Status of the MUonE experiment

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DISCRETE 2022

Anomalous magnetic moment of the muon

$$\vec{M_l} = g_l \frac{e}{2m_l}\vec{S}$$ → Dirac prediction $g_l = 2$ → Quantum corrections give the **anomaly**: $a_l = \frac{g_l - 2}{2}$

Why those **discrepancies**? Hint of **new physics?**

Most precise LQCD result
T. Borsanyi et al., (2021) arXiv:2002.12347v3

VS

Experimental average **FERMILAB-BNL**
B. Abi et al., (2021) arXiv:2104.03281v1

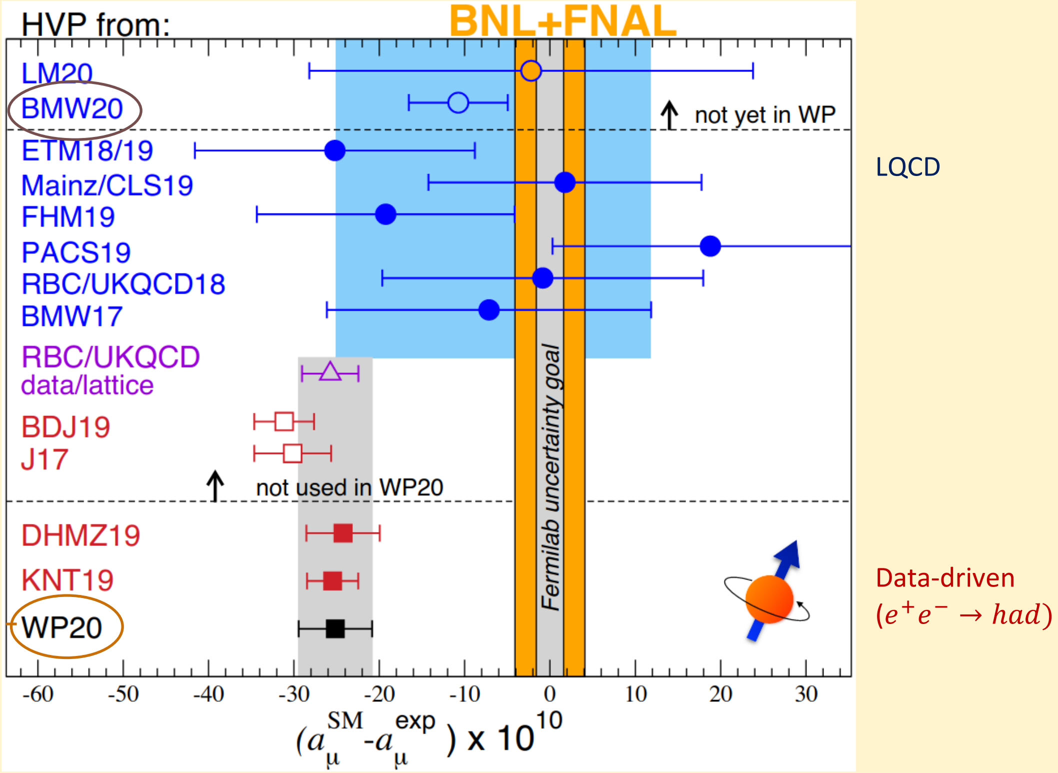
$\Delta a_\mu(th - exp)$
$\mathbf{1.5\,\sigma}$

Theoretical **reference value** (WP)
T. Aoyama et al., (2020) arXiv:2006.04822

VS

Experimental average **FERMILAB-BNL**
B. Abi et al., (2021) arXiv:2104.03281v1

$\Delta a_\mu(th - exp)$
$\mathbf{4.2\,\sigma}$



TI Snowmass paper 2022 arXiv:2203.15810

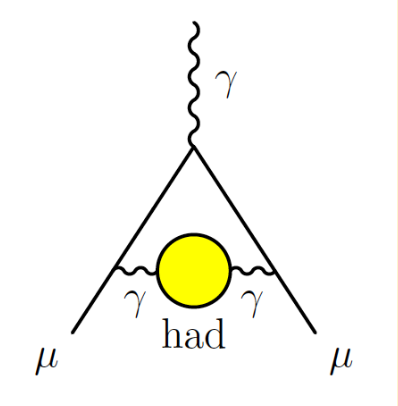
1. Reduce the **experimental** error → Fermilab g-2 goal (0.54 ppm (BNL) → 0.46 ppm $\xrightarrow{goal}$ 0.14 ppm)
2. Improve **theoretical** precision → Dominant contribution: LO hadronic vacuum polarization term < $a_\mu^{HLO} \to \mathbf{0.6\%}$

Anomalous magnetic moment of the muon

$$a_\mu^{SM} = \underbrace{a_\mu^{QED} + a_\mu^{EWK}}_{} + a_\mu^{had}$$

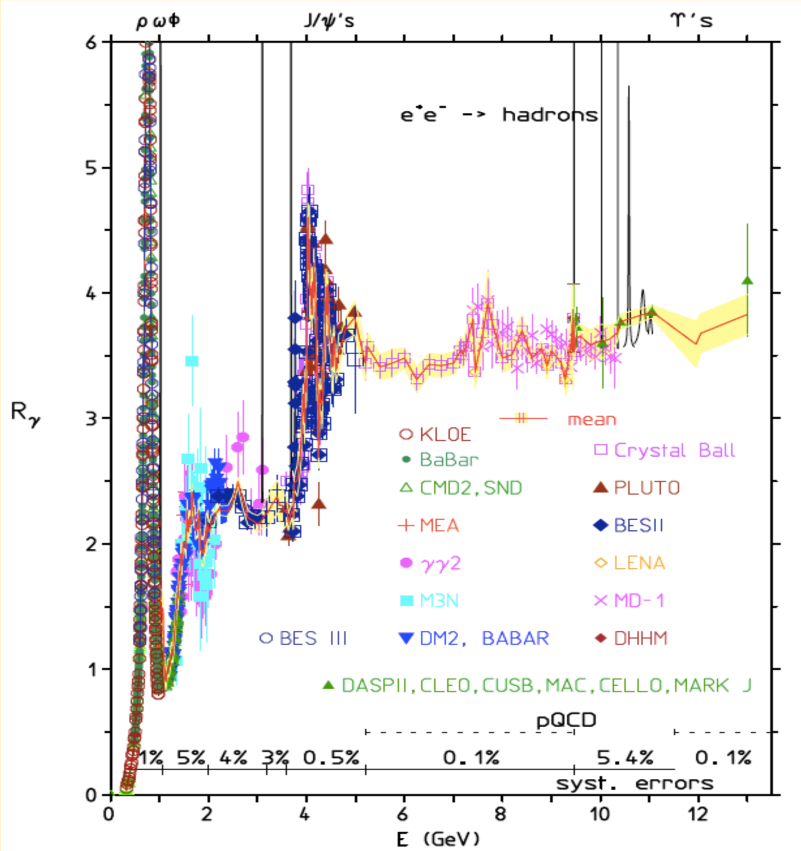
Precise estimates from perturbation theory

$\rightarrow$ a_μ^{HLO} + *higher order terms*



Hadronic contribution to the LO vacuum polarization term a_μ^{HLO} is not calculable through pQCD

Dominates theoretical uncertainty $\rightarrow \mathbf{0.6\%}$



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

Reference approach (WP before BMW) is **data-driven**:

$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2} \longrightarrow R_{had}(s) \propto \sigma(e^- e^+ \rightarrow had)$$

measurements

Alternative methods are needed

Main contribution: region of *low energies*, highly *fluctuating* because of **hadronic resonances** and **threshold effects**

The new estimate of a_μ^{HLO} from LQCD (BMW) ***weakens*** $\Delta a_\mu(th - exp)$ discrepancy, but introduces some ***tensions*** with the data-driven method.

MUonE proposal

Independent estimate of a_μ^{HLO} through innovative method:
C.M. Carloni Calame, et al. Phys.Lett.B746(2015)325

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

Space-like

Smooth function →

Proposed process to measure $\Delta\alpha_{had}$: **elastic *scattering***
G.Abbiendi et al., Eur.Phys.J.C77(2017)139

