

Muon $g-2$ present and future experiments

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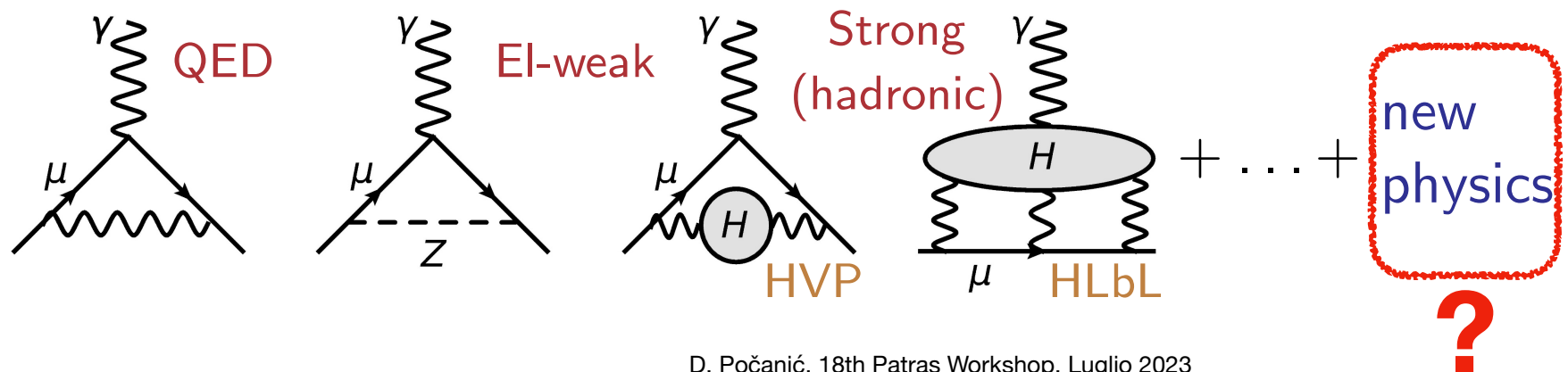
Outline

- **Why muon $g-2$?**
- **Experimental panorama**
 - E989 recall (see presentation by M. Sorbara)
 - MUonE (see also presentation by F. Piccinini)
 - G-2/EDM@JPARC (seminar by Tsutomu Mibe)
 - MuSEUM (Muonium Spectroscopy Experiment Using Microwave) at JPARC
- **Conclusions**

Why muon $g-2$

- Quantum fluctuations are responsible for the anomalous magnetic moments of leptons
- Magnetic anomaly $a_{lep} = (g_{lep} - 2)/2$
- The muon anomaly, a_μ , is more sensitive to loops with massive particles, due to $m_\mu > m_e$
- a_μ is an excellent probe of SM & BSM physics... if it exists!

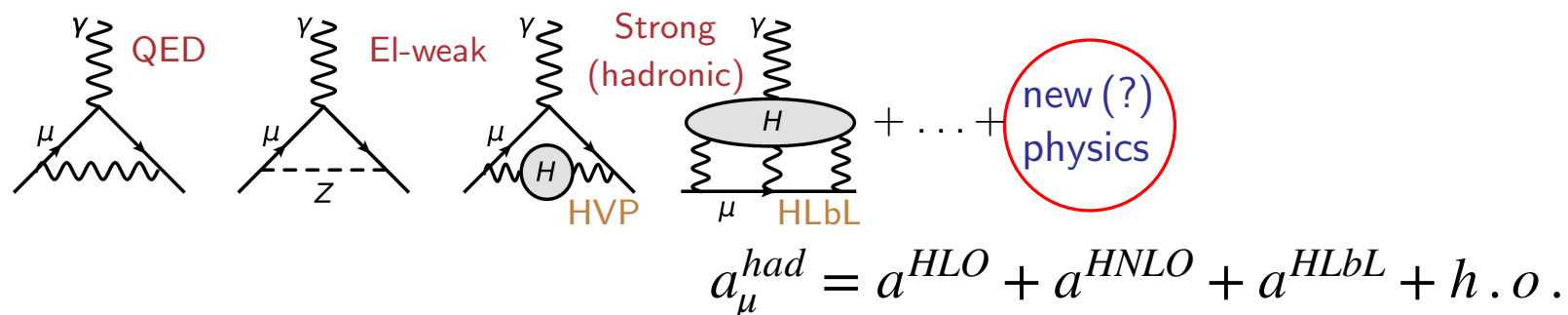
Leading order
processes contributing
to a_μ :



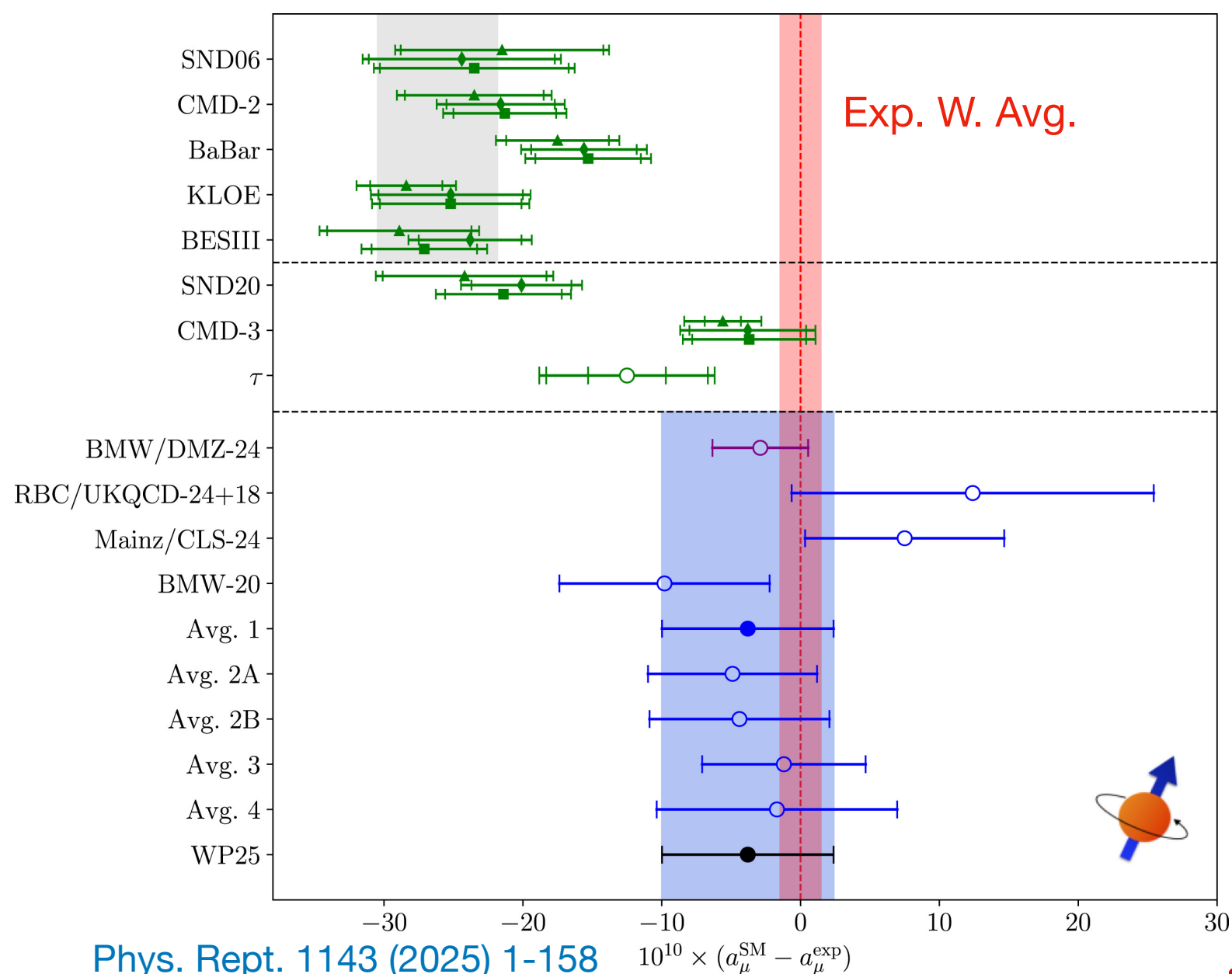
D. Počanić, 18th Patras Workshop, Luglio 2023

Why muon g-2

- **Leading order processes contributing to a_μ**



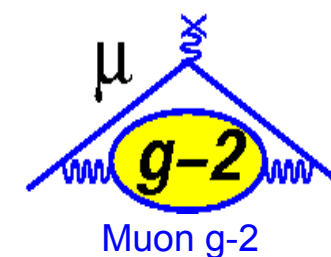
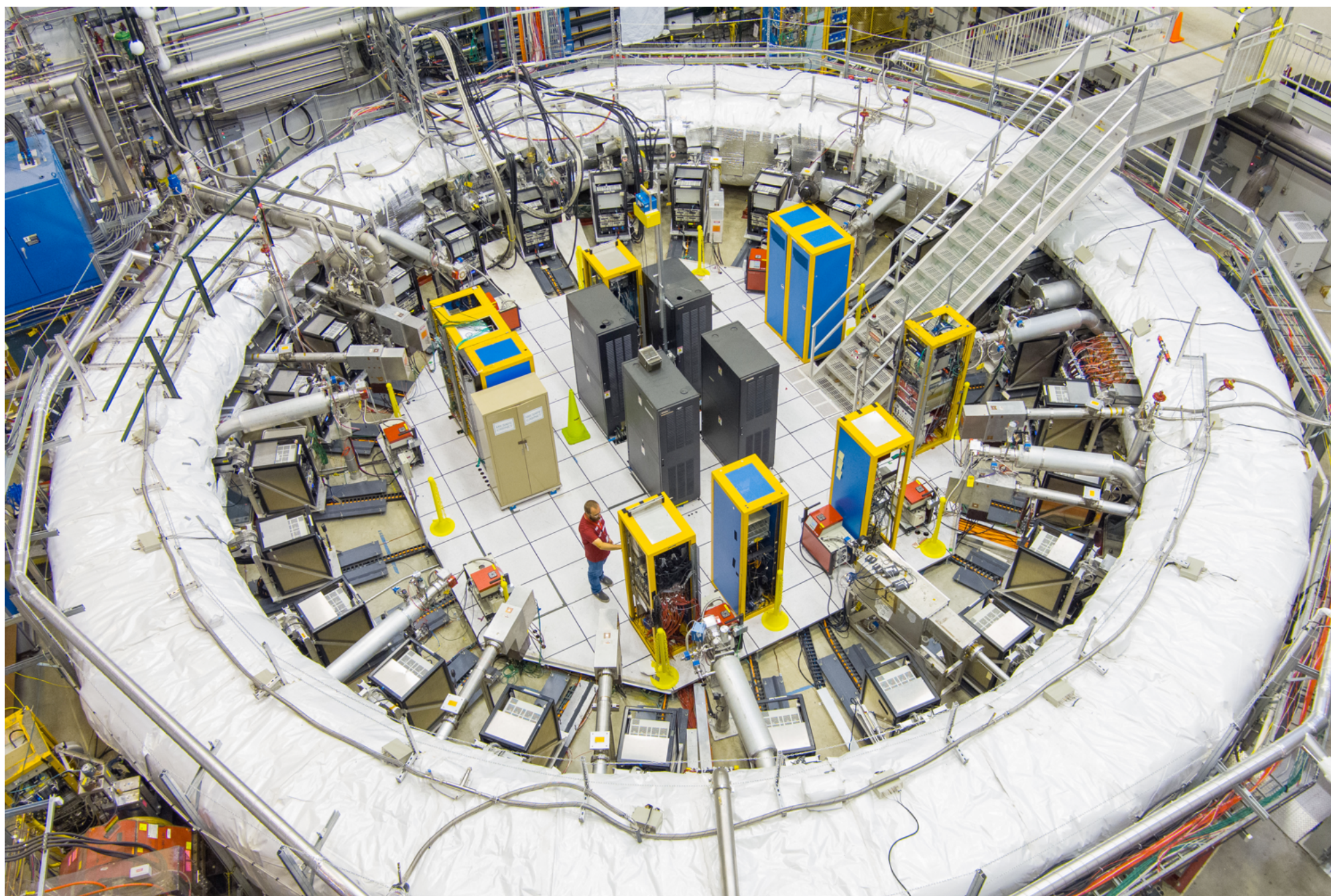
- **HVP = hadronic vacuum polarization**
- **HLbL = hadronic light by light scattering**
- **a_μ SM calculations, 2025 status from the g-2 Theory Initiative white paper**



