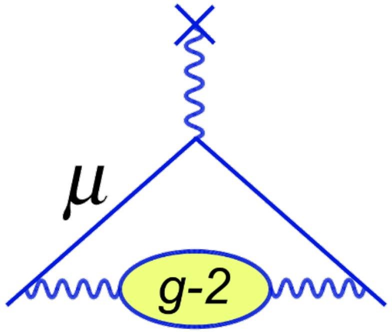
Improving the sensitivity with resonant RF fields in Muon $g-2$ experiment at Fermilab and Storage ring axion-EDM experiment

On Kim

Center for Axion and Precision Physics

2021 Sep. 16th

5th TAU Collaboration Meeting



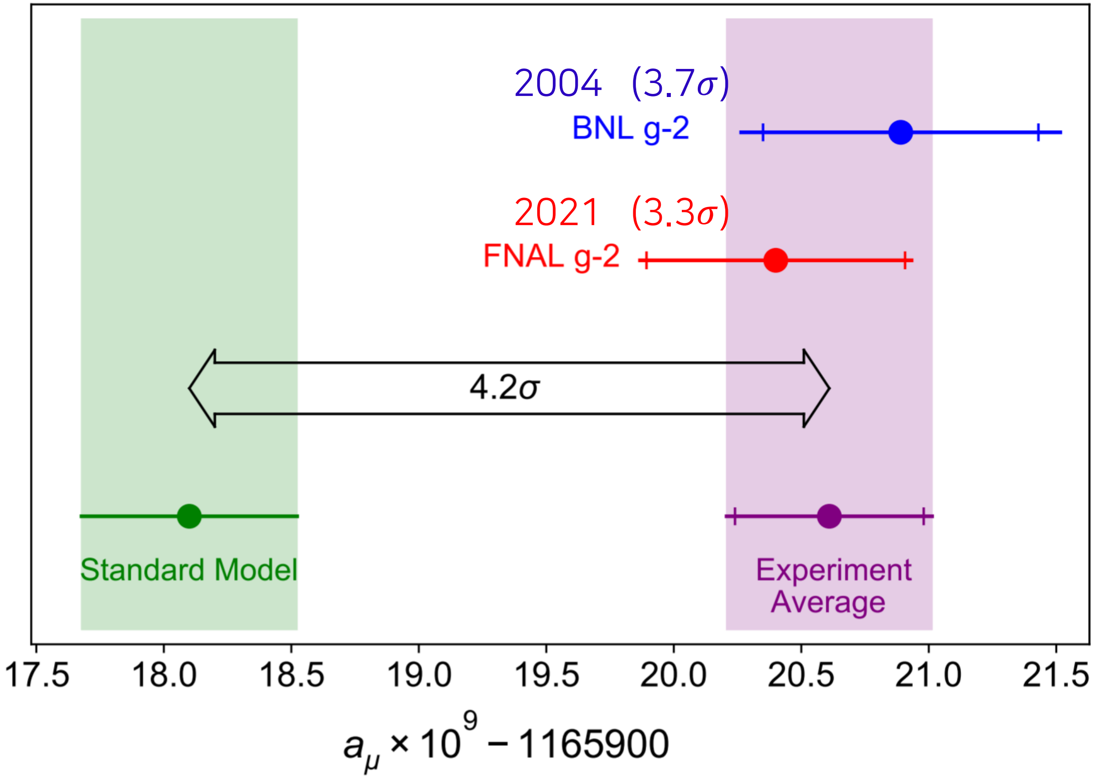
Institute for Basic Science
ibs
기초과학연구원
CAPP
Center for Axion and Precision Physics Research

PHYSICAL REVIEW LETTERS **126**, 141801 (2021)

Editors' Suggestion | Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

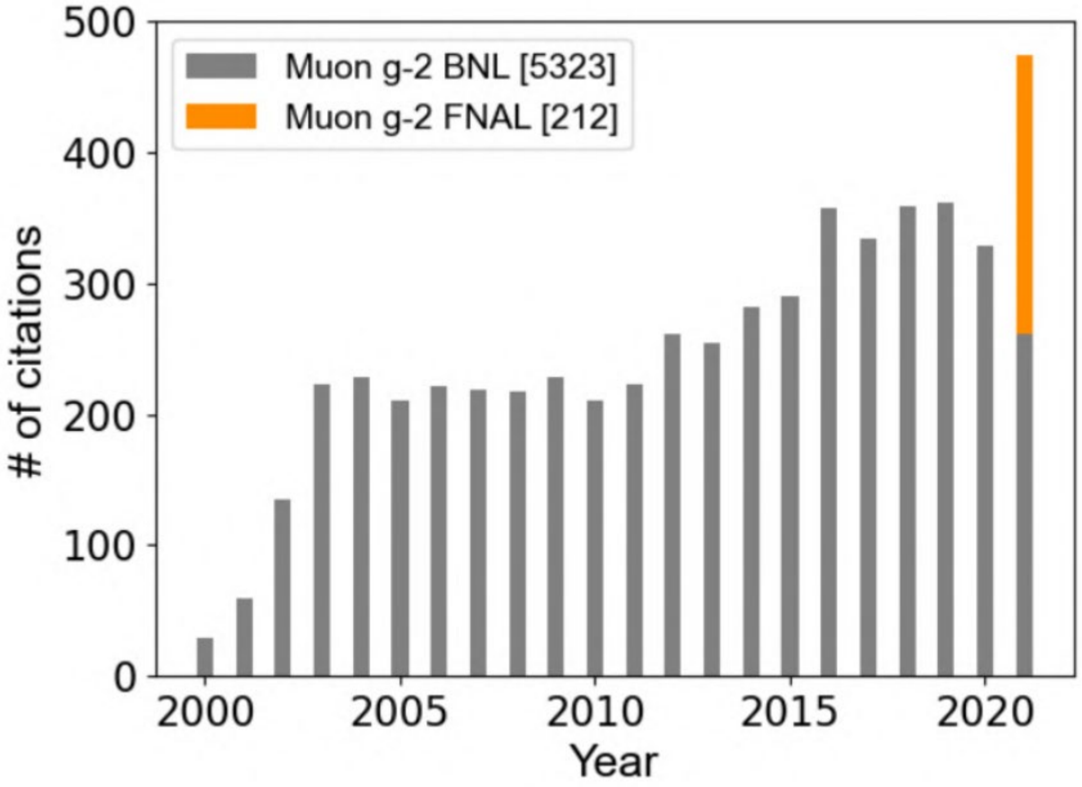
- Confirmation of the previous experiment at BNL.
- New experimental average has 4.2σ tension with SM.



$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$$

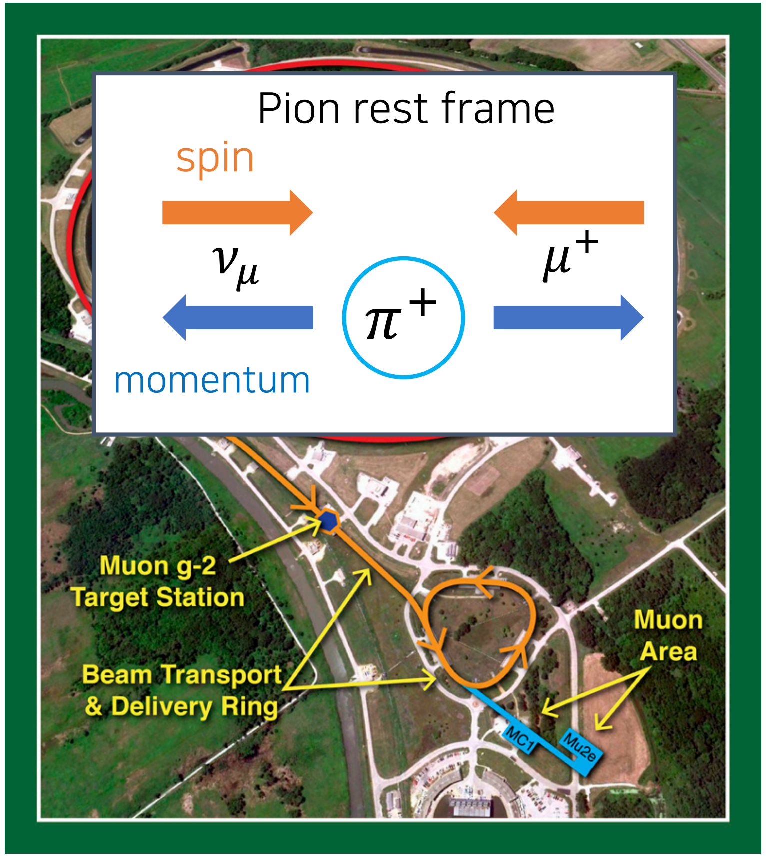
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$$

- Immediate large impact on physics community since the official announcement on April 7th, 2021.

