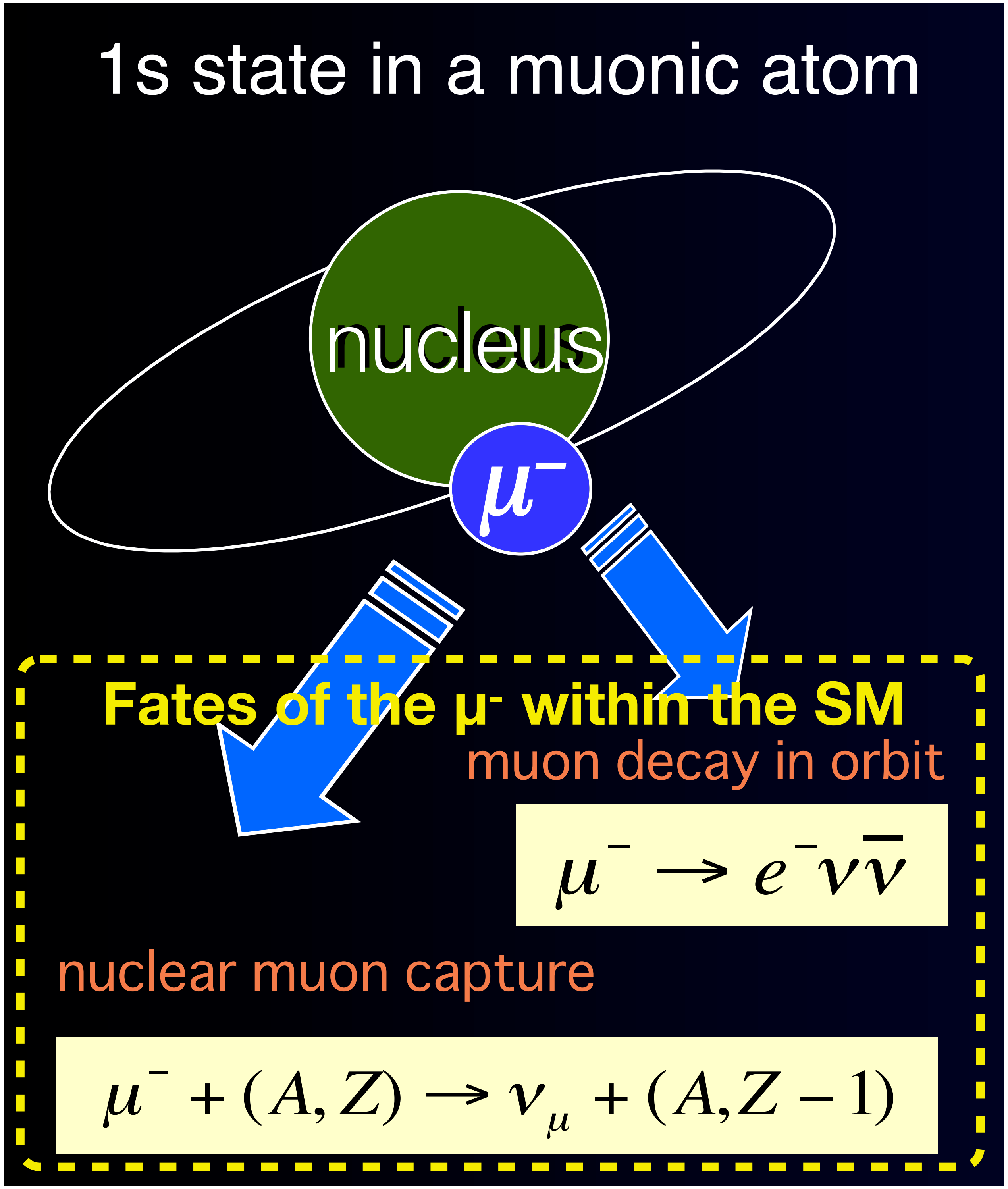
High purity and high brightness muon beam for next generation muon-electron conversion experiments

Akira Sato, Osaka University

NuFact2023, 2023/08/22, Seoul National University, Korea

What is a Muon to Electron Conversion?



Beyond the SM

μ-e conversion

$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

Forbidden by the SM, because
the lepton flavor is changed to μ-flavor to e-flavor.

Event signature :

a single mono-energetic electron of 105MeV (for Al)

in the SM + ν masses

μ-e conversion can be occur via ν-mixing, but expected rate is well below the experimentally accessible range. Rate ~O(10^{-54})

Discovery of the μ-e conversion is a clear evidence of new physics beyond the SM.

in the SM + new physics

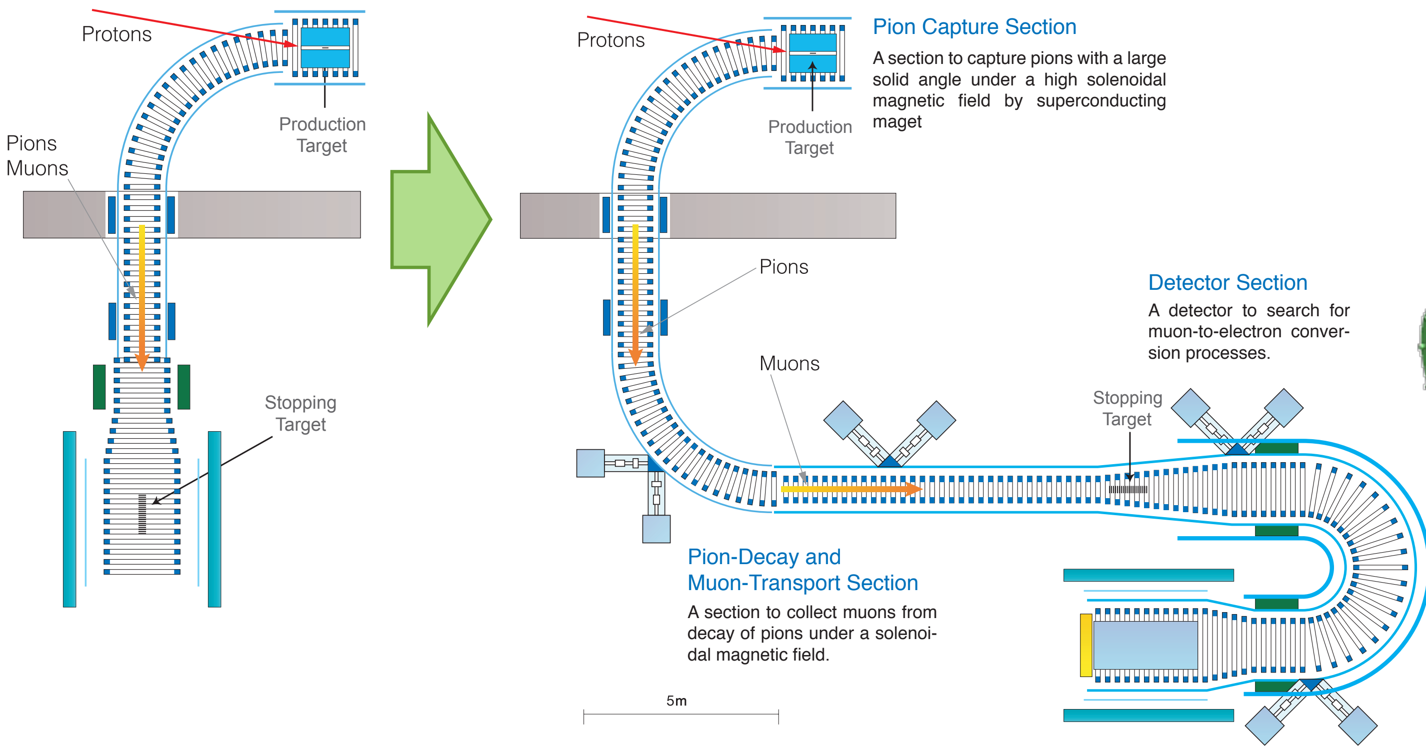
A wide variety of proposed extensions to the SM predict observable μ-e conversion rate.

