The COMET Experiment Search for Muon to Electron Conversion at J-PARC

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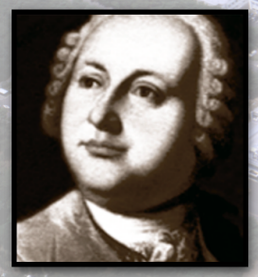


19th Lomonosov Conference on Elementary Particle Physics
22-28 Aug 2019, Moscow

Outline

COMET … **CO**herent **M**uon to **E**lectron **T**ransition

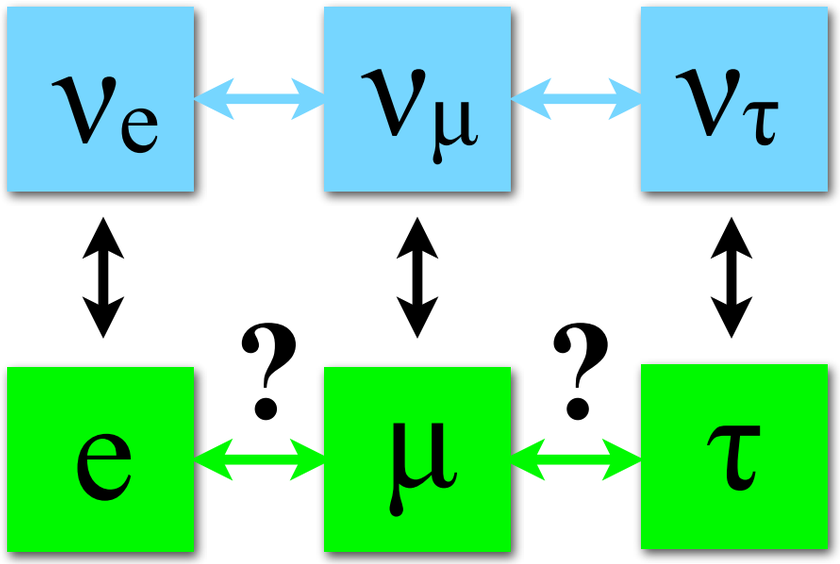
Experiment searching for **charged Lepton Flavor Violation** utilizing intense muon beam

- Physics Motivation
- COMET Experiment
- Development & Status
- Summary

Physics Motivation

Charged Lepton Flavor Violation

neutrino oscillation



- **Lepton Flavor Violation**
  is forbidden
  in the original Standard Model(SM).

- Neutrino oscillation
  = Flavor Violation of neutral leptons

cLFV

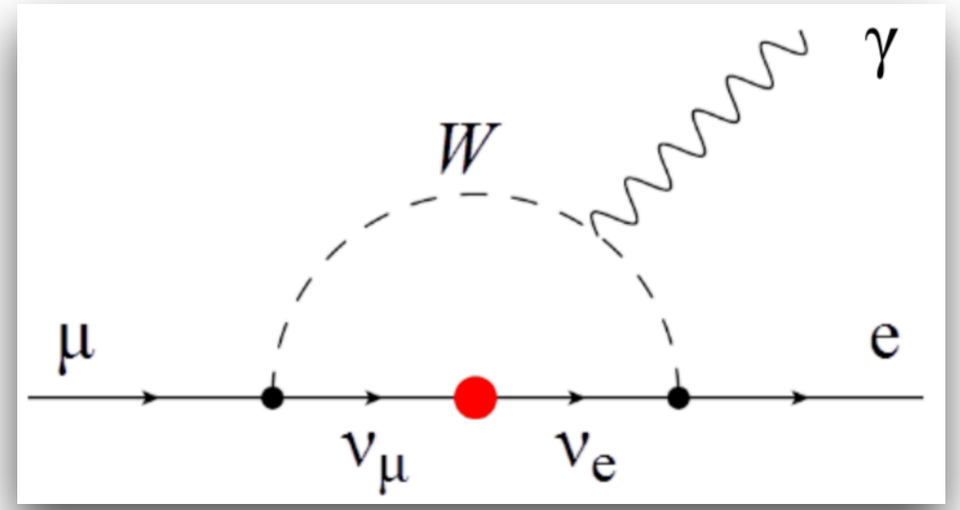
- charged Lepton Flavor Violation (cLFV)
  - process: **μ→ e γ , μ → e e e , μ N → e N**
  - **not observed yet**

Charged Lepton Flavor Violation

- cLFV induced by neutrino flavor mixing

$BR(\mu \rightarrow e\gamma) \propto (\Delta m_{vij}^2/M_W^2)^2 \sim \mathbf{10^{-54}}$

too small to be observed
experimentally
in the framework of the SM

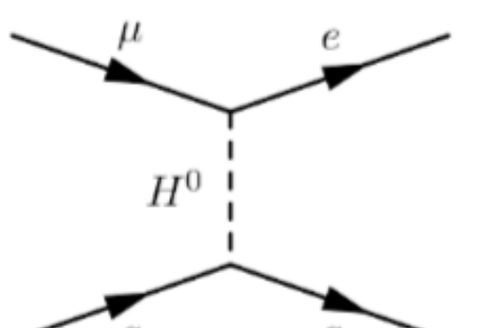


Experimental observation of cLFV process
||
Clear evidence of the new physics beyond the SM

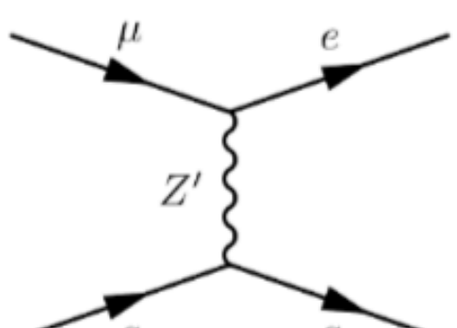
Charged Lepton Flavor Violation

- Theoretical models beyond SM

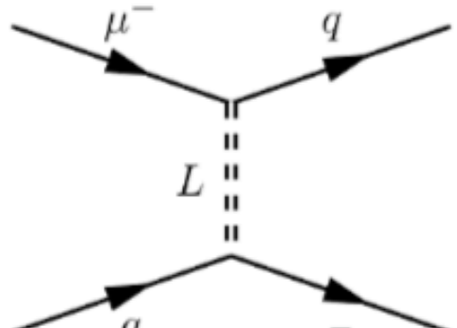
  sizable branching ratio of cLFV predicted = $\mathbf{10^{-14} \sim 10^{-18}}$



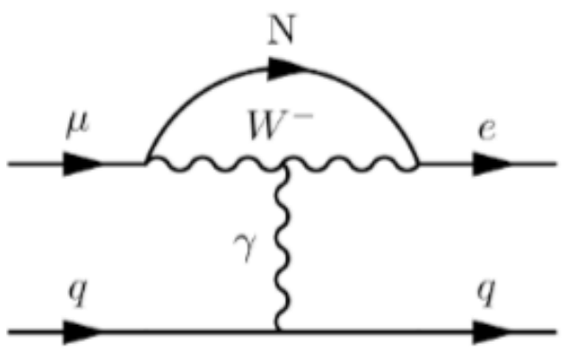
Exotic Higgs



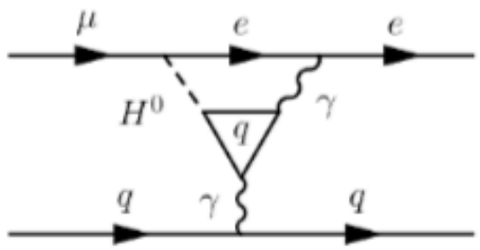
Z-prime



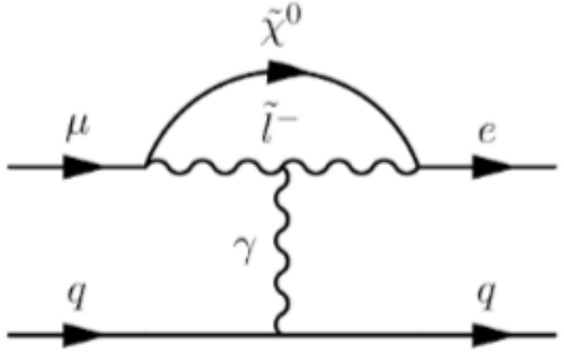
Leptoquarks



Heavy Neutrinos



Exotic Higgs



Supersymmetry

etc.

Charged Lepton Flavor Violation

- Current Upper Limits from Experiments

predicted = $\mathbf{10^{-14} \sim 10^{-18}}$

$\mu^- N \rightarrow e^- N$
SIMDRUM-II: BR(μ^- Au$\rightarrow e^-$ Au) < $\mathbf{7 \times 10^{-13}}$
SIMDRUM-II: BR(μ^- Ti$\rightarrow e^-$ Ti) < $\mathbf{4.3 \times 10^{-12}}$
TRIUMF : BR(μ^- Ti$\rightarrow e^-$ Ti) < $\mathbf{4.6 \times 10^{-12}}$

$\mu^+ \rightarrow e^+\gamma$
MEG: BR($\mu^+ \rightarrow e^+ \gamma$) < $\mathbf{4.2 \times 10^{-13}}$

The discovery is right around the corner.

Discovering new physics and precise measurement with Extreme Sensitivity!

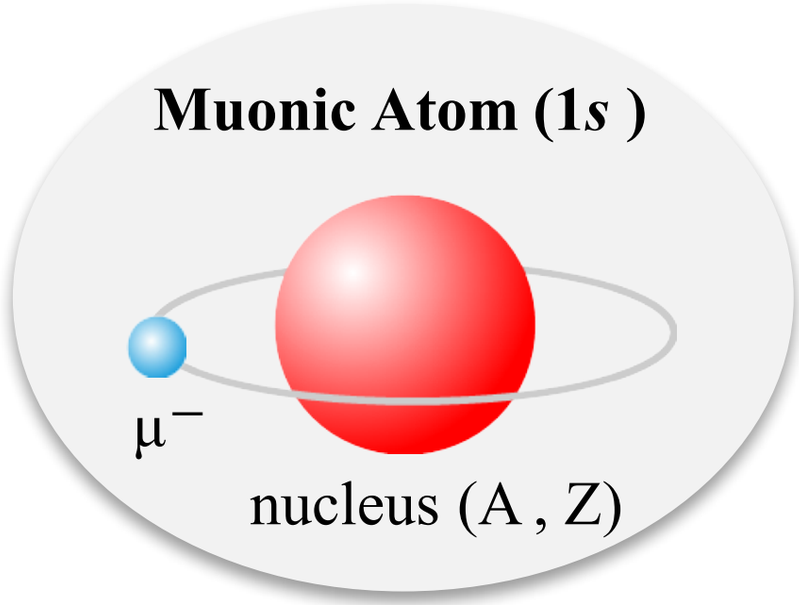
Muon to Electron Conversion in the Nuclear Field

Decay-In-Orbit (DIO)

$$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$$

Muon Capture

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



μ - e Conversion

$$\mu^- N \rightarrow e^- N$$

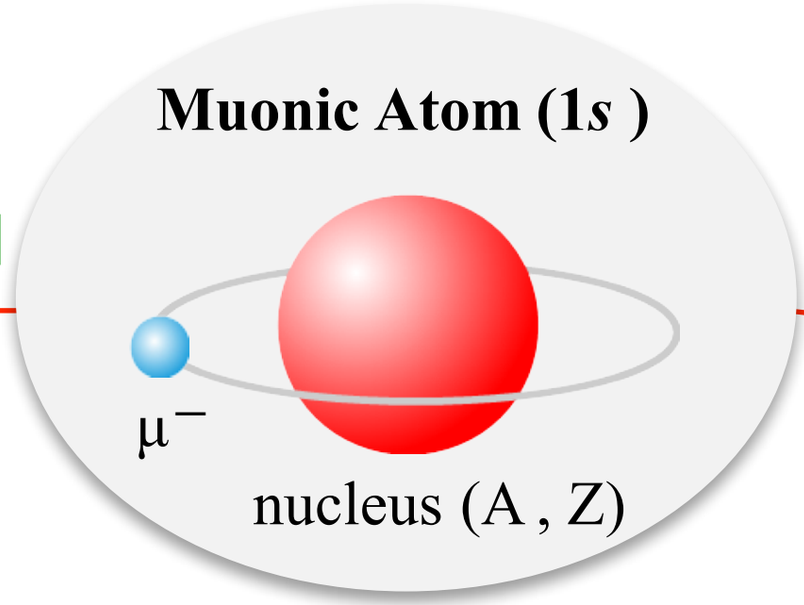
- Mono-energetic signal electron (**~105 MeV/c**) will be searched.

Muon to Electron Conversion in the Nuclear Field

Decay-In-Orbit (DIO)

$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$

Muon Capture



μ - e Conversion $\mu^- N \rightarrow e^- N$

- Beam related background

  prompt timing ex. Radiative Pion Capture

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

  can be avoided by **selecting delayed e^-**

- Cosmic ray background

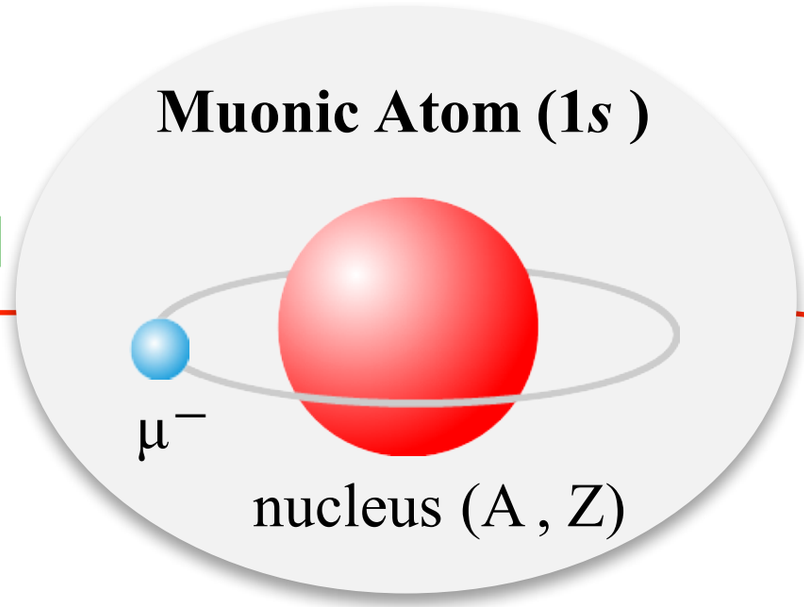
  surround the whole system with veto counters.

Muon to Electron Conversion in the Nuclear Field

Decay-In-Orbit (DIO)

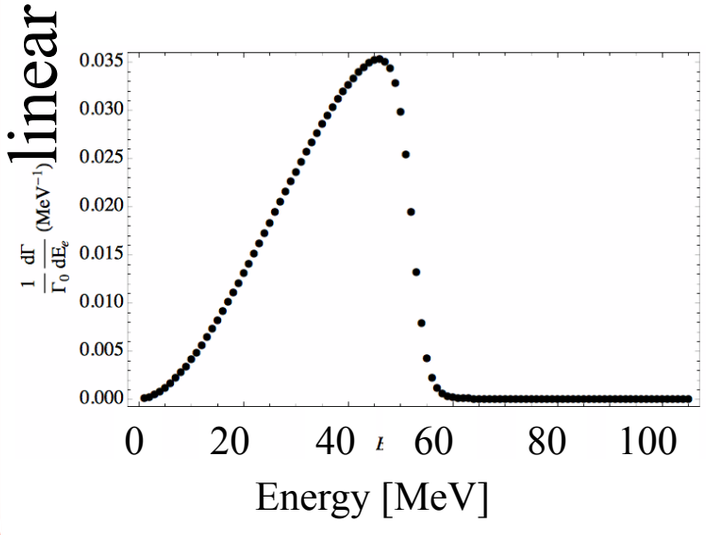
$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$

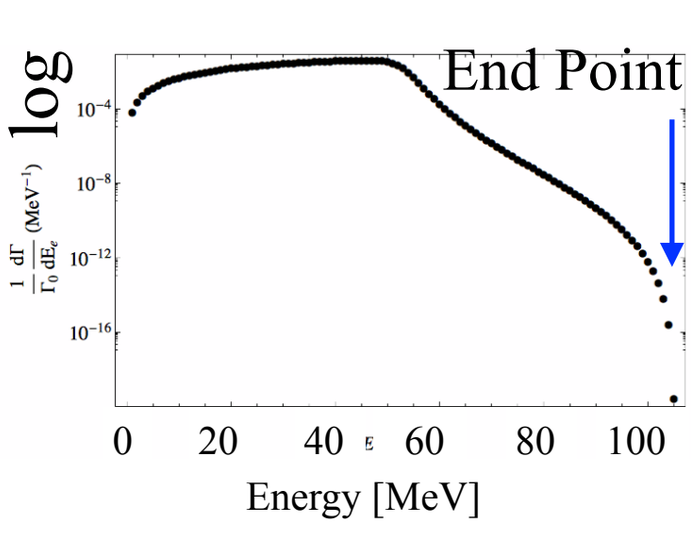
Muon Capture

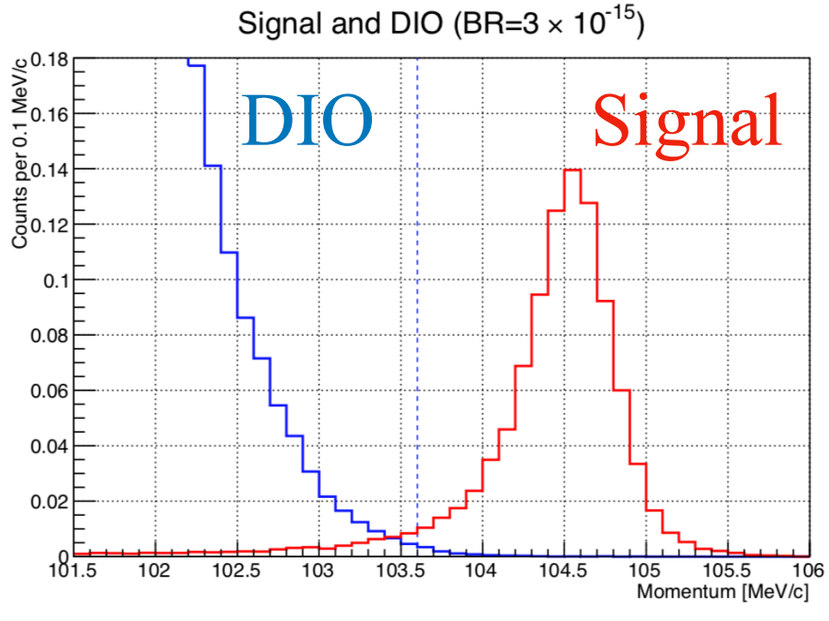


μ - e Conversion $\mu^- N \rightarrow e^- N$

- The most important background **Decay-In-Orbit** nucleus recoil … higher tail extended → close to the signal region
- **need precise momentum measurement**





