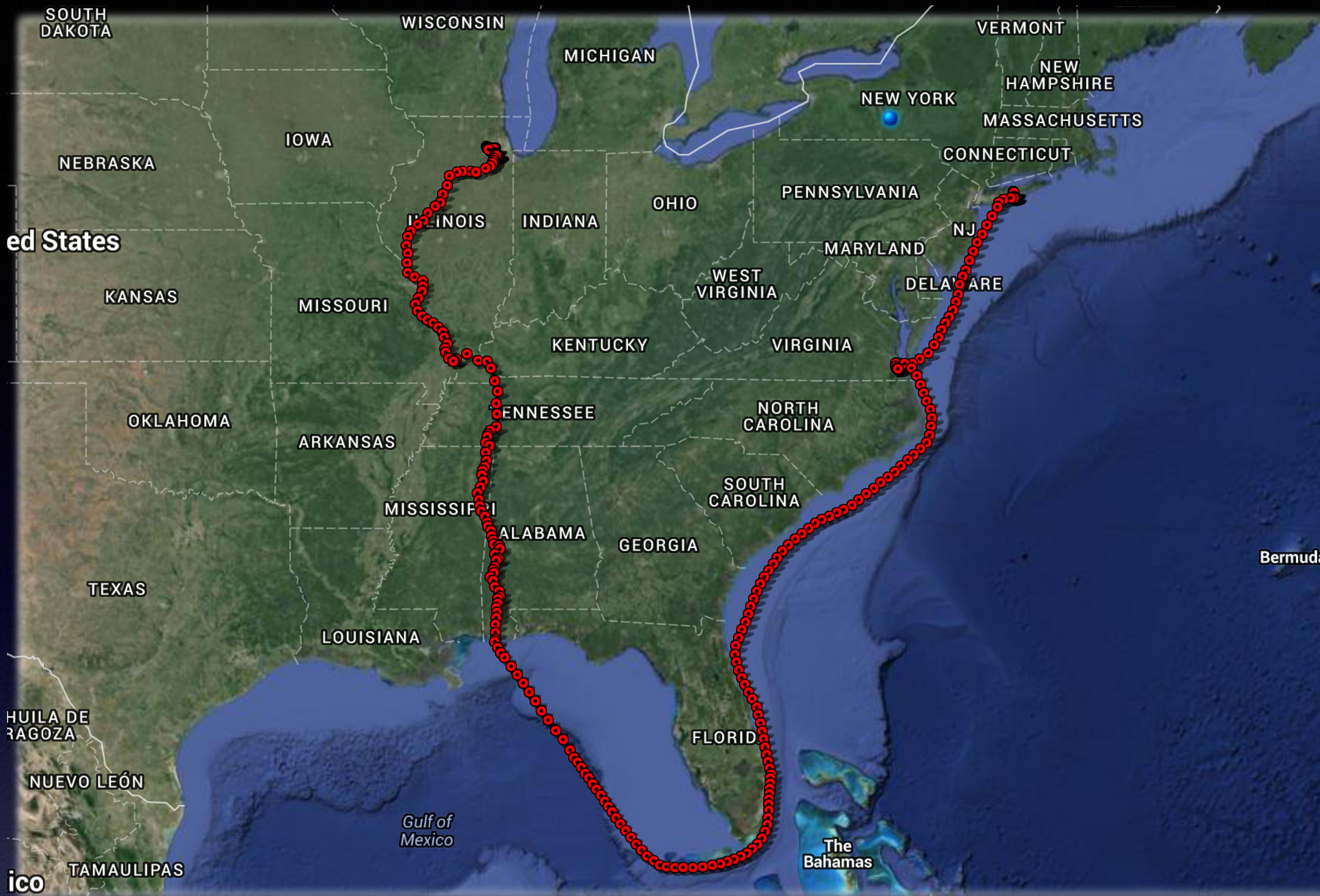
Taking the Muon for a Spin

AN Overview of g-2 for the Muon

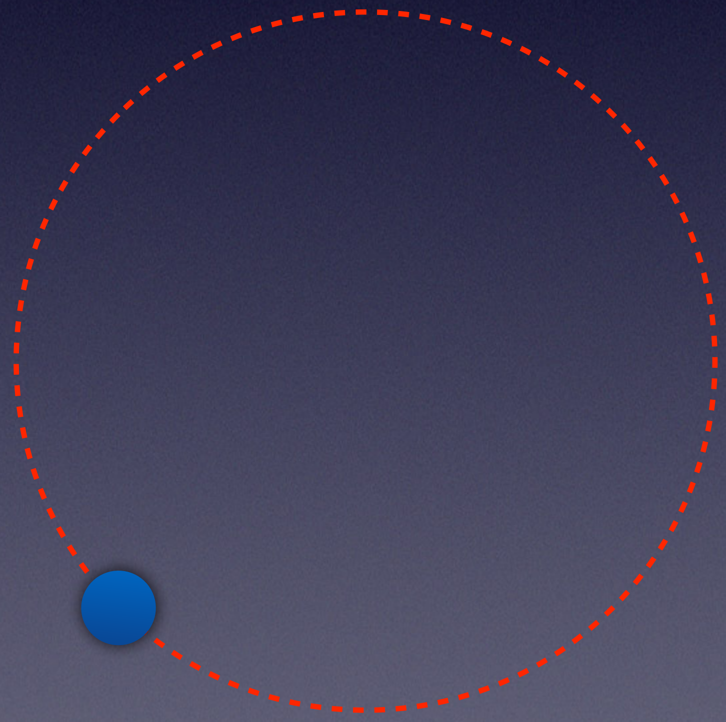
Lawrence Gibbons
Cornell University
Fermilab Muon g-2

Roadmap



- A moment on history
- The current spin on g-2
- Muon g-2 experiments: theme and variations

The gyromagnetic ratio



Classical particle in orbit

$$\vec{\mu} = I\vec{a} = \frac{q\omega}{2\pi}\pi r^2 \hat{a} \quad = \quad \frac{q}{2m} m\omega r^2 \hat{a}$$

$$= \quad \frac{q}{2m}\vec{L}$$

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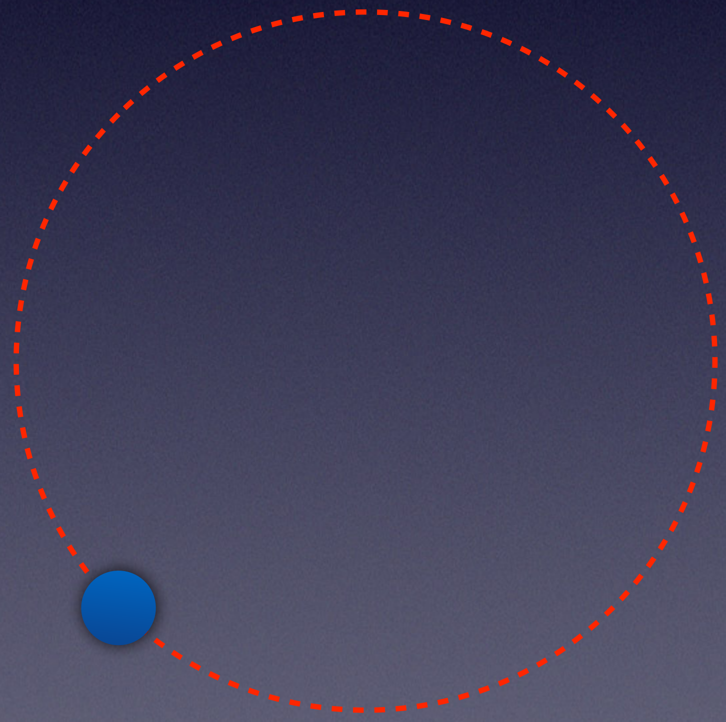

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Particle with intrinsic spin

$$\vec{\mu} \quad = \quad g\frac{q}{2m}\vec{S}$$

The gyromagnetic ratio

Classical particle in orbit

$$
\begin{aligned}
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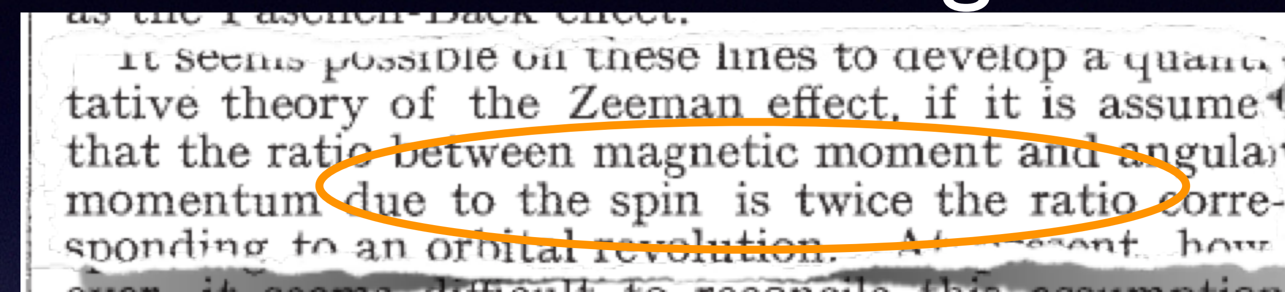
&= \frac{q}{2m}\vec{L}
\end{aligned}
$$

Particle with intrinsic spin

$$
\vec{\mu} = g\frac{q}{2m}\vec{S}
$$

g for fermions: instructive!

g = 2 has been around as long as spin ½!


It seems possible on these lines to develop a quantitative theory of the Zeeman effect, if it is assumed that the ratio between magnetic moment and angular momentum due to the spin is twice the ratio corresponding to an orbital revolution.

Uhlenbeck and Goudsmit, "Spinning Electrons and the Structure of Spectra", Nature 117, 264-265, 1926

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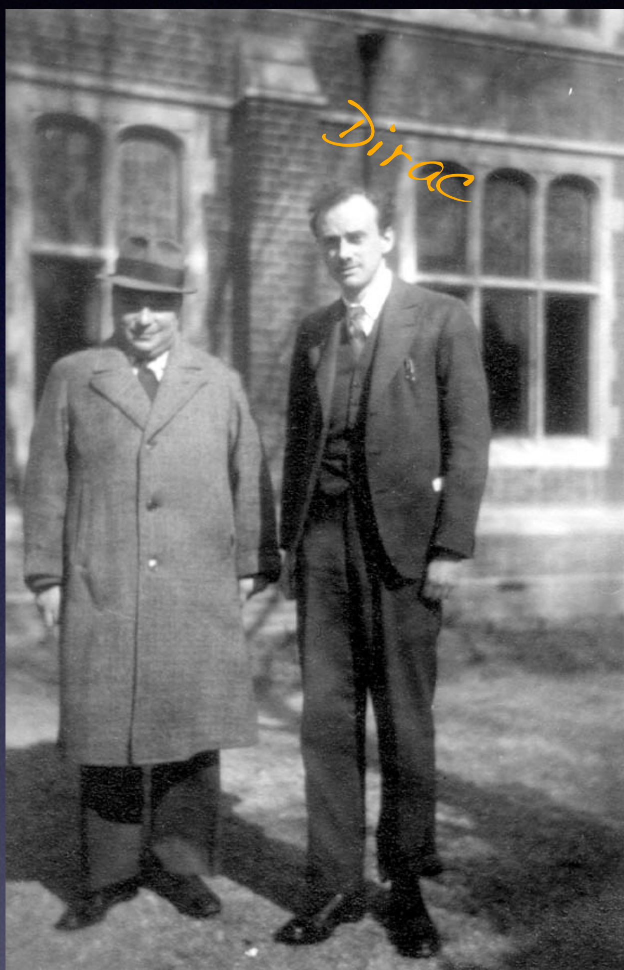

Dirac Eqn: framework beautifully incorporates g = 2

Pauli to Stern on g for proton:

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known." (Ridgen)

"Don't you know the Dirac theory? It is obvious from Dirac's equation that [g_p=2]" (Tomonaga)

Stern and Estermann (1933)…

- $g_p \approx 5.6$!
- Rabi: deuteron infers $g_n \approx -3.8$

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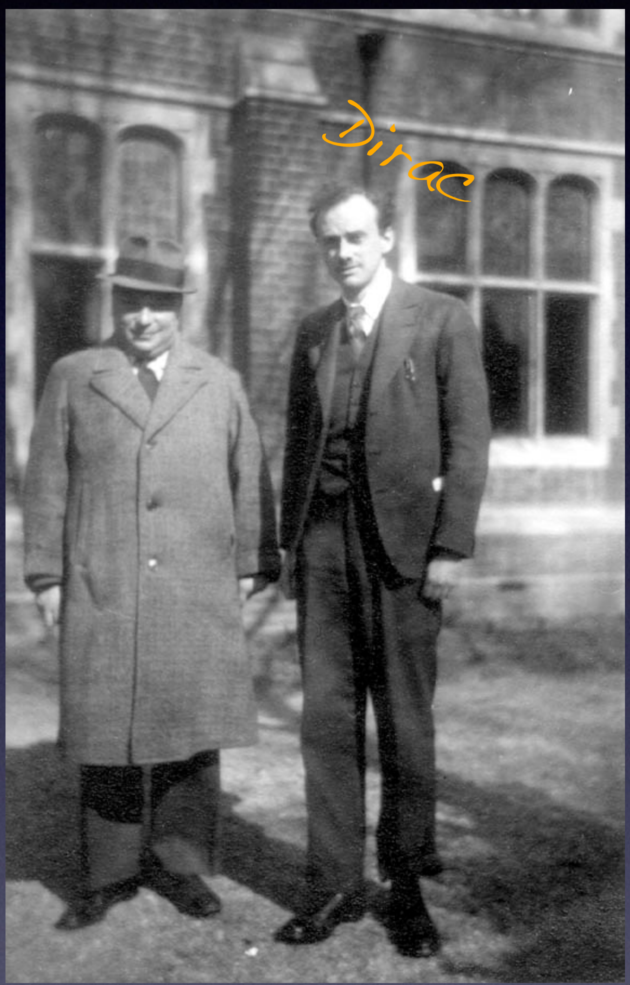

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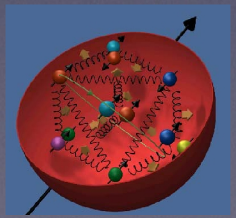

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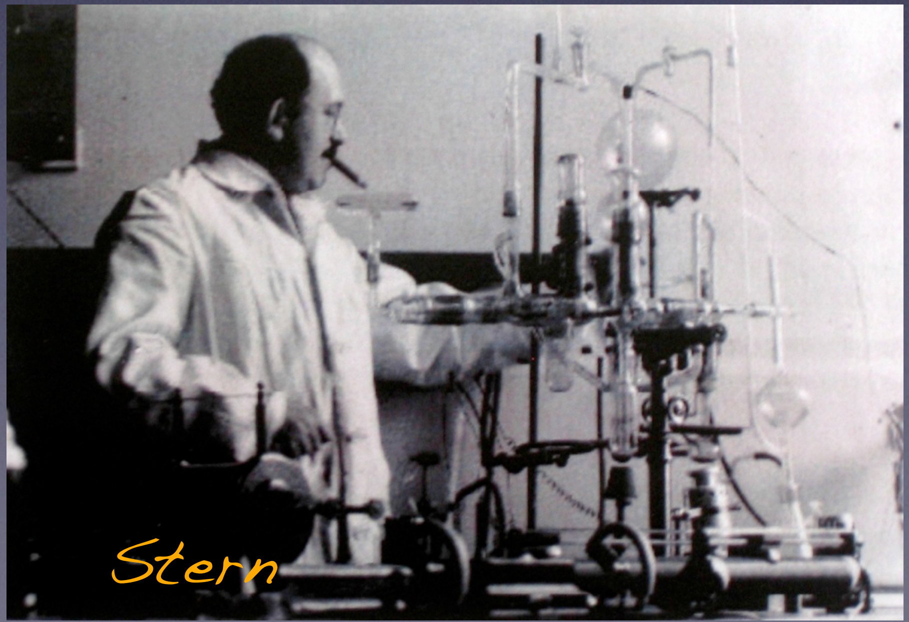

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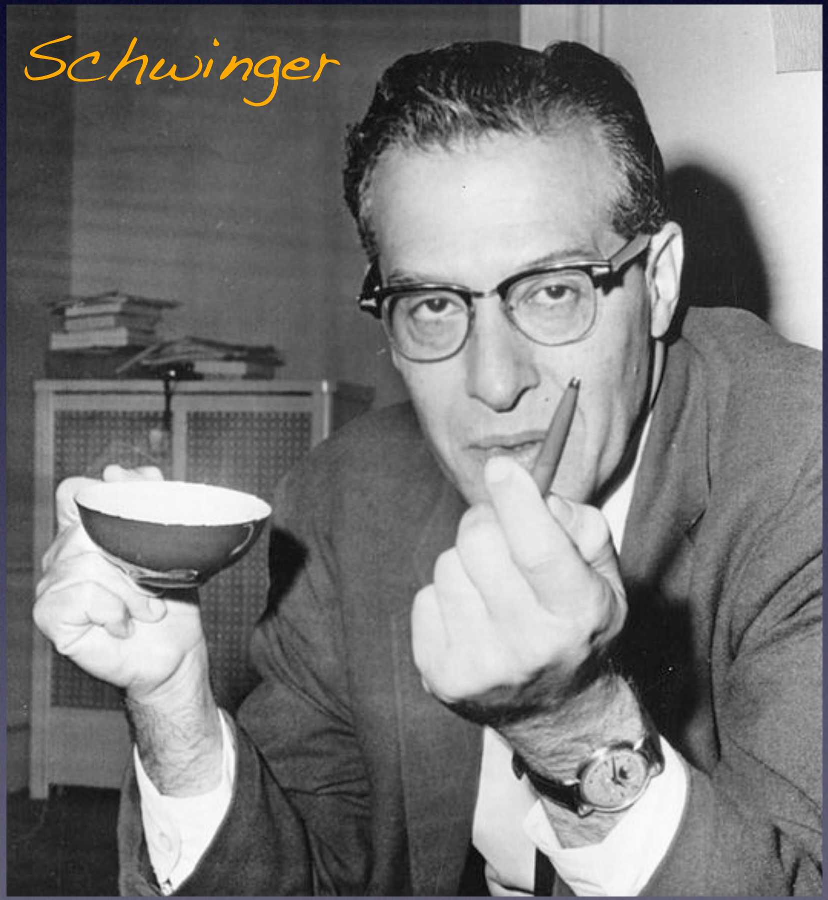
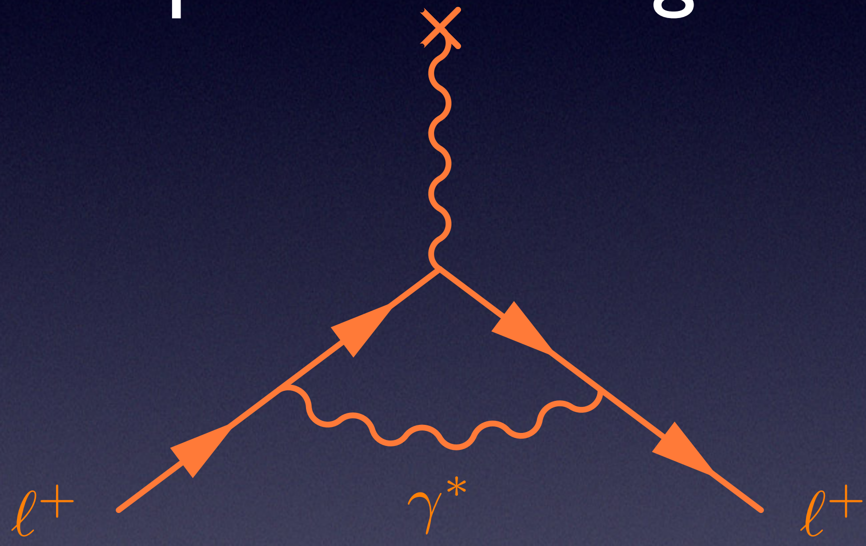
Kusch and Foley (enabled by WWII radar technology)

- $g_e = 2.00229 \pm 0.00008_{1947}$: inspires Schwinger





$$g_e \approx 2(1 + \frac{\alpha}{2\pi}) \approx 2(1.00116)$$

K&F $:2(1.00119 \pm 0.00005)_{1948,\text{final}}$

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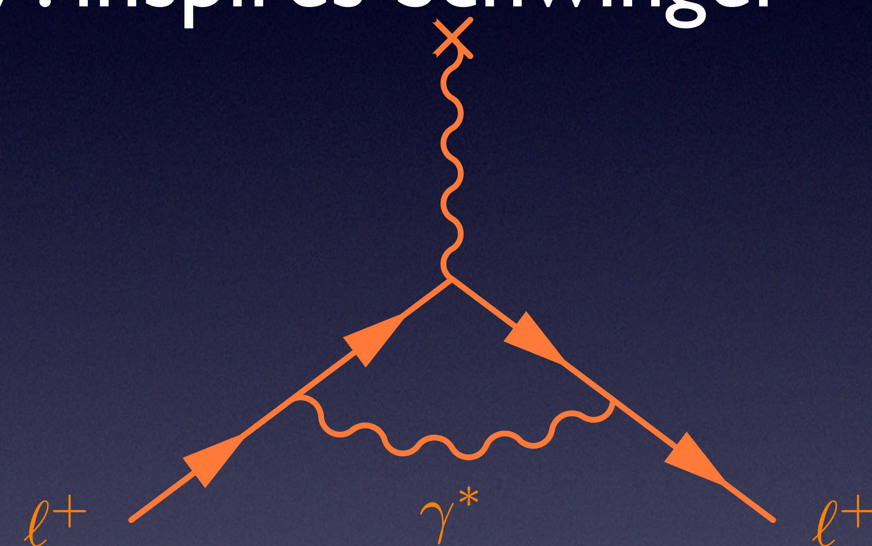

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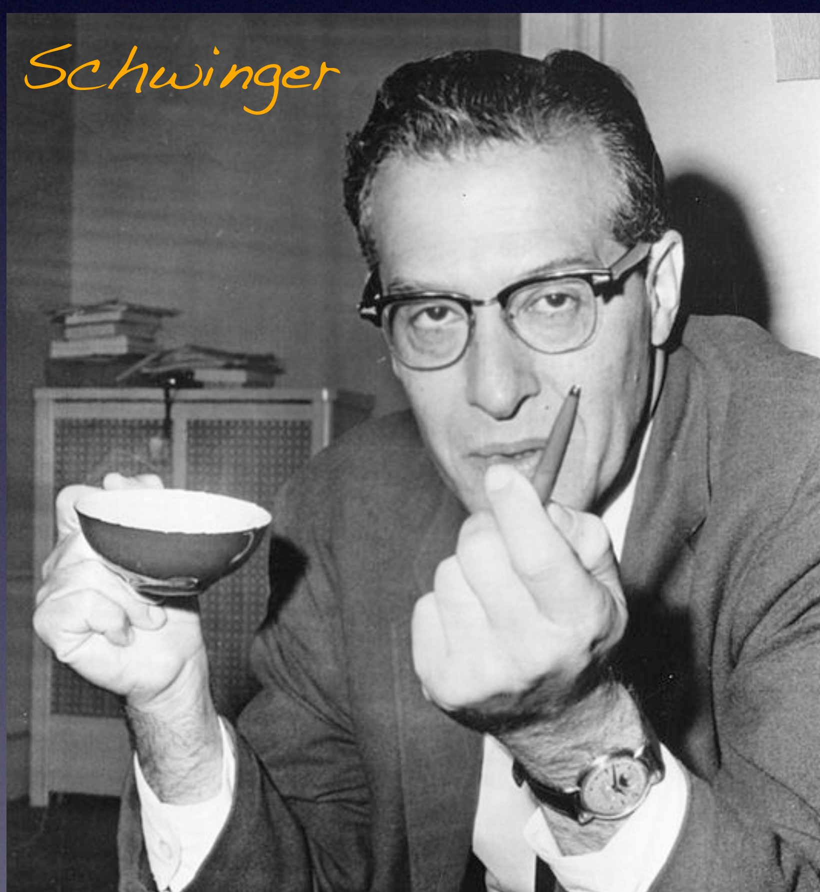

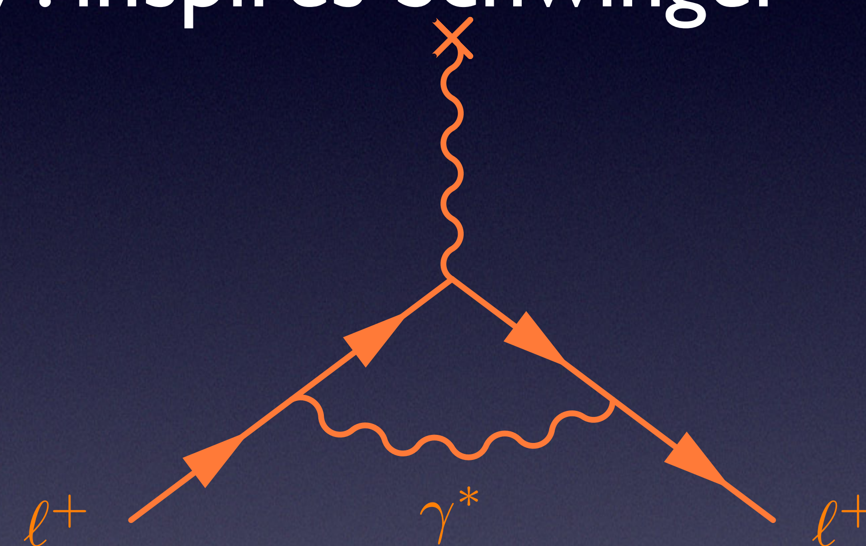

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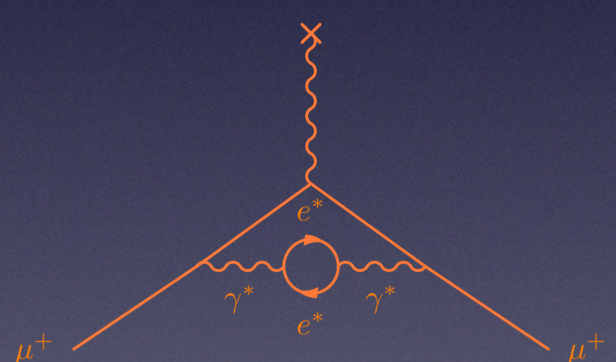
Anomalous magnetic moment:
a ≡ (g − 2) / 2

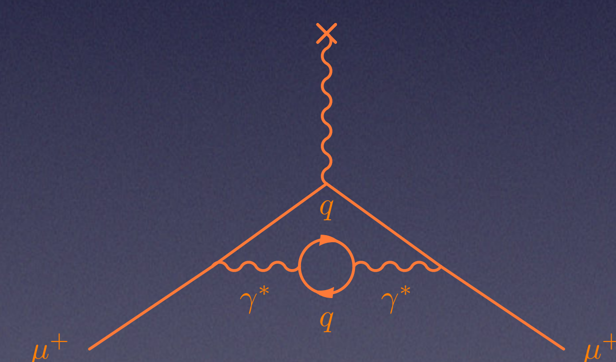
The current spin on a_e, a_μ

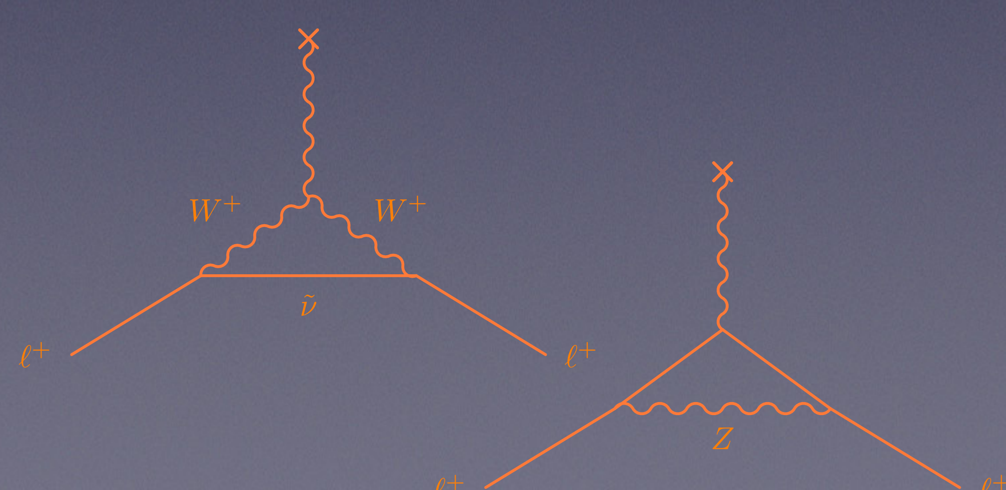
Much more happens than just virtual photon exchange

Higher order QED

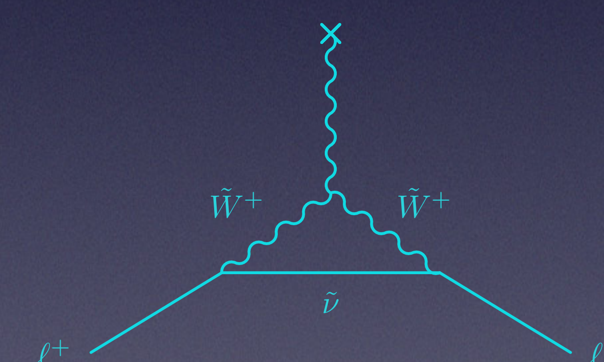


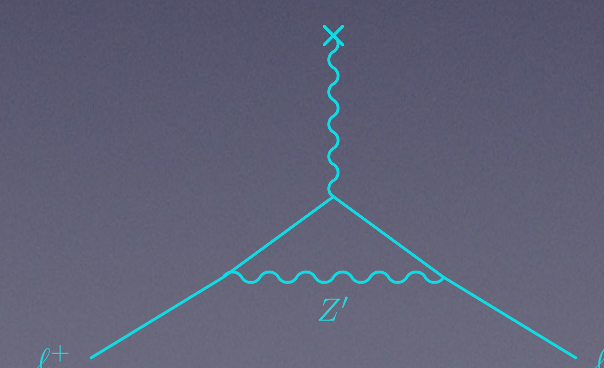
Strong, Weak Contributions





Something New??!!





