The MUonE project

Measurement of the leading hadronic contribution to the muon g-2
with μe elastic scattering at CERN

Giovanni Abbiendi (INFN Bologna)
on behalf of the proponents

Riunione locale Gruppo-1, Bologna, 30 January 2020

MUonE motivations

- completely independent and complementary method to measure the leading hadronic contribution to the running of α and to the muon g-2. Standard approach involves ~40 cross section measurements fitted together, quoted precision is quite aggressive and has reached its limits. MUonE aims at a similar or better precision in a single experiment.

F. Jegerlehner, [arXiv1804.07409]
"the very different Euclidean approaches, lattice QCD and the proposed alternative direct measurements of the hadronic shift $\Delta\alpha(-Q^2)$ [MUonE], in the long term will be indispensable as complementary cross-checks."

- in the context of (g-2)μ, the measurement of the hadronic contribution makes the theoretical expectation more precise, trying to cope with the improving experimental uncertainty (Fermilab and JPARC experiments)

MUonE: alcune date

- 7 Settembre 2016: prima presentazione al Workshop «*Physics Beyond Colliders*» al CERN
- **Paper** sottomesso a rivista, pubblicato in **Eur.Phys.J. C(2017)77** `doi:10.1140/epjc/s10052-017-4633-z`
- 12 Maggio 2017: prima presentazione all'INFN CSN1
- 2017 Test Beam al CERN (setup UA9)
  - Paper pubblicato in JINST. 15 (2020) P01017
- 2018 Test Beam al CERN (North Area)
- Maggio 2019: INFN referees: T.Dorigo, T.Lari, P.Meridiani, F.Petrucci
- 5 Giugno 2019: **Letter of Intent**, presentata al SPSC, CERN-SPSC-2019-026 , SPSC-I-252, `http://cds.cern.ch/record/2677471`
- 1 Ottobre 2019: INFN CSN1 ha approvato un finanziamento di 105 KEu per il 2020, per la preparazione di un Pilot Run nel 2021
- 14 Ottobre 2019: Prima discussione con i referees del CERN (Arnaud Ferrari, Urs Wiedemann)
- 20 Gennaio 2020: Seconda discussione con i referees (oltre a U.W. e A.F., Marcella Bona)
- 21 Gennaio 2020: prima **presentazione MUonE nella sessione aperta del SPSC** (C.Matteuzzi)
- 22 Gennaio 2020: decisione interna del SPSC

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

June 5, 2019

CERN-SPSC-2019-026 / SPSC-I-252
05/06/2019

Letter of Intent: The MUonE Project

The MUonE Collaboration

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‡also at University of Illinois at Urbana-Champaign

Istituti / Attività Sperimentali (pre-approval)

Sede	Attività prevista
Bologna	DAQ, simulazioni e analisi
MI-Bicocca	Calorimetro, meccanica di supporto, analisi
Padova	Calorimetro, codice GEANT, simulazioni
Pisa (+Firenze)	Meccanica (alloggiamento, raffreddamento), qualifica sensori, analisi
Trieste	Allineamento sensori con metodo olografico
IC London	DAQ e sistemi di controllo; trigger FPGA
Budker inst. Novosbisrsk	Monitoring, simulazione, analisi
U. Krakow	DAQ, pattern recognition
U. Liverpool	Tracking
U. Shanghai	Calorimetro
U. Virginia	Calorimetro
CERN	Survey, alignment, thermalization, beam optimization

+ Attività teoriche a: Padova, Parma, Pavia, PSI, U.Dublin

Outcome of the SPSC

Urs Wiedemann <Urs.Wiedemann@cern.ch>

22 January 2020 at 13:00

Hide

UW

feed-back from the SPSC referees

To: Clara Matteuzzi <Clara.Matteuzzi@cern.ch>,

Cc: Arnaud Ferrari <arnaud.ferrari@physics.uu.se>, giovanni.abbiendi@bo.infn.it <giovanni.abbiendi@bo.infn.it>, massimo.passera@pd.infn.it <massimo.passera@pd.infn.it>, fulvio.piccinini@pv.infn.it <fulvio.piccinini@pv.infn.it>, Graziano Venanzoni <graziano.venanzoni@lnf.infn.it>, umberto.marconi@bo.infn.it <umberto.marconi@bo.infn.it>, Marcella Bona <m.bona@qmul.ac.uk>

Informal message containing the SPSC recommendation. The final decision will be taken by the Research Board and CERN management

Dear Clara and all,

This is to give you some feed-back from the internal deliberations of the SPSC. The fundamental interest of your proposal was recognized by the committee and the test beam in 2021 will be recommended. The relevant part of the SPSC minutes (this is a preliminary draft) read as follows

The SPSC takes note of the presentation in the Open Session of the Letter of Intent SPSC-I-252 for measuring the running of alpha through the elastic scattering of high energy muons on atomic electrons. The Committee recognises the fundamental interest of the result of such a measurement, and appreciates the proposed method to access the Hadronic Vacuum Polarisation via space-like processes.

The SPSC recommends that MUonE performs a test-beam with two tracking stations in the M2 beam-line in 2021. The aim of this run should be to accurately evaluate the experimental systematics and to assess the potential of the proposed detector design to yield a competitive constraint on the dominant hadronic contribution of the muon anomalous magnetic moment. Further recommendations by the Committee are contingent on an approved proposal, and will depend on the results of the test-beam.

Outcome of the SPSC (II)

The committee debated internally the perspectives of MUonE beyond the test beam in 2021.

- 1. At this moment, MUonE is not yet a Collaboration. You do not have yet a collaboration MoU. That's also the reason for why the SPSC minutes talk about recommending a "test beam" in the M2 beam line, rather than a pilot run. Prior to SPSC recommending substantial beam time beyond this test beam, MUonE should become an approved collaboration.
- 2. Beam beyond the 2021 test beam will be contingent on assessing in detail the feasibility of your detector design. This would require a fully worked-out proposal including relevant MC simulations. The 2021 testbeam results will verify and reassess your key experimental benchmarks.
- 3. As you know, there are several competitive and mutually incompatible requests for use of the M2 beam line in the years 2022-24. While at present, SPSC is not in a position to recommend beam for MUonE in these years, the SPSC has avoided fully committing the use of the M2 beam line in the outyears. This means that there remains a window of opportunity for a substantial MUonE run [order of magnitude 1 year] prior to LS3 in case that you can address point 2. above in a timely manner.

The MUonE Pilot Run

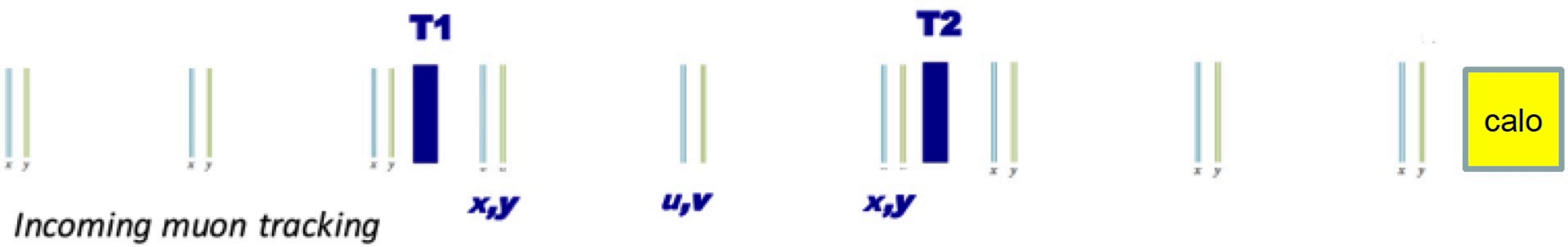
In the LoI, the MUonE requests the M2 beam

- **Location:**

  upstream COMPASS after the B*eam* M*omentum* S*tation* (BMS)

- **3 weeks at the end of 2021** *(due to the Si planes availability)*

  ➡ to run with 2 full stations in the configuration:



➡ the apparatus will be in a thermalized volume

at the end of the 2 stations, a calorimeter ~ 20x20 cm^2 under study

The pilot run should provide ~ 10^{8} elastic events

The aims of the Pilot Run (*quoted from the LoI*):

13.2 Pilot run motivations

Aim of the Pilot Run is to demonstrate the validity of the design and the operation of the MUonE project. The main objectives are:

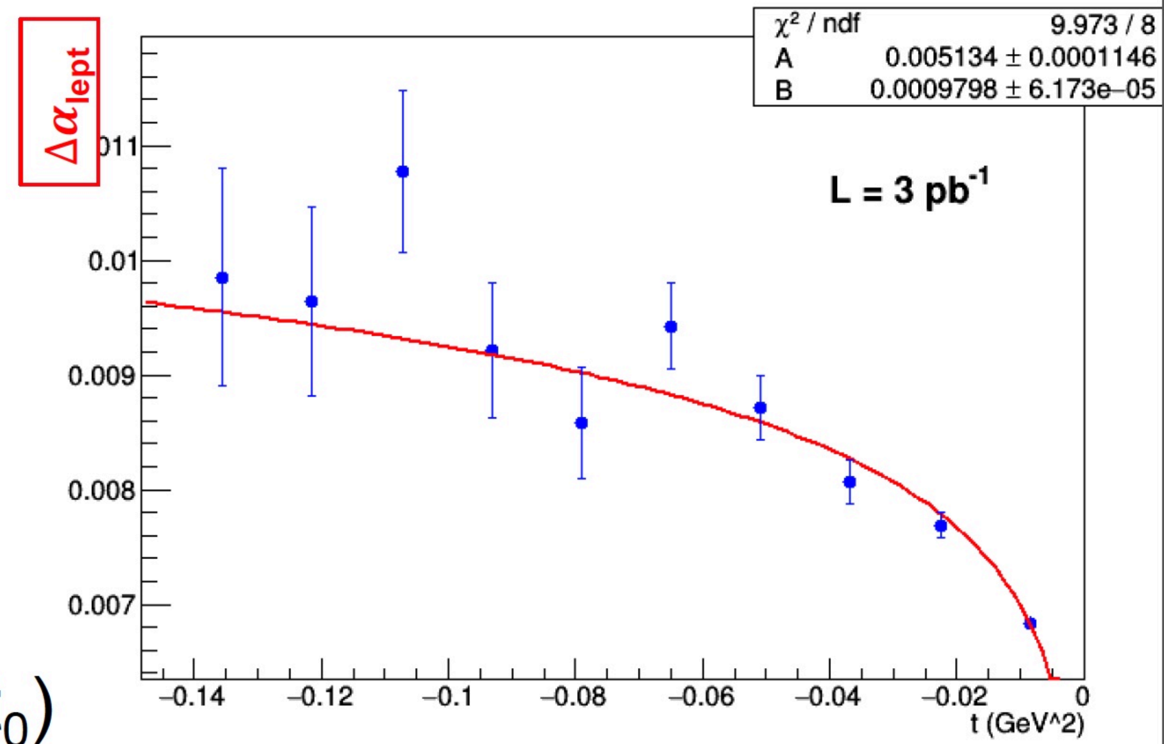
- Confirm the system engineering, i.e. assembly, mounting and cooling;
- Assessing the detector counting rate capability;
- Checking the signal integrity in the process of data transfer for the DAQ;
- Proving the validity of the trigger-less operation mode;
- Evaluate the FPGA real-time processing, to distinguish muons passing stations without interacting, to demonstrate the ability to identify and reconstruct $\mu - e$ events in real time.
- Testing the procedure for the alignment of the sensors: tools and methodology;
- Monitoring mechanical and thermal stability;

With ~3 weeks of good data ~10^8 elastic events could be collected (with Ee>1 GeV)
Preliminary meas. of the differential cross section and test of the leptonic running

The measurement of $\Delta\alpha_{lept}$ with the pilot run data

Very preliminary!

$\delta\Delta\alpha_{lept} \approx 6\%$
with Pilot run data



Fit with

$$\Delta\alpha_{lept} = A + B \times \log(t/t_0)$$

(t_0=-0.0015)

Potential sensitivity to the hadronic running ~ 3 σ

Tentative time profile schedule

If the Pilot Run will validate the design and the performance, then MUonE will request (a ***very*** tentative schedule…):

- **2022** Some time *(of the order of 4 weeks)* with ½ of the apparatus towards the end of the running time (due to availability of the Si modules and their mounting/aligning on the supports)

- **2023 – 2024** Consistent time of running to collect as much statistics as possible. The total amount of necessary statistics corresponds to ~4 x 10^7 s of running time *(~3 years assuming the present parameters of the M2 at 150 GeV)*

The beam requests are related to the scheduled delivery by *CMS (has to produce/test the full tracker apparatus, 280 Si modules):*
50% of stations by spring 2022
50% of stations by end of 2022

Need to collect ~4 x 10^{12} elastic events with E_e> 1 GeV to achieve a statistical error of ~0.3 %

Conclusions

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

The experiment is very challenging from the experimental point of view considering the systematic uncertainty which must be achieved.

The MUonE collaboration presents a request for **a pilot run** in 2021 to assess in the best and convincing way possible the validity of the setup design and feasibility of the measurement. *A first measurement of the leptonic contribution to the running seems possible with the first collected data.*

BACKUP

Muon anomalous magnetic moment

Dirac equation - the magnetic dipole moment of a spin ½ particle (l = e, μ) is:

$$\vec{M}_l = g_l \frac{e}{2m_l}\vec{S}$$

gyromagnetic ratio $g_l = 2$

QED – loop corrections give rise to the anomaly:

$$\boxed{a_l \equiv \frac{g_l - 2}{2}}$$

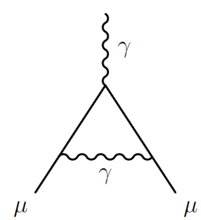
This observable can be both precisely measured experimentally and predicted in the Standard Model, providing powerful tests of the SM.

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{Had}$$

$$= (11659182.0 \pm 3.6) \times 10^{-10}$$

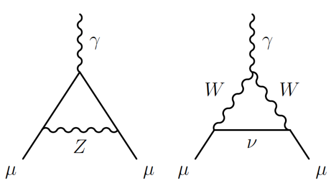
Keshavarzi, Nomura, Teubner, Phys. Rev. D 97, 114025 (2018)

0.3 ppm



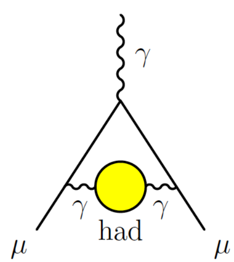
QED corrections known up to 5 loops, rel. precision ~7×10^{-10}

Leading order term (Schwinger) = $\alpha/2\pi$ ~ 0.00116



EWK corrections ~ 10^{-9}

rel. uncertainty less than 1%



Hadronic LO contribution

-not calculable by pQCD-

$a_\mu^{HLO} = (693.3 \pm 2.5) \times 10^{-10}$

rel. uncertainty ~0.4%

Dominant Theoretical uncertainty

Measurement of a_μ

E821 experiment at BNL : Bennett et al, Phys.Rev.D73 (2006) 072003

$$a_\mu^{E821} = 11659209.1(5.4)(3.3) \times 10^{-10}$$

Precise measurement : 0.54 ppm
Dominated by statistics

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (27.1 \pm 7.3) \times 10^{-10}}$$

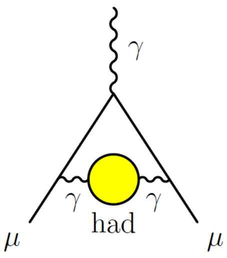
Intriguing discrepancy with Standard Model: about 3.5 σ

Sensitive to new physics (Supersymmetry, dark photons)

New g-2 experiment at Fermilab has started, targeting **a reduction of the experimental error by a factor of 4**
First results expected by summer 2020

➡ **Theoretical precision should be improved as well**

a_μ^{HLO}: standard approach



Dispersion relations, optical theorem:

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

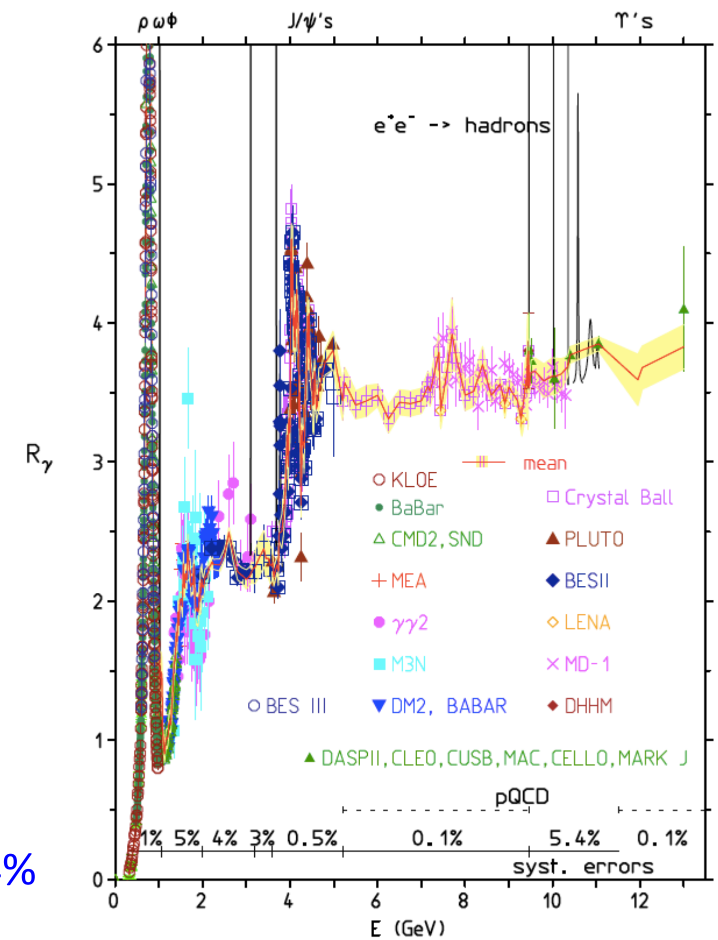
$R_{had}(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$
K smooth function

