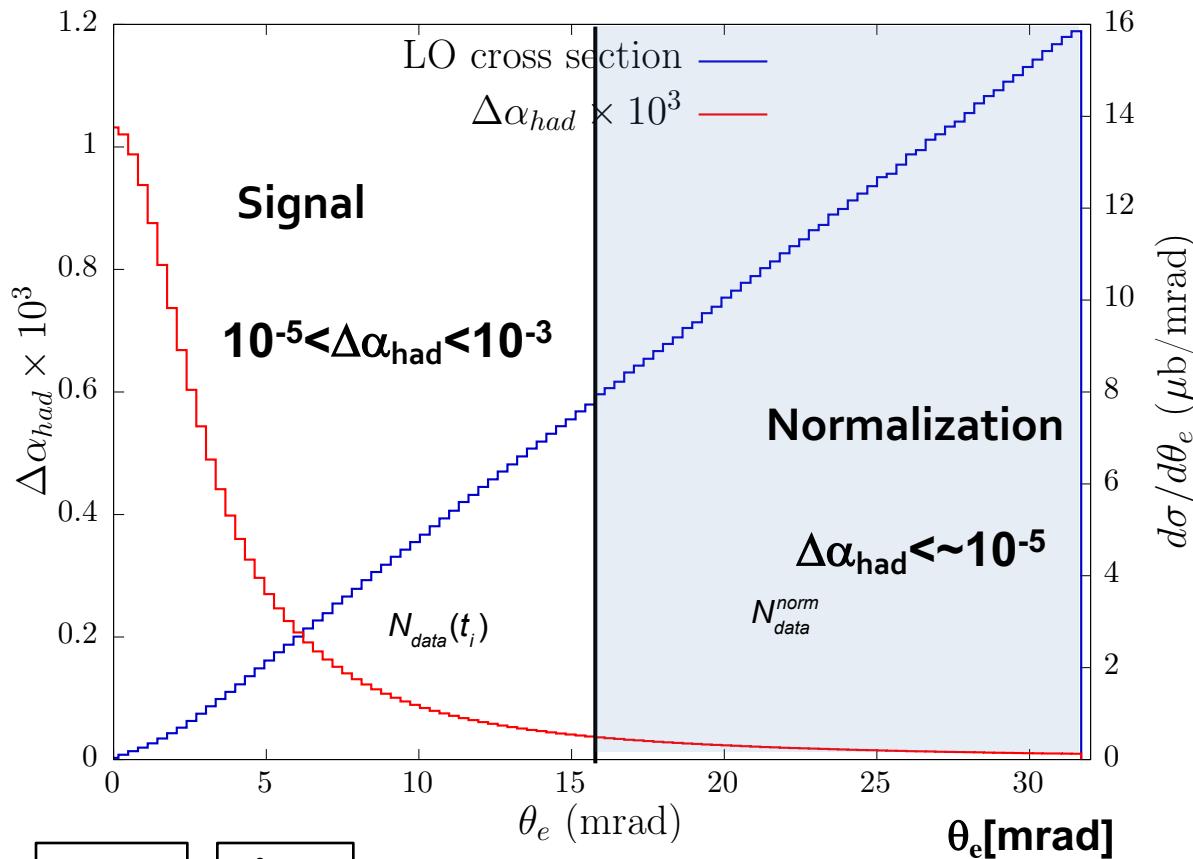
It looks an ideal process!

- $\mu e \rightarrow \mu e$  is pure t-channel (at LO)
- It gives  $0 < -t < 0.161 \text{ GeV}^2$  ( $0 < x < 0.93$ ) →
- The kinematics is very simple:  $t = -2m_e E_e$
- High boosted system gives access to all angles ( $t$ ) in the cms region
 

$\theta_e^{\text{LAB}} < 32 \text{ mrad } (E_e > 1 \text{ GeV})$   
 $\theta_\mu^{\text{LAB}} < 5 \text{ mrad}$
- It allows using the same detector for signal and normalization
- Events at  $x \lesssim 0.3$  ( $t \sim 10^{-3} \text{ GeV}^2$ ) can be used as normalization ( $\Delta\alpha_{had}(t) \lesssim 10^{-5}$ ) →



# MUonE : signal/normalization region



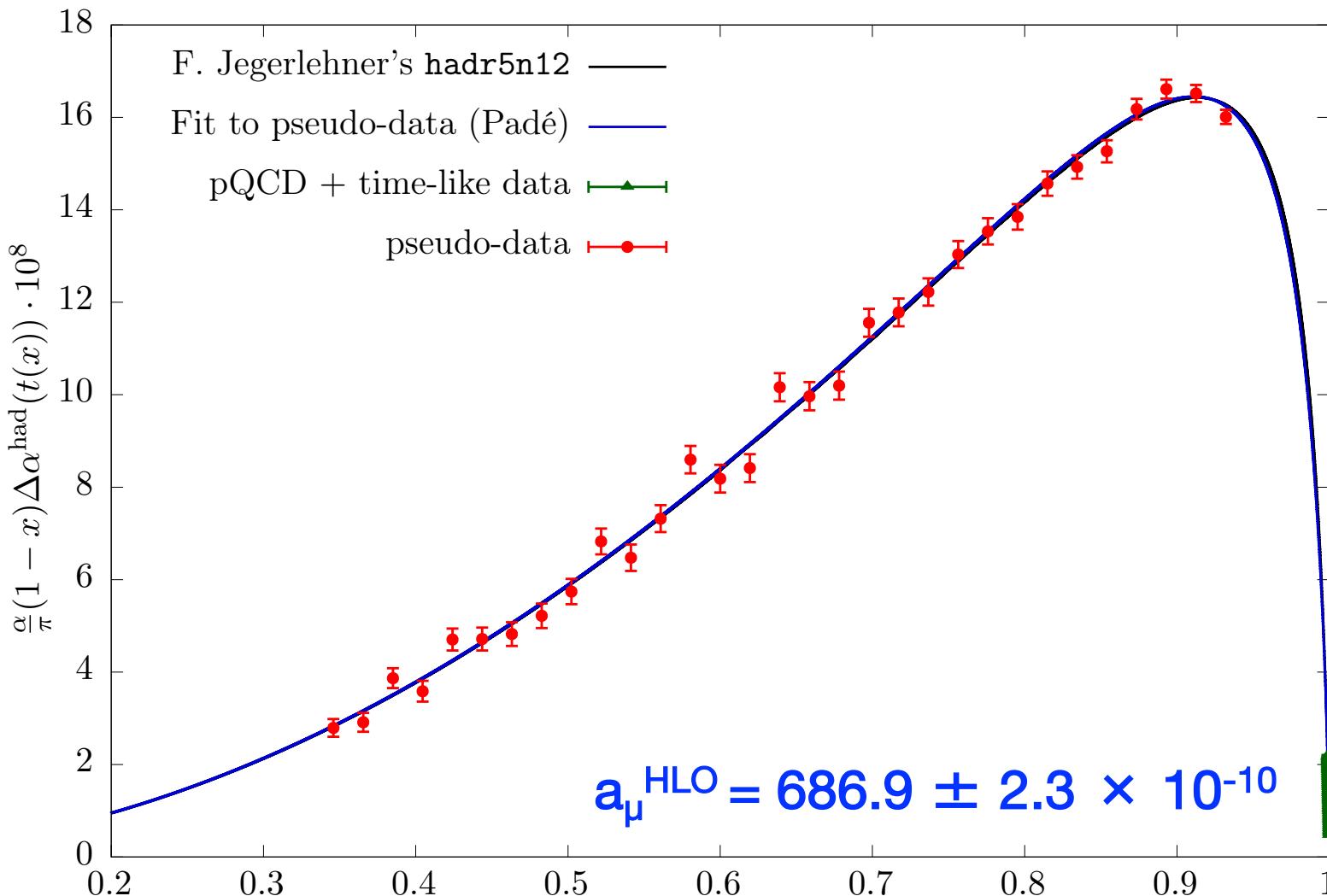
$$\frac{N_{data}(t_i)}{N_{MC}^0(t_i)} = \left[ \frac{N_{data}(t_i)}{N_{data}^{norm}} \right] \times \left[ \frac{\sigma_{MC}^{0,norm}}{\sigma_{MC}^0(t_i)} \right] \sim 1 - 2(\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i))$$

Ratio of the  
theoretical cross  
section (with no VP)

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

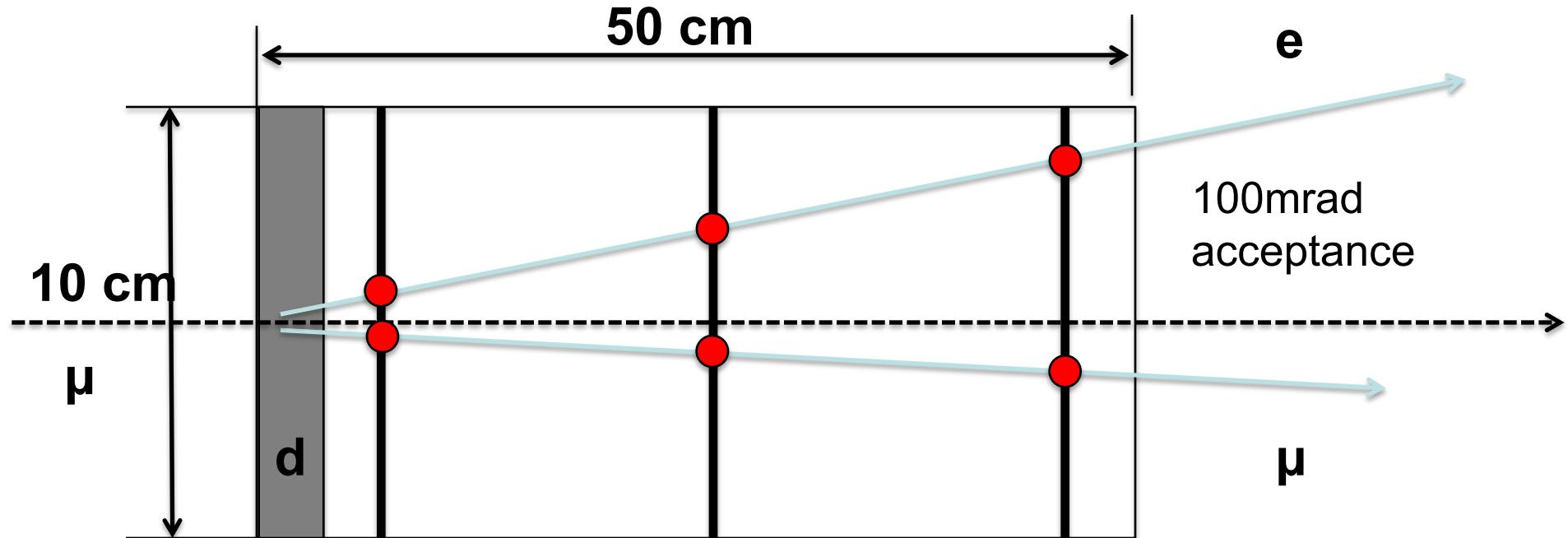
$a_\mu^{\text{HLO}}$  at 0.3% → These two  
ratios should be known at  $10^{-5}$

