10th Anniversary J-PARC Symposium 2019

The COMET experiment: Search for muon-to-electron conversion

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On behalf of the COMET Collaboration

The 3rd J-PARC Symposium (J-PARC2019)

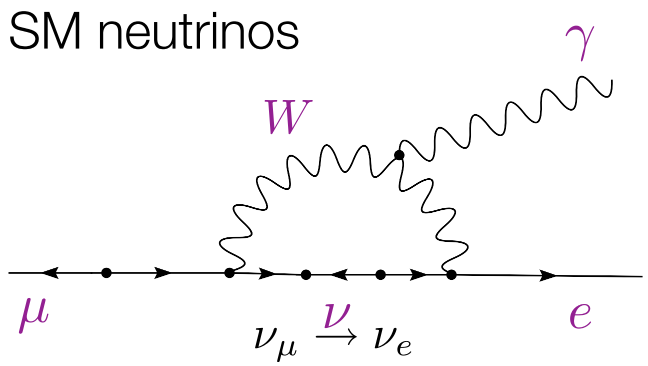
26th Sep., 2019, Tsukuba, Japan

Charged Lepton Flavor Violation in Muon

3 Major Processes

- $\mu^+ \rightarrow e^+ \gamma$
- $\mu^+ \rightarrow e^+ e^+ e^-$
- $\mu^- N \rightarrow e^- N$ (μ-e conversion)

SM neutrinos



$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W{}^2} \right|^2$$

≲ 10^-54

due to small mass ratio of neutrino to weak boson

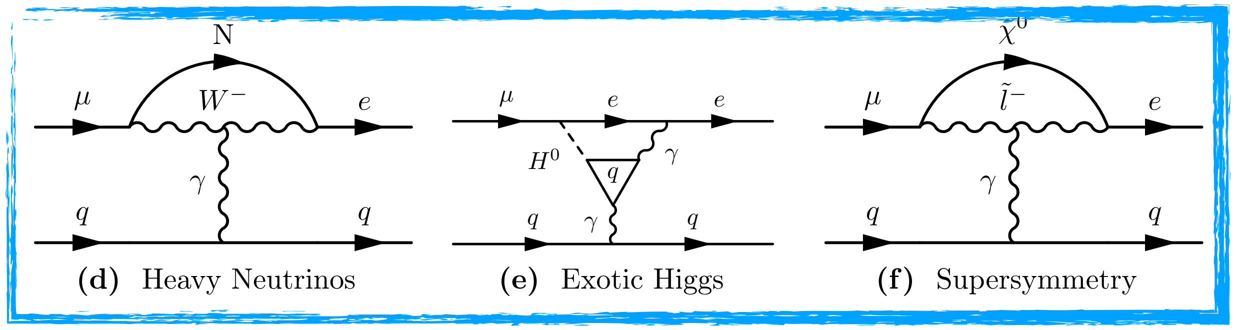
Since the SM contribution is negligibly small,

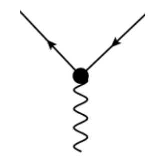
Observation of CLFV indicates a clear evidence of **New Physics**.

CLFV and New Physics

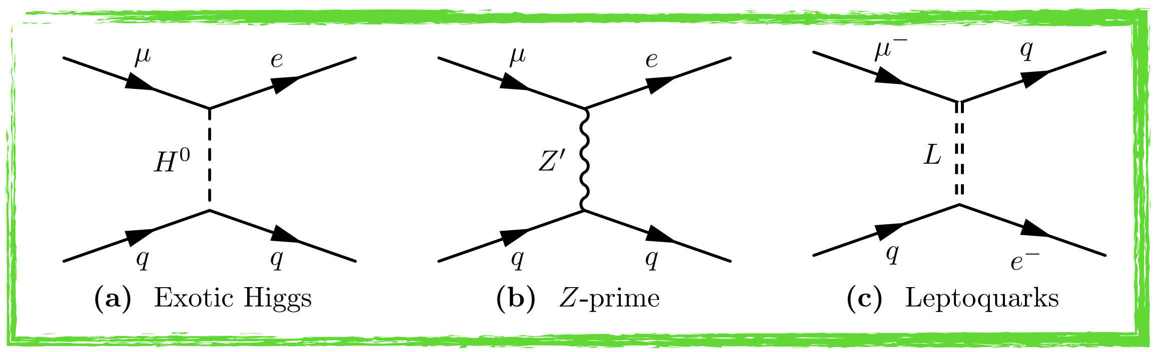
New Physics contributions

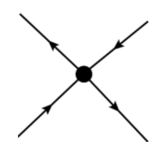
Photonic (dipole) term





4-fermion (contact) term





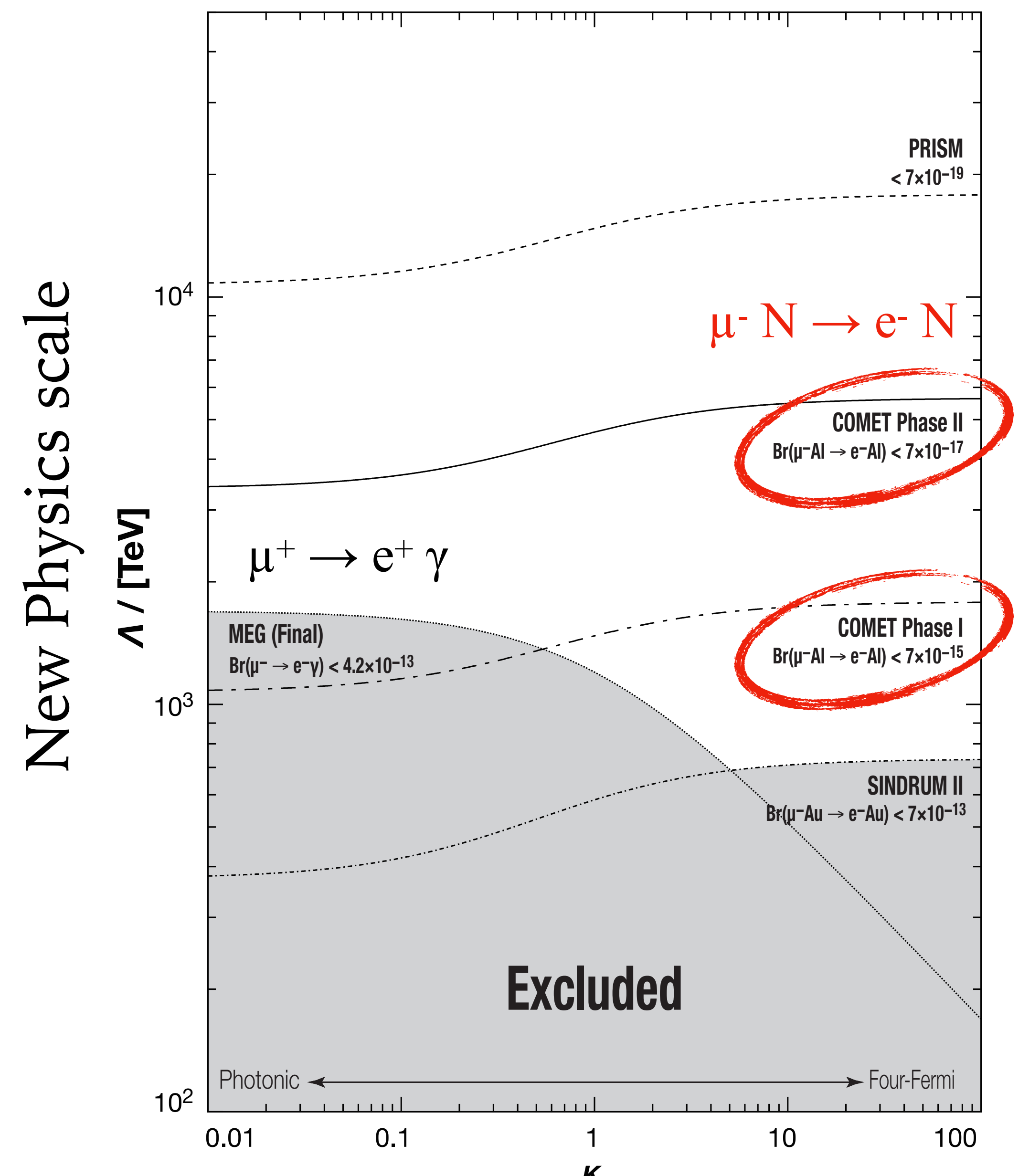
- ✓ *Different measurements are complementary.*
- ✓ *μ-e conversion is sensitive to both contributions.*

We can explore NP scale beyond 1000 TeV !!

Effective Lagrangian

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$

Photonic 4-fermion

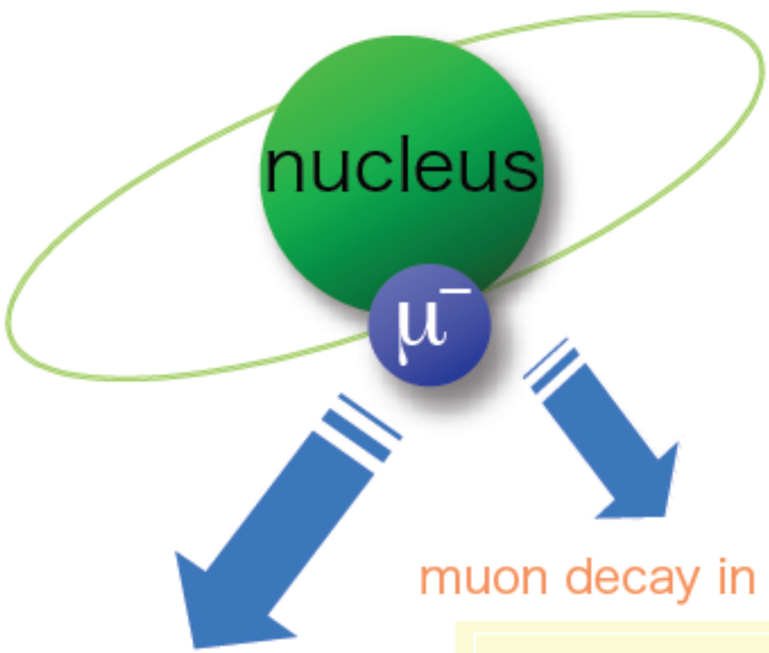


Photonic ← → 4-fermion

Muon-to-electron conversion

Fate of muonic atom

1s state in a muonic atom



muon decay in orbit (39% in Al)

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

nuclear muon capture (61% in Al)

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

μ-e conversion

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

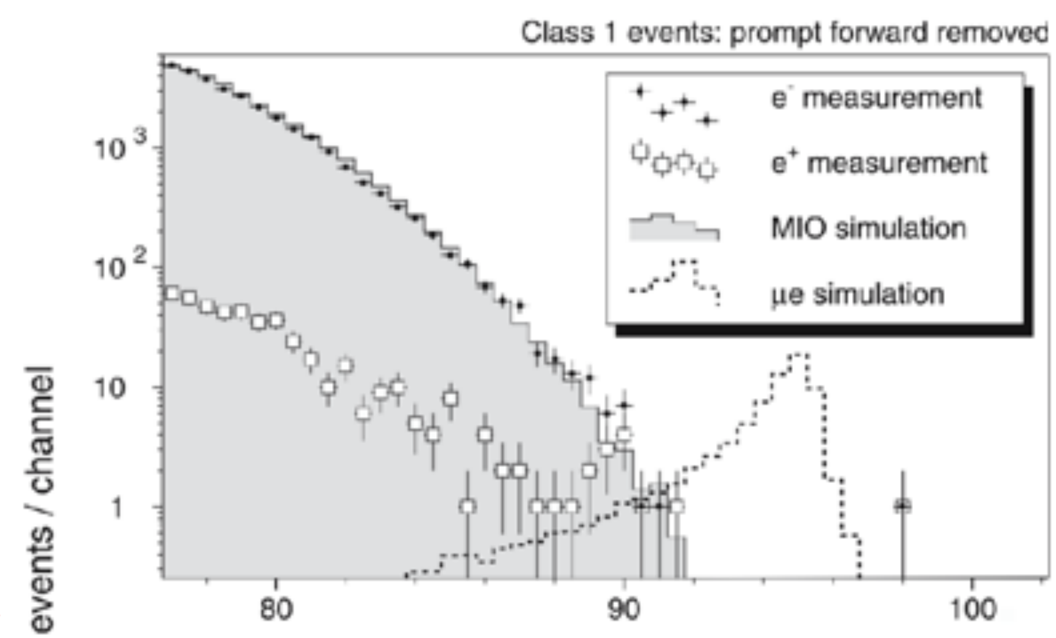
single mono-energetic electron

$$E_{\mu e} = m_\mu - B_\mu - E_{\mathrm{rec}} = 104.97 \text{ MeV for Al}$$

Current upper limit

SINDRUM-II, EPJ C47, 337 (2006)

Br(μ^- Au → e^- Au) < **7 x 10^{-13}**



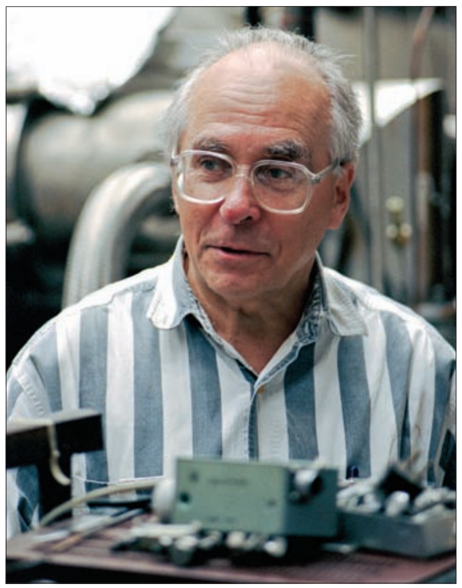
Concept of
modern μ-e conversion search

Muon Source

BG Rejection

Ancestor of COMET/Mu2e

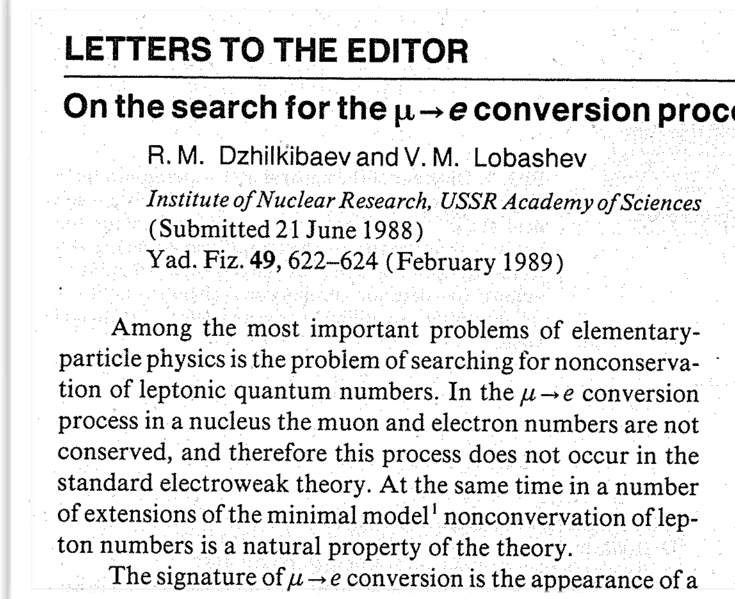
Vladimir Lobashev 1934–2011



Vladimir Lobashev. (Image credit: INR.)

CERN Courier 51, 8 (2011)

Yad. Fiz. 49, 622 / Sov. J. Nucl. Phys. 49, 384 (1989)



LETTERS TO THE EDITOR

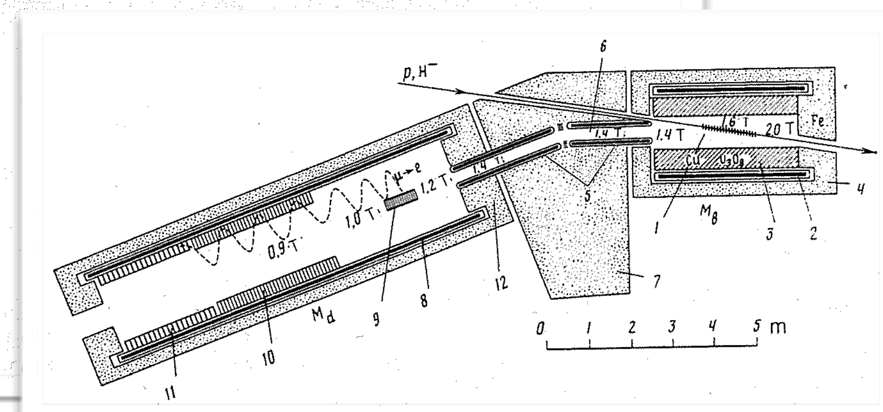
On the search for the $\mu \rightarrow e$ conversion process in a nucleus

R. M. Dzhilkibaev and V. M. Lobashev

Institute of Nuclear Research, USSR Academy of Sciences
(Submitted 21 June 1988)
Yad. Fiz. **49**, 622–624 (February 1989)

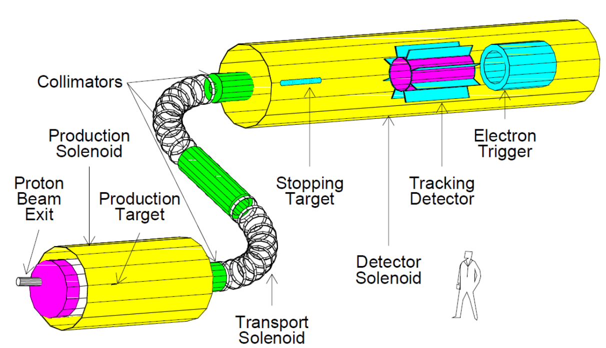
Among the most important problems of elementary-particle physics is the problem of searching for nonconservation of leptonic quantum numbers. In the $\mu \rightarrow e$ conversion process in a nucleus the muon and electron numbers are not conserved, and therefore this process does not occur in the standard electroweak theory. At the same time in a number of extensions of the minimal model[1] nonconvervation of lepton numbers is a natural property of the theory.

