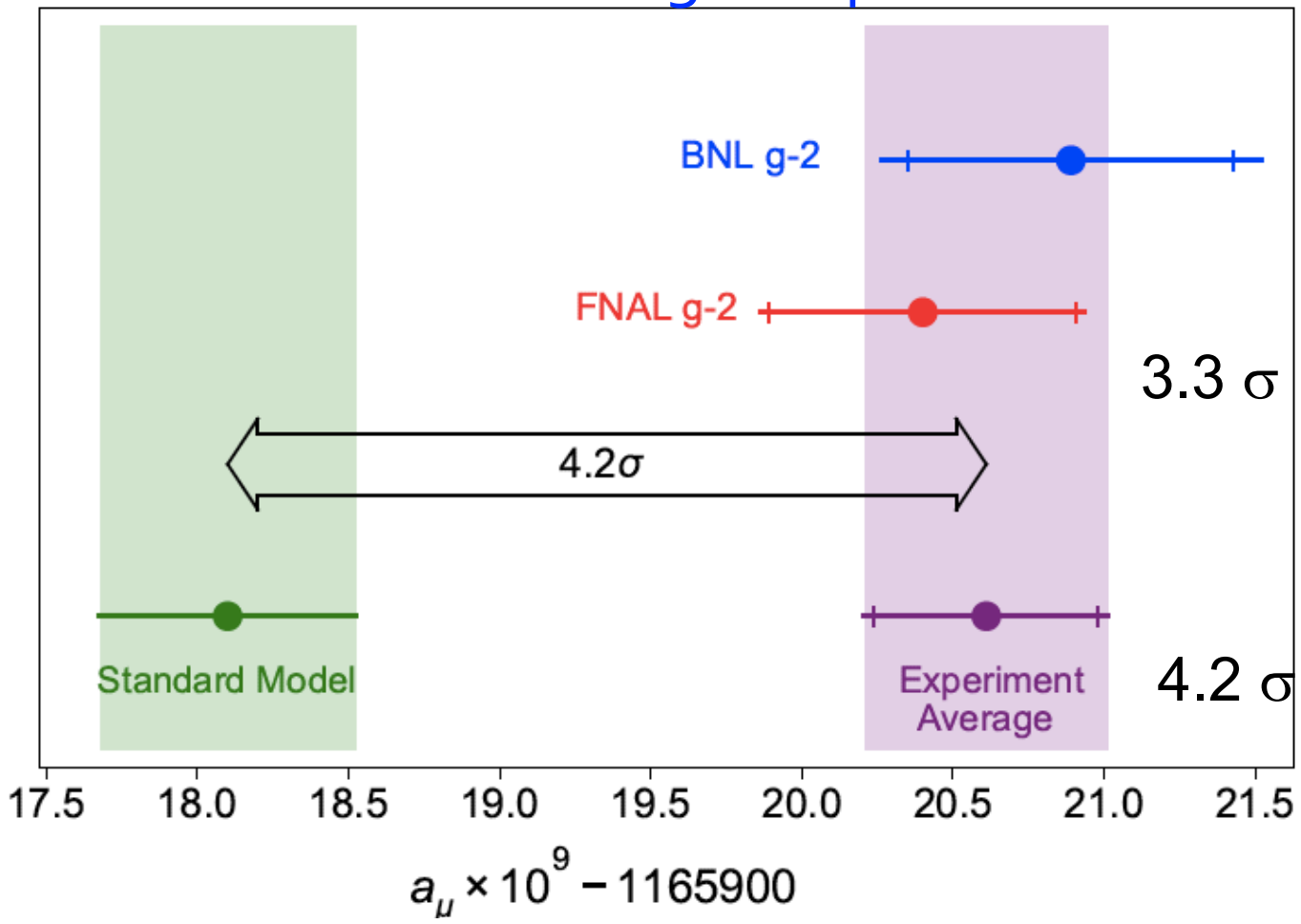
Status and prospects of the MUonE experiment

G. Venanzoni

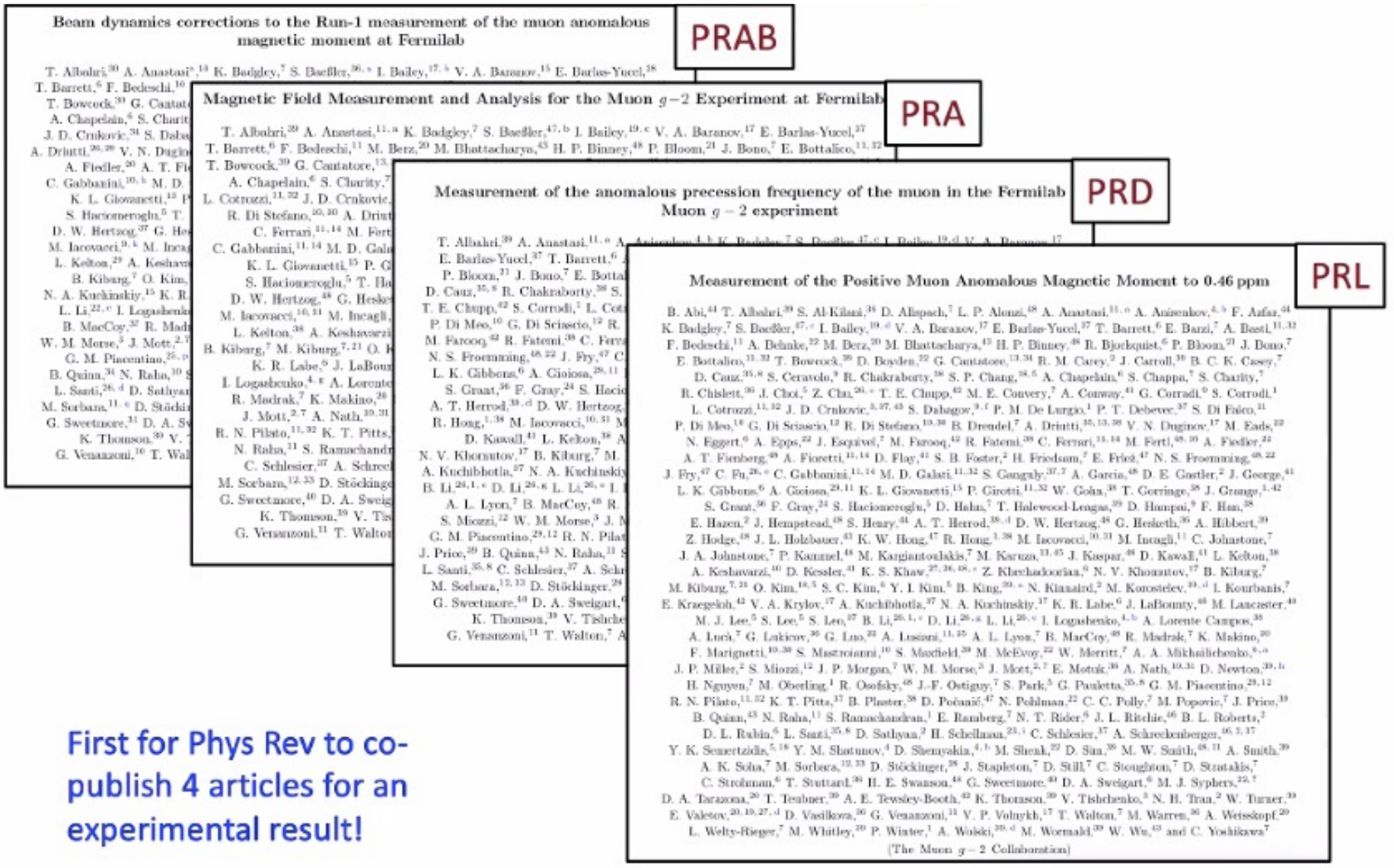
Liverpool University and INFN/Pisa

April 7th 2021:
First results from the Muon g-2 experiment at Fermilab



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

4 Phys Rev journals on April 2021(>1000 citations)



First for Phys Rev to co-publish 4 articles for an experimental result!

New York Times

News reported in all newspapers, socials

8 April 2021

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, mostly sunny, remaining quite cold for early April, high 47. Tonight, partly cloudy, low 16. Tomorrow, variably cloudy, a bit cooler, high 42. Weather map, Page B10.

VOL. CLXX .... No. 59,022 © 2021 The New York Times Company NEW YORK, THURSDAY, APRIL 8, 2021 $3.00

Biden Tax Plan Aims to Curtail Use of Havens

Loophole Has Enriched Global Corporations

By JIM TANKERSLEY and ALAN RAPPEPORT

WASHINGTON — Large companies like Apple and Bristol Myers Squibb have long employed complicated maneuvers to reduce or eliminate their tax bills by shifting income on paper between countries. The strategy has enriched accountants and shareholders, while driving down corporate tax receipts for the federal government.

President Biden sees ending that practice as central to his $2 trillion infrastructure package, pairing changes to the tax code that his administration says will ensure American companies are contributing tax dollars to help invest in the country's roads, bridges, water pipes and in other parts of his economic agenda.

On Wednesday, the Treasury Department released the details of Mr. Biden's tax plan, which aims to raise as much as $2.5 trillion over 15 years to help finance the infrastructure proposal. That includes bumping the corporate tax rate to 28 percent from 21 percent, imposing a strict new minimum tax on global profits and cracking down on companies that try to move profits offshore.

The plan also aims to stop big companies that are profitable but have no federal income tax liability from paying no taxes in the Treasury Department by imposing a 15 percent tax on profits they report to investors. Such changes would affect about 55 companies, according to the Biden administration's estimates, because it would be limited to companies earning $2 billion or more per year.

"Companies aren't going to be able to hide their income in places like the Cayman Islands and Bermuda in tax havens," Mr. Biden said on Wednesday during remarks at the White House. He defended the tax increases as necessary to pay for infrastructure investments that America needs and to help reduce the federal deficit over the long term.

Still, his 15 percent tax is a narrower version of the one he proposed in the 2020 campaign that would have applied to companies with $100 million or more in profits per year.

Continued on Page A18

Contagious Variant Is Fueling Surge in Infections Across the U.S.

Some states where new cases of the coronavirus are rising have been hit hard by the B.1.1.7 variant. Page A6.

Michigan
Estimated share of cases from B.1.1.7
New Covid-19 cases per 100,000
7-day avg. of virus cases over 31
B.1.1.7 cases
FEB. 1 MAR. 28 FEB. 1 MAR. 28

Texas
Estimated share of cases from B.1.1.7
New Covid-19 cases per 100,000
FEB. 1 MAR. 28 FEB. 1 MAR. 28

Georgia
Estimated share of cases from B.1.1.7
New Covid-19 cases per 100,000
FEB. 1 MAR. 28 FEB. 1 MAR. 28

Florida
Estimated share of cases from B.1.1.7
New Covid-19 cases per 100,000
FEB. 1 MAR. 28 FEB. 1 MAR. 28

Source: New York Times database of reports from state and local health agencies

PAIR OF SETBACKS FOR ASTRAZENECA OVER ITS VACCINE

BLOOD CLOT CONCERNS

U.K. Curbs Use by Adults Under 30 as the E.U. Outlines Risks

By BENJAMIN MUELLER

LONDON — Britain said on Wednesday that it would curb the use of AstraZeneca's vaccine in adults under 30 because of the risk of rare blood clots, a blow to the efforts of scores of countries reliant on the vaccine to stamp out the coronavirus pandemic amid a global surge in cases.

Adding to the unease, the European Medicines Agency outlined a "possible link" between the vaccine and rare clots, even as it said that Covid-19 remained the far greater threat, leaving decisions about how to use the vaccine in the hands of the 27 member states of the European Union.

Taken together, the decisions represented a considerable setback for the AstraZeneca shot, which has been seen as the principal weapon in the battle to reduce deaths in the vaccine-starved global south.

The world's most widely administered coronavirus vaccine, it is far less expensive and easier to store than some of the alternatives, spurring its use in at least 70 countries, rich and poor. AstraZeneca, based in Britain, has promised to deliver three billion doses this year, enough to inoculate nearly one in five people worldwide.

Britons under 30 will receive another vaccine if one is available, with limited exceptions, officials said. Until Wednesday, Britain had not wavered in its use of the homegrown vaccine, holding out even as many European neighbors paused injections over the unusual, though sometimes fatal clots.

But cases began to appear in Britain as well, and a consensus has since emerged among global regulators that the evidence points to a plausible link, as yet unexplained, between the vaccine and rare clots.

Amid a vicious wave of Covid-19 in Europe, the safety concerns have delayed inoculations, sunk confidence in the shot and created

Continued on Page A9

ISIS and African Militants Join In a Marriage of Convenience

'Terrorist' Group Using Attacks on Continent to Raise Its Profile

By CHRISTINA GOLDBAUM and ERIC SCHMITT

JOHANNESBURG — The Islamic State's self-declared caliphate has fallen, its fighters have dispersed and its leader, Abu Bakr al-Baghdadi, has been killed.

But two years after it suffered stinging defeats in Syria and Iraq, the terrorist group has found a new lifeline in Africa, where analysts say it has forged alliances with local militant groups in symbiotic relationships that have pumped up their profiles, fundraising and recruitment.

Many of those homegrown insurgencies are only loosely connected to the Islamic State, also known as ISIS. Still, over the past year, as violence from Islamist extremists on the African continent reached a record high, the Islamic State has trumpeted those battlefield wins to project an image of strength and inspire its supporters worldwide.

Most recently, the Islamic State claimed credit last week for a day-long rampage in war-afflicted northern Mozambique, where militants with distant ties to the terrorist organization unleashed a key port town. The attack left dozens of people dead, including at least one South African and one British citizen, and set off talk on the Islamic State's online forums of the establishment of a new caliphate there, according to researchers.

"As an organization more broadly, ISIS is hurting," said Col-

Continued on Page A11

New York to Provide $2.1 Billion For Undocumented Immigrants

Covid Relief Plan Rifles G.O.P. and Worries Some Democrats

By ANNIE CORREAL and LUIS FERRÉ-SADURNÍ

When the coronavirus arrived in New York City a year ago, it hit enclaves of undocumented immigrants with a fury, killing thousands and wiping out the service and construction jobs that kept many families afloat.

Lifelines like unemployment insurance and federal stimulus checks were out of reach because undocumented people are ineligible for most government aid. Instead, they have relied on food pantries, lenient landlords and loans from friends.

But after a sweeping move by lawmakers this week, New York will now offer one-time payments of up to $15,600 to undocumented immigrants who lost work during the pandemic. The effort — a $2.1 billion fund in the state budget — is by far the biggest of its kind in the country and a sign of the state's shift toward policies championed by progressive Democrats.

"I've met neighbors who have not been able to pay rent, or put food on the table, or been able to provide their children with a laptop when a public school has not been able to provide one," said State Senator Jessica Ramos, a Democrat from Queens and lead proponent of the fund.

The excluded workers fund, part of the state's new $212 billion budget deal that was reached on Tuesday, was one of the most contentious points of debate during

Continued on Page A19

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

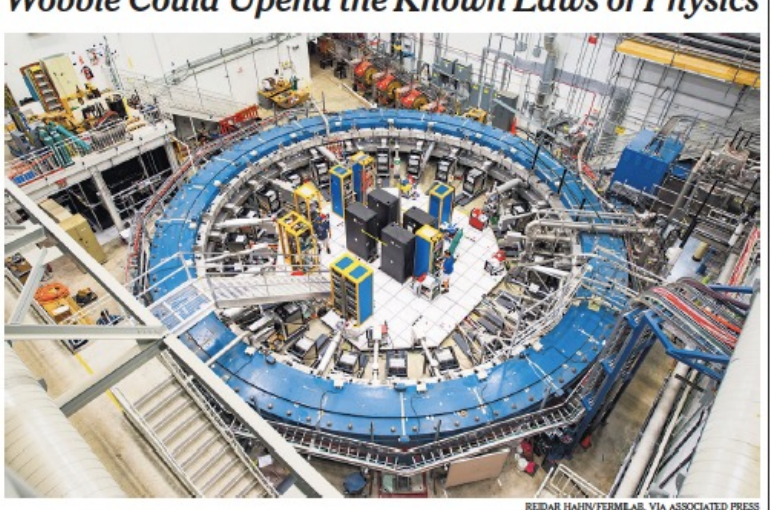
The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

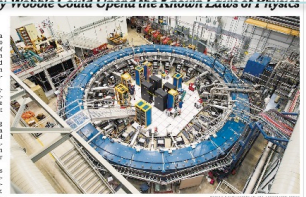
At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A19



REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.



A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

PINEDALE, Wyo. — Kenna Tatum and her team can list the cases from memory: There was the woman who got lost and did not see her finishing her hike; the couriers, in shorts during a blizzard; the base jumper, misjudging his leap from a treacherous granite cliff face; the ill-equipped snowmobiler, buried up to his neck in an avalanche.

All of them were pulled by Ms. Tatum and the Tip Top Search and Rescue crew from the rugged Wind River mountain range in the vast, mostly undeveloped, remote pocket of western Wyoming. And all of them, their rescuers said, were wildly unprepared for the harsh backcountry in which they were traveling.

"It is super frustrating," said Ms. Tatum, Tip Top's director. "We just wish that people respected the risk."

If the throes of a pandemic that has made the indoors inherently dangerous, tens of thousands of Americans than usual have fled to outdoors, forcing crowded parks for national parks and the public lands around them. But as these hordes of inexperienced adventurers explore the treacherous terrain of the backcountry, many inevitably call for help. It has fallen to the patrolmen, volunteer-based search-and-rescue

Continued on Page A17

A trail in the Wind River Range in western Wyoming.

INTERNATIONAL A10-13

A Pivot by Piñata Makers

To survive in an industry dependent on gatherings, Mexican artisans have added coronavirus figures to their product lines. PAGE A10

Aid Restored to Palestinians

The Biden administration's move will again make the United States a leading donor to the U.N. agency that assists about 5.7 million Palestinians. PAGE A11

TRACKING AN OUTBREAK A4-9

Food Industry's Race for Shots

As states open vaccines and restaurants to all, workers may be left behind. Some chefs have opened pop-up spots to get employees vaccinated. PAGE A8

NATIONAL A16-21

McConnell Digs In Again

The top Senate Republican, who has fought campaign finance limits, is aiming to stop a voting rights bill. PAGE A20

Classes Study Chauvin Trial

Educators in Minneapolis, where George Floyd was killed, have students examining race and policing. PAGE A15

BUSINESS B1-6

Spying and Swedish Meatballs

In a case that is riveting France, Ikea is charged with surveilling unions, employees and customers. PAGE B3

'Green' Debt Relief

With many countries struggling to manage staggering debt and mounting climate disasters, some leaders are seeking a way to address both. PAGE B1

SPORTS THURSDAY B7-11

Woods Was Doing 80-Plus

When he crashed on a winding road, Tiger Woods was going nearly twice the speed limit, the police said. PAGE B9

THURSDAY STYLES D1-6

'Baby Botox' Destigmatized

People are starting injections at their 20s and 30s, seeking a wrinkle-free look that's refreshed, not frozen. PAGE D6

Curtains Up for the 1 Percent

While many Americans were stockpiling toilet paper, the ultrarich splurged on feathering their new nests. PAGE D1

ARTS C1-8

At 91, Ready for His Next Act

John Cullum planned a cabaret show in 2019. Illness hit, then the pandemic. But the actor hasn't been stopped. PAGE C1

A Spare Homage at City Ballet

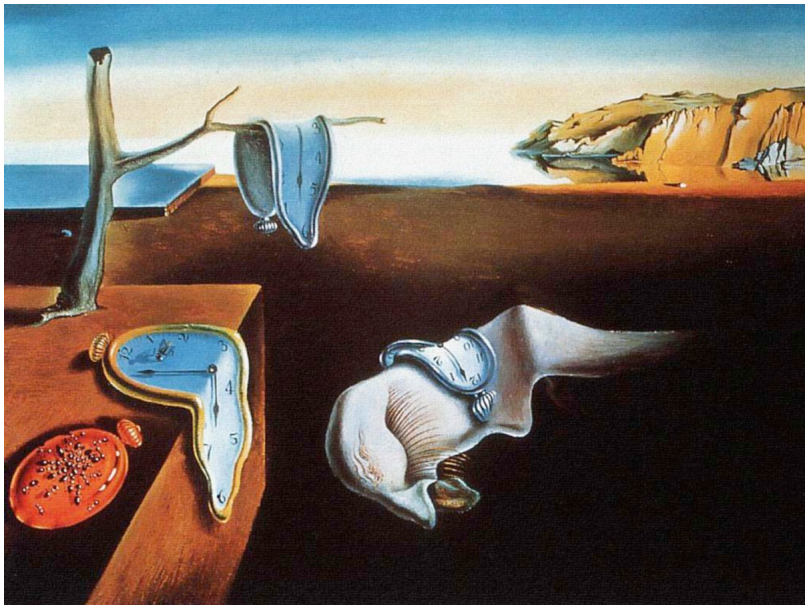
For "When We Fell," the choreographer Kyle Abraham took cues from Proust's film "Under the Cherry Moon." PAGE C3

EDITORIAL, OP-ED A22-23

Jennifer Finney Boylan PAGE A22

April 7 2021

"DOES THE MUON G-2 EXPERIMENT OPEN A NEW ERA FOR PHYSICS?"

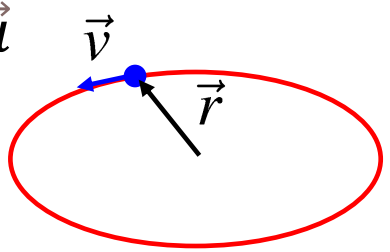


"What **monsters** might be lurking there?" (Chris Polly, April 7 2021)

The Muon g-2

- A charge particle in a plane orbit has **angular momentum** $\vec{L}$ and **magnetic moment** $\vec{\mu}$

$$\vec{\mu} = \frac{q}{2m}\vec{L}$$



- The ratio $\dfrac{\vec{\mu}}{\left(\frac{q}{2m}\right)\vec{L}}$ is called gyromagnetic ratio g. Classically **g=1**

- For an elementary particle of Spin = 1/2 (e,μ) Dirac equation predicts **g = 2**

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma} \equiv g\frac{e}{2m}\vec{S};\quad \vec{S} = \frac{\vec{\sigma}}{2};\quad g = 2$$

- The magnetic anomaly is defined as **a = (g-2)/2. g=2 → a=0** according to Dirac

1948: Measurement of g of the electron

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY
Department of Physics, Columbia University, New York, New York

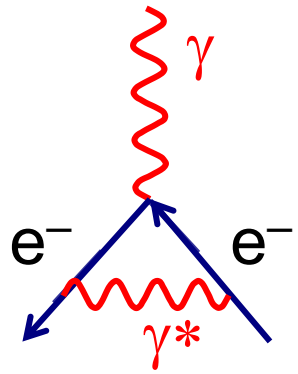
(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L=1$ and $g_S=2(1.00119\pm0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

$$g = 2(1.00119 \pm 0.00005); a = \frac{(g-2)}{2} = 0.00119 \pm 0.00005$$

a= 0 according to Dirac

1948: Triumph of Quantum Field Theory (QED)



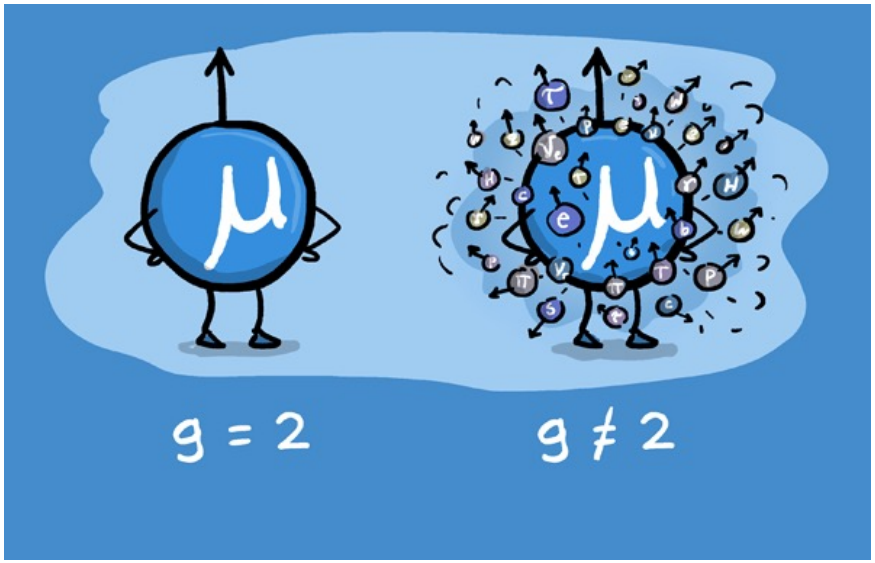
$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$

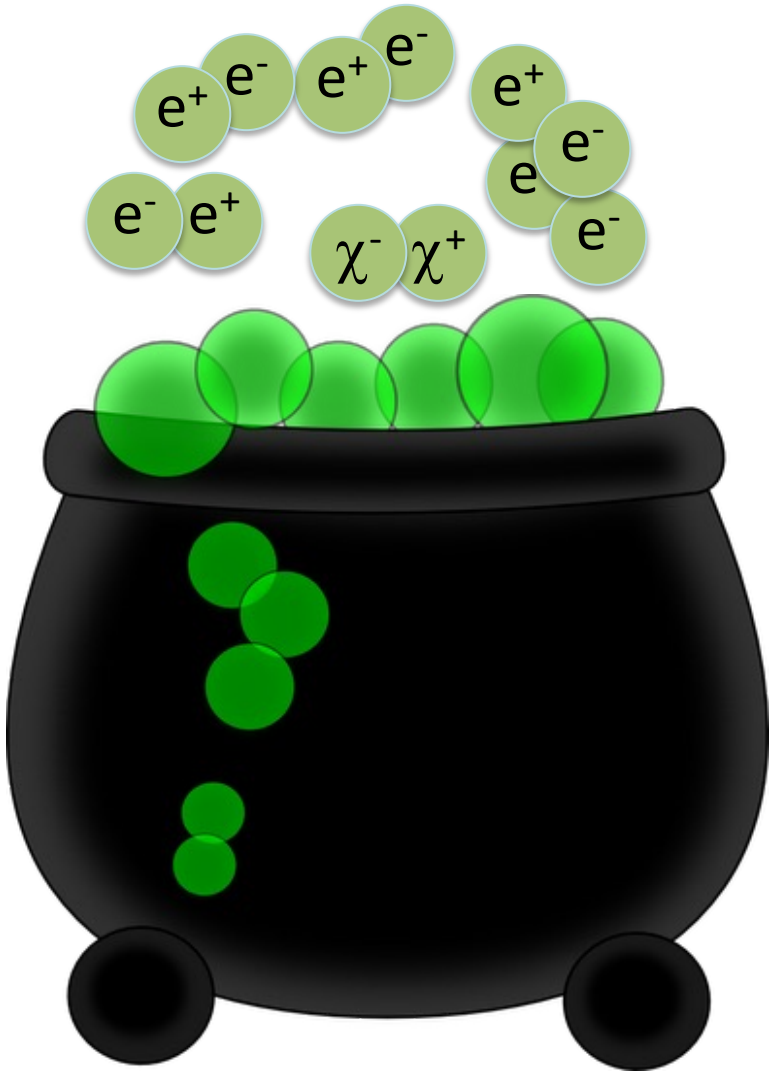
a>0; g>2

At the end it's all the Quantum Vacuum

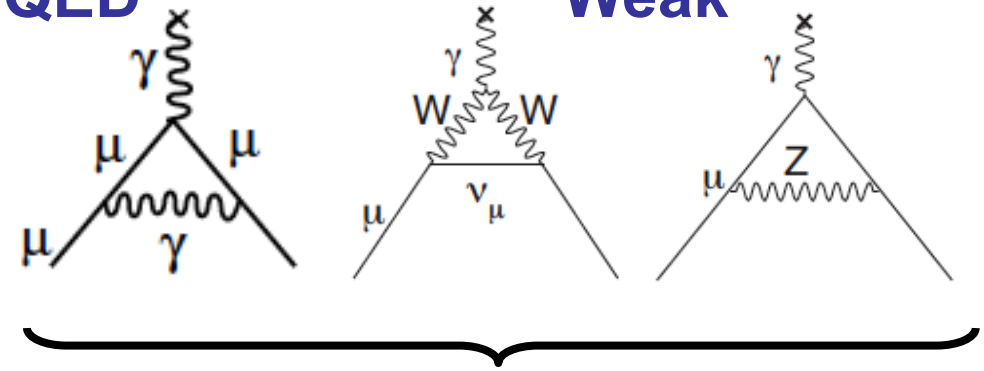
- The vacuum is filled with pairs of particles and antiparticles that exist for a very short time and are therefore called **virtual**.