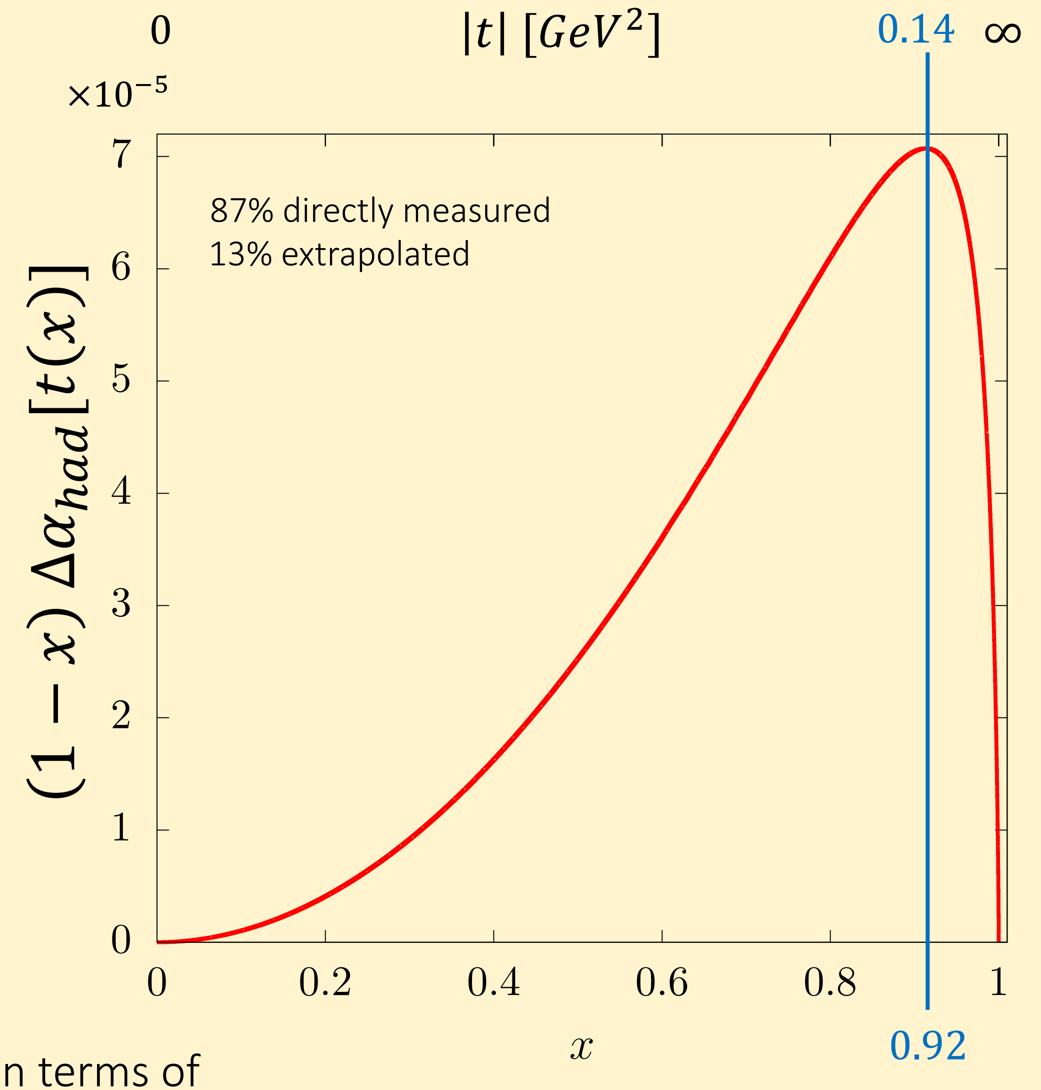
$$\mu\,(160GeV) + e^-(rest) \rightarrow \mu\ + e^-$$

M2 muon beam at CERN SPS

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2 \xrightarrow{\text{Template fit}} \Delta\alpha_{had}(t) \xrightarrow{\text{Master integral}} a_\mu^{HLO}$$

$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

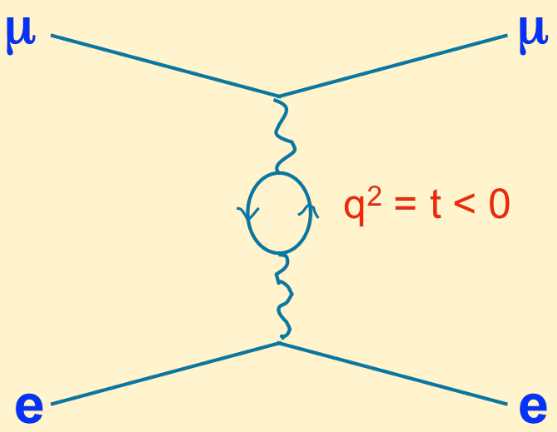
THEORETICAL MODEL



Required precision on $a_\mu^{HLO} < 1\%$ implies a relative precision of $\sim\mathbf{10^{-5}}$ on the <u>shape of</u> **<u>the elastic differential cross section</u>**

Great challenge in terms of required **precision!**

$\mu - e$ elastic scattering



$$\frac{d\sigma_{el}}{dt} \longleftrightarrow \frac{d\sigma_{el}}{d\theta_l}$$

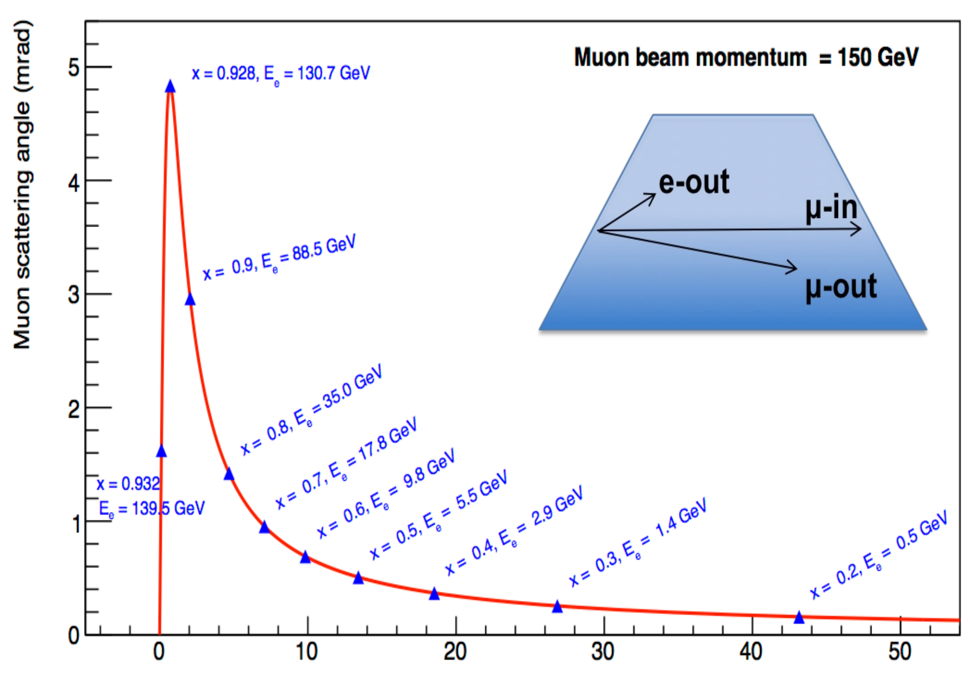
Simple kinematic relations ($t \leftrightarrow \theta_l$)

Measuring the **leptons scattering angles**

Precise correlation

$0 < \theta_\mu < 5\, mrad$
$0 < \theta_e \lesssim 50\, mrad$

ELASTIC CURVE

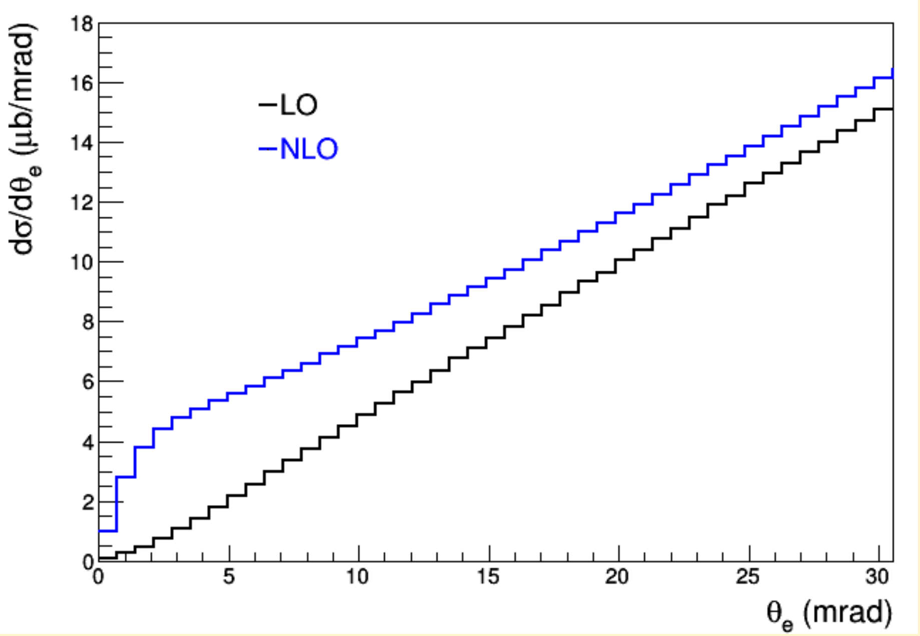


Abbiendi et al, [Eur. Phys. J. C 77.3 (2017), 139]

