g-2 experiments (and other muon experiments)

Joseph Price, University of Liverpool

UK HEP forum, Cosener's house

September 24th, 2019

Outline

- What is g-2 and why is it interesting to measure?
  - How is it calculated?
- Fermilab and J-PARC muon g-2 experiments
  - How is it measured?
  - Prospects and timeline
- Precision muon measurements beyond g-2
  - Where/How is it measured?
  - Prospects and timeline
- Conclusions

Magnetic Moment

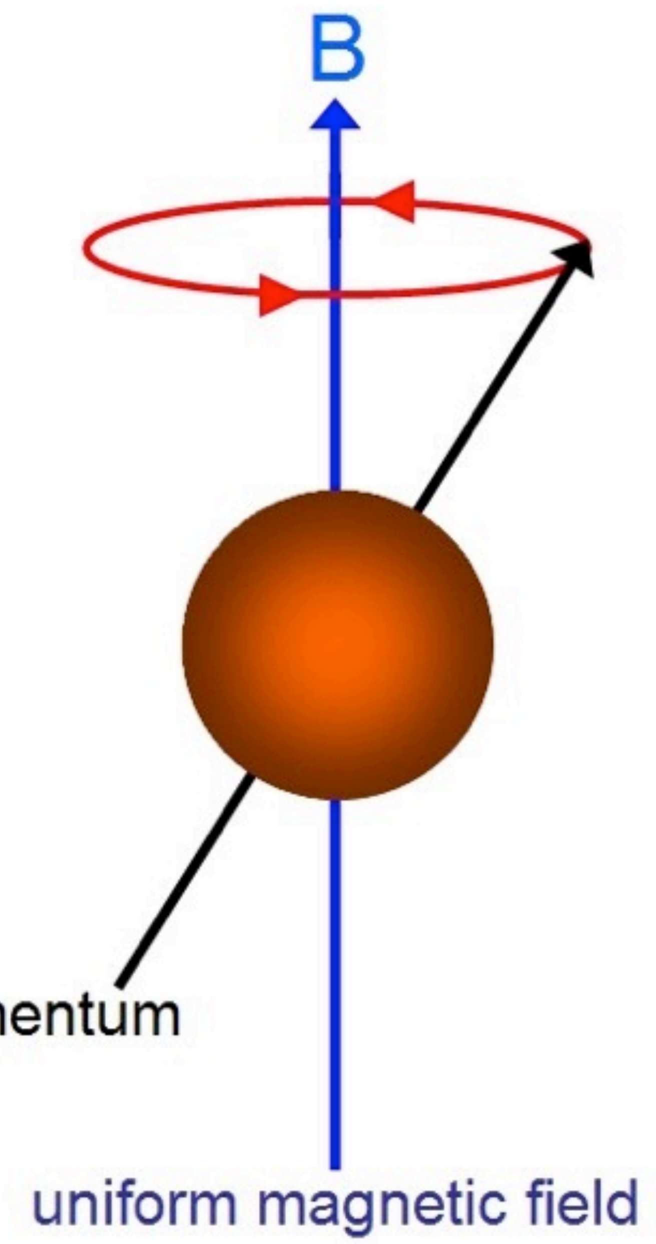
- Each charged lepton has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

$$\vec{\mu} = g_l \frac{e}{2m_l} \vec{S}$$

- Magnetic moment (spin) interacts with external B-fields

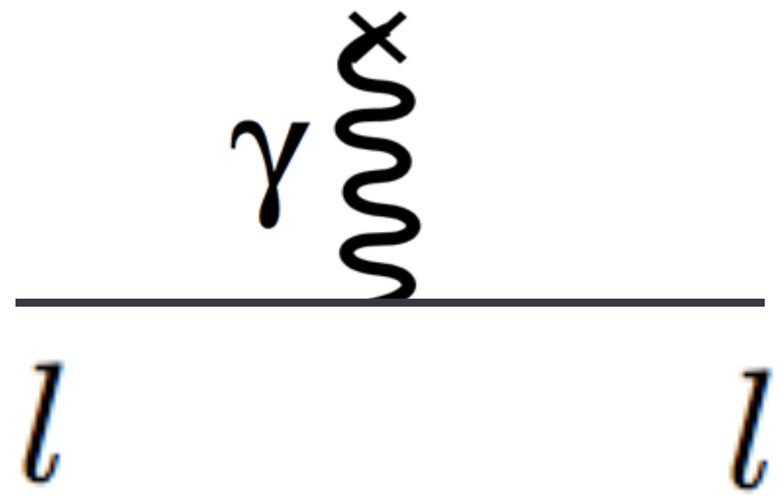
$$\vec{\mu} \times \vec{B}$$

- Makes spin precess at frequency determined by *g*

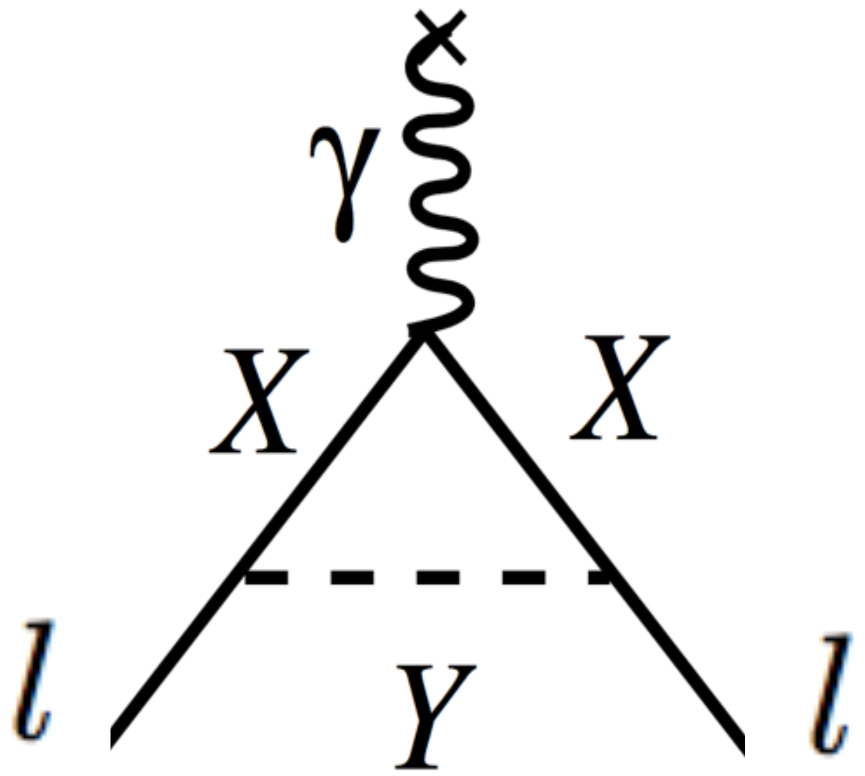


Magnetic Moment & Virtual Loops

- For a pure Dirac spin-½ charged fermion, g is exactly 2

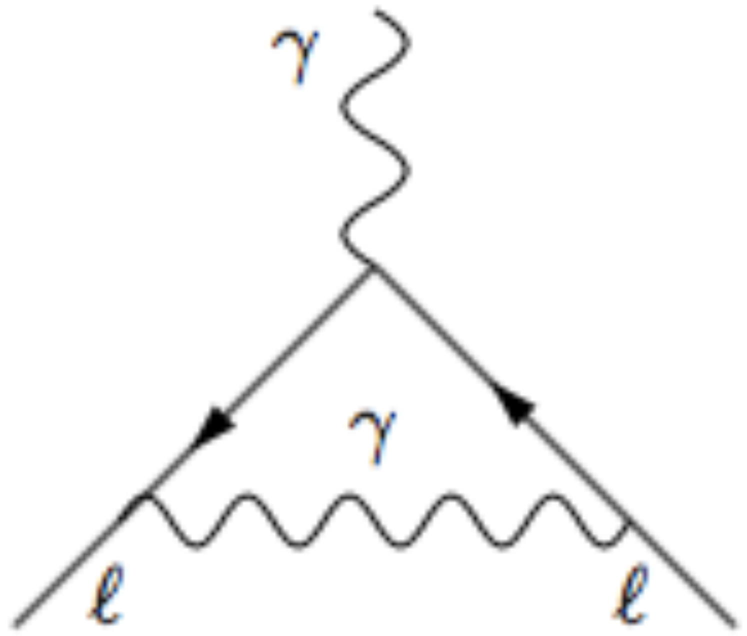


- Interactions between the fermion and virtual loops change the value of g - X & Y particles could be SM or new physics:



Schwinger Correction

- The most simple correction is 1st order QED, calculated by Schwinger in 1948:



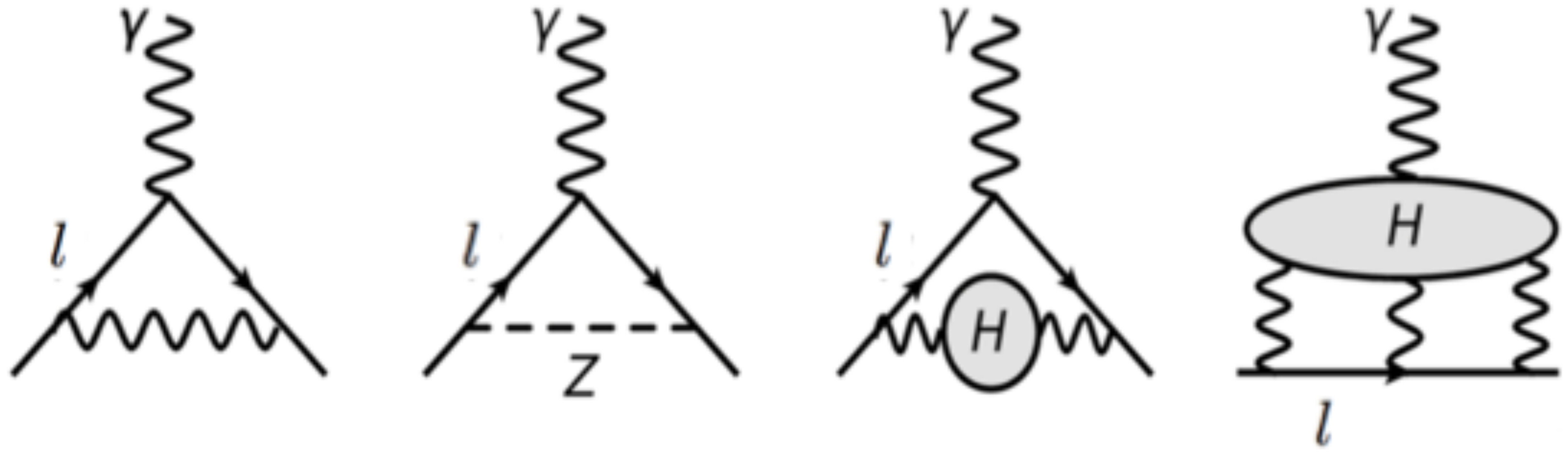
$$g = 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$

- Resolved the discrepancy in g_e as measured by Kusch-Foley in 1947

- This correction is the same for all generations of charged leptons

Higher order terms

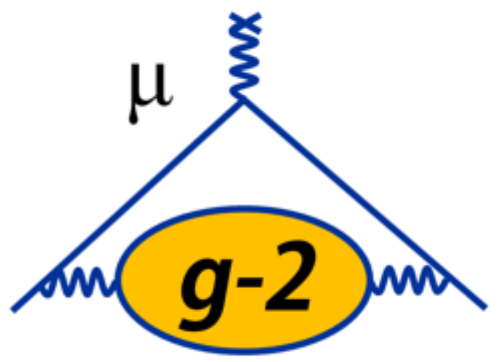
- There are higher order QED, QCD and EW corrections that need to be included

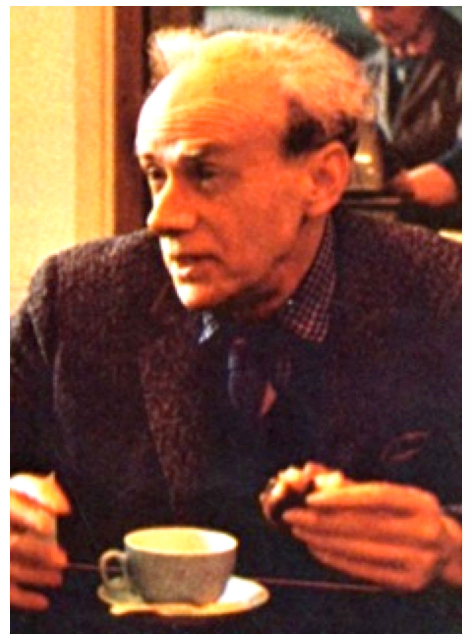


- The size of the higher order corrections depends on mass of the lepton, and the scale of the physics

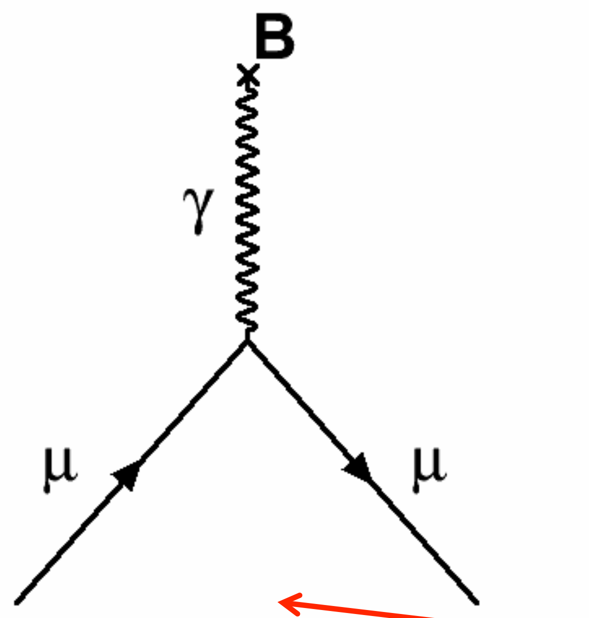
- Let’s look at the calculation for the muon…

Standard Model Components of muon g-2





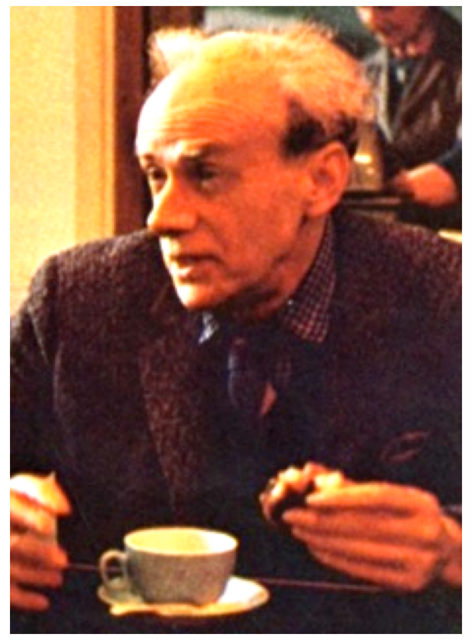
Charged,
spin ½ particle



$$g_\mu = 2$$

Standard Model Components of muon g-2

Dirac



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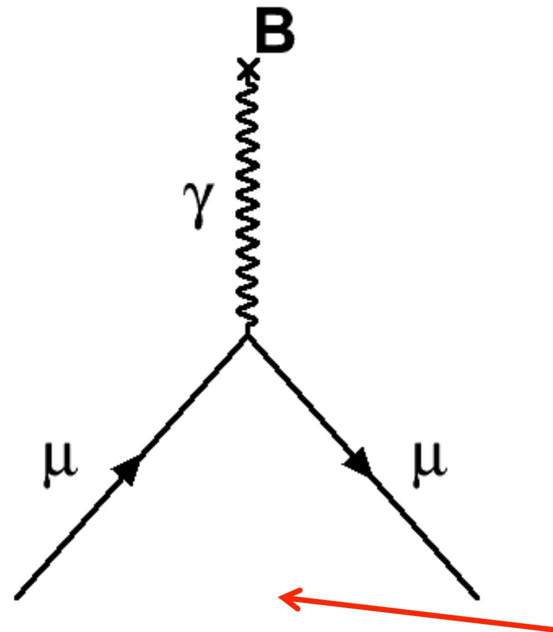
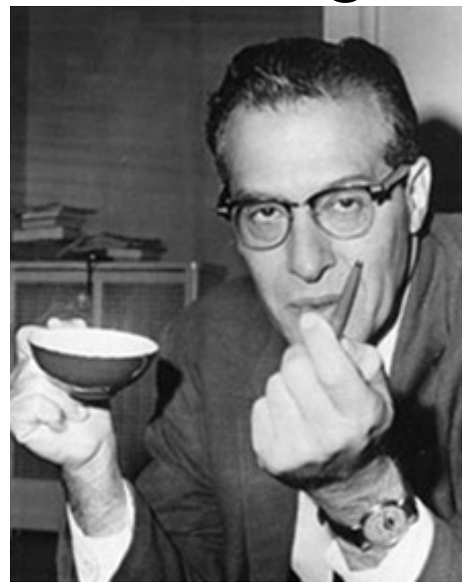
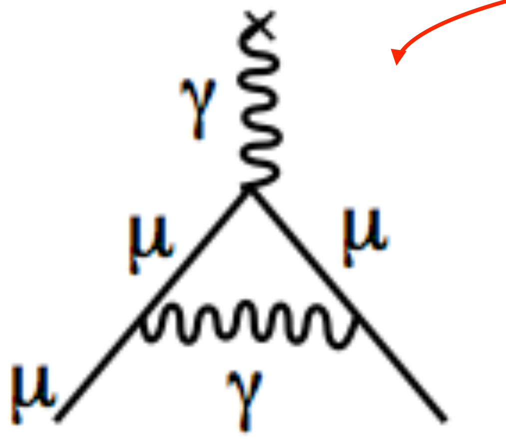


$$g_\mu = 2.0023$$

Schwinger





1st Order QED

$$\frac{\alpha}{2\pi} = 0.00232$$

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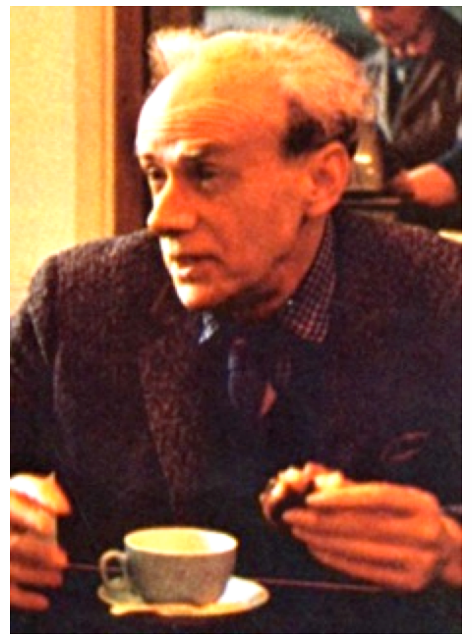

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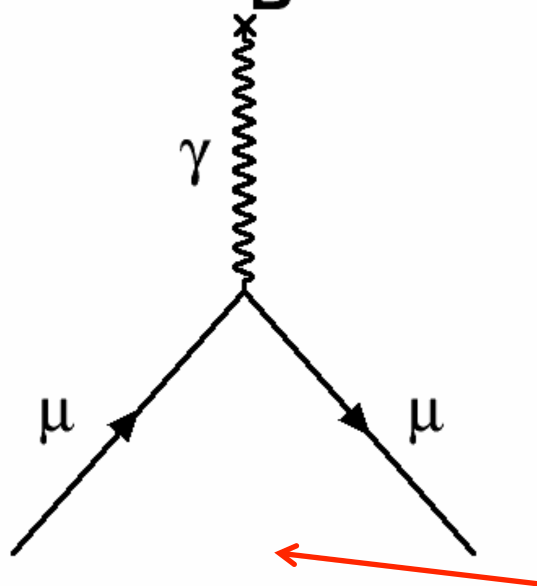
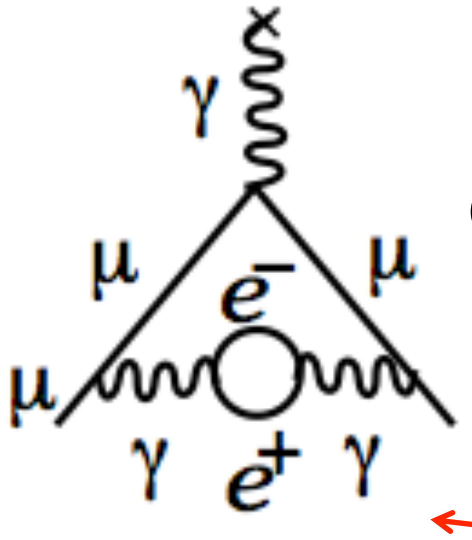


Kinoshita

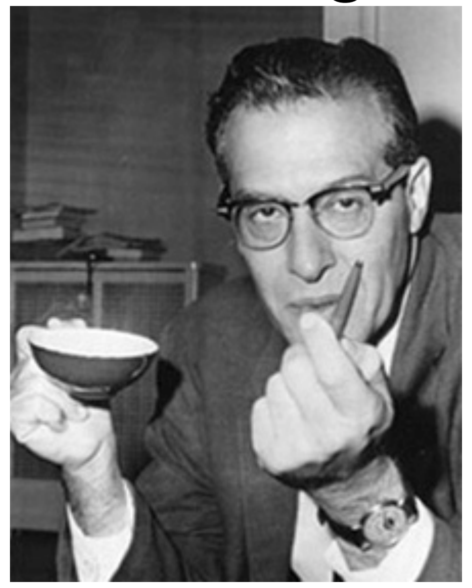
Up to 10th
Order QED

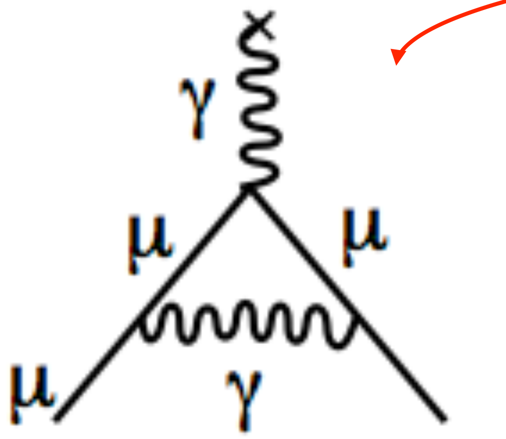


+12671
diagrams

$$g_\mu = 2.002331$$

Schwinger





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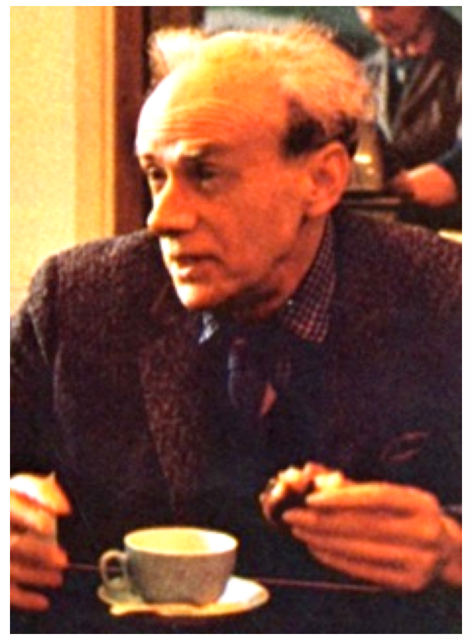

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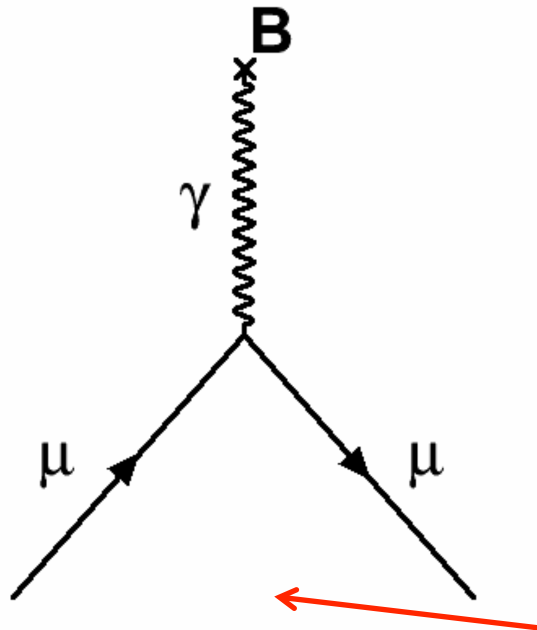

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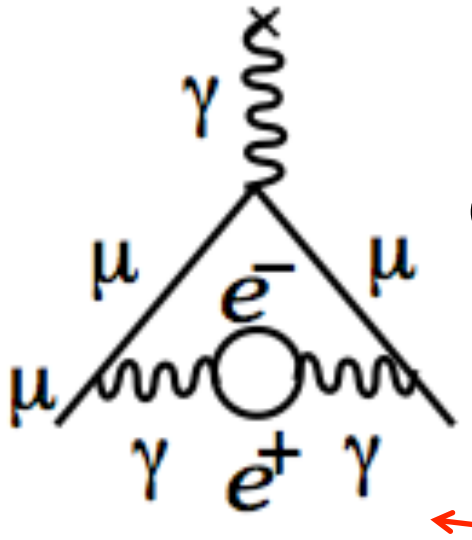
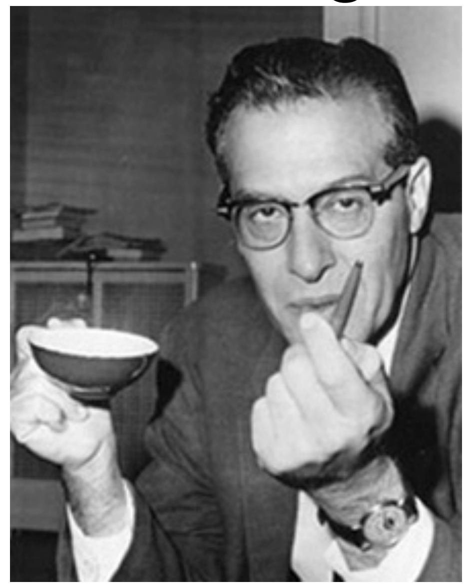
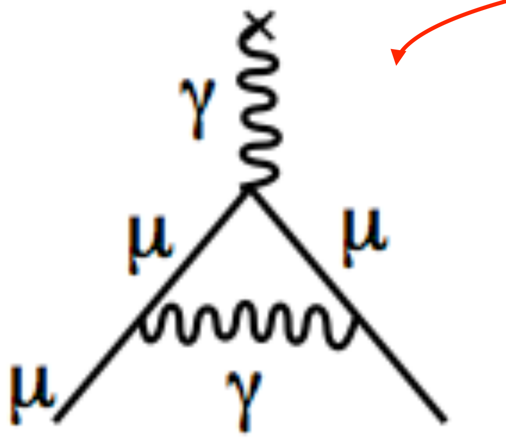


+12671 diagrams

$$g_\mu = 2.00233183$$

Schwinger





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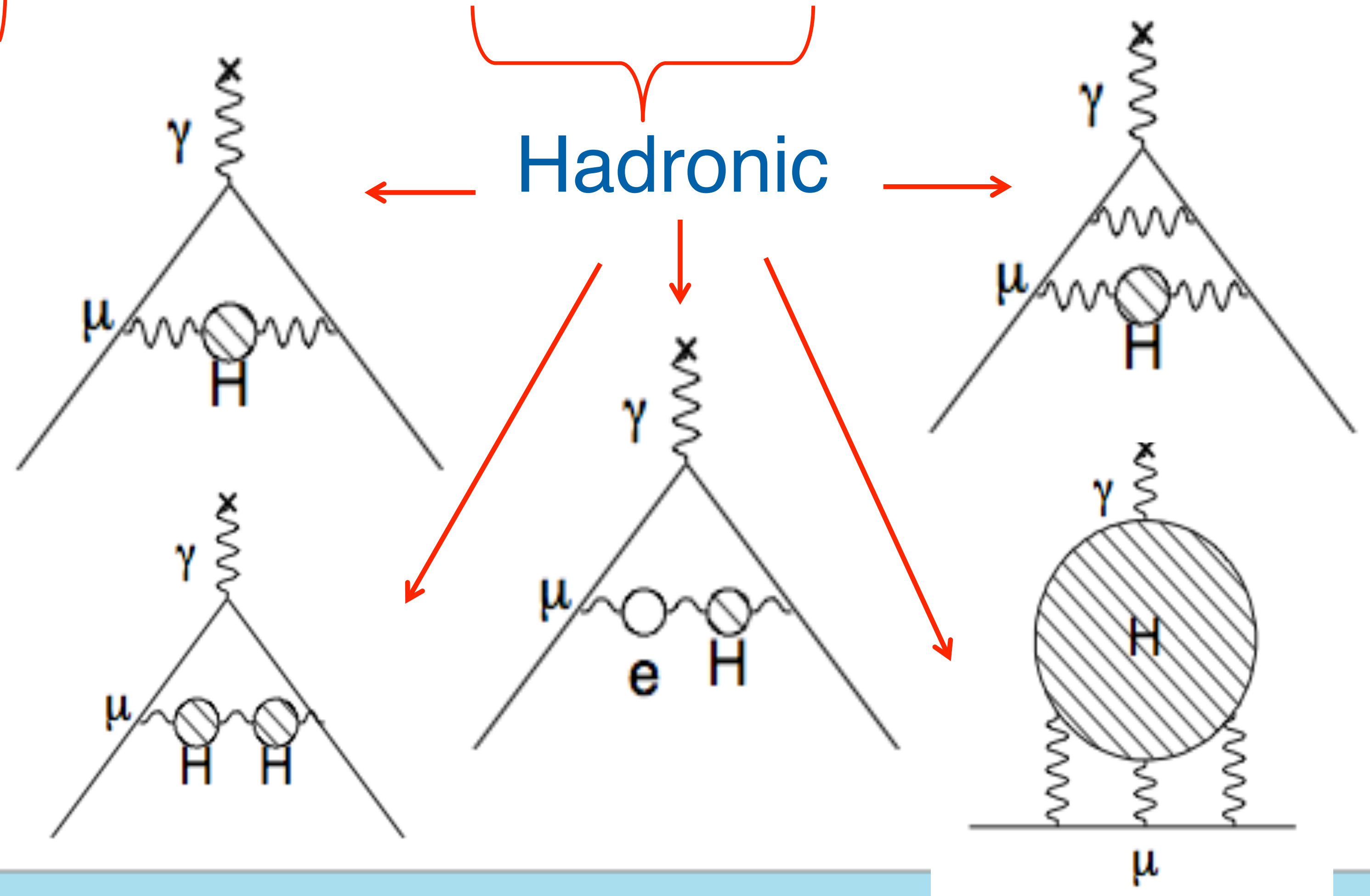
Hadronic



Fermilab

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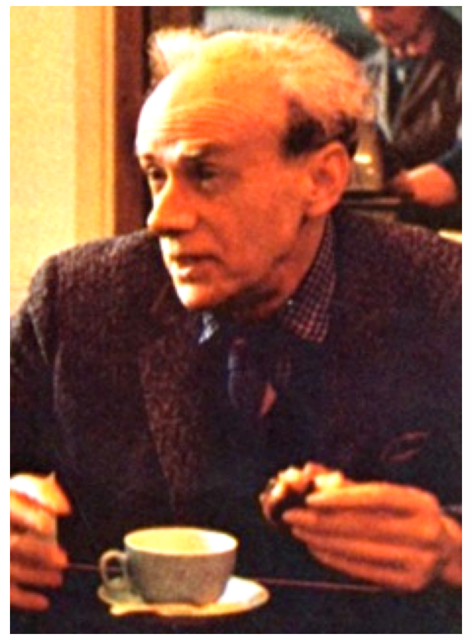

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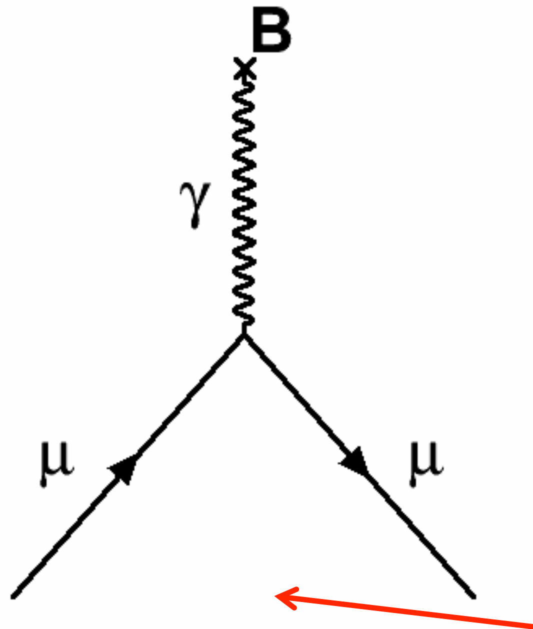

Kinoshita

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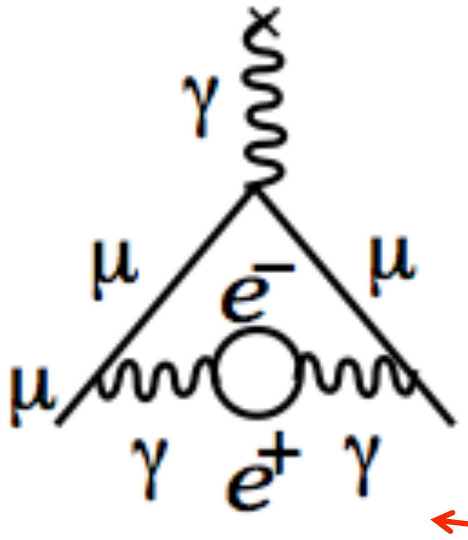

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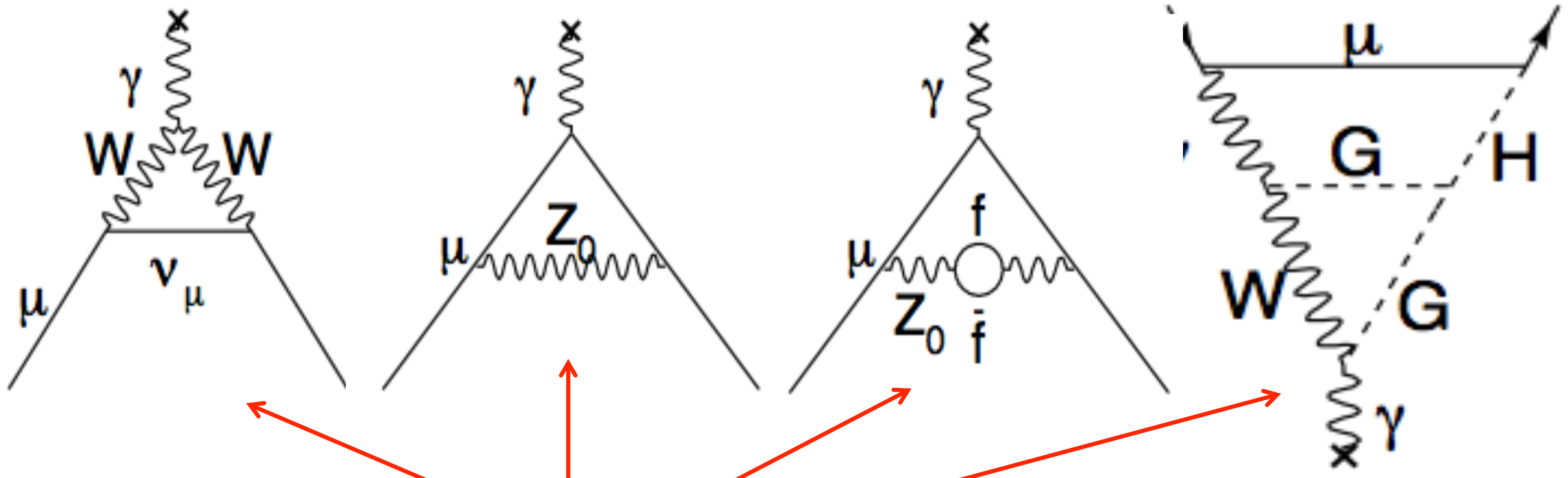
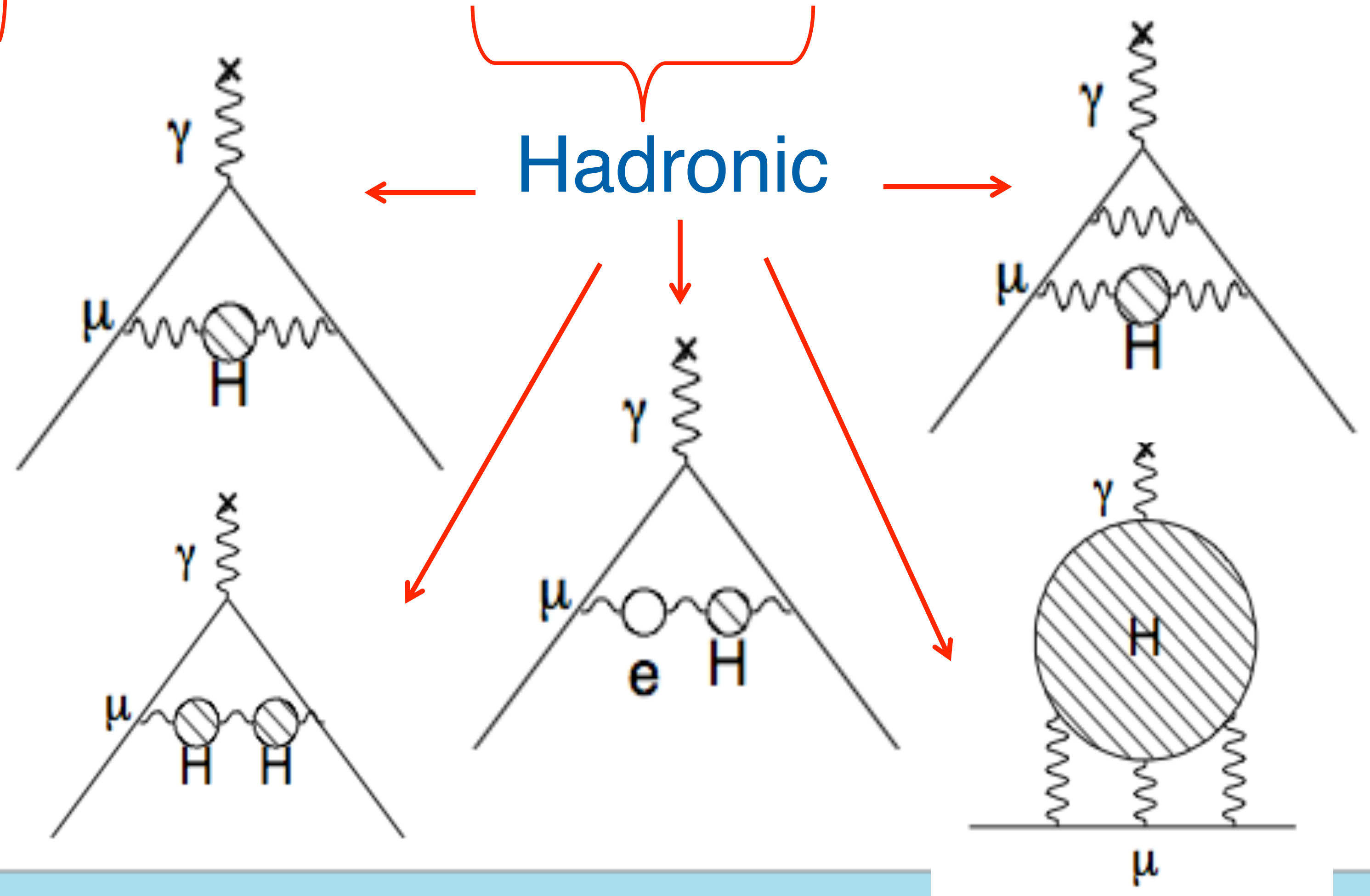


Electroweak

$$g_\mu = 2.00233183636$$

Hadronic



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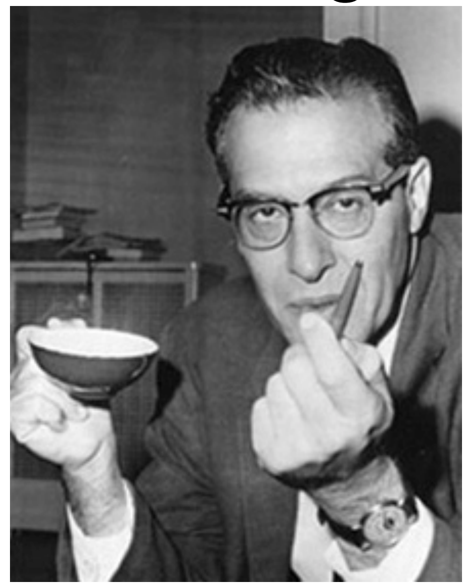

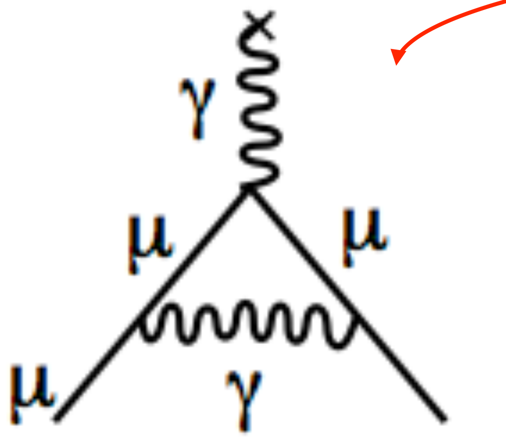

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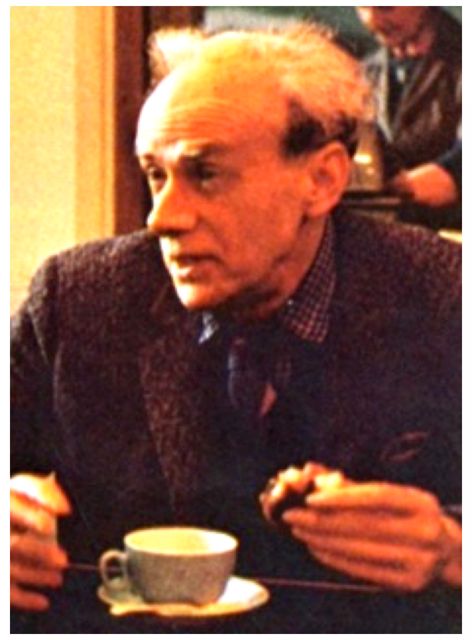

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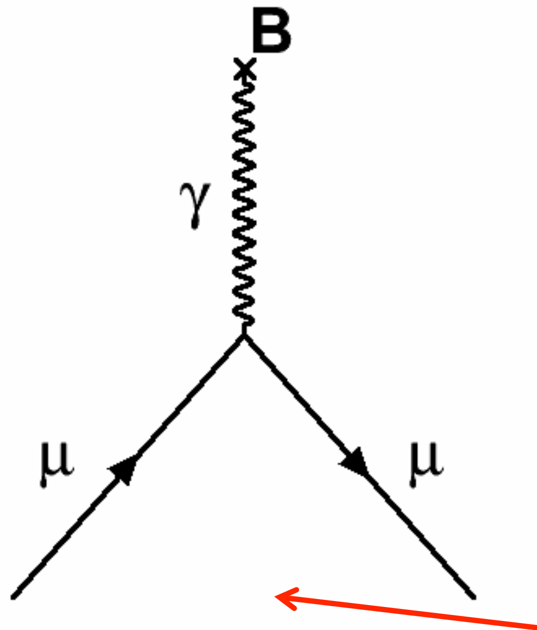