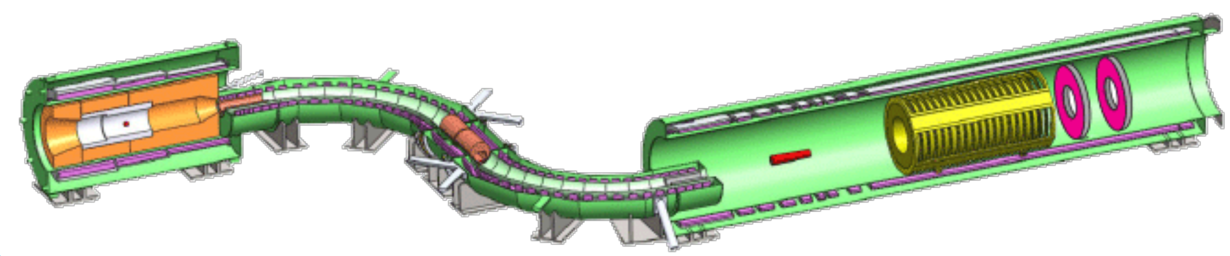
- μ-e conversion search can achieve ~10^4 TeV energy scale.

COMET and Mu2e

COMET @J-PARC

Mu2e @FNAL





COMET Phase-I : S.E.S. ~ 3 x 10^{-15} on Al — Under construction

COMET Phase-II : S.E.S. ~ 3 x 10^{-17} on Al — Planed

Mu2e: S.E.S. ~ 3 x 10^{-17} on Al — Under construction

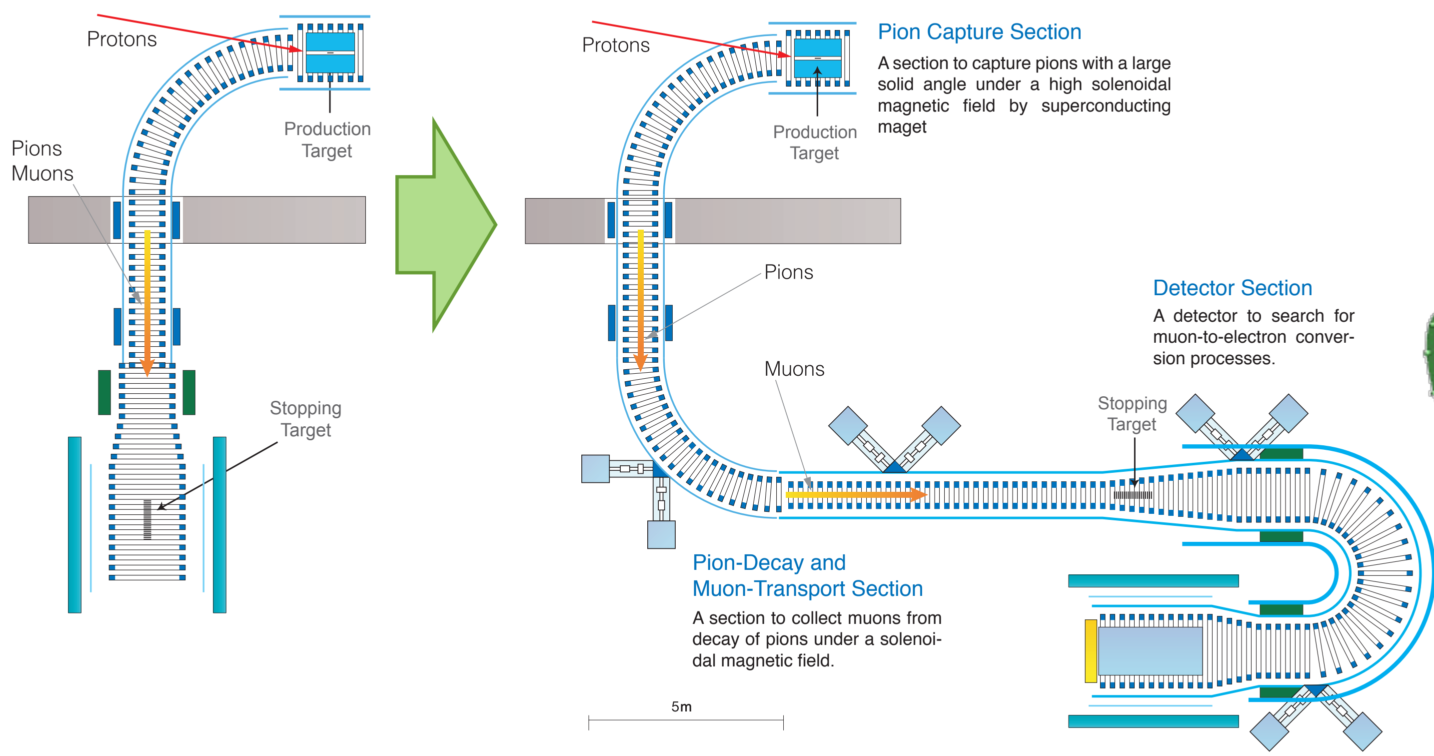
Mu2e-II: S.E.S. **~ 3 x 10^{-18}** on Al — Under discussion

Features of the Setup

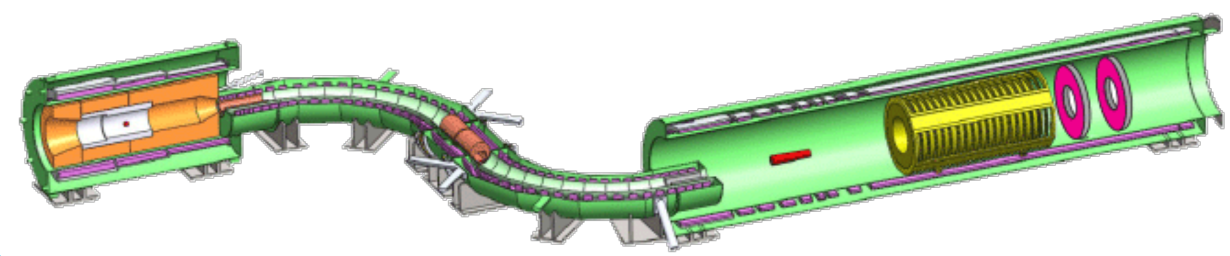
- Solenoid channel
- Stop μ^- at the stopping targets.
- ID single electron from the target and measure its energy precisely.

