缪子物理国际前沿动态

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大阪大学核物理研究中心

基于HIAF集群的高精度测量和新物理前沿研讨会

2023/7/6, 惠州

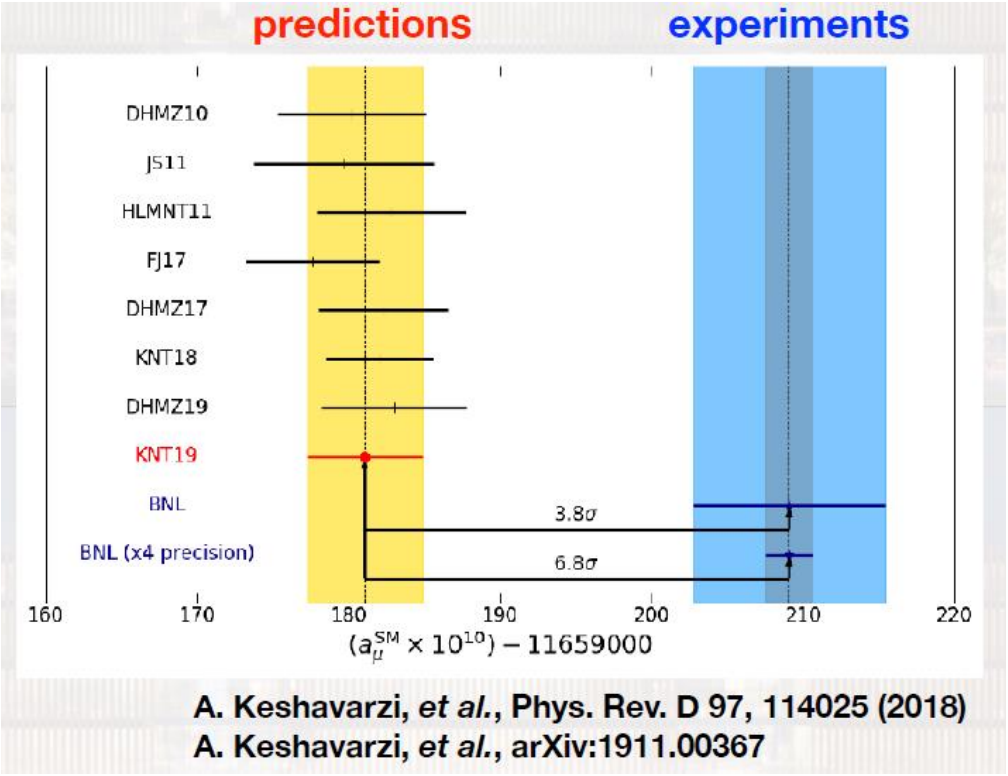
Muon as a probe to new physics

- Neutrino oscillations gradually verified by experiments:
  - neutrinos are massive, and lepton flavor conservation is violated.
- Too many mysteries about neutrino masses and mixings
  - New physics models needed! SeeSaw, SUSY, extra-Dimension, …
- Difficult to search for new physics directly on energy frontier
- Indirect search: precision frontier
  - Muons are particularly important: relatively long lifetime, easy to produce, not too light, simple SM physics.
  - Processes to search for new physics: CLFV, g-2, EMD

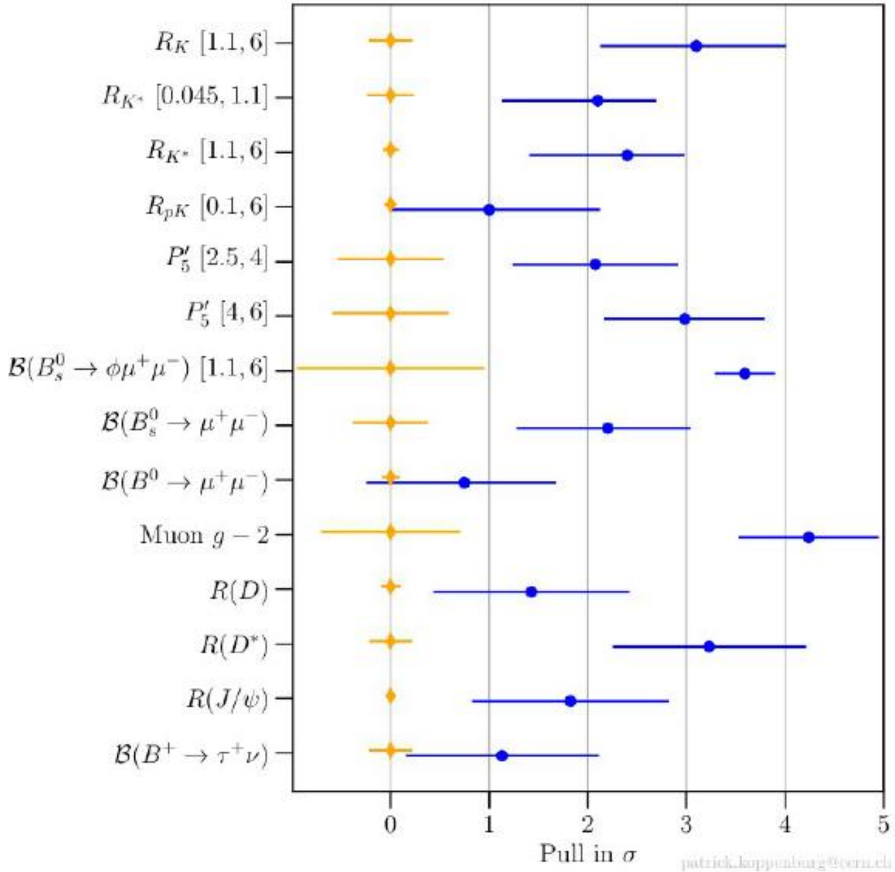
Hints for new physics (in lab): muon?

couplings of electroweak gauge bosons are "blind" to lepton flavor: lepton flavor universality.

g-2 anomaly: since 2006

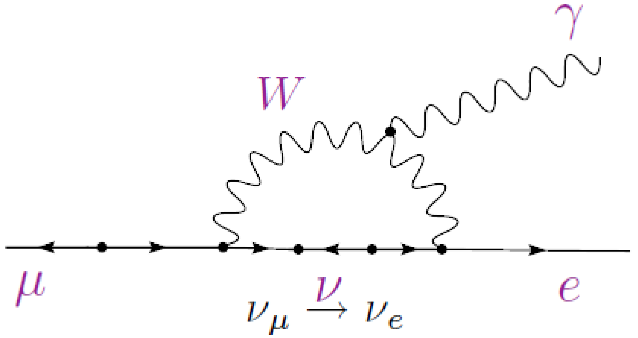


Lepton flavor universality anomaly



Charged Lepton Flavor Violation (CLFV)

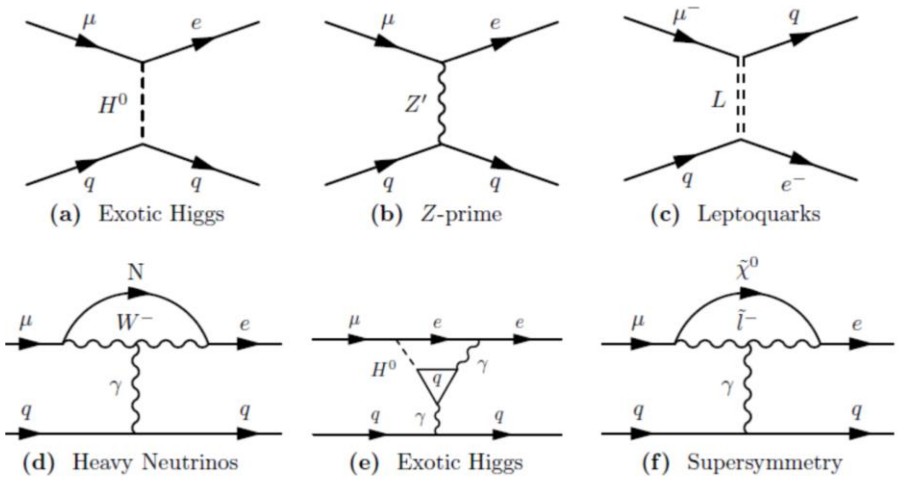
Highly suppressed in SM+m_ν by GIM due to the smallness of m_ν

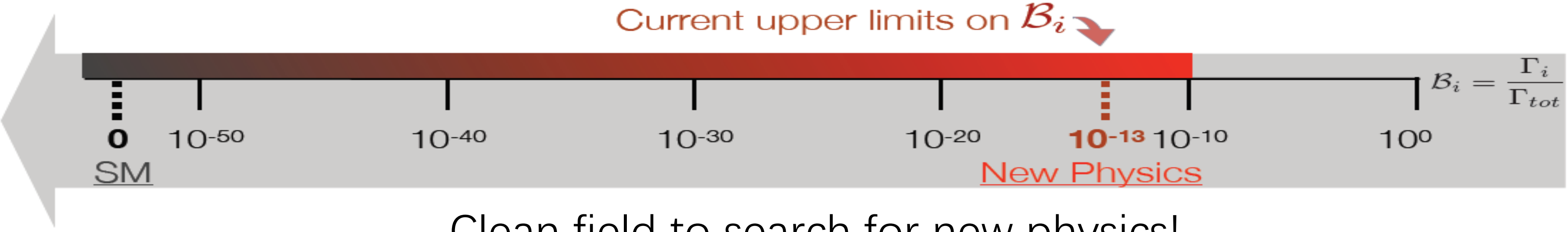


$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

CLFV Widely predicted in NP models related to neutrino mass origin.

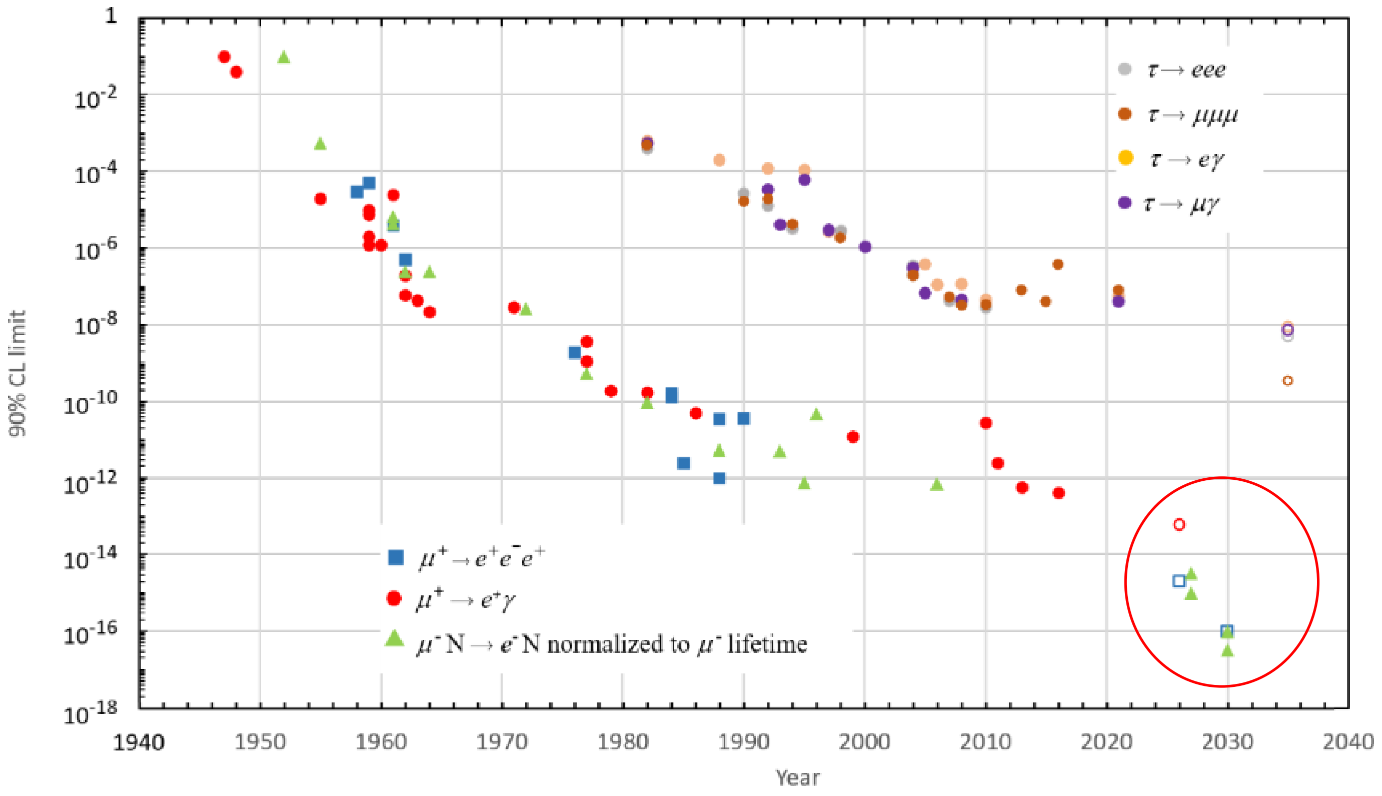


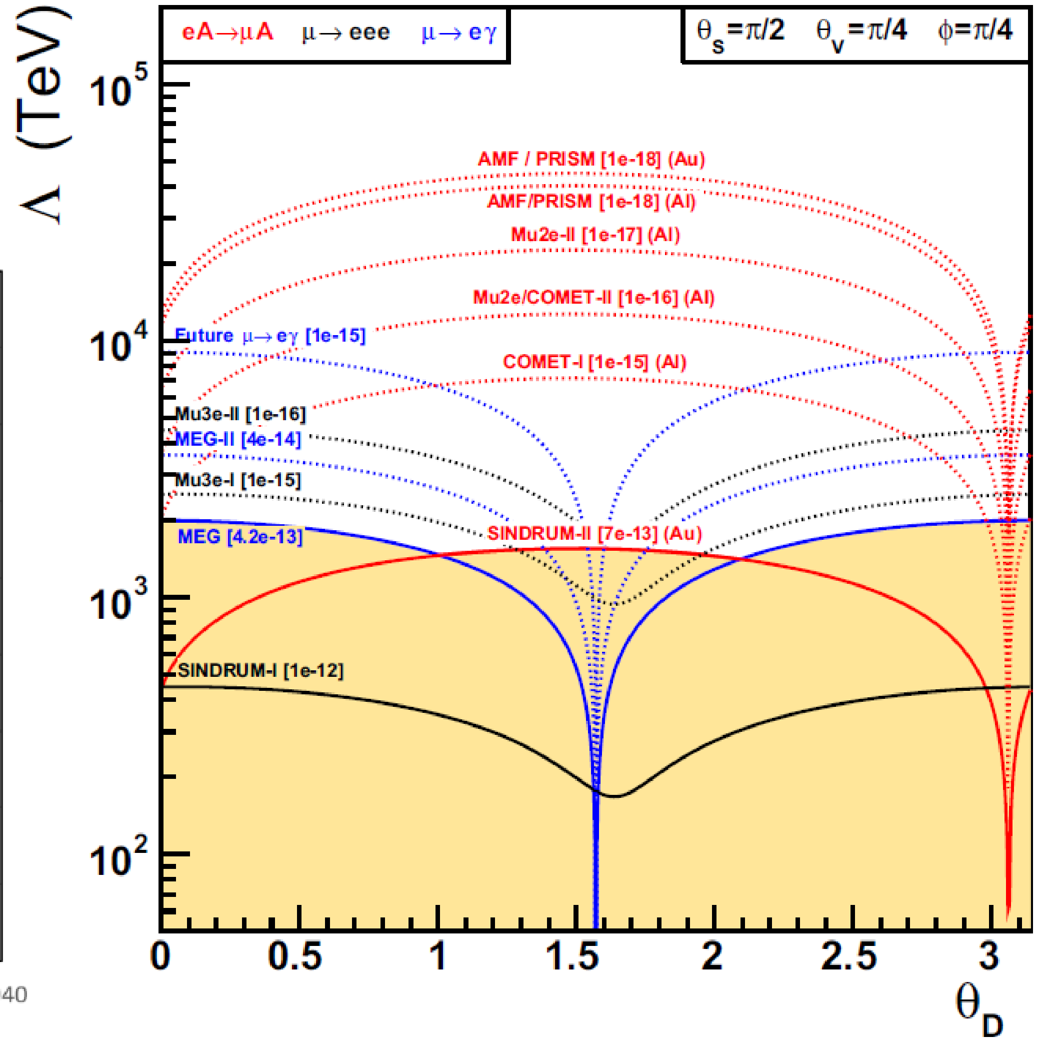


Clean field to search for new physics!

CLFV experiments: muons!

