PRISM/PRIME Overview

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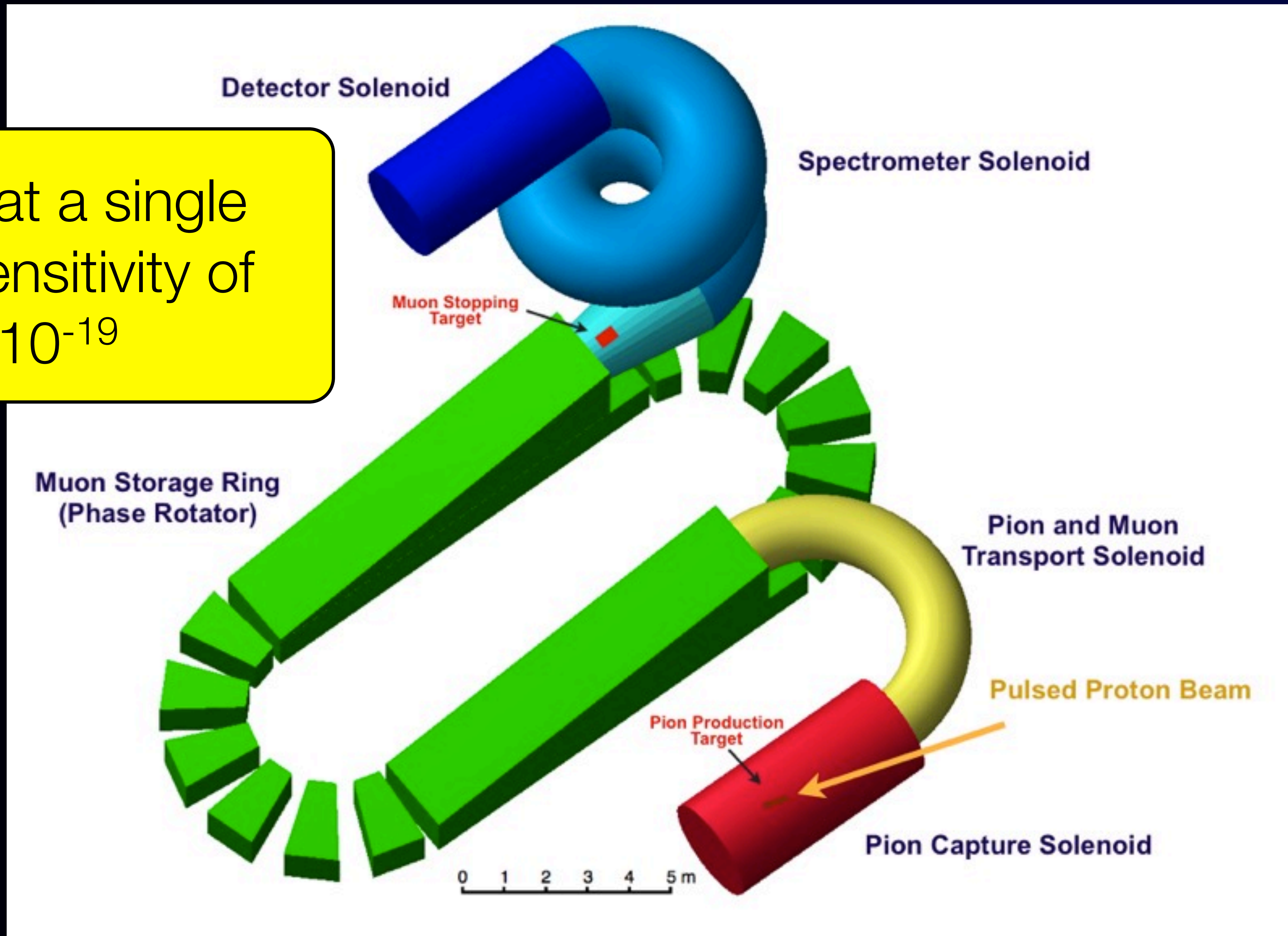
November 8th, 2010
Project-X Muon Workshop