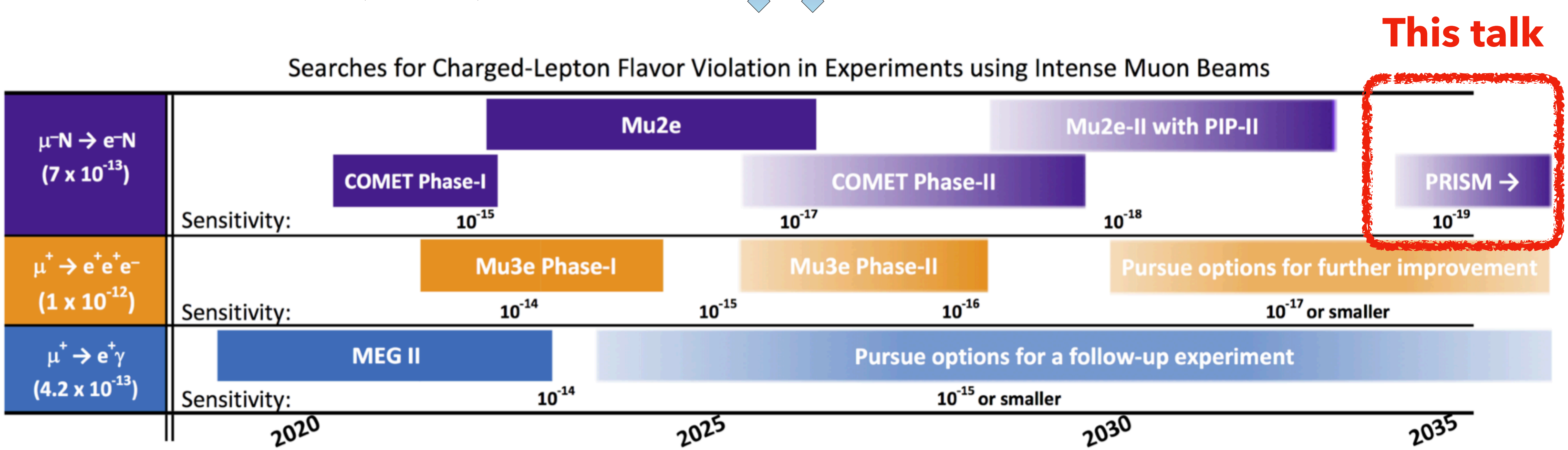
COMET and Mu2e

COMET @J-PARC



Mu2e @FNAL

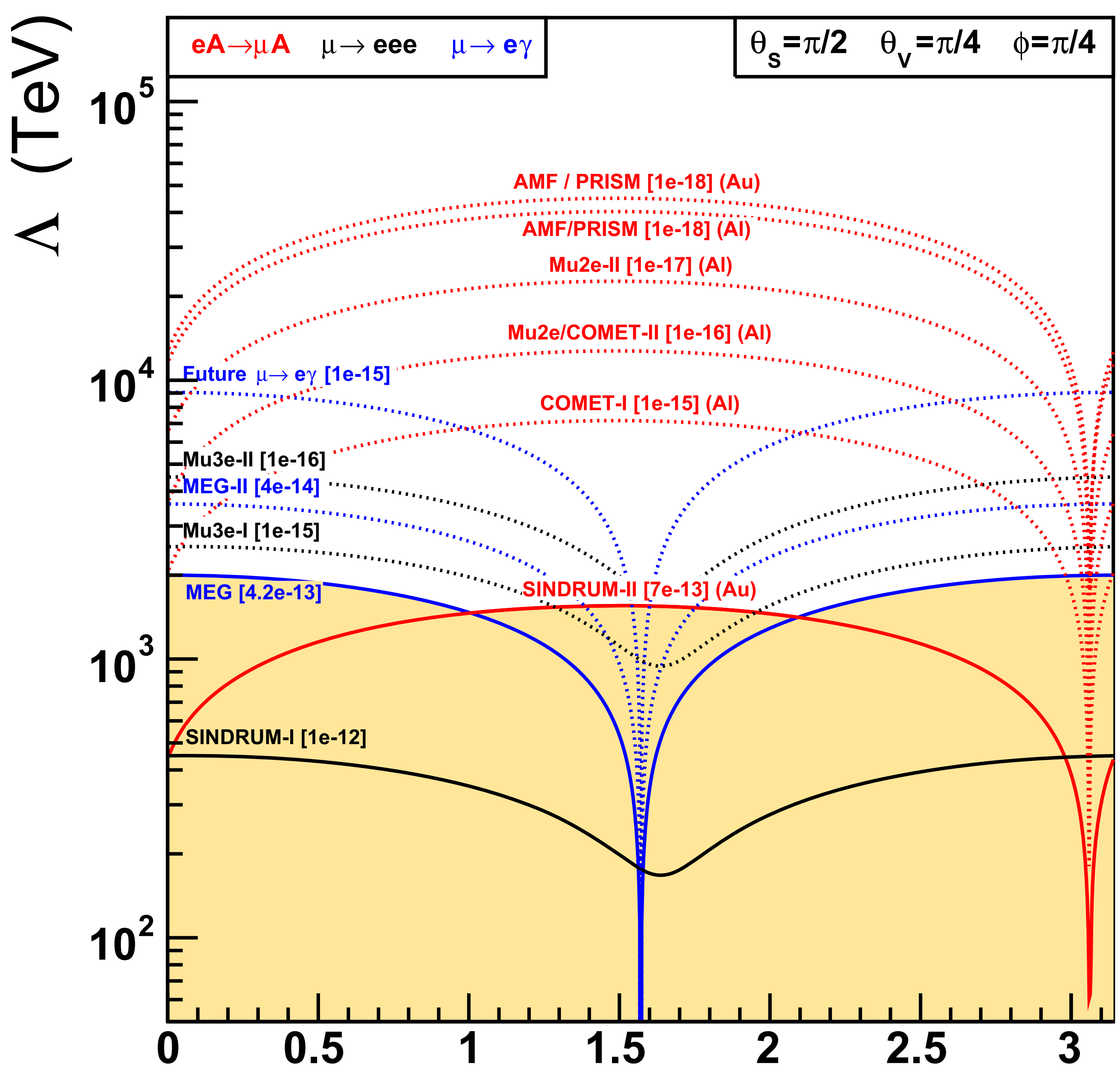




https://arxiv.org/pdf/1812.06540.pdf

What to aim for in the next experiment

- **Case 1:** No signal discovery in COMET and Mu2e
  - BR < 6.3 x 10^{-17} (90% CL) will be achieved
  - **Next: Further sensitivity improvement** (Mu2e-II: < 5.8×10^{-18})