Muons are bringing the biggest improvements!
Can probe new physics up to at $\mathcal{O}(10^4 \sim 10^5)$ TeV



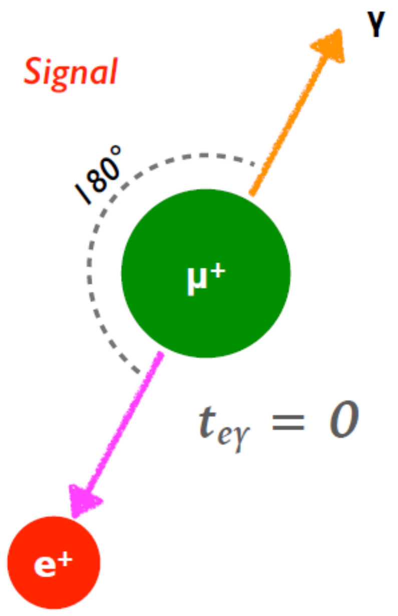


Eur. Phys. J. C (2022) 82:836

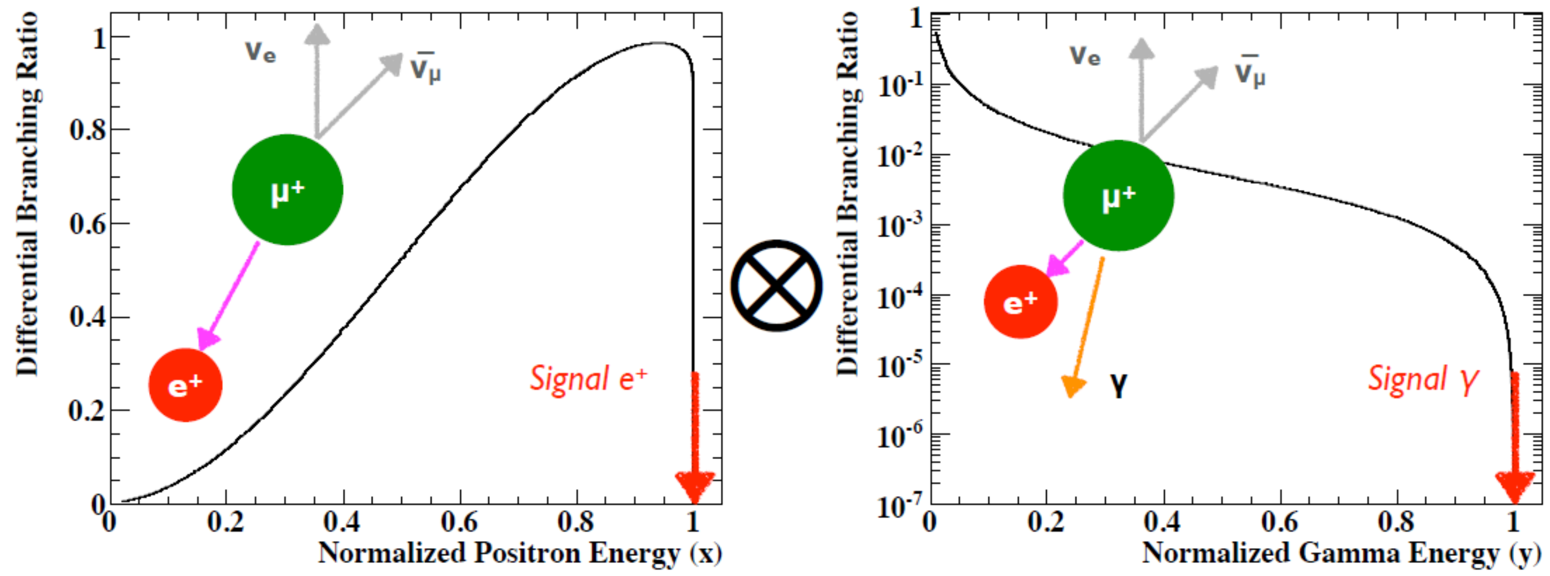
θ_D parameterizes the relative magnitude of dipole and four-fermion coefficients

$\mu \to e\gamma$

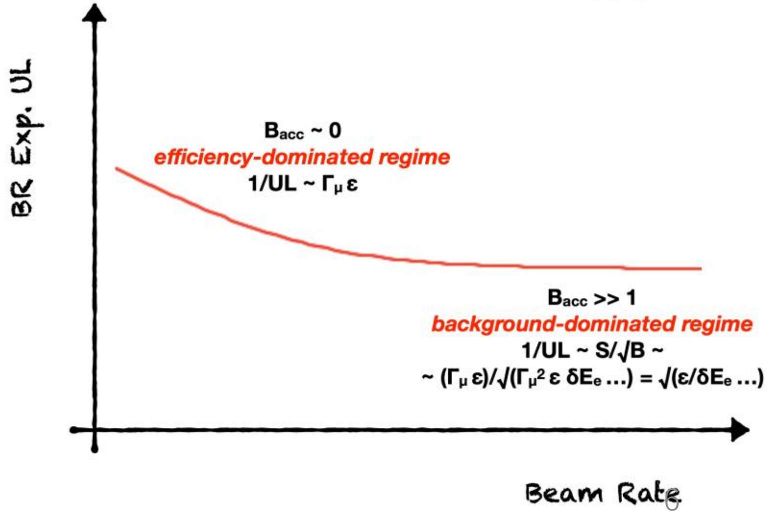
- Starting from positive muons stopped in target.
- Signal is back-to-back electron positron pair.
- Background dominated by accidental events:
  - **DC beam** preferred. Detector resolution limit.
- Can search for $\mu \to eX(\gamma)$in the meantime



Accidental Background



$$B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^2$$

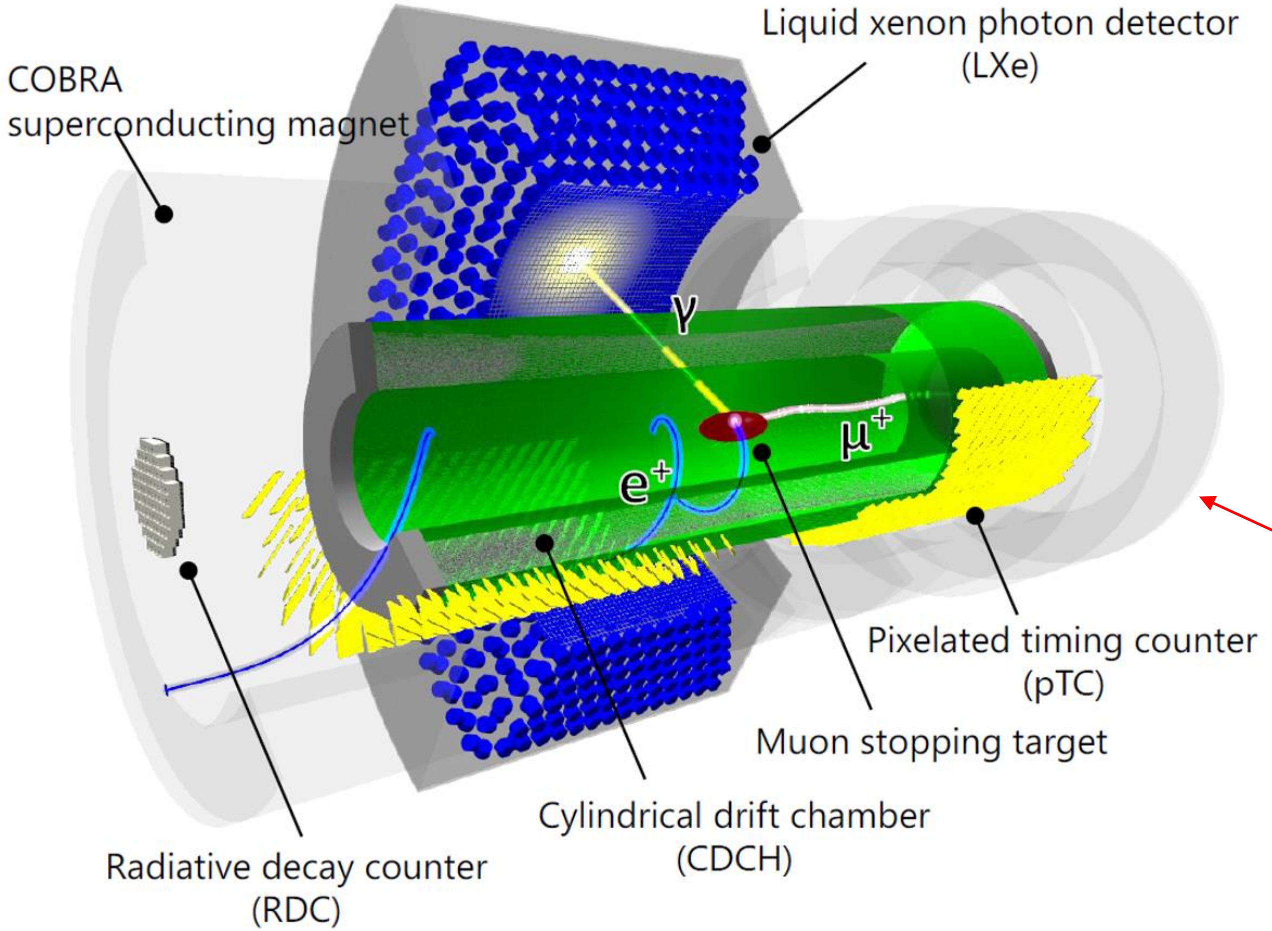


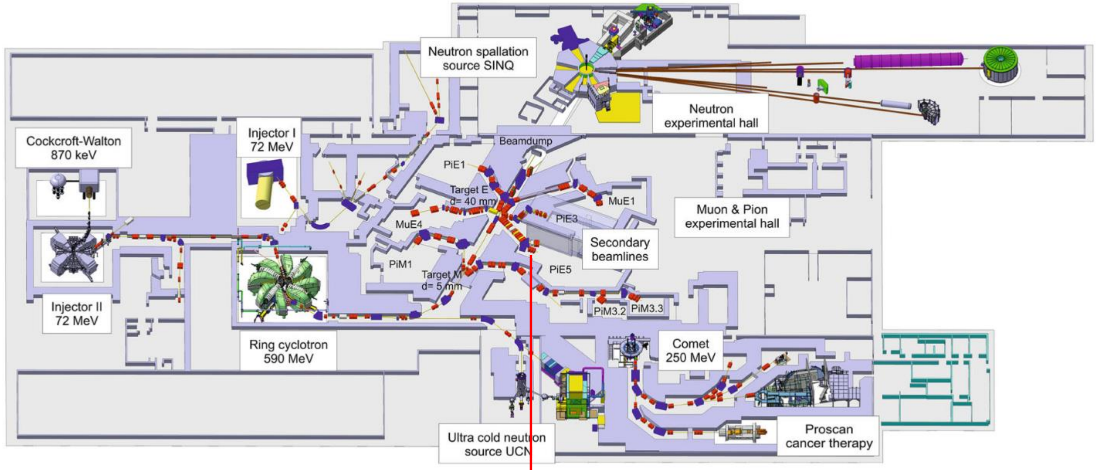
Yuki Fujii, Muon4Future workshop

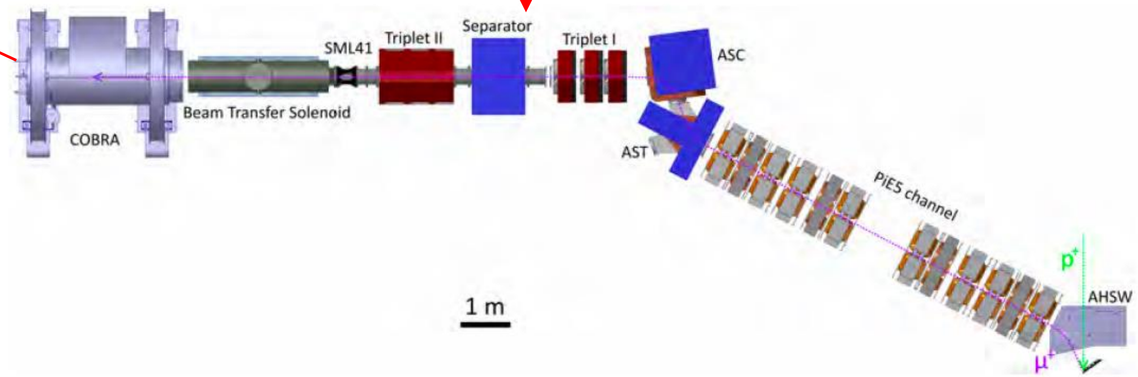
Cecilia Voena, Muon4Future workshop

Yuki Fujii, Muon4Future workshop

$\mu \to e\gamma$: MEG-II @ PSI







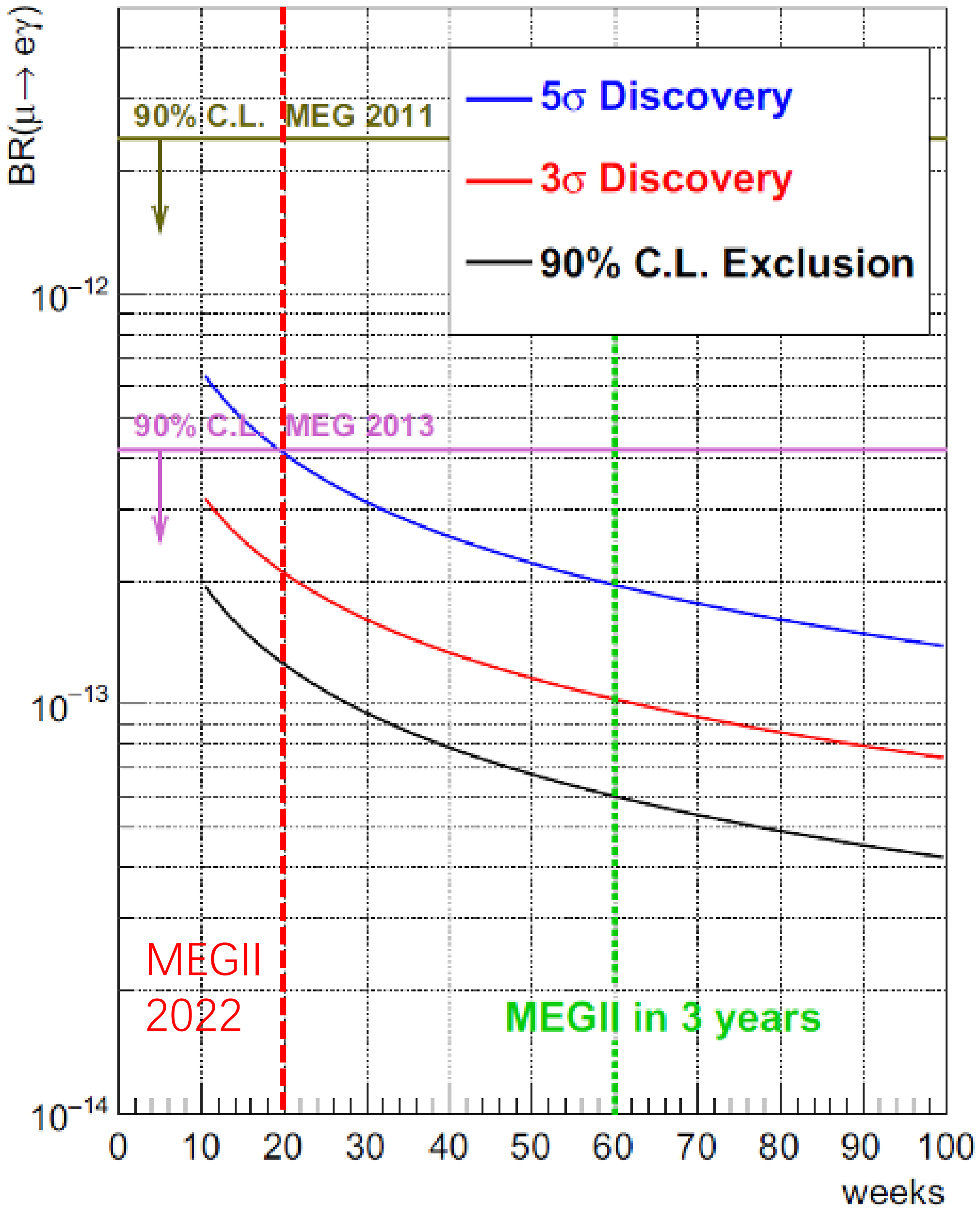
[Link](#) to the MEG II design paper

$\mu \to e\gamma$: MEG-II VS MEG

- MEG: operated 2008~2013, 90% CL upper limit set to 4.7×10^{-13}
- MEG II: 2021~2026, aims at 4×10^{-14}
  - detector resolution and efficiency x2
  - Beam intensity x2: $3 \times 10^{7}/s \to 5 \times 10^{7}/s$. Can achieved: $10^{8}/s$.

$$B_{acc} \propto \Gamma_{\mu}^{2} \cdot \delta E_{e} \cdot (\delta E_{\gamma})^{2} \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^{2}$$

	MEG	MEG II (design)	MEG II (Meas.)
ΔE_e [keV]	380	130	90
$\Delta\theta_e$ / $\Delta\varphi_e$ [mrad]	9/9	7.0/5.5	**8/7**
e^+ Eff. [%]	40	70	65
ΔE_γ [%] (deep/shallow)	1.7/2.4	1.0/1.1	**1.7/2.0**
Δpos_γ [mm]	5	2.4	**2.5**
γ Eff. [%]	60	70	60
$\Delta t_{e\gamma}$ [ps]	120	85	80

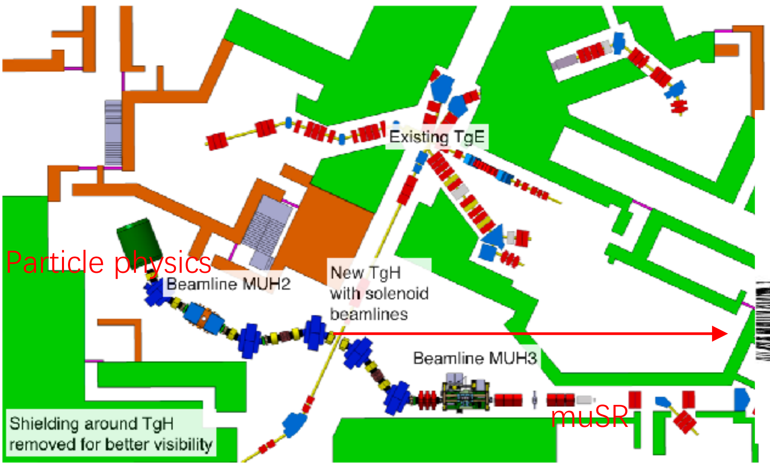


Yuki Fujii, Muon4Future workshop

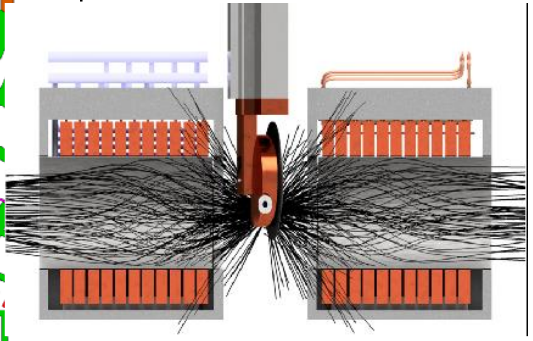
New muon beamline design in PSI: HiMB

- Aim: $10^{10} \mu/s$, surface muon, DC beam.
- Schedule: long shutdown 2027~2028
- Serves for particle physics ($\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, muEDM) and muSR research.
- Optimizations on target, capture and transmission are ongoing.

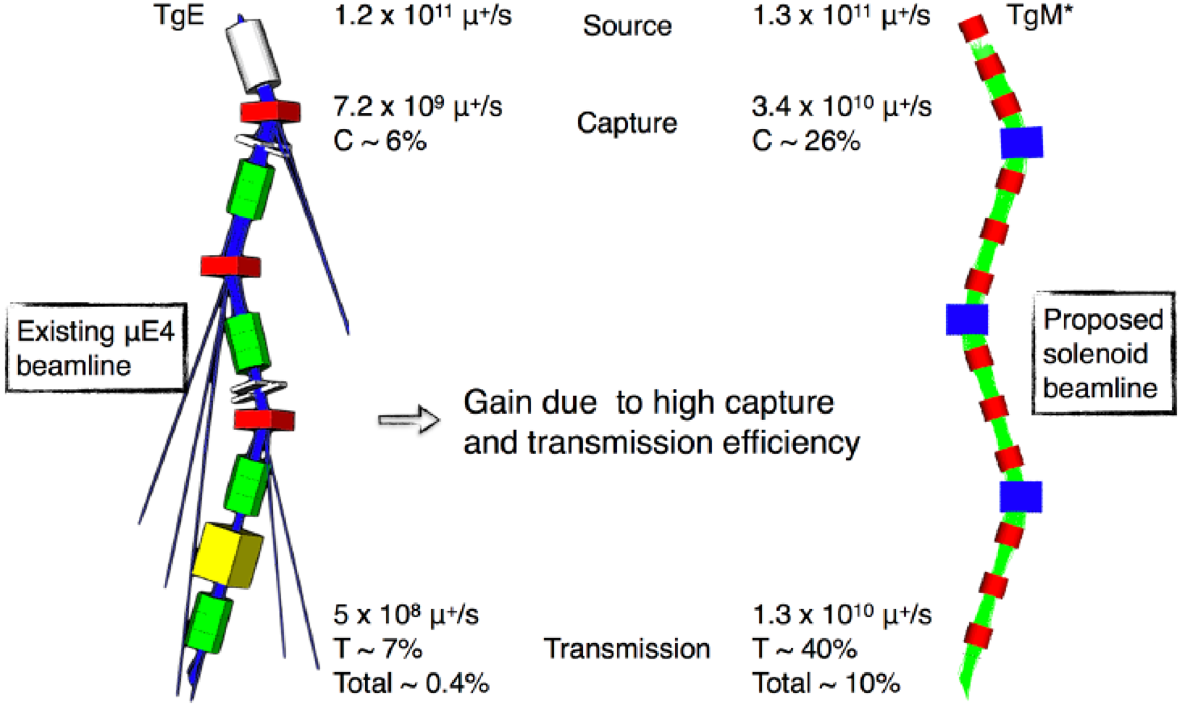
Proposed solenoidal beam line to increase the transmission efficiency



Normal-conducting, radiation-hard solenoids to capture surface muons.