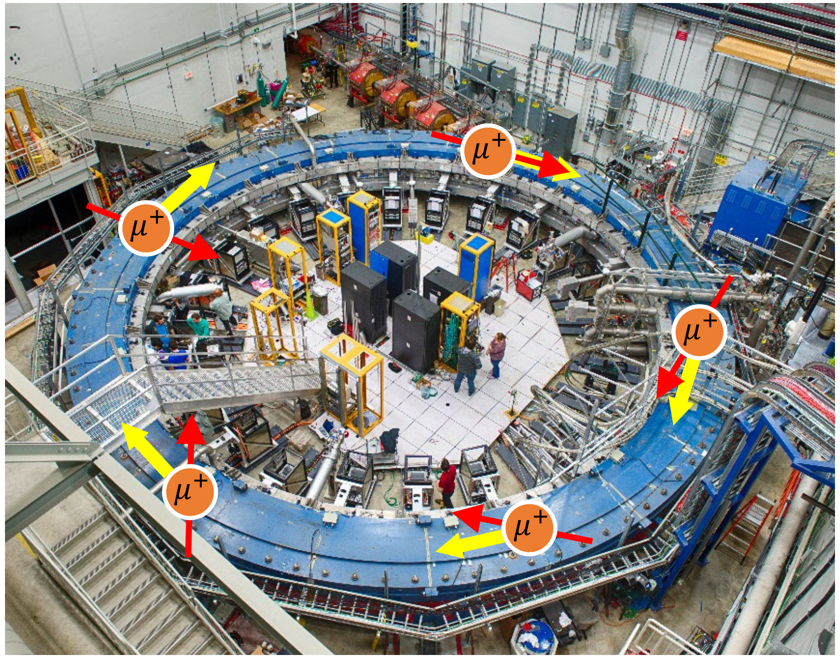


Bird(μ^+)'s Eye View of the Muon $g-2$ Experiment

Production | **Storage** | **Decay**



▶ High energy muons are highly polarized.



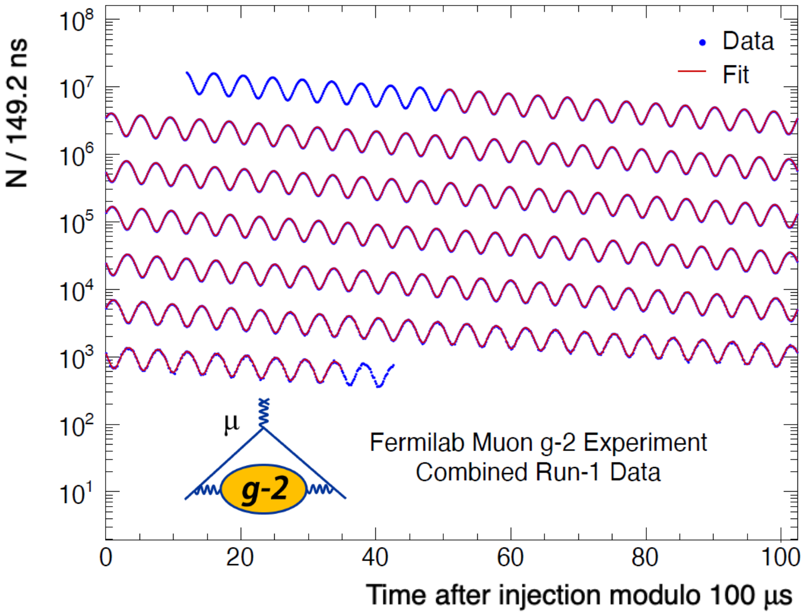
▶ The spin precesses under $\mathbf{B}$ field.

▶ Precession frequency $\omega_a \propto a_\mu$.

$$\omega_a = \frac{q}{m} a_\mu B$$

$$\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

▶ High energy positrons are preferentially emitted along the muon spin direction.



Uncertainty Budget

What we measure.

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

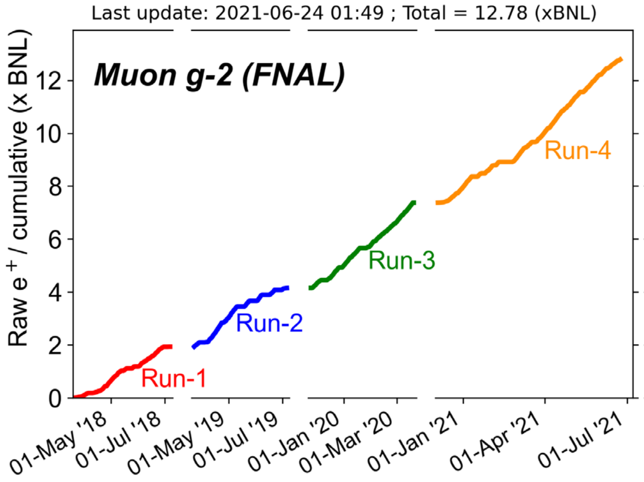
Known to 24 ppb

$$\left(\frac{\delta a_\mu}{a_\mu}\right)_{\text{BNL (E821)}} = 540 \text{ ppb}$$

Target sensitivity

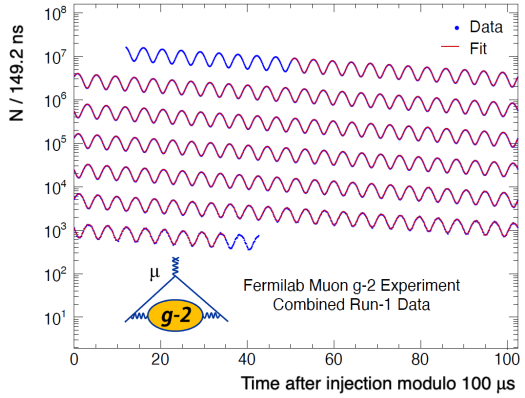
$$\left(\frac{\delta a_\mu}{a_\mu}\right)_{\text{FNAL (E989)}} = 140 \text{ ppb}$$

Statistical (100 ppb)



▶ Needs 150 billion decay e^+ data!

Systematic (ω_a) (70 ppb)

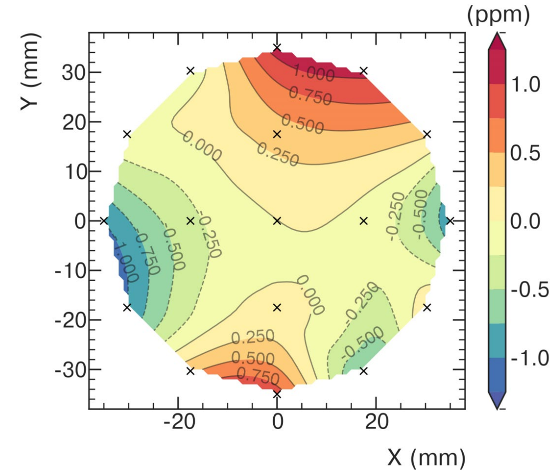


▶ Calorimeter gain changes (20 ppb)

▶ Pileup (40 ppb)

▶ Beam dynamics (Lost muons, CBO, ω_a corrections⋯.) (50 ppb)

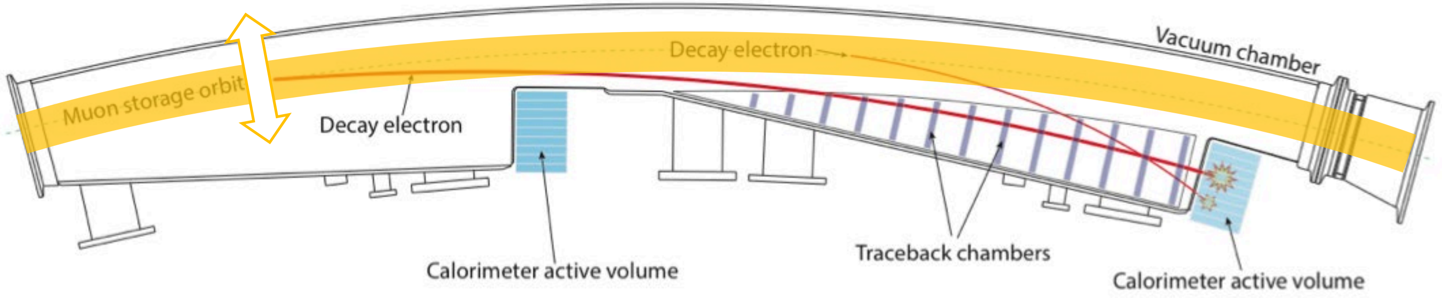
Systematic ($\tilde{\omega}_p$) (70 ppb)



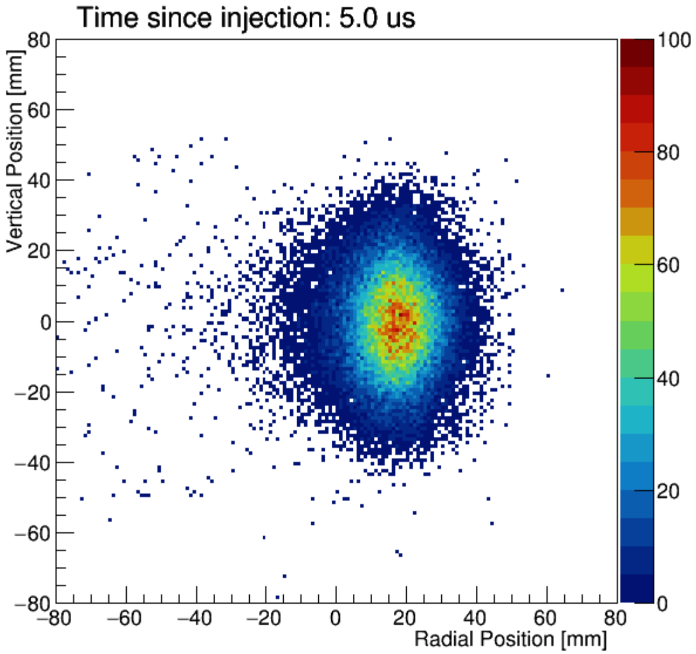
▶ Calibration, temperature fluctuation, tracking error, muon weighting, transient field⋯.