The signature of $\mu \rightarrow e$ conversion is the appearance of a

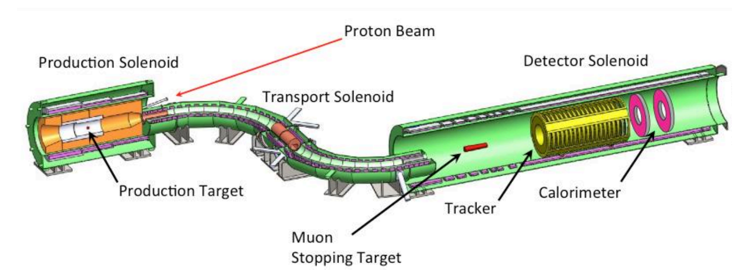


MELC@INR, Moscow proposed (1992)

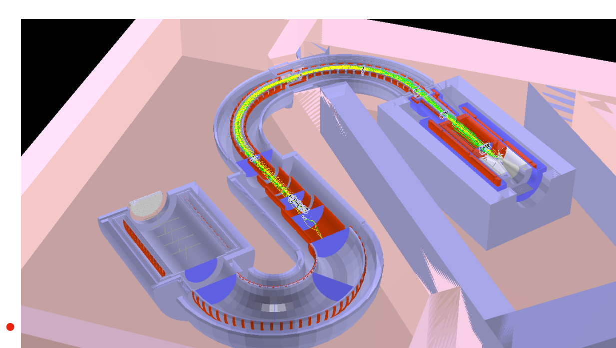
MECO@BNL cancelled



Mu2e@FNAL

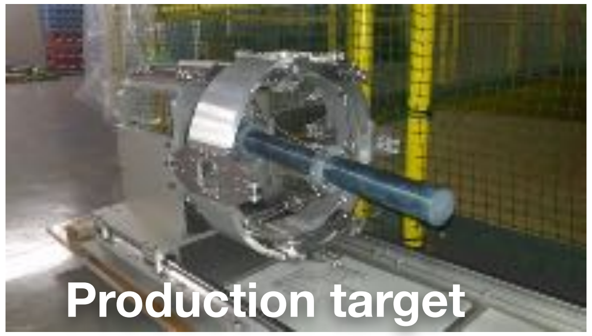


COMET@J-PARC



30 years from First Idea

Muon source



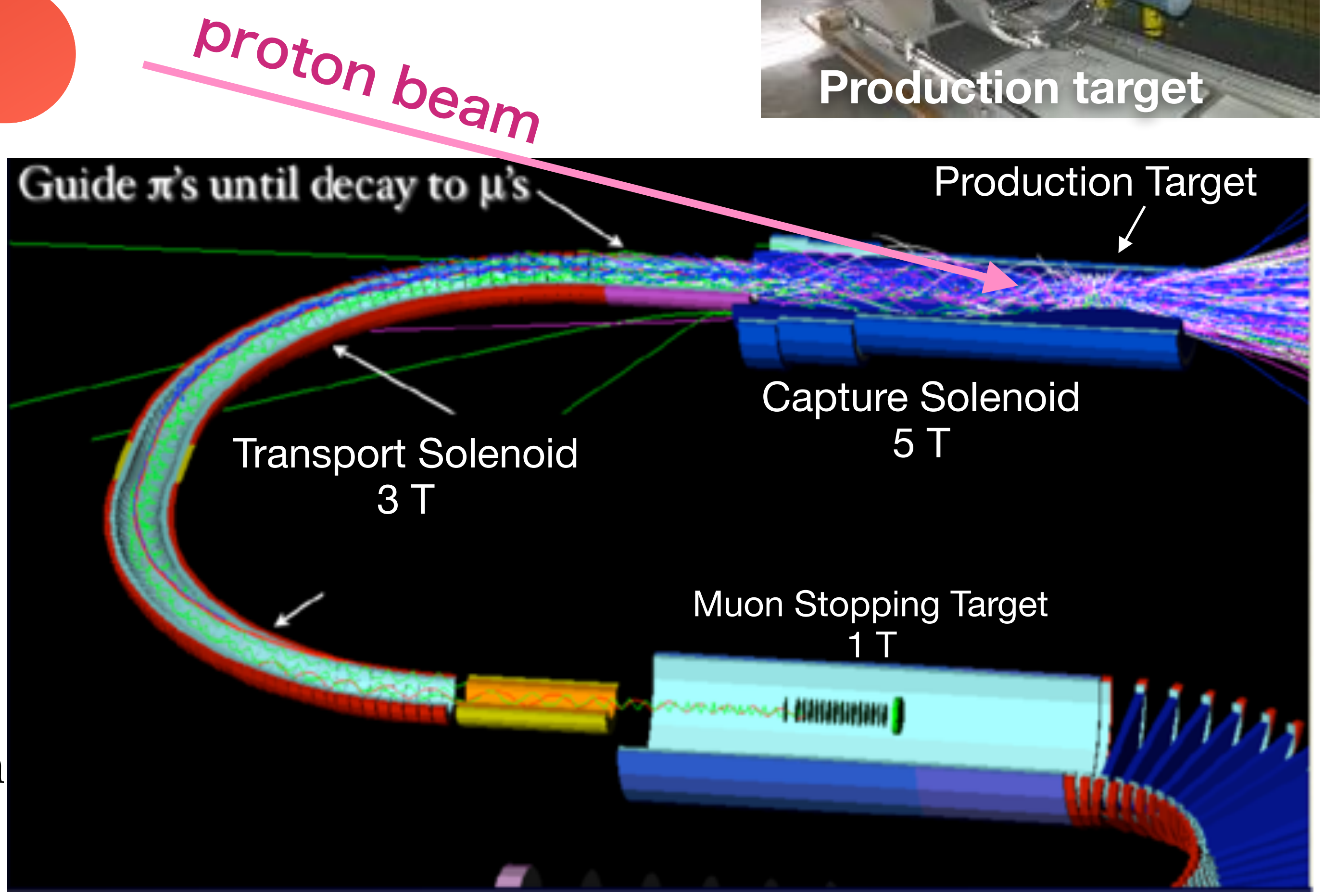
Powerful muon source is mandatory !!

To achieve 10^{-17} sensitivity,

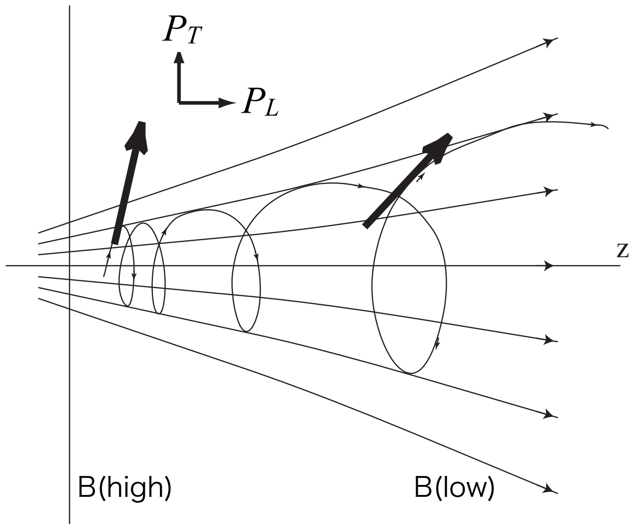
~10^{11} muons/sec

(with 10^7 sec running time.)

- Long production target
- Capture solenoid
  - Backward generated pion → muon
- Curved Transport solenoid
  - Vertical drift → Momentum & charge selection

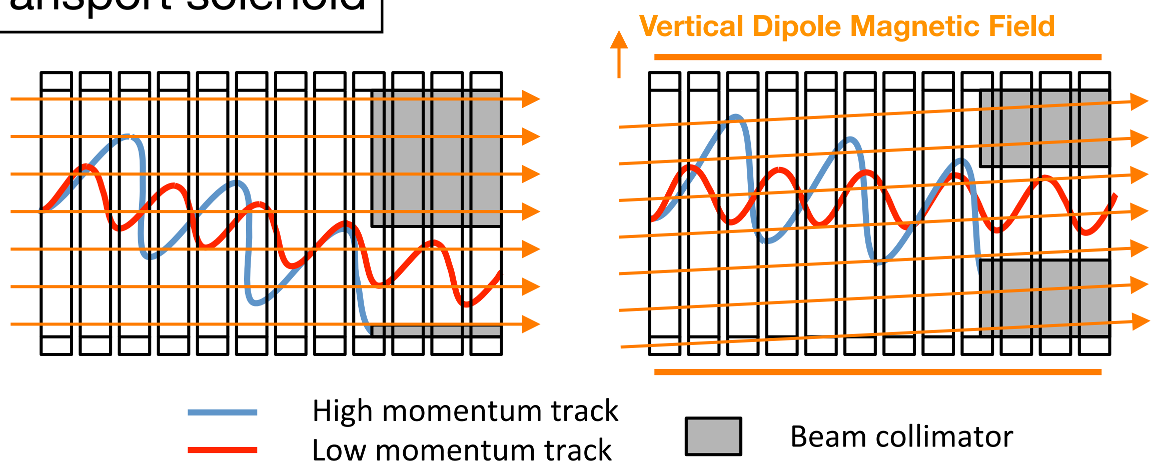


Capture solenoid



gradient magnetic field

Transport solenoid



$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + \frac{1}{2}p_T^2}{p_L}, \qquad B_{\mathrm{comp}} = \frac{1}{qR}\frac{p_0}{2}\left(\cos\theta_0 + \frac{1}{\cos\theta_0}\right)$$

Background rejection

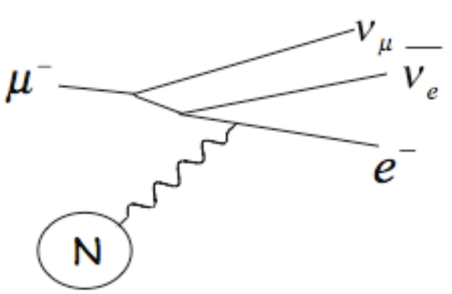
①	Decay-in-orbit	→ Detector
②	Beam-related prompt BG	→ Beam
③	Cosmic-ray induced	→ Veto

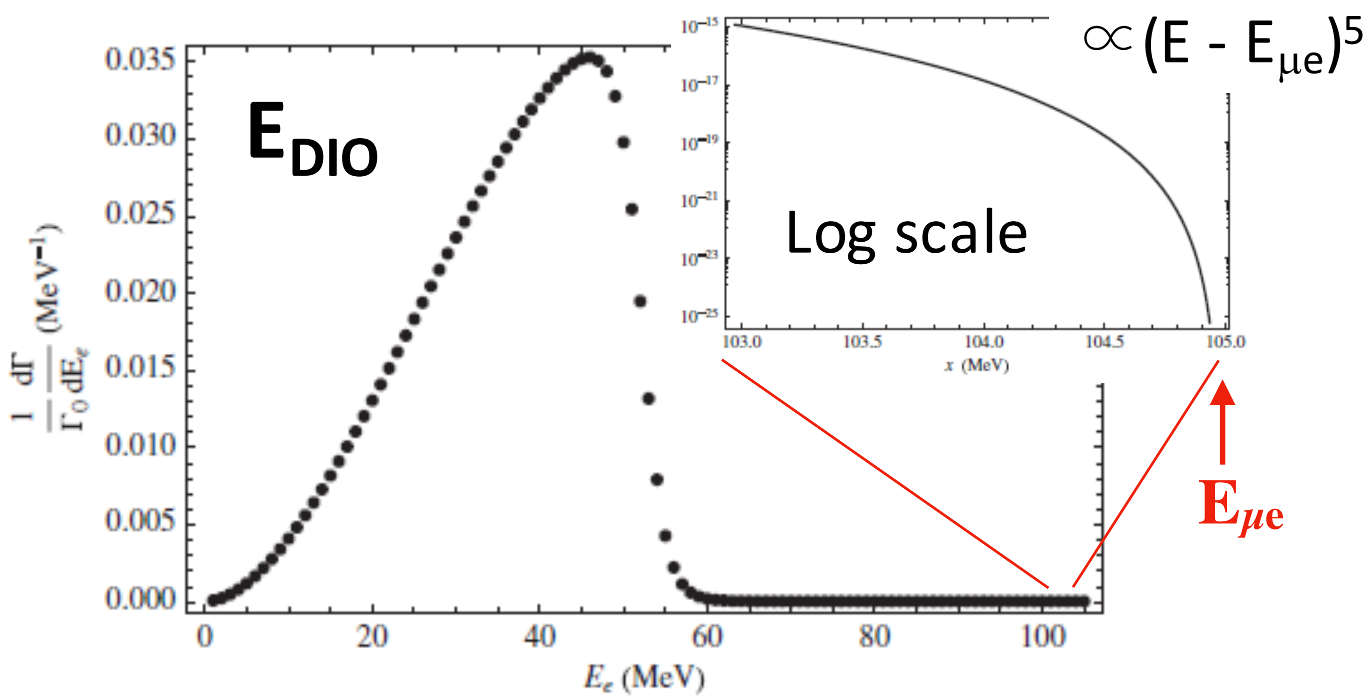
Background rejection (1)

① Decay-in-orbit → Detector resolution

Intrinsic physics background

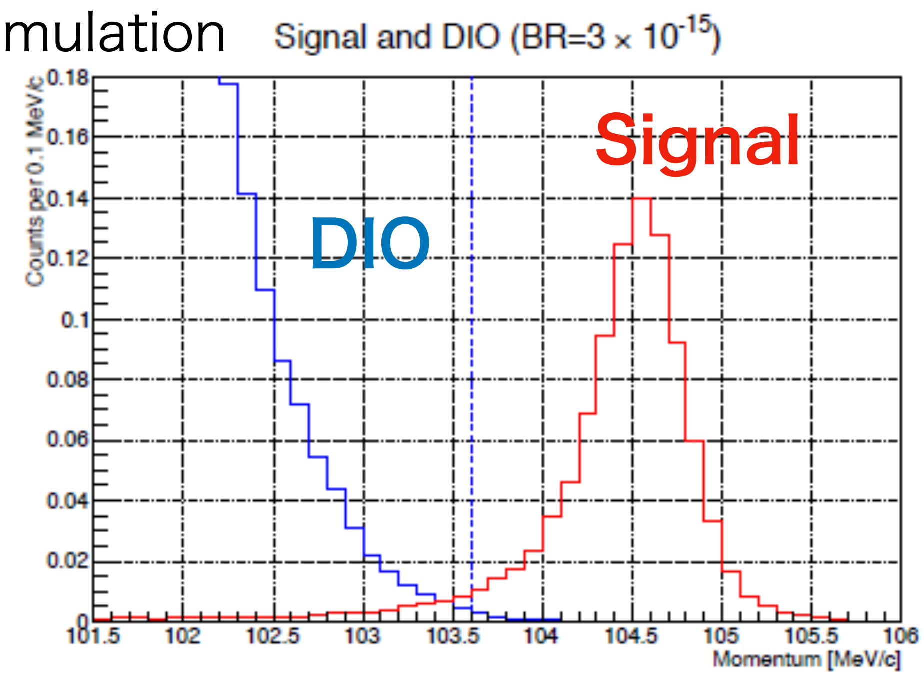
Muon decay in orbit





A.Czarnecki, X.G.i Tormo, W.J.Marciano, PRD 84, 013006 (2011).

Simulation



Required momentum resolution

Δp < 200 keV/c for BR~10^{-15}

< 150 keV/c for BR~10^{-17}

for 105 MeV/c electrons

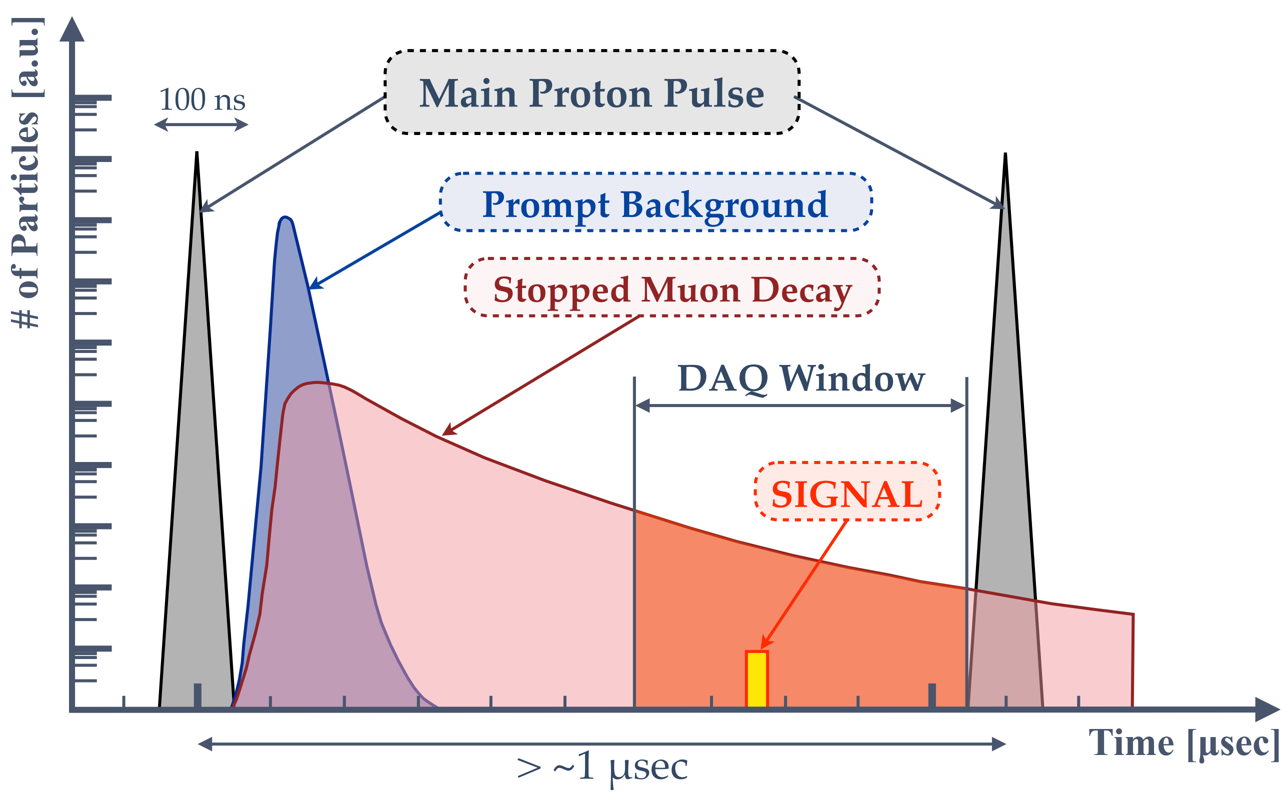
Background rejection (2)

② Beam-related prompt BG → Pulsed Beam

Muon beam is contaminated by pions, and the momentum is spreading in a wide range.

- Radiative pion capture, π^- (A,Z) → (A,Z-1) γ, γ → $e^+ e^-$
- Muon decay in flight, p_μ > 75 MeV/c
- Anti-proton induced, etc.

} correlated with beam timing



Cf.) τ_μ(Al) = 0.9 μsec

✔ Long muon beam line
- reduce π contamination

✔ Pulsed beam
- prompt vs. delayed

➡ Delayed-timing measurement

Lifetime of the muonic atom should be comparable to the pulse interval

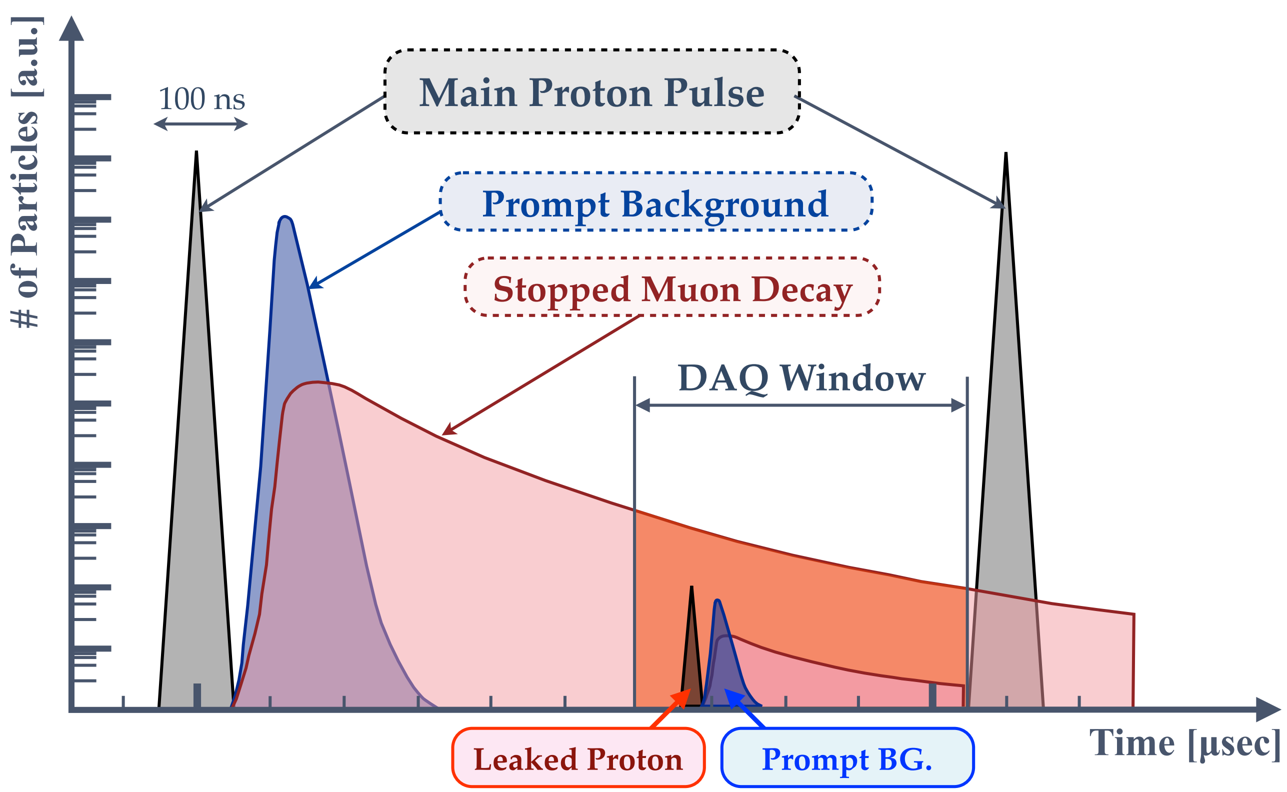
Background rejection (2)

② Beam-related prompt BG → Pulsed Beam

Muon beam is contaminated by pions, and the momentum is spreading in a wide range.

