Experimental Measurements of the Muon g-2 & Searches for Charged Lepton Flavor Violation using Muons

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25th International Workshop on Neutrinos from Accelerators (NuFact)

19th Sept. 2024

Argonne National Laboratory

Caltech

Muons as probes for New Physics

How can muons help us explore New Physics?

- Muons as Probes of New Physics
- Muon g-2
- Muon CLFV Searches: Motivations
- Muon CLFV Searches: Design, Status
- What happens next?

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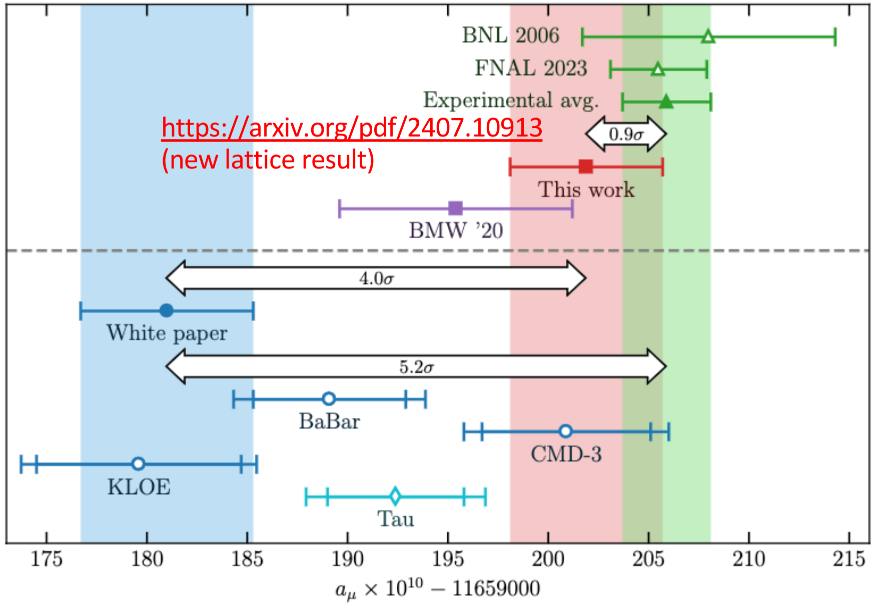
Muons as Probes for New Physics

- Muons have been an invaluable probe of the Standard Model.
- Precision muon searches and searches for muon/electron flavor transitions are indirect probes of new physics:

Muon g-2 anomaly



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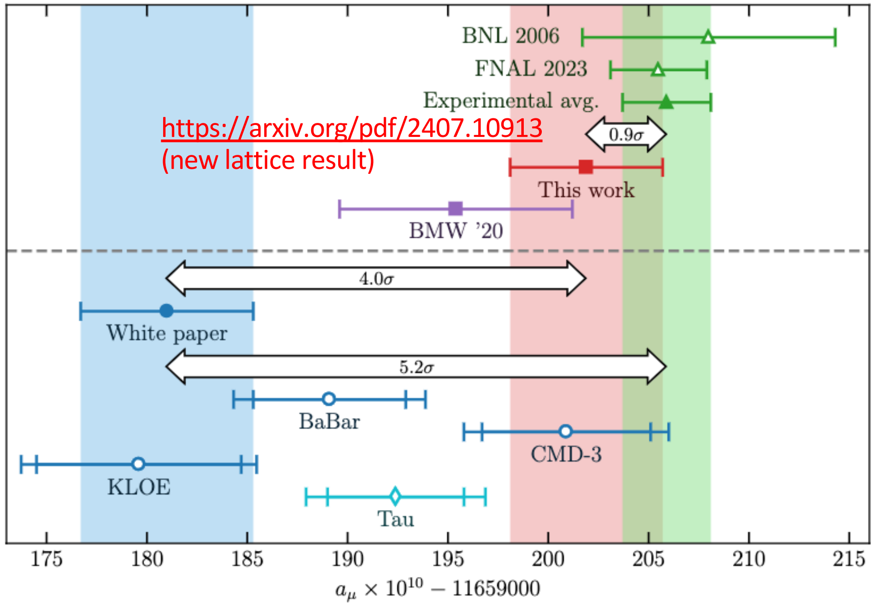

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In general:

- *Do not decay hadronically → clean, well-understood backgrounds.*
- *Lifetime ~2.2 μs → can be stored efficiently before decay, decay easy to measure.*

Plus:

- *Mass scaling could mean 10^4 enhancement in coupling to BSM over electrons.*

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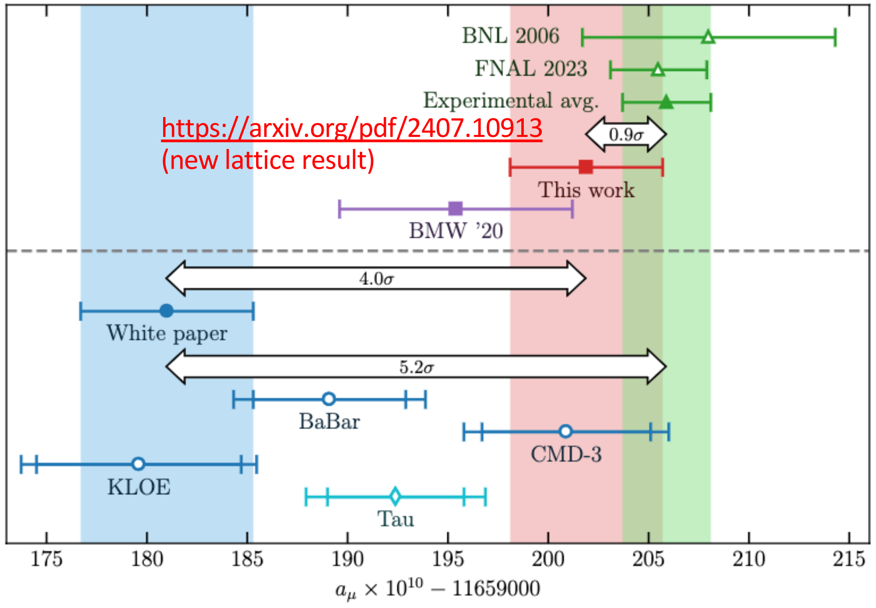

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Can create high-intensity, clean, background-free, experimental environment to probe new physics.

Many experimental searches looking for new physics in the muon sector or ways to elucidate the apparent g-2 discrepancy will come online this decade…..

…. the 2020's are proving to be a very exciting time for muon physics!

Muon g-2

Is the g-2 measurement an indication of new physics?

Muons as Probes of New Physics

Muon g-2

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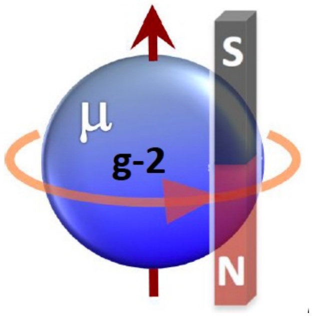
What happens next?

Muon g-2

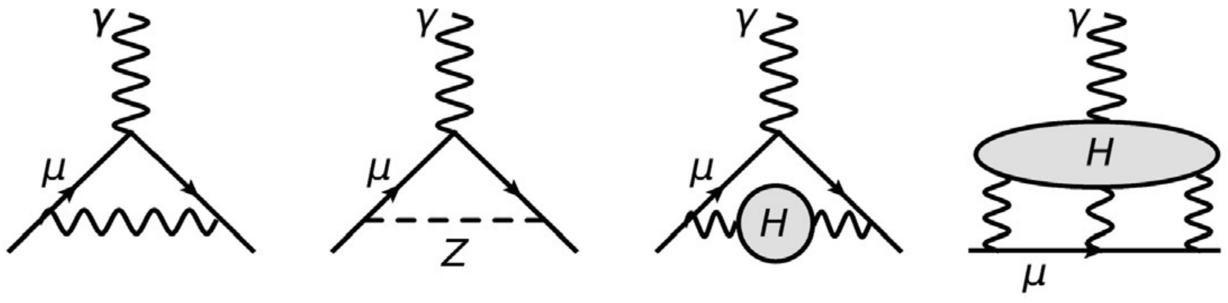
Magnetic moment and spin



$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

corrections to g called the anomalous magnetic moment:

$$a_\mu = \frac{g-2}{2}, \text{g} = 2 \text{ at tree level}$$

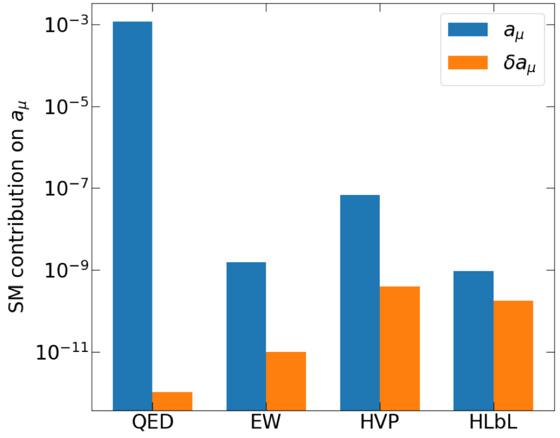


QED **Electroweak** **Hadronic Vacuum Polarization** **Hadronic Light-by-light**

- Relativistic quantum field theory leads to small radiative corrections.
- g-2 can be measured and calculated to high-precision (sub-ppm).
- It has become a powerful discriminant for BSM physics.

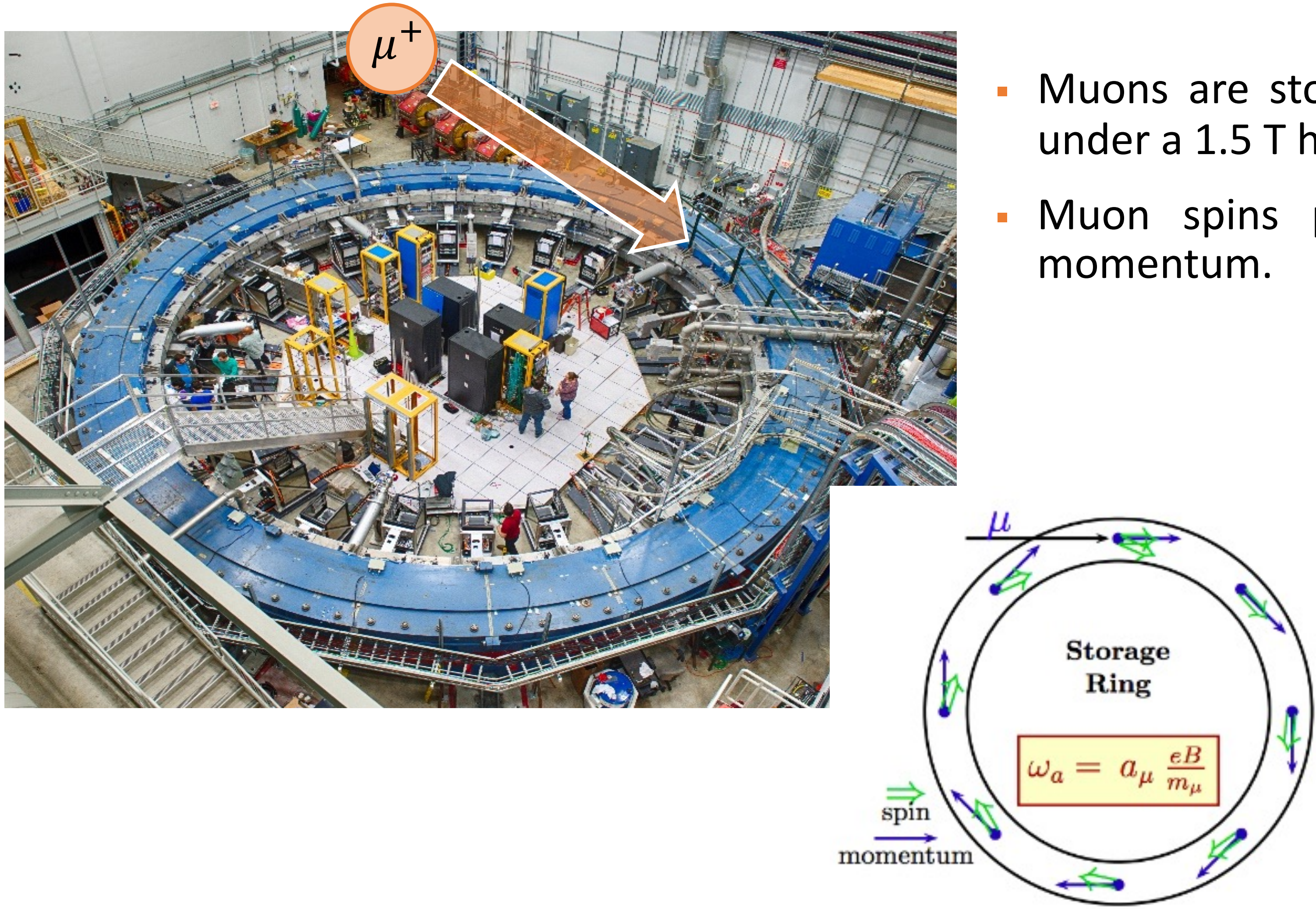
$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\ LO} + a_\mu^{\rm HVP,\ NLO} + a_\mu^{\rm HVP,\ NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\ NLO}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Theory Initiative White Paper
T. Aoyama et al. Phys. Rept. **887** (2020)

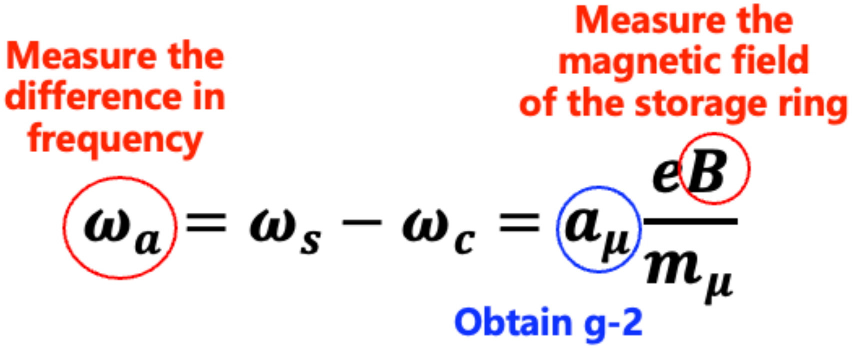


See Talk by O. Kim

Muon g-2 Experiment at FNAL



- Muons are stored in the storage ring (~15 m diameter) under a 1.5 T homogeneous magnetic field.
- Muon spins precess at a rate: ω_a with respect to momentum.



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

$p_{\text{magic}} \simeq 3.09 \text{ GeV/c}$

ω_s= spin precession frequency;
ω_c= cyclotron frequency.

Status of Experiment

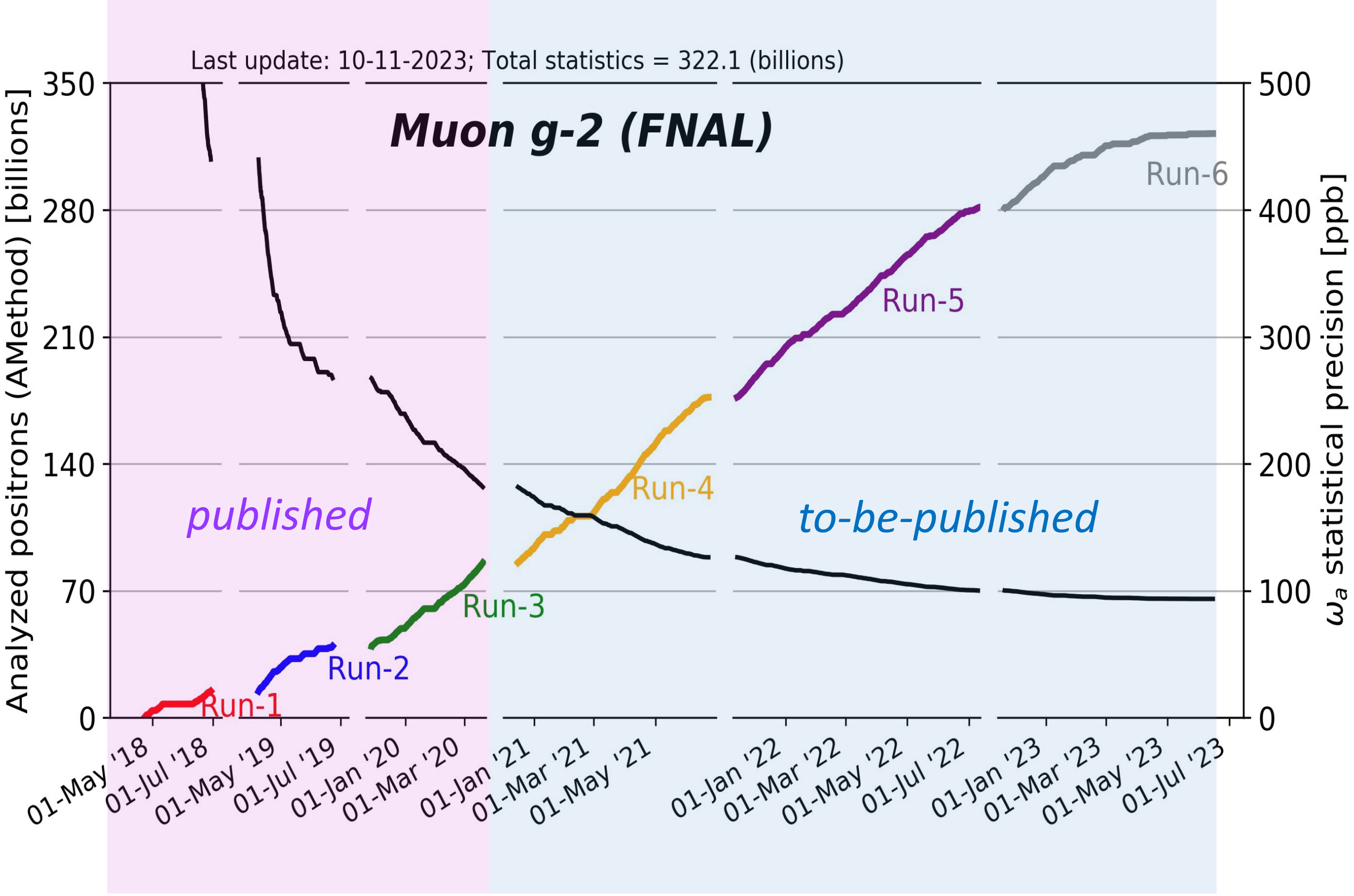
Apr 2021: Run-1 Result (2018 data):

*PRL **126**, 141801 (2021)*

Aug 2023: Run-2/3 Result (2019-20 data):