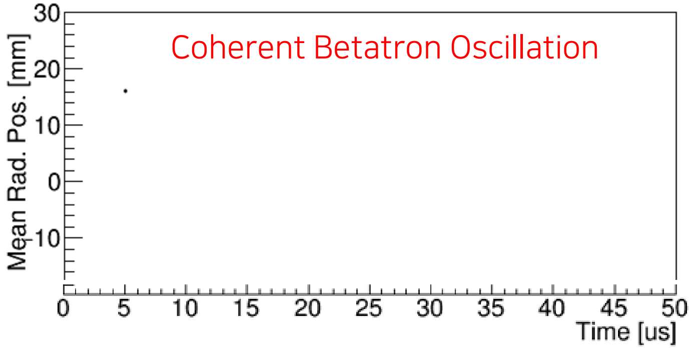
Beam Dynamics Systematics

- One of the dominant sources is Coherent Betatron Oscillations (CBO).



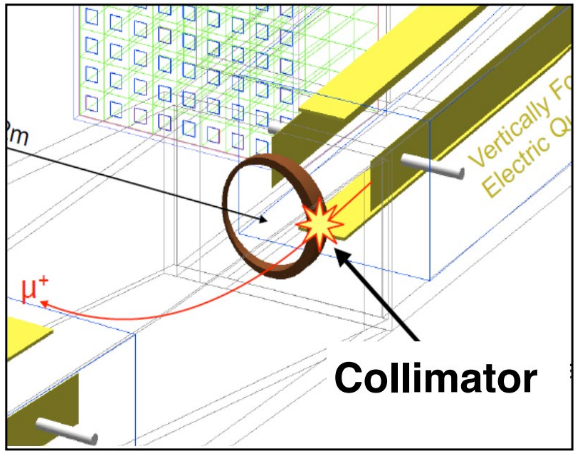
Muon beam coherently oscillates in transverse direction with respect to the central orbit.



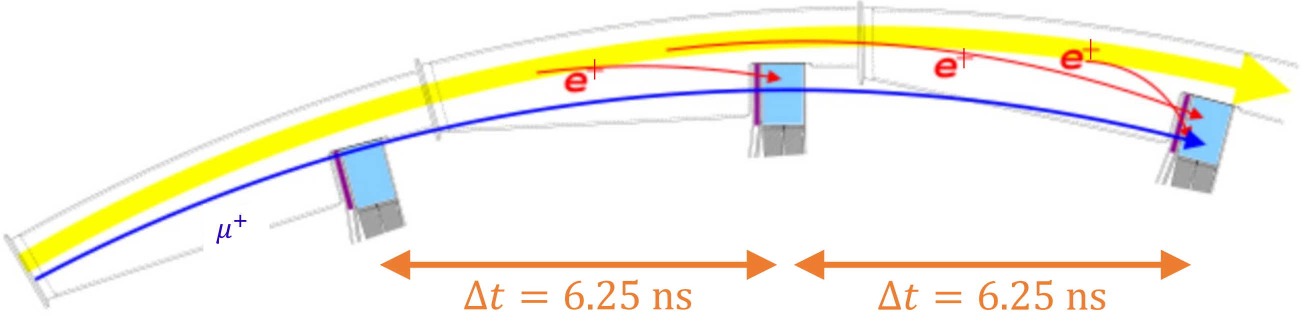


Beam Dynamics Systematics

- Muon losses: unwanted muon depletion due to the material effects during the fitting period.

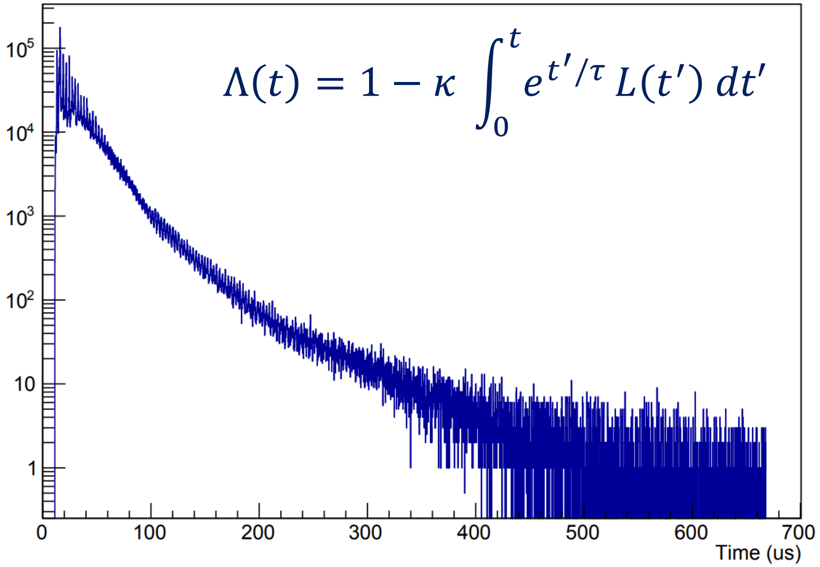


▶ Measured by a triple coincidence technique.



▶ Muon loss time spectrum ≠ Decay e^+ time spectrum
→ Fit function should be modified accordingly.

$$F(t) \rightarrow \Lambda(t)F(t)$$



Beam Dynamics Systematics

- Final fit model function which incorporates all important beam dynamics effects.

$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot$$
$$[1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

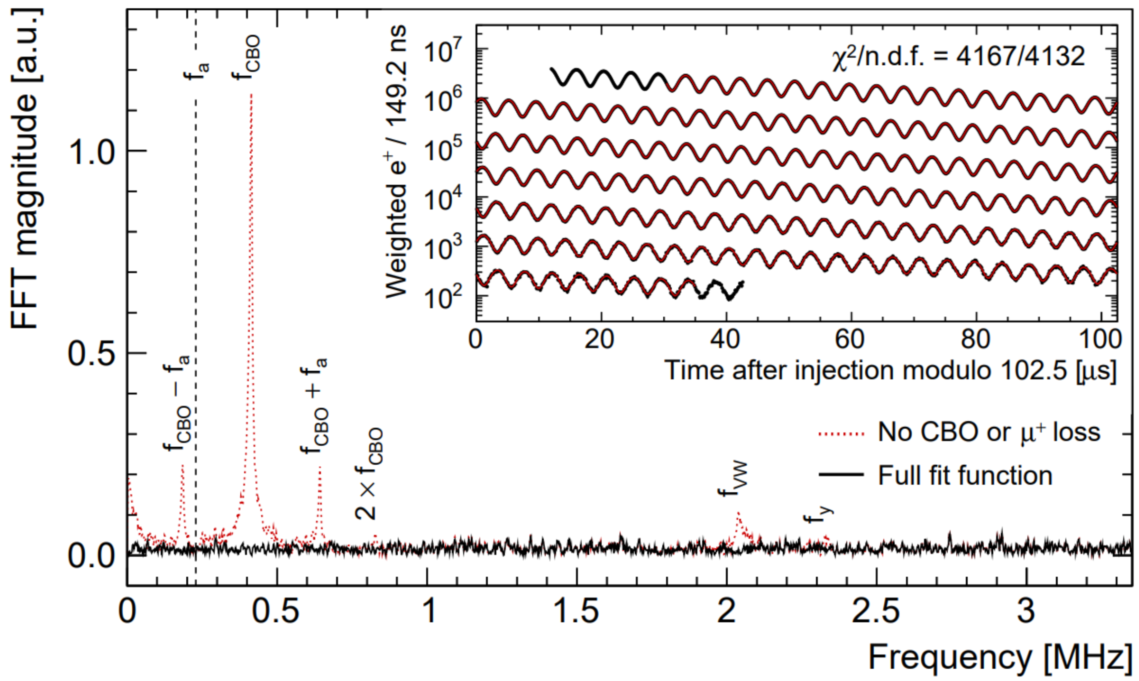
CBO
$$N_x(t) = 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{N,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{N,x,1}) + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2})$$

Vertical CBO
$$N_y(t) = 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2})$$

Muon losses
$$\Lambda(t) = 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, \mathrm{d}t'$$

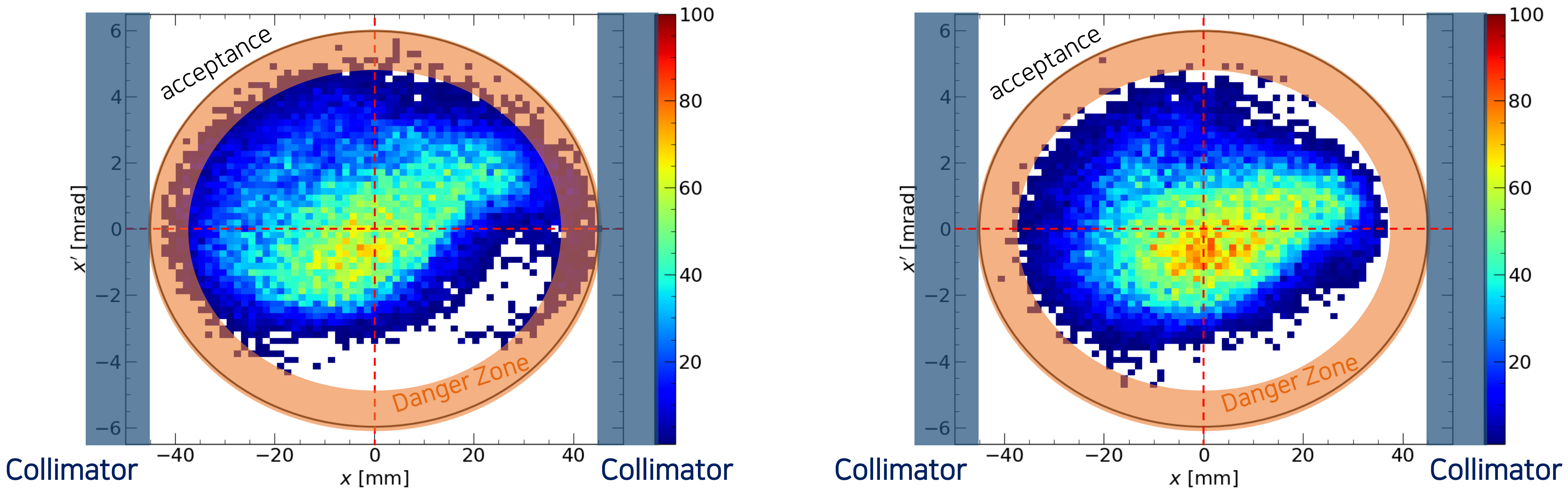
CBO
$$A_x(t) = 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{A,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{A,x,1})$$