# Statistical reach of MUonE on $a_\mu^{\text{HLO}}$ (2 years of data taking at $1.3 \times 10^7 \mu/\text{s}$ )



A **0.3%** stat error can be achieved on  $a_\mu^{\text{HLO}}$  in 2 years of data taking with  $\sim 10^7 \mu/\text{s}$  ( $4 \times 10^{14} \mu$  total)

# Measuring e- and muon angle: Repetition (x50) of this single module



~1cm

State-of-art Silicon detectors

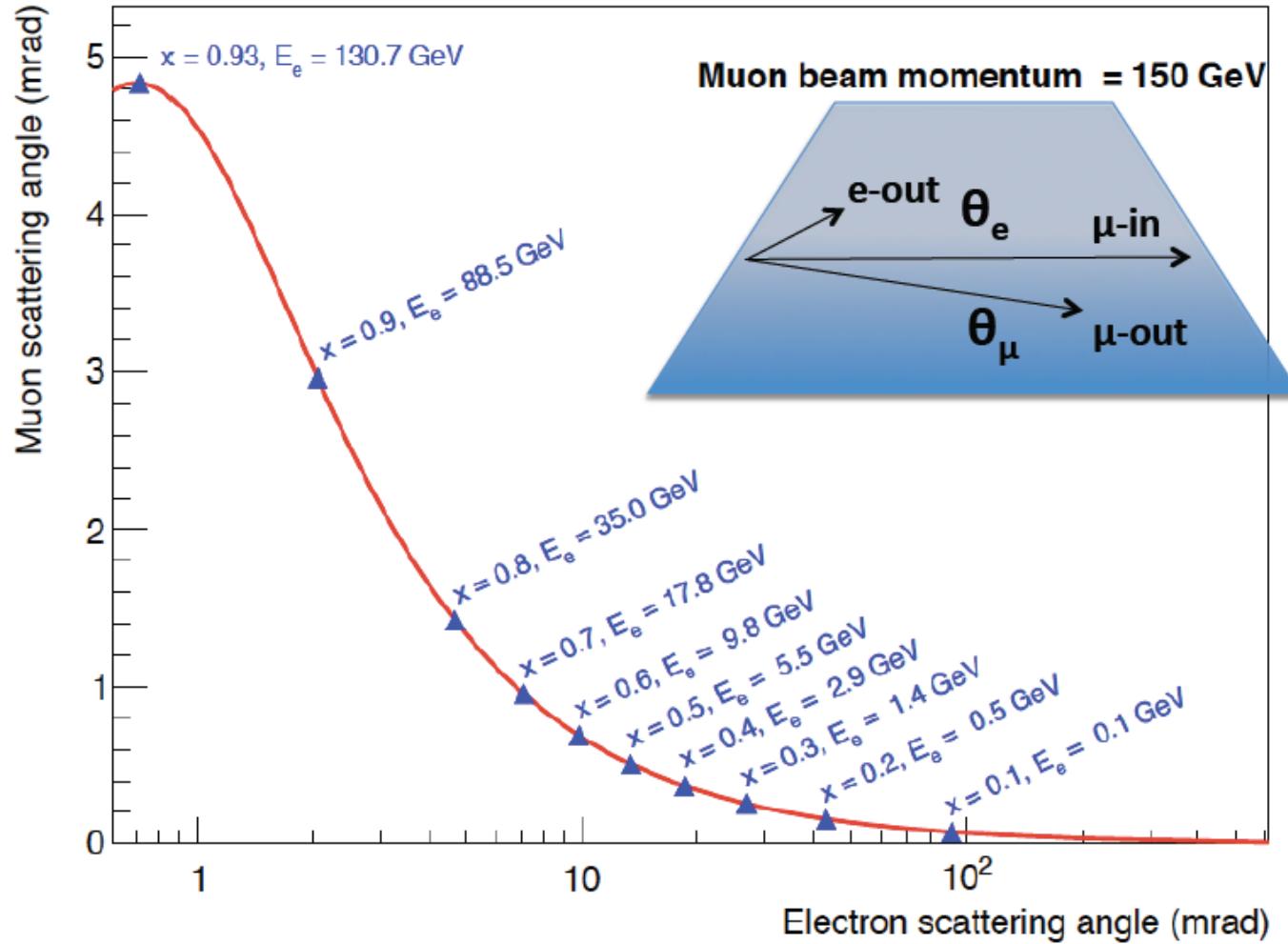
Be Target

hit resolution ~10 μm

expected angular resolution ~ 10 μm / 0.5 m = 0.02 mrad

# Elastic scattering in the $(\theta_e, \theta_\mu)$ plane

Coplanarity of the momentum vectors and angular kinematical constraint



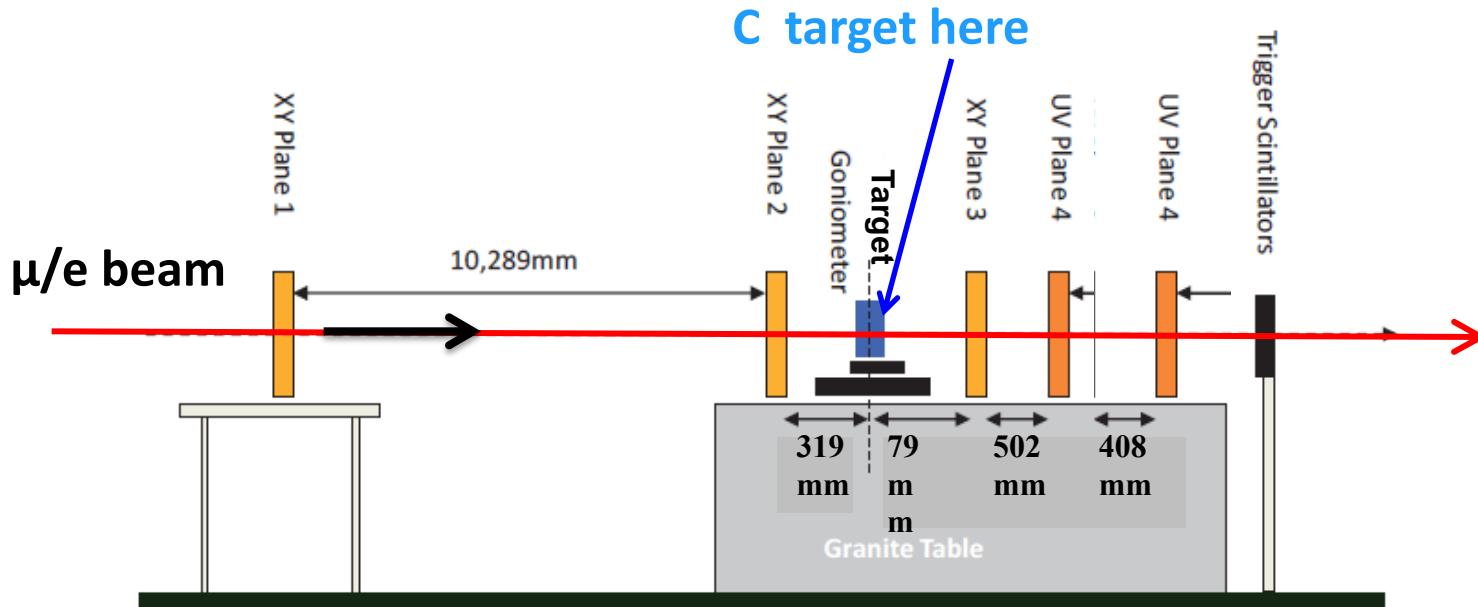
1. Multiple scattering
2. Tracking (alignment & misreconstruction)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the mu-e cross section (see later)
7. ...

All the systematic effects must be known to ensure an error on the <sub>12</sub>  
cross section < 10ppm

# Multiple Scattering studies: Results from Test Beam 2017

Check GEANT MSC prediction and populate the 2D ( $\theta_e$ ,  $\theta_\mu$ ) scattering plane

