Working Group 4 (Muon Physics) Summary

Gavin Hesketh, UCL, 21st September 2024

NuFact 2024, Argonne National Laboratory

Q1) Status: what can and will we learn from muons at existing facilities?
Q2) Opportunities: what are the opportunities for muon physics from future facilities for example PIP-II at Fermilab, HiMB at PSI?
Q3) Requirements: What beams/facilities are needed for future muon experiments?

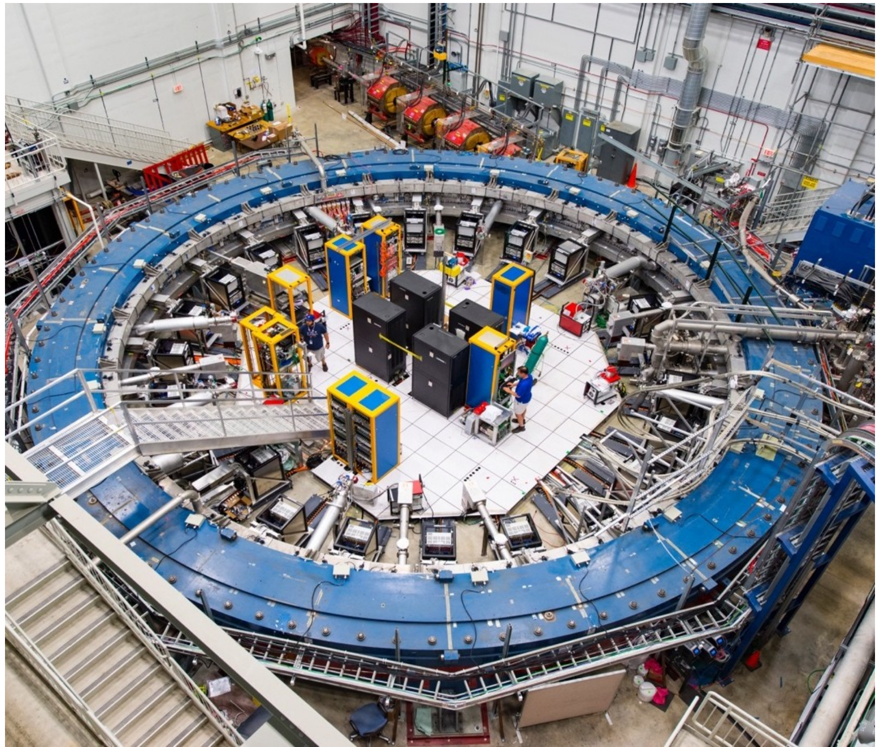
$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} + \vec{\omega}_{EDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E}) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}.$$

$$a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s},$$

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} + \vec{\omega}_{EDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{\beta} \times \vec{E}) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right]$$

EDM causes vertical spin precession
- In the Standard Model, $\eta \sim 0$
- ongoing search at FNAL Muon g-2



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Choose "magic momentum" $\gamma = 29.3$
- spin precession ~only depends on a and B.

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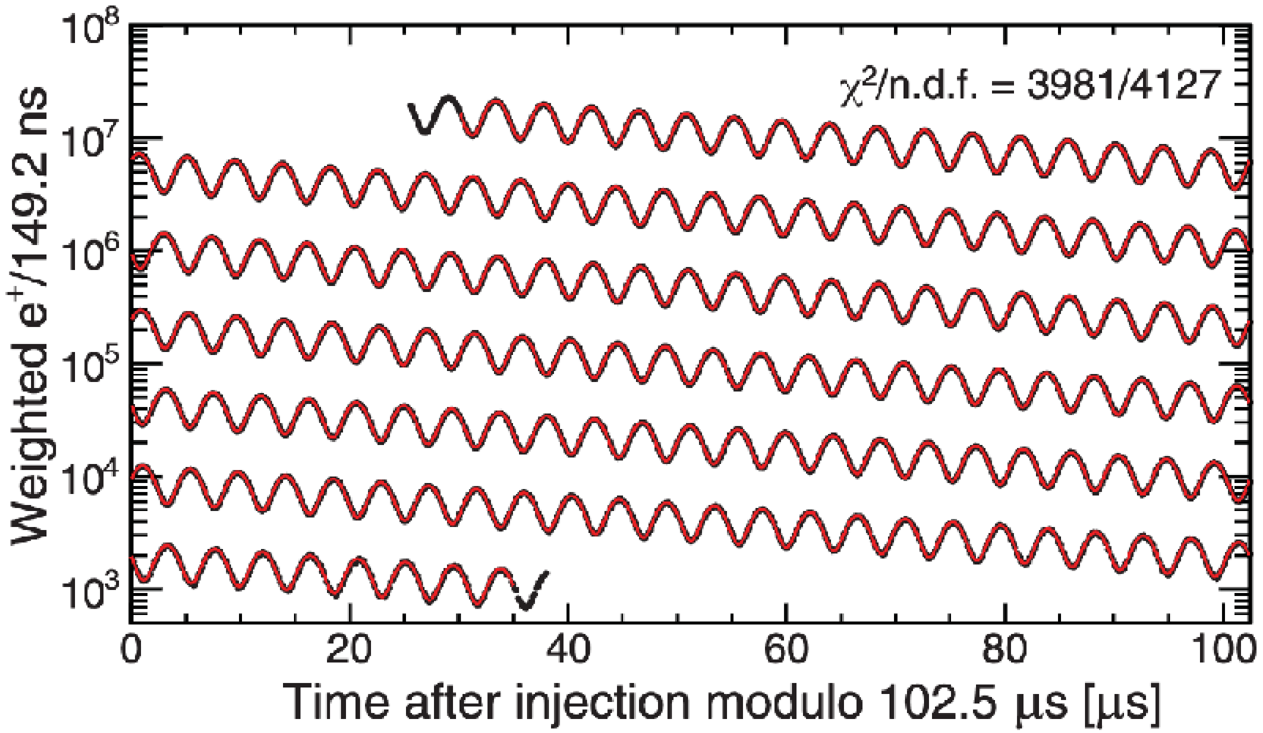

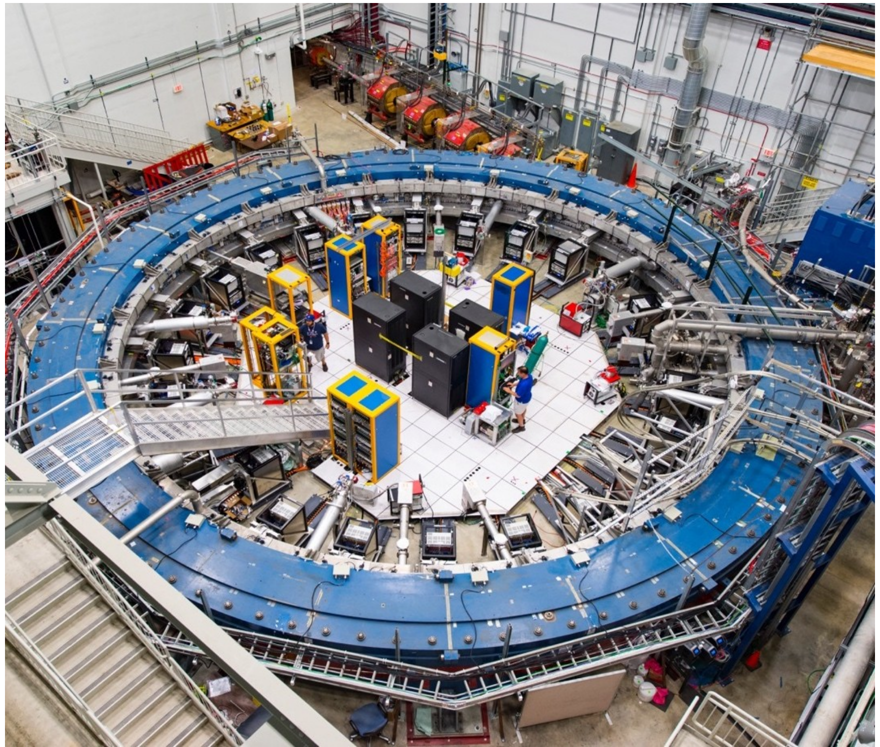

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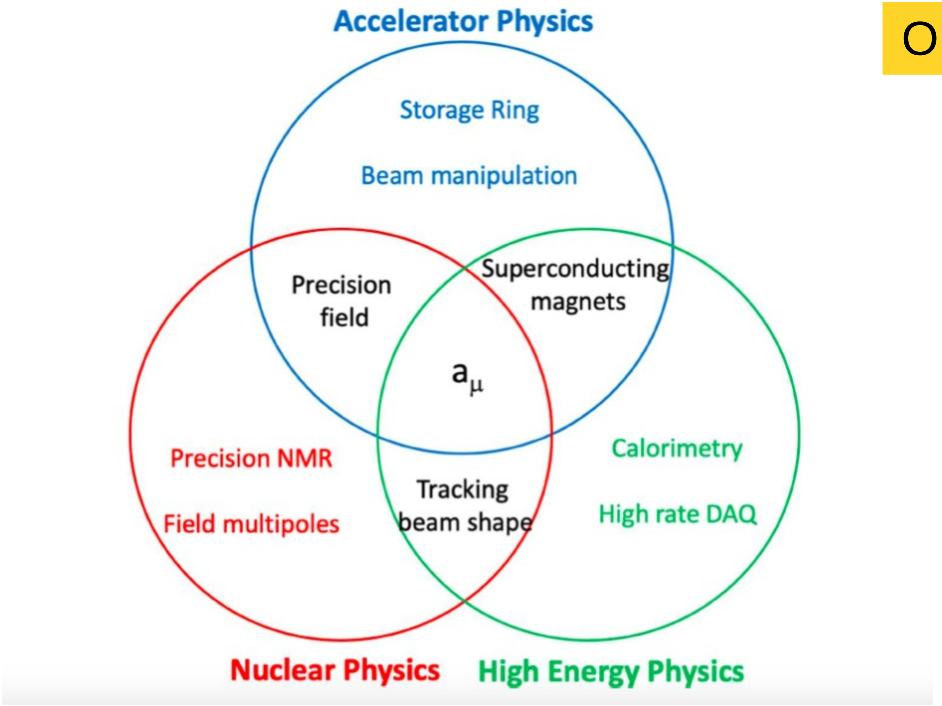
Choose "magic momentum" $\gamma = 29.3$
- spin precession ~only depends on a and B.

