



The Muon g-2 Beamline

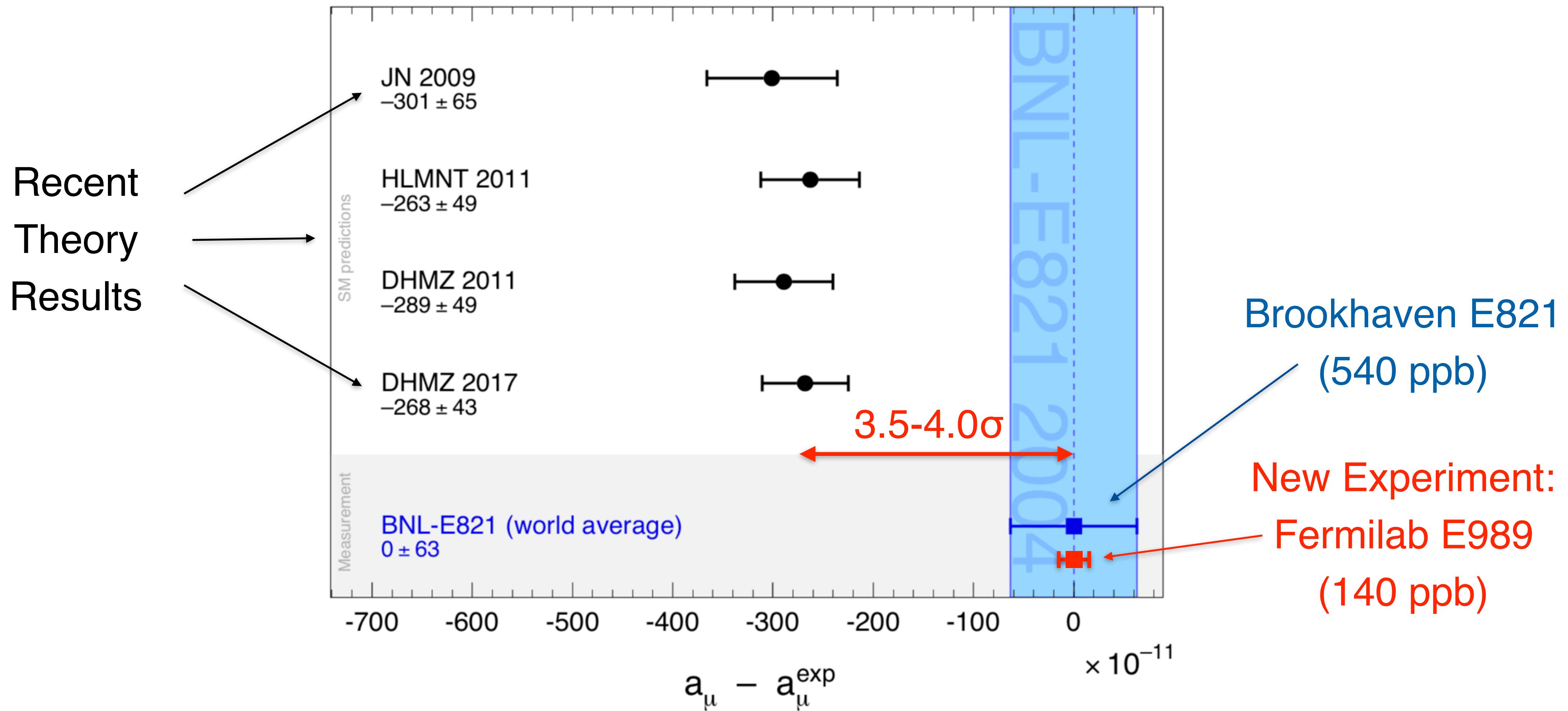
Nathan S. Froemming

NuFact18

17 Aug 2018

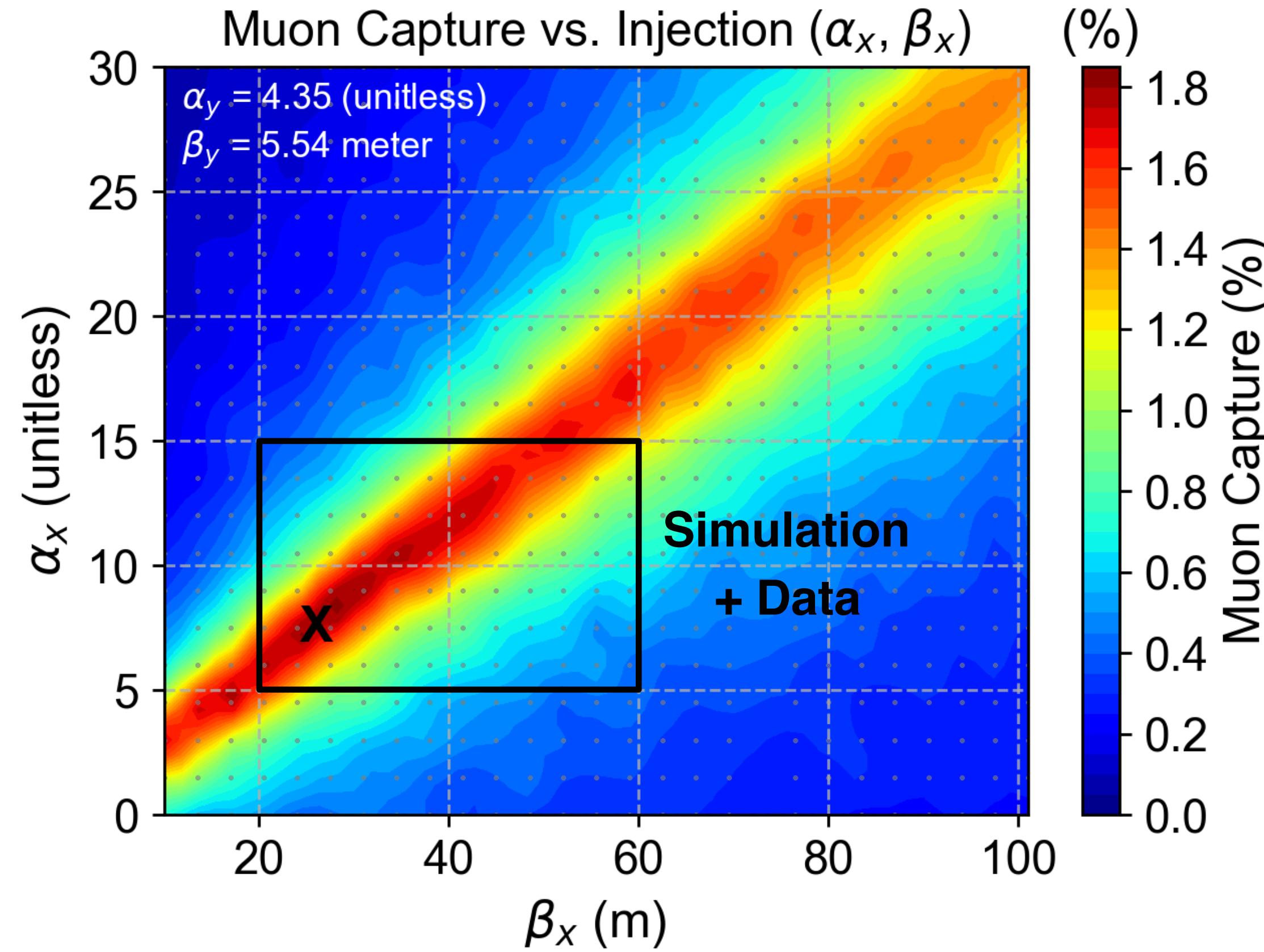
Background & Motivation

Muon Magnetic Anomaly: Theory vs. Experiment

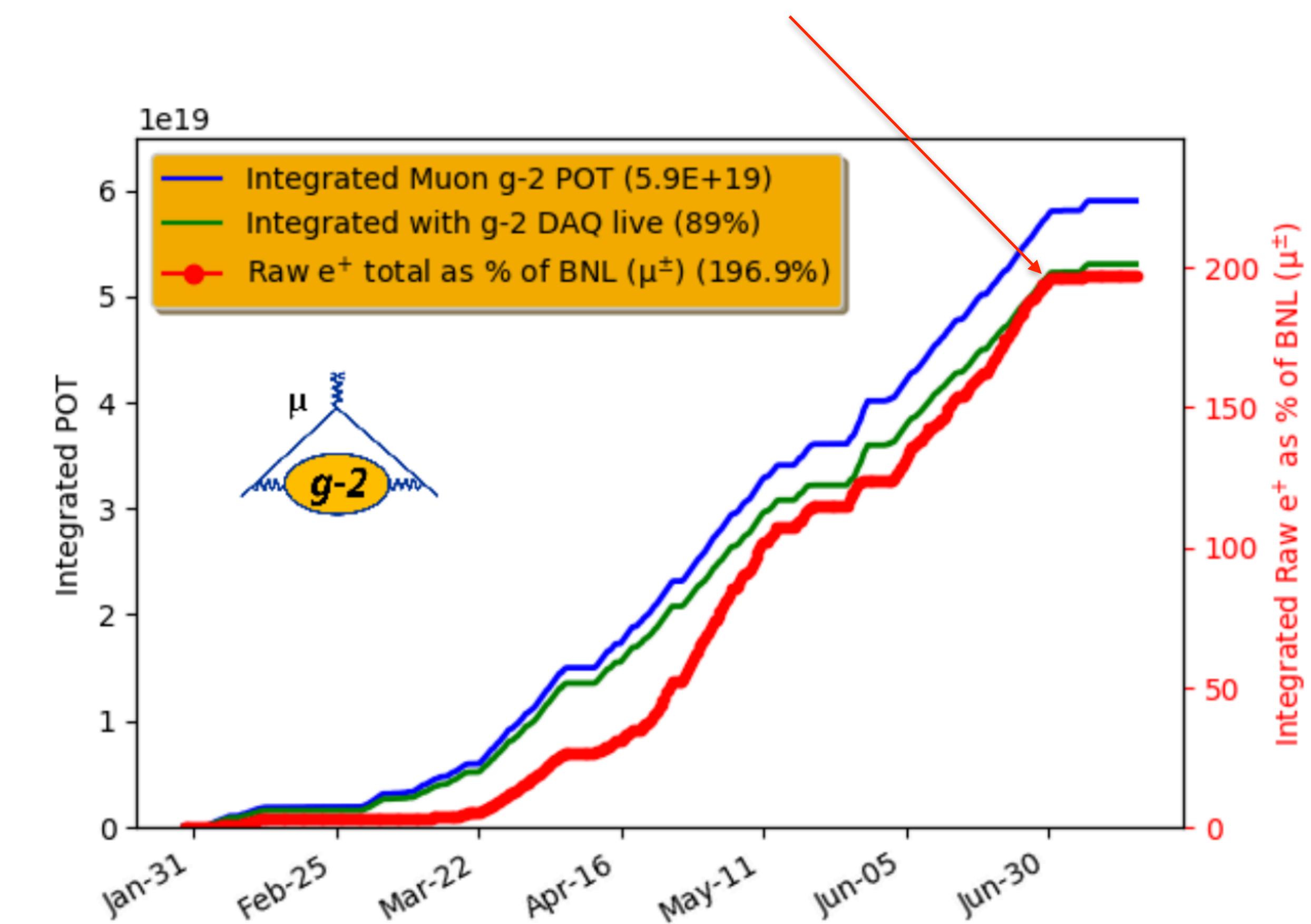


Bottom Line

Successful commissioning
and beamline optimizations



Successful Run 1: ~2X BNL statistics



Outline

- Experiment overview
- Optimization of the muon g-2 beamline
- Discovery of a problem
- Conclusion & path forward

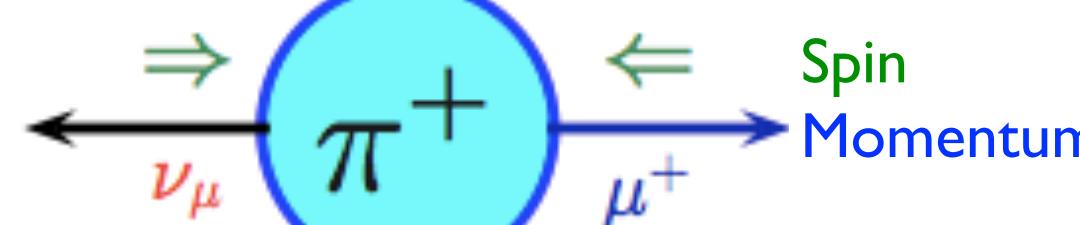
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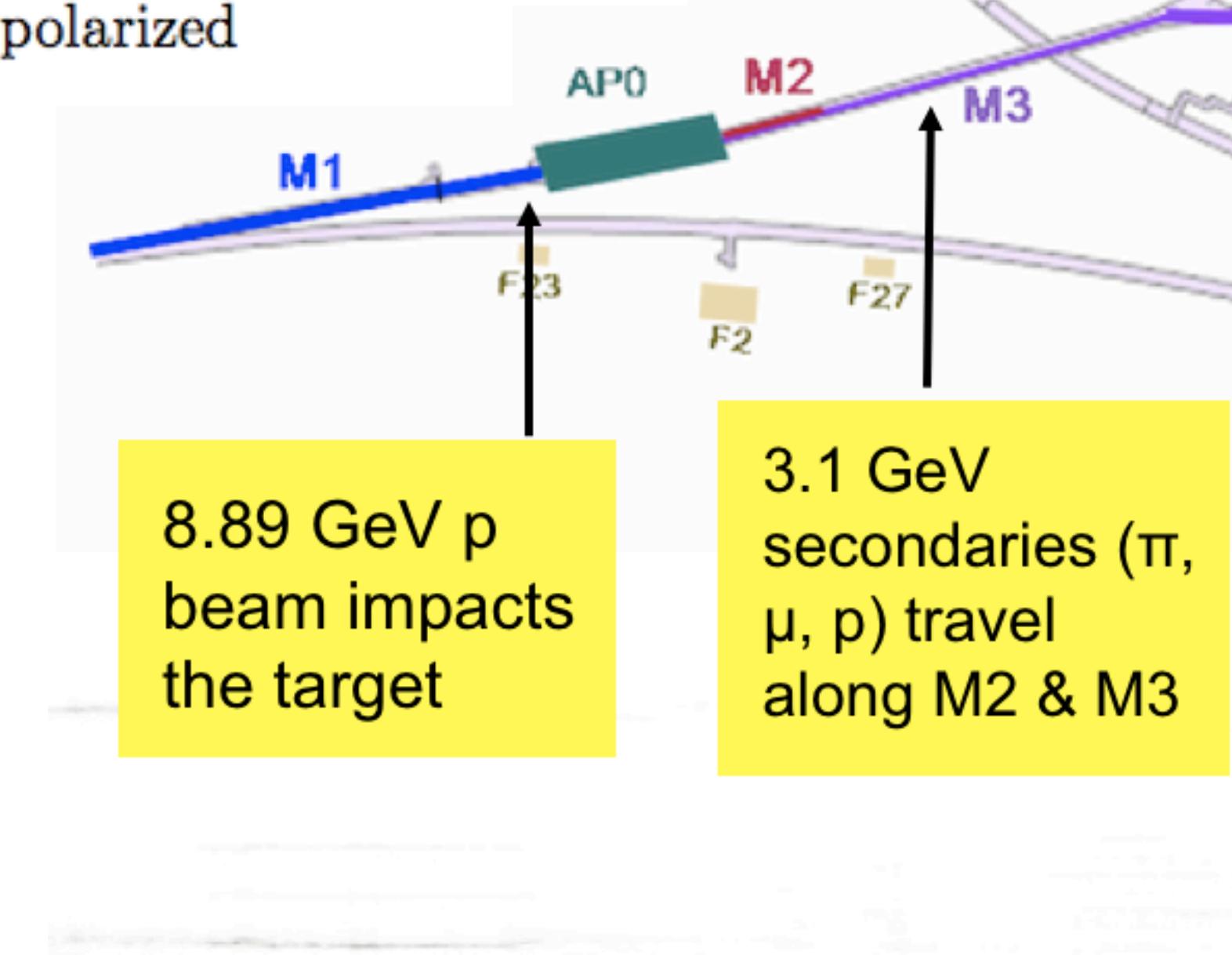
Obtaining a polarized muon beam at Fermilab Muon Campus^[1]

[1] NuFact18, D. Stratakis, "Commissioning and first results of the Fermilab Muon Campus"

Pion Decay



"Forward" Decay Muons
are highly polarized



8.89 GeV p
beam impacts
the target

Protons separate
and are removed

3.1 GeV
secondaries (π ,
 μ , p) travel
along M2 & M3

$C \approx 505\text{m}$

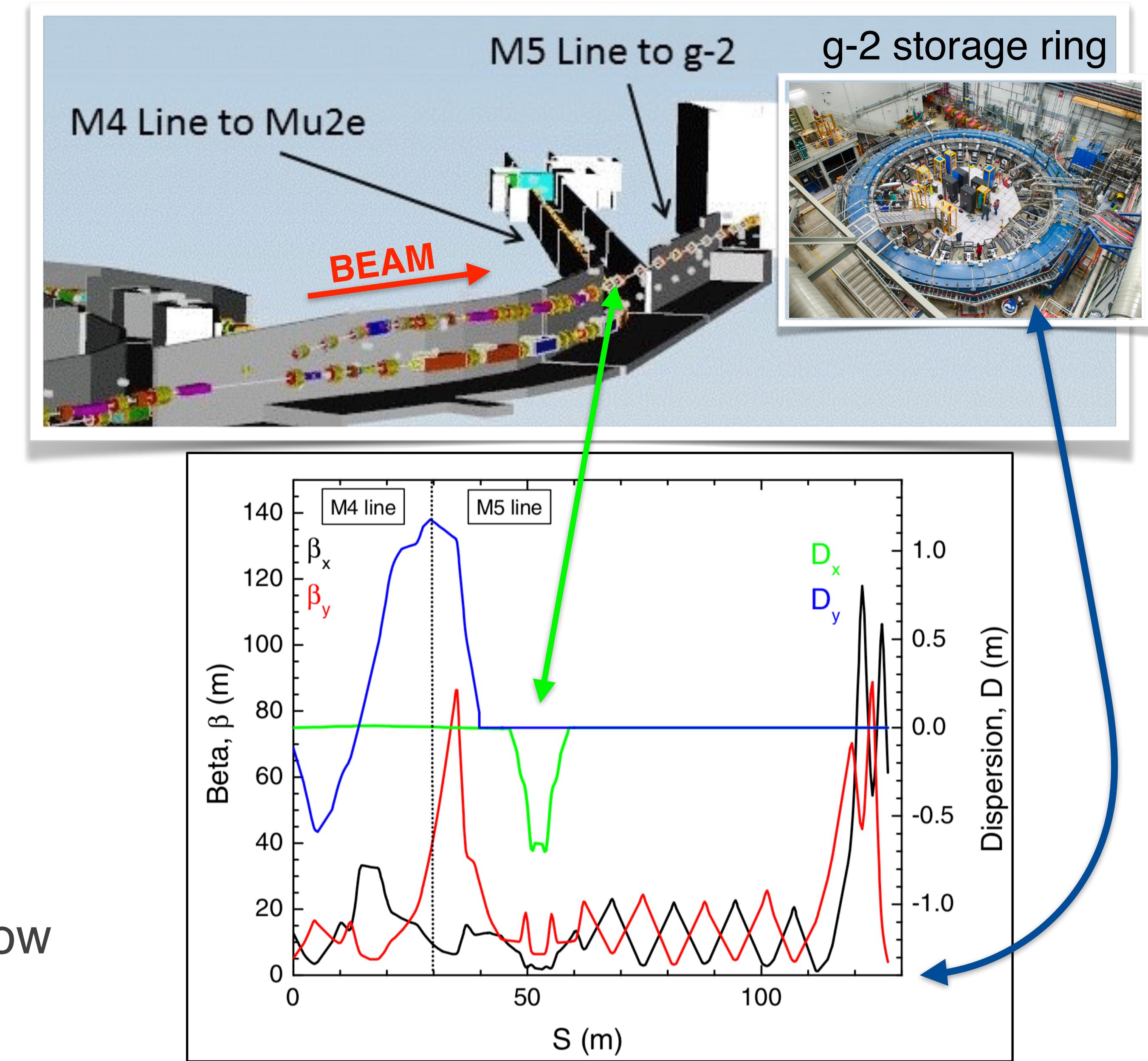
After a few turns all
 π^+ convert to μ^+