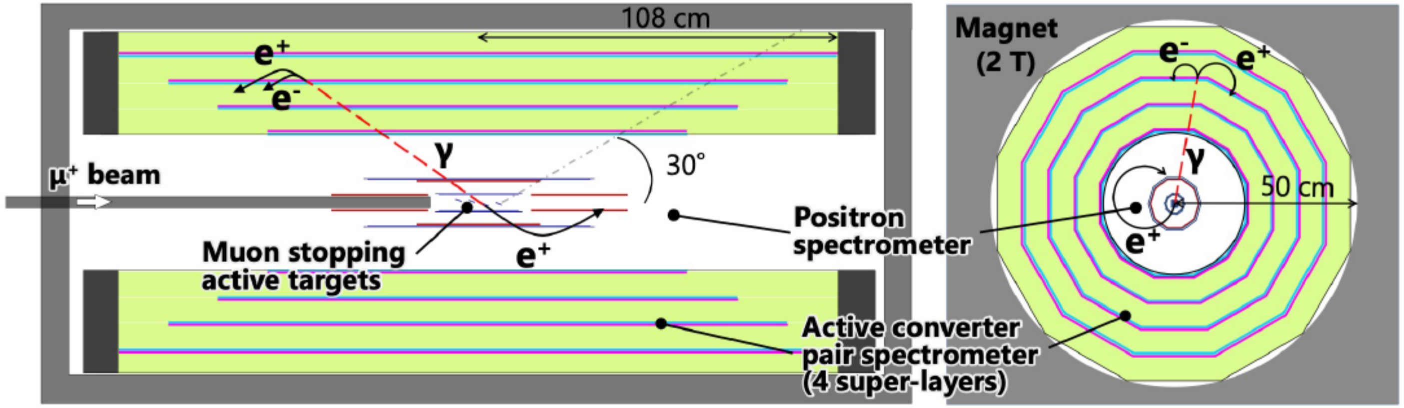
0.45 T 0.1 T 0.45 T



Angela Papa, Muon4Future workshop

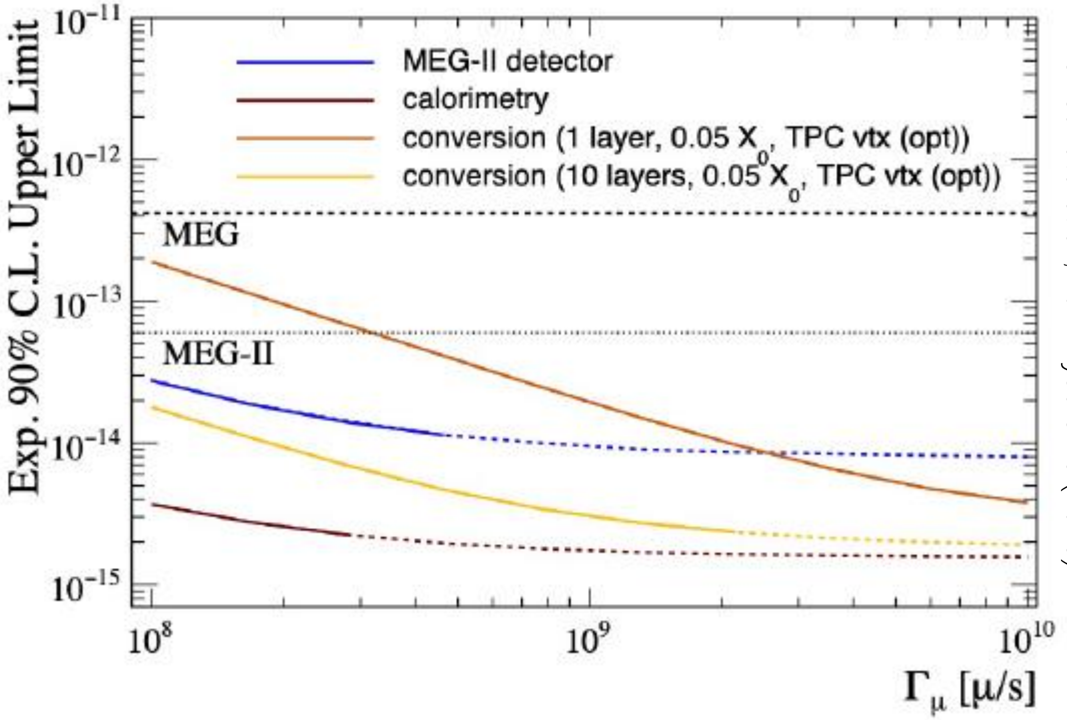
$\mu \rightarrow e\gamma$: next generation experiment

- HiMB Physics Case Workshop started from April 2021.
  - Positron detection: gaseous of silicon
  - Photon detection: calorimetry or conversion layer.



The plan with active multiple layer conversion layers.
Silicon detector for positron.

A few 10^{-15} level seems to be within reach for 3 years running at 10^9 μ/s
(further improvements possible with R&D)

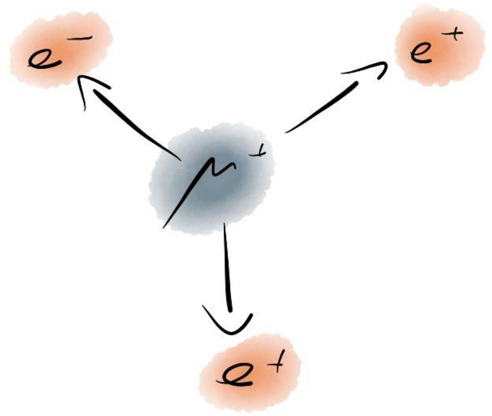


G. Cavoto et al., Eur.Phys.J.C 78 (2018)

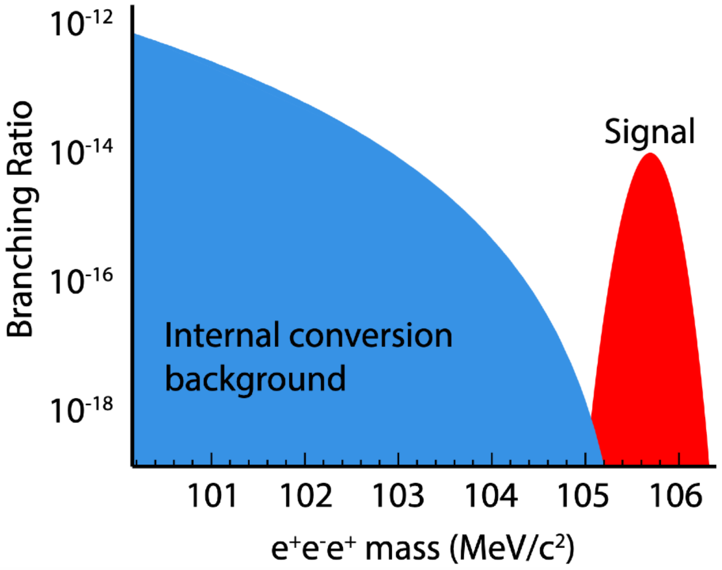
$\mu \rightarrow eee$

- Starting from positive muons stopped in the target.
- Signal: 3 electrons from the same vertex.
- Background: internal and combinatorial events:
  - **DC beam** preferred. Detector resolution limit.
- Can search for $\mu \rightarrow eX(\gamma)$in the meantime

