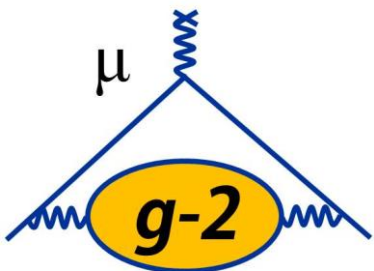


Measurement of the anomalous spin precession frequency ω_a in the Muon $g - 2$ experiment at Fermilab

Lorenzo Cotrozzi, on behalf of the Muon $g - 2$ collaboration

18/07/2024 | ICHEP 2024 | Prague

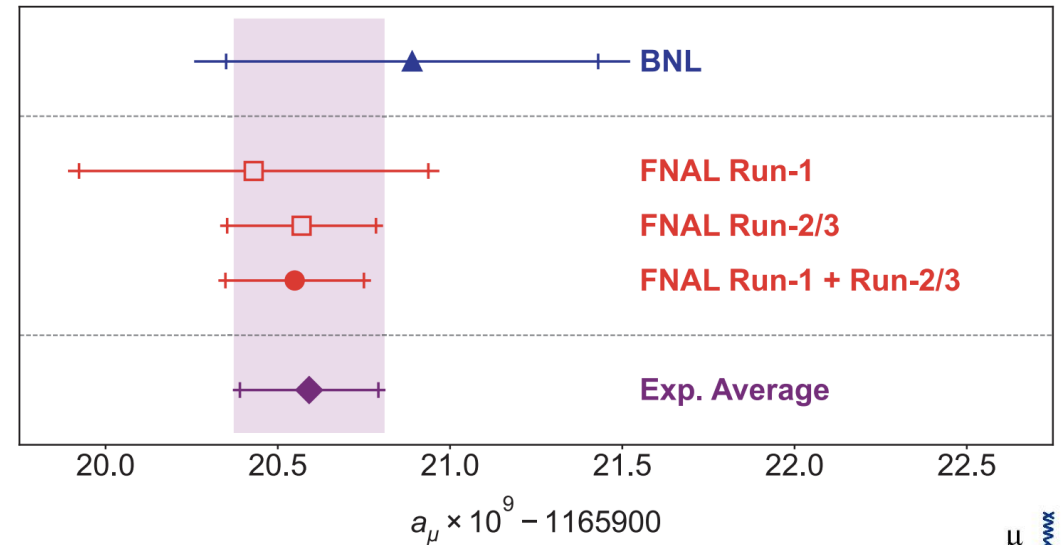
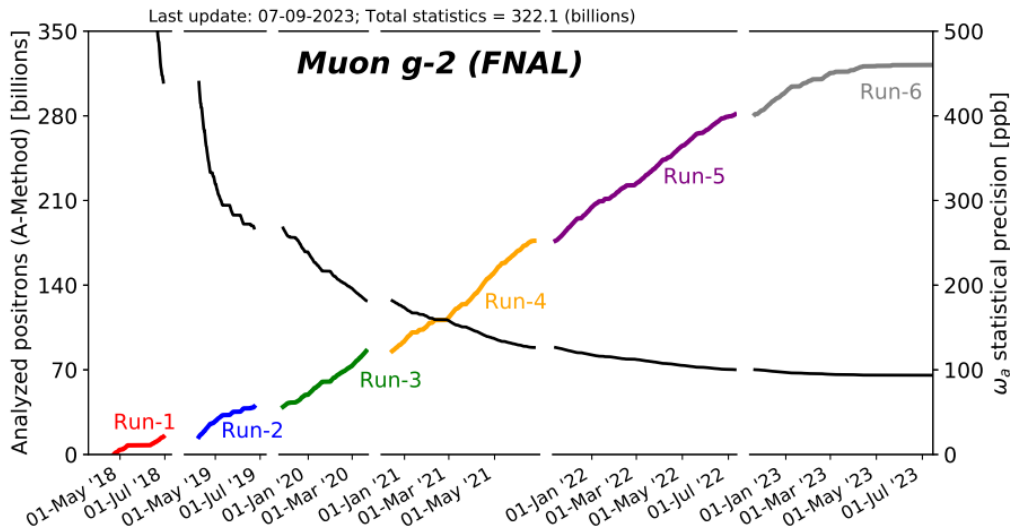
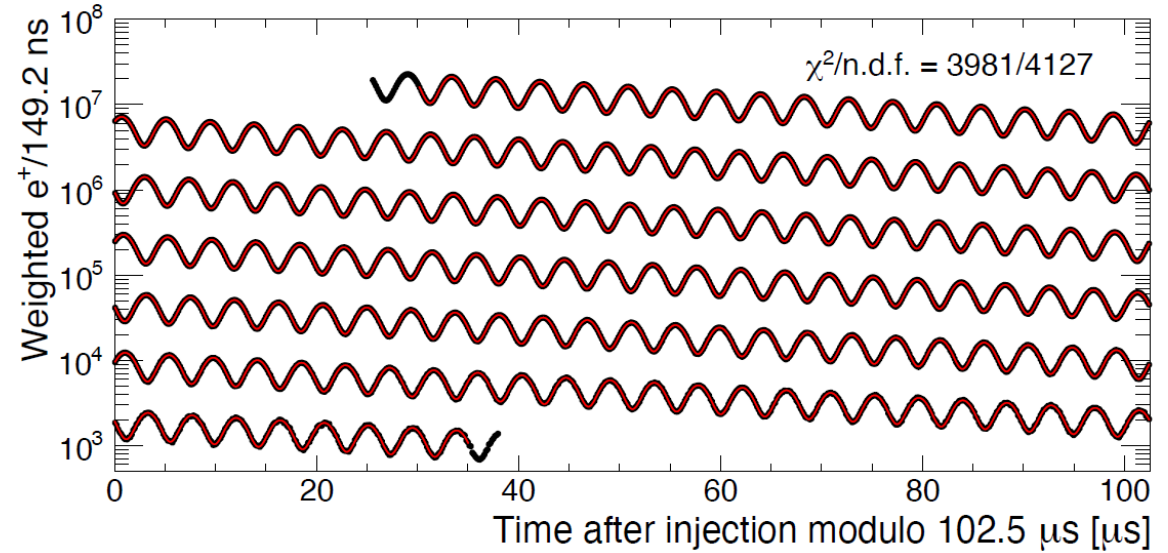


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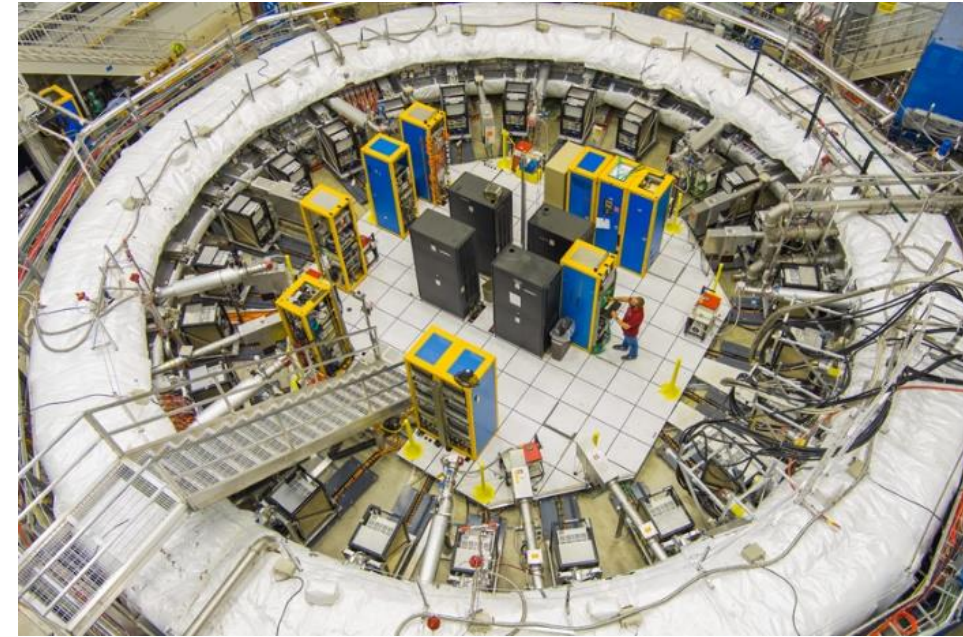


Outline

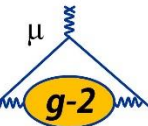
- Anomalous precession frequency ω_a in the Muon $g-2$ experiment at FNAL
- Run-2/3 result (2023) vs Run-1 (2021)
- Projections for Run-4/5/6 result



Experiment at Fermilab Muon Campus



Presented in the previous talk by **Kim Siang**



Anomalous spin precession in B-field

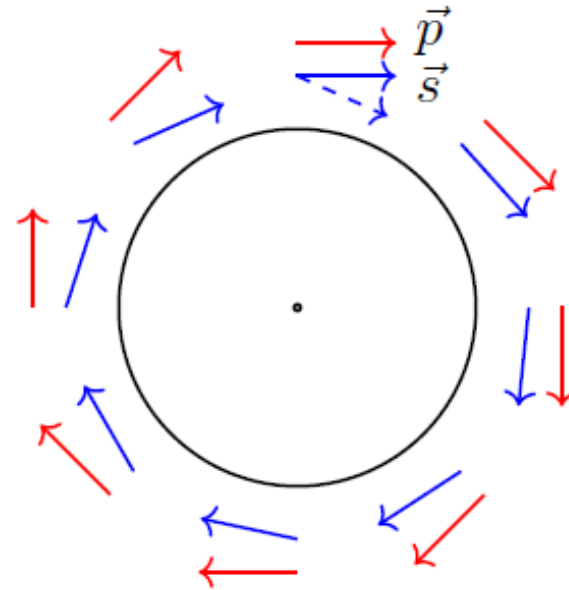
$g - 2 \neq 0$
 $a_\mu \neq 0$

\rightarrow spin precesses with anomalous frequency $\vec{\omega}_a = \vec{\omega}_{\text{spin}} - \vec{\omega}_c$

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

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

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



$$\omega_c \sim 42.1 \text{ rad}/\mu\text{s}$$

$$\omega_a \sim 1.439 \text{ rad}/\mu\text{s} \sim 12.4^\circ \text{ per turn}$$

Master formula for a_μ

External factors, known to 25 ppb

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

Make spin precess slower (E-field, vertical motion)

Make phase change within 700 μs

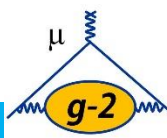
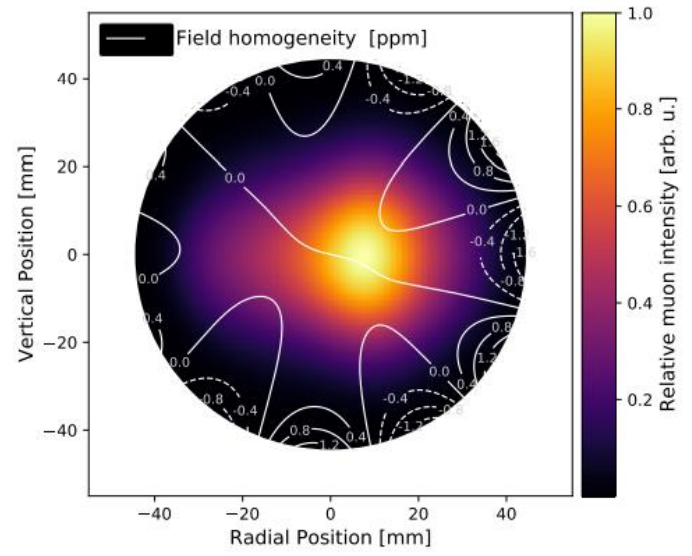
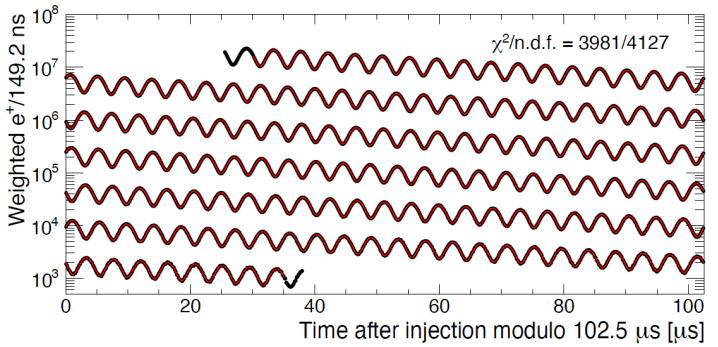
Induce transient magnetic fields

See poster tonight by Kim Siang

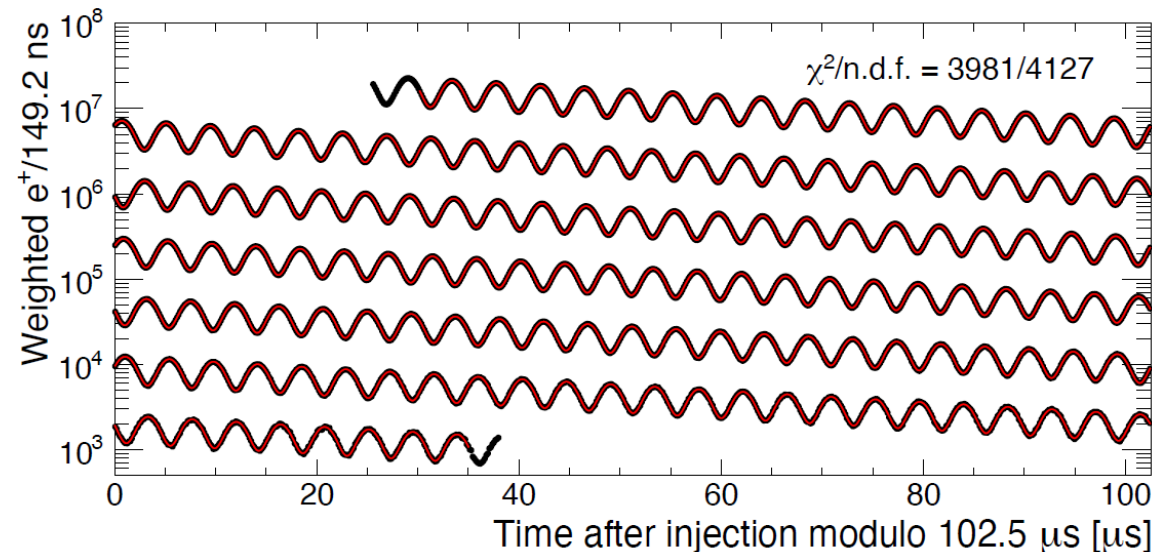
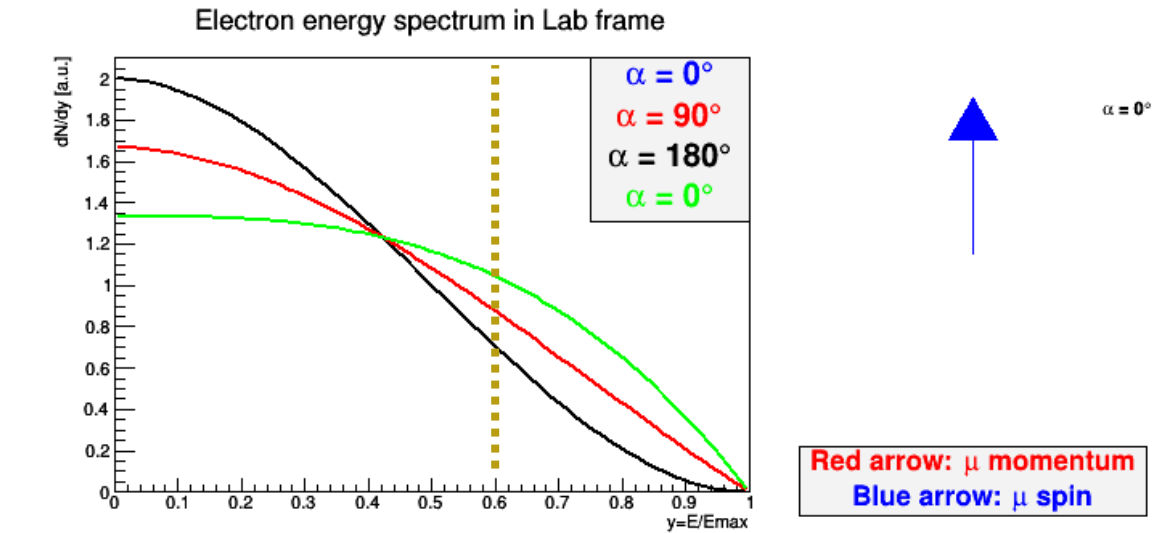
corrections for effects that...

