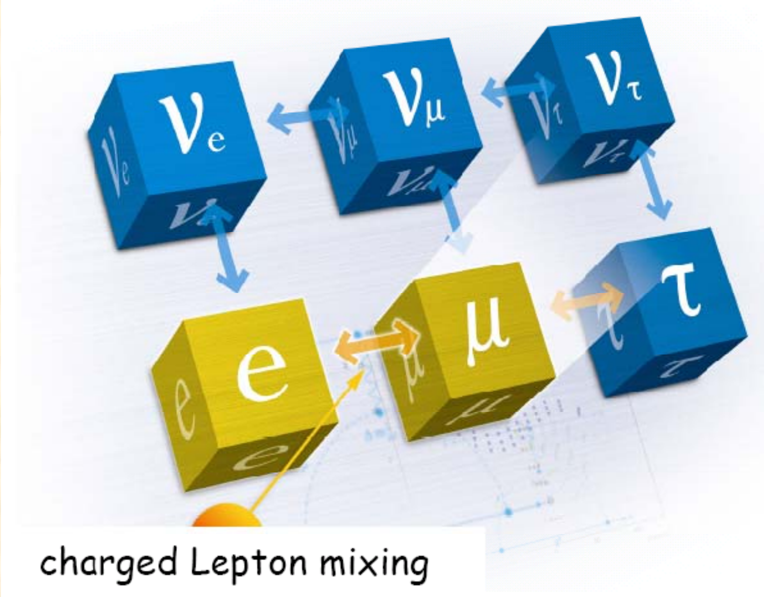
COherent Muon to Electron Transition (COMET)

Ye Yuan

On behalf of COMET Collaboration
Institute of High Energy Physics
Beijing



NuFact 2013
Aug. 21st, 2013
IHEP

Outline

- **Physics motivation of charged Lepton Flavor Violation**
- **What's COMET (J-PARC E21) Phase-I and Phase-II**
- **Recent progress from COMET**
- **Strategic plan**
- **Summary**

Thanks to my COMET colleagues
Most of my slides are stolen from their previous presentations.

Quarks,Neutrinos,and then Charged Leptons

Quarks

2008 Noble Prize

Quark mixing observed

Leptons

Neutrino mixing observed
Last θ_{13} observed by Daya Bay

Charged lepton mixing not observed

Is it possible? Do $\mu^- \to e^- \gamma$, $\tau^- \to \mu^- \gamma$ exist?

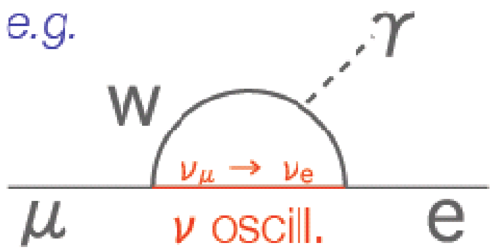
Charged Lepton Flavor Violation (cLFV)

Muon-to-electron flavour violation

Minimal SM: $m_\nu = 0$ → strictly zero transitions between lepton flavours
SM extension to $m_\nu \neq 0$ → unobservable tiny cLFV rates predicted (GIM)

SM + simple ν Oscillation

- charged LFV is possible



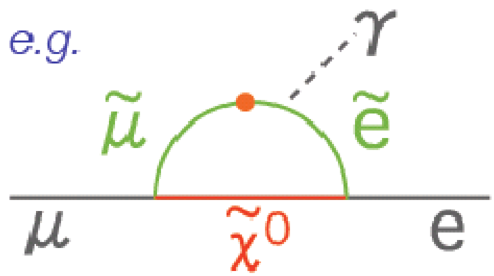
- but extremely rare

$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

- $B(\mu \rightarrow e\gamma) \leq 10^{-54}$!!!

beyond SM (SUSY-GUT *etc.*)

- charged LFV is largely enhanced



- still rare but observable level

$$\mathcal{B}(\mu \rightarrow e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

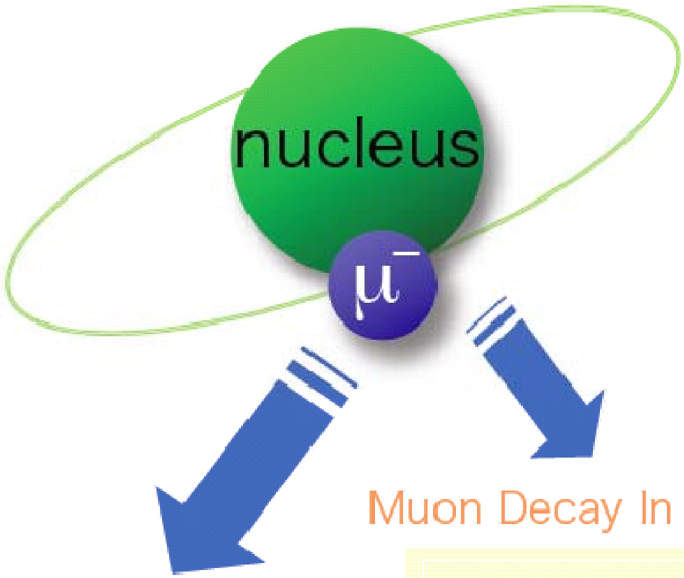
- $B(\mu \rightarrow e\gamma) = 10^{-15} \sim 10^{-11}$!!!

Observation of CLFV would indicate a clear signal of physics beyond the SM with massive neutrinos

$\mu^- \to e^-$ conversion

$\mu^- \to e^-$ conversion

1s state in a muonic atom



Muon Decay In Orbit

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

nuclear muon capture

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

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

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

- ✓ Signal:
  monoenergetic electron
  104.96 MeV for Al, 95.56 MeV for Au
- ✓ Main background:
  Muon Decay in Orbit (10^{-16})
  Radiative muon Capture

$$\mu^-(A,Z) \to \gamma(A,Z-1)^* \nu_\mu$$

  Radiative pion capture

$$\pi^- + (A,Z) \to (A,Z-1)^* \to \gamma + (A,Z-1)$$
$$\gamma \to e^+ e^-$$

- ✓ No limit from random background, higher beam intensity!

Rating of DNA of New Physics

Prof. Dr. A. J. Buras

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

★★★ Large effects

★★ Small effects

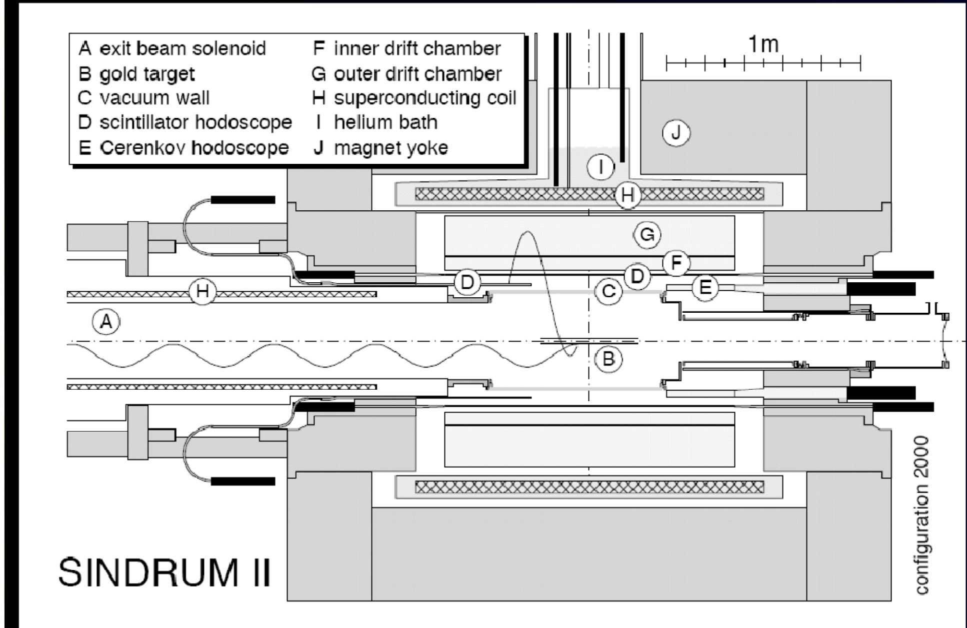
★ Not observable

Theoretical models

AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

Previous measurement

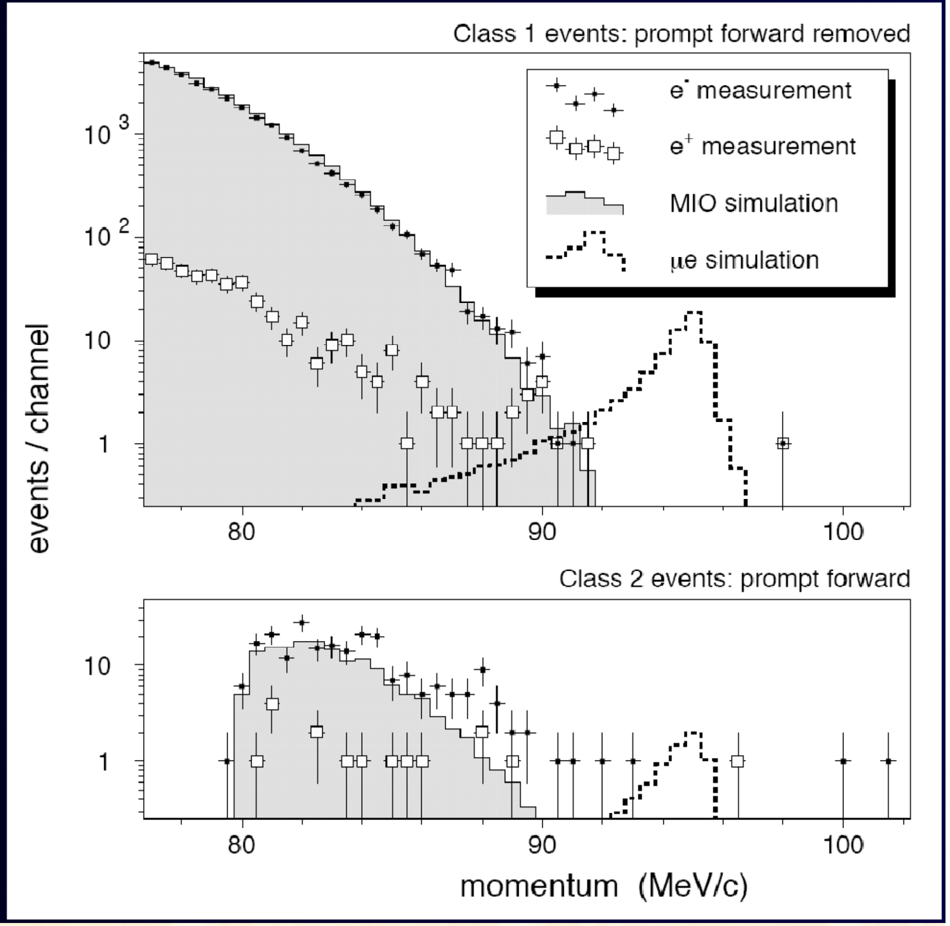
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/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.

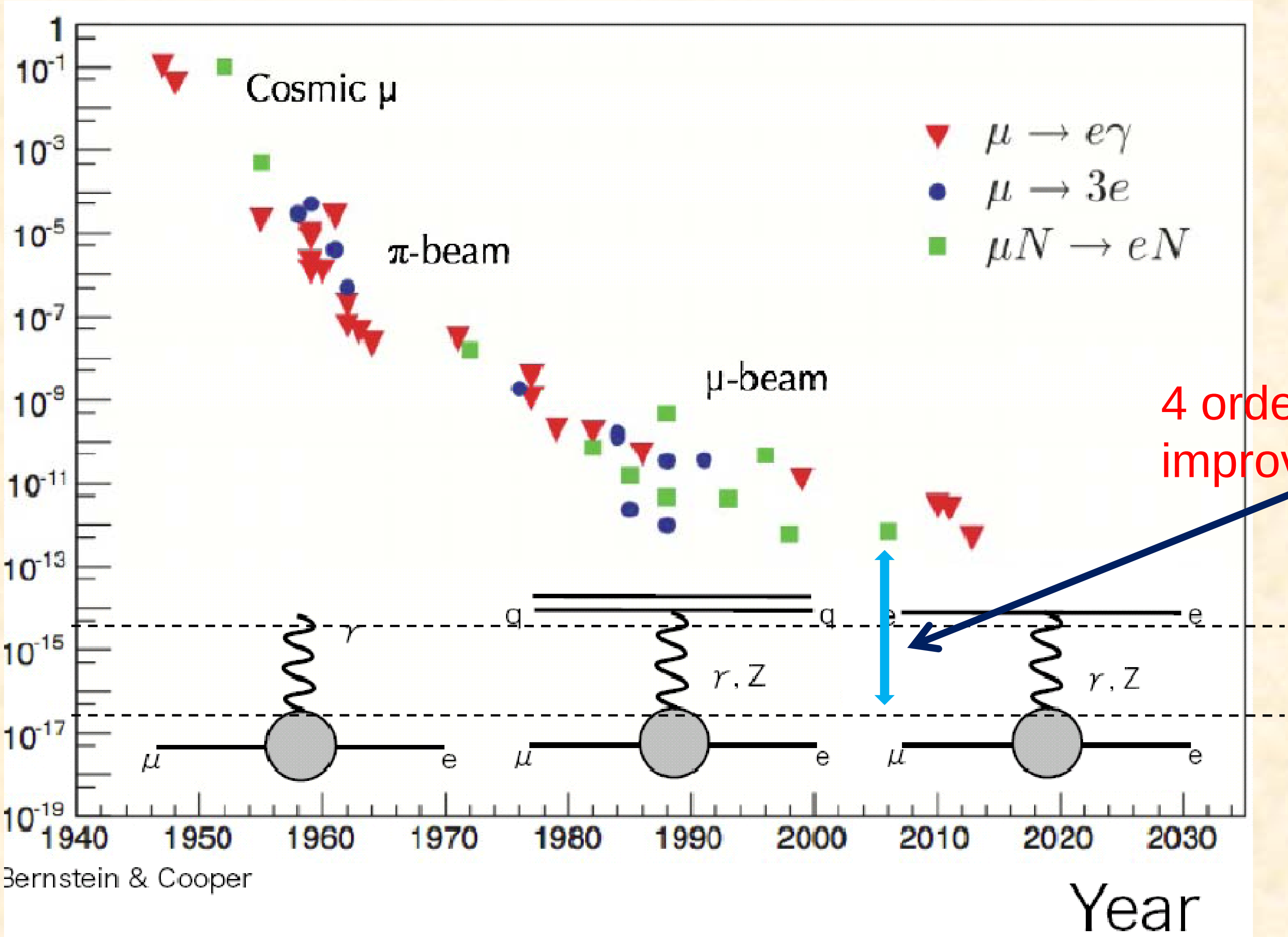
Published Results (2004)

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



SINDRUM-II EPJ C 47, 337 (2006)

μ⁻→e⁻ historical limits



4 orders of magnitude improvement!

