Muon $g-2$ and KLOE activities in Liverpool

Lorenzo Cotrozzi

Particle Physics Annual Meeting 2024 | Liverpool

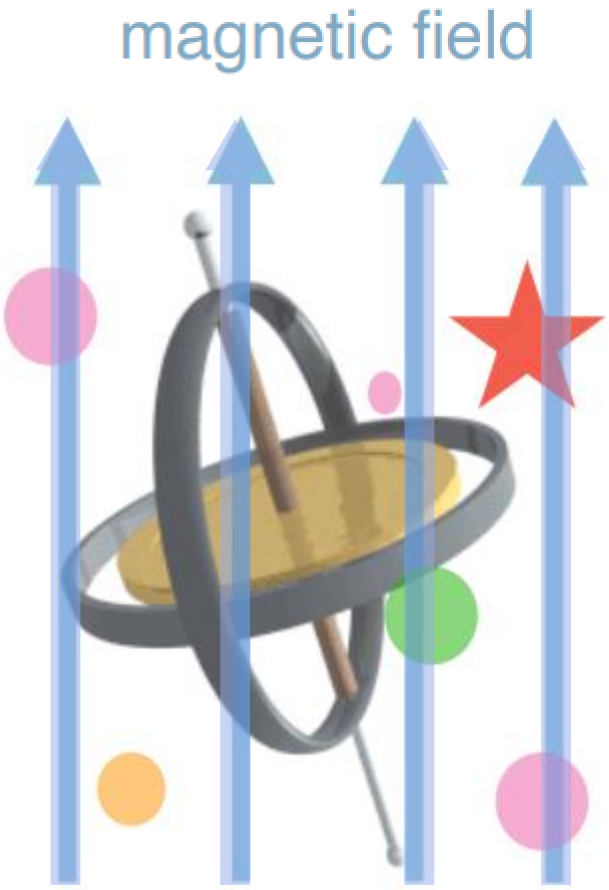
23/05/2024

UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

The anomalous magnetic moment

- Particle with spin in magnetic B-field: $\vec{\mu} \equiv g \frac{e}{2m} \vec{S} \rightarrow \tau = \vec{\mu} \times \vec{B}, \mathrm{U} = -\vec{\mu} \cdot \vec{B}$
- Dirac's prediction for spin-$\frac{1}{2}$ charged particles: $g = 2$



$$\boldsymbol{g - 2 = 0}$$

The anomalous magnetic moment

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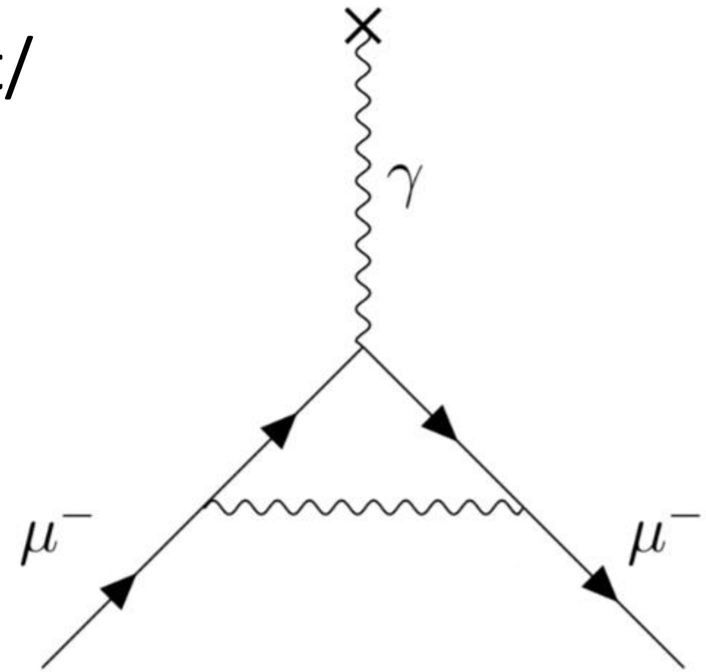
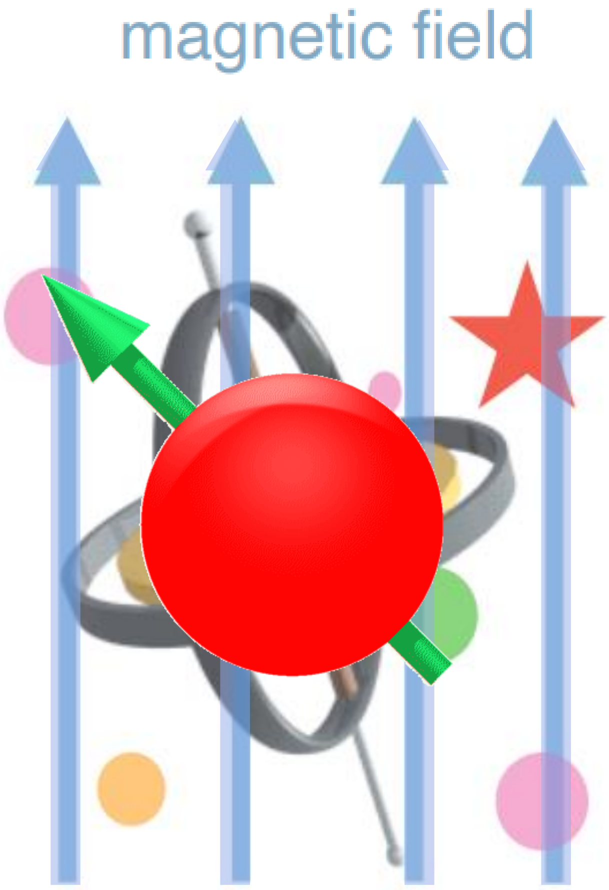
- Dirac's prediction for spin-$\frac{1}{2}$ charged particles: $g = 2$
- Radiative corrections in Quantum Field Theories: $g \neq 2$
- Kusch and Foley's measurement/ Schwinger's prediction: (1948, electron $g_e - 2$)

  $\frac{g_e - 2}{2} \equiv a_e \approx 0.00116$

  1st order QED term: $\frac{\alpha}{2\pi}$

  universal to all leptons: e, μ, τ

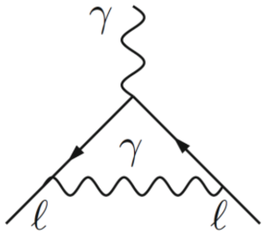




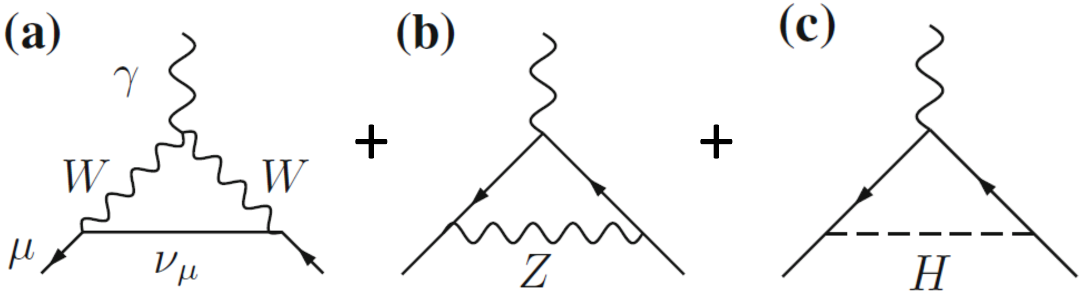
$g - 2 > 0$

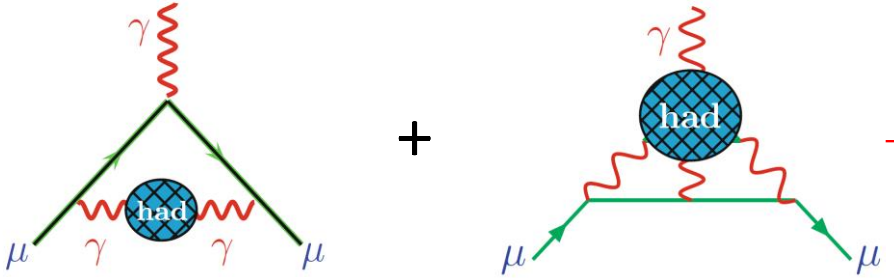
Standard Model prediction of muon $g-2$

$$a_\mu \equiv \frac{g_\mu - 2}{2} \qquad a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

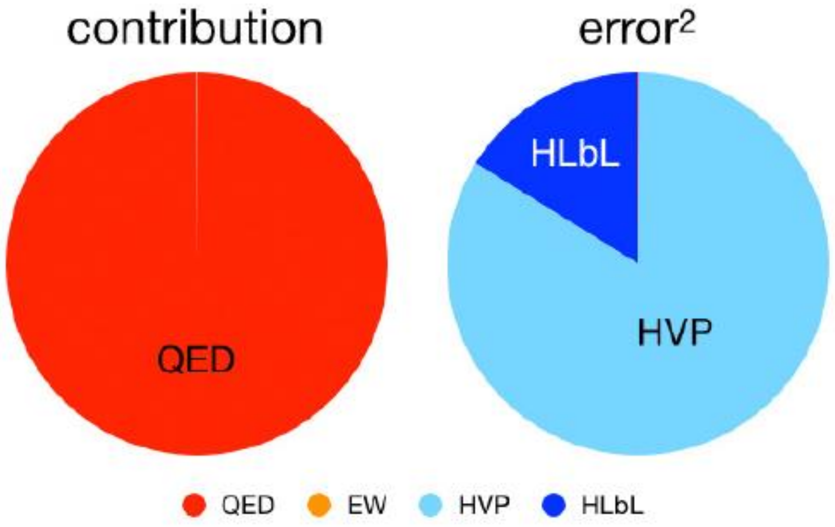
$a_\mu^{QED} =$ 

+ over 14’000 diagrams

$a_\mu^{EW} =$ 

$a_\mu^{had} =$ 

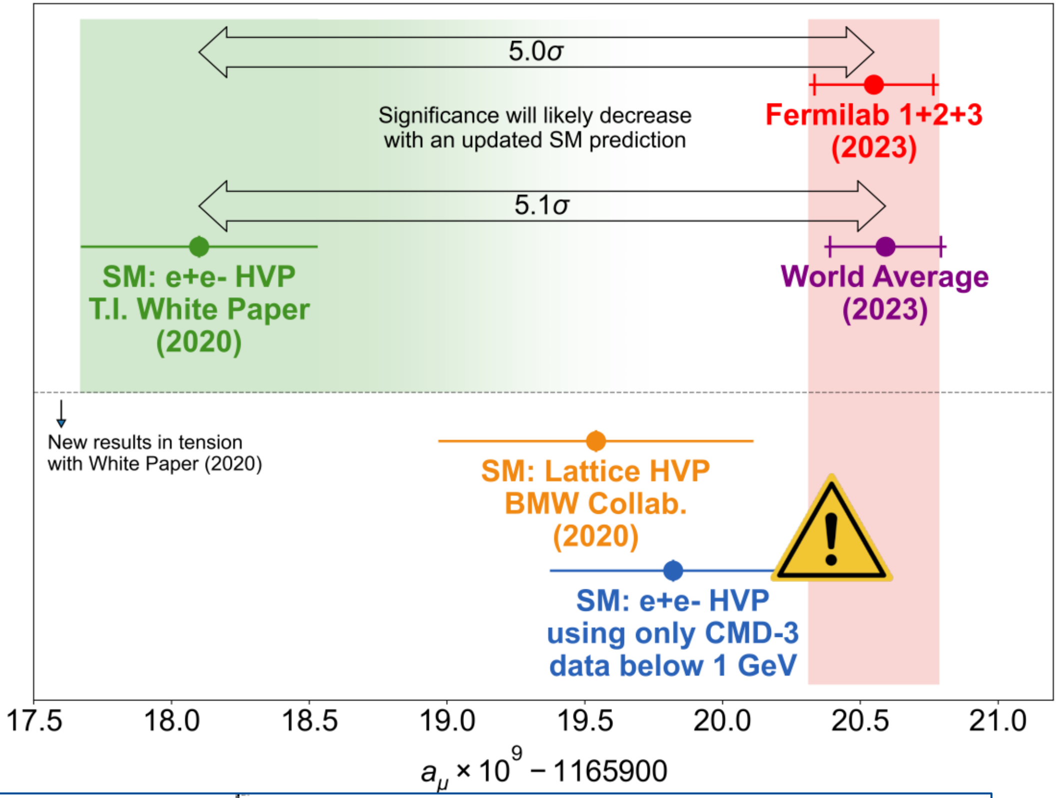
HVP HLbL



a_μ^{had} cannot be evaluated perturbatively!