m = Measured values

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \times$$



Principle of ω_a measurement

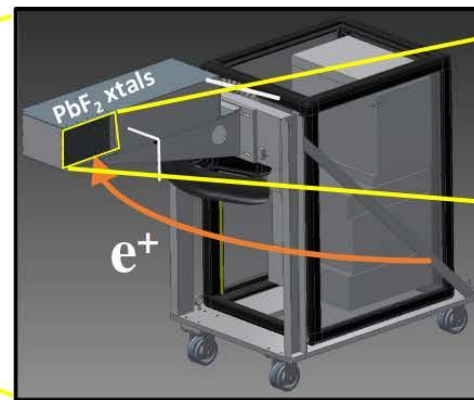
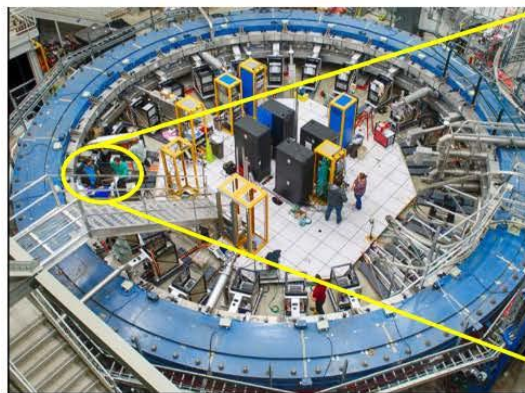


1. Weak decays violate parity:
 - polarized muon beam
 - preferred high-energy e^+ direction
2. Correlation in the lab frame between e^+ energy spectrum and ω_a phase
3. «Wiggle plot»: count high-energy e^+ over time, for about 700 μs (muon lifetime is $\sim 64 \mu\text{s}$ in the lab)

Detectors

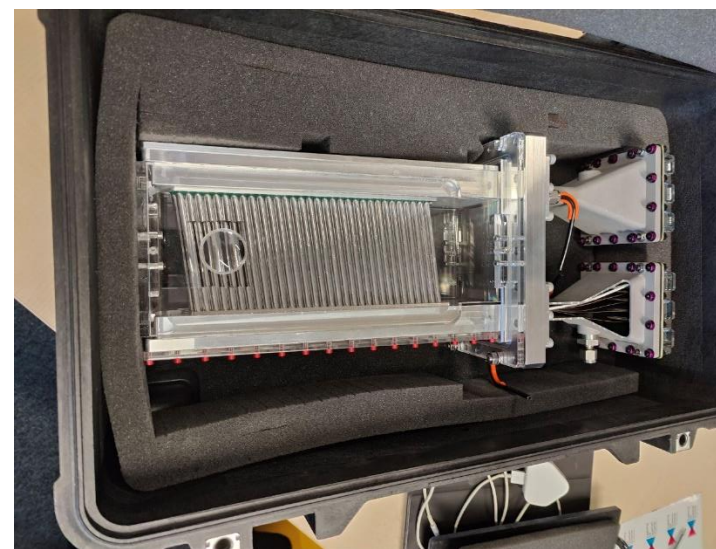
24 e.m. calorimeters

- Measure (E,t) of e^+
- Each made of 6×9 PbF_2 crystals, $15X_0$, read out by large-area SiPMs
- e^+ generate electromagnetic shower, SiPMs detect Cherenkov light ($n = 1.8$)

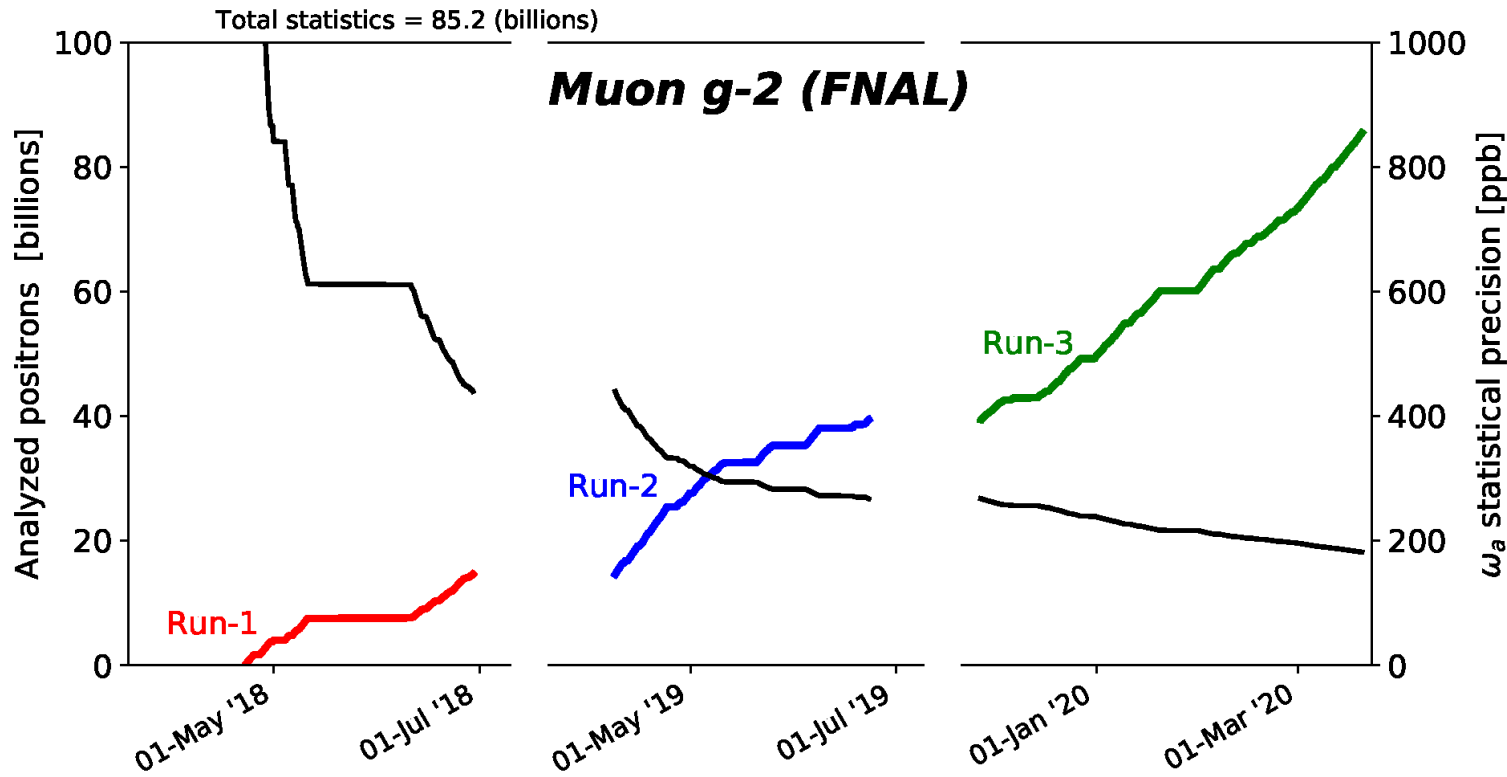


2 straw tube trackers

- Each has 8 modules and 32 planes
- 50:50 Argon:Ethane at 1 atm pressure
- Extrapolate decay vertex location to measure beam distribution

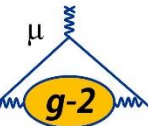


Run-2/3 (2019-2020 campaign)

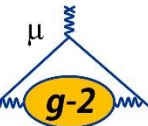
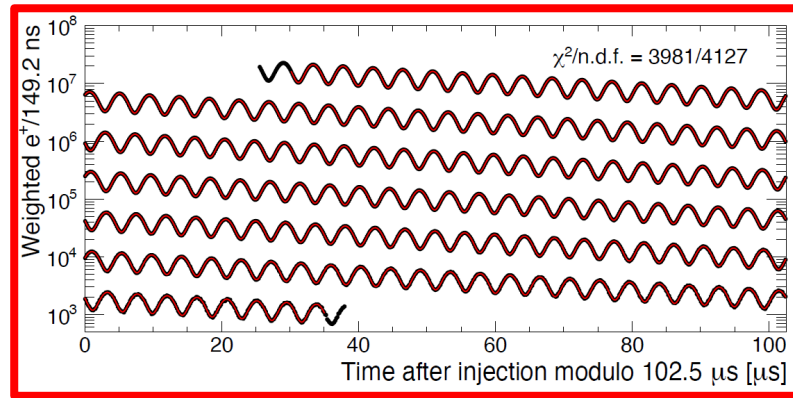
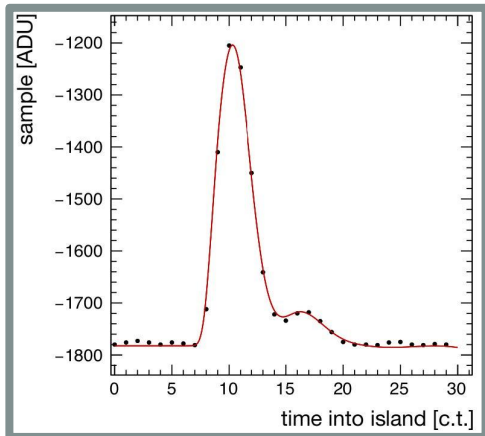
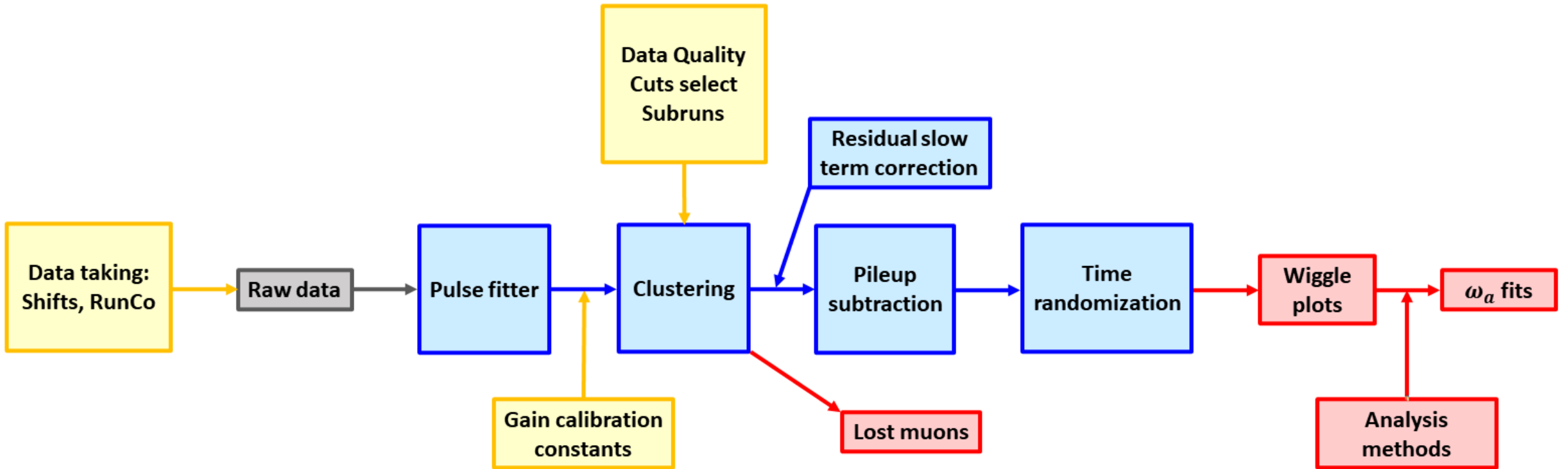


Dataset	Stat. unc. [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
FNAL design goal	100

Statistics: ~ 5 more muon decays than Run-1. Systematic limitations in Run-1 were fixed: reached 25 ppb on ω_a , 70 ppb on a_μ , surpassed design goal of 100 ppb

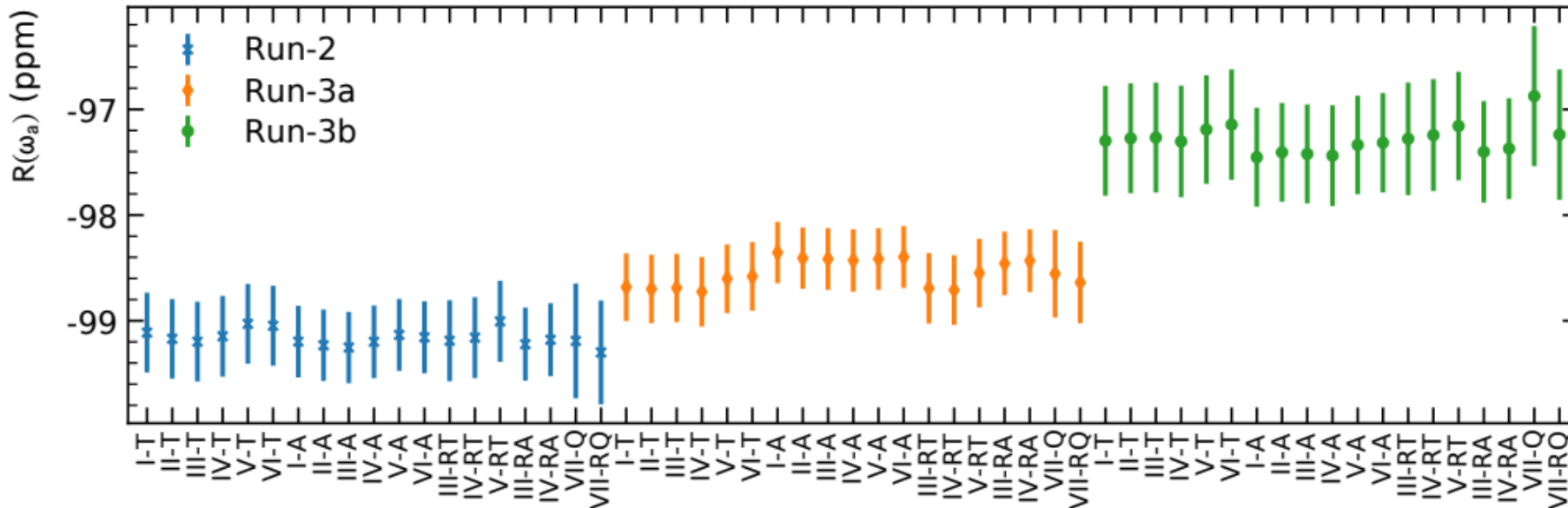


ω_a analysis flowchart

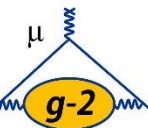


Run-2/3 ω_a analysis teams

Group	I	II	III	IV	V	VI	VII
Pulse fitting & clustering	Local	Local $\Delta t'$	Local «ITA»	Local $\Delta t'$	Global	Global	Q
Pileup subtraction	Shadow	Empirical	«Semi» empirical	Empirical	Empirical	Empirical	-
Analysis methods	T, A	T, A	T, A, RT, RA	T, A, RT, RA	T, A, RT	T, A	Q, RQ

