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

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BESIII粲物理研讨会 2018

Outline

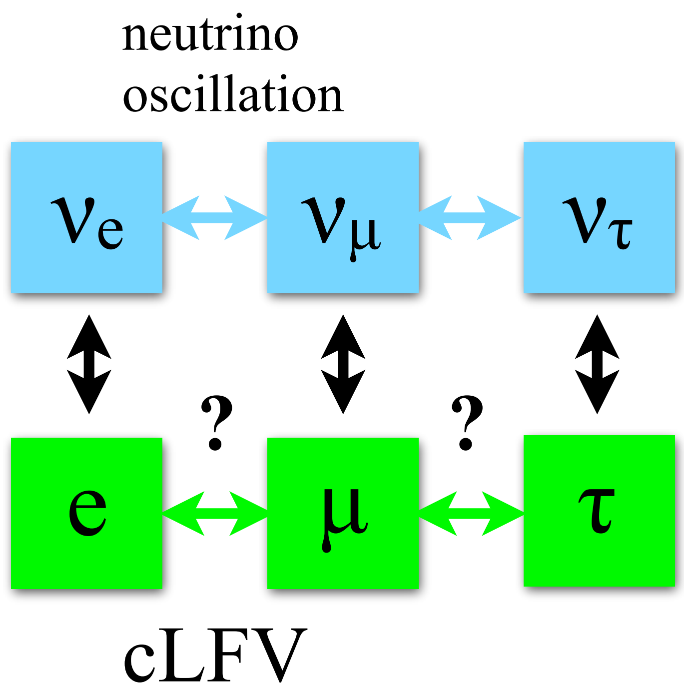
COMET … **CO**herent **M**uon to **E**lectron **T**ransition

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

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

Physics Motivation

Charged Lepton Flavor Violation

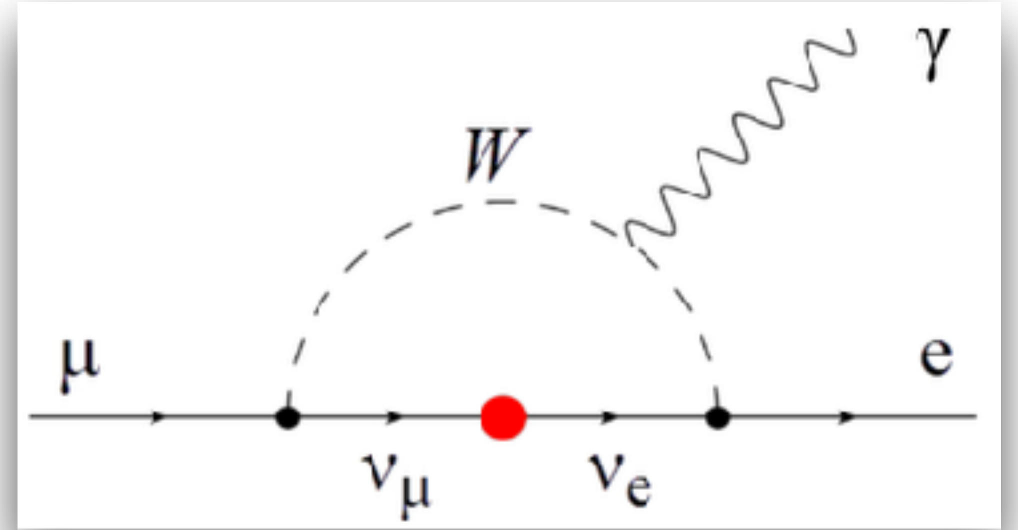


- **Lepton Flavor Violation** is forbidden in the original Standard Model(SM).
- Neutrino oscillation = Flavor Violation of neutral leptons
- charged Lepton Flavor Violation (cLFV)
  - process: $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu N \rightarrow eN$
  - **not observed yet**

- cLFV induced by neutrino flavor mixing

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

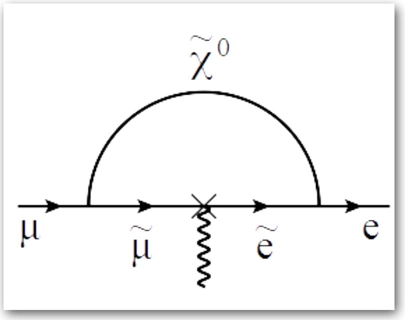
too small to be observed experimentally
in the framework of the SM

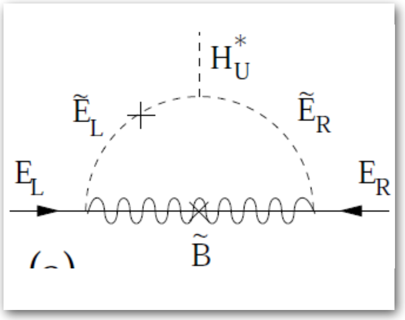


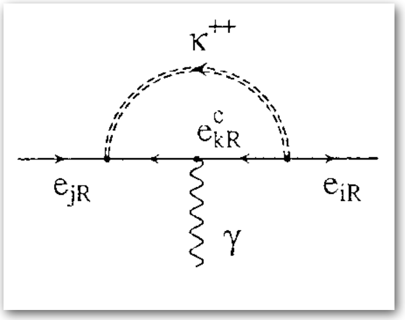
experimental observation of cLFV process
||
clear evidence of the new physics beyond the SM

Charged Lepton Flavor Violation

- Theoretical models beyond SM
  (SUSY-GUT, SUSY-seesaw, Doubly Charged Higgs, etc…)







sizable branching ratio of cLFV

predicted branching ratio = $\mathbf{10^{-14} \sim 10^{-18}}$ (ex.SUSY-GUT)

- Current Upper Limit from Experiments

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

SIMDRUM-II: BR(μ^- Au→e^- Au) < **7×10^{-13}**
SIMDRUM-II: BR(μ^- Ti→e^- Ti) < **4.3×10^{-12}**
TRIUMF : BR(μ^- Ti→e^- Ti) < **4.6×10^{-12}**

$\mu^+ \rightarrow e^+\gamma$

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

The discovery is right around the corner.

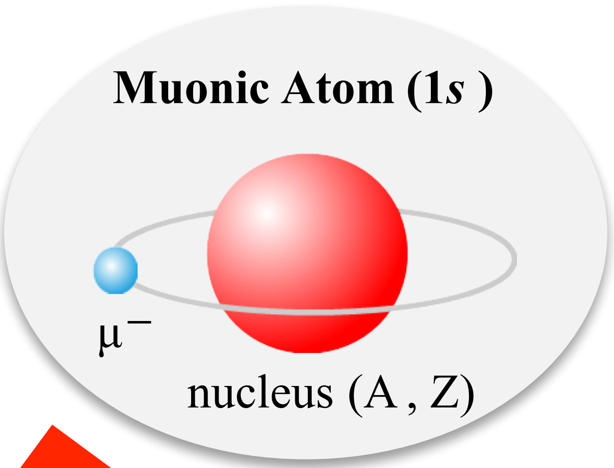
Discovering new physics and precise measurement with Extreme Sensitivity!

Decay-In-Orbit (DIO)

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

Muon Capture

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

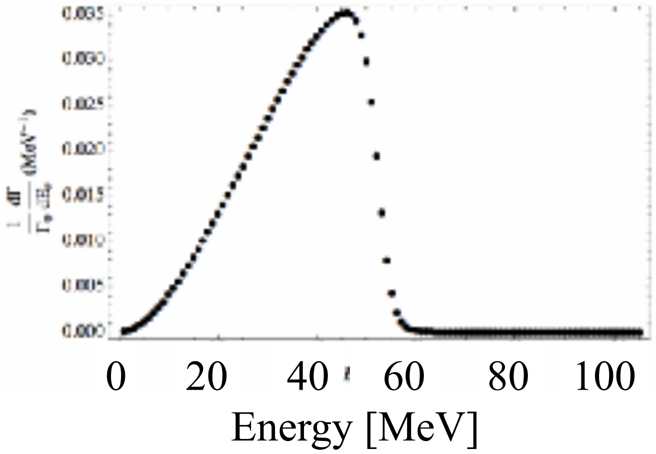


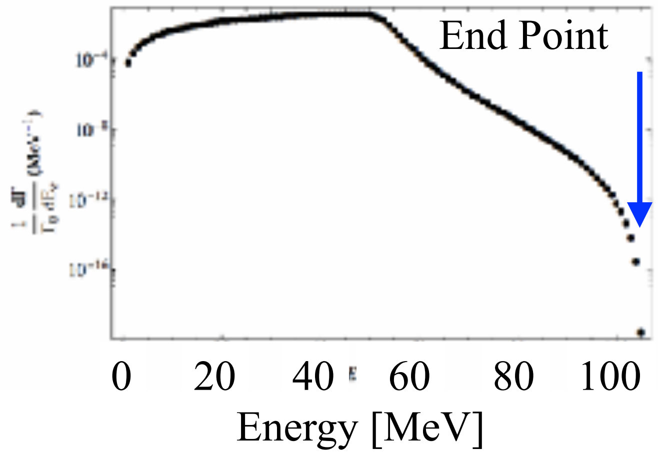
μ - e Conversion

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

- mono-energetic signal electron (~**105 MeV/c**) identified by momentum
- The most important Background **Decay-In-Orbit**

nucleus recoil … higher tail extended → close to the signal region





- **prompt timing BG**

Radiative Pion Capture

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

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

can be avoid

by **selecting delayed e-**

Sensitivity to Reaction Mechanism

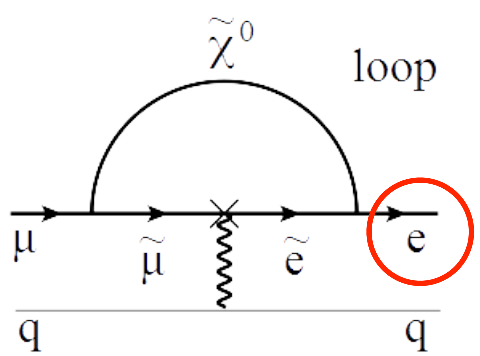
- Effective Lagrangian

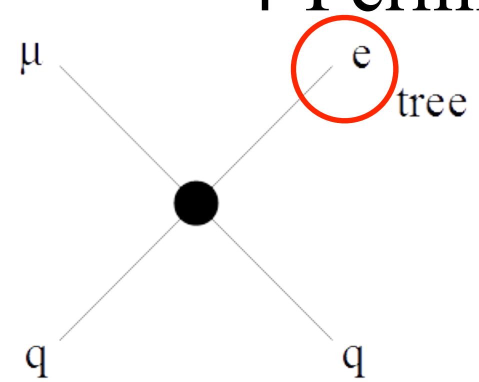
$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$

Photonic

Non-Photonic

4-Fermion

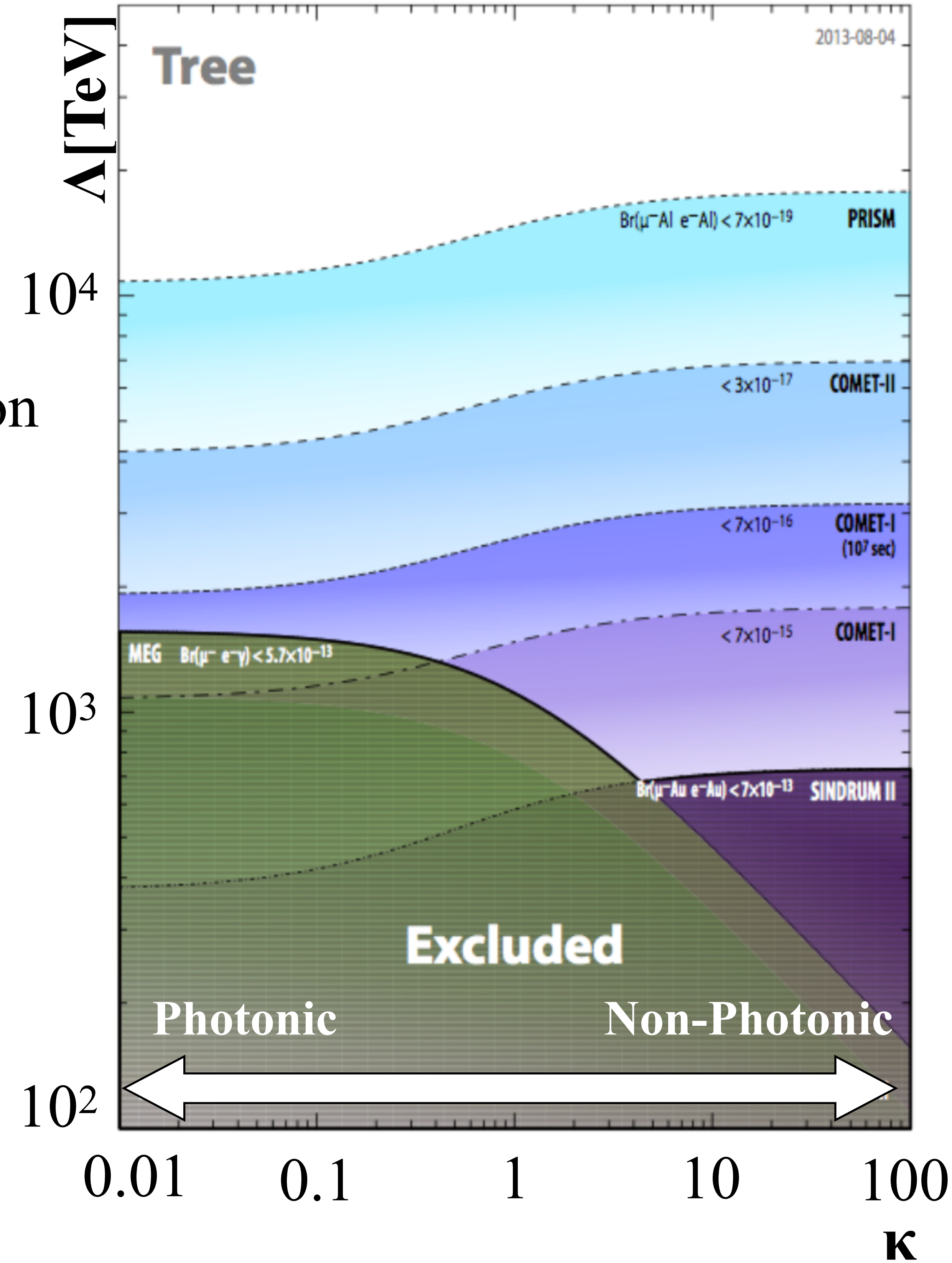




μ-e conversion in the nuclear field

= Sensitive to both Photonics and Non-Photonic processes