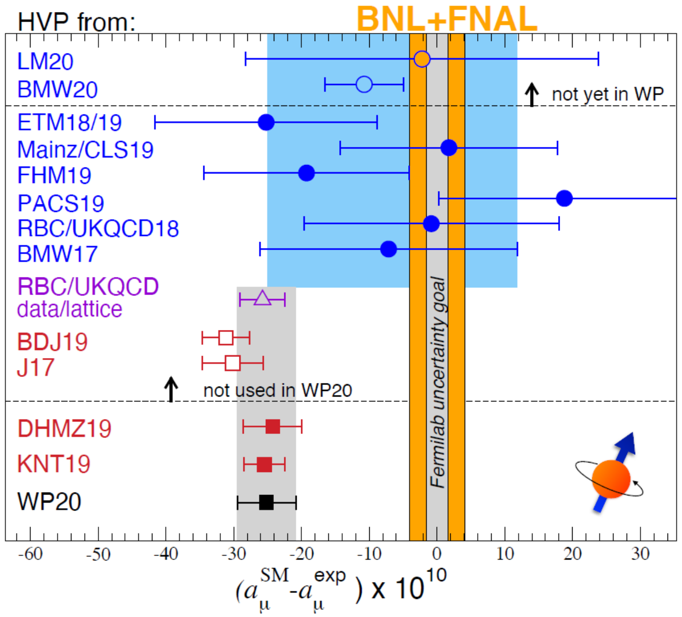
QCD dominates the uncertainty

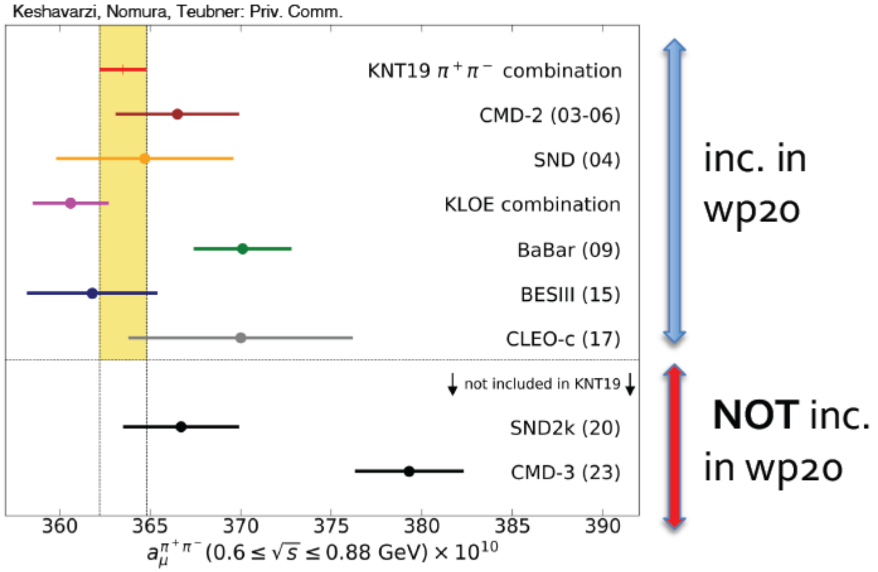
Tensions in theoretical prediction



IMPORTANT: THIS PLOT IS VERY ROUGH!

- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → <u>should not be taken as final!</u>





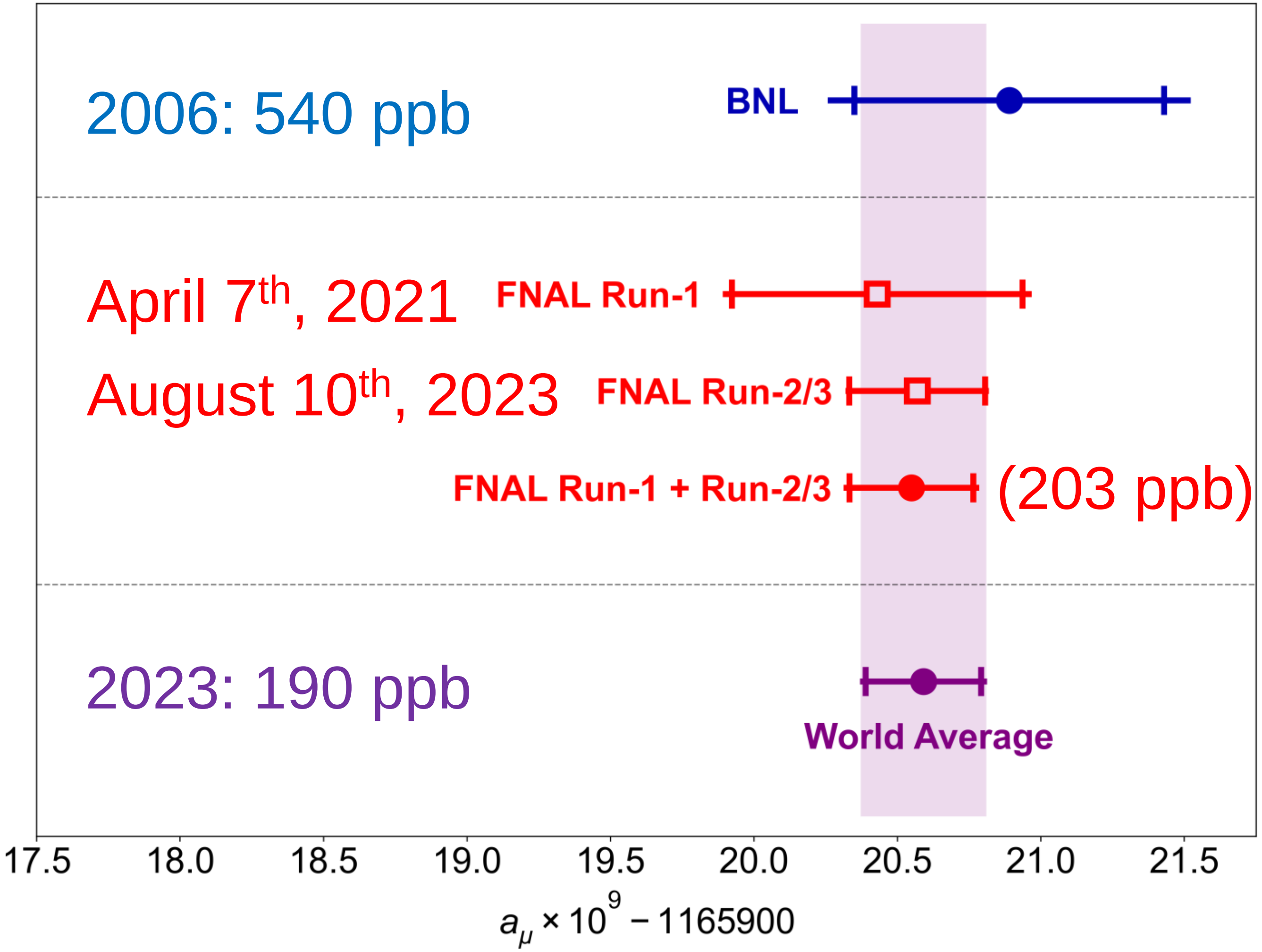
-Lattice results with sub-percent precision

-New experimental $e^+e^- \rightarrow hadrons$ cross section inputs for dispersive method

2023 Muon g-2 results

D. P. Aguillard et al, Phys. Rev. Lett. 131.161802 (2023)
D. P. Aguillard et al, arxiv:2402.15410 (2024)

Accepted yesterday for publication on PRD!



Unblinding last year (last step before release of result), here at The Spine :D

Experiment at Fermilab Muon Campus

Liverpool contributions highlighted throughout the slides

Anomalous spin precession in B-field

$$\left.\begin{array}{l} g-2 \neq 0 \\ a_\mu \neq 0 \end{array}\right\} \rightarrow \text{spin precesses with anomalous frequency } \vec{\omega}_a = \vec{\omega}_{\text{spin}} - \vec{\omega}_{\text{c}}$$

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$

Anomalous spin precession in B-field

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$a_\mu \neq 0$

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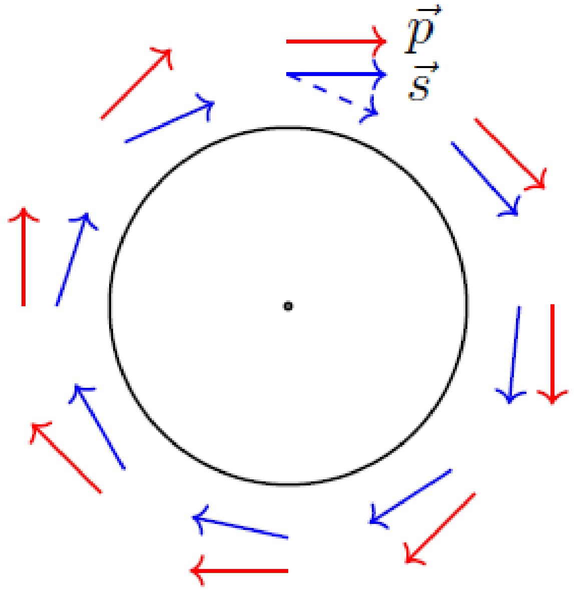
$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} - a_\mu \frac{\gamma}{\gamma + 1}\left(\vec{\beta} \cdot \vec{B}\right)\vec{\beta}\right]$$

$\gamma = 29.3 \rightarrow p = 3.094\ \text{GeV/c}$
"magic momentum"