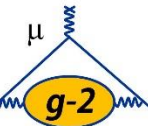
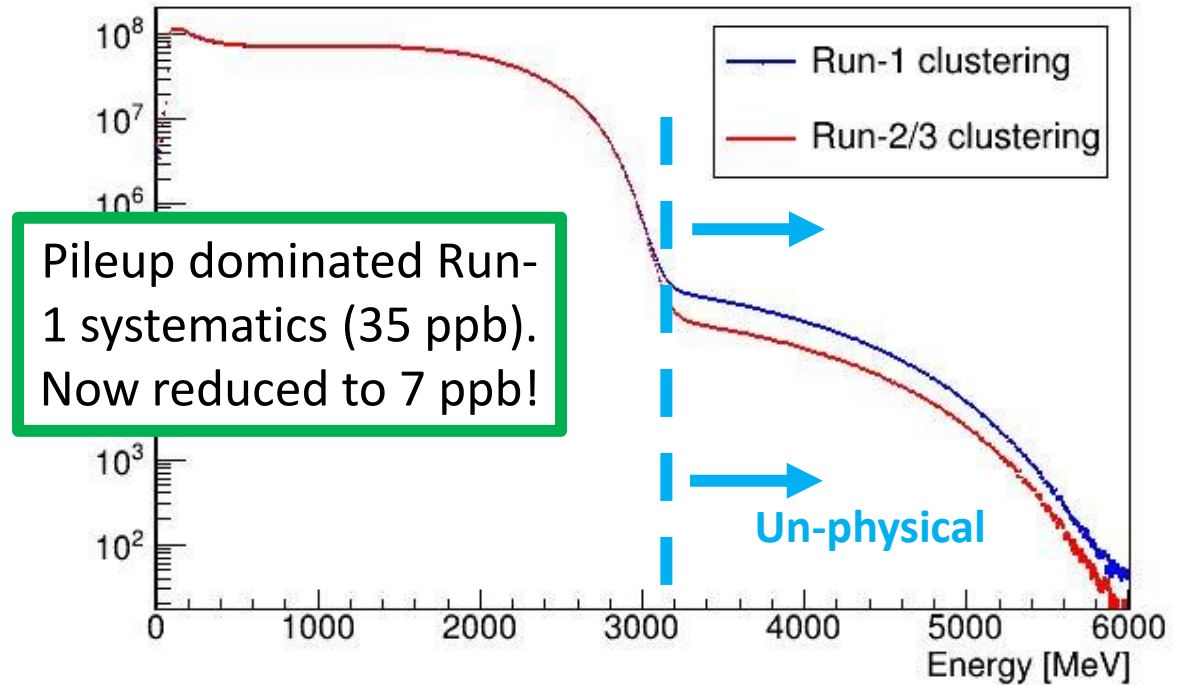
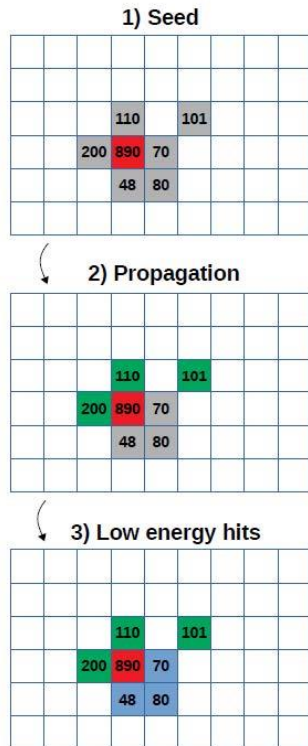
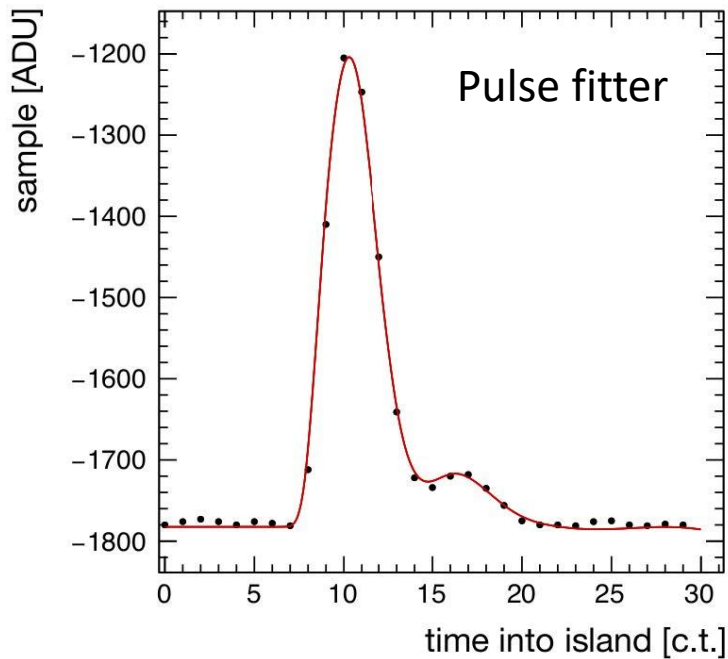
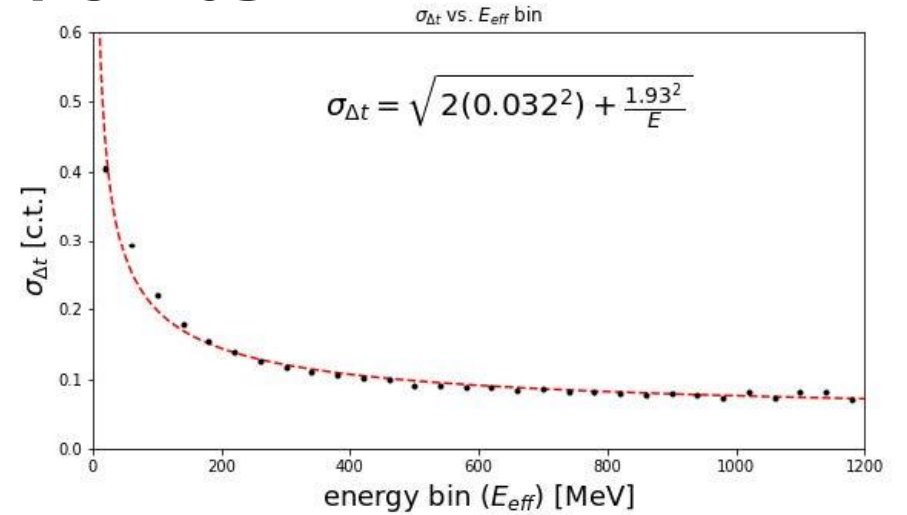


For details on combination: see next talk by Alberto Lusiani

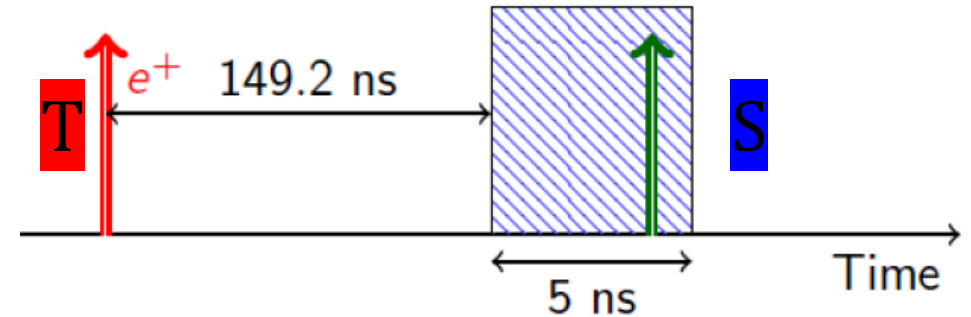
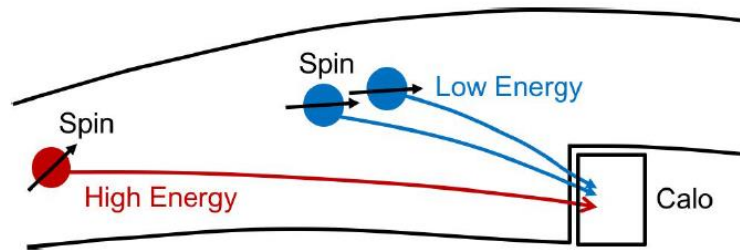


Reconstruct e^+ events

- Pulse fitter identifies traces on crystals
- New algorithms took into account detector's time and energy resolutions
- Reduced pileup in un-physical region

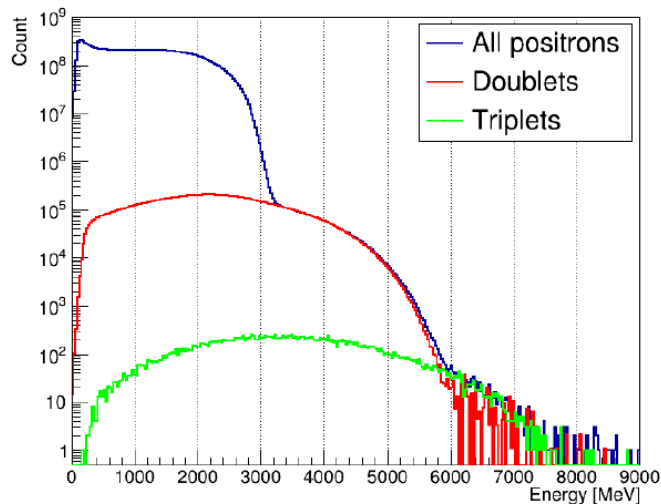


Improved pileup correction since Run-1 (example for «local» method)



For each **T** (Trigger) cluster that we find:

- Search for coincidence e^+ in **S** (Shadow) window, after 149.2 ns
- Superimpose the two clusters and pass to reconstruction algorithm



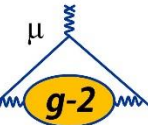
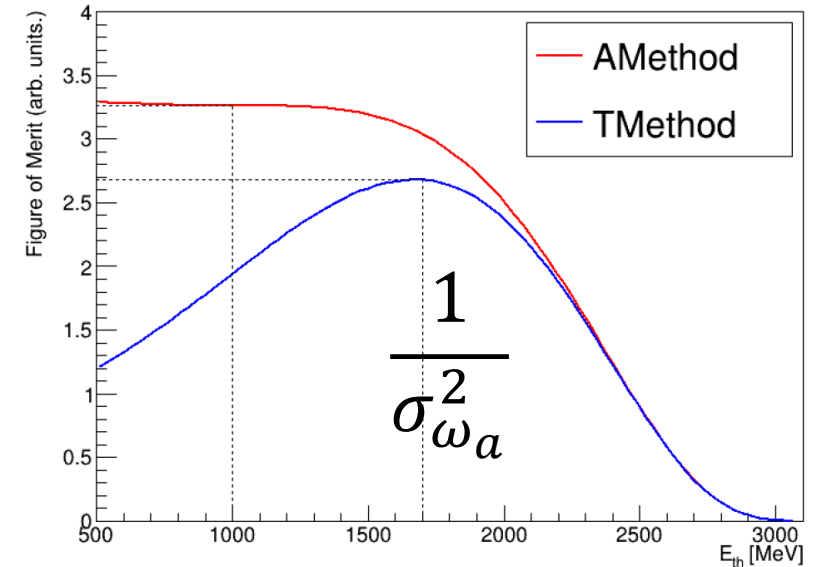
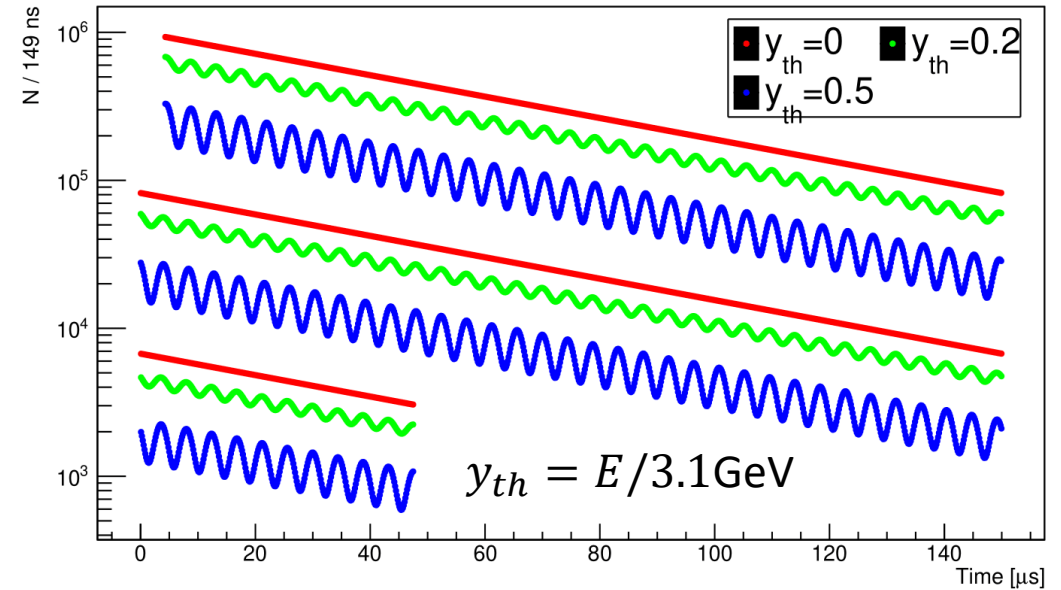
If not resolved: merge them and build pileup

In Run-2/3: also searched for triplets (2 shadows)



Methods for ω_a analysis

Wiggle plots for different energy thresholds



T-Method:

- Greater threshold: wider ω_a oscillations
- Lower threshold: more positrons
- Compromise: 1.7 GeV

A-Method:

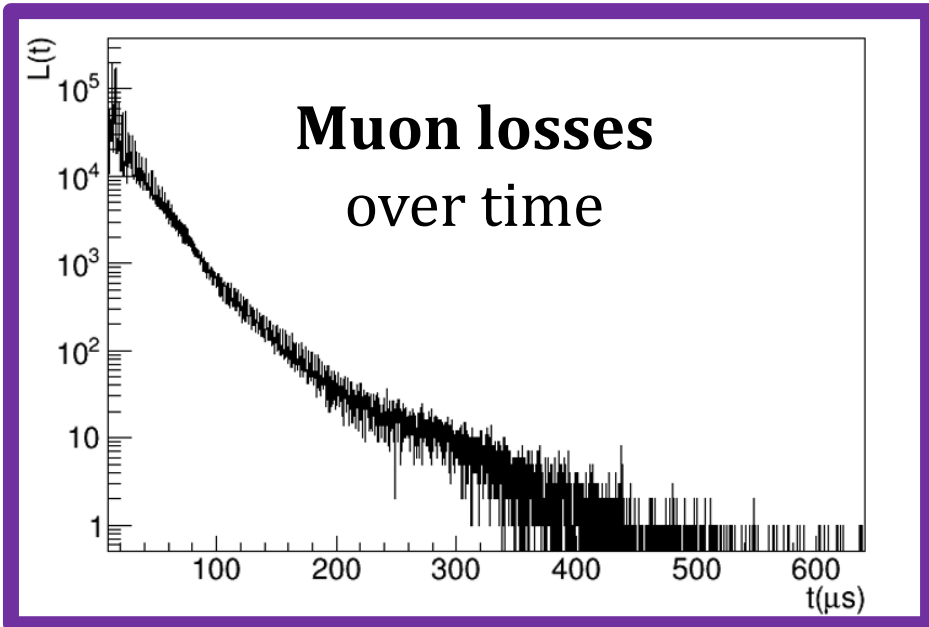
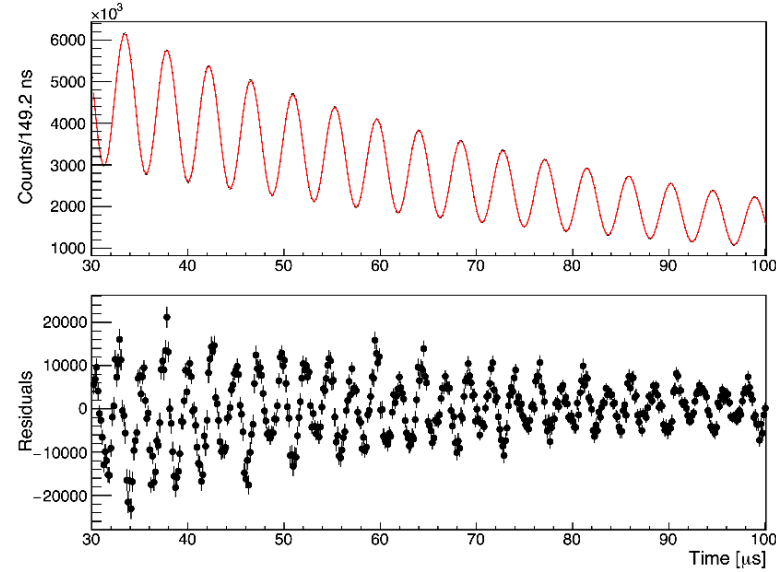
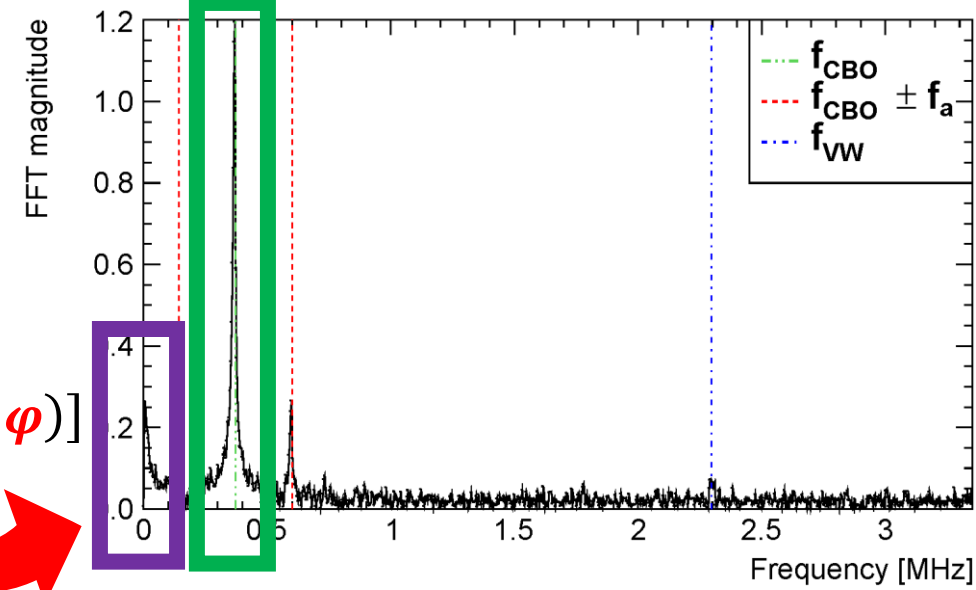
- Extract asymmetry (oscillation amplitude) as function of positron energy $\rightarrow A(E)$
- Weight each positron event with $A(E)$
- $\sigma_{\omega_a}(\text{A-Method}) \sim 90\% \sigma_{\omega_a}(\text{T-Method})$