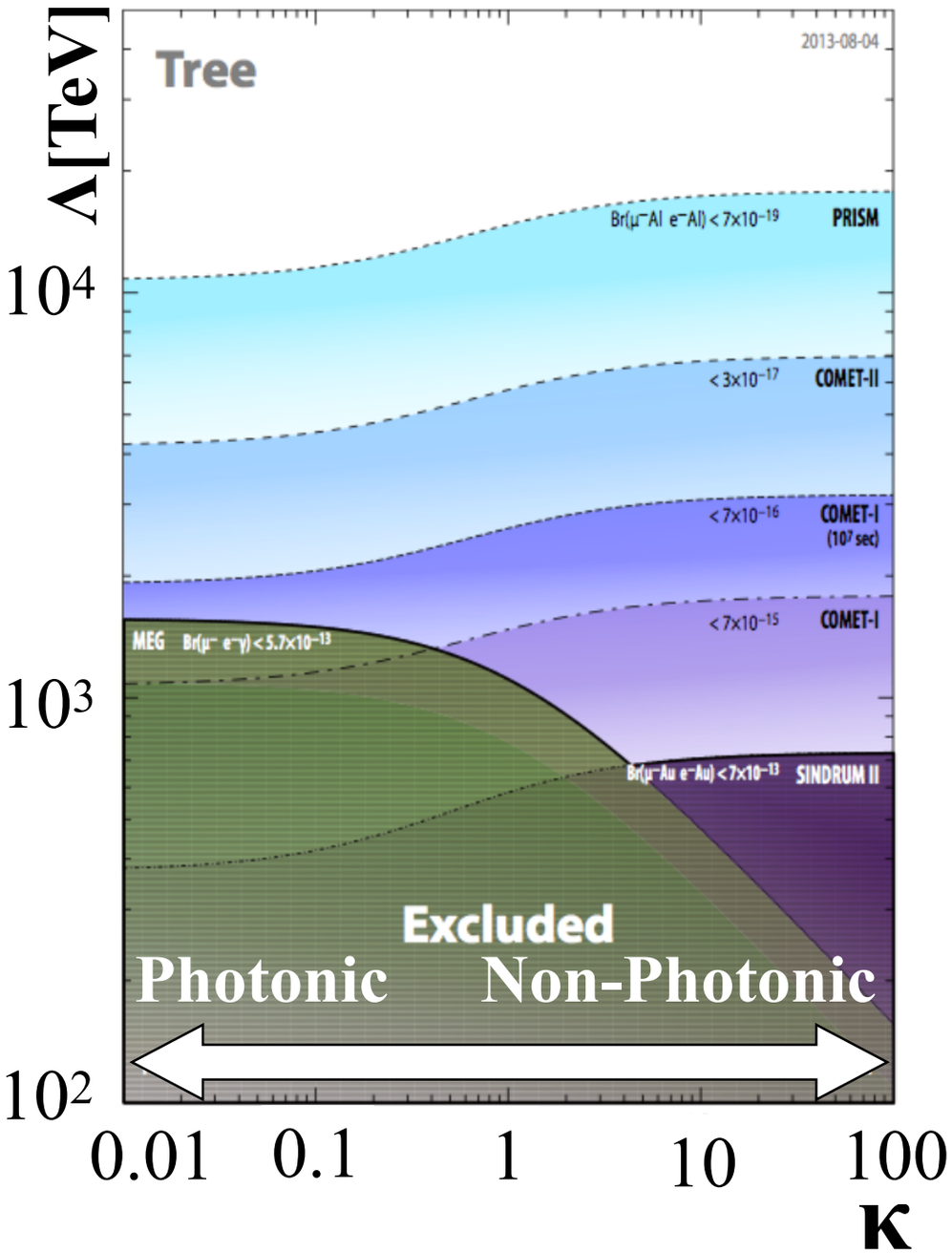


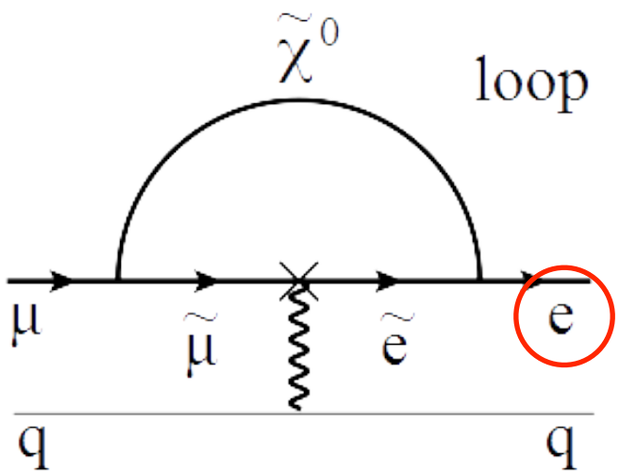
Sensitivity to Reaction Mechanism

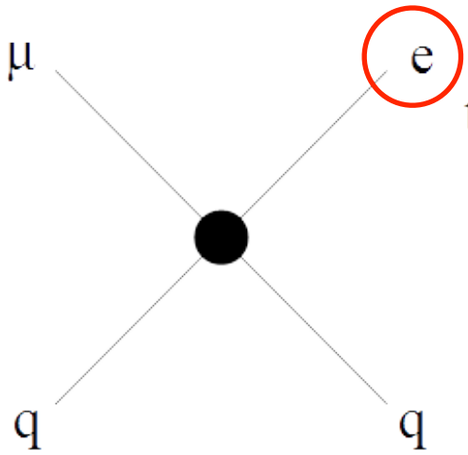
- Effective Lagrangian

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

Photonic　　Non-Photonic







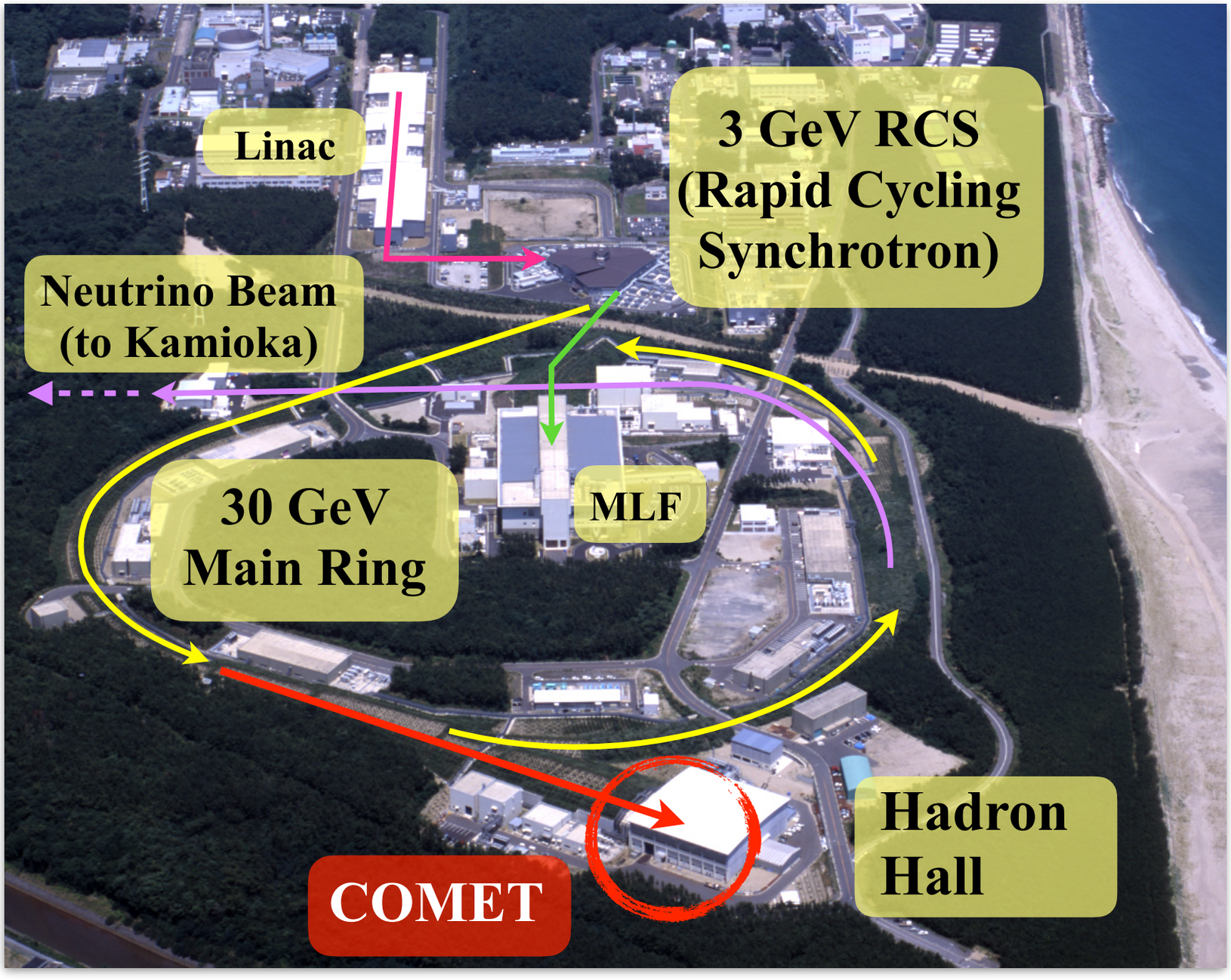
μ-e conversion in the nuclear field

= Sensitive to both Photonic and Non-Photonic processes

conf.　MEG　$\mu^+ \rightarrow e^+\gamma$

COMET Experiment

- **J-PARC (Tokai, Japan)**
  - Extending the Hadron Hall
  - Staging approach (Phase-I, Phase-II)



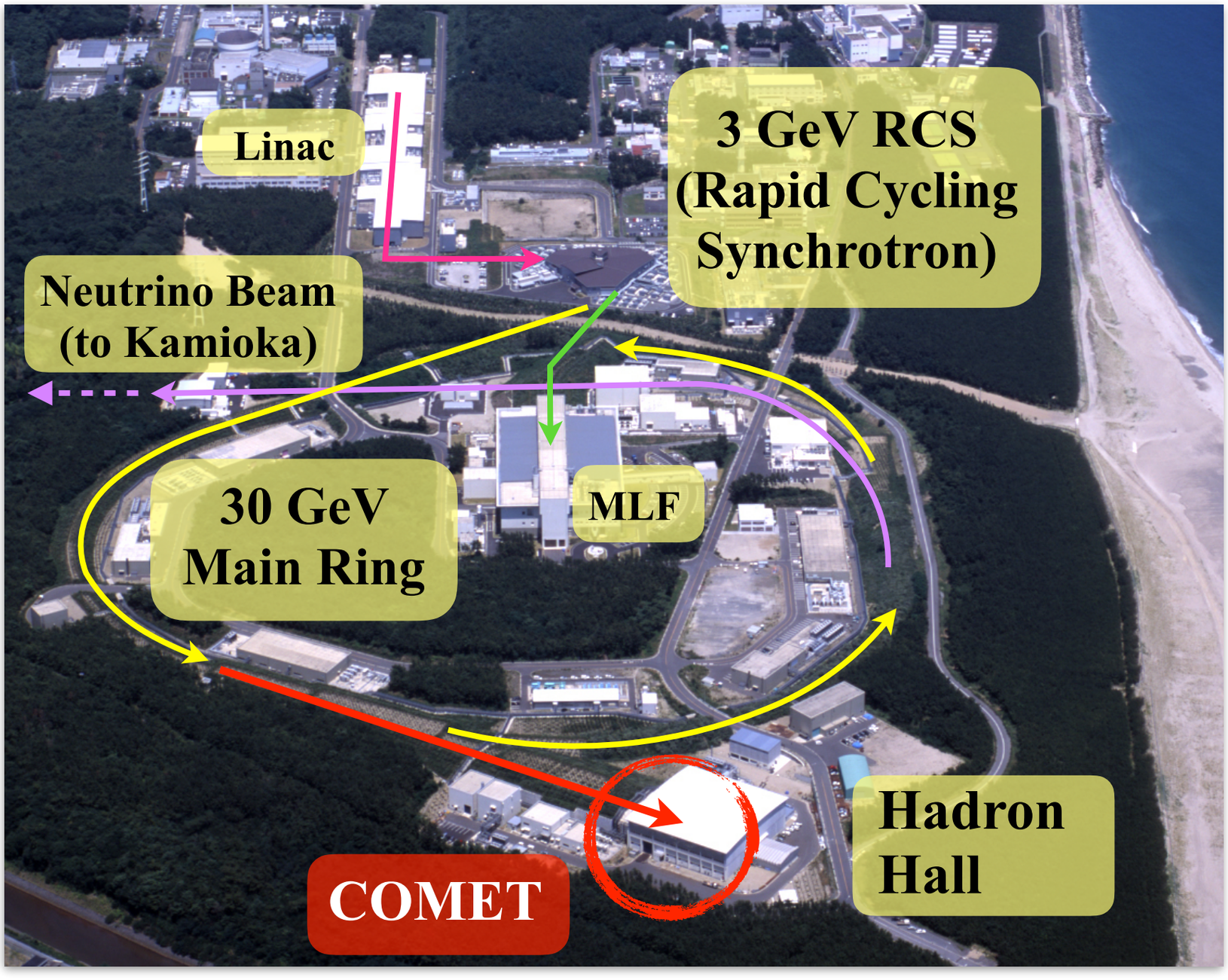
COMET Experiment

- Proton beam from Main Ring

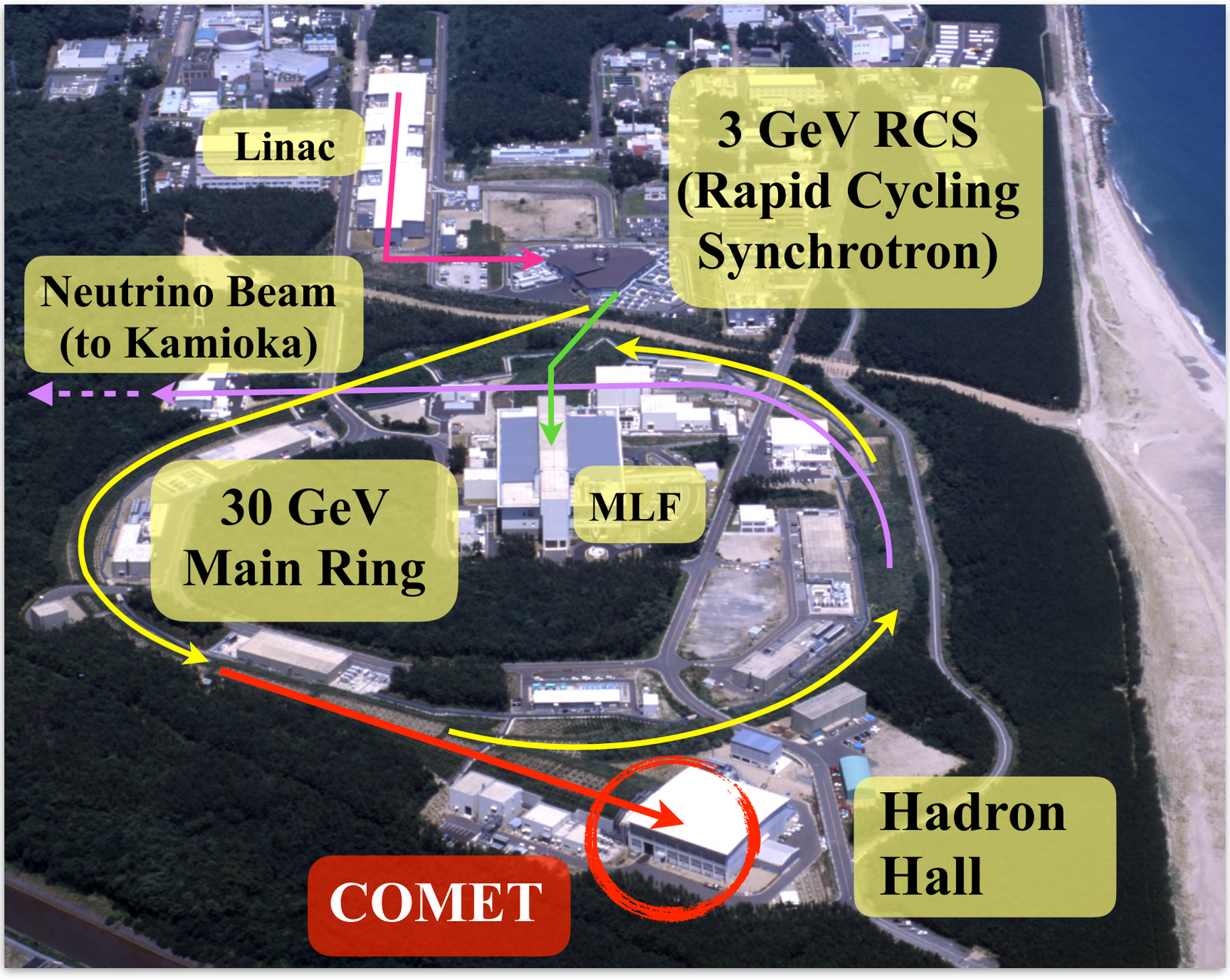
  - **8 GeV**
  - **1.17 μsec** repetition
  - Beam Power

    3.2 kW for Phase-I

    56 kW for Phase-II



- Good Extinction Factor
  - ratio of off-timing protons = $\dfrac{\text{(protons between buckets)}}{\text{(protons in filled buckets)}}$



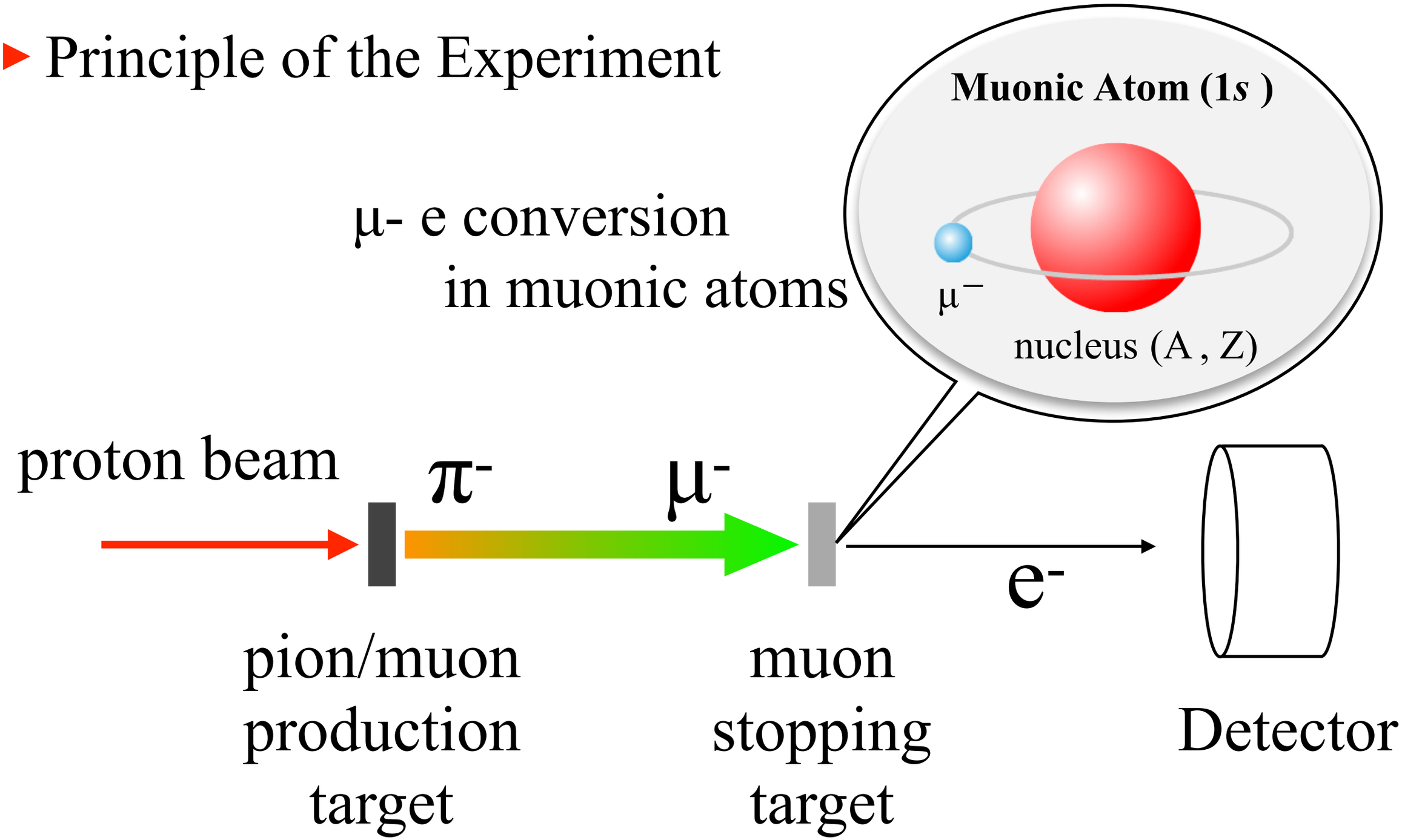
- requirement < $\mathbf{10^{-10}}$
- measured $\mathbf{6\times10^{-11}}$

(described later)

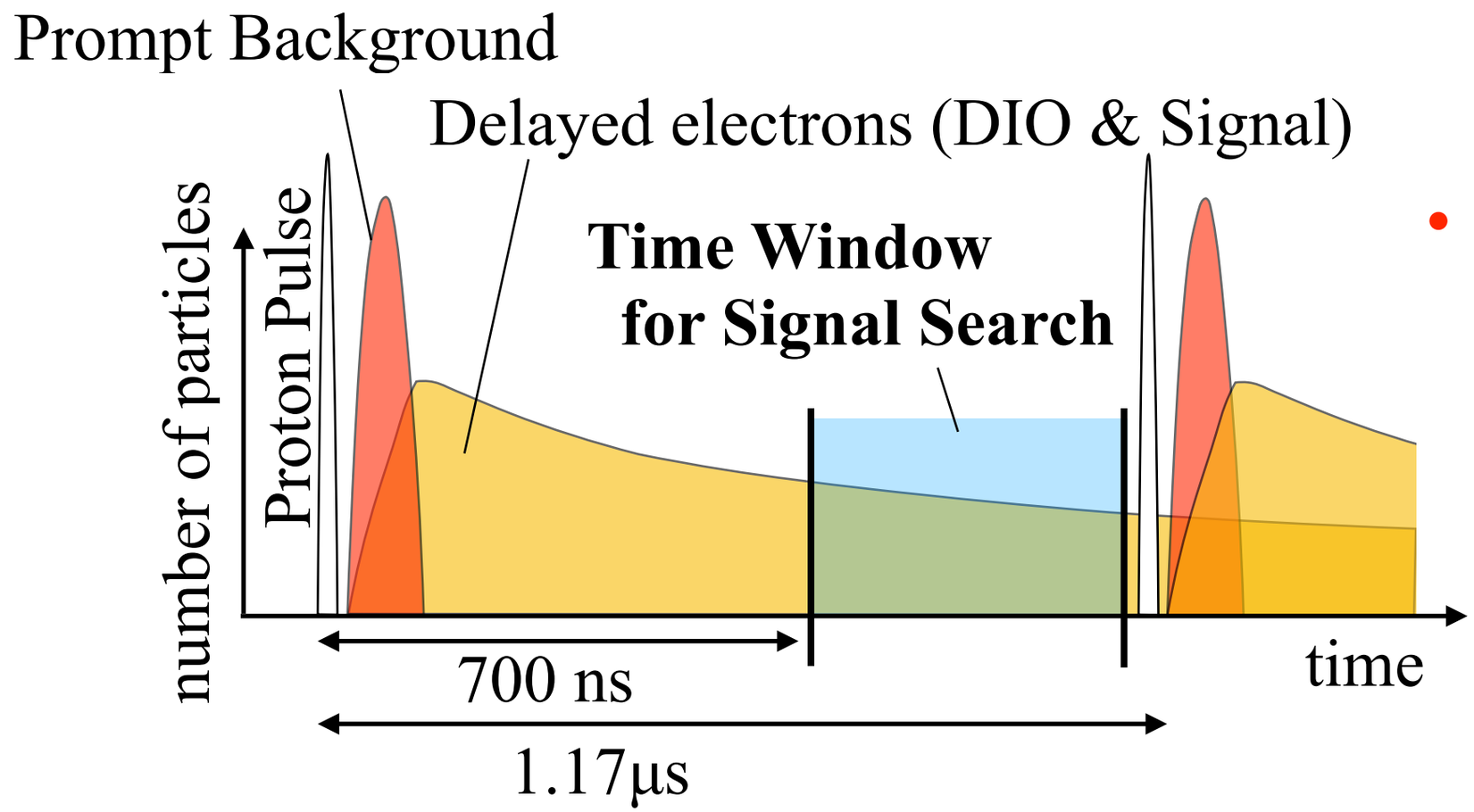
COMET Experiment

- Principle of the Experiment

μ- e conversion
in muonic atoms



▶ Utilizing a Pulsed Beam



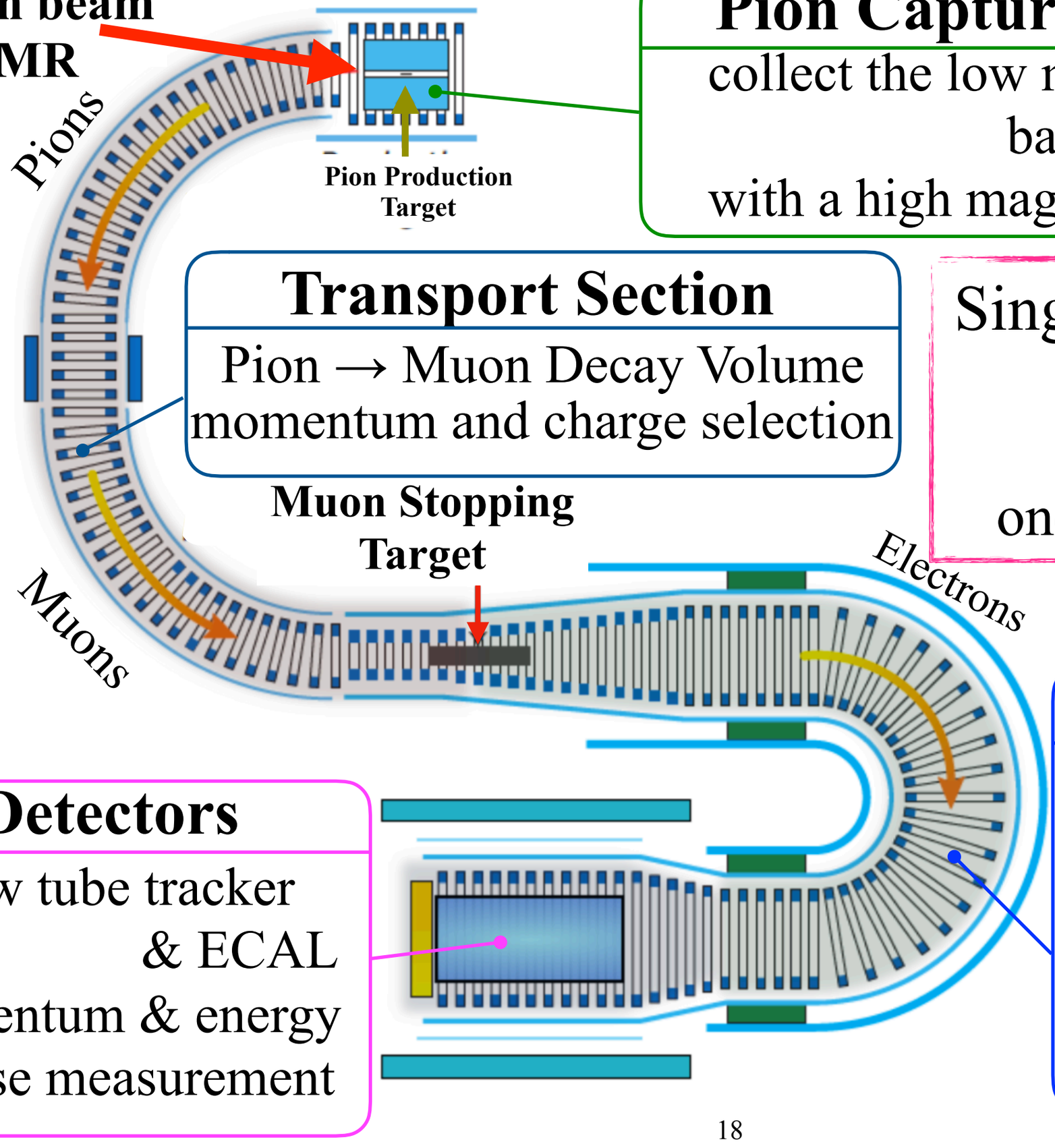
- Delayed Time Window
  avoid
  prompt beam-related
  backgrounds

- Material of stopping target
  heavier nucleus … large overlap with muon wave function
  but, short life time of muon
  - **Aluminum** stopping target will be used for COMET.