Muon g-2
storage ring
 $R \approx 7.112\text{m}$

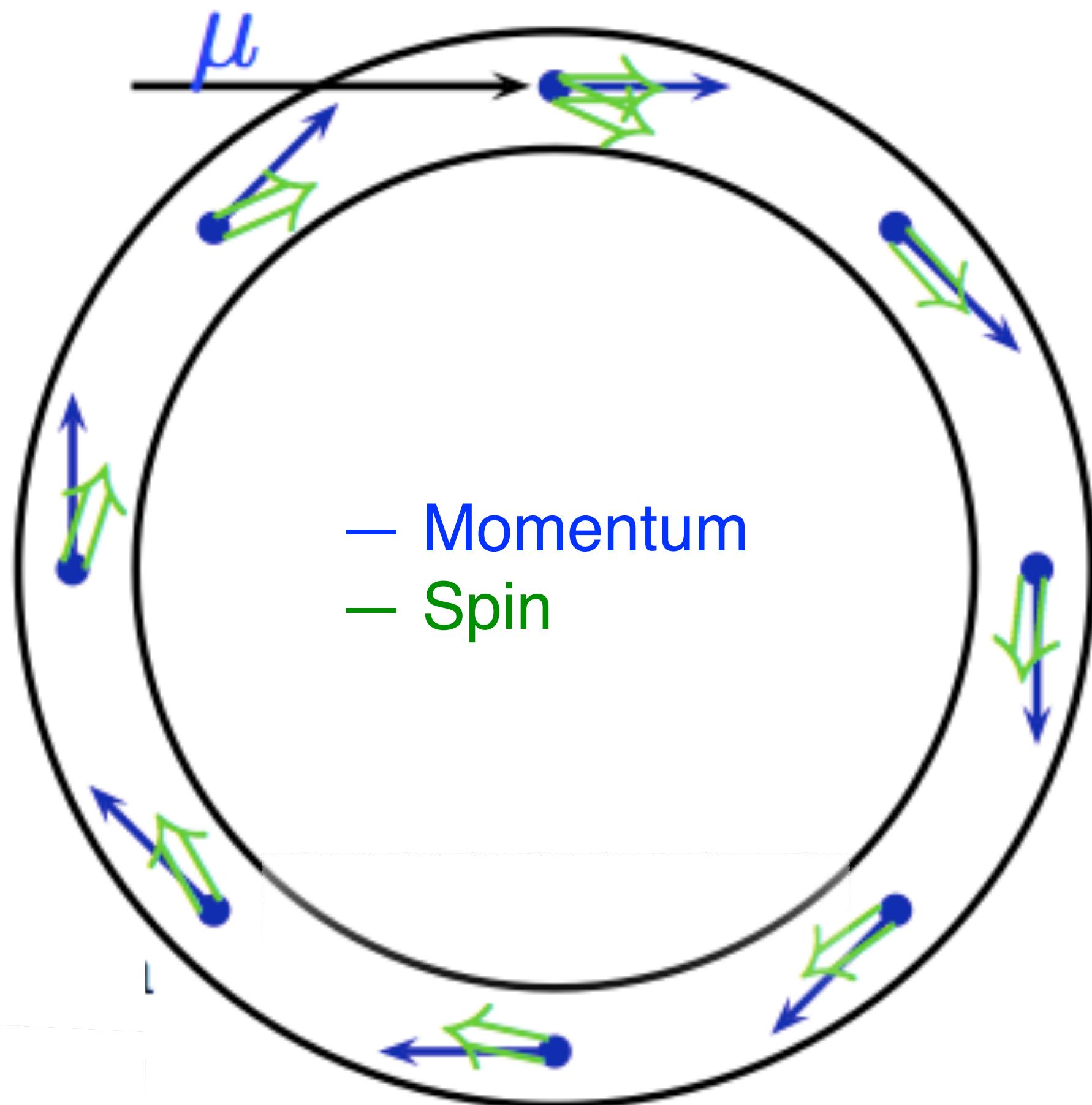
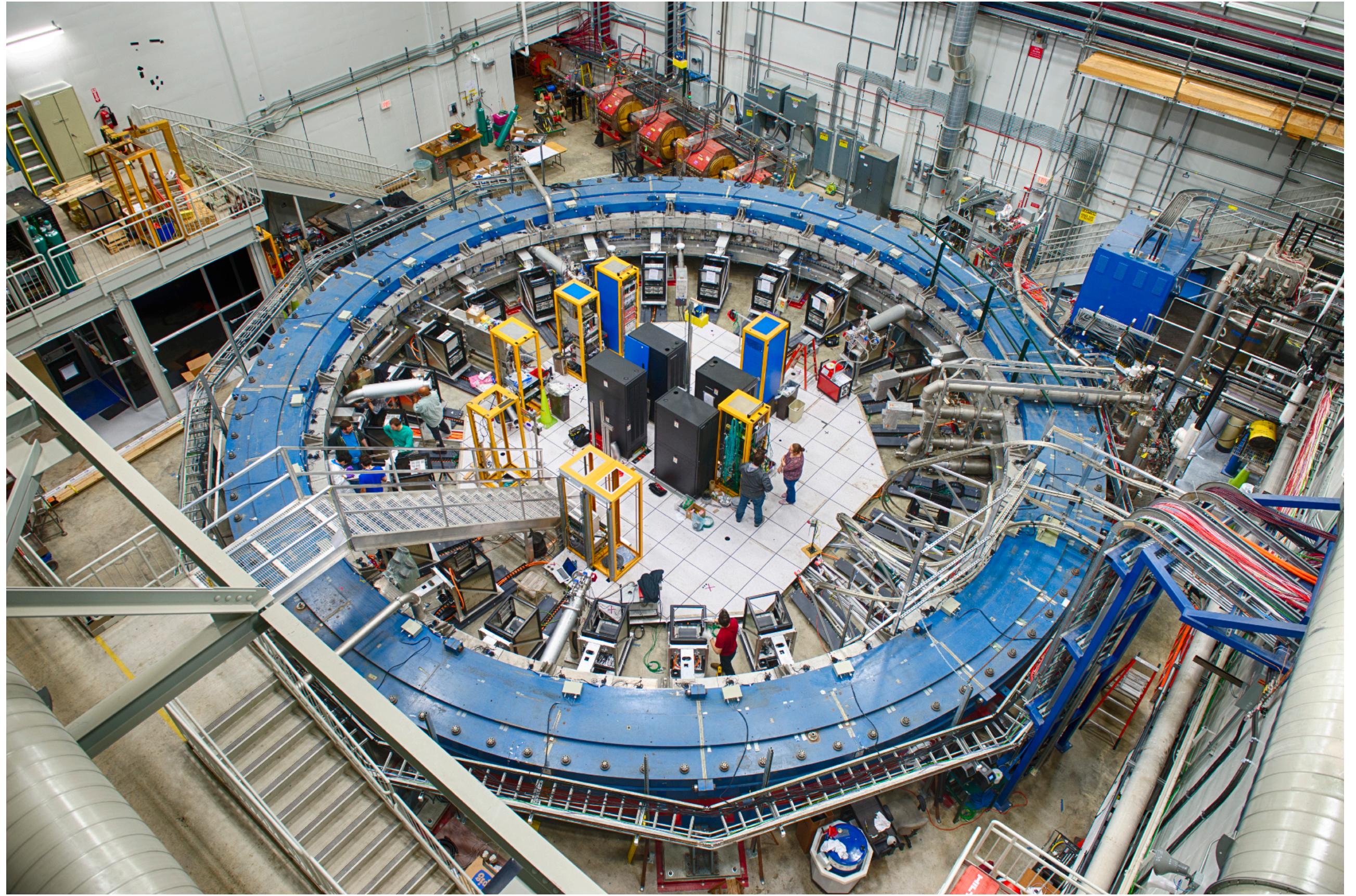
Focus on tuning beam into the muon g-2 storage ring

- M4/M5 beamline: Transport beam from Delivery Ring to Muon g-2
 - Vertical extraction from Delivery Ring occurs in two stages:
 - +4-ft into M4 beamline (Mu2e + g-2)
 - +6.2-ft into M5 beamline (g-2 only)
 - 27.1° horizontal triple-bend achromat
 - 90° FODO transport
 - M5 Final Focus into moun g-2 storage ring, zero dispersion (ring: $D_x = 8.1\text{m}$)
 - Injection properties dominated by narrow “inflector” aperture, discussed below



Muons inside the storage ring

$$g_\mu = 2(1 + a_\mu)$$



Muons inside the storage ring

$$g_\mu = 2(1 + a_\mu)$$

- In a uniform B-field, the momentum rotates as angular frequency

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

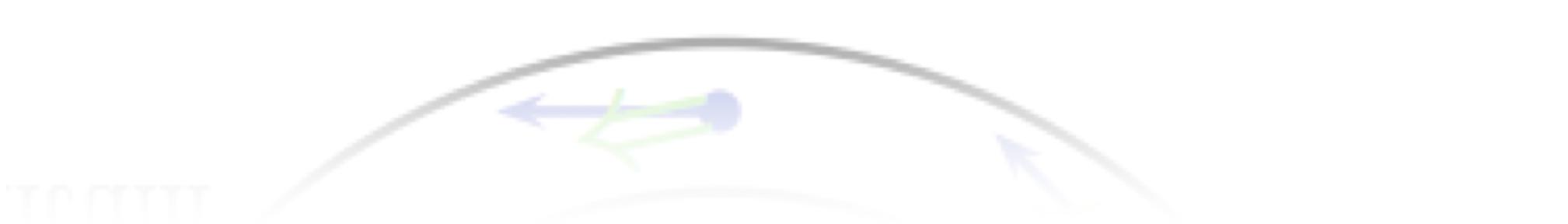
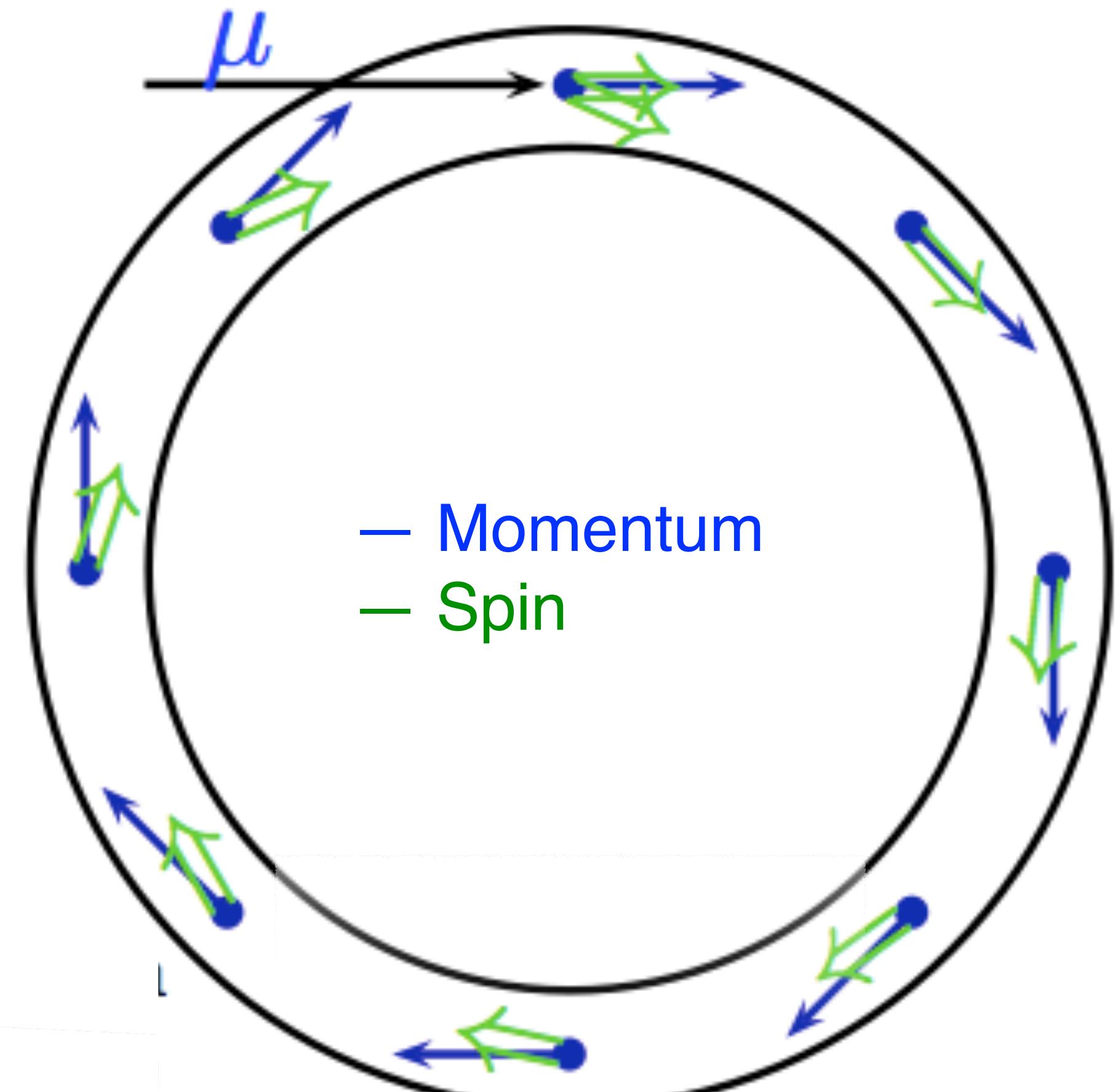
- The spin rotates at

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

- The *difference* rotates at

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

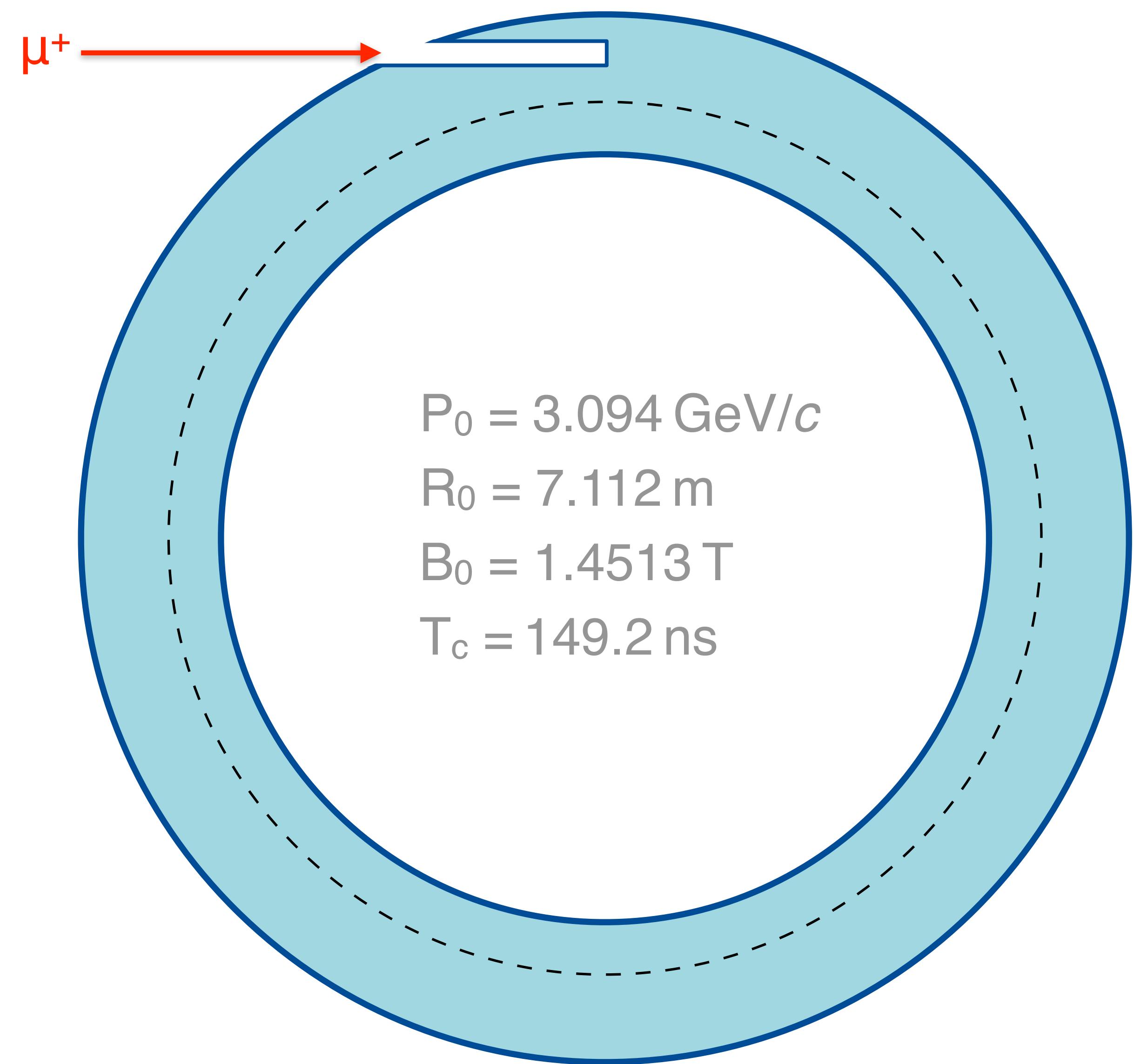
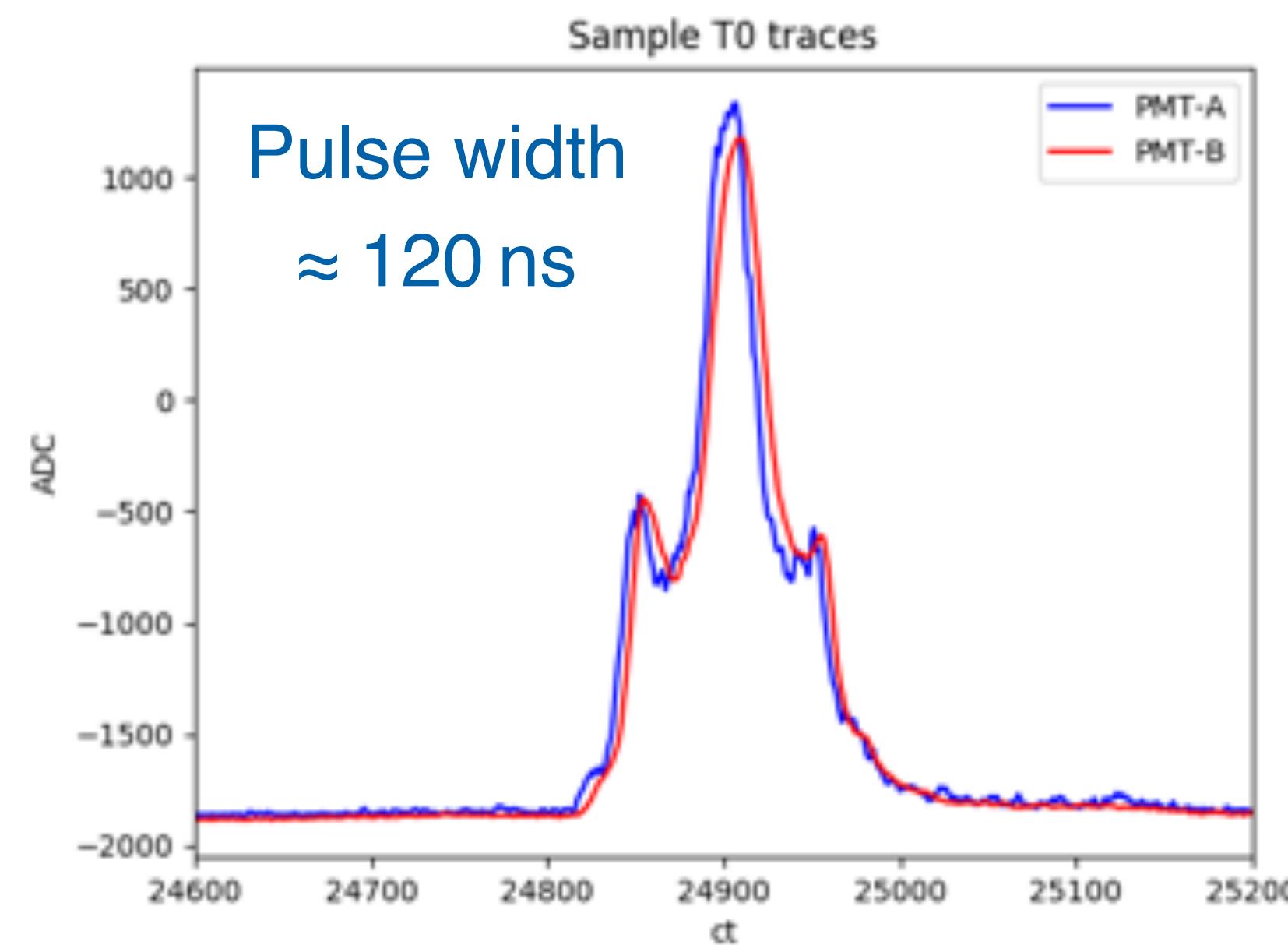
Want
Measure