ω_a fit

5-parameter fit

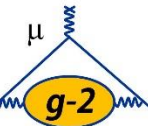
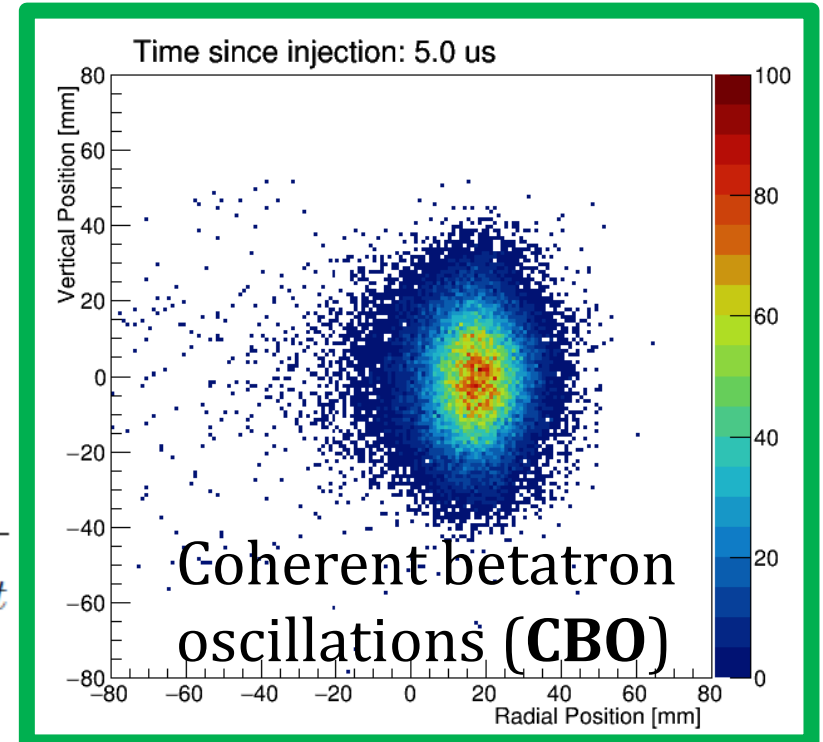
$$N(t) = N_0 e^{-\frac{t}{\gamma\tau_\mu}} [1 + A \cos(\omega_a t + \varphi)]$$

FFT of residuals



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

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

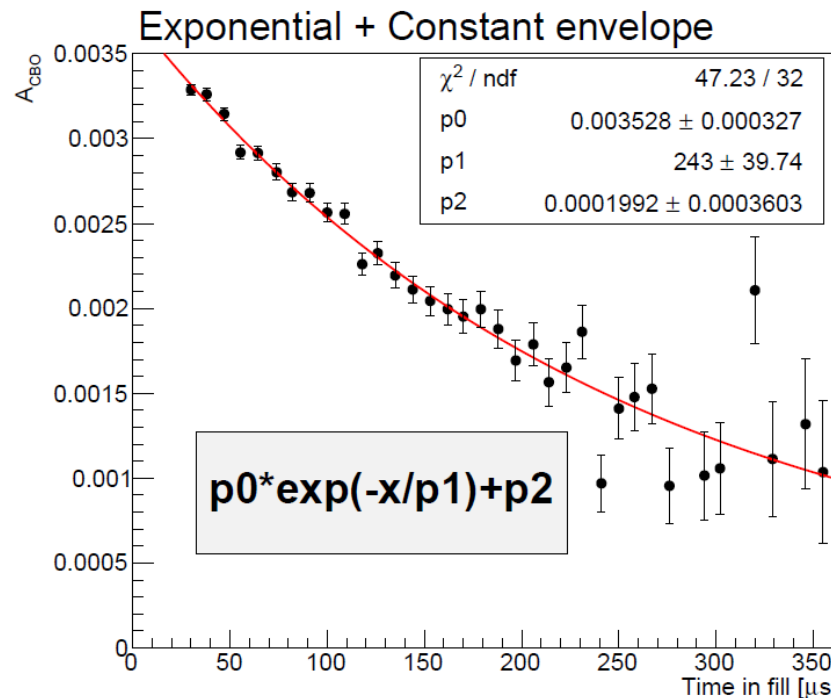
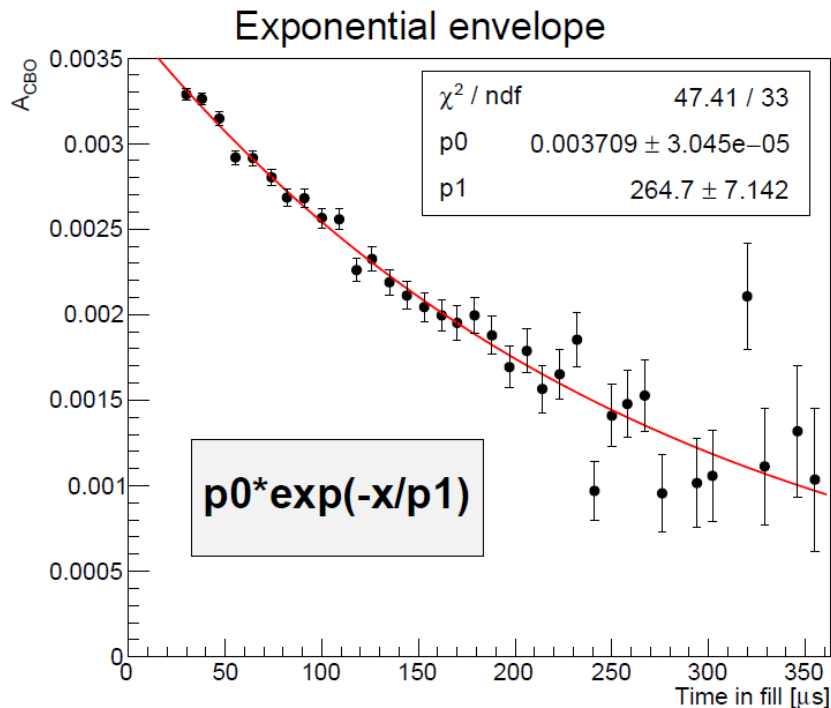


CBO model: amplitude vs time

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

$$CBO(t) = 1 + A_{CBO} \cos(\omega_{CBO}t + \varphi_{CBO}) \times e^{-t/\tau} \rightarrow \text{Decoherence}$$

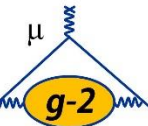
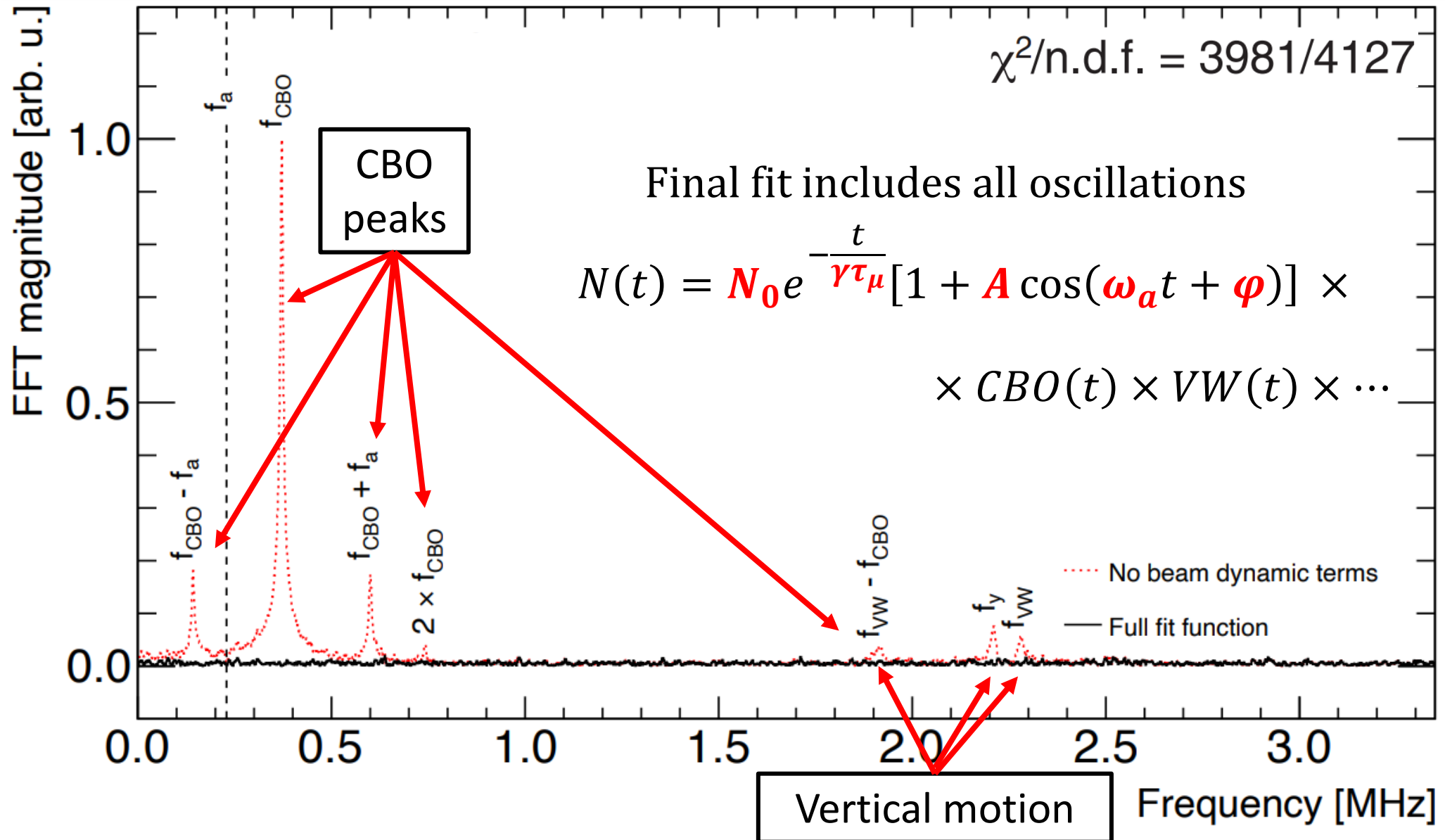
- Muons are an ensemble: betatron oscillations decohere over time
- Sliding window fits to determine good or bad envelopes: more statistics → more studies than Run-1; also input from tracker data



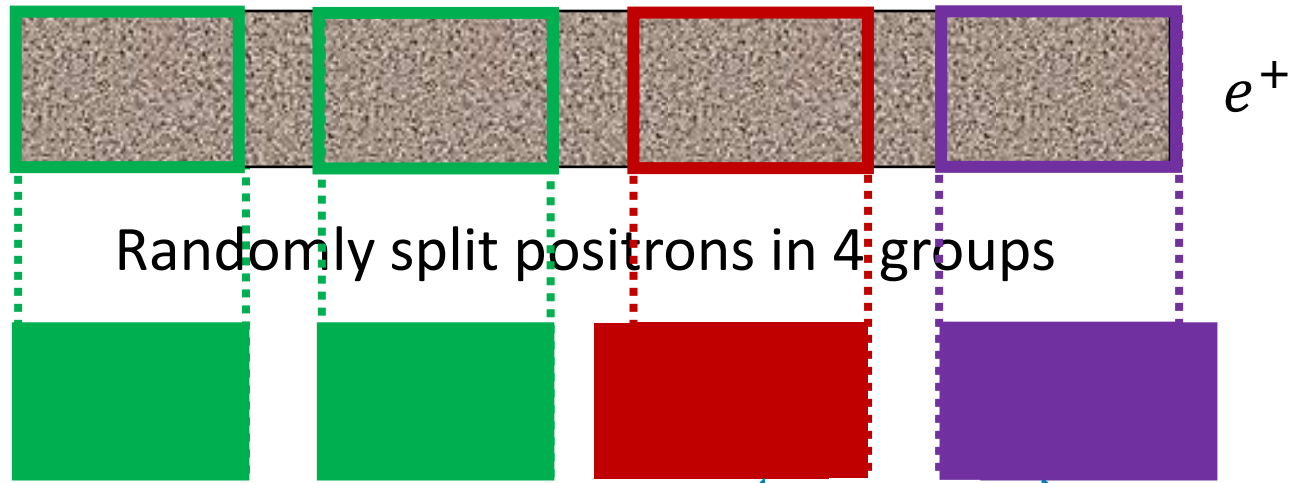
... and many other models tested



Run-2/3: ω_a fit and FFT of residuals



Ratio method wiggle plots

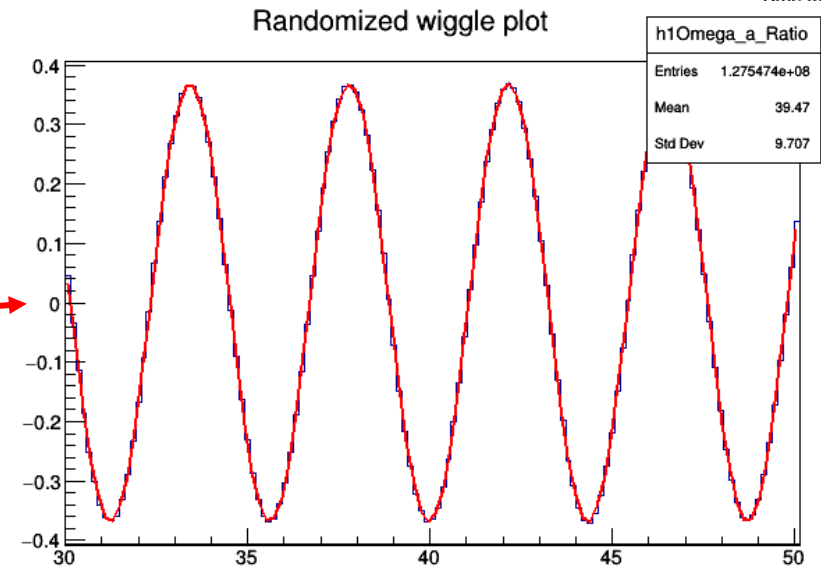
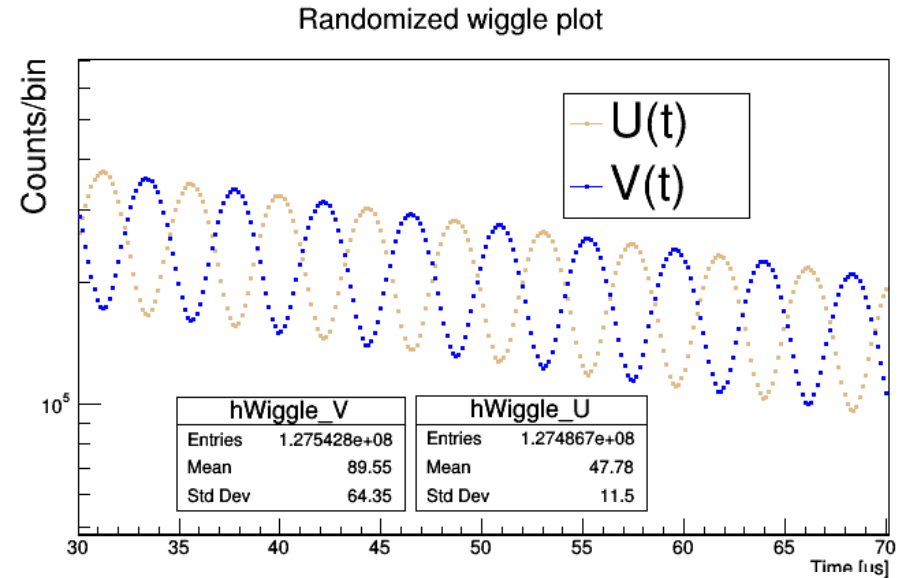


Shift two groups in time by \pm half precession period $T_a/2$. Recombine:



$$R(t) = [V(t) - U(t)]/[V(t) + U(t)]$$

It gets rid of muon lifetime and normalization N_0 in fit function. Any «slow» effect is highly reduced!