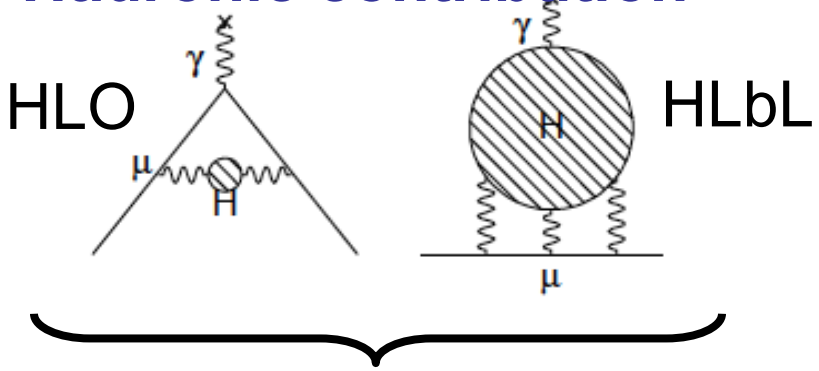
- They produce tangible effects on the physical phenomena we observe → g ≠2





In the SM a_μ can be computed very precisely!





Precisely known

Large uncertainty
(significant work going on)

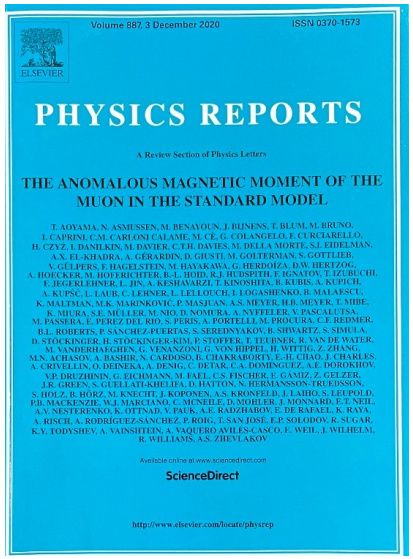
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

$$a_\mu(\mathrm{SM}) = 116\,591\,810(43)\times 10^{-11} \quad (0.37\,\mathrm{ppm})$$

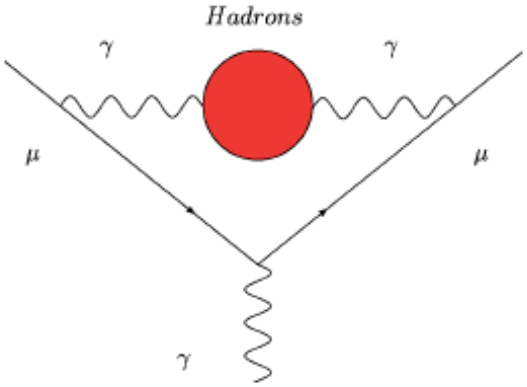
$a_\mu^{QED} \sim \alpha/2\pi \sim O(10^{-3})$ $a_\mu^{Weak} \sim O(10^{-9})$ $a_\mu^{HAD} \sim O(10^{-8})$

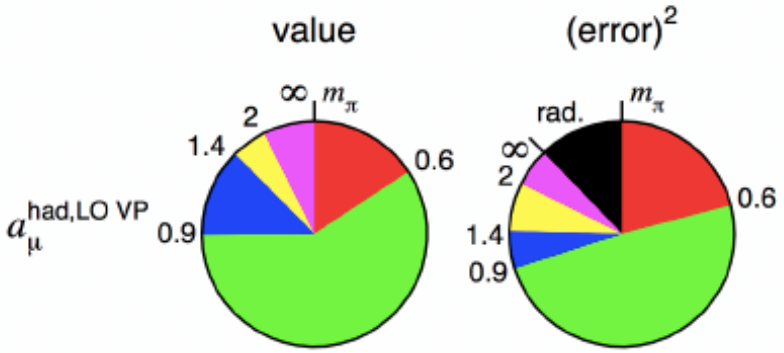
$\delta a_\mu^{QED} \sim 1.4\times10^{-12}$ $\delta a_\mu^{Weak} \sim 2\times10^{-11}$ $\delta a_\mu^{HAD} \sim 5\times10^{-10}$

Theory Initiative (TI): T. Aoyama et al. Phys.Rept. 887 (2020)



The hadronic LO contribution





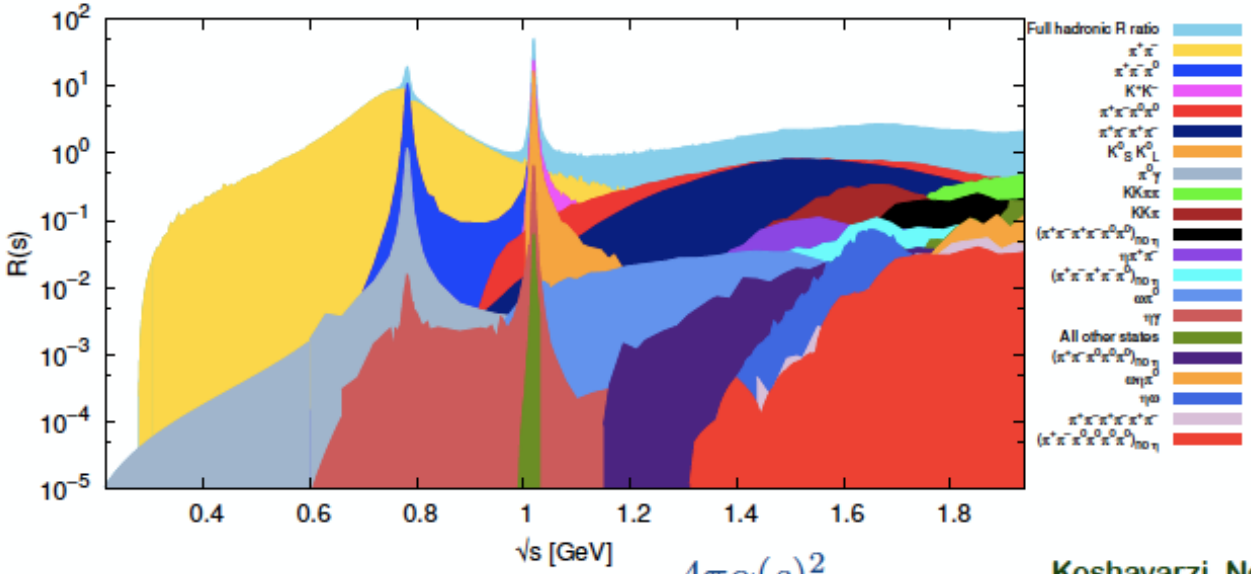
Keshavarzi, Nomura, Teubner 2018

$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\,\sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}\,K(s)R(s) \qquad K(s) = \int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)(s/m^2)}$$

a_μ^{HLO} = 6895 (33) x 10^{-11}	F. Jegerlehner, arXiv:1711.06089
= 6939 (40) x 10^{-11}	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
= 6928 (24) x 10^{-11}	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
= 6931 (40) x 10^{-11} (0.6%)	WP20 value

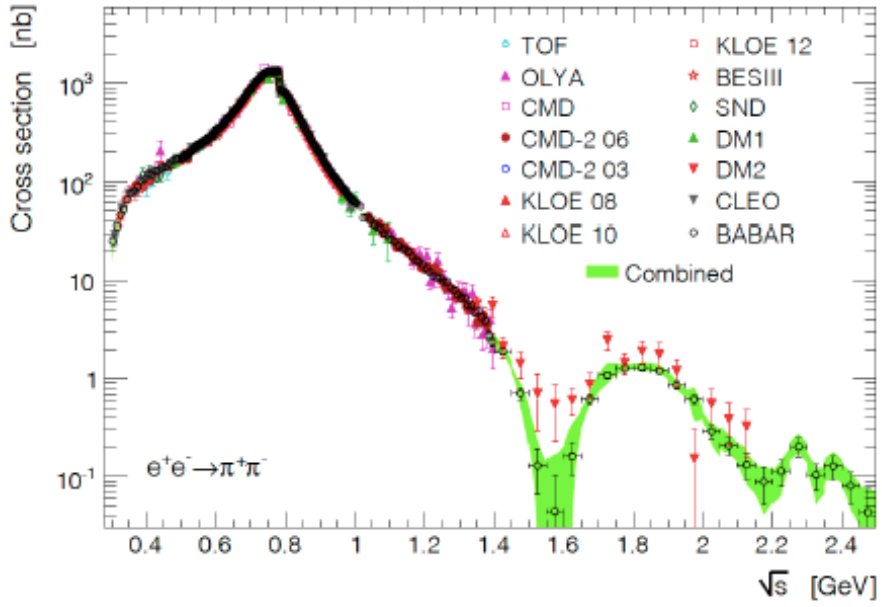
- **WP20 value obtained merging conservatively DHMZ + KNT + constraints from CHHKS**
  Colangelo, Hoferichter, Hoid, Kubis, Stoffer 2018-19
- **Radiative Corrections to σ(s) are crucial.** S. Actis et al, Eur. Phys. J. C66 (2010) 585

The low-energy hadronic cross section



$$R(s) = \sigma(e^+e^- \to \text{hadrons})/\frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner
PRD 2018

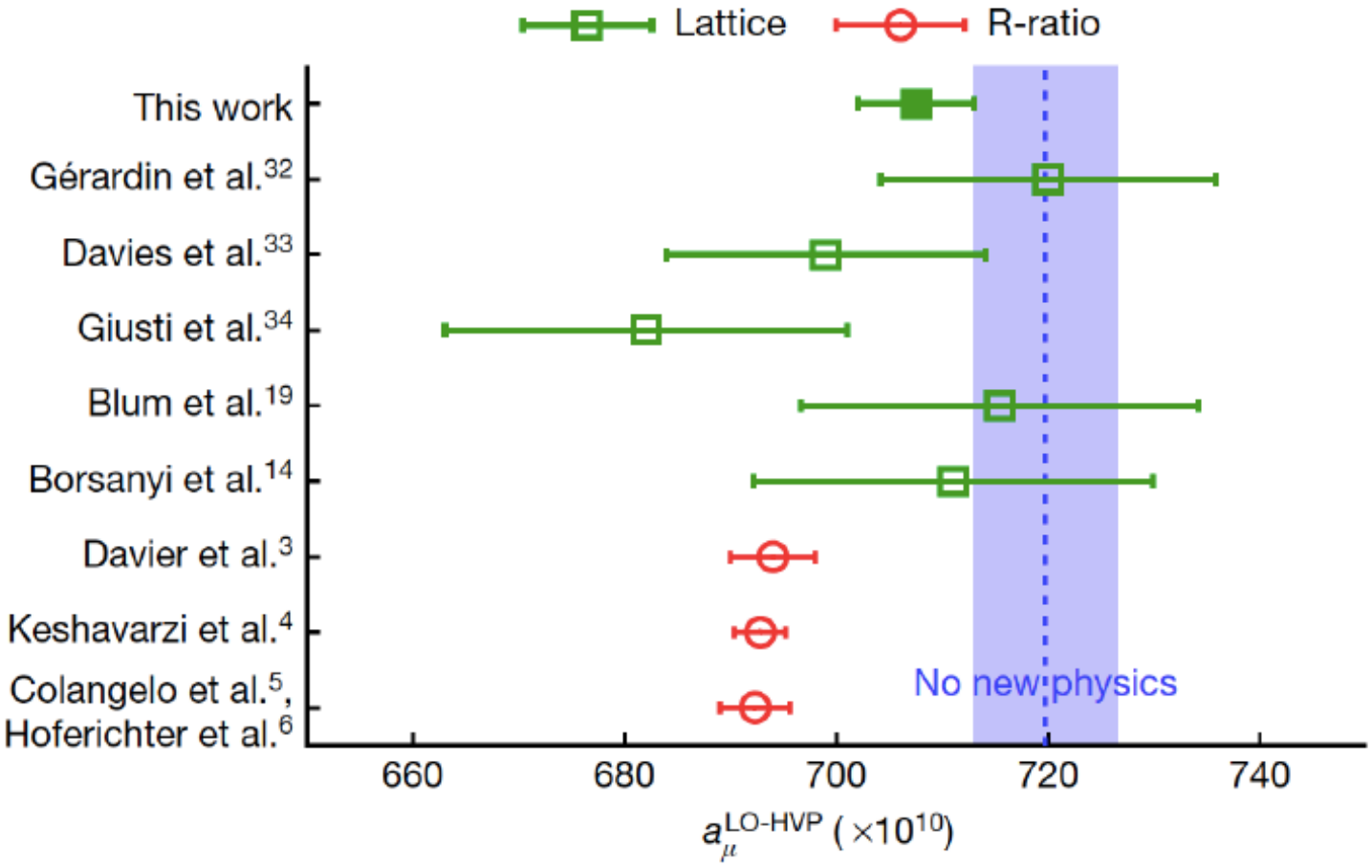


Davier, Hoecker, Malaescu, Zhang
EPJC 2020

The hadronic LO contribution from lattice QCD

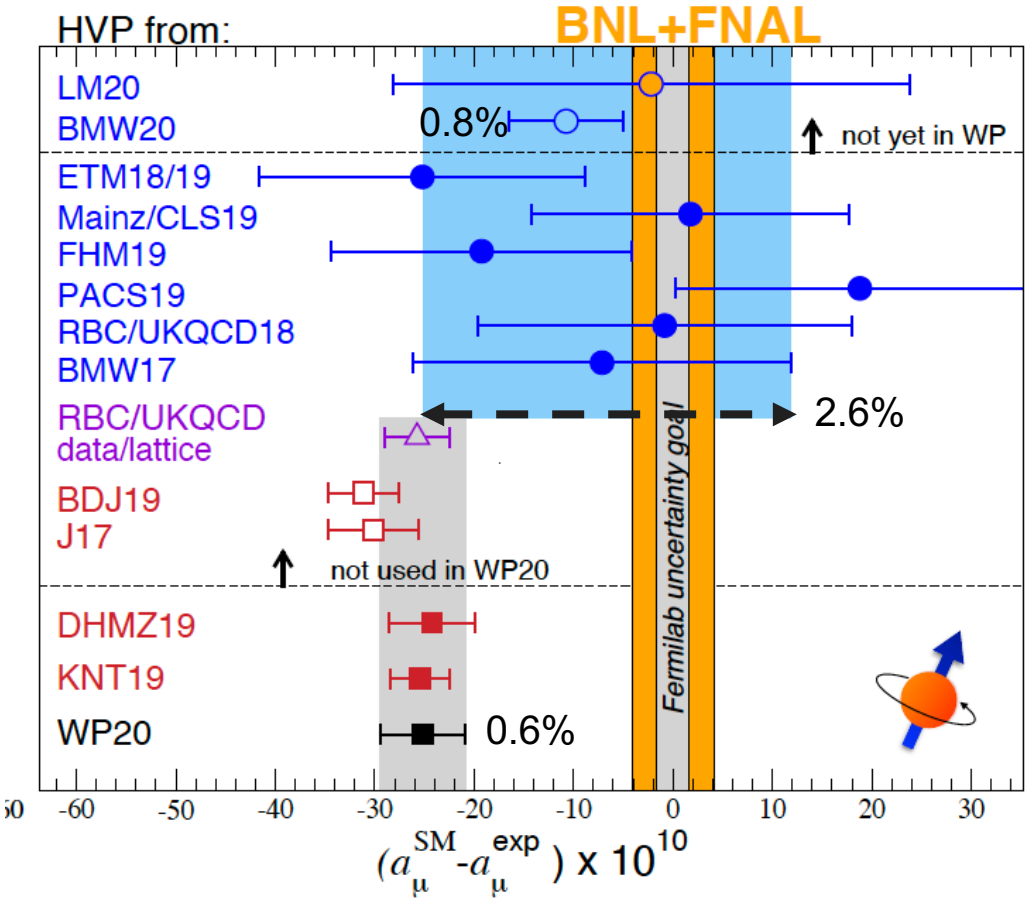
- **Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision:** $a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst} \times 10^{-11}$. **Some tension with dispersive evaluations.** BMWc 2021

55



Borsanyi et al (BMWc), Nature 2021

a_μ^{HLO} (HVP): present status



- HVP is the main limitation to the improvement in precision to the SM evaluation a_μ
- Recent evaluation(s) of HVP from lattice (BMW20) in tension with the e^+e^- evaluation (WP20)

a_μ^{HLO} (HVP)

"Further insights into these connections will be provided by another complementary method for HVP, which is expected to become available over the next years at the MUonE experiment" (TI Snowmass paper 2022 Snowmass Summer Study https://arxiv.org/pdf/2203.15810.pdf)

MUonE: 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]

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[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*

Phys. Lett. B 746 (2015) 325

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

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[6] *INFN, Sezione di Pisa, Pisa, Italy*
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[8] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

Eur. Phys. J. C (2017) 77: 139.

A «Third way»: MUonE at CERN

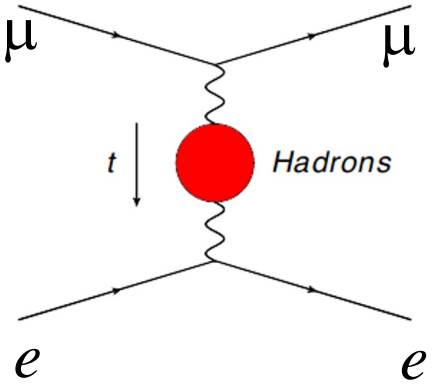
(a space-like approach of a_μ^{HLO})

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

[B.E. Lautrup, A. Peterman, E. de Rafael, Phys. Rept. 3 (1972) 193]

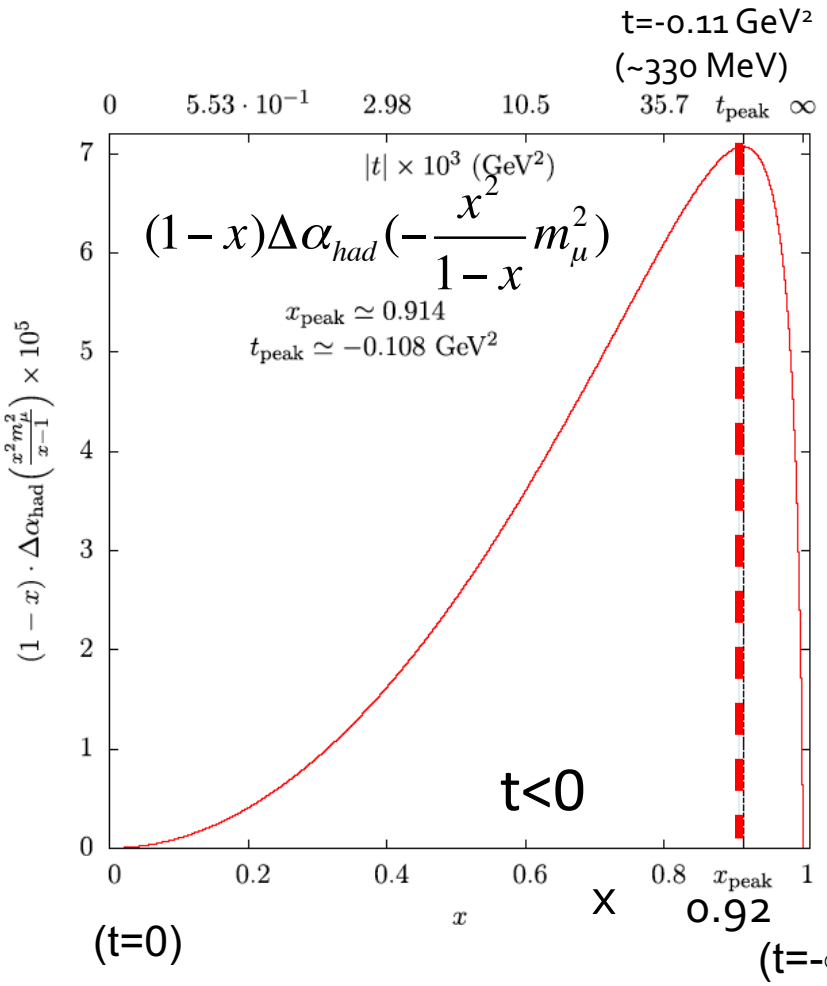
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

$$t = (p_\mu^i - p_\mu^f)^2 = (p_e^i - p_e^f)^2$$



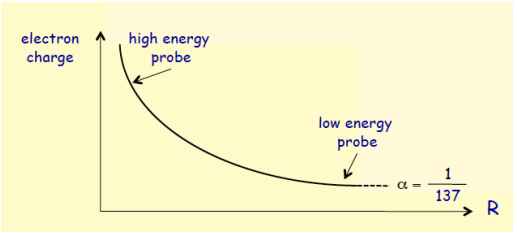
Measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.

Integral over a smooth behavior function ($\Delta\alpha_{had}(t)$ t<0), at relatively low t (<400 MeV)

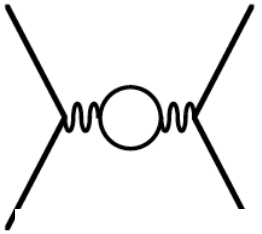


α running and the Vacuum Polarization

- Due to Vacuum Polarization effects $\alpha(q^2)$ is a running parameter depending on the 4-momentum transfer q^2

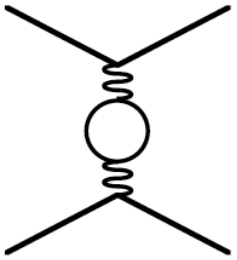


- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:



$$e^2 \to e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

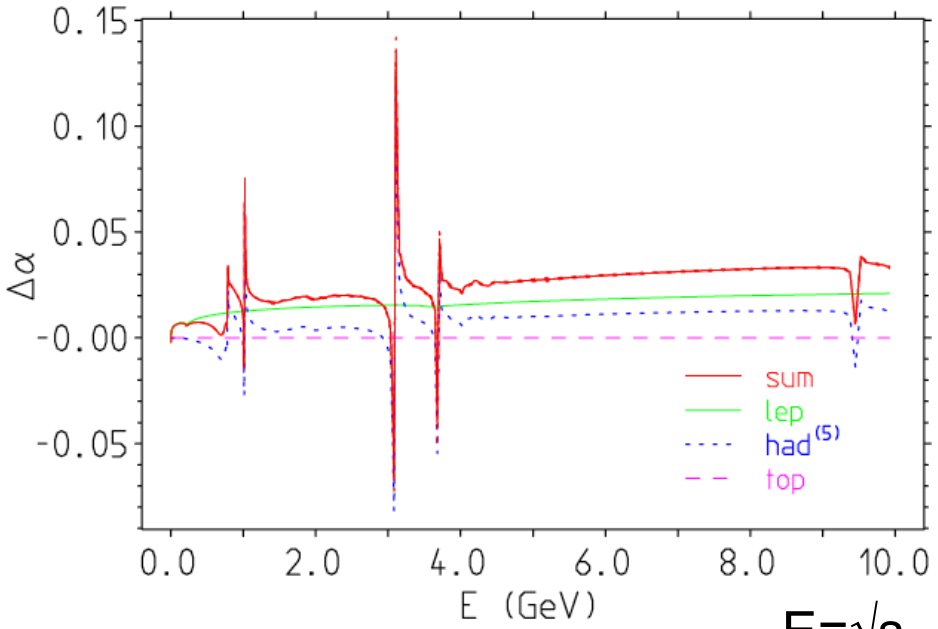
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$



- Δa takes a contribution by non perturbative hadronic effects ($\Delta a^{(5)}_{had}$) which exibits a different behaviour in time-like and space-like region

- $\Delta\alpha^{(5)}_{had}$ at limits precision physics (EW fit) at M_z!