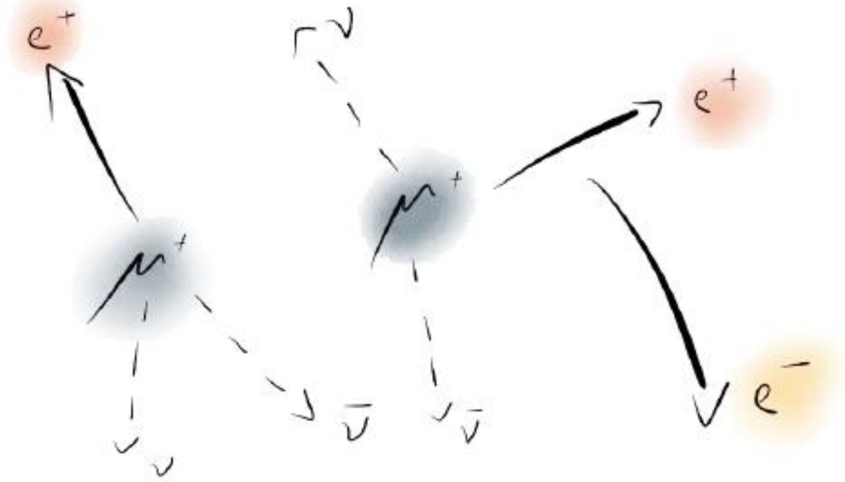
Signal



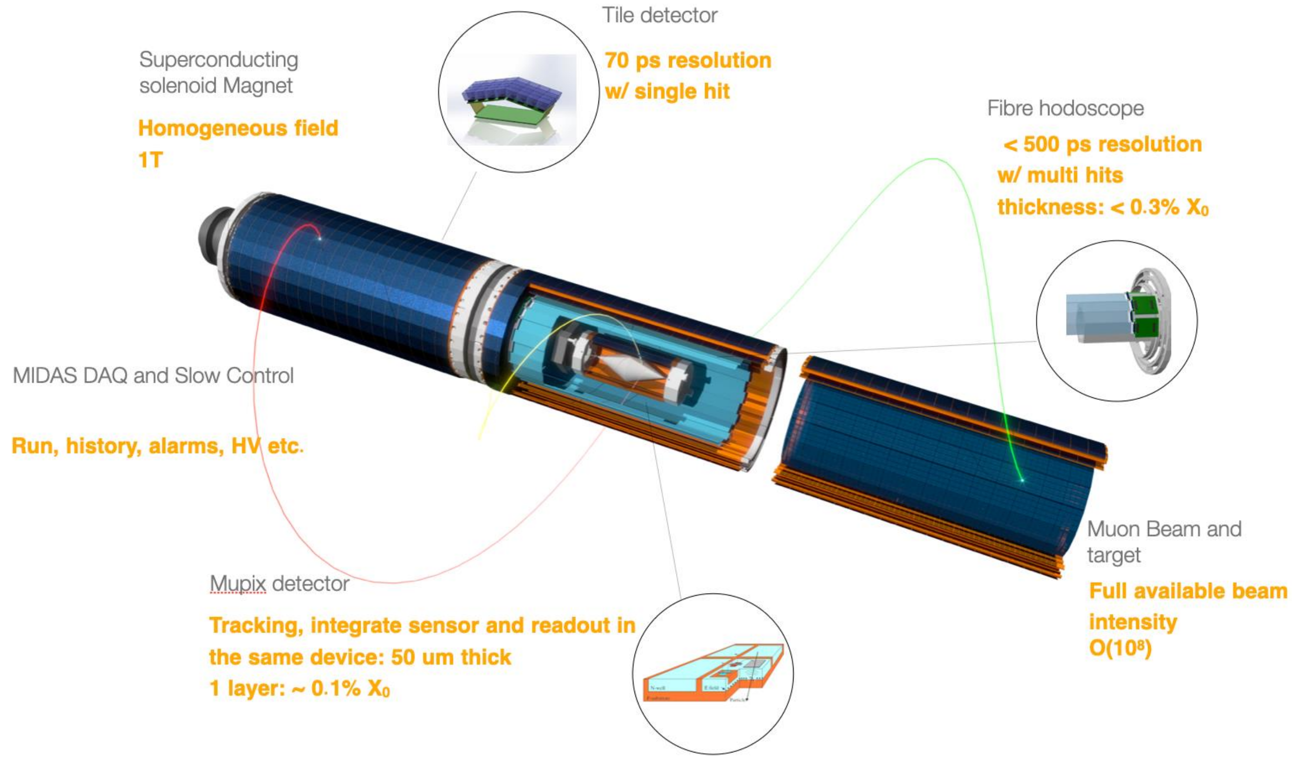
Internal background

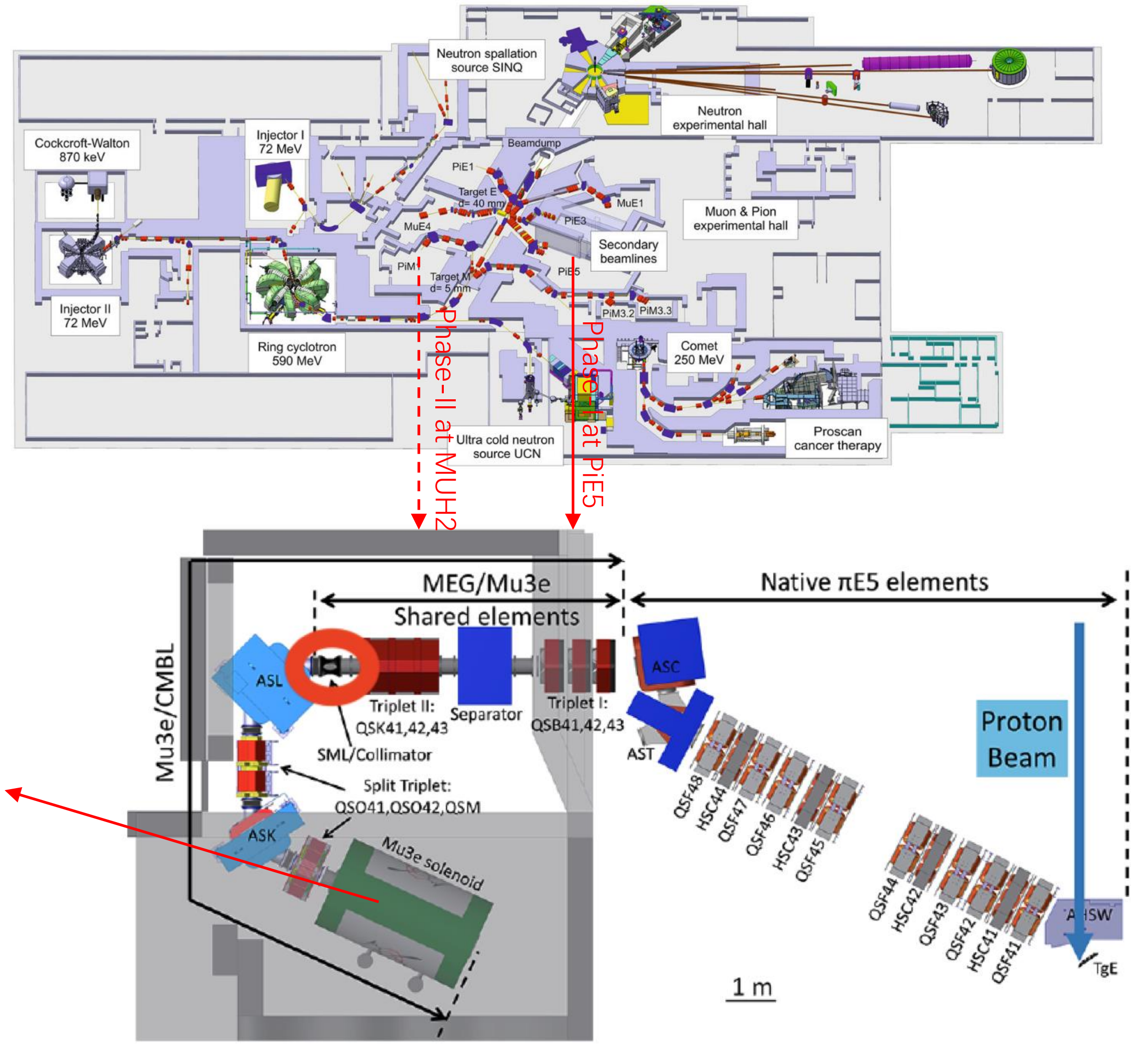


Combinatory background



$\mu \to eee$: Mu3e @ PSI

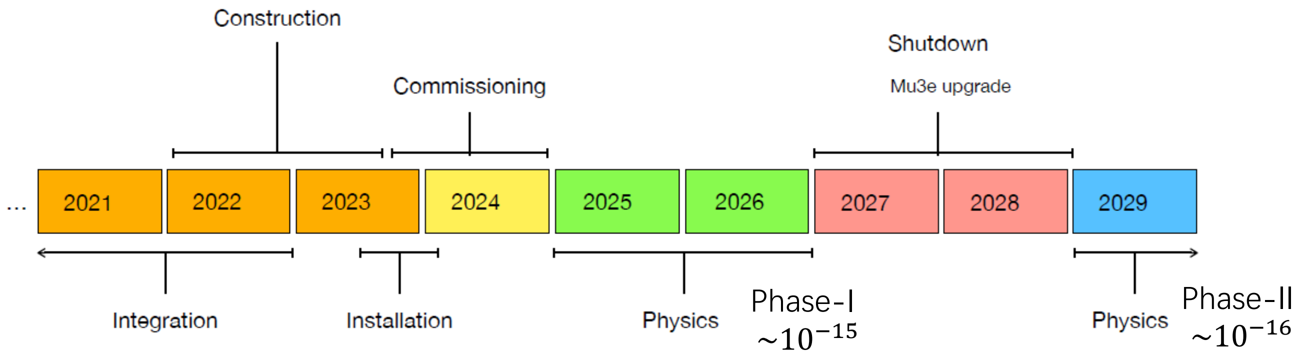


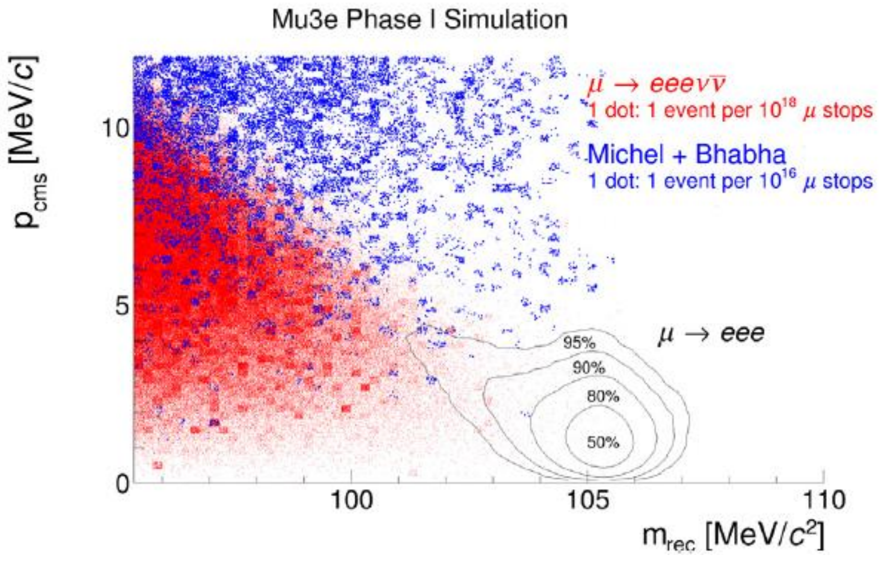


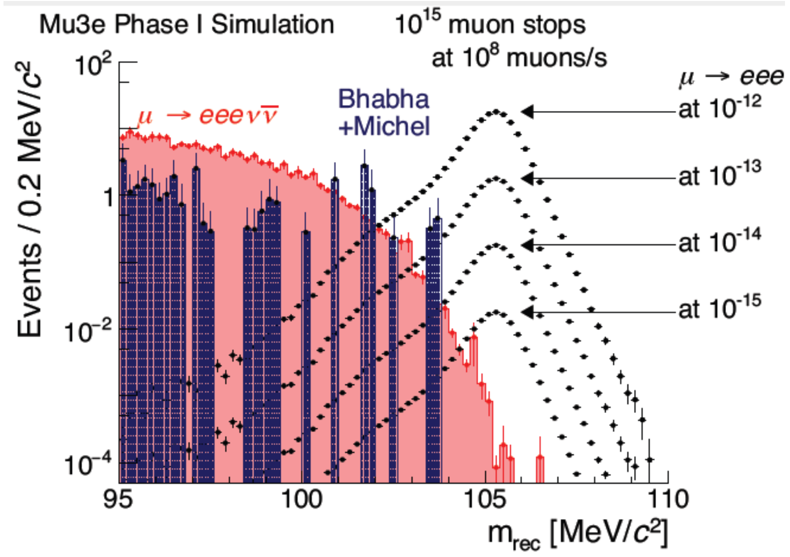
[Link](#) to the Mu3e design paper

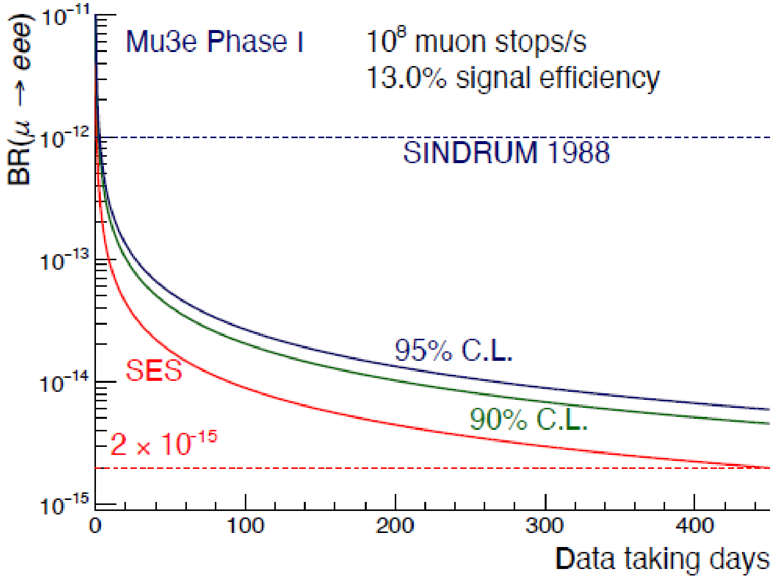
$\mu \rightarrow eee$: Mu3e @ PSI

- Phase-I aims at $\sim 10^{-15}$ sensitivity.
- Phase-II aims at $\sim 10^{-16}$ sensitivity.
  - Will use muons from HiMB: $10^9 \mu/s$
  - Detector needs upgrade.





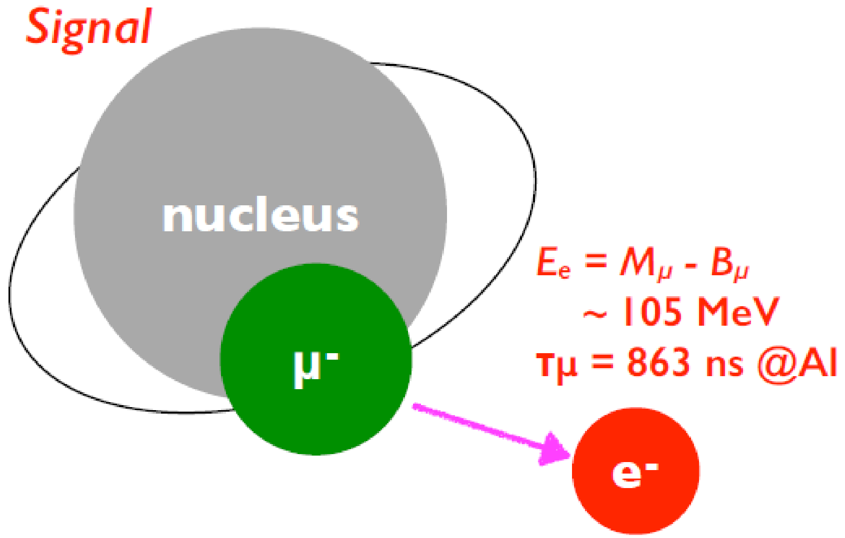




Technical design of the Phase I Mu3e Experiment

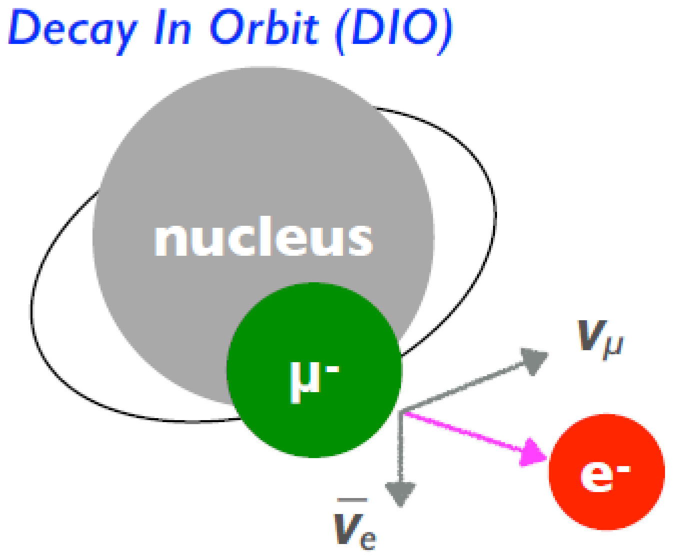
$\mu N \to eN$

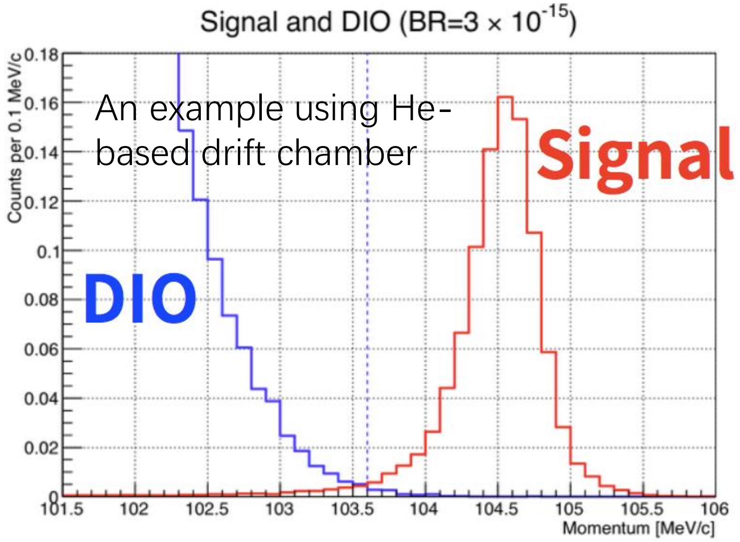
- Starting from negative muons stopped in the target.
- Signal: 1 mono-energetic electron.
- Background: intrinsic, beam related, cosmic ray
  - **Pulsed beam** preferred. Excellent extinction factor required.
  - Cosmic ray veto needed.
- Can search for $\mu^- N \to e^+ N$, $\mu \to eX$ in the meantime.

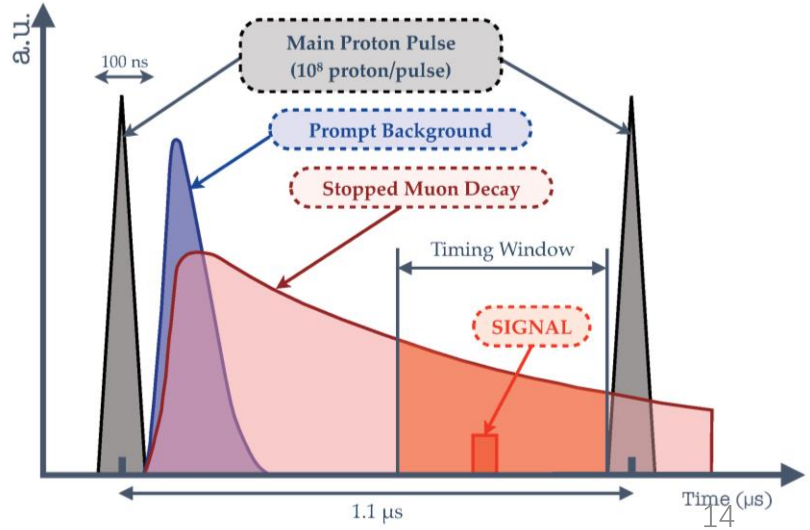


Using pulsed beam and delayed window to avoid beam related background.

Intrinsic background: DIO. Can be well separated with current detector.

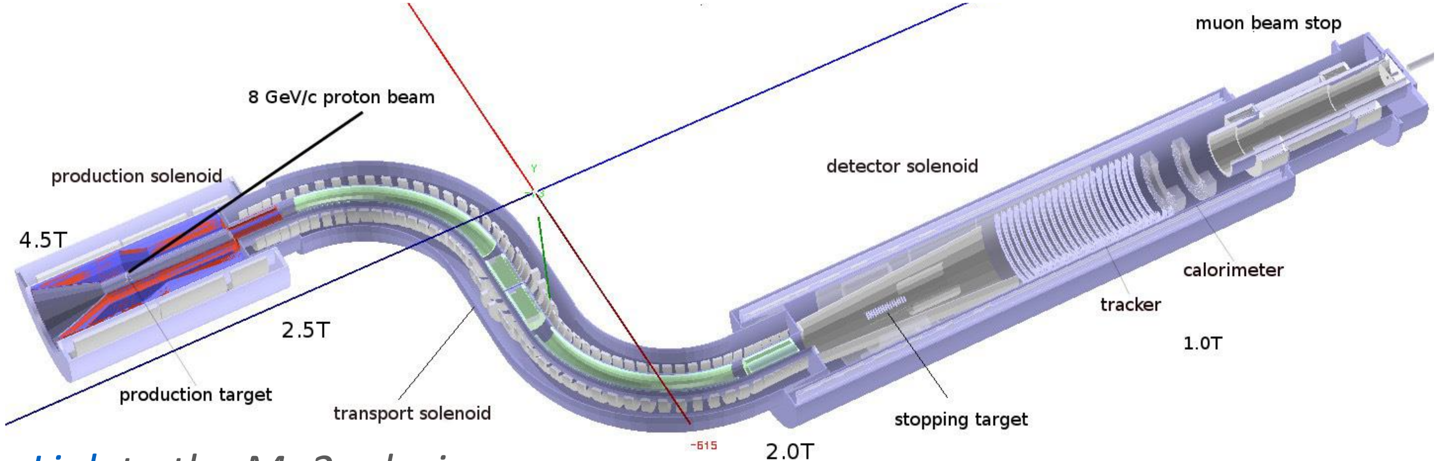


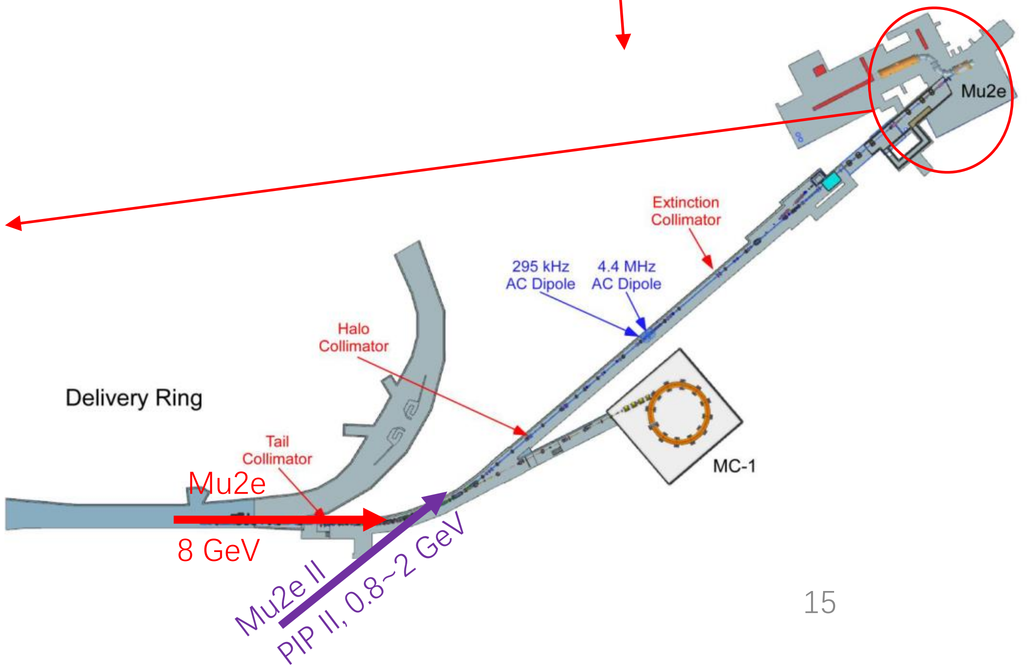




$\mu N \to eN$: Mu2e @ FermiLab

- Mu2e aims at 90% CL upper limit $8 \times 10^{-17}$with 8 kW proton beam.
  - Under construction. Data taking from 2025~2026.
  - 1/2y before shutdown (run 1), 4y after (run 2).
- Mu2e II aims at 8×10^{-18} with 100 kW proton beam.
  - planed after PIP-II upgrade. Somewhere after 2030.
  - Needs 5 years data taking.
  - Infrastructure will be reused. Target/Detectors need upgrade.

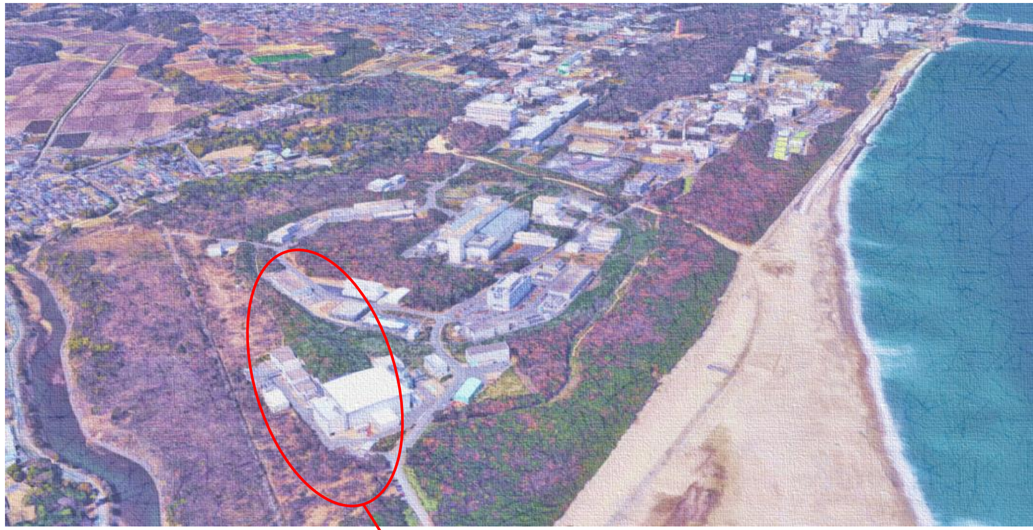


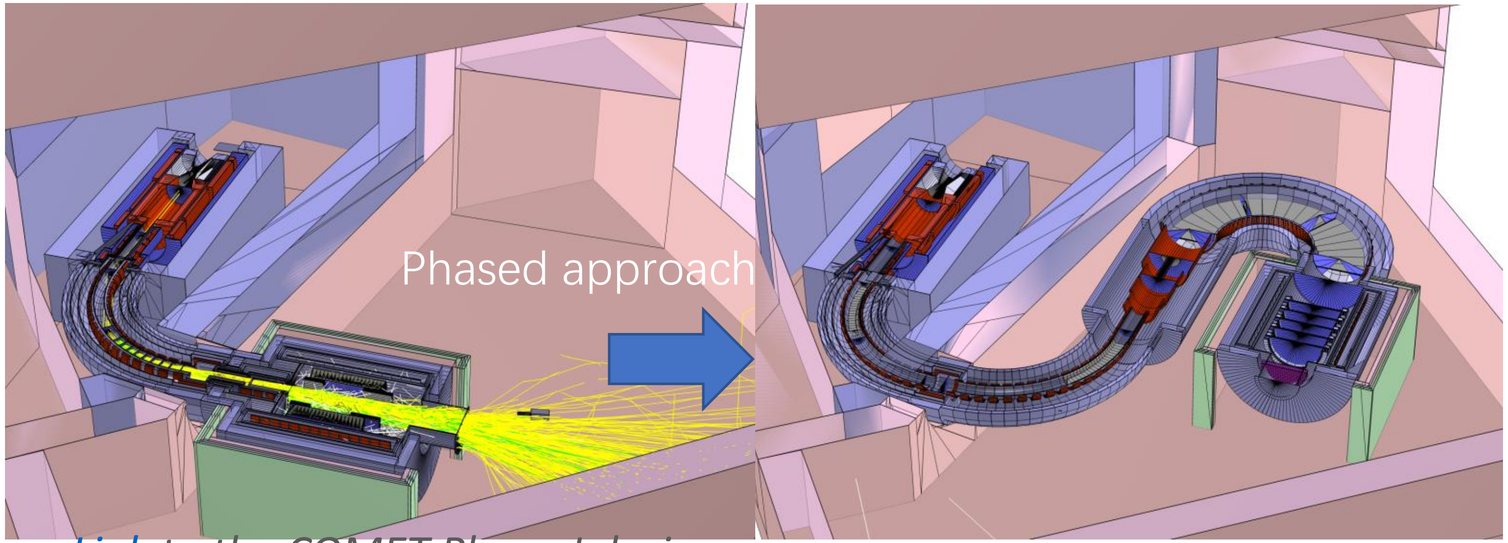


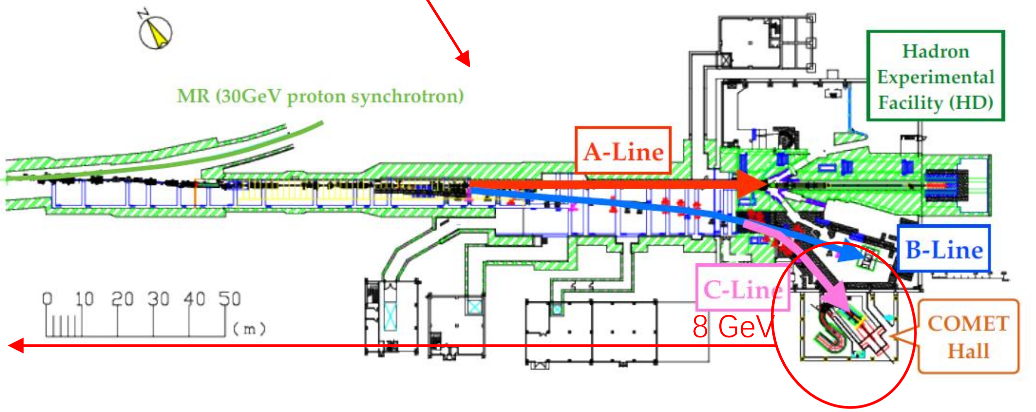
Link to the Mu2e design paper

$\mu N \rightarrow eN$: COMET @ J-PARC

- Phase-I aims at 90% CL upper limit 7×10^{-15} with 3.2 kW proton beam
  - Under construction. Data taking from 2024~2025.
  - 150 days data taking.
- Phase-II aims at 4.6×10^{-17} with 56 kW proton beam
  - Planned 3 years after Phase-I. Needs 1 year data taking.
  - May aim at 7×10^{-18} in case of schedule delay.
  - Infrastructure will be reused. Target/Detectors need upgrade. SC beamline needs extension.



