Precision Physics at High Intensities

Conveners:
Dylan Palo, Paul King,
Allison Zec, Emanuele Mereghetti

Talks

Talk	Speaker	Room	Time
Theoretical Advances in g-2	*Shaun Lahert*	*Multicultural Greek*	13:30 - 14:00
Dispersive determinations of lattice muon g-2 HVP contributions	*Kim Maltman*	*Multicultural Greek*	14:00 - 14:30
Status of the MUonE experiment	*Dinko Pocanic*	*Multicultural Greek*	14:30 - 15:00
Measurement of the muon's anomalous spin precession frequency in the Fermilab Muon g-2 Experiment	*Scott Israel*	*Multicultural Greek*	14:00 - 14:30
Precision Magnetic Field Measurements in Muon g-2	*David Kessler*	*Multicultural Greek*	14:30 - 15:00
PSI's MuonEDM experiment	*Diego Sanz-Becerra*	*Multicultural Greek*	15:00 - 15:30

Talk	Speaker	Room	Time
Simultaneous Measurement of Electron- and Muon-Proton Elastic Scattering with the MUSE Experiment at PSI	*Paul Reimer*		
Current status of precise measurement of muonium hyperfine structure in high magnetic field at J-PARC MUSE	*Takayuki Yamazaki*		
X-Ray Spectroscopy of Light Muonic Atoms	*Katharina von Schoeler*	*Multicultural Greek*	20:00 - 20:30

Talk	Speaker	Room	Time
Ab initio overlap integrals for $\mu \rightarrow e$ conversion in nuclei	*Matthias Heinz*	*Multicultural Greek*	13:30 - 13:55
Searching for Lepton Flavor Violation	*Kaori Fuyuto*	*Multicultural Greek*	13:55 - 14:20
Mu2e at Fermilab : Charged Lepton Flavor Violation Experiment	*Mamta Jangra*	*Multicultural Greek*	14:20 - 14:45
A new method to calibrate the momentum scale of the Mu2e experiment	*Pavel Murat*	*Multicultural Greek*	14:45 - 15:10

Talk	Speaker	Room	Time
Muon-electron conversion from Lorentz- and CPT-violating operators	*William McNulty*	*Multicultural Greek*	19:00 - 19:25
PIONEER: A next-generation rare pion decay experiment	*Emma Klemets*	*Multicultural Greek*	19:25 - 19:50
Precision measurements of kaon and pion decays at NA62	*Peter Cooper*	*Multicultural Greek*	19:50 - 20:15
Studies of τ and dark sector decays at Belle and Belle II	*William Jacobs*	*Multicultural Greek*	20:15 - 20:40

Talk	Speaker	Room	Time
Constraints on the weak mixing angle from future facilities	*Wally Melnitchouk*	*Beefeaters*	14:00 - 14:25
Measuring the Weak Charge of the Electron - The MOLLER Experiment	*Kent Paschke*	*Beefeaters*	14:25 - 14:50
A high precision determination of the weak mixing angle at low momentum transfer - The P2 experiment	*Caryn Palatchi*	*Beefeaters*	14:50 - 15:15
NOPTREX: Neutron Optics Parity and Time Reversal Experiment	*Sepehr Samiei*	*Beefeaters*	15:15 - 15:40

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g-2 / Muon EDM

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Muonic Atoms/Scattering

Simultaneous Measurement of Electron- and Muon-Proton Elastic Scattering with the MUSE Experiment at PSI	
Paul Reimer	
Current s ... MUSE	
Takayuki	
X-Ray Spectroscopy of Light Muonic Atoms	*Katharina von Schoeler*
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Charged Lepton Flavor Violation

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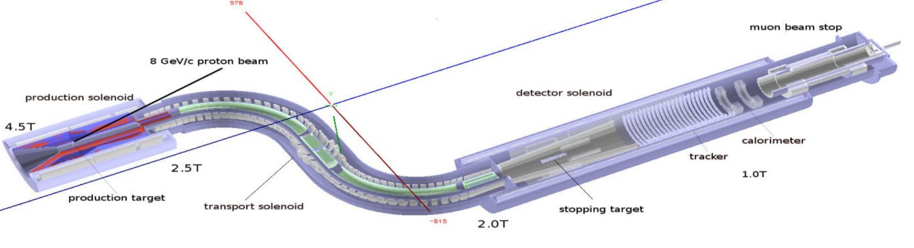
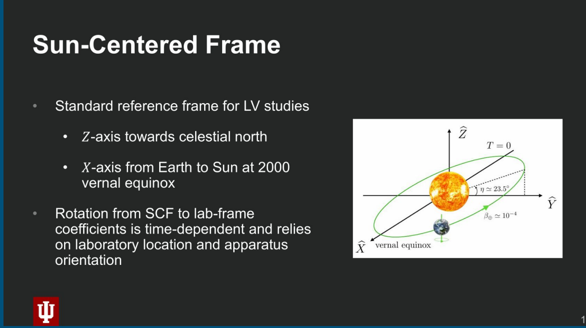
Rare Decays

Muon-electron conversion from Lorentz- and CPT-violating operators	*William McNulty*
Multicultural Greek	19:00 - 19:25
PIONEER: A next-	*Emma Klemets*
Multicultural Greek	19:25 - 19:50
Precision measure	*Peter Cooper*
Multicultural Greek	19:50 - 20:15
Studies of τ and dark sector decays at Belle and Belle II	*William Jacobs*
Multicultural Greek	20:15 - 20:40

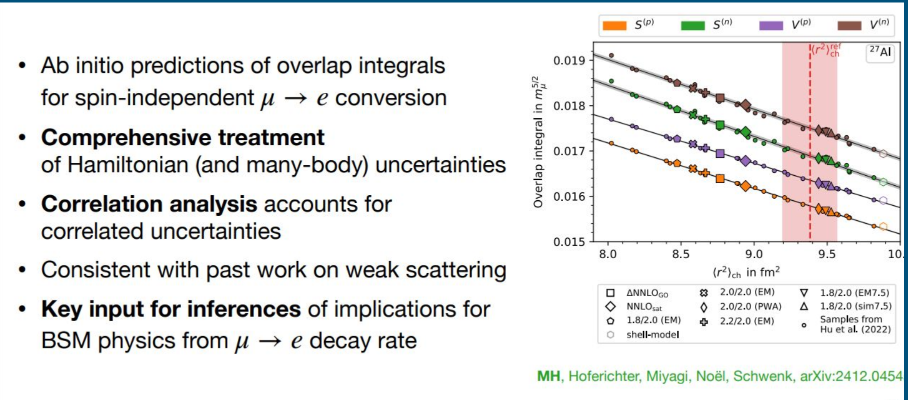
Parity Violation/Weak Mixing Angle

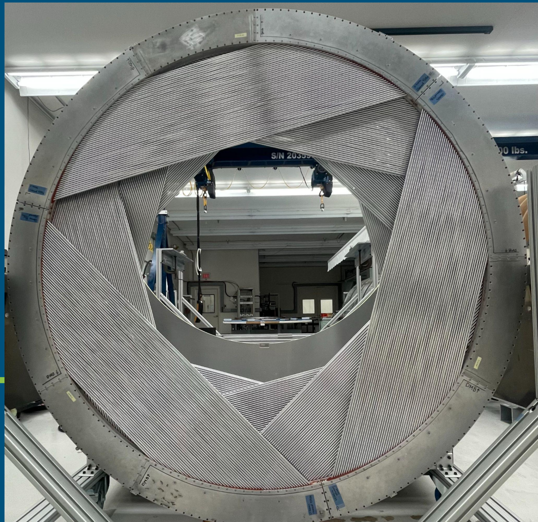
Constraints on the weak mixing angle from future facilities	*Wally Melnitchouk*
Beefeaters	14:00 - 14:25
NOPTREX: Neutron Optics Parity and Time Reversal Experiment	*Sepehr Samiei*
Beefeaters	15:15 - 15:40





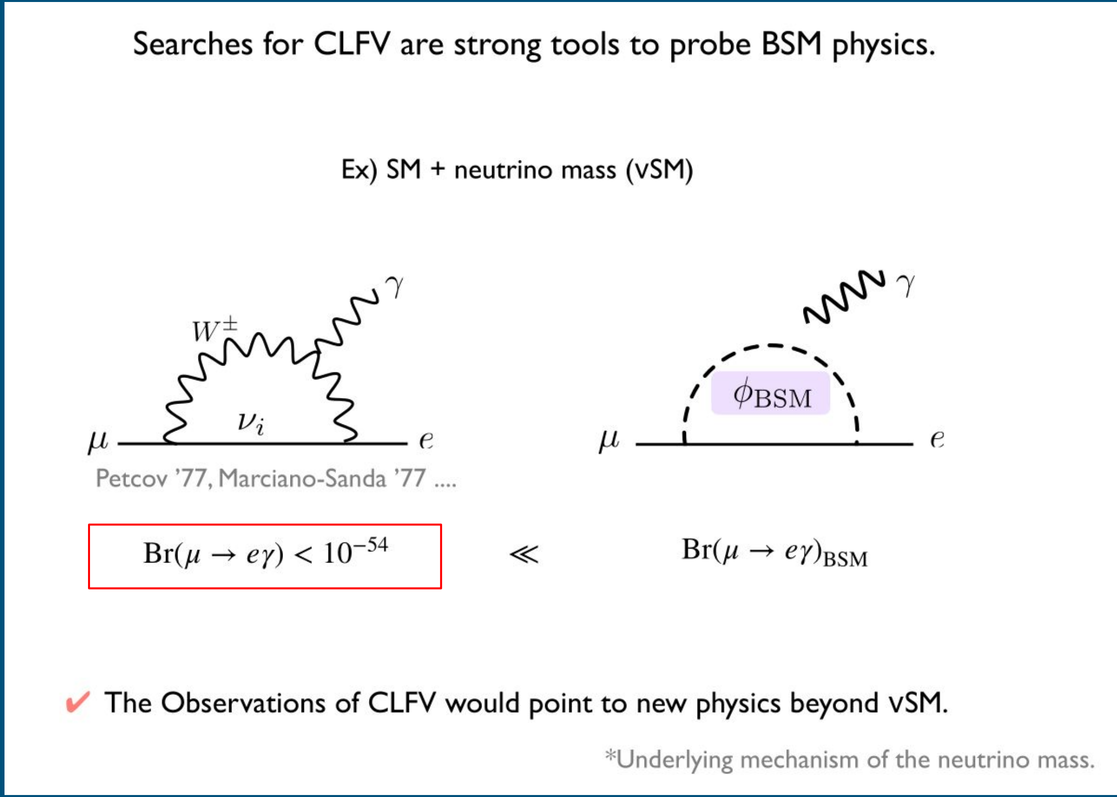
Charged Lepton Flavor Violation





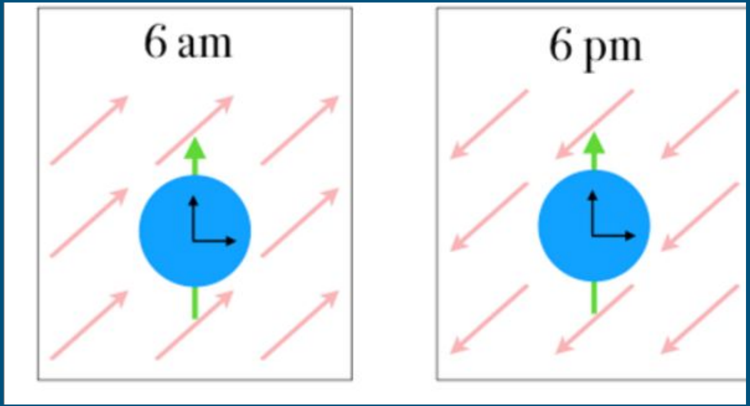
Charged Lepton Flavor Violation Introduction

- CLFV occurs at a negligible rate in the SM
- BSM physics could allow for CLFV at a potentially observable level
- Signal would be unambiguous evidence of BSM physics



CLFV Through Lorentz Violation

- Among other BSM physics, CLFV can be a result of Lorentz violation (symmetry under rotations and boosts)
- SM+GR allows for additional lagrangian terms

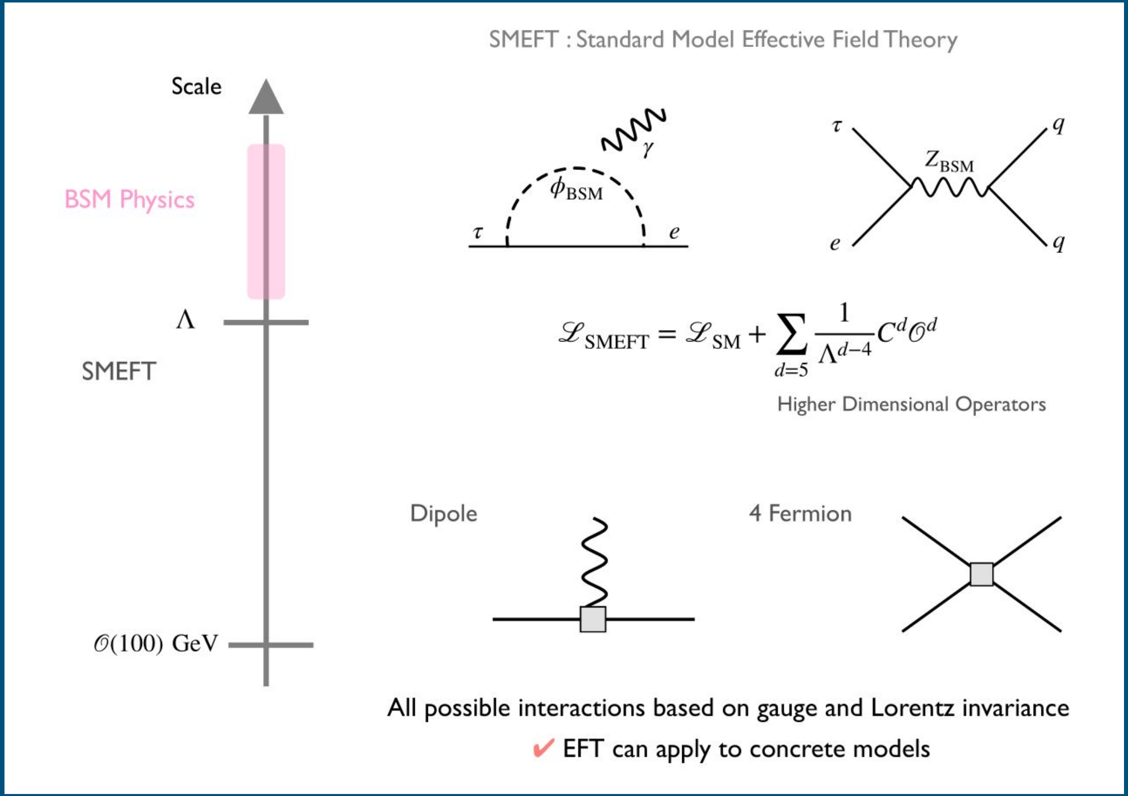


- Lorentz violation means location, time, and orientation of the experiment matter
  - Leading effect is rotation of Earth with respect to fixed SME background coefficients