What we measure. Known to 24 ppb

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

On Kim



Omega-a Team (talk by On Kim)

Beam Dynamics Team (talk by David Tarazona)

Unblinding conversion factor

Measured frequency

Beam dynamics corrections

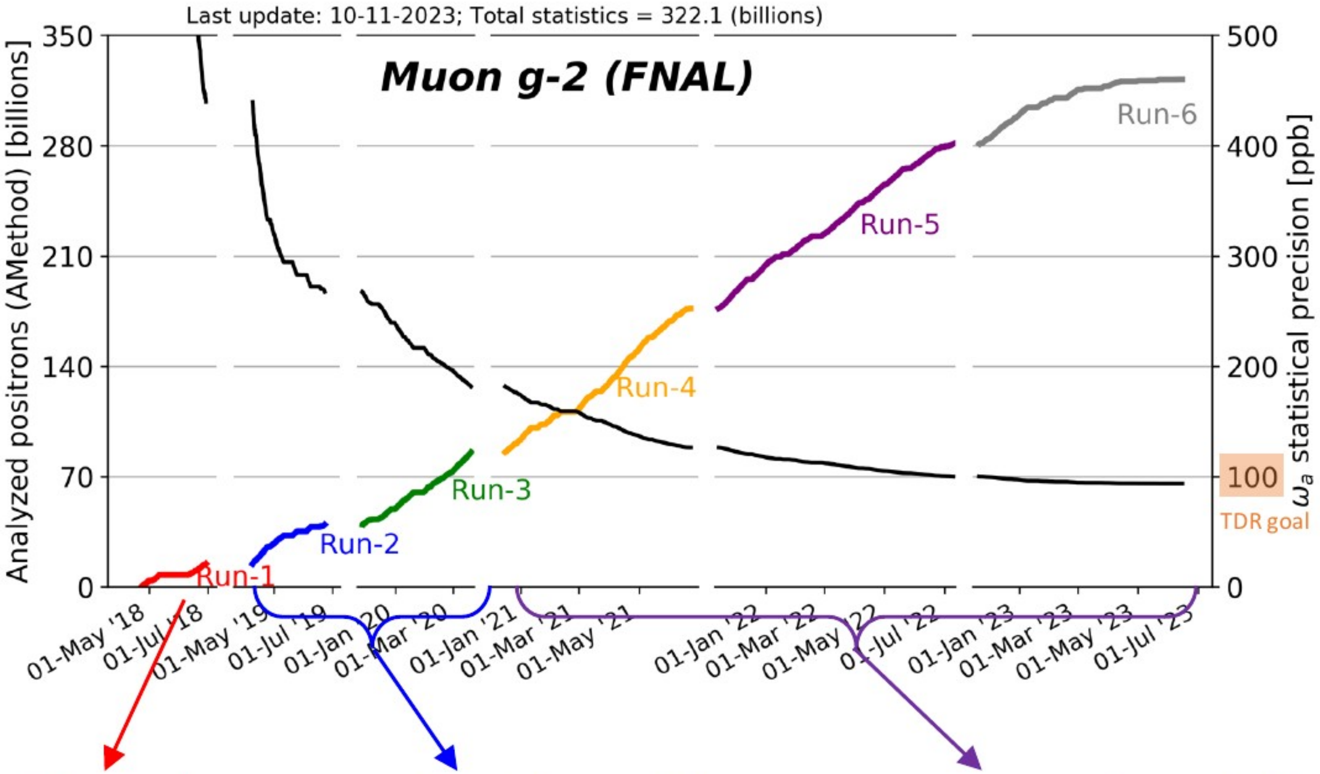
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

NMR probe calibration factor

Magnetic field weighted over the muon distribution

Corrections from the transient magnetic field

Magnetic Field Team (talk by David Kessler)



First result (Run-1)
(published 2021)

Second result (Run-2/3)
(published 2023)

Final result (Run-4/5/6)
(anticipated 2025)

Our physics operation terminated in June 2023.

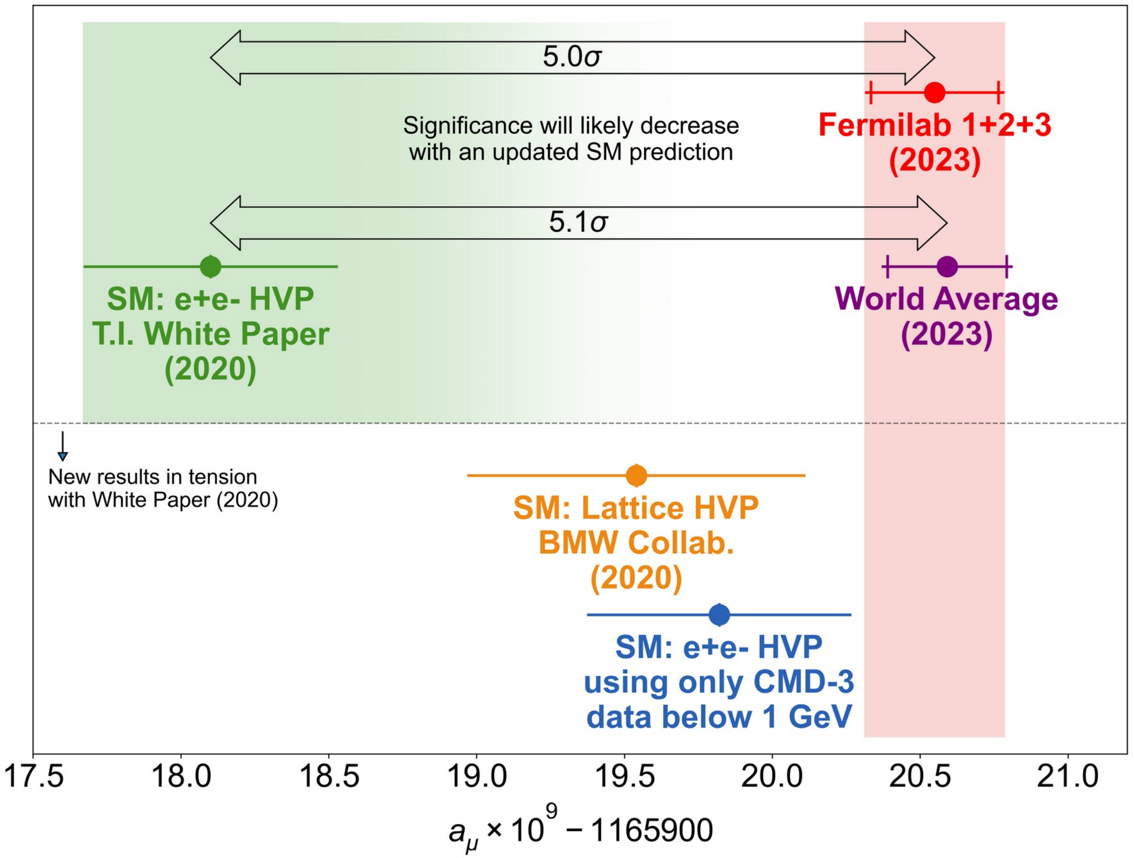
We met the TDR statistics goal!
And surpassed the systematics goal in the Run-2/3 analysis!

Stay tuned for the final result! (2025)

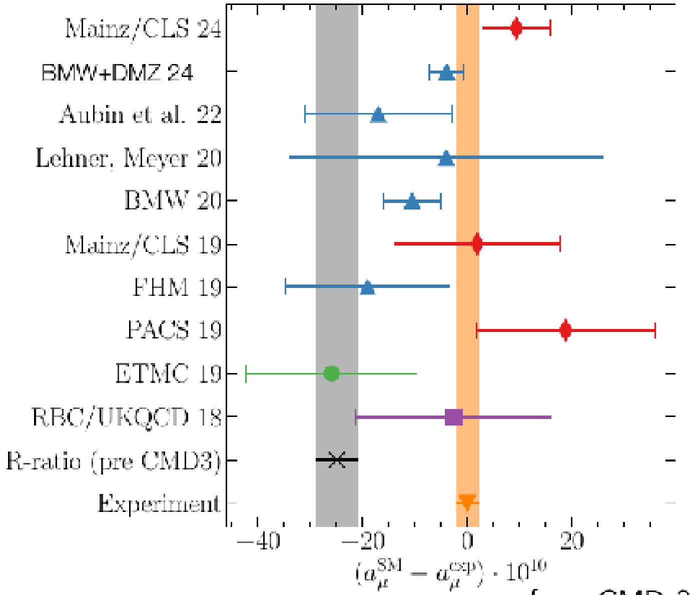
On Kim

2025 will be an interesting year
- final Muon g-2 result
- first EDM search at FNAL Muon g-2
- update on the theory picture

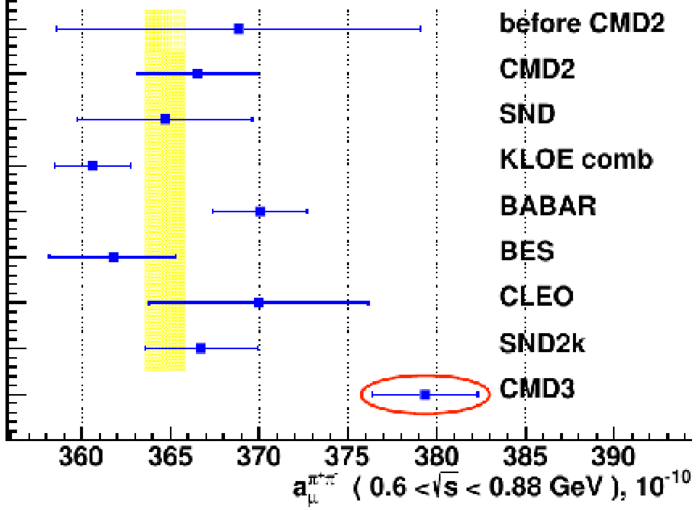
Muon g-2 Theory Status:
Plenary talks by Aida El-Khadra & Sophie Middleton



S. Kuberski @ KEK 2024



from CMD-3 [F. Ignatov et al, arXiv:2302.08834, PRD 2024]



A. Keshavarzi, Lattice 2023:

IMPORTANT: THIS PLOT IS VERY ROUGH!

- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Lots of work ongoing
- further ahead, MuOnE will help

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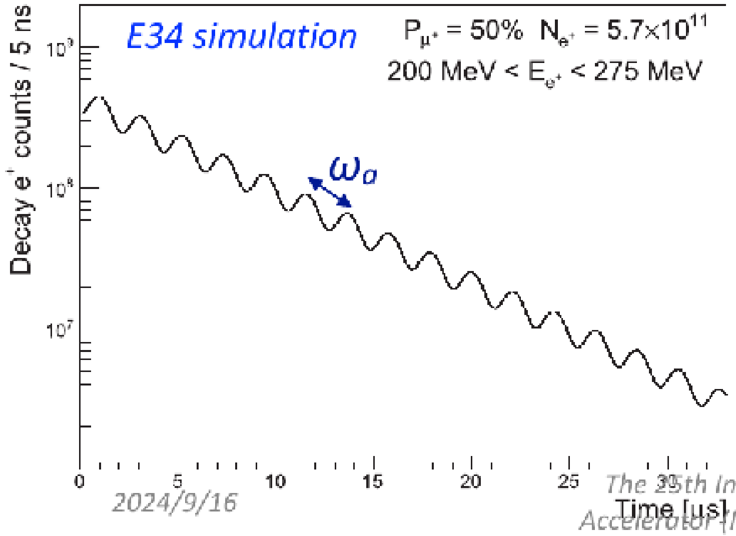
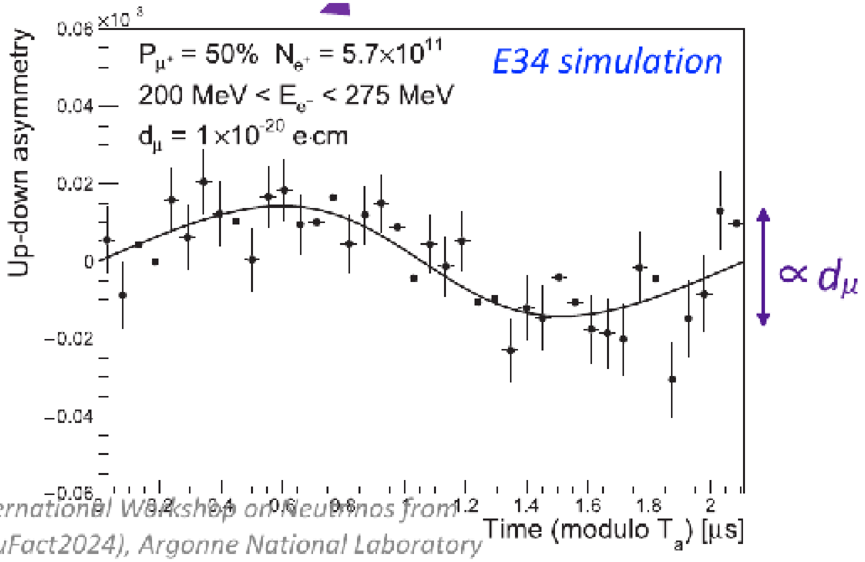
Use setup with no electric field: JPARC g-2 + EDM