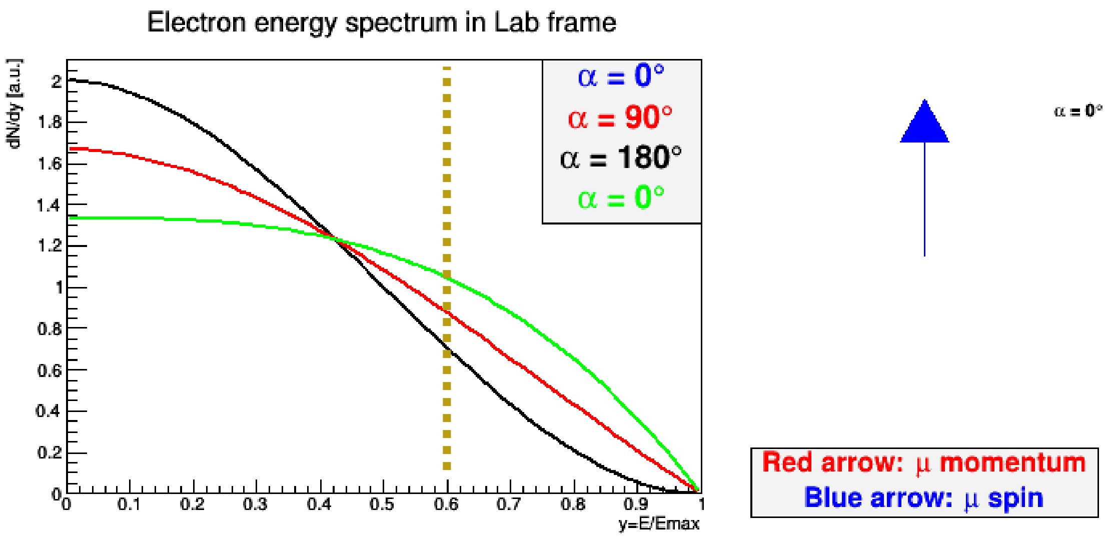
$\vec{\beta} \cdot \vec{B} = 0$

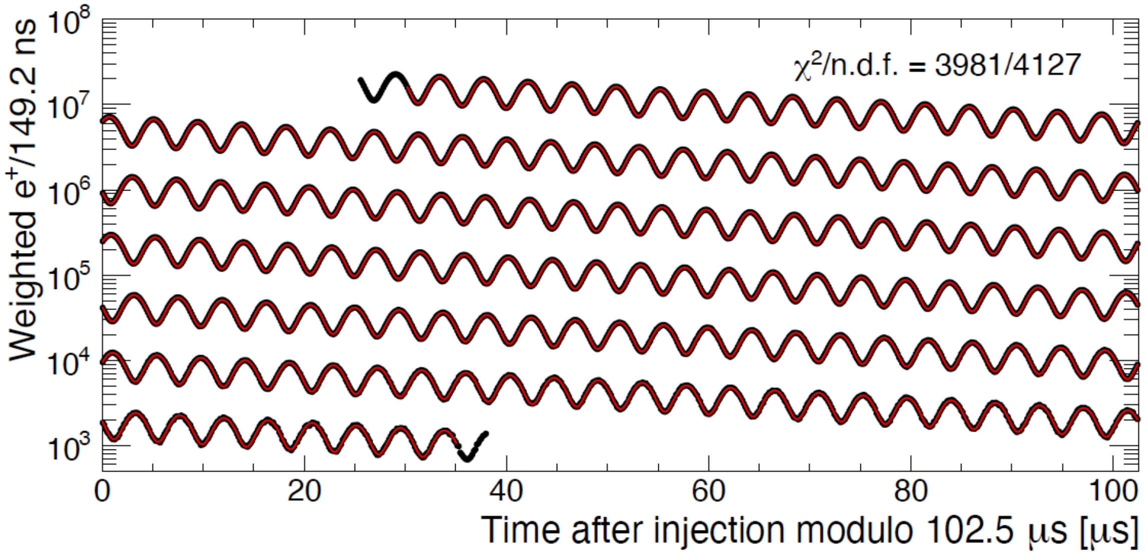


$\omega_c \sim 42.1$ rad/μs

$\omega_a \sim 1.439$ rad/μs ~
~ 12.4° per turn

Principle of ω_a measurement



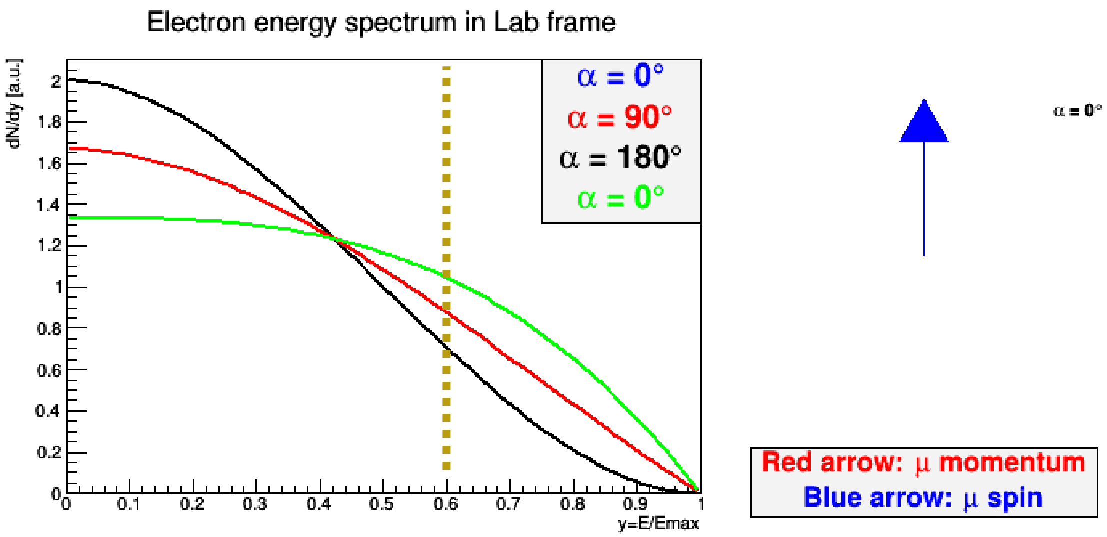


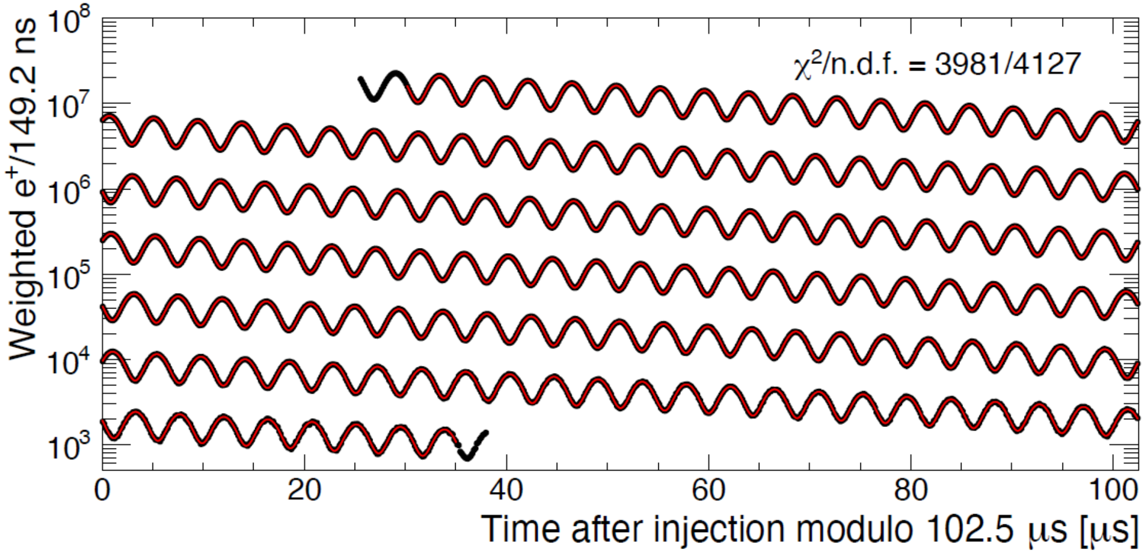
1. Weak decays violate parity:
   - polarized muon beam
   - preferred high-energy e^+ direction
2. Correlation in the lab frame between e^+ energy spectrum and ω_a phase
3. «Wiggle plot»: count high-energy e^+ over time, for about 700 μs (muon lifetime is ~ 64 μs in the lab)

6 teams with independent analyses, one of which is waEurope

In Liverpool: LC, C. Zhang, E. Zaid

Principle of ω_a measurement





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My PhD Thesis, March 2024

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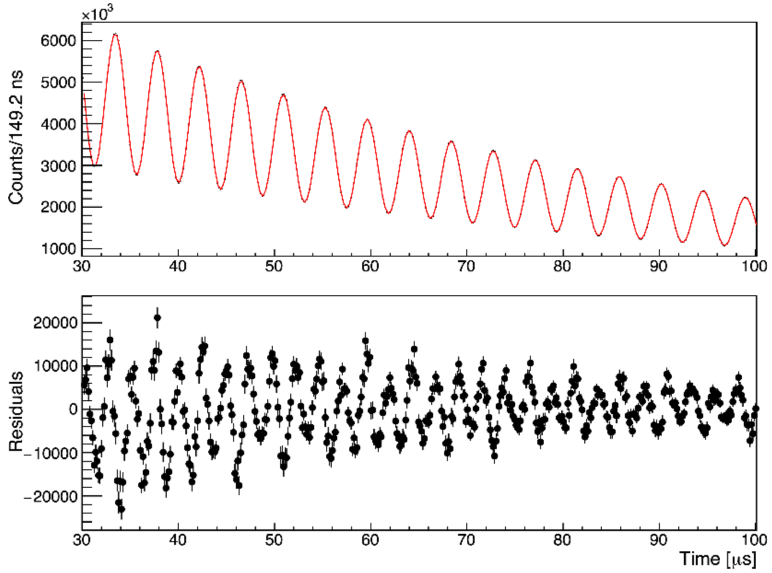
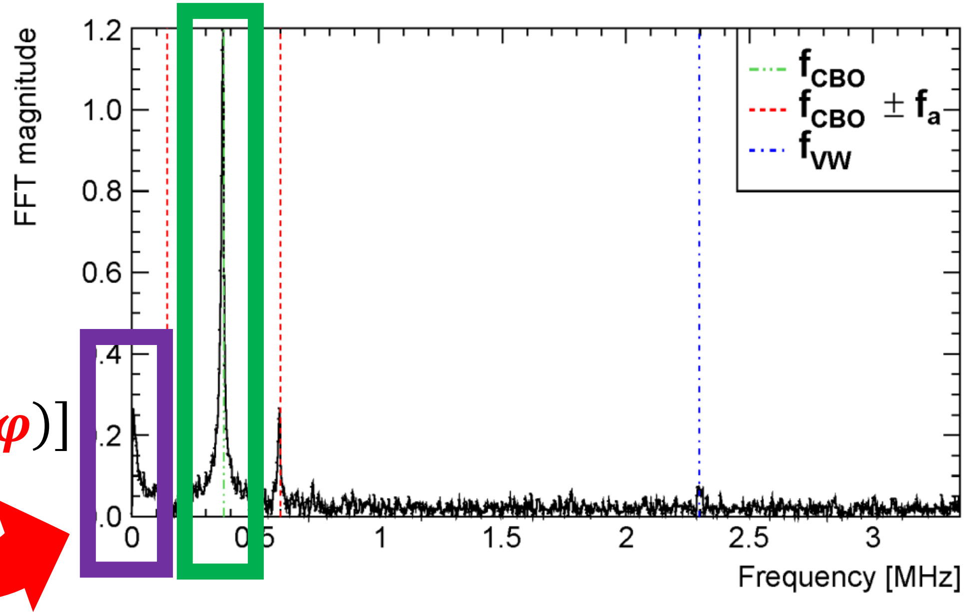
ω_a fit

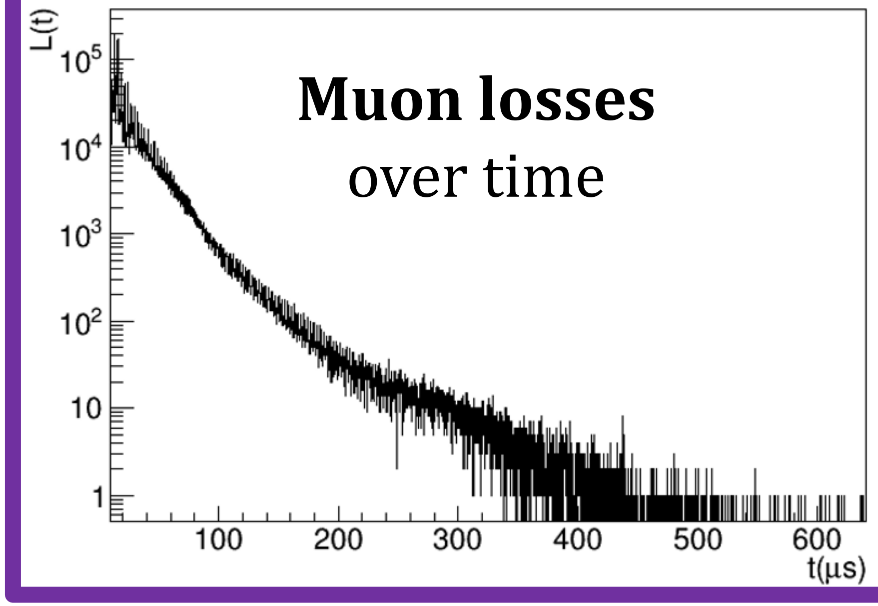


5-parameter fit

$$N(t) = N_0 e^{-\frac{t}{\gamma\tau_\mu}}[1 + A\cos(\omega_a t + \varphi)]$$

FFT of residuals



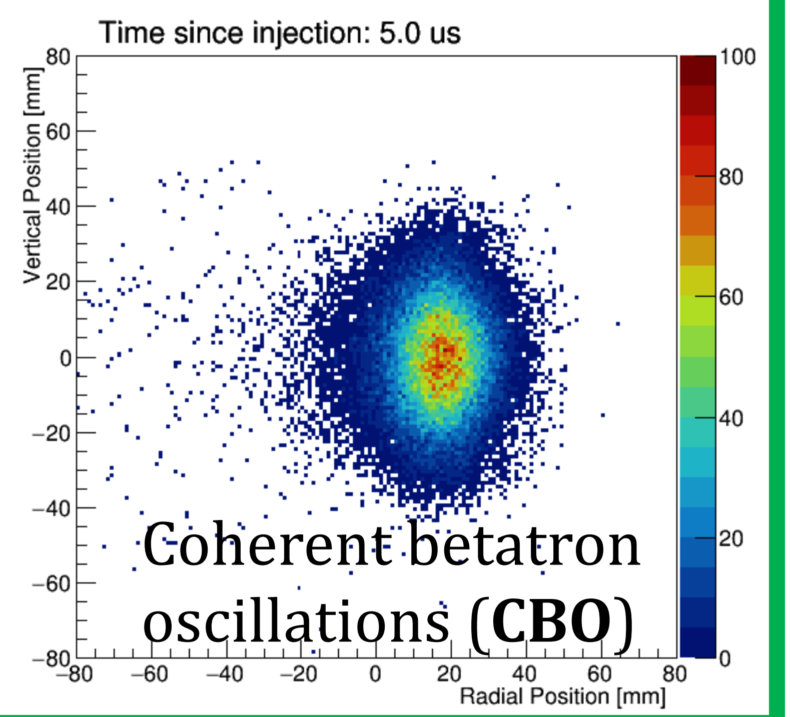


Muon losses

over time

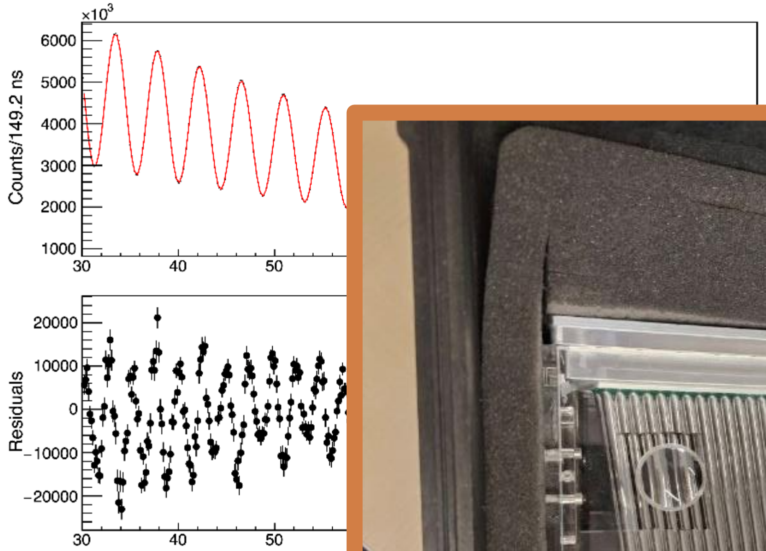
$$\Lambda(t) = 1 - k_{LM} \cdot J(t)$$

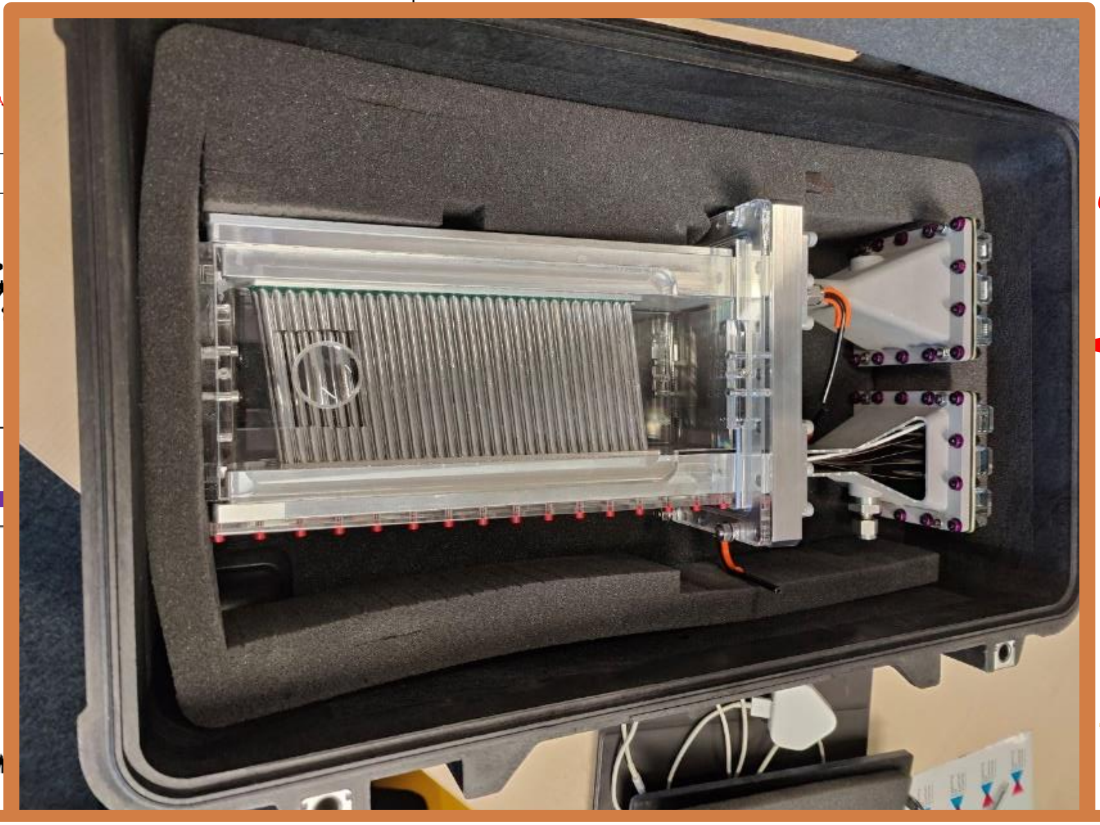
$$J(t) = \frac{\int_{t_0}^{t} L(t')e^{t'/\gamma\tau}dt'}{\int_{t_0}^{t_{end}} L(t)e^{t/\gamma\tau}dt}$$