Muon injection and storage proceeds as follows

TØ counter

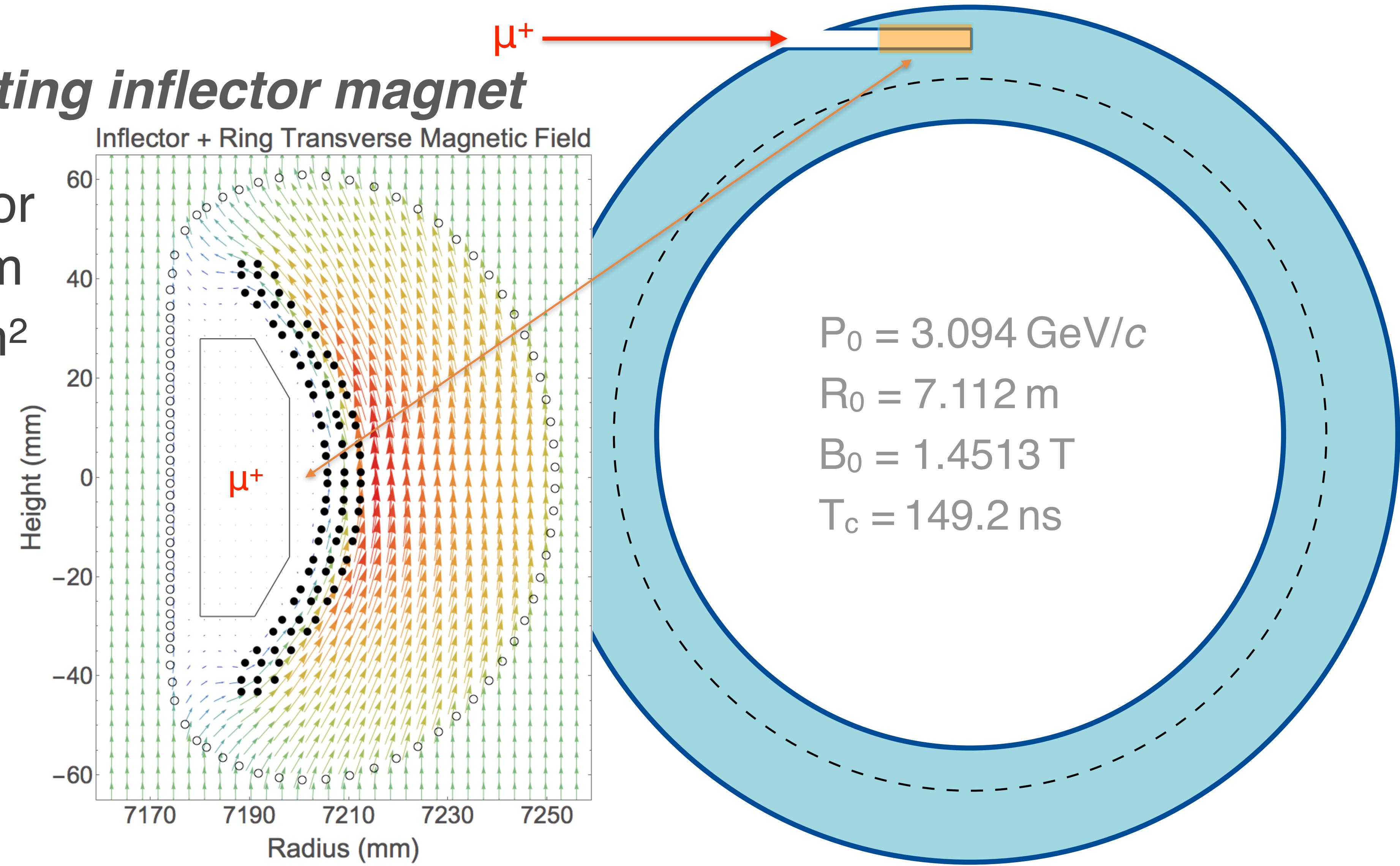
- Thin scintillator detector installed at entrance of magnet
- Provides longitudinal beam profile



Muon injection and storage proceeds as follows

Superconducting inflector magnet

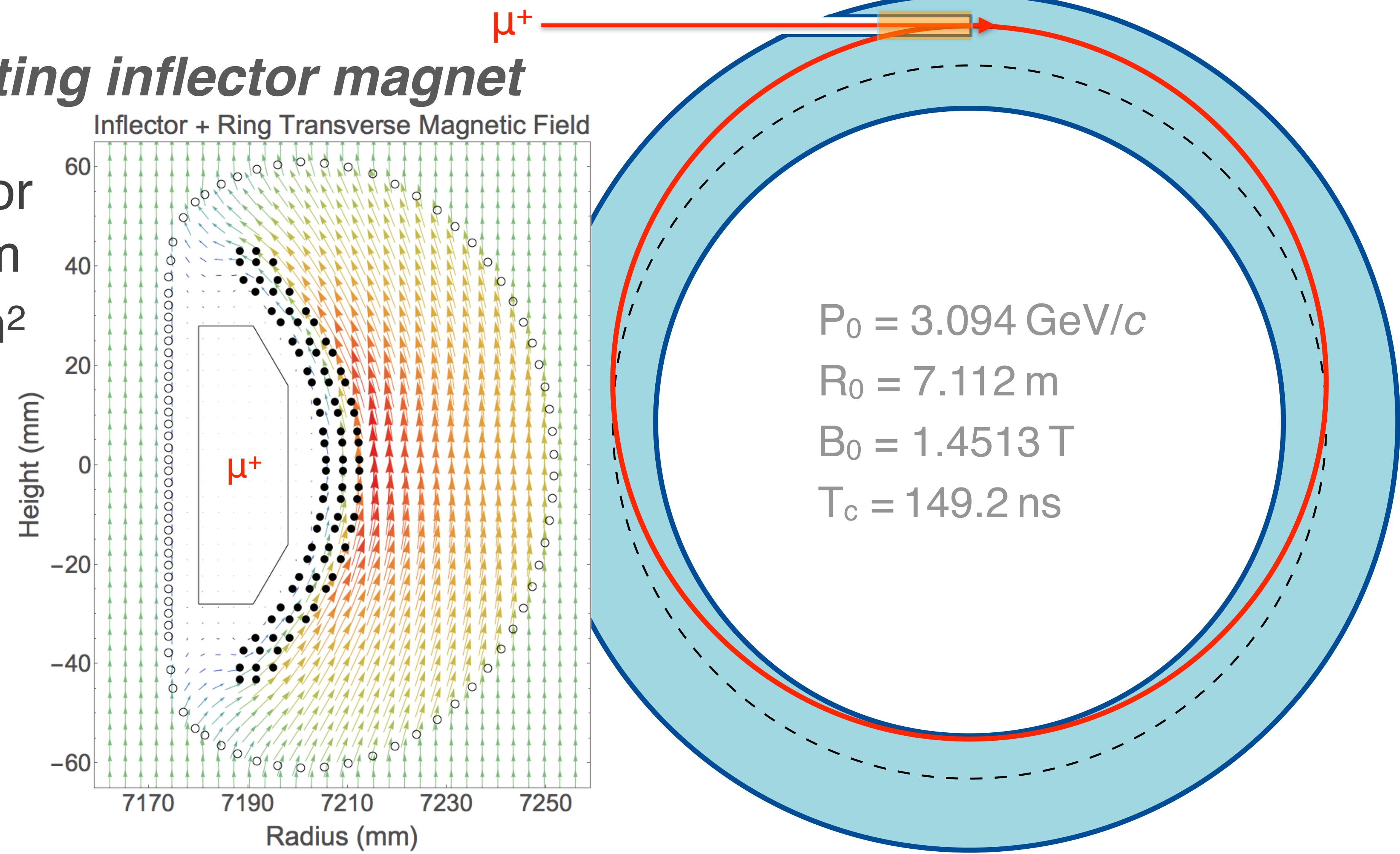
- Field-free corridor for injected beam
- $18(W) \times 56(H)\text{mm}^2$
- 1.7 m long



Muon injection and storage proceeds as follows

Superconducting inflector magnet

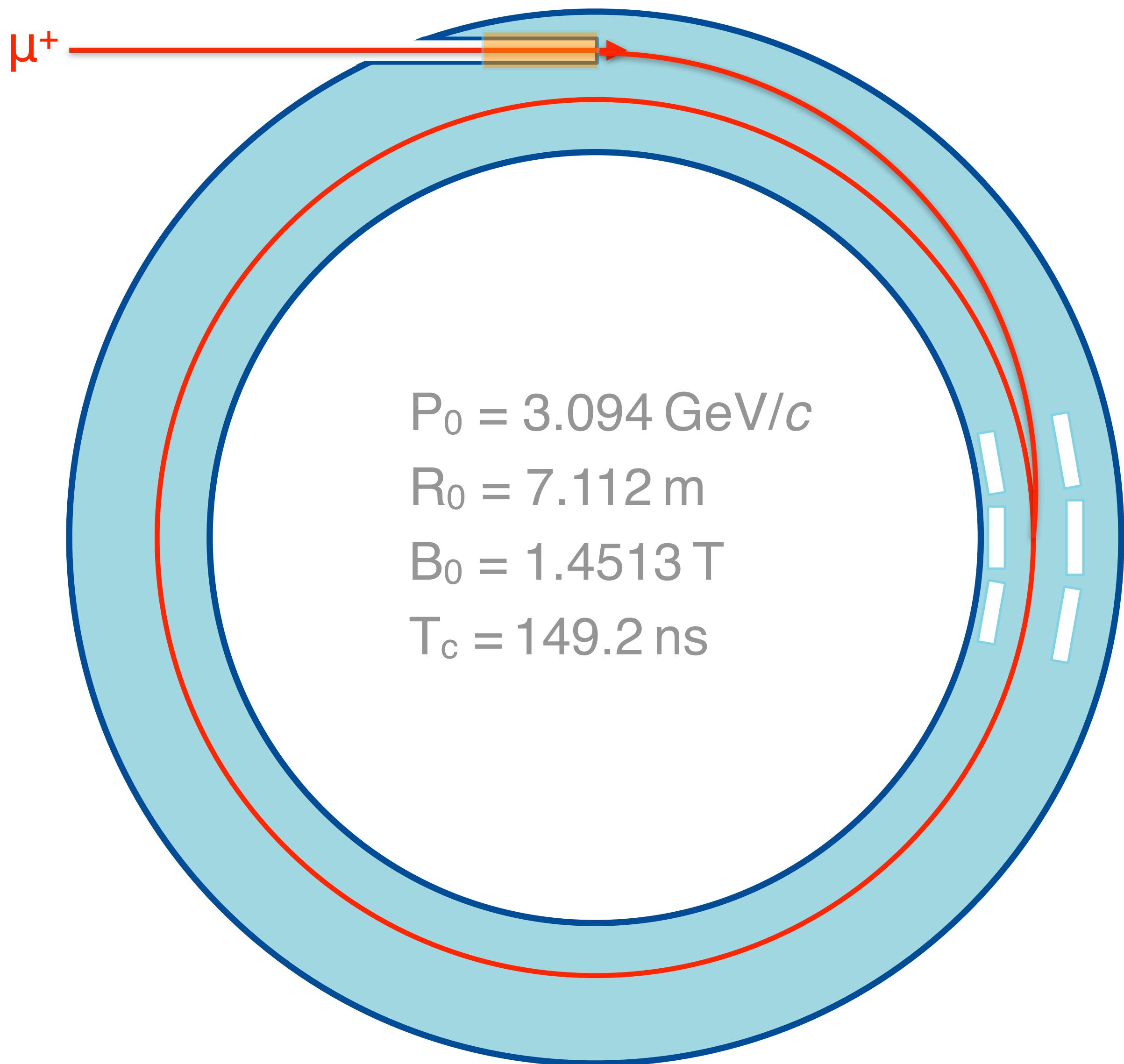
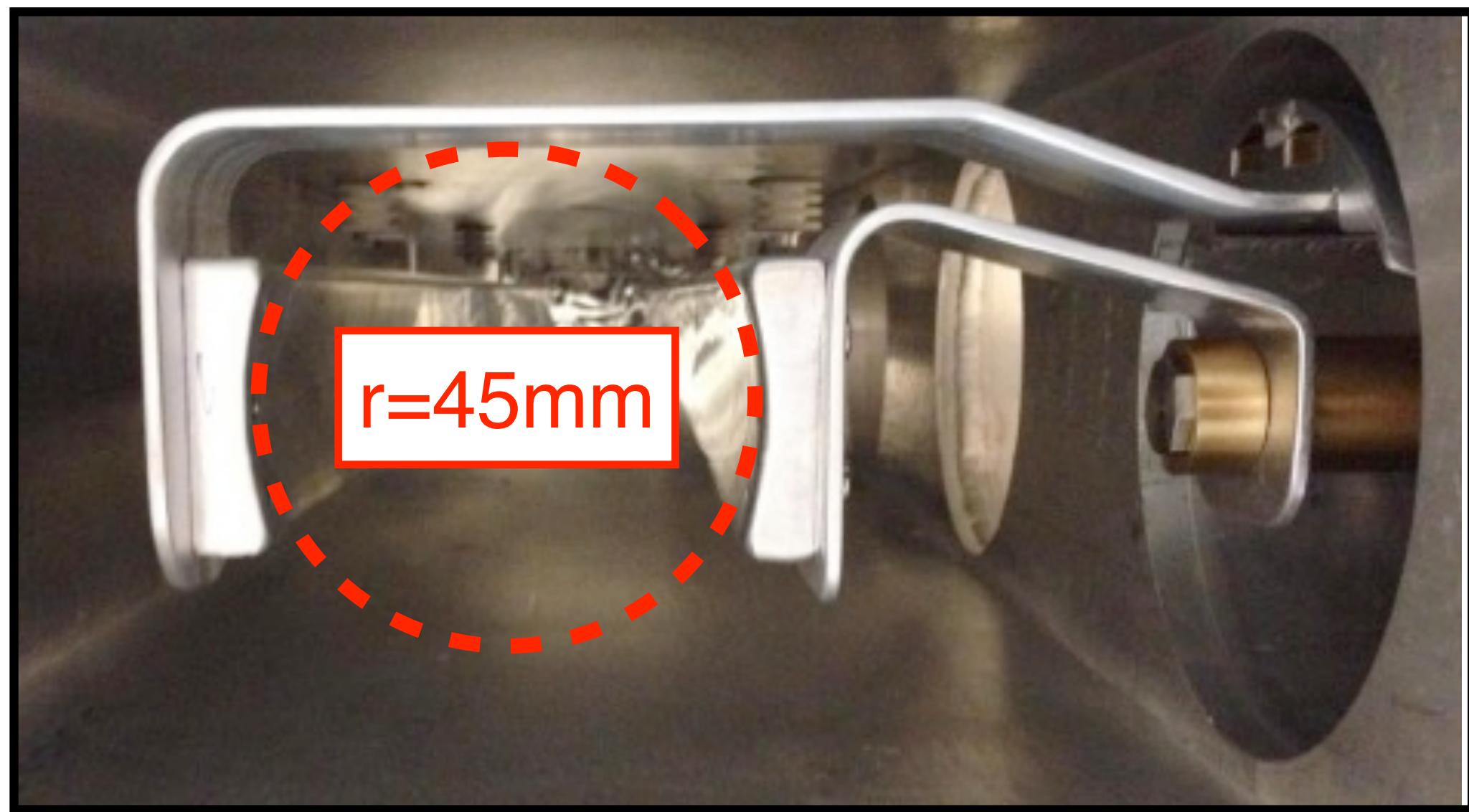
- Field-free corridor for injected beam
- $18(W) \times 56(H)\text{mm}^2$
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Muon injection and storage proceeds as follows

Fast pulsed kicker magnets

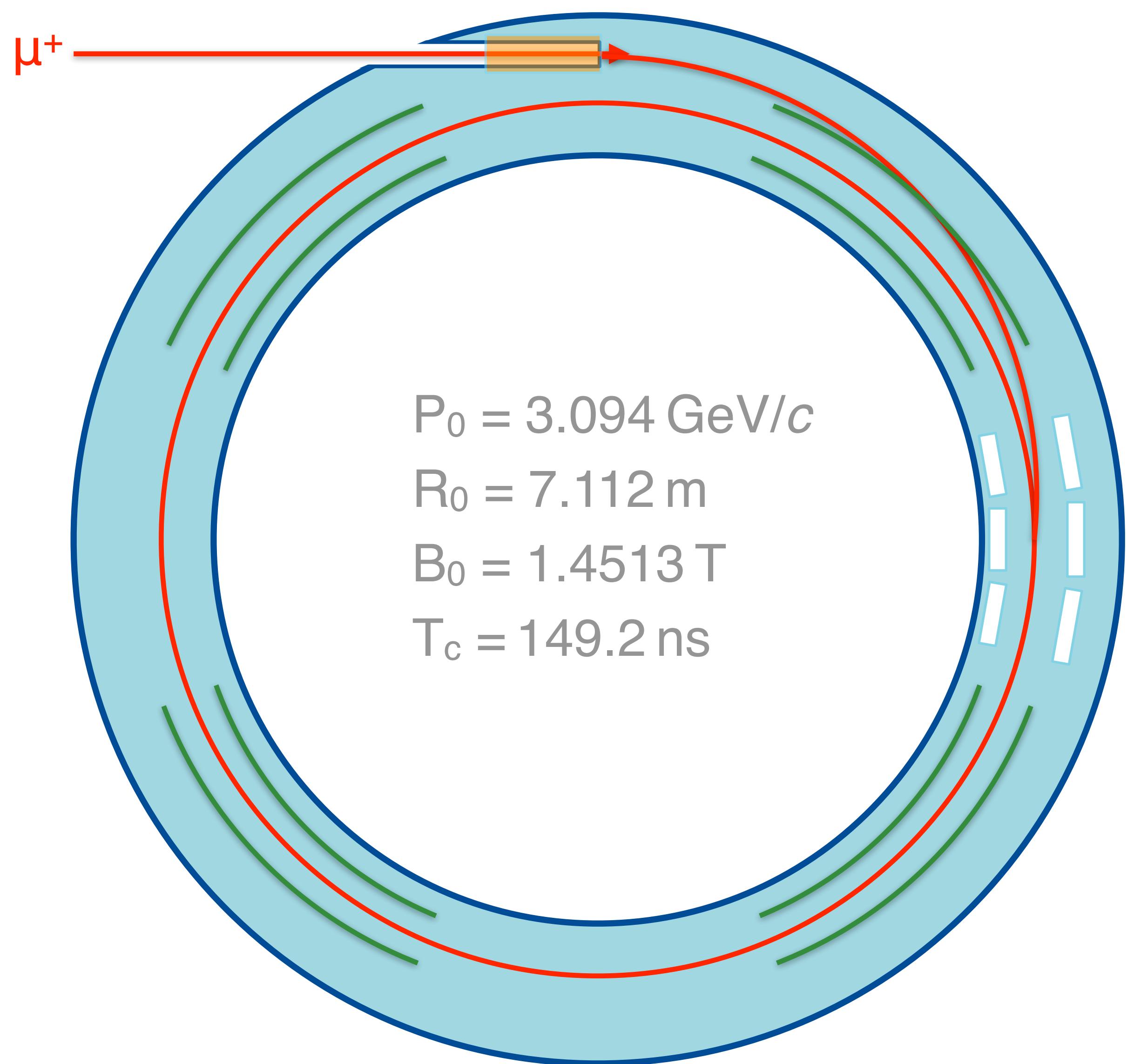
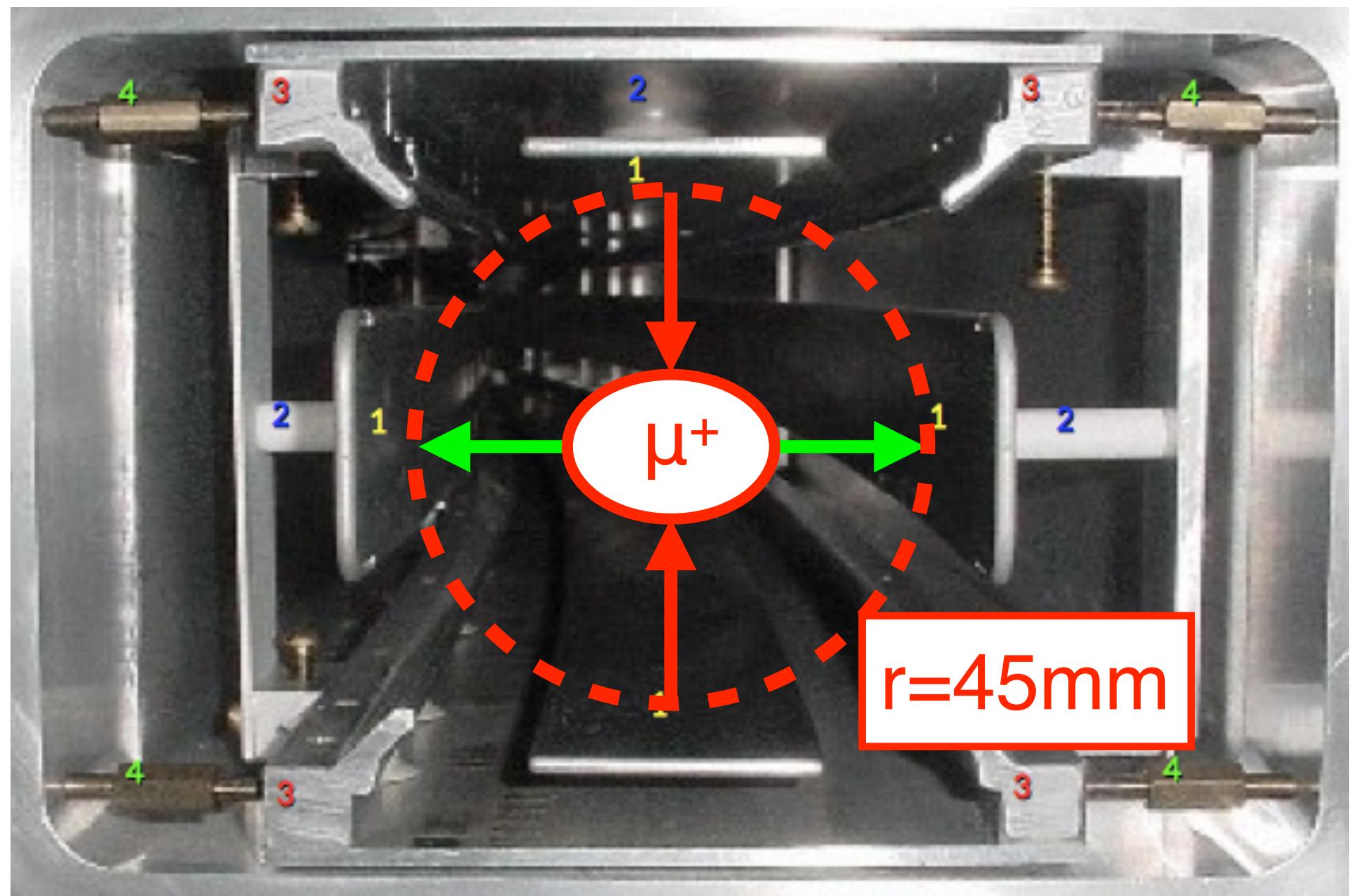
- Deflect momentum of injected beam radial outward by 10.8 mrad at 90°
- On/Off within $t < T_c = 149$ ns