*PRL **131**, 161802 (2023)*

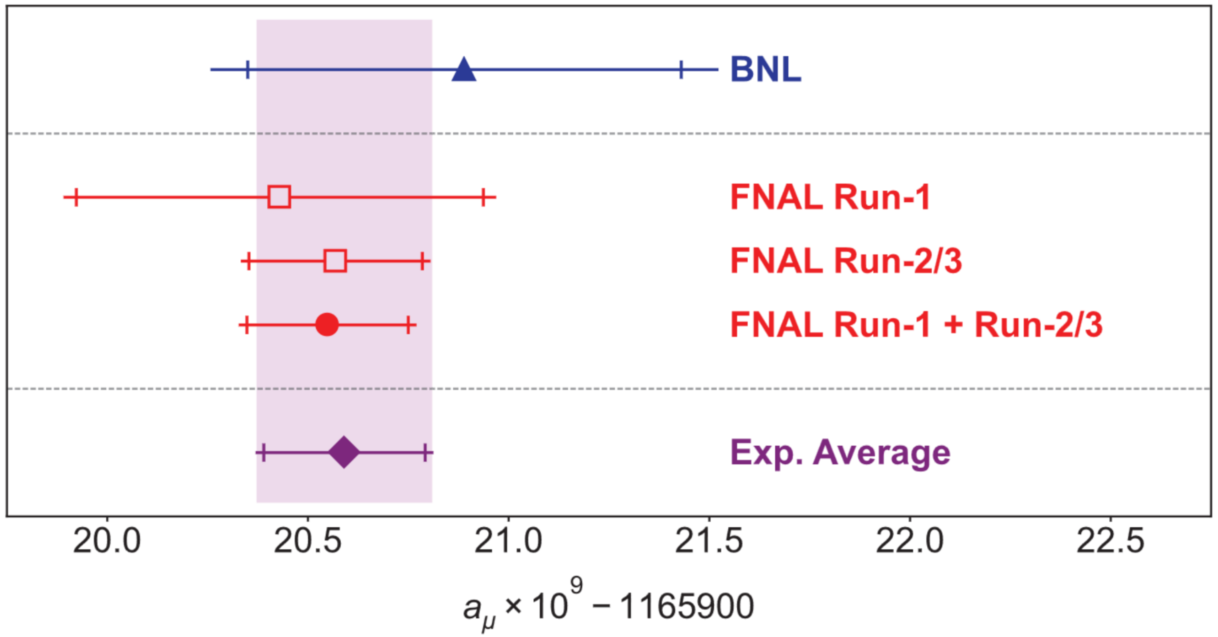
Expected ~ 2025: Run-4/5/6 Result (2021-23 data)



First (2021) and Second (2023) Results

*PRL **126**, 141801 (2021)*
*PRL **131**, 161802 (2023)*

- Run-1 result (2018 data) and Run-2/3 result (2019/2020 data) were consistent.
- **Both renewed the most precise measurement of muon magnetic anomaly.**



$$a_\mu(\mathbf{Exp}) = \mathbf{0.00\,116\,592\,059\,(22)}\ [\mathbf{190\ ppb}]$$

See Talk by O. Kim

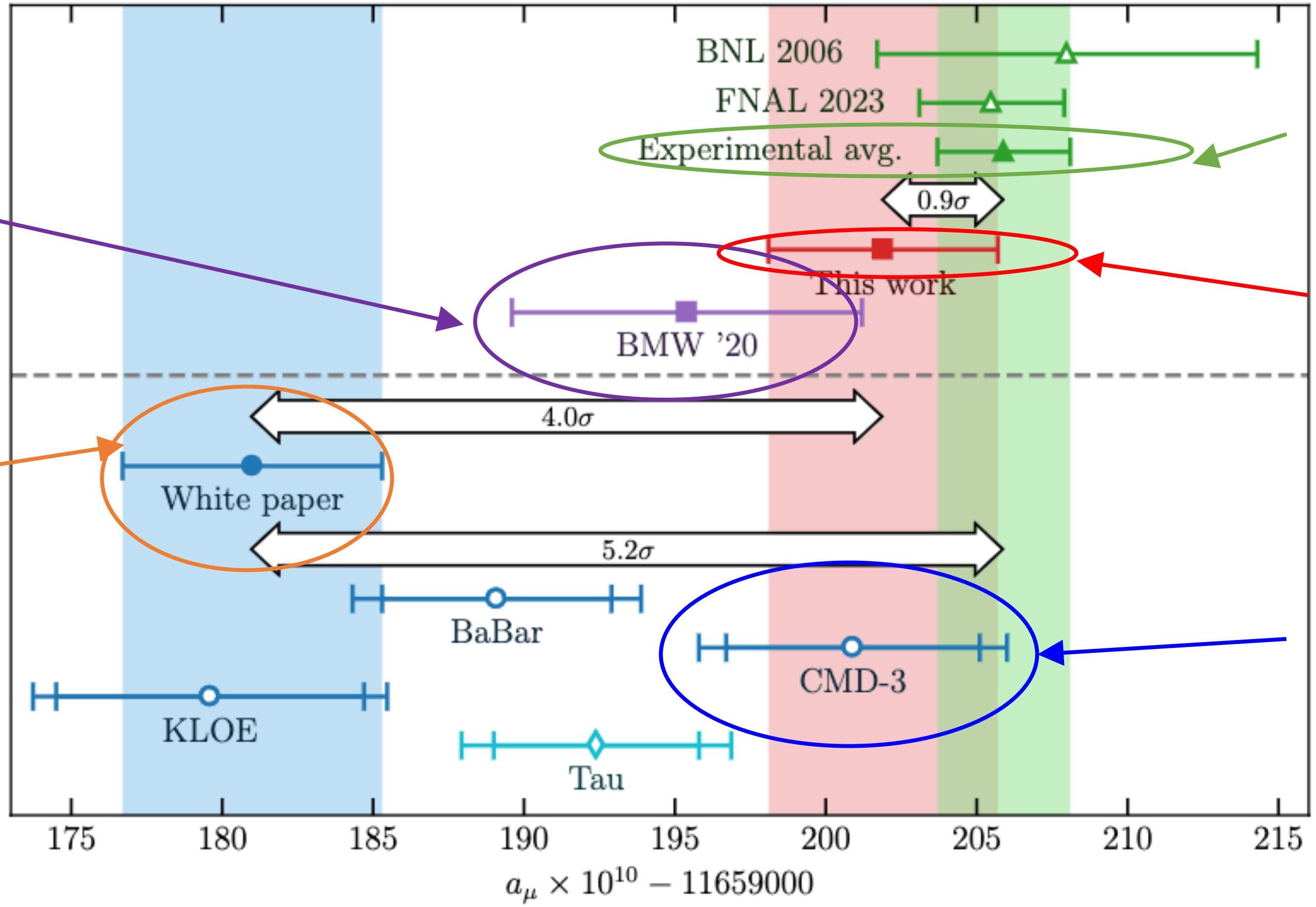
Experiment vs. Theory (SM)

Theory predictions from different approaches (for $a_\mu(\mathrm{HVP})$, hadronic vacuum polarization) **don't agree!**

Ab-initio lattice QCD calculation favors the measured value much better than the dispersive method.

Muon $g-2$ Theory Initiative compiled the SM estimation primarily using the dispersive method for the hadronic vacuum polarization (HVP).

It uses 20+ years of e^+e^- data (contribution dominated by $e^+e^- \to \pi^+\pi^-$) from various collaborations (BaBar, KLOE, SND, BESIII, etc.)



$> 5\sigma$ significance by comparing the experiment average and 2020 WP, but several other results sit closer.

New result
https://arxiv.org/pdf/2407.10913 (2024)

New dispersive approach result from CMD-3 has a strong tension with the other dispersive method results (even with the previous themselves: CMD-2).

See g-2 theory talk for more discussion!

Experiment vs. Theory (SM)

Several on going efforts: https://muon-gm2-theory.illinois.edu/

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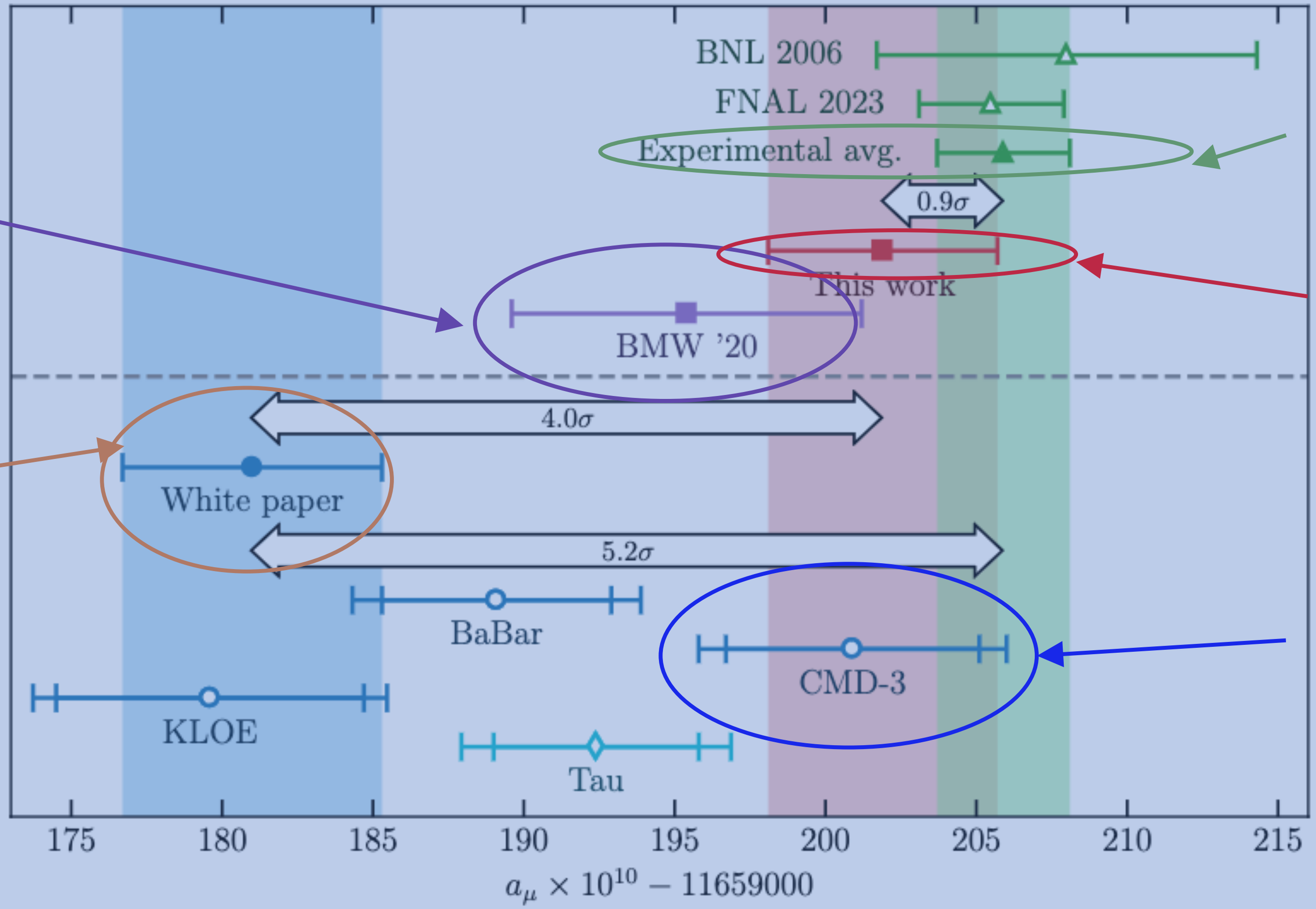

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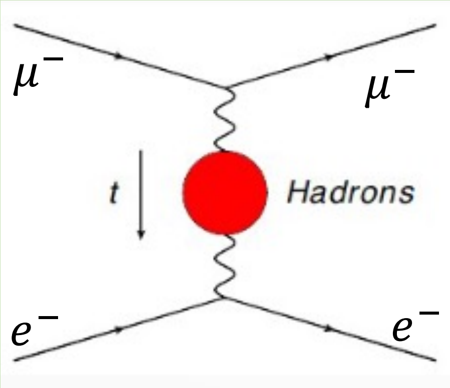
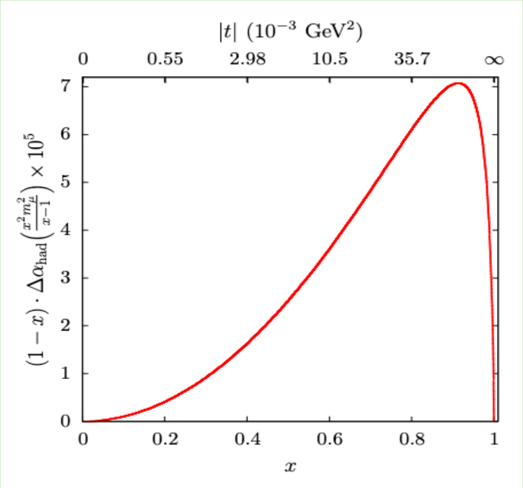
What’s next?: MuonE Experiment

- **MuonE @ CERN (Eur. Phys. J. C (2017) 77:139):** will make independent determination of hadronic leading order contribution to a$_{\mu}$.
- Measure the hadronic contribution using space-like elastic scattering of 150GeV μ beam on atomic electrons.

$$a_{\mu}^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

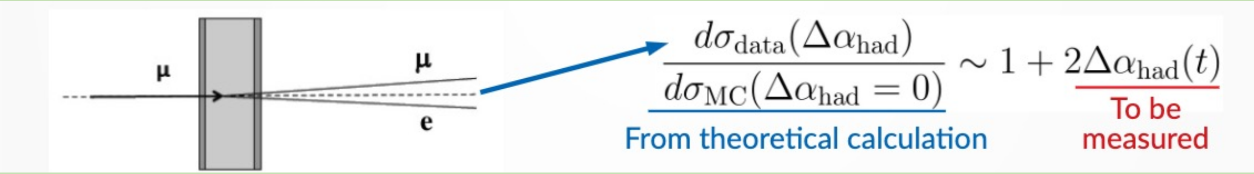
$$t(x) = \frac{x^2 m_{\mu}^2}{x-1} < 0$$





Based on the measurement of Δα$_{\rm had}$(t): hadronic contribution to the running of the QED coupling constant α(t).

Extract Δα$_{\rm had}$(t) from shape of differential cross-section.



$$\underline{\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)}} \sim 1 + \underline{2\Delta\alpha_{\rm had}(t)}$$

From theoretical calculation

To be measured

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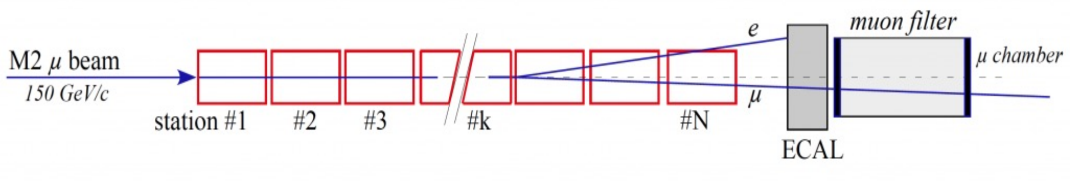
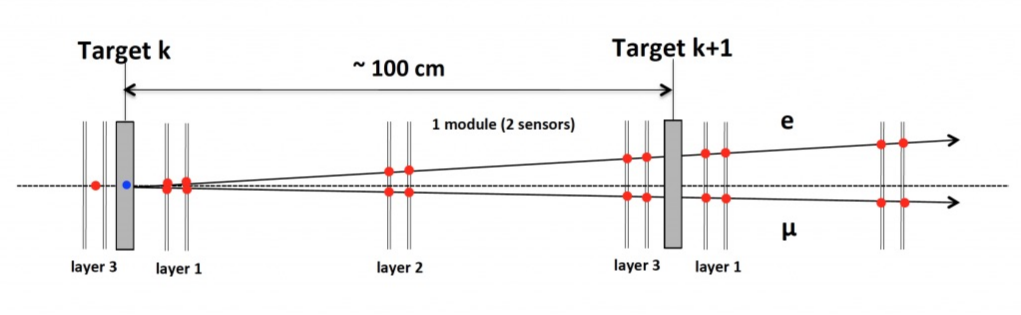
- Measure the hadronic contribution using elastic scattering μ − e with 150GeV Muon beam.

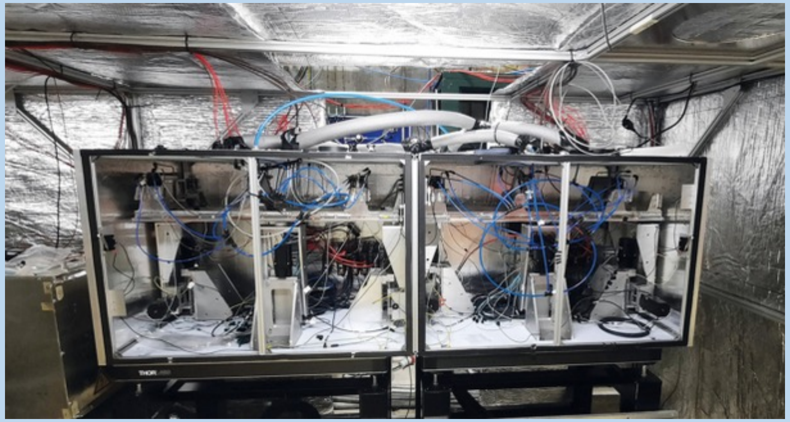
40 identical stations made of thin Be target interspersed Si trackers.

Calorimeter helps with final PID.





Test beam: 2023, pic from CERN Courier



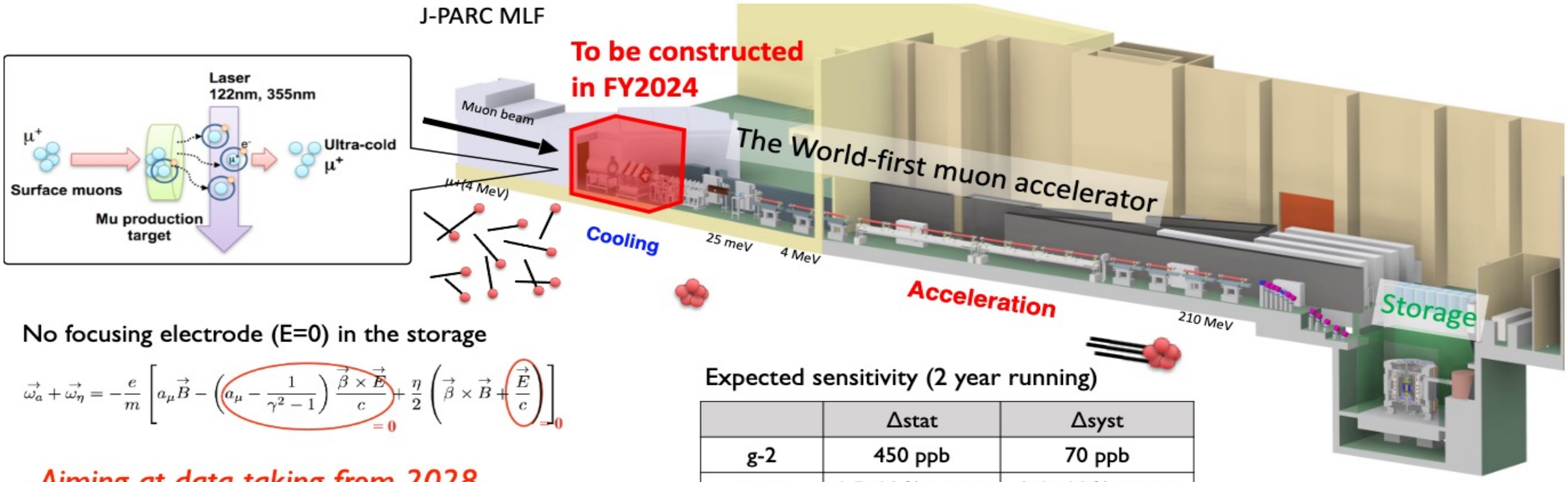
Goal: 3.5 × 10^{12} elastic scattering events with an electron energy larger than 1 GeV, in 3 years. Aim to achieve a stat error of 0.3% and 10 ppm sys. error. comparable with the results from the time-like dispersive approach and the lattice simulations.