Coherent betatron oscillations (**CBO**)

ω_a fit

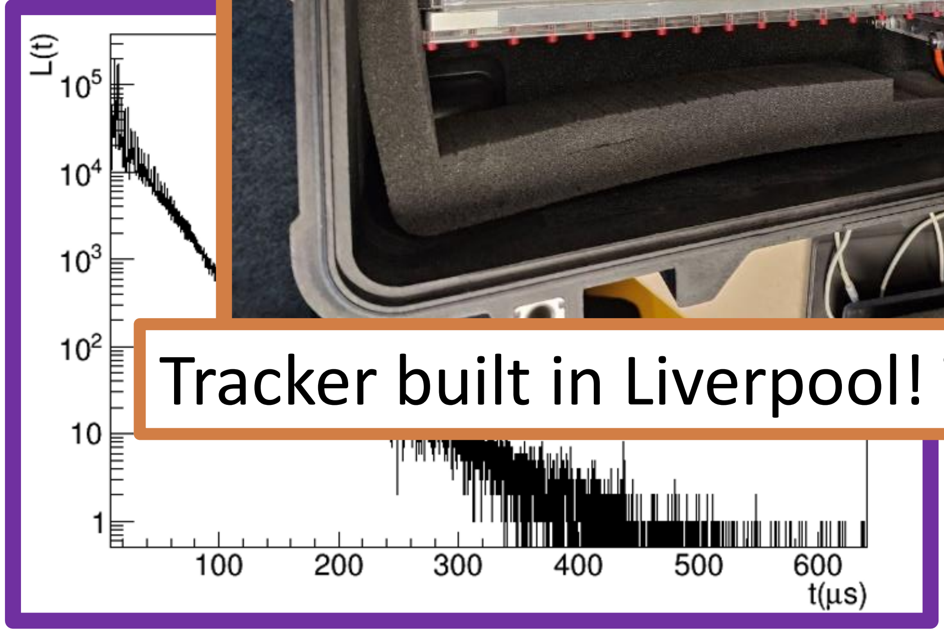




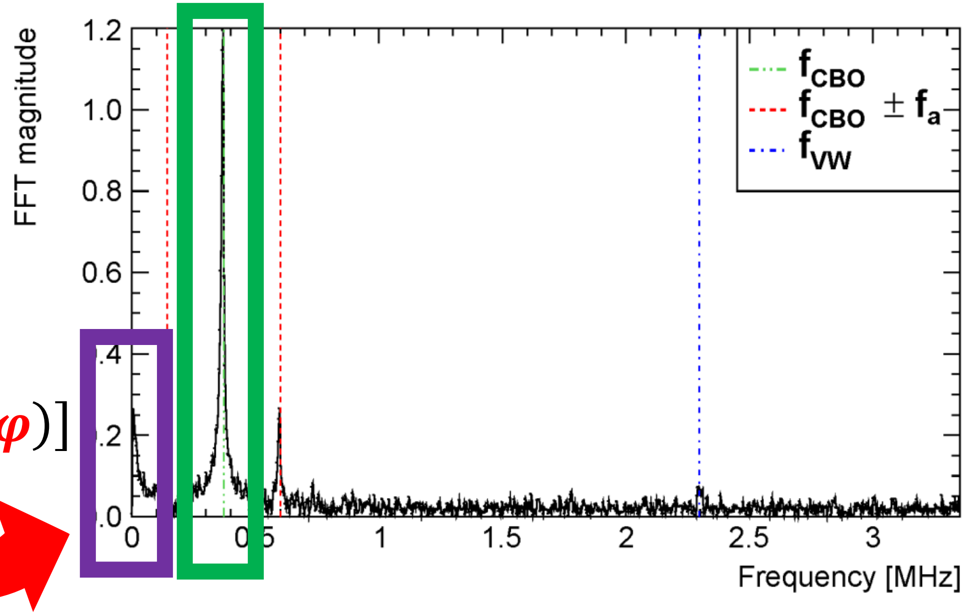
$_a t + \varphi)]$

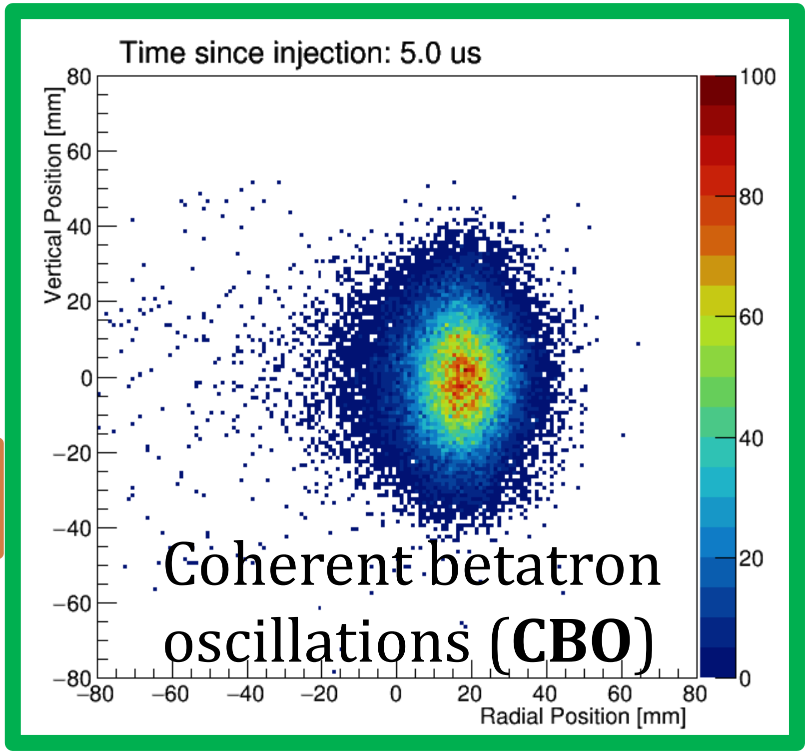
$J(t)$

$\int_{t_0} L(t)e^{t/\gamma\tau}\,dt$



Tracker built in Liverpool! Tracker plot →

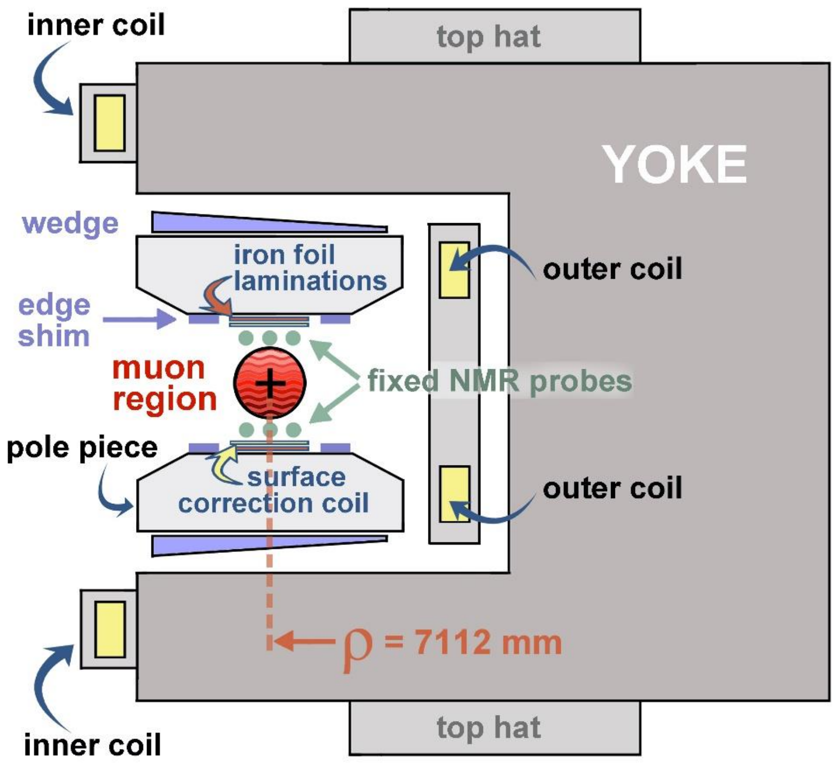


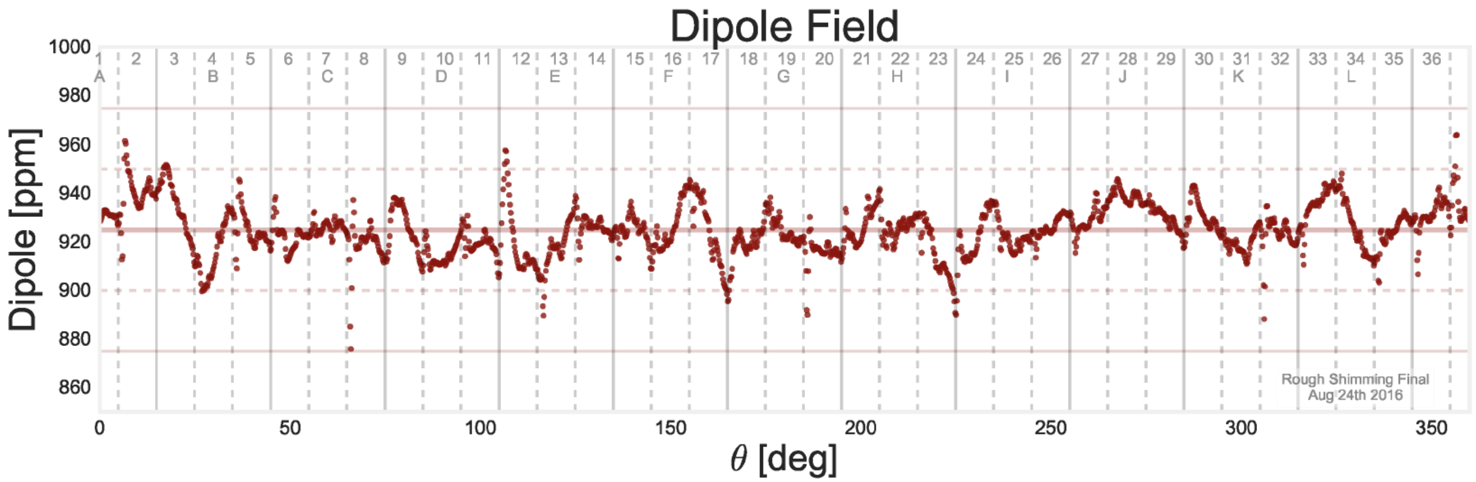


Coherent betatron oscillations (**CBO**)

Magnetic field

- 3.1-GeV muons are stored for 700 μs in the superconductive storage ring, kept at ~ 5K
- Highly uniform vertical magnetic field: 1.45 T
- Shimmed passively by wedges, iron top hats and surface iron foils
- Actively stabilized by surface current coils

