UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

Muon g-2 puzzle and KLOE, MUonE experiments

Fedor Ignatov

Particle Physics Annual Meeting

22 May 2026

The Muon g-2 Theory Initiative

White Paper 2020

Data-driven based HVP number

White Paper 2025, update

Lattice based HVP number

the community of theorists and experimentalists with goal to provide consensus number for the theoretical estimate of a_μ within the SM.

Physics Reports 1143 (2025) 1–158

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Review article

We dedicate this paper to the memory of Simon Eidelman.

The anomalous magnetic moment of the muon in the Standard Model: an update

R. Aliberti [1,2], T. Aoyama [3], E. Balzani [4,5], A. Bashir [6,7], G. Benton [8,9], J. Bijnens [10], V. Biloshytskyi [1,2], T. Blum [11,12], D. Boito [13], M. Bruno [14,15], E. Budassi [16,17], S. Burri [18], L. Cappiello [19], C.M. Carloni Calame [17], M. Cè [14,15], V. Cirigliano [20,21], D.A. Clarke [22], G. Colangelo [18,*], L. Cotrozzi [23], M. Cottini [18], I. Danilkin [1,2], M. Davier [24,*], M. Della Morte [25], A. Denig [1,2,26,27], C. DeTar [22], V. Druzhinin [28], G. Eichmann [29], A.X. El-Khadra [8,9,*], E. Estrada [30], X. Feng [31,32,33], C.S. Fischer [34,35], R. Frezzotti [36], G. Gagliardi [37], A. Gérardin [38], M. Ghilardi [16,17], D. Giusti [39,40], M. Golterman [41], S. Gonzàlez-Solís [42,43], S. Gottlieb [44], R. Gruber [45], A. Guevara [46], V. Gülpers [47], A. Gurgone [48,49], F. Hagelstein [1,2], M. Hayakawa [50,51], N. Hermansson-Truedsson [10,47], A. Hoecker [52], M. Hoferichter [18,*], B.-L. Hoid [1,2], S. Holz [18], R.J. Hudspith [53], F. Ignatov [23], L. Jin [11], N. Kalntis [18], G. Kanwar [47], A. Keshavarzi [54], J. Komijani [45], J. Koponen [1,2], S. Kuberski [55], B. Kubis [56], A. Kupich [28], A. Kupść [57,58], S. Lahert [22], S. Laporta [4,5], C. Lehner [40,*], M. Lellmann [1], L. Lellouch [38,*], T. Leplumey [59,60], J. Leutgeb [61], T. Lin [31], Q. Liu [62], I. Logashenko [28], C.Y. London [13], G. López Castro [30], J. Lüdtke [63], A. Lusiani [49,64], A. Lutz [24], J. Mager [61], B. Malaescu [65], K. Maltman [66,67], M.K. Marinković [45], J. Márquez [30], P. Masjuan [68,69], H.B. Meyer [1,2,26,27], T. Mibe [70,*], N. Miller [26,27], A. Miramontes [71,72], A. Miranda [68], G. Montagna [16,17], S.E. Müller [73], E.T. Neil [74], A.V. Nesterenko [28], O. Nicrosini [17], M. Nio [51,75], D. Nomura [76], J. Paltrinieri [23], L. Parato [45], J. Parrino [40], V. Pascalutsa [1,2], M. Passera [5,77], S. Peris [68,69], P. Petit Rosàs [23], F. Piccinini [17,78], R.N. Pilato [23], L. Polat [65,24], A. Portelli [47], D. Portillo-Sánchez [30], M. Procura [63], L. Punzi [49,64], K. Raya [7], A. Rebhan [61], C.F. Redmer [1,2], B.L. Roberts [79,*], A. Rodríguez-Sánchez [72], P. Roig [30,72], J. Ruiz de Elvira [80], P. Sánchez-Puertas [81], A. Signer [82,60], J.W. Sitison [74], D. Stamen [56]

Large Contribution from Liverpool:

One of Committee members:

Thomas Teubner

One of coordinators for data-driven HVP WG:

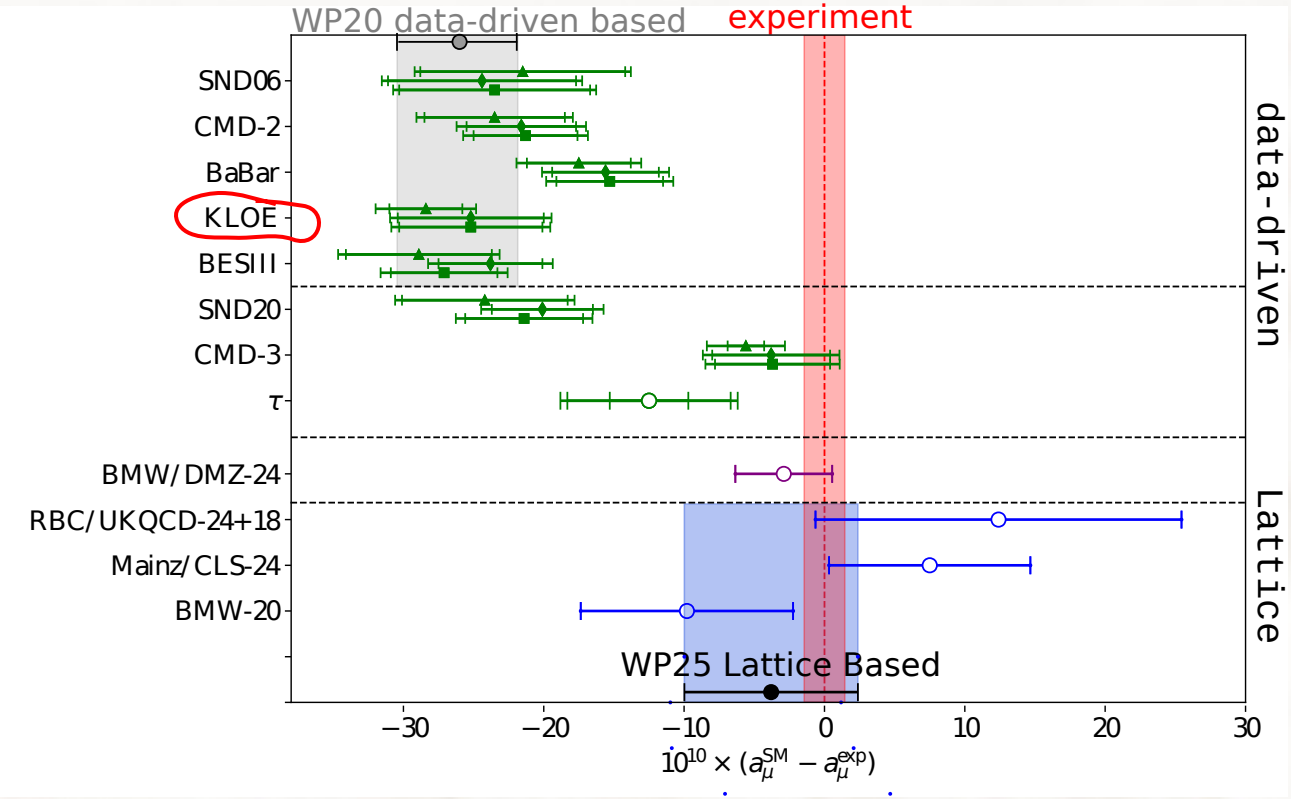
Fedor Ignatov

Contributions to the writing of the White Paper:

L. Cotrozzi, J. Paltrinieri, P. Petit Rosàs, R. N. Pilato, W. J. Torres Bobadilla, Y. Ulrich, G. Venanzoni, A. Wright, E. Zaid

Many others signed the White Paper 25 or contributed via used underline data

State-of-art in g-2 Theory



e+e- had increased the tensions after CMD-3 results

Tau is placed back on the table

Lattice starts to be consolidated

Hybrid gives better precision

Despite the present difficult situation, a data-driven estimate of HVP remains an important goal of the Theory Initiative and an essential cornerstone on which to build future precise SM predictions.

The SM prediction will remain unsatisfactory until we will understand the situation

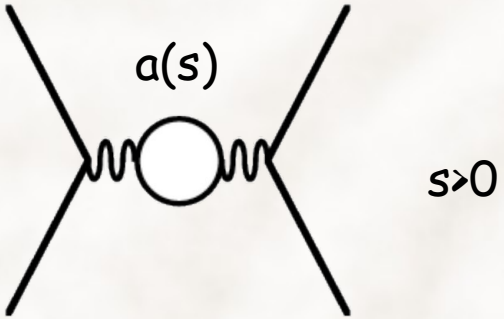
Answer: **KLOE** and **MUonE** are crucial parts of the puzzle

KLOE vs MUonE

KLOE experiment

$e^+e^- \rightarrow \pi^+\pi^-(\gamma)$

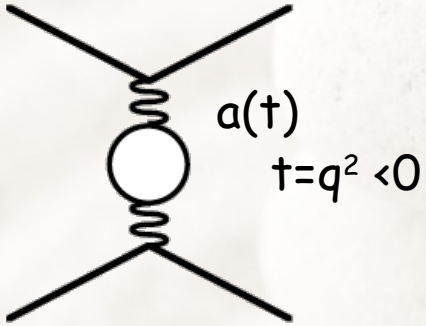
Time-like data



MUonE experiment

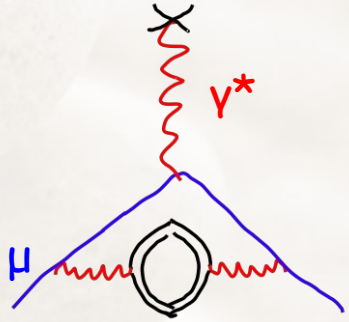
$\mu^+e^- \rightarrow \mu^+e^-$

space-like data



g-2 experiment

Virtual corrections



KLOE came from the past:
was in operation until 2018
Renewed analysis is leaded by Liverpool

MUonE looks to the Future:
expected data-taking in ~ 203x
Analysis of test-beam data now
One of the largest group is based in Liverpool

KLOE Liverpool group

Liverpool is the core group doing π+π− analysis at KLOE,
and also provides a major contribution to maintaining the overall KLOE computing

Data analysis:
Graziano Venanzoni, Fedor Ignatov,
Lorenzo Cotrozzi, Estifa'a Zaid, Paolo Beltrame,
Niels Vestergaard

Theoretical aspects (MC generators,...):
Thomas Teubner, William Torres Bobadilla,
Pau Petit Rosas, Aidan Wright, Tom Dave, Jeremy Paltrinieri,
Lois Flower, Yannick Ulrich

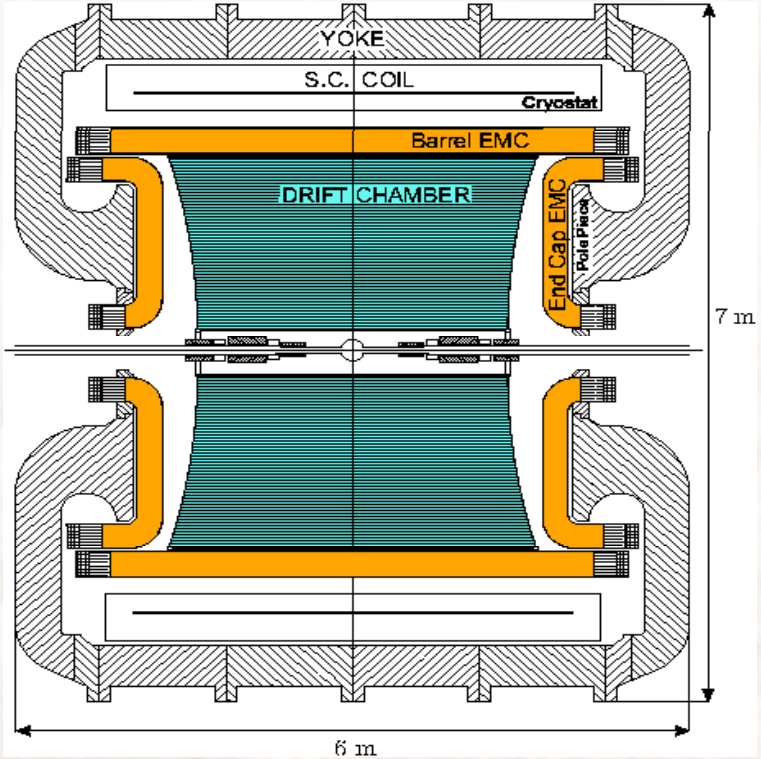
+ few collaborators from SNS, INFN, HZDR, Uppsala
(+ much wider effort on the MC generators)