- Radiative pion capture, π^- (A,Z) → (A,Z-1) γ, $\gamma \to e^+ e^-$
- Muon decay in flight, $p_\mu > 75$ MeV/c
- Anti-proton induced, etc.

} correlated with beam timing



✓ Long muon beam line
- reduce π contamination

✓ Pulsed beam
- prompt vs. delayed

➡ Delayed-timing measurement

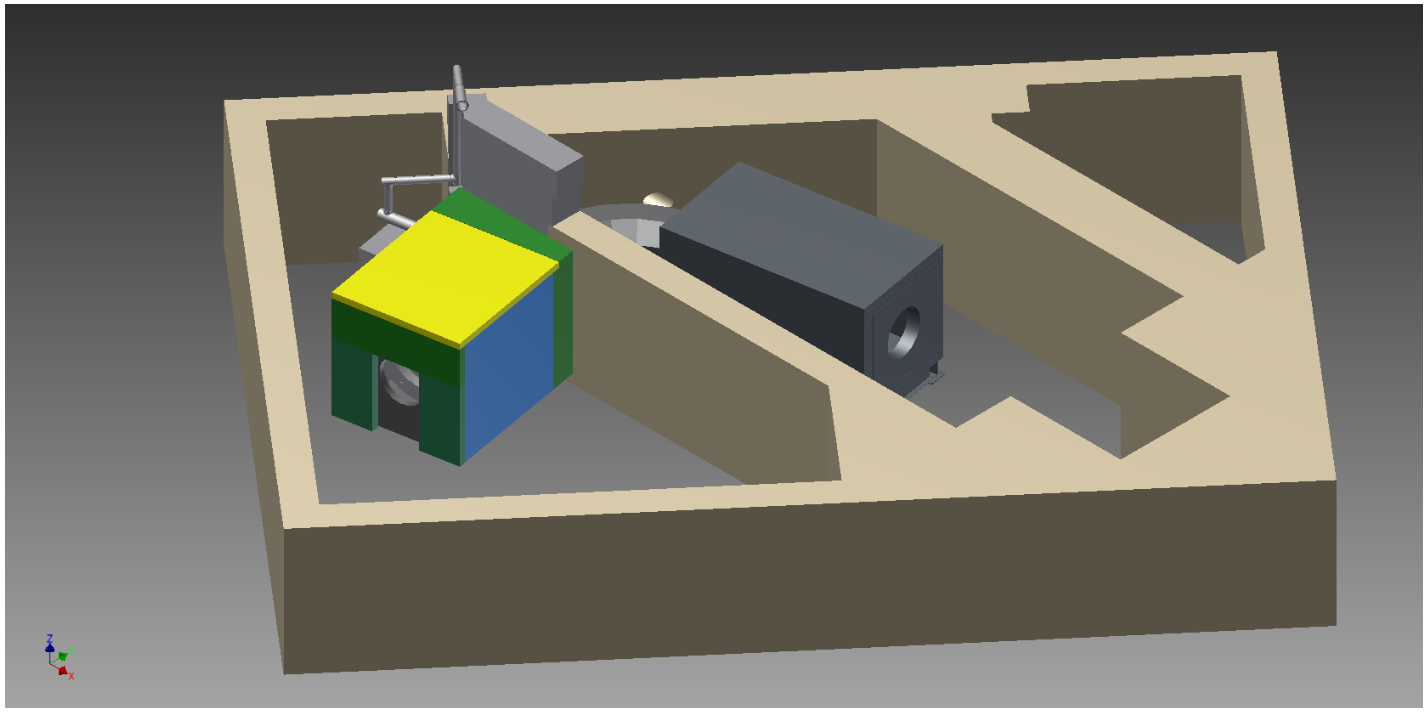
✓ Extinction factor $< 10^{-10}$

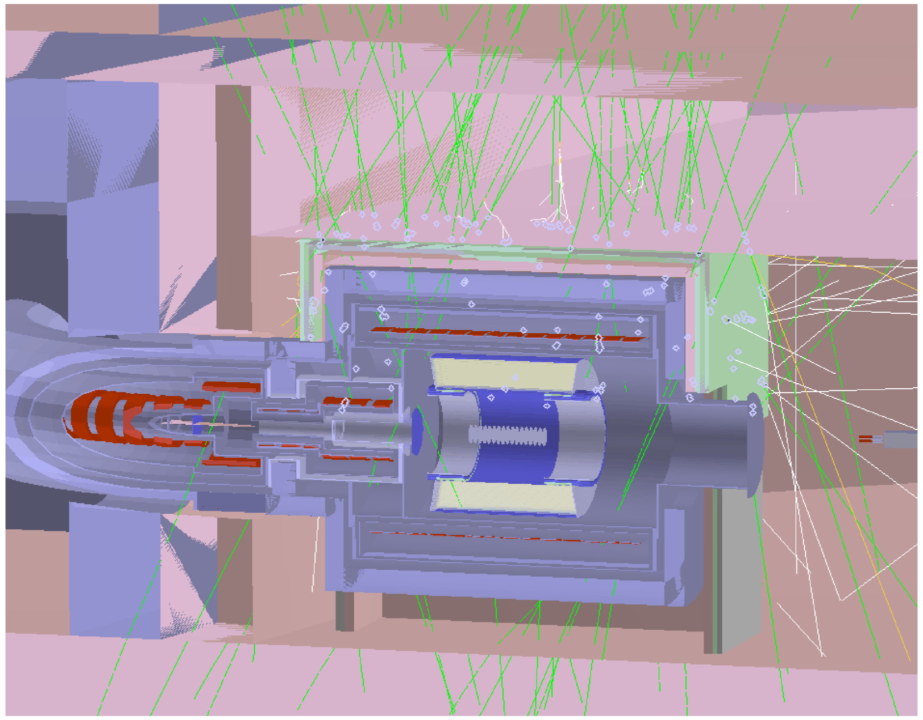
$$R_{ext} = \frac{\text{\# of protons in between pulses}}{\text{\# of protons in pulses}}$$

Leaked protons are dangerous to make the beam BG in the timing window.

Background rejection (3)

③ Cosmic-ray induced → Veto





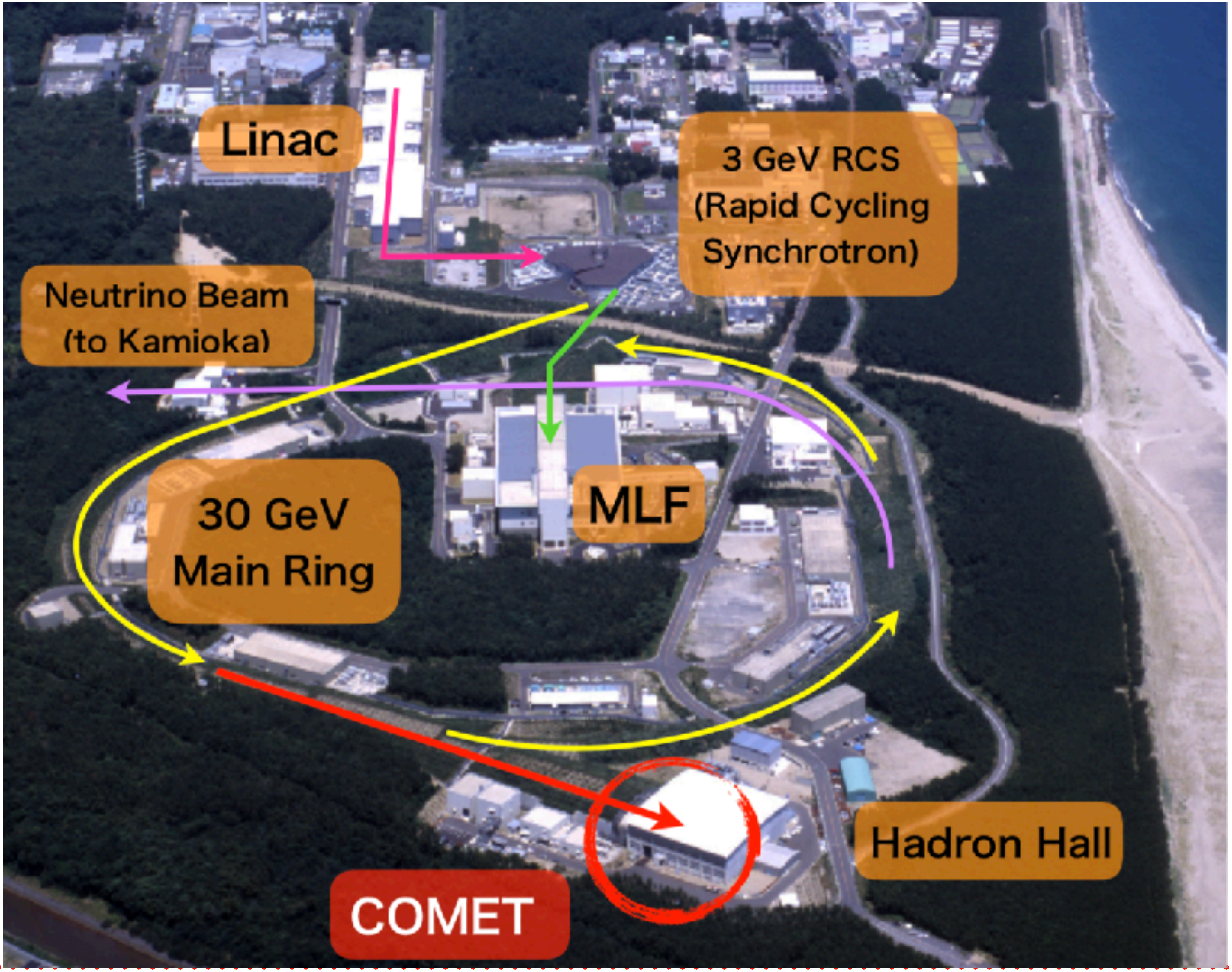
- Cosmic rays may create 105-MeV electrons that come into a detector and make trigger.
- To avoid these CR induced BG, detector region have to be covered by veto counters.
- Required performance: **CRV inefficiency ~ 10^{-4}**
- CR background ∝ data taking time (→ shorter running time with higher beam intensity is better)

The COMET Experiment

Collaboration Meeting @ Osaka, 2018/Jan

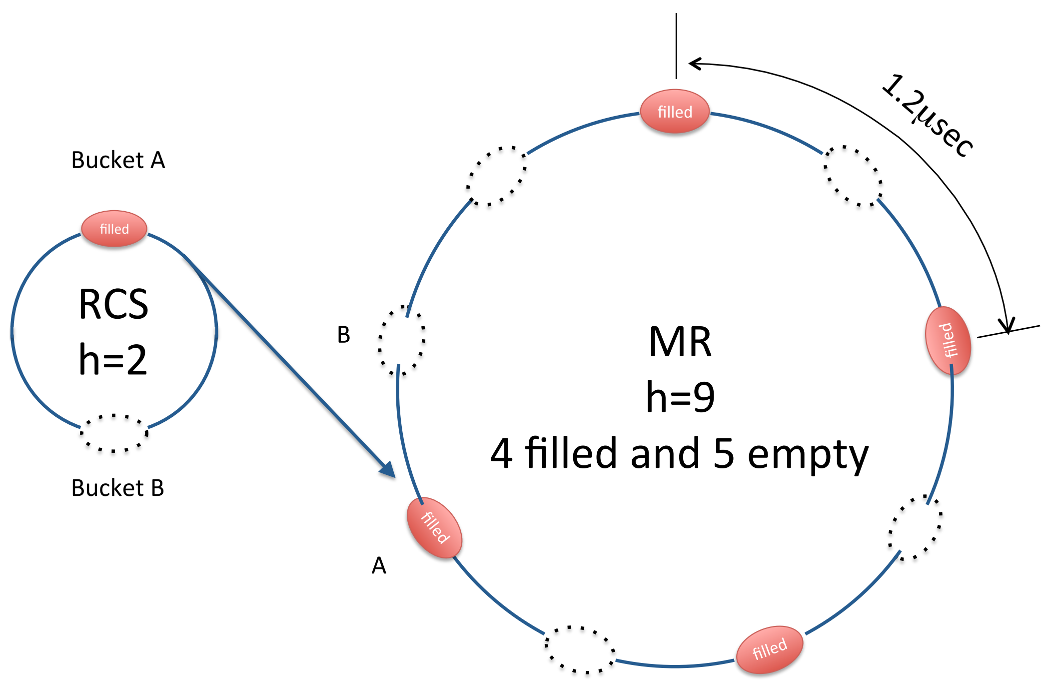
~200 collaborators,
41 institutes, 17 countries

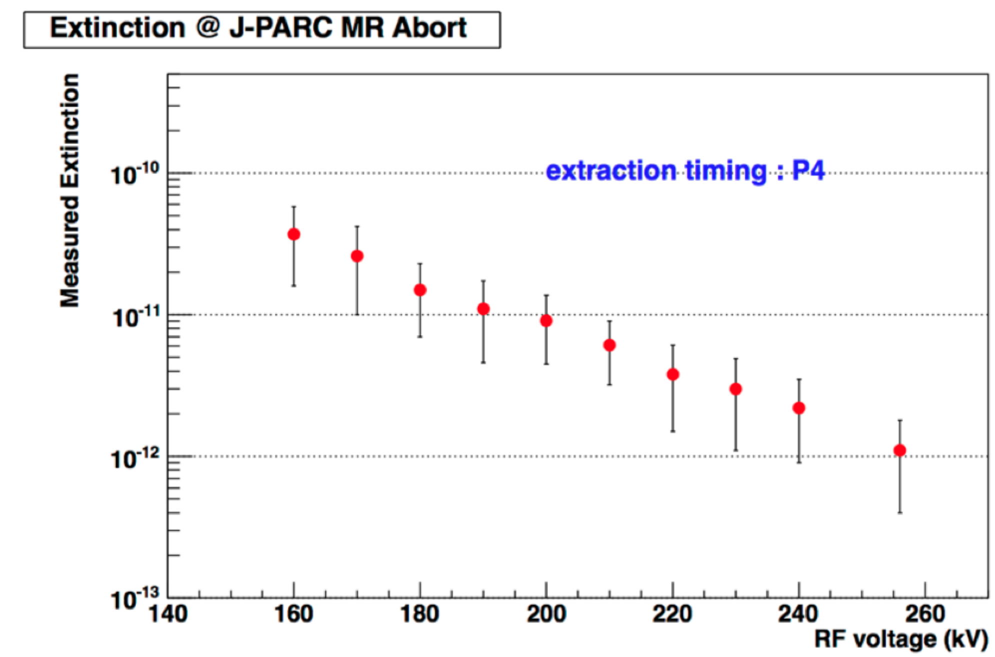
Accelerator



Proton beam for COMET

Cf.) Requirement < 10^{-10}

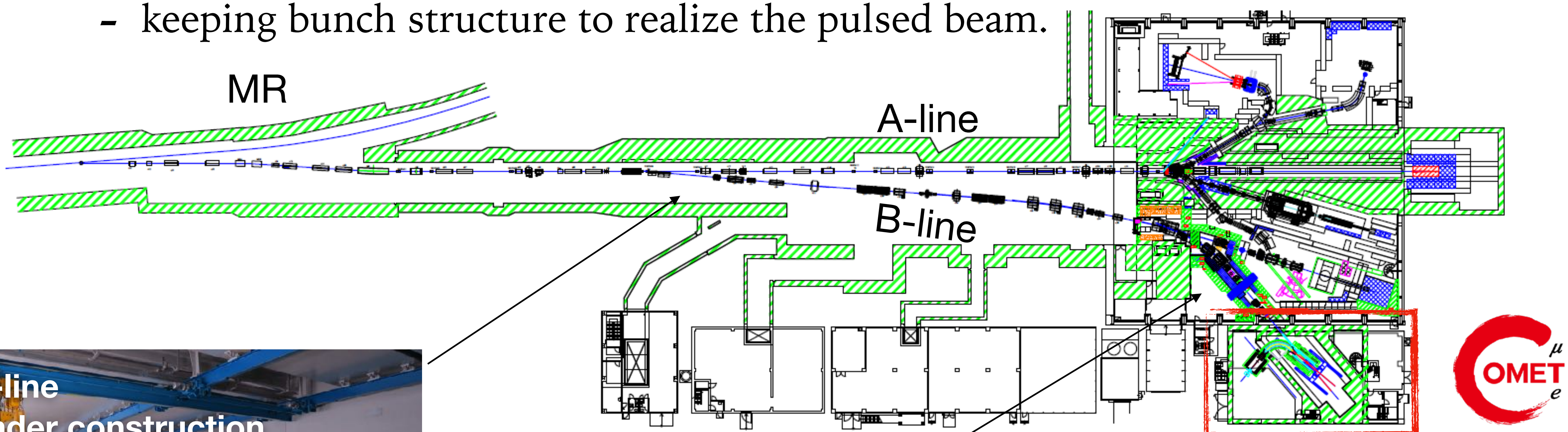


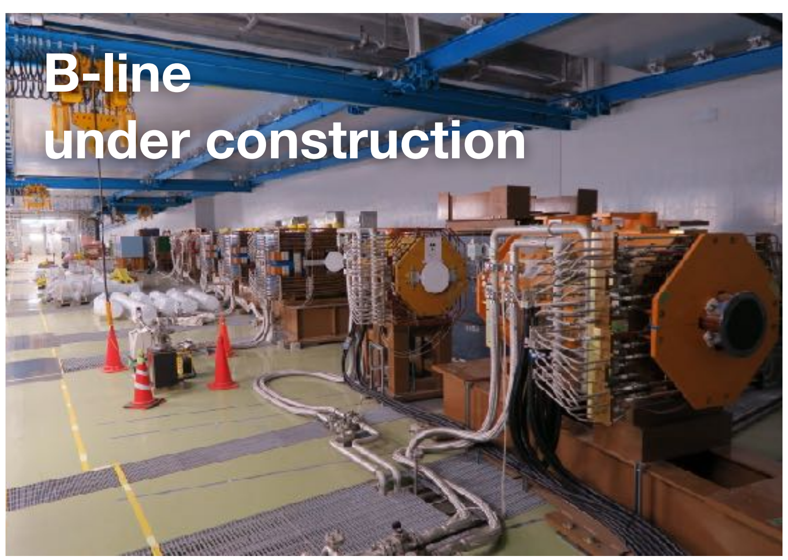


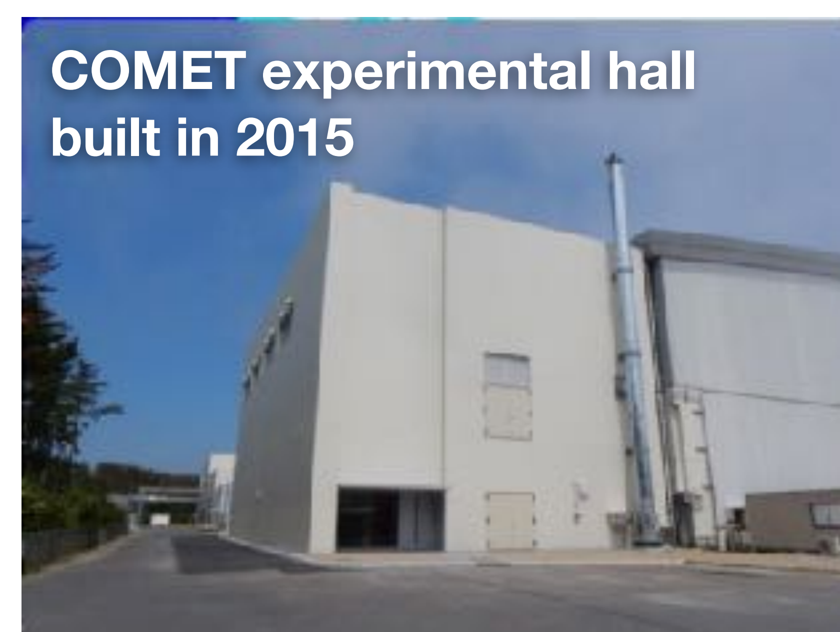
- **COMET dedicated operation**
  - Energy: 8 GeV
  - Pulsed beam: 1.17-μsec interval
  - 3.2 kW for Phase-I
  - 56 kW for Phase-II
- **Obtained Extinction**
  - = $\mathbf{10^{-12} \sim 10^{-11}}$ @ FX abort
  - Good enough for COMET