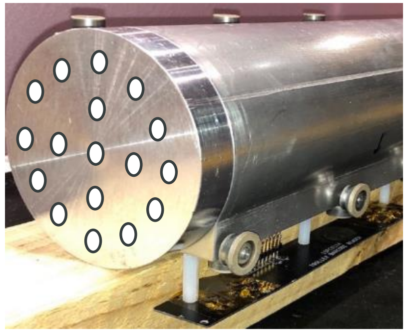




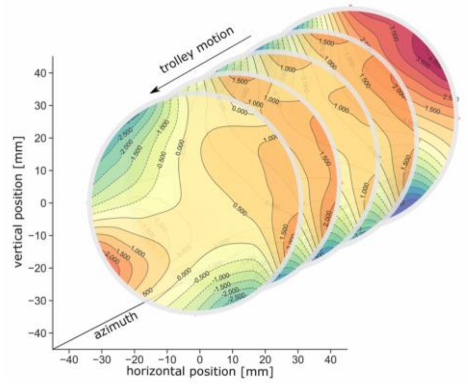
14 ppm RMS across azimuth

Principle of ω_p measurement $(\hbar\omega_p = 2\mu_p B)$

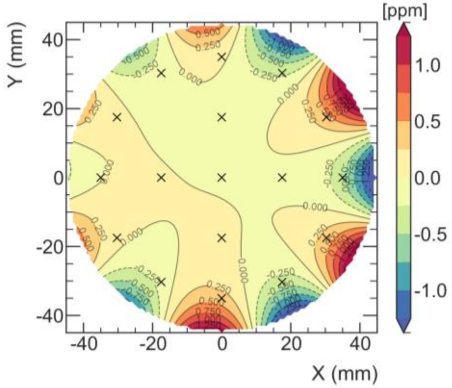
S. Charity coordinates the analysis



17 petroleum jelly NMR probes

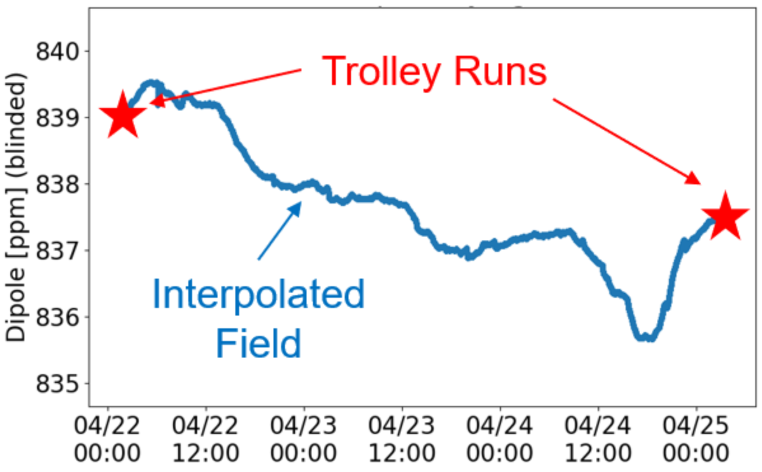


2D field maps (~8000 points)



Azimuthally-Averaged
Variation < 1 ppm

17 NMR (Nuclear Magnetic Resonance) probes: placed on trolley for special runs, every 2 or 3 days between muon fills, to provide 3-D map

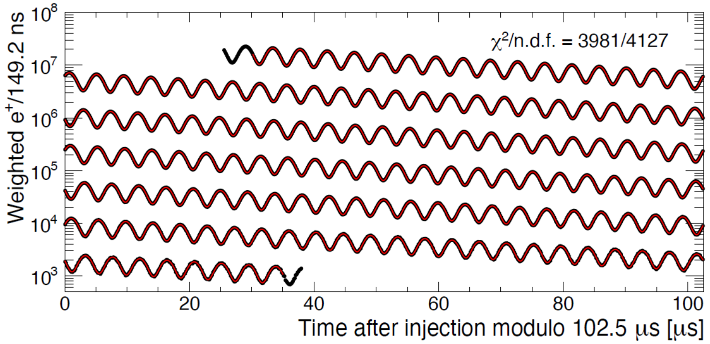


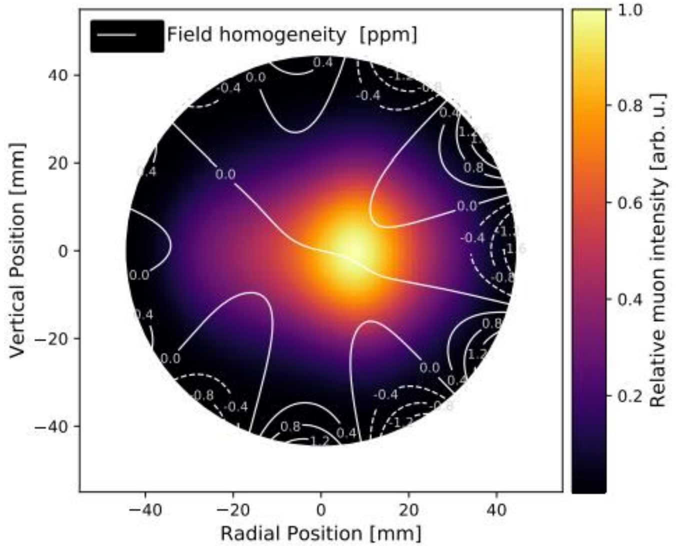
378 fixed NMR probes continuously monitor field during muon storage at 72 azimuthal locations

Absolute calibration with water probes

Field is weighted with muon distribution, measured by trackers

Master formula for a_μ





$$a_\mu = \frac{\omega_a}{\omega_p} \times \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

External factors, known to 25 ppb

Beam dynamics corrections

E. Bottalico coordinates the BD analysis; also contribution by C. Zhang

Make spin precess slower

Make phase change within 700 μs

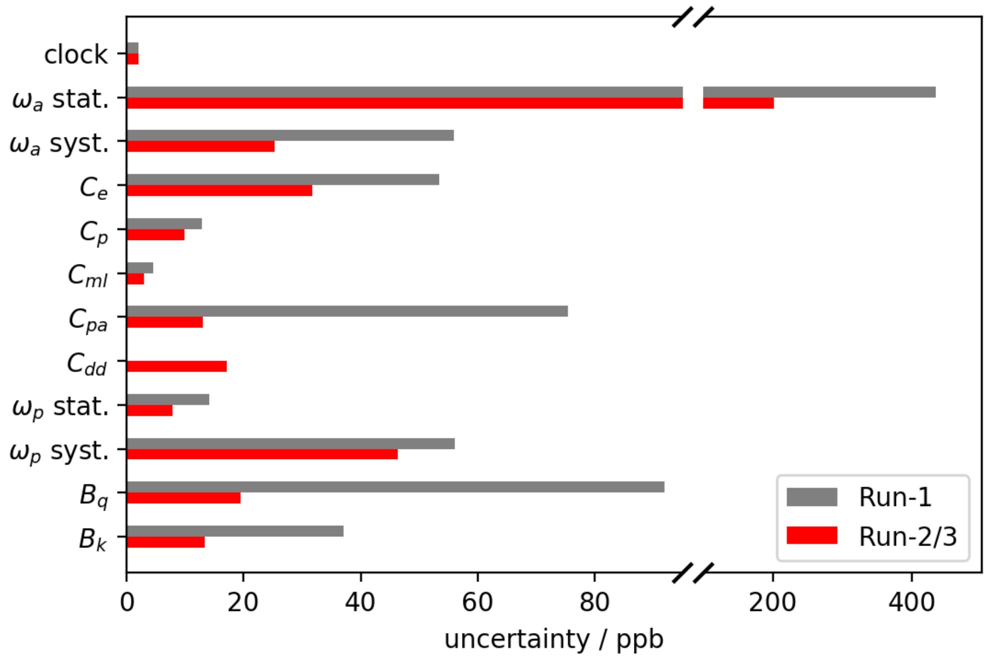
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \times \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_q + B_k}$$

m=Measured values

Induce transient magnetic fields

Improvements from Run-1 to Run-2/3

- Running improvements: fixed damaged resistors in ESQ system, which limited systematics; stabilized temperature; improved kicker
- ~ 5x more muon decays → ~ 2.2 reduction in statistical uncertainty
- Analysis improvements (more CBO studies, reduced pileup thanks to new reconstructions, more transient field measurements…)



Dataset	Stat. unc. [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
FNAL design goal	100

- 70 ppb systematic uncertainty: exceeded goal of 100 ppb!

Search for Muon EDM @FNAL

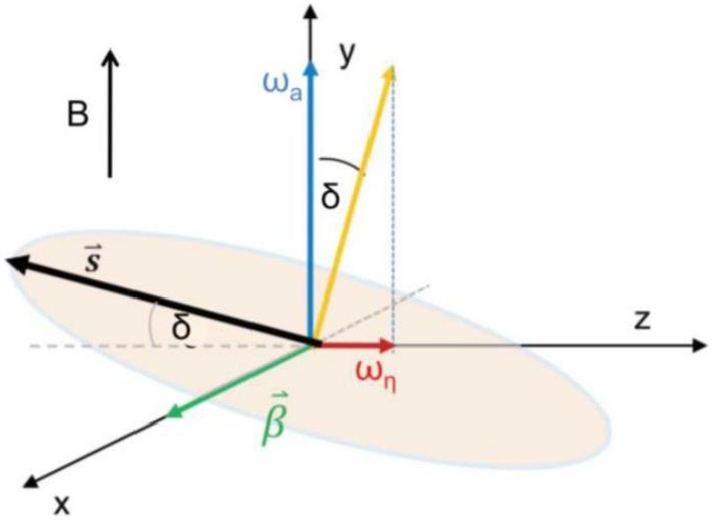
Carried out in Liverpool by J. Price (coordinator), D. Vasilkova, K. Ferraby

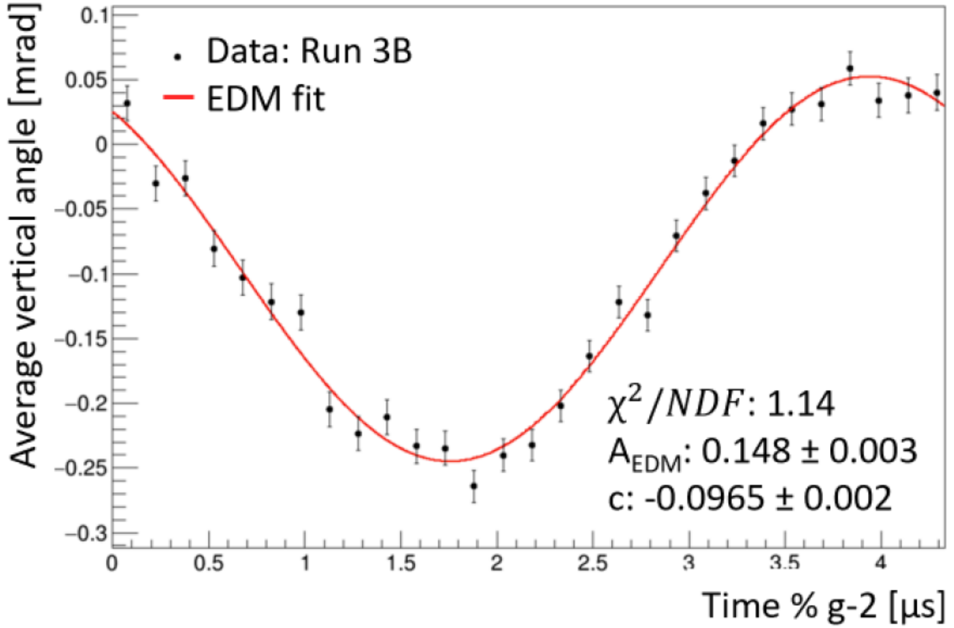
Motivation:

- Intrinsic EDM: $H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$
- SM prediction $\sim 10^{-35}\mathrm{e} \cdot \mathrm{cm}$, well beyond experimental limits. BNL: $1.9 \times 10^{-19}\mathrm{e} \cdot \mathrm{cm}$
- CP-odd → would be new source of CP-violation in leptons

Principle of measurement:

- EDM introduces tilt in precession plane: measure EDM directly from tracker data, vertical angle vs time





Muon EDM @ FNAL: challenges and status

Systematic sources of uncertainty:

- Detector acceptance, corrected by MC acceptance maps
- Non-zero radial field: from Run-4/5/6 studies, extrapolated to Run-2/3, it resulted that this is not a systematic limitation
- MC/Data matching

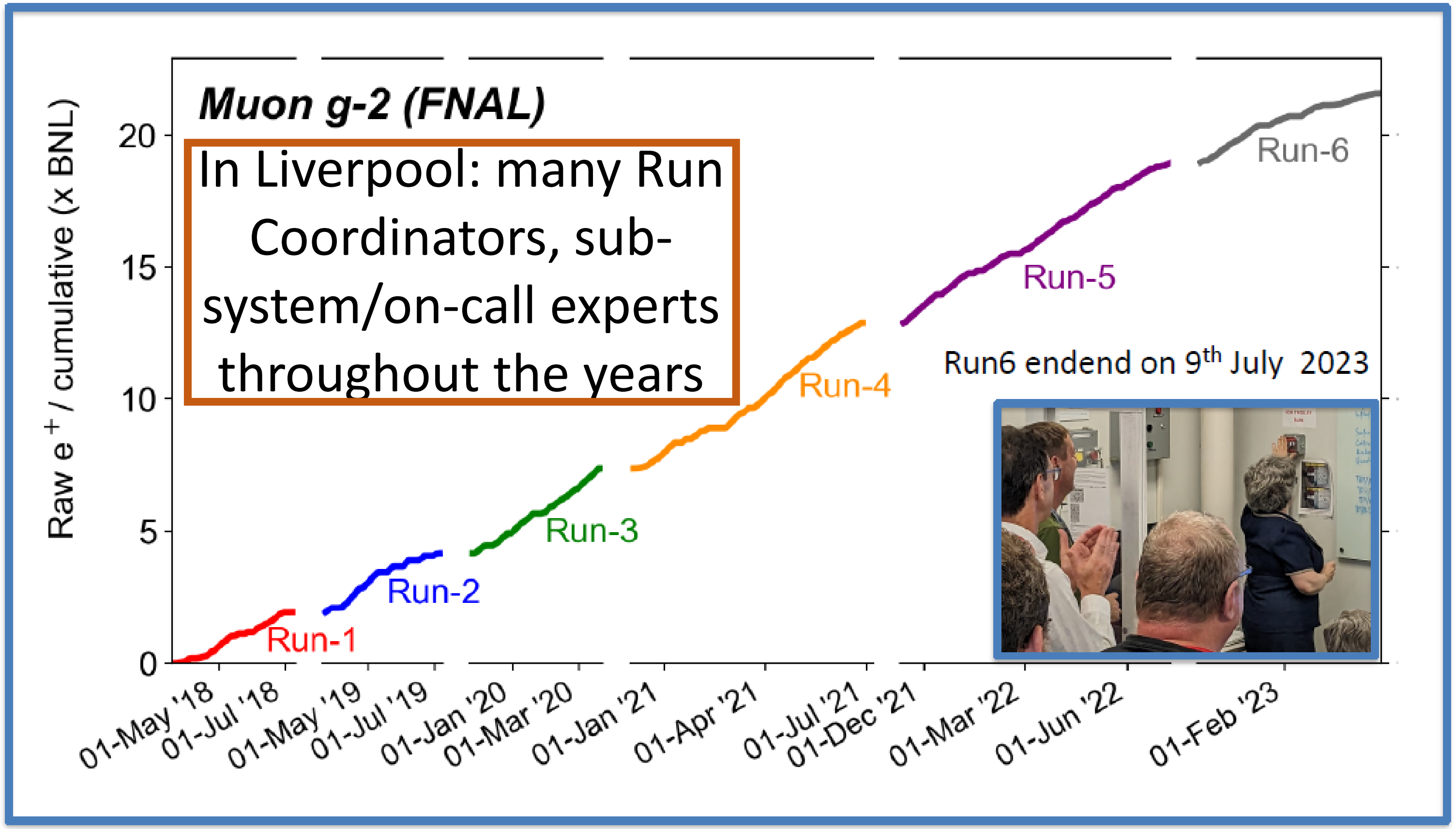
Expected limits (assuming zero signal):

- Run-1 (under review): $|d_\mu| < 2.0 \times 10^{-19} \mathrm{e} \cdot \mathrm{cm}$
- Run-2/3 (analysis ongoing): $|d_\mu| < 2.8 \times 10^{-20} \mathrm{e} \cdot \mathrm{cm}$

Also see presentation tomorrow morning by K. Ferraby

Future Muon g-2 results @ FNAL

On 27 February 2023: proposal Goal of x21 BNL datasets!



