PRISM / PRIME experiments at J-PARC

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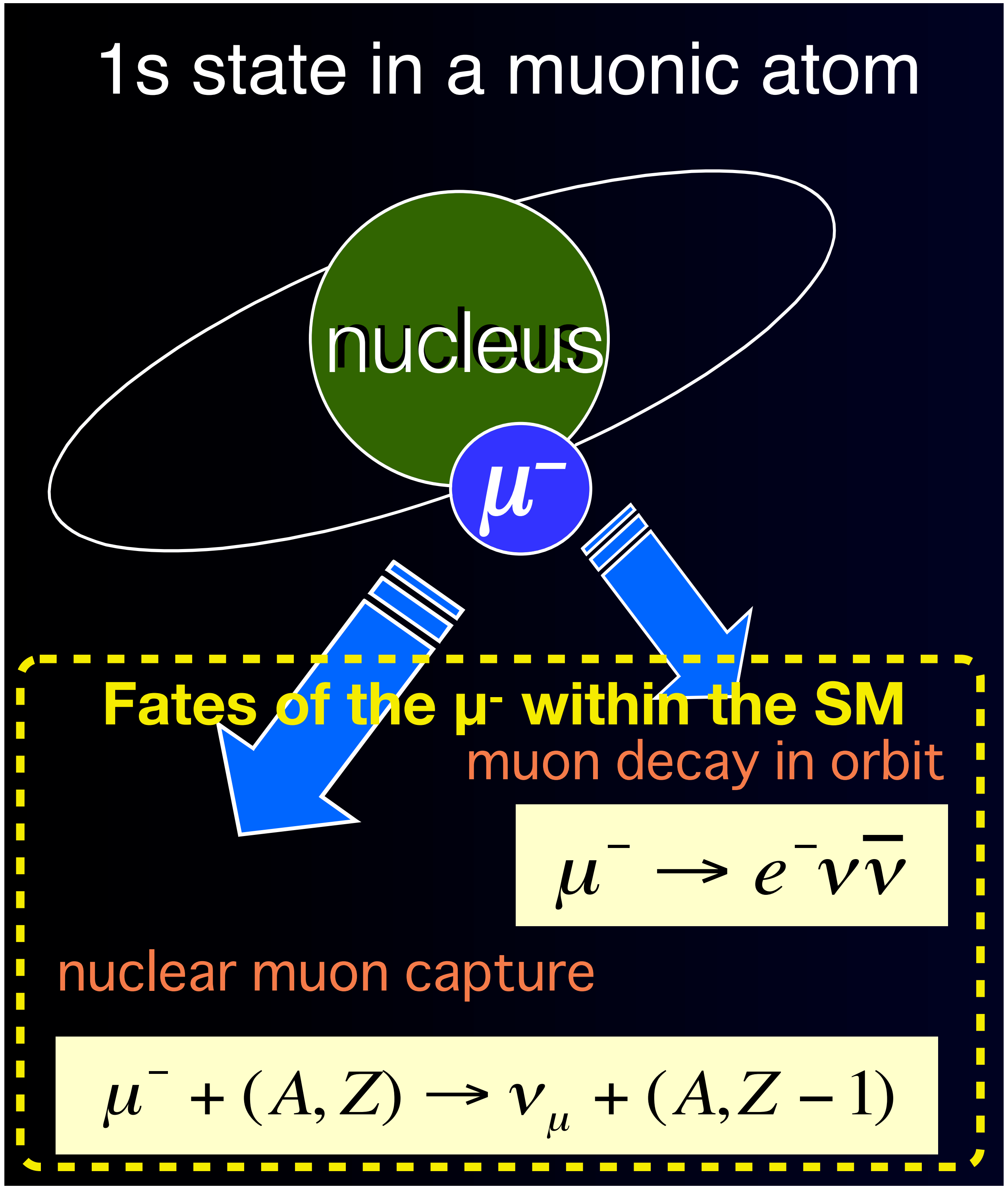
RF05: CLFV with high intensity muon factories
10 December 2020

Outline

- μ-e conversion
- Limits for the COMET and Mu2e experiment
- PRISM/PRIME concept
  - Pion capture solenoid
  - Muon Storage ring and Phase Rotator
  - Electron Spectrometer
- R&Ds and achievements
- Summary

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.

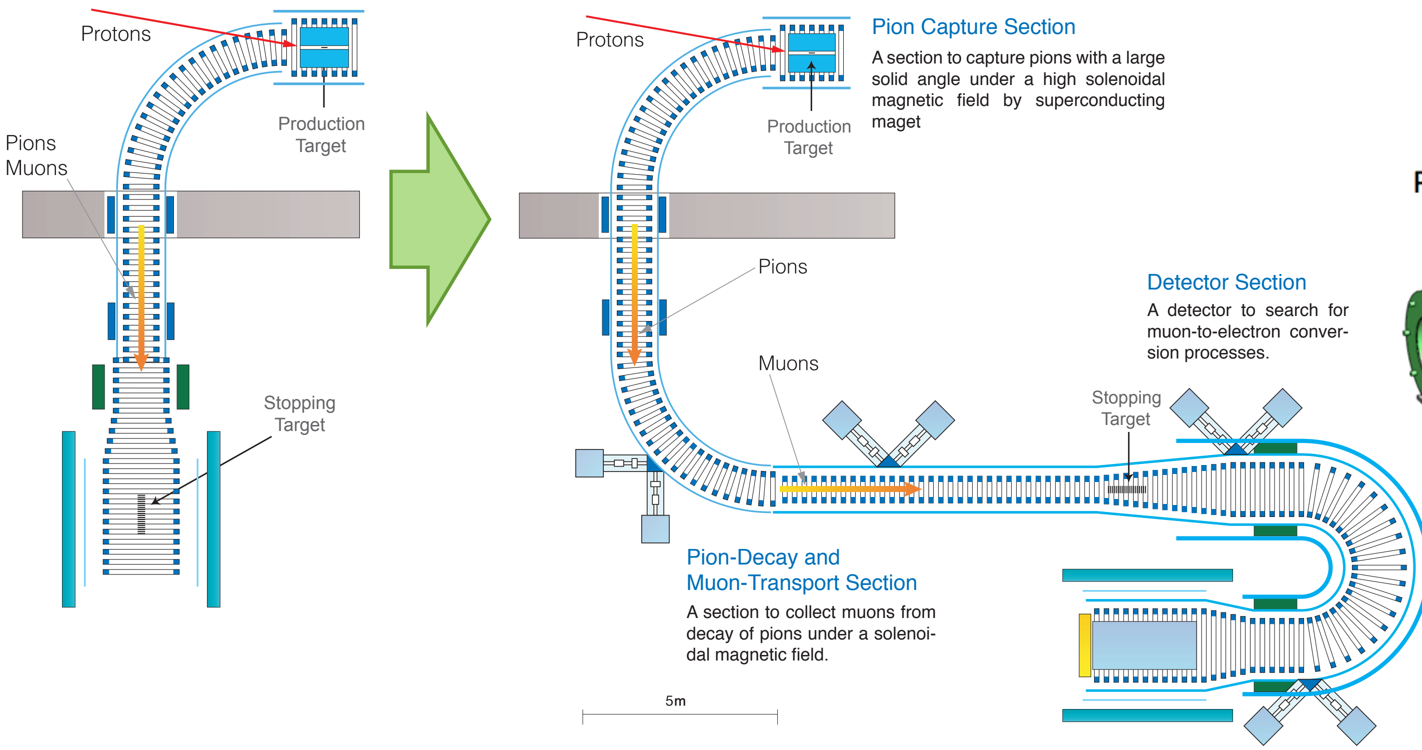
in the SM + new physics

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

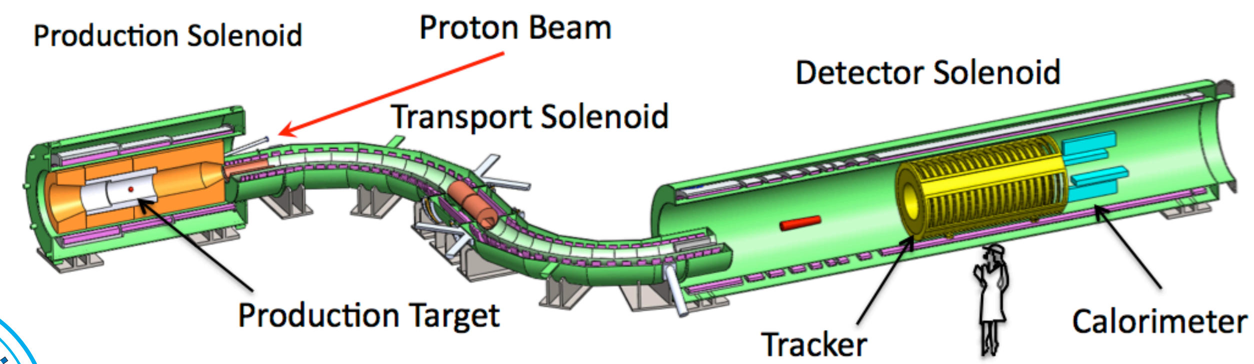
COMET and Mu2e

PRISM

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.

The COMET/Mu2e type experiments have some limitation on the achievable sensitivity and physics studies.

Potential Backgrounds for μ-e Conversion

PRISM

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
	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
	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
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

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

(1) Beam background rejection is heavily relined on proton beam extinction of 10^{-10}, which is uncertain.

(2) The solenoid beam line is not long enough, so that late pions might come in a beam.

  (1) The measurement starts after 700 nsec after the prompt.