τ_μ in Al ~ **0.9μsec**

COMET Experiment (Full setup, Phase-II)

Proton beam from MR



Pion Capture Section

collect the low momentum, backward pions with a high magnetic field (**5T**)

Transport Section

Pion → Muon Decay Volume
momentum and charge selection

Single event sensitivity
2.6×10^{-17}
(potentially one more order better)

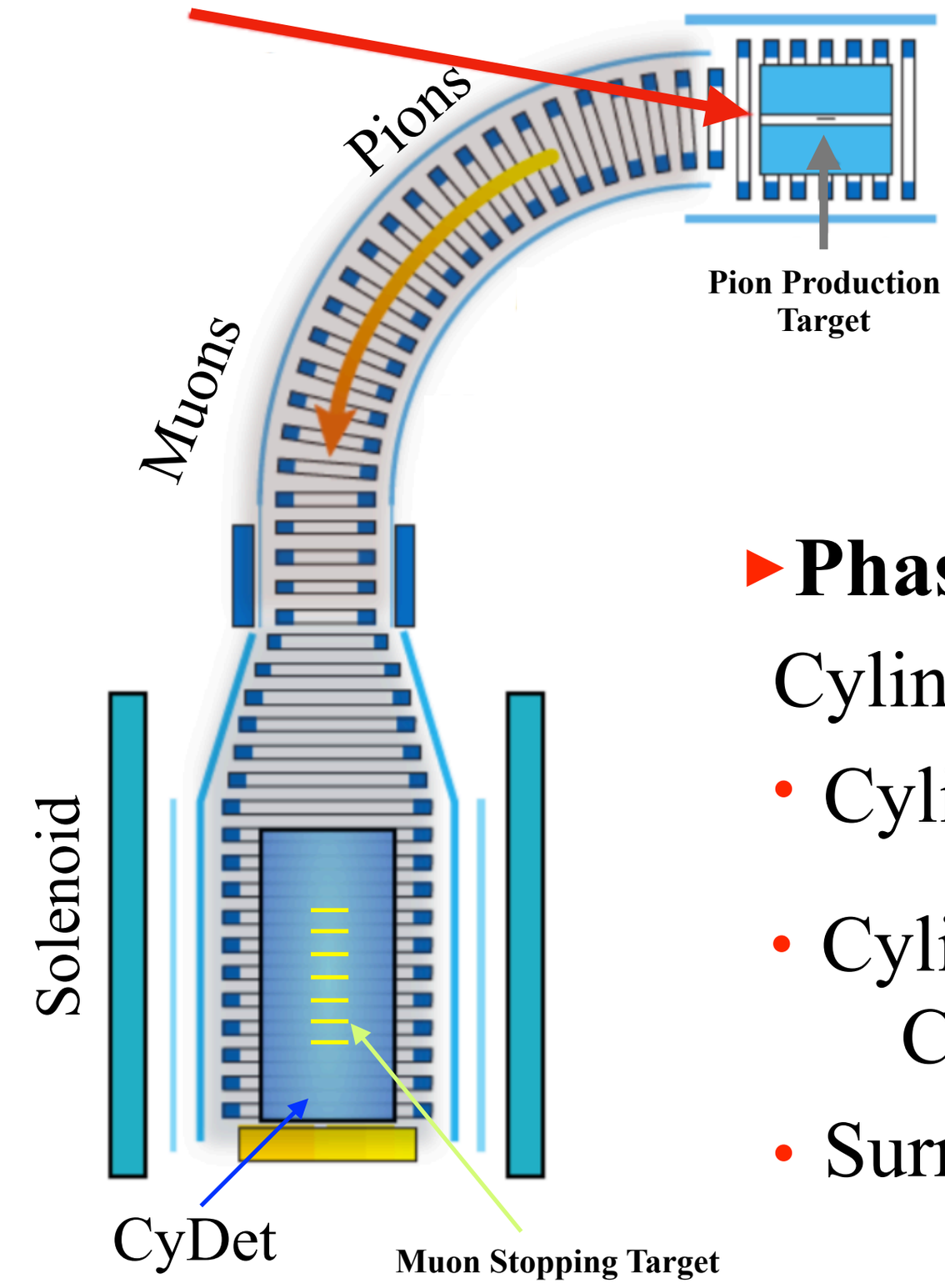
Electron Spectrometer

select momentum (~**105 MeV/c**) & charge
eliminate off-momentum BG

Detectors

Straw tube tracker & ECAL
momentum & energy precise measurement

COMET Experiment (Phase-I)



Aims of Phase-I

- Search for μ - e conversion with single event sensitivity of 3×10^{-15}
- Direct measurement of backgrounds for Phase-II

Phase-I detector

Cylindrical Detector system (**CyDet**)

- Cylindrical Drift Chamber (CDC)
- Cylindrical Trigger Counter (CTH)
  Cherenkov & Scintillator
- Surrounding the muon stopping target (17 Aluminum disks)

Single Event Sensitivity

- Single Event Sensitivity $= \dfrac{1}{N_\mu \times f_{cap} \times f_{gnd} \times A_{\mu e}}$

N_μ = number of muons stopping on the target

f_{cap} = fraction of muon capture

f_{gnd} = fraction of nucleus which is not excited by μ-e conv.

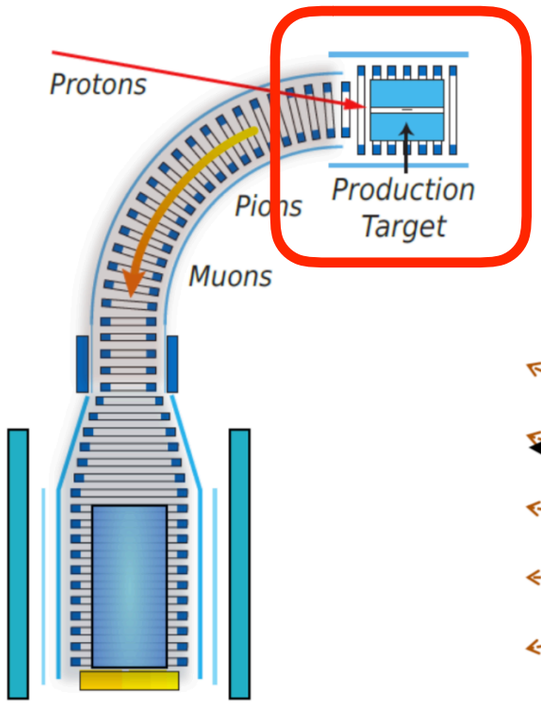
$A_{\mu e}$ = total acceptance for e^- from μ-e conv.

	Phase I	Phase II
Beam power	3.2 kW	56 kW
Protons on target	3×10^{19}	3×10^{21}
Stopped muons on	1.5×10^{16}	1.5×10^{18}
Running time	~ 5 months	~ 1 year
S.E.S	**3×10^{-15}**	**2.6×10^{-17} (potentially ~10^{-18})**

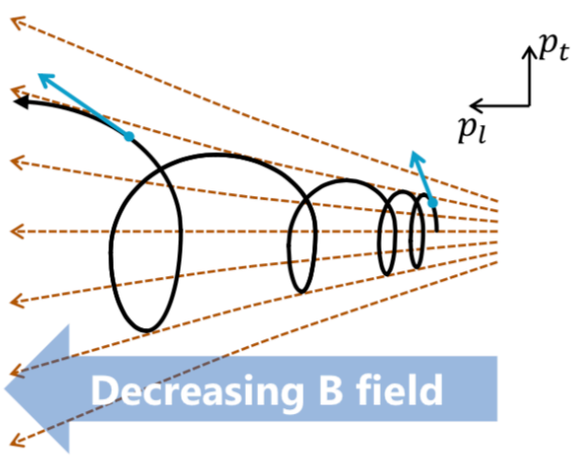
c.f. SIMDRUM-II: BR($\mu^- Au \rightarrow e^- Au$) < **$7 \times 10^{-13}$**

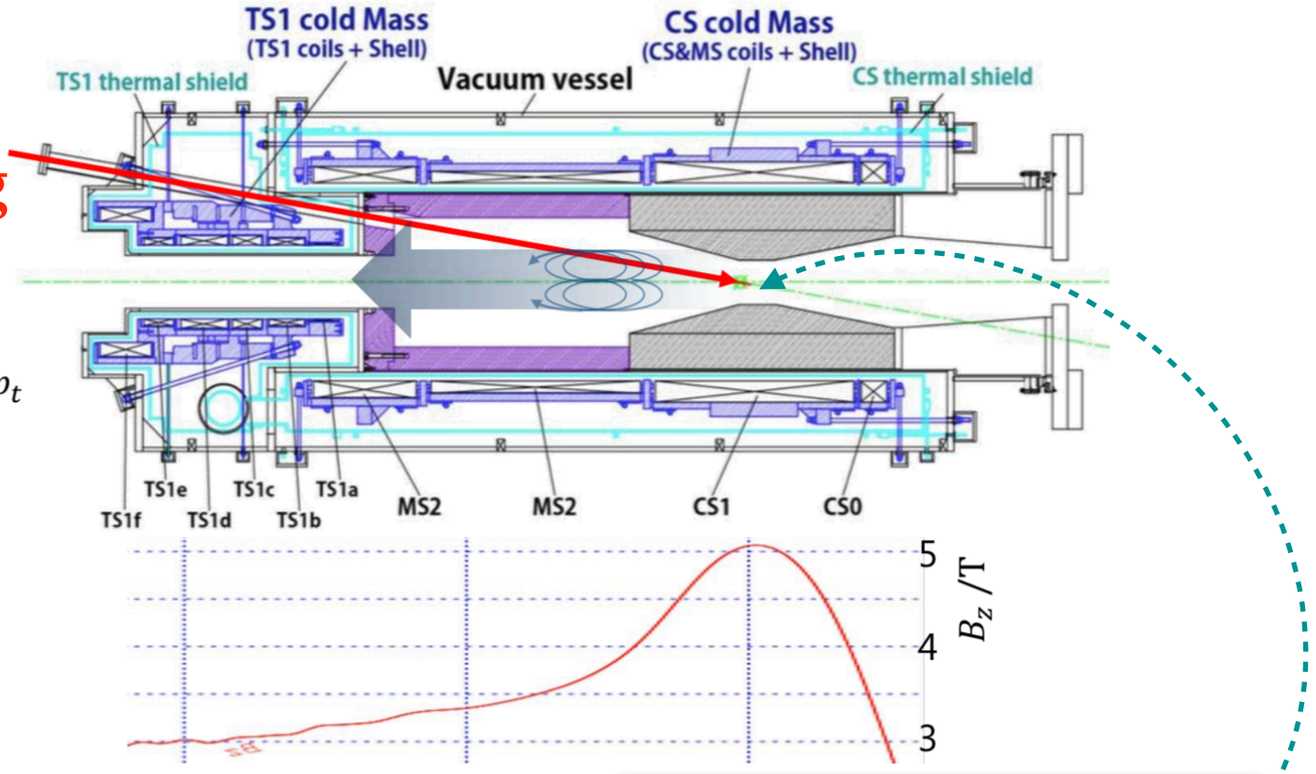
Development & Status

Production Target & Pion Capture Solenoid

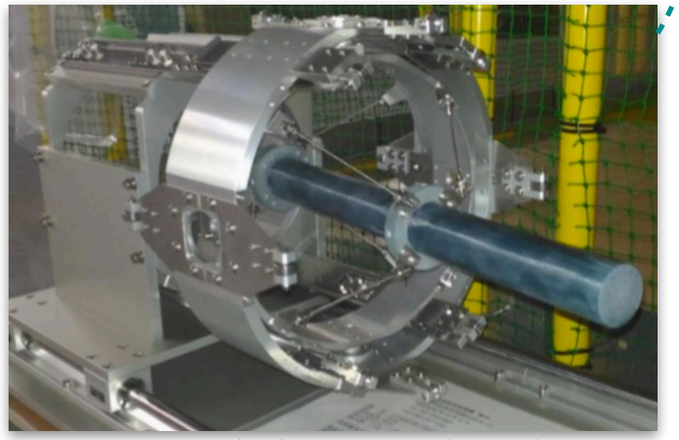


Proton beam from Main Ring

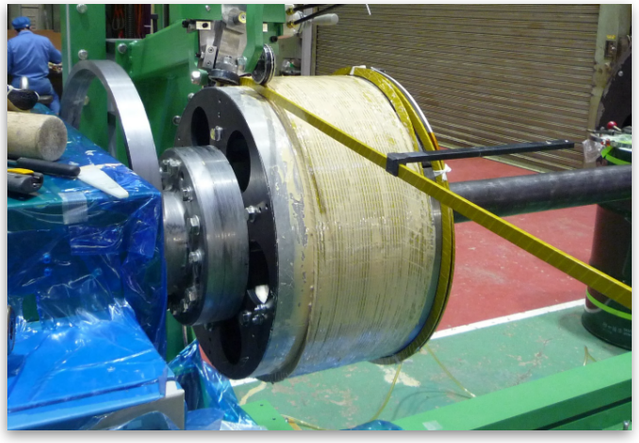




- Target rod
  - Graphite , **700 mm** length, **13 mm** radius
- Capture Solenoid
  - Collect backward pions
  - Maximize field at target (**5 T**) to give larger aperture angle
  - Winding of the final coil ongoing

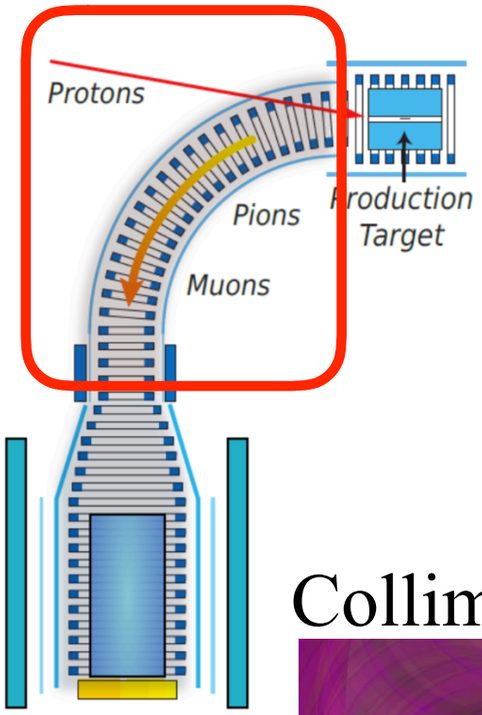


Prototype of the production target



Capture solenoid coil winding

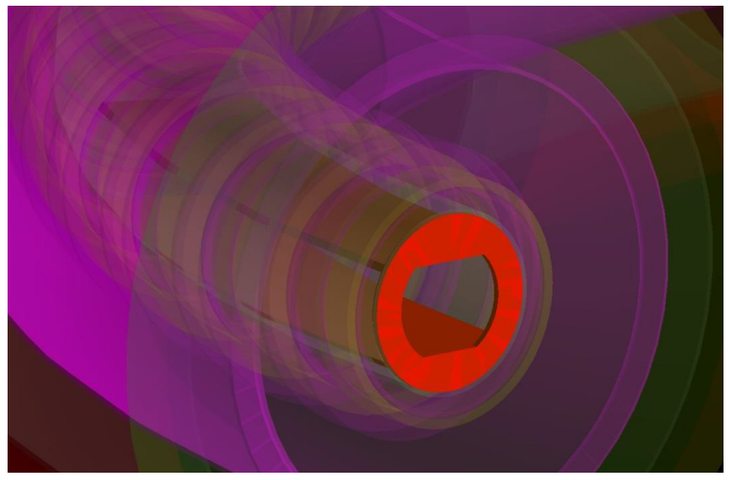
Muon Transport

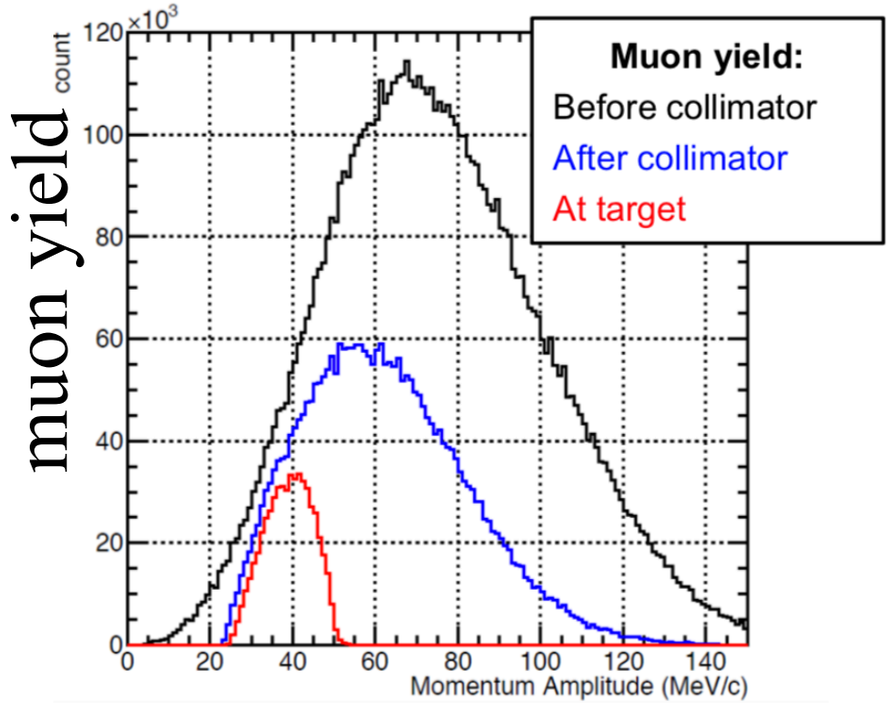


- Curved solenoid
  - 90 degree bend
  - High transmission efficiency for **40 MeV/c μ^-**
  - Collimator … block high momentum muons
    - High stopping rate at the target
    - Stopped muons in target

$= 4.7 \times 10^{-4}$ [1/proton]
(1.25×10^{8} [1/sec])

Collimator

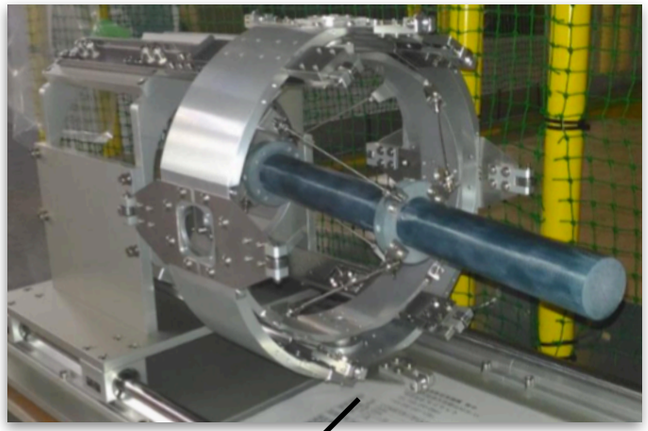




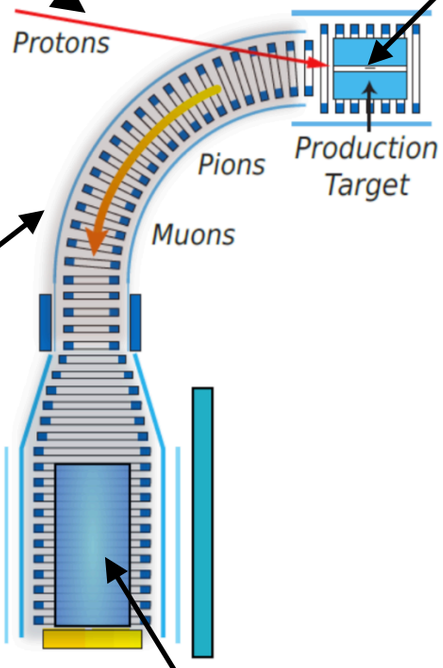
- Transport solenoid is already installed.