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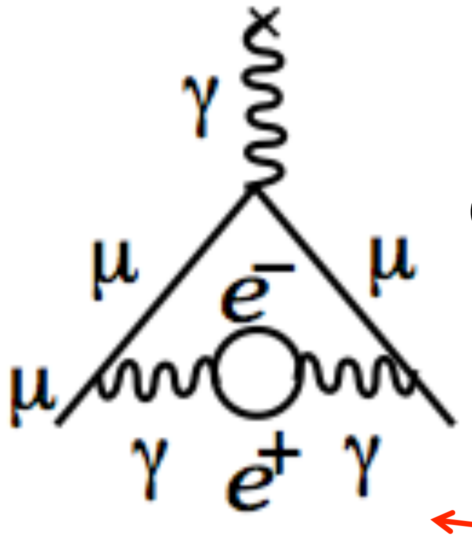

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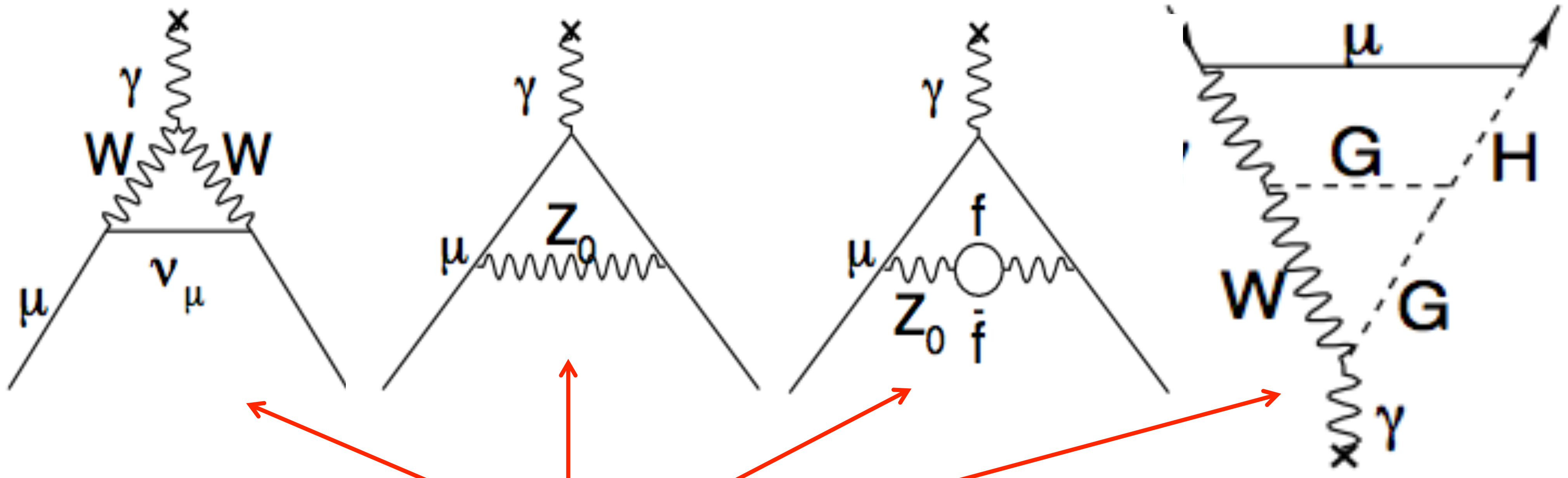
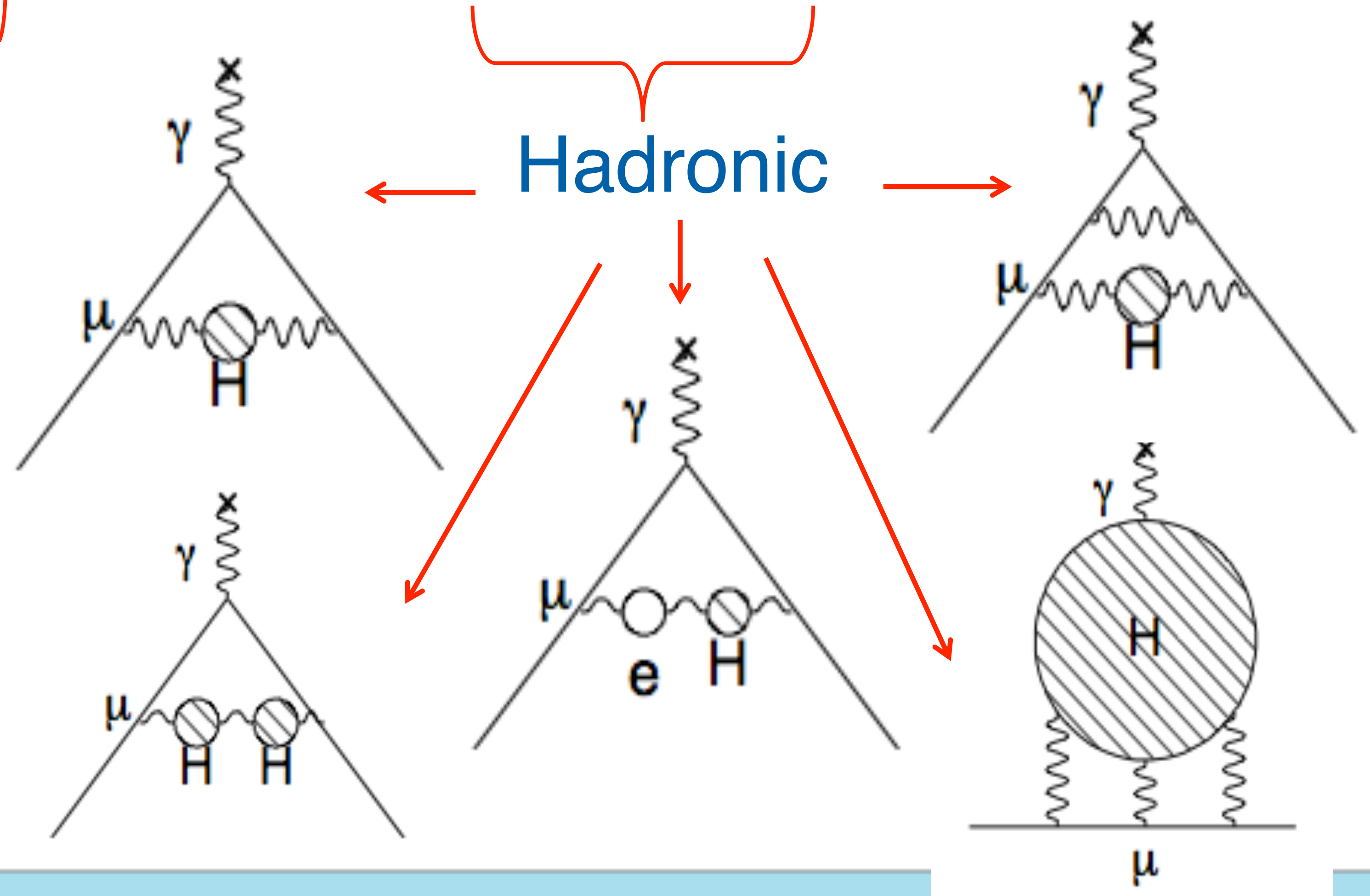


Electroweak

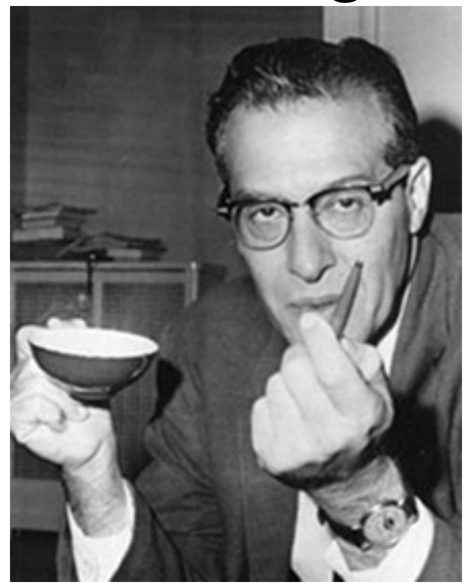
$$g_\mu = 2.00233183636(86)$$

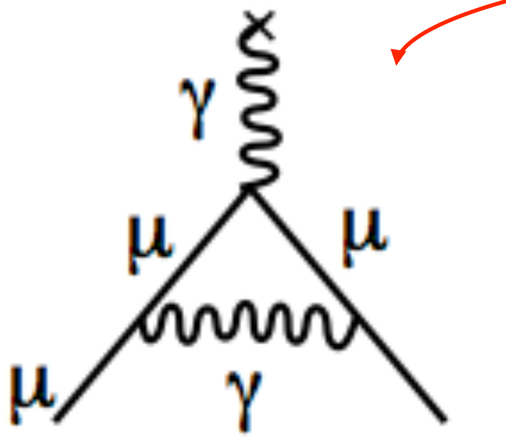


Hadronic

SM uncertainty

Schwinger





1st Order QED

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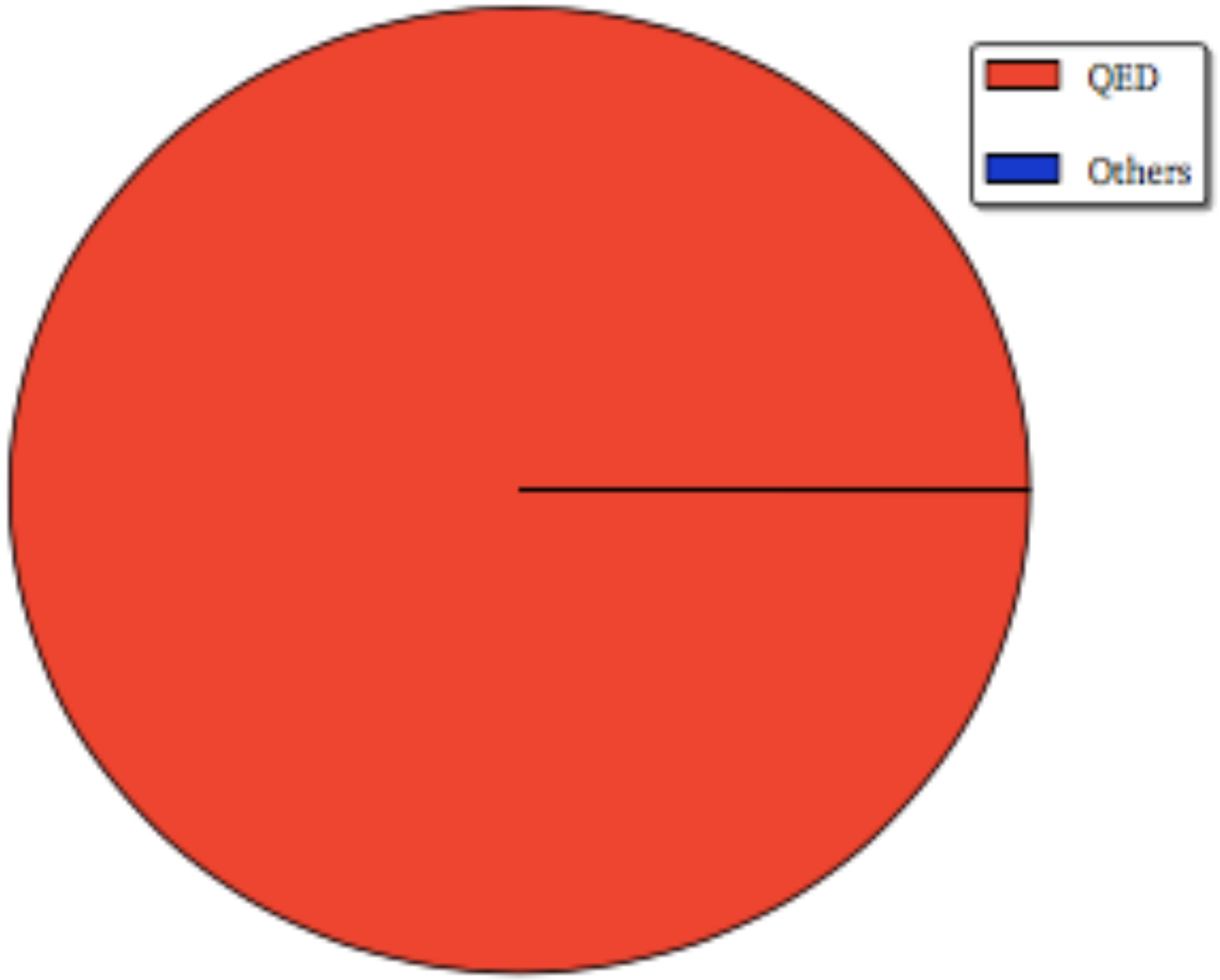
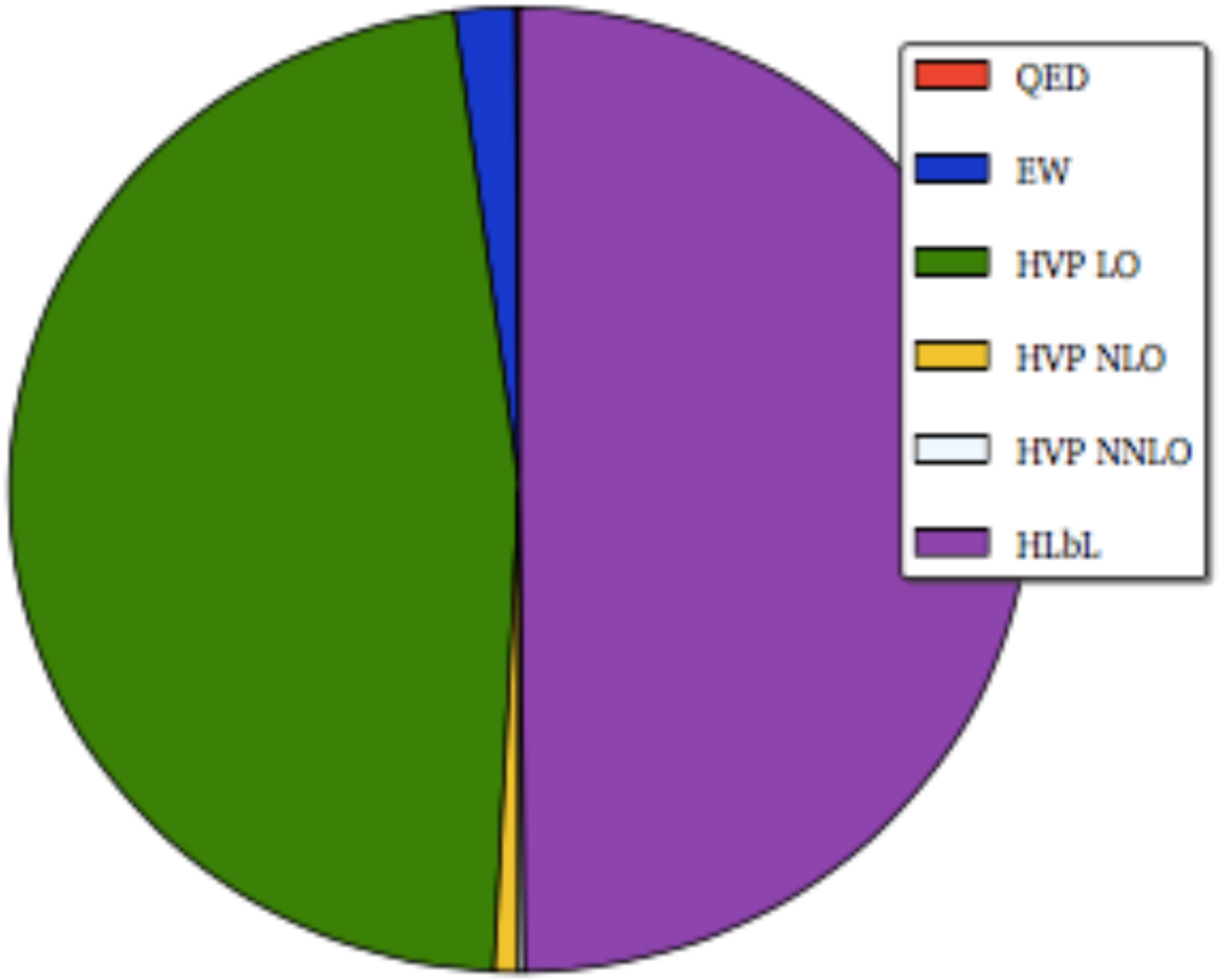
Standard Model Uncertainties

$$a_\mu = \frac{g_\mu - 2}{2}$$

a_μ^{SM}



δa_μ^{SM}



- The SM value of a_μ is dominated by QED
- But its uncertainty is dominated by Hadronic contributions
- Split into Hadronic Vacuum Polarisation (HVP) & Hadronic Light by Light (HLbL)

a_μ Theoretical Status

Contribution	Value (x 10^{-11})	Reference
QED	116 584 718.95 ± 0.08	PRL **109** 111808 (2012)
EW	153.6 ± 1.0	PRD **88** 053005 (2013)

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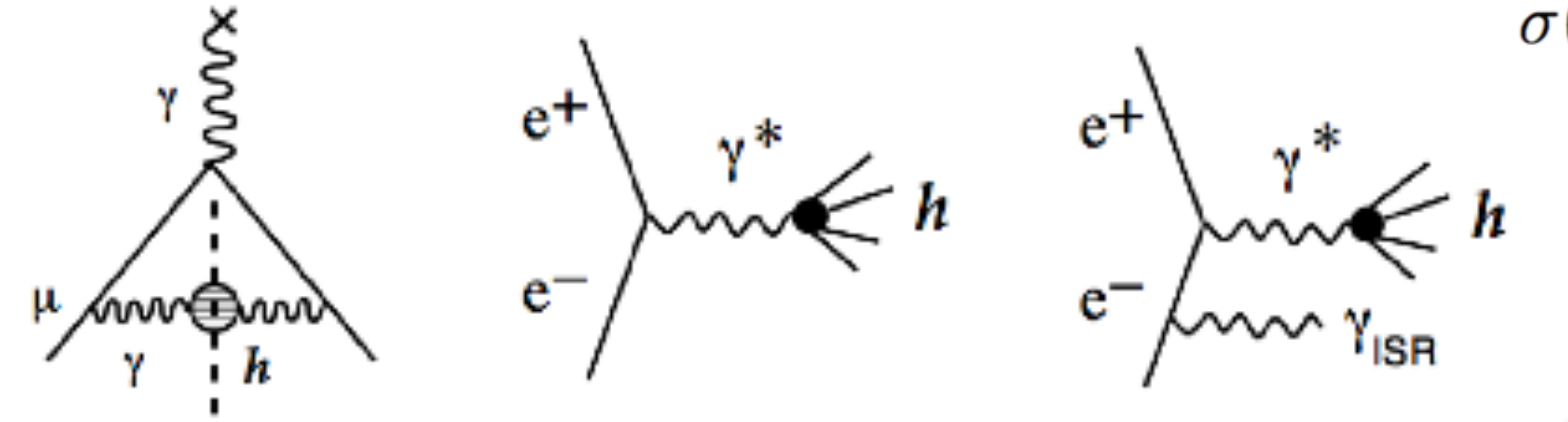
HVP (LO)	**6933 ± 25**	PRD **97** 114025 (2018)

HVP (LO): Lowest-Order Hadronic Vacuum Polarization

- **Critical input** from e^+e^- colliders (data from SND, CMD3, BaBar, KLOE, Belle, BESIII), δa_μ^{HVP} ~ 0.5%; extensive physics program in place to reduce δa_μ^{HVP} to ~ 0.3% in coming years
- **Progress on the lattice**: Calculations at physical π mass; goal: δa_μ^{HVP} ~ 1—2% in a few years (cross-check with e^+e^- data)

$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

$$R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



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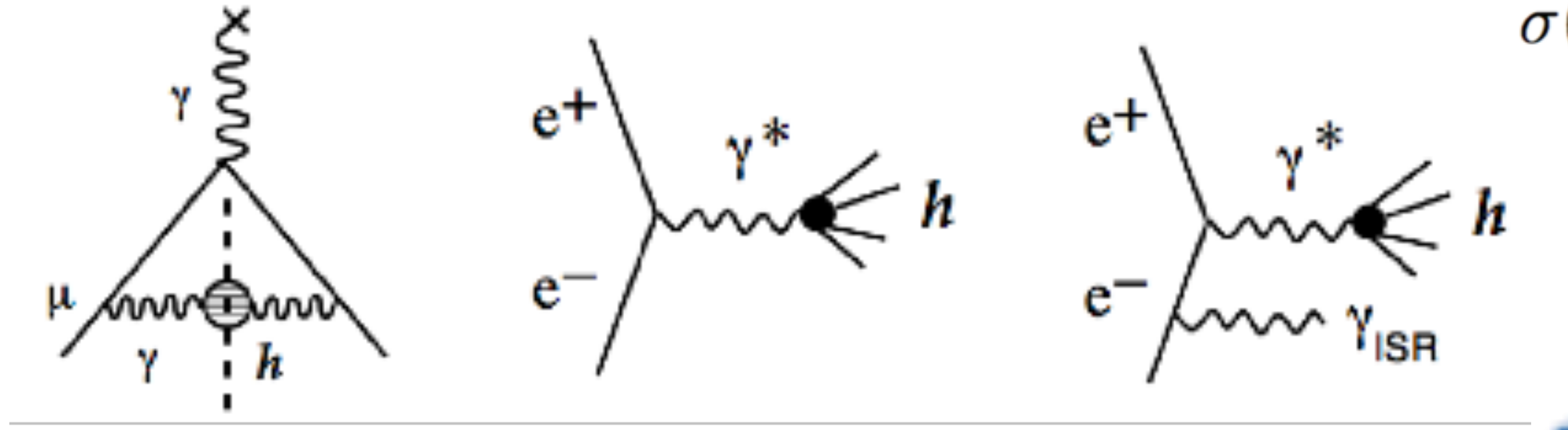

a_μ Theoretical Status

New *ab initio* approaches [PRD **98** 094503 (2018)] finding consistent result of (-93 ± 13) x 10^{-11} — **lattice making big strides**

		12)
		13)
		7)
H... O)	**6933 ± 25**	PRD **97** 114025 (2018)
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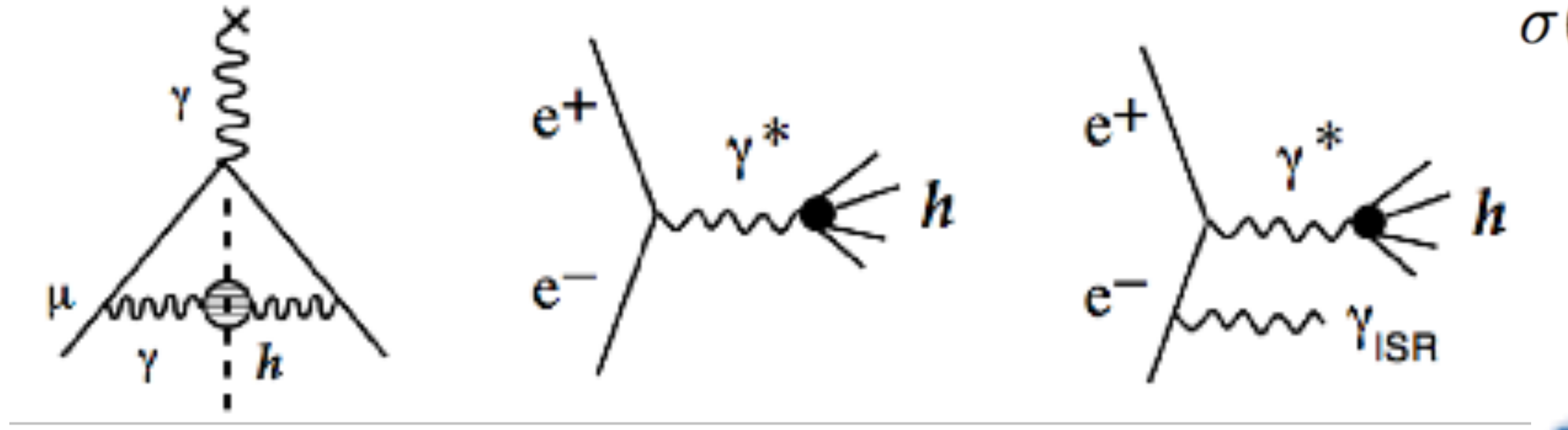

a_μ Theoretical Status

[illegible]	[illegible]	[illegible]
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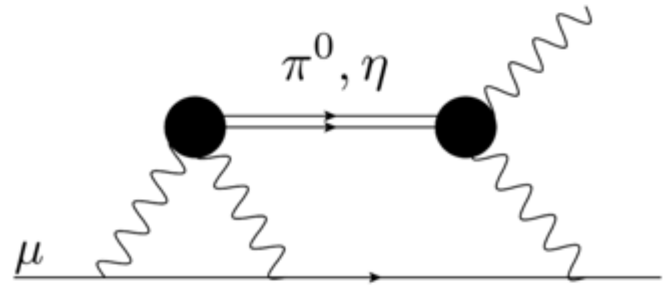
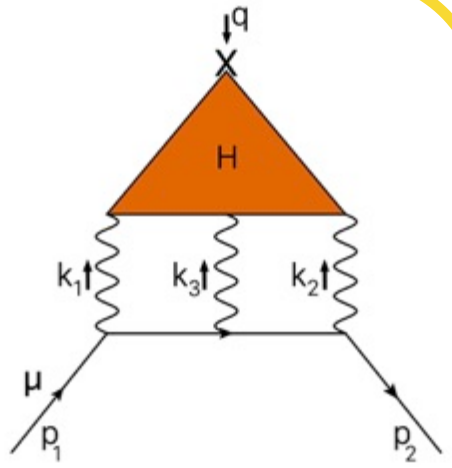
HLbL (LO + NLO)	101 ± 26	PLB 735 90 (2014), EPJ Web Conf 118 01016 (2016)
Total SM	**116 591 818 ± 43 (368 ppb)**	
	116 591 821 ± 36 (309 ppb)	

New *ab initio* approaches [PRD **98** 094503 (2018)] finding consistent result of $(-93 \pm 13) \times 10^{-11}$ — **lattice making big strides**

HLbL: Hadronic Light-by-Light





- Model dependent: based on χPT + short-distance constraints (operator product expansion)
- Difficult to relate to data like HVP (LO); γ* physics, π^0 data (BESIII, KLOE) important for constraining models
- **Theory Progress**: New dispersive calculation approach; extend the lattice (finite volume, disconnected diagrams); Blum et al. making excellent progress

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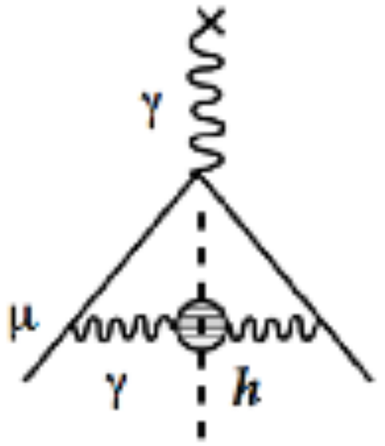

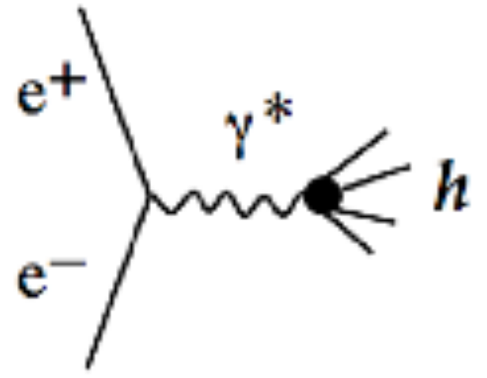

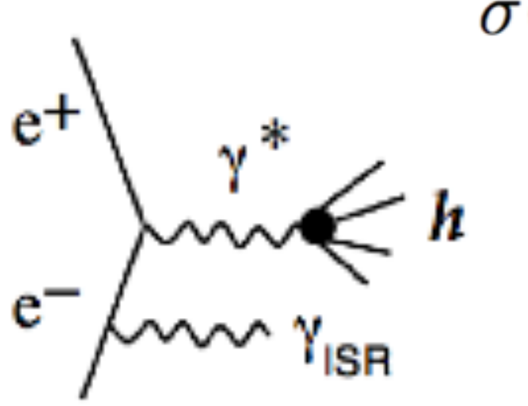

Fermilab

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	...91 818 ± 43	
	...91 821 ± 36	

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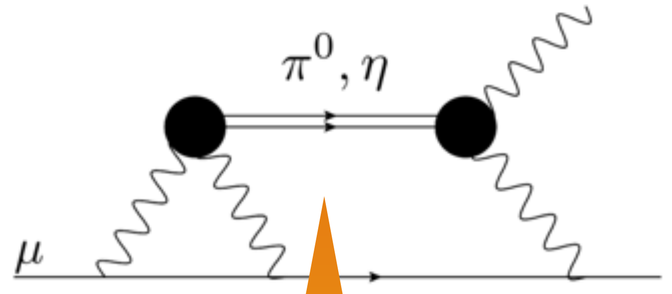
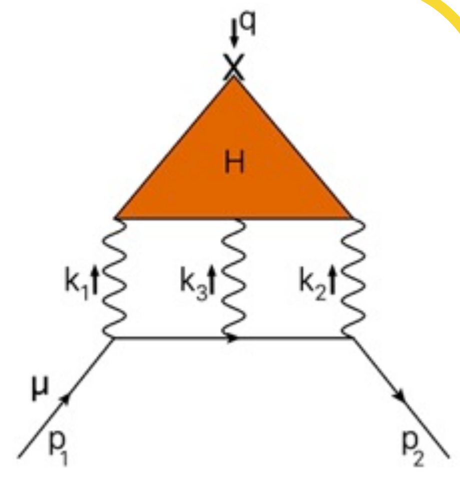
Builds confidence in HLbL term

HLbL: Hadronic Light-by-Light





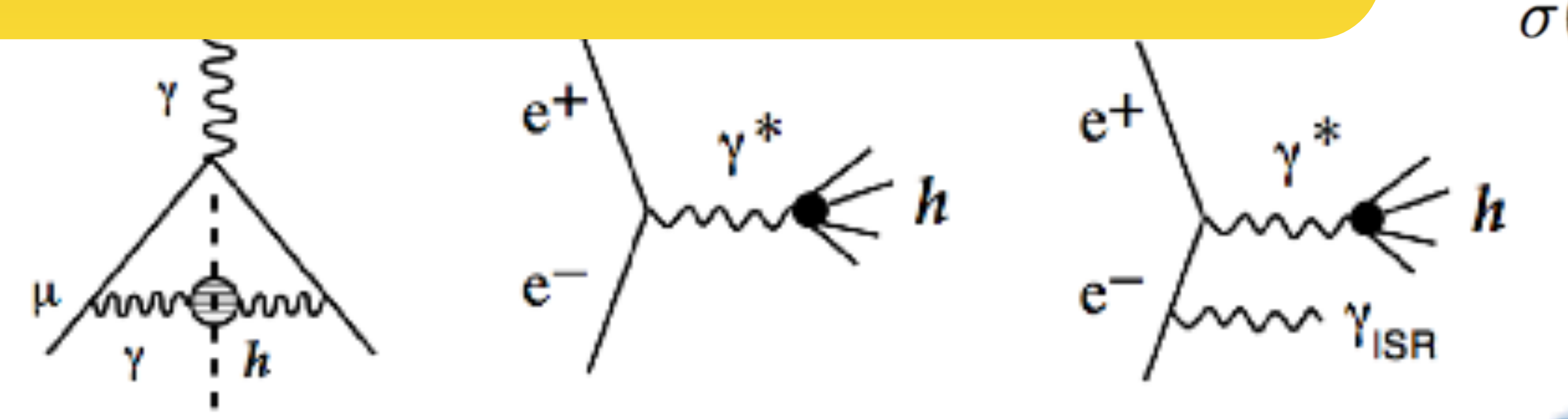
- Model depende...: based on χPT + short-distance constraints (op...tor product expansion)
- Difficult to rel... data like HVP (LO); γ* physics, π^0 data (BESIII, KLOE...ortant for constraining models
- **Theory Prog...** ...ew dispersive calculation approach; extend the l... ...ite volume, disconnected diagrams); ...gress

Recent data-driven calculation [PRL **121** 112002 (2018)] for $a_\mu^{\pi^0-\text{pole}}$ is consistent with earlier vector-, lowest-meson dominance calcs [PRD **65** 073034 (2002), PRD **94** 053006 (2016), EJC **75** 586 (2015)]

HVP (LO): Lowest-Order Hadro...

- **Critical input** from e^+e^- colliders (data ... BaBar, KLOE, Belle, BESIII), δa_μ^{HVP} ~ 0... program in place to reduce δa_μ^{HVP} to ~ 0.3% in coming years
- **Progress on the lattice**: Calculations at physical π mass; goal: δa_μ^{HVP} ~ 1—2% in a few years (cross-check with e^+e^- data)

$$R(s) \equiv \frac{\sigma_{tot}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Lepton Magnetic Moment - Measurement Status

Charged lepton	a_l	Reference	Experiment/author
e [α(Rb)]	[115965218073 ± 28] × 10^{-14}	PRL **100** 120801 (2008)	Gabrielse et. al
e [α(Cs)]	[115965218161 ± 23] × 10^{-14}	Science **360** 191 (2018)	Parker et. al
μ^+	[116592020 ± 130] × 10^{-11}	PRL **86** 2227 (2001)	BNL
μ^-	116592140 ± 70] × 10^{-11}	PRL **92** 161802 (2004)	BNL
μ (combined)	116592080 ± 54] × 10^{-11}	PRD **73** 072003 (2006)	BNL
τ	$-0.052 < a_\tau < 0.013$ (95%)	Eur. Phys. J C35 (2004)	DELPHI

- Electron limit improved by new α_{EM}, gives $a_e \sim -2.5\sigma$ from SM expectation
- Muon limit gives tantalising discrepancy of $a_\mu \sim 3.5\sigma$ from SM
- Potential new a_τ at LHC using heavy ions? **arxiv: 1908.05180**

BSM contributions?

- Sensitivity to new physics is proportional to the squared mass of the probe

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 4 \times 10^4 \qquad \left(\frac{m_\tau}{m_e}\right)^2 \sim 1 \times 10^7$$

- 5TeV scale NP would affect a_e, a_μ, a_τ at $1{\times}10^{-14}$, $4{\times}10^{-10}$, $1{\times}10^{-7}$ level
- Muons offer most realistic opportunity for NP observation

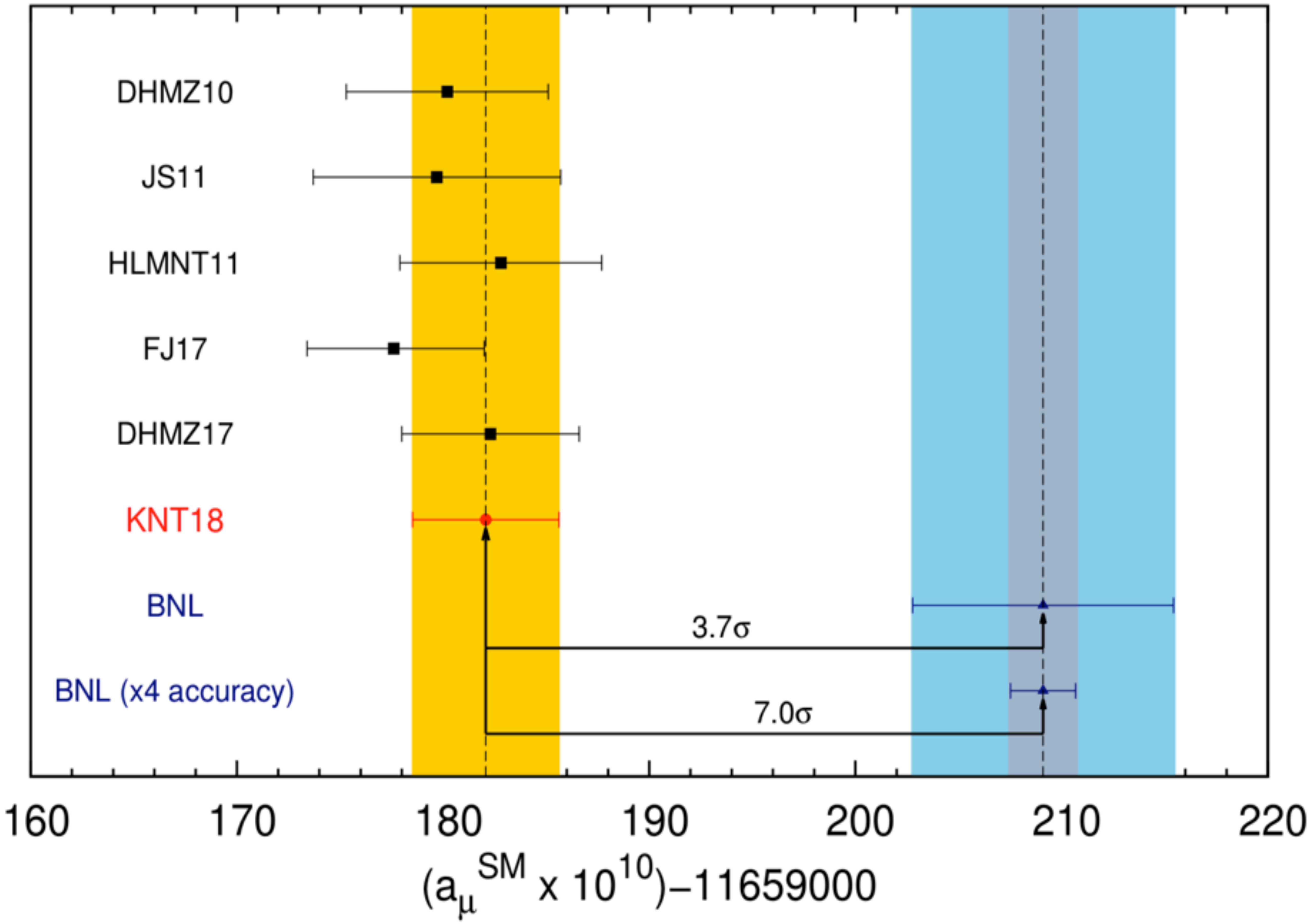
- Note also that the NP has to be flavour and CP conserving, and chirality flipping - related to EWSB
- Motivates extended Higgs models (2-Higgs doublet, high tan(β) SUSY)

- Sensitivity outside of EWSB - Dark sector

Muon - Current status

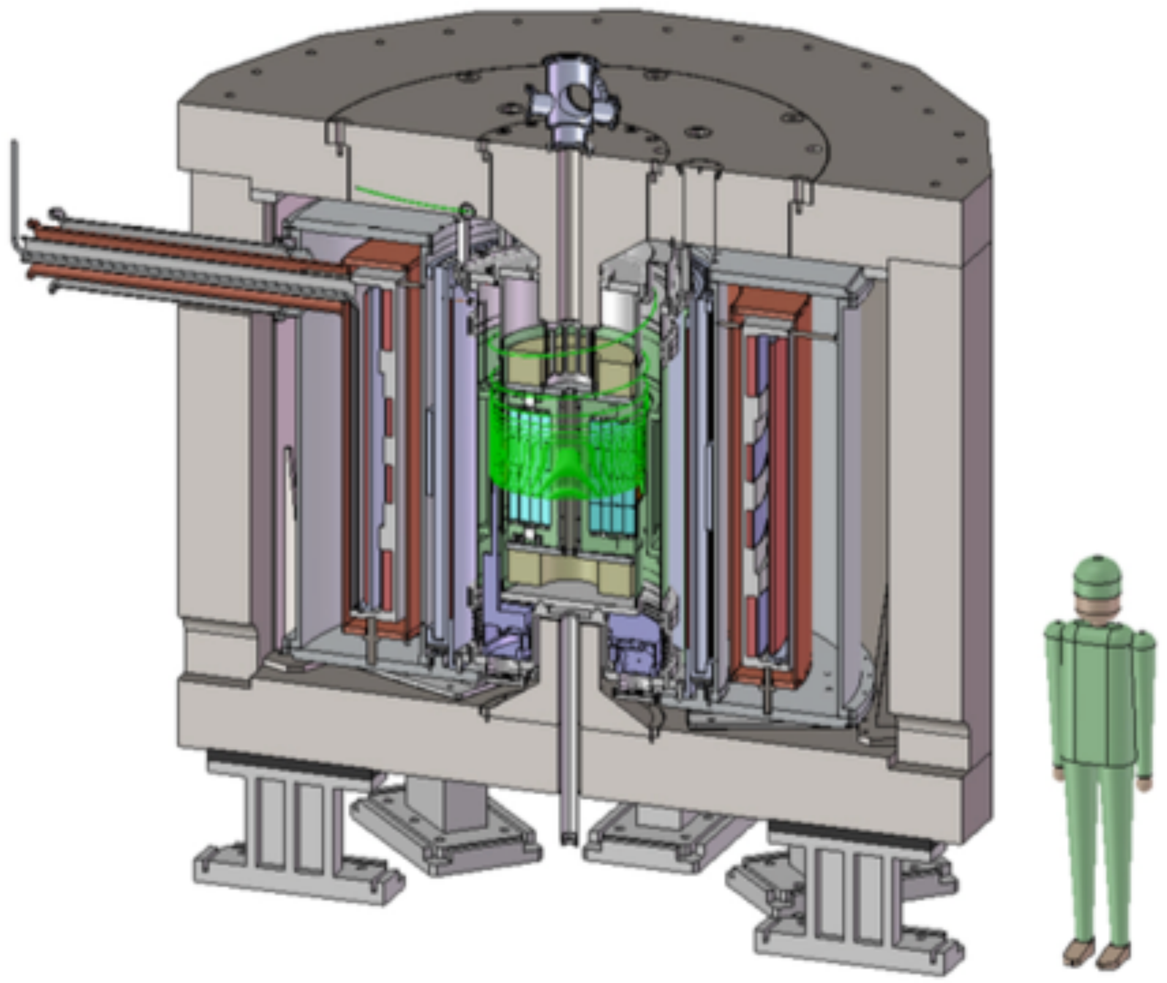
- New combination (KNT18) has not moved central value significantly, reduced uncertainties
- > 3.5σ discrepancy persists
- Theory groups are making progress to achieve competitive uncertainties on same time scale as new g-2 experiments…

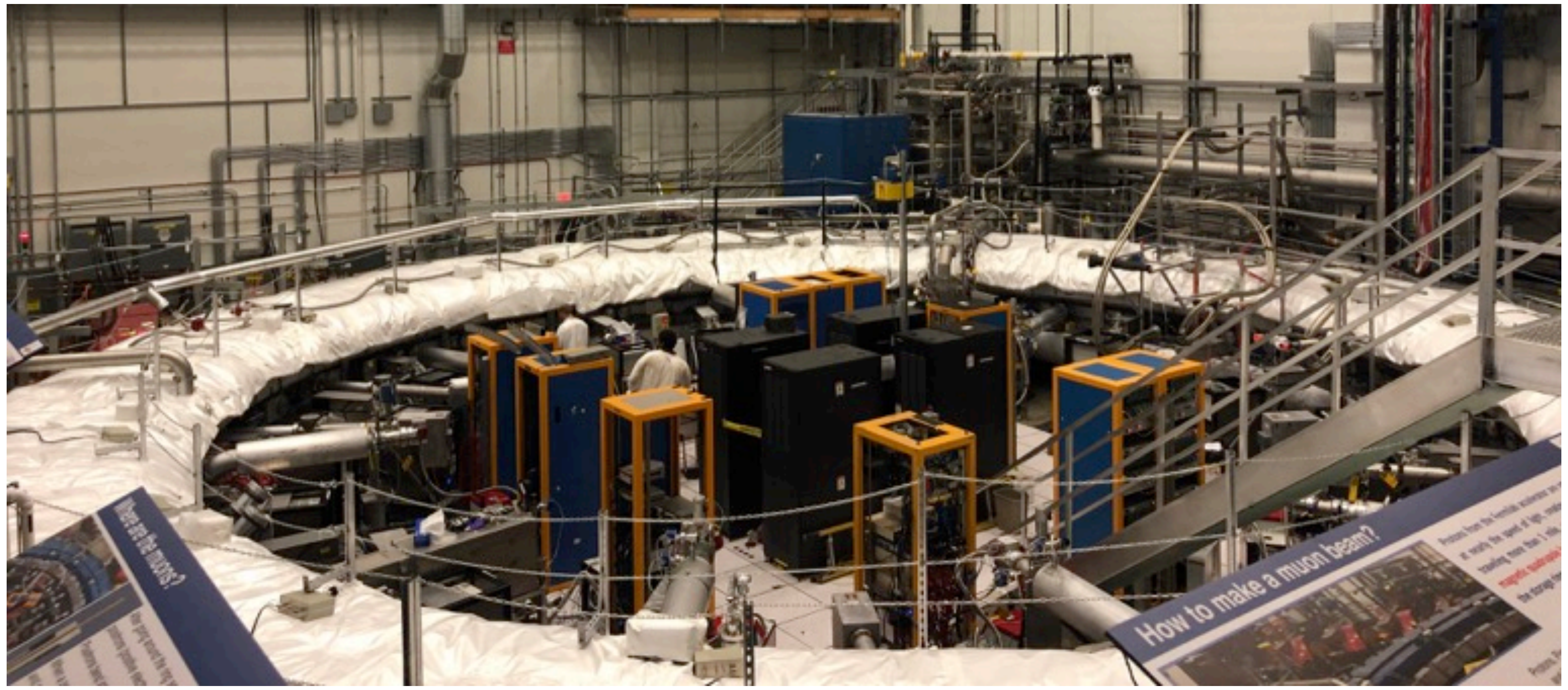
PRD **97** 114025 (2018)



Upcoming muon g-2 measurements

- BNL measurement was statistically limited!
- 2 experiments that aim to measure a_μ: Fermilab and JPARC
- Both rely on highly uniform B-field and high intensity polarised muon beams





- Fermilab g-2 ia BNL style experiment that has been taking data for 2 years
- Aiming for factor 4 improvement on BNL number, 21 × total muons!

