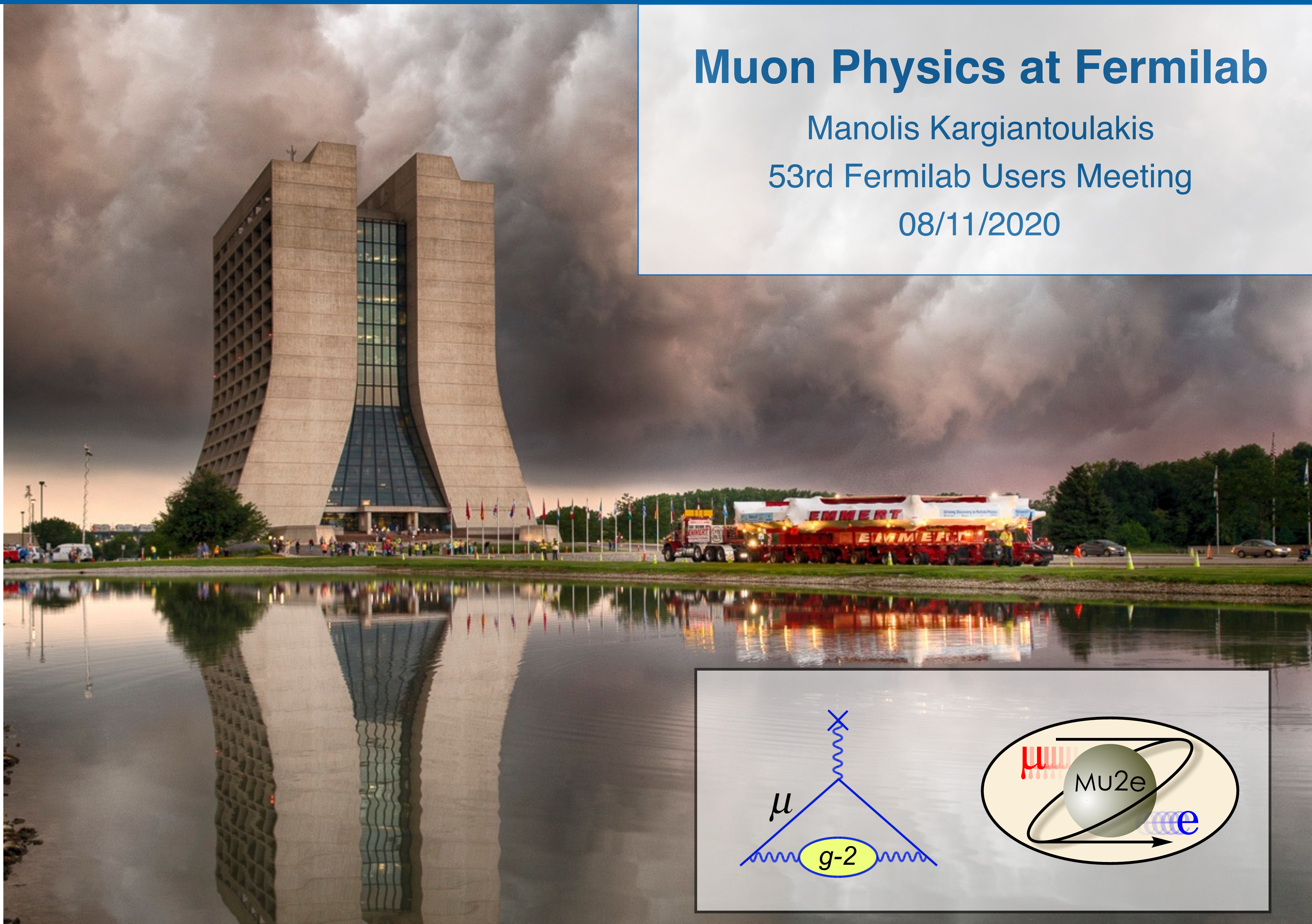
Muon Physics at Fermilab

Manolis Kargiantoulakis

53rd Fermilab Users Meeting

08/11/2020



Fermilab is a global leader in Muon Physics

The Fermilab Muon Campus

2 of the most powerful and promising tests of the SM

The Fermilab Muon g-2 experiment

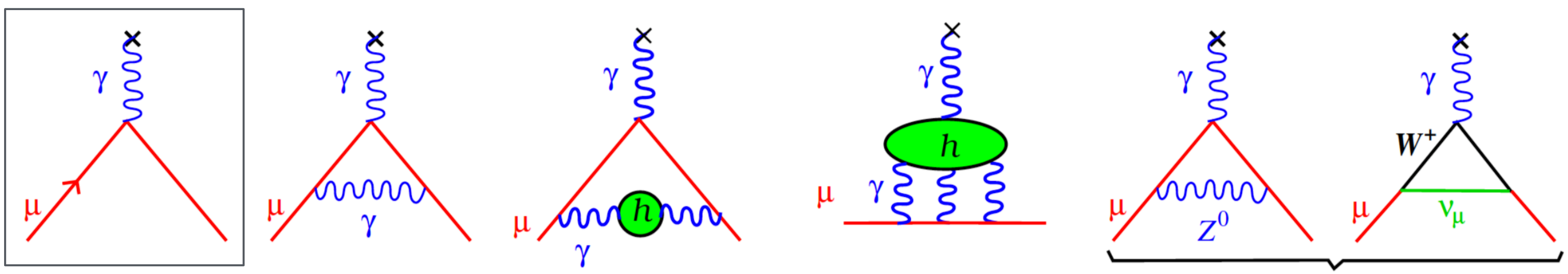
Anomalous Magnetic Moment

Muon magnetic moment: $\vec{\mu} = g_\mu \frac{e}{2m} \vec{s}$

The anomalous magnetic moment: $a_\mu \equiv \frac{g_\mu - 2}{2}$

Dirac theory predicts g=2

Quantum fluctuations give rise to a_μ



Dirac	QED	Hadronic VP	Hadronic LbL	Electroweak
	$\sim 1 \times 10^{-3}$	$\sim 7 \times 10^{-8}$	$\sim 9 \times 10^{-10}$	$\sim 15 \times 10^{-10}$

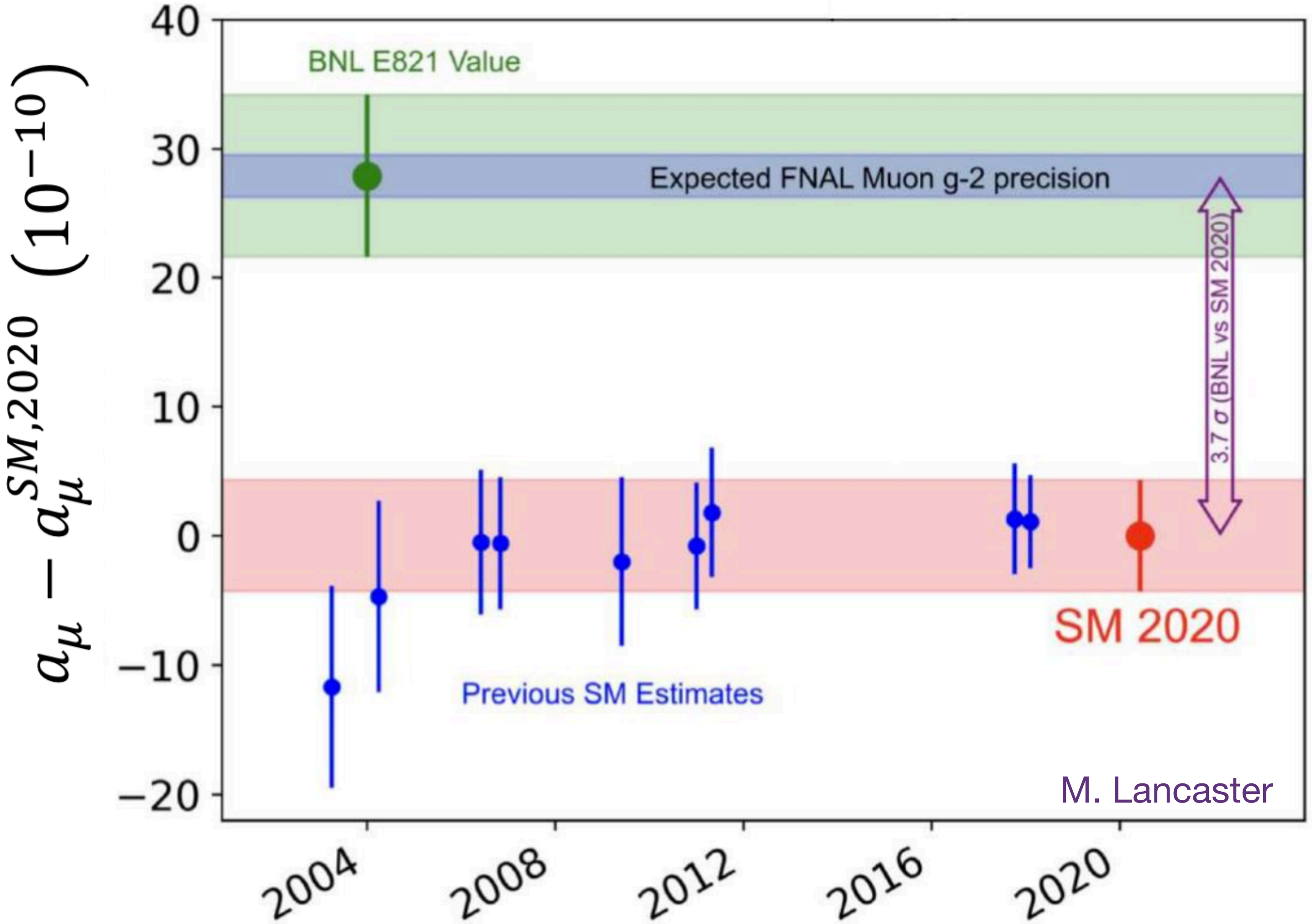
Entire theory encoded into *g*-2

A powerful precision test of SM validity

The a_μ discrepancy

BNL E821 measured a_μ to 540 ppb

- Discrepancy with SM



Muon *g*-2 Theory Initiative

https://muon-gm2-theory.illinois.edu

Full re-evaluation of SM value

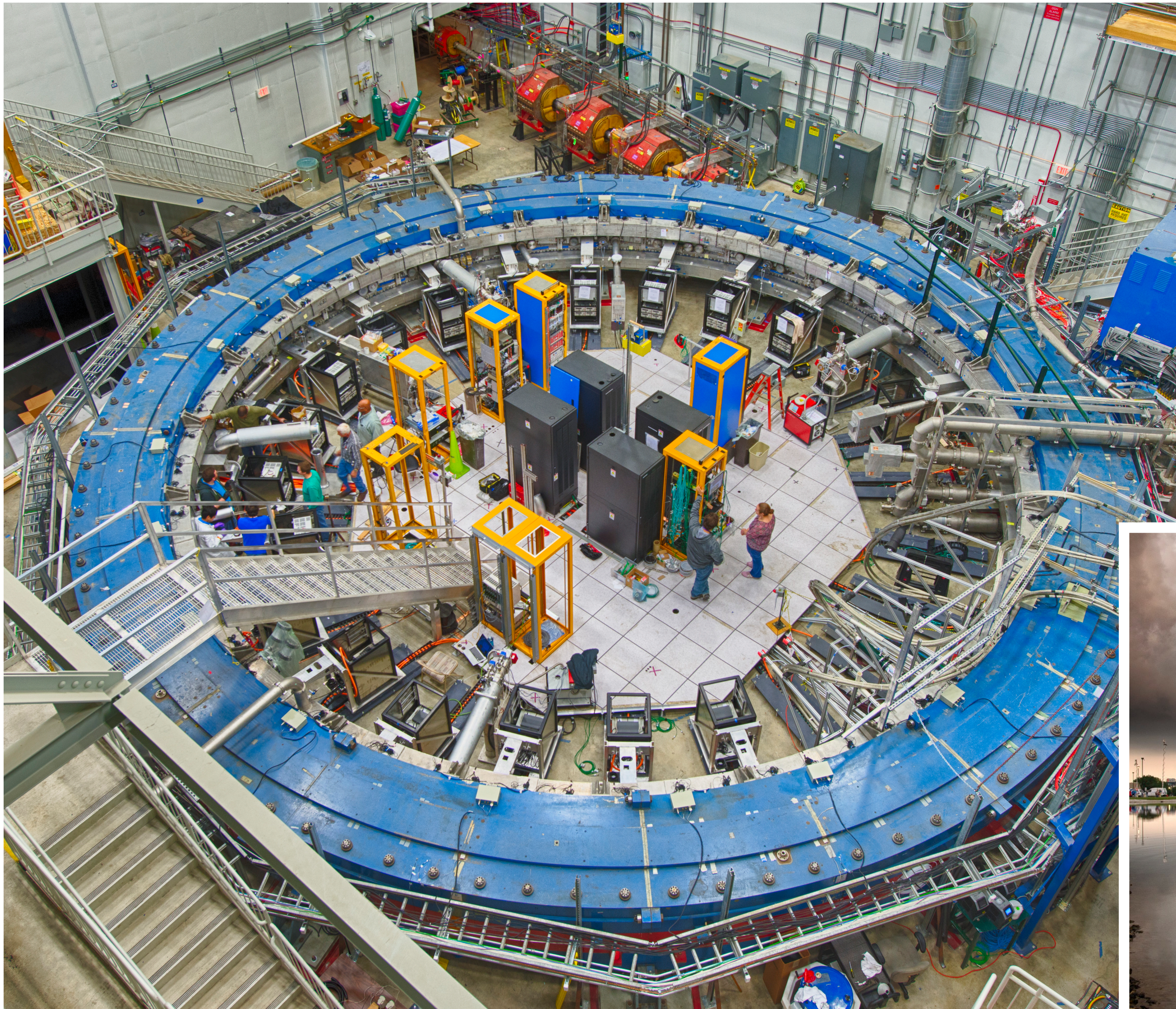
The discrepancy stands at 3.7σ

$$a_\mu^{exp} - a_\mu^{SM} = (27.9 \pm 7.6) \times 10^{-10}$$

arXiv:2006.04822 [hep-ph]

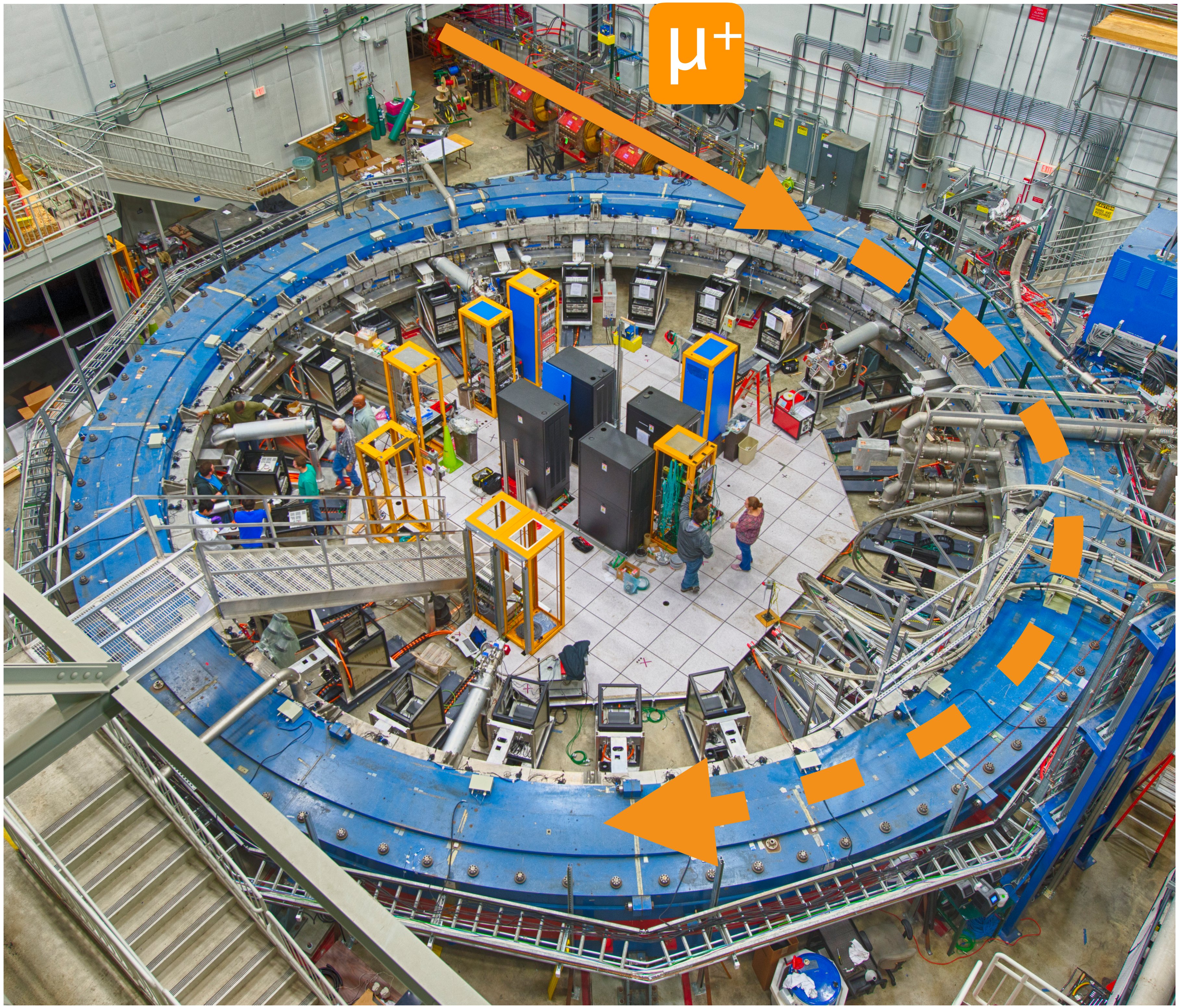
Fermilab E989 aims to improve precision on a_μ^{exp} by x4