Traditionally the integral is calculated by using the experimental measurements up to an energy cutoff, beyond which perturbative QCD can be applied.
Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

$$\boxed{a_\mu^{HLO} = (693.3 \pm 2.5) \times 10^{-10}}$$

Rel. uncertainty ~0.4%

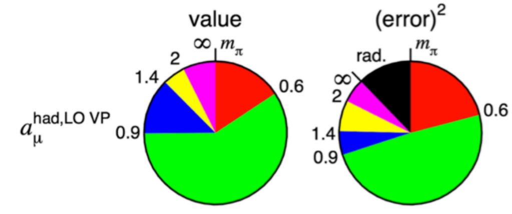
F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016



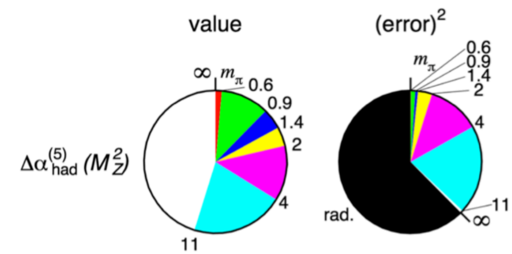
Alternative evaluations by lattice QCD not yet competitive, though expected to improve

Channel	Energy range [GeV]	$a_\mu^{\text{had,LO VP}} \times 10^{10}$	$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) \times 10^4$	New data
		Chiral perturbation theory (ChPT) threshold contributions		
$\pi^0\gamma$	$m_\pi \le \sqrt{s} \le 0.600$	0.12 ± 0.01	0.00 ± 0.00	...
$\pi^+\pi^-$	$2m_\pi \le \sqrt{s} \le 0.305$	0.87 ± 0.02	0.01 ± 0.00	...
$\pi^+\pi^-\pi^0$	$3m_\pi \le \sqrt{s} \le 0.660$	0.01 ± 0.00	0.00 ± 0.00	...
$\eta\gamma$	$m_\eta \le \sqrt{s} \le 0.660$	0.00 ± 0.00	0.00 ± 0.00	...
		Data based channels ($\sqrt{s} \le 1.937$ GeV)		
$\pi^0\gamma$	$0.600 \le \sqrt{s} \le 1.350$	4.46 ± 0.10	0.36 ± 0.01	[65]
$\pi^+\pi^-$	$0.305 \le \sqrt{s} \le 1.937$	502.97 ± 1.97	34.26 ± 0.12	[34,35]
$\pi^+\pi^-\pi^0$	$0.660 \le \sqrt{s} \le 1.937$	47.79 ± 0.89	4.77 ± 0.08	[36]
$\pi^+\pi^-\pi^+\pi^-$	$0.613 \le \sqrt{s} \le 1.937$	14.87 ± 0.20	4.02 ± 0.05	[40,42]
$\pi^+\pi^-\pi^0\pi^0$	$0.850 \le \sqrt{s} \le 1.937$	19.39 ± 0.78	5.00 ± 0.20	[44]
$(2\pi^+2\pi^-\pi^0)_{\text{no}\eta}$	$1.013 \le \sqrt{s} \le 1.937$	0.99 ± 0.09	0.33 ± 0.03	...
$3\pi^+3\pi^-$	$1.313 \le \sqrt{s} \le 1.937$	0.23 ± 0.01	0.09 ± 0.01	[66]
$(2\pi^+2\pi^-2\pi^0)_{\text{no}\eta\omega}$	$1.322 \le \sqrt{s} \le 1.937$	1.35 ± 0.17	0.51 ± 0.06	...
K^+K^-	$0.988 \le \sqrt{s} \le 1.937$	23.03 ± 0.22	3.37 ± 0.03	[45,46,49]
$K_S^0K_L^0$	$1.004 \le \sqrt{s} \le 1.937$	13.04 ± 0.19	1.77 ± 0.03	[50,51]
$KK\pi$	$1.260 \le \sqrt{s} \le 1.937$	2.71 ± 0.12	0.89 ± 0.04	[53,54]
$KK2\pi$	$1.350 \le \sqrt{s} \le 1.937$	1.93 ± 0.08	0.75 ± 0.03	[50,53,55]
$\eta\gamma$	$0.660 \le \sqrt{s} \le 1.760$	0.70 ± 0.02	0.09 ± 0.00	[67]
$\eta\pi^+\pi^-$	$1.091 \le \sqrt{s} \le 1.937$	1.29 ± 0.06	0.39 ± 0.02	[68,69]
$(\eta\pi^+\pi^-\pi^0)_{\text{no}\omega}$	$1.333 \le \sqrt{s} \le 1.937$	0.60 ± 0.15	0.21 ± 0.05	[70]
$\eta 2\pi^+2\pi^-$	$1.338 \le \sqrt{s} \le 1.937$	0.08 ± 0.01	0.03 ± 0.00	...
$\eta\omega$	$1.333 \le \sqrt{s} \le 1.937$	0.31 ± 0.03	0.10 ± 0.01	[70,71]
$\omega(\to \pi^0\gamma)\pi^0$	$0.920 \le \sqrt{s} \le 1.937$	0.88 ± 0.02	0.19 ± 0.00	[72,73]
$\eta\phi$	$1.569 \le \sqrt{s} \le 1.937$	0.42 ± 0.03	0.15 ± 0.01	...
$\phi \to$ unaccounted	$0.988 \le \sqrt{s} \le 1.029$	0.04 ± 0.04	0.01 ± 0.01	...
$\eta\omega\pi^0$	$1.550 \le \sqrt{s} \le 1.937$	0.35 ± 0.09	0.14 ± 0.04	[74]
$\eta(\to \text{npp})K\bar{K}_{\text{no}\phi\to K\bar{K}}$	$1.569 \le \sqrt{s} \le 1.937$	0.01 ± 0.02	0.00 ± 0.01	[53,75]
$p\bar{p}$	$1.890 \le \sqrt{s} \le 1.937$	0.03 ± 0.00	0.01 ± 0.00	[76]
$n\bar{n}$	$1.912 \le \sqrt{s} \le 1.937$	0.03 ± 0.01	0.01 ± 0.00	[77]
		Estimated contributions ($\sqrt{s} \le 1.937$ GeV)		
$(\pi^+\pi^-3\pi^0)_{\text{no}\eta}$	$1.013 \le \sqrt{s} \le 1.937$	0.50 ± 0.04	0.16 ± 0.01	...
$(\pi^+\pi^-4\pi^0)_{\text{no}\eta}$	$1.313 \le \sqrt{s} \le 1.937$	0.21 ± 0.21	0.08 ± 0.08	...
$KK3\pi$	$1.569 \le \sqrt{s} \le 1.937$	0.03 ± 0.02	0.02 ± 0.01	...
$\omega(\to \text{npp})2\pi$	$1.285 \le \sqrt{s} \le 1.937$	0.10 ± 0.02	0.03 ± 0.01	...
$\omega(\to \text{npp})3\pi$	$1.322 \le \sqrt{s} \le 1.937$	0.17 ± 0.03	0.06 ± 0.01	...
$\omega(\to \text{npp})KK$	$1.569 \le \sqrt{s} \le 1.937$	0.00 ± 0.00	0.00 ± 0.00	...
$\eta\pi^+\pi^-2\pi^0$	$1.338 \le \sqrt{s} \le 1.937$	0.08 ± 0.04	0.03 ± 0.02	...
		Other contributions ($\sqrt{s} > 1.937$ GeV)		
Inclusive channel	$1.937 \le \sqrt{s} \le 11.199$	43.67 ± 0.67	82.82 ± 1.05	[56,62,63]
J/ψ	...	6.26 ± 0.19	7.07 ± 0.22	...
ψ'	...	1.58 ± 0.04	2.51 ± 0.06	...
$\Upsilon(1S-4S)$	...	0.09 ± 0.00	1.06 ± 0.02	...
pQCD	$11.199 \le \sqrt{s} \le \infty$	2.07 ± 0.00	124.79 ± 0.10	...
Total	$m_\pi \le \sqrt{s} \le \infty$	693.26 ± 2.46	276.11 ± 1.11	...

39 measurements



(a) Fractional contributions to $a_\mu^{\text{had, LO VP}}$.



(b) Fractional contributions to $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$

KESHAVARZI, NOMURA, and TEUBNER
PHYS. REV. D 97, 114025 (2018)

A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 97, 114025 (2018)

a_μ^{HLO}: alternative approach (space-like data)

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni Phys.Lett. B746 (2015) 325

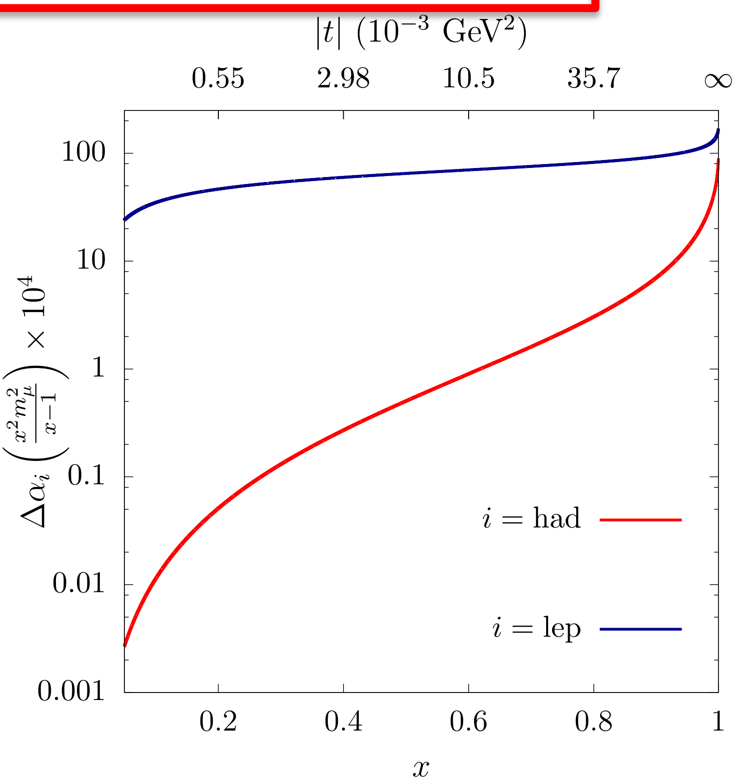
-Initially proposed for use with Bhabha scattering data from flavour factories-

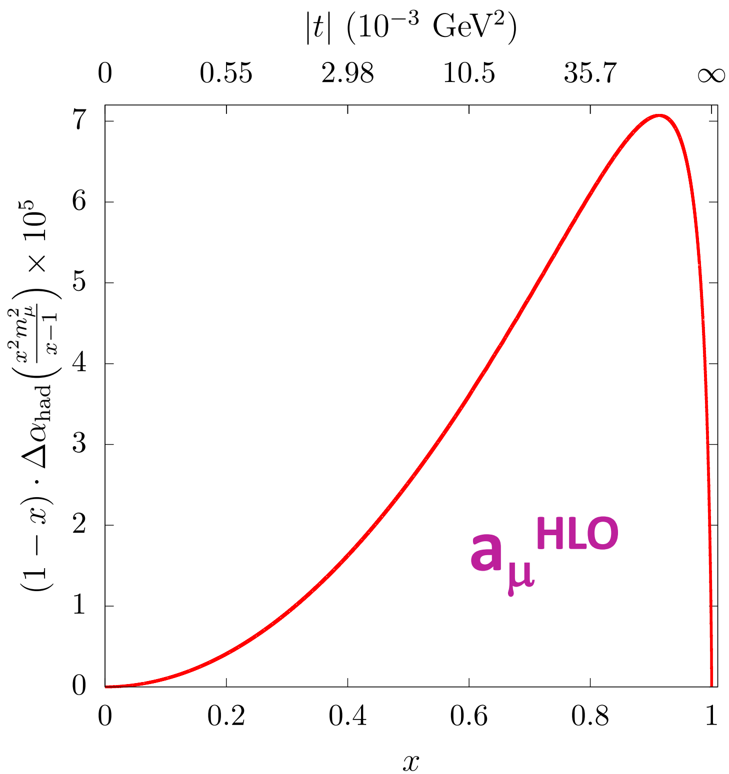
$$\boxed{a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]} \qquad t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad \begin{array}{l} 0 \le -t < \infty \\ 0 \le x < 1 \end{array}$$

$\Delta\alpha_{had}$ is the hadronic contribution to the running of α in the space-like region (t<0)

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$





Integrand function smooth: no resonances

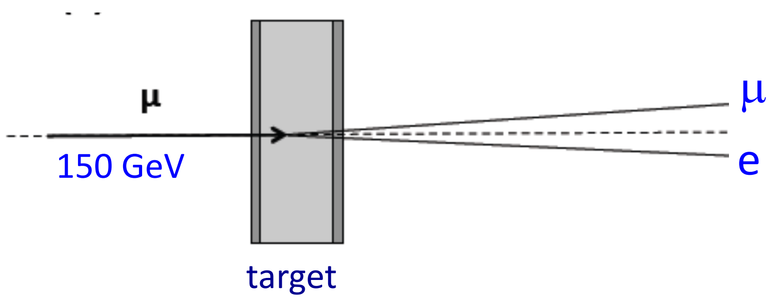
Low-energy enhancement: peak of the integrand at x=0.914 -> t=-0.108GeV^2 → $\Delta\alpha_{had}$ ~ 0.8x10^{-3}

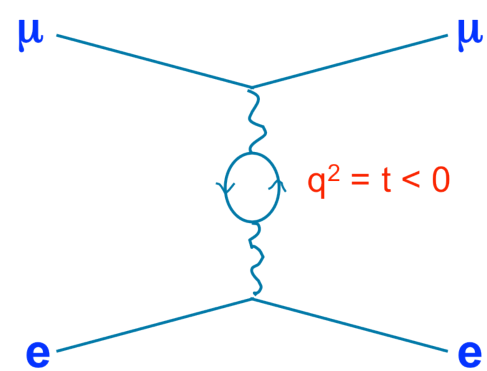
MuonE experimental Proposal

Elastic scattering $\mu e \rightarrow \mu e$ with a μ beam of E=150 GeV on atomic electrons of a fixed target with low Z (Be or C)

- From the measured differential cross section determine $\Delta\alpha_{had}(t)$ and then a_μ^{HLO} by the space-like approach

G.Abbiendi, C.M.Carloni Calame, U.Marconi, C.Matteuzzi, G.Montagna, O.Nicrosini, M.Passera, F.Piccinini, R.Tenchini, L.Trentadue, G.Venanzoni, Eur.Phys.J.C 77 (2017) 139



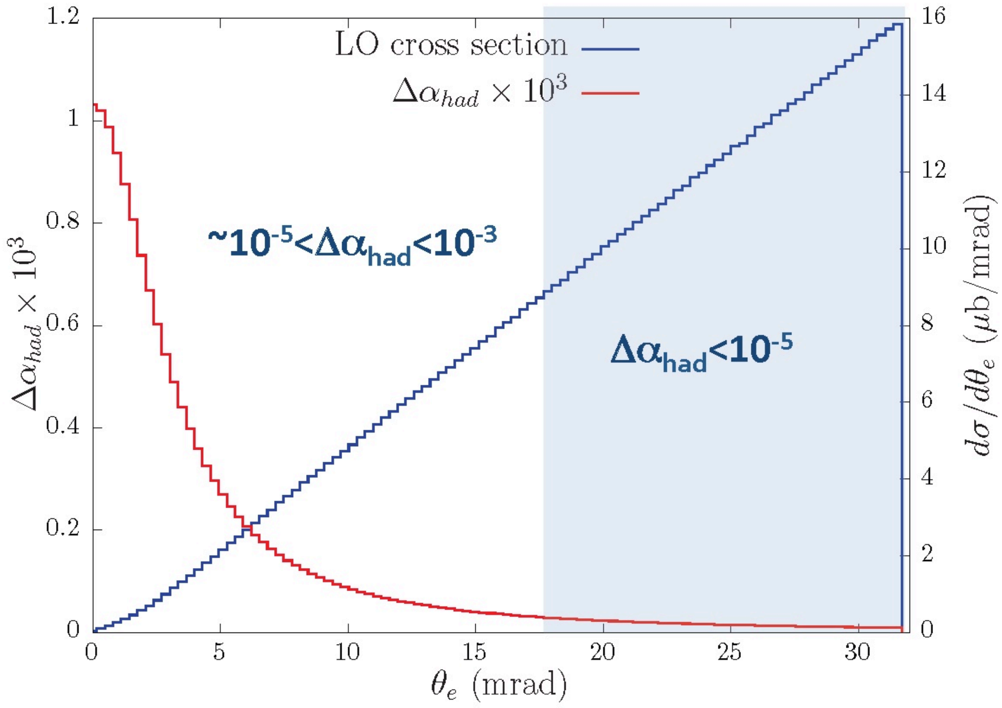


$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\underbrace{\left|\frac{1}{1-\Delta\alpha(t)}\right|^2}_{\text{running of } \alpha}$$

$$\Delta\alpha(t) = \underbrace{\Delta\alpha_{lep}(t)}_{\text{known from QED}} + \underbrace{\Delta\alpha_{had}(t)}_{\text{to be measured !}}$$

Leading mechanism. Higher-order corrections to be considered as well…

LO μ-e elastic scattering



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

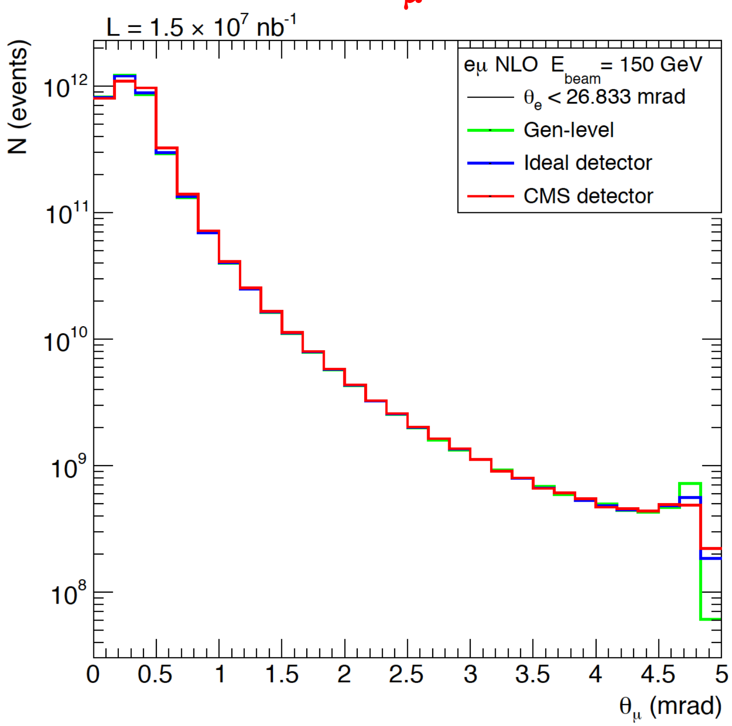
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)} \qquad \Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