- Most relevant for nuclear $\mu - e$ conversion are EM (mass dim. 5) and 4-point quark-lepton (mass dim. 6) operators
- Lagrangian ($Q \in \{u, d, s\}, q \in \{u, d\}$; red = CPT-odd) is given by

$$\begin{aligned}
\mathcal{L} \supset\ & -\frac{1}{2} F_{\alpha\beta} \overline{\psi_e} \left(\left(m_F^{(5)}\right)_{e\mu}^{\alpha\beta} + i \left(m_{5F}^{(5)}\right)_{e\mu}^{\alpha\beta} \gamma_5 + \left(a_F^{(5)}\right)_{e\mu}^{\mu\alpha\beta} \gamma_\mu + \left(b_F^{(5)}\right)_{e\mu}^{\mu\alpha\beta} \gamma_5 \gamma_\mu + \frac{1}{2} \left(H_F^{(5)}\right)_{e\mu}^{\mu\nu\alpha\beta} \sigma_{\mu\nu} \right) \psi_\mu \\
& + \overline{\psi_Q} \psi_Q \overline{\psi_e} \left(\left(k_{SV}^{(6)}\right)_{QQe\mu}^{\lambda} \gamma_\lambda + \left(k_{SA}^{(6)}\right)_{QQe\mu}^{\lambda} \gamma_5 \gamma_\lambda + \frac{1}{2} \left(k_{ST}^{(6)}\right)_{QQe\mu}^{\kappa\lambda} \sigma_{\kappa\lambda} \right) \psi_\mu \\
& + \overline{\psi_q} \gamma_0 \psi_q \overline{\psi_e} \left(\left(k_{VS}^{(6)}\right)_{qqe\mu}^{0} + i \left(k_{VP}^{(6)}\right)_{qqe\mu}^{0} \gamma_5 + \frac{1}{2} \left(k_{VV}^{(6)}\right)_{qqe\mu}^{0\lambda} \gamma_\lambda + \left(k_{VA}^{(6)}\right)_{qqe\mu}^{0\lambda} \gamma_5 \gamma_\lambda + \frac{1}{2} \left(k_{VT}^{(6)}\right)_{qqe\mu}^{0\kappa\lambda} \sigma_{\kappa\lambda} \right) \psi_\mu
\end{aligned}$$

Effective Field Theory: Comparison of CLFV Channels



Effective Field Theory: Comparison of CLFV Channels

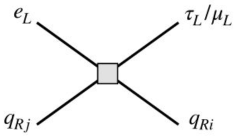
CLFV operators

Total : 16 different types of LFV operators (dim 6)

$$\mathscr{L}_{\mathrm{LFV}} = \mathscr{L}_{\psi^2\varphi^2 D} + \mathscr{L}_{\psi^2 X\varphi} + \mathscr{L}_{\psi^2\varphi^3} + \mathscr{L}_{\psi^4}$$

X : Gauge boson ψ : Fermion φ : Higgs

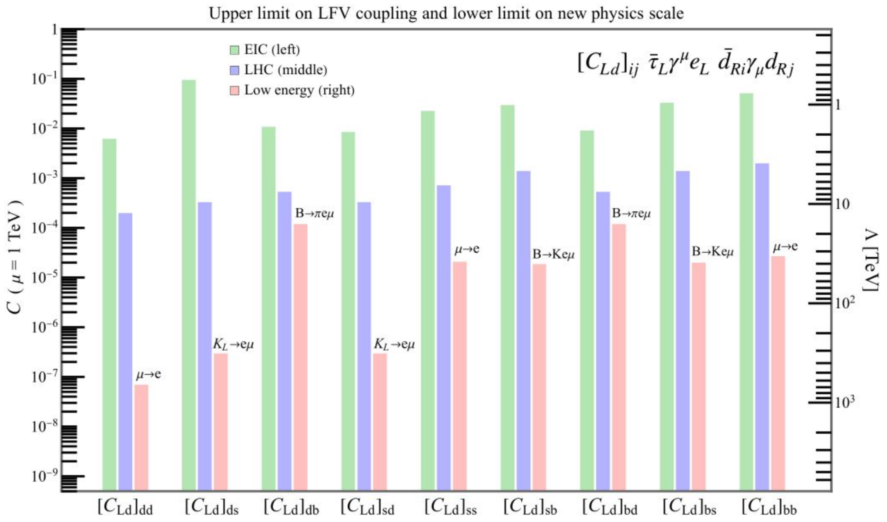
$$\supset -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\ell=\tau,\mu \\ q=u,d}} [C_{Lq}]_{\ell eij}\; \bar{\ell}_L \gamma^\mu e_L\; \bar{q}_{Ri}\gamma_\mu q_{Rj}$$



*Assume a generic quark flavor structure

$$\text{Ex)}\quad [C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

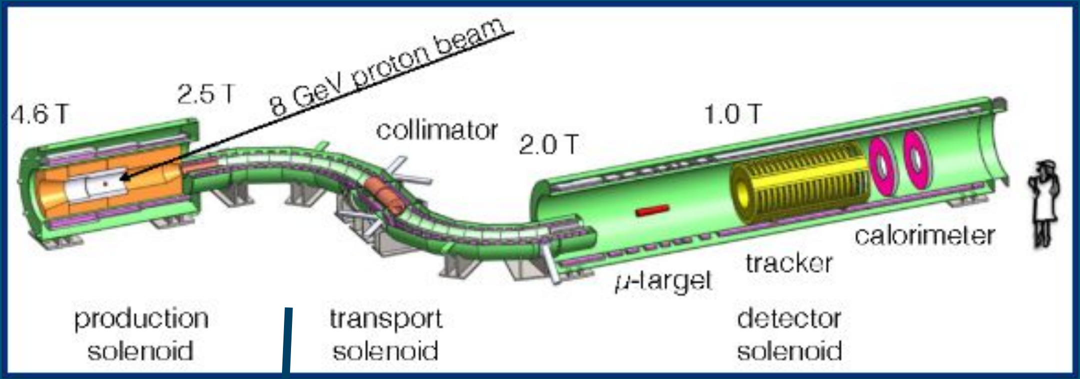
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

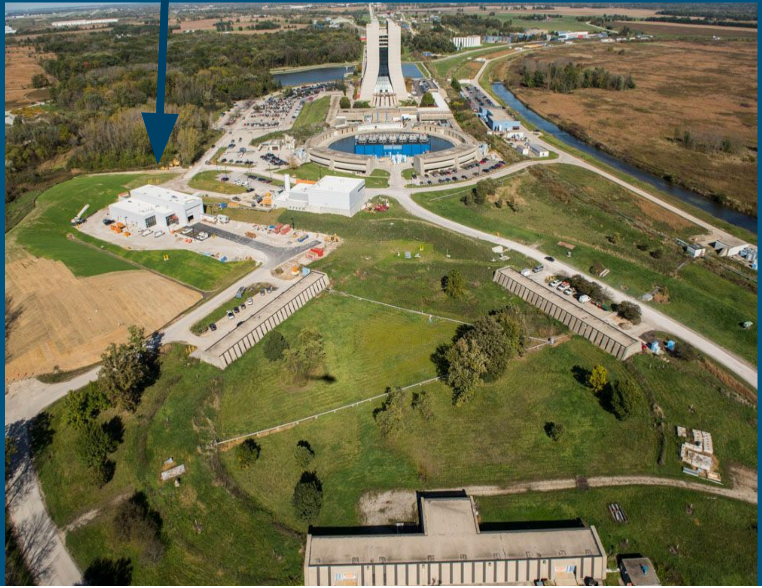


- $\mu \to e$ conversion currently gives strong bound

Mu2e Experiment

- Experiment searching for μ→e conversion starting in 2027 at Fermilab
- Plans for a 10000x improvement in the sensitivity over its predecessor experiment



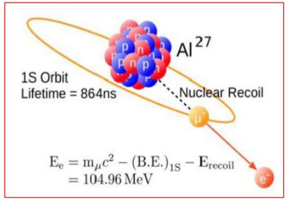


Mu2e Signal/Background

- Signal:
  - Monochromatic energy electron at ~105 MeV
- Backgrounds
  - Decay in orbit (DIO):
    - **Precise Momentum Resolution**
  - etc…

- When muons stopped in Al, a muonic atom is formed. 61% undergo nuclear capture, 39% decay in orbit.
- Neutrino-less conversion of a negative muon to an electron in the presence of a nucleus

$$\mu^- + {}^{27}Al \rightarrow e^- + {}^{27}Al$$



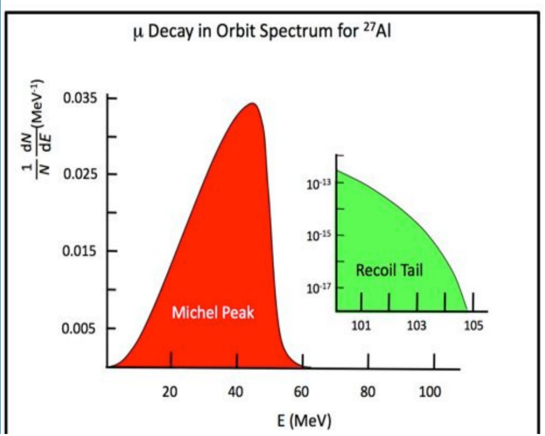
- Signal : Monochromatic energy electron

$$E_{e-} = M_{\mu-} - E_b - E_{recoil} = 104.96 \text{ MeV}$$

- Mu2e aims to improve the current upper limit on the sensitivity by **four orders of magnitude**

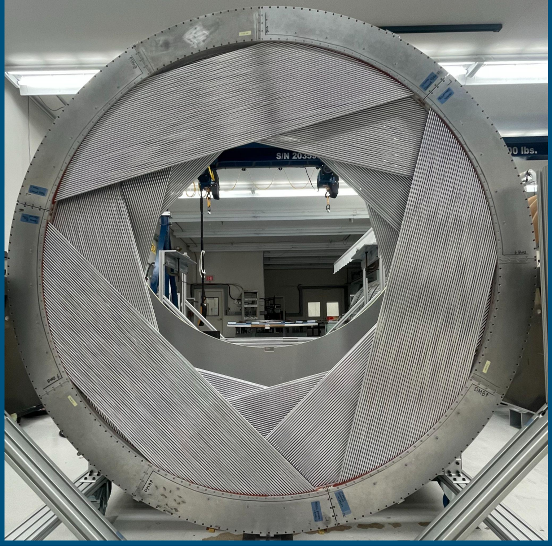
$$R_{\mu e} = \frac{\mu^- N \rightarrow e^- N}{\mu^- N \rightarrow \text{all muon captures}}$$

Current upper limit on $\mu^- N \rightarrow e^- N$ is set by SINDRUM II (Au target)* $R_{\mu e} < 7\times10^{-13}$ (90% CL)

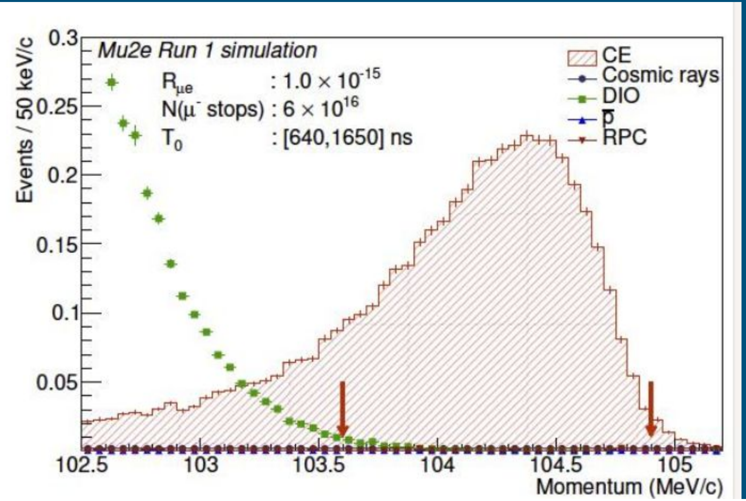


Mu2e Tracker/ Resolution

18x

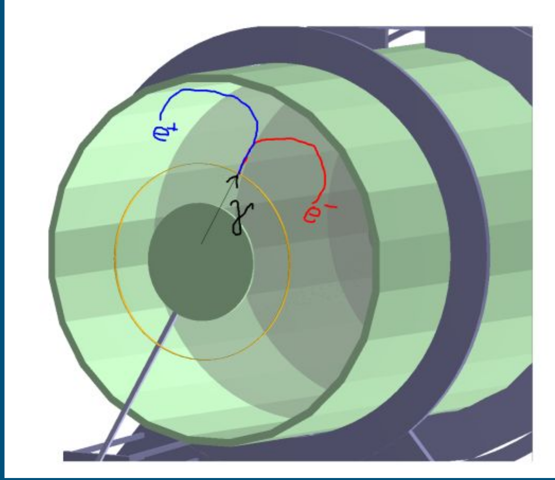


- 20k straw tubes
- ~180 keV detector resolution for ~105 MeV electron
- Require energy scale of the order ~100 keV