Contributions:

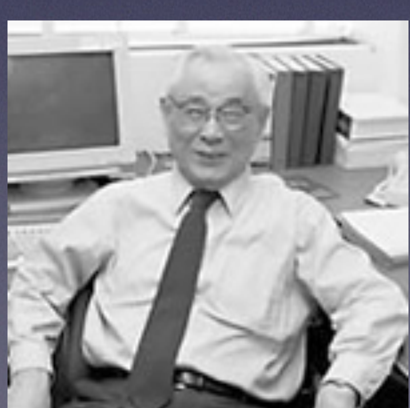
$$\delta a_\ell \sim q^2 \times \left(\frac{m_\ell}{\Lambda}\right)^2$$

The current spin on a_e, a_μ

Standard Model Calculations (units 10^{-12})

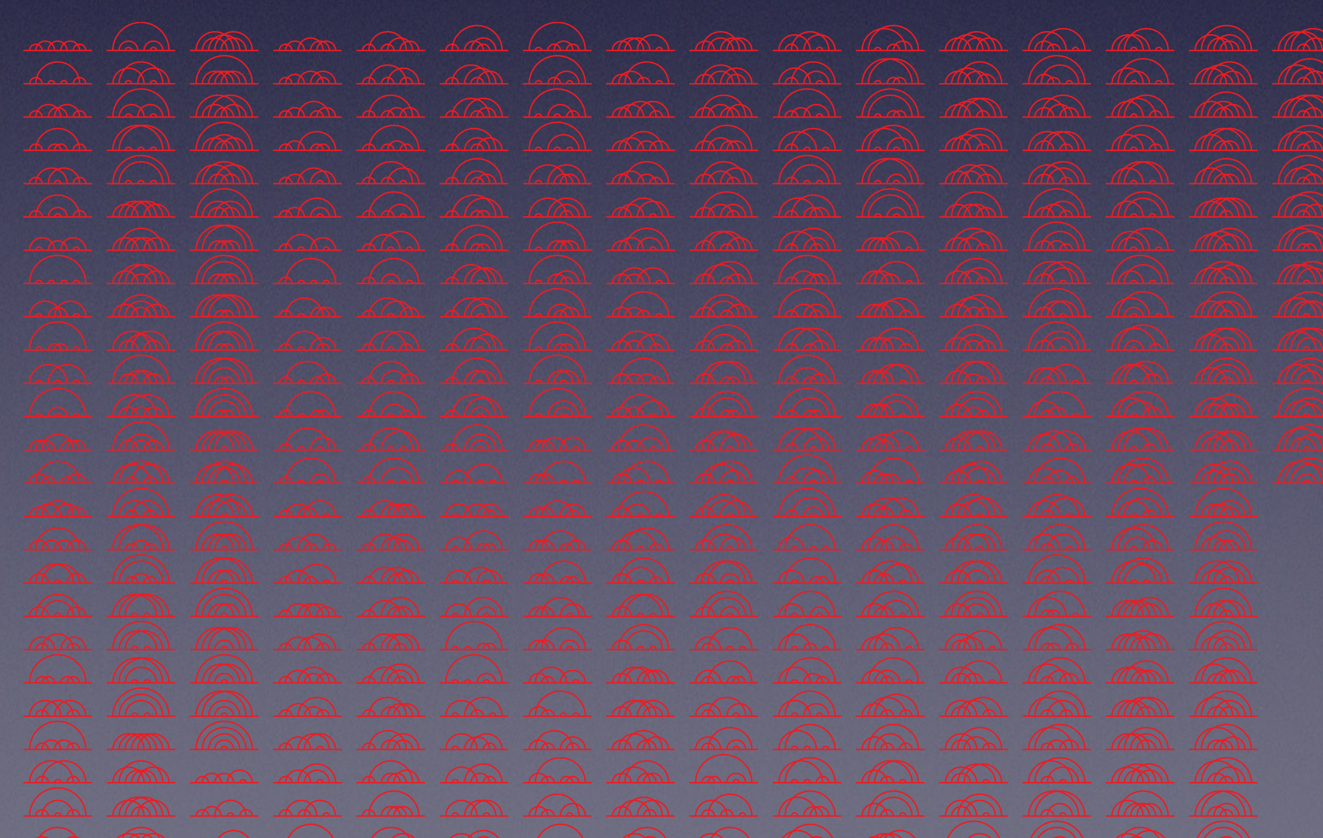
	a_e	a_μ
QED	1 159 652 180.03	1 165 847 188.6
to 10^{th} order	$(0.06)_8(0.04)_{10}(0.77)_{\alpha_{Rb(2011)}}$	$(0.09)_{mass}(0.19)_8(0.07)_{10}(0.30)_{\alpha_{a_e}}$

Aoyama, Hayakawa, Kinoshita and Nio,
PRL 109, 111807 & 111808 (2012)



Kinoshita

12,672 diagrams
at 10th order!



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Weak (to 2 loops)	0.03(0)	1 536(11)

Gnendiger, Stöckinger, H. Stöckinger-Kim, PRD 88, 053005 (2013)
Czarnecki, Marciano, Vainshtein, PRD 67, 073006, erratum 73.119901 (2006)

$$\frac{\alpha_{\text{weak}}}{4\pi}\left(\frac{m_e}{M_W}\right)^2 \sim 10^{-13}$$

$$\frac{\alpha_{\text{weak}}}{4\pi}\left(\frac{m_\mu}{M_W}\right)^2 \sim 4\times 10^{-9}$$

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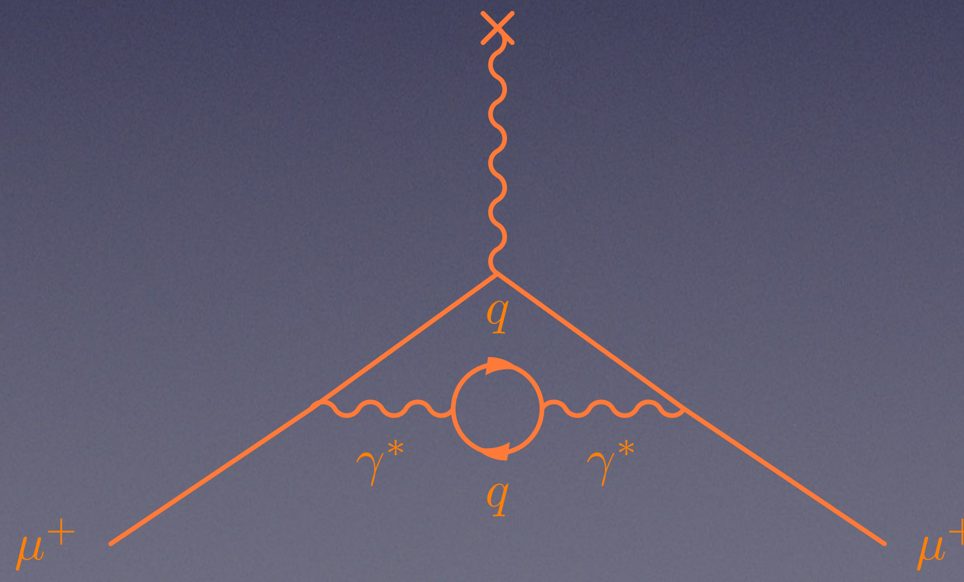
Vacuum polarization:
F. Jegerlehner, arXiv:1711.06089 [hep-ph]
(representative)



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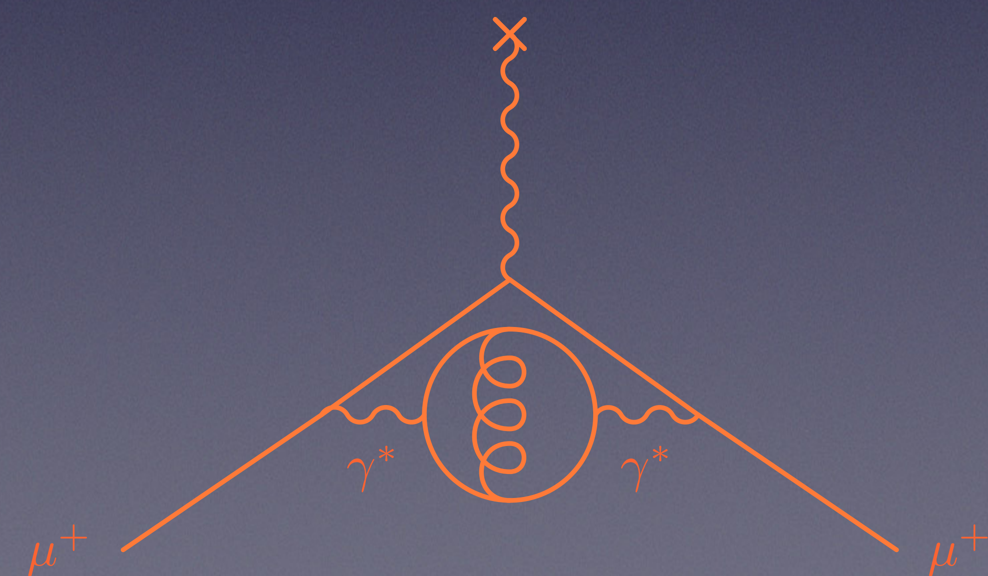

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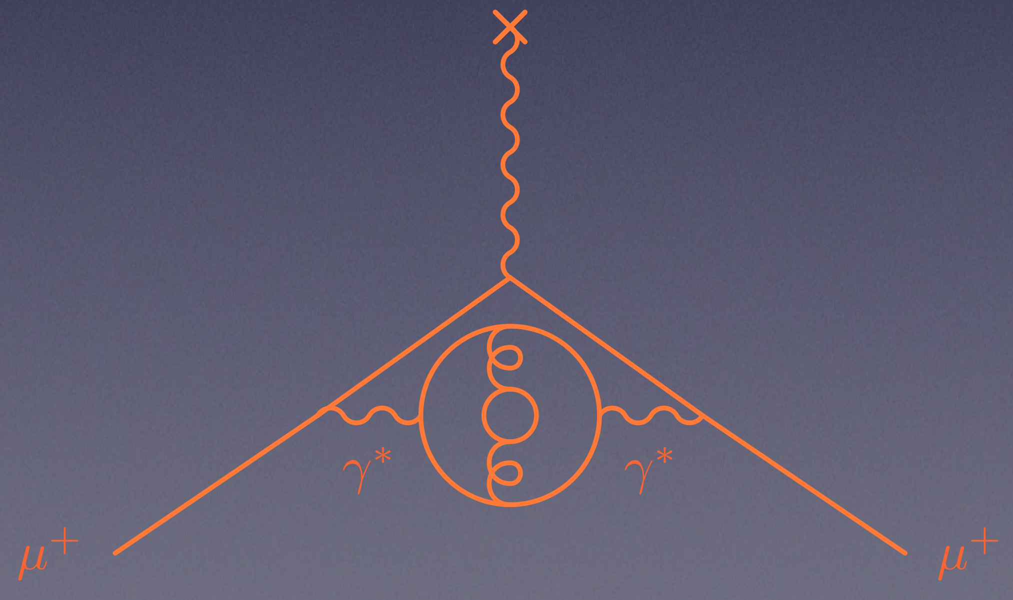

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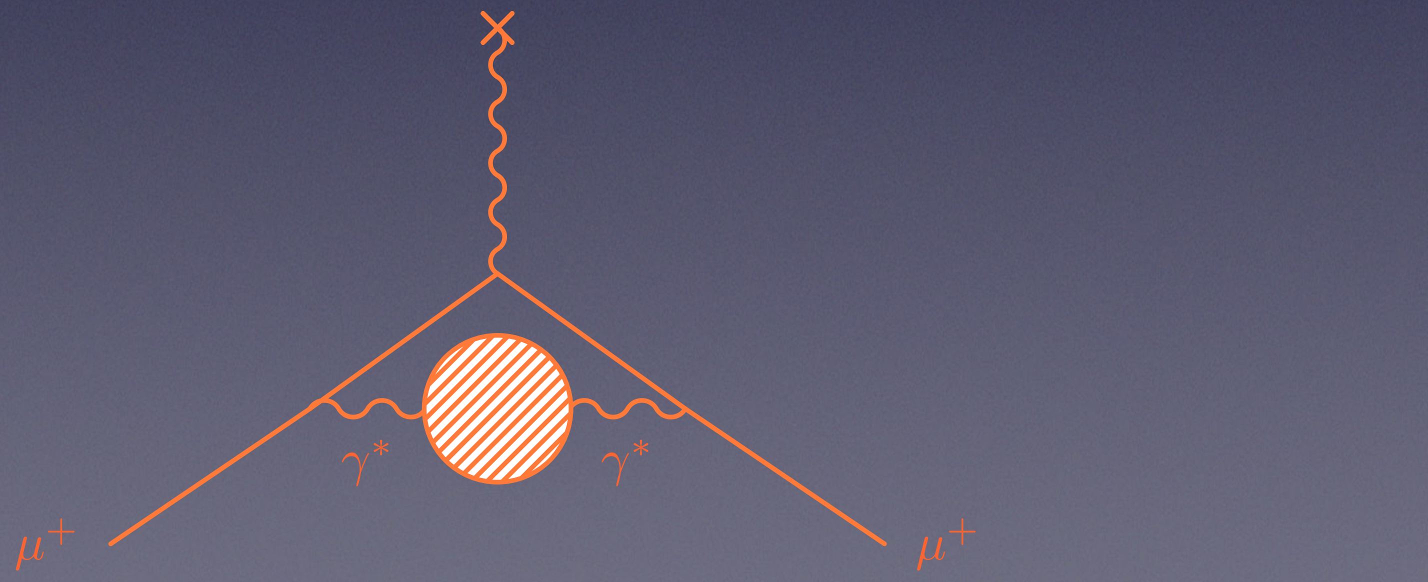

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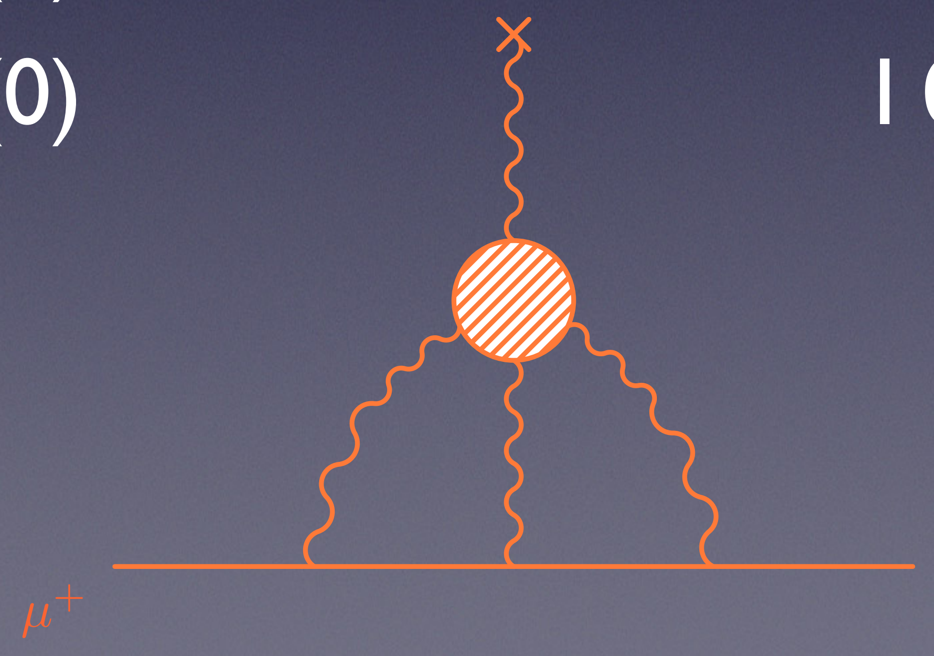
QCD_{II}	0.04(0)	1 034(288)

Hadronic "light × light"
F. Jegerlehner, arXiv:1711.06089 [hep-ph]
(representative)



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expt	1 159 652 180.73(28)	$1\,165\,920\,91_0(63_0)$

New α!

R. H. Parker et al. Science 360, 191 (2018)

Hanneke, Fogwell, and Gabrielse, PRL 100, 120801 (2008)

G.W. Bennett et al., Phys. Rev. D 73 (2006) 072003.

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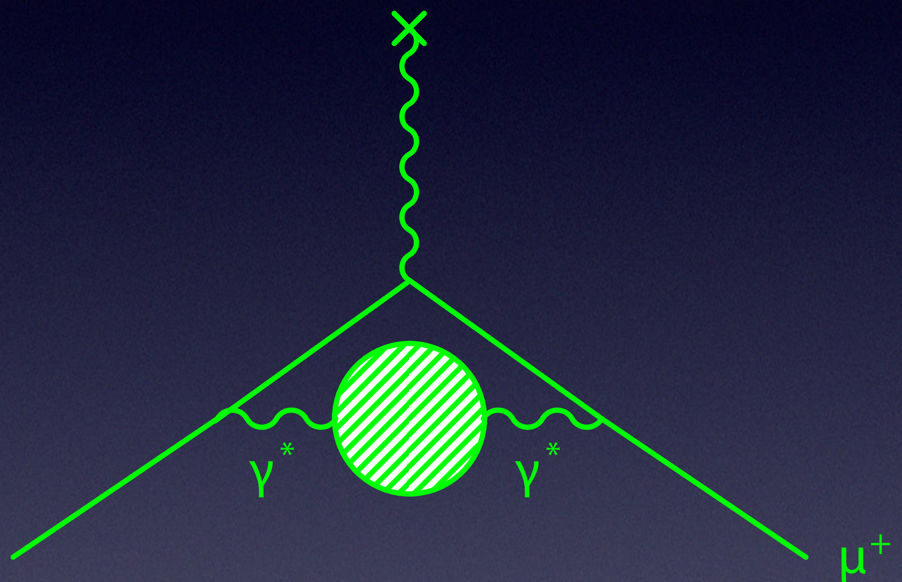
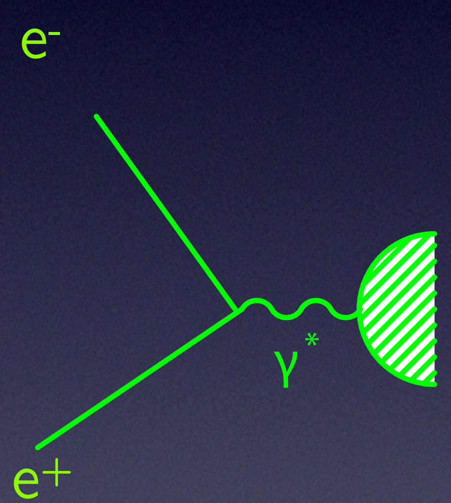
The current spin on a_e, a_μ

Hadronic Vacuum polarization (QCD_I)



The current spin on a_e, a_μ

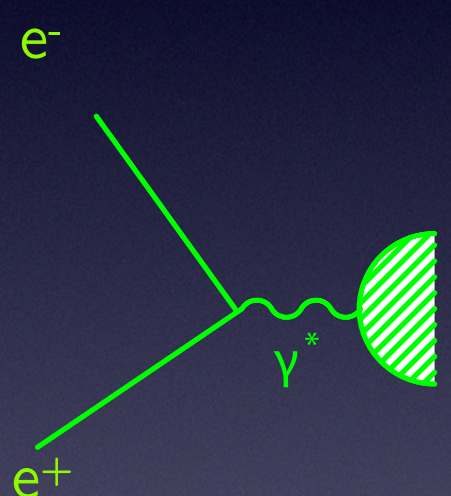
Hadronic Vacuum polarization (QCD_l)



$$\sigma(e^+e^- \rightarrow \text{hadrons})$$

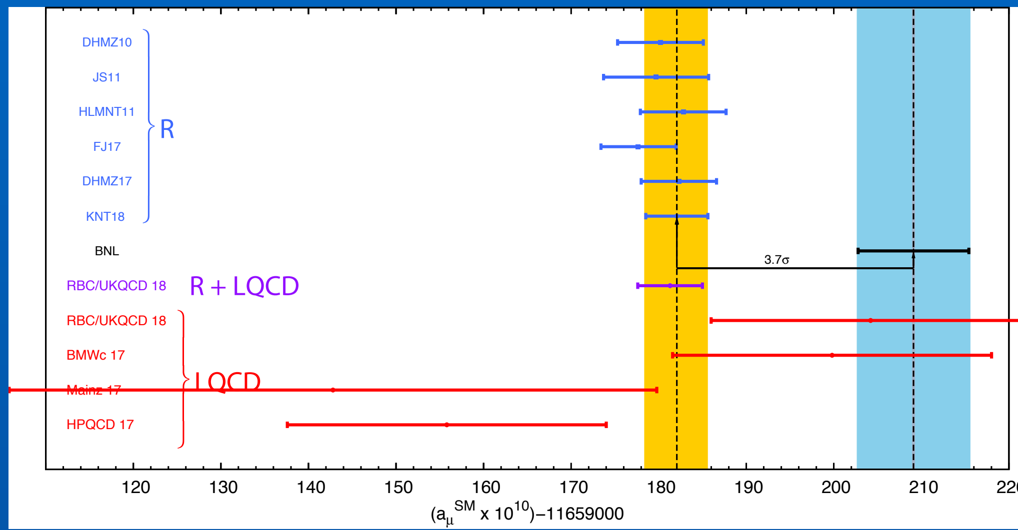
The current spin on a_e, a_μ

Hadronic Vacuum polarization (QCD$_I$)



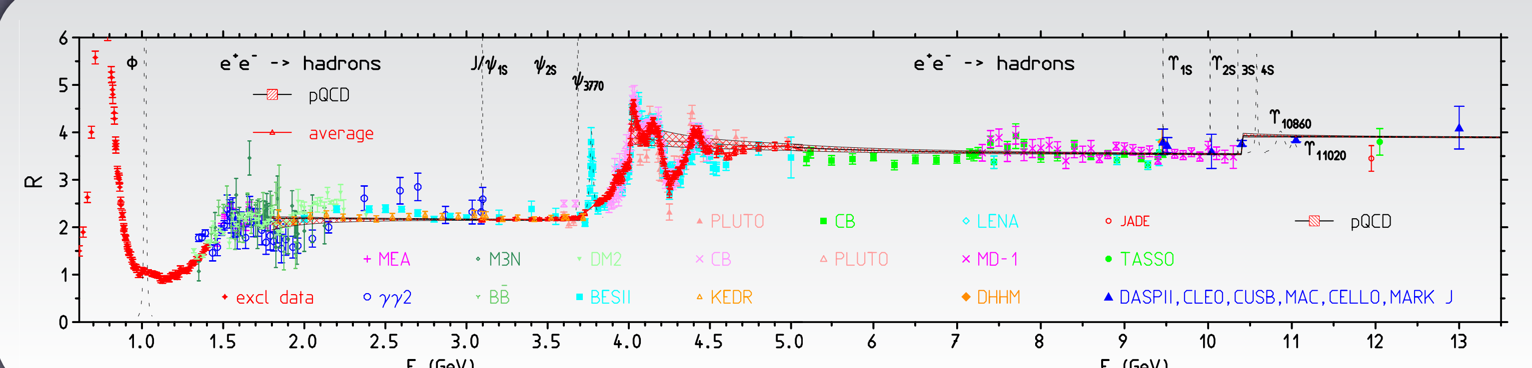
$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

$$a_\mu(HVP) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2} ds \frac{R(s)\hat{K}(s)}{s^2}$$



Lattice QCD efforts maturing.

- HVP: optimally combining LQCD and R methods can provide best precision
- HL×L: LQCD crucial to eliminate models. Verified that HL×L estimates not responsible for discrepancy



The current spin on a_e, a_μ

- experiment vs SM prediction

  $\Delta a_\mu \sim (271 - 306) \pm 73 \times 10^{-11}$

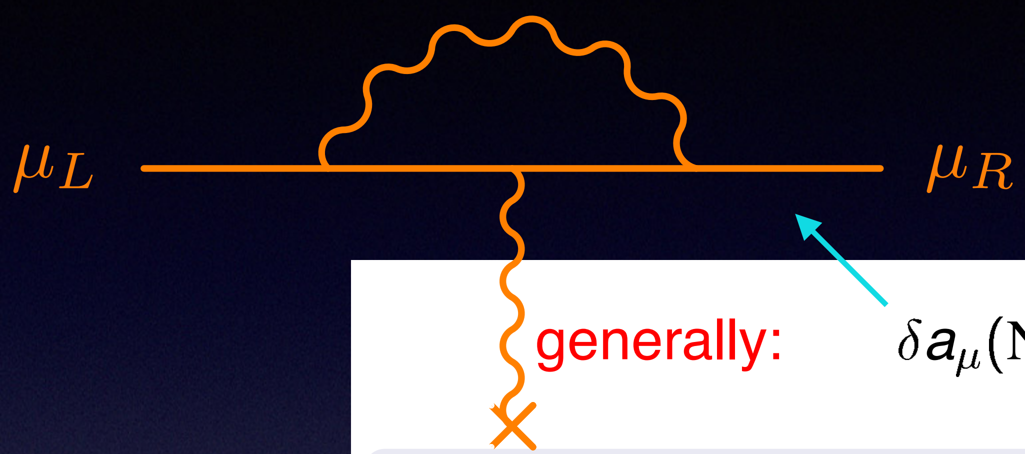
- **deviation > 3.7 σ!**

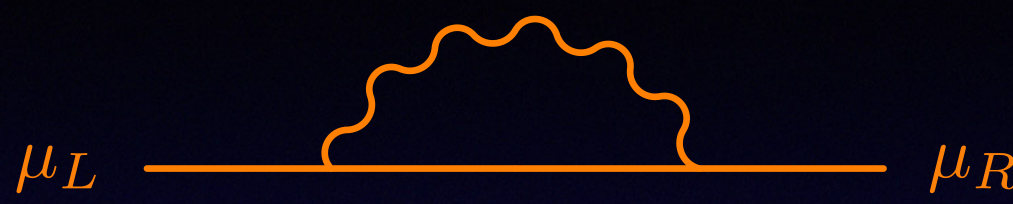
- $\Delta a_\mu > 2 \cdot a_\mu(\text{Weak})$!

Is it real? Remeasure!

- Fermilab - running: goal 540 ppb BNL precision → 140 ppb
- J-PARC (Japan) - proposing new technique: goal 460 ppb

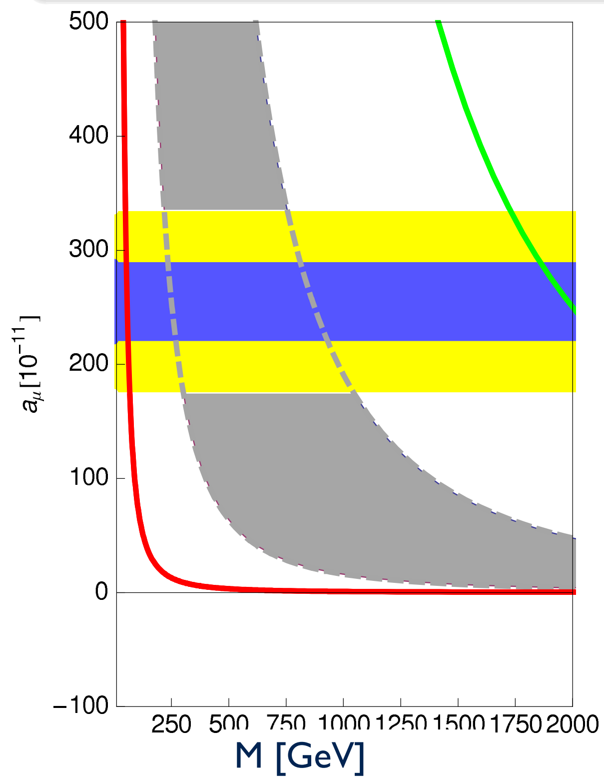
Beyond Standard Model





generally: $\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$

classify new physics: *C* **very** model-dependent



$\mathcal{O}(1)$	radiative muon mass generation ... [Czarnecki,Marciano '01]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)... [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

Stockinger

Measurement of a_μ

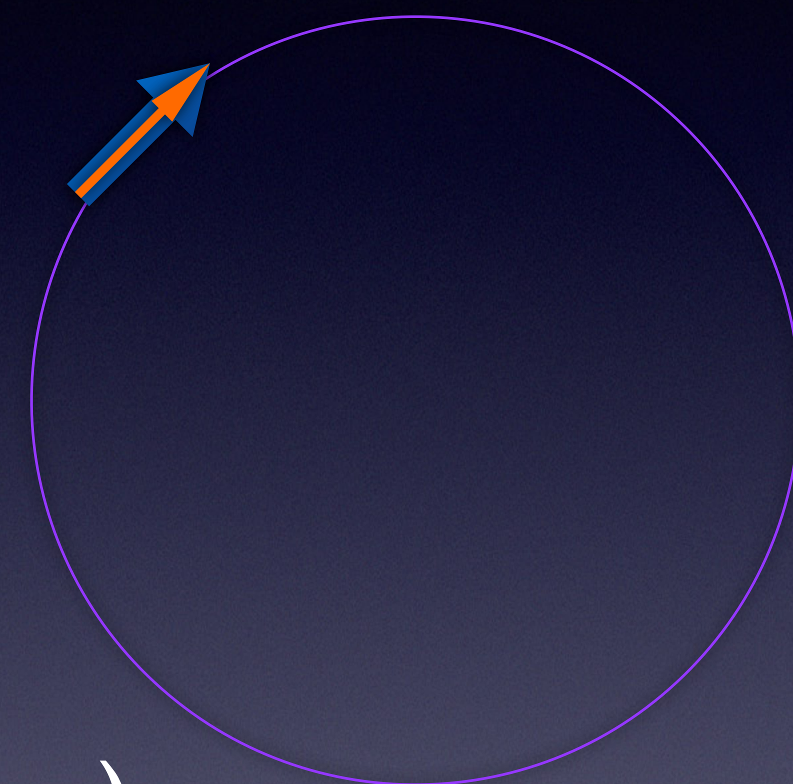
Theme and Variations

Fermilab Muon g-2

J-PARC Muon g-2

Measurement of a_μ

Theme



Motion in a B field

$(\vec{\beta} \perp \vec{B}, \vec{E} = 0)$ (Jackson Ch. 11.11)

- cyclotron frequency (→)

$$\omega_C = B \frac{e}{m_\mu c} \frac{1}{\gamma}$$

- spin precession frequency (→)

$$\omega_s = B \frac{g_\mu}{2} \frac{e}{m_\mu c} + B \frac{e}{m_\mu c} \left(\frac{1}{\gamma} - 1 \right)$$

Larmor Thomas

Measurement of a_μ

Theme

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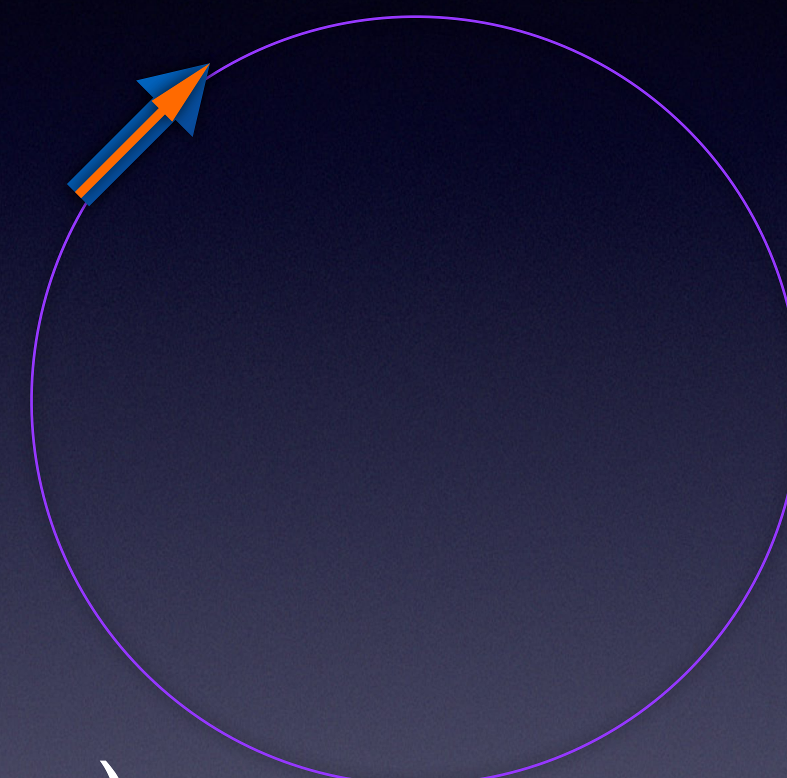