Helps in the selection of **purely elastic events**

Radiative events with real photons are expected

DIFFERENTIAL CROSS SECTION



Analysis: $\Delta\alpha_{had}$ parametrization and a_μ^{HLO} estimate

G. Abbiendi,
Phys. Scr. 97 (2022) 054007;
[arXiv: 2201.13177]

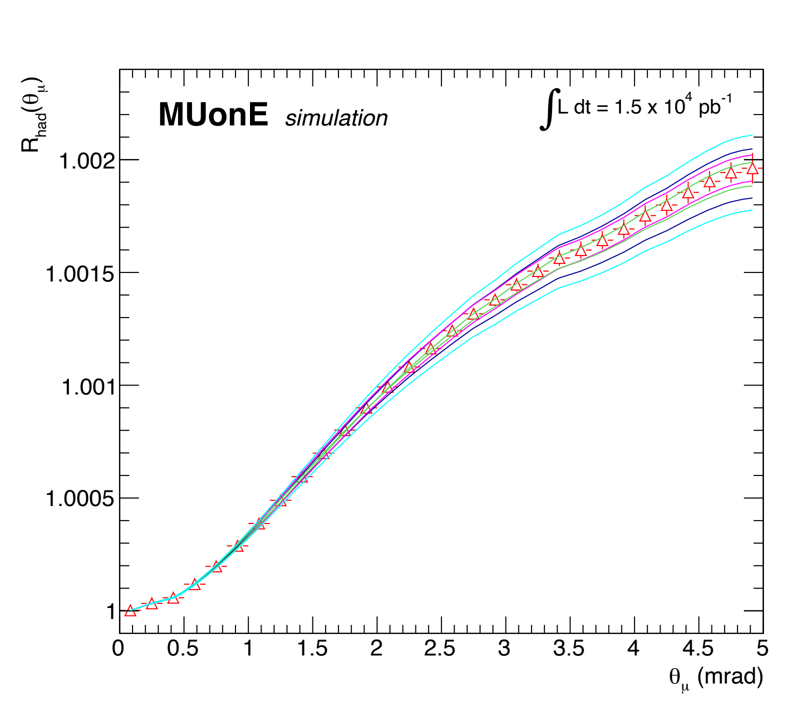
Inspired to the 1 loop QED calculation of the leptonic and $t\bar{t}$ pair vacuum polarization term

Parametrization with **two** variables K e M:

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

1. *Template fit*: generation of a grid of points in the parameters space (K, M);
2. R_{had} distribution as a function of the leptons scattering angle **for different templates**;
3. χ^2 of the data/pseudo-data and templates.

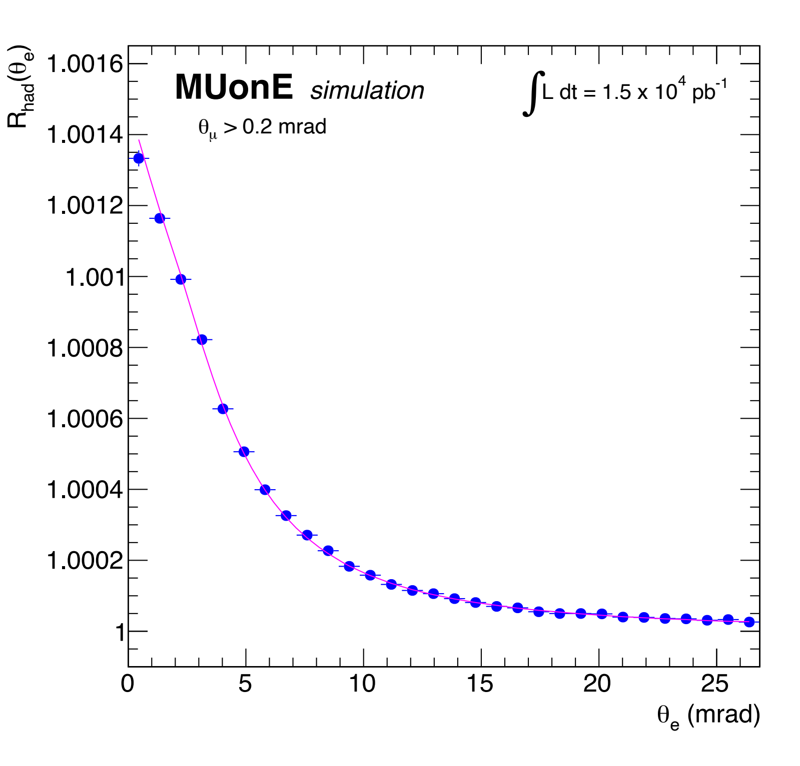
$$R_{had} = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had}=0)}$$

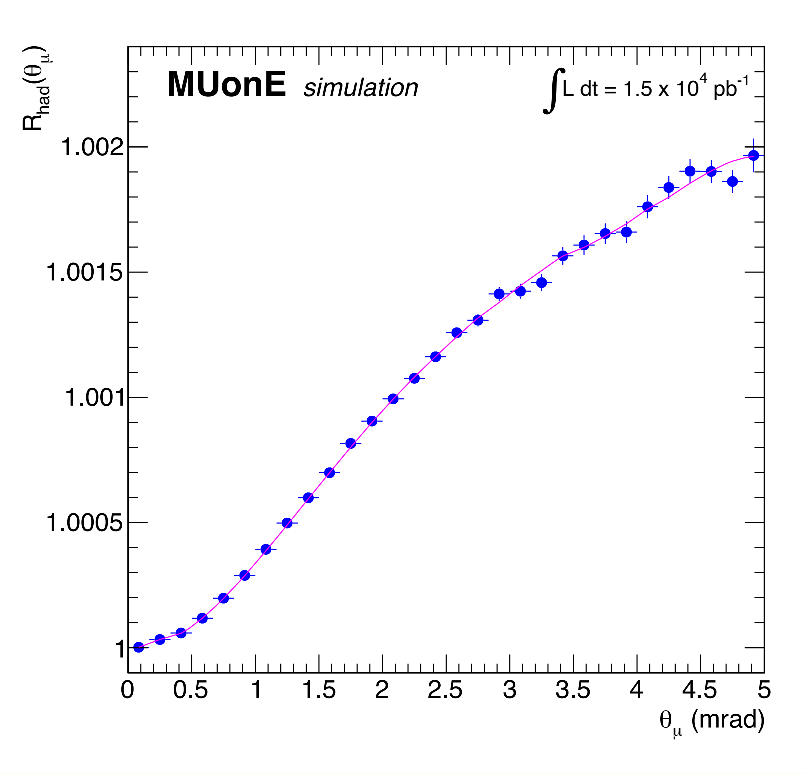


Analysis: $\Delta\alpha_{had}$ parametrization and a_μ^{HLO} estimation

G. Abbiendi, Phys. Scr. 97 (2022) 054007; [arXiv: 2201.13177]

Example of a pseudo-experiment:





Simulation result:

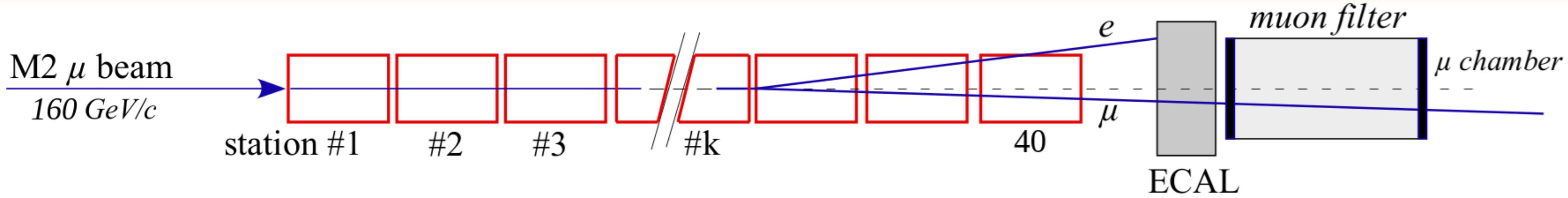
$$a_\mu^{HLO} = (688.8 \pm 2.4)\times 10^{-10}$$

Input value for generation:

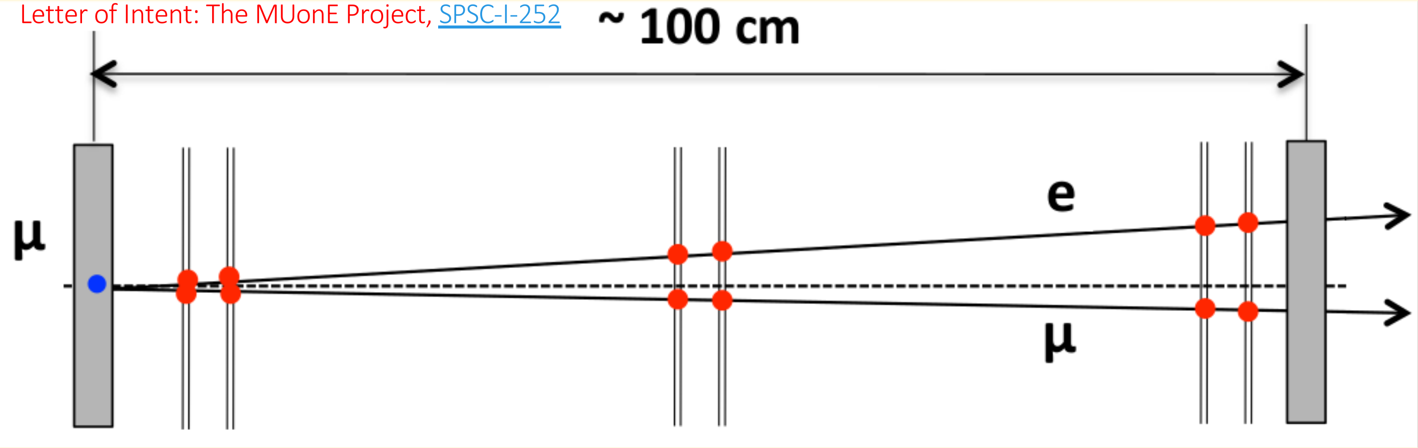
$$a_\mu^{HLO} = 688.6\times 10^{-10}$$

Experimental apparatus

40 tracking stations + Electromagnetic calorimeter + Muon chambers



Each <u>tracking station</u> behaves as an independent *detector*
- **3 pairs** of silicon strip modules (CMS 2S modules)
- **1** beryllium or carbon target ($1.5\ cm$)