Muon injection and storage proceeds as follows

Pulsed electric quadrupoles

- Provide vertical focusing in order to prevent beam from diverging out of storage ring



Muon injection and storage proceeds as follows

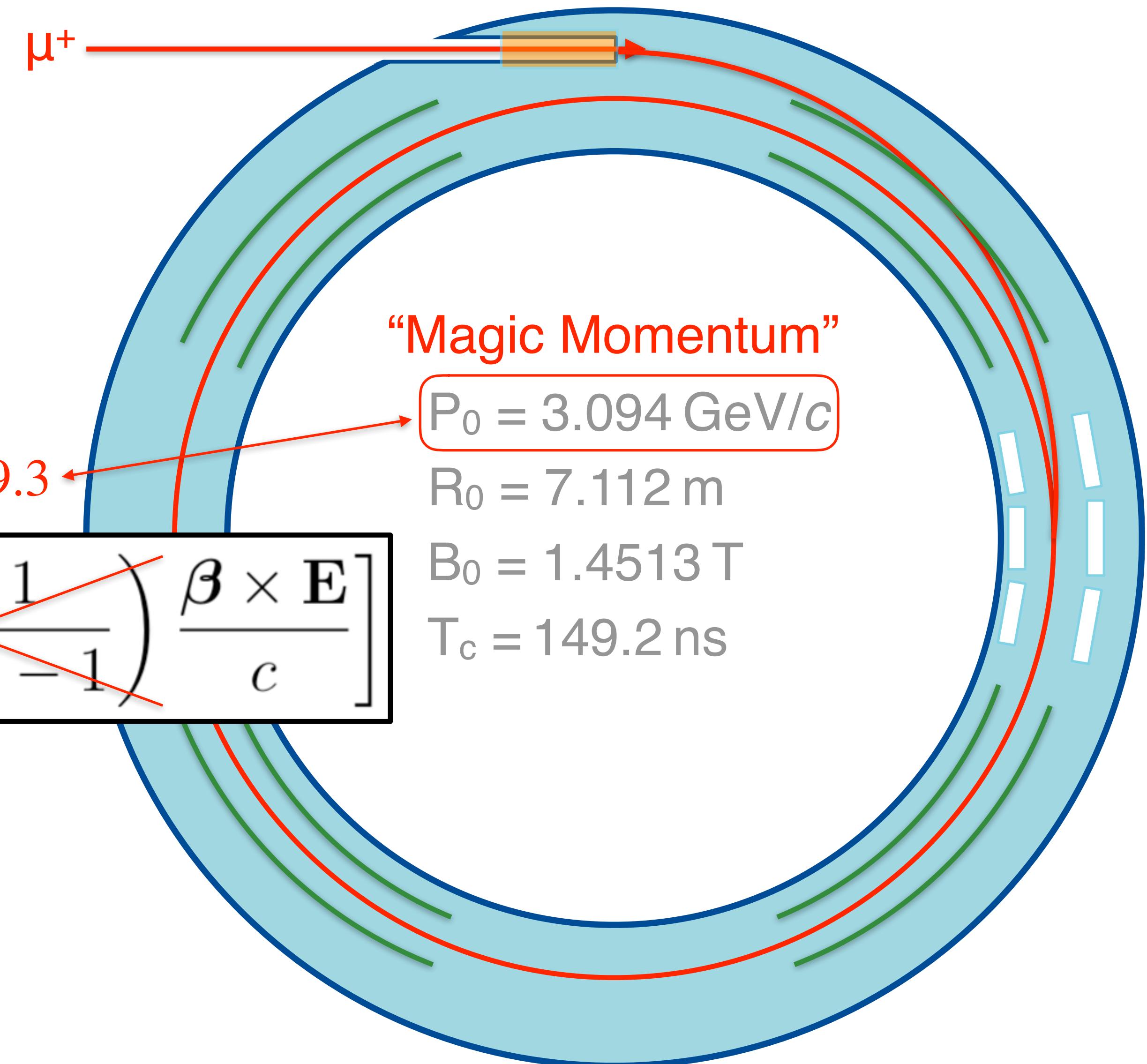
Pulsed electric quadrupoles

- Provide vertical focusing in order to prevent beam from diverging out of storage ring

Measure

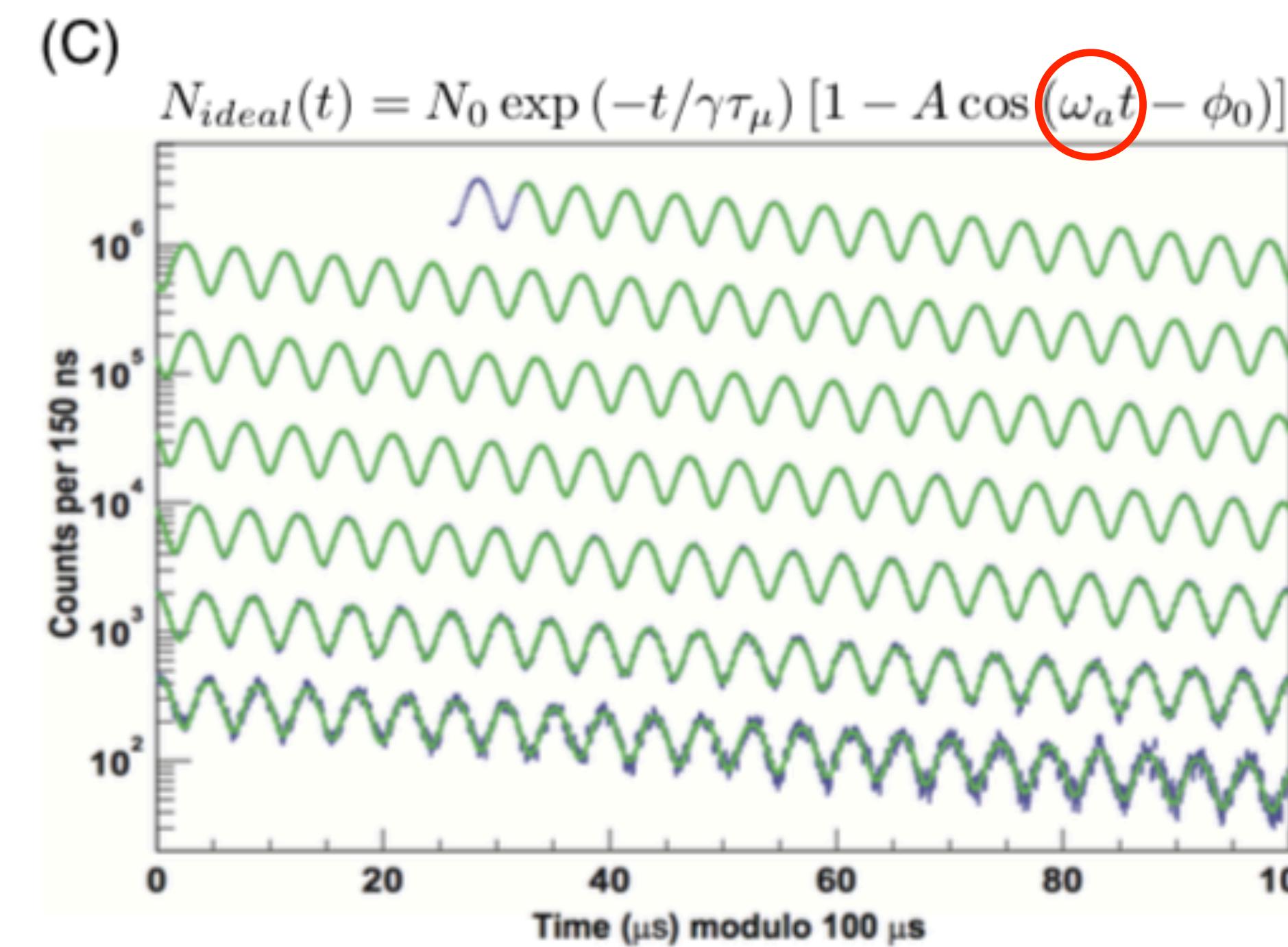
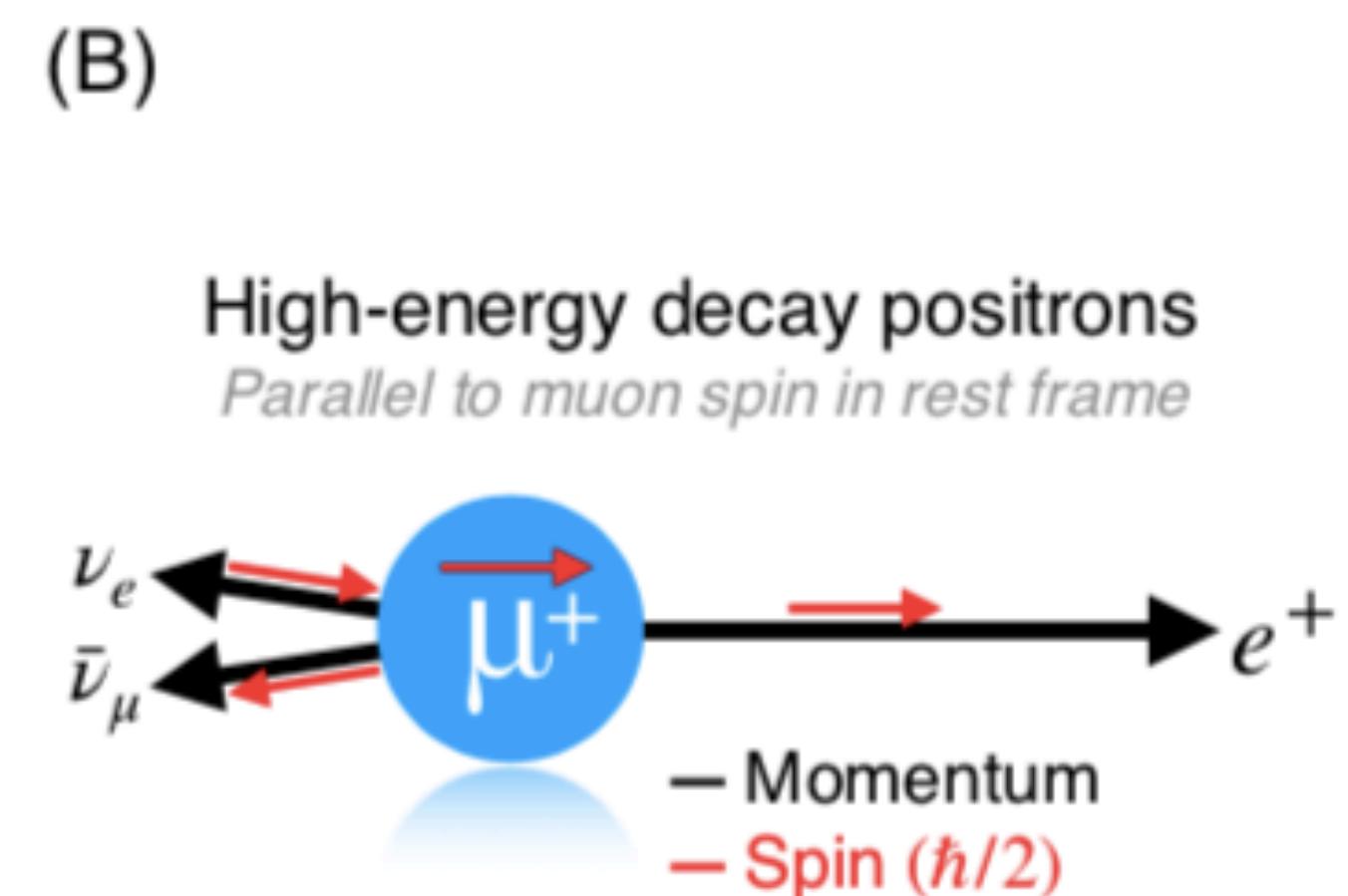
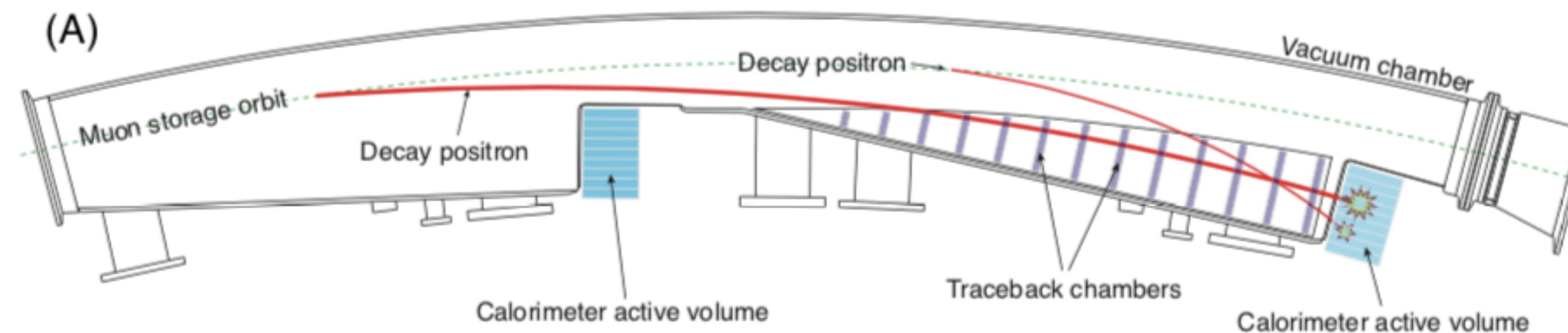
$$\omega_a = \omega_s - \omega_c = -\frac{q}{m} \left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times E}{c} \right]$$

Obtain



Observe decay positrons

Parity
Violation In
Weak Decay
(again)



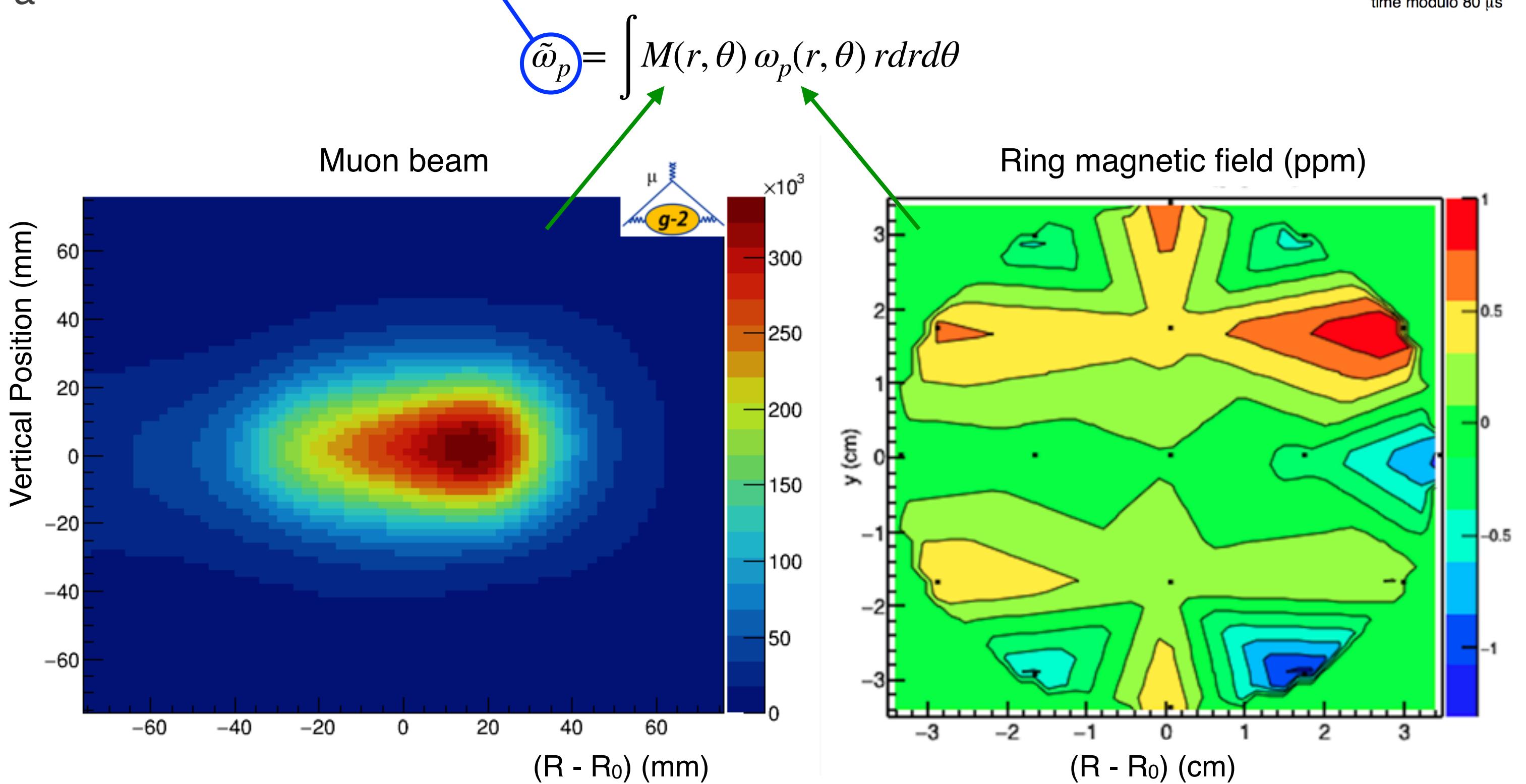
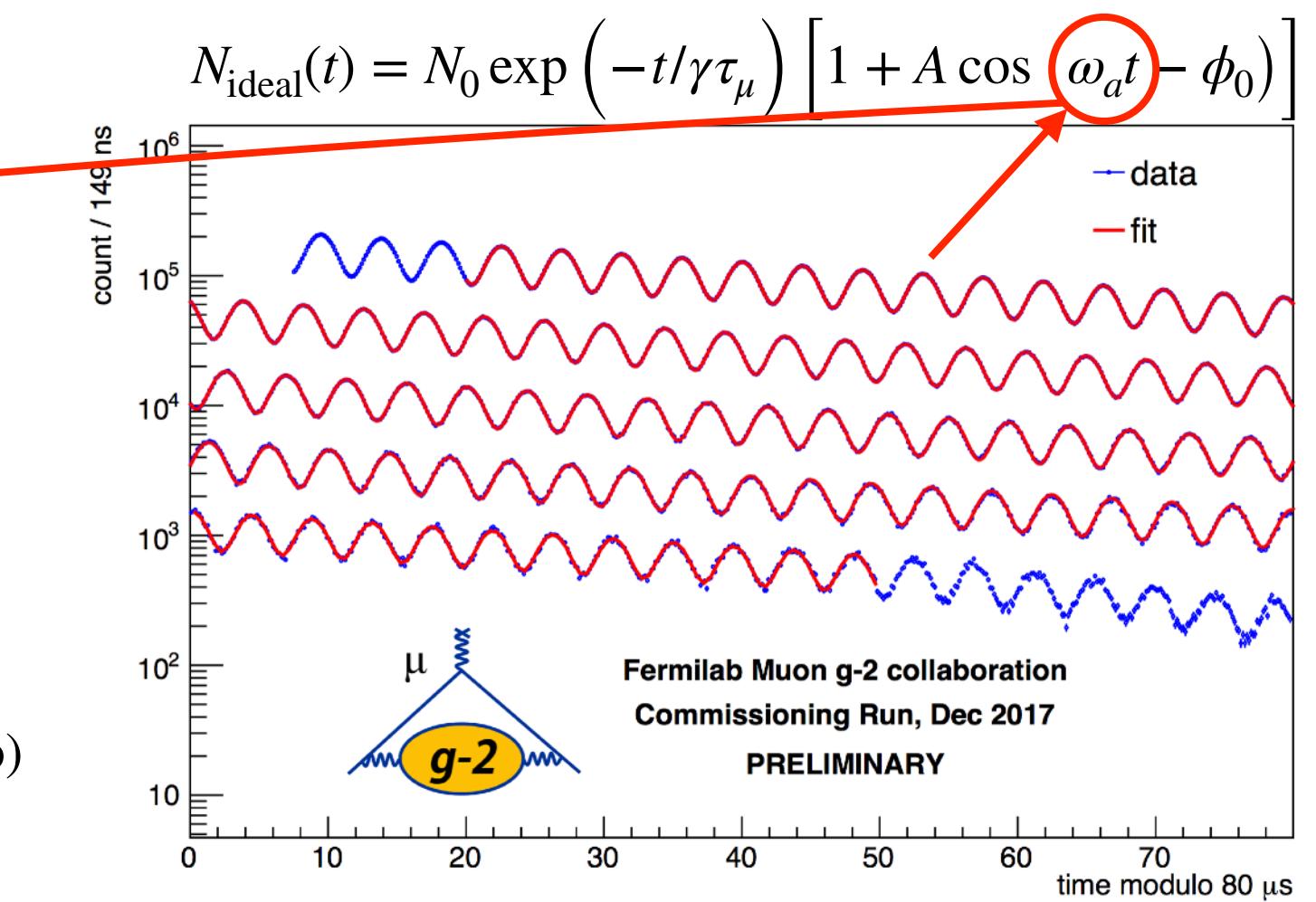
Collect
Billions
Of Events