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$$\omega_C = B\frac{e}{m_\mu c}\frac{1}{\gamma}$$

- spin precession frequency ( )

$$\omega_s = B\frac{g_\mu}{2}\frac{e}{m_\mu c} + B\frac{e}{m_\mu c}\left(\frac{1}{\gamma} - 1\right)$$

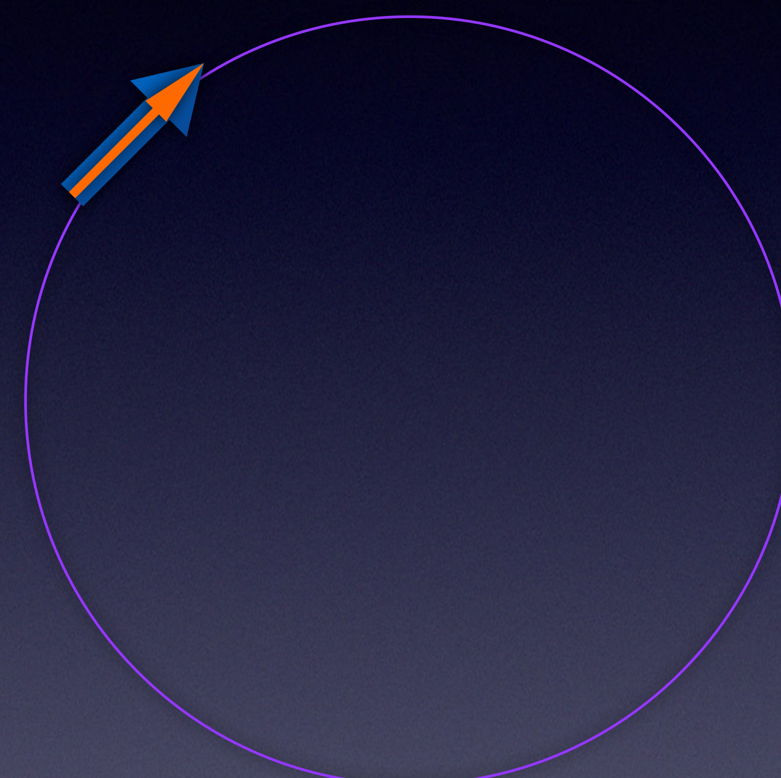
g = 2: $\omega_s = \omega_C$

Measurement of a_μ

Theme

Motion in a B field

$(\vec{\beta} \perp \vec{B}, \vec{E} = 0)$ (Jackson Ch. 11.11)



- cyclotron frequency

$$\omega_C = B\frac{e}{m_\mu c}\frac{1}{\gamma}$$

- spin precession frequency

$$\omega_s = B\frac{g_\mu}{2}\frac{e}{m_\mu c} + B\frac{e}{m_\mu c}\left(\frac{1}{\gamma} - 1\right)$$

g ≠ 2: relative precession $\omega_s - \omega_C = B\frac{e}{m_\mu c}\left(\frac{g_\mu}{2} - 1\right)$

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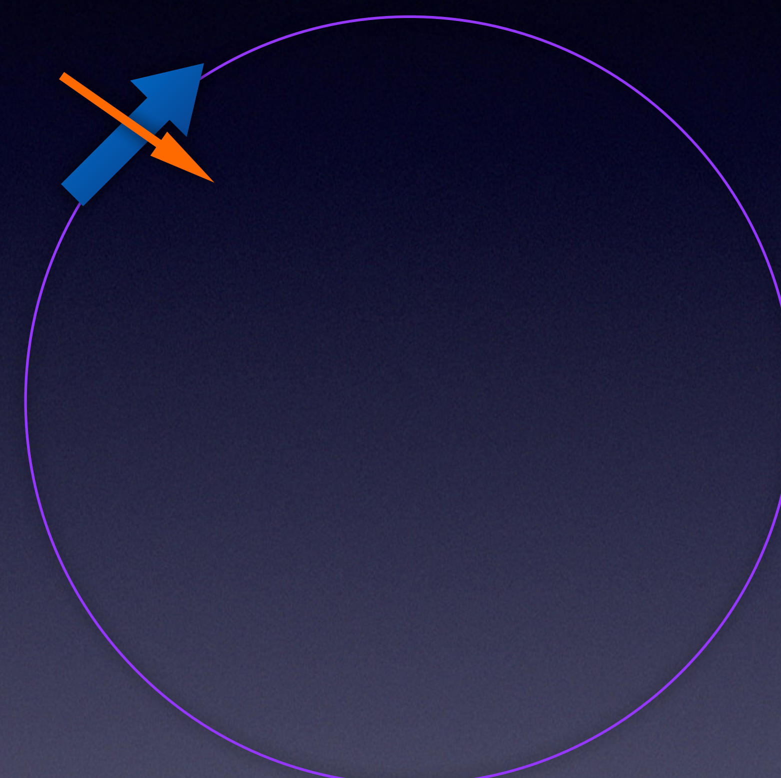

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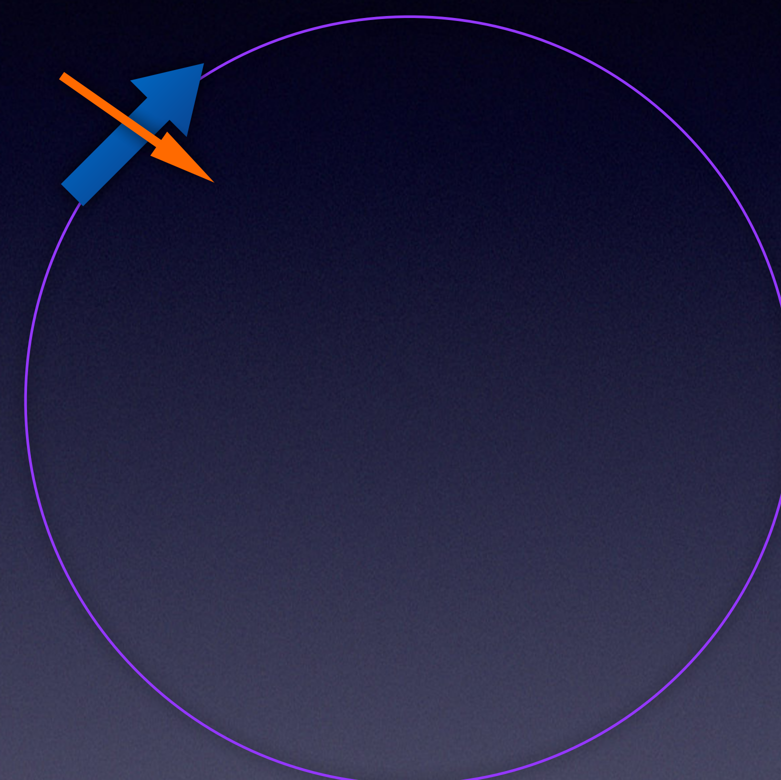

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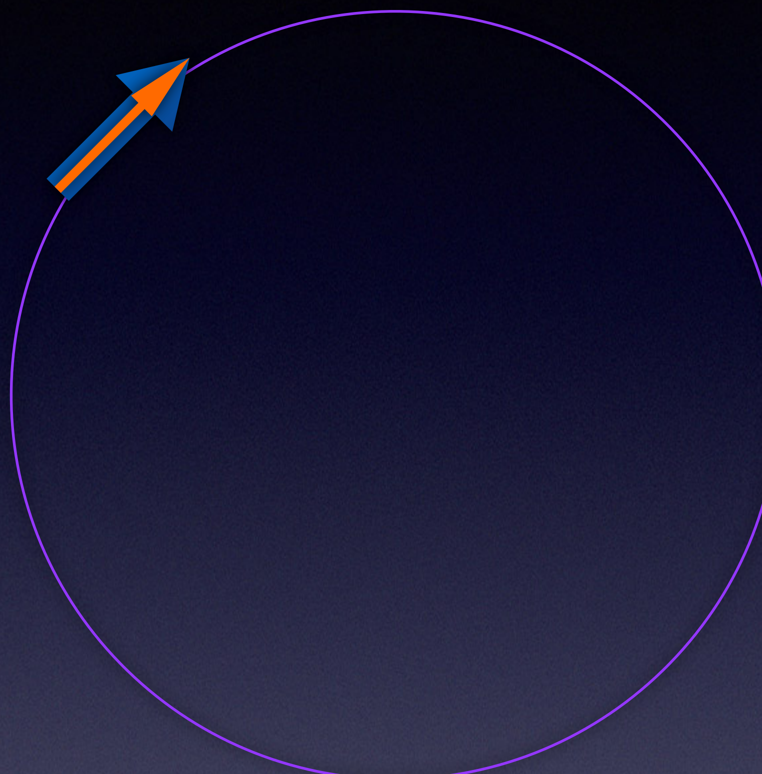
ω_a

a_μ!

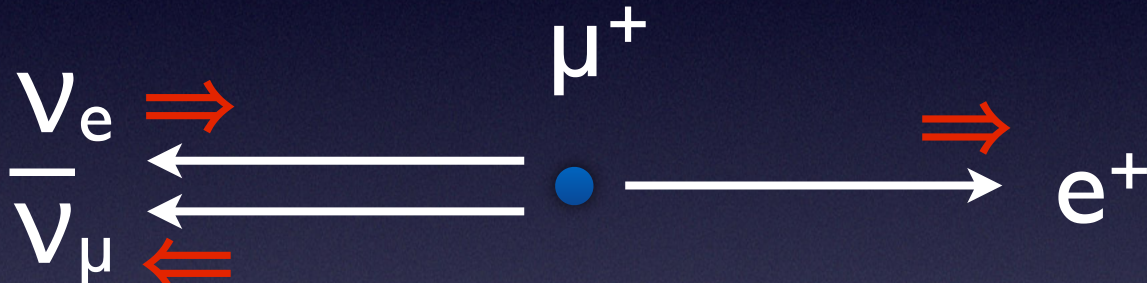
g ≠ 2: relative precession $\omega_s - \omega_C = B \frac{e}{m_\mu c} \left(\frac{g_\mu}{2} - 1 \right)$

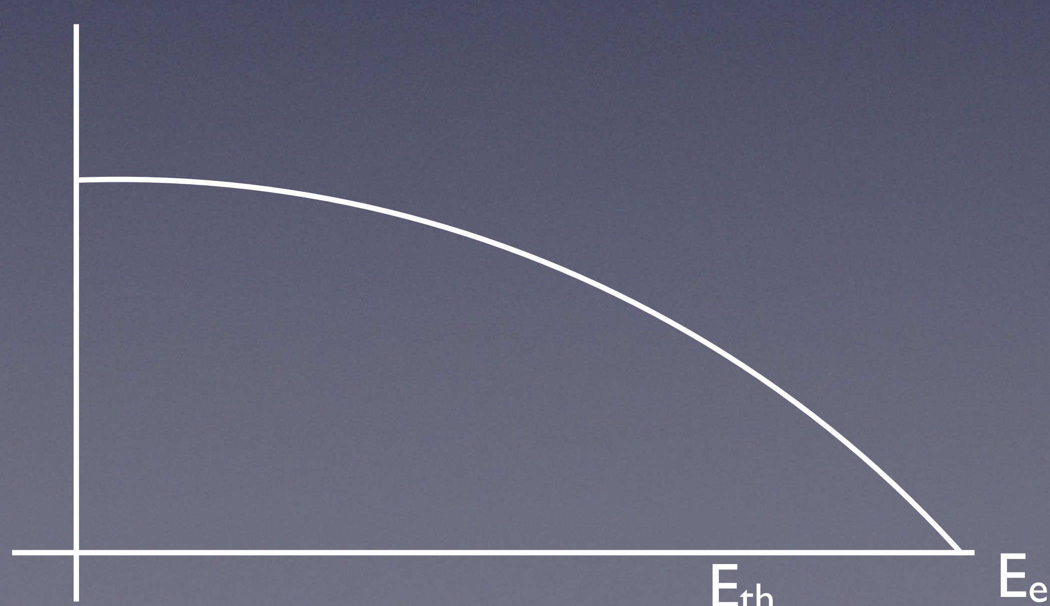
Measurement of a_μ

Theme



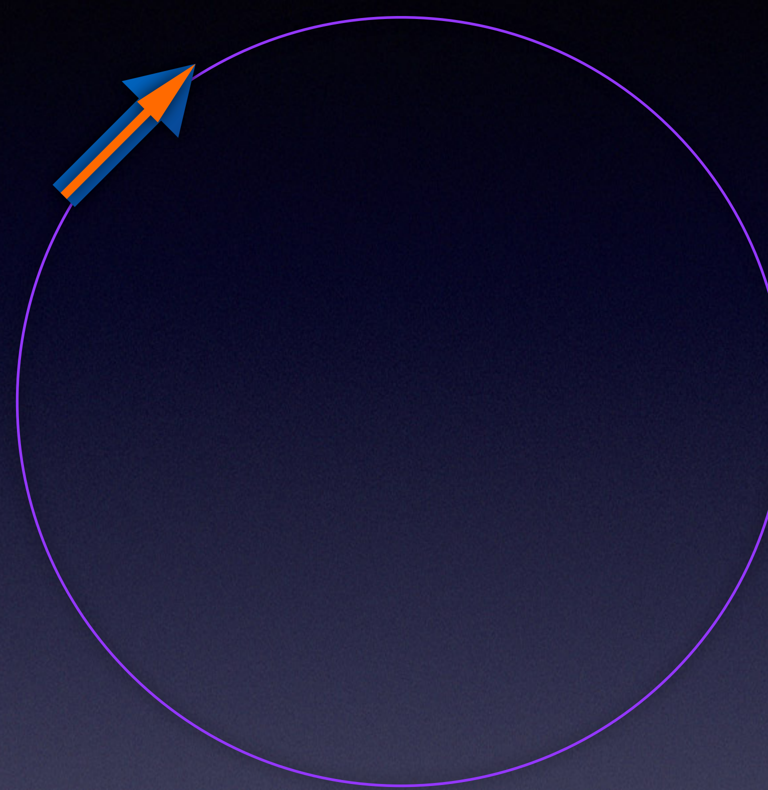
Most energetic e^+ from μ^+ decay





Measurement of a_μ

Theme



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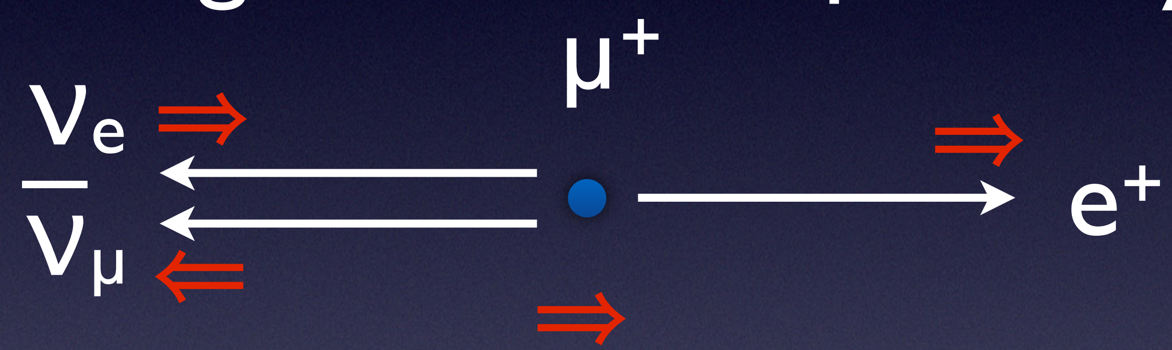
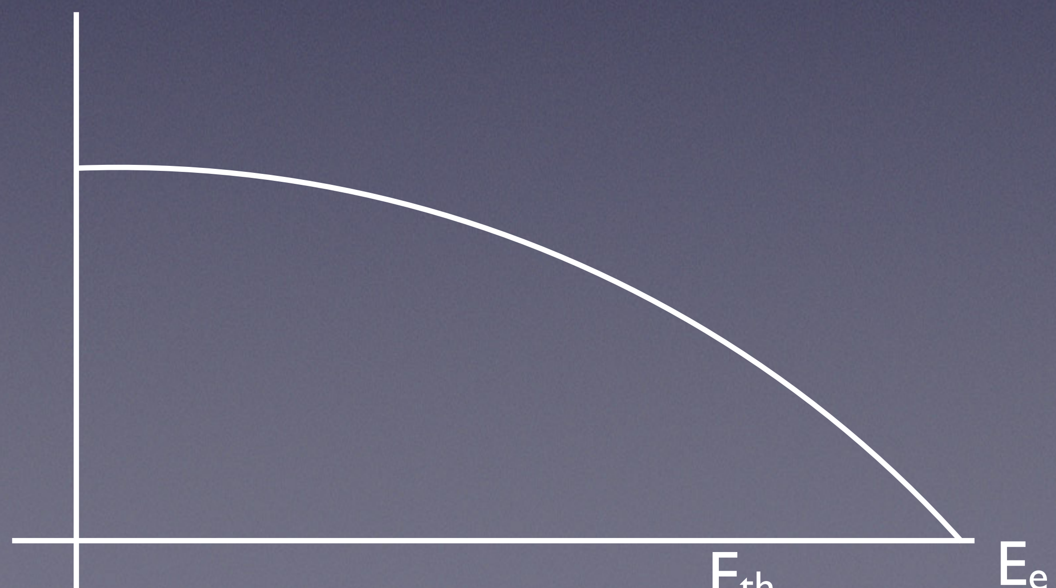
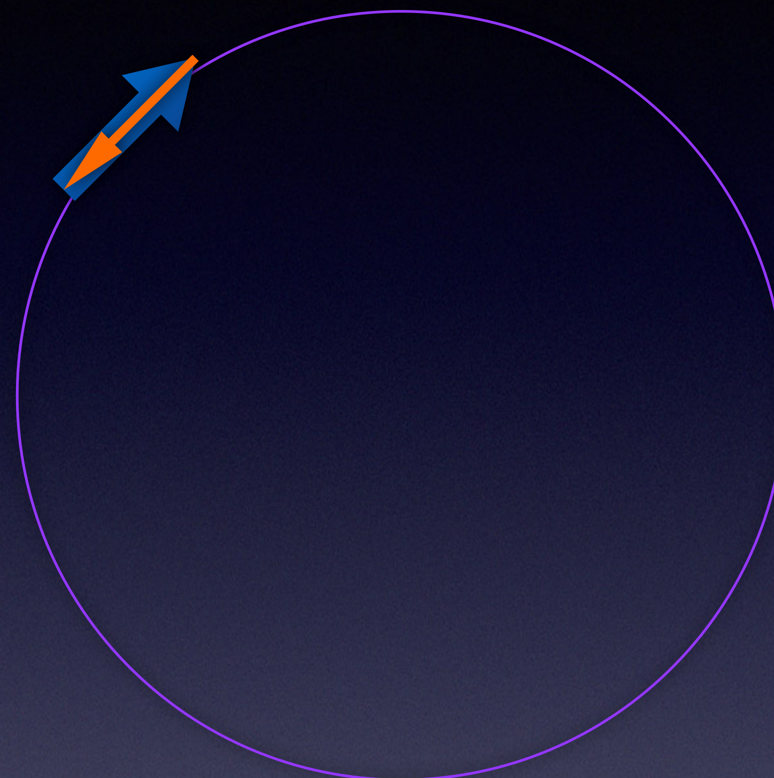


aligned with μ+ spin direction!



Measurement of a_μ

Theme



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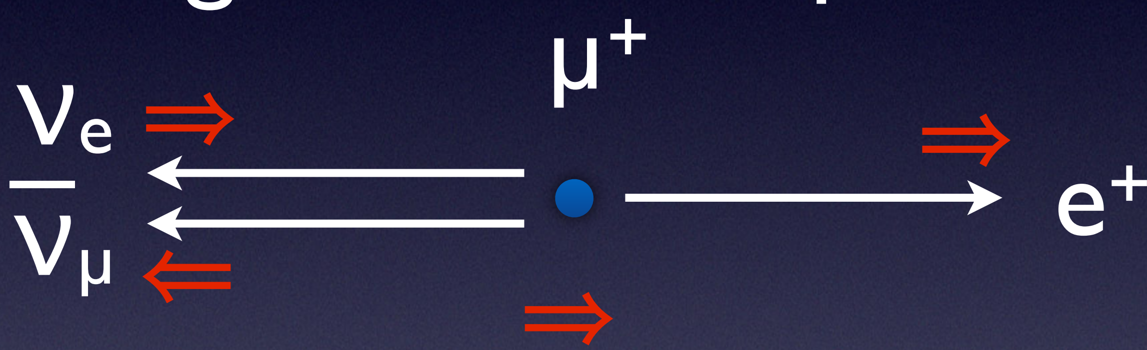

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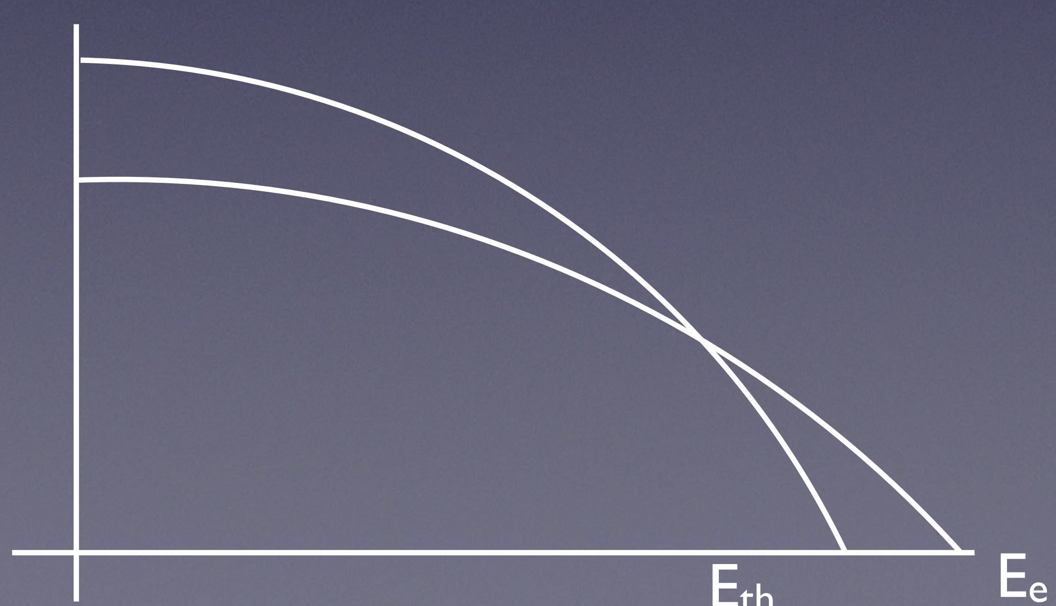
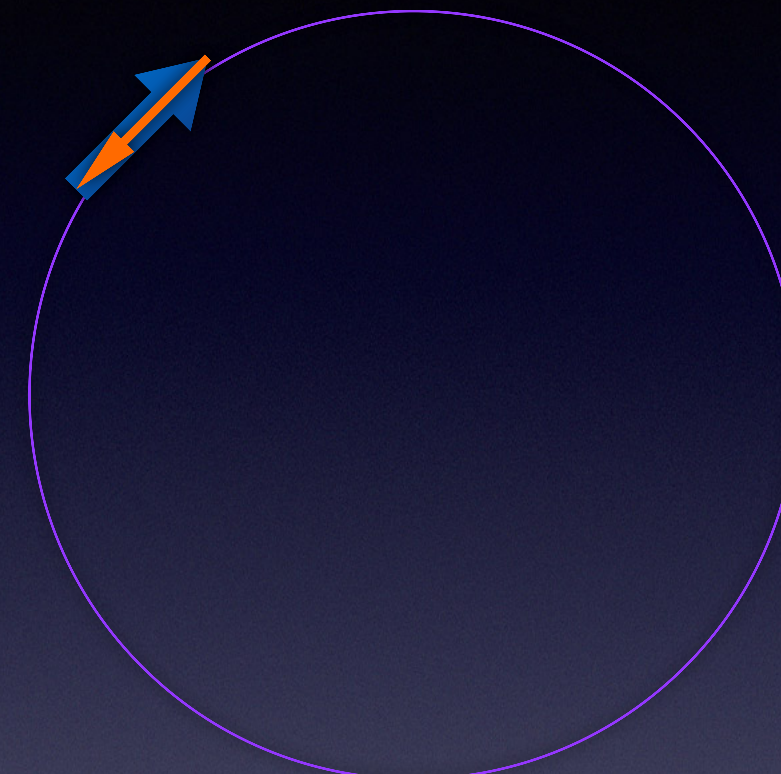


Measurement of a_μ

Theme



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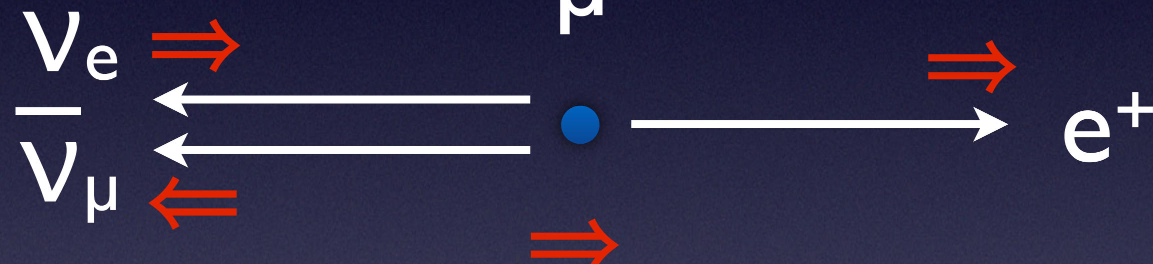
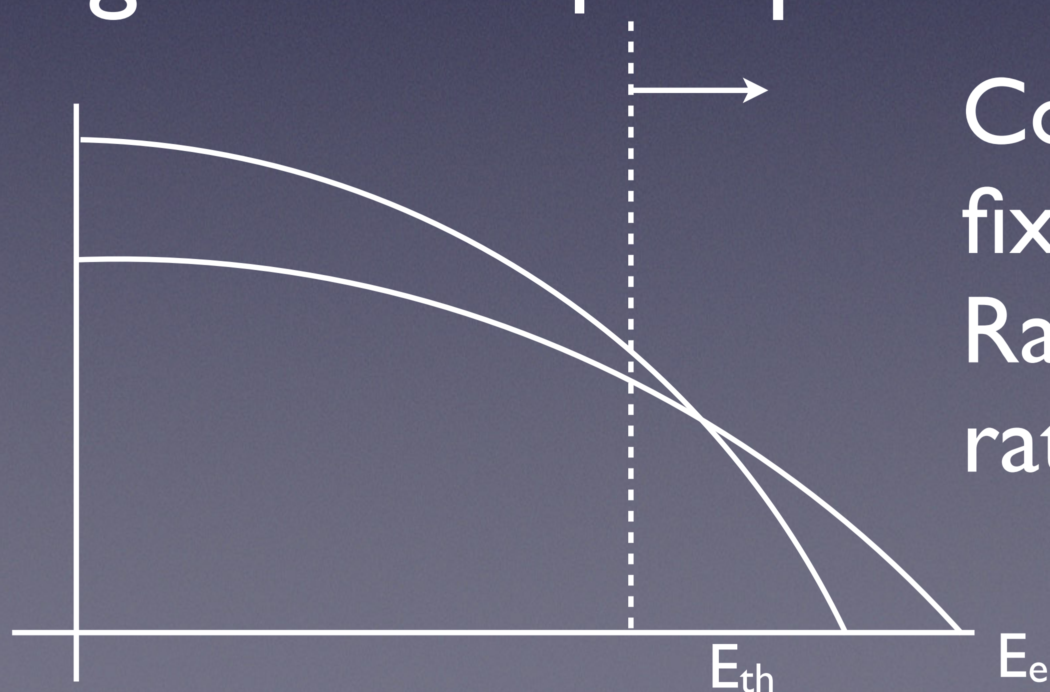
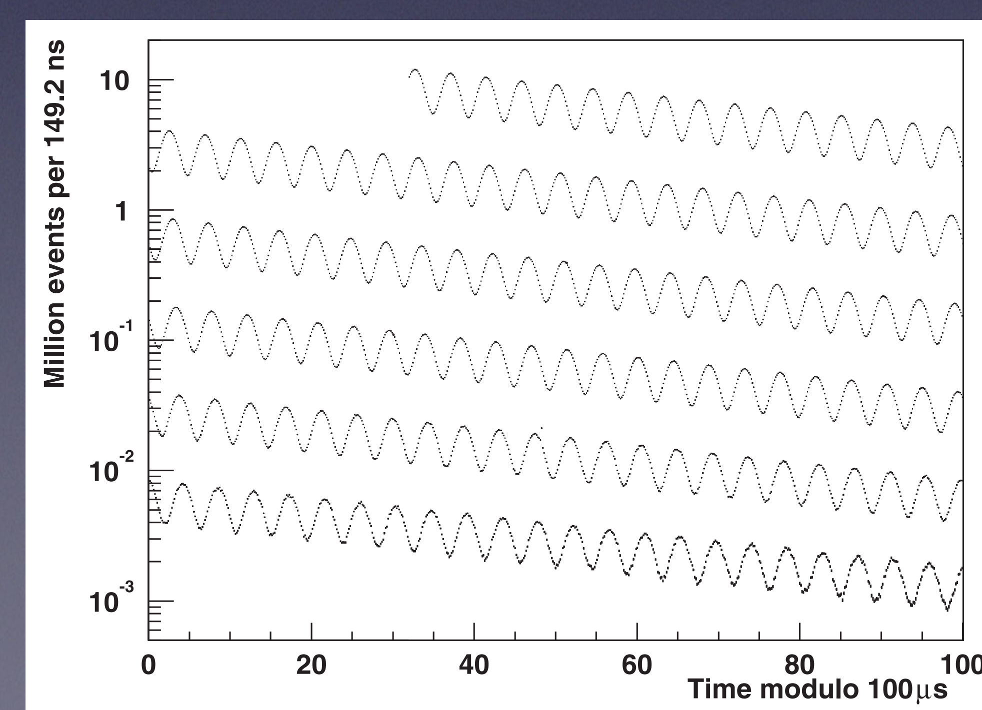
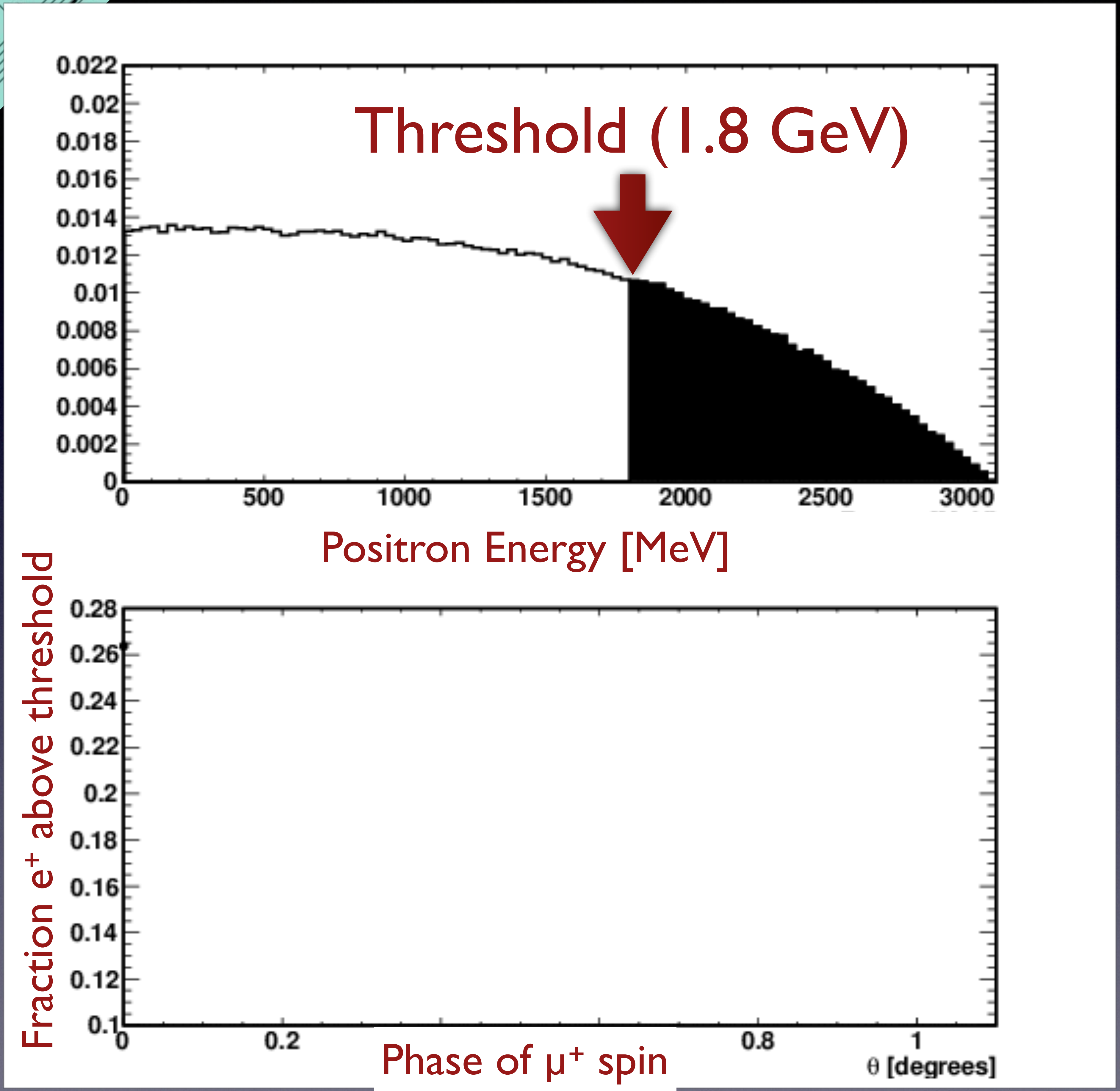


aligned with μ+ spin direction!