Panorama of experiments

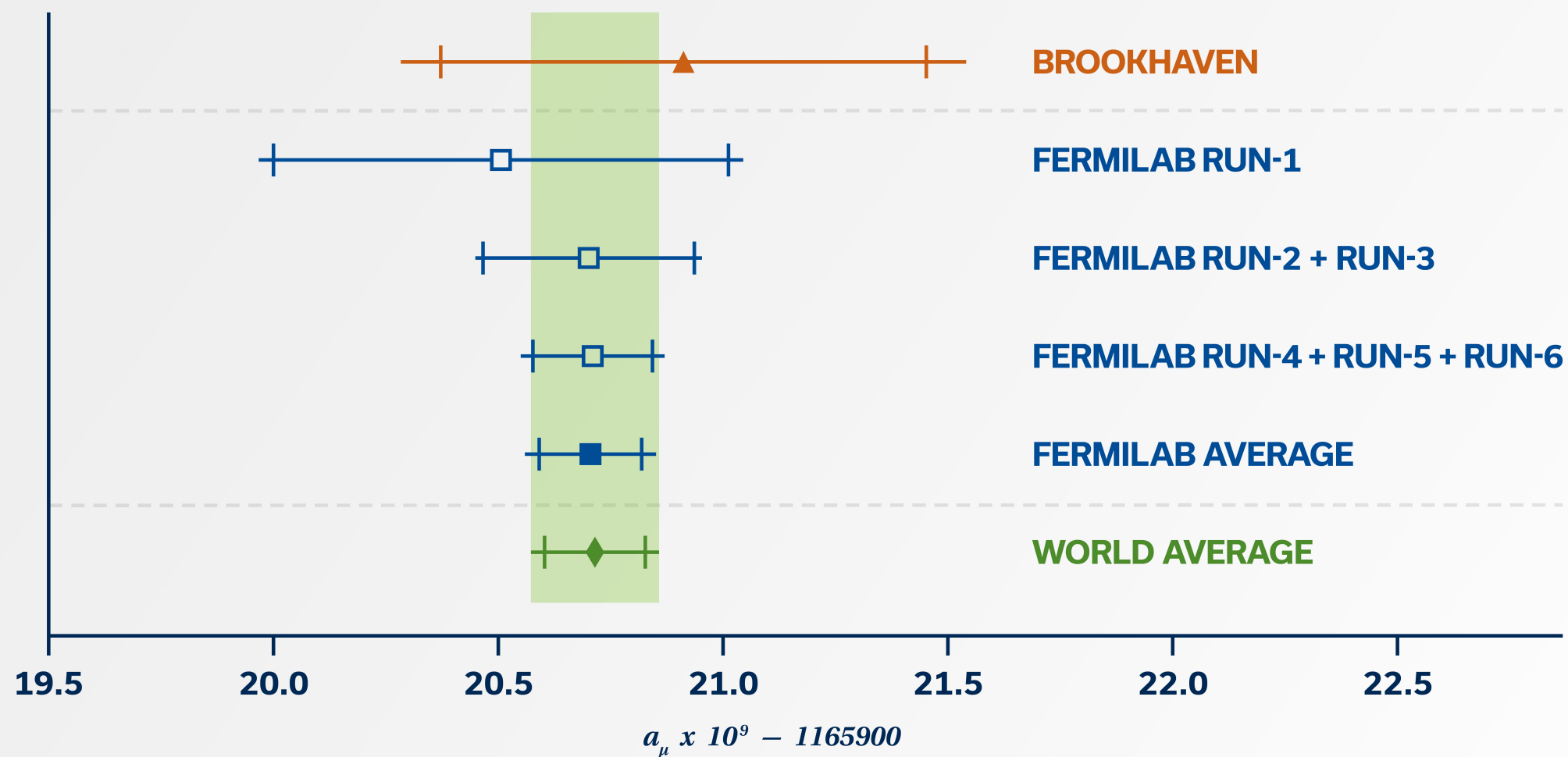
- **Muon g-2/E989 at Fermilab**
 - a_μ from muon precession in a magnetic field
- **MUonE at CERN**
 - HVP contribution to a_μ from mu-e elastic scattering
- **Muon g-2/EDM at JPARC**
 - a_μ from muon precession in a magnetic field
- **MuSEUM at JPARC**
 - muon magnetic moment from the hyperfine structure of muonium

Muon g-2/E989 at Fermilab



Muon g-2/E989 - the final result

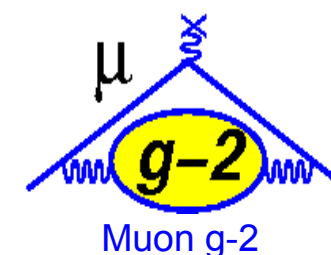
MUON g-2 2025 RESULTS



$$a_\mu(\text{Run-4/5/6}) = 0.001165920710(162)$$

$$a_\mu(\text{Run-1-6}) = 0.001165920705(148)$$

$$a_\mu(\text{exp}) = 0.001165920715(145)$$

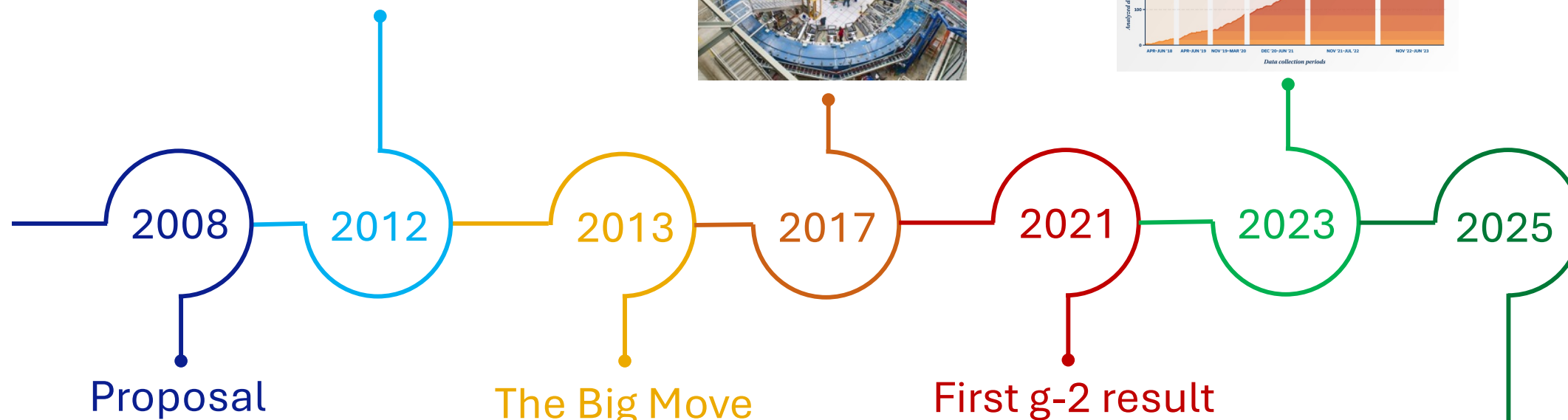
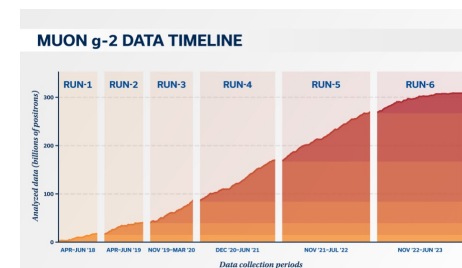


Big milestones for Muon g-2

End of data taking
and second result

Muon g-2
Critical Decision-0

1st muon beam



The New (g - 2) Experiment:
A Proposal to Measure the Muon Anomalous
Magnetic Moment to ± 0.14 ppm Precision

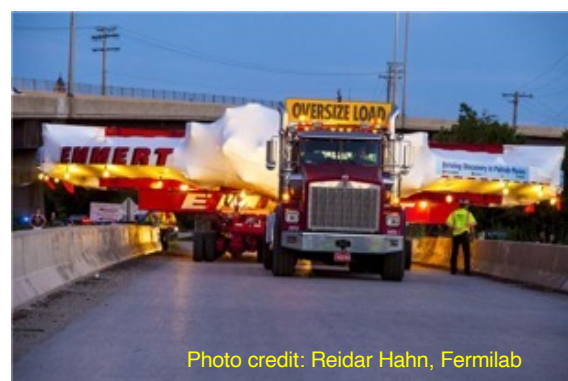
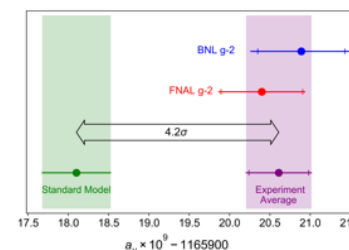


Photo credit: Reidar Hahn, Fermilab



Final g-2 result

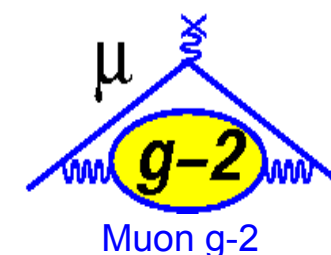
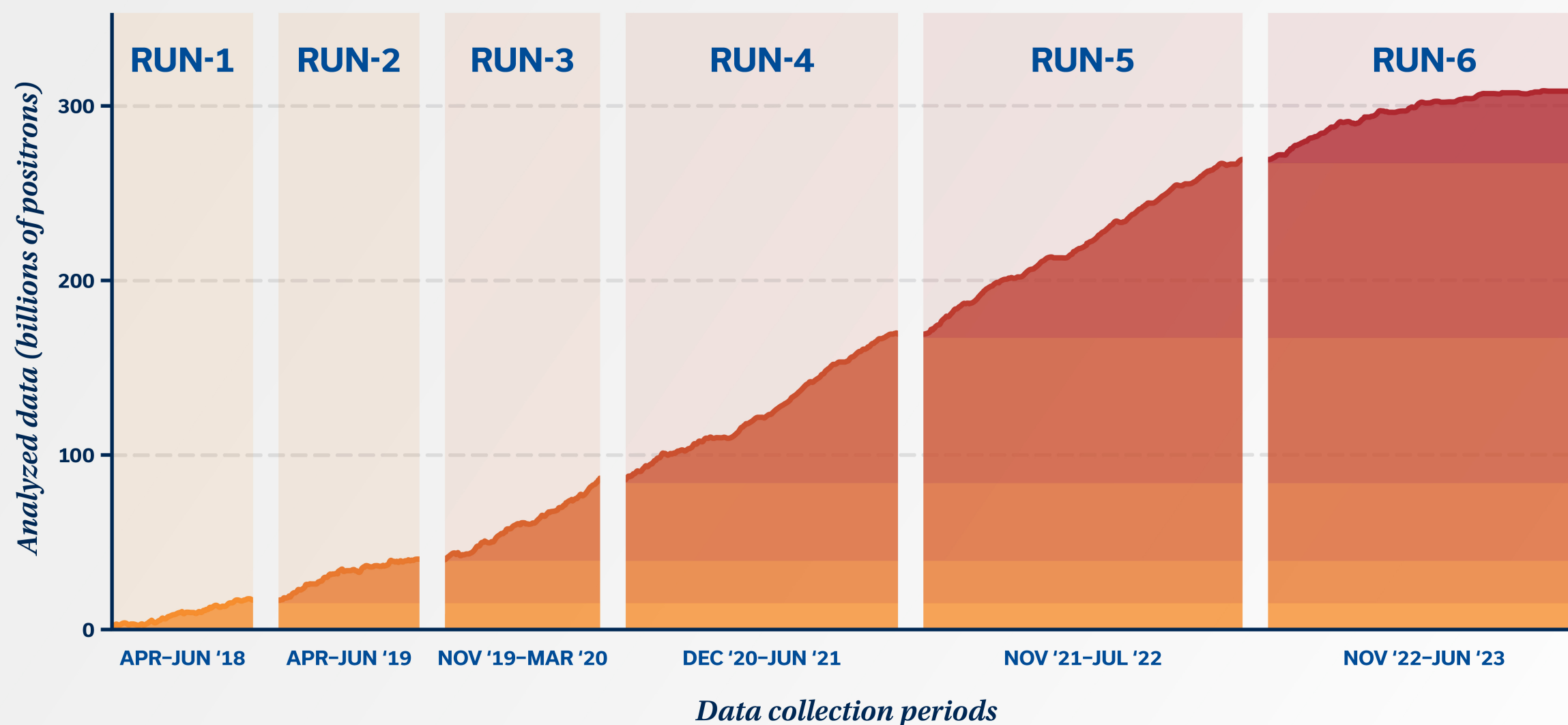


Now we know!

Slide from S. Corrodi, G-2 release talk, 3/6/2025

Muon g-2/E989 - data log

MUON g-2 DATA TIMELINE



Muon $g-2/E989$: precision

Run 1 - 2021

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	—	434
ω_a^m (systematic)	—	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}} \langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \rangle$	—	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	—	10
m_μ/m_e	—	22
$g_e/2$	—	0
Total systematic	—	157
Total fundamental factors	—	25
Totals	544	462

Run 2-3 2023

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	201
ω_a^m (systematic)	...	25
C_e E-field	451	32
C_p Up/Down motion	170	10
C_{pa} Phase acceptance	-27	13
C_{dd} Differential decay	-15	17
C_{ml} Muon losses	0	3
$f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	...	46
B_k Kicker eddy currents	-21	13
B_q Quad vibrations	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	...	11
m_μ/m_e	...	22
$g_e/2$	...	0
Total systematic for $\mathcal{R}'_\mu$	...	70
Total external parameters	...	25
Total for a_μ	622	215

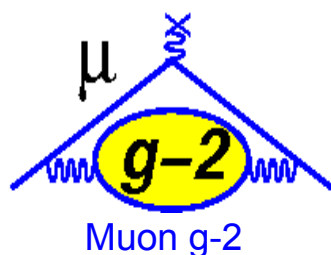
Run 4-5-6 2025

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	114
ω_a^m (systematic)	...	30
C_e	347	27
C_p	175	9
C_{pa}	-33	15
C_{dd}	26	27
C_{ml}	0	2
$\langle \omega'_p \times M \rangle$ (mapping, tracking)	...	34
$\langle \omega'_p \times M \rangle$ (calibration)	...	34
B_k	-37	22
B_q	-21	20
μ'_p/μ_B	...	4
m_μ/m_e	...	22
Total systematic for $\mathcal{R}'_\mu$	...	76
Total for a_μ	572	139