Measurement Principle

- Inject polarized muon beam into magnetic storage ring
- Measure **difference** between spin precession and cyclotron frequencies
- If g = 2, $\omega_a = 0$
- $g \neq 2$, $\omega_a \cong (e/m_\mu)a_\mu B$

Spin precession freq.

$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

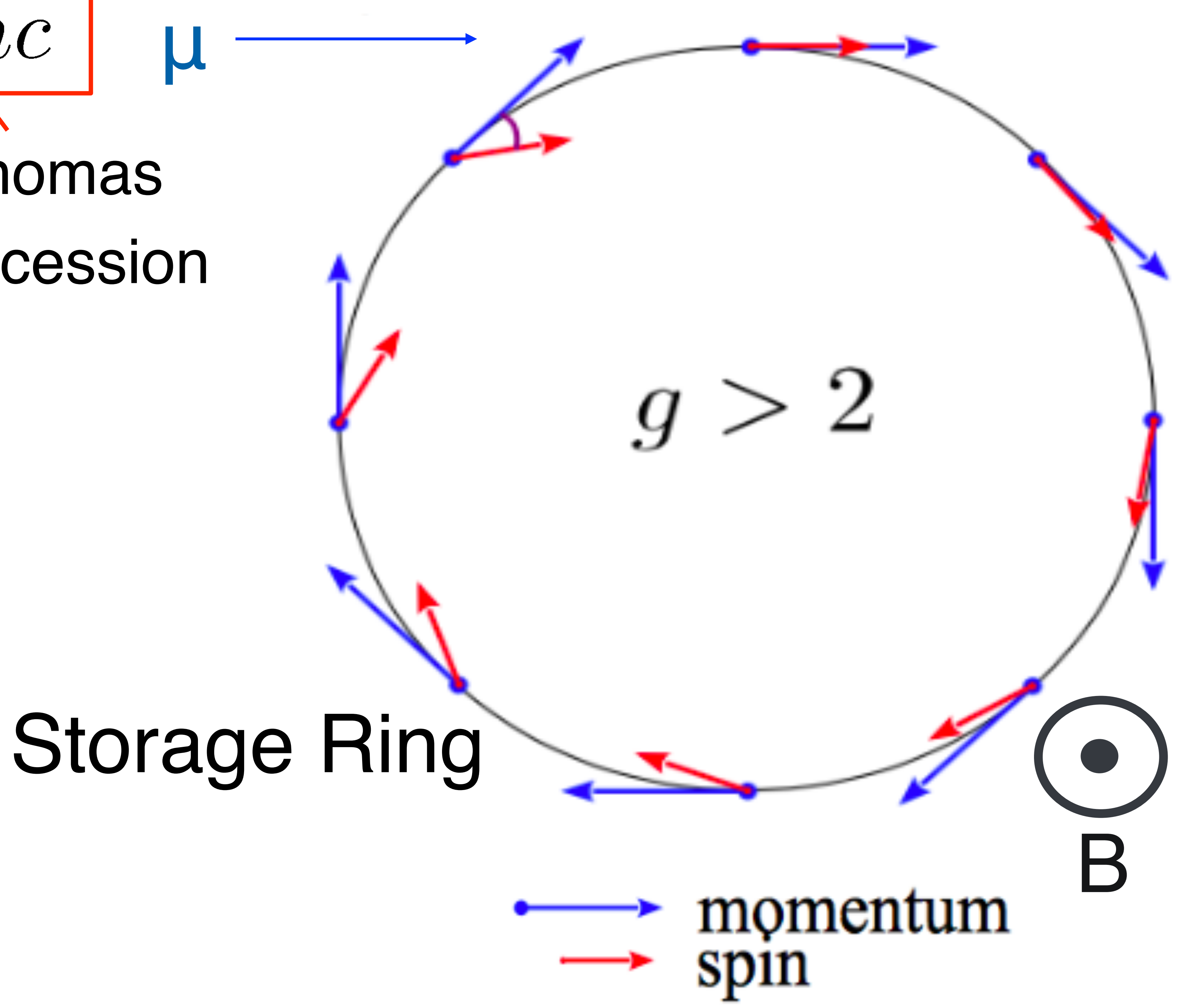
Larmor precession

Thomas precession

Cyclotron freq.

$$\omega_c = \frac{eB}{\gamma mc}$$

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$



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

3 ppb 22 ppb 0.3 ppt

Rev. Mod. Phys. **88**, 035009 (2016)

- We measure ω_a and ω_p separately
- Aiming for 70 ppb precision on each (systematic)
- **Target: δa_μ(syst) = 140 ppb; factor of 4 improvement over BNL**

Real World Considerations

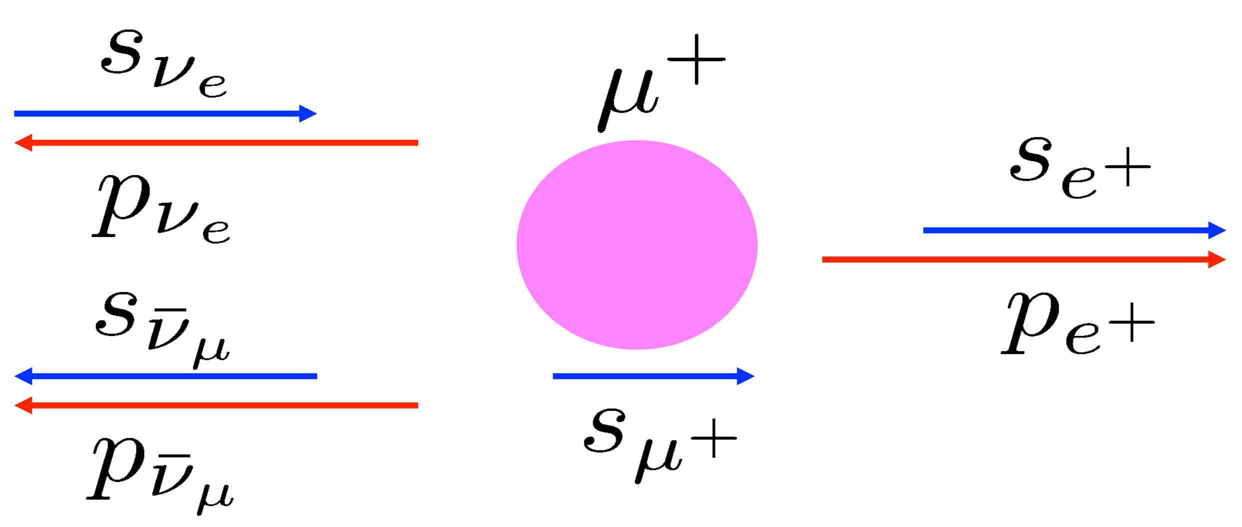
- Muon beam has a small vertical component
- We need to use Electric fields to focus the beam so we can store the muons

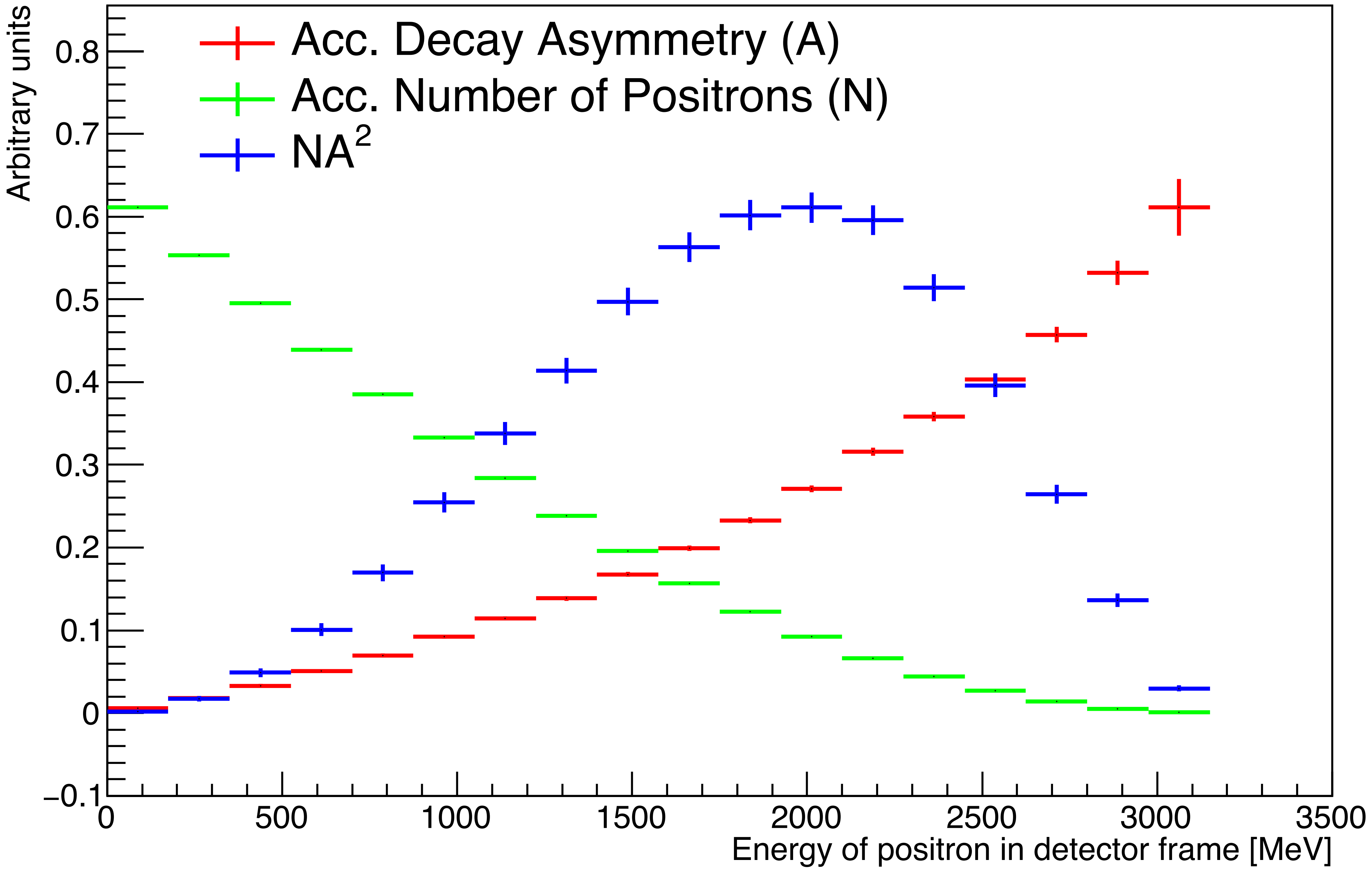
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}\right]$$

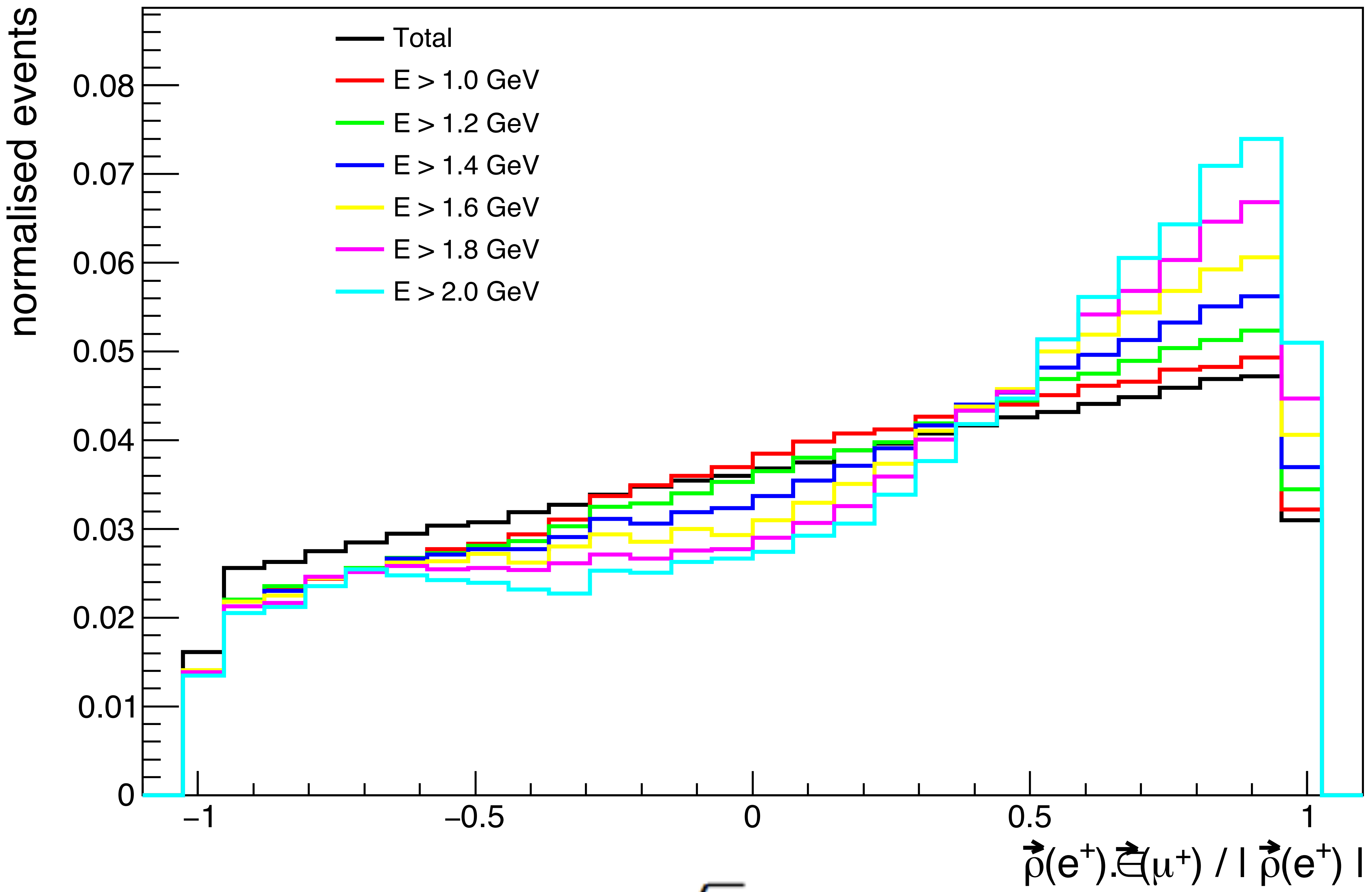
- This introduces an unwanted $\beta \times E$ term…
- …unless γ = 29.3, then E-field term vanishes: we call this the "magic" momentum (3.094 GeV)
- Leaves 2 effects that we can't ignore:
  - Not all muons are exactly at magic momentum
  - Some small degree of vertical motion of muons (reduces effective B-field)
- We use tracker and beam dynamics models to calculate the small corrections for these (< 1 ppm)

Measuring the muon spin…

- e^+ preferentially emitted in direction of muon spin





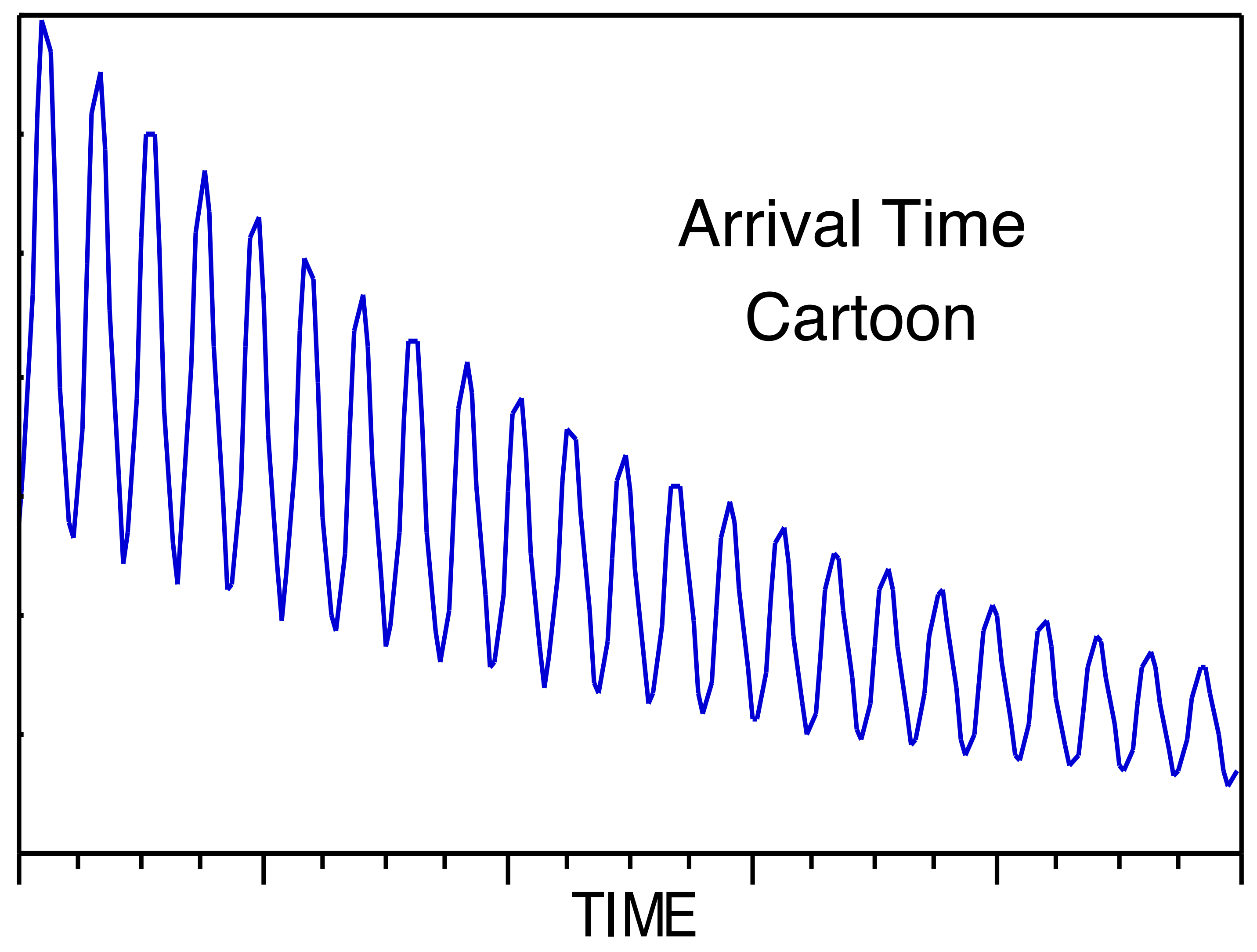


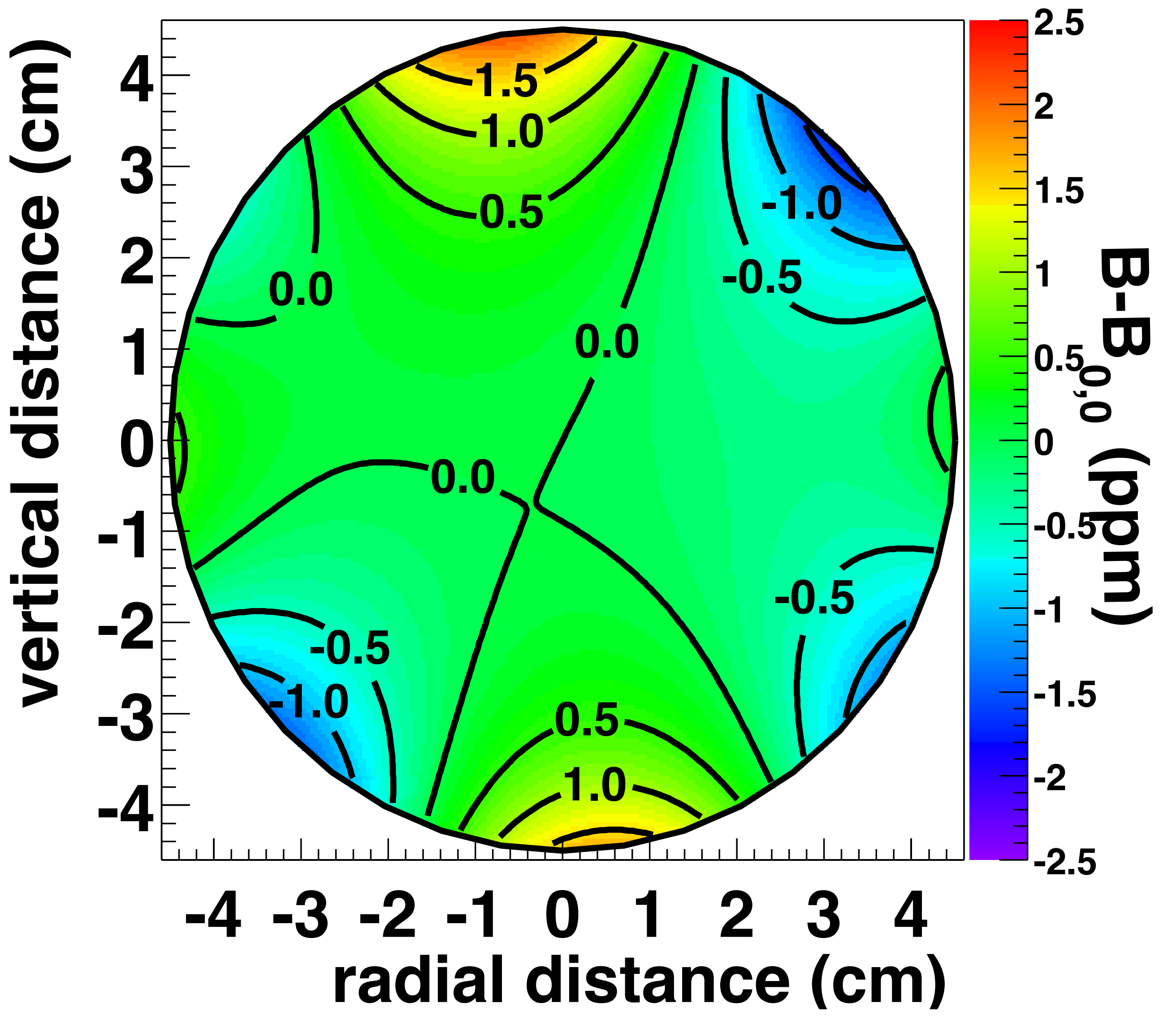
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{NA^2}}$$

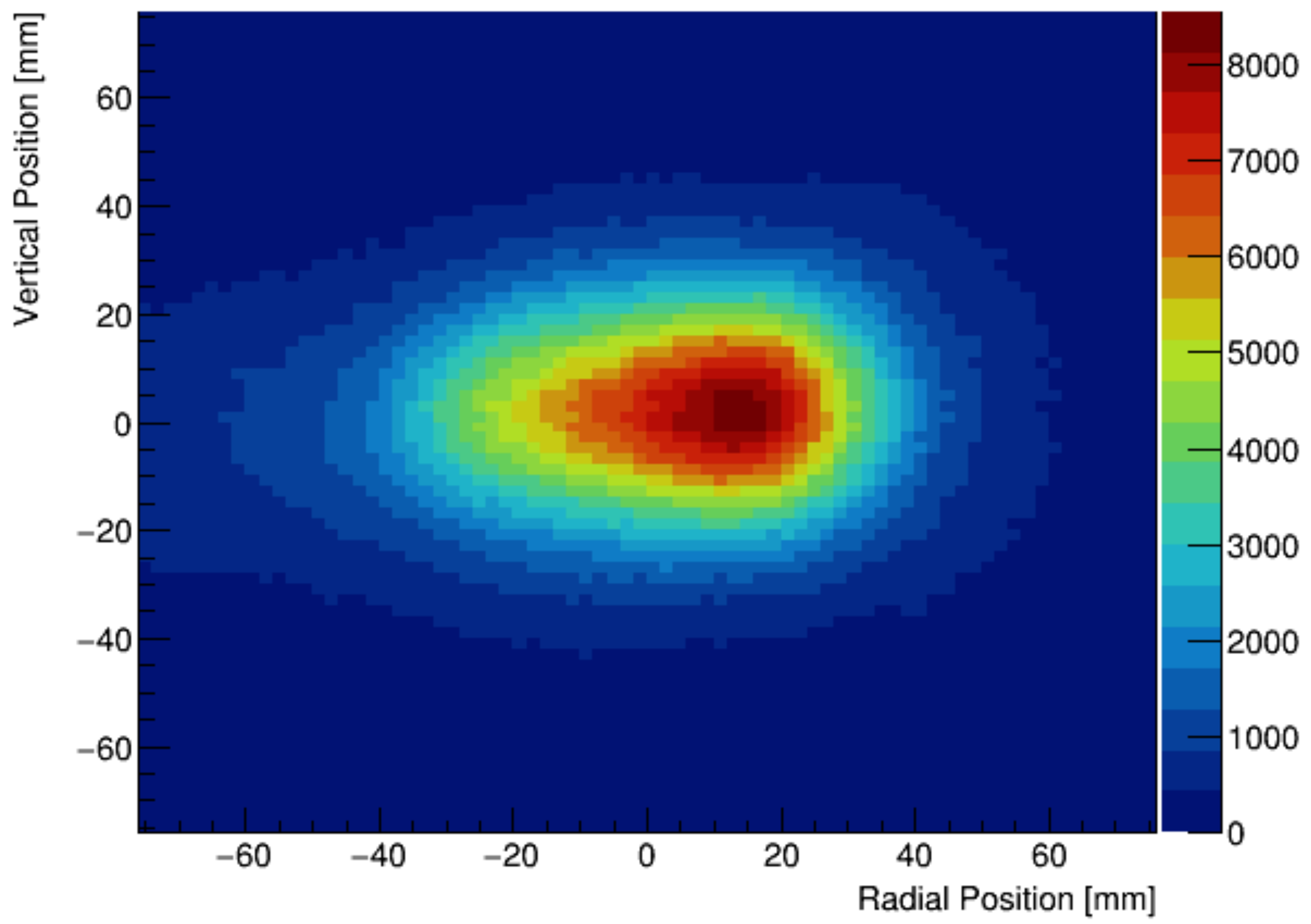
- Asymmetry is larger for high momentum e+
- Optimal cut at E~1.8 GeV

Measurement Principle

- Three ingredients to measure $a_\mu \sim (\omega_a / \tilde{\omega}_p)$
  - ω_a: Arrival time spectrum of high energy positrons
  - ω_p: Magnetic field in storage region measured by proton NMR
  - $\tilde{\omega}_p$: Muon distribution to get weighted magnetic field frequency







Systematic Uncertainty Comparison: E821 and E989

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

ω_a Goal: Factor of 3 Improvement		
Category	**E821 (ppb)**	**E989 Goal (ppb)**
Gain Changes	120	20
Lost Muons	90	20
Pileup	80	40
Horizontal CBO	70	< 30
E-field/pitch	110	30
Quadrature Sum	**214**	**70**

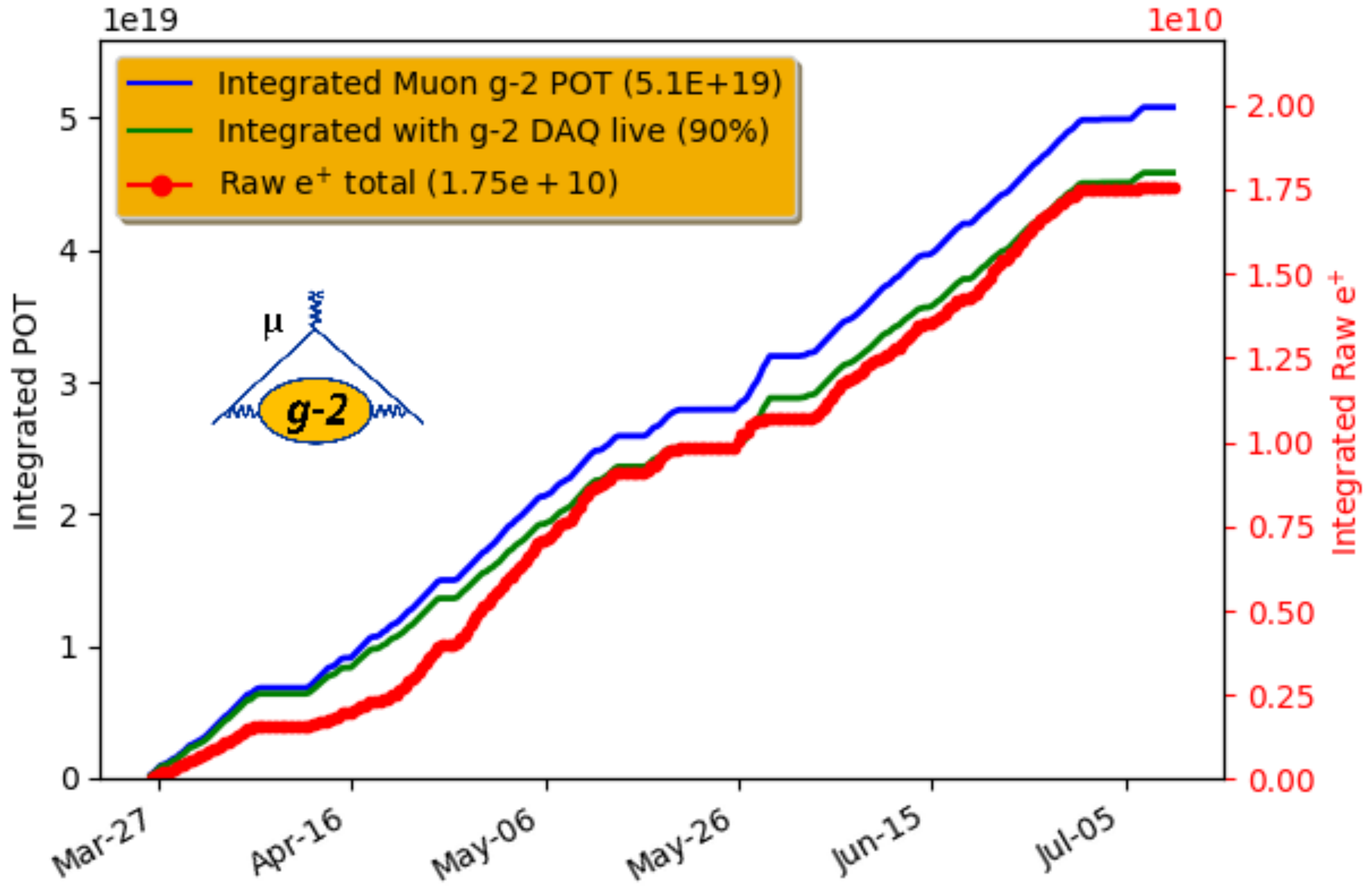
- New hardware (calorimeters, trackers, NMR)
- Improved analysis techniques
- Reduce uncertainties by at least a factor of 2.5

ω_p Goal: Factor of 2.5 Improvement		
Category	**E821 (ppb)**	**E989 Goal (ppb)**
Field Calibration	50	35
Trolley Measurements	50	30
Fixed Probe Interpolation	70	30
Muon Convolution	30	10
Time-Dependent Fields	–	5
Others	100	50
Quadrature Sum	**170**	**70**

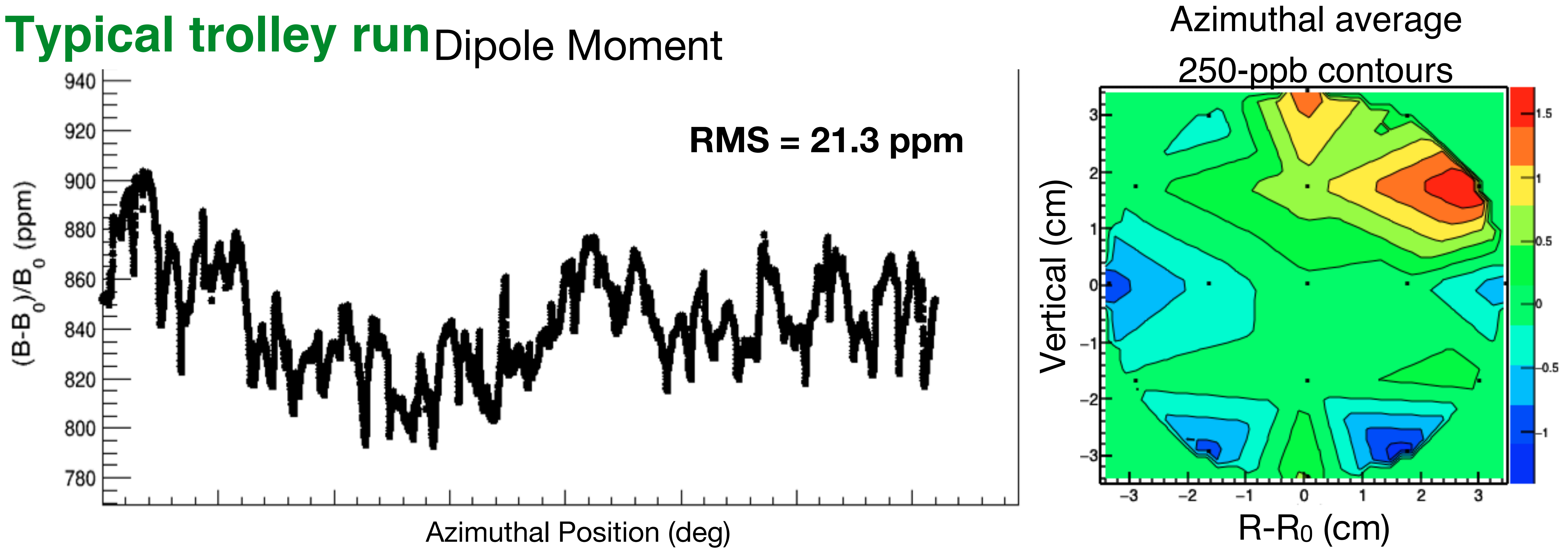
Run 1 Overview

- Data taking period: April—July 2018
- Accumulated ~ 1.4 x BNL statistics (after data quality cuts) — **$\delta\omega_a$(stat) ~ 350 ppb**
- Field uniformity ~ 2x better than BNL