Eur. Phys. J. C (2022) 82:836
https://doi.org/10.1140/epjc/s10052-022-10773-4

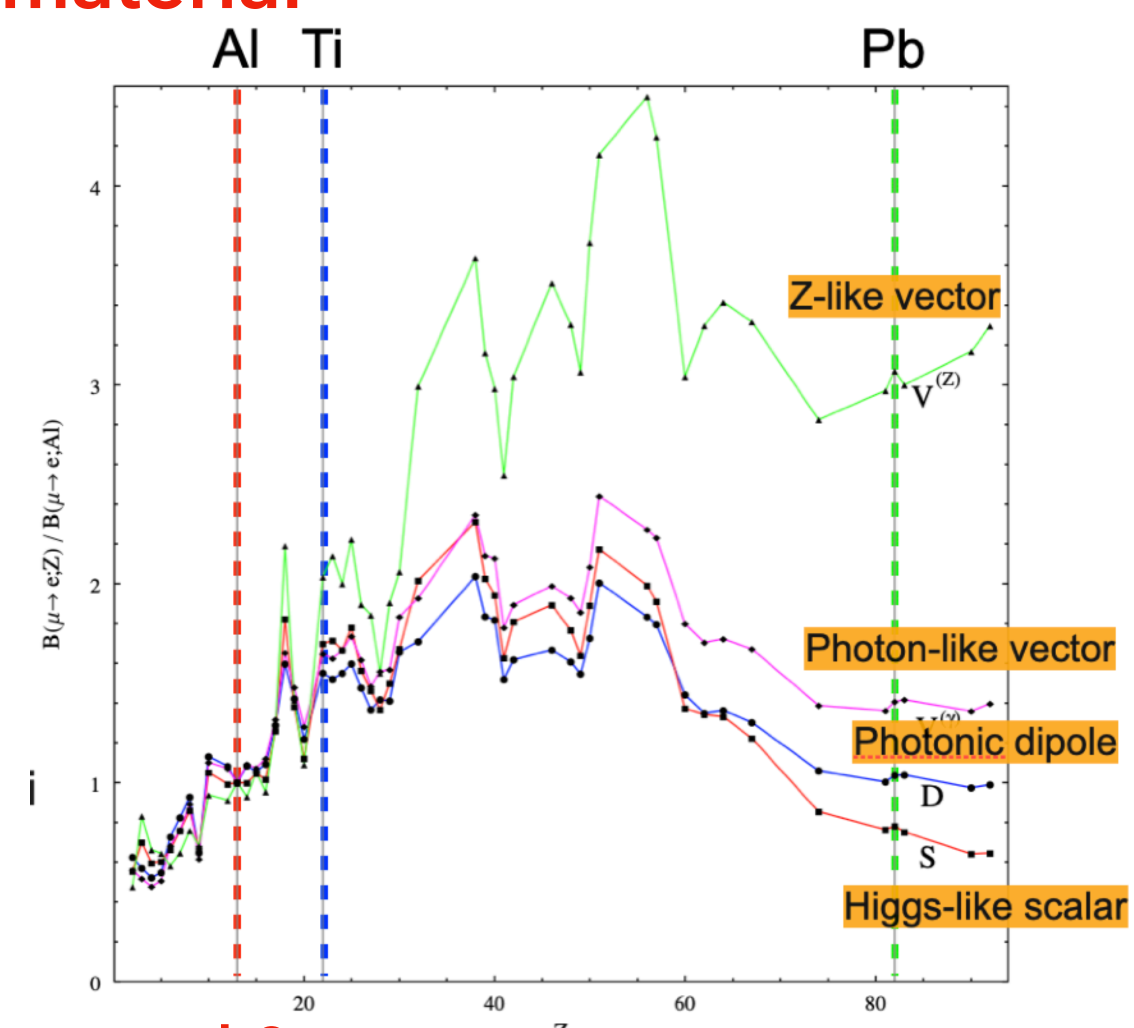
$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re)$$
$$+C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re)$$
$$+C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight}$$
$$+C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big] \quad (2.1)$$

Table 2 Dimensionless operator coefficients expressed in the angular coordinates. The radial coordinate is $1/\Lambda^2_{LFV}$, $\theta_I : 0..\pi$ and $\phi : 0..2\pi$. As discussed in Appendix 1, the $\vec{e}_{VL} \times \vec{e}_{VR}$ plane was projected to a line, deviations from which are measured by θ_V. In general, the basis vectors $\{e_A\}$ are not unit vectors, and their normalisation is given in Table 5 and after Eq. (C.3) for the primed vectors

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

What to aim for in the next experiment

- **Case 1:** No signal discovery in COMET and Mu2e
  - BR < 6.3 x 10^{-17} (90% CL) will be achieved.
  - **Next: Further sensitivity improvement** (Mu2e-II: < 5.8x10^{-18})
- **Case 2:** Signal event discovered in COMET and/or Mu2e
  - BR(Al) will be determined.
  - **Next: Change the stopping target material**
    - To study physics mechanism
      - (A,Z) dependence
      - Spin dependence
  - Candidate target material
    - Al (τ~880ns), SI, SD (COMET/Mu2e)
    - Ti (τ~330ns)
      - (Nuclear spin=0; SI),
    - Pb,Au (τ~80ns)



V.Cirigliano et al. Phys. Rev. D 80 013002 (2009)

How? Higher intensity muon beam is needed. It is enough?

Potential Backgrounds for μ-e Conversion

- Because μ-e conversion is an ultra rare decay process, in the future experiments, we need to improve not only the **muon intensity**, but also the **background reduction** power.

Table 14. Summary of the estimated background events for a single-event sensitivity of 3×10^{-15} in COMET Phase-I with a proton extinction factor of 3×10^{-11}.

Type	Background	Estimated events	
Physics	Muon decay in orbit	0.01	DIO
	Radiative muon capture	0.0019	
	Neutron emission after muon capture	< 0.001	
	Charged particle emission after muon capture	< 0.001	
Prompt beam	* Beam electrons		
	* Muon decay in flight		
	* Pion decay in flight		
	* Other beam particles		
	All (*) combined	≤ 0.0038	
	Radiative pion capture	0.0028	RPC
	Neutrons	$\sim 10^{-9}$	
Delayed beam	Beam electrons	~ 0	
	Muon decay in flight	~ 0	
	Pion decay in flight	~ 0	
	Radiative pion capture	~ 0	
	Antiproton-induced backgrounds	0.0012	DB
Others	Cosmic rays†	< 0.01	
Total		0.032	

† This estimate is currently limited by computing resources.

The COMET Collaboration, “COMET Phase-I technical design report”, Progress of Theoretical and Experimental Physics, Volume 2020, Issue 3, March 2020, 033C01, https://doi.org/10.1093/ptep/ptz125

Ways for BG reduction in COMET/Mu2e for SES ~ 10^{-17}

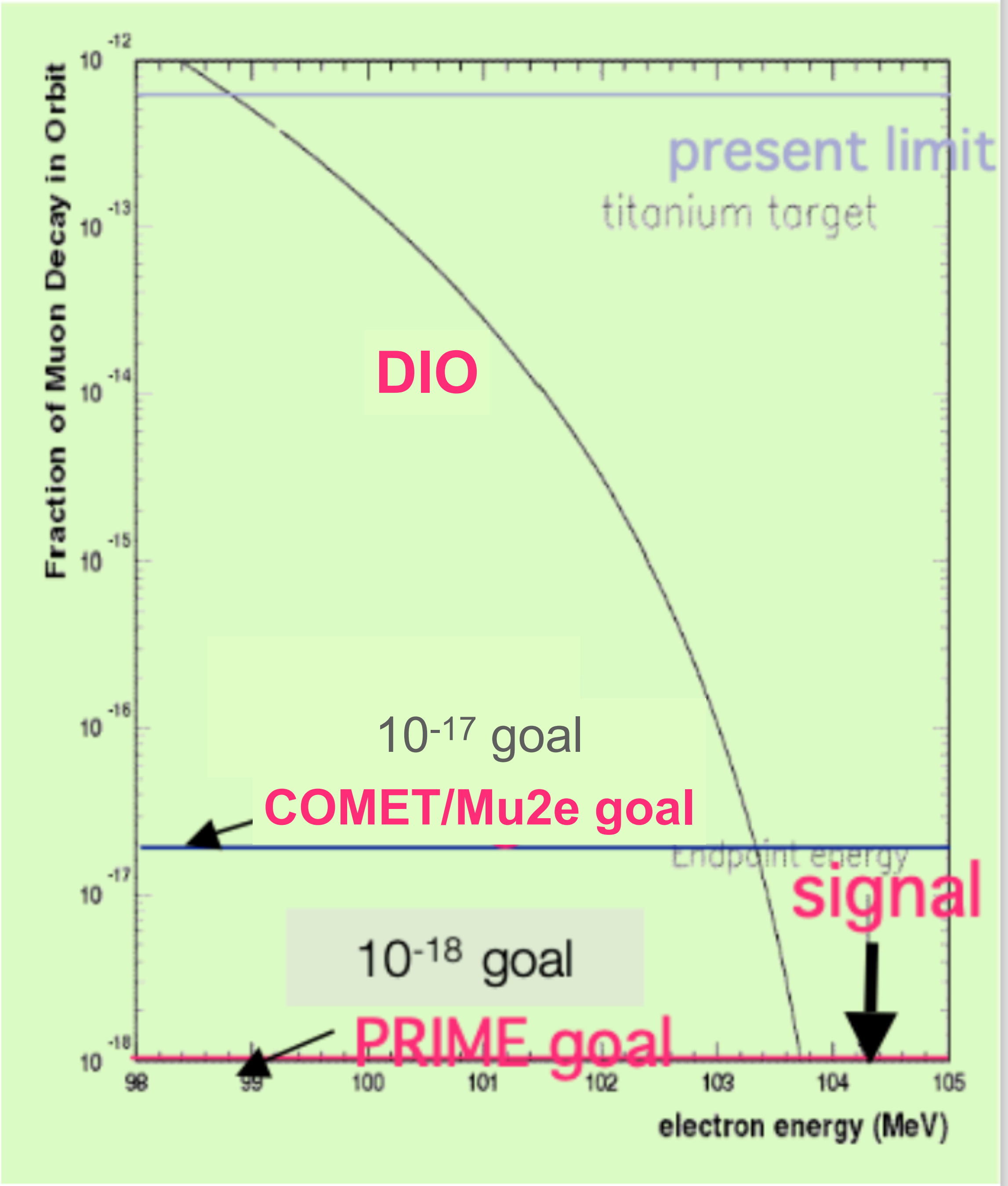
- **Low mass tracker** — Improve e- energy resolution
- **Beam pulsing with separation of ~1 μs** — Measure between the beam pulses
- **High proton beam extinction: ~10^{-10}**
- **Curved solenoids for momentum selection** — Eliminate energetic muon (>75MeV/c)
- **Long muon transport** — Reduce pion contamination