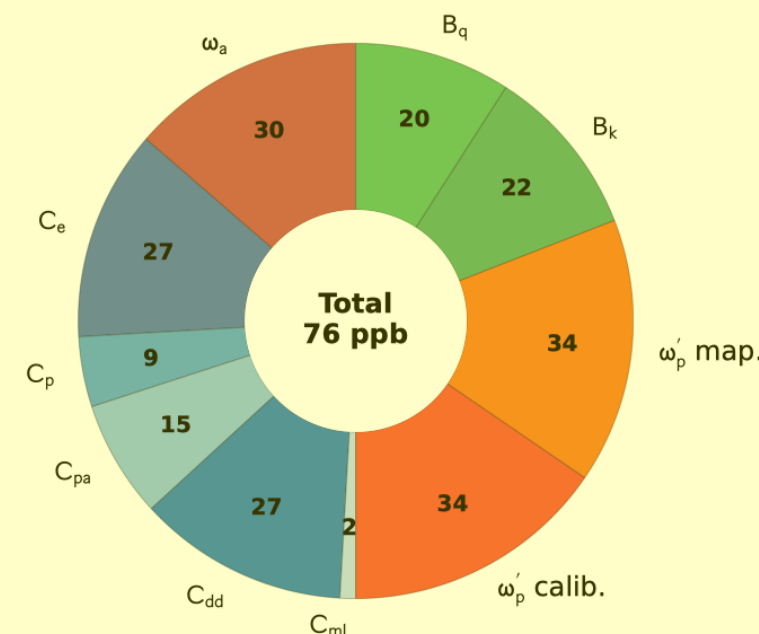
• “master formulas”

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} = \frac{\omega_a^{\text{mis}}}{\omega_p^{\text{mis}}} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \frac{\mu'_p}{\mu_B} \frac{m_\mu}{m_e}$$



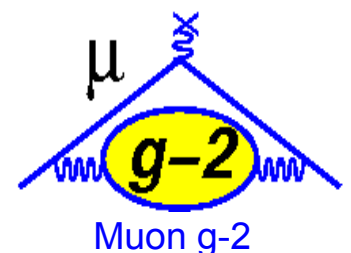
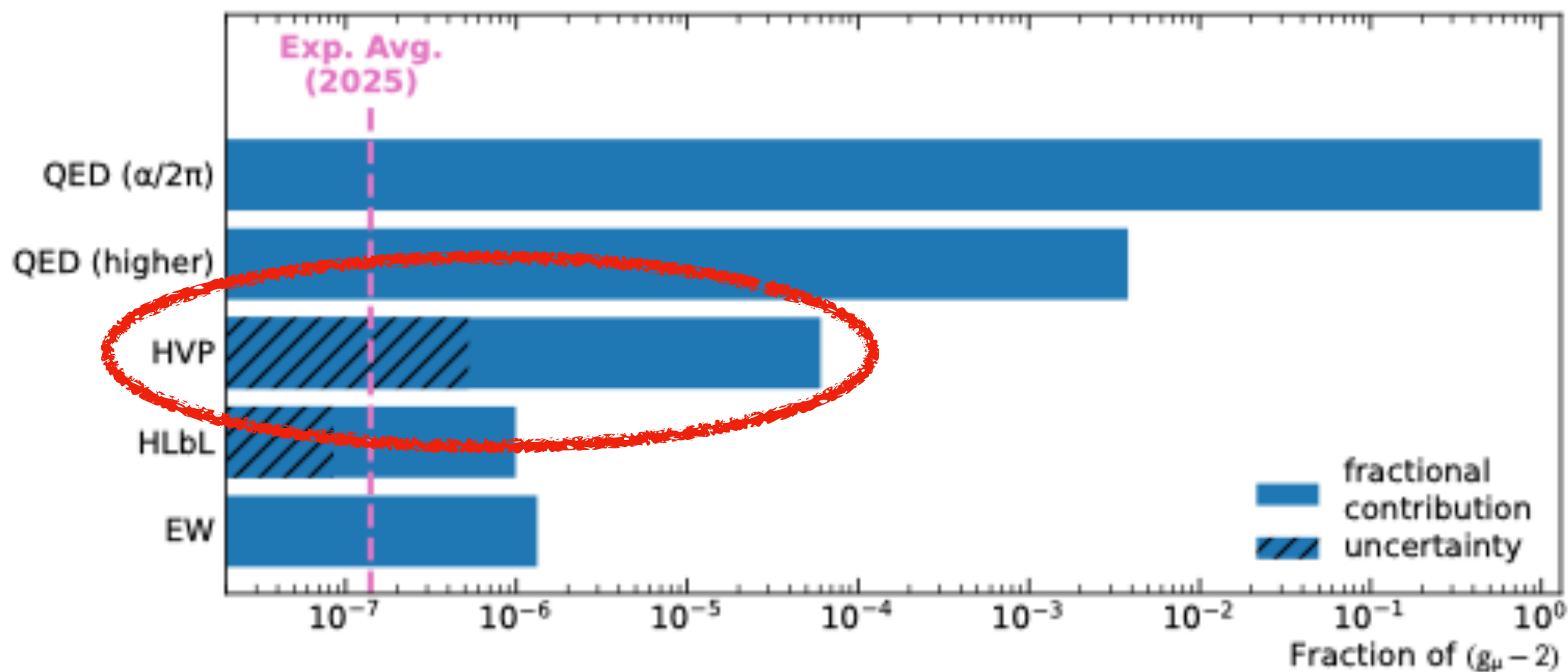
- Systematic uncertainties uniformly distributed
- design goal 100 ppb



Muon $g-2/E989$ and (B)SM

$$a_{\mu}(\text{Run-1-6}) = 0.001165920705(148)$$

- The **127 ppb level precision** measurement achieved by Muon $g-2/E989$ enables testing all contributions predicted by the Standard Model
- **Stringent benchmark** for all BSM theories with new particles and interactions



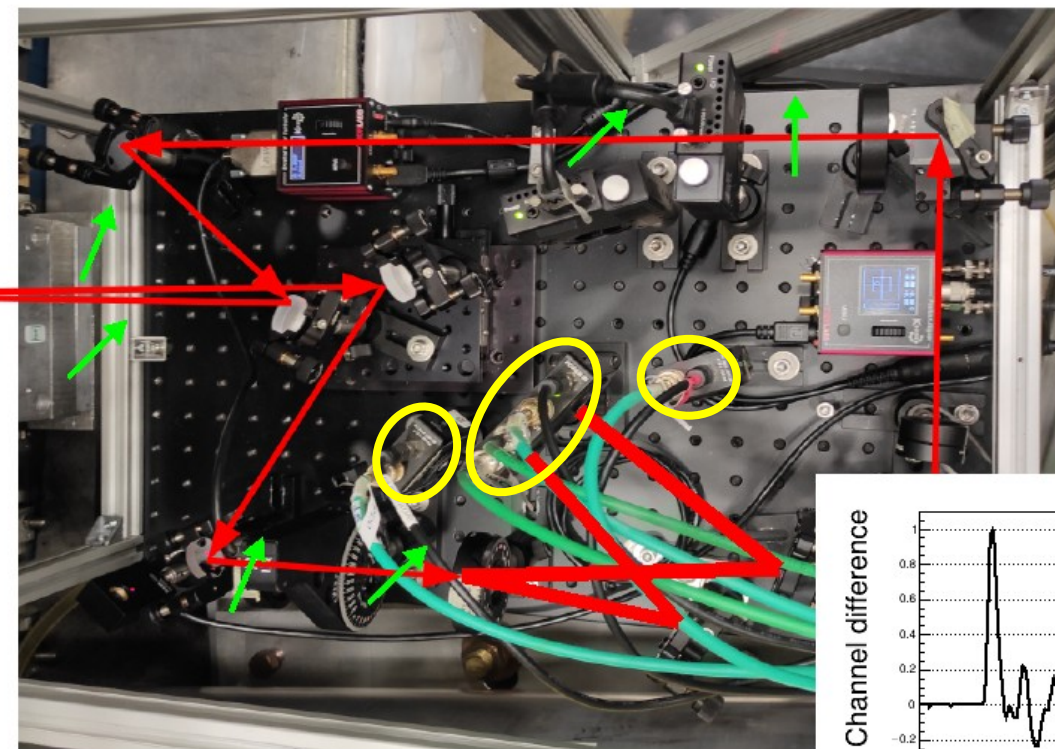
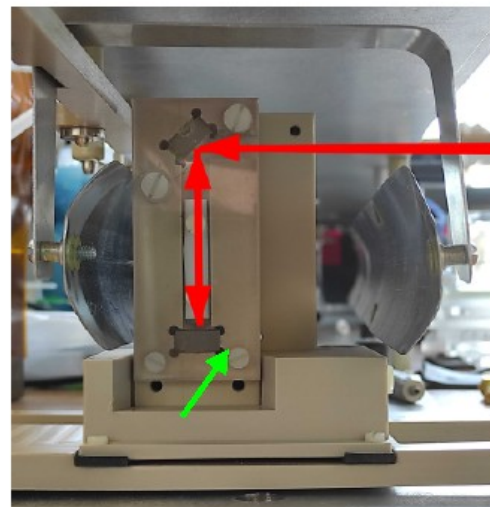
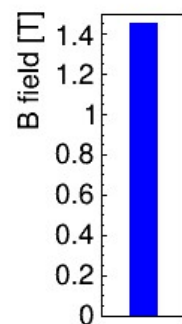
Principio della misura

- la rotazione della polarizzazione di un fascio laser in un cristallo otticamente attivo è proporzionale all'intensità del campo magnetico (**effetto Faraday**)
- le componenti della polarizzazione in uscita sono rivelate separatamente in modo da realizzare una **misura differenziale**
- inserendo all'ingresso una lamina quarto d'onda (QWP) si possono **escludere gli effetti magnetici** e si può studiare meglio la natura dei rumori

INFN Magnetometer

- Primary goal: measure $\sim 10^{-7}$ T transients with $\sim \mu\text{s}$ sampling
- Secondary goal: measure $\sim 10^{-2}$ T kick shape with $\sim \text{ns}$ sampling

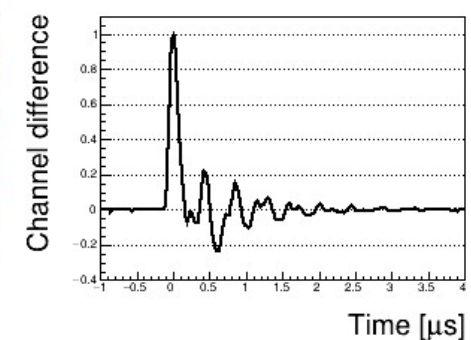
Two periscopes with 32 mm TGG crystals at magic radius and +17.5 mm