Simple kinematics: $t \cong -2\, m_e E_e$

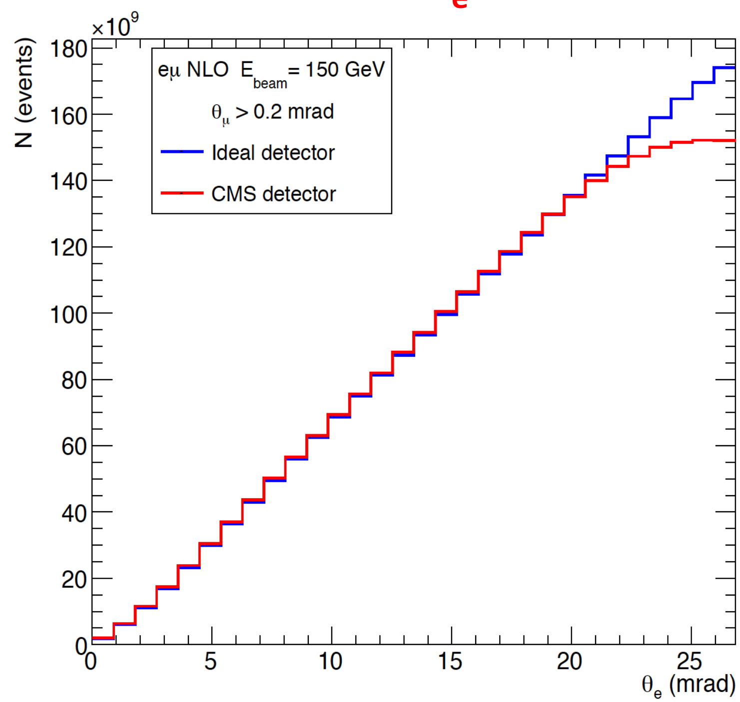
E_e can be determined from the scattering angle θ_e and the beam energy

Angular distributions

θ_μ



θ_e

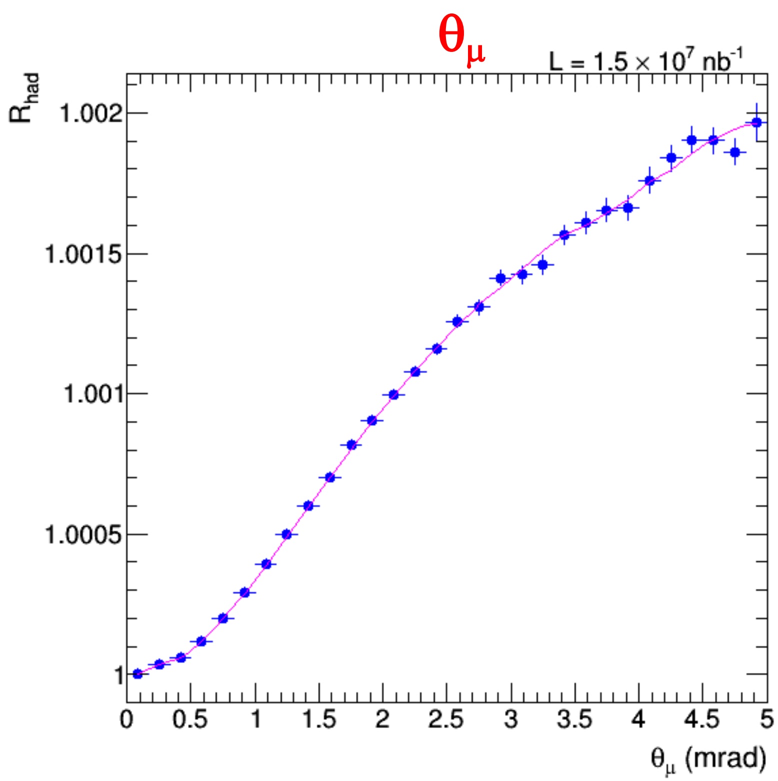


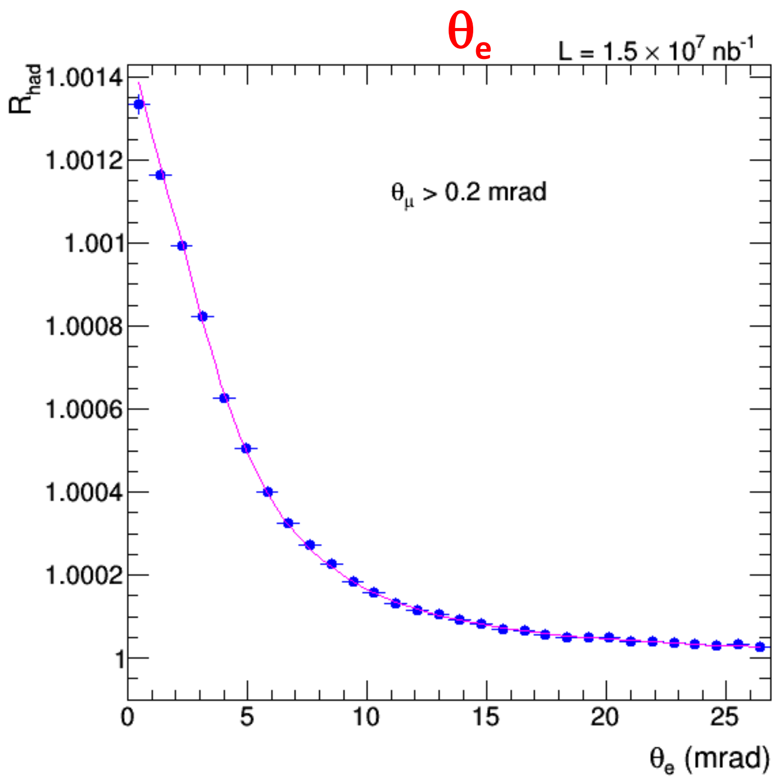
statistics corresponding to the nominal integrated Luminosity L = 1.5 x 10^7 nb^{-1}

Running α

The hadronic running of α is most easily displayed by taking ratios of the observed angular distributions and the theory predictions evaluated for $\alpha(t)$ corresponding to only the leptonic running.

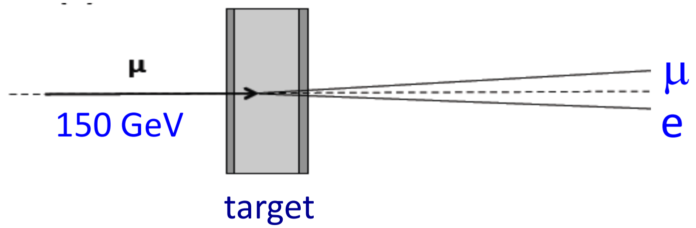
Example toy experiment shown with statistics corresponding to the nominal integrated Luminosity L = 1.5 x 10^7 nb^{-1}





Experimental proposal

Elastic scattering $\mu e \rightarrow \mu e$ with a μ beam of E=150 GeV on atomic electrons of a fixed target with low Z



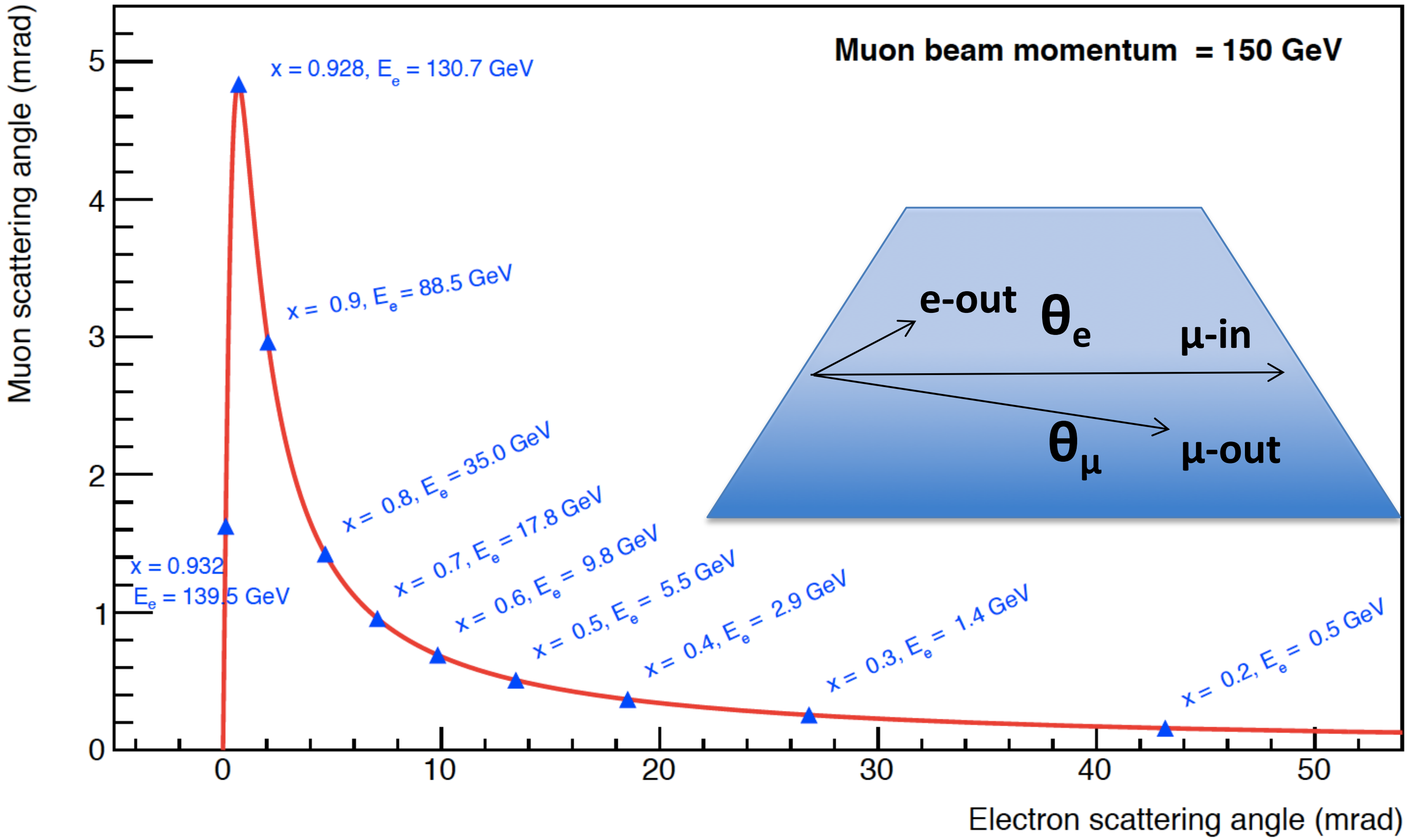
- Only t-channel at LO: running coupling $\alpha^2(t)$ factorized in the cross section
  - Instead Bhabha scattering at flavour factories involves both s- and t- channel diagrams

- Simple kinematics determined from the initial muon energy and either one energy or angle of the scattered particles, e.g. $t \cong -2m_e E_e$
  - Or incoming muon energy determined from both θ_e and θ_μ

- For beam E=150 GeV the phase space extends up to:
  x<0.932, –t<0.143 GeV^2 corresponding to 87% of the a_μ^{HLO} integral.
  - The full integral can be obtained with a proper fit model with negligible error.

- Boosted kinematics: θ_e<32mrad (for E_e>1 GeV), θ_μ<5mrad
  the whole acceptance can be covered with one 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

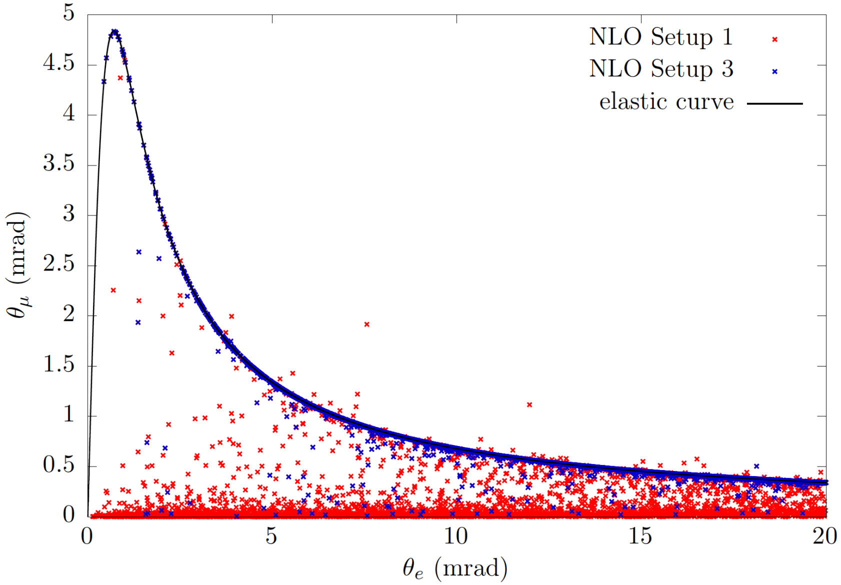
Elastic scattering in the (θ_e , θ_μ) plane



- The scattering angles θ_e and θ_μ are correlated: important constraint to select elastic events, rejecting radiative or inelastic processes.
  - Ambiguity for scattering angles of 2-3 mrad to be solved by pID

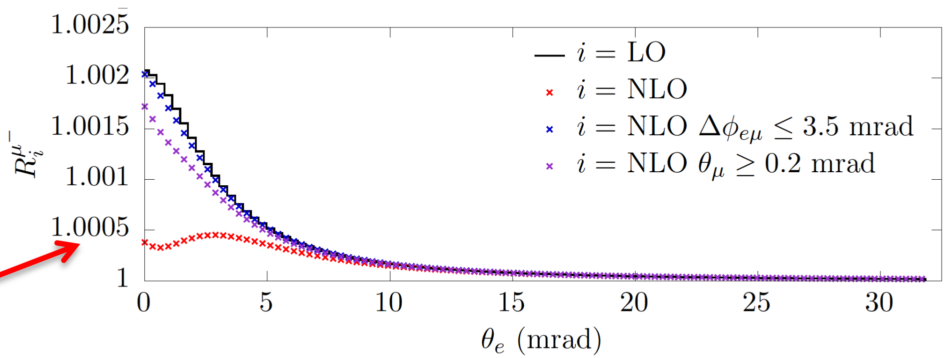
- Similar technique already used in the past by the NA7 experiment

NLO MC and elastic selection

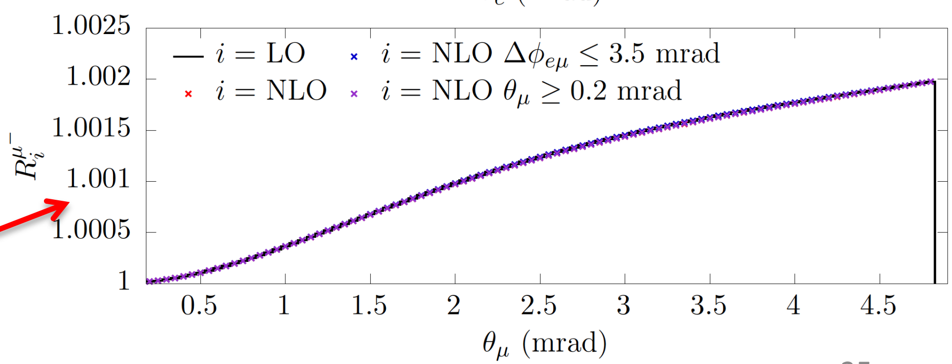


M.Alacevich et al, JHEP02(2019)155

NLO Setup 1 is the inclusive selection (no cuts)
Setup 3 has an acoplanarity cut $|\pi-(\phi_e-\phi_\mu)|<3.5$ mrad



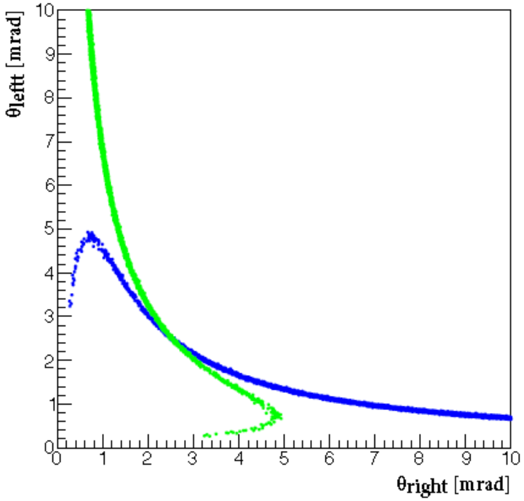
Without any selection the signal sensitivity of the electron angle is destroyed -> necessary to implement an "elastic" selection

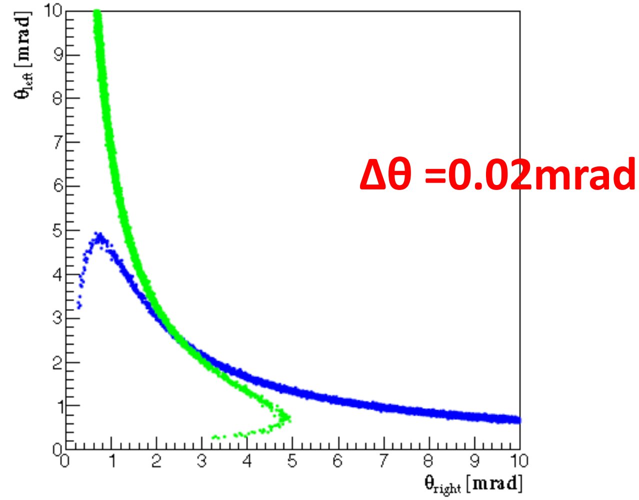


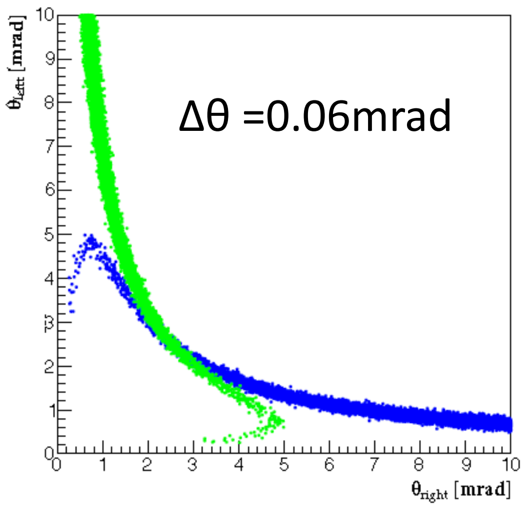
Instead the muon angle is a robust observable, stable w.r.t. radiative corrections -> it can be used with an inclusive selection (theoretically advantageous)