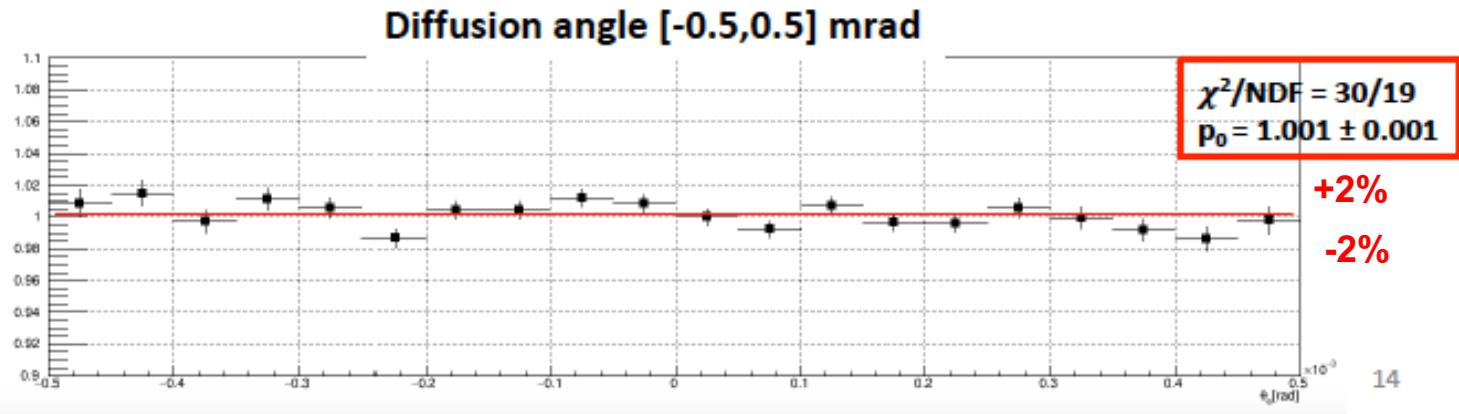
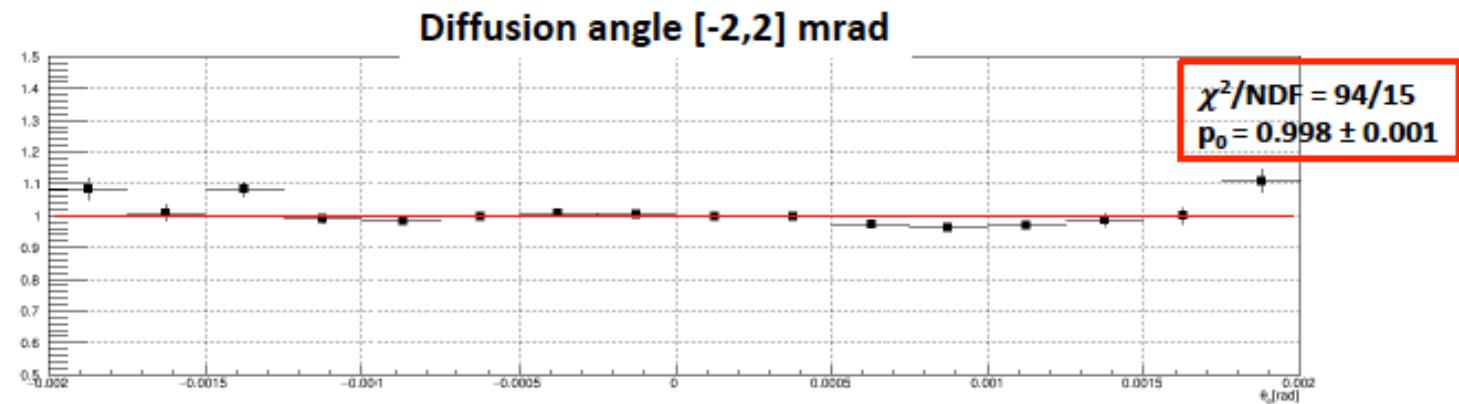
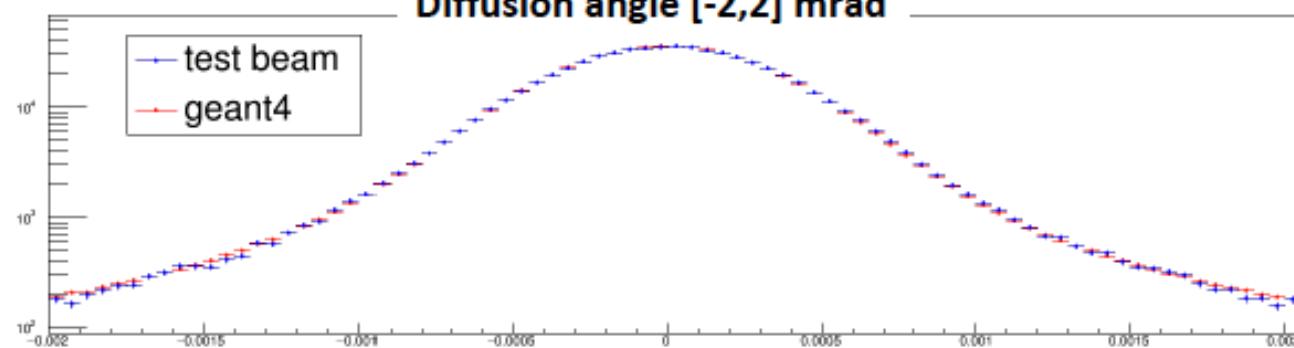
- 27 Sep-3 October 2017 at CERN "H8 Beam Line"
- Adapted UA9 Apparatus
- Beam energy: e- of 12/20 GeV;  $\mu$  of 160 GeV
- $10^7$  events with C targets of different thickness (2,4,8,-20mm)



Adapted UA9 apparatus

5 Si planes: 2 before and 3 after the target,  $3.8 \times 3.8 \text{ cm}^2$  intrinsic resolution  
 $\sim 100 \mu\text{rad}$

20mm, 12 GeV



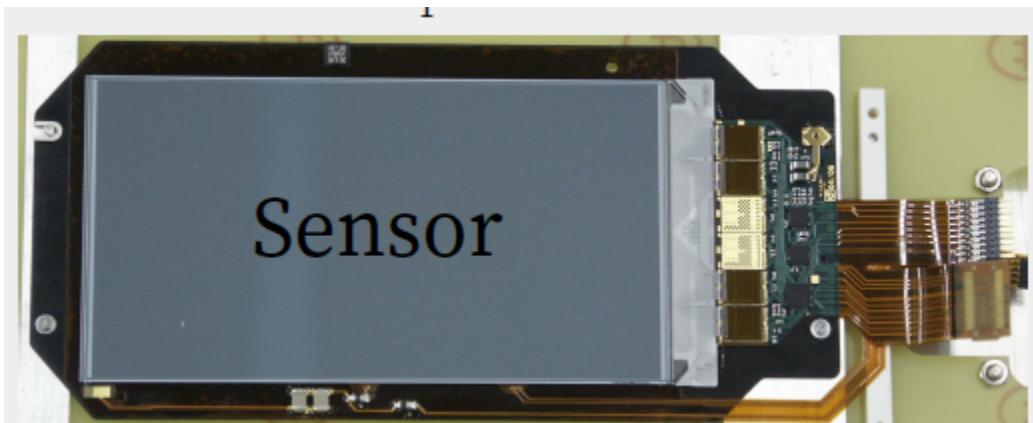
# Detector optimization

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

# Silicon detectors survey

Stefano Mersi - MUonE Mainz Workshop 2018

	ALICE Upg Inner	ALICE Upg Outer	CMS Upg 2S	2×CMS Upg 2S	CMS Upg PS	CMS Upg Pixel	2×CMS Current	Mimosa26	LHCb VELO-pix
Technology	MAPS	MAPS	Hybrid strip	Hybrid strip	Hybrid strip/px	Hybrid pixel	Hybrid strip	MAPS	Hybrid pixel
active x [cm]	27	21	10	10	10	33	10	1.06	4.246
active y [cm]	1.5	3	10	10	5	44.2	10	2.12	1.408
pixel size x [ $\mu\text{m}$ ]	30	30	90	90	100	50	90	18.4	55
pixel size y [ $\mu\text{m}$ ]	30	30	50000	90	1400	50	50000	18.4	55
$\sigma_x$ [ $\mu\text{m}$ ]	2	2	26	26	29	7	18	3.2	12
$\sigma_y$ [ $\mu\text{m}$ ]	2	2	14434	26	404	7	18	3.2	12
Material [x/ $X_0$ ]	0.3%	0.8%	2.3%	4.5%	3.8%	2.0%	4.5%	0.10%	0.94%
Sensor mat. [x/ $X_0$ ]	0.3%	0.8%	0.3%	0.6%	3.8%	2.0%	0.6%	0.10%	0.94%



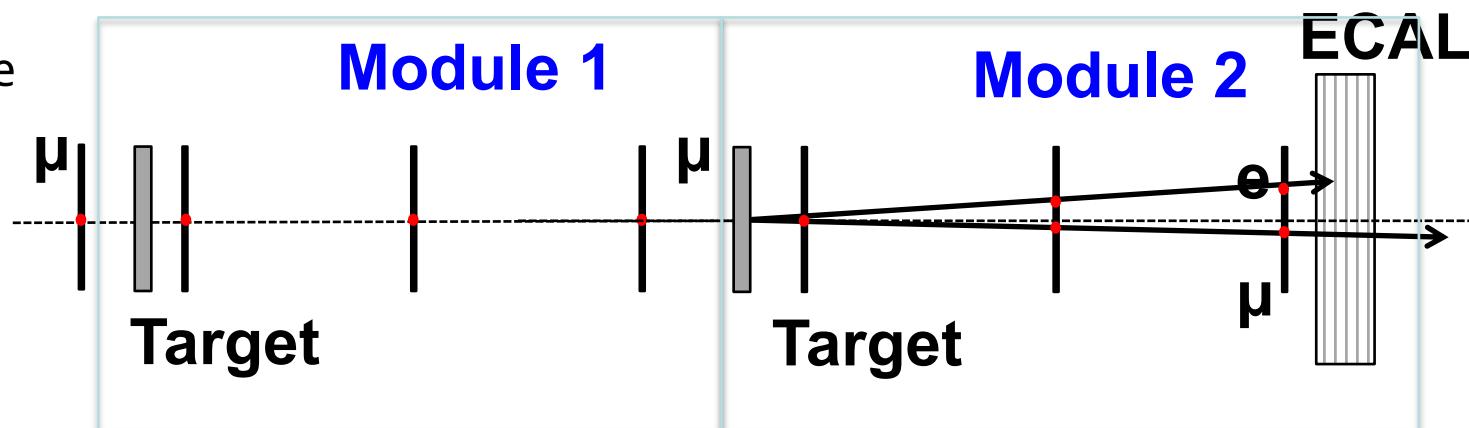
# 2018 Test run: Full scale prototype (2 modules) on M2 muon beam at CERN behind Compass



- Study of the detector performance: signal/background; tracking efficiency; understand the systematics



- It takes data since April 9
- 300M events already collected

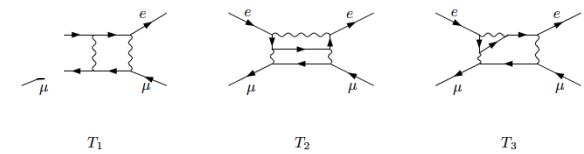


# Theory

- QED **NLO MC** generator with full mass dependence has been developed and is currently under use (Pavia group)
- 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** JHEP1711(2017)198

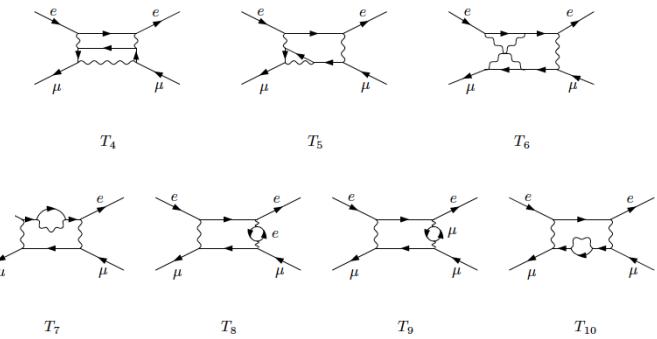
Pierpaolo Mastrolia,<sup>a,b</sup> Massimo Passera,<sup>b</sup> Amedeo Primo,<sup>a,b</sup> Ulrich Schubert<sup>c</sup>



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

Stefano Di Vita,<sup>a</sup> Stefano Laporta,<sup>b,c</sup> Pierpaolo Mastrolia,<sup>b,c</sup> Amedeo Primo,<sup>d</sup> Ulrich Schubert<sup>e</sup>

1806.08241



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

# Theory: international community!

- 2017: Sept 4-5: A **kick-off** theory meeting in Padova:

<https://agenda.infn.it/internalPage.py?pageld=o&confld=13774>.