HWP_{in}: 22.5°



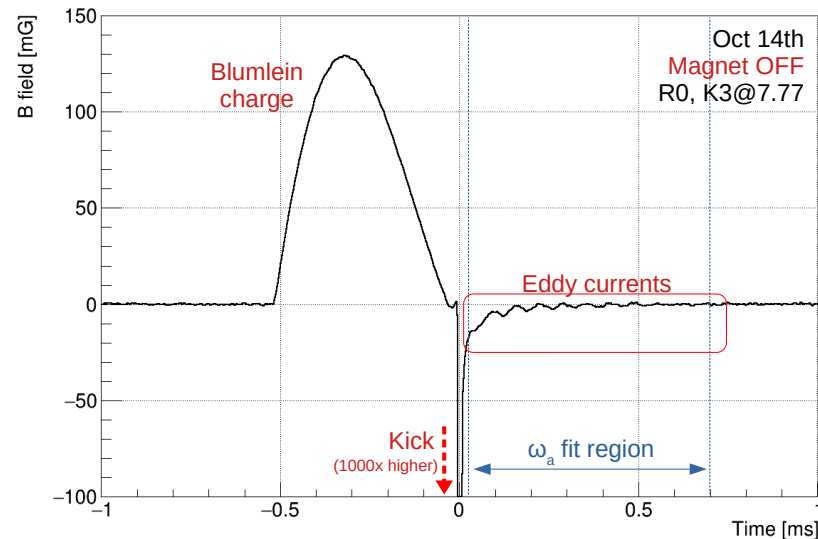
HWP_{out}: 33.2°



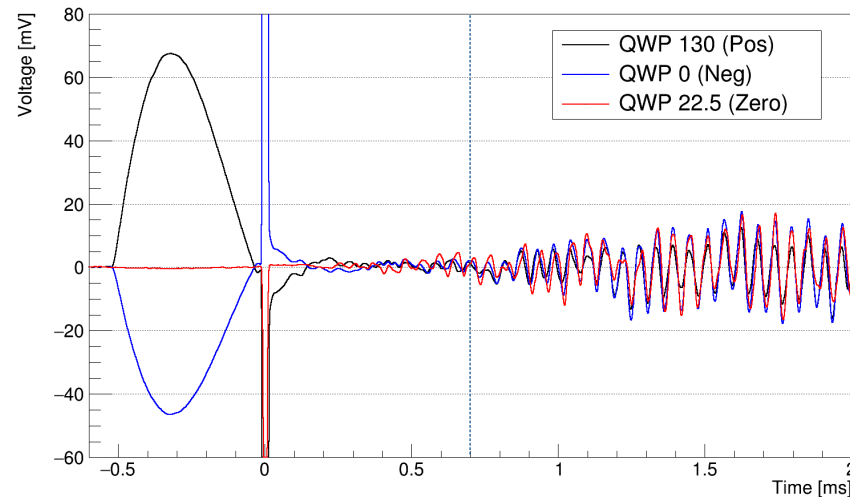
06/27/24

P. Girotti | INFN Magnetometer

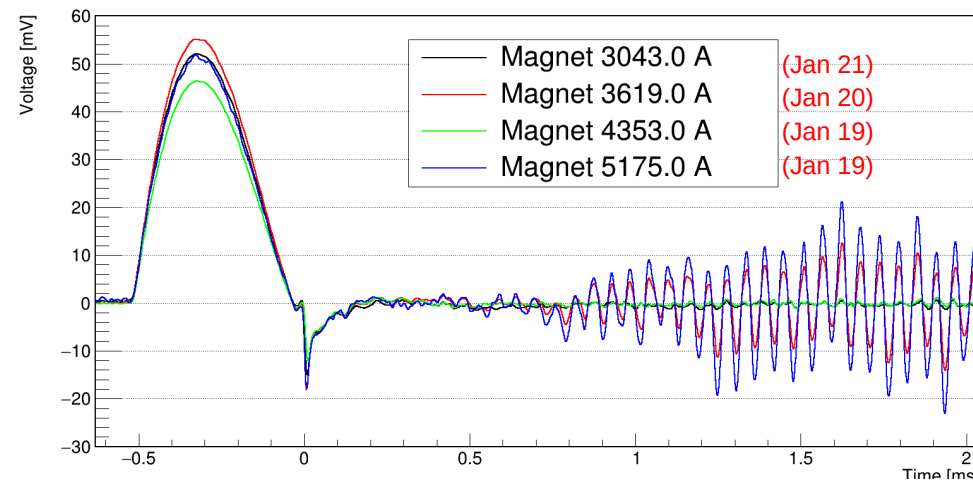
3 / 20



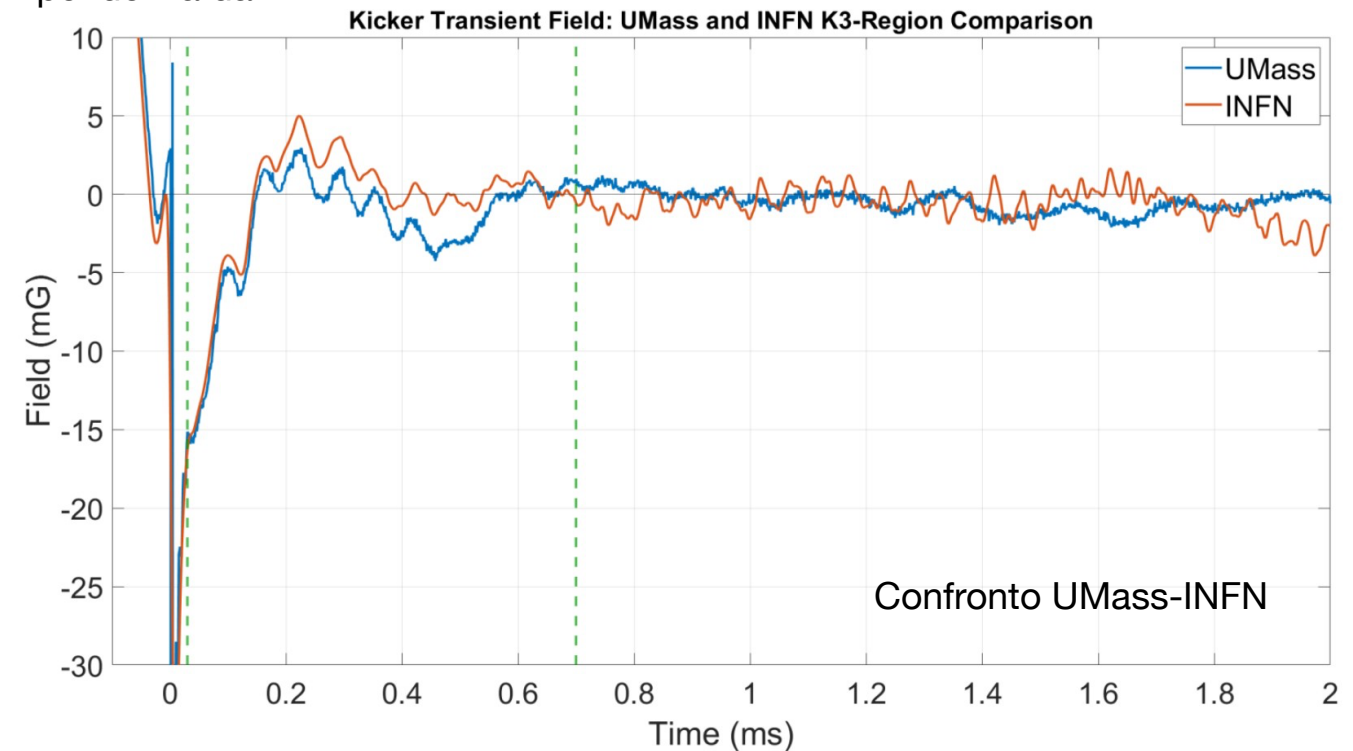
Forma attesa del segnale



Effetti magnetici esclusi con QWP



Dipendenza da B



Confronto UMass-INFN

grafici da P. Girotti

Compatibilità con i risultati del magnetometro in fibra UMass nella regione del Kicker 3

Cancellazione quasi completa delle vibrazioni

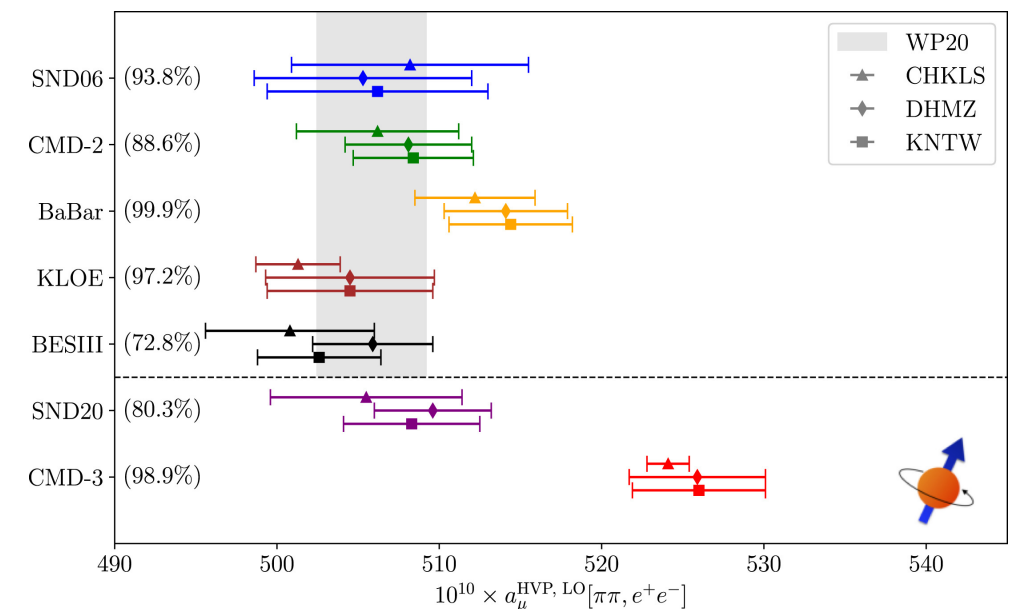
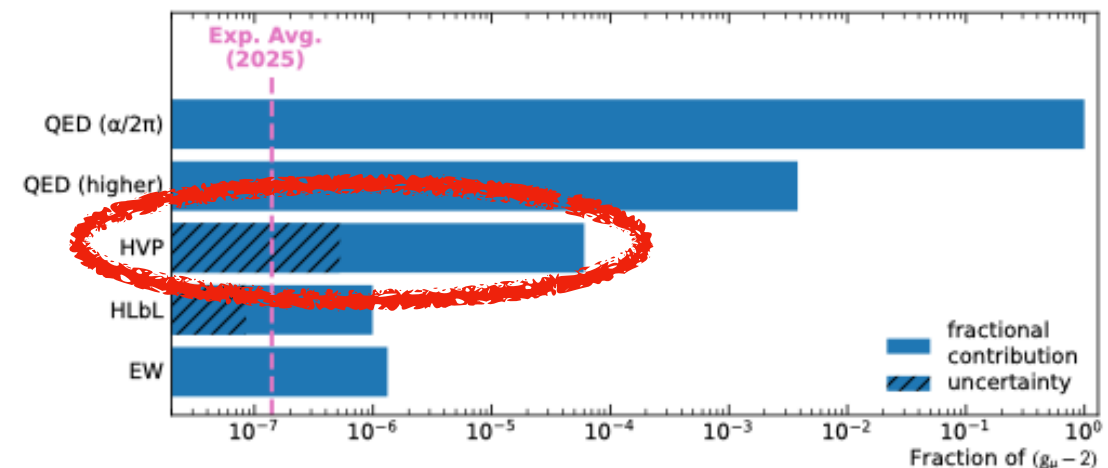
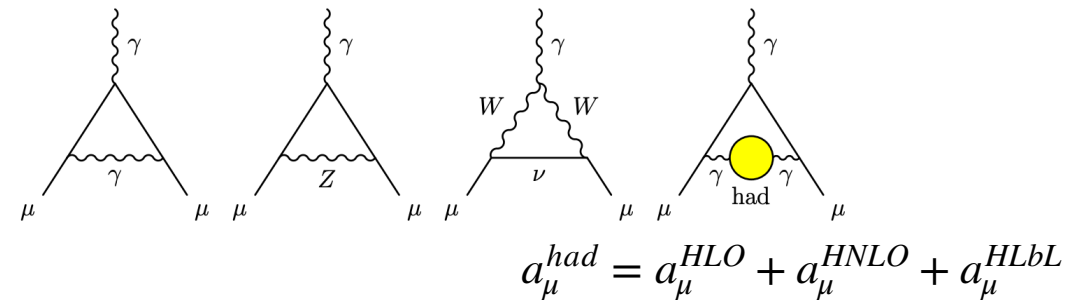
In fase di analisi

- dipendenza dalla posizione radiale nell'anello
- incertezze sistematiche e calcolo del termine B_k

Why MUonE in a nutshell

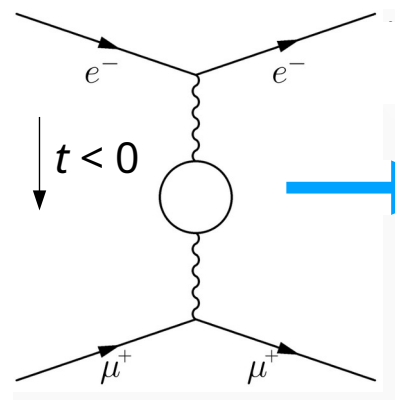
- Hadronic effects dominate the theoretical uncertainty on a_μ
- Lattice QCD seems to have tackled this problem
- But..
 - discrepancy between the data-driven calculation and the lattice approach
 - unexplained tension between the bulk of experimental e^+e^- measurements and the *outlier* represented by the CMD-3 results
- MUonE aims at an **independent** direct measurement of a_μ^{HLO}

SM contributions to the muon anomaly



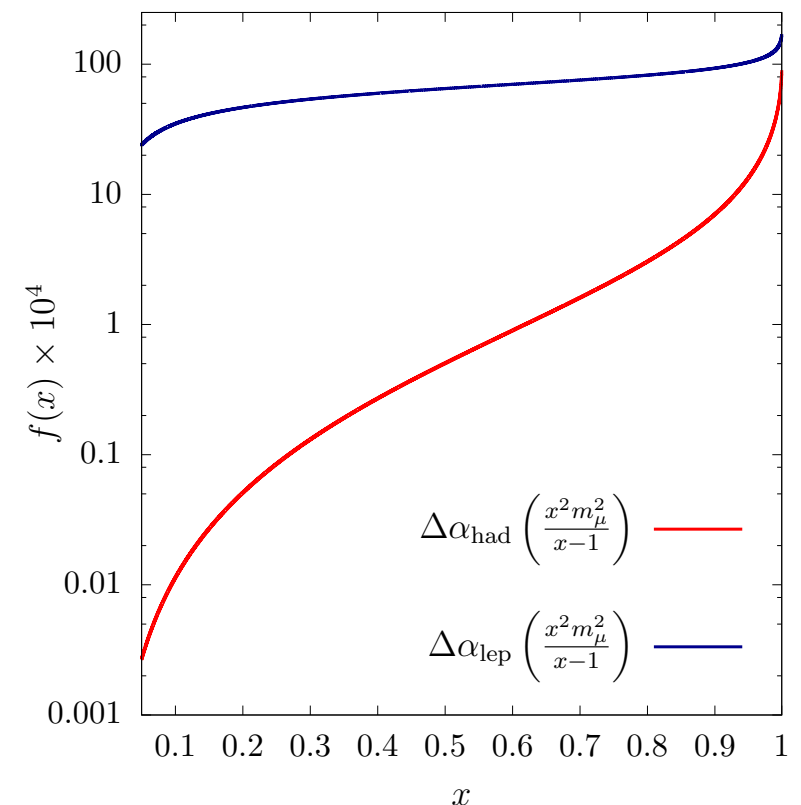
The MUonE method - I

- In the novel MUonE approach, a_μ^{HLO} is evaluated from a space-like integral, where $t = q^2$ is the squared momentum transfer and $\Delta\alpha_{had}(t)$ is the “running” with t of the fine structure constant



$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)] \quad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

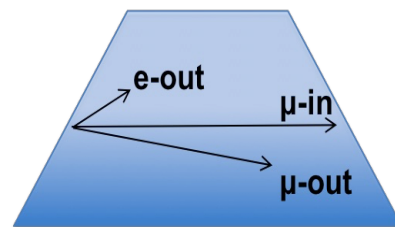
- Key advantage: $\Delta\alpha_{had}(t)$ is a smooth function free of resonances



The MUonE method - II

- $\Delta\alpha_{had}(t)$ can be extracted from the shape of the $\mu - e$ elastic scattering differential cross-section by comparing data with a MC