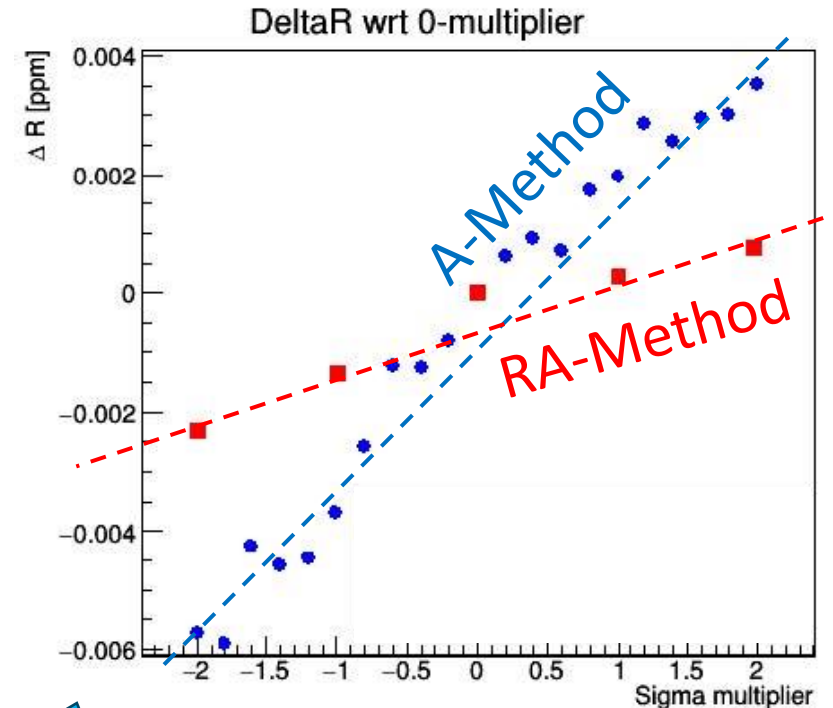
New “Ratio” A-Method

- Weight each positron with asymmetry function (like A-Method)

$$\mathbf{R}: \{V(t); U(t)\} \rightarrow \mathbf{RA}: \{\bar{V}(t) = \sum_E A(E) V(E, t); \bar{U}(t) = \sum_E A(E) U(E, t)\}$$

$$\mathbf{R}: \frac{V(t) - U(t)}{V(t) + U(t)} \rightarrow \mathbf{RA}: \frac{\bar{V}(t) - \bar{U}(t)}{\bar{V}(t) + \bar{U}(t)}$$

- Statistical uncertainty on ω_a is minimized
- Exponential due to muon lifetime is cancelled
- Reduces the sensitivity of ω_a to most «slow effects», such as **SiPM gain fluctuations!**



Prospects for ω_a analysis in Run-4/5/6

Statistical uncertainty:

- With Runs 1-->6, we expect to surpass design uncertainty of 100 ppb
- 21.9 times the previous BNL experiment

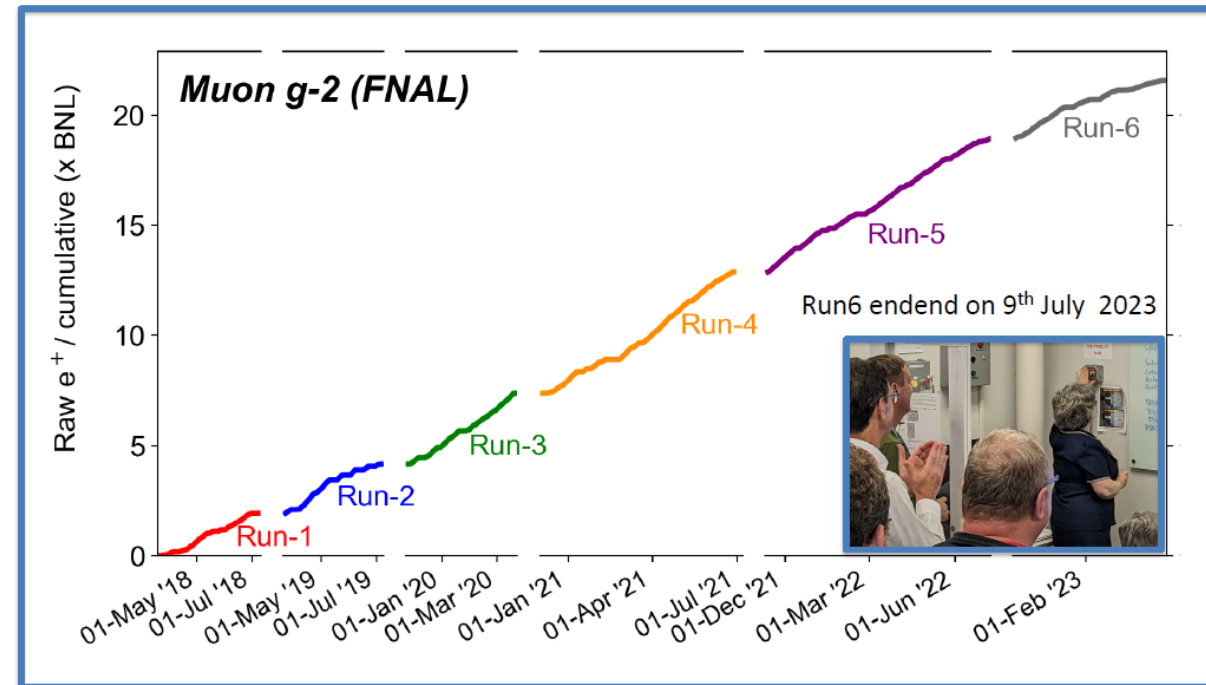
Running conditions in Run-4/5/6:

- Quadrupole Radio-Frequency switched on during Run-5 \rightarrow reduced radial and vertical motion of muons, more stable beam and less muon losses

Systematic sources of uncertainty:

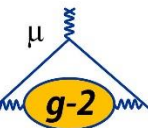
- CBO expected to be reduced, thanks to Quad RF and to dedicated studies in task forces

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



Summary and conclusions

- ❖ New muon a_μ experimental average has **unprecedented precision of 190 ppb**:
 - Factor ~ 2 improvement in statistical and systematic uncertainties on ω_a
 - Improved running conditions; upgraded reconstruction and pileup subtraction algorithms; more studies on beam dynamics effects
- ❖ Future analysis is expected to meet design goals:
 - Surpassed goal statistics: 21+ times w.r.t. previous BNL experiment
 - RF system ON: improved beam stability, ongoing evaluation of systematics



... and more details in recent 2024 paper

❖ «Detailed Report on the Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm» on [arXiv:2402.15410 \[hep-ex\]](https://arxiv.org/abs/2402.15410)

Soon to be published on Phys. Rev. D

Accepted Paper

Detailed report on the measurement of the positive muon anomalous magnetic moment to 0.20 ppm

Phys. Rev. D

D. P. Aguillard et al.

Accepted 21 May 2024

arXiv:2402.15410v3 [hep-ex] 22 May 2024

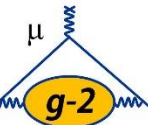
Detailed Report on the Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

D. P. Aguillard,²³ T. Albaladejo,²⁰ D. Allpach,⁷ A. Anisenkov,^{4,*} K. Badgley,⁷ S. Baessler,^{25,*} I. Bailey,^{17,*} L. Bailey,²⁷ V. A. Baranov,¹⁵ E. Barlas-Yucel,²⁸ T. Barrett,⁶ E. Barzil,⁷ F. Bedeschi,¹⁰ M. Bera,¹⁴ M. Bhattacharya,⁷ H. P. Binney,²⁶ P. Bloom,¹³ J. Bono,⁷ E. Bottalico,^{20,*} T. Bowcock,²⁰ S. Brann,²⁶ M. Bressler,²² G. Cantatore,^{12,*} R. M. Carey,² B. C. K. Casey,⁷ D. Cauz,^{26,*} R. Chakraborty,²⁹ A. Chapelain,⁶ S. Chappas,⁷ S. Charity,³⁰ C. Chen,^{23,22} M. Cheng,²⁹ R. Chislett,²⁷ Z. Chu,^{22,*} T. E. Chupp,²³ C. Ciaccione,²⁶ M. E. Convery,⁷ S. Corradi,¹ L. Cotrozzi,^{19,20,*} A. J. D. Czirjak,⁷ S. Dabagov,^{4,*} P. T. Debevec,²⁸ S. Di Falco,¹⁰ G. Di Sciascia,¹¹ S. Donati,^{10,*} B. Drexler,⁷ A. Triantafyllidis,^{19,*} V. N. Dugina,^{15,*} M. Eick,²⁹ A. Etkin,^{2,*} J. Esquivel,⁷ M. Farooq,³³ R. Fatemi,²⁹ C. Ferrari,^{10,*} M. Ferli,¹⁴ A. T. Fienberg,²⁶ A. Fioretti,^{10,*} D. Flay,³² S. B. Foster,² H. Friedrich,² N. S. Froemming,²⁰ C. Gabbaiani,^{10,*} I. Gaines,⁷ M. D. Galati,^{10,*} S. Ganguly,⁷ A. Garcia,²⁶ J. George,^{32,*} L. K. Gibbons,⁶ A. Giocola,^{25,*} K. L. Giovanetti,¹² P. Girotti,¹⁰ W. Golin,²⁹ L. Goodenough,⁷ T. Gorringe,²⁹ J. Grange,³³ S. Grant,^{1,*} F. Gray,²³ S. Hacıomeroglu,^{5,*} T. Halewood-Leagas,²⁰ D. Hampal,⁸ F. Han,²⁹ J. Hempstead,²⁶ D. W. Hertzog,²⁶ G. Heskel,²⁷ E. Heus,¹⁰ A. Hibbert,²⁹ Z. Hodzic,²⁹ K. W. Hong,³⁵ R. Hong,^{1,29} T. Hu,^{23,22} Y. Hu,^{22,*} M. Iaconacci,^{9,*} M. Incagli,¹⁰ P. Kammel,²⁶ M. Karjalainen,¹ M. Karuz,^{12,*} J. Kaspar,²⁶ D. Kawada,²⁹ L. Keilman,²⁹ A. Keshavarzi,³⁴ D. S. Kosler,²⁷ K. S. Kwon,^{23,22} Z. Khechikourian,⁶ N. V. Khomutov,¹⁵ B. Kilburg,⁷ M. Kilburg,⁷ O. Kim,³⁴ N. Kinnaird,² E. Kraeghshøj,³³ V. A. Krylov,¹⁵ N. A. Kuchinskiy,¹⁵ K. R. Labé,⁶ J. Labounty,²⁶ M. Lancaster,³¹ S. Lee,⁵ B. Li,^{22,*} D. Li,^{22,*} L. Li,^{22,*} I. Logashenko,^{4,*} A. Lorente Campos,²⁹ Z. Lu,^{22,*} A. Lucà,⁷ G. Lukicov,²⁷ A. Lusiani,^{10,*} A. L. Lyon,⁷ B. MacCoy,²⁶ R. Madrak,⁷ K. Makino,¹⁸ S. Mastroianni,⁹ J. P. Miller,² S. Miozzi,¹³ B. Mitra,³⁴ J. P. Morgan,⁷ W. M. Morse,³ J. Mott,^{7,2} A. Nath,^{6,*} J. K. Ng,^{23,22} H. Nguyen,⁷ Y. Okuzian,¹ Z. Omarov,^{14,5} R. Ososky,²⁶ S. Park,² G. Pauer,^{26,*} G. M. Piacentino,^{25,*} R. N. Pilaos,²⁹ K. T. Pitts,^{29,*} B. Plaster,²⁹ D. Počanić,²⁵ N. Pohlman,²⁹ C. C. Polly,⁷ J. Price,²⁶ B. Quinn,³⁴ M. U. H. Qureshi,¹⁴ S. Ramachandran,^{14,*} E. Rasmberg,⁷ R. Reimann,¹⁴ B. L. Roberts,⁷ D. L. Rubin,⁶ M. Sakurai,¹ L. Sauti,²⁶ C. Scholer,^{26,*} A. Schreckenberger,⁷ Y. K. Semertzidis,^{5,16} D. Shemyakin,^{4,*} M. Sorbara,^{11,*} J. Stapleton,⁷ D. Still,⁷ D. Stöckinger,²⁴ C. Stoughton,⁷ D. Stratakis,⁷ H. E. Swanson,²⁶ G. Sweetser,³¹ D. A. Sweigart,⁶ M. J. Syphers,²⁰ D. A. Tarasova,^{5,30,18} T. Teubner,³⁰ A. E. Tewsley-Booth,^{23,22} V. Tishchenko,³ N. H. Tran,^{2,*} W. Turner,³⁰ E. Valetov,¹⁸ D. Vasilkova,^{27,30} G. Venanzoni,^{30,*} V. P. Volynik,¹⁵ T. Walton,⁷ A. Weisskopf,¹⁸ L. Welty-Rieger,⁷ P. Winter,¹ Y. Wu,³⁴ M. Yucel,⁷ Y. Zeng,^{23,22} and C. Zhang²⁰

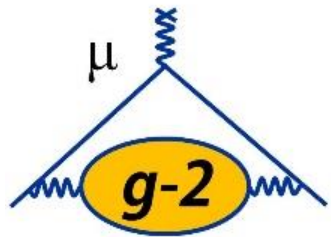
(The Muon $g-2$ Collaboration)

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²⁵Università del Molise, Campobasso, Italy

❖ A few more physics papers will come out in the future, e.g. Beyond Standard Model searches: see tomorrow's talk on CPT/LIV by Baisakhi Mitra



THANK YOU FOR YOUR ATTENTION!