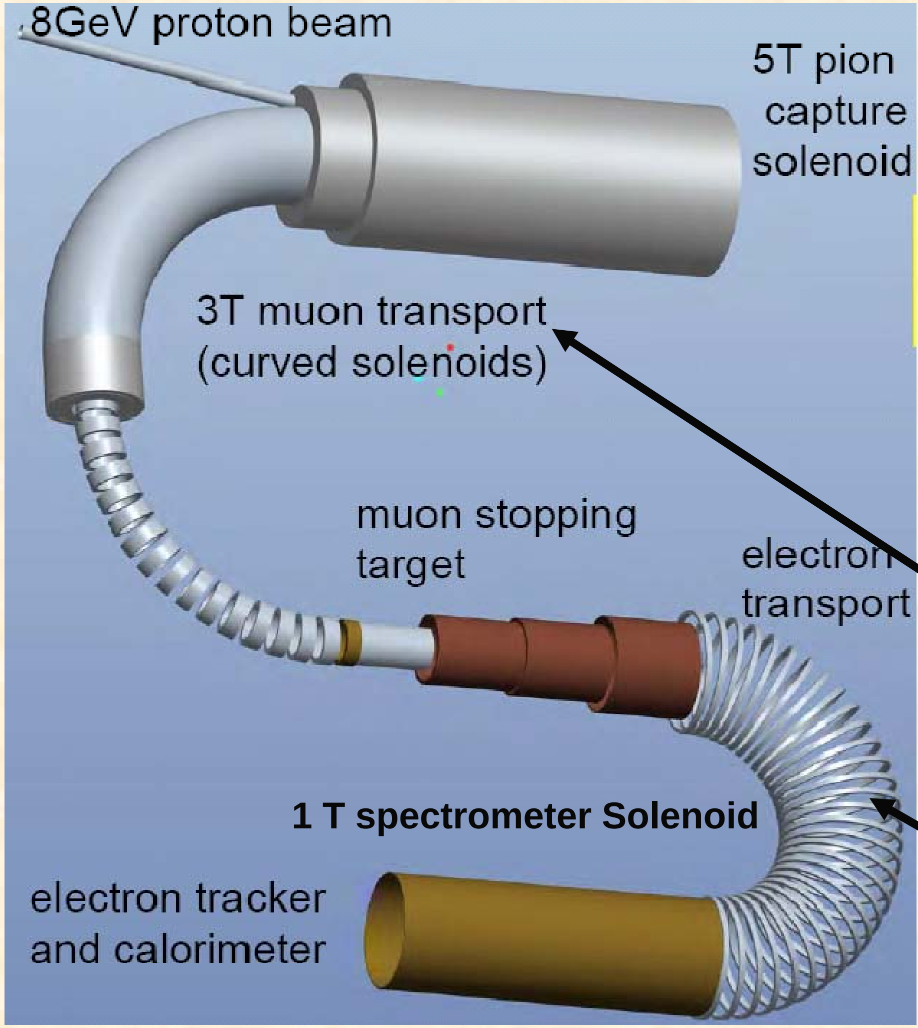
COMET
Phase-I (2017)

Phase-II (2022)

From 1947, best from MEG: 5.7×10^{-13} @ 90% C.L.

PRL 110 (2013) 201801

$\mu \rightarrow e$ conversion: COMET(E21) at J-PARC

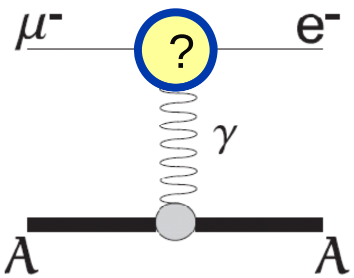


- Pulsed proton beam
- 10^{11} muons/stops/sec. for 56kW proton beam power (~850 protons required to produce 1 muon)
- Curved solenoids for muon charge and momentum selection
- C-shaped transport for better P_μ selection
- C-shaped detector section eliminates low-*E DIO* **electron** and protons.

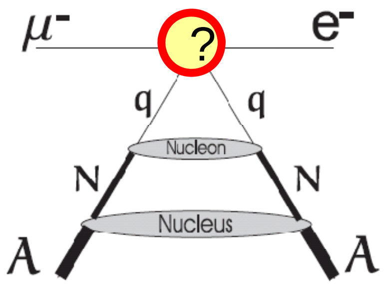
CLFV Sensitivity of COMET

$$L_{\mathrm{CLFV}} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\mathrm{R}}\sigma^{\mu\nu}e_{\mathrm{L}}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\mathrm{L}}\gamma^{\mu}e_{\mathrm{L}})(\bar{q}_{\mathrm{L}}\gamma_{\mu}q_{\mathrm{L}})$$

Λ: Effective mass scales

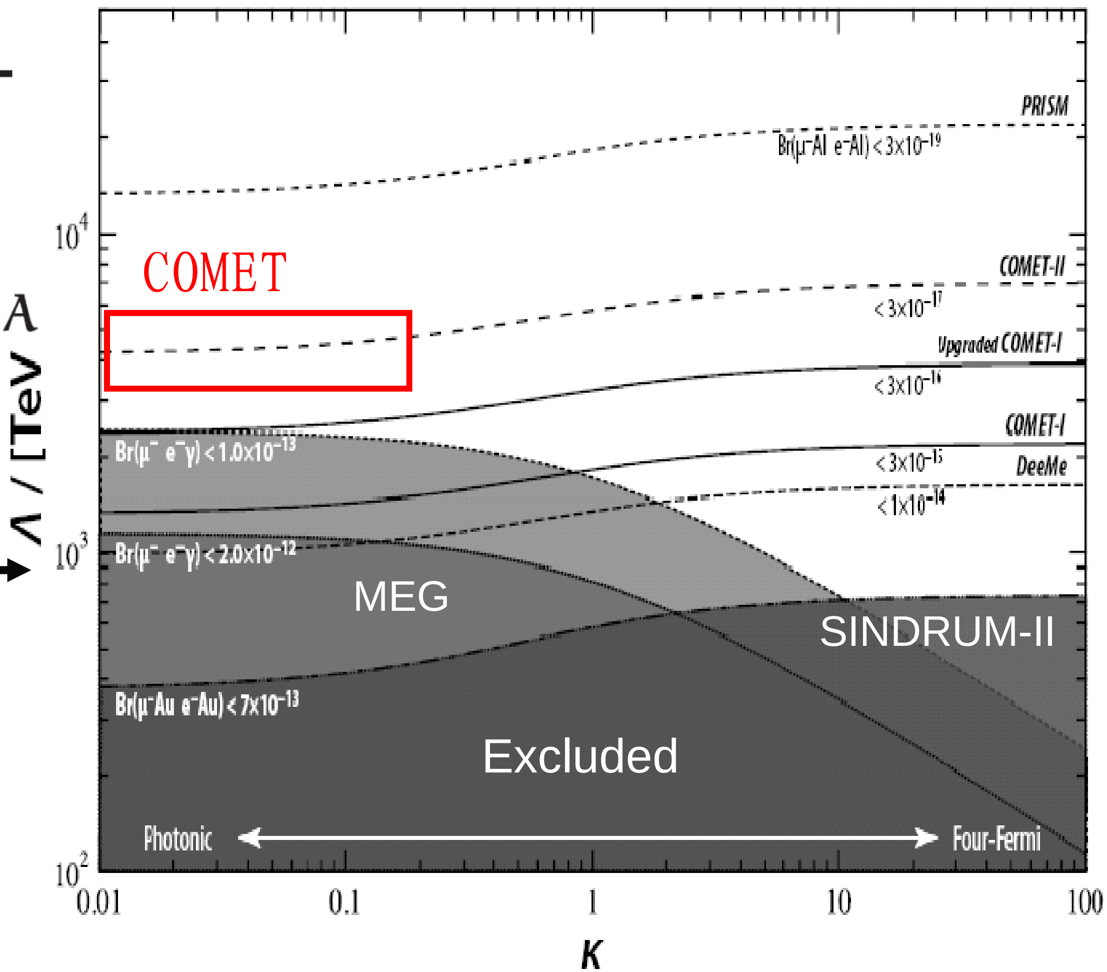


Photonic

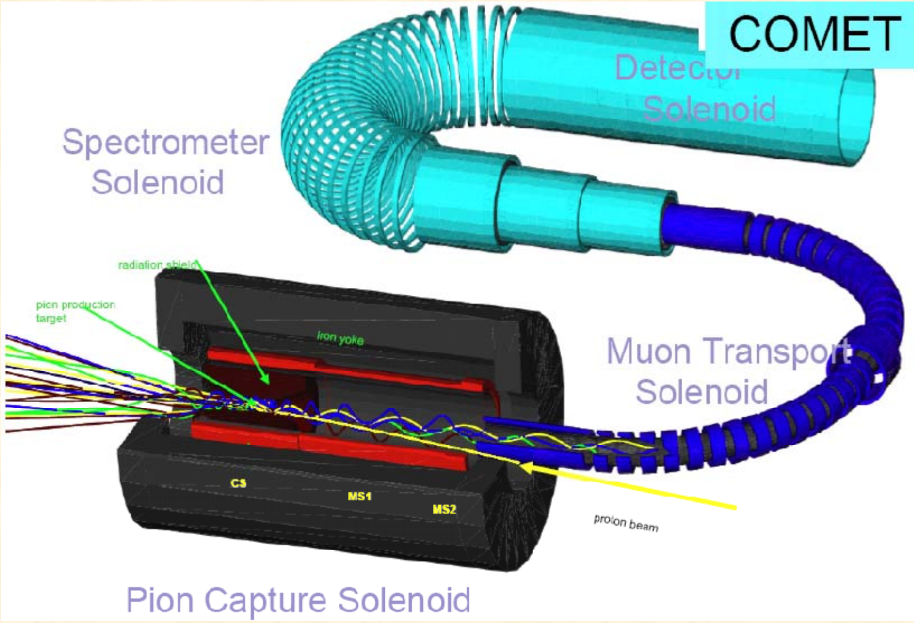


Four fermi

10^3TeV now →



R&D milestones for mu-e conversion



- **Reduction of backgrounds with pulsed proton beam:**

  measurement is done between beam pulses to reduce beam related backgrounds. And proton beam extinction of $< 10^{-9}$ is required, 10^{-11} achieved!

- **Increase of Muon intensity:**

  High field superconducting solenoid surrounding a pion capture production target:

  measurement of Muon yields at
  MuSIC: 3×10^{8} μ^{+}/s for 400W
  1×10^{8} μ^{-}/s for 400W
  PSI: 10^{8}/s for 1MW
  improved by 1000 times.

S.E.S:

$$B(\mu^{-} + Al \rightarrow e^{-} + Al) = 2.6\times10^{-17}$$

$$B(\mu^{-} + Al \rightarrow e^{-} + Al) < 6\times10^{-17} \text{ @90\% C.L.}$$

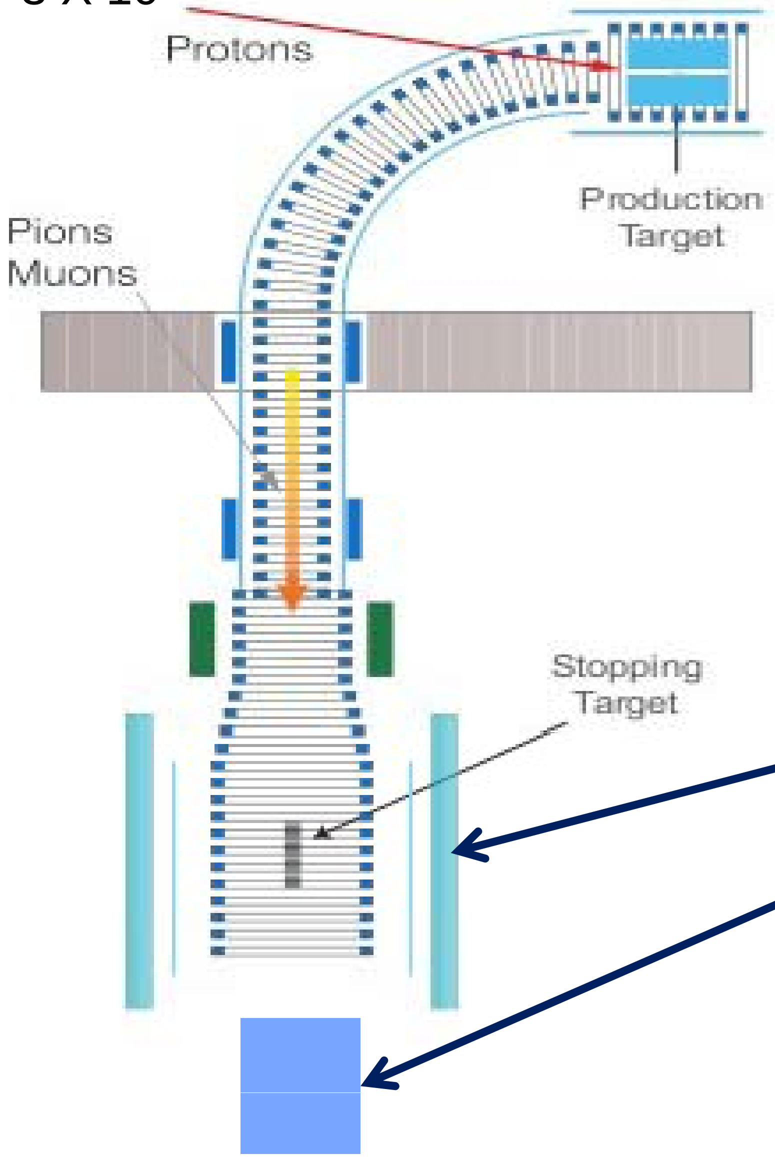
COMET is separated into two Phase: Phase-I and Phase II

Got funding for Phase-I from KEK in the JFY 2012 budget

Construction has begun!

Starting in 2016
Measurement in 2017
S.E.S=3 X 10^{-15}

COMET(Phase-I)



Pion Capture Section

Has a high(5T) magnetic field to collect the low momentum, backwards travelling pions

