The Muon g-2 experiment: Current status and outlook

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On behalf of the Muon g-2 Collaboration

August 2, 2022

Outline

- Introduction to Muon g-2
- Fermilab Muon g-2 experiment
  - Run 1 result and current status
  - How we measure a_μ
- a_μ systematics and prospects for improvements
  - Analysis improvements
  - Hardware upgrades
  - Special measurements

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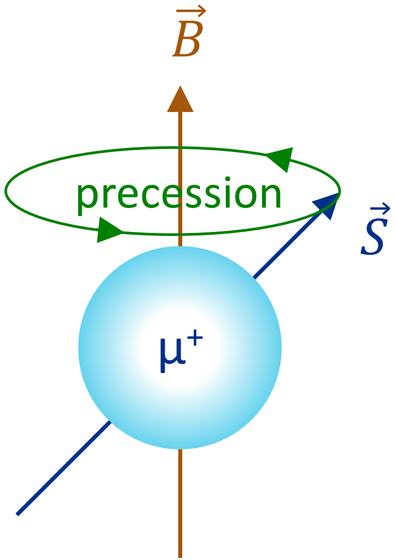
Magnetic moments

- Charged particle with angular momentum has magnetic moment
  - Classical: $\vec{\mu} = \frac{q}{2m}\vec{L}$
  - Spin: $\vec{\mu} = \mathrm{g}\frac{q}{2m}\vec{S}, \quad \omega = \mathrm{g}\frac{q}{2m}B$ Spins precess in external B field
- Dirac equation for spin $\frac{1}{2}$ particles: $g = 2$
- Loop corrections lead to deviation → anomalous magnetic moment $g_\mu = 2(1 + a_\mu)$



Standard model prediction for muon a_μ

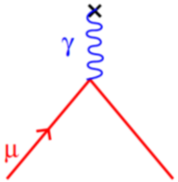
Theory prediction: include all Standard Model interactions

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

Correction	Value (Error) $\times 10^{11}$	Error [ppb]
QED	116 584 718.931(104)	0.9
EW	153.6(1.0)	9
HVP	6845(40)	343
HLbL	92(18)	154
Total a_μ^{SM}	116 591 810(43)	369

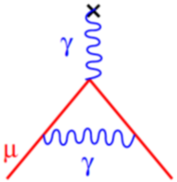
Muon g-2 Theory Initiative recommended values
T. Aoyama et. al., Phys. Rept. 887 (2020) 1-166

tree-level



g=2

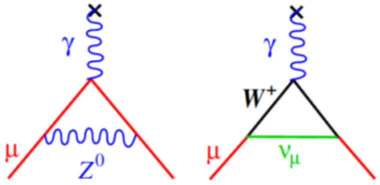
QED



Schwinger: $a \rightarrow \alpha/2\pi$

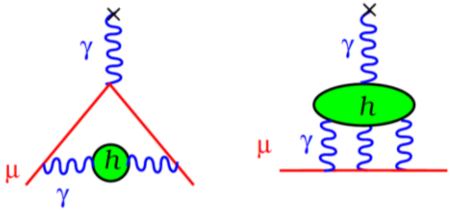
- Leptons, photons
- Terms to $O(\alpha^5)$

Electroweak



- Corrections $\sim m_\mu^2/M_W^2$
- W, Z, Higgs bosons

Hadronic



Hadronic vacuum polarization (HVP)

Hadronic light-by-light scattering (HLbL)

- Difficult because QCD nonperturbative
- HVP calculated from $e^+e^- \rightarrow$ hadrons cross section data
- HVP lattice calculations approaching required precision, in tension with data-driven calculations

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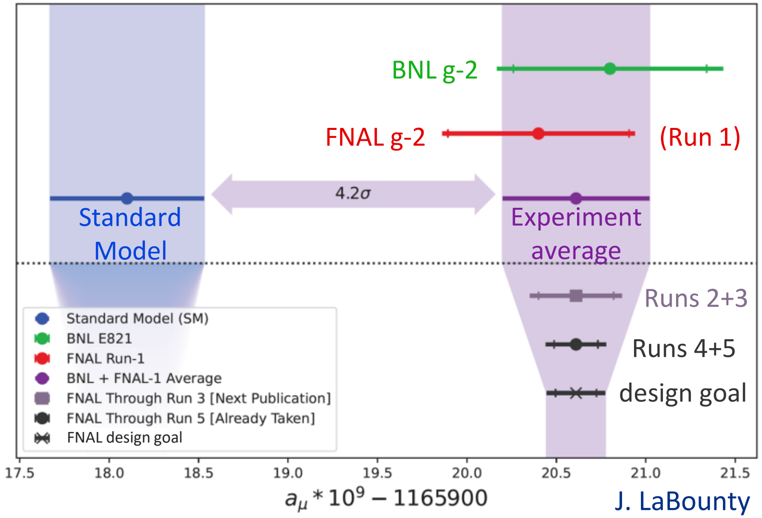
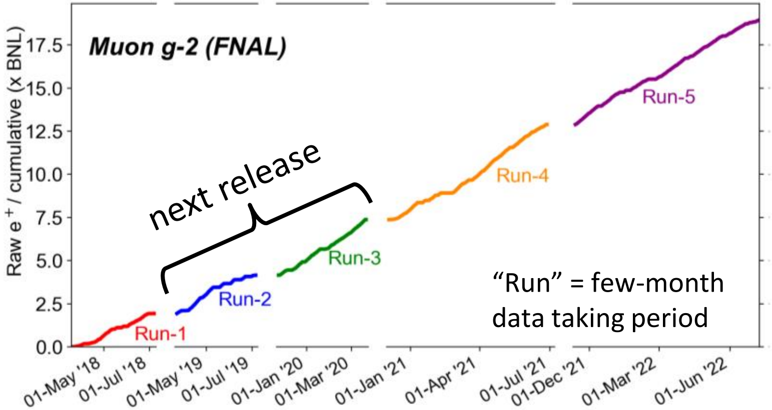
Fermilab Muon g-2 experiment

- 2006: BNL g-2 measured a_μ to 540 ppb
- 2021: FNAL g-2 measured a_μ to 460 ppb
- Combined 4.2σ discrepancy between experiment and SM prediction
- Fermilab g-2 goal: 4× higher precision than BNL

140 ppb total → 100 ppb systematic (2.8× improvement)
140 ppb total → 100 ppb statistical (4.6× improvement, 20× more muons)





Very close to 20× BNL goal!

- Experiment status
  - Finished Run 5 in July 2022
  - Run 2+ analysis in progress
  - Run 6 (final run) to start in fall

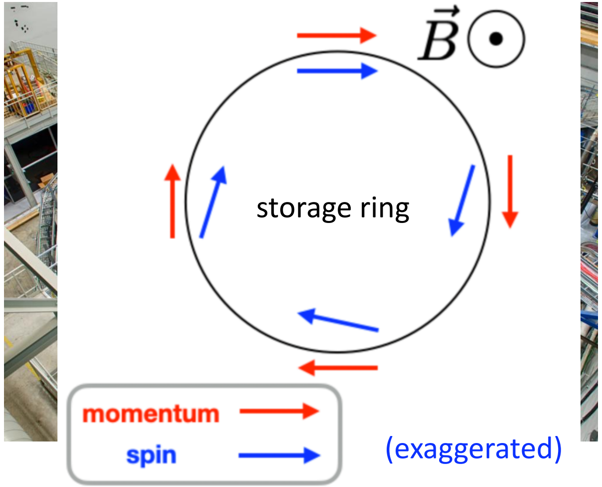
Measuring a_μ at Fermilab Muon g-2

- Inject polarized relativistic μ^+ into magnetic storage ring

- $g > 2$: anomalous precession $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{e}{m}\vec{B}$

measure with calorimeters

measure with NMR probes



- Express a_μ in terms of experimental constants, with $B = \frac{\hbar\omega_p'}{2\mu_p'}$:

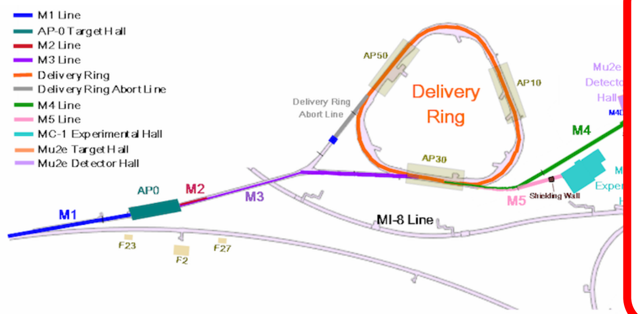
$$a_\mu = \frac{g_\mu - 2}{2} = \frac{\omega_a}{\tilde{\omega}_p'} \frac{\mu_p'}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

measure other experiments

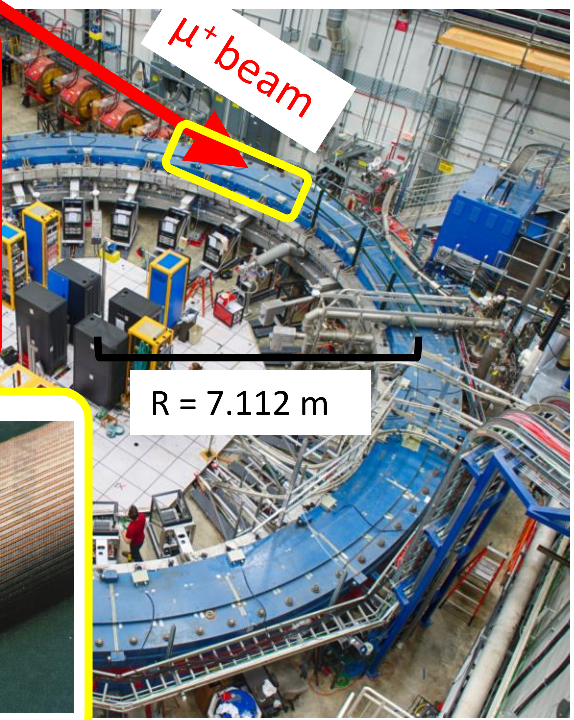
Constant	Source	Uncertainty [ppb]
g_e	Quantum cyclotron spectroscopy Hanneke et. al. 2011.	0.00028
m_μ/m_e	Muonium spectroscopy Liu et. al. 1999.	22
μ_p'/μ_e	Hydrogen spectroscopy, NMR Phillips et. al. 1977.	10.5
a_μ	Fermilab g-2 goal	140