CBO
$$\phi_x(t) = 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{\phi,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1})$$



RF Phase Space Matching

- Can we get rid of the CBO and muon losses in the first place, rather than accommodating their effects in analysis?
- The beam phase space should be “trimmed” to suppress them – Resonant E-field will do!
  - The more centered the beam is, the smaller the CBO amplitude is.
  - The less spread near the acceptance the beam is, the less the muon losses are.



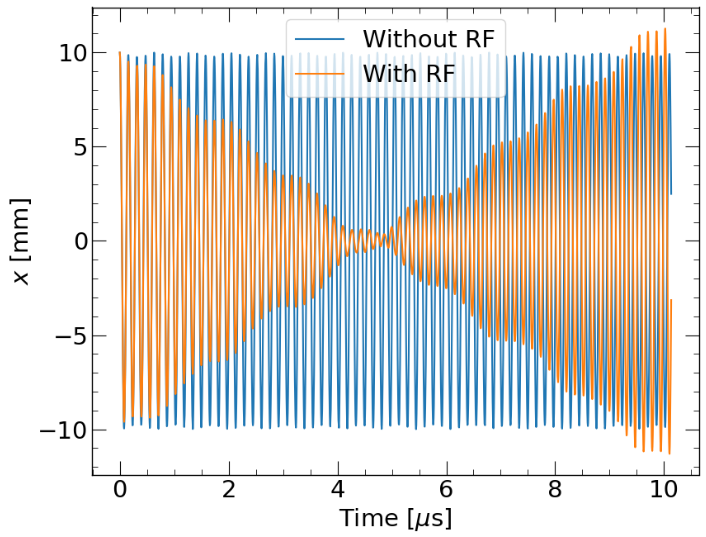
▶ Simulation results without/with the RF phase space matching

New J. Phys. **22**, 063002 (2020)

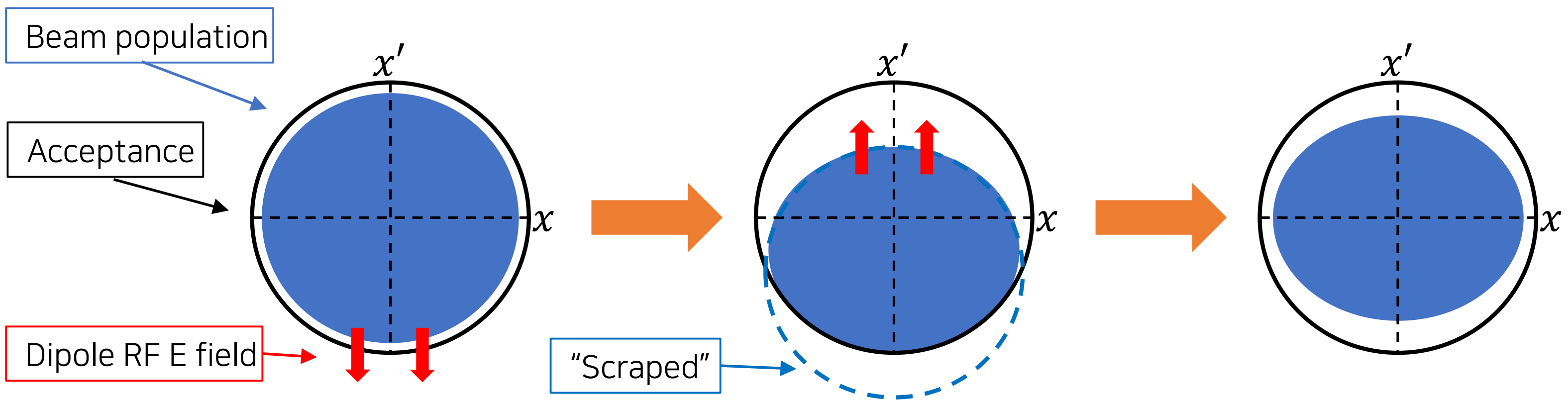
RF Phase Space Matching

"What you just saw looks simple, but it's a combination of 3 RF matching skills."

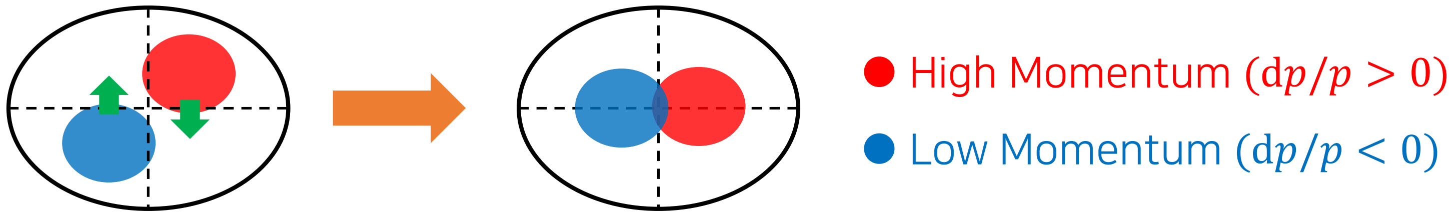
▶ Dipole RF resonantly reduces the CBO.



▶ RF scraping by pushing the beam towards the collimator.



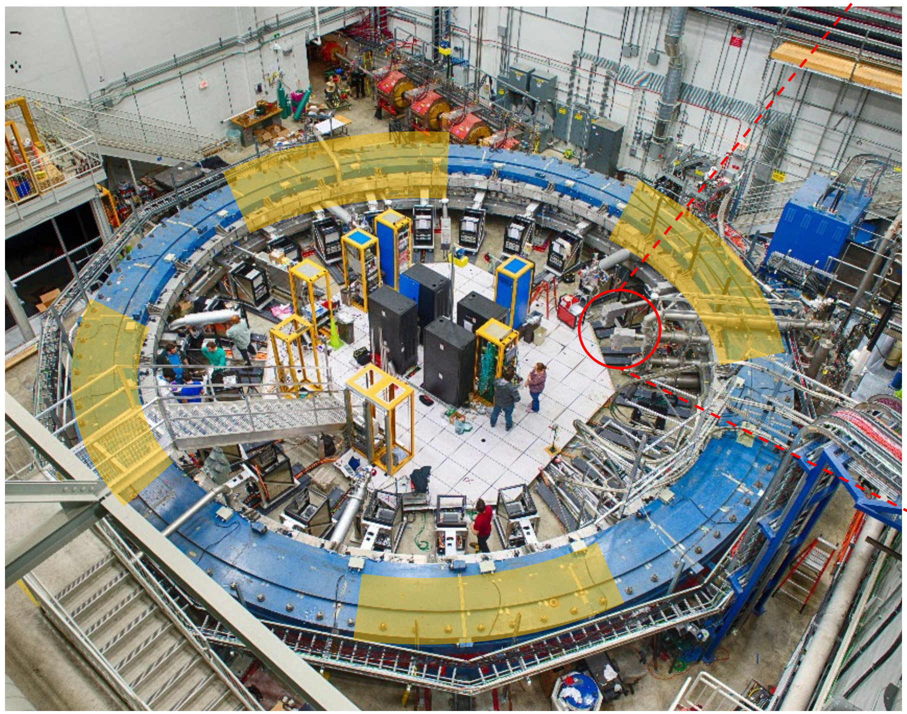
▶ Quadrupole RF resonantly squeezes the beam (exploiting the symmetry between the high/low momenta particles).