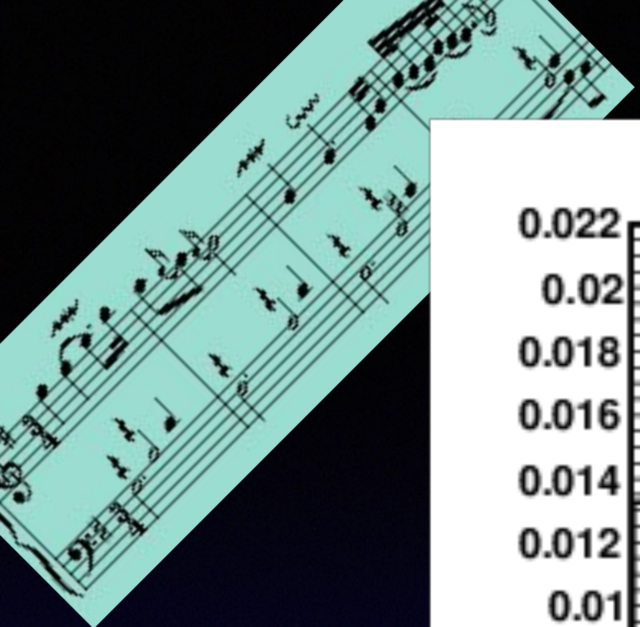


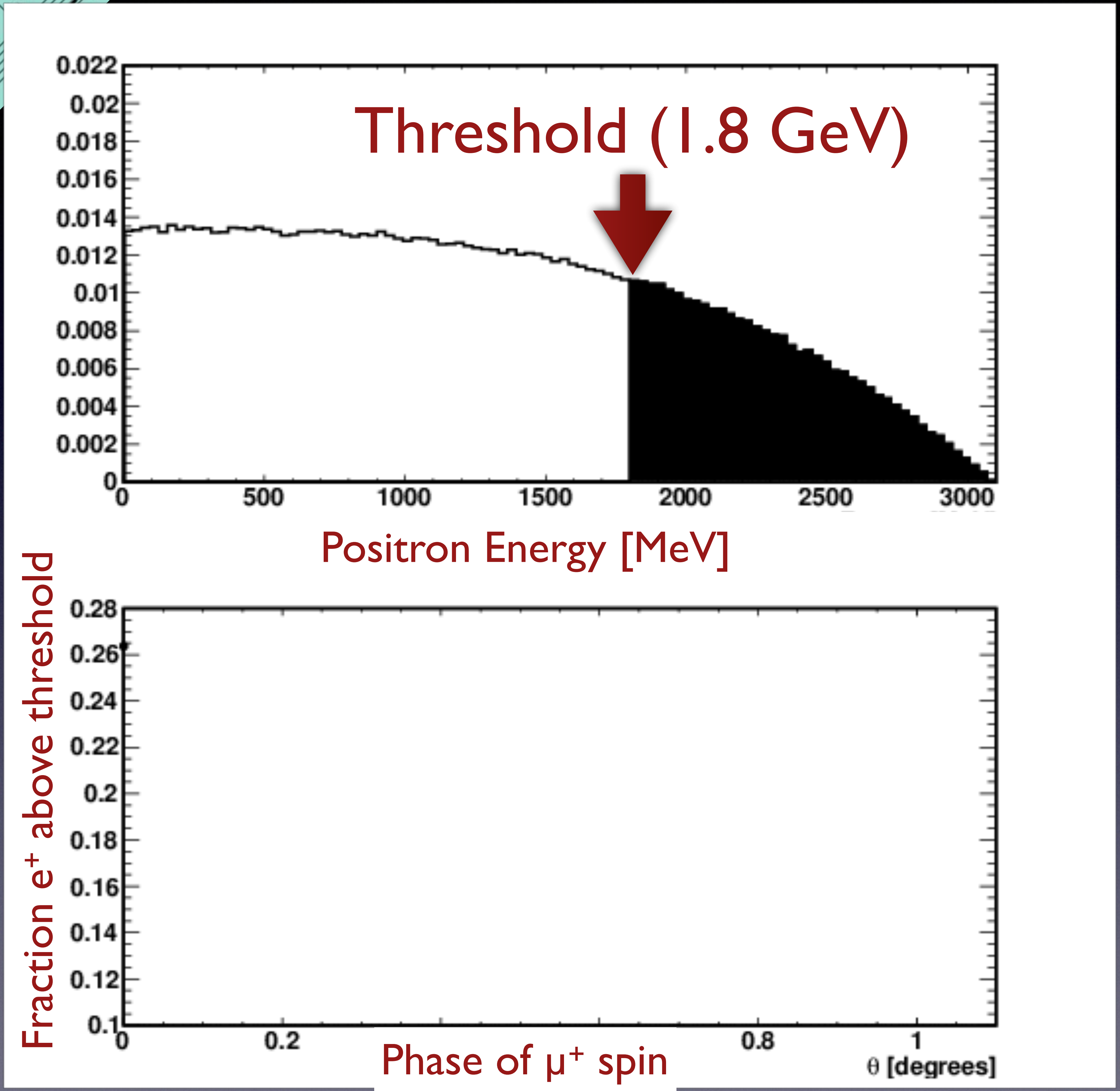
Count above fixed threshold. Rate oscillation rate $\propto g_\mu$-2





Threshold (1.8 GeV)
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
500
1000
1500
2000
2500
3000
Positron Energy [MeV]
Fraction e⁺ above threshold
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0
0.2
0.8
1
θ [degrees]
Phase of μ⁺ spin

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0
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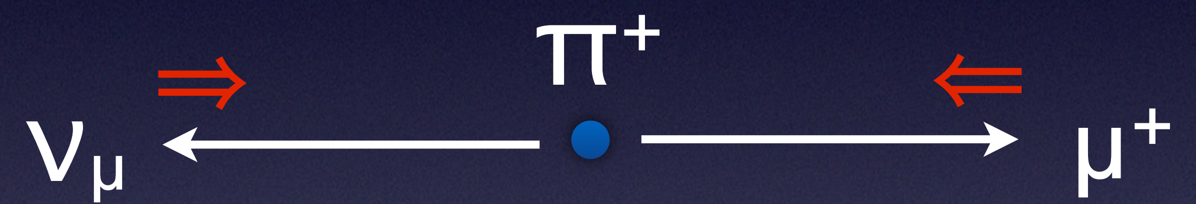
0.8
1
θ [degrees]
Phase of μ+ spin

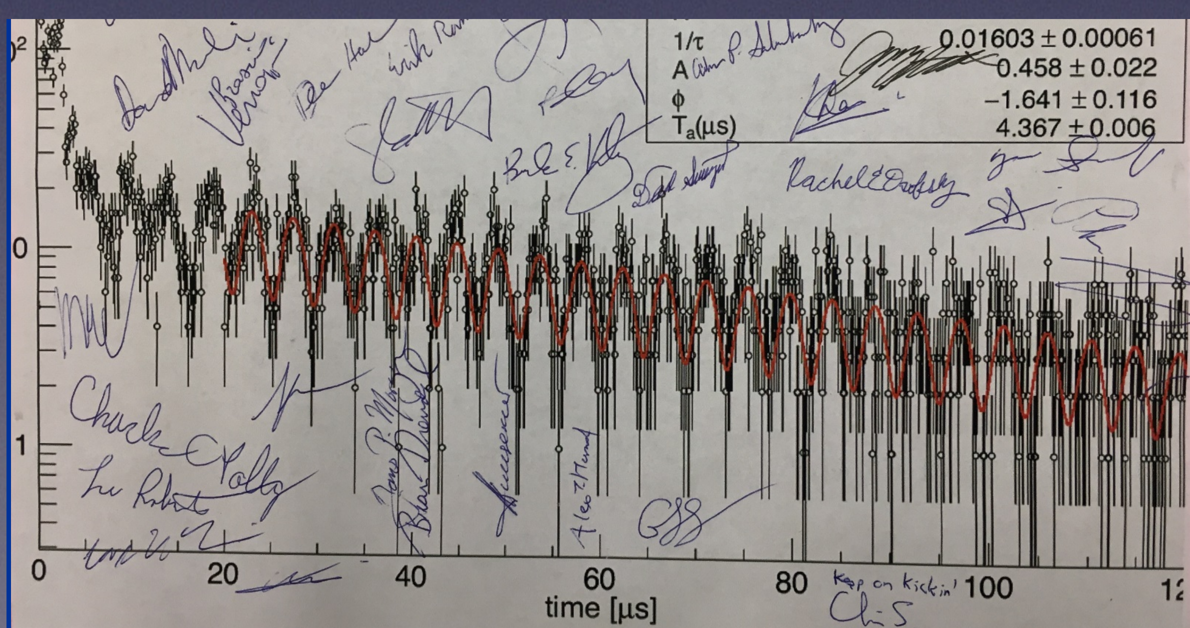
Measurement of a_μ

Theme

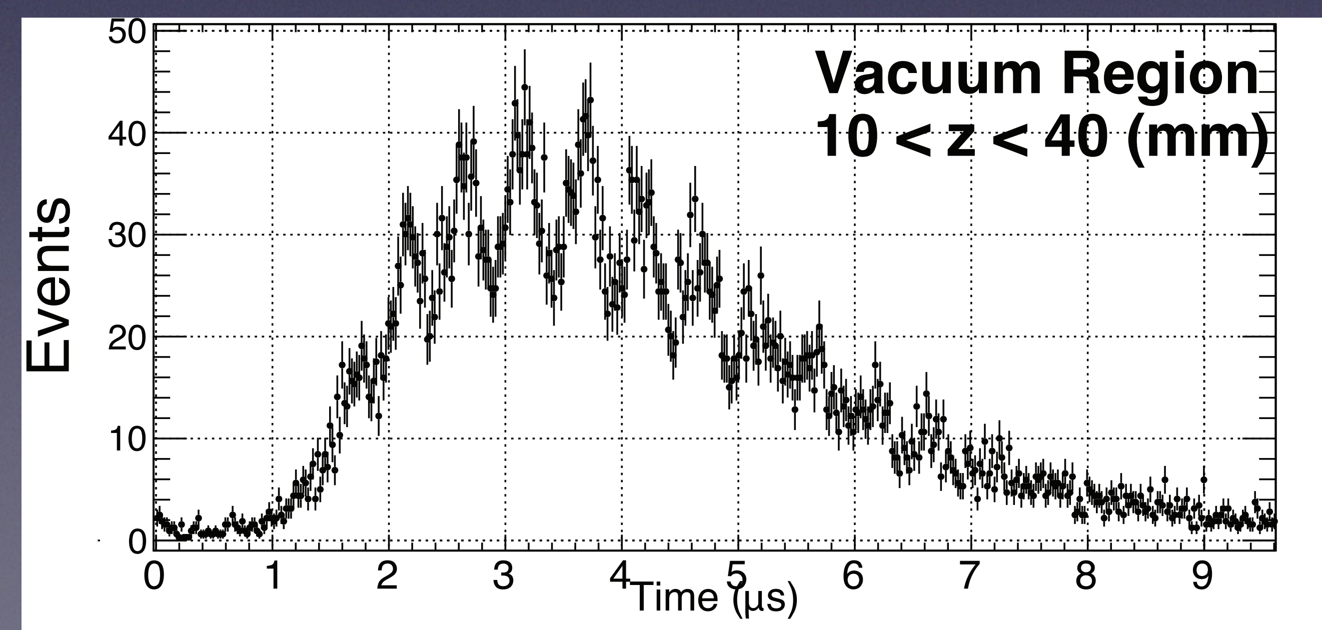
Polarized μ^+ production: Parity Violation!!

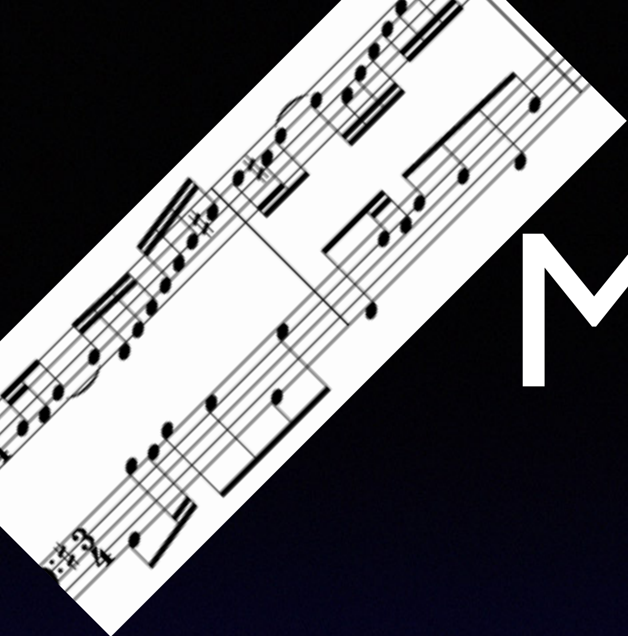


Fermilab: first hour of (low rate) data

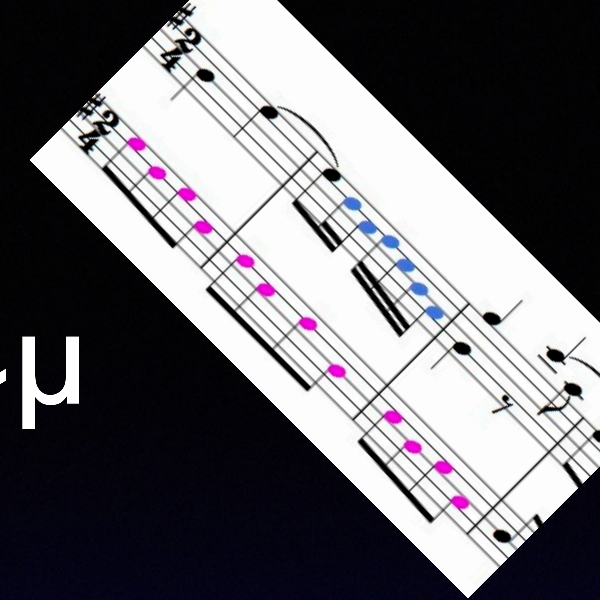


J-PARC: TRIUMF muonium test beam data





Measurement of a_μ

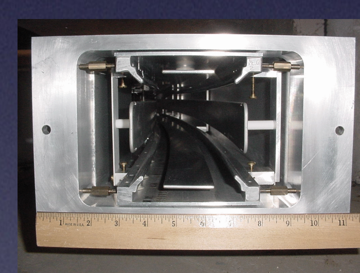


and Variations

Measure

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$(\vec{\beta} \perp \vec{B})$



Relativistic μ beam

- high rate, polarization
- vertical focusing ($\vec{E} \neq 0$) required
- choose $\gamma_\mu^2 = 1 + 1/a_\mu$
- O(ppm) correction for p_μ spread
- CERN, BNL, now FNAL approach
- Goal: 140 ppb (21×BNL statistics)

Ultracold μ beam

- no transverse momentum ↔ no strong focusing ($\vec{E} = 0$)
- challenging production
- lower polarization
- new J-PARC approach
- Goal (Phase 1): 460 ppb

Measurement of a_μ

Variation 1: relativistic μ

Booster:
4x10^{12} protons per batch

Main Injector rebunch to 4 batches of 10^{12} → 12 Hz rep. rate

μ^+ / proton
11.5 × BNL

Measurement of a_μ

Variation 1: relativistic μ

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Measurement of a_μ

Variation 1: relativistic μ

Measurement of a_μ

Variation 1: relativistic μ

Measurement of a_μ

Variation 1:
relativistic μ

Measurement of a_μ

Variation 1:

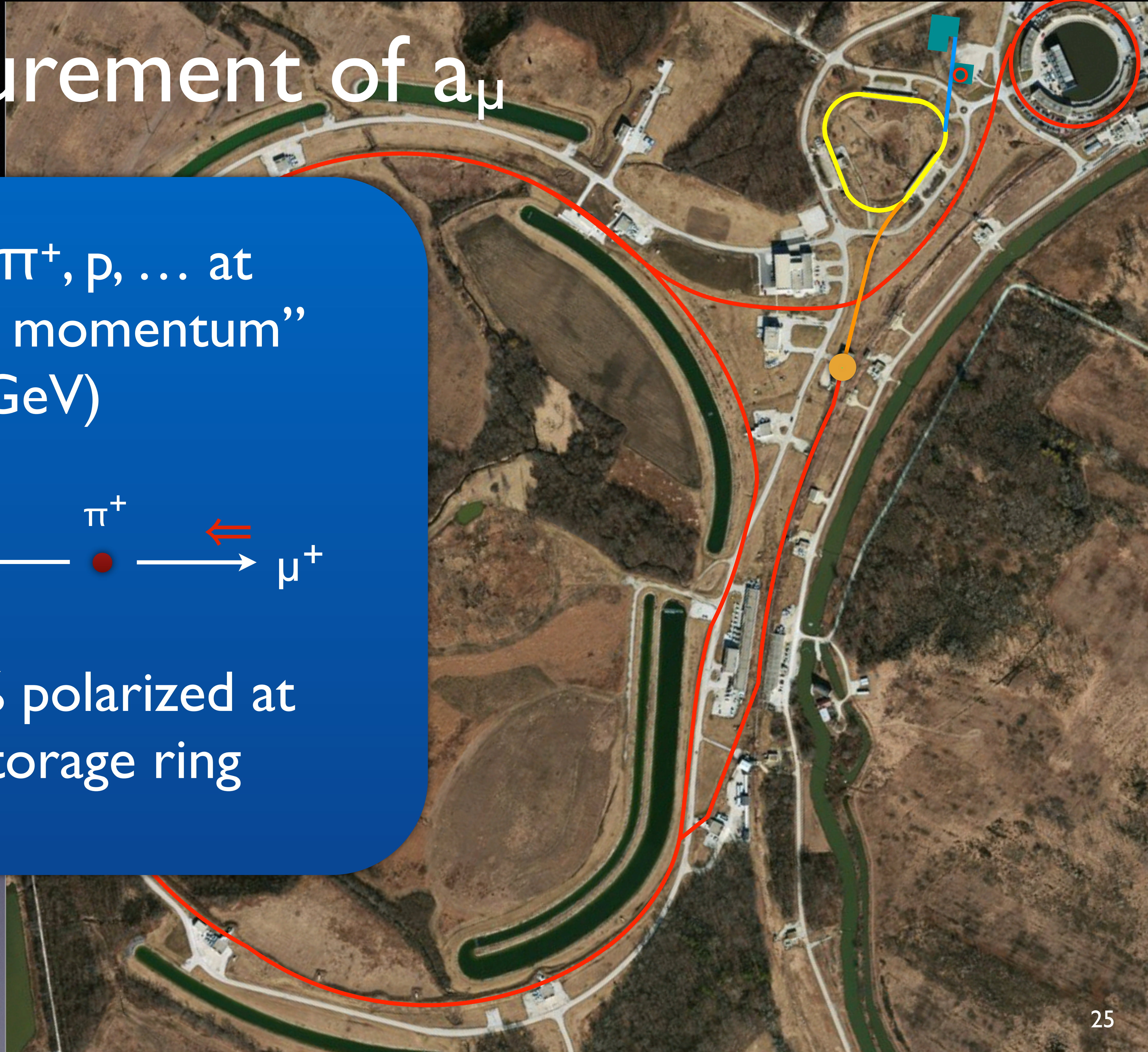
re

Select π^+, p, … at “magic momentum” (~3.1 GeV)

π^+

ν_μ ⟵ • ⟶ μ^+

$\gtrsim$ 95% polarized at storage ring



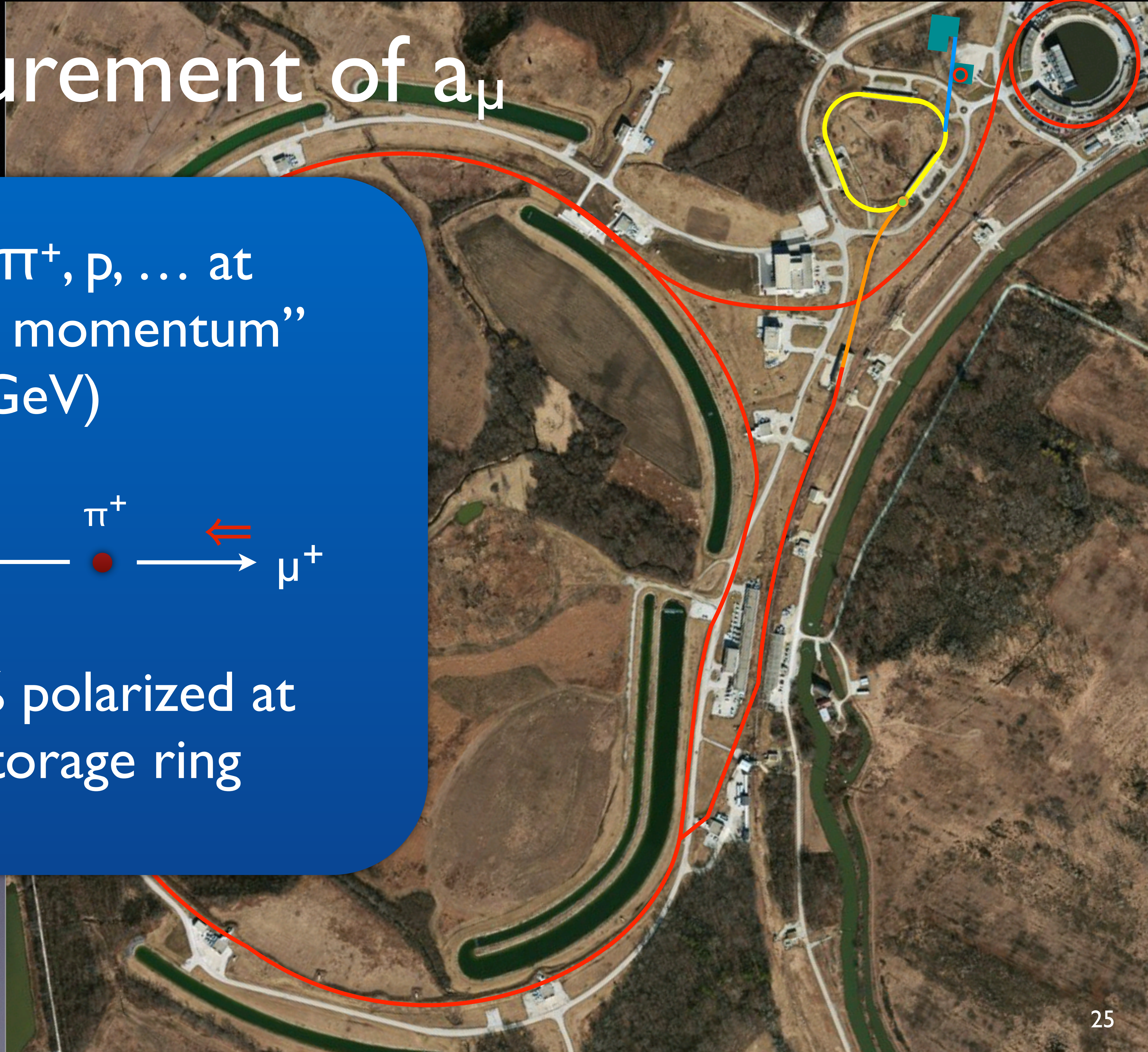
Measurement of a_μ

Variation 1:
re

Select π^+, p, … at "magic momentum" (~3.1 GeV)

ν_μ ⇒ ← ● π^+ → ⇐ μ^+

≳ 95% polarized at storage ring



Measurement of a_μ

Variation 1: relativistic μ

Measurement of a_μ

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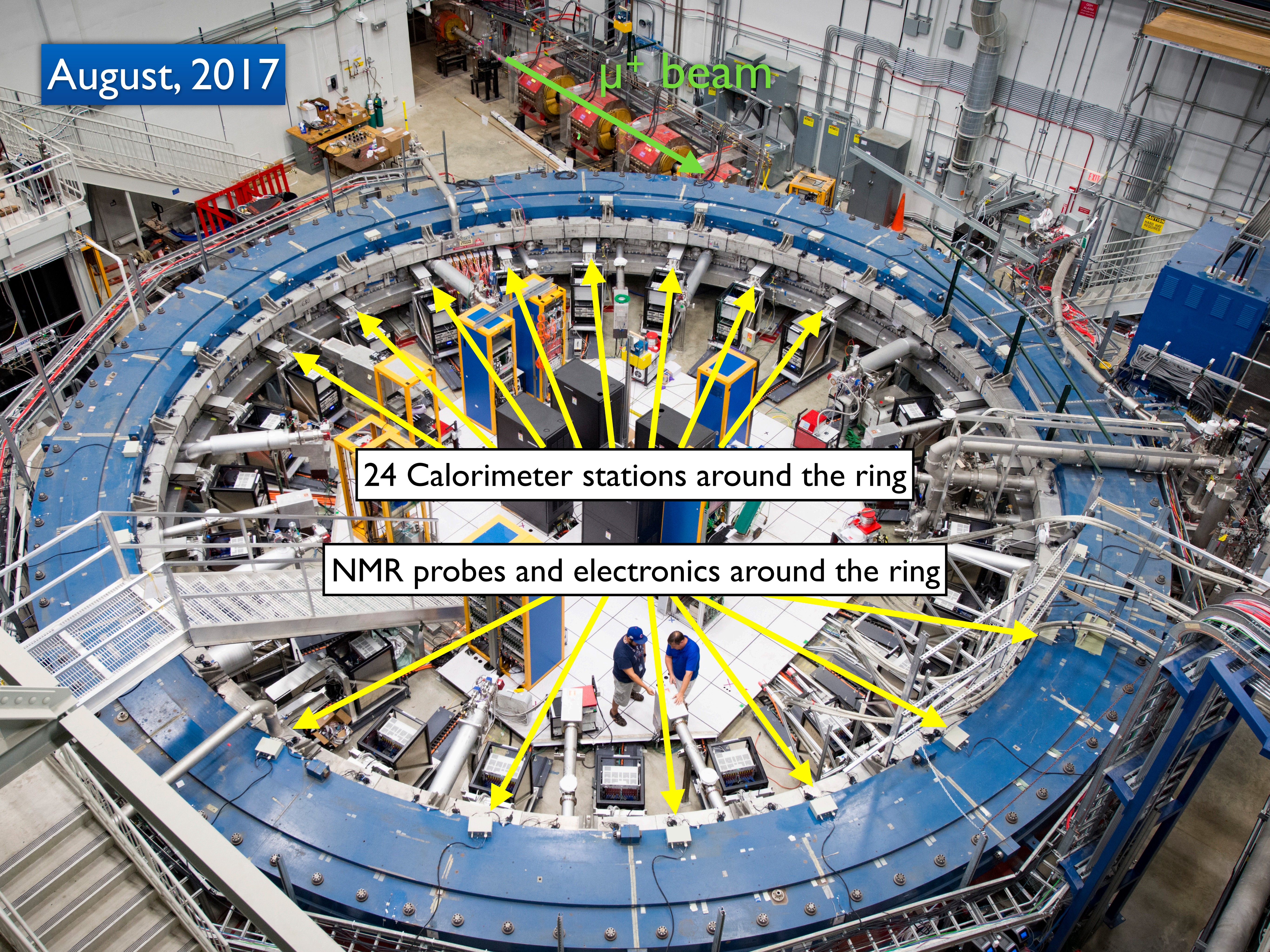
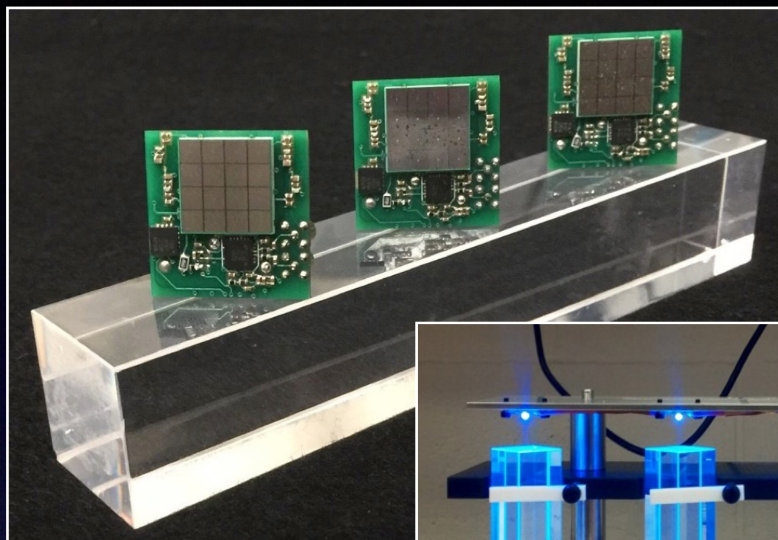
Measurement of a_μ