Modular layout to achieve the <u>necessary interaction rate</u> *minimizing* systematic effects (e.g. **MCS**)

Angular resolution needed $\sim 10^{-2}\ mrad$

Achievable precision

To be **competitive** with previous theoretical estimates:

precision on $a_\mu^{HLO} < 1\%$

40 stations
(tot: $\mathbf{60\ cm}$ Beryllium)

+

3 years of data taking with an *integrated luminosity* of $\mathbf{1.5 \times 10^7\ nb^{-1}}$

=

Error statistical on $\boldsymbol{a_\mu^{HLO} < 0.5\%}$

⇓

The challenge is to keep **precision** on *systematic effects* at the **same level**

Main systematic effects:

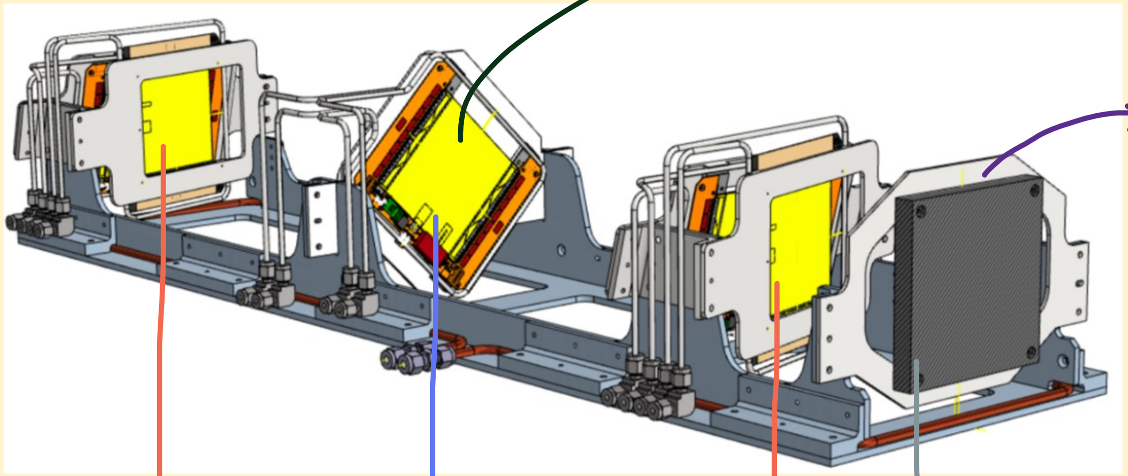
1. Multiple **scattering**;
2. **Beam energy** knowledge (few MeV);
3. **Longitudinal** alignment;
4. Intrinsic **angular** resolution.

The experimental apparatus: **tracker and calorimeter**

Thickness: $2 \times 320\ \mu m$
Pitch: $90\ \mu m$ ($\sigma_x \sim 26\ \mu m$)
Readout rate: $40\ MHz$
Active area: $10 \times 10\ cm^2$

1 CMS 2S module = 2 coupled **silicon strip** sensors (for the *CMS-Phase2 upgrade*) reading the same coordinate

6 modules pairs:



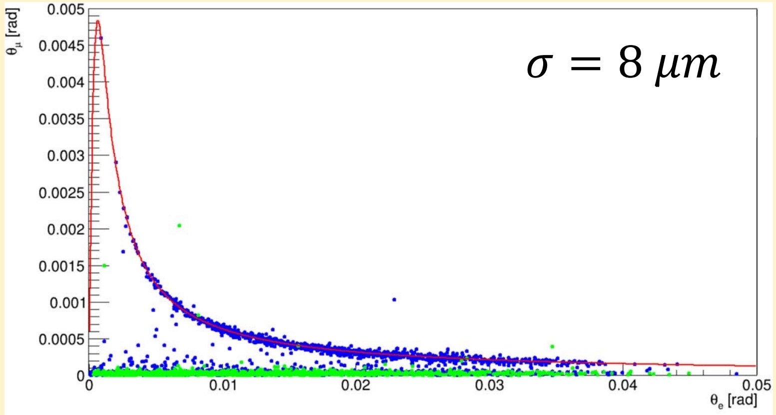
- (x, y) **tilted** with respect **z** direction of $233\ mrad$ as resolution on single hit is **improved** ($\sim 10\ \mu m$) in simulations;
- (u, v) needed to solve tracks **ambiguities**.

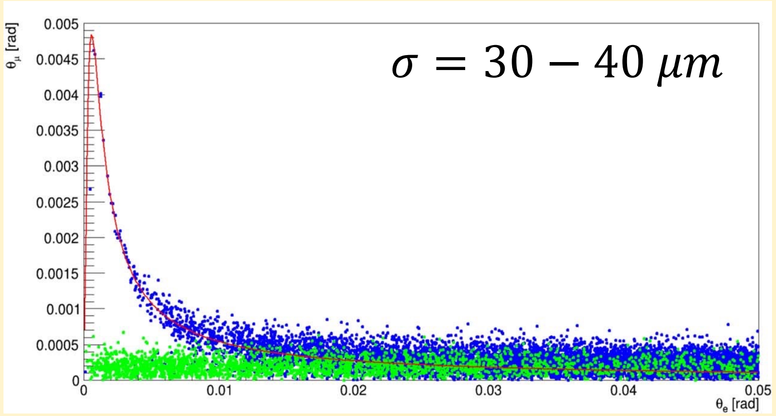
Actually in a reduced format for the future **Test Run** approved by the SPSC aimed at the validation of the the experimental proposal

- 25 cells in $PbWO_4$ ($22\ \chi_0$)
- Surface $\sim 14 \times 14\ cm^2$
- Readout: APDs
- **Laser pulse system** (at $\mathbf{450\ nm}$) for APD calibration

The importance of having a good single hit resolution

Angular distribution of two tracks event





☆ Elastic curve

☆ Simulated events (GEANT4): μe elastic events

e^+e^- pair production

The better is the **resolution**, *the better* is the capability of selecting elastic events

Fundamental request: stability of geometry

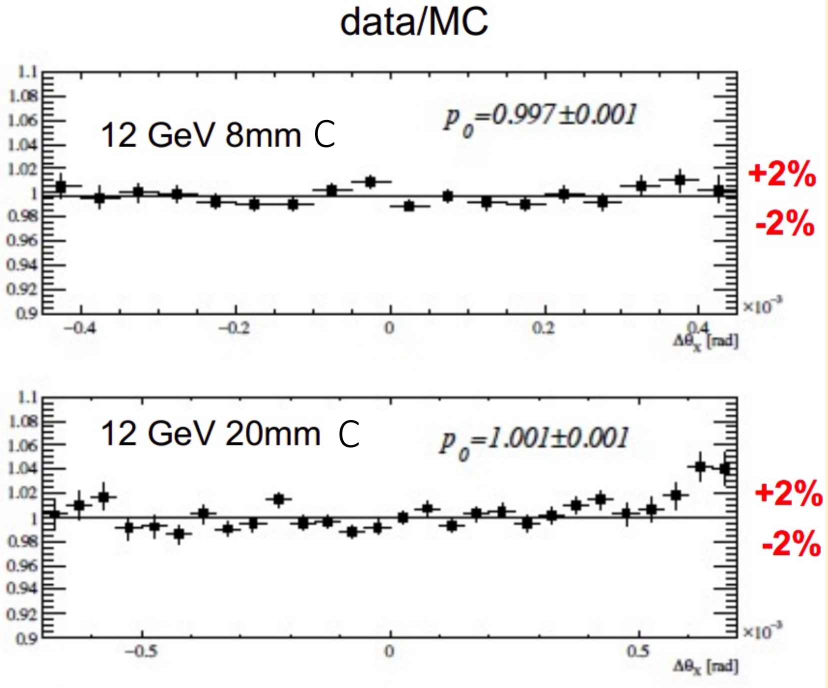
- Tilted modules ($\sigma \sim 8\ \mu m$)
- INVAR structure with low thermal expansion coefficient
- Cooling system ($1 - 2^\circ C$)
- Holographic system to monitor stability