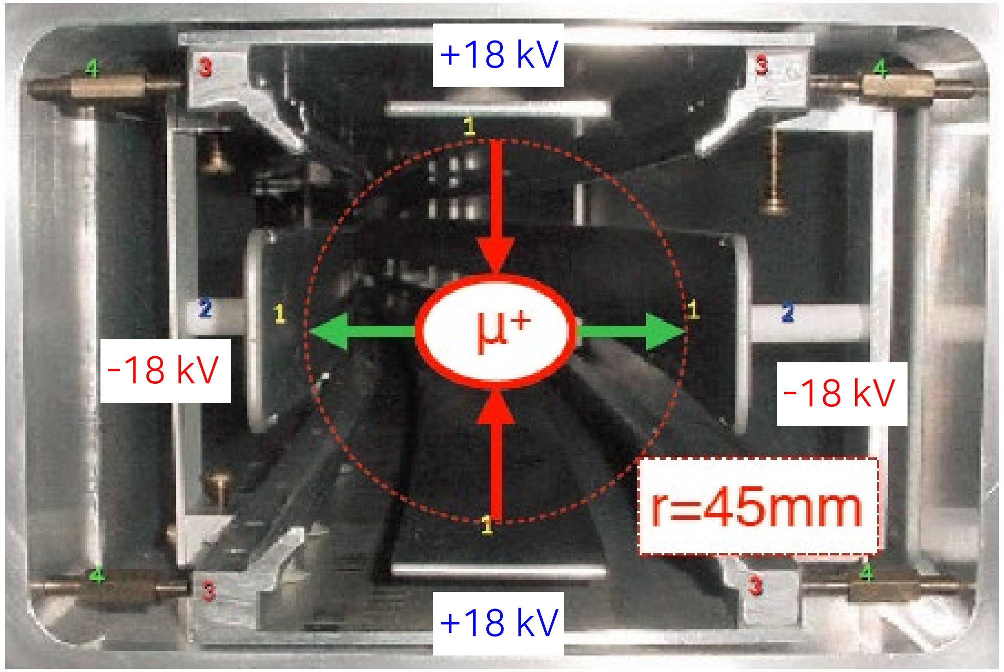
RF System

- The RF system is attached as an add-on to the existing electrostatic quadrupole (ESQ) system.

▶ ESQs cover ~40% of the circumference.



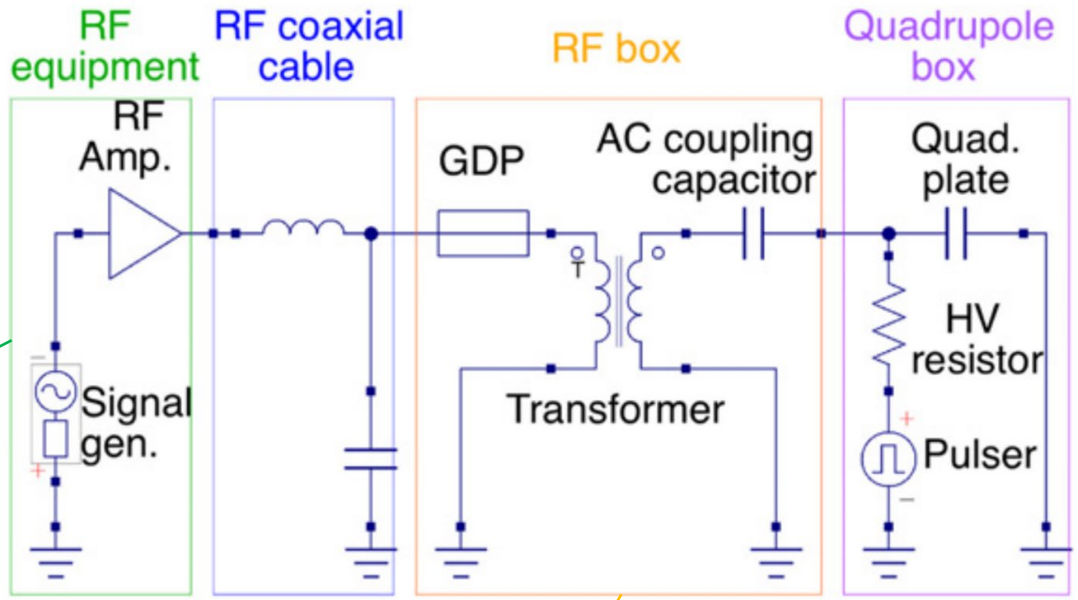
▶ High voltage is applied via feedthrough box.

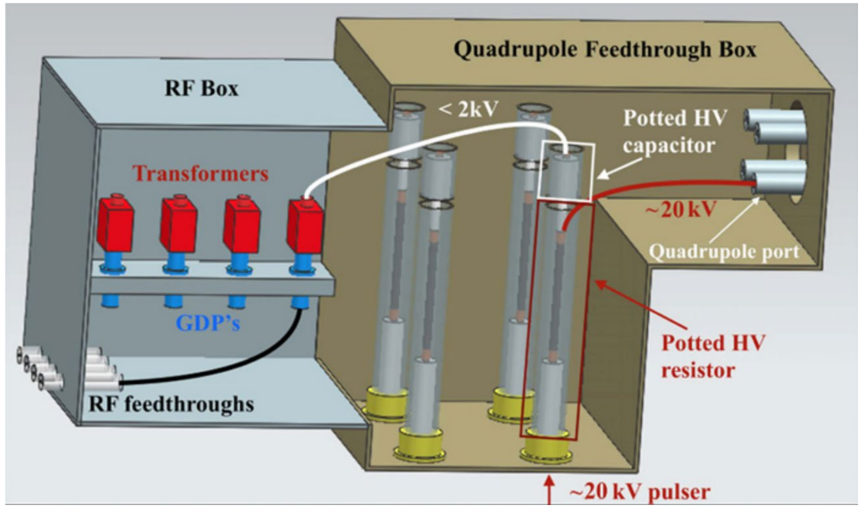


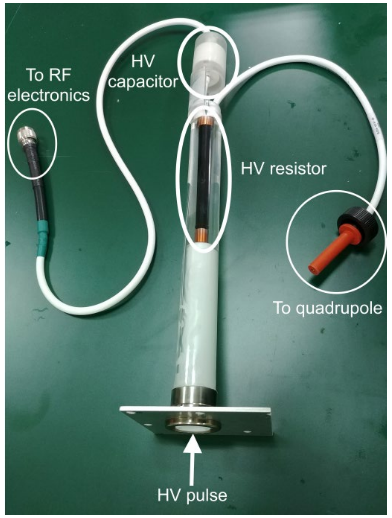
▶ Quadrupole E-field focuses the beam vertically.

RF System

- RF rack



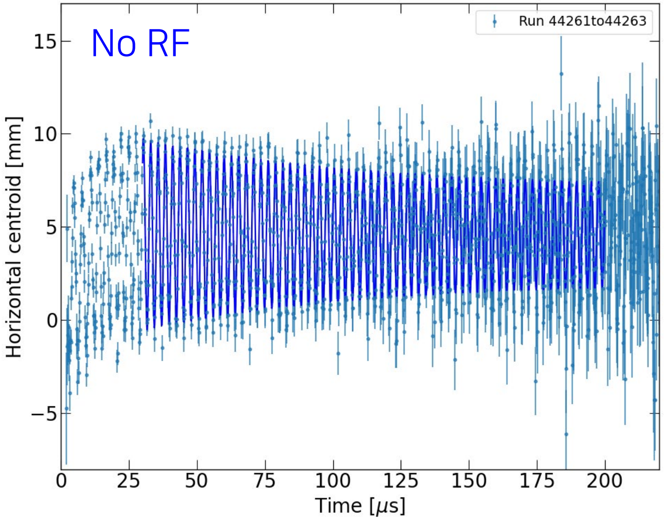


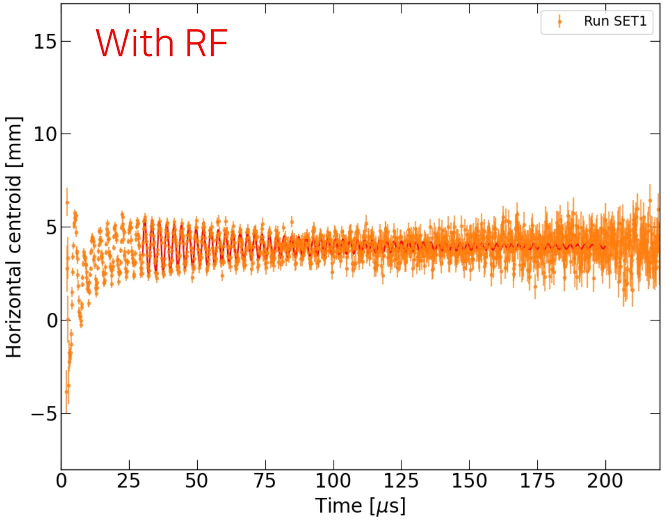


Commissioning Results and Analysis

- Both CBO amplitude and muon losses were reduced by several factors.

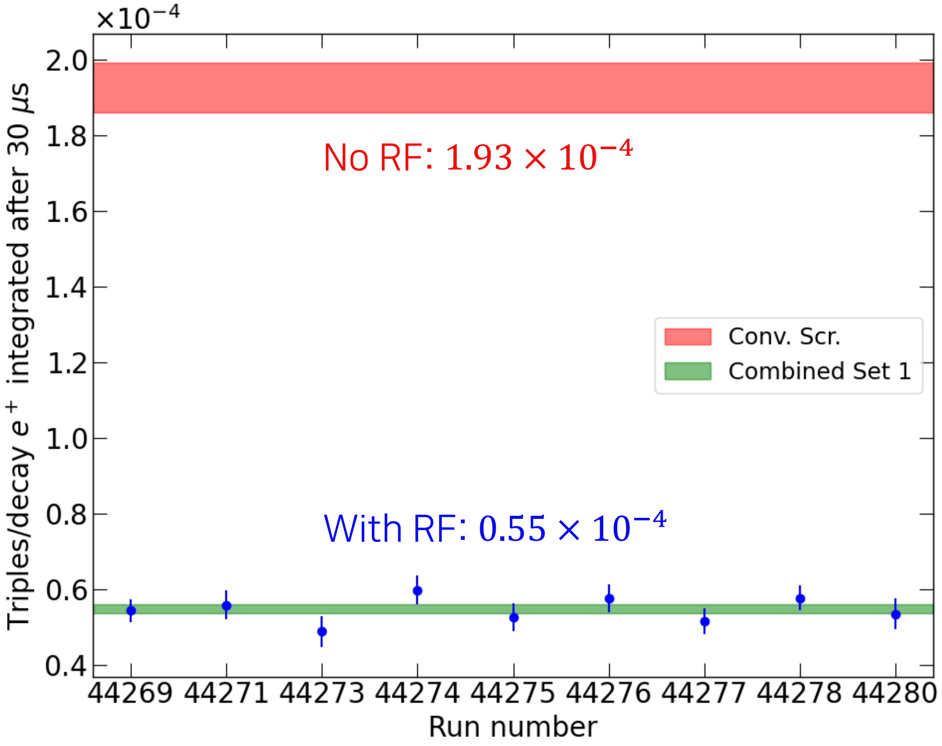
▶ CBO amplitude was reduced by a factor of 4.