What’s next?: Alternative g-2 measurement

Alongside further results from Fermilab there are complementary experimental efforts:

See Talk by K. Suzuki

- **J-PARC g-2 experiment:** provide complementary approach to measure a at the J-PARC facility
    - low emittance muon beam by cooling and re-acceleration:
        - no strong focusing & good injection efficiency (x10)
        - much more compact storage magnet



No focusing electrode (E=0) in the storage

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{=0} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \underbrace{\frac{\vec{E}}{c}}_{=0}\right)\right]$$

Expected sensitivity (2 year running)

	Δstat	Δsyst
g-2	450 ppb	70 ppb
EDM	1.5×10^{-21} e · cm	0.4×10^{-21} e · cm

Aiming at data taking from 2028.

W… measurement

Al… …mental efforts:

- … a at the J-PARC facility

Progress

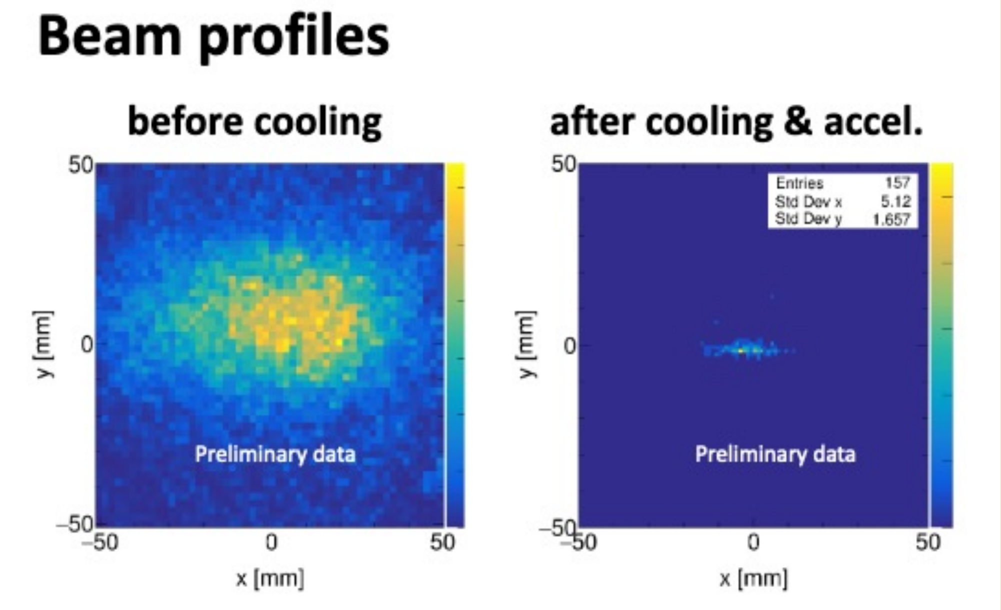
A communication resource from the **world's particle physics laboratories.**

World's first cooling and acceleration of muon

A muon is an elementary particle like an electron. Muons were first discovered in 1936 as cosmic rays falling from the sky. Natural muons originated from cosmic rays have been used to see through the interior of large and/or thick objects, such as pyramids. Presently, muons can be produced in much higher intensity using accelerators for the use of various research and applications.

https://www.interactions.org

World first The experimental set up for muon cooling and acceleration at J-PARC. A beam of antimatter muons enters the apparatus from the right. Credit: J-PARC


Beam profiles

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Muons CLFV Searches: Motivations

Why search for CLFV in the muon sector?

Muons as Probes of New Physics

Muon g-2

Muon CLFV Searches: Motivations

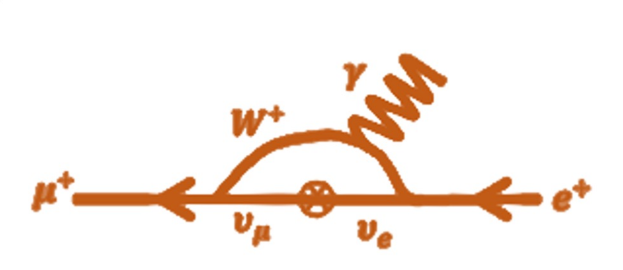
Muon CLFV Searches: Design, Status

What happens next?

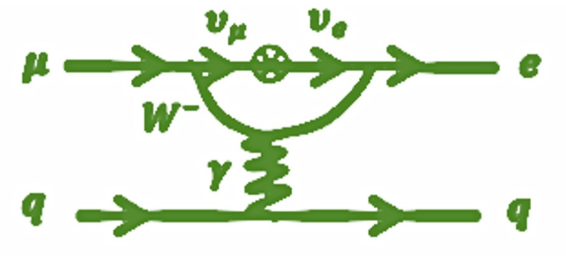
Charged Lepton Flavor Violation (CLFV)

- Adding neutral lepton flavor violation to the Standard Model, introduces CLFV at loop level, mediated by W bosons:

$\mu^+ \rightarrow e^+\gamma$



$\mu^- N \rightarrow e^- N$



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

No outgoing neutrinos!

- Rates heavily suppressed by GIM suppression and are far below any conceivable experiment could measure:

$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{1}{4}\right) sin^2 2\theta_{13} sin^2\theta_{23} \left|\frac{\Delta m^2_{13}}{M^2_W}\right|^2$$

$$B(\mu \rightarrow e\gamma) \sim \vartheta(10^{-54})$$

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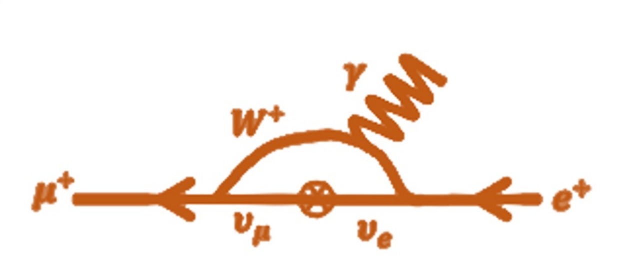

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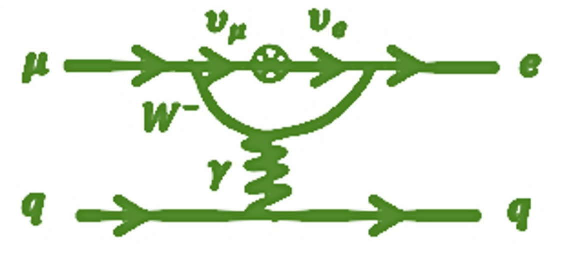

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits O(10^{-13}).

Muon CLFV is an indirect search for New Physics and offers a deep probe of well-motivated BSM theories.

Current Experimental Searches for CLFV

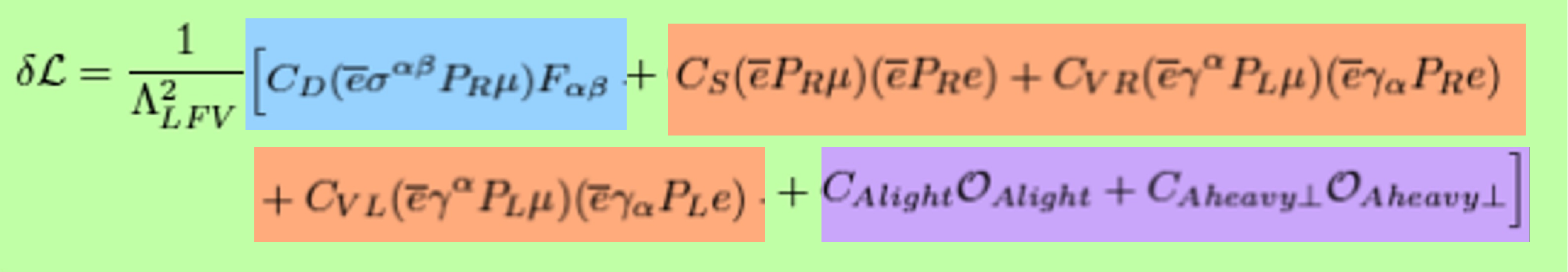
- There is a global program of experiments currently coming online and which seek to observe several types of muon CLFV:

Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	3.1×10^{-13}	4×10^{-14}	MEG II
$\mu^+ \rightarrow e^+e^+e^-$	1.0×10^{-12}	5×10^{-15} 10^{-16}	Mu3e Phase-I Mu3e Phase-II
$\mu^- N \rightarrow e^- N$	7×10^{-13} (SINDRUM-II, 2006)	8×10^{-15} 6×10^{-16} 8×10^{-17} (Mu2e)	COMET Phase-I Mu2e Run-I Mu2e Run-II/ COMET Phase-II

Tight limits already due to nature of the muon allowing for intense muon beam and reducible, well understood backgrounds

Effective Physics Reach

- Can think of indirect searches in terms of Effective Field Theories;
- 90+ operators describe these processes;
- *Eur.Phys.J.C* 82 (2022) 9, 836 reduced to 6 terms for $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and spin-independent $\mu^- N \rightarrow e^- N$;
- These represent different types of physics contributing to the three channels:



$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(\overline{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\overline{e}P_R\mu)(\overline{e}P_Re) + C_{VR}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Re) + C_{VL}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

Λ = Effective Mass Reach, **D** = dipole, **V** = vector, **S** = scalar

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Effective Physics Reach

Dipole Term:
Mediating $\mu^+ \to e^+\gamma$
Contributing to $\mu^+ \to e^+ e^+ e^-$ and
$\mu^- N \to e^- N$ at loop level

$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(\overline{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\overline{e}P_R\mu)(\overline{e}P_Re) + C_{VR}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Re)$$
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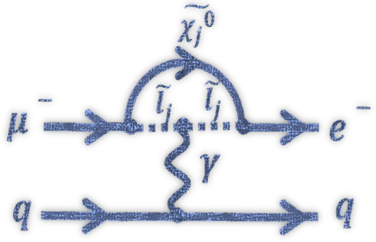
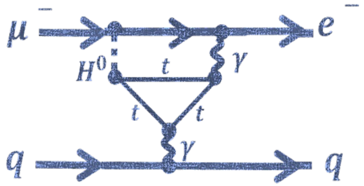
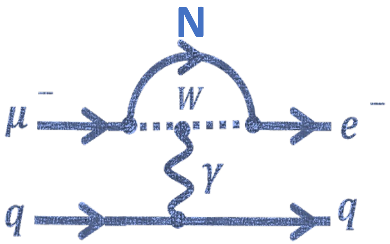


SO(10) SUSY
Rate ~ 10^{-15}

2 Higgs Doublets



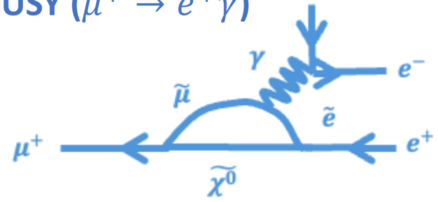
$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Heavy Neutrinos

$|U_{\mu N} U_{eN}|^2 \sim 8 \times 10^{-13}$

SUSY ($\mu^+ \to e^+\gamma$)



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Effective Physics Reach

"Contact"
Scalar
$\mu^+ \rightarrow e^- e^+ e^+$

Leptonic "Contact" term
i.e. 4 Fermion Term
$\mu^+ \rightarrow e^- e^+ e^+$ at leading order.
Heavily suppressed in $\mu^+ \rightarrow e^+ \gamma$

$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(\overline{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\overline{e}P_R\mu)(\overline{e}P_Re) + C_{VR}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Re)$$
$$+ C_{VL}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

e.g. New boson

"Contact"
Vector
$\mu^+ \rightarrow e^- e^+ e^+$

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Effective Physics Reach

quark “Contact” term

i.e. 4 Fermion Term

$\mu^- N \rightarrow e^- N$ at leading order.

Heavily suppressed in $\mu^+ \rightarrow e^+\gamma$

Au and Al are prototypical “heavy” and “light” targets

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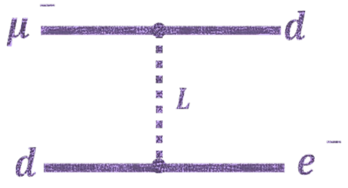
$$+ C_{VL}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

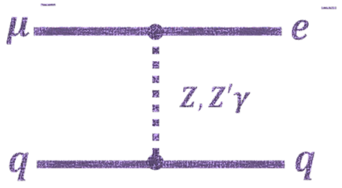
Leptoquarks

$M_{LQ} = 3000(\lambda_{\mu d}\lambda_{ed})^{\frac{1}{2}}\,TeV/c^2$



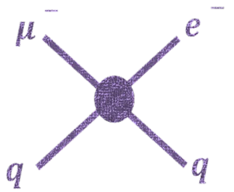
New Bosons

$M_{Z'} = 3000\,TeV/c^2$



Compositeness

$\Lambda_c \sim 3000\,TeV$



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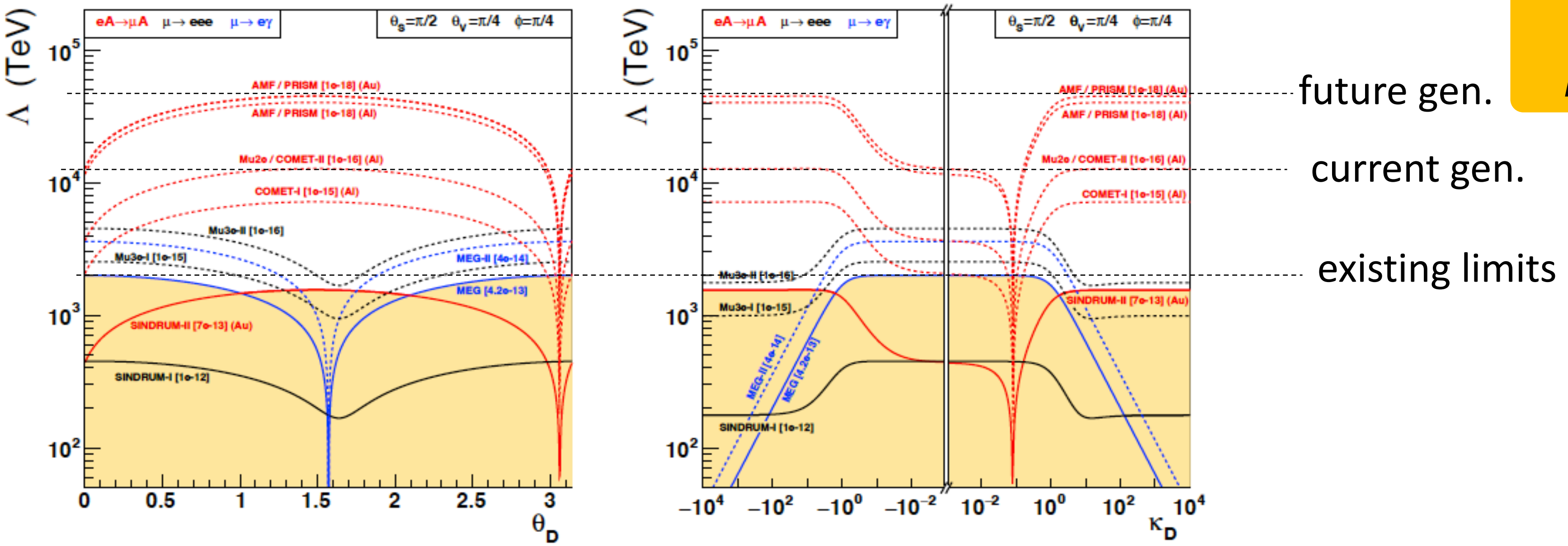
Davidson & Echenard

Effective Physics Reach

$\vec{C}\cdot\vec{e}_D$	$\lvert\vec{e}_D\rvert\cos\theta_D$
$\vec{C}\cdot\vec{e}_S$	$\lvert\vec{e}_S\rvert\sin\theta_D\cos\theta_S$
$\vec{C}\cdot\vec{e}_{VL}$	$\lvert\vec{e}'_{VL}\rvert\sin\theta_D\sin\theta_S\cos\theta_V$
$\vec{C}\cdot\vec{e}_{VR}$	$\lvert\vec{e}'_{VR}\rvert\sin\theta_D\sin\theta_S\cos\theta_V$
$\vec{C}\cdot\vec{e}_{Alight}$	$\lvert\vec{e}_{Alight}\rvert\sin\theta_D\sin\theta_S\sin\theta_V\sin\phi$
$\vec{C}\cdot\vec{e}_{Aheavy\perp}$	$\lvert\vec{e}_{Aheavy\perp}\rvert\sin\theta_D\sin\theta_S\sin\theta_V\cos\phi$

Current physics reach at O(10^3) TeV, Projections of upto O(10^4) TeV in next generation.

Parameterize coefficient space with spherical coordinates *lets you express constraints on all three processes simultaneously.*



$$\kappa_D = \text{cotan}(\theta_D - \pi/2)$$

where angle θ_D , parametrizes relative magnitude of dipole and four-fermion coefficients.

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High magnitude κ_D= contact-like, closer to zero is dipole-like

Λ = effective mass reach

Note: plots are a slice in multi-dimensional space, several other plots shown in paper for different slices

Caltech

Complementarity amongst channels

- All three channels are sensitive to many New Physics models → discovery sensitivity across the board.
- Relative Rates however will be model dependent and can be used to elucidate the underlying physics.

Mode	$\mu^+ \to e^+ e^+ e^-$	$\mu^- N \to e^- N$	$\frac{BR(\mu^+ \to e^+ e^+ e^-)}{BR(\mu^+ \to e^+ \gamma)}$	$\frac{BR(\mu^- N \to e^- N)}{BR(\mu^+ \to e^+ \gamma)}$
MSSM	**Loop**	**Loop**	**~ 6×10^{-3}**	**$10^{-3} – 10^{-2}$**
Type I Seesaw	**Loop**	**Loop**	**$3 \times 10^{-3} – 0.3$**	**0.1-10**
Type II Seesaw	**Tree**	**Loop**	**$(0.1 – 3) \times 10^{3}$**	**10^{-2}**
Type III Seesaw	**Tree**	**Tree**	**~10^{3}**	**10^{3}**
LFV Higgs	**Loop**	**Loop**	**10^{-2}**	**0.1**
Composite Higgs	**Loop**	**Loop**	**0.05-0.5**	**2-20**

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Type III Seesaw	Tree	Tree	~10^{3}	10^{3}
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CLFV: Experimental Design

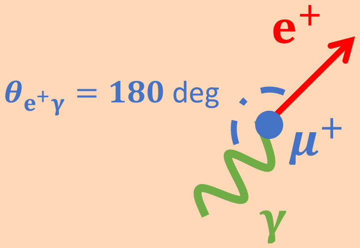
Current experiments, design and status updates.