Test Beam 2017 - 2018

Test Beam 2017

Multiple scattering analysis

MUonE collaboration, arXiv:1905.11677

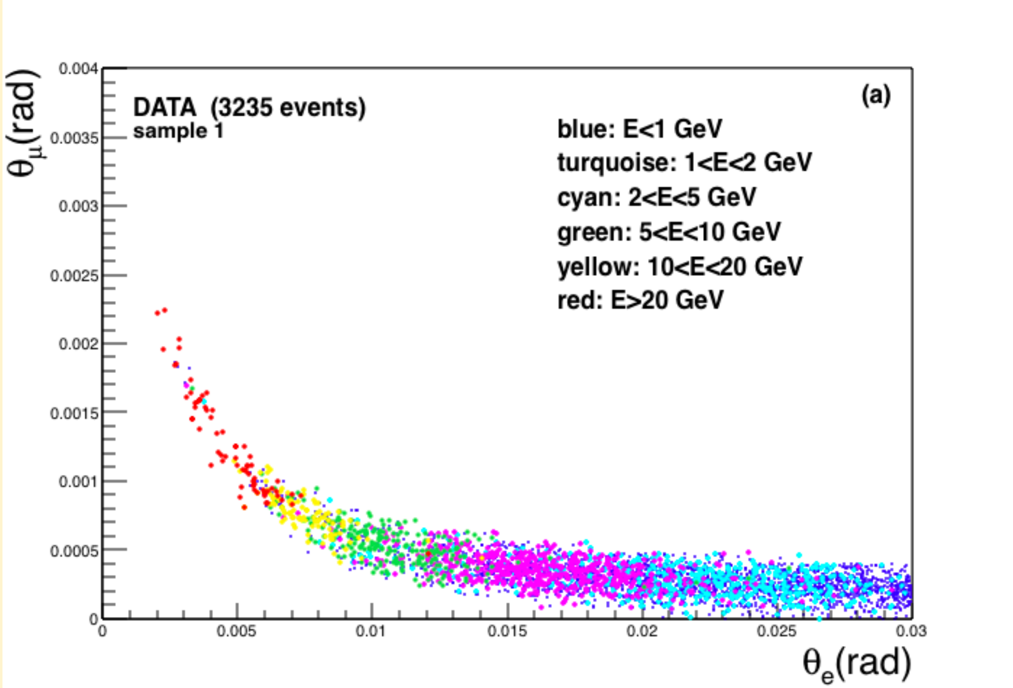


- *H8 line* at CERN with **UA9 apparatus**
- Data VS MC: *agreement* within 1% in the central region **MCS distribution** (90% of the events)
- **GEANT4 simulations** satisfy **MUonE needs in the** central region of the MCS distribution

Test Beam 2018

$\mu - e$ elastic scattering

MUonE collaboration, arXiv: 2102.11111



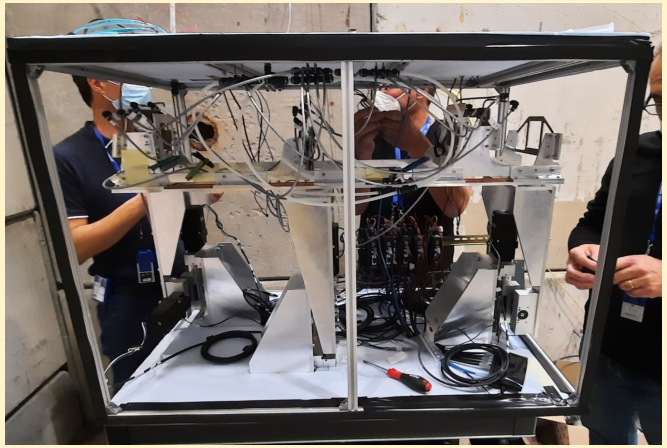
- *M2 line* at CERN behind **COMPASS**
- **Worst resolution and conditions** with respect to the expected final ones
- **A first test of the capability of** selecting elastic events

Tracker test beam October-November 2021

Parasitic test beam **M2** muon beam at CERN, 3 weeks in October/November 2021 in *collaboration* with CMS tracker team

- Test **4 2S CMS modules** and **Serenity board** for the DAQ
- Muons at $160\ GeV$ with ***asynchronous*** rate of $\sim 16\ kH$
- Electronics rate $\sim 40\ MHz$

MUonE station

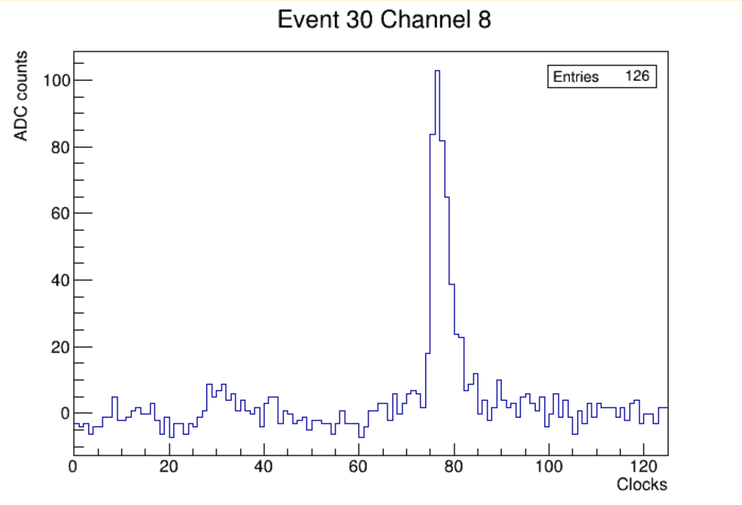


Achieved goal: demonstrate *that the entire DAQ chain works properly* with *asynchronous* muon beam

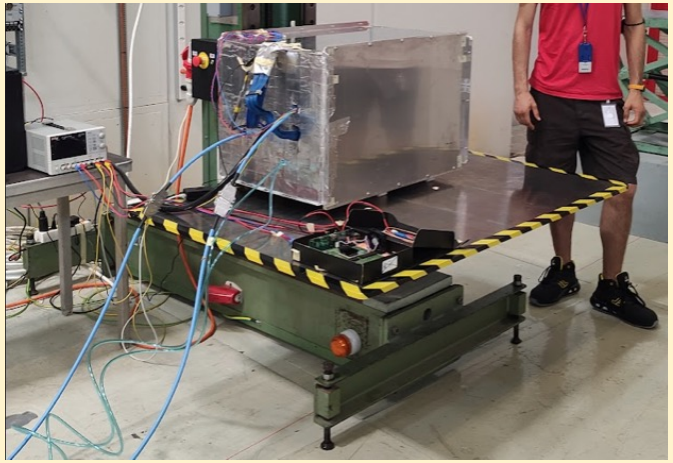
Calorimeter test beam July 2022

Test Beam with **T9** electron beam at CERN, 1 week July 20-27 2022

Image: example of a signal in a calorimeter cell during a spill



- Calorimeter with 25 cells $PbWO_4$ in a box
- $1 - 10\ GeV$ *electrons*
- **APD readout**
- *Water chiller* as a **cooling system**
- *Laser system* to control APD **stability**

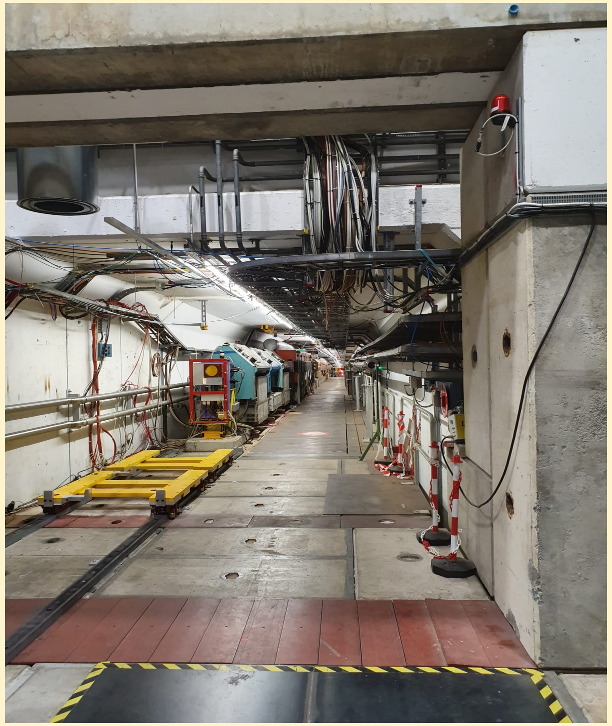


Successful test as we've detected, amplified, red and wrote data, but several points to be improved

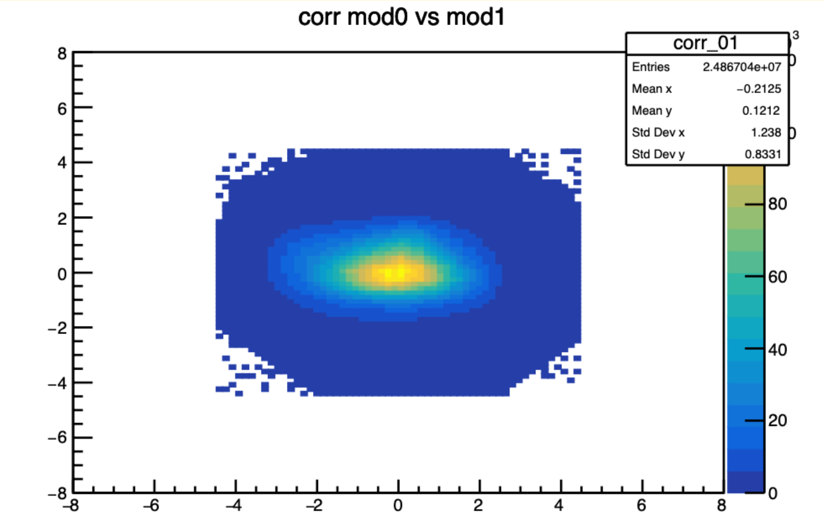
Test Beam 2022

Until the end of October tracker was under test (in collaboration with CMS):

1. June-October *2022*;
2. Placed *before* COMPASS on M2 beam
3. Taking data **with beam** when COMPASS (main user) doesn't use it or **displaced from beam line** when it is used (so taking data with halo beam). Displacement through a cart
4. Stations with **4 modules**



One week as **main user this October**, test beam calorimeter+tracker:



- **Simultaneous** data taking with both detector *synchronized*
- **One complete station** with **6 modules**
- First time with ***high*** intensity muon beam.