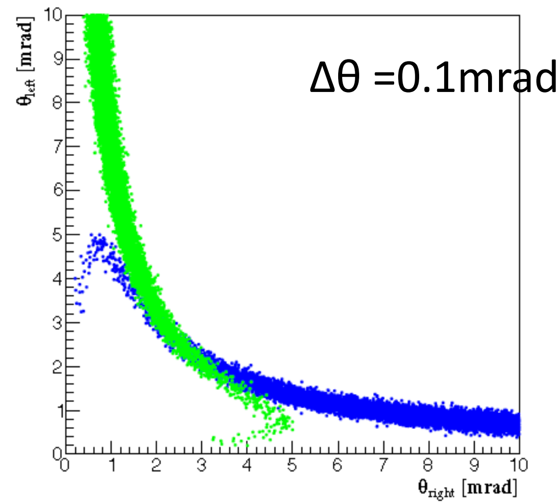
Detector resolution and PID

Target
MSC effects

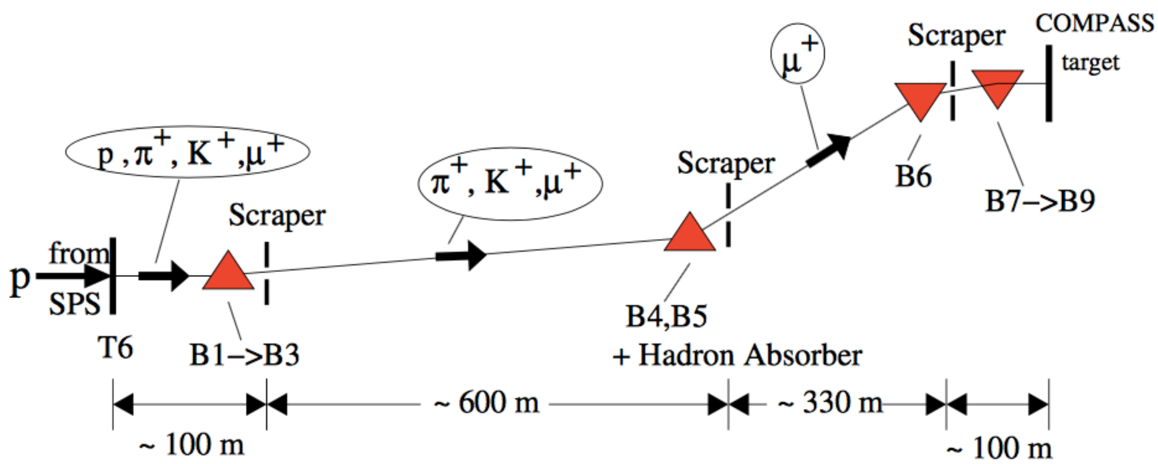








CERN muon beam M2



From SPS

COMPASS exp. P.Abbon et al, Nucl.Instrum.Meth.A 577 (2007) 455

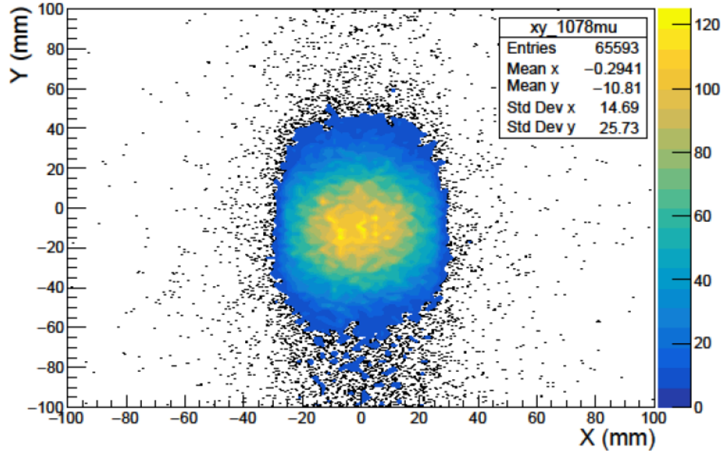
Table 3
Parameters and performance of the 160 GeV/c muon beam

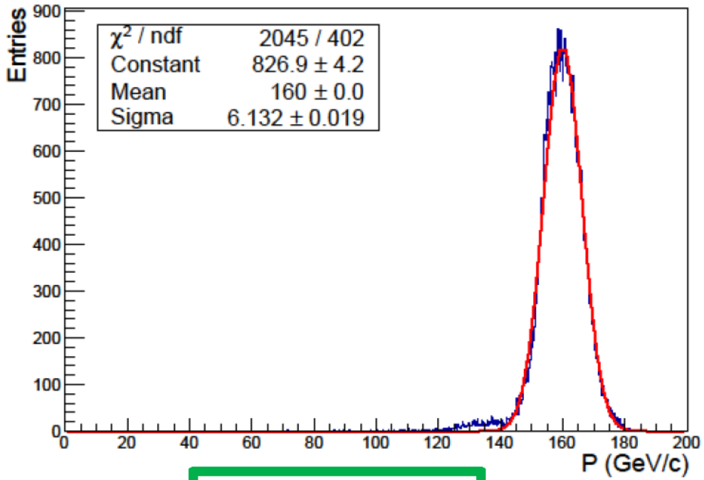
Beam parameters	Measured
Beam momentum $(p_\mu)/(p_\pi)$	(160 GeV/c)/(172 GeV/c)
Proton flux on T6 per SPS cycle	1.2×10^{13}
Focussed muon flux per SPS cycle	2×10^{8}
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS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

Spill duration: 4.8 s
within the SPS cycle of 16.8 s

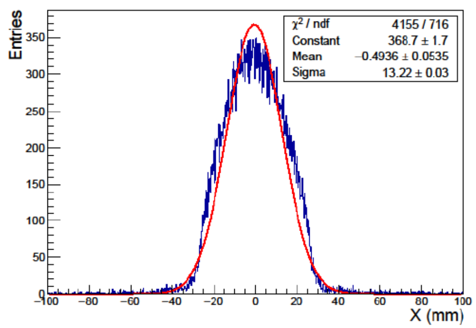
High average intensity
$> 10^7\ \mu$/s

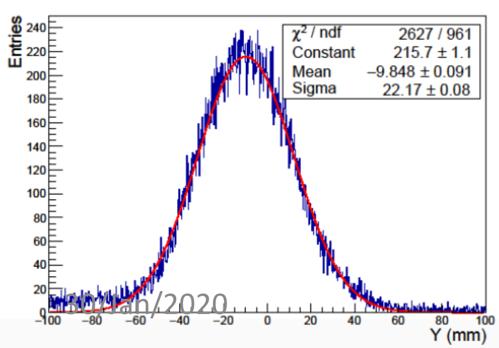
Beam parameters for MUonE *(from Dipanwita B., sept 2019)*





$E\mu$ = 160 GeV

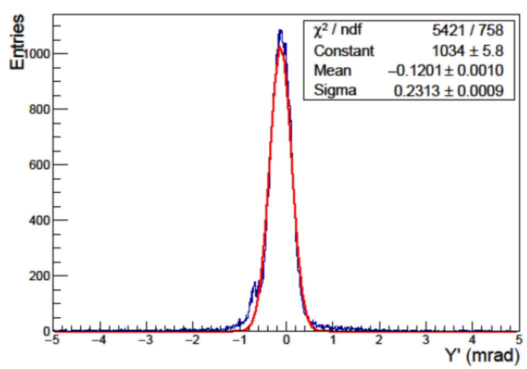


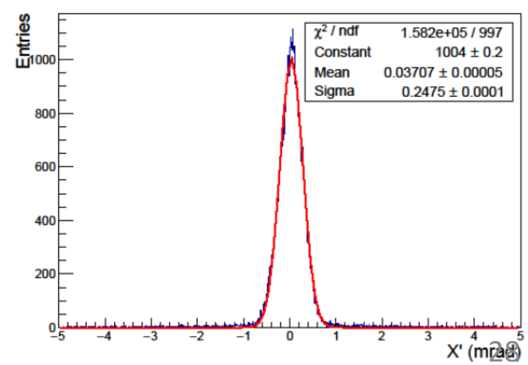


Very low divergence

0.23 mrad

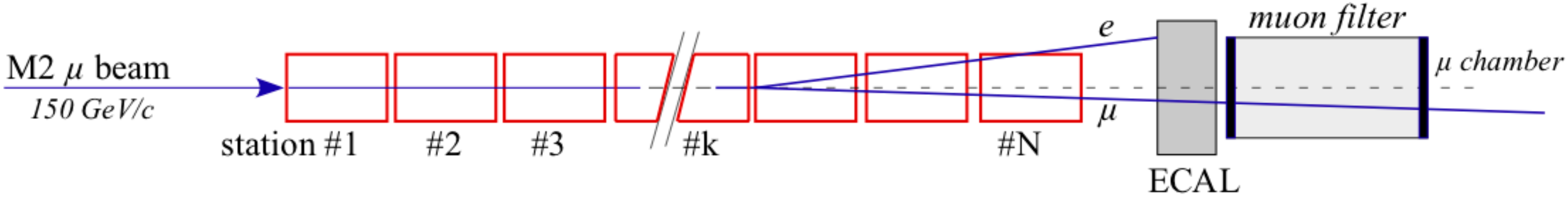
0.24 mrad





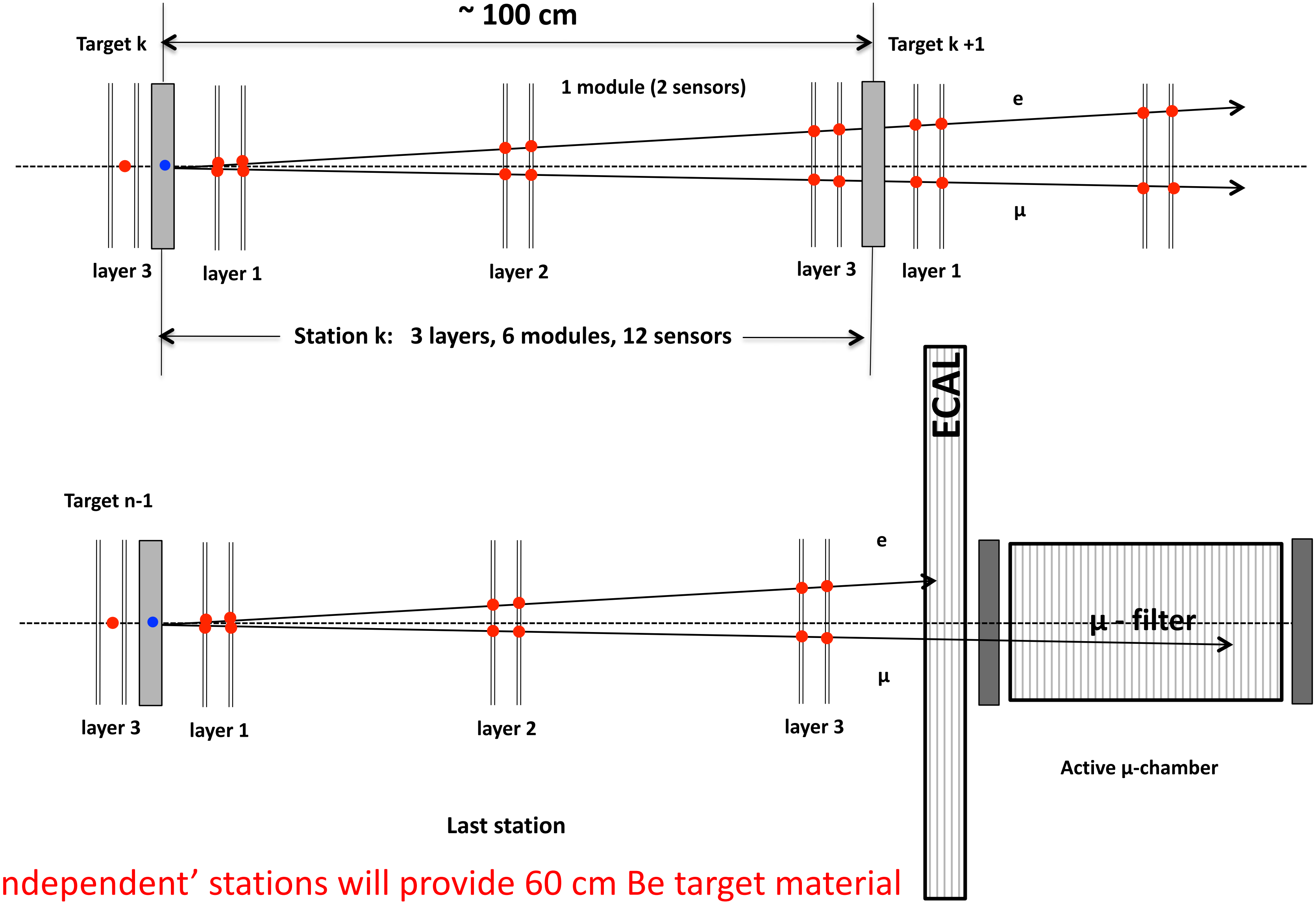
Experimental apparatus

The experiment has a 'simple' setup, but it is extremely challenging and difficult, due to the request of keeping the systematics at the same level as the statistical error .



40 'independent' stations will provide 60 cm Be target material (1.5cm each)

Detector (not on scale)



40 ‘independent’ stations will provide 60 cm Be target material

Location at CERN M2

- **Between BSM and COMPASS**

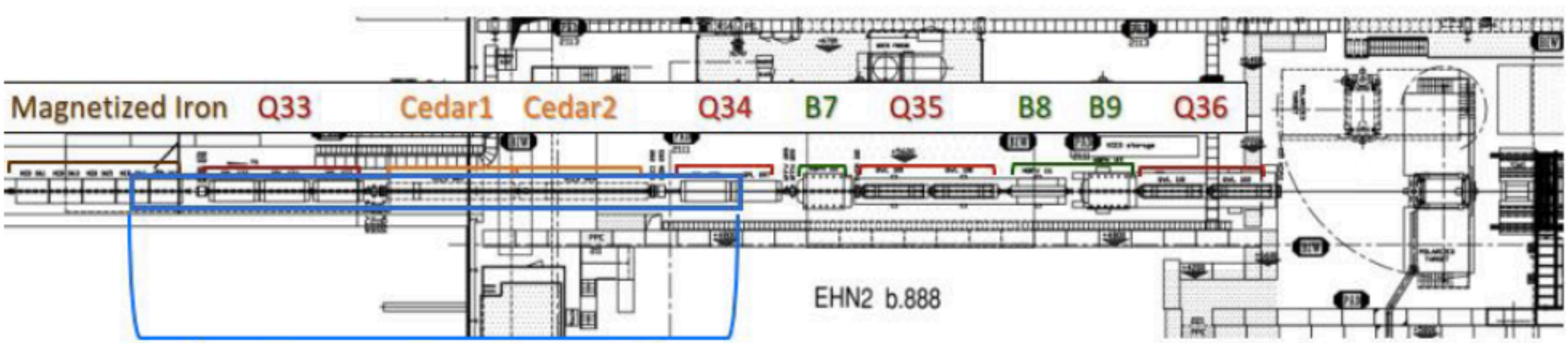
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)

- Pro: Could allow running μ-e/μ-p_{Radius} in parallel.

- Questions: will require displacements (also removal) of some M2 components.

- Beam(s) compatibility for μ-e & μ-p_{Radius} : Optic's wise looks OK (see Add. Sl.14 from D.B.)



μ-e Upstream (under-study)
~ 30 m

⟸

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m

10

Space available : 40 m upstream COMPASS

Location at CERN M2

Testbeam performed

★ **2017** *: study of Multiple Scattering of electrons of 12 and 20 GeV in H8 area*

The study has been concluded with the paper

"Results on multiple Coulomb scattering from 12 and 20 GeV electrons on carbon targets"

published on JINST 15 (2020) P01017

★ **2018** *: study of μ-e -> μ-e elastic events*

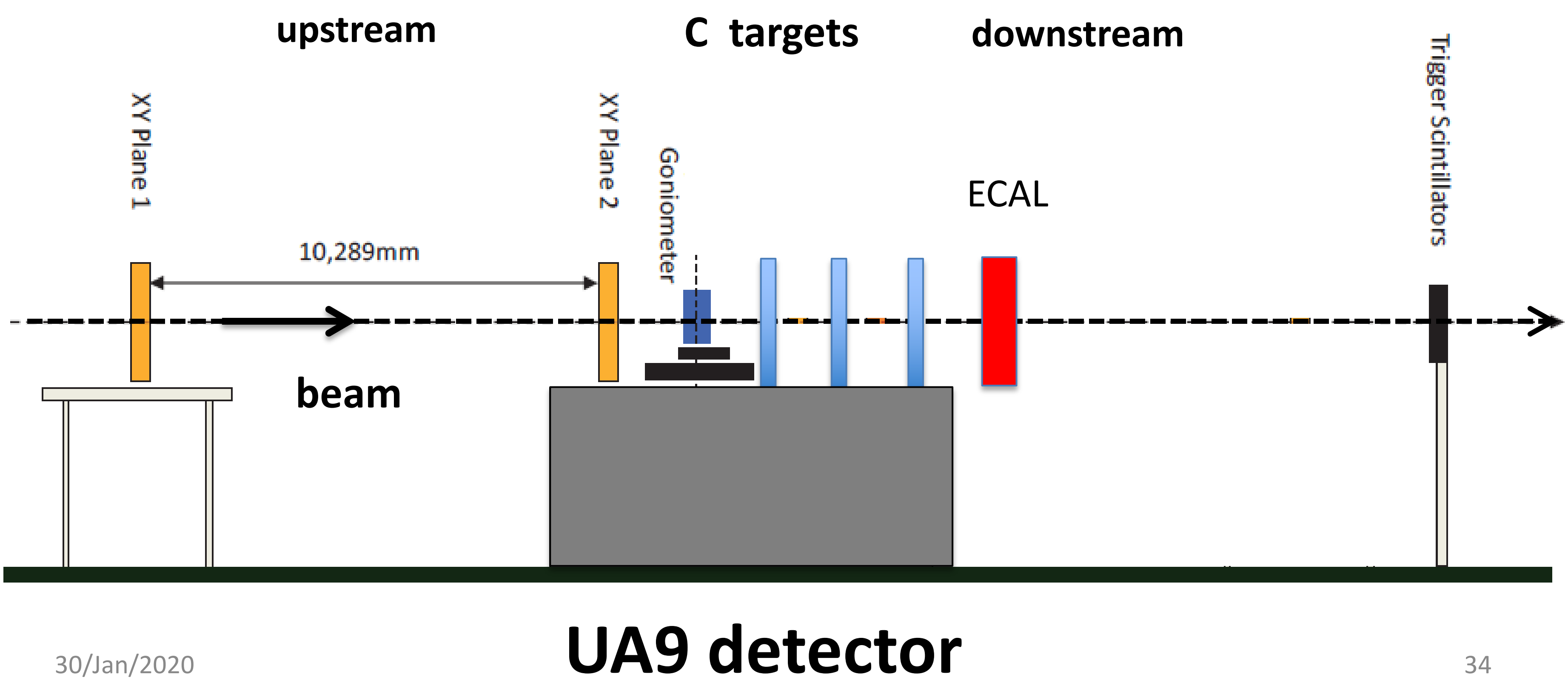
~ 6 months running with several different configurations, 3 different kinds of calorimeters.