Mu2e Momentum Scale

- Data-driven momentum scale
- RPC on polyethylene target results in ~128 MeV photon
- Convert photon and reconstruct e+/e-



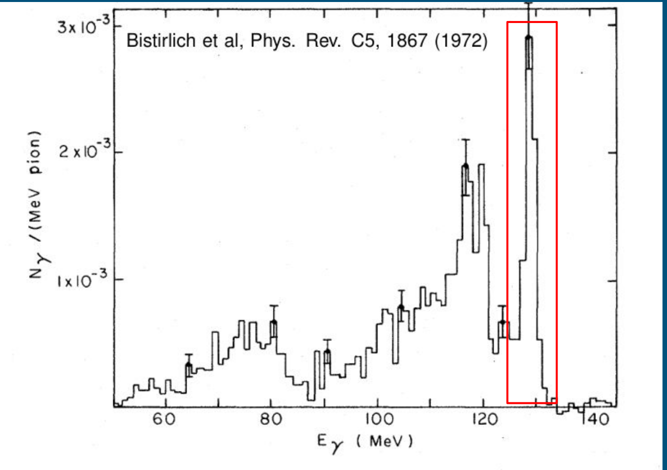
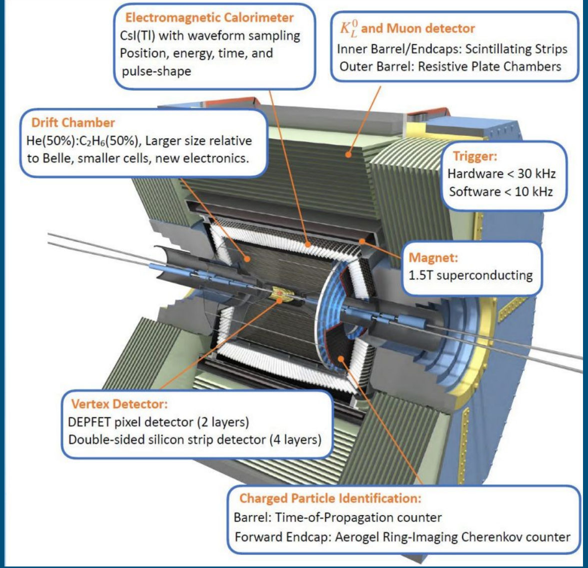
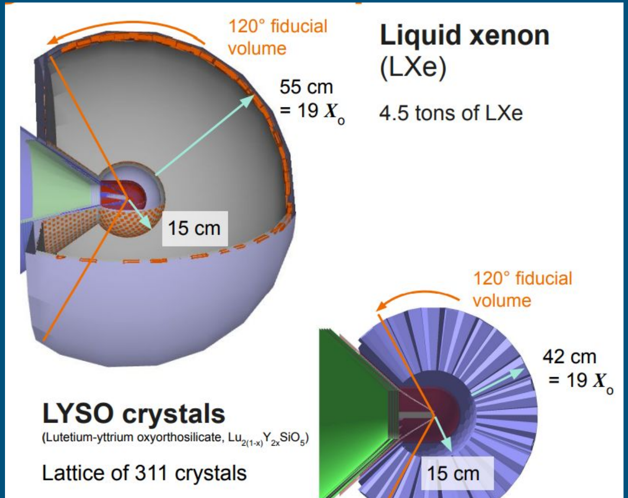


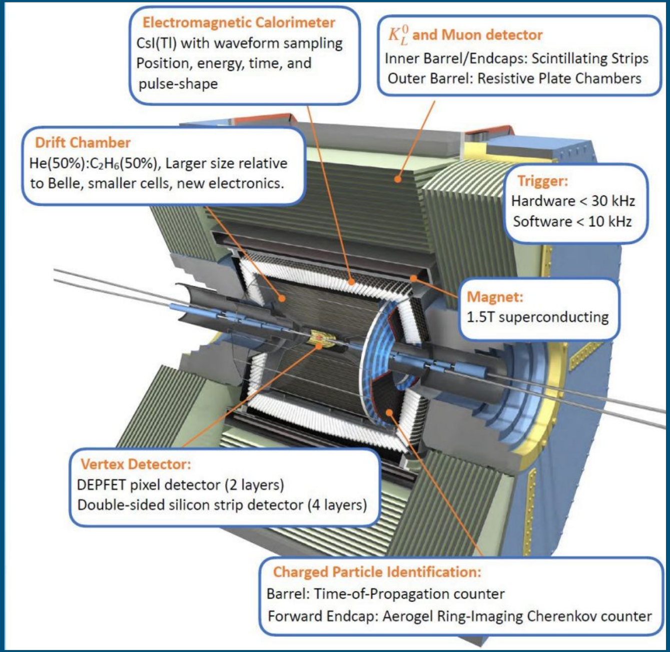
FIG. 9. Photon energy spectrum from π^- capture in CH_2.


Electromagnetic Calorimeter
CsI(Tl) with waveform sampling
Position, energy, time, and
pulse-shape
K_L^0 and Muon detector
Inner Barrel/Endcaps: Scintillating Strips
Outer Barrel: Resistive Plate Chambers
Drift Chamber
He(50%):C_2H_6(50%), Larger size relative
to Belle, smaller cells, new electronics.
Trigger:
Hardware < 30 kHz
Software < 10 kHz
Magnet:
1.5T superconducting
Vertex Detector:
DEPFET pixel detector (2 layers)
Double-sided silicon strip detector (4 layers)
Charged Particle Identification:
Barrel: Time-of-Propagation counter
Forward Endcap: Aerogel Ring-Imaging Cherenkov counter

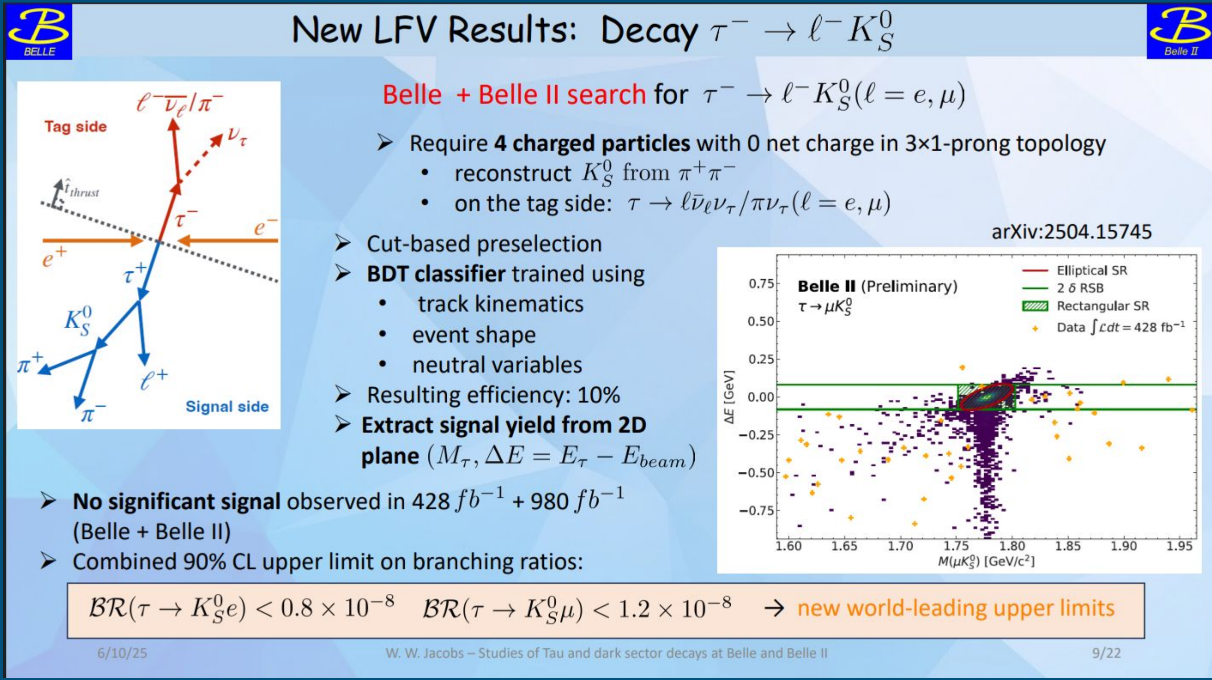
Rare Decays


120° fiducial
volume
Liquid xenon
(LXe)
55 cm
= 19 X_o
4.5 tons of LXe
15 cm
120° fiducial
volume
42 cm
= 19 X_o
LYSO crystals
(Lutetium-yttrium oxyorthosilicate, $Lu_{2(1-x)}Y_{2x}SiO_5$)
Lattice of 311 crystals
15 cm

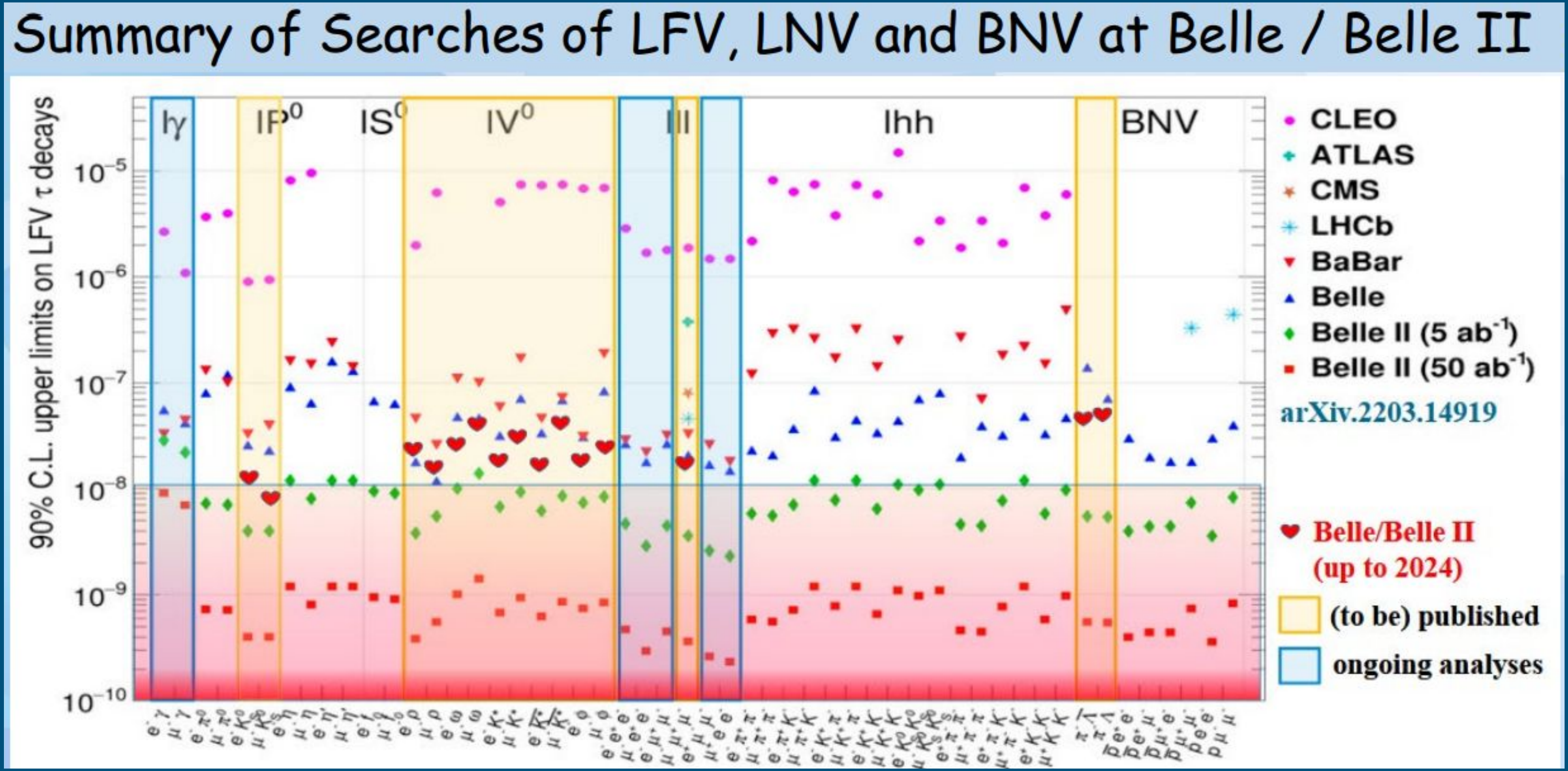
Belle II: B-Factory



CLFV

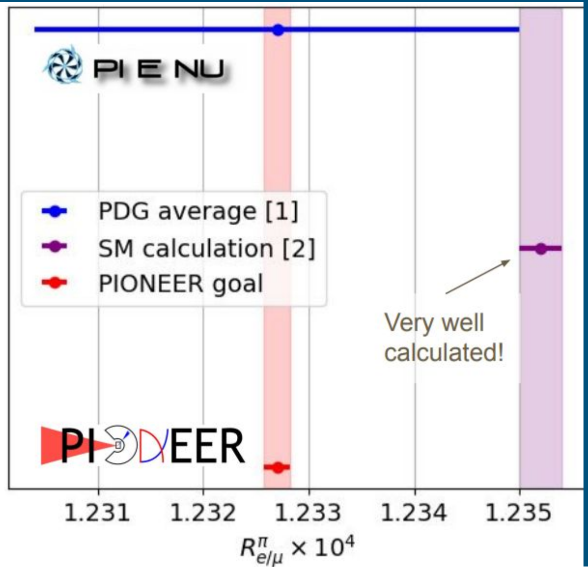


Belle II: Many Channels!