Muon beam spot during the test beam

$g - 2$ and behind

K. Asai et al.,
Phisical review D 106, L051702 (2022)
arXiv:2109.10093

Also small region for Z' in
$m_{Z'} < 200\ GeV$

MUonE potential is not over:
Sensitivity to regions of the parameter space for

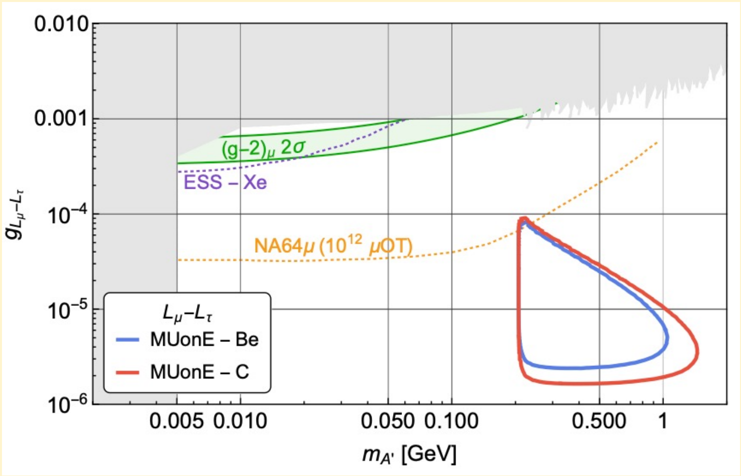
G. Grilli di Cortona, E. Nardi;
Phisical review D 105, L111701 (2022)
arXiv:2204.04227
I. Galon et al.,
arXiv:2202.08843

$L_\mu - L_\tau$ gauge bosons

$\mu e \to \mu e A' \to \mu e \nu\nu / \ell^+\ell^-$

$200 < m_{A'} < 10^3 MeV$

- If $\nu\nu$: Remove SM processes through precise selection criteria which *exclude* elastic regions
- If $\ell^+\ell^-$: displaced vertex in a certain fiducial volume

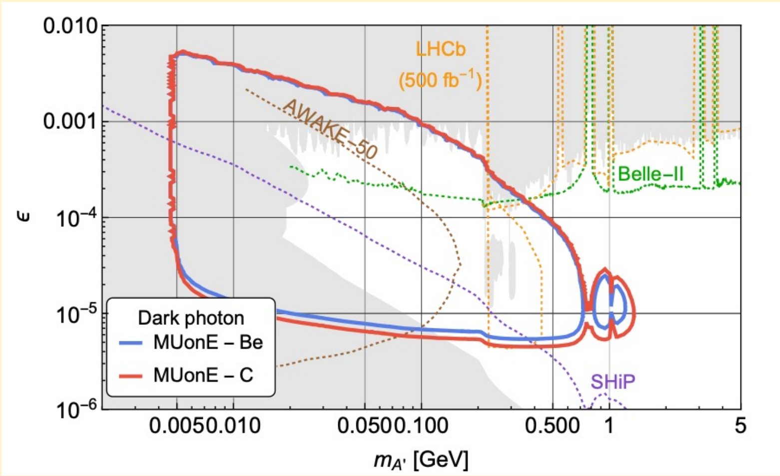


Dark photons

$\mu N \to \mu N A' \to \mu N \ell^+\ell^-$

$5 < m_{A'} < 10^3\ MeV$

Selecting events requiring a displaced vertex in a certain fiducial volume

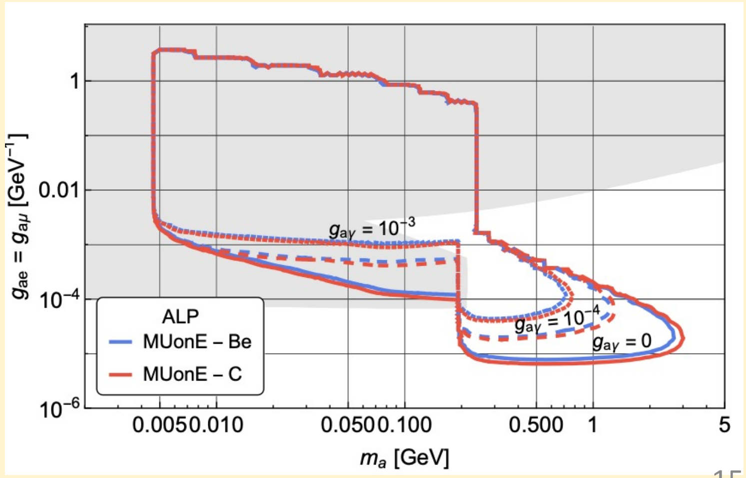


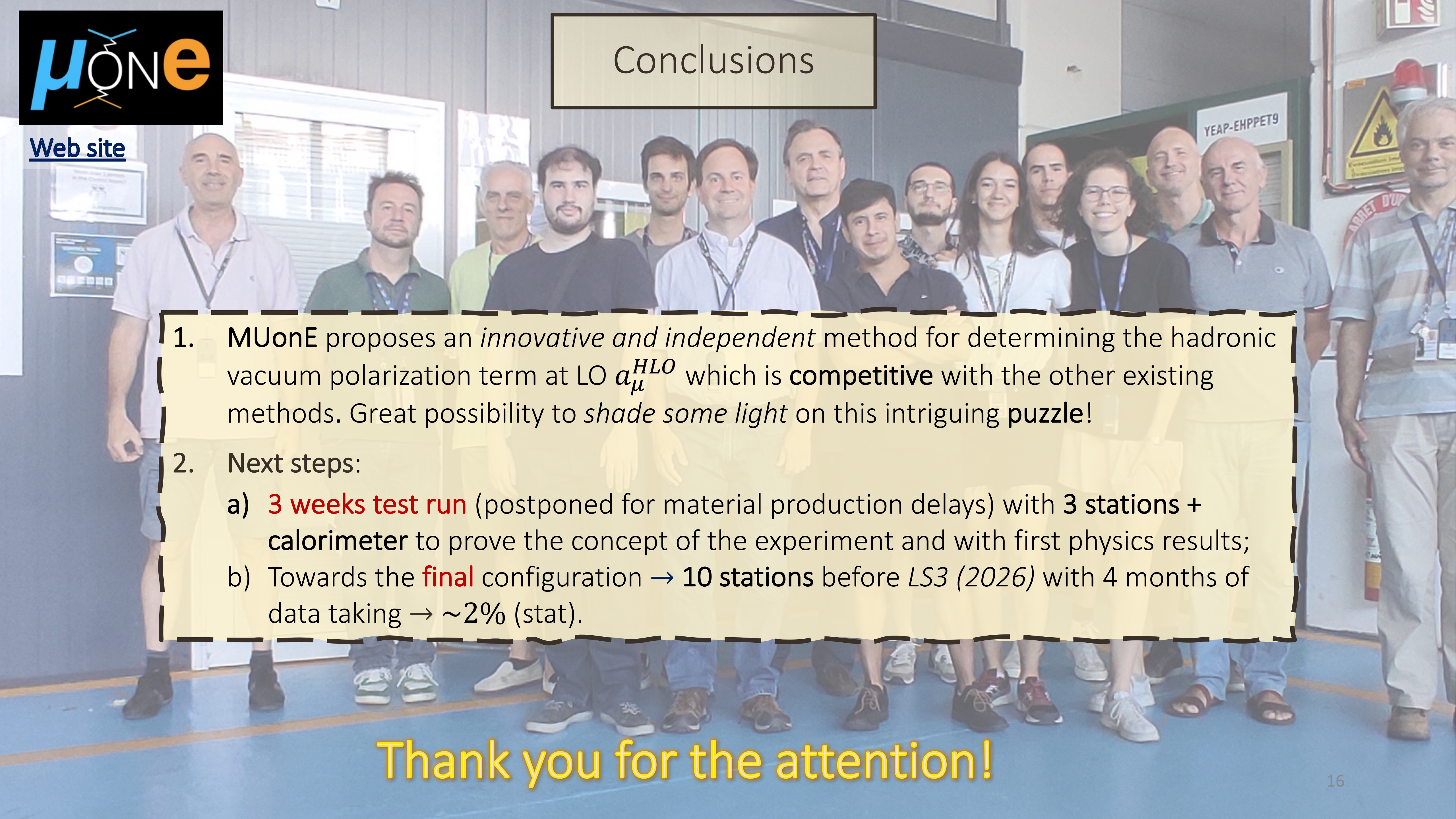
Axion like particles (ALP)

$\mu N \to \mu N a \to \mu N \ell^+\ell^-$

$5 < m_{Z'} < 3\times10^3\ MeV$

Selecting events requiring a displaced vertex in a certain fiducial volume





Web site

Conclusions

1. **MUonE** proposes an *innovative and independent* method for determining the hadronic vacuum polarization term at LO a_μ^{HLO} which is **competitive** with the other existing methods. Great possibility to *shade some light* on this intriguing **puzzle**!
2. Next steps:
   a) 3 weeks test run (postponed for material production delays) with **3 stations + calorimeter** to prove the concept of the experiment and with first physics results;
   b) Towards the final configuration → **10 stations** before *LS3 (2026)* with 4 months of data taking → $\sim 2\%$ (stat).