Dataset	Stat. unc. [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
Expected total from Run-1 to Run-6	≤100

We expect to complete the analysis by 2025

- Quadrupole Radio-Frequency switched on during Run-5 → reduced radial and vertical motion of muons, more stable beam and less muon losses
- Ongoing studies to reduce largest systematics: C. Zhang leads of one of the task forces

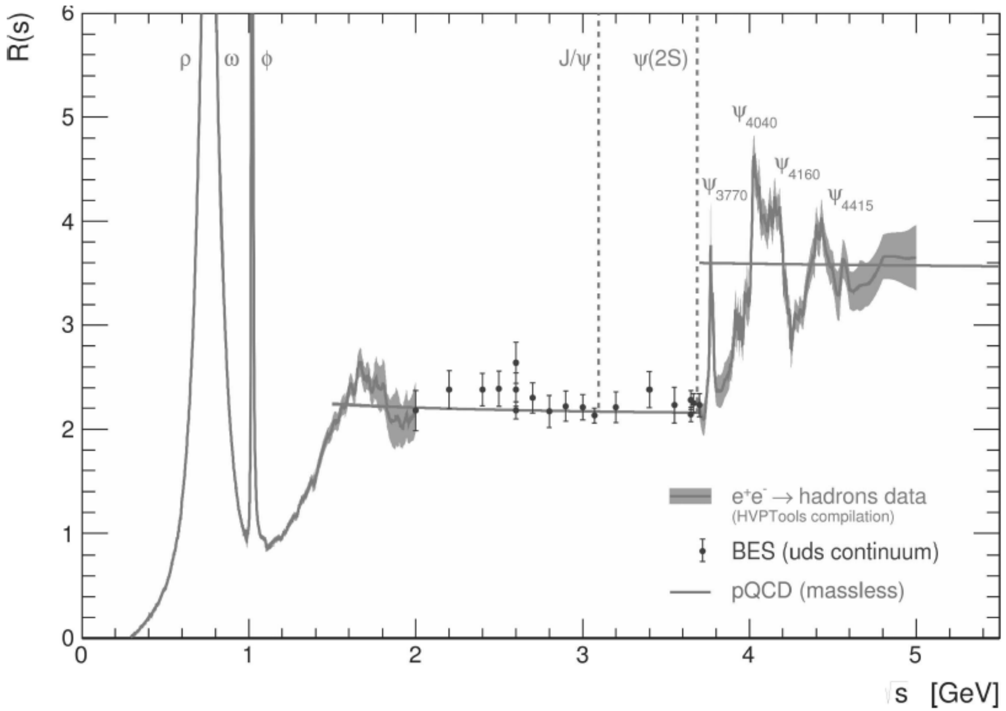
KLOE HVP analysis

Data-driven approach for the theoretical prediction of a_μ (hadronic contribution): experimental efforts to discern the current tensions

KLOE HVP will perform the analysis of $e^+e^- \to \pi^+\pi^-$ cross section: this channel contributes as $\sim 65\%$ to a_μ^{HLO}

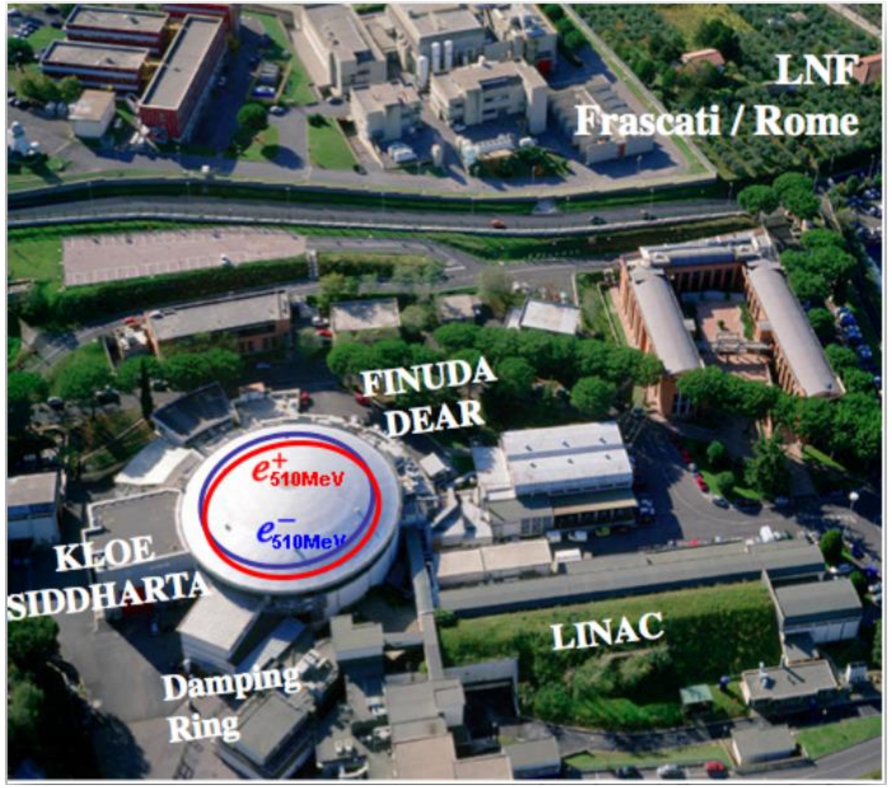
This analysis will:

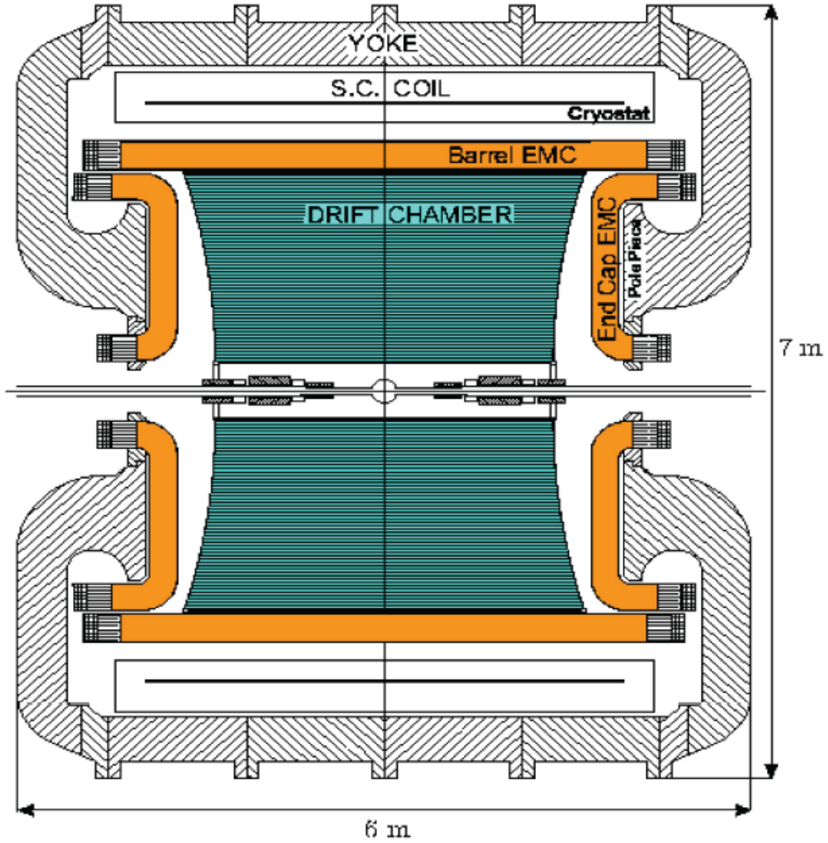
- Use 1.7 fb^{-1} from 2004/2005 data, with 25 million $\pi\pi\gamma$ events never analyzed before
- Improve previous KLOE analyses, e.g.: MC/data tuning, tracking efficiencies, background subtractions, new MC for radiative corrections, …, new blinding!



Liverpool leads all aspects of this analysis

Experimental facility in Frascati



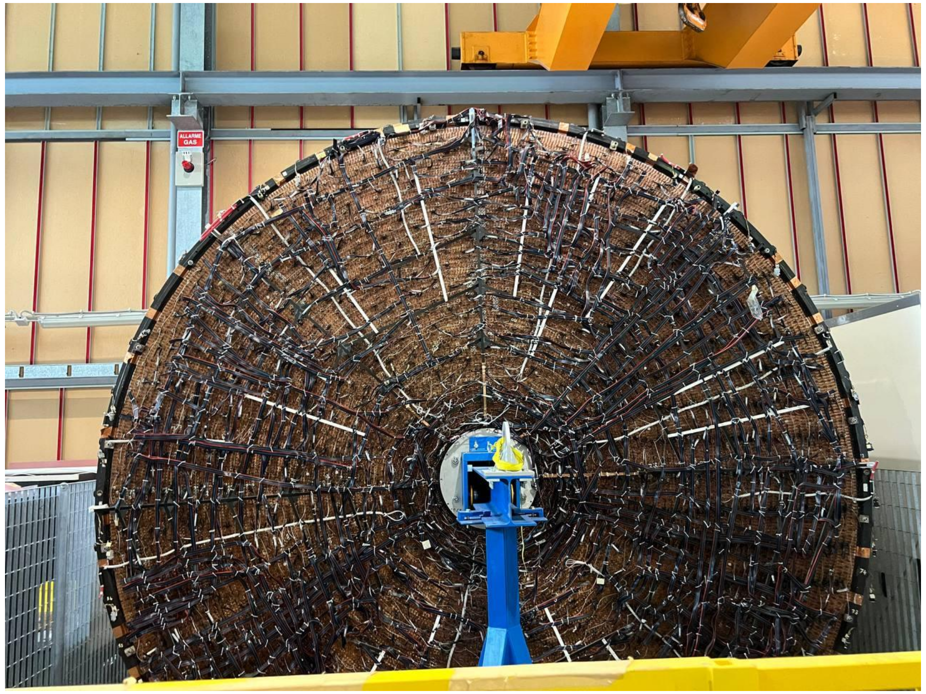


Mostly operated at $\sqrt{s} = 1020$ MeV (510 MeV e+, 510 MeV e-)

Method of Radiative return: hard ISR photon allows to scan over continuous $\sqrt{s}$ range