Variation 1:
relativistic μ


August, 2017
μ+ beam
24 Calorimeter stations around the ring
NMR probes and electronics around the ring

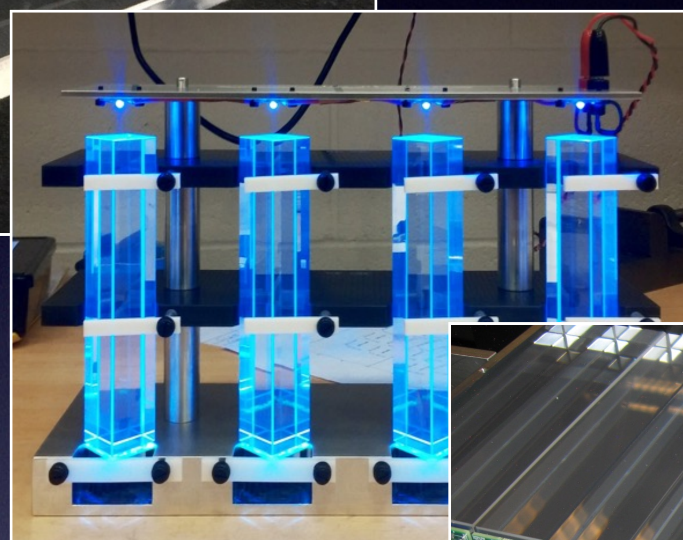
Watching the spin spin (at ω_a)

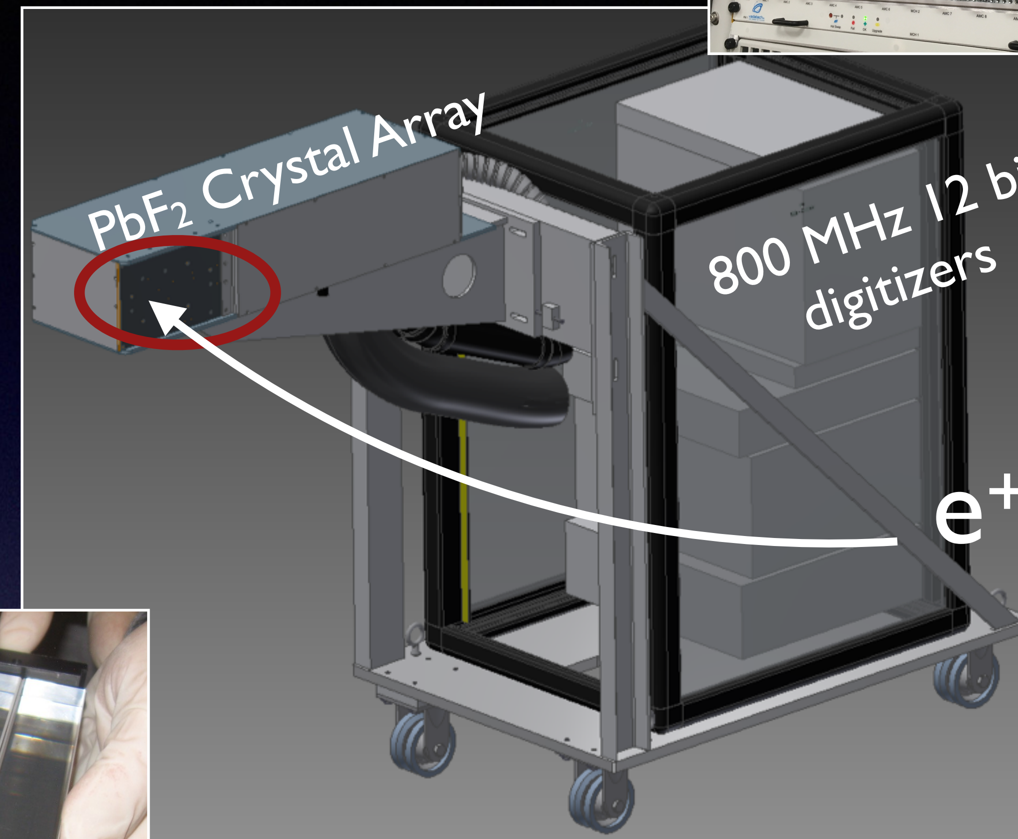


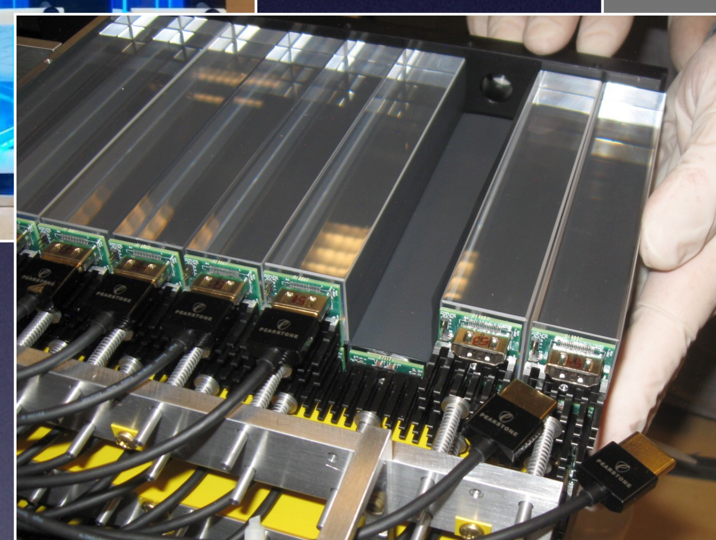
9x6 array PbF_2 crystals

(2.5x2.5) cm

(Čerenkov radiation)

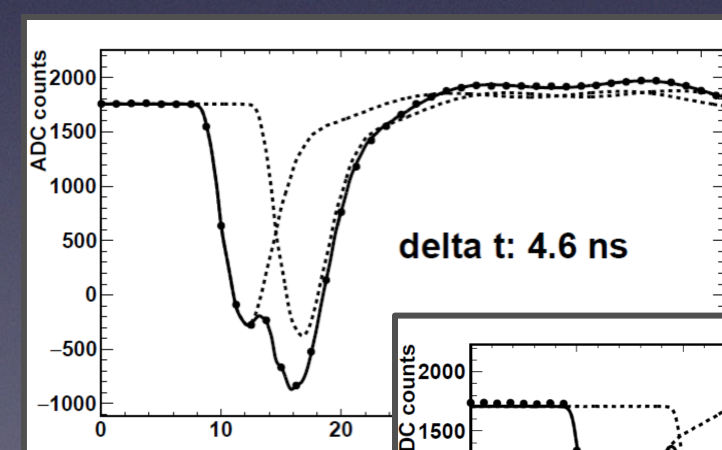


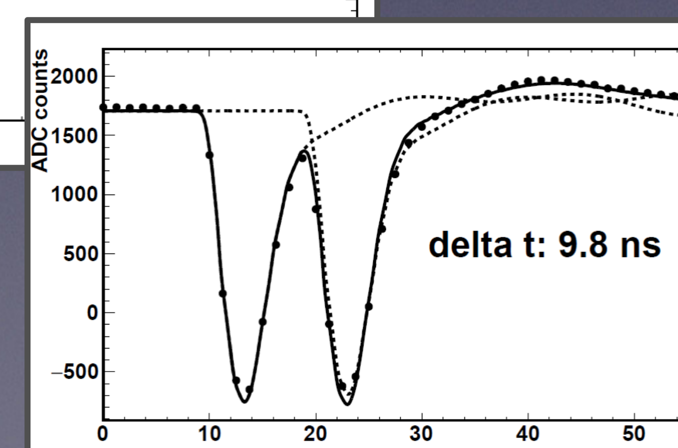




Fast SiPM

photodetectors





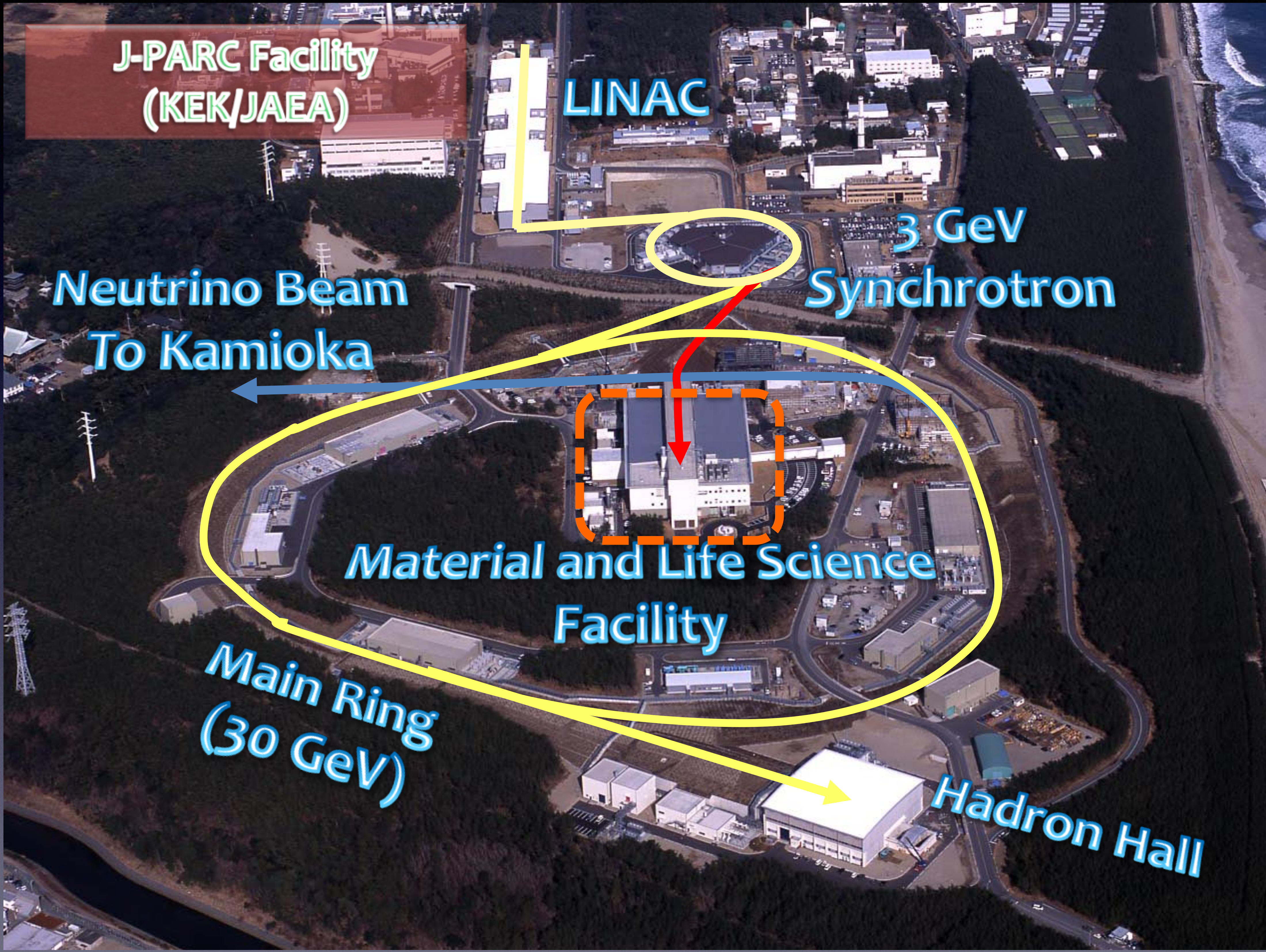
Pileup:

- distorts precession phase
- $\varphi(t) \sim \varphi_0 + \alpha t + \ldots$

Fast SiPM + fast digitizers = pileup id (much) better than 5 ns

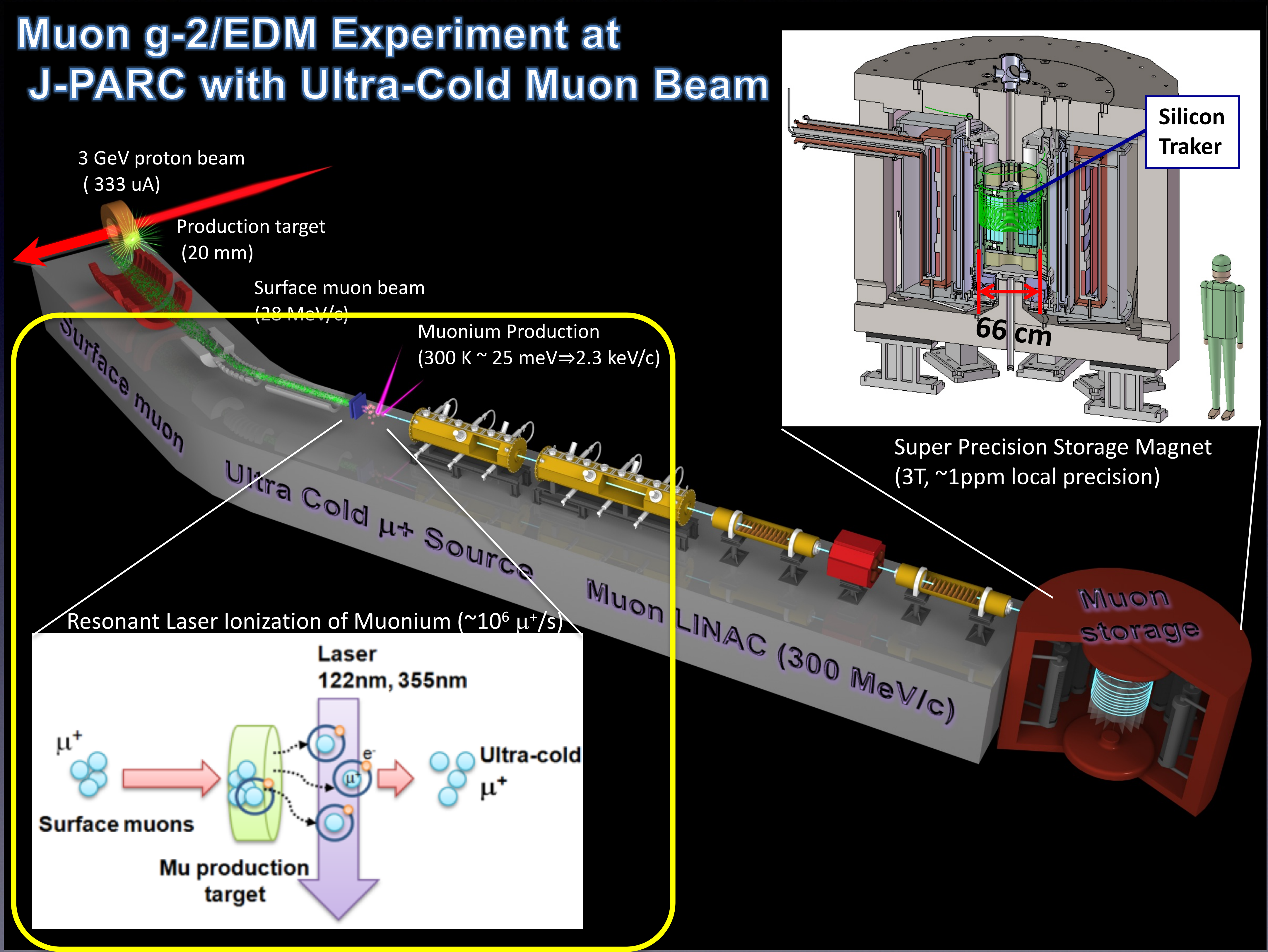
Measurement of a_μ

Variation 2: ultracold μ



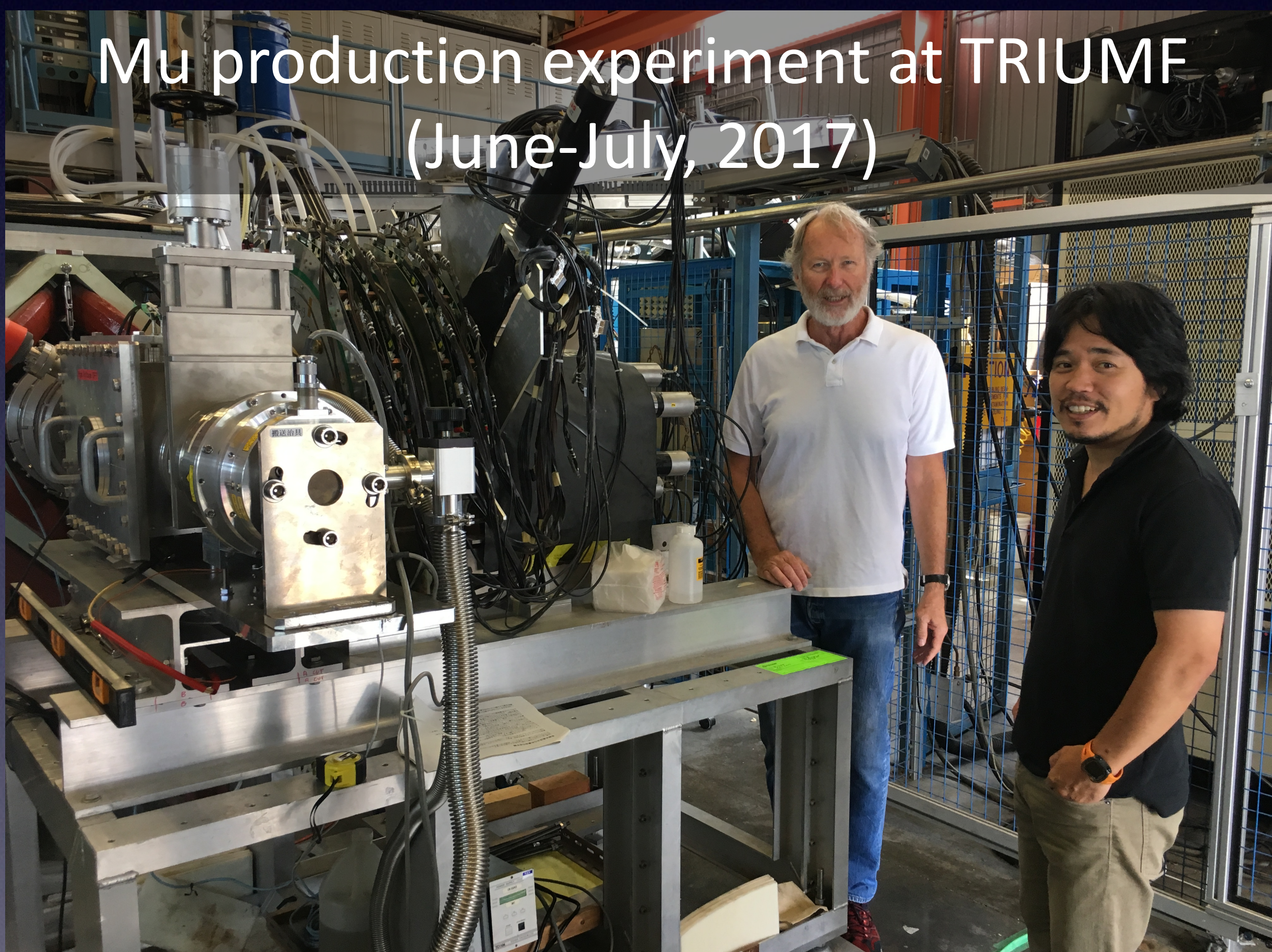
Measurement of a_μ

Variation 2: ultracold μ

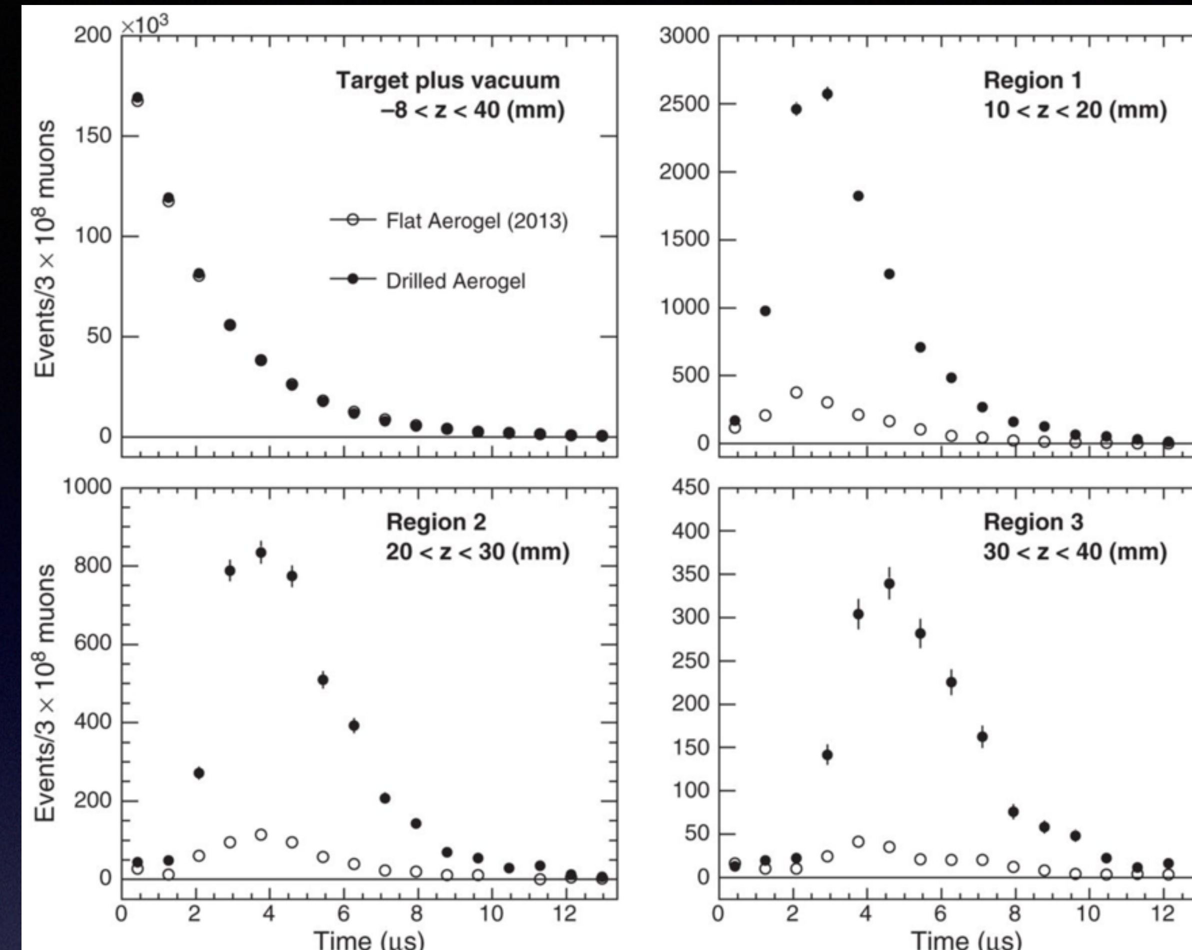


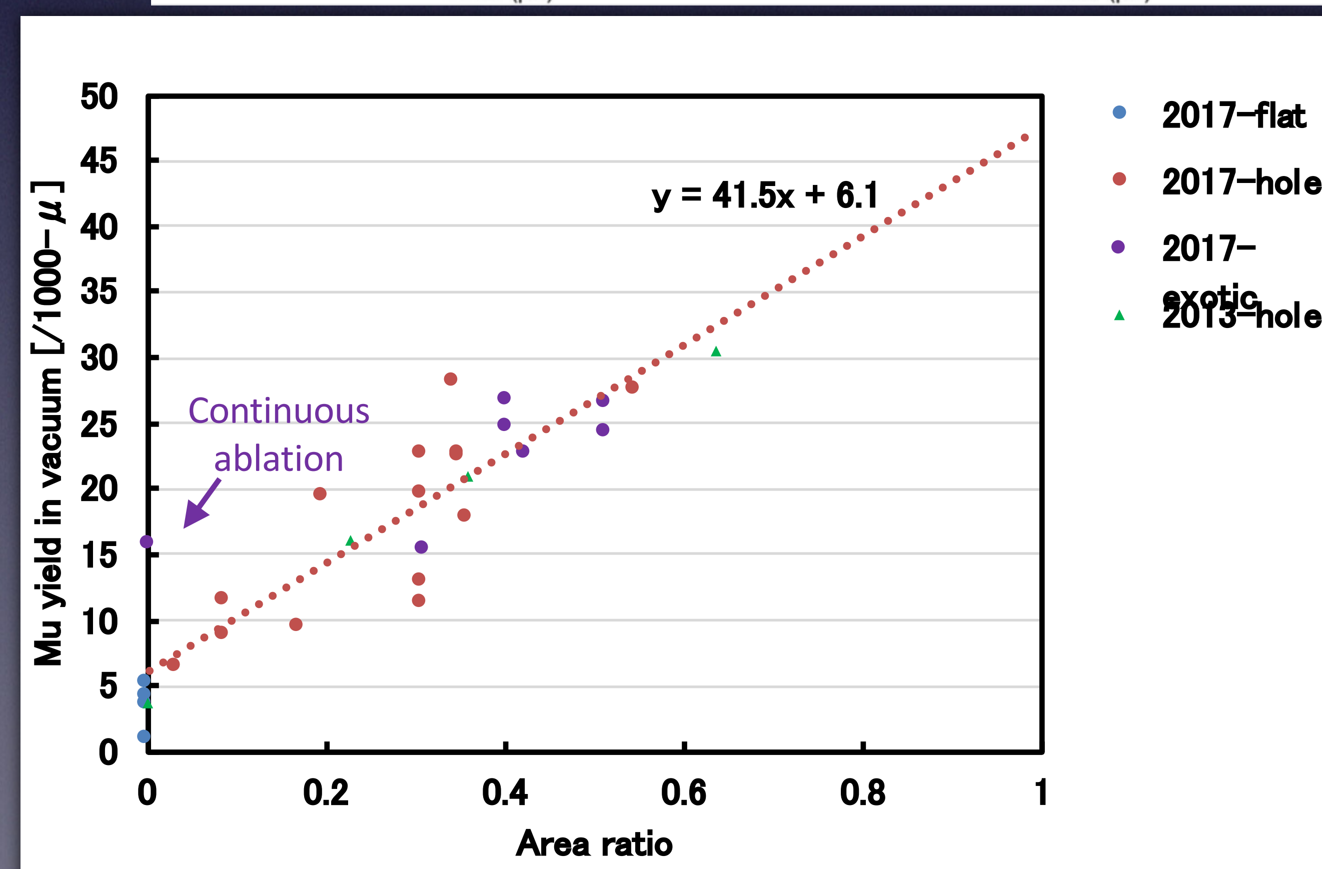
Measurement of a_μ

Variation 2: ultracold μ



Muon Yield





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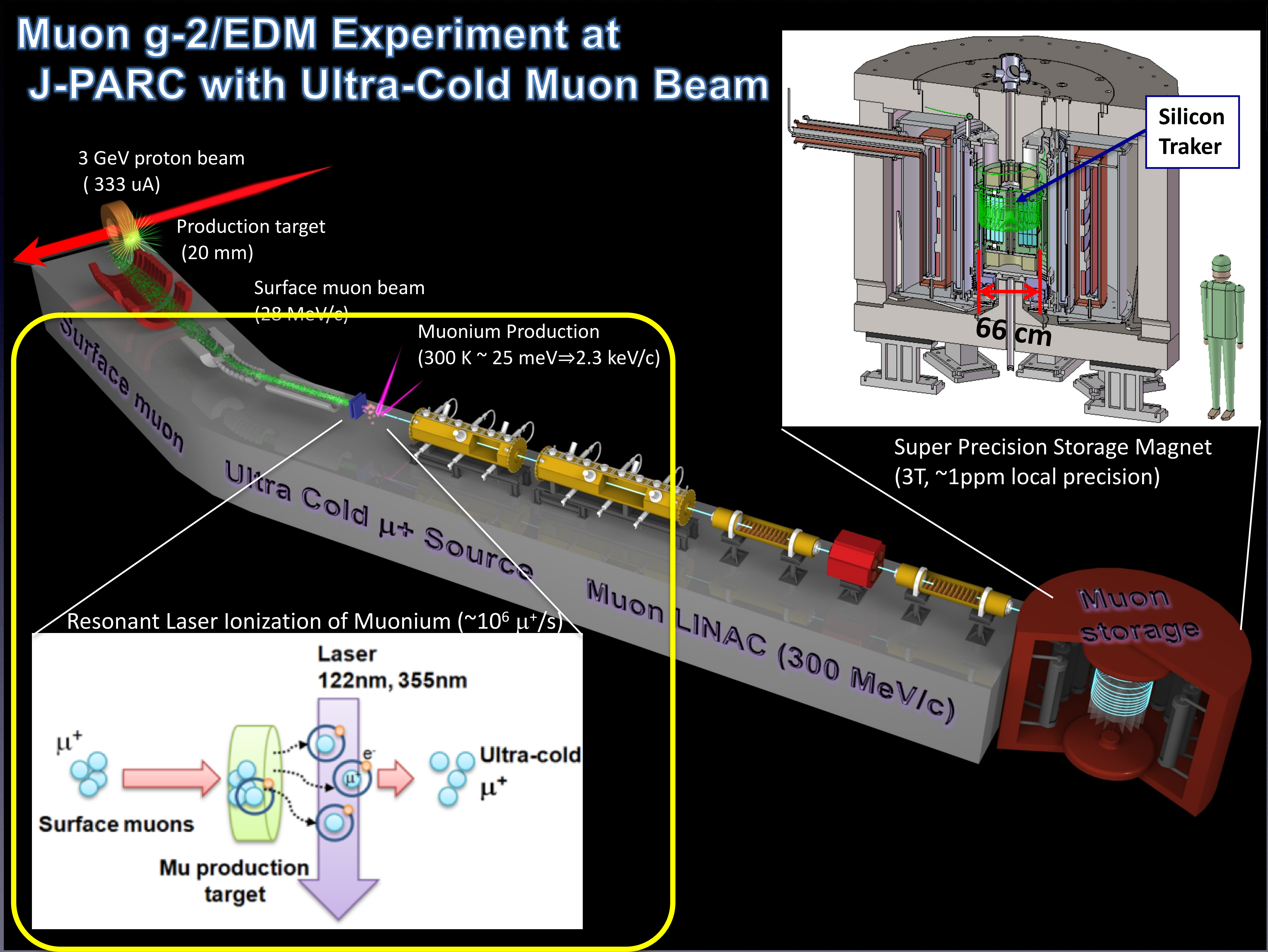

