Muon g-2 E989 at Fermilab: current and future activities in Italy

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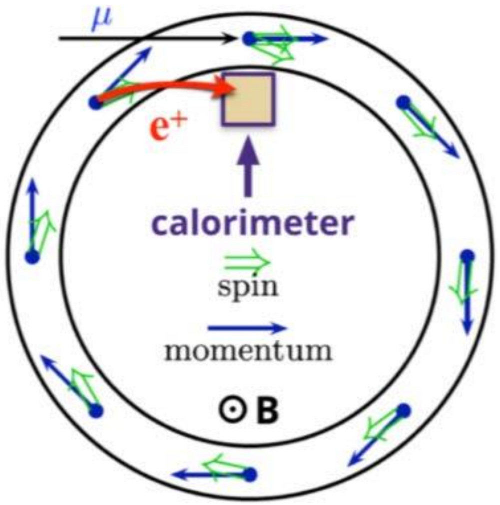
Workshop on Muon Precision Physics – Liverpool, 09/11/2022

I’ll talk about several different things…

- ω_a precession frequency analysis
- Laser monitoring system
- ReconITA reconstruction
- Beam dynamics corrections
- Transient fields: magnetometer

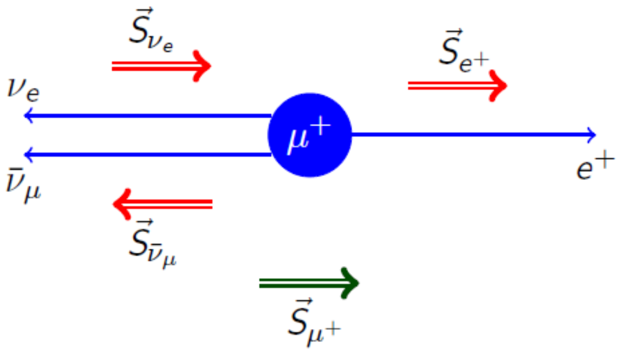
ω_a precession frequency

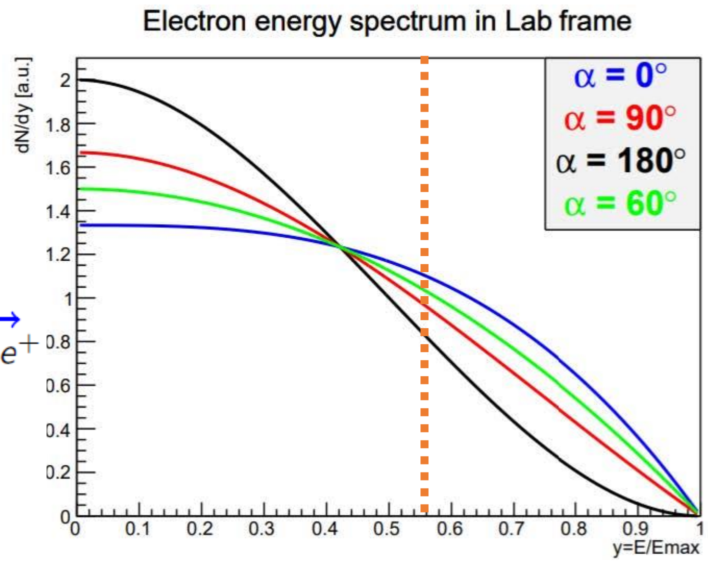


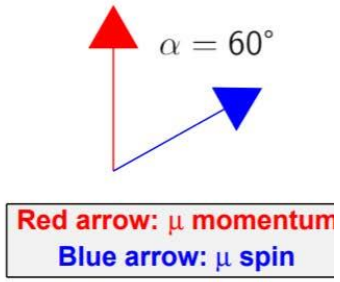
$$\frac{g-2}{2} \equiv a_\mu \neq 0$$

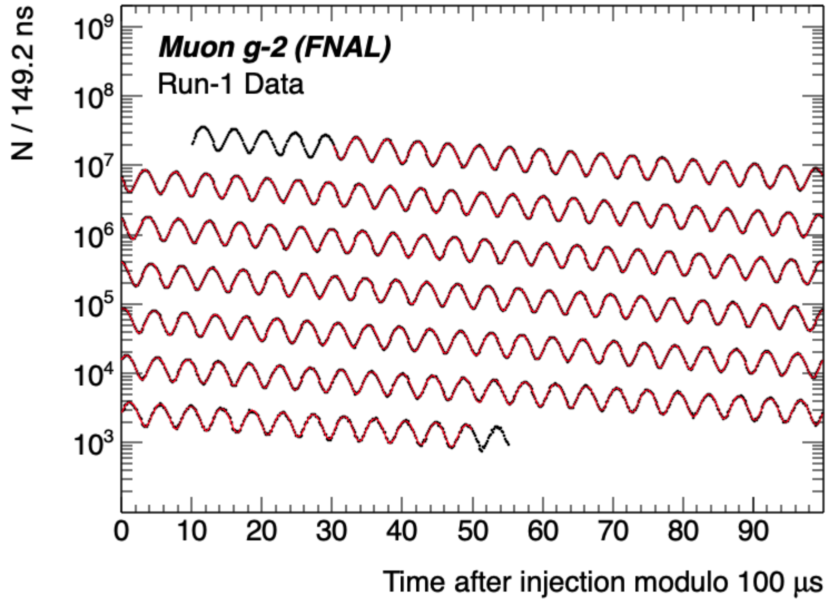
$$\omega_s - \omega_c \equiv \boxed{\omega_a} = a_\mu \cdot \frac{e\boxed{B}}{mc}$$

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



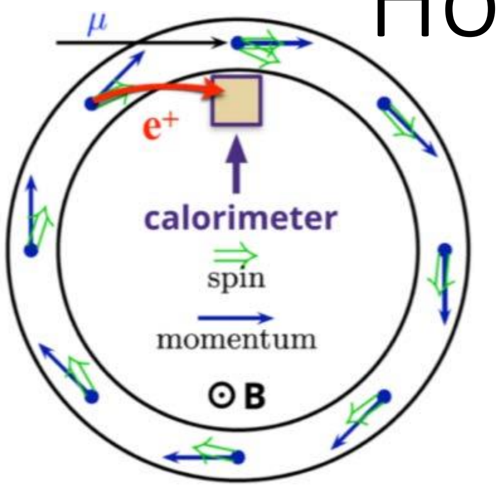


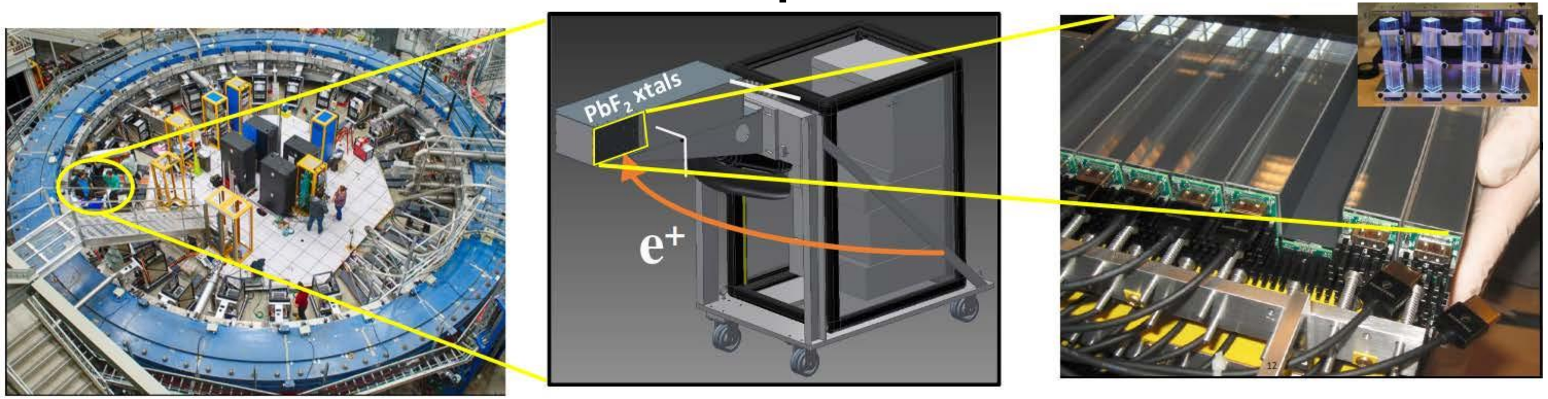




Wiggle plot: count high-energy positrons over time

How can we detect positrons?





- 24 homogeneous electromagnetic calorimeters: arrays of 9×6 $\mathrm{PbF_2}$ crystals, with refractive index $n = 1.8$, which are 14 cm $(15\ \mathrm{X_0})$ long
- Positrons travel faster than light in the crystals: we detect Cherenkov light produced by the e.m. shower
- Each crystal is coupled to a SiPM working in Geiger mode: their gain is sensitive to many effects (e.g. temperature) and must be monitored at high precision to reduce systematics → laser system

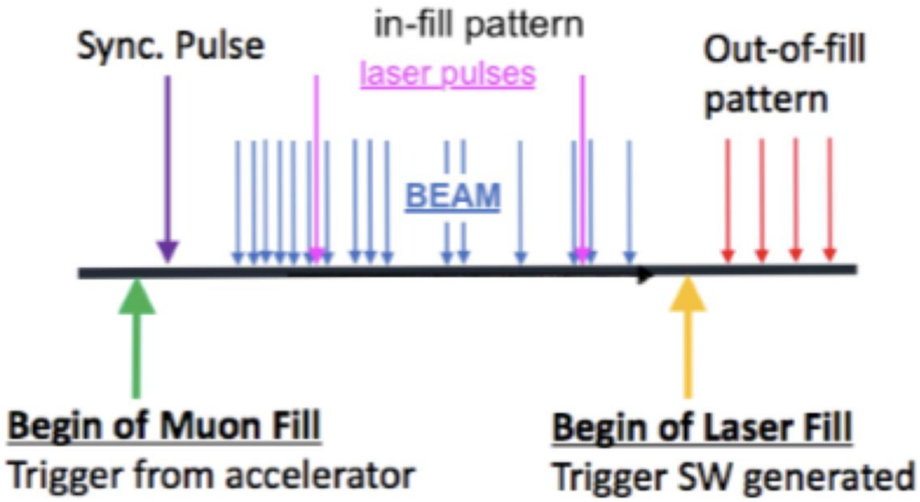
Laser-based gain monitoring system

A. Anastasi *et al* 2019 JINST **14** P11025

It is able to correct SiPM’s gain fluctuations at timescales from ns to months: calibration at 0.04% level during fill time (i.e. $700\mu\text{s}$ in which muons are stored)

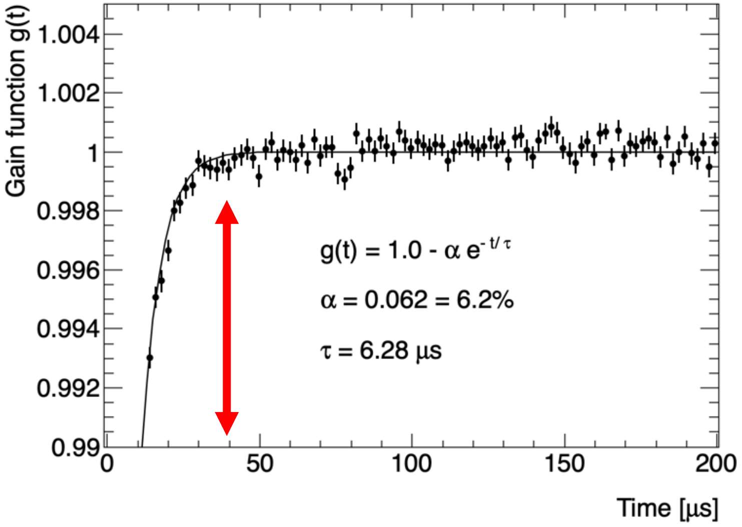
Standard operating mode:

- **Sync. pulse**: time synchronization of 1296 SiPMs at 0.1 ns
- **In-Fill pulses**: series of laser pulses during μ^+ storage time, for rate-dependent fluctuations
- **Out-of-Fill pulses**: 4 laser shot in the time gap between fills, which monitor the stability over days and normalize In-Fill pulses



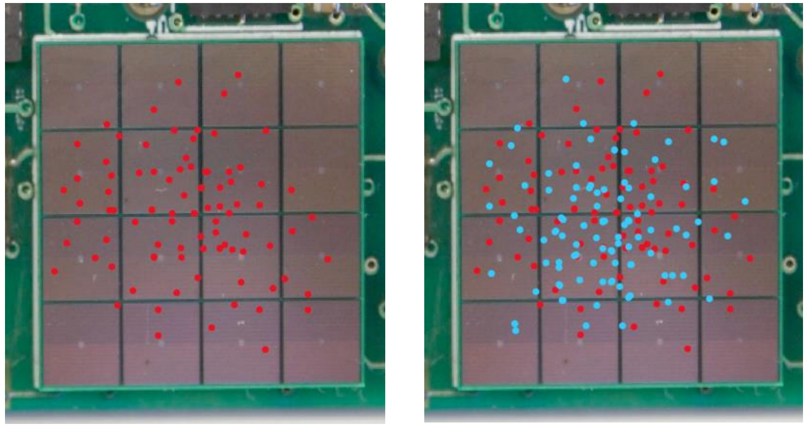
Gain fluctuations during fill time

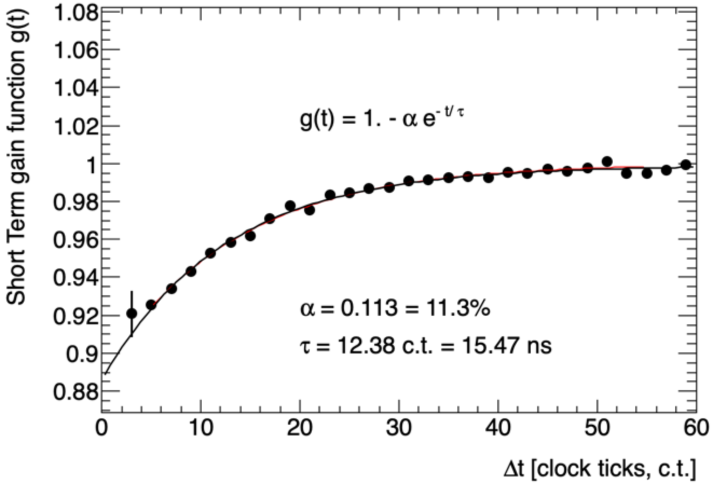
- **In-Fill**: SiPMs have a gain sag due to charge depletion after injection splash.
  Timescale: $\mathcal{O}(10\ \mu\text{s})$. Correction at $t = 0$: 1%-20%



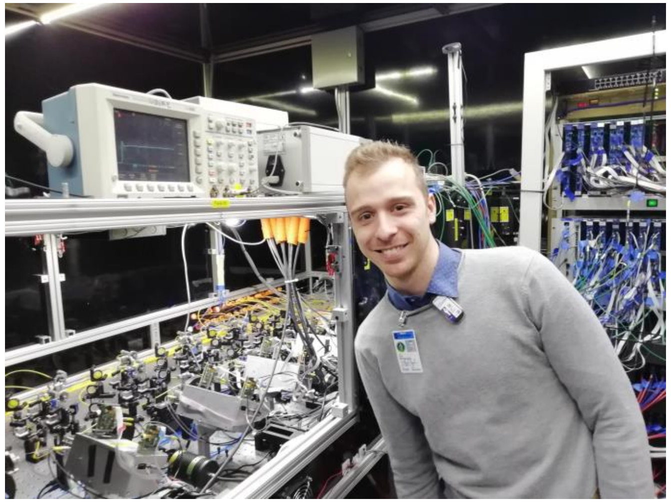
- **Short-term**: close, within $\mathcal{O}(100\ \text{ns})$ consecutive positron hits. After the first hit, the recovery time of the SiPM and amplifier reduce the gain experienced by the second hit

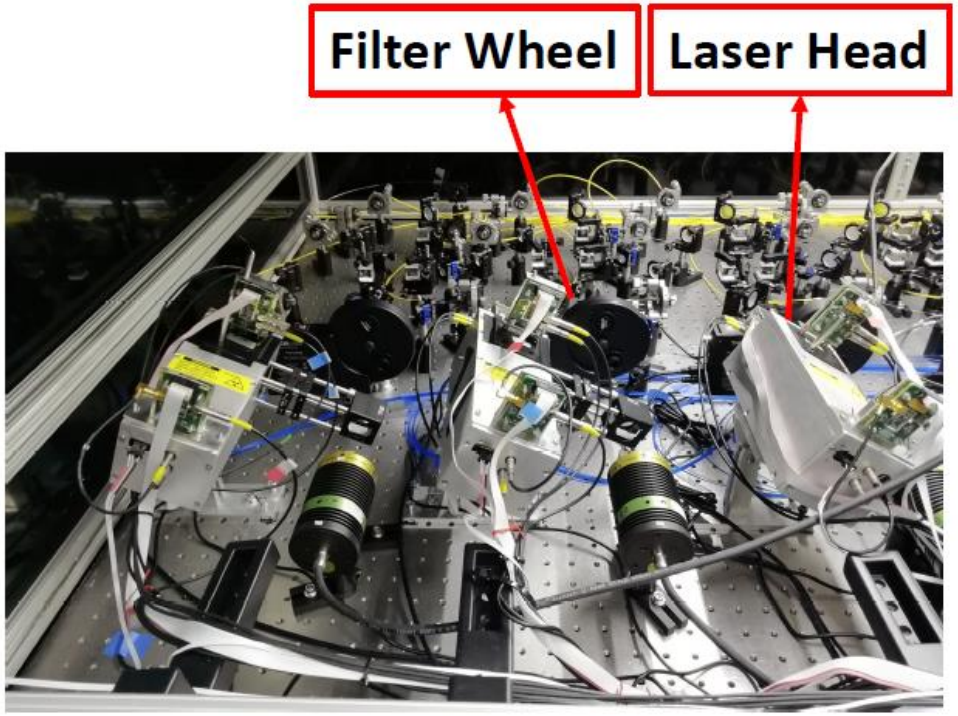
16-channel SiPM, 54k pixels
About 10^3 photons per positrons, 1 photon per MeV





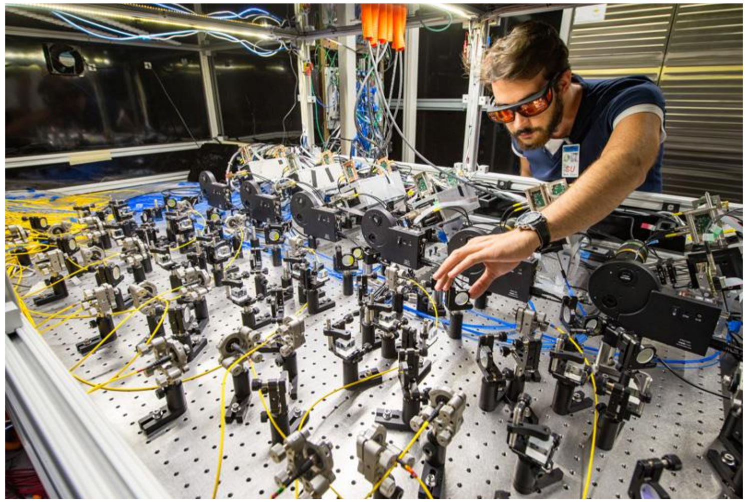
Some pictures from the laser hut

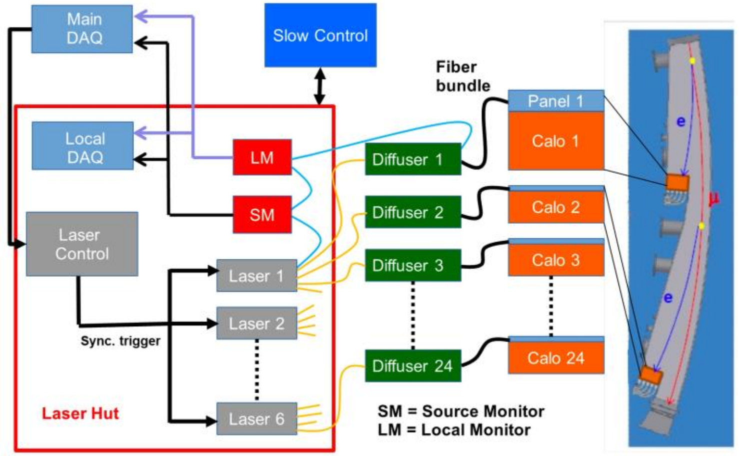




<u>Source monitor</u>: 2 PIN diodes at laser heads

<u>Local monitors</u>: 2 PMTs read the signal sent to calorimeters

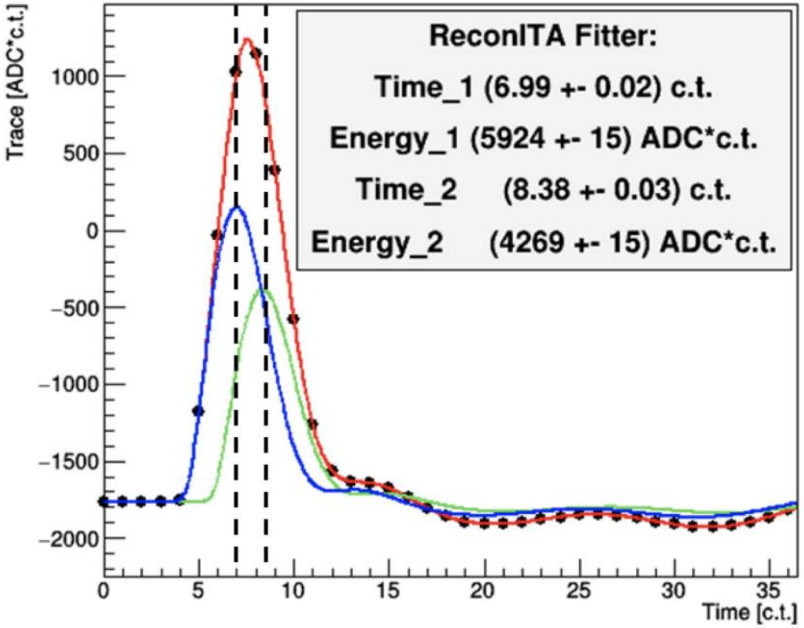


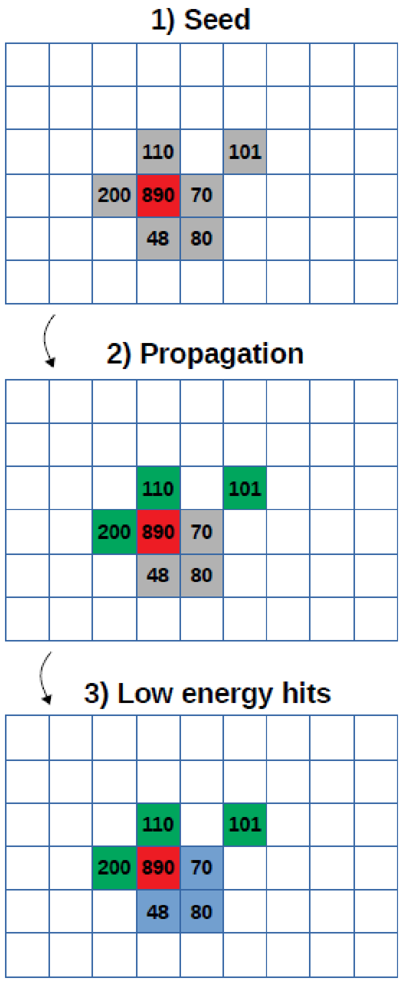


SM = Source Monitor
LM = Local Monitor

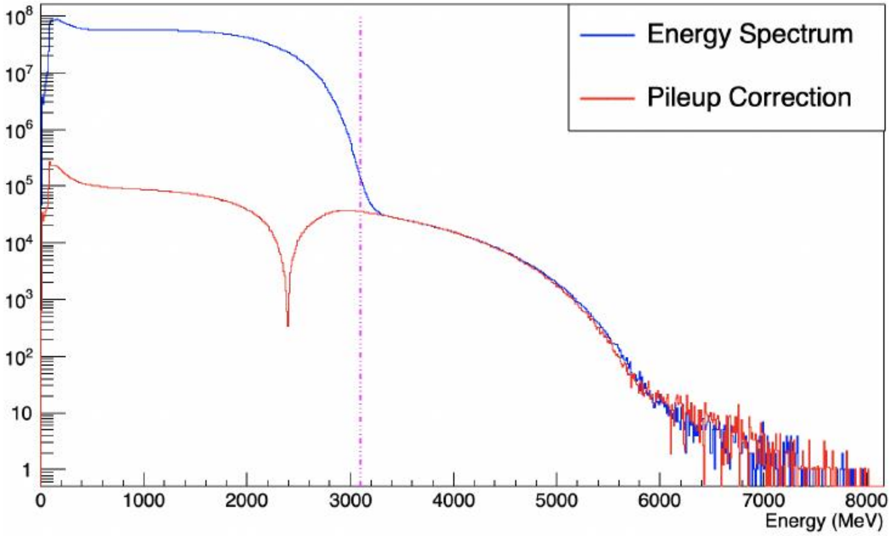
Positron reconstruction: reconITA

Positron traces: resolve pileup better than Run-1 (35 ppb)





- New pulse fitter and clustering
- Semi-empirical pileup subtraction of double and triple coincidences: takes fitter efficiency into account
- Goal for Run-2/3: reduce pileup systematics by factor of 2

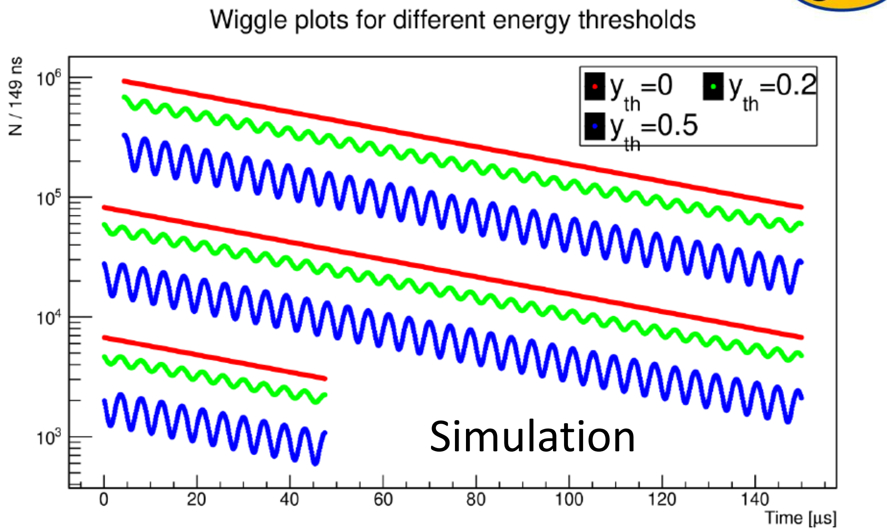


P. Girotti's PhD Thesis

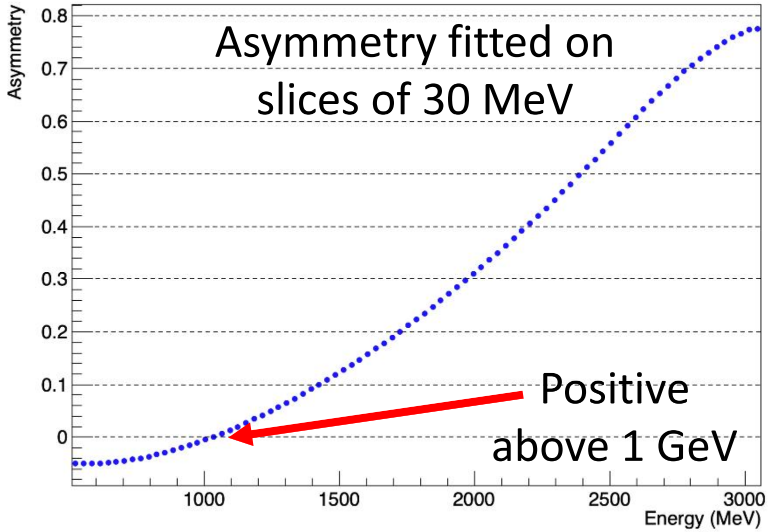
Different methods for ω_a analysis

T-Method: count all positrons above fixed energy treshold. Which threshold? Compromise between statistics and sensitivity to $\omega_a \Rightarrow 1.7$ GeV.

Plot on the right: y_{th} is energy normalized by 3 GeV. $y_{th} = 0$ → max statistics, but no oscillation. Higher y_{th} → less statistics, larger amplitude.



Simulation



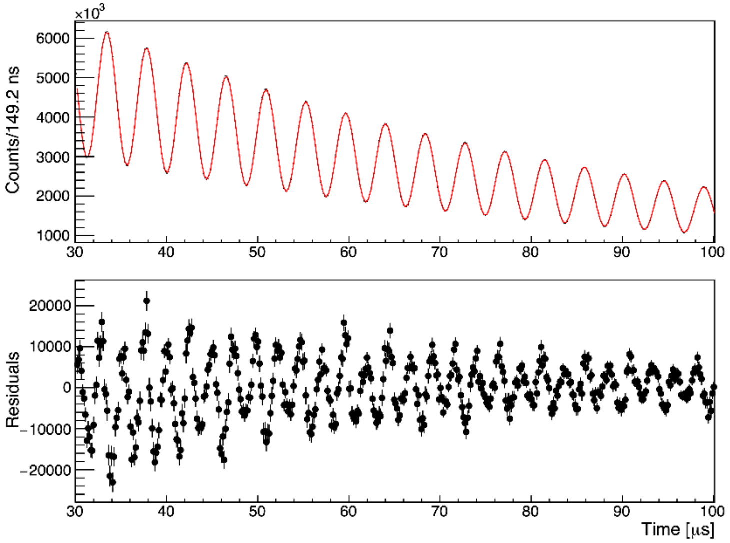
Asymmetry fitted on slices of 30 MeV

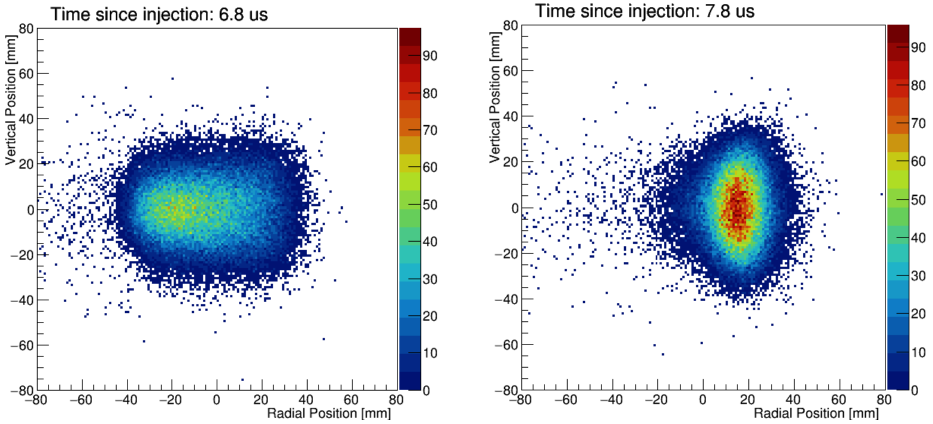
Positive above 1 GeV

A-Method: weight each positron with asymmetry function, to enhance statistical power of the analysis. Threshold of 1 GeV → more statistics, $\delta\omega_a$ 10% smaller than T-Method.

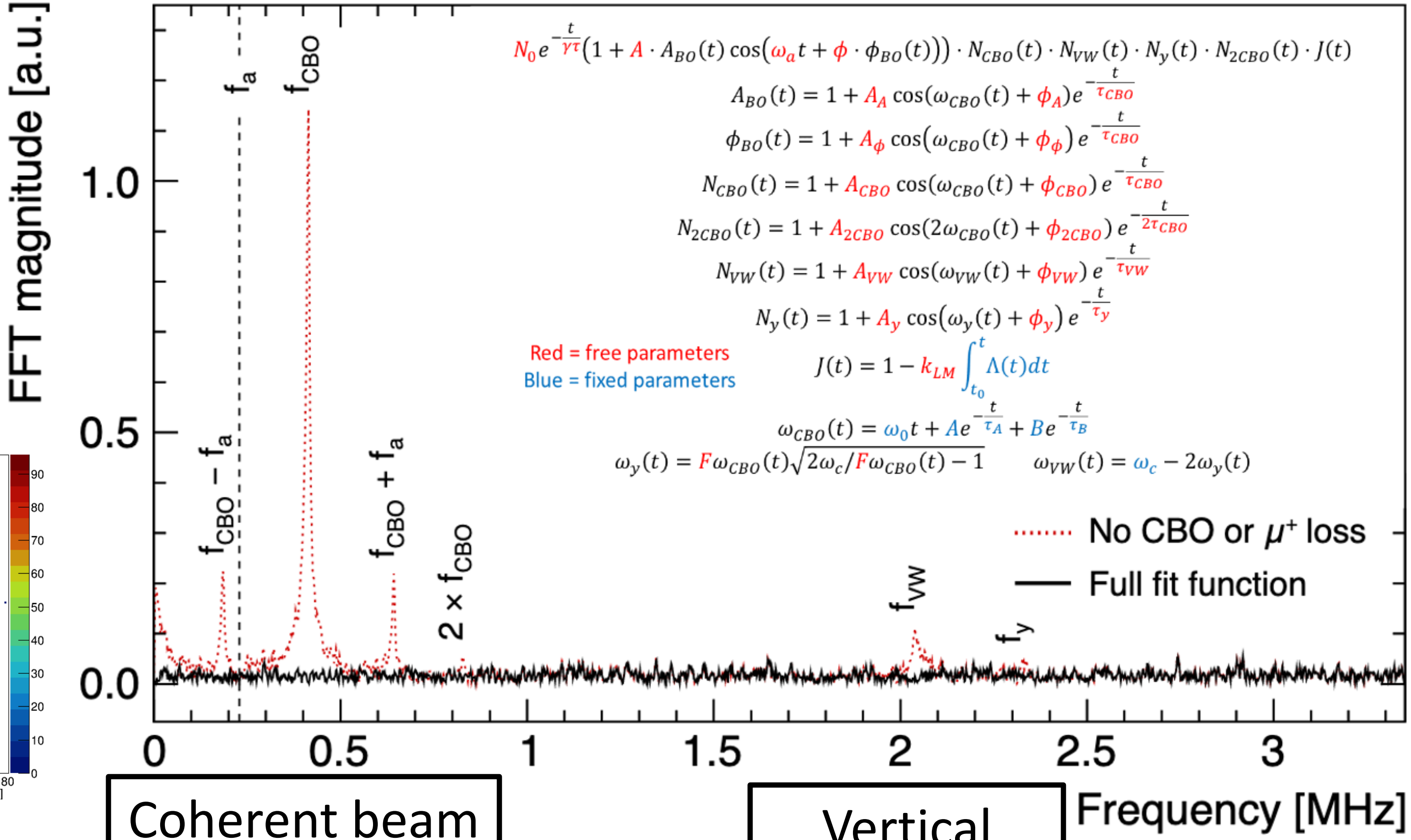
Run-1 was the combination of 4 A-Method analyses, but more methods had been developed.

ω_a complete fit (Run-1 function)





M. Sorbara's PhD Thesis



$$N_0 e^{-\frac{t}{\gamma\tau}}\left(1 + A \cdot A_{BO}(t)\cos\left(\omega_a t + \phi \cdot \phi_{BO}(t)\right)\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot N_y(t) \cdot N_{2CBO}(t) \cdot J(t)$$

$$A_{BO}(t) = 1 + A_A \cos(\omega_{CBO}(t) + \phi_A) e^{-\frac{t}{\tau_{CBO}}}$$

$$\phi_{BO}(t) = 1 + A_\phi \cos\left(\omega_{CBO}(t) + \phi_\phi\right) e^{-\frac{t}{\tau_{CBO}}}$$

$$N_{CBO}(t) = 1 + A_{CBO} \cos(\omega_{CBO}(t) + \phi_{CBO}) e^{-\frac{t}{\tau_{CBO}}}$$

$$N_{2CBO}(t) = 1 + A_{2CBO} \cos(2\omega_{CBO}(t) + \phi_{2CBO}) e^{-\frac{t}{2\tau_{CBO}}}$$

$$N_{VW}(t) = 1 + A_{VW} \cos(\omega_{VW}(t) + \phi_{VW}) e^{-\frac{t}{\tau_{VW}}}$$

$$N_y(t) = 1 + A_y \cos\left(\omega_y(t) + \phi_y\right) e^{-\frac{t}{\tau_y}}$$

Red = free parameters
Blue = fixed parameters

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

$$\omega_{CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

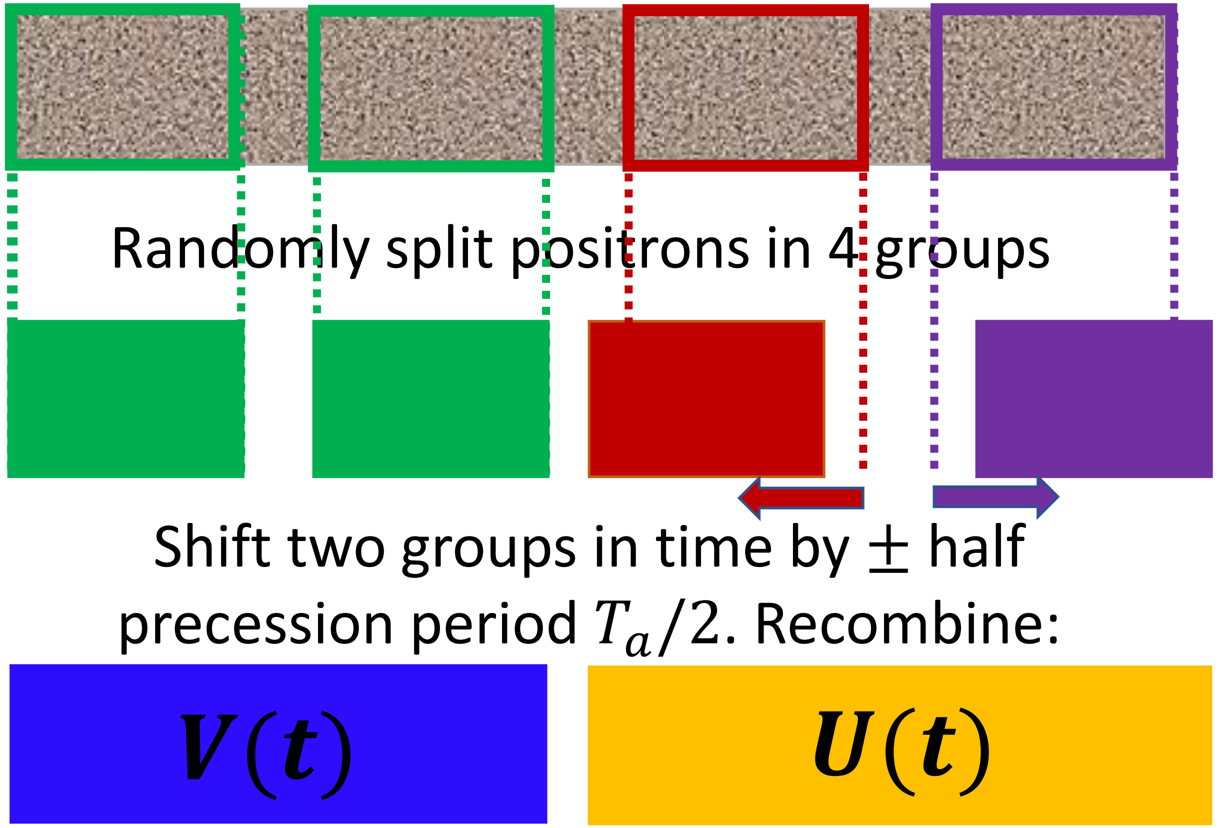
$$\omega_y(t) = F\omega_{CBO}(t)\sqrt{2\omega_c / F\omega_{CBO}(t) - 1} \qquad \omega_{VW}(t) = \omega_c - 2\omega_y(t)$$

Coherent beam oscillation

Vertical oscillation

Ratio method

My PhD Thesis

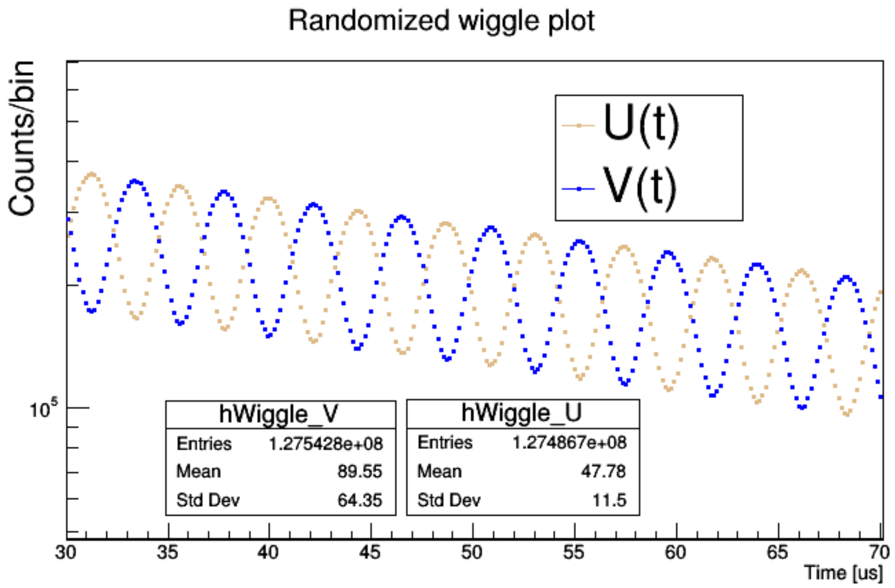


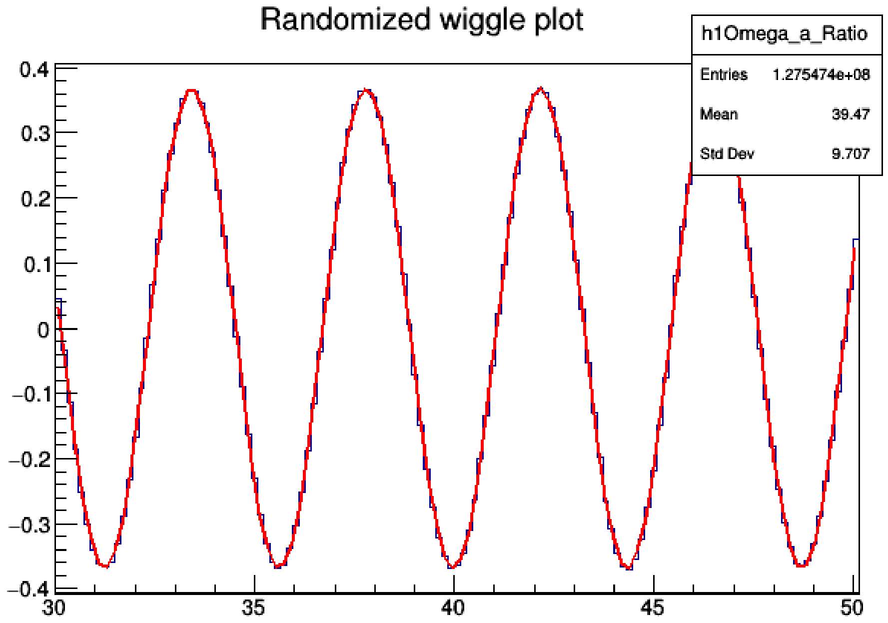
Randomly split positrons in 4 groups

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

$R(t) \equiv \frac{V(t)-U(t)}{V(t)+U(t)}$: reduces slow terms (e.g. μ decay)

If: we weight each e^+ by asymmetry → RA-Method





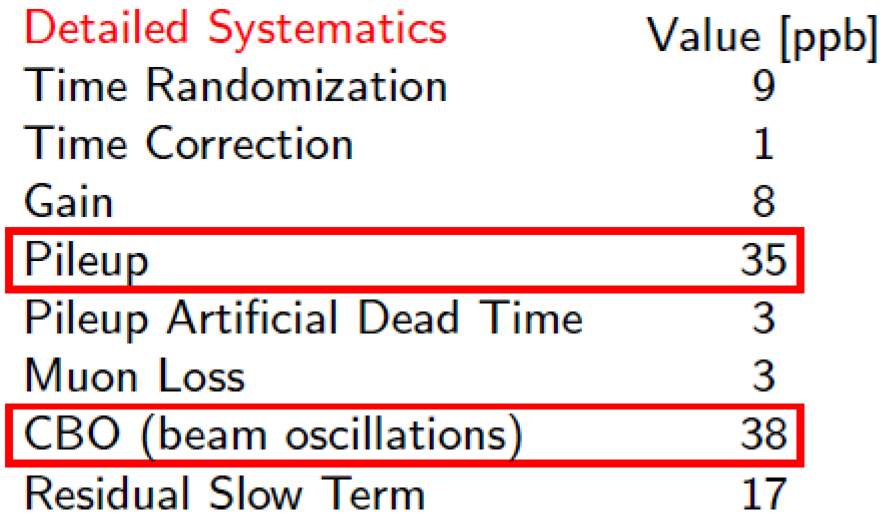
Systematic effects on ω_a

My PhD Thesis

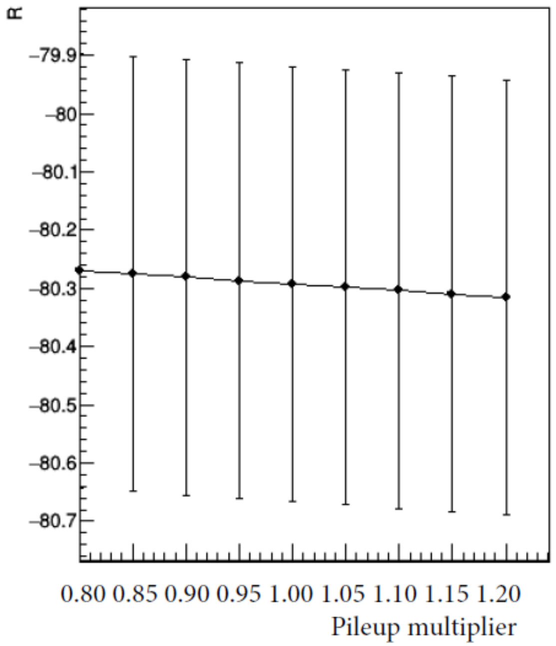
Run-1: total systematic on ω_a amounted to 56 ppb, where the biggest contributions were CBO and pileup

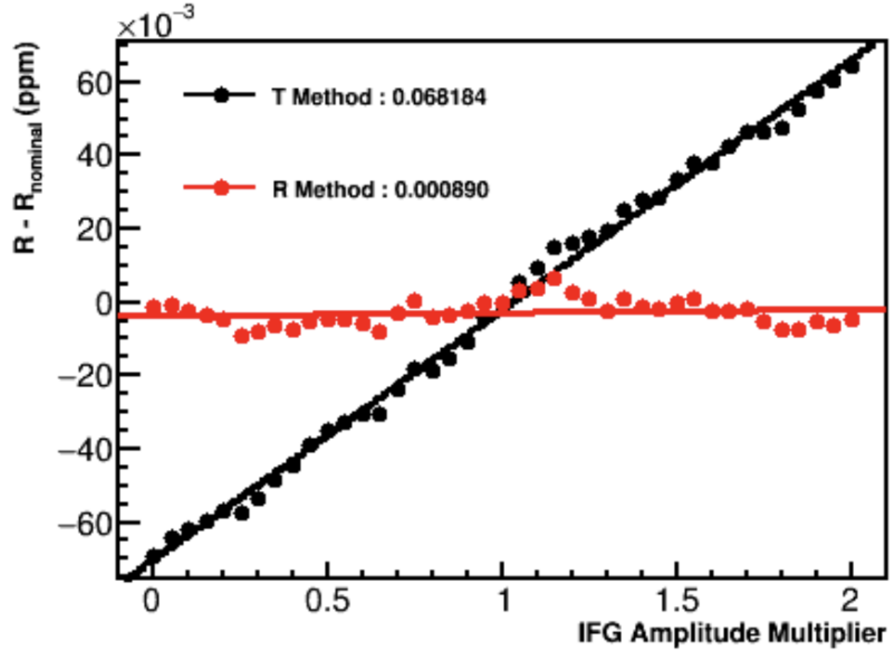
Run-2/3: we expect reduction thanks to hardware and software improvements

Ratio-Method less sensitive to some effects than T-Method



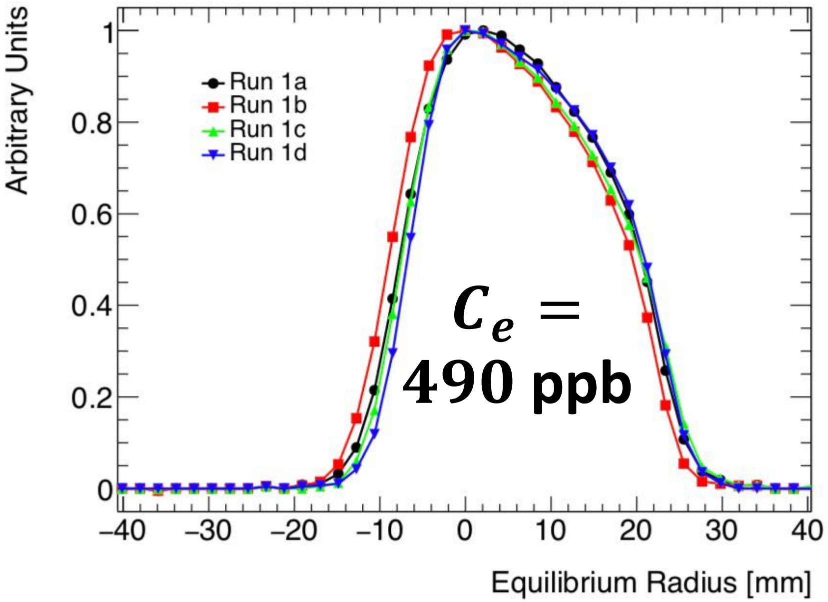
Detailed Systematics	Value [ppb]
Time Randomization	9
Time Correction	1
Gain	8
Pileup	35
Pileup Artificial Dead Time	3
Muon Loss	3
CBO (beam oscillations)	38
Residual Slow Term	17



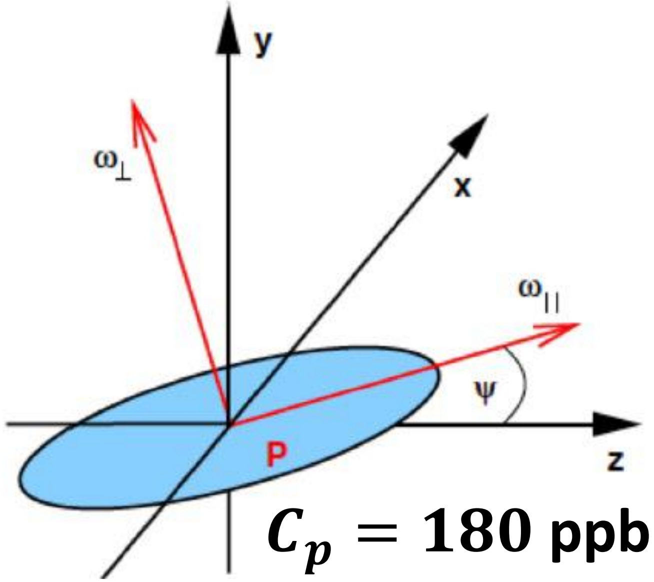


Beam dynamics corrections

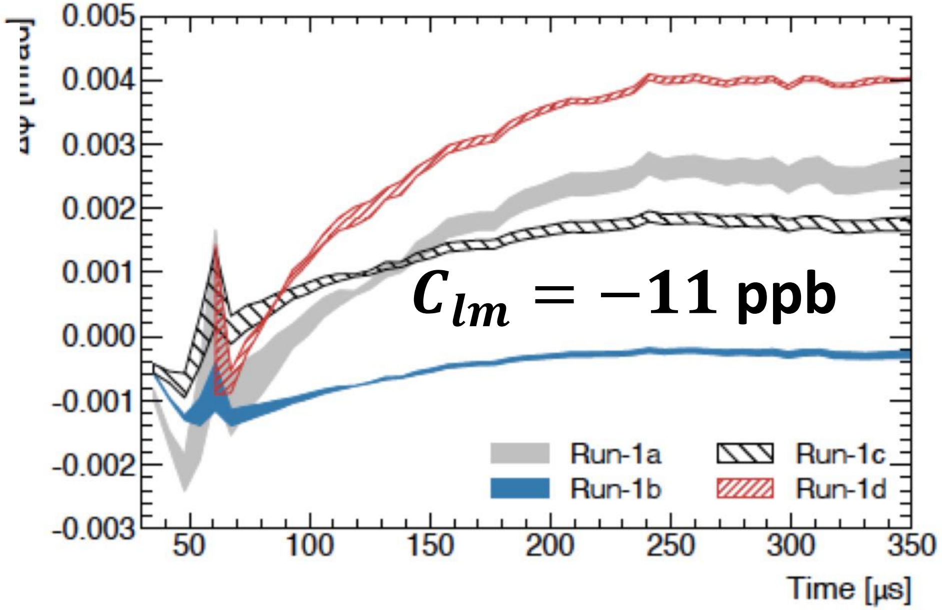
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{clock}\,\omega_a^m\left(1+\boxed{\boldsymbol{C_e}+\boldsymbol{C_p}+\boldsymbol{C_{lm}}+\boldsymbol{C_{pa}}}\;\right)}{f_{calib} < \omega'_p(x,y,\phi)\times M(x,y,\phi) > \left(1+B_k+B_q\right)}$$



$\boldsymbol{C_e} =$ **490 ppb**



$\boldsymbol{C_p} =$ **180 ppb**



$\boldsymbol{C_{lm}} = -11$ **ppb**

C_e: electric field corr. related to equilibrium radii distribution.

C_p: pitch corr. related to vertical oscillation of the beam.

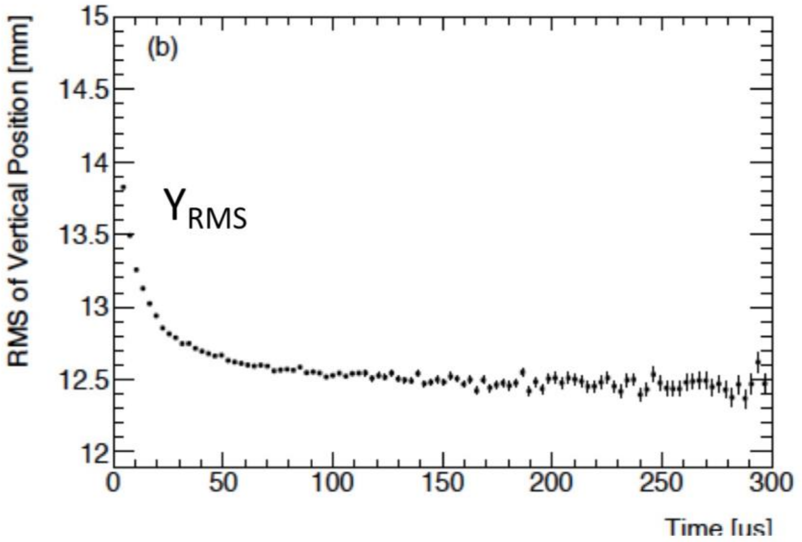
C_{lm}: momentum distribution of lost muons ↔ different phases lost.

Beam dynamics: Phase Acceptance

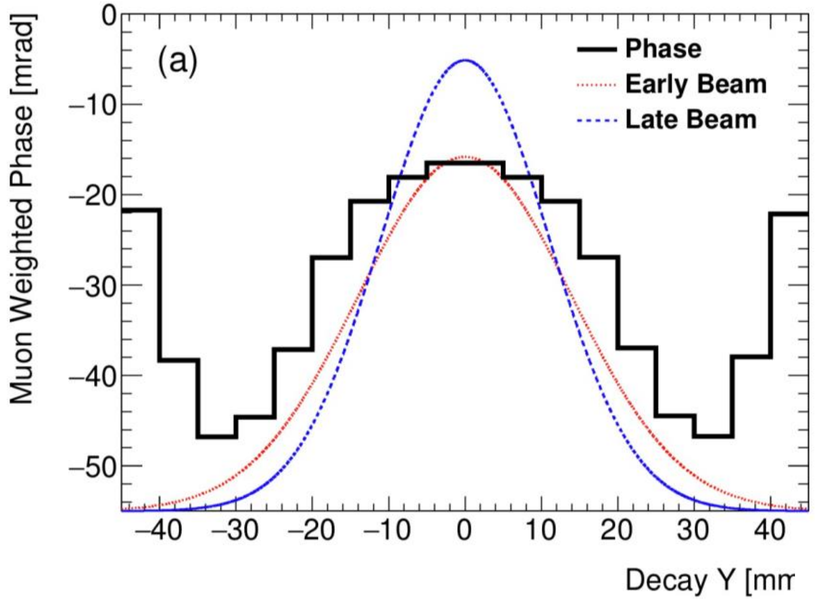
1. Beam profile changes over muon fill
2. The measured ω_a phase changes as a function of the decay position
3. $C_{pa} = \frac{dY_{RMS}}{dt} \cdot \frac{d\varphi}{dY_{RMS}} = -158 \pm 75$ ppb

Large correction, with the largest systematic uncertainty amongst the beam dynamics corrections in Run-1: there were broken ESQ resistors which enhanced the effect, and which were fixed in Run-2/3.

Elia’s PhD thesis: determination of C_{pa} for Run-1 and Run-2/3 (next publication).



$$\frac{dY_{RMS}}{dt}$$



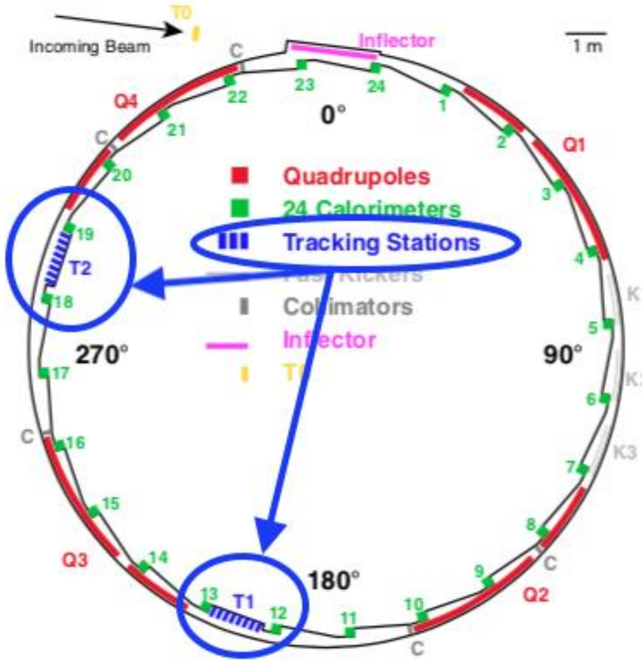
$$\frac{d\varphi}{dY_{RMS}}$$

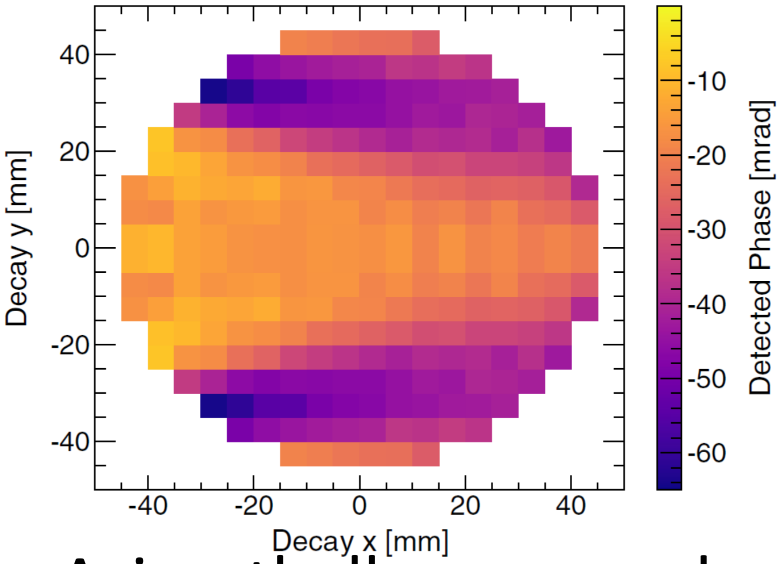
Simulation for Phase-Acceptance

Time-dependence of beam spatial distributions are measured by two tracker stations (blue circles)

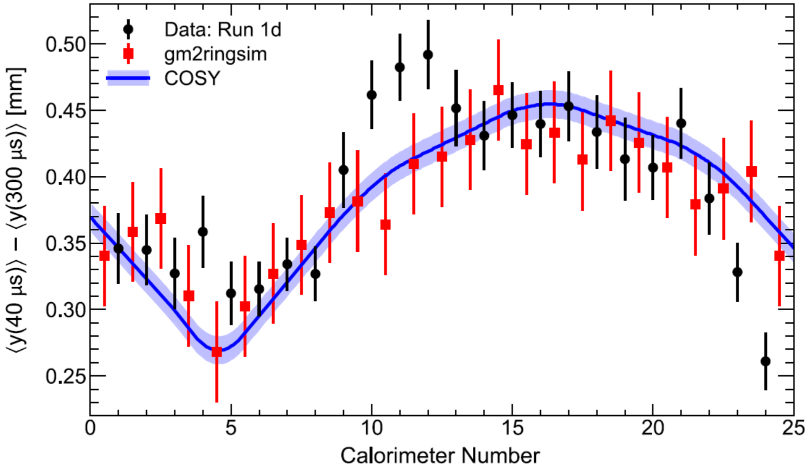
Geant-4 based simulation of storage ring (from injection to detection): extrapolate beam profiles around the ring

A. Driutti's and simulation group's work





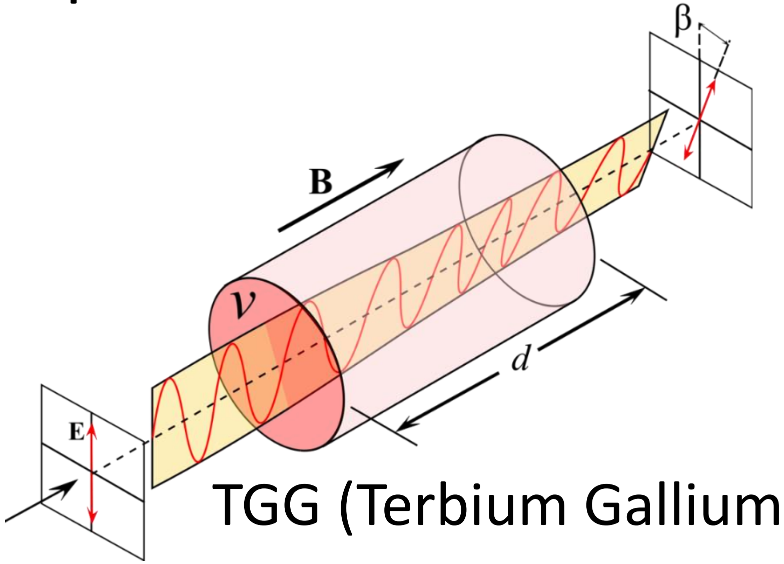
Azimuthally-averaged phase maps



Vertical distribution

Transient kicker field

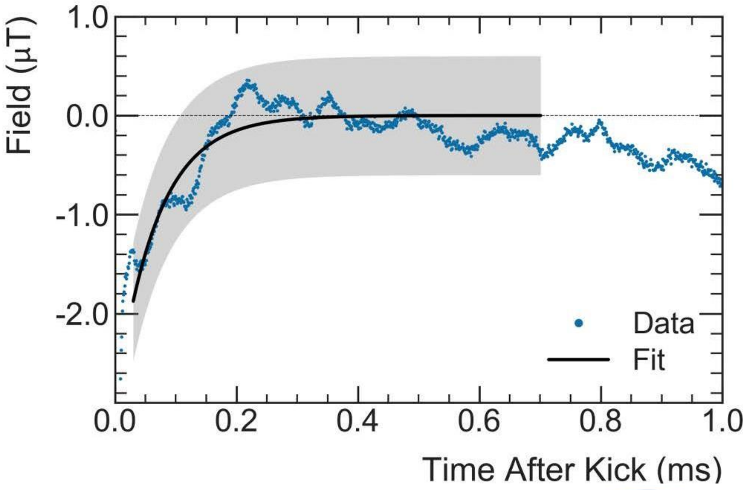
- Kicker magnetic pulses induce eddy currents in nearby metal, affecting the field experienced by stored muons
- We need to measure residual kicker field during 1 ms of data: aiming at a few mG sensitivity over 1.45 T constant field
- «Faraday rotation»: in a magnetic field, left and right circular polarizations experience different refraction; polarization of light is rotated by θ:



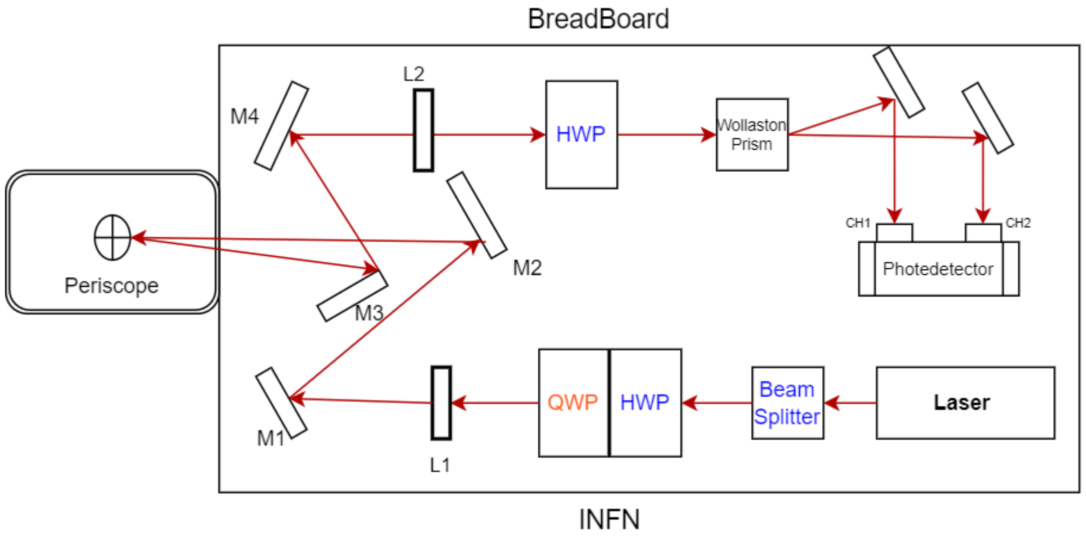
$$\theta = VBd$$

V: Verdet constant ~ 450 rad/Tm
B: magnetic field
d: crystal length

TGG (Terbium Gallium Garnet) crystal

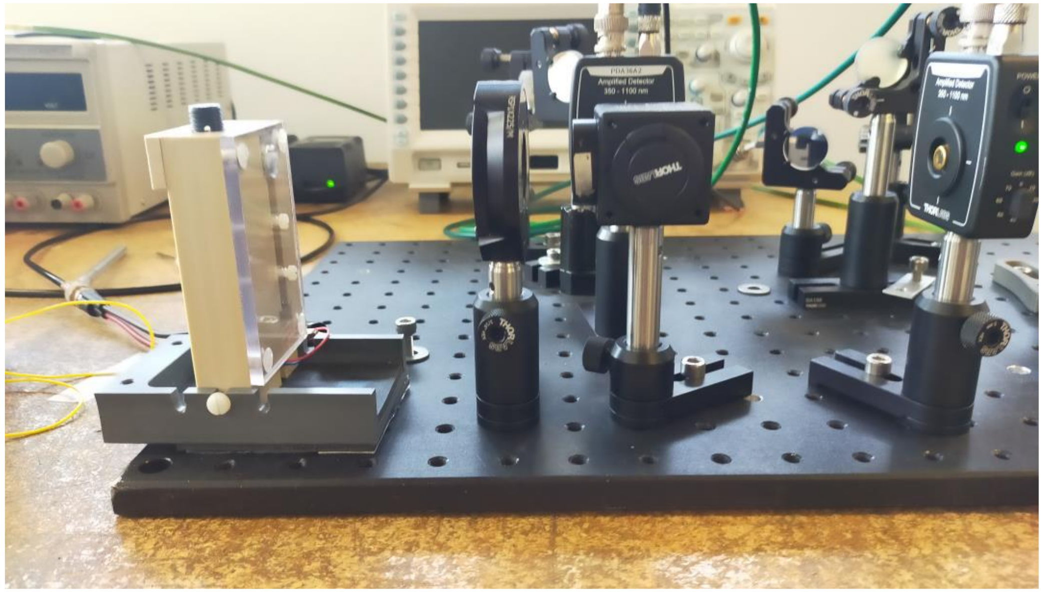


INFN magnetometer



Summer 2022 campaign:

- Involvement of summer student at FNAL
- Installation successful, the acquired data was analyzed



What's next?

- Preparing next campaigns
- Technological development to mitigate vibrations of the apparatus
- Assess systematic uncertainty

Summary and conclusions

- Laser monitoring system is the major INFN contribution to E989
- Gain systematics are required to be < 20 ppb by TDR (improvement of factor 6 wrt previous BNL experiment). Since Run-1, we have reached a systematic below this goal → all under control
- Italian contributions to production setup, production and data analysis; systematic uncertainties on ω_a, beam dynamics and field transients; data quality checks; g-2 simulation that is the key to extract corrections, together with data
- Summer students: significant help in analysis and hardware development

THANKS! ANY QUESTIONS?

Paolo Girotti

Spin precession in a magnetic field

- $g > 2 \rightarrow$ spin precesses with anomalous frequency $\vec{\omega}_a = \vec{\omega}_{\text{spin}} - \vec{\omega}_{\text{cyclotron}}$

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

Spin precession in a magnetic field

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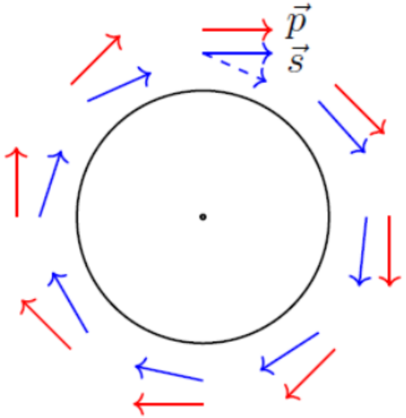
$$\boxed{\vec{\omega}_a = -\frac{e}{mc}\Big[a_\mu \vec{B}} - \xcancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}} - \xcancel{a_\mu \frac{\gamma}{\gamma + 1}\left(\vec{\beta} \cdot \vec{B}\right)\vec{\beta}}\Big]$$

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

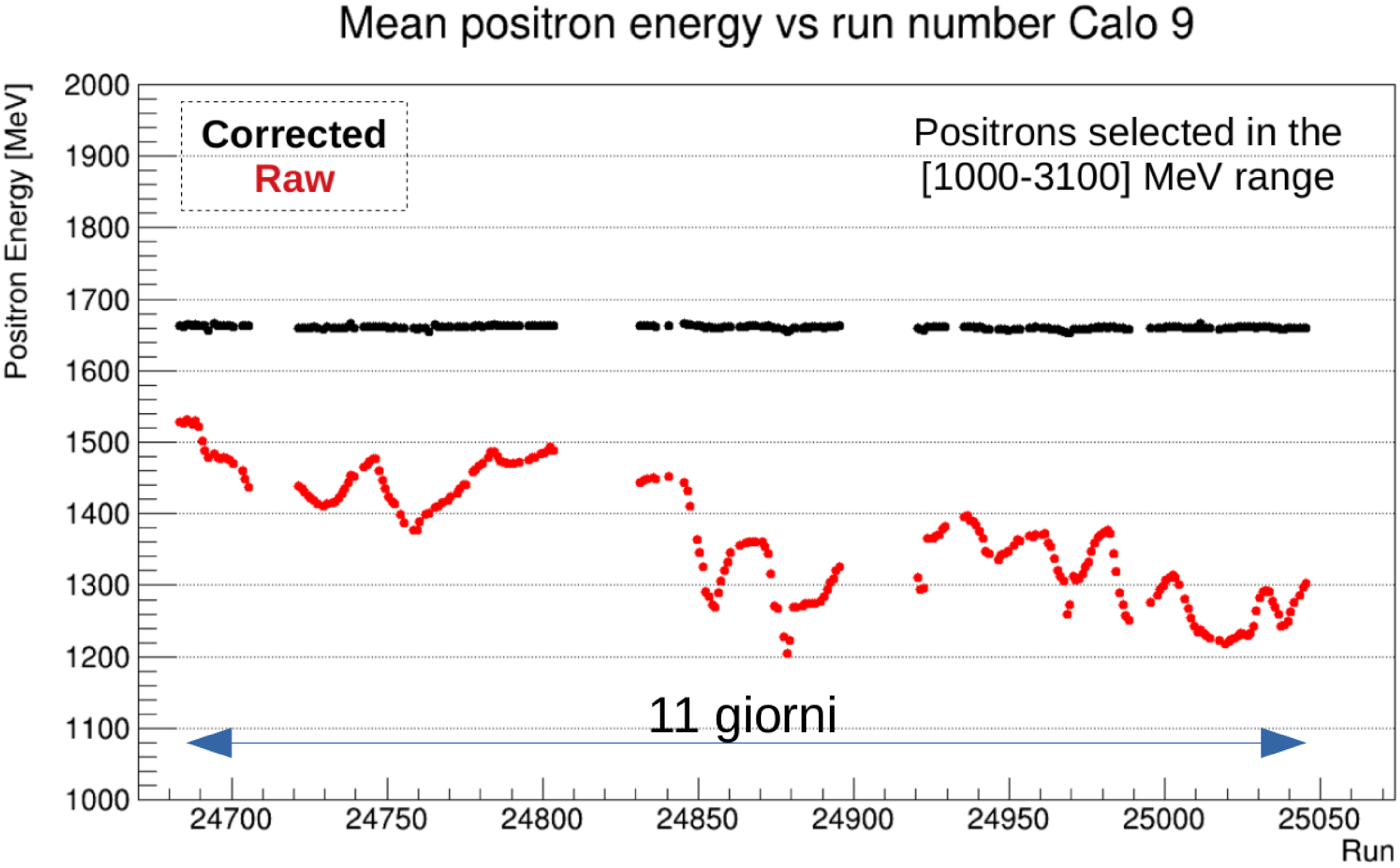
$\vec{\beta} \cdot \vec{B} = 0$

- $\omega_{\text{cyclotron}} = 42.1$ rad/μs → cyclotron period of 150 ns
- $\omega_a = 1.439$ rad/μs → anomalous precession period of 4365 ns
- The spin precesses ~ 12° per-turn



The figure on the right shows one turn starting from parallel vectors. Dashed blue: final spin.

Long-term gain fluctuations



Laser activities

- **Before** production runs:

1. Short-Term-Double-Pulse campaigns to extract correction for short-term gain fluctuation, which will be applied during reconstruction
2. Long-Term-Double-Pulse campaigns to extract the lifetime of long-term gain fluctuation. The amplitude is obtained with In-Fill pulses

- **During** production runs, standard operating mode with sync pulse, in-fill laser pulses, and out-of-fill laser pulses to monitor stability over days/months
- **After** production runs (when reconstructing data):

1. Extract corrections and upload them to database
2. Data-quality-check: «good» production data has sync pulse, end-of-fill pulse, laser energy is stable over time and energy, etc …