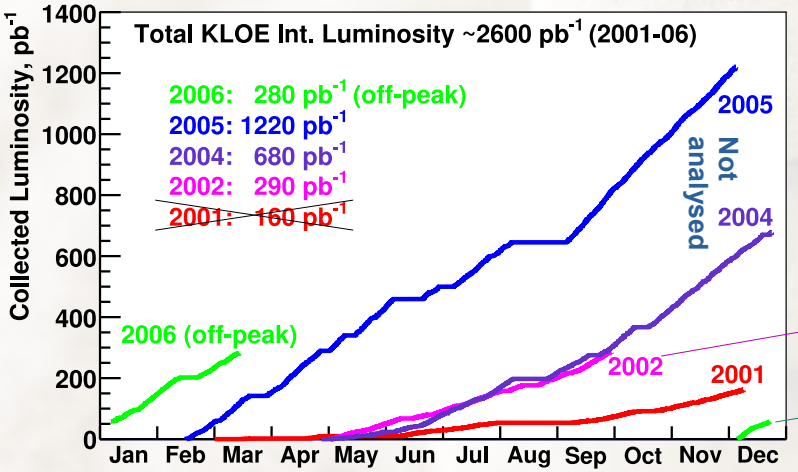
Extremely crucial:
Data analysis is backed by
strong theoretical support

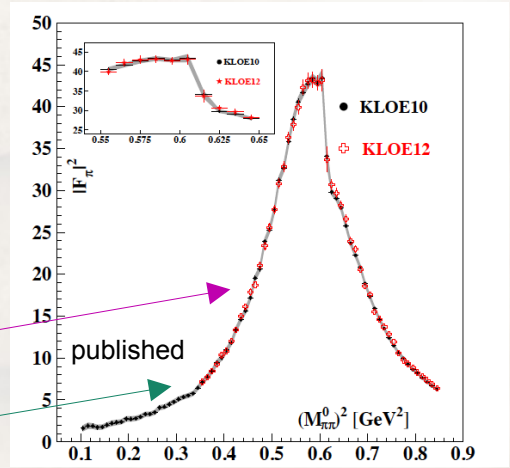
KLOE experiment

KLOE experiment
(1999 - 2006,2014 - 2018)
Biggest Drift Chamber ever built (Ø4m)
Largest Φ-meson statistics ever produced: ~25 billions

Previous e+e- → π+π-γ KLOE publications are based on 2002,2006 data:
JHEP 1803 (2018) 173
3 analyses: with ISR photon on small angles/ large angle/ using radiator function from ISR μ+μ-







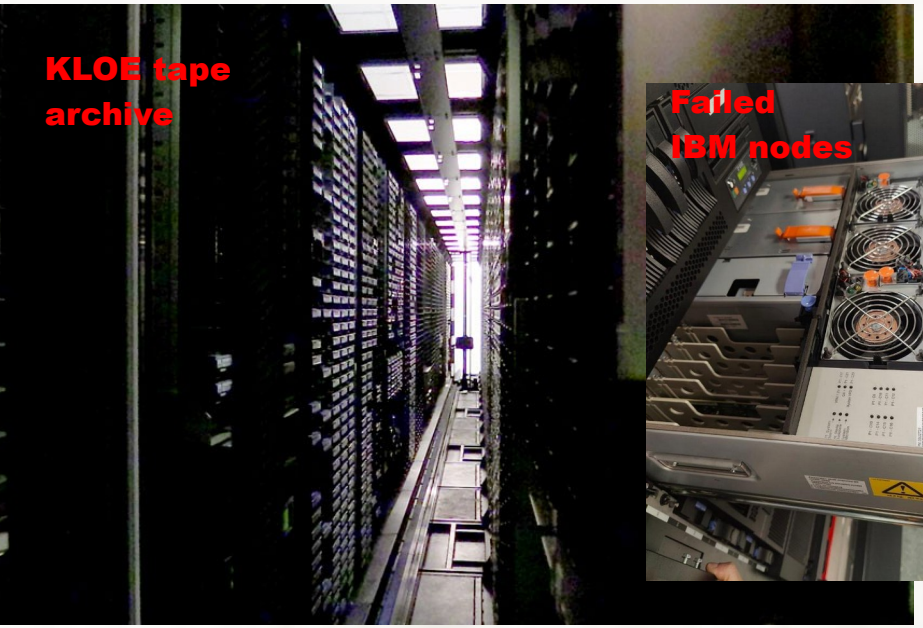
KLOE-nxt

- x7-8 in statistics – **crucial for studying systematics:**
- Stress of systematic effects
- Modernized and more robust analysis techniques
- ISR + scan measurements (on φ-peak + off-peak data)

Challenges

We lost 2 years due to technical aspects which required our full-time effort:

KLOE computing relied on a IBM infrastructure that **is now completely outdated**: tape library, computing nodes, AIX OS, etc . Hardware is near dying and mostly impossible to replace, no administrations



No Access to data, tape library:

~ 3k tapes, 7PB of data-was most performant tape archive in INFN at the time
Broken tape arms,
not bootable nodes with the library database

No Access to KLOE reconstruction and simulation code:

The software stack was adopted from Tevatron ages (framework, zebra banks, fortran, CVS repo, etc)
Everything was stuck within IBM: Power8 CPU memory endianess, x32 addressing, xlf compiler, AIX OS functions, DB2 database, etc
bugs in the code.