Not enough for future experiments. Need new ideas.

Problems to go beyond the 10^{-18} sensitivity

- COMET/Mu2e scheme has some critical problems in further improving experimental sensitivity for 10^{-18} level and the detailed study changing the stopping target.

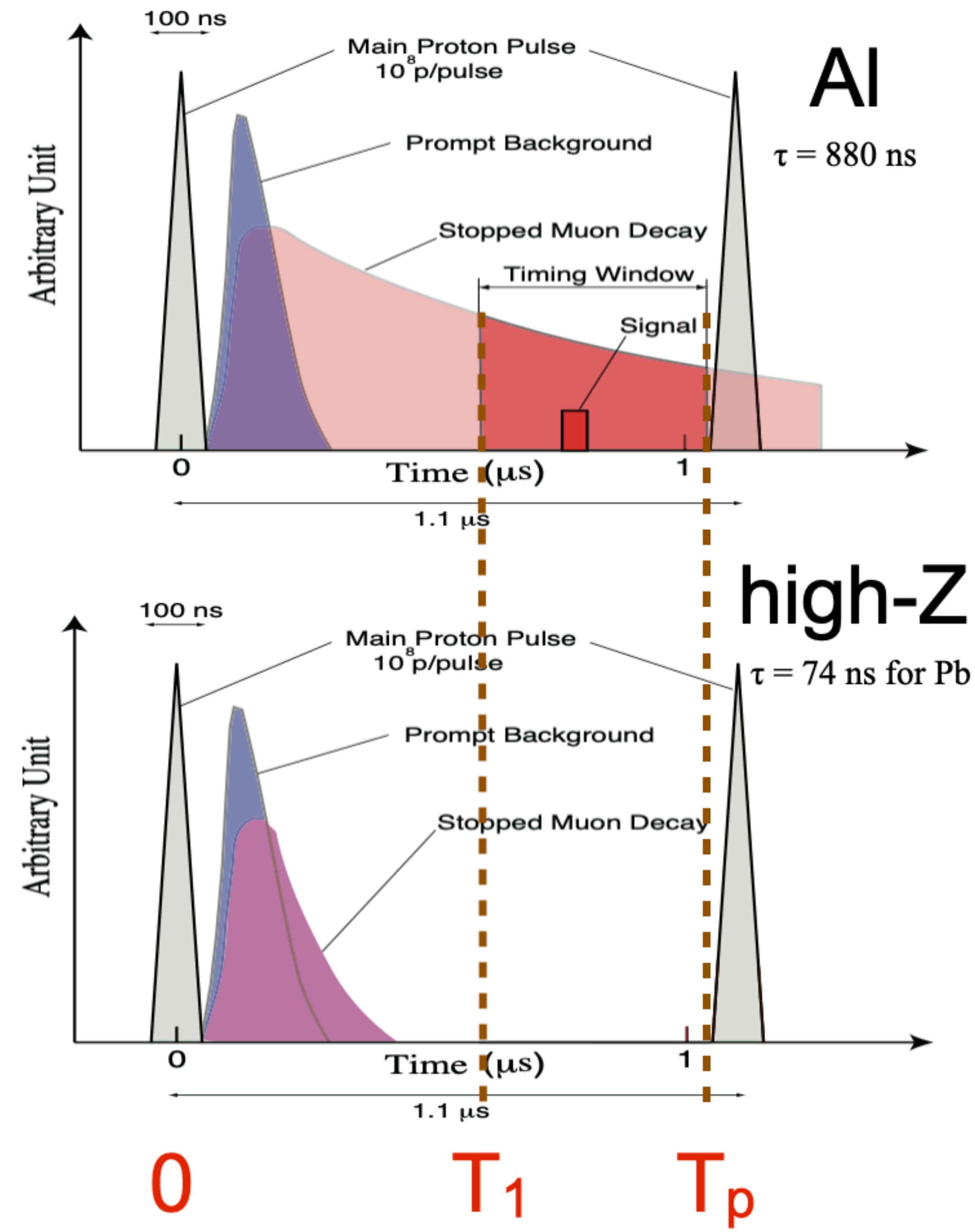
- **DIO reduction is not enough**
  - Reconstructed momentum resolution is not enough to reject DIO electrons.
    - σ_p: mainly from tracker performance and energy struggling in the target.
  - Energy struggling in the stopping targets is not negligible.
- **Cannot use the heavy target material**
  - The measurement starts after 700 nsec after the prompt. Material of a muon stopping target is limited to low Z.
  - For high Z target, muon life is short (~80ns). We have to open the measurement window as early as possible, but there are a lot of prompt BG.
  - The solenoid beam line is not long enough, so that late pions might come in a beam. Radiative Pion Capture can be a crucial BG.
- **Beam background rejection is not enough**
  - It is heavily relined on proton beam extinction of 10^{-10}, which is uncertain.



Problems to go beyond the 10^{-18} sensitivity

- COMET/Mu2e scheme has some critical problems in further improving experimental sensitivity for 10^{-18} level and the detailed study changing the stopping target.