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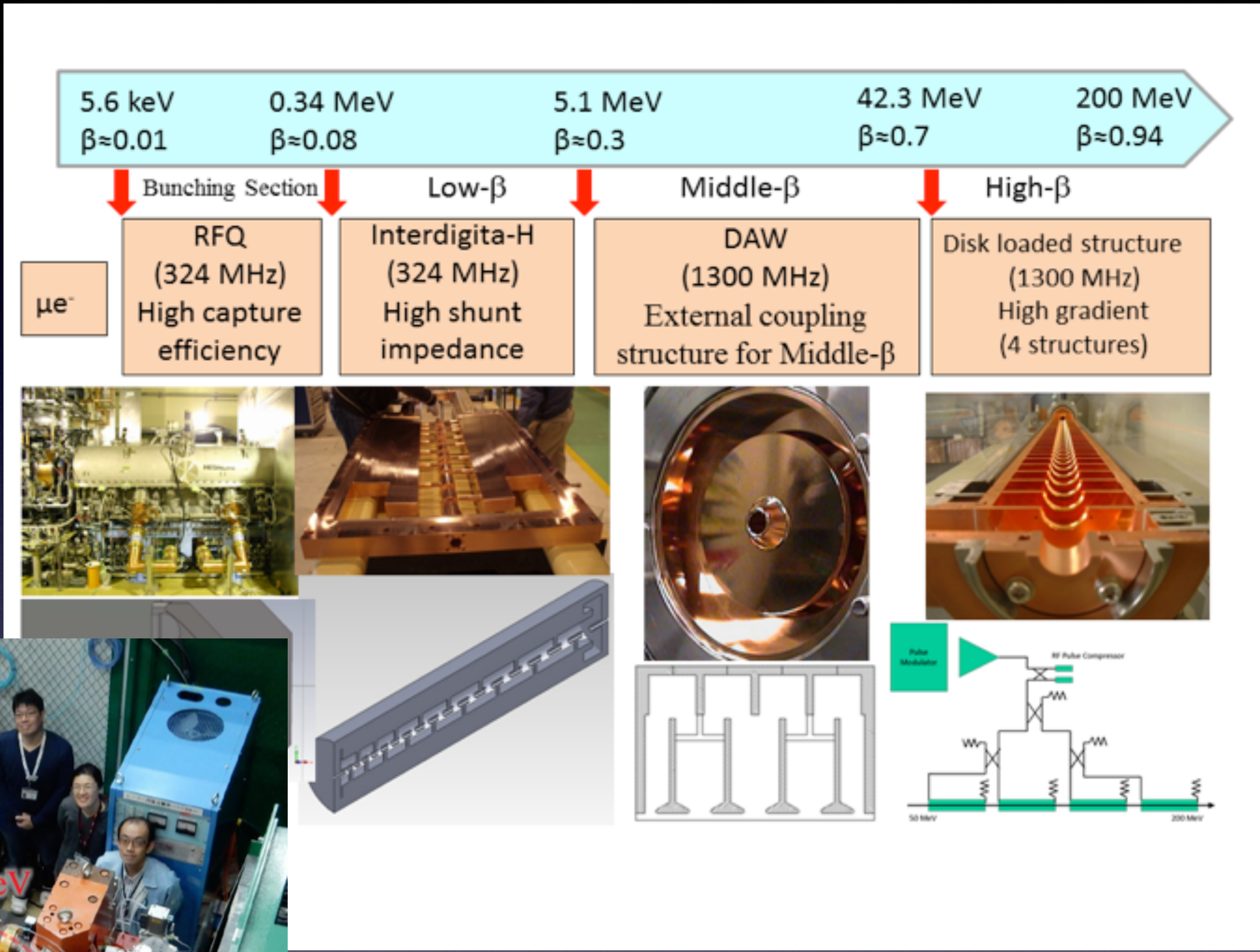
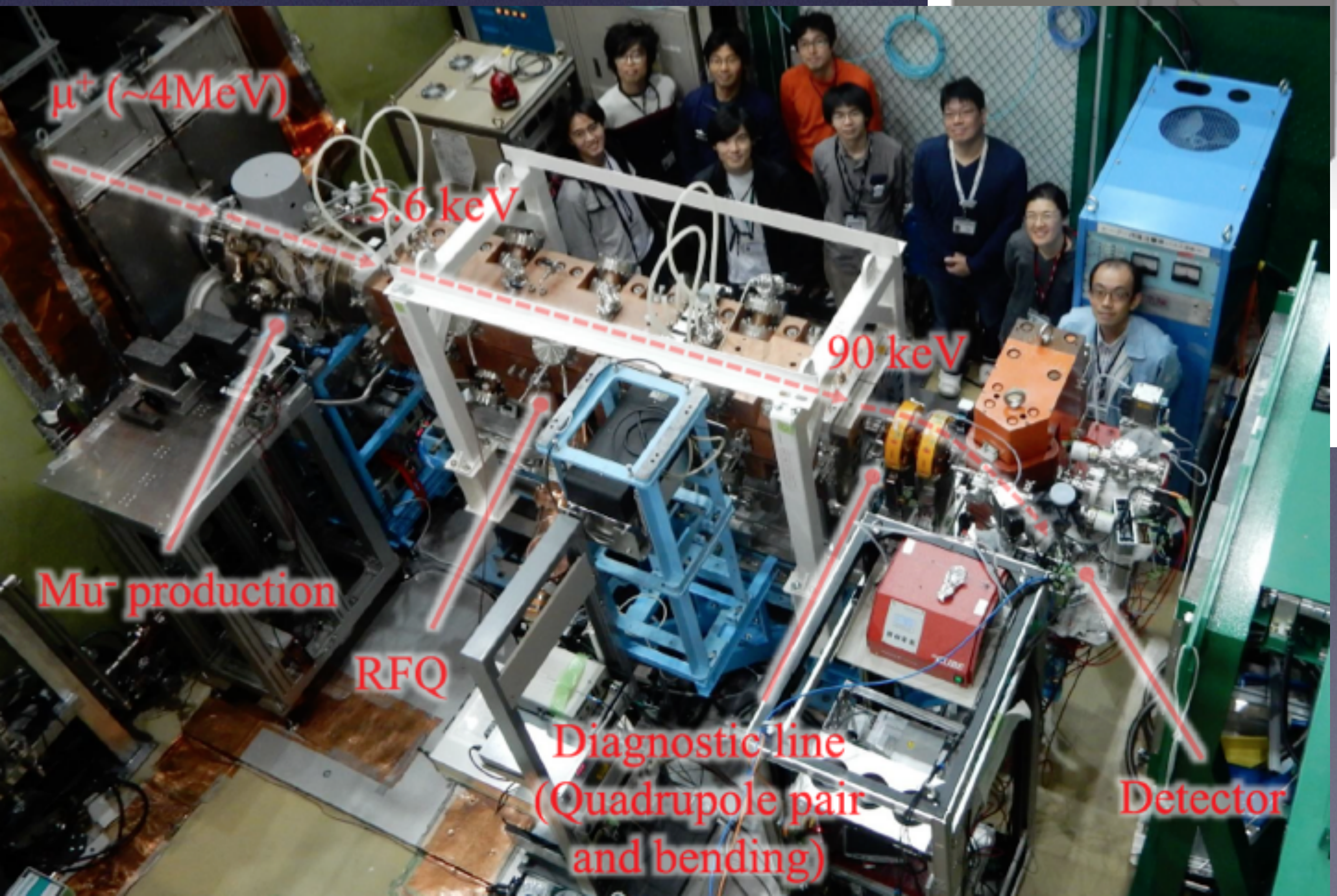
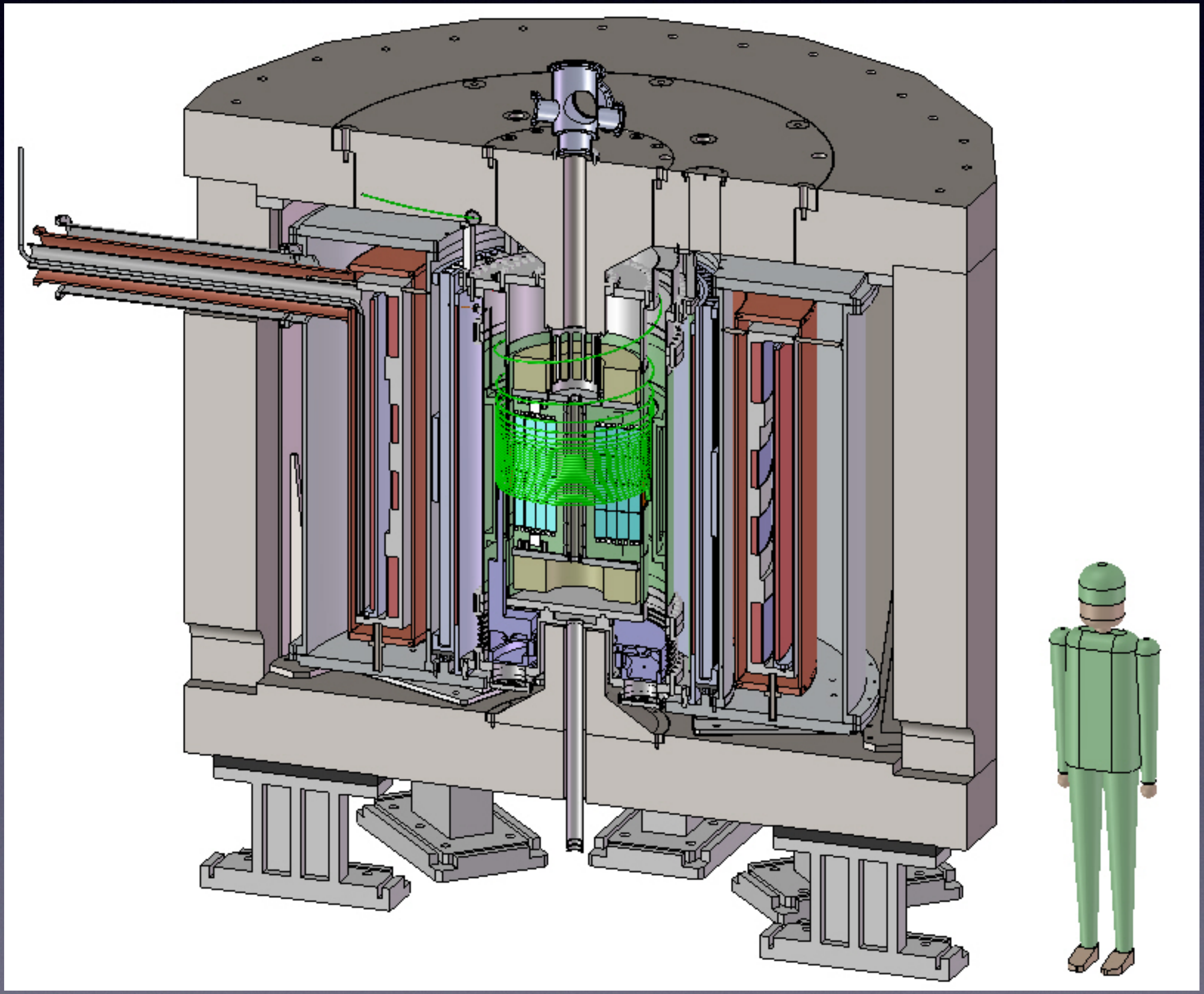
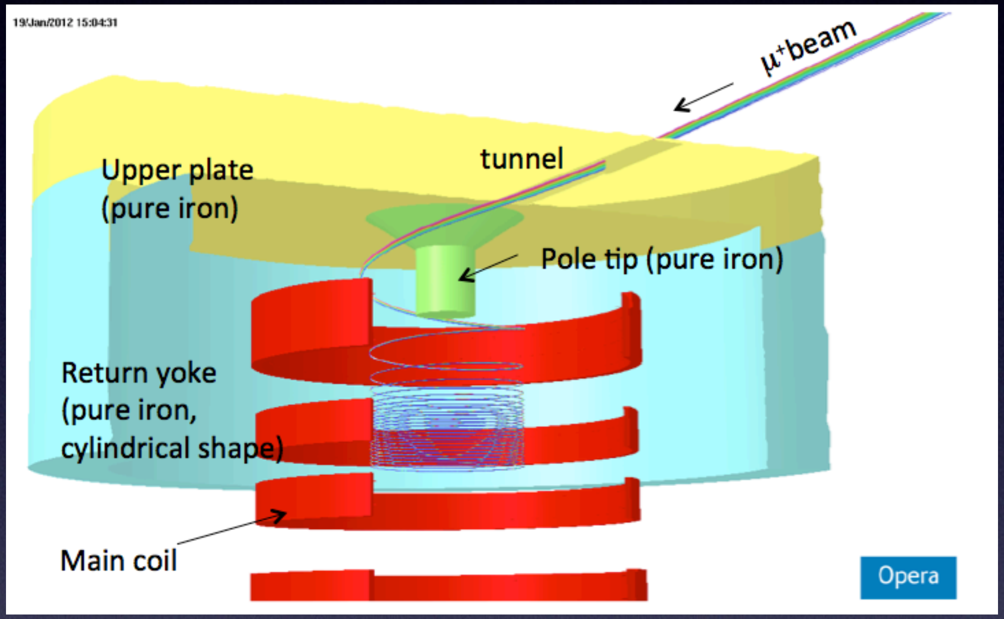




Measurement of a_μ

Variation 2: ultracold μ





Radial $\vec{B}$ compresses spiral

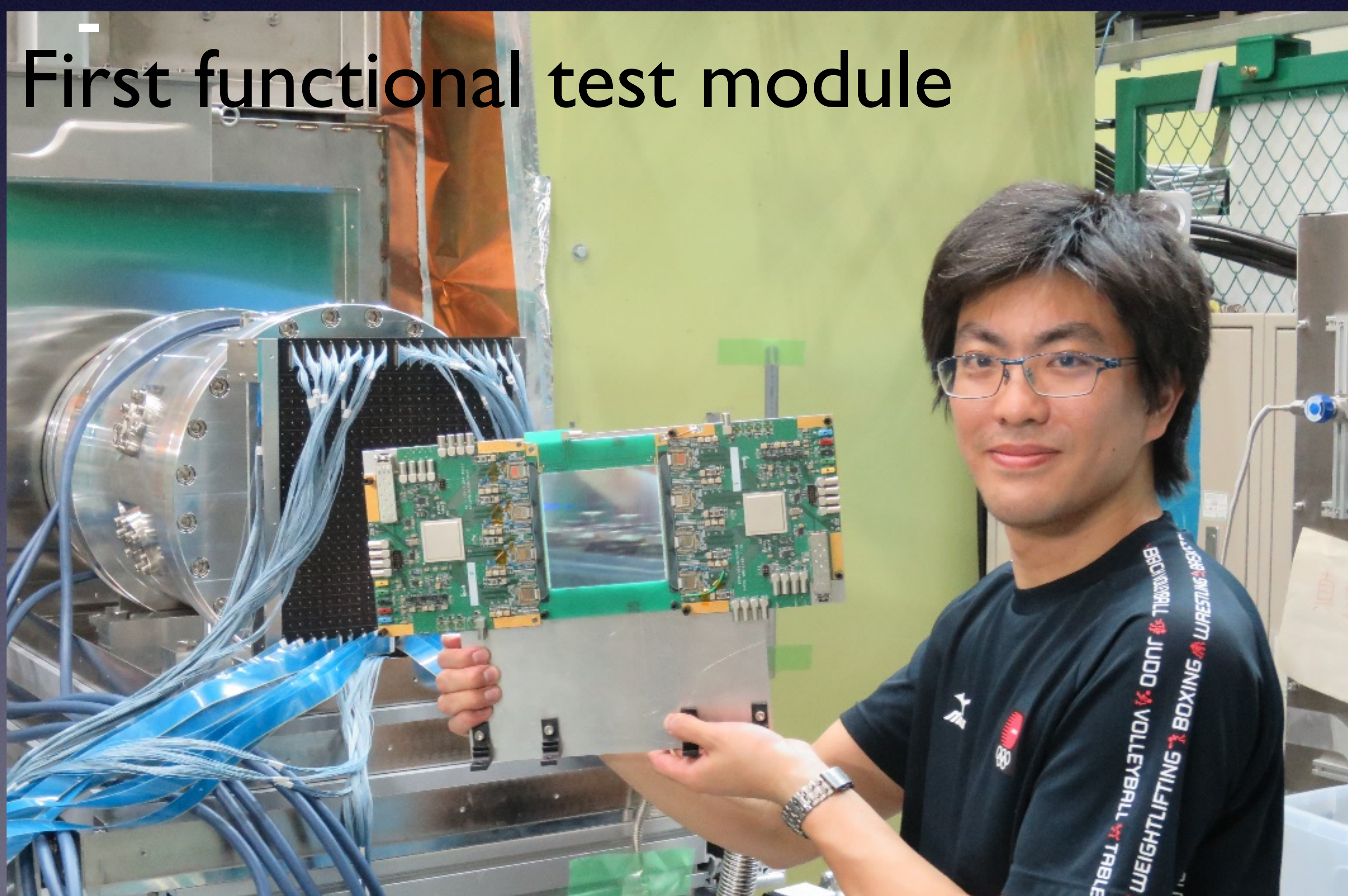
- 33.3 cm storage radius
- pulsed kicker centers orbit in storage volume

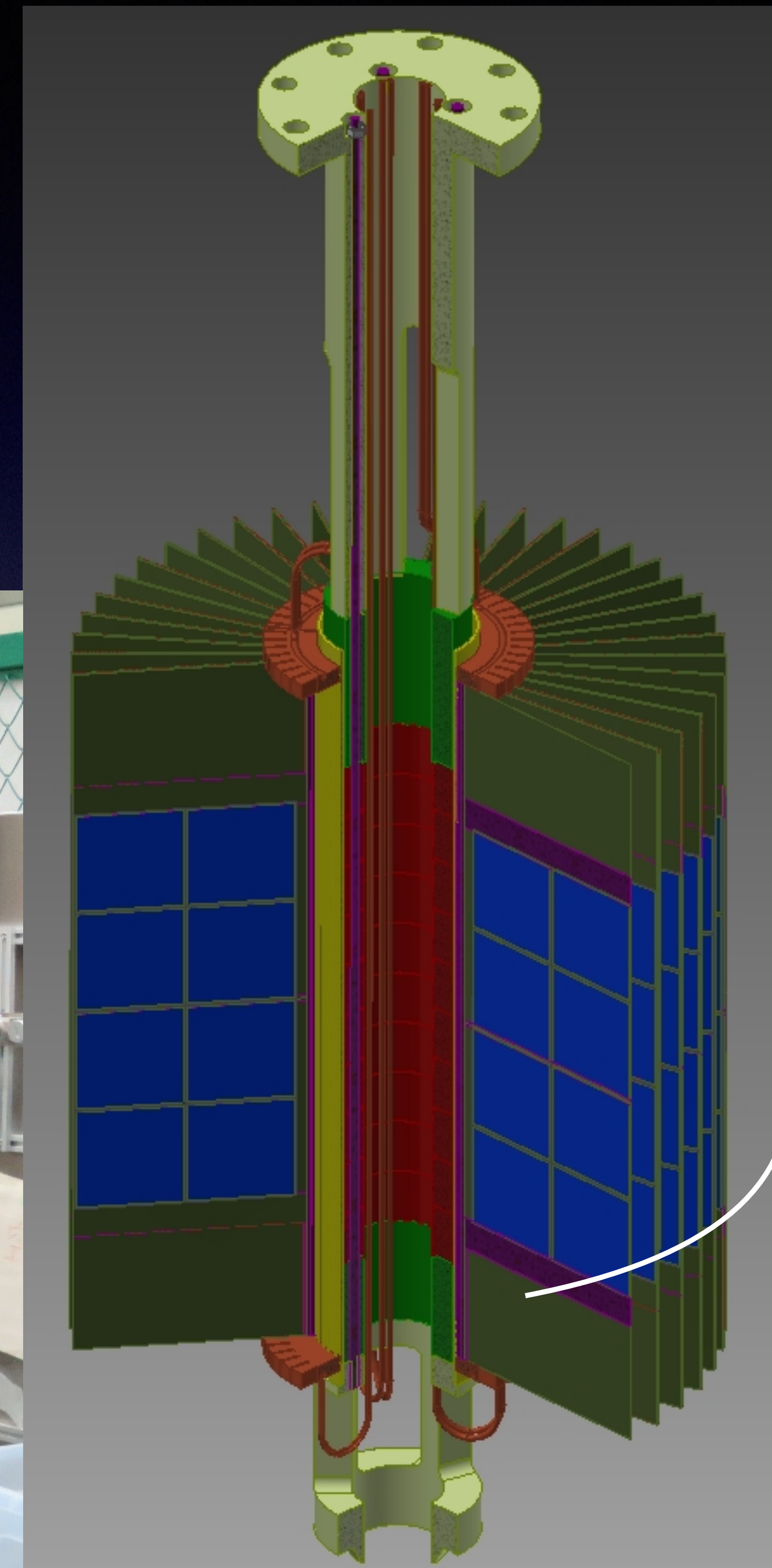
Measurement of a_μ

Variation 2:
ultracold μ

Silicon strip tracking modules
- detect e^+ from μ^+ decay
- inside stored μ^+ orbit
-

First functional test module





Measurement of a_μ

What about $\vec{B}$?

Measure

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$(\vec{\beta} \perp \vec{B})$

Measure $\vec{B}$ using pulsed NMR:

- ω_p: proton Larmor frequency in pulsed NMR free induction decay
- two approaches to extract a_μ from measured $\omega_a/\tilde{\omega}_p$

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

0.26 ppt

22 ppb

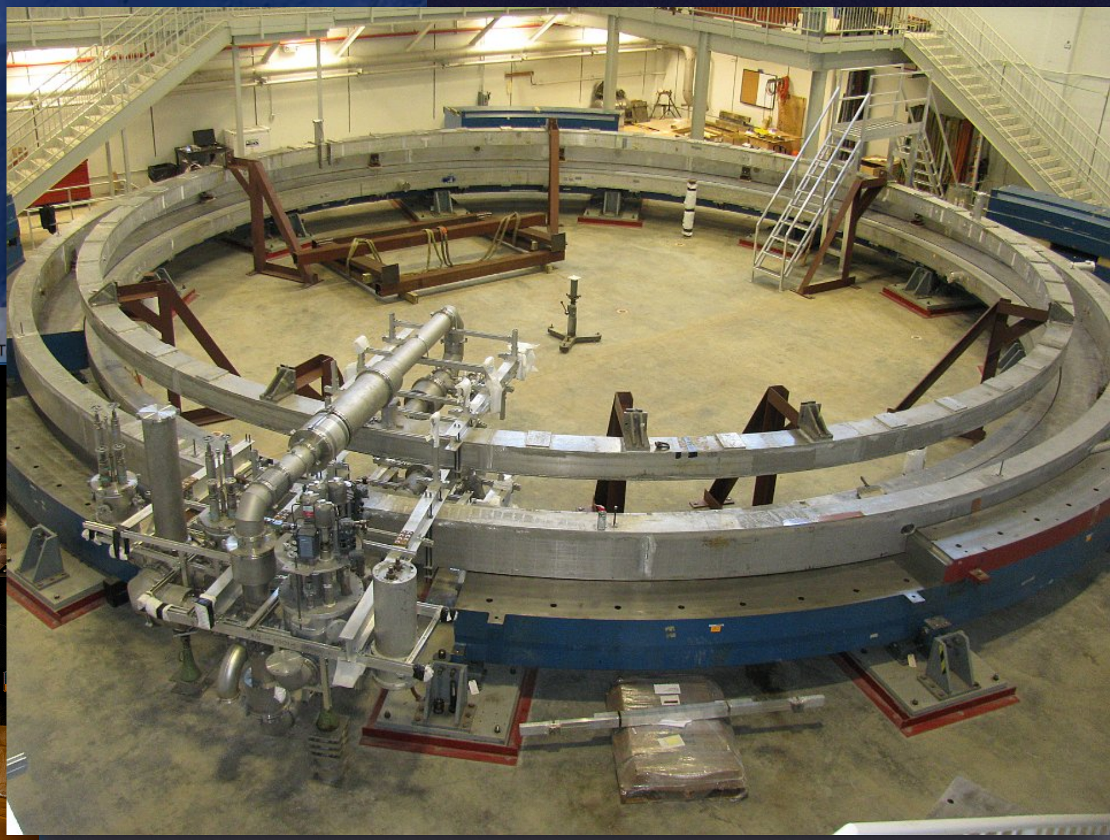
3 ppb

$$a_\mu(\mathrm{expt}) = \frac{\omega_a/\tilde{\omega}_p}{\mu_\mu/\mu_p - \omega_a/\tilde{\omega}_p}$$

LANL: 120 ppb
J-PARC MuSEUM: 10 ppb goal

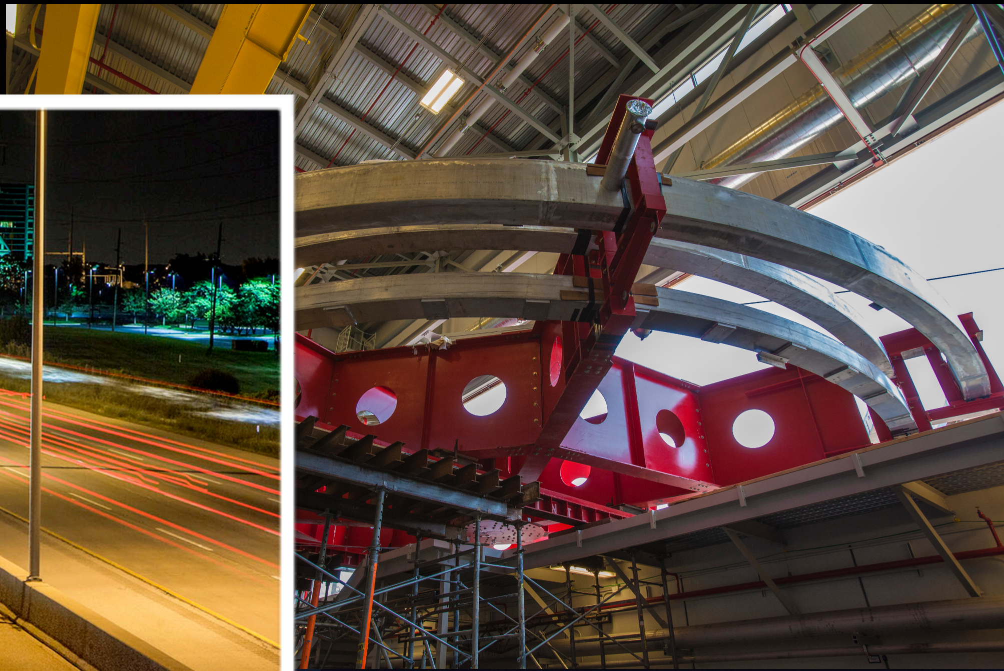
FNAL: Reuse BNL solenoid

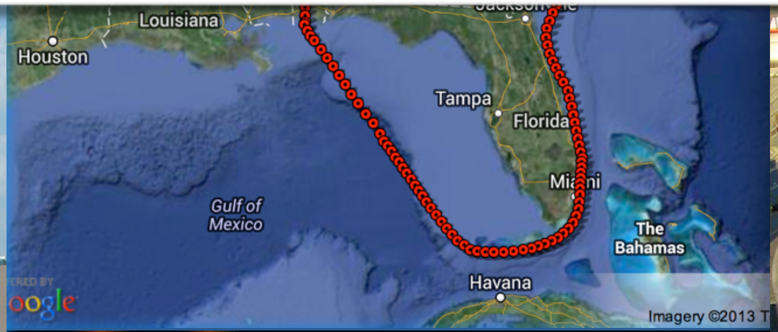
6” clearance!