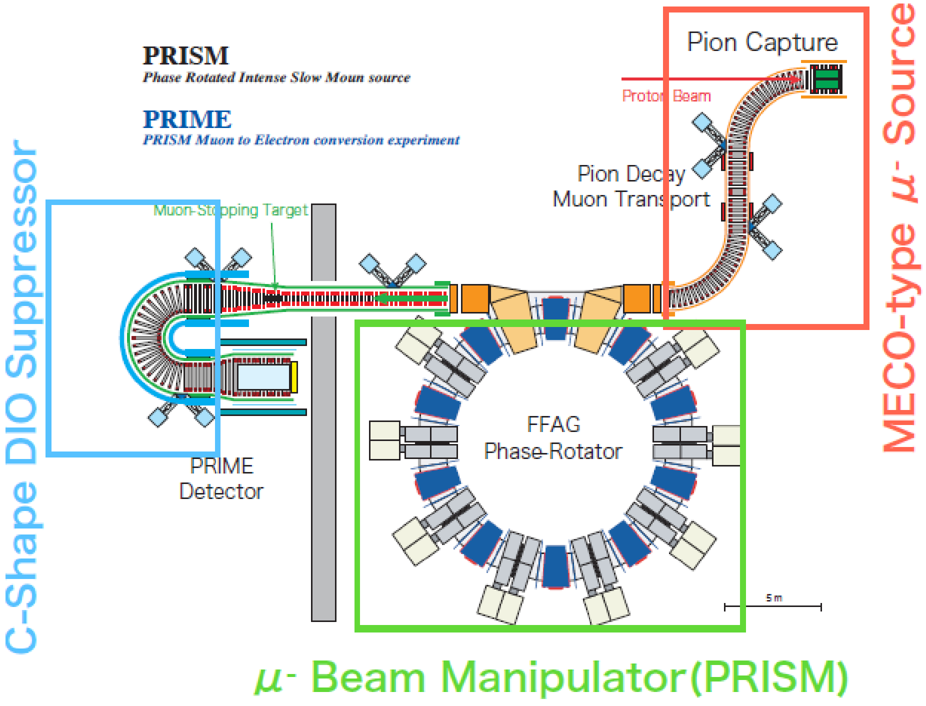




[Link](#) to the COMET Phase-I design paper

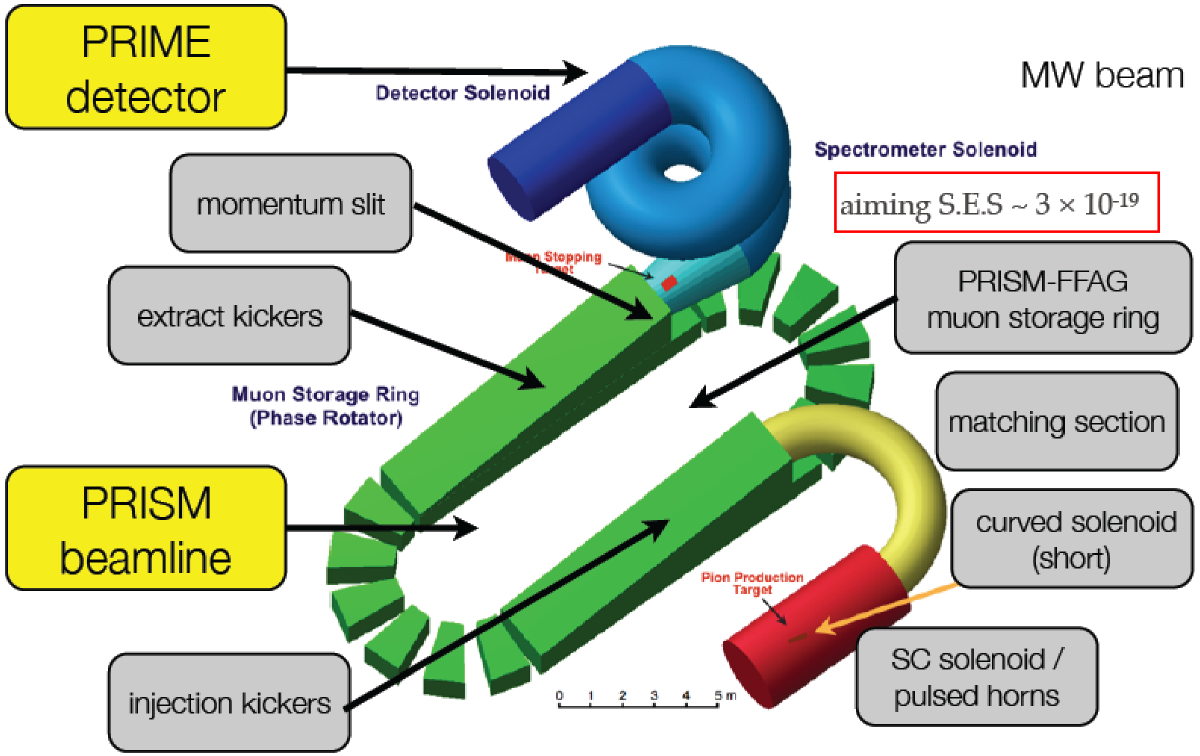
$\mu N \to eN$: Next generation

The original design before COMET
Started from 2005.



Aiming to achieve an ultimate sensitivity: BR<10^{-18}

The PRISM group is still updating the design to achieve an ultimate search for $\mu N \to eN$



In synergy with muon collider: target, capture, and storage ring. Might be the most intense muon beam before muon collider.

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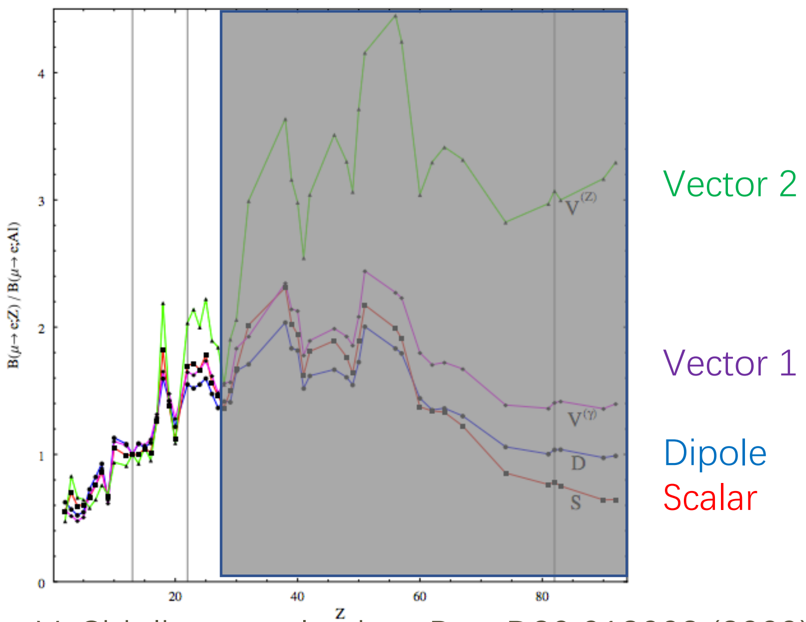
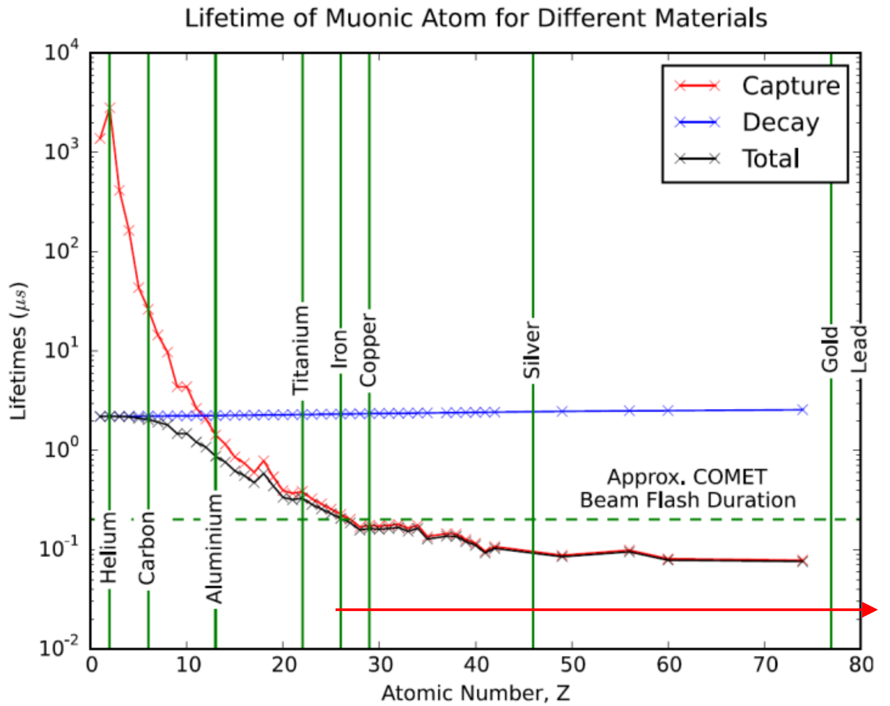
$\mu N \to eN$: Next generation

- Issues
  - FFA needs special muon beam input: narrow bunch, low rate.
  - 1 MW brings challenge to target station and detector/electronics.
- Benefits
  - Pure low energy muon beam: no longer relies on delay window. We can finally probe high-Z material: possible to tell apart different NP models.



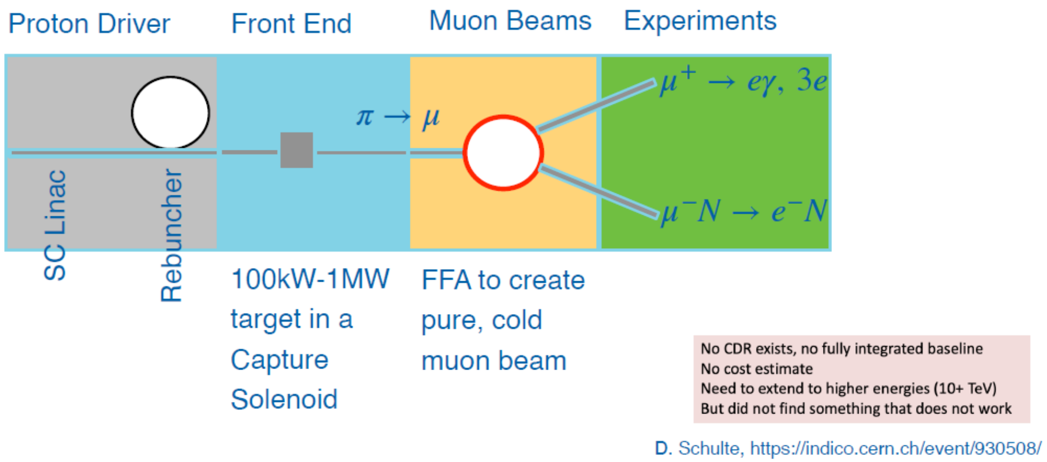
V. Cirigliano et al., phys. Rev. D80 013002 (2009)

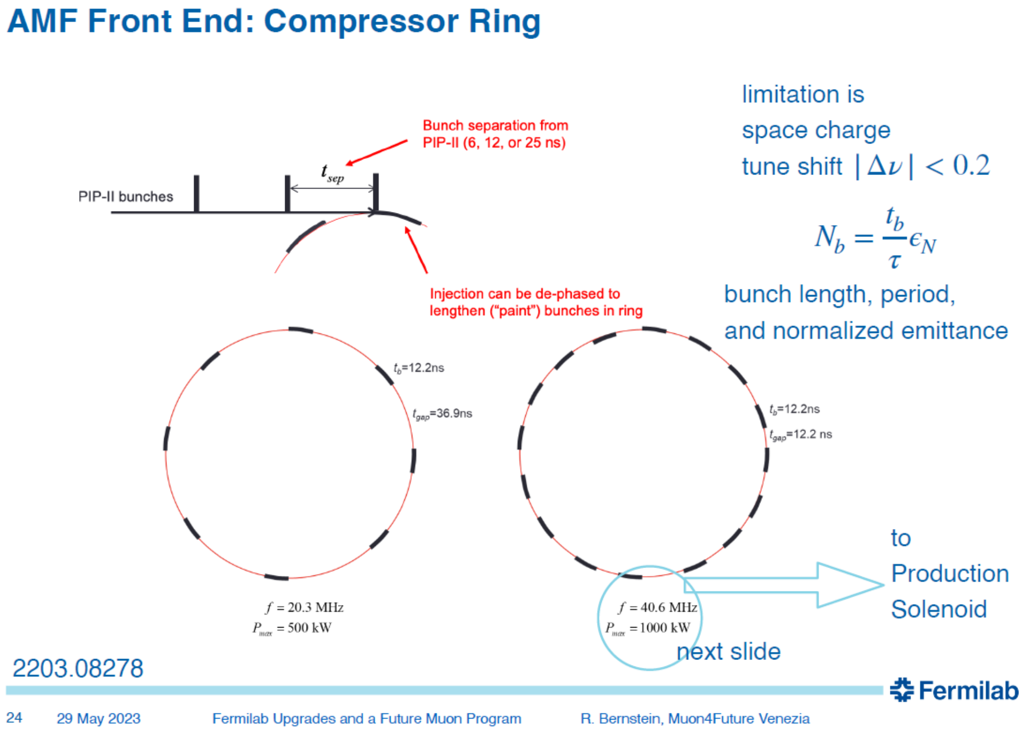


Impossible In current generation's design

$\mu N \rightarrow eN$: Next generation

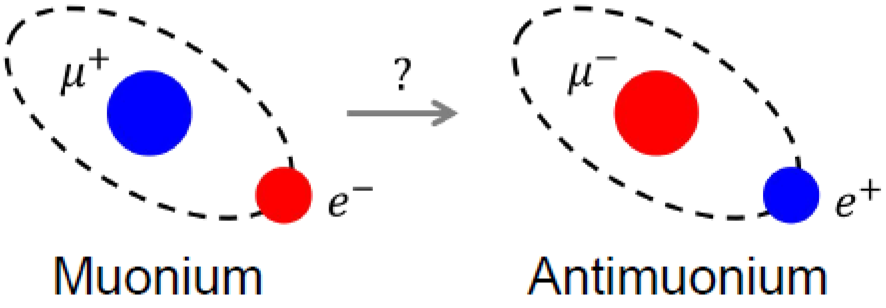
- FermiLab will have its accelerator upgraded: PIP-II, 8kW -> 100 kW
- Advanced Muon Facility (AMF) was proposed to make use of PIP-II for next generation muon physics
- $\mu N \rightarrow eN$ plan in AMF took the idea from PRISM: in cooperation.
- AMF proposed to use compressor ring to make beam structure for FFA
  - 10 ns bunches at 100-1000 Hz
- Pile-up effect will be too much
  - Need PRISM type detector: select electrons.
  - $\mu^- N \rightarrow e^+ N$ needs separate run in this case.