PIONEER: Lepton Flavor Universality

- **Test of lepton flavor universality via pion decay ratio at PSI**
- Current ratio error bars are 15x larger than the theory
- Plan to match theoretical level of uncertainty



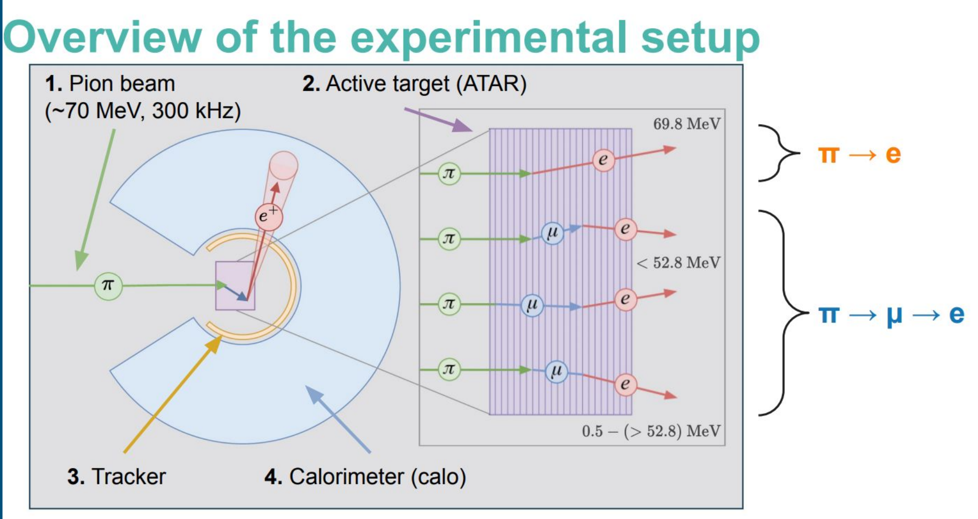
Measure the pion decay ratio:

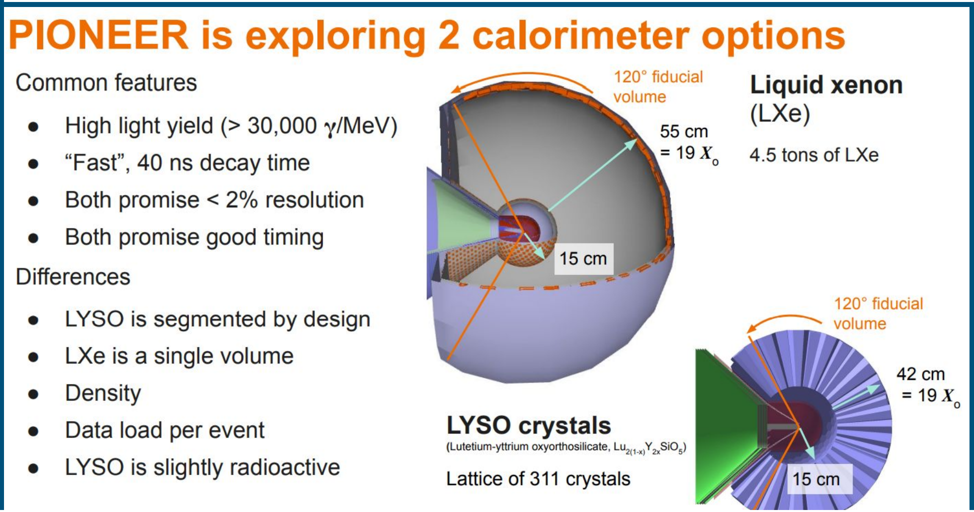
$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma))}$$

$$= 1.2327(23) \times 10^{-4} \text{ (Exp) [1]}$$

PIONEER: ATAR/CAL

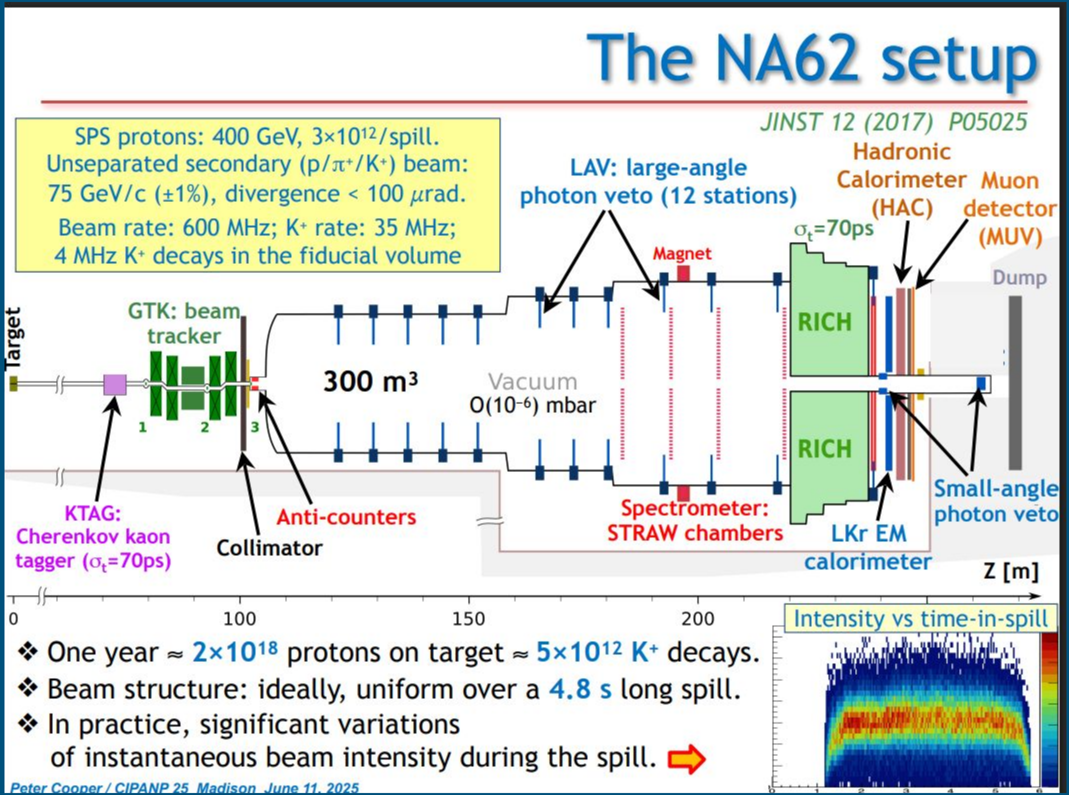
- ATAR:
  - Determines pion/muon decay points
  - 5D (x,y,z,t,E) tracking system
  - O(50) layers
  - Good time resolution: < 100 ps
  - Sufficient granularity: < 200 μm
- Calorimeter:
  - Measure electron momentum/time
  - Exploring prototypes in LXe/LYSO





NA62

- Charged Kaon experiment at CERN
- Measuring many Kaon/pion branching fractions
- Presented the Run1 results.. Run 2 is ongoing until 2026



$K^+\to\pi^+\mu^+\mu^-$, $K^+\to\pi^+\gamma\gamma$, $K^+\to\pi^0 e^+\nu\gamma$, $\pi^0\to e^+e^-$

$K^+\to\pi^+\nu\nu$

NA62 $K^+ \to \pi^+ \mu^+ \mu^-$

- Chiral perturbation theory parameters
- Lepton flavor universality (along with other search)
- Observed 27k signal candidates with only 8 background events!
- Extremely clean signal
- Run 1 has already improved on limit by factor of 3

$$W(z) = G_F m_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z)$$

a_+, b_+: real parameters
$W^{\pi\pi}(z)$: complex function, two-pion loop

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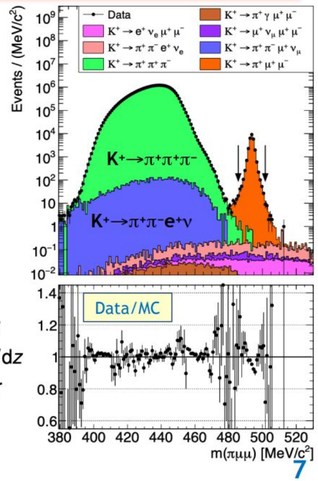
- Dedicated di-muon trigger line.
- Normalisation: $K^+ \to \pi^+\pi^+\pi^-$ decay.
- Effectively $(3.48 \pm 0.09) \times 10^{12}$ kaon decays.
- Signal candidates observed: 27679.
- Negligible background: about 8 events.

Analysis:

- Data divided in 50 equipopulated bins in z:
$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$
- Integrating $d\Gamma(z)/dz \to$ model-independent $\mathcal{B}$
- $|W(z)|^2$ function values extracted from $d\Gamma(z)/dz$
- Fit of $|W(z)|^2$ data points $\to$ ChPT form factor parameter measurement



Peter Cooper / CIPANP 25 Madison June 11, 2025

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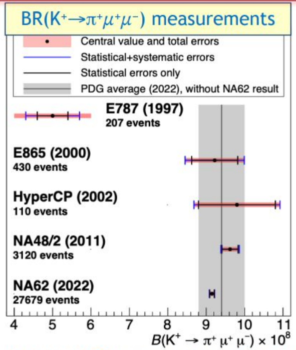

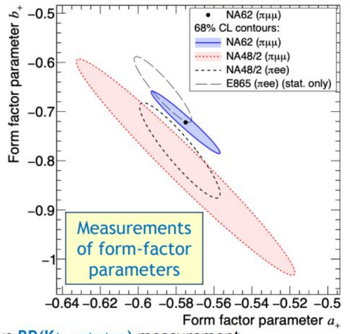

- A factor of 3 improvement on best previous BR($K^+ \to \pi^+ \mu^+ \mu^-$) measurement.
- Measured form-factor parameters (a_+, b_+) are compatible between $K^+ \to \pi^+ \mu^+ \mu^-$ and $K^+ \to \pi^+ e^+ e^-$ decays: lepton universality.
- Next step: $K^+ \to \pi^+ \mu^+ \mu^-$ and $K^+ \to \pi^+ e^+ e^-$ measurement with full dataset; dedicated LFU test, search for a scalar contribution

(see D'Ambrosio, Iyer, Mahmoudi, Neshatpout, arXiv:2404.03643)

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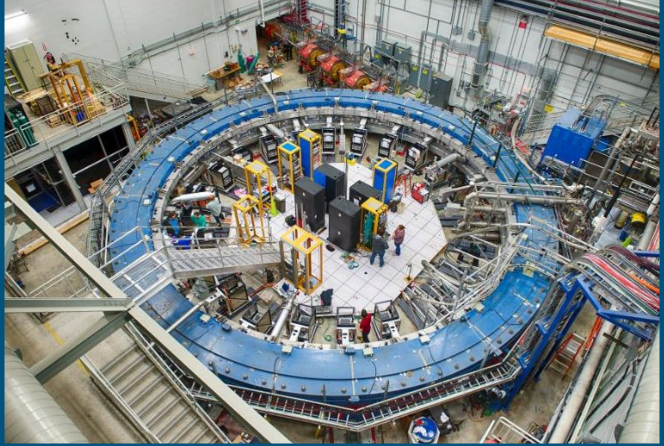
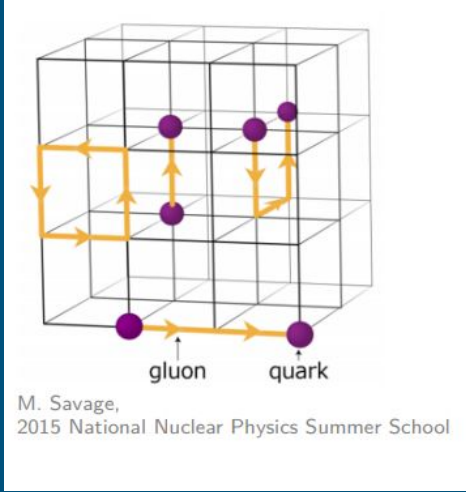
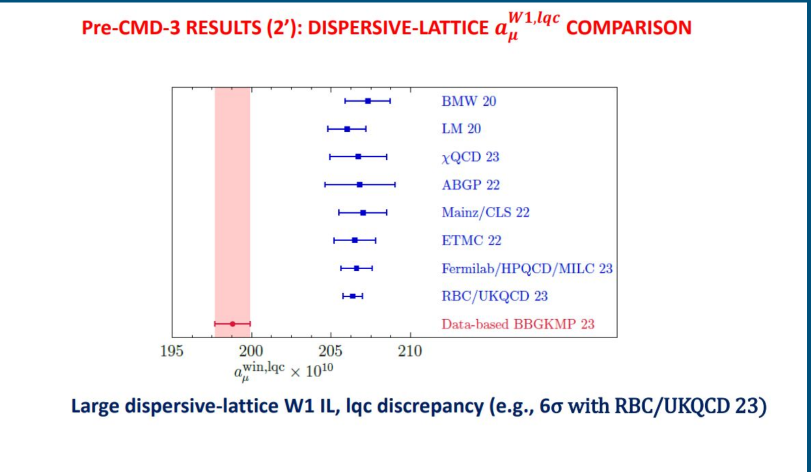
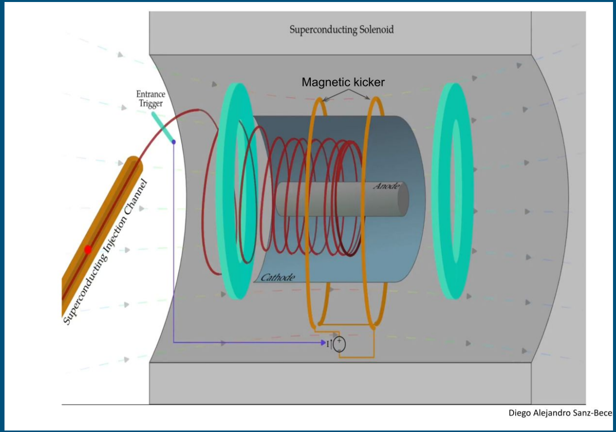



gluon
quark
M. Savage,
2015 National Nuclear Physics Summer School

g-2/Muon EDM


Pre-CMD-3 RESULTS (2'): DISPERSIVE-LATTICE $a_\mu^{W1,lqc}$ COMPARISON
BMW 20
LM 20
χQCD 23
ABGP 22
Mainz/CLS 22
ETMC 22
Fermilab/HPQCD/MILC 23
RBC/UKQCD 23
Data-based BBGKMP 23
195
200
205
210
$a_\mu^{\mathrm{win,lqc}} \times 10^{10}$
Large dispersive-lattice W1 IL, lqc discrepancy (e.g., 6σ with RBC/UKQCD 23)

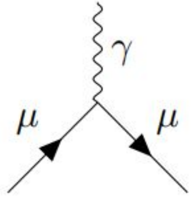

Superconducting Solenoid
Magnetic kicker
Entrance Trigger
Anode
Cathode
Superconducting Injection Channel
Diego Alejandro Sanz-Bece

Anomalous Magnetic Moment

- Experimental deviation from theory would imply new physics!