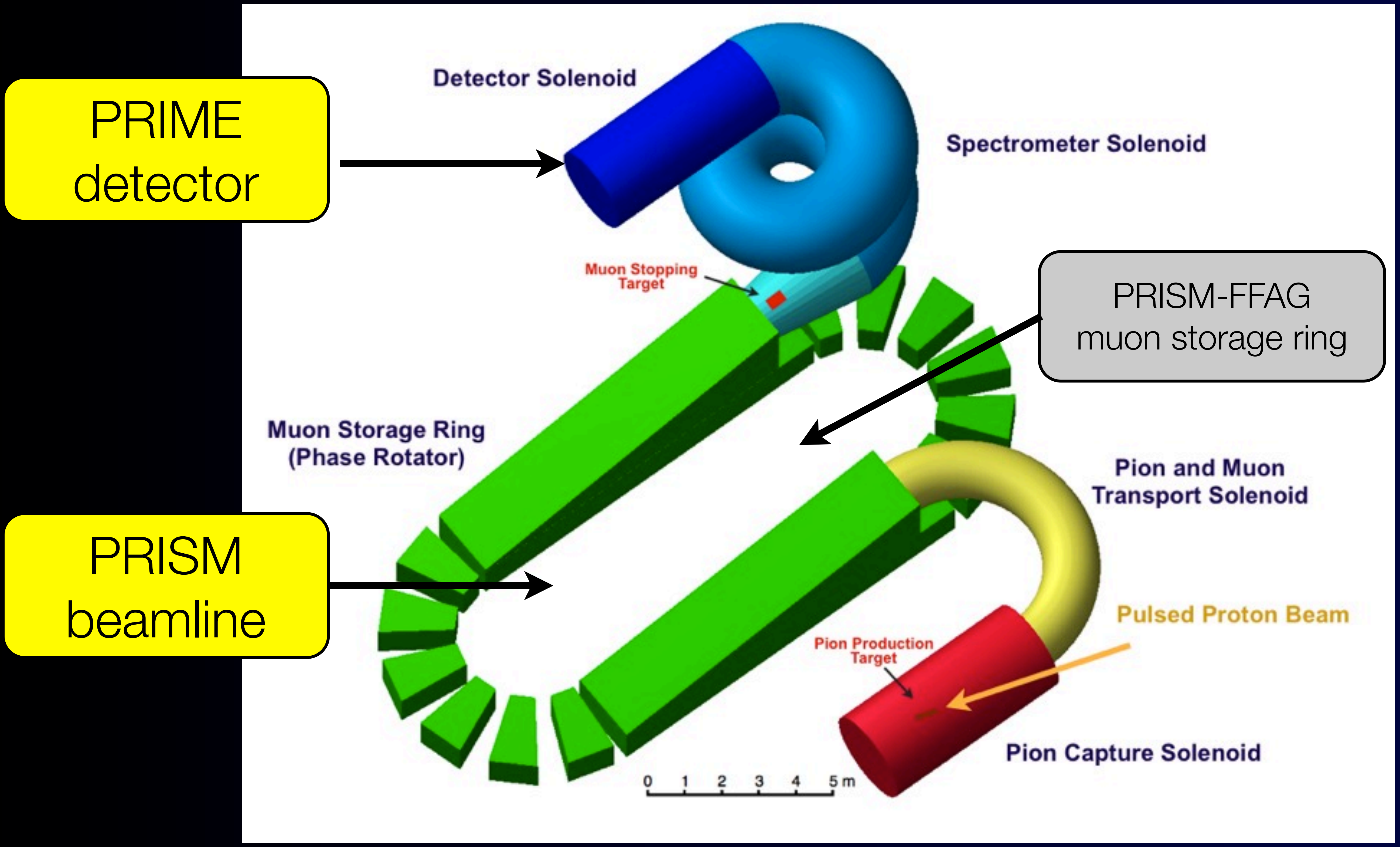
PRISM/`PRIME
Option

PRISM/PRIME Detector Layout

Aiming at a single event sensitivity of $3x10^{-19}$

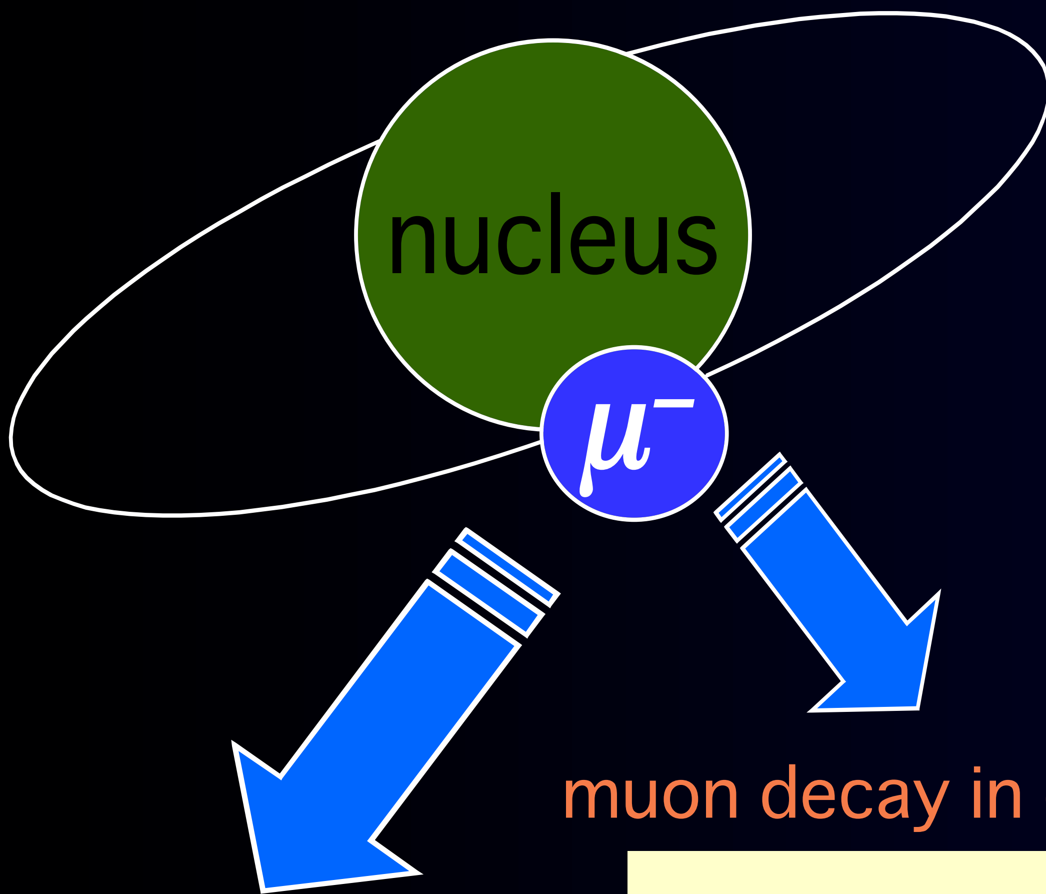


PRISM/PRIME Detector Layout



What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

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

lepton flavors changes by one unit.

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Search for μ-e Conversion is like ....

meditation (since no complicated analysis).

But make sure you are ready in advance.

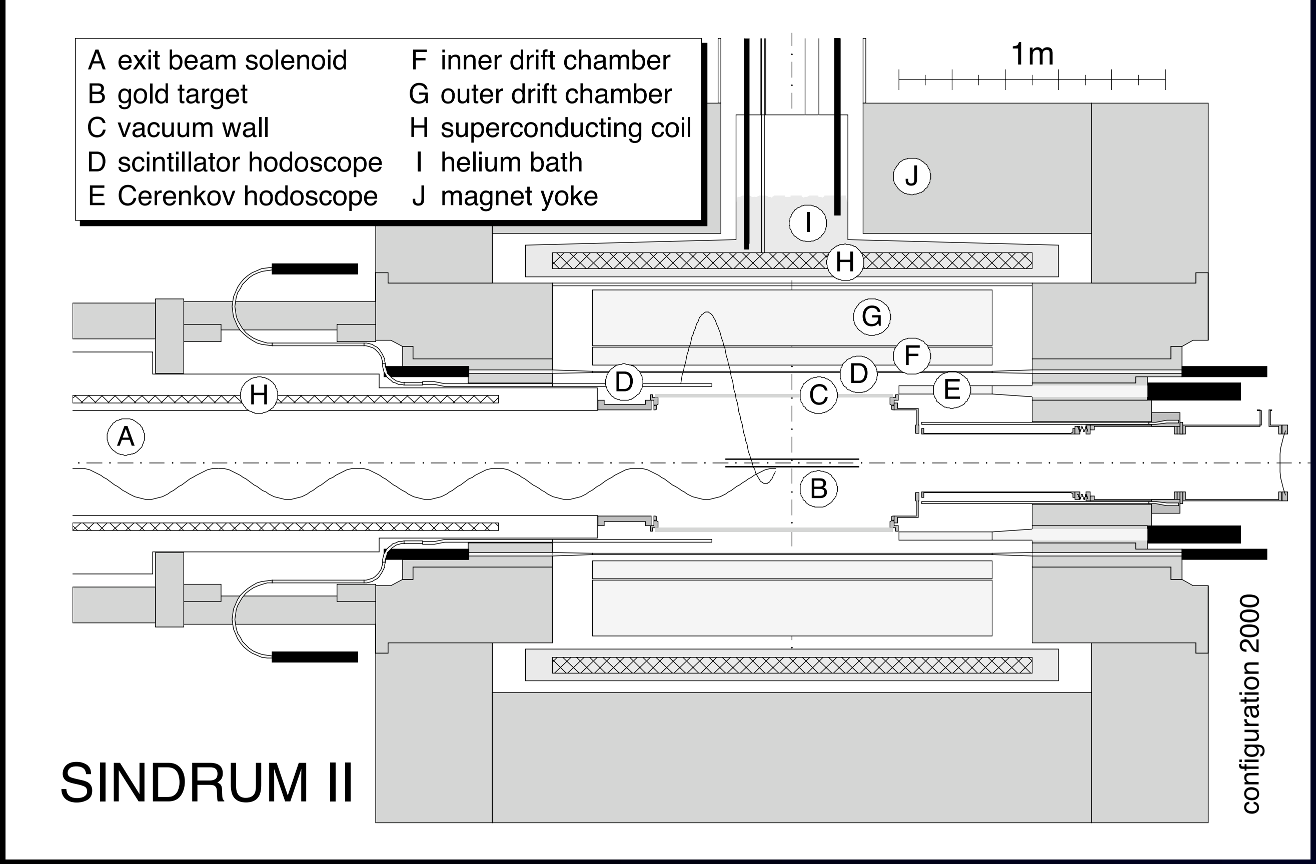
Potential Background for μ-e Conversion

- Background rejection is the most important in searches for rare decays.
- Types of backgrounds for $\mu^- + N \rightarrow e^- + N$ are,

Intrinsic backgrounds	originate from muons stopping in the muon stopping target.	• muon decay in orbit • radiative muon capture • muon capture with particle emission
Beam-related backgrounds	caused by beam particles, such as electrons, pions, muons, and anti-protons in a beam	• radiative pion capture • muon decay in flight • pion decay in flight • beam electrons • neutron induced • antiproton induced
Other backgrounds	anything others	• cosmic-ray induced • room-background induced • pattern recognition error