Beam line

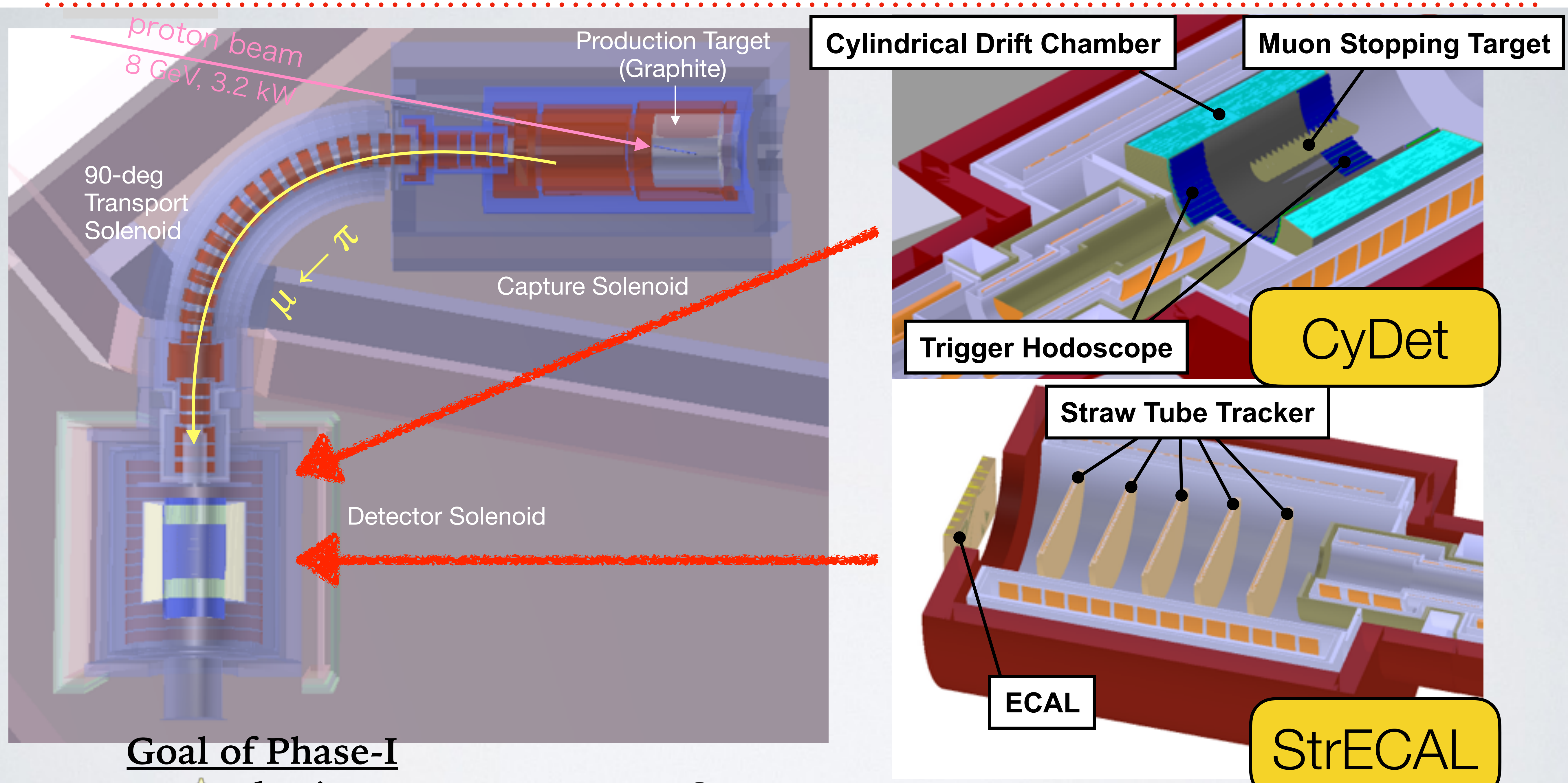
- New beam line & experimental hall were constructed.
- Bunched Slow Extraction (BSX)
  - keeping bunch structure to realize the pulsed beam.







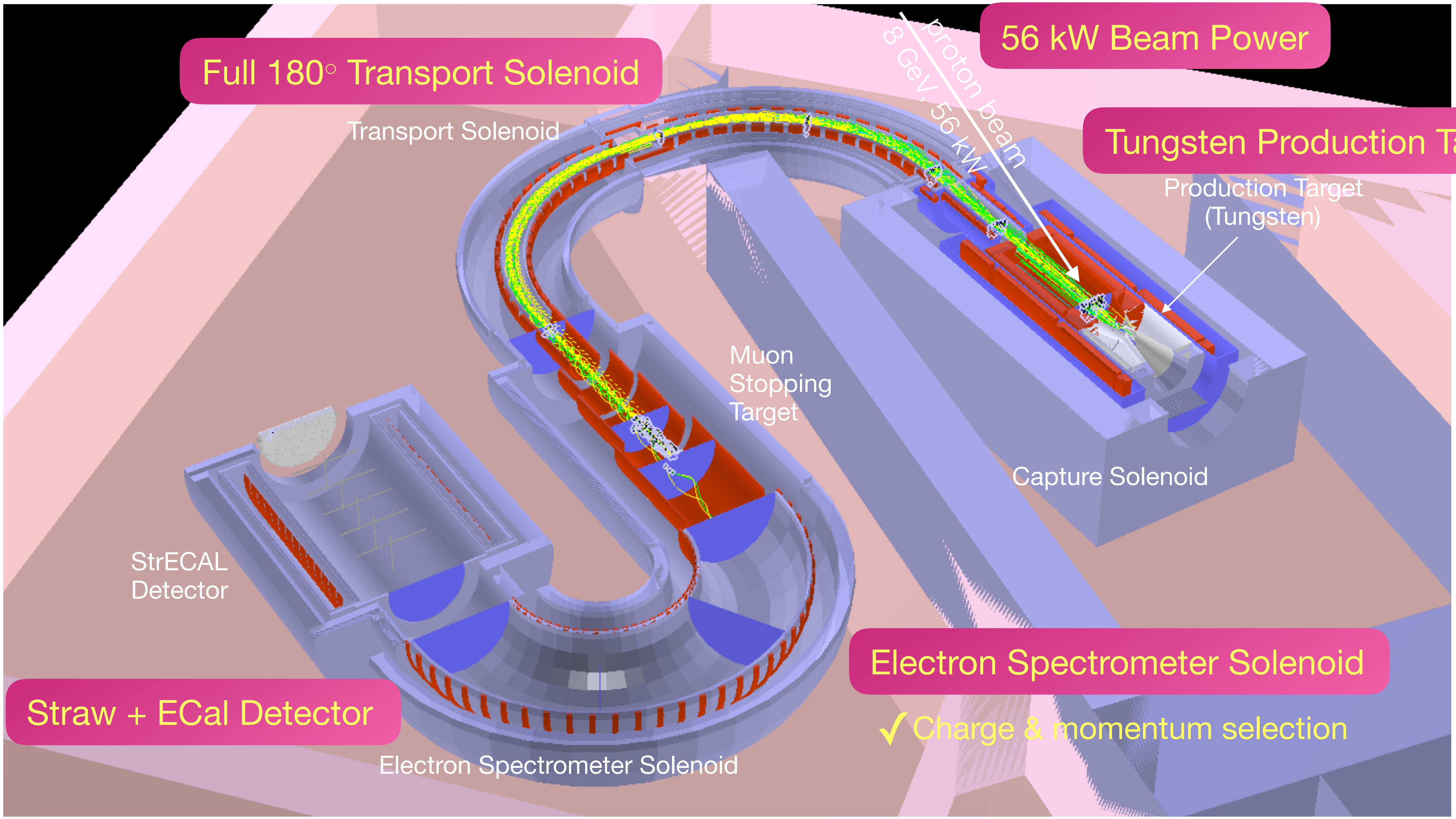
COMET Phase-I



<u>Goal of Phase-I</u>

- ☆ **Physics measurement** → **CyDet**
  - μ-e conversion search, SES: 3×10^{-15} (×100 improve), 150 days running
- ☆ **Beam measurement** → **StrECAL**
  - to understand beam quality and background (PID, momentum, timing)

COMET Phase-II



- SES: 2×10^{-17} ($\times$10,000 improve)
- 1 year running

Sensitivity

Detector acceptance + efficiency

$$B(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}},$$

Number of muons stopped inside targets

Fraction of μ-e conversion to the ground state = 0.9

Fraction of muons to be captured by Al target = 0.61

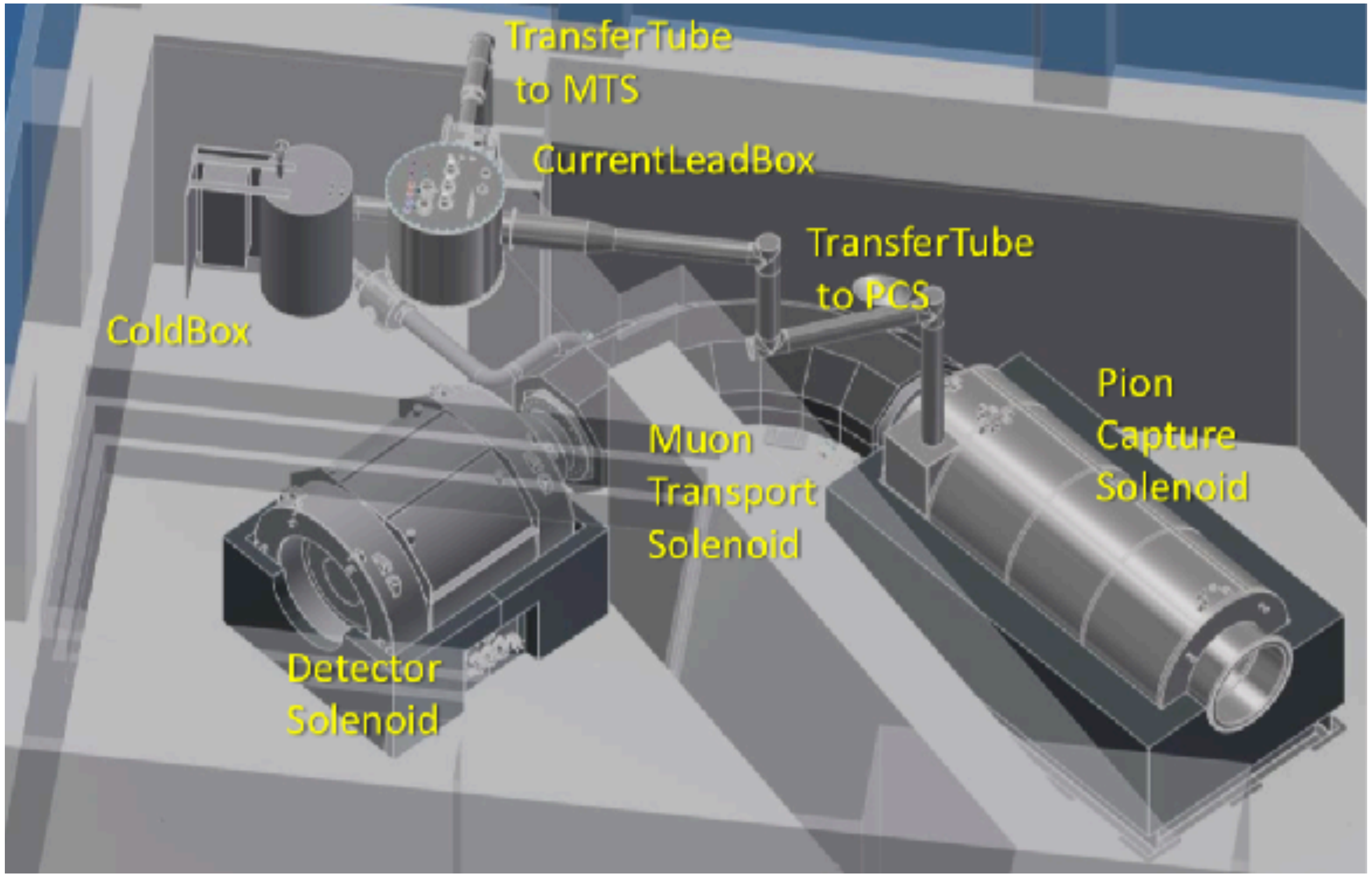
	Phase-I	Phase-II
Proton Beam Power	3.2 kW	56 kW
DAQ time	150 days	~ 1 year
Total muons stop, N_μ	1.5×10^{16}	1.4×10^{18} #
Detector Acceptance+Efficiency, $A_{\mu\text{-}e}$	0.041	0.057 #
S.E.S.	**3.0×10^{-15}**	**2.0×10^{-17} #**
# of BG	0.032	< 1

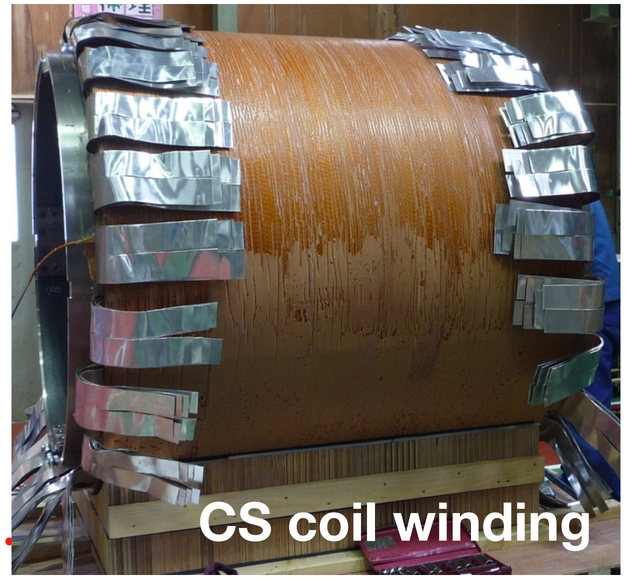
Based on recent study, we are considering **$O(10^{-18})$** sensitivity with optimized setup in Phase-II.

Recent Status

Technical Design Report, arXiv:1812.09018

Solenoid magnet status



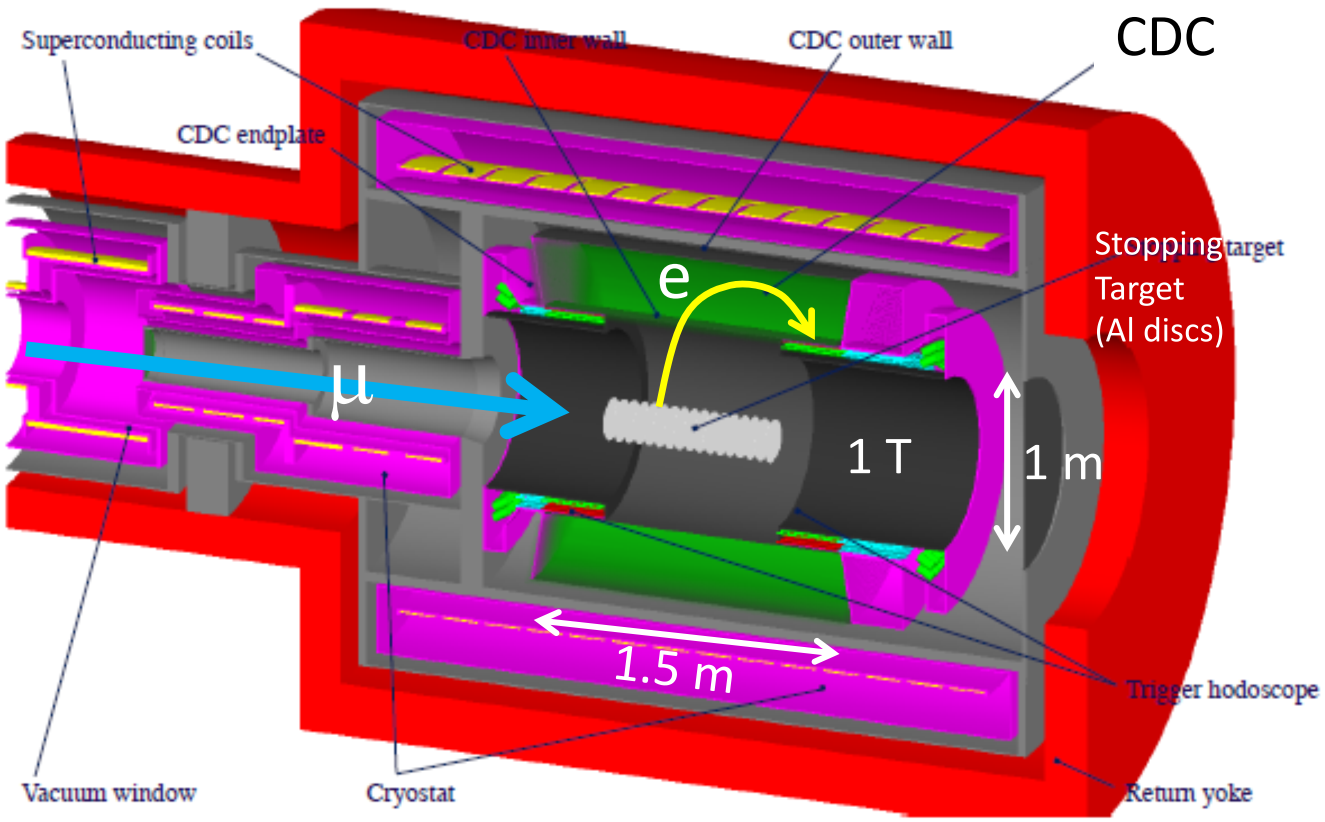


- **Capture solenoid:**
  - Coil winding & cold mass assembly in progress. Cryostat design ongoing.
- **Transport solenoid:**
  - Installed and ready for cryogenic test
- **Bridge & Detector solenoids:**
  - DS & BS coils ready. DS vessel delivered.
- **Cryogenic System:**
  - Refrigerator test completed. Helium transfer tube in production.