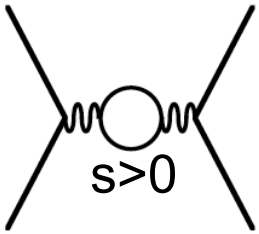
Running of $\alpha(q^2)$



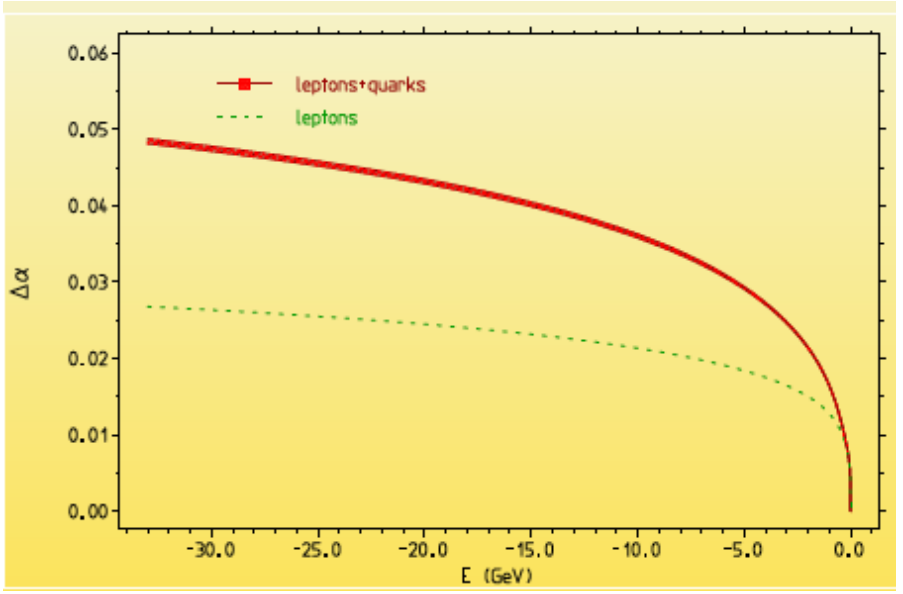
E=√s

Time-like

Behaviour characterized by the opening of resonances



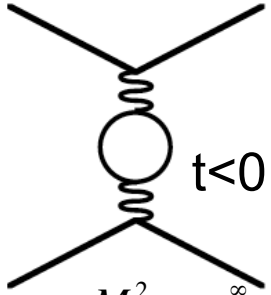
$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$



E=-√-t

Space-like

Very smooth behaviour



$$\Delta\alpha^{(5)}_{had}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s+q_0^2)}$$

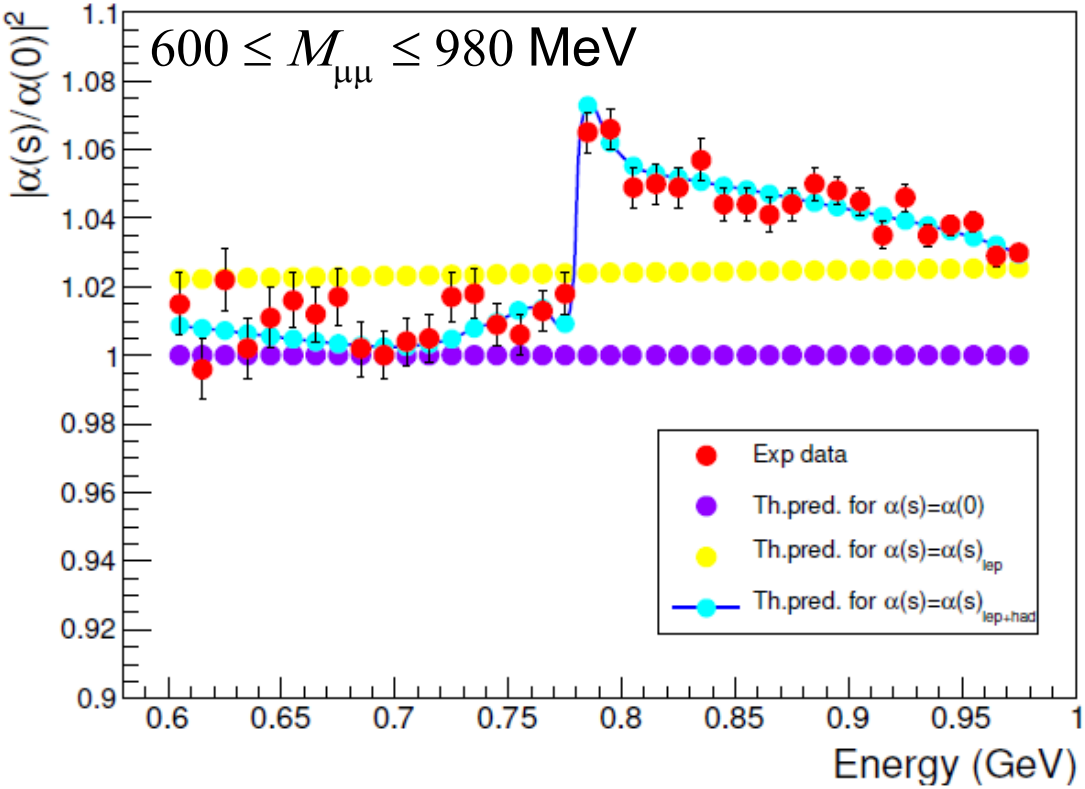
Measurement of $\Delta\alpha(s)$ time-like at KLOE ($e^+e^- \rightarrow \mu^+\mu^-\gamma$)

Phys. Lett. B 767 (2017) 485-492

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{1}{|1-\Delta\alpha(s)|^2}$$

$\Delta\alpha(s) = \Delta\alpha_{lep} + \Delta\alpha_{had}$
(we neglect the top contribution)



Systematic error at ~1% level

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha(0)s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)} \qquad R(s) = \frac{\sigma_{tot}(e^+e^- \rightarrow \gamma* \rightarrow hadrons)}{\sigma_{tot}(e^+e^- \rightarrow \gamma* \rightarrow \mu^+\mu^-)}$$

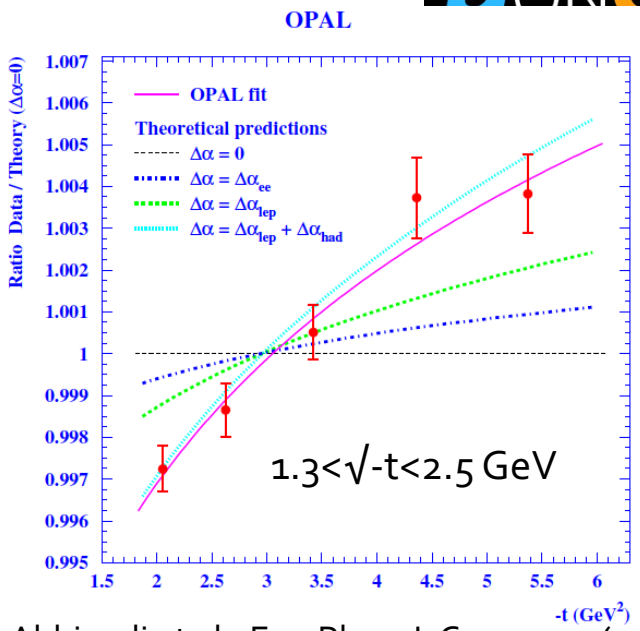
Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP
($e^+e^- \rightarrow e^+e^-$)

- $\Delta\alpha_{had}$ (t) (t<o) has been measured at LEP using small angle Bhabha scattering

$$f(t) = \frac{N_{\mathrm{data}}(t)}{N^0_{\mathrm{MC}}(t)} \propto \left(\frac{1}{1-\Delta\alpha(t)}\right)^2 .$$

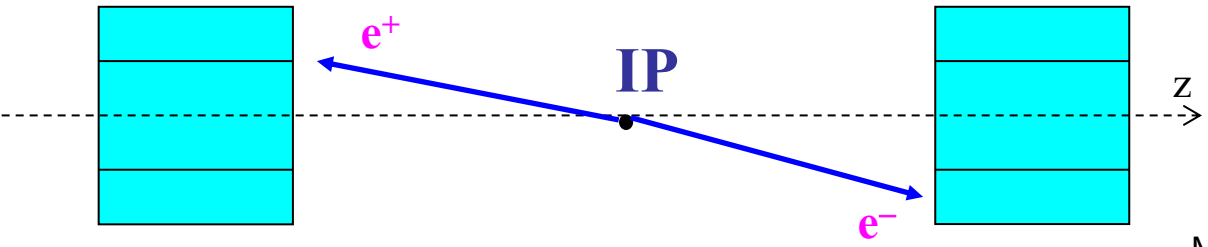
Accuracy at per mill level was achieved!

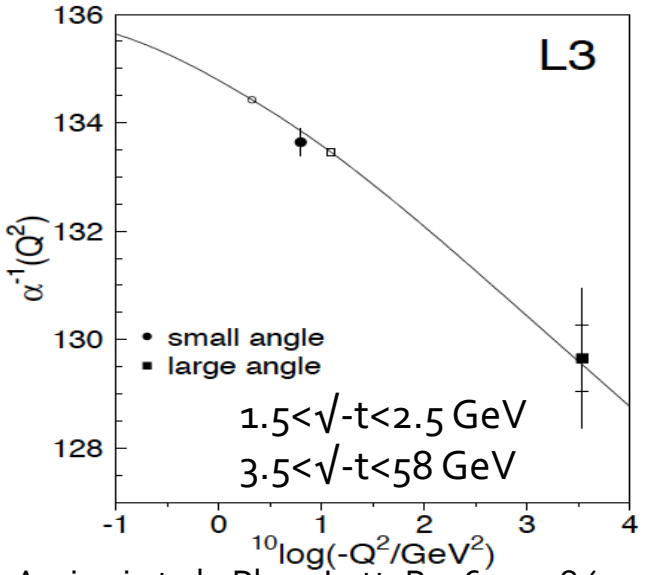
[see also A. Arbuzov et al. **Eur.Phys.J. C34 (2004) 267-275]**



G. Abbiendi et al., Eur. Phys. J. C 45, 1–21 (2006)

- For low t values (≤o.11 GeV²) and higher precision (~10^{-5}) as in our case a different approach is needed!

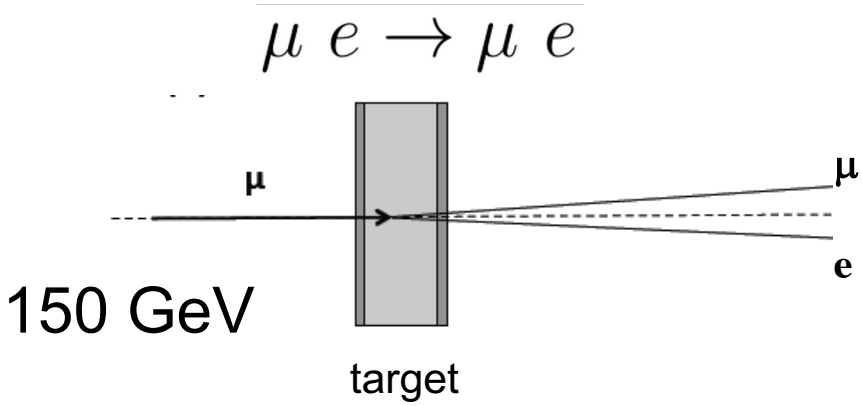




M. Acciarri et al., Phys. Lett. B476 40-48 (2000)

Experimental approach:

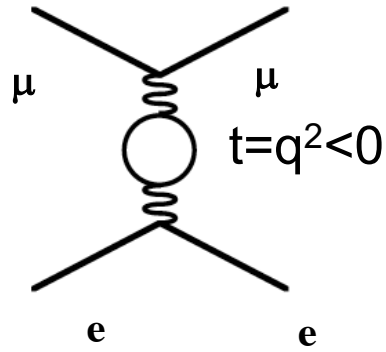
Extract $\Delta\alpha_{had}(t)$ from process μe →μe using 160 GeV μ on beryllium target. The measurement doesn't rely on the precise knowledge of the luminosity but on the shape of the distribution (relative measurement)



$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{\text{no VP}}/dt} = \frac{1}{|1-\Delta\alpha_{lep}(t)-\Delta\alpha_{had}(t)|^2}$$

From theoretical calculation

To be measured



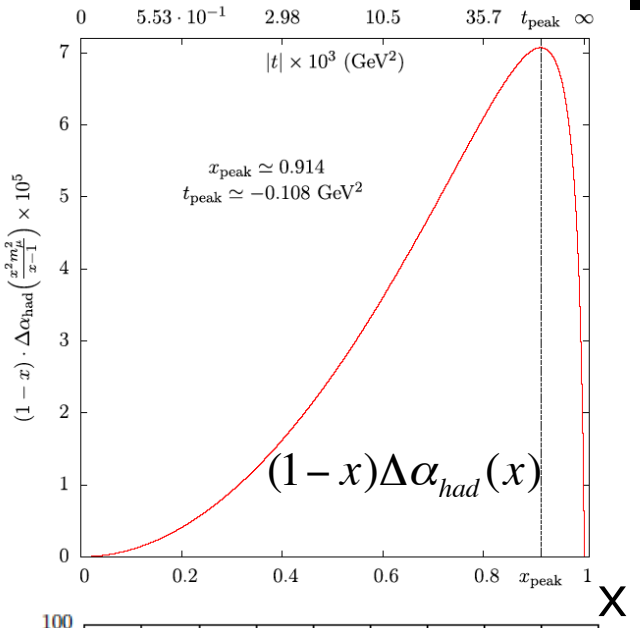
Why measuring $\Delta\alpha_{had}(t)$ with a 160 GeV μ beam on e^- target ?

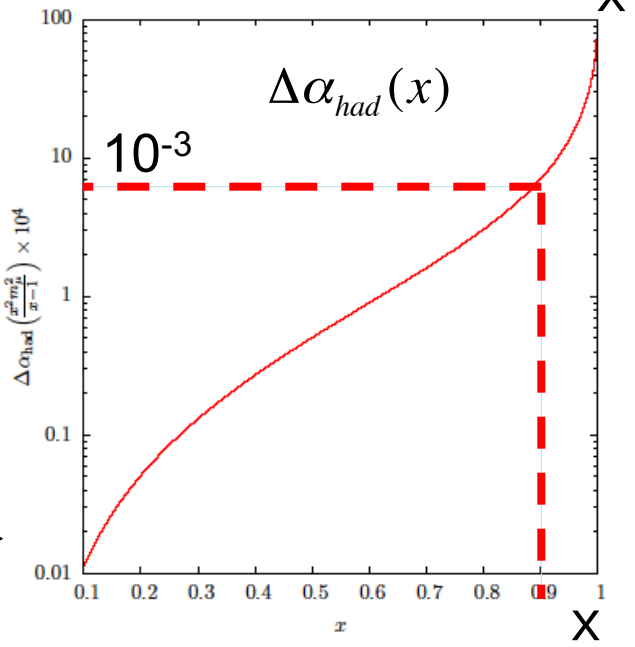
It looks an ideal process!

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

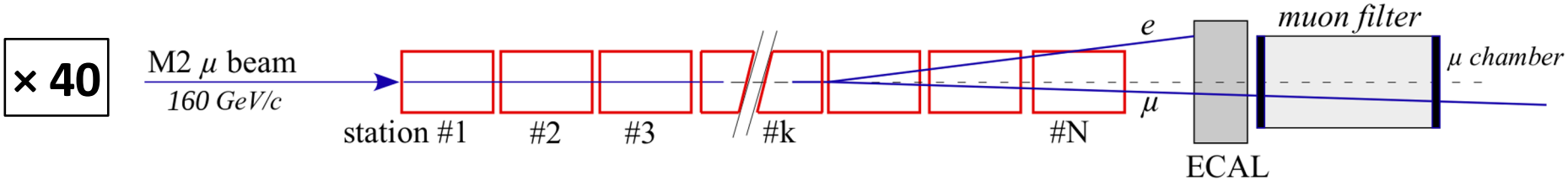
  $\theta_e^{LAB}<32$ mrad ($E_e>1$ GeV)
  $\theta_\mu^{LAB}<5$ mrad

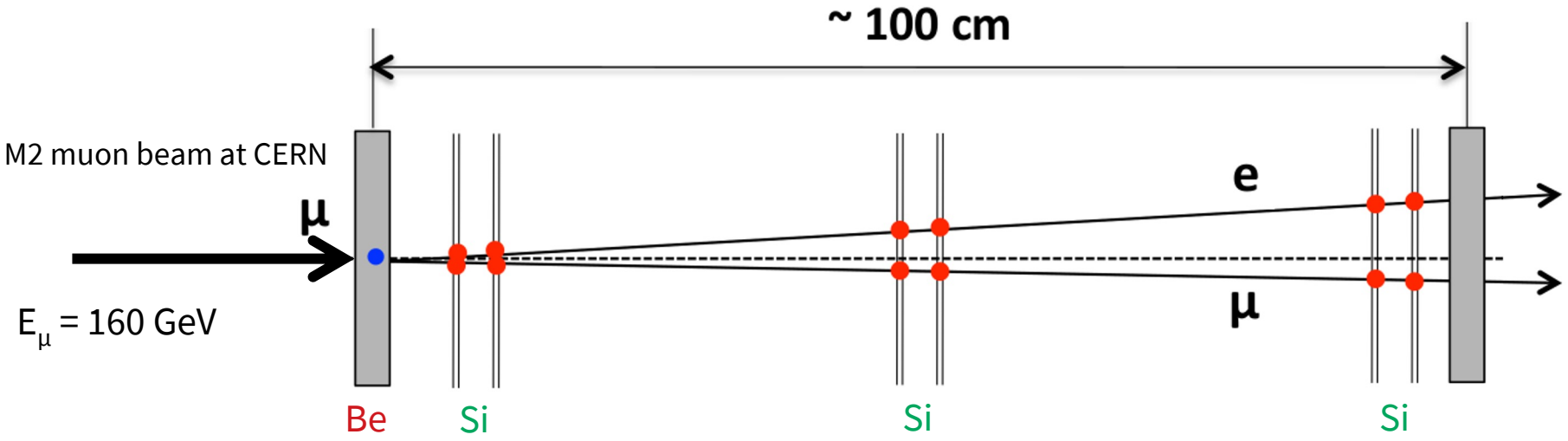
- It allows using the same detector for signal and normalization
- It will be an angular measurement





The experimental apparatus





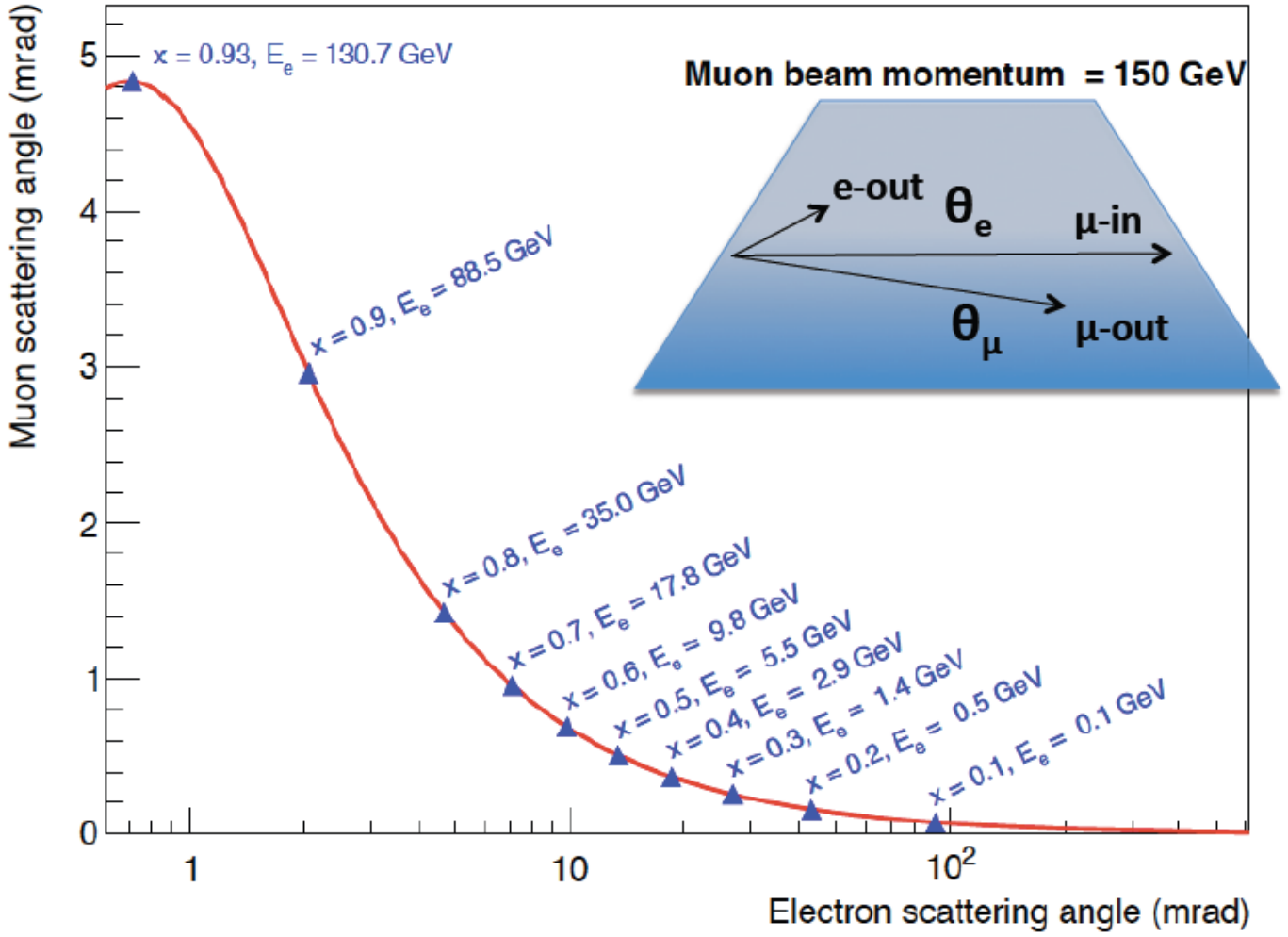
Beryllium target 1.5 cm thickness

Tracking system: 3 pairs of silicon strip detectors

0.02 mrad resolution on the scattering angle

Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint



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".