- Muons as Probes of New Physics
- Muon g-2
- Muon CLFV Searches: Motivations
- Muon CLFV Searches: Design, Status
- What happens next?

$\mu^+ \to e^+\gamma$: Physics

Signal:

- Two body decay:
  - $e^+\gamma$ coincidence in time;
  - $E_{e^+} = E_\gamma$ 52.8 MeV;
  - $\theta_{e^+\gamma} = 180$ deg. i.e. back-to-back.



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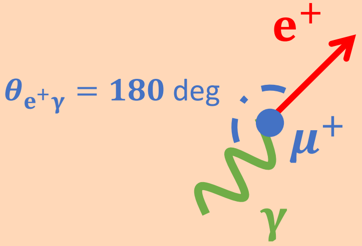
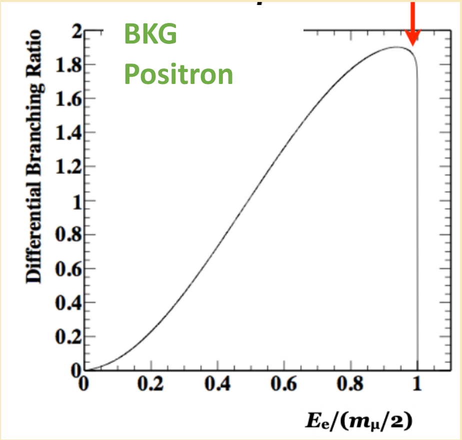
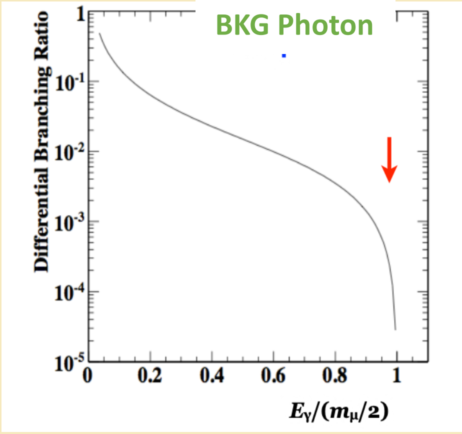


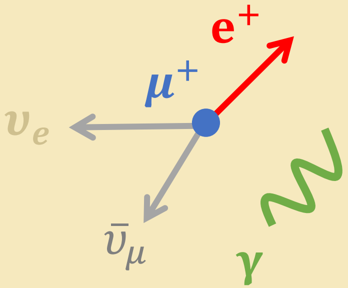
Backgrounds:

- Dominant background from **accidentals**:

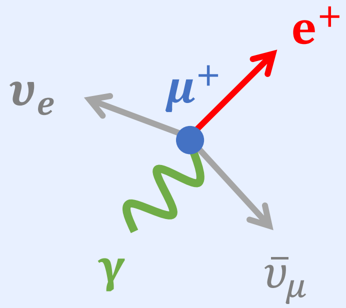
W. Otani (ICHEP 2024)







Also, **rare physics background**:



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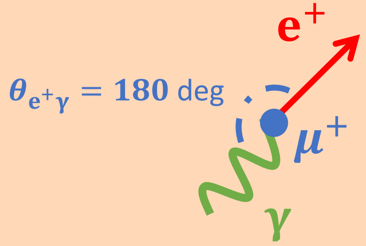

Strategy:

- Measure $E_\gamma, p_{e+}, \theta_{\gamma e+}, t_{e+}$ with the best possible resolutions.

Signal

$$N_{\text{sig}} = \overset{\text{Beam intensity}}{R_\mu} \times T \times \overset{\text{Acceptatnce}}{\Omega} \times \overset{\text{Branching ratio}}{\mathscr{B}} \times \overset{\text{Efficienies}}{\epsilon_\gamma} \times \epsilon_e \times \epsilon_{\text{sel}}$$

Background

$$N_{\text{acc}} \propto R_\mu^2 \times \underset{E_\gamma\text{ resolusion}}{\Delta E_\gamma^2} \times \underset{E_e\text{ resolution}}{\Delta E_e} \times \underset{\text{Angular reslution}}{\Delta\Theta_{e\gamma}^2} \times \underset{\text{Time resolution}}{\Delta t_{e\gamma}} \times T$$

Backgrounds:

- Dominant background from **accidentals**:

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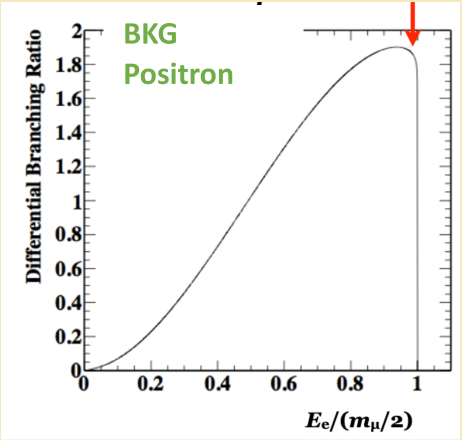

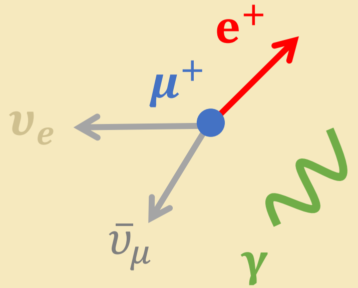

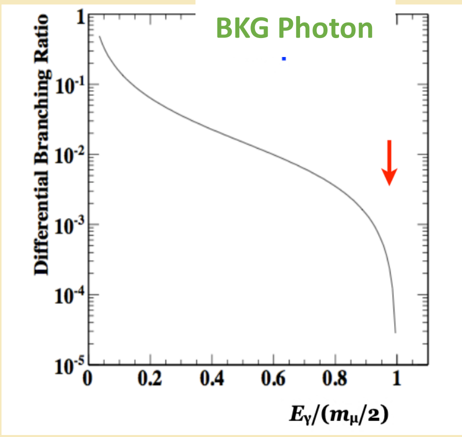

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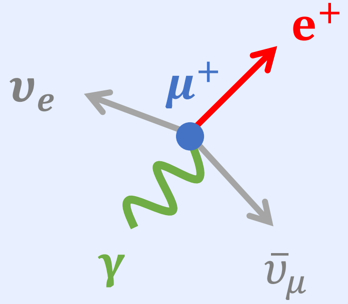
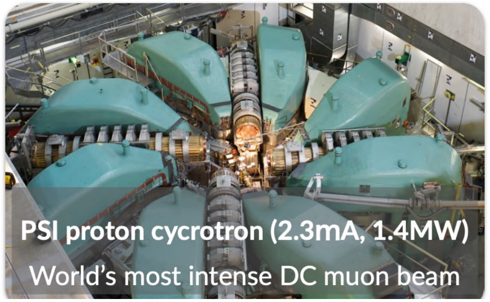


$\mu^+ \to e^+\gamma$: MEG-II Design

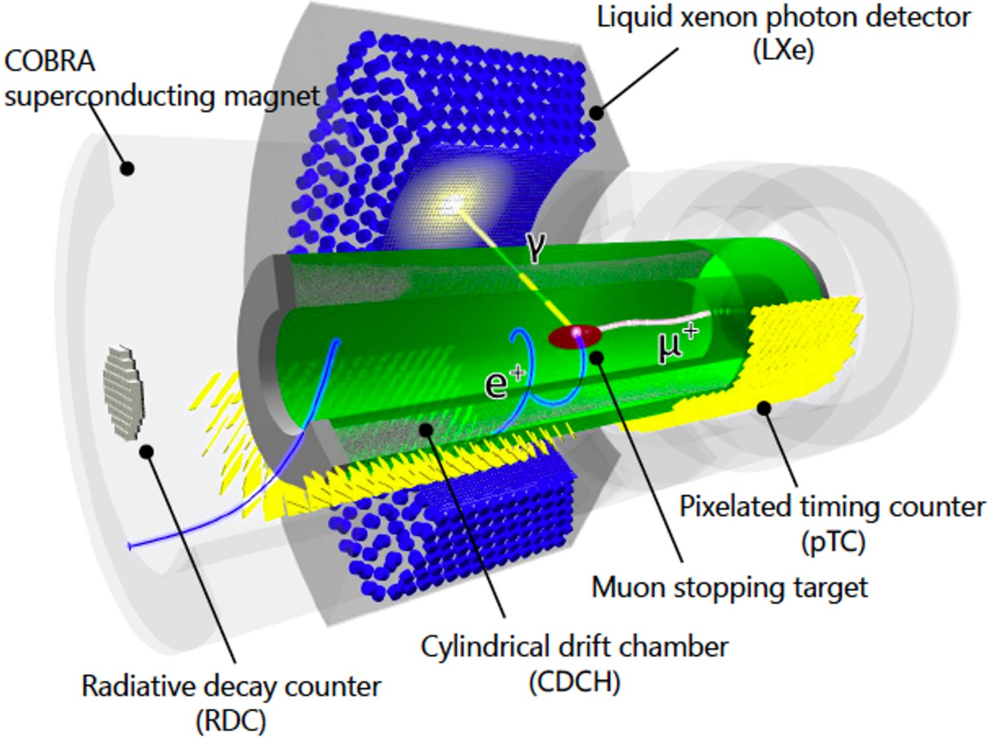


PSI proton cyclotron (2.3mA, 1.4MW)

World's most intense DC muon beam

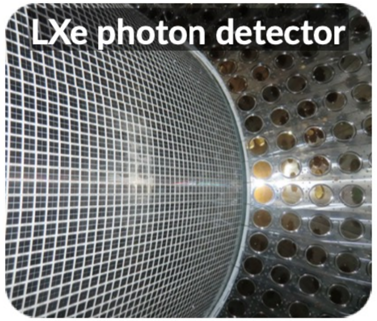
Radiative decay counter

- BKG photon suppression by identifying associated low mom. positron.



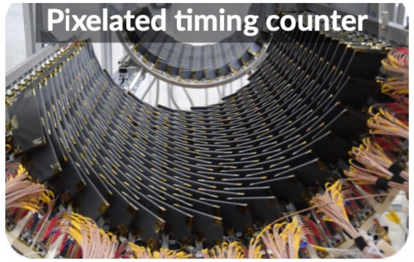
Design:

- Based at PSI, muon stopping rate of 10^7 μ^+/s, p = 28 MeV/c.
- μ^+ stopped on thin plastic target - decay at rest to exploit the two-body kinematics.
- Accurate reconstruction of photon and positron energy and time:
  - **Magnetic spectrometer and low mass drift chamber** to track the candidate positron.
  - **LXe photon detector** measures the timing, energy and position of the photon.



LXe photon detector

- **900L of LXe**
- **Highly granular scintillation readout with 4092 SiPM and 668 PMT**



Pixelated timing counter

- **512 plastic scintillator plates**
- **40 ps time resolution average**

Cylindrical drift chamber

- **Low mass design with single gas volume**
- **Drift cells with stereo wires**

$\mu^+ \rightarrow e^+\gamma$: Status

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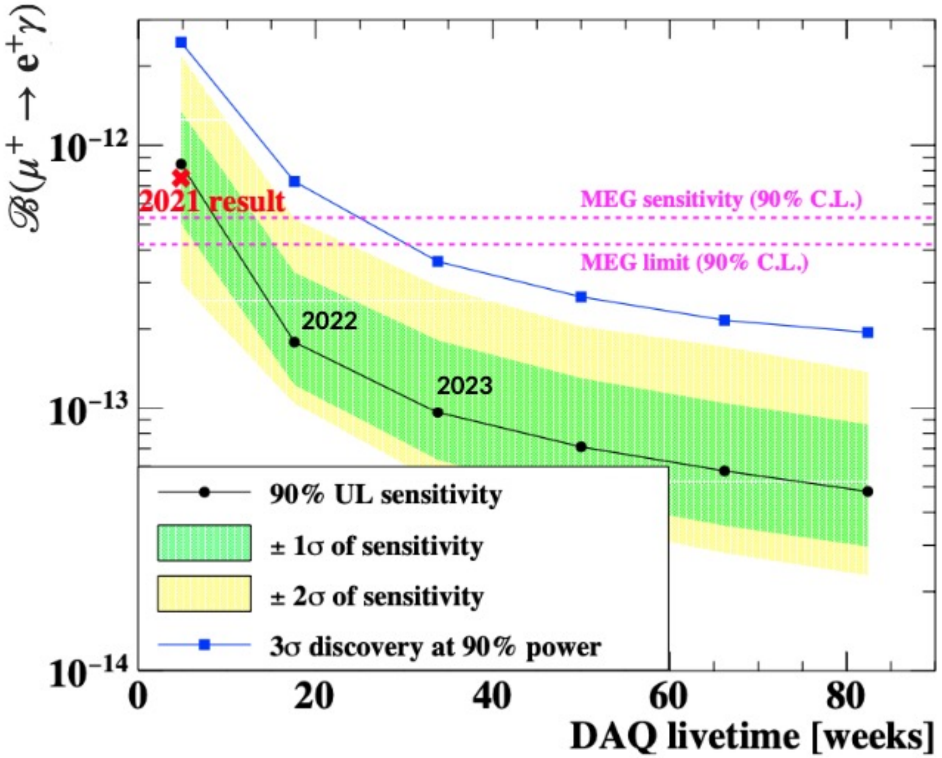
Status:

- MEG-II has been taking physics data since 2021.
- Results from the first physics run show:
  - No excess over background-only hypothesis:
    - Upper limit **B($\mu^+ \rightarrow e^+\gamma$) < 7.5 x 10^{-13} (90% C.L.)**
    - Combined with MEG: **B($\mu^+ \rightarrow e^+\gamma$) < 3.1 x 10^{-13} (90% C.L.)**
- x10 more data already taken: new results coming soon!
- Physics run will continue until PSI shutdown in 2027.
  - Goal to reach 6 x 10^{-14} (x10 on MEG) and potential discovery.

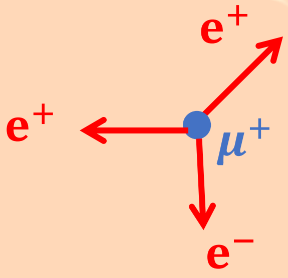


See Talk by M. De Gerone

$\mu^+ \to e^+e^+e^-$: Physics

Signal:

- **Three body decay:**
  - Common vertex
  - Coplanar
  - $\sum p_i = 0, \sum E_i = m_\mu, \Delta t_{eee} = 0$



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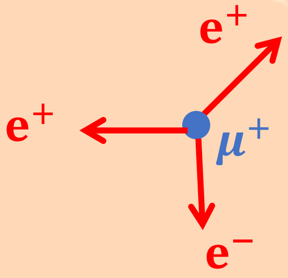
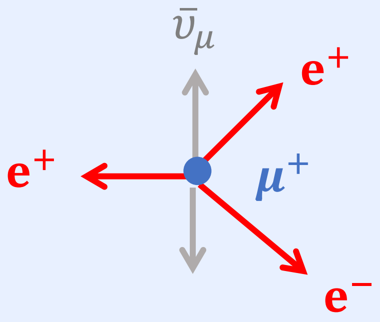


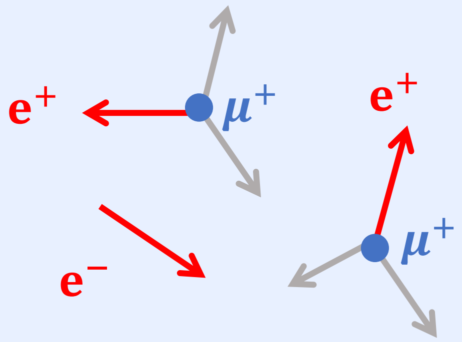
Backgrounds:

Internal conversions:



- Common vertex
- $\sum p_i \neq 0,$
- $\sum E_i < m_\mu,$
- $\Delta t_{eee} = 0$

Combinational:



- No common vertex
- $\sum p_i \neq 0,$
- $\sum E_i \neq m_\mu,$
- $\Delta t_{eee} \neq 0$

$\mu^+ \to e^+e^+e^-$: Physics

Signal:

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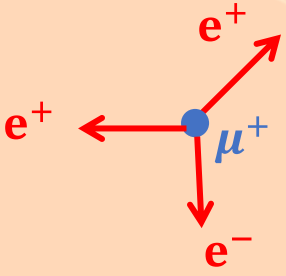
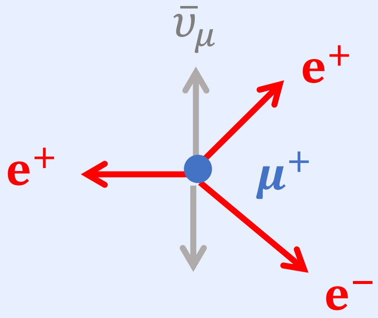


Strategy:

Need to establish that three charged tracks (total +) emanate from the same location and coincide in time, this requires:

- Precise time resolution;
- Excellent position and momentum resolution.