Magnetic moment of muon μ:

$$\vec{\mu}_\mu = g\frac{e}{2m_\mu}\vec{S}$$

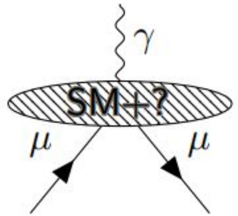


Dirac eqn. (tree-level QFT):

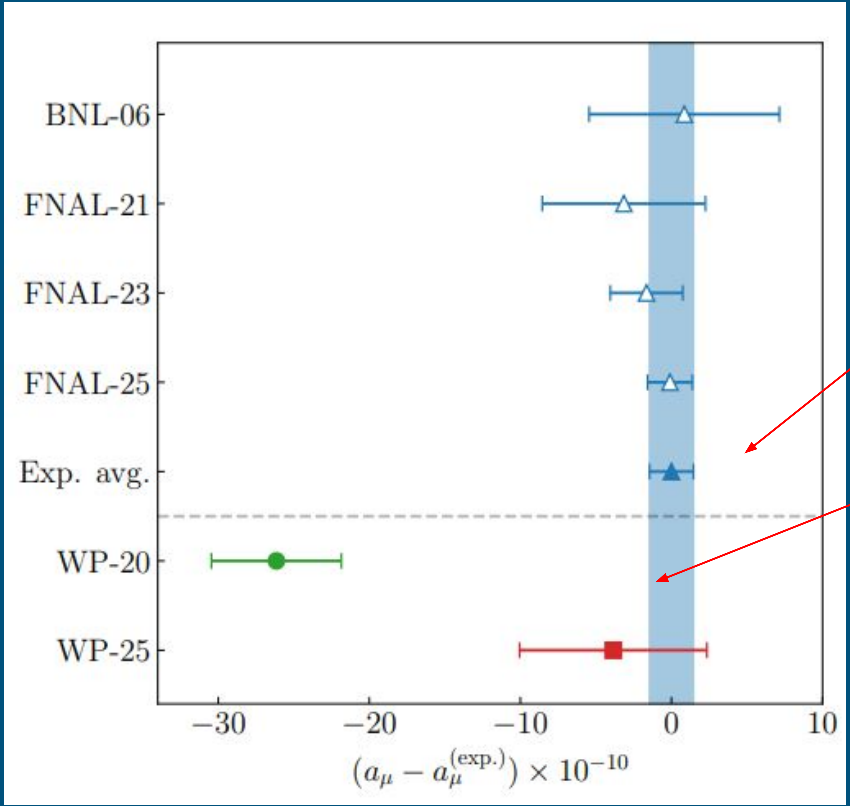
$$g = 2$$

Anomalous moment from loop effects:

$$a_\mu = (g-2)/2$$



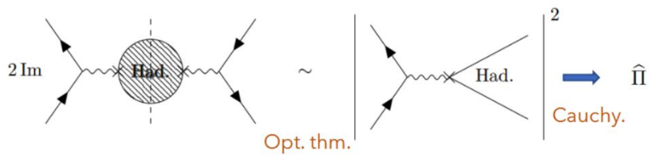
Anomalous Magnetic Moment



- Muon g-2 collaboration just finished their final result. Parallel talks on:
  - The precision frequency measurement
  - Magnetic field Measurement
- Theory community posted 2025 White Paper using lattice QCD
  - Two talks on the status/recent advances in theory

g-2 HVP Data-driven

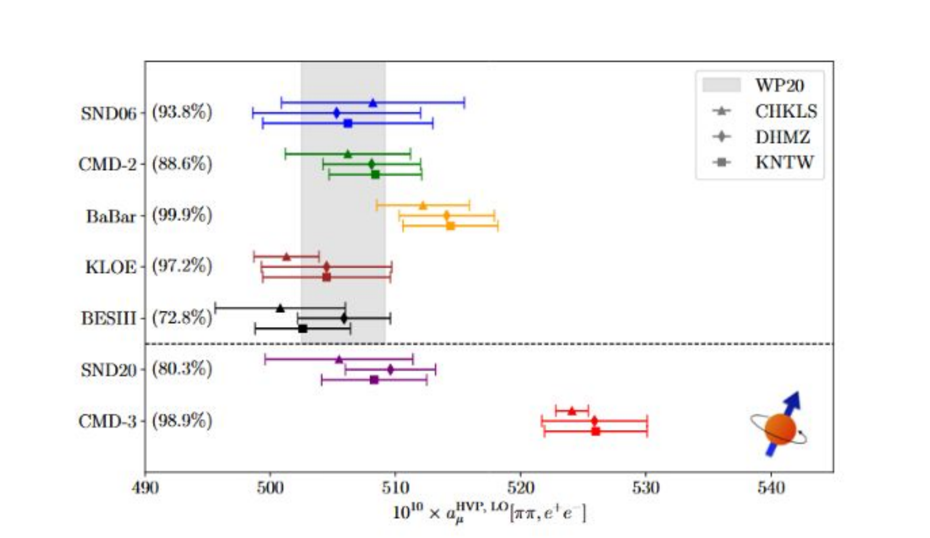
- Calculate using hardon cross-section data
- Dominated by e+ e⟶ pi+ pi-
- Significant discrepency when using the recent CMD-3 data (post WP-20)



"R-ratio"

$$\widehat{\Pi}\left(q^2\right) = \frac{4\pi\alpha^2 q^2}{9}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^-e^+\to Had.}(s)}{s^2\left(s-q^2\right)}ds$$

$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{\mathrm{thr}}}^{\infty} ds \frac{\hat{K}(s)}{s^2} R_{\mathrm{Had.}}(s), \quad R_{\mathrm{Had.}}(s) = \frac{3s}{4\pi\alpha^2}\sigma\left[e^+e^- \to \text{Hadrons } (+\gamma)\right]$$

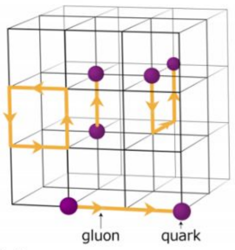


g-2 HVP Lattice Measurement

- Alternatively HVP contribution can be performed on a lattice
- Calculated in three seperate regions:
  - High energy, Low energy, and “Goldilocks”

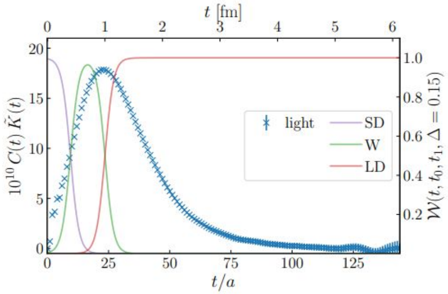
Lattice perscription: Wick rotate ($t \to it$) and discretize ($a \neq 0$) the path integral.

$$\langle O \rangle = \frac{1}{Z_{\mathrm{LOCD}}} \int \mathcal{D}\left[q_f, \bar{q}_f\right] \mathcal{D}[U] e^{-S_F[q_f,\bar{q}_f,U]-S_G[U]} O\left[q_f, \bar{q}_f, U\right]$$



M. Savage,
2015 National Nuclear Physics Summer School

- Quarks on sites, gluons ($U_\mu(n) \equiv \exp(iaG_\mu(n))$) on links.
- Perform path integral:
  - Fermionic: Analytic $\to$ Wick contractions.
  - Bosonic: Markov Chain Monte Carlo (Importance Sampling).
- Observables: $\langle O \rangle(\{a, L, m_q\})$.
- Extrapolate, interpolate, or correct (EFT/pQCD) to continuum, infinite volume, physical point.

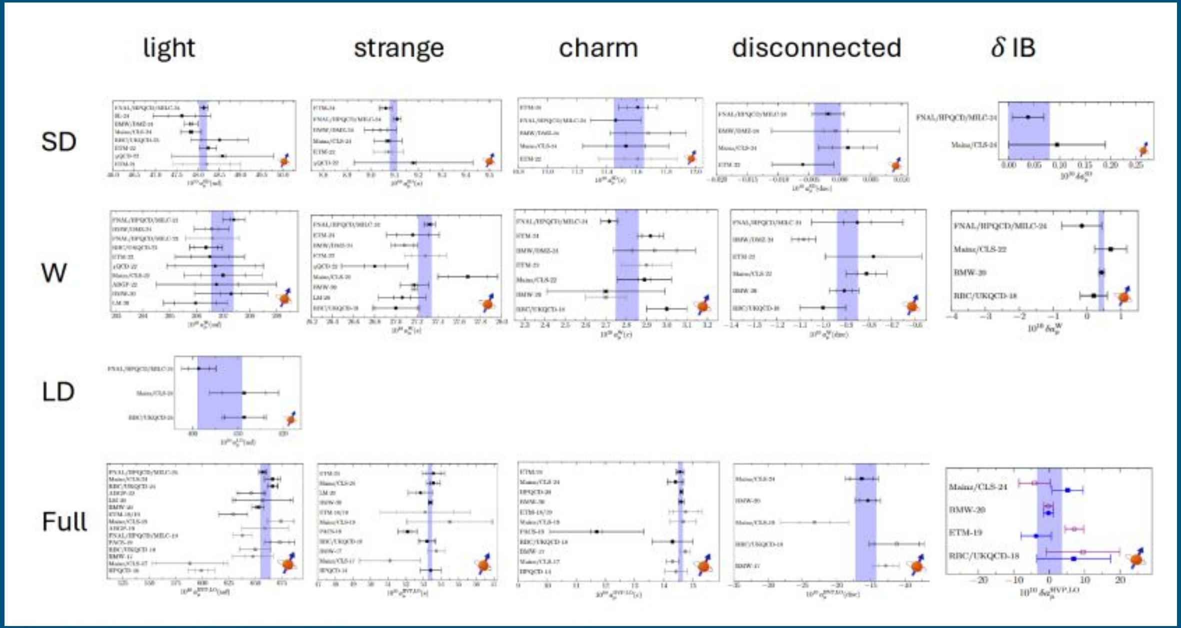


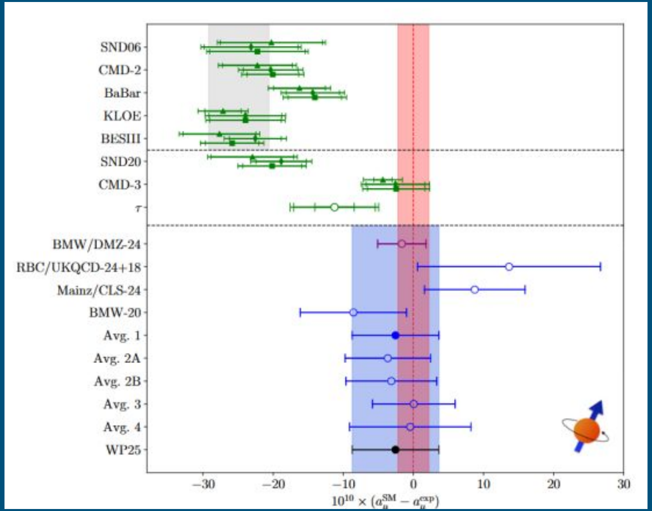
$$a_\mu^{\mathrm{W}} = 4\alpha^2 \int_0^\infty dt\, \tilde{K}(t)\, C(t)\, \mathcal{W}(\mathrm{W}, t)$$

- SD($\sim$ high energy (pQCD)):
  - sensitive to a (lattice spacing).
- LD($\sim$ low energy (χPT)):
  - sensitive to L (lattice length).
- W: *Goldilocks* window.
- $a_\mu^{\mathrm{HVP,LO}} = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$

g-2 Theoretical Measurement

- Calculations were performed by several groups
- All groups in strong agreement with one another





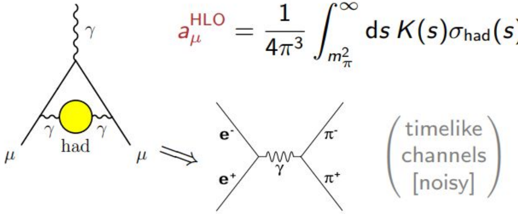
MUonE Experiment

- To help resolve this discrepancy..
- MUonE offers an alternative **spacelike** determination of the HVP contribution
- Measure scattering angles of muons

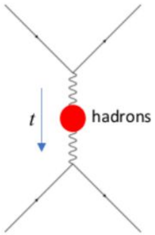
MUonE experiment: **spacelike** determination of a_μ^{HVP}

Instead of the dispersion approach:

$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\mathrm{had}}(s)\,;$$



$\Rightarrow$



we swap the s and x integrations:

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha(0)}{\pi}\int_0^1 \mathrm{d}x\,(1-x)\Delta\alpha_{\mathrm{had}}(t)\,;$$

$$t \equiv t(x) = \frac{x^2 m_\mu^2}{x-1} < 0\,.$$

Task: measure the change (running) of the eff. FS const. $\alpha(0) \simeq 1/137 \to \alpha(t)$ in a single scattering process $\mu^+ + e^- \to \mu^+ + e^-$:

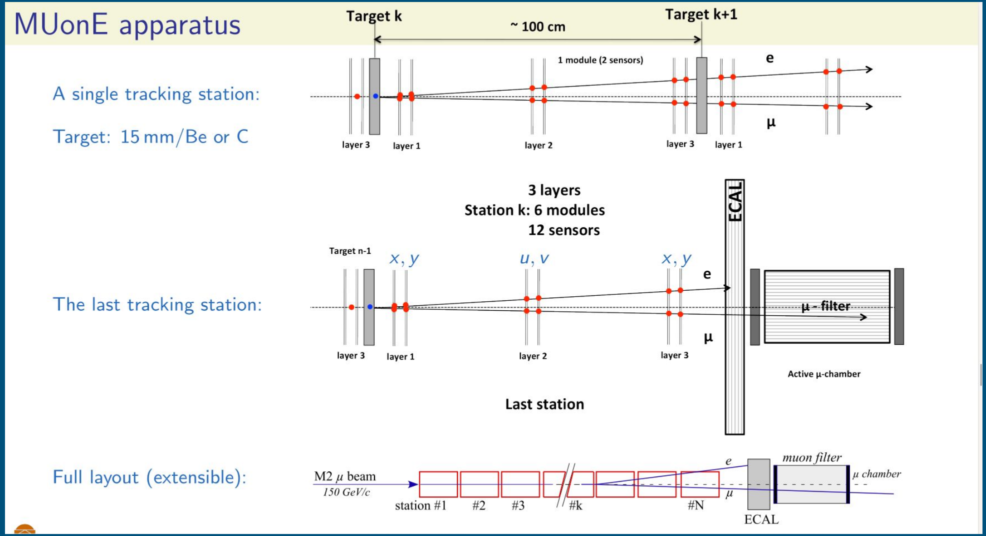
known extremely well

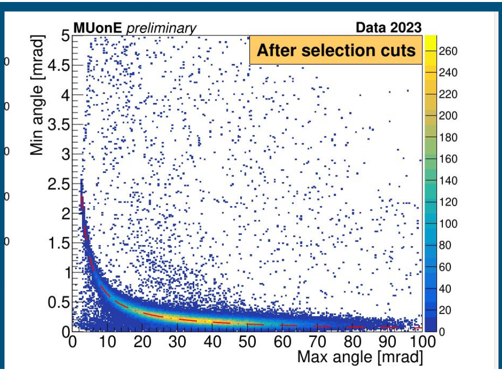
$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}, \quad \text{with} \quad \Delta\alpha = \Delta\alpha_{\mathrm{lepton}} + \Delta\alpha_{\mathrm{hadron}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{weak}}\,.$$

The sole integral is over a single well-behaved, smooth function.

MUonE Experiment: Detector

- ~40 tracking stations combined with an electromagnetic calorimeter and a muon filter
- Angular resolution (muons) of ~ 0.04-5 mrad
- Preliminary data with 2 stations showed proof of principle
- Physics run in 2026





Muon g-2

Experimental principle

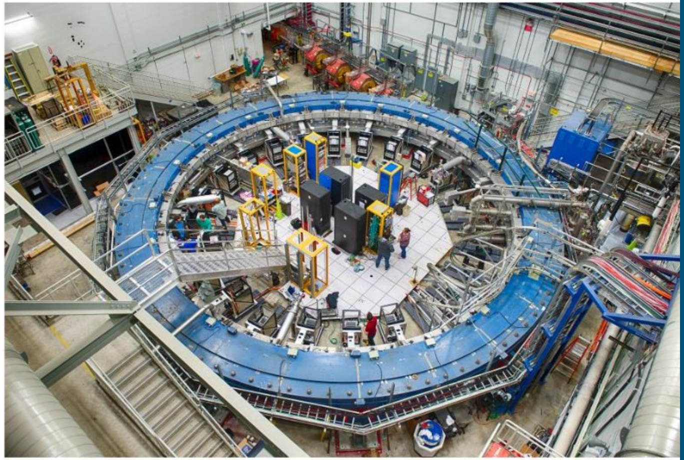
- Storing anti-polarized positive muons in a *magnetic storage ring* using electrostatic quadrupoles
  - Momentum ***rotates*** w.r.t. storage ring
  - Spin ***precesses*** w.r.t. ring because $g > 2$
- Difference in frequencies proportional to magnetic moment

$$\omega_s - \omega_c = \omega_a \propto \left(\frac{g-2}{2}\right)\frac{eB}{m} = \frac{a_\mu eB}{m}$$

We measure ω_a, B

This talk!

Next talk by David Kessler

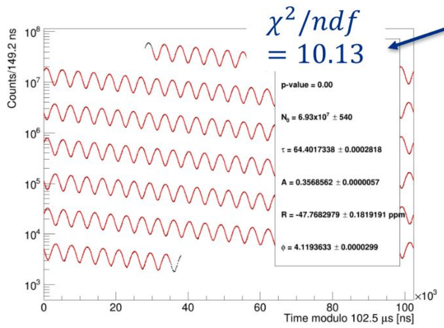


Via Reidar Hahn

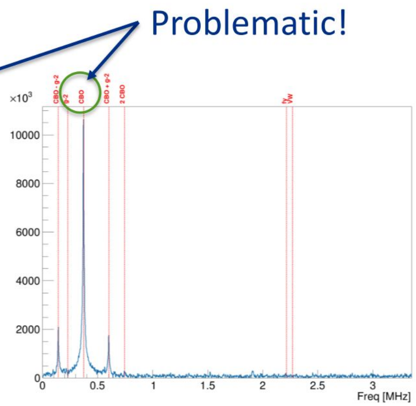
Muon g-2

- The number of highest energy e+s oscillates – via parity violation!
- Fit yields w_a
- Need many corrections!:
  - Detector gain
  - Coherent betatron motion

How good is the fit?



Simple fit – only muon decay and g-2 oscillations accounted for, fit can be improved



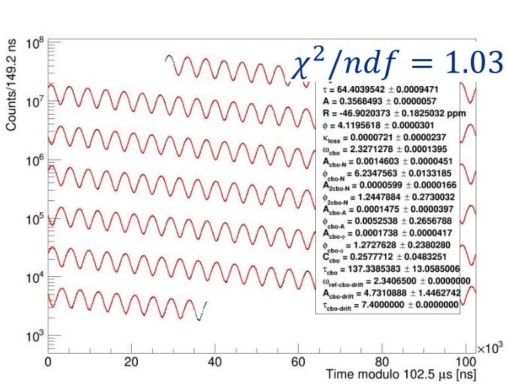
FFT of residuals highlights unaccounted for beam dynamics

$$f(t) = N_0 e^{-\frac{t}{\tau_\mu}}(1 + A\cos(\omega_a t - \phi))$$

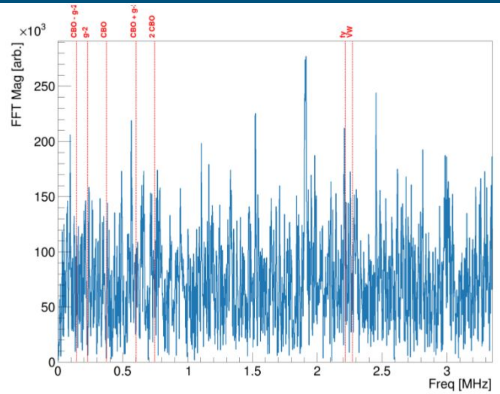
- Basic 5-parameter fit
- Captures two physical processes
  - Muon decay
  - g-2 oscillation

Muon g-2

- 7 different and independent analysis groups fit for beam dynamic corrections, muon loses, etc.
- Dramatically suppress residuals



Full fit – muon decay, g-2 oscillations, muon losses, beam dynamics accounted for

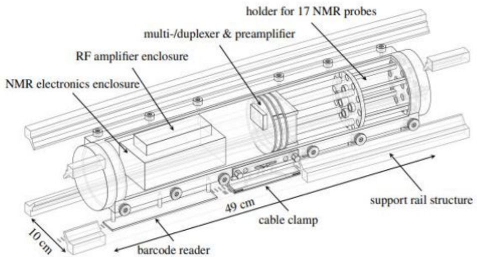


Much better residuals – no strong stand-outs for beam dynamics / unaccounted for physical effects

Muon g-2 Magnetic Field

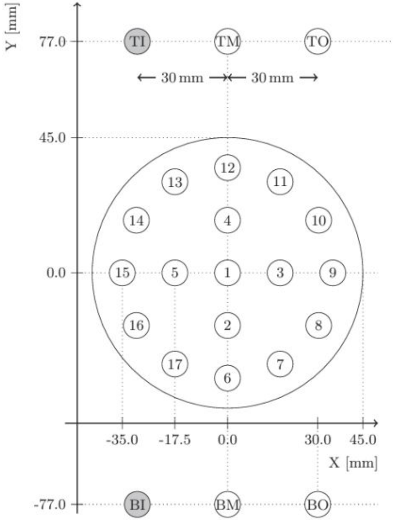
Measurement Overview

- Trolley Probes and Fixed Probes:



17 **trolley probes** map the field along the muon beam path.

378+ **fixed probes** track changes in the field while muons are running.



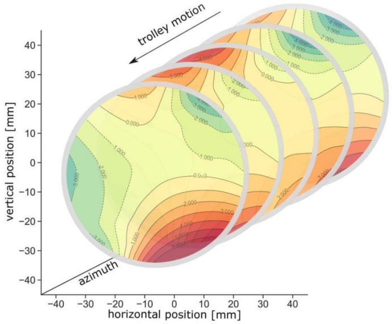
Relative positions of trolley and fixed probes.

Muon g-2 Magnetic Field

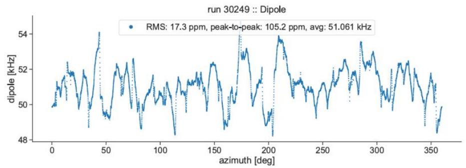
- Discussed the trolley data, calibration NMRs, calibration of the calibration NMRs
- Interpolation between the fixed probes and the trolley, etc.
- Reached 56 ppb uncertainty!
- Overall systematic of 76 ppb

Trolley Runs

Trolley runs were performed every ~3 days, with muon beam off.



Trolley readings per slice are fit to 2D multipole expansions.



Each trolley run covers the circumference of the storage ring.

Run-4/5/6 Uncertainties Table

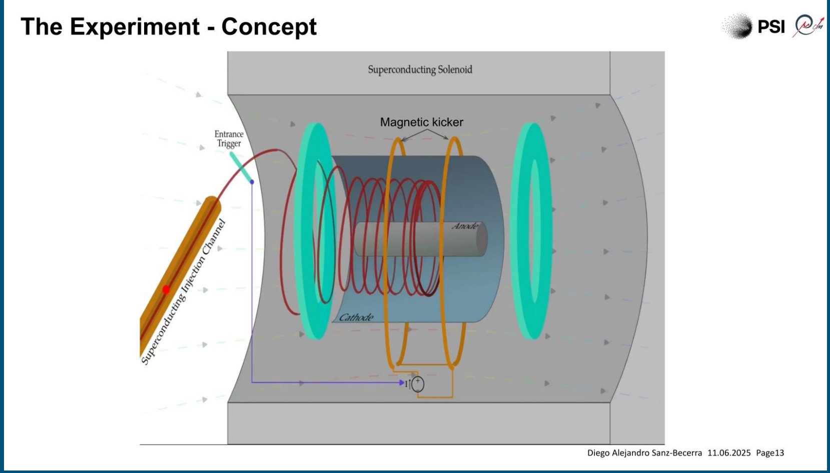
Quantity		Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		$\cdots$	114
ω_a^m (systematic)		$\cdots$	30
C_e	Electric Field	347	27
C_p	Pitch	175	9
C_{pa}	Phase Acceptance	-33	15
C_{dd}	Differential Decay	26	27
C_{ml}	Muon Loss	0	2
$\langle \omega_p' \times M \rangle$ (mapping, tracking)		$\cdots$	34
$\langle \omega_p' \times M \rangle$ (calibration)		$\cdots$	34
B_k	Transient Kicker	-37	22
B_q	Transient ESQ	-21	20
μ_p'/μ_B		$\cdots$	4
m_μ/m_e		$\cdots$	22
Total systematic for $\mathcal{R}_\mu'$		$\cdots$	76
Total for a_μ		572	139

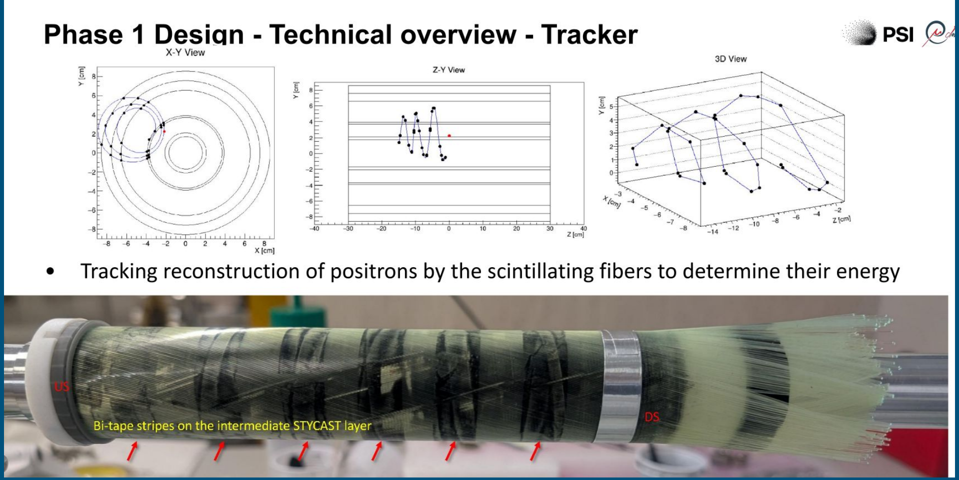
Field uncertainty total: **56 ppb**.