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LEVERHULME
TRUST

lorenzo.cotrozzi@liverpool.ac.uk



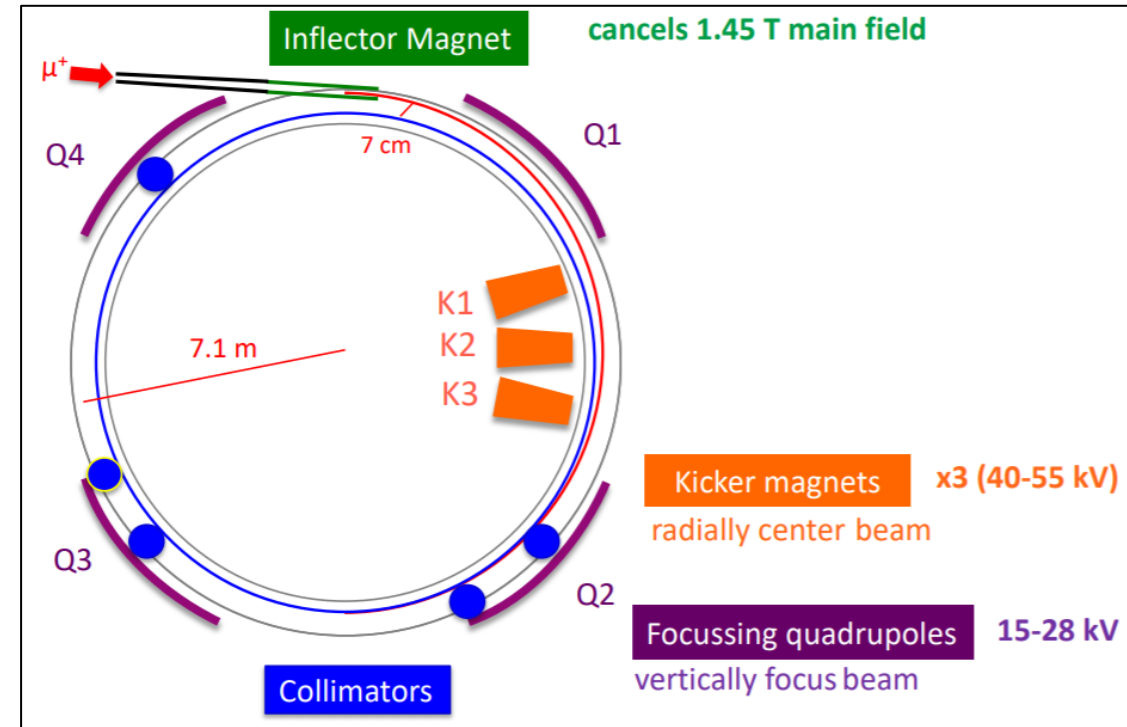
July 2023 collaboration meeting @ Liverpool, UK

ICHEP 2024 | PRAGUE

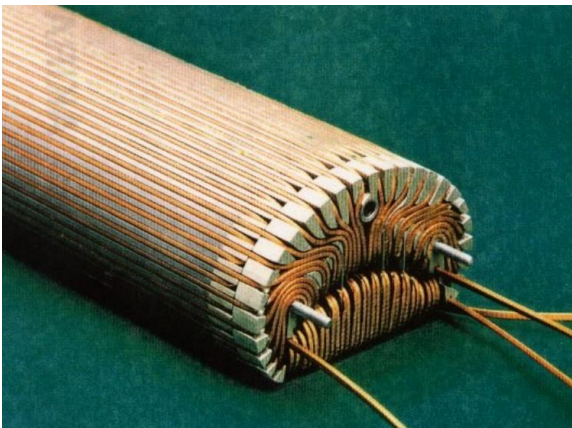
Extra: Bad resistors backup

Injection and muon storage

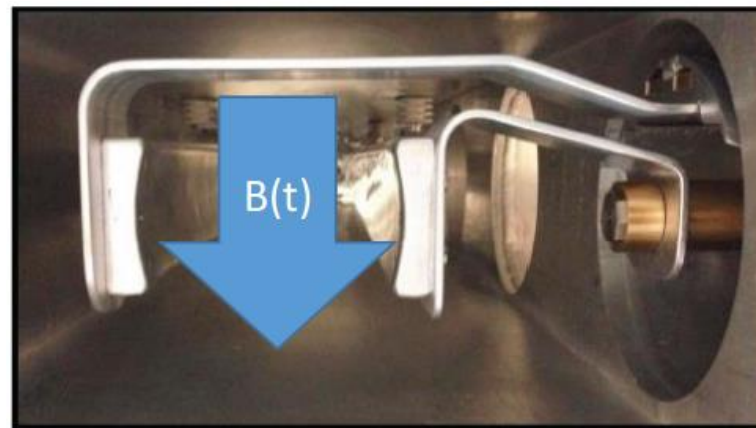
1. **Inflector** cancels main dipole field and injects at ~ 8 cm radially away from nominal orbit
2. **3 fast magnetic kickers** provide 10 mrad kick and place muons in orbit
3. **8 Electrostatic Quadrupoles** (ESQ) focus in the vertical direction



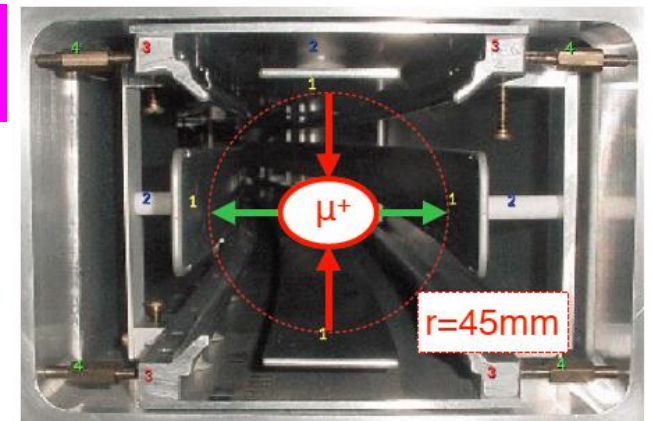
1.



2.

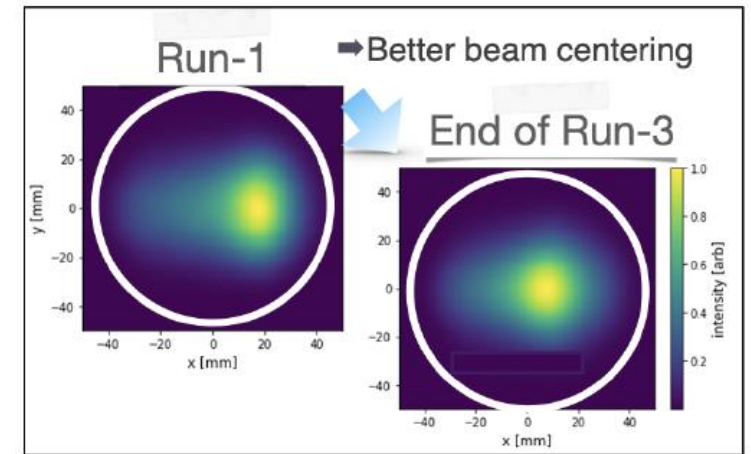
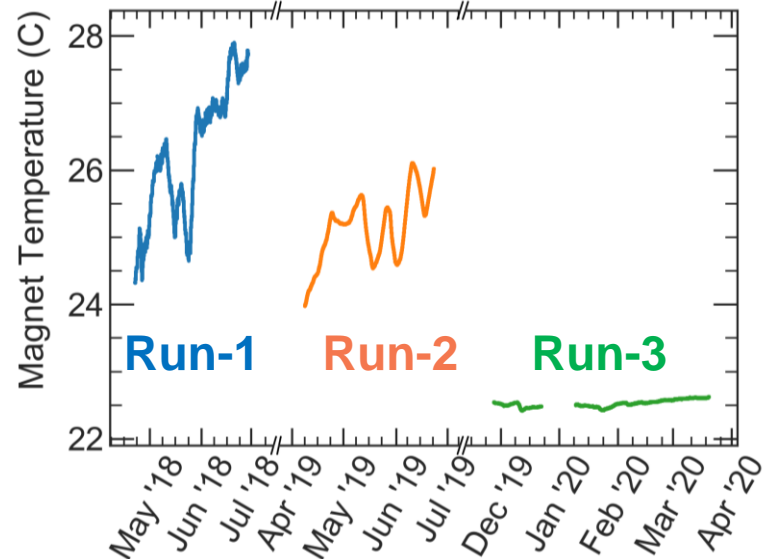
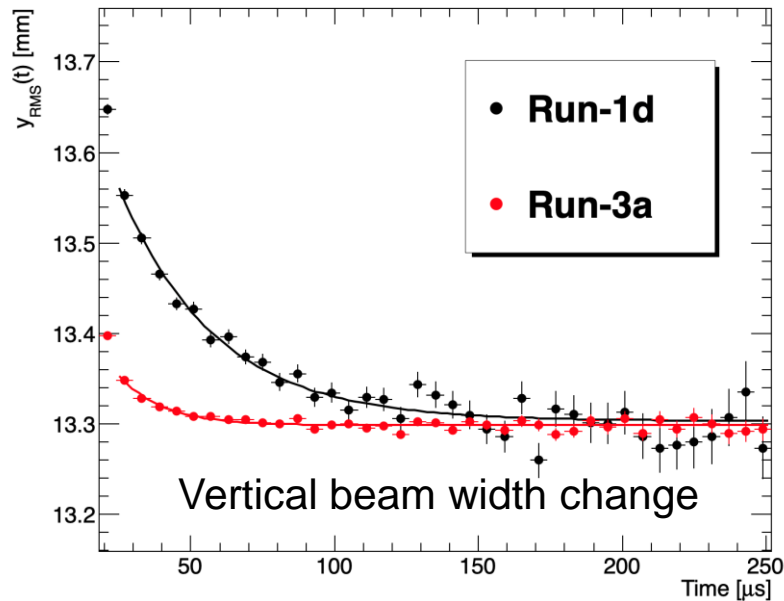


3.



Run-2/3 improved running conditions

- Before Run-2: **fixed faulty resistors** in 2/32 quadrupole plates → better storage, more stable beam oscillations and reduced systematics
- After Run-2: added thermal insulation to ring → less variable magnetic field
- Mid Run-3: **upgraded kicker** cables for optimal kick → more centered beam



Extra: ω_a backup

Run-1 vs Run-2/3 systematics

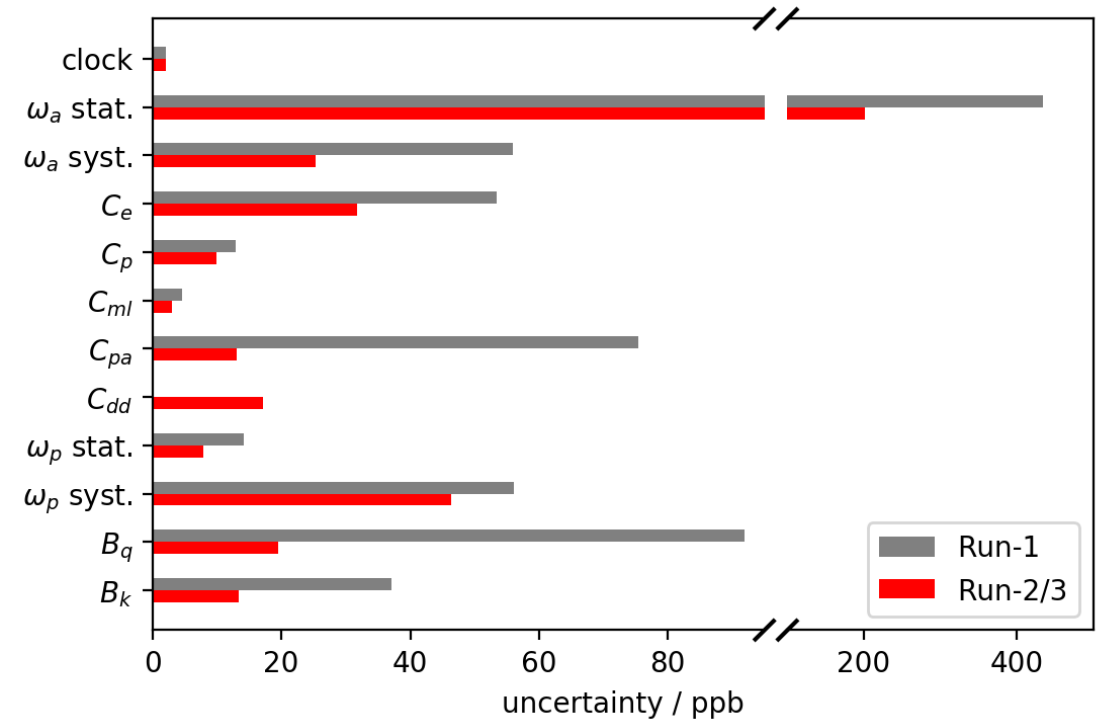
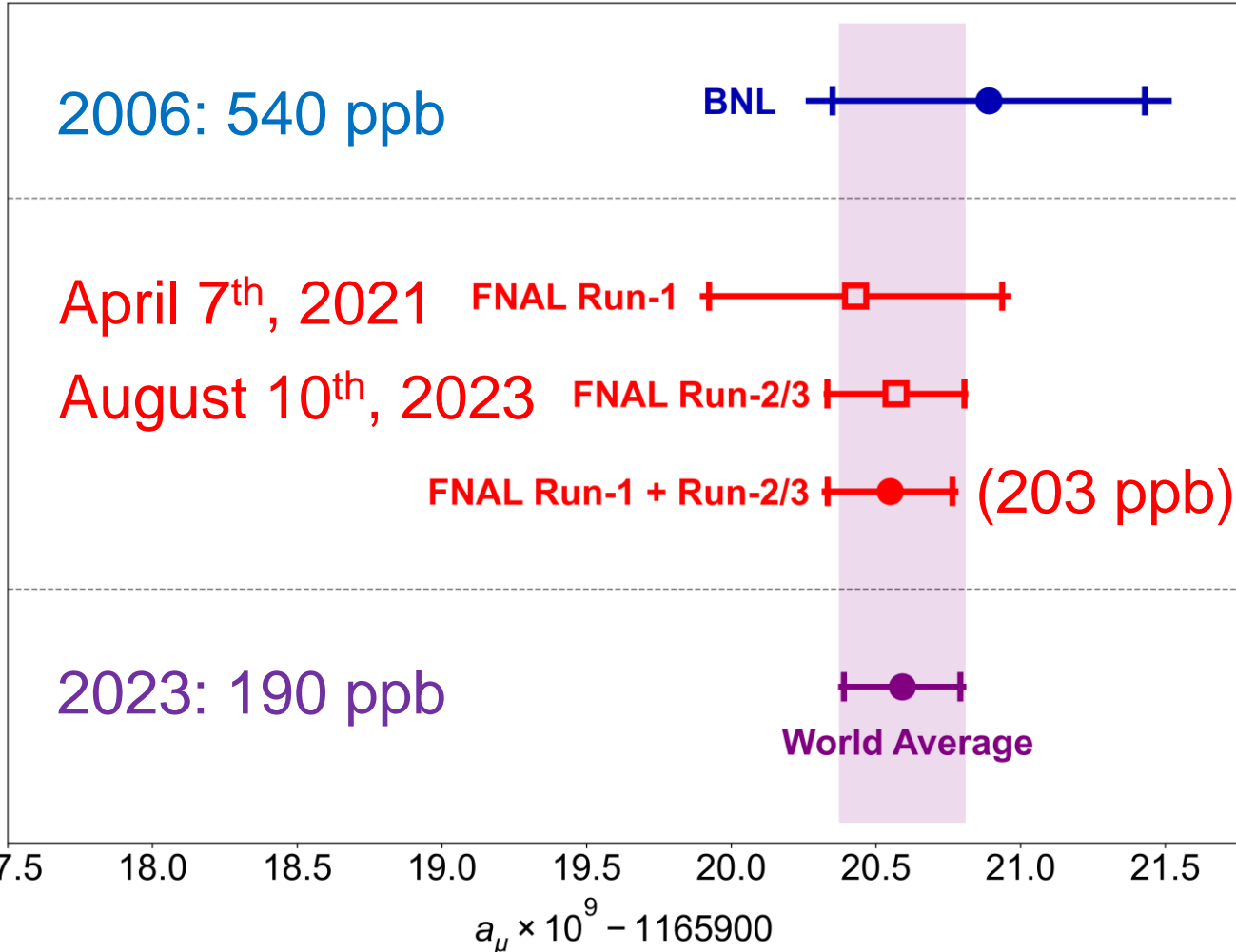
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	434
ω_a^m (systematic)	...	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$	...	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	...	10
m_μ/m_e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

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

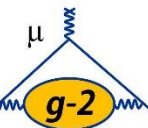
Run-2/3 Result: FNAL + BNL Combination

D. P. Aguillard et al, Phys. Rev. Lett. 131.161802 (2023)

D. P. Aguillard et al, arxiv:2402.15410 (2024)



- Running improvements
- ~ 5x statistics
- Analysis improvements (CBO, pileup, reconstruction, ...)
- 70 ppb syst. → exceeded goal!