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



The Evaluation of the Leading Hadronic Contribution to the Muon Anomalous Magnetic Moment

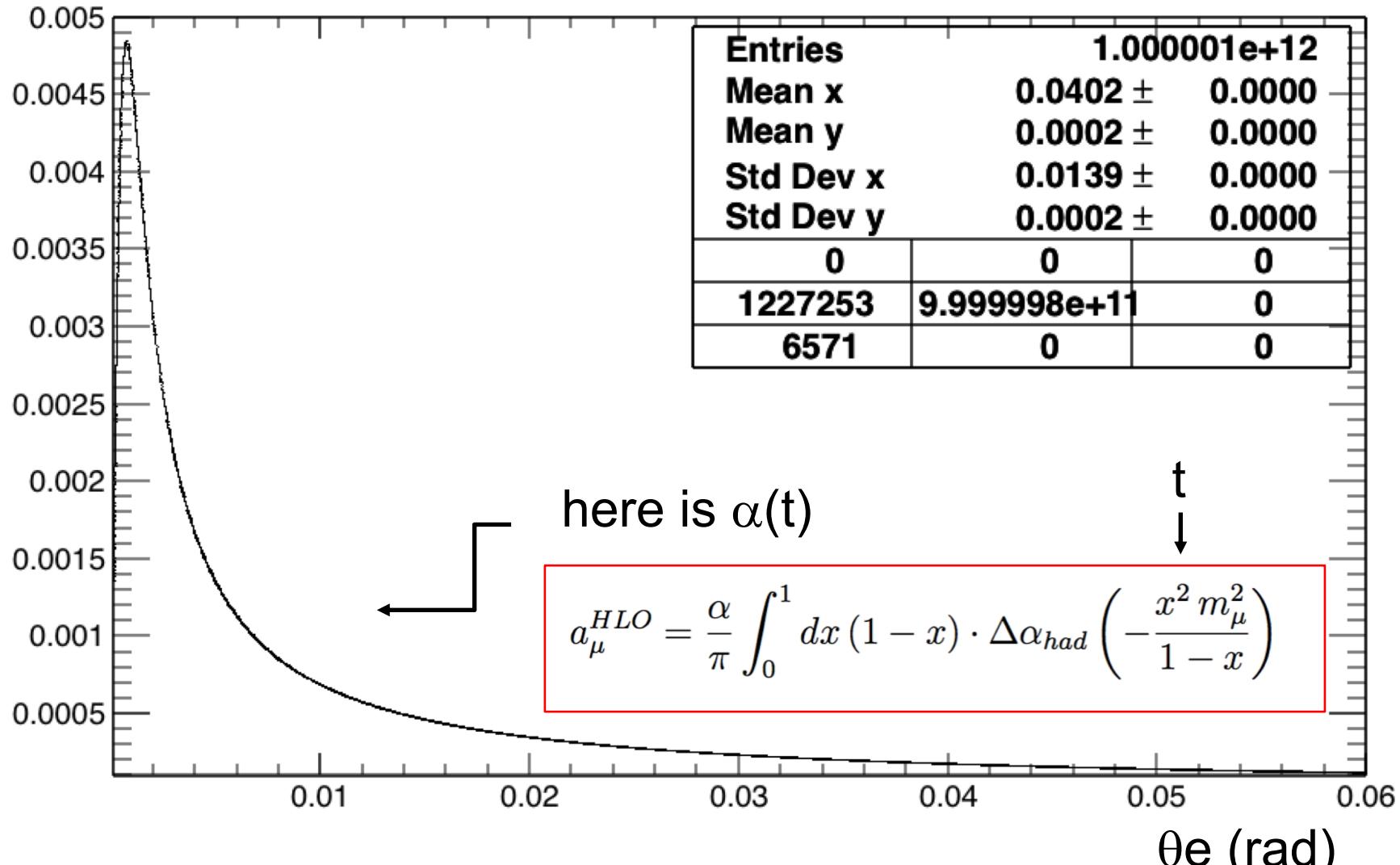


- 2019, Feb 4-7: Workshop on "Theory for muon-electron scattering @ 10ppm" in Zurich

# «Blindly» Extraction of $a_\mu^{HLO}$

$\theta_\mu$  (rad)

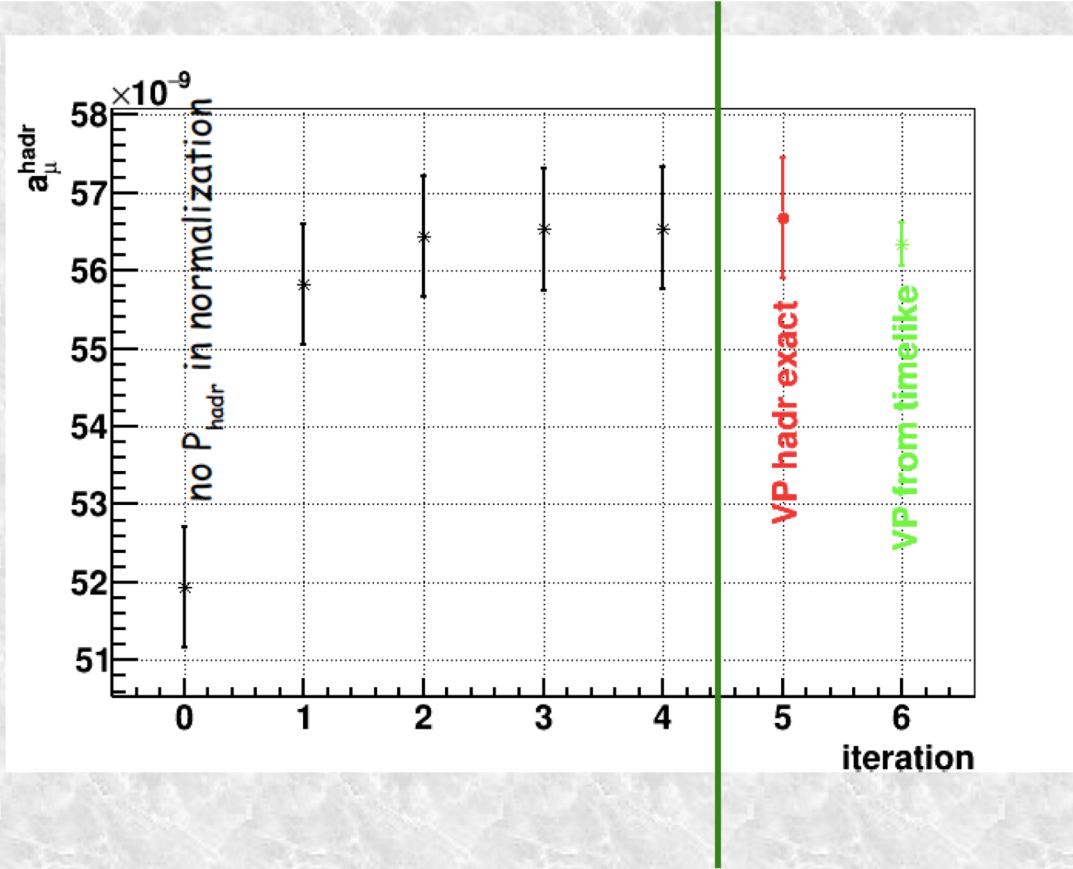
HISTO1



$\theta_e$  (rad)

20

# «Blindly» Extraction of $a_\mu^{\text{HLO}}$



$$X = 0.377952 - 0.931984$$

From timelike data:

$$\Delta a_\mu^{\text{LO}} = 563.4 \pm 2.8 \times 10^{-10}$$

Integral After last iteration:  
 $565.5 \pm 7.8 \times 10^{-10}$

Precision 1.37%

Compatible with 0.4%

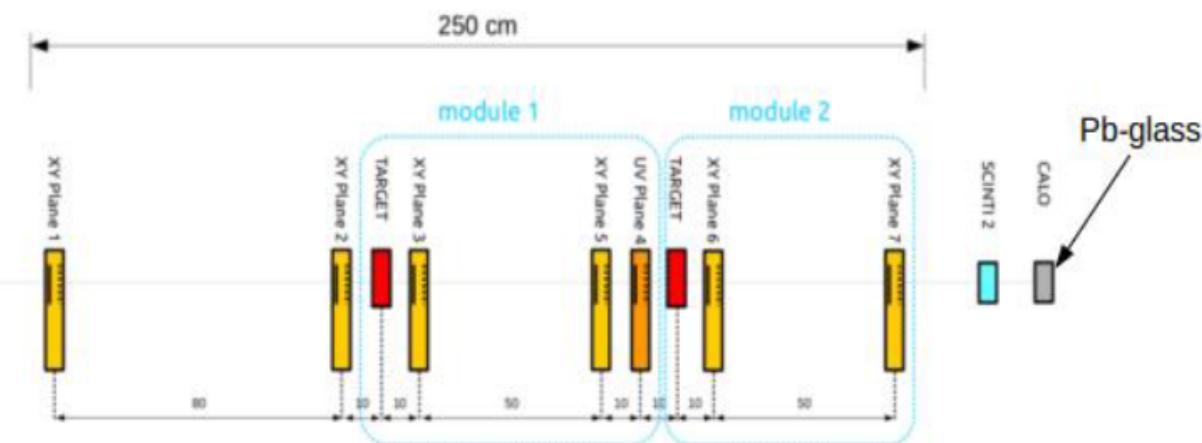
Last iteration consistent (at  $0.3\sigma$ ) with the input value for  $a_\mu^{\text{HLO}}$

- Collaboration is growing and interest from International groups from CERN, Poland, Russia (Novosibirsk), UK, USA (Virginia) has been expressed.
- Results so far encouraging; we are part of “Physics Beyond Collider” process at CERN (<http://pbc.web.cern.ch/>); we are working hard toward a formal LoI (2019).