▶ Preliminary study also showed the CBO decoheres faster with RF – needs more investigation.

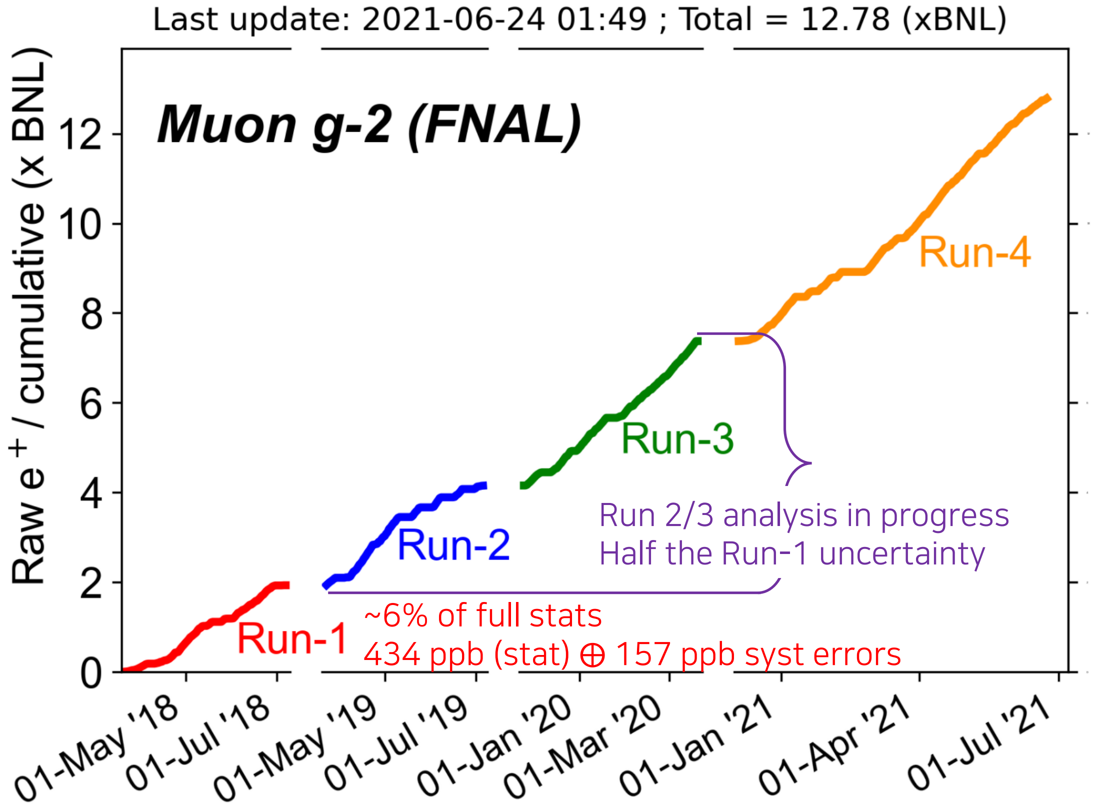
▶ Muon losses reduced by a factor of ~4.



Outlook

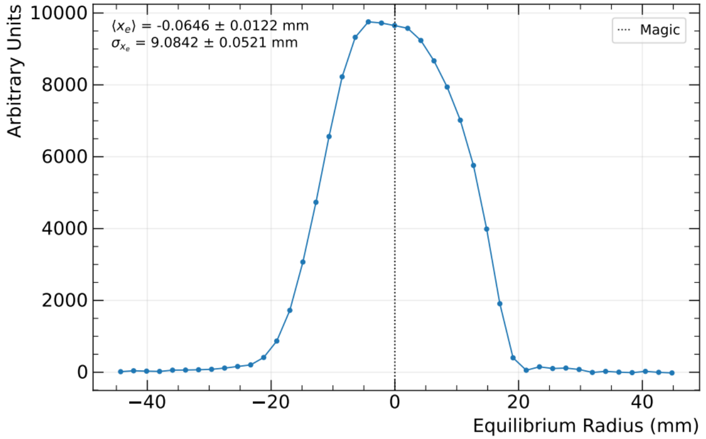
▶ Statistics status

- TDR goal is to take ~21 × BNL statistics.
- Run-5 will start in several weeks.
- Run-2/3 analysis results would come in 2022, with half the Run-1 uncertainty.



▶ RF matching run in Run-4

- Total 60 hours of RF data has been collected at the end of Run-4 (currently under production).
- Nearline analysis is ongoing.



▶ RF matching run in Run-5

- Currently in Summer Shutdown, our system is under the maintenance check, upgrade on the monitoring system, etc.
- Will be fully implemented in Run-5.

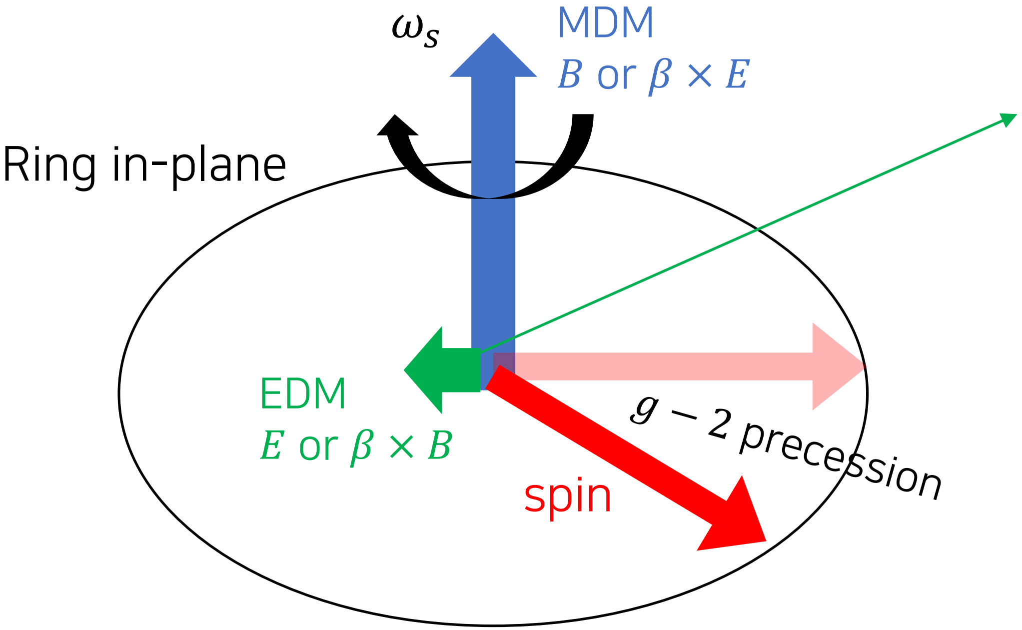
Storage Ring Axion-EDM Experiment

- Axion-like particles (ALPs) couple to nucleons, which induces an oscillating nucleon electric dipole moment (EDM)[1]:

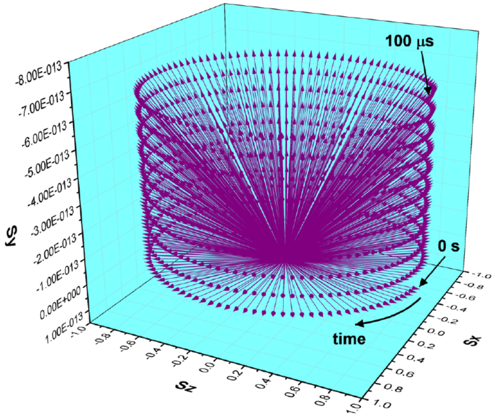
$$d_n = g_d a$$

- For QCD axion dark matter, for instance, this gives $d_n^{\mathrm{QCD}} \approx (9 \times 10^{-35}\, e \cdot \mathrm{cm}) \cos(m_a t)$.

- Storage ring EDM method can be sensitive to search for low-mass ALPs ($\ll \mu\mathrm{eV}$)



EDM generates (extremely small) radial component of ω_s vector $\propto d_n$.
It makes S_y oscillate feebly (unless the spin is "frozen" – then it grows).
What if d_n oscillates as well?
What if d_n oscillates by the same rate with the spin?



▶ Spin resonance! S_y grows[2].

[1]Phys. Rev. D **88**, 035023 (2013)
[2]Phys. Rev. D **99**, 083002 (2019)

New Idea using an RF Wien Filter

- Spin resonance condition with the oscillating EDM in the previous method is: $\omega_{g-2} = m_a$.
  - The $g-2$ frequency is normally given as: $\omega_{g-2} = \frac{q}{m}\left[GB_0 - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{E_0}{c}\right]$
  - One can tune E_0 or B_0 to sweep ω_{g-2} in the desired range, but the momentum of the particle should be changed accordingly ($p \propto E^* R$).