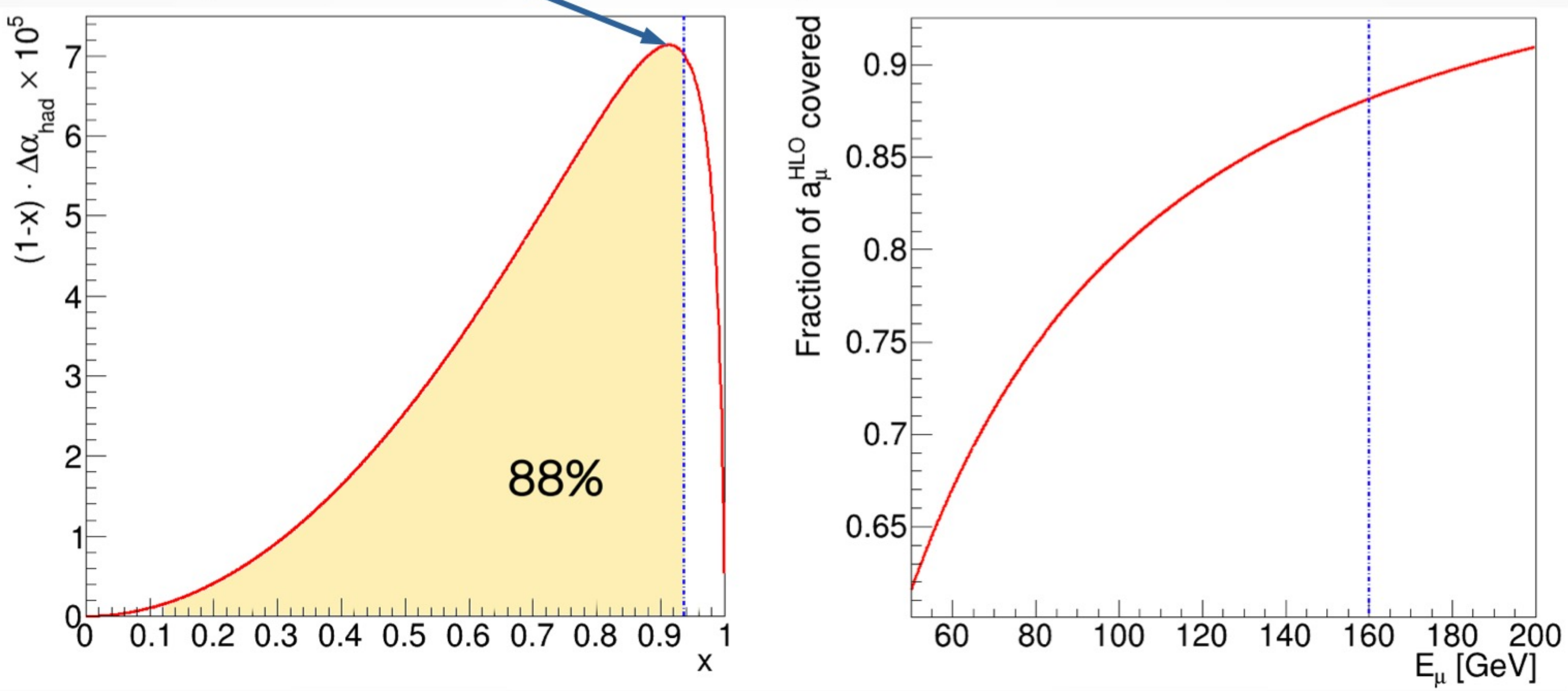
Thank you for the attention!