- simultaneous MDM & EDM
- different systematics to FNAL

Kazuhito Suzuki





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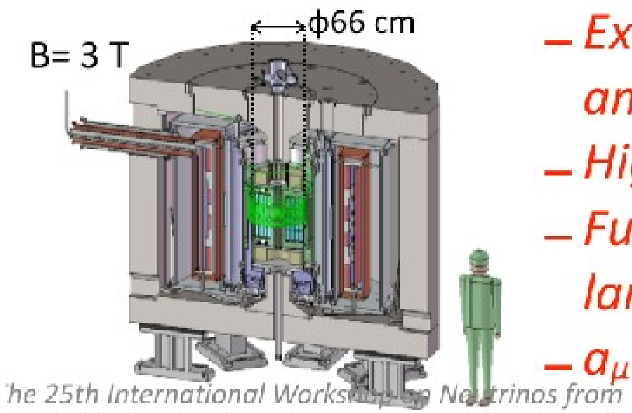
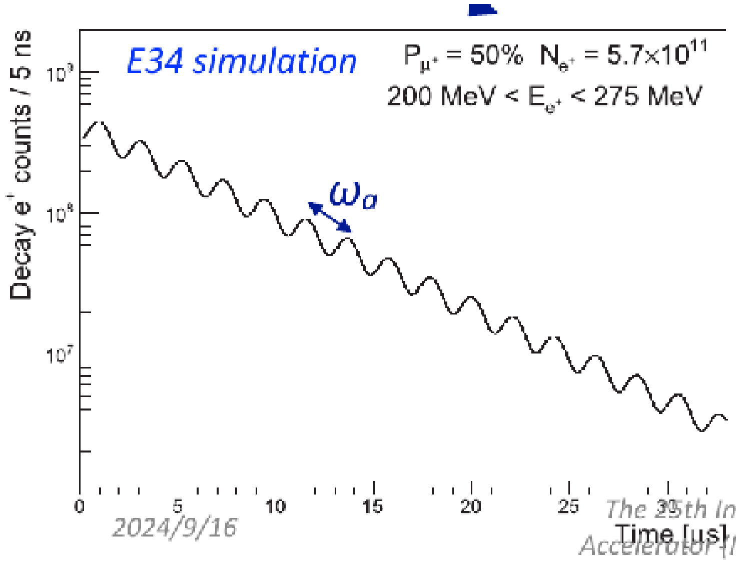
Use setup with no electric field: JPARC g-2 + EDM
- simultaneous MDM & EDM
- different systematics to FNAL

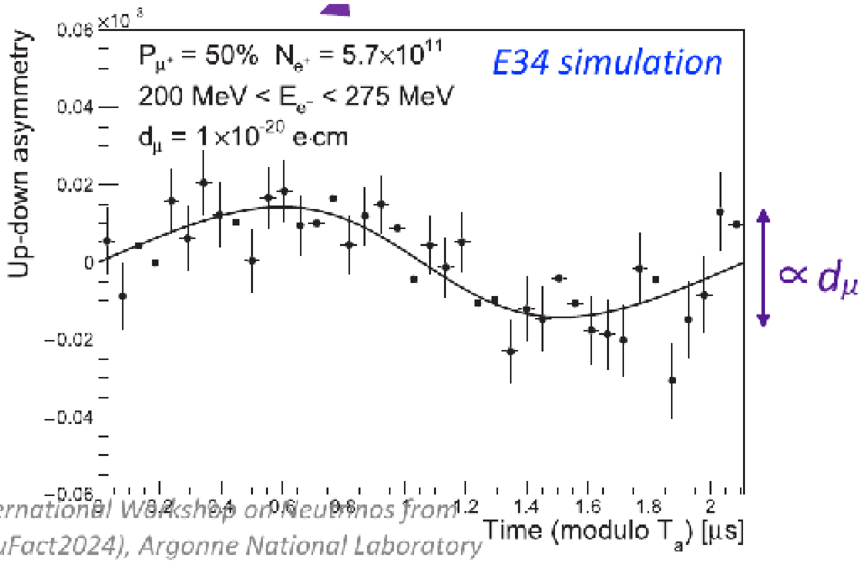
Kazuhito Suzuki

→ *Compact storage magnet*

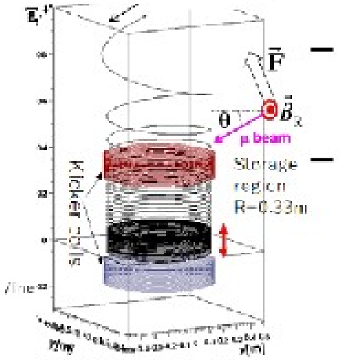


- *Existing MRI technology with an excellent local uniformity,*
- *High injection efficiency,*
- *Full-tracking capability with large acceptance,*
- *a_μ and d_μ simultaneous meas.*





- *3D spiral injection with vertical kicks*



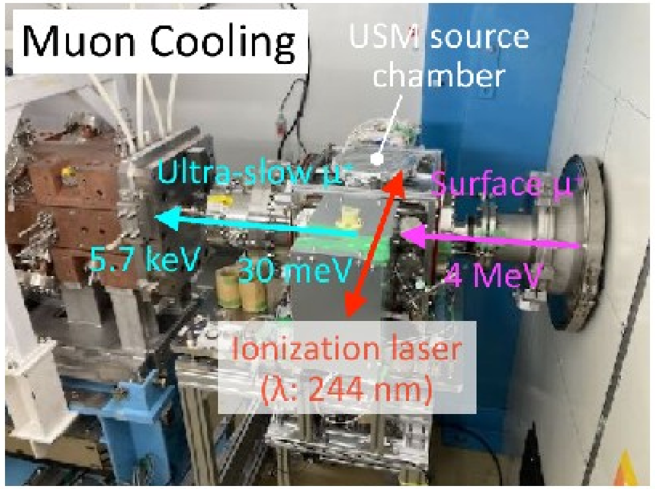
NIM A832 (2016), 51-62.

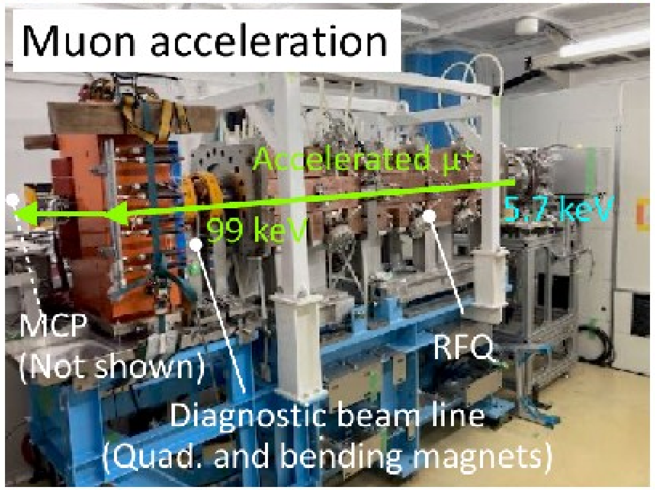
- *To inject into the small orbit with high efficiency.*
- *Extensive studies are on-going for*
  - *Injection parameters,*
  - *Kicker bench tests.*
- *The injection scheme has been successfully demonstrated using e- beam (80 keV).*

Recent achievement

- *Acceleration of USMs*

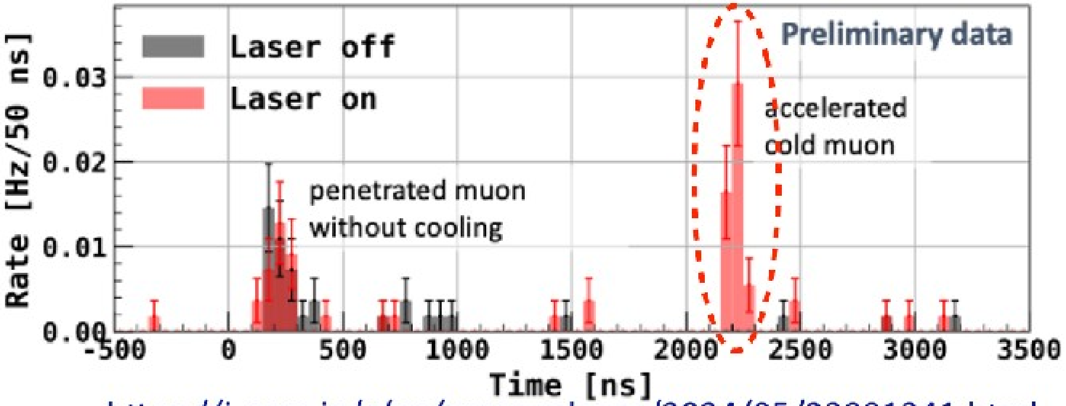
MLF S2 area (April 2024)





- *World's first muon acceleration!*

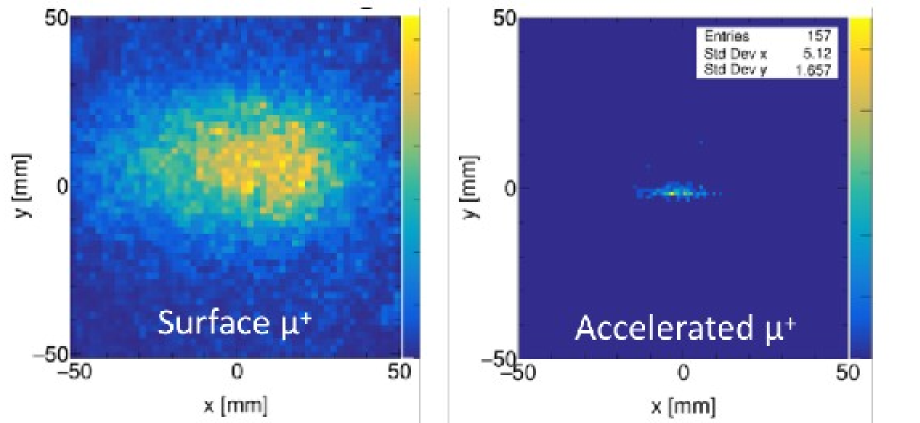
Time-of-flight at the MCP detector



https://j-parc.jp/c/en/press-release/2024/05/23001341.html

- *Much smaller μ^+ beam profile after cooling*

Scintillator & image intensifier   MCP & Phosphor plate & CCD



Kazuhito Suzuki

Next step: acceleration to 4 MeV at H2 using IH-DTL (JFY2025).

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EDMs violate CP, sensitive probes of BSM: dedicated search!