Phase-I Aims

Search for $\mu \rightarrow e$ conversion process with a S.E.S. of 3 X 10^{-15}

Study the backgrounds for Phase-II

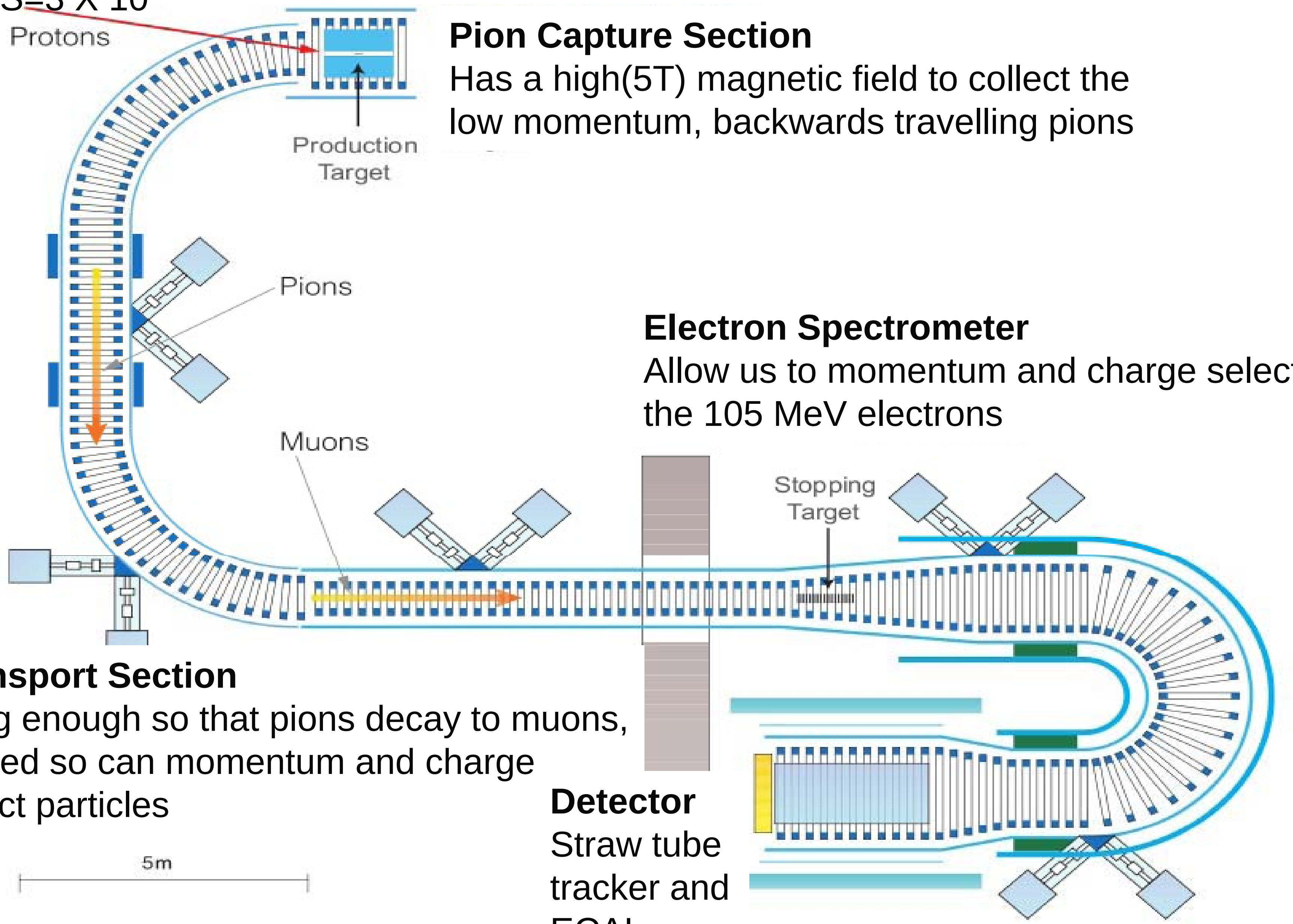
Phase-I Detector

A cylindrical drift chamber (CDC) for the $\mu \rightarrow e$ conversion search

A prototype ECAL and straw tube tracker for the background studies

Starting in 2020
Measurement in 2022
S.E.S=3 X 10^{-17}

COMET(Phase-II）



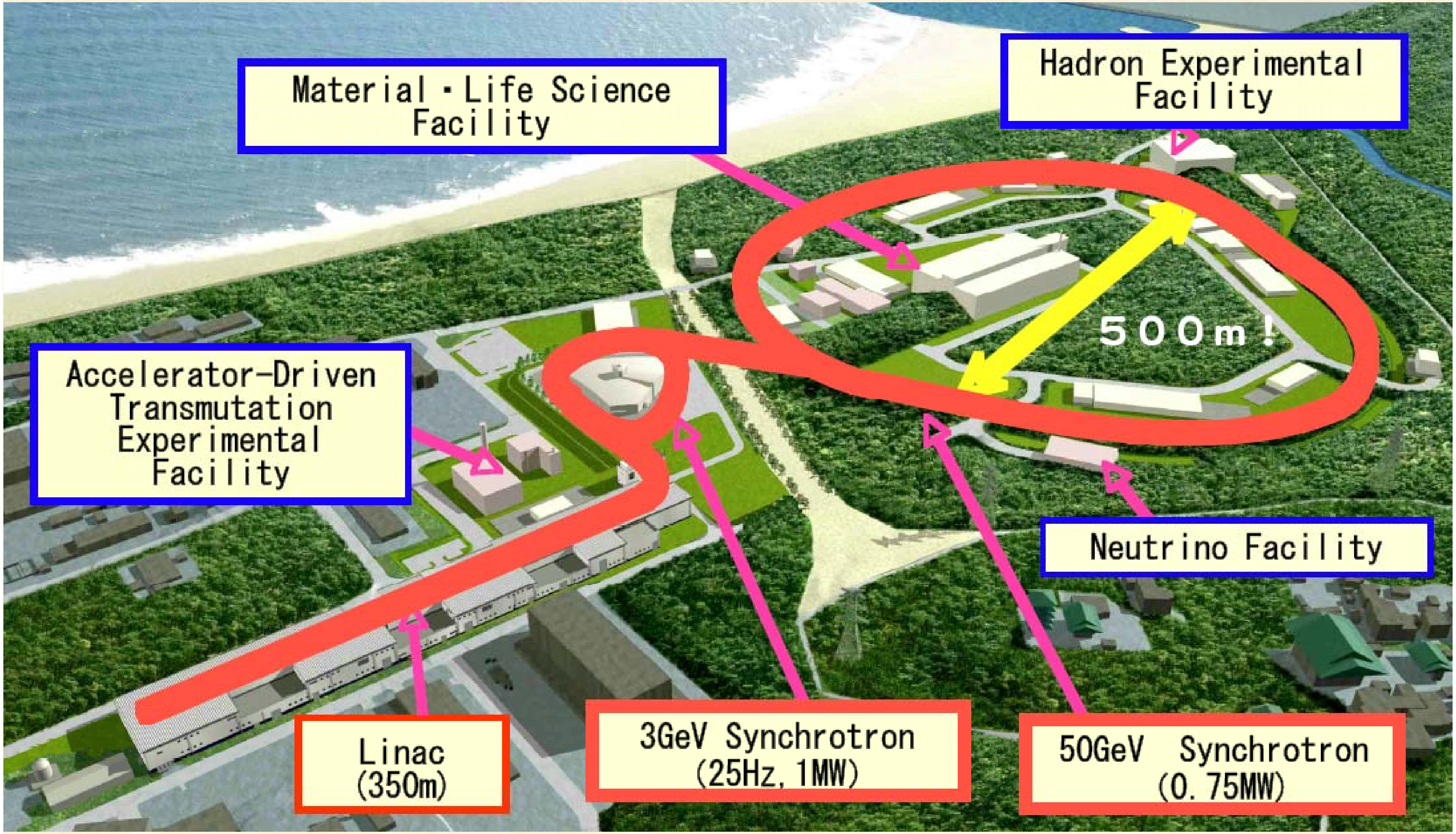
Pion Capture Section
Has a high(5T) magnetic field to collect the low momentum, backwards travelling pions

Electron Spectrometer
Allow us to momentum and charge select the 105 MeV electrons

Transport Section
Long enough so that pions decay to muons, curved so can momentum and charge select particles

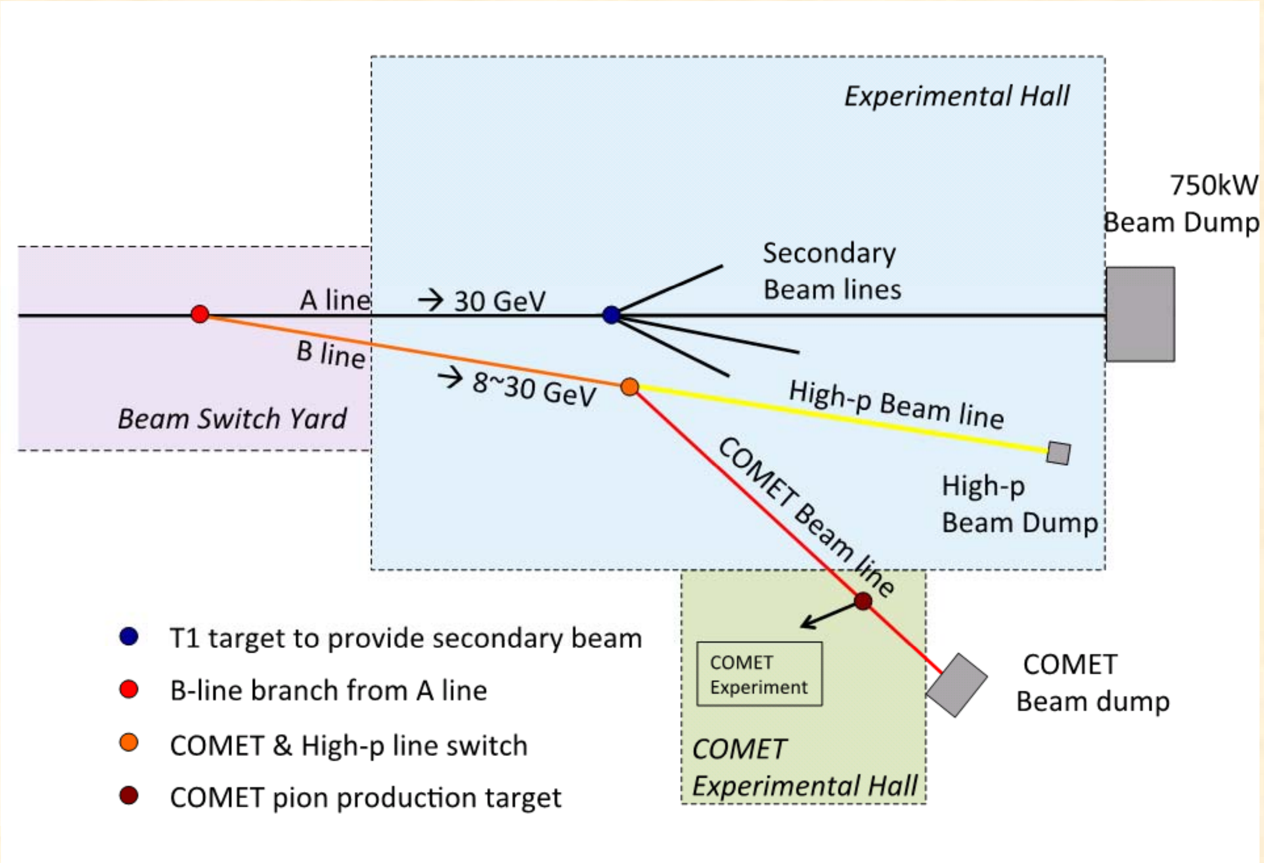
Detector
Straw tube tracker and ECAL

J-PARC layout



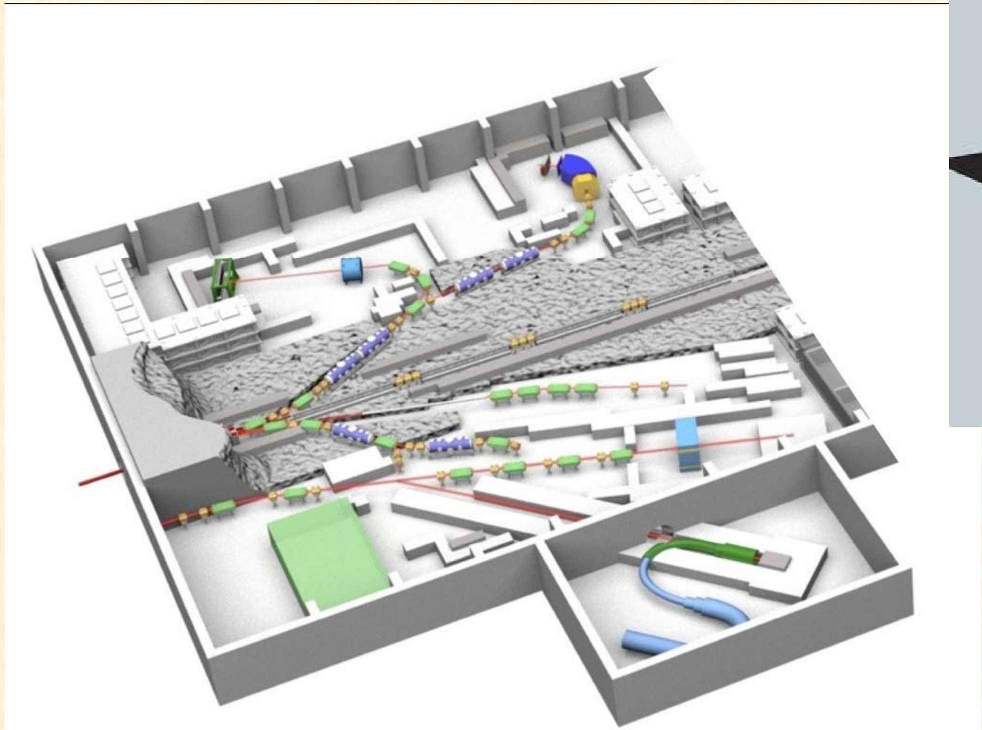
Beamline Construction

✓$35M funding, will be completed in spring 2015



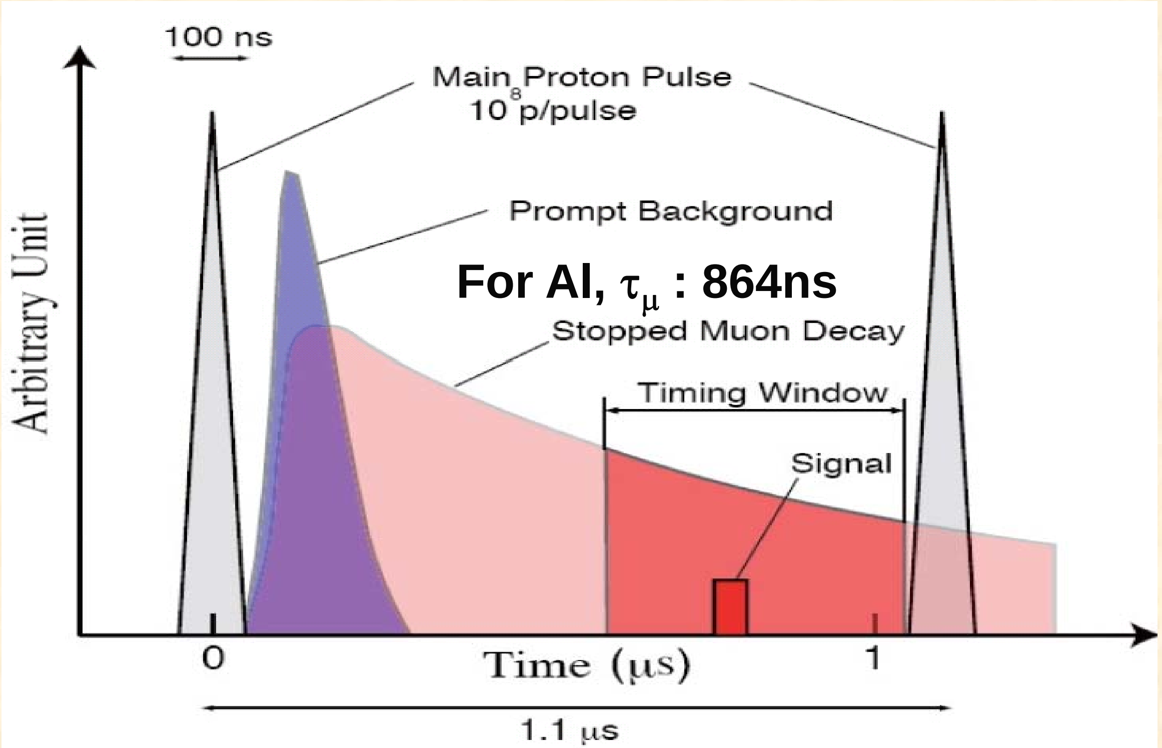
Facility Construction

✓Work already under way

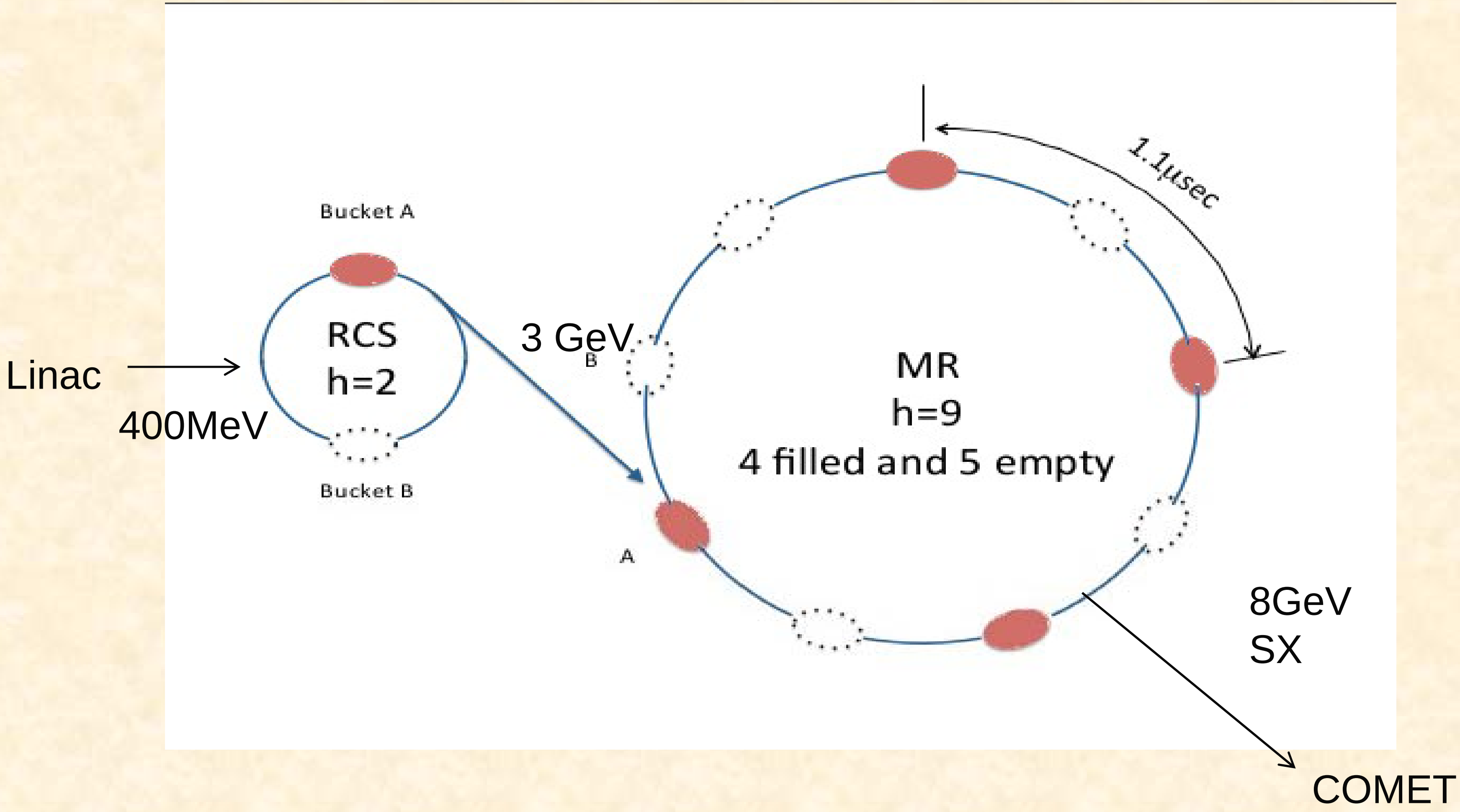


Proton Beam

- Energy: 8 GeV
- Power: 3.2 kW / 56 kW (Phase-I/Phase-II)
- Pulsed
  - – Allows us to measure in a timing window and reduce beam-related backgrounds