# 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  $a_\mu^{\text{HLO}}$   
**Certainly very challenging**  
I (Alain Magnon) DO NOT SEE a priori showstopper(s)

- **2018-2019**

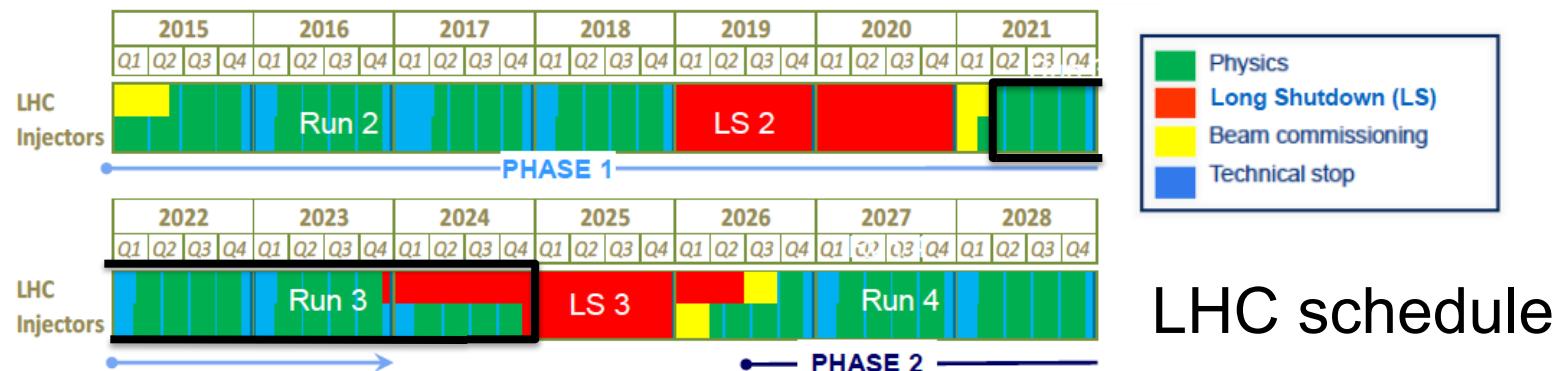
- Detector optimization studies: simulation; Test Run at CERN (2018); TB with e- in Europe and  $\mu/\pi$  at Fermilab?
- Theoretical studies
- Set up a collaboration
- **Letter of Intent** to the SPSC

- **2020-2021**

- **Detector construction** and installation  
(a staged version of the detector may be)

- **2022-2024**

- **Start the data taking** after LS2 to measure  $a_\mu^{\text{HLO}}$   
(not necessarily the ultimate precision)

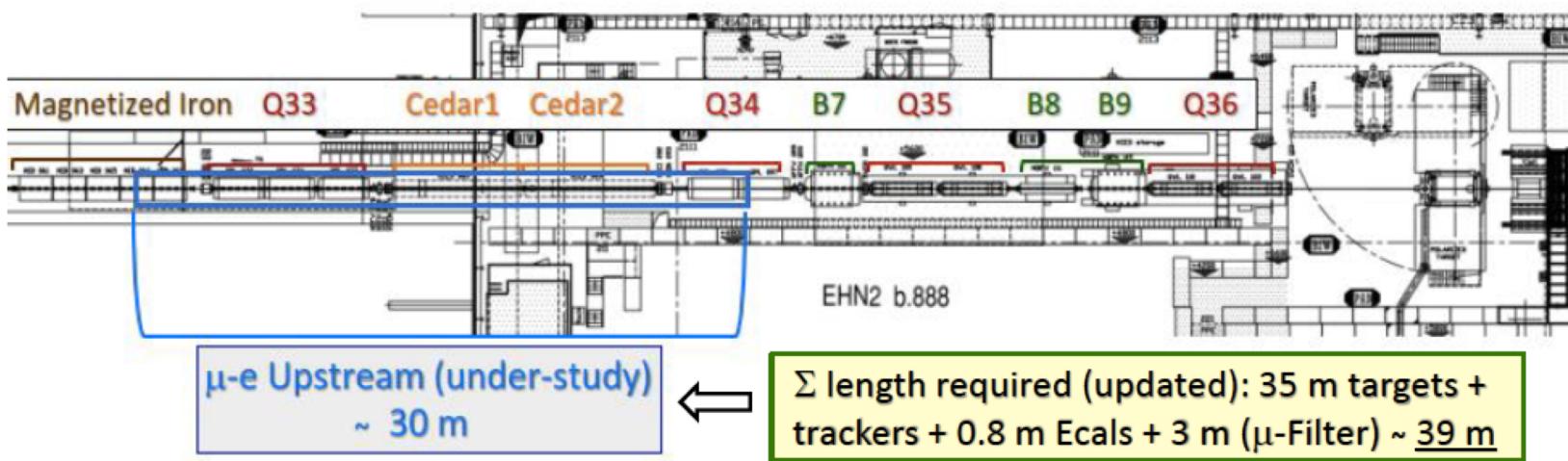


# Possible location at CERN M2

- Between BSM and COMPASS

1/  $\mu$ -e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)
  - Pro: Could allow running  $\mu$ -e/ $\mu$ -p<sub>Radius</sub> in parallel.
  - Questions: will require displacements (also removal) of some M2 components.
  - Beam(s) compatibility for  $\mu$ -e &  $\mu$ -p<sub>Radius</sub>: Optic's wise looks OK (see Add. Sl.14 from D.B.)



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A. Magnon & C. Valle document

# Conclusion

- Exciting times for the muon g-2!
- Alternative/competitive determinations of  $a_\mu^{\text{HLO}}$  are essential:
  - Time-like (dispersive) approach
  - Lattice
  - Space-like approach (MUonE)
- Progress on MUonE:
  - Analysis of MS 2017 TB data
  - Detector optimization
  - Silicon detector procurement
  - Progress on the Theory side
  - Test run in 2018; planned tests for 2019
  - Growing interest from both experiment and theory community
  - Lol planned for 2019; if approved/funded start of data taking in 2021/22 for 2 years (with a pilot run first)

# MUonE Collaboration (in progress)



G. Abbiendi, M. Alacevich, M. Bonomi, T. Bowcock, C. Brizzolari, A. Broggio, C.M. Carloni Calame, E. Conti, S. Eidelman, M. Fael, A. Ferroglio, D. Galli, F.V. Ignatov, M. Incagli, A. Keshavarzi, M. Lancaster, F. Ligabue, I. Logashenko, U. Marconi, M.K. Marinković, V. Mascagna, P. Mastrolia, C. Matteuzzi, S. Mersi, G. Montagna, O. Nicrosini, G. Ossola, L. Pagani, M. Passera, P. Paradisi, C. Patrignani, F. Piccinini, F. Pisani, D. Pokanic, M. Prest, A. Primo, A. Principe, M. Rocco, U. Schubert, F. Simonetto, R. Stroili, L. Tranchetti, R. Tenchini, W. Torres-Bodabilla, L. Trentadue, E. Vallazza, G. Venanzoni,...





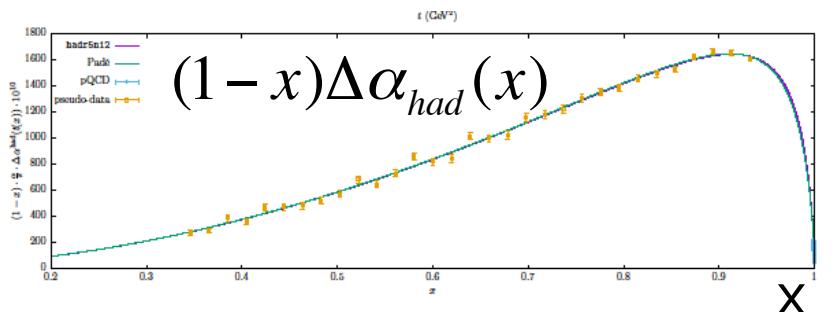
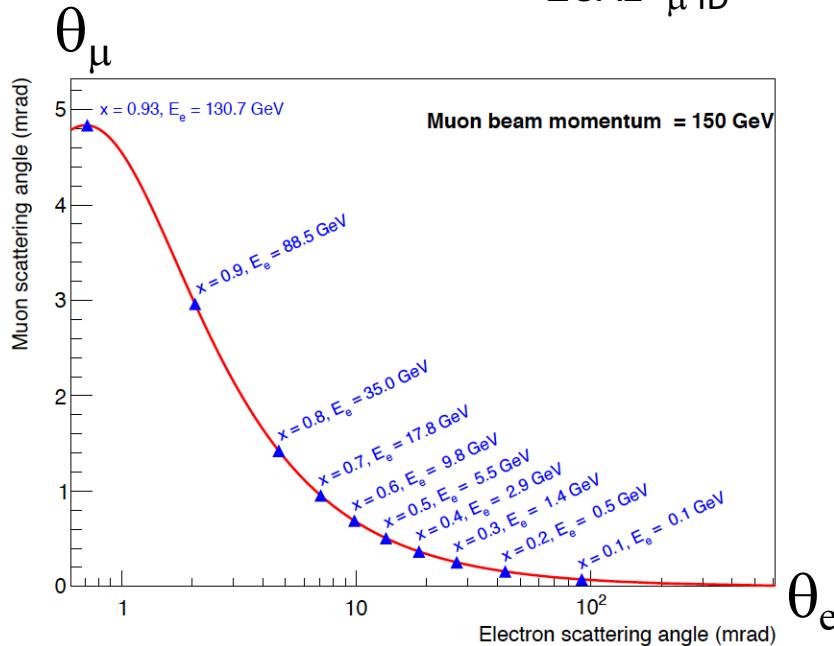
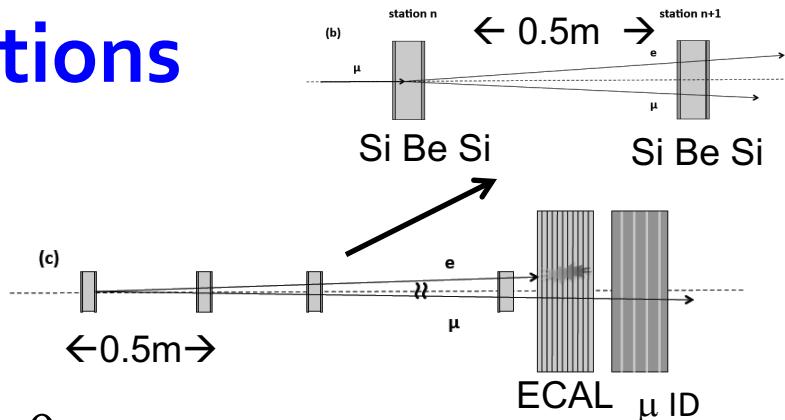
THE END



# SPARE

# Detector considerations

- Modular apparatus: 60 layers of  $\sim 1$  cm Be (target), each coupled to  $\sim 0.5$  m distant Si ( $0.3$  mm) planes. It provides a 0.02 mrad resolution on the scattering angle
- The  $t=q^2 < o$  of the interaction is determined by the electron (or muon) scattering angle (a' 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  $\sim 10^7 \mu/\text{s}$  ( $4 \times 10^{14} \mu$  total)