KLOE detectors

Tracker

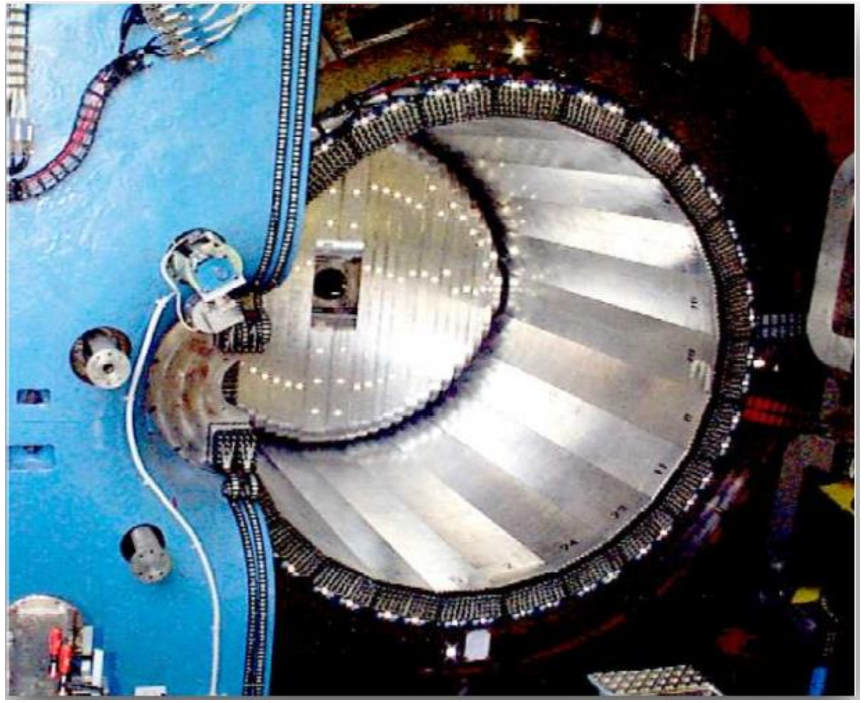


Excellent momentum resolution:

$$\sigma_p/p = 0.4\%$$

$$\sigma_{r\phi} = 150\mu\text{m}, \sigma_z = 2\text{mm}$$

Calorimeter



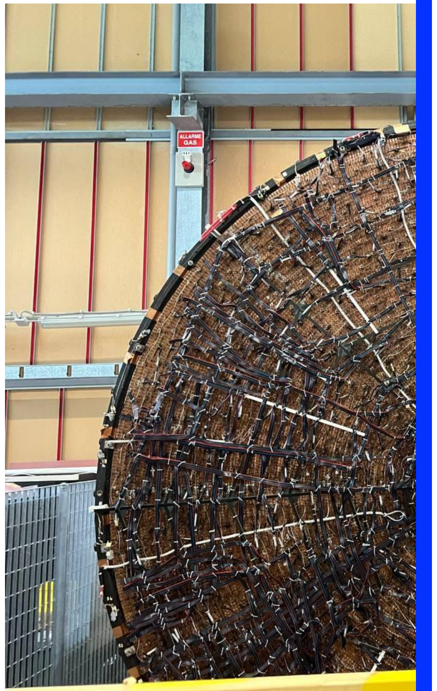
Excellent time resolution:

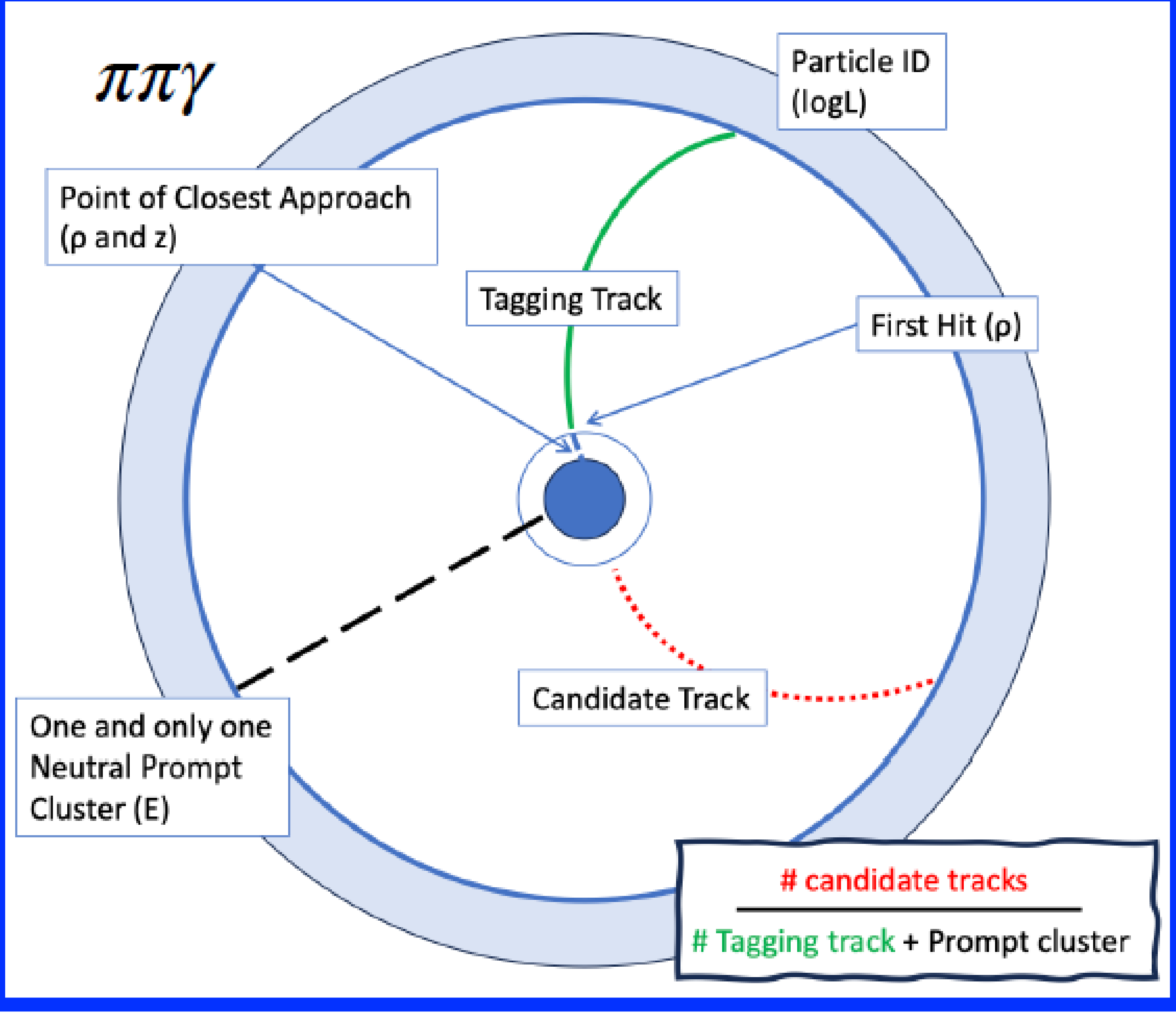
$$\sigma_t[\text{ps}] = 54/\sqrt{E[\text{GeV}]} \oplus 100$$

$$\sigma_E/E = 5.7\%/\sqrt{E[\text{GeV}]}$$

KLOE detectors

Tr eter





Excellent mom resolution:

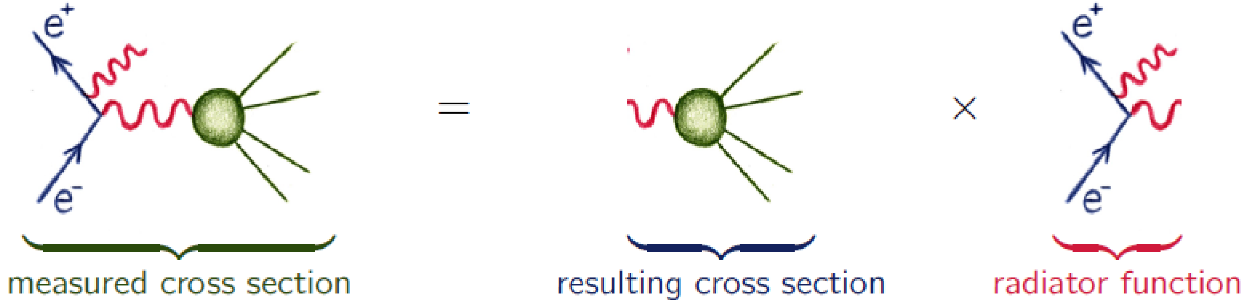
σ_p/p [GeV] $\oplus$ 100

$\sigma_{r\phi} = 150$μ $/\sqrt{E[\text{GeV}]}$

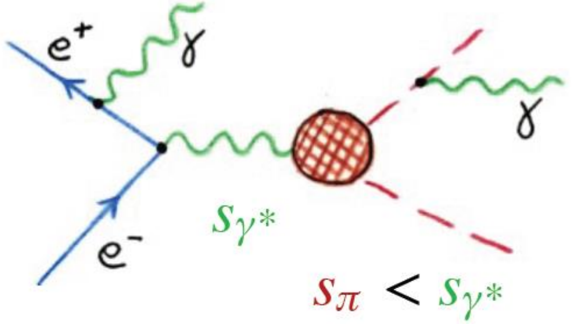
Much theory work

- ISR technique to scan $\sqrt{s}$: radiator function $H(s, M_{had}^2)$ relates differential cross section $e^+e^- \to \pi^+\pi^-\gamma$ to $e^+e^- \to \pi^+\pi^-$

$$\frac{d\sigma(e^+e^- \to \text{had} + \gamma)}{d M_{\text{had}}^2} = \frac{\sigma(e^+e^- \to \text{had}, M_{\text{had}}^2)}{s} \times H(s, M_{\text{had}}^2)$$



- Phokhara MC calculates: ISR at NLO; Radiative corrections such as vacuum polarisation and FSR



Normalisation to muon ISR

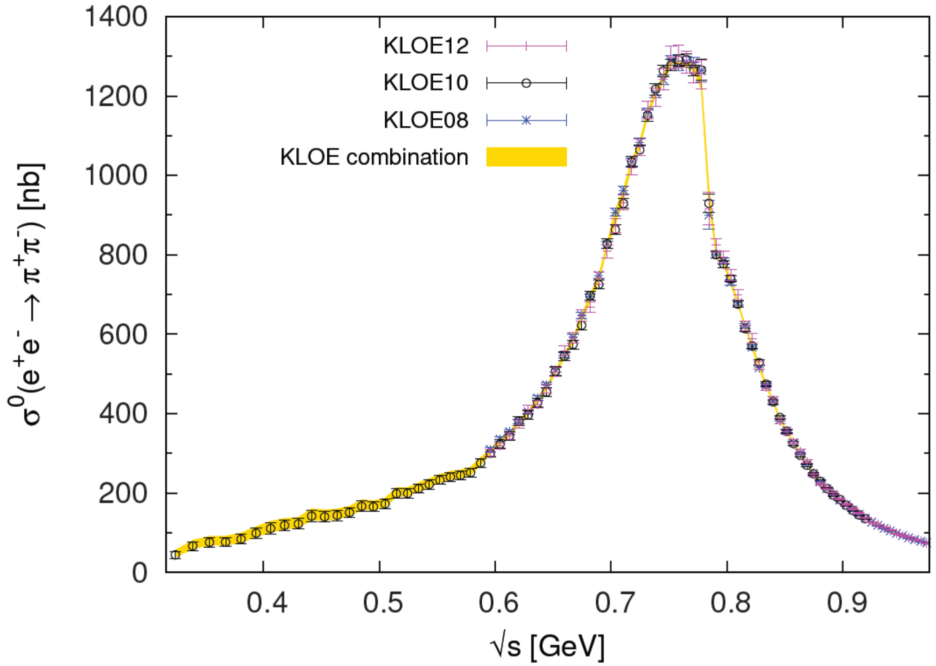
Two methods to extract cross section:

- KLOE08, KLOE10: absolute normalisation to luminosity (from Bhabha events):
$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{N-N_{bkg}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon} \cdot \frac{1}{\int L\,dt} \rightarrow \sigma_{\pi\pi}(M^2_{\pi\pi}) = s \cdot \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} \cdot \frac{1}{H(s, M^2_{\pi\pi})}$$
- KLOE12: normalize $\pi\pi\gamma$ sample with $\mu\mu\gamma$ events → for each energy bin:
$$|F_{2\pi}(s')|^2 = \frac{4(1+2m^2_\mu/s')\beta_\mu}{\beta^3_\pi} \cdot \frac{d\sigma_{\pi\pi\gamma}/dM^2_{\pi\pi}}{d\sigma_{\mu\mu\gamma}/dM^2_{\mu\mu}} \rightarrow \sigma_{\pi\pi}(s') = \frac{\pi\alpha^2\beta^3_\pi}{3s'} \cdot |F_{2\pi}(s')|^2$$

Advantage of muon ISR normalization: systematic effects and radiative corrections cancel!

Total uncertainty on Radiative Effects	
$a^{\pi\pi}{}_{\mu\mu}$ abs	0.1% + 0.3% + 0.5%
$a^{\pi\pi}{}_{\mu\mu}$ ratio	/ + 0.3% + /

Experimental goals for new KLOE HVP analysis



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Syst. errors (%)	$\Delta^{\pi\pi}a_\mu$ abs [4]	$\Delta^{\pi\pi}a_\mu$ ratio
Background Filter (FILFO)	negligible	negligible
Background subtraction	0.3	0.6
Trackmass	0.2	0.2
Particle ID	negligible	negligible
Tracking	0.3	0.1
Trigger	0.1	0.1
Unfolding	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1
Luminosity	0.3 ($0.1_{th} \oplus 0.3_{exp}$)	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	0.7
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.2
Rad. function H	0.5	-
Total theory systematics	0.6	0.2
Total systematic error	0.9	0.7

Combination of previous KLOE measurements:

$$a_\mu^{\pi\pi}[0.1 < s < 0.95\text{GeV}^2] = 489.8 \pm 1.7_{stat} \pm 4.8_{sys} \times 10^{-10}$$

Goal for new analysis: reduce uncertainties, achieve 0.4% total (0.1% stat., 0.2% th. and 0.3% syst.)

Overview of g-2/KLOE Liverpool activities

❖ Muon g-2 @ FNAL:

- Strong involvement in operations while running (ended Summer 2023)
- ω_a analyzers: L.C., C. Zhang, E. Zaid
- ω_p analyzer: S. Charity (coordinator)
- Beam dynamics analyzers: E. Bottalico (coordinator), C. Zhang
- EDM: J. Price (coordinator), D. Vasilkova, K. Ferraby
- Various institutional roles (e.g. co-spokesperson G. Venanzoni)
- Help in analysis/review of other Beyond SM searches (Dark Matter, CPT/LIV)

❖ KLOE HVP analysis:

- From HEP department: G. Venanzoni, P. Beltrame, L.C., F. Ignatov, A. Kumari, N. Vestergaard, E. Zaid
- From Theoretical department: T. Teubner, W.J. Torres-Bobadilla, T. Dave, J. Paltrinieri, P. Petit-Rosas, A. Wright

THANK YOU FOR YOUR ATTENTION!