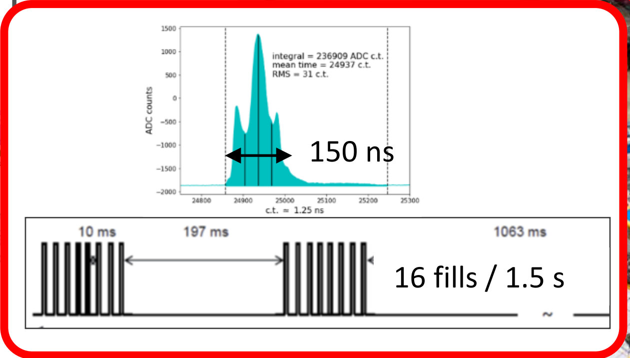
Injecting the muons into the storage ring

Polarized 3.1 GeV μ^+ beam produced at FNAL Muon Campus

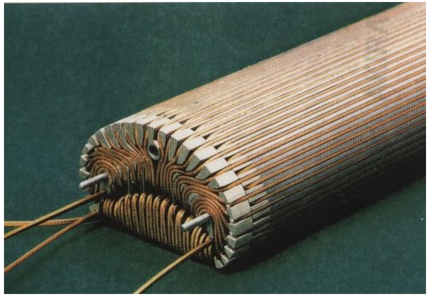


Pulsed μ^+ beam injected into g-2 storage ring



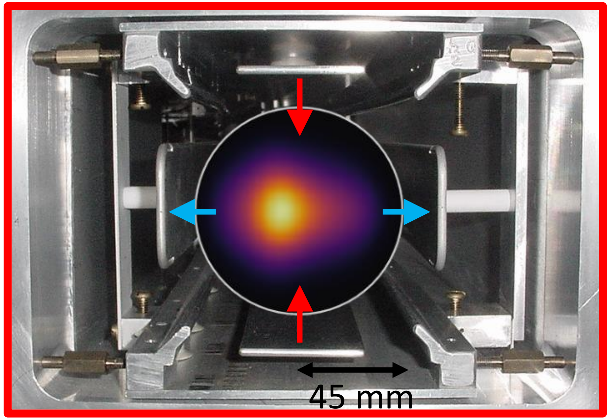


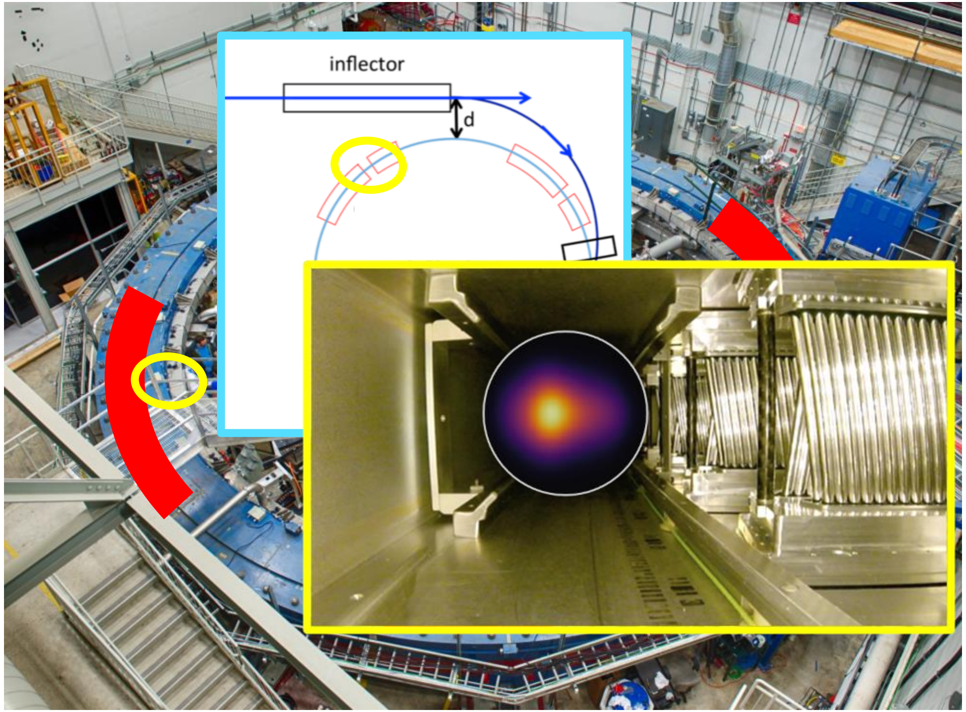
Field-canceling superconducting inflector magnet



Storing the muons in the ring

- Storage ring magnet: 1.45 T
- Pulsed kicker magnets shift beam to nominal orbit
- Electrostatic quadrupoles focus beam vertically
- Straw tracking detectors reconstruct muon distribution





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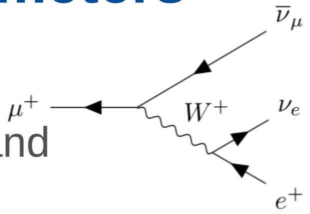
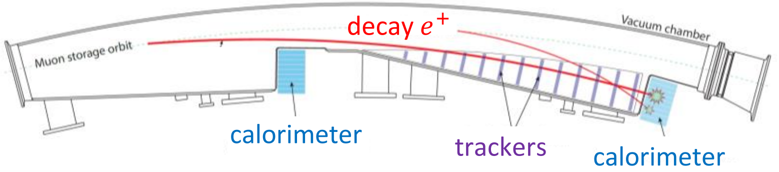
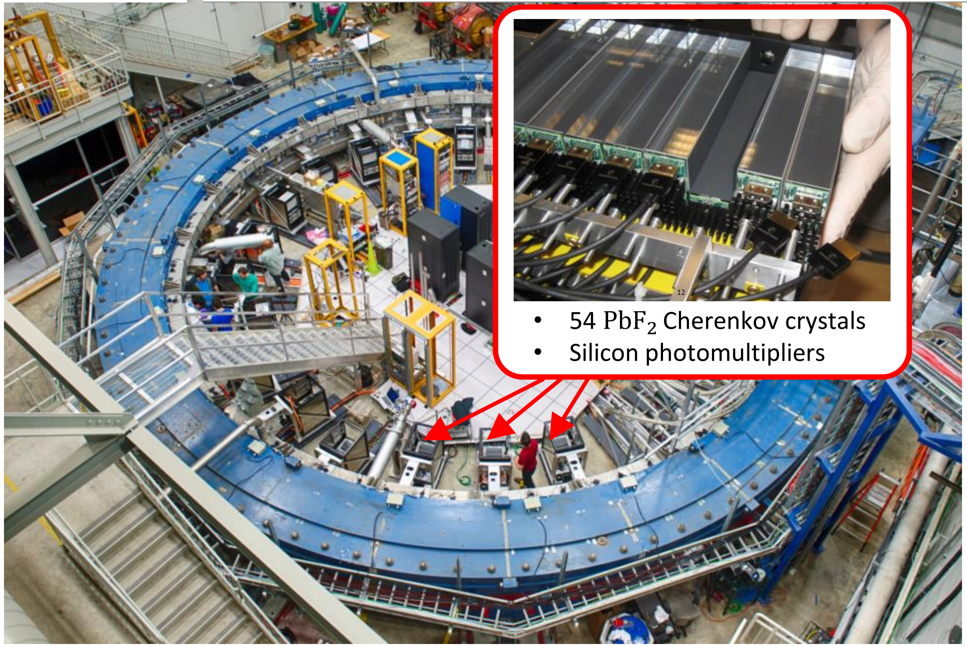
Measuring ω_a with calorimeters

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

- μ^+ decay to e^+
- 24 calorimeters measure energy and arrival time of decay e^+