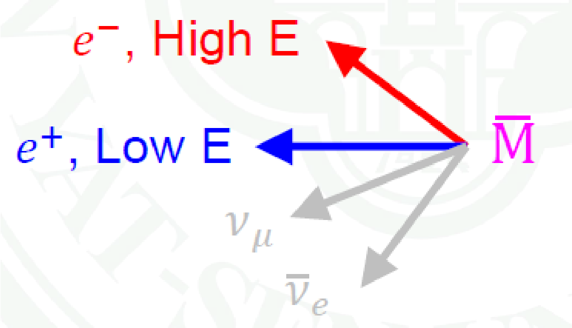




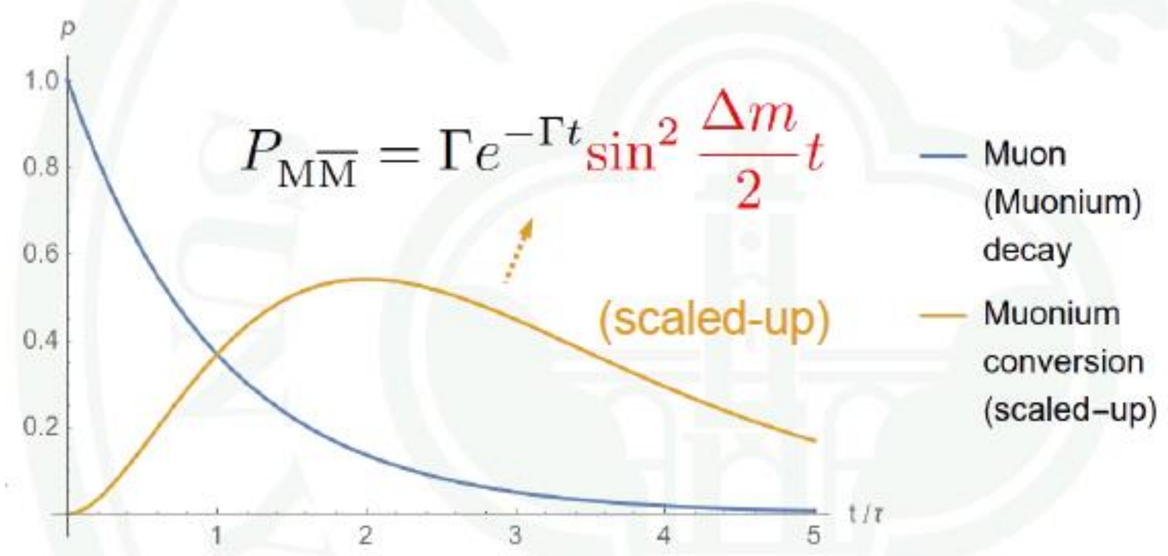
AMF: hep-ex 2203.08278

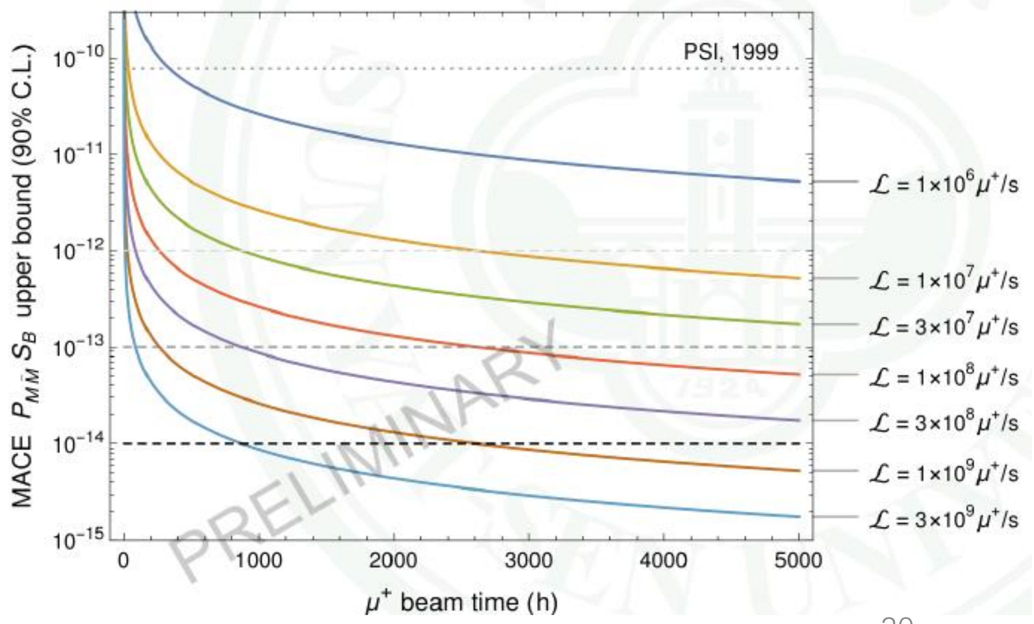
$$M \to \bar{M}$$





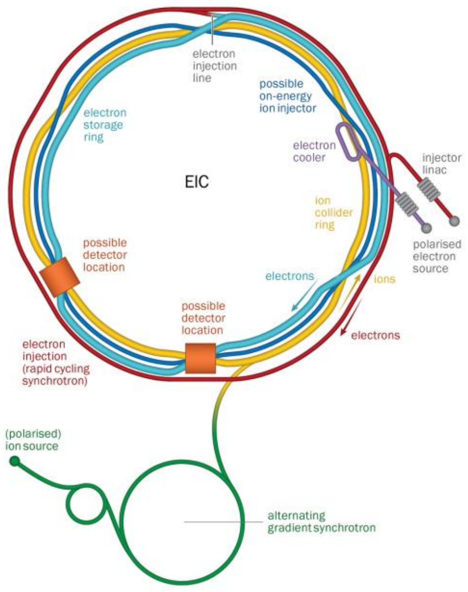
- Starting from muonium formed in special target (Aerogel/SF-He/⋯)
- Search for the the high-E electron and low-E positron.
- Background: internal ($\mu \to ee e\nu\nu$) and combinatorial events

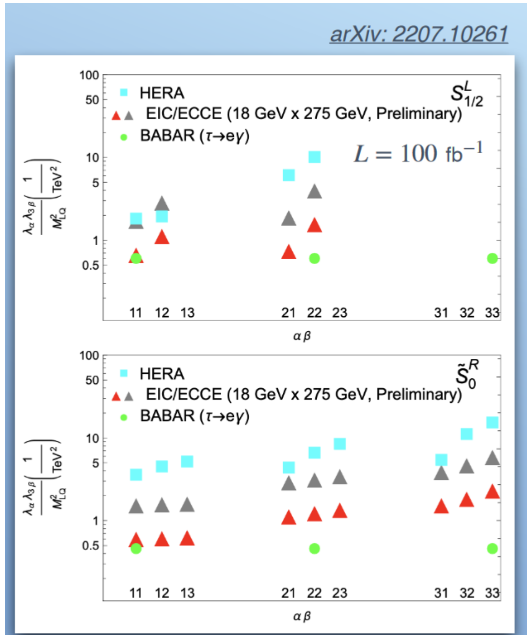


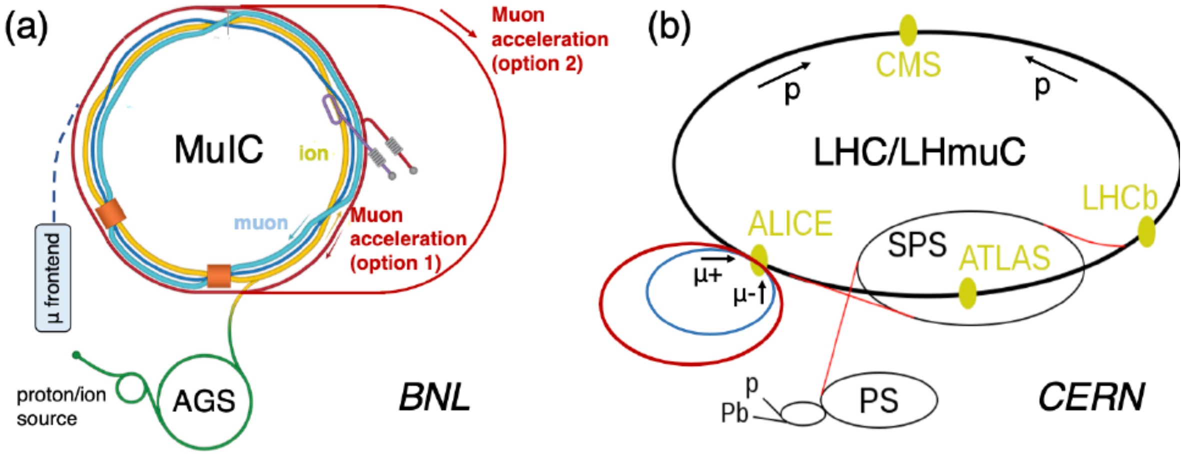


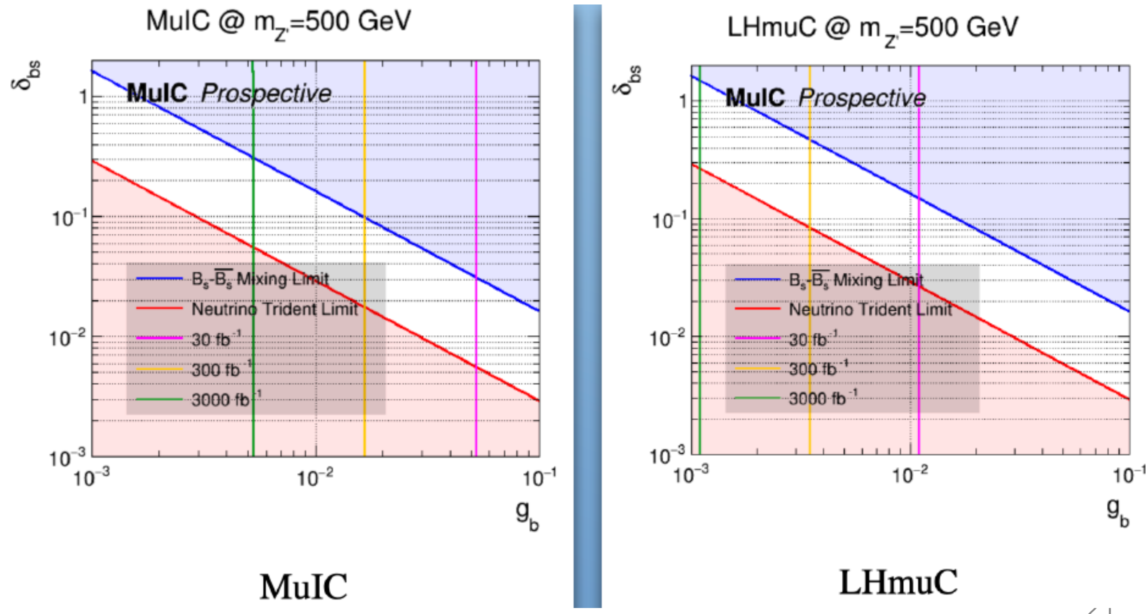
Prospect in the future: EIC, MuIC, LHC/LHmuC

- EIC and MuIC, LHmuC provide sensitivities on unique channels.
  - Two examples shown here.



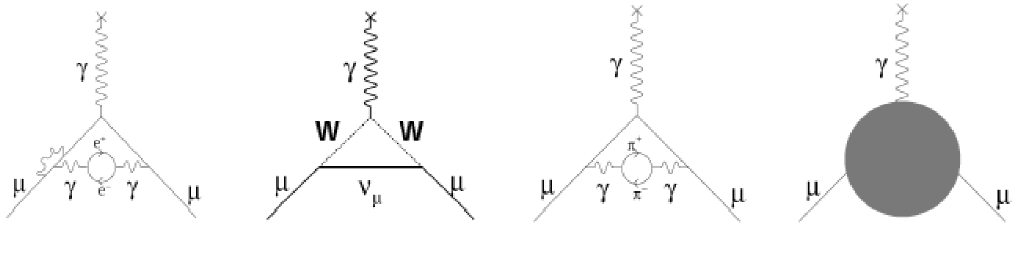




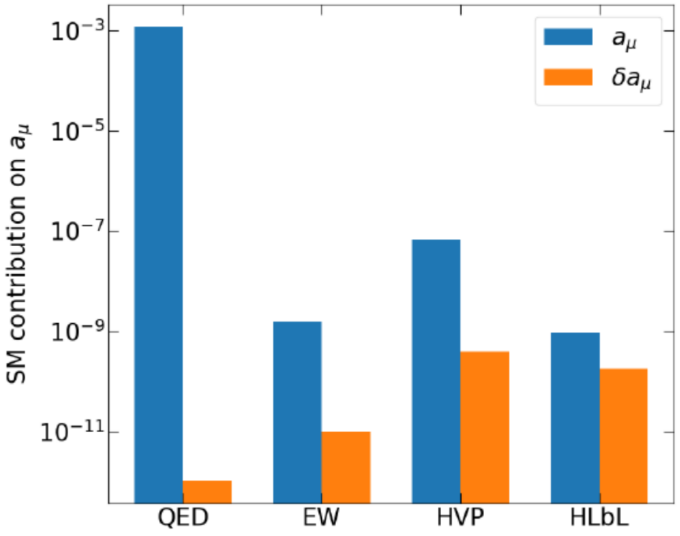


Muon g-2

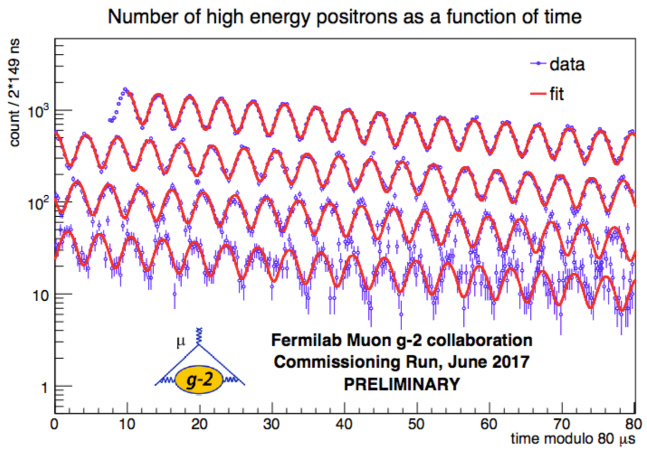
After solving out the SM components with high precision, muon g-2 is a good place to search for new physics.



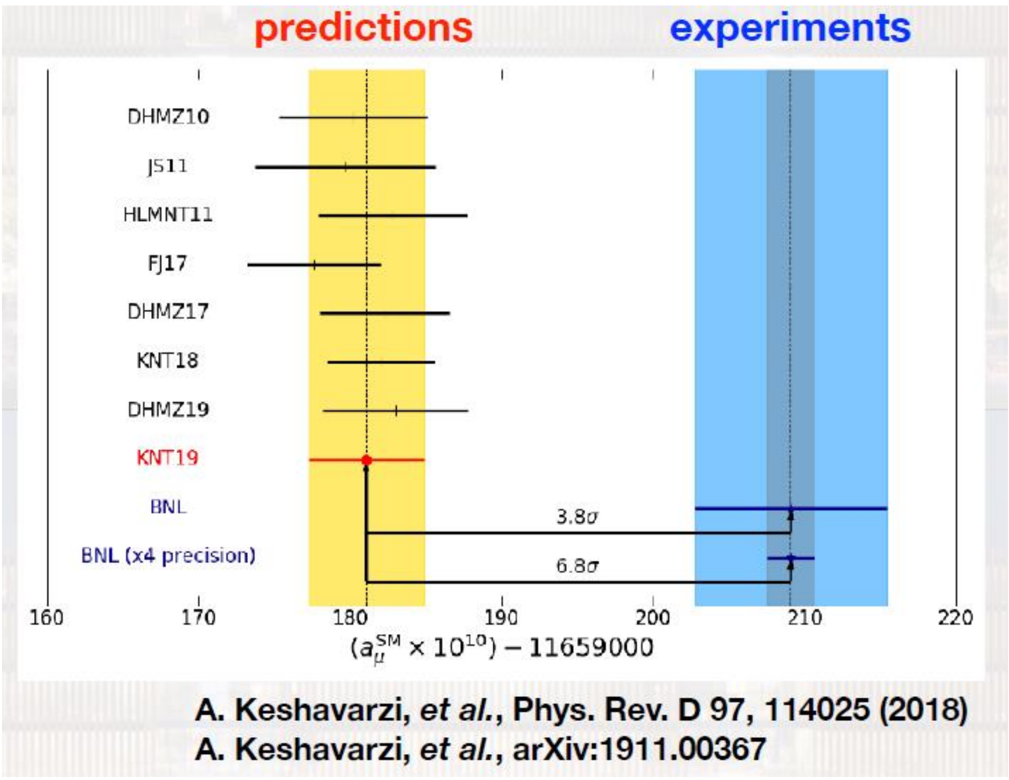
https://doi.org/10.1016/j.physrep.2020.07.006



Get g-2 by measuring spin precession frequency under magnetic field.



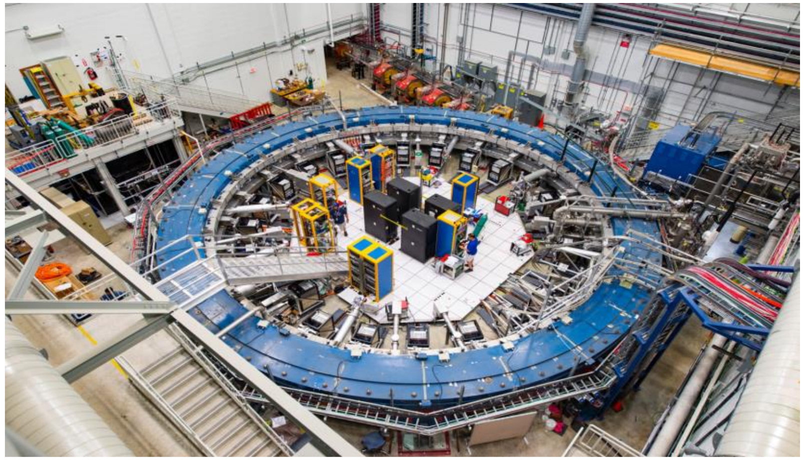
Best measurement result: 2006 at BNL, 0.53 ppm
3.8 sigma discrepancy lasted ~20 years!



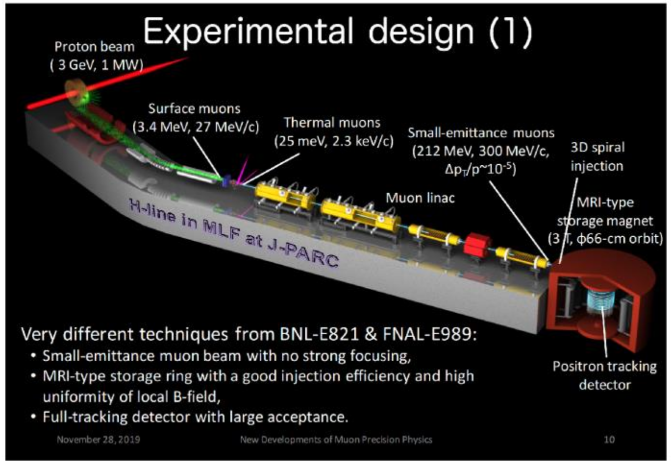
Muon g-2: after BNL

FermiLab

Same design
Upgraded beam
and detector



J-PARC



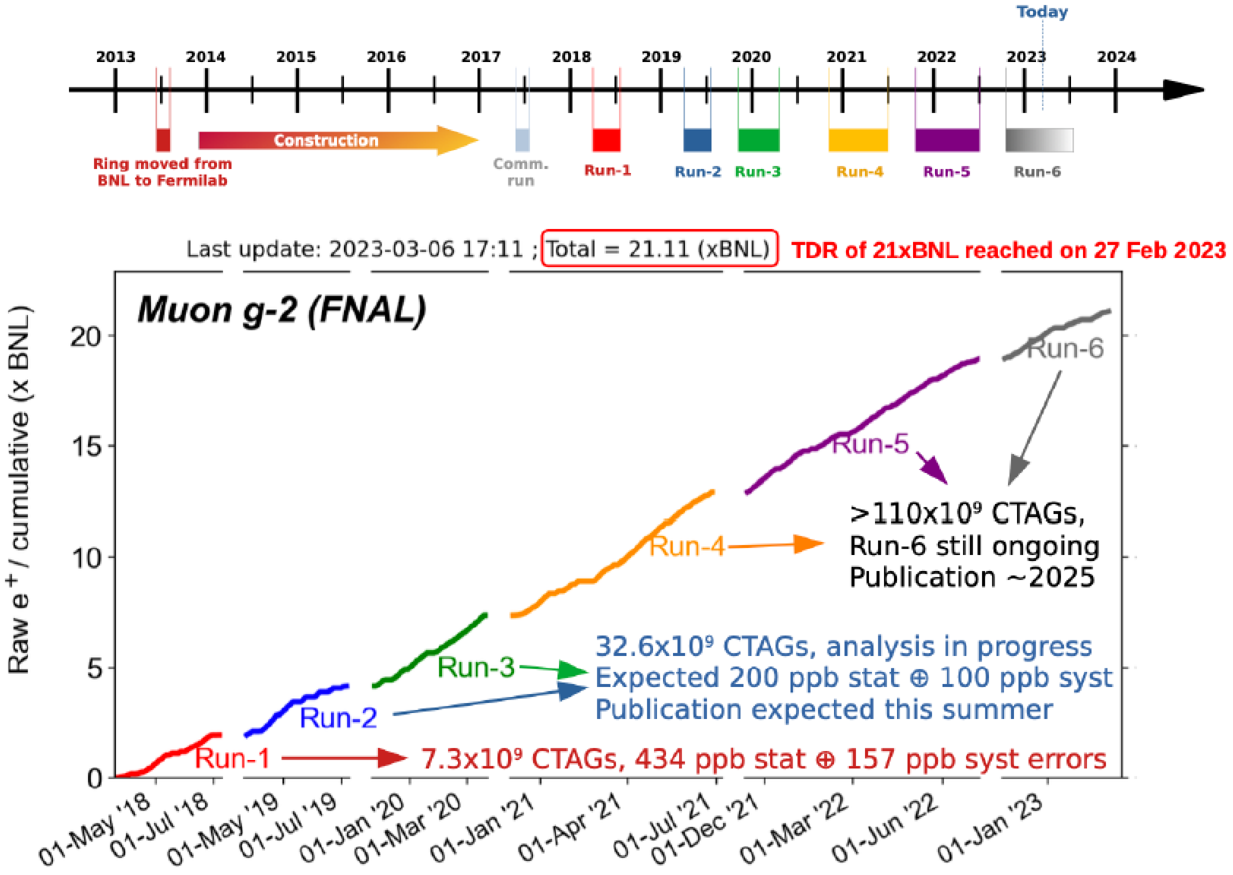
Totally new design.