- What if we add another degree of freedom (knob) to tune at the resonance?

Some RF EM field ω_{RF}.

Rather "discrete" ω_{g-2}.

More statistics!

▶ RF Wien Filter is a perfect candidate!
Since it does not affect the beam dynamics but only spin!

$$\mathbf{E}_{\mathrm{WF}} = E_0^{\mathrm{WF}} \cos(\omega_{\mathrm{WF}} t + \phi_{\mathrm{WF}})\hat{e}_x,$$

$$\mathbf{B}_{\mathrm{WF}} = \frac{E_0^{\mathrm{WF}}}{\beta c} \cos(\omega_{\mathrm{WF}} t + \phi_{\mathrm{WF}})\hat{e}_y$$

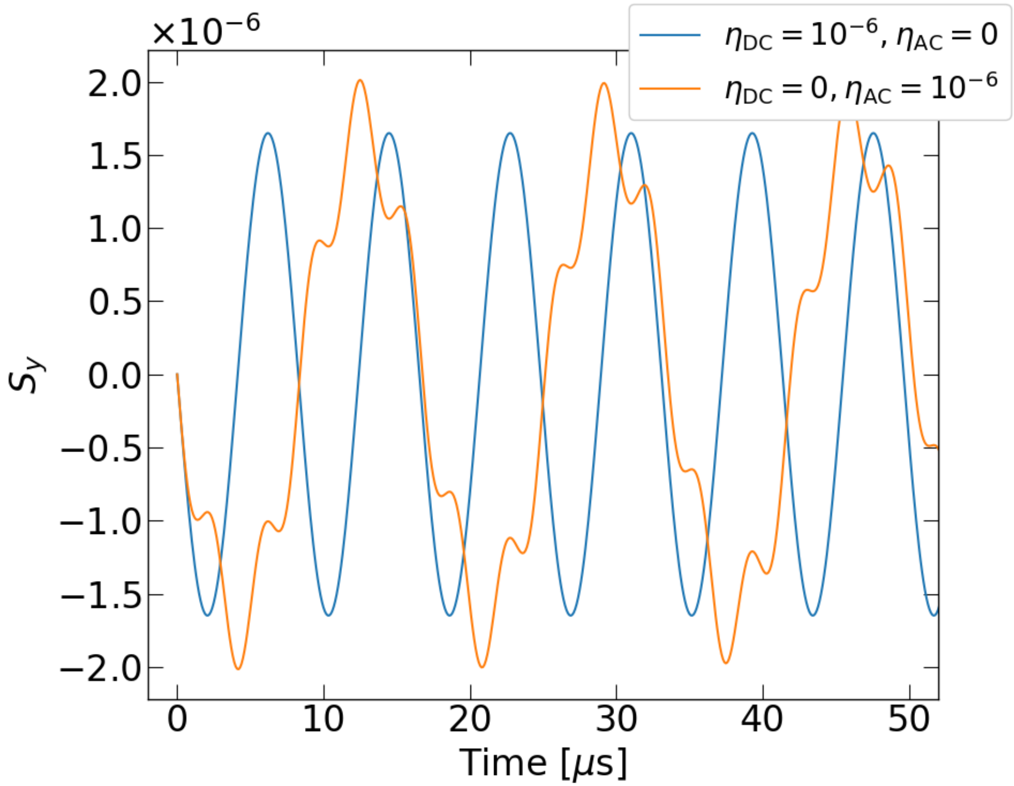
$$\mathbf{F}_{\mathrm{WF}} = q(\mathbf{E}_{\mathrm{WF}} + \mathbf{v} \times \mathbf{B}_{\mathrm{WF}}) = 0$$

AxionEDM-WF Resonance

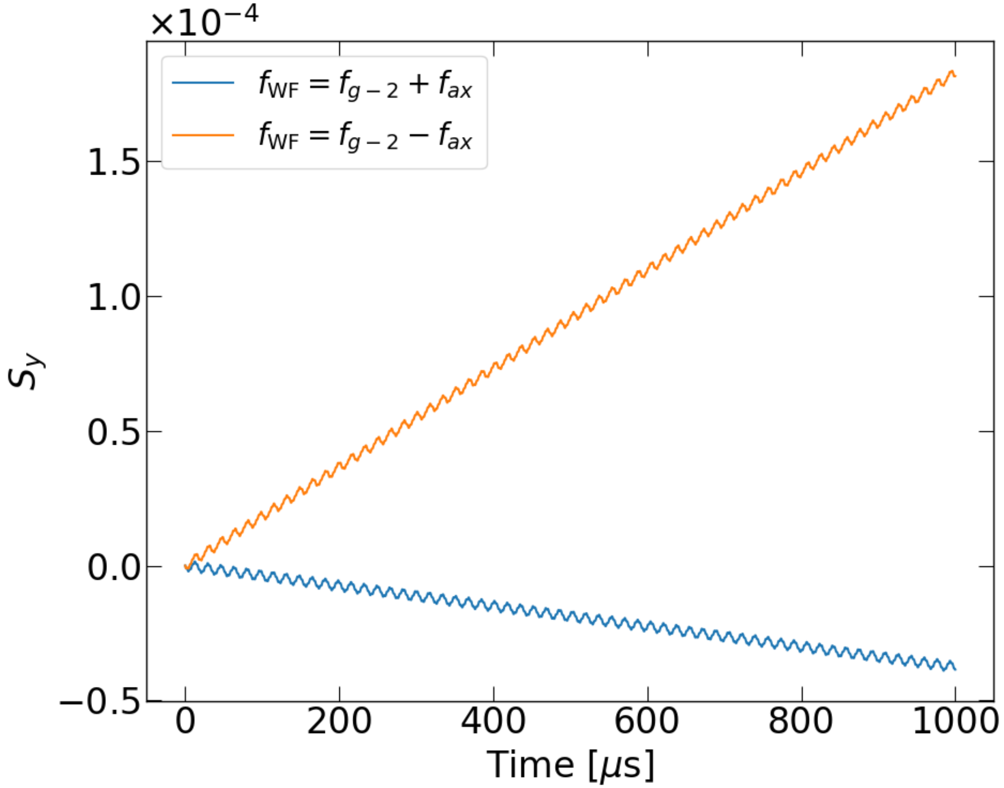
- The new resonance condition is[1]: $\omega_{\mathrm{WF}} = |\omega_{g-2} \pm m_a|$

[1]arXiv:2105.06655

▶ Without the WF



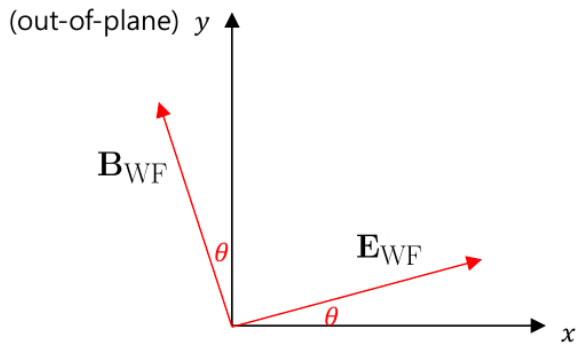
▶ With the WF (on resonance)



Systematics from the WF Misalignment

- Similarly as $\omega_{\mathrm{WF}} = |\omega_{g-2} \pm m_a|$ is sensitive to d_{AC}, $\omega_{\mathrm{WF}} = \omega_{g-2}$ is sensitive to d_{DC}[1].
- However, the latter is vulnerable to a WF misalignment (tilt).

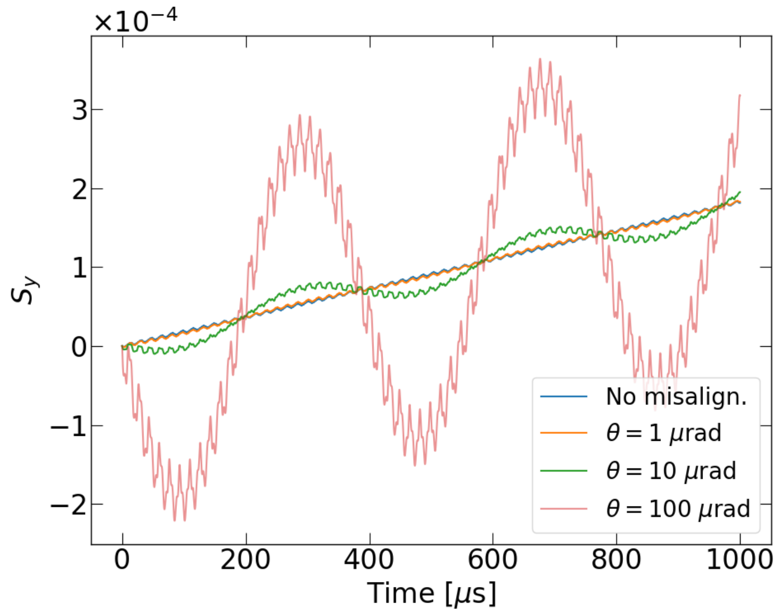
[1] Phys. Rev. ST Accel. Beams **16**, 114001 (2013)



Systematic signal scales with the misalignment angle: $\dot{S}_y \propto \theta$
The "real" signal could be an order of nrad/s

- On the other hand, being away from the systematic resonance ($\omega_{\mathrm{WF}} = \omega_{g-2}$), this method doesn't suffer from the misalignment.