# 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”.

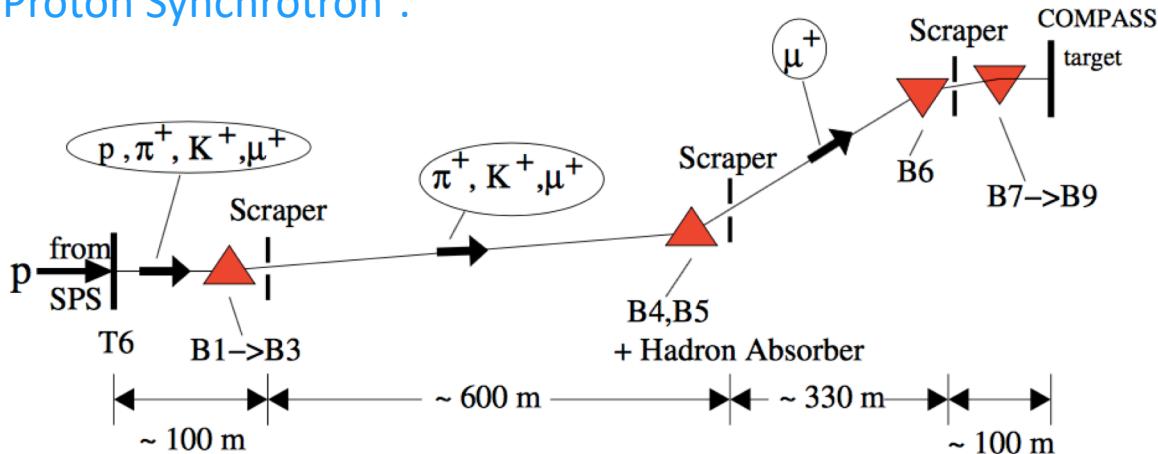
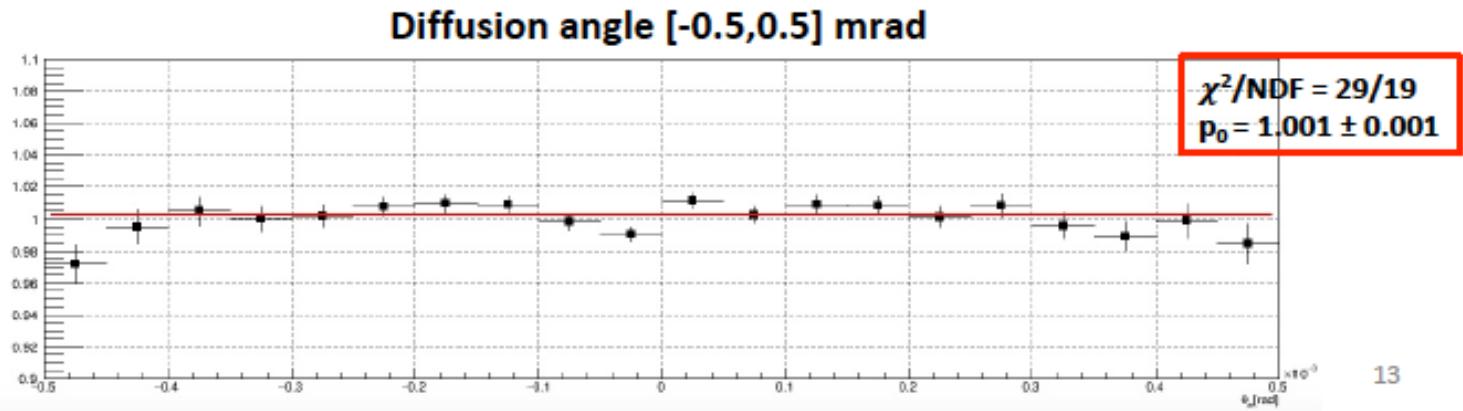
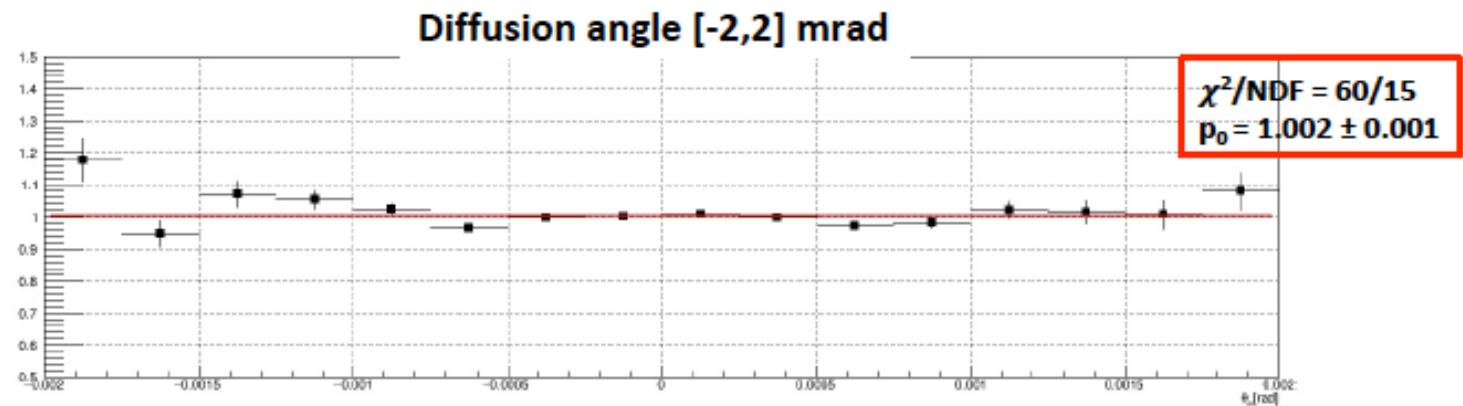
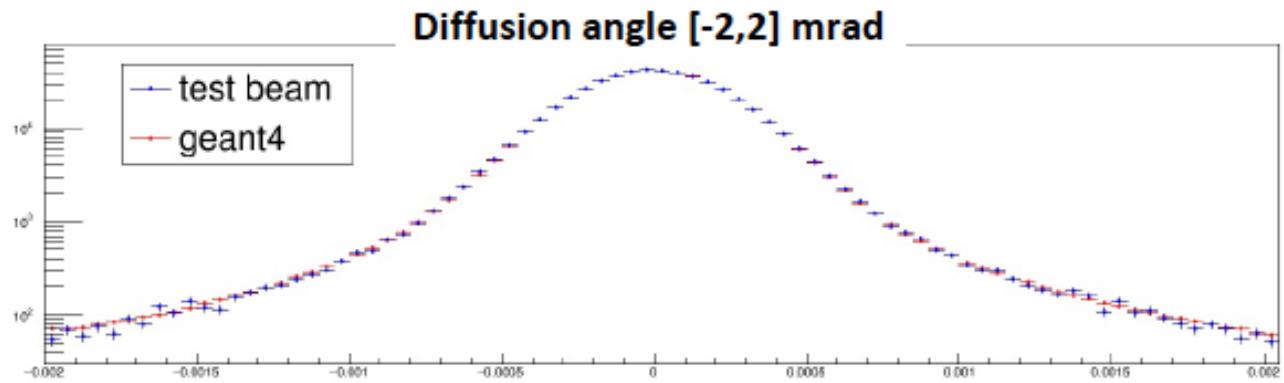


Table 3  
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	Measured
Beam momentum ( $p_\mu)/(p_\pi)$	(160 GeV/c)/(172 GeV/c)
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^8$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target ( $\sigma_x \times \sigma_y$ )	$8 \times 8 \text{ mm}^2$
Divergence at COMPASS target ( $\sigma_x \times \sigma_y$ )	$0.4 \times 0.8 \text{ mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment ( $3.2 \times 2.5 \text{ m}^2$ ) at $ x, y  > 15 \text{ cm}$	7%

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

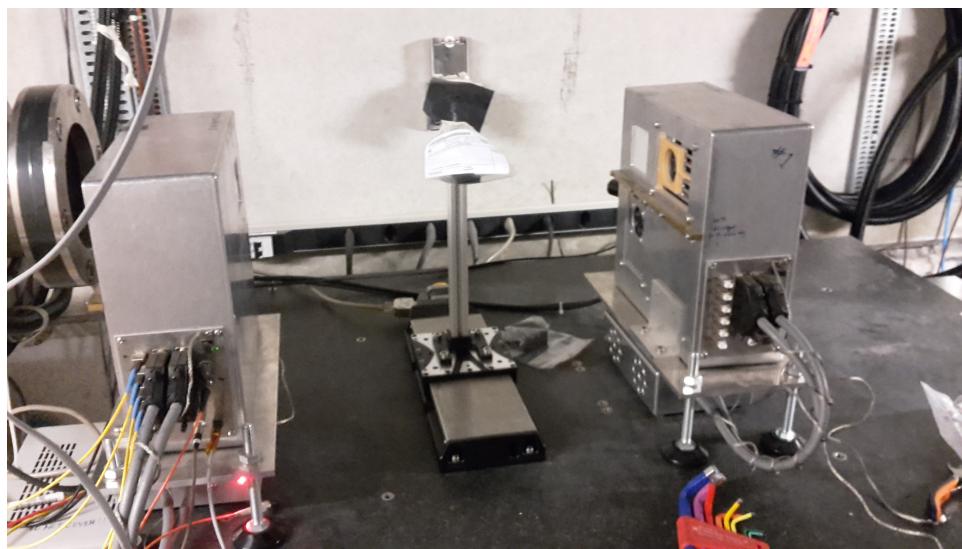
8mm, 12 GeV



# Test Beam setup and target

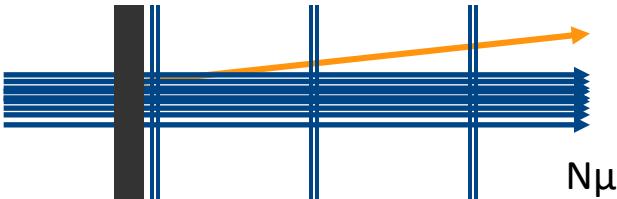


Thanks to the UA9 Collaboration  
(particularly M. Garattini, R. Iaconageli,  
M. Pesaresi), J. Bernhard



# Detector integration time

- Hybrid pixels & strips for (HL-)LHC: 25 ns
- ALPIDE: 1  $\mu$ s
- Mimosa26: 112  $\mu$ s