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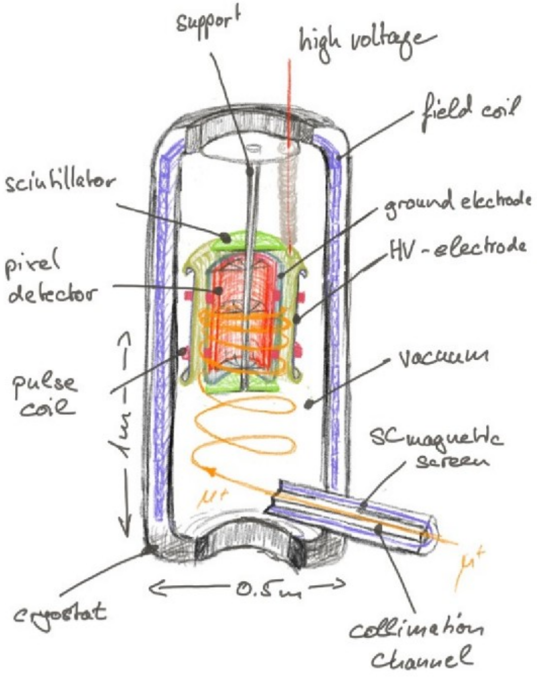
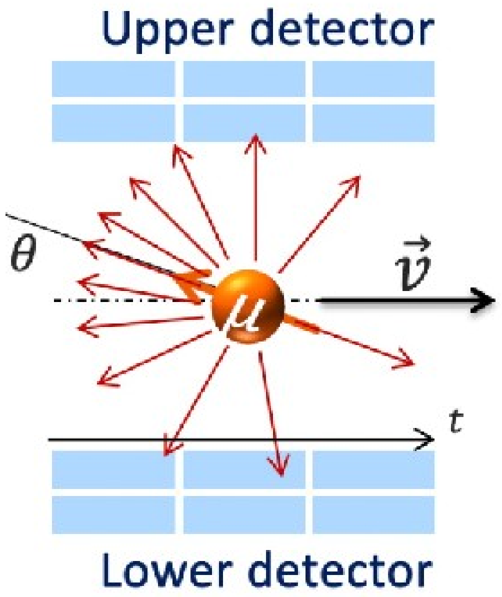
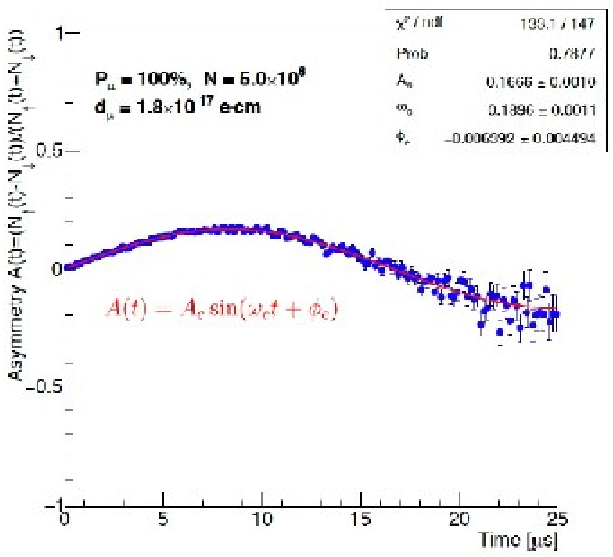
EDMs violate CP, sensitive probes of BSM: dedicated search!
- tune E and B to cancel precession due to magnetic moment
→ “frozen spin”

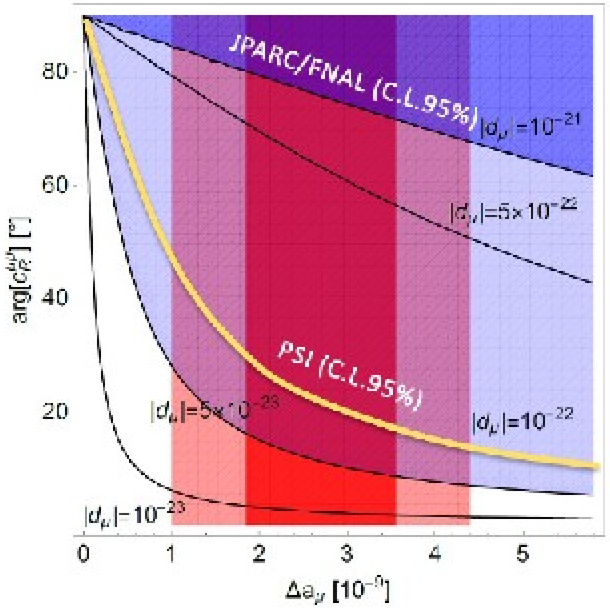
MuEDM @ PSI, aim: sensitivity of 10^{-23} e.cm

Kim Siang Khaw









PRD 98 (2018) 113002

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EDMs violate CP, sensitive probes of BSM: dedicated search!

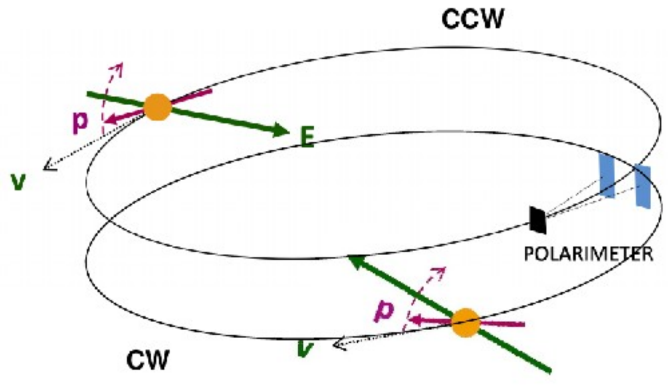
- tune E and B to cancel precession due to magnetic moment

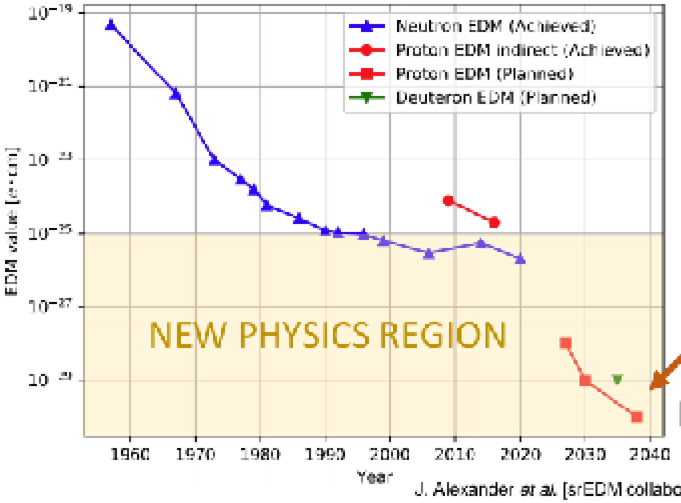
→ "frozen spin"

MuEDM @ PSI, aim: sensitivity of 10^{-23} e.cm

Proton EDM, aim: sensitivity of 10^{-30} e.cm

Alex Keshavarzi



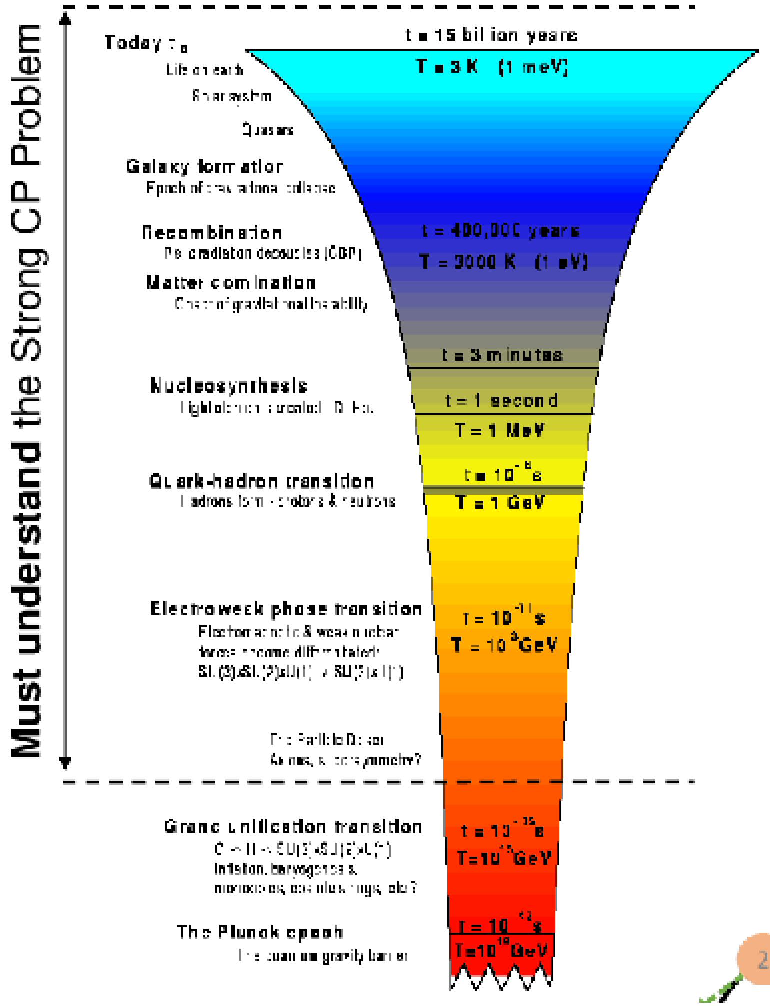


New paradigm of sensitivity

[Statistics > nEDM.]

J. Alexander et al. [srEDM collaboration], arXiv:2205.00830.

Proton EDM experiment sensitivity ~ 10^{-30} $e \cdot cm$!



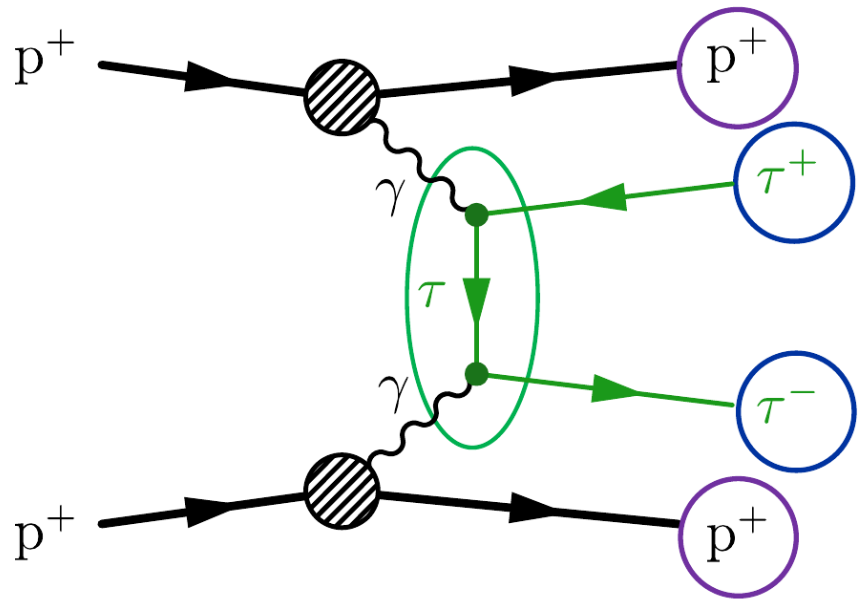
Cécile Caillol

Tau g-2

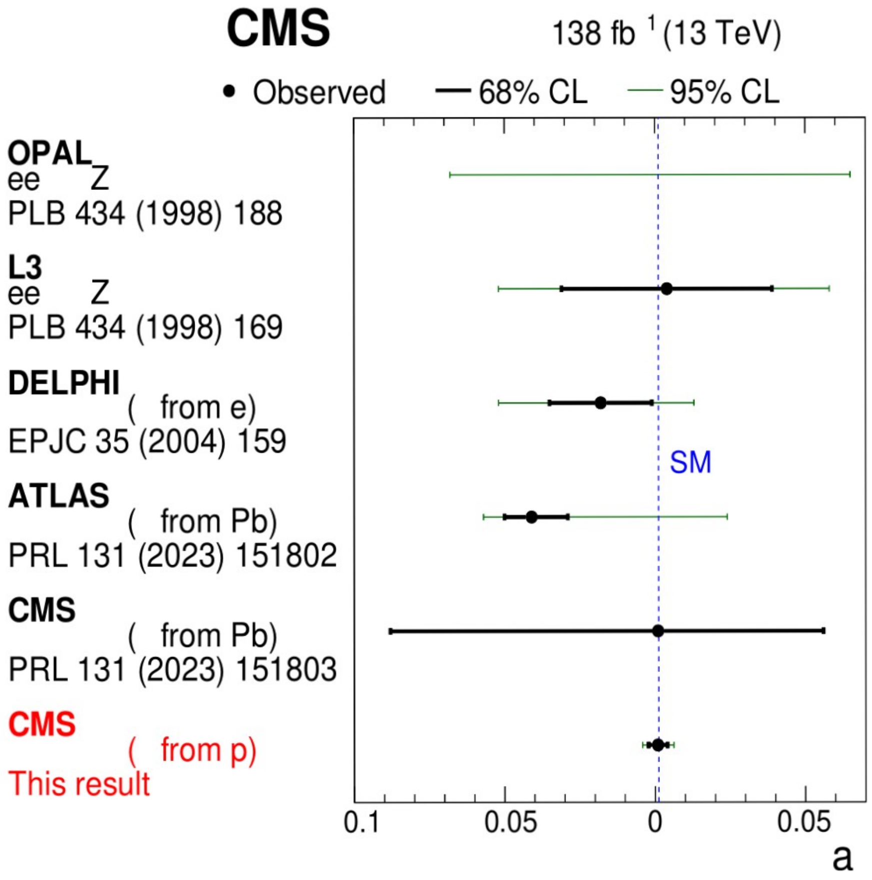
If BSM effects scale with the squared lepton mass...