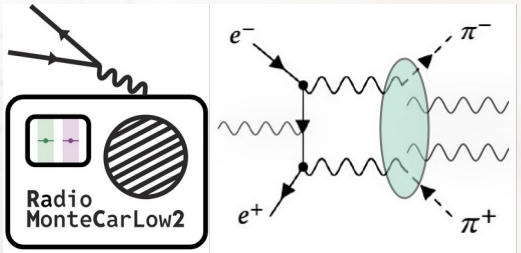
We mostly overcome these difficulties! (happened only this winter – spring):

- ✔ The data has been migrated to CNAF INFN (still missing ~10% of KLOE-1)
- ✔ The code has been ported to Linux, git, DB2 in VM
- ✔ Working environment and copy of data at CNAF and Liverpool
- ✔ First KLOE-1 raw data re-processing and MC production on Linux is completed!

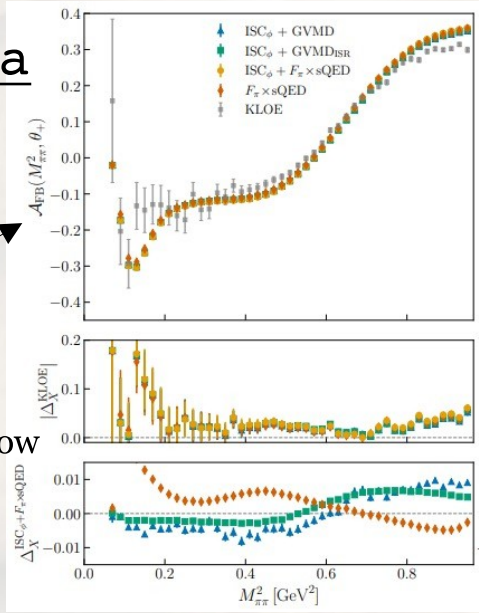
We can start going forward with analysing the data

Updates on the theory side

- Part of the **RadioMonteCarLow2** community, leading updated comparisons of MC generators for low-energy physics: from NLO to NLO+ predictions



- Theoretical support for the **KLOE Experiment:**
  - * Focus on the radiative return processes $e^+e^- \to \pi^+\pi^-\gamma$
  - * Extend fixed order calculation NLO to NLO+ through soft-QED approximation
  - * Improve theoretical prediction within event generator `Phokhara`



- Preliminary results:
  - * 2 recent publications, implemented in Phokhara:
  - 1. Generalised vector-meson dominance model (π-γ interaction):

hep-ph:2603.13171. Forward-backward asymmetry in LA KLOE selection, $\sqrt{s} = 1$GeV
Good agreement in the [0.4,0.8] GeV^2; future KLOE-nxt precision will improve the comparisons and allow to draw conclusions on the impact of GVMD implementation

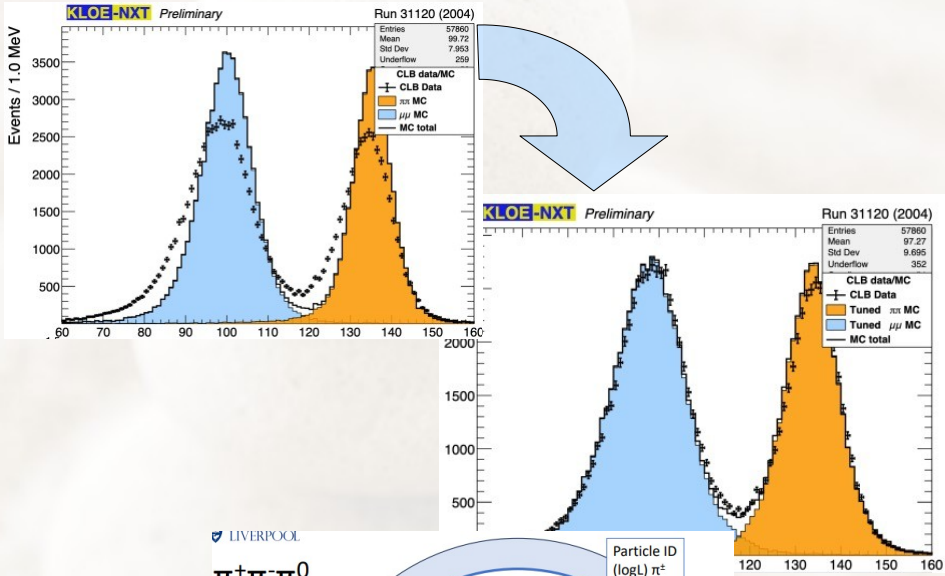
  - 2. one-loop to higher order: hep-ph:2604.16251

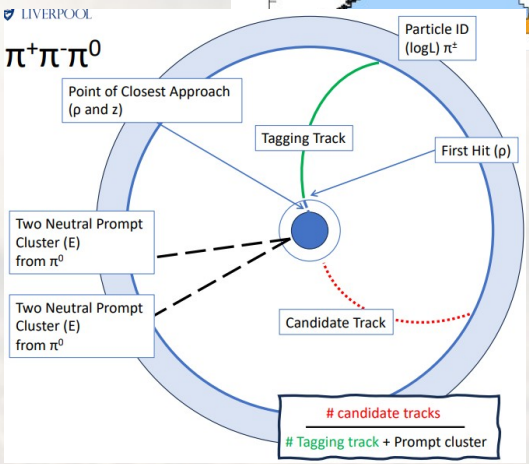
  - * Ultimate goal: NNLO accuracy. $e^+e^- \to \gamma\gamma^* \to \pi^+\pi^-$ **[to appear soon]**