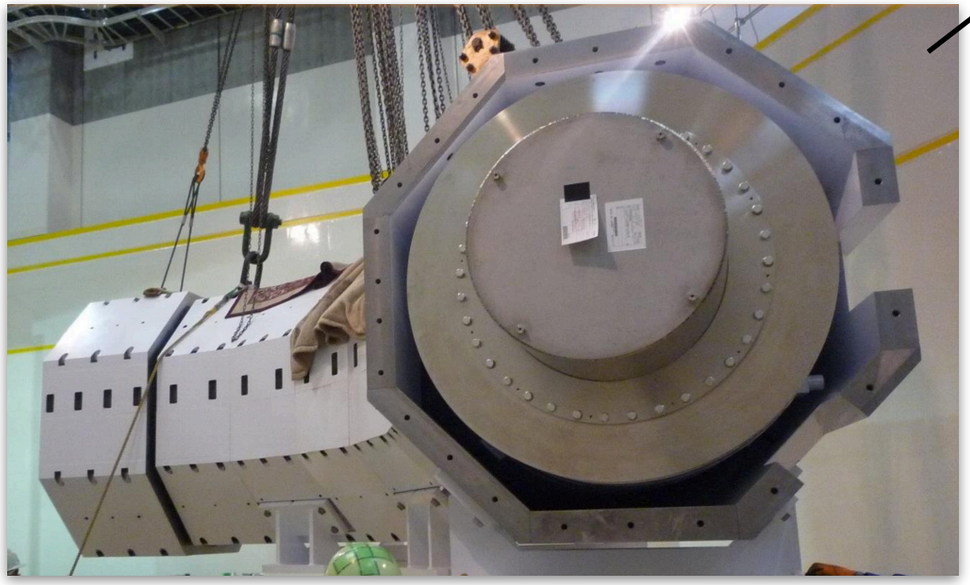
  ready for cryogenic test

Facility Status

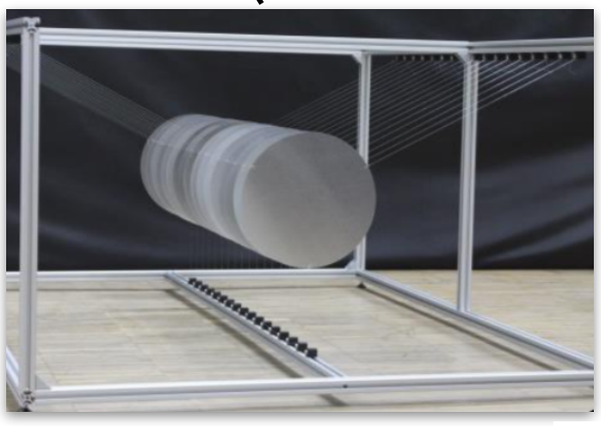


Production Target Prototype





Transport Solenoid Installed



Muon Stopping Target Prototype

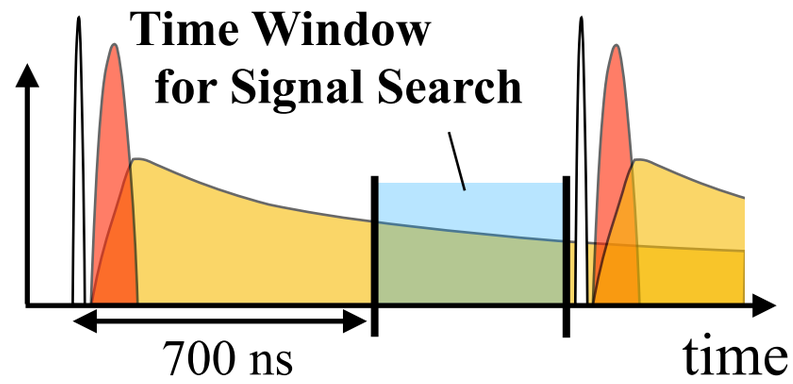
COMET Experimental Hall

Proton Extinction

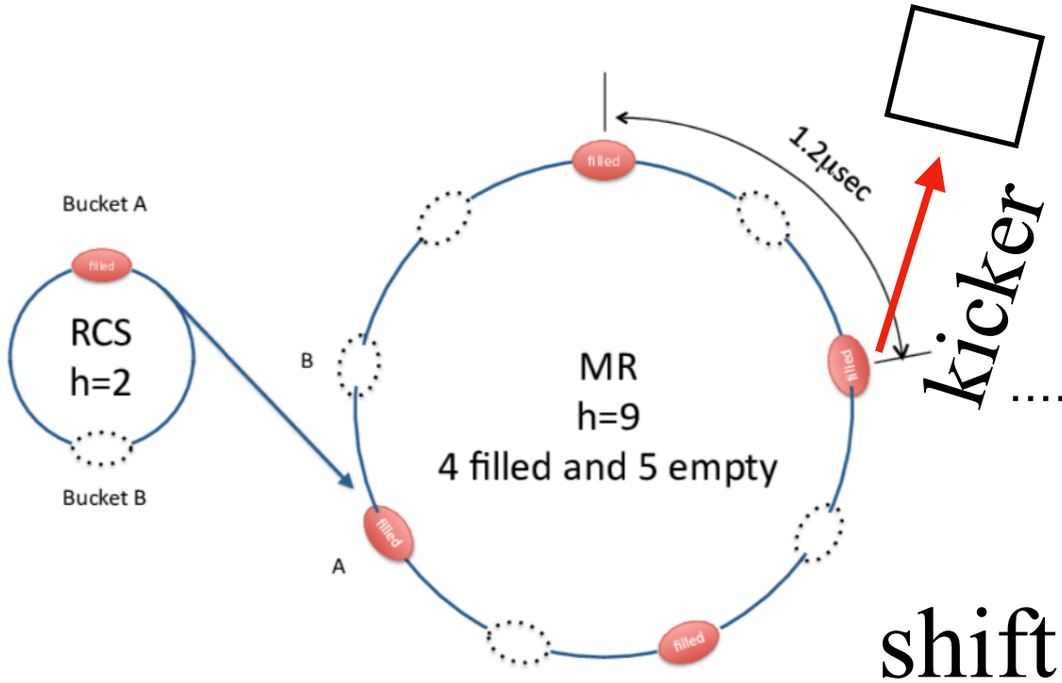
- Protons between bunches

  ⇨ background
  in the time window for signal

  Extinction factor $<10^{-10}$ required

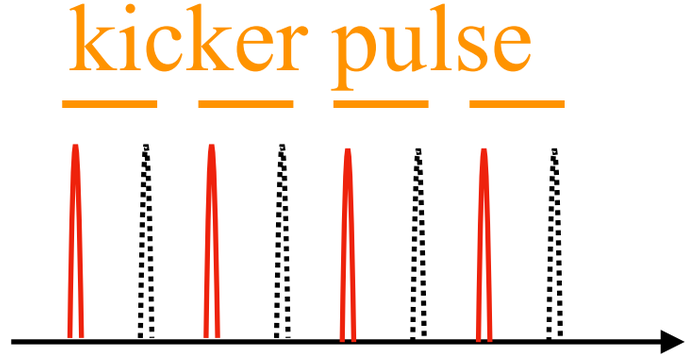


- Accelerator operation mode for COMET



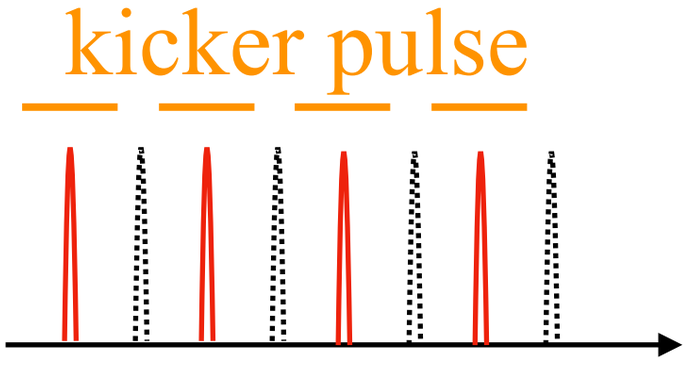
filled
empty

Normal



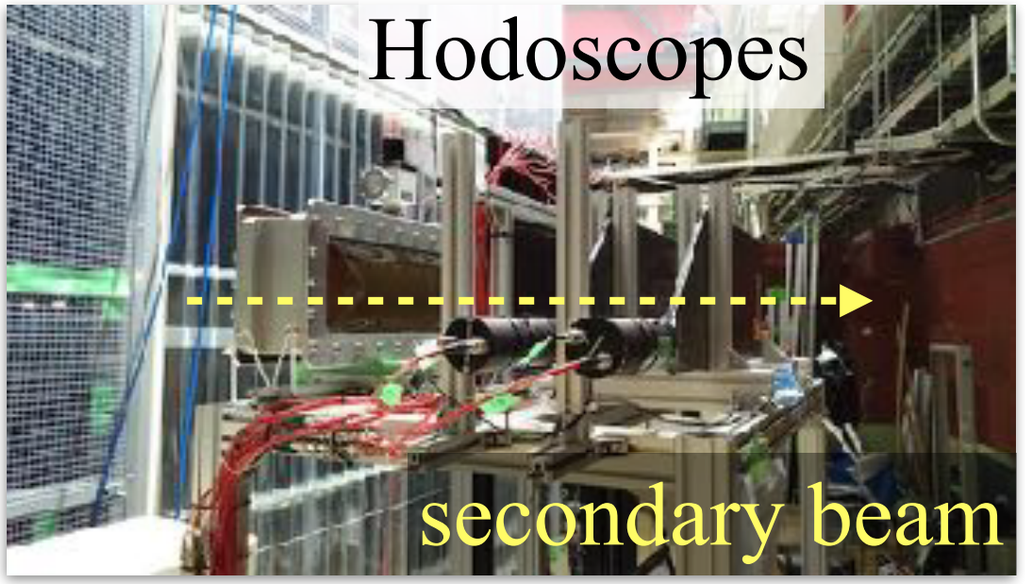
COMET

shift kicker timing
avoid empty buckets

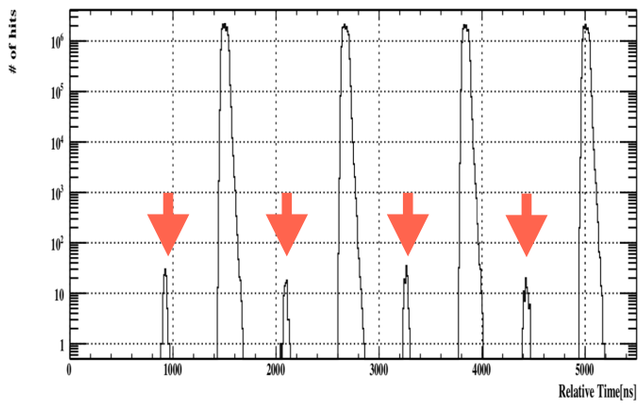


Proton Extinction

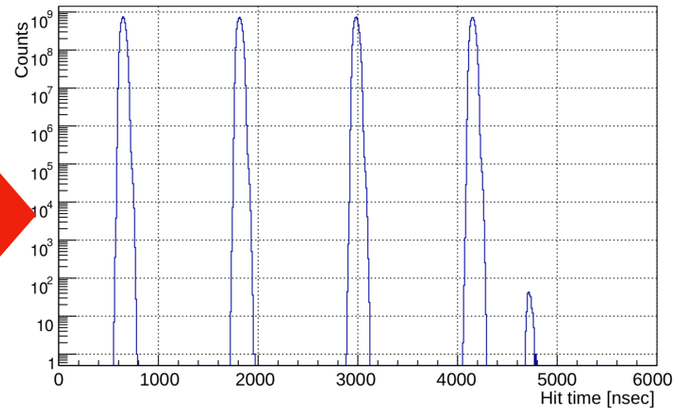
- Measurement
  - MR 8 GeV proton beam
  - Slow extraction @ Hadron Hall
  - Utilizing secondary particles from the target in Hadron Hall



Normal



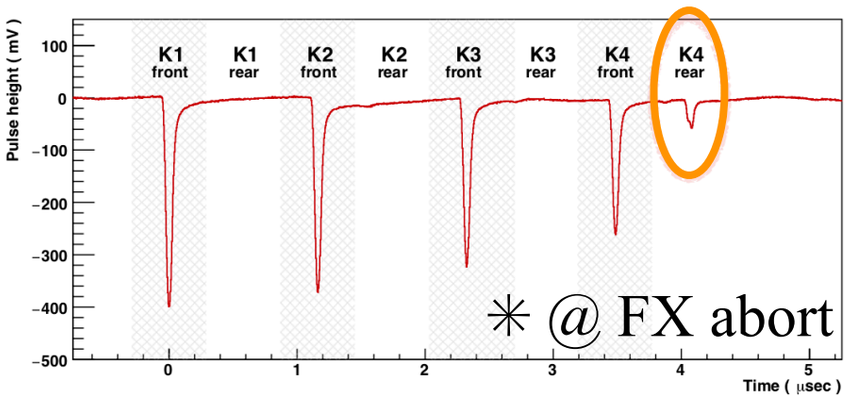
shift kicker by 600 nsec (half bunch)



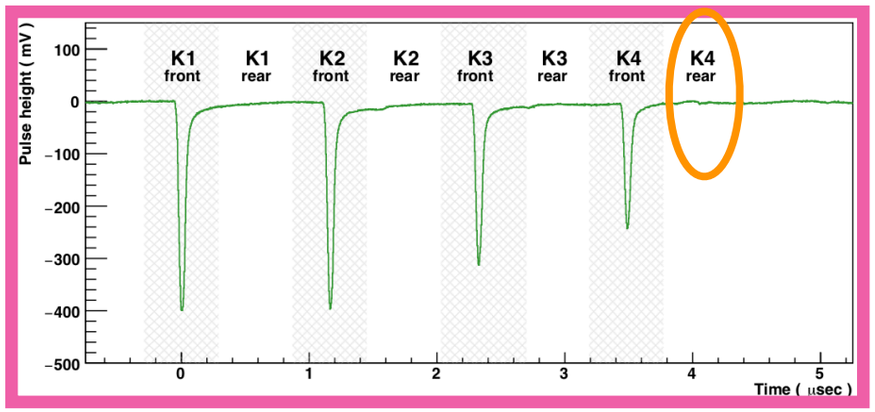
- leakage after the last bunch

… solved by shifting kicker more

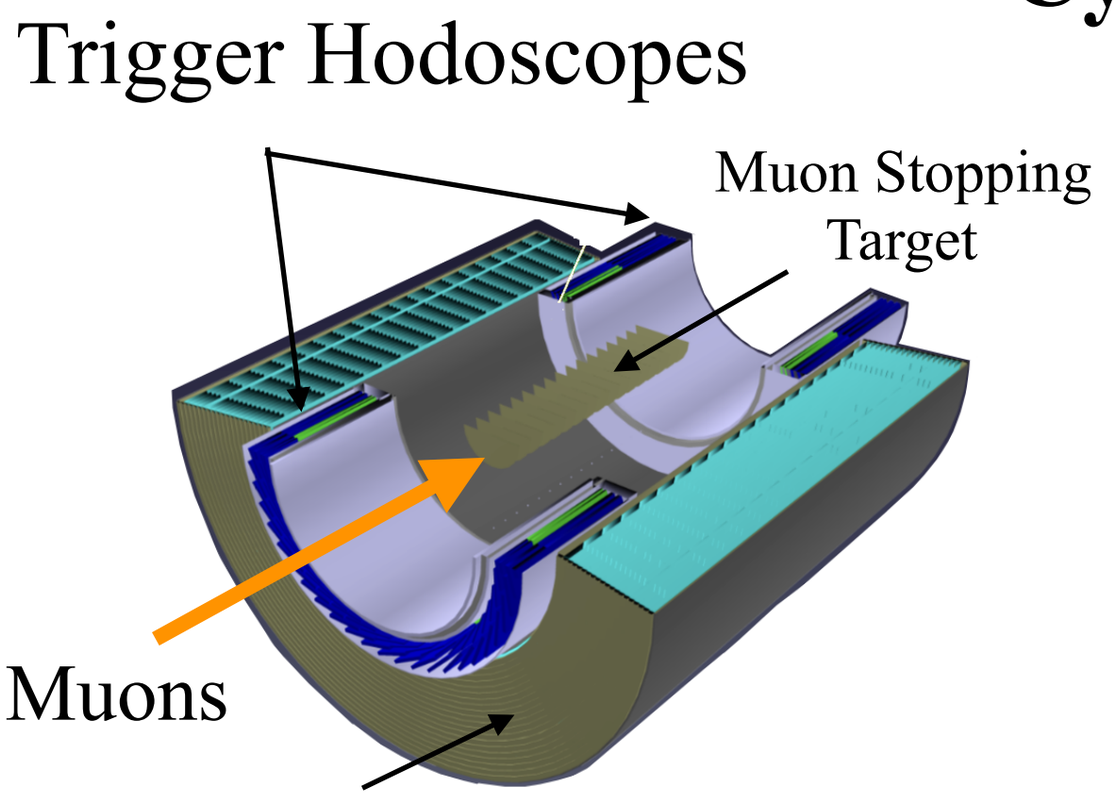
Extinction Factor
$< \mathbf{6\times10^{-11}}$ achievable



800 nsec shift

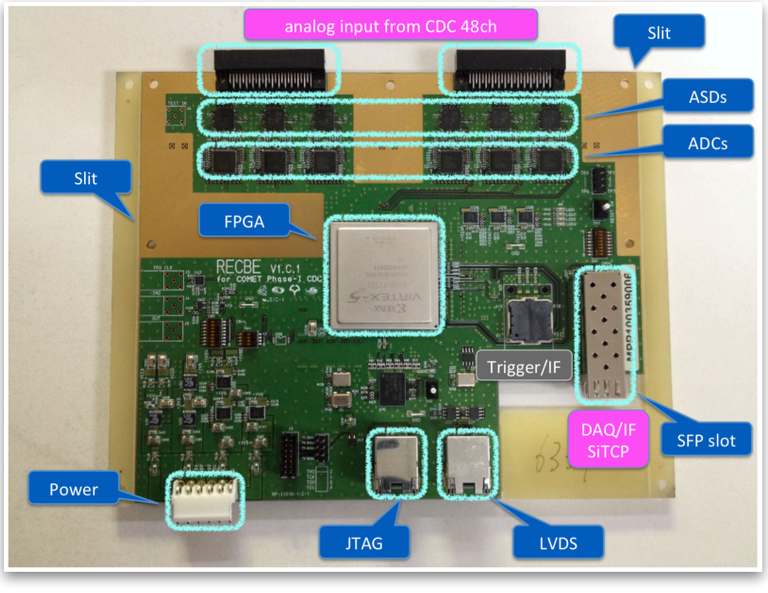


Phase-I Detector System CyDet



▶ Cylindrical Drift Chamber (CDC)

- Magnetic Field: **1T**
- Gas: **He/iC$_4$H$_{10}$(90/10)**
- **20** Layers,
  4986 sense wires (all stereo)



RECBE board

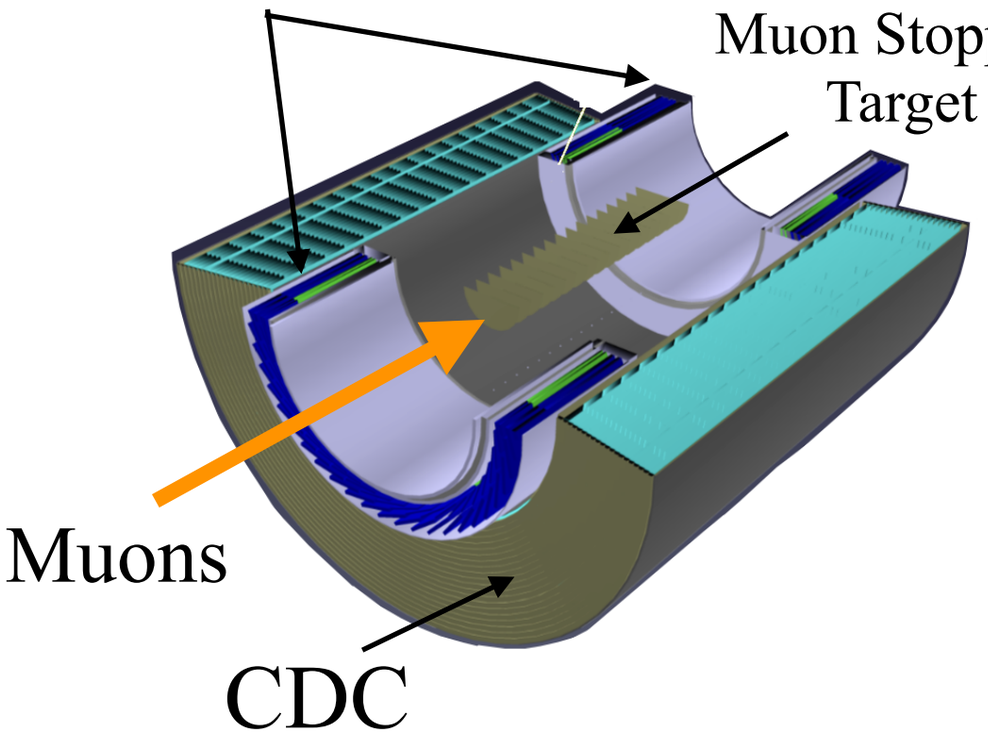
- Readout : developed for COMET based on BELLE-II (RECBE)

Mass production finished.