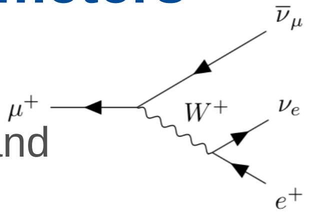


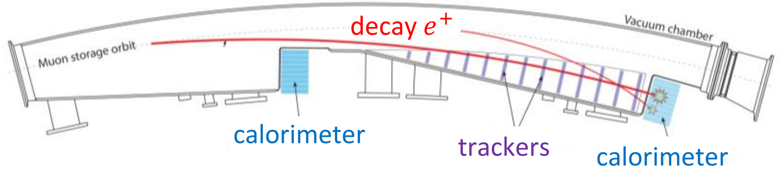


Measuring ω_a with calorimeters

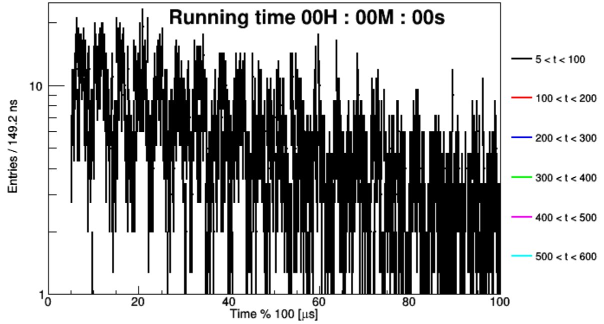
$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

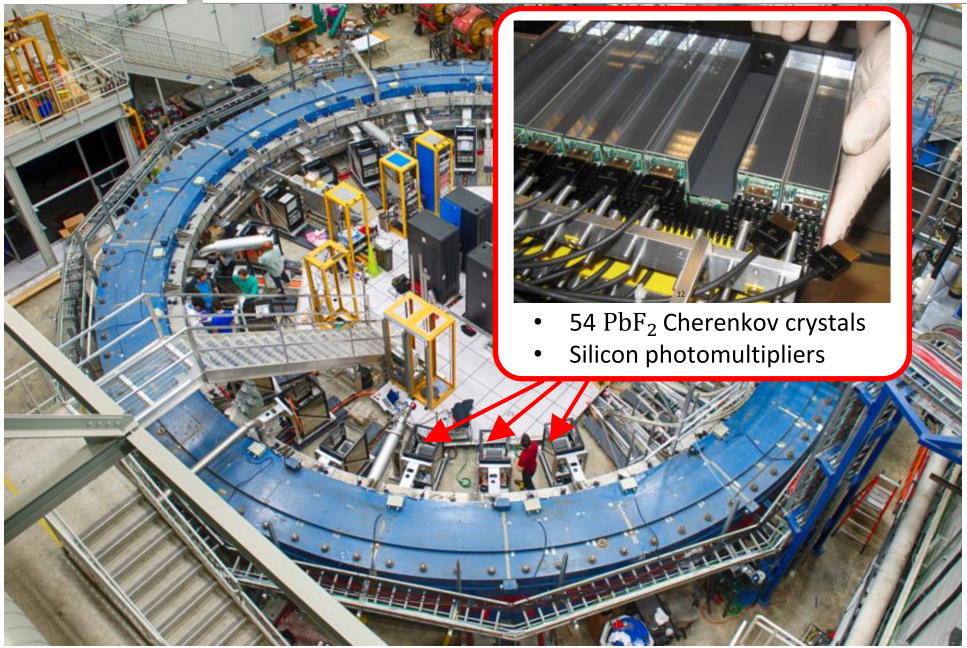
- μ^+ decay to e^+
- 24 calorimeters measure energy and arrival time of decay e^+
- Parity violation in weak interaction → e^+ counts above energy threshold modulated by ω_a
- Extract ω_a from fit to e^+ hits vs. time





e^+ above E threshold vs time in fill





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Extracting ω_a from e^+ histogram

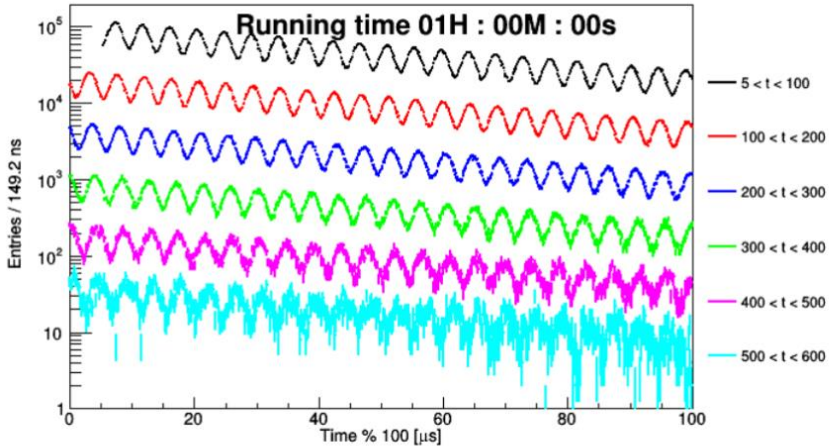
$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

5 parameters

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

- Initial beam intensity (N_0)
- Time-dilated muon lifetime (τ)
- Asymmetry due to energy-spin correlation (A)
- Anomalous precession frequency (blinded) (ω_a)
- Initial spin phase (ϕ)

e^+ above E threshold vs time in fill



Extracting ω_a from e^+ histogram

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

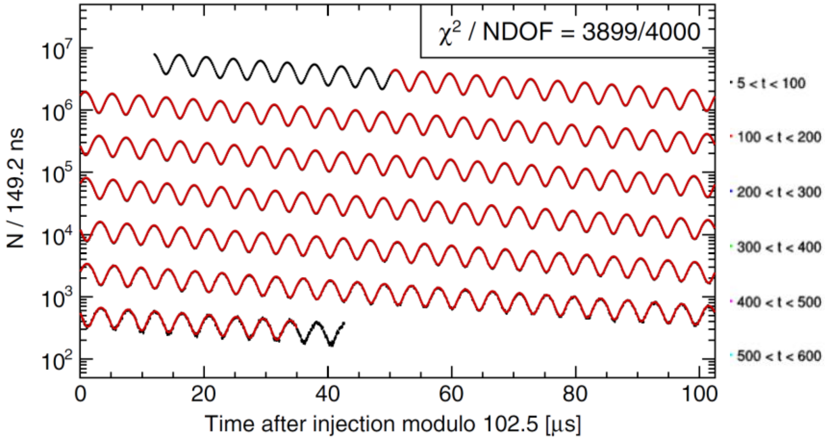
5 parameters

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)] + \text{many (28) terms to account for beam dynamics effects}$$

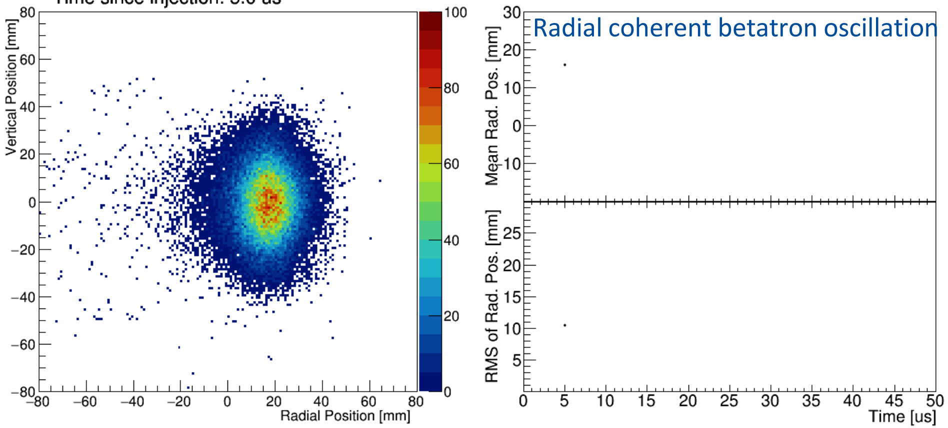
Position-dependent calo acceptance couples beam motion to $N(t)$

- N_0: Initial beam intensity
- τ: Time-dilated muon lifetime
- A: Asymmetry due to energy-spin correlation
- ω_a: Anomalous precession frequency (blinded)
- ϕ: Initial spin phase

Good fit when all terms included



Dynamic beam motion after injection

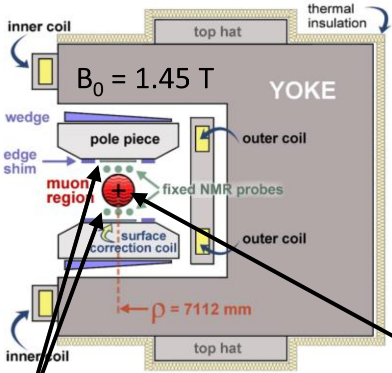


From straw tracker data

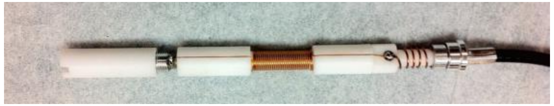
Measuring ω_p with NMR probes

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

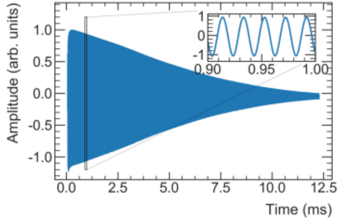
- Pulsed NMR probes measure ω_p = proton precession frequency ($\omega_p \propto B$)
- Trolley maps field all around ring every few days
- Fixed probes outside storage region monitor field drift between trolley runs
- Interpolate field map between trolley runs using fixed probes