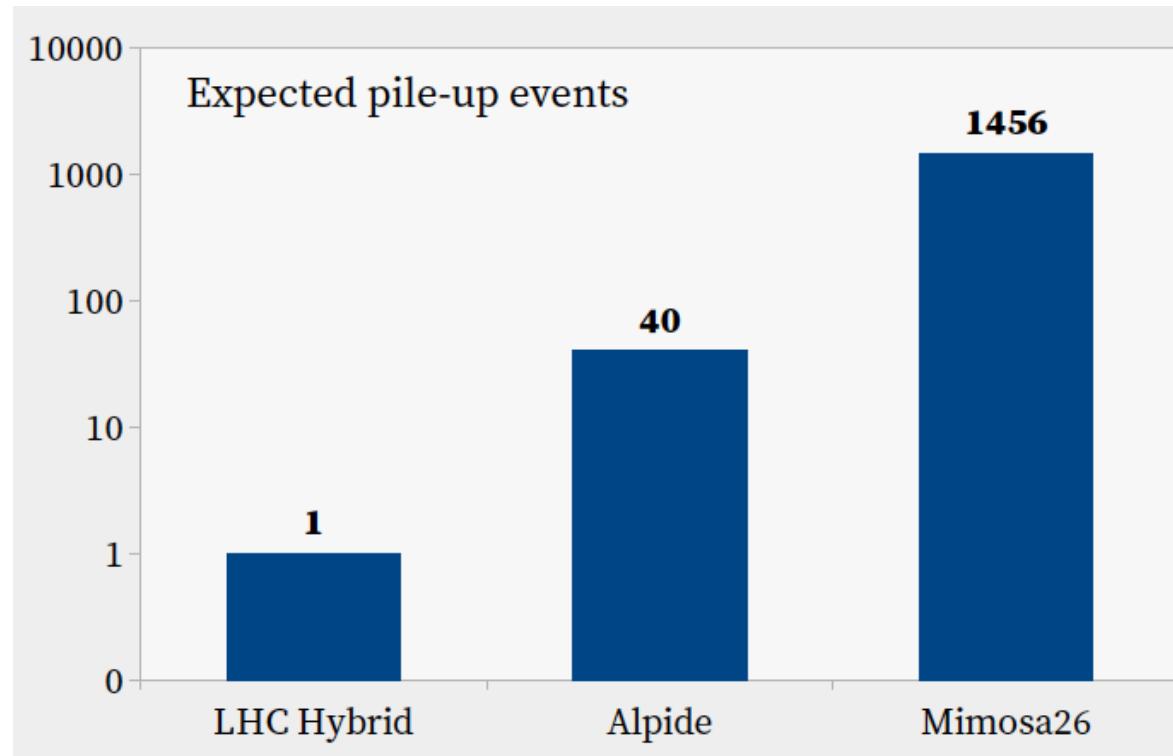


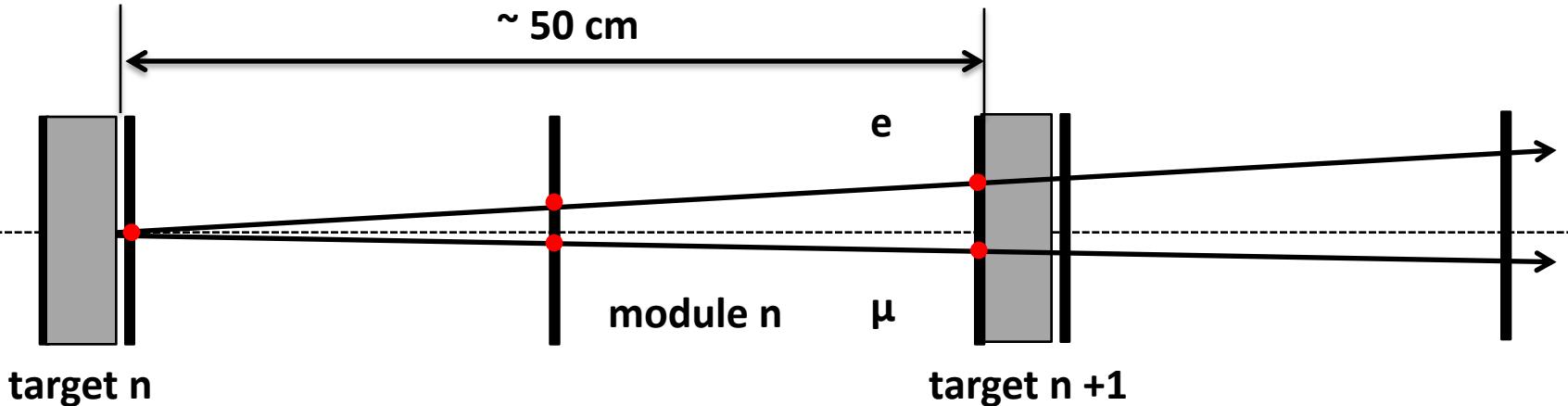
$$N_\mu = r \times \tau$$

e.g.  $N_\mu = 40 \text{ MHz} \times 25 \text{ ns} = 1$

e.g.  $N_\mu = 40 \text{ MHz} \times 1 \mu\text{s} = 40$

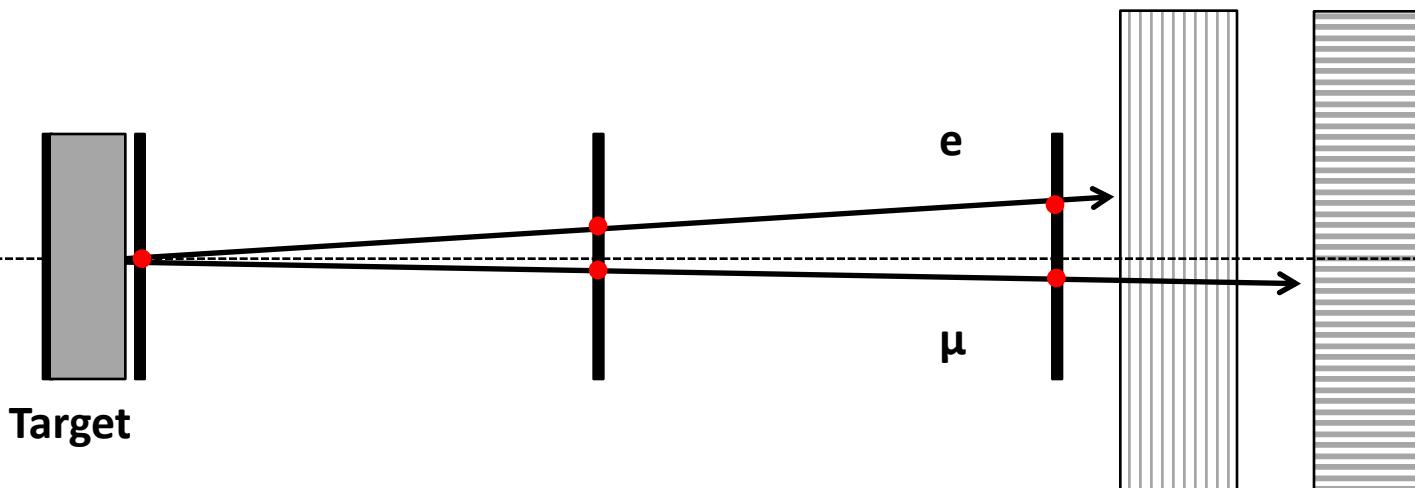
Expected pile-up events  
(per 40MHz)