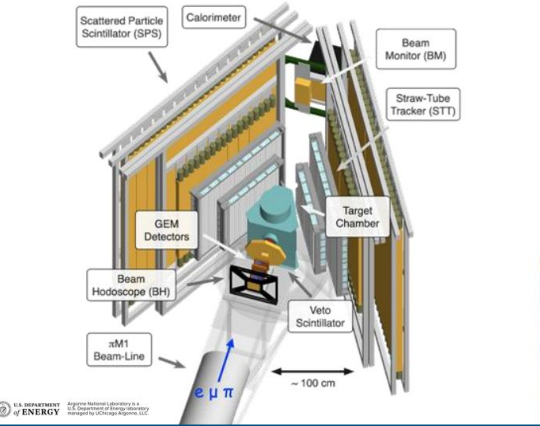
Target Achieved!

Muon EDM

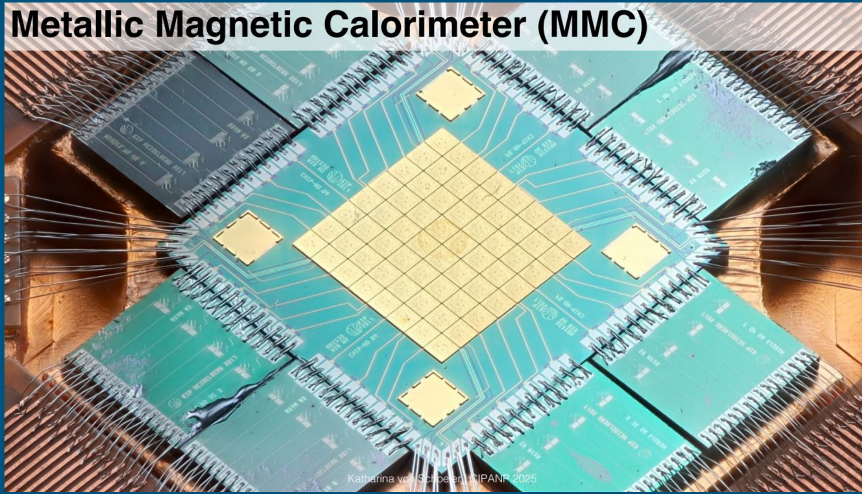
- Electric field set to "freeze" the muon's spin
- Detector measures the decay positrons on the two trackers
- Asymmetry on the two trackers yields the EDM
- Prototypes of trackers







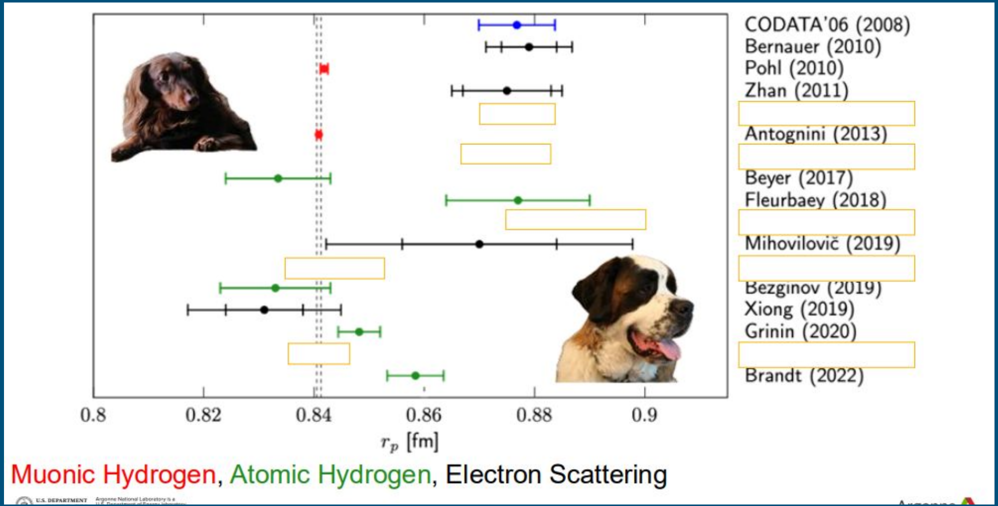
Muon Scattering/ Muonic Atoms



The Muon Proton Scattering Experiment (MUSE)

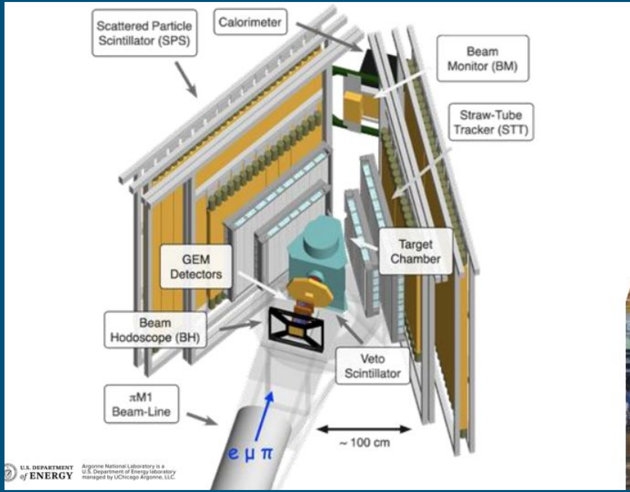
- Measure the proton's charge radius:
  - Discrepancy between recent measurements
- Mott Cross Section: point scattering of structureless spin-½ particles
  - Cross section adding a form factor
- MUSE will measure e+ p, μ+ p, e- p, μ- p elastic scattering

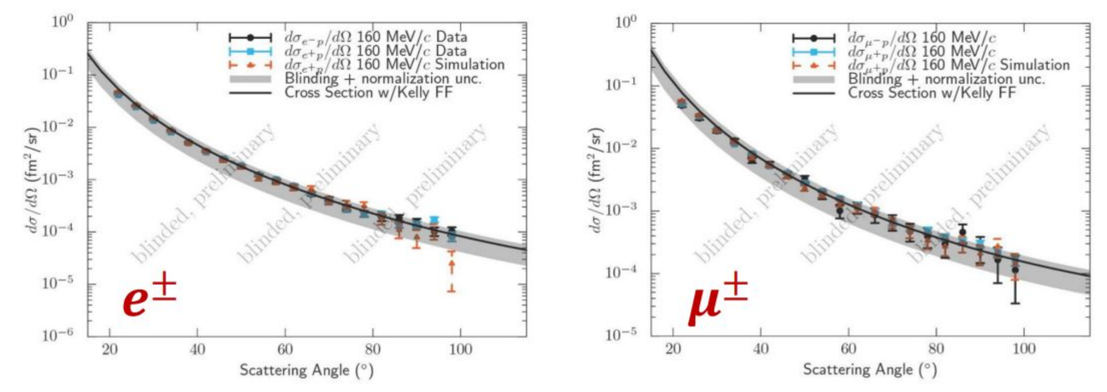
$$\langle r \rangle^2 \equiv 6 \frac{dG_E}{dQ^2}\bigg|_{Q^2=0}$$



The Muon Proton Scattering Experiment (MUSE)

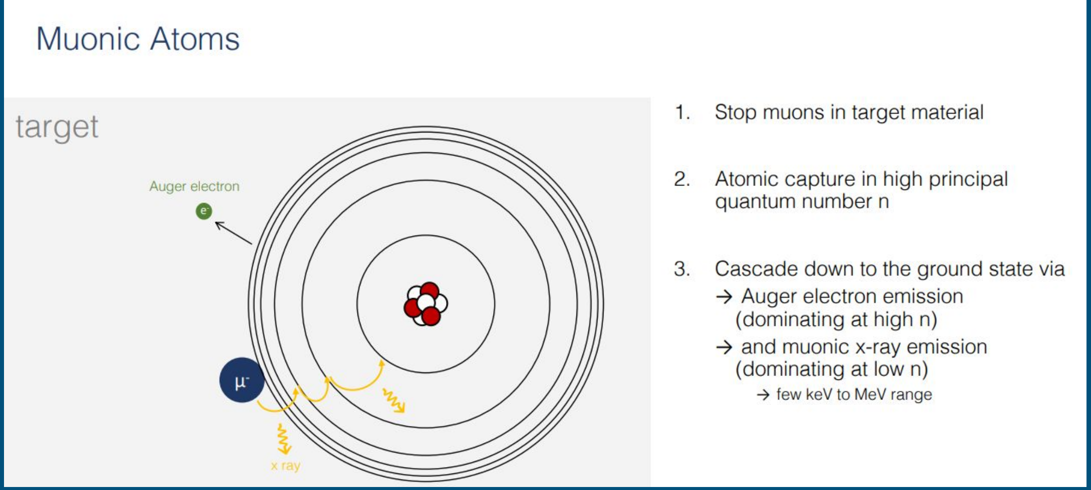
- Most of the data is already recorded..
- Waiting to unblind all of the data

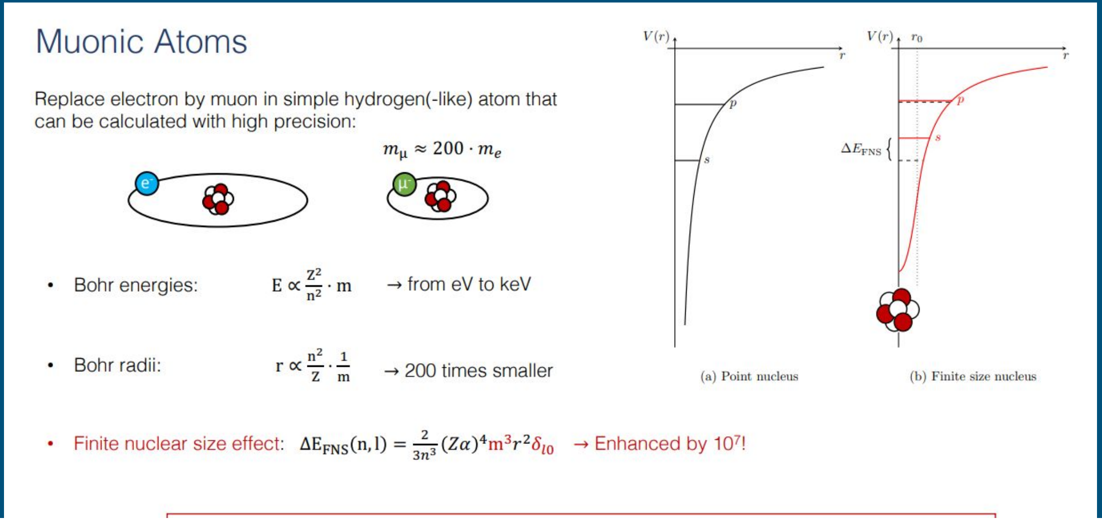




QUARTET Collaboration

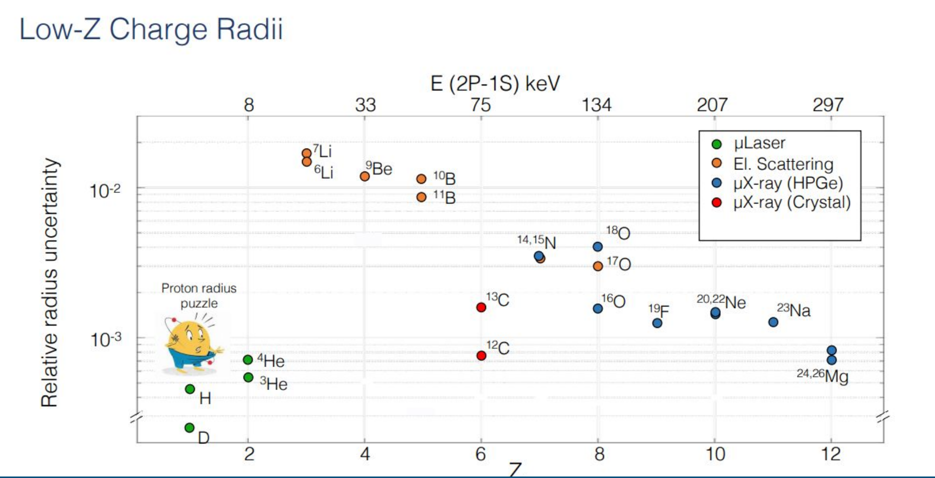
- Muonic atoms formed by stopping muons in target
- Muon cascades to ground state
  - Can emit x-rays
- Use x-rays to observe 2p -> 1s transition
- Measure charge radius

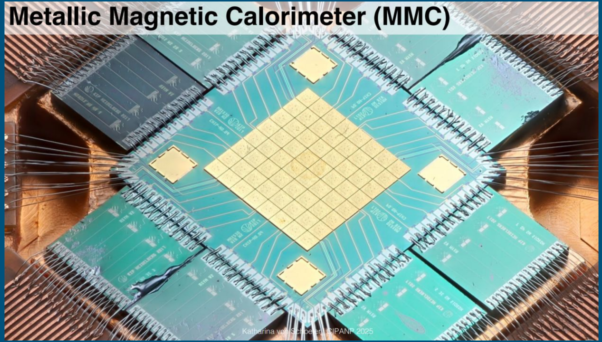


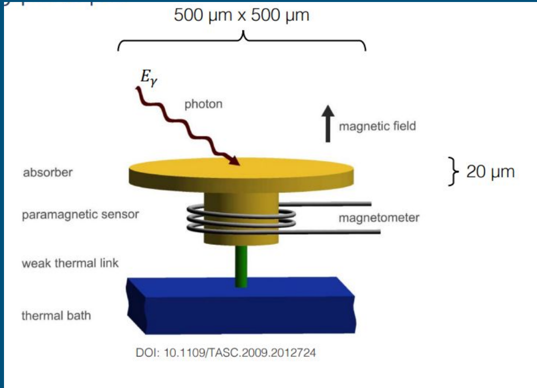


QUARTET Collaboration

- Many targets will be tested
- X-rays measured using metallic magnetic calorimeter