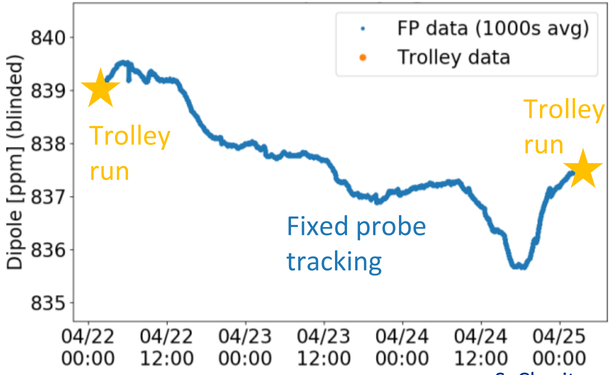
Nuclear magnetic resonance (NMR) probe



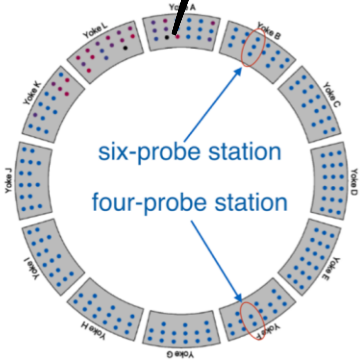
Free induction decay signal (ω_p)



Field interpolation

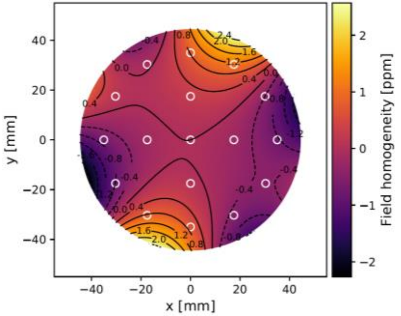


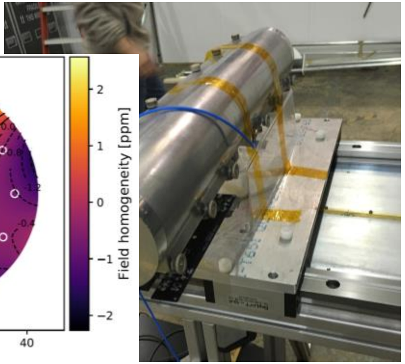
S. Charity



Fixed NMR probes (72 stations)

NMR probe trolley





Field map in muon region

Weighting ω_p with muon distribution

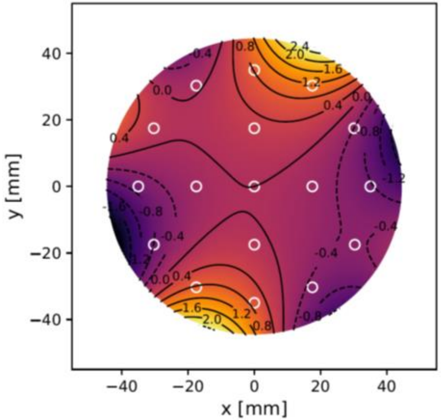
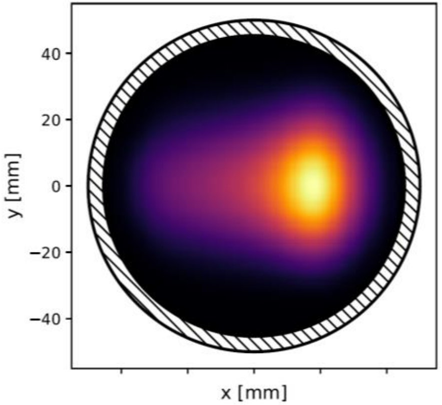
$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$

Average magnetic field experienced by muons

$$\tilde{\omega}_p = \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$$

field map

muon distribution

$= \langle$  $\times$  $\rangle$

- Weight field map by muon distribution in azimuthal slices
- Then average around the ring to get $\tilde{\omega}_p$

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Now have all ingredients!

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p}$$

Anomalous precession frequency of muons

Magnetic field experienced by muons

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Correcting the measured components

$$a_\mu \propto \frac{\omega_a^m}{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}$$

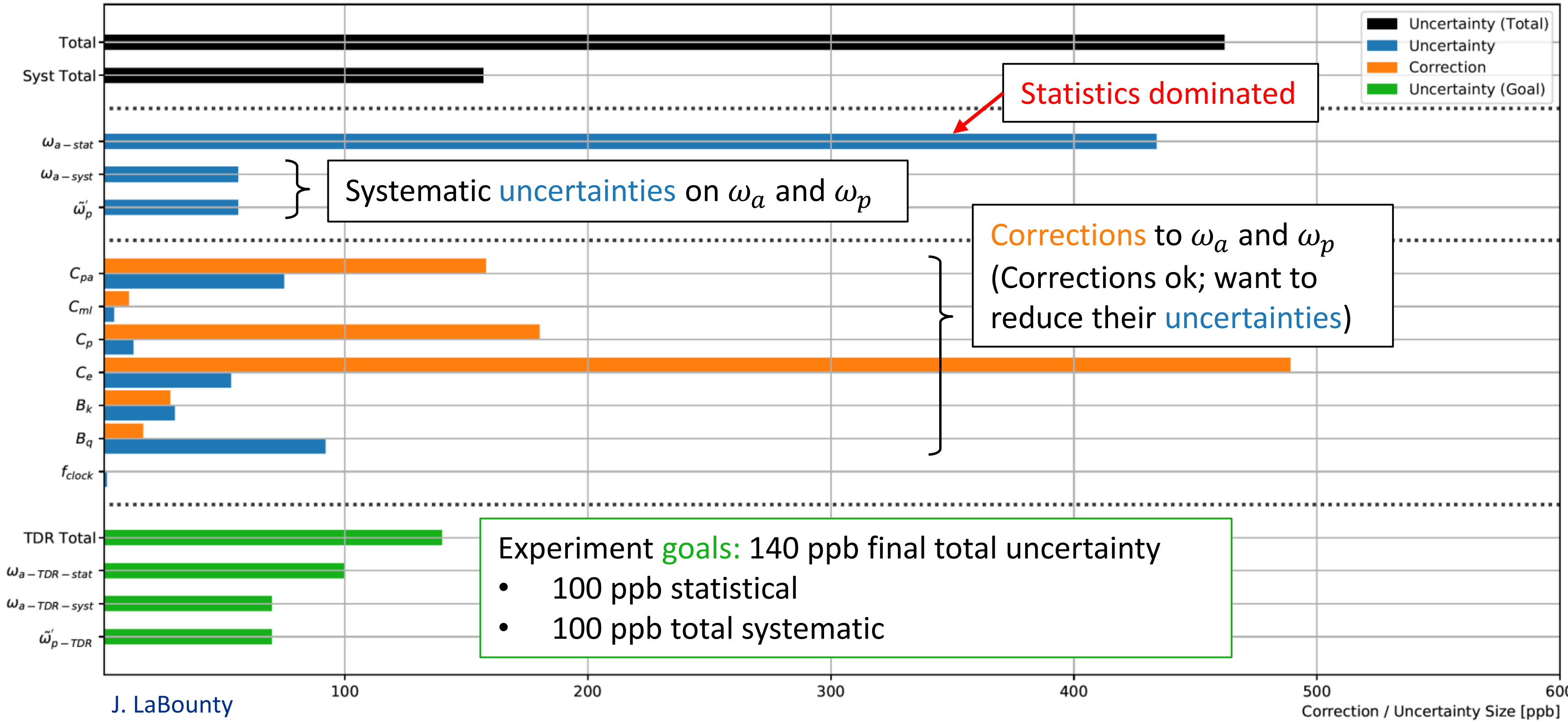
- ω_a^m: Measured precession frequency
- $\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$: Muon-weighted magnetic field, $\tilde{\omega}_p$

Now need to include corrections for both terms

- f_{clock}: ω_a clock blinding
- C terms: Beam dynamics corrections to ω_a
- f_{calib}: Absolute magnetic field calibration for ω_p
- B terms: Transient magnetic field corrections to ω_p

Run 1 uncertainties and corrections

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$



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Run 1 uncertainties and corrections

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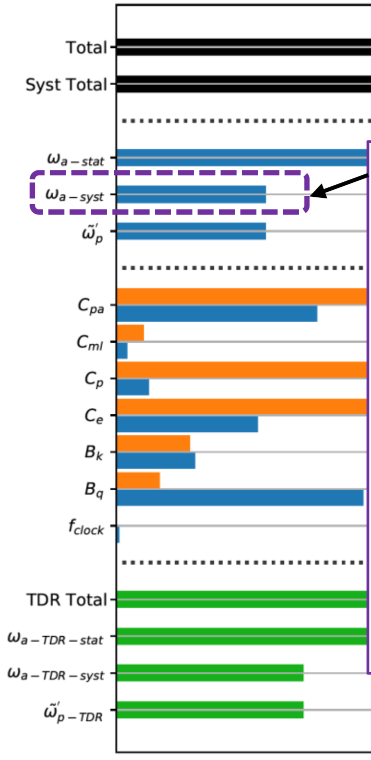
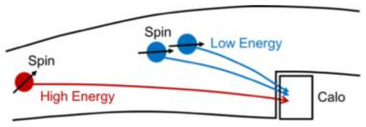
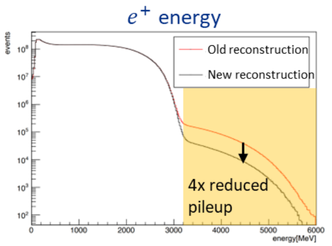