Proton Beam Acceleration

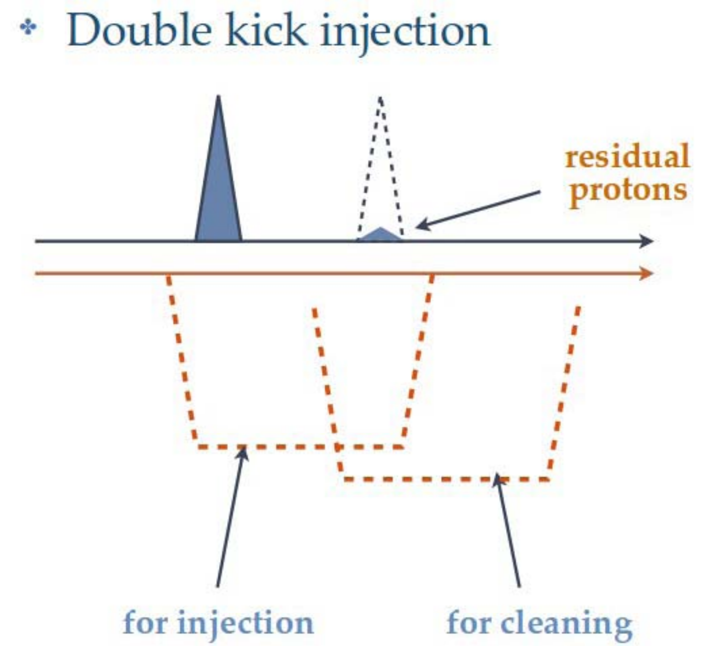


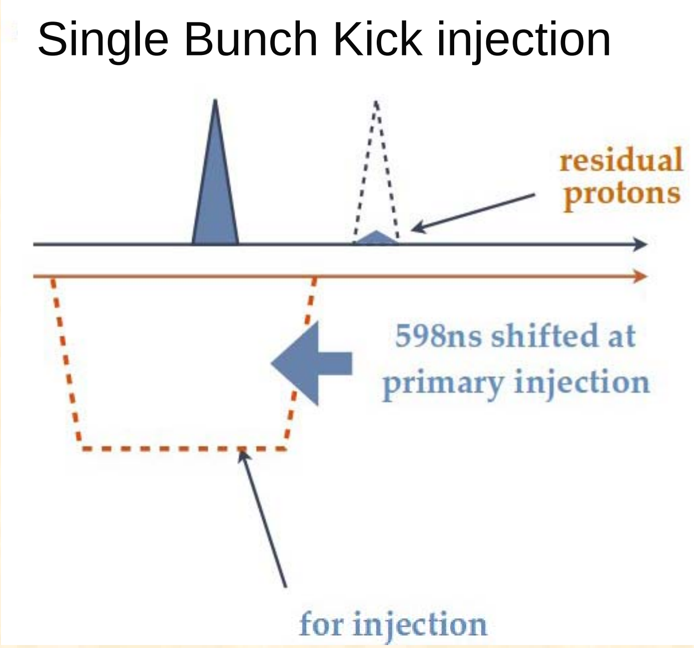
Proton Beam Extinction

- Extinction is the residual protons between pulses

$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

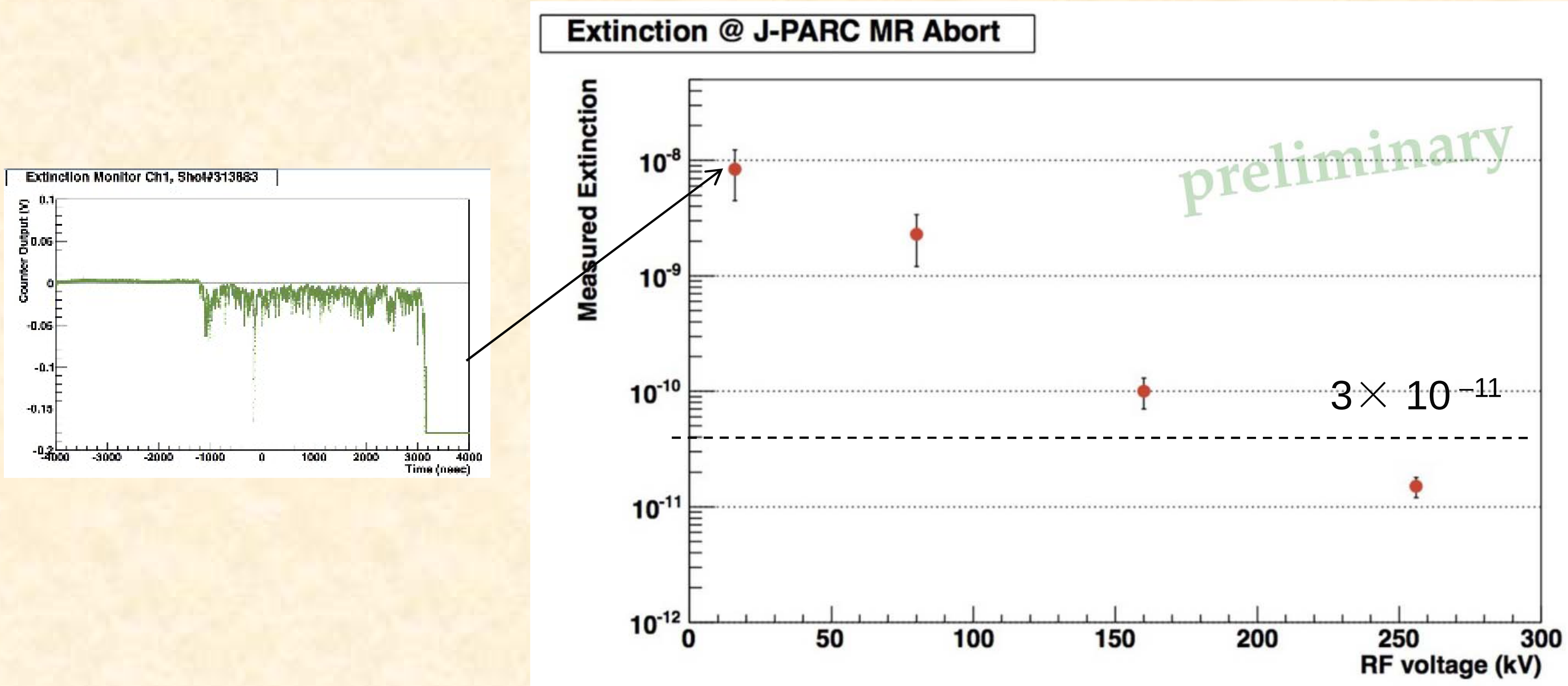
- Plan to use a novel kick injection method such that residual protons don't enter MR Pulsed





Proton Beam Extinction

- Single bunch kick injection method successfully demonstrated in June 2012 at J-PARC



Pion Production Target

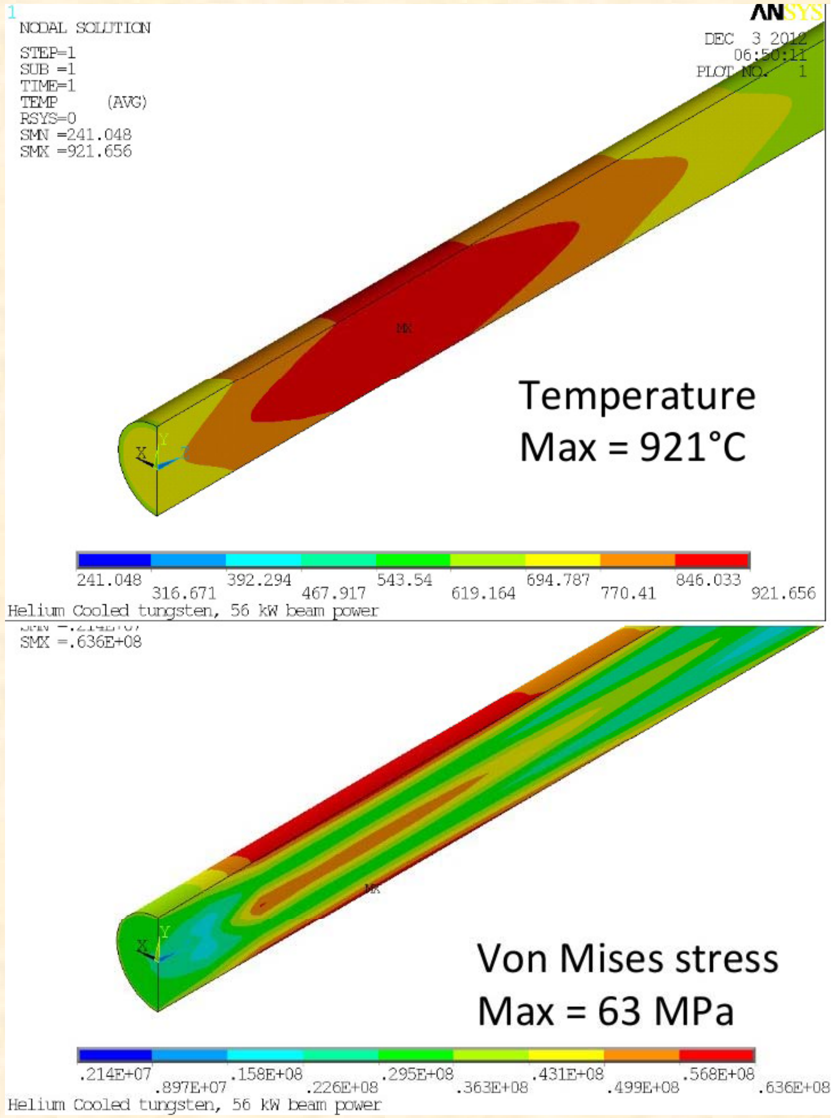
- Phase-I will use a graphite target

  -- Radiation cooling

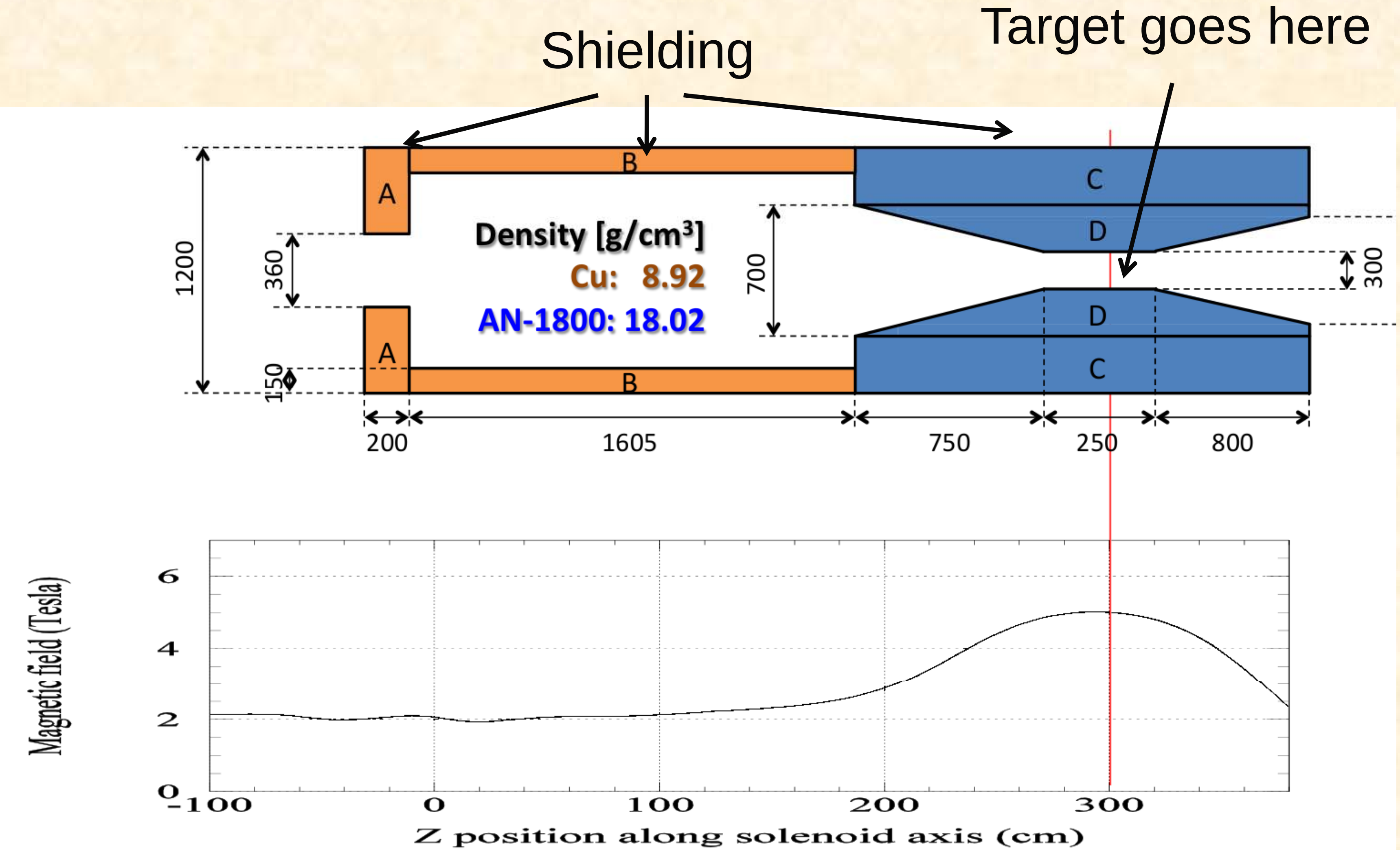
- Phase-II will move to a tungsten Target