Backgrounds:



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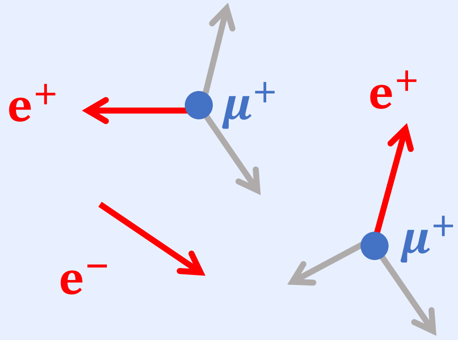

- No common vertex
- $\sum p_i \neq 0,$
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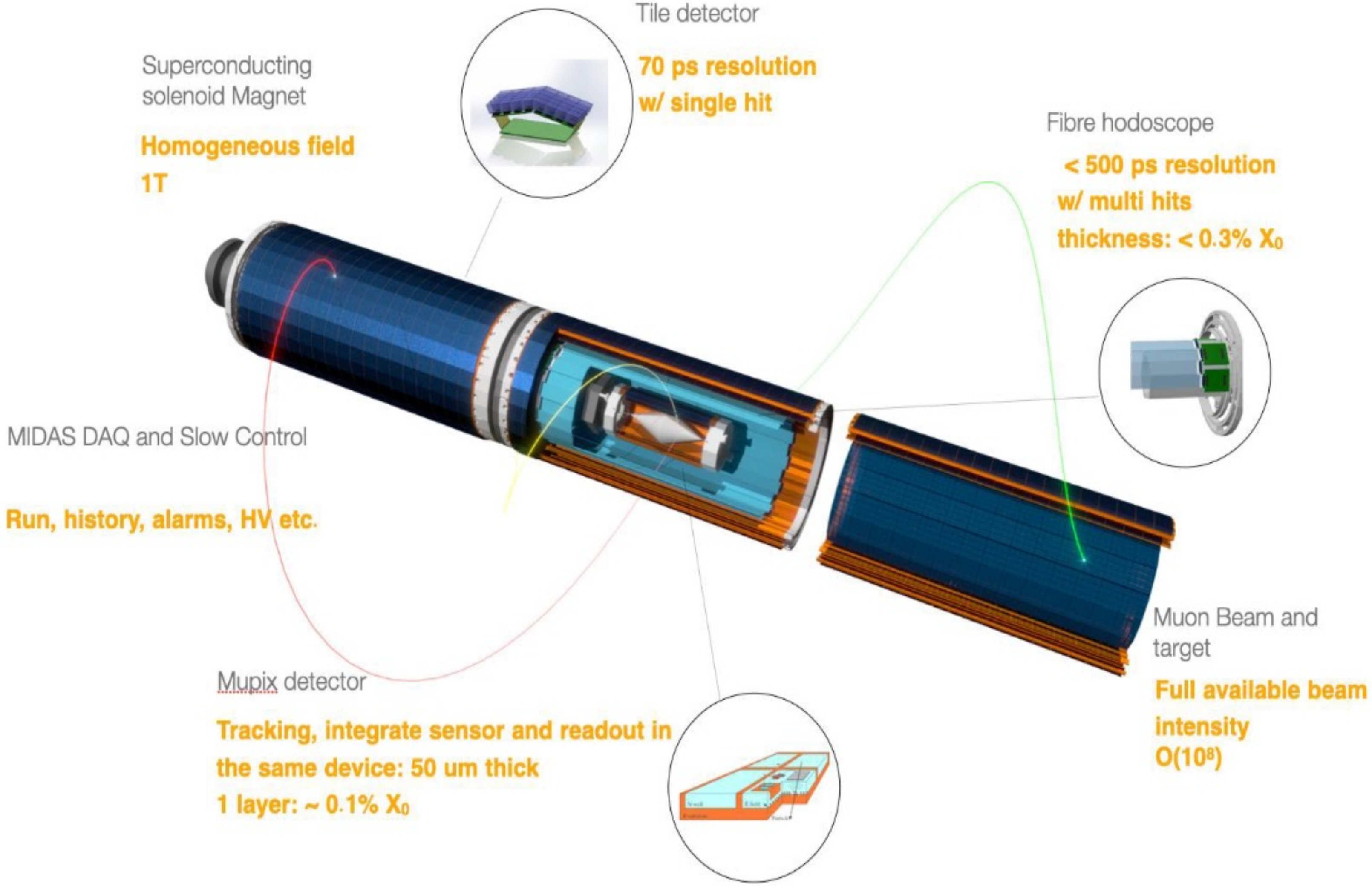
- $\Delta t_{eee} \neq 0$

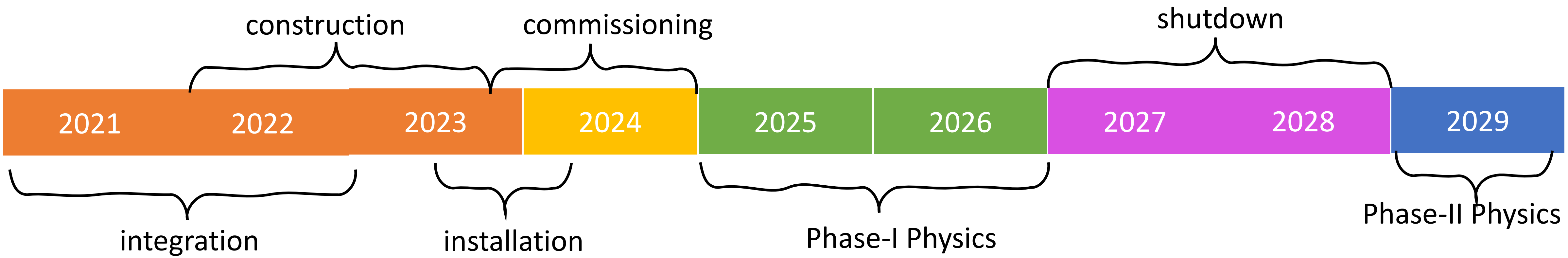
$\mu^+ \rightarrow e^+e^+e^-$: Mu3e Design



Design:

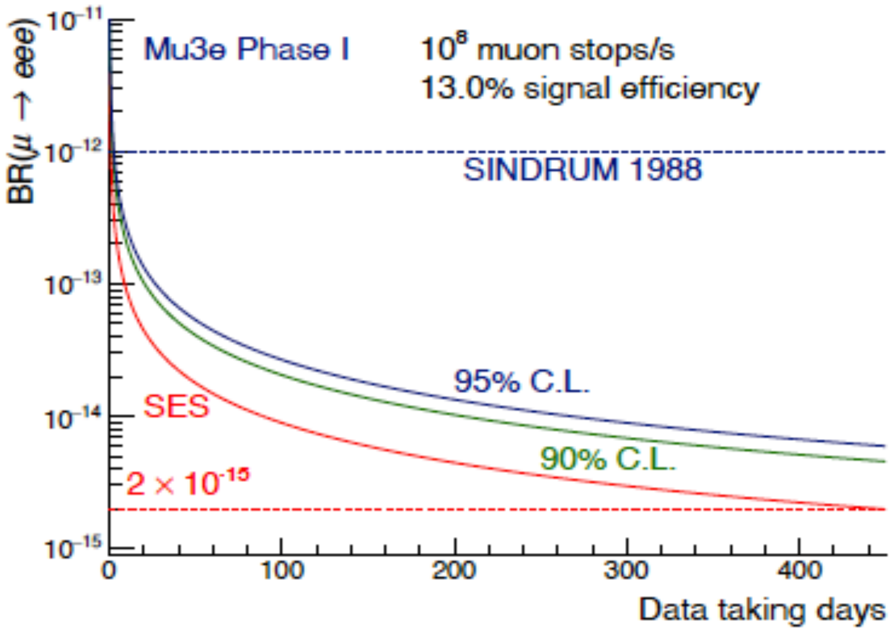
- High tracker occupancy requires excellent timing and position resolution to select hits belonging to the same track: thin, fast, high-resolution detectors:
  - 175 HV-MAPS channels
  - ~3000 SciFi and ~7K Tile TOF channels.
- Method of recurling tracks allows good momentum resolution.
- Superconducting magnet (not shown).

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



Status:
- Based at PSI, expect data-taking by 2025-26.
- Two Phased implementation:
    - **Phase-I** – Sensitivity 10^{-15};
    - **Phase-II** – Sensitivity 10^{-16} (requires beam upgrade).

See Talk by R. Amarinei



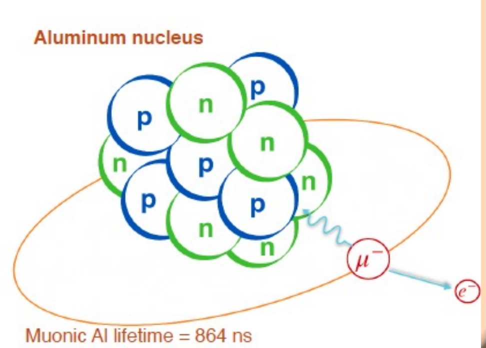
$\boldsymbol{N\mu^-} \rightarrow \boldsymbol{Ne^-}$: Physics

Signal:

- Monoenergetic electron (1st order)

$E_e = m_\mu - E_{recoil} - E_{1S\,B.E}$, e.g For Al: E_e = 104.97 MeV

- Coherent = nucleus stays intact.
- Will be smeared by scattering and energy losses



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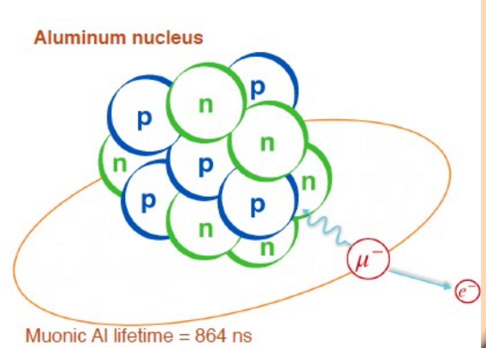

Backgrounds:

- **Decay in Orbit:**
  - 39 % of stopped muons decay :

$$\mu \rightarrow e + \bar{\upsilon}_e + \upsilon_\mu$$

- **Radiative Pion Capture:**
  - Pions captured into Al nucleus, undergo a radiative process (internal or external), results in: $\gamma \rightarrow e^+e^-$
  - Electrons have energy up to ~pion mass.
- **Cosmic Induced:**
  - Cosmic muons or secondary particles can be confused for signal is appear to emanate from target.

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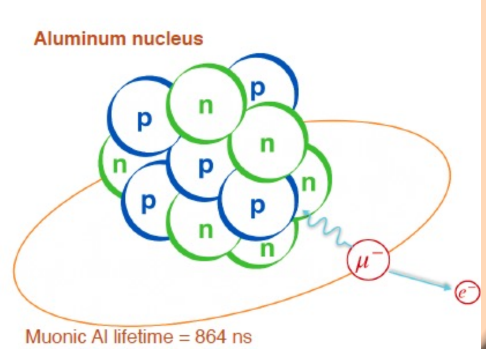

Strategy:

Stop 10^{18} muons with << 1 background in signal region:

- Intense muon beam;
- Efficient transportation and collection of muons;
- Pulsed beam to eliminate pions;
- Precise momentum resolution to remove decay backgrounds.

Backgrounds:

- **Decay in Orbit:**
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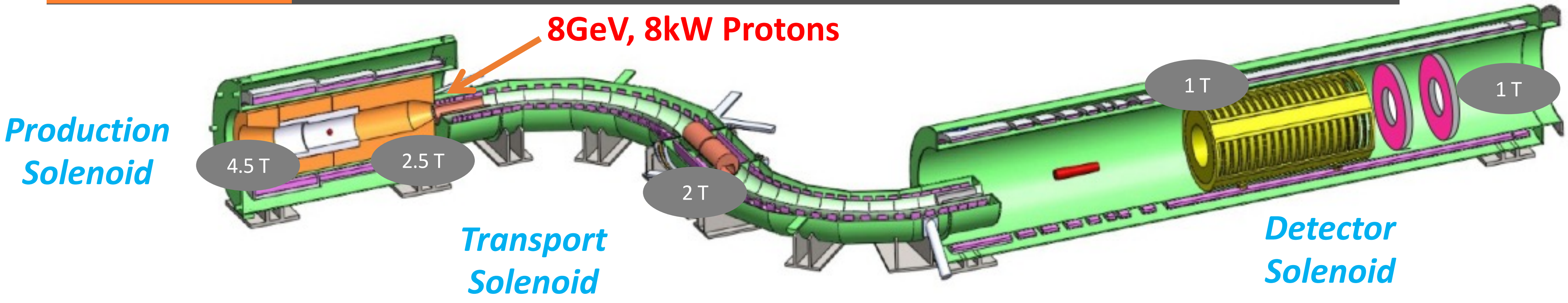
$N\mu^- \rightarrow Ne^-$: Mu2e Design

Intense muon beam;
Efficient transportation and collection;



Production Solenoid:

- Pulsed 8 GeV Protons enter, hit Production Target. π produced, decay to μ.
- Graded magnetic field reflects muons to transport solenoid.

Transport Solenoid:

- “S” shape removes line of sight backgrounds.
- Collimators select low momentum, negative muons.

Detector Solenoid:

- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

See Talk by A. Gapanenko

$N\mu^- \rightarrow Ne^-$: Mu2e Projections

2027 Run-I:
- 1×10^{-15} 5σ discovery,
- Single-Event-Sensitivity = 2×10^{-16}
- U.L : 6×10^{-16} (90% C.L.)
  - **1000 x current limit.**
  - **Universe 2023, 9, 54 shows simulated analysis for Run-I.**

Total (Run-I + Run-II) end-goal:
- 2×10^{-16} 5σ discovery,
- Single-Event-Sensitivity = 3×10^{-17}
- U.L : 8×10^{-17} (90% C.L.)
  - **10000 x current limit.**

Need to stop O(10^{18}) muons and have << 1 background event over entire lifetime of the experiment to achieve these numbers!

$N\mu^- \to Ne^-$: (Mu2e) Backgrounds

Beam delivery and detector systems optimized for high intensity, pure muon beam – must be “background free”:

Type	Source	Mitigation	Yield (for Run-I only)*
Intrinsic	**Decay in Orbit (DIO)**	**Tracker Design/ Resolution**	$0.038 \pm 0.002\ (\mathrm{stat})^{+0.025}_{-0.015}$ (sys)
Beam Backgrounds	**Pion Capture**	**Beam Structure/ Extinction**	(in time) $0.010 \pm 0.002\ (\mathrm{stat})^{+0.001}_{-0.003}$ (sys) (out time) $(1.2 \pm 0.001\ (\mathrm{stat})^{+0.1}_{-0.3}\ (\mathrm{sys})) \times 10^{-3}$
Cosmic Induced	**Cosmic Rays**	**Active Veto System**	0.046 ± 0.010(stat) ± 0.009 (sys)

* assumes signal region of $103.6 < p < 104.9$ MeV/c and $640 < t < 1650$ ns

Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

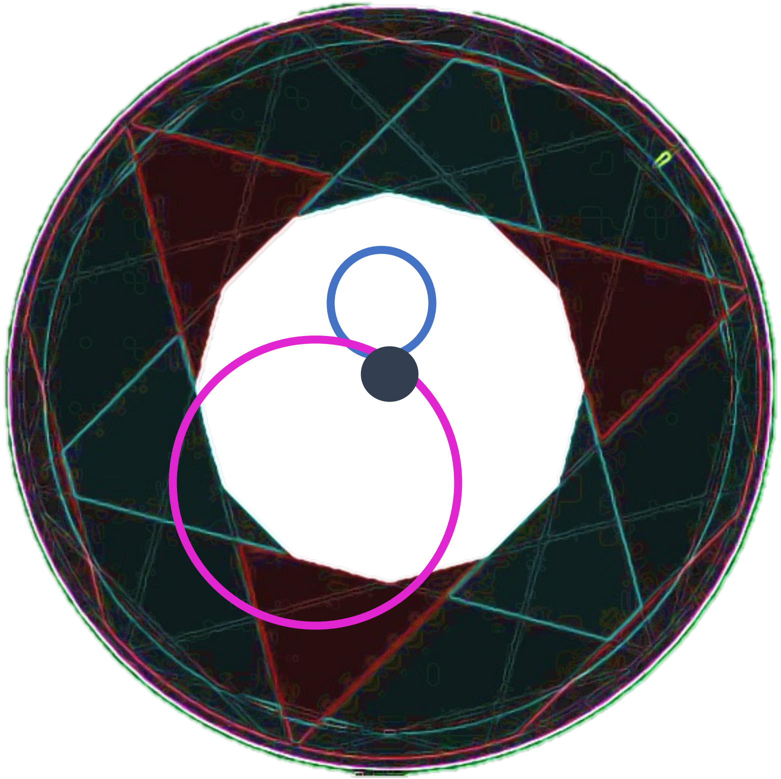
Background free

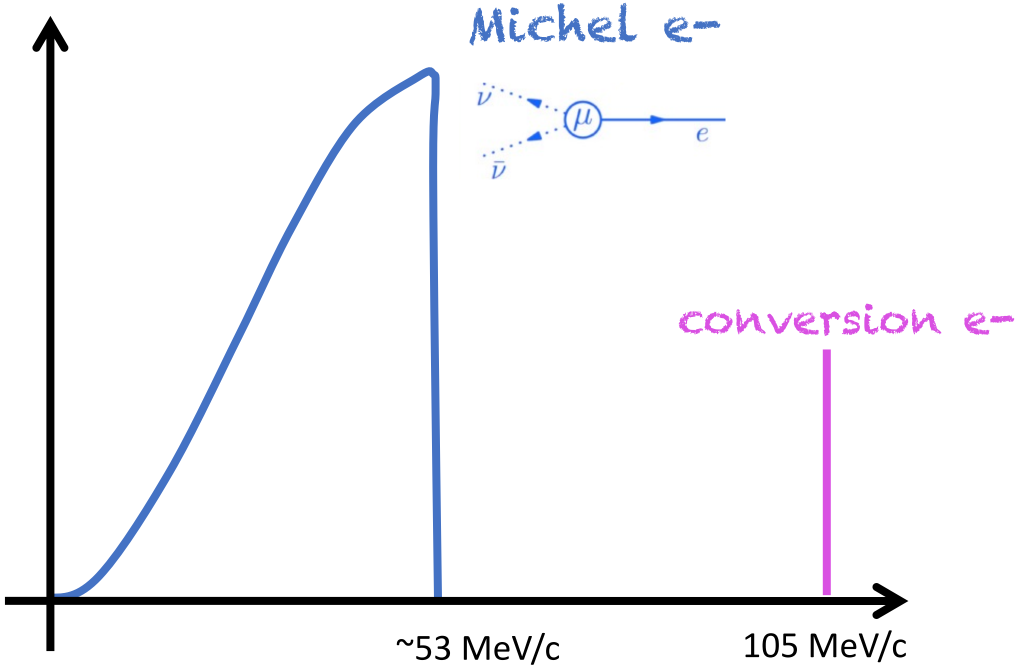
(Mu2e) Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.

$$R = \frac{p_\perp}{qB} = 35cm$$

- Michel Electron (< 52MeV/c)
- Signal (105MeV/c)