Extract a_μ

- Three pieces needed
 1. Muon beam
 2. Magnetic field
 3. Anomalous precession, ω_a

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \left(\frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e} \frac{g_e}{2} \right)$$

$(m_\mu/m_e) = 206.7682826(46)$ (22 ppb)
 $(\mu_e/\mu_p) = -658.2106866(20)$ (3.0 ppb)
 $(g_e/2) = -1.00115965218091(26)$ (0.00013 ppb)



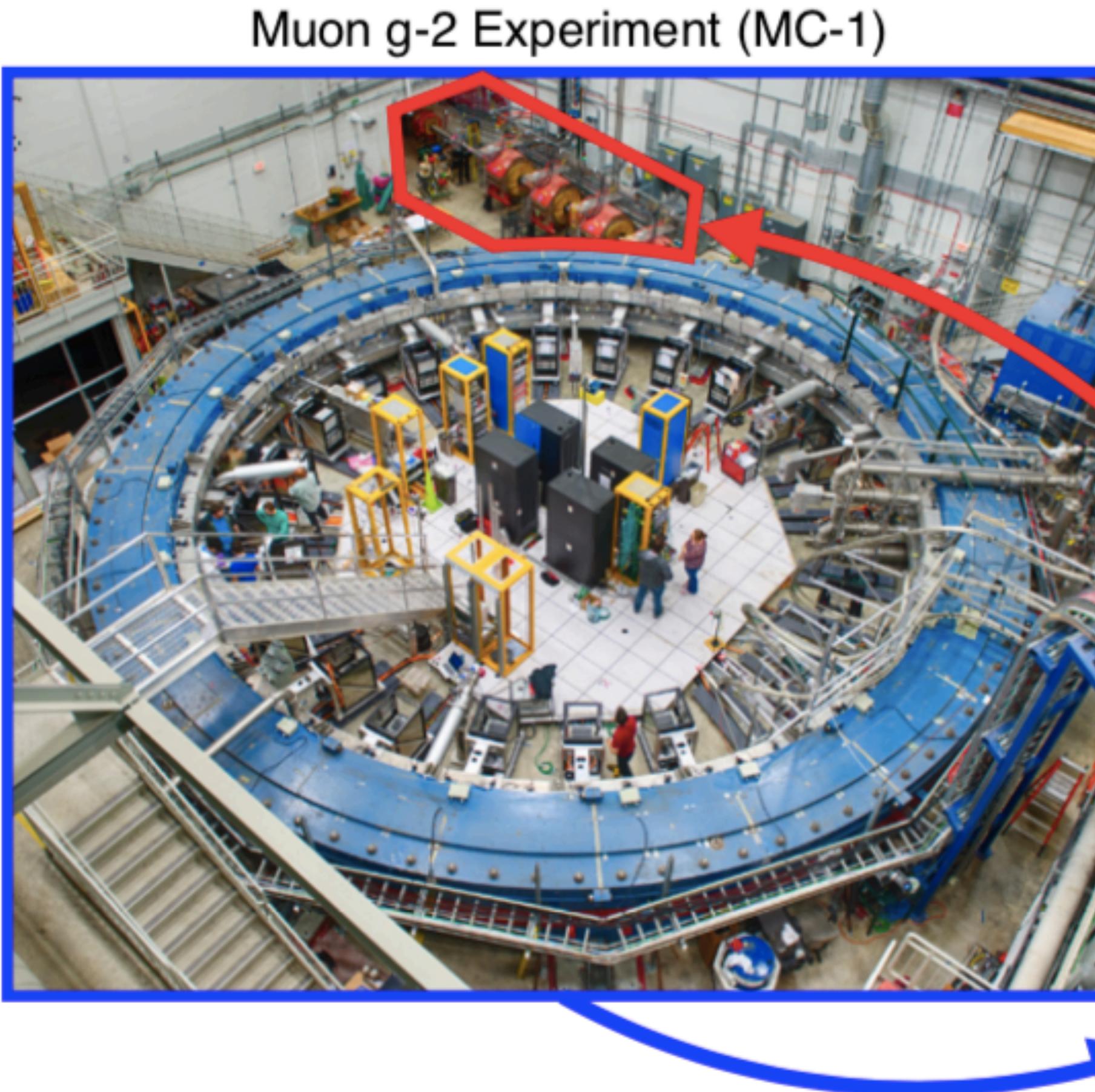
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Beam delivered to g-2 for Run1 (17 Nov 2017)



New beam-tuning parameters for injection optimization



Fermilab Accelerator Controls Network (ACNET)

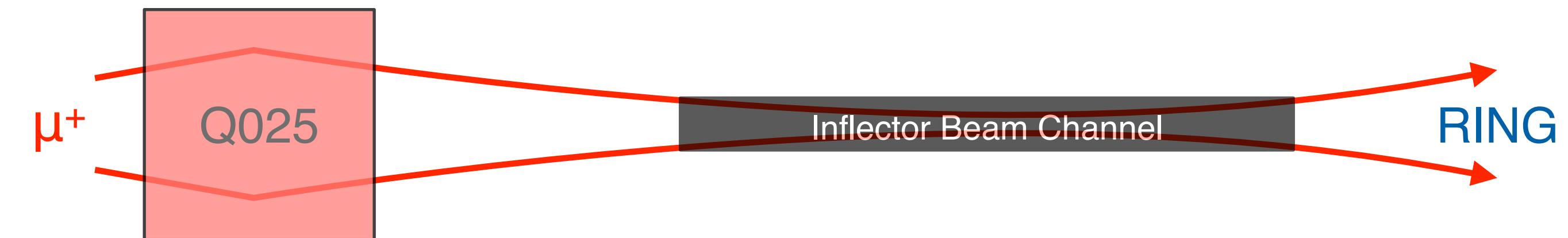
```
PS H60 Power Supply Panel Node01EN-CLX23 (302)
M60 G-2 Injection Tuning      SET   D/A   A/D Com-U ♦Pgm_Tools♦
-<FTP>+ *SA* X-A/D X=TIME    Y=D:ICABT ,E:G2DCAY,E:G2TOB ,D:IC025
COMMAND BL-- Eng-U I= 0       I= 0 , 0 , 0 , 0
-< 2>+ rSUP AUTO F= 60      F= 44 , 400 , 400000 , 1
m1 tgt m2 m3 dr10 dr30 dr50 abt m4 m5 EXPER
! Upstream Beamlines
M:T0R107          AP1 PQ9B Beam Toroid .74200552 E12
D:IC804           M2 804 ION CHAMBER 7.9806 *E07
D:IC740           M3 740 ION CHAMBER .0564 *E07
D:IC209           DR 209 ION CHAMBER .0846 *E07
D:IC105           DR 105 ION CHAMBER 0 *E07
D:ICABT           ABORT LINE ION CHAMBER 35.8422 *E07
D:IC902           M4 902 ION CHAMBER 0 *E07
D:IC025           M5 025 ION CHAMBER 0 *E07
! M5 Final-Focus Quads
-D:Q020          Q020 MEASURED I 171.8 171.2 Amps ...
-D:Q021          Q021 MEASURED I 2.1 1.648 Amps ...
-D:Q022          Q022 MEASURED I 328.5 328.4 Amps ...
-D:Q023          Q023 MEASURED I 643.7 643.8 Amps ...
-D:Q024          Q024 MEASURED I 790.5 790.4 Amps ...
-D:Q025          Q025 MEASURED I 840 839.1 Amps ...
! M5 Final-Focus Trims
-D:VT018          Vert trim 018 - M5 line -2.5 -2.495 Amps ...
-D:VT023          Vert trim 023 - M5 line -6 -5.995 Amps ...
-D:HT020          Horz trim 020 - M5 -12.5 -17.1 *-17.07 Amps ...
-D:HT024          Horz trim 024 - M5 -10 -7.3 *-7.29 Amps ...
! MC-1 Storage Statistics
E:G2RNID          g-2 RUN ID 15500
E:G2EVID          g-2 EVENT ID 9178
E:G2TOA           g-2 TO PMT A INTEGRAL 228946.27
E:G2TOB           g-2 TO PMT B INTEGRAL 231281.83
E:G2CLST          g-2 ALL CLUSTERS 1847.125
E:G2LNCH          g-2 LAUNCH 14.875
E:G2DCAY          g-2 e+ FROM MUON DECAY 387.25
```

- Muon g-2 Experiment (MC-1)
- Fermilab Accelerator Division
- Real-time Feedback

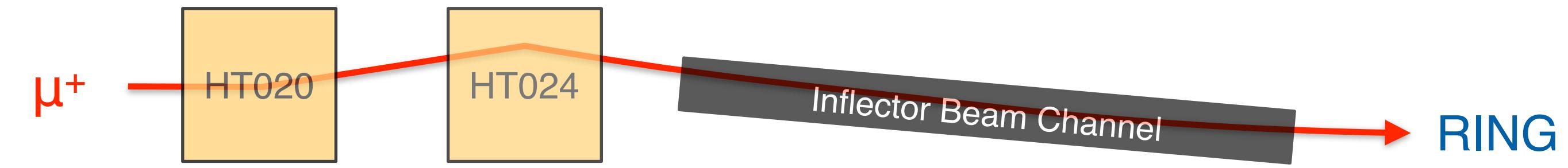
Two types of studies: (1) beam focusing, (2) beam steering



Quad studies: Beam focusing

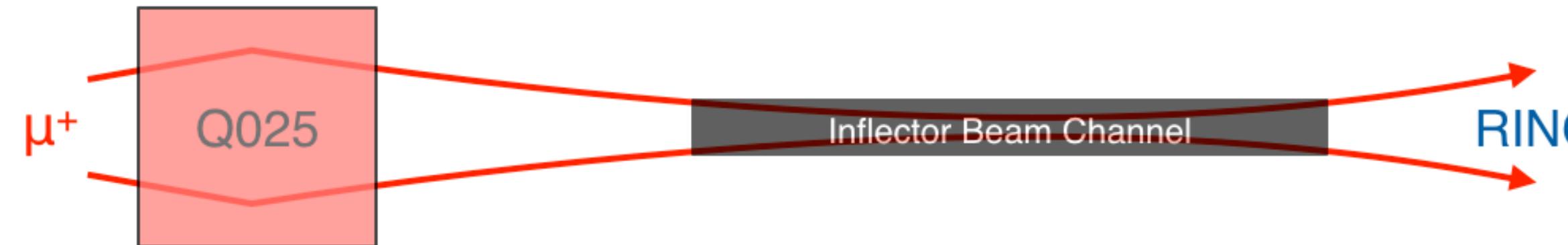


TRIM studies: Beam steering



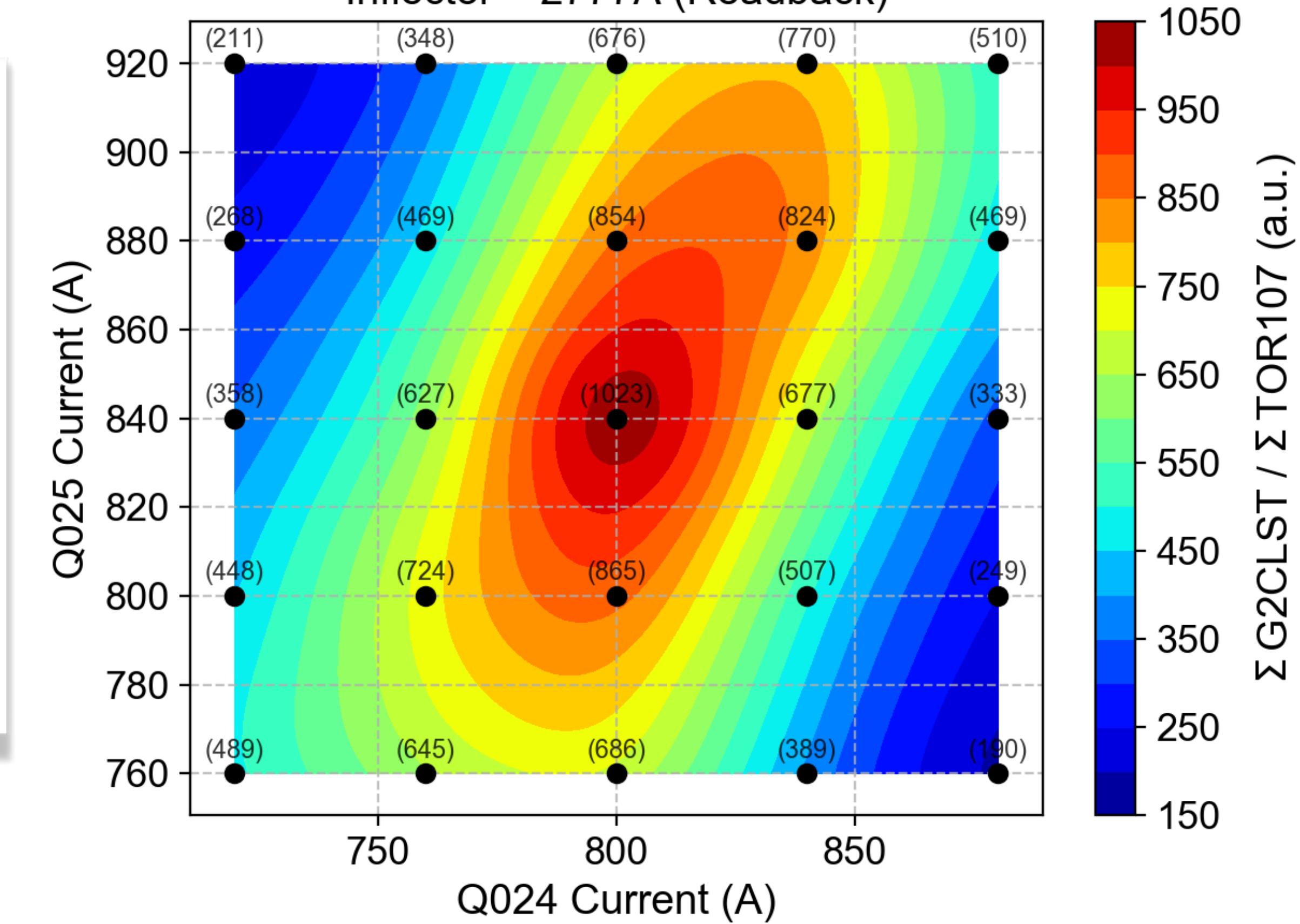
Beam-focusing studies

Quad studies: Beam focusing



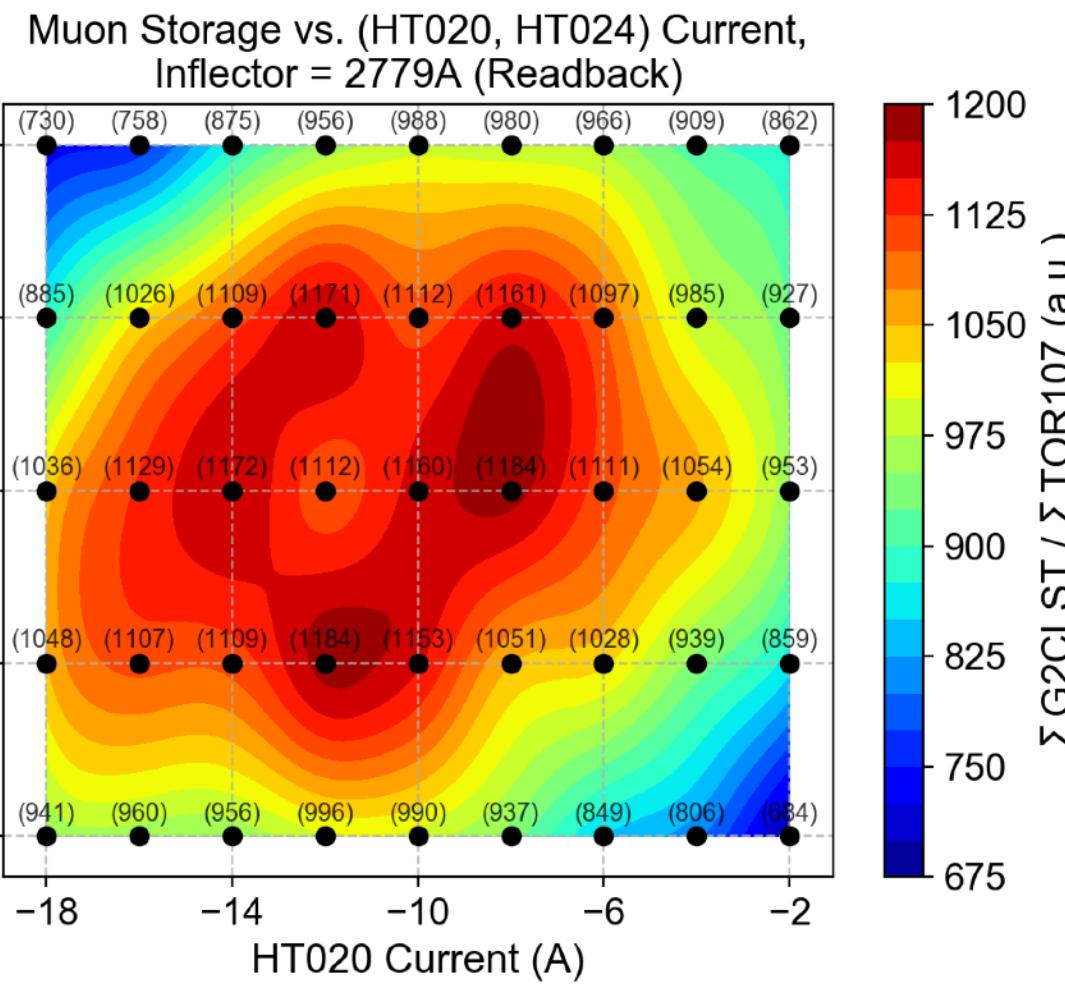
Use new tuning variables in ACNET

Muon Storage vs. (Q024, Q025) Current,
Inflector = 2777A (Readback)