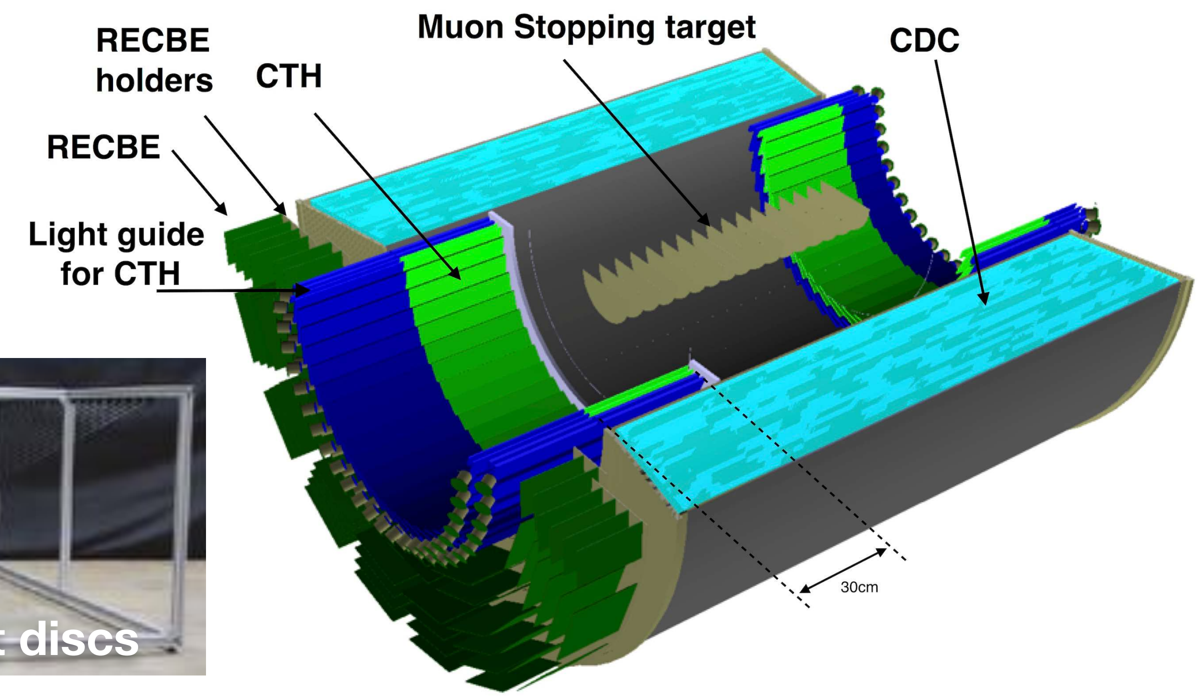
CyDet system

For details, See Yuki Fujii's Talk
PN-DDB, 25/Sep

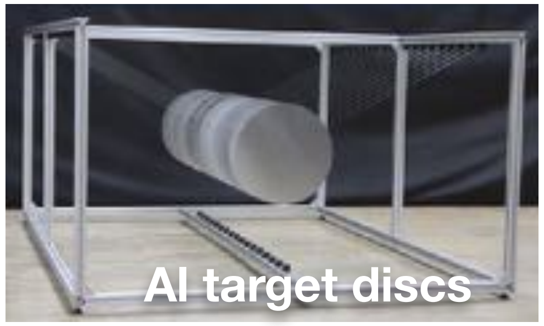
Detector for μ-e search in Phase-I



- **CDC** (Cylindrical Drift Chamber)
  - electron tracking in 1 T
  - Δp = 200 keV/c (for p=105 MeV/c)
  - Low-mass chamber
    - He:i-C_4H_{10} (90:10)
    - 0.5-mm CFRP inner wall
    - Al field wire, 126μm, 4986
    - Au-W sense wire, 25μm, 14562
  - Alternating all stereo layer
    - 20 layers, ±64~75 mrad



- **CTH** (Cylindrical Trigger Hodoscopes)
  - Scintillator & Acrylic Cherenkov
  - Finemesh PMT readout
  - 4-fold coincidence trigger

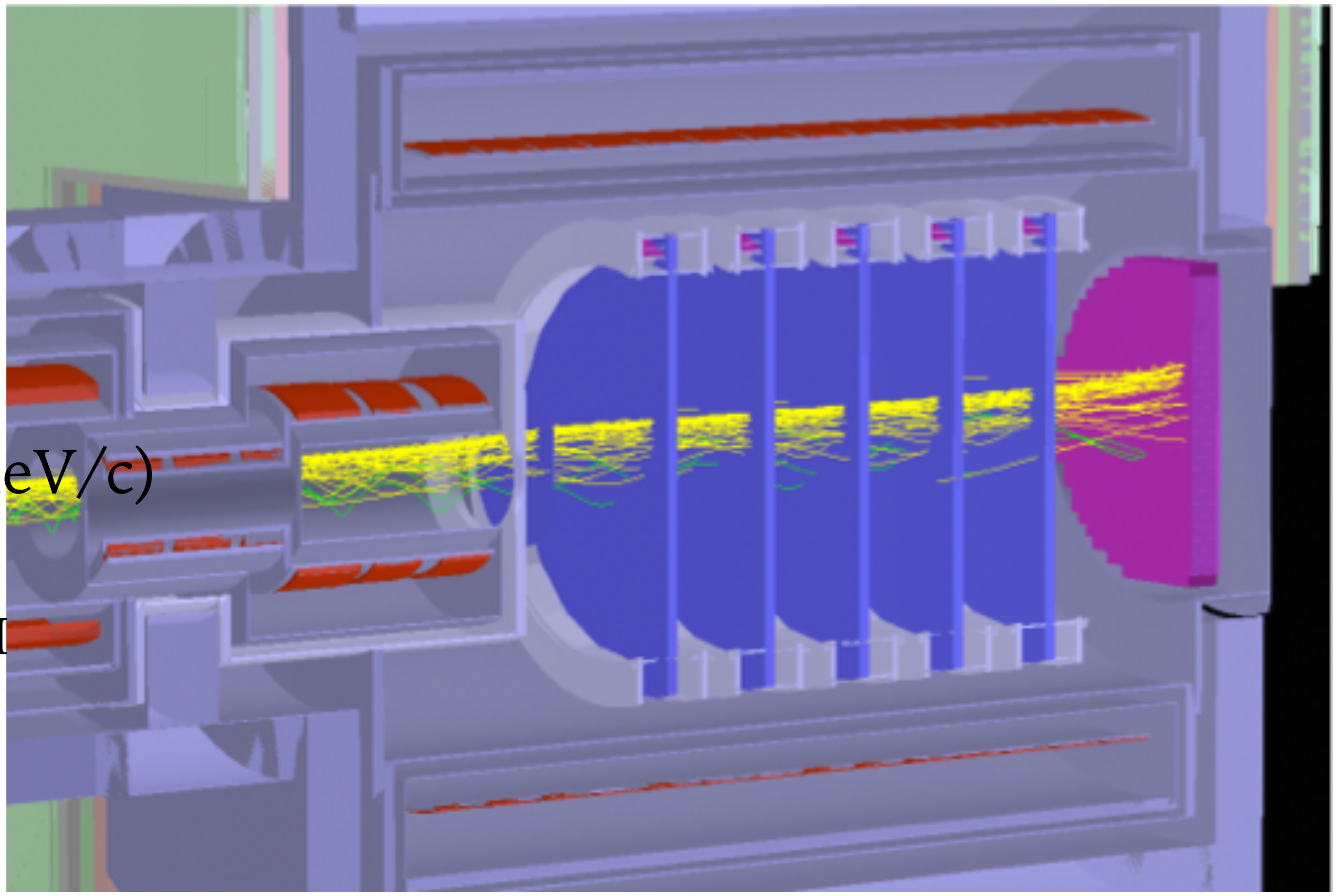


- **Stopping Target**
  - Al target consists of 17 discs
  - 100-mm radius, 0.2-mm thickness, 50-mm spacing.

StrECAL system

For details, See Yuki Fujii's Talk
PN-DDB, 25/Sep

Detector for beam measurement in Phase-I,
and μ-e search in Phase-II



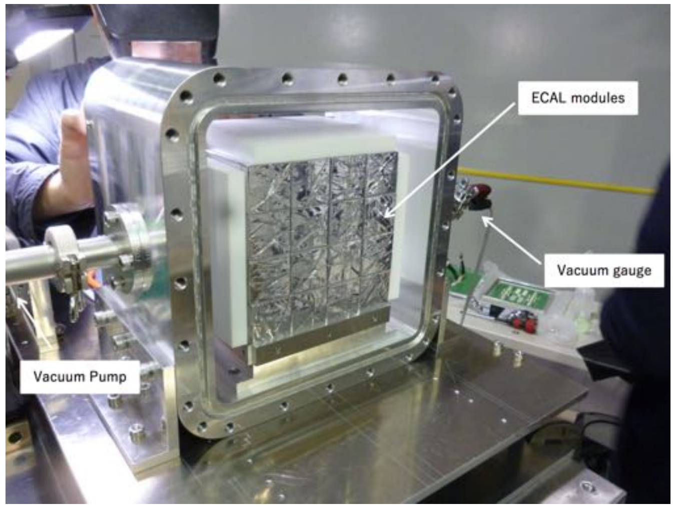
Straw Tube Tracker

- Operational in vacuum in 1 T
- Δp = 150~200 keV/c (for p=105 MeV/c)
- Straw tube
  - 20 μm thick, 9.75 mm diameter for Phase-I
  - 12 μm thick, 5 mm diameter for Phase-II
- 5 stations (xx'yy'×5)
- Ar:C_2H_6 (50:50)

Electron Calorimeter

- 1,920 LYSO crystals
  - 2×2×12 cm (10.5 radiation length)
- $\Delta E/E$ = 5% (for E=105 MeV)
- 40-ns decay time
- APD readout

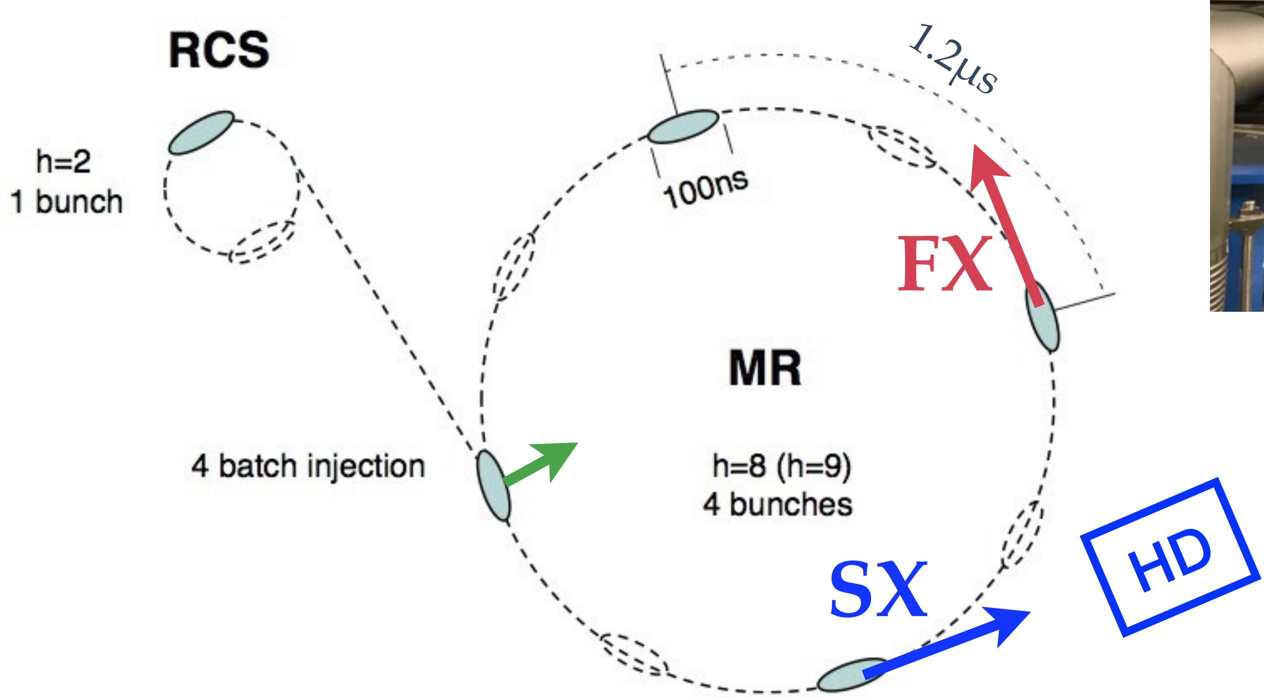
Straw Tracker prototype

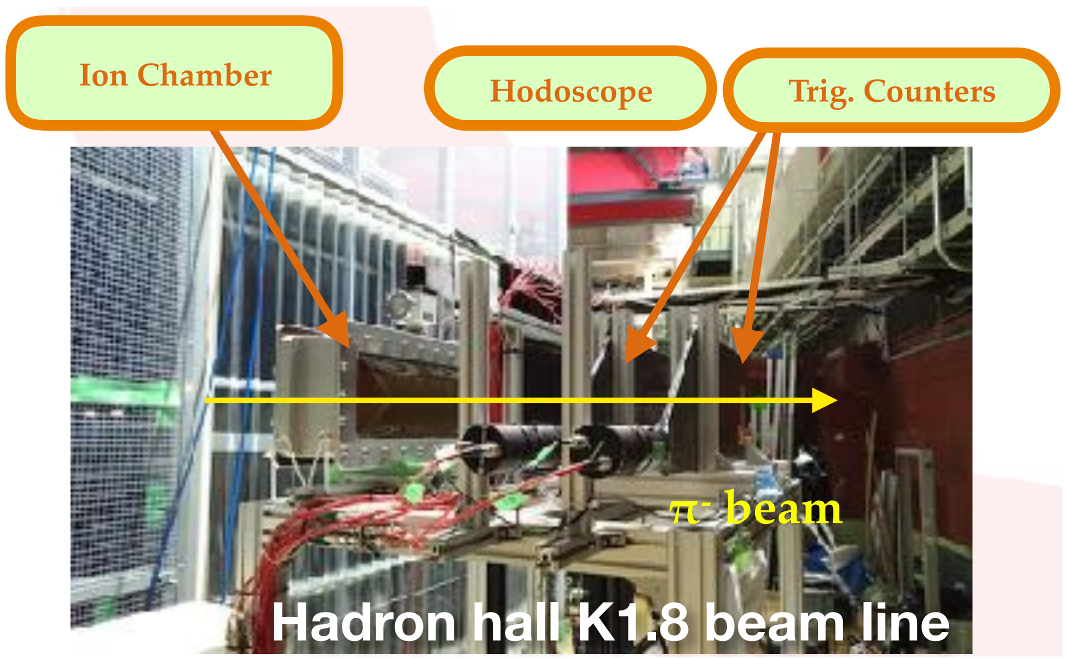


ECAL prototype

8 GeV test & Extinction measurement

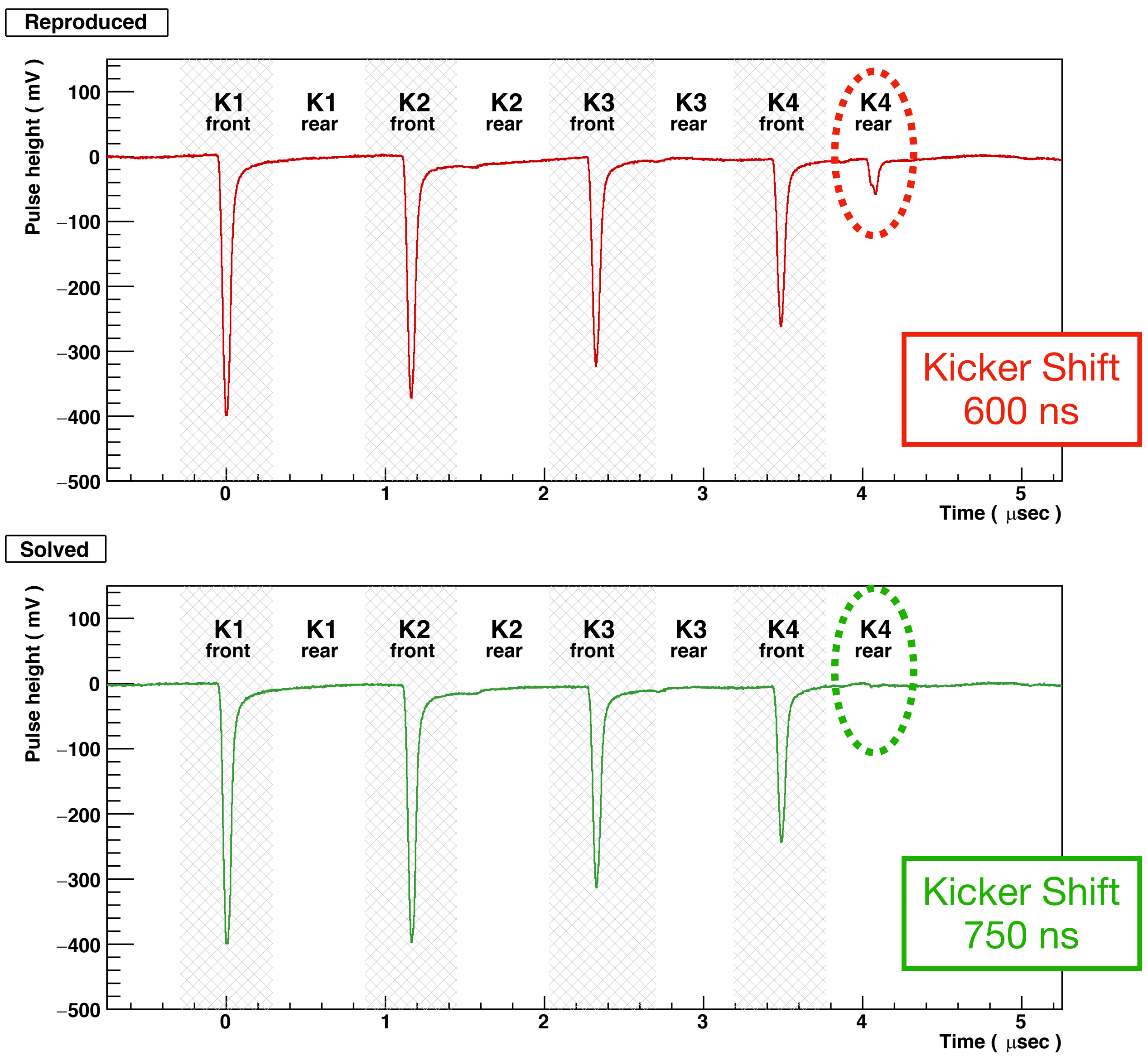
8-GeV operation & extinction measurement were done at J-PARC in Jan.-Feb., 2018.





- Campaign was successfully carried out.
- Extinction was measured by both FX & SX.
  ✓ First trial of 8-GeV Bunched SX.