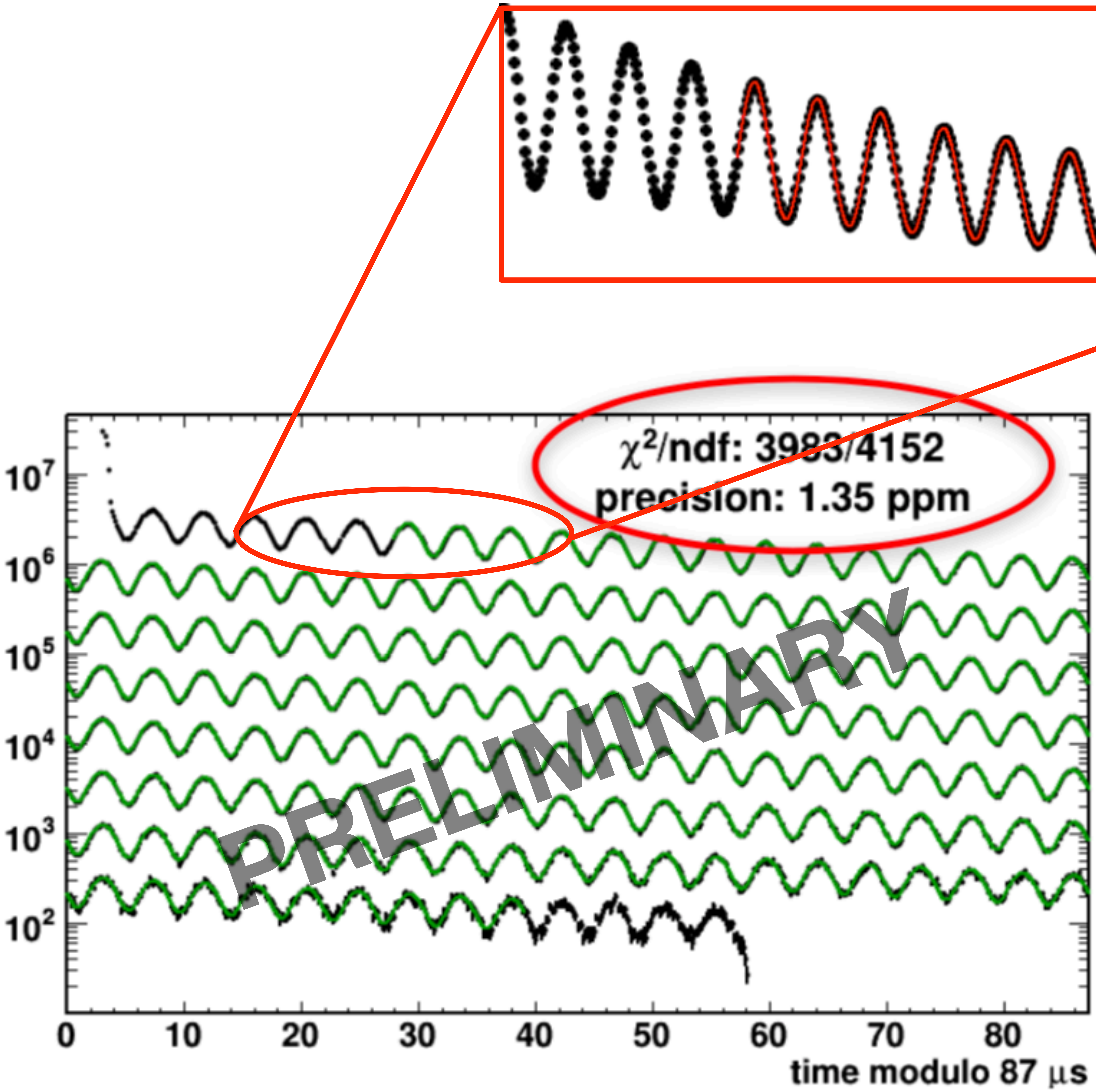
Accumulated statistics



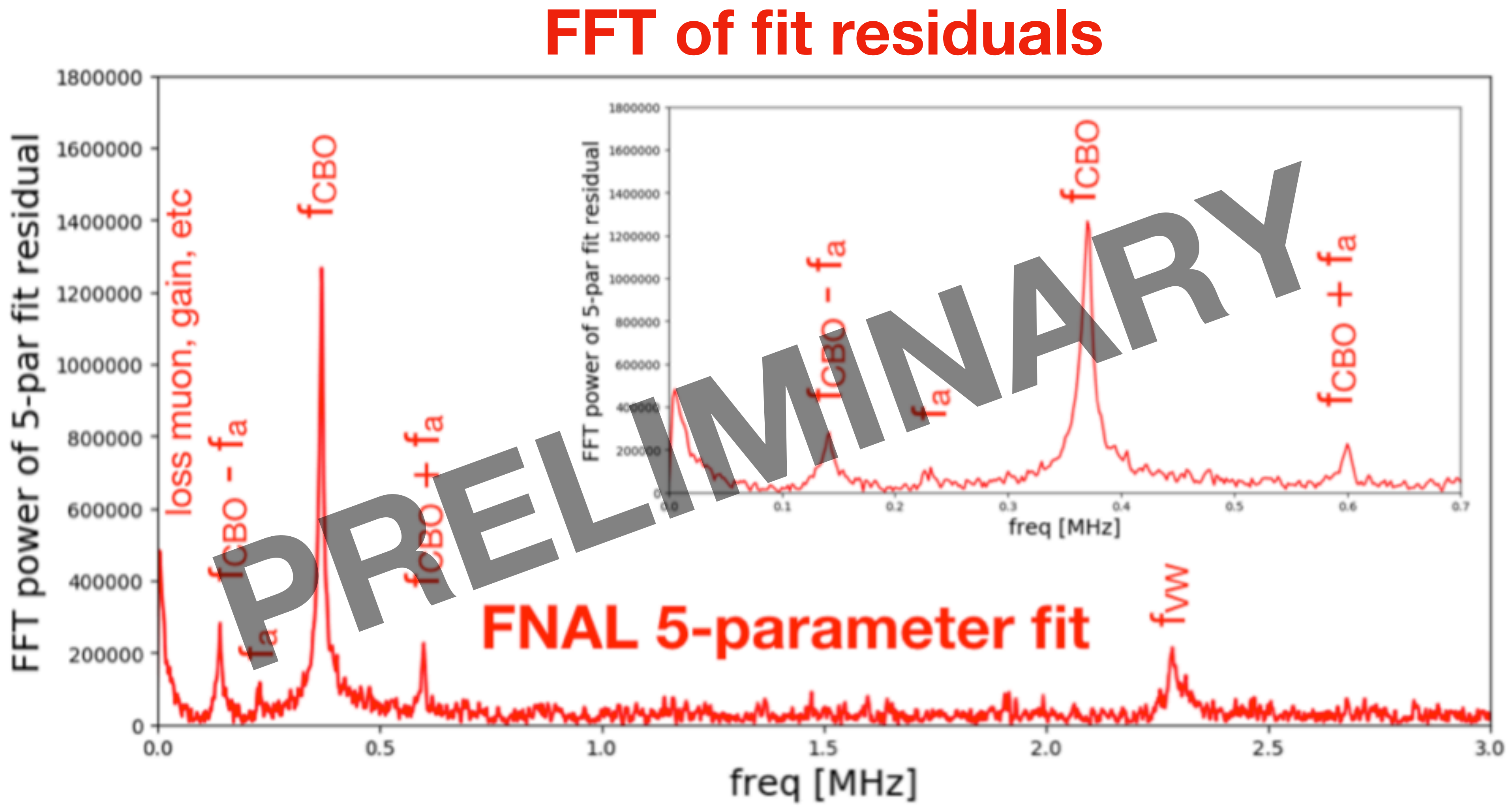
Typical trolley run



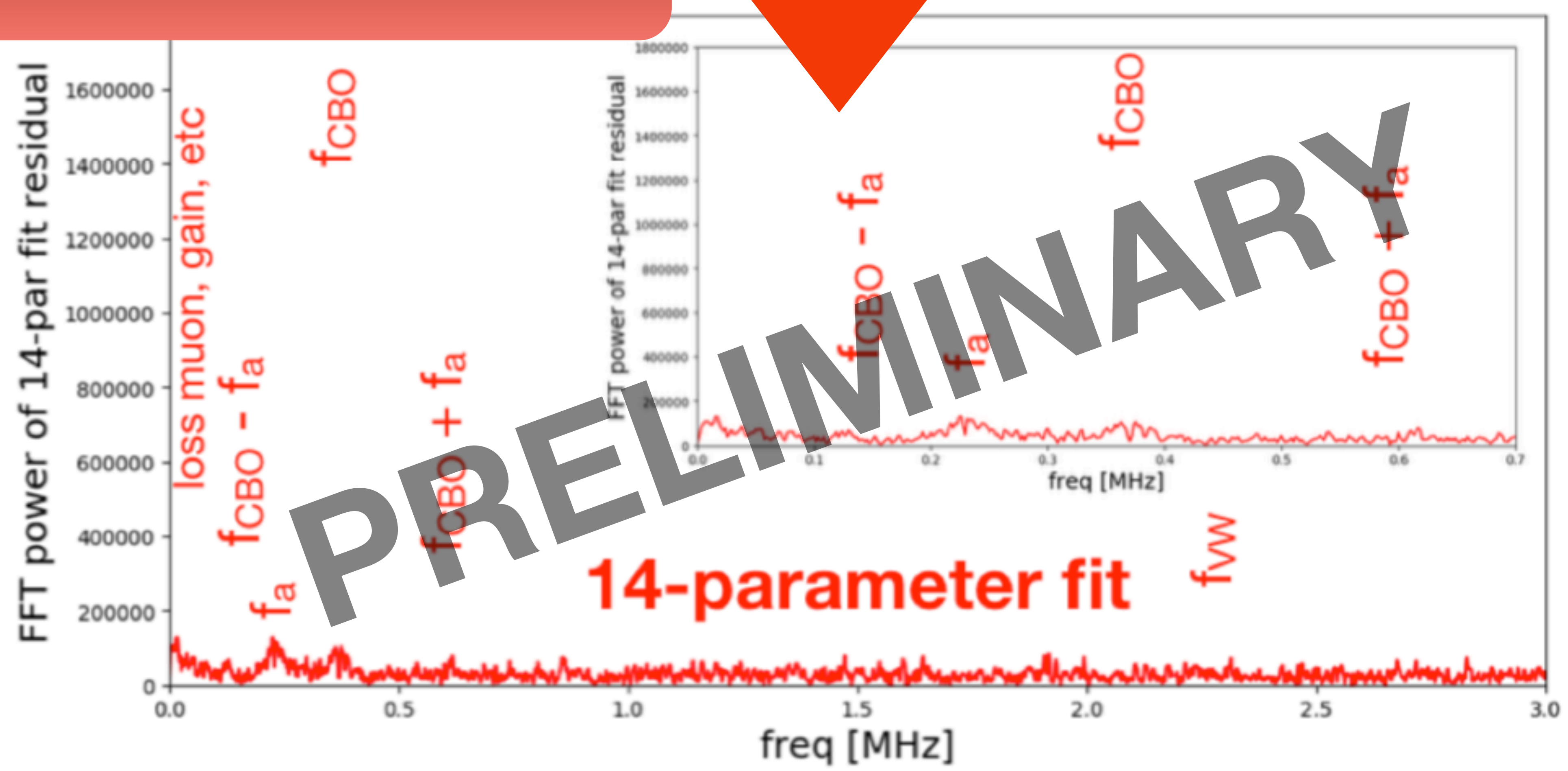
Run 1 Analysis Status: ω_a



Simple five-parameter fit



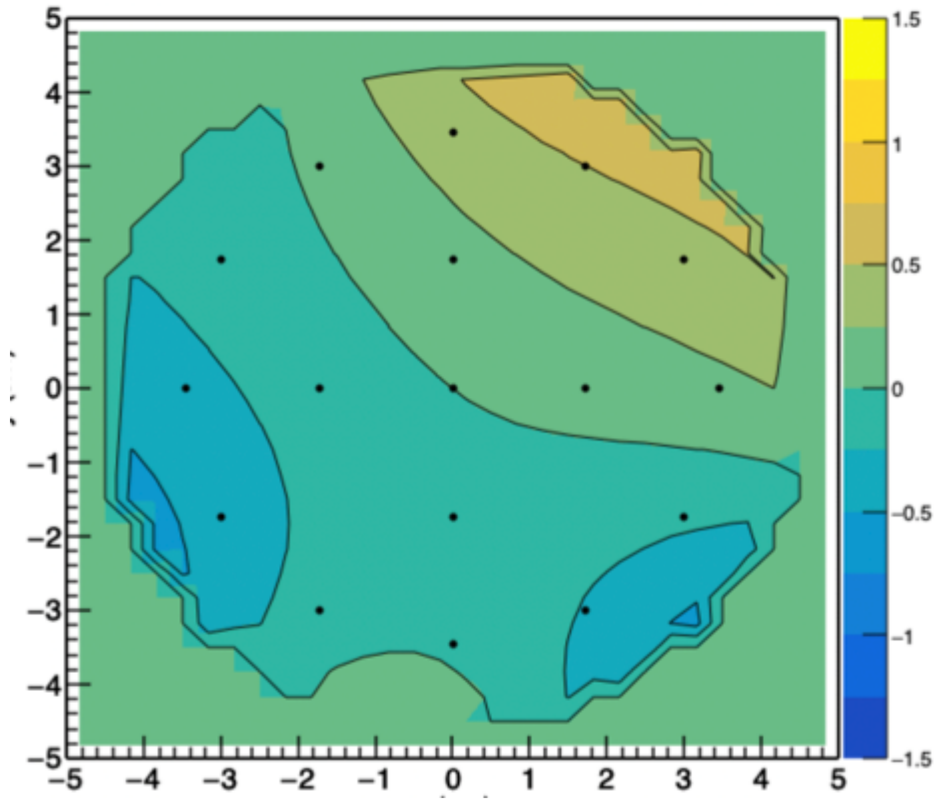
Big improvements when accounting for CBO, lost muons,…



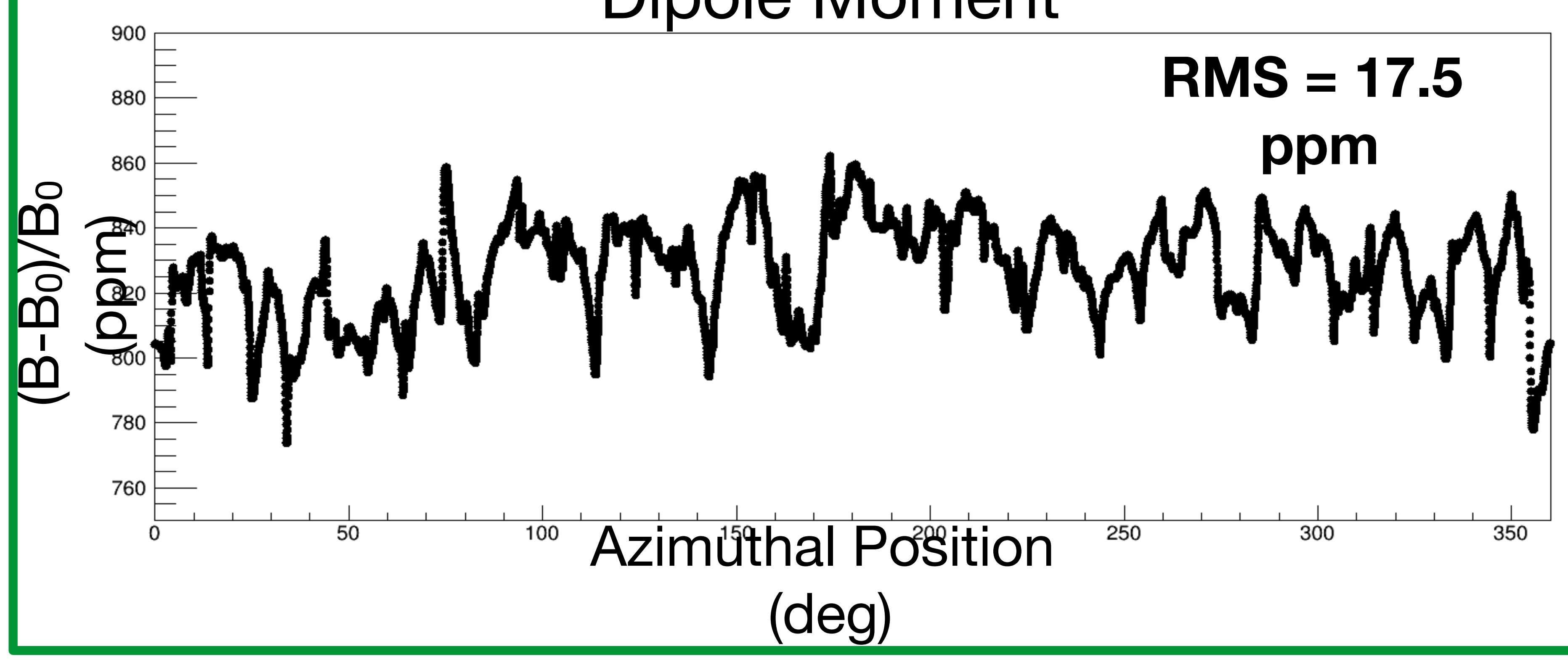
Run 2 Overview

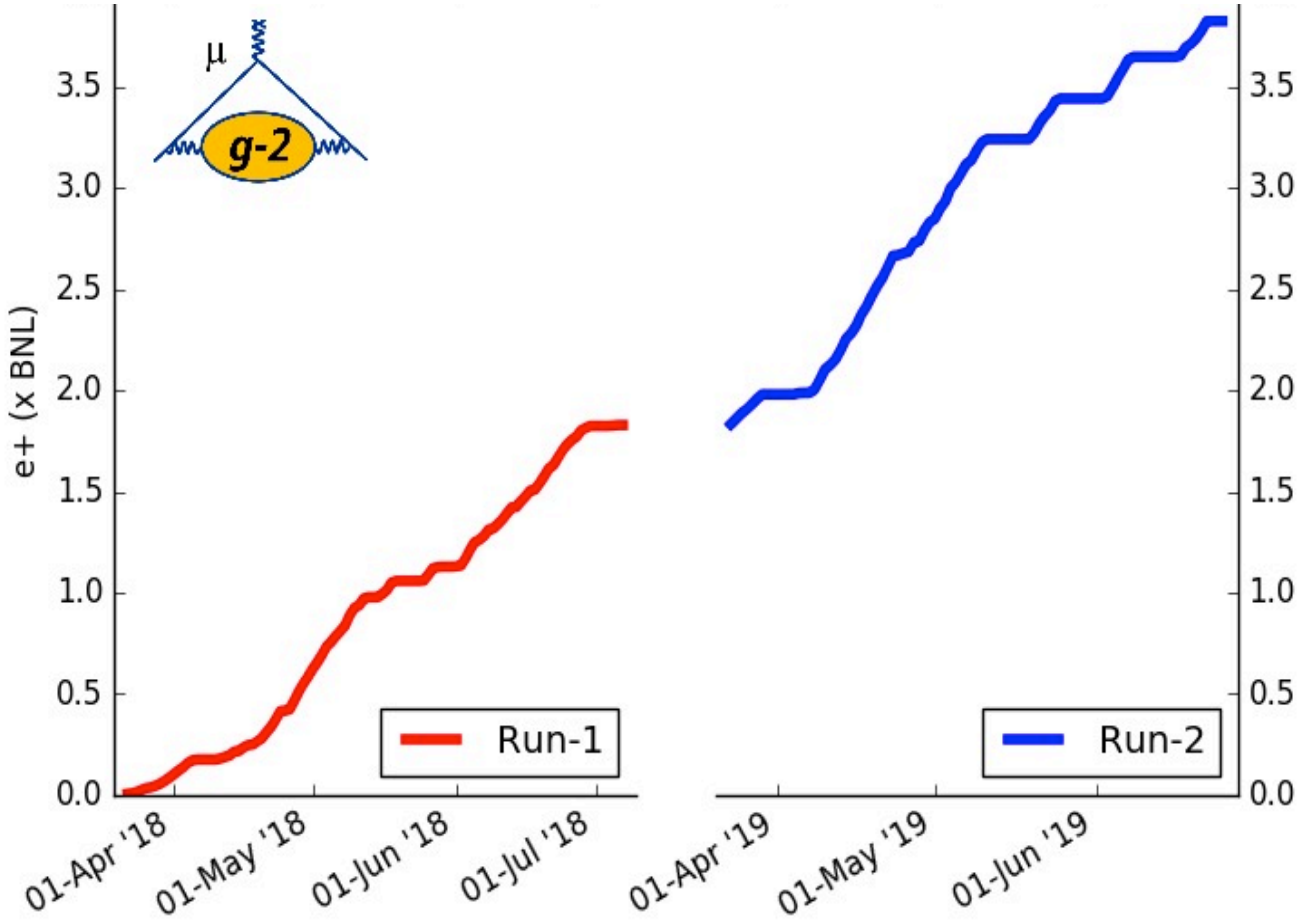
- More data taken during 2019
- Field uniformity expected to be similar to run 1

Azimuthal average
250-ppb contours



Run 2 trolley run





Can take 5% of a BNL per day!

Muon g-2 summary

Theoretical calculations

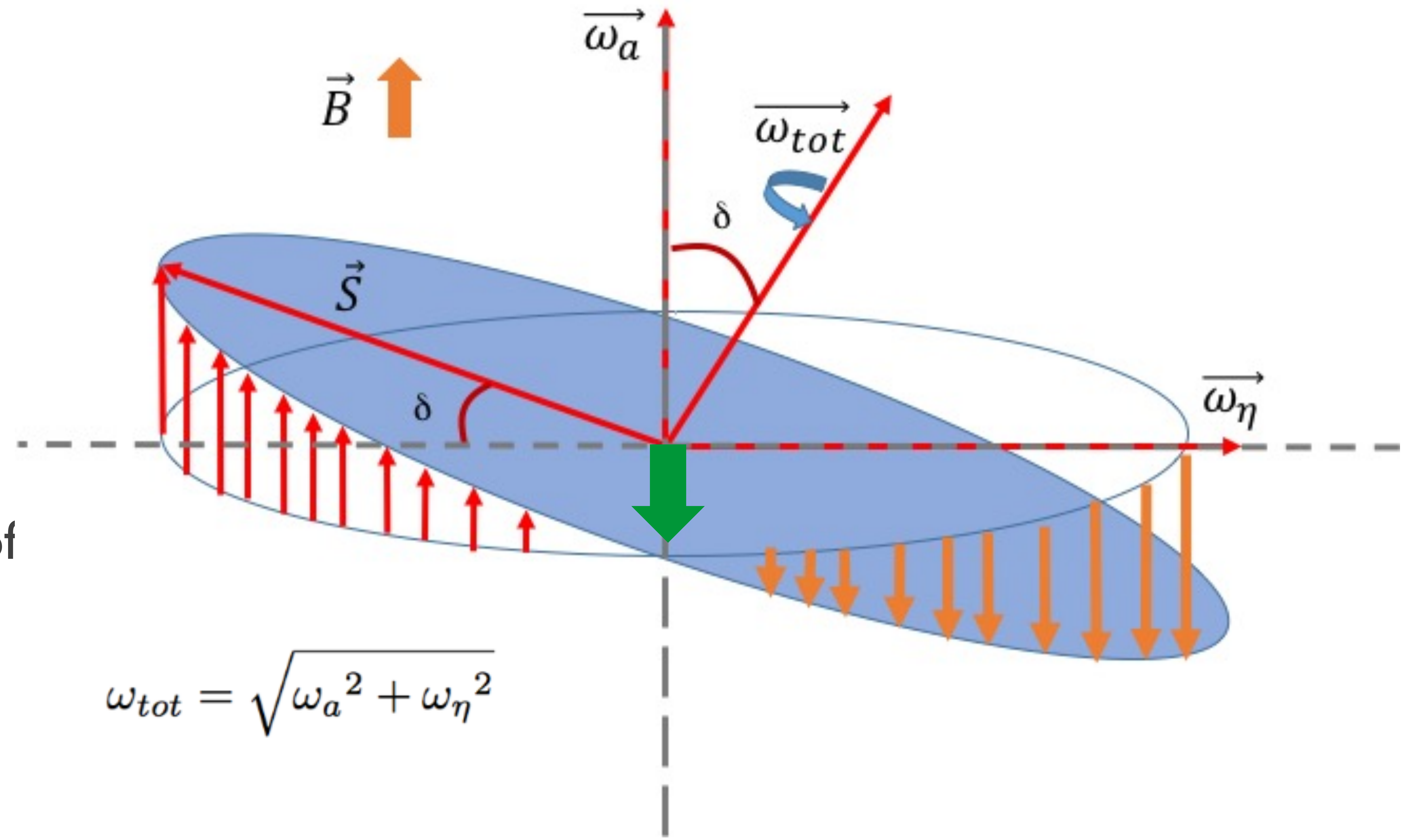
- Highly sensitive test of the SM with discrepancy between theory and experiment at the 3.7σ level
- Improvements in Lattice techniques becoming competitive for HVP uncertainty
- New data for HVP improving uncertainty, and not moving central value
- Data driven methods for HLbL agree with theory, too soon for competitive uncertainties
- On course for improvement on same time scale as Fermilab result

The Fermilab Muon g-2 Experiment

- Completed Run 1 in July 2018: result planned for late 2019. Statistic ~1.5 x BNL
- Run 2 completed July 2019 — another ~1.8 x BNL
- Taking 5% of a BNL a day, on course for 21 BNLs over next 2 years - Run 3 begins next month
- No new systematic uncertainties unearthed, all at or below target level for run 1
- Aiming for >5σ result (if central value remains the same as BNL) at end of year

EDM measurements at muon storage rings

- Precession plane tilts towards center of ring
- Causes an increase in muon precession frequency
- Oscillation is 90° out of phase with the a_μ oscillation



- 10 x improvement to current limit expected at FNAL - trackers improved since BNL
- JPARC g-2/EDM is more sensitive - possible 100 x improvement

Beyond Diagonal terms - Flavour violation

Charged counterpart to neutrino oscillations

$$\begin{pmatrix} ee & e\mu & e\tau \\ \mu e & \mu\mu & \mu\tau \\ \tau e & \tau\mu & \tau\tau \end{pmatrix}$$

ch = chirality
CP = charge parity
F = flavour

- MDM: Diagonal terms - ~~ch~~ CP F
- EDM: Phase - ch ~~CP~~ F*
- CLFV: Off diagonal terms: ch CP* ~~F~~

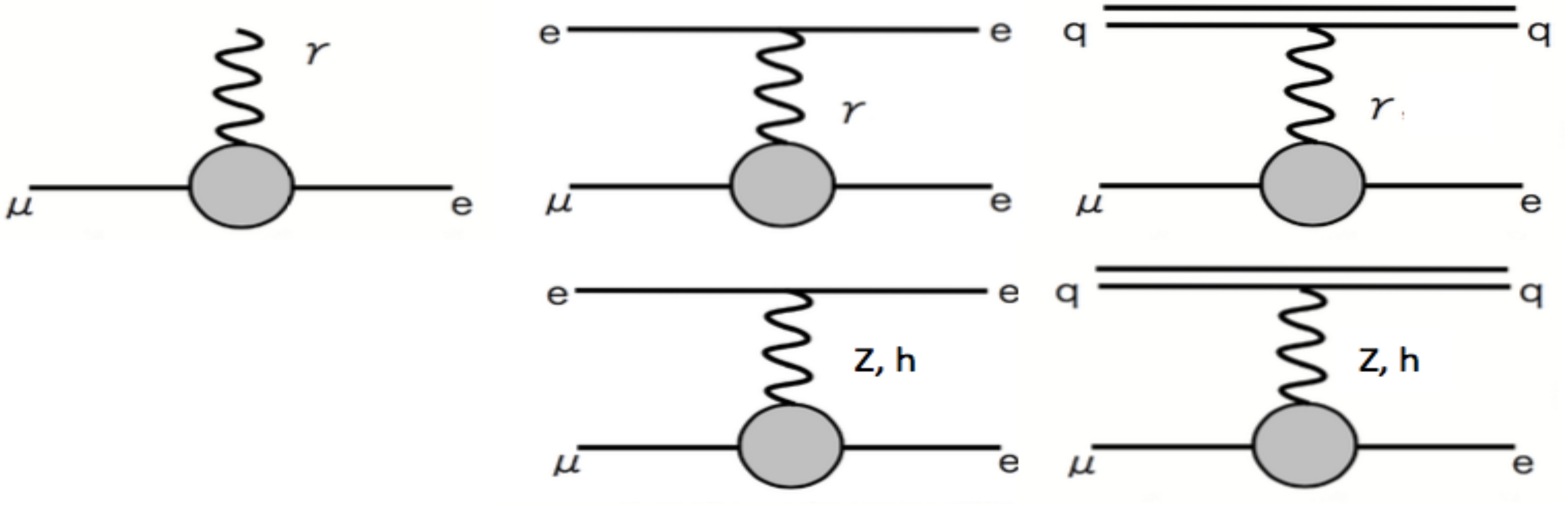
*(potential F violation if not linear mass scaling arxiv:1807.11484)

* (CP violation possible in off diagonal terms)

- Sensitive to NP independent to MDM, and probe higher scales (10^4 TeV)
- CLFV already exists in SM, via neutrino mixing at $\sim 10^{-54}$ level
- BSM models that generate small m_ν often involve CLFV

Charged Lepton Flavour Violation (CLFV)

$\mu \rightarrow e\gamma$ | $\mu \rightarrow eee$ | $\mu N \rightarrow eN$

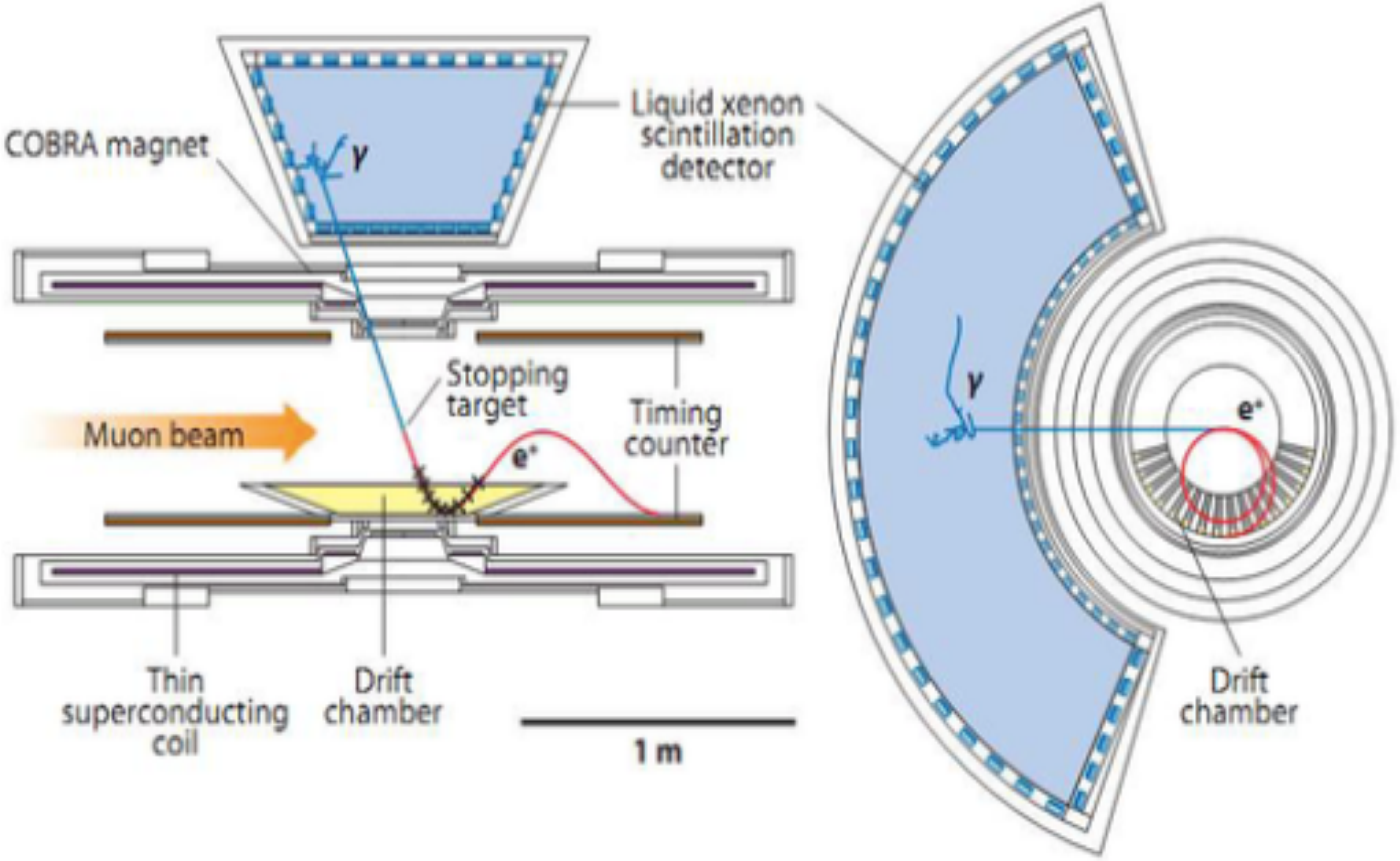


- Can use high intensity muon beams to look for charge lepton flavour violation
- Require muons p < 50MeV and stopping target (thickness ~1mm)
- Look for $\mu \rightarrow e$ in 3 channels, UK involvement in all 3

MEG and MEG II

- Located at PSI $\mu^+ \rightarrow e^+\gamma$
- Signal: simultaneous e^+, γ both $E=m_\mu/2$, 180°
- Use low rate beam to reduce accidental bg

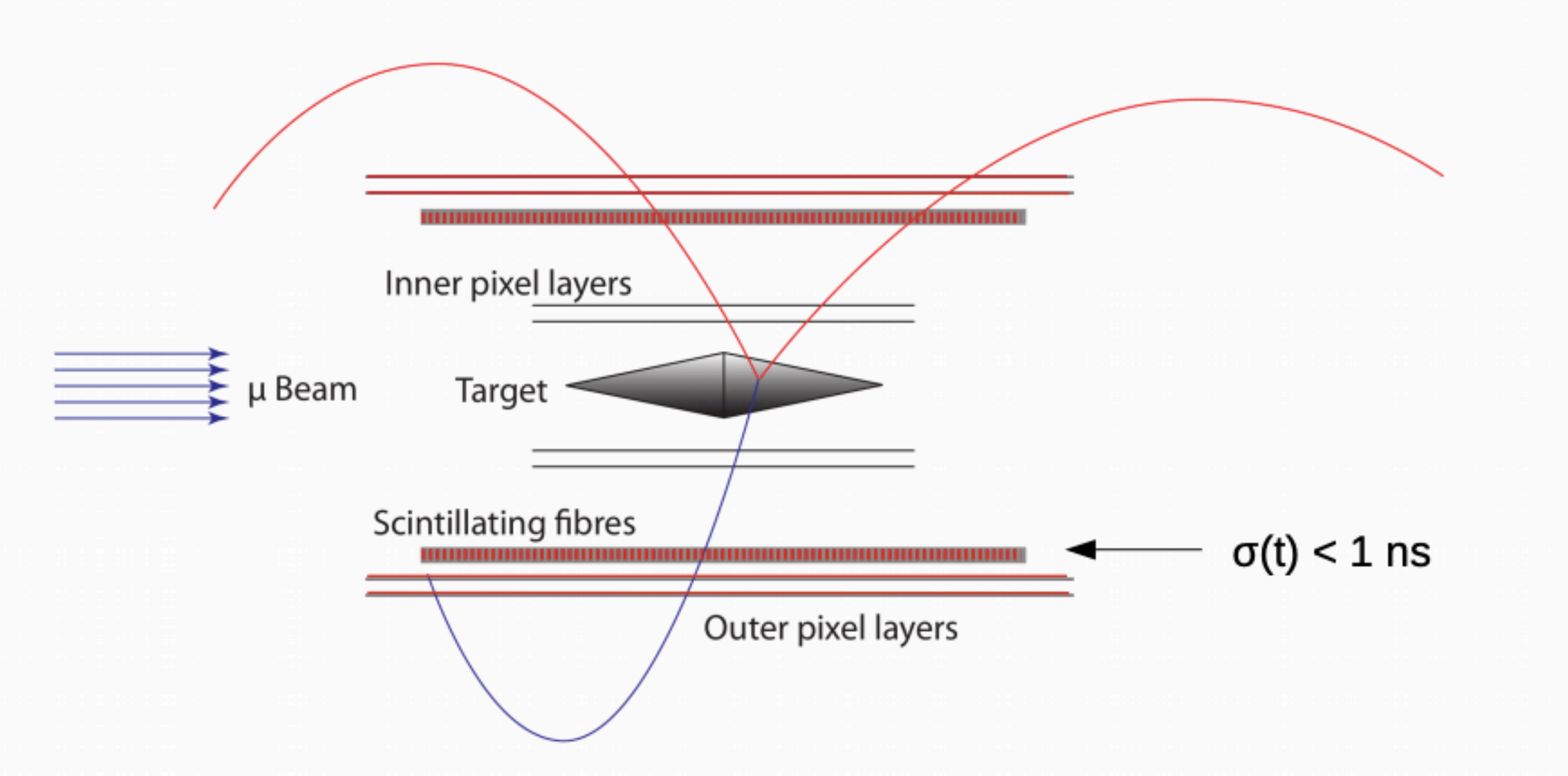
- Upgrade starts this autumn
- Aiming for factor 10 improvement

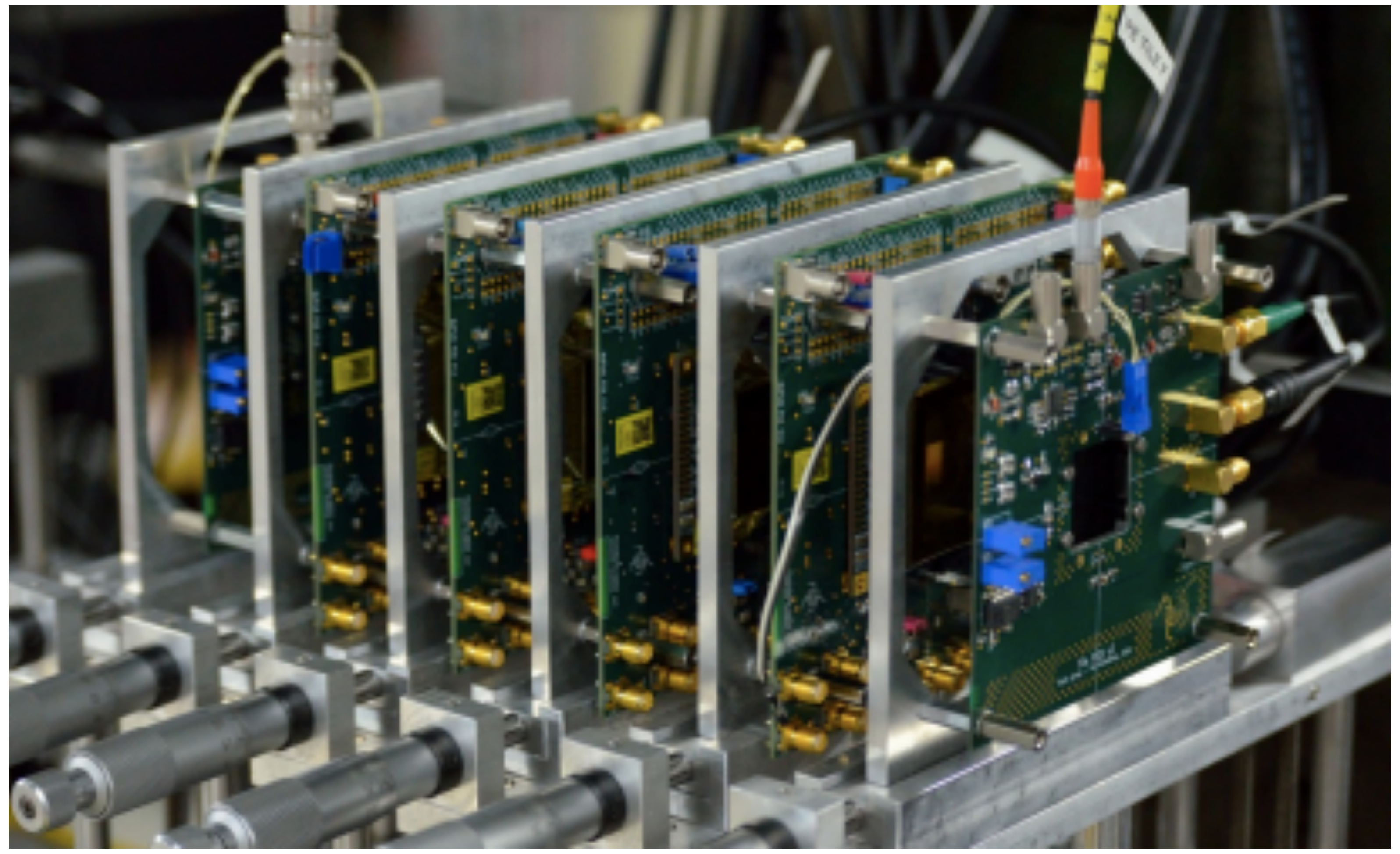


$BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ (@90% CL)

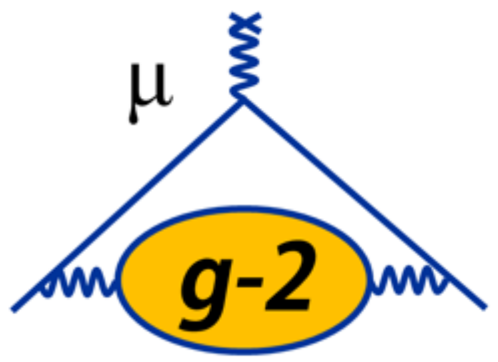
Mu3e $\mu^+ \rightarrow e^+e^+e^-$

- Located at PSI
- Signal: 3 simultaneous e (1MeV < E < $m_\mu/2$), same vertex
- Accidental and can be kept down with energy and vertex resolution
- Aiming for BR($\mu^+ \rightarrow e^+e^+e^-$) < 5×10^{-15} (@90% CL) in Phase I