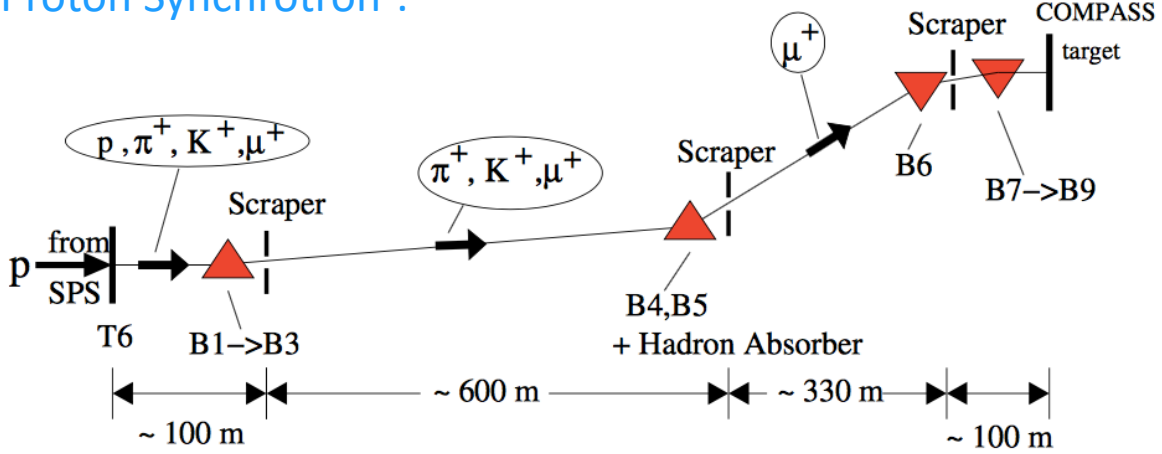


Table 3
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	**Measured**
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
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 $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $\lvert x, y\rvert > 15\,\mathrm{cm}$	7%

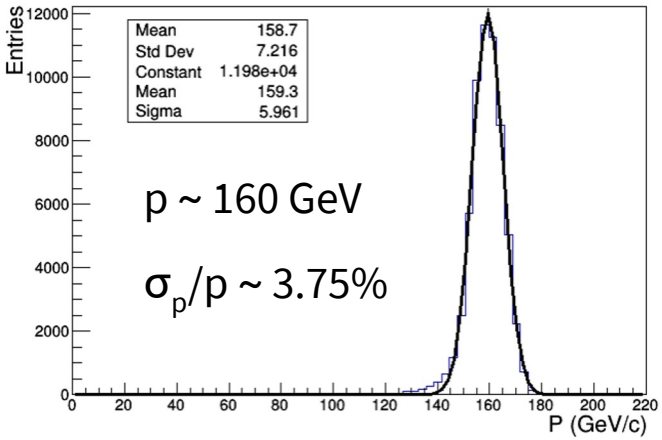
$I_{beam} > 10^7$ muon/s, $E_\mu = 150$ GeV

https://arxiv.org/pdf/hep-ex/0703049.pdf

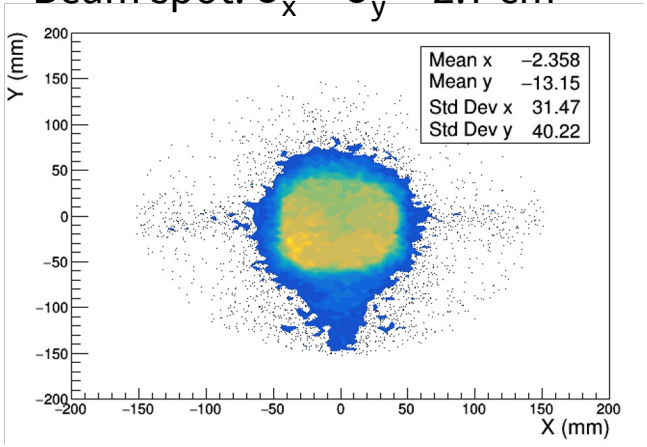
Location: M2 beam line at CERN

- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 3×10^8 μ^+/spill).

Beam momentum

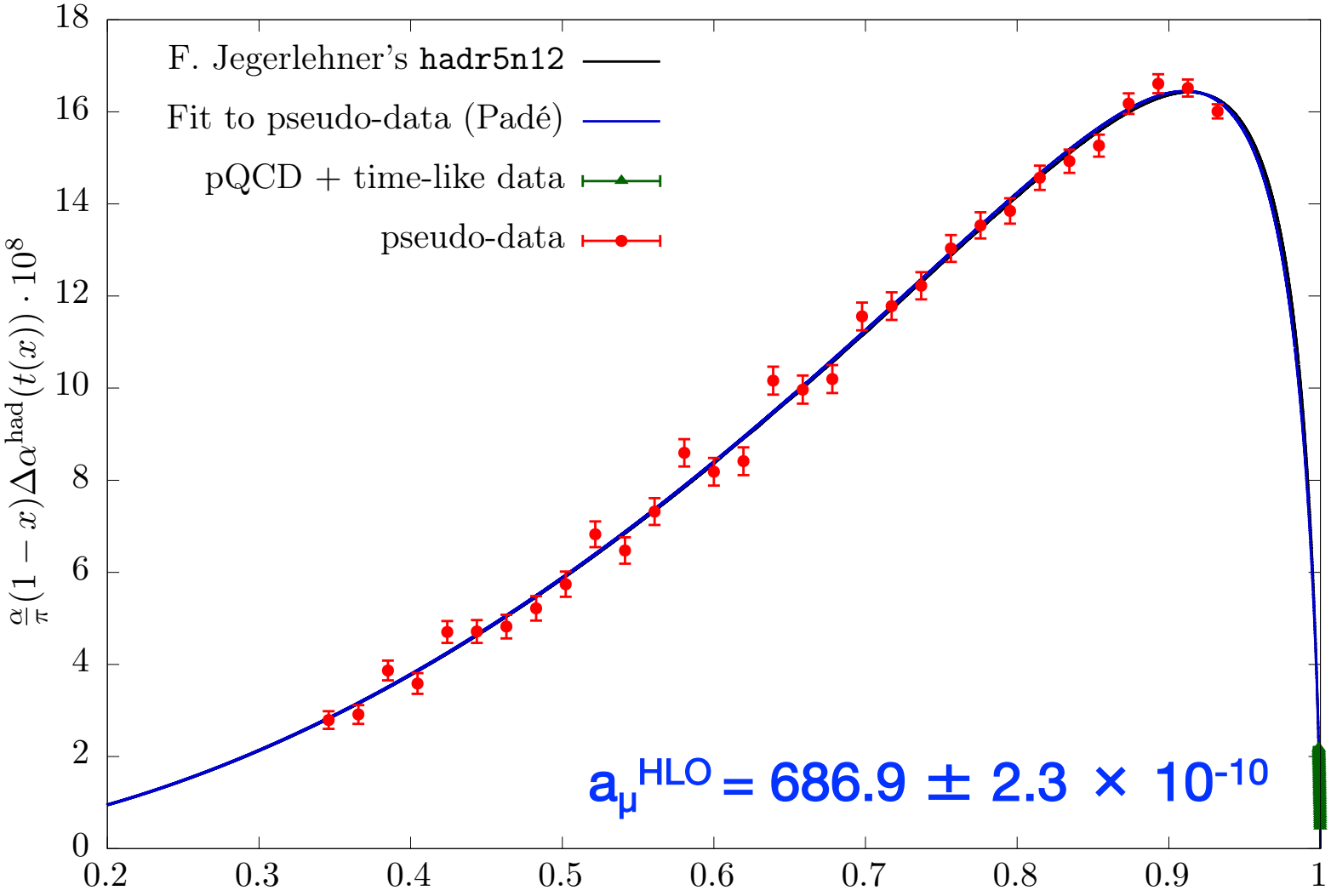


Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm



Statistical reach of MUonE on a_μ^{HLO}

(2 years of data taking at 1.3 x10^{7}μ/s)



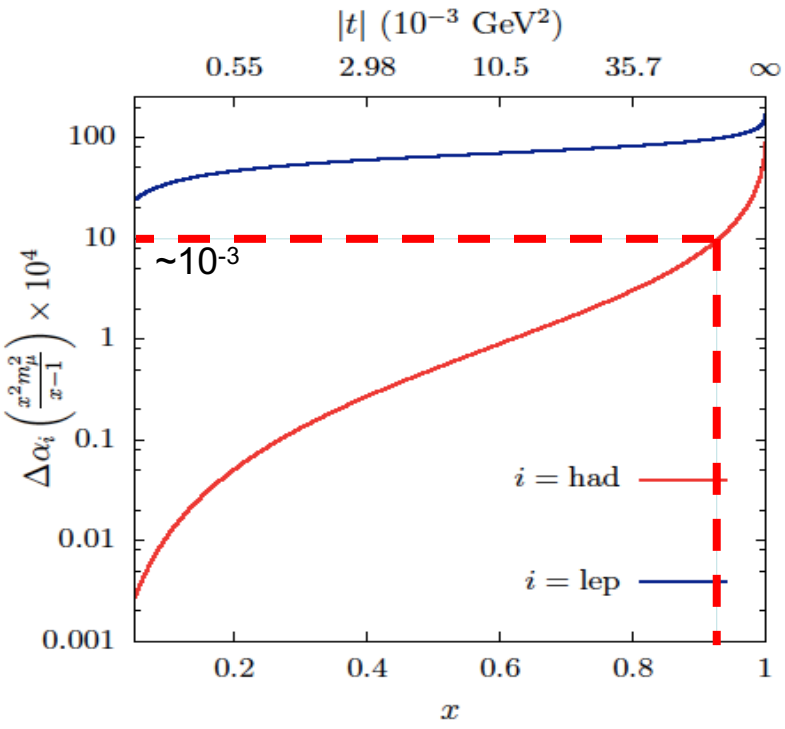
A **0.3%** stat error can be achieved on a_μ^{HLO} in 3 years of data taking with ~10^7 μ/s (4x10^{12}μe events)

Systematics considerations

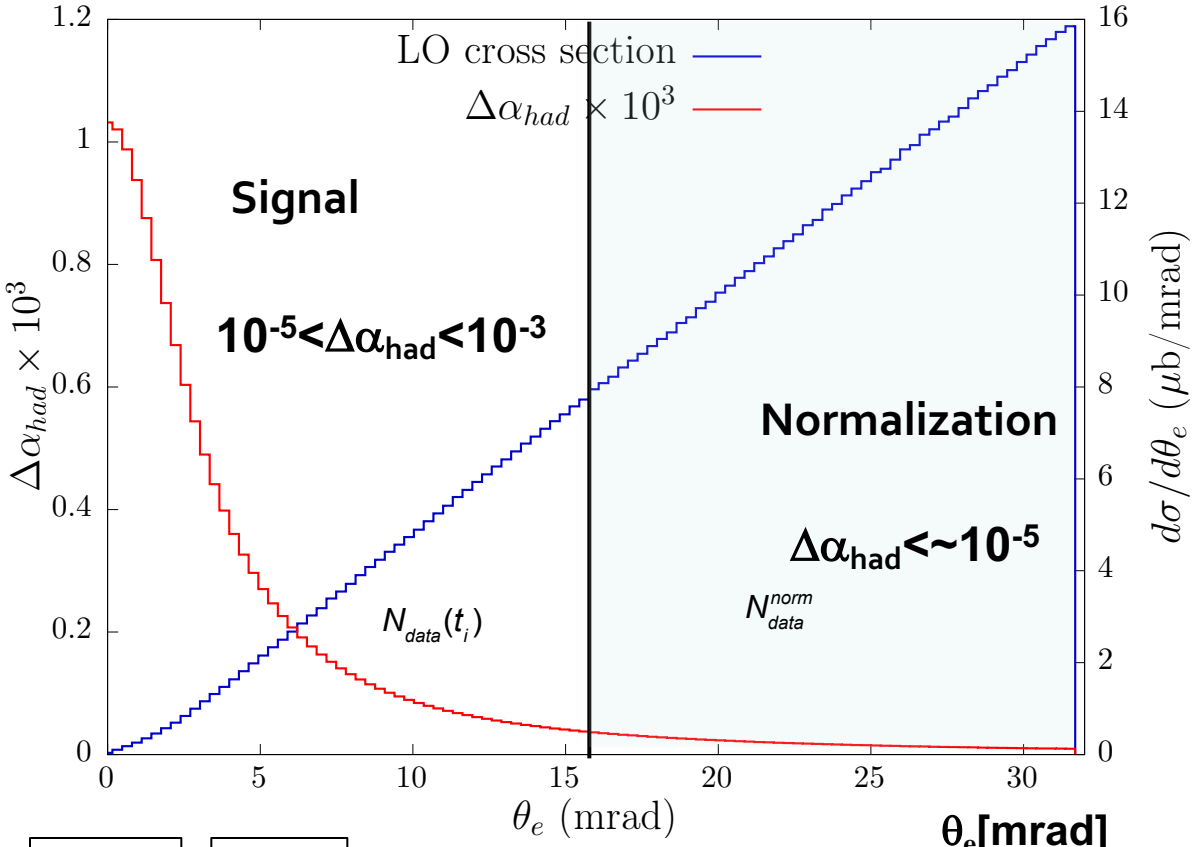
- In order to be competitive with a_μ^{HLO} from time-like data: $\delta\Delta\alpha_{had}/\Delta\alpha_{had}$ <0.5%
  → $\delta N_{e\mu}/N_{e\mu}$~10^{-5} (Δa_{had}~10^{-3} at peak region (x=0.92))

$$\delta\Delta\alpha_{had} \sim \frac{1}{2}\frac{\delta N_{e\mu}}{N_{e\mu}}$$

- Systematic uncertainty of 10 ppm at the peak of the integrand function:
  - Longitudinal alignment (~10 μm)
  - Knowledge of the beam energy (few MeV)
  - Multiple scattering (~1%)
  - Angular resolution (few %)
  - Efficiency
  - NNLO MC
  - Background subtraction
  - ….



MUonE : signal/normalization region



$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \frac{N_{data}(t_i)}{N^{norm}_{data}} \times \frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)} \sim 1 - 2(\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

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

a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

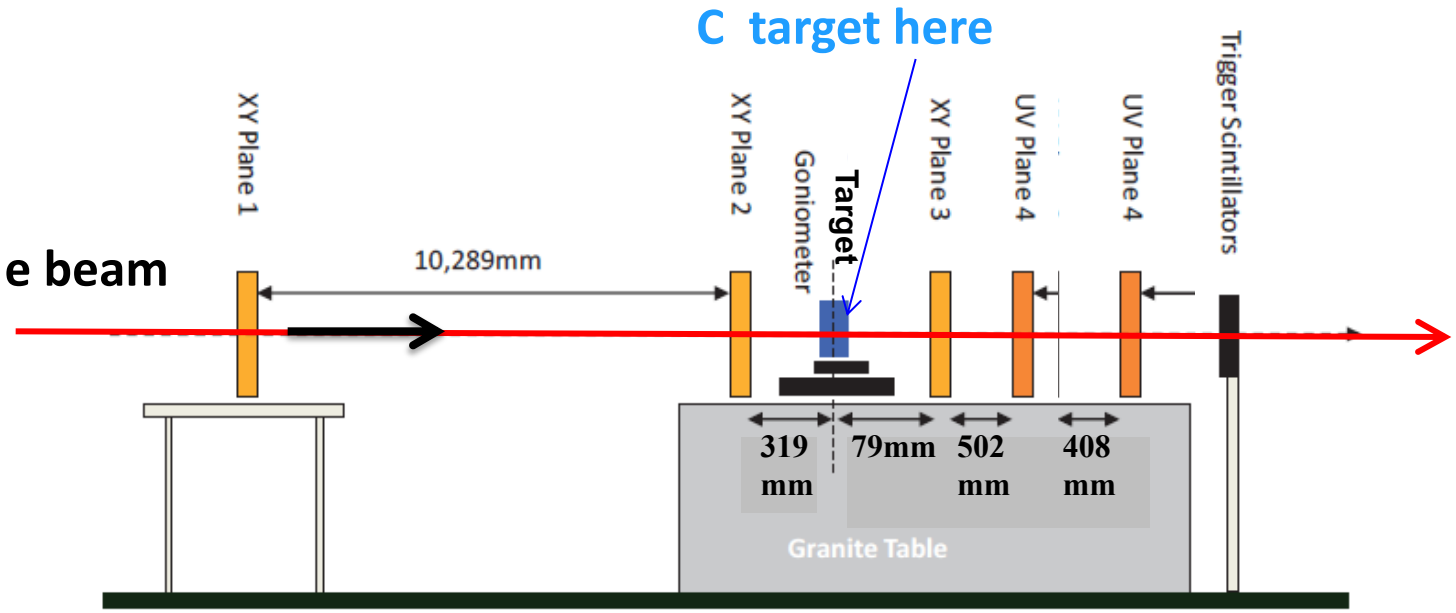
Last years progress

1. Multiple scattering studies (TB 2017)
2. Test beam at μ beamline (M2) at CERN in 2018
3. Optimization of the detector → LoI at SPSC (2019)
4. Test Run in 2021
5. Test Run in 2022/23
6. Extraction of $\Delta\alpha_{had}(t)$
7. Systematic uncertainty
8. Theory towards NNLO MC

-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf
- G. Abbiendi et al Phys. Scripta 97 (2022) 054007 [arXiv:2201.13177]

Test Beam 2017at H8: the setup

- We used the UA9 tracking system to record scattering data
- Alignment, tracking, pattern recognition, comparison with Geant4 simulation.
- **The goal**: reach **~1%** in the **core** of the MS distributions and **few per cent on the tails**



Adapted UA9 apparatus

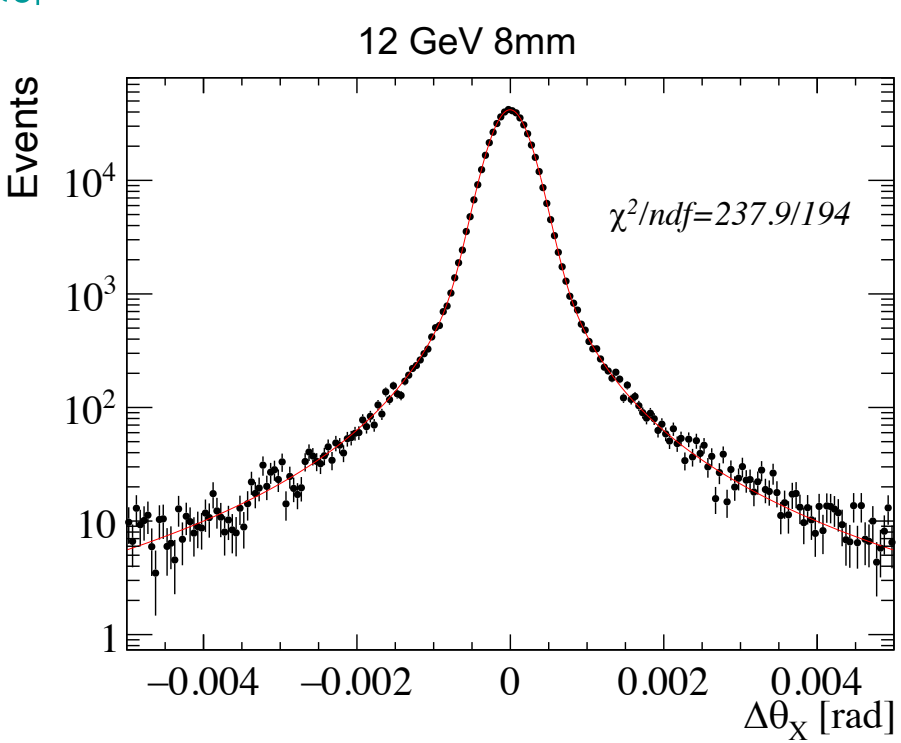
5 Si planes: 2 before and 3 after the target, 3.8x3.8 cm2 intrinsic angle resolution ~**20** µrad

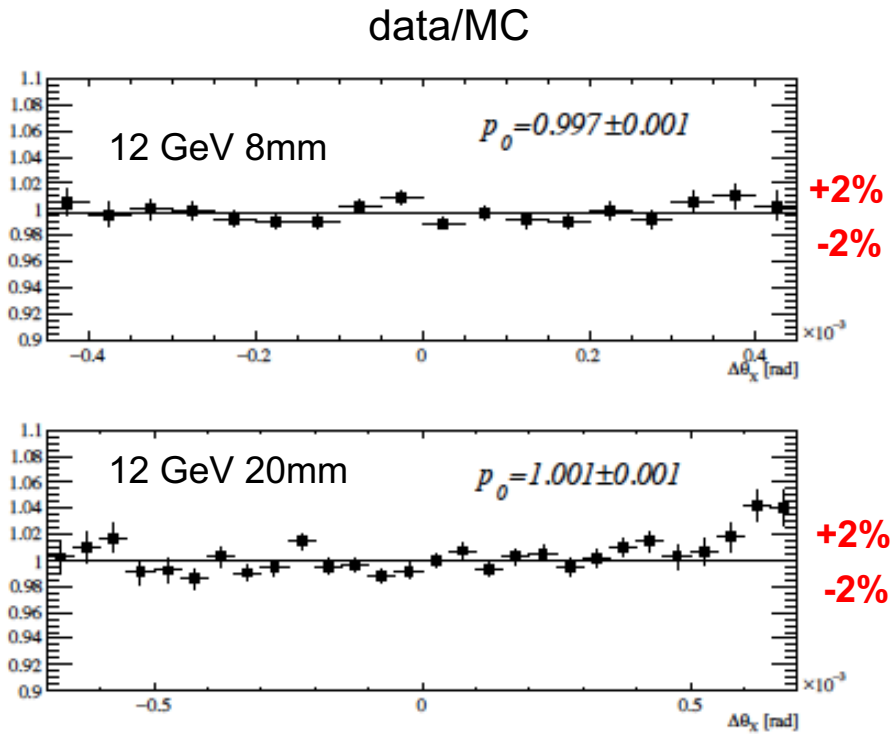
arXiv:1905.11677

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets (8, 20 mm)

JINST 15 (2020) 01, 01

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]

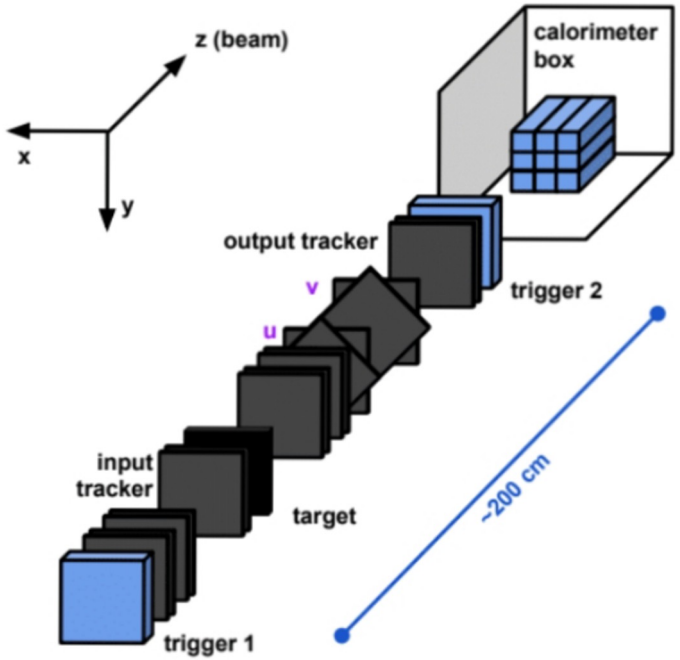


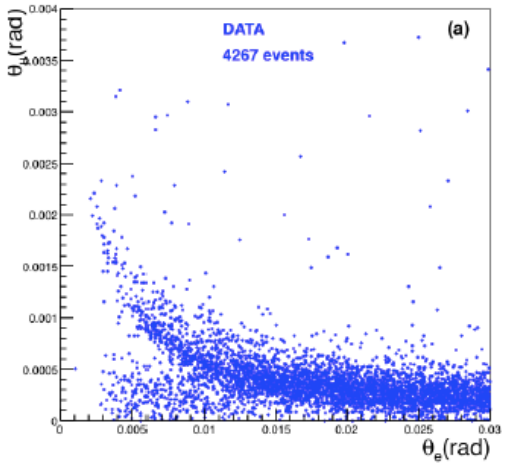


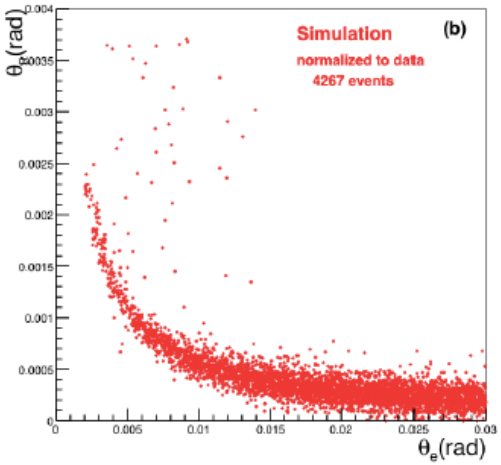
Test beam at M2 in 2018

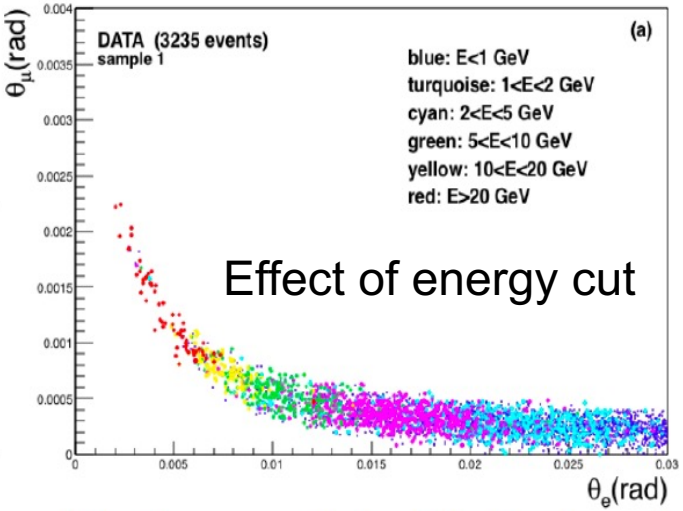
G. Abbiendi et al JINST 16 (2021) 06, P06005