The g-2 experiment at Fermilab



Muon *g*-2 storage ring, moved from BNL

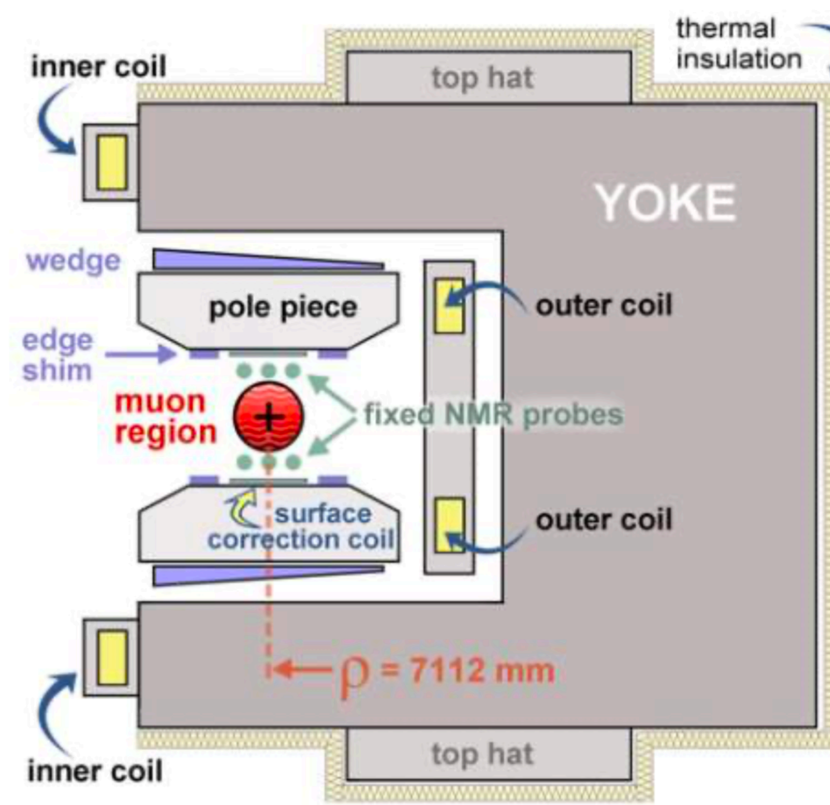
The g-2 experiment at Fermilab



3.1 GeV/c muons injected in storage ring

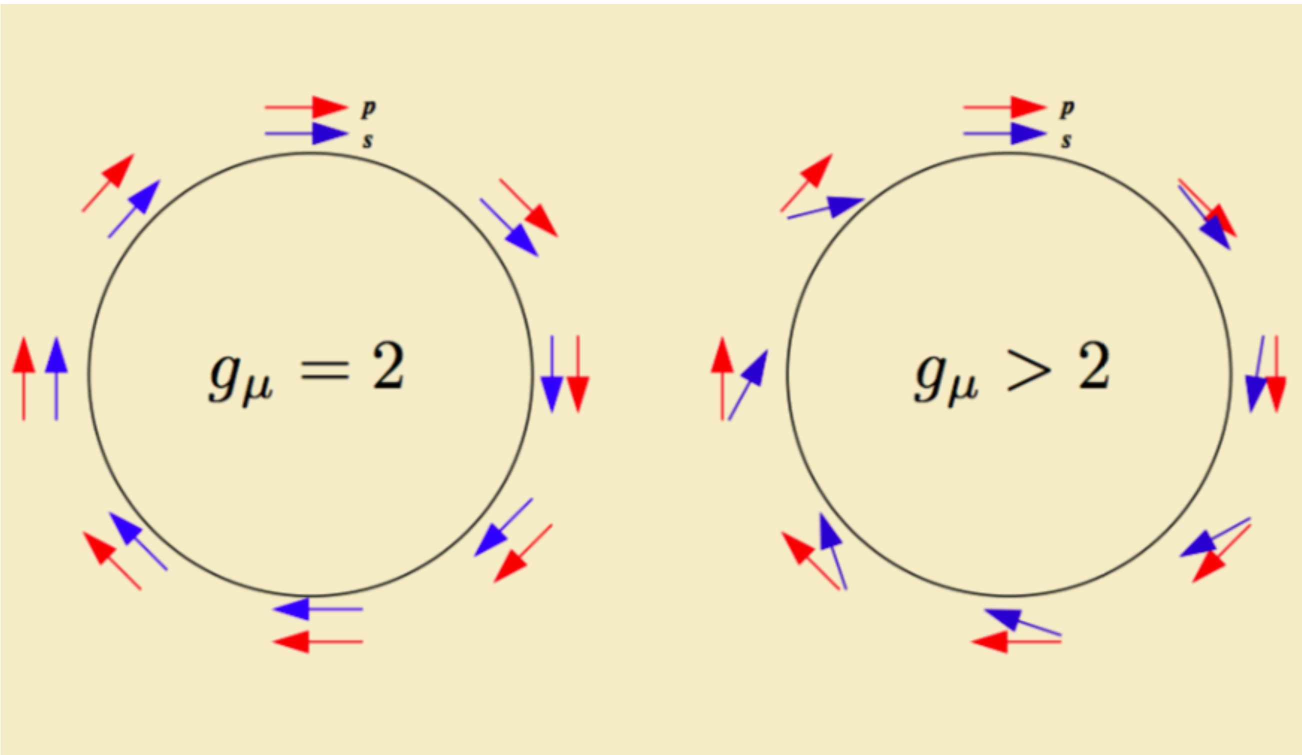
Highly longitudinally polarized

Muon spin precesses in 1.45 T field

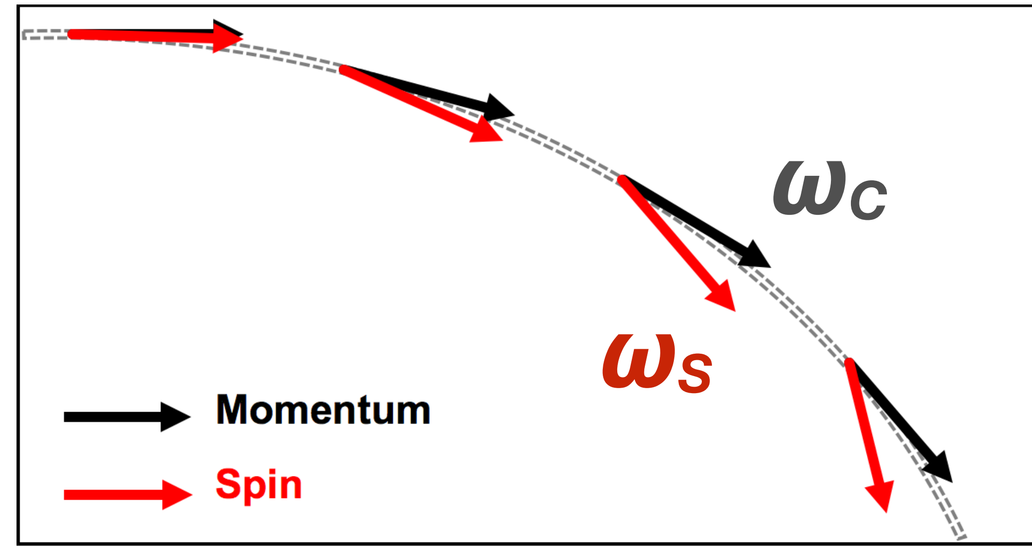


Spin precession

Muon spin precession inside the magnetic storage ring



Anomalous precession due to g≠2



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

$$\vec{\omega_s} = -\frac{geB}{2m} - (1-\gamma)\frac{eB}{m\gamma}$$

Anomalous precession frequency:

(idealized expression: perfect motion, field, "magic momentum")

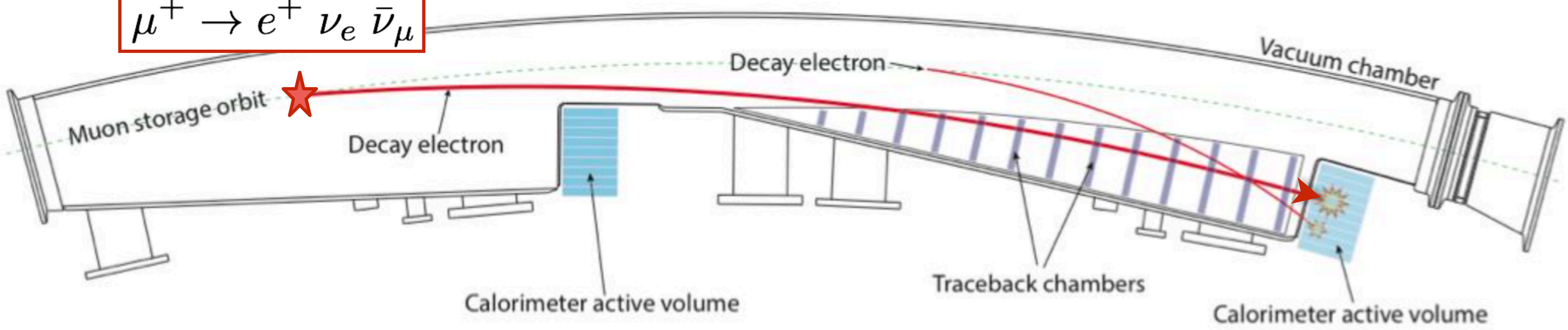
$$\vec{\boldsymbol{\omega_a}} \equiv \vec{\omega_s} - \vec{\omega_c} = a_\mu \frac{e\vec{B}}{m}$$

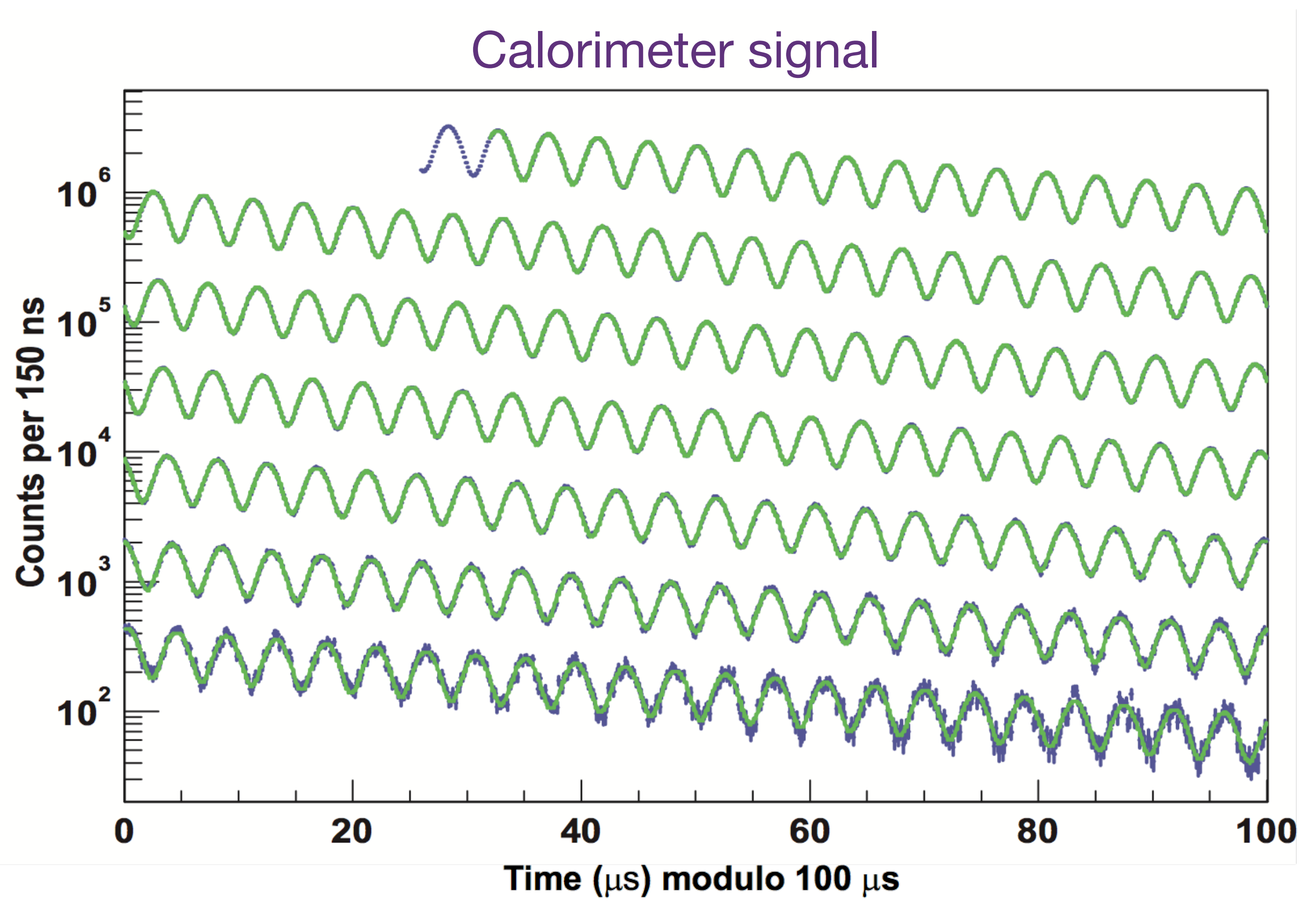
Need measurement of ω_a, B

Precession signal

Self-analyzing decay: highest-E e^+ emitted preferentially along μ^+ spin

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$





ω_a extracted from fit to calorimeter signal:

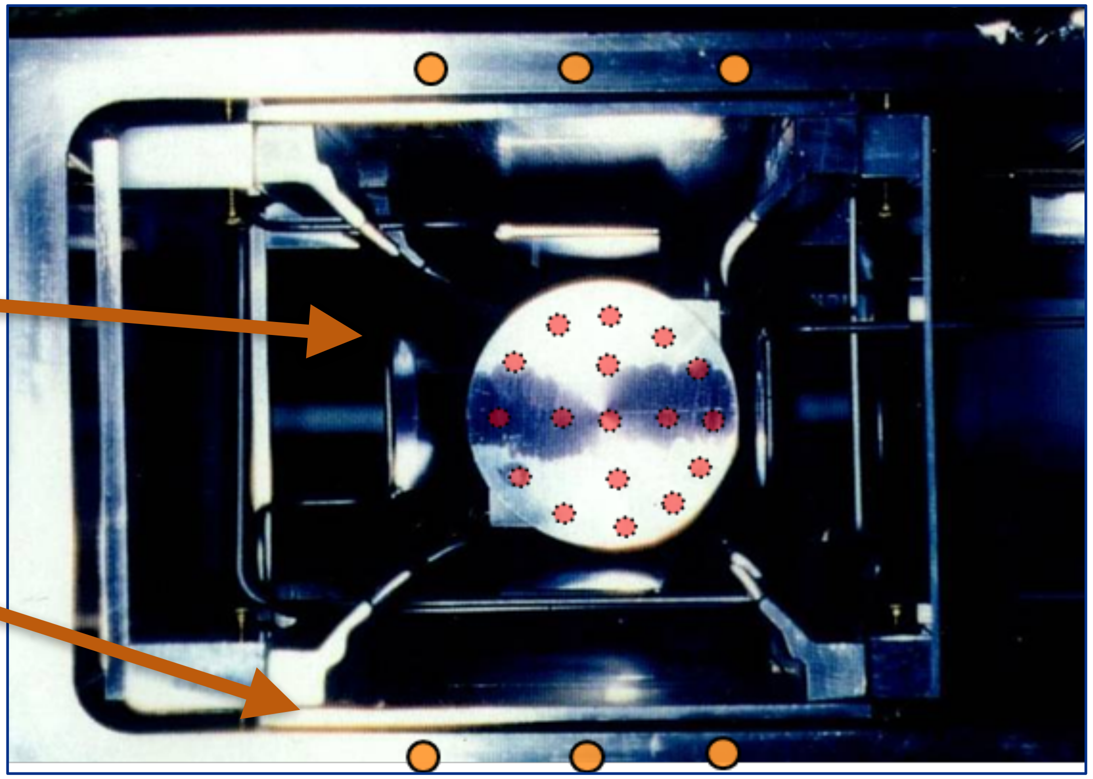
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \varphi)]$$

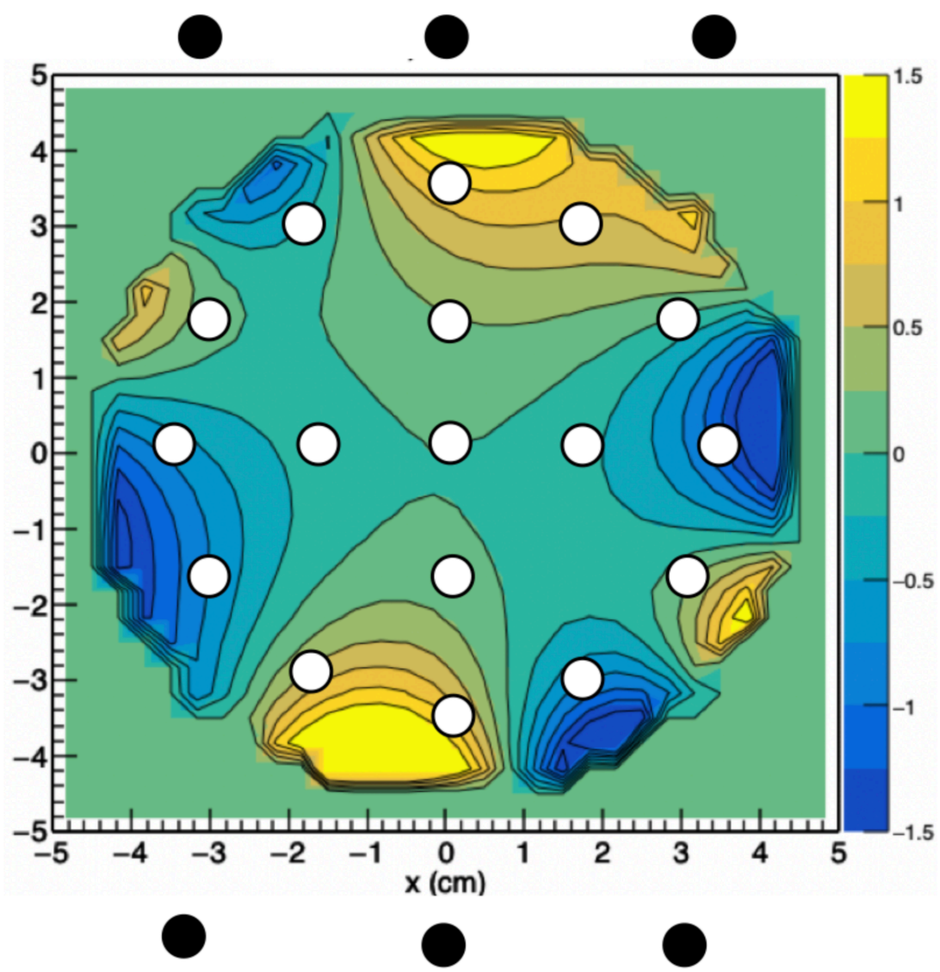
(Muon decay) × (Oscillation due to precession)

Magnetic field

Monitored with proton NMR probes

- Probes pulled in trolley for measurement in muon region (~3 days)
- Fixed probes for interpolation





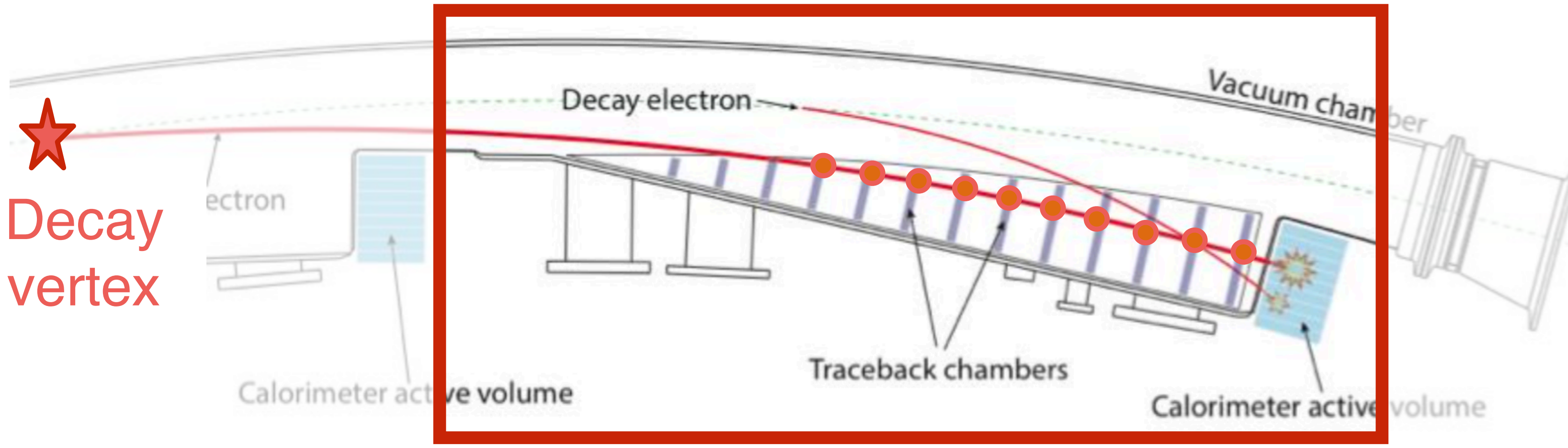
Azimuthally averaged, 250 ppb contours

Field maps from multipole decomposition:

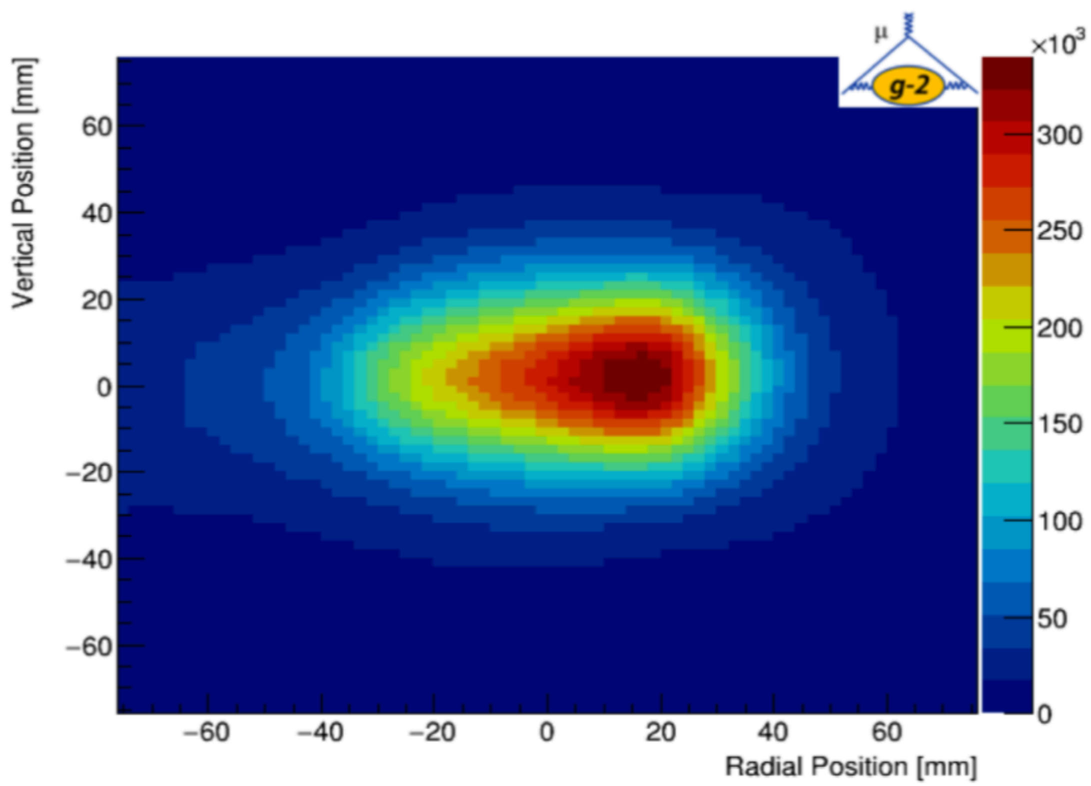
$$B(r,\theta) = B_0 + \sum_{n=0}^{4} \left(\frac{r}{r_0}\right)^n \left[a_n \cos(n\theta) + b_n \sin(n\theta)\right]$$

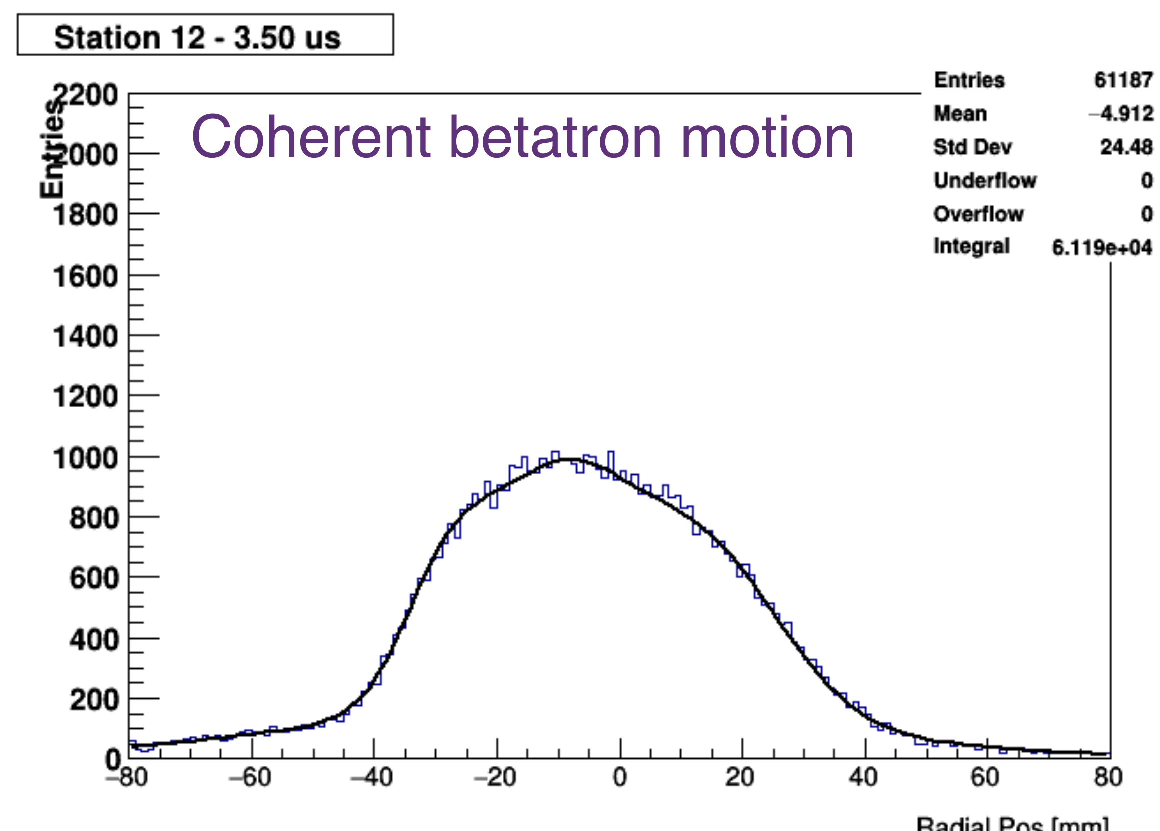
Field map to be convoluted with muon distribution

Muon distribution from trackers



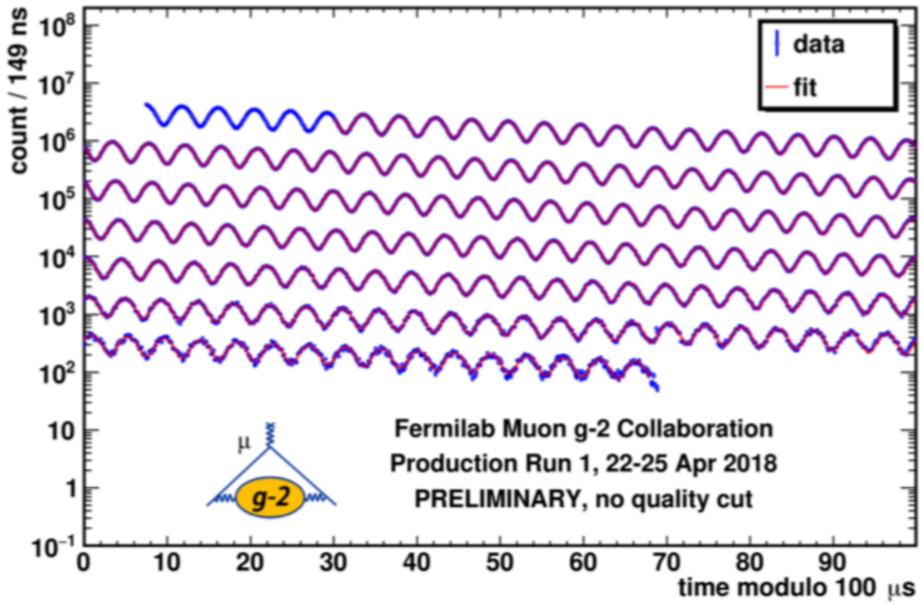
Straw trackers reconstruct muon distribution, determine complex beam dynamics





J. Mott

Run1 ω_a analysis



Simplistic 5-parameter fit:

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

Realistic, with beam dynamics:

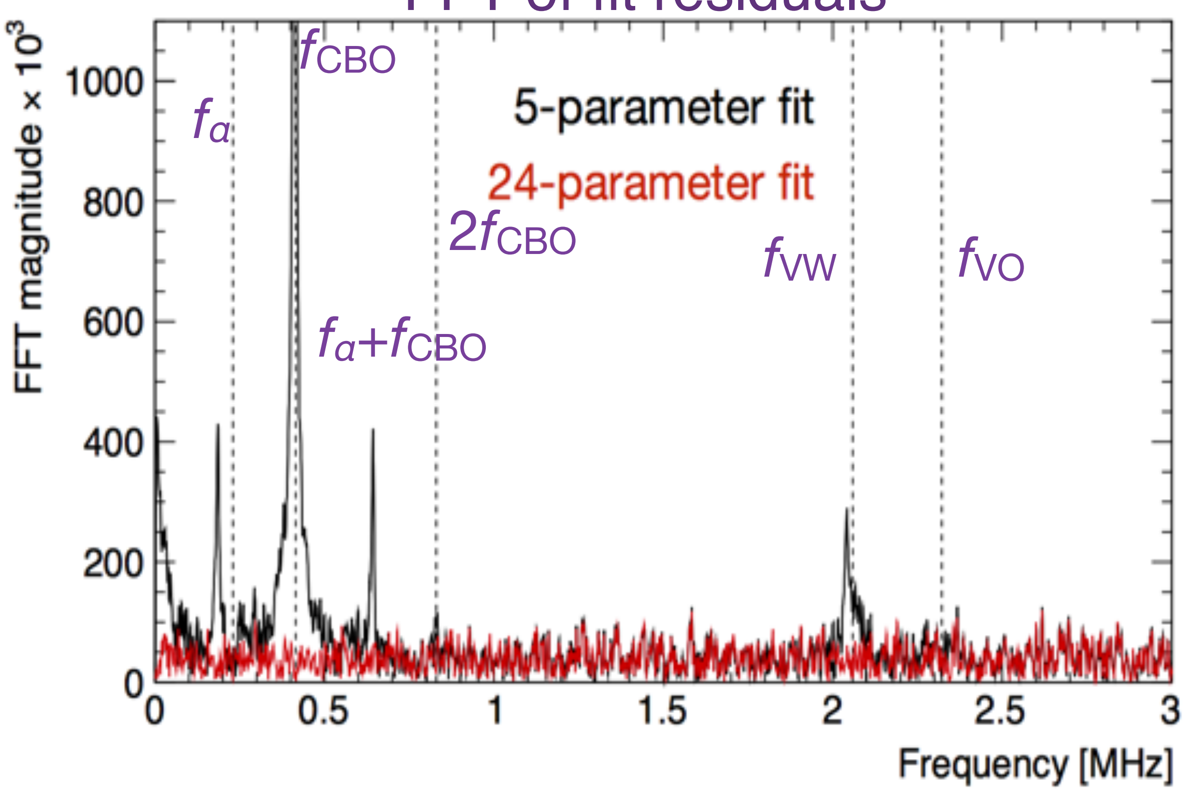
$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A_{cbo}(t)cos(\omega_a t + \phi_{cbo}(t))] \times N_{2cbo}(t)$$
$$\times [1 + A_{cbo} \,.\, e^{-t/\tau_{cbo}} \,.\, cos(\omega_{cbo} t + \phi_0)]$$
$$\times [1 + A_{vw} \,.\, e^{-t/\tau_{vw}} \,.\, cos(\omega_{vw}(t)t + \phi_{vw})]$$
$$\times [1 - K_{loss}\int_{t_0}^{t} e^{t/\tau_\mu} L(t)dt]$$

$$A_{cbo}(t) = A(1 + A_{cbo-A}e^{-t/\tau_{cbo}}cos(\omega_{cbo}t + \phi_{cbo-A}))$$

$$\phi_{cbo}(t) = \phi_0 + A_{cbo-\phi}e^{-t/\tau_{cbo}}cos(\omega_{cbo}t + \phi_{cbo-\phi})$$

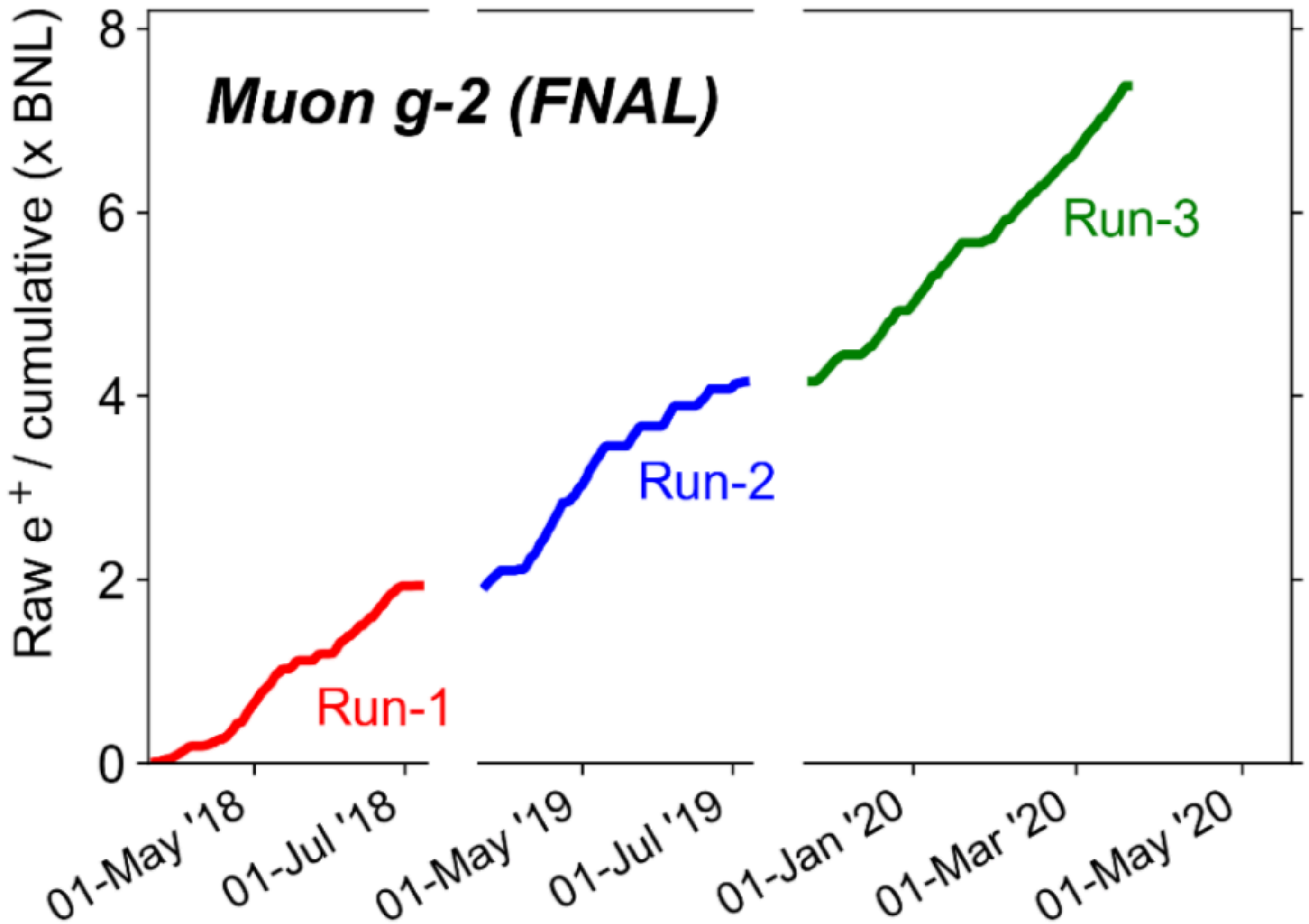
$$N_{2cbo}(t) = (1 + A_{2cbo-N}e^{-2t/\tau_{cbo}}cos(2\omega_{cbo}t + \phi_{2cbo-N}))$$

FFT of fit residuals



D. Sweigart URA Thesis Award

Current status



Up to 8x BNL raw statistics collected so far

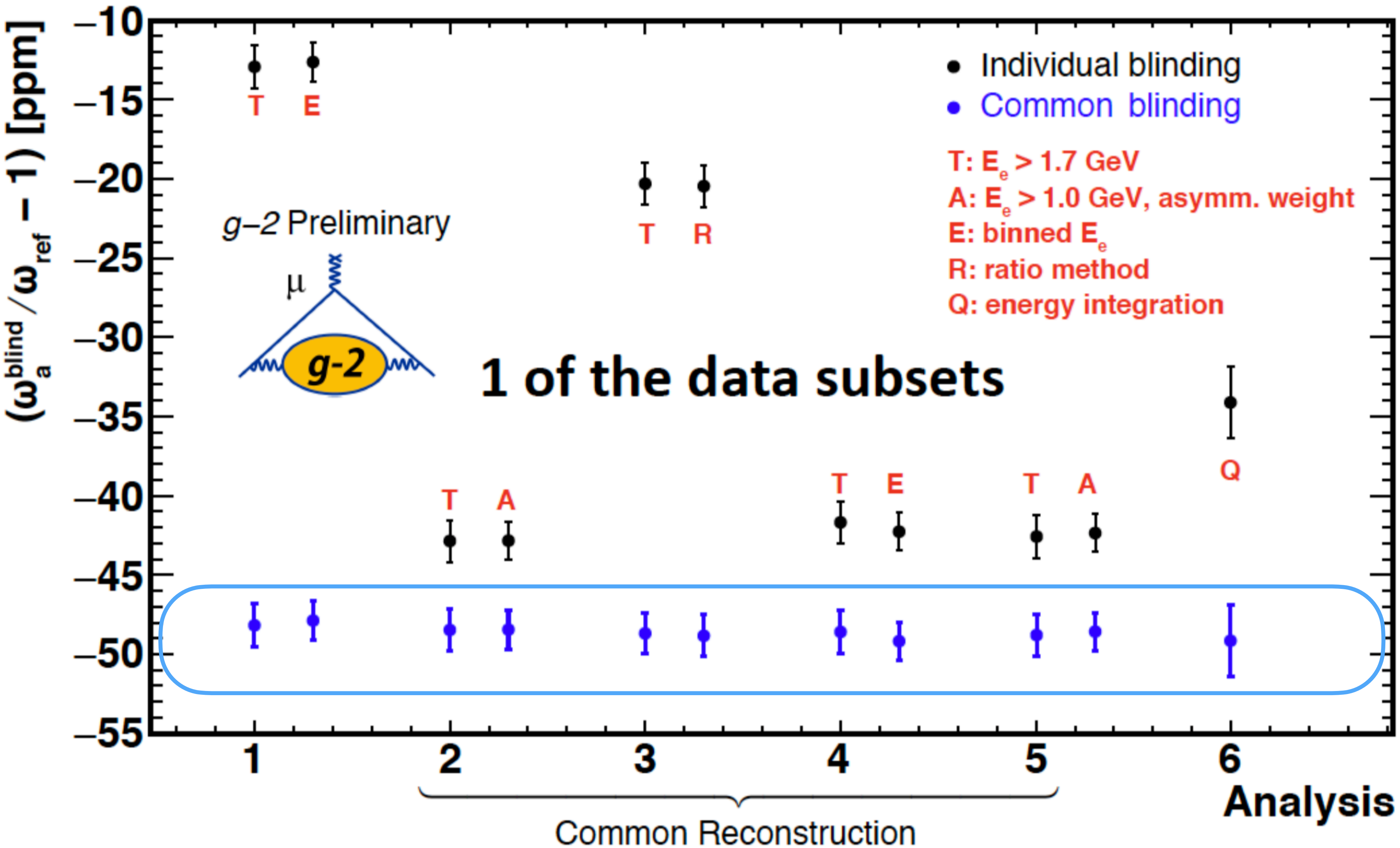
Run3 cut short due to pandemic, planning to resume in fall 2020