Previous Measurements

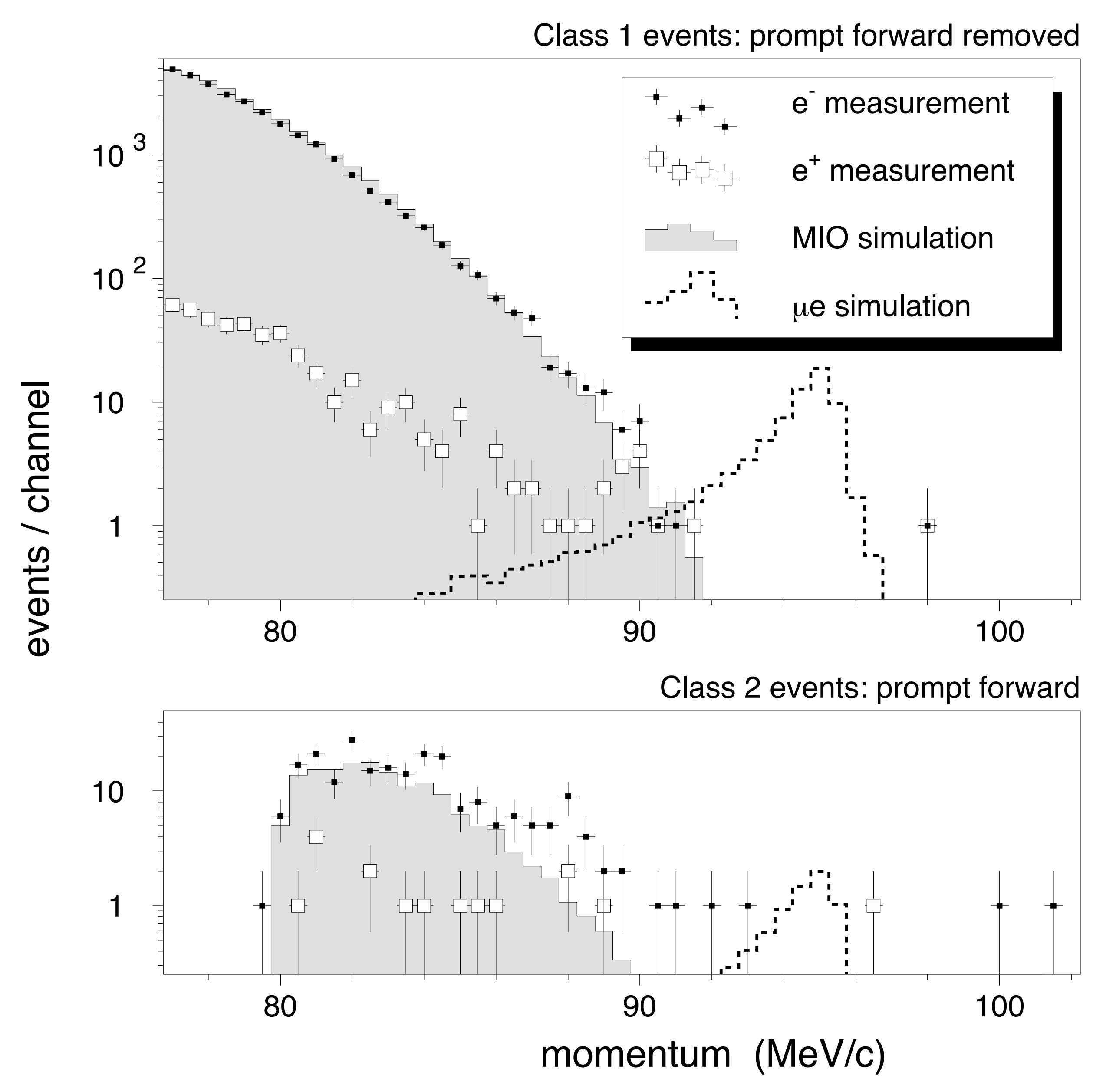
SINDRUM-II (PSI)



PSI muon beam intensity ~ 10^{7-8}/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



Improvements for Background Rejection at Mu2e and COMET at 10^{-16}

Beam-related backgrounds → Beam pulsing with separation of 1 μsec — measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse < 10^{-9}

Muon DIO background → low-mass trackers in vacuum & thin target — improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

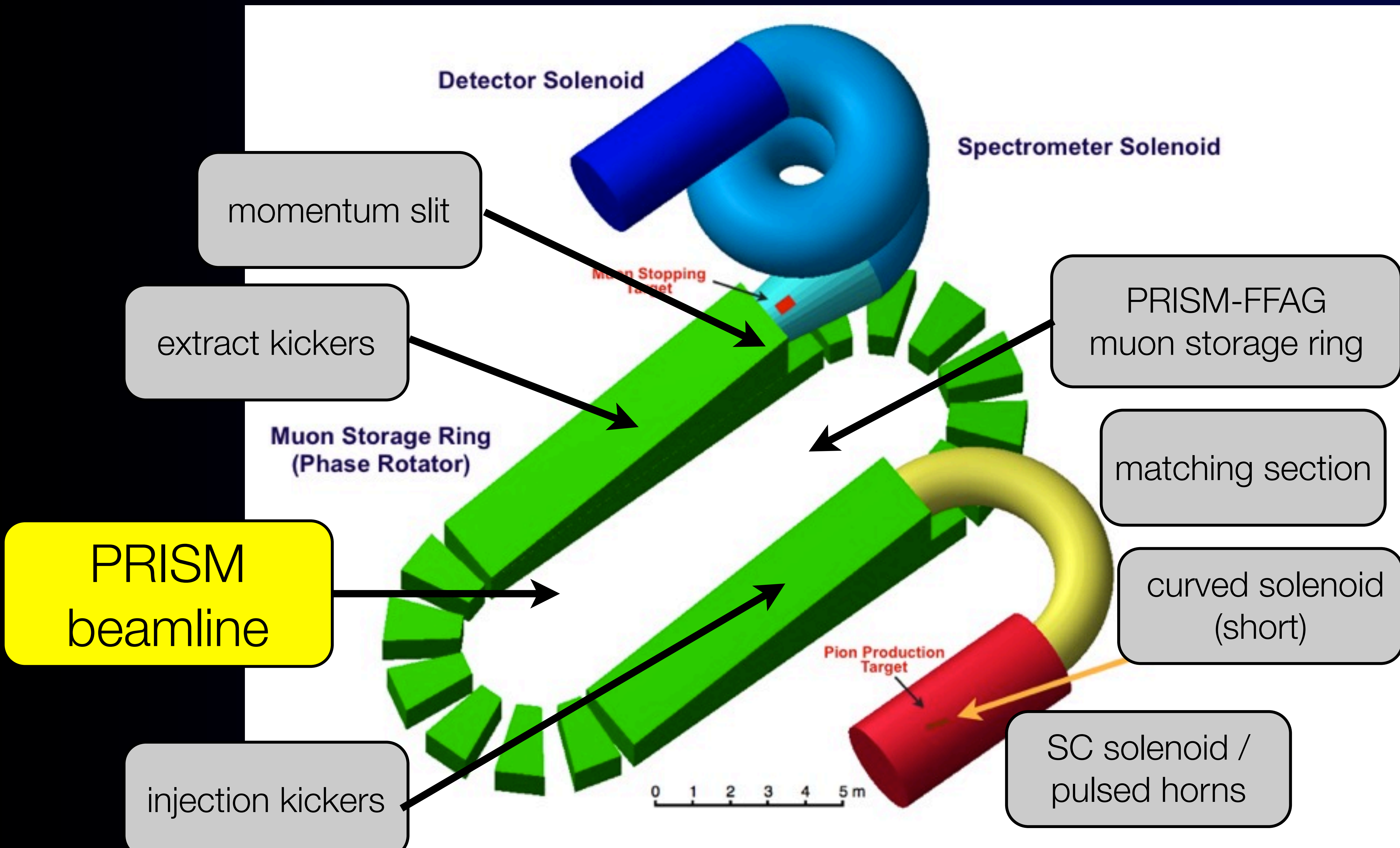
base on the MELC proposal at Moscow Meson Factory

Why Mu2e and COMET cannot go beyond ?

- (1) Beam background rejection is heavily relined on proton beam extinction of 10^{-9}, which is uncertain.
- (2) The beam line is not long enough, so that late pions might come in a beam.
  - The measurement starts after 700 nsec after the prompt.
  - Material of a muon stopping target is limited to low Z.