15 m diameter coils
1 mm vertical flex tolerance

FNAL: Reuse BNL solenoid





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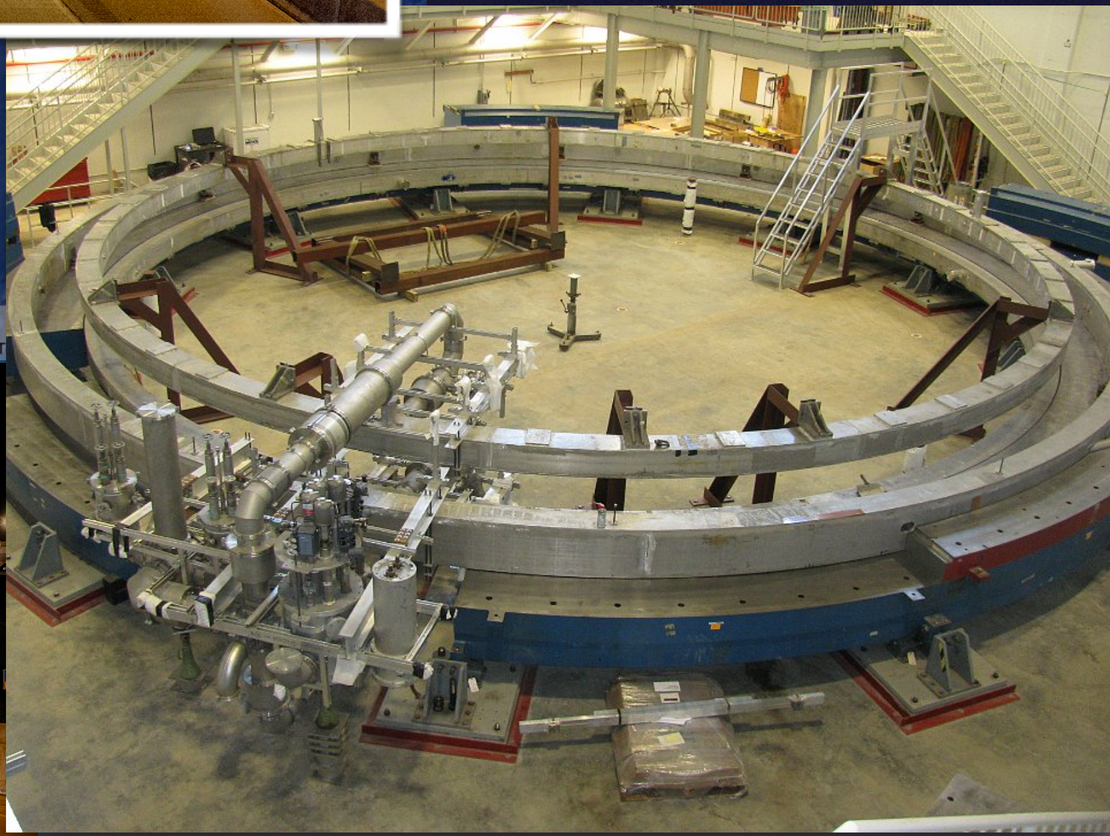
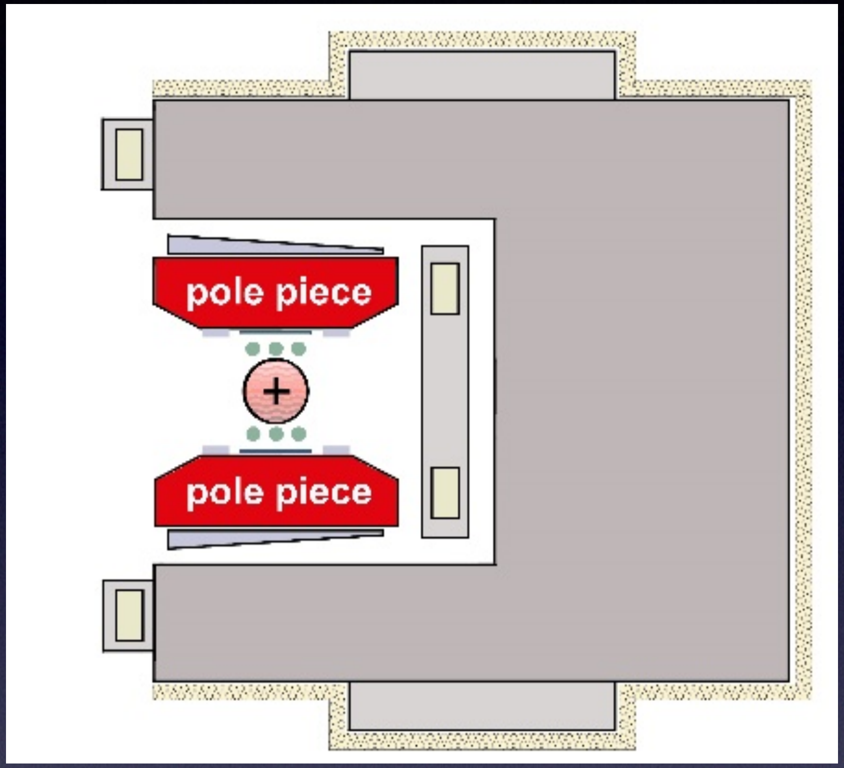


15 m diameter coils
1 mm vertical flex tolerance

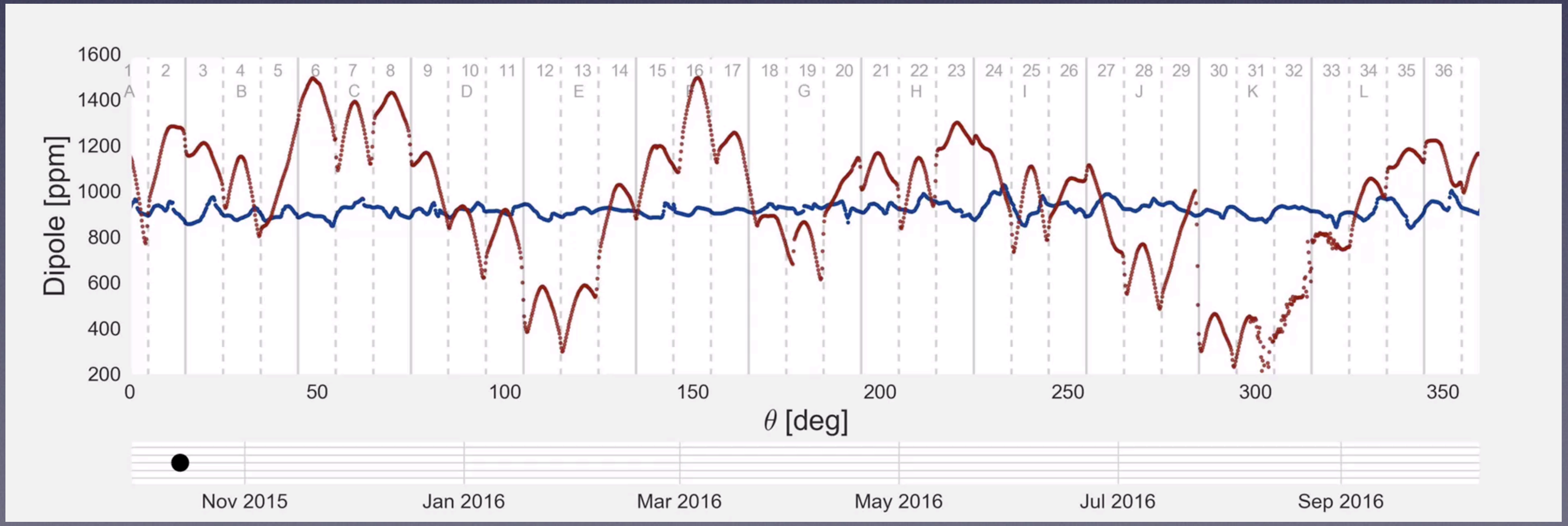
Creating the precision 1.45 T B field

1) Align the pole faces only

- painstaking and iterative!



- red: before and during shimming
- blue: E821 after *all* shimming



Date →

Nov 2015 Sep 2016

Creating the precision 1.45 T B field

1) Align the pole faces only

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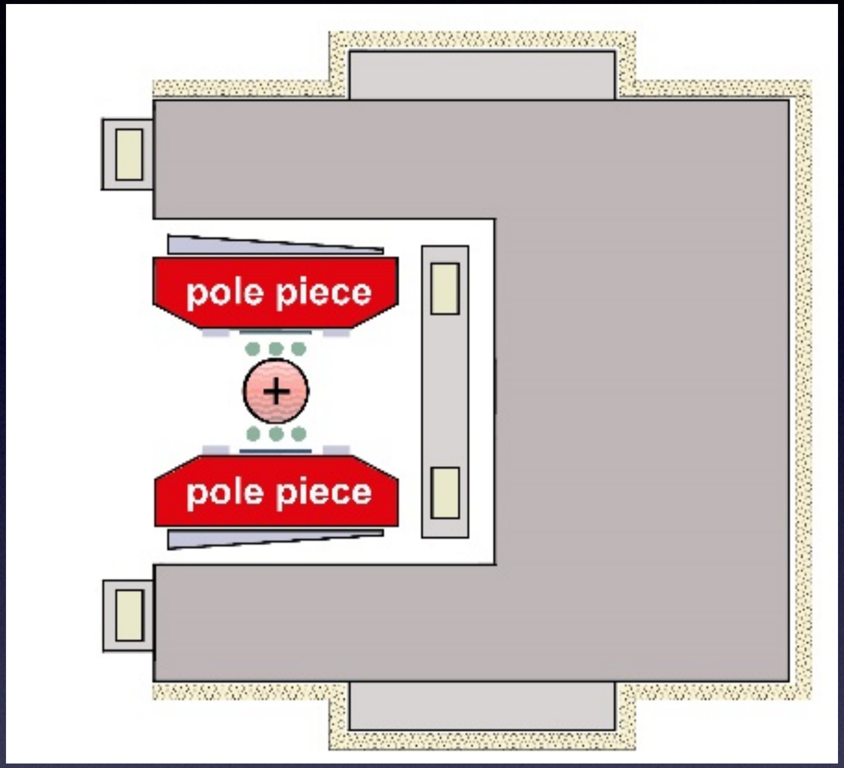
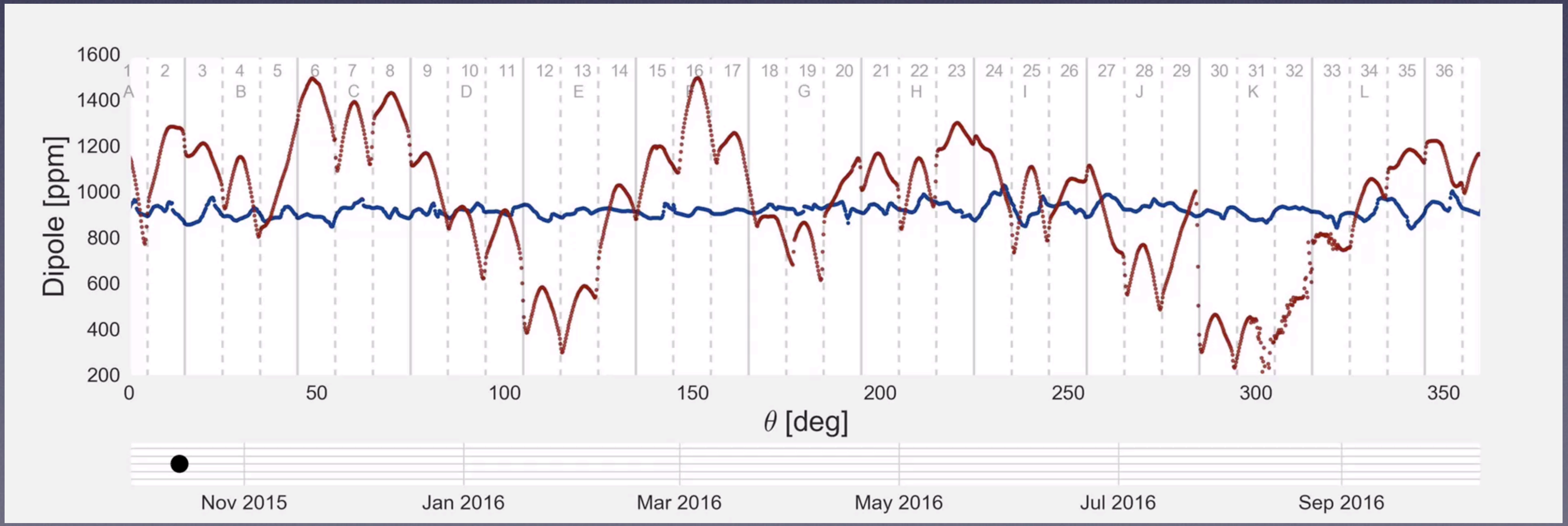


- red: before and during shimming
- blue: E821 after *all* shimming



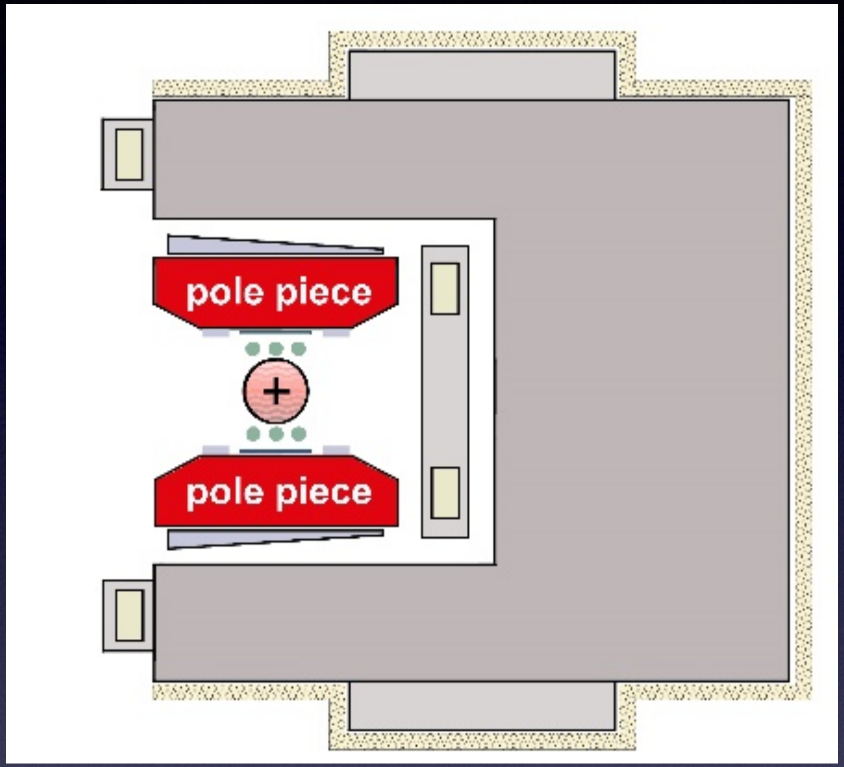
Date →

Nov 2015 Sep 2016

Creating the precision 1.45 T B field

1) Align the pole faces only

- painstaking and iterative!



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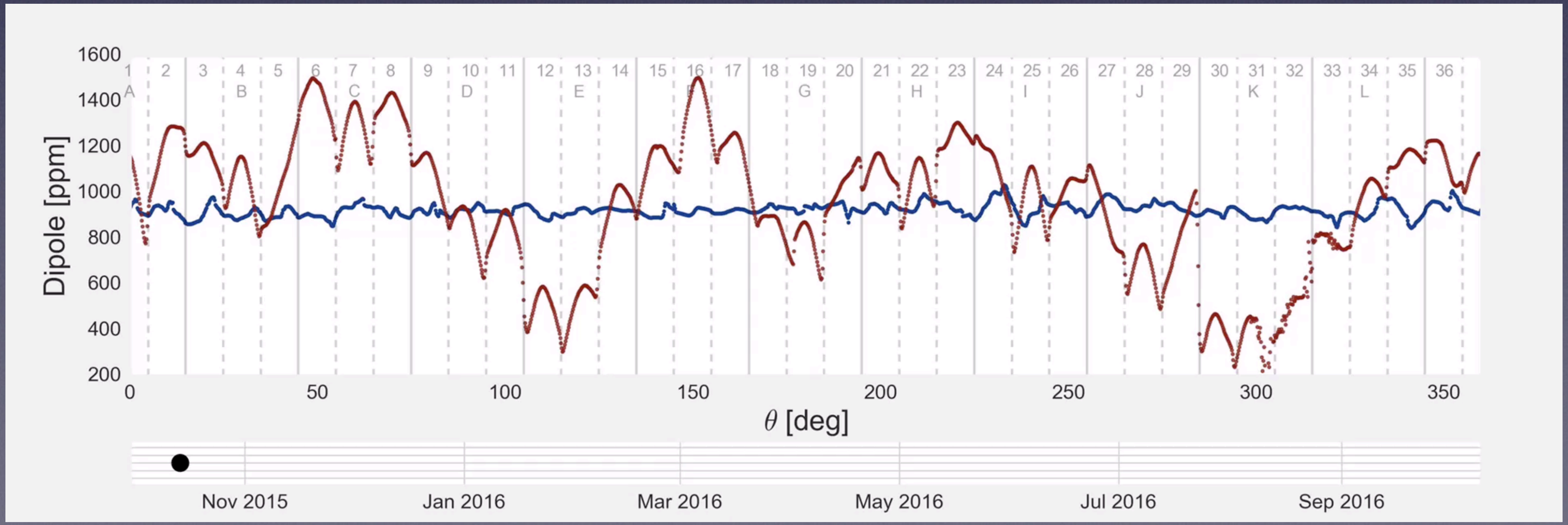
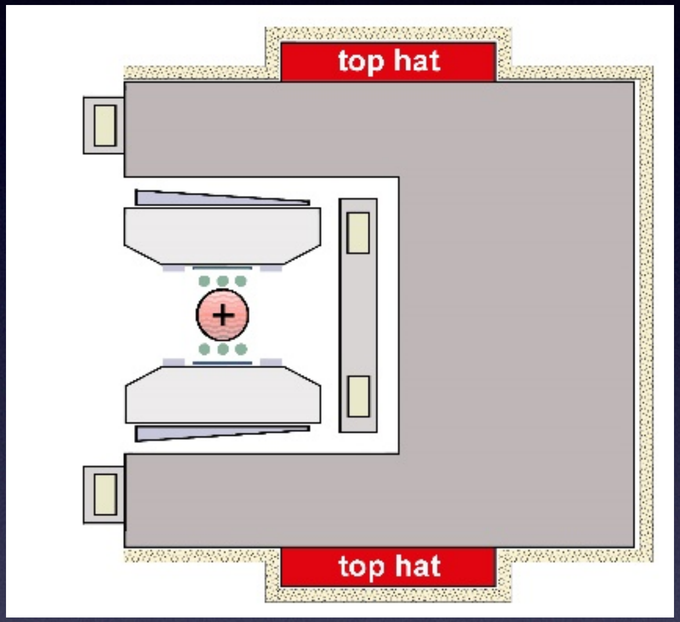


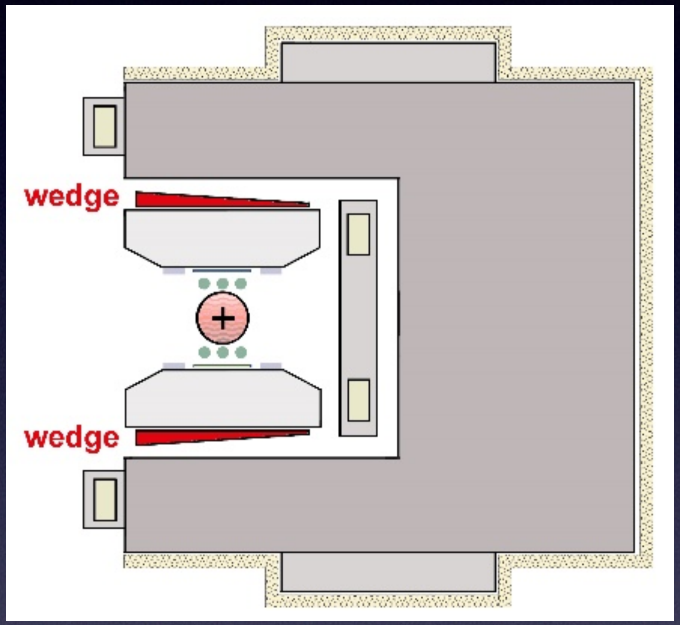
Date →

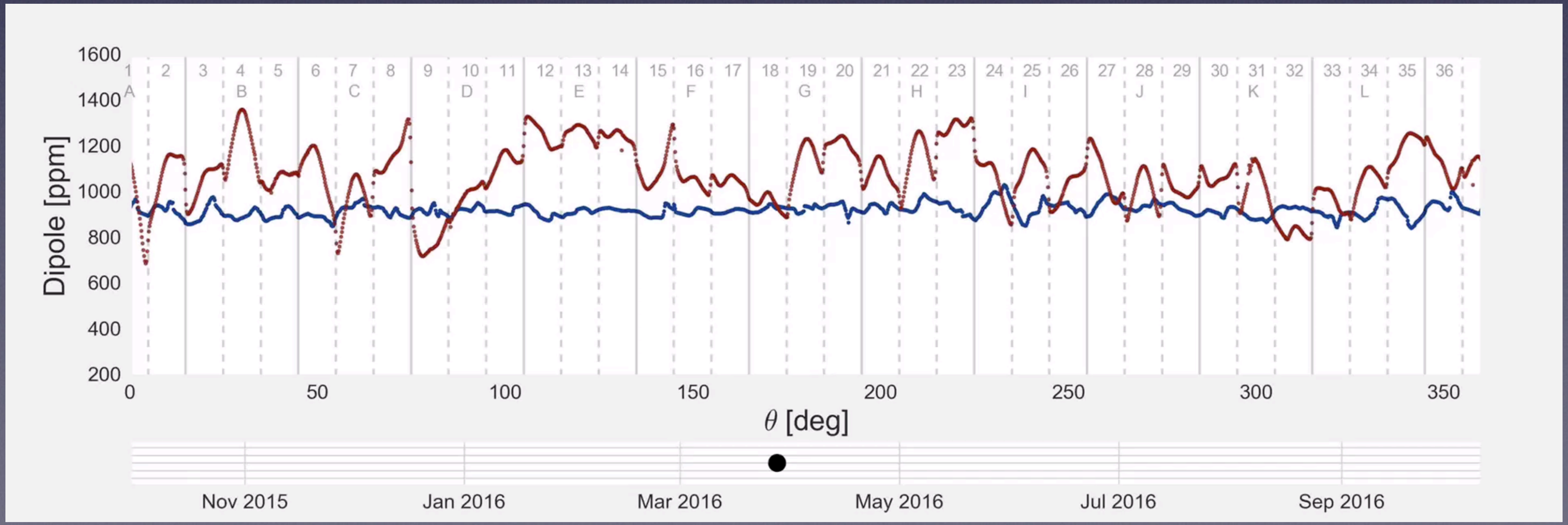
Nov 2015 Sep 2016

Creating the precision 1.45 T B field

2) Adjust Top Hats and Wedges







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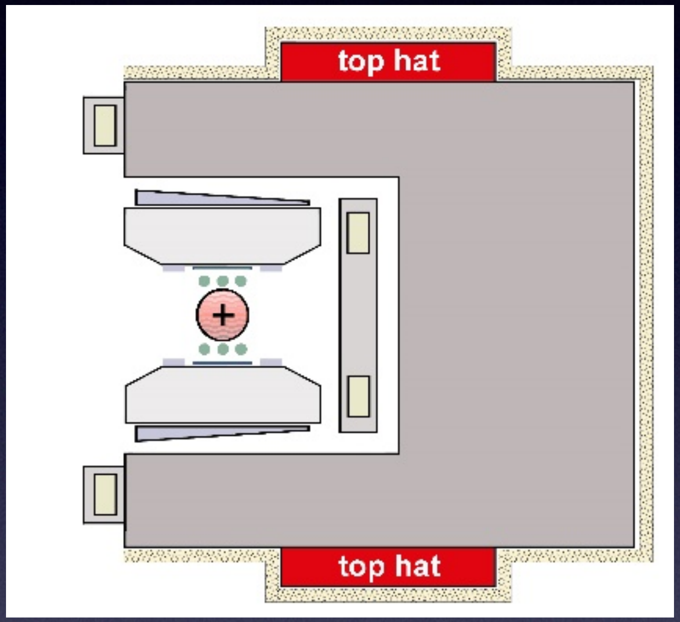

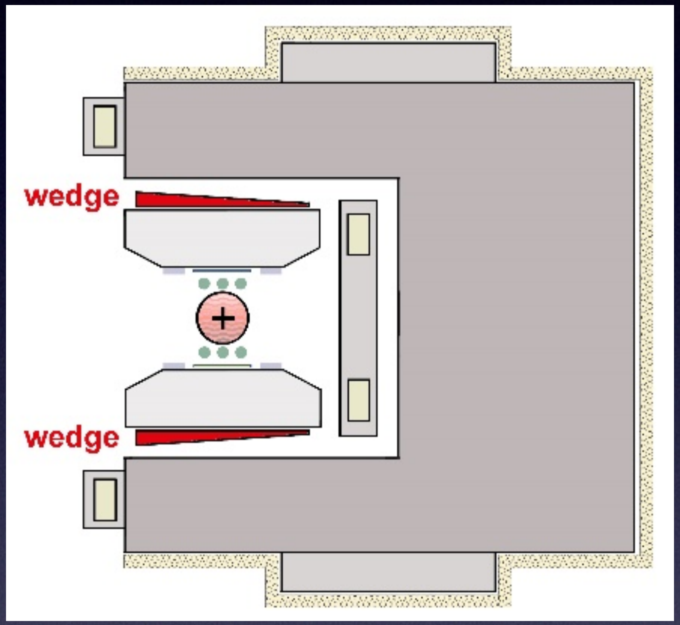

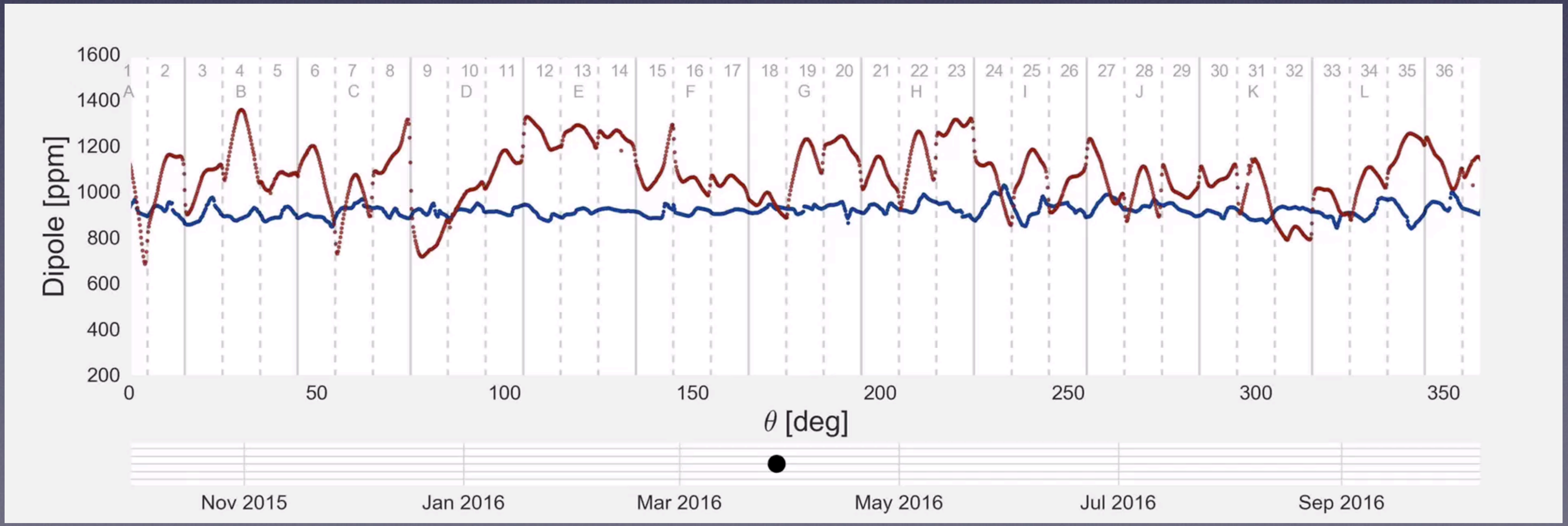

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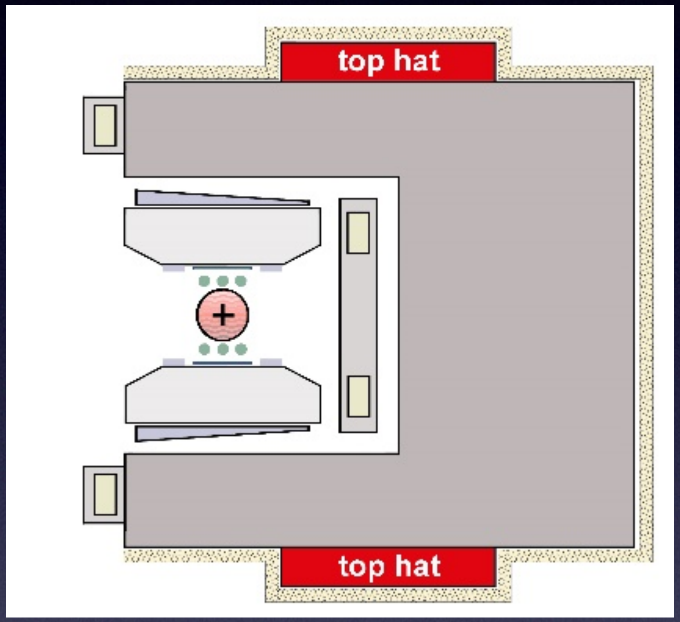

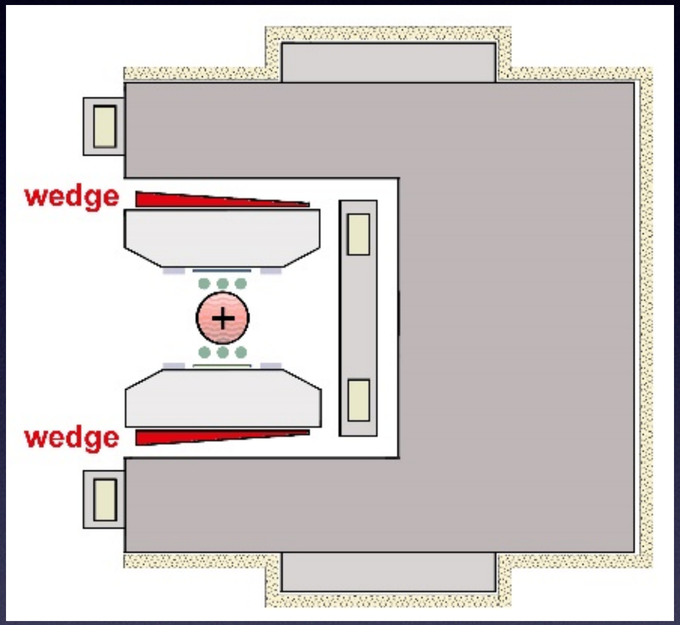

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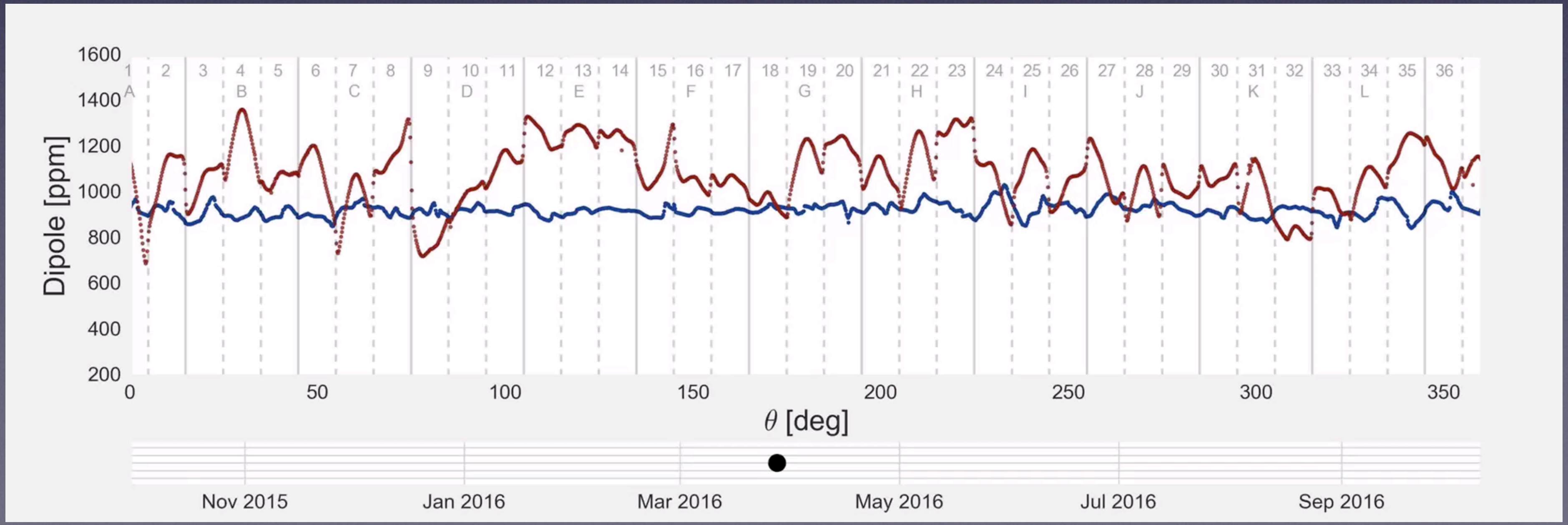