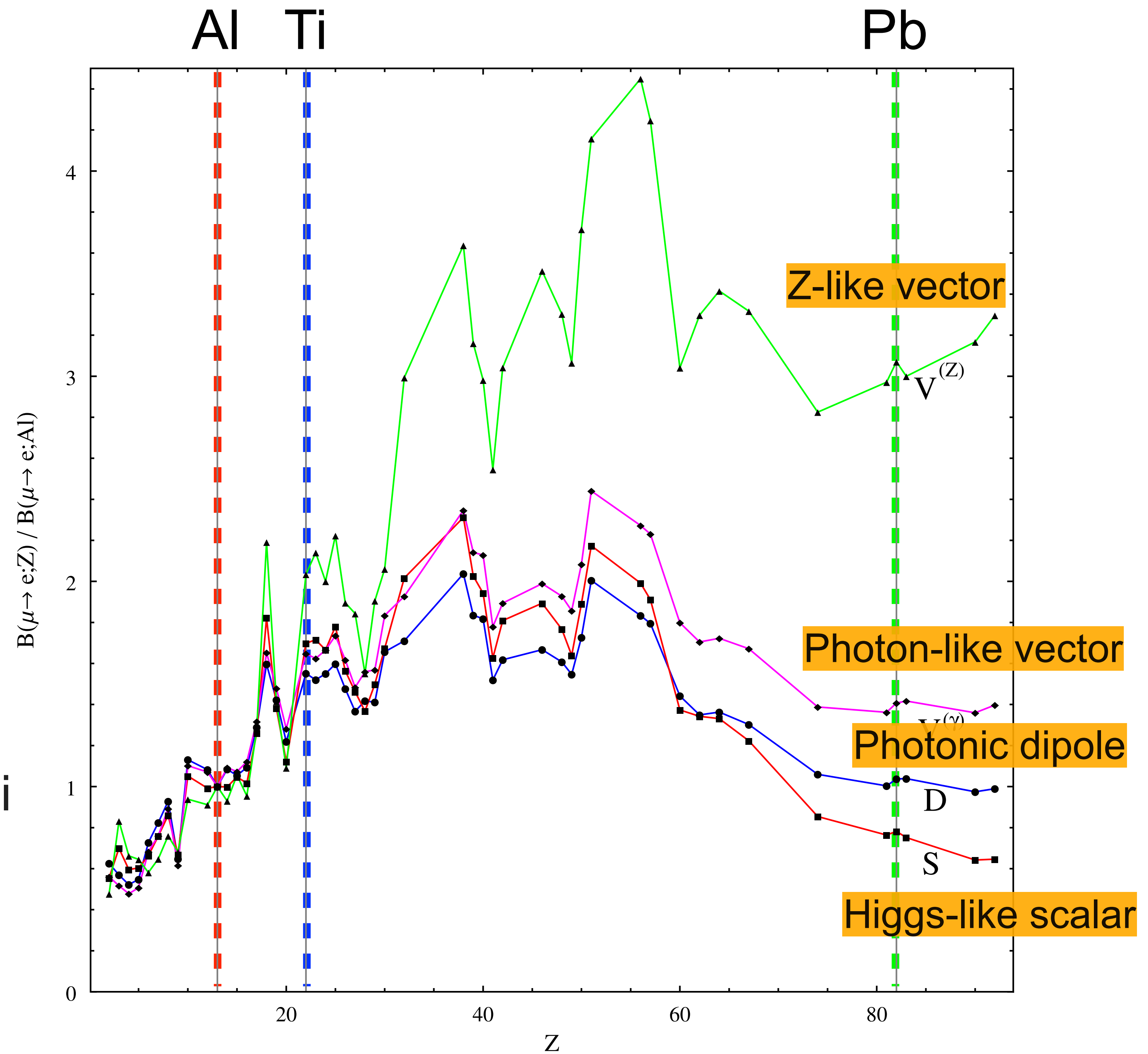
  (2) Material of a muon stopping target is limited to low Z.

(3) Reconstructed momentum resolution is not enough to reject DIO electrons.

  (1) Energy struggling in the stopping targets is not negligible.

Target dependence of μ-e conversion

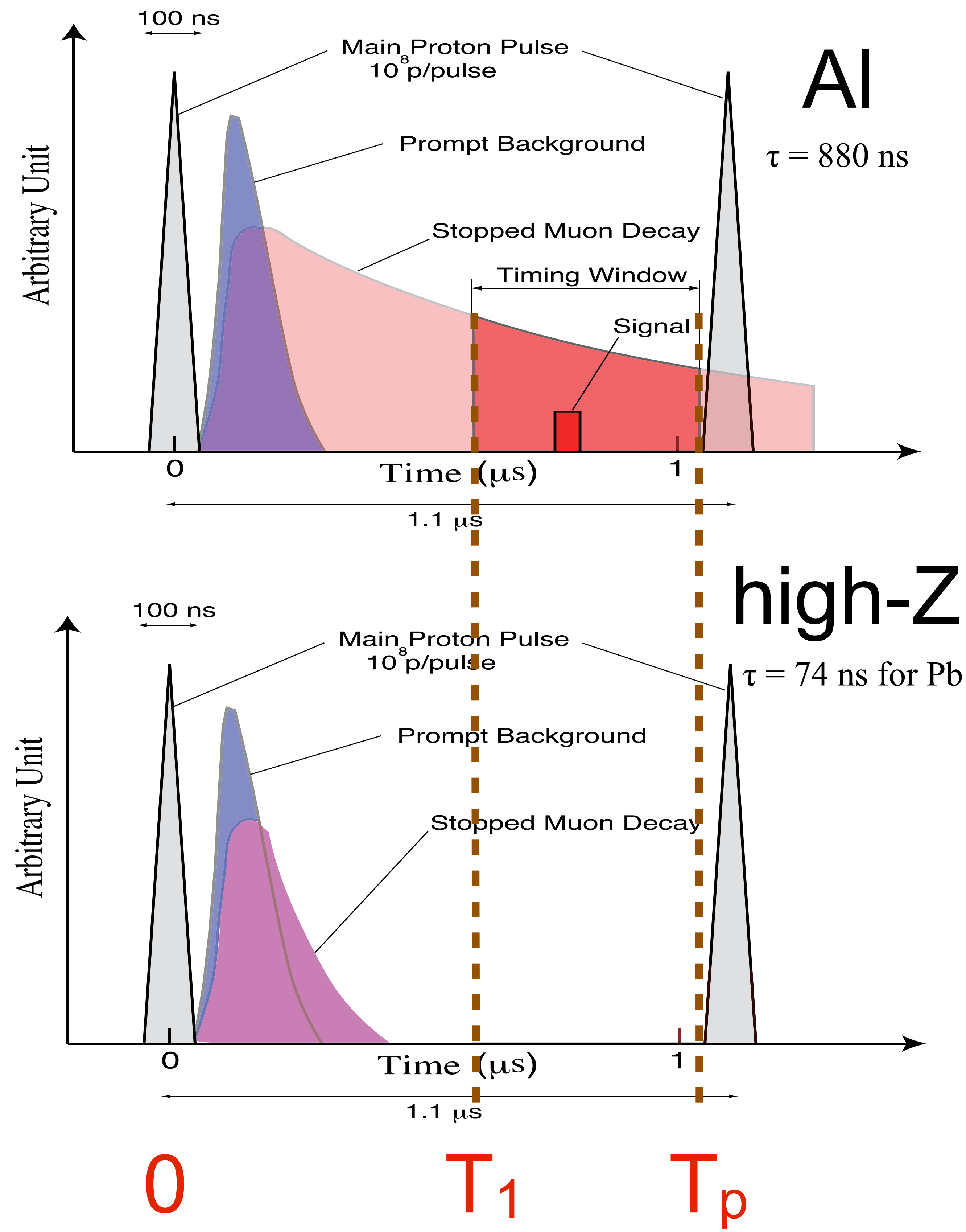
- Once a signal of the μ-e conversion is observed, one can obtain information on models of the new physics, by changing the target material, even if μ→eγ is not observed.
- Contribution of different type of LFV operators is different from each nuclei.
  - Maximal in the intermediate nuclei
  - Significantly Different Z dependence for heavy nuclei
- BUT, higher Z target makes shorter μ lifetime in a muonic atom.
  - Al : 880ns, Ti : 329ns, Pb : 82ns



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

Time distribution of backgrounds and signal

- The muons stopped in the muon-stopping target have the lifetime of a muonic atom. The time distribution of muon decays with the distribution of muon arrival timing is shown in Figure.
- Huge prompt BG exists just after the prompt timing. BUT Some beam-related backgrounds would come even after the prompt timing. Therefore, the measurement time window is selected to start after the prompt timing.
- The time window acceptance depends on the muon lifetime.



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PRISM

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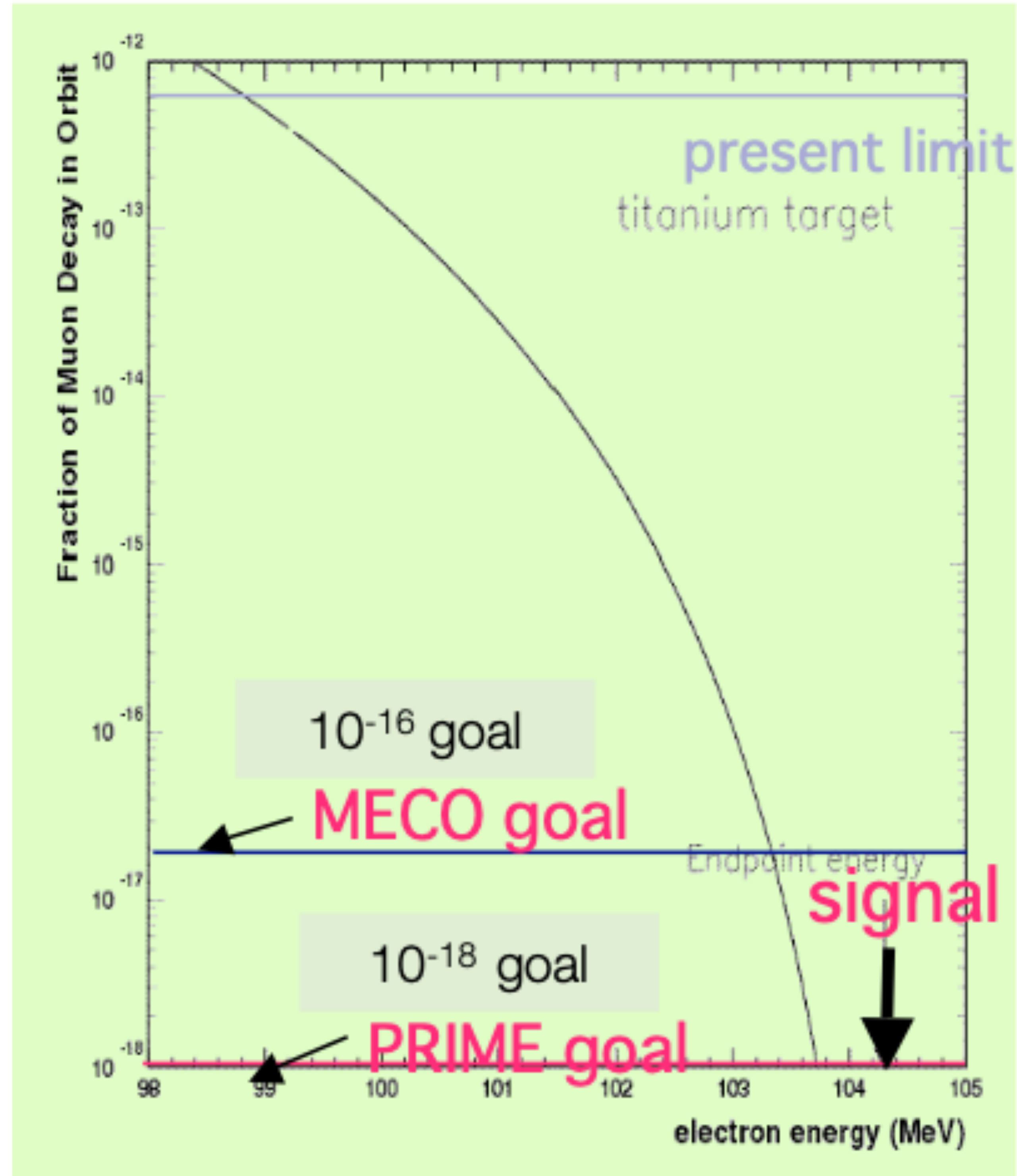
Muon Decay In Orbit (DIO) in a Muonic Atom