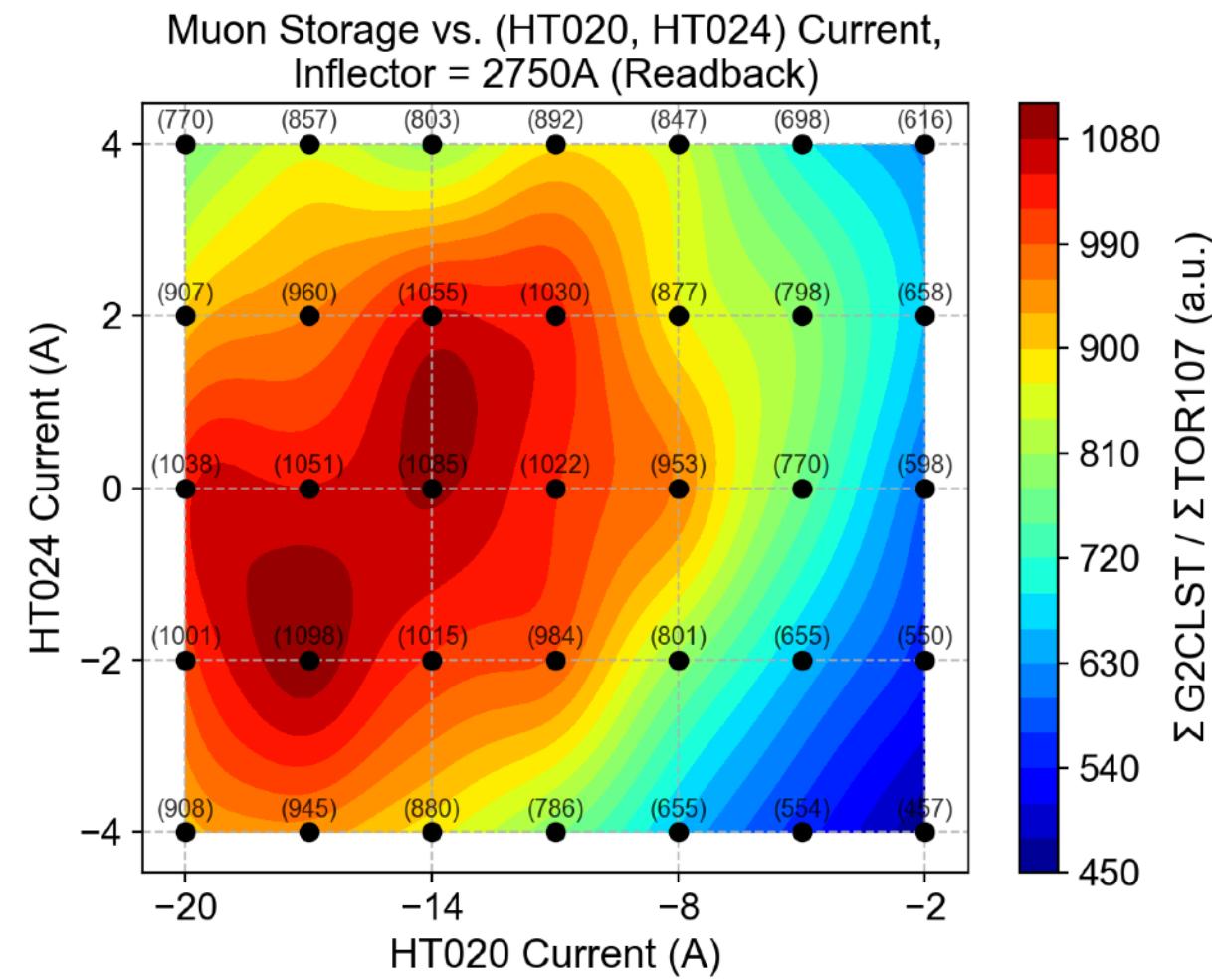


Beam steering studies

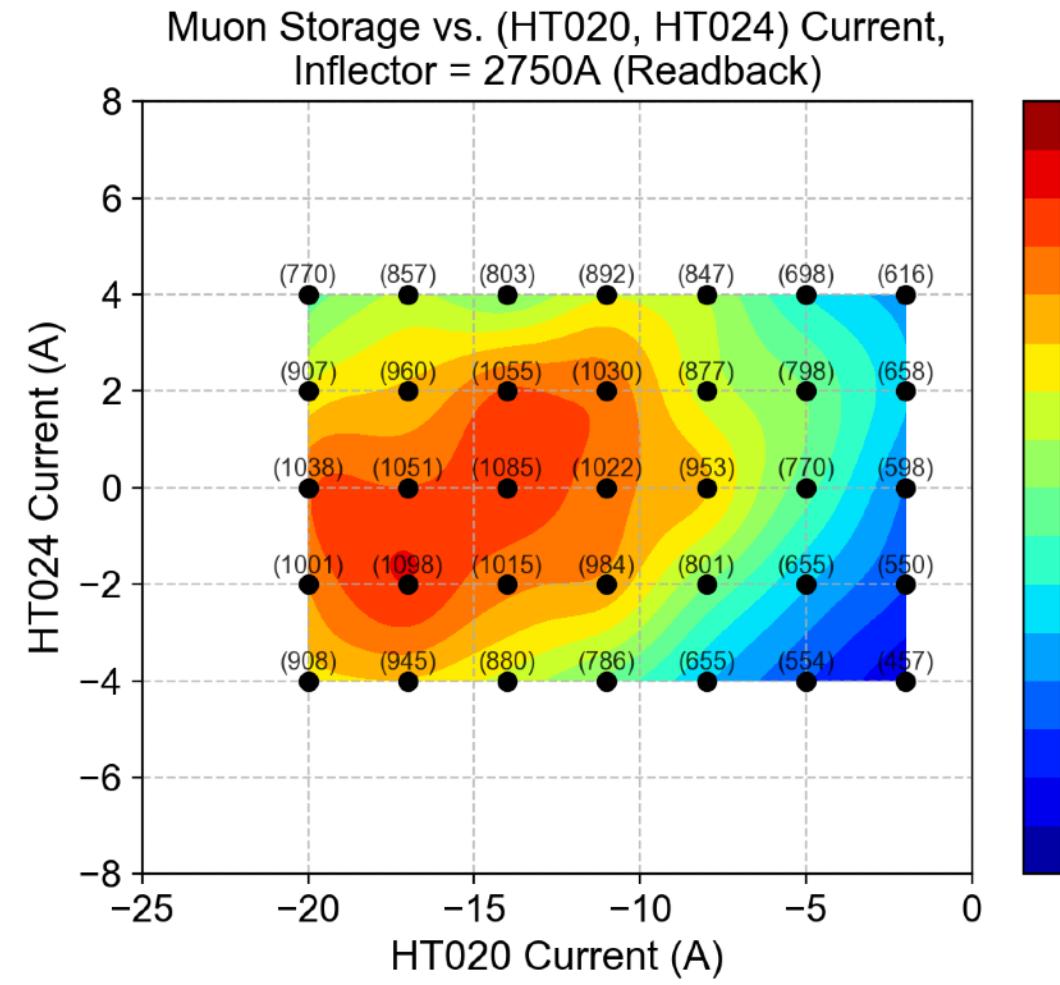
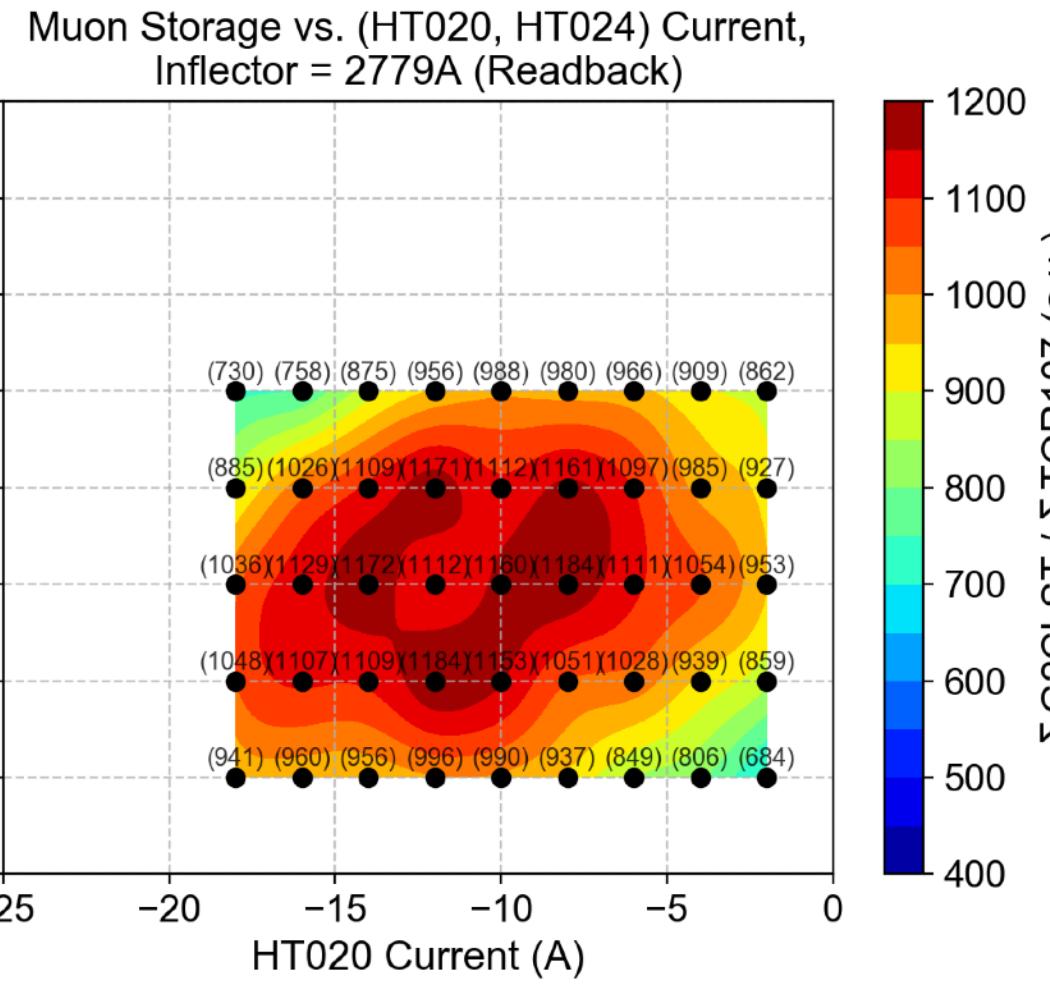
Inflector = 2779A



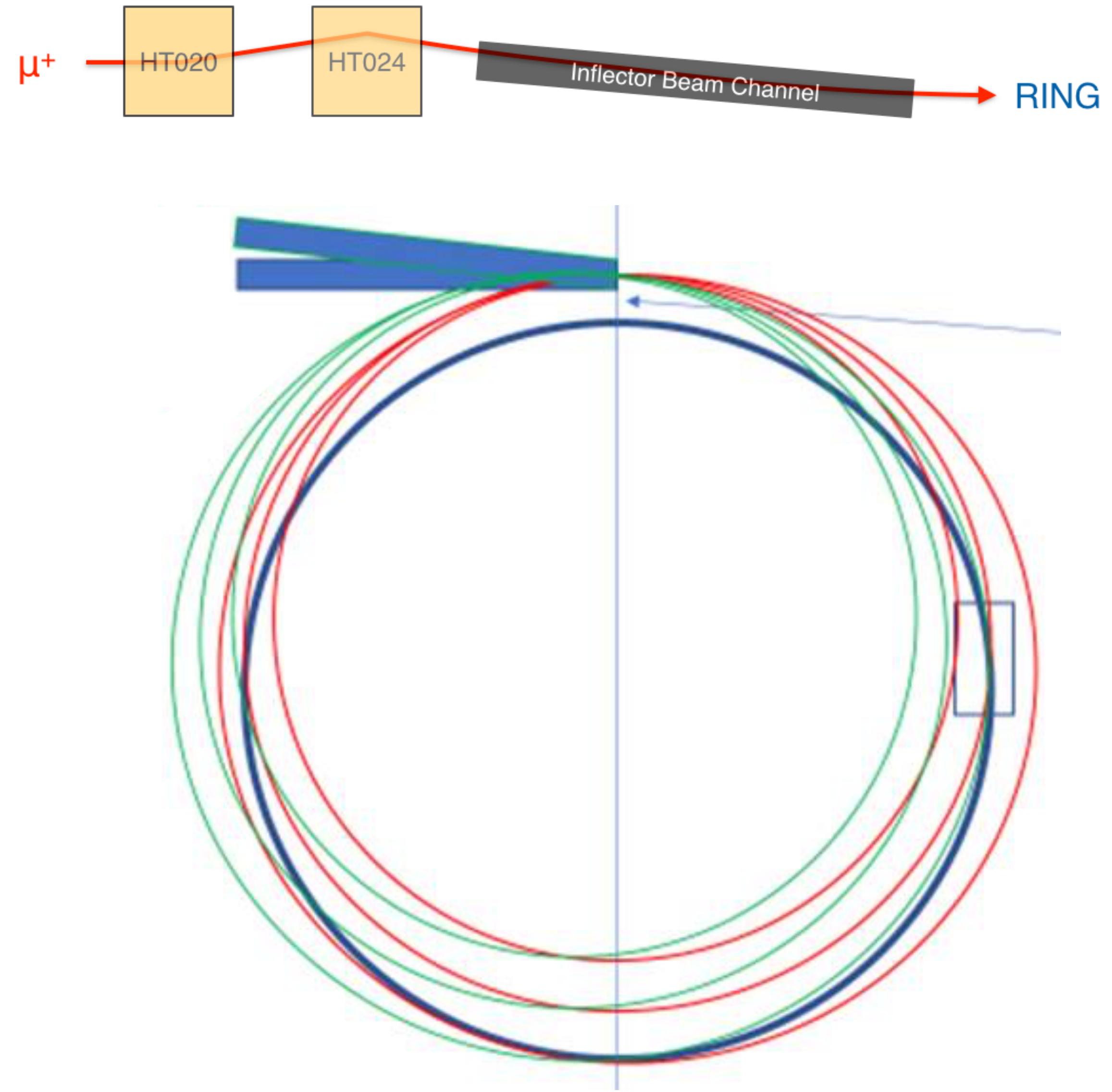
Inflector = 2750A



Same as above, but all plots on same scale:



TRIM studies: Beam steering

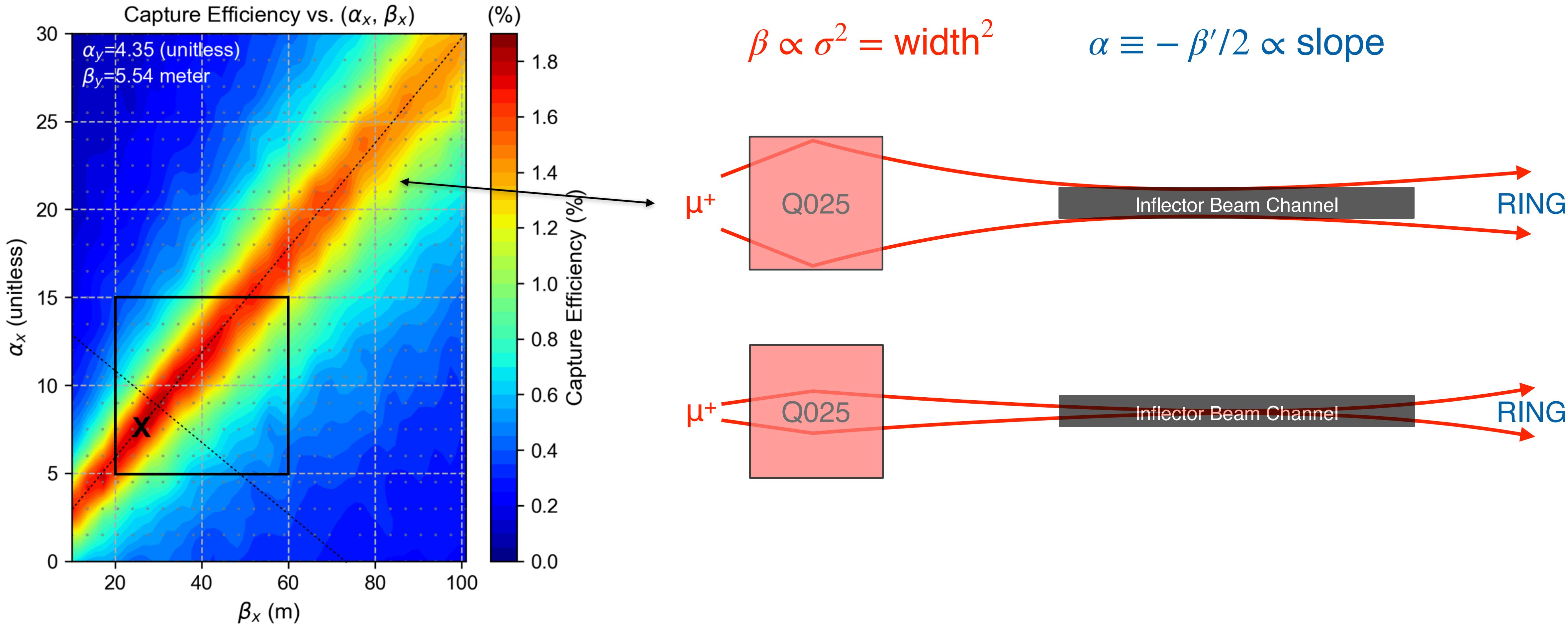


Major problem at this point:

**Only ~20% of design value
observed for decay e+/fill! 😞**

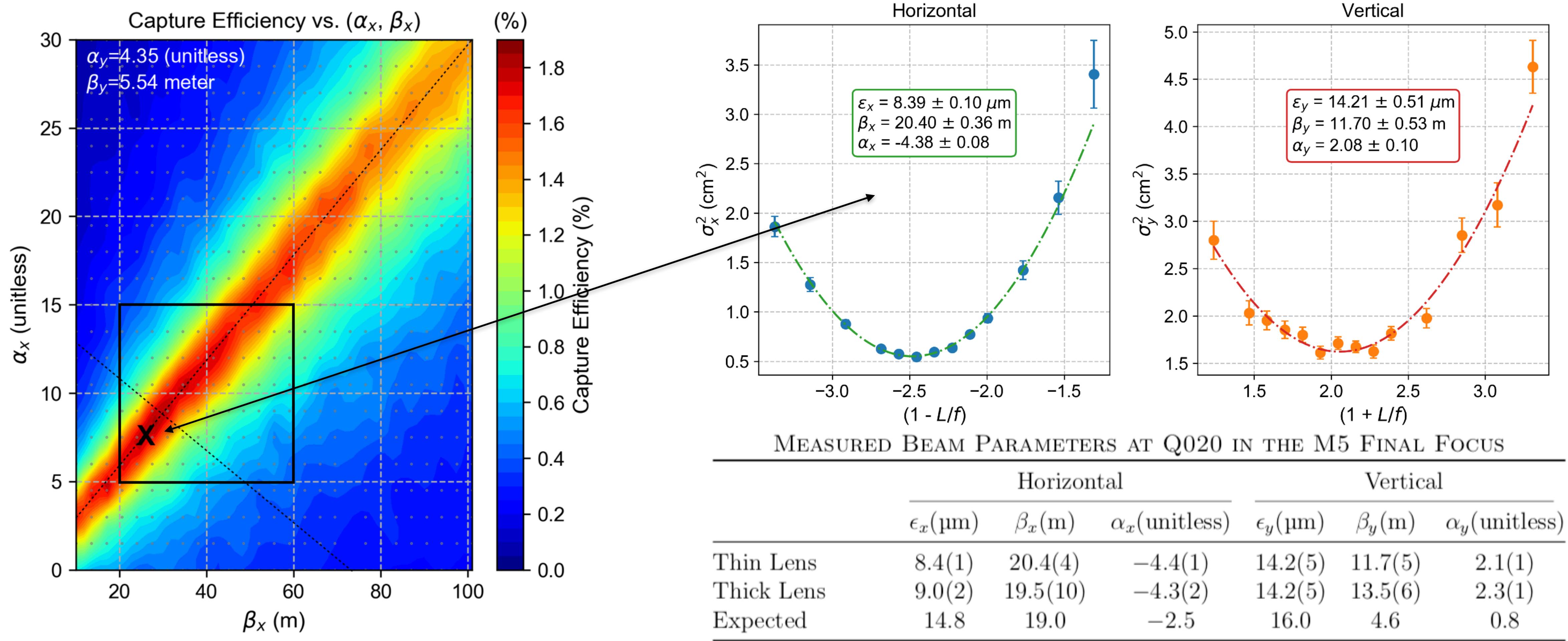
Design more sophisticated studies

Muon Capture vs. Injection Beam Width/Focusing Parameters @M5end



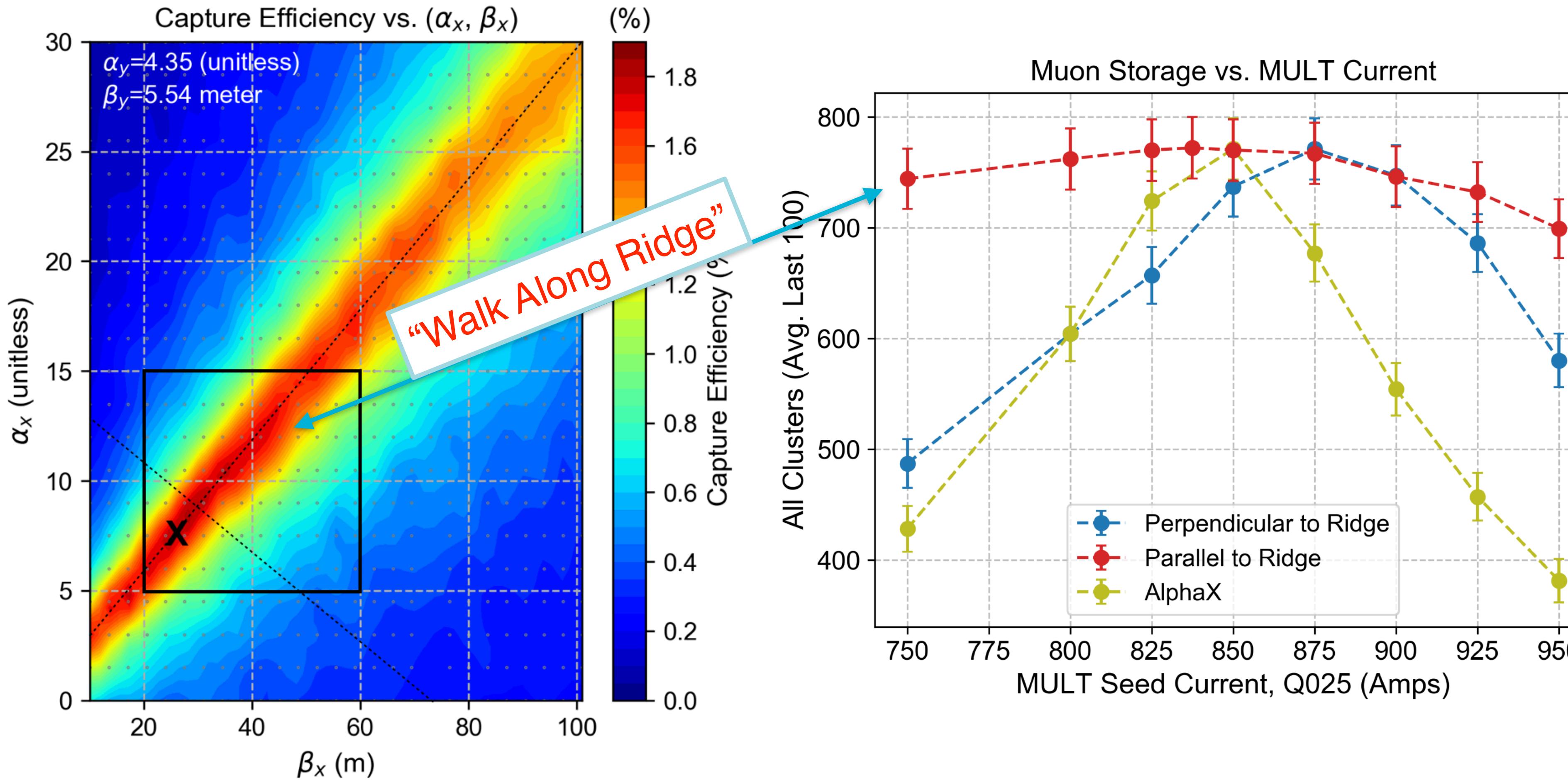
Direct measurement of the beam Courant-Snyder parameters