arXiv:2102.11111





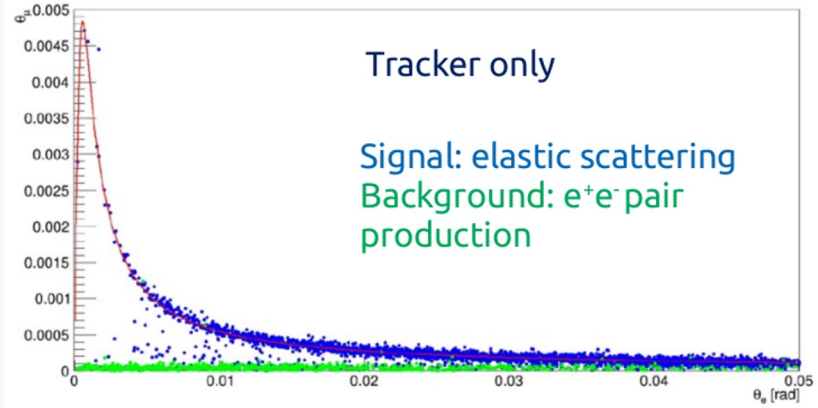


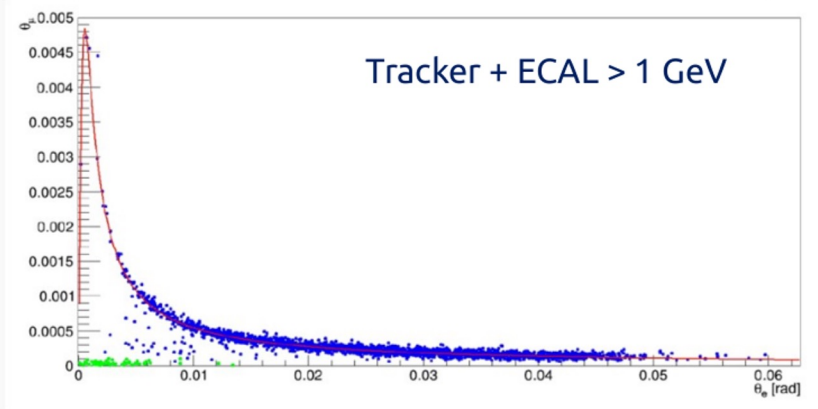


Role of detector hit (angular) resolution

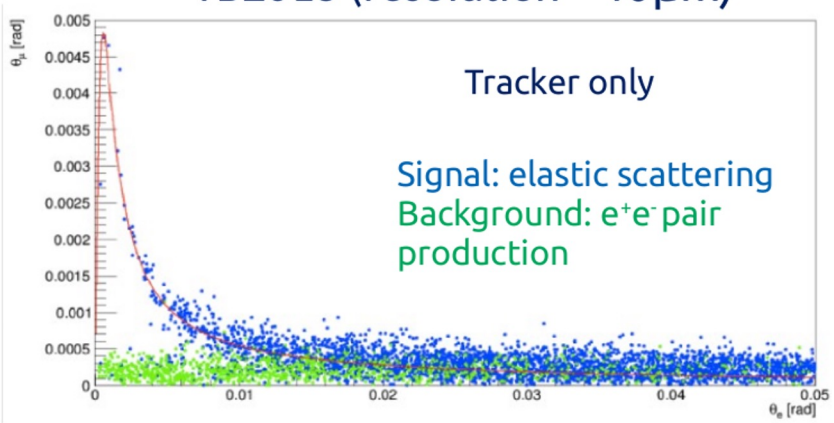
GEANT4 Simulation

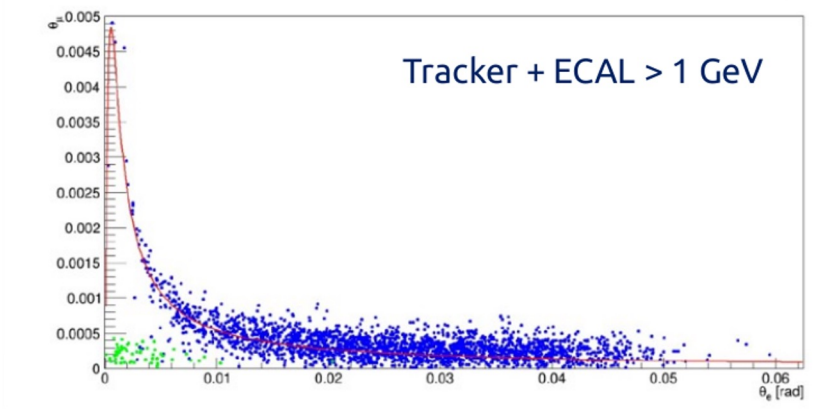
TB2017 (resolution ~7μm)





TB2018 (resolution ~40μm)





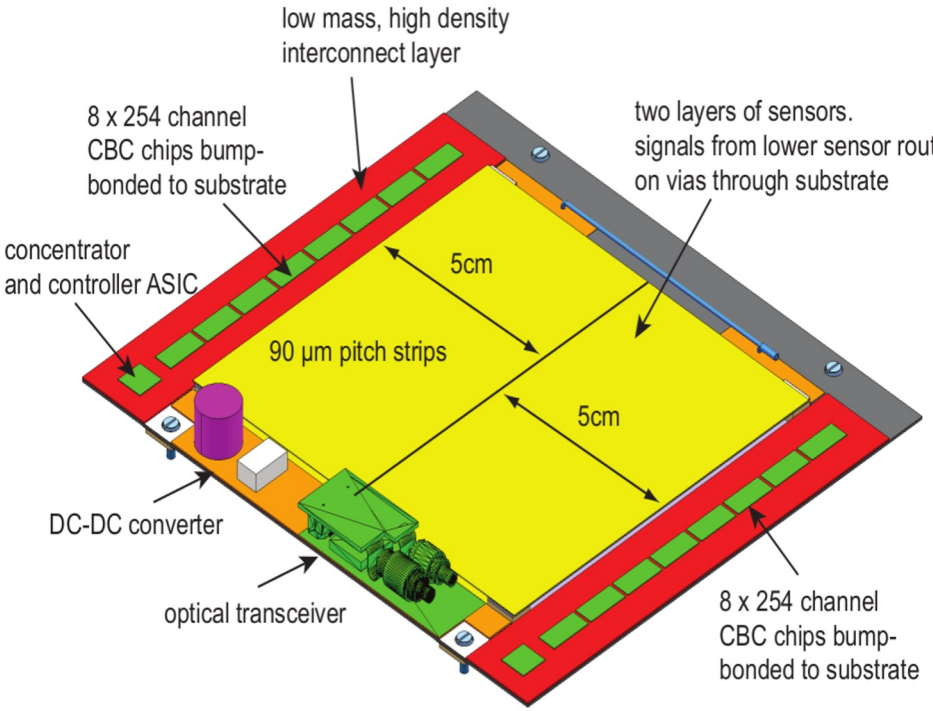
Tracking system: CMS 2S Module (baseline choice)

Requirements:

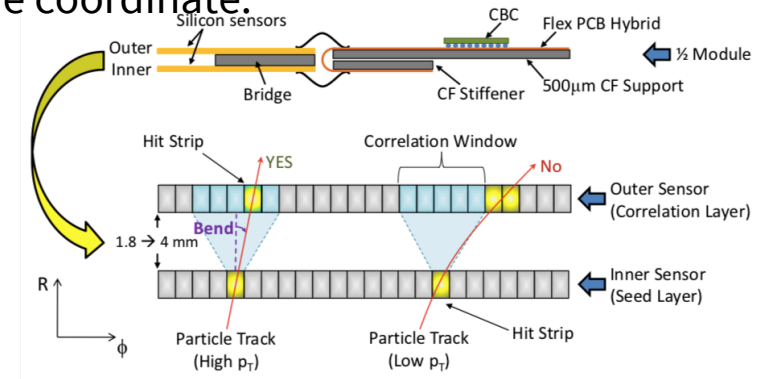
- Good resolution (~ 20 μm)
- High uniformity
- Sustain high rate (50 MHz)
- Available technology

Achievement: CMS 2S Module

- Thickness : 2 × 320 μm
- Pitch: 90 μm → σ_x = 26 μm
- Angular resolution: σ_θ ~ 26 μrad
- Readout rate: 40 MHz
- Area: 10 cm × 10 cm



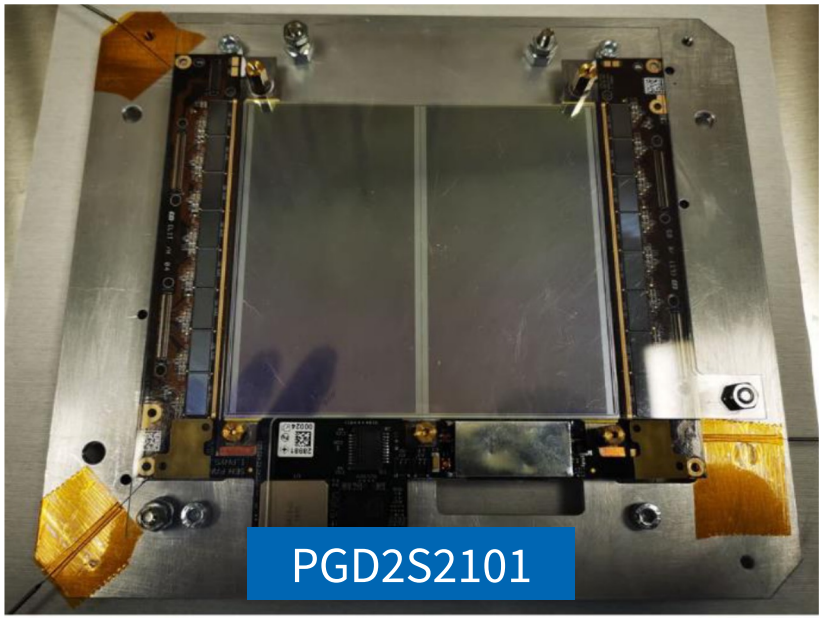
Stub: Two close-by strip sensors reading the same coordinate.



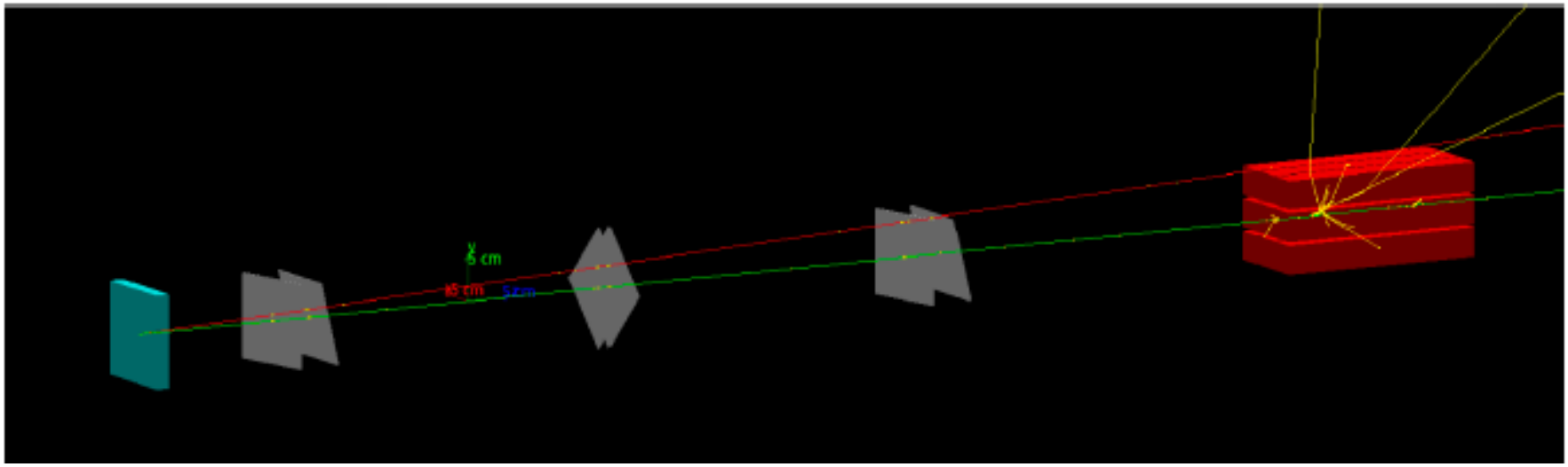
Provide complete and uniform angular acceptance, background suppression from single-sensor hits and rejection of large angle tracks.

Tracker: CMS 2S modules readiness

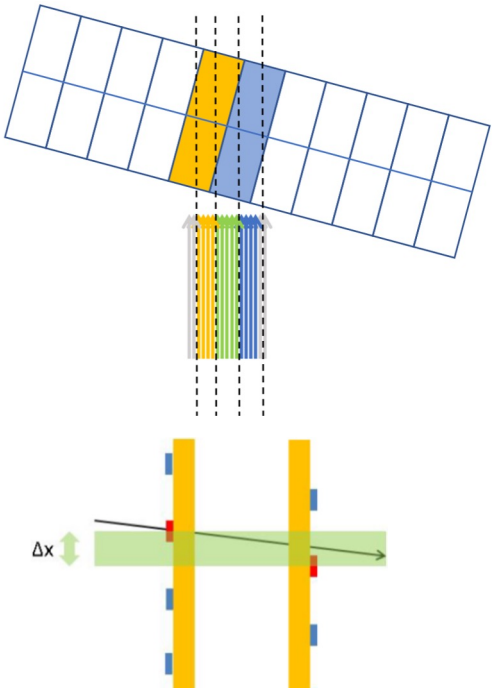
- Four 2S modules have been assembled in Perugia and shipped to CERN
- Assembly procedure is well defined, metrology measurements meet the CMS quality requirements.
- Four of these modules have been used in the in 2022 Test Run (see next slides)



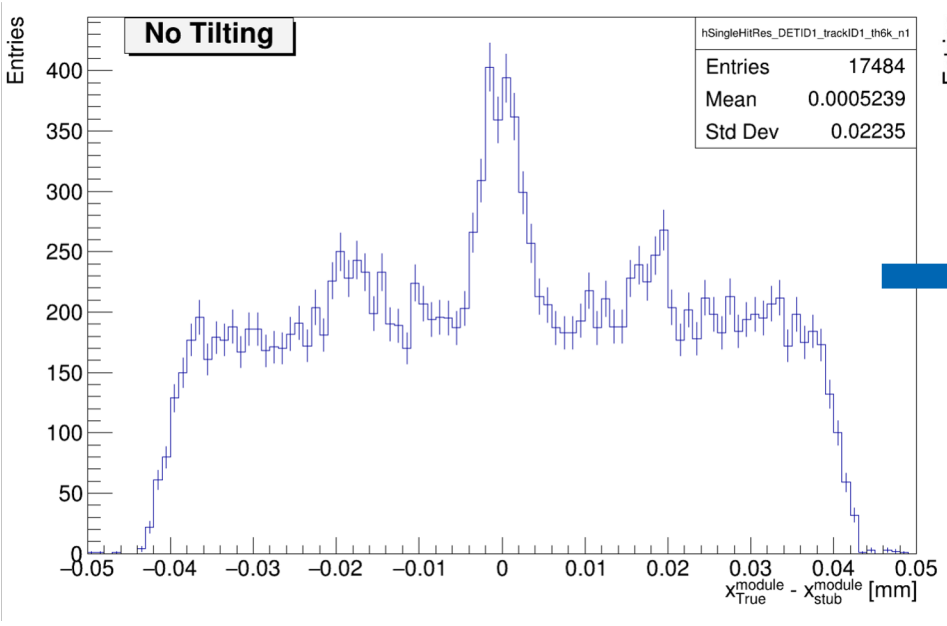
Rotating 2S sensors

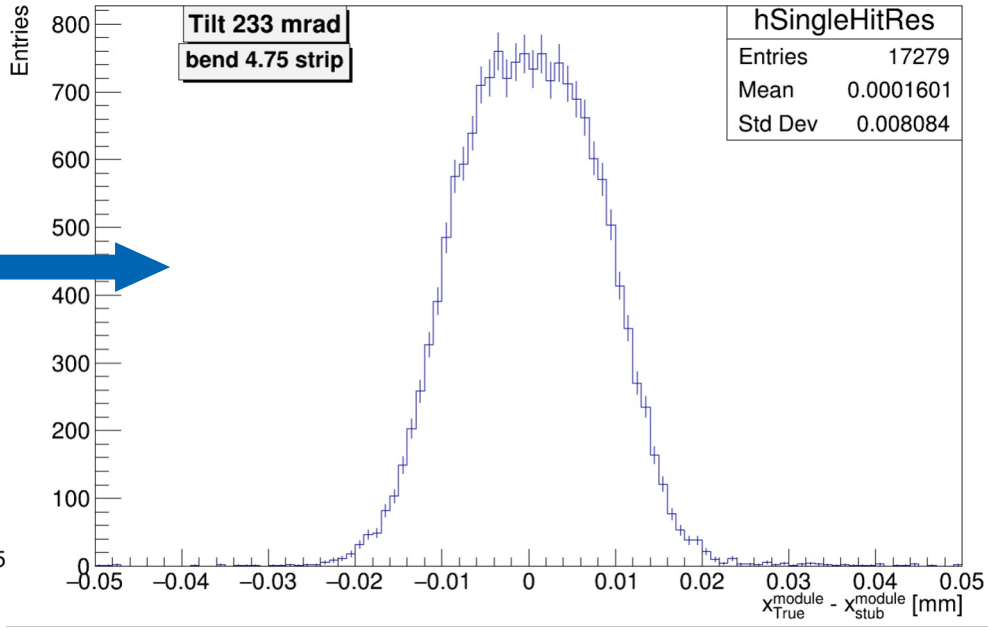


- With a pitch of 90μm the expected resolution for the 2S module is 90/sqrt(12) ~26 μm
- **Rotating a sensor** aroung an axis parallel to the strips direction improves the hit resolution
- **Optimal performance** is obtained for a tilt angle of ~14 degress
- **Further improvement** by a small tilt of 25 mrad, which is equivalent to an half-strip staggering of the two sensor layers of a 2S module



Simulation:
Improving resolution - tilted geometry





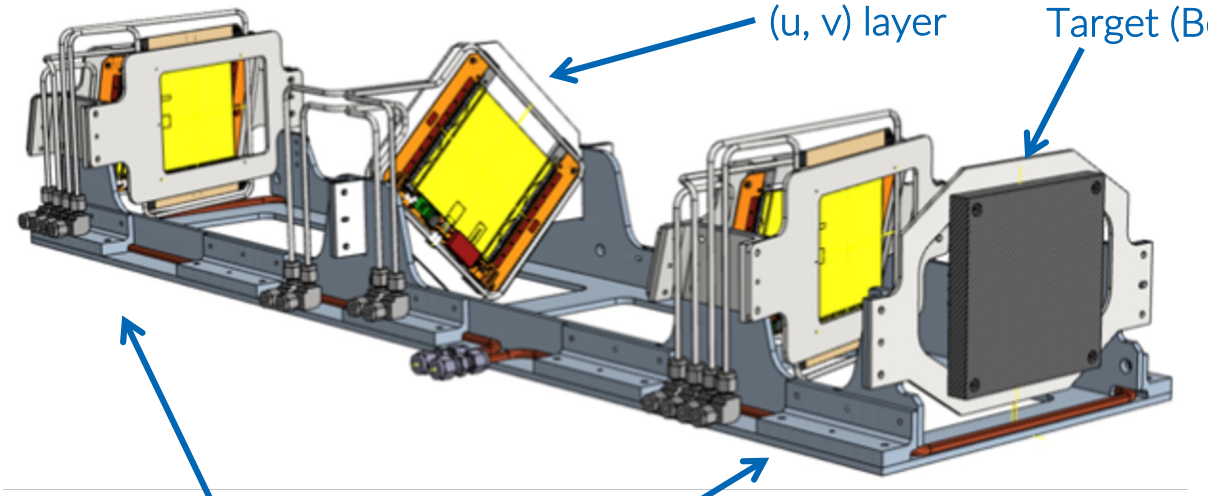
Improvement due to:

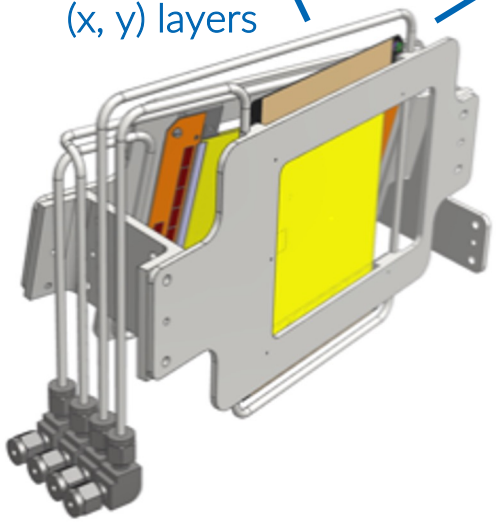
- charge sharing between adjacent strips
- effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½ pitch

Final resolution

$22\ \mu m \rightarrow O(10)\ \mu m$

Tracking station



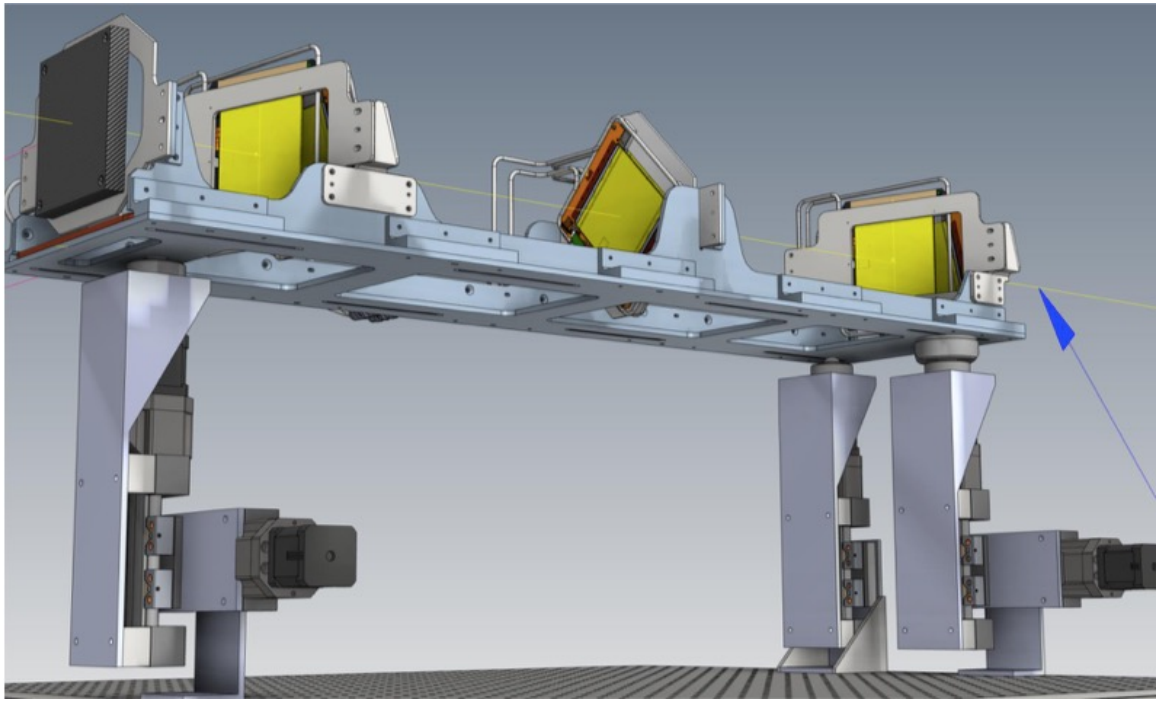


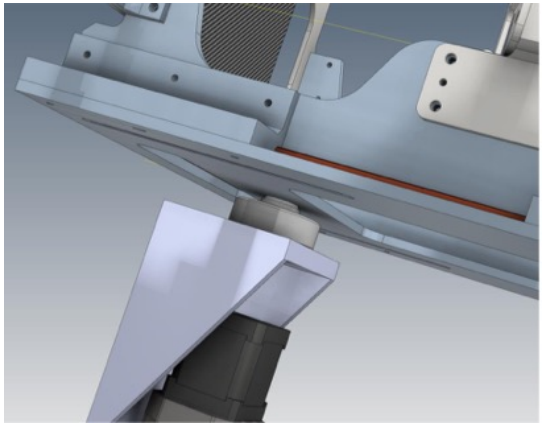
Relative position within a station must be stable at 10 µm.