Blinded analysis

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

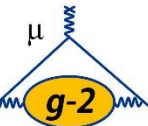
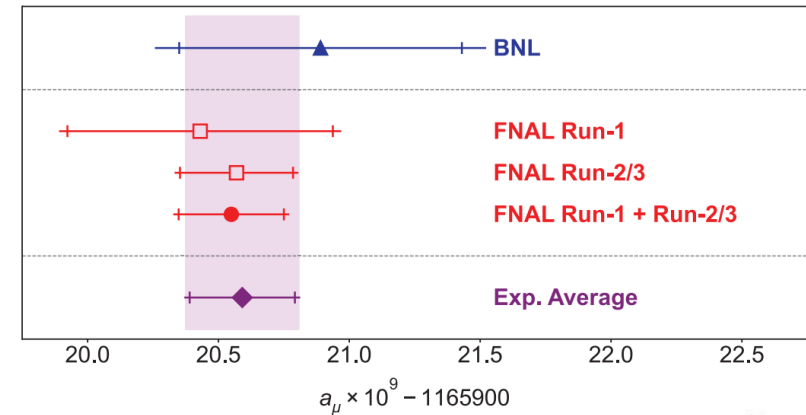
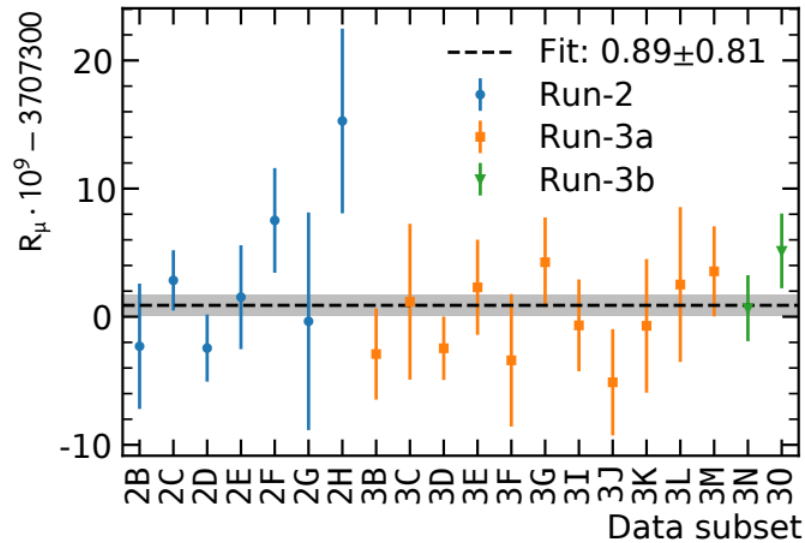
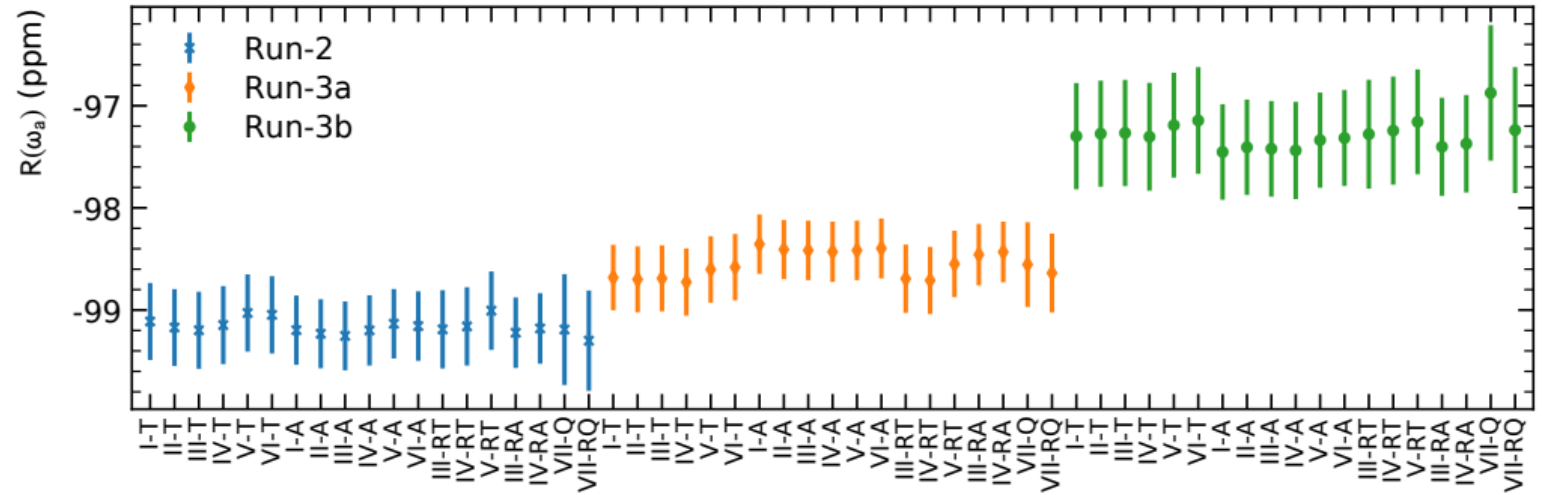


- **Software:** each ω_a analyzer applies their own, secret offset to their results

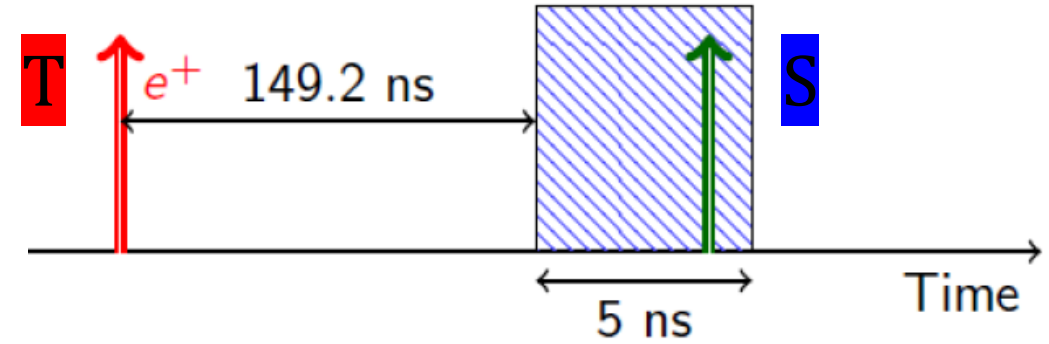
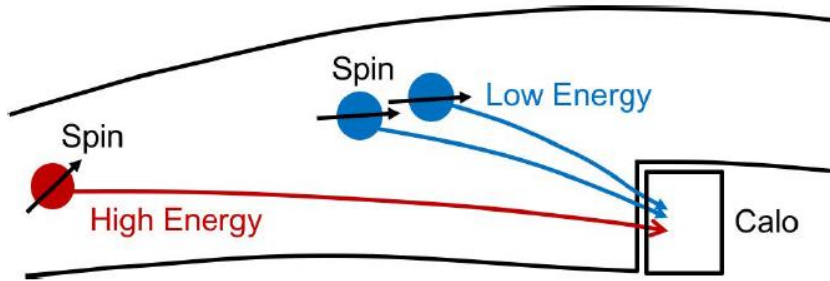
Run-2/3 unblinding

- Software unblinding

- Hardware unblinding



Example of new method to subtract pileup

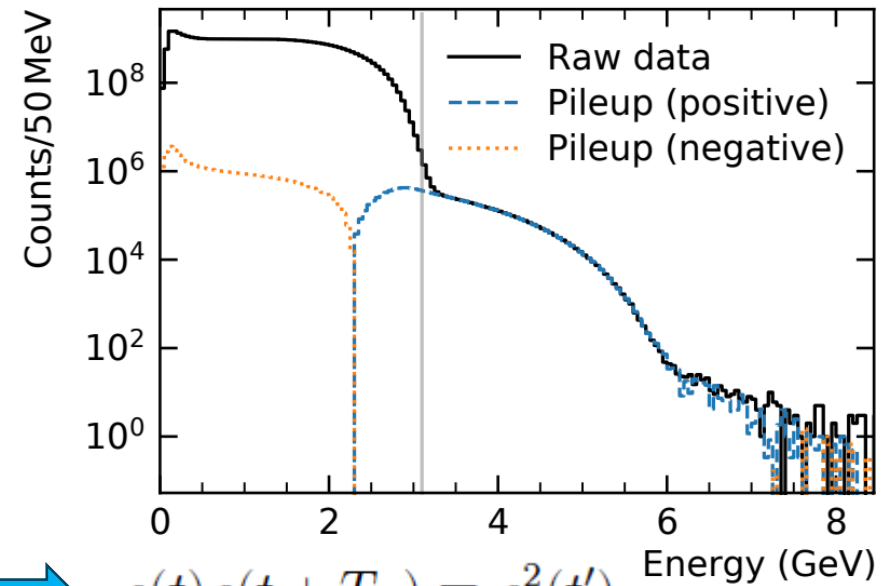


For each **T** (Trigger) cluster that we find:

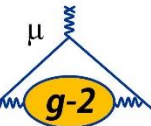
- Search for coincidence e^+ in **S** (Shadow) window, after 149.2 ns
- Superimpose the two clusters and pass to reconstruction algorithm

→ If not resolved: merge them and build pileup

$$E_2 = (E_T + E_{S_1}) \quad t_2 = \frac{(t_T + T_G/2)E_T + (t_{S_1} - T_G/2)E_{S_1}}{E_T + E_{S_1}} \quad \longrightarrow \quad \rho(t)\rho(t + T_G) \equiv \rho^2(t')$$

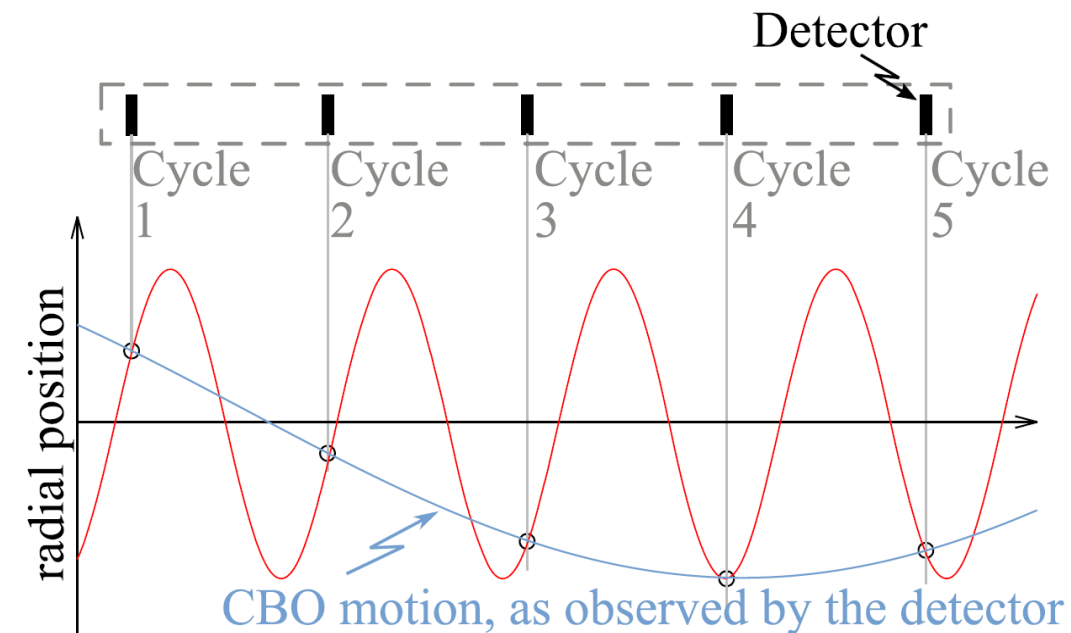
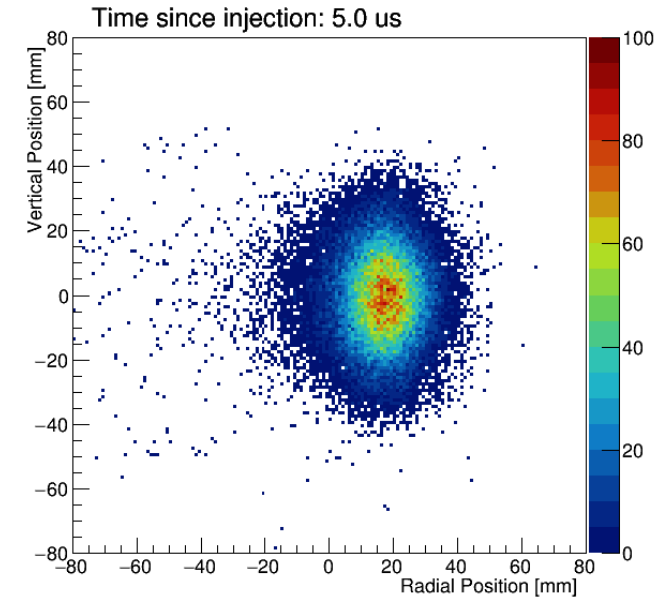


Finally: subtract merged event and add single events



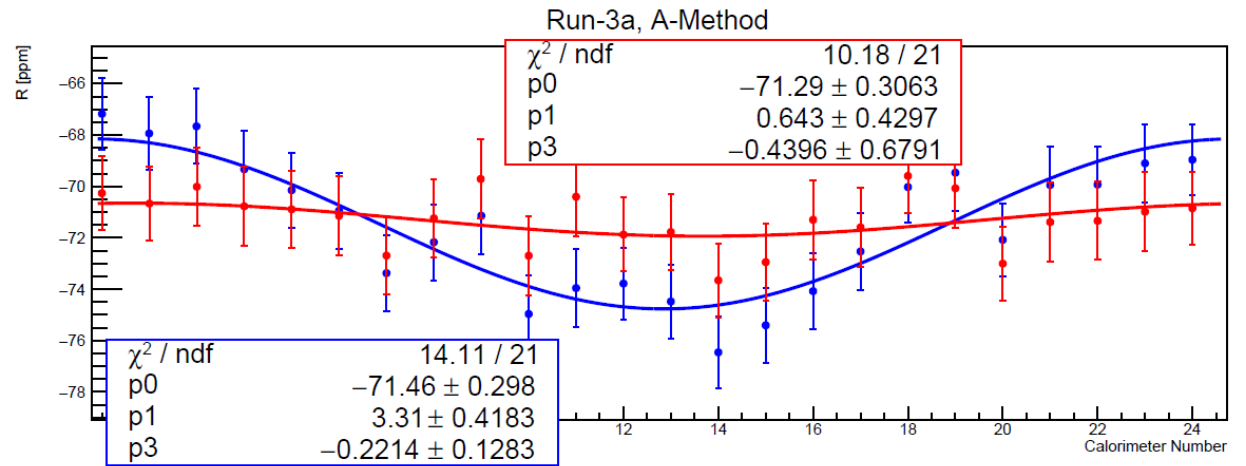
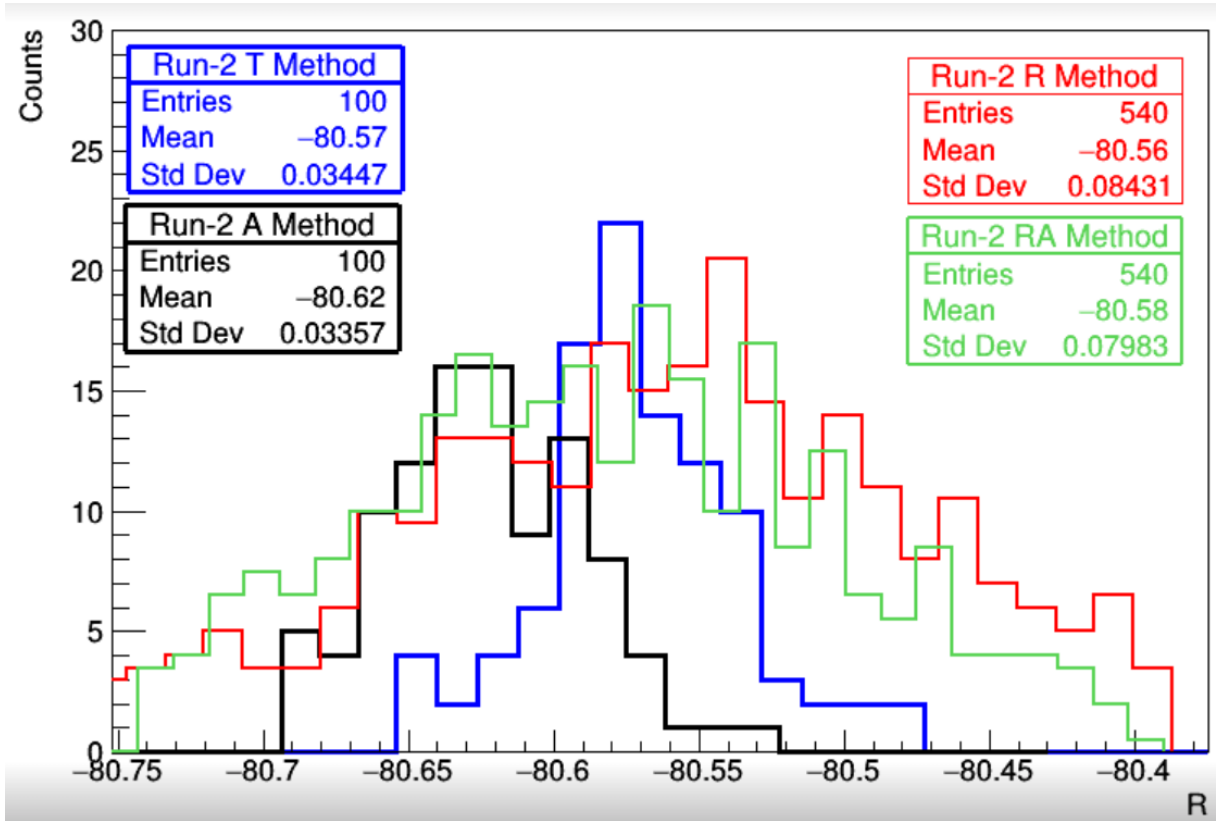
Radial and vertical motion of the beam