Nov 2015 Sep 2016

Creating the precision 1.45 T B field

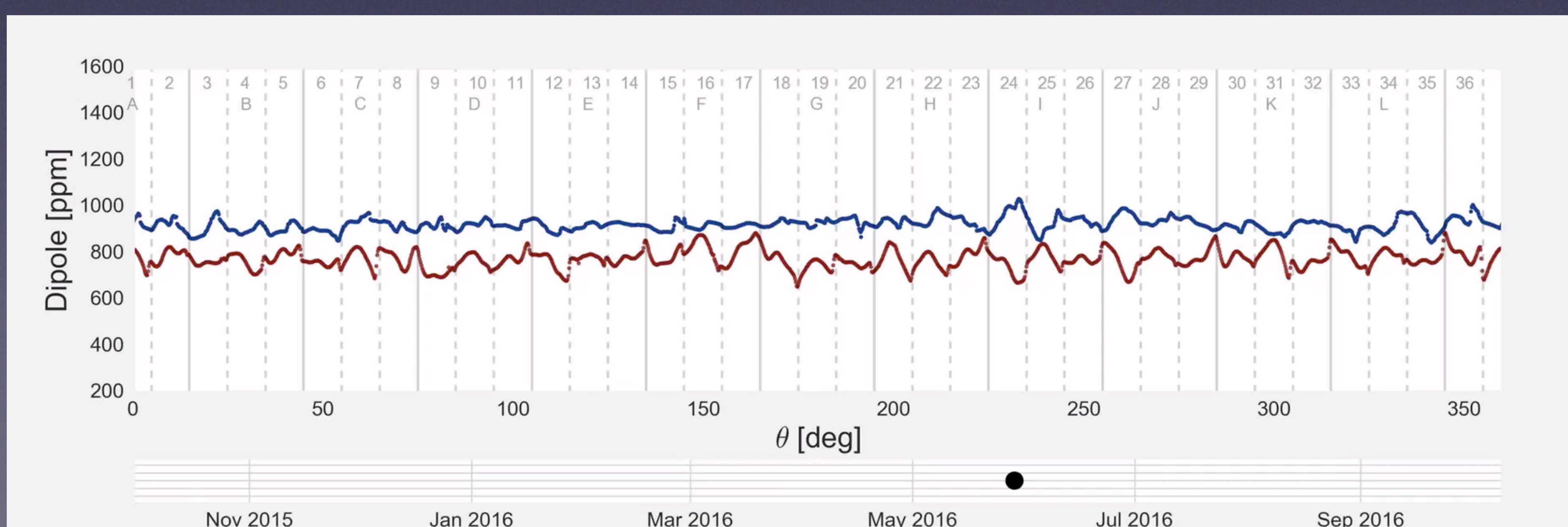
3) Move beyond E821: iron laminations

- adjust effective μ locally via foil patchwork

Azimuthal uniformity

- meets Muon g-2 design spec
- significant improvement over E821

Date →



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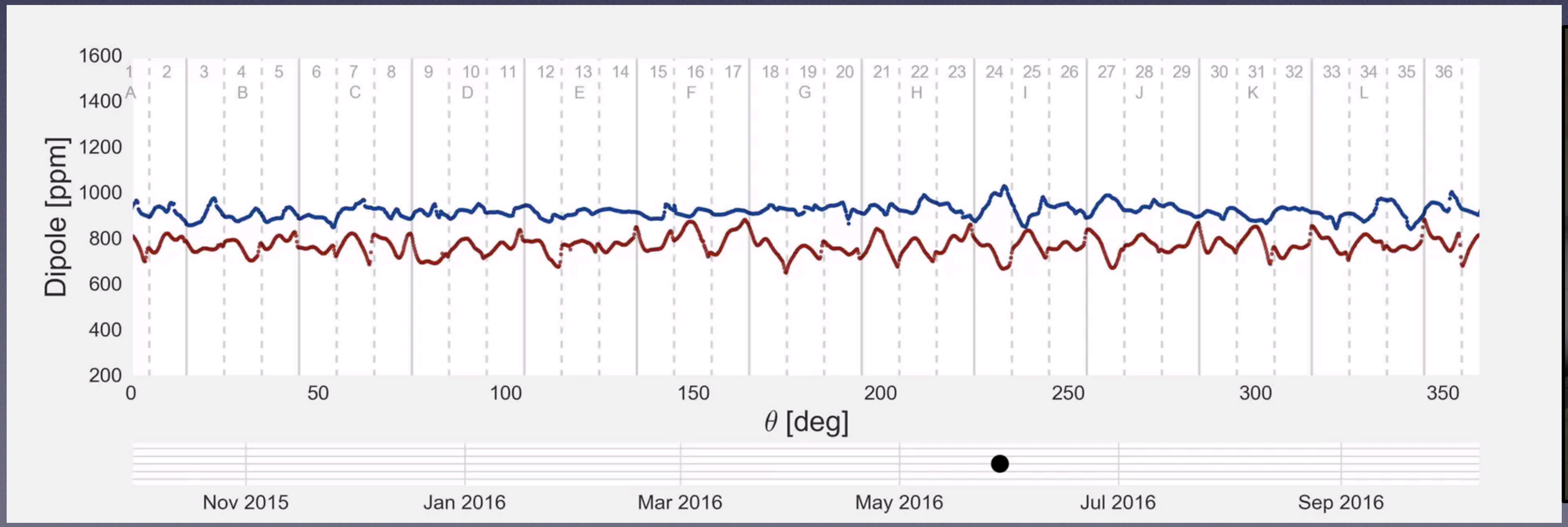

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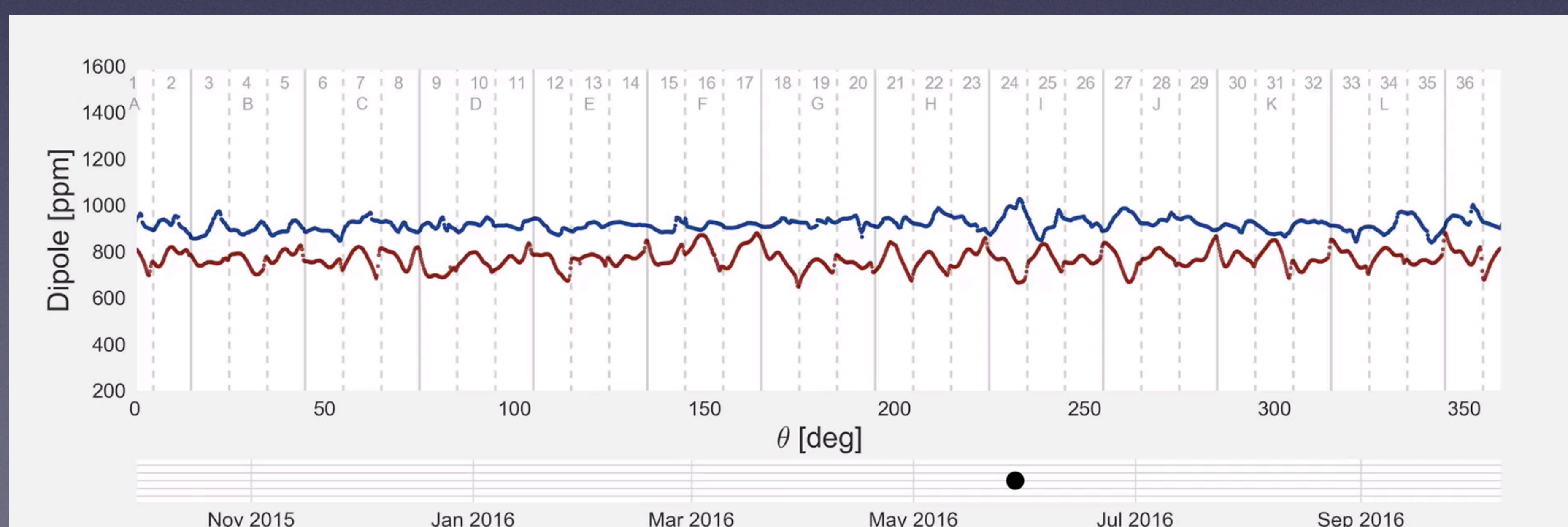
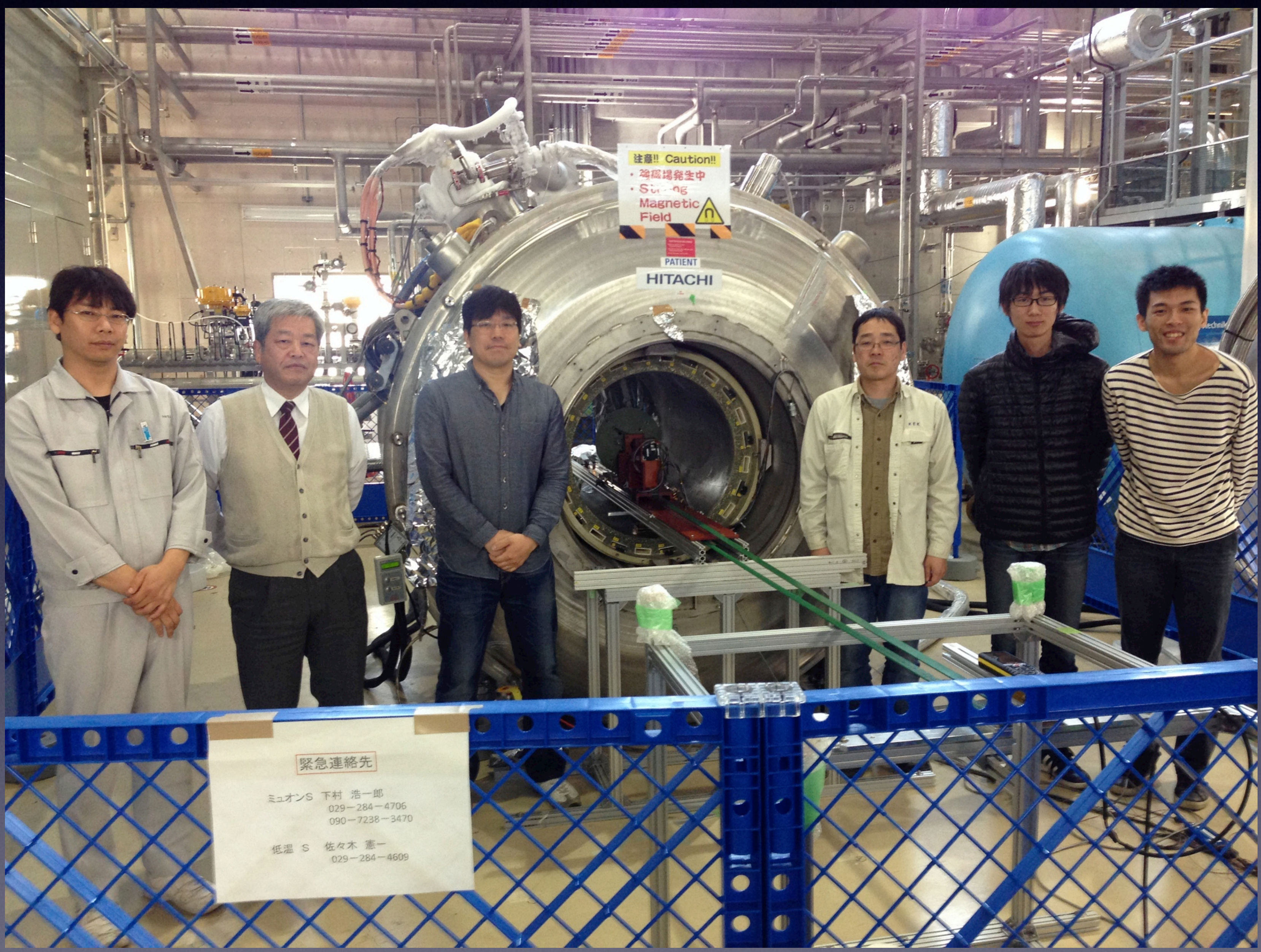


Nov 2015 Sep 2016

J-PARC: 3T MRI-style



Must shim for

- uniform $\vec{B}$ for μ+ storage
- radial (fringe) $\vec{B}$ for spiral injection scheme

Learning to shim with MuSEUM 1.7T solenoid

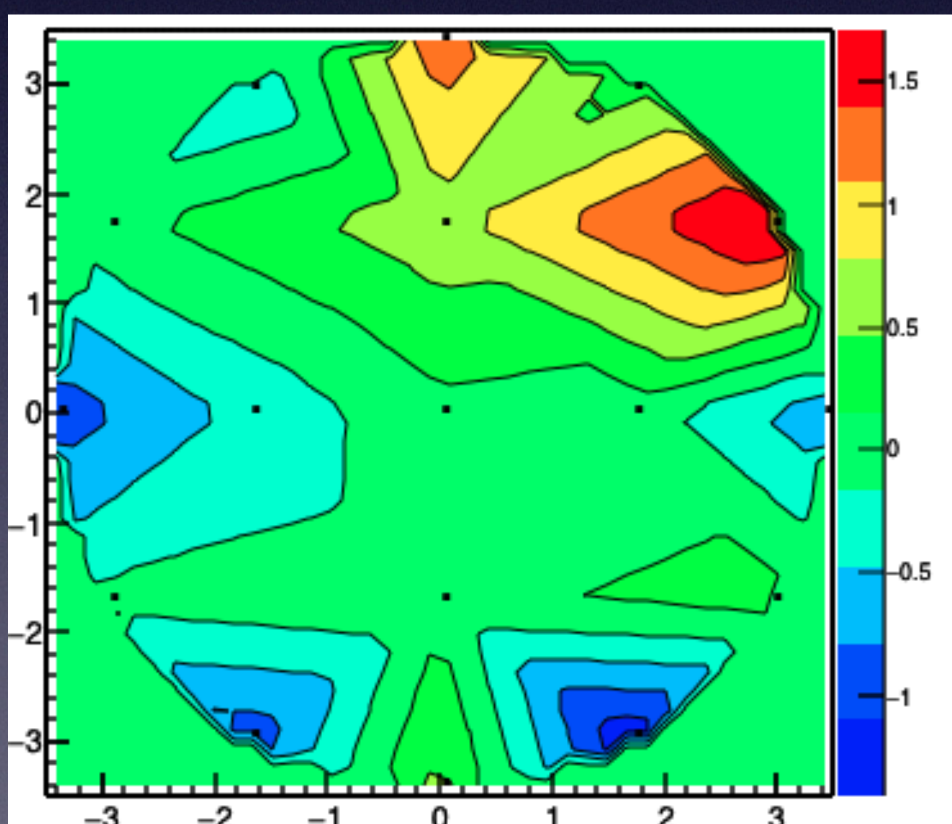
Measurement of a_μ

What about $\vec{B}$?

Fermilab

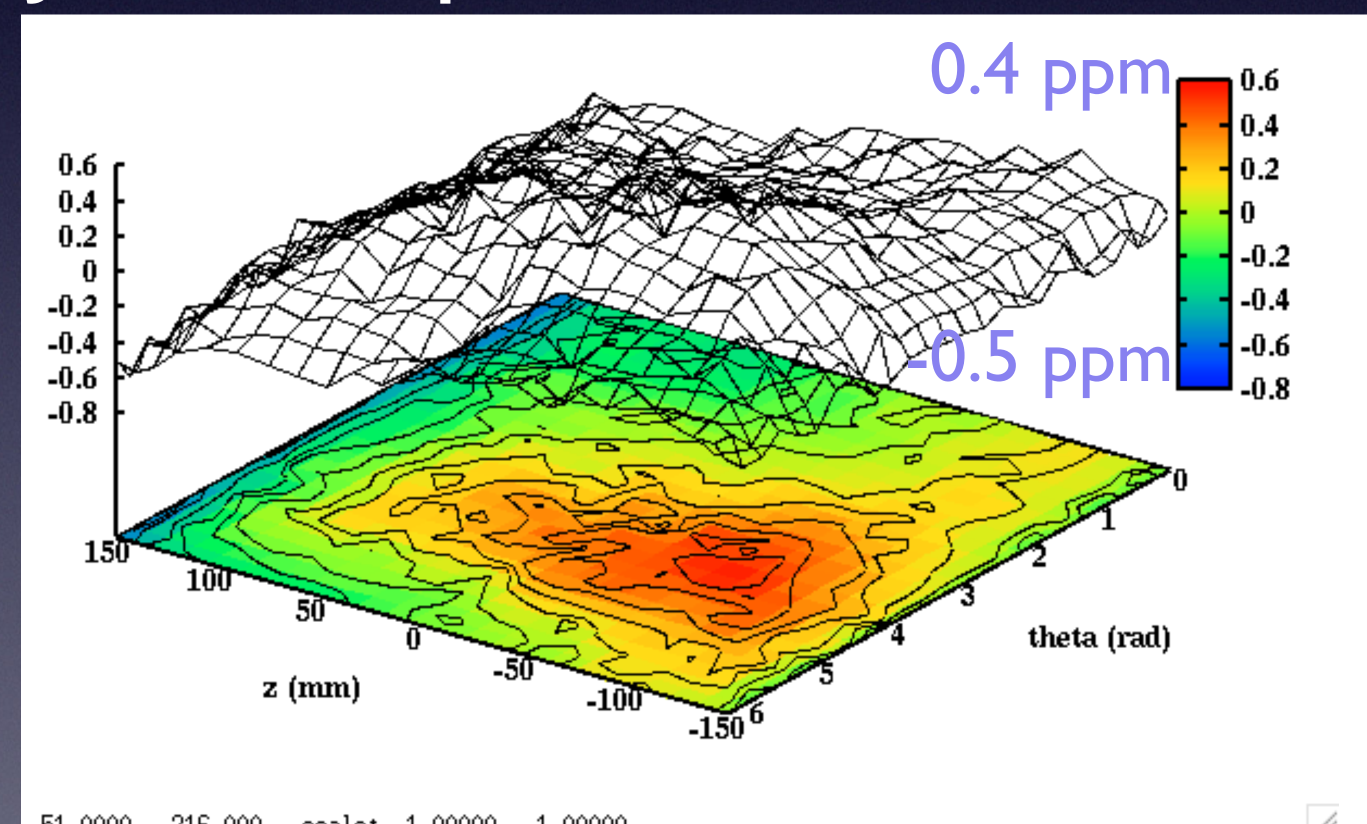
J-PARC “practice”

Vertical position (cm)



Horizontal position (cm)

cf. beam sigma ~ 10 cm

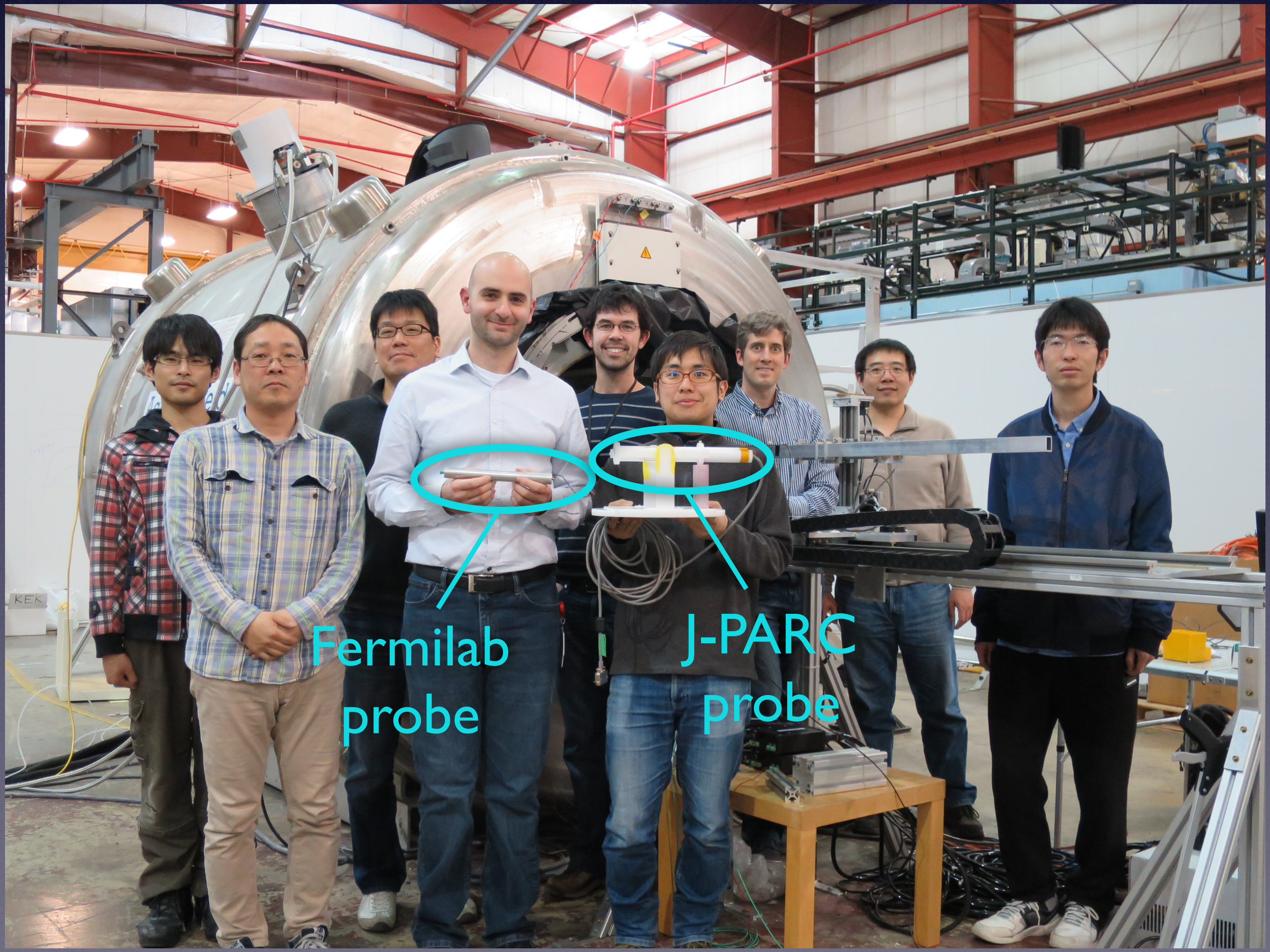


15 cm radius (expt: 33 cm)

Measurement of a_μ

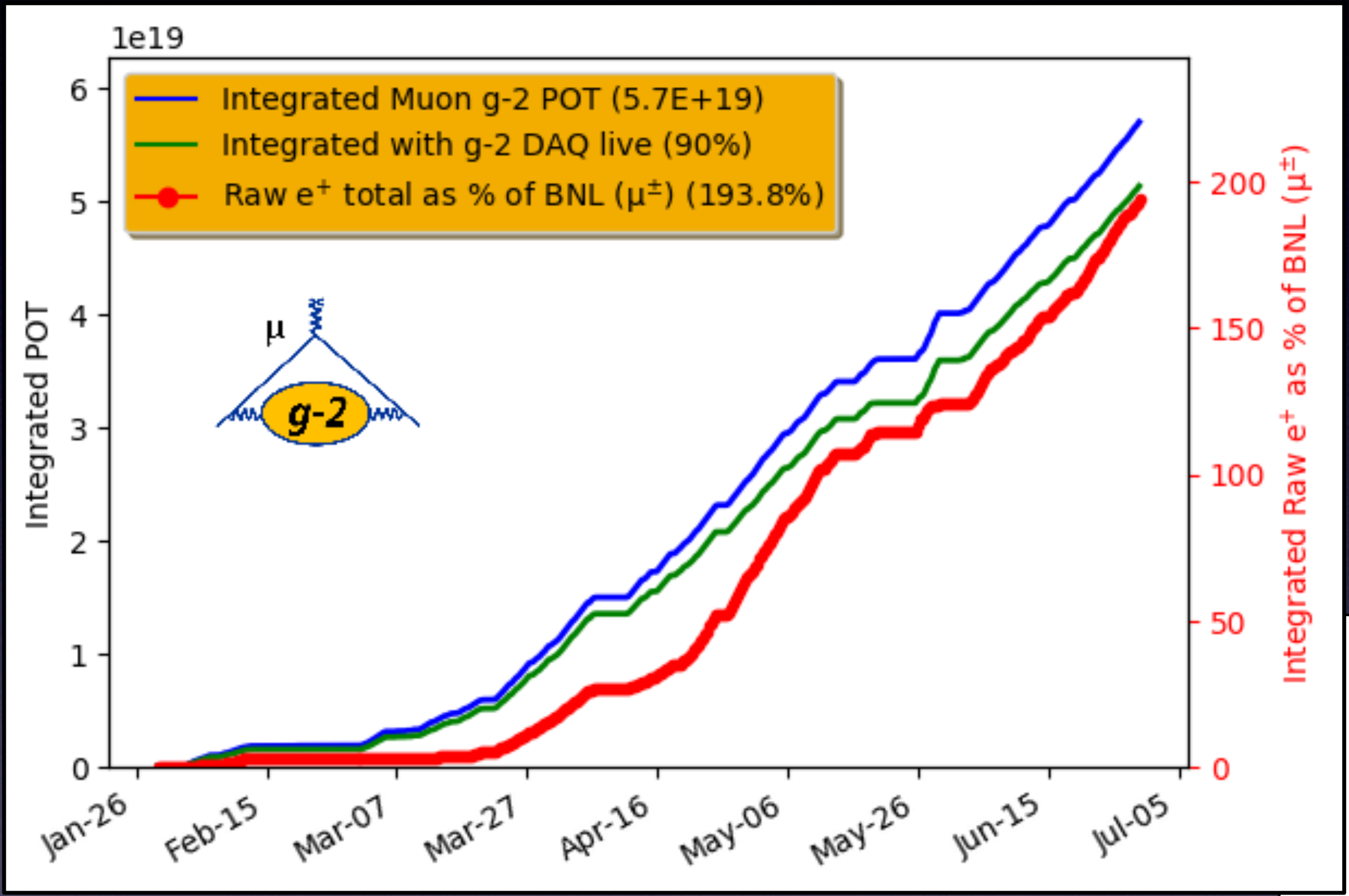
What about $\vec{B}$?

Fermilab + J-PARC Absolute Cross calibration



- Two experiments cross-calibrating absolute NMR probes using FNAL g-2 MRI magnet at ANL
- First round: agreement to 21 ppb
- Second round of testing completed March, 2018, analysis proceeds

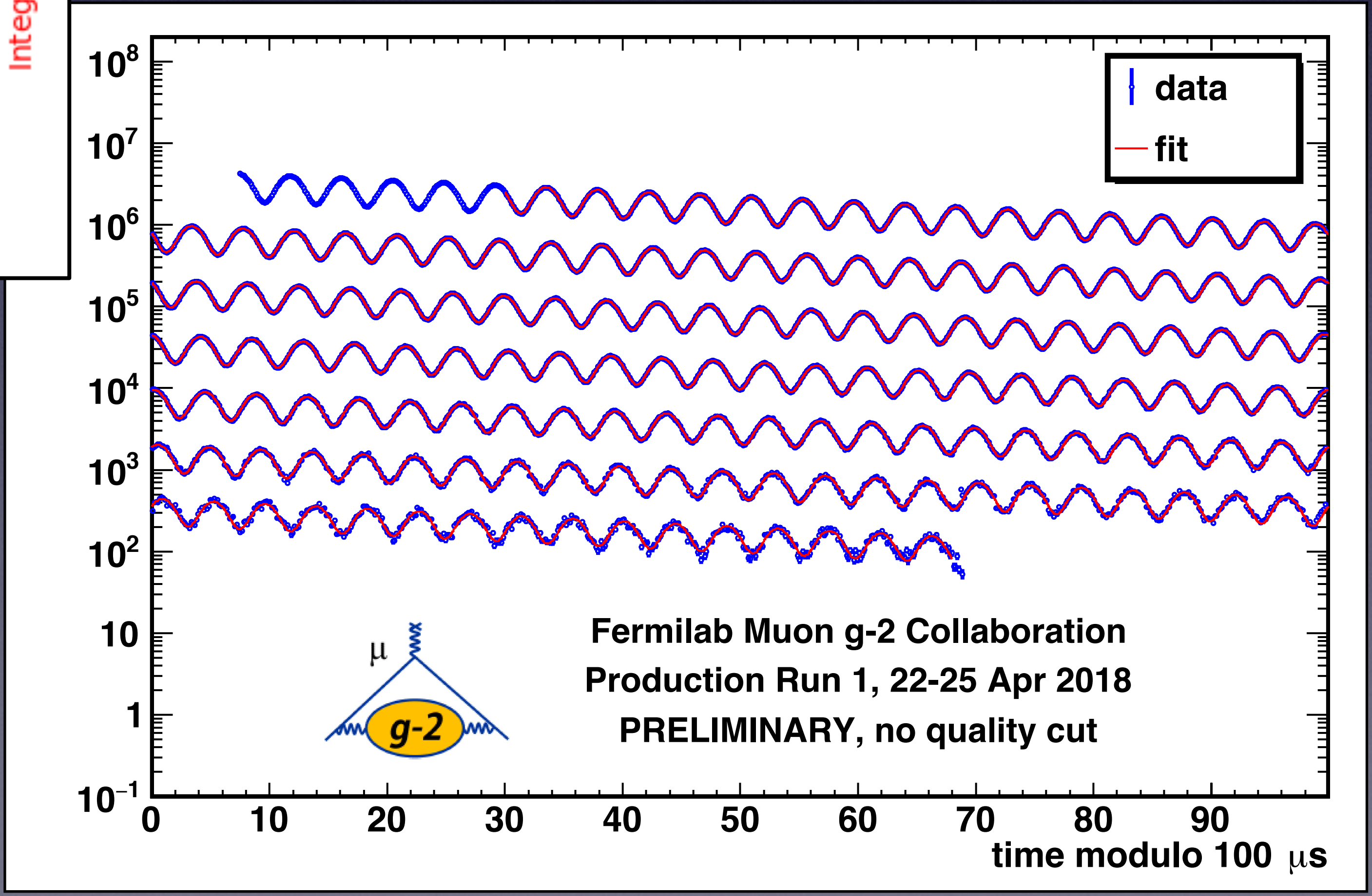
Fermilab g-2 status



2018 run: expect ~ 2.3 × BNL stats

Many lessons learned:

- summer tune-up begins 7/7



Analysis underway!

See talk by Nandita Raha, Saturday

Summary

Muon g-2 Standard Model prediction rock solid!

- precision continues to improve
- already reached precision goal estimated for FNAL g-2 Technical Design Report (TDR)

Fermilab Muon g-2 experiment underway

- Very informative first year of running, ~2x BNL dataset in hand
- on track for 140 ppb measurement!

J-PARC Muon g-2 TDR in progress

- Complementary technique at 460 ppb in phase 1
- many critical steps have been achieved

Thanks!