The Muon $g - 2$ Experiment at Fermilab

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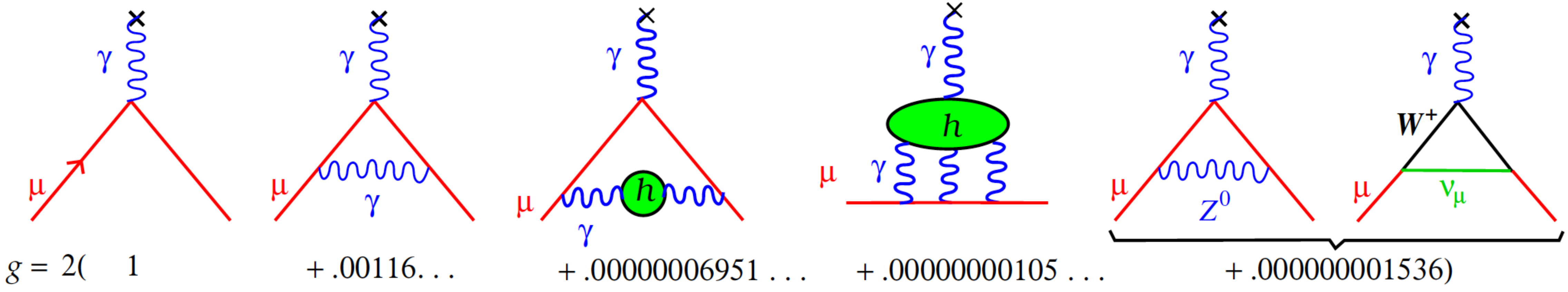
PSI

1 April 2019

Introduction and Motivation

a_μ is **predictable** using the Standard Model



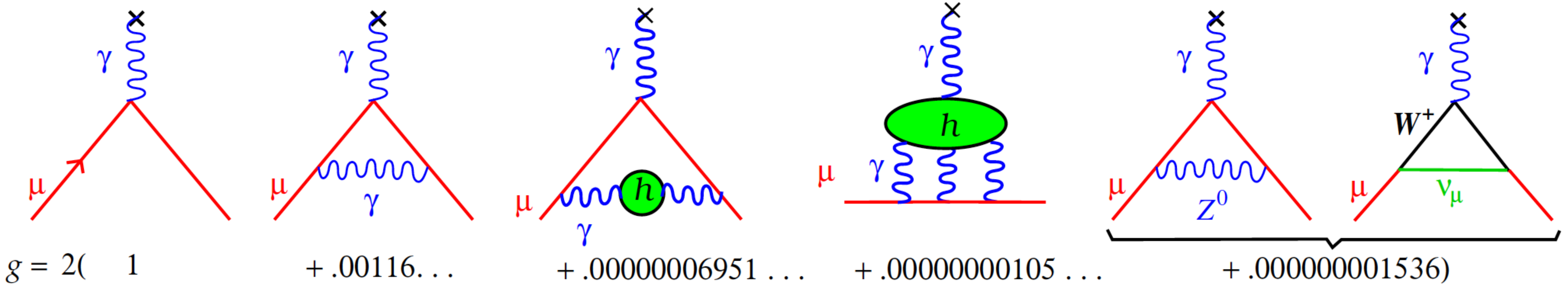
$$g = 2(\quad 1 \quad + .00116\ldots \quad + .00000006951\ldots \quad + .0000000105\ldots \quad + \underbrace{.000000001536)}$$

QED **HVP** **HLbL** **Electroweak**

$$\vec{m} = \frac{ge}{2m}\vec{s}$$

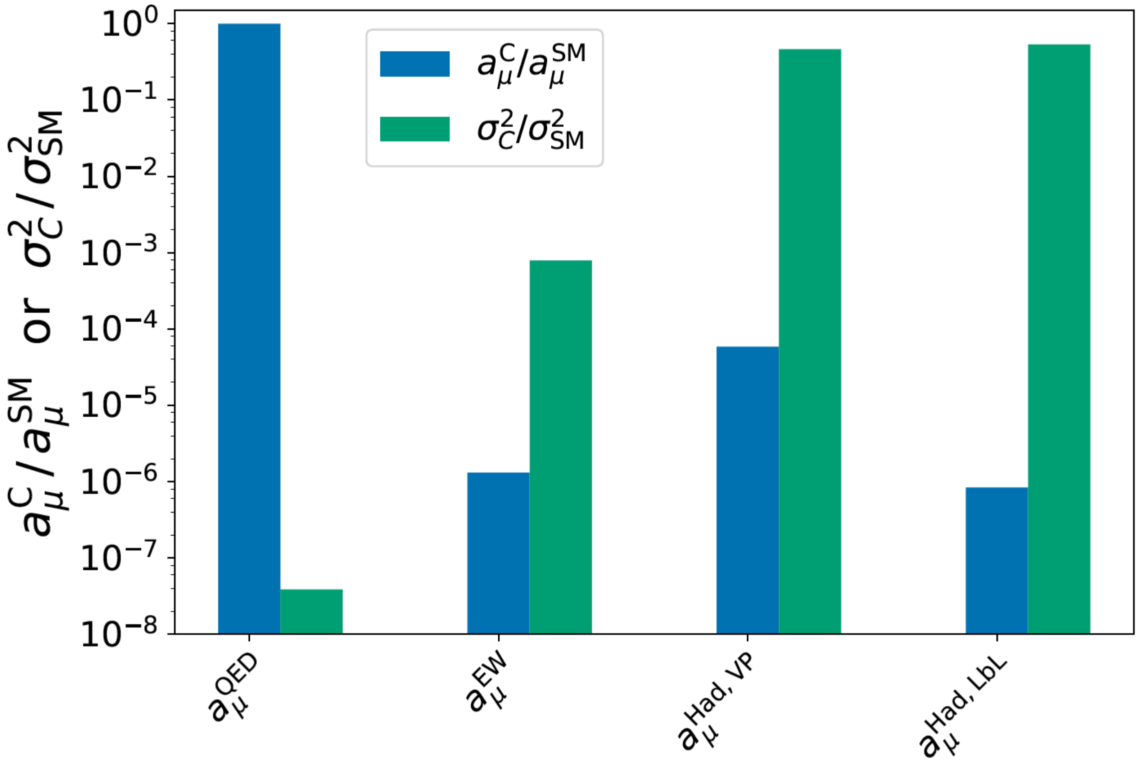
$$\boxed{a_\mu \equiv \frac{g_\mu - 2}{2}}$$

a_μ is **predictable** using the Standard Model



QED	**HVP**	**HLbL**	**Electroweak**
• known to five loops	• from R-ratio data	• "most challenging"	• known to two loops
• < 1 ppb precision	• ~0.5% precision	• 25% precision	• 0.7% precision
• dominant contribution	• 60 ppm contribution	• ~1 ppm contribution	• ~1 ppm contribution

a_μ is **predicted** to ~350 ppb

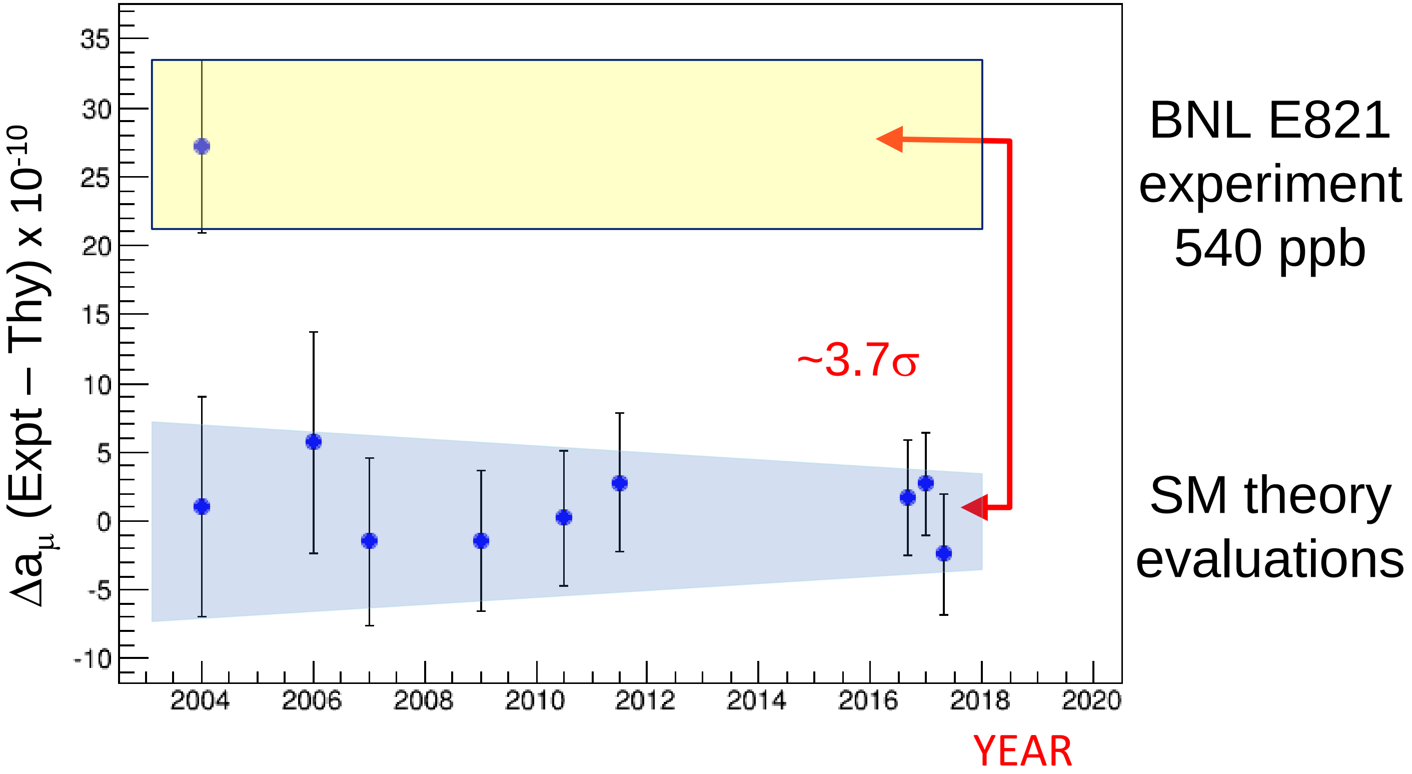


$$a_\mu^{SM} = (11659182.04 \pm 3.56) \times 10^{-10}$$

significant deviations indicate new physics

number from Keshavarzi et al., 2018

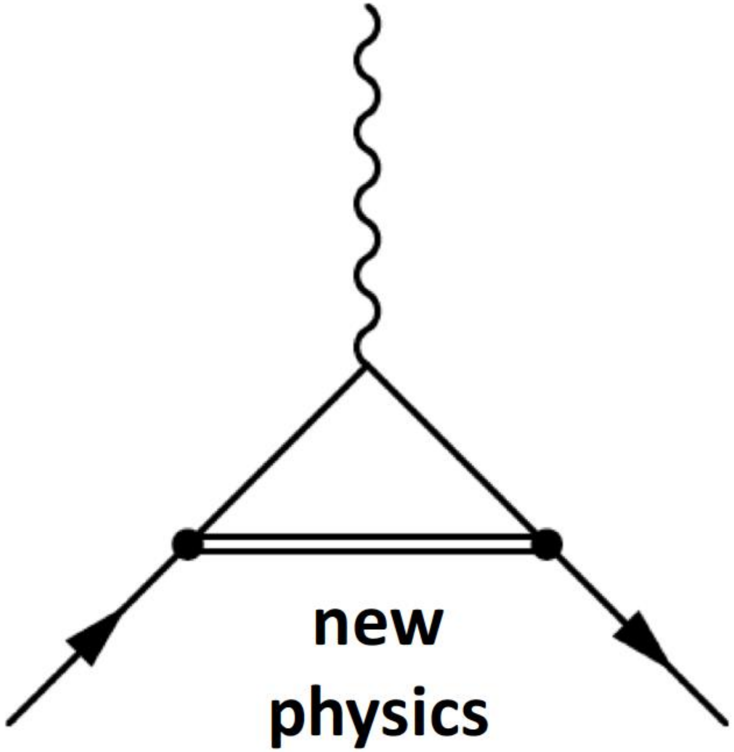
a_μ has been **measured** to 540 ppb



- **discrepancy** with theory, currently at 3.5-4σ

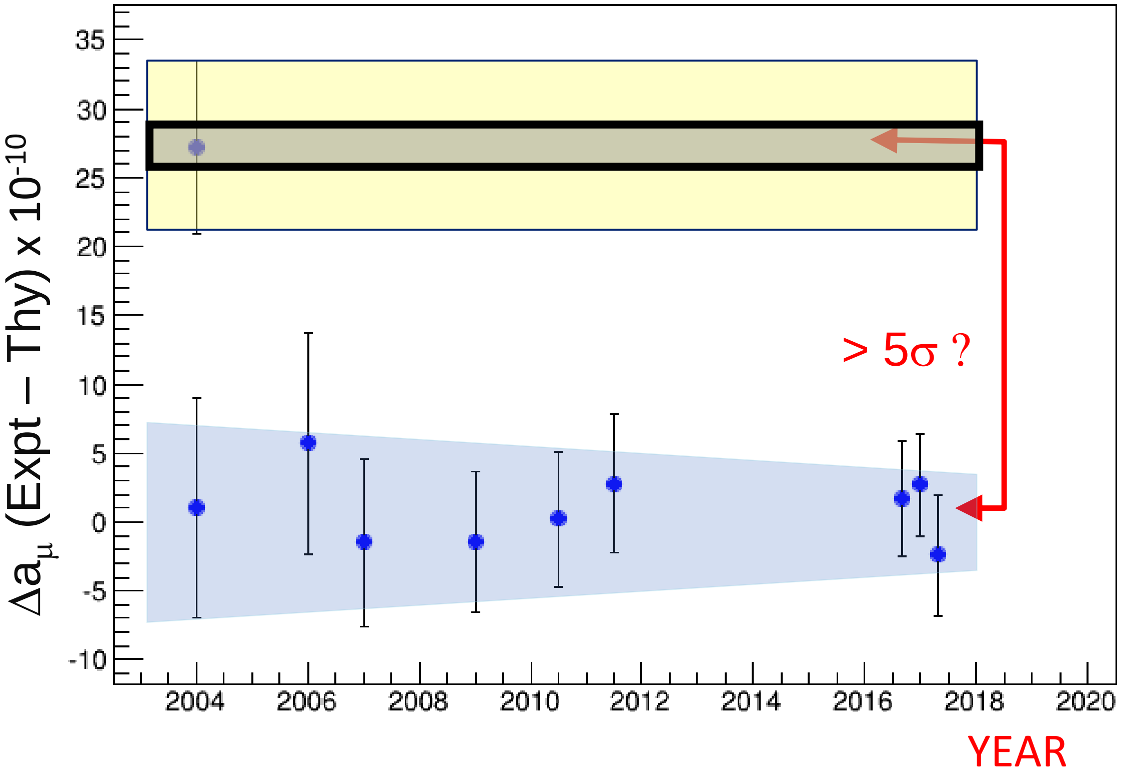
$$a_\mu^{exp} - a_\mu^{SM} = (26.6 \pm 7.2) \times 10^{-10}$$

New physics interpretations include:



- **supersymmetry**
  - Czarnecki and Marciano. *Phys. Rev.*, D64:013014, 2001
- **dark photons**
  - Pospelov, *Phys. Rev.*, D80:095002, 2009
- **light scalar particles**
  - Chen et al. *Phys. Rev.*, D98(3):035006, 2016
- **axion-like pseudoscalar particles**
  - Marciano et al. *Phys. Rev.*, D94(11):115033, 2016
- **vectorlike fermions**
  - Crivellin et al. *Phys. Rev.*, D98(11):113002, 2018
- the not-yet invented.
- **… but the discrepancy must be verified!**

E989 experiment’s goal is **140 ppb**



FNAL E989
expt. goal

SM theory
evaluations

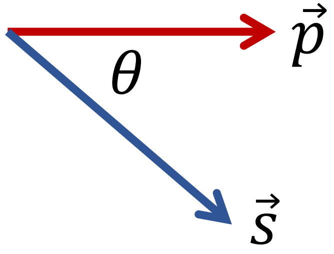
- independent confirmation
- improved precision
- designed for a definite result
- requires ~ $\mathbf{10^{12}}$ **stored muons**
- in parallel:
  Muon $g-2$ Theory Initiative

The $\boldsymbol{a_\mu}$ Measurement Technique

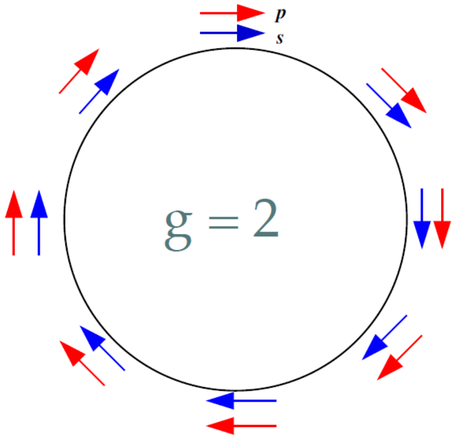
Muon g-2 Collaboration, 2015

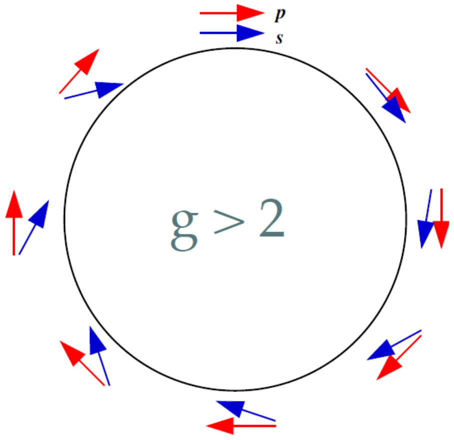
(190 collaborators, 34 institutes, 7 countries)

a_μ is extracted from **anomalous precession** in a magnetic storage ring



$$\omega_a = \dot{\theta}$$





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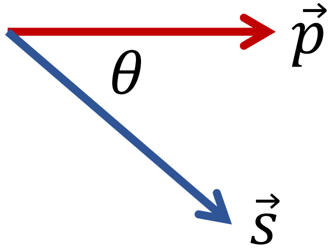

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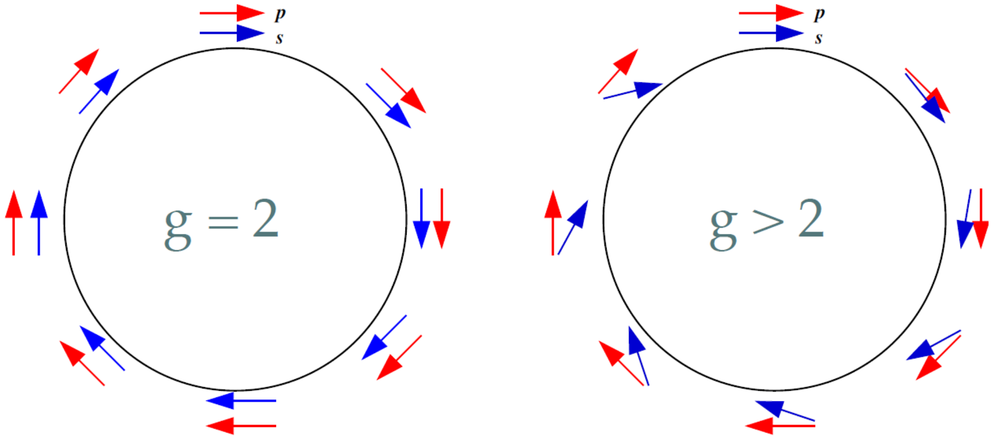


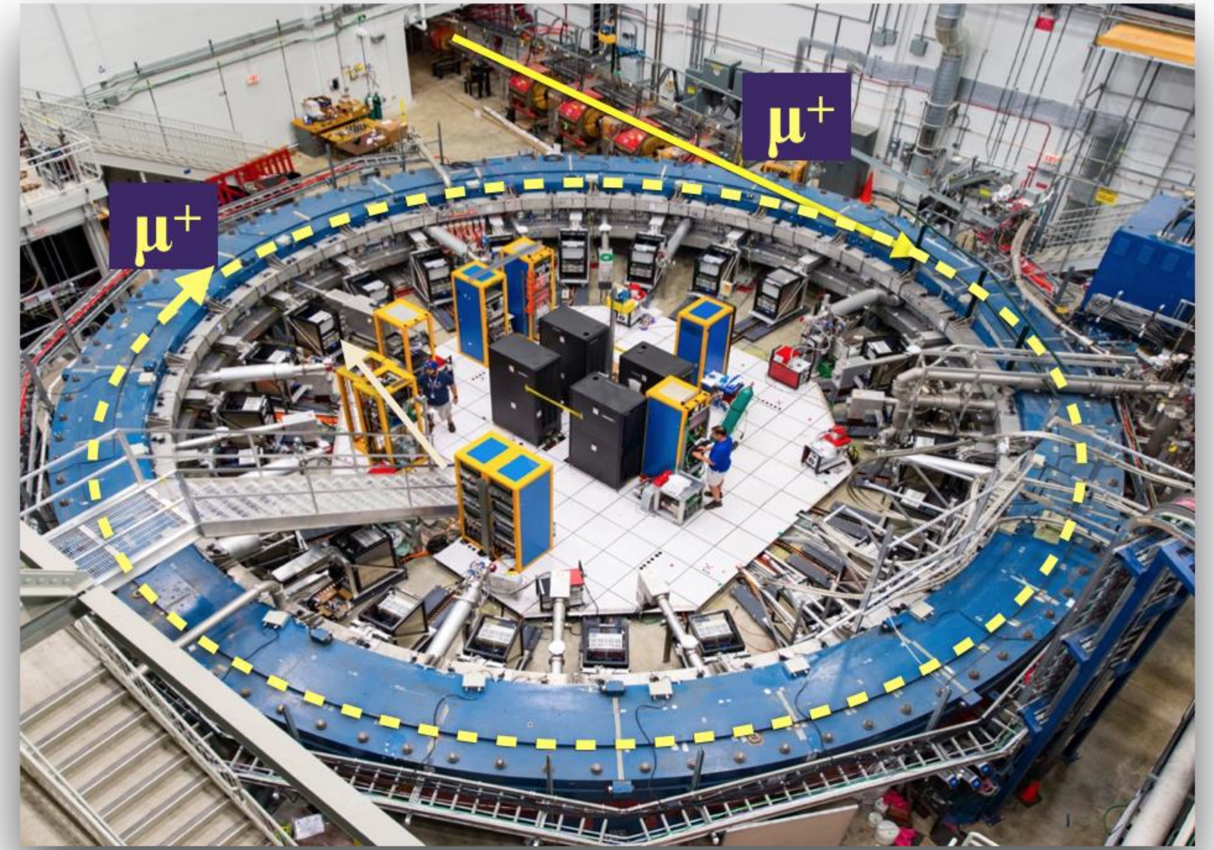
$$\overrightarrow{\omega_s} = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$$

$$\overrightarrow{\omega_c} = -\frac{e\vec{B}}{m\gamma}$$

$$\boldsymbol{\overrightarrow{\omega_a}} \equiv \overrightarrow{\omega_s} - \overrightarrow{\omega_c} = \boldsymbol{a_\mu}\frac{e\vec{B}}{m}$$

applies for motion entirely perpendicular to a perfectly uniform field

a_μ is extracted from **anomalous precession** in a magnetic storage ring



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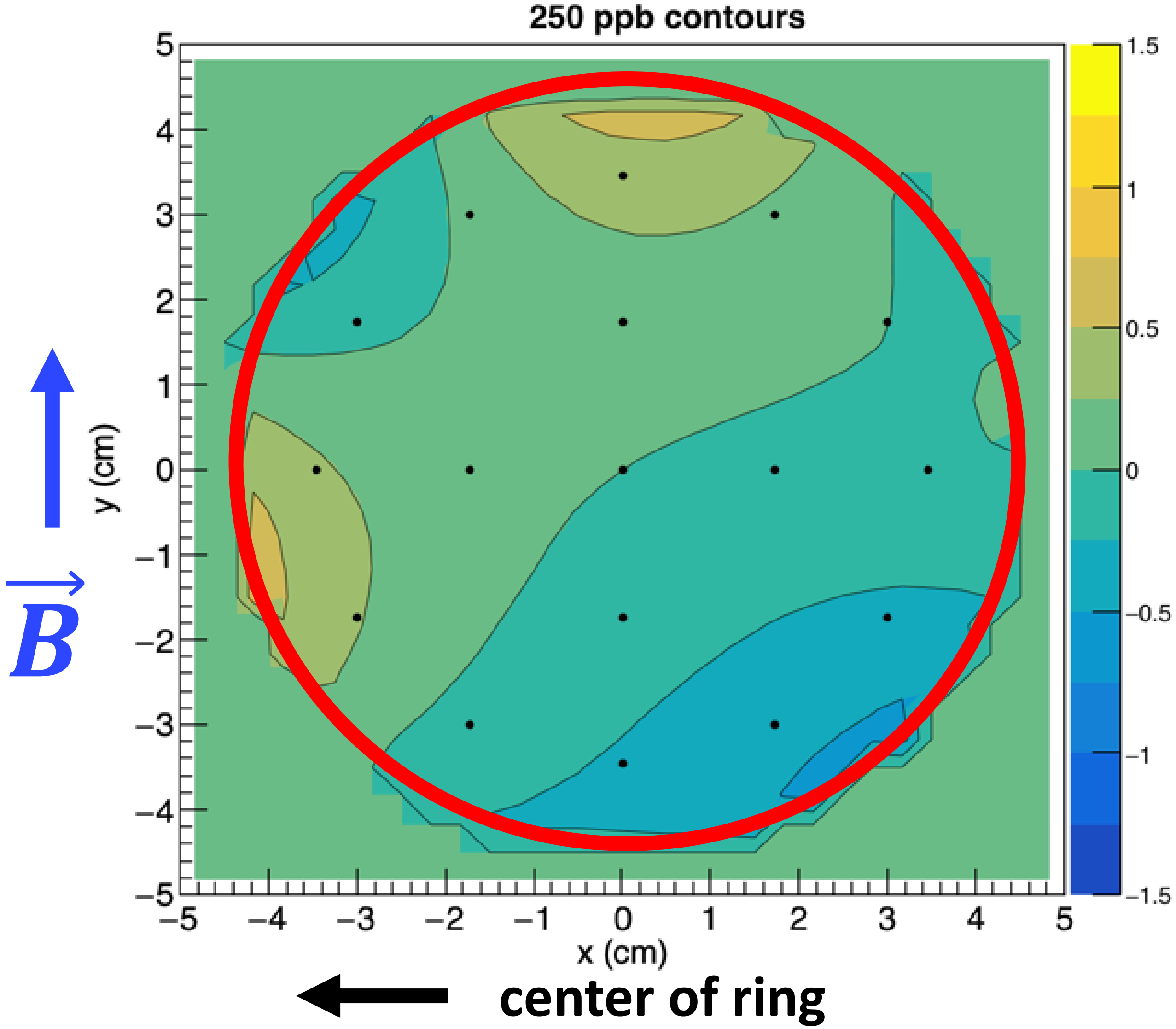
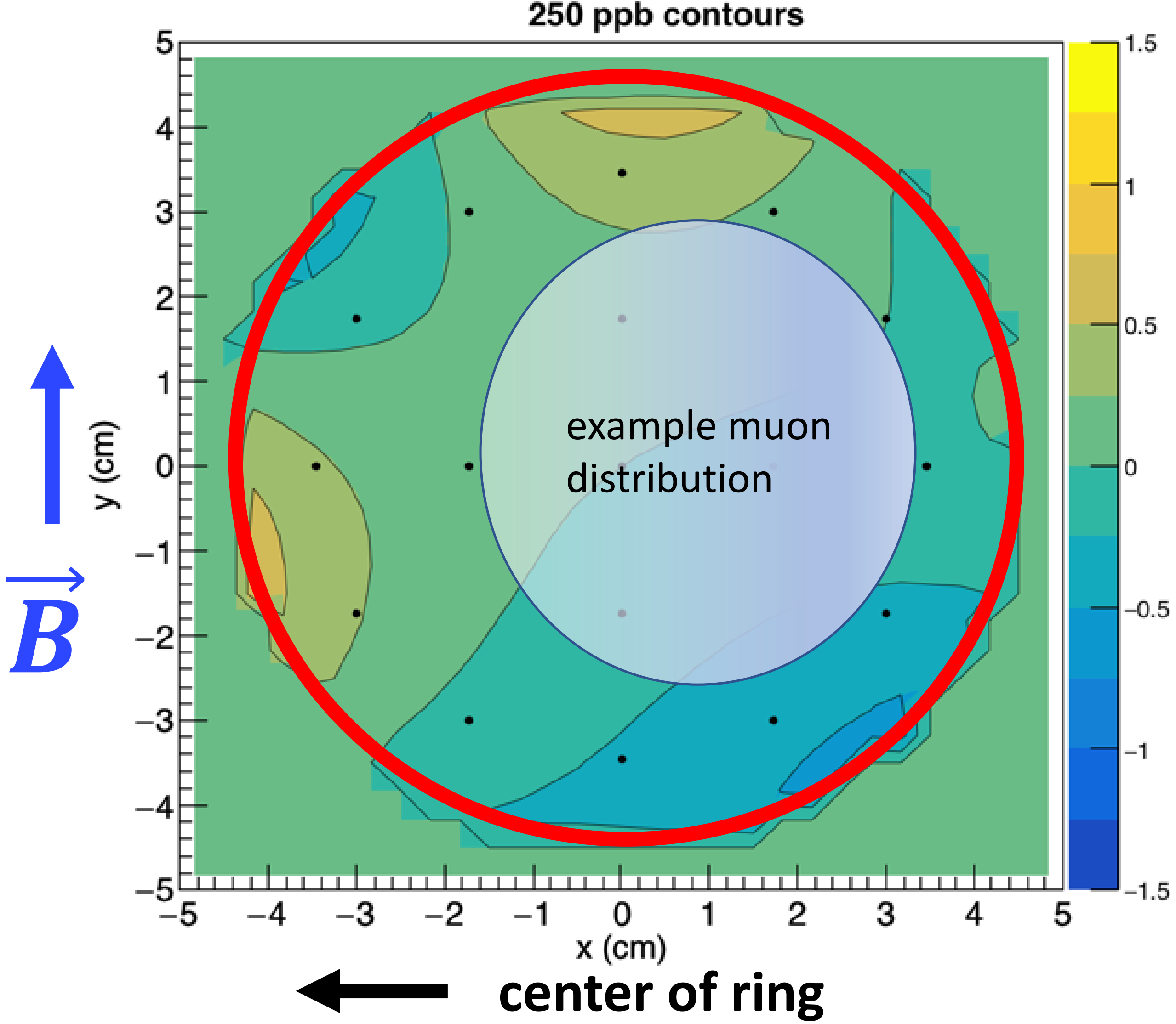
$\boldsymbol{B}$ is measured with proton NMR



$$\boldsymbol{B} = \frac{\hbar}{2\mu_p}\omega_p$$

$\widetilde{\boldsymbol{B}}$ is measured with proton NMR



$$\widetilde{\boldsymbol{B}} = \frac{\hbar}{2\mu_p}\widetilde{\omega_p}$$

distribution-weighted value, $\widetilde{\omega_p}$

will be measured to 70 ppb

a_μ is related to $\boldsymbol{\omega_a}/\widetilde{\omega}_p$ and well-known constants

$$a_\mu = \frac{m_\mu}{eB}\,\boldsymbol{\omega_a}$$

$$a_\mu = \frac{g_e}{2}\cdot\frac{\boldsymbol{\omega_a}}{\widetilde{\boldsymbol{\omega}}_{\boldsymbol{p}}}\cdot\frac{m_\mu}{m_e}\cdot\frac{\mu_p}{\mu_e}$$

0.26 ppt*

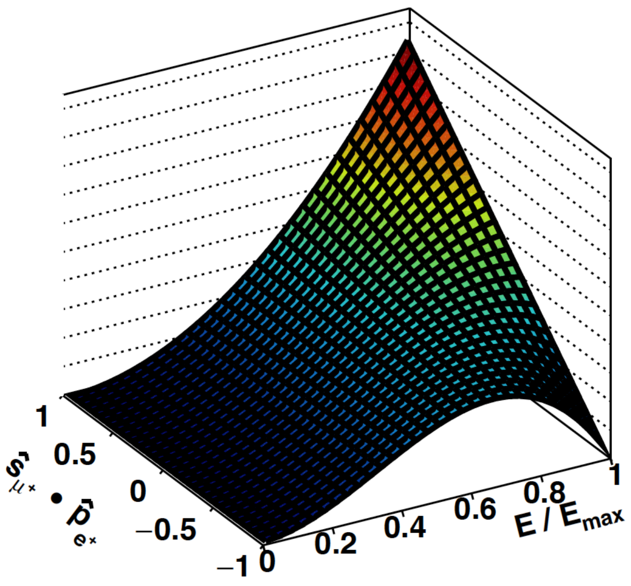
E989: 140 ppb

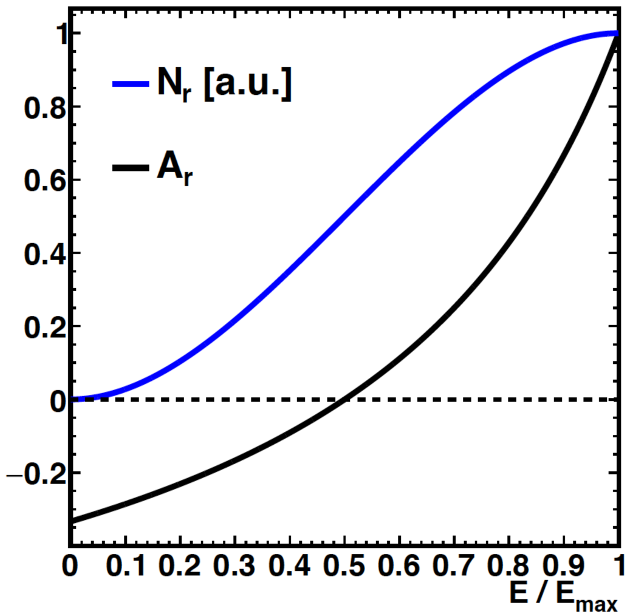
22 ppb*

3 ppb*

*CODATA 2016

$\boldsymbol{\omega_a}$ is measured through e^+ from muon decay





decay distribution of e^+ in the **muon rest frame**

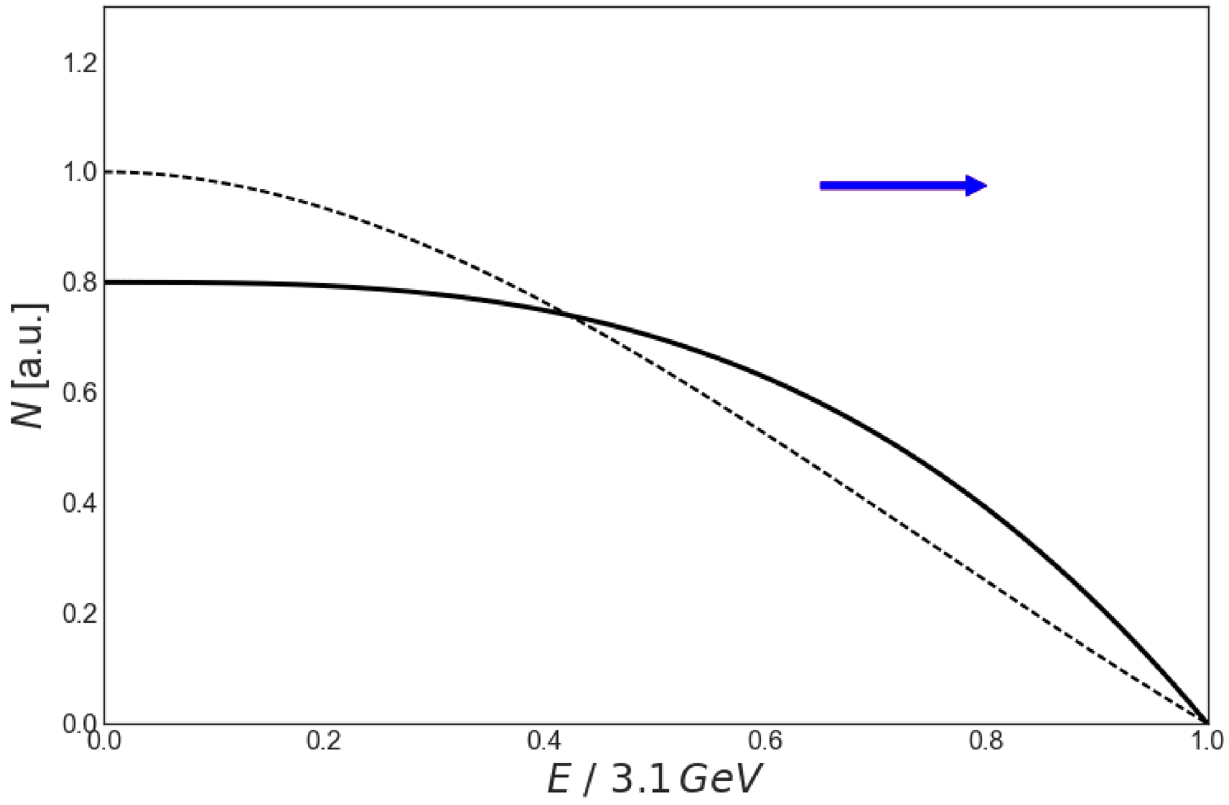
$$\rho_r(E,t) = N_r(E)[1 + A_r(E)\cos(\theta)]$$

θ relative to muon spin

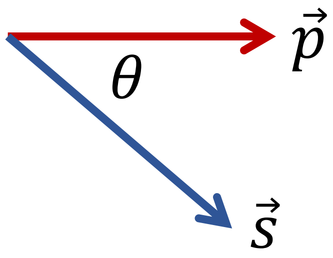
high-energy e^+ emitted along spin

lab frame spectrum is time-dependent

$\boldsymbol{\omega_a}$ is measured through e^+ from muon decay



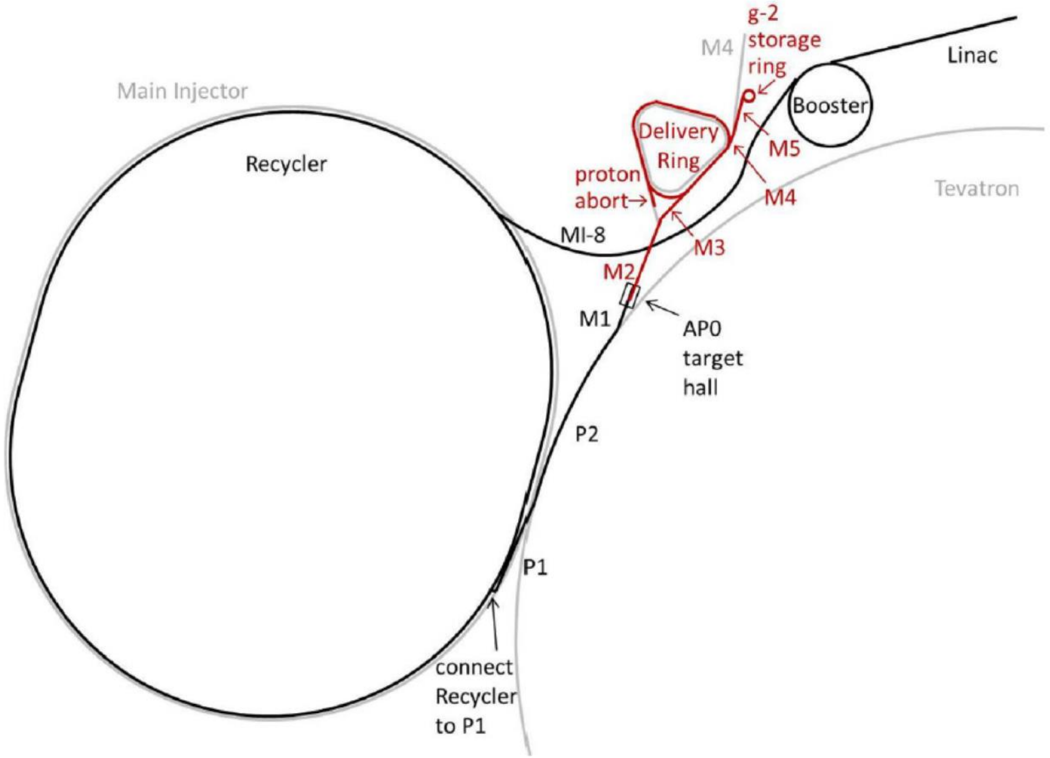
decay e^+ energy spectrum in the **lab frame**



$$\boldsymbol{\omega_a} = \frac{d\theta}{dt}$$

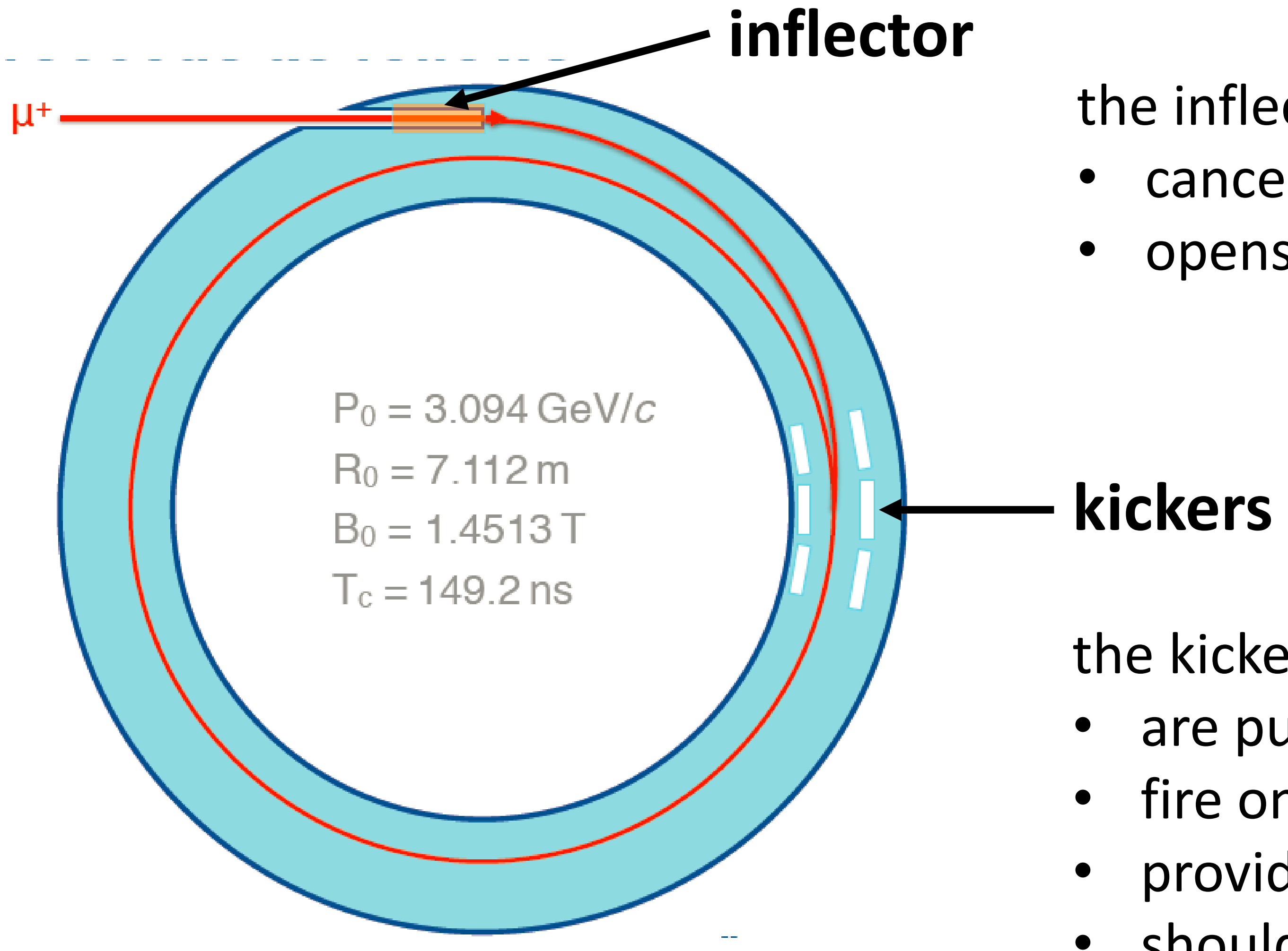
lab frame e^+ spectrum oscillates at ω_a

$\boldsymbol{\omega_a}$ measurement requires polarized muons



- 8 GeV protons impact π^+ production target
- 3.1 GeV positive particles are selected
- pions decay to muons along beamline
- excess protons removed in delivery ring (time-of-flight separation)
- 95% polarized muon beam injected into E989 storage ring
- 11.4 Hz average injection (fill) rate
- ~10,000 stored muons per fill
- muons observed for > 10 lifetimes

The inflector and kickers enable beam injection



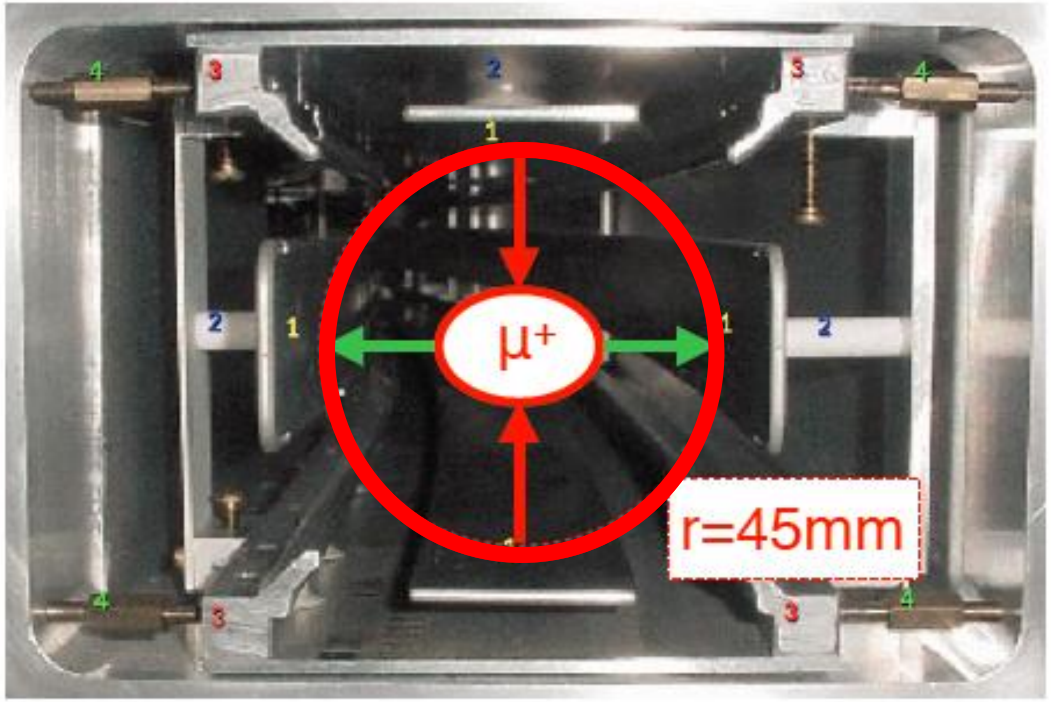
the inflector:

- cancels fringe field of storage magnet
- opens field-free channel for injection

the kickers:

- are pulsed electromagnets
- fire on the first turn after injection
- provide ~11 mrad radial deflection
- should be on and off in < 150 ns

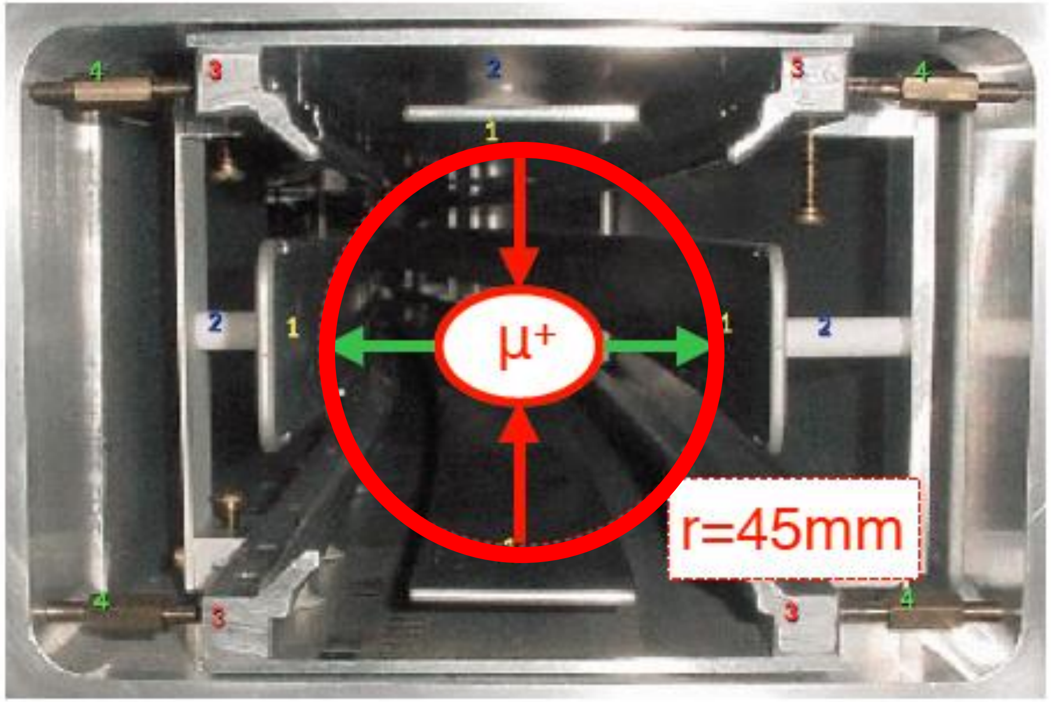
Electrostatic quadrupoles focus vertically



with electric field:

$$\overrightarrow{\boldsymbol{\omega_a}} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Electrostatic quadrupoles focus vertically



with electric field:

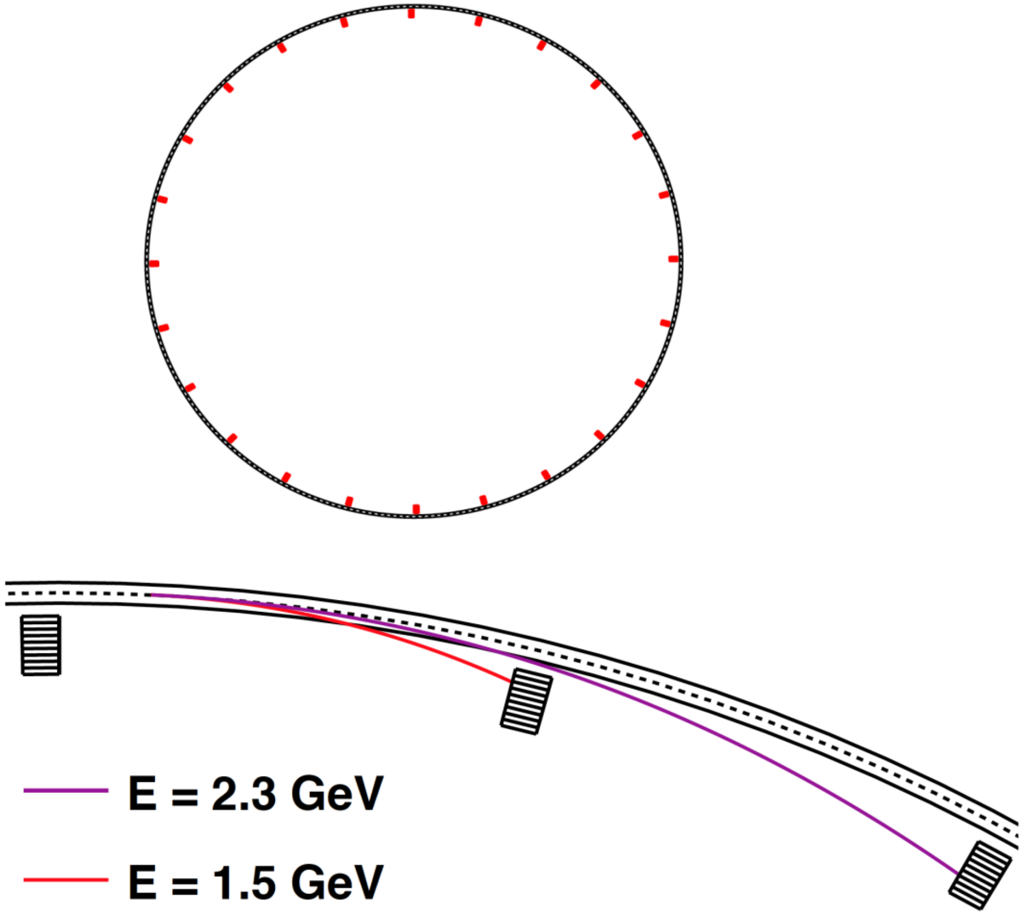
$$\overrightarrow{\boldsymbol{\omega_a}} = -\frac{e}{m}\left[a_\mu\vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

"magic" momentum:

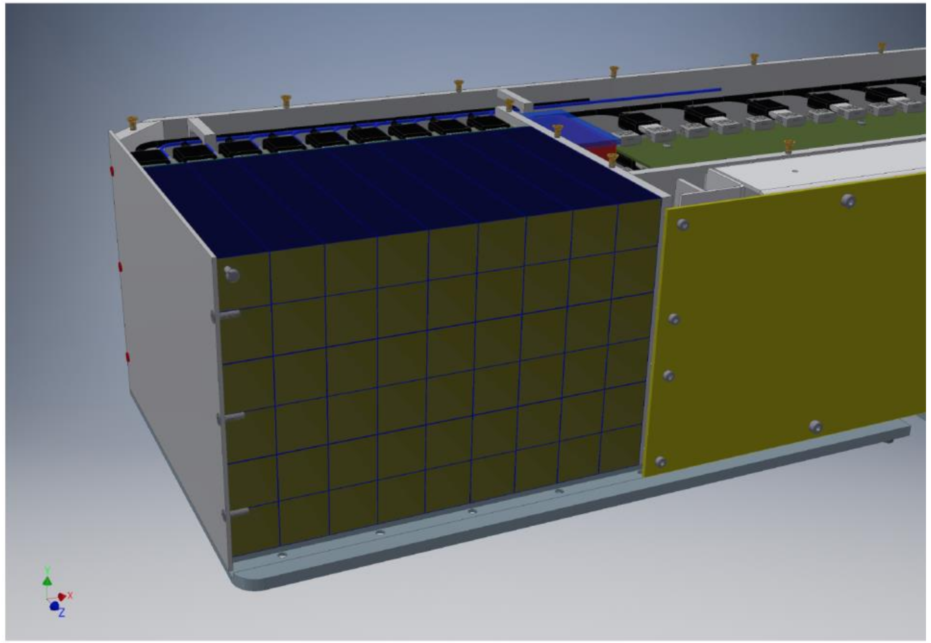
$$\gamma \approx 29.3$$

$$p_0 \approx 3.094\ GeV/c$$

Calorimeters catch high energy decay positrons

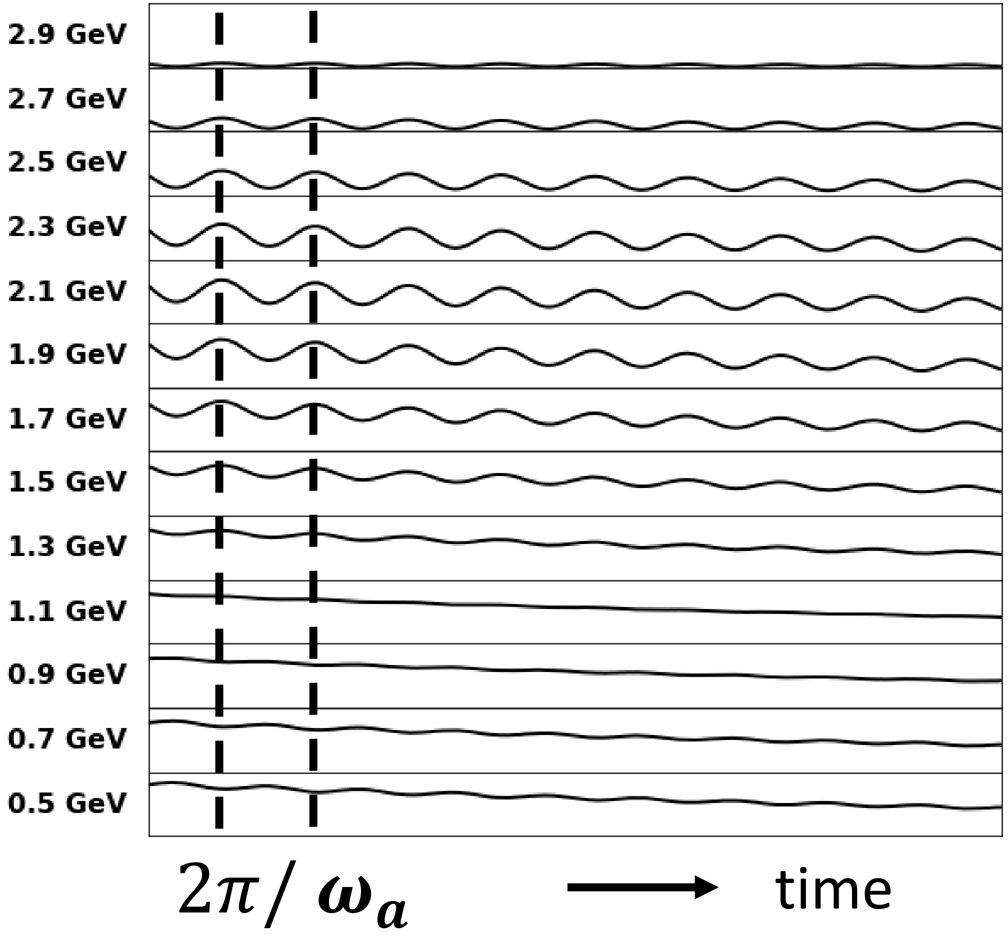


- 24 evenly-spaced calorimeters
- large acceptance (80%) for high-energy positrons
- report energies and times of incident positrons



Positron time-spectra “wiggle” at $\boldsymbol{\omega_a}$

positrons measured at the calorimeters



→ time

$$\rho(E,t) \propto e^{-\frac{t}{\gamma\tau}} N(E)[1 + \mathrm{A(E)}\cos(\boldsymbol{\omega_a} t\ - \phi)]$$

calorimeter spectra are fit for $\boldsymbol{\omega_a}$

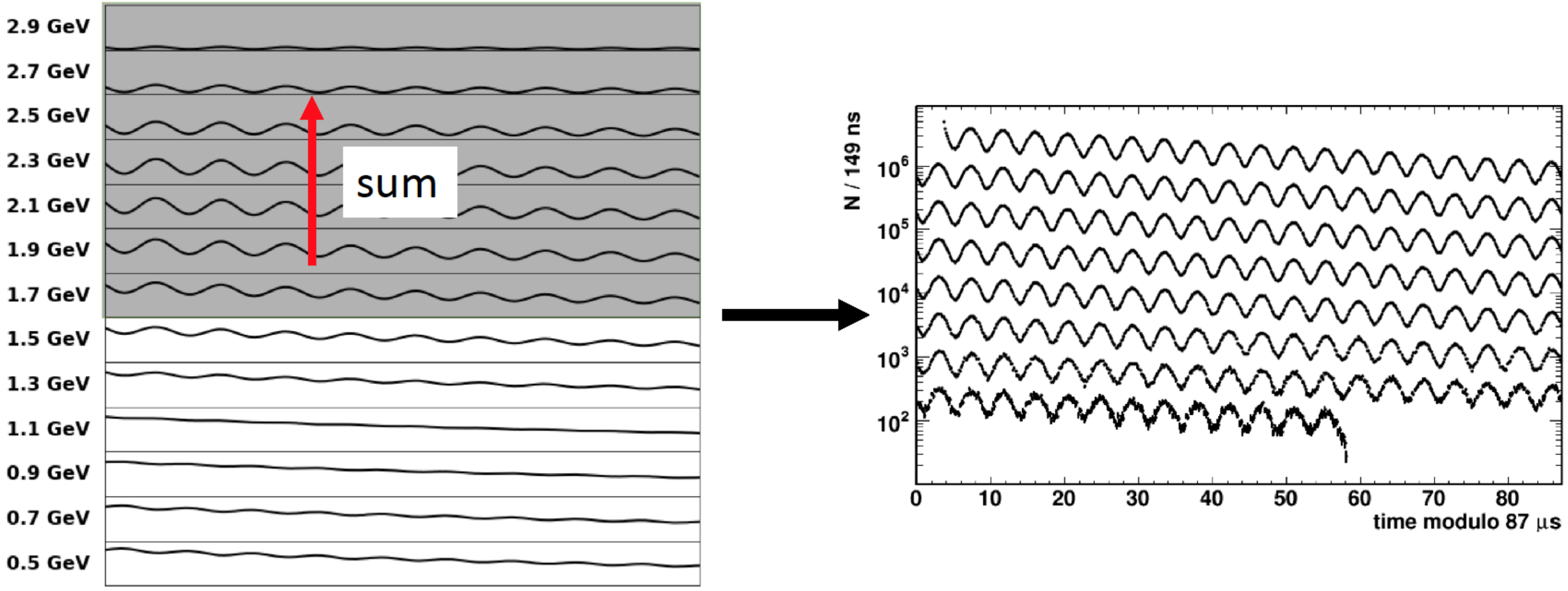
aim to extract $\boldsymbol{\omega_a}$ with:

- 100 ppb statistical uncertainty
- 70 ppb systematic uncertainty

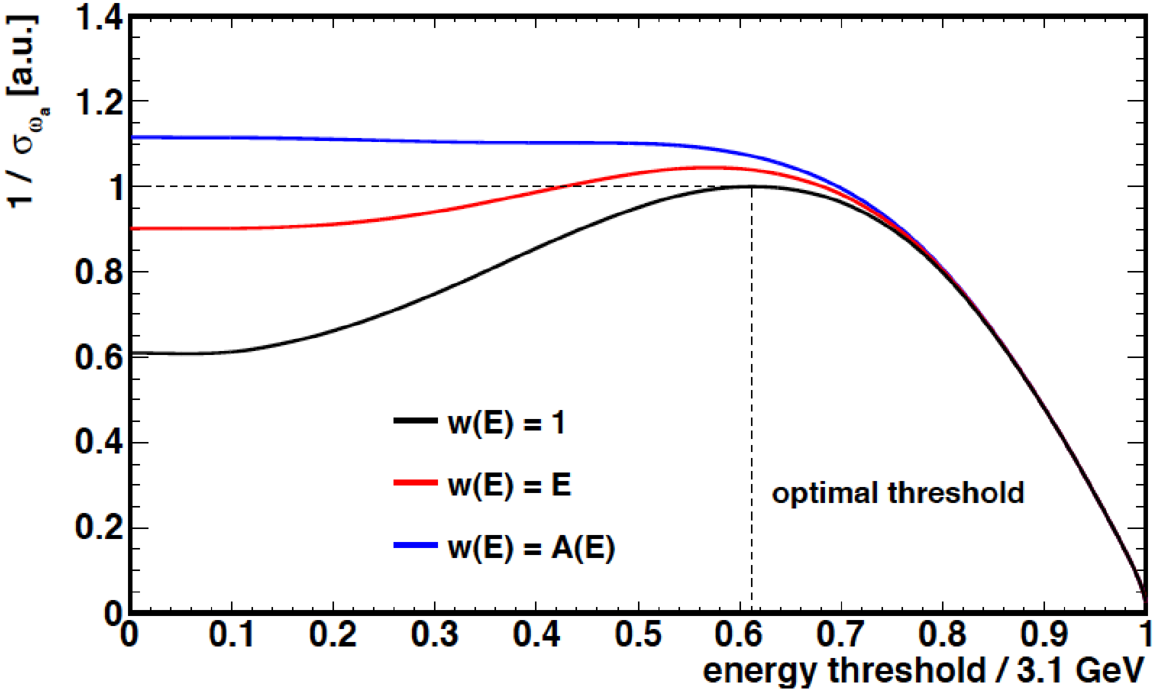
Collapsing the energy axis creates a one-dimensional time spectrum

$$f(t) = \int_{E_T}^{\infty} w(E) \cdot \rho(E,t)\, dE$$

$$f(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left[1 + \frac{\langle wA \rangle}{\langle w \rangle} \cos(\boldsymbol{\omega_a} t - \phi) \right]$$ **five-parameter function**



E989 employs multiple weighting schemes



$$\left(\frac{\sigma_{\omega_a}}{\omega_a}\right)^2 = \frac{2\langle w^2\rangle}{N_{e^+}\langle wA\rangle^2\gamma^2\tau_\mu^2\omega_a^2}$$

- $w(E) = 1$: T-Method (baseline)
- $w(E) = E$: Q-Method
- $w(E) = A(E)$: A-Weighted (**optimal**)

differing systematics; all will be conducted

E989 employs multiple weighting schemes

100 ppb statistical uncertainty requires

$$160 \times 10^9 \, e^+$$

$$\left(\frac{\sigma_{\omega_a}}{\omega_a}\right)^2 = \frac{2\langle w^2\rangle}{N_{e^+}\langle wA\rangle^2\gamma^2\tau_\mu^2\omega_a^2}$$

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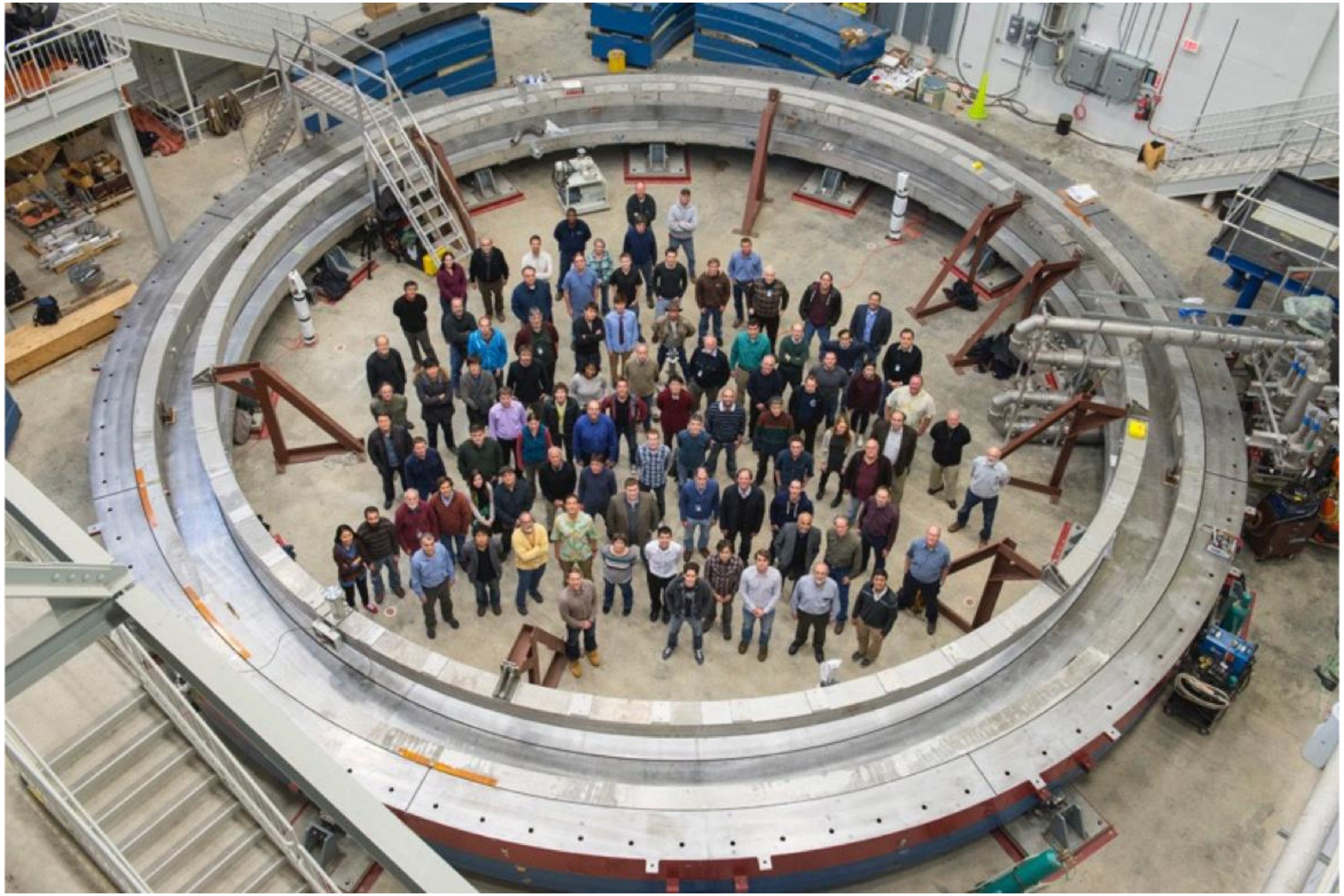
Beam Dynamics and Systematic Errors



A time-dependent phase biases $\boldsymbol{\omega_a}$

$$\begin{aligned}\cos(\omega_a t - \phi) &= \cos\left[\omega_a t - \phi_0 - \frac{\mathrm{d}\phi}{\mathrm{d}t} t + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right] \\ &= \cos\left[\left(\omega_a - \frac{\mathrm{d}\phi}{\mathrm{d}t}\right) t - \phi_0 + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right] \\ &= \cos\left[\omega_a' t - \phi_0 + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right]\end{aligned}$$

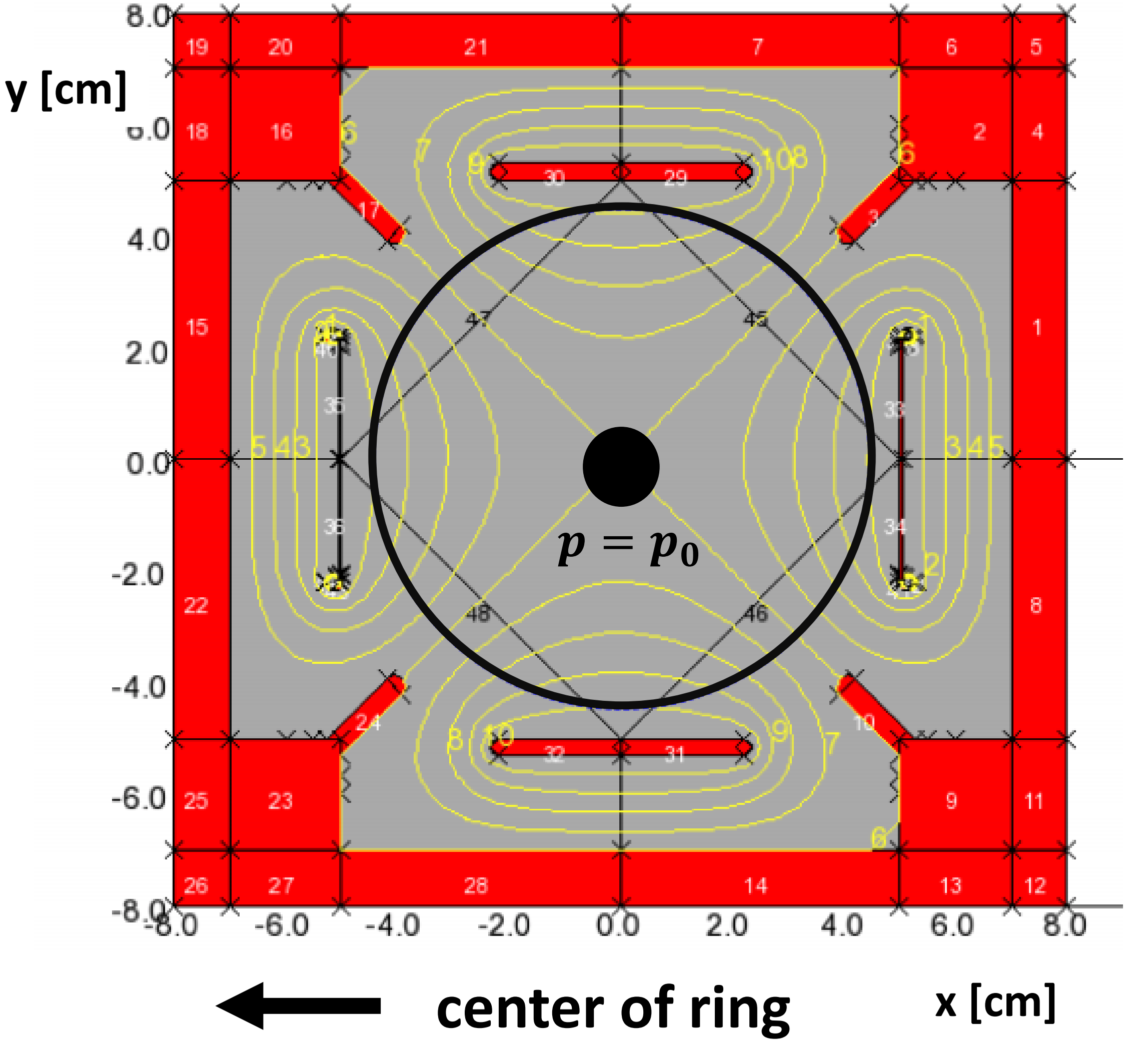
70 ppb implies:

- $\frac{d\phi}{dt}$ < 0.07 mrad / 700 μs
- time shifts < 50 ps / 700 μs

"early-to-late" effects include:

- beam distortions
- muon losses
- varying lifetimes
- rate-dependent reconstruction

Muons oscillate about their equilibrium orbits



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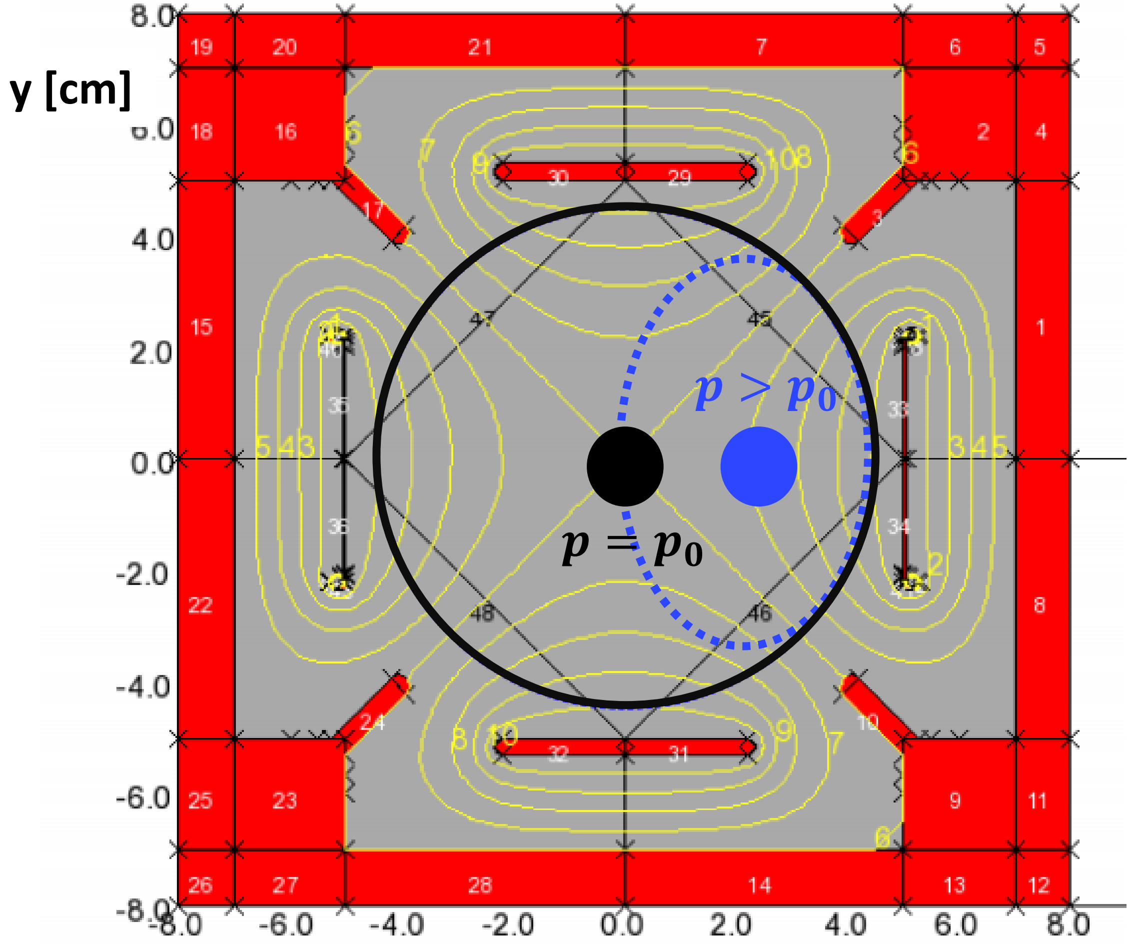
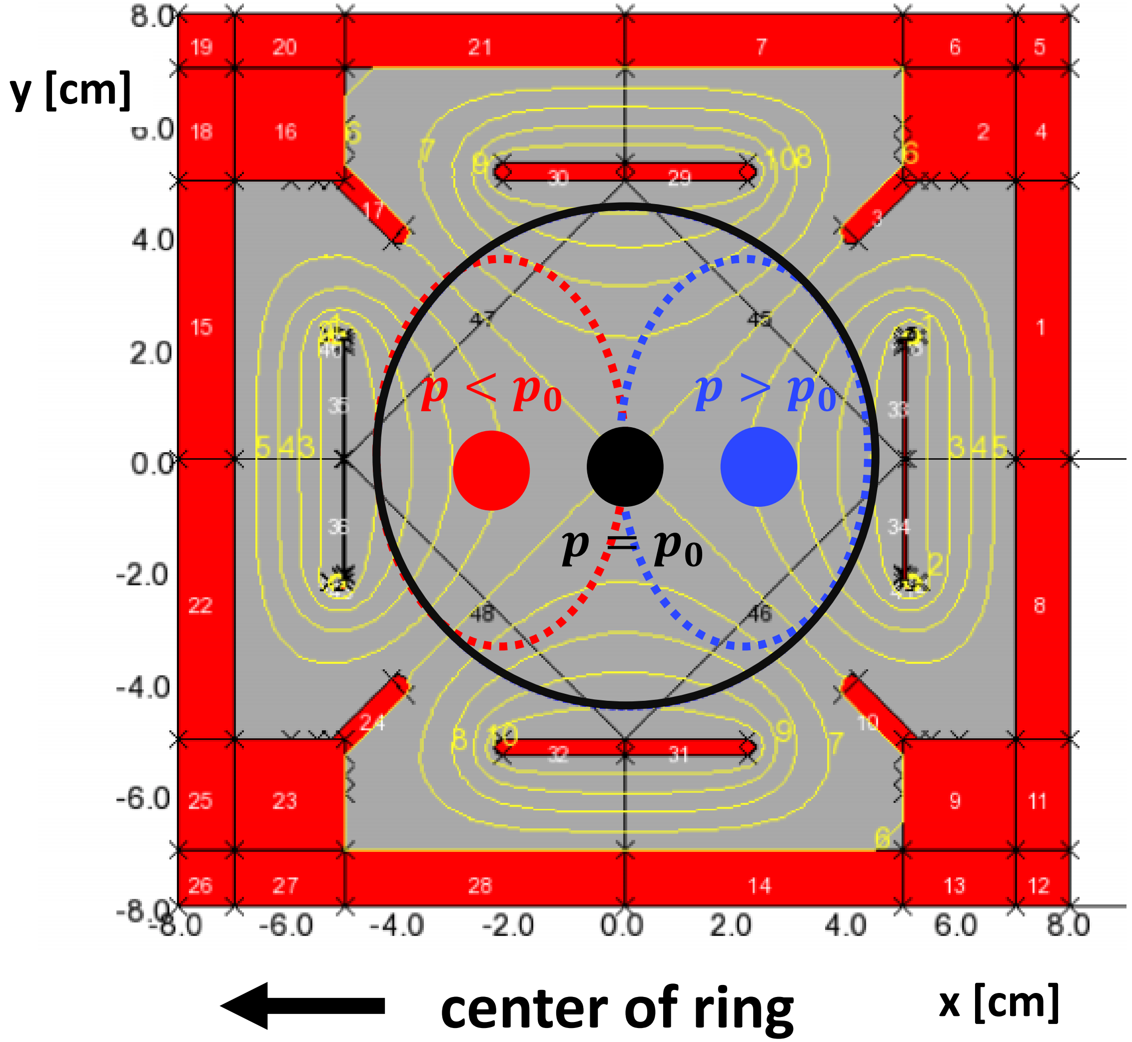


← **center of ring**

x [cm]

Muons oscillate about their equilibrium orbits



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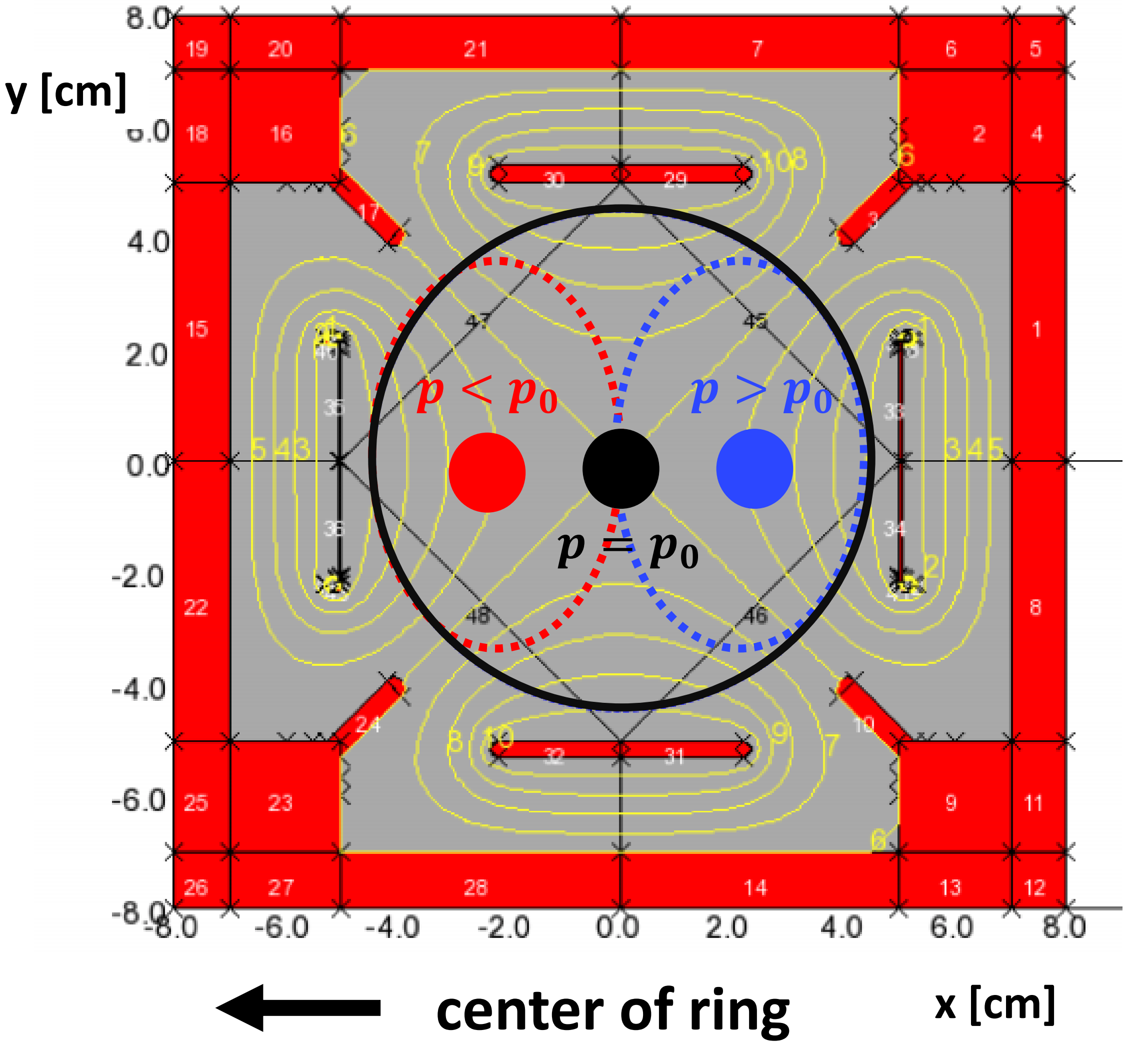


$$n \approx 0.1 \propto \left(\frac{dE}{dy}\right)\frac{R_0}{B_0}$$

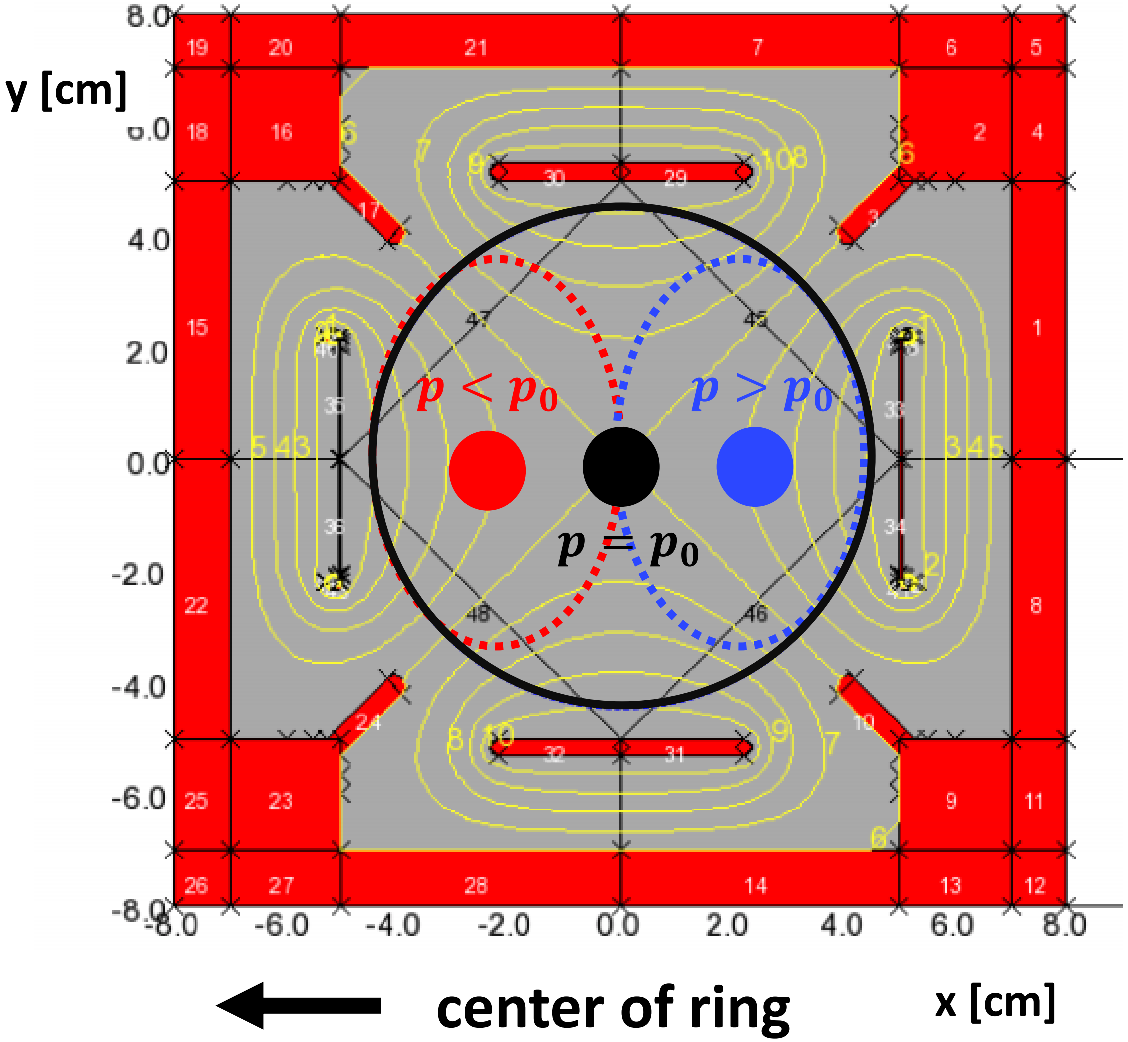
$$R \approx R_0\left[1 + \frac{1}{1-n}\left(\frac{\Delta p}{p_0}\right)\right]$$

$$\omega_c \approx \omega_{c,0}\left[1 - \frac{1}{1-n}\left(\frac{\Delta p}{p_0}\right)\right]$$

$$y(t) \approx A_y \cos(\sqrt{n}\,\omega_c t - \phi_y)$$

$$x(t) \approx A_x \cos(\sqrt{1-n}\,\omega_c t - \phi_x)$$

Muons oscillate about their equilibrium orbits

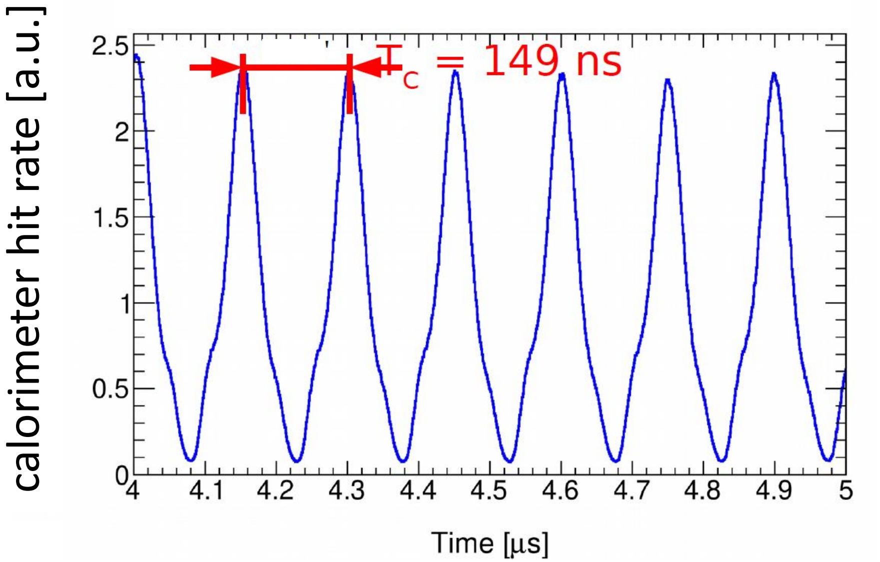


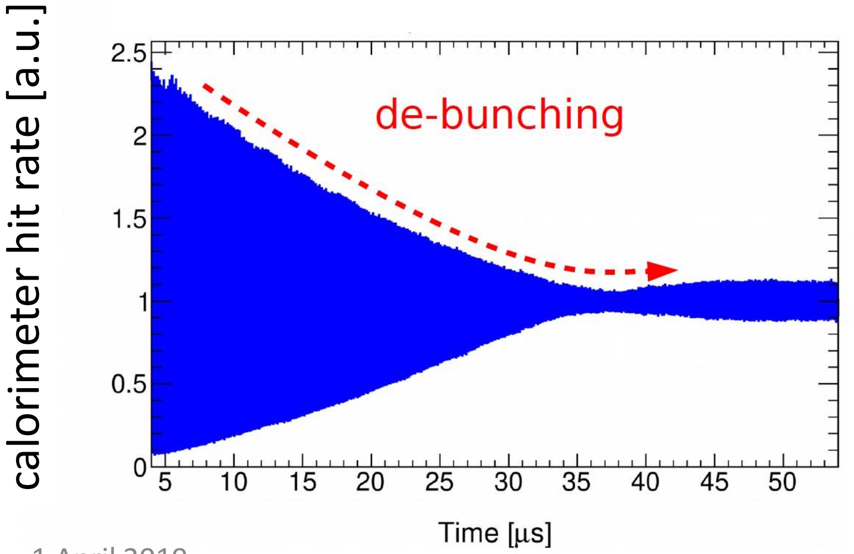
	symbol	value
cyclotron	f_c	6.7 MHz
precession	$\boldsymbol{f_a}$	**0.2 MHz**
radial	f_x	6.3 MHz
vertical	f_y	2.2 MHz
CBO	$f_c - f_x, f_{CBO}$	0.4 MHz
vertical waist	$f_c - 2f_y, f_{vw}$	2.3 MHz

potential issues:

- changing *n* value
- changing momentum distribution
- decoherence

Not all muons are at the “magic momentum”





$$\overrightarrow{\boldsymbol{\omega_a}} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(\boldsymbol{a_\mu} - \frac{\mathbf{1}}{\boldsymbol{\gamma^2 - 1}}\right)\frac{\vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{E}}}{\boldsymbol{c}}\right]$$

- momentum distribution must be measured
- extracted from cyclotron frequencies
  - “debunching”
- ∼**500 ppb** “electric field” correction
- target **30 ppb** systematic from correction

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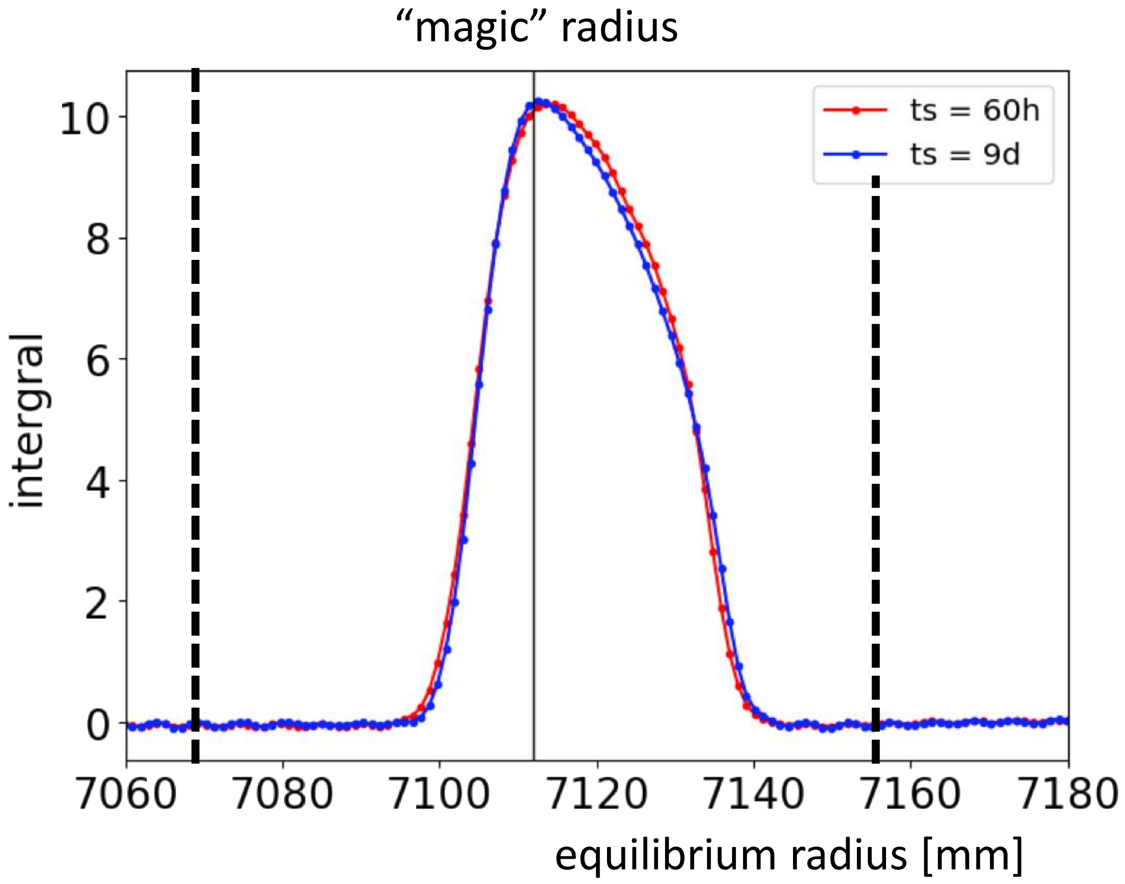

momentum ↔ equilibrium radius

$$\overrightarrow{\boldsymbol{\omega_a}} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(\boldsymbol{a_\mu} - \frac{\mathbf{1}}{\boldsymbol{\gamma}^{\mathbf{2}}-\mathbf{1}}\right)\frac{\vec{\boldsymbol{\beta}}\times\vec{\boldsymbol{E}}}{\boldsymbol{c}}\right]$$

- momentum distribution must be measured
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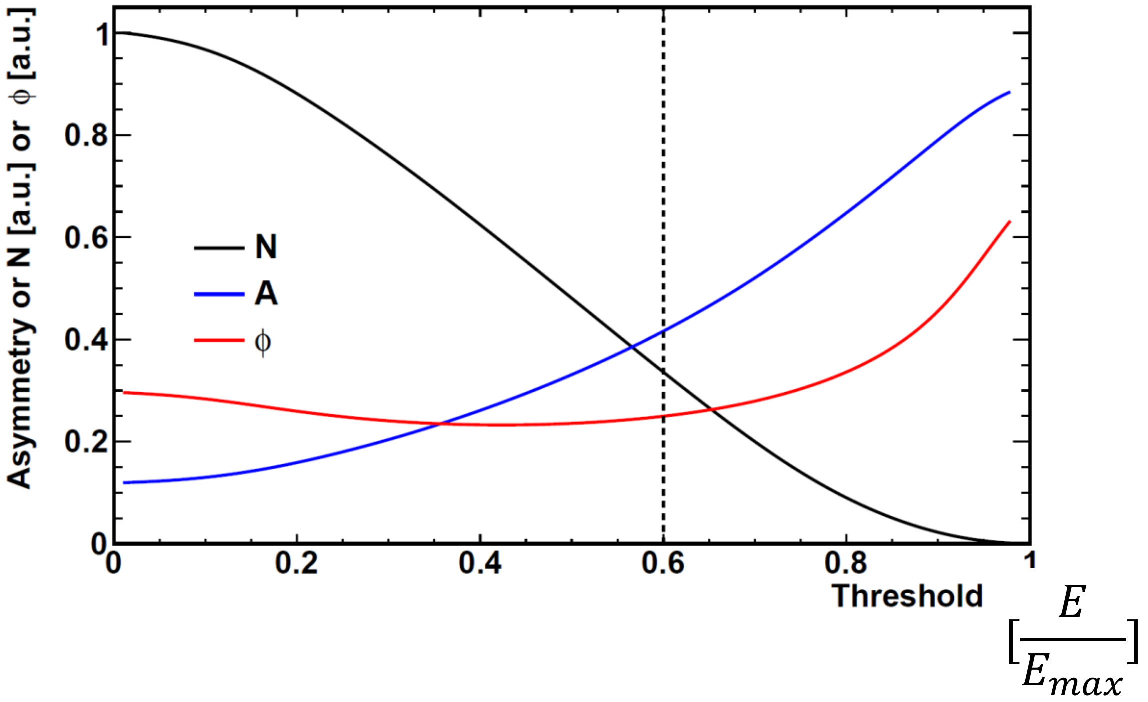
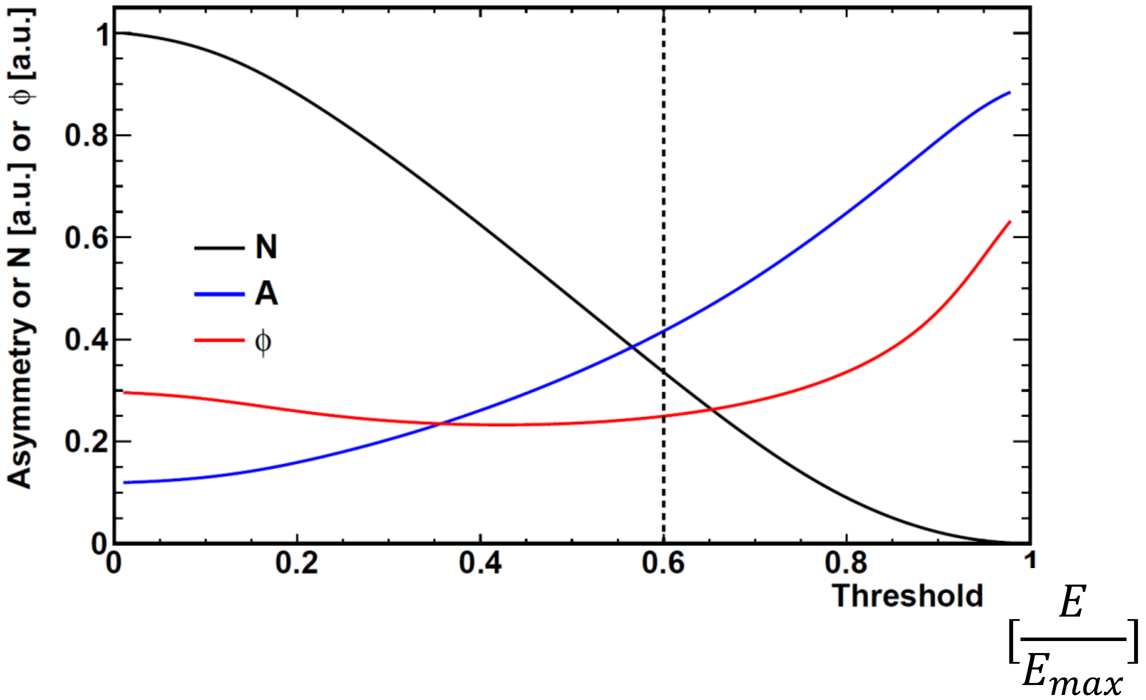
Detectors can introduce early-to-late effects



changing gains move the energy threshold,
shift the observed phase

must avoid time-dependent gain perturbations

Detectors can introduce early-to-late effects



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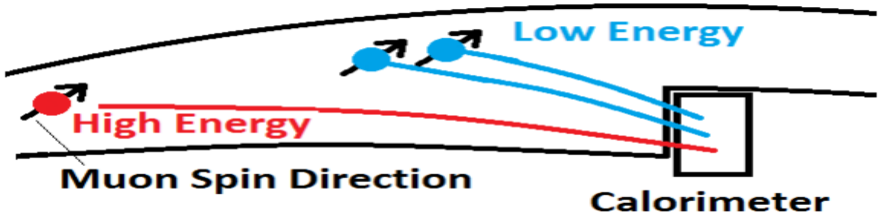
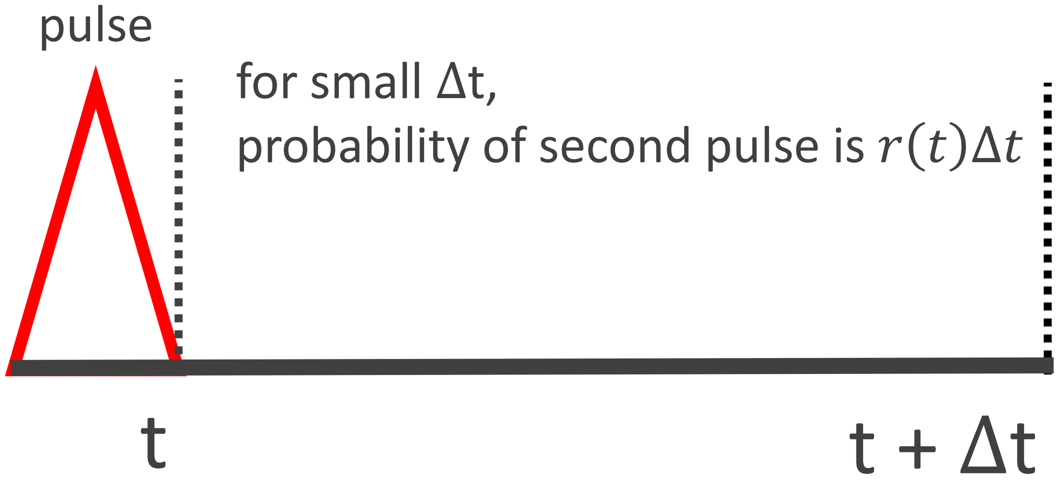


unresolved pileup pulses have the wrong phase

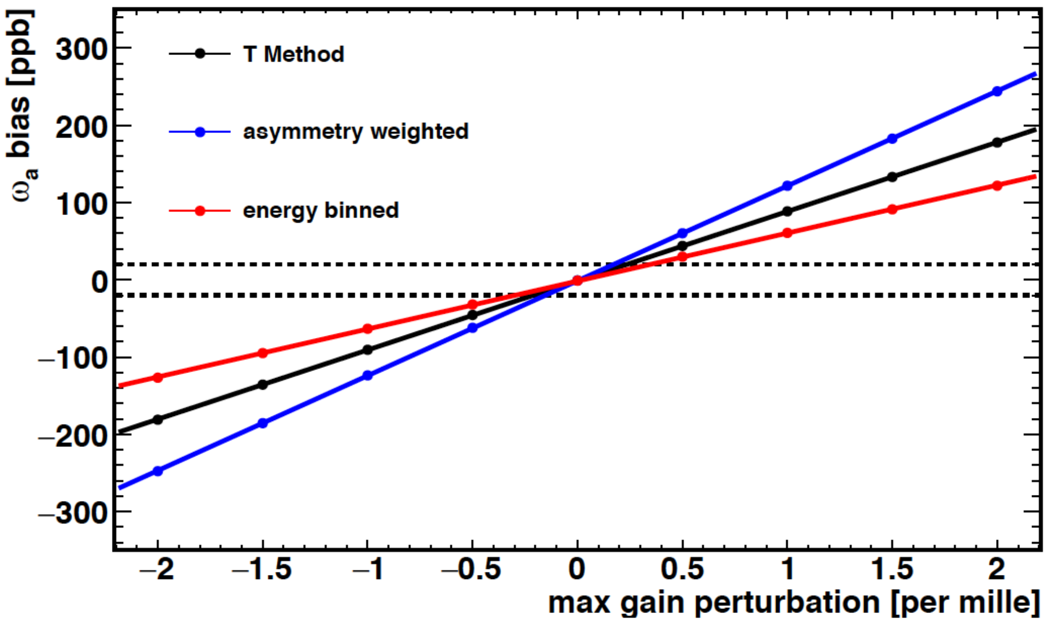


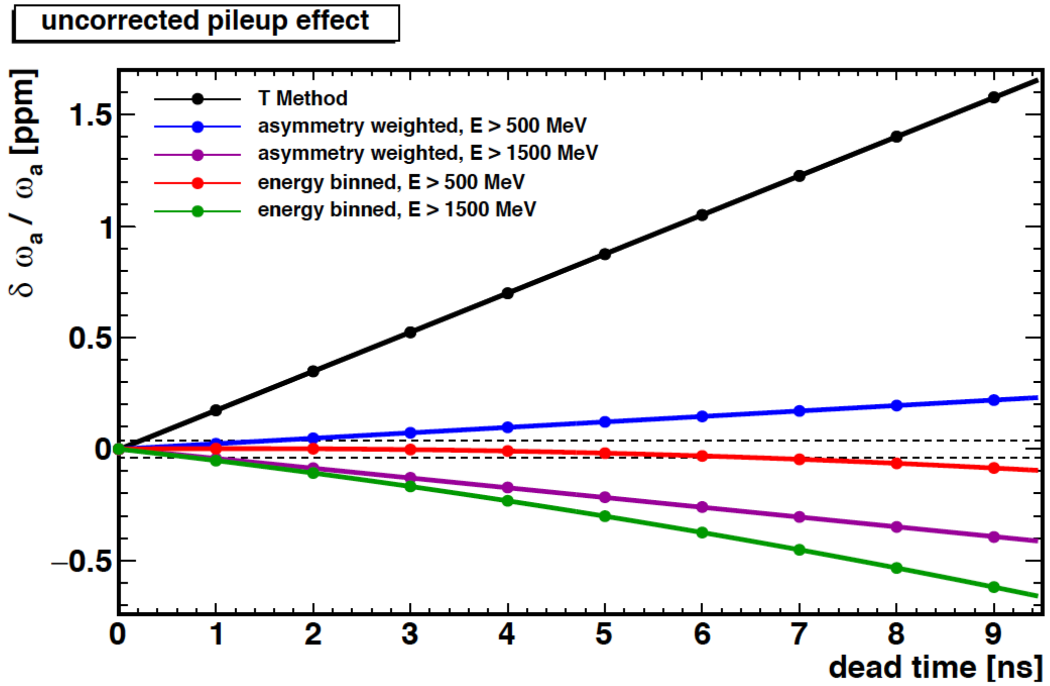
for small Δt,
probability of second pulse is $r(t)\Delta t$

pileup fraction is rate-dependent

Detectors can introduce early-to-late effects

results from toy MC



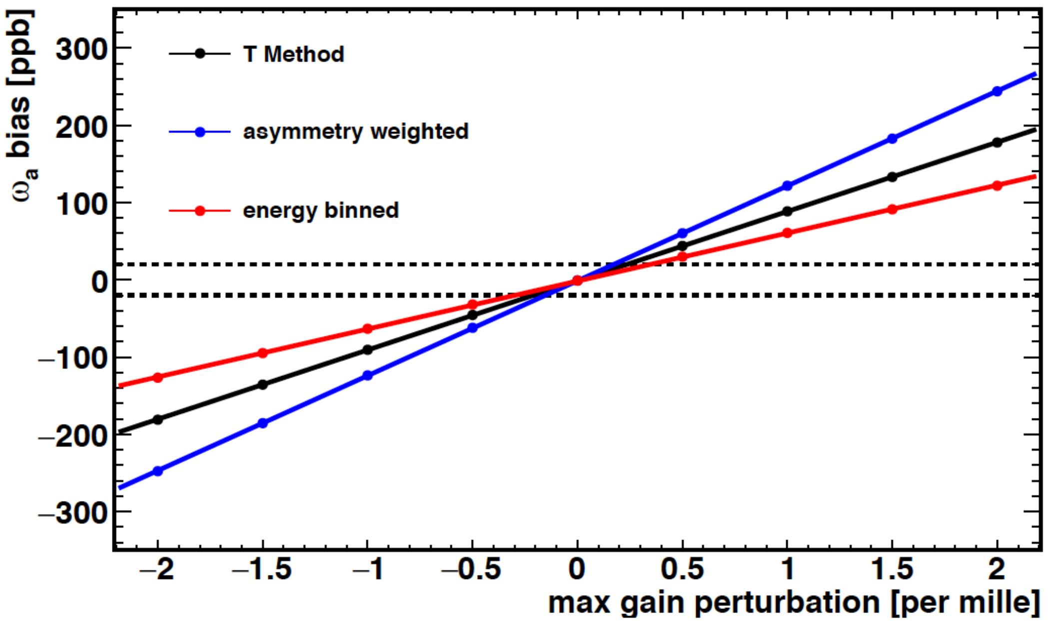


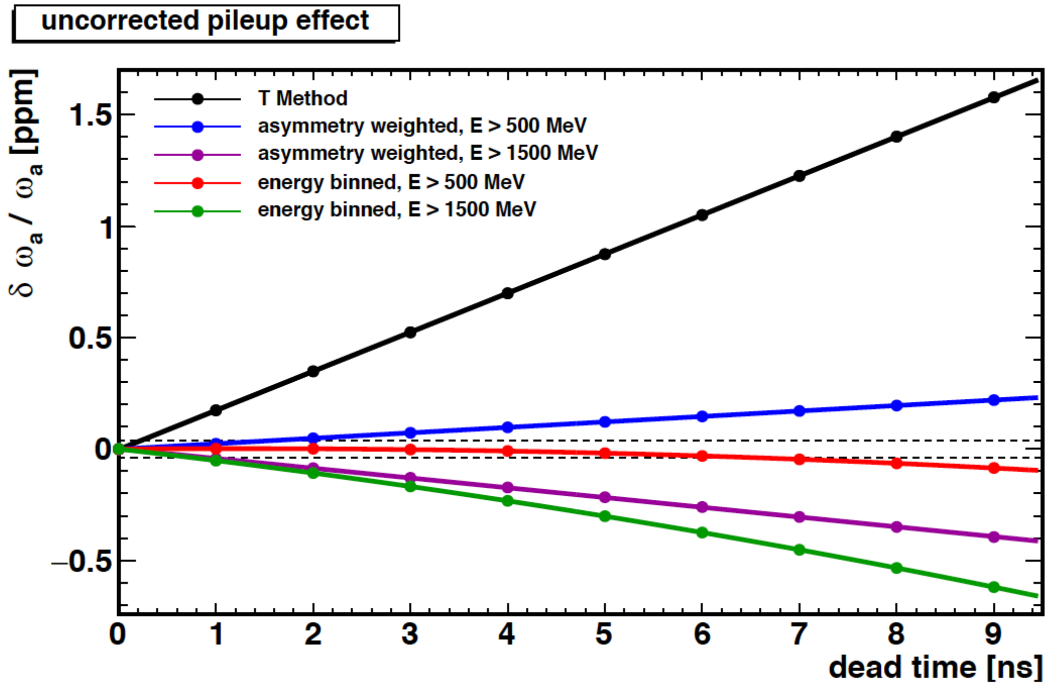
gain must be stable to better than 0.05%

corrected deadtime must be below 1 ns

Detectors can introduce early-to-late effects

results from toy MC



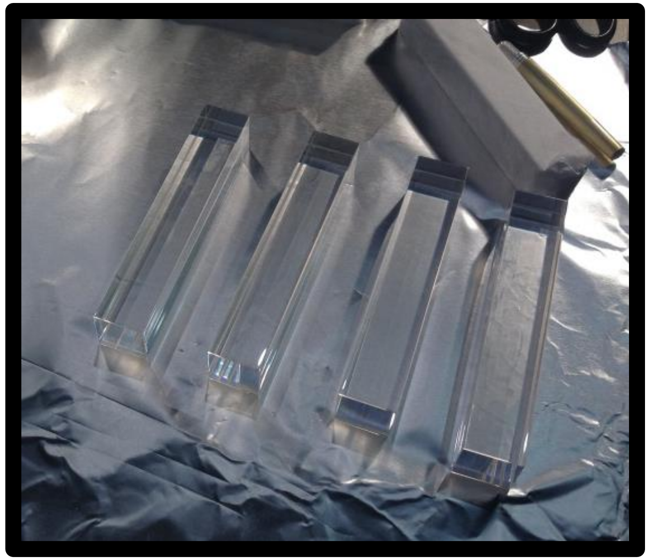


gain must be stable to better than 0.05%

corrected deadtime must be below 1 ns

these targets drove the **E989 calorimeter** design

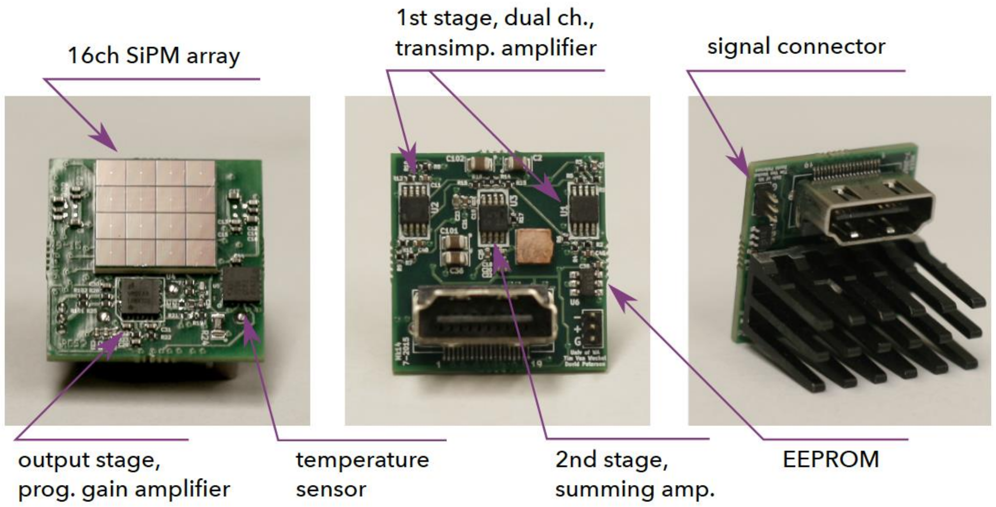
The E989 Calorimeter

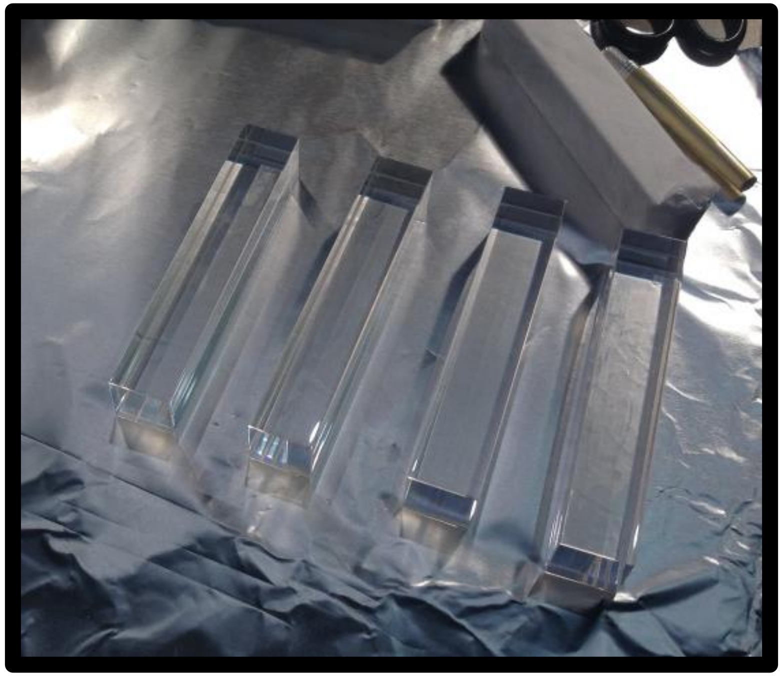


June 2013

June 2016

Segmented PbF_2 Calorimeter with SiPMs

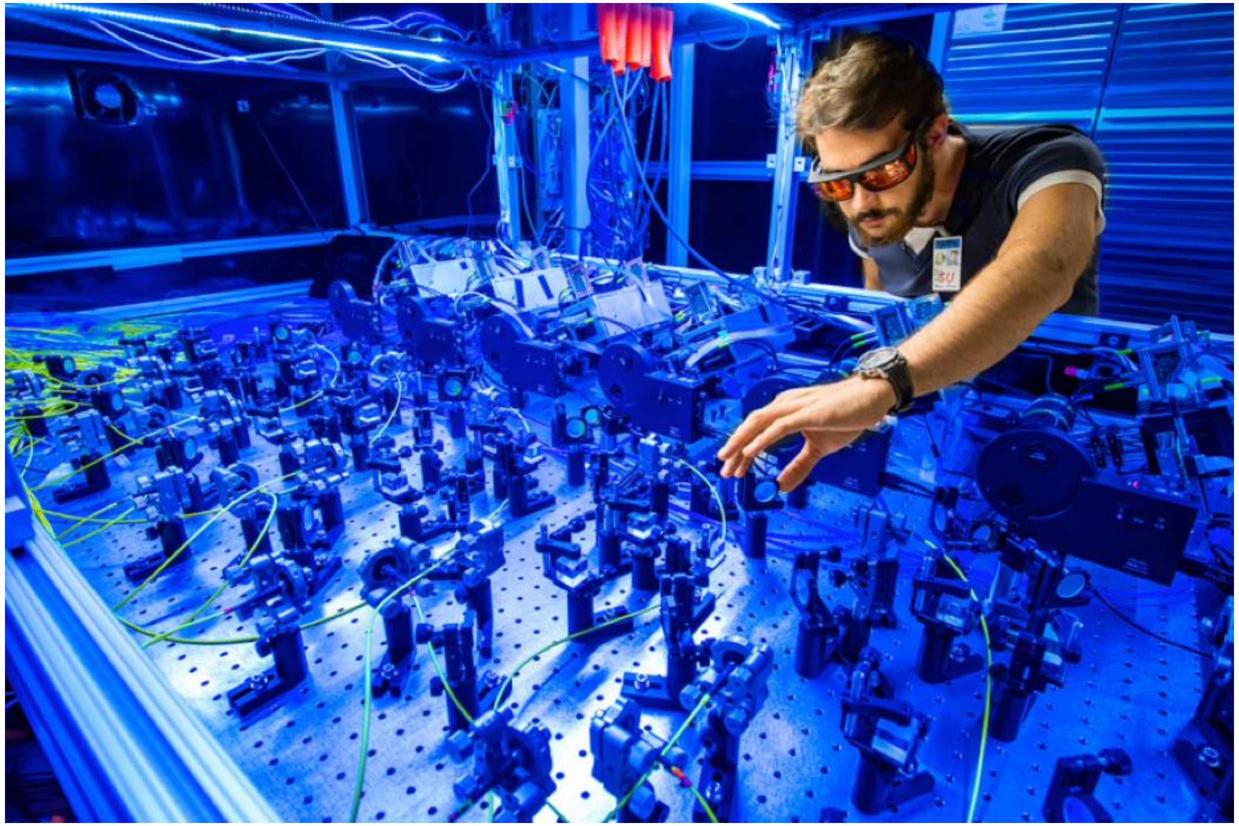




- SiPM readout designed at CENPA (UW)
- one per crystal
- 54 per calo, 1296 channels total
- ~10 ns pulses, operate in B field

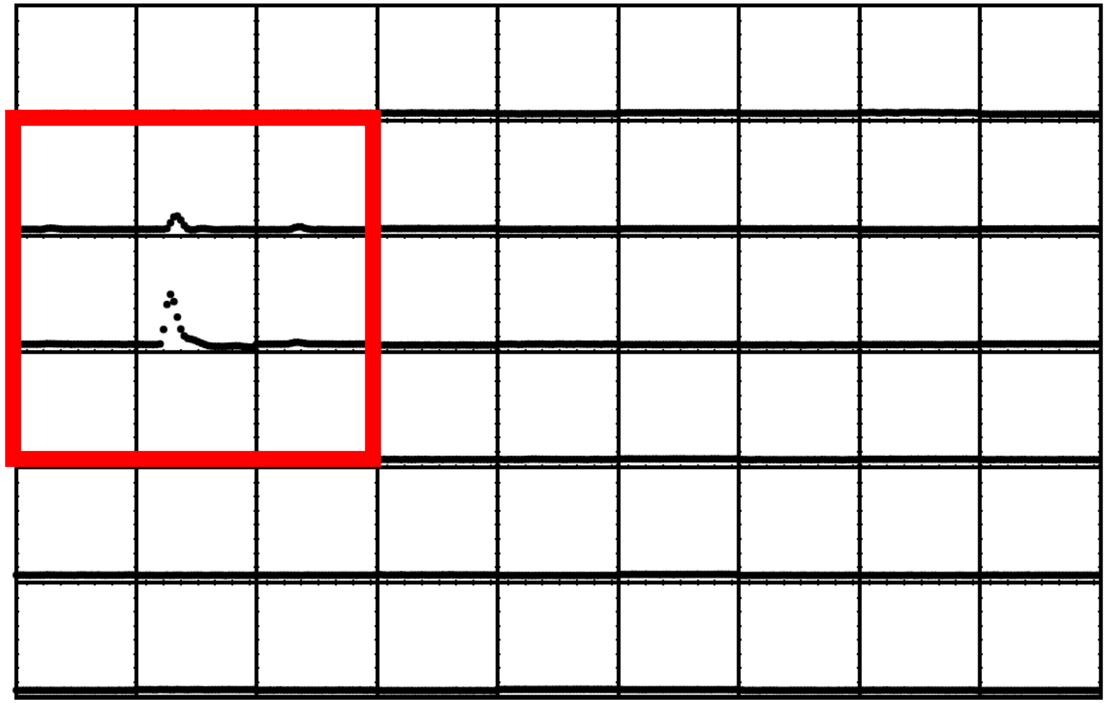
- PbF_2 grown by SICCAS
- dense Cherenkov radiator
- 2.5 cm by 2.5 cm by 14 cm
- 6 x 9 array

Laser system enables gain tracking and time synchronization



- feeds each calo channel
- per-fill time sync pulse
- in-fill, out-of-fill gain tracking
- dedicated systematic tests
- rigorous source monitoring

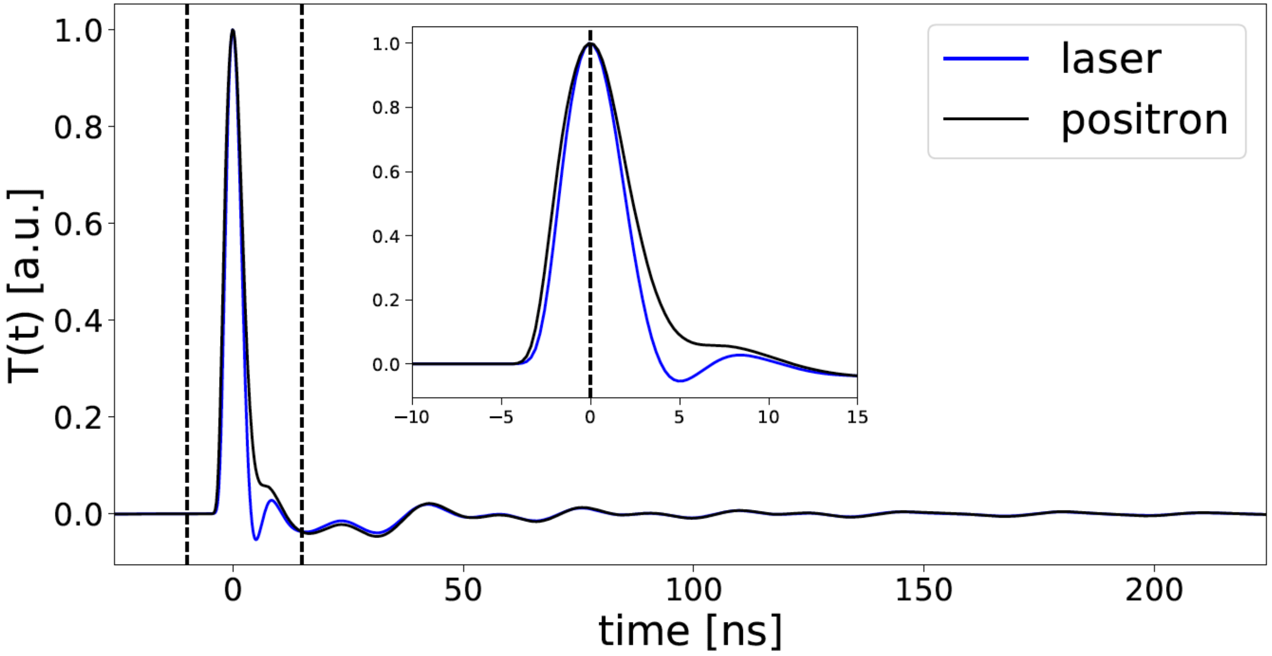
SiPM waveforms are digitized at 12-bit, 800 MS/s



digitized calorimeter island

- continuous digitization during muon fills
- ~40 ns islands saved for each pulse
- islands are initial input to reconstruction, $\boldsymbol{\omega_a}$ analysis
- reconstruction produces energies, times from islands

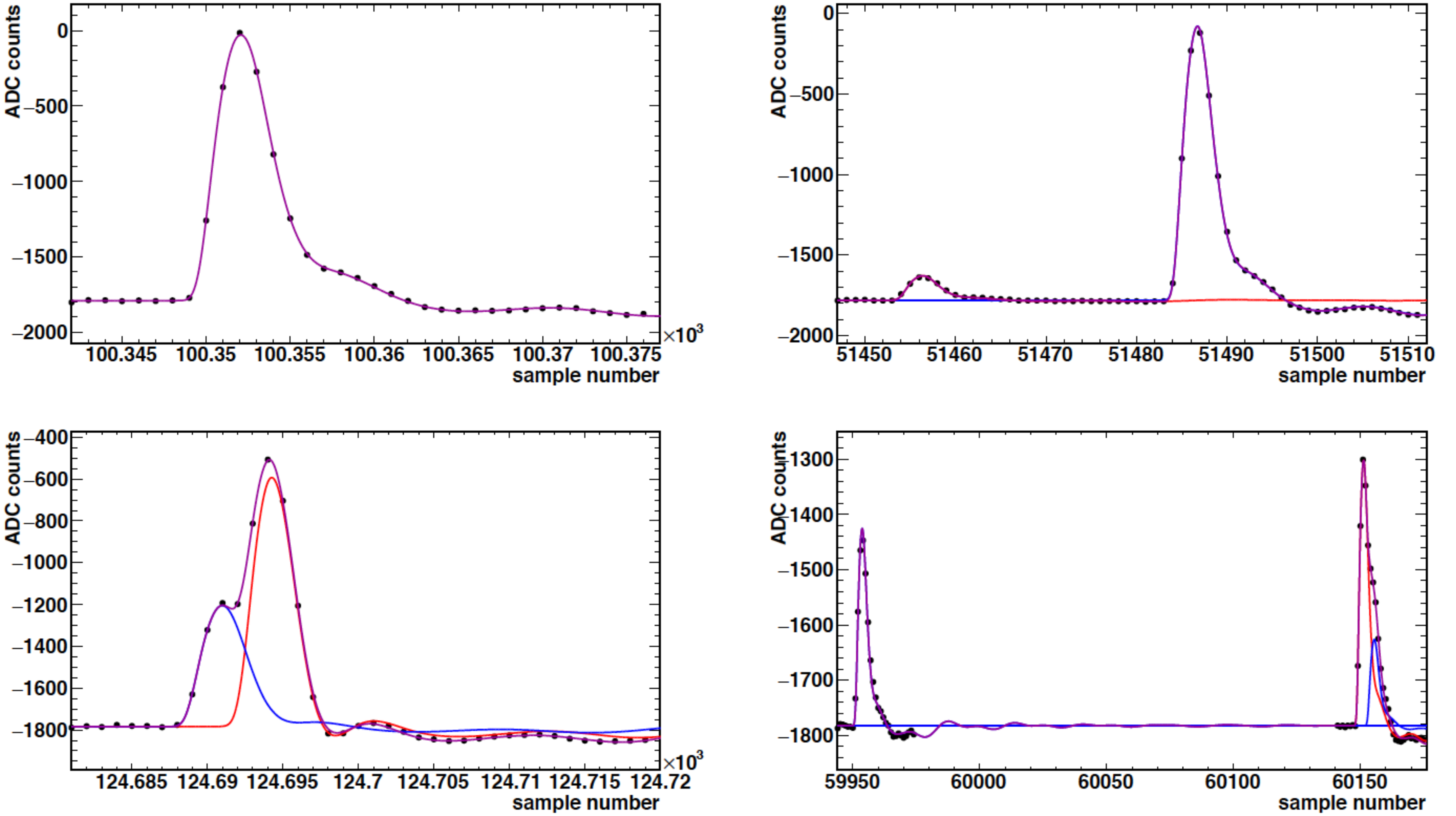
Pulses are fit with individualized templates



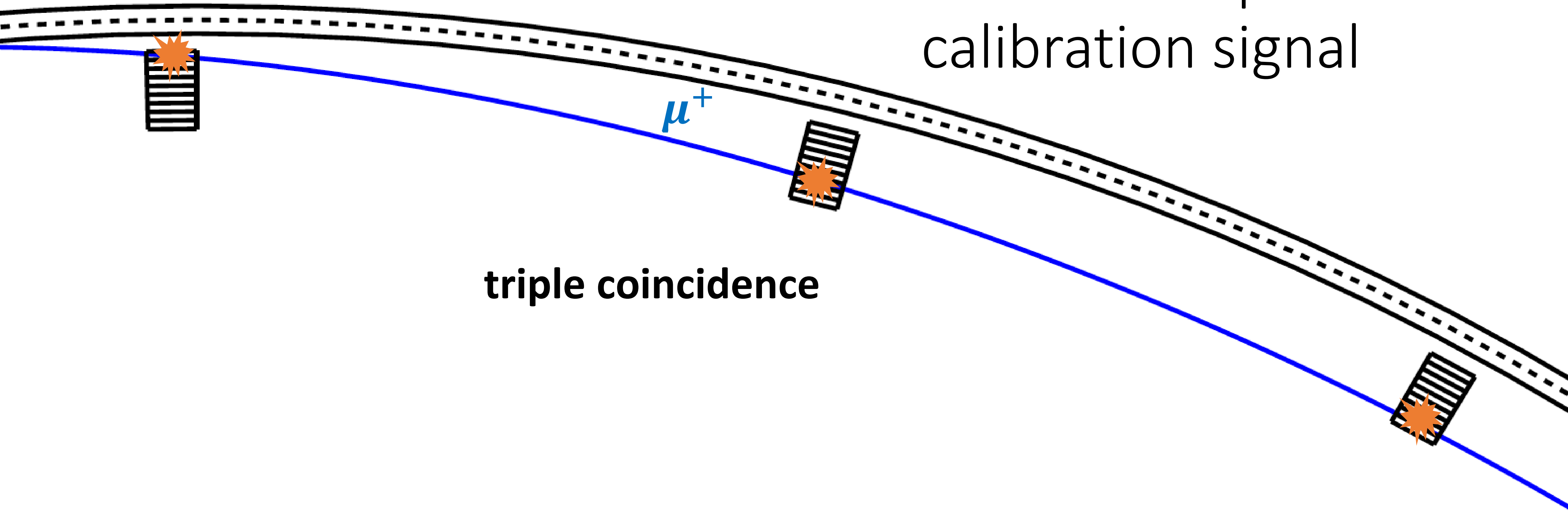
example SiPM templates

- dedicated templates for each channel
- separate laser, beam templates
- template stability verified, monitored
- enables fast multi-pulse fitting
- 2.5 ns fitting deadtime

Pulses are fit with individualized templates

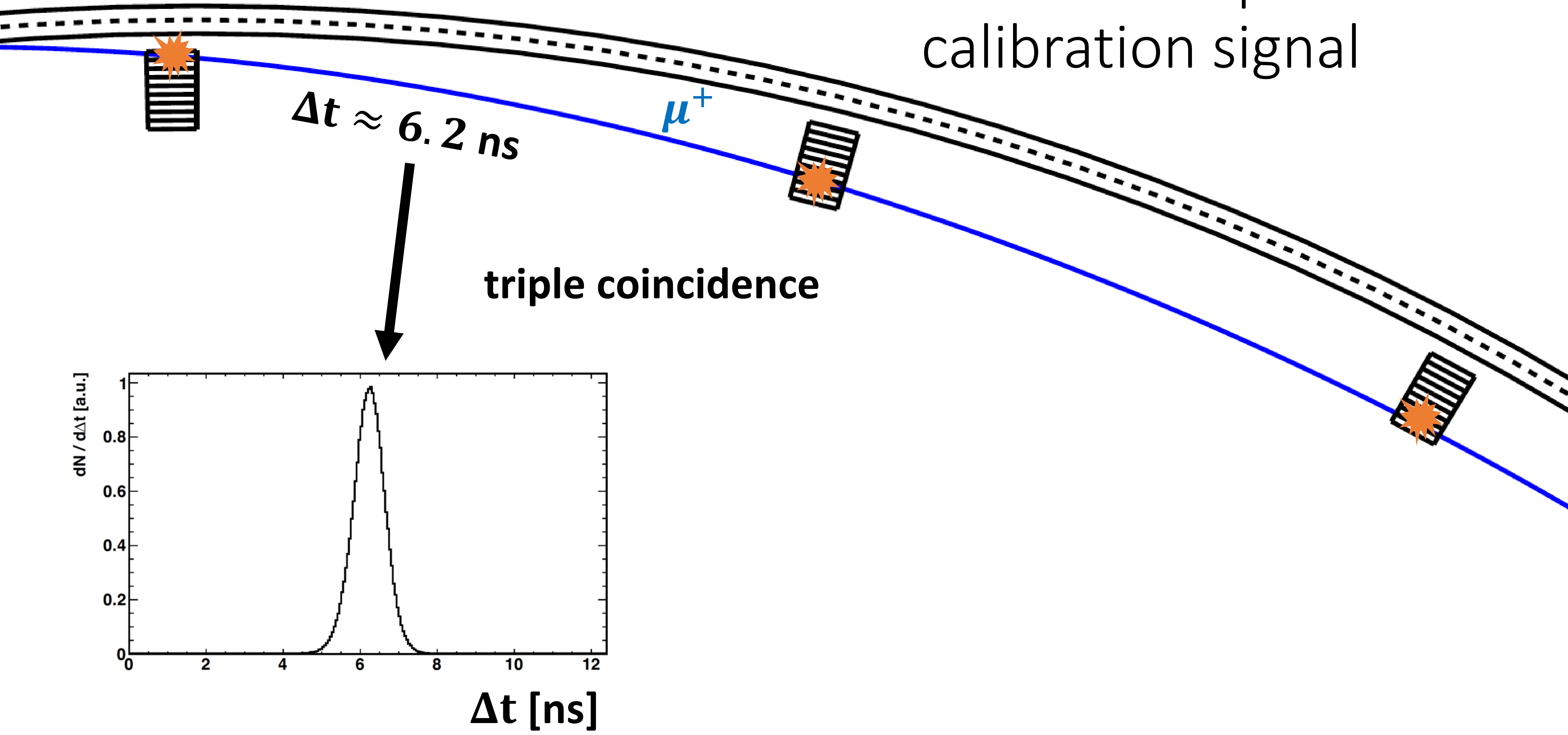


Lost muons provide a calibration signal



triple coincidence

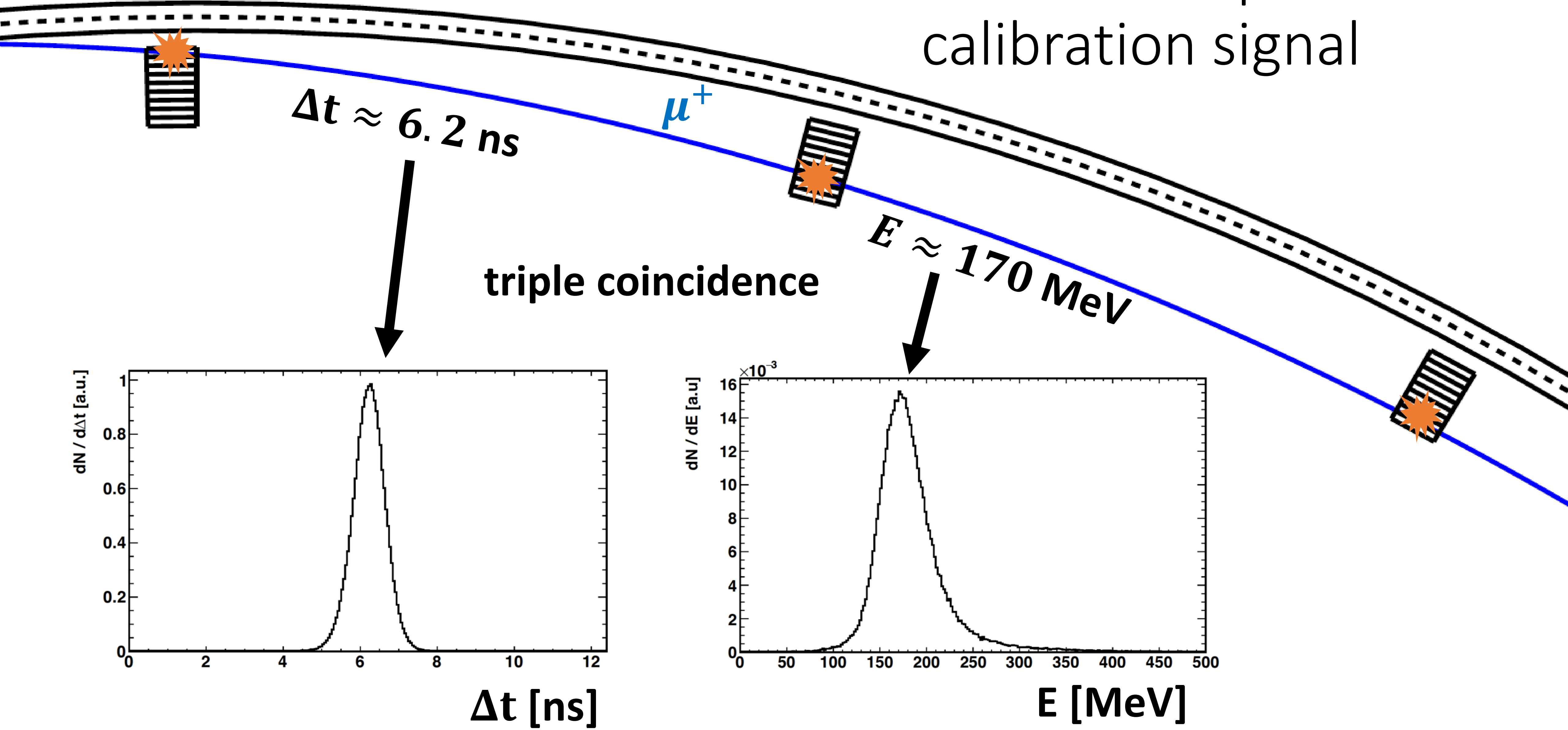
Lost muons provide a calibration signal



$\Delta t \approx 6.2\ ns$

triple coincidence

Lost muons provide a calibration signal



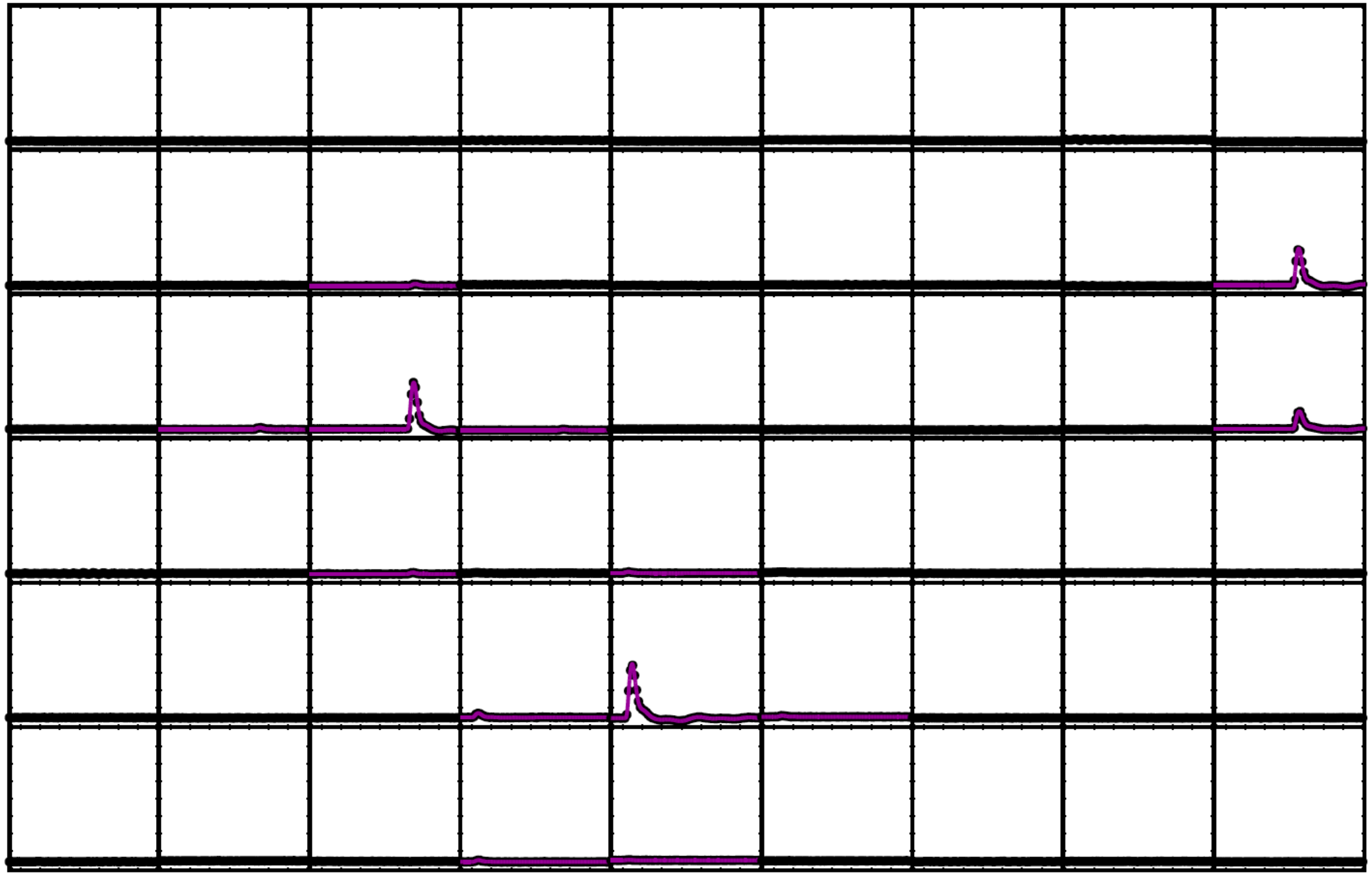
$\Delta t \approx 6.2\ ns$

μ^+

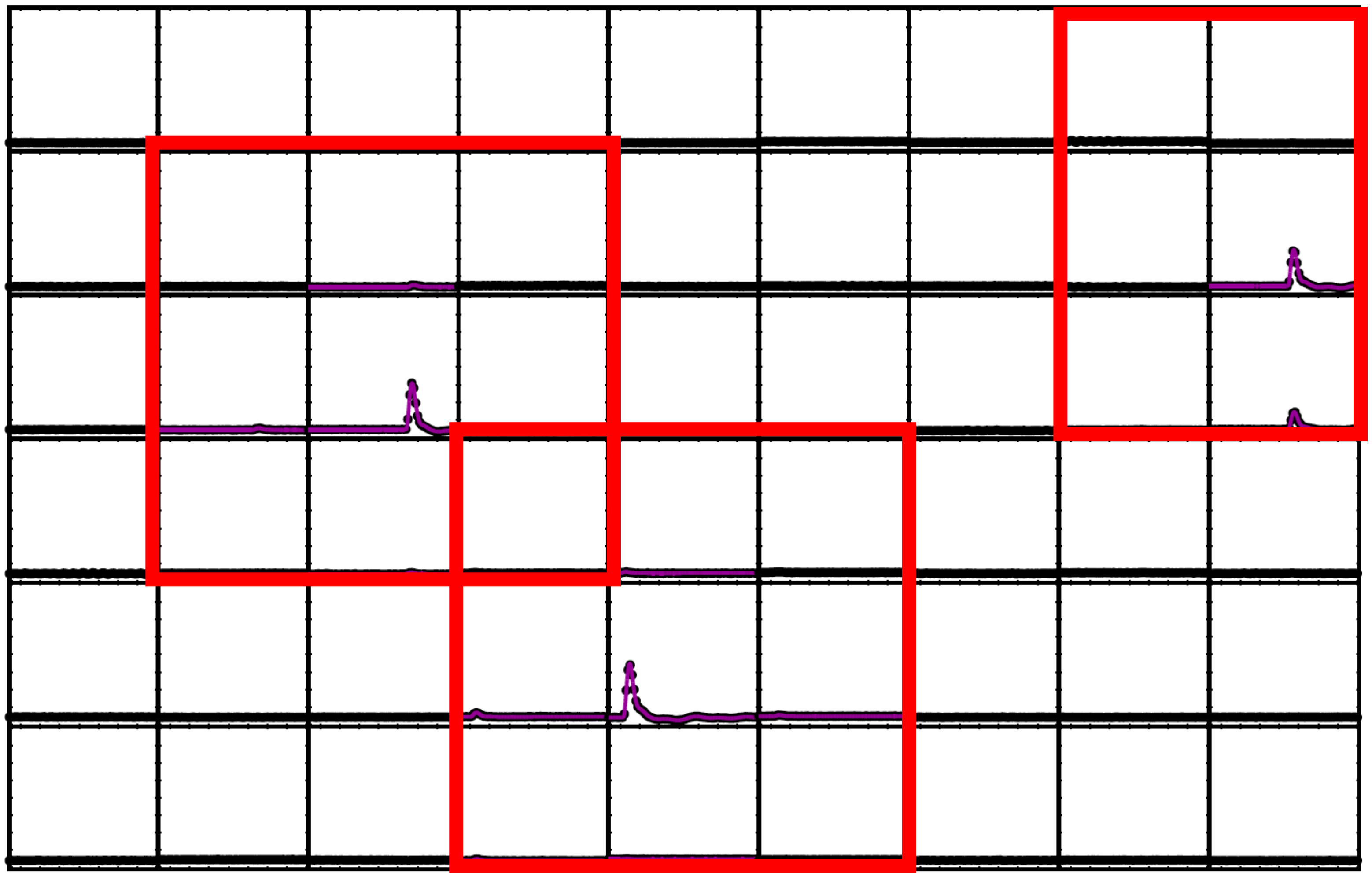
$E \approx 170\ MeV$

triple coincidence

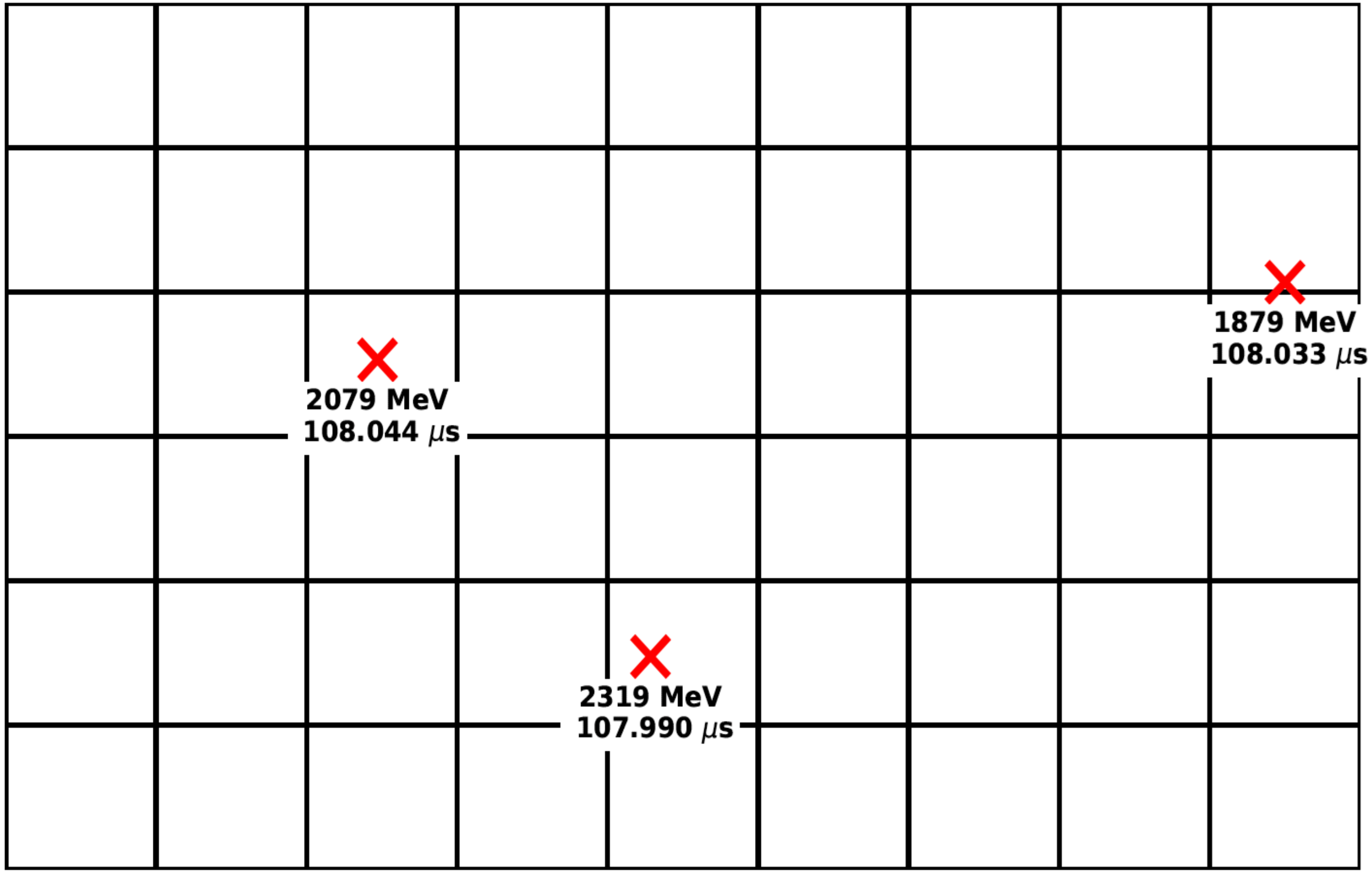
Calibrated fit results are combined into (E,t) pairs



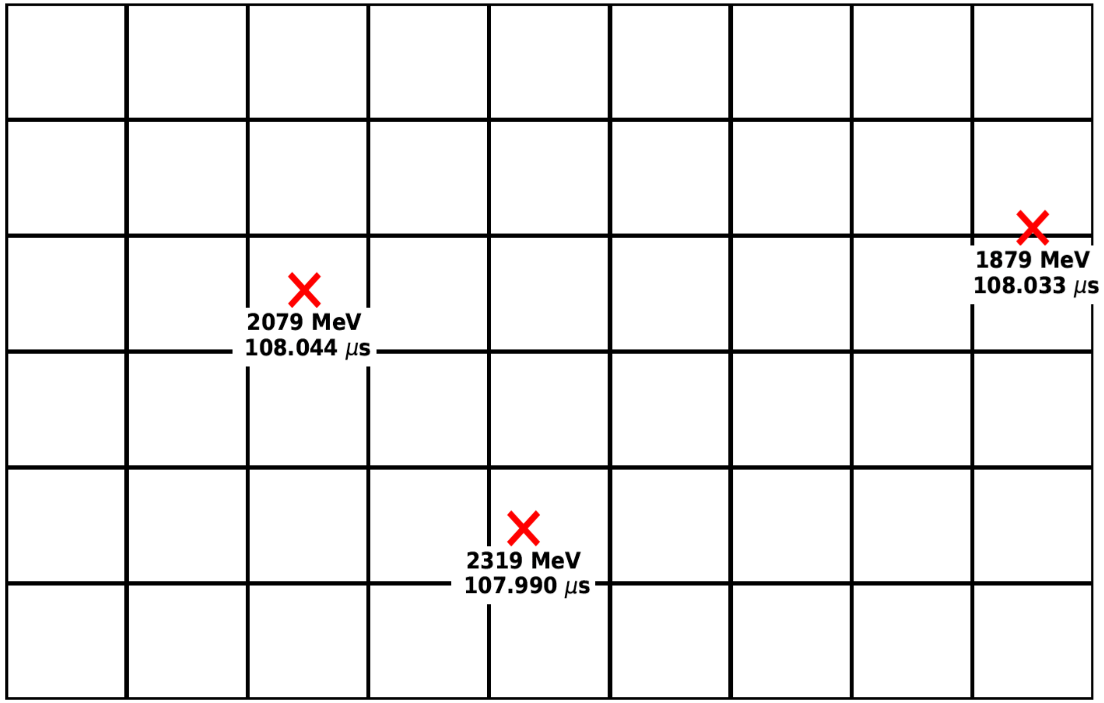
Calibrated fit results are combined into (E,t) pairs



Calibrated fit results are combined into (E,t) pairs



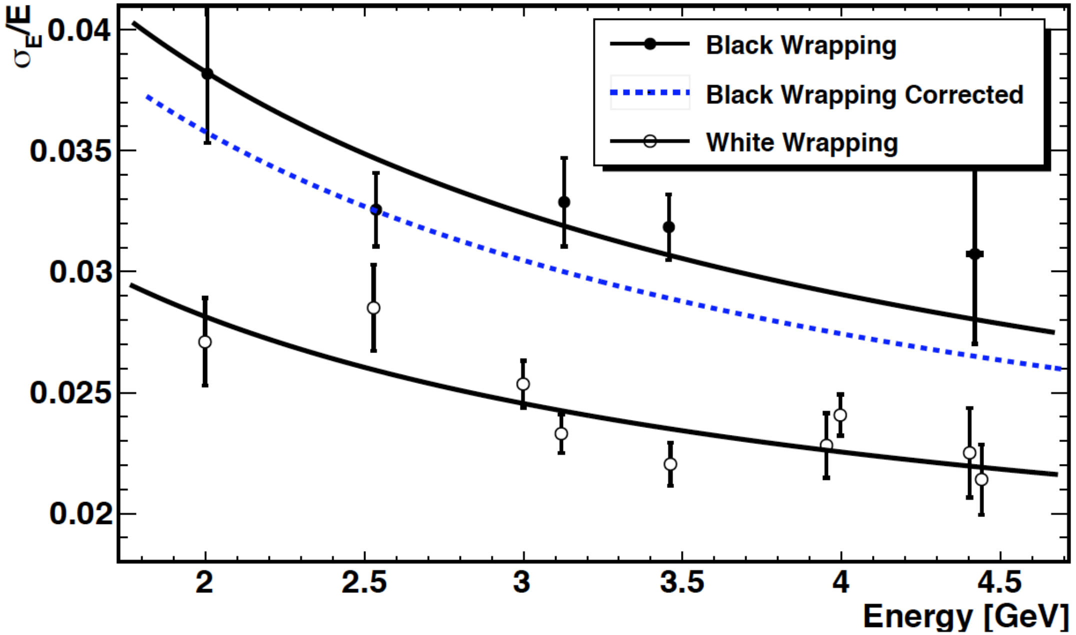
Calibrated fit results are combined into (E,t) pairs



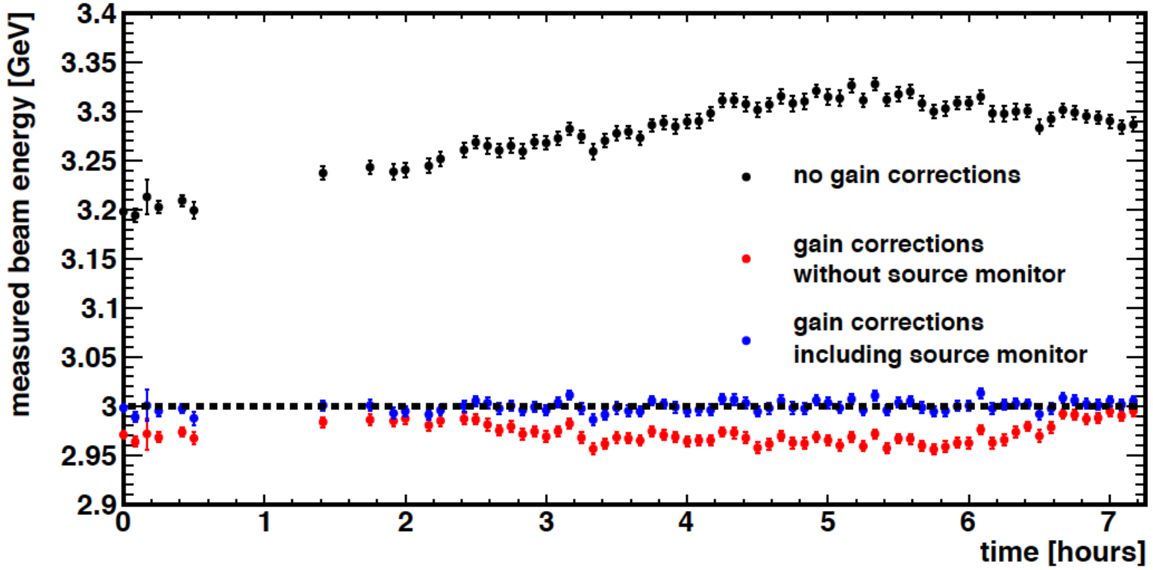
- multiple clustering algorithms
- position reconstruction
- optional spatial pileup separation
  - ~70% separation efficiency

The calorimeter exceeds design specifications

energy resolution $\sim 4.5\% / \sqrt{\mathrm{E/GeV}}$



corrected gain stability < 0.1% / hour



selected test beam results

five technical publications on calorimeter development

Experiment Status and Analysis Progress

All frequency results are blinded

- digitizer frequency shifted by unknown value in range of ± 25 ppm

- relative analysis blinding according to:

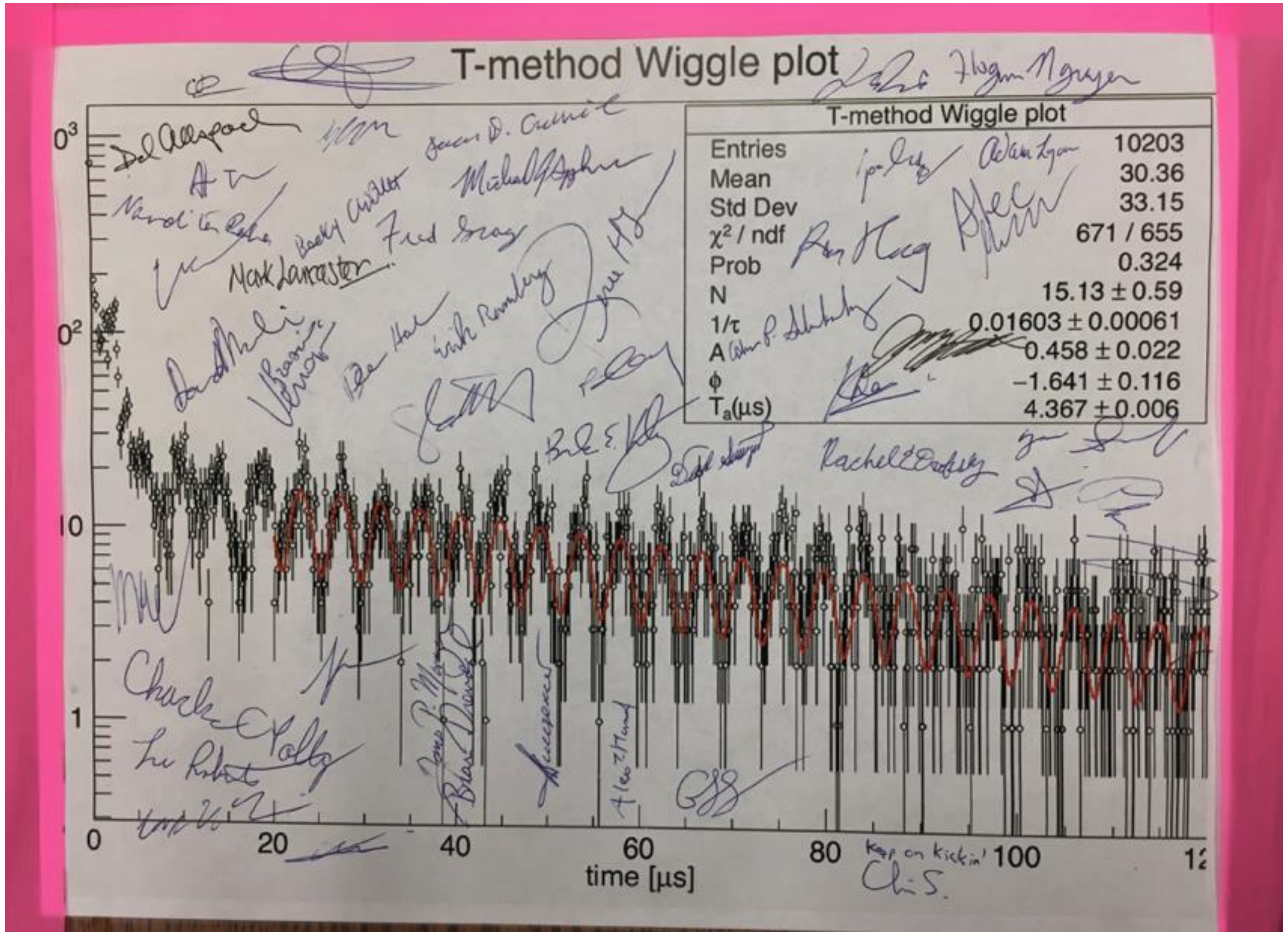
$$\boldsymbol{\omega_a}(R) = 2\pi\, 0.2291\, MHz \cdot [1 + (R \ - \Delta\mathrm{R}) \ \times \ 10^{-6}]$$

- field and precession analyses independent, different groups,
  - separately blinded
  - neither provides $\boldsymbol{a_\mu}$ on its own

2017 Commissioning: first ω_a measurement

June 10-11, 2017

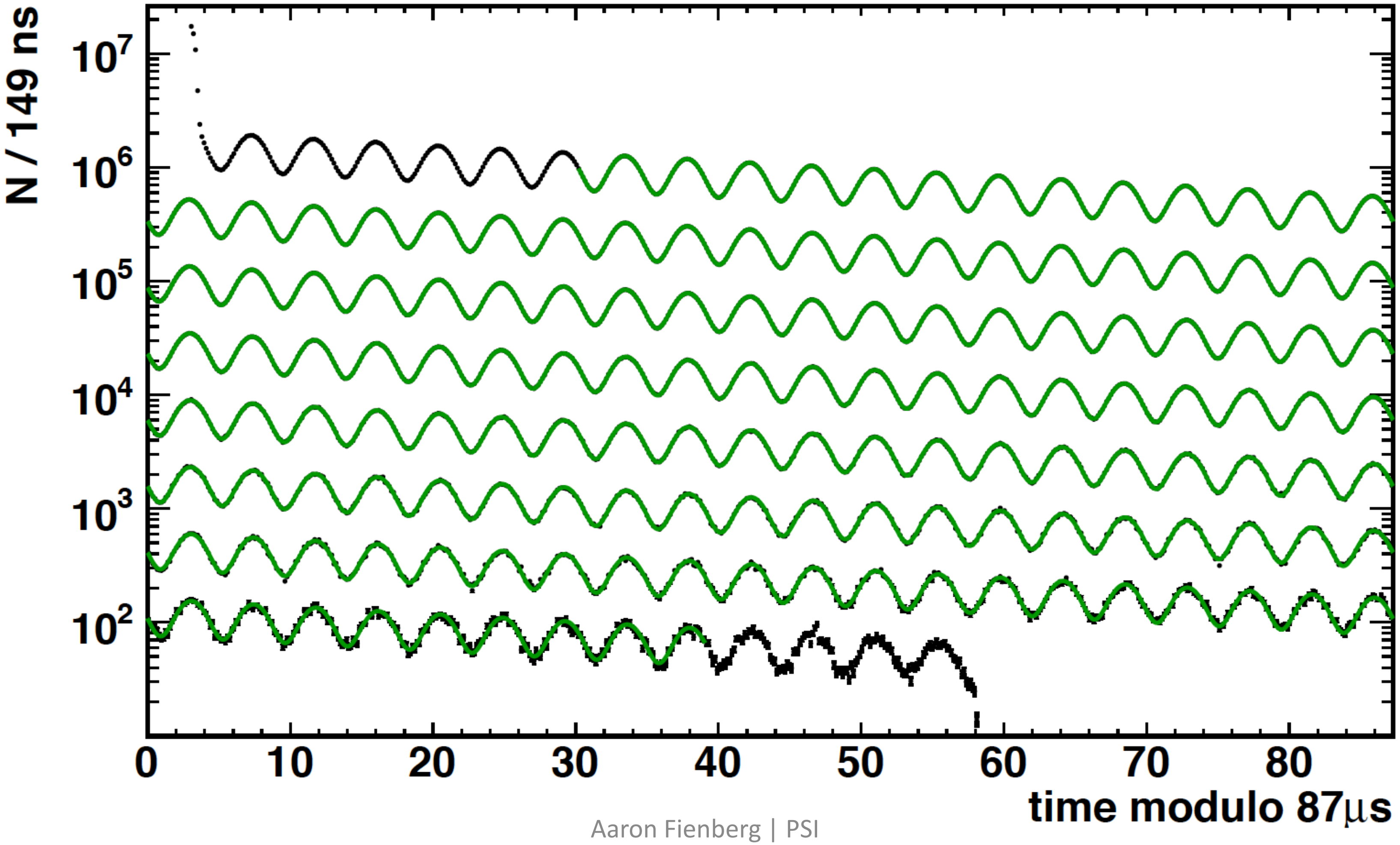
10^4 e^+, 0.1% precision



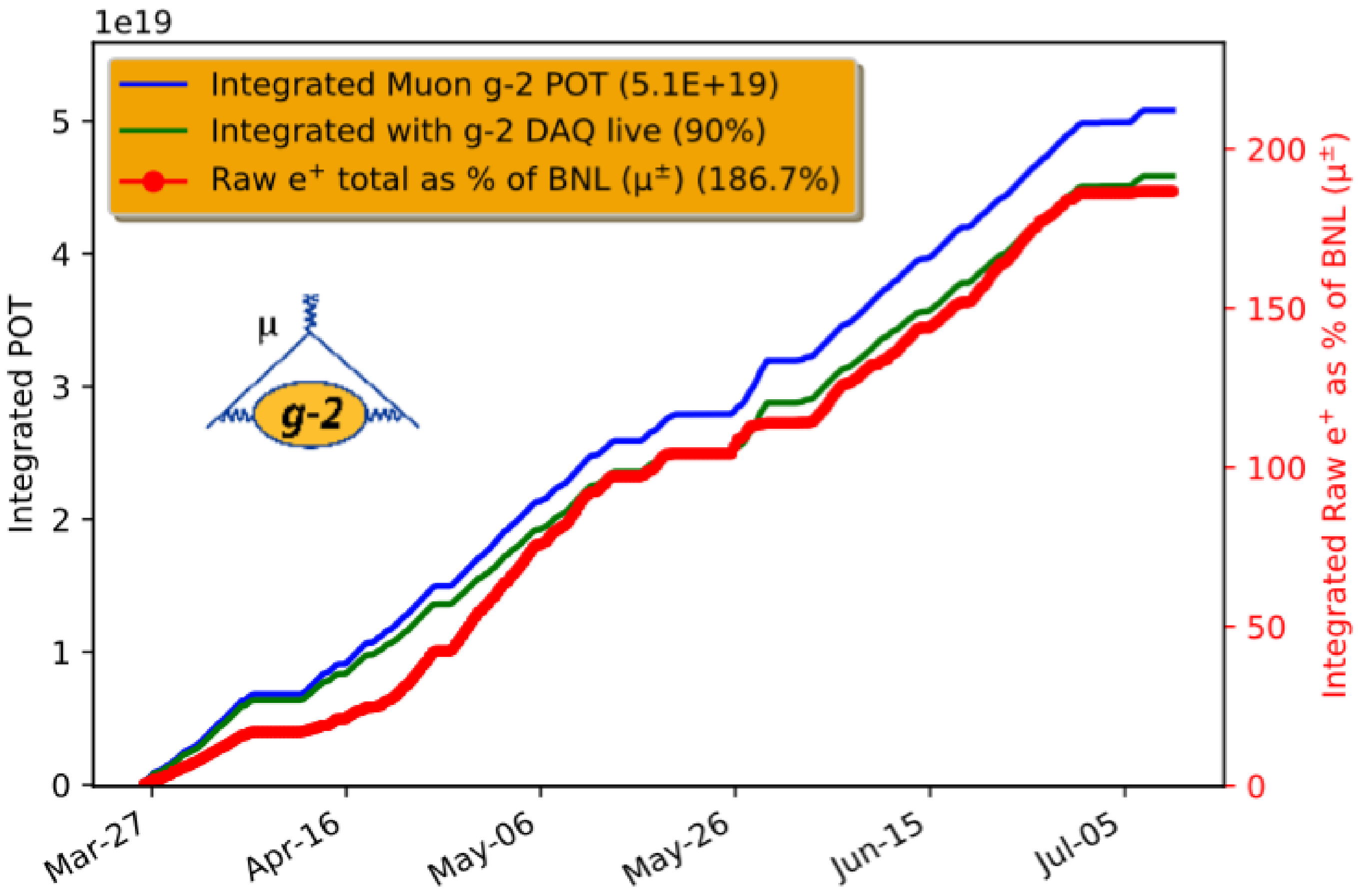
2018 Physics Run: 60-Hour Dataset

April 22-25, 2018

$10^9\ e^+$, 1.2 ppm precision

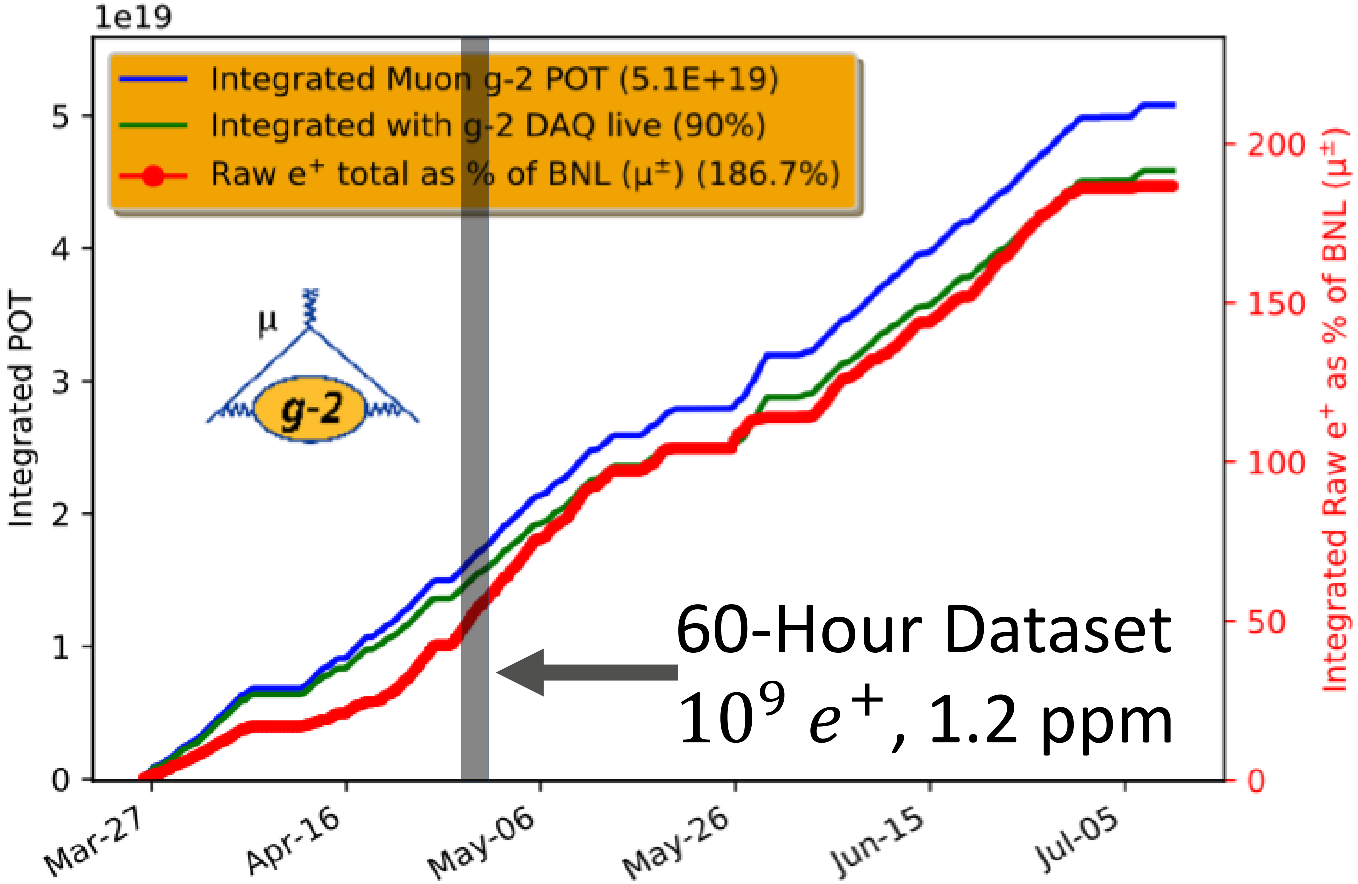


2018: E989 Physics Run 1 completed



- twice as many muons as BNL
- expect 400 ppb measurement
- analysis in progress
- planning for result this year

Analysis developed with the 60-Hour Dataset

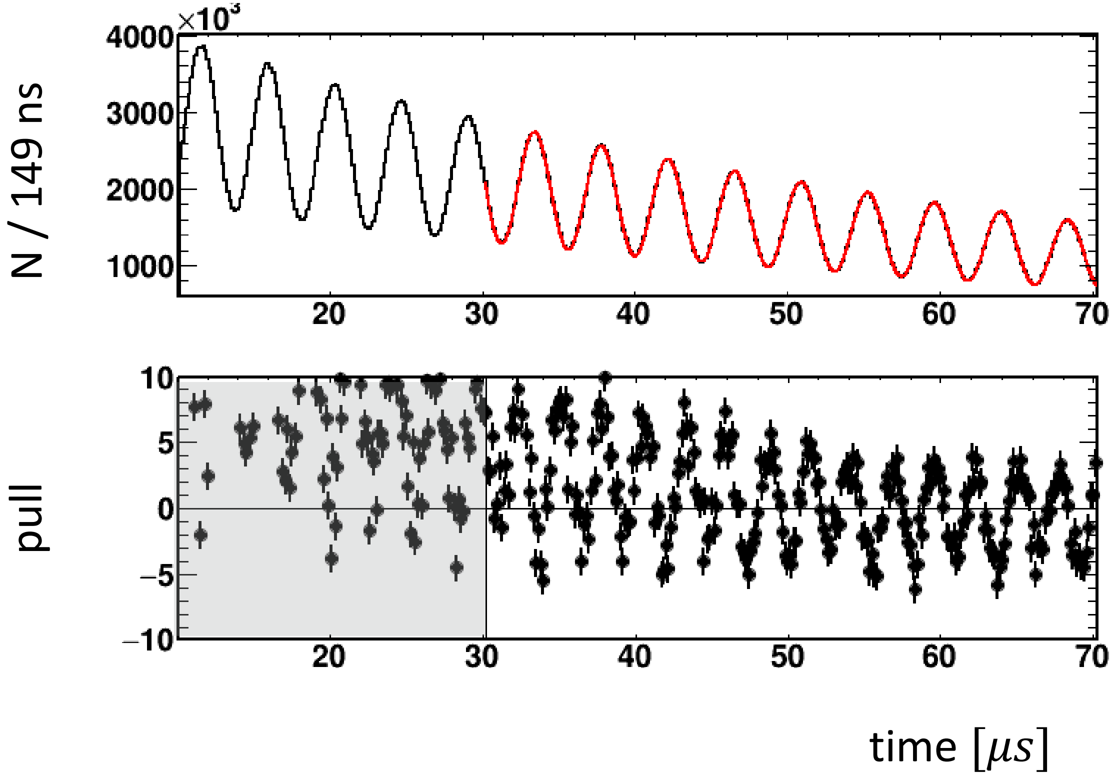


60-Hour Dataset
$10^9\ e^+$, 1.2 ppm

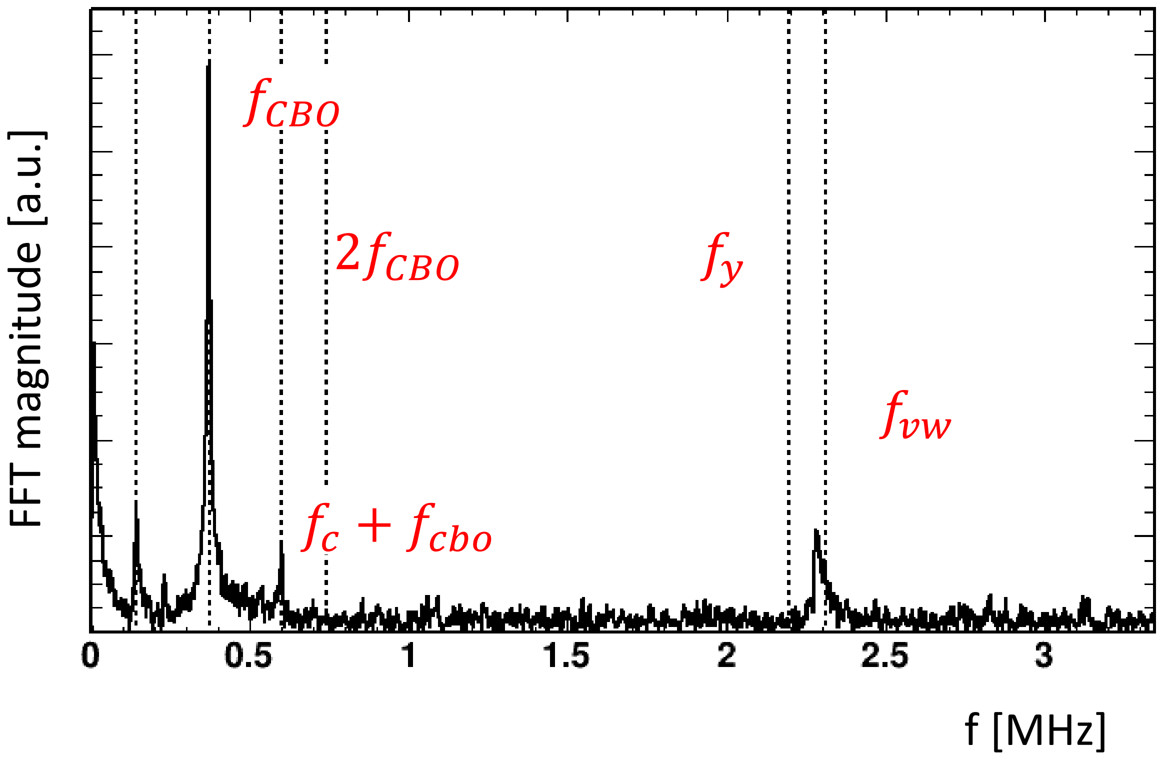
- six analysis teams
- three reconstructions
- many systematic effects

Model with only muon precession is inadequate

$\chi^2/\,ndf = 9500/4150$



FFT of fit residuals

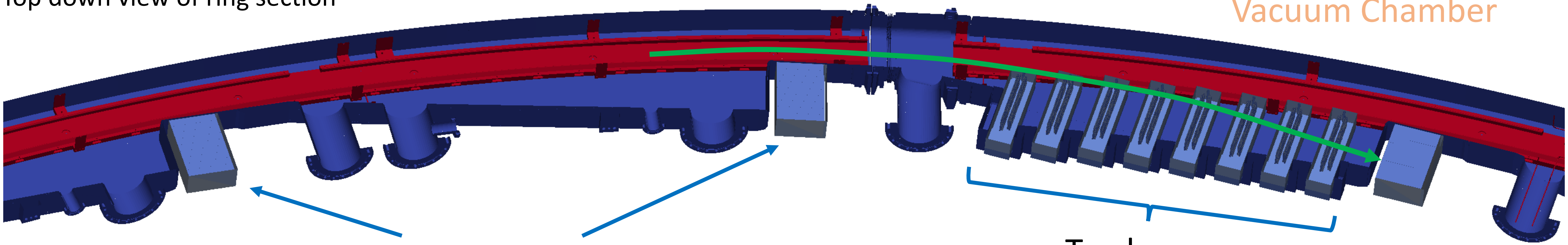


slow component

beam oscillation frequencies evident

Tracking detectors inform beam oscillation models

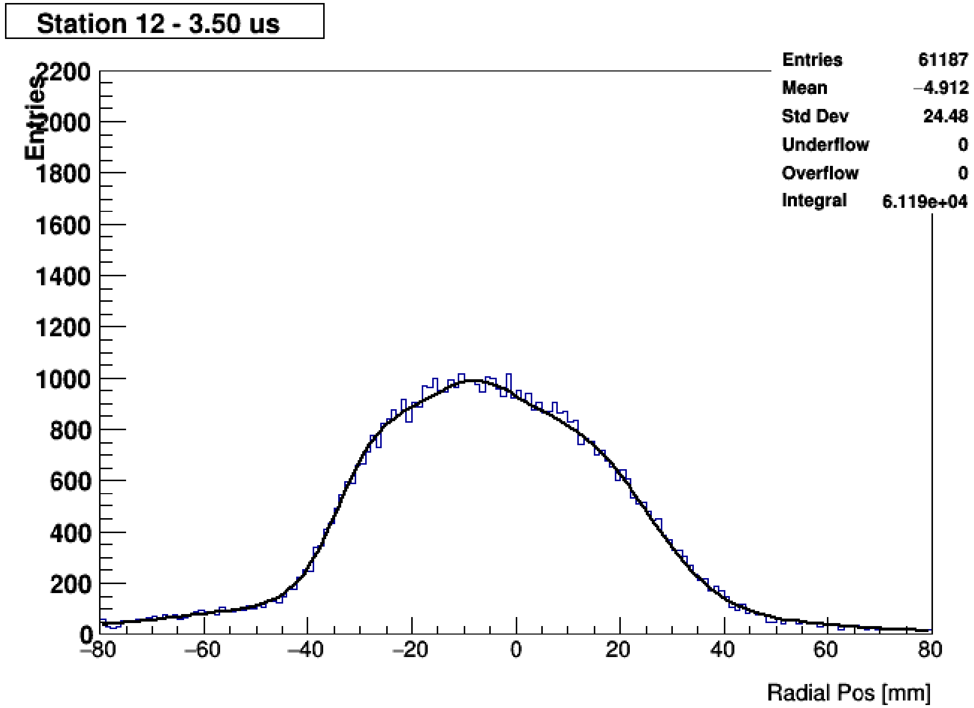
Top down view of ring section

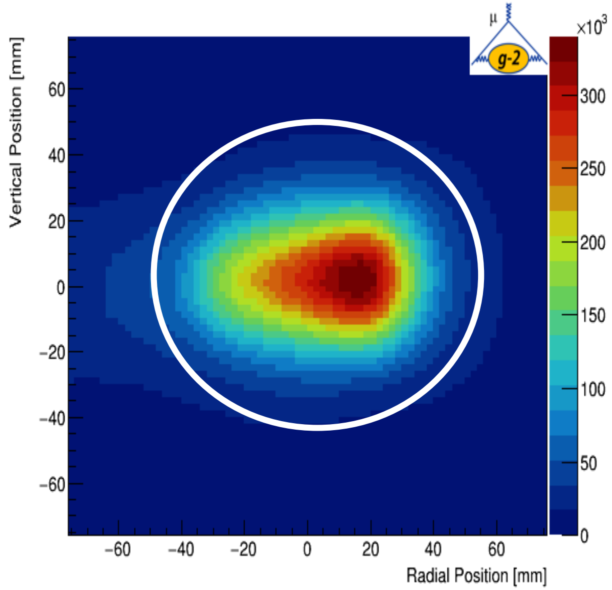


Vacuum Chamber

Calorimeters

Tracker

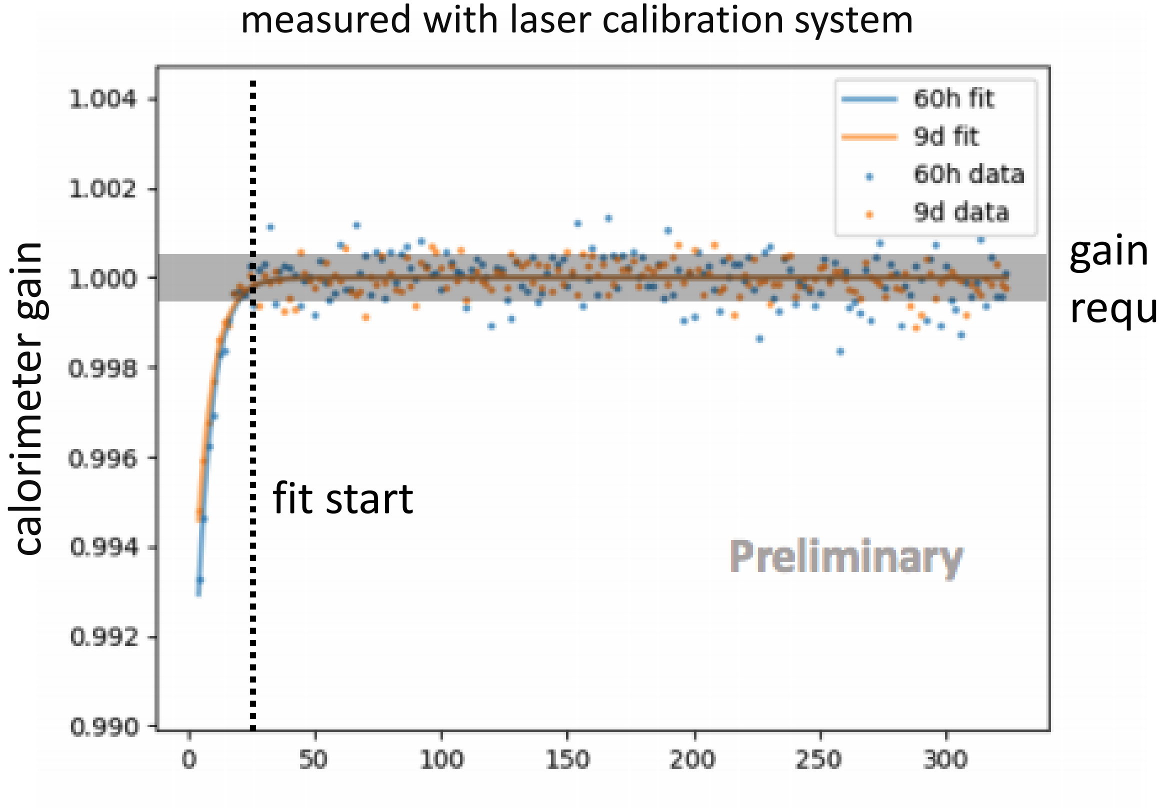




extrapolated decay vertices

Detector effects are also significant

measured with laser calibration system



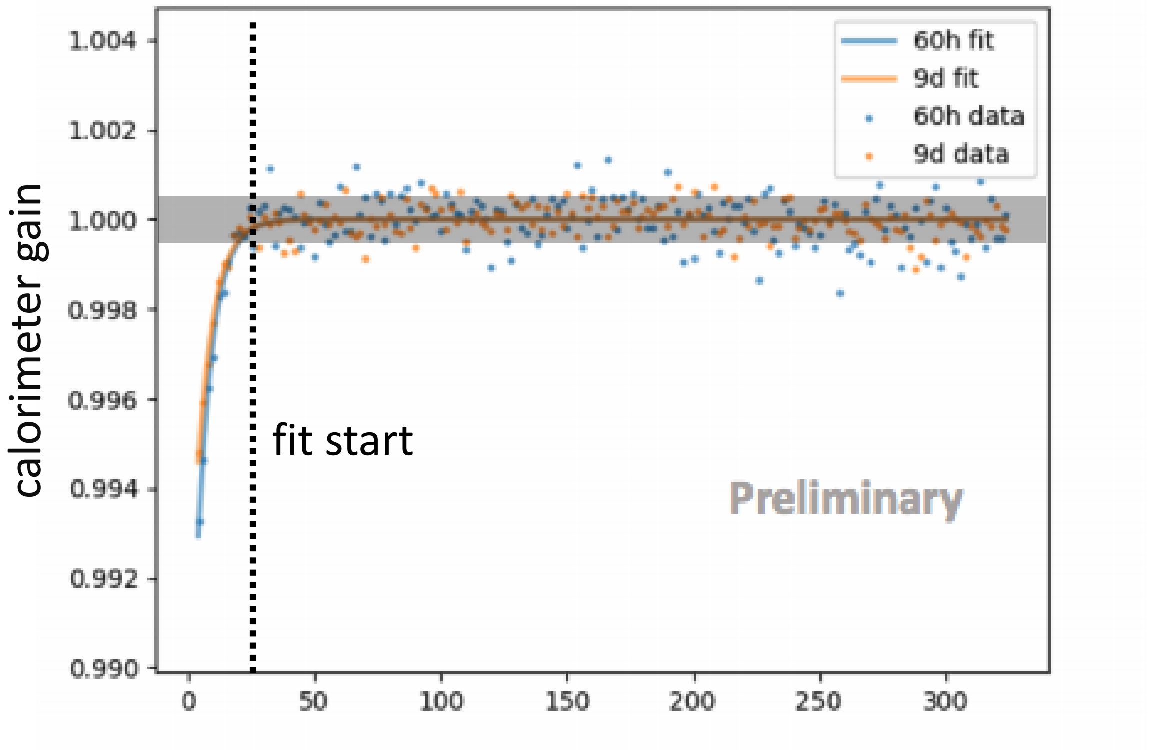
fit start

gain stability requirement

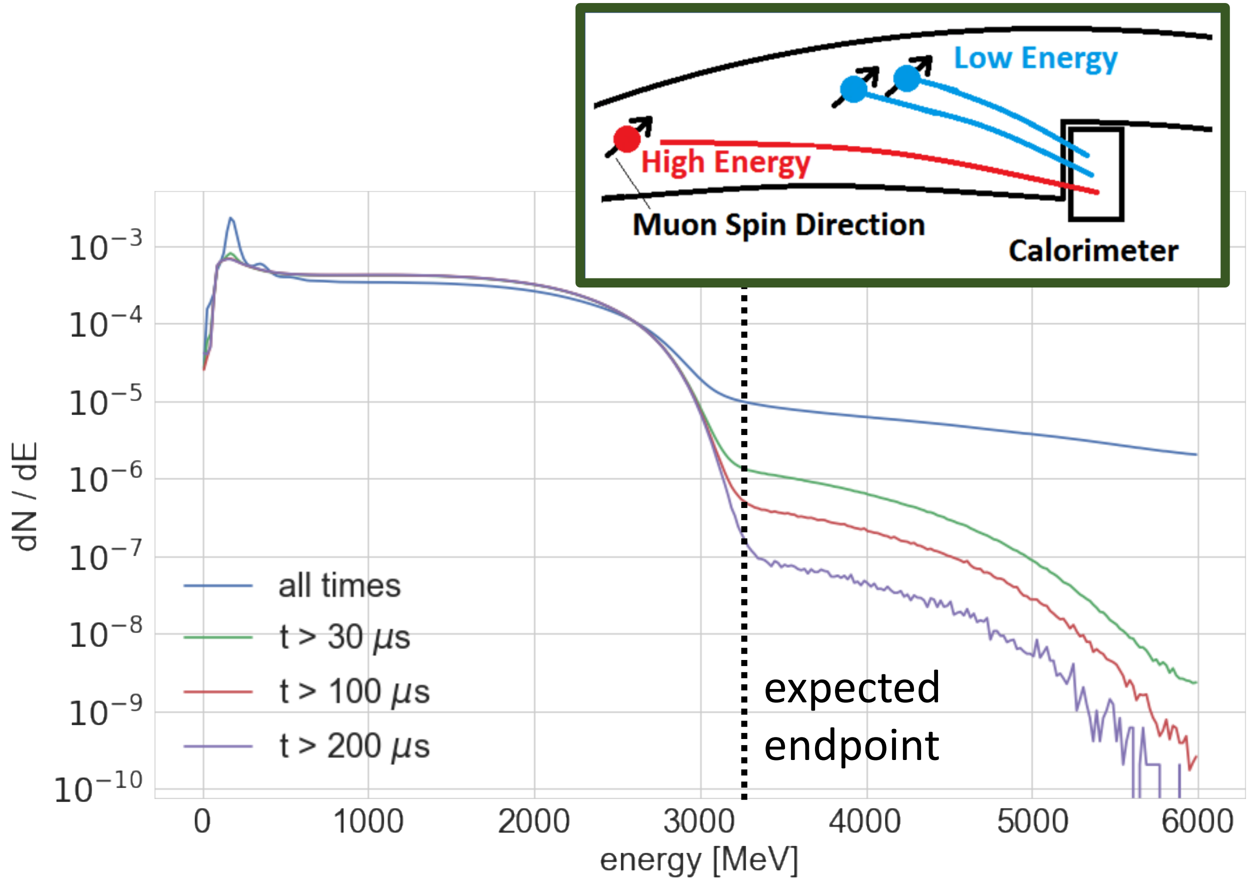
time correlated gain changes measured with laser system

Detector effects are also significant

measured with laser calibration system

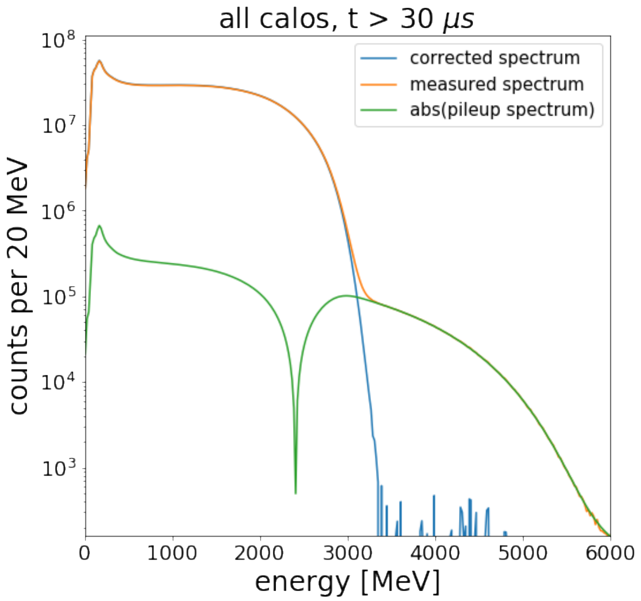


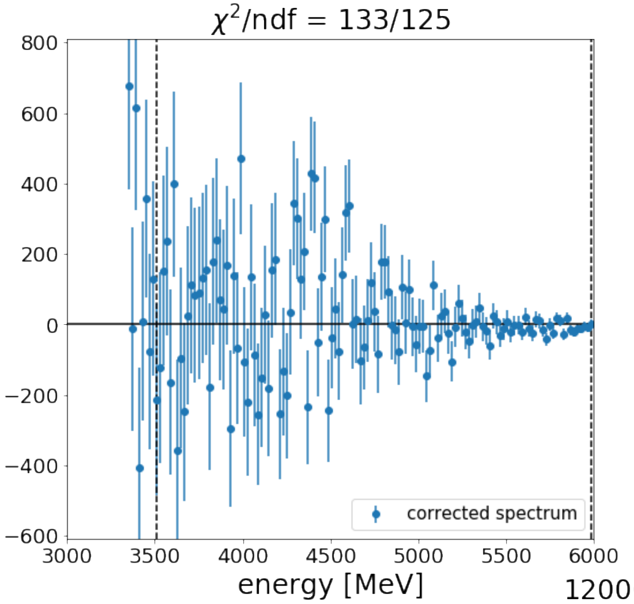
time correlated gain changes measured with laser system



unresolved pulse pairs (pileup)

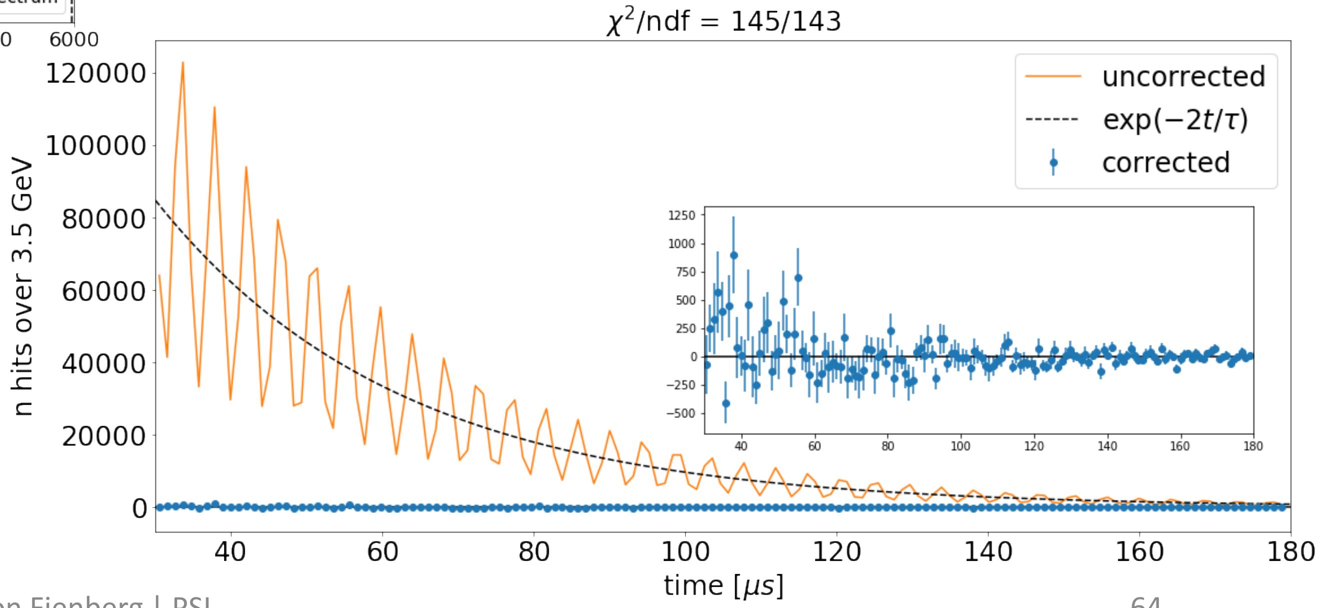
A pileup correction is extracted from the data



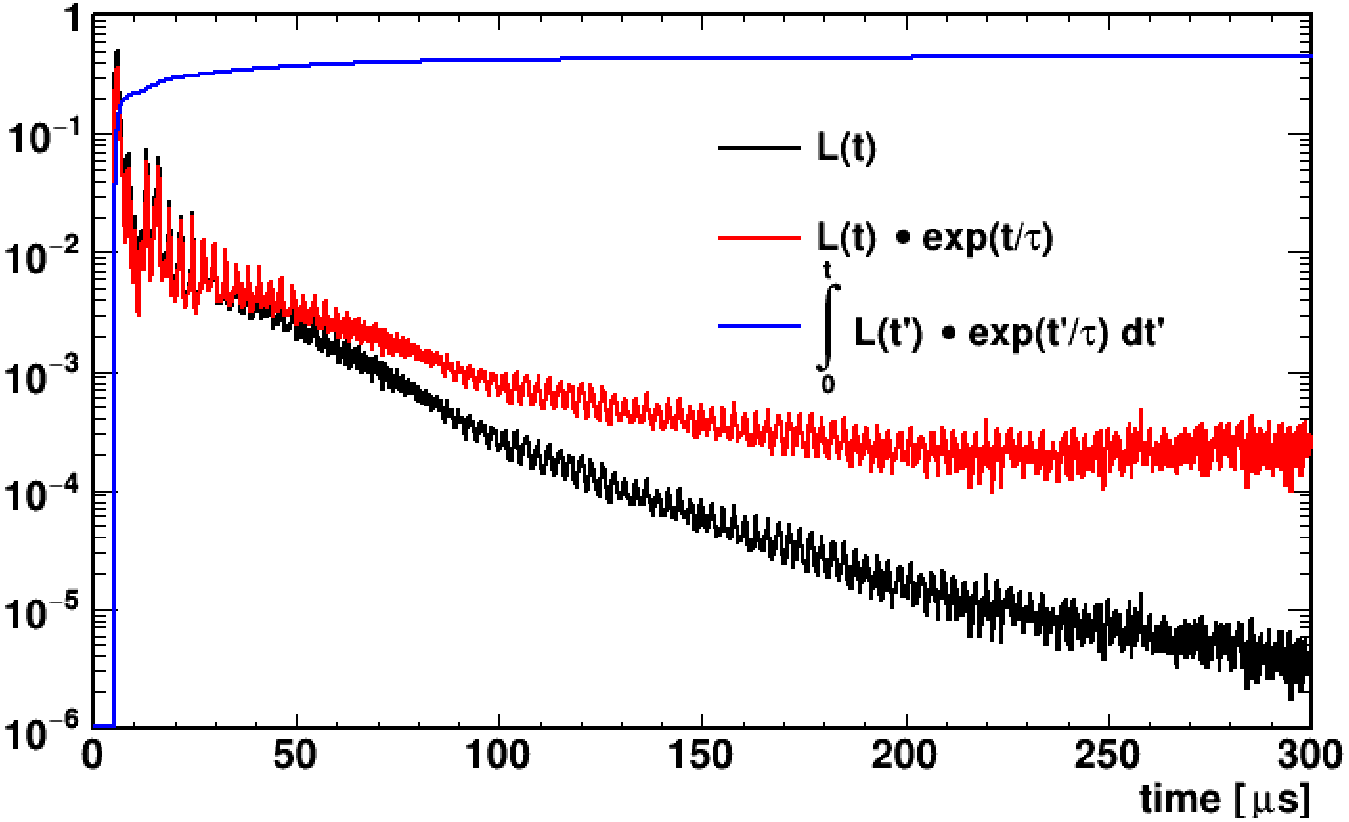


pileup correction removes high energy tail

does so at all times



A correction for muon losses is required

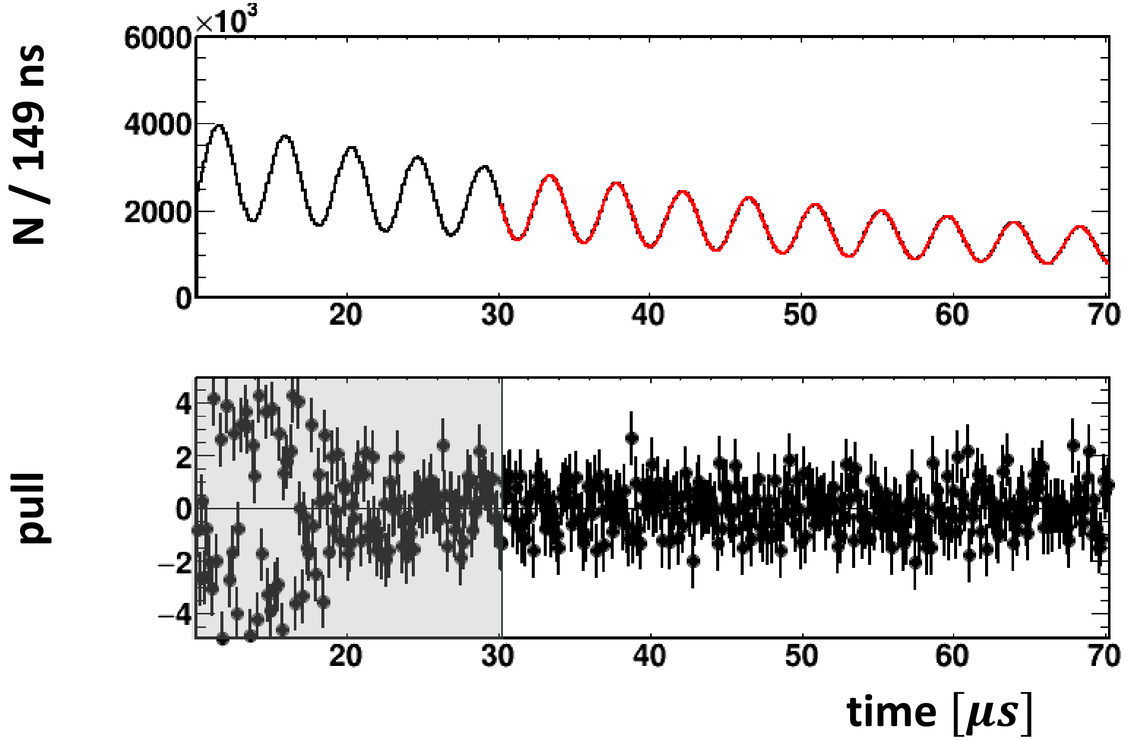


- L(t) is loss rate
- taken from triple coincidences
- $N_0 \rightarrow N_0 \left(1 - K_{loss} \int_0^t e^{t'/\tau} L(t') dt' \right)$

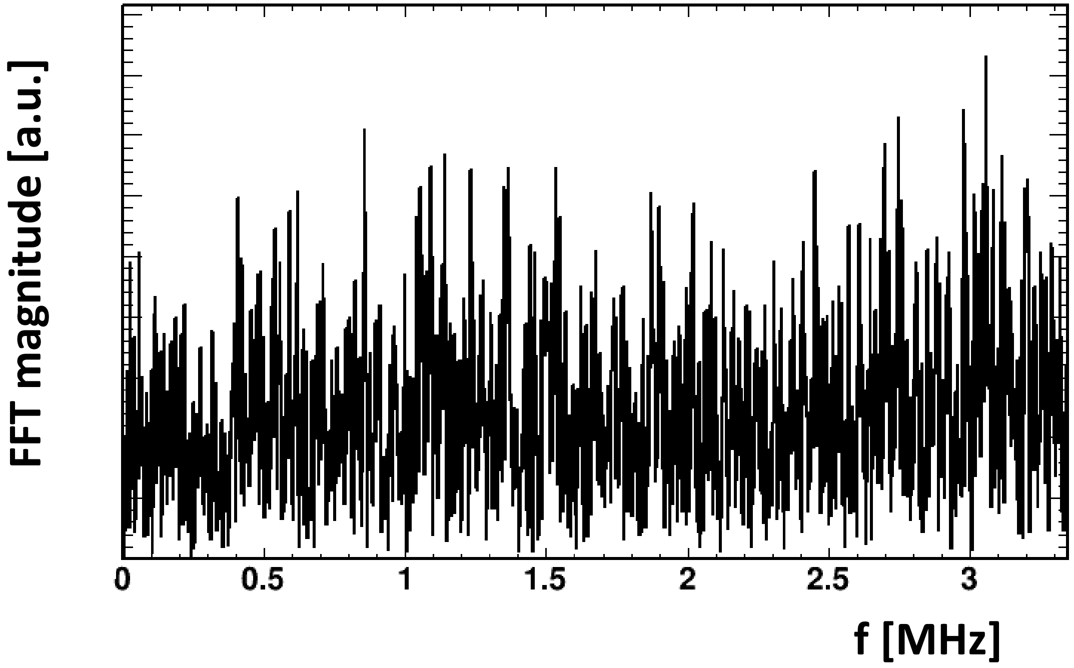
ω_a fit with beam dynamics model and all corrections:

$\chi^2 / ndf = 4041/4137$

p-value: 0.91

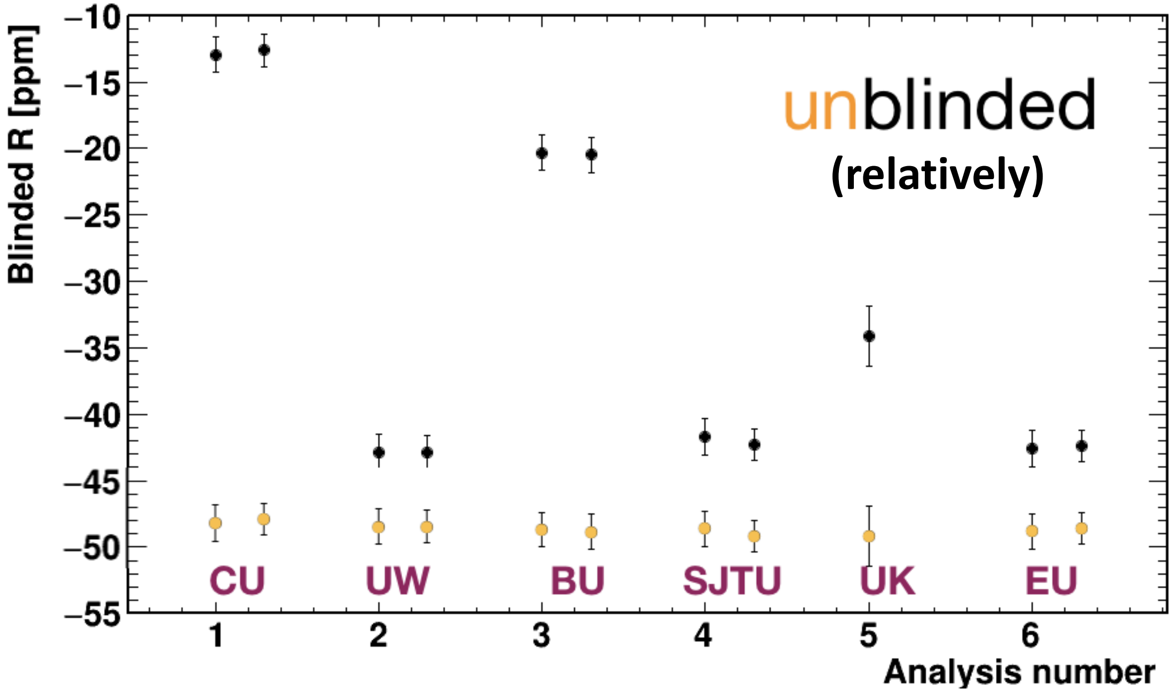


FFT of fit residuals



12x smaller y-axis scale compared to basic model

Recent (relative) unblinding shows agreement between all ω_a analyzers



60-h unblinding workshop February 2019

- independent reconstructions
- different treatment of detector and beam dynamics effects
- various fitting procedures
- agreement within allowed statistical variations

Run 1 ω_a systematics appear under control

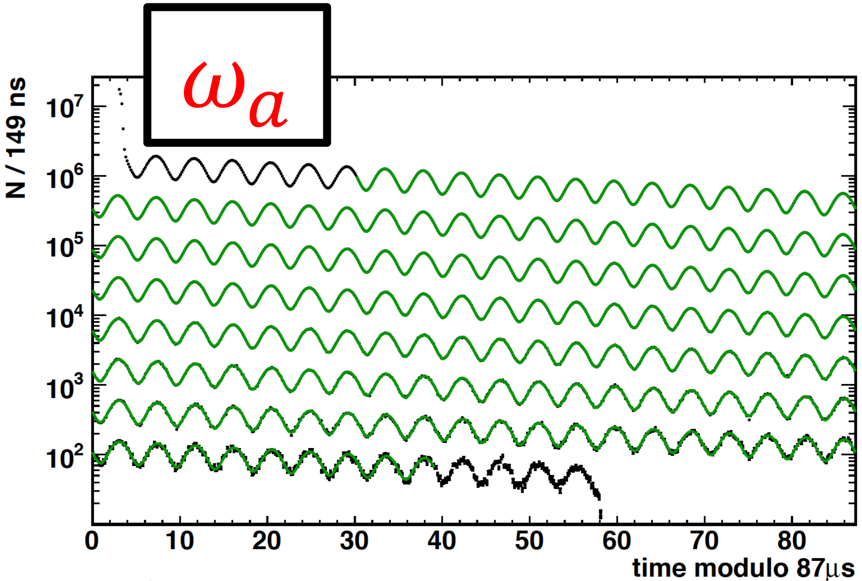
Uncertainty Source	Run 1 Estimate	Target Value
Beam dynamics		
Lost muons*	< 125 ppb	20 ppb
CBO	30 ppb	30 ppb
E-field and pitch*	< 70 ppb	30 ppb
Detector effects		
Gain changes*	< 60 ppb	20 ppb
Pileup	20 ppb	40 ppb
Total	**< 160 ppb**	70 ppb

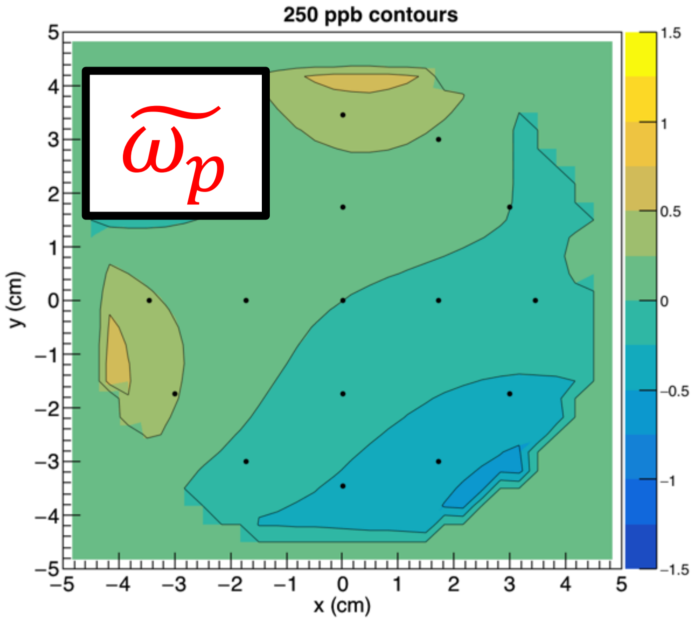
compare to projected: 350 ppb statistical uncertainty,
140 ppb* magnetic field uncertainty

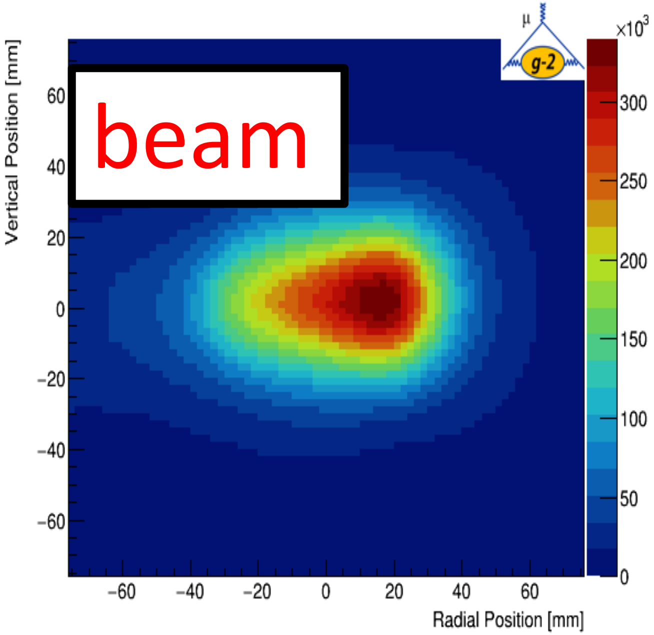
*separate analyses by dedicated teams, in progress

Next steps

- mature analysis tools will be applied to all Run 1 data
- if all goes well, final internal reviews will occur this summer
    - on track so far
- Run 2 data collection to begin soon
- thank you!







Backup slides

E989 scientific collaboration

- Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Kentucky
  - Massachusetts
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois
  - Regis
  - UT Austin
  - Virginia
  - Washington
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

China
- Shanghai

Germany
- Dresden

England
- Lancaster
- Liverpool
- University College London

Korea
- CAPP/IBS
- KAIST

Russia
- JINR/Dubna
- Novosibirsk

7 countries

35 institutions

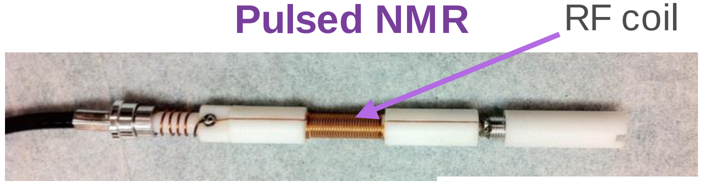
~200 authors

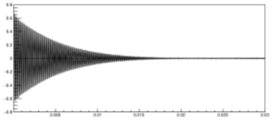
Improvements for Run 2

- kicker stability and high voltage
- further beamline optimization
- additional beam injection monitoring detectors
- experiment hall temperature control
- improved magnet temperature stability

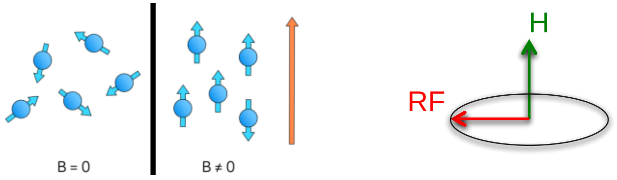
Monitoring and Mapping the Magnetic Field

Pulsed NMR

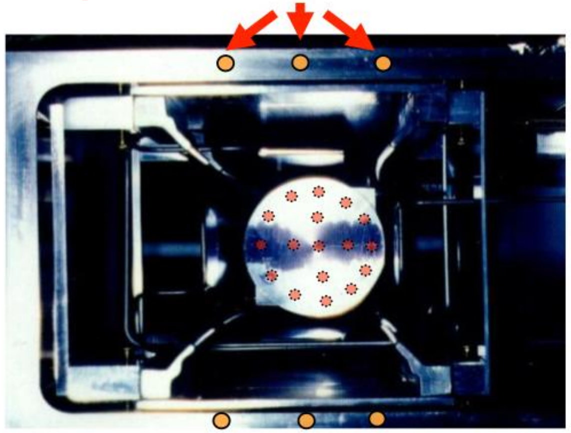




- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID

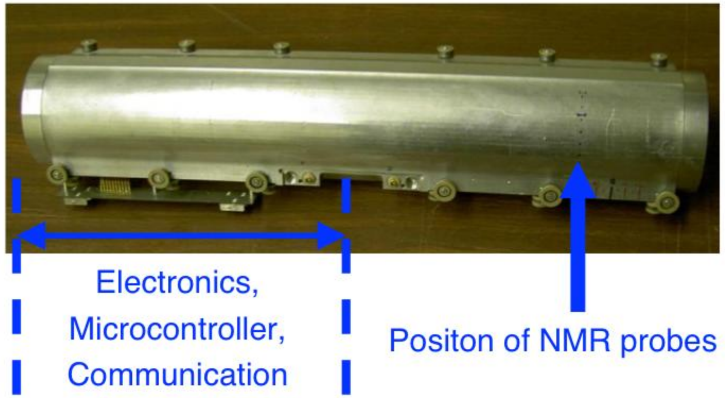


Fixed probes on vacuum chambers



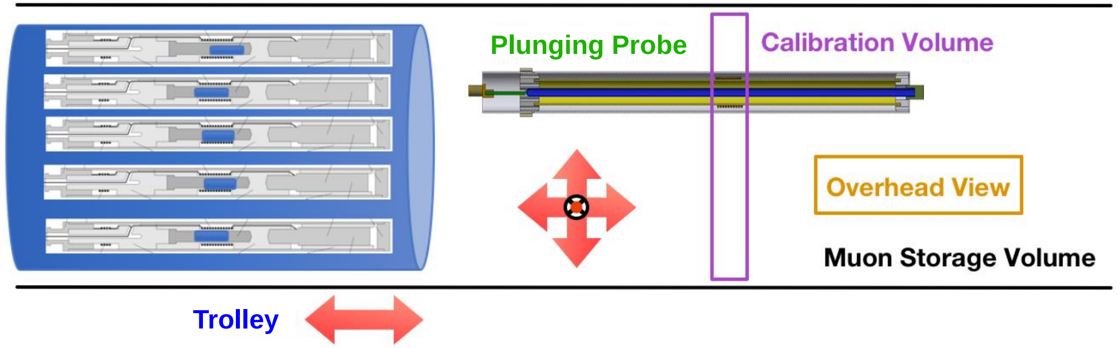
- Measure field while muons are in ring — 378 probes **outside** storage region

Trolley matrix of 17 NMR probes

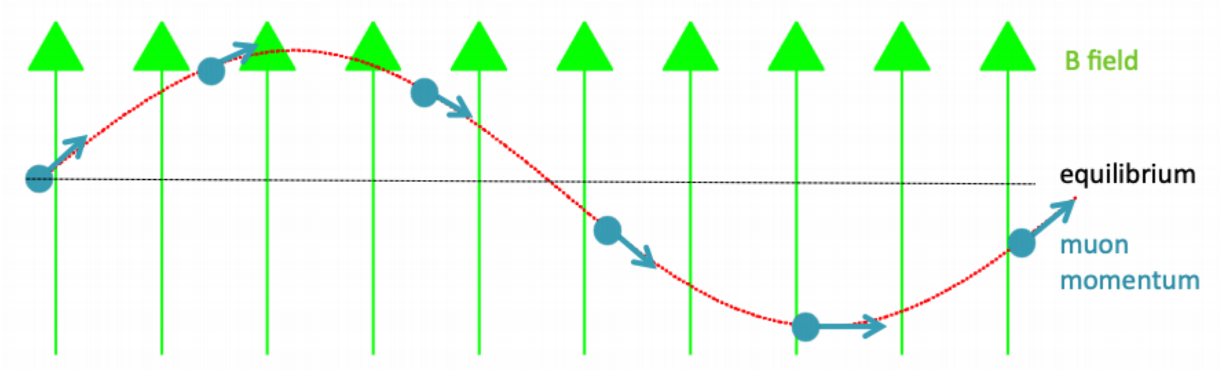


- Measure field in storage region during **specialized runs** when **muons are not being stored**
- Map the field every 3–4 days

- **Trolley** probes **calibrated to free-proton Larmor frequency**
  - Calibrate trolley probes using a special probe that uses a water sample
  - Measurements in specially-shimmed region of ring



Pitch Correction

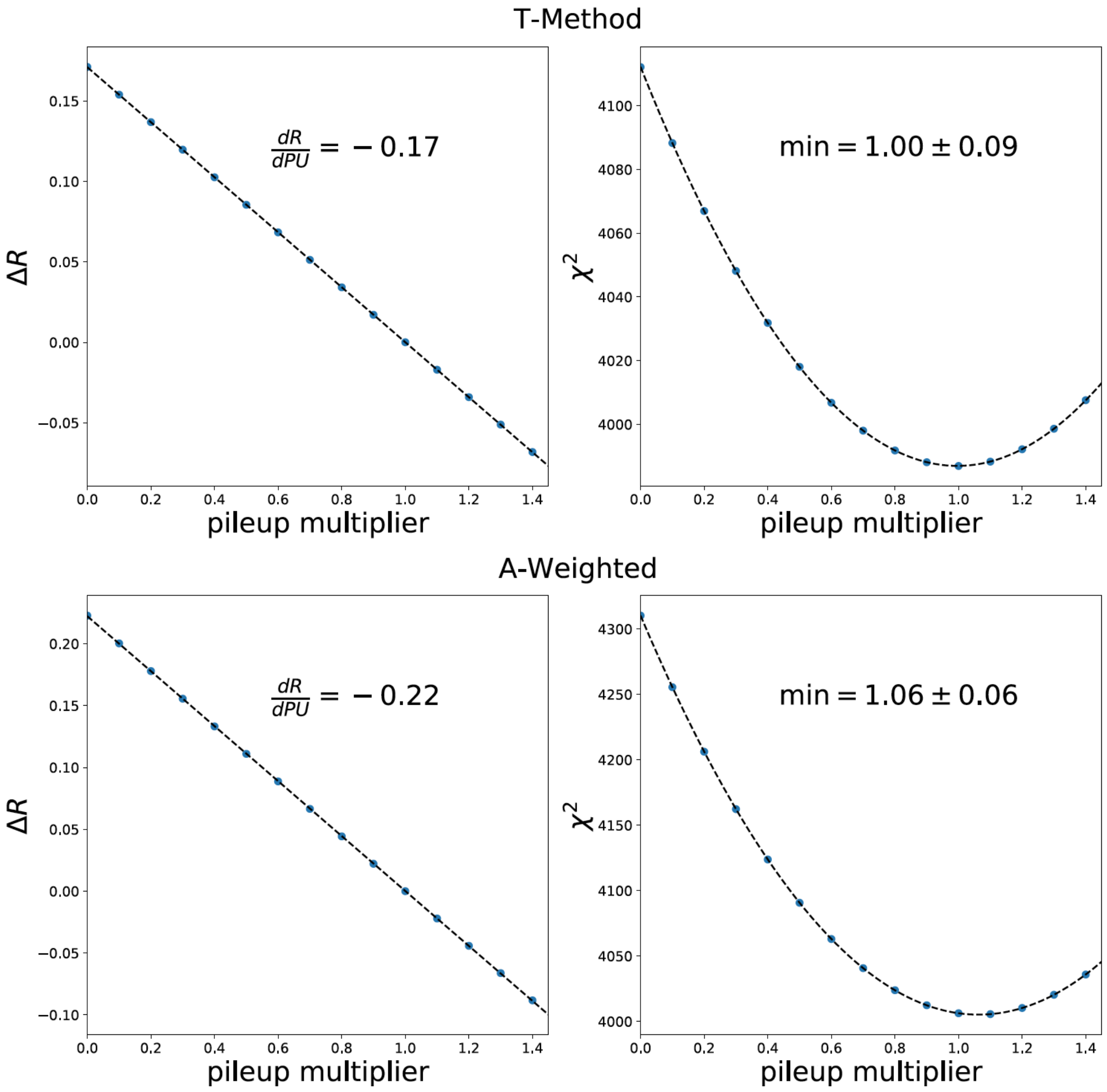


precession not perpendicular to momentum!

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\left\langle y^2 \right\rangle$$

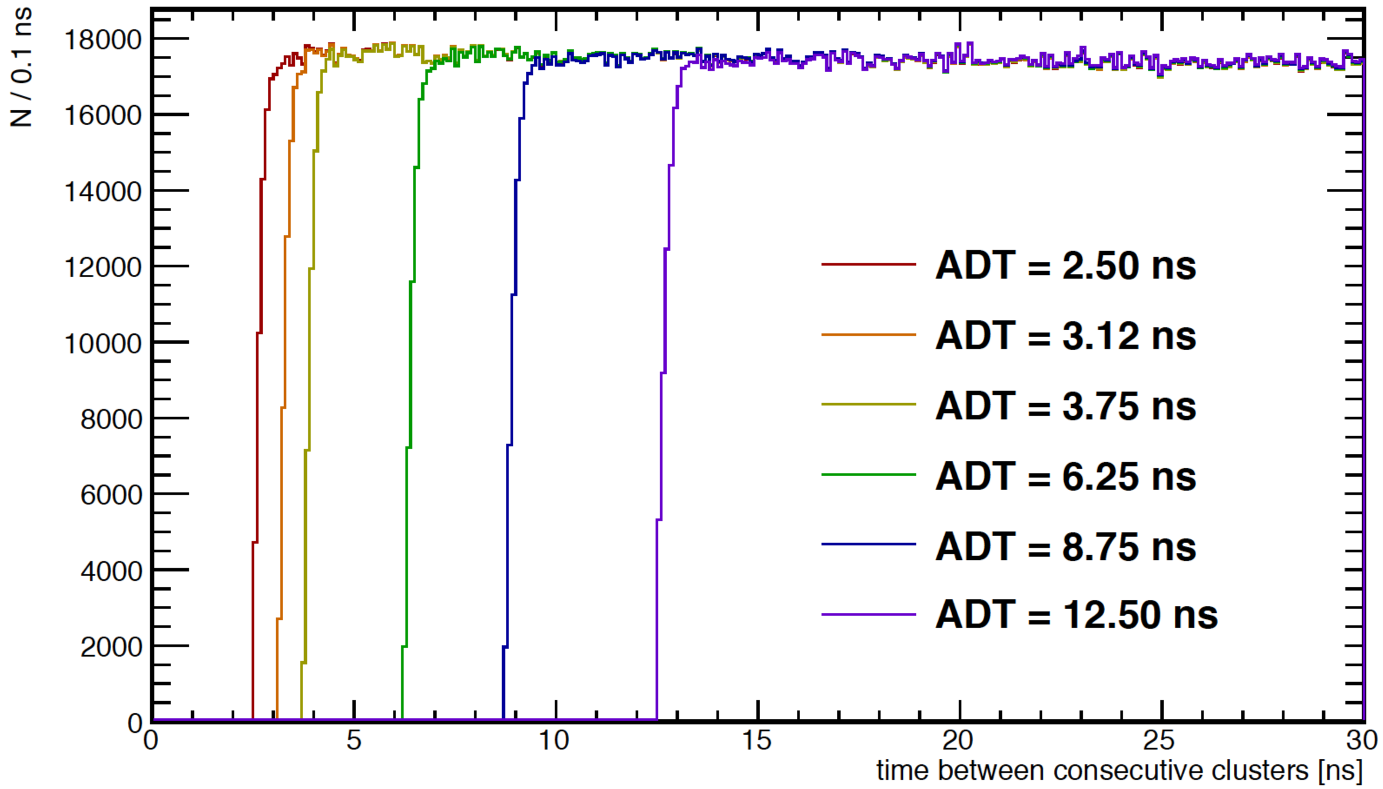
- ~300 ppb correction
- related to vertical distribution of beam
- measured using trackers
- aim for **30 ppb** systematic

Pileup systematic uncertainty is < 40 ppb



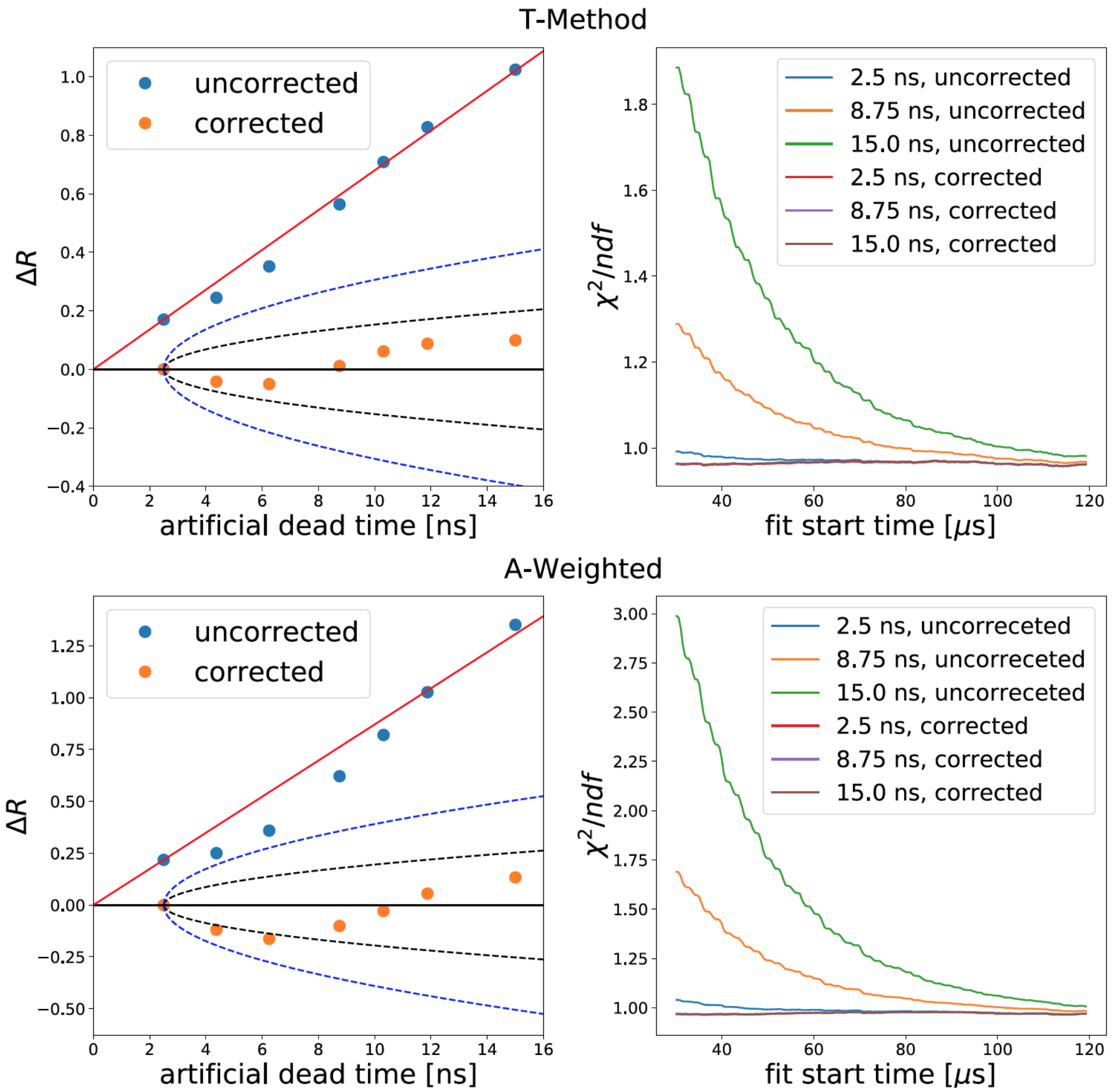
- scale of pileup correction is varied
- $\frac{dR}{dPU} \cdot \sigma_{PU} = \sigma_{R,PU}$
- similar treatments for gain, beam oscillations, muon losses, …

Consistency check: artificial deadtime scan



- artificially increase deadtime in reconstruction
- reanalyze with multiple deadtimes
- evaluate effect on extracted $\boldsymbol{\omega_a}$

Consistency check: artificial deadtime scan



- results consistent within allowed statistical drifts
- correction can remove 1 ppm pileup bias
- power of this technique increases with improved statistical precision