Ongoing KLOE-nxt work and plans

Thanks to recently available DSTs/MC and to processing of raw files/MC at CNAF:

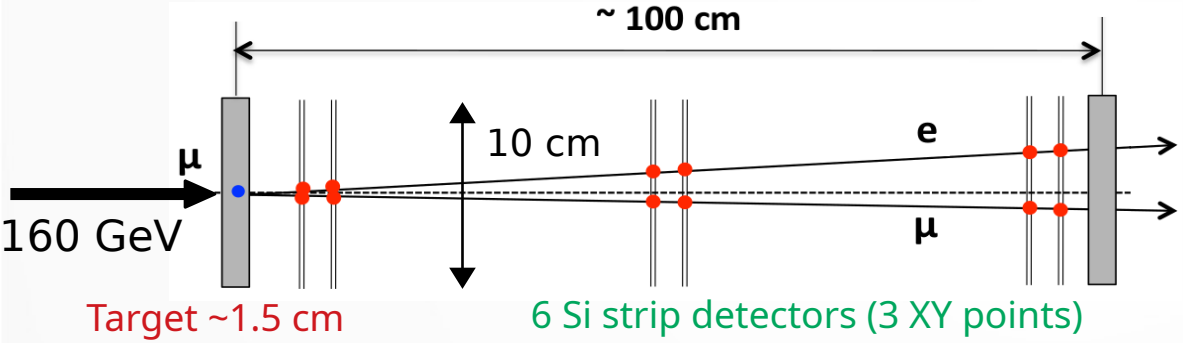
- **Data-MC tuning:** working on new methods, like template fits, to improve consistency of MC with data. Plots: tuning of M_{trk} in control samples
- **Background subtraction**: started comparing MC generators after subtraction; M_{trk} and θ variables
- **Luminosity:** comparisons with previous KLOE12 work ongoing; will assess systematics next
- **Tracking efficiency:** finalizing work on 3π sample and ready to move to $\pi\pi\gamma$ and $\mu\mu\gamma$ samples
- **Normalization, QED check**: started looking at $\mu\mu\gamma$ sample
- **Collinear events study:** FormFactor, asymmetry. Interplay with efficiencies, systematics, etc for ISR sample, Luminosity





The MUonE experiment

- New independent evaluation of $a_\mu^{HVP,LO}$, based on the extraction of $\Delta\alpha_{had}(t)$ from ***μe → μe*** scattering
- Experiment in the M2 beamline at CERN-SPS
- Modular apparatus: 40 tracking stations arranged sequentially to re-use the muon beam

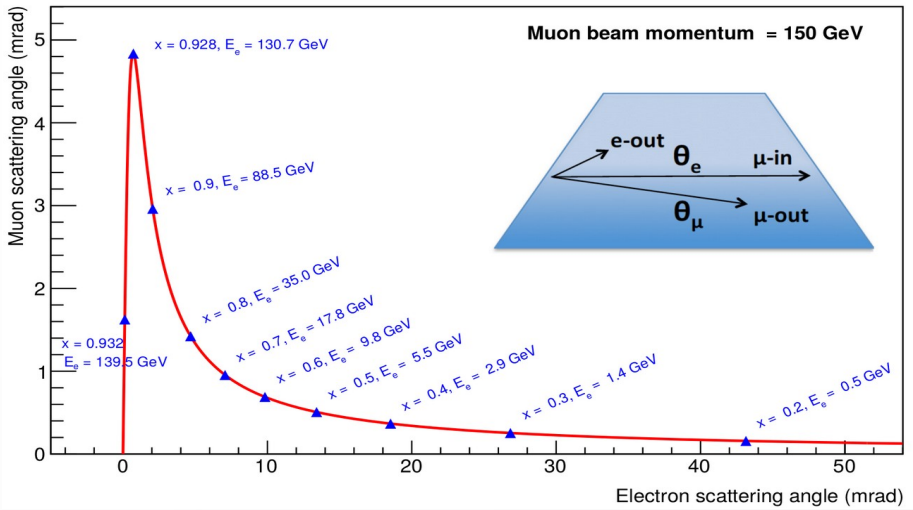


- Observables: (θ_e, θ_μ)
- Exploit (θ_e, θ_μ) correlation to reject background (main source: μ N → μ N e^+e^-)

Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026
Proposal for Phase 1 of the MUonE experiment

Challenging experiment at precision frontier:
10 ppm systematic error on *μ-e* scattering

Thanks Riccardo Pilato for providing the slides



Liverpool in MUonE

- Liverpool is the largest group of the collaboration:
  - 6 Staff: T. Bowcock, S. Charity, F. Ignatov, T. Jones, G. Venanzoni, J. Vossebeld
  - 6 PostDocs: E. Bottalico, L. Cotrozzi, R. Pilato, A. Taylor, E. Zaid, C. Zhang
  - 6 PhDs: G. Cacciola, C. Devanne, K. Ferraby, T. Lenane, S. Pipraiya, N. Vestergaard
  - Technical staff: J. Carroll, A. Greenall, M. Whitley, D. Sim, T. Smith
  - Theory: 2 staff: T. Teubner, Y. Ulrich, 2 PostDocs: W. Torres Bobadilla, J. Paltrinieri, 2 PhD students: P. Petit Rosas, T. Dave

- Leadership roles:
  - Institutional board: G. Venanzoni
  - Editorial board: S. Charity
  - Run coordinator: R. Pilato
  - Software manager: C. Devanne

- Major contributions to all areas of the experiment:
  - Track reconstruction and alignment
  - Detector simulation
  - Background rejection analysis
  - Event selection and $\Delta\alpha$ extraction
  - Detector design and construction
  - Data Quality Monitoring