First results from Run1 expected in few months

$\gtrsim$ BNL statistics

Run1 ω_a analysis

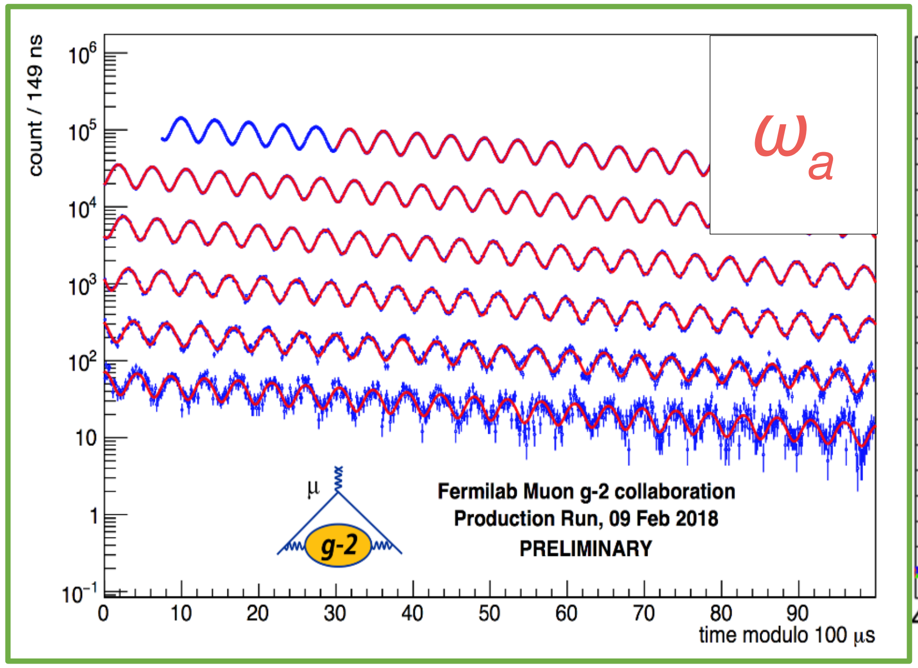
- 6 independent analysis teams
  - Different algorithms, sensitivities, reconstructions

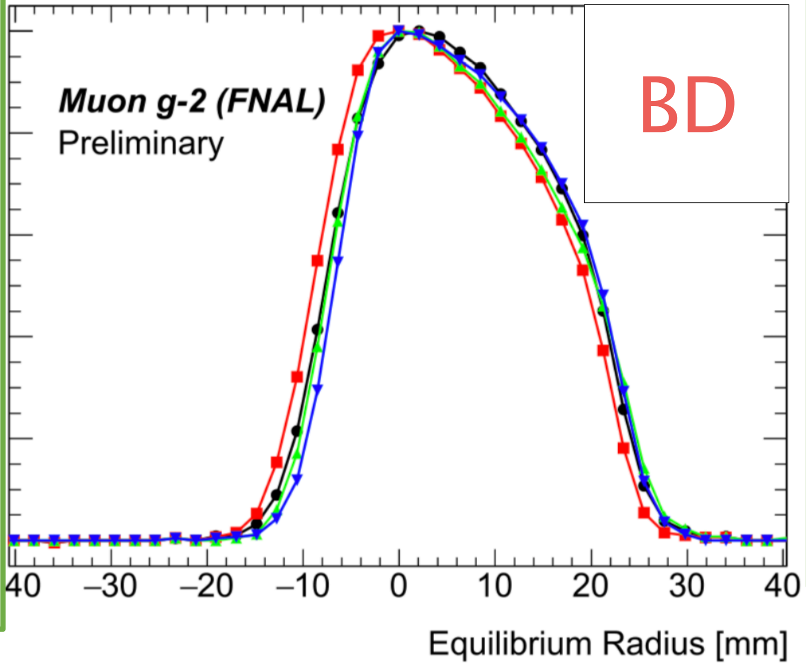


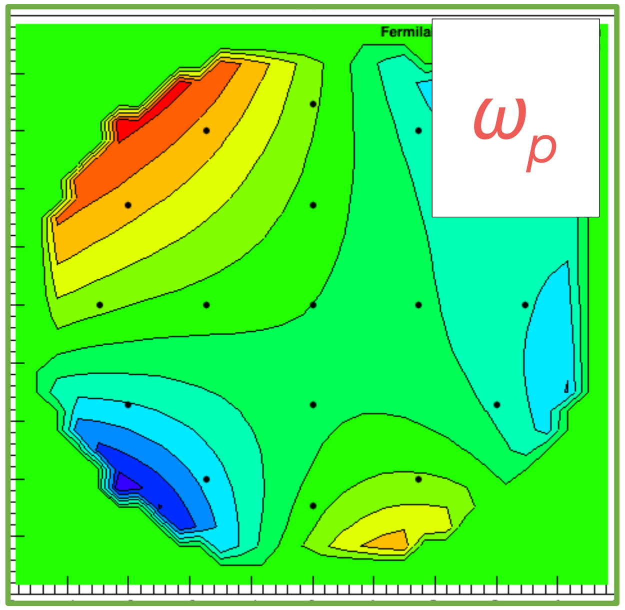
Agreement fully within statistically allowed variance

- Similarly great agreement between independent analysis teams for field measurement

Run1 result expected soon!



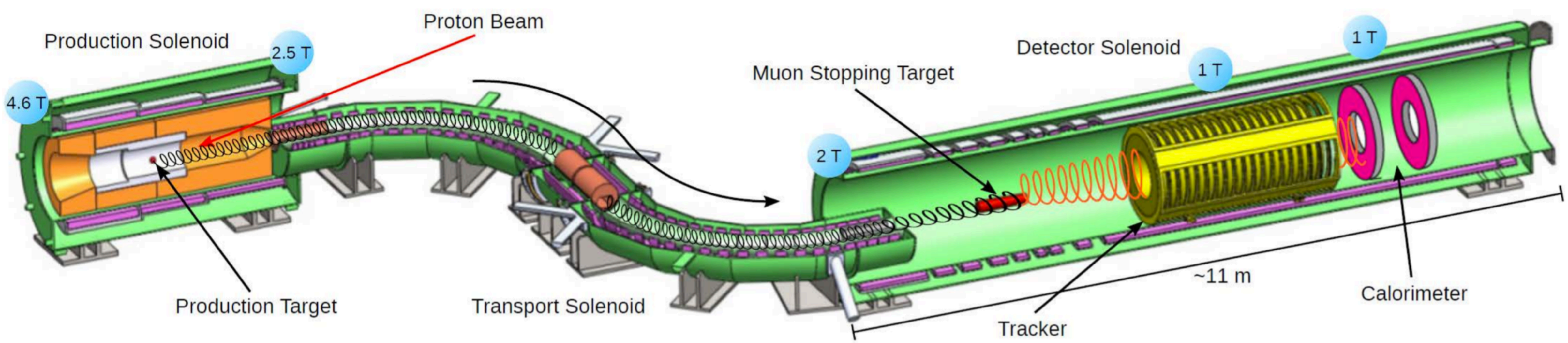




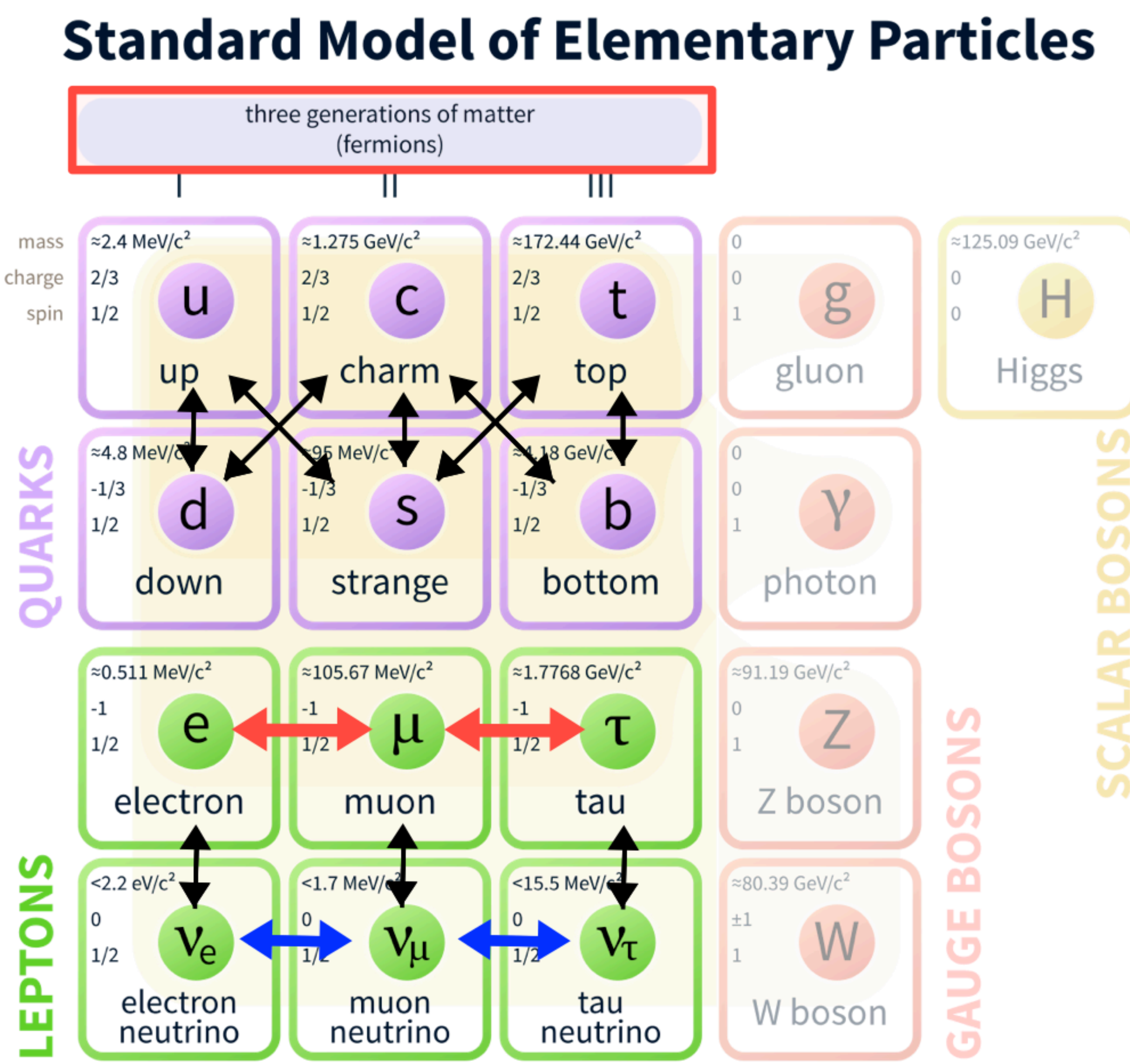
- Tremendous work done on systematic cross-checks
- Run1 result, highly anticipated by global community, is expected in few months!
- First cross-check to BNL discrepancy after nearly 2 decades
- Hugely important for future prospects of the field

The Mu2e Experiment

- Scheduled to start after Muon g-2
- Currently in construction phase



Flavor in the SM



Mixing between flavors in SM

- Neutrino oscillations
  - Lepton flavor violated!
- Mixing between charged leptons: never observed
  - Powerful probe of flavor models
  - Especially well motivated given *ν*-oscillations, LFU-violation

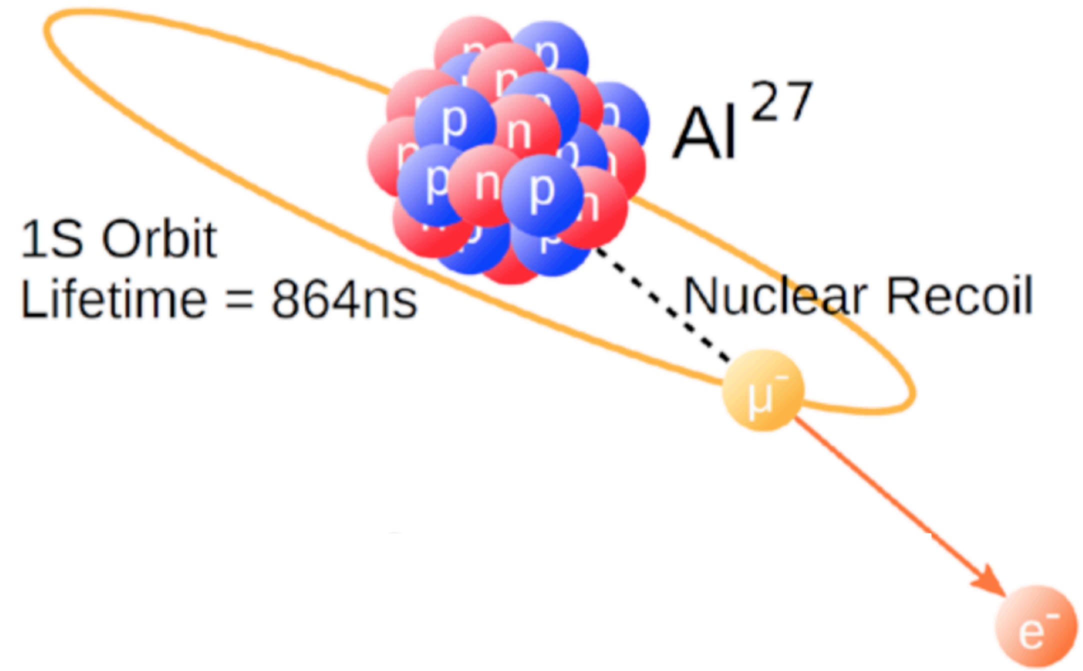
Any observation of Charged-Lepton Flavor Violation (CLFV) would be unambiguous evidence of New Physics

The charged-lepton analog to neutrino oscillations

$\mu \rightarrow e$ conversion: The Mu2e search

Coherent conversion $\mu \rightarrow e$ in the field of a nucleus

$$\mu^- + \mathrm{A(Z,N)} \rightarrow e^- + \mathrm{A(Z,N)}$$



Clean experimental signature

- mono-energetic e^- – for Al:

$$E_{\mu e}(\mathrm{Al}) = m_\mu - E_\mathrm{b} - E_\mathrm{rec} = 104.97\,\mathrm{MeV}$$

Current limit (SINDRUM-II, 90% CL):

$$R_{\mu e} = \frac{\mu^- + N \rightarrow e^- + N}{\mu^- + N \rightarrow \text{nuclear capture}} < 7 \times 10^{-13}$$

Mu2e aims to improve on $R_{\mu e}$ by 4 orders of magnitude

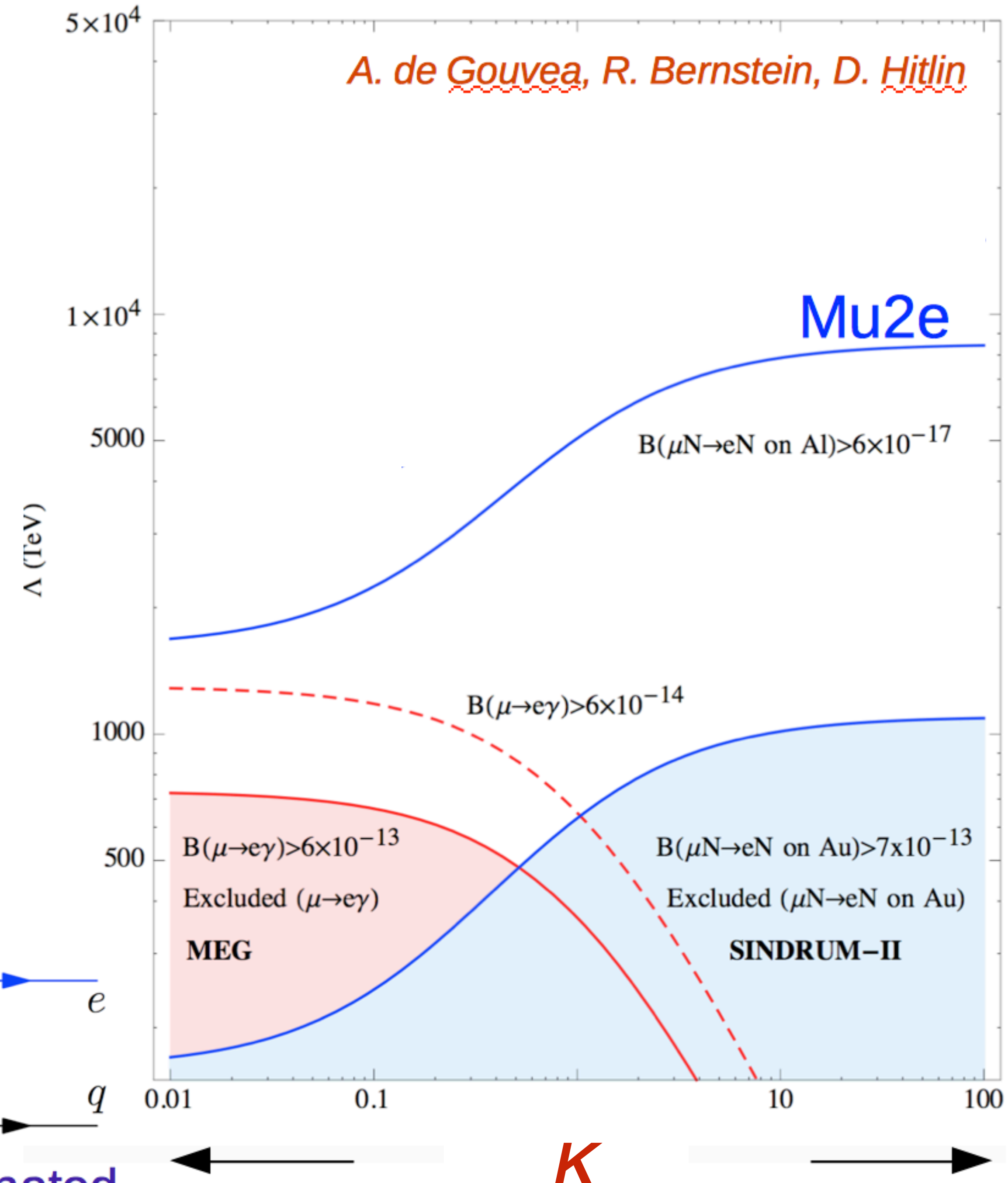
A vast increase in sensitivity covering unconstrained phase space