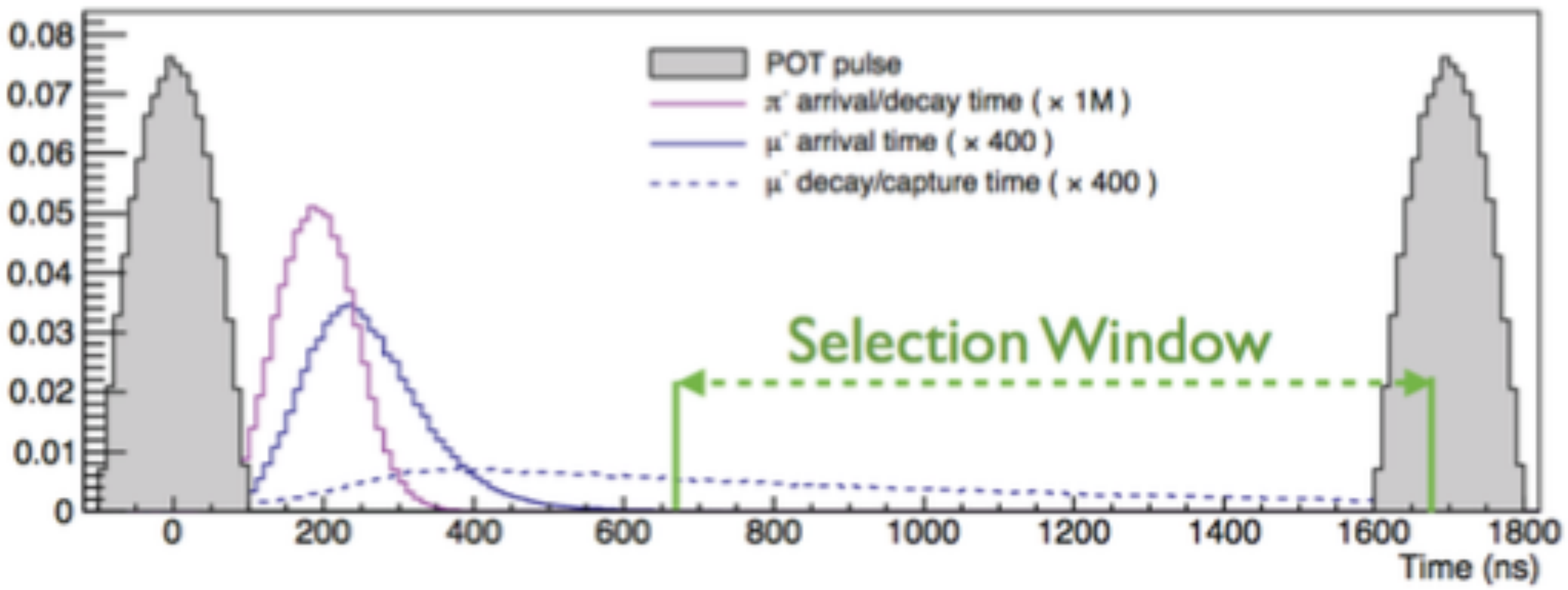


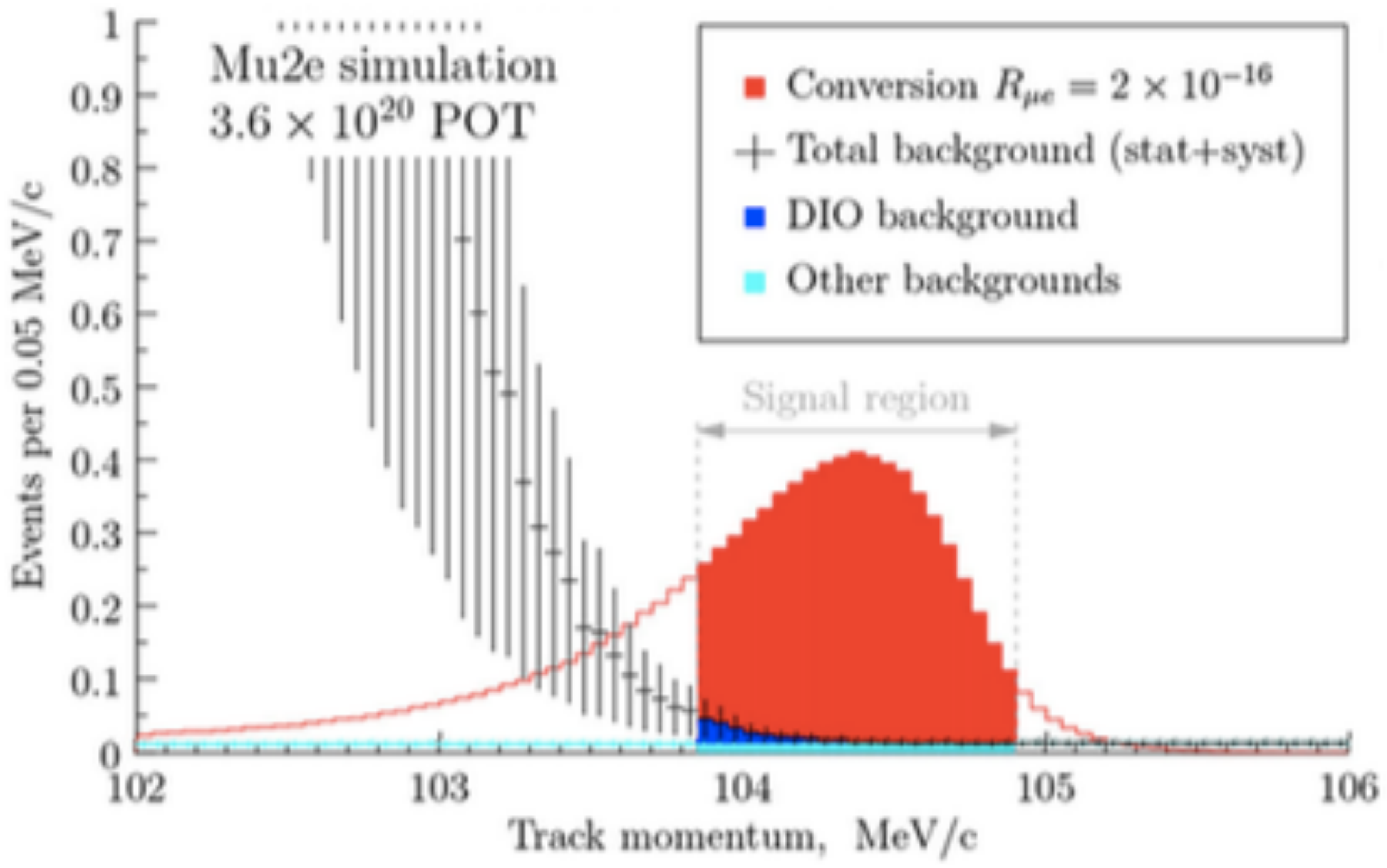


Mu2e and COMET $\mu^- N \to e^- N$

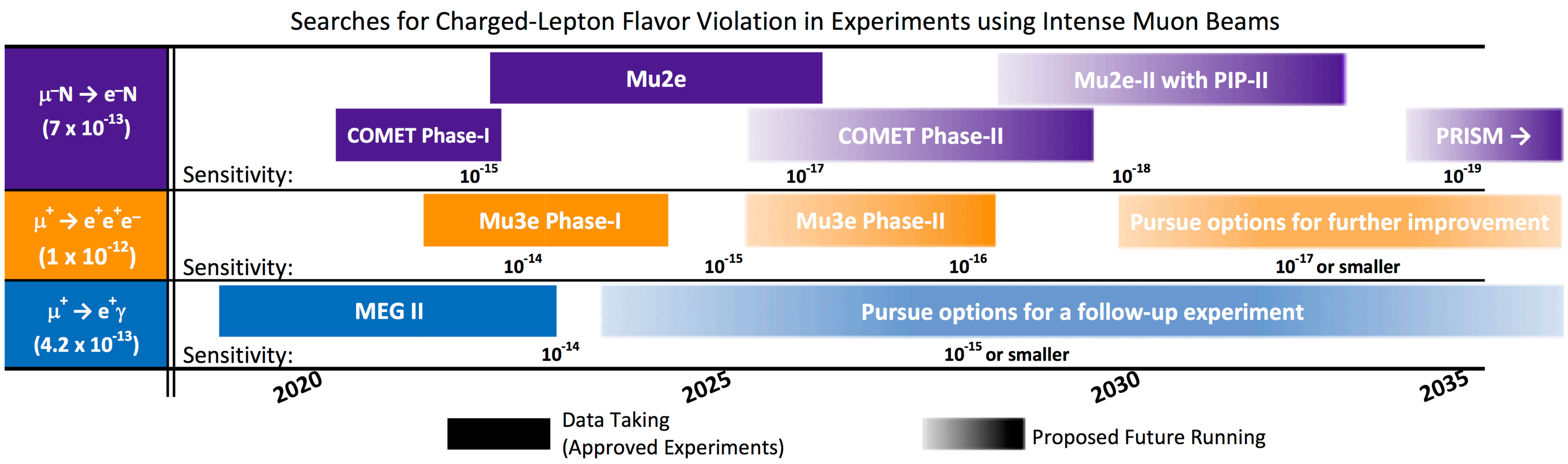


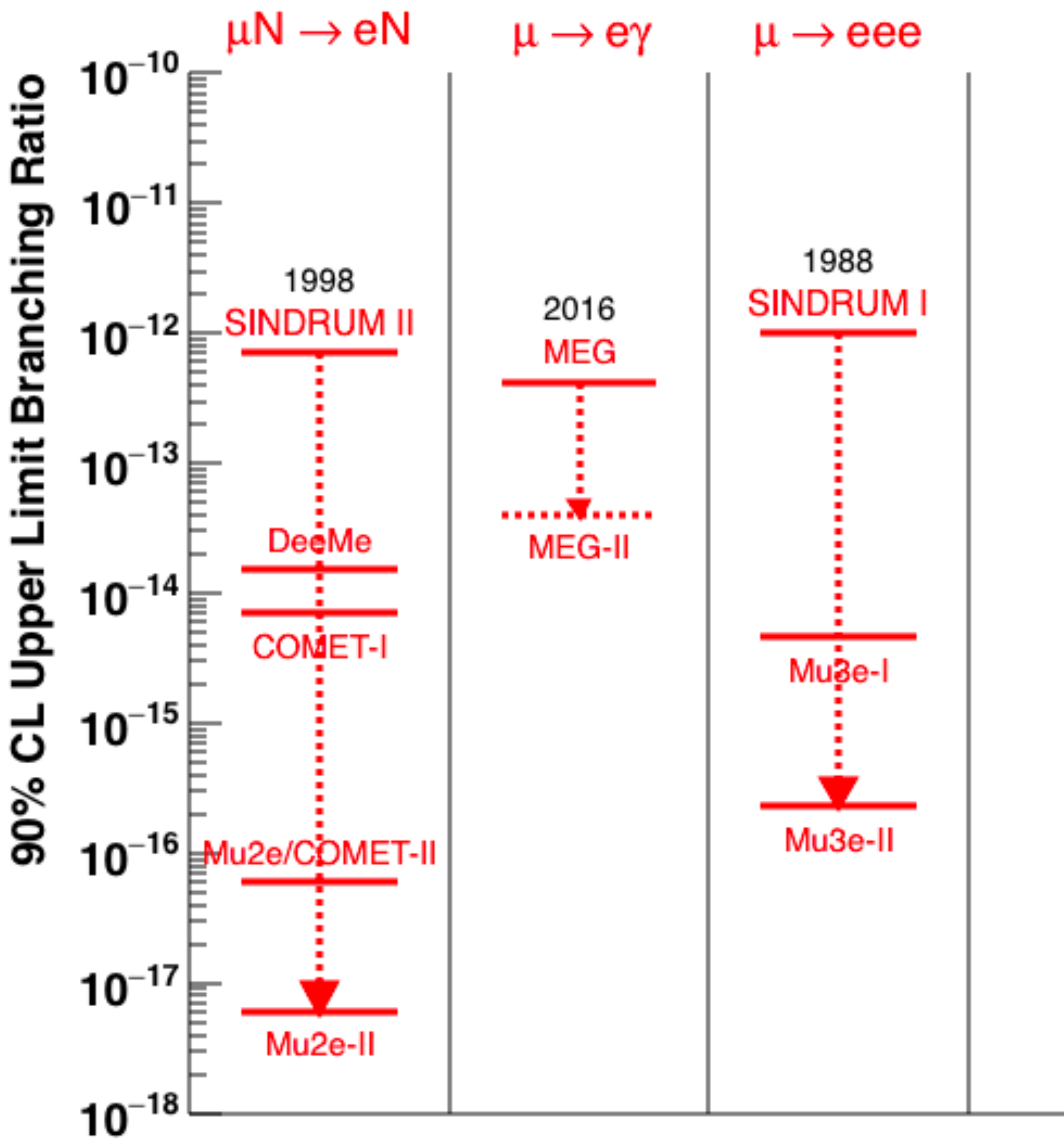
- Enhancement in sensitivity to CLFV due to small orbital radius of trapped μ
- Measure rate of conversions to tnuclear muon capture ($R_{\mu e}$(Al))
- Signal: monoenergetic electron at E_e = 104.394 MeV/c
- COMET Phase I will improve current limit by 2 orders of magnitude
- Mu2e and COMET Phase II will both get to $R_{\mu e}(Al) = 7 \times 10^{-17}$ (@90% CL)





Timescale and Physics Reach





- 10 - 10^4 improvement in current limits in all 3 channels within 10 years
- Physics program extends beyond the next 10 years with COMET and Mu2e upgrades, and possible tau flavour violating experiments

Fermilab

Conclusions

- 10 years ago the UK had very little involvement in muon physics program
- Now play a significant role in COMET, mu2e, mu3e and Muon g-2

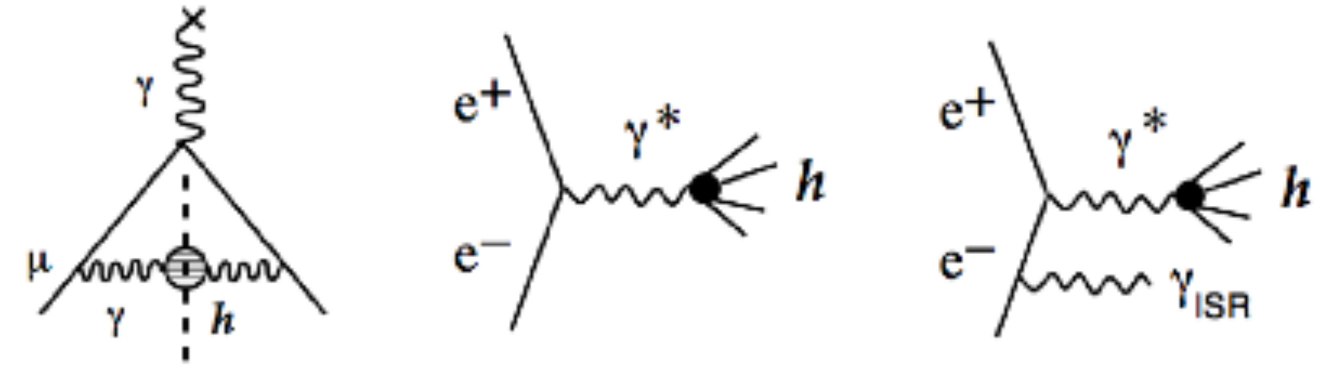
- Dipole moments:
  - Short term (~1 yr): μ g-2 result and μEDM search FNAL
  - Longer term (~10 yrs): μ g-2 @ JPARC, further sensitivty to μEDM

- CLFV:
  - Short term (~5 yrs): Mu3e and Mu2e data taking, COMET phase I result
  - Longer term: Mu2e II, PRSIM, Mu3e phase II

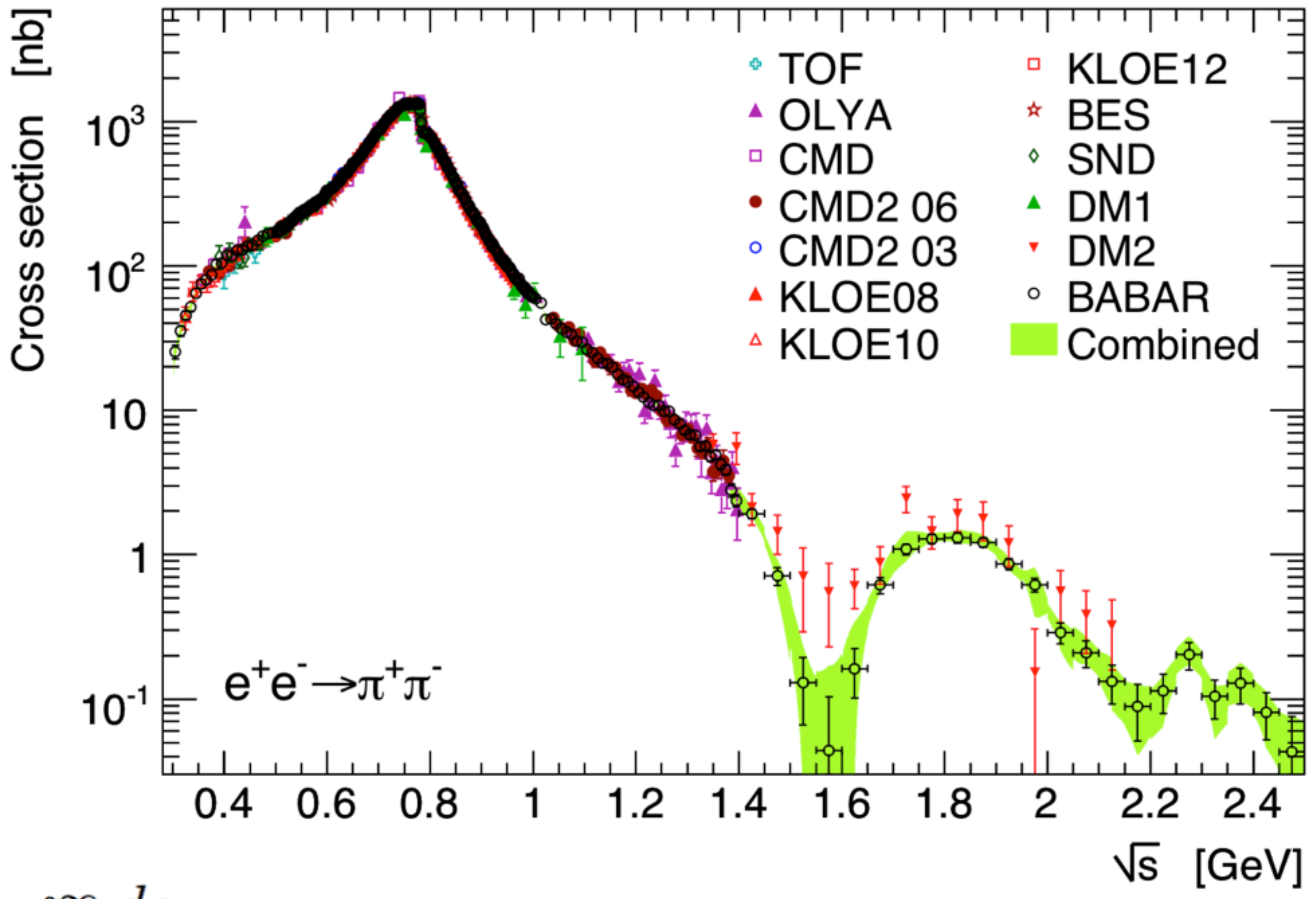
Thank you!

Backup

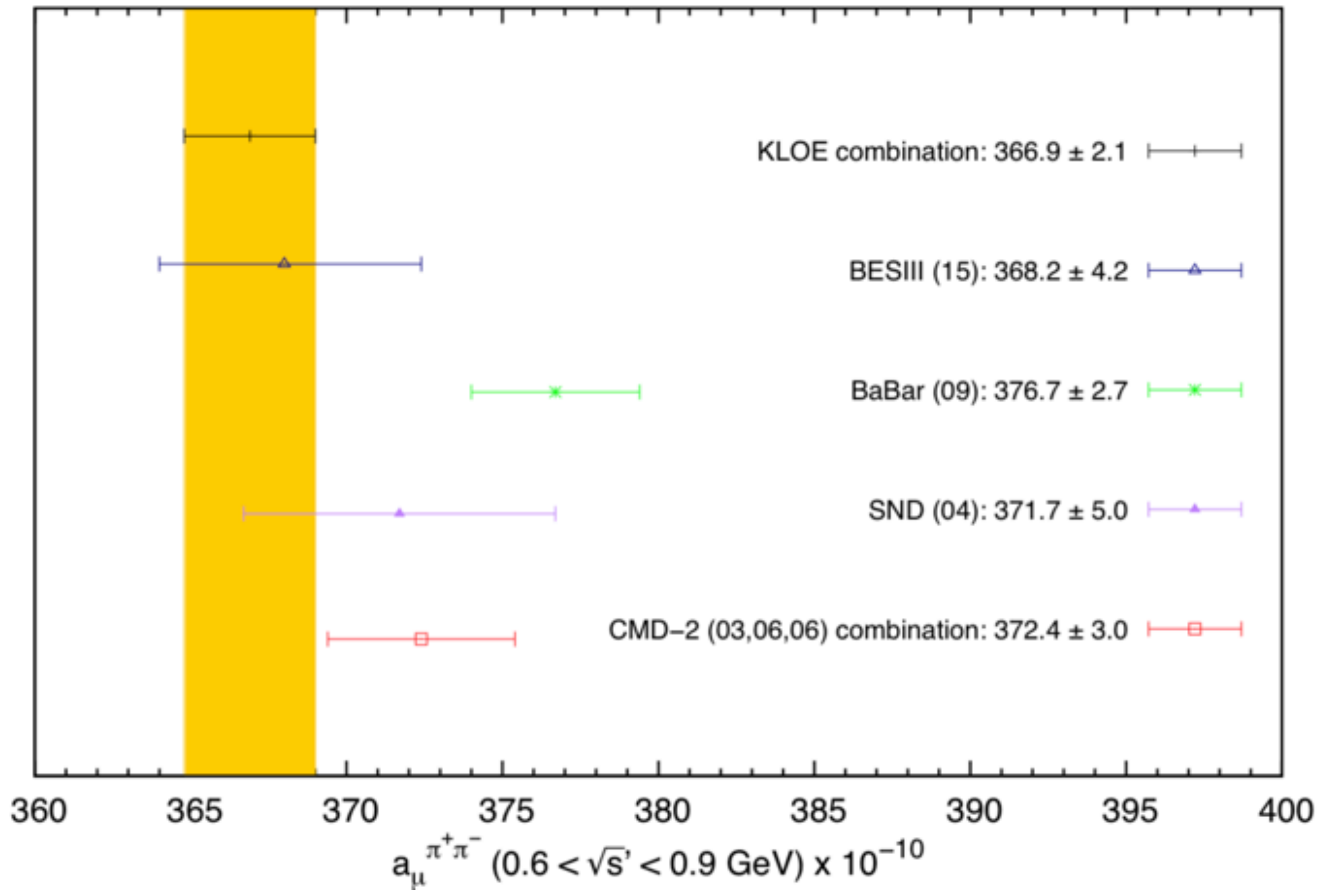
Hadronic Vacuum Polarization



M. Davier et al., arXiv:1706.09436 [hep-ph]



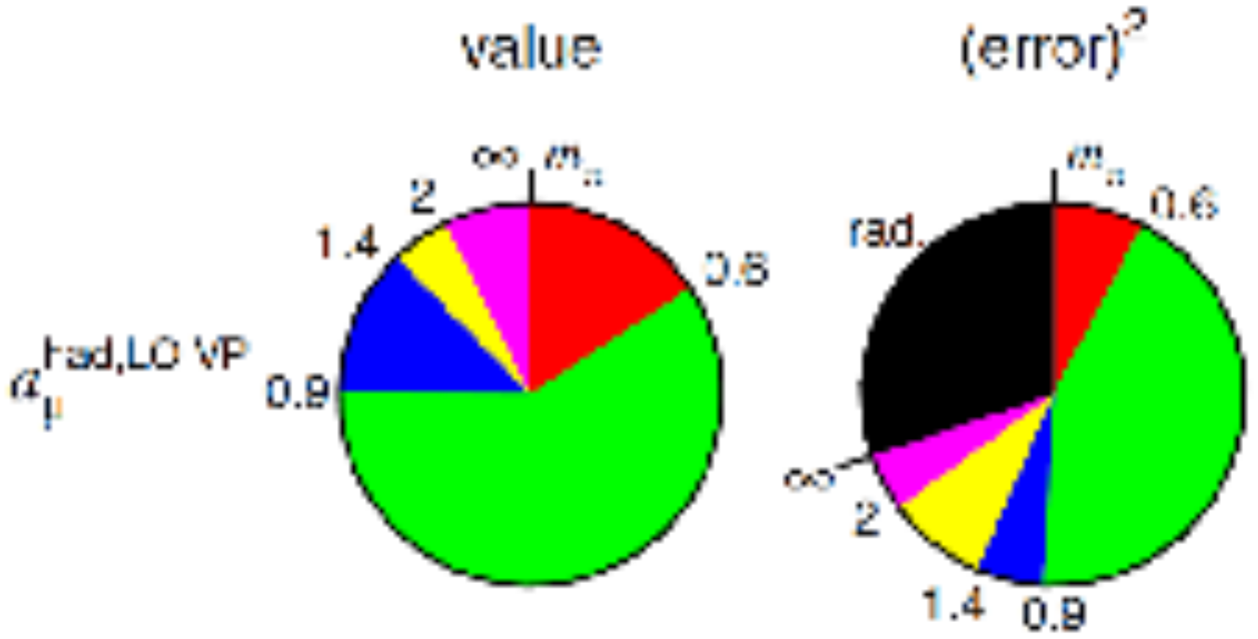
- **Critical input to HVP** from e^+e^- colliders (SND, CMD3, BaBar, KLOE, Belle, BESIII)
- **BESIII:** 3x more data available, luminosity measurement improvements
- **VEPP-2000:** Aiming for 0.3% (fractional) uncertainty; radiative return + energy scan
- **CMD3:** Will measure up to 2 GeV (energy scan, ISR — good cross check)



A. Anastasi et al., arXiv:1711.03085 [hep-ex]

$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

$$R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

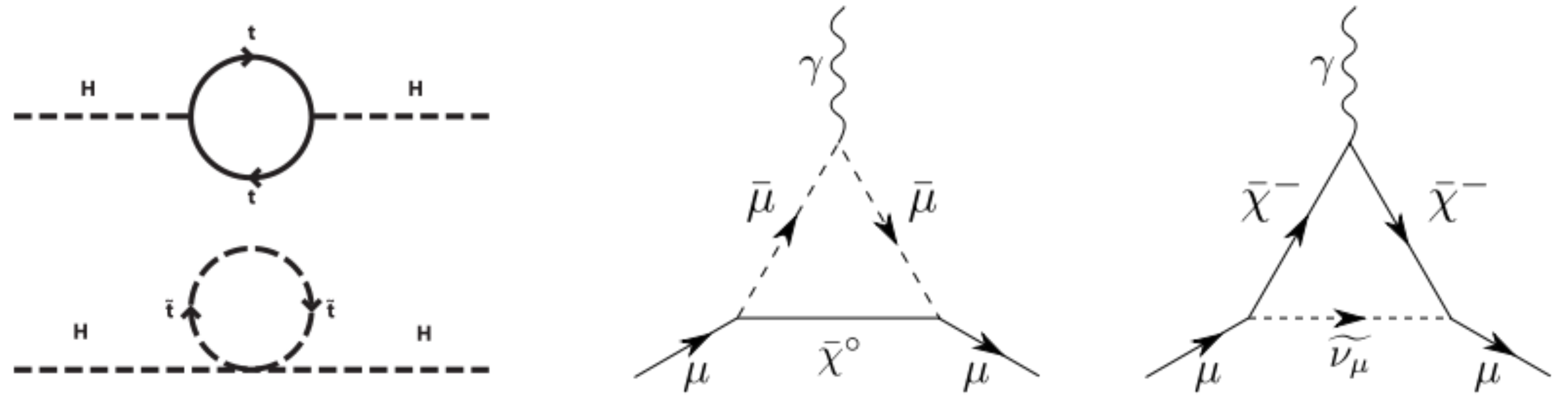


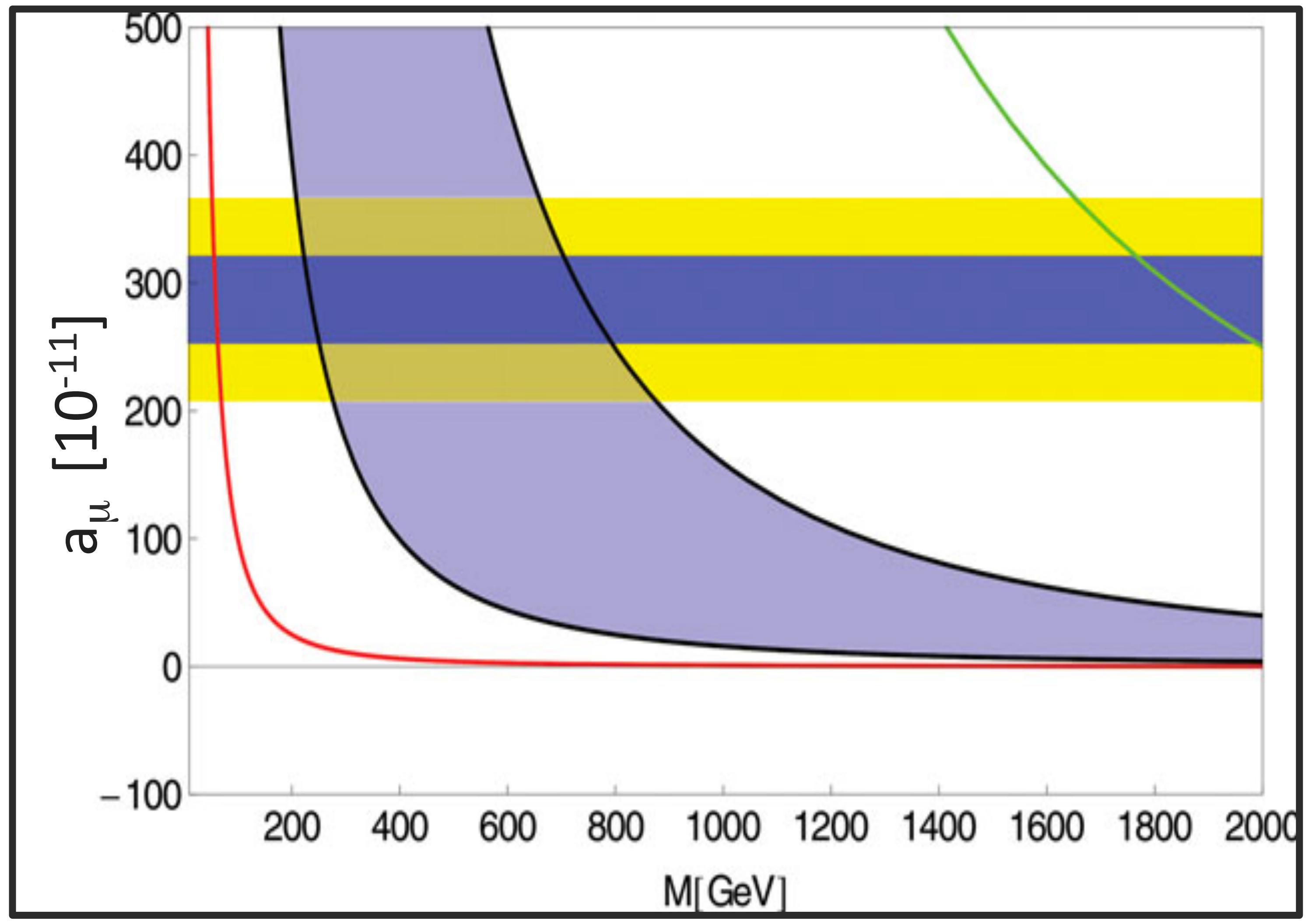
- **Lattice calculations** of a_μ^{HVP} to 1% possible, 30% for HLbL in 3—5 years

Physics Beyond the Standard Model?

SUSY, TeV-Scale Models

- Higgs measured at the LHC to be ~125 GeV
- Theory: Higgs should acquire much heavier mass from loops with heavy SM particles (e.g., top quark)
  - **Supersymmetry: new class of particles** that enters such loops and **cancels this contribution**





D. Hertzog, Ann. Phys. (Berlin), 2015, courtesy D. Stockinger

- **Complementary to direct searches at the LHC**
  - Sensitivity to sgn(μ), tan(β)
  - Contributions to a_μ arise from charginos, sleptons
  - LHC searches sensitive to squarks, gluinos

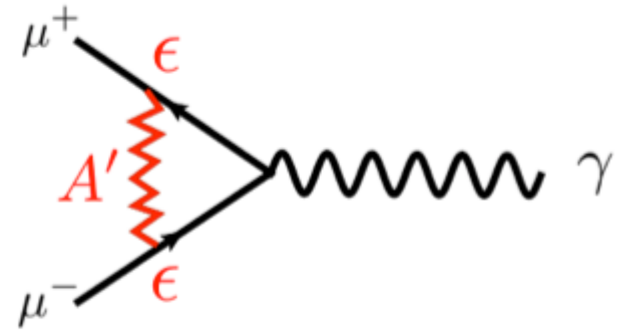
Z', W', UED, Littlest Higgs
- Assumes typical weak coupling

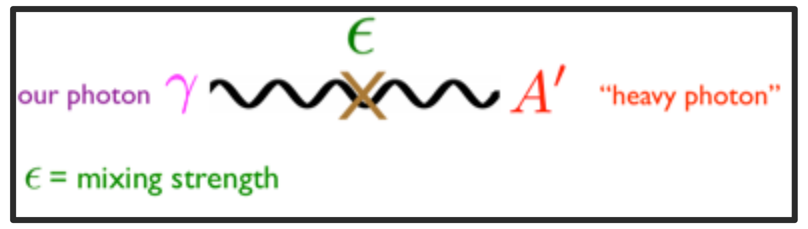
Radiative muon mass generation

Unparticles, Extra Dimension Models, SUSY (tan β = 5 to 50)

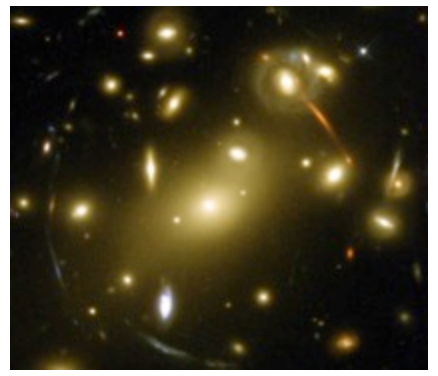
Dark Matter

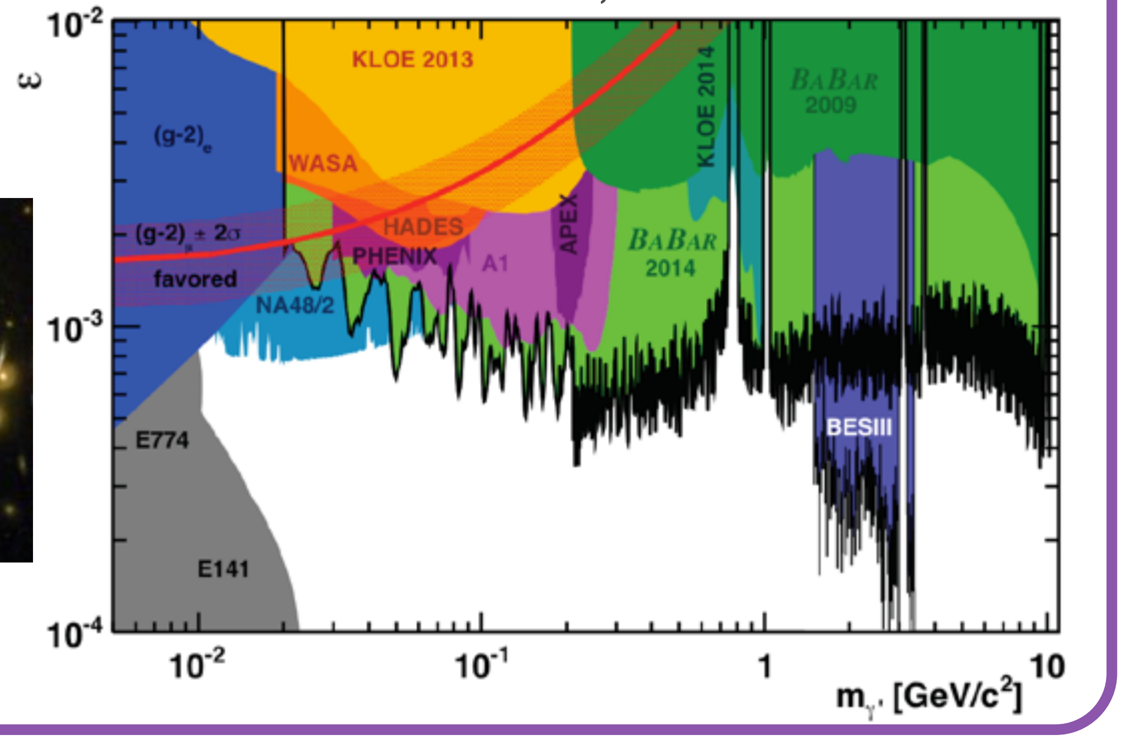
- **Cosmological observations** (galaxy rotation curves, lensing) point to much **more mass in the universe** than expected
- Many **theories** to explain dark matter
- **A new U(1)' symmetry: dark photon A'**
  - Could impact the muon's magnetic moment
  - Many direct-detection searches underway





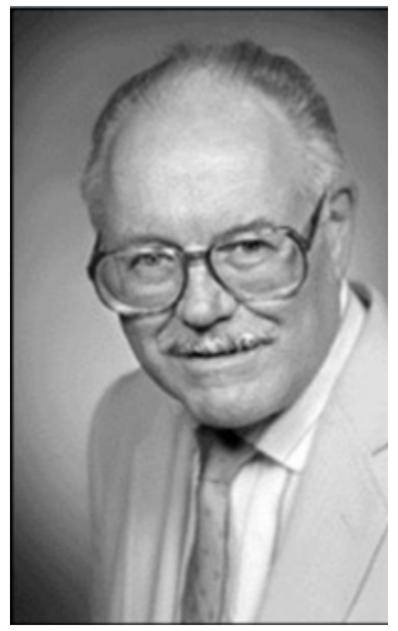
A. Soffer, arXiv:1507.02330





Magnet Anatomy

- For E821, Gordon Danby had a brilliant magnet design



B = 1.45 T (~5200 A)

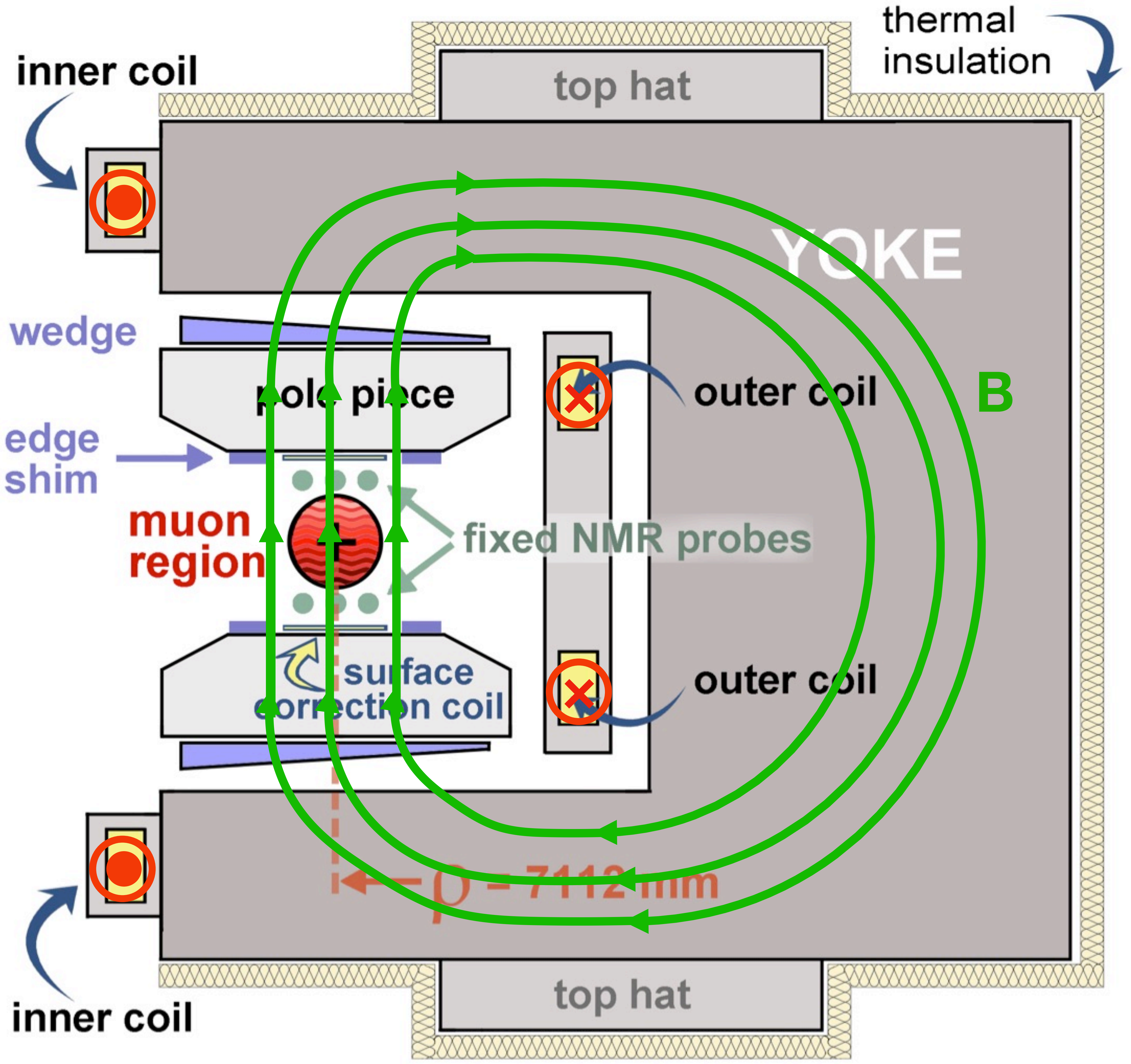
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 upper and 3 lower poles per yoke
- 72 total poles

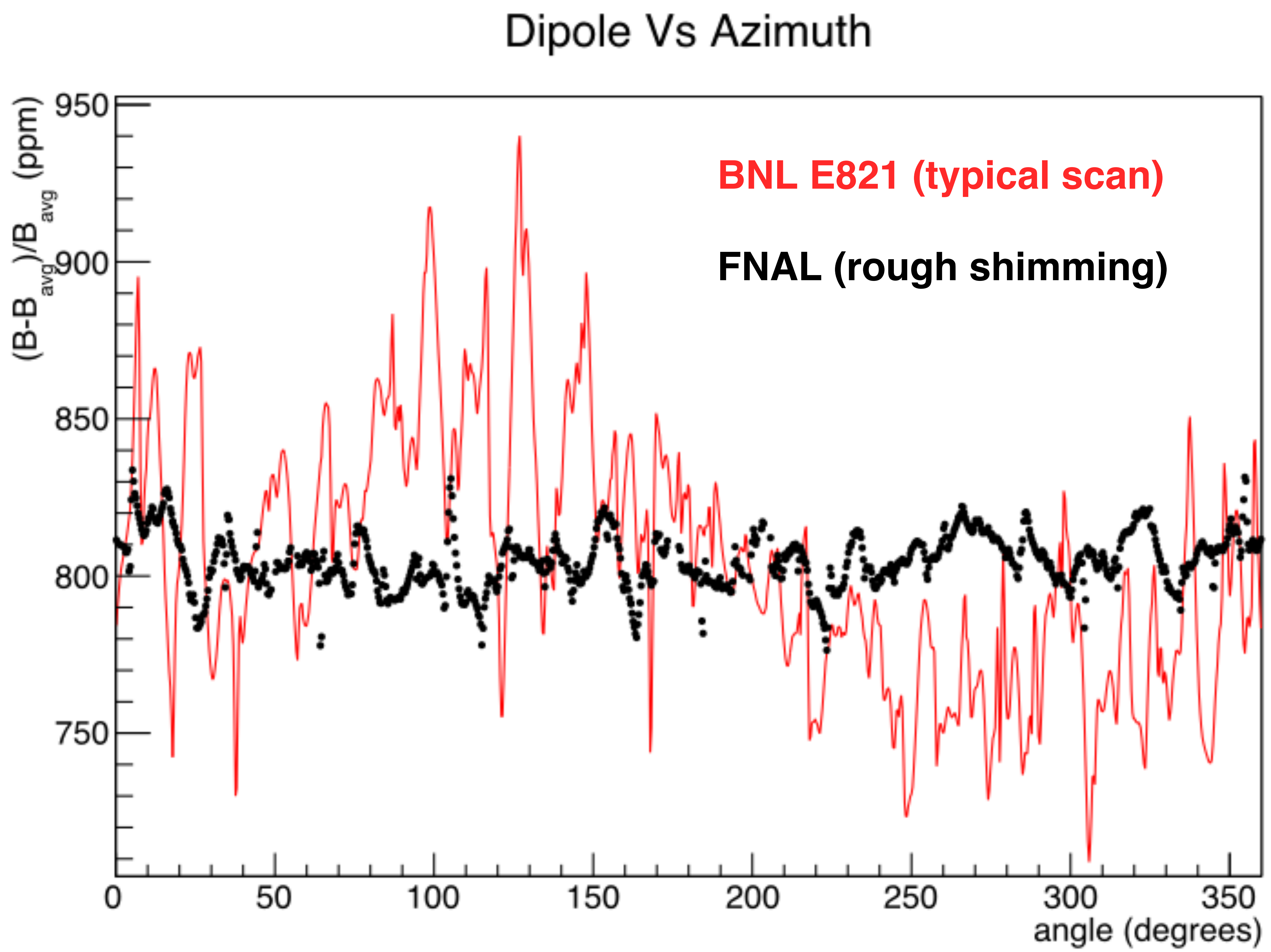
Shimming knobs

- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (30 deg effect, dipole)
- Wedges (10 deg effect, dipole, quadrupole)
- Edge shims (10 deg effect, dipole, quadrupole, sextupole)
- Laminations (1 deg effect, dipole, quadrupole, sextupole)
- Surface coils (360 deg effect, quadrupole, sextupole,…)