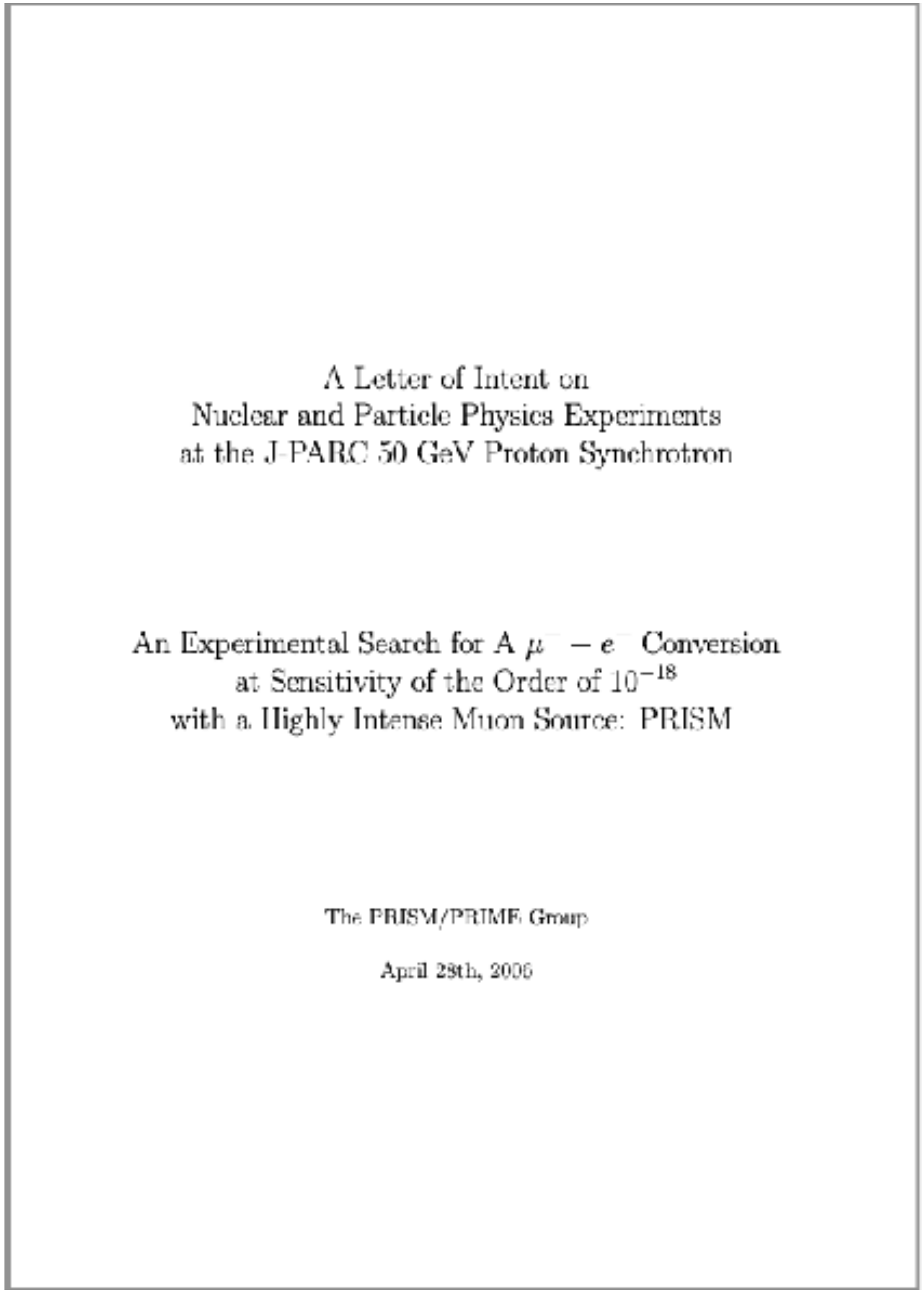
- Energy of electrons from the normal muon decay has an endpoint of 52.8 MeV, whereas the endpoint of muon decay in orbit comes to the signal region.
  - $(E_{Signal} - E_{DIO})^5$

- Good momentum resolution of electrons is needed.
  - Intrinsic resolution of tracker
  - Energy straggling in the stopping target

- For COMET/Mu2e, σ~200 keV/c is OK. But it is not enough to achieve < 10^{-18} sensitivity.



A LoI to J-PARC for PRISM/PRIME



A Letter of Intent on
Nuclear and Particle Physics Experiments
at the J-PARC 50 GeV Proton Synchrotron

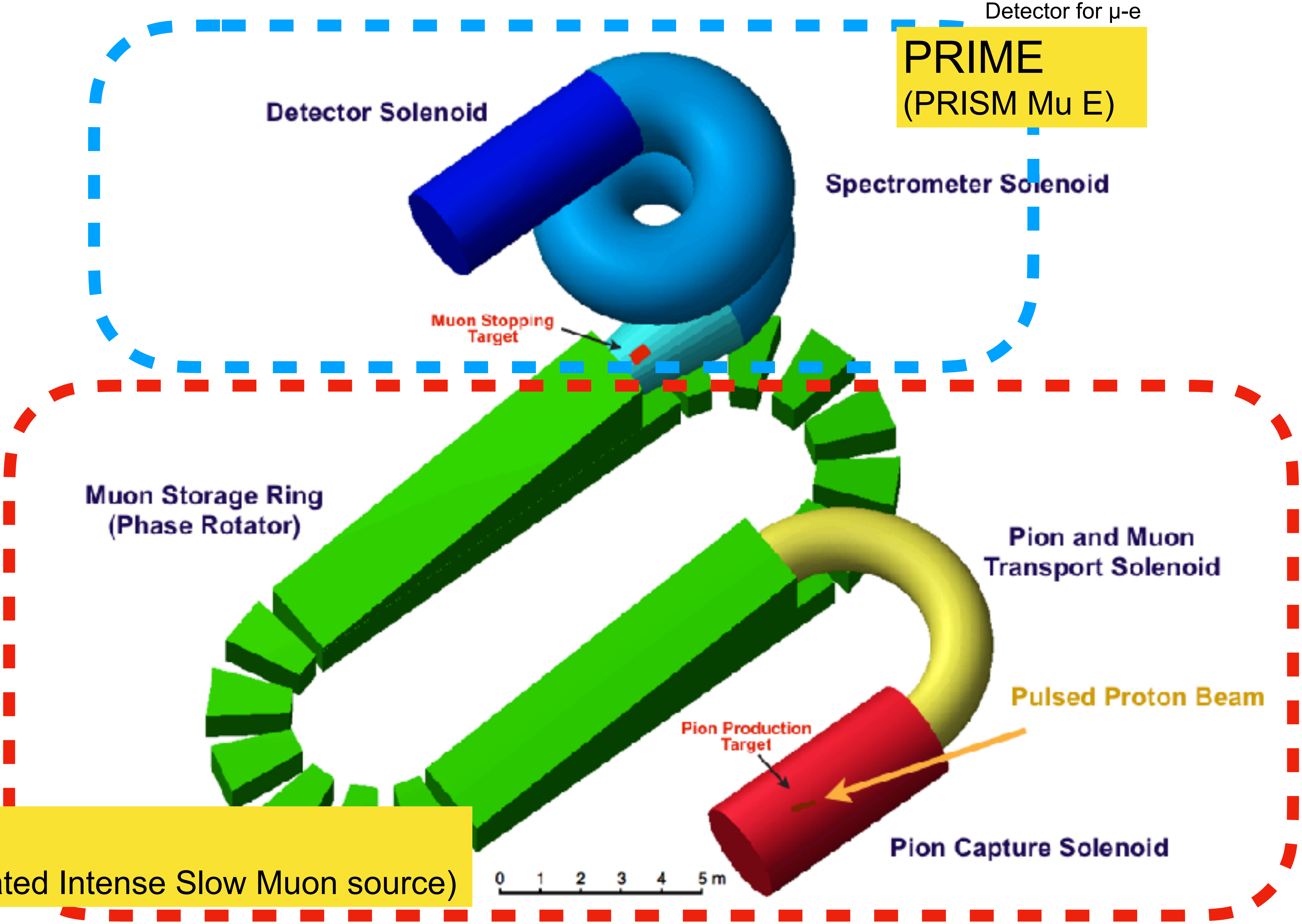
An Experimental Search for A $\mu^- - e^-$ Conversion
at Sensitivity of the Order of 10^{-18}
with a Highly Intense Muon Source: PRISM

The PRISM/PRIME Group

April 28th, 2006

- A LoI for a μ-e conversion experiment at SES of $\sim 10^{-18}$ was submitted to J-PARC in 2003 and 2006
  - https://www-ps.kek.jp/jhf-np/LOIlist/pdf/L24.pdf
  - https://www-ps.kek.jp/jhf-np/LOIlist/pdf/L25.pdf
  - http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p20-Kuno.pdf
- Then, COMET experiment was approved.
- But PRISM study is on going in the PRISM Task Force.

PRISM/PRIME



Detector for μ-e

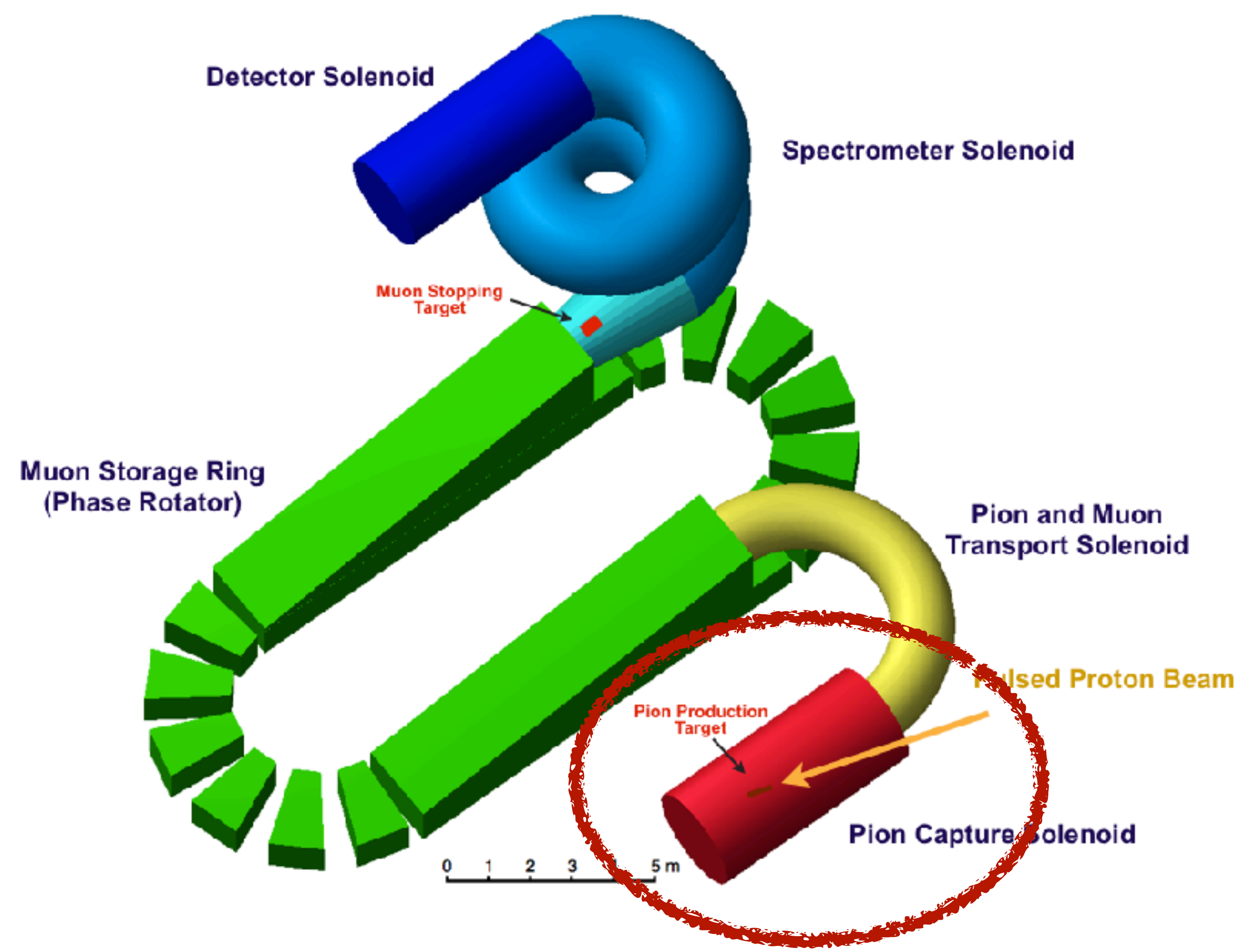
PRIME
(PRISM Mu E)