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

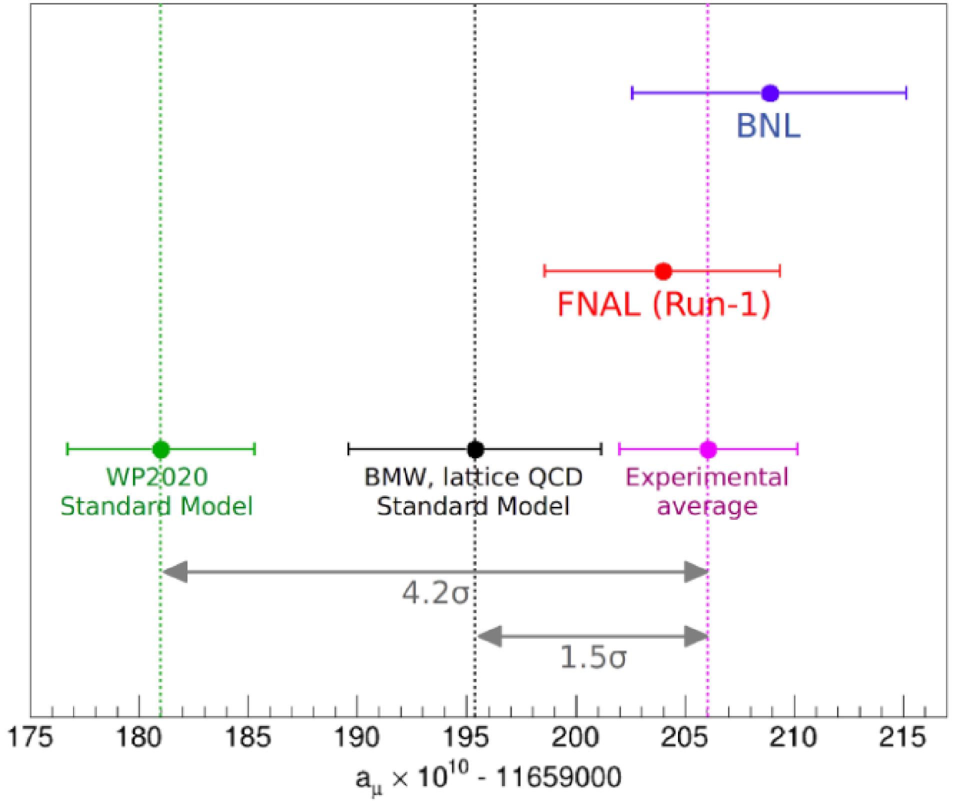
Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

Muon g-2: FermiLab

About to finish data taking of Run-6.

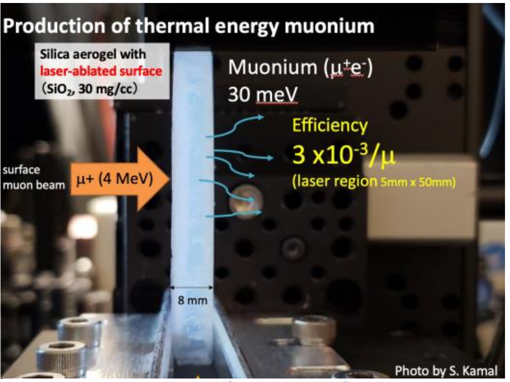


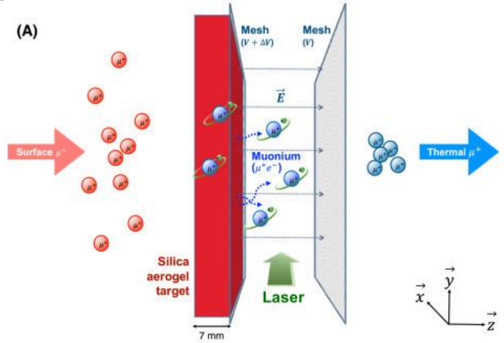
Current result with Run-1.

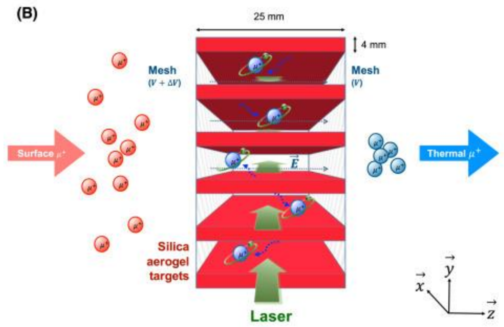


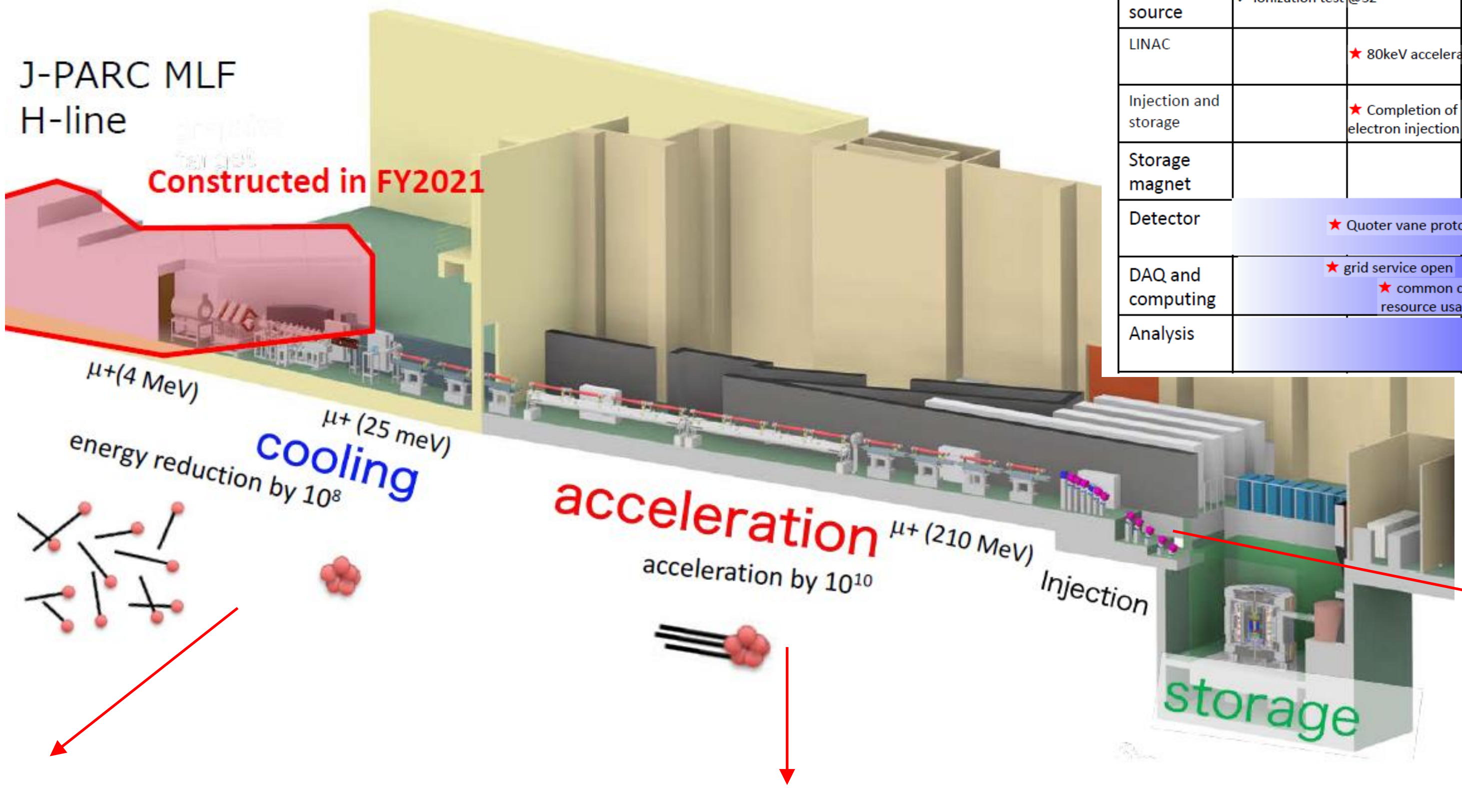
New results coming soon!

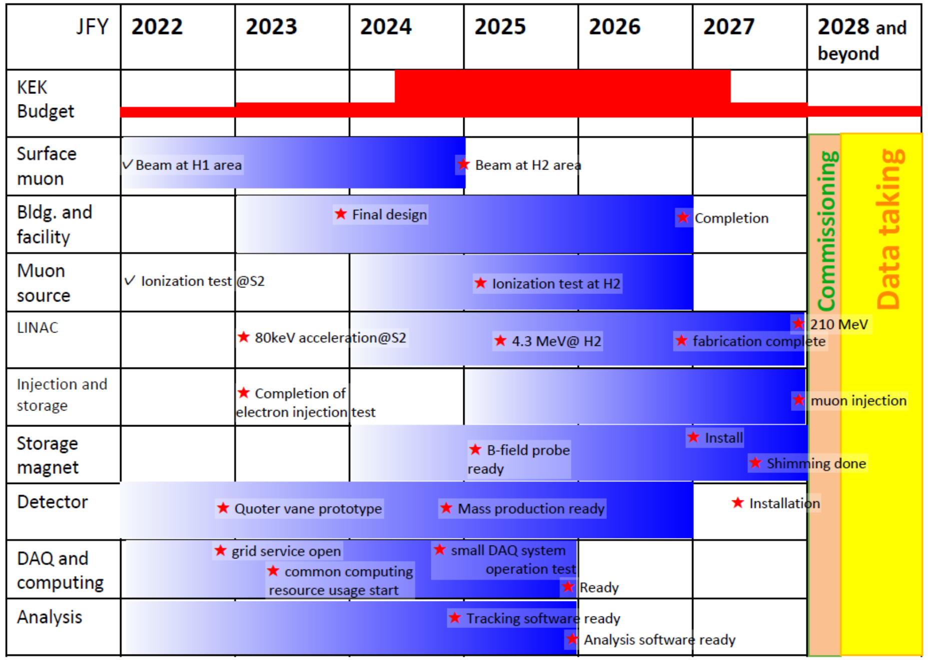
Muon g-2: J-PARC

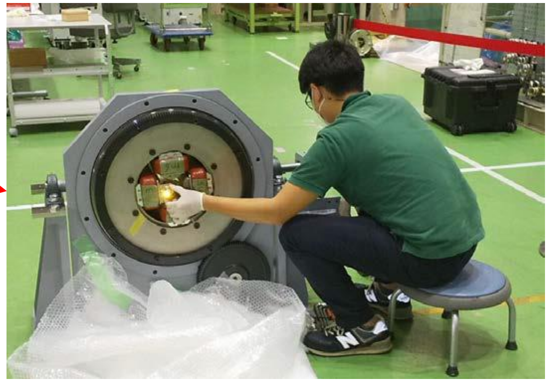


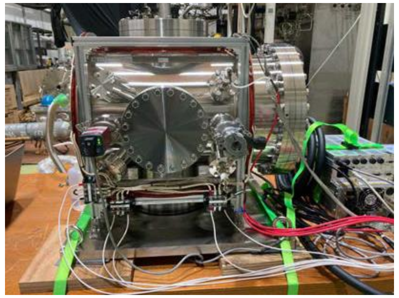










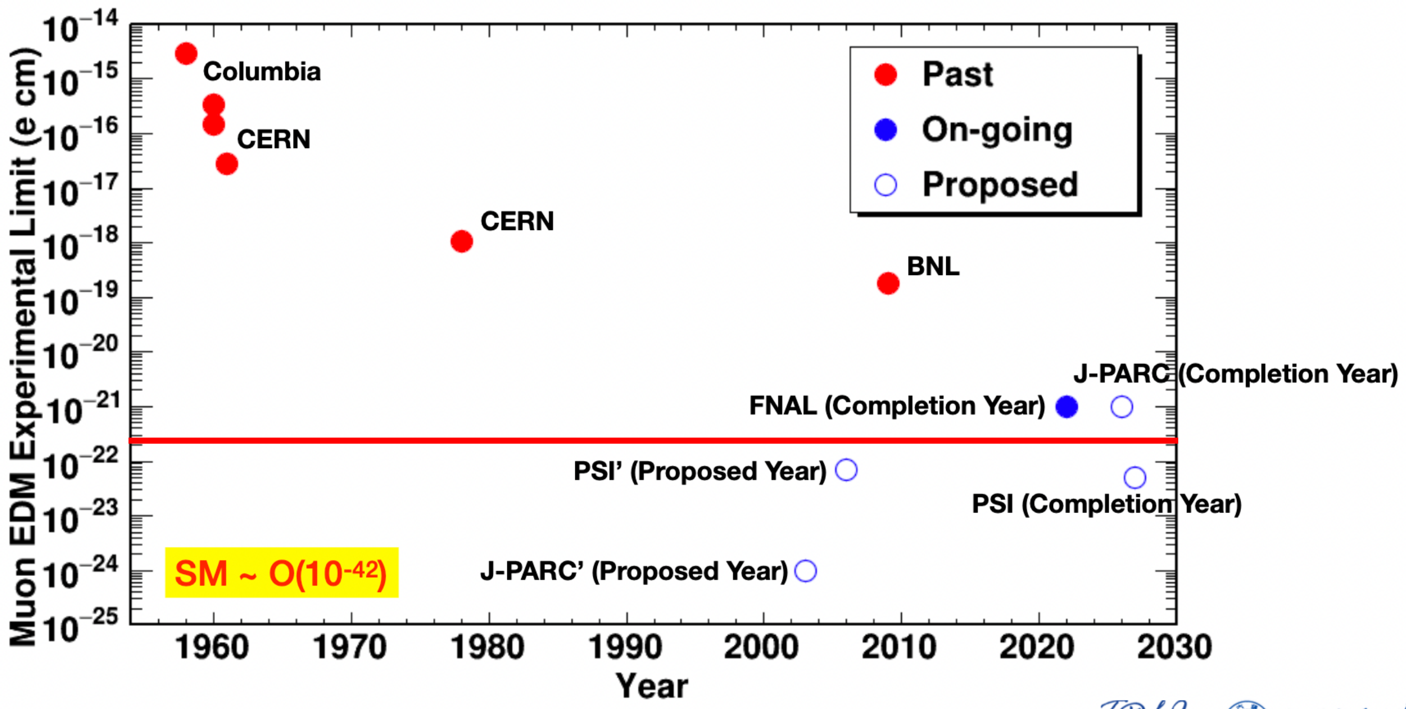


Muon EMD

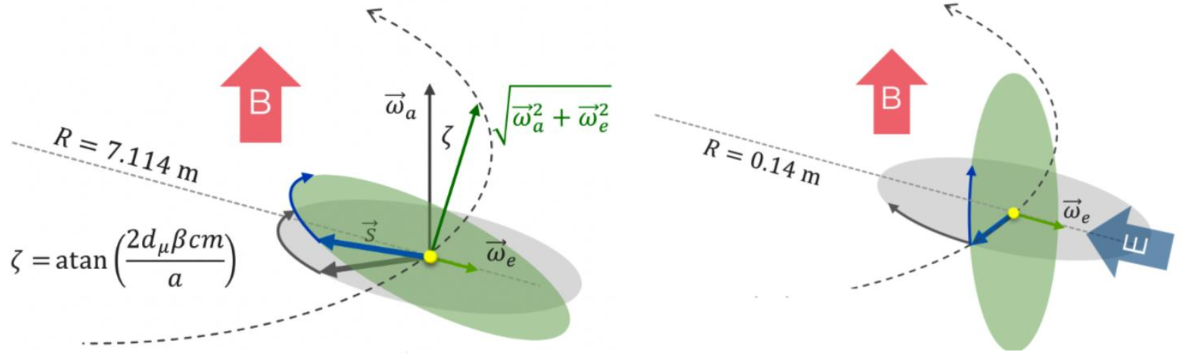
cf. Contribution to the muon g-2 implies …

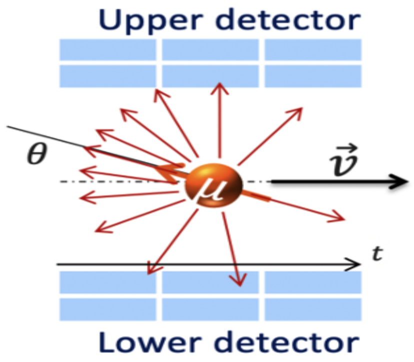
$$|d_\mu| \sim \frac{e}{2m_\mu}\Delta a_\mu \sim 2.34 \times 10^{-22}\, e\,\mathrm{cm}$$