  -- Greater pion yield

  -- Requires helium cooling



Pion Capture Solenoid

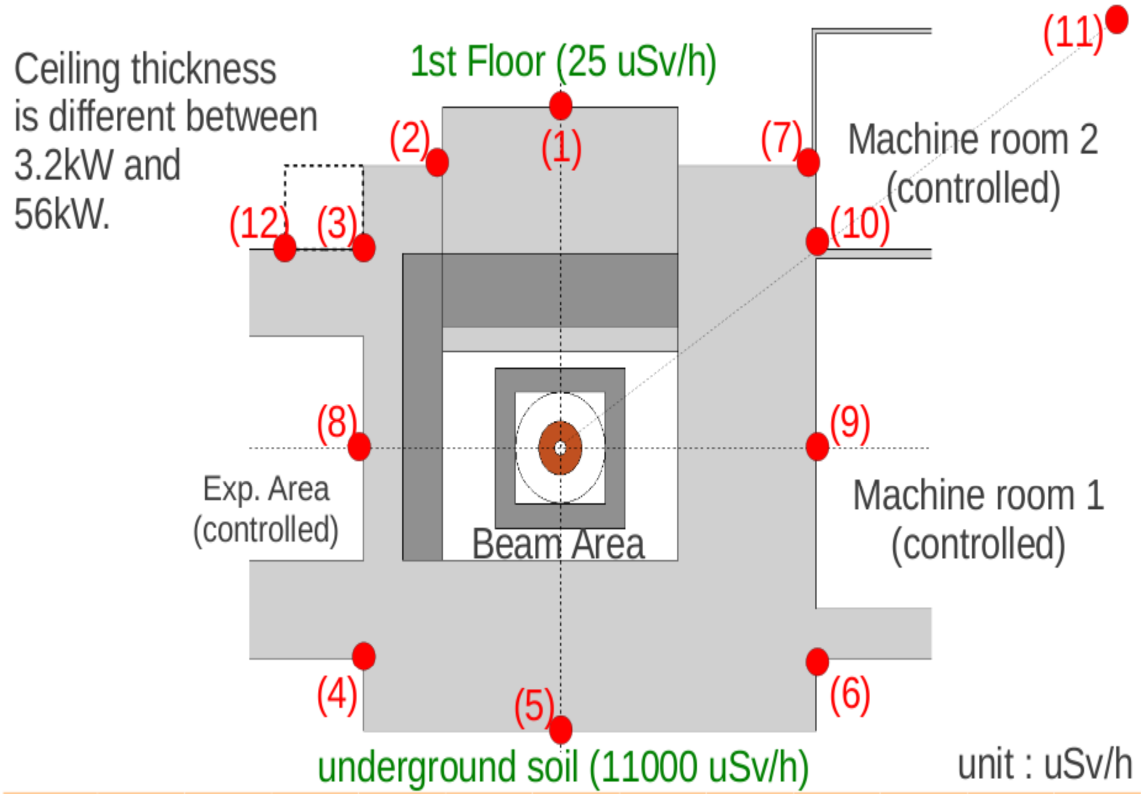


Neutron Backgrounds of Phase-I

- Regulations
  - -- <25 μSv/h at 1F
  - -- <11 mSv/h in underground soil

- Performed calculation with Moyer modle

- Will calculate with PHITS and MARS

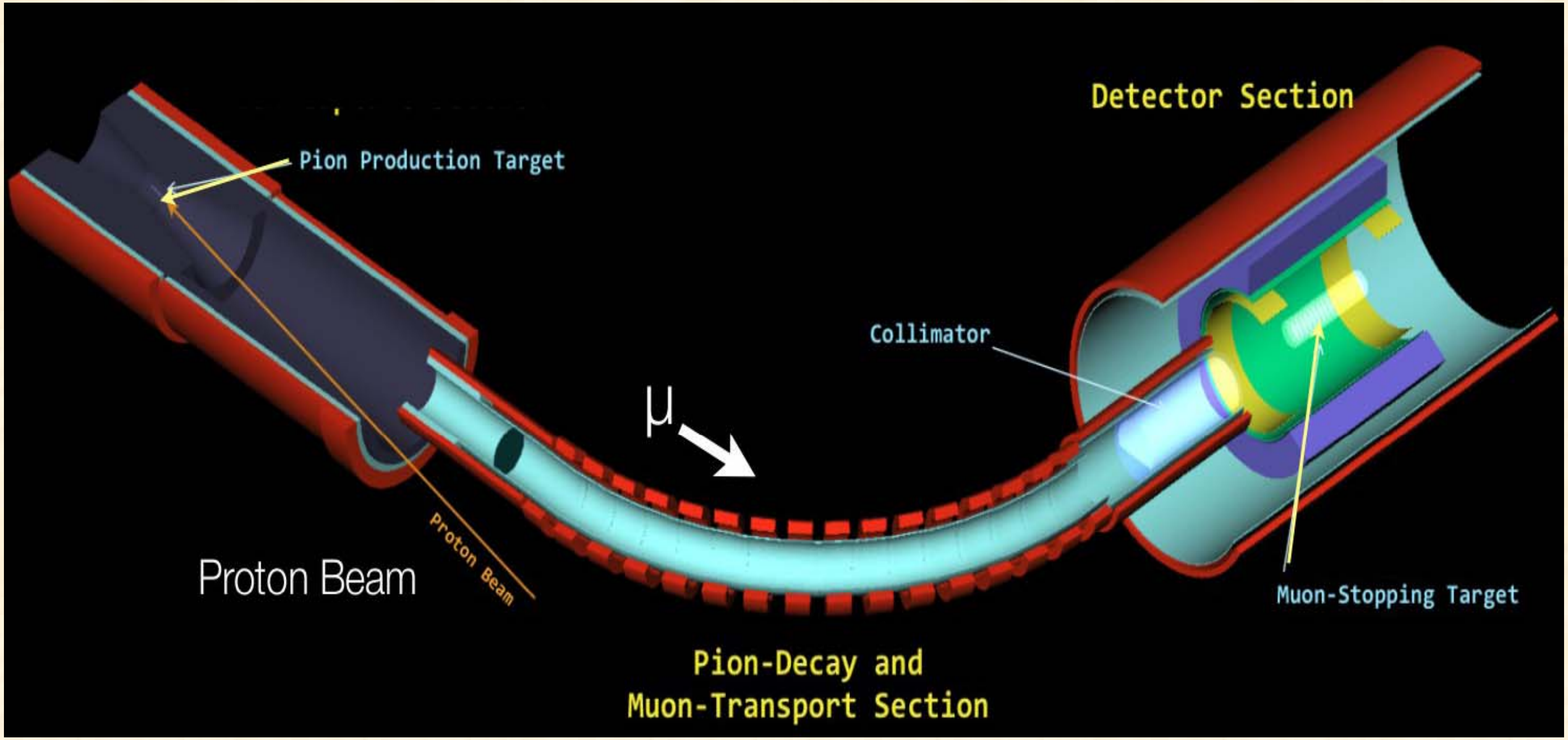


unit : uSv/h

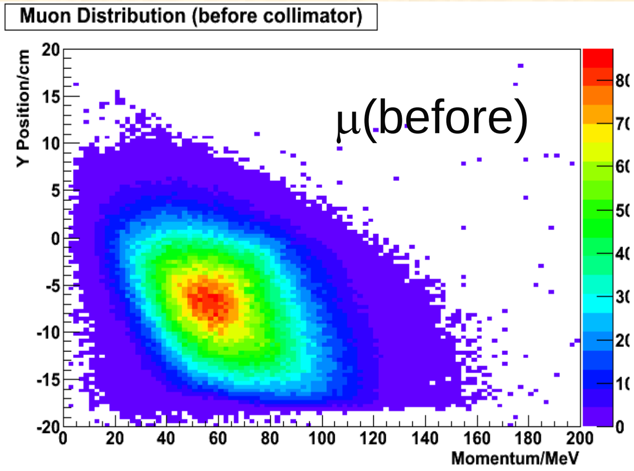
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
3.2kW	4.8	3.5	6.9	248	360	42	1.2	378	485	83	1.3	1.1
56kW	4.4	6.9	56.8	2038	2964	345	9.7	3107	3988	683	10.3	9.2

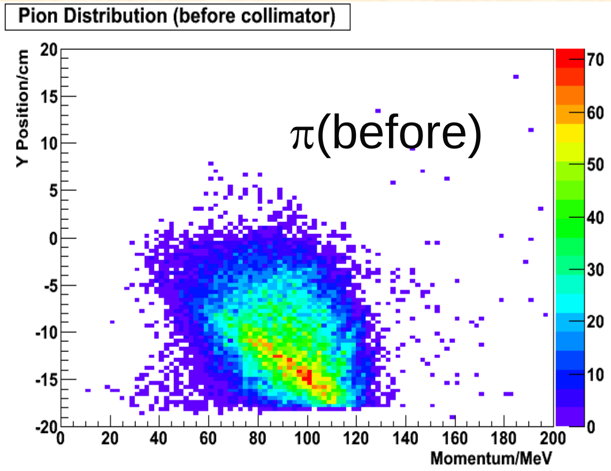
Muon Transport for Phase-I

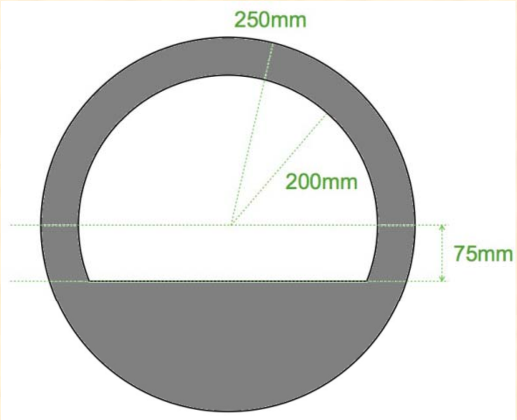
- Bending to 90 degree
- Collimator to reduce high momentum muons and all pions



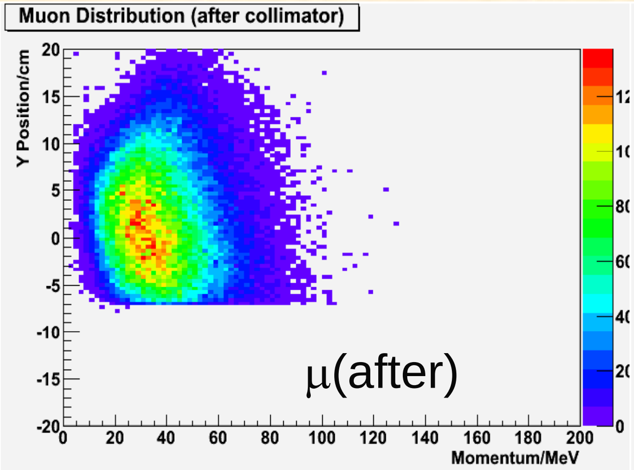
Muon Transport for Phase-I

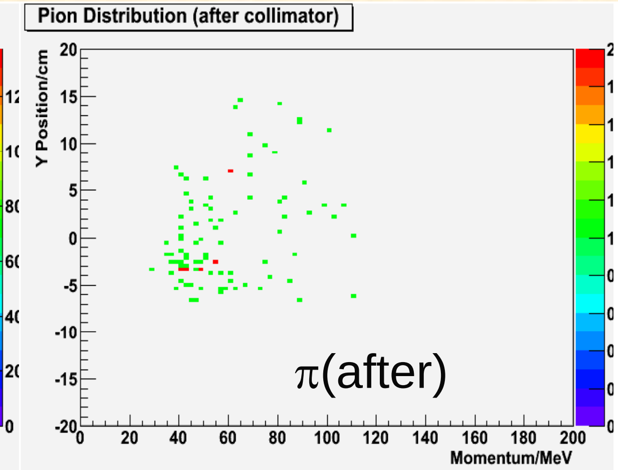


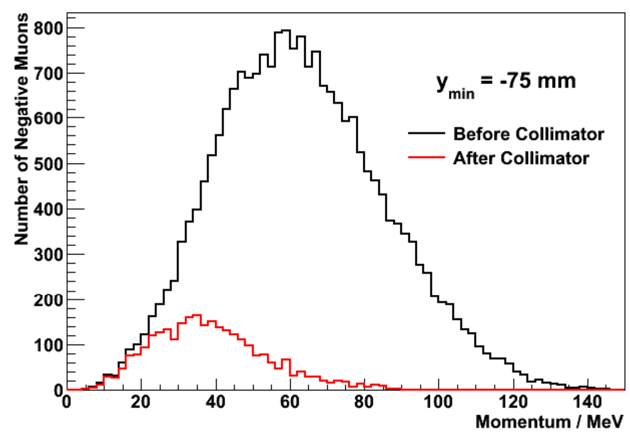




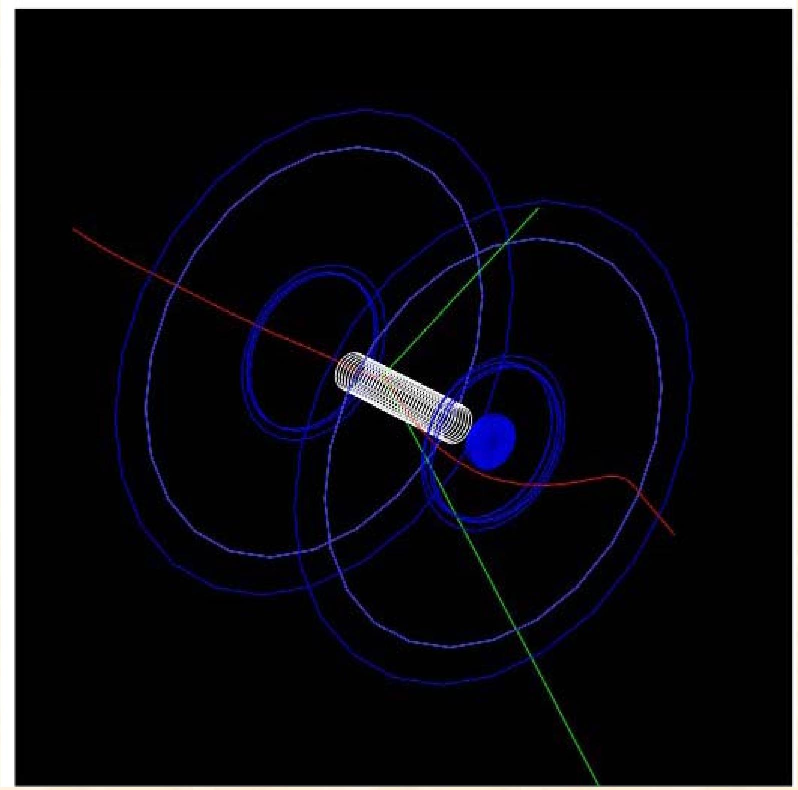
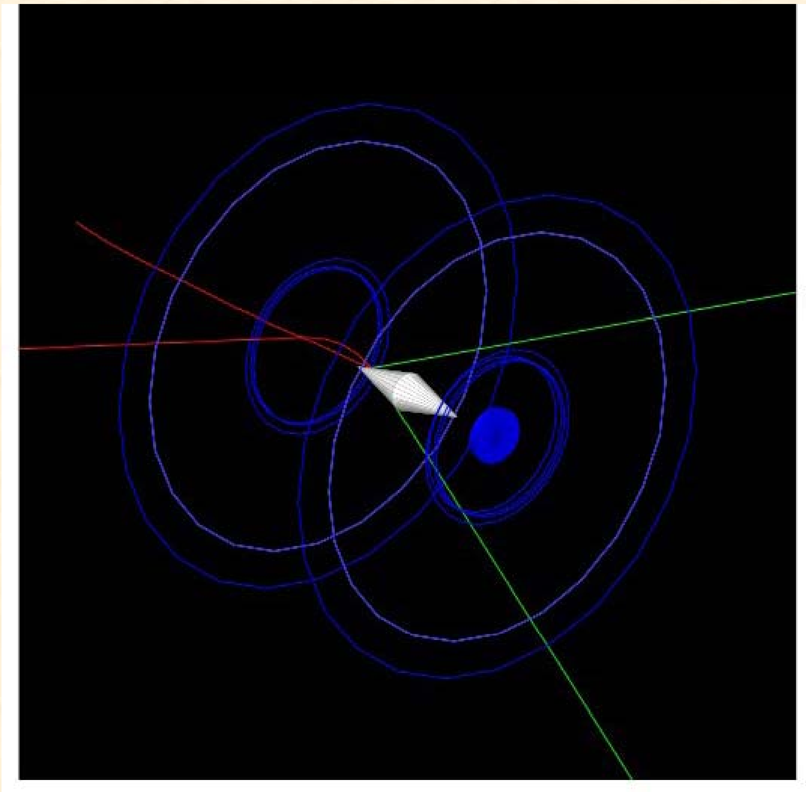
Shape of Collimator