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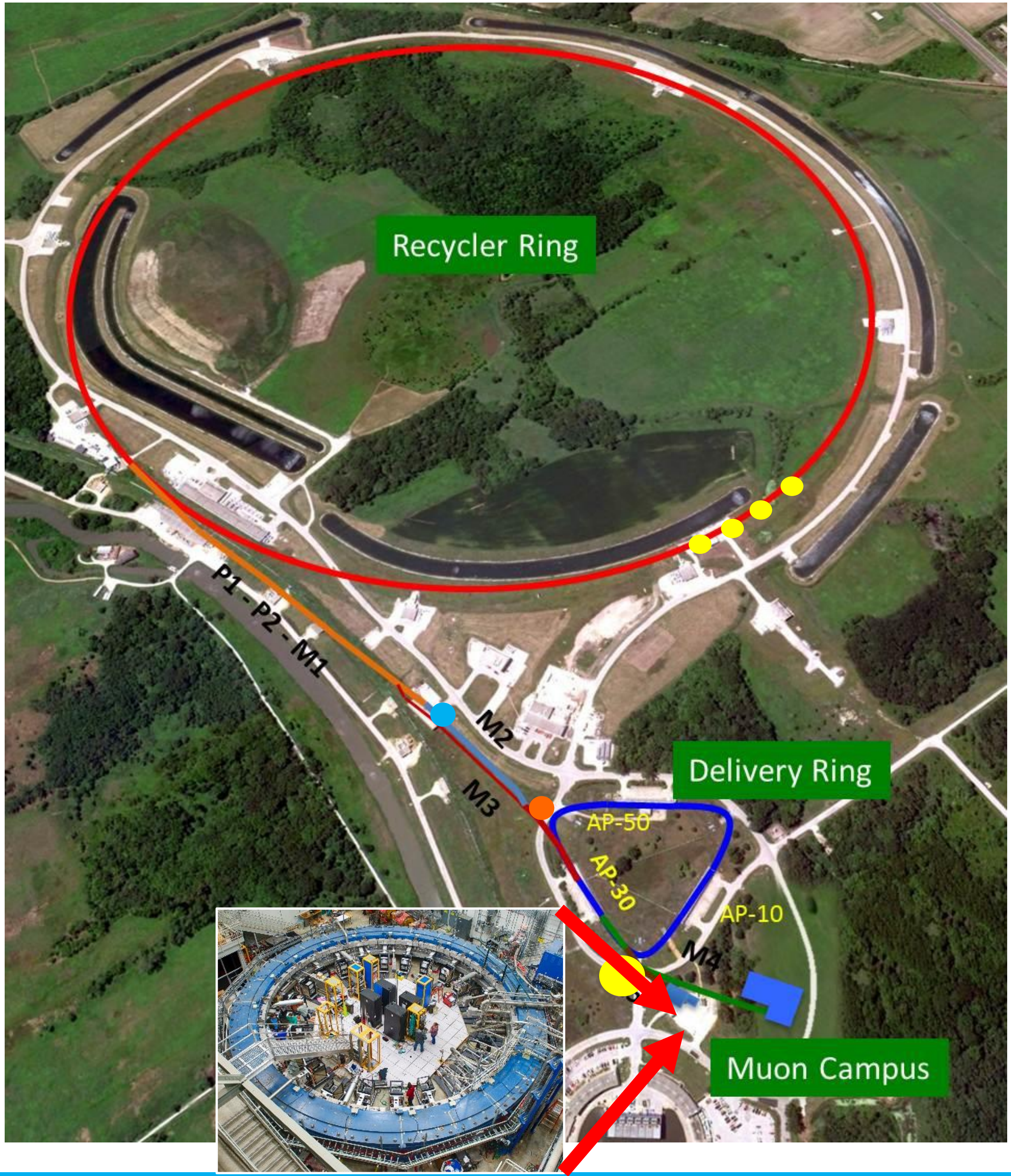
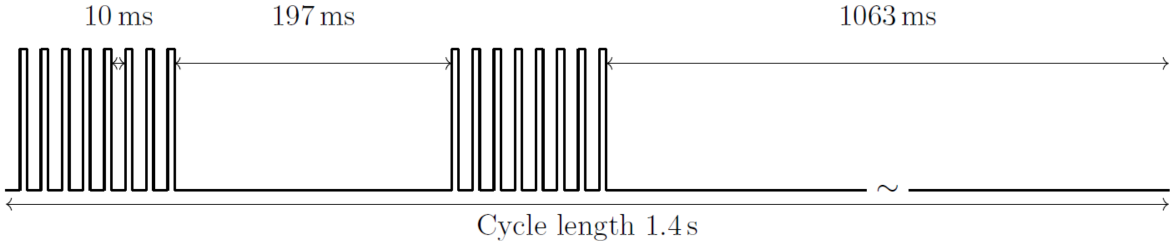
Fermilab

July 2023 collaboration meeting @ Liverpool, UK

FNAL accelerator complex



- Bunches of 4×10^{12} protons @ 8 GeV
- Boosted and delivered via the recycler ring every 1.4 s



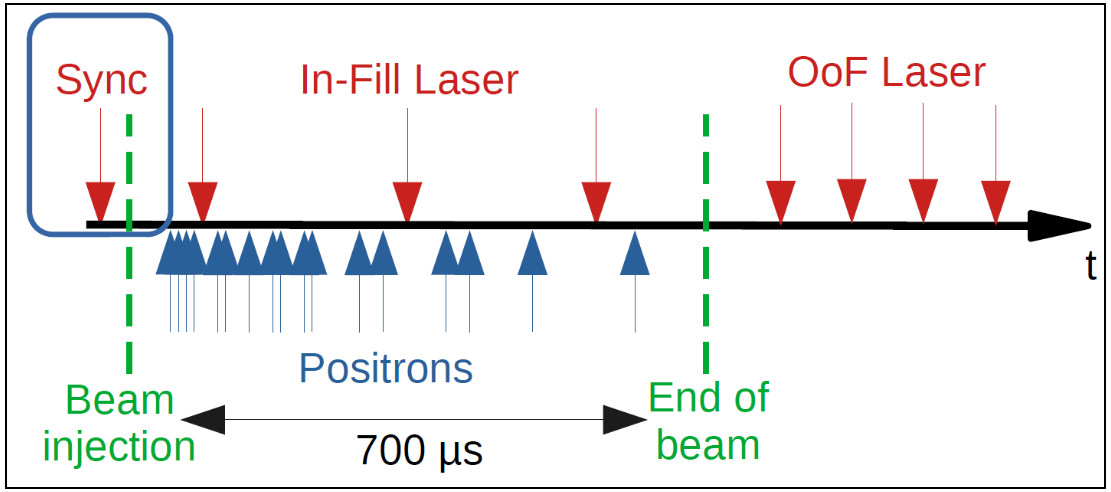
- Collide against fixed target and generate pions
- Pions decay into muons along ~ 2 km line in Delivery Ring
- Muons are injected into the 7 m radius $g-2$ storage ring

Laser-based gain monitoring system

Built by INFN/CNR-INO: time synchronization and calibration of 1296 SiPMs on timescales from ns to days/weeks. Gain changes dominated ω_a systematics at BNL: exceeded goal of 20 ppb at FNAL.

Standard operating mode:

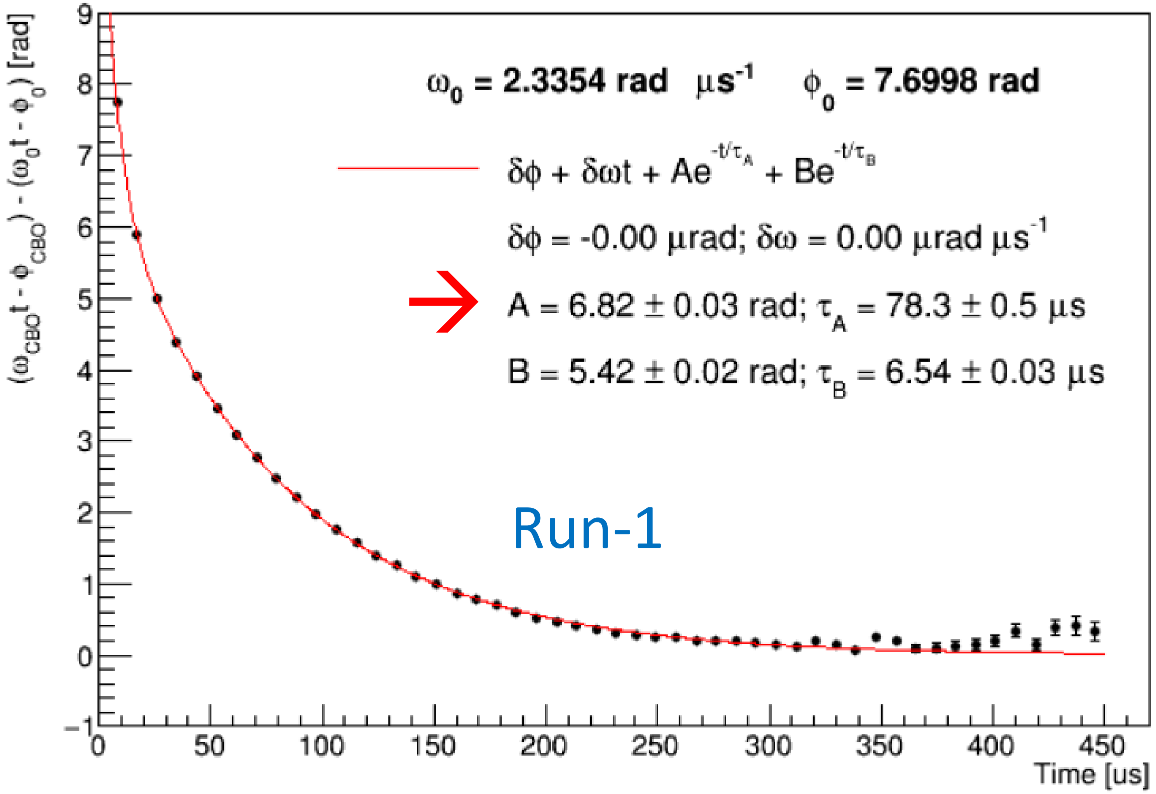
- **Sync pulse**: time synchronization at ~ 50 ps
- **In-Fill pulses**: monitor rate-dependent gain changes at 10^{-4} during 700 µs of μ^+ beam
- **Out-of-Fill pulses**: monitor stability over days

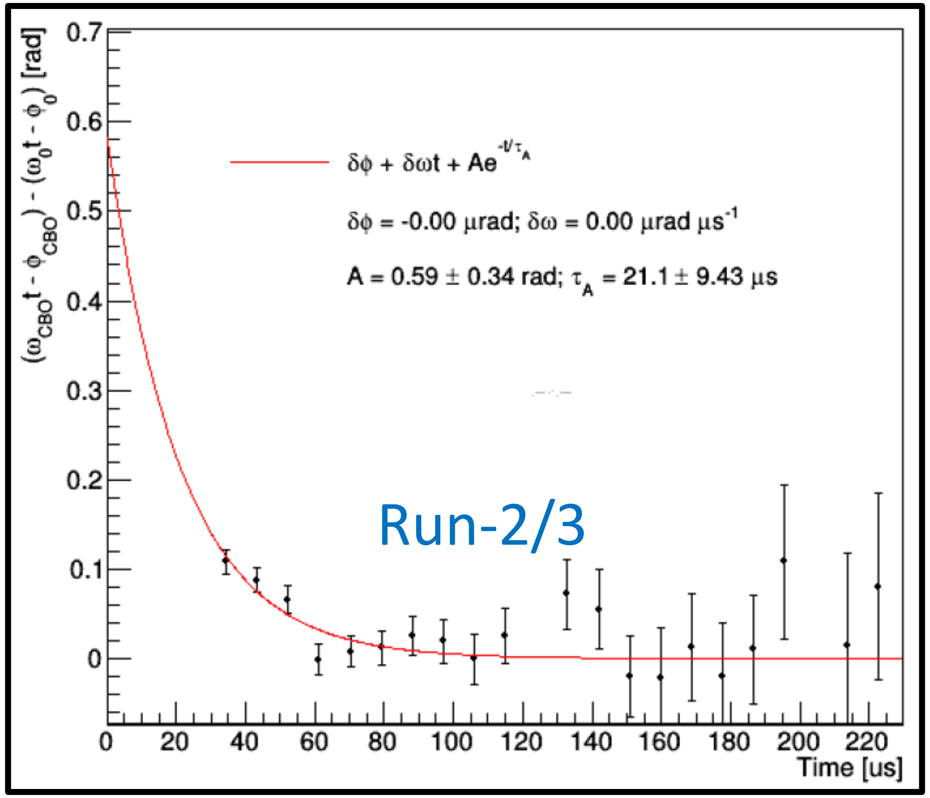


CBO model: frequency vs time

CBO dominated Run-1 systematics (38 ppb). Now reduced to 21 ppb!

- Exponential relaxation of CBO frequency
- Run-1: faulty ESQ resistors enhanced this effect 10 times!
- Sliding window fits to determine lifetime and constrain it in ω_a fits





Blinded analysis

- **Hardware**: main clock is tuned at $(40 - \varepsilon)$ MHz
  Offset only known to two scientists external to the collaboration

- **Software**: each ω_a analyzer applies their own, secret offset to their results