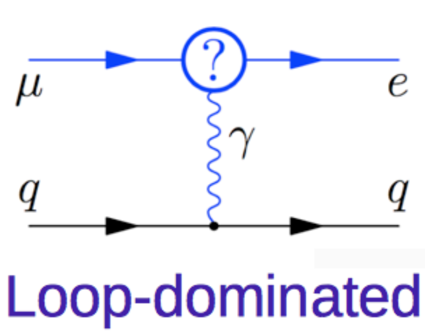
Physics reach

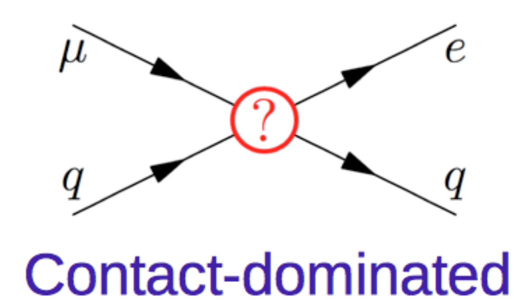
$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Λ: effective mass parameter

κ: relative strength of loop- and contact-dominated terms





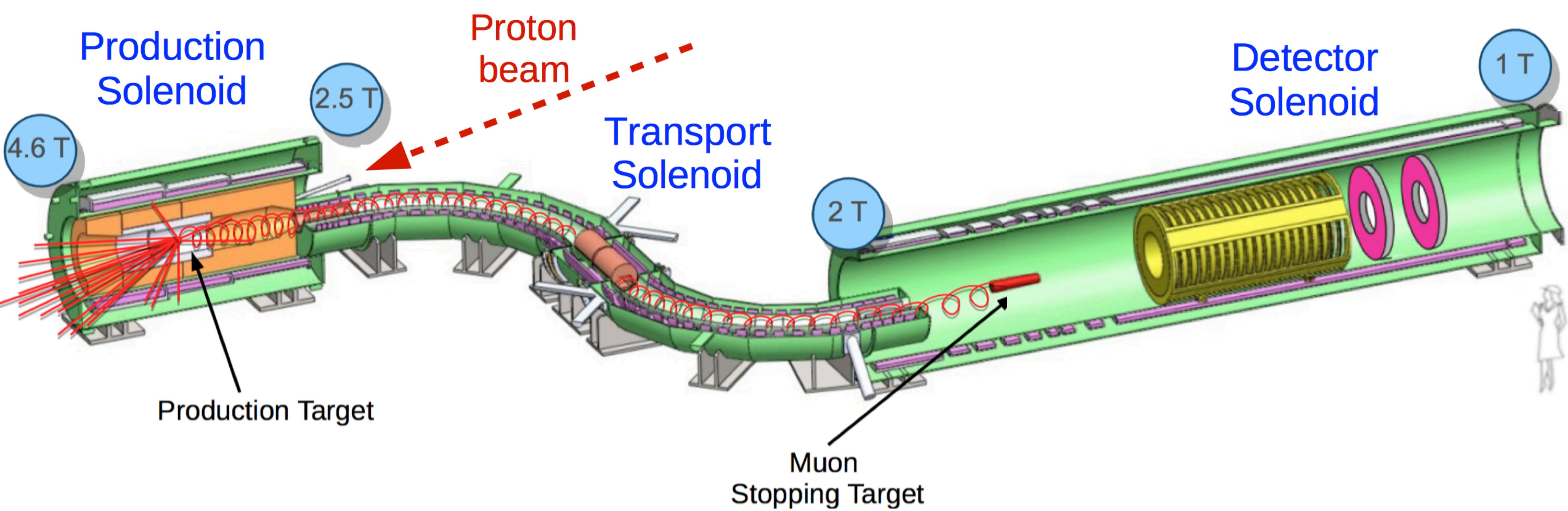


Mu2e improves sensitivity in all NP scenarios

Effective mass scale reach up to 10^4 TeV

Mu2e solenoids

System of 3 functional solenoid units

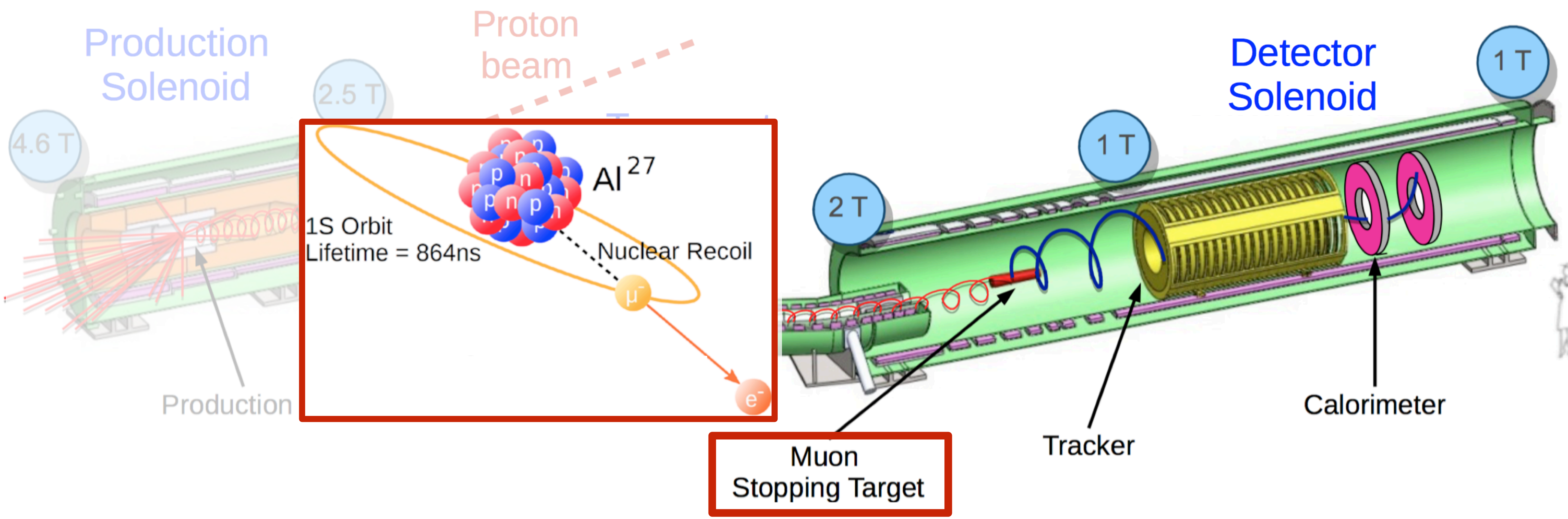


8 GeV pulsed proton beam, ~7e12 protons/s on W production target

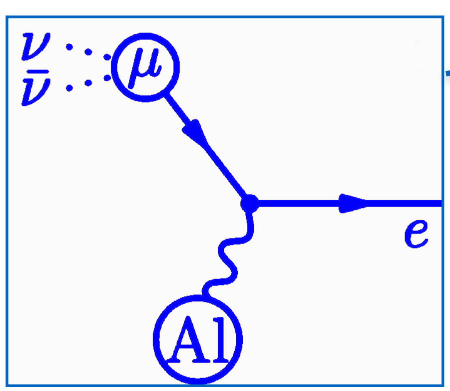
Efficient collection and transport: 10^{10} stopped muons/s on Al stopping target

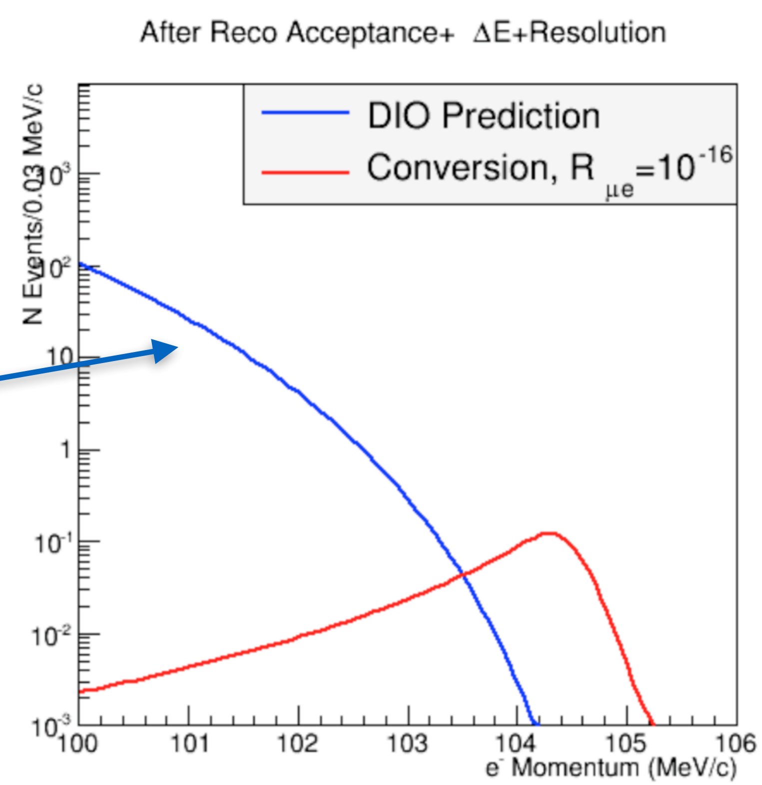
→ World's most intense muon beam

Mu2e solenoids: Detector



Background:
Standard muon
decay-in-orbit (DIO)



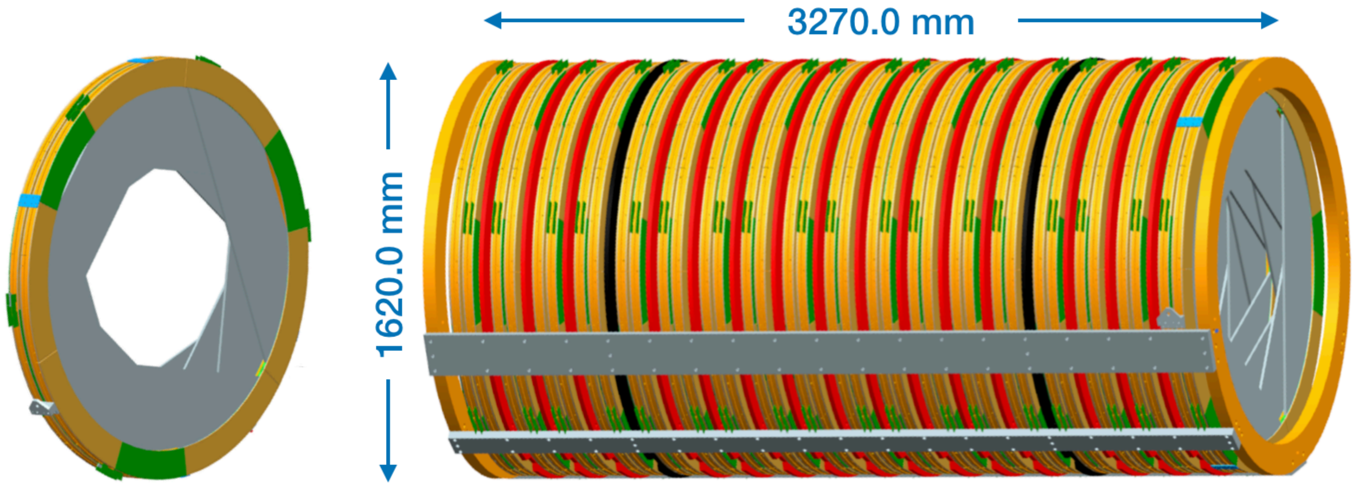


Detector system:
Straw tracker and calorimeter

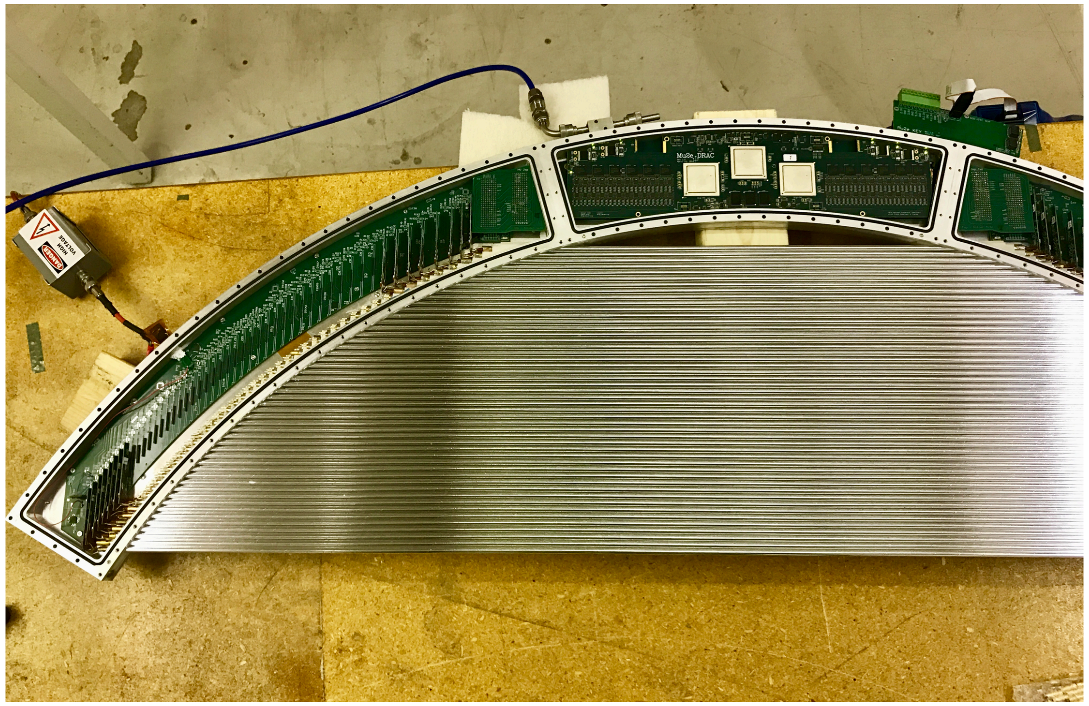
Identify 105 MeV conversion electron

Reject backgrounds from conventional processes

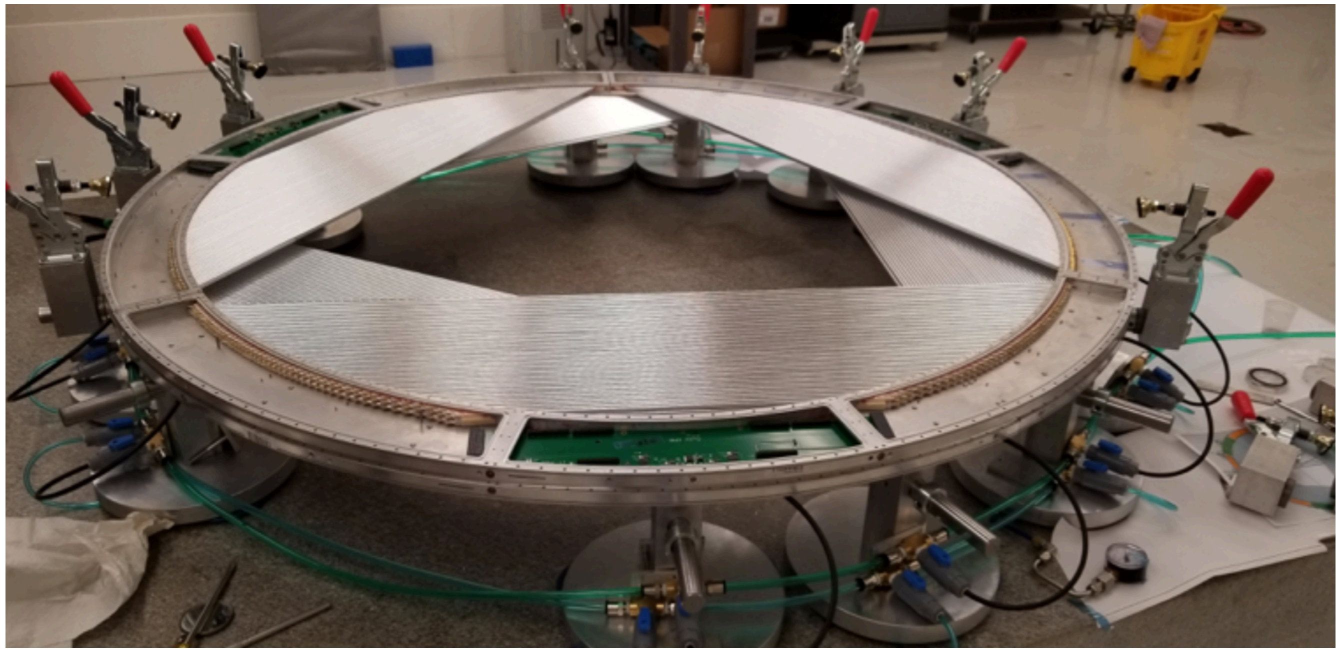
Straw tracker



Tracker panels being constructed at UMN



Full tracker "vertical slice"