...deviations from the SM could be 280 times larger for a_τ than for a_μ

...BUT Tau leptons have a very short lifetime and cannot be stored in storage rings



- 2 diffracted protons
- 2 back-to-back OS τ leptons
- No hadronic activity close to the di-τ vertex
  - $N_{tracks} = 0$



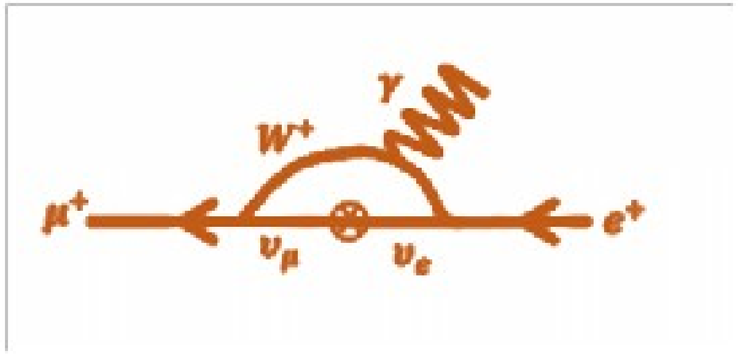
Sensitivity improved from 20x to 3x the Schwinger term!

Charged lepton flavour violation:

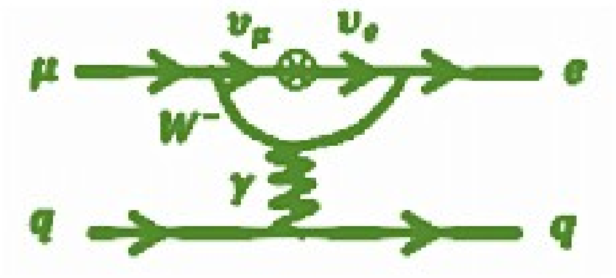
- flavour is an "accidental conservation laws" of the Standard Model
- violate in many BSM scenarios

Three "golden channels" for muons:

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



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



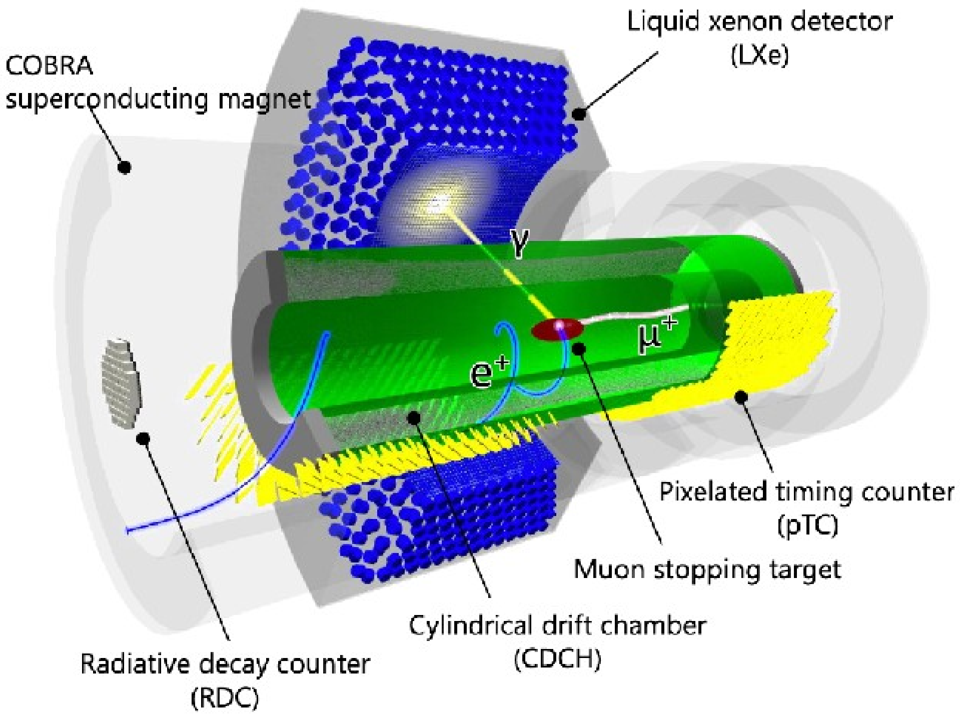
$\mu^+ \rightarrow e^+e^+e^-$

No outgoing neutrinos!

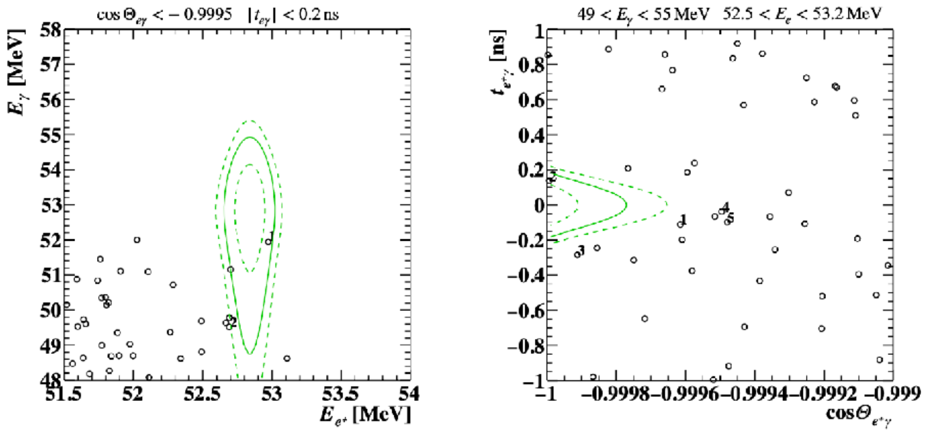
Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	3.1×10^{-13}	4×10^{-14}	MEG II
$\mu^+ \rightarrow e^+e^+e^-$	1.0×10^{-12}	5×10^{-15} 10^{-16}	Mu3e Phase-I Mu3e Phase-II
$\mu^- N \rightarrow e^- N$	7×10^{-13} (SINDRUM-II, 2006)	8×10^{-15}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

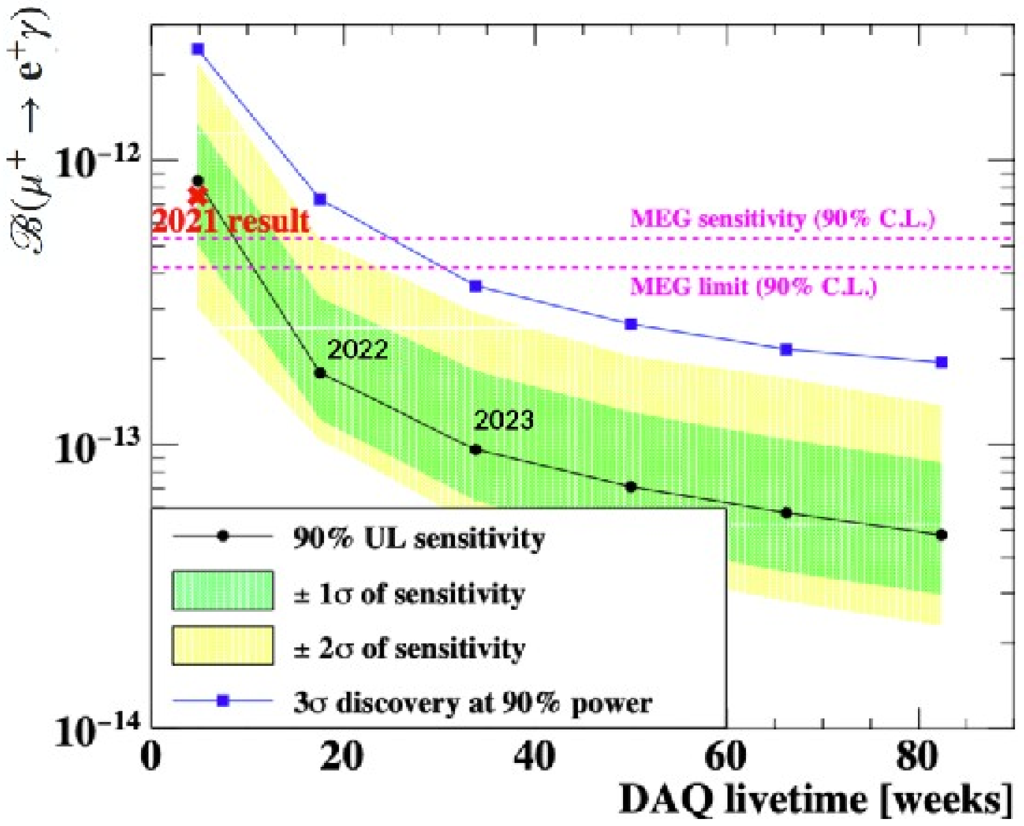
Muon CLFV Overview: Sophie Middleton

First results from MEG-II: Matteo De Gerone
- search for μ→eγ



EPJ C 84:190 (2024)