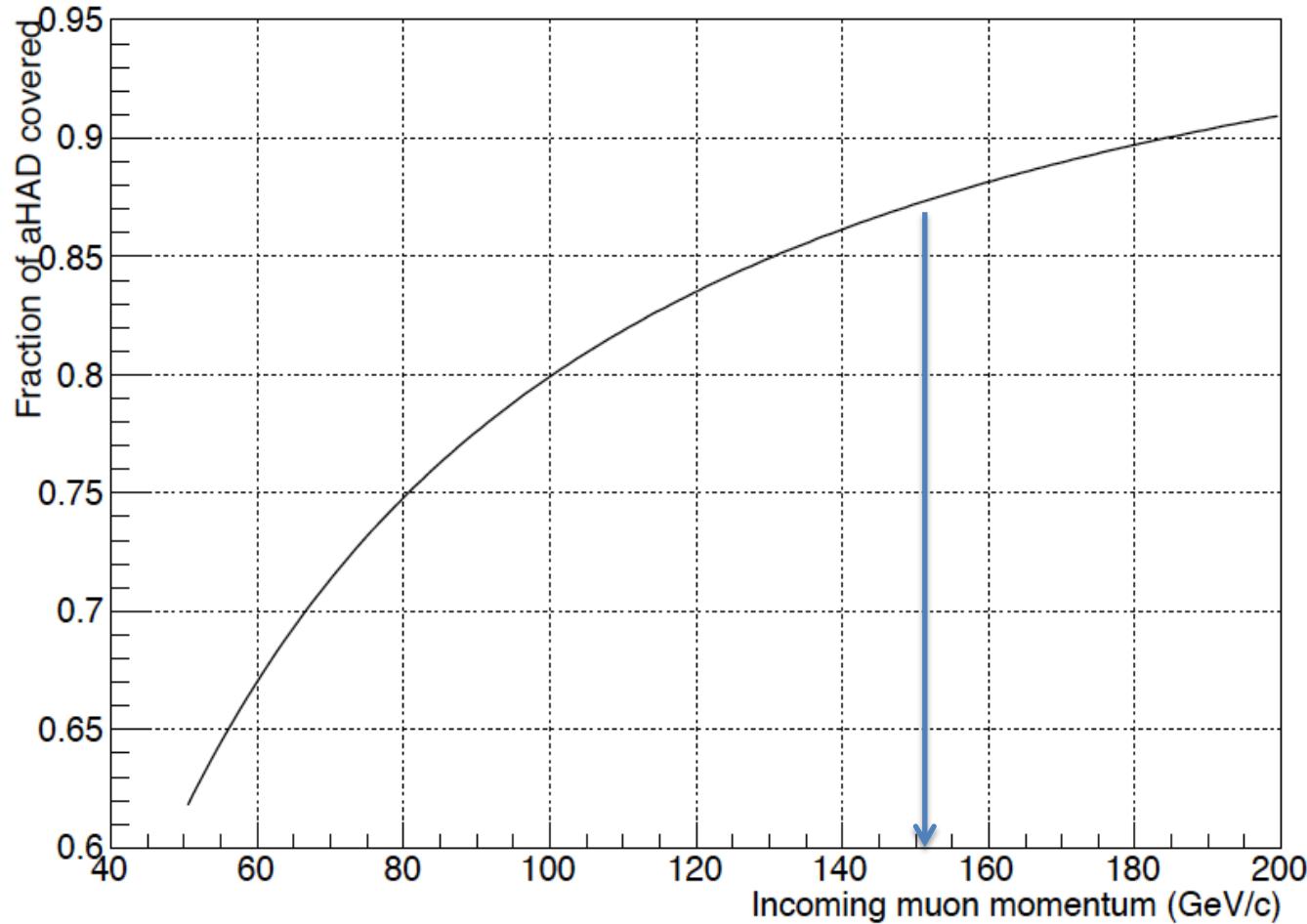
## Last module of the detector

ECAL MUON



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

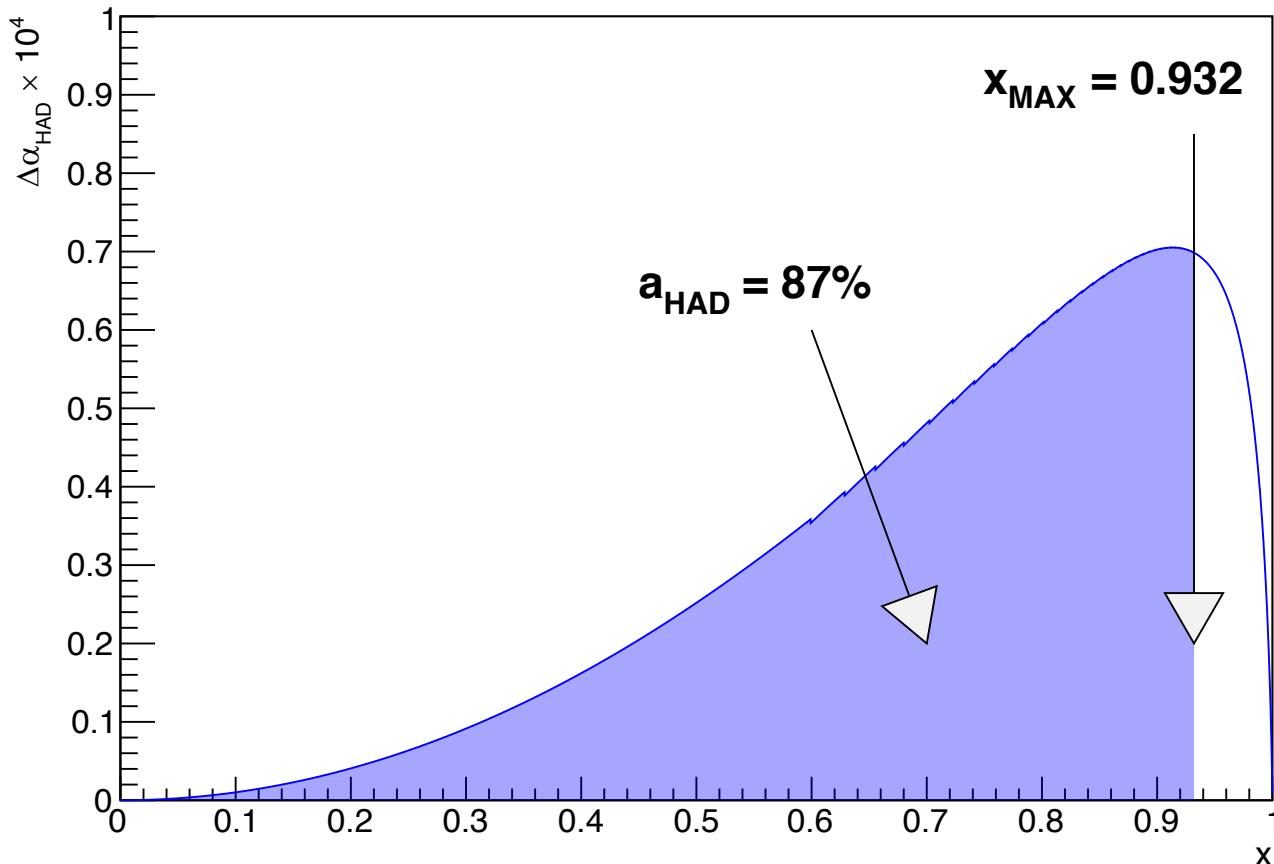


87% of  $a_{\mu}^{\text{HLO}}$  covered with  $P_{\mu}=150$  GeV

# Fraction of $a_{\mu}^{\text{HLO}}$ covered



$P_{\mu} = 150 \text{ GeV}/c$



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

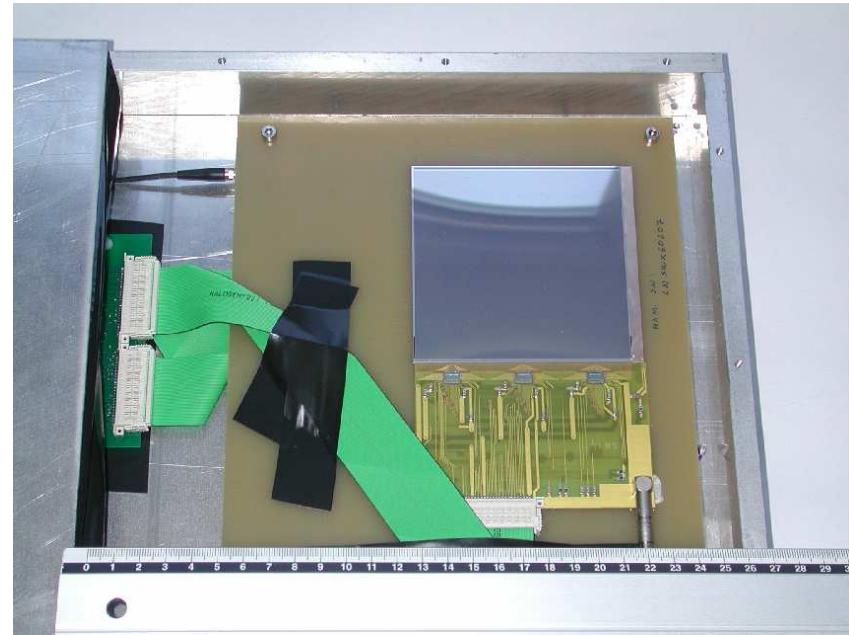
(courtesy of M. Incagli)

# The silicon detectors

Sensors developed for AGILE, being used by LEMMA

Table 1  
Main features of the AGILE silicon detector

Item	Value
Dimension (cm <sup>2</sup> )	9.5 × 9.5
Thickness (μm)	410
Readout strips	384
Readout pitch (μm)	242
Physical pitch (μm)	121
Bias resistor (MΩ)	40
AC coupling Al resistance (Ω/cm)	4.5
Coupling capacitance (pF)	527
Leakage current (nA/cm <sup>2</sup> )	1.5



M. Prest et al., NIM A, 501:280–287, 2003

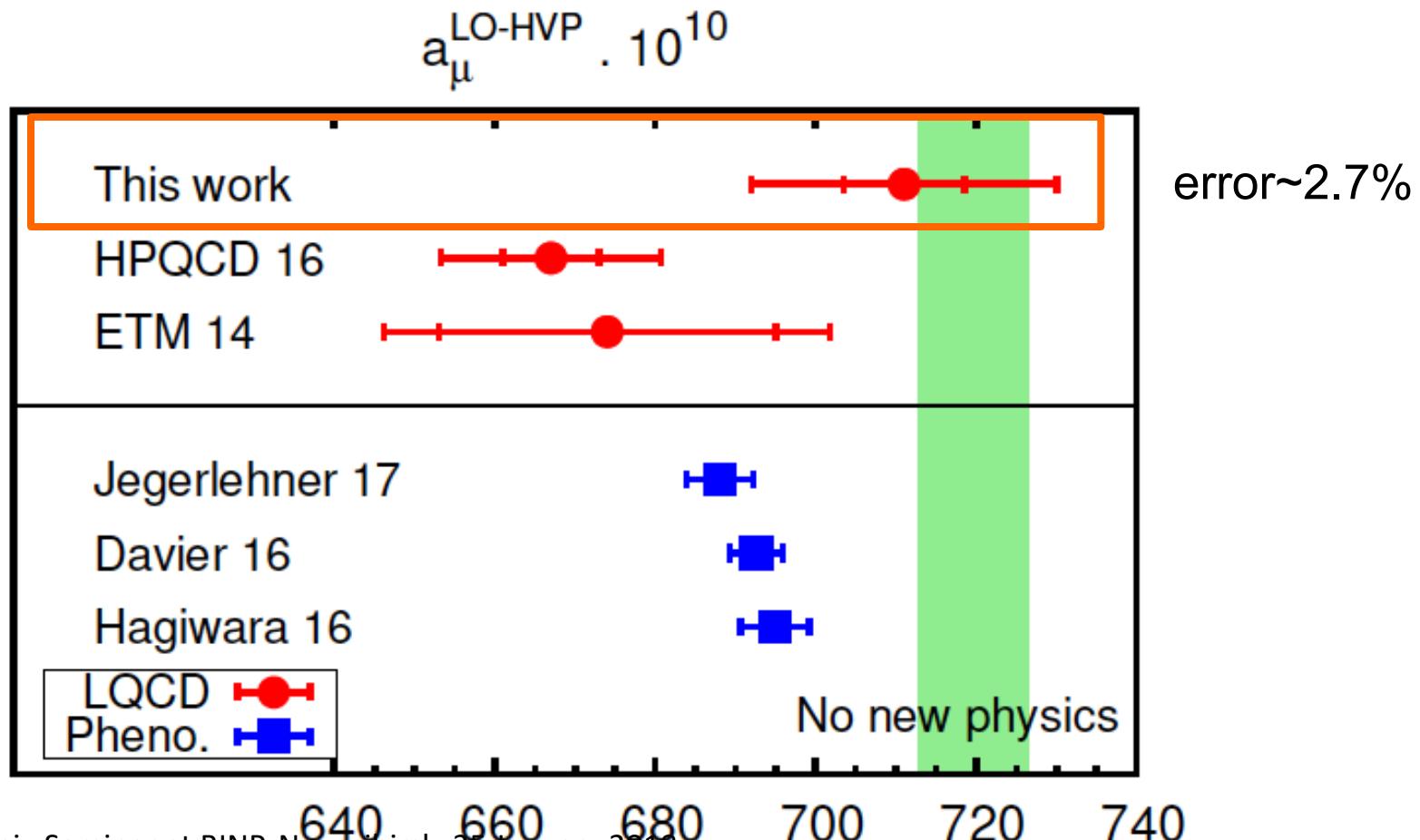
Daniela Lietti, PhD thesis. VISION: a Versatile and Innovative SilicON tracking system

[http://insulab.dfm.uninsubria.it/images/download\\_files/thesis\\_phd\\_lietti.pdf](http://insulab.dfm.uninsubria.it/images/download_files/thesis_phd_lietti.pdf)

# However: Recent Lattice evaluation

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

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L. Lellouch,<sup>4</sup> R. Malak,<sup>4, 5</sup> K. Miura,<sup>4</sup> K.K. Szabo,<sup>1, 3</sup> C. Torrero,<sup>4</sup> and B.C. Toth<sup>1</sup>  
(Budapest-Marseille-Wuppertal collaboration)



$$a_\mu^{\text{LO-HVP}} = 711.0(7.5)(17.3) \times 10^{-10}$$

stat                    syst  
                        \longrightarrow 2.7%

(NP). Using the SM contributions summarized in [8], we find  $a_{\mu, \text{noNP}}^{\text{LO-HVP}} = (720.0 \pm 6.8) \times 10^{-10}$ . 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  $a_{\mu, \text{noNP}}^{\text{LO-HVP}}$ . 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.

# Some numbers:

- 60 cm total Be target ( $2X_0$ ) segmented in 60 stations with 1 cm target ( $0.03 X_0$ )
- ~30 m total detector length
- 10x10 cm<sup>2</sup> silicon detectors
- Resolve each  $\mu, e$  track with uniform efficiency
- Best possible resolution on  $\theta\mu$  (<5mrad),  $\theta e$  (<50 mrad)
- $\mu$  rate: ~60 MHz (peak) → 15 MHz (averaged)
- $\mu$  separation: 17 ns (peak) → 68 ns (averaged)
- Collect  $4 \times 10^{12}$  events with  $E_e > 1\text{GeV}$  in ~2 years
- Scattering probability ( $E_e > 1\text{GeV}$ ):  $1.7 \times 10^{-4}/\text{cm}$
- Scattering event rate ( $E_e > 1\text{GeV}$ ): ~10 kHz per station (peak); 2.5 (avg)
- Scattering separation ( $E_e > 1\text{GeV}$ ): 100  $\mu\text{s}$  per station

# Data: using the Calorimeter