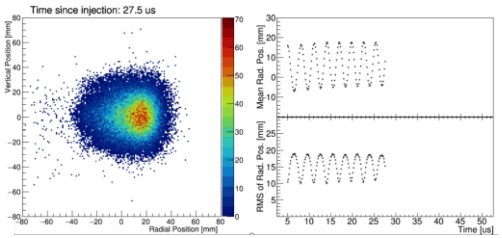
Efforts to improve ω_a systematics

- Improved event reconstruction and correction for "pileup" events which bias ω_a (Run 1: 40 ppb → Run 2 aim: <20 ppb)





- Upgrades in Runs 3-5 reduce coherent betatron oscillation, expect reduced uncertainty in ω_a fit



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Run 1 uncertainties and corrections

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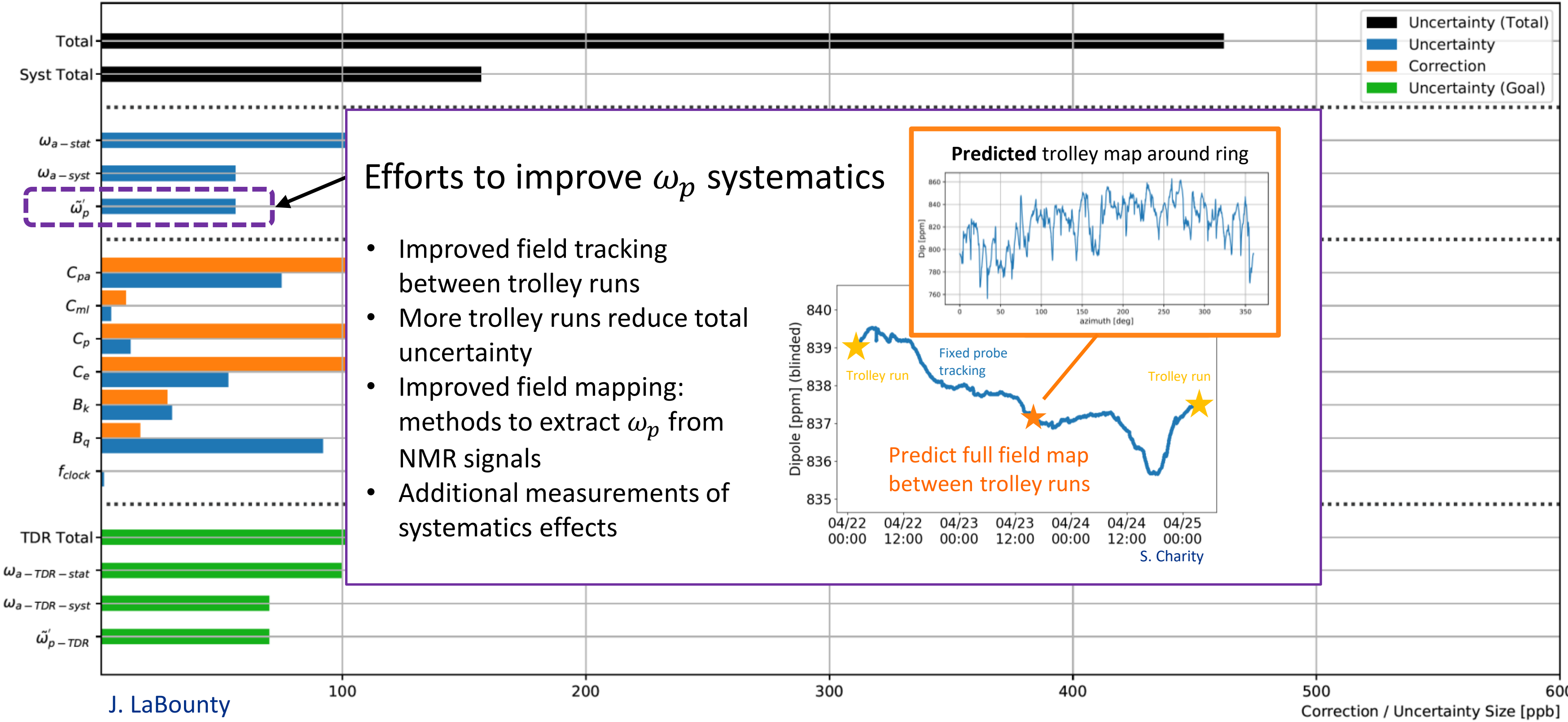

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Run 1 uncertainties and corrections

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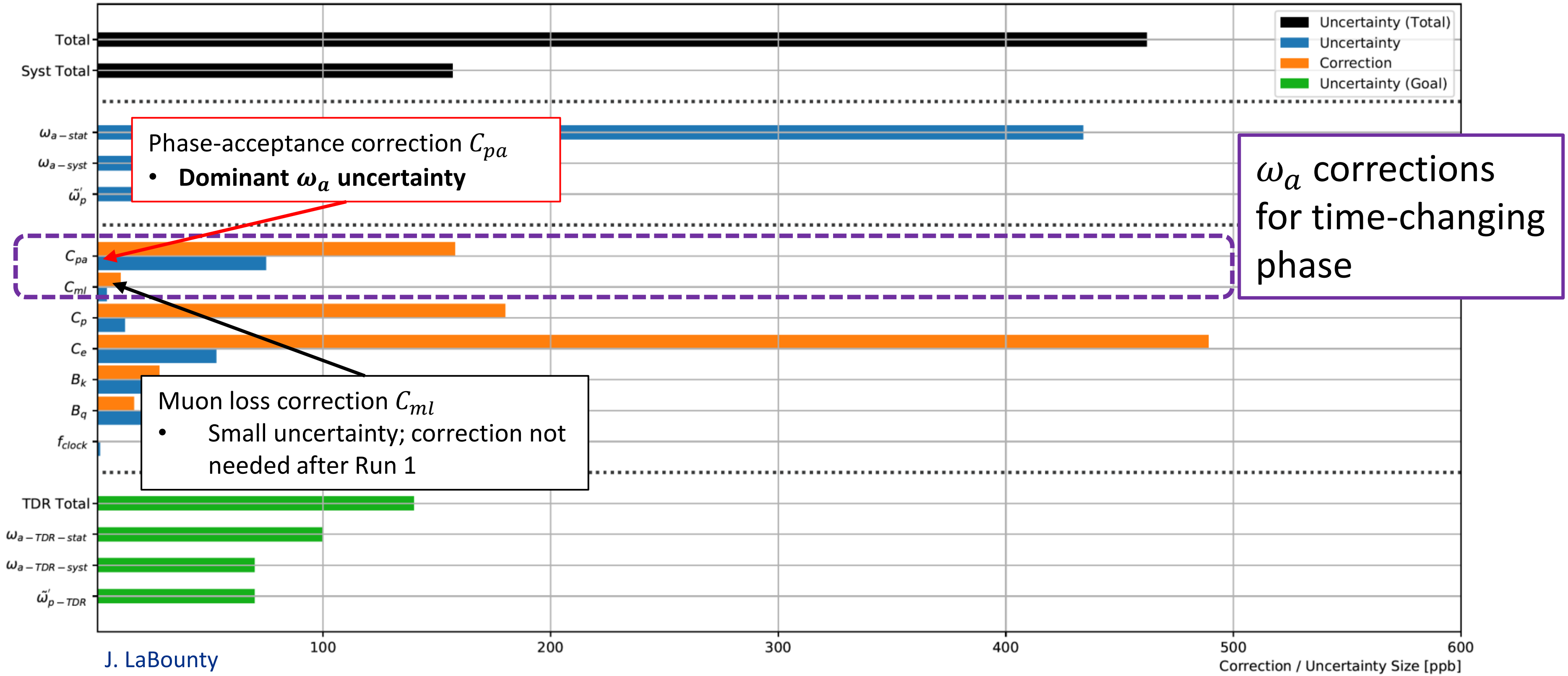

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Run 1 uncertainties and corrections