~2M triggers with one target and a PbWO4 crystal calorimeter.

➡ ***Analysis in progress***

Test Beam 2017: the setup

- Feasibility studies: Multiple Scattering and elastic events signature
- We used the UA9 tracking system to record scattering data
- Alignment, tracking, pattern recognition developed from scratch



Paper: MSC results of the TB

JINST 15 (2020) P01017

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets

G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j], and G. Venanzoni[j,1]

[a] *INFN Sezione di Bologna, Viale Carlo Berti-Pichat 6/2, 40127 Bologna, Italy*
[b] *CERN, 1211 Geneva 23, Switzerland*
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[i] *Budker Institute of Nuclear Physics, SB RAS, and Novosibirsk State University, Novosibirsk, 630090, Russia*
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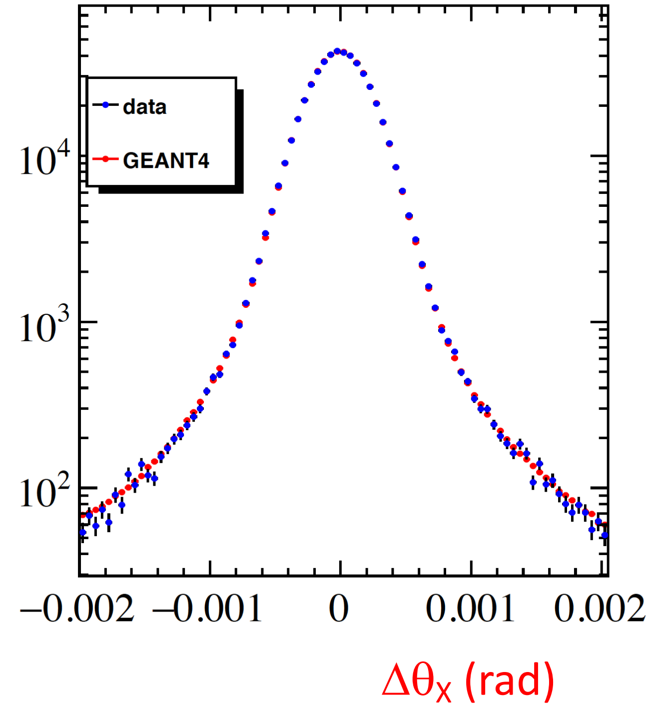
[k] *Tomsk State University, 634050 Tomsk, Russia*
[l] *Scuola Normale Superiore, Pisa, Italy*
[m] *INFN Sezione di Padova, Via Francesco Marzolo 8, 35131 Padua, Italy*
[n] *Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy*



Testbeam in 2017 *(Multiple Scattering study)*

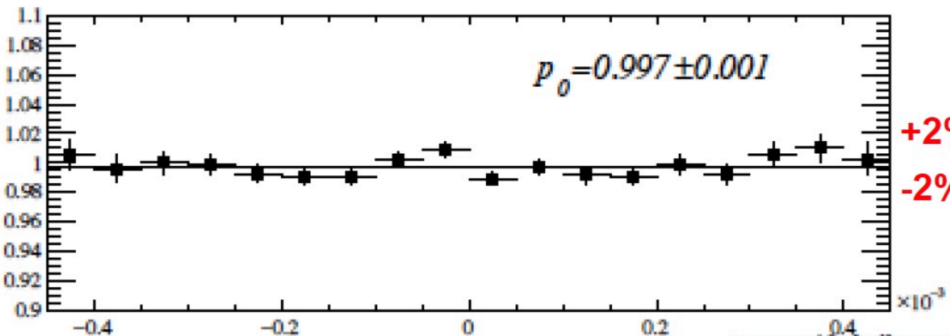
Dedicated test in H8 with electron beams and UA9 apparatus (7 μm intrinsic resolution)

JINST 15 (2020) P01017

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets

G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j], and G. Venanzoni[j,1]

data/MC

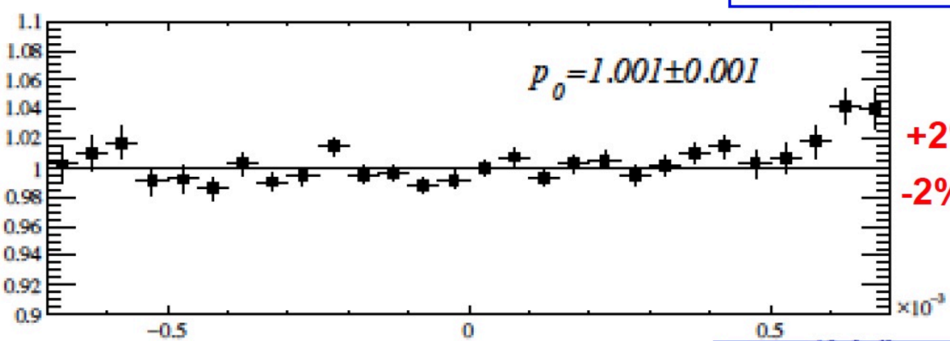


+2%

-2%

$\theta_{in} - \theta_{out}$(mrad)

12 GeV electrons, 8 mm graphite
Comparison DATA/GEANT



+2%

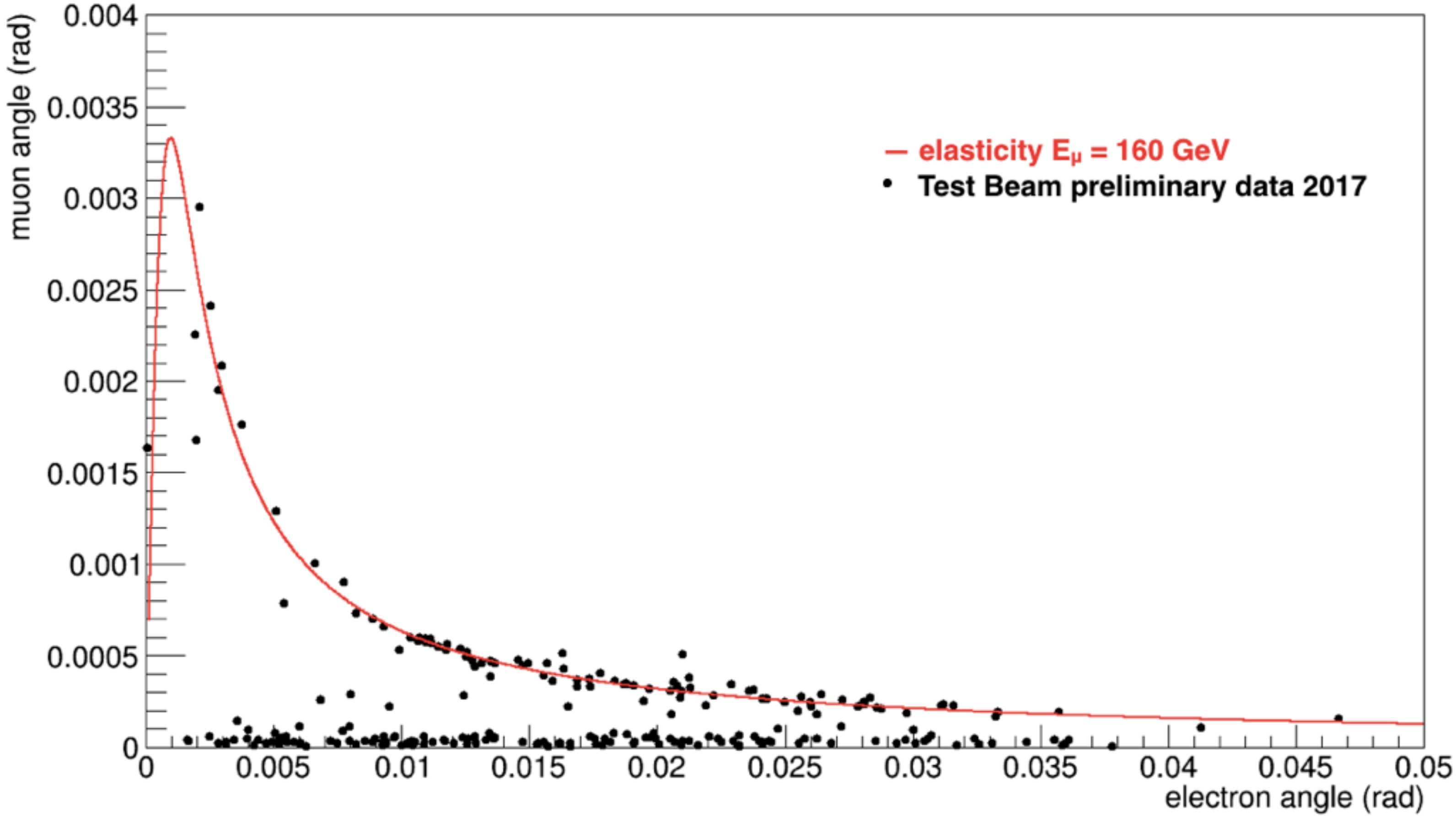
-2%

$\theta_{in} - \theta_{out}$(mrad)

12 GeV electrons, 20 mm graphite
DATA/GEANT

2017 Test Beam Result

Evidence of the elastic scattering



160 GeV muon beam, 8 mm C target
Golden selection: single track in, and two tracks out

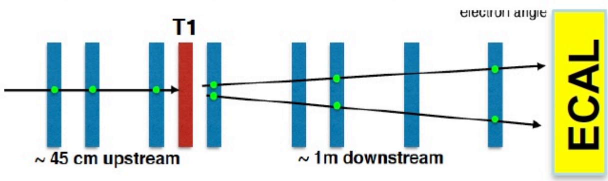
Testbeam in 2018 *(μ-e elastic scattering study)*

- **The setup was located downstream COMPASS**

  (behind the Tungsten hadrons filter)

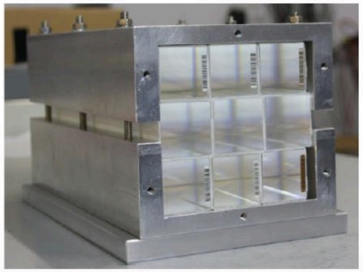
- **Aim to measure $\mu - e$ elastic scattering**
  - *Using muons from pions decays (hadron beam) with an estimated beam momentum p = (187±7) GeV*
  - *To measure the correlation between the scattering angles: muon angle vs the electron angle;*
  - *Electron energy vs the electron angle correlation and PID.*

- **The detector consists of:**
  - Tracking system: stations equipped with the **AGILE** silicon strip sensors: 400 micron thick, single sided about 40 μm intrinsic hit resolution.



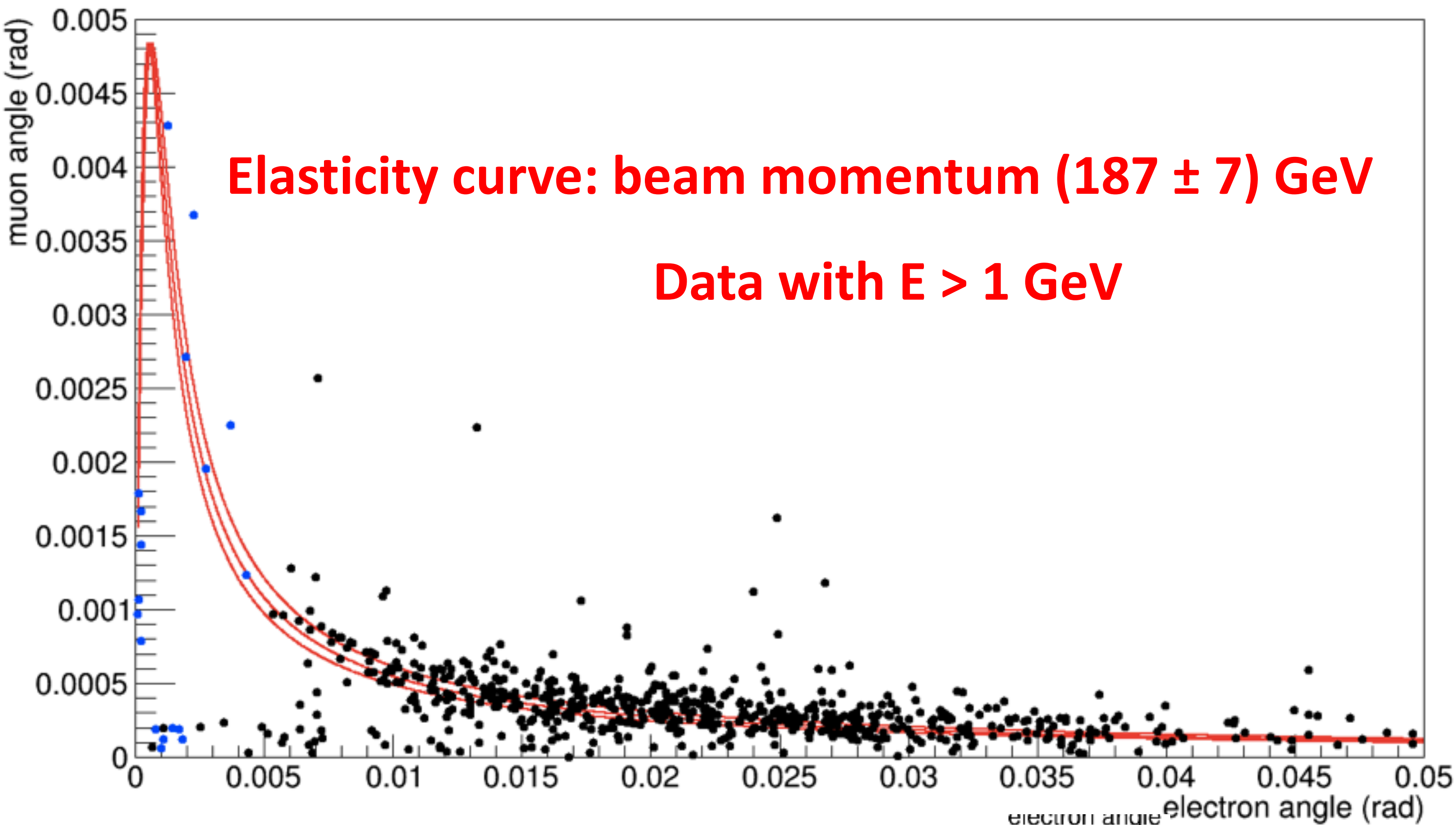
  - Electromagnetic calorimeter: 3x3 crystals matrix (CMS $PbWO_4$)