- $\theta_e, \theta_\mu \rightarrow x \rightarrow t$

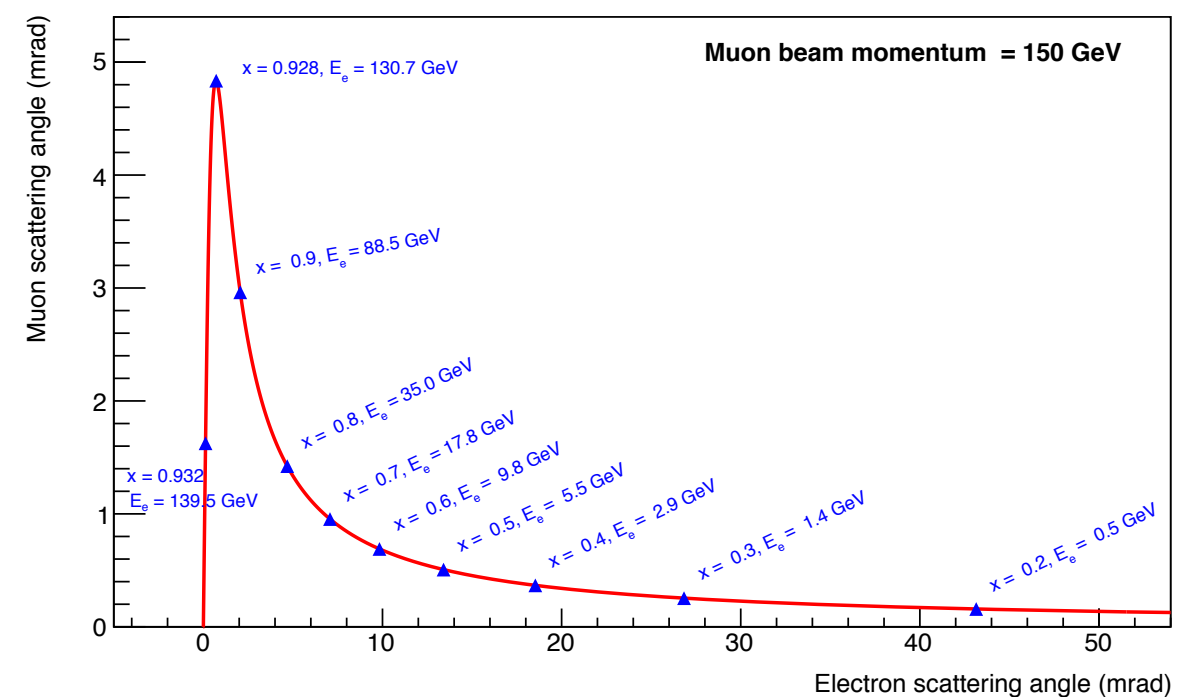


- the elastic curve also rejects main background $\mu N \rightarrow \mu N e^+ e^-$

$$\frac{d\sigma_{data}(\Delta\alpha_{had})}{d\sigma_{MC}(\Delta\alpha_{had} = 0)} \sim 1 + 2\Delta\alpha_{had}(t)$$

From MC

$$\frac{d\sigma_{elastic}}{dt} \xleftrightarrow{\text{Simple kinematics relations } (t \leftrightarrow \theta_l)} \frac{d\sigma_{elastic}}{d\theta}$$

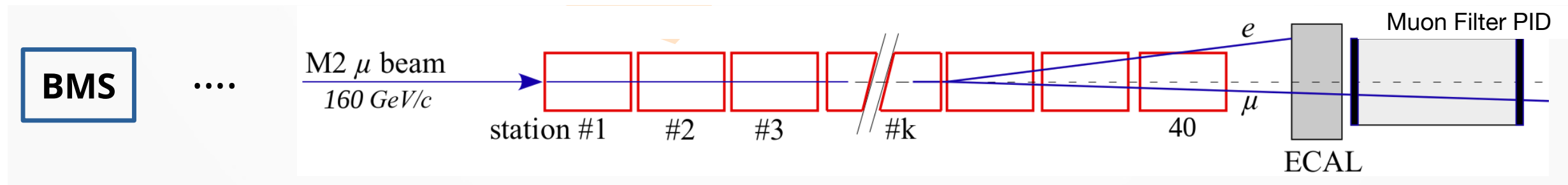


Elastic curve

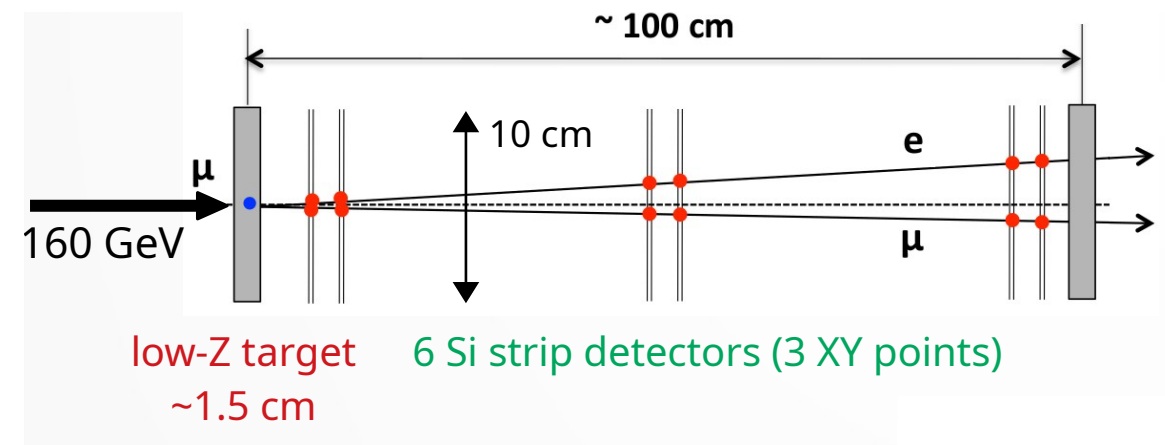


MUonE apparatus

- String of tracking stations, each with a thin low-Z target
 - “re-use” through-going muons
 - modular construction, up to 40 stations



- Beam Momentum Spectrometer
- ECAL - PID and e^- energy
- Muon Filter PID - small angle muon track ID



Figures from R. Pilato, FCCP workshop, Anacapri, Italy 2025



Tracking station I

- **“Gondola”**

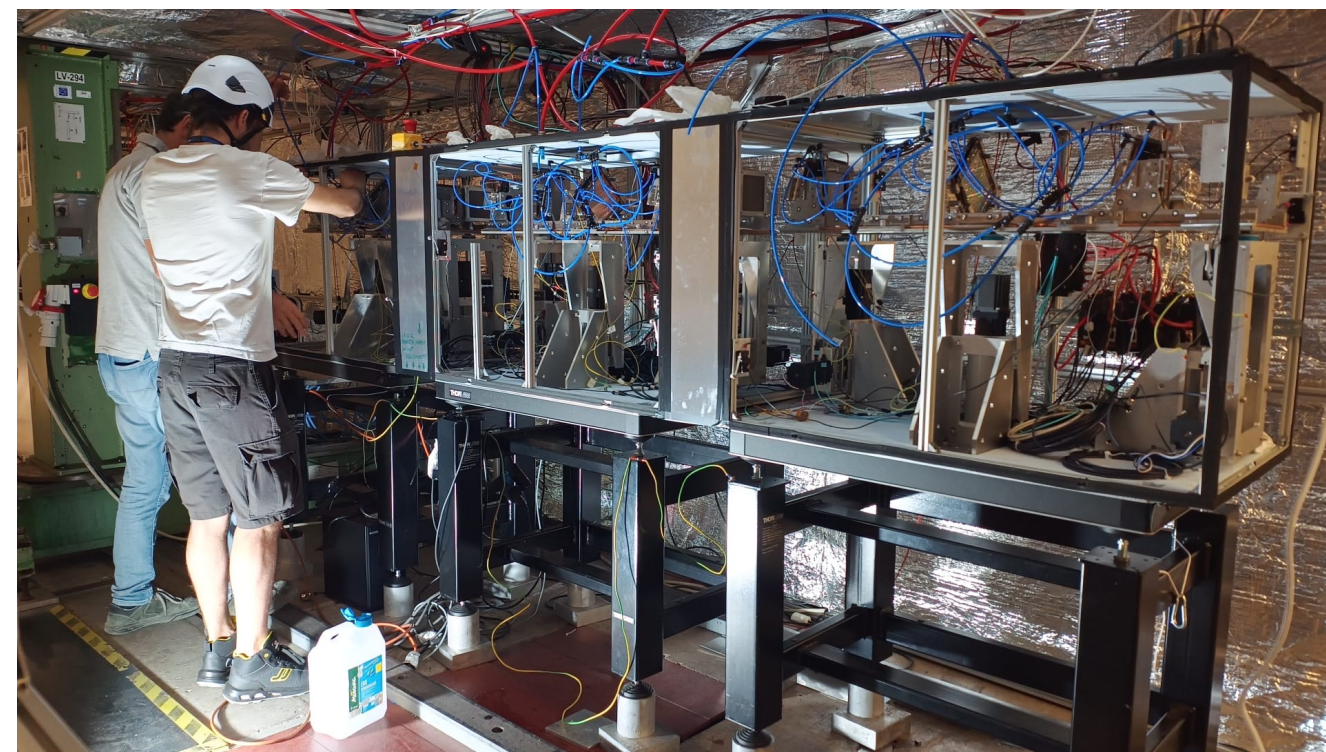
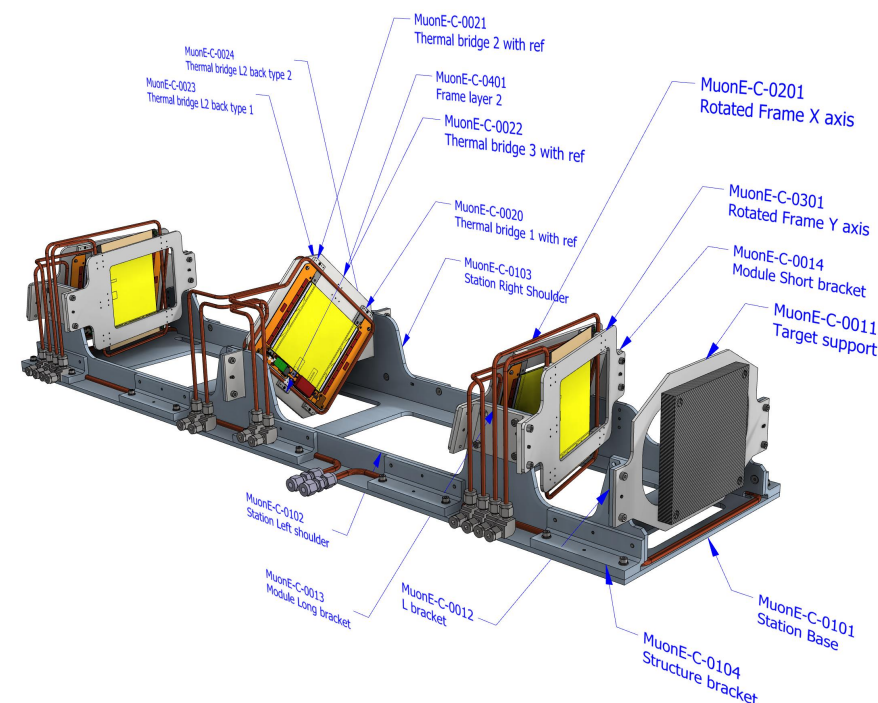
- InVar constuction (Fe/Ni alloy with 1.2 ppm/K CTE)
- requirement: 10 μm stability
- Holographic Alignment Monitor

- **6 x 2S Si tracking modules from CMS Phase 2**

- 2 tilted pairs for x-y coordinates
- 1 pair (u,v coords) to solve ambiguities
- global resolution $\sim 20 \mu m$

- **Gondola mounted on a 3-point motorized support system**

- **Entire assembly enclosed in an environmental box with dry air flux for temperature and humidity control**