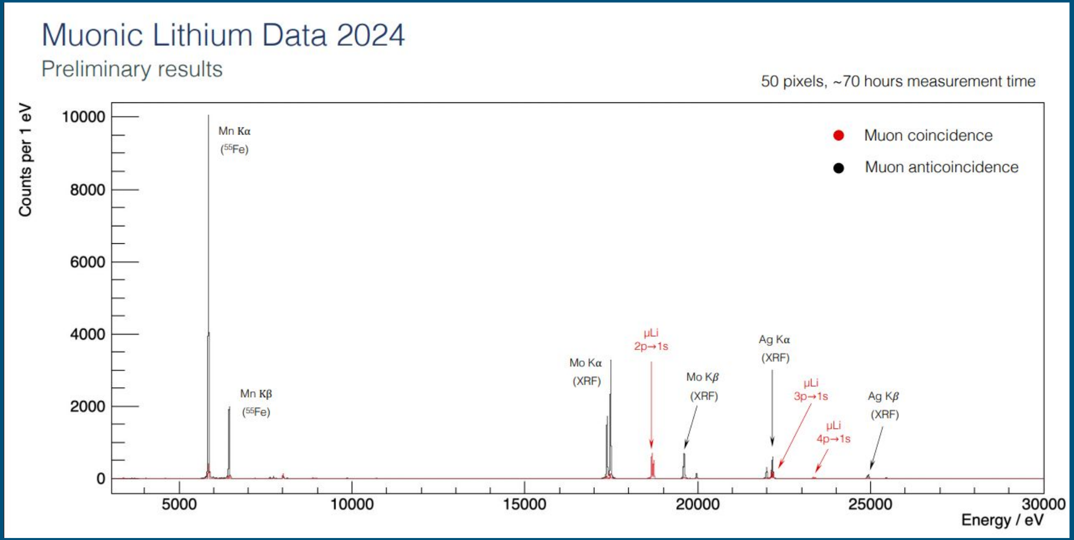


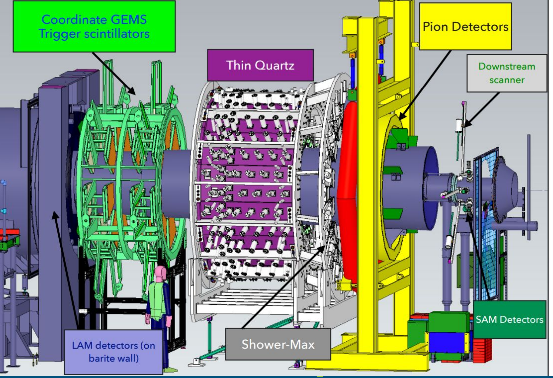


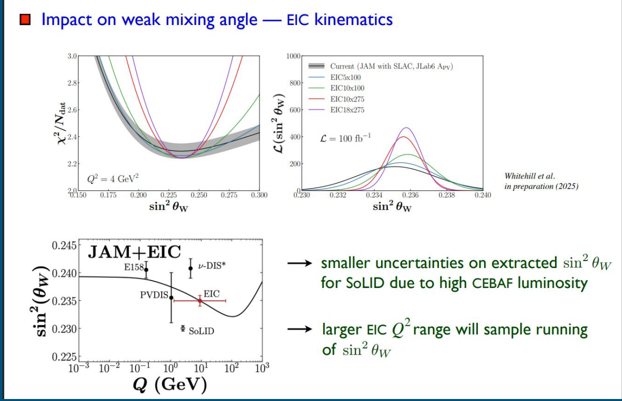


QUARTET Collaboration

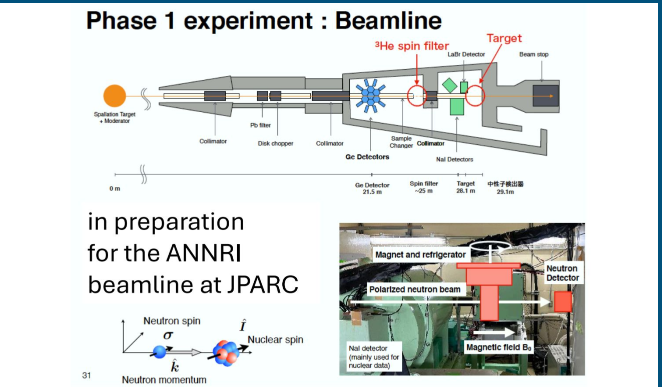
- Data with Lithium (2024)
- Current uncertainty in the radius >100% from 1968
- Next plan to measure oxygen

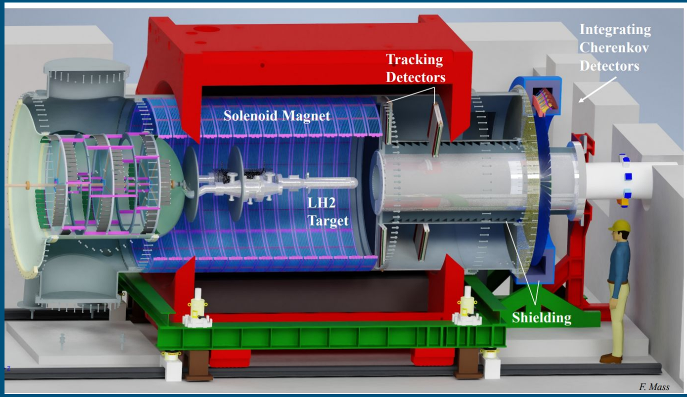






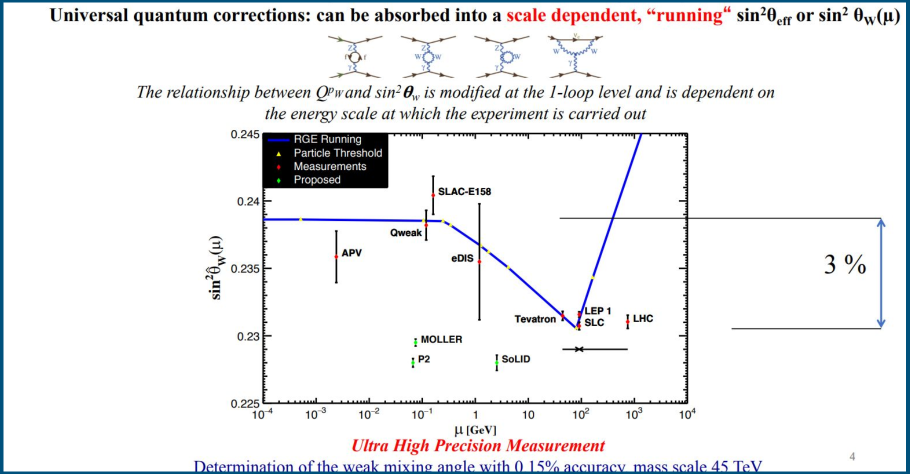
Parity Violation
Weak-Mixing Angle

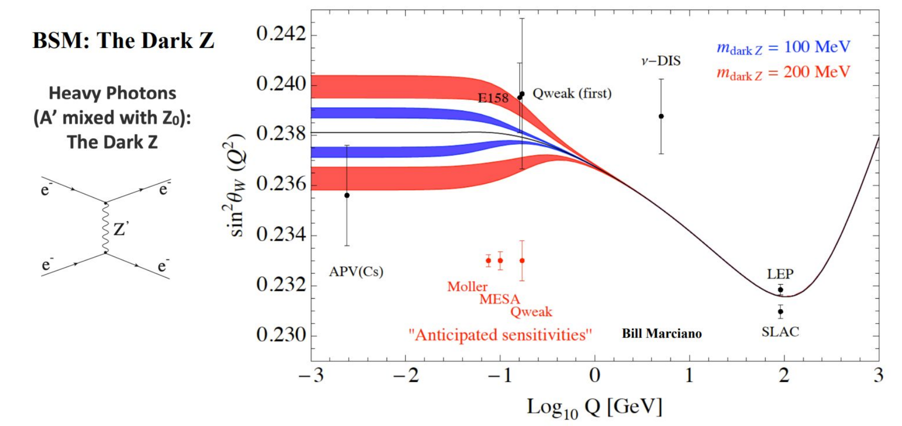




Parity Violation: Weak Mixing Angle

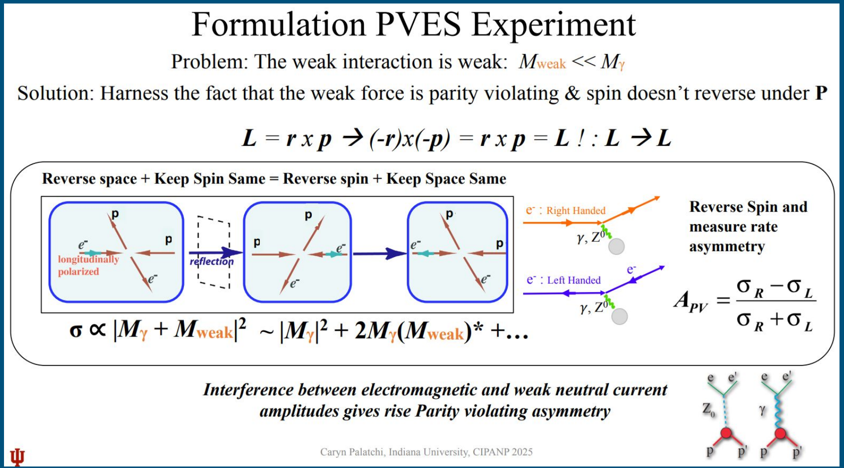
- Talks on several parity violation experiments
- Examples: Moller and P2 will both measure weak mixing angle at low Q < 0.1 GeV
- Deviations from the SM prediction would indicate BSM physics

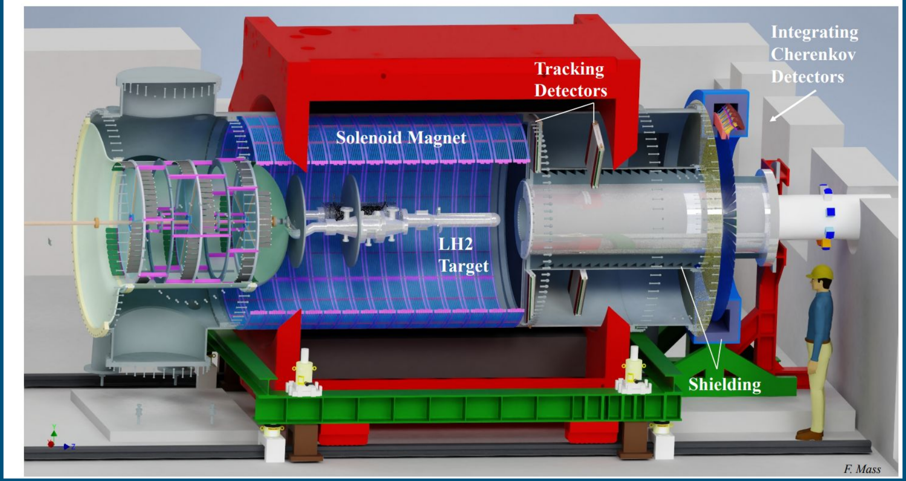




P2 Experiment

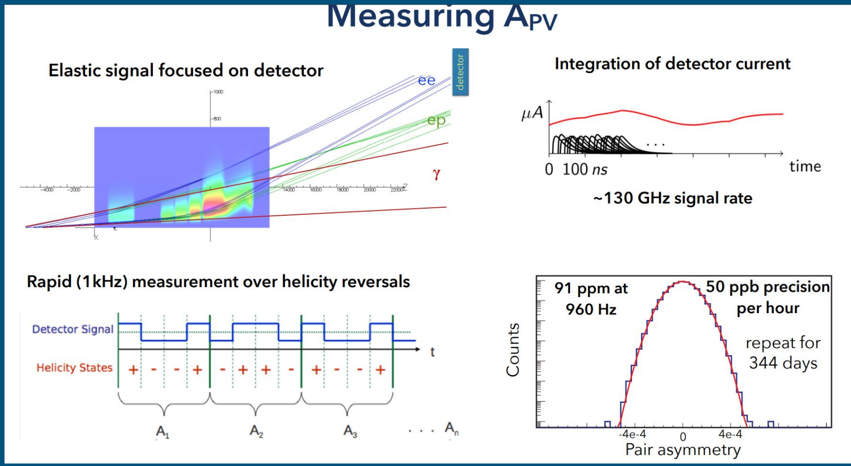
- Goal is a fractional precision of 0.15%..on par with higher energy weak mixing angle measurements
- Hit fixed protons with right and left polarized electrons
- Comparing right and left handed scattering rate
- Liquid hydrogen target..
- Cherenkov detector -> silica bars
- MuPix tracking detector
- Plans to start in 2026

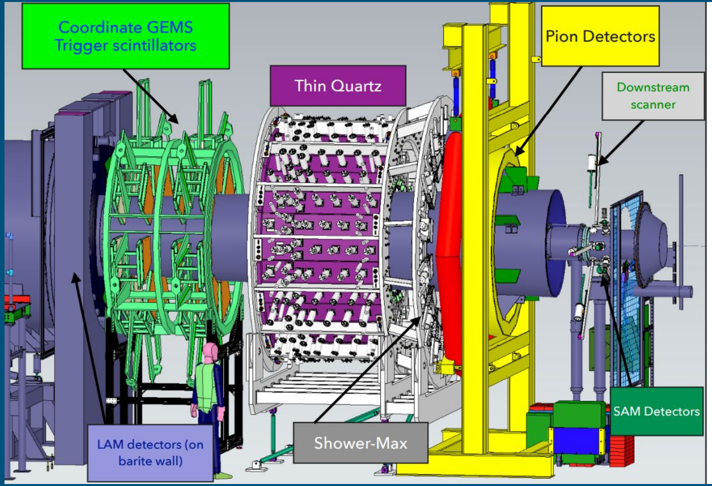




Moller Experiment

- Alternatively, Moller will use electron-electron collisions to measure the weak mixing angle
- Fractional precision of ~0.1%
- Switch between polarizations rapidly at 1kHz
- Looking for a difference in scattering angle as the polarity is switched
- Physics expected in 2027






Thank you!!