PRISM Beamline

PRISM
(Phase Rotated Intense Slow Muon source)



PRISM to reject beam-related backgrounds (1)

most important

- (1) Rejection of pions in a beam (like radiative π capture)
  - long flight length of a beam
    - use 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.....
- (2) Rejection of beam particles with wrong momenta from upstream
  - dipole magnet and momentum slits before a muon stopping target
    - 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 to reject beam-related backgrounds (2)

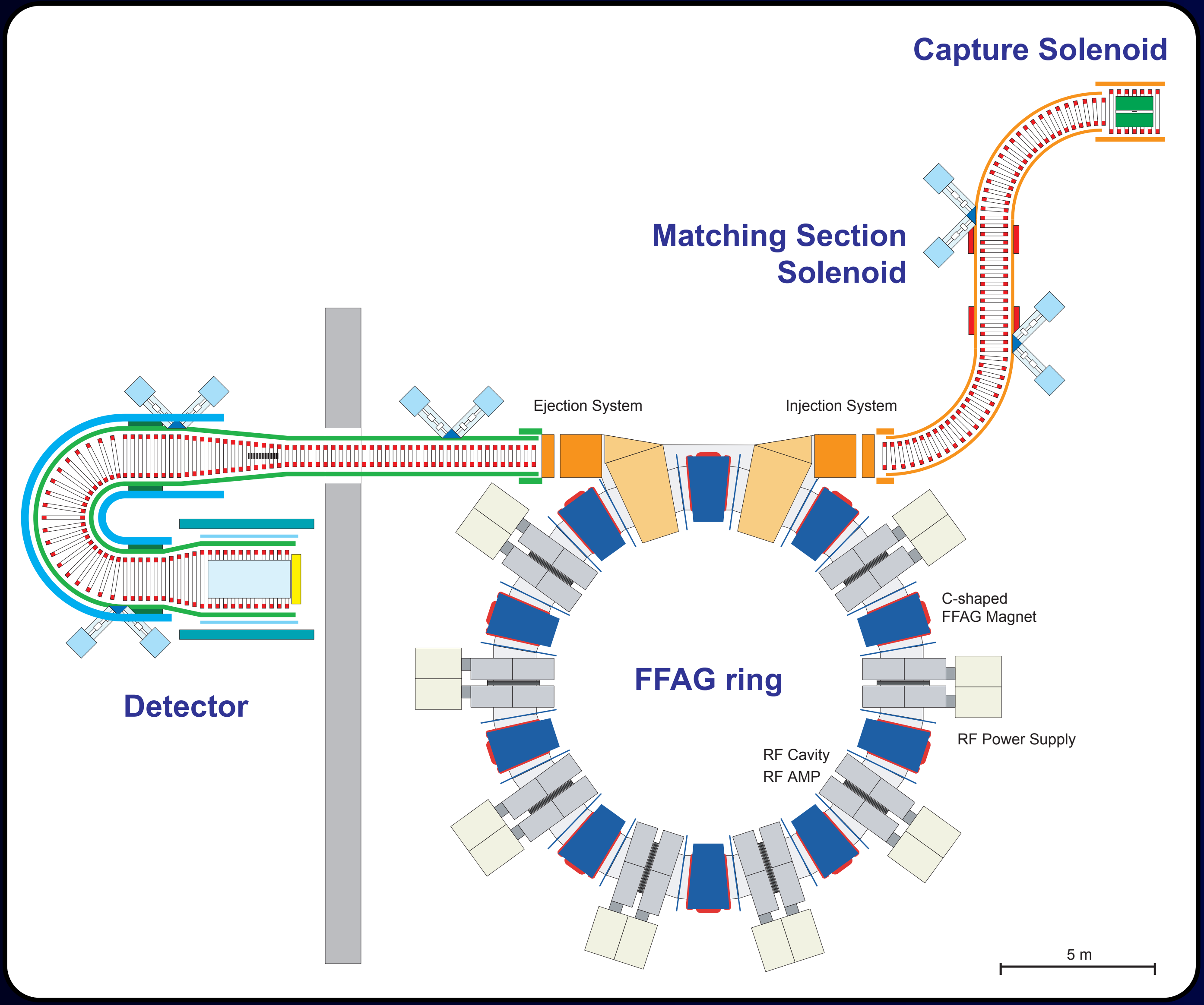
    - The curved-solenoid momentum selection may not be sharp enough for 10^{-18}
- (3) Beam extinction at both proton and muon beams
  - (injection) kicker magnets for the storage ring does this for muons,
    - in addition to proton beam extinction
    - a total beam extinction of 10^{-11}
- (4) Narrow muon beam energy spread
  - allow a thinner muon stopping target (1/10 of Mu2E and COMET)
  - by phase rotation in a muon storage ring
    - goal is +- 3% from +-30 %
  - This is not a critical issue, since we can make tight momentum selection of the signal electron (just a loss of acceptance).

PRISM to reject cosmic/exp. hall backgrounds

- (1) Rejection of cosmic-induced or neutrons/gammas-induced backgrounds
  - low duty factor running might help.....

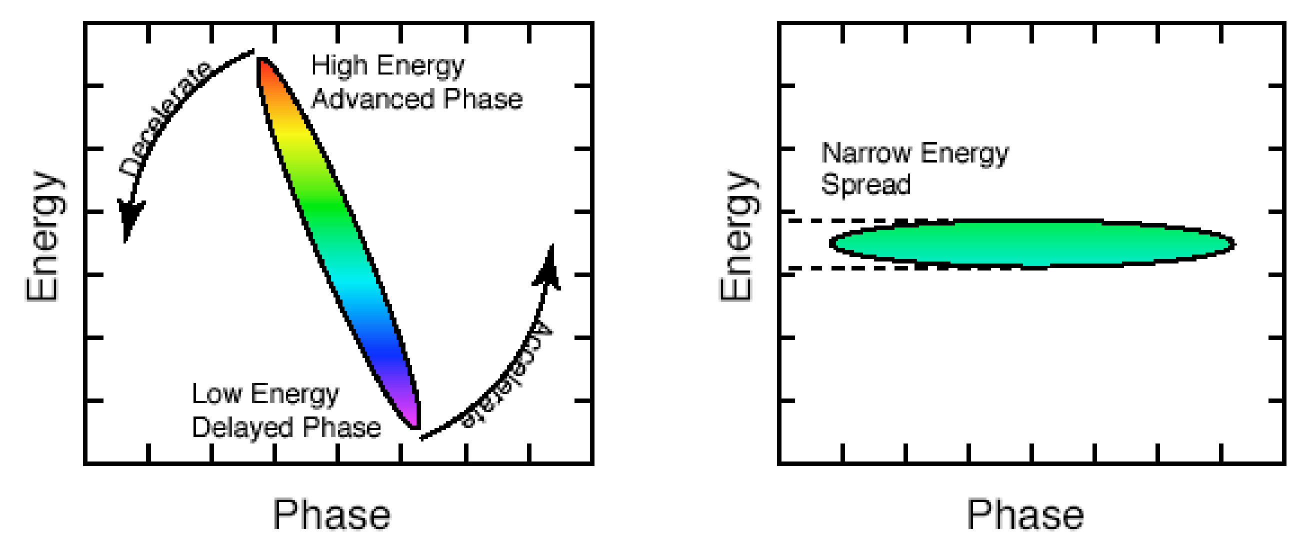
PRISM Specifications

- 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.



... To Make Narrow Beam Energy Spread

- A technique of phase rotation is adopted.
- 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 nsec).
- Phase rotation is a well-established technique, but how to apply a tertiary beam like muons (broad emittance) ?



Phase Rotation for a Muon Beam

Use a muon storage ring ?

(1) Use a muon Storage Ring :

A muon storage ring would be better and realistic than a linac option because of reduction of # of cavities and rf power.

(2) Rejection of pions in a beam :

At the same time, pions in a beam would decay out owing to long flight length.

Which type of a storage ring ?

(1) cannot be cyclotron, because of no synchrotron oscillation.
(2) cannot be synchrotron, because of small acceptance and slow acceleration.