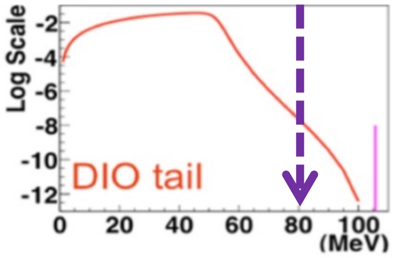
Background free

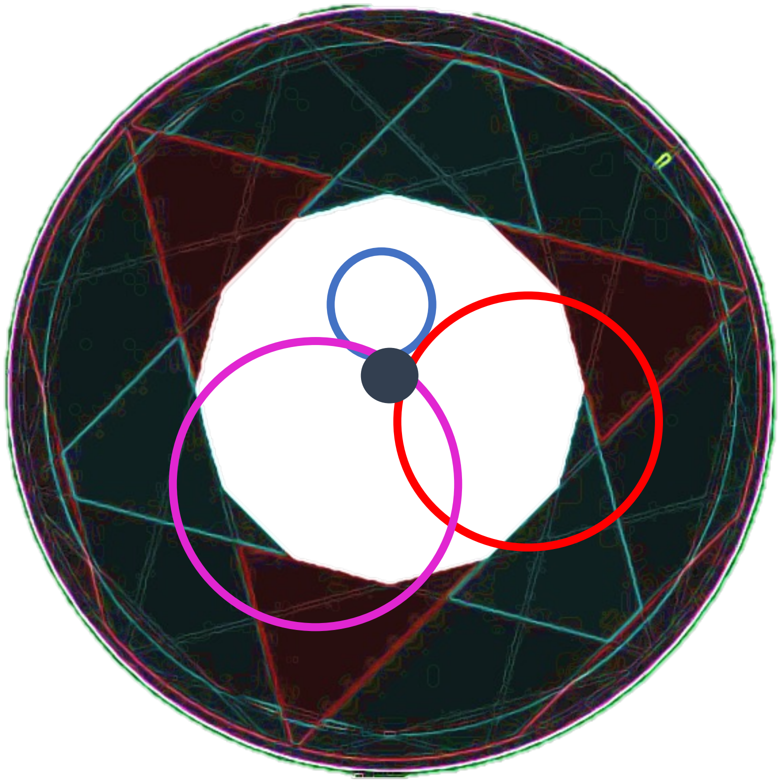
(Mu2e) Decay in Orbit (DIO) Backgrounds

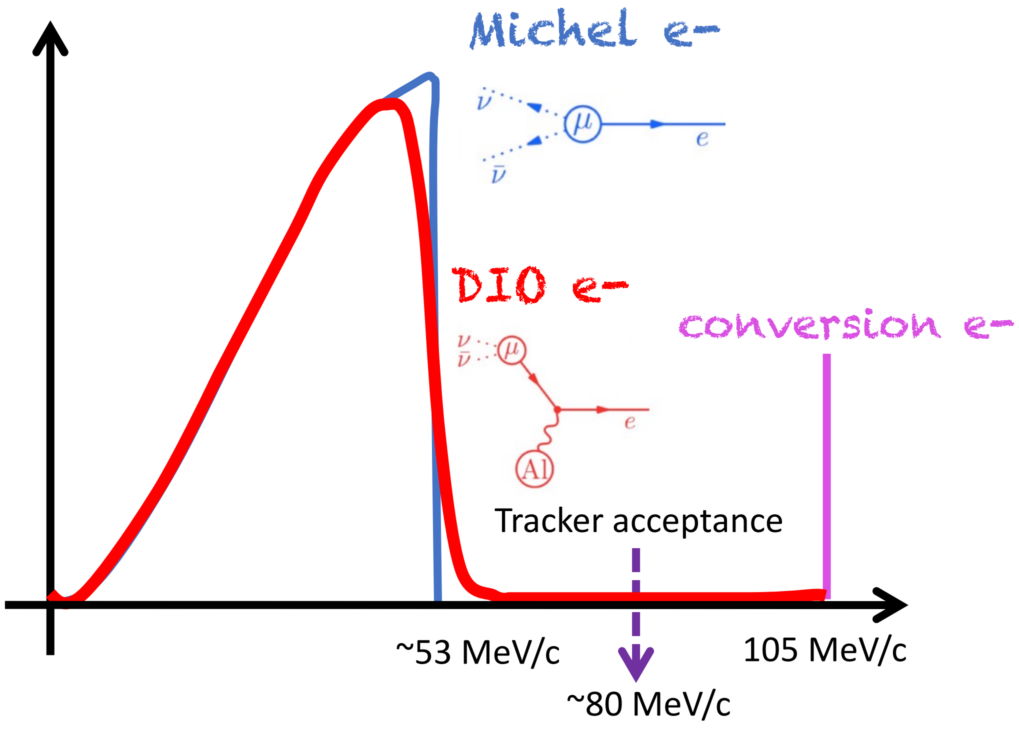
- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.
- However, when decay happens in orbit, exchange of momentum produces recoil tail close to signal region (105 MeV/c).
- To remove remaining backgrounds necessitates < 200 keV/c momentum resolution.

$$R = \frac{p_\perp}{qB} = 35cm$$

- Michel Electron (< 52MeV/c)
- Signal (105MeV/c)
- **Problematic Tail (>100MeV/c)**

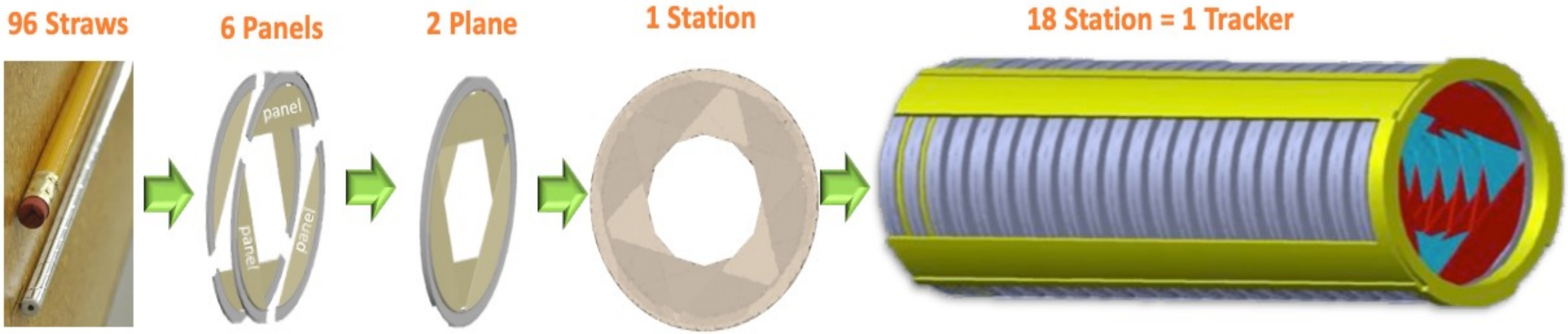






(Mu2e) Straw Tracker: achieving resolution

- Need a high-resolution (< 200 keV/c) momentum measurement to distinguish tail DIO from signal:
  - Minimize energy loss by operating in vacuum and using low mass straws of 15 μm thickness filled with 80:20 Ar:CO_2 ;
  - Include extra hit position information with high-angle stereo overlaps and readout on both ends of straw.

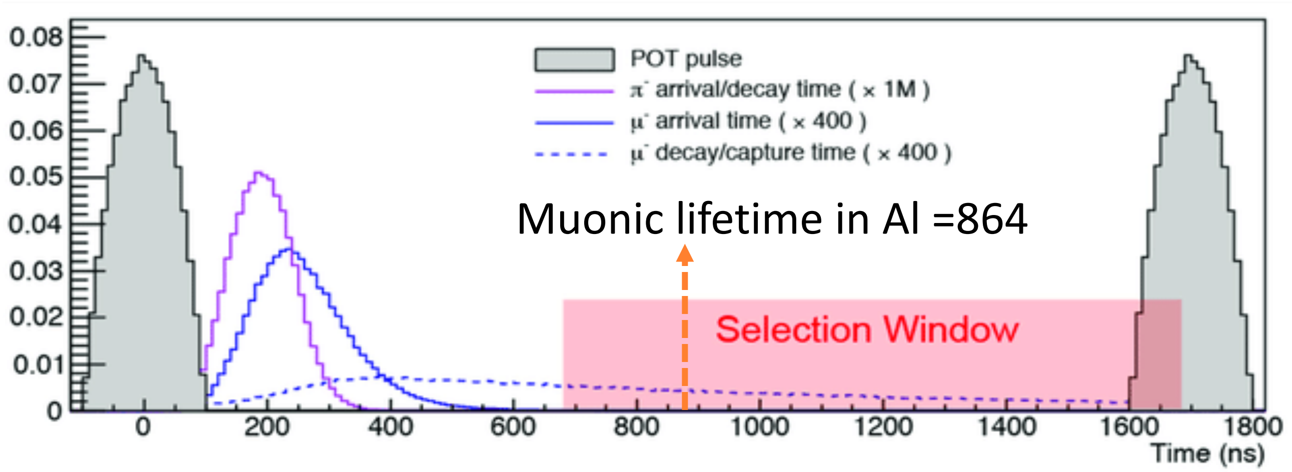


Radiative Pion Capture Backgrounds

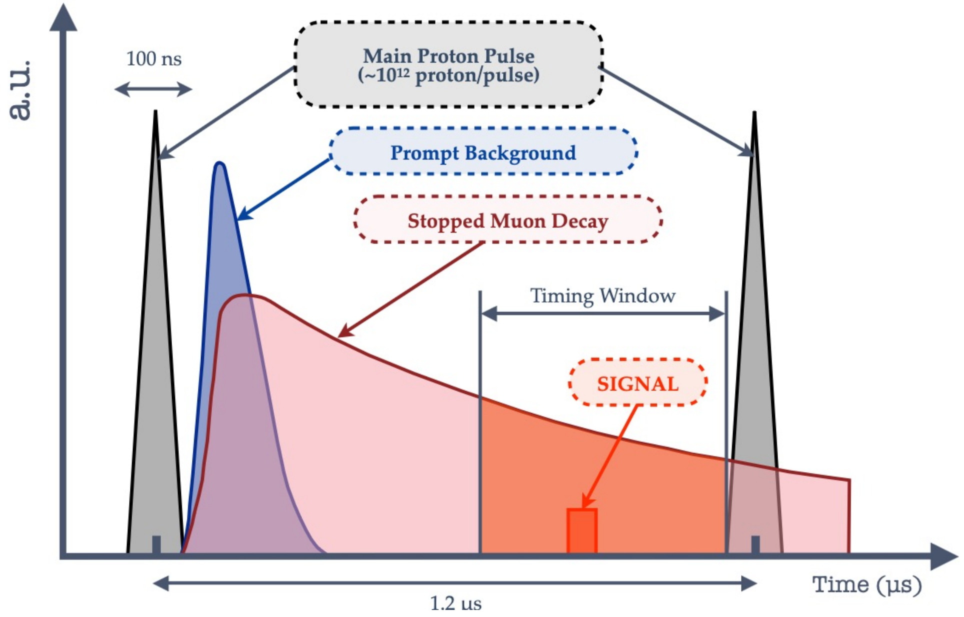
- **Use timing information!**
- Pion lifetime 26 ns at rest. Pulsed proton beam (250 ns wide, pulses 1695 ns apart) → wait out pion decay.
- In addition, upstream extinction removes out-of-time protons.

Delayed live-gate helps remove pion and beam backgrounds.

Mu2e



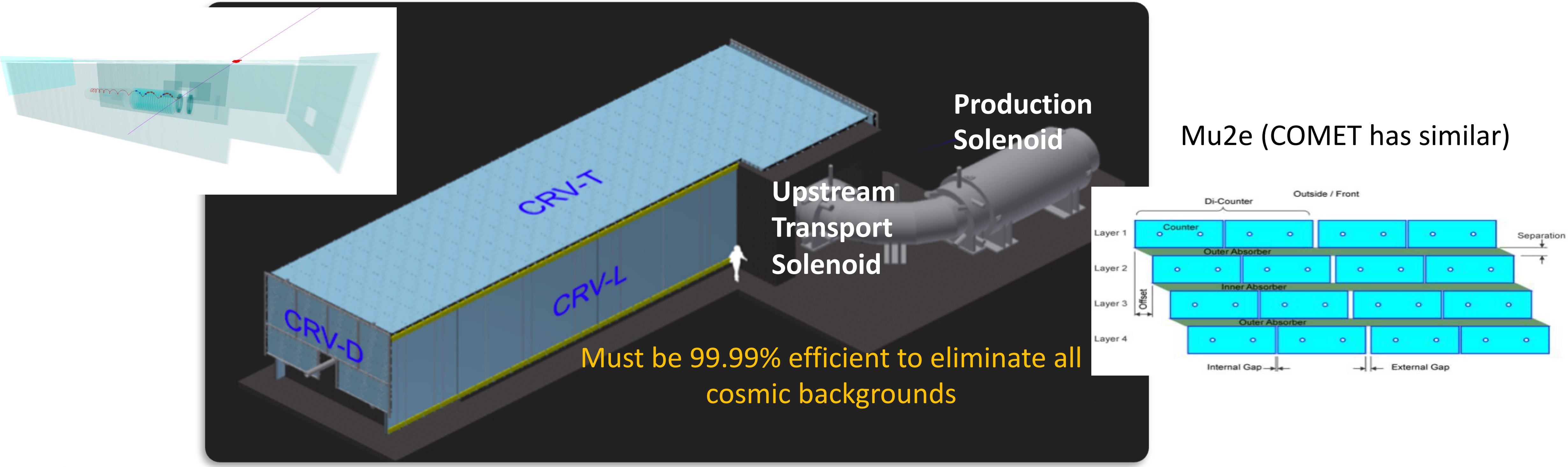
COMET



Cosmic Induced Backgrounds

- Cosmic-ray muons can initiate 105 MeV particles that appear to emanate from the stopping target.
- Remove using active veto (CRV) + overburden and shielding concrete surrounding the Detector Solenoid.

Active Cosmic Ray Veto system is key to eliminating cosmic induced backgrounds.



Mu2e (COMET has similar)

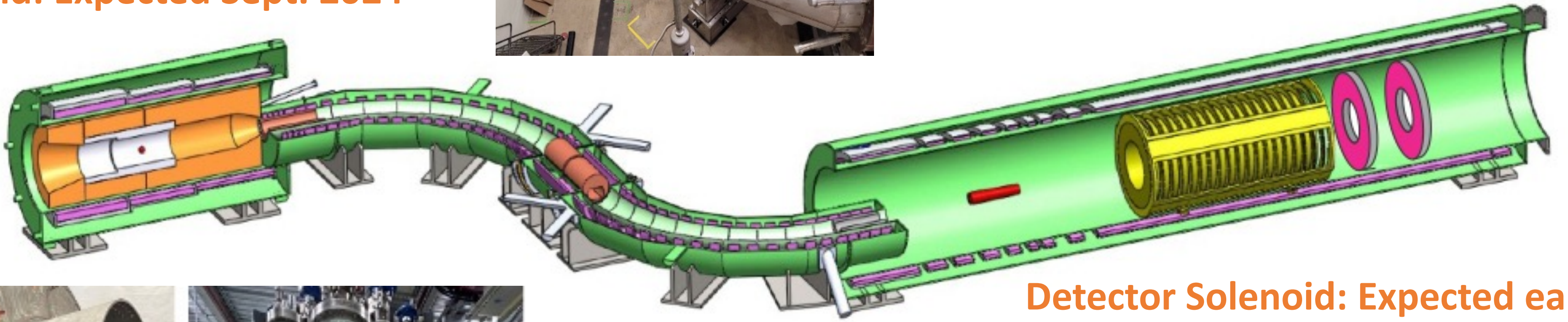
Must be 99.99% efficient to eliminate all cosmic backgrounds

$N\mu^- \rightarrow Ne^-$: Mu2e Status (solenoids)

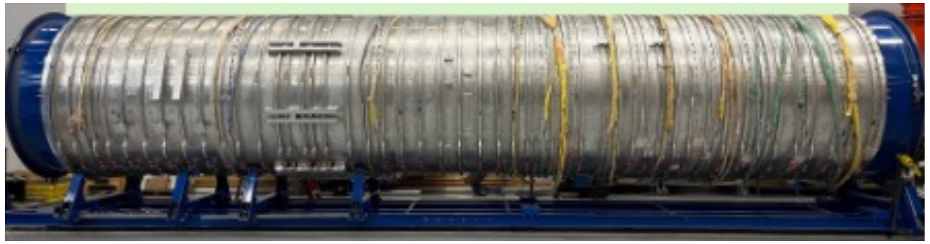
See Talk by A. Gapanenko

Transport Solenoid: Installed in Mu2e Hall in 2024

Production Solenoid: Expected Sept. 2024



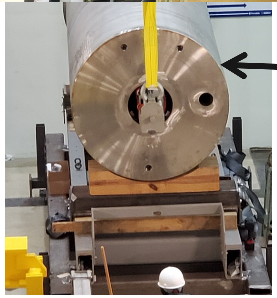
Detector Solenoid: Expected early 2025



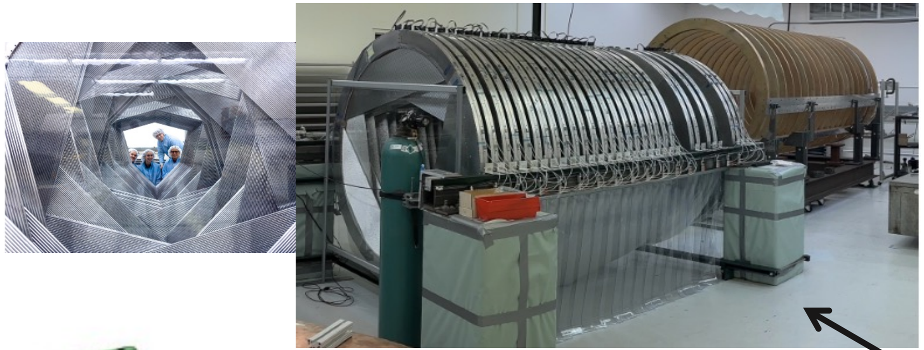
$N\mu^- \to Ne^-$: Mu2e Status

See Talk by A. Gapanenko

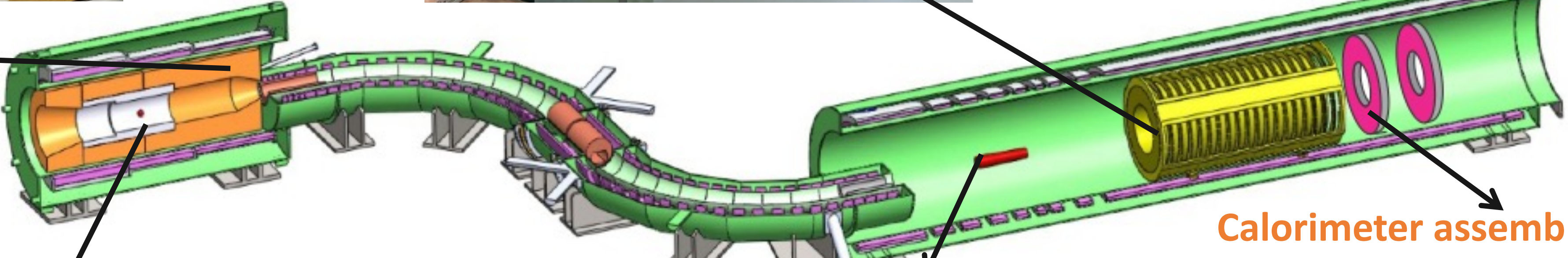
Heat Shield @ FNAL



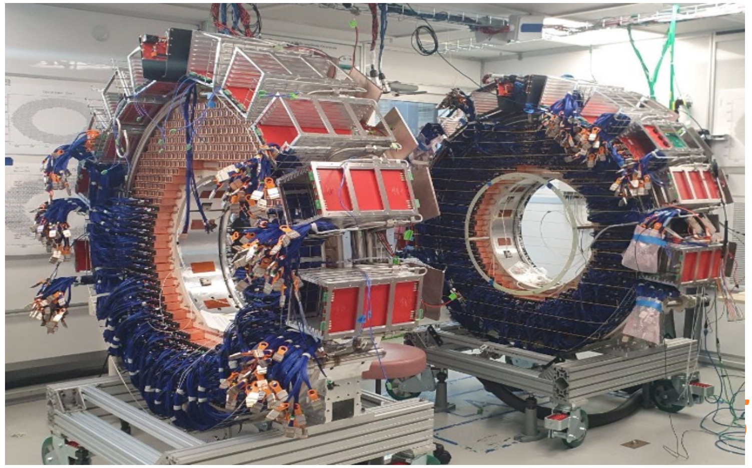
Tracker being assembled @ FNAL



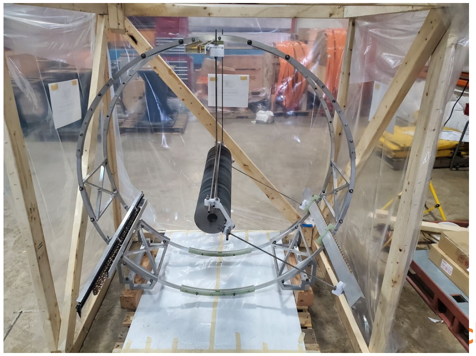
CRV: modules fabricated, testing with cosmics @ FNAL



Calorimeter assembled @ FNAL



Stopping Target constructed, now at FNAL



Production Target @ FNAL

What happens next?