Muon Capture vs. Injection Beam Width/Focusing Parameters @M5end



Develop multi-parameter tuning knobs (MULTs)

Muon Capture vs. Injection Beam Width/Focusing Parameters @M5end



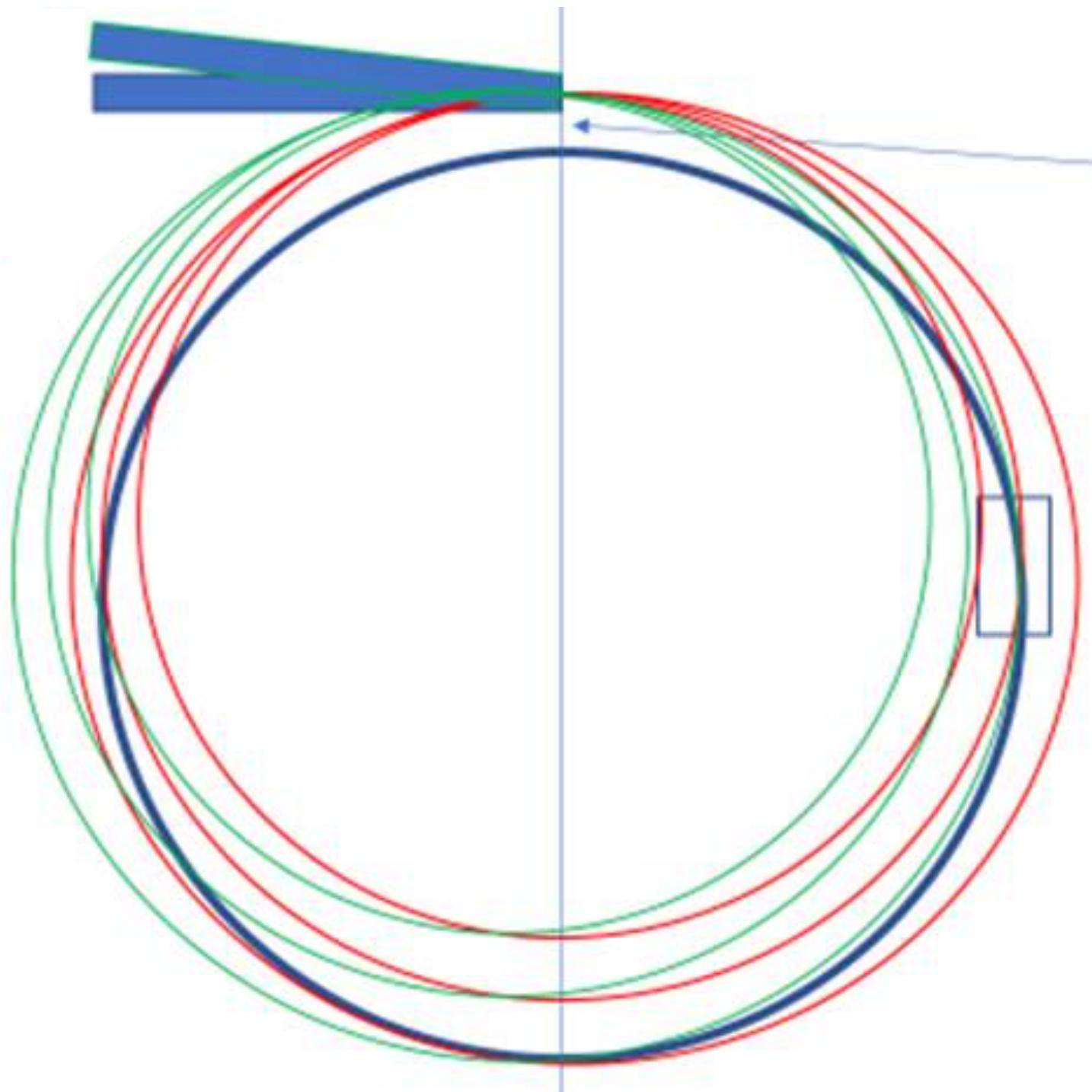
~6-8% gain, but
counts still low
overall 😞

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- Optimization of the muon g-2 beamline
- **Discovery of a problem**
- Conclusion & path forward

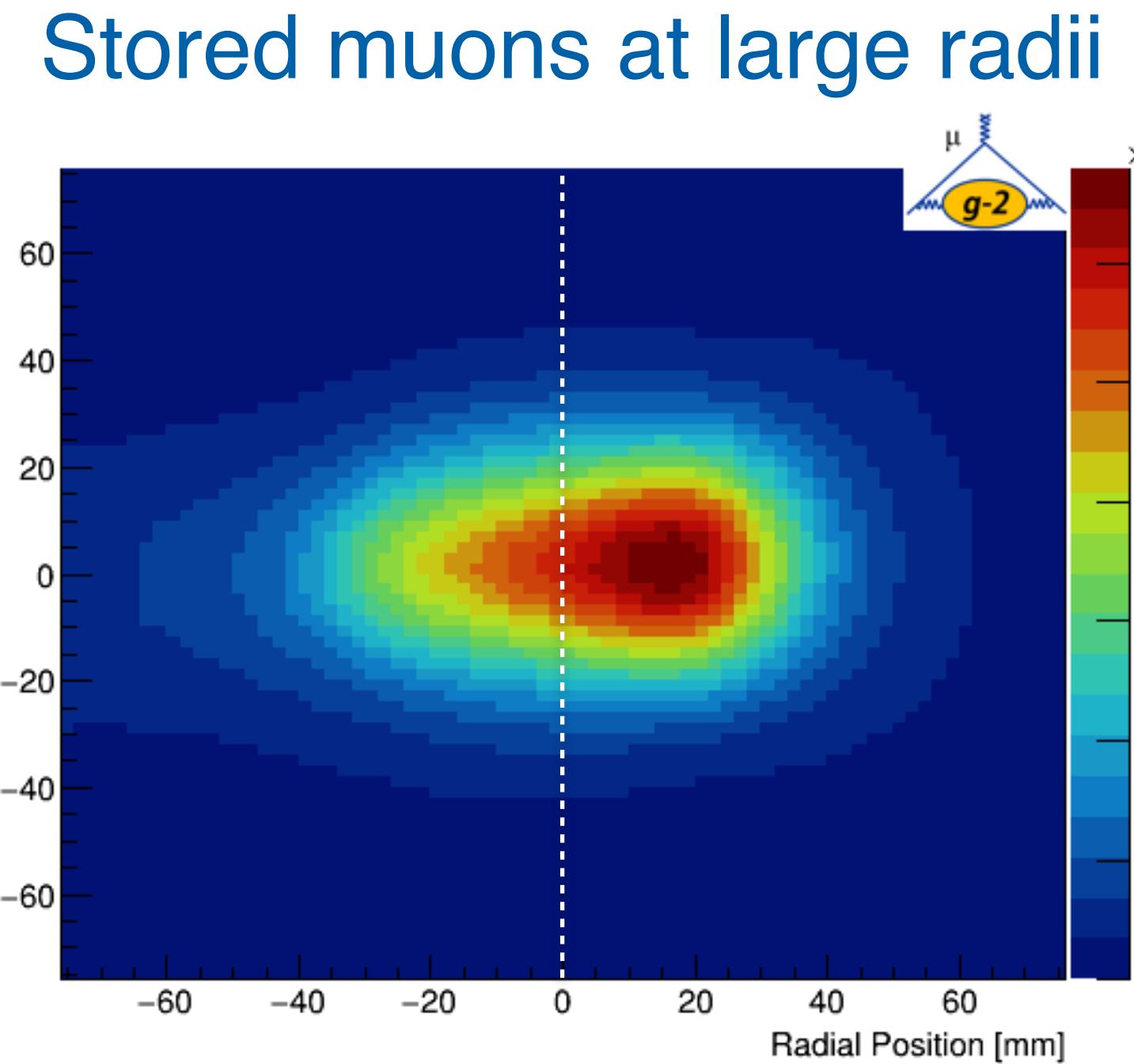
The required kick $\Delta x'$ is provided by the kicker field strength

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} \approx \underbrace{\begin{pmatrix} \cos(\sqrt{1-n}\theta) & \frac{\rho_0}{\sqrt{1-n}} \sin(\sqrt{1-n}\theta) & \frac{\rho_0}{1-n}(1 - \cos(\sqrt{1-n}\theta)) \\ -\frac{\sqrt{1-n}}{\rho_0} \sin(\sqrt{1-n}\theta) & \cos(\sqrt{1-n}\theta) & \frac{1}{\sqrt{1-n}} \sin(\sqrt{1-n}\theta) \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Transport beam } \sim 90^\circ \text{ downstream from inflector exit to kickers}} \begin{pmatrix} x \\ x' \\ \delta \end{pmatrix},$$



$$\Delta x'_{\text{kick}} \approx +\frac{x_{\text{inf}}}{\rho_0} - M_{22}x'_{\text{inf}} - \delta$$

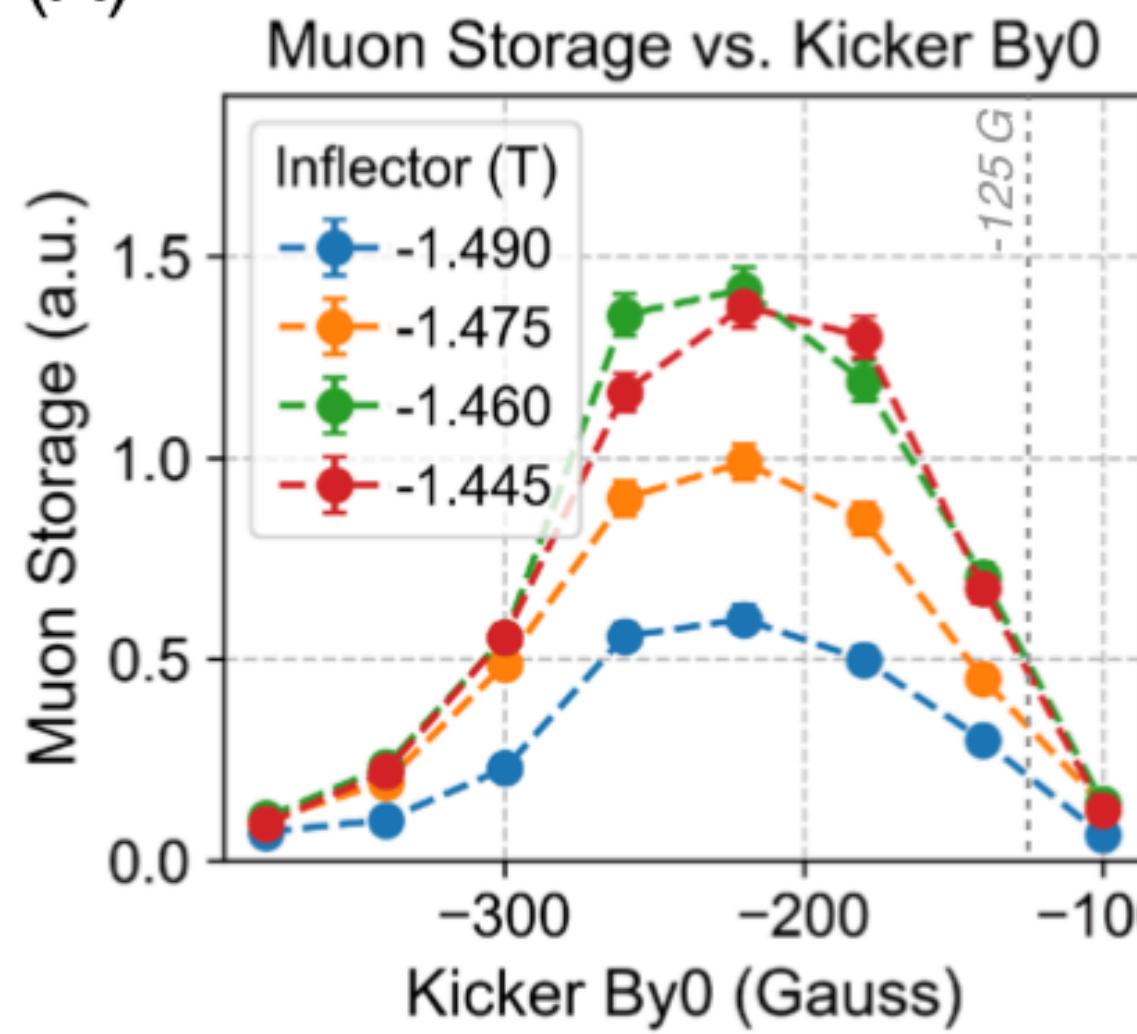
$\equiv \textcircled{1} + \textcircled{2} + \textcircled{3}.$



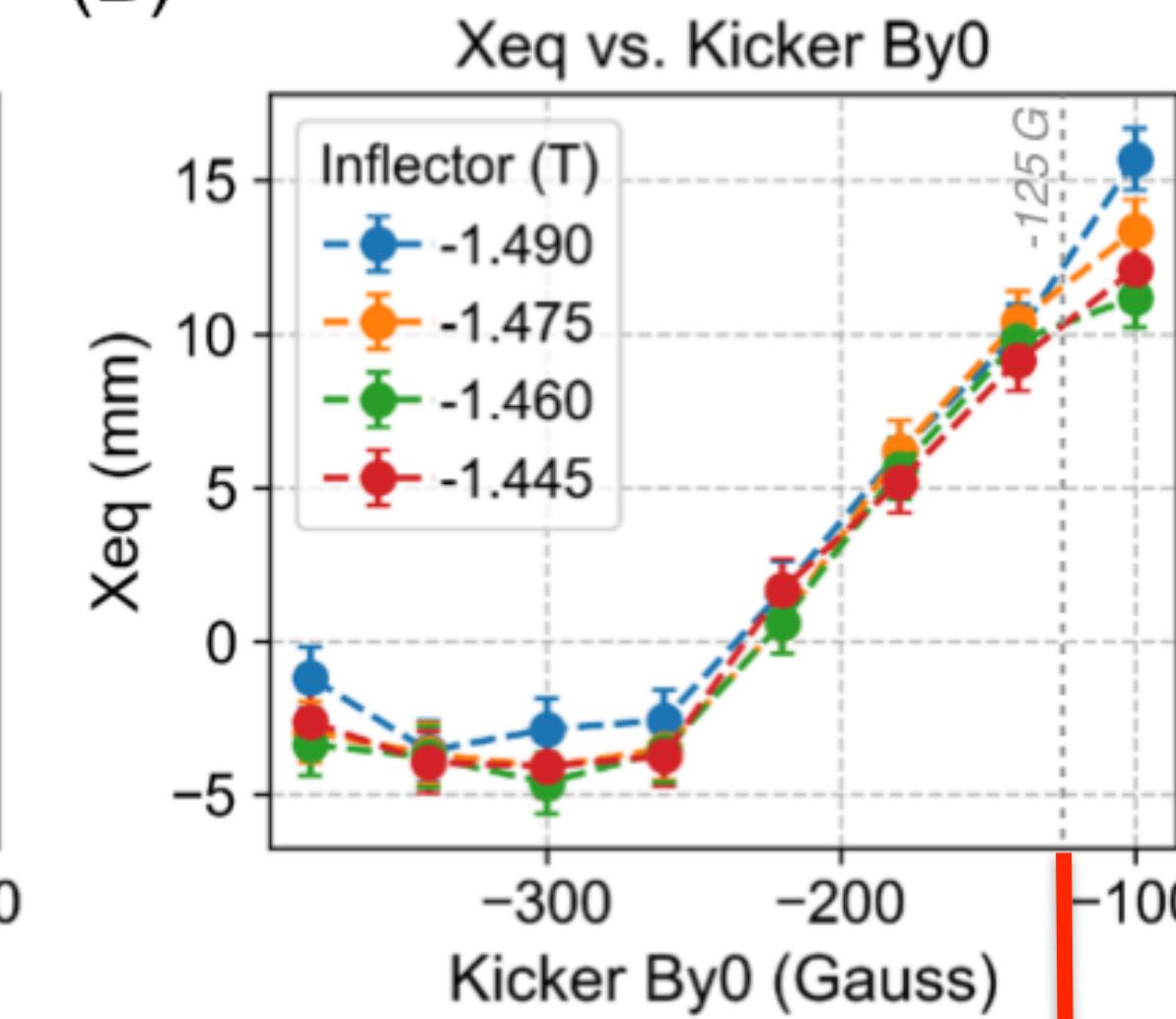
Strong indications from simulation the kickers are weak

Effects of kicker strength

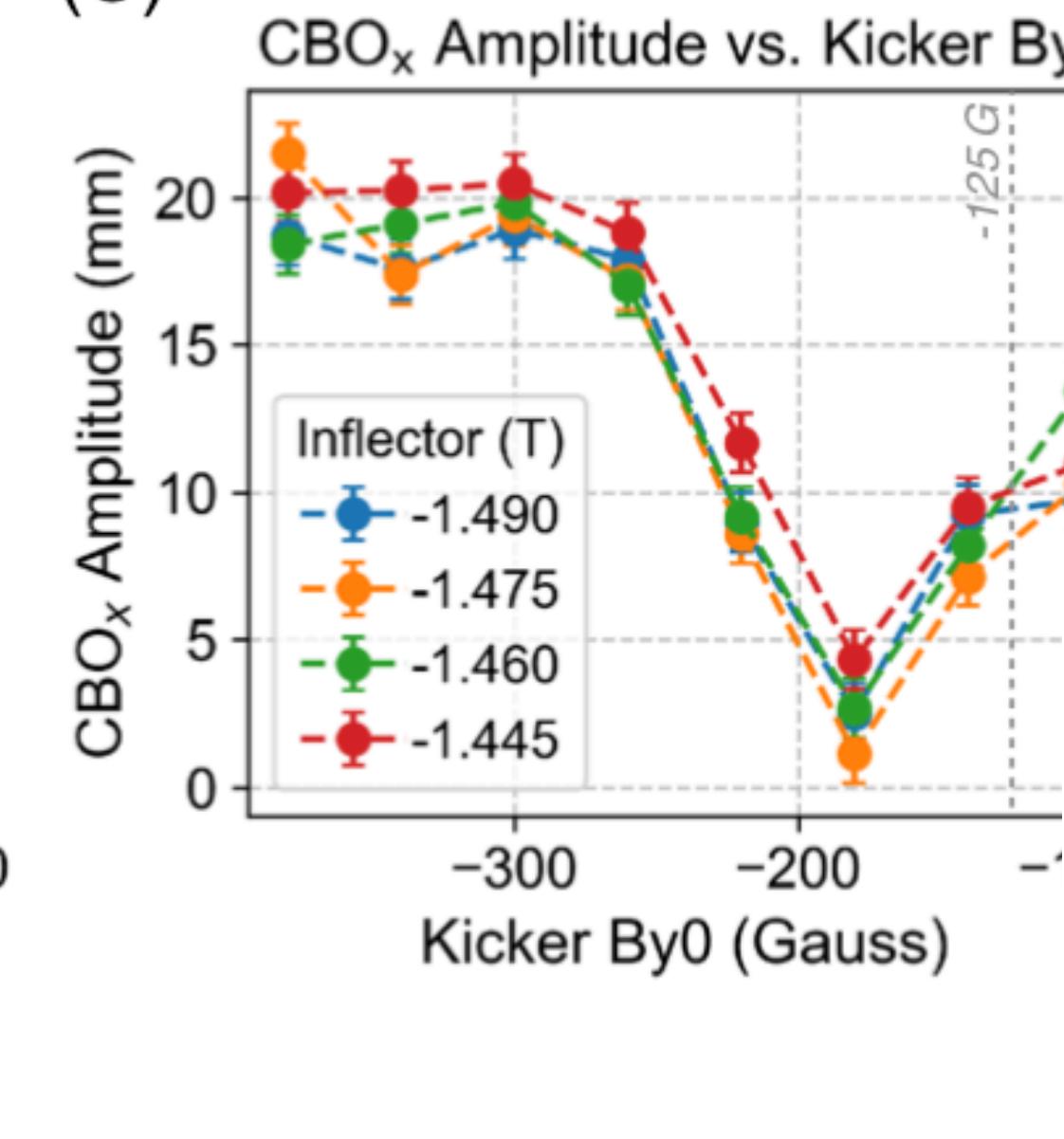
(A)