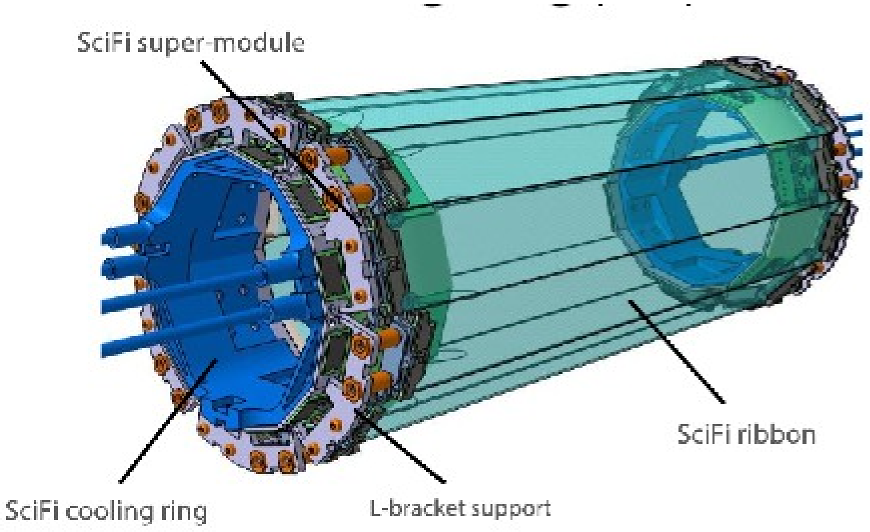


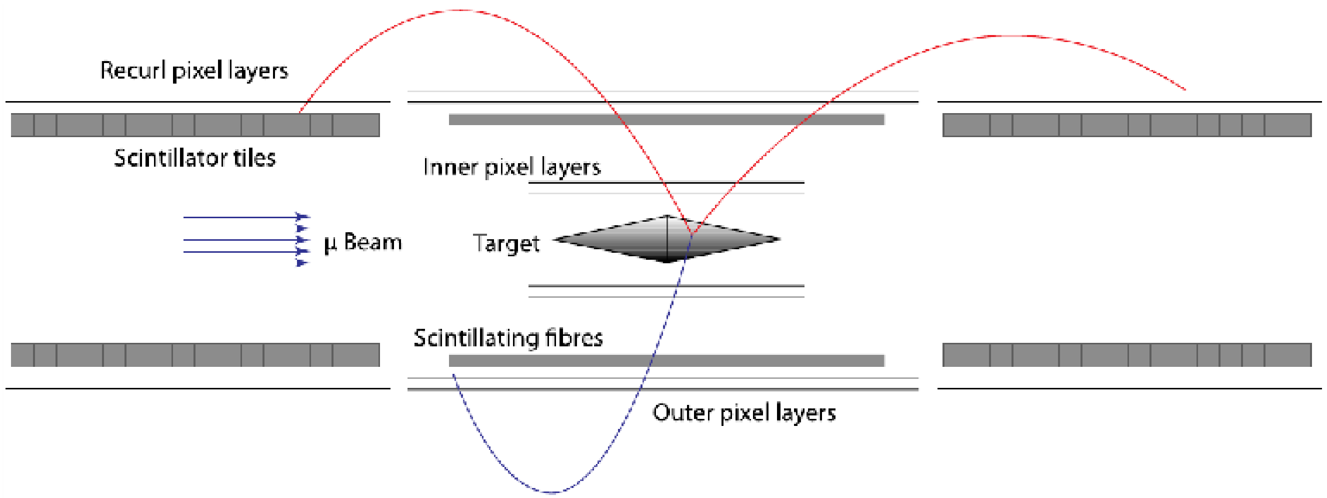
7 week run from 2021 almost matched full MEG sensitivity
Combination with MEG set most stringent limit to date:

BR(μ→eγ) < 3.1 10^{-13} @90% CL

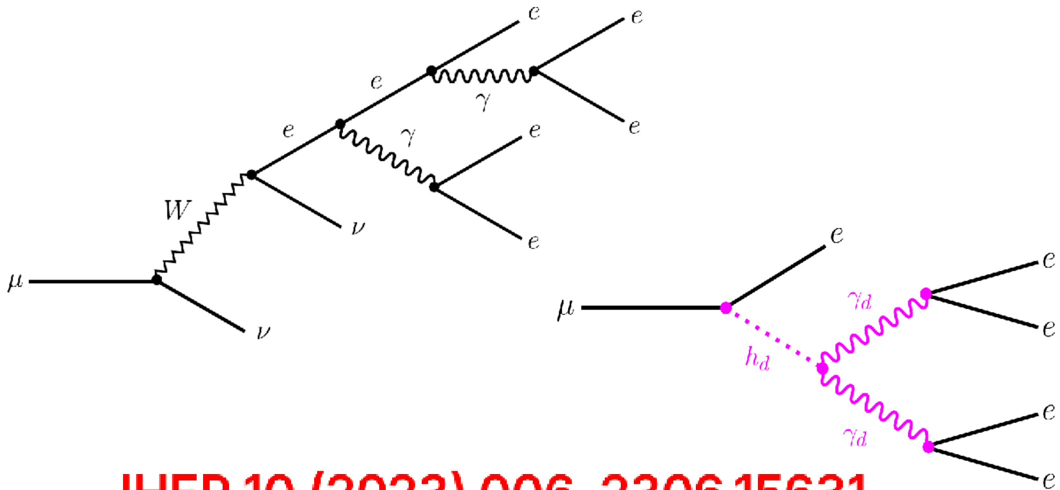
Mu3e Status Robert-Mihai Amarinei
- search for $\mu\rightarrow eee$
- aim for 10^4 improvement in sensitivity

Need excellent momentum, vertex & timing information
- for low-energy electrons





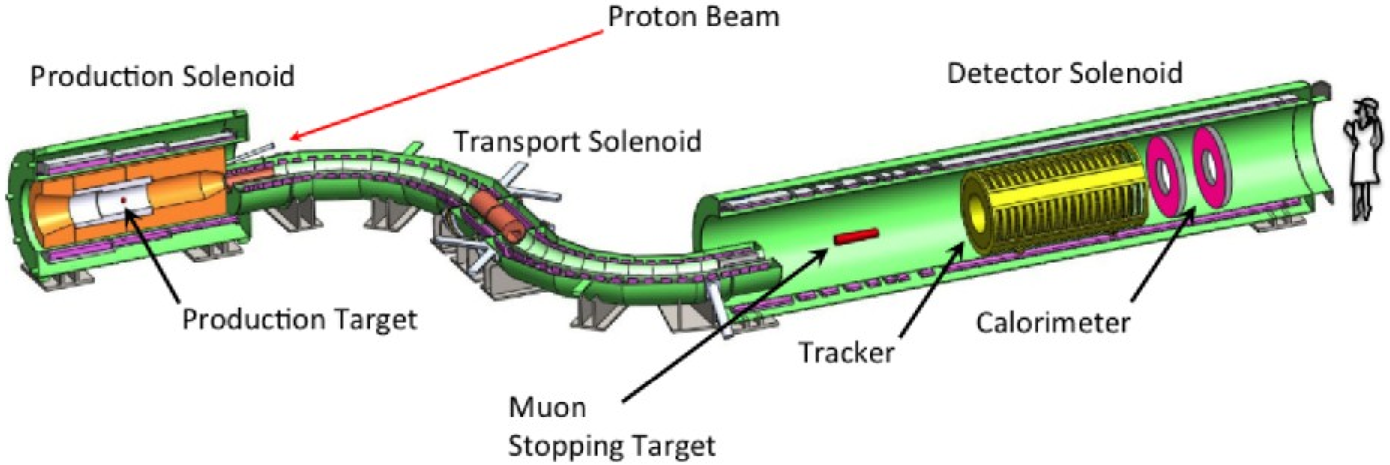
Mu5e?! Tony Menzo
- Mu3e should see 100's SM events
- can set limits on BSM enhancements

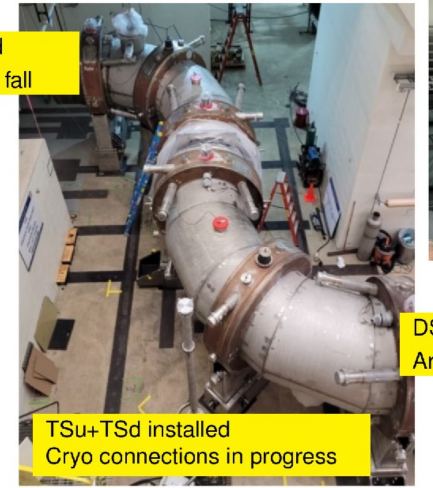


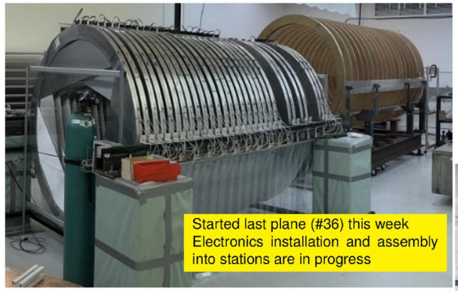
JHEP 10 (2023) 006, 2306.15631

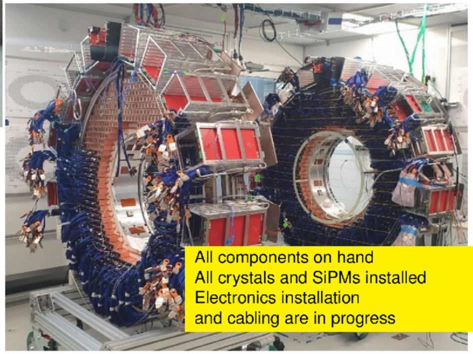
Mu2e Status: Andrei Gaponenko

- search for $\mu N \to eN$
- physics data before 2027 shutdown
- x1000 on current sensitivity
- COMET similar



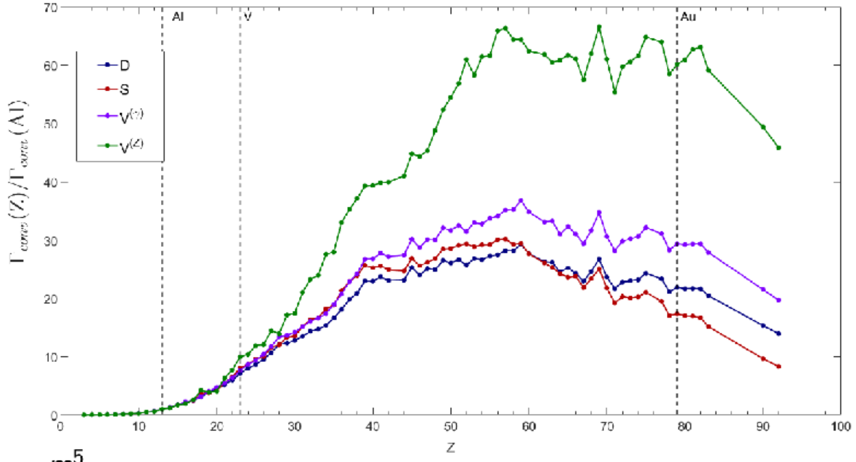






New study of stopping target dependence:

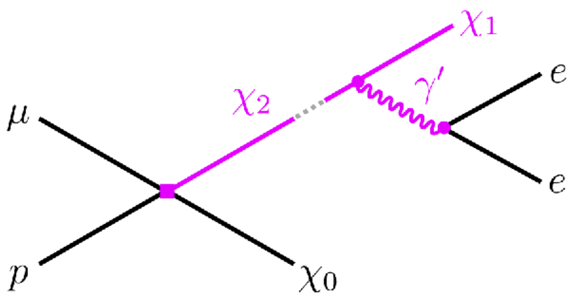
- Leo Borrel, arXiv:2401.15025
- Al → V for Mu2e-II?



$$\Gamma^N_{\mu\to e} = \frac{m_\mu^5}{4\Lambda^4}\left|eC_L^D D_N + 4\left(G_F m_\mu m_p \tilde{C}^{SL}_{(p)} S_N^{(p)} + \tilde{C}^{VR}_{(p)} V_N^{(p)} + p \to n\right)\right|^2 + L \leftrightarrow R$$

More BSM scenarios: Tony Menzo

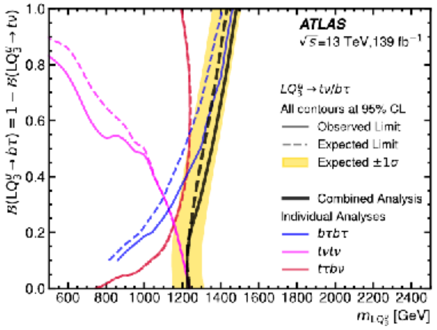
- $E_e > 105$ GeV

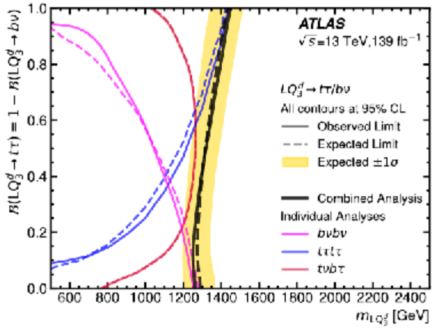


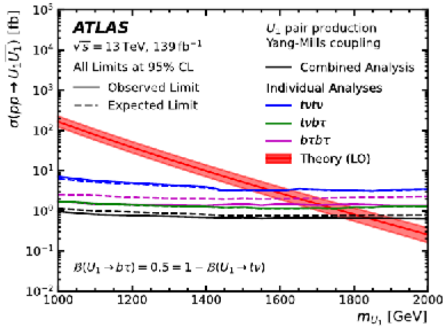
ATLAS, CMS, Belle can test huge range of LFV BSM models