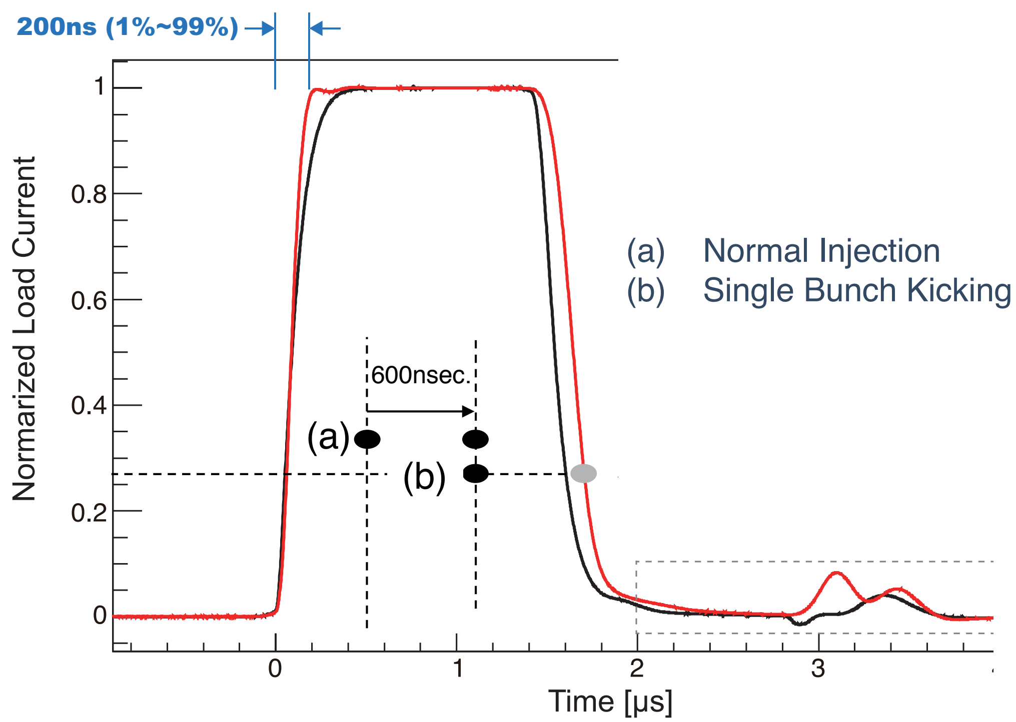
Extinction study



Nishiguchi et al., IPAC2019

doi:10.18429/JACoW-IPAC2019-FRXXPLS2

Injection kicker field & beam bunches



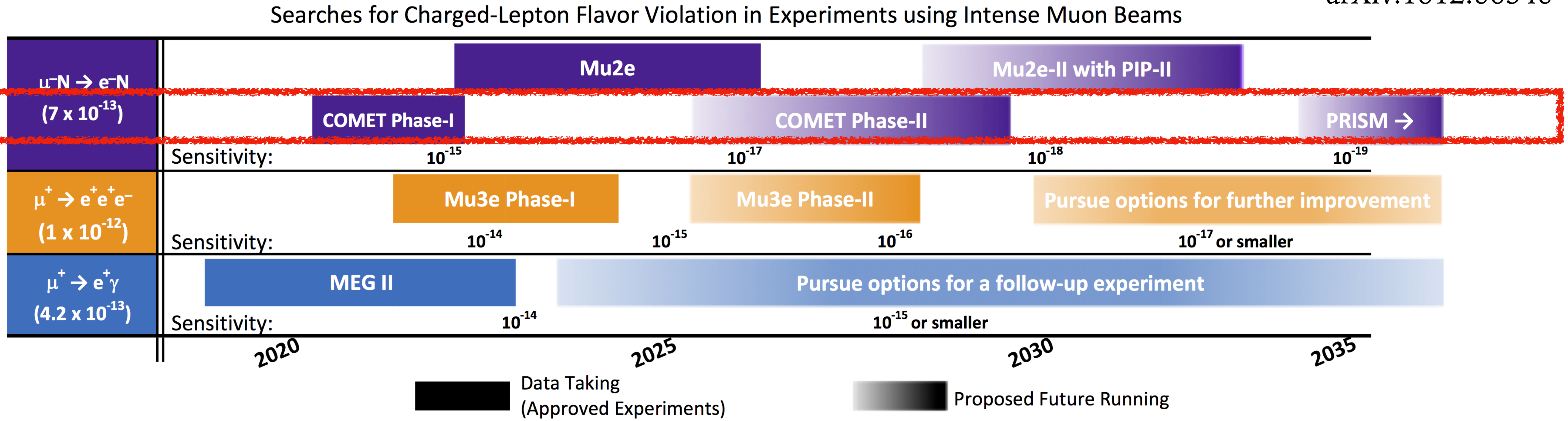
- Perfect Extinction (= No Leak) was realized for 3 Injection Batches (K1, K2 and K3),
- But, small amount of residual protons were observed in **K4 rear**.
- Because of the tail of Injection Kicker excitation.
- By longer kicker timing shift, **no leak proton is observed in K4 rear**.
- **Extinction < 6 $\times 10^{-11}$** is expected. —> Need confirmation at BSX.

Cf.) Requirement < 10^{-10}

Schedule and Summary

Schedule & Summary

Input to European Strategy for Particle Physics Upgrade
arXiv:1812.06540



COMET (Phase-I) will start early 2020's

Summary

- COMET aims to search for μ-e conversion with sensitivity of 3×10^{-15} / 2×10^{-17} at Phase-I / II.
- Detector & beam line preparation is intensively in progress for Phase-I.
- Phase-II study is also in progress. We are able to optimize the Phase-II parameters based on the coming Phase-I results.

Backup

Summary of COMET Phase-I / II

	Phase-I	Phase-II #
Proton Beam Power	3.2 kW (8 GeV×0.4 μA)	56 kW (8 GeV×7 μA)
# of protons / acc. cycle	6.2×10^{12} / 2.48 sec	4.4×10^{13} / 1.0 sec
DAQ time	1.26×10^{7} sec (146 days)	2.0×10^{7} sec (231 days)
Total protons on target	3.2×10^{19}	9.0×10^{20}
# of muons stop / proton	4.7×10^{-4}	1.6×10^{-3}
Total muons stop	1.5×10^{16}	1.4×10^{18}
Detector Acceptance+Efficiency	0.041	0.057
S.E.S.	**3.0×10^{-15}**	**2.0×10^{-17}**
# of BG	0.032	< 1

Phase-II parameters are tentative, more improvement under study

Sensitivity

Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window (ε_{mom})	0.93
Timing window (ε_{time})	0.3
Total	0.041

$103.6 < p_e < 106.0$ MeV/c

$700 < t_e < 1170$ ns

@ Phase-I

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu\text{-}e}},$$

= 3×10^{-15}

Number of muons stopped inside targets

Fraction of μ-e conversion to the ground state = 0.9

Fraction of muons to be captured by Al target = 0.61

$N_\mu = 1.5\times10^{16}$ → **150 days by 3.2 kW**

@ Phase-II

1 year by 56 kW
+ Tungsten production target
+ 180° Transport Solenoid
+ Electron Spec. Solenoid

S.E.S **= 2×10^{-17}**

Background estimation

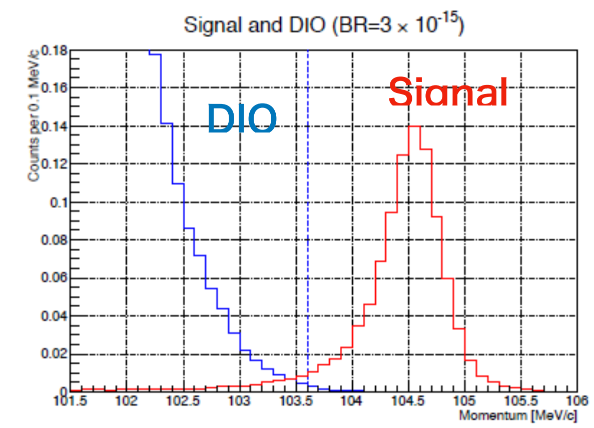
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	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
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Detector

Beam

CR



$103.6 < p_e < 106.0$ MeV/c

Assuming
$R_{ext} = 3\times10^{-11}$

$700 < t_e < 1170$ ns

@ Phase-I

BG is small enough

@ Phase-II

BG is still less than 1 by simulation

to be confirmed by Phase-I Beam Measurement

Related (byproduct) measurements

$$\mu^- + (A,Z) \to e^+ + (A,Z-2)$$

B.Yeo, Kuno, MJ.Lee, Zuber, PRD96, 075027 (2017)

- Lepton Number Violation process.
- Target nucleus mass relation is required: $M(A,Z-2) < M(A,Z-1)$,
  - to eliminate radiative muon capture BG
- 10,000× sensitivity improvement is possible.
- Promising isotopes: ^{40}Ca, ^{32}S

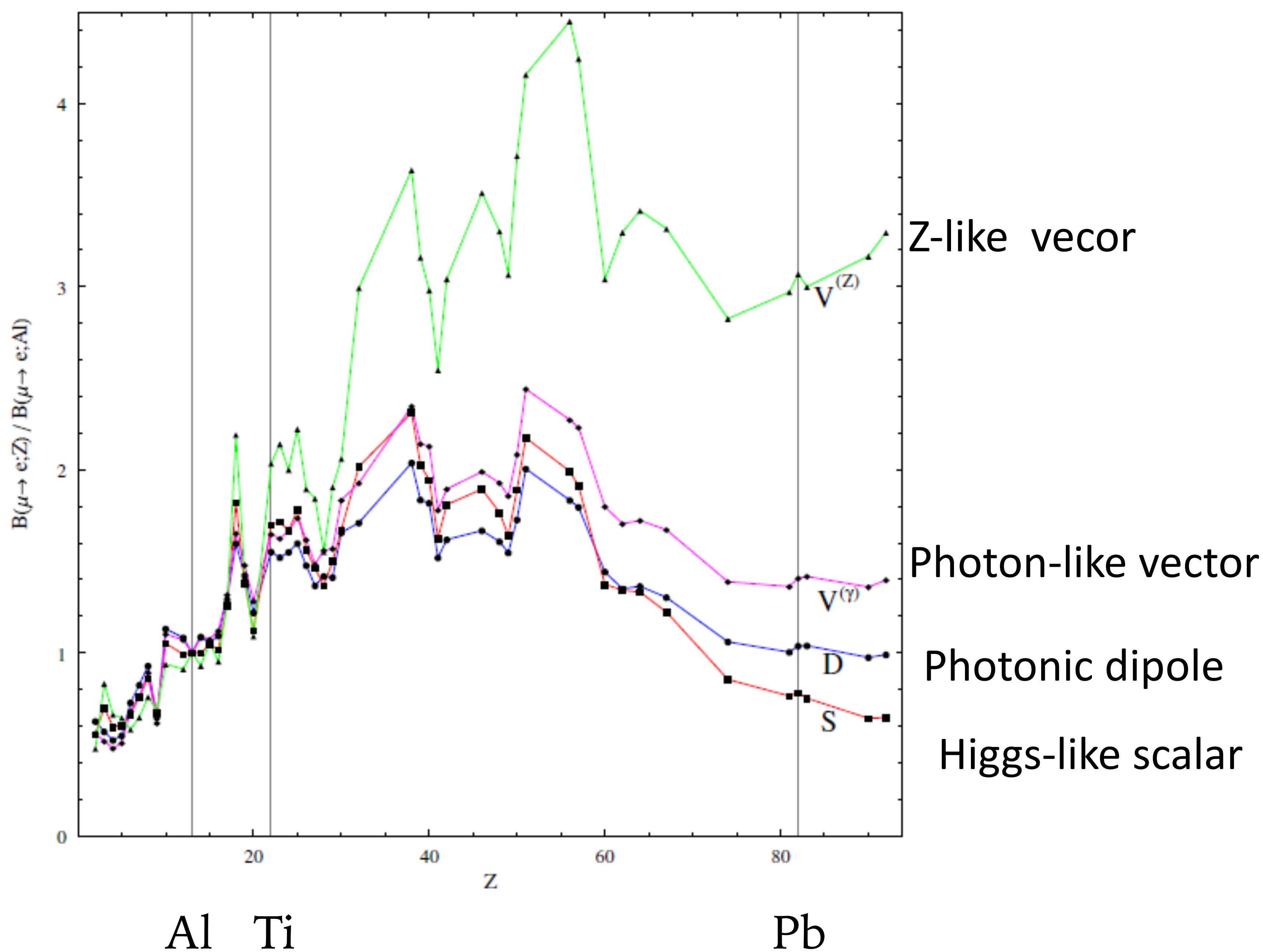
$$\mu^- + e^- \to e^- + e^-$$

Koike, Kuno, J.Sato, Yamanaka, PRL105, 121601 (2010).
Uesaka, Kuno, J.Sato, T.Sato, Yamanaka, PRD93, 076006 (2016), PRD97, 015017 (2018).

- The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate.
- Z dependence could be used to distinguish interaction types.

Feasible in Phase-I

Target dependence to discriminate interactions

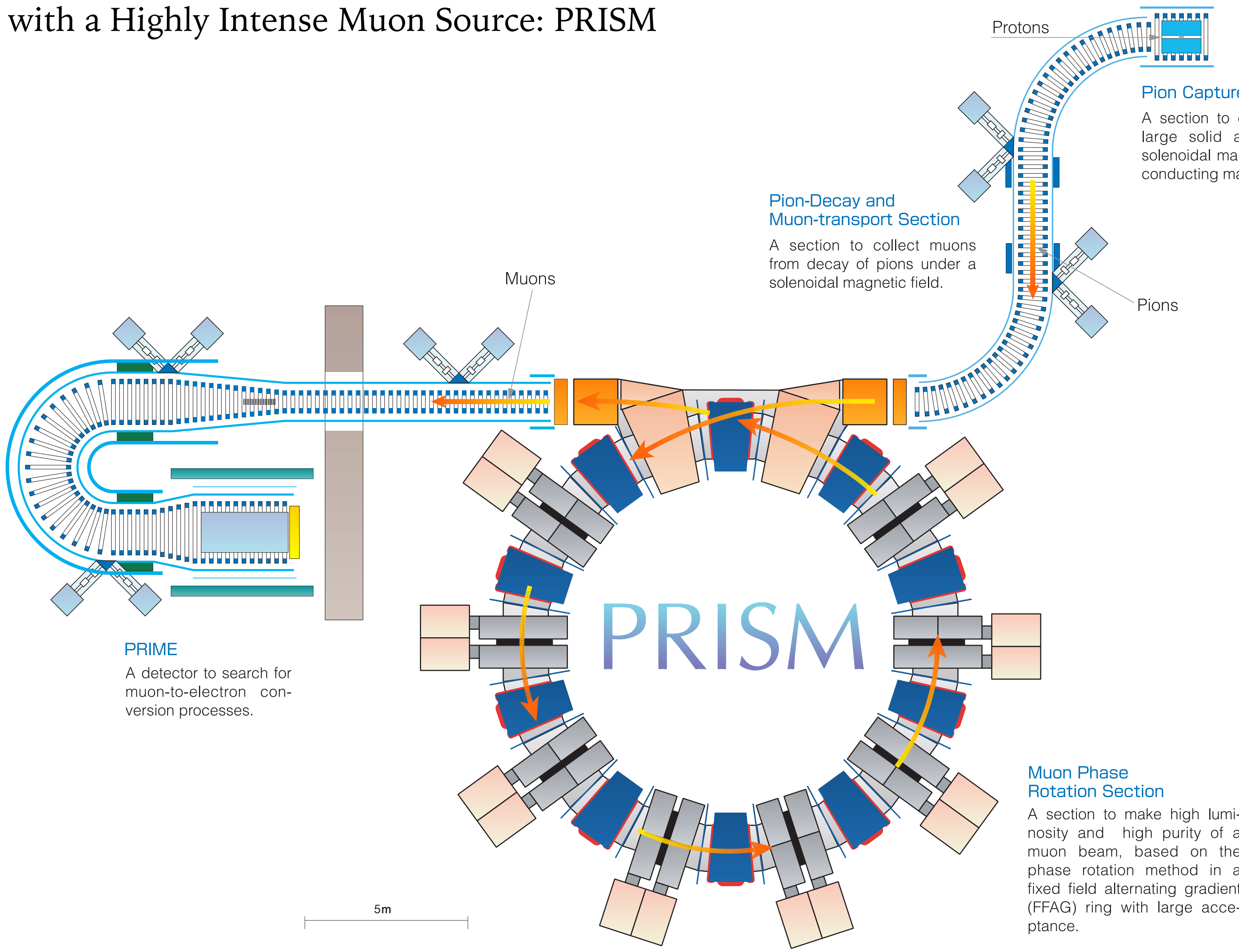


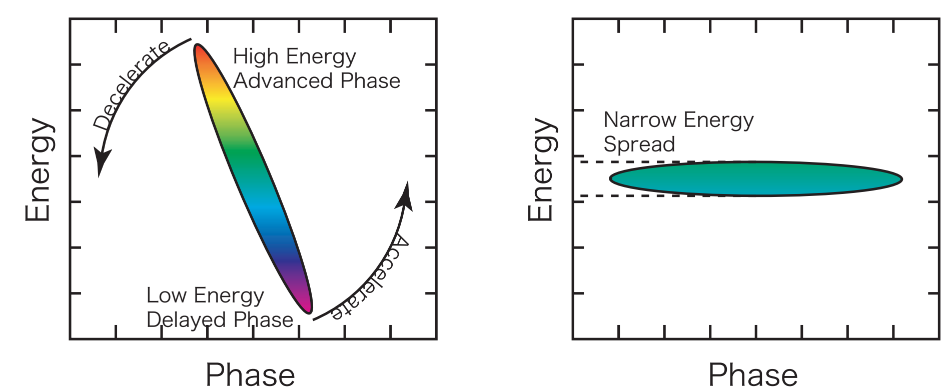
V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D 80, 013002 (2009).

PRISM

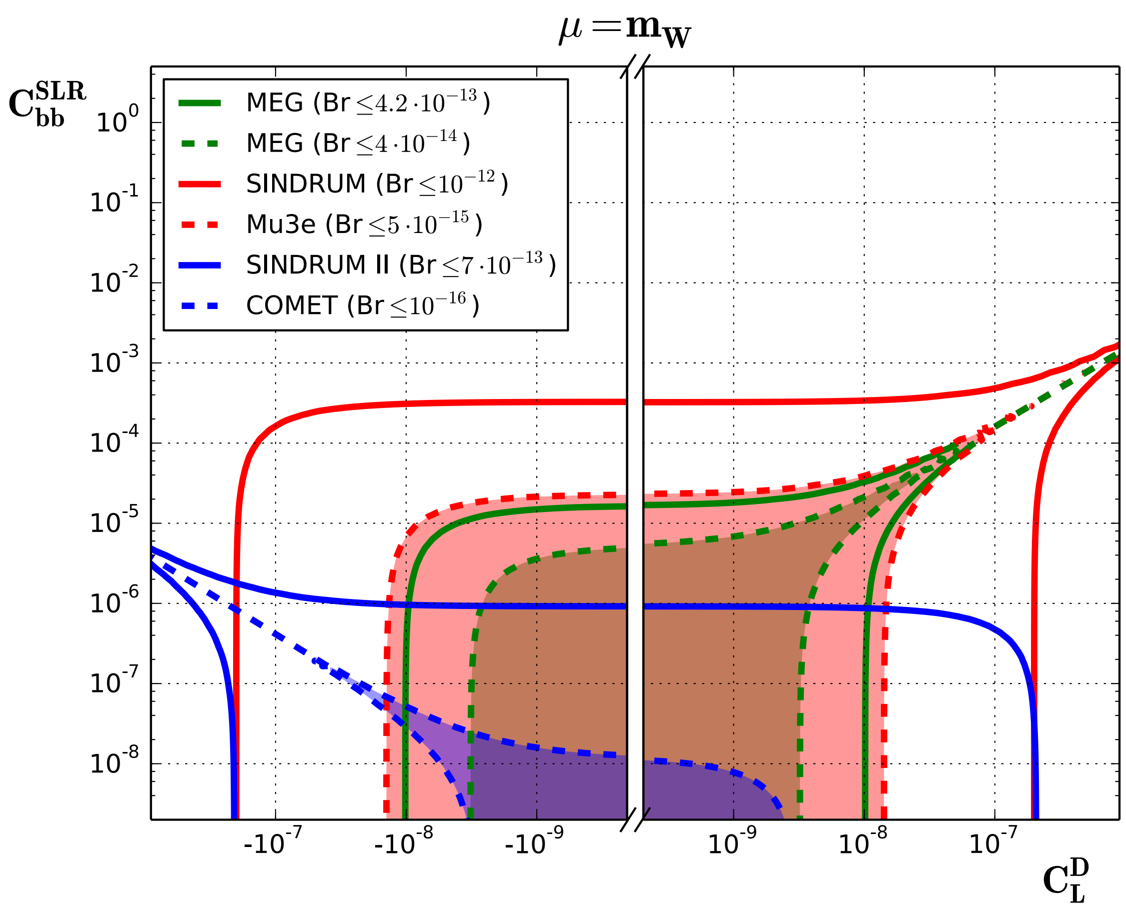
Letter of Intent, J-APRC P20 (2006).