2025 test run: MUonE Phase-1

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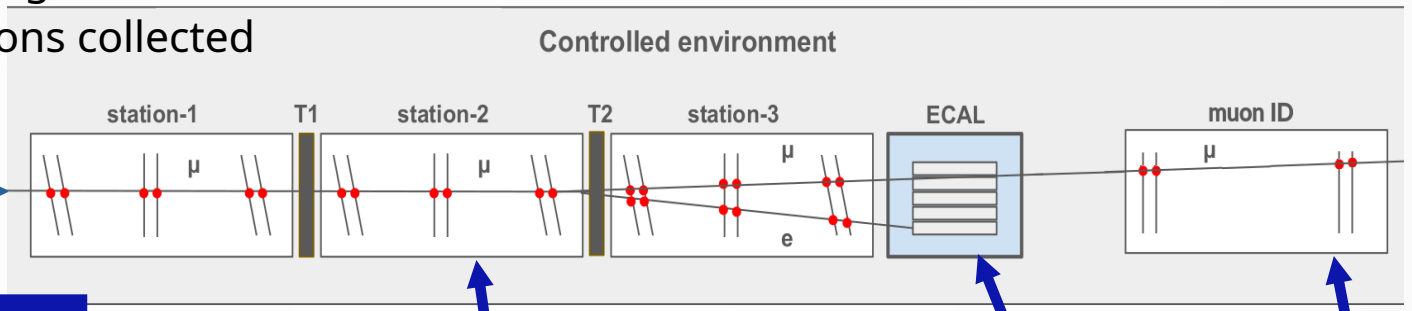
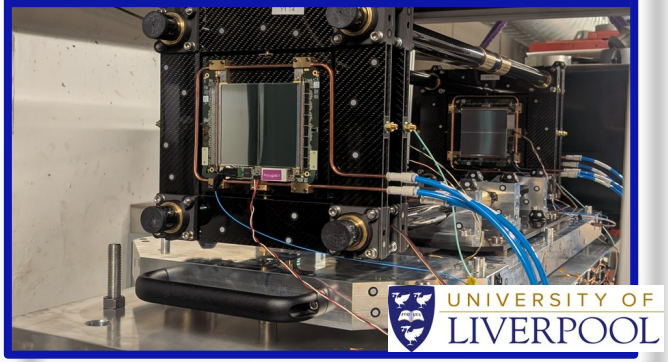
3 months of the data taking
550 billion interacted muons collected
Goal to extract $\Delta a_{lep}(t)$

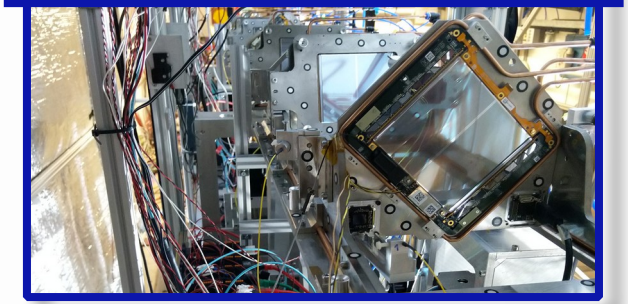


2×carbon fibre tracking stations
4×2S-modules each



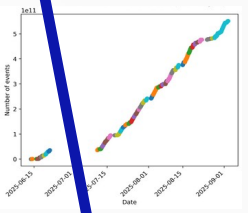
- Ultimate goal:
  $\Delta E_\mu \sim 0.1\%$ event-by-event
- Challenges:
  - Alignment < 100μm over 40 m
  - B-field measurement ~0.1%

Tracking stations equipped with 6×2S-modules (CMS Phase2)

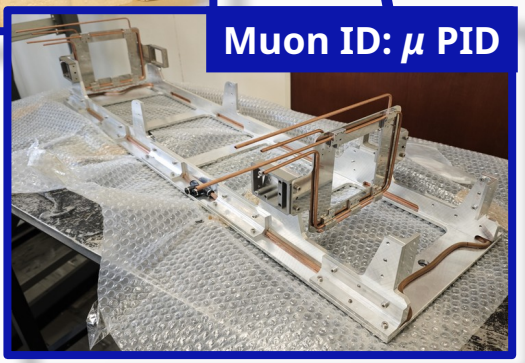


- Challenges:
  - Longitudinal alignment < 10 μm
  - Transverse alignment < 0.1 μm
  - Hit resolution < 10 μm
    with sub-0.1 micron control
  - Hit efficiency > 99.5%
    with sub-permille uniformity