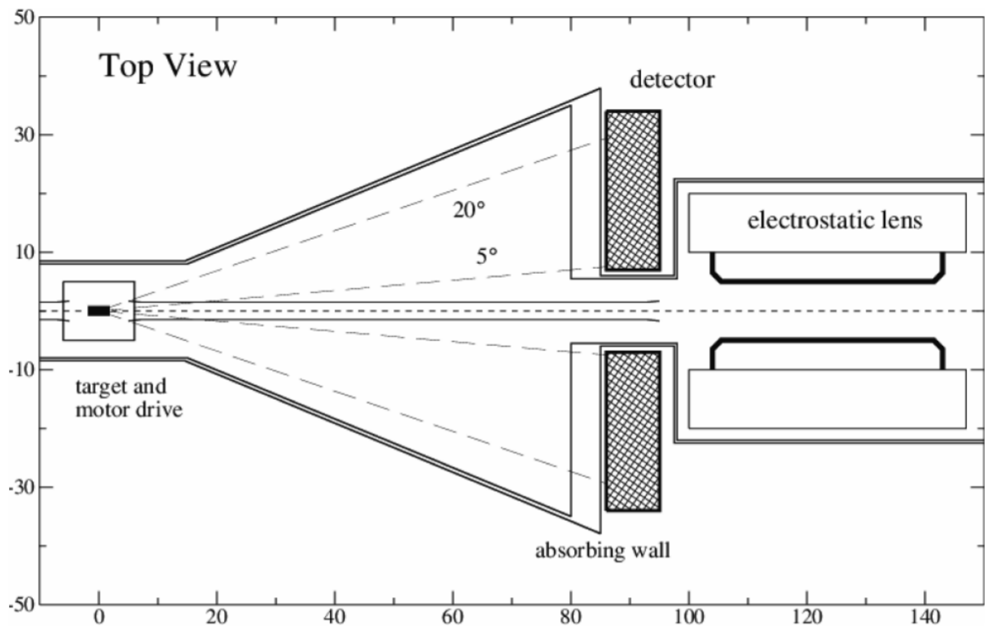
- Nonetheless, other systematics such as momentum dispersion, radial B field, intrinsic resonances, etc. should be studied in more details.



Polarimeter Statistical Sensitivity

- Detecting apparatus is a polarimeter[1].

[1]Rev. Sci. Instrum. **87**, 115116 (2016)



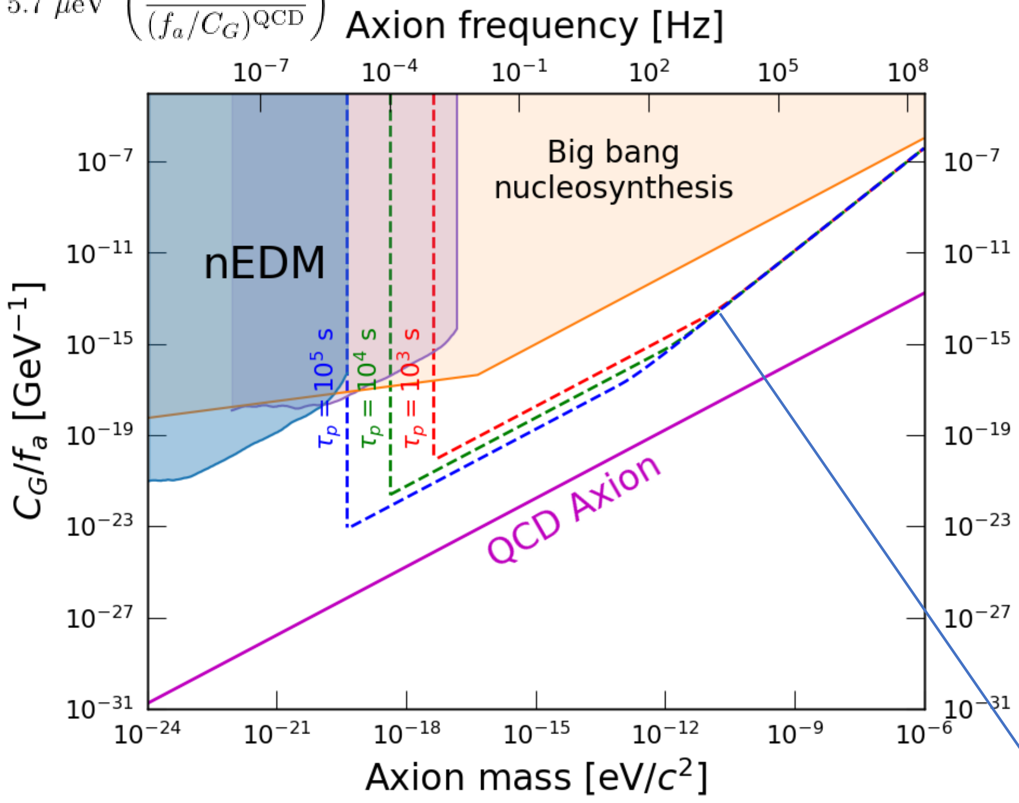
- Estimated statistical sensitivity with the WF.

$$\sigma_d = 9.3 \times 10^{-31}\ [e \cdot \text{cm}] \left(\frac{s}{1/2}\right)\left(\frac{0.8}{P_0}\right)\left(\frac{0.6}{A}\right)\left(\frac{100\ \text{MV/m}}{E^*}\right)\left(\frac{0.59}{C_{\text{WF}}}\right)\sqrt{\left(\frac{1.1\%}{\kappa}\right)\left(\frac{10^{11}}{N_{\text{cyc}}}\right)\left(\frac{1\ \text{yr}}{T_{\text{exp}}}\right)\left(\frac{10^3\ \text{s}}{\tau_p}\right)}$$

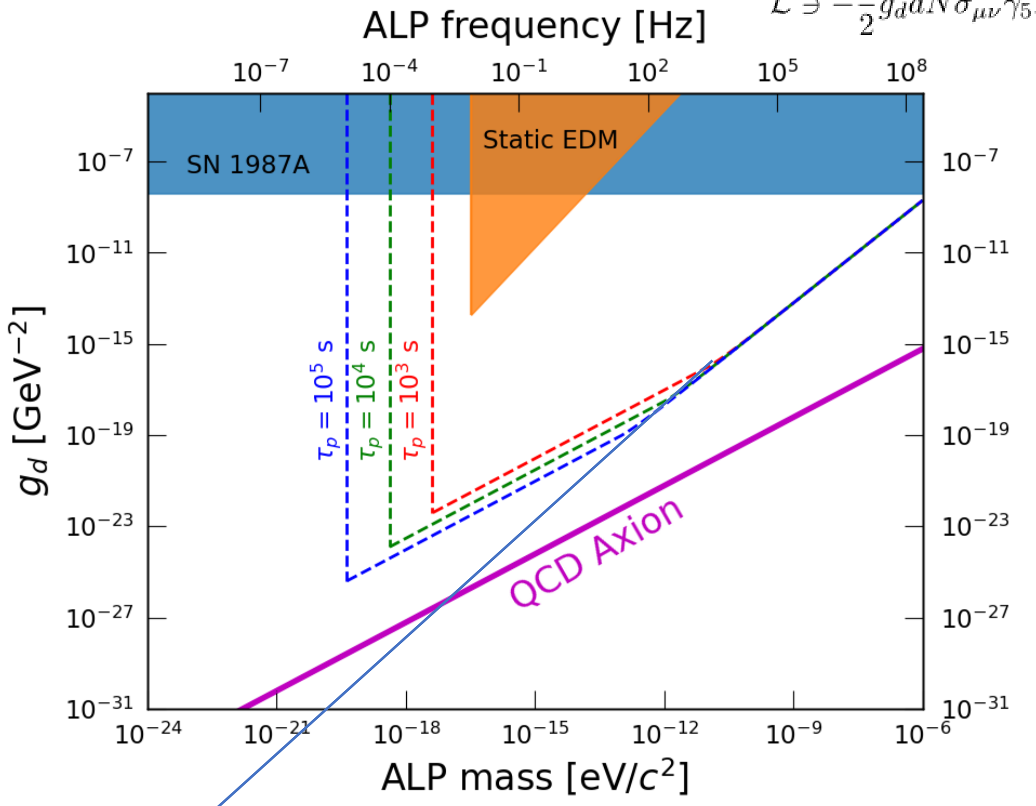
Projected Sensitivity for ALP Parameter Space

- Assuming the experimental parameter values which optimize the statistical sensitivity.

$$m_a^{\rm QCD} \approx 5.7\ \mu{\rm eV}\left(\frac{10^{12}\ {\rm GeV}}{(f_a/C_G)^{\rm QCD}}\right)$$



$$\mathcal{L} \ni -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$



Right side of the kink is restricted by the axion DM Q-factor (10^6)

$$T = \min\left\{\frac{Q_{\rm axion}}{f_{\rm axion}}, \frac{\tau_p}{2}\right\}$$

Summary

- Muon $g-2$ experiment at Fermilab has announced its first result – consistent with the previous experiment at BNL and the combined experimental value has 4.2σ tension with the SM!
- Beam phase space matching with an resonant RF electric field can reduce some important beam dynamics systematic effects – CBO, Muon losses.
  - Full implementation on Run 5 is planned.

- Storage ring axion-EDM experiment utilizes a novel method to look for low-mass axionlike dark matter in storage rings (2019).
- Another new idea using an RF Wien Filter to detect the axion-induced oscillating EDM has been proposed more recently (2021).

- The resonant RF (to beam & spin) is of service to improve sensitivity in storage ring experiments!

Backups