How do we understand a signal?

Muons as Probes of New Physics

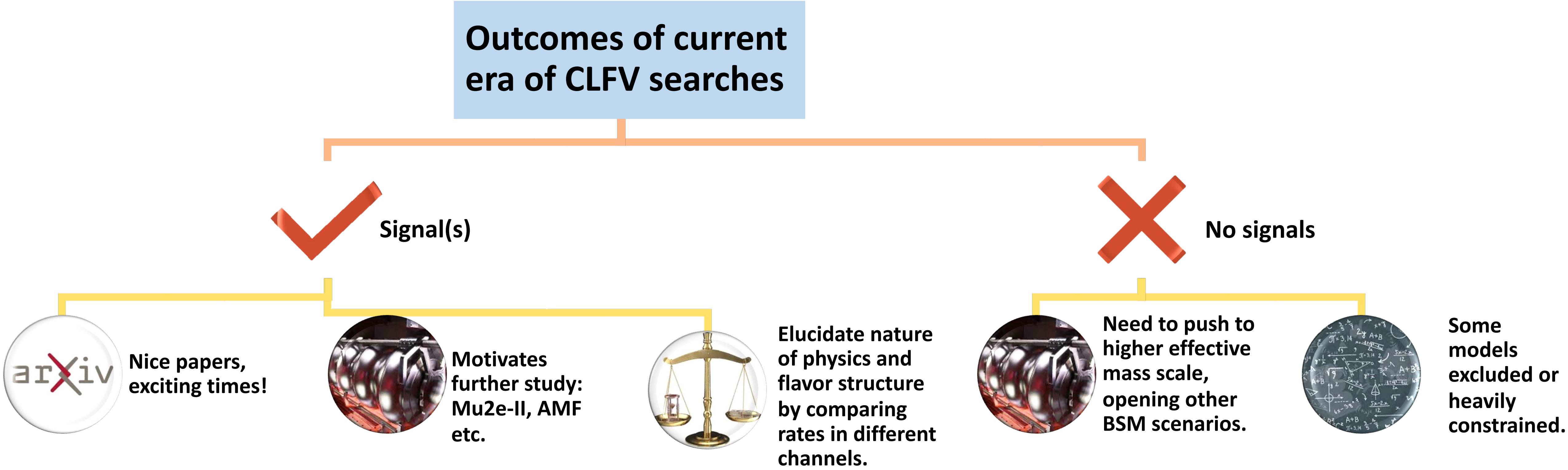
Muon g-2

Muon CLFV Searches: Motivations

Muon CLFV Searches: Design, Status

What happens next?

Possibilities



Outcomes of current era of CLFV searches

✓ Signal(s)

- Nice papers, exciting times!
- Motivates further study: Mu2e-II, AMF etc.
- Elucidate nature of physics and flavor structure by comparing rates in different channels.

✗ No signals

- Need to push to higher effective mass scale, opening other BSM scenarios.
- Some models excluded or heavily constrained.

<u>What's next???</u> – In either scenario additional searches are motivated. This motivates: Mu2e-II, AMF or PRISM/PRIME.

Next Generation Searches

Proposed multi-decade muon CLFV at Fermilab which would utilize PIP-II and ACE 2GeV ring:

Mu2e-II [see: arXiv: 2203.07569 [hep-ex]] (mid-2030s):

- ***Similar design to Mu2e, reuses much of the hardware but requires new production target and detector systems.***
- Uses pulsed beam as necessary to remove pion backgrounds.
- Lots or R&D on-going including 2 LDRD proposals: tracker and production target.

PRISM/PRIME:

- PRISM uses an FFA to provide monoenergetic muon beam. PRIME is a conversion search.

The Advanced Muon Facility (AMF) [see: arXiv: 2203.08278 [hep-ex]] (mid 2040s):

- ***A multi purpose muon facility which would search for all three muon CLFV channels at Fermilab.***
- Would utilize a fixed field alternating (FFA) gradient synchrotron which would provide:
  - Monoenergetic beam of central momentum 20-40 MeV/c: thin target, minimizing material effects, retaining momentum resolution.
  - Pure muon beam: don’t need the pulsed beam and delayed signal window.
    - Can utilize a high Z material to elucidate physics if signal at Mu2e/COMET or Mu2e-II.
    - Has smaller decay branching fraction.
- R&D required and lots of opportunities to get involved.

See talk by L. Borrel

See my talk on AMF

Summary

Muon g-2:

- Discrepancy with SM theory predictions, experiments are making more precise determination, and theorists and experimentalists are working to resolve the theoretical discrepancies between measurement and each other.

Muon CLFV:

- Muon CLFV channels offer deep indirect probes into BSM and part of an active global CLFV program.
- These experiments have discovery potential over a wide range of well motivated BSM models.
- Three muon CLFV channels form part of a global search for CLFV which will take place this decade.
- Looking further ahead Mu2e-II, PRISM/PRIME and AMF would help elucidate any signal and push to higher mass scales (if no signal).

Thank you for listening!

Any Questions?

Back up

Extra things which did not fit

Muons as Probes of New Physics

Muon g-2

Muon CLFV Searches: Motivations

Muon CLFV Searches: Design, Status

What happens next?

Slide from On Kim, UMiss.

Measurement Quantity Anatomy (g-2 FNAL)

$$\omega_a = a_\mu \frac{qB}{m} \Rightarrow a_\mu = \overset{\text{What we measure.}}{\boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}} \overbrace{\frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}^{\text{Known to 24 ppb}}$$

Category	TDR Target Uncertainty [ppb]
Statistical (ω_a)	100
Systematic (ω_a)	70
Systematic ($\tilde{\omega}_p$)	70
Total	**140**

Omega-a Team

Measured $g-2$ frequency

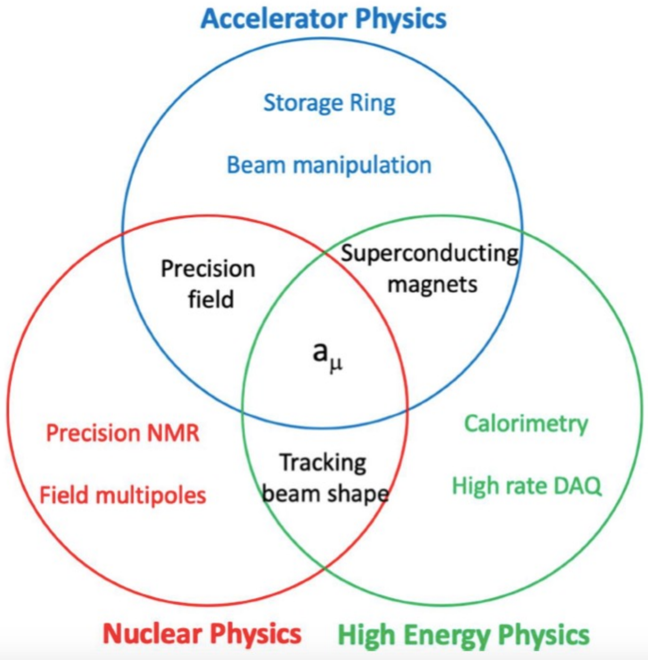
Beam Dynamics Team

Unblinding conversion factor

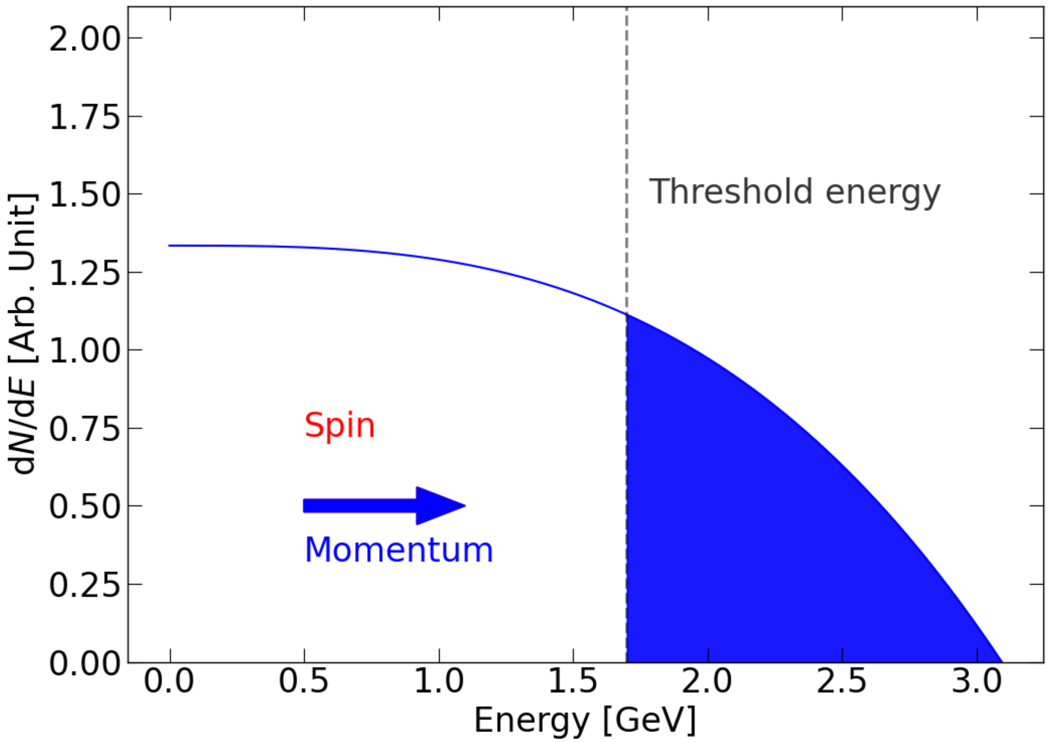
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Beam dynamics corrections}})}{f_{\text{calib}}\ \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted over the muon distribution}}(1 + \underbrace{B_k + B_q}_{\text{Corrections from the transient magnetic field}})}$$

Field Team

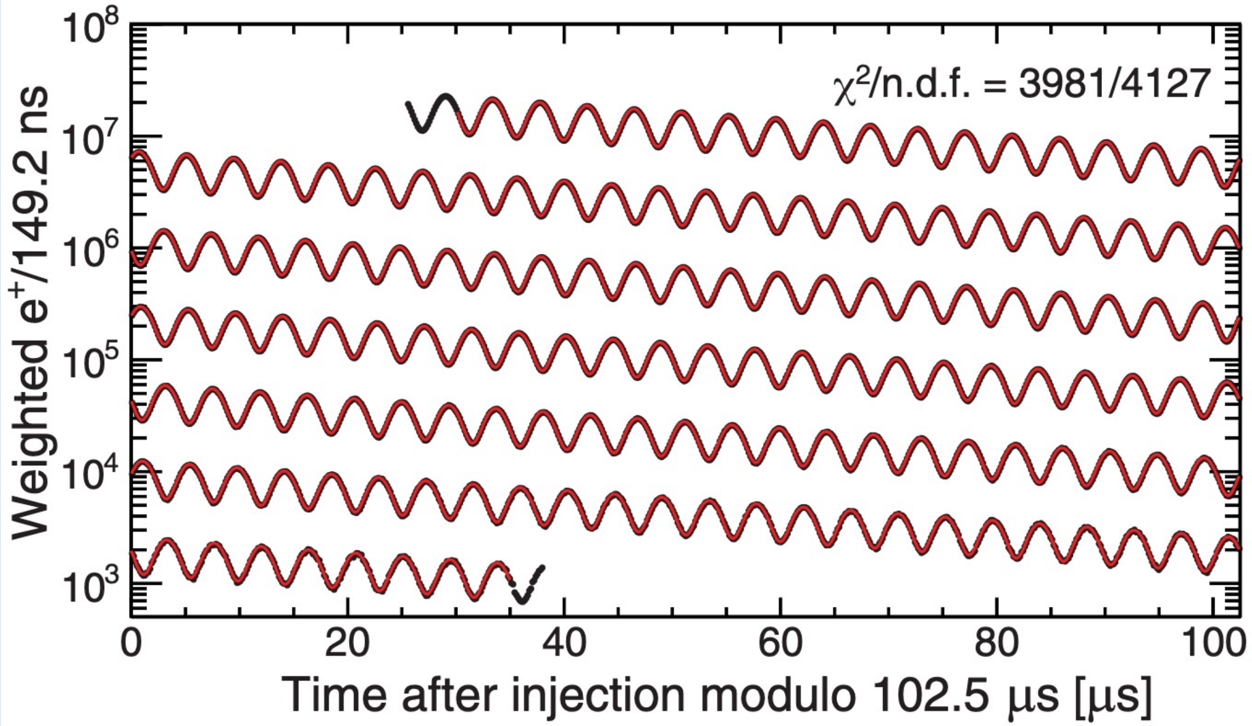
NMR probe calibration factor



Muon g-2 Experiment at FNAL



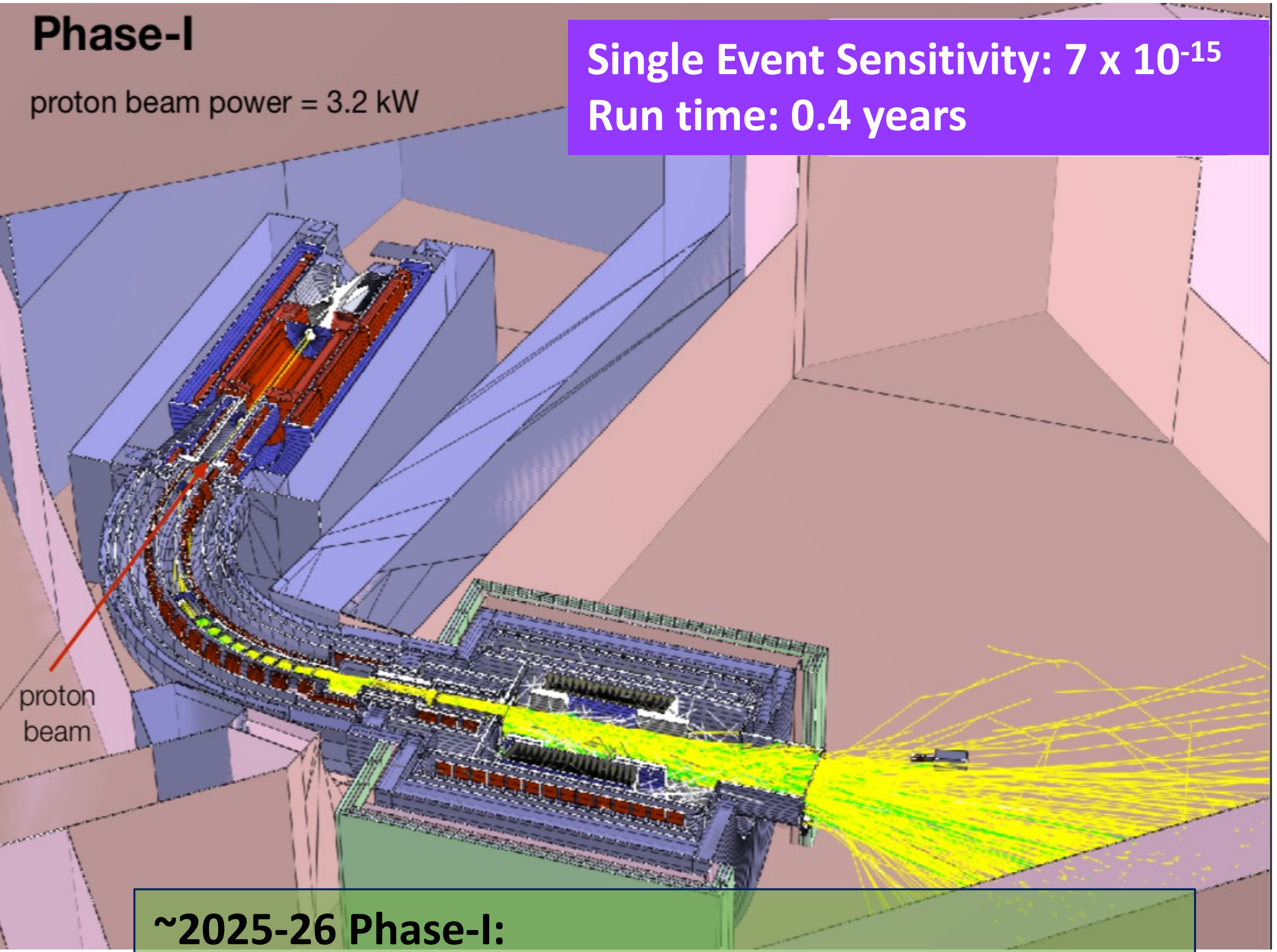
- Resulting "Wiggle plot"



- Fit the wiggle plot to extract ω_a (simplified function).