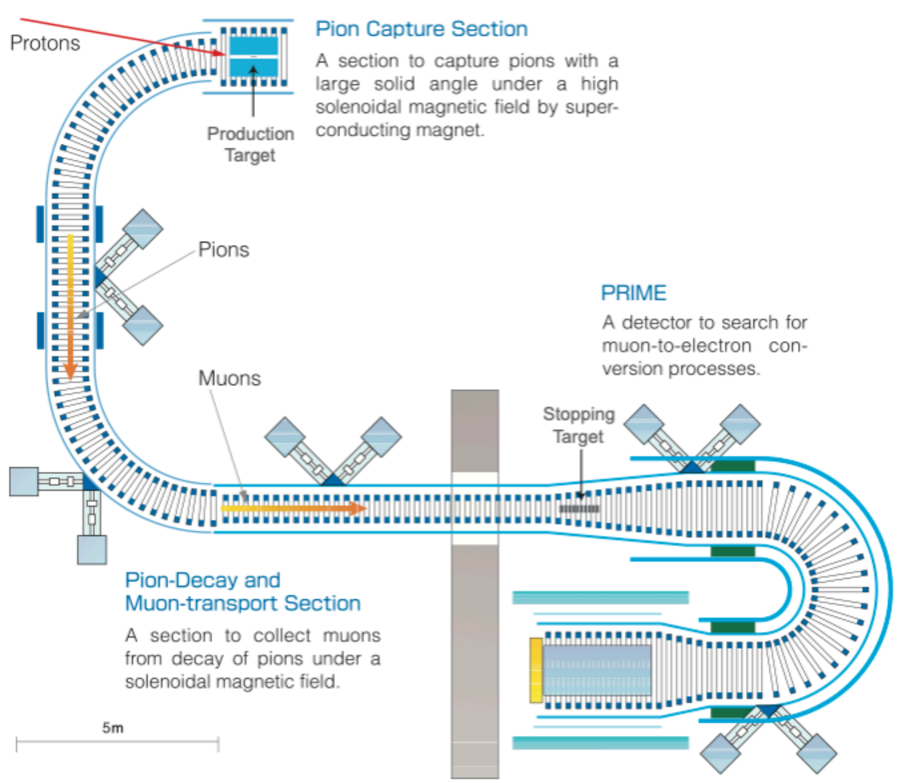
- **DIO reduction is not enough**
  - Reconstructed momentum resolution is not enough to reject DIO electrons.
    - σ_p: mainly from tracker performance and energy struggling in the target.
  - Energy struggling in the stopping targets is not negligible.
- **Cannot use the heavy target material**
  - The measurement starts after 700 nsec after the prompt. Material of a muon stopping target is limited to low Z.
  - For high Z target, muon life is short (~80ns). We have to open the measurement window as early as possible, but there are a lot of prompt BG.
  - The solenoid beam line is not long enough, so that late pions might come in a beam. Radiative Pion Capture can be a crucial BG.
- **Beam background rejection is not enough**
  - It is heavily relined on proton beam extinction of 10^{-10}, which is uncertain.



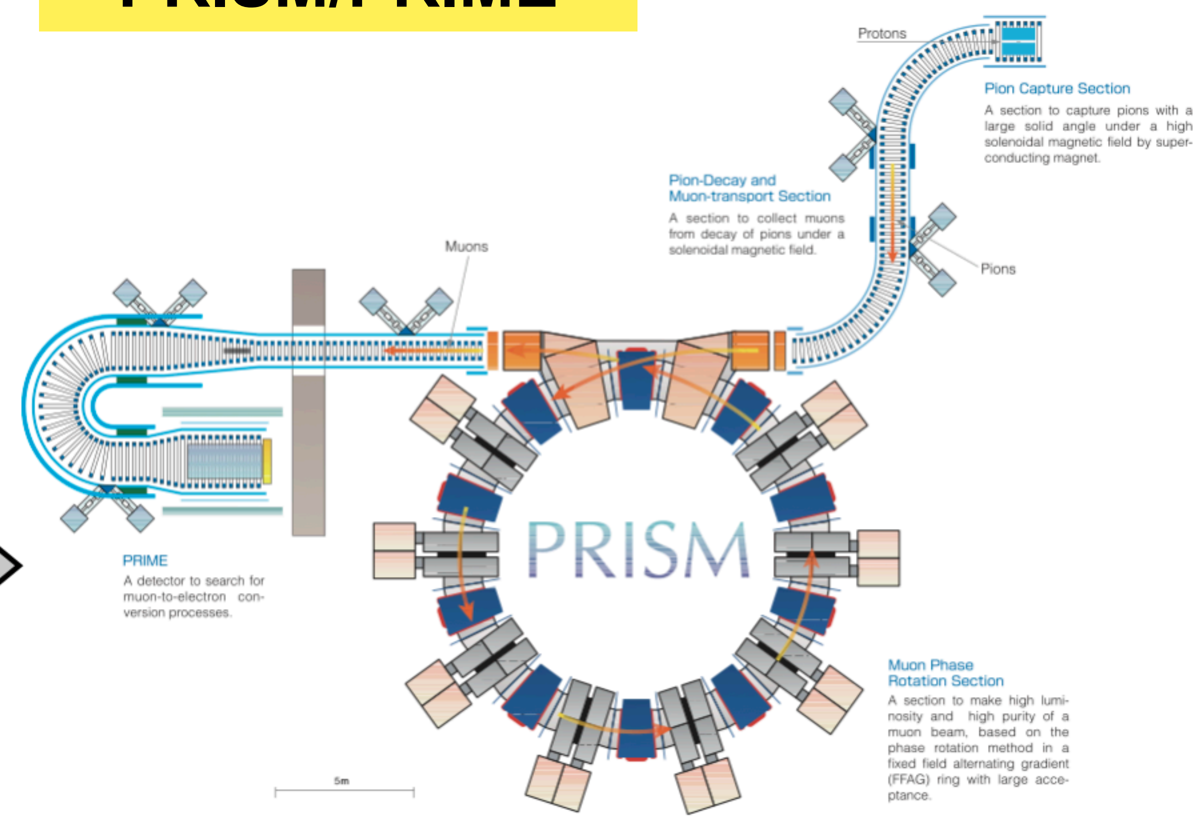
PRISM/PRIME as the next μ-e experiment

- We proposed the PRISM/PRIME idea as a solution of these problems for below the 10^{-18} level μ-e conversion experiment.

COMET



PRISM/PRIME



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

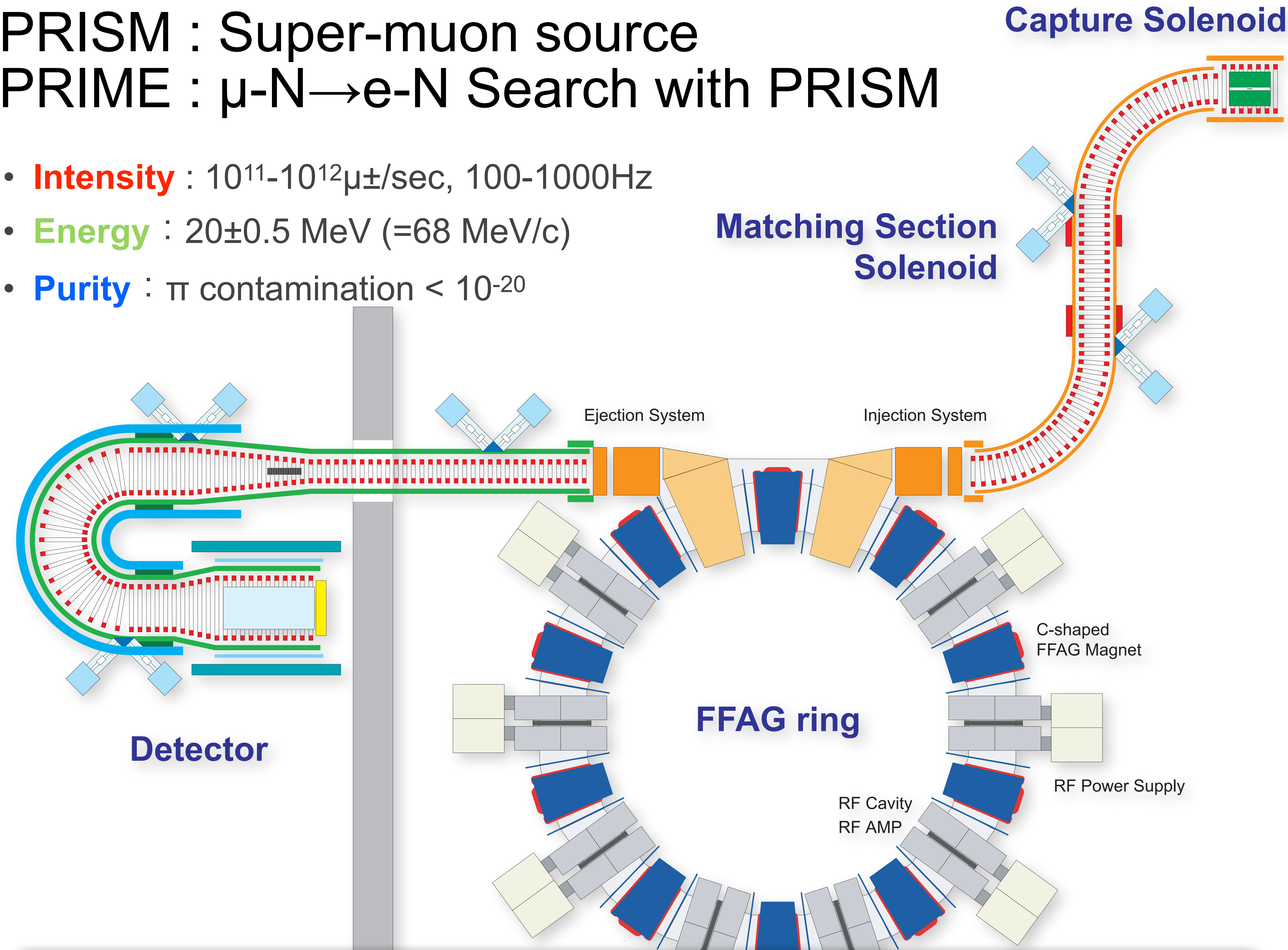
- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