Fixed field Alternating Gradient Ring (FFAG)

R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

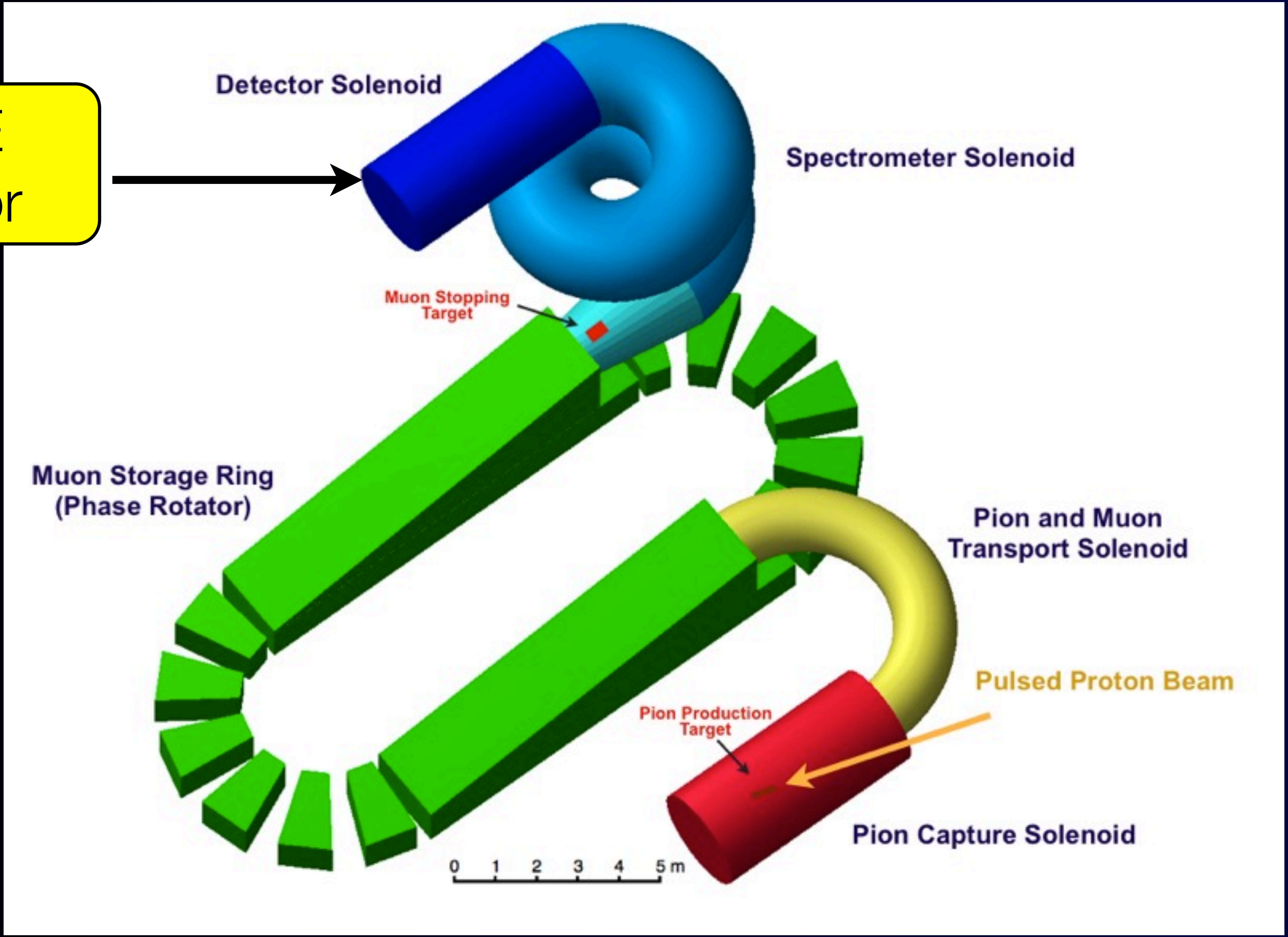
demonstration of phase rotation has been done.

PRIME Detector

PRISM

PRIME Detector

PRIME detector



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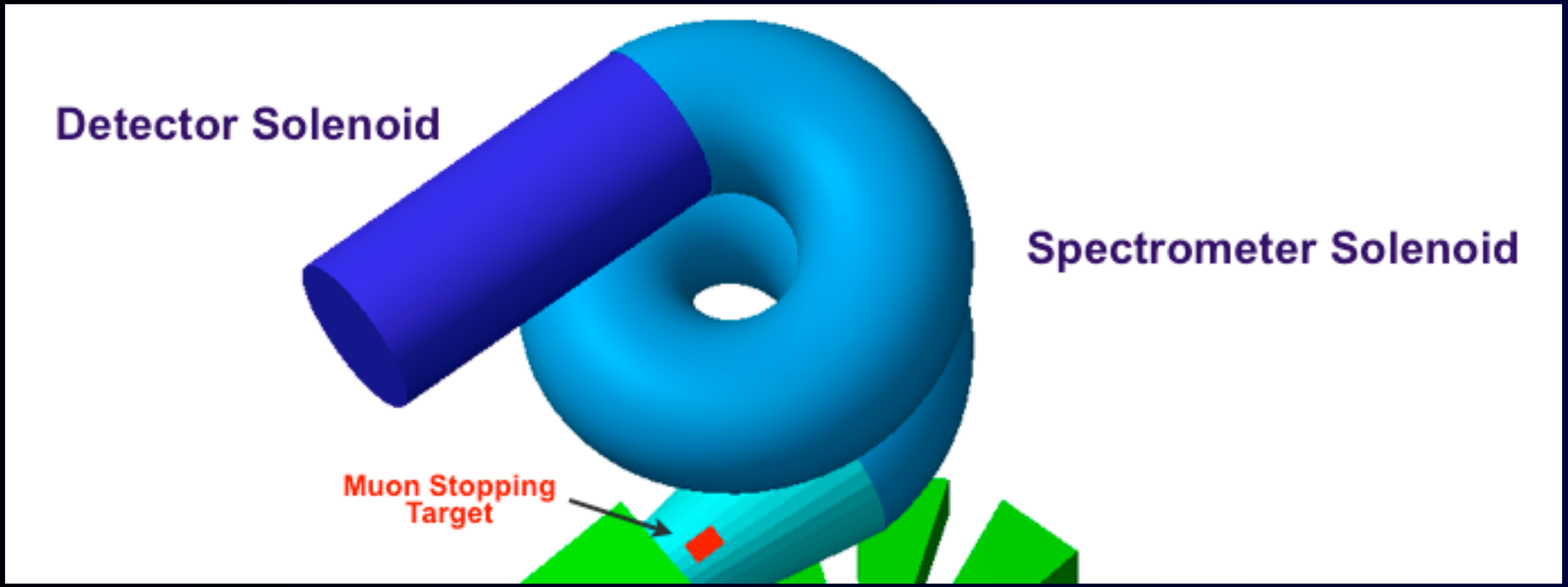
PRIME to reject muon-induced backgrounds

- (1) Rejection of protons and neutrons from muon nuclear capture
    - each stopped muon produces about 2 neutrons, 0.1 protons, and two photons. In paricular, 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