Ben Wilson, Federica Simone, Paolo Leo

Leptoquarks: up to 100 GeV improvement in limits



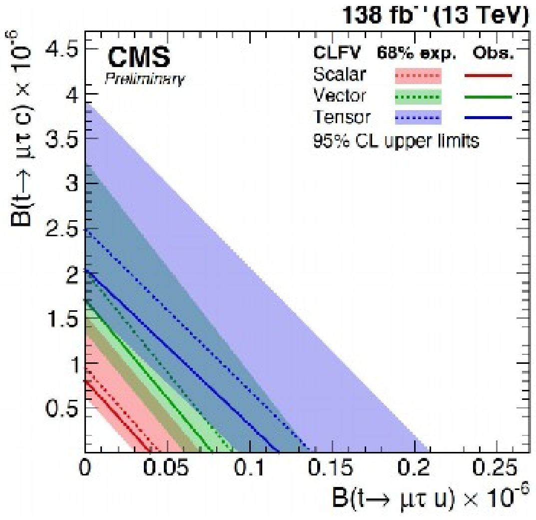


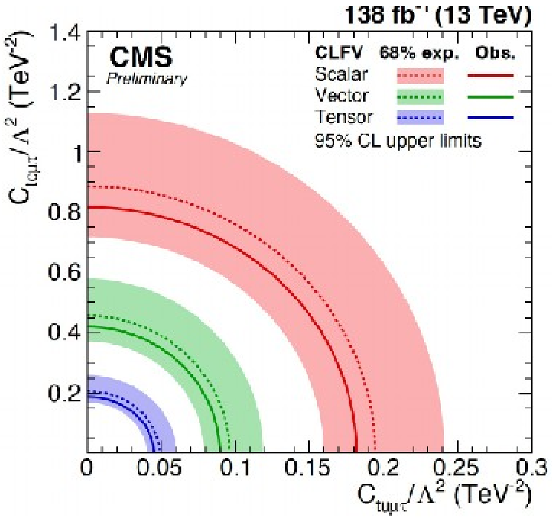


τ→μμμ

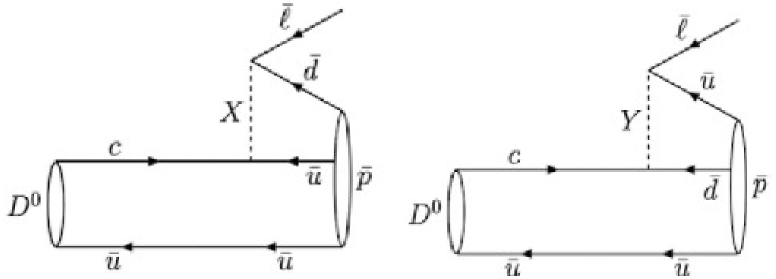
	UL at 90% C.L. on $\mathcal{B}(\tau \to 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3$ fb^{-1})
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0$ fb^{-1})
CMS	2.9×10^{-8} ($\mathcal{L} = 131$ fb^{-1})
Belle	2.1×10^{-8} ($\mathcal{L} = 782$ fb^{-1})
BaBar	3.3×10^{-8} ($\mathcal{L} = 486$ fb^{-1})
Belle II	1.9×10^{-8} ($\mathcal{L} = 424$ fb^{-1})

CLFV in top decays:

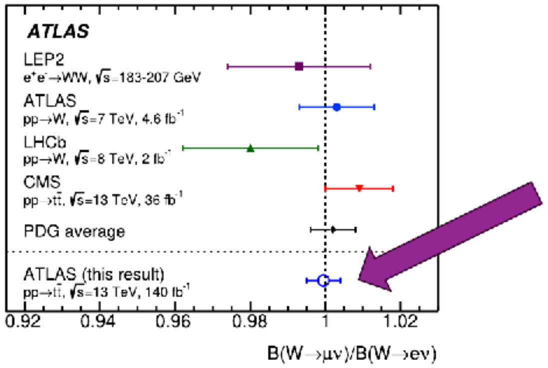




A range of heavy flavour LFV searches:



...and new measure of lepton universality in W decays

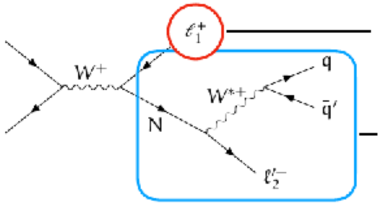


Searches for Heavy Neutral Leptons as ATLAS and CMS

Martin Kwok, Ben Wilson

- new ideas being explored to push param. space!

Displaced object reconstructions with ML

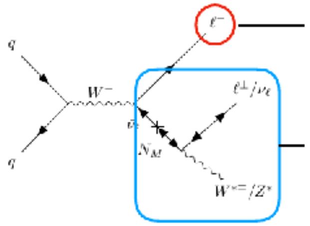


Prompt lepton

Displaced $N \to \ell qq$

EXO-21-011, EXO-21-013

Novel displaced signature - Muon Detector Shower

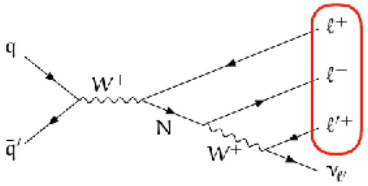


Prompt lepton

Displaced N inclusive decay

EXO-22-017

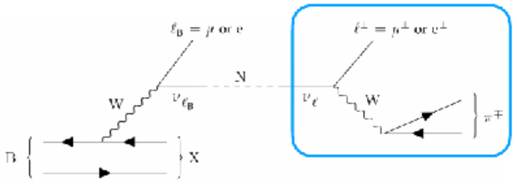
Prompt $3\ell = (e, \mu, \tau)$



Prompt leptons from PV

EXO-22-011

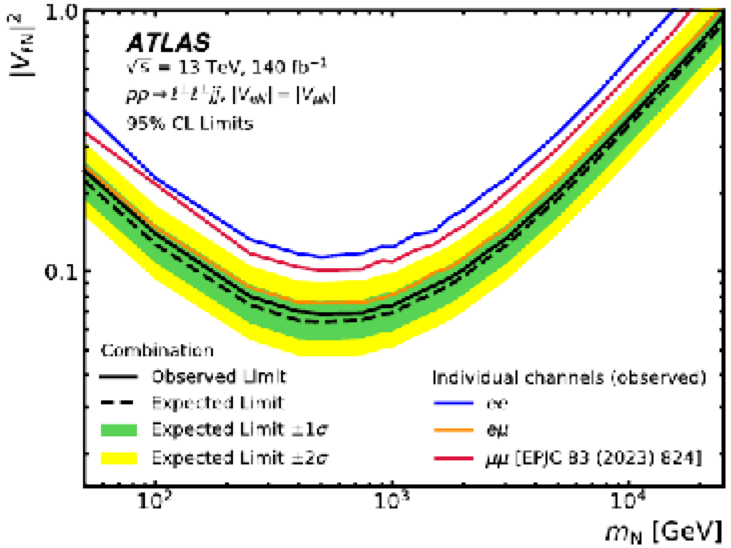
Novel data stream - HNL with B-parking dataset