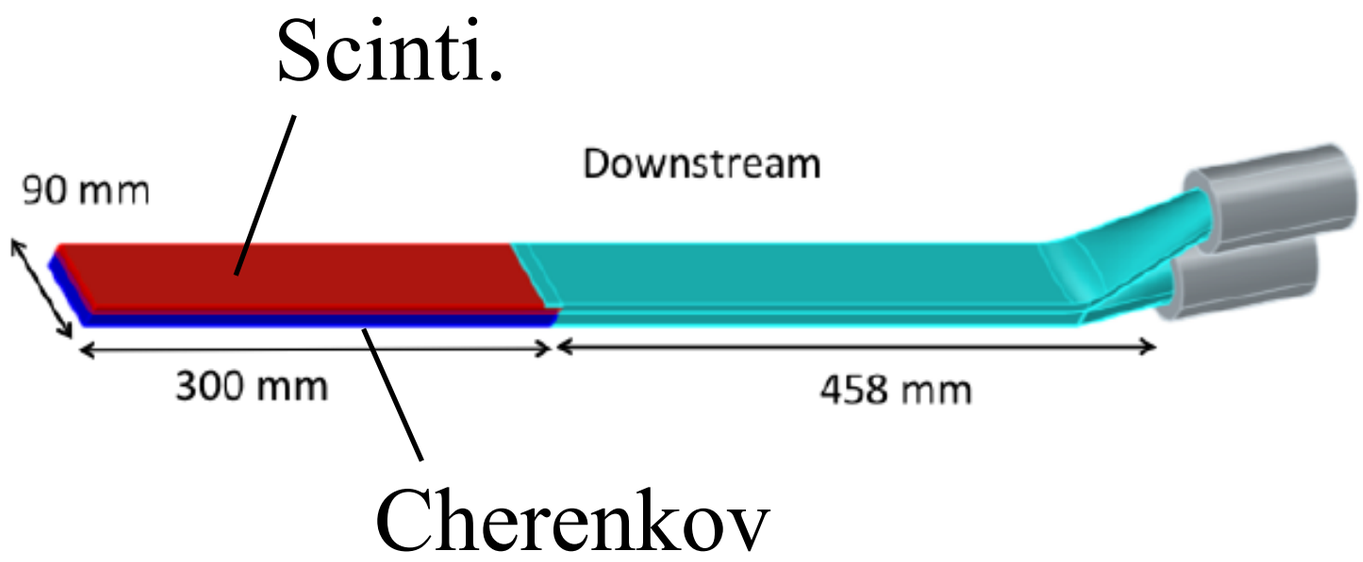
<u>Final Detector completed (2016 Jun)</u>

▶ Cylindrical Trigger Hodoscope (CTH)

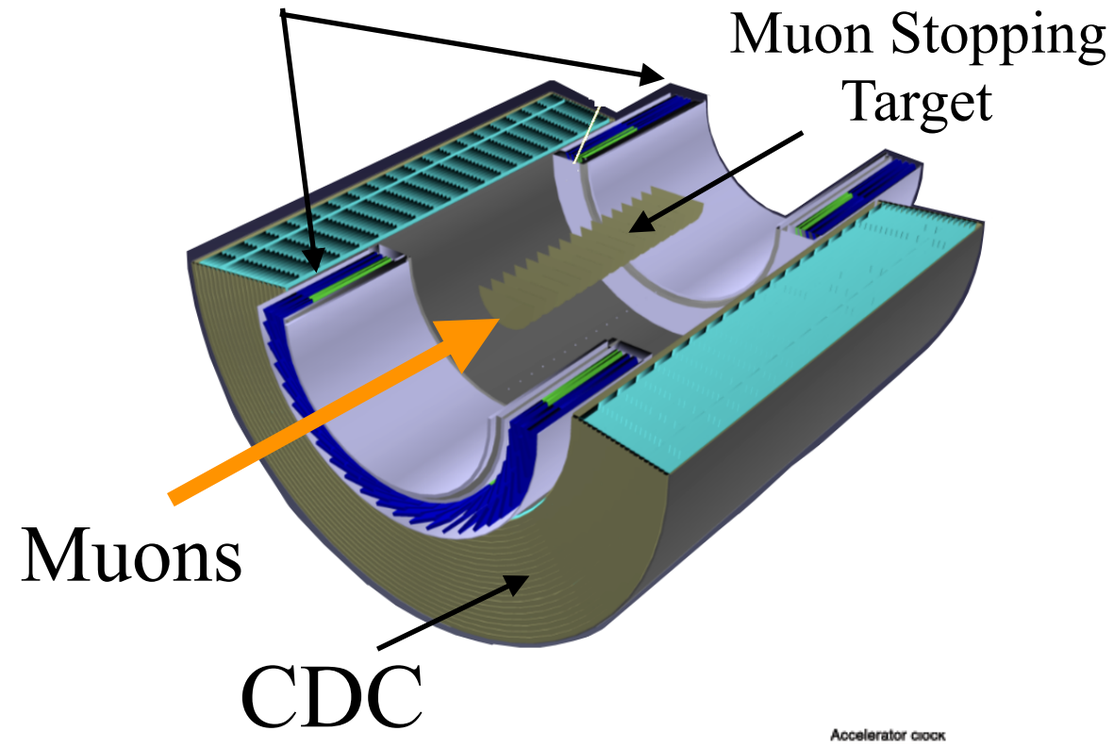
Trigger Hodoscopes



- Cherenkov counter
  … particle ID
- Scintillation counter
  … precise timing
- 48 sets for each ring



Trigger Hodoscopes

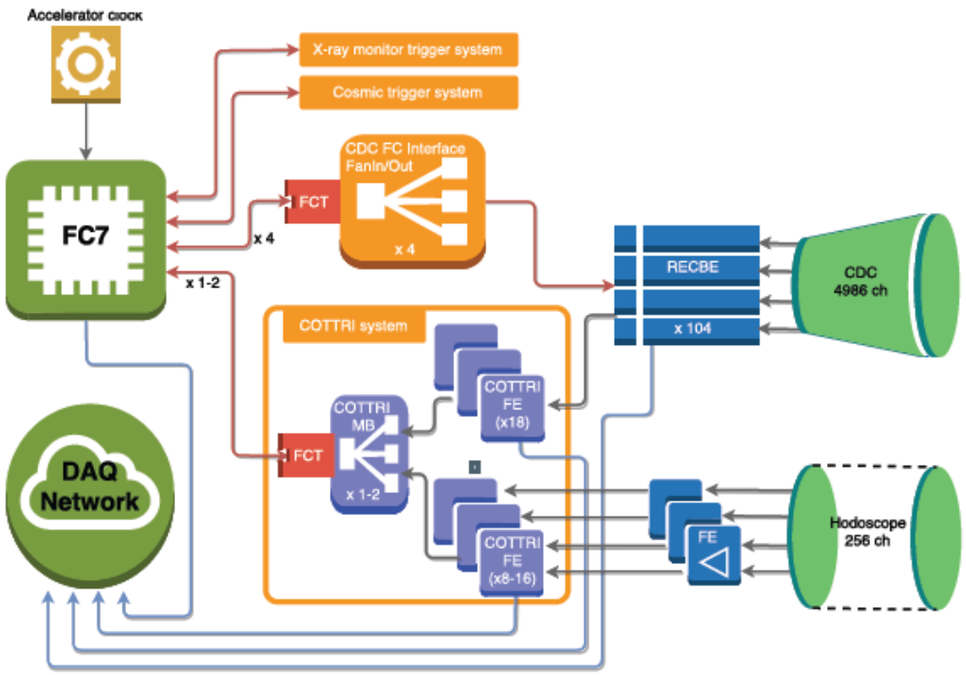


▸ Trigger System

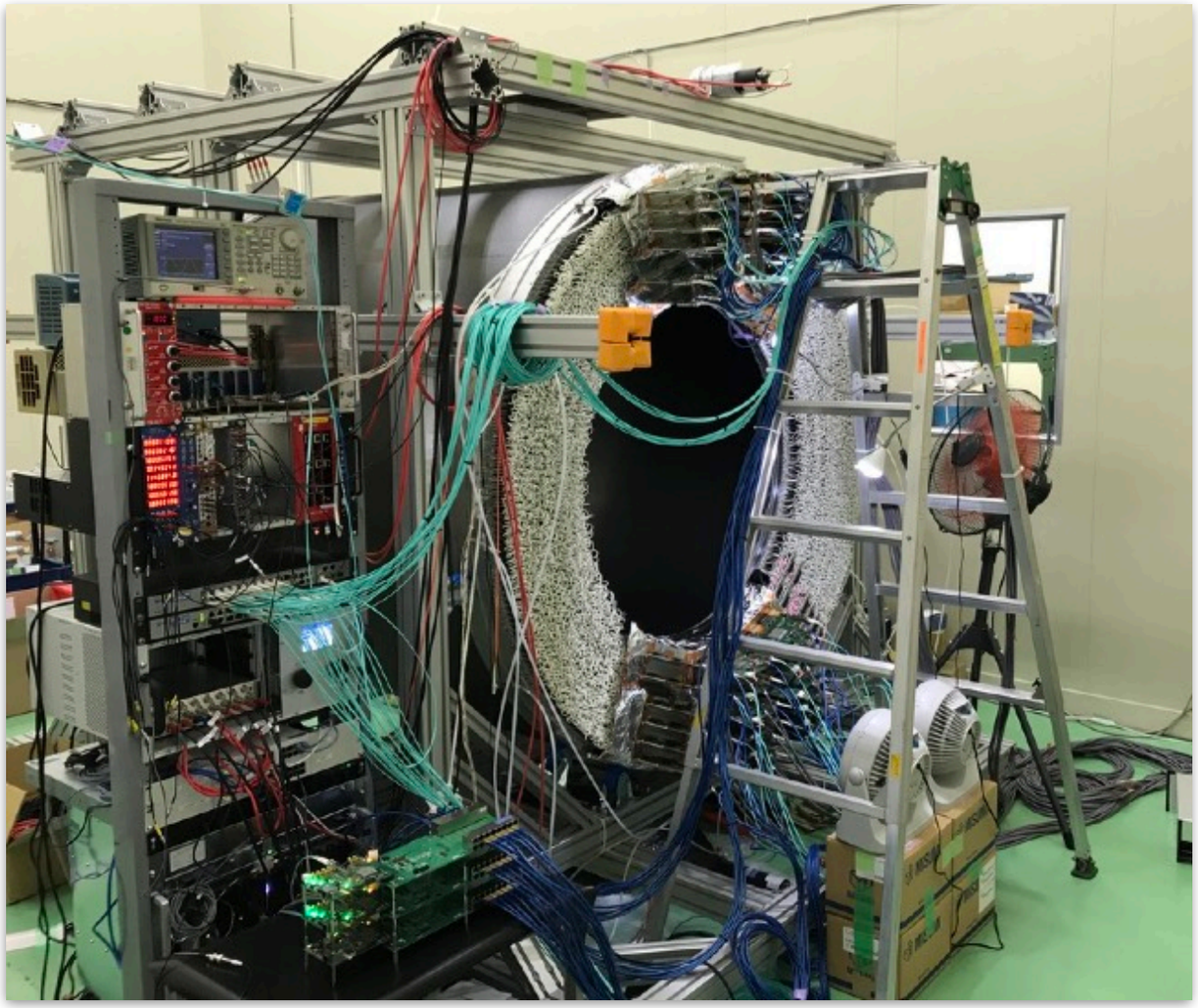
- Hit patterns of CDC & CTH

⇨ Fast Online Trigger with FPGA

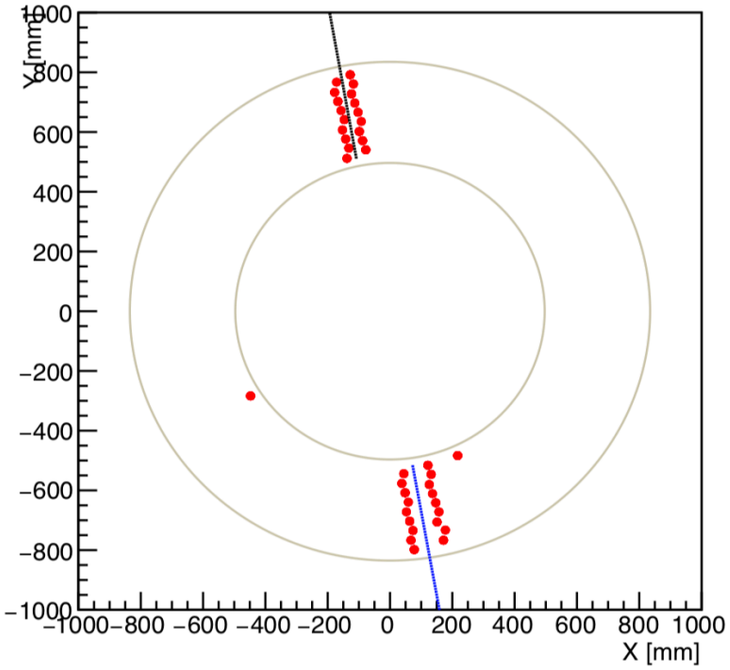
- Trigger board test ongoing



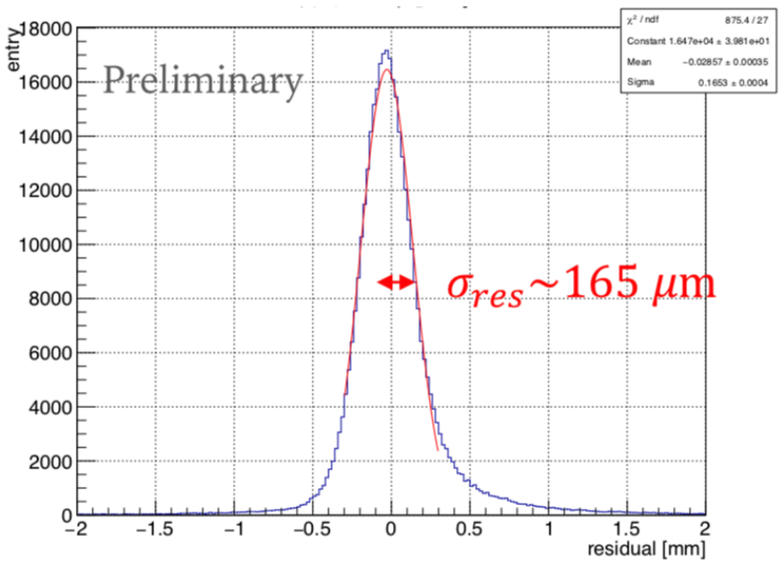
- **Cosmic ray test of CDC** ongoing with the final detector
  - spatial resolution ~**165 μm**
  - efficiency ~**98%** so far



Setup of cosmic ray test



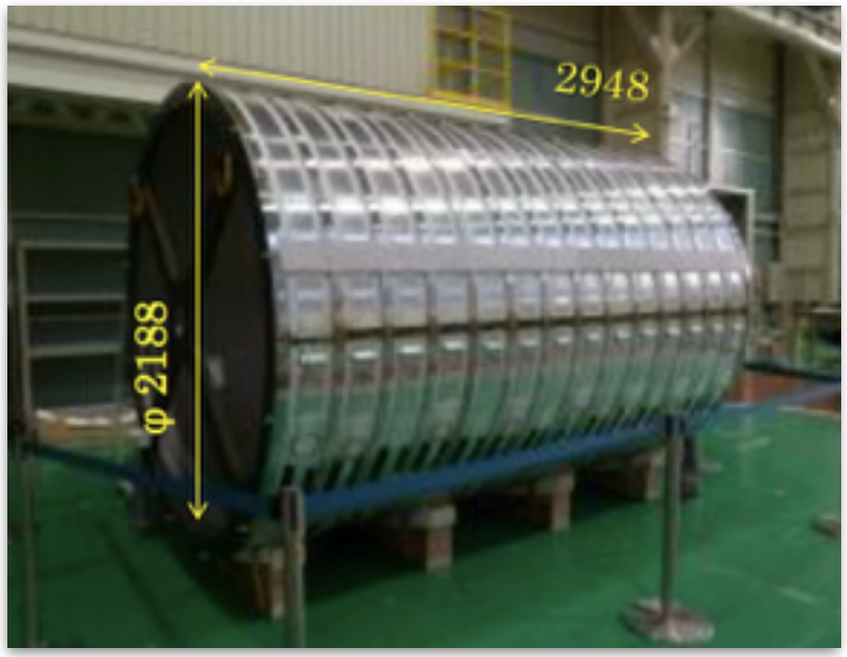
Event display of cosmic ray test



Residual distribution of position

Phase-I Detector System CyDet

- Detector Magnet
  - Coil & Cyostat ready
  - Outer & Inner cylinder delivered



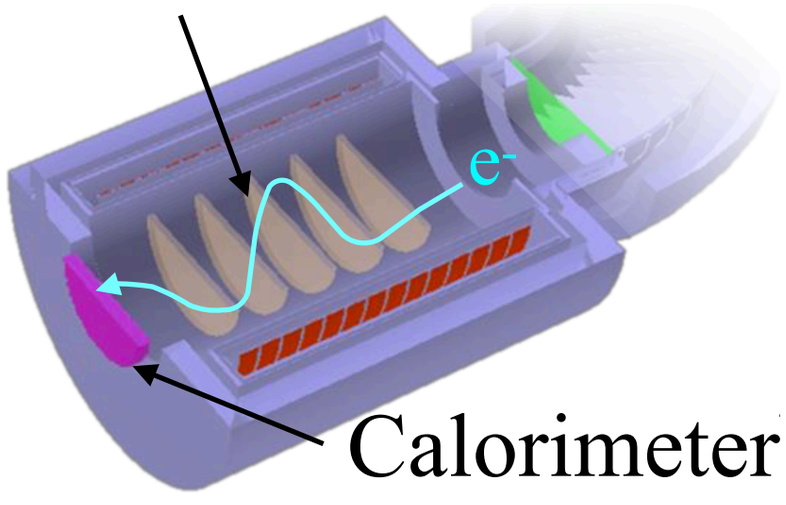
StrEcal

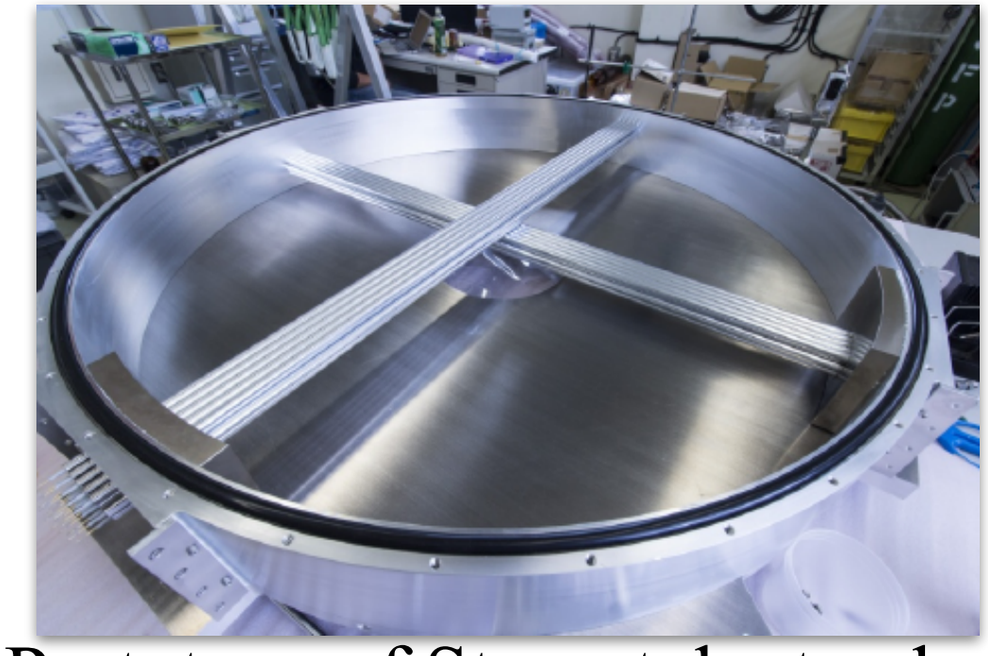
- Phase-I beam mesurent & Phase-II main detector
- Straw tube tracker

  4 planes × 5　　Low mass … less scattering

  - Al laminated Mylar tubes (12μm thickness, 5mmφ for Phase-II)
  - Ar/Ethane
  - Position resolution **~150μm** (prototype)
  - Operation in vacuum (<**0.1Pa**) (<u>achieved with prototype</u>)

straw tube tracker





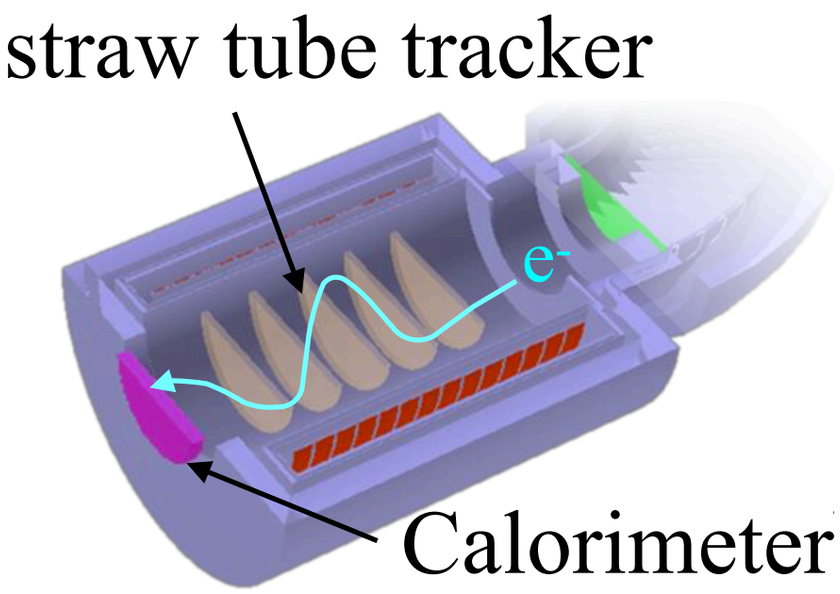
Prototype of Straw tube tracker

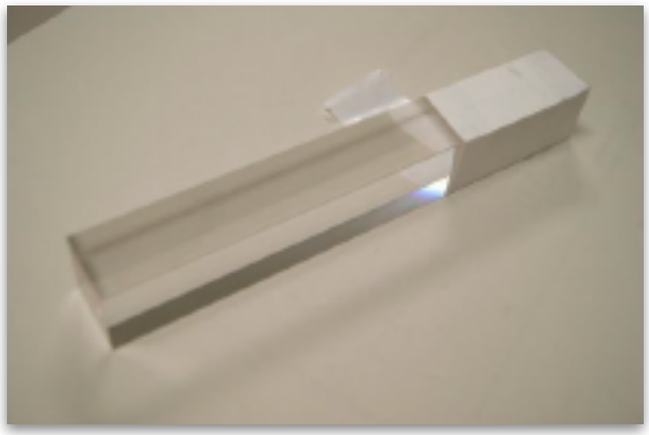
StrEcal

- Calorimeter **2000 LYSO** crystals
  - $20 \times 20 \times 120$ mm^3
  - readout = 10×10 mm^2 APD
  - performance of prototype