BACKUP

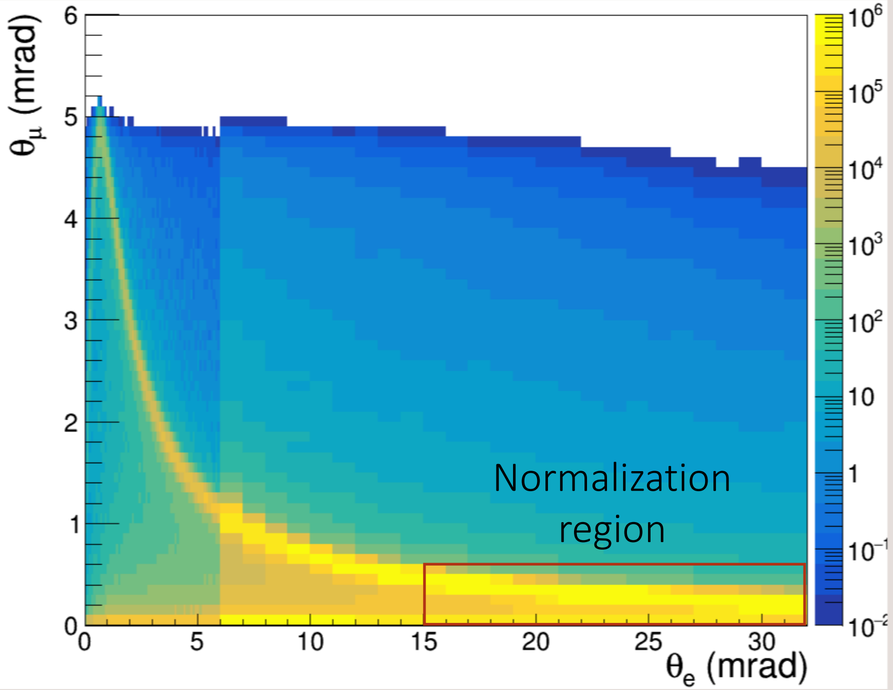
Limite misura

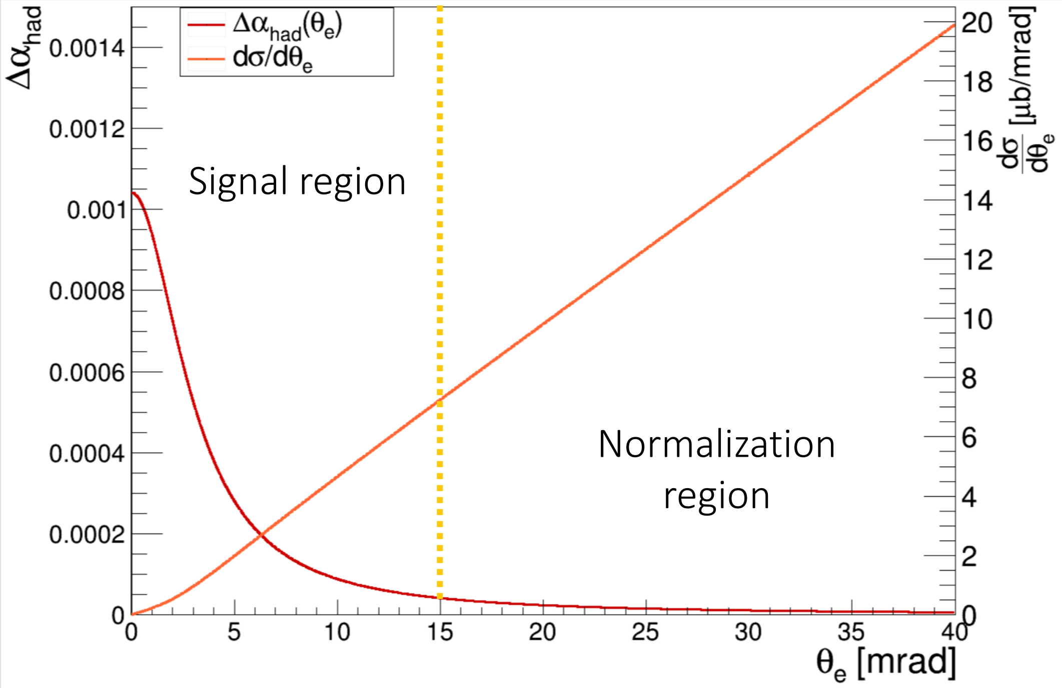
$x < 0.936$

$t_{peak} \sim -0.108\ \mathrm{GeV}^2$ $\quad$ $x_{peak} \sim 0.92$



Strategy for systematic effects

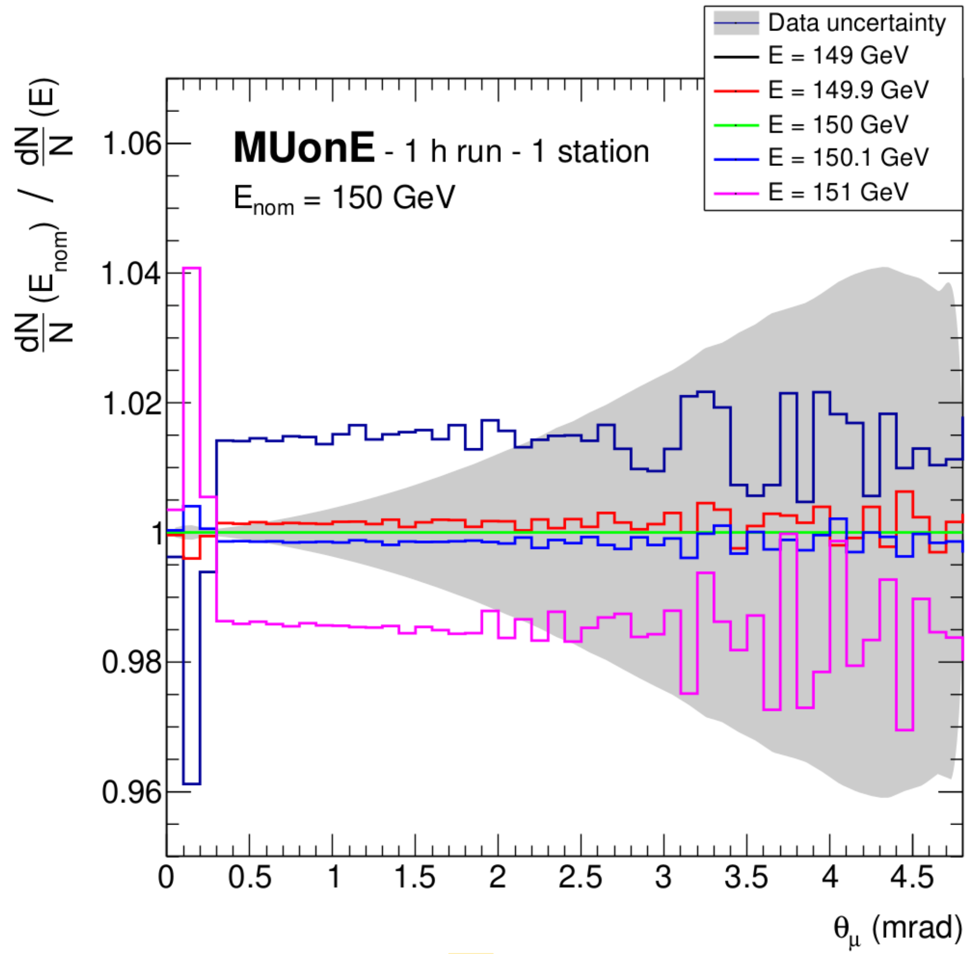




1) Larger systematic effects (intrinsic angular resolution, beam energy): use normalization region -many events there- to *calibrate* them;
2) Other systematics: included as nuisance parameters in a *combined fit with signal* (CMS Combine tool).

Systematic error on the muon beam energy

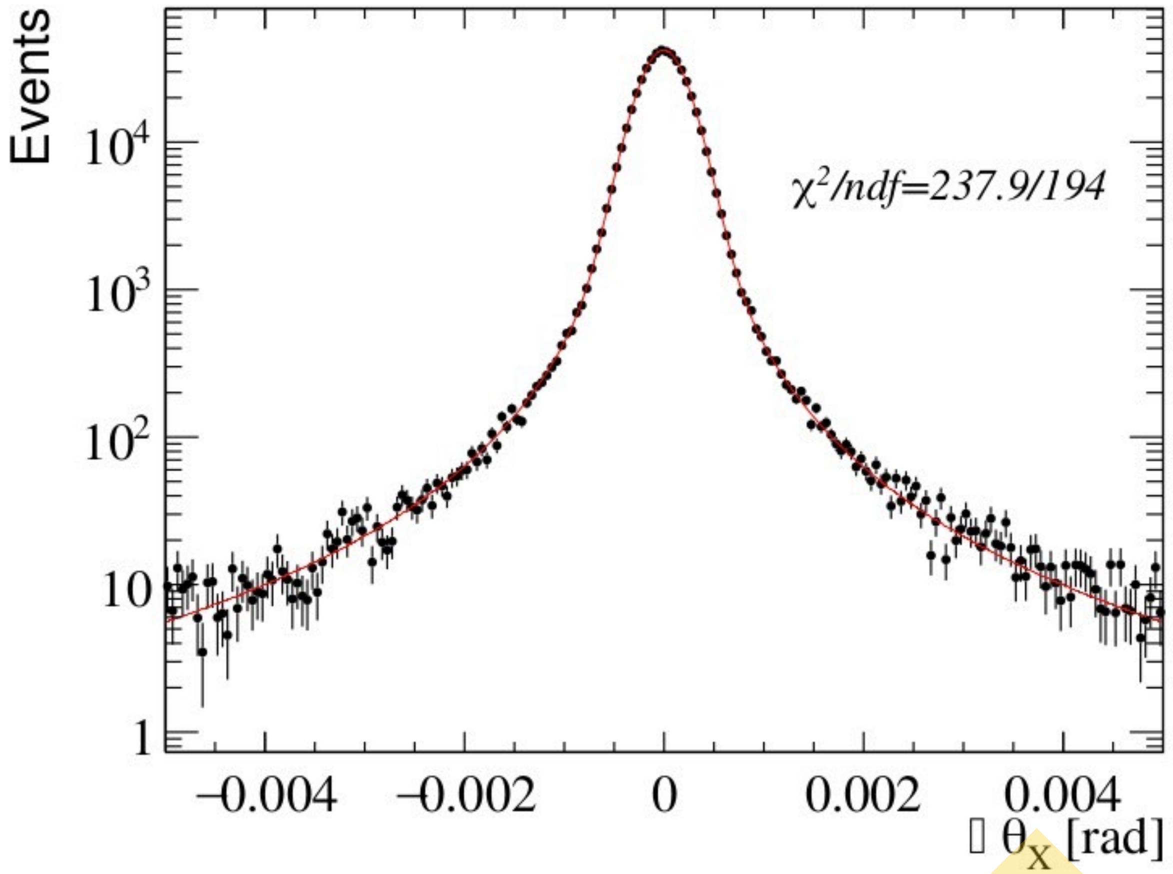
Accelerator division provides Ebeam with O(1%) precision
(~ 1 GeV).
It must be controlled by a physical process.



Forma del modello MCS

Nucleo + coda

$$f_e(\delta\theta_e^x) = N\left[(1-a)\frac{1}{\sqrt{2\pi}\sigma_G}e^{-\frac{(\delta\theta_e^x-\mu)^2}{2\sigma_G^2}} + a\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma_T\Gamma(\frac{\nu}{2})}\left(1+\frac{(\delta\theta_e^x-\mu)^2}{\nu\sigma_T^2}\right)^{-\frac{\nu+1}{2}}\right]$$



Tracker: moduli CMS 2S

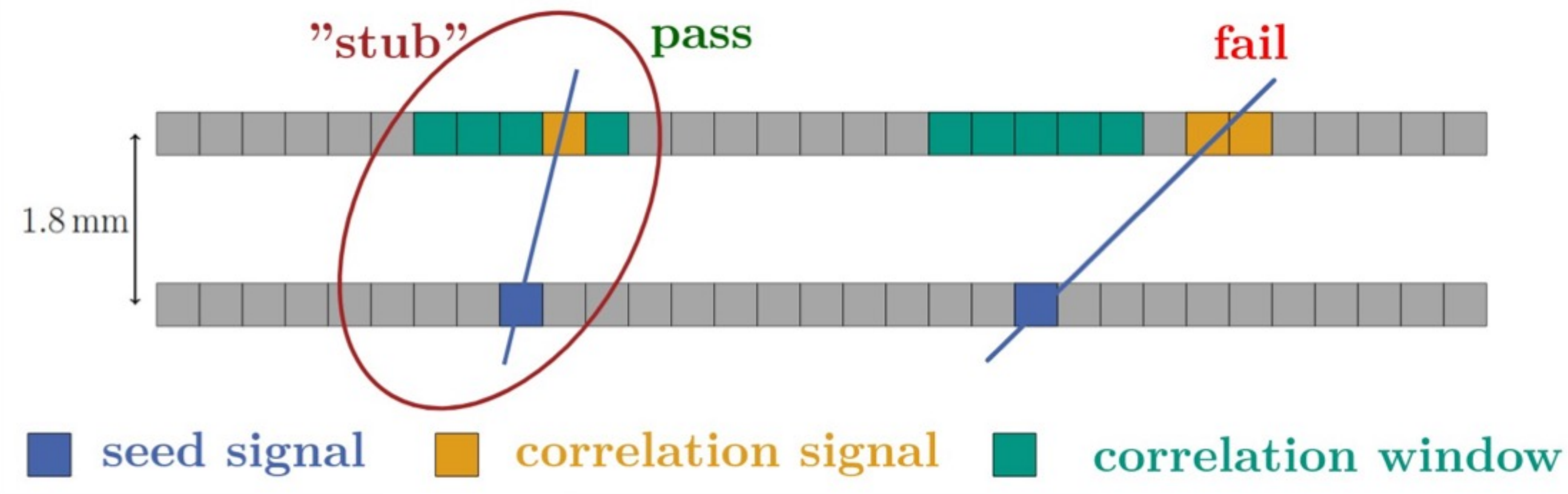
CMS Tracker Phase2 Upgrade - TDR

Two sensors reading the same coordinate:

- Background suppression from single-sensor hits.
- Rejection of large angle tracks.

- x_{seed}
- bend = $x_{corr} - x_{seed}$

$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$



Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)