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





Effective Field Theory



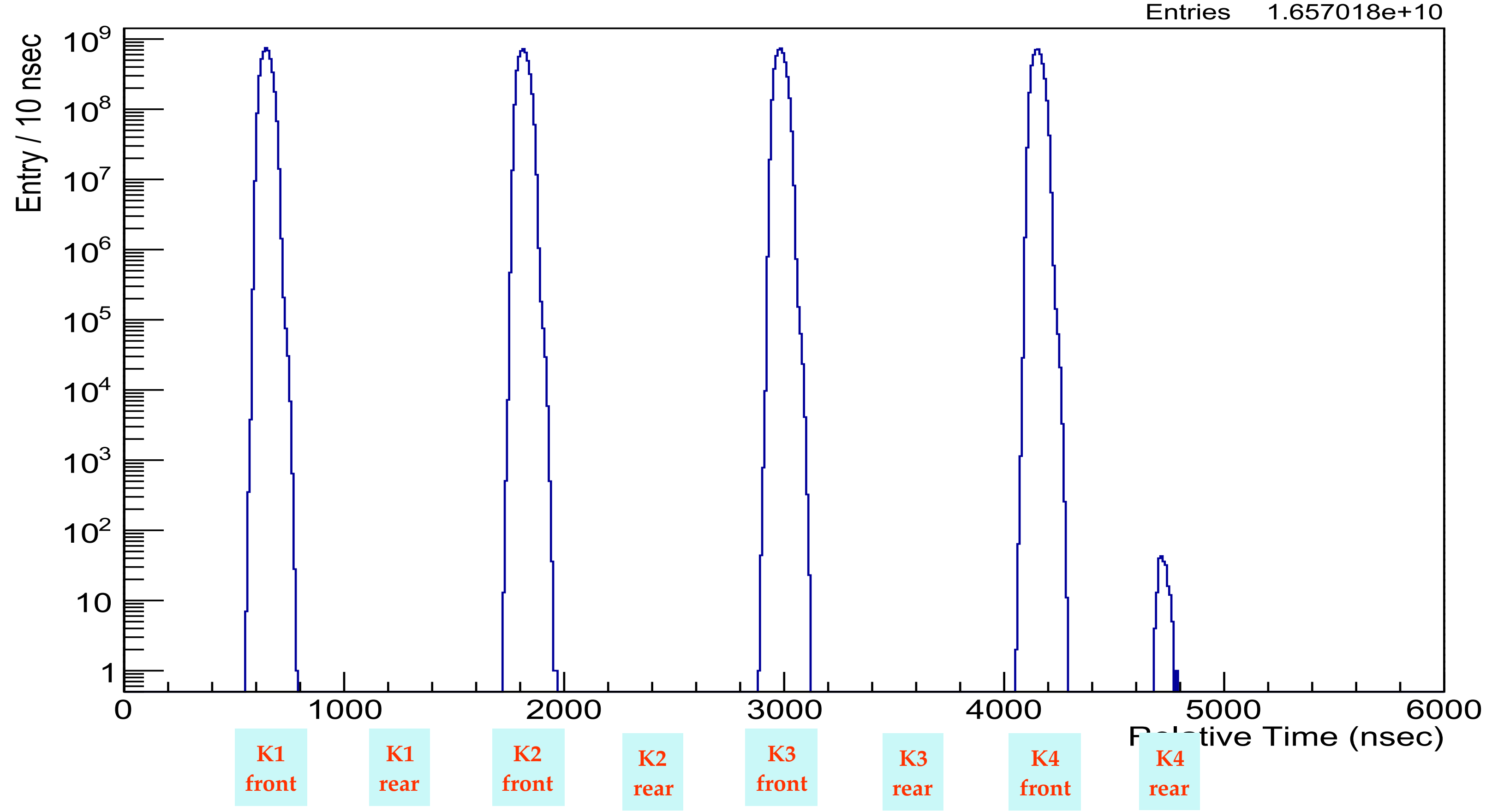
A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, JHEP 05, 117 (2017).

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} + \frac{1}{\Lambda^2}\Big\{ C_L^D O_L^D + \sum_{f=q,\ell} \left(C_{ff}^{V\,LL} O_{ff}^{V\,LL} + C_{ff}^{V\,LR} O_{ff}^{V\,LR} + C_{ff}^{S\,LL} O_{ff}^{S\,LL} \right) + \sum_{h=q,\tau} \left(C_{hh}^{T\,LL} O_{hh}^{T\,LL} + C_{hh}^{S\,LR} O_{hh}^{S\,LR} \right) + C_{gg}^{L} O_{gg}^{L} + L \leftrightarrow R \Big\} + \text{h.c.},$$

	$\text{Br}(\mu^+ \to e^+\gamma)$		$\text{Br}(\mu^+ \to e^+e^-e^+)$		$\text{Br}^{\text{Au/Al}}_{\mu\to e}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
$C_{\tau\tau}^{S\,LR}$	$9.4 \cdot 10^{-6}$	$2.9 \cdot 10^{-6}$	$1.8 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$2.7 \cdot 10^{-6}$
$C_{bb}^{S\,LL}$	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
$C_{bb}^{T\,LL}$	$2.1 \cdot 10^{-9}$	$6.4 \cdot 10^{-10}$	$4.1 \cdot 10^{-8}$	$2.9 \cdot 10^{-9}$	$4.2 \cdot 10^{-8}$	$6.0 \cdot 10^{-10}$
$C_{bb}^{S\,LR}$	$1.7 \cdot 10^{-5}$	$5.1 \cdot 10^{-6}$	$3.2 \cdot 10^{-4}$	$2.3 \cdot 10^{-5}$	$9.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
$C_{cc}^{S\,LL}$	$1.4 \cdot 10^{-6}$	$4.4 \cdot 10^{-7}$	$2.8 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-9}$
$C_{cc}^{T\,LL}$	$3.5 \cdot 10^{-9}$	$1.1 \cdot 10^{-9}$	$6.8 \cdot 10^{-8}$	$4.8 \cdot 10^{-9}$	$6.6 \cdot 10^{-8}$	$9.5 \cdot 10^{-10}$
$C_{cc}^{S\,LR}$	$1.2 \cdot 10^{-5}$	$3.6 \cdot 10^{-6}$	$2.3 \cdot 10^{-4}$	$1.6 \cdot 10^{-5}$	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-9}$
$C_{ee}^{V\,RR}$	$3.0 \cdot 10^{-5}$	$9.4 \cdot 10^{-6}$	$2.1 \cdot 10^{-7}$	$1.5 \cdot 10^{-8}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
$C_{ee}^{V\,RL}$	$6.7 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$2.6 \cdot 10^{-7}$	$1.9 \cdot 10^{-8}$	$4.0 \cdot 10^{-6}$	$6.7 \cdot 10^{-8}$
$C_{\mu\mu}^{V\,RR}$	$3.0 \cdot 10^{-5}$	$9.4 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$	$1.1 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
$C_{\mu\mu}^{V\,RL}$	$2.7 \cdot 10^{-5}$	$8.5 \cdot 10^{-6}$	$2.9 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$	$6.6 \cdot 10^{-8}$
$C_{\tau\tau}^{V\,RR}$	$1.0 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.9 \cdot 10^{-8}$
$C_{\tau\tau}^{V\,RL}$	$1.2 \cdot 10^{-4}$	$3.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$	$3.6 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$	$7.6 \cdot 10^{-8}$
$C_{bb}^{V\,RR}$	$3.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.8 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{bb}^{V\,RL}$	$5.3 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$6.6 \cdot 10^{-5}$	$4.7 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$9.9 \cdot 10^{-8}$
$C_{cc}^{V\,RR}$	$8.1 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-5}$	$1.6 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$3.4 \cdot 10^{-8}$
$C_{cc}^{V\,RL}$	$6.7 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
C_{gg}^{L}	N/A	N/A	N/A	N/A	$6.2 \cdot 10^{-3}$	$8.1 \cdot 10^{-5}$

Extinction at “Hadron” with Bunched-SX beam -2-

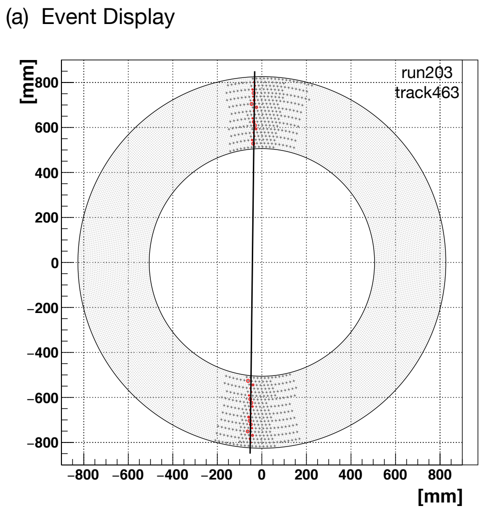
- **Result with kicker shift to realize an excellent extinction**

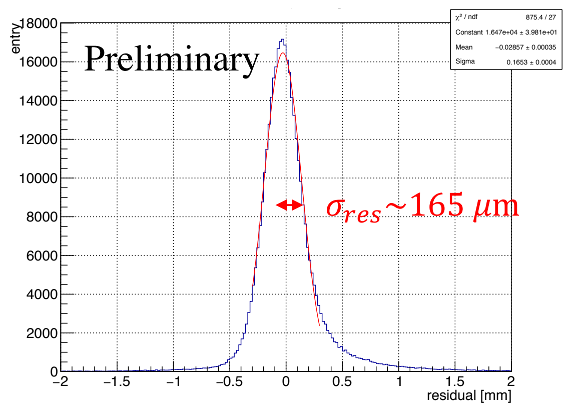


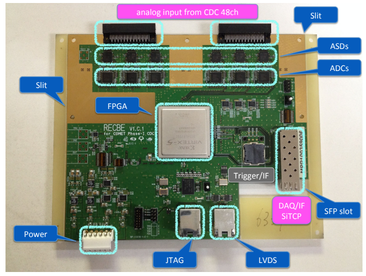
- Front buckets were filled with protons of COMET intensity (1.6×10^{12} ppp) and Injection Kicker was shifted 600 nsec forward
- **Perfect Extinction (= No Leak)** was realized for 3 Injection Batches (K1, K2 and K3)
- But…
  - Small amount of residual protons are shown in K4 rear…

CyDet status

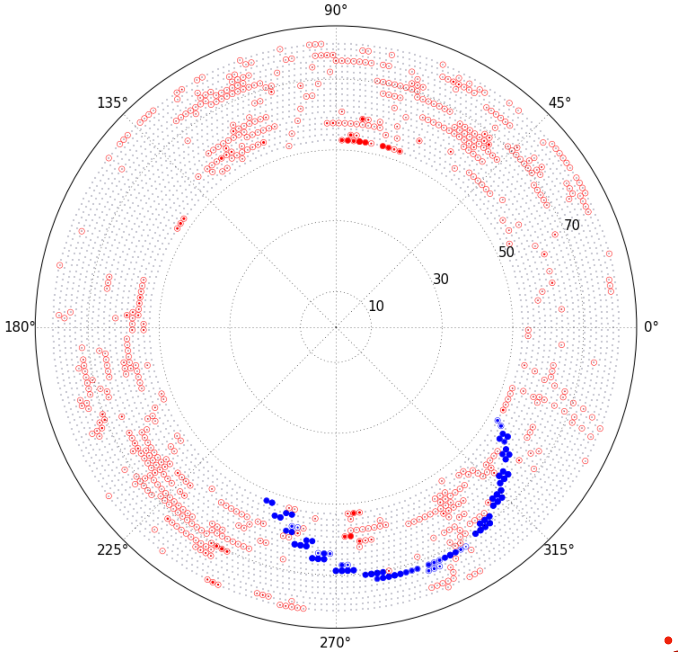
CDC cosmic-ray test is ongoing in KEK. Good performance was obtained.





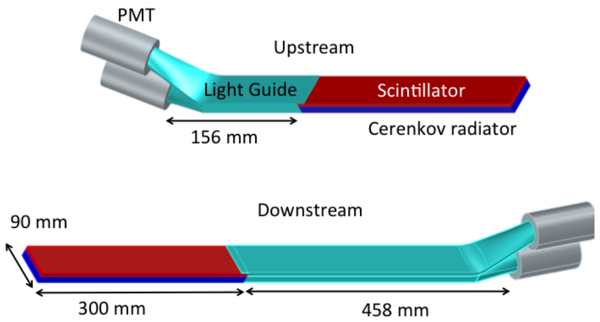


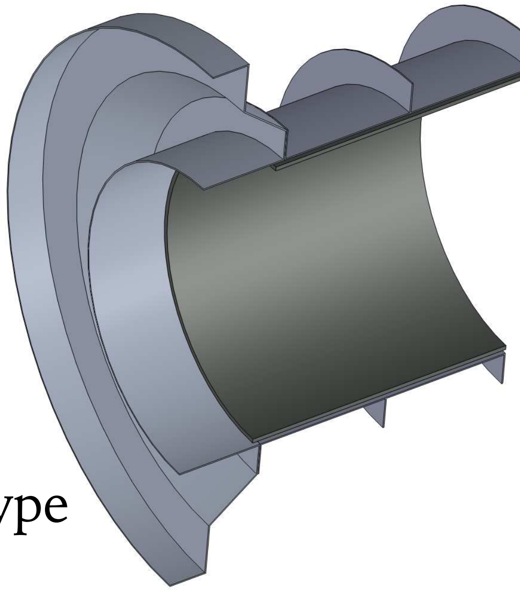
All 120 CDC FE boards were fabricated, and QA was finished in IHEP.



High-level track trigger

- Software-level algorithm was already established.
- can reduce background hits into 1/20 while retaining 99% of signals.

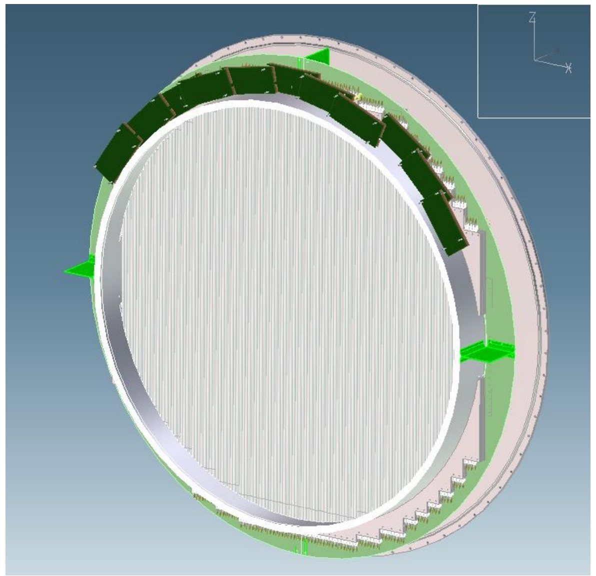




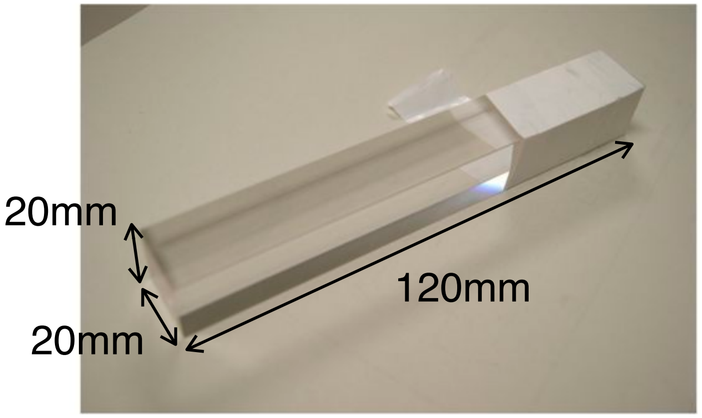
CTH structure prototype is under construction.

StrECAL status

Straw tube production for Phase-I was completed.

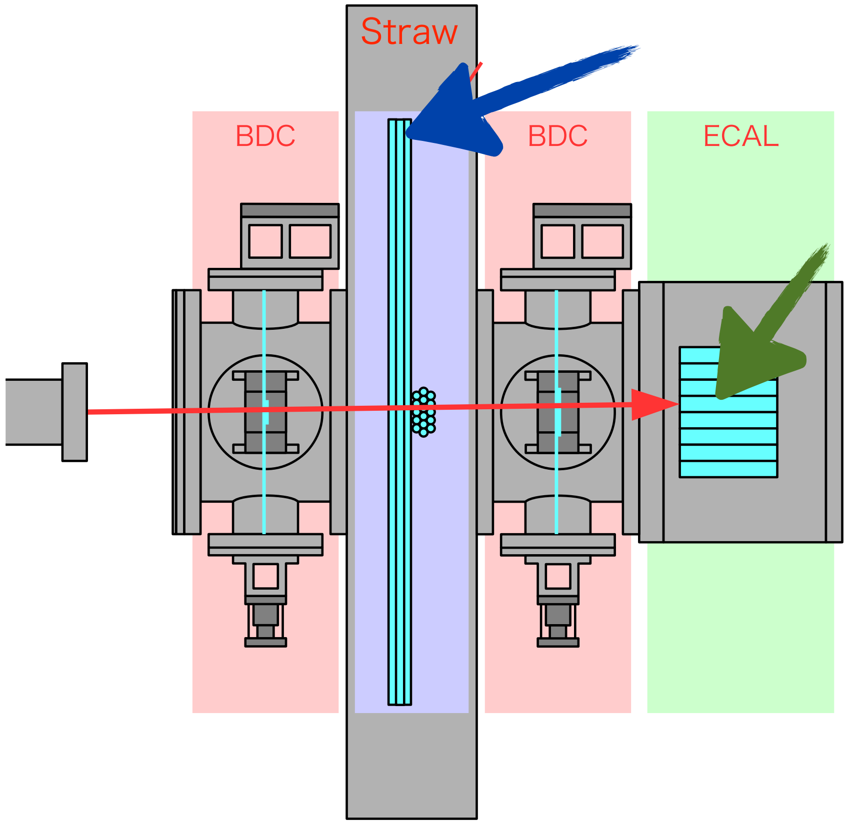


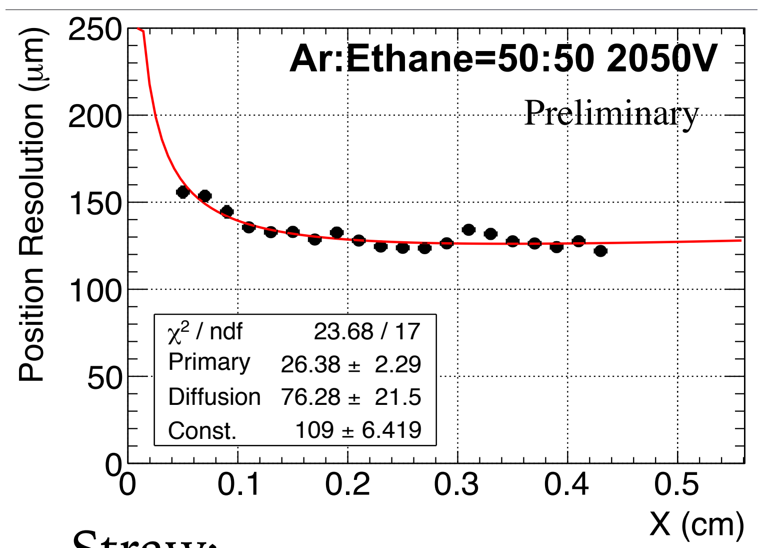
Thermal study of FE in gas manifold was carried out.
Straw station assembly is ongoing.