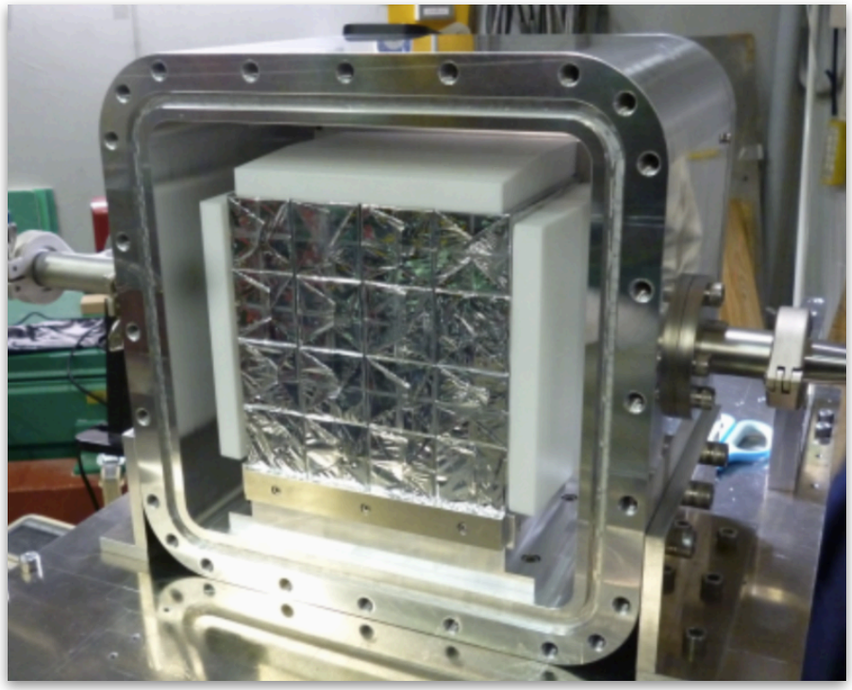
    Energy resolution … **4.6 %**

    Time resolution … **0.4 ns**





LYSO crystal



Prototype of Calorimeter

Software Development

▶ Analysis Framework for COMET , ICEDUST

(Integrated Comet Experimental Data User Software Toolkit)

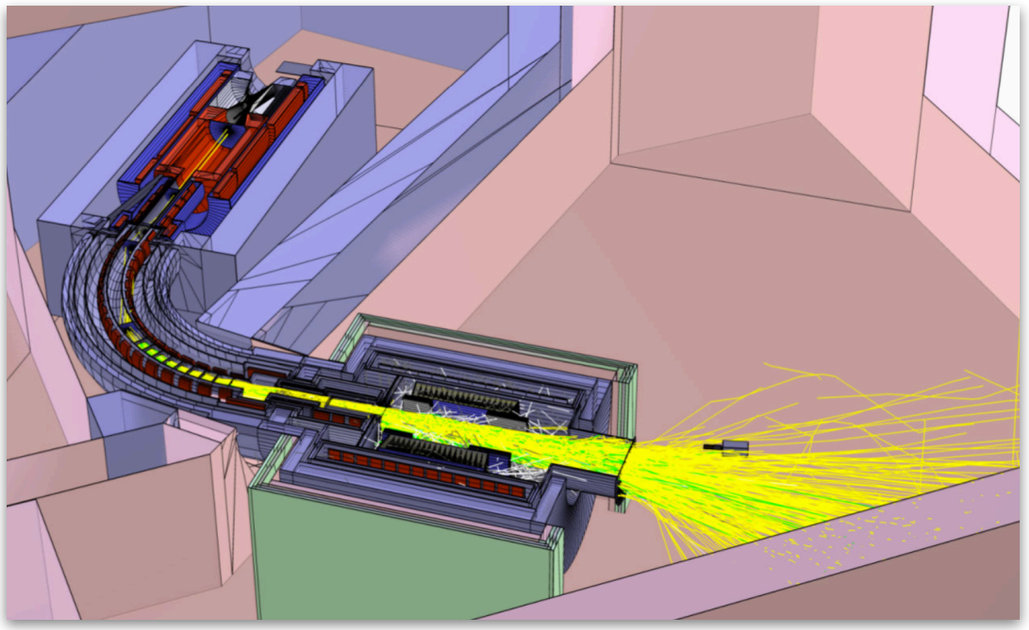
- **Event generation** for MC simulation
  - Particle production
  - Beam transportation
  - Detector response

⇩

MC samples

⇩

Various studies

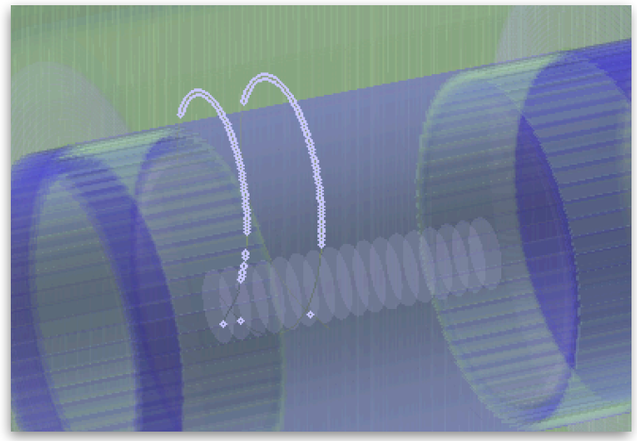


Software Development

- **Analysis Framework for COMET , `ICEDUST`**
  - Development of **Track Finding & Fitting** Algorithms

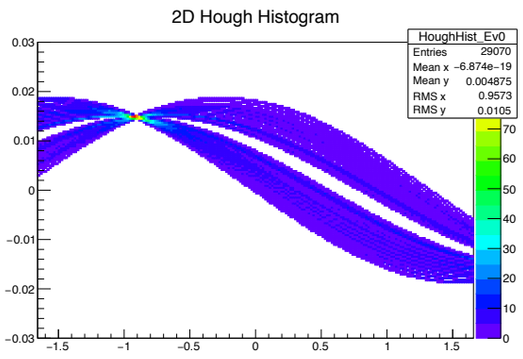
Challenge for Phase-I

… Multi-turn separation in CDC

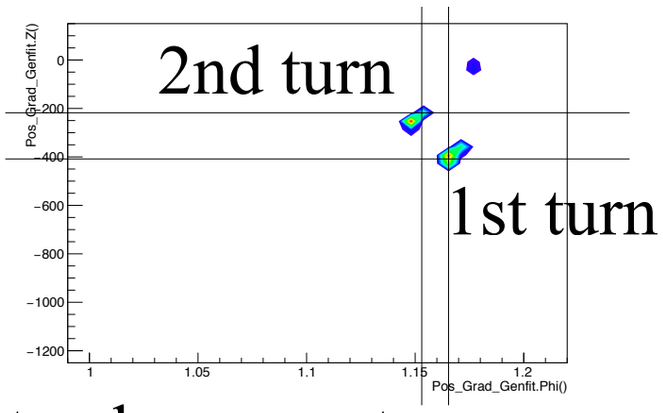


- Classical Method

based on Hough Transform & Helix Fitting



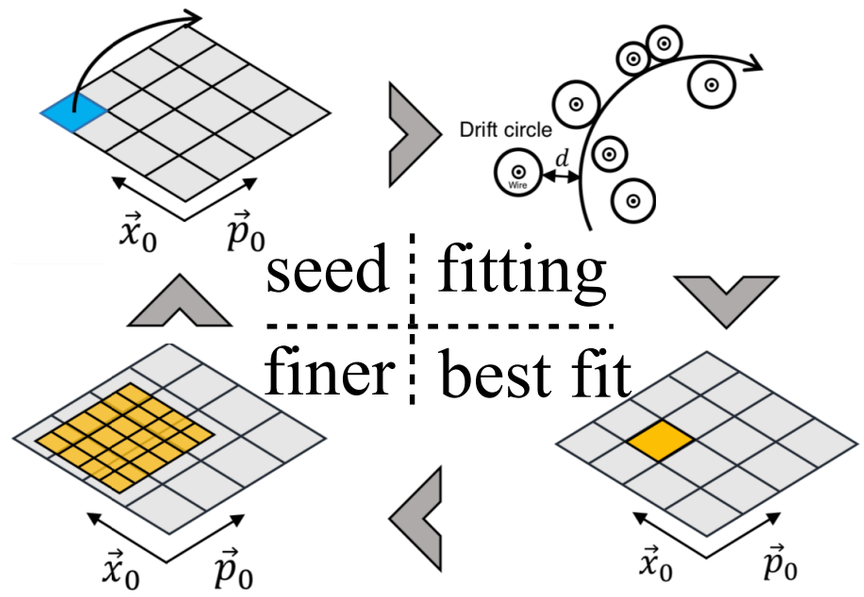
Hough Trans.



track parameter space

- Powerful Technique

scanning track seed utilizing GPGPU



- Modern Way

adopting Deep Learning

etc.

Various Options

Software Development

- **Analysis Framework for COMET , `ICEDUST`**
  - Study of **Phase-II configuration** by MC

    to be more sensitive (originally **2.6×10^{-17}**) …

    <u>further optimization ongoing</u>

    - targets

      production target … geometry & location

      stopping target … geometry , number of disks

    - beamline
    - detector

    ⇒ likely to improve the S.E.S by one order (**~10^{-18}**)

  - **Real Data Analysis** with `ICEDUST`

    ⇨ Cosmic ray test of CDC

Summary

- COMET Experiment is planned at J-PARC

  Search for muon-to-electron conversion

  ・charged Lepton Flavor Violation

  ・New Physics beyond the SM

  Staging approach

  ・Phase-I : μ-e conversion search with sensitivity of **10^{-15}**

  Direct measurement of background

  ・Phase-II: Sensitivity of **10^{-17}** (potentially **10^{-18}**) with full setup

- Detector & Software development
  facility construction … ongoing

- Prospects
  - Proton beam at upstream point of COMET in early 2020.
  - Phase-I : 5 months data taking
  - Phase-II : 1 year data taking

Welcome to the COMET Collaboration !

~200 Collaborators
17 Counties, 41 Institutes
… increasing!

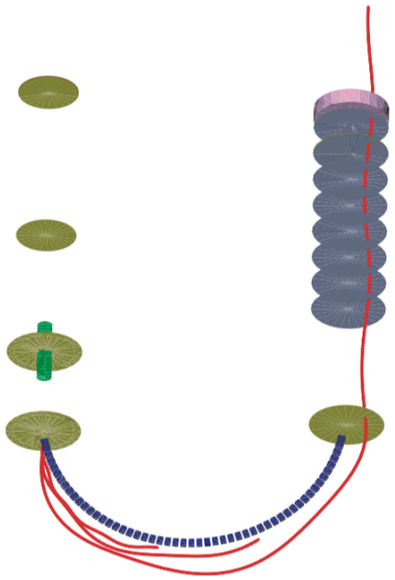
Join us !!!

End of Slide

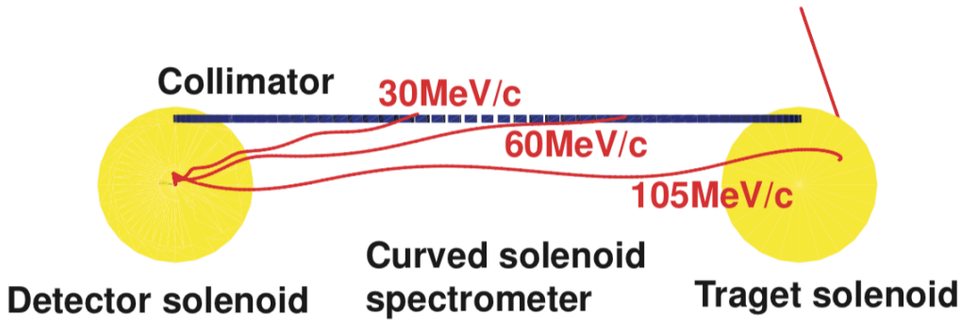
Transport Solenoid

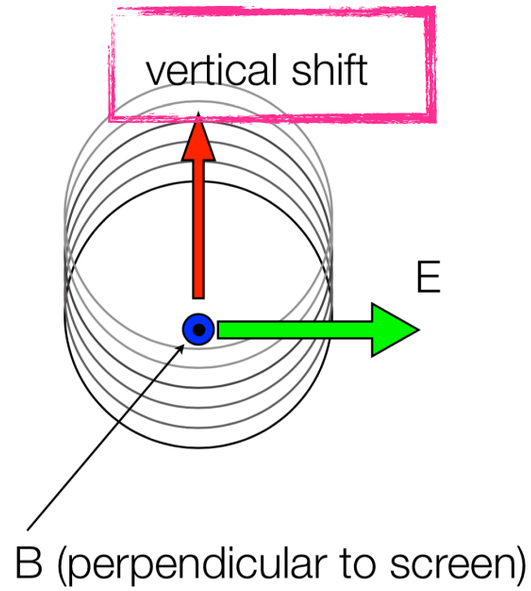
- Momentum & Charge selection in a Curved Solenoid

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

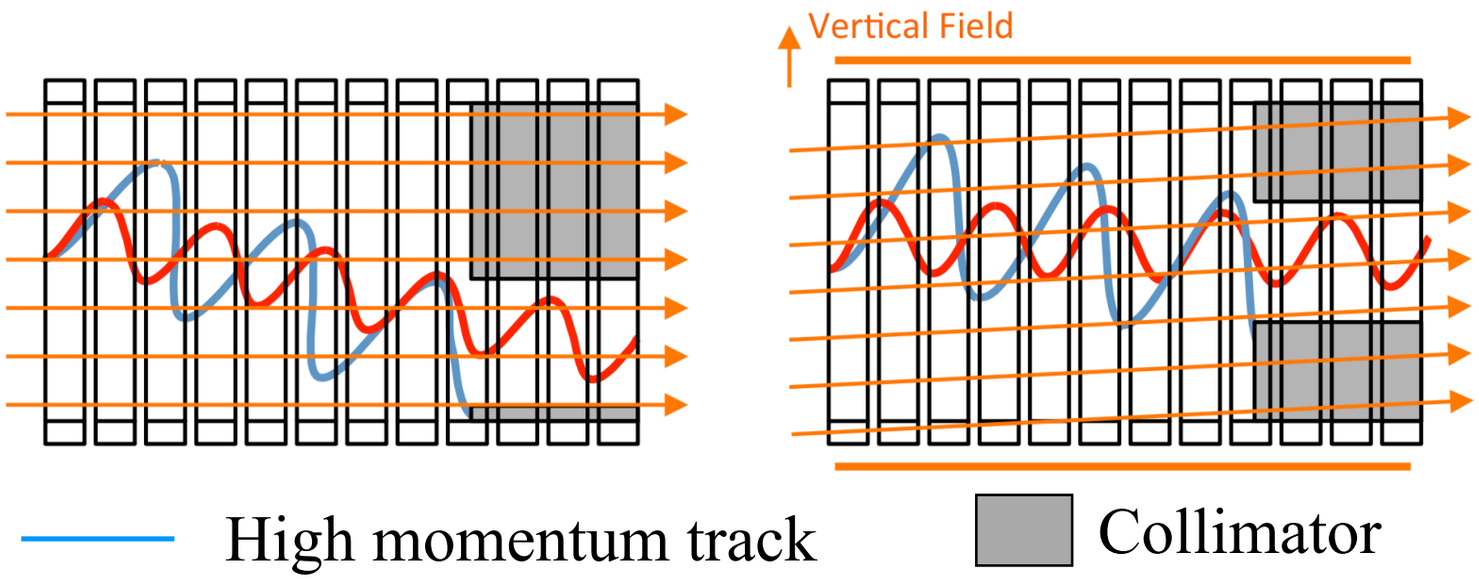


Top view





Side view



momentum selection
by applying correction field

Single Event Sensitivity (Phase-I)

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.

Beam Power = **3.2 kW**

Beam Time
= **1.26×10^{7} sec (146days)**

Background Estimate

Total Background: 0.032

- Single Event Sensitivity

$$= \frac{1}{N_\mu \times f_{cap} \times f_{gnd} \times A_{\mu e}}$$

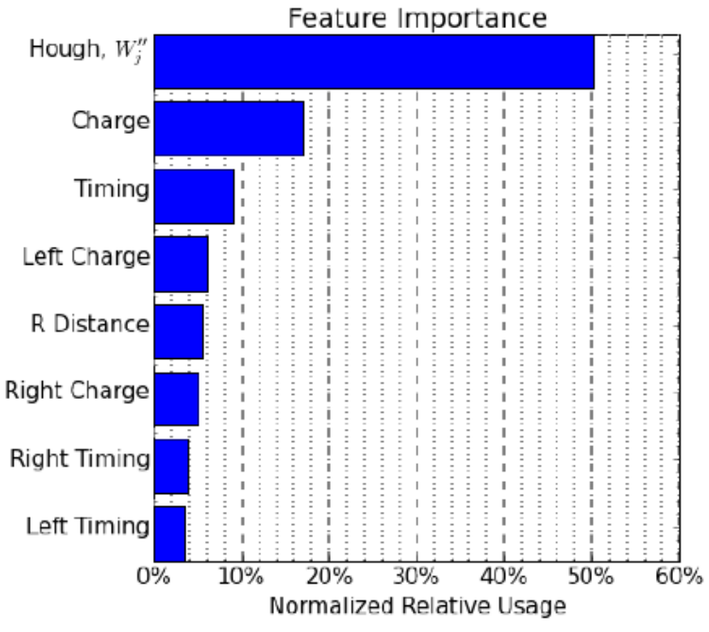
$$= \mathbf{3 \times 10^{-15}}$$

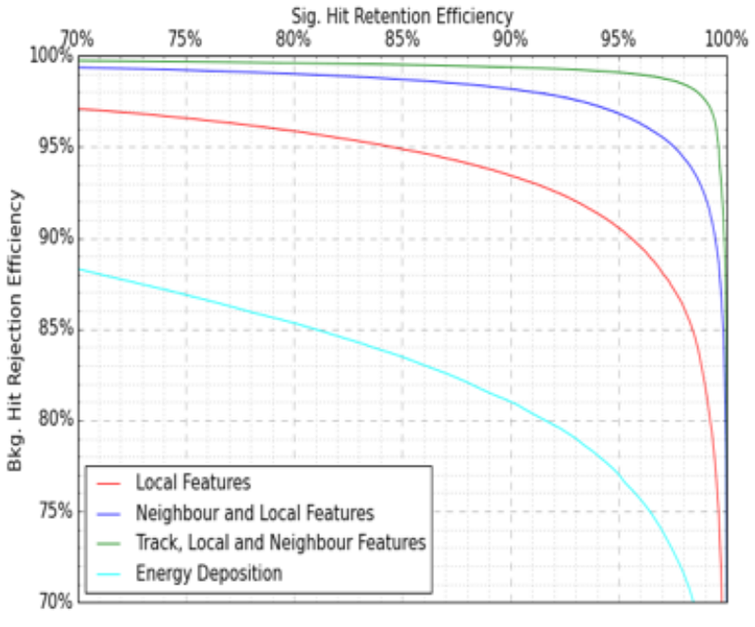
N_μ(number of muons stopping on the target) = **1.5×10^{16}**
f_{cap}(fraction of muon capture) = **0.61**
f_{gnd}(fraction of nucleus which is not excited by μ-e conv.) = **0.9**
$A_{\mu e}$(Total Acceptance for e^- from μ-e conv.) = **0.041**

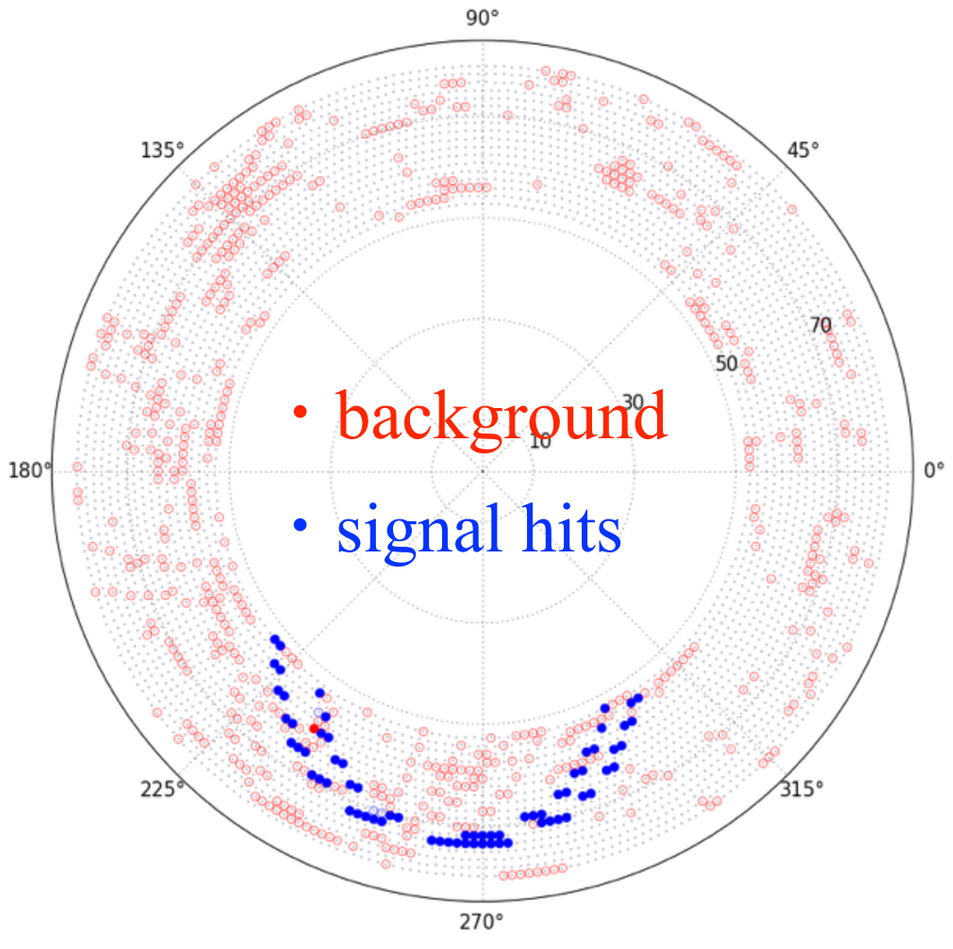
Upper Limit = **7×10^{-15}**, 90% C.L.