ECAL: e^- PID + E_e measurement



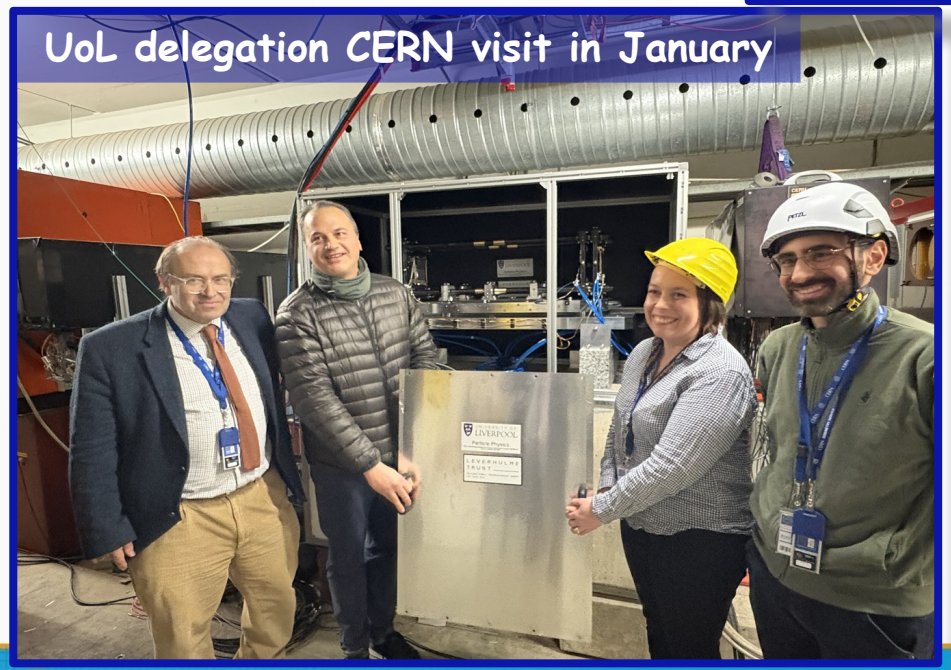
Muon ID: μ PID

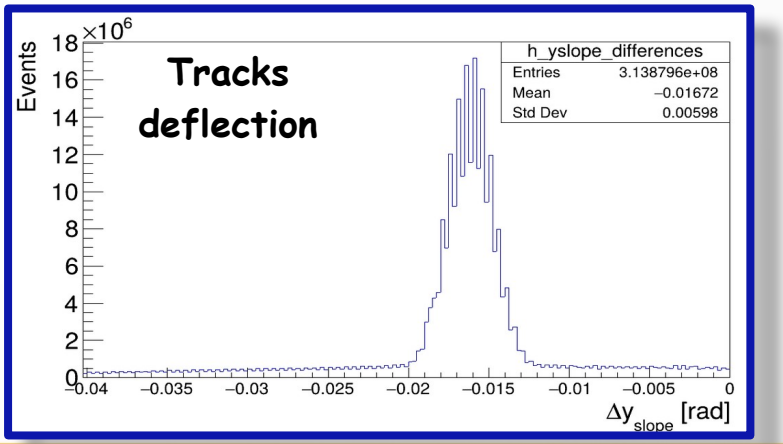


BMS (Beam Momentum Spectrometer)

- Huge effort by workshop to deliver the detector for the 2025 run!
- Data analysis ongoing (precision limited by B-field measurement and alignment)
- Parasitic data taking in 2026

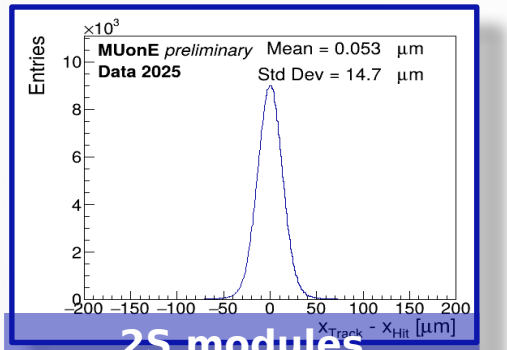
Carbon Fibre Structure with zero CTE O(1ppm/K)



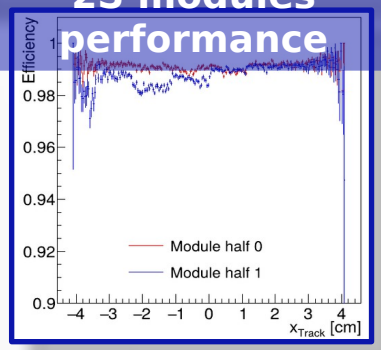


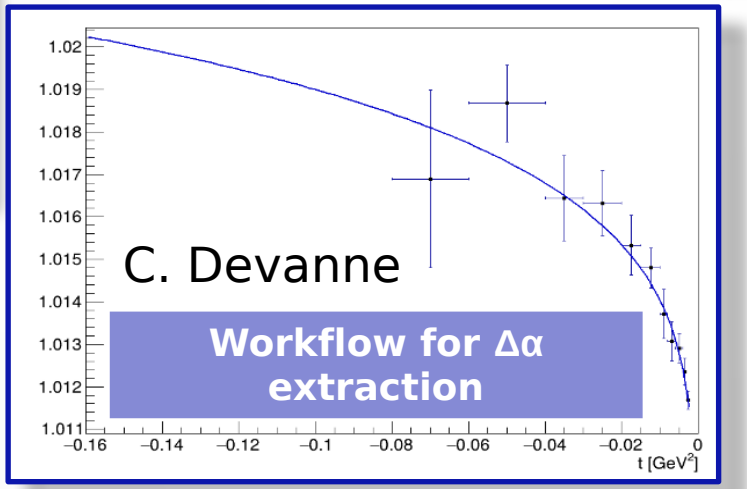
Analysis activities

- Liverpool leads the analysis of 2025 data and simulation development:
  - Proof of principle measurement of $\Delta\alpha_{lep}(t)$
  - Study systematic effects
- Main contributing institution to the first MUonE paper about 2S-modules performance, currently in preparation.