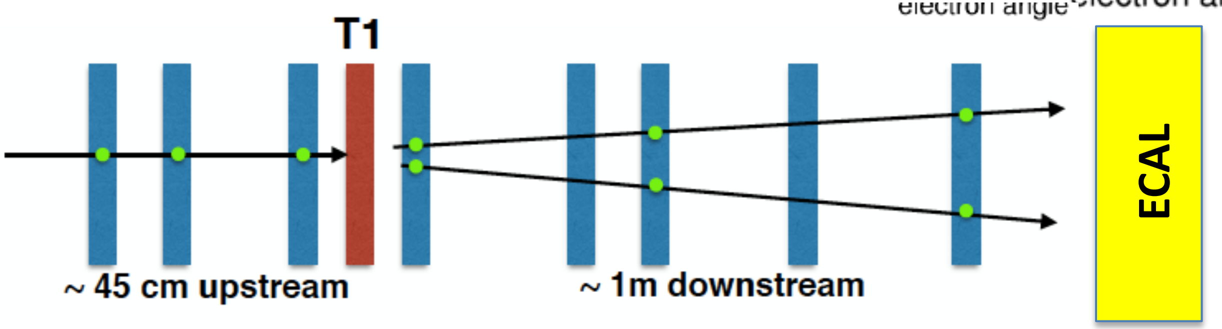
    $25X_o$, 9.9 cm^2



Test beam 2018
With remote control

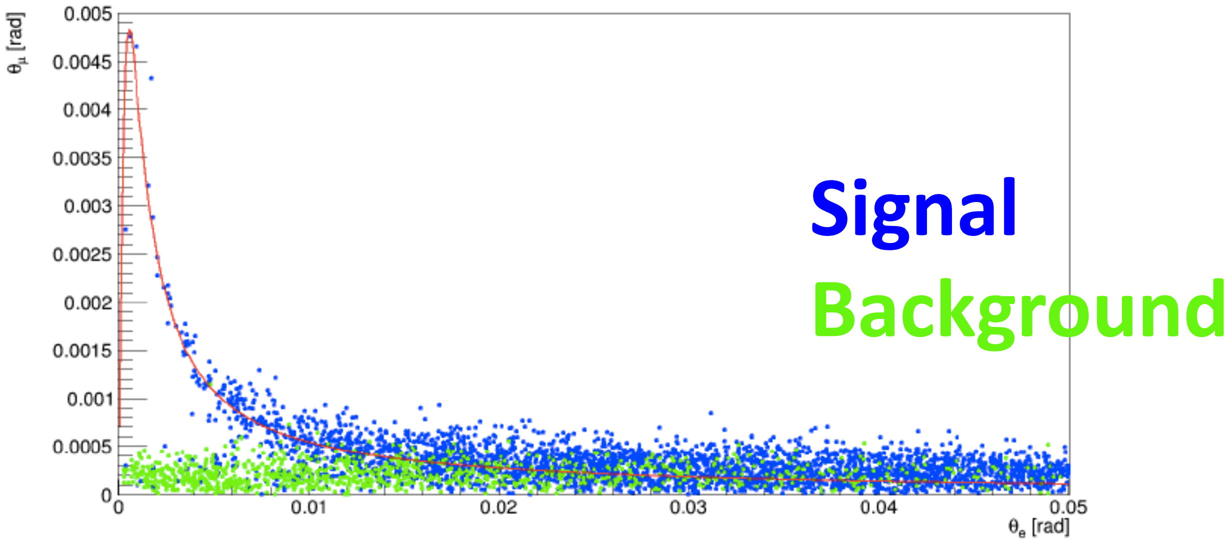
Data: using the Calorimeter

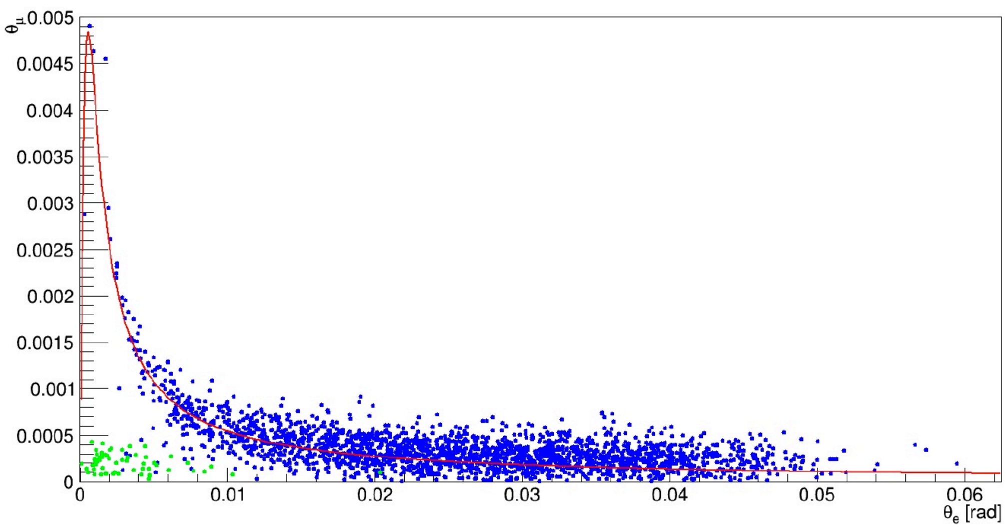




Simulation: Test beam 2018, GEANT4

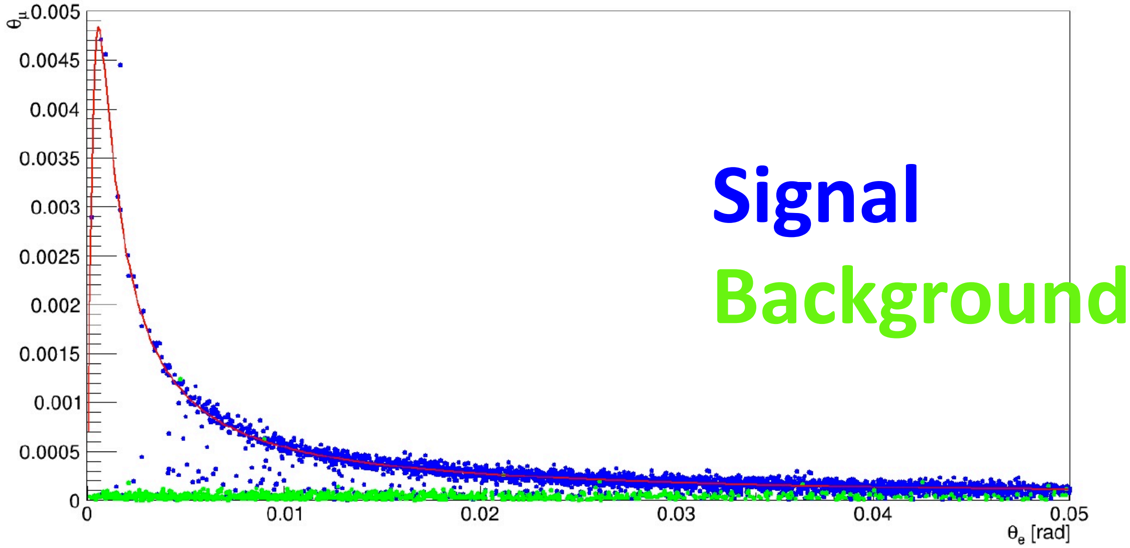
angle_μ vs angle_e

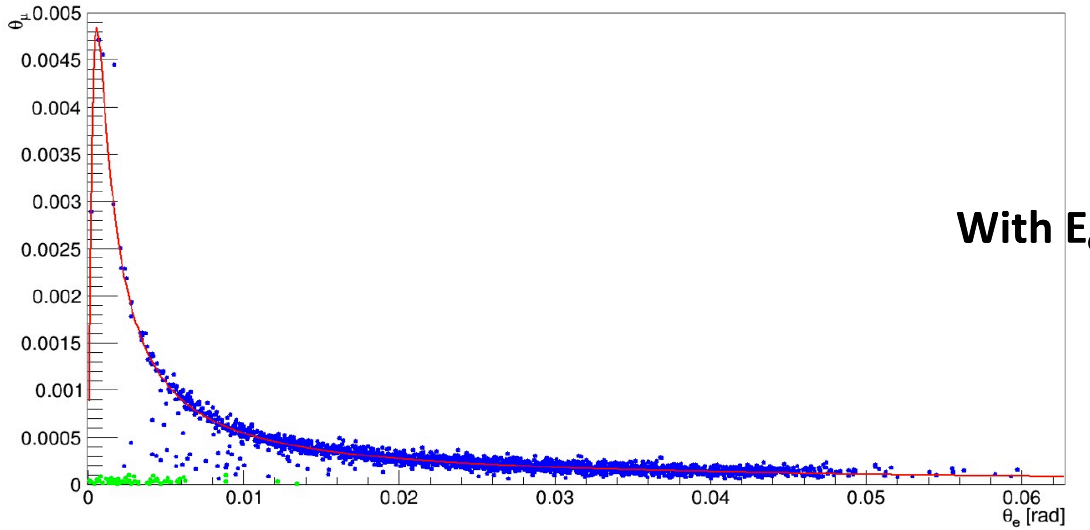




With E_e > 1 GeV energy cut

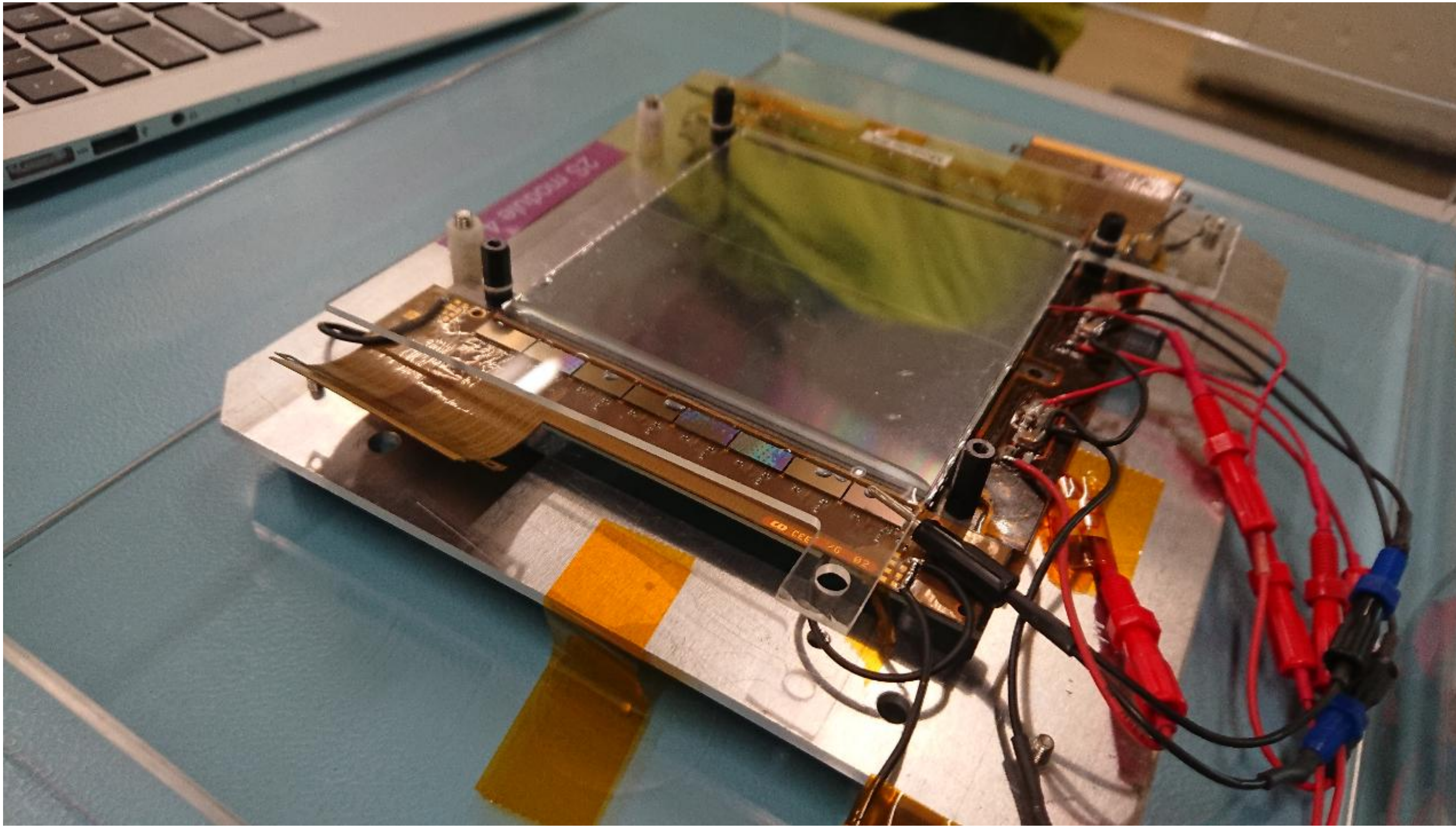
Effect of the resolution: GEANT4 UA9 resolution 7μm





With E_e > 1 GeV energy cut

Detector choice: CMS Phase2 Outer Tracker 2S module



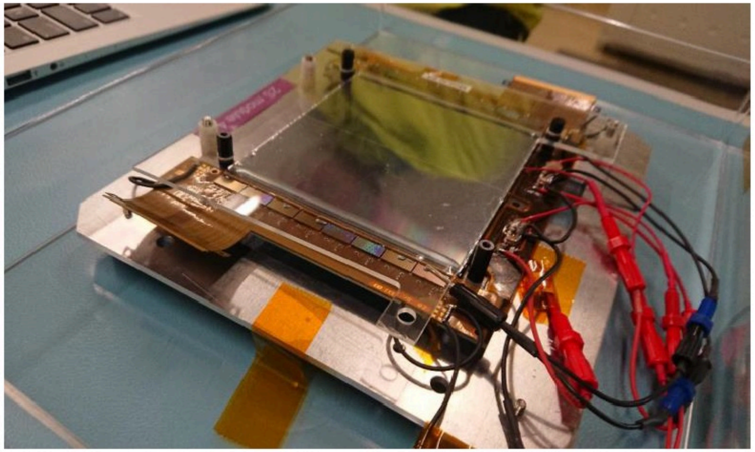
Tracking system

★ **The tracker must provide:**
- A very good angular resolution ~ 20 μrad
- High uniformity
- Capable to sustain high rate ~50 MHz

All the Si planes and the electronics will be provided by the CMS Upgrade-II project

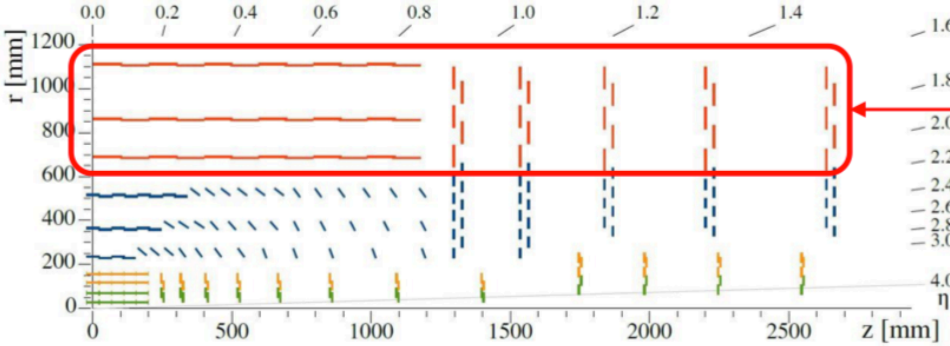
Characteristics of the CMS 2S Modules comply with the requirements

Thickness : 2 × 320 μm
Pitch: 90 μm → σ_x = 26 μm
Area: 10 cm × 10 cm

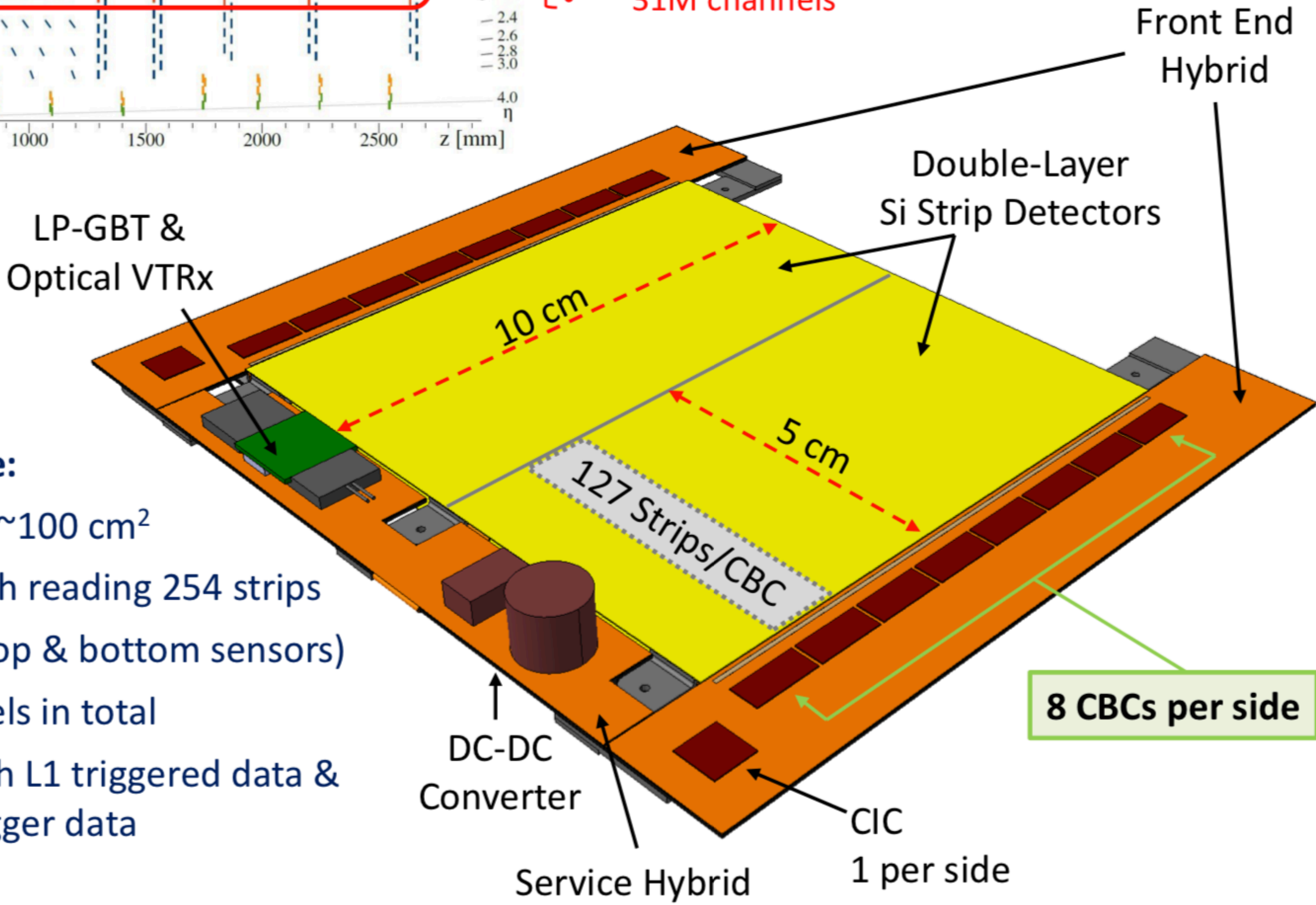


The electronics (CBC3 chips) and DAQ (Serenity boards) are also from the R&D of CMS

R/O by 16 CBC3 (8 per side) each reading 254 strips
Efficiency= 99.988 ± 0.008 (CERN-LHCC-2017-009)