Signal Hit Selection

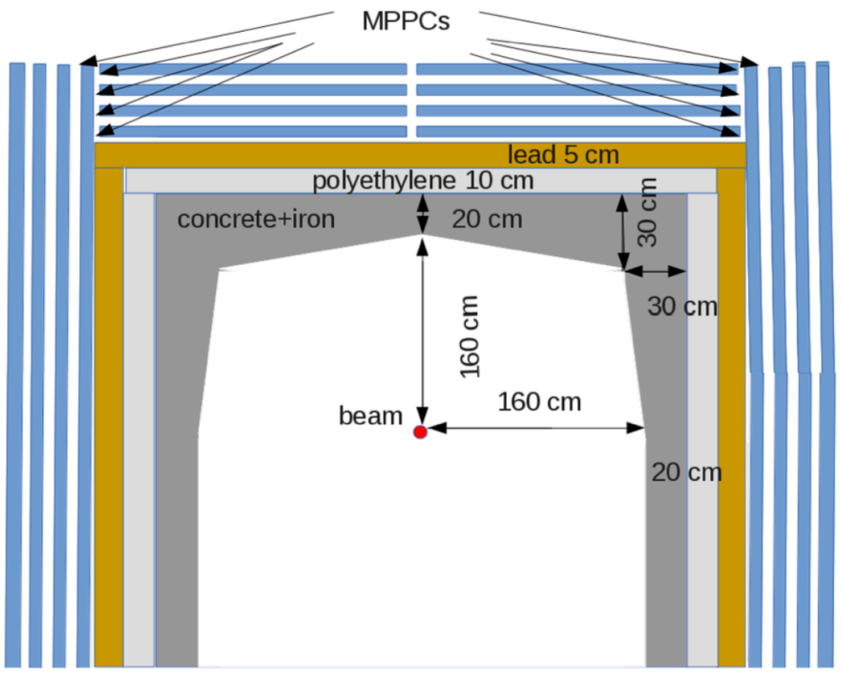
- Hit selection using Gradient Boosted Decision Trees (GBDT) and Reweighted Inverse Hough Transform
- Background hits are rejected based on timing, charge & local features
- **99%** of background rejected & keeping **99%** of signal hits

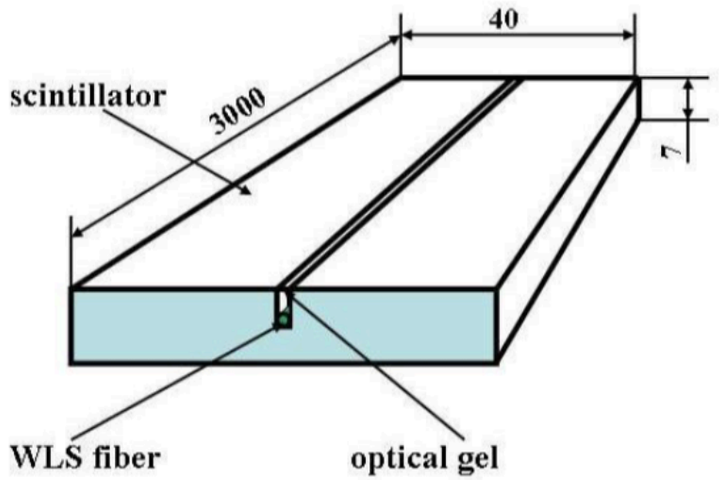


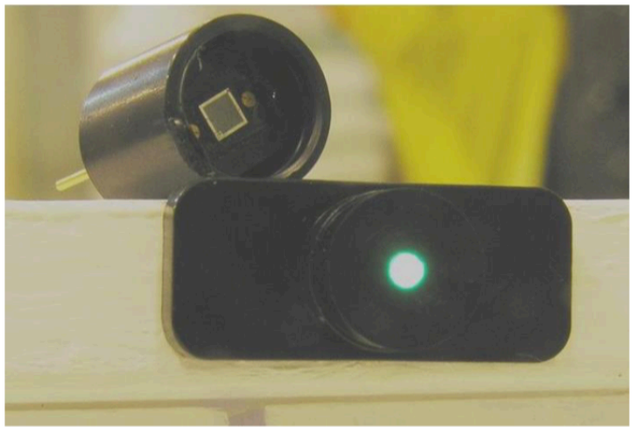


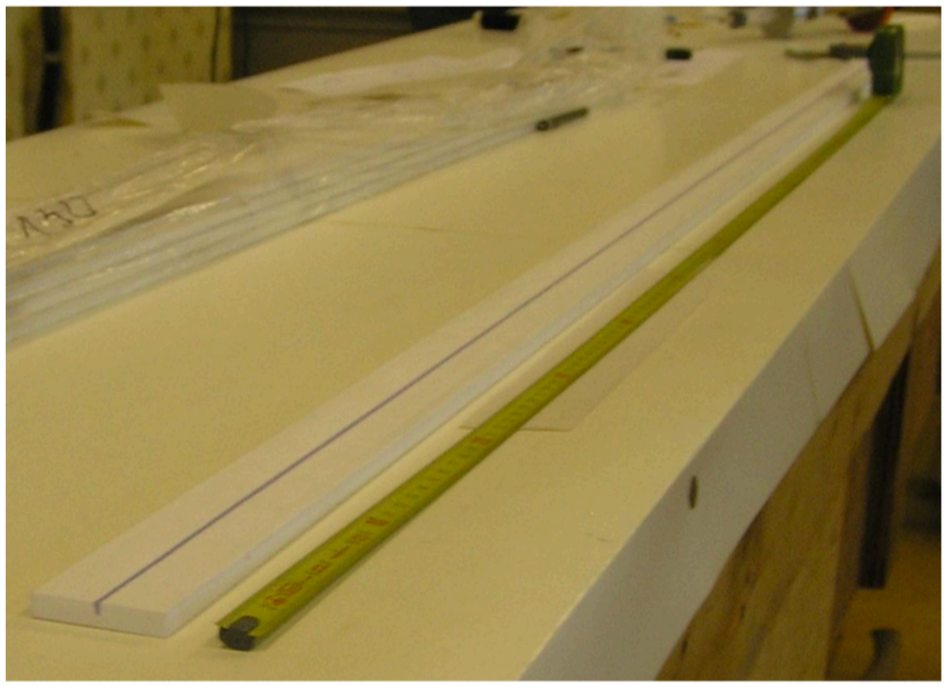


Cosmic Ray Veto



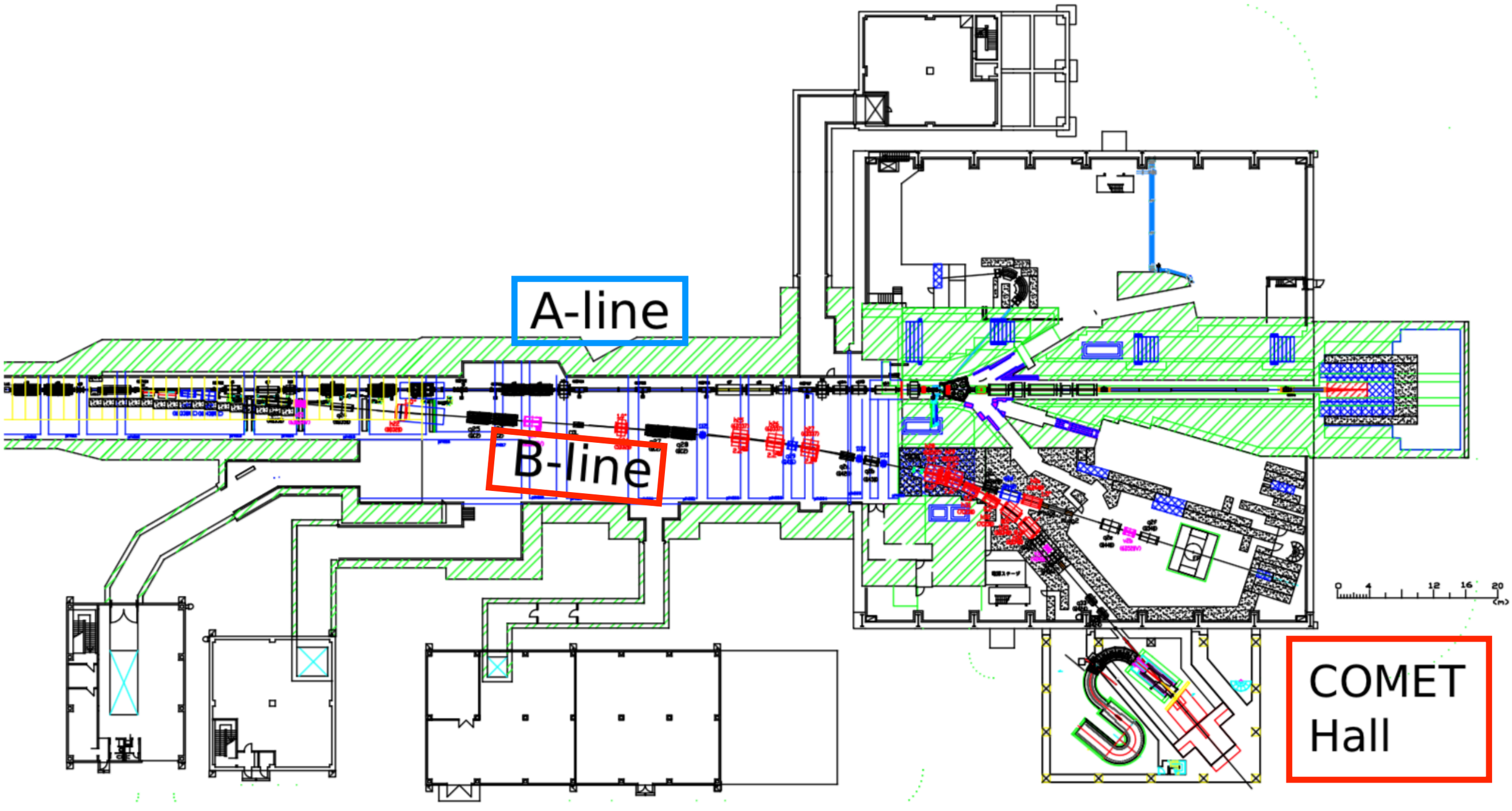






- requirement … inefficiency < 10^{-4}
- Plastic scintillator readout with WLS+SiPM
- The design in progress

Primary Proton Beam Line



Optimization of COMET beamline

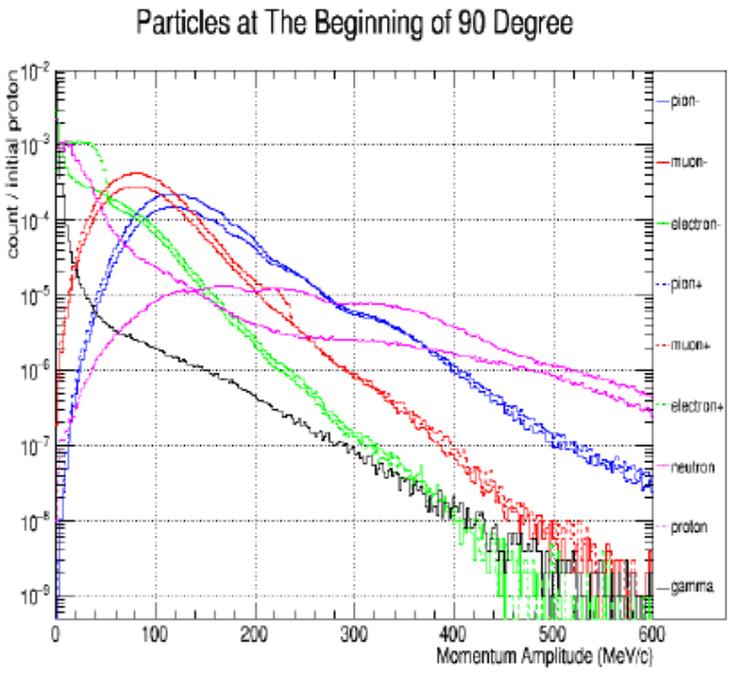
Based on various simulation studies

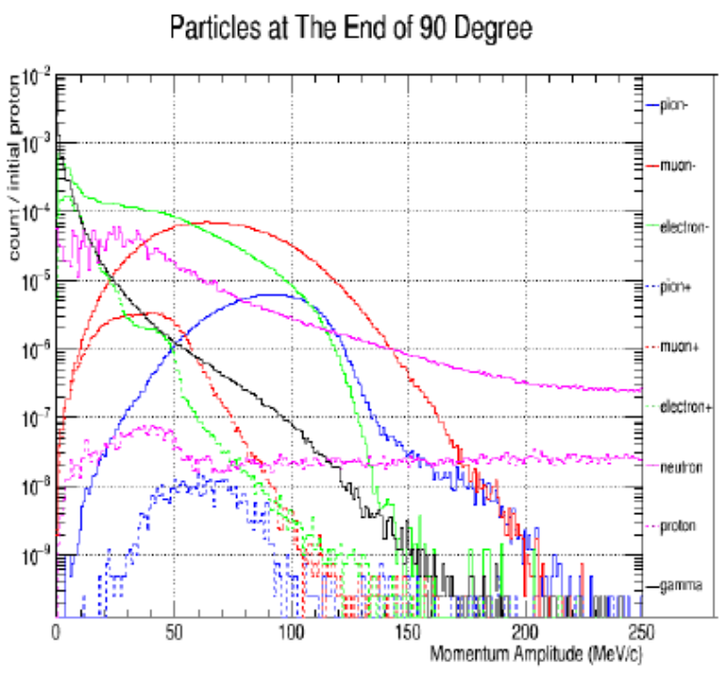
optimizing target dimension … maximum pion yield at the production target

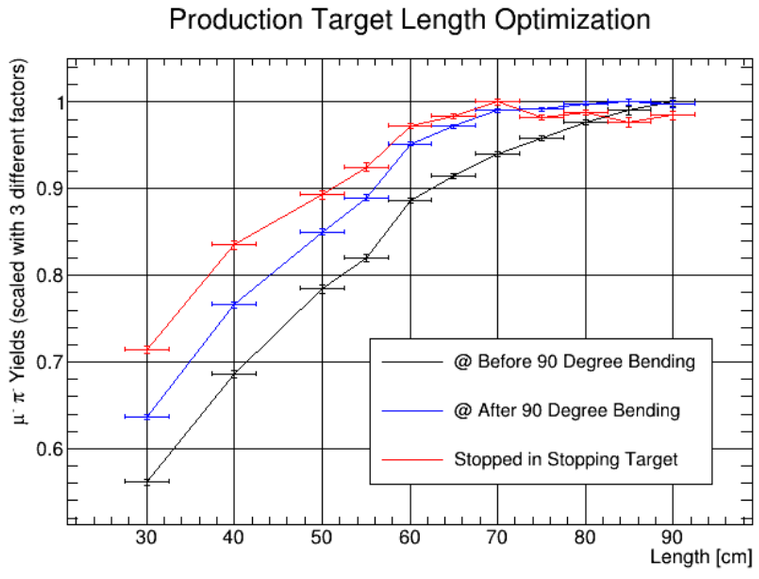
field strength … efficient transport of muons

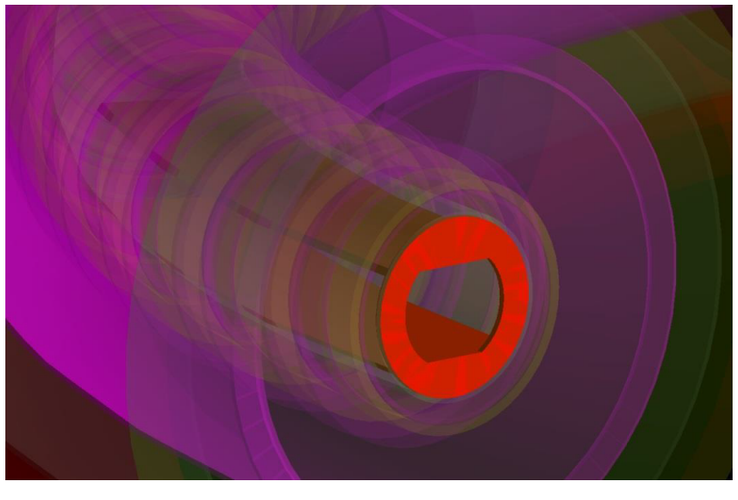
collimator size … rejection of off-momentum particles

… etc



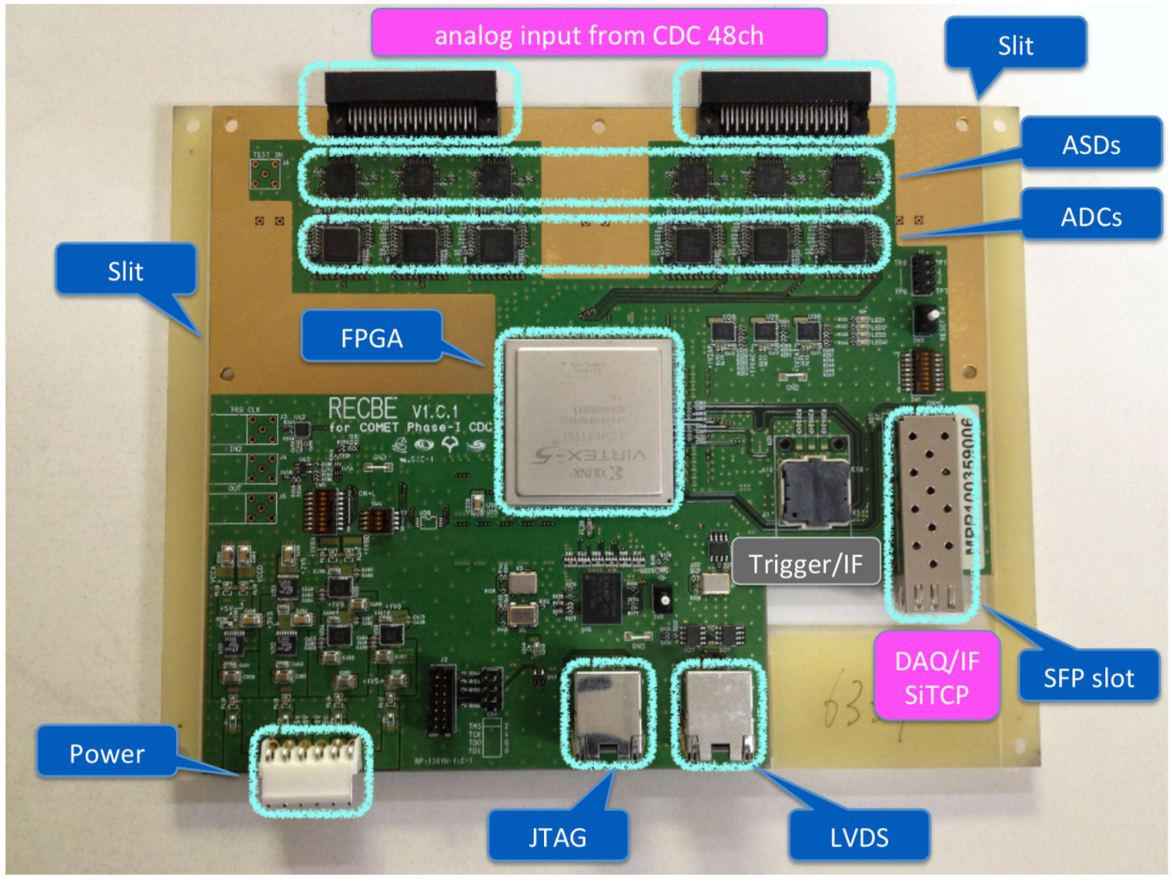






Readout Electronics

- Development of Electronics for **CDC** readout



- based on the BELLE-II CDC readout board **RECBE**
- 48 input channels
- 6 ASD ASIC chips
  (Amplifier Shaper Discriminator)
- 6 ADCs
- 1 FPGA (`Virtex-5 XC5VLX155T`)

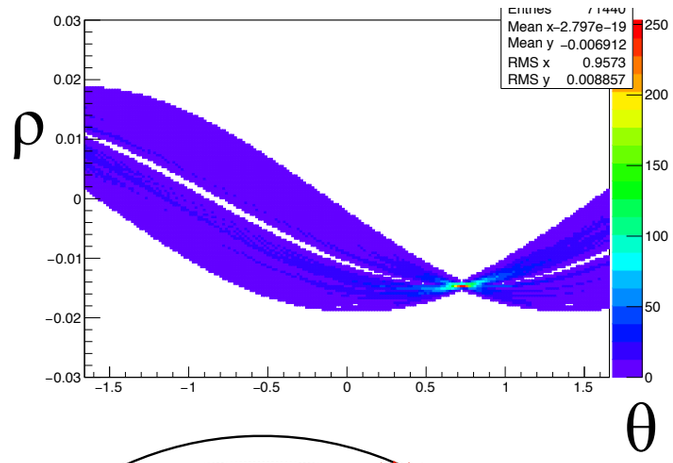
- Development and Mass Production already finished (IHEP Electronics Group)

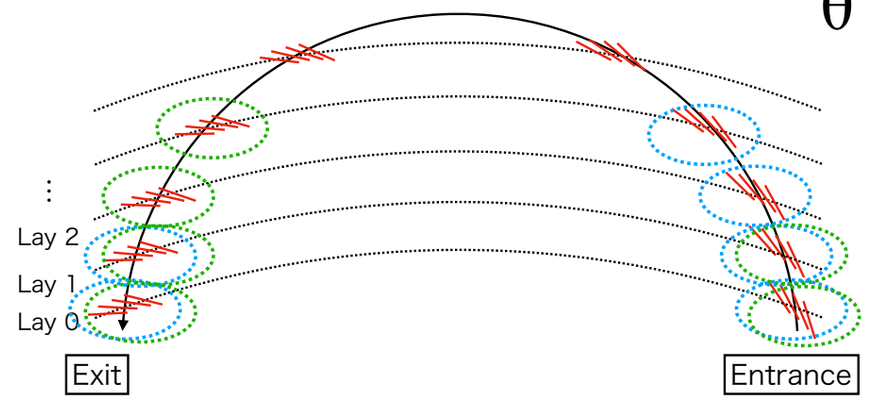
CDC Tracking

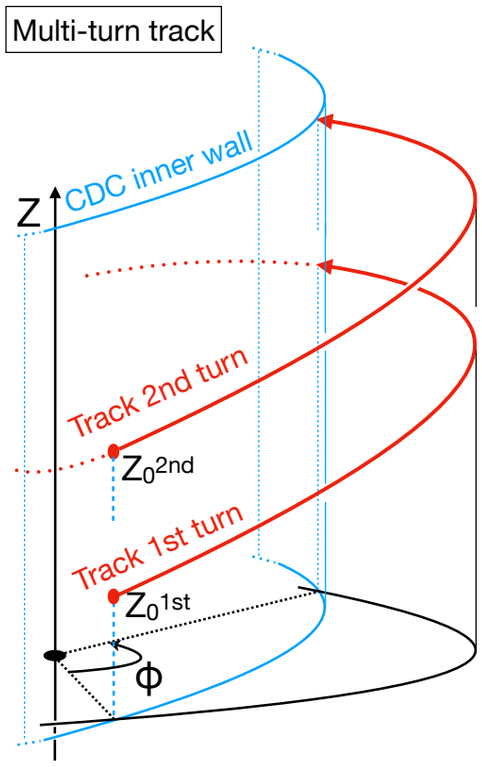
- Challenge = recognition of Multi-turn track in the CDC