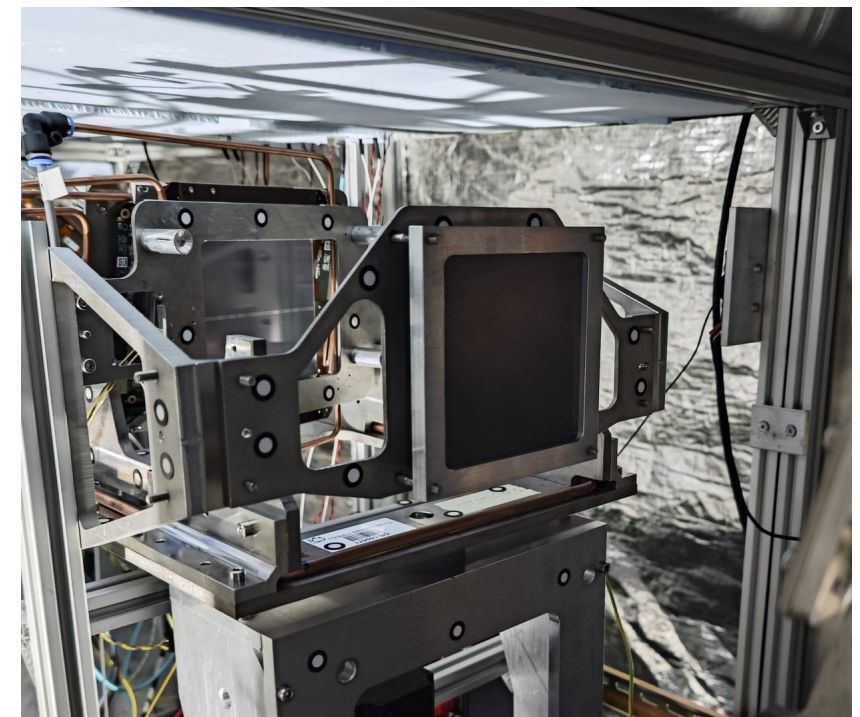
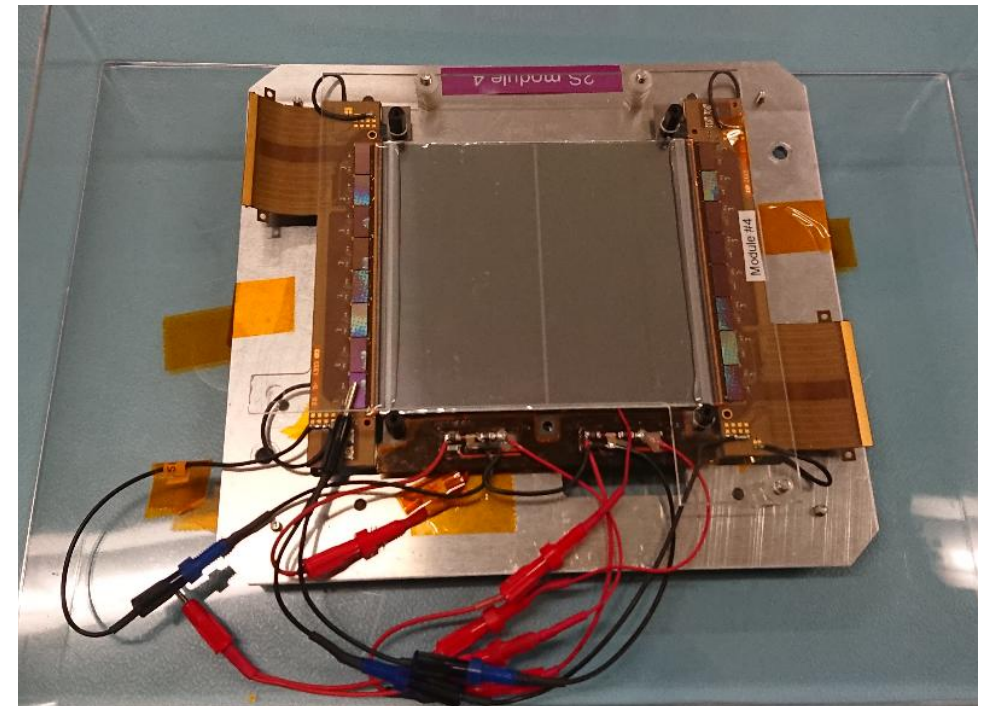
Tracking station II

- **2S tracking module from CMS Phase2 upgrade**

- ~90 cm² active area
- 2 × 320 μm thickness
- 40 MHz, binary readout
- 90 μm pitch
- ~26 μm hit resolution
- **MUonE workhorse detector**

- **target**

- graphite
- interchangeable to vary thickness



HAM system

- **Holographic Alignment Module - HAM**

- monitors distance changes between tracking planes at the sub- μm level
- lens-less, fiber coupled digital holographic inteferometry

- **Monitoring protocol**

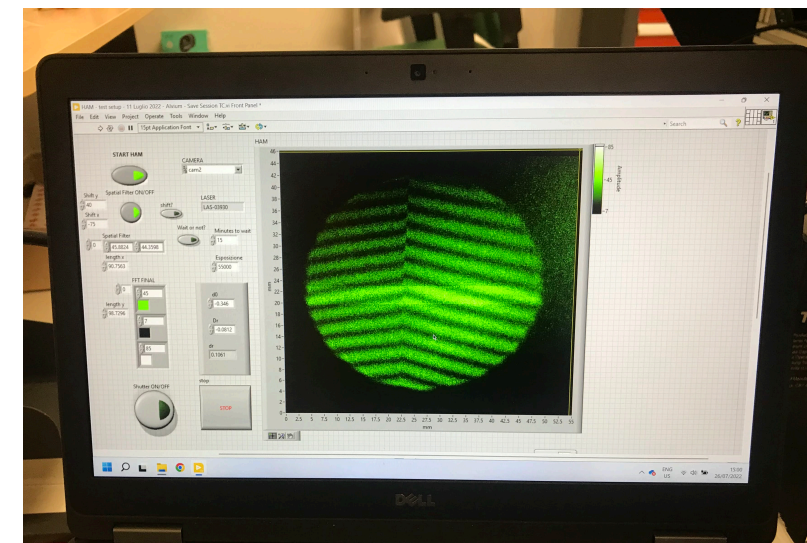
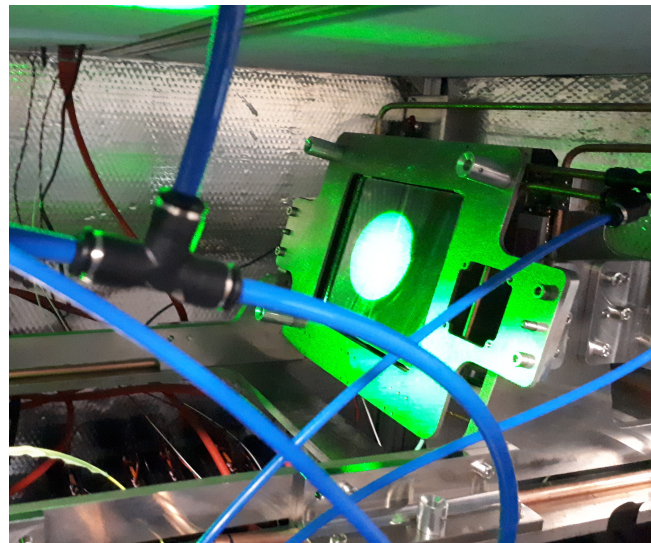
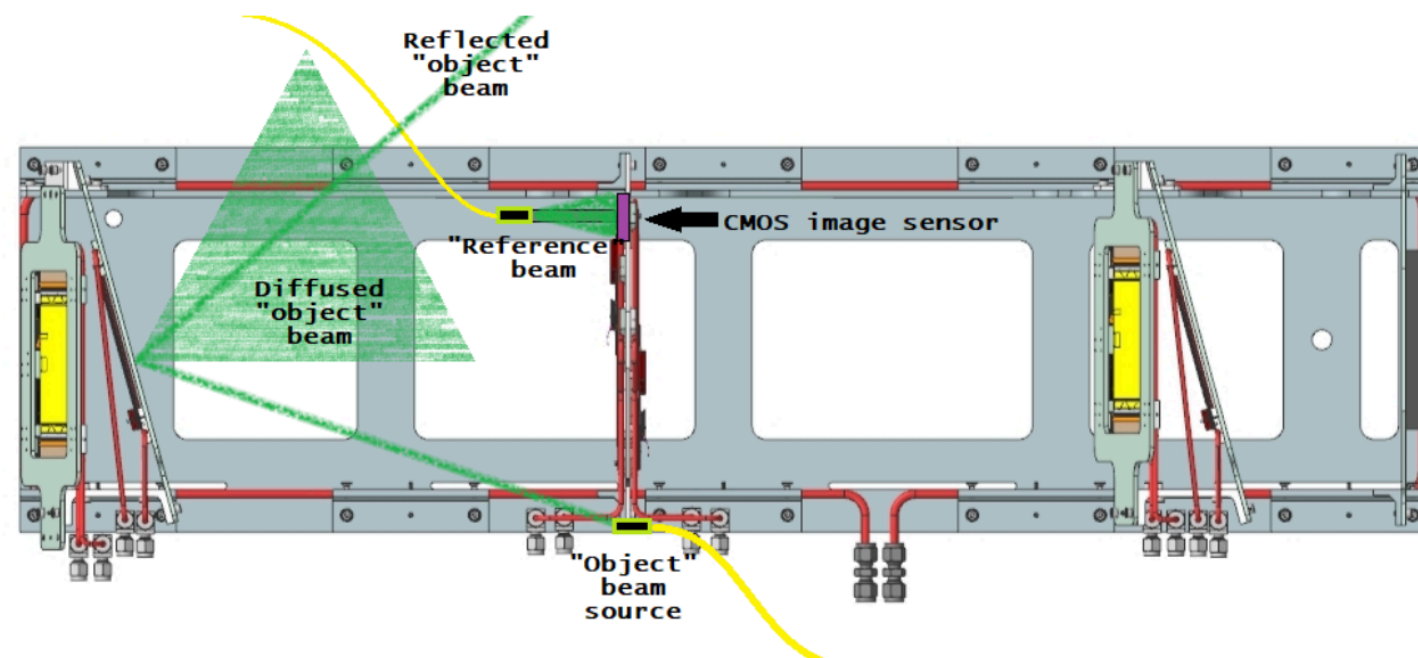
- time-lapse holographic images compared with an initial reference image
- interference fringes evidence relative movements, 1 fringe = $\lambda/2$ displacement

- **Visible HAM**

- 532 nm $\Rightarrow$ 0.25 μm sensitivity
- monitoring possible when trackers are off

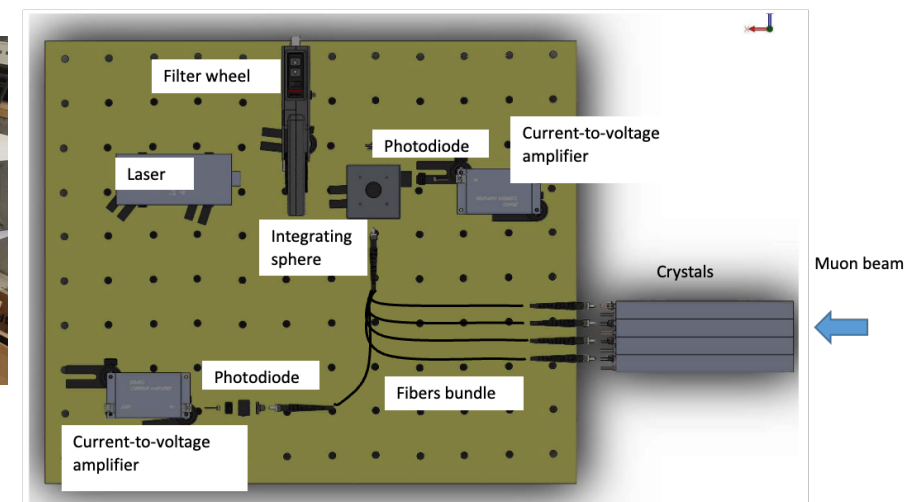
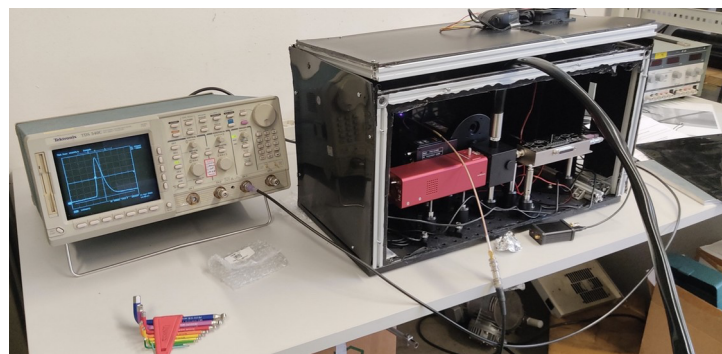
- **IR HAM**

- testing phase, next upgrade
- 1550 nm $\Rightarrow$ 0.75 μm sensitivity
- continuous monitoring during data taking



ECAL

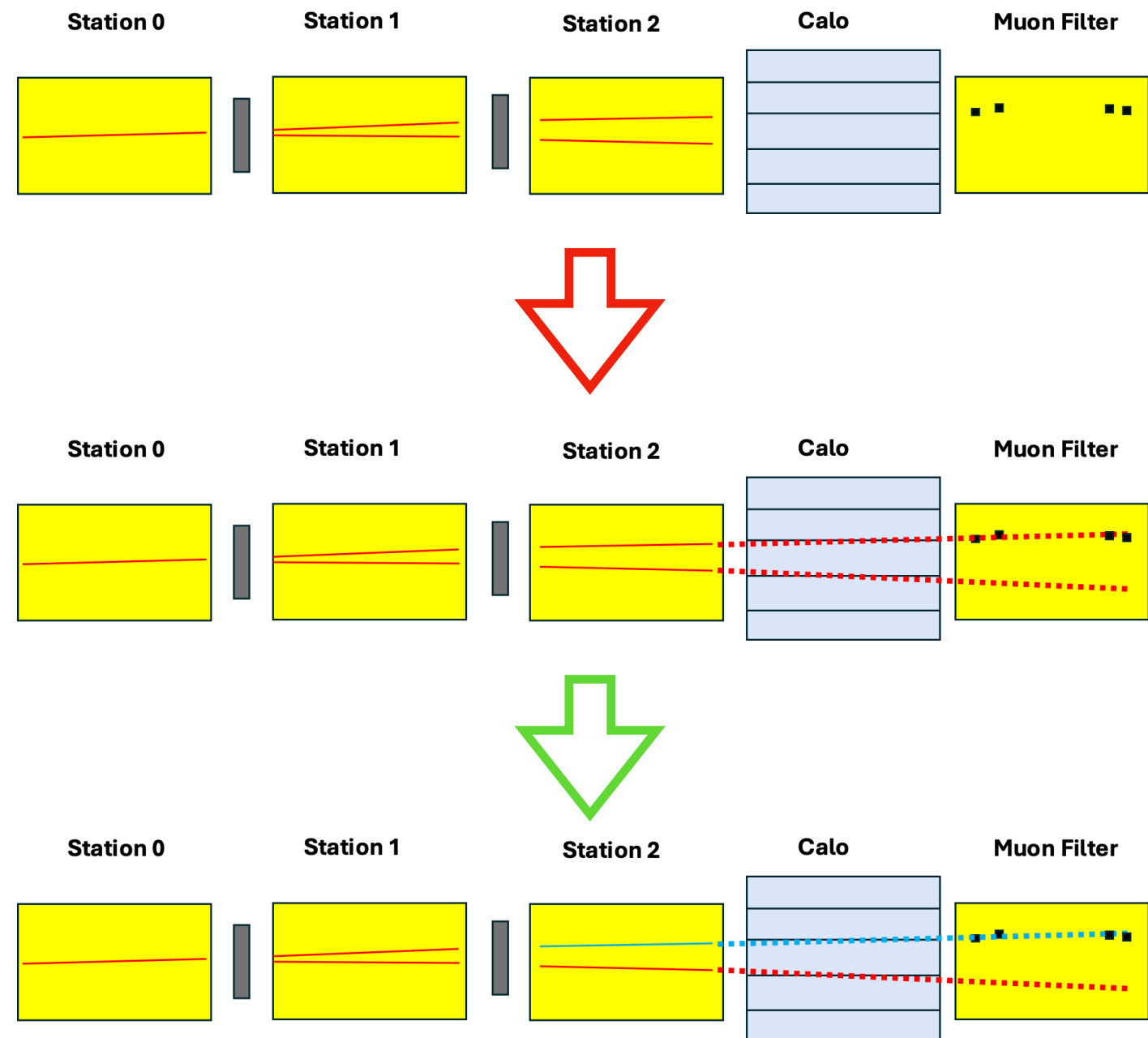
- **25 PbWO₄ crystals (as used in the CMS ECAL)**
 - (2.85 cm)x(2.85 cm) cross section
 - 23 cm long (~25 X₀)
- light readout with APDs directly coupled to the crystals
- measures 1-150 GeV electron energies
- calibrated with a fiber-coupled laser system “à la Muon g-2”