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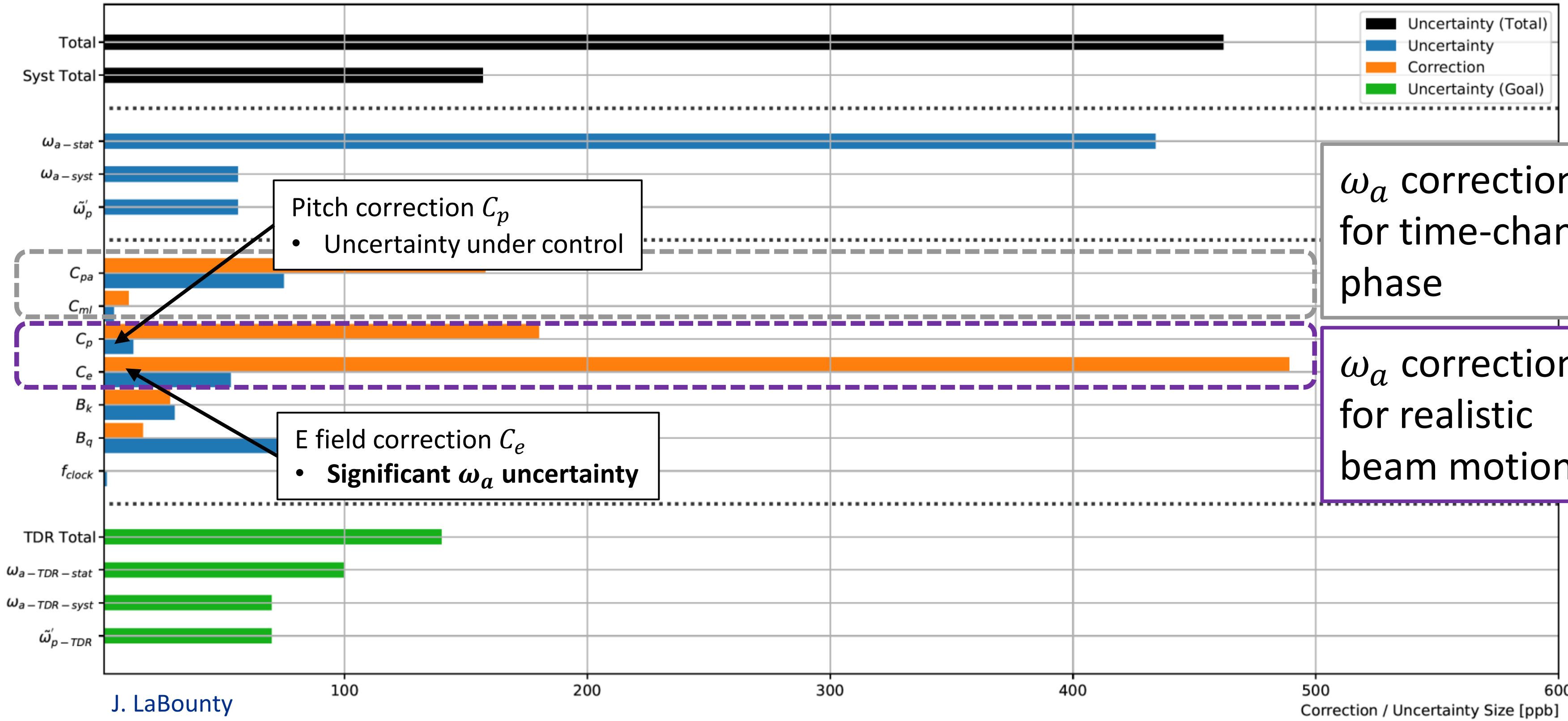

Pitch correction C_p
- Uncertainty under control

E field correction C_e
- **Significant ω_a uncertainty**

ω_a corrections for time-changing phase

ω_a corrections for realistic beam motion

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Corrections for realistic beam

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

- Original expression: Ideal horizontal (perpendicular) motion in vertical B field
- More complicated with realistic motion

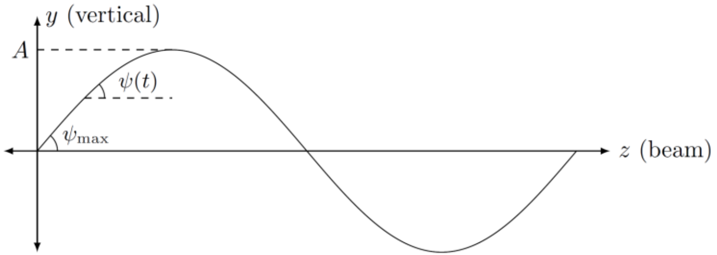
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu\vec{B} - a_\mu\frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

Pitch correction

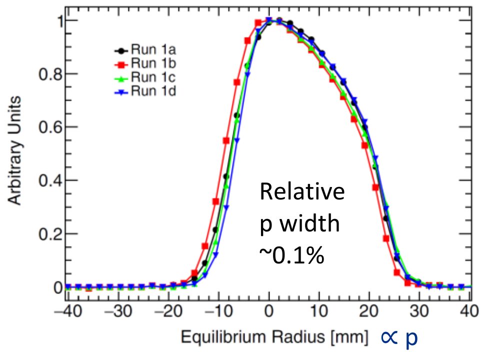
- Zero for motion $\vec{\beta} \perp \vec{B}$
- Nonzero due to vertical betatron oscillation caused by quads

E field correction

- Zero for nominal momentum 3.094 GeV
- Nonzero due to finite momentum spread



Momentum distribution



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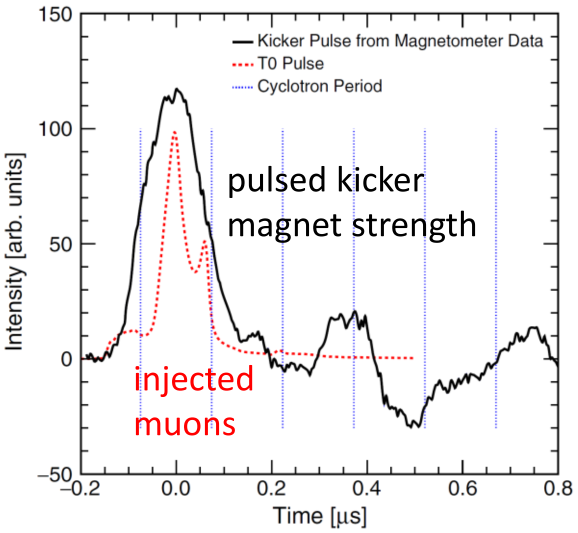
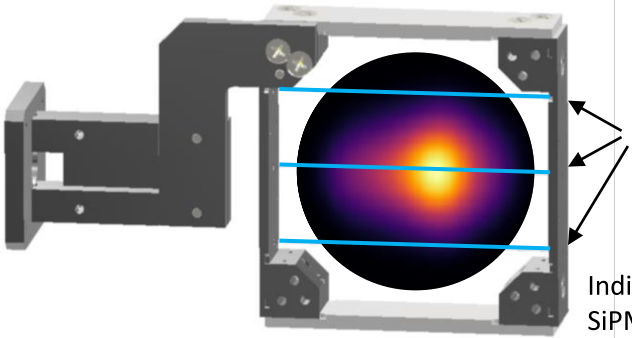
Reducing uncertainty on E field correction

- Uncertainty dominated by kicker effect
  - Varying kick strength over injection time → time dependence of stored momentum
  - Target uncertainty reduction: 53 ppb → 25 ppb
- Improvements in Run 2/3
  - Momentum reconstruction algorithm improvements
  - Verified simulation inputs and benchmarks
- Measurement campaign in Run 4/5

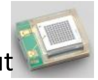


New detector for direct in-beam measurement

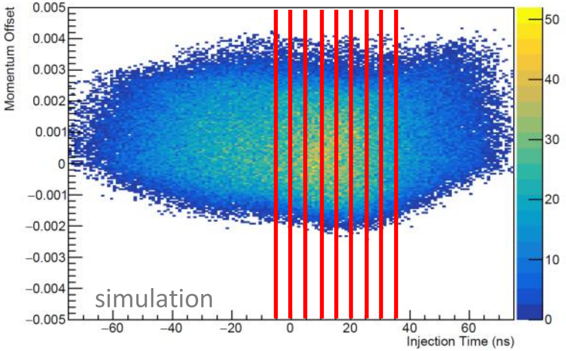


3 scintillating fibers, 250 μm diameter → minimal material

Individual SiPM readout



Map momentum vs. injection time slice



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Phase-acceptance correction

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

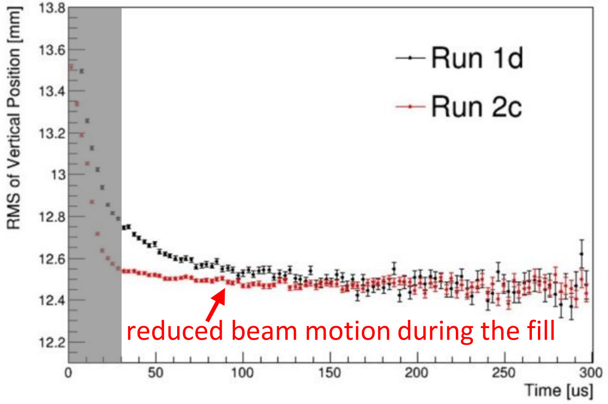
Any time-varying phase leads to incorrect extracted ω_a

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi(t))] \rightarrow \Delta\omega_a \approx -\frac{d\phi}{dt}$$

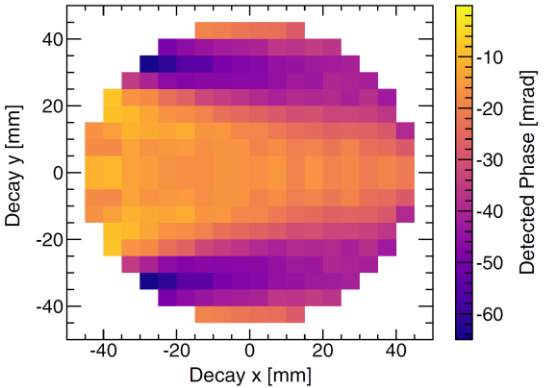
- **Replaced damaged quad resistors** in Run 2
- Significantly reduced correction and uncertainty
  - Run 1: 75 ppb → Run 2 aim: <20 ppb