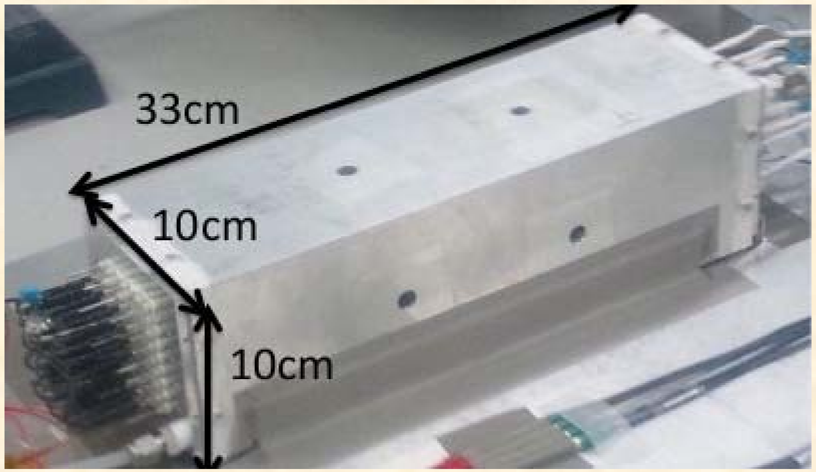
Stopping Target

- Currently 17 Al disks but also looked at double cone
- Radius:10cm, Thickness:200 μm, Length:80cm

Phase-I detector: Cylindrical Drift Chamber

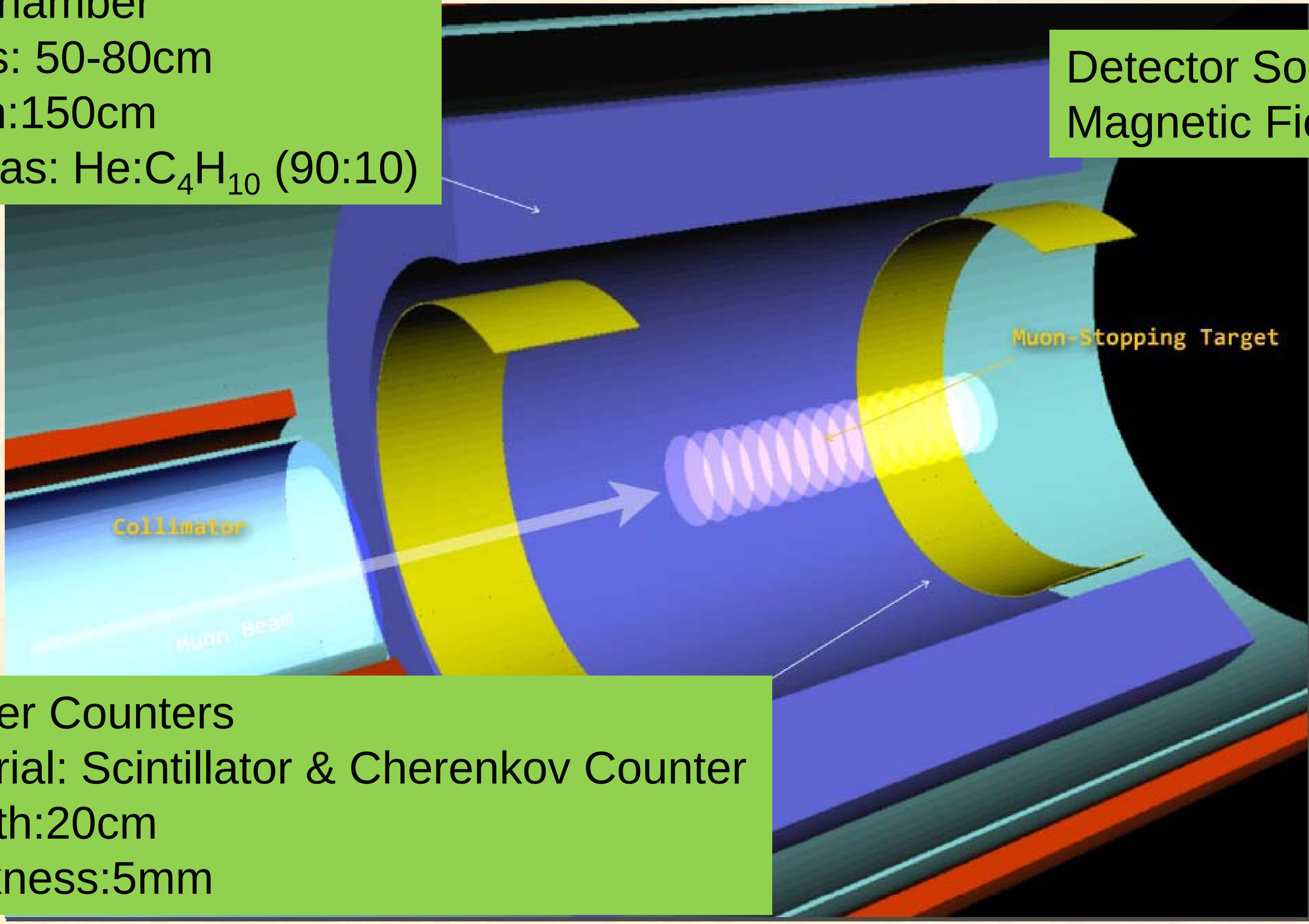
- Requirements
  - -- Gas gain $>10^5$
  - -- Position resolution(x,y) < 150 μm
  - -- Position resolution(z) <2 mm
  - -- Reduce multiple scattering for good momentum resolution
- Small prototype at Osaka shows that this is achievable
- Current simulation suggests the resolution will be ~410 keV/c



Cylindrical Drift Chamber

Drift Chamber
Radius: 50-80cm
Length:150cm
Drift Gas: He:C_4H_{10} (90:10)

Detector Solenoid
Magnetic Field:1T



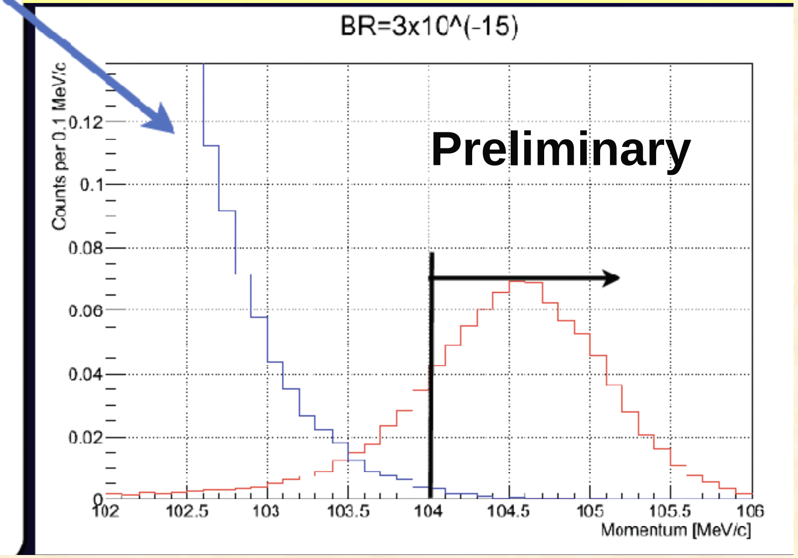
Trigger Counters
Material: Scintillator & Cherenkov Counter
Length:20cm
Thickness:5mm

Background estimation for COMET Phase I

Source of backgrounds: beam-related prompt backgrounds
beam-related delayed backgrounds
intrinsic physics backgrounds
cosmic-ray and other backgrounds

Background	estimated events
Muon decay in orbit	0.01
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.0096*
Beam electrons Muon decay in flight Pion decay in flight	< 0.00048*
Neutron induced background	~ 0*
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Electrons from cosmic ray muons	< 0.0002
Total	0.03

Assuming $B(\mu^- + Al \rightarrow e^- + Al) = 3\times10^{-15}$



*** Proportional to proton extinction factor.**

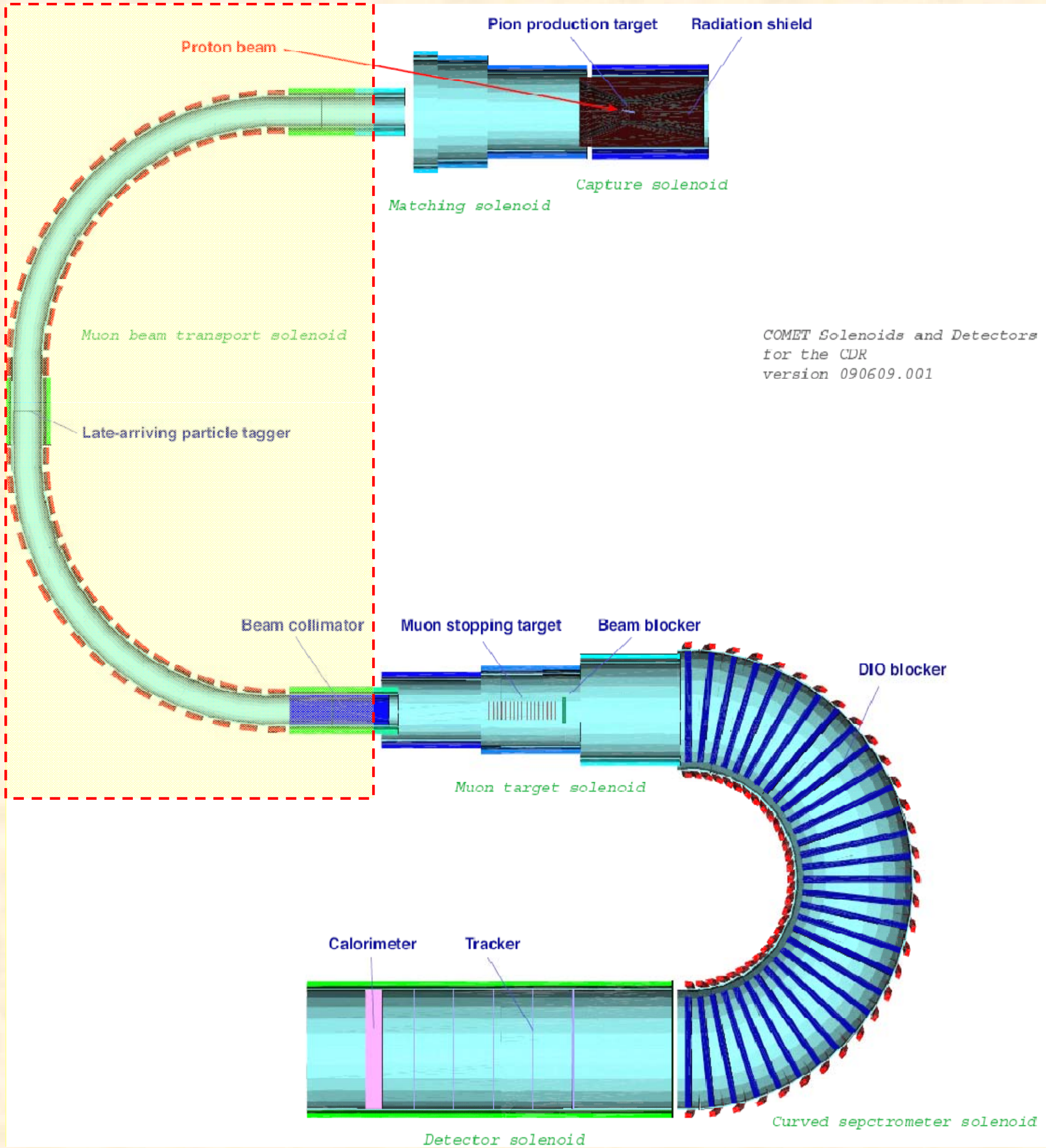
With proton extinction factor of 3×10^{-11}

Expected background rate is 0.03 @ SES of 3.1×10^{-15}

Phase-II

Muon transport system for Phase-II

- The muon transport system consistent of curved solenoids:
  - bore radius: 175 mm
  - magnetic field: 3 T
  - bending angle: 180 degrees
  - radius of curvature: 3 m
- Dispersion is proportional to bending angle
- Muon collimator after 180 degree bending
- Elimination of muon momentum >70 MeV/c



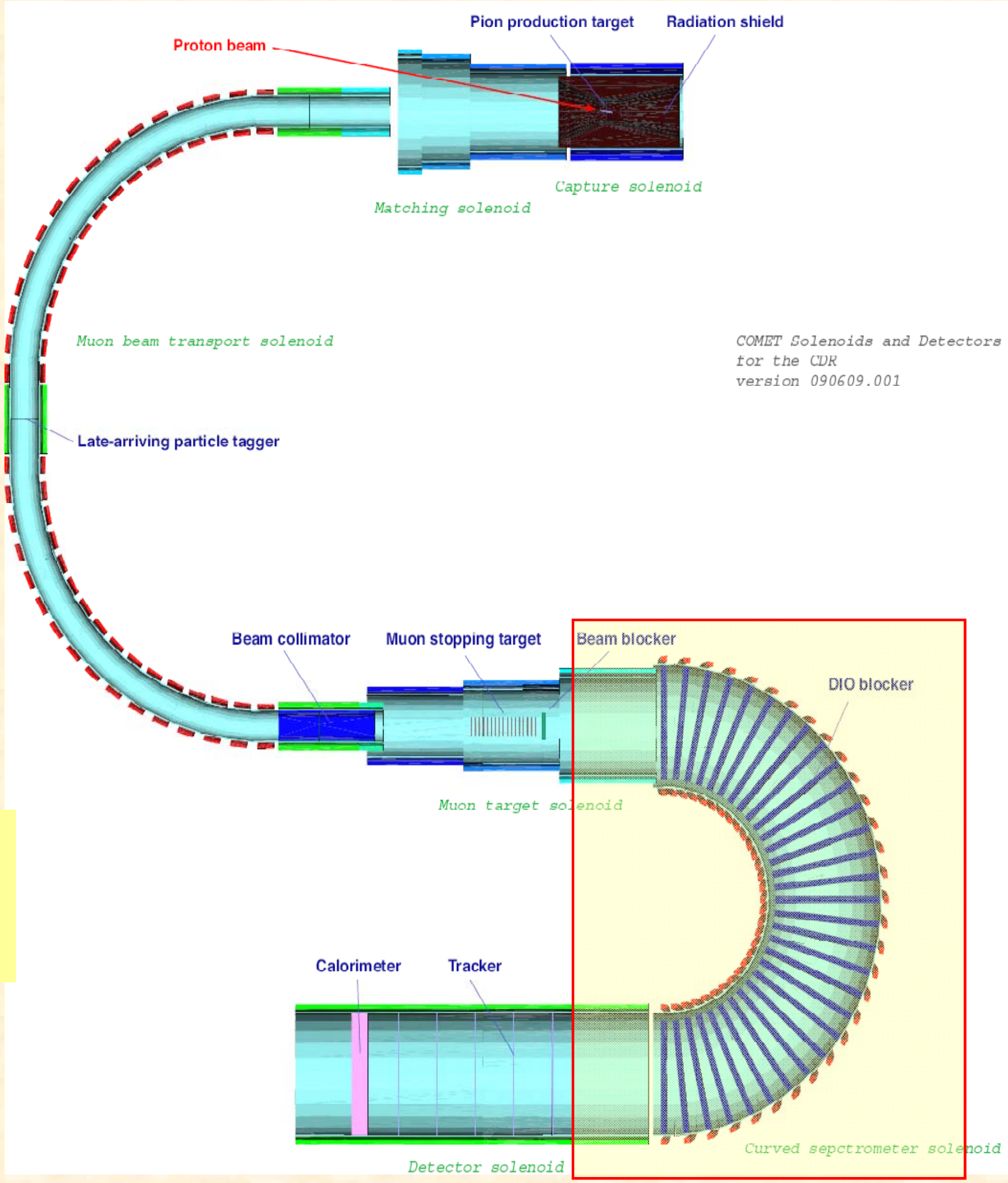
Good charge and momentum selection and no high energy muons