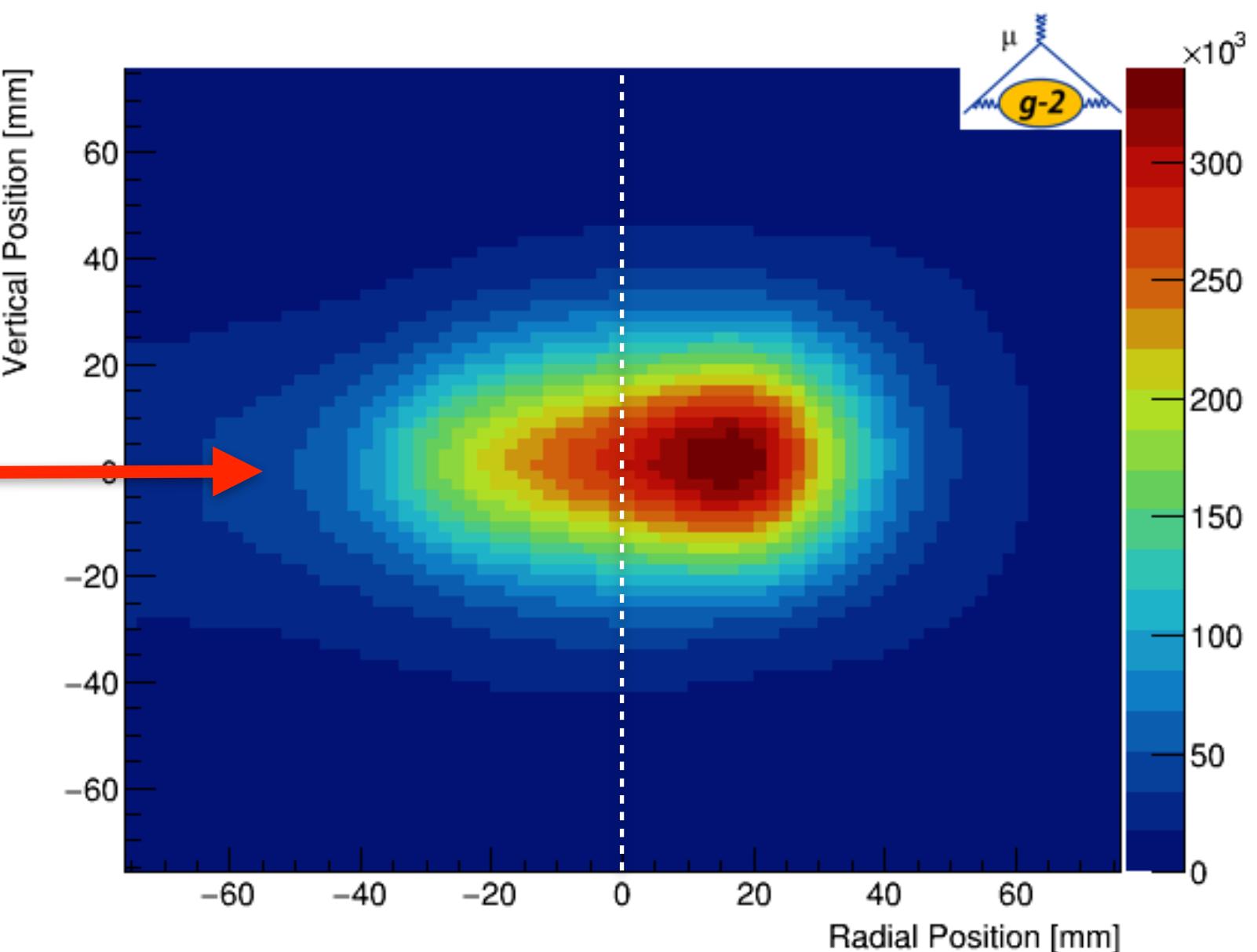
(B)



(C)



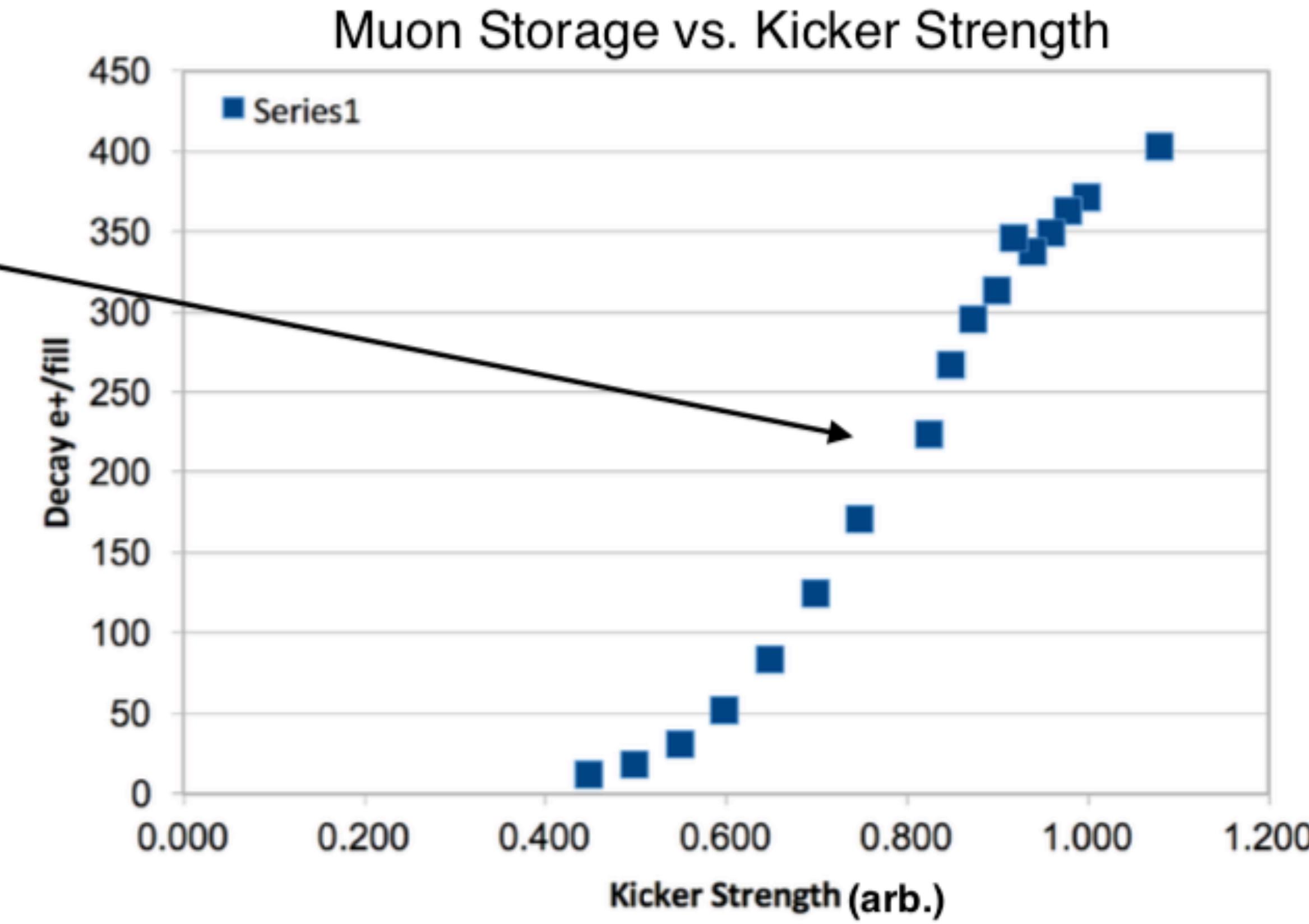
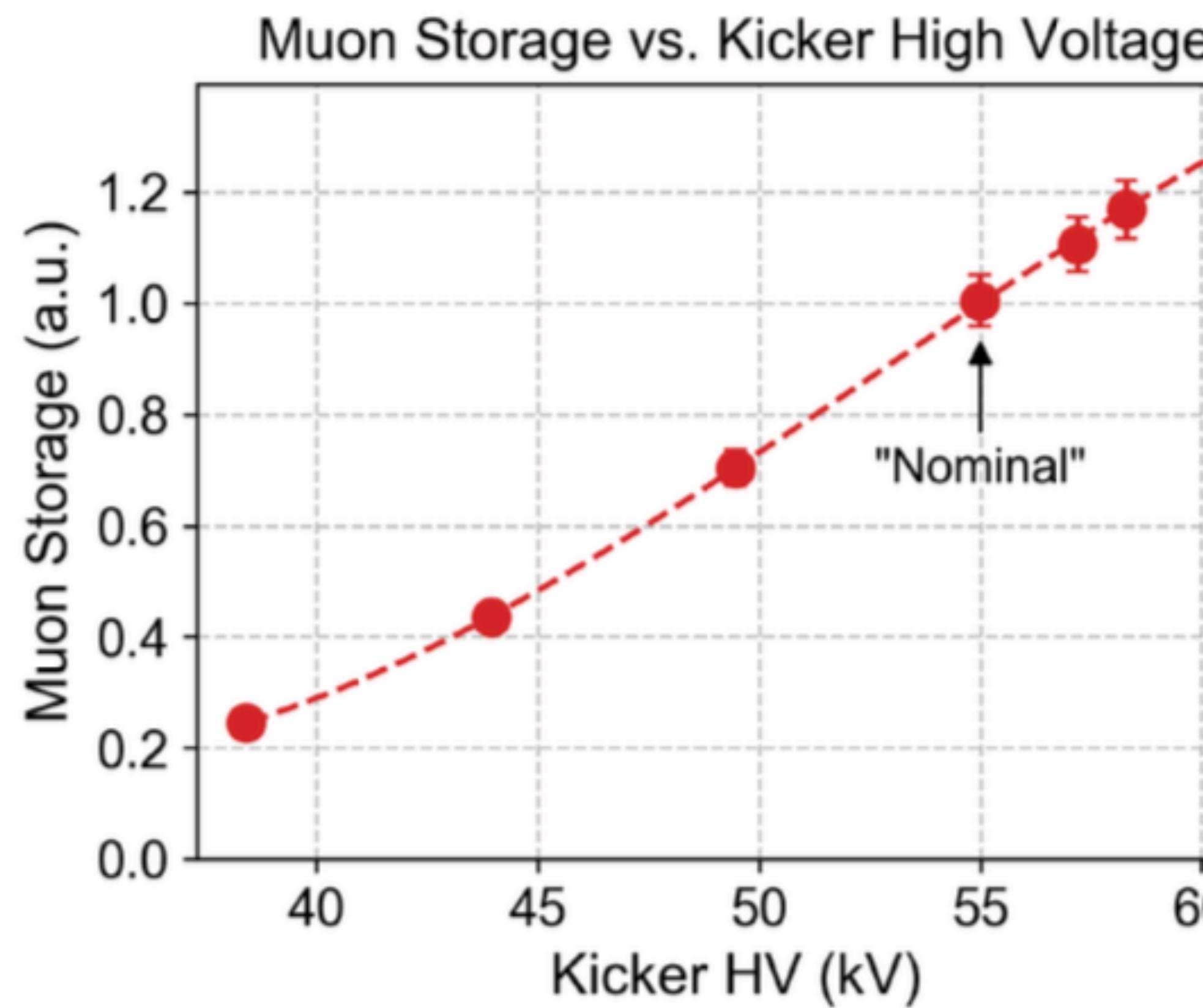
Stored muons at large radii



The only way my simulations could reproduce the observed beam profile is if the kick was very, very weak (125G vs. 250G)

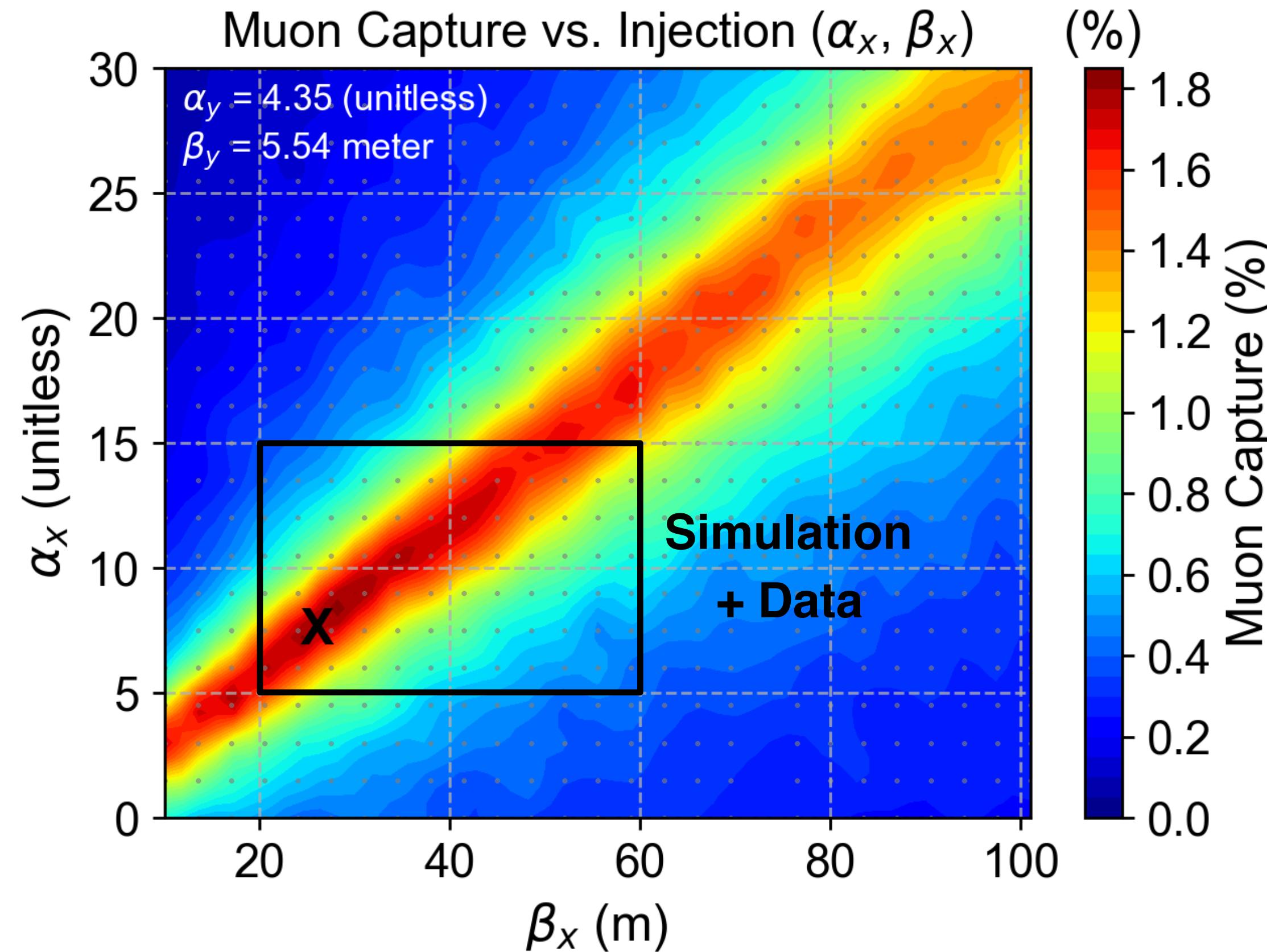
The kick was increased, stored beam was DOUBLED

225e+/fill => 580 e+/fill

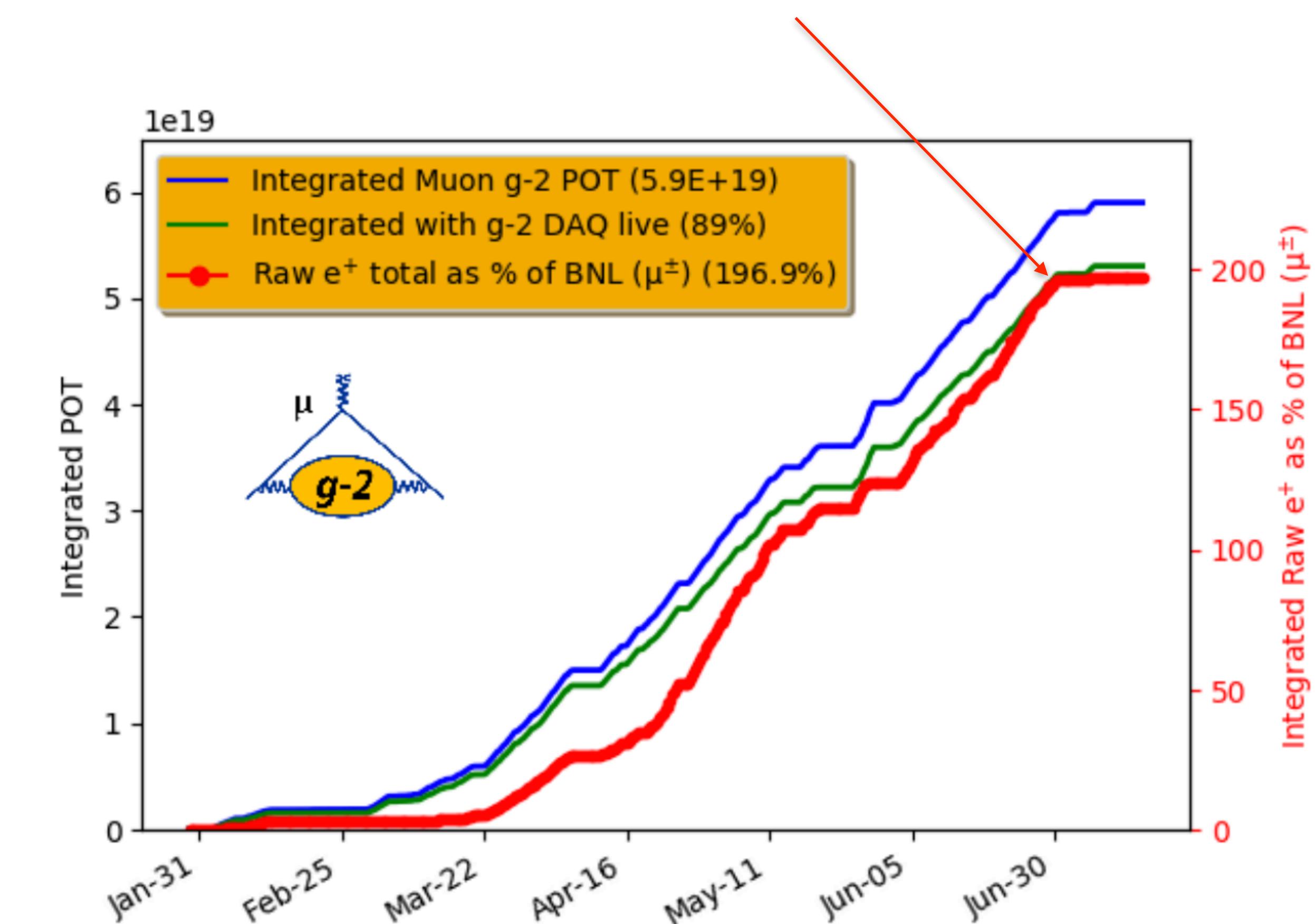


Conclusion

Successful commissioning
and beamline optimizations



Successful Run 1: ~2X BNL statistics



Conclusion

- The g-2 experiment is now well on its way
 - First publication expected within one year
 - Kicker improvements this summer
 - Quad reliability this summer
 - Ionization cooling in upstream beamline => higher muon flux in g-2 ring
 - 10X BNL next year
 - 10X BNL following year
 - Stay tuned
- $\left. \begin{array}{l} 10\text{X BNL} \\ 10\text{X BNL} \end{array} \right\} \sim 20\text{X BNL}$

BACKUP

Measured g-2 ring kicker pulses