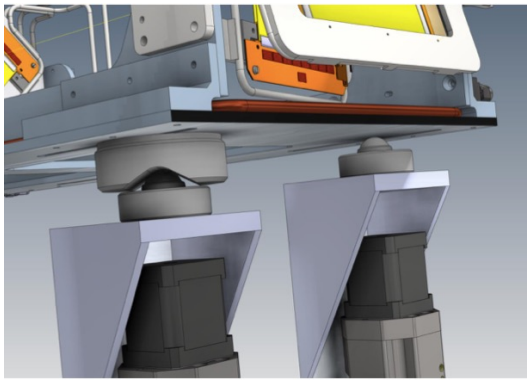
Low CTE mechanical structure: INVAR (alloy of 65%Fe, 35%Ni)
Holographic system to monitor the distance between two modules

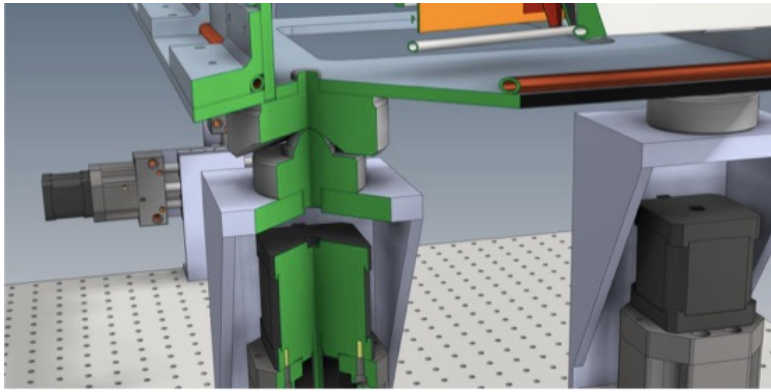
- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

Tracking station



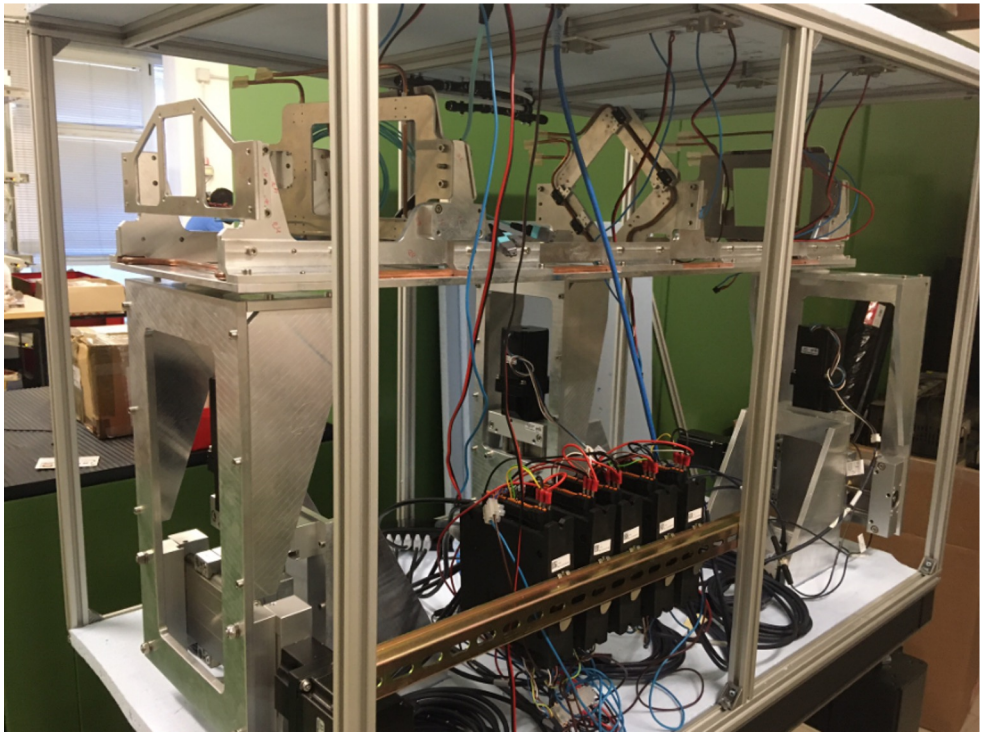


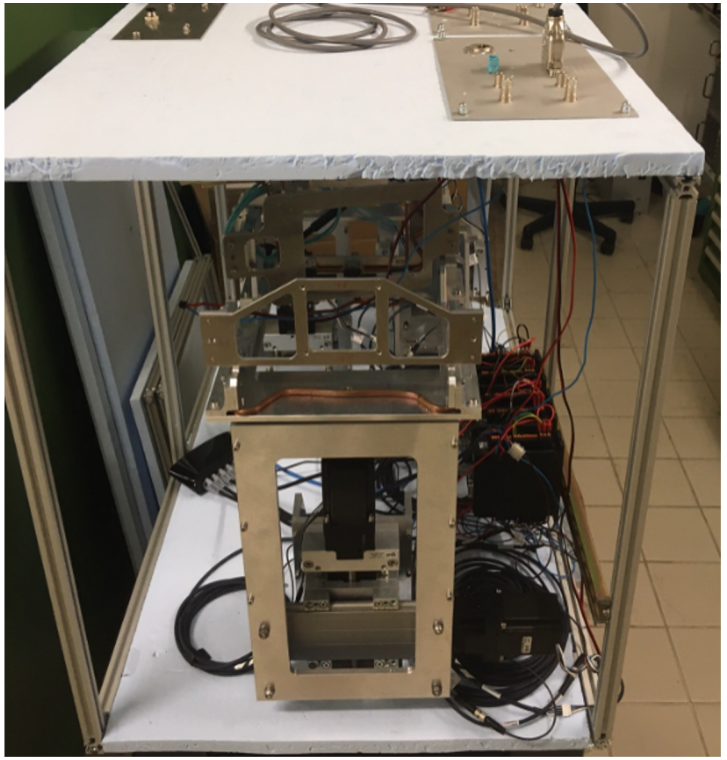




Tracking station

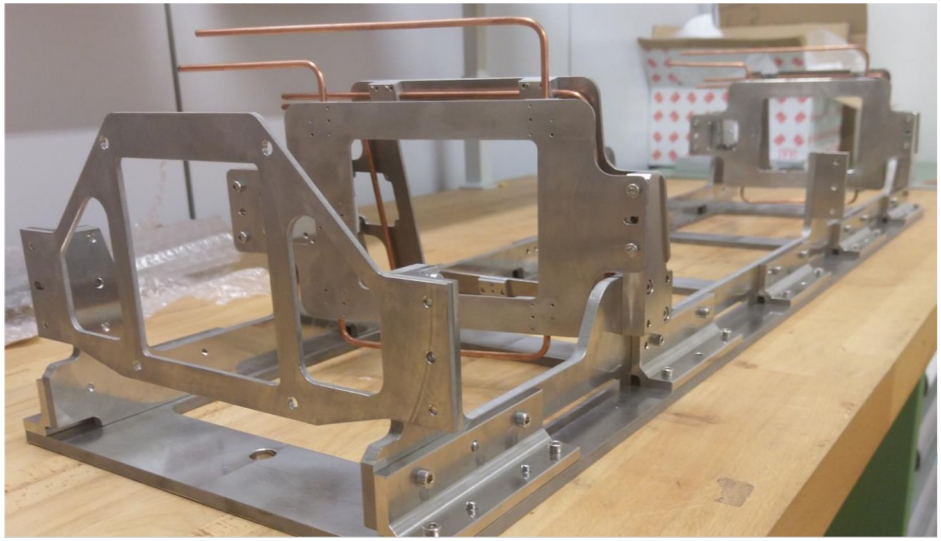
- Two Invar Stations ready
- Stepper motors will be used to align the station to the beam.
- The station is now at CERN for Test Run 2022 (see next slides)

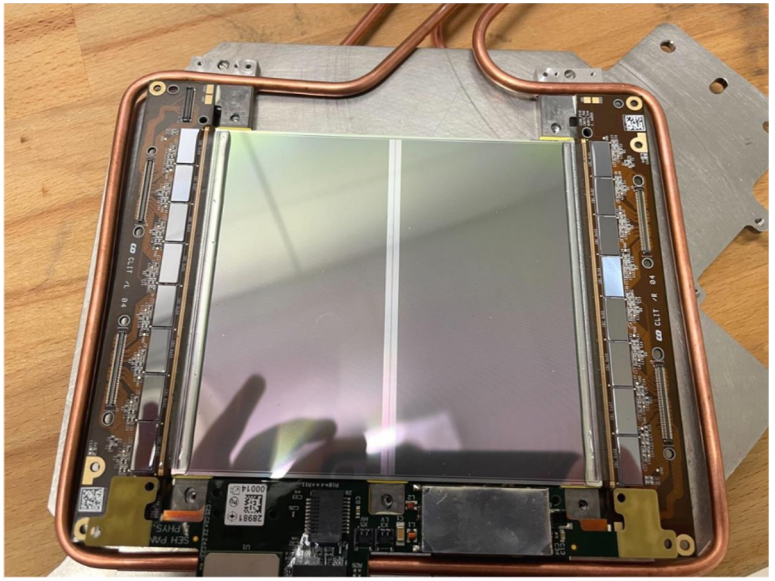




2S module on its frame

The support structure in INVAR



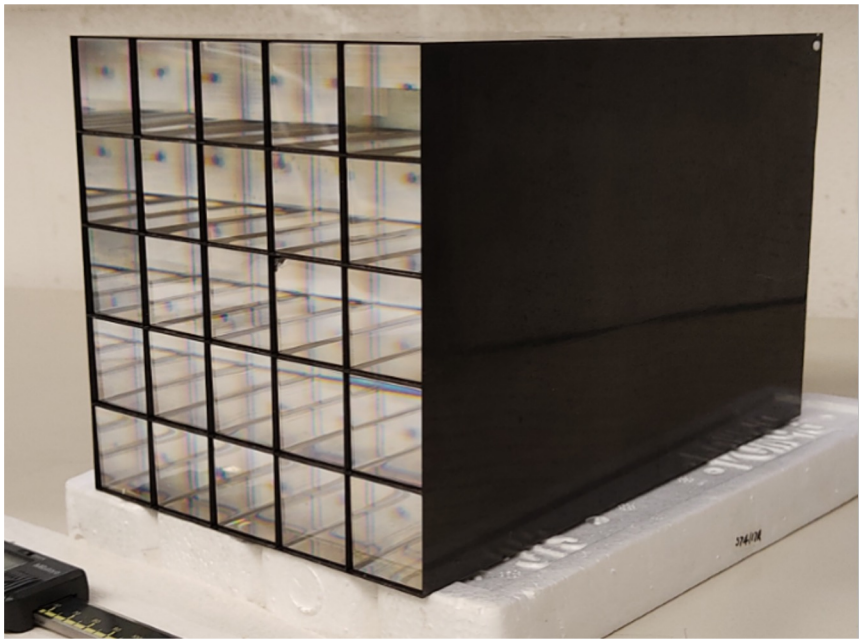


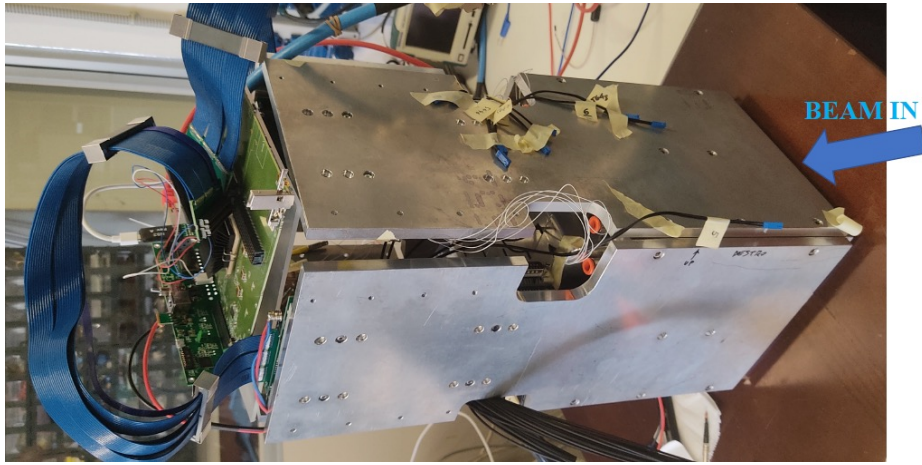
Very expensive
Difficult to machine

ECAL

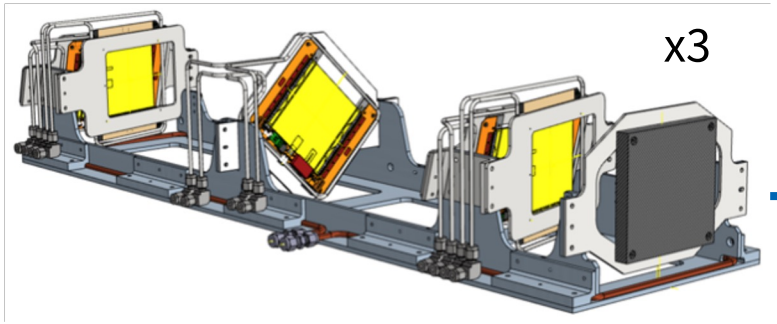
- 5x5 $PbWO_4$ crystals (CMS ECAL).
  - 2.85x2.85 cm2.
  - Length: 22cm (~25 X0).
  - Total area: ~14x14 cm2.
- Readout: APD sensors, 10x10mm² photosensitive area.
- Assembly of the prototype completed
- 16 channels digitizer boards designed and tested
- Laser pulse system in construction
- DAQ system for integration of the calorimeter with tracker under development

Test with e- beam at CERN in July 2022; analysis in progress



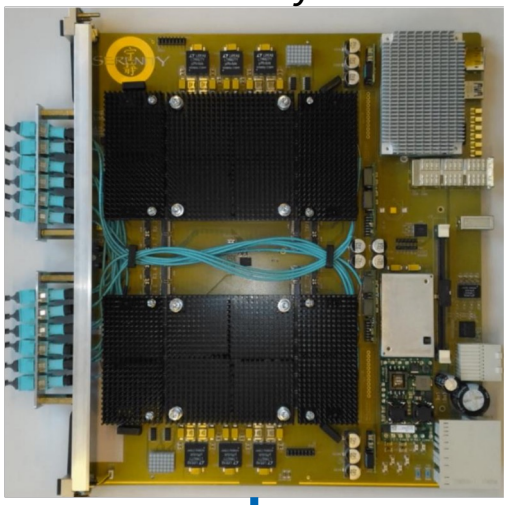


DAQ system

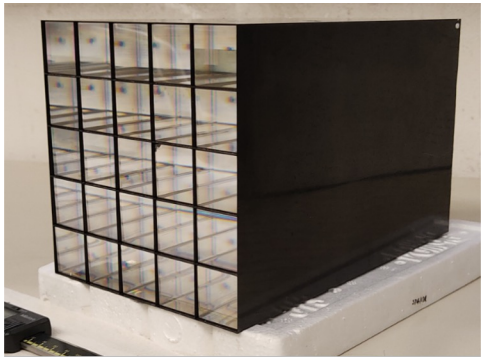


~ 35Gbps per spill (TR)

CMS Serenity board



ECAL

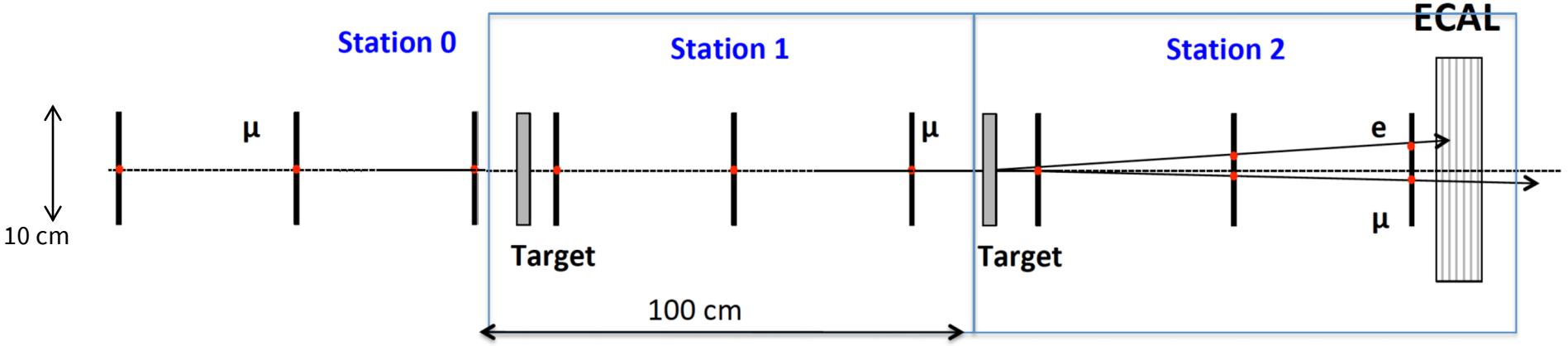


STORAGE

- Test Run: read all data with no event selection.
- "Serenity" board served as interface between the FE modules and downstream PC
- Information will be used to determine online selection algorithms to be used in the Full Run.
- Large fraction of firmware in common with CMS (but asynchronous mode)

Milestone: Test Run with 3 stations

A Test Run with a reduced detector (2+1 stations) has been approved by SPSC in 2020 to validate our proposal.



- Pretracker +
- 2 MUonE stations +
- ECAL

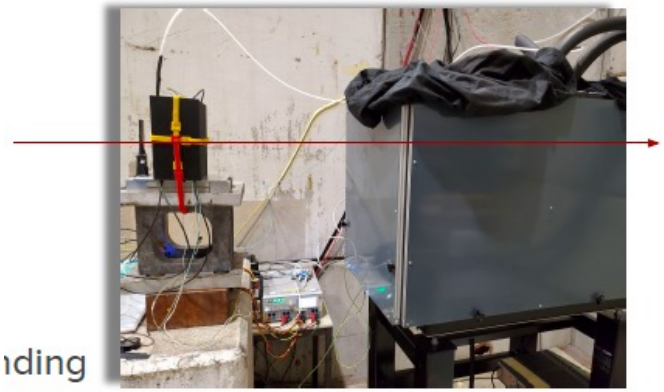
Main goals:

- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Check the DAQ system.
- Extract $\Delta\alpha_{lep}(t)$.

Delayed to 2023 due to covid and delay with modules procurement …meanwhile

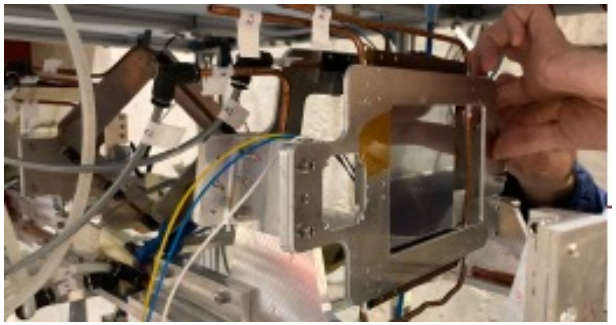
Test Run 2021

- Parasitic beam test,3 weeks in Oct/Nov 2021
  - M2 muon beam in CERN NA
  - 160 GeV muons, asyncronous of 10 kHz
  - Join test with CMS Tracker



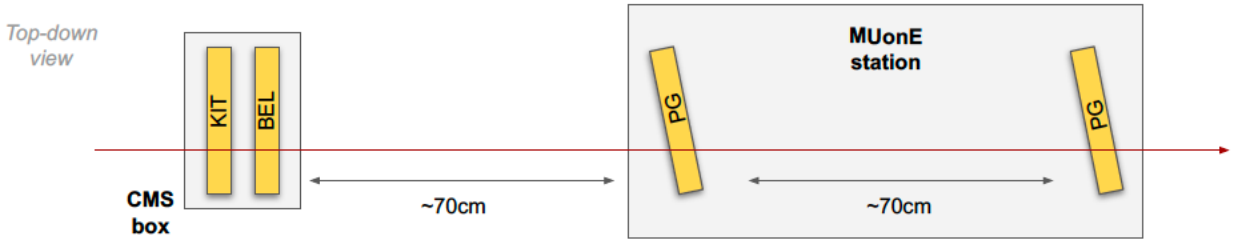
- First demostration of a full electronics chain

- Four 2S modules tested in beam
- 2 modules in MUonE enclosure
- 2 module in CMS box



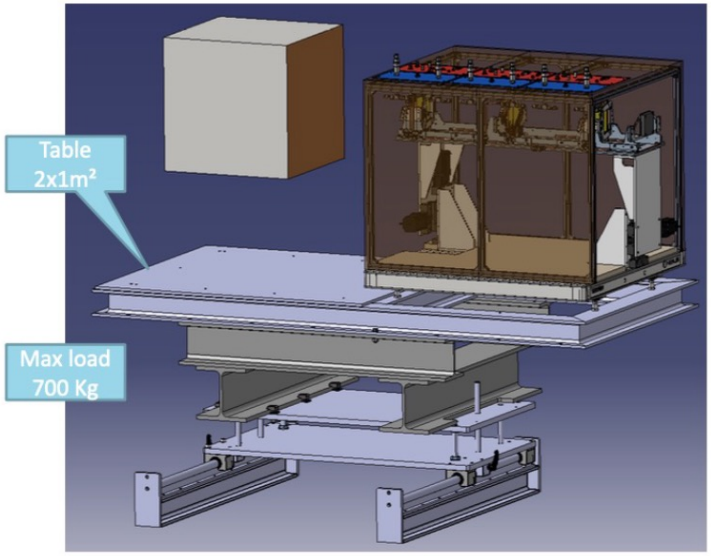
- Module readout via Serenity prototype

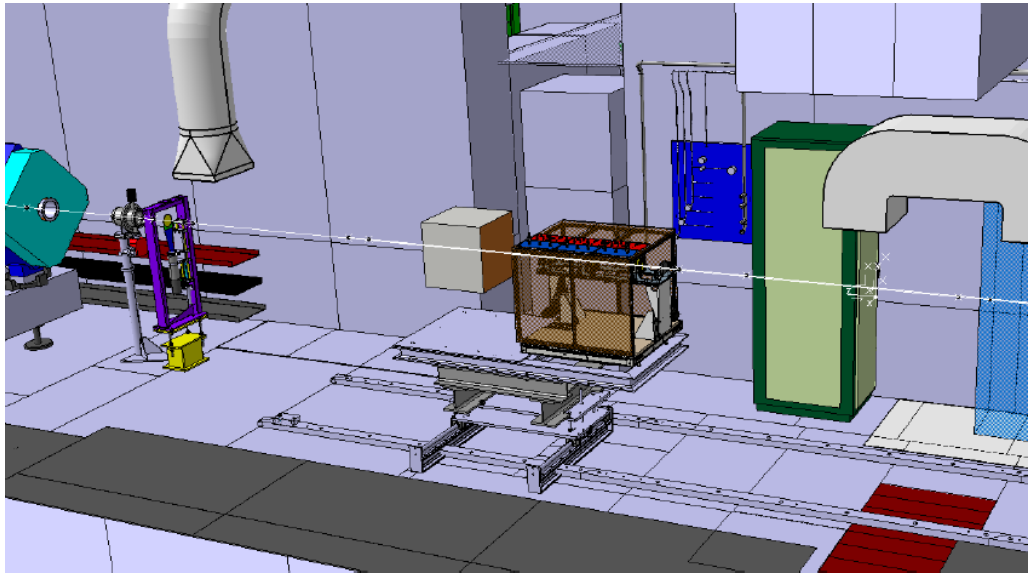
- 40MHz continuous readout of 2S modules
- 30 TB of data collected to disk



Test Run 2022

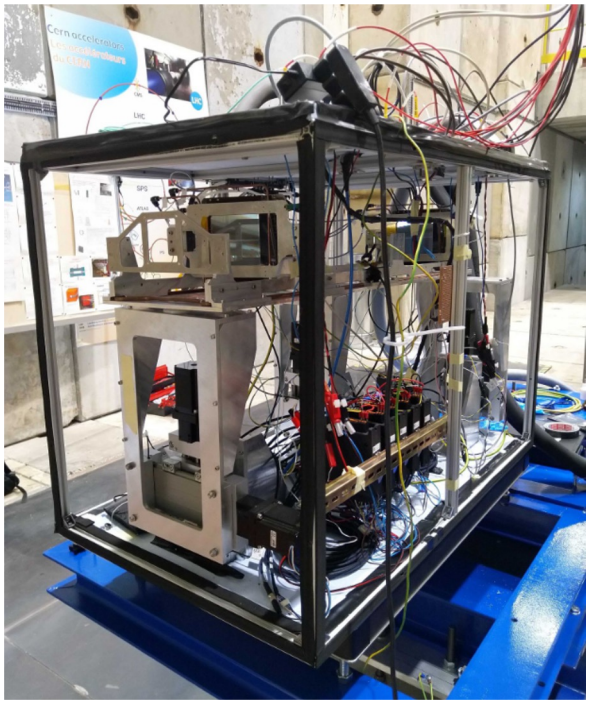
- Test with one station
- 4 of 6 2S modules installed (U, V modules in centre are missing)
- Take beam intermittently for ~2 days every ~2 weeks, when Compass doesn't take beam
- System (trolley) to insert/remove our station from the beam
- This test allows to commission a tracking station and study the performances on M2 beam





Test Run 2022

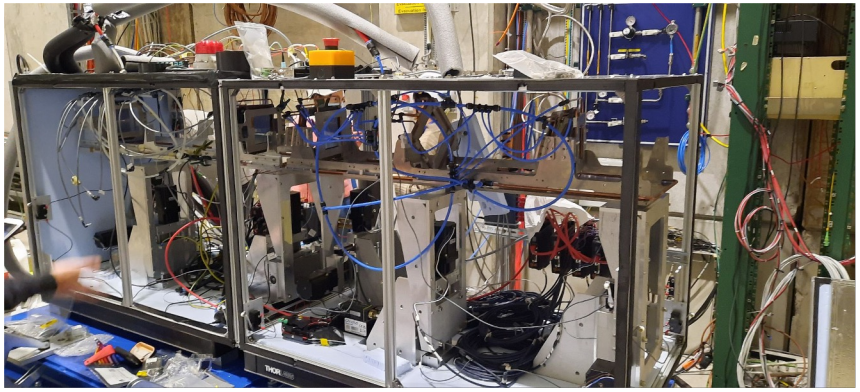
The station is placed on beam
Beam arrives in front of the picture
Behind the station there is Compass

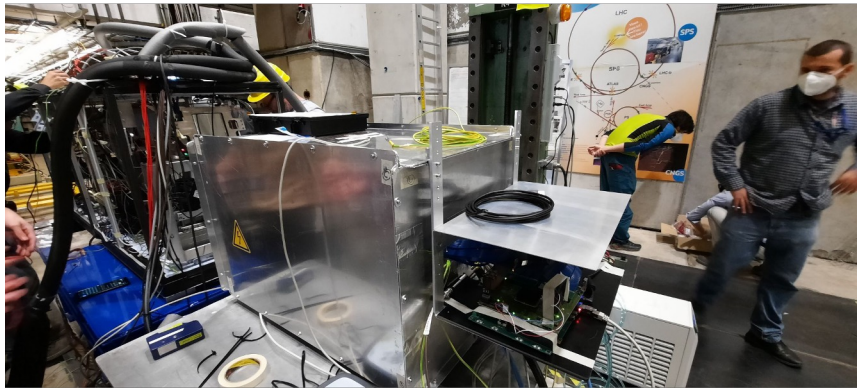


(June 2022)