Current direction indicated by red markers

Magnetic Field Comparison: BNL 821 and FNAL E989

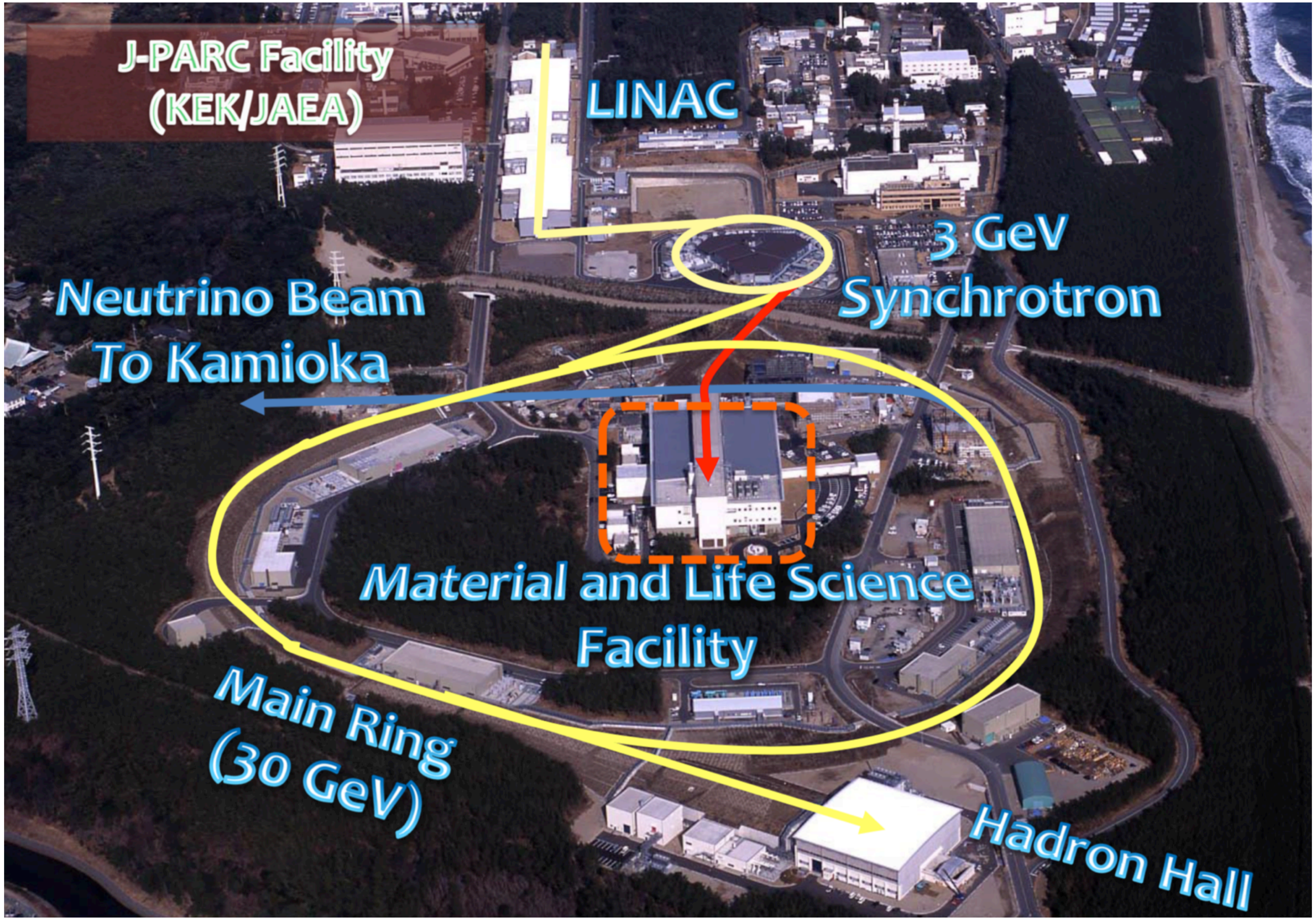


- Laminations very successful in reducing field variations

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

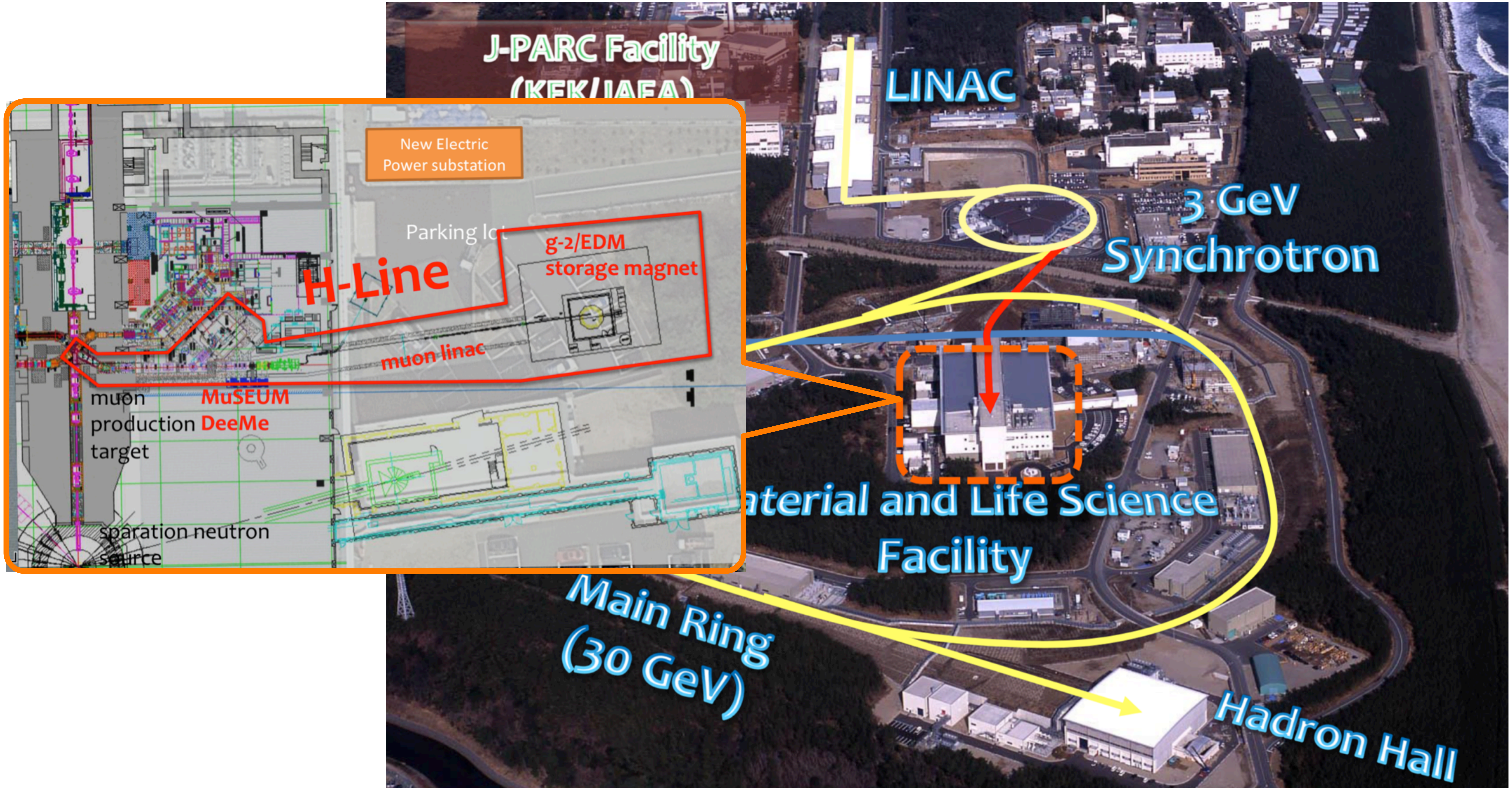
Muon g-2 at JPARC

JPARC Facilities



Images from Tsutomu Mibe

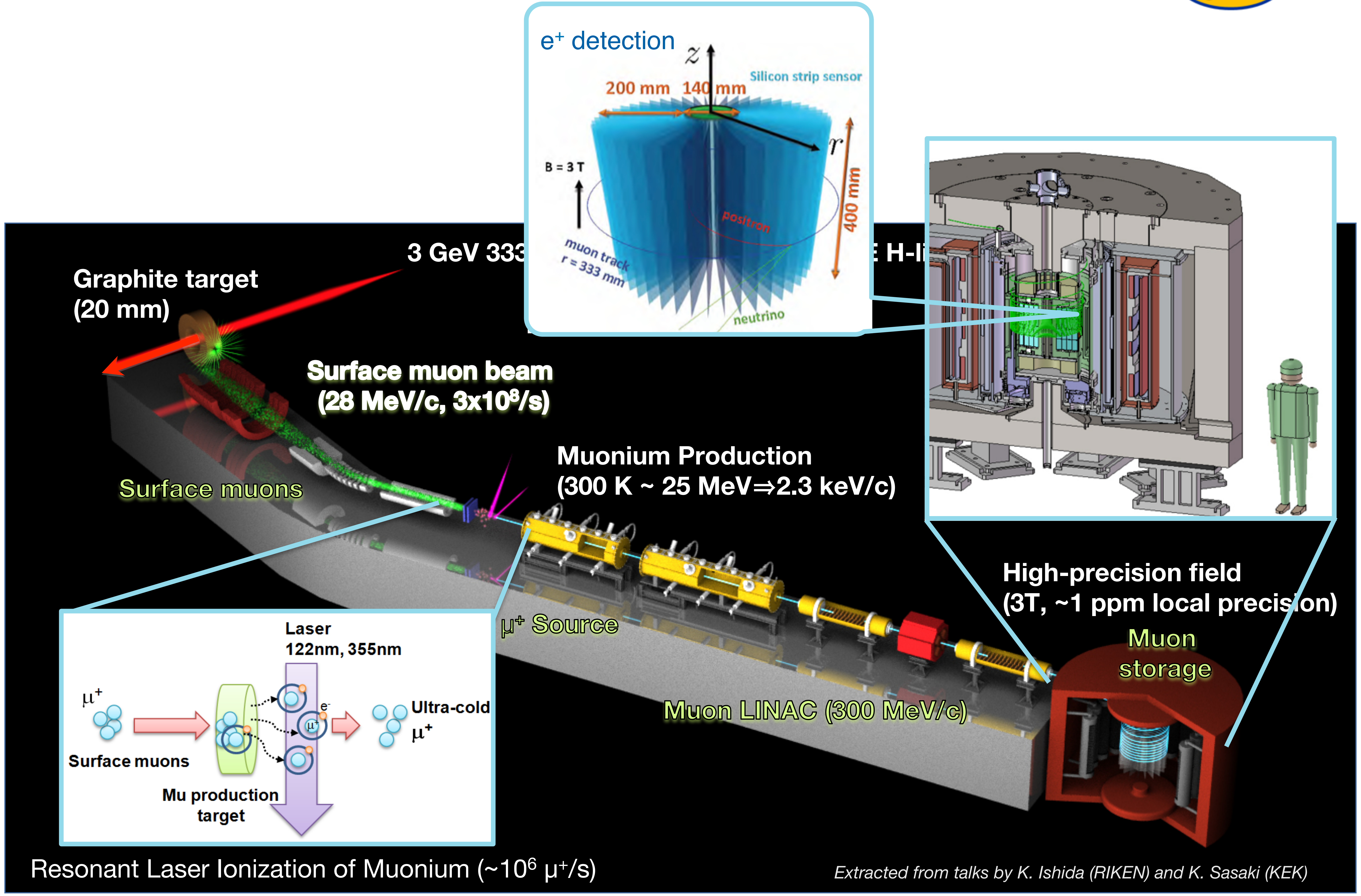
JPARC Facilities



Images from Tsutomu Mibe

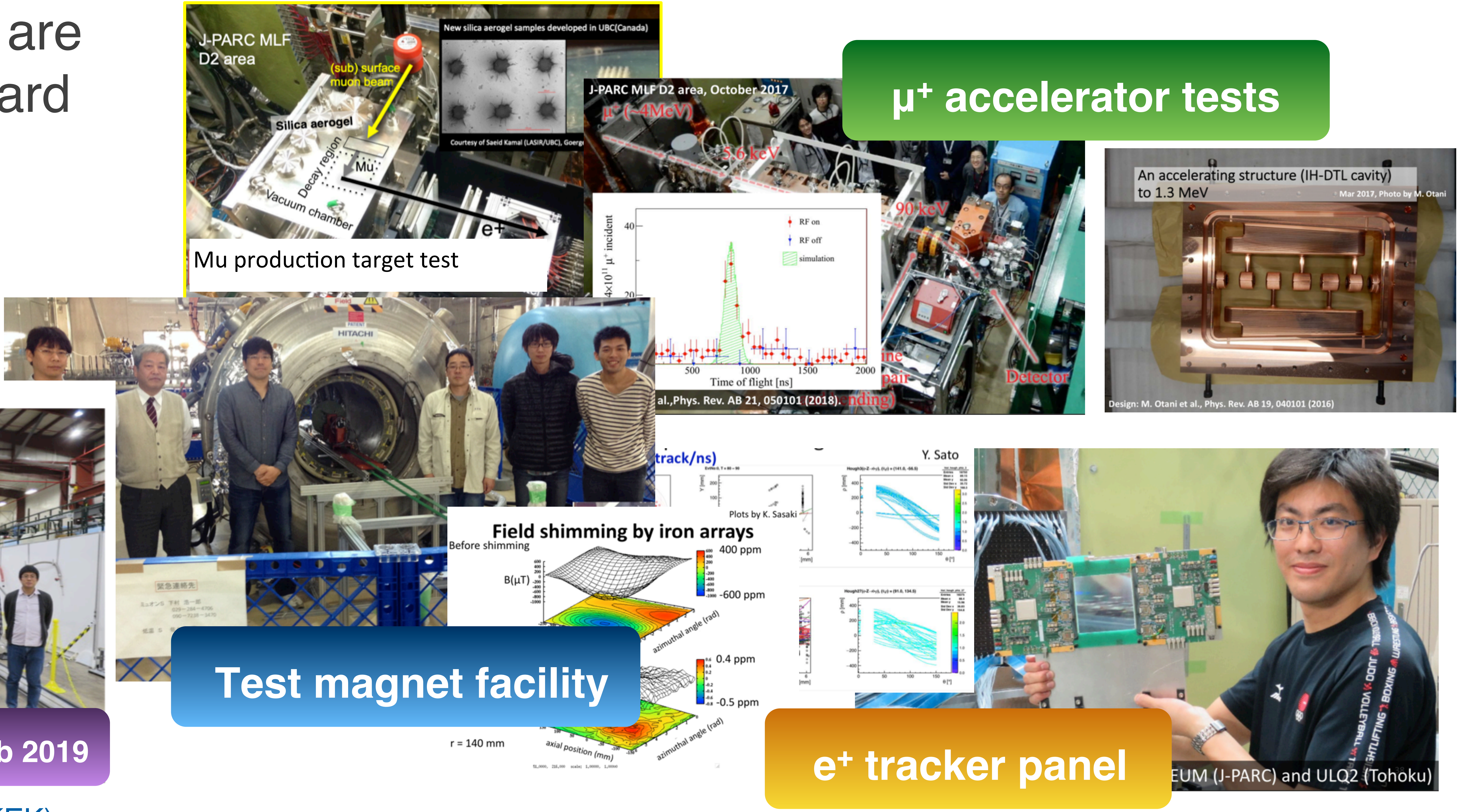
The Muon g-2 Experiment at JPARC

- New experiment being prepared in Japan
- Features
  - **Low-emittance muon beam**
  - 40 silicon **high-resolution tracking** vanes
  - **High-uniformity storage field** (~ 1 ppm)
- Different technique → different systematics
  - Excellent cross-check against E989 at FNAL



The Muon g-2 Experiment at JPARC: Current Status

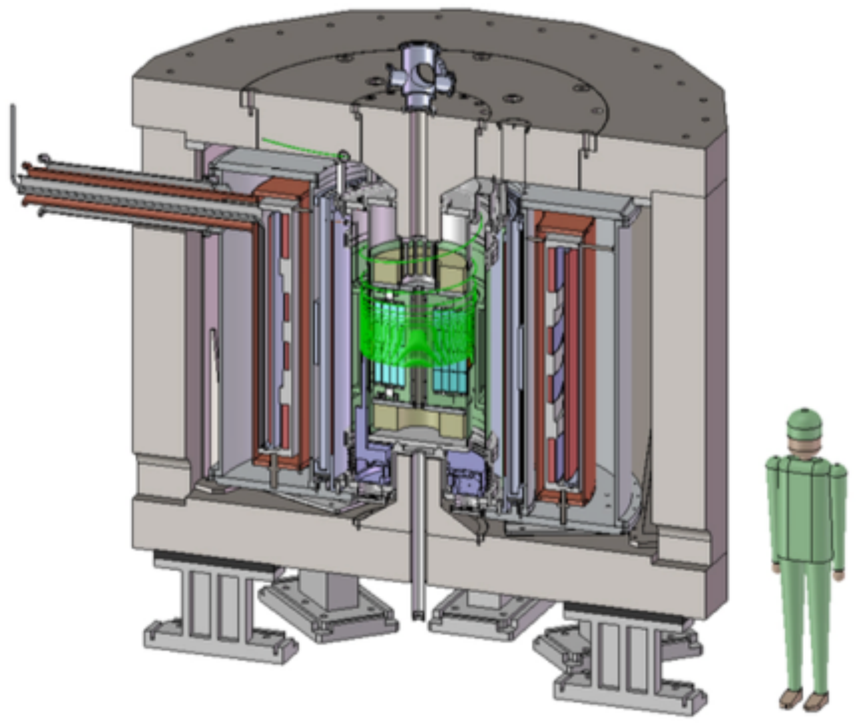
- Various systems are progressing forward
  - **Beamline**
  - **e^+ trackers**
  - **Magnetic field**

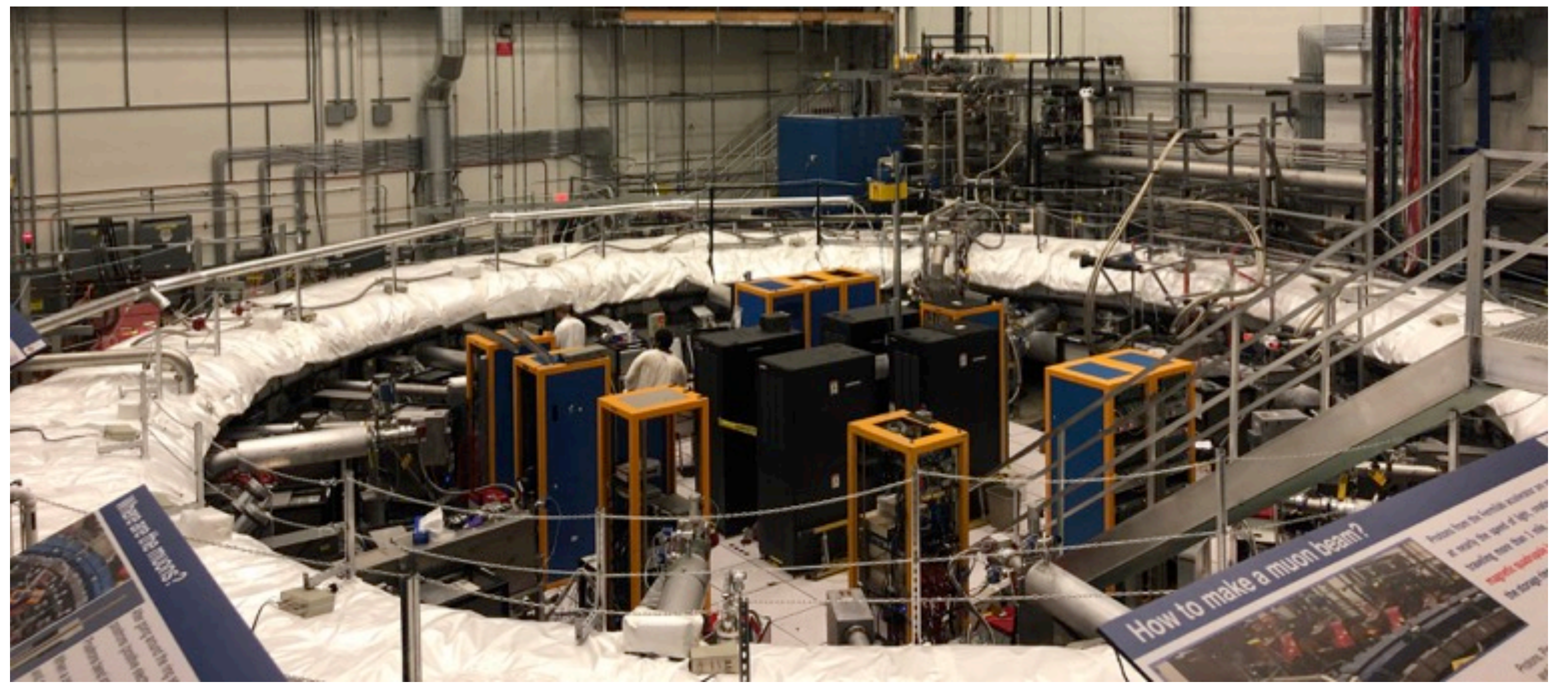


Images from Tsutomu Mibe (KEK)

Fermilab

Muon g-2 Experiment Comparison





Parameter	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/c)
Polarization	P_{max} = 50-90% (spin reversal possible)	$P \approx$ 97% (no spin reversal)
Magnet	MRI-like solenoid ($r_{storage}$ = 33 cm)	Storage ring ($r_{storage}$ = 7 m)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Injection	Spiral + kicker (~90% efficiency)	Inflector + kicker (~5% efficiency)
Positron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	450 ppb	140 ppb

Related Muon Physics

Ingredients to Extracting a_μ

- Recall the expression for a_μ:

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

Ingredients to Extracting a_μ

- Recall the expression for a_μ:

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

- m_μ/m_e value based on muonium hyperfine theory:

$$\Delta\nu_{\mathrm{Mu}}(\mathrm{Th}) = \frac{16}{3} c R_\infty \alpha^2 \frac{m_e}{m_\mu} \left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \text{higher order terms}$$

- Equate theory to experiment, treat m_μ/m_e as a free parameter, obtain m_μ/m_e to 22 ppb

Ingredients to Extracting a_μ

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

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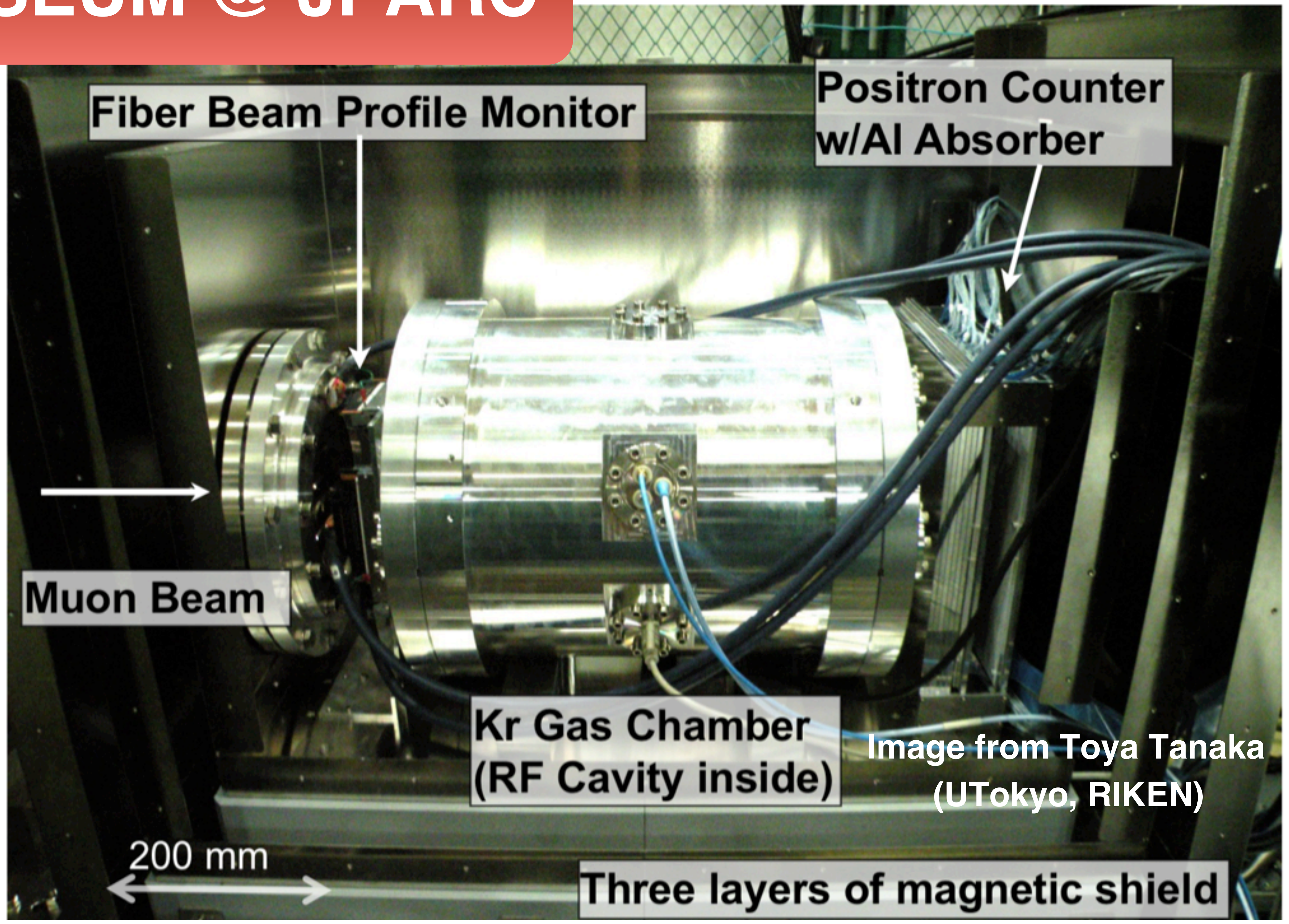
- Equate theory to experiment, treat m_μ/m_e as a free parameter, obtain m_μ/m_e to 22 ppb
- **Muonium hyperfine splitting at JPARC** aims to improve precision by a factor of 10 for μ_μ/μ_p to << 120 ppb

MuSEUM @ JPARC



Ingredients to Extracting a_μ

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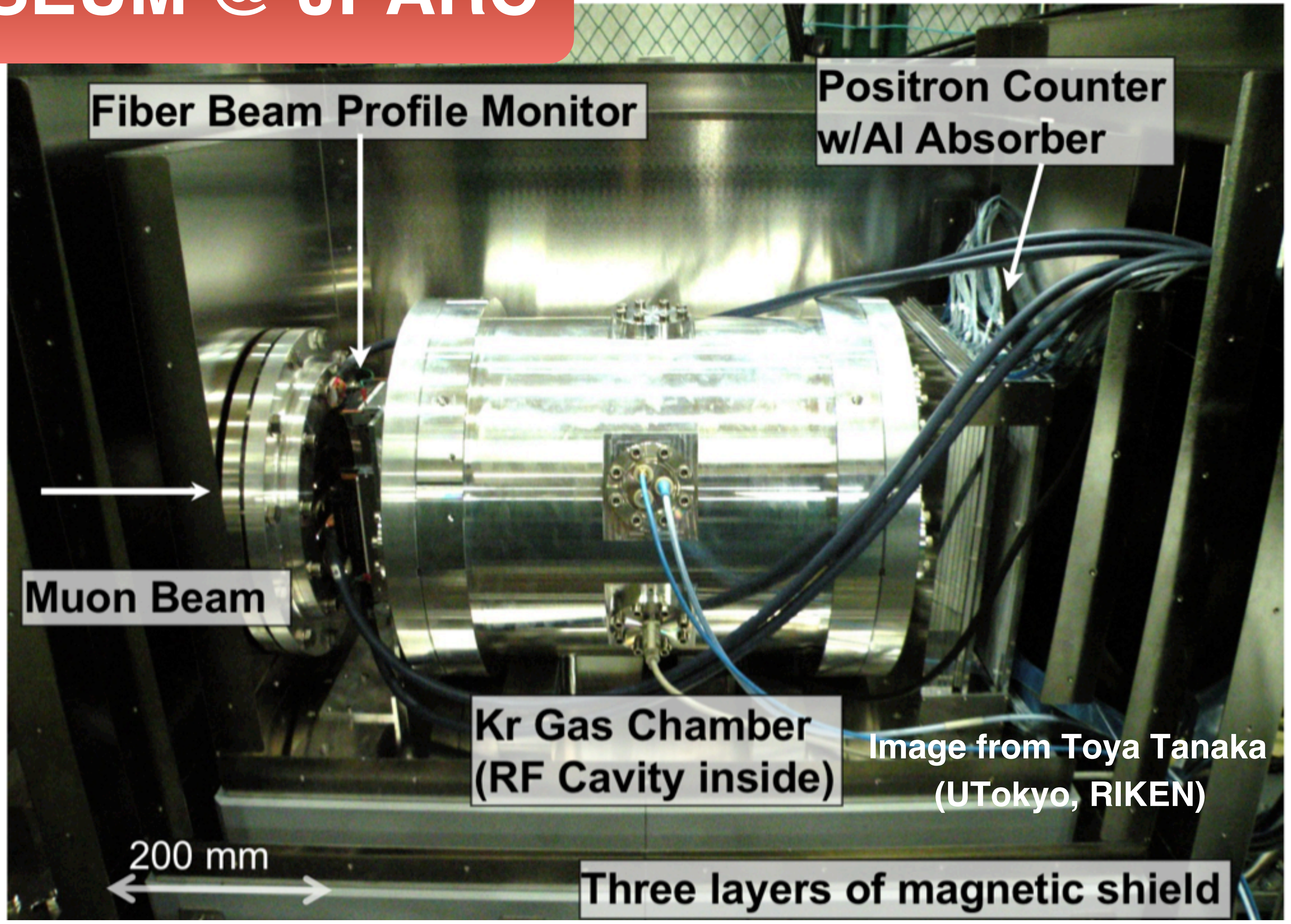
- Equate theory to experiment, treat m_μ/m_e as a free parameter, obtain m_μ/m_e to 22 ppb
- **Muonium hyperfine splitting at JPARC** aims to improve precision by a factor of 10 for μ_μ/μ_p to << 120 ppb
- Allows extraction of a_μ **independent of theory**:

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

MuSEUM @ JPARC

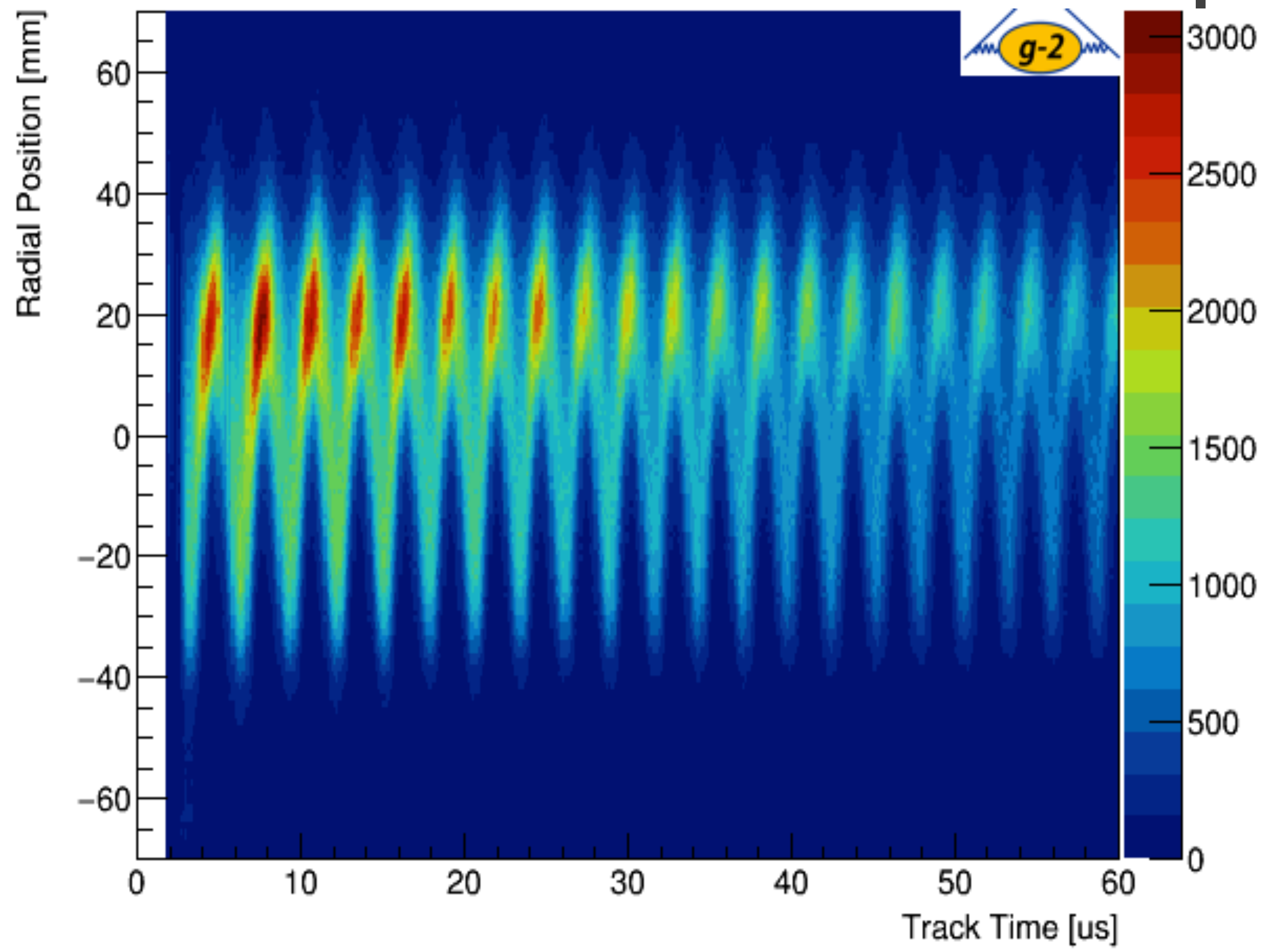


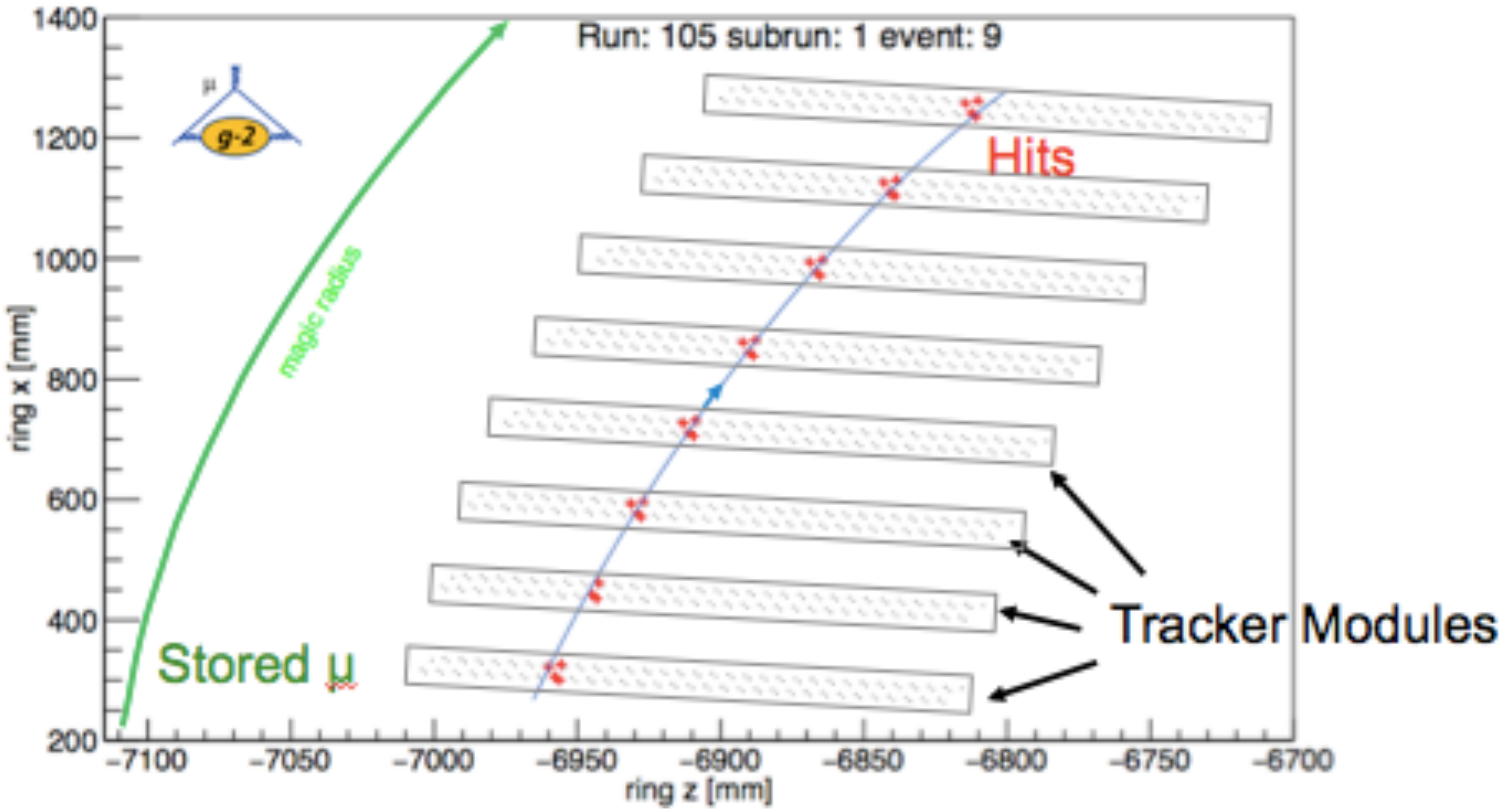
Run-1 Analysis Status — $\tilde{\omega}_p$

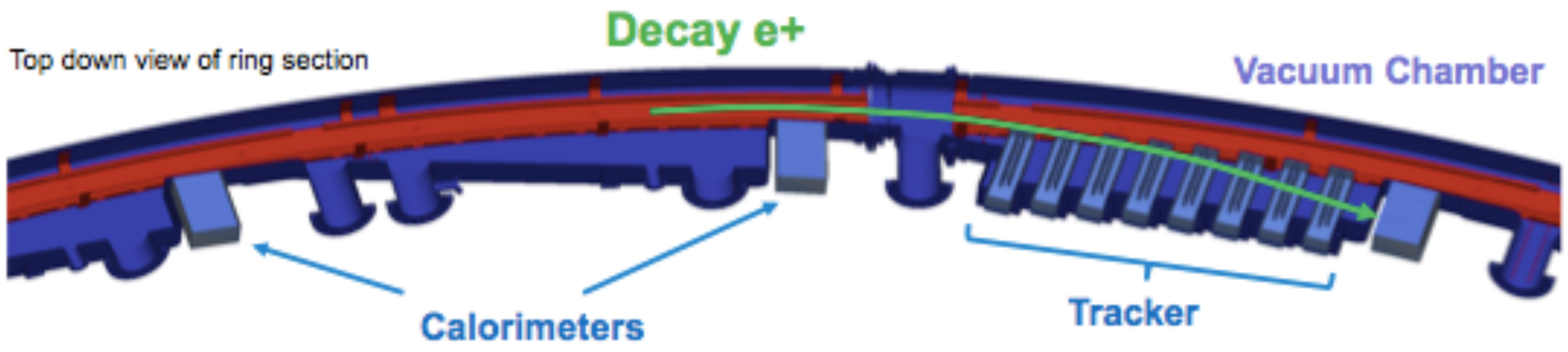
Fermilab

Position of the beam

- Use Trackers to measure the beam
- Extrapolate tracks back through B-field to point of radial Tangency
- Observe beam moving in time
- Use Trolley-Fixed probe interpolation to tell us the field at these positions

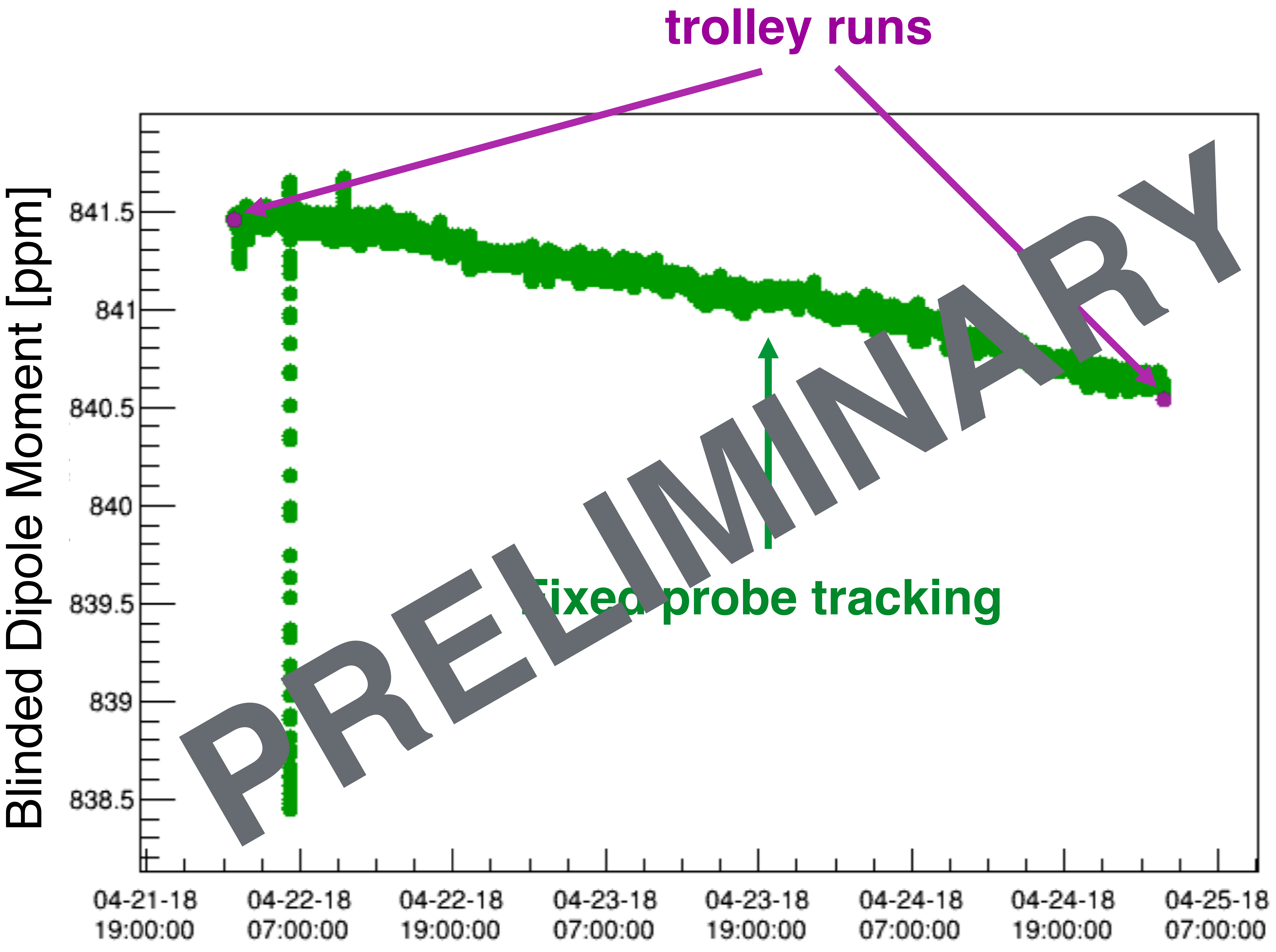




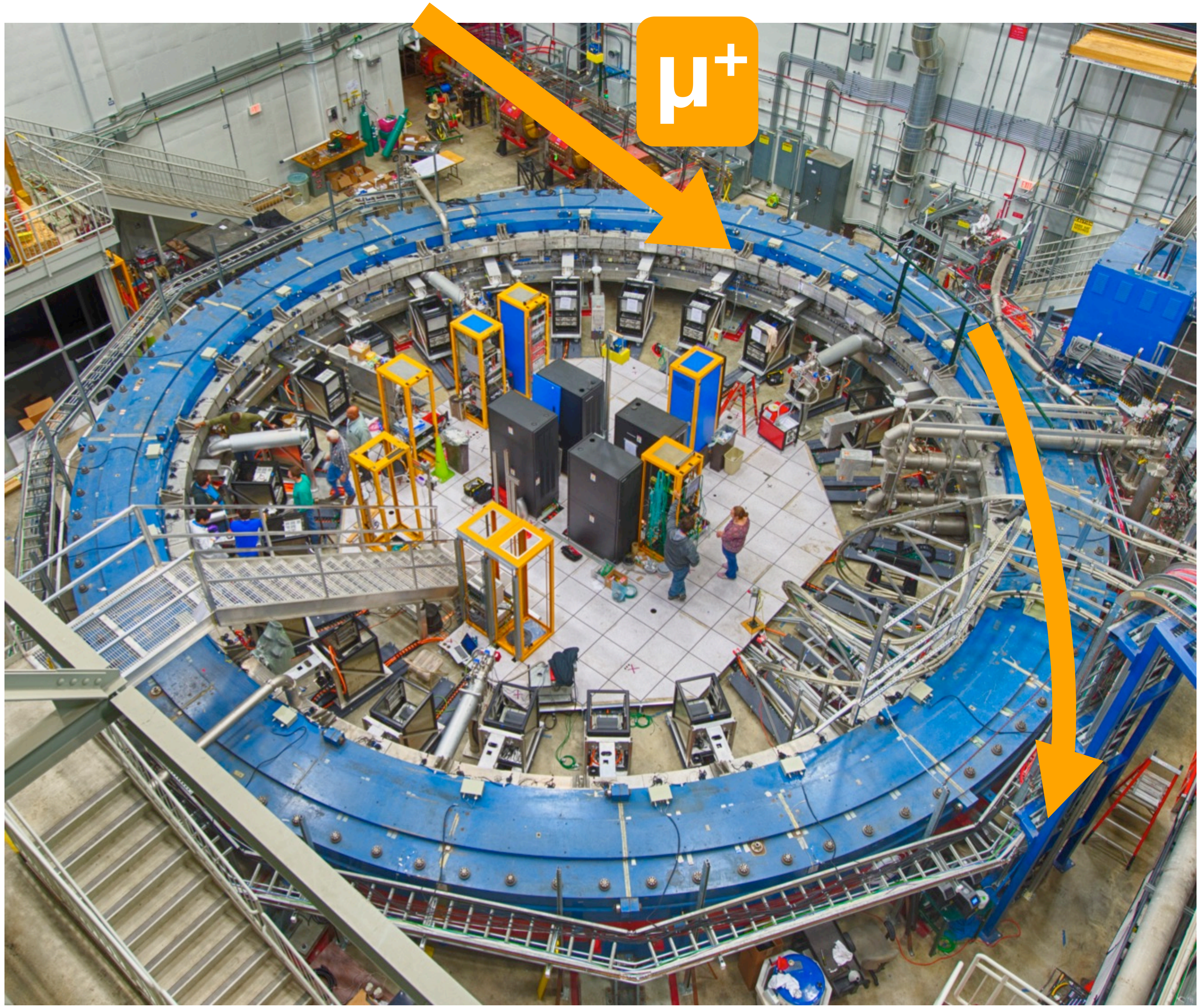


Run 1 Analysis Status: $\tilde{\omega}_p$ — Field Interpolation

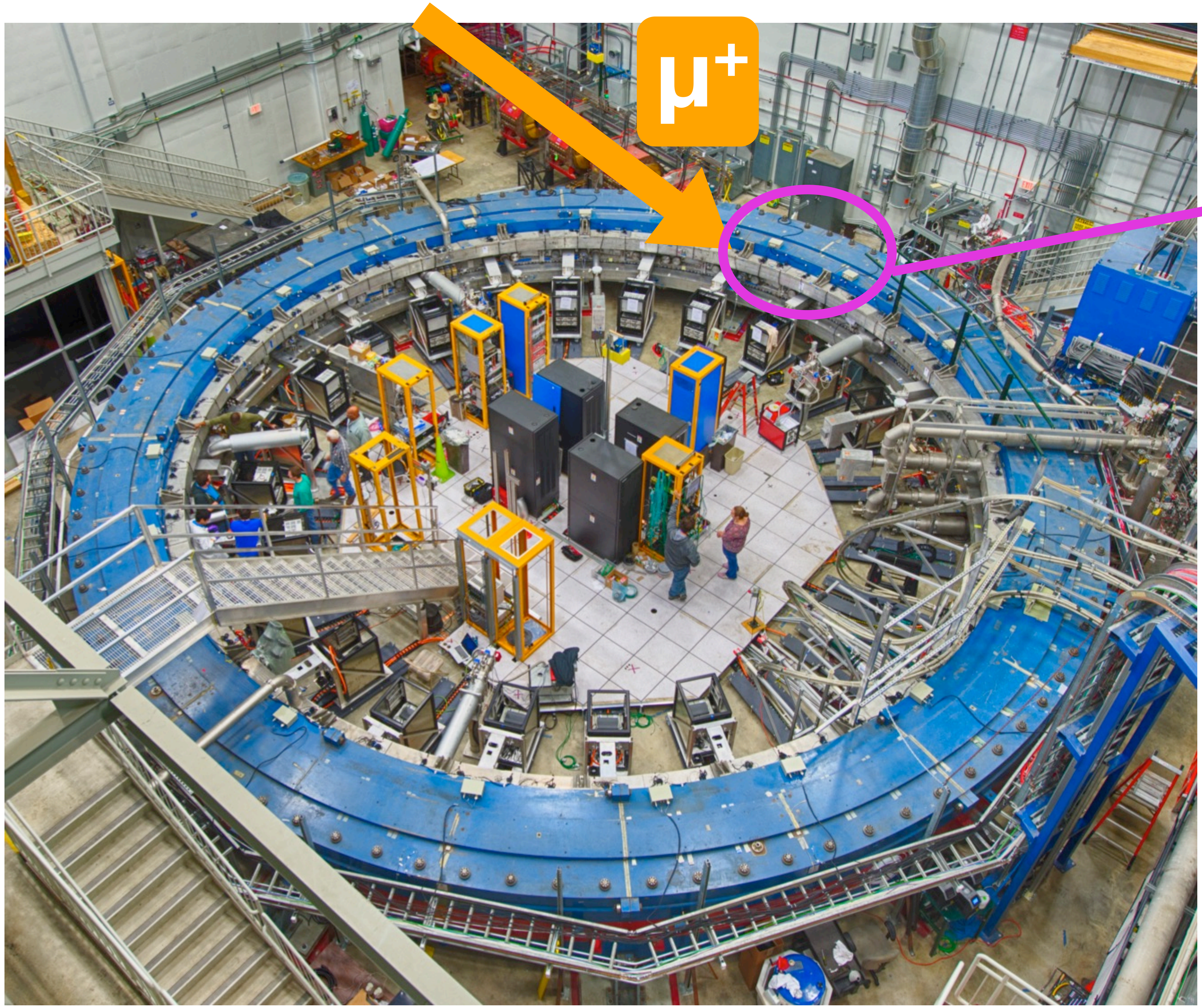
- Need to determine ω_p at all times while storing muons
- Interpolate between trolley maps using fixed probe data
- Tracking algorithms showing good agreement with trolley runs
- Also tracking higher-order multipole moments — important for extracting $\tilde{\omega}_p$