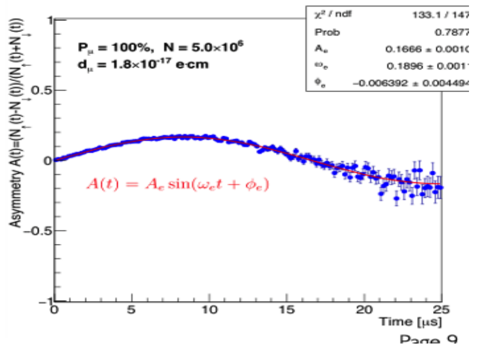
History of muon EDM searches

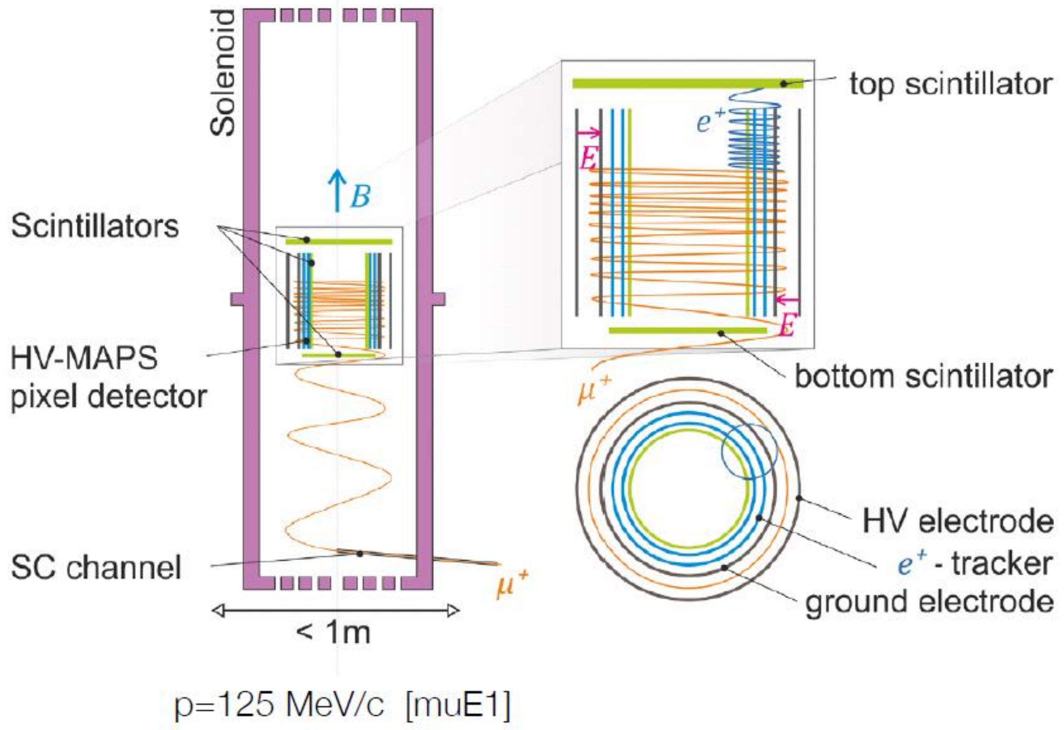


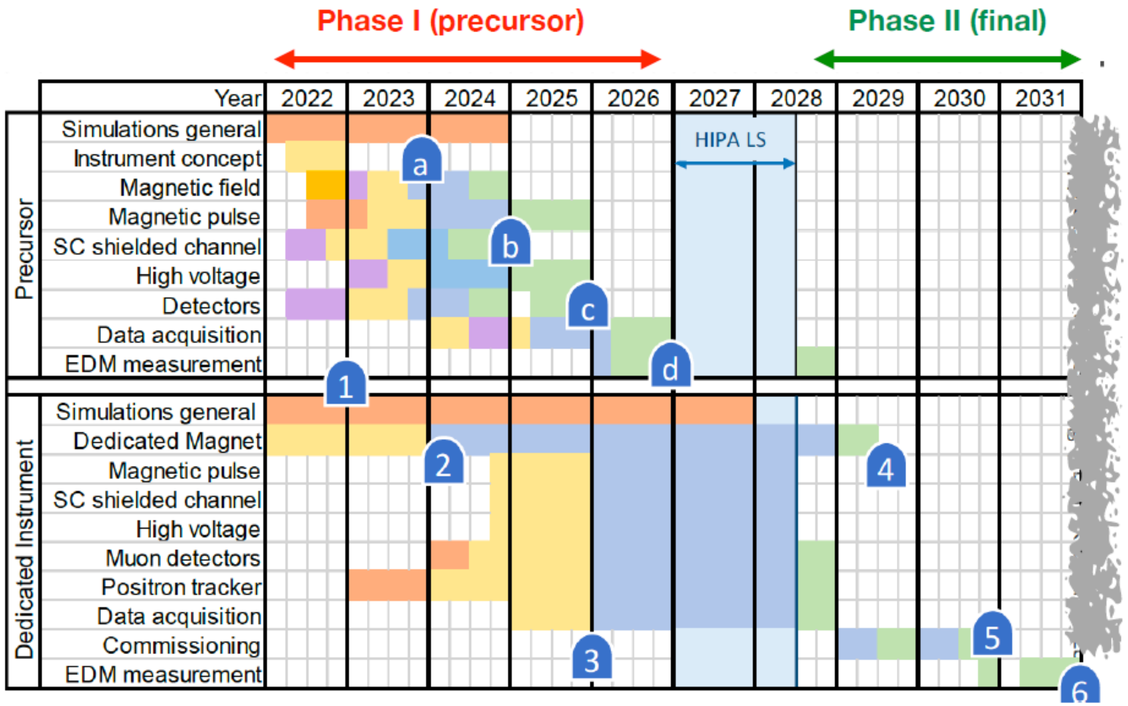
MuEDM at PSI


B
R = 7.114 m
$\vec{\omega}_a$
ζ
$\sqrt{\vec{\omega}_a^2 + \vec{\omega}_e^2}$
$\vec{s}$
$\vec{\omega}_e$
$\zeta = \text{atan}\left(\frac{2d_\mu \beta c m}{a}\right)$
B
R = 0.14 m
$\vec{\omega}_e$
E


Upper detector
θ
μ
$\vec{v}$
t
Lower detector

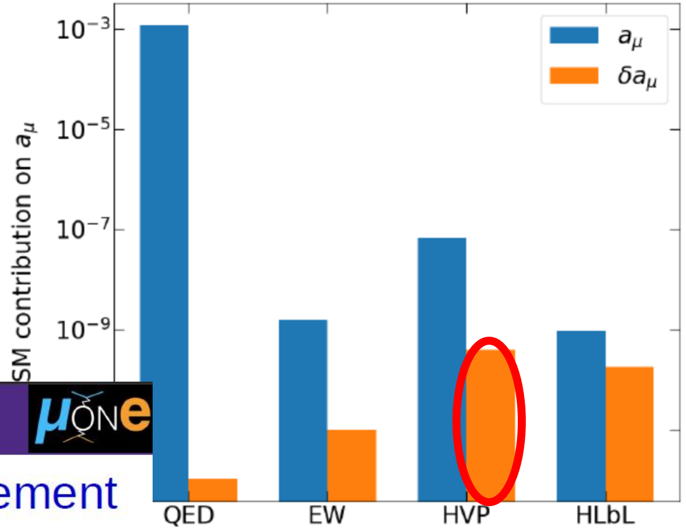

P_μ = 100%, N = 5.0×10^6
d_μ = 1.8×10^-17 e·cm
$A(t) = A_e \sin(\omega_e t + \phi_e)$
Time [µs]


Solenoid
B
Scintillators
HV-MAPS
pixel detector
SC channel
< 1m
top scintillator
e^+
E
bottom scintillator
μ^+
HV electrode
e^+ - tracker
ground electrode
p=125 MeV/c [muE1]


Phase I (precursor)
Phase II (final)
Year 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031
Precursor
Simulations general
Instrument concept
Magnetic field
Magnetic pulse
SC shielded channel
High voltage
Detectors
Data acquisition
EDM measurement
HIPA LS
a
b
c
d
1
Dedicated Instrument
Simulations general
Dedicated Magnet
Magnetic pulse
SC shielded channel
High voltage
Muon detectors
Positron tracker
Data acquisition
Commissioning
EDM measurement
2
3
4
5
6

Muons for precise measurement

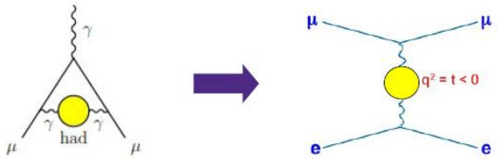
MuonE @ CERN



The MuonE Experiment

A proposal for a complementary data-driven a_μ^{HVP} measurement

- Directly measure the running of α(t) in a kinematic region of sensitivity
- *Spacelike* elastic scattering of muons from atomic electrons



$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)} \qquad \Delta\alpha(t) = \Delta\alpha_{\rm lep}(t) + \Delta\alpha_{\rm had}(t)$$

- Normalize observation to precision calculation (NNLO) with no hadronic contribution

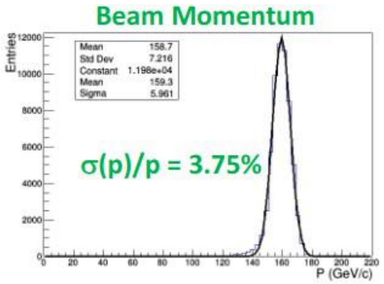
$$R = \frac{d\sigma\left(\Delta\alpha_{had}(q^2)\neq 0\right)}{d\sigma\left(\Delta\alpha_{had}(q^2)=0\right)} \qquad R^{LO}_{had}(t) = \left(1-\frac{\Delta\alpha_{had}(t)}{1-\Delta\alpha_{lep}(t)}\right)^{-2} \simeq 1+2\frac{\Delta\alpha_{had}(t)}{1-\Delta\alpha_{lep}(t)}$$

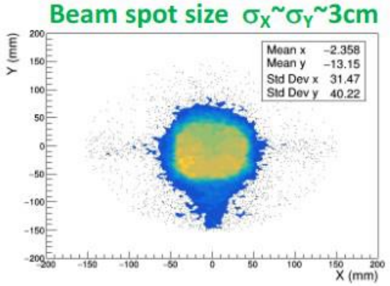
- And obtain leading contribution to a_μ^{HVP} from a similar dispersion relation

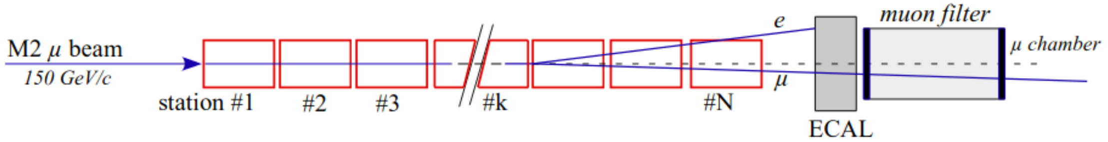
$$a_\mu^{\rm HVP,\,LO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

Letter of Intent: [The MuonE Project](#)

21/06/23 K. Hahn - CLFV 2023 - Heidelberg 5





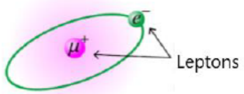


Muonic atom spectroscopy at J-PARC

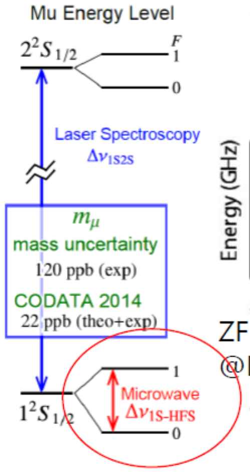
Mu HFS @H1 area

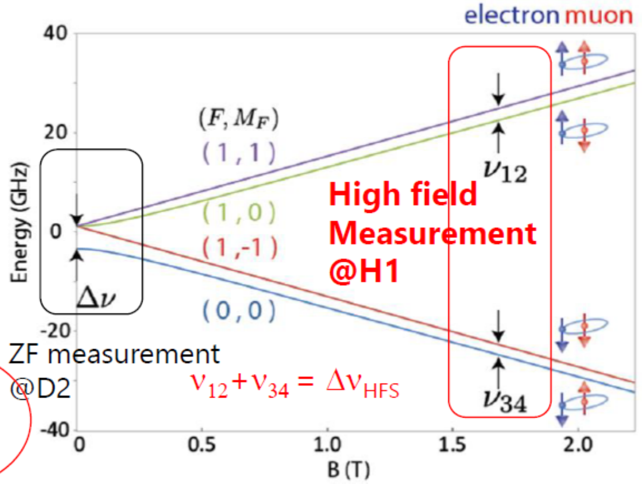
→ Iwai-san's talk

Muonium (Mu)



- Precise measurement of the hyperfine structure of muonium
- MuSEUM: **Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave





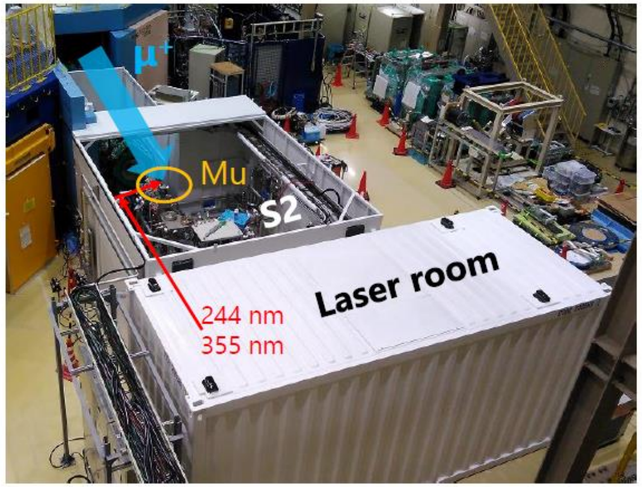
Previous experiment: 4 463.302 765 (53) MHz (LAMPF1999)

Precision of 8 Hz will be reached by a high field measurement at the H-line.

This experiment is going to conducted after the Wien filter is installed.

S2 area and Mu 1S-2S

- 2nd branch of S line for Mu 1S-2S spectroscopy
  - ✓ Surface muon beamline: 2×10^6 μ^+/s
  - ✓ In operation since FY2021

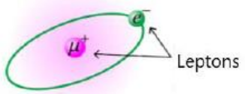


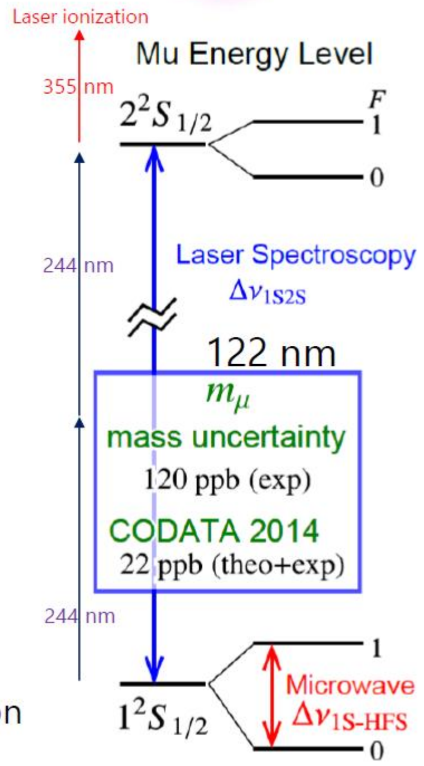
$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$$

mass

Goal:
10 kHz precision
Δm_μ = 1 ppb

Muonium (Mu)

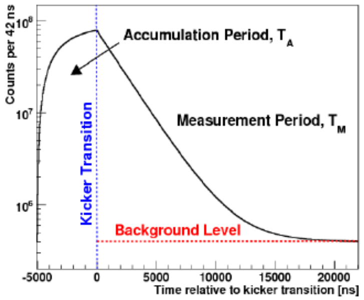


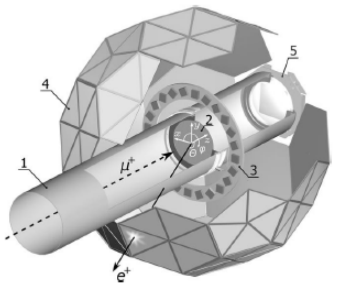


Precise measurement at PSI

MuLan at PSI

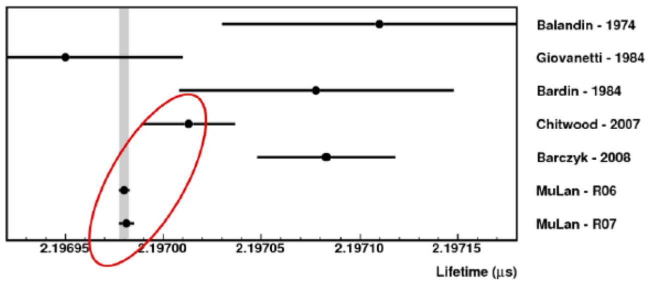
- Strategy
  - pulsed time structure with kicker
  - segmented, fast, simple detector





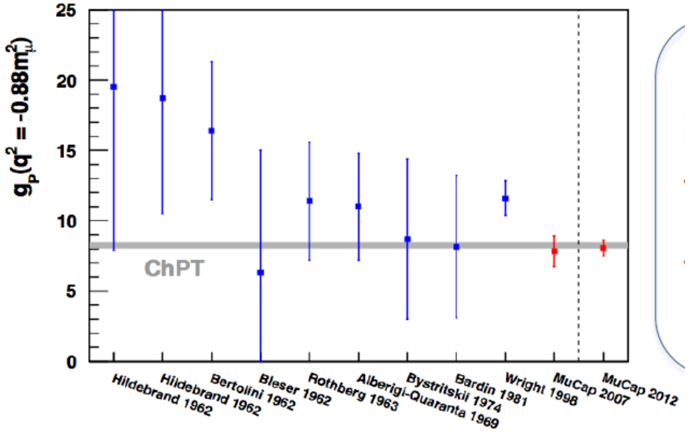
- Result
  - $\tau_{\mu+}$ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

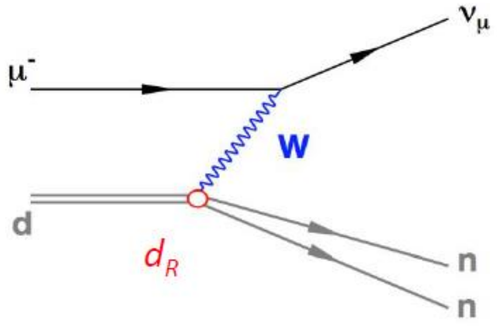
    The most precise particle or nuclear or atomic lifetime ever measured
  - G_F (30x improved since 1999)



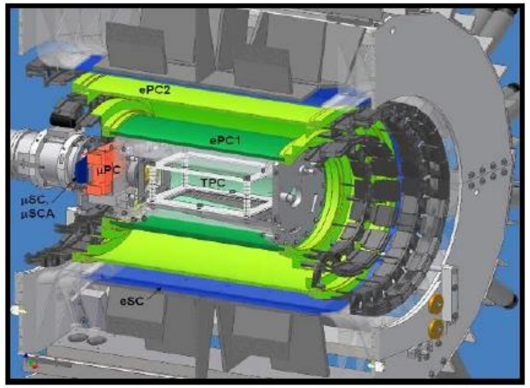
G_F(MuLan) = 1.1663787(6)x10^{-5} GeV^{-2} (0.5 ppm)

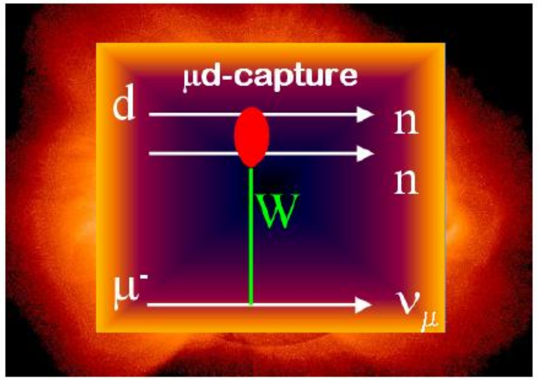
MuLan Collaboration
*PRD **87**, 052003 (2013)*





Measure rate to 1.5%
determine d_R 5x better





- Basic QCD Symmetries
- Axial nucleon current

- Weak few nucleon reactions
- Neutrino astrophysics

Summary

- Muons have unique properties:
  - Not too heavy, not too light, very clean.
- Muons play important role in the precision frontier searching for the new physics beyond the standard model:
  - CLFV, EDM, g-2.
  - Can probe 10^5 TeV indirectly
  - In synergy with energy frontier: muon collider?
- Muons provide unique playgrounds for precise measurements
  - Muonic atom spectroscopy, muon nuclear capture, muon scattering, muonium gravity…