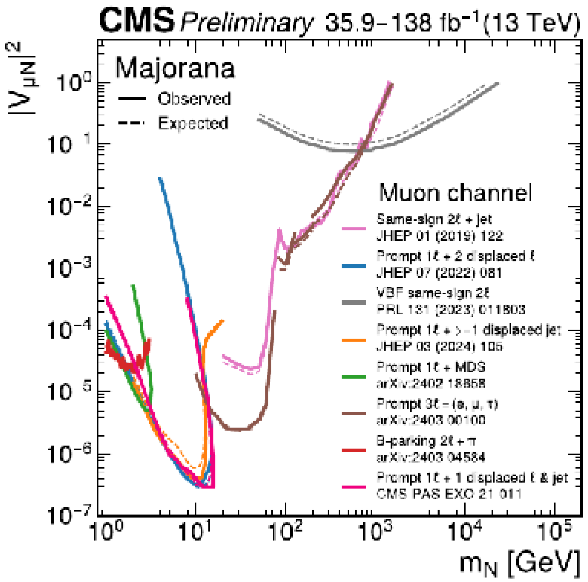
$N \to l\pi$

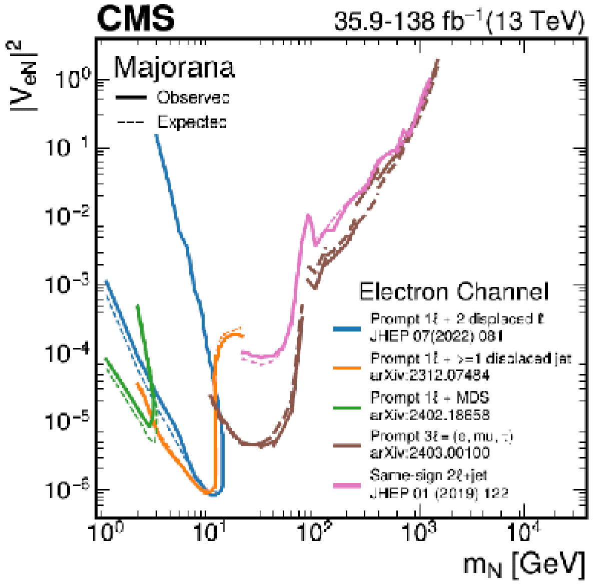
EXO-22-019

Phys. Lett. B 856 (2024) 138865



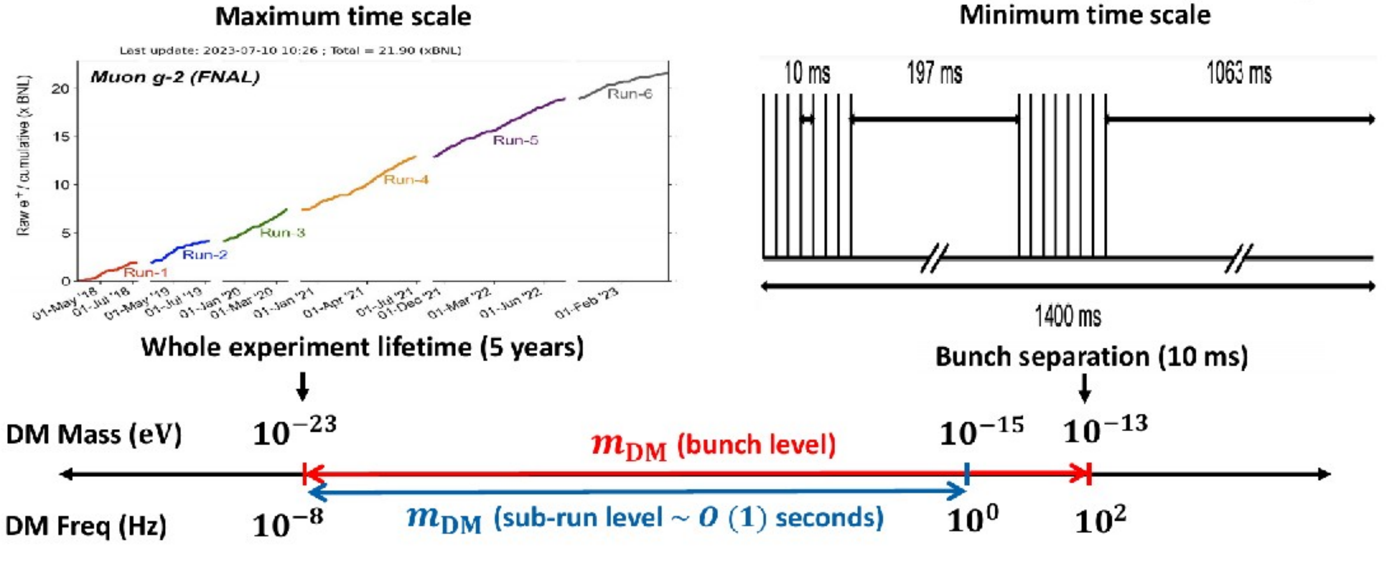
EXO-23-006



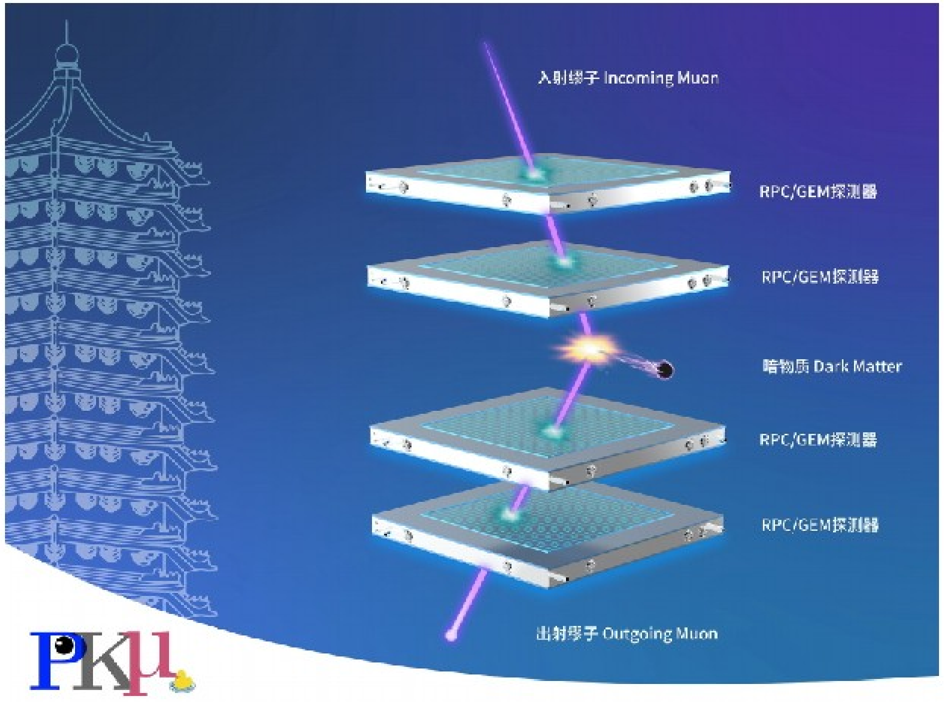


Byungchul Yu
Scalar DM search with Muon g-2:
- induce oscillation in muon mass at DM freq.

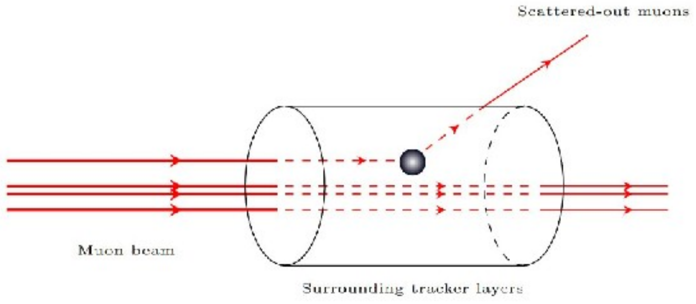
$$\omega_a(t) = a_\mu \frac{q}{m(t)} B$$

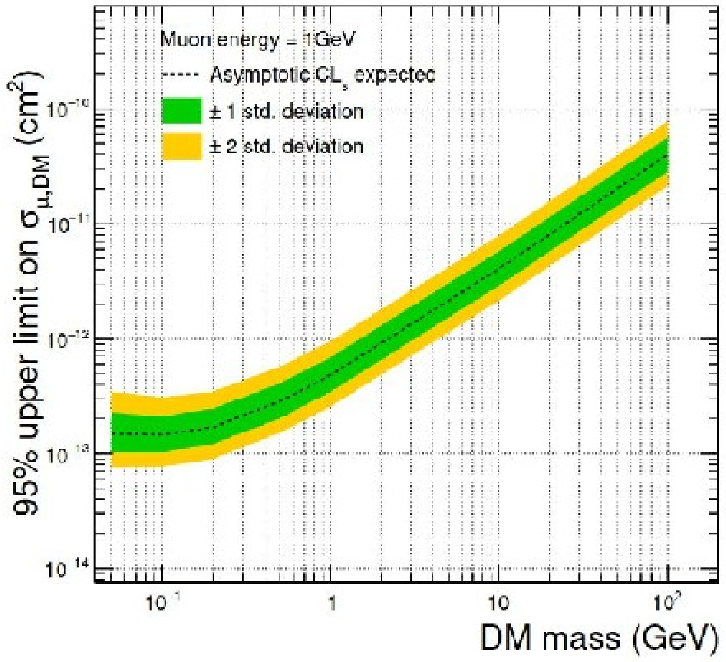


Expected Dark Matter mass range with its corresponding frequency

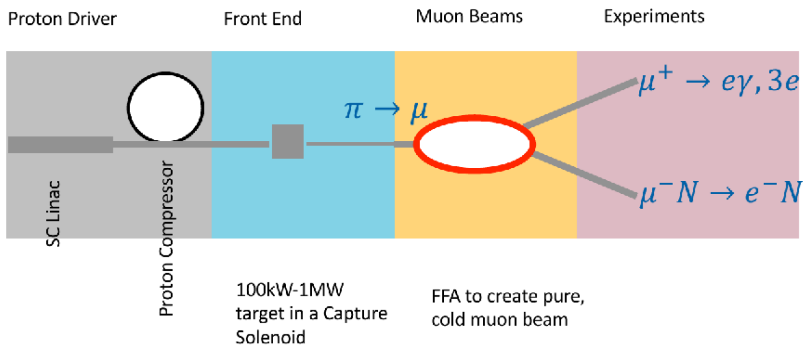


Qiang Li
Muon – DM scattering
- tomography, or muon beam

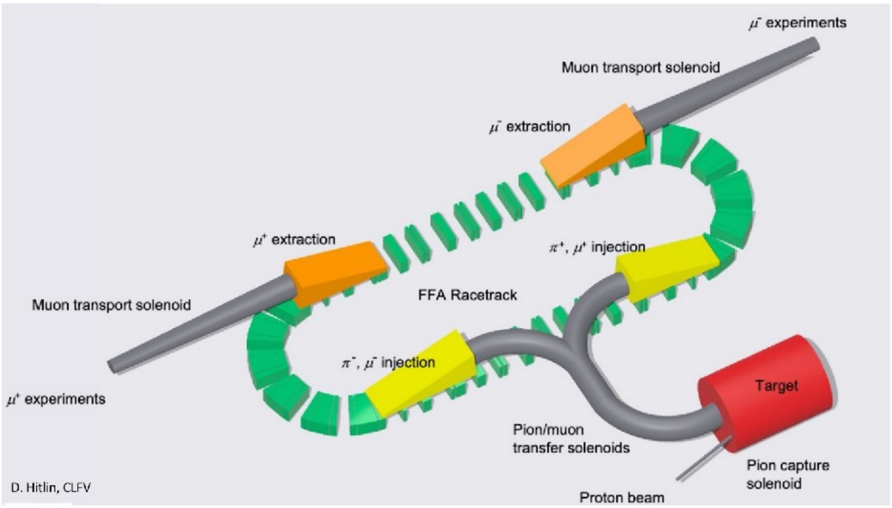




Q1) Status: what can and will we learn from muons at existing facilities?
Q2) Opportunities: what are the opportunities for muon physics from future facilities
for example PIP-II at Fermilab, HiMB at PSI?
- also upcoming Chinese Facilities: CSNS, CiADS, SHINE
Q3) Requirements: What beams/facilities are needed for future muon experiments?
- or: *What can the Muon Collider do for you?*

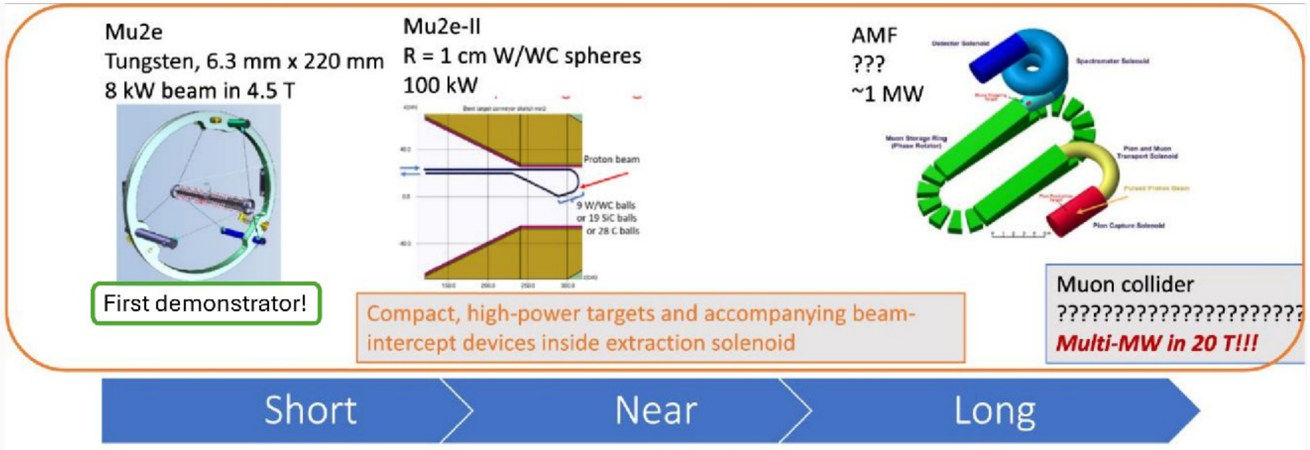


Looks familiar!
→ Synergies with MuC effort
→ Need to explore overlaps and utilize shared expertise



- A concept based on the racetrack evolution of PRISM
- Would be designed for the lowest practical muon momentum (30-40 MeV/c)
- The + and – beams are quite diffuse and do not interact, so can co-exist in the ring
- Charge selection in the transfer solenoids is done by displacement
- The yellow and orange boxes (not to scale) represent the kickers and matching sections
- Injection and extraction kickers are rather different
- Injection/extraction is done out of the plane vertically due to beam aspect ratio
  - Can this be done with two beams?

AMF, Sophie Middleton
MW Beams plenary, Kevin Lynch
Targetry parallel, Michael Hedges



Synergies with Muon Collider could be crucial for muons
- and an important theme in future WG4 NuFact streams

Working Group 4 (Muon Physics) Summary

Exciting few years ahead for Muon Physics
- final results from Muon g-2, first data and results from many others

...and lots to think about longer term.
- NuFact can be a great forum for those discussions!

Thanks:
- **to all the speakers for very interesting talks**
- **to my fellow conveners Simon Corrodi and Kim Siang Khaw**
- **to the organisers for a great conference!**