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

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

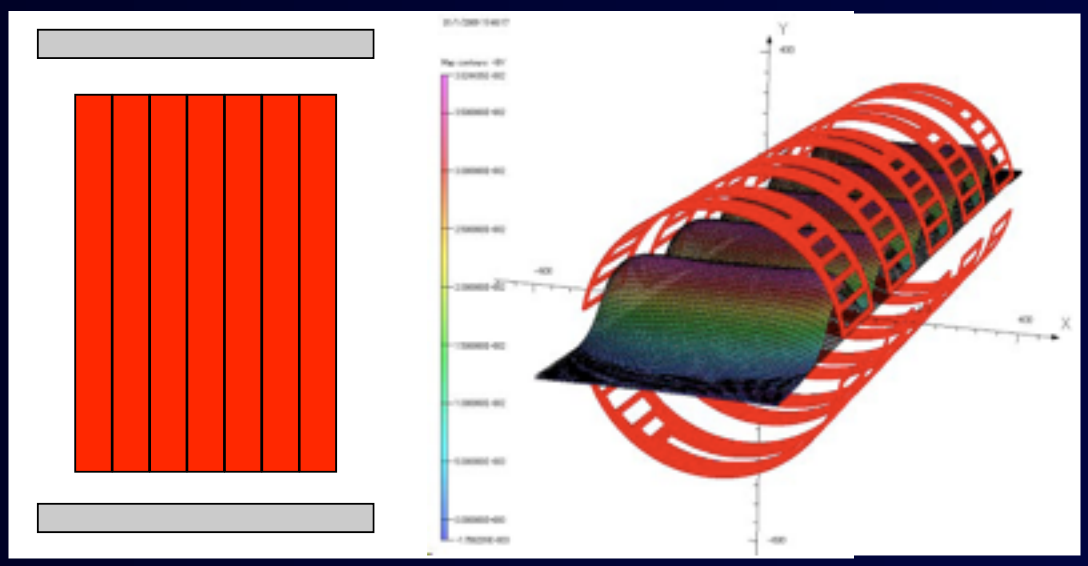
D : *drift distance*
B : *Solenoid field*
θ_{bend} : *Bending angle of the solenoid channel*
p : *Momentum of the particle*
q : *Charge of the particle*
θ : *atan*(P_T/P_L)

  - This can be used for charge and momentum selection.

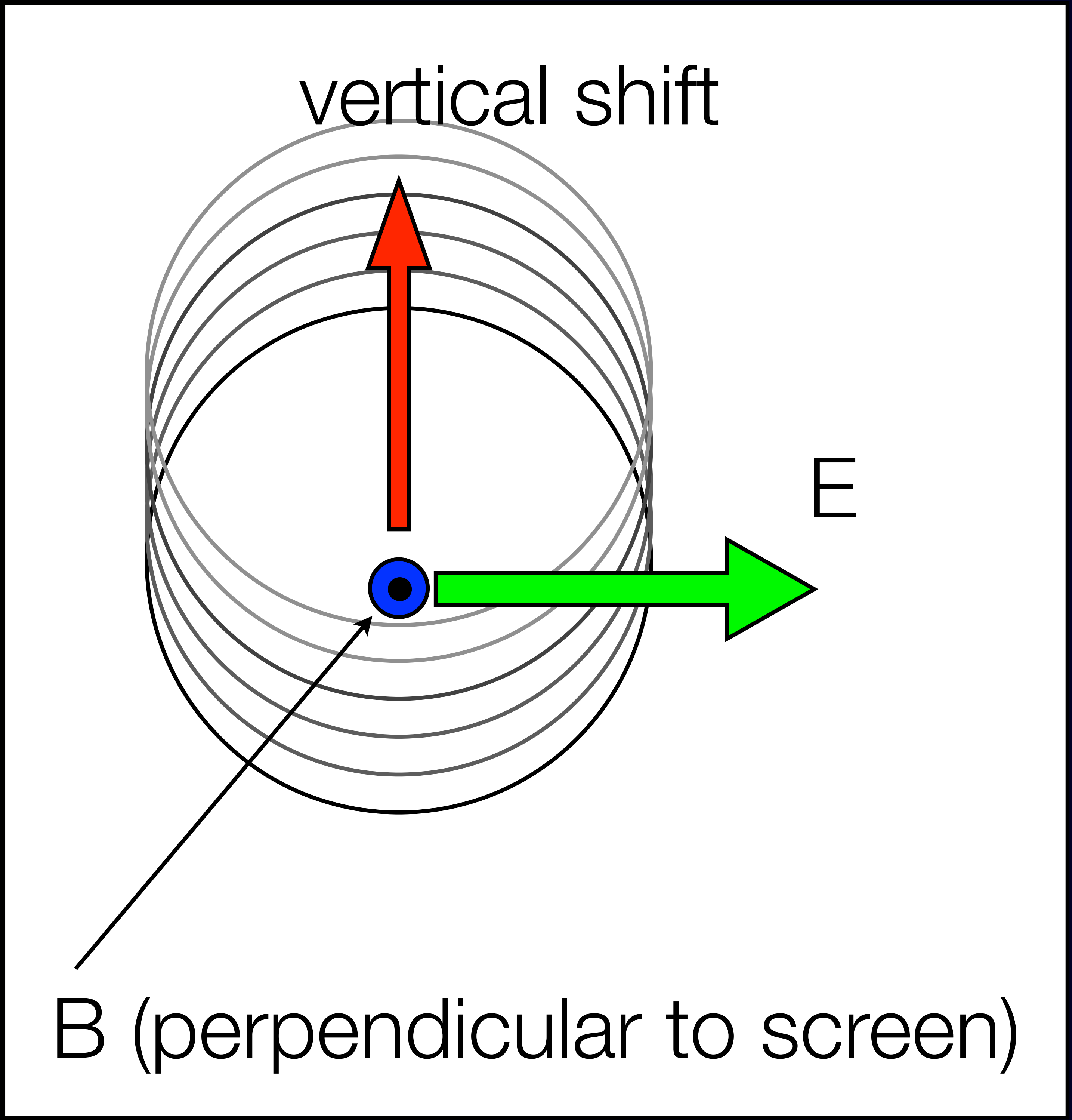
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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