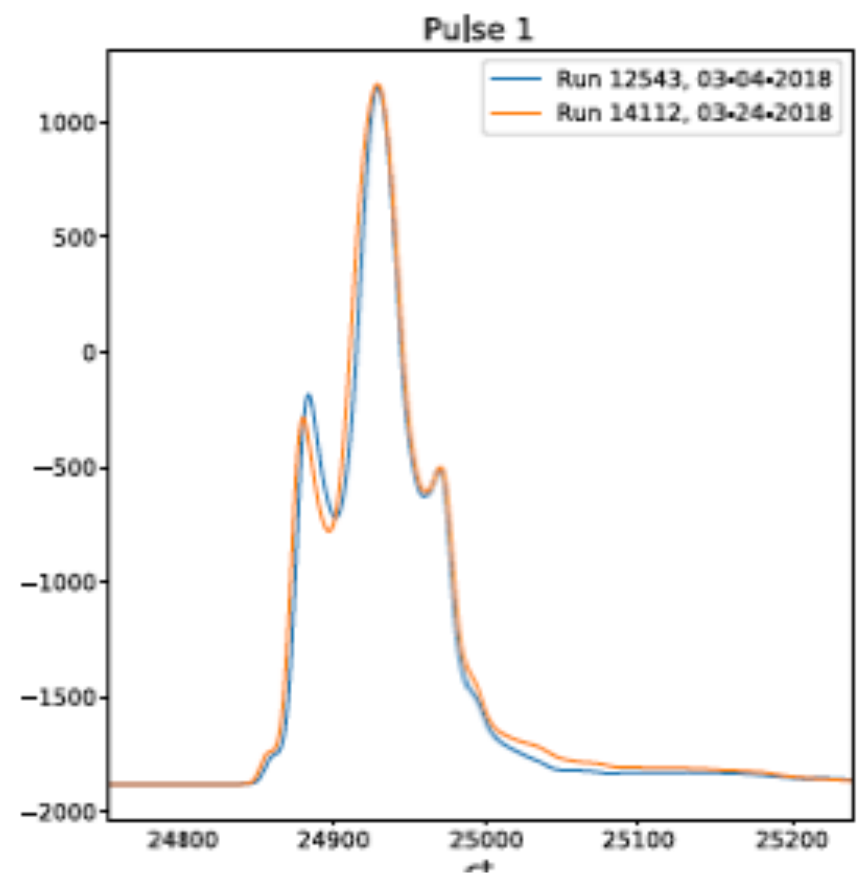
Muon Beam Injection



Muon Beam Injection

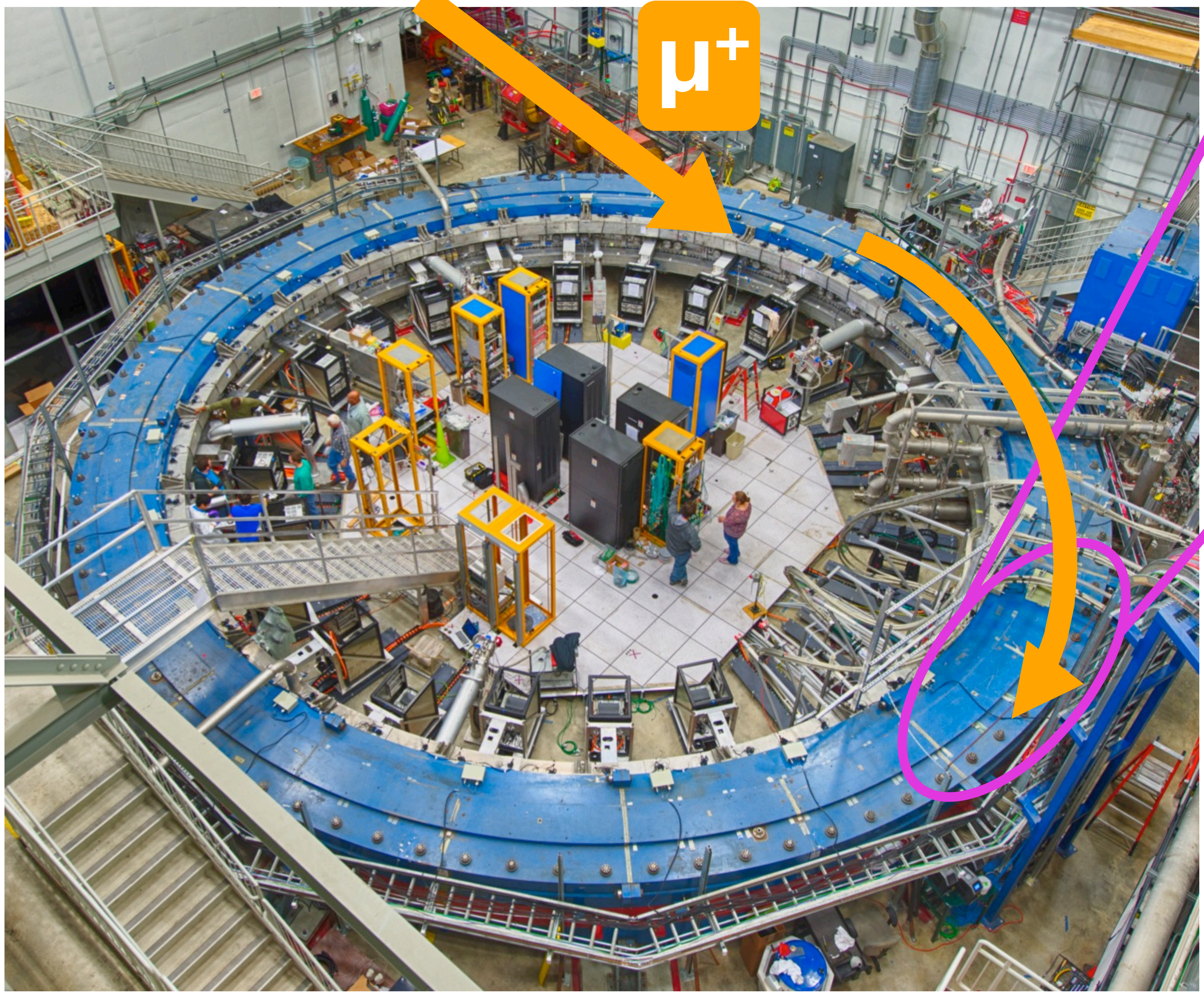


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

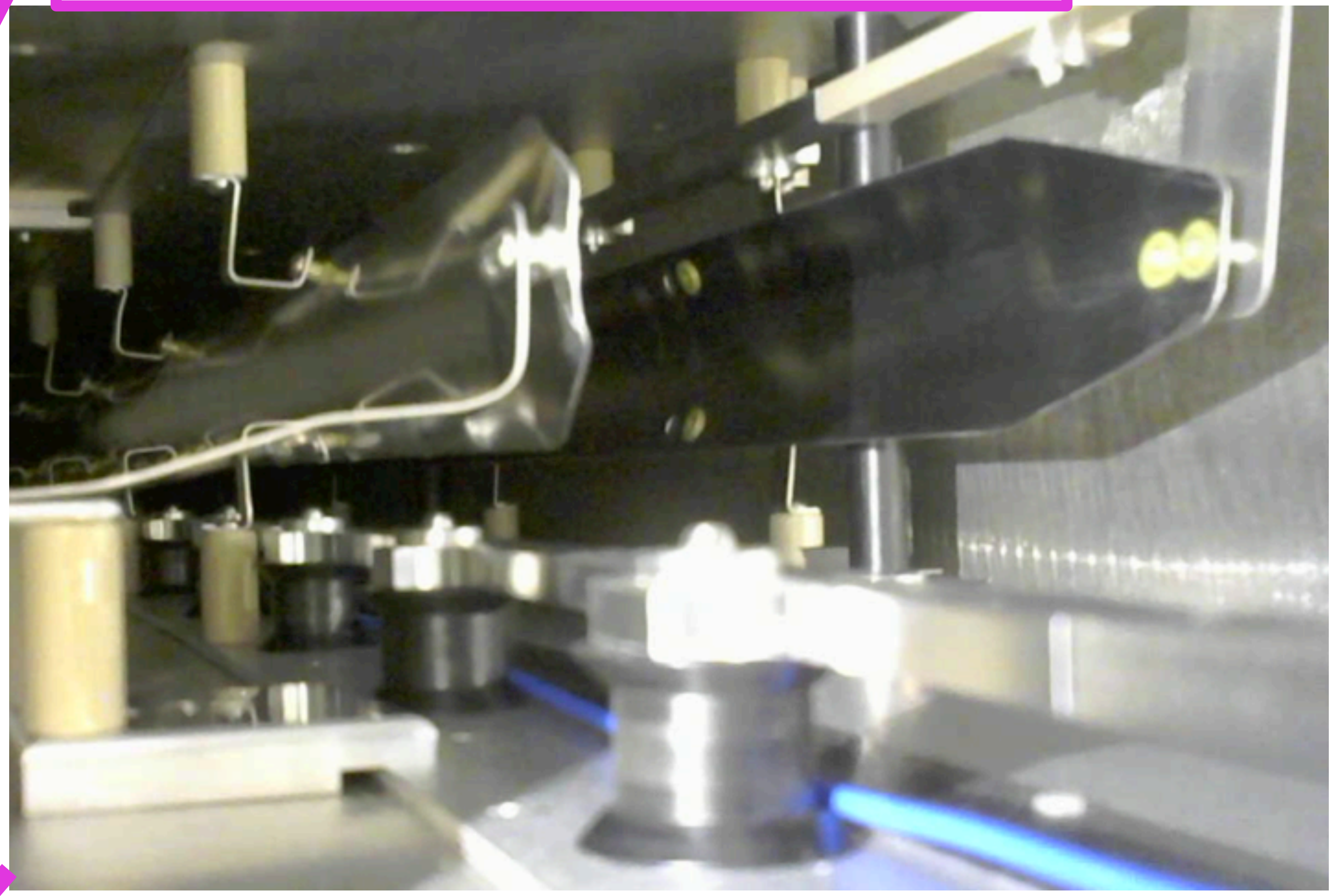


- Cancel B-field during injection using Inflector, so muons can get into the ring

Muon Beam Injection

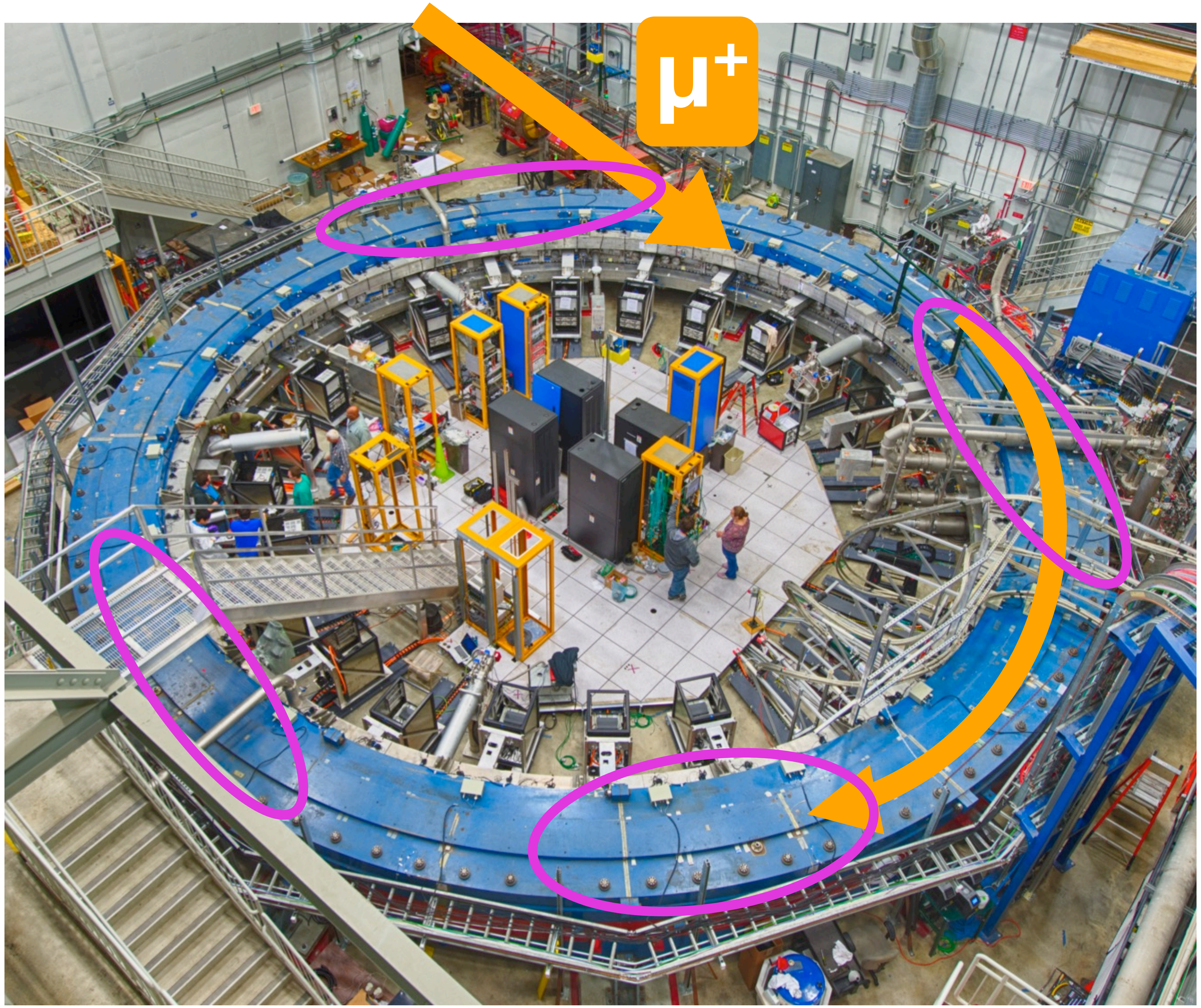


Kicker magnets



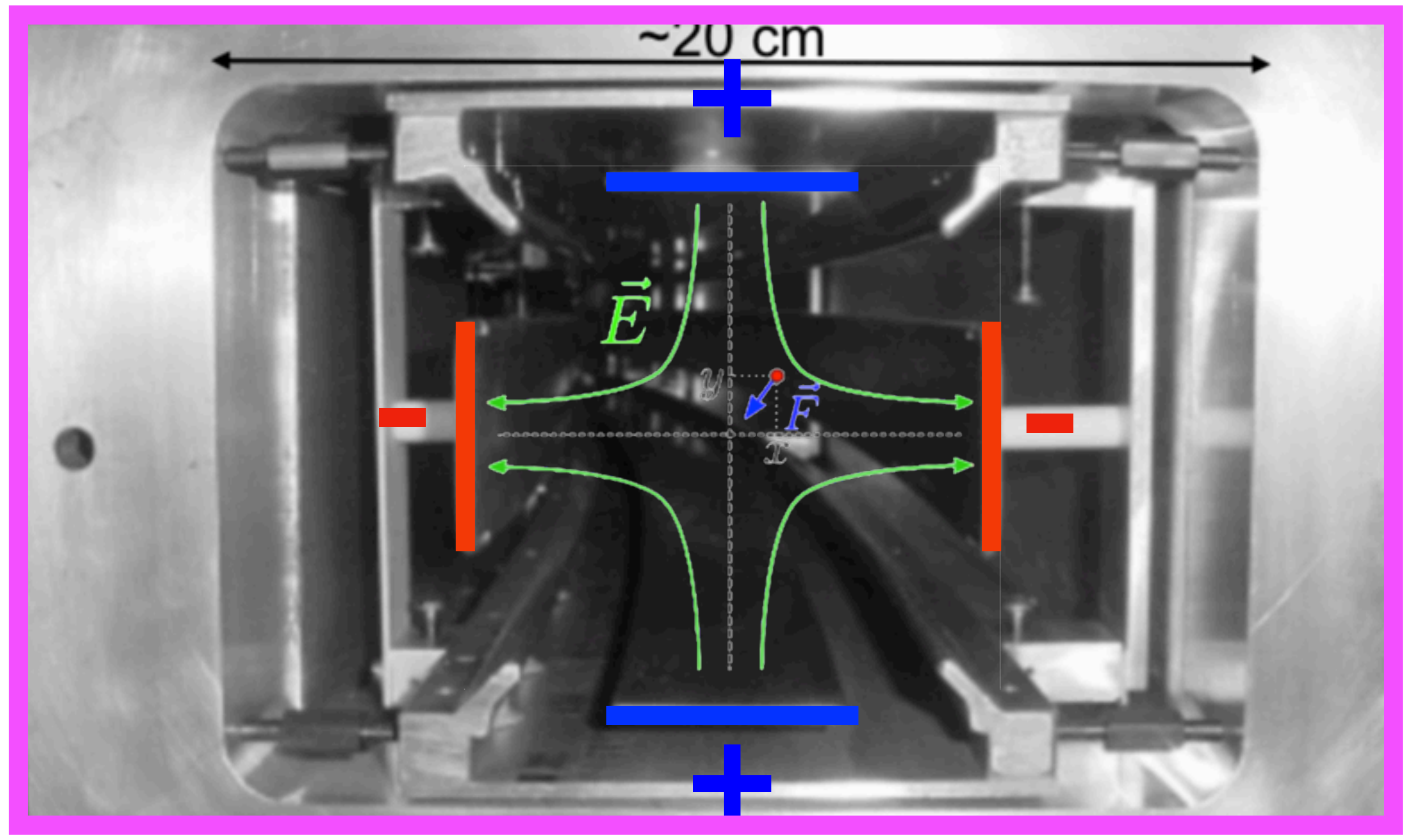
- After inflector, muons enter storage region at r = 77 mm outside central closed orbit
- Deliver pulse in < 149 ns to muon beam
- Steer muons onto stored orbit

Muon Beam Injection

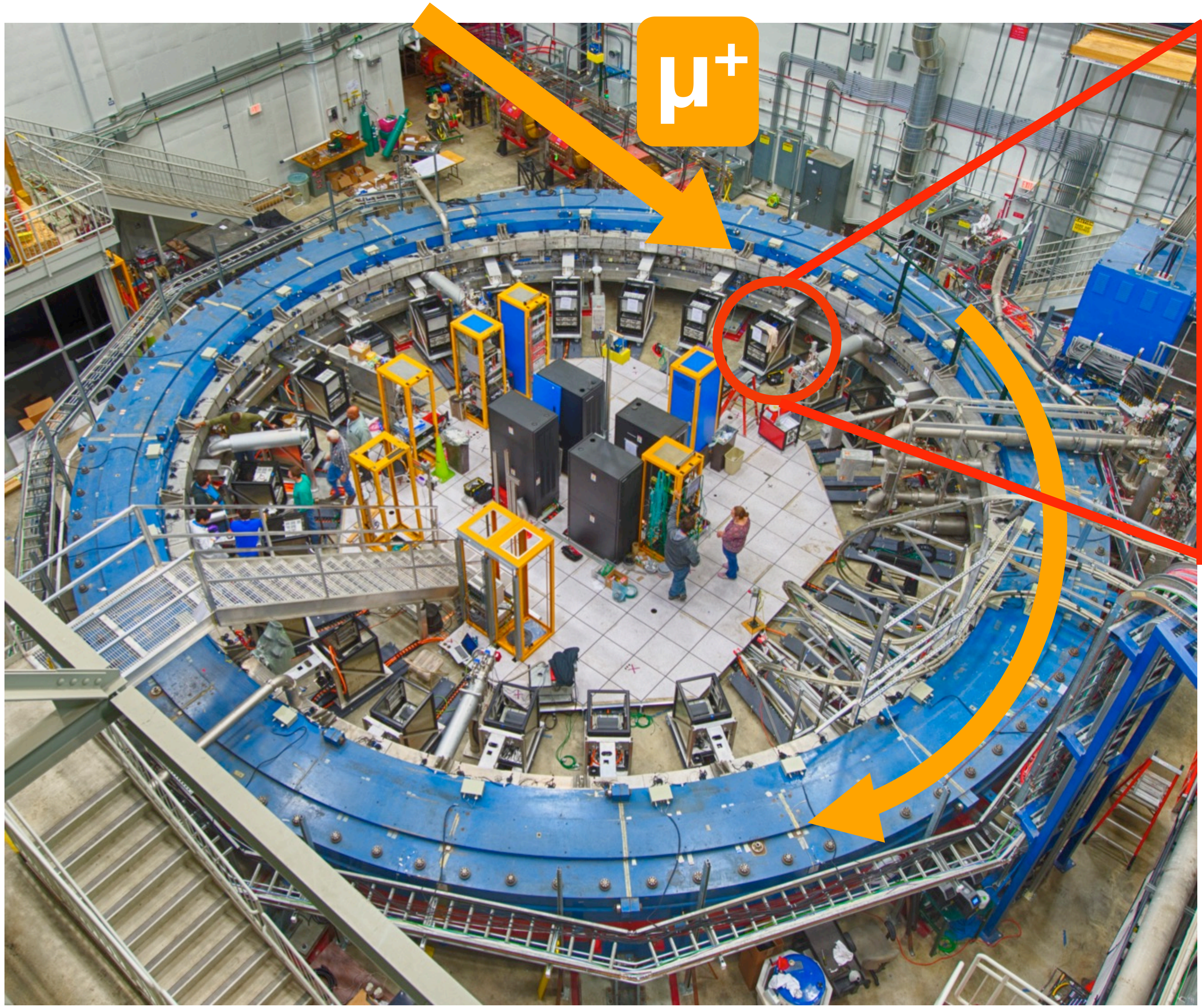


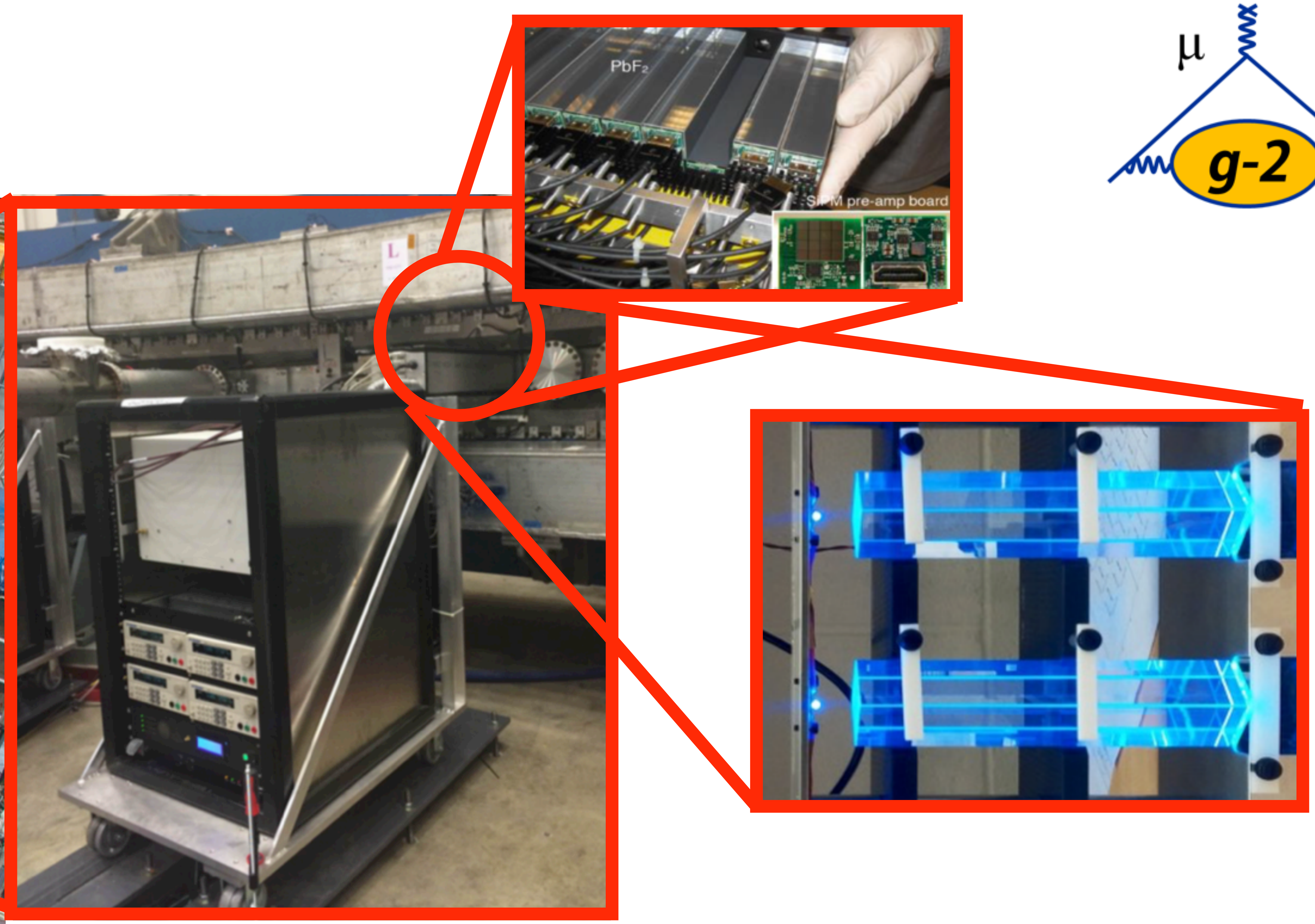
Electrostatic quadrupoles

- Drive the muons towards the central part of storage region vertically
- Minimizes beam “breathing”, improves muon orbit stability
- Aluminum electrodes cover ~43% of total circumference



Muon Beam Injection

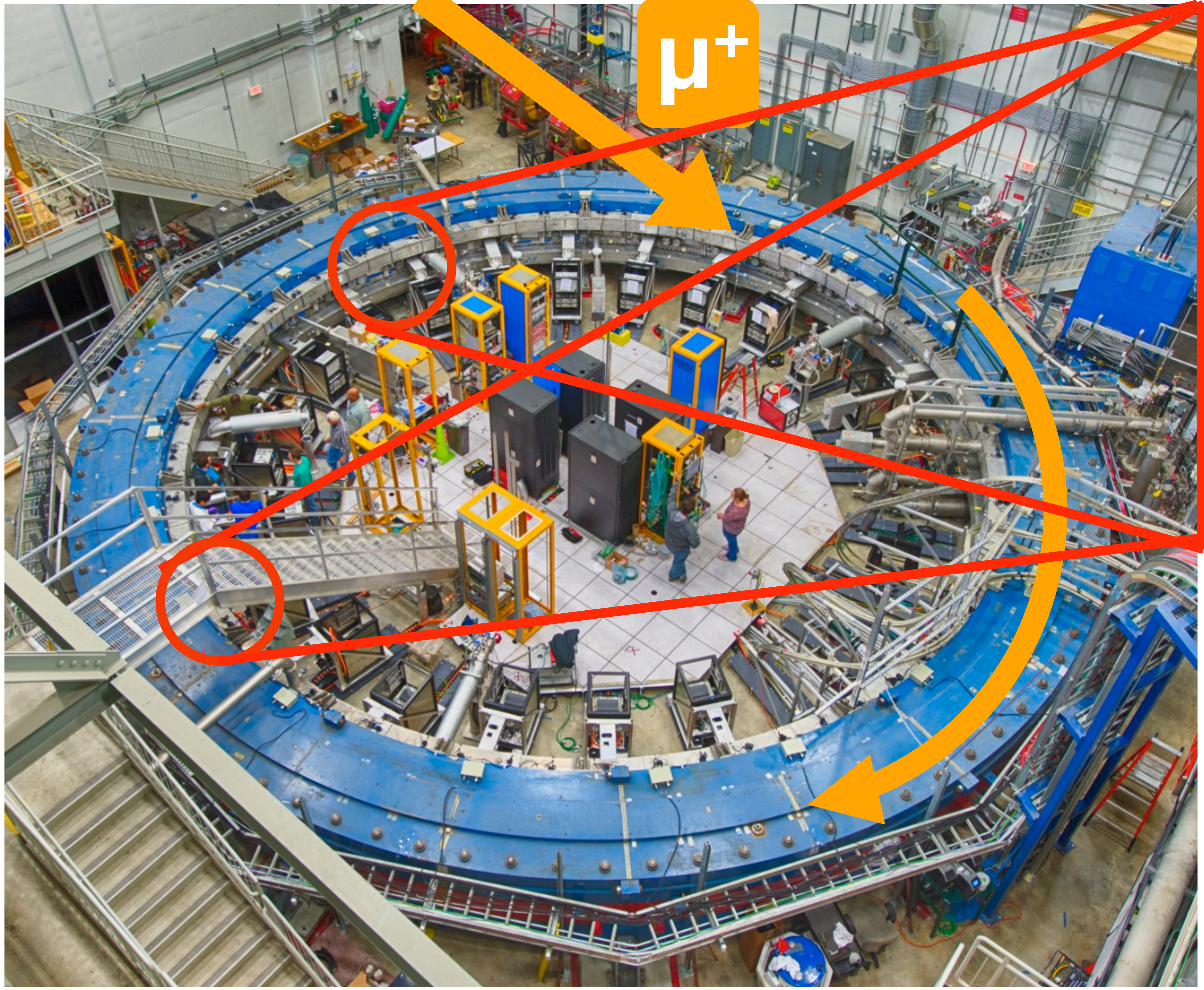


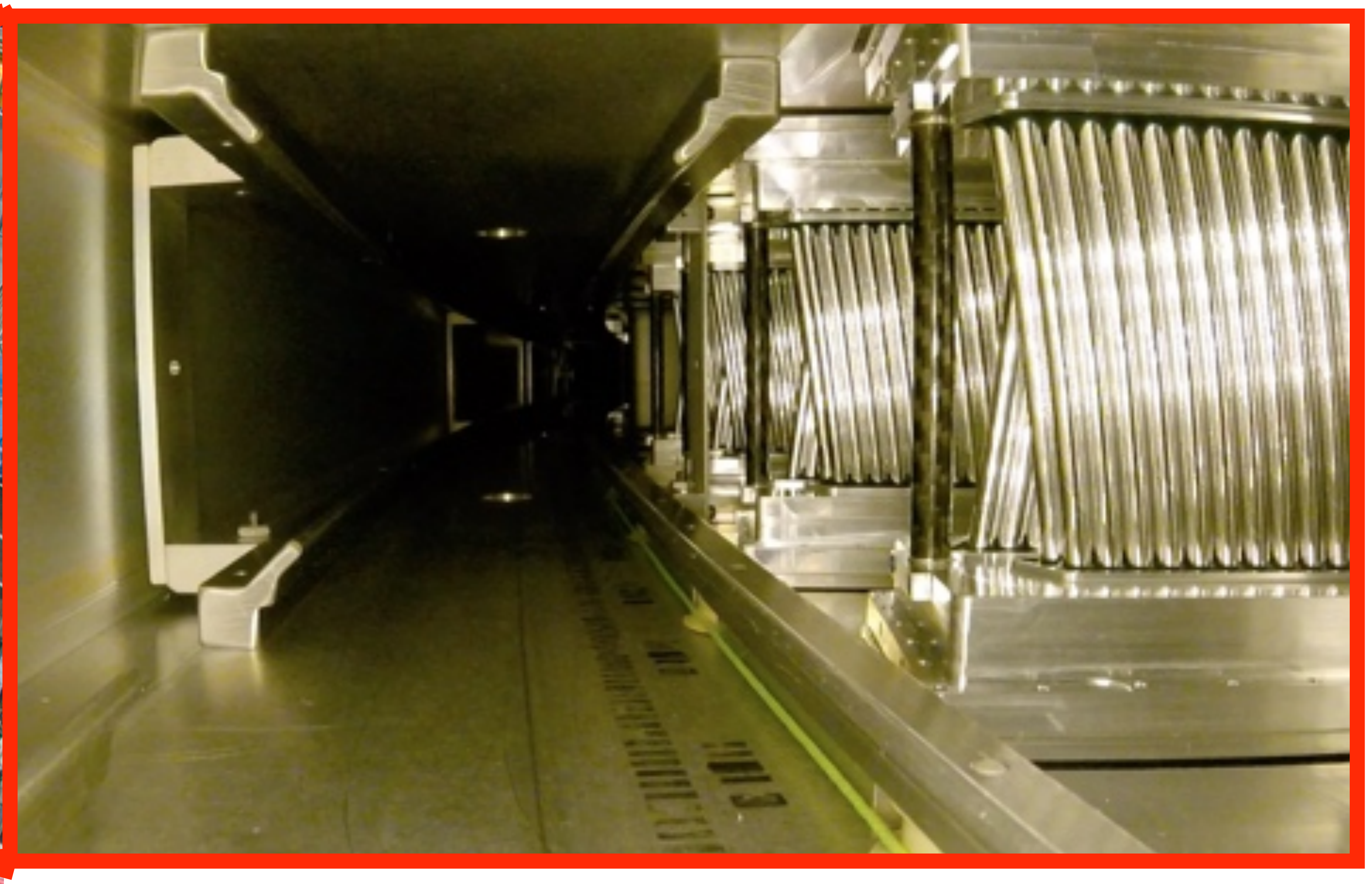


24 segmented PbF_2 crystal calorimeters

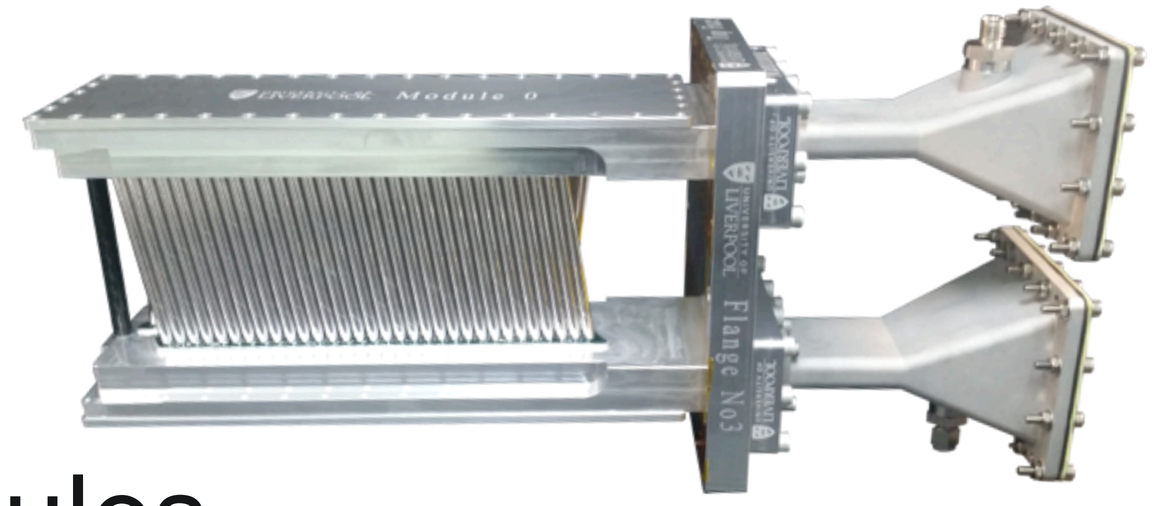
- Each crystal array of 6 x 9 PbF_2 crystals
  - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

Muon Beam Injection





2 Tracking stations

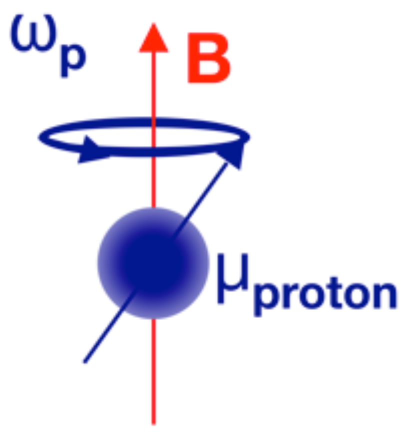


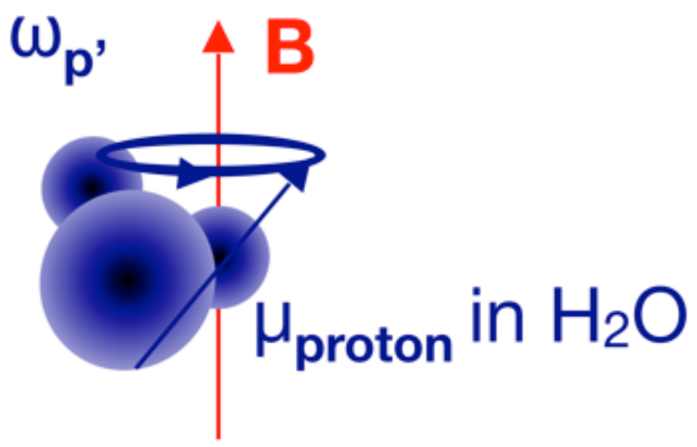
- Each contain 8 modules
- 128 gas filled straws in each module
- Traceback postrons to their decay point

Run-1 Analysis Status — ω_p

Run 1 Analysis Status: ω_p — Field Calibration

- In the experiment, need to extract ω_p; however, don't have free protons
  - Need a calibration
- Field at the proton differs from the applied field





$$\omega_p^{\mathrm{meas}} = \omega_p^{\mathrm{free}}\left[1 - \sigma(\mathrm{H_2O}, T) - \left(\varepsilon - \frac{4\pi}{3}\right)\chi(\mathrm{H_2O}, T) - \delta_m\right]$$

Protons in H_2O molecules, diamagnetism of electrons screens protons => local B changes

- **Known to 2.5 ppb**

Magnetic susceptibility of water gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (sphere), 2π (cylinder) when probe is perpendicular to B
- **Known to 5 ppb**

Magnetization of probe materials perturbs the field at site of protons

- **Measured to 6.5 ppb**

Goal: Determine total correction to ≤ 35 ppb accuracy

These are **static** corrections; need to worry about **dynamic** ones too (radiation damping, RF coil inhomogeneity, time dependence of gradients, …)