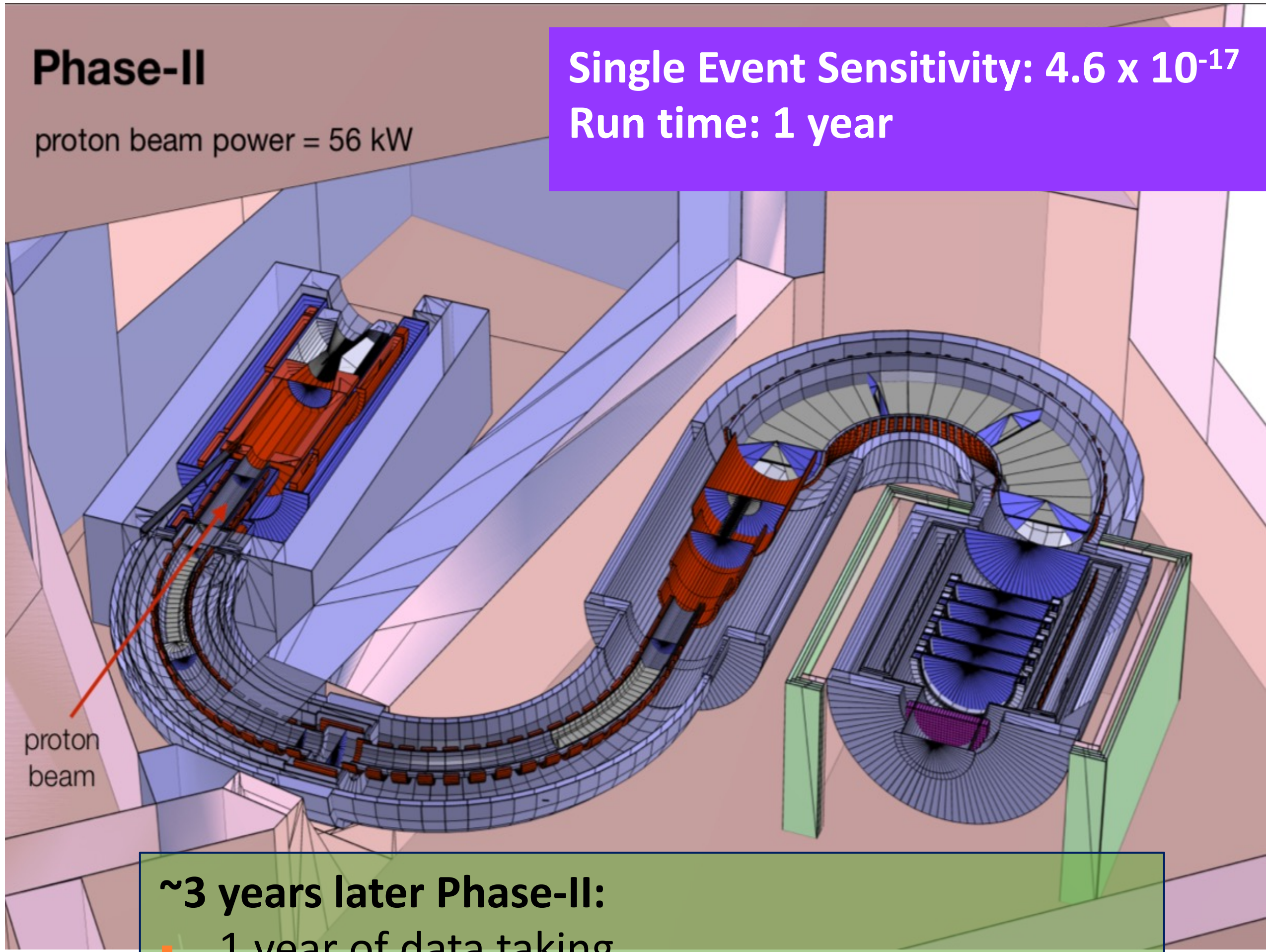
$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t - \phi)\right]$$

$N\mu^- \to Ne^-$: COMET Design



Single Event Sensitivity: 7 x 10^{-15}
Run time: 0.4 years

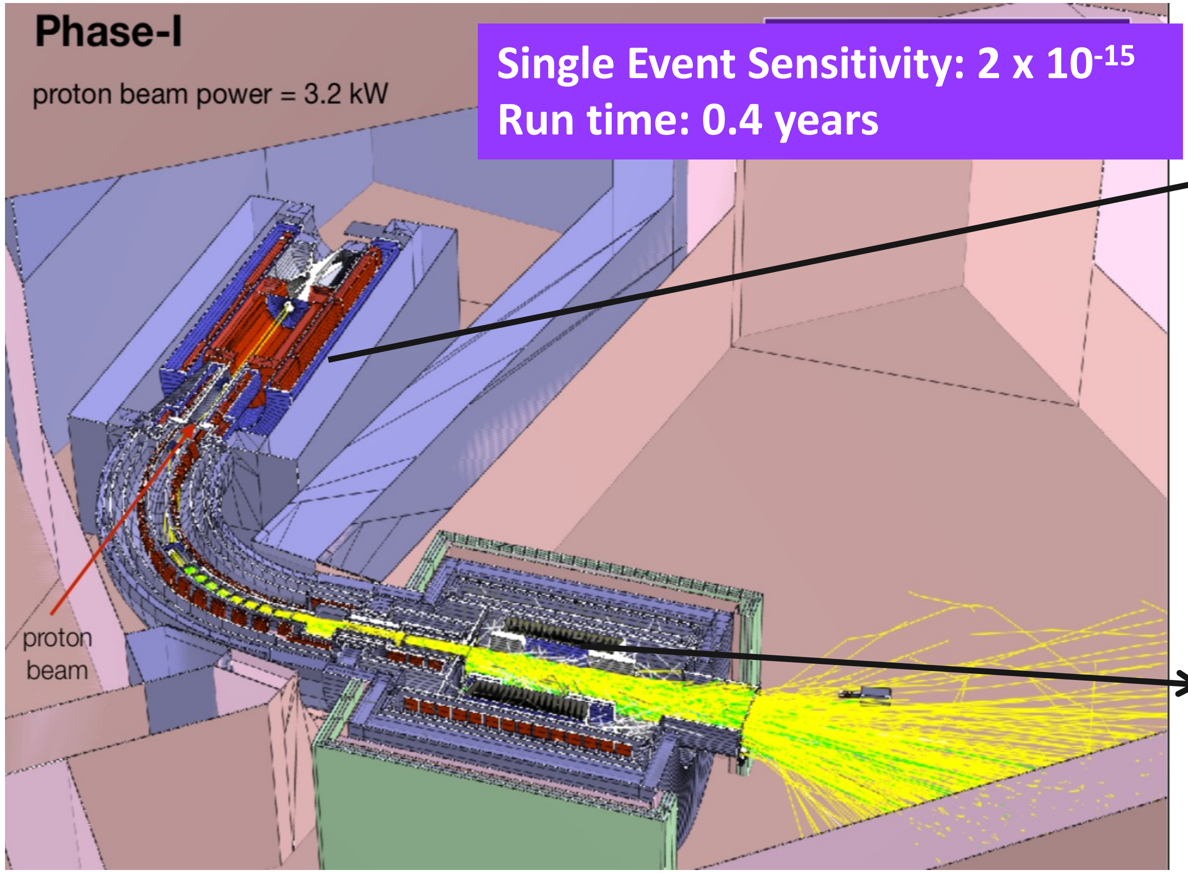
~2025-26 Phase-I:
- 3 months of data provides sensitivity of 7 x 10^{-15}



Single Event Sensitivity: 4.6 x 10^{-17}
Run time: 1 year

~3 years later Phase-II:
- 1 year of data taking
- Single-Event-Sensitivity = 4.6 x 10^{-17}

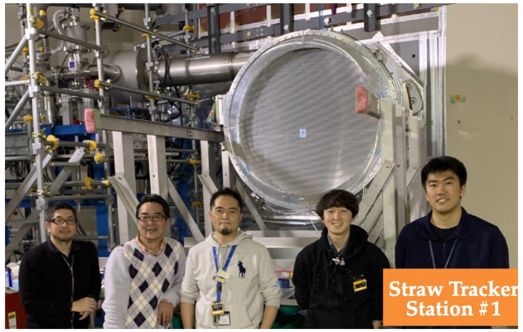
$N\mu^- \to Ne^-$: COMET Status



Single Event Sensitivity: 2 x 10^{-15}
Run time: 0.4 years

Pion Capture Solenoid complete, delivered to JPARC soon

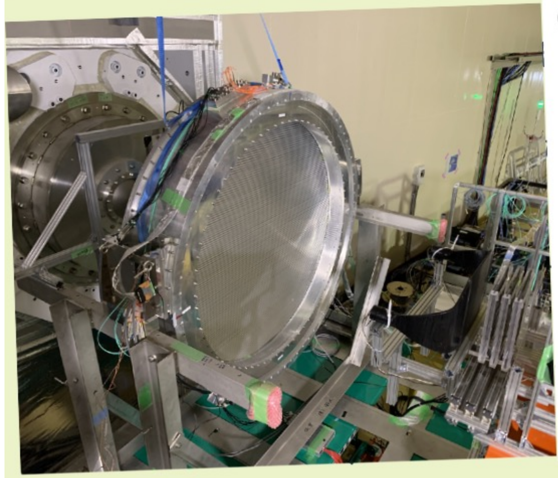
StrECAL (for beam measurement) – to be completed in 2025

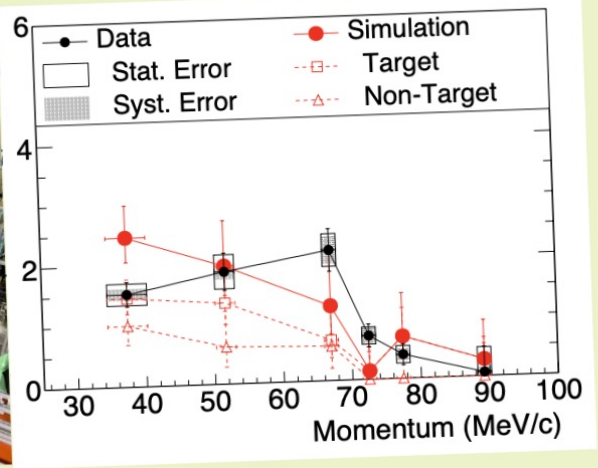


CyDet completed, commissioning with cosmics underway.

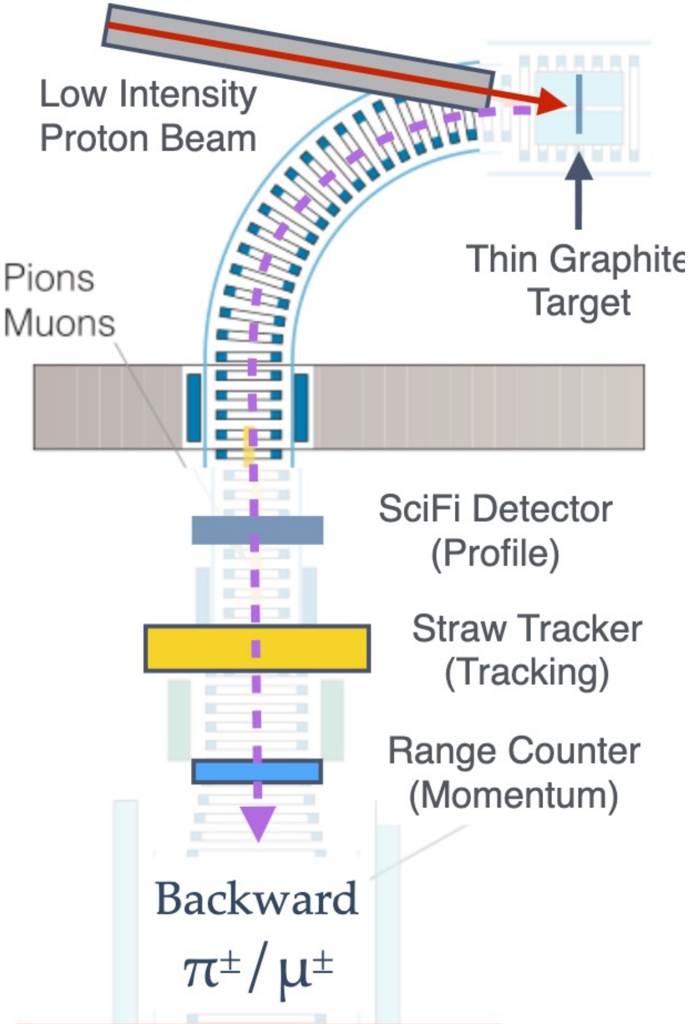
$N\mu^- \to Ne^-$: COMET Phase α

- Dedicated primary proton beam-line completed in 2022
- Low intensity proton (Phase-I x0.1) was delivered and commissioned in 2023 with muon transport solenoid but no pion capture solenoid.





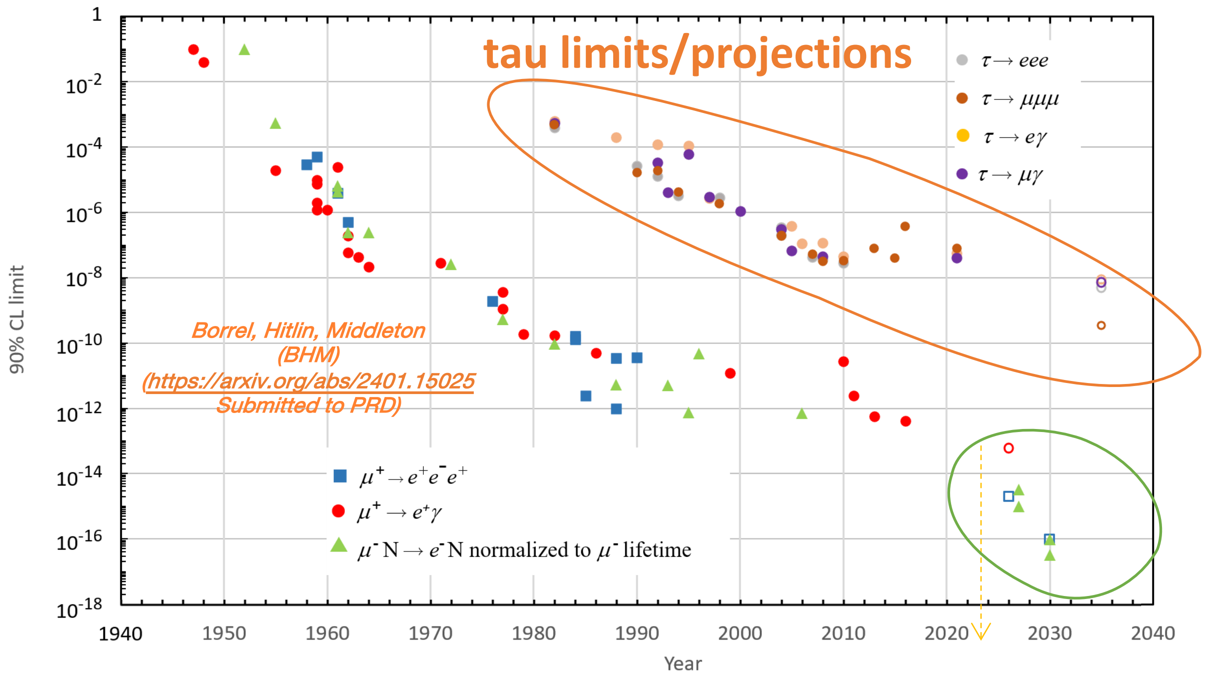
The First Proton-beam Commissioning dedicated for COMET



Phase-α

Complementarity with collider searches for CLFV

- Less stringent limits in 3rd generation, but here BSM effects may be higher.
- τ LFV searches at Belle II will be extremely clean, with very little background (if any), thanks to pair production and double-tag analysis technique.
- **To determine type of mediator:**
  - Compare muon channels to each other.
- **To determine the source of flavor violation:**
  - Compare muon rates to tau rates.



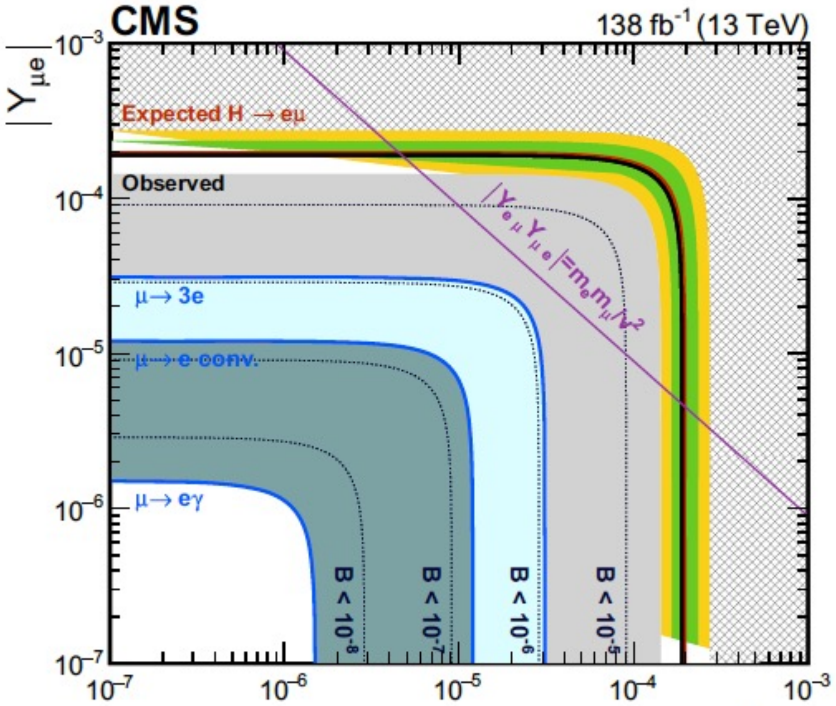
tau limits/projections

Borrel, Hitlin, Middleton (BHM) (https://arxiv.org/abs/2401.15025 Submitted to PRD)

muon projections

Complementarity with collider searches for LFV

$$\Gamma(H \to e\mu) = \frac{m_H}{8\pi}(|Y_{e\mu}|^2 + |Y_{\mu e}|^2).$$



Phys. Rev. D 108, 072004 (2023)

- Higgs LFV decays arise in many frameworks of New Physics at the electroweak scale such as **two Higgs doublet models, extra dimensions, or models of compositeness**.
- The $\mu \to e\gamma$ and $\mu \to 3e$ channels provide constraints but conversion searches such as Mu2e provide tightest projected constraints
- Current $\mu \to e$ conversion implies:

$$\boldsymbol{\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 4.6 \times 10^{-5}}$$

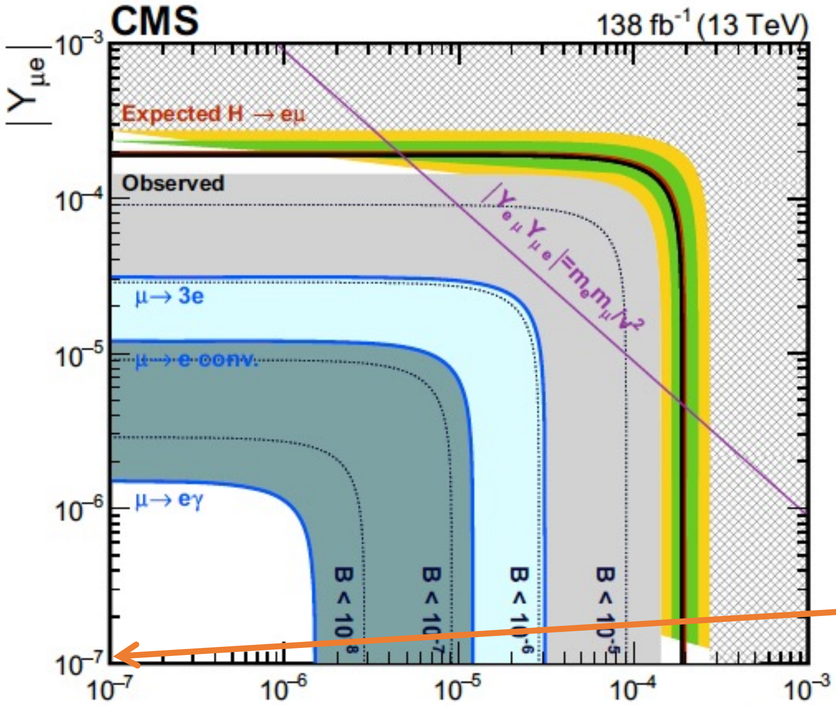
- Mu2e is expected to be sensitive to:

$$\boldsymbol{\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} \sim \mathrm{O}(10^{-7})}$$

where$|Y_{\mu e}|$ and $|Y_{e\mu}|$ are off-diagnol flavor-violating Yukawa couplings for a 125 GeV Higgs boson i.e. $H \to \mu e$.

Caltech

Complementarity with collider searches for LFV



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