Muon source

PRISM
(Phase Rotated Intense Slow Muon source)

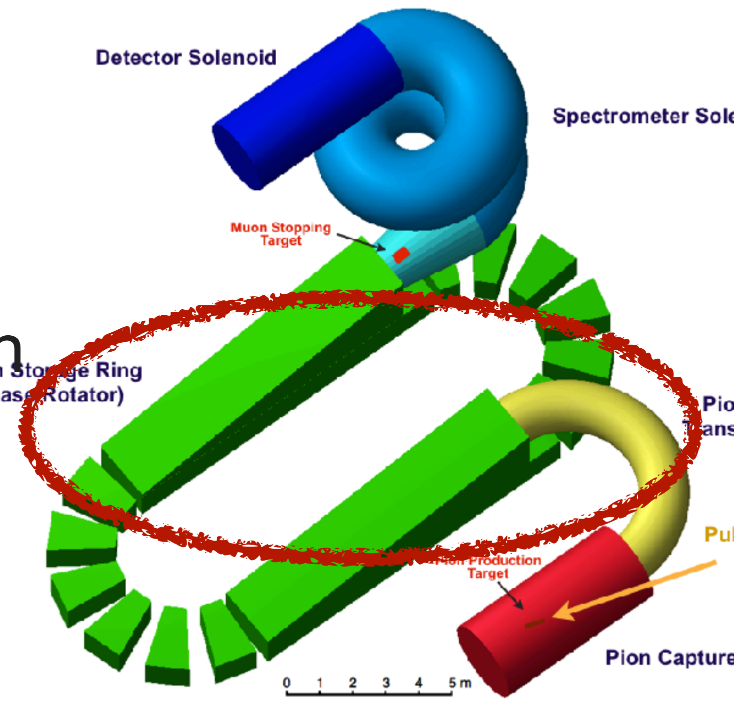
PRISM Features

- **Intense low energy muon beams**
  - The pion/muon production target is located in a strong magnetic field produced by a superconducting capture solenoid.
  - It is followed by a large acceptance transport solenoid and an FFA ring.



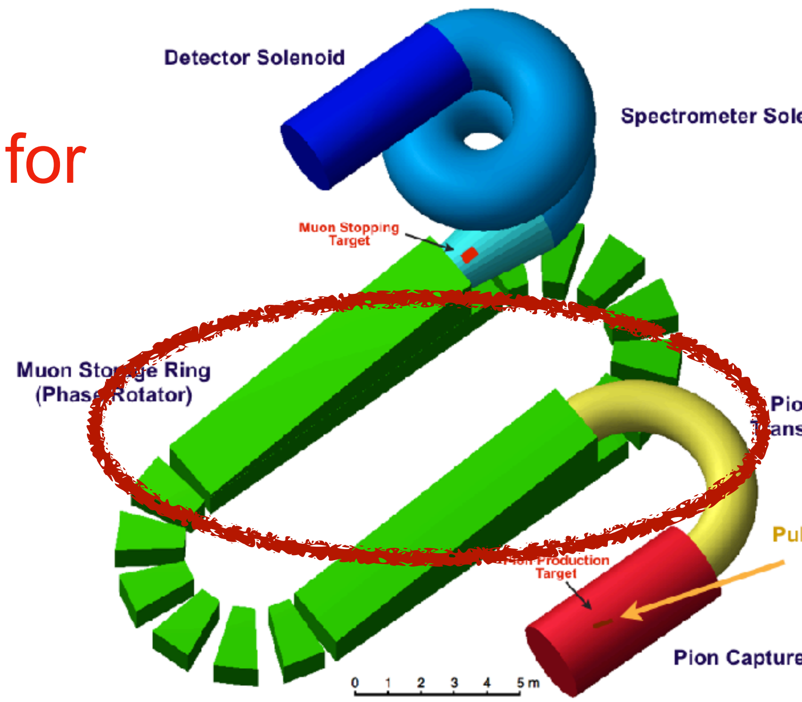
PRISM Features

- **Rejection of pions in the beam**
  - long flight length on a beam
    - use a FFA as a muon storage ring.
    - in PRISM, a circumference of the PRISM FFAG muon storage ring is about 40 meters, and 5-6 turns would give about 200 meters. then, pion survival rate is < 10^{-20}.
    - alternative is a long solenoid, but very expensive…..
    - reduce radiative π backgrounds
- **Rejection of beam particles with wrong momenta**
  - dipole magnet and momentum slits before a muon stopping target. the FFA works as a spectrometer.
  - very narrow momentum slit allowing only 40 MeV/c +- 3%
  - no 100 MeV particles coming in (such as muon decay inflight)
  - selecting of muons that would stop in a muon-stopping target
  - no beam dump needed and no flush

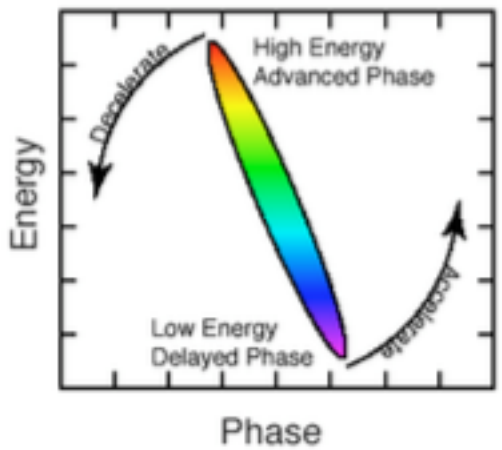


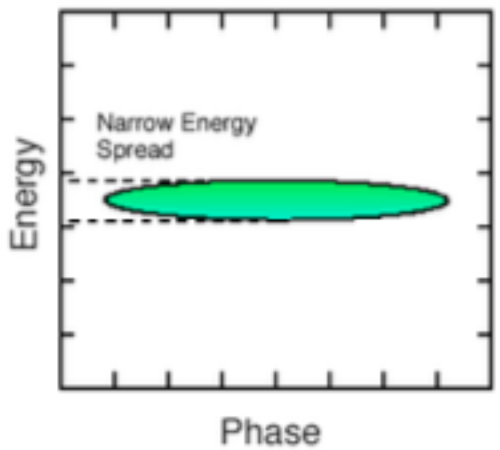
PRISM Features

- **Beam extinction at both proton and muon beams**
  - (injection) kicker magnets for the storage ring does this for muons,
    - in addition to proton beam extinction
    - a total beam extinction is below 10^{-11}



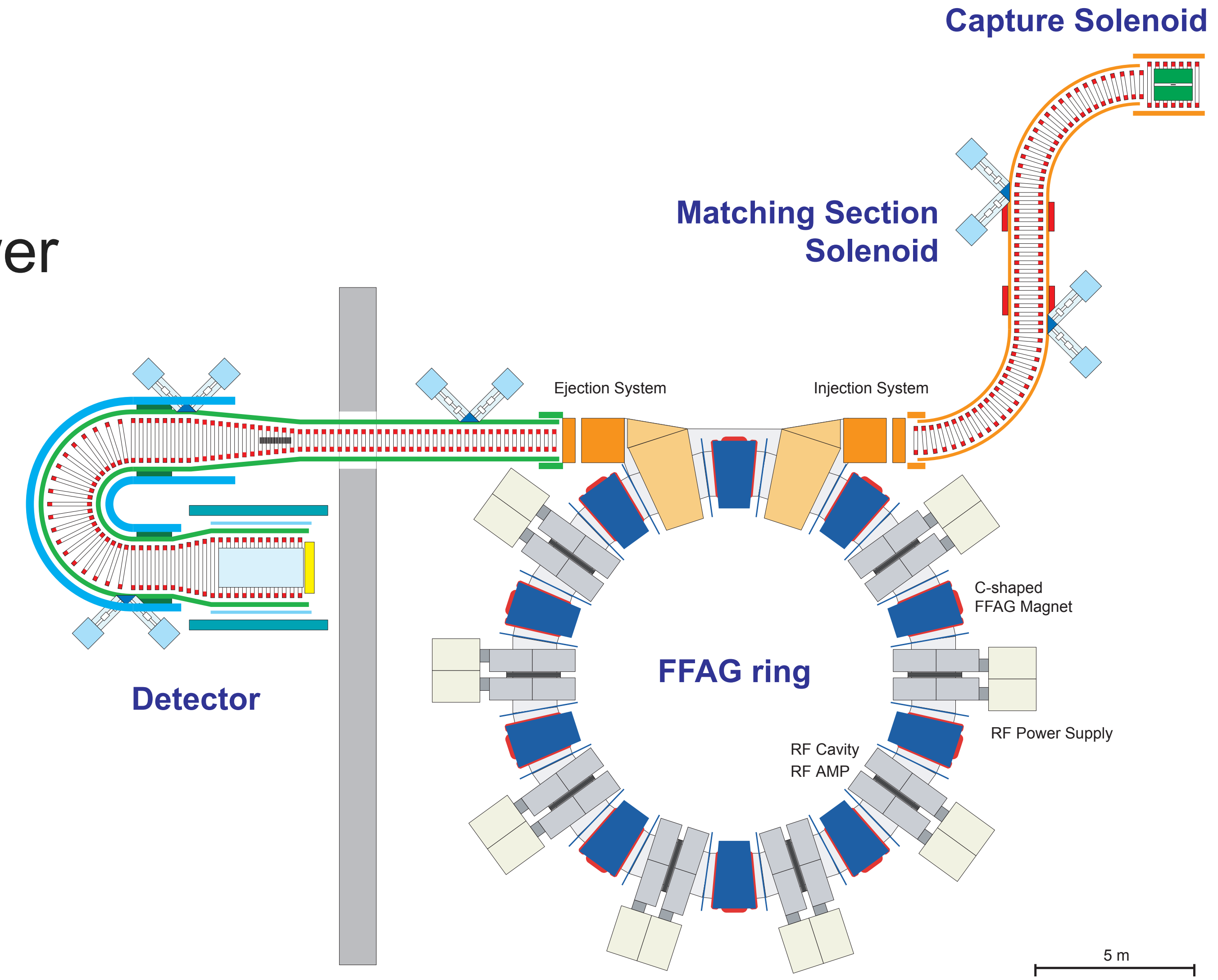
- **Narrow muon beam energy spread**
  - by phase rotation in a muon storage ring
    - goal is +- 3% from +-30 %
  - allow a thinner muon stopping target (1/10 of COMET and Mu2e)
  - improve the electron momentum resolution to reject DIOs