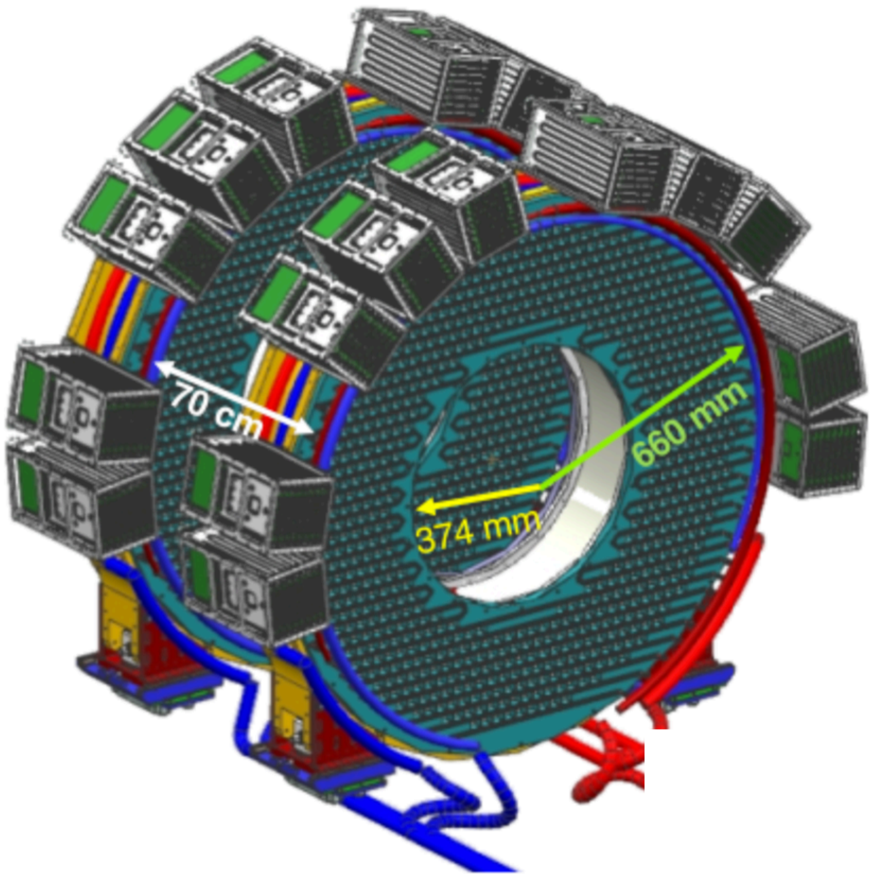


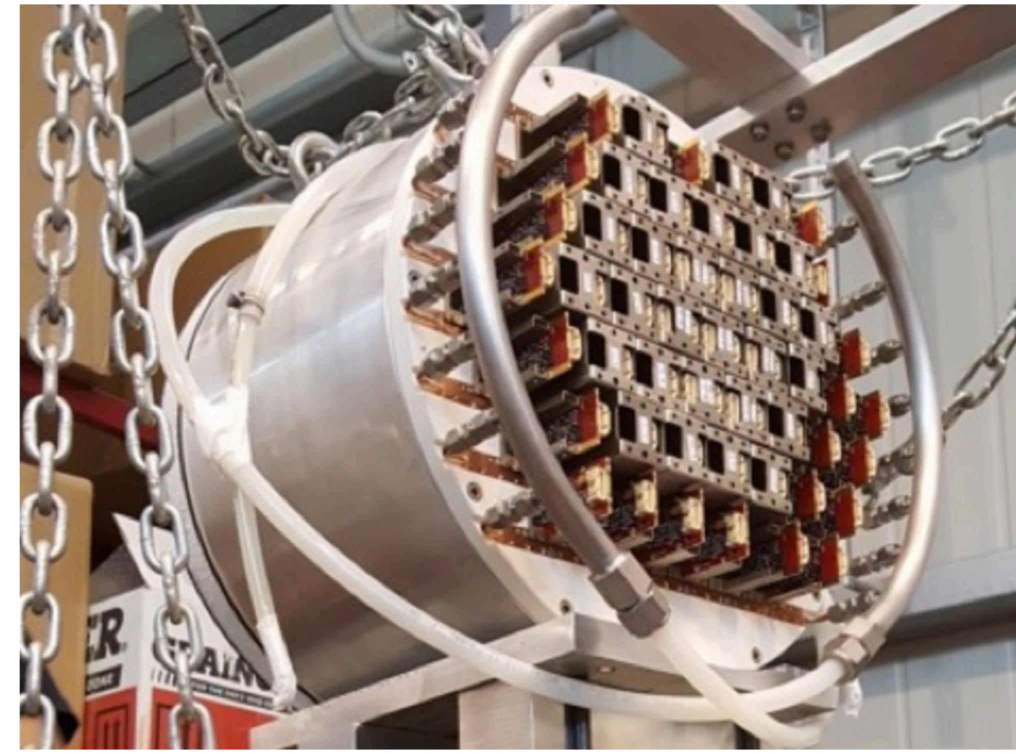
Hole-in-center annular design: Detector blind to nearly all backgrounds and remnant beam

Resolution <180 keV @ 105 MeV

Performance validated with prototypes

EM Calorimeter





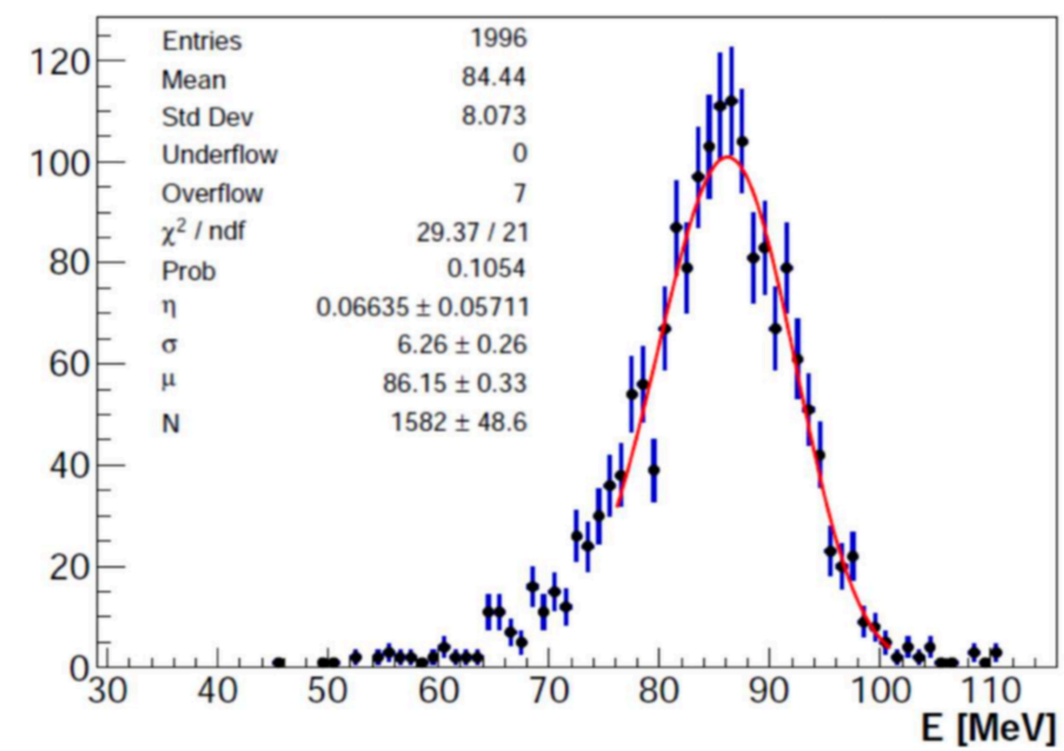
Atanov et al, arXiv:1801.02237

1348 CsI crystals, SiPM readout

Redundant E, position, timing information

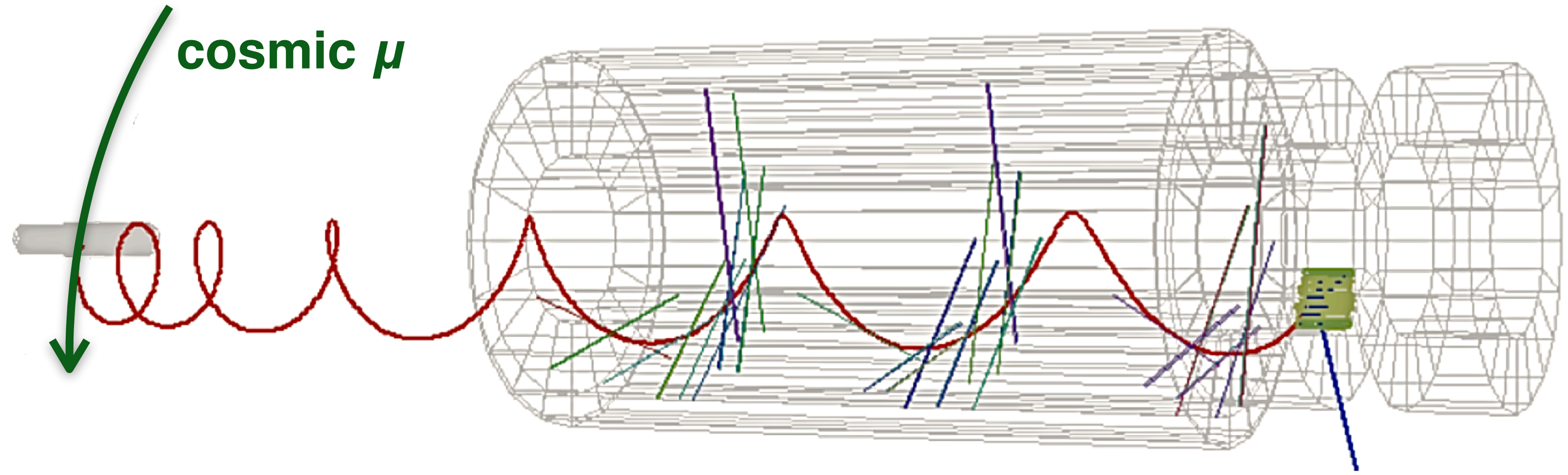
Prototype in Frascati demonstrated

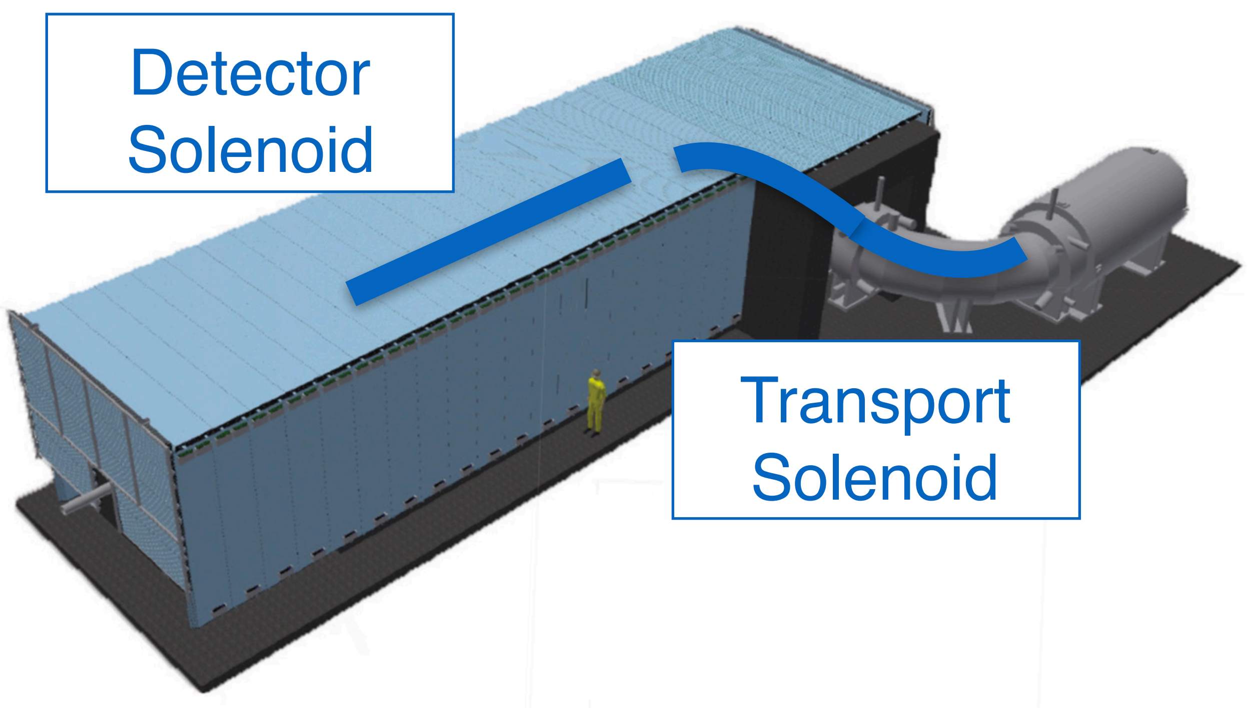
$\sigma_E \sim 7\%$, $\sigma_t \sim 150$ ns, well within spec



Cosmic backgrounds

Cosmic events may produce 105 MeV *e*





Cosmic Ray Veto system

encases DS and downstream TS

4 layers of extruded polystyrene

Under construction in UVA

Background budget

Expected total number of background events from each source, over entire Mu2e:

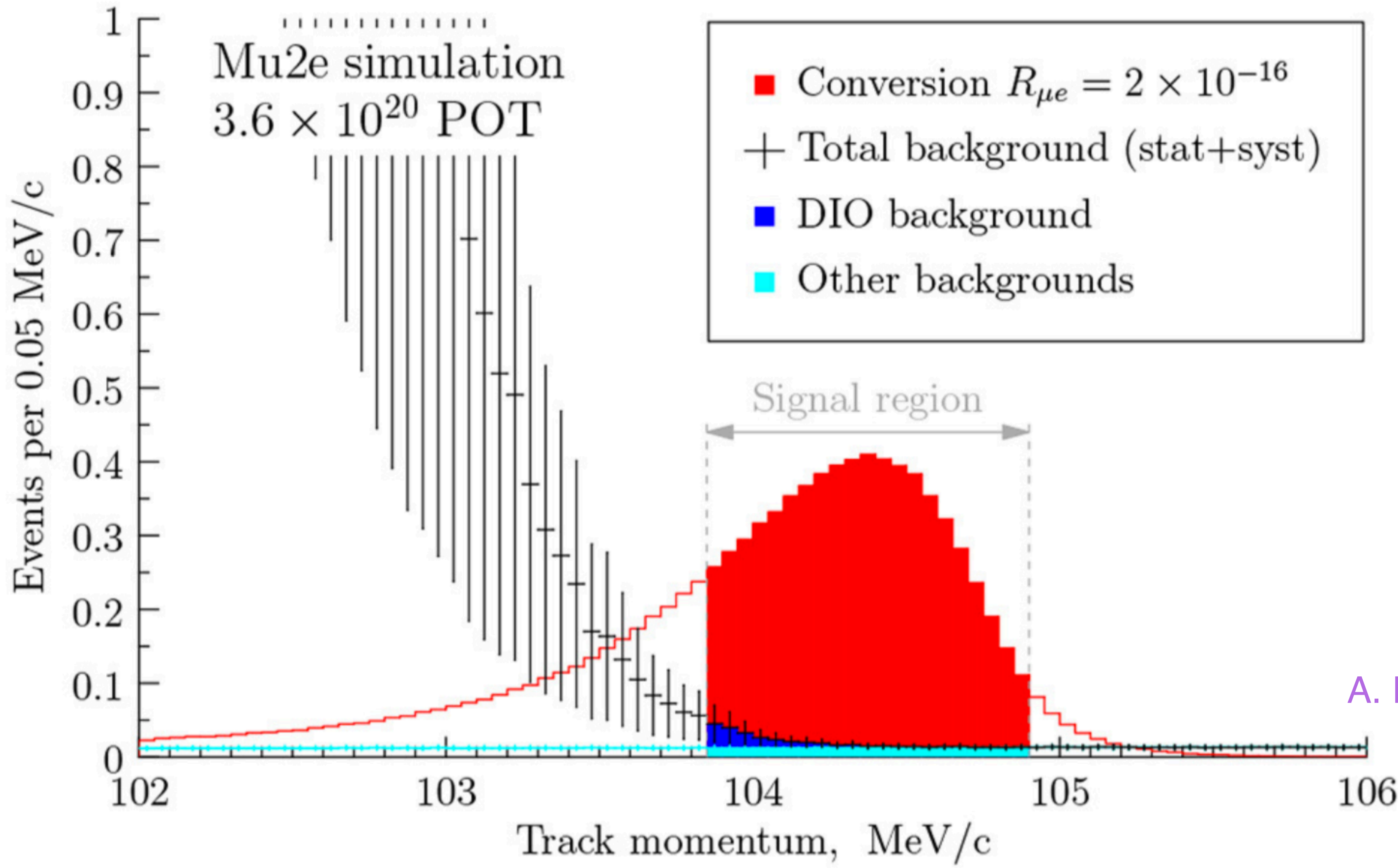
3 years at $1.2{\times}10^{20}$ p/yr
(8 kW beam power)

Background process		Expected events
Cosmic ray muons		$0.21 \pm 0.02 \pm 0.055$
Intrinsic	DIO	$0.14 \pm 0.03 \pm 0.11$
	RMC	$0.000^{+0.004}_{-0.000}$
Prompt, late-arriving	RPC	$0.021 \pm 0.001 \pm 0.002$
	Muon DIF	< 0.003
	Pion DIF	$0.001 \pm < 0.001$
	Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Antiproton-induced		$0.04 \pm 0.001 \pm 0.02$
Total		**0.41 ± 0.03 (stat+syst)**

Expect <0.5 background event in 3 years

Any observation will be strong evidence for CLFV

Sensitivity



A. Edmonds

5σ discovery sensitivity at $R_{\mu e}=2\times10^{-16}$

orders of magnitude beyond currently constrained

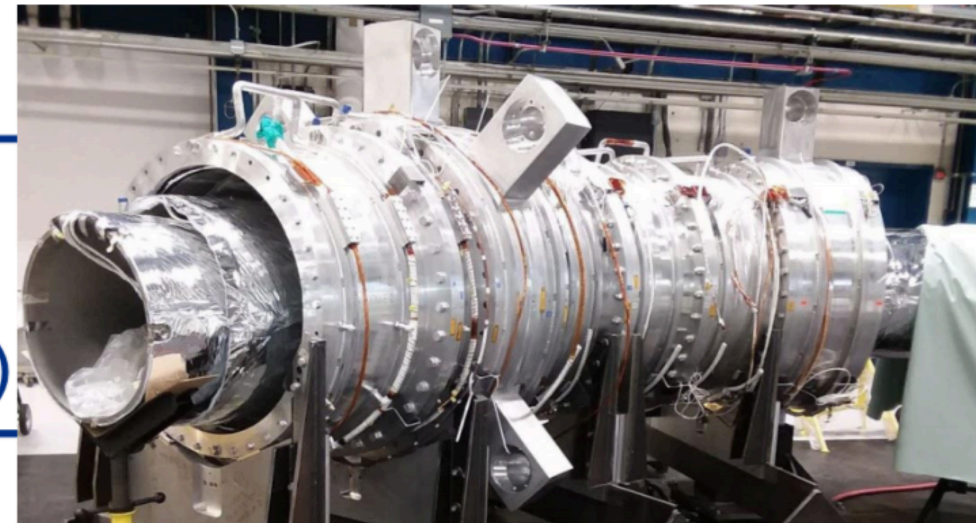
Single-event sensitivity at $R_{\mu e}=3\times10^{-17}$