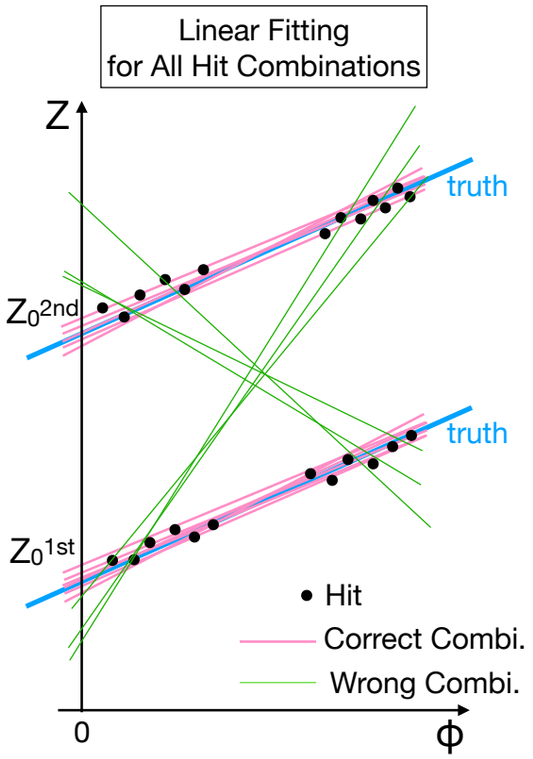
- Track Finding
  - Get track circle by Hough transform … initial parameter
  - Make combinations of 6 hits
  - Linear fitting on φ-Z plane
    χ^2 minimize by optimizing circle parameter
  - Peak finding in the track parameter space
    = track candidate

Hough Transform

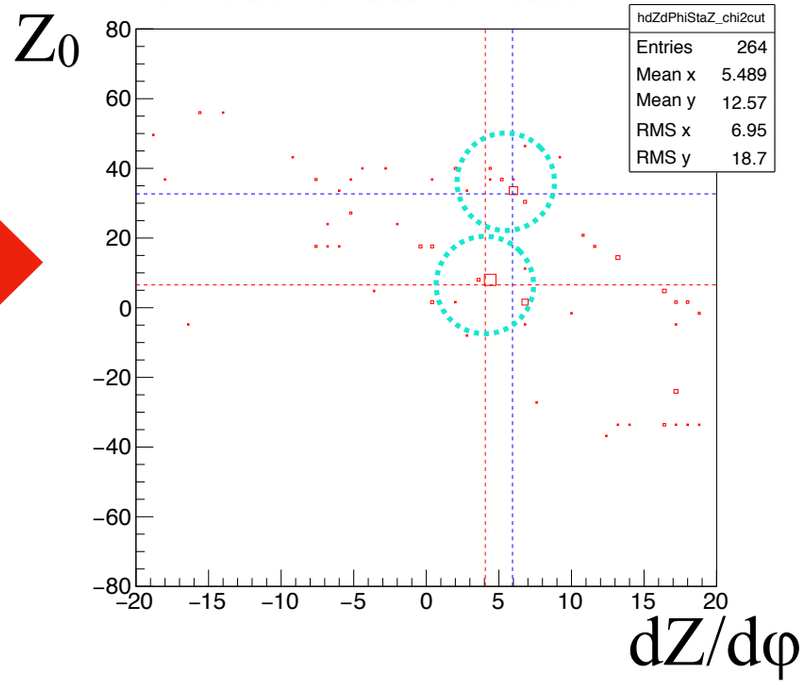








double-turn event

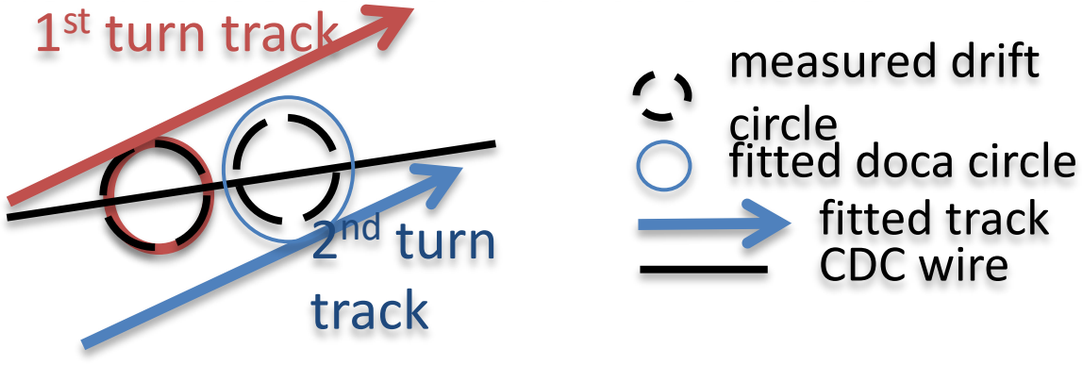


CDC Tracking

- Multi-turn Track Fitting
  - based on genfit2
  - Multi track fitting: Simultaneous fit different turn hypo thesis
  - Hit competition: Weighted mean assignment for each hit at the same detector plane
  - Annealing: Iteratively fitting with the changing of weight to avoid local minimum

- Weighted measurement for multi-turn tracks

one hit associated with two tracks



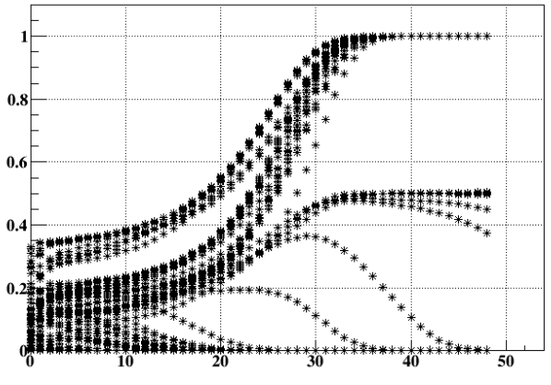
- The possibility of hit i assigned to track j

$$(\Phi)_{ij} = \varphi_{ij} = \varphi(y_i; Hx_j, V_i),$$

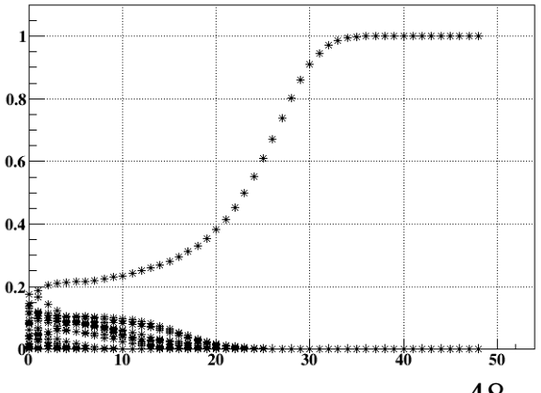
Assignment weight of hit i to track j

$$p_{i_k j} = \frac{\varphi_{i_k j}}{\sum_l \sum_\alpha \varphi_{i_\alpha l} + c}.$$

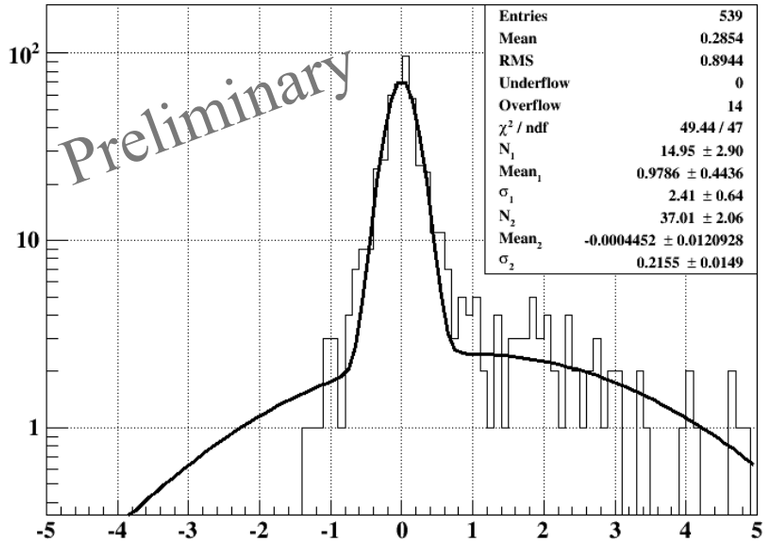
Weight from right turn vs iteration



Weight from wrong turn vs iteration

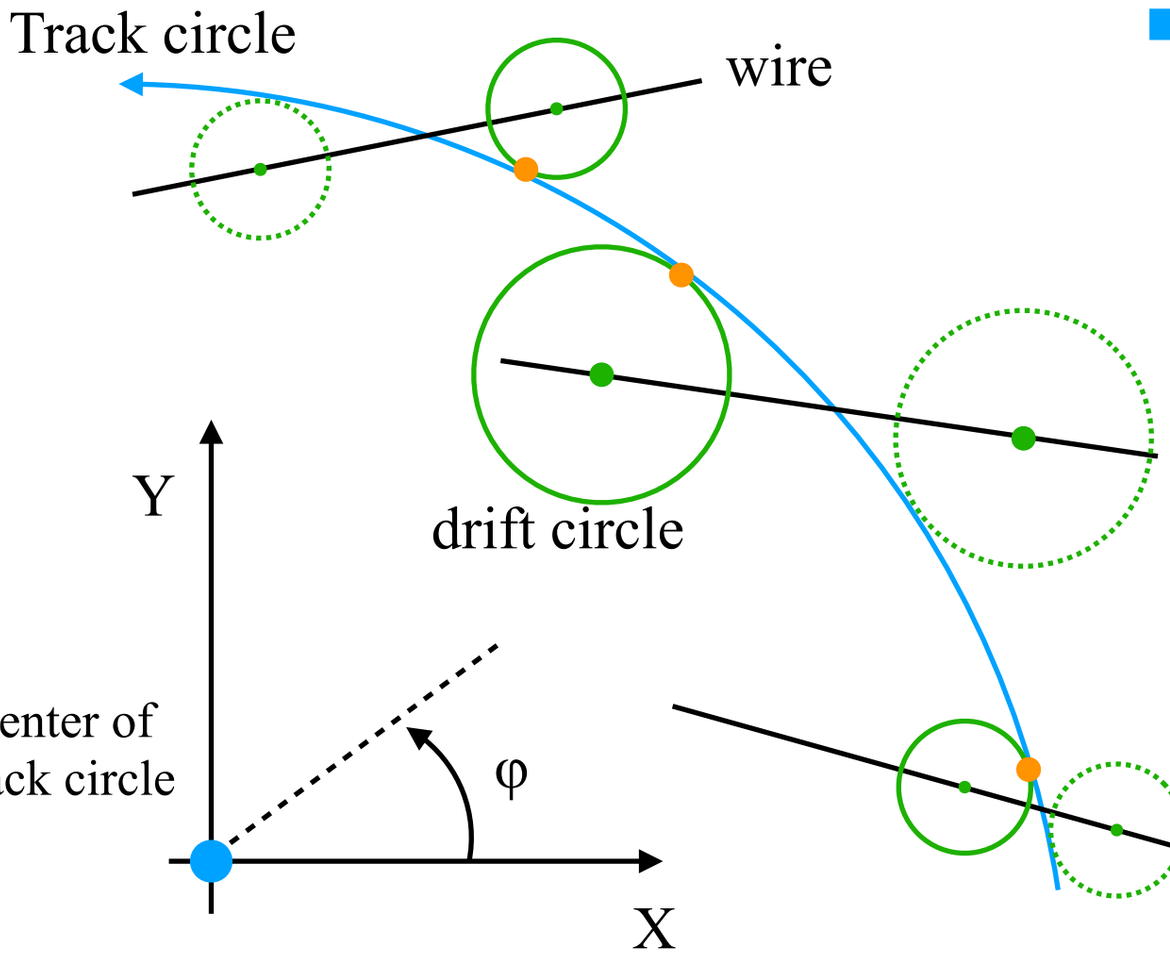


fitted result



Linear Fitting in ϕ-Z plane

Assuming Track is Helix



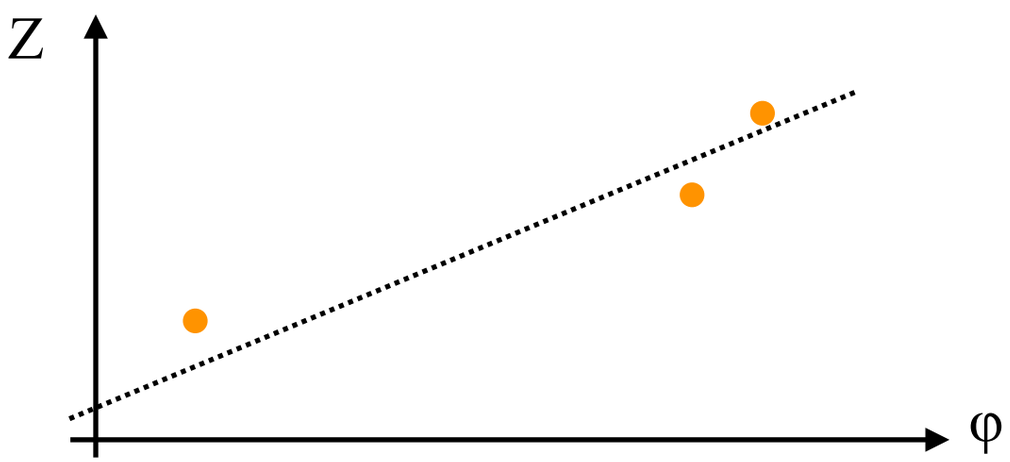
Once circle parameters are geven…

→ Contact point between track and drift circle
(sliding the center of drift circle along wire)
for fixed Left-Right assignment

→ Position of drift circle on wire
→ Z coordinate

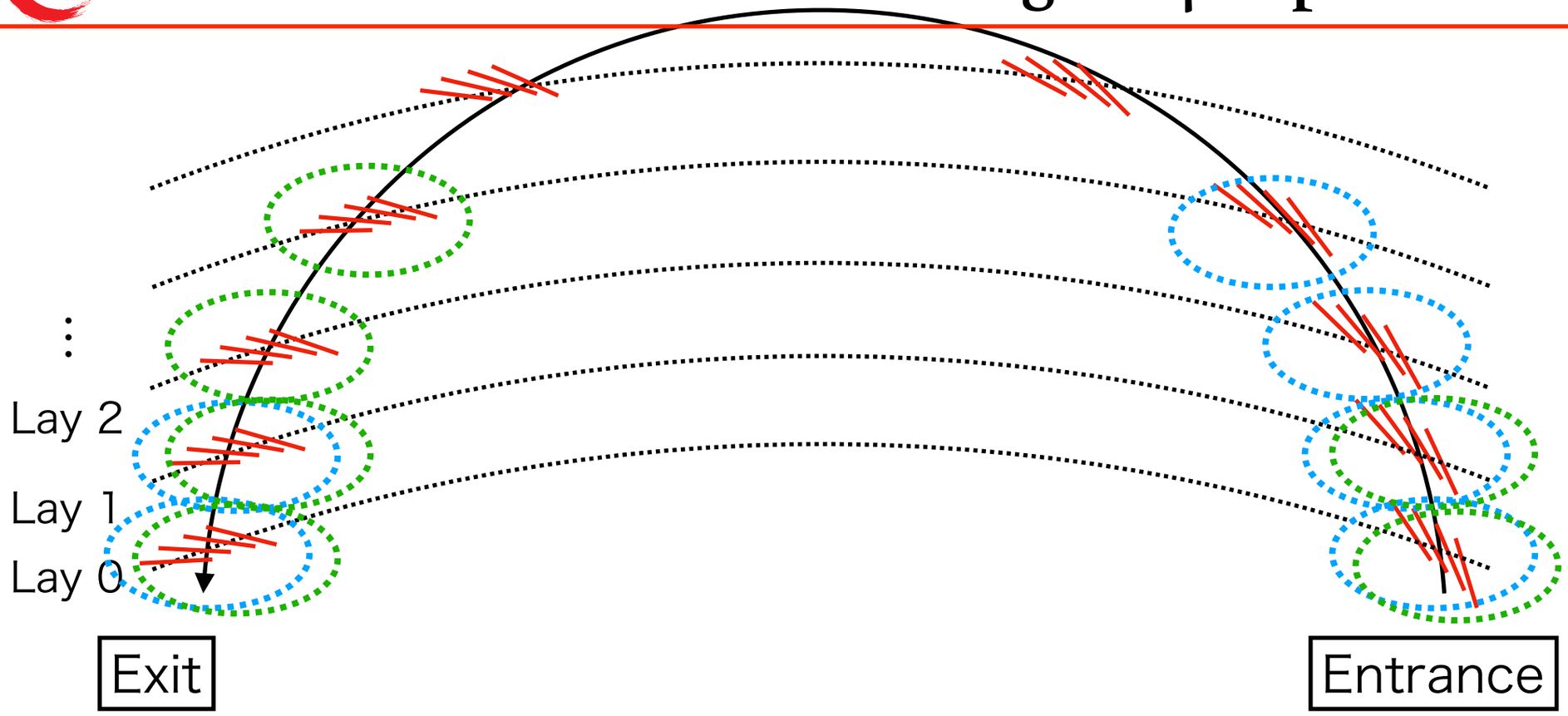
→ φ - Z coordinate

→ Linear Fitting in φ-Z plane



Minimize chi square of linear fitting
by
optimizing circle parameters

Linear Fitting in ϕ-Z plane



◯ **use 6 Clusters**

> Entrance: Layer0-3 (4 clusters) + Exit:Layer0,1 (2 clusters)

> Exit: Layer0-3 (4 clusters) + Entrance:Layer0,1 (2 clusters)

◯ take 1 hit (wire) from 1 cluster … totally 6 hits for 1 fitting combination

◯ do the Circle-Linear Fitting **for all Left-Right combinations** for 1 hit combination
→ take the L-R assignment which gives least chi square

◯ do the Fitting **for all hit combinations**

Intensity of stopped μ^-

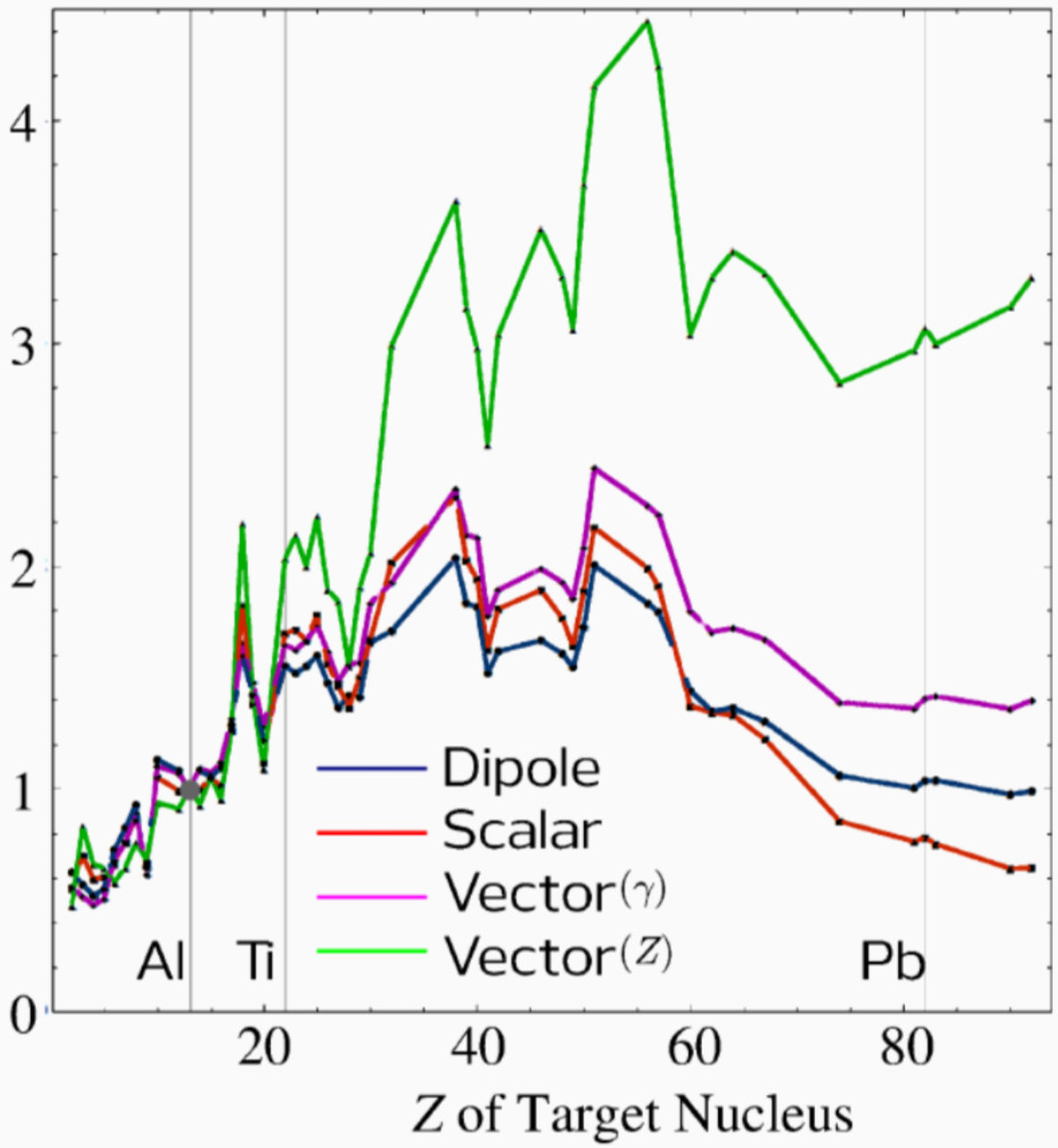
	Phase-I	Phase-II
protons on target per second	2.5×10^{12} (3.2 kW)	4.3×10^{13} (56 kW)
stopped μ^- per second	1.25×10^{8}	4.8×10^{10}

Dependence on the Target Nucleus

Relative dependences of the muon-to-electron conversion branching ratio on the target nucleus

For different nuclei, different

size of nucleus,
radius of orbit,
u- and d-quark composition



Schedule

The COMET Collaboration will have its **detector systems commissioned and tested by the end of JFY 2019**, to be ready for the beam which will arrive subsequently. Beam studies in the "B-line" proton beam line which supplies COMET will commence at this time.