Electron transport section for Phase-II

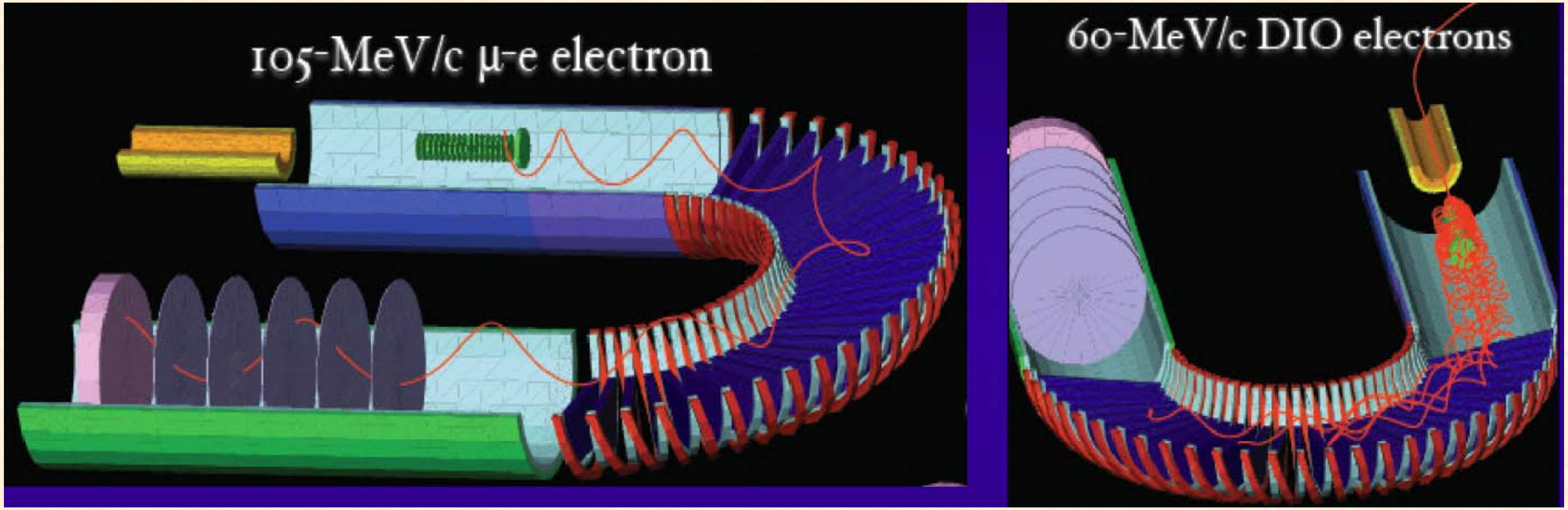
- The electron transport:
  bore: 700 mm
  magnetic field: 1 T
  bending angle: 180 degrees
- Electron momentum: 105 MeV/c
- Elimination of negative-charged particles less than 80 MeV/c
- Elimination of positive-charged particles: proton from muon capture

Reduction of detector rates
No protons in the detectors

- Detectors are placed in a straight solenoid after the curved spectrometer.



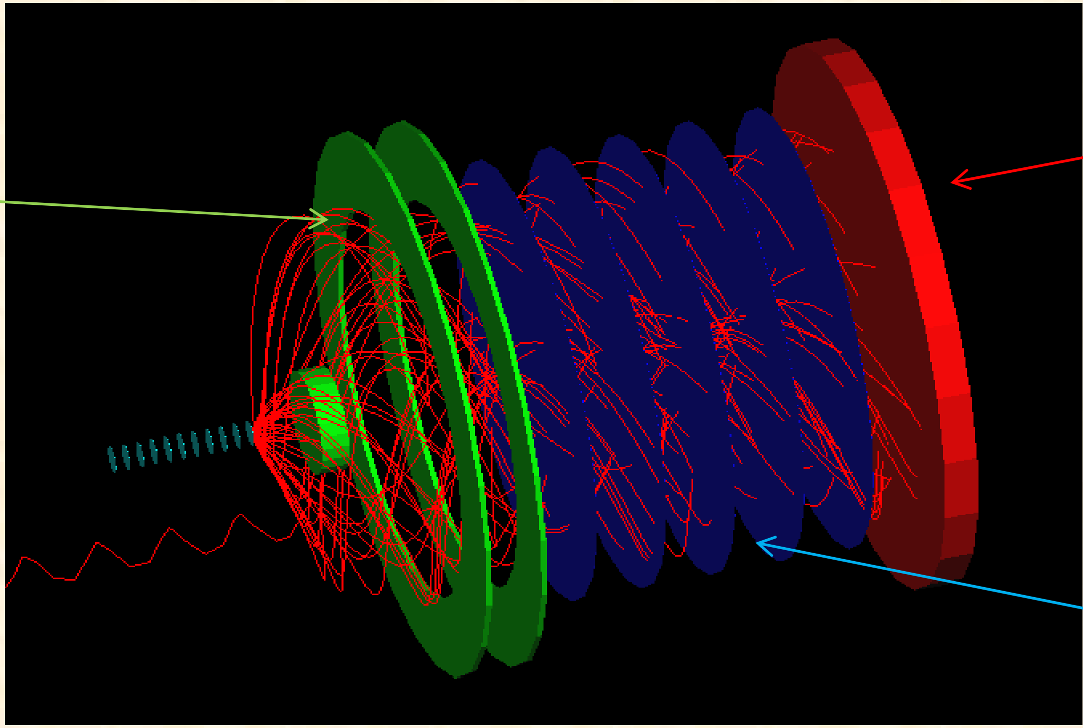
Electron spectrometer



- 1T solenoid with additional 0.17 T dipole field
- Vertical dispersion of toroidal field is able to remove electrons with P<80 MeV/c, so that reduces rate in tracker to 1kHz.

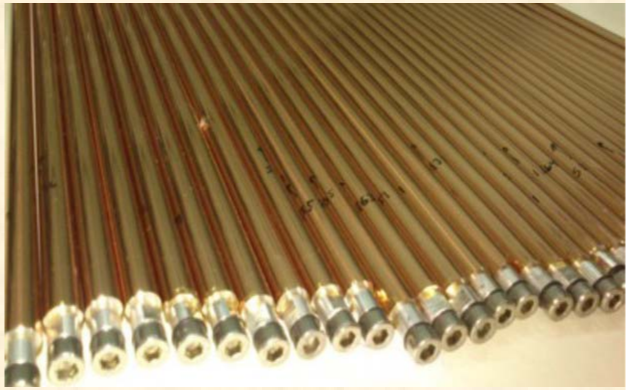
Final Phase-II Detector

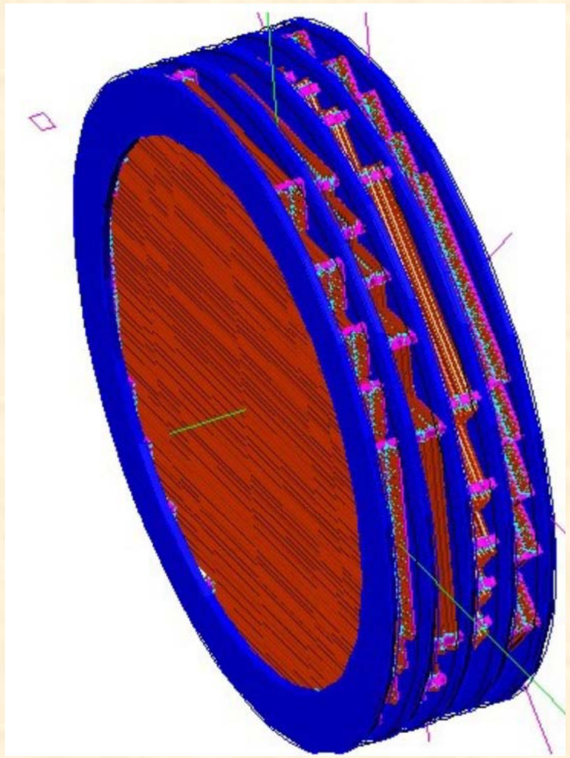
- Consist of a straw tube tracker and an electromagnetic calorimeter
- Phase-I will develop prototypes of these for background measurements



Straw Tube Tracker

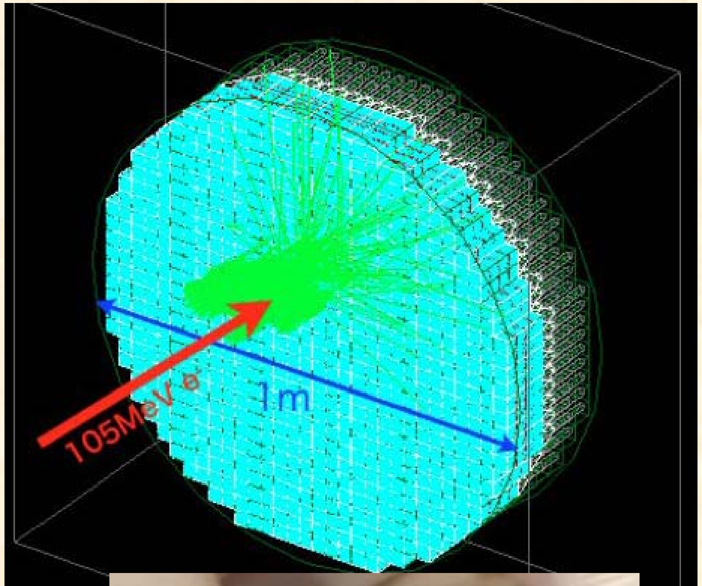
- Proposing to use the same straws developed at JINR for NA62
- COMET straws will probably be thinner to improve resolution
- KEK-JINR collaboration setup to develop the COMET straw tube tracker
- Prototype will be built with NA62 straws for detector R&D
- Current design is to have 5 super-layers each with 4 layers of straws

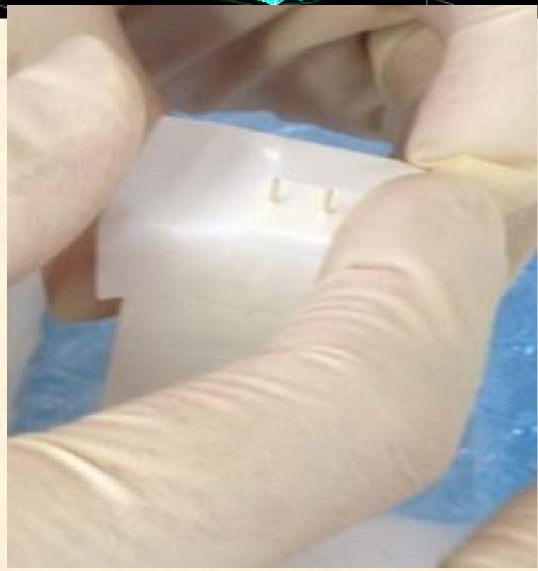




Electromagnetic Calorimeter

- Requirements
  - -- Resolution: <5% at 105MeV/c
  - -- Trigger Rate: <5 KHz
  - -- Spatial resolution(z): <1.5 cm
  - -- Response: <100ns
- Two candidate crystals
  - -- GSO and LYSO
- Beam test at KEK(28th Apr -2nd May)
  - -- Both crystals used
  - -- 7x7 crystal array
- Planning future beam test(KEK and BINP)





COMET Collaboration

The COMET Collaboration

R. Akhmetshin, A. Bondar, L. Epshteyn, G. Fedotovich, D. Grigoriev, V. Kazanin, A. Ryzhenenkov, D. Shemyakin, Yu. Yudin
Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

R. Palmer
Department of Physics, Brookhaven National Laboratory, USA

Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto, Y. Makida, T. Mibe, S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, N. Saito, K. Sasaki, M. Sugano, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida, A. Yamamoto, M. Yamanaka, M. Yoshida, Y. Yoshii, K. Yoshimura
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Yu. Bagaturia
Ilia State University (ISU), Tbilisi, Georgia

P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. Pasternak, Y. Uchida
Imperial College London, UK

P. Sarin, S. Umasankar
Indian Institute of Technology Bonbay, India

Y. Iwashita
Institute for Chemical Research, Kyoto University, Kyoto, Japan

V.V. Thuan
Institute for Nuclear Science and Technology, Vietnam

H.-B. Li, C. Wu, Y. Yuan
Institute of High Energy Physics (IHEP), China

A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trekov, N. Tsverava
Institute of High Energy Physics of I.Javakhishvili State University (HEPI TSU), Tbilisi, Georgia

S. Dymov, P. Evtoukhovich, V. Kalinnikov, A. Khvedelidze, A. Kulikov, G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsmalaidze, E. Velicheva
Joint Institute for Nuclear Research (JINR), Dubna, Russia

M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky
Institute for Theoretical and Experimental Physics (ITEP), Russia

T. Ota
Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), Munchen, Germany

Y. Mori, Y. Kuriyama, J.B. Lagrange

4

Kyoto University Research Reactor Institute, Kyoto, Japan

C.V. Tao
College of Natural Science, National Vietnam University, Vietnam

M. Aoki, I.H. Hasim T. Hayashi, Y. Hino, T. Iwami, T. Itahashi, S. Ito, Y. Kuno*, Y. Matsumoto, T.H. Nam, H. Sakamoto, A. Sato, N.D. Thong, N.M. Truong, K. Yai
Osaka University, Osaka, Japan

M. Koike, J. Sato
Saitama University, Japan

D. Bryman
University of British Columbia, Vancouver, Canada

S. Cook, R. D'Arcy, A. Edmonds, M. Lancaster, M. Wing
University College London, UK

J.F. Solehan, W.A. Tajuddin
University of Malaya, Malaysia

R.B. Appleby, W. Bertsche, M. Gersabeck, H. Owen, C. Parkes, G. Xia
University of Manchester, UK