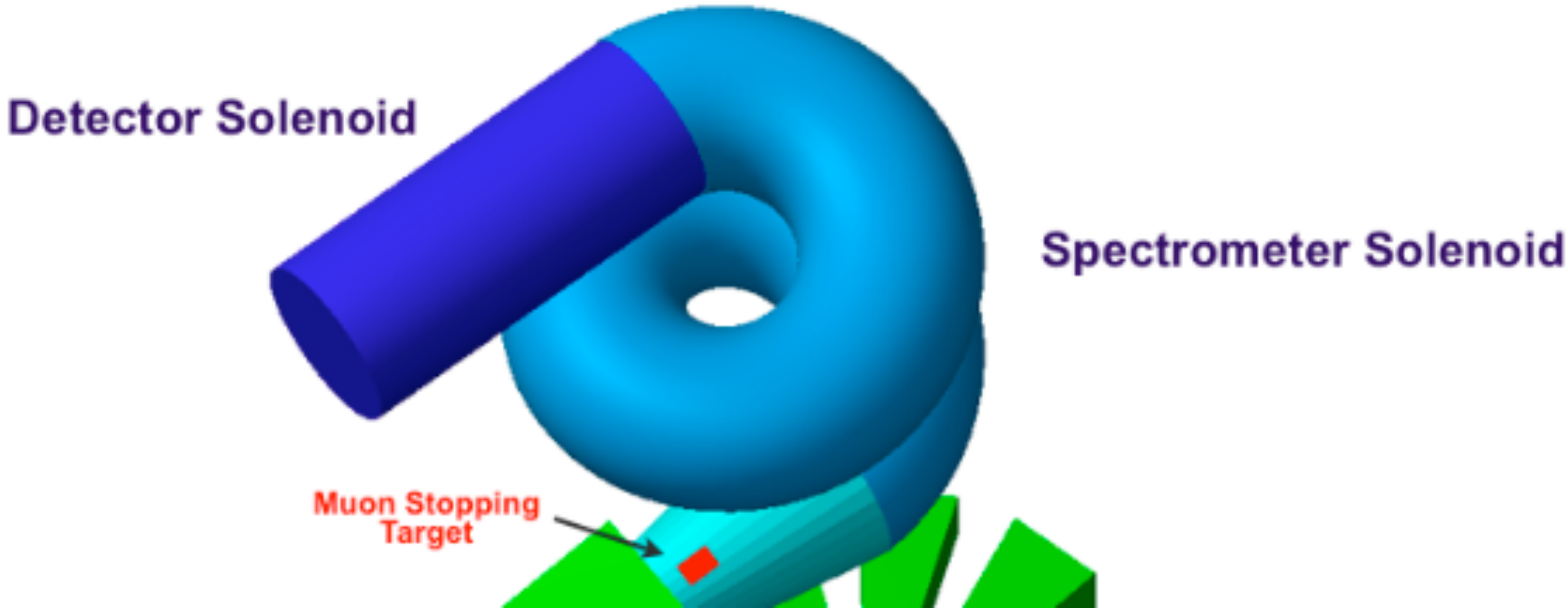
PRISM Specifications

- **Intensity :**
  - $2x10^{12}$ muons/sec.
  - for multi-MW proton beam power
- **Central Momentum :**
  - 40 MeV/c
- **Momentum Spread :**
  - phase rotation
  - ±3% (from ±30%)
- **Beam Repetition :**
  - 100 - 1000 Hz
  - due to repetition of kicker magnets of the muon storage ring.
- **Beam Energy Selection :**
  - 40 MeV/c ±3%
  - at extraction of the muon storage ring.



PRIME Detector

- **Rejection of the intrinsic backgrounds**
  - protons and neutrons from muon nuclear capture
    - each stopped muon produces about 2 neutrons, 0.1 protons, and two photons. In particular, protons are problematic.
  - curved solenoid transport system to reject low energy charged particles and neutral particles
    - remove primary as well as secondary and tertiary.....
    - more than 360 degree curve might be needed....



Selection of Charge and Momentum in Curved Solenoids

PRISM

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

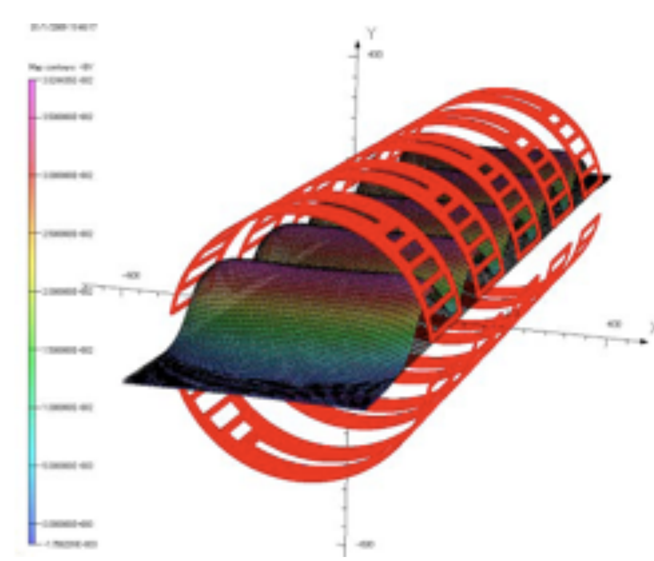
D : drift distance
B : Solenoid field
θ_{bend} : Bending angle of the solenoid channel
p : Momentum of the particle
q : Charge of the particle
θ : atan(P_T/P_L)

- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

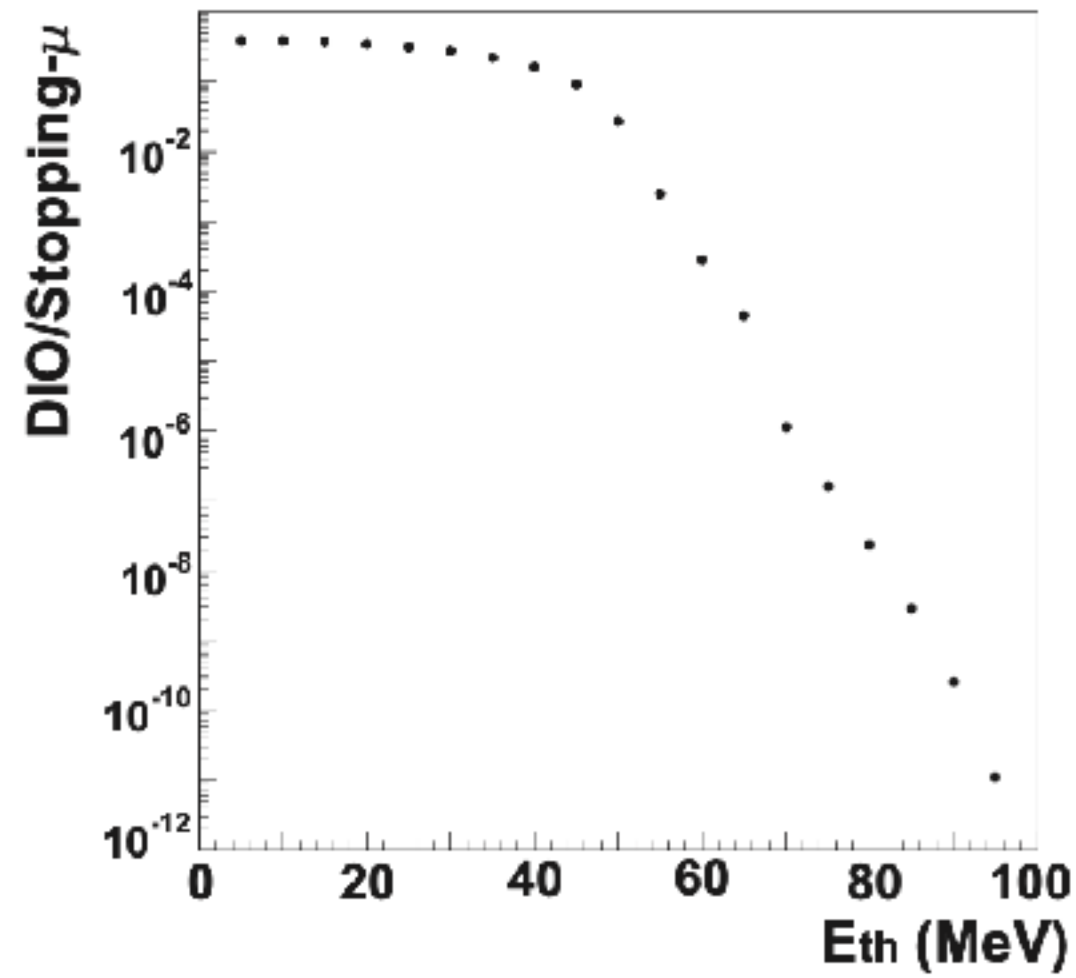
p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ : atan(P_T/P_L)

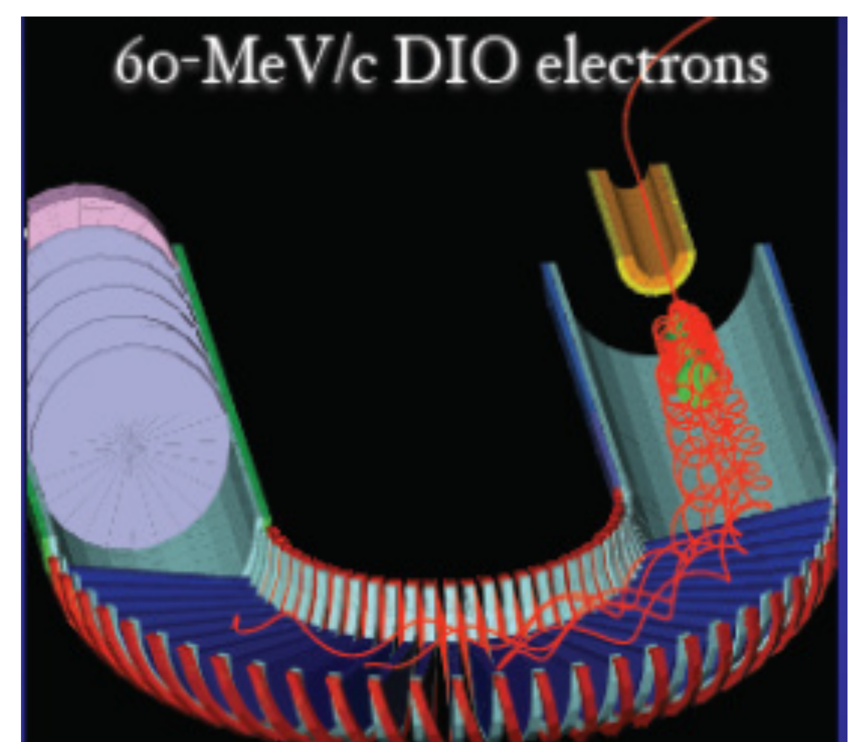
- This can be used for charge and momentum selection.