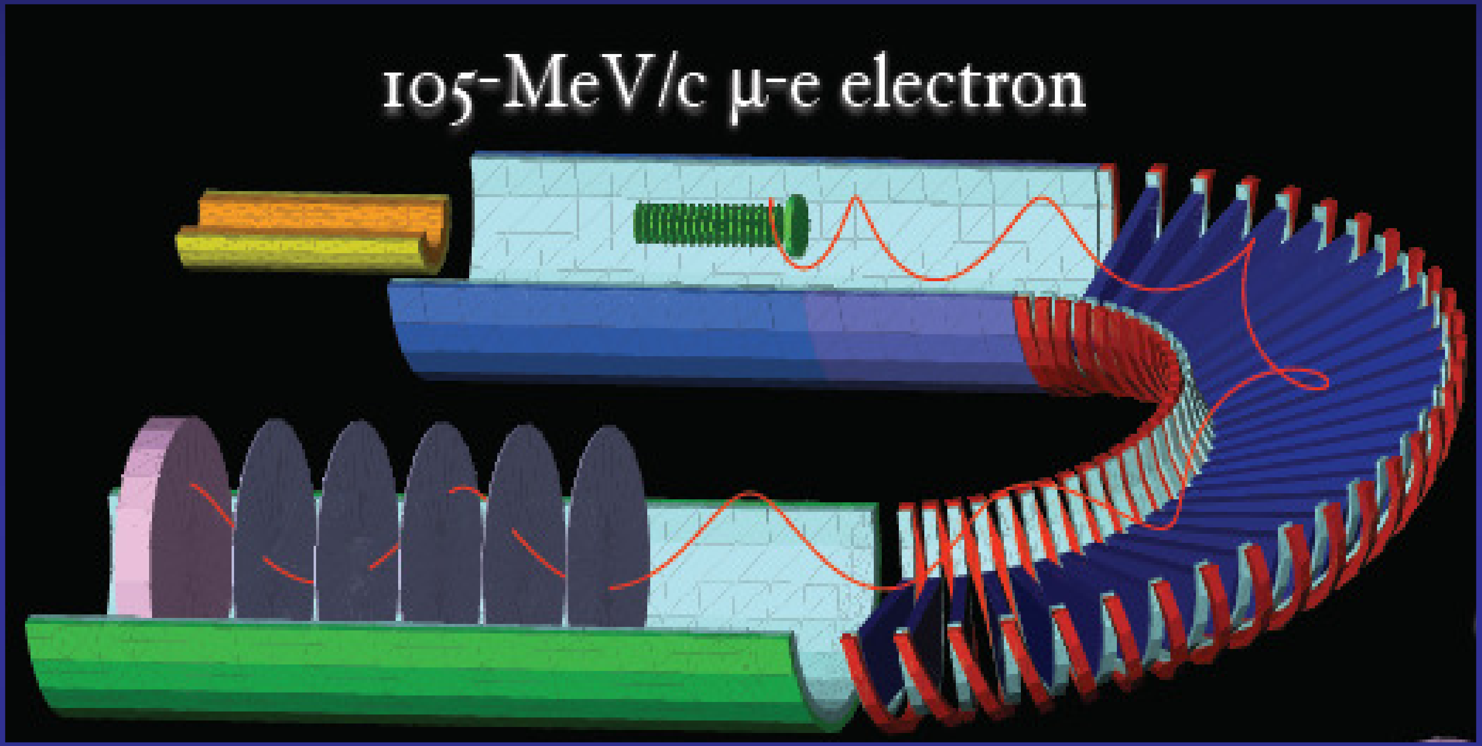


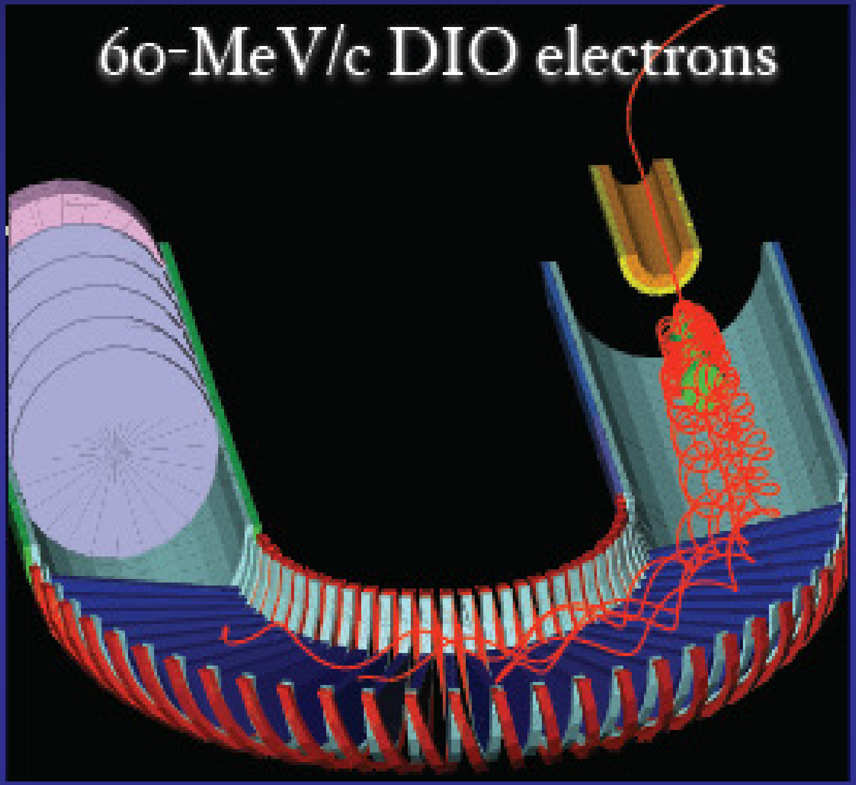
EM Physics for Particle Trajectories in Toroidal Magnetic Field



- For helical trajectory in a curved mag. field, a centrifugal force gives E in the radial direction.
- To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by v x B, can be applied.

Electron Spectrometer at COMET

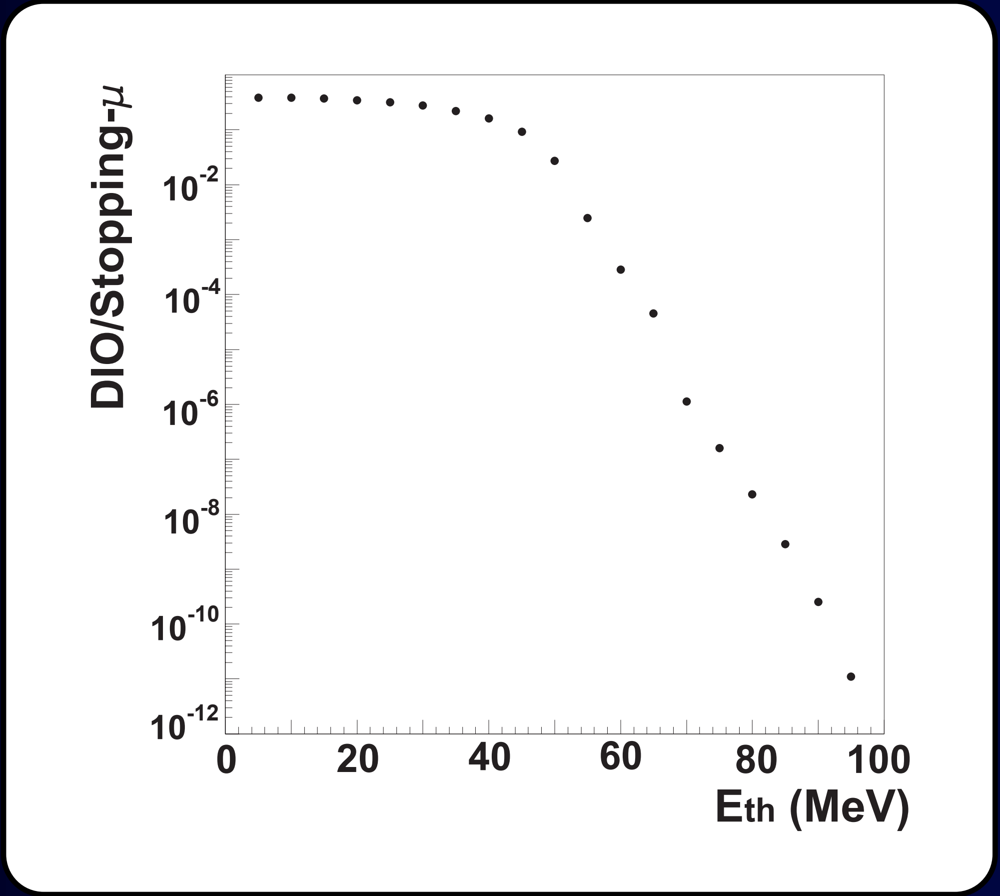




- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~ 1kHz.

PRIME detector: detector single rates

- (1) PRIME electron transport might set momentum threshould at 80 MeV/c (and above).
  - It is assumed that all other particles are completely removed by the PRIME detector.
- (2) Remaining events to the detector region are electrons from muon decay in orbit in a muonic atom.
  - 10^{-8} per muons stopped (see fig.)
  - For $2x10^{12}$ muons stopped /second, $2x10^{4}$ DIOs come to the detector.
  - At 1000 Hz repetition, 20 events/pulse come to the detector. It should be OK.