- Field index: n (quad voltages)
- Radial motion of the beam: $\omega_x = \omega_C \sqrt{1 - n}$
- CBO is the aliased frequency $\omega_{CBO} = \omega_C - \omega_x$
- CBO period of about $2.7 \mu\text{s}$



Quantity	Expression	Frequency		Period [ns]
		[MHz]	[rad/ μs]	
ω_a	$ea_\mu B/m$	0.23	1.439	4365
ω_C	v/R_0	6.7	42.0	149.2
ω_x	$\omega_C \sqrt{1 - n}$	6.3	39.7	158.0
ω_y	$\omega_C \sqrt{n}$	2.2	13.8	454.2
ω_{CBO}	$\omega_C - \omega_x$	0.37	2.33	2686
ω_{VW}	$\omega_C - 2\omega_y$	2.3	14.4	435.3

Randomization

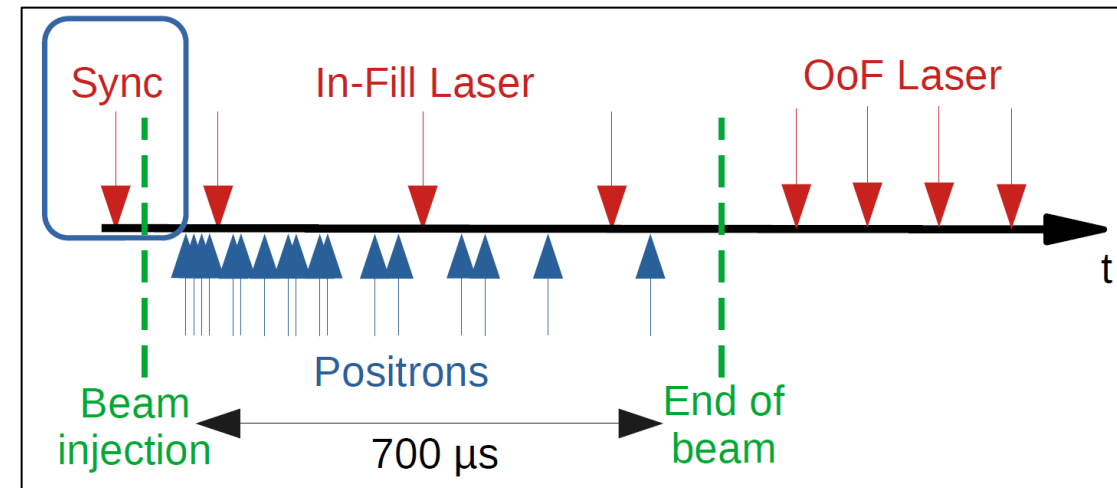


Laser-based gain monitoring system

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 $700 \mu\text{s}$ of μ^+ beam
- **Out-of-Fill pulses:** monitor stability over days



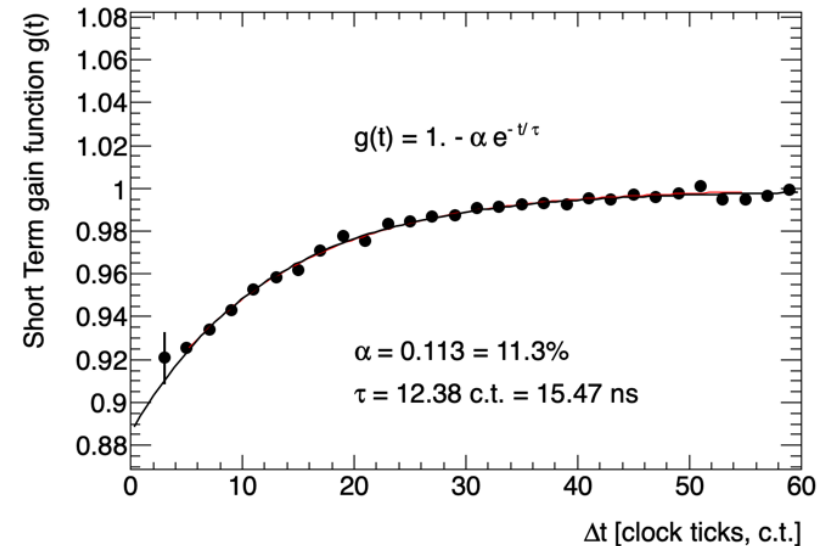
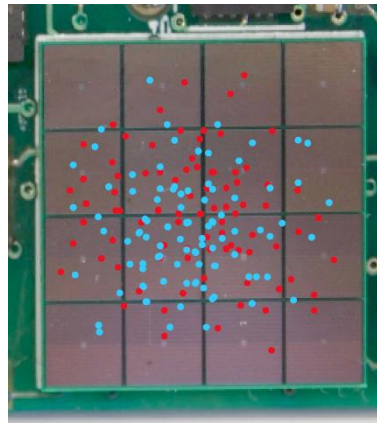
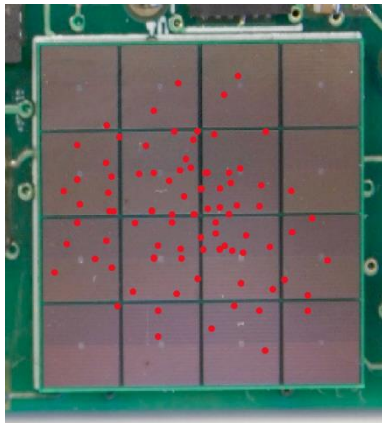
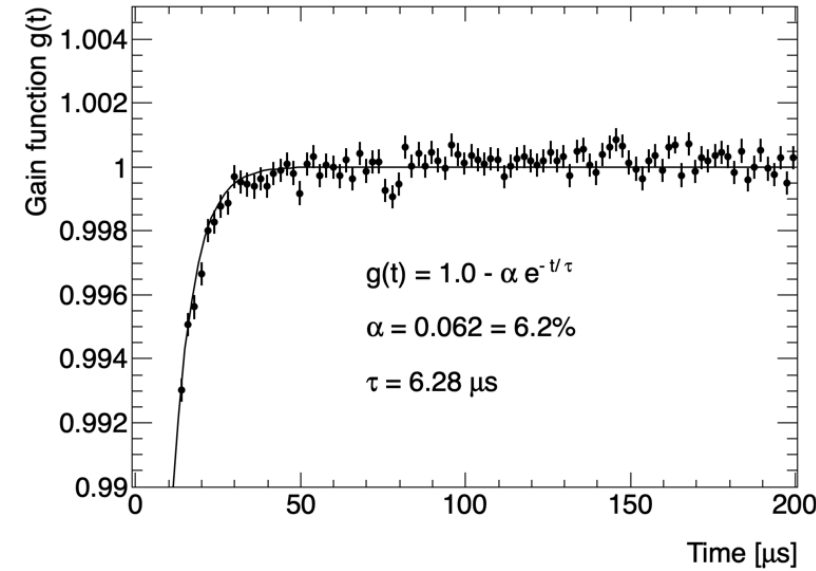
SiPM gain calibration

In-Fill: sag in power supply due to initial injection splash.

Recovery timescale of front-end electronics: $\mathcal{O}(10 \mu\text{s})$.

Short-term: consecutive positron hits within $\mathcal{O}(100 \text{ ns})$.

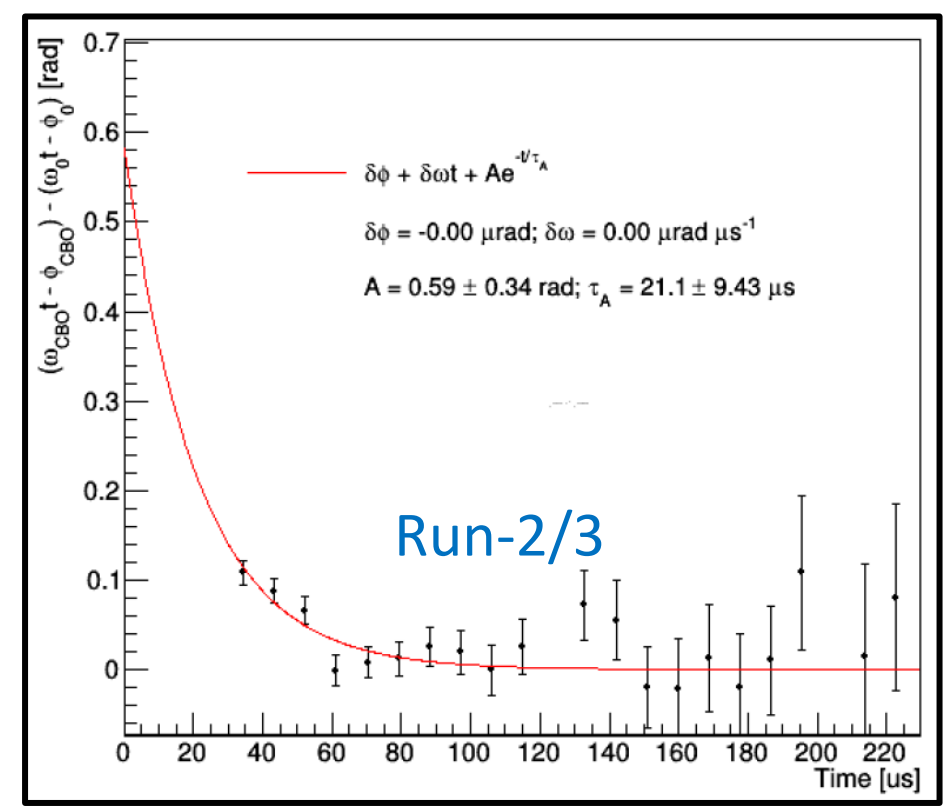
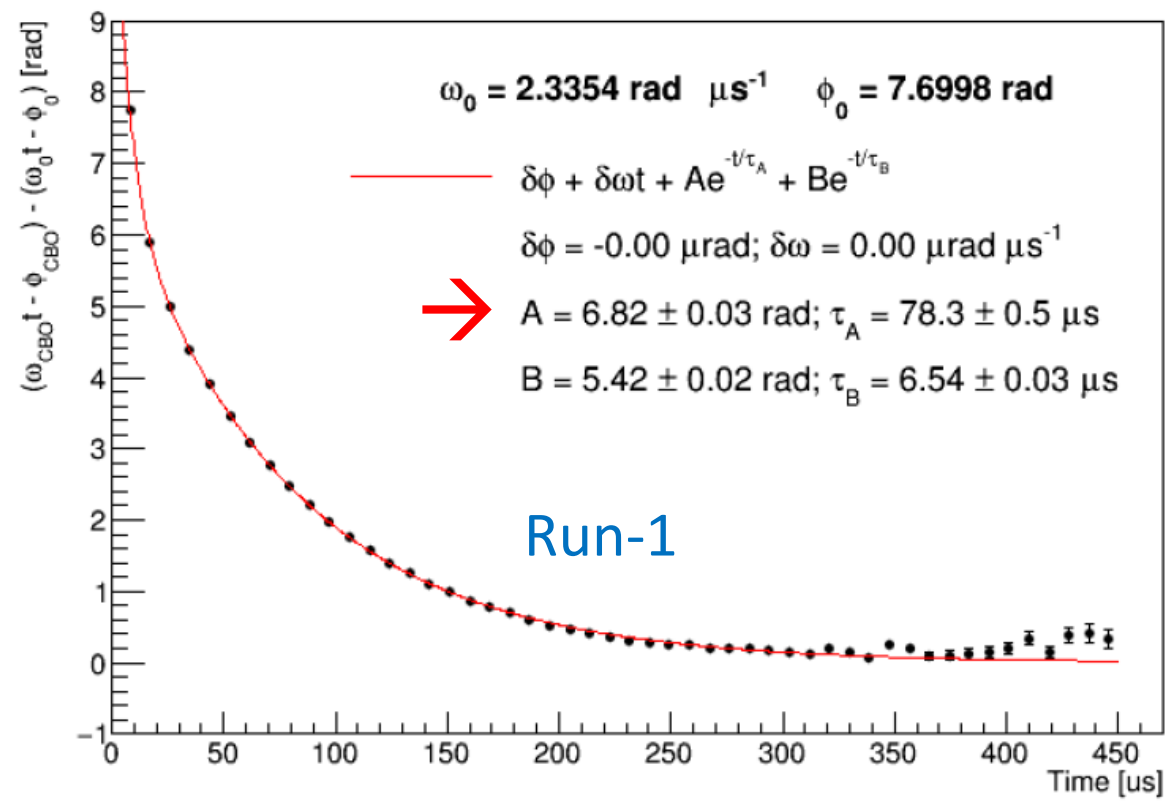
After the first hit, the recovery time of pixels reduce the gain experienced by the second hit.



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

CBO model: frequency vs time

- 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



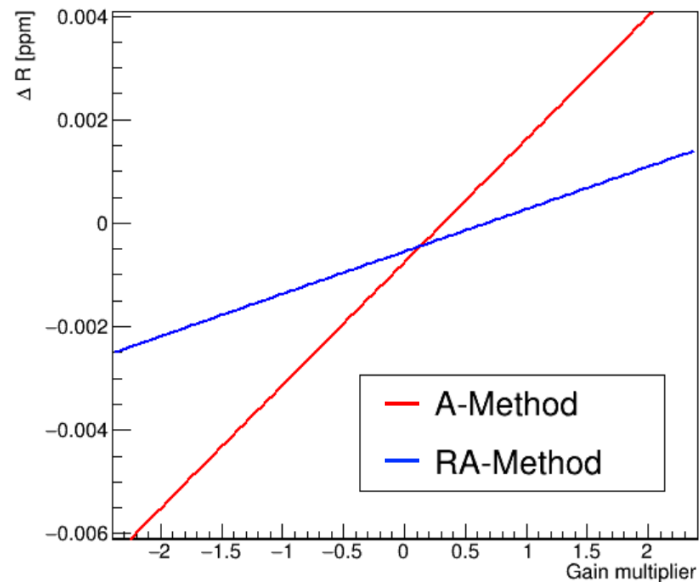
Run-4/5/6: current status and puzzles

- With much more statistics, we can investigate the residual slow term
 - energy leakage in calorimeters?
 - reconstruction effect?
- Further improved reconstruction with new pulse fitting technique
- Task forces in place to address dominating Run-2/3 systematics
- Quadrupole Radio-Frequency switched on during Run-5, to highly reduce radial and vertical motion of muons → more stable beam dynamics and much fewer lost muons!

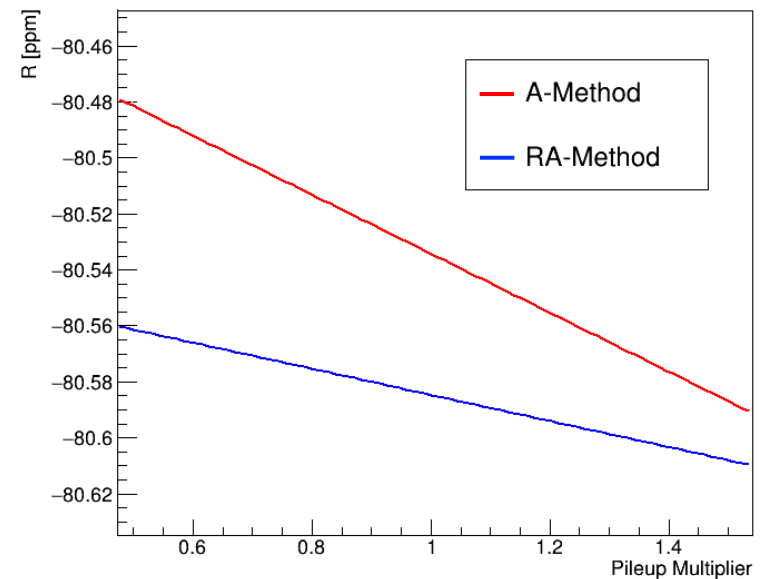
«Slow» effects: ratio vs non-ratio

$$\frac{d\langle p \rangle}{dt} \neq 0 \rightarrow \frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a} \cdot \frac{d\langle \varphi \rangle}{dt} = \frac{1}{\omega_a} \cdot \frac{d\langle \varphi \rangle}{d\langle p \rangle} \cdot \frac{d\langle p \rangle}{dt} \neq 0$$

$$\varphi(t) = \varphi(0) + \dot{\varphi}t + \dots \rightarrow \omega_a t + \varphi(t) = (\omega_a + \dot{\varphi})t + \dots$$



Gain calibration



Pileup