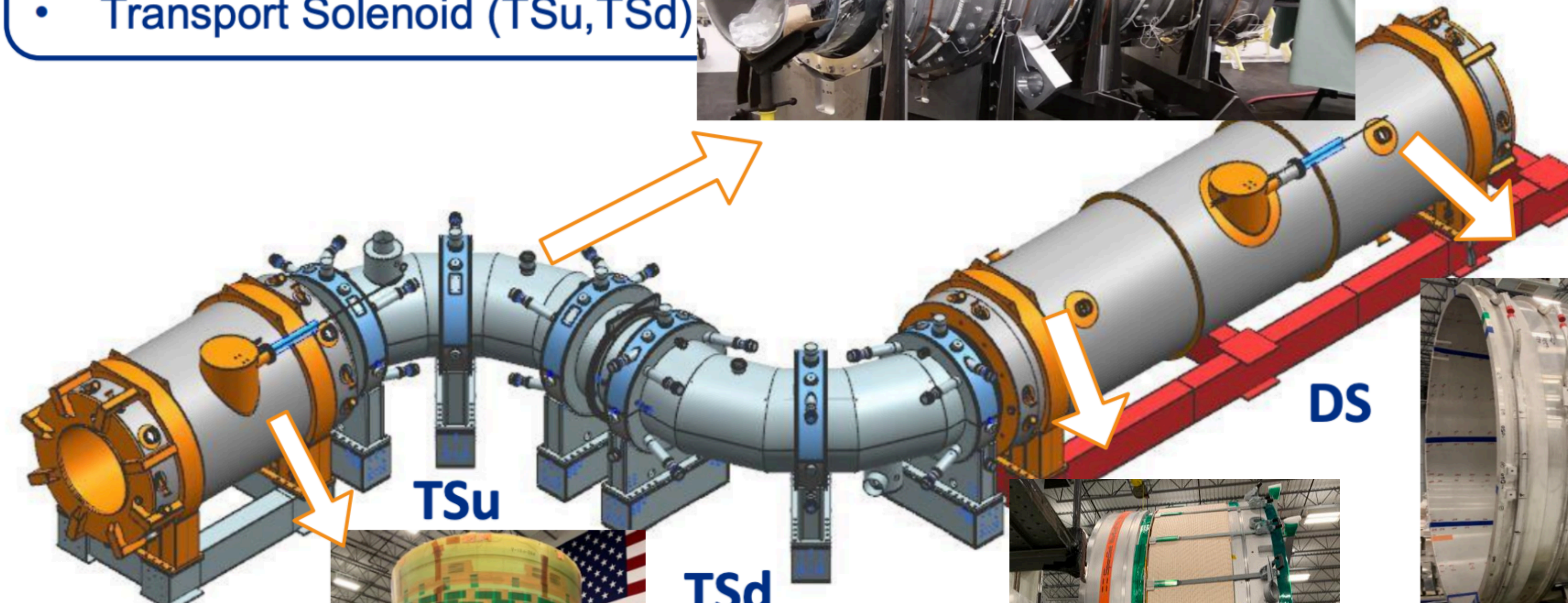
Real discovery potential

Solenoids - progress

- Production Solenoid (PS)
- Detector Solenoid (DS)
- Transport Solenoid (TSu,TSd)

Fully tested and assembled @ HAB





Post VPI

Coil layer compaction

DS10 shell

K. Badgley
M. Yucel

Mu2e outlook

- Begin installation in 2021
- Physics data beginning 2024
- Aim for 10^3 improvement on $R_{\mu e}$ by 2025
- LBNF/PIP-II accelerator shutdown
- By end of decade: complete data taking, improve 10^4 on $R_{\mu e}$

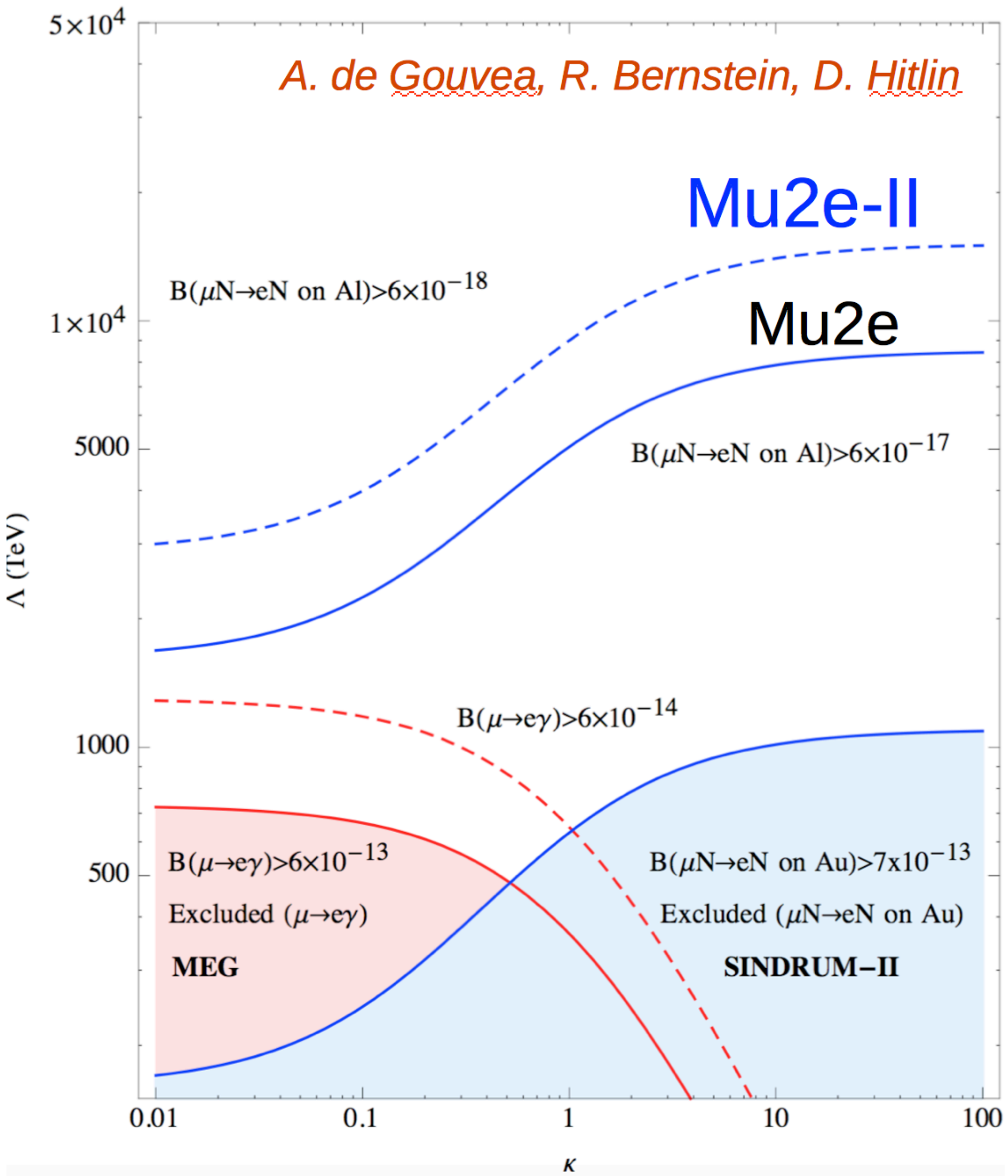
Intense effort over next years as project nears completion

Global program may well produce first observations of CLFV this decade

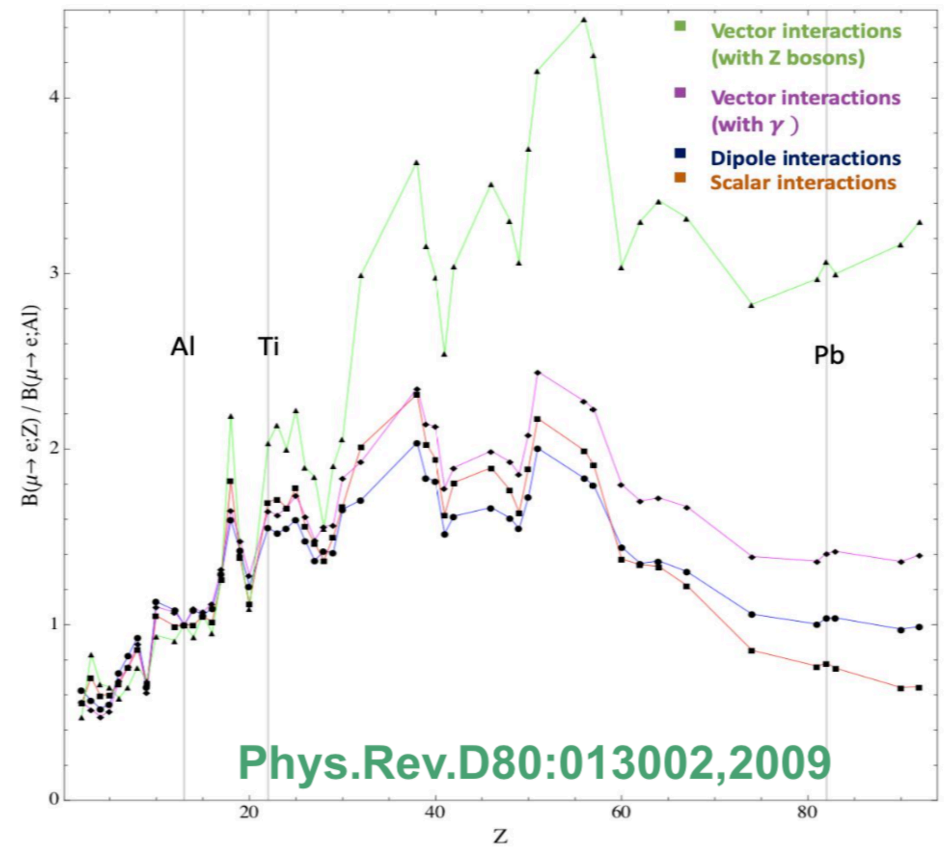
Defining the Next Decade

Mu2e-II, evolution to Mu2e with PIP-II

- Improving sensitivity by another order of magnitude
- Powerful in any scenario



$R_{\mu e}$ Z-dependence to study structure of new physics



Many more proposals for physics at the Muon Campus in the PIP-II era, integrated into the Snowmass process

Summary

Fermilab is a global leader in Muon Physics

Muon g-2

Highly anticipated Run1 result out soon, full result in few years

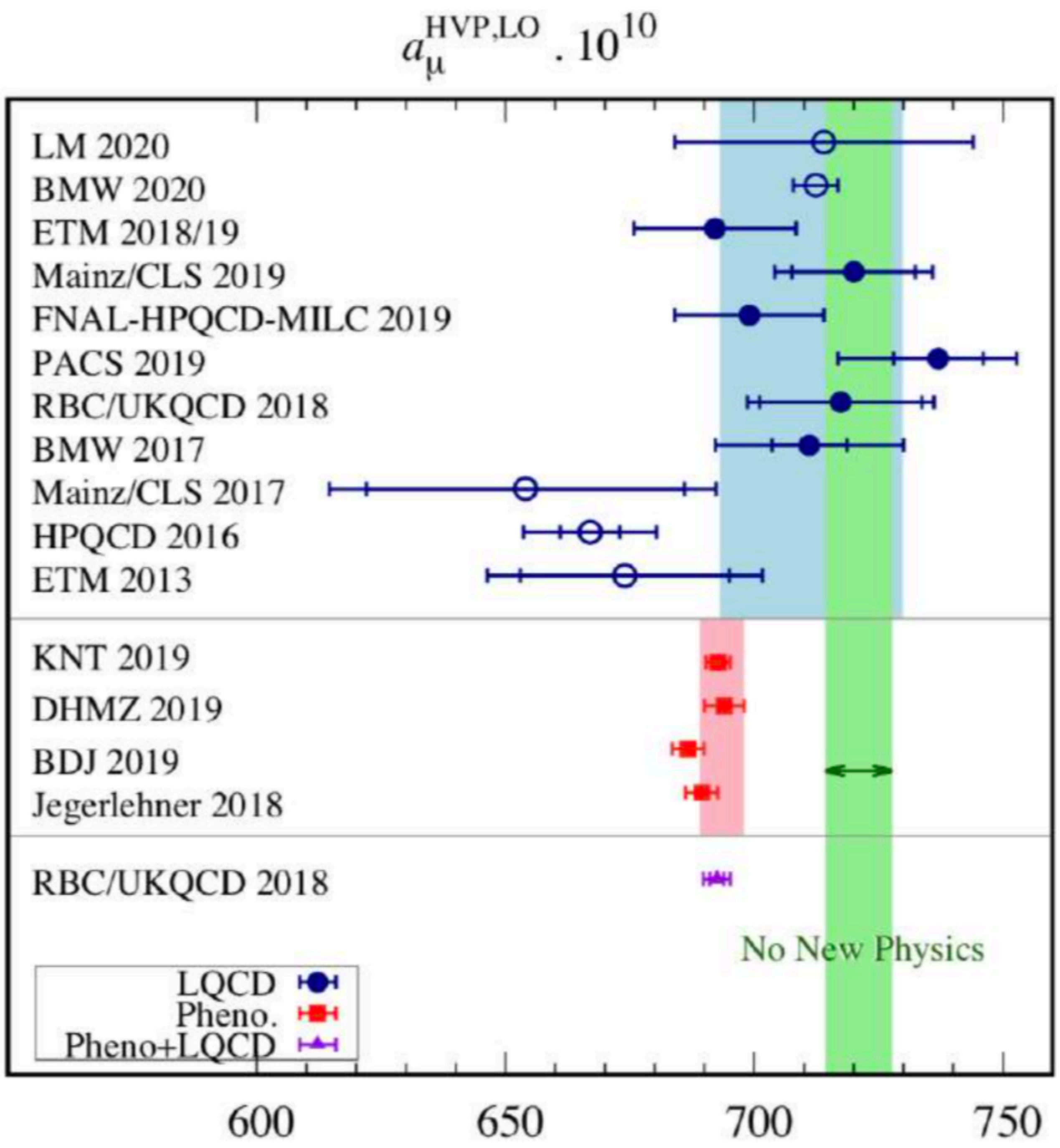
Mu2e

Large increase in sensitivity, well motivated physics, real discovery potential

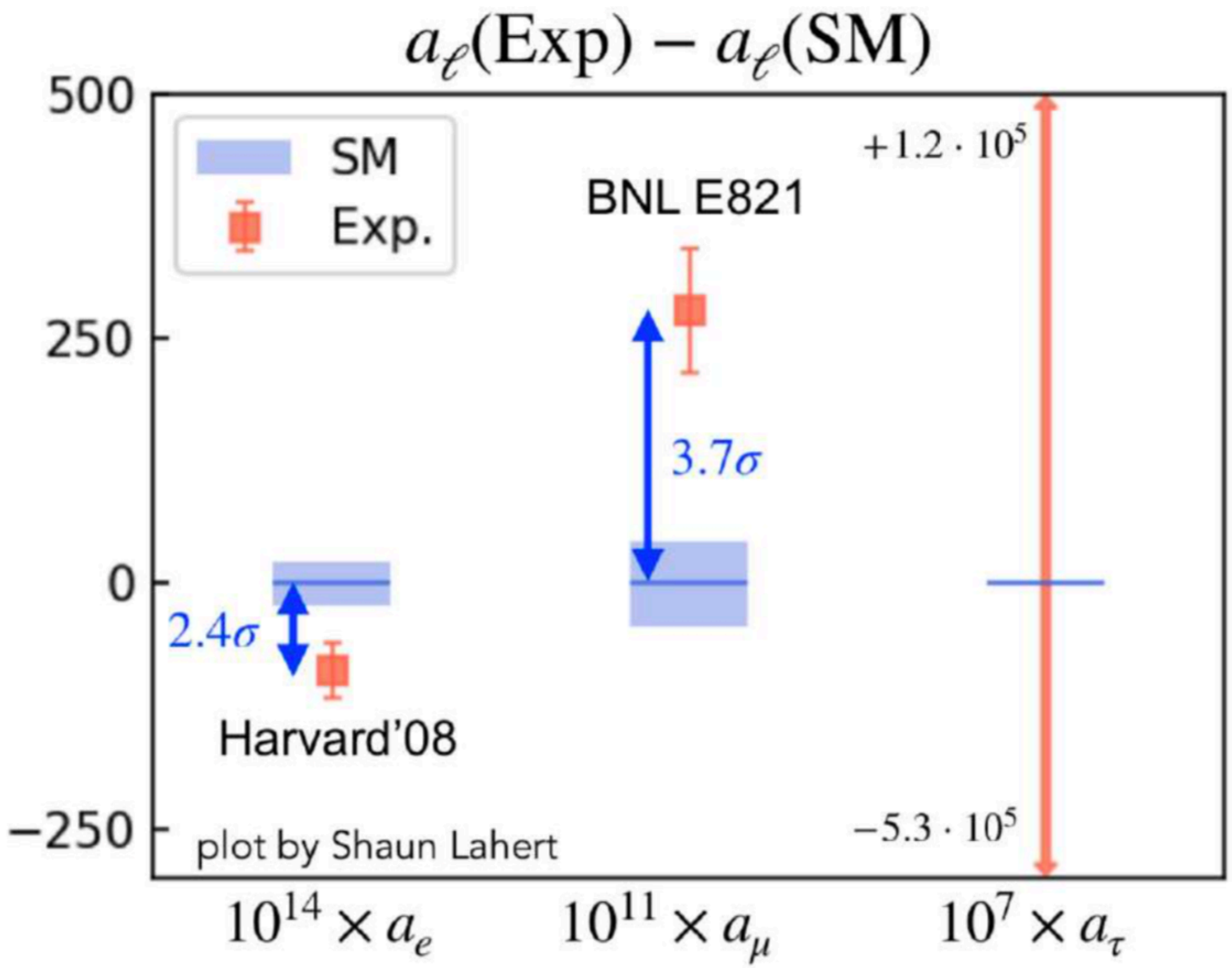
Results will be decade-defining for Fermilab and entire field

Extra slides

Lattice HVP: BMW 2020



Lepton moments

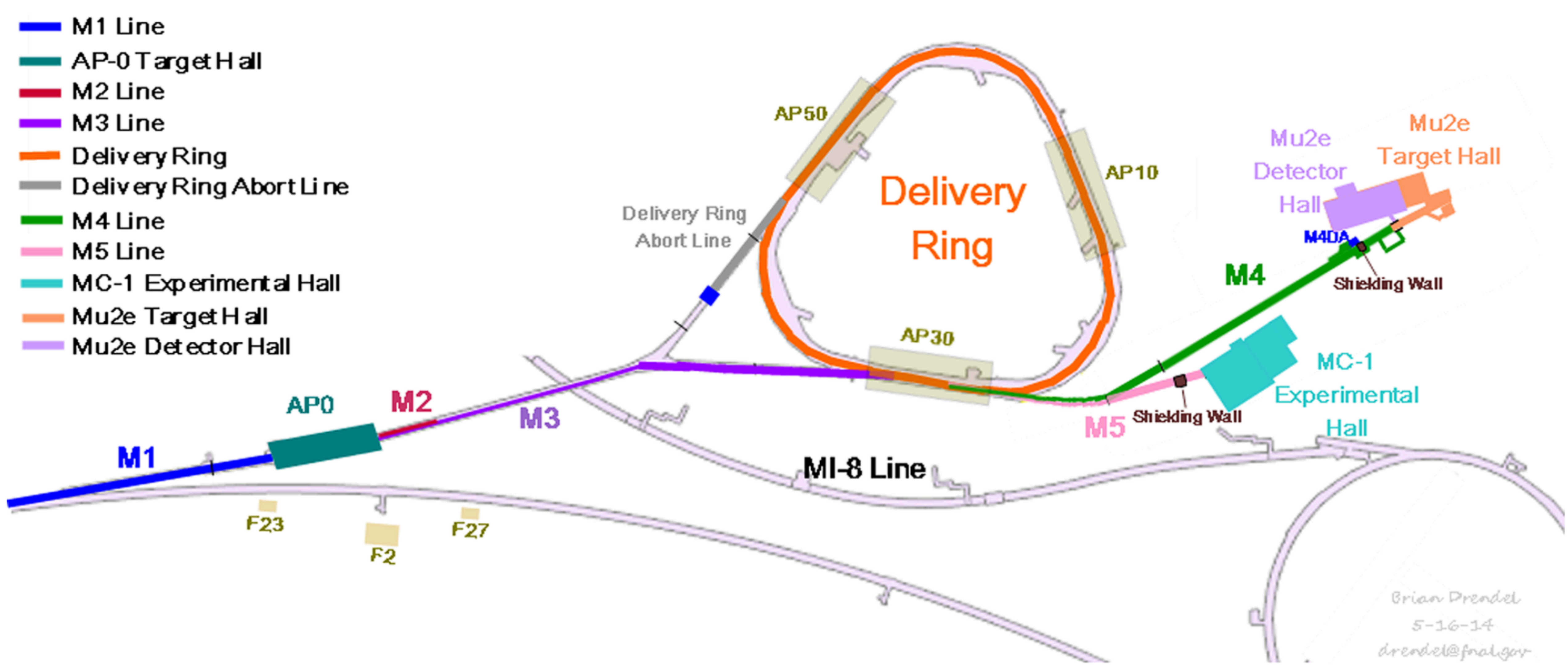


Sensitivity to heavy new physics:

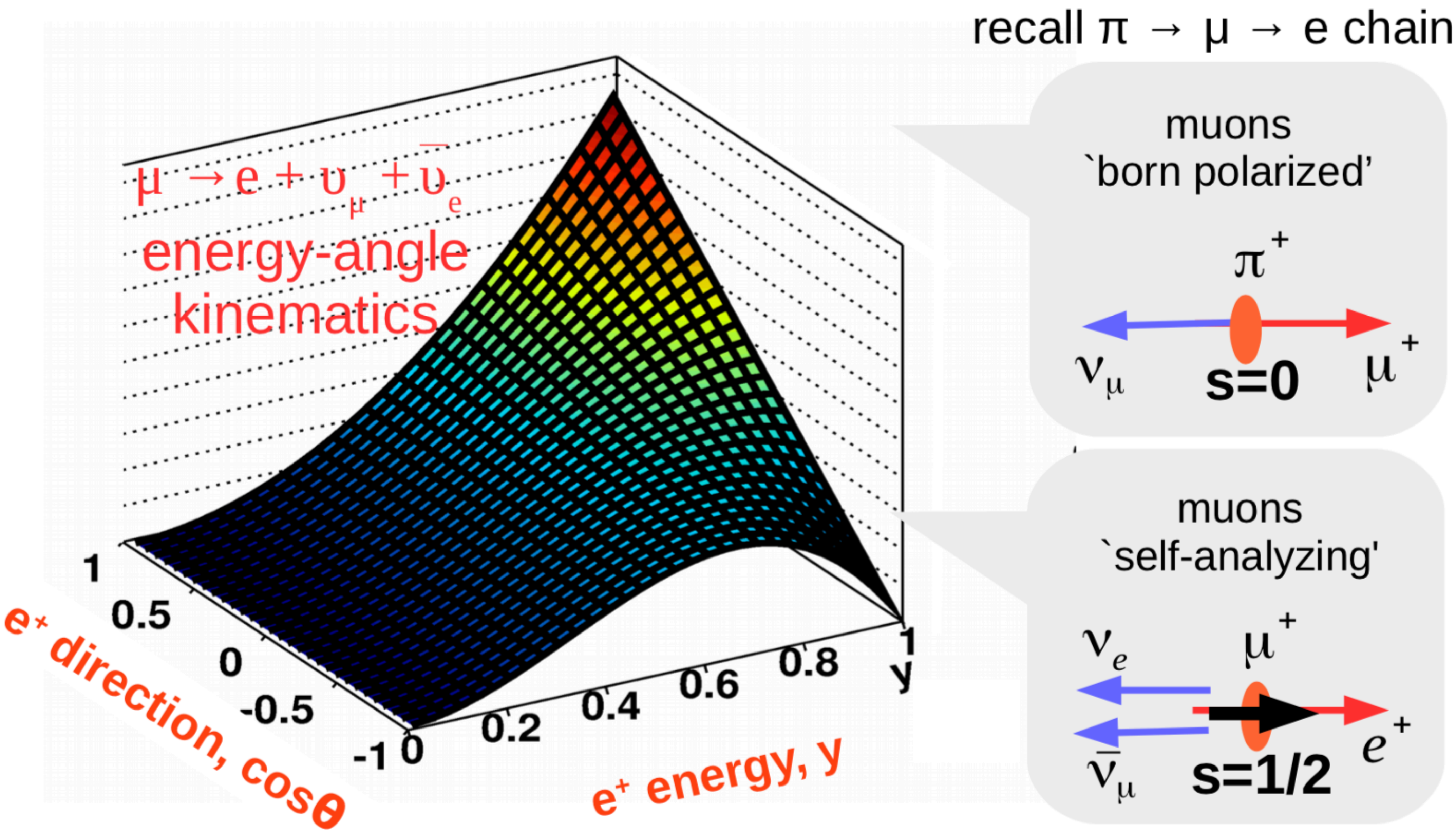
$$a_\ell^{\text{NP}} \sim \frac{m_\ell^2}{\Lambda^2}$$

$$(m_\mu/m_e)^2 \sim 4 \times 10^4$$

Beam to Muon Campus



How to measure the anomalous frequency



- transform from μ-rest frame to lab frame yields higher energy positrons when emitted along μ-direction (i.e. spin along momentum)

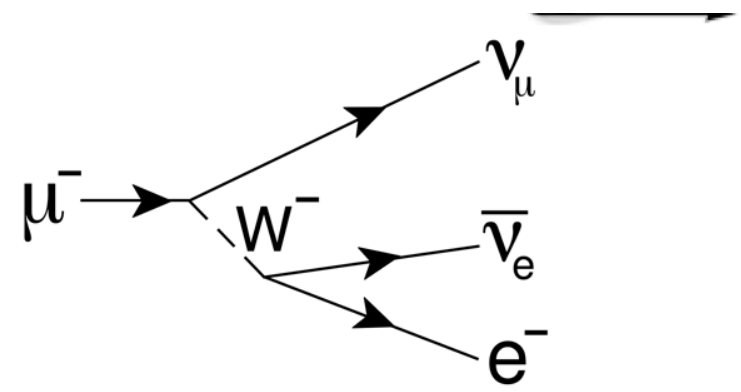
- transform from μ rest frame to lab frame yields lower energy positrons when emitted opposite μ-direction (i.e. spin opposite momentum)

CLFV

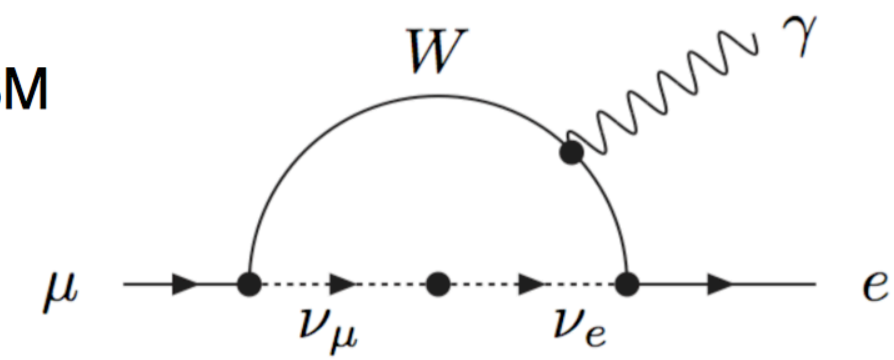
Ordinary muon decay conserves lepton flavor:

$$\mu^- \rightarrow e^- \, \overline{\nu}_e \, \nu_\mu$$

	μ^-	e^-	$\overline{\nu}_e$	ν_μ
L_μ	1	0	0	1
L_e	0	1	-1	0



Violation of charged lepton flavor "forbidden" in SM



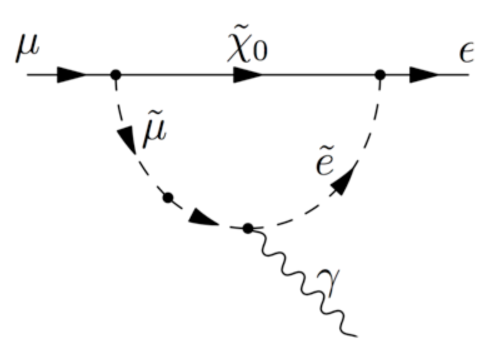
$$\mathrm{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

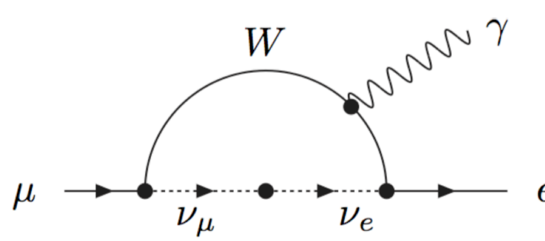
Loophole: neutrino oscillations

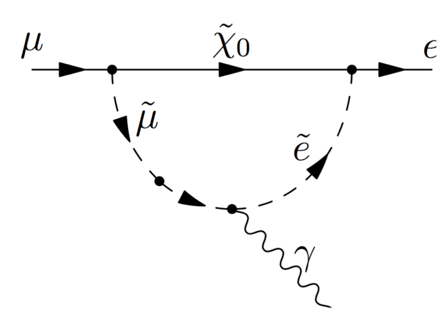
- Some CLFV *must occur*
- But rate is vanishingly small, $<10^{-50}$

Any CLFV observation would be evidence that rate is enhanced by new physics

- A search for rare forbidden processes at the Intensity Frontier
- Complementarity and synergy with LHC







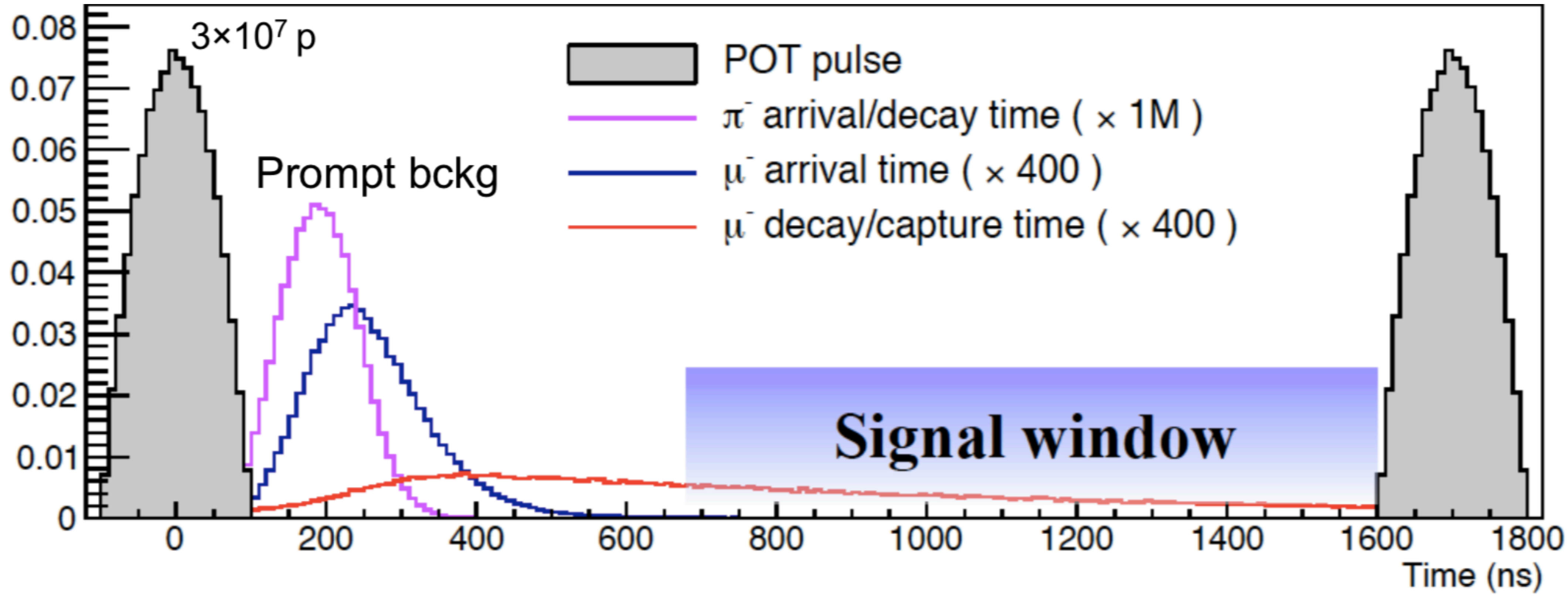
- The charged-lepton analog to neutrino oscillations!

Complementarity between searches

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

W. Altmanshofer et al. 0909.1333v2

Mu2e time structure



Several prompt background sources could give 105 MeV *e*

Characteristic: pion lifetime 26 ns

Concept: Simply wait for prompt bkgds to decay

- Delayed signal window by 700 ns
- Muonic Al lifetime 864 ns
- Proton pulse period 1695 ns, from Fermilab Delivery Ring

Time structure eliminates prompt backgrounds

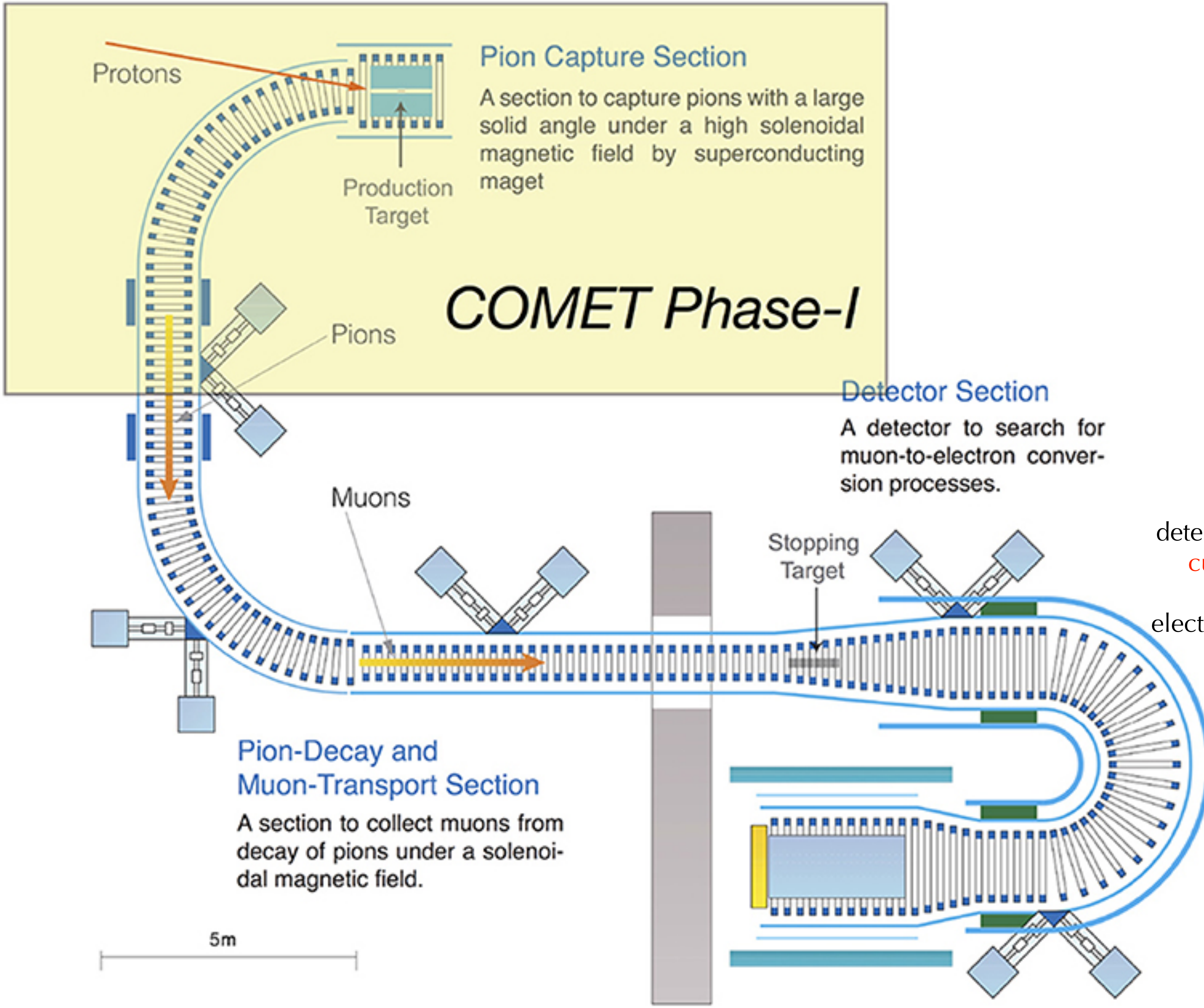
Example:

Radiative pion capture

$$\pi^- N \rightarrow \gamma N$$

$$\gamma \rightarrow e^- e^+$$

COMET



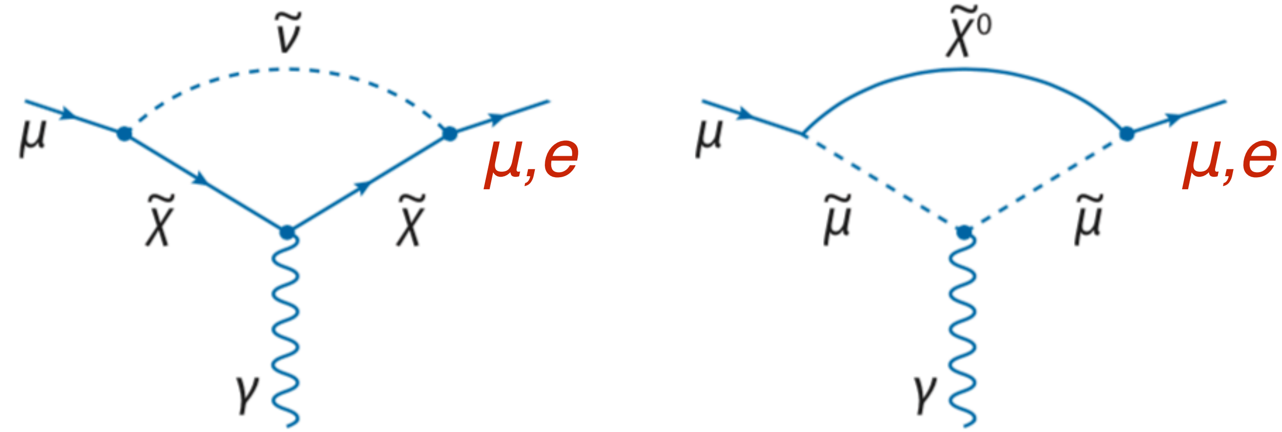
detector has an extra curved magnet acting as an electron spectrometer

CLFV and g-2

Loop terms:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}$$

$$\mathcal{L}_{g-2} \supset \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}\mu_L F^{\mu\nu} + h.c.\,.$$



Andre de Gouvea, Petr Vogel, arXiv:1303.4097 [hep-ph]

Loop operator relates to Muon g-2

- The CLF-violating part of any NP that modifies g-2 would give Mu2e events
- MEG already constrains Λ>1000 TeV, or NP not very CLF-violating
- For the given Δa_μ:

$$\mathcal{B}(\mu^+ \to e^+\gamma) \simeq 6\times 10^{-3}|\varepsilon_{e\mu}|^2$$

William J. Marciano, Toshinori Mori, and J. Michael Roney
https://doi.org/10.1146/annurev.nucl.58.110707.171126

Flavor violating suppression factor