Test with a full station and a calorimeter (October '22)

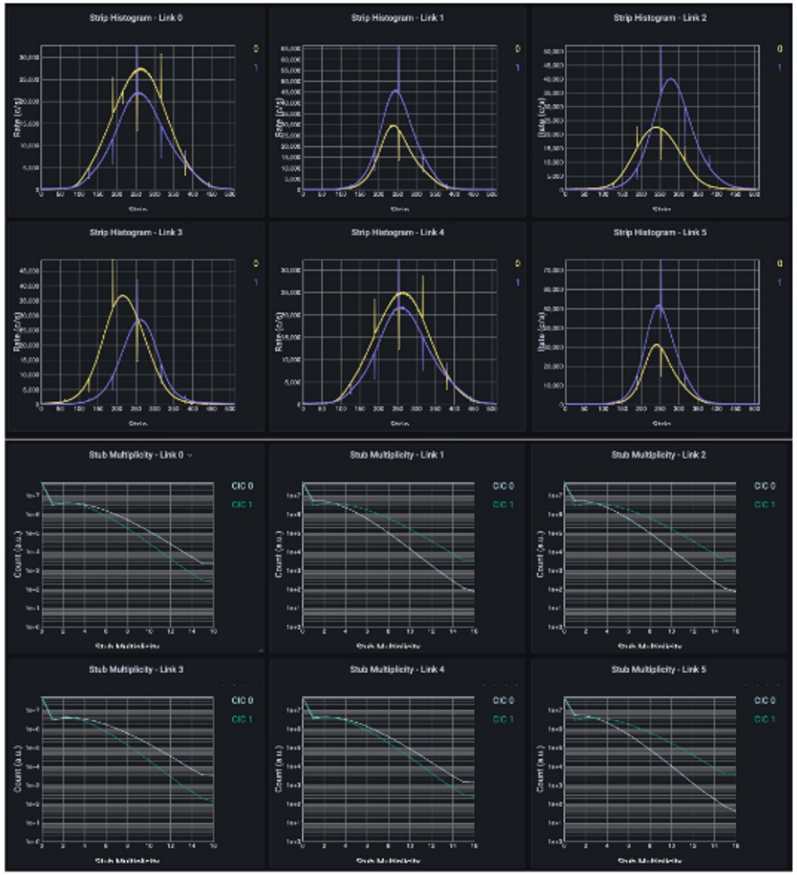
- A fully equipped tracking station and the calorimeter
- One week of test in M2 as main users performed the last October
- High intensity muon beam, up to 2×10^8 muon/spill, for the first time





Fast DQM

- Some metrics recorded directly on the FPGA
  - Check of system stability before starting data-taking
  - Fast tuning without needing access to data
- Key metrics exported:
  - Beam Profile
  - Stub multiplicity
  - Link status & errors
  - Stub rate



Analysis is in progress

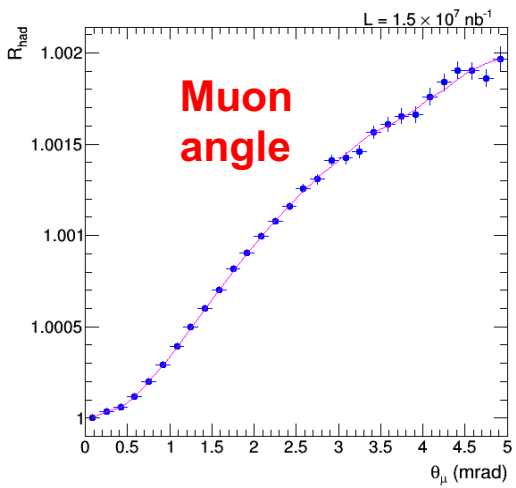
Extraction of a_μ^{HLO}

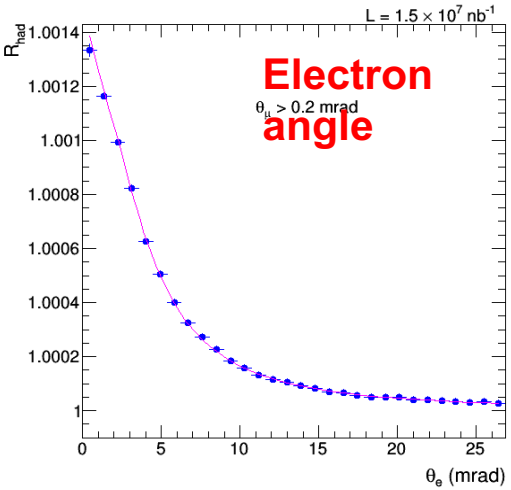
$\Delta\alpha_{had}(t)$ parameterised according to the "Lepton-Like" form.

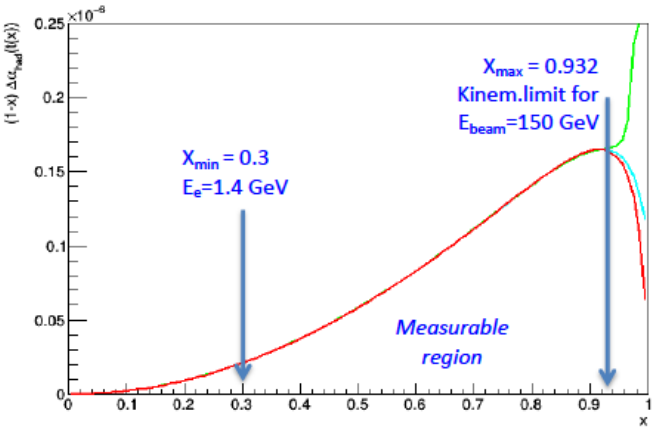
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9}-\frac{4}{3}\frac{M}{t}+\left(\frac{4}{3}\frac{M^2}{t^2}+\frac{M}{3t}-\frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2-parameters function (K, M)

Template fit to the 2D (θ_e, θ_μ) angular distribution from NLO MC generator with parameterised detector resolution → $\Delta\alpha_{had}(t)$ best fit







$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

From $\Delta\alpha_{had}(t)$ best fit → a_μ^{HLO}

a_μ^{HLO} (MUonE) = (688.8 ± 2.4) × 10^{-10} vs 688.6 x10^{-10} (input value)

[full statistics, 1.5 x10^4 pb^{-1} (4x10^{12} evts with E_e>1 GeV)]

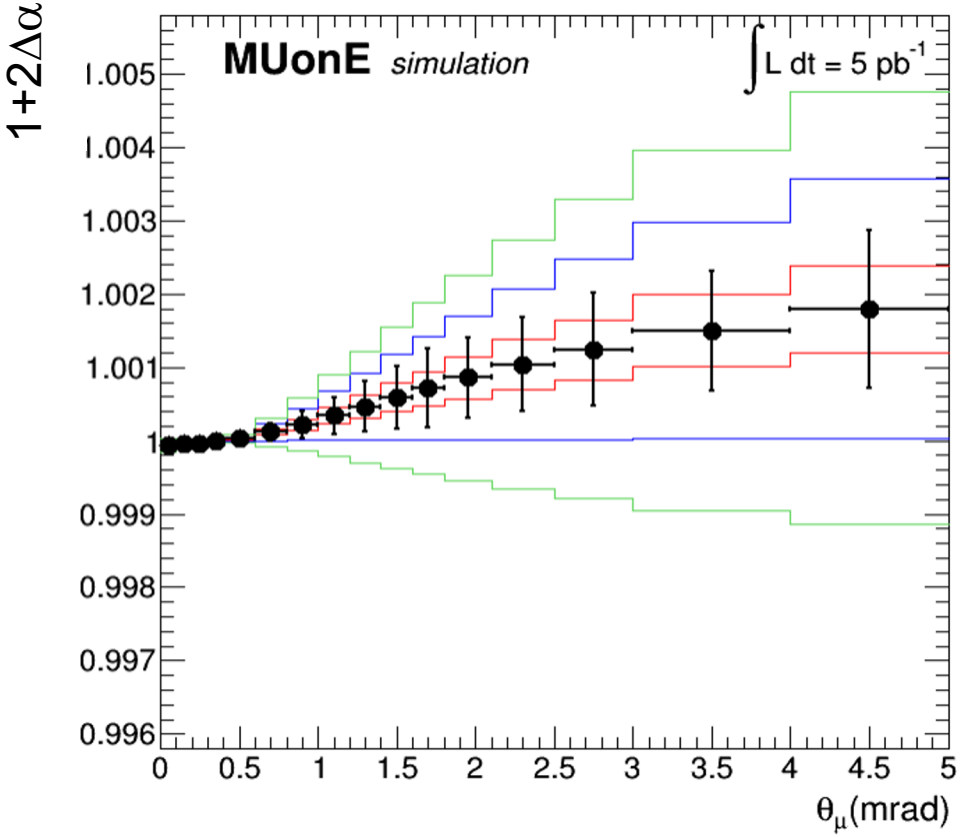
0.3% statistical error confirmed

Sensitivity to $\Delta\alpha_{had}(t)$ Test RUN

Expected luminosity for the Test Run: L = 5 pb^{-1}

$$\frac{d\sigma(\Delta\alpha_{had}(t) \neq 0)}{d\sigma(\Delta\alpha_{had}(t) = 0)} \cong 1 + 2\Delta\alpha_{had}(t)$$

~10^9 events with E_e > 1 GeV (θ_e < 30 mrad)



We will be able to extract the leptonic running ($\Delta\alpha_{lep} \sim 10^{-2}$)

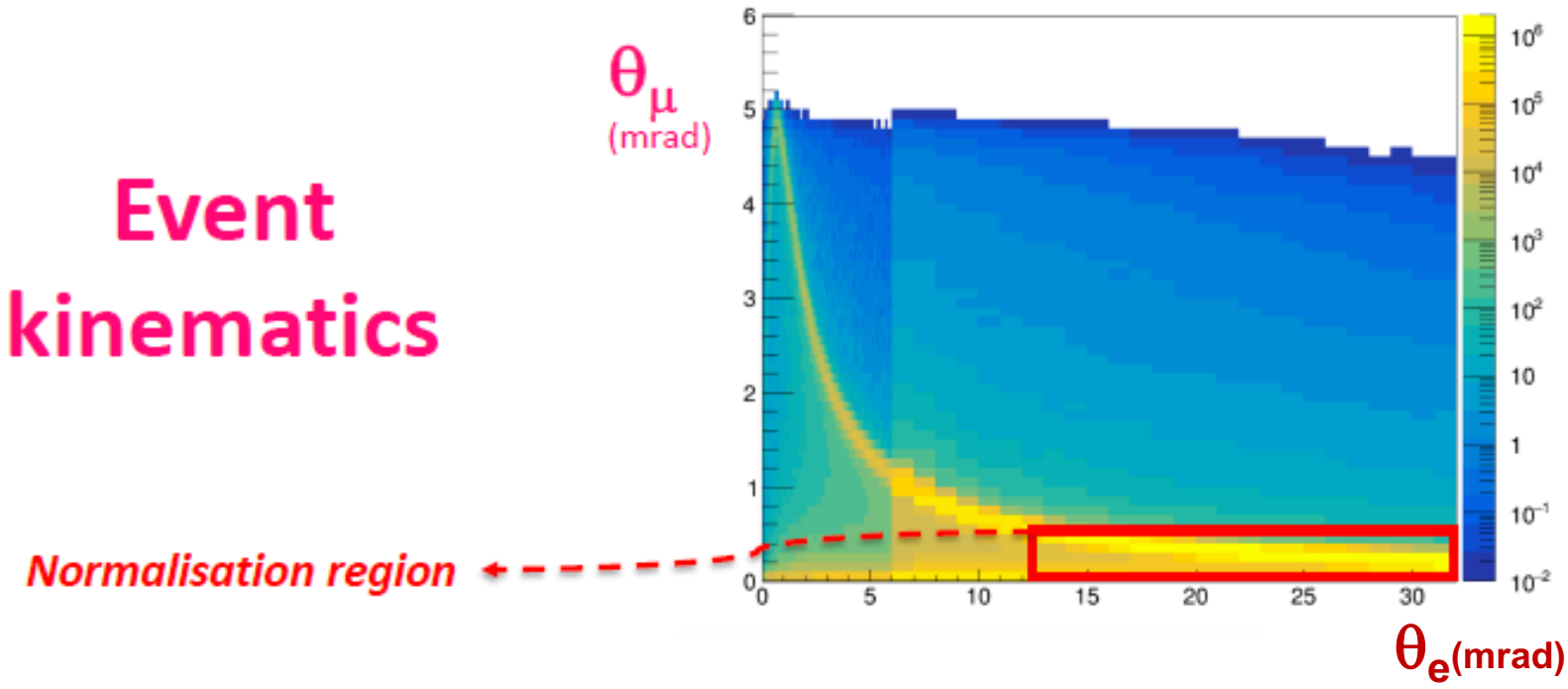
Marginal sensitivity also to the hadronic running ($\Delta\alpha_{had} \sim 10^{-3}$)

$$K = 0.137 \pm 0.027$$

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

Template fit with just one fit parameter K= k/M in the $\Delta\alpha_{had}$ parameterization. The other parameter fixed at its expected value: M = 0.0525 GeV^2

Importance of the normalization region



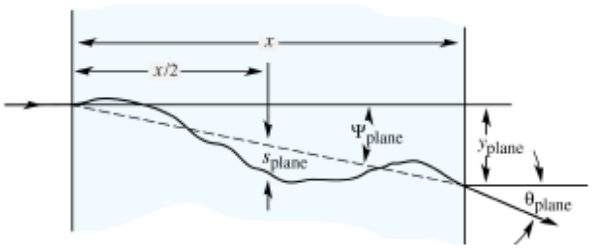
- Three main sources of systematic errors (Multiple Scattering, Intrinsic angular resolution, miscalibration of energy beam) give large effects in the normalization region
- Calibration of these effects by fitting the data in the normalization (control) region .
- Residual systematic uncertainties will be included as nuisance parameters in a likelihood fit and will be determined simultaneously with the signal.

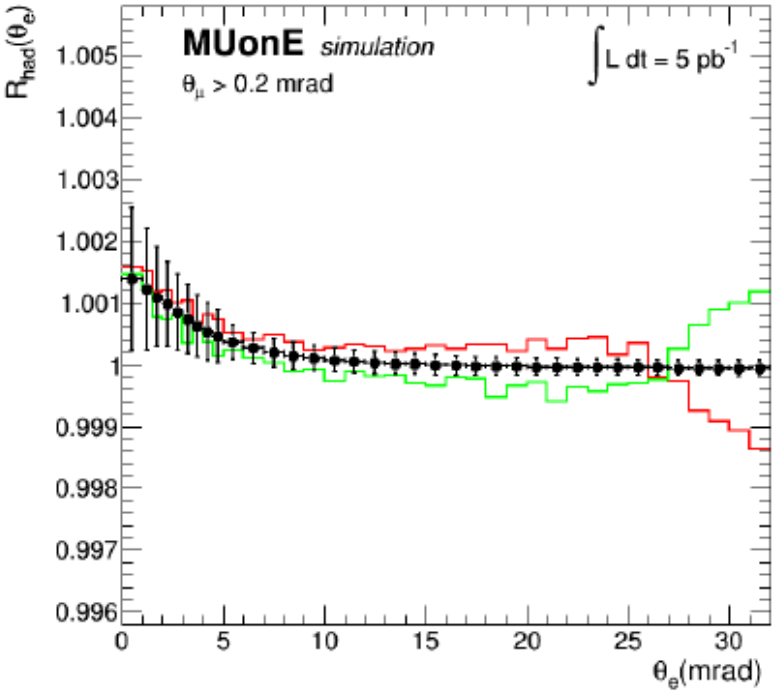
Systematic Effects: Multiple Coulomb Scattering

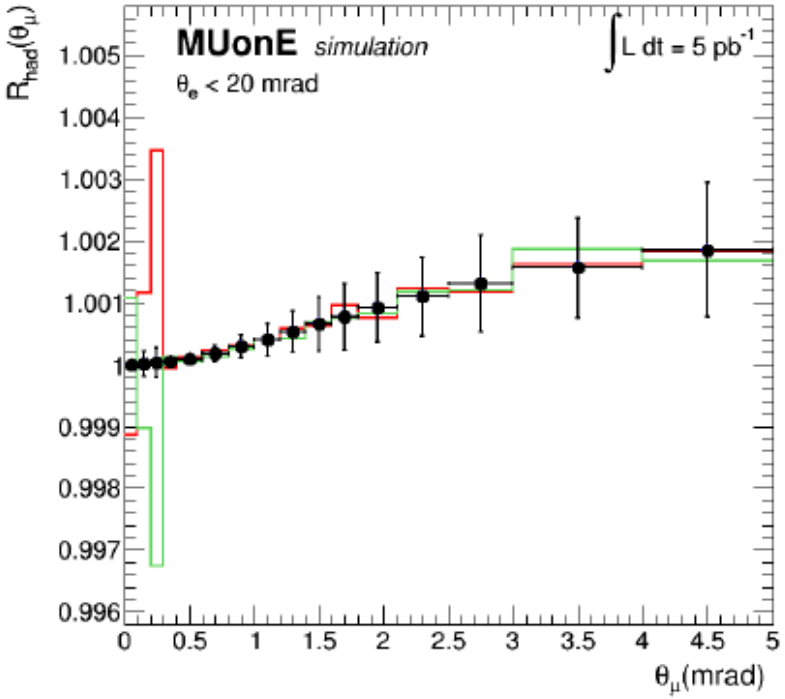
Effect of a flat error of ±1% on the core width of multiple scattering

+1%

-1%



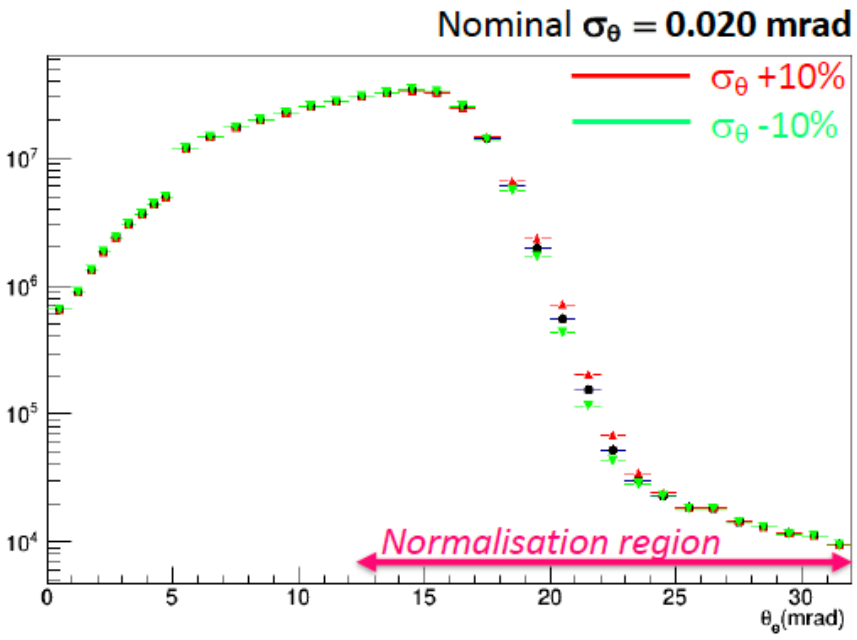


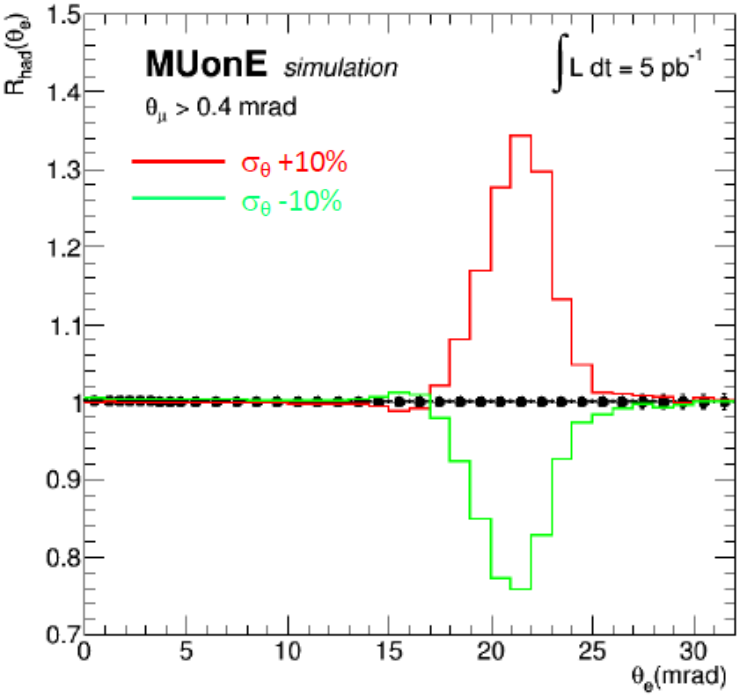


- Large effect in the normalization region
- Excellent way to control this parameter from a clean control region

Systematic Effects: Intrinsic angular resolution

The **intrinsic angular resolution** can be probed by looking at the θ_e distribution after a cut on θ_μ distribution, e.g. cutting at $\theta_\mu > 0.4$ mrad

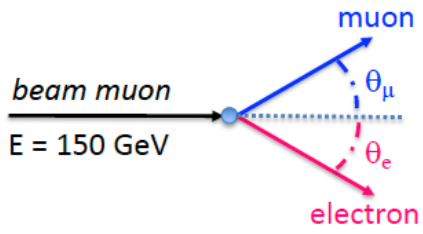




- Huge effect! (20-30%)
- Normalization region: no effect on the signal region
- Excellent way to control this parameter from a clean control region

Systematic Effects: Beam Energy Scale

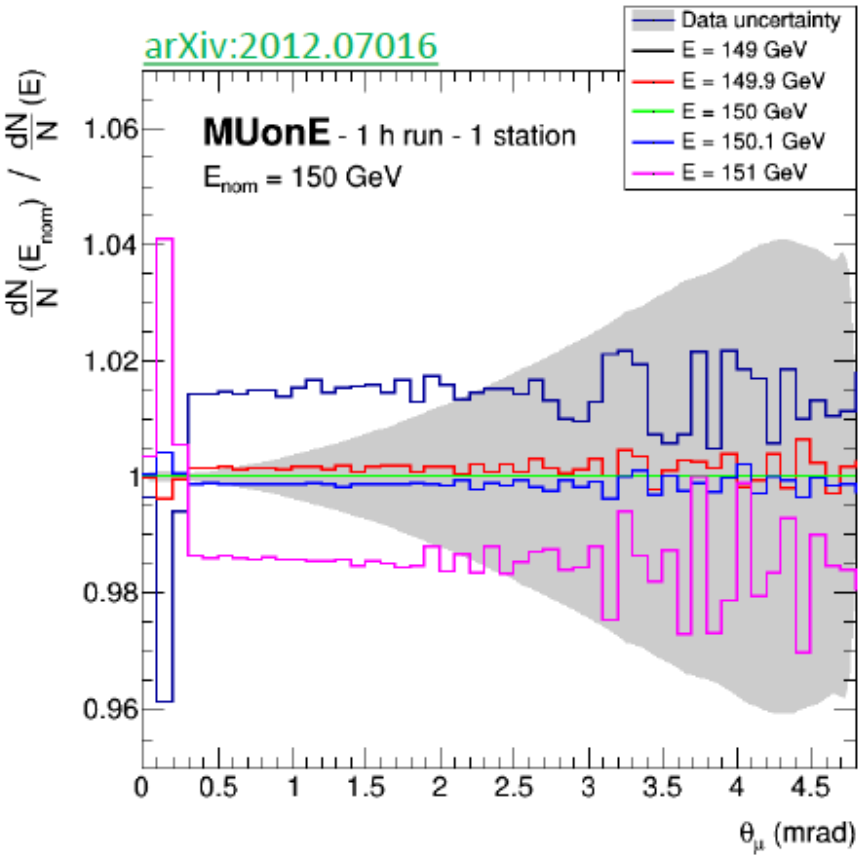
- Beam energy scale must be known at 6 MeV level
- COMPASS BMS spectrometer gives with ~0.8% resolution (~1 GeV)
- Absolute energy scale has to be controlled by a physics process:
  - ❖ Inverse kinematic method on elastic μe events
  - ❖ Fit of the average angle distribution



For equal angles: $\theta_\mu = \theta_e \equiv \theta$ $\quad \theta \simeq \sqrt{\frac{2m_e}{E}}$

- Can reach <3 MeV uncertainty in a single station in less than one week

Effect of a syst shift of the average beam energy on the q_m distribution: 1h run / 1 station



- Large effect in the normalization region

Systematic studies (Test Run)

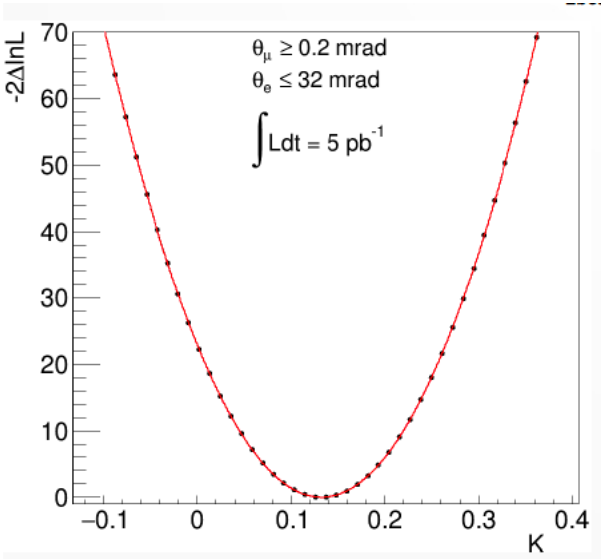
- Systematic errors (multiple scattering, intrinsic resolution and beam energy scale) are take into account in the template method by nuisance parameters (with NLO MC)

- Use of "Combine" package (https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/) to performs a likelihood fit to the nuisance parameters for each template

- Systematic effects identified with good precision, without worsening the precision on the parameter of interest (still room for improvement).