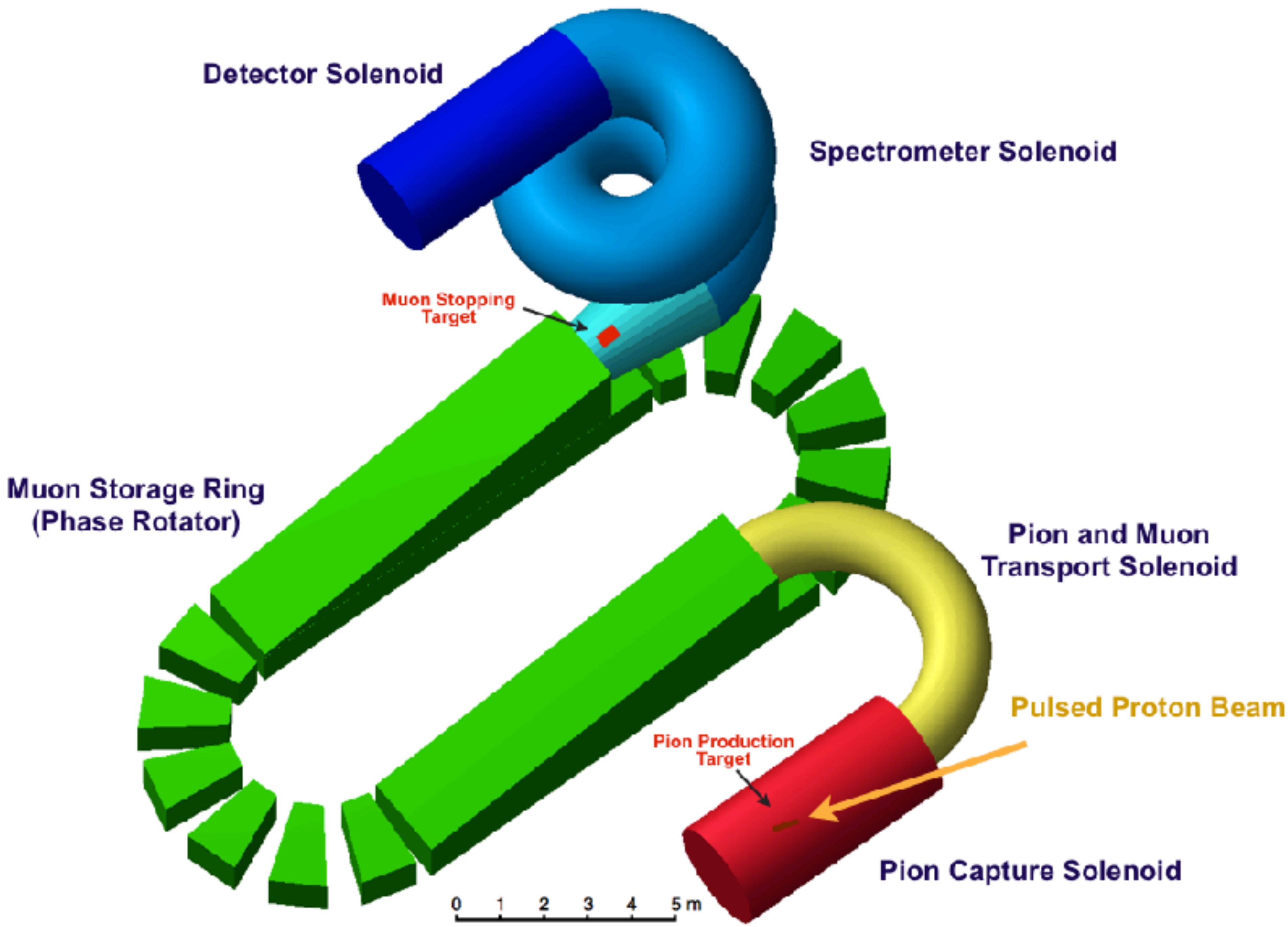
PRIME Detector

- **Reduce the detector hit rate**
  - PRIME electron transport might set momentum threshold at 80 MeV/c (and above).
    - It is assumed that all other particles are completely removed by the PRIME detector.
  - Remaining events to the detector region are electrons from muon decay in orbit in a muonic atom.
    - 10^{-8} DIO electrons per muons stopped (see fig.)
    - For 2×10^{12} muons stopped / second, 2×10^{4} DIOs come to the detector.
    - At 1000 Hz repetition, 20 events/ pulse come to the detector.
    - It should be OK.