- 2S Modules: Two-strip double-layers
- 7680 modules
- ~31M channels

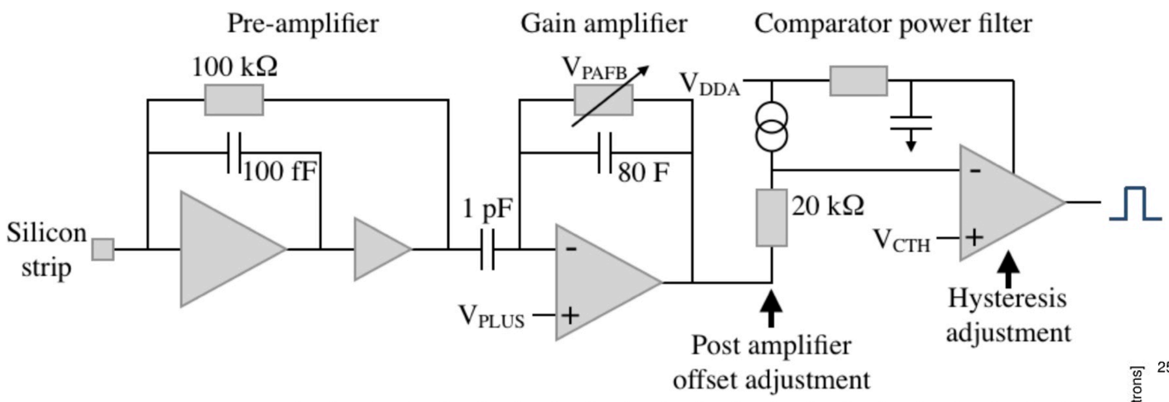


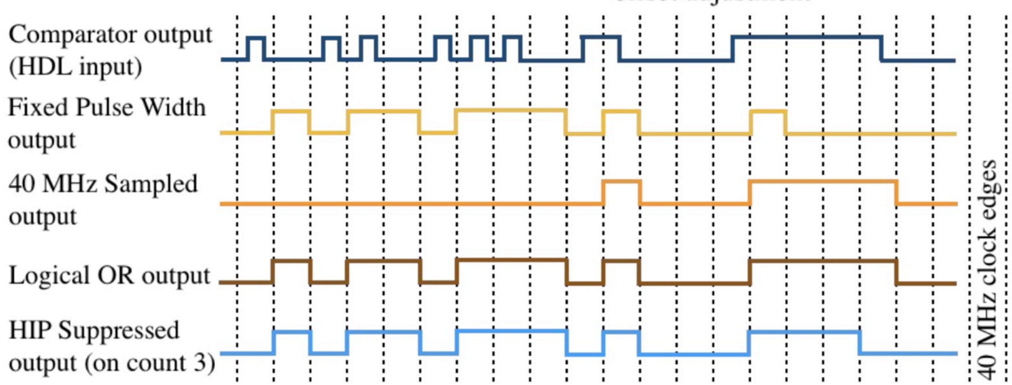
Each 2S Module:

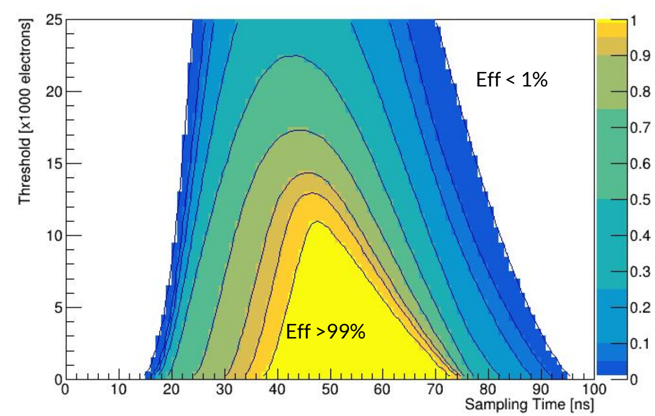
- Sensor Area ~100 cm^2
- 16 CBCs, each reading 254 strips (127 from top & bottom sensors)
- 4064 Channels in total
- Readout both L1 triggered data & Primitive trigger data

Signals generation

- Muons (average intensity ~50 MHz) have a random phase with respect to the reference clock at 40 MHz.
- CBC has several options for selecting the duration of the comparator output, which can be studied for optimized performance.

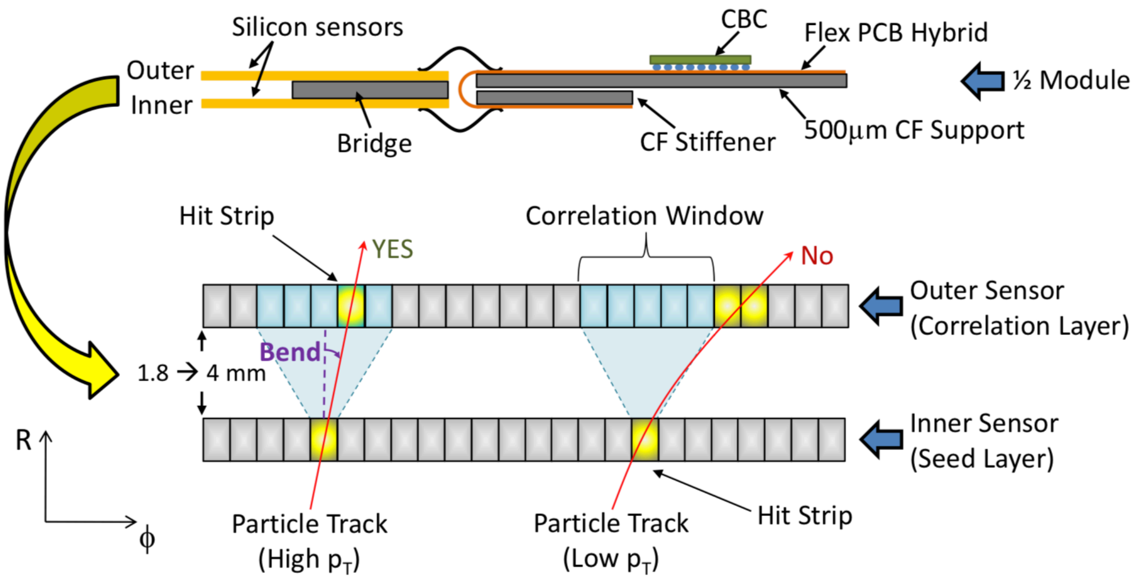


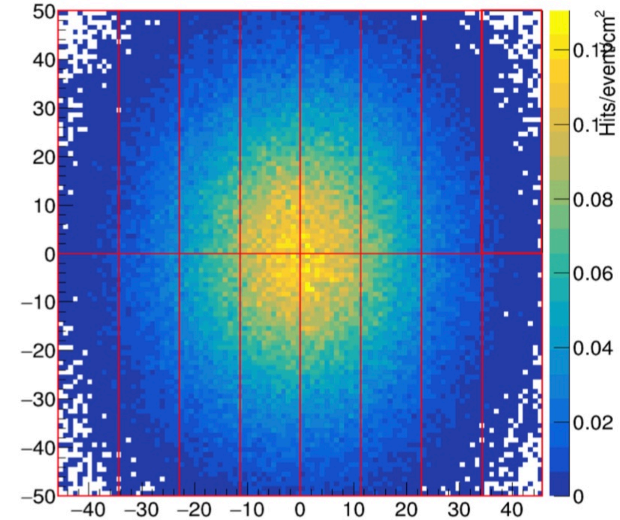




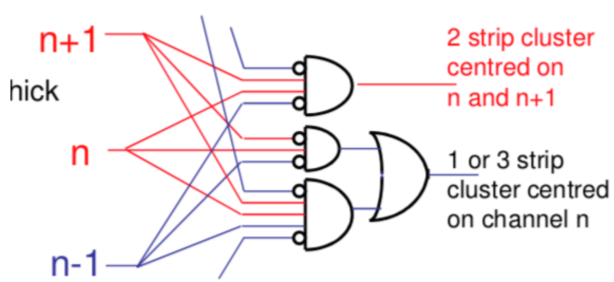
Simulated efficiency for the CBC to detect a minimum ionising particle signal as a function of comparator threshold and sampling time.

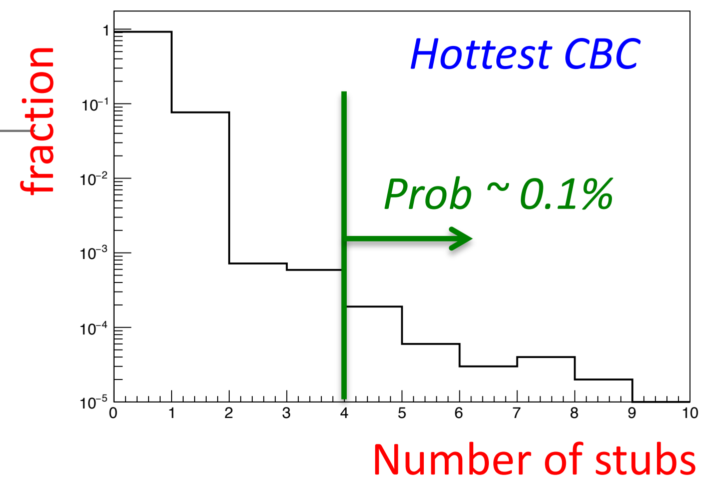
CBC3 stubs





- High-PT tracks (**Stubs**) can be identified if cluster centre in top layer lies within a correlation window in R-Φ (rows)
- p_T cut given by: module radius (z), sensor separation and correlation window





The calorimeter

- **Particle Identification based on ECAL is important when both the angles are in the region of 2.5 mrad and $\theta_\mu \sim \theta_e$**

- **Measuring the electron energy would enable:**
  - Triggering on the calo energy (in OR with the track trigger).
  - Performing background studies with data
  - Determining the electron (angle,energy) relation
  - Checking possible bias, systematic effects, related to the tracks selection.

Calorimeter type is still under study

(philosophy is to recycle existing and working technologies, if possible)

Present ideas are to have

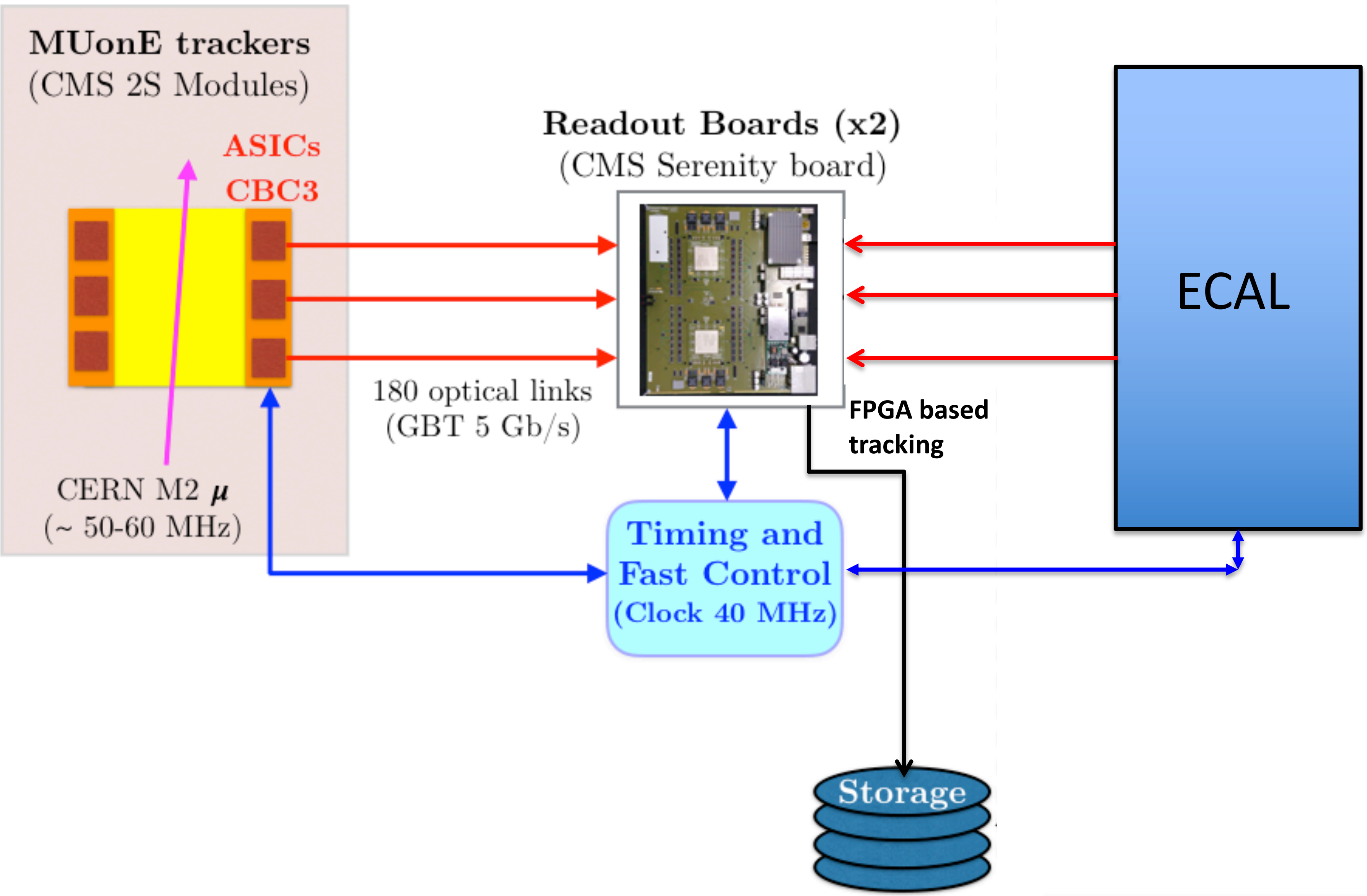
➡ an Inner ECAL of ~ 40 cm × 40 cm of $PbWO_4$ crystals

➡ an Outer ECAL extending up to ~ 100 cm × 100 cm *with same/other crystals*

with ex-OPAL lead glass (rather large size 9.5x9.5 cm) or

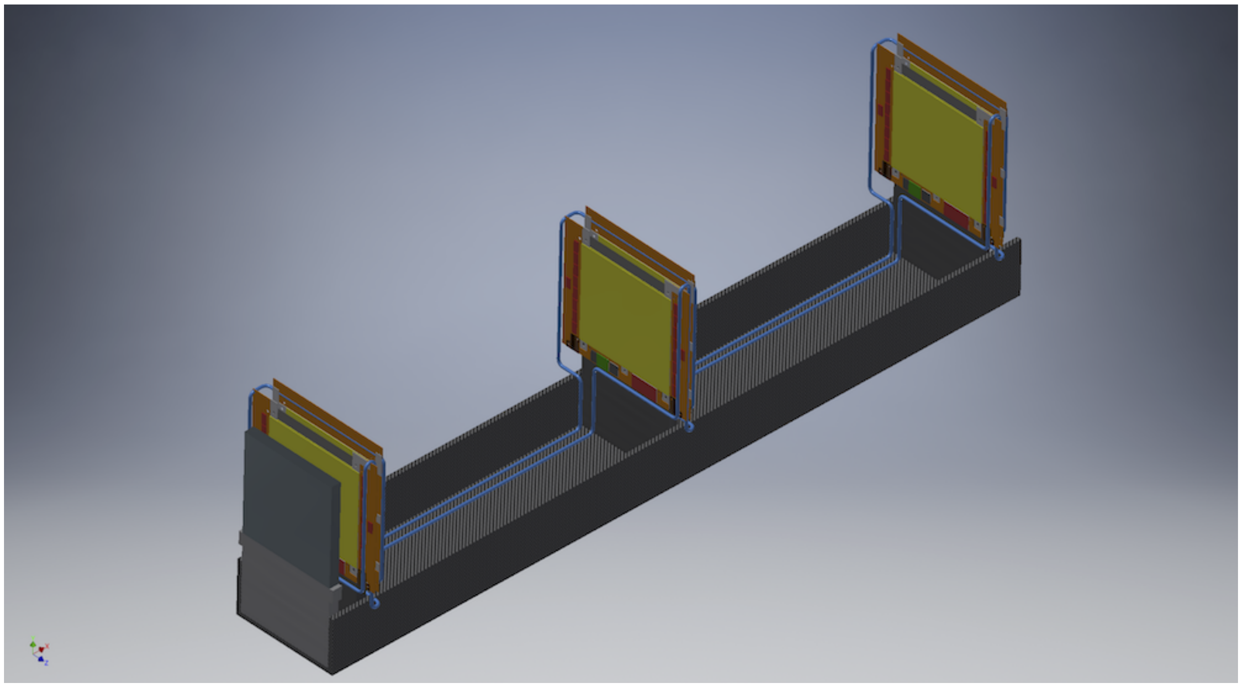
new $PbW0_4$ new crystals ***(GEANT4 simulation study under way)***

The DAQ and trigger system



Mechanics and cooling

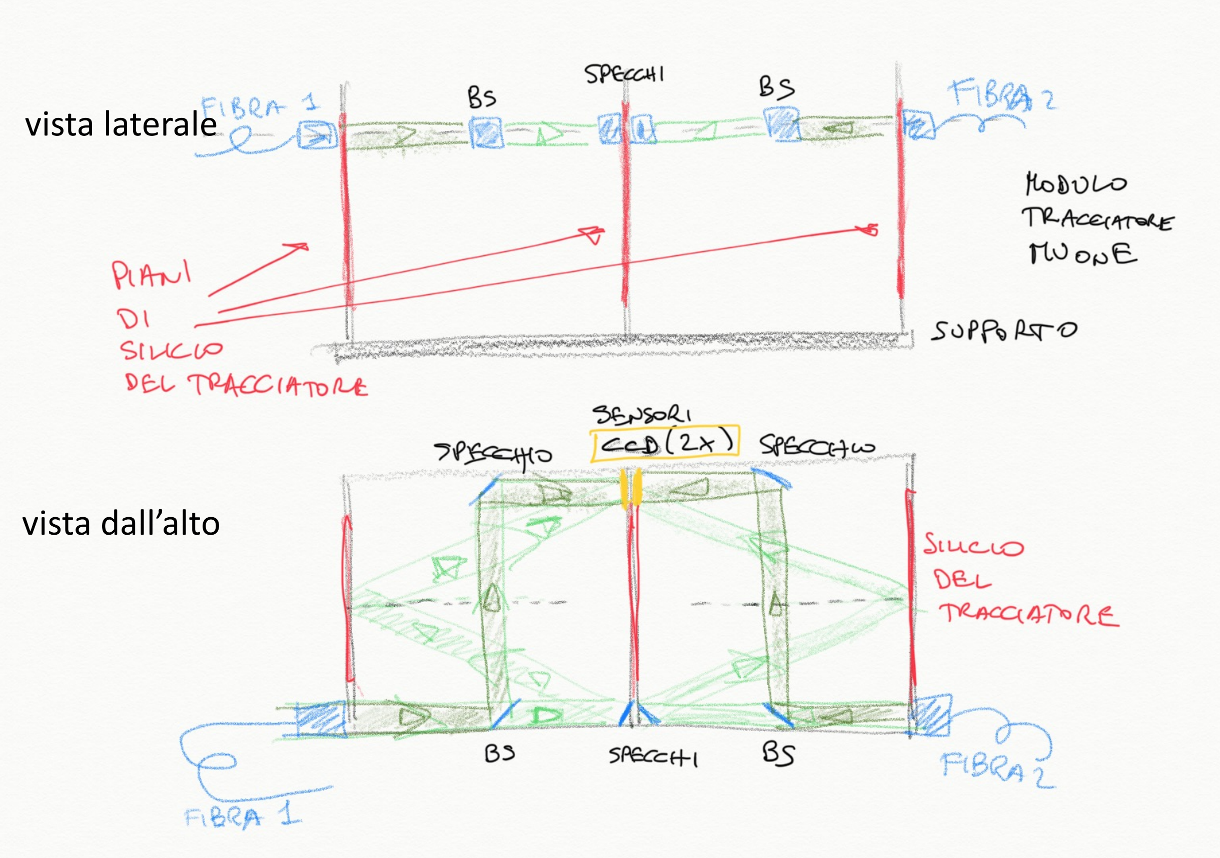
A station 1m long requires a CTE of the order of 10^{-6} K^{-1} to keep the z position stable within 10 μm for temperature variations of $\Delta T < 1^{\circ}$



- The tracker mechanics is based on a Carbon Fiber structure with inserts supporting the Beryllium target and the Silicon modules.