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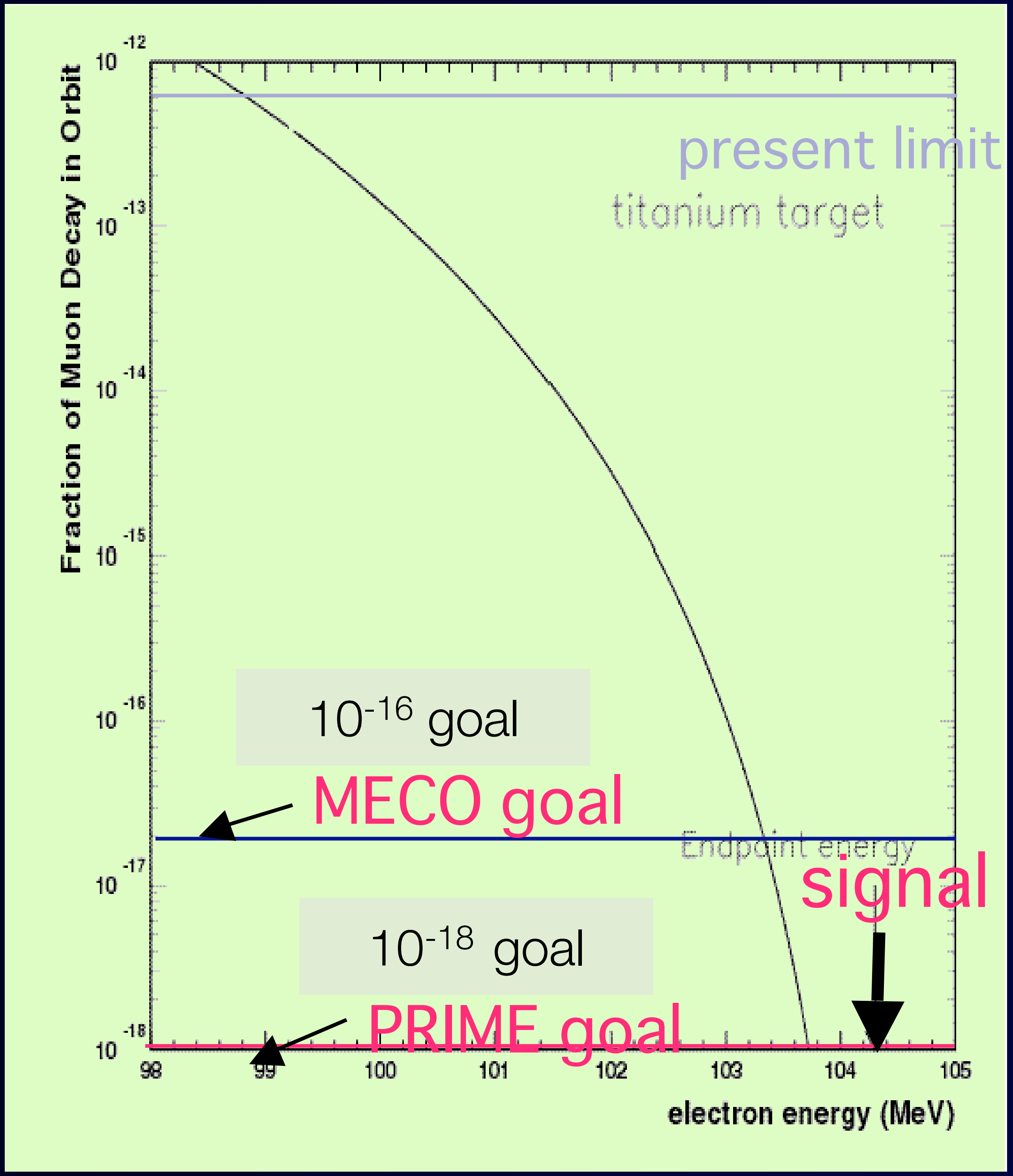
Muon Decay In Orbit (DIO) in a Muonic Atom

- Normal muon decay has an endpoint of 52.8 MeV, whereas the end point of muon decay in orbit comes to the signal region.
- good resolution of electron energy (momentum) is needed.

$$\propto (\Delta E)^5$$

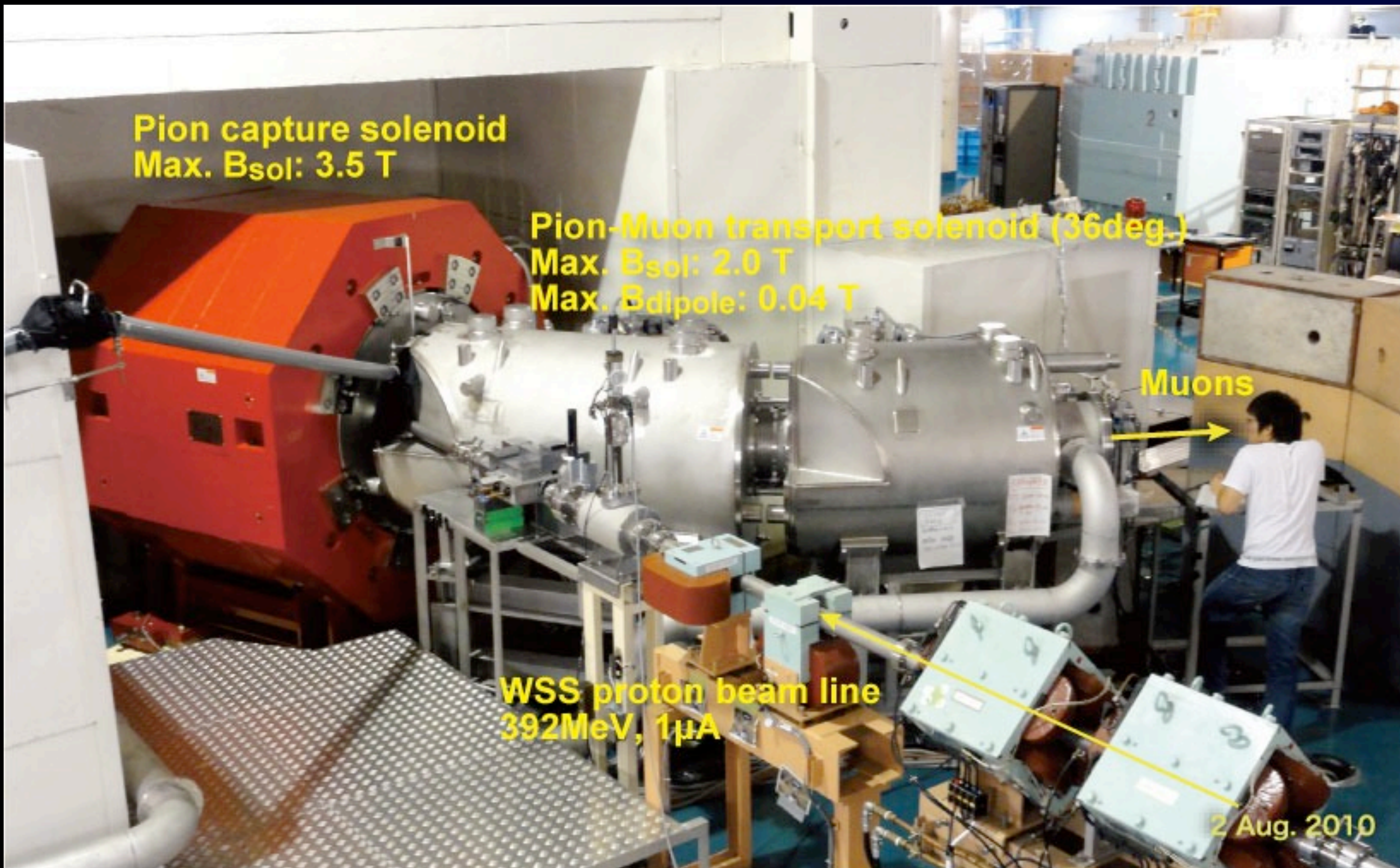
- Tracker resolution of 150 keV will suffice.



PRISM/PRIME Following Presentations

- Proton beam for PRISM/PRIME (Keith Gollwitzer)
  - a bunched proton beam (not CW) is required.
  - repetition rate is about 1000 Hz.
  - a beam pulse width is about 10 nsec (or less).
  - an additional accumulation ring and a buncher ring
    - synergy for neutrino factory and muon collider ???
- PRISM FFAG muon storage ring R&D (Jaroslaw Pasternak)
  - FFAG reference design and alternative designs
    - acceptance
  - Design of injection and kicker magnet
- PRIME detector (Akira Sato)
- Sensitivity and Backgrounds (Yoshi K.)
- By-product physics (Ed Hungerford)

MuSIC


Pion capture solenoid
Max. B$_{sol}$: 3.5 T
Pion-Muon transport solenoid (36deg.)
Max. B$_{sol}$: 2.0 T
Max. B$_{dipole}$: 0.04 T
Muons
WSS proton beam line
392MeV, 1μA
2 Aug. 2010