Run 1 Analysis Status: ω_p — Field Calibration

Plunging Probe

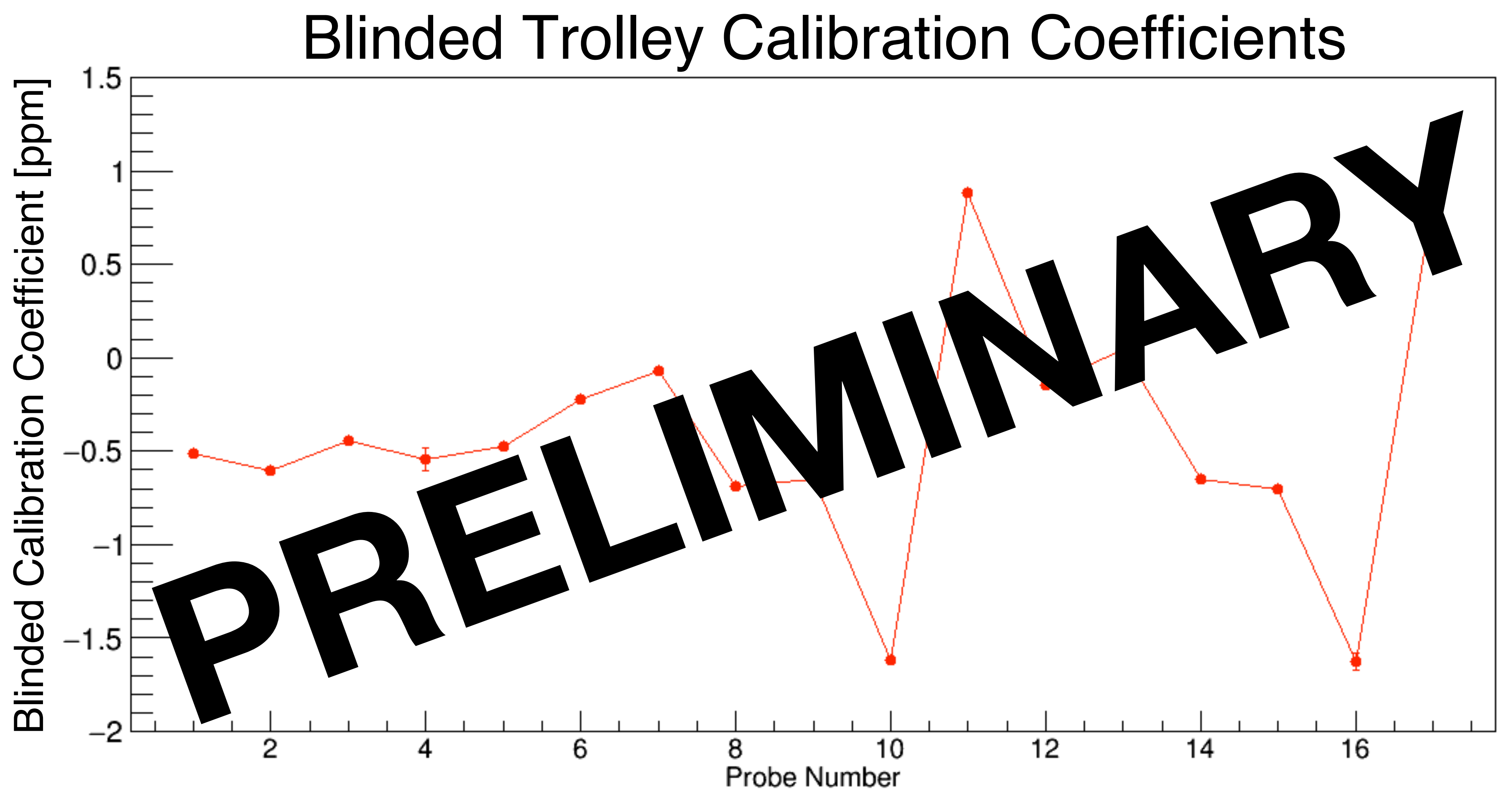
- Achieved **small perturbation of plunging probe** ~ (-5.0 ± 6.5) ppb
- Quantified uncertainties on plunging probe material, dynamic effects — **under budget of 35 ppb**

Plunging Probe Uncertainties	
Effect	**Uncertainty (ppb)**
Probe Perturbation to Field (includes images)	6.5
Radiation Damping	20
Proton Dipolar Field	2
Oxygen Contamination of Water Sample	< 1
TOTAL	**21**

PRELIMINARY

Trolley Calibration

- **Calibration of trolley probes under control**
- Factor of ≥ 2 improvement on uncertainties for nearly all probes compared to E821
- Uncertainty is ~ 26 ppb on average per probe — **under budget of 30 ppb**



Run-1 Analysis Status — ω_a

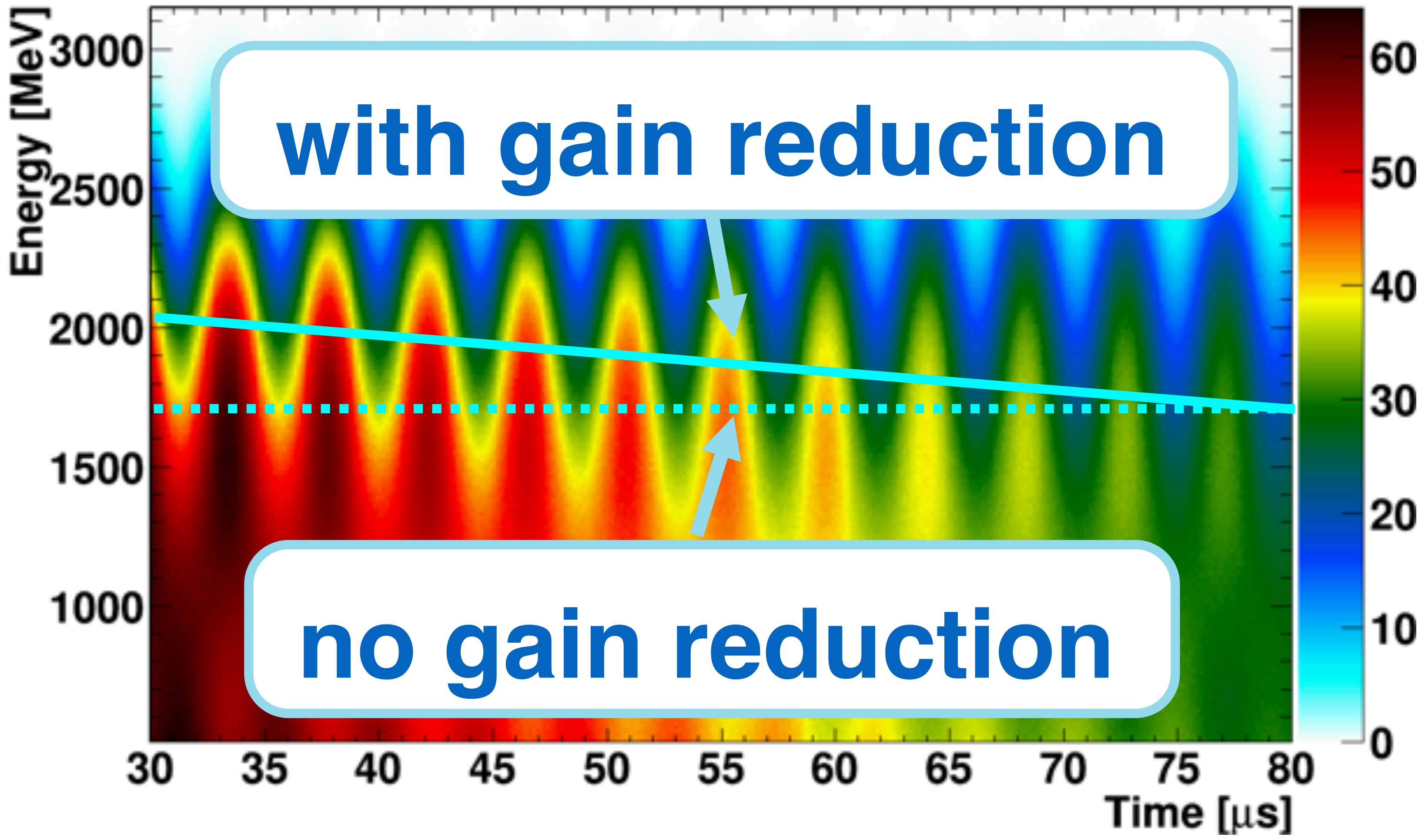
Run 1 Analysis Status: ω_a

- Account for a number of effects that can affect the extraction of ω_a

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

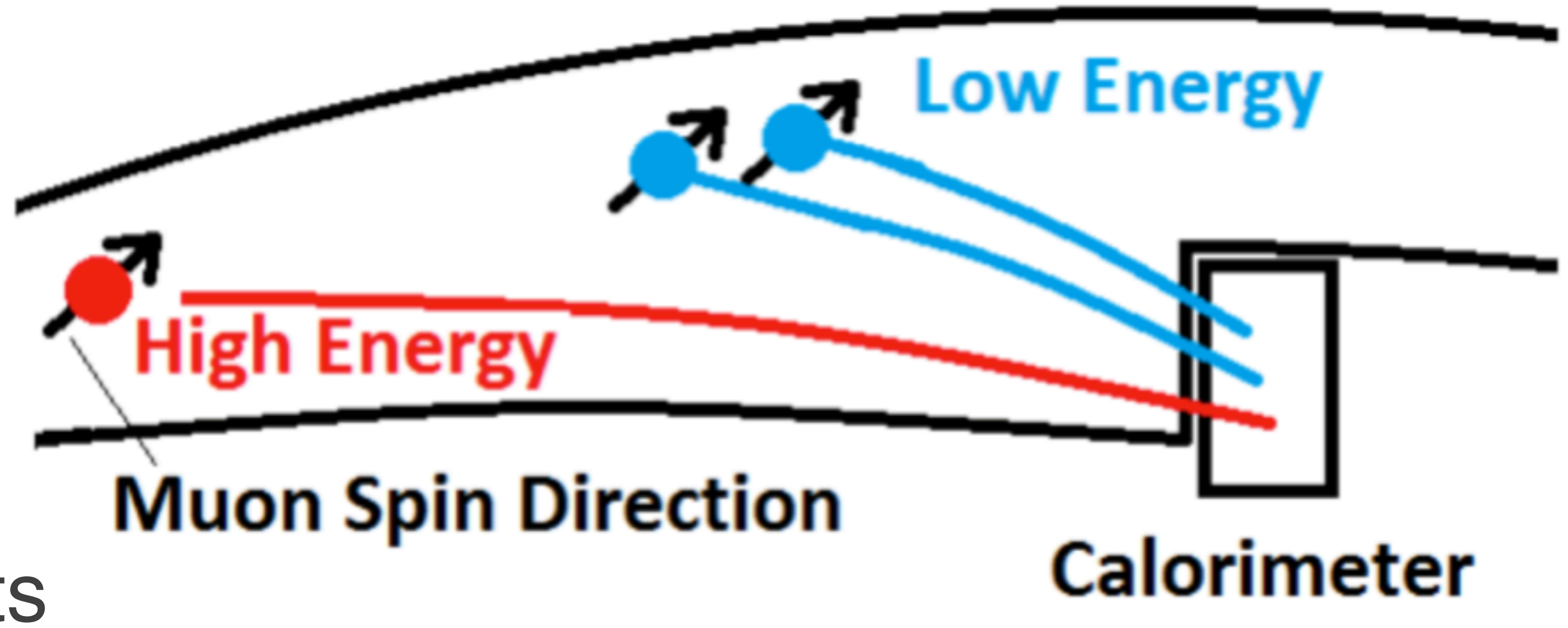
Detector effects

Gain instability



- Gain changes over time in calorimeters affects phase of signal: $N \rightarrow N(t)$, $A \rightarrow A(t)$, $\phi \rightarrow \phi(t)$
- Laser system provides corrections

Event pileup



- Low-energy events can mimic high-energy events in calorimeter
- Spin precession phase varies with energy — apparent high-energy decay carries phase of low-energy decays

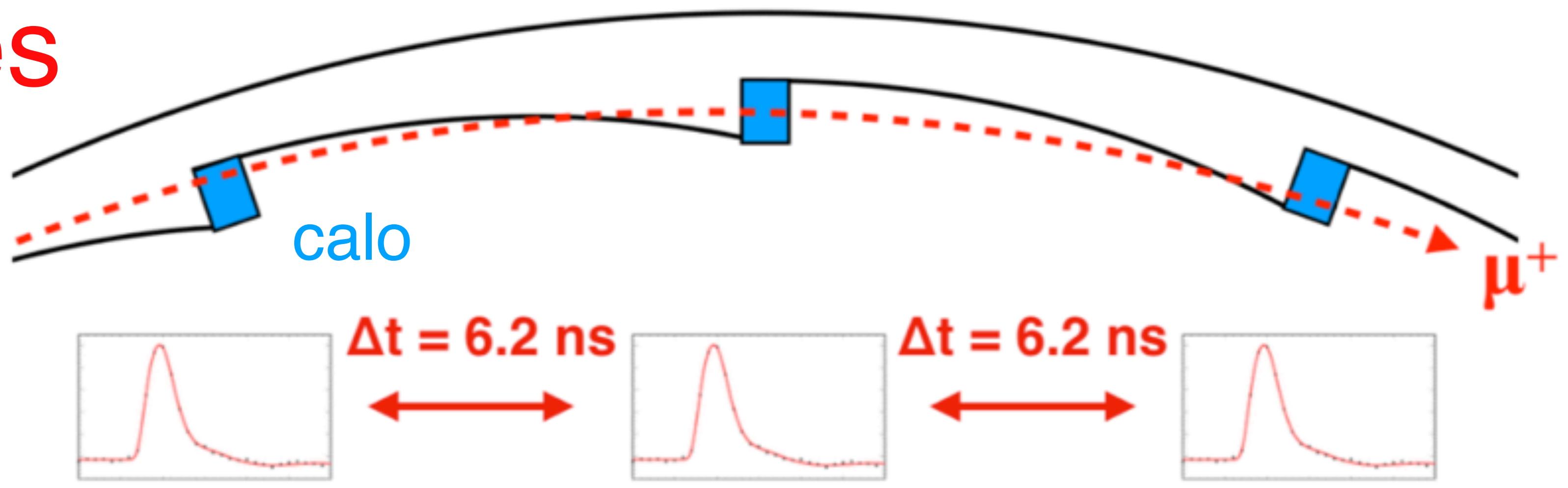
Run 1 Analysis Status: ω_a

- Account for a number of effects that can affect the extraction of ω_a

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

Beam dynamics

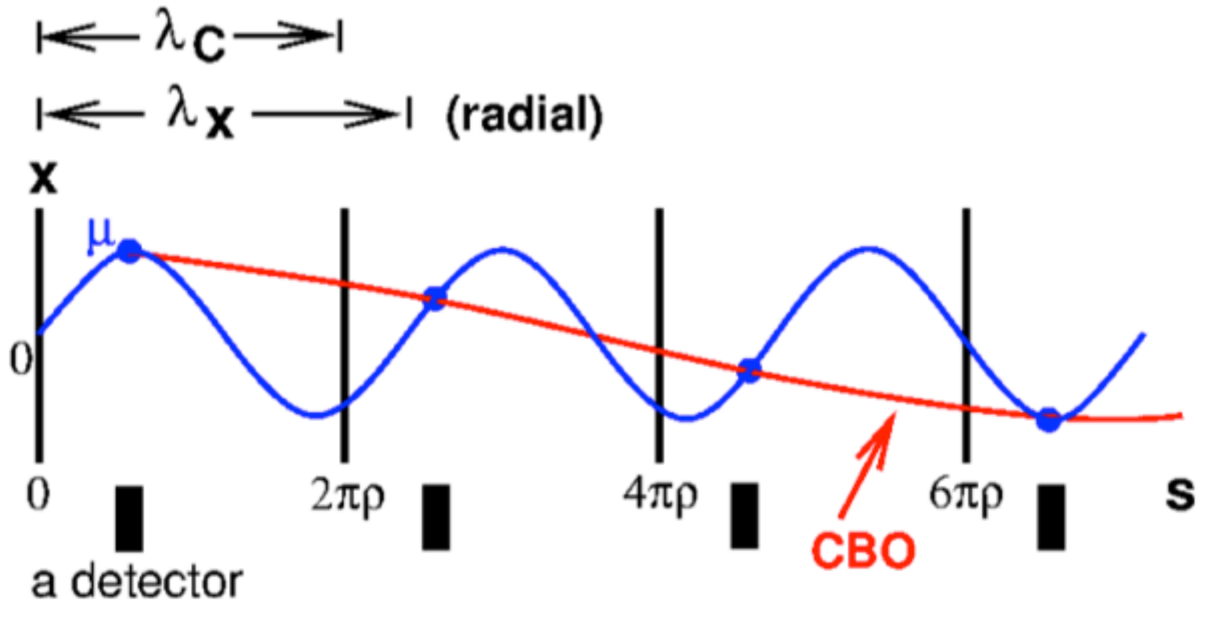
Muon losses

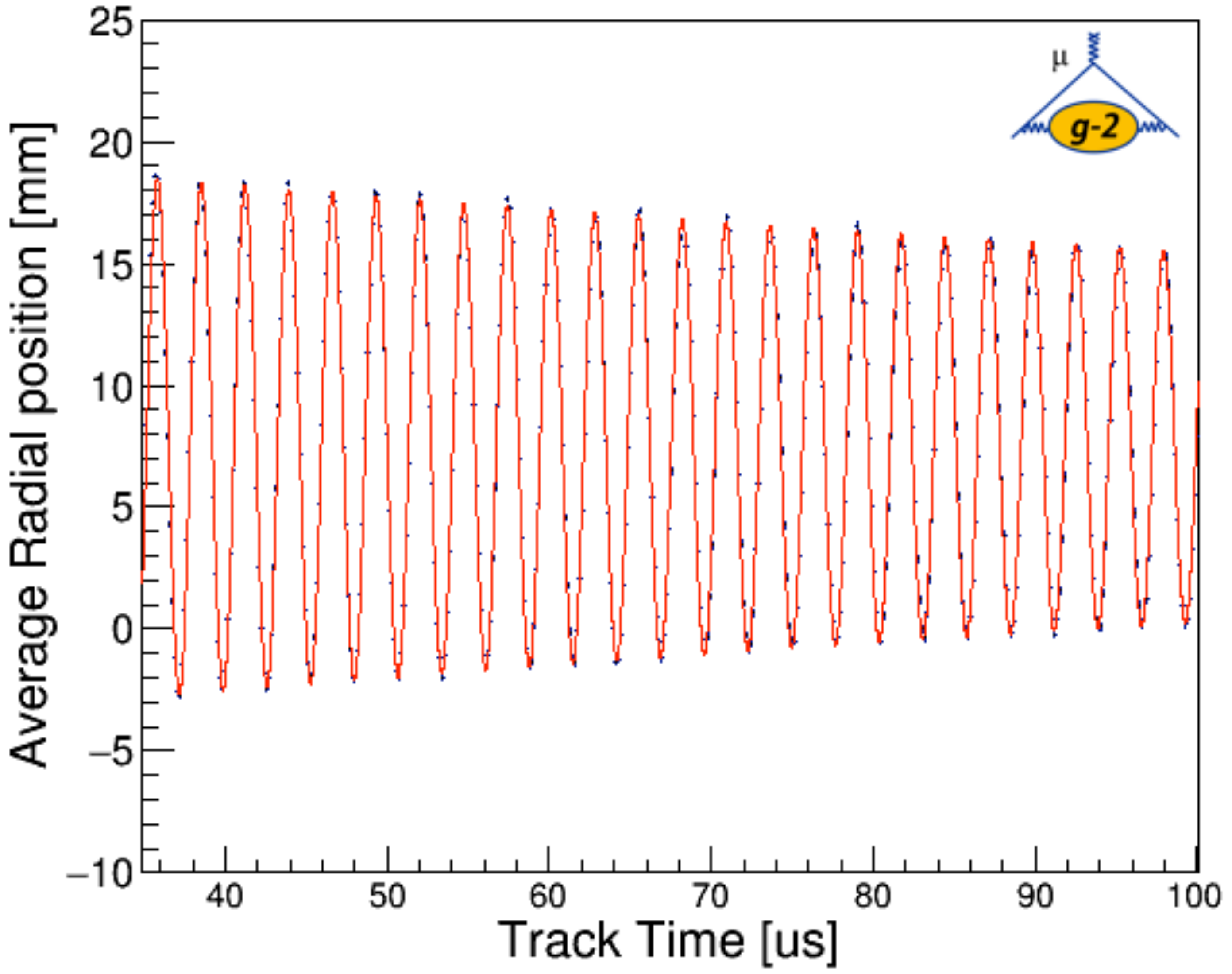


- Muons can leave storage ring by decaying or escaping
- Exhibit specific signature in multiple calorimeters
- Amplitude N_0 scaled by:

$$\Lambda(t) = 1 - K_{\text{loss}} \int_0^t e^{t'/\tau} L(t') dt'$$

Coherent betatron oscillations (CBO)





- Acceptance of calorimeters affected by coherent radial beam motion
- Amplitude N_0 scaled by:

$$C(t) = 1 - e^{-t/\tau_{\text{CBO}}} A_1 \cos\left(\omega_{\text{CBO}} t + \phi_1\right)$$

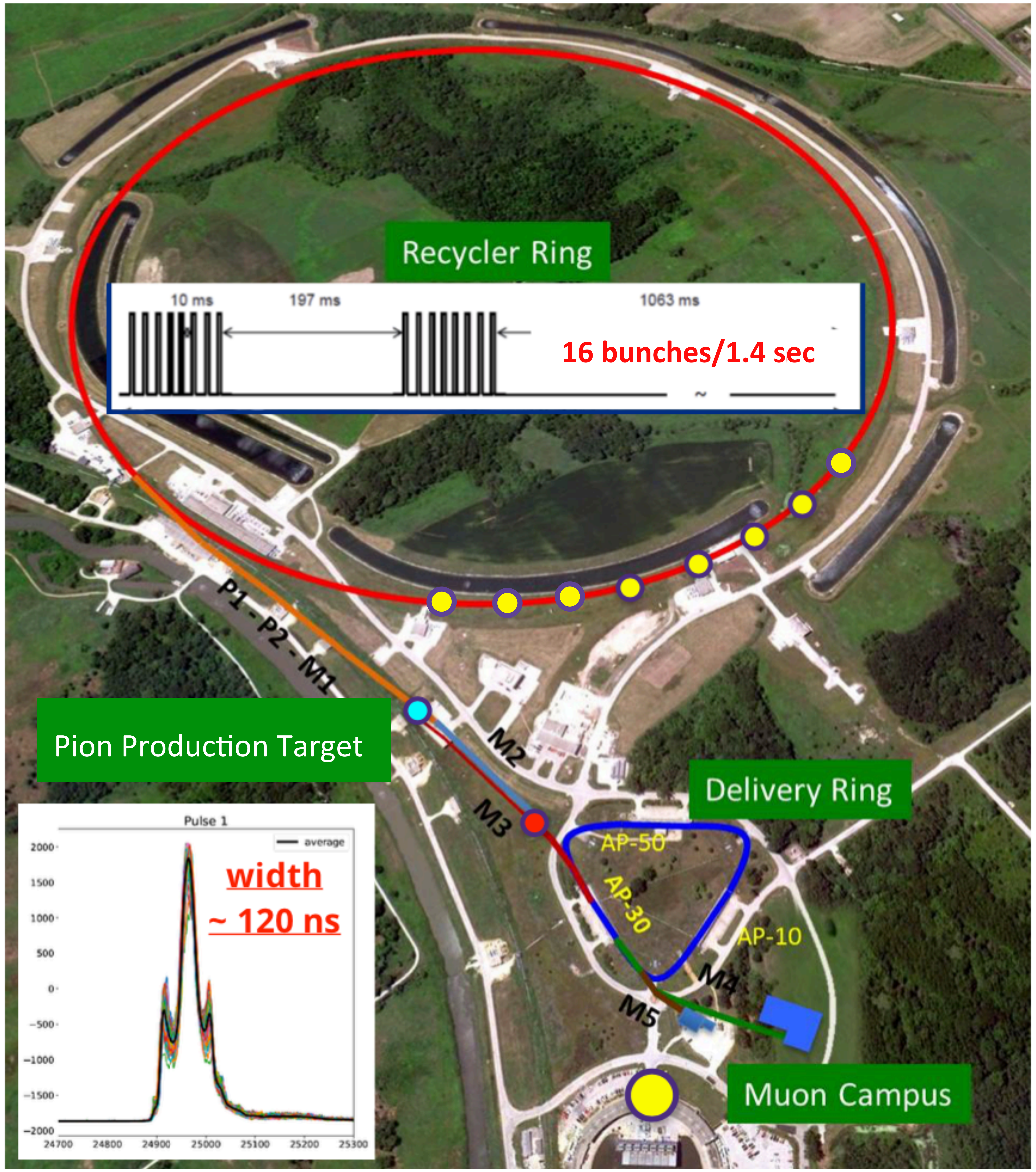
Fermilab

Why Fermilab?

- BNL limited by statistics (540 ppb on 9 x 10^9 detected e^+)
- E989 goal: Factor of 21 more statistics (2 x 10^{11} detected e^+)

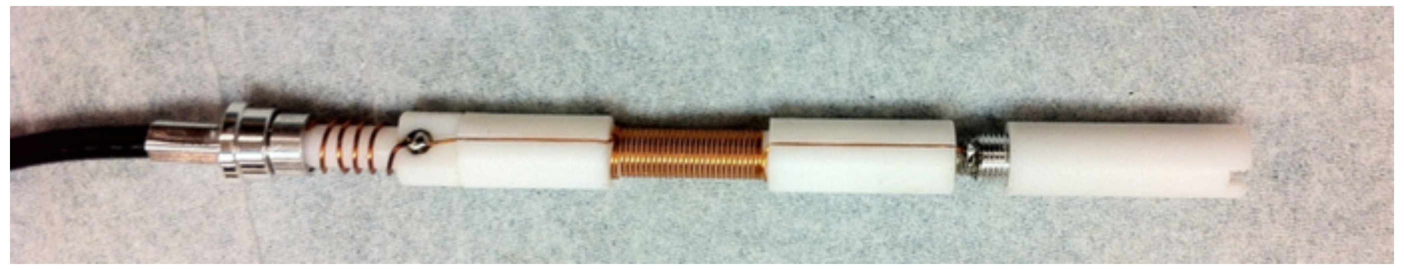
Fermilab advantages

- Long beam line to collect $\pi^+ \rightarrow \mu^+$
- Much reduced amount of p, π in ring
- 4x higher fill frequency than BNL

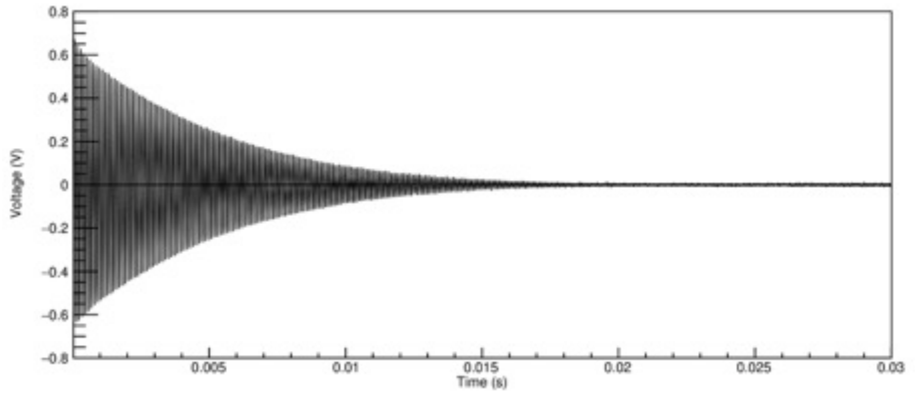


Monitoring and Mapping the Magnetic Field

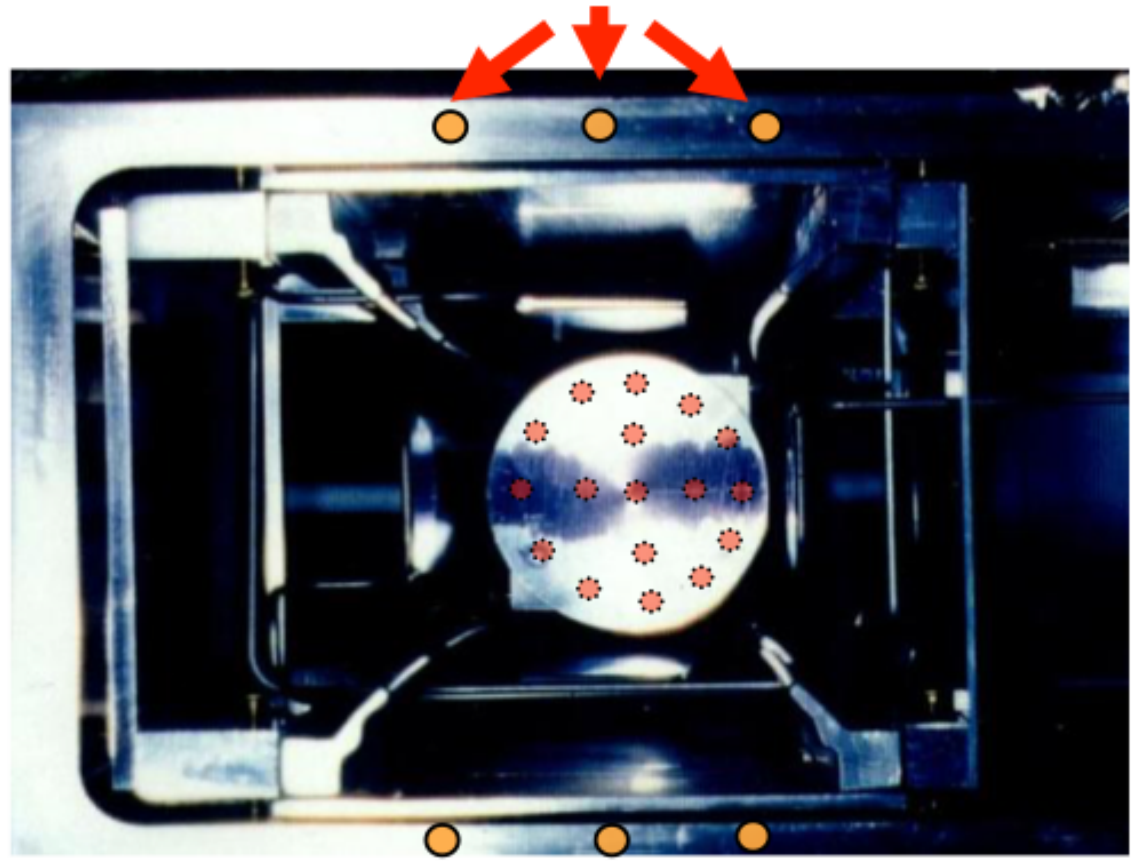
Pulsed NMR



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

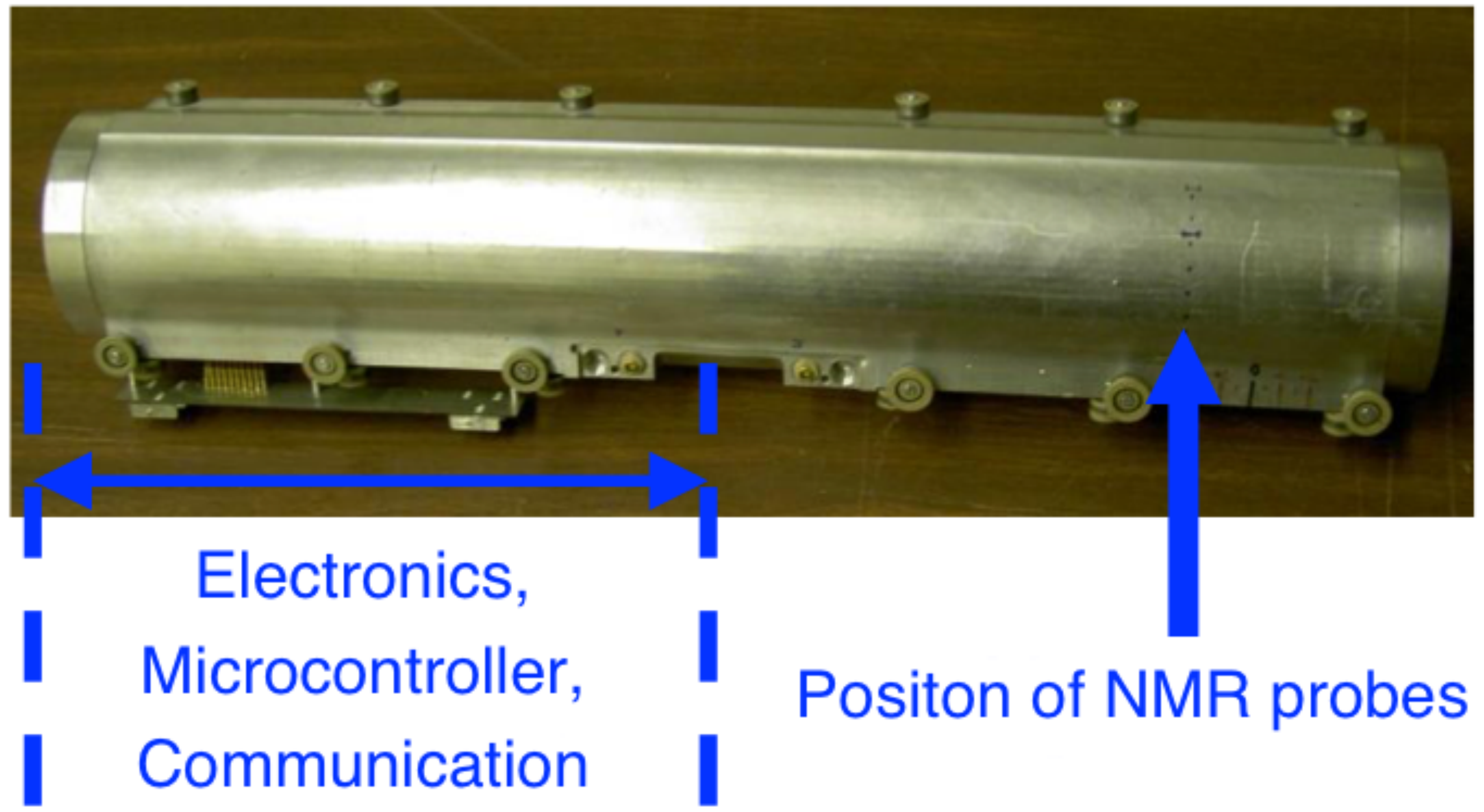


Fixed probes on vacuum chambers



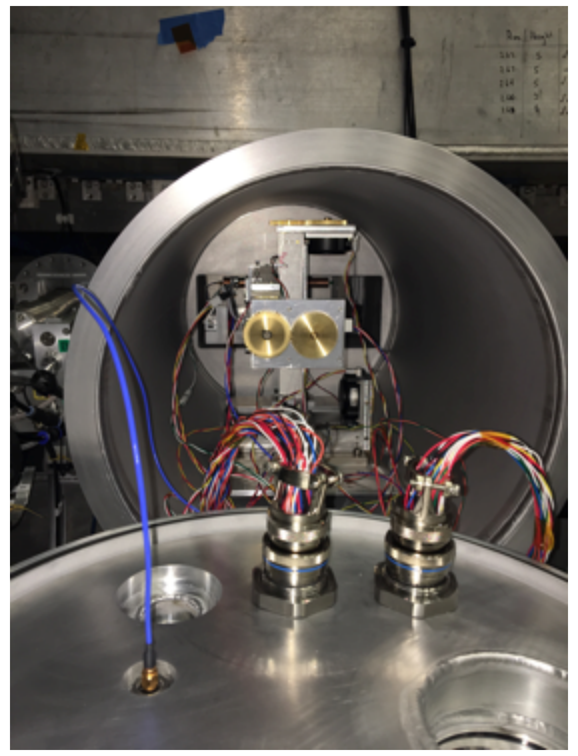
- Measure field while muons are in ring – 378 probes **outside** storage region

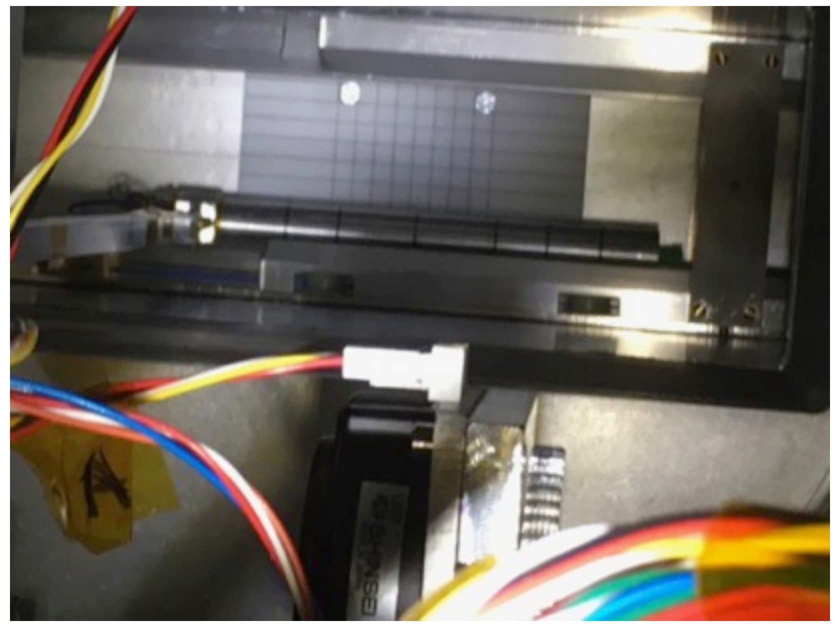
Trolley matrix of 17 NMR probes



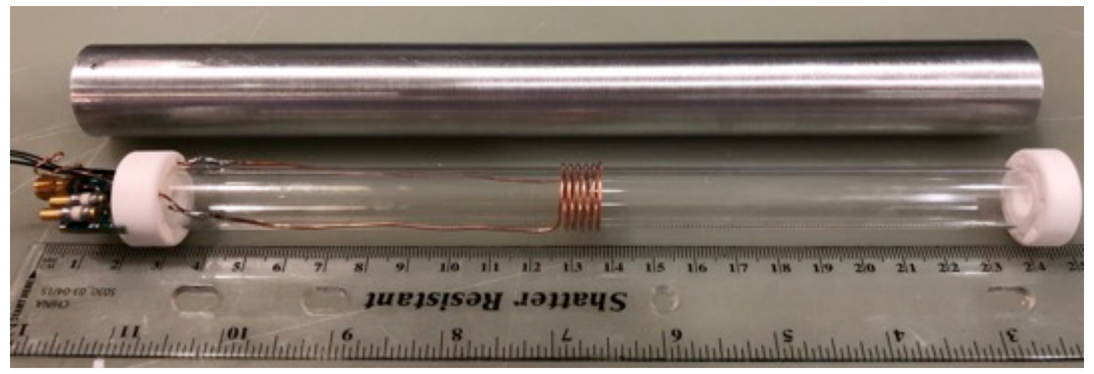
- Measure field in storage region during **specialized runs** when **muons are not being stored**

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

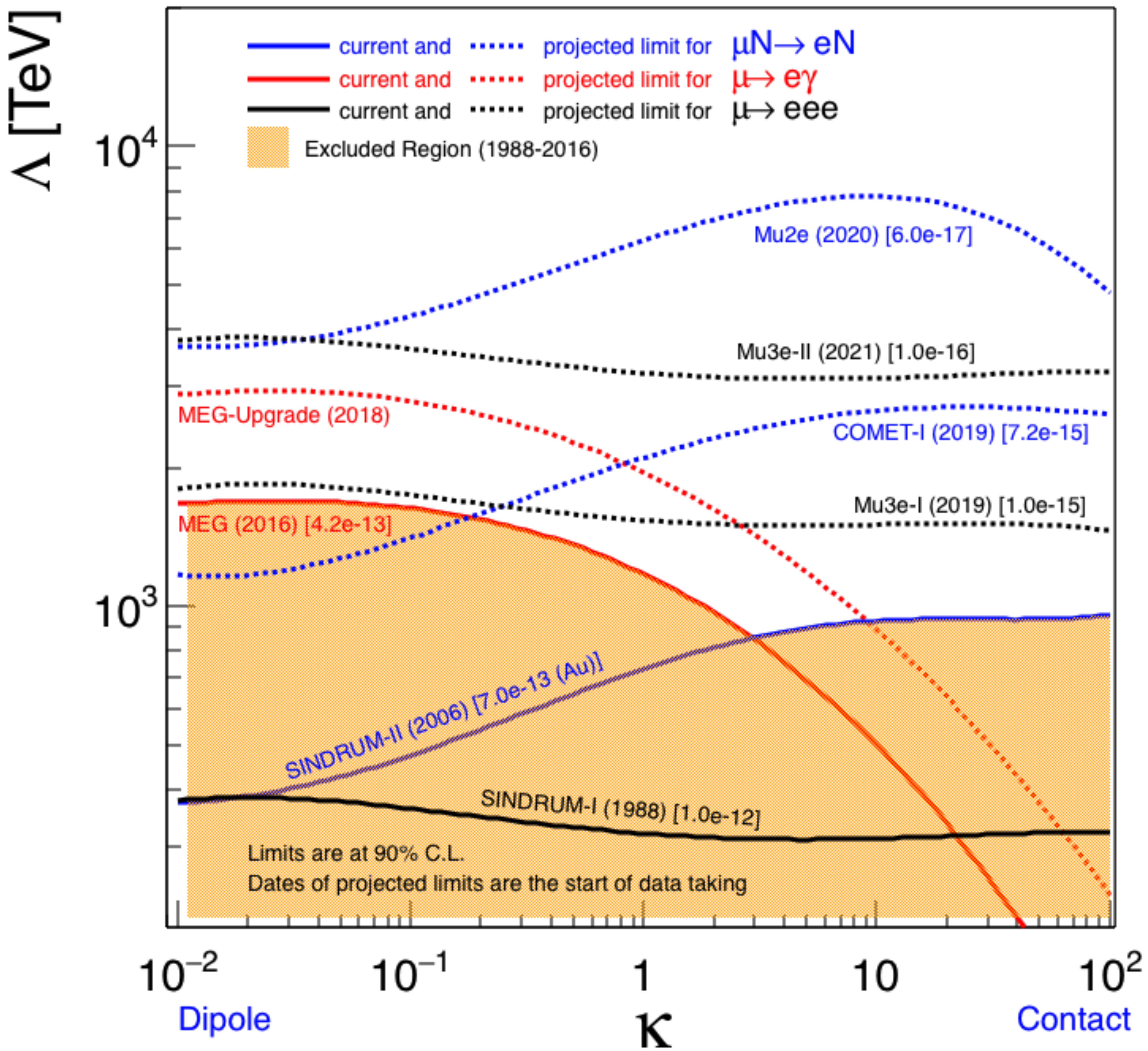




Plunging Probe



- arxiv 1303.4097



Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097