F. Azfar, M. John
University of Oxford, UK

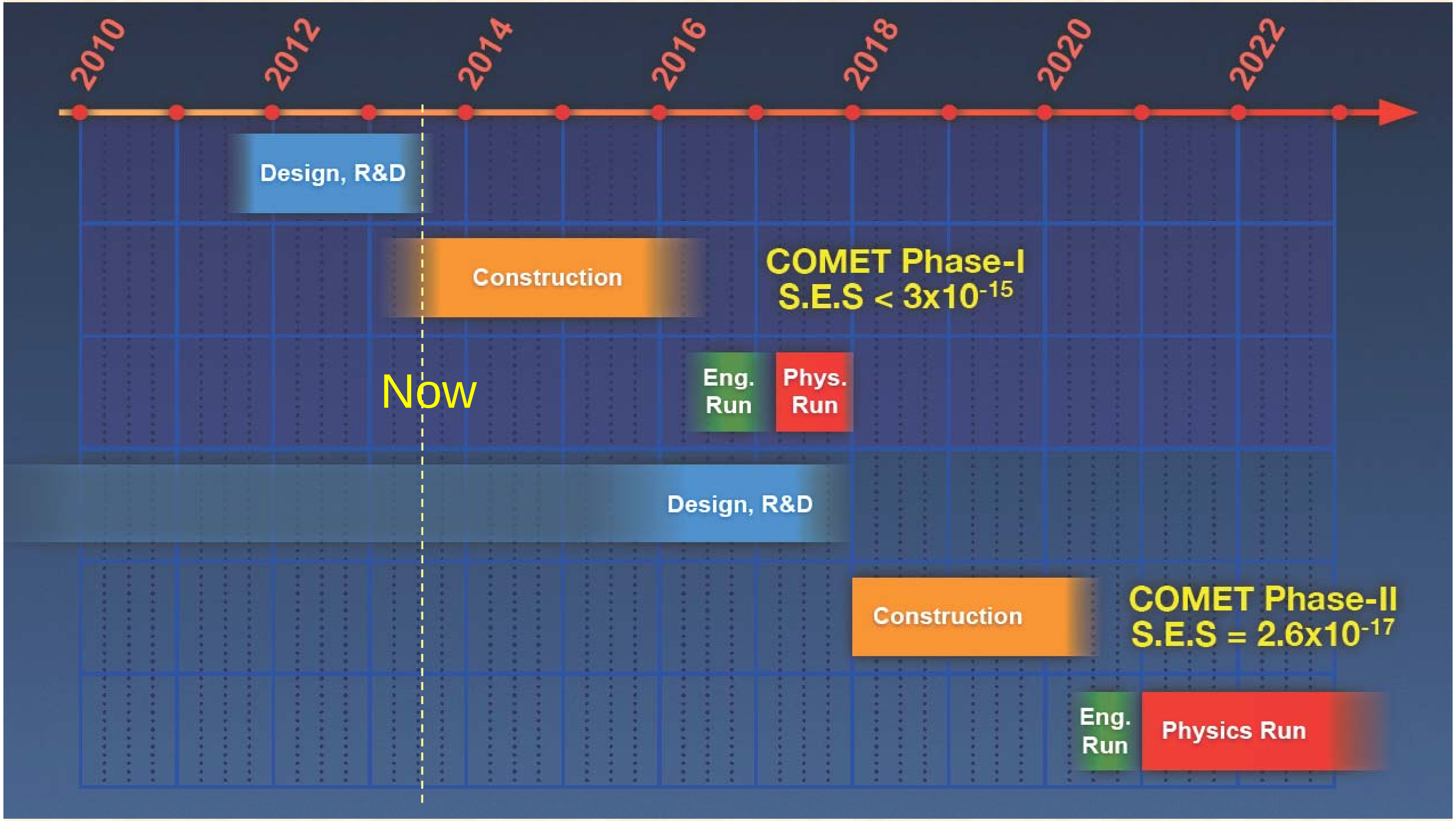
Md. I. Hossain
University Technology Malaysia

T. Numao
TRIUMF, Canada

* Contact Person

117 collaborators
27 institutes
12 countries

Timeline



2010
2012
2014
2016
2018
2020
2022
Design, R&D
Construction
COMET Phase-I
S.E.S < 3x10-15
Now
Eng. Run
Phys. Run
Design, R&D
Construction
COMET Phase-II
S.E.S = 2.6x10-17
Eng. Run
Physics Run

Summary

We all are passionately following LHC in their direct searches for EW symmetry breaking remnants and new physics at the TeV-scale energy frontier

Probing new physics orders of magnitude beyond that scale and helping to figure out possible TeV-scale new physics requires to work hard on the intensity and precision frontiers

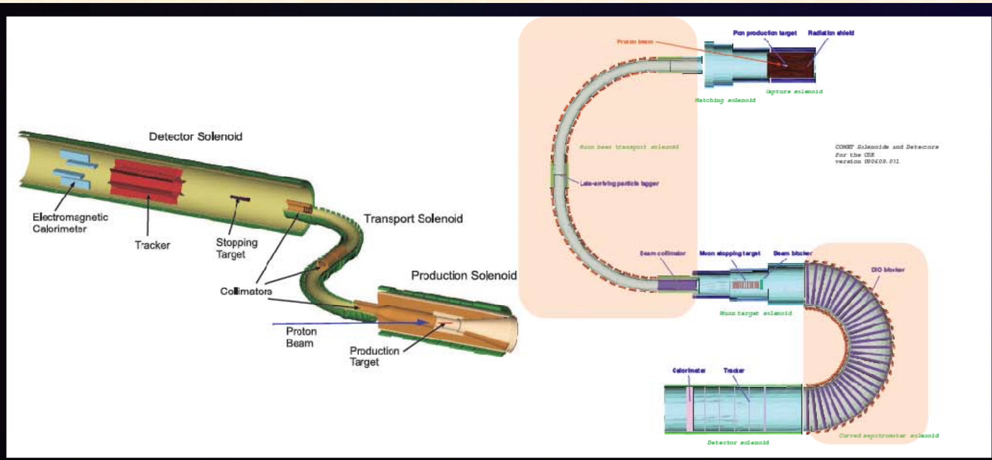
Charged leptons offer an important spectrum of possibilities:

- ✓ **CLFV has SM-free signal for New Physics at low energy and complementary to LHC physics.**
- ✓ **COMET at J-PARC is aiming at S.E. sensitivity of 3×10^{-17}.**
- ✓ **The COMET Phase-I is aiming at S.E. sensitivity of 3×10^{-15} (in 2016).**
- ✓ **Design and R&D is well underway**
- ✓ **Funding secured and construction started for COMET Phase-I**

Thanks!

Back up slides

Comparison: COMET vs. Mu2e



	Mu2e@FNAL	COMET@J-PARC
muon beamline	S-shape	C-shape
electron spectrometer	Straight solenoid	Curved solenoid

Selection of low momentum muons

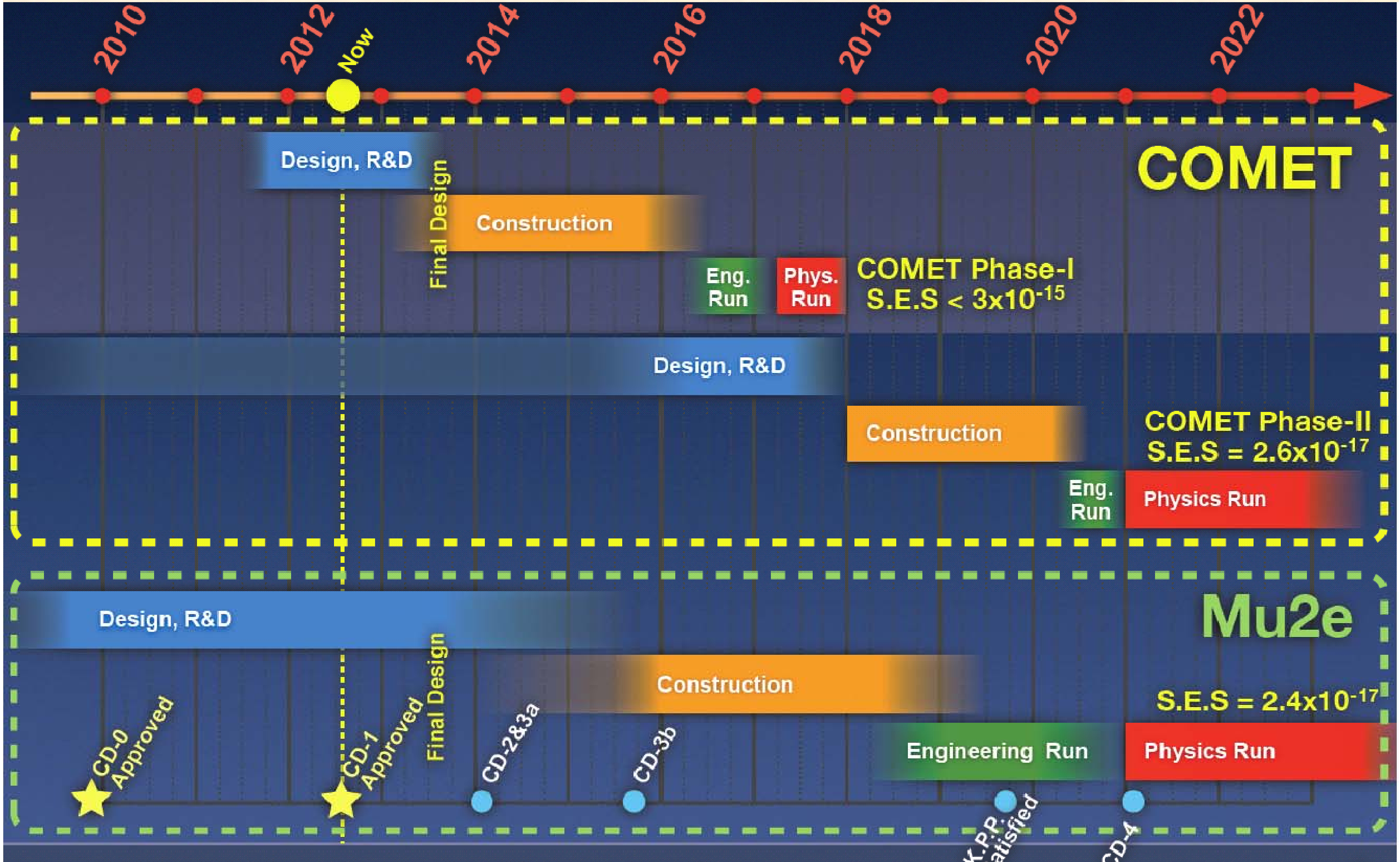
eliminate background from muon decay in flight

Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

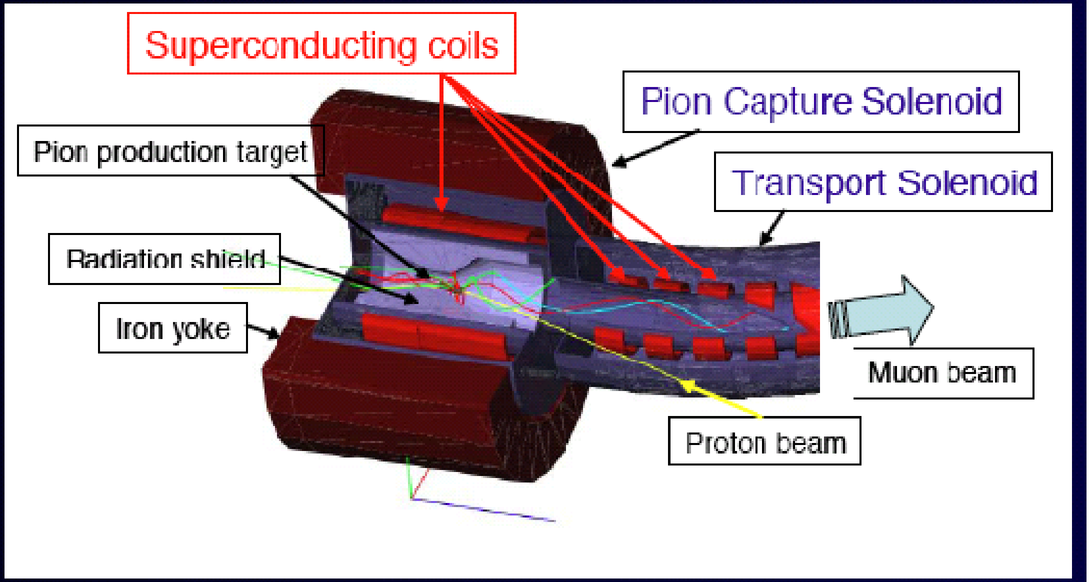
eliminate low energy events to make the detector quiet.

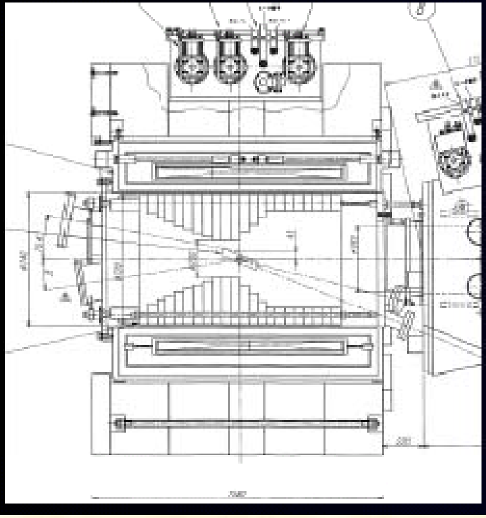
Schedules for COMET and Mu2e

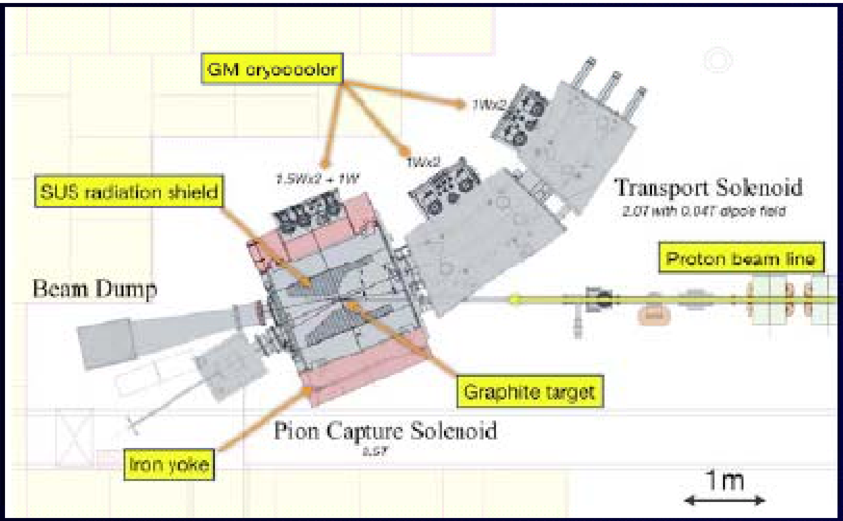


Pion Capture System at MuSIC@Osaka-U

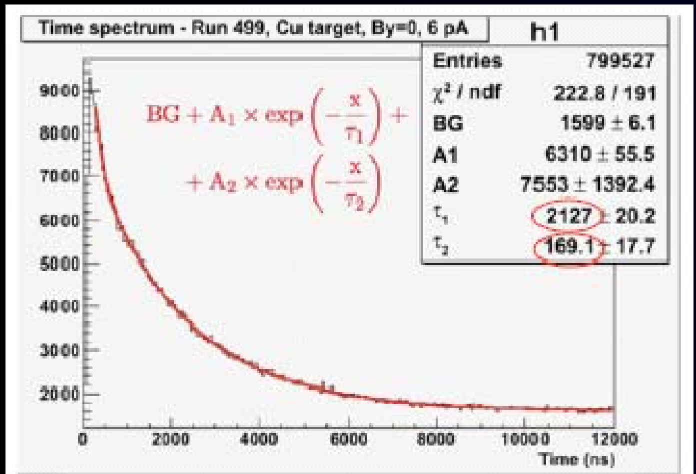
- Pion Capture SC Solenoid :
  - 3.5 T at central
  - diameter 740mm
  - SUS radiation shield
- Transport SC solenoids
  - 2 T magnetic field
  - 8 thin solenoids
- Graphite target for pion production



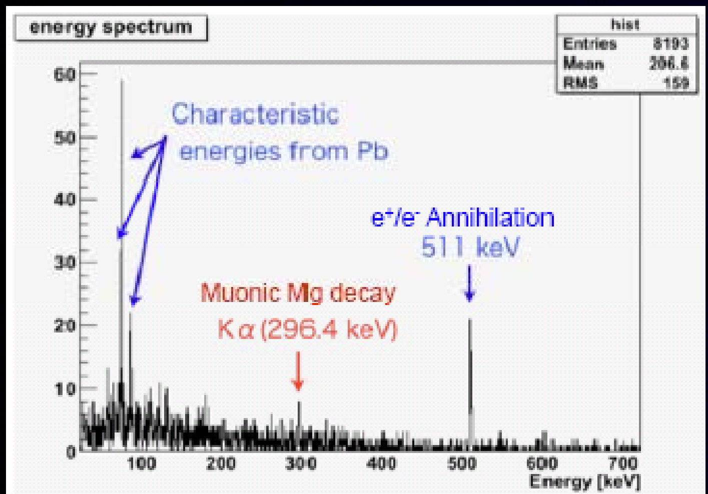




MuSIC Beam Test in 2011



	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



preliminary

MuSIC muon yields

μ^+ : 3×10^8/s for 400W

μ^- : 1×10^8/s for 400W

cf. 10^8/s for 1MW @PSI
Req. of $\times10^3$ achieved...

Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (6 pA)