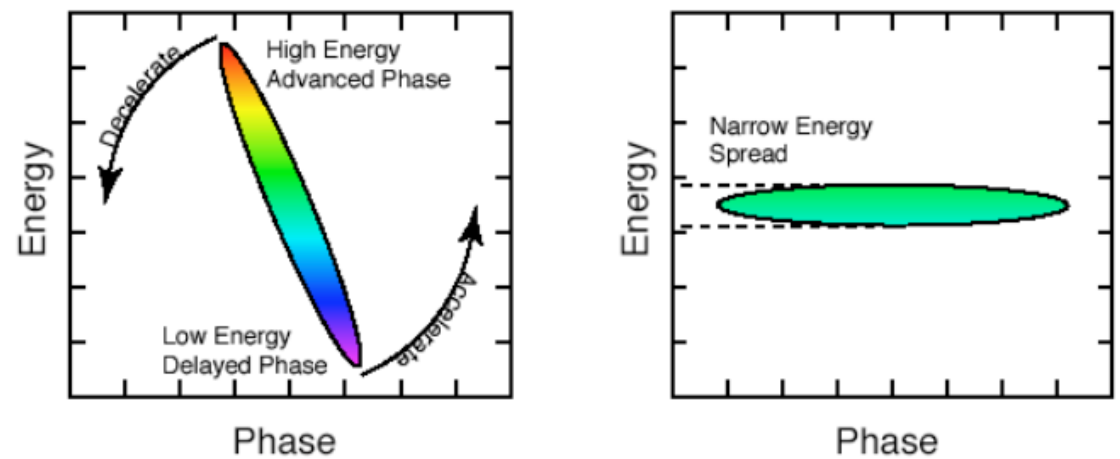
- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}



PRISM-FFAG is a key device to achieve the mono-energetic and pure muon beam. Phase rotation is applied in the ring.

High brightness beam by PRISM

- To make a narrow energy spread muon beam, a technique of phase rotation is adapted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles.



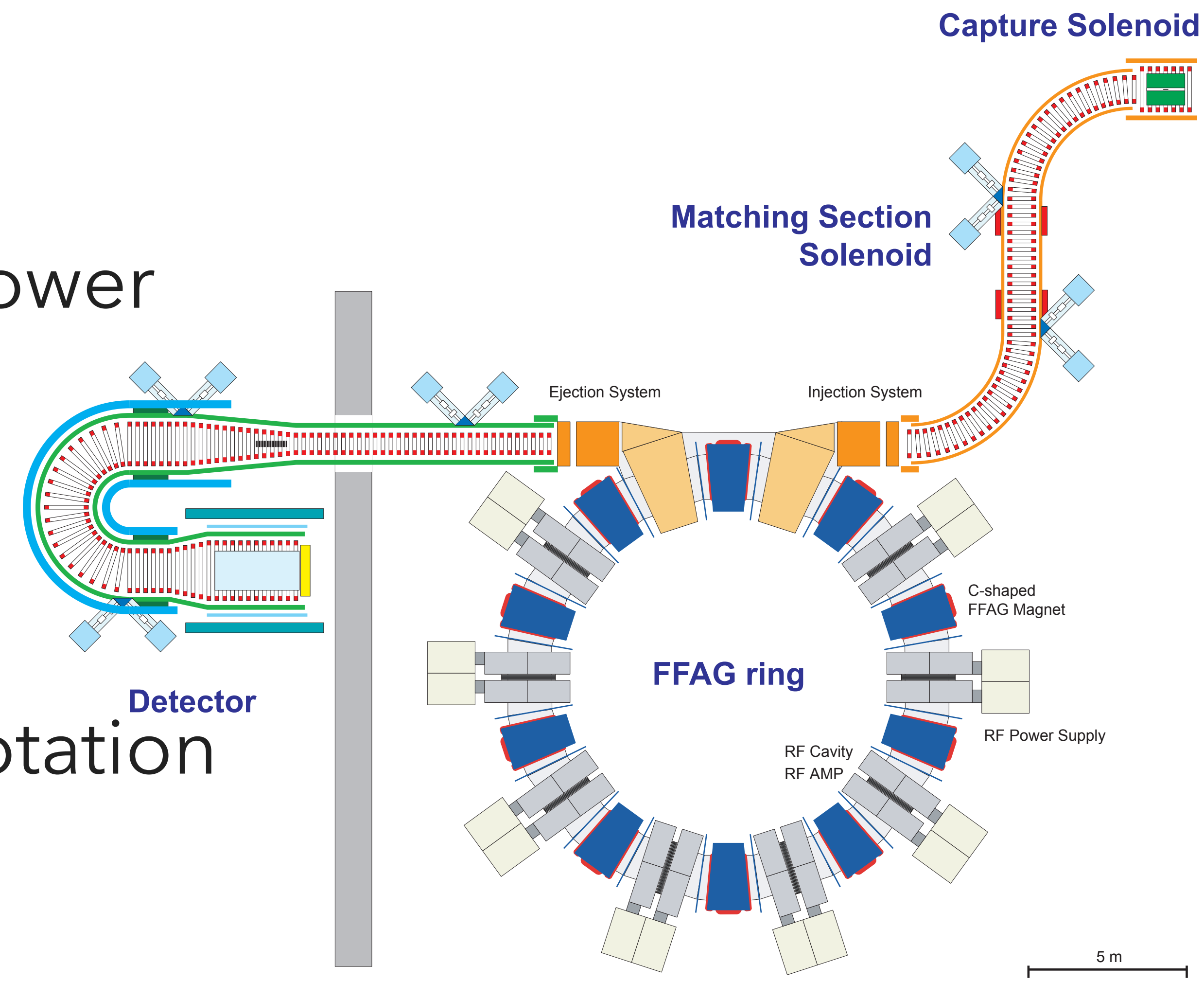
- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
  - Fast particle comes earlier and slow particle comes late.
- Proton beam pulse should be narrow (< 10 ns).
- Phase rotation is a well established technique. To adapt it to muon beam (large emittance), FFA ring provides a good solution.