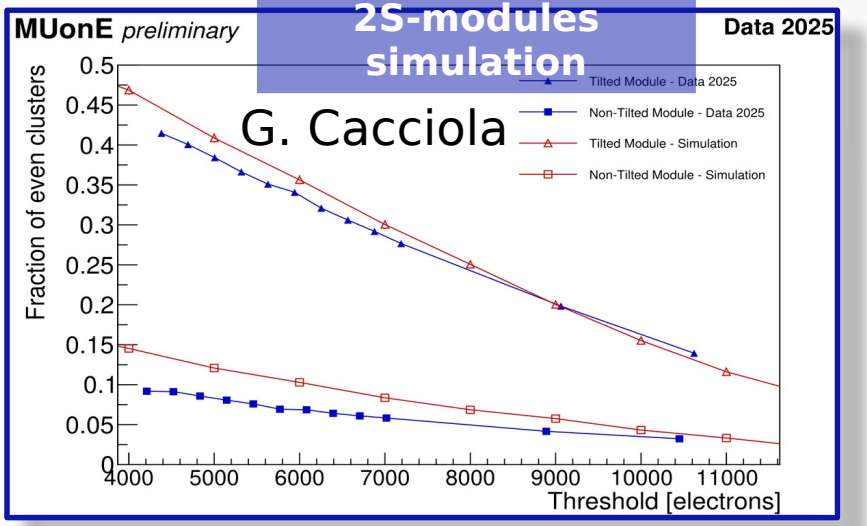


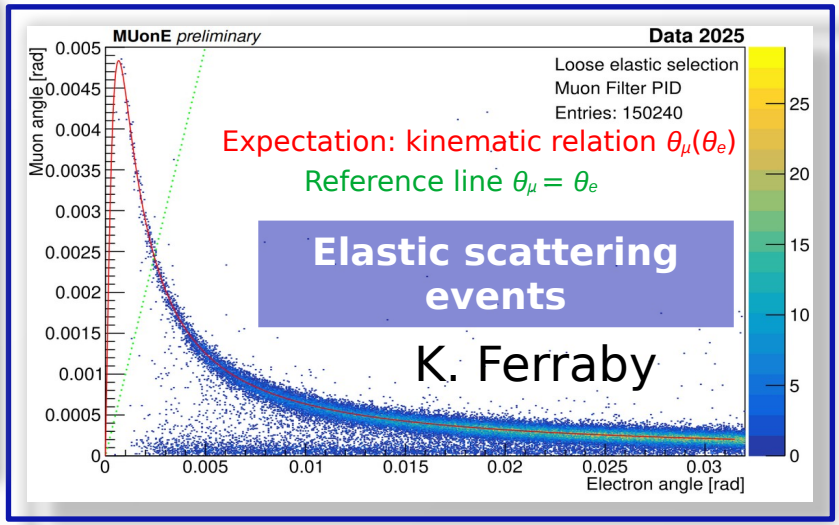
2S modules performance





2S-modules simulation





Hardware activities

G. Cacciola, A Greenall, A. Taylor

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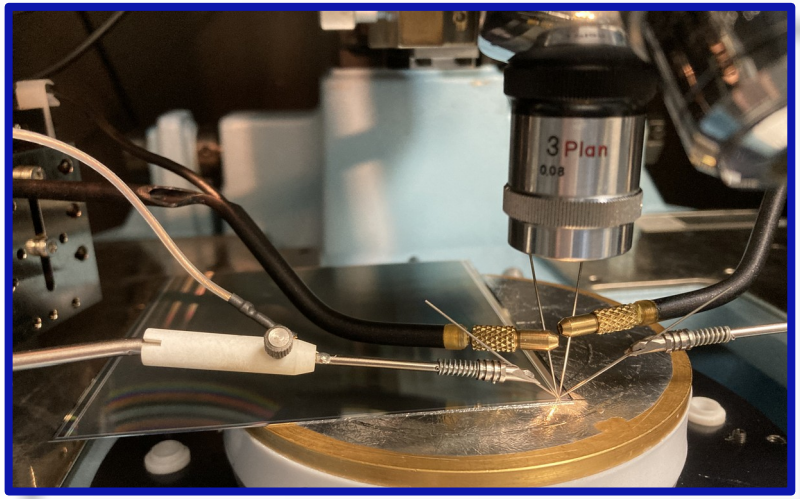
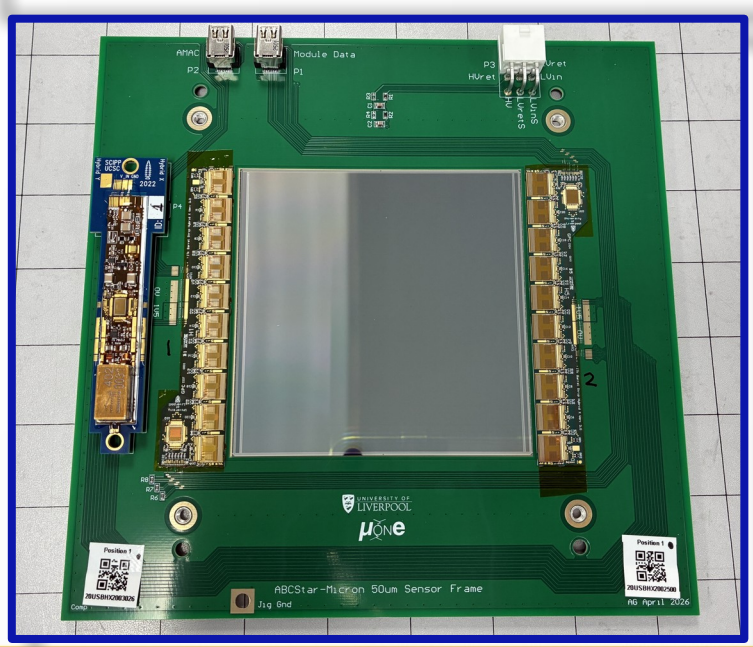
- MUonE has challenging requirements on detector resolution, efficiency and stability of performance
- Liverpool is investigating alternatives to upgrade the current silicon detector
- Purchased 10 Si sensors (Micron Semiconductor):
  - Sensitive area: 10×10 cm^2
  - Thickness: 300 µm
  - Strip pitch: 50 µm
- Sensors qualification is ongoing
- Goal is to couple this sensor to an analog chip capable of sustaining > 40 MHz beam intensity
- **LASH project: 160 k€** funded by **Horizon-Europe** to hire a PDRA/technician dedicated to this development (start Oct26)





Outline

The muon g-2 puzzles are not yet solved

Liverpool is one of the leading contributor to g-2 experiment and theory
KLOE and MUonE experiments are key part of the muon anomaly puzzle

KLOE analysis is ongoing

we have successfully overcome technical challenges in accessing the data and the reconstruction/simulation code

MUonE has successful Phase-I data-taking during 2025

with goal: Proof of principle measurement of $\Delta a_{lep}(t)$

Full-scale experiment proposal (40 tracking stations + ancillary detectors) to be prepared during Long Shutdown

Backup