Monitoraggio olografico della distanza e della posizione relative tra i piani di tracciamento

- Materiale ottico di base per l'equipaggiamento di una "station" di prova
  - laser 532 nm (P~ mW)
  - 2x fibre ottiche multimodo
  - 2x beamsplitter (BS)
  - 4x specchi
  - 2x sensori CCD



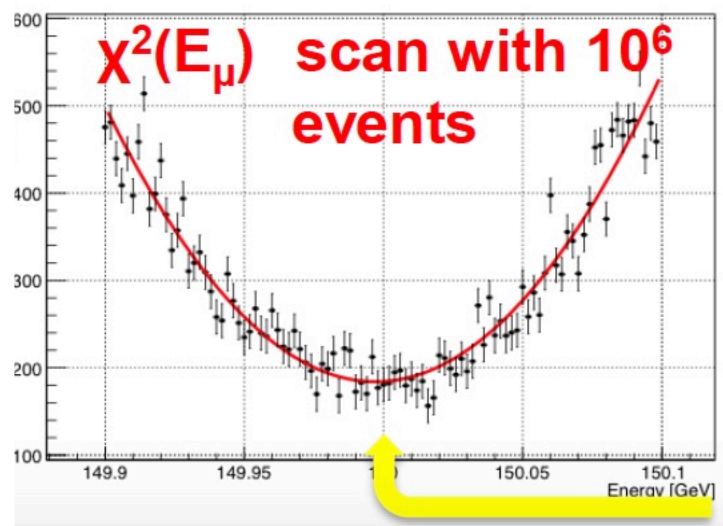
Requirements in sensors positioning

- Systematics due to the uncertainty δz on the longitudinal position: $\Delta\theta / \theta = \delta z / L$
- $\langle E_{beam} \rangle$ measurable by reverting the kinematics

μe equal-angle related to the beam energy

$$\theta_{eq} \simeq \sqrt{\frac{2m_e}{P_{beam}}}$$

- ~40 hours of data taking to get 10^6 useful elastic events
- $N \sim 10^6$ implies $\delta\langle\theta\rangle \sim 0.02$ mrad/sqrt(10^6) ~ 2×10^{-5}
- It sets the scale of the systematics: 10 μm/ 1m



Min. chi2: 150.000±0.002 GeV

$\Delta\alpha_{had}$ parameterization

Physics-inspired from the calculable contribution of lepton-pairs and top quarks at t<0

$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

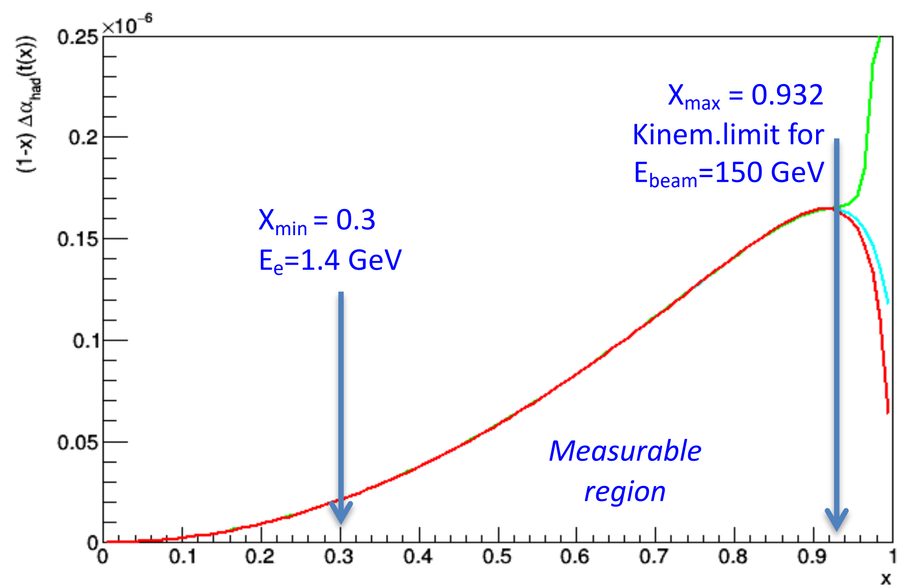
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

Low-|t| behavior dominant in the MUonE kinematical range:

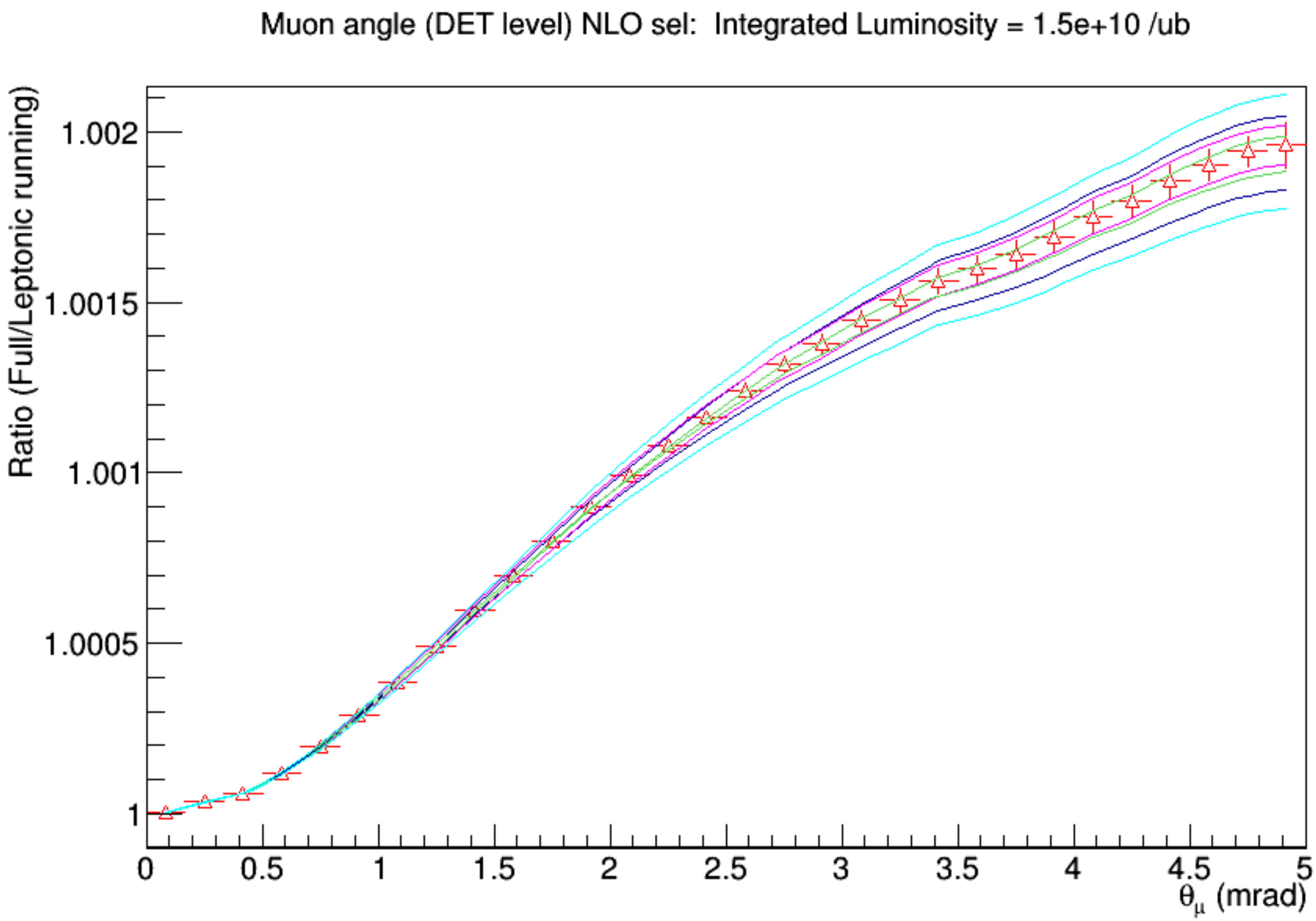
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}\frac{k}{M}t$$

a_μ^{HLO} calculable from the master integral in the FULL phase space with this parameterization.

Instead simple polinomials diverge for x->1 (green is a cubic polinomial in t)

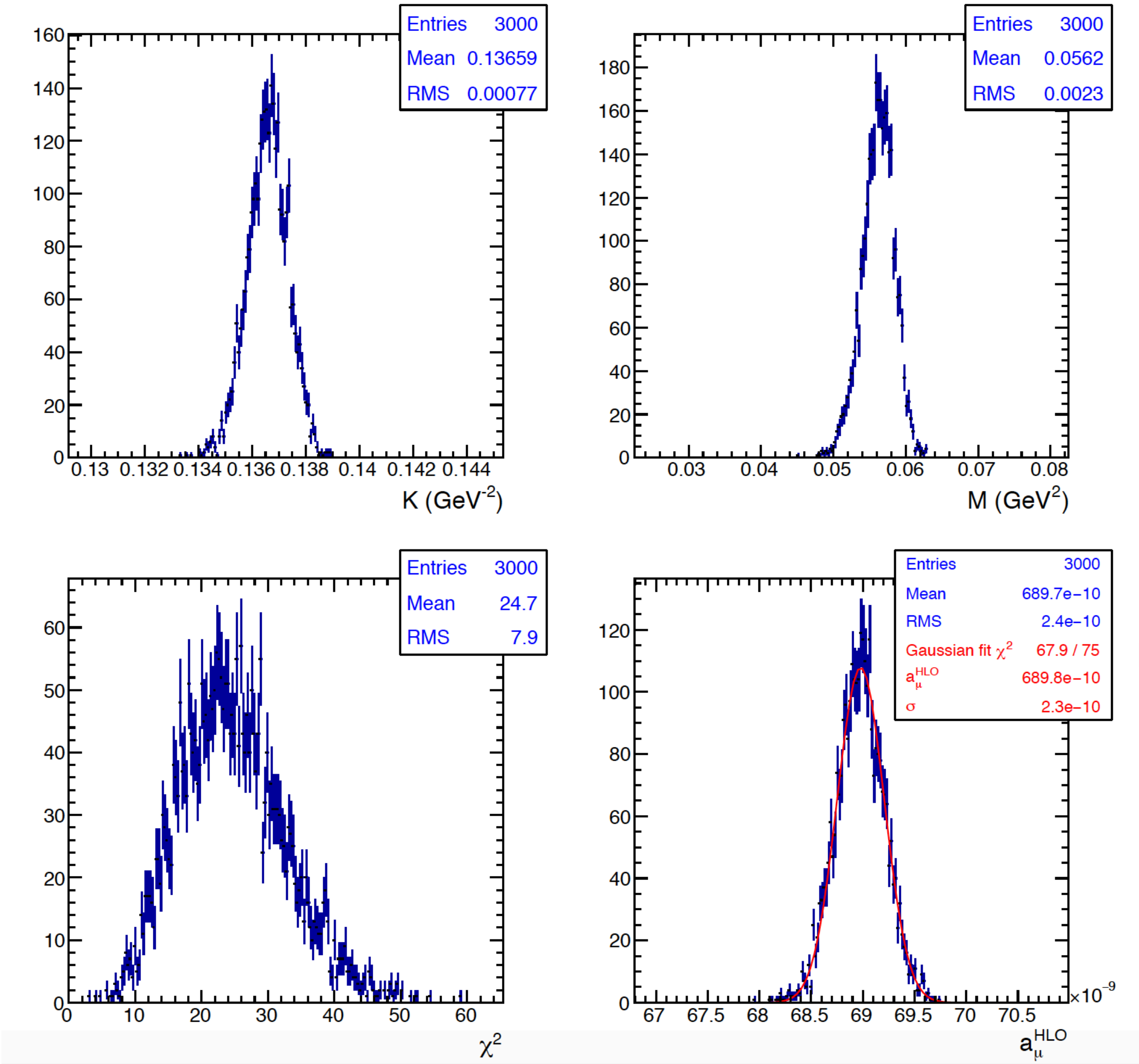


Template fit



Statistical Significance: toy experiments

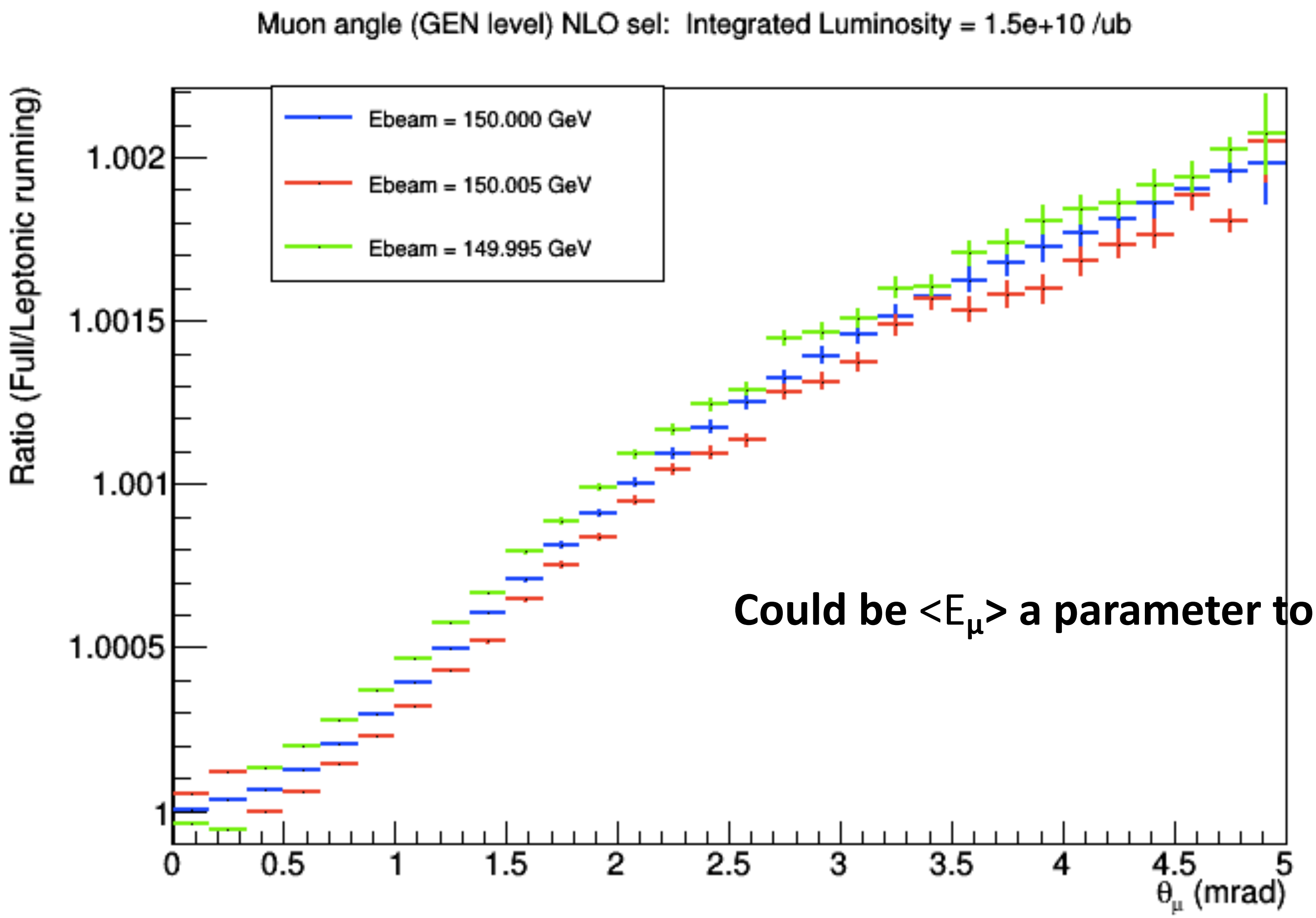
Template fit of muon angle (NLO inclusive, with detector resolution and beam E spread)



$$a_\mu^{HLO} = (689.8 \pm 2.3) \times 10^{-10}$$

0.3% (stat. only)

Effects of the energy scale $<E_\mu>$



Could be $<E_\mu>$ a parameter to fit?

The theory: status

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

M. Alacevich, *et al* **arXiv:1811.06743**.

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

P. Mastrolia, *et al*, **JHEP 1711 (2017) 198**;
S. Di Vita, *et al.* **JHEP 1809 (2018) 016**;
M. Fael, **arXiv:1808.08233**;
M. Fael , M. Passera **arXiv:1901.03106;**

resummation (effects beyond fixed-order perturbation theory) and mass effects including the electron mass (PSI group)→

differential cross section (A. Signer, Y. Ulrich)

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy) → **International efforts under way, a report is in preparation**