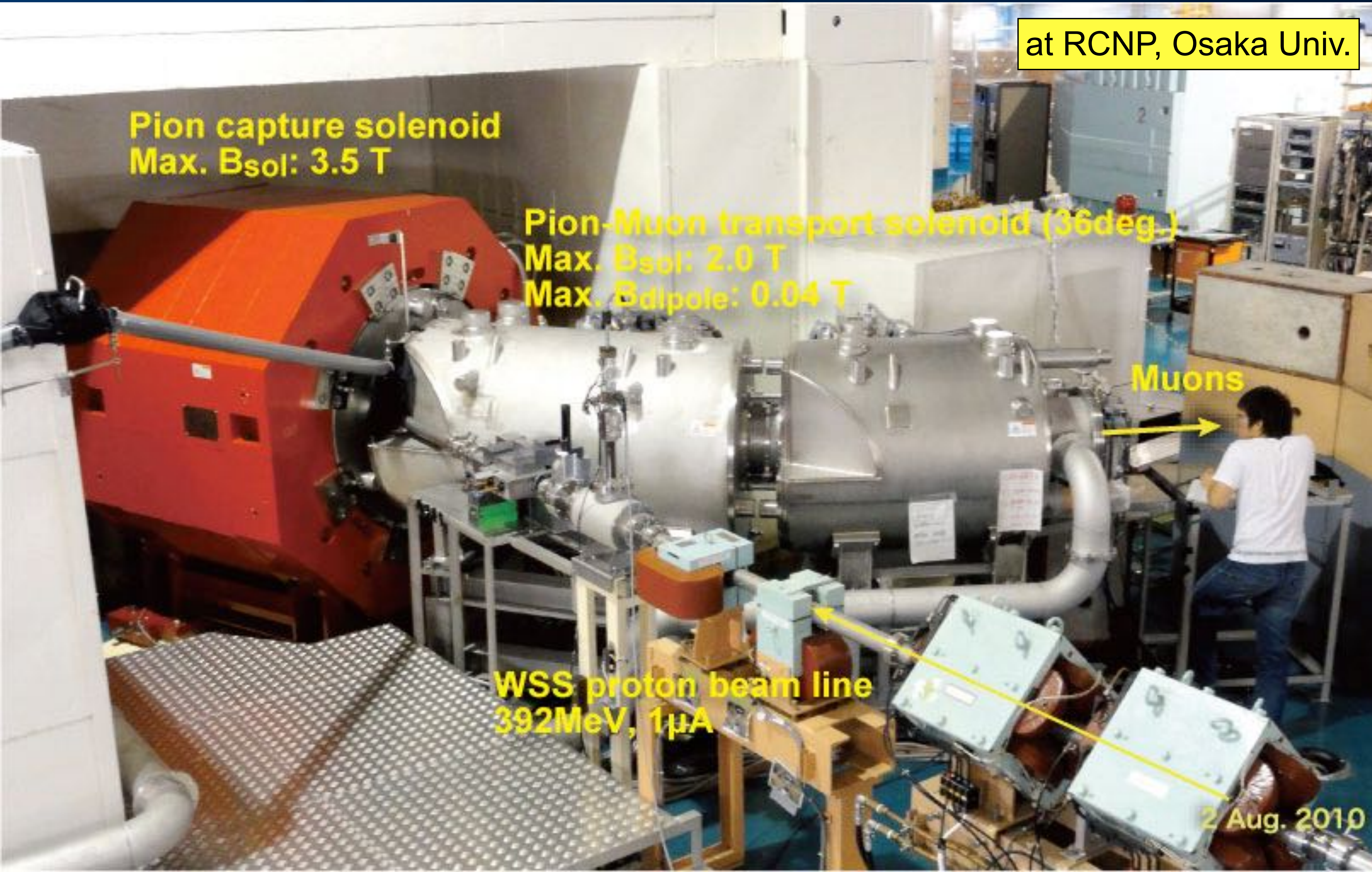


Achievements towards the PRISM/PRIME

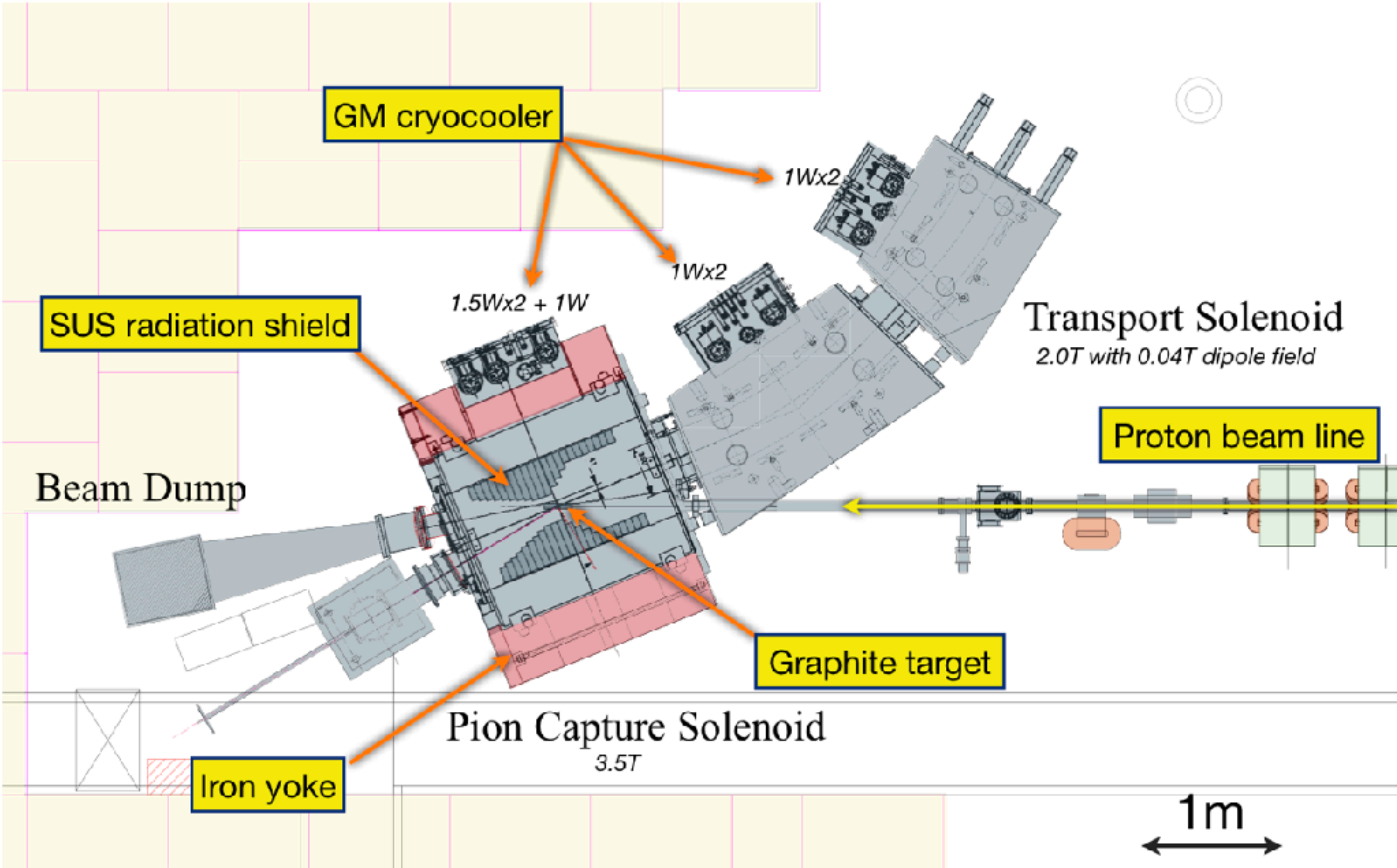


The 1st pion capture system : MuSIC

at RCNP, Osaka Univ.