Shape nuisances

- μ_{MS} → multiple scattering
- μ_{Intr} → intrinsic resolution
- μ_{Ebeam} → beam energy



- $K_{ref} = 0.137$
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

Selection cuts	Fit results
$\theta_e \leq 32\,\text{mrad}$ $\theta_\mu \geq 0.2\,\text{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\text{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\text{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\text{E}_{\text{Beam}}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$

Theory

- QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group)
- MC with approximate NNLO: MESMER (Pavia) and MCMule (PSI)
- **Huge theoretical activity (***"Theory for muon-electron scattering @ 10ppm"*, P.Banerjee et al, Eur.Phys.J.C80(2020)591**):**
-

.P. Mastrolia, M. Passera, A. Primo, U. Schubert, JHEP 1711 (2017) 198
.S. Di Vita, S. Laporta, P. Mastrolia, A. Primo, U. Schubert, JHEP 1809 (2018) 016
.M. Alacevich et al, JHEP 02, 155 (2019)
.M. Fael, JHEP 1902 (2019) 027
.M. Fael, M. Passera, PRL 122 (2019) 192001
.C.M. Carloni Calame et al, JHEP 11, 28 (2020)
.P. Banerjee at al, SciPost Phys. 9, 27 (2020)
.R. Boncianiet al, arXiv:2106.13179

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)
→ **International** efforts!

being formed, still growing up

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

CERN
Exp

Imperial College (London)
Liverpool U.
Exp-Th

Krakow IFJ Pan
Exp

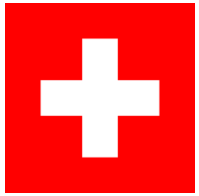
The MUonE Collaboration

Northwestern U.,
Virginia U.
Regis U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos
INPP (Athens)
Exp

Shanghai Jiao Tong U.
Exp



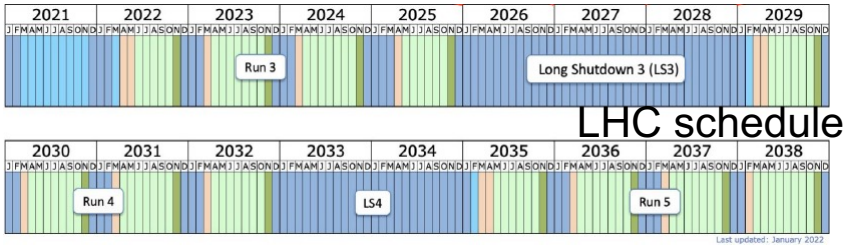
PSI (Villigen), ETH and U.Zürich
Th

+ other involved theorists from: U.Valencia (E), KIT/Karlsruhe (D), New York City Tech (USA)

Conclusion

- Exciting times for the muon g-2!
- Alternative/competitive determinations of a_μ^{HLO} are essential.
- MUonE: a novel way (space-like region) to measure a_μ^{HLO} at per mille accuracy
- Many progress in the last years, inc. detector under optimization
- Staged approach towards the full experiment: one station (2022) , two stations (2023); possible 10 stations before LS3 (2026)?
- Growing interest from both experiment and theory community
- Collaborators are welcome!!

Thanks!



LEVERHULME TRUST

UNIVERSITY OF LIVERPOOL

INFN
Istituto Nazionale di Fisica Nucleare

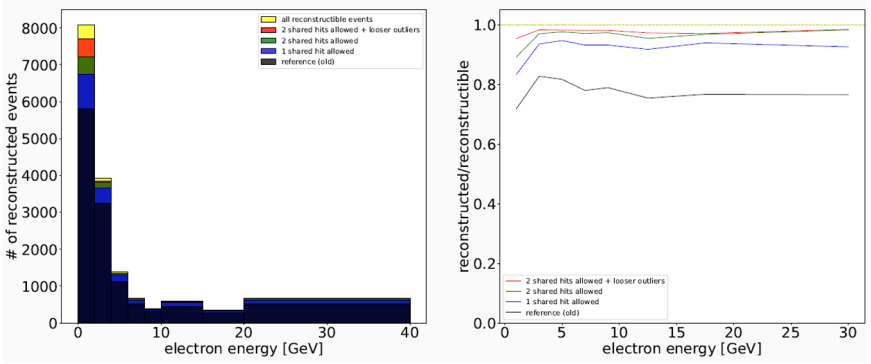
THE END

Software

- **FairMUonE**:
  FairRoot based software, for generation, simulation, digitization and reconstruction
- **Event generation**:
  NLO Mesmer generator for μ - e scattering
  Accurate beam profile description
- **Simulation:**
  Geant4 v10.7.1 implemented in FairRoot
  Detailed geometry description implemented, scalable to any number of stations
  Common geometry files (.yaml files) for simulation/digitization/reconstruction
- **Digitization:**
  Digitization for tracking stations ready
  Realistic electronic noise and channel cross-talk added
  Calorimeter digitization is ongoing

Software

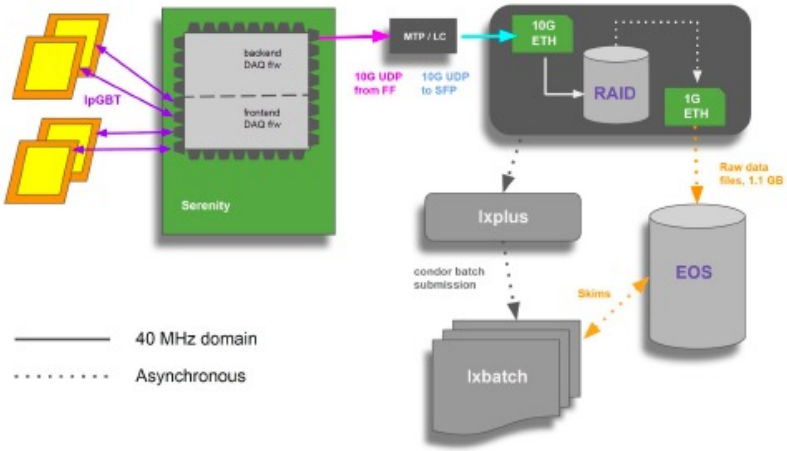
- **Track reconstruction**:
  Kalman filter for tracking implemented
  Tracking efficiency studies ongoing:
  Allowing shared hits improves track reconstruction efficiency dramatically in the whole energy range



- **Vertex reconstruction**:
  Kinematic fit constraining three tracks to meet in the middle of a given target
  Adaptive vertex fitter developed for the alignment

Test Run 2021

- Checkout of DAQ, build up software and analysis tools



- Analysis activities:
  - Data integrity & DAQ errors
  - Modules synchronisation
  - Correlations and track reconstruction
  - Efficiency studies
  - Beam behaviour and non-beam background checks
  - Alignment

Detector alignment

- Initial conditions set by means of the mechanical survey: **Δz ~ 50 - 100 μm**
- Software alignment shall reach the ultimate precision
- Alignment parameters will be determined by minimizing the **global χ^2**
  MUonE is perfectly suited for the global χ^2 approach because of the linearity.

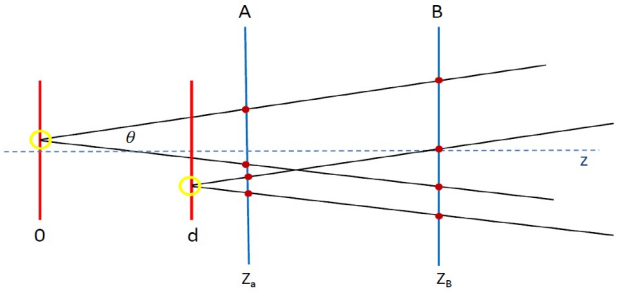
$$\chi^2_{\text{global}} = \sum_i \chi^2_i, \qquad \frac{\mathrm{d}\chi^2}{\mathrm{d}\boldsymbol{\alpha}} = 0, \qquad \boldsymbol{\rho} \equiv \boldsymbol{\rho}(\boldsymbol{\pi}(\boldsymbol{\alpha}), \boldsymbol{\alpha})$$

Residuals **ρ** depend on the alignment parameters **α** as well as track parameters **π**

- The required precision for the alignment is **Δz ~ 10 μm**
- **How to get the longitudinal scale to such a precision?**
  Use thin targets located to a known distance and reconstruct vertices from these targets to gauge the scale

Detector alignment (cont.)

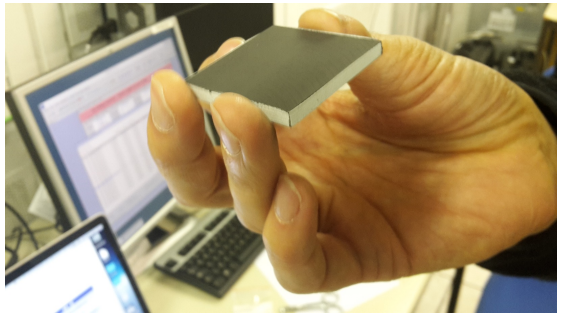
- Design and construction of the targets system by the CERN accelerator group

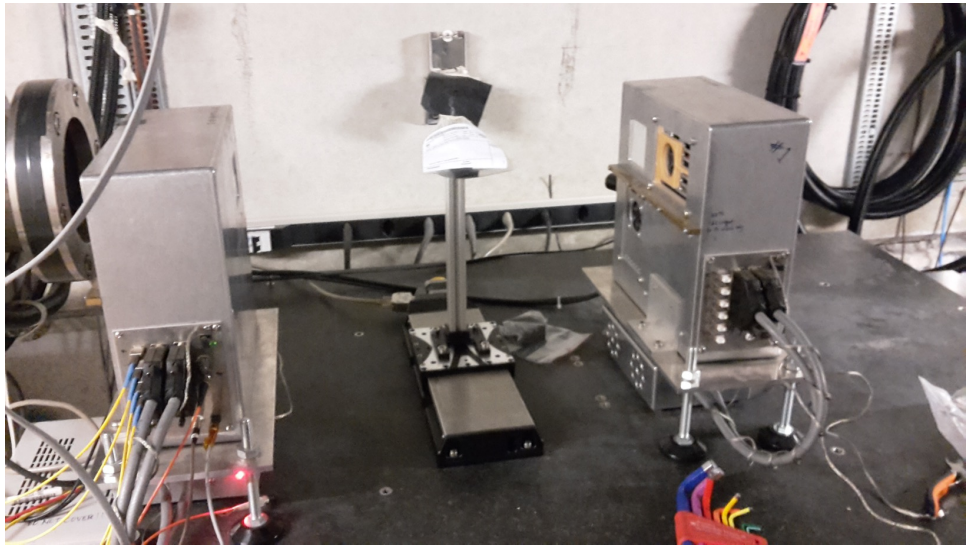


- Use pion beams to enhance the multiplicity of tracks from the vertices in the thin targets
- Use the adaptive vertex fitter to determine the vertices positions
- Use the global alignment method to get the alignment parameters

Test Beam setup and target

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

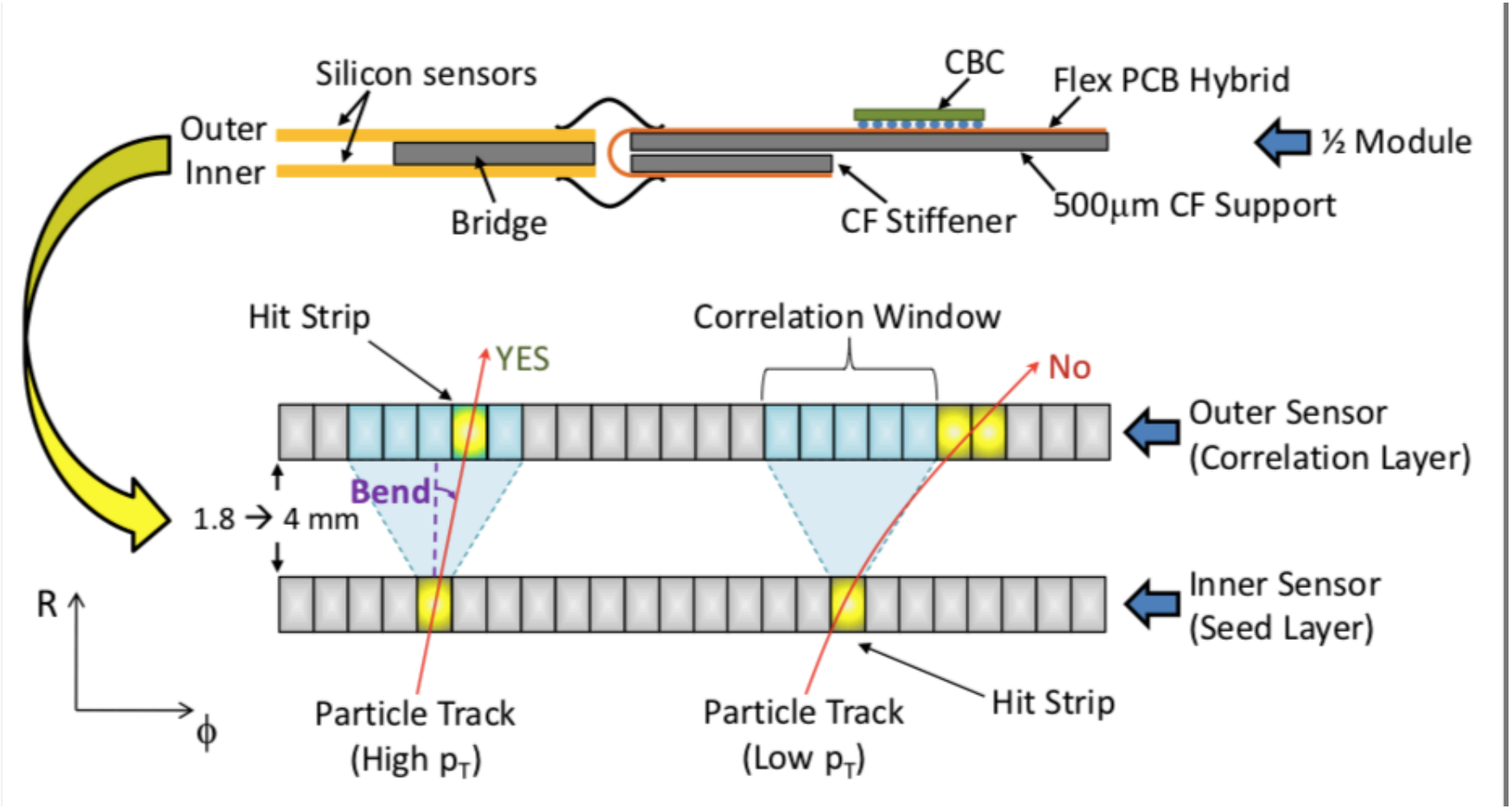




Some numbers:

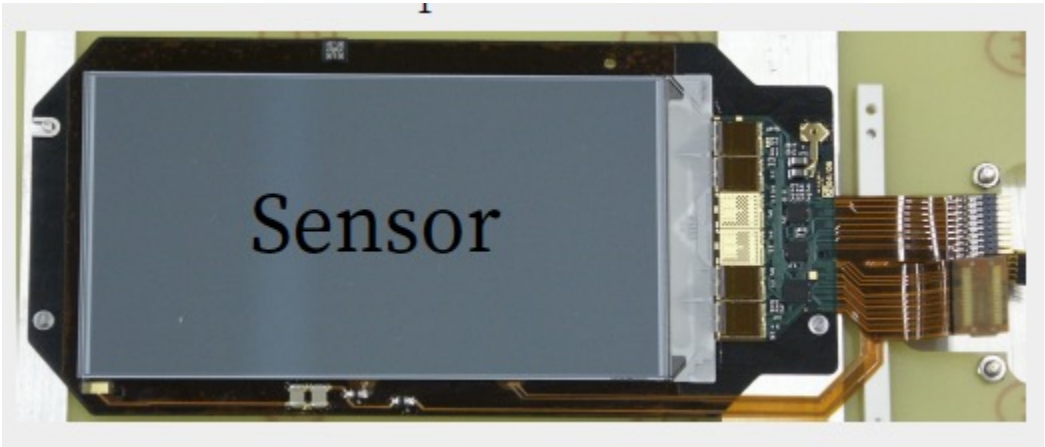
- 60 cm total Be target ($2X_0$) segmented in 40 stations with 1.5 cm target ($0.03\ X_0$)
- ~40 m total detector length
- 10x10 cm^2 silicon detectors
- Resolve each μ,e track with uniform efficiency
- Best possible resolution on θμ (<5mrad),θe (<50 mrad)
- μ rate: ~60 MHz (peak) → 15 MHz (averaged)
- μ separation: 17 ns (peak) → 68 ns (averaged)
- Collect $4x10^{12}$ events with E_e>1GeV in ~2 years
- Scattering probability (E_e>1GeV): $1.7x10^{-4}$/cm
- Scattering event rate (E_e>1GeV): ~10 kHz per station (peak); 2.5 (avg)
- Scattering separation (E_e>1GeV): 100 μs per station

The concept of stub



Silicon detectors survey

	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 [μm]	30	30	90	90	100	50	90	18.4	55
pixel size y [μm]	30	30	50000	90	1400	50	50000	18.4	55
σx [μm]	2	2	26	26	29	7	18	3.2	12
σy [μm]	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%



Possible location at CERN M2

- Between BSM and COMPASS

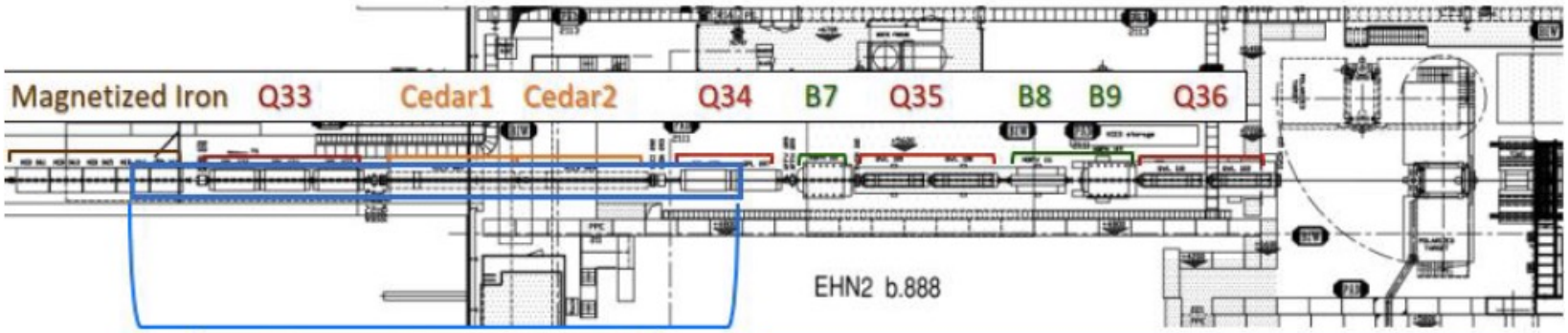
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- 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

Beam Synergy/sharing at M2 under study (thanks to A. Magnon)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent

To be specified

(submitted to SPSC in June)

70 authors; 16 Institutions

Letter of Intent: The MUonE Project

MUonE Collaboration

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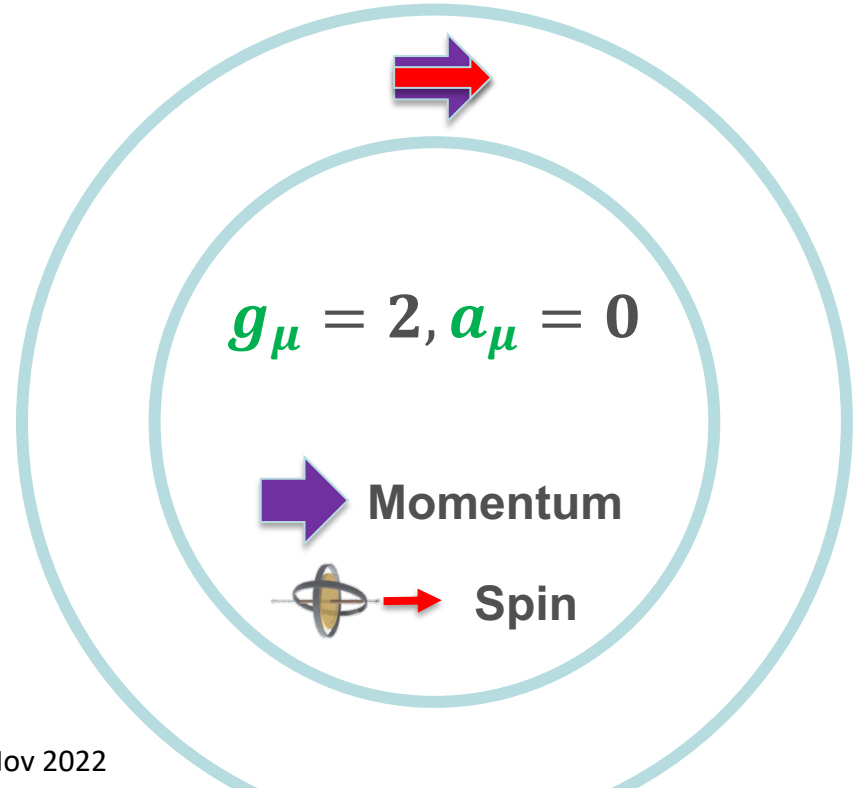
a_μ can be measured very precisely …

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g=2 (a=0) spin remains locked to momentum



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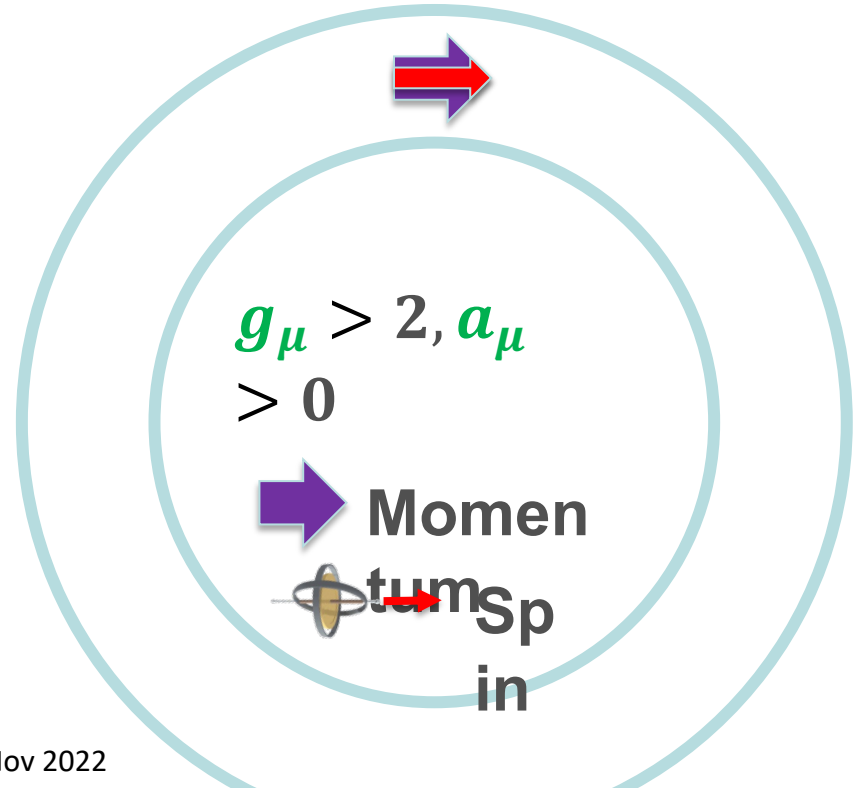
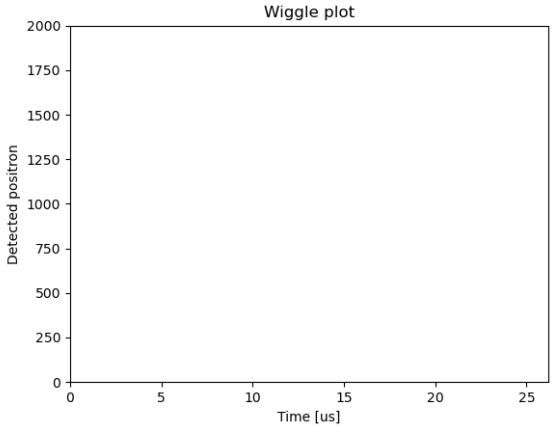
- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin advances respect to the momentum





By measuring directly a_μ x800 more sensitive than an experiment which measures g

Current experiments δa_μ < 1ppm