Background rejection by PRISM

- **(1) Narrow muon beam energy spread**
  - goal : +- 3 %; **High brightness beam**
  - by phase rotation at the PRISM-FFA ring
  - Muons can easily stop in a very thin stopping target (1/10 of COMET/Mu2e). Reduce energy struggling in the target. Improve the resolution of the reconstructed momentum.
- **(2) Long muon flight length**
  - about 40 m circumference x 5-6 turns at PRISM-FFA ring
  - pion survival rate of $<10^{-20}$; No pion contamination
  - Pion Radiative Capture BG is negligible
- **(3) Muon beam energy selection before the detector**
  - momentum slit after the PRISM-FFAG ring
  - 68 MeV/c +- 3% (not 104 MeV)
  - Muon decay in flight BG is negligible. No signal like e- in the beam. **Pure low-μ^- beam**
- **(4) Beam extinction at muons**
  - Kicker magnets of the PRISM-FFA ring
  - no proton extinction needed
- **(5) Small duty factor of detection**
  - ~ 10^{-4} for a detection of 1 μs with 100 Hz repetition
    - The rep. rate depends on the kicker specification.
    - Better suppression of Cosmic-ray BG

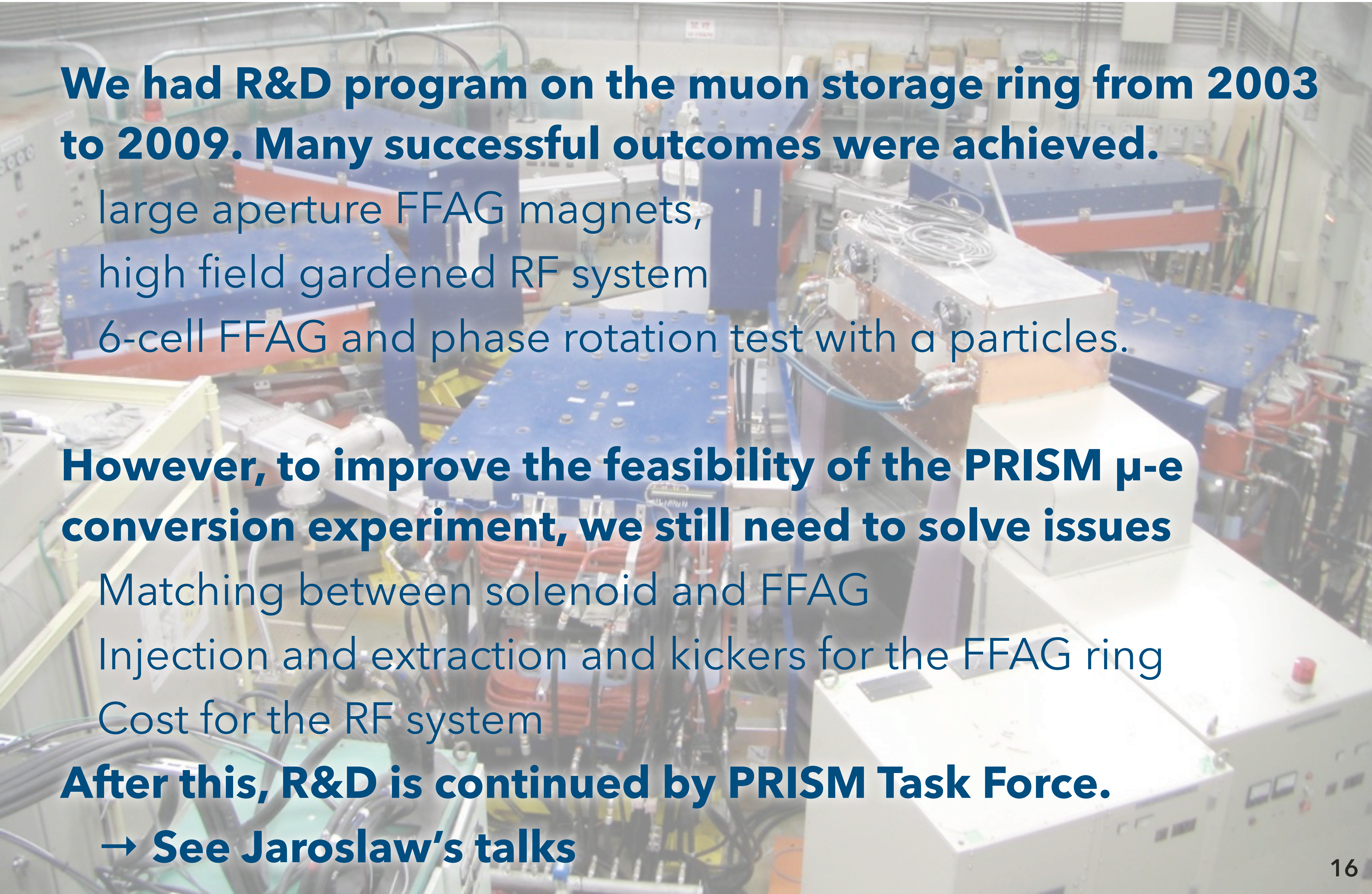
PRISM specifications (Akira's baseline lattice)

- Intensity :
  - 2x10^{12} muons/sec.
  - for multi-MW proton beam power
- Central Momentum :
  - 68 MeV/c
- Momentum Spread :
  - ±3% (from ±20%) by phase rotation
- Beam Repetition :
  - 100 - 1000 Hz
  - due to repetition of kicker magnets of the muon storage ring.
- Beam Energy Selection :
  - 68 MeV/c ±2%
  - at extraction of the muon storage ring.



6-sector PRISM-FFAG at RCNP, Osaka Univ.

6-sector PRISM-FFAG at RCNP, Osaka Univ.



We had R&D program on the muon storage ring from 2003 to 2009. Many successful outcomes were achieved.

- large aperture FFAG magnets,
- high field gardened RF system
- 6-cell FFAG and phase rotation test with α particles.

However, to improve the feasibility of the PRISM μ-e conversion experiment, we still need to solve issues

- Matching between solenoid and FFAG
- Injection and extraction and kickers for the FFAG ring
- Cost for the RF system

After this, R&D is continued by PRISM Task Force.

→ See Jaroslaw's talks

FNAL-AMS plan

- The discussion in Snawmass2021 has brought renewed attention to the potential of the PRISM idea in future muon research.

New Facility: AMF

hep-ex 2203.08278

- The "Advanced Muon Facility" would use PIP-II to enable
  - ***CLFV in all three muon modes: world-leading facility***
    - two new small rings for $\mu N \to eN$ at high *Z* and additional x100 in rate
      - with a possible DM experiment
    - x100-1000 more beam for $\mu \to e\gamma$ and $\mu \to 3e$ than are possible at PSI
  - Possible muonium-antimuonium and muon EDM

R. Bernstein, FNAL 15 Snowmass RPF5

Use PRISM for these experiments to use bright and pure mu+/mu- beams

- I and Bob Bernstein are making a plan to revisit the PRISM idea and initiate a collaborative effort for its realistic design for use in future muon research programs in Japan and the US.
  - You are welcome to join us.

Summary

- μ-e conversion experiments are very important because it is sensitive to physics at high energy scales and allows us to explore the mechanism of the new physics even after the discovery of the event.
- In Japan and the U.S., though, the COMET and Mu2e experiment are just about to begin, we are starting to consider the design of the next experiment to be carried out after COMET Phase-II and Mu2e-II.
- The PRISM concept with a FFA muon storage ring has the potential to solve various difficulties in future experiments.
- We plan to obtain a joint project budget from Japan and the U.S. and begin revisiting the PRISIM idea. We also plan to consider the use of PRISIM for positive muon experiments.
  - If you are interested, please join us.