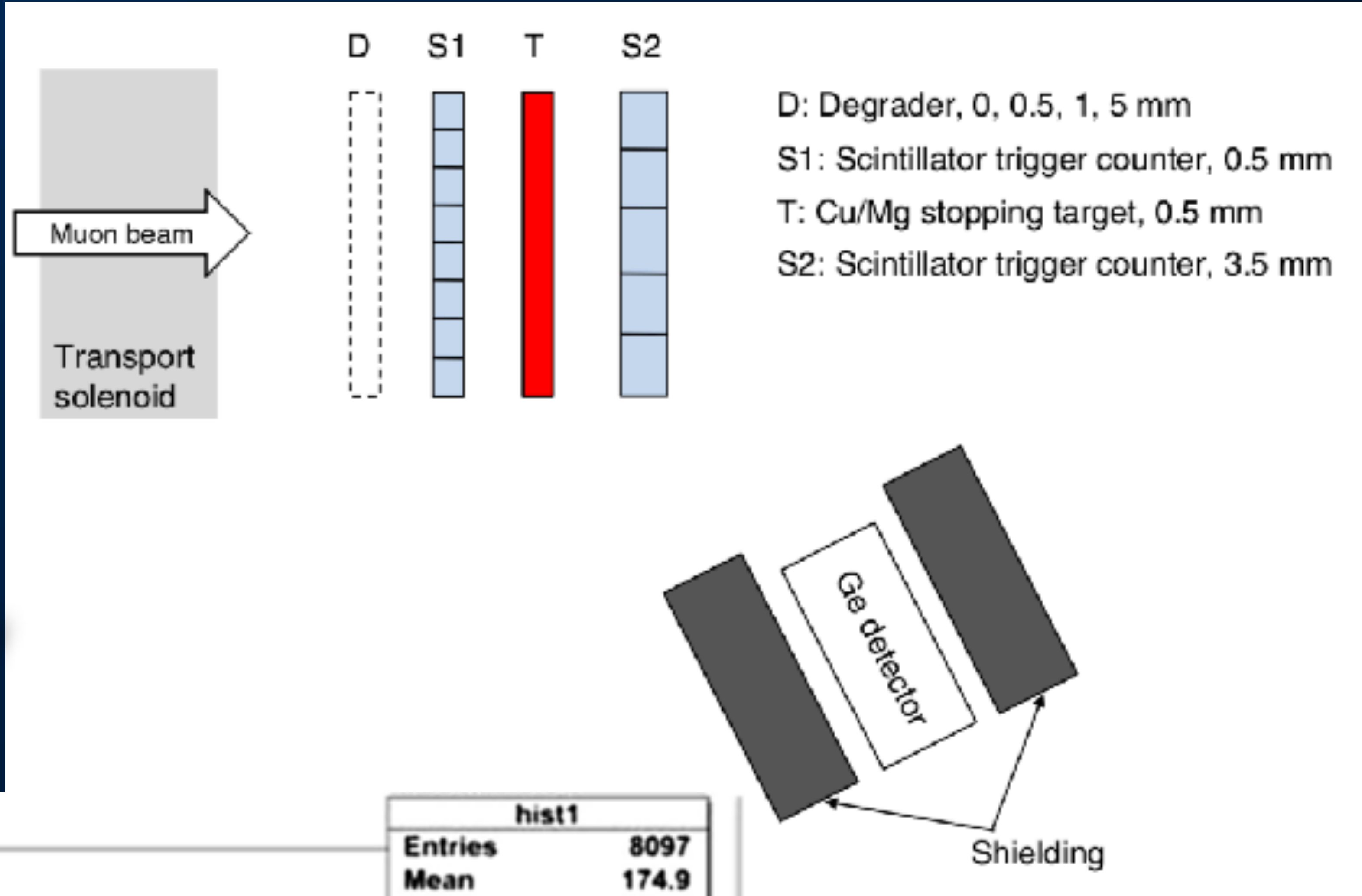


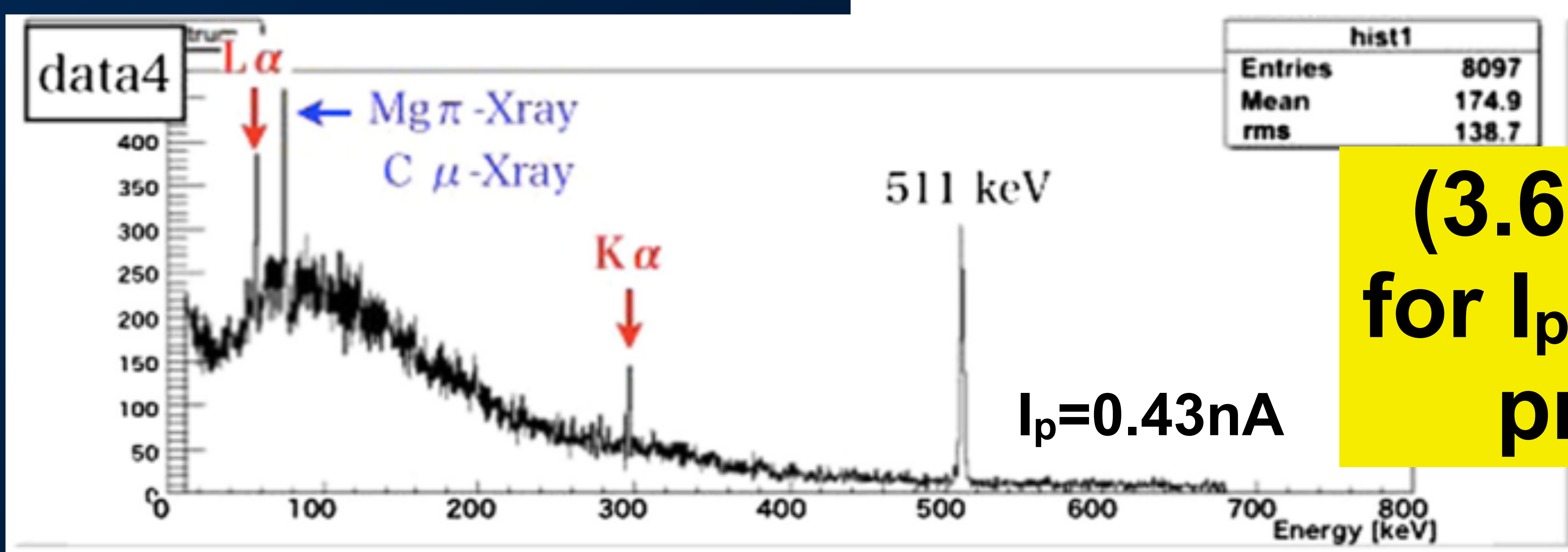
MuSIC: Present Layout



Muon yield @ the solenoid exit

Muonic X-rays were measured at the end of the solenoid

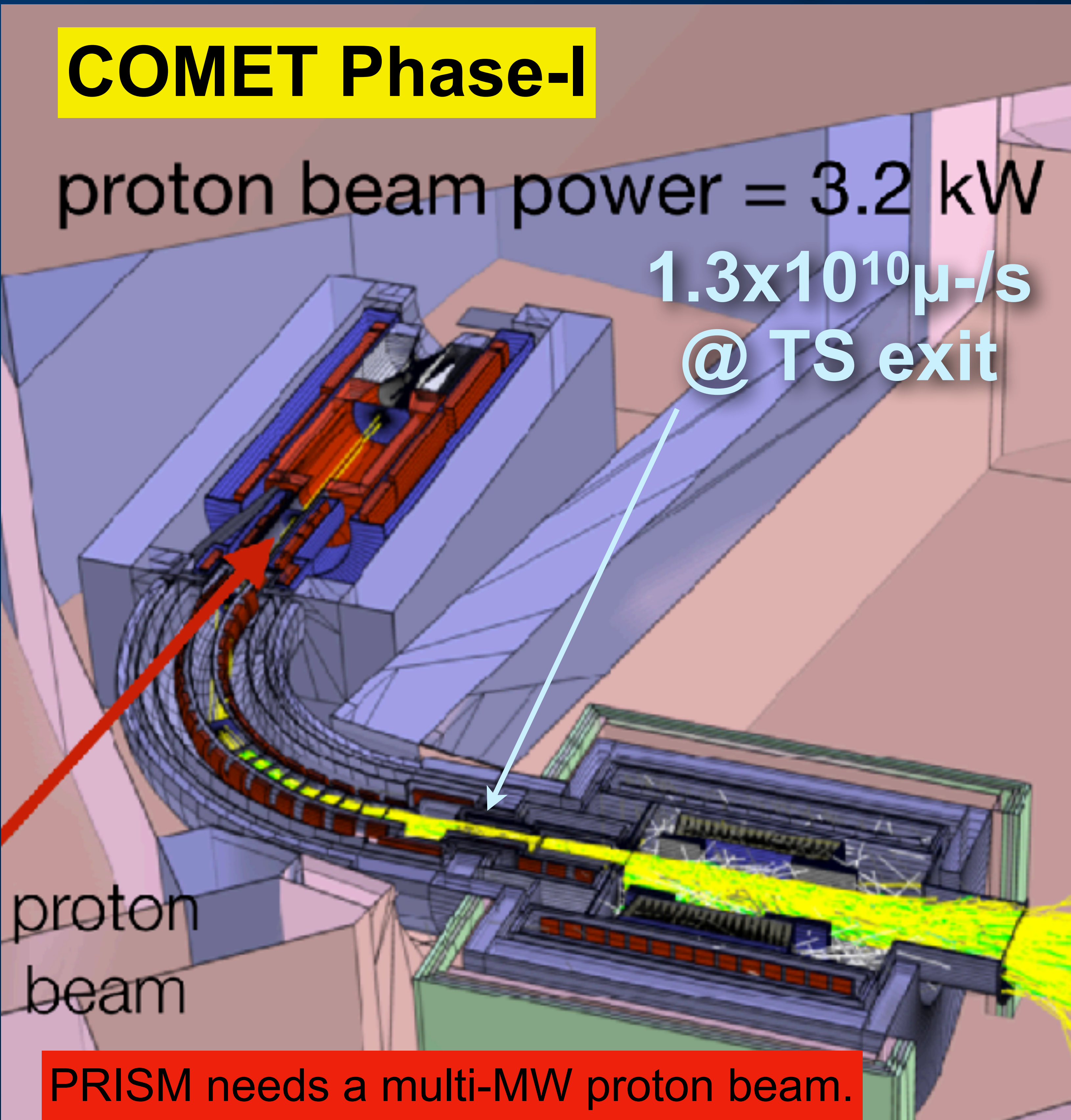




$(3.6\pm0.4)\times10^7$ μ^-/s for I_p=1μA, 392MeV proton beam

S. Cook, et al., PHYS. REV. ACCEL. BEAMS 20, 030101 (2017)

The 2nd Pion Capture System



Under construction for J-PARC COMET

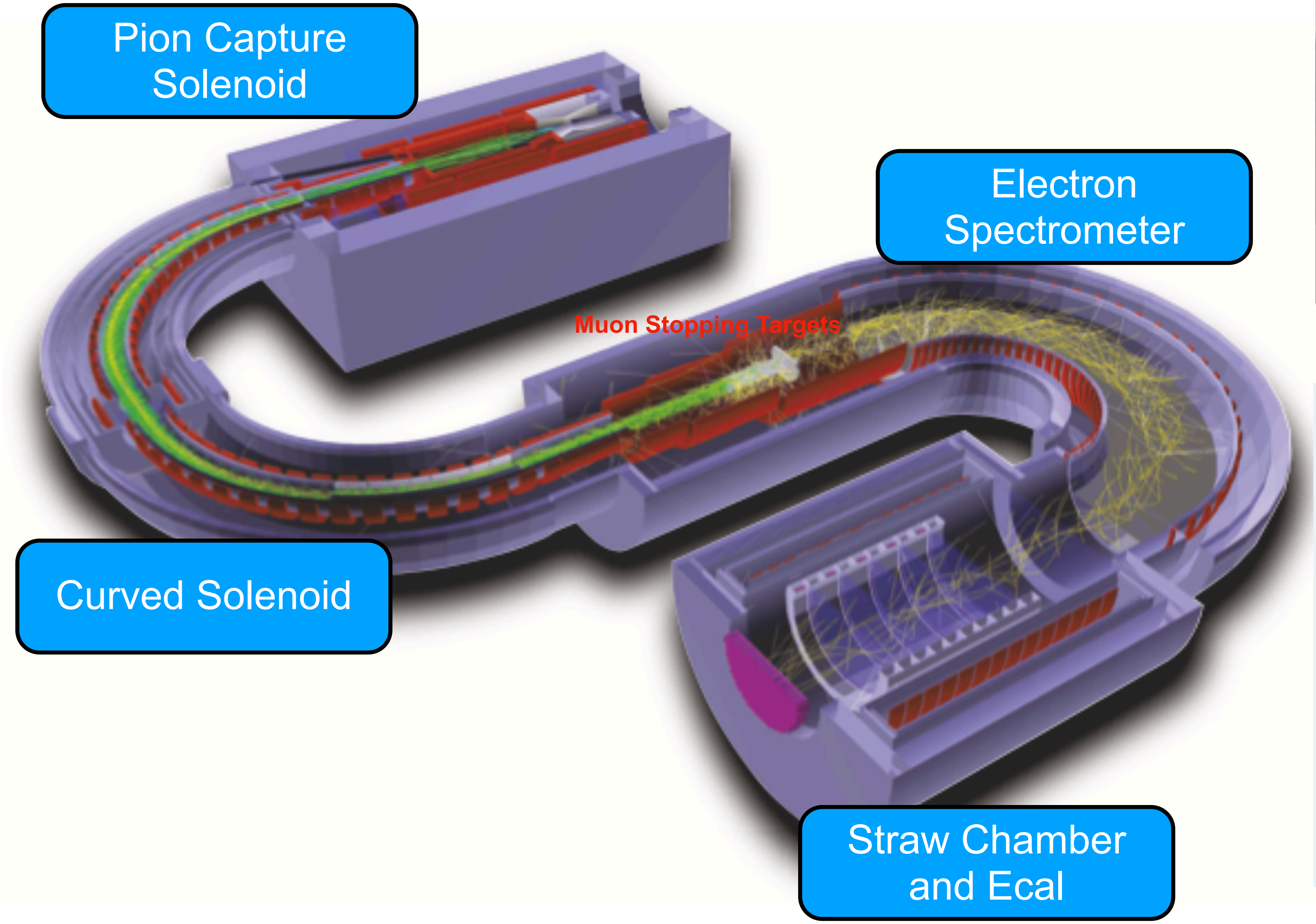
PRISM needs a multi-MW proton beam.
Radiation is a critical issue.

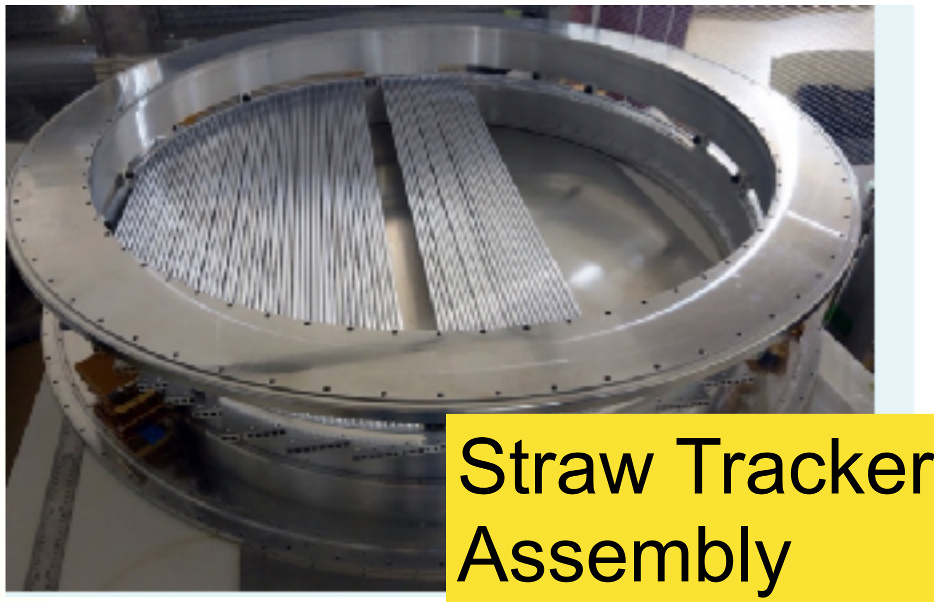
Muon Strage Ring: PRISM-FFA

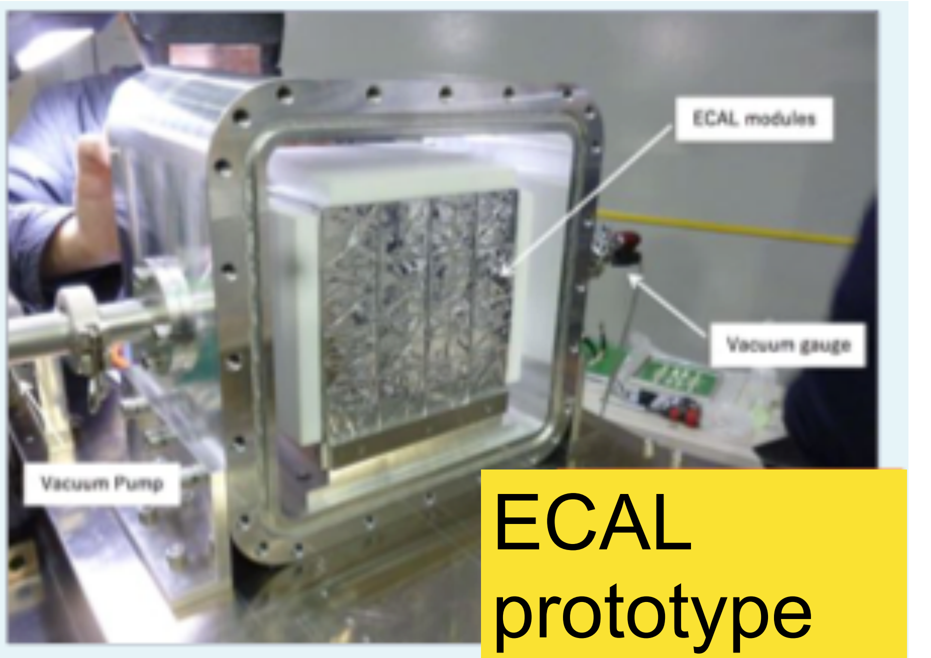
- Improved design by PRISM-TF (Jaroslow's talk)
  - New Lattice, Injection and Extraction …

PRIME

- The PRIME detector will be constructed for the COMET Phase-II experiment, 180 degrees version.
  - Intensive simulation studies
  - Building straw trackers







Summary

- Search for the charged lepton flavor violation (cLFV), in particular μ-e conversion search, can be a promising probe to the TeV-scale physics.
- The current experiments, COMET, Mu2e and Mu2e-II, are aiming the sensitivity of ~10^{-17}~10^{-18}.
- The next step for μ-e conversion experiment would be
  - Improve the sensitivity below the 10^{-18} for the discovery. Or,
  - Measure the BR changing the stopping target material including high-Z material.
- The COMET and Mu2e has the limitations to achieve these goles.
- As a solution, we propose the PRISM/PRIME experiment aiming the sensitivity below 10^{-18} combining new ideas:
  - Pion capture solenoid
  - Curved solenoid with a dipole field
  - Muon storage ring, PRISM-FFA
  - PRIME, electron spectrometer
- Most of these items can be adopted for other muon projects: NuSTORM, NuFact, Muon collider and Low energy muon programs.
- The Snowmass 2021 is a good opportunity for further discussion.