Muon Filter PID

• Muon Filter PID

- reconstruct muon tracks after the ECAL
- connect with tracks before the ECAL $\Rightarrow$ PID at small angles < 5 mrad
- must cover entire beam cross section after the ECAL
- requires 2 pairs of x-y coordinates $\Rightarrow$ 4 tracking planes



Muon Filter HW

- **2025 “baseline” hardware**

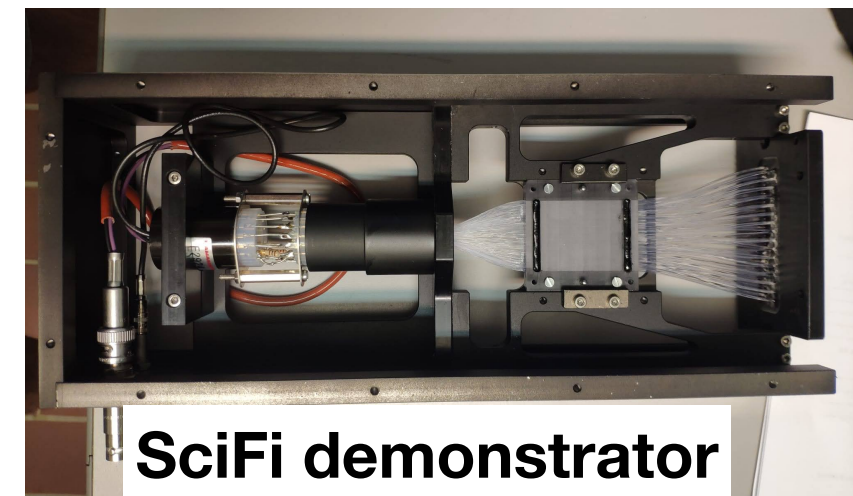
- 2 pairs of non-tilted 2S modules as in the tracking stations
- cross section coverage (90 mm)x(90 mm) $\Rightarrow$ sufficient for the 2025 test run setup

- **SciFi Muon Filter upgrade - 2026 $\rightarrow$**

- Scintillating Fiber tracking planes
 - 1.25 mm pitch, scalable area
 - SiPM readout
 - PMT trigger signal from fiber bundle



2025 baseline Muon Filter



SciFi demonstrator



Beam Momentum Spectrometer

- Every by event muon momentum measurement with 2 BMS stations

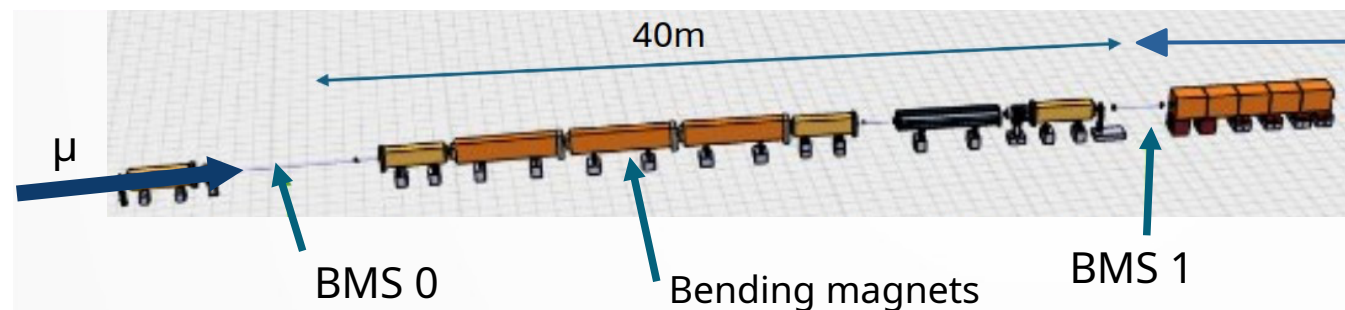
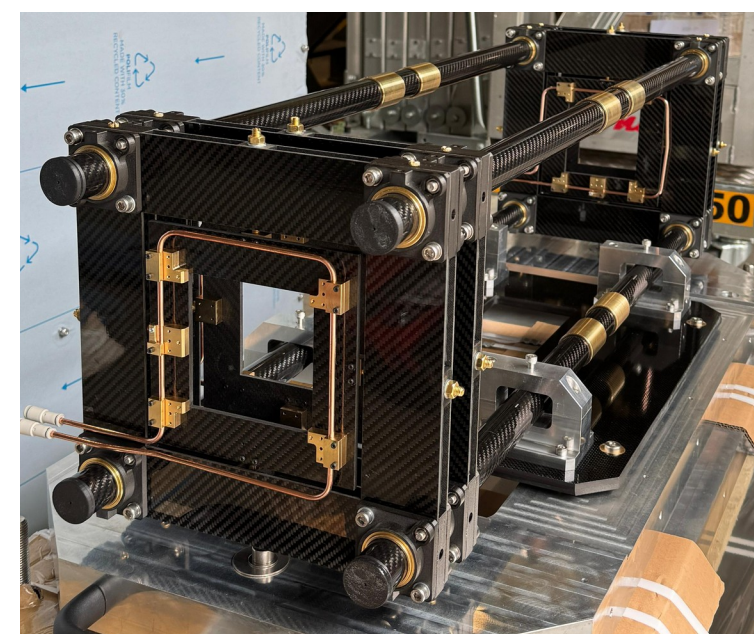


Figure from R. Pilato, FCCP workshop, Anacapri, Italy 2025

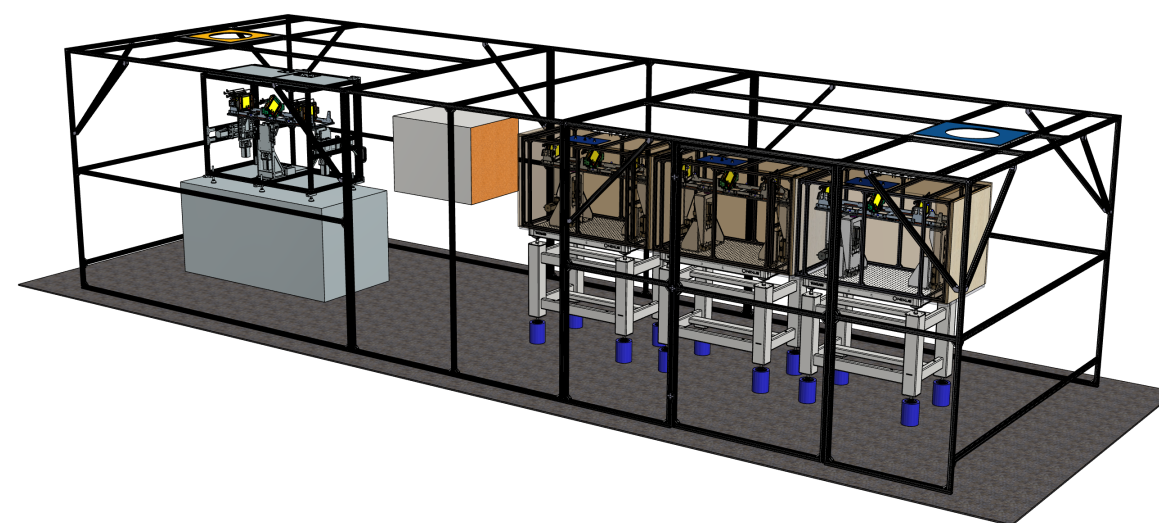
**MUonE
tracker**

- Goal resolution $< 0.5 \%$
 - Bending power: $16 \text{ T}\cdot\text{m}$, 30 mrad at 160 GeV
 - 1 m long carbon fiber structure
 - 2 x-y non tilted tracking planes equipped with 2S modules
- First tests in 2025



2025 test run

- **July-August 2025: test run at the CERN M2 beamline with 160 GeV muons**
- **main goals**
 - demonstrate detection integration
 - validate DAQ chain
 - identify elastic events
- **setup**
 - 3 tracking stations, 2 stations equipped with 2 cm thick C targets
 - ECAL
 - Muon Filter PID
 - BMS (2 stations)
 - timing scintillators at both ends of the line



MUonE current status

- **2025 test run**

- several weeks of data taking with a fully integrated pilot apparatus

- **preliminary sample**

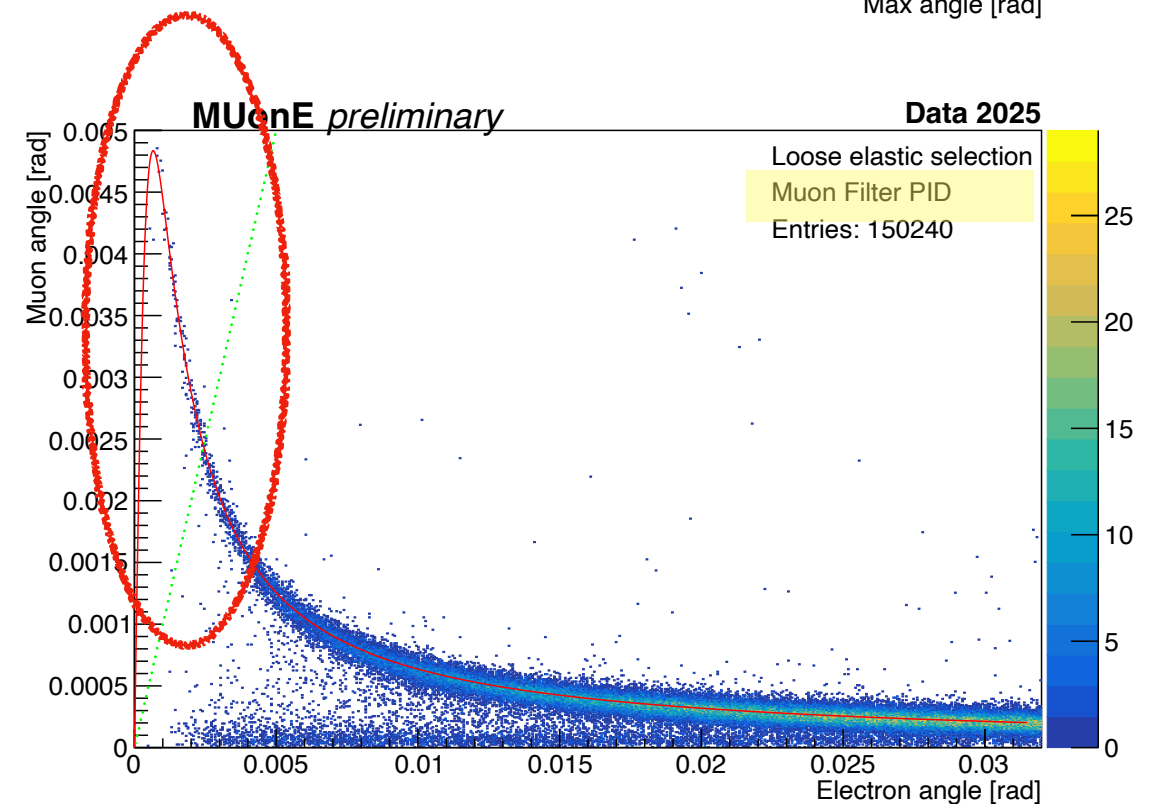
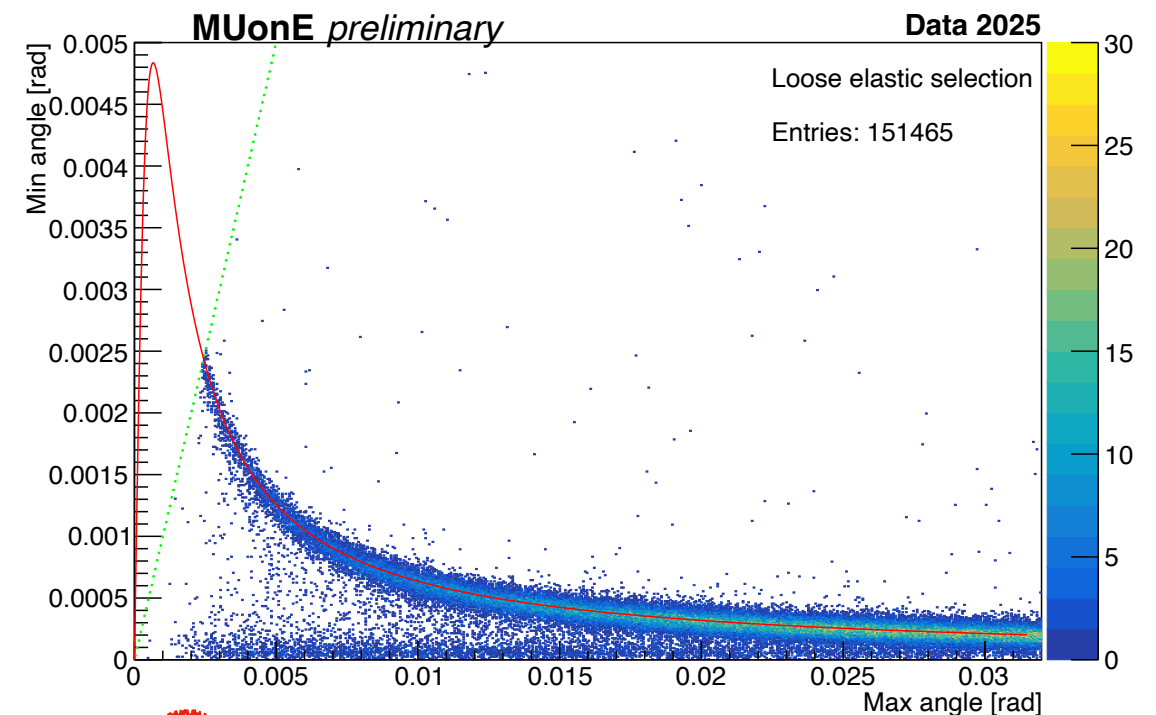
- elastic events
- small angle PID

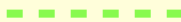
- **Ongoing analysis campaign**

- study systematic effects
- preliminary measurements of $\Delta\alpha_{had}(t)$ at $\sim 20\%$ level (syst. & stat.)

- **Main directions 2026 →**

- detector review
- detailed proposal to SPSC
- goal: achieve full setup after the LHC long shutdown (2029 →)



 $\theta_\mu = \theta_e$ reference
 $\theta_\mu - \theta_e$ kinematic relation

Perspectives at JPARC

- **MuSEUM+AMuLET**

- ground-state hyperfine splitting of muonium atoms $\Rightarrow$ muon magnetic moment, muon mass

- independent precision measurement of “auxiliary” quantities entering a_μ

- **G-2/EDM (seminar on 13/10 by Tsutomu Mibe)**

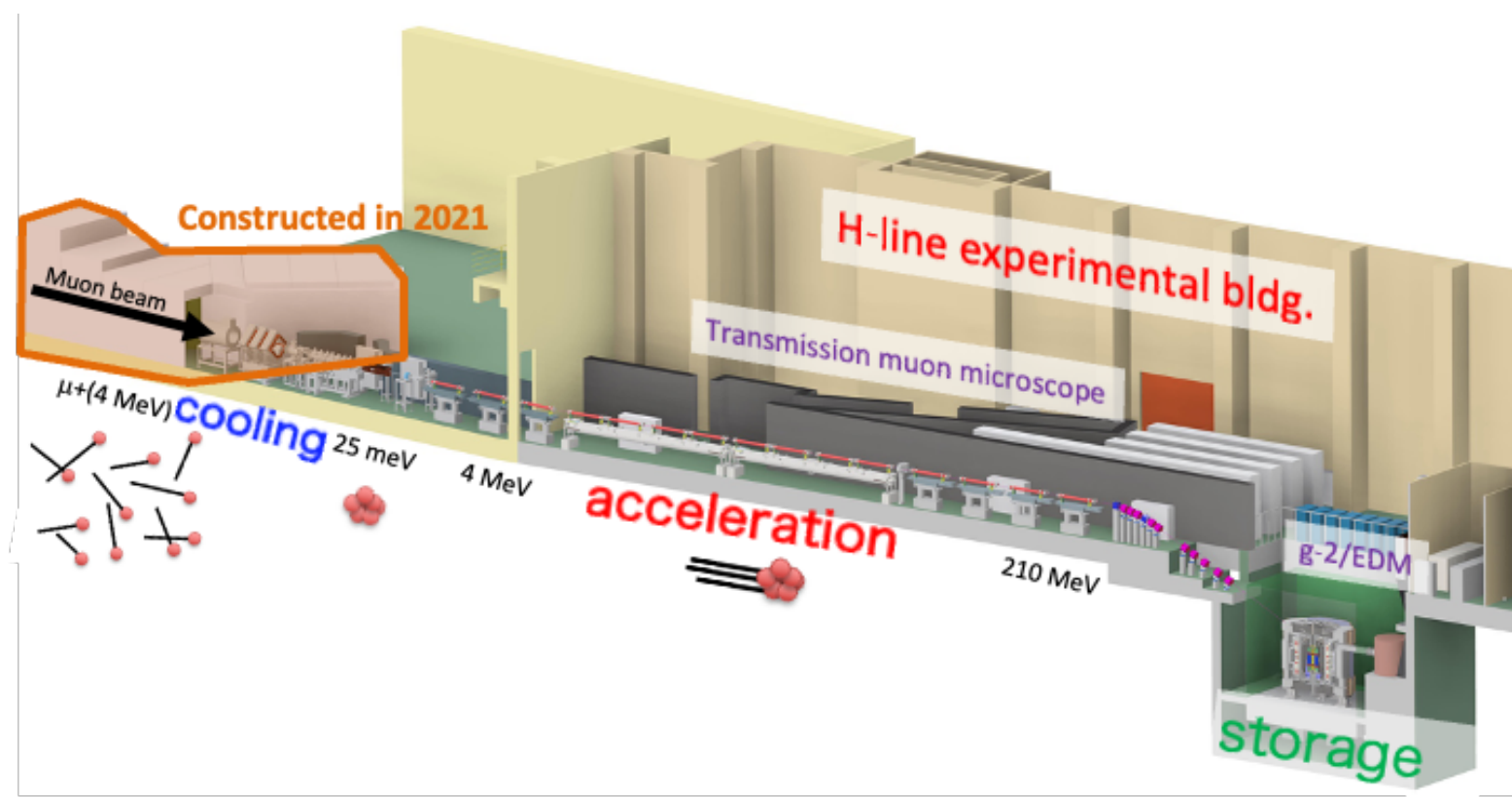
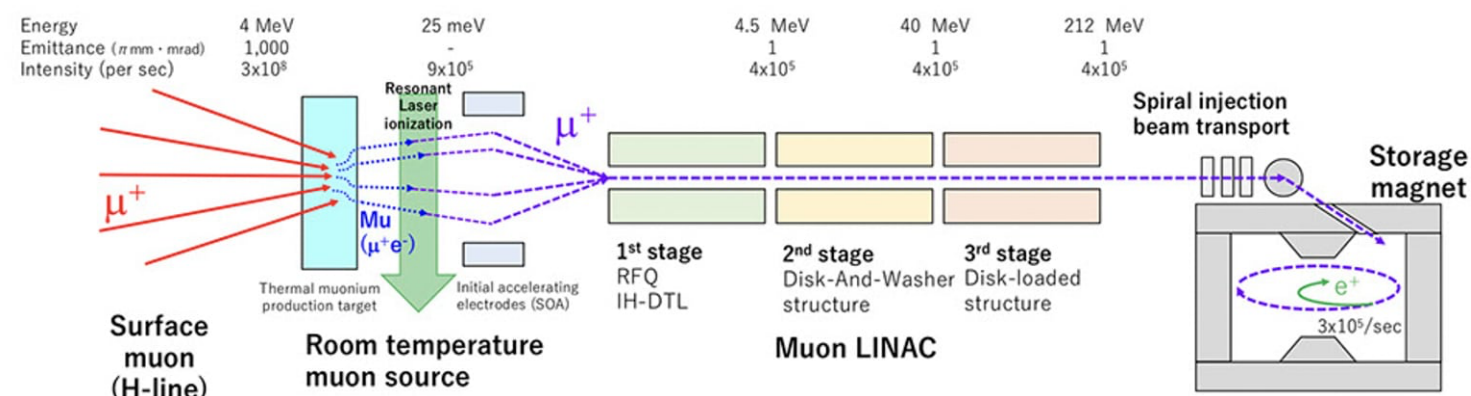
- muon precession in a magnetic field

- independent measurement of a_μ and muon EDM

G-2/EDM@JPARC

• Main differences w.r.t. E989 - Fermilab

- no electric field and weak magnetic focusing
- simultaneous measurement of a_μ and EDM of the muon
- high emittance re-accelerated thermal muons
 - muon loss
 - “strong focusing”
 - pion background
- ➔ different systematics
- 300 MeV/c muons
 - compact magnetic ring $\Rightarrow$ uniformity
 - complete tracking of decay positrons



G-2/EDM@JPARC
<https://g-2.kek.jp/overview/>

Possible INFN contributions

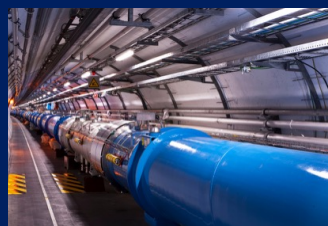
- **tracking detectors diagnostics**
 - holographic interferometry “à la MUonE”
- **transient field magnetometry**
 - optical magnetometer developed for E989
- **high emittance thermal muon source**
 - muonium ionization and “laser cooling” - INO colleagues
- **high field solenoid (6 T ?)**
 - magnet experts - INFN Genova group - S. Farinon
 - feasibility study by ASG Superconductors



ASG APPLIED SUPERCONDUCTIVITY WORLDWIDE



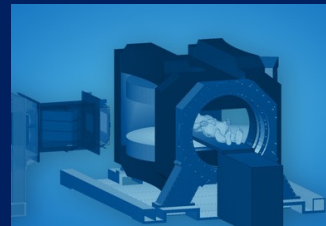
1. IBA | THERAPY SYNCHROCYCLOTRON **Belgium**



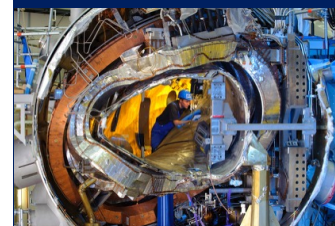
2. CERN | RESEARCH HI-LUMI LHC **Swiss**



3. CERN | RESEARCH MGB2 HIGH CURRENT LINKS **Swiss**



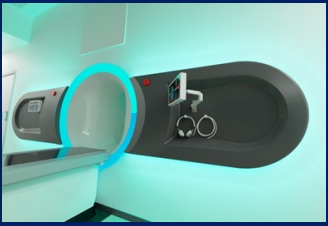
4. HZDR | THERAPY MR GUIDED PROTON THERAPY **Germany**



5. IPP | FUSION W7X STELLARATOR **Germany**



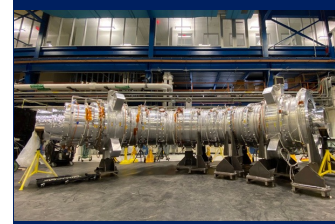
6. GSI | RESEARCH SUPER FRS MULTIPLETS **Germany**



7. MAGNET TX | THERAPY MR GUIDED RADIOTHERAPY **Canada**



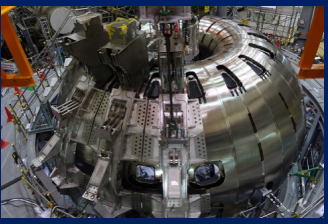
8. JINR | RESEARCH MULTI PURPOSE DETECTOR **Russia**



9. FERMILAB | RESEARCH MU2E TS MAGNETS **USA**



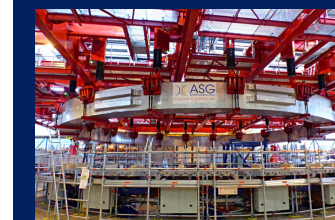
10. GACHON | RESEARCH UHF MRI MAGNETS **South Korea**



11. ENEA | FUSION JT-60SA TOROIDAL FIELD COILS **Japan**



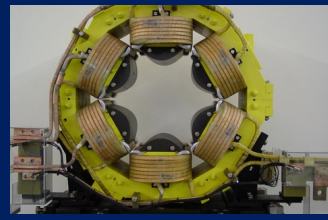
12. F4E | FUSION ITER TOROIDAL FIELD COILS **France**



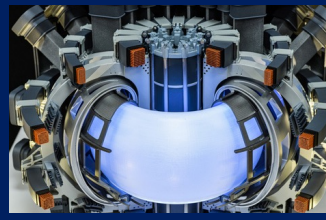
F4E | FUSION ITER POLOIDAL FIELD COILS **France**



14. DIAGNOSTICS MROPEN EVO **EU | UK | USA | Kuwait**



15. CNAO | THERAPY SYNCHROCYCL. & TL MAGNETS **Italy**



16. ENEA | FUSION DTT TOROIDAL FIELD COILS **Italy**



ASG has a solid know-how based on many decades of manufacturing of superconducting devices

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Conclusions

- The **high precision experimental value of a_μ** recently released by E989 at Fermilab is a solid benchmark. **It is not, however, the end of the story.**
- **Discrepancies** between lattice and data-driven calculations and unresolved **tensions** in the current experimental determinations of the leading **hadronic vacuum polarization** contribution, call for a new independent measurement. The **MUonE experiment** at CERN tries to address this concern.
- A new measurement of a_μ **with different systematic effects** and uncertainties is clearly highly desirable.
- The **Muon g-2/EDM@JPARC** project in Japan promises such a new precision measurement of the muon gyromagnetic anomaly

“Before I came here I was confused about this subject. Having listened to your lecture I am still confused, but on a higher level.”

E. Fermi