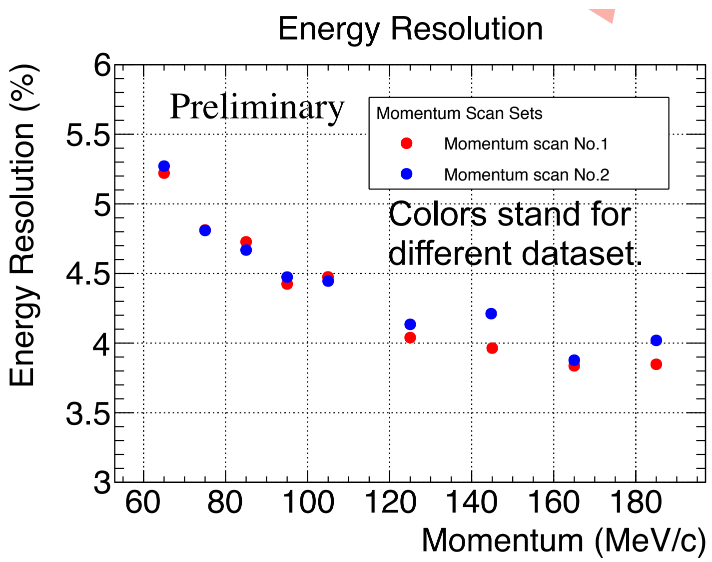
Buying procedure of ~500 LYSO for Phase-I is ongoing.

StrECAL Beam Test @ 2017





Straw:
position resolution < 150 μm



ECAL:
$\Delta E/E$ < 4.4% @ 105 MeV

Cosmic-Ray Veto detector

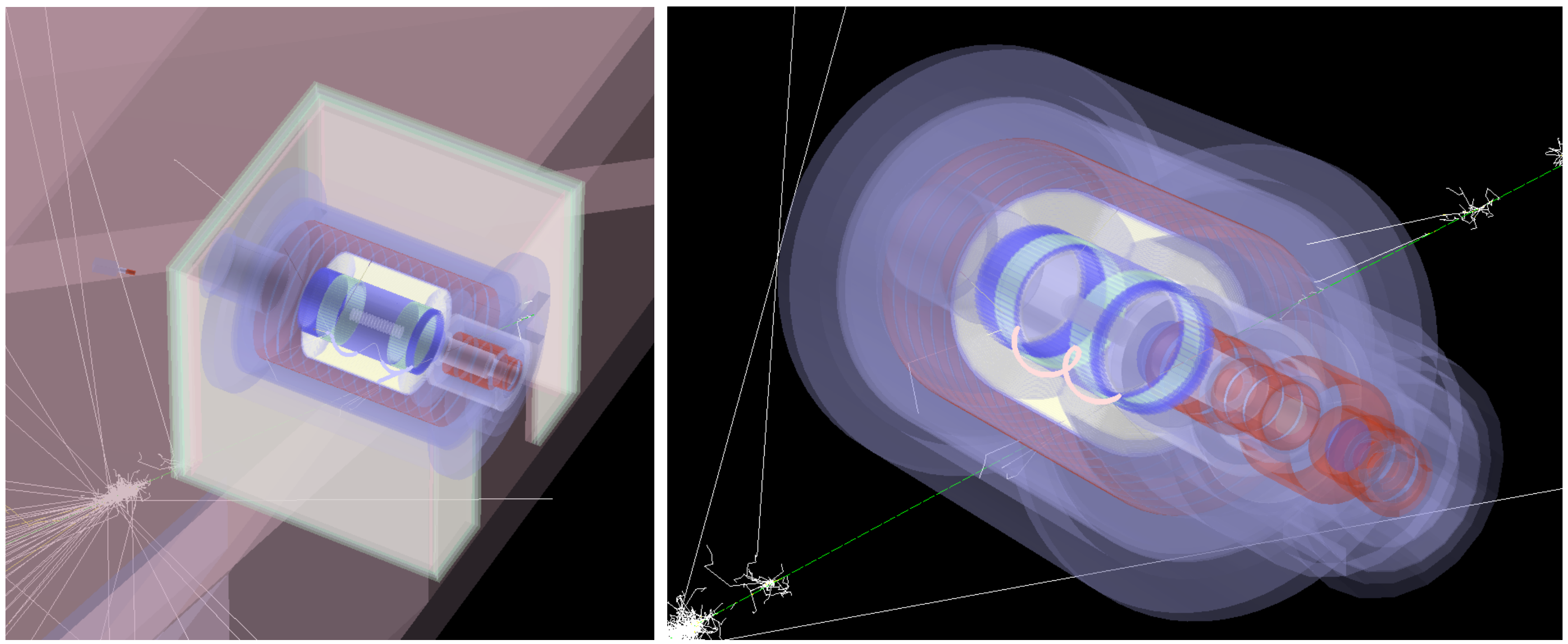
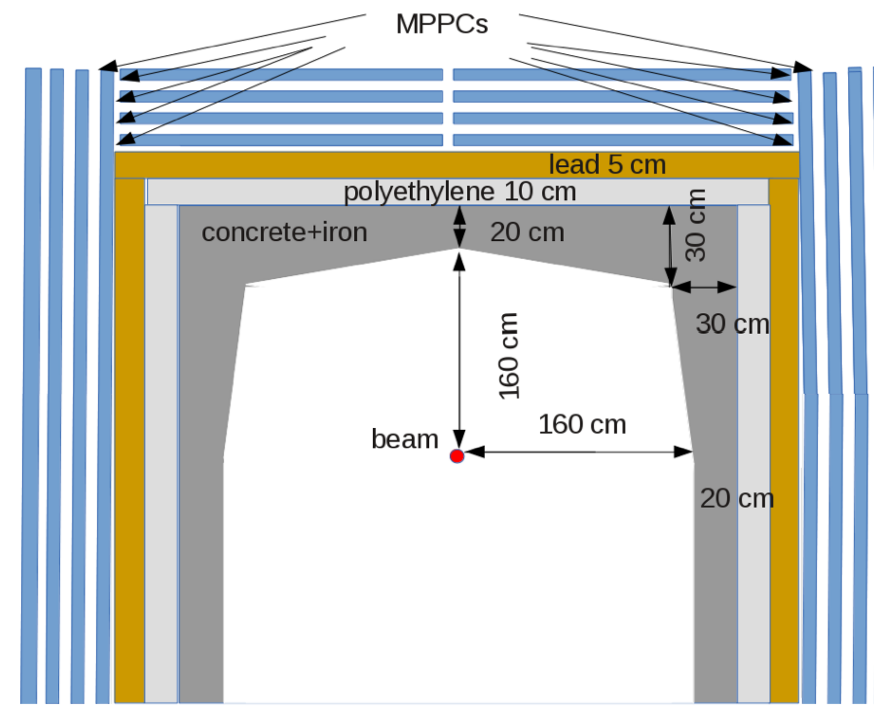
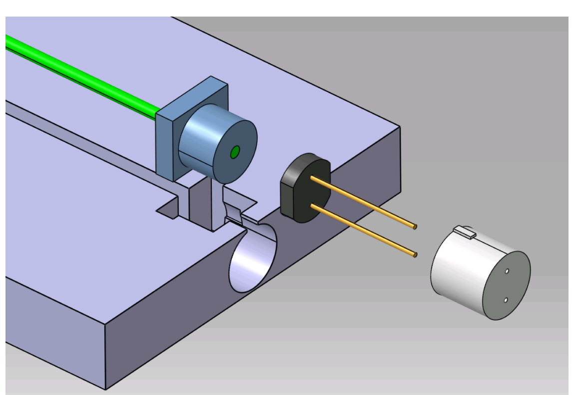


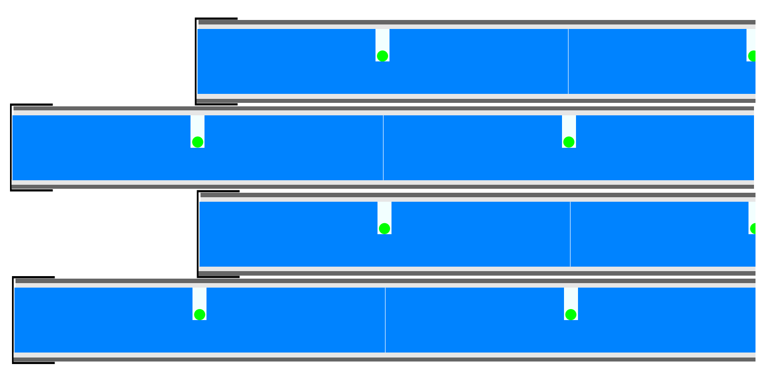
Figure 12.20: *One of the cosmic ray events which escapes the detection by the CRV and enters the BS region, creating an electron reaching the CDC. The same event shown for the whole detector region (left) and a zoomed view (right).*



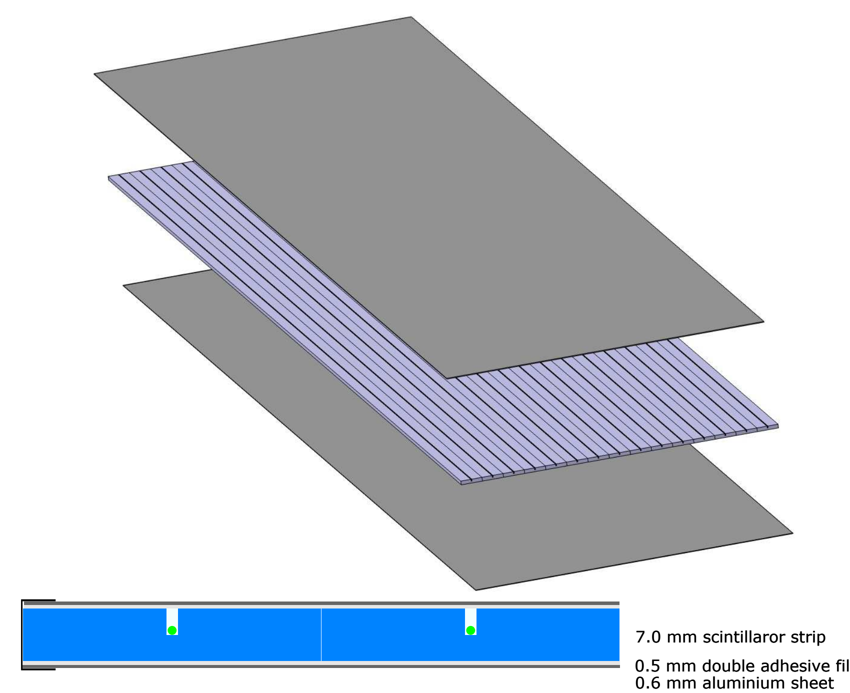
CRV inner shield



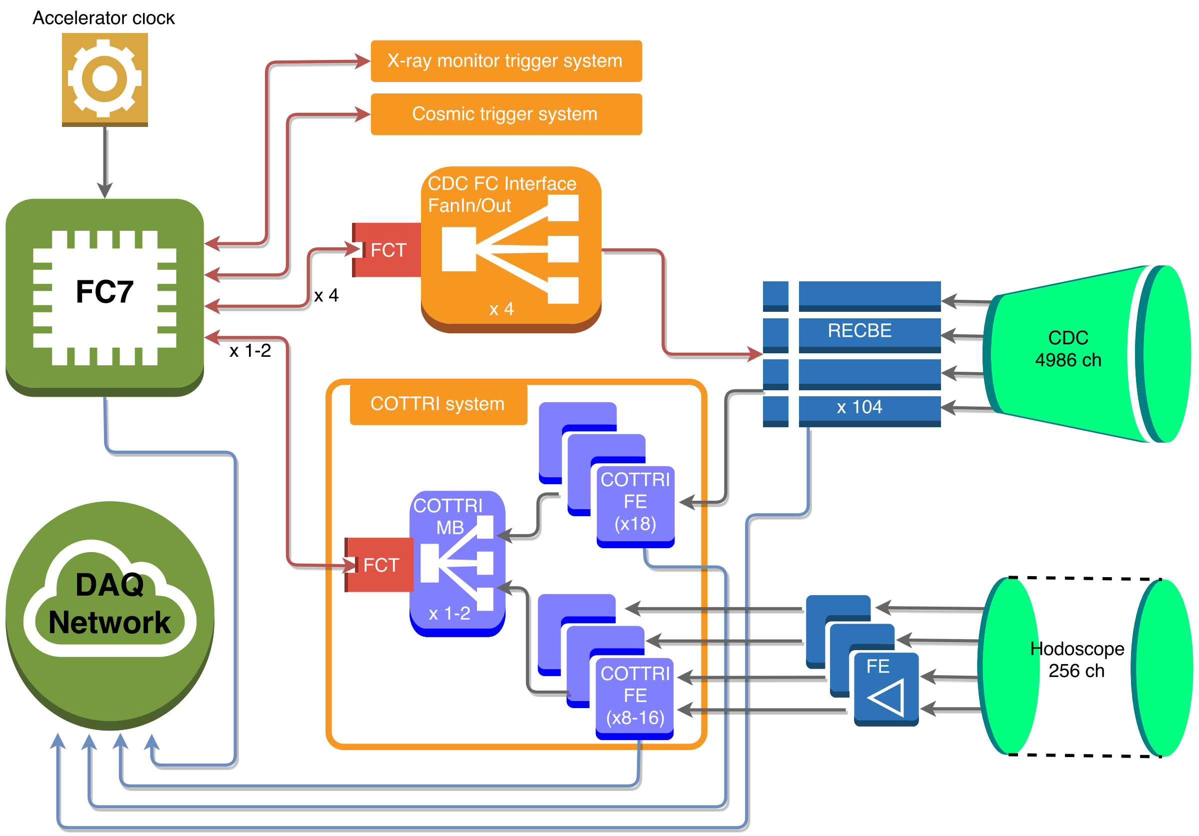
coupling mechanism of SiPM to WLS fibre

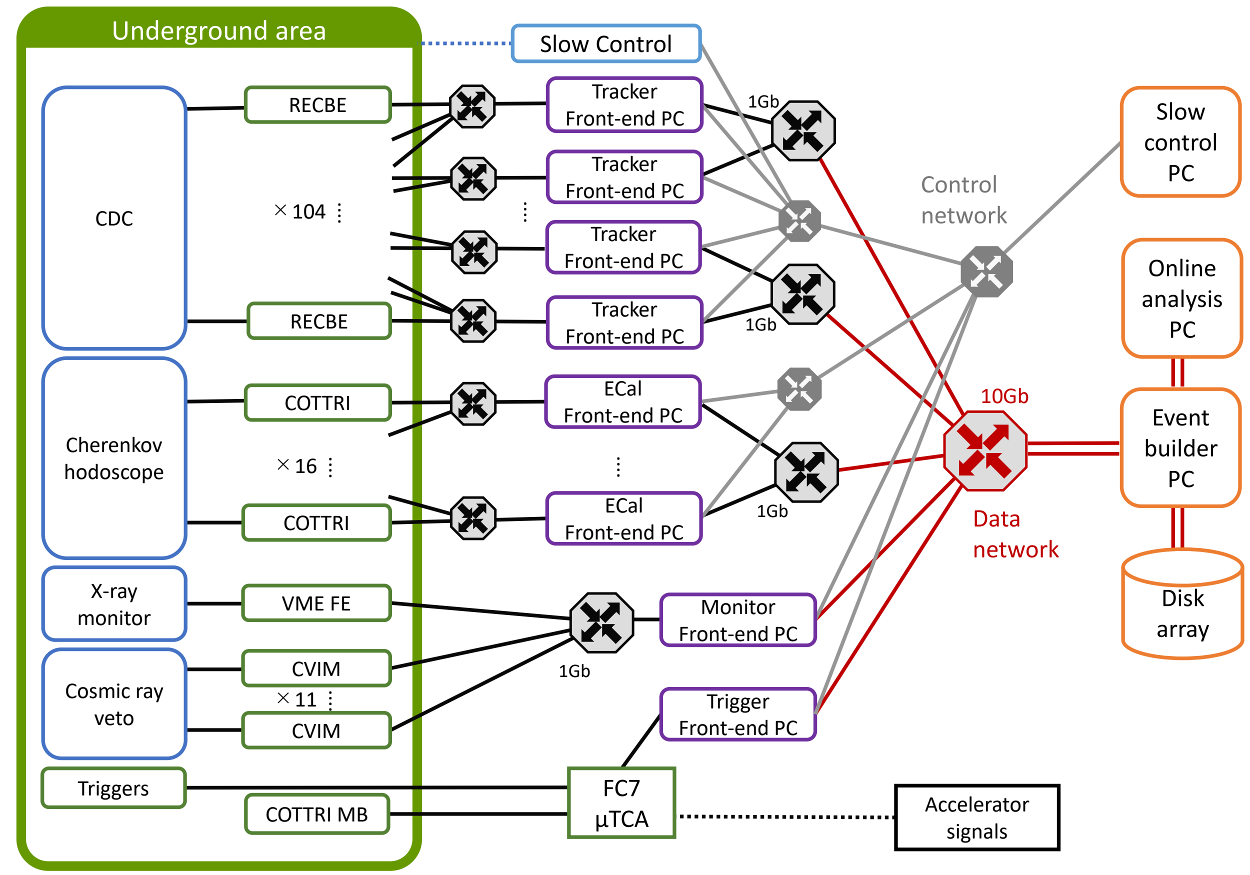


CRV strip layout

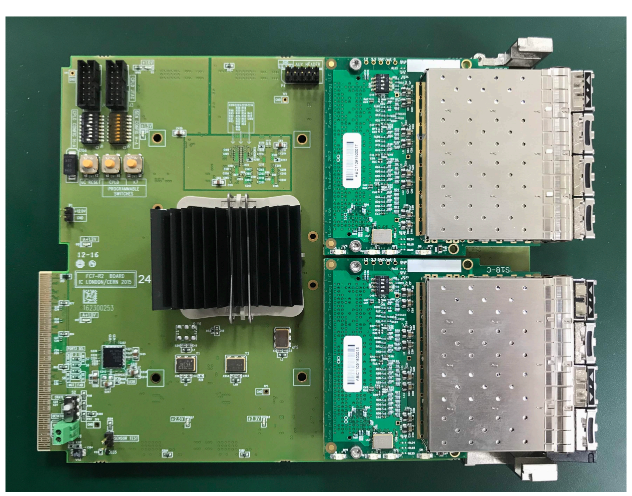


Trigger & DAQ

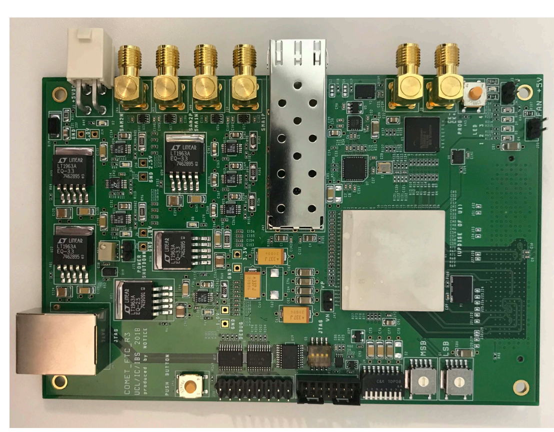




FC7



FCT



I/F board for FCT & RECBE