- Calo acceptance depends on position → detected $\phi(t)$

vertical beam width vs. time in fill



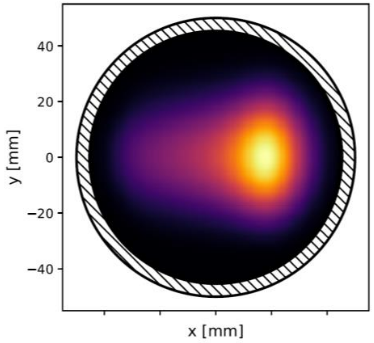
Position-dependent detected ϕ



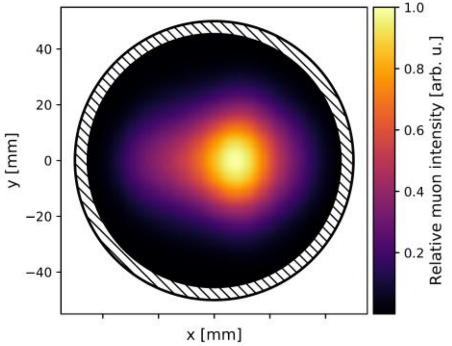
More hardware improvements: Kickers upgrade during Run 3

Stronger kick moved beam closer to storage region center

Run 1 beam distribution



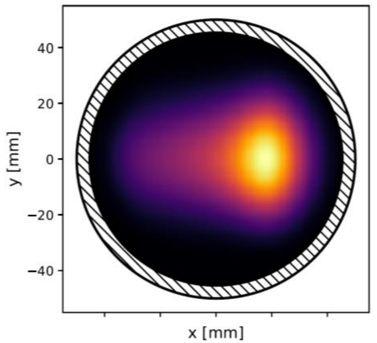
Late Run 3 beam distribution

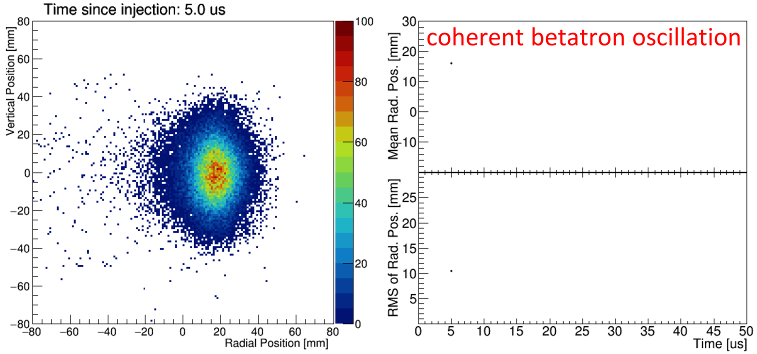


More hardware improvements: Kicker upgrade during Run 3

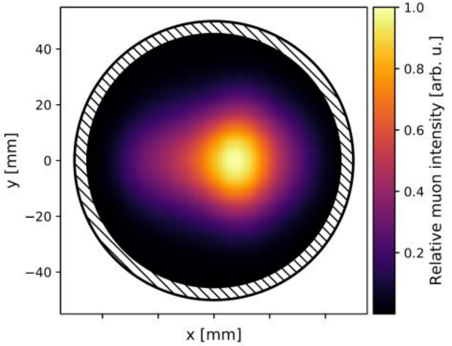
Stronger kick moved beam closer to storage region center

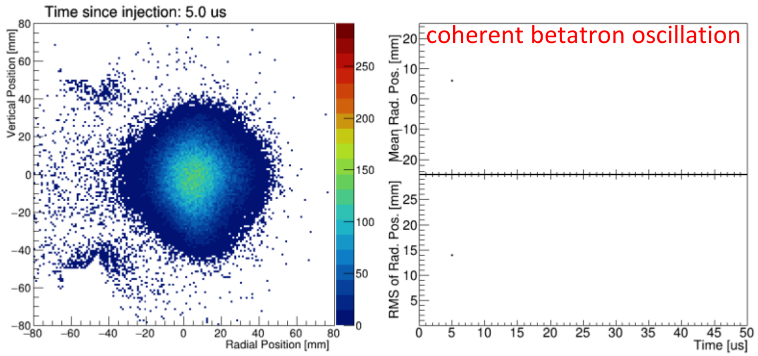
Run 1 beam distribution





Late Run 3 beam distribution





Reduced coherent betatron oscillation

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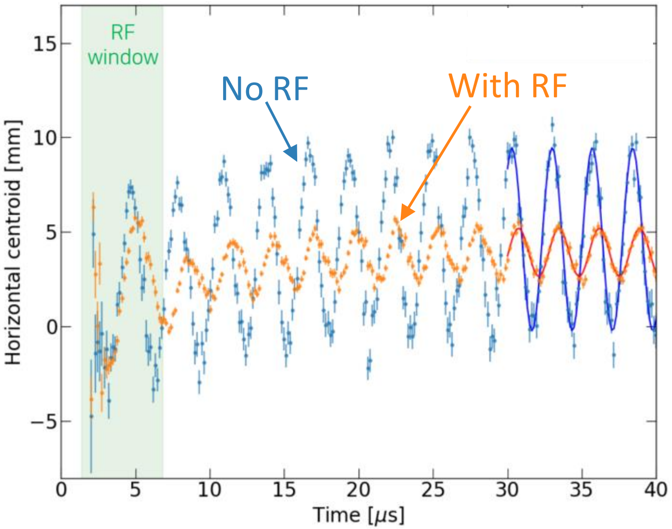
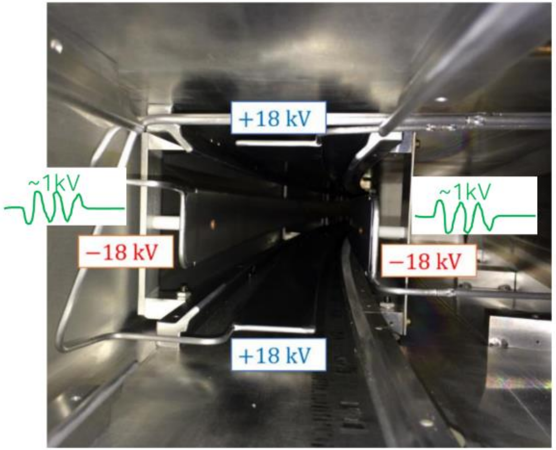
More hardware improvements: Quadrupole RF in Run 5

- Apply horizontal RF field with electric quadrupoles
- Damp horizontal coherent betatron oscillation

Further reduced coherent betatron oscillation

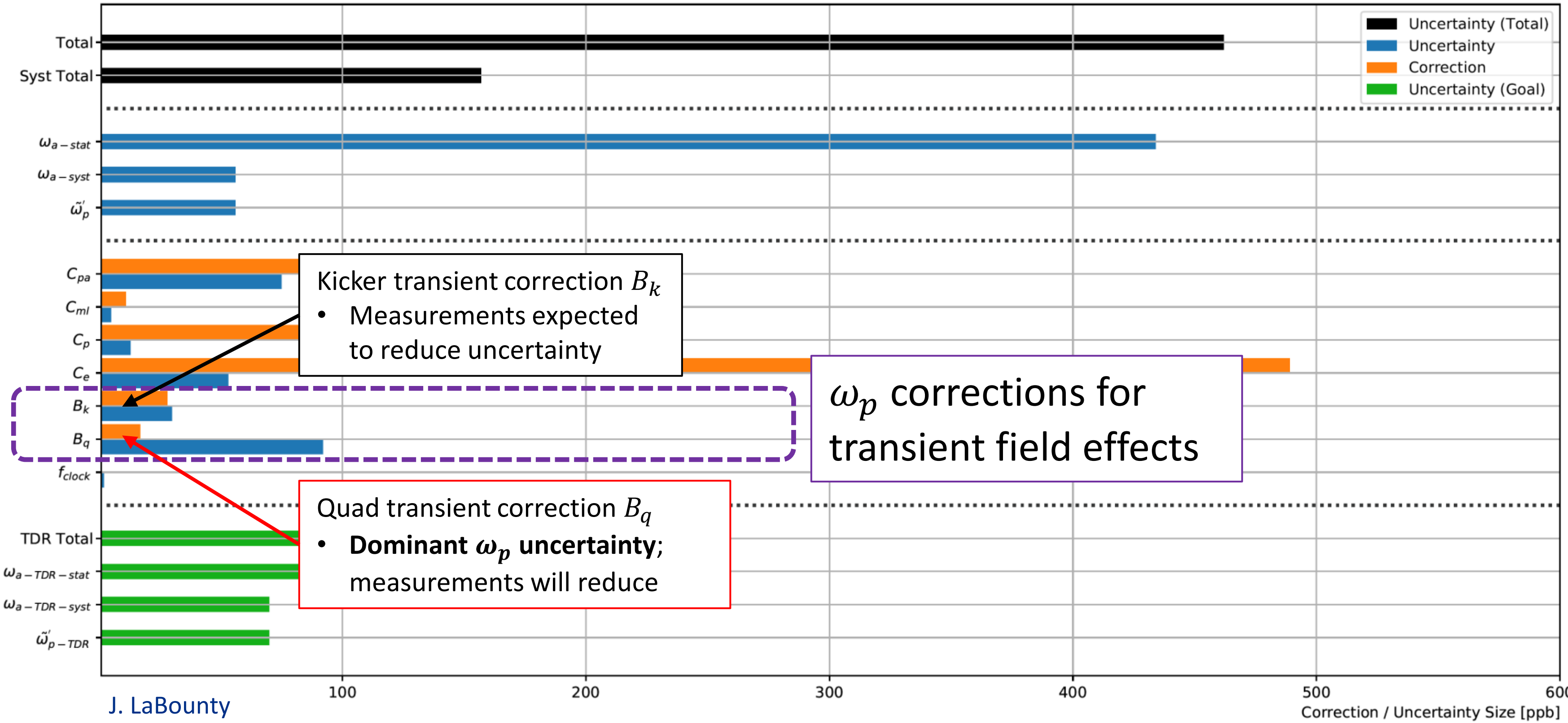


O. Kim



Run 1 uncertainties and corrections

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$



Kicker transient correction B_k
- Measurements expected to reduce uncertainty

Quad transient correction B_q
- **Dominant ω_p uncertainty**; measurements will reduce

ω_p corrections for transient field effects

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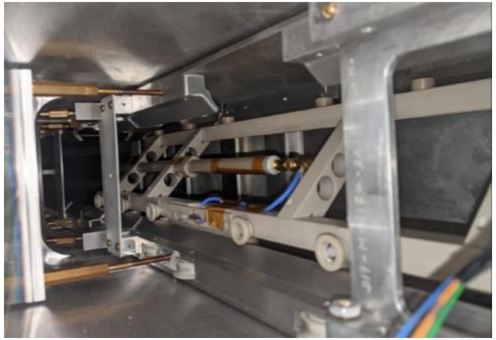
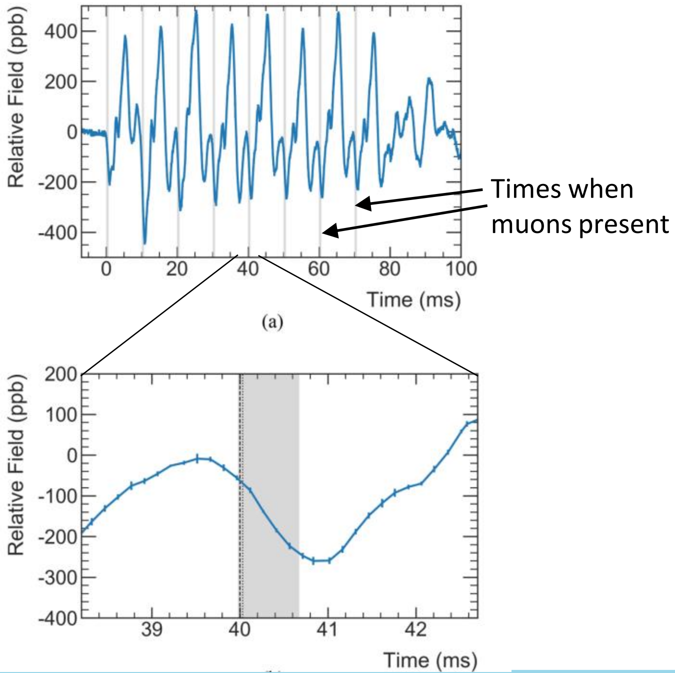
Quad transient correction

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

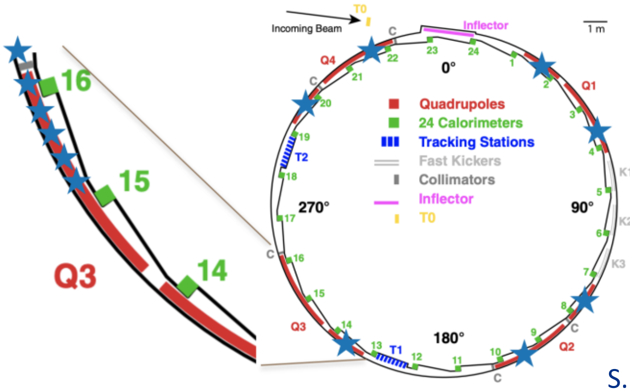
Mechanical vibrations in pulsed electric quadrupoles → transient magnetic field perturbation

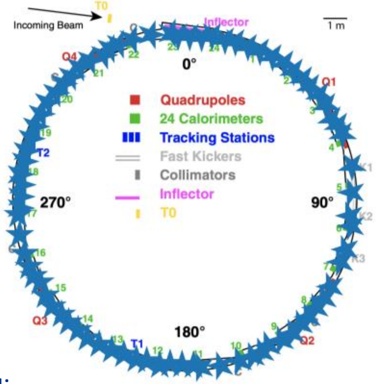
- Run 1 uncertainty (92 ppb): incomplete azimuth / time map
- Run 2+: Extensive mapping around ring with special NMR probes + trolley; aim for <40 ppb uncertainty





Run 1: few measured positions → Run 2+: map full ring





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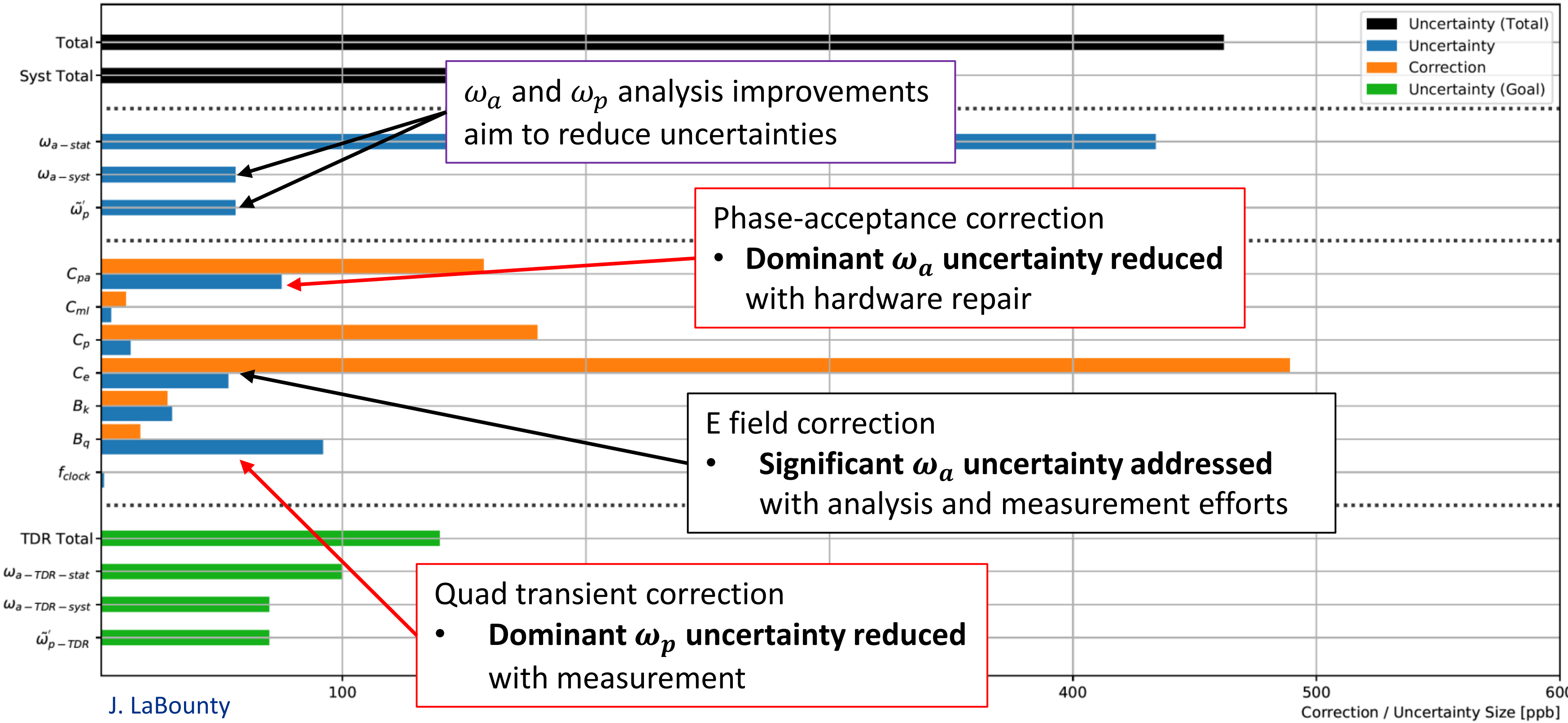
Run 1 uncertainties and corrections

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$



J. LaBounty

Conclusions

- Muon g-2 measured a_μ to 460 ppb (Run 1) → combined 4.2σ tension with SM
- Run 2+3 data processed, analysis in progress
  - Expect ~2× total precision improvement with higher statistics
- Many analysis and hardware efforts to reduce systematic uncertainties
  - Expect to achieve 100 ppb systematic uncertainty goal
- Run 5 data collection finished in July 2022
  - Very close to 20× BNL statistics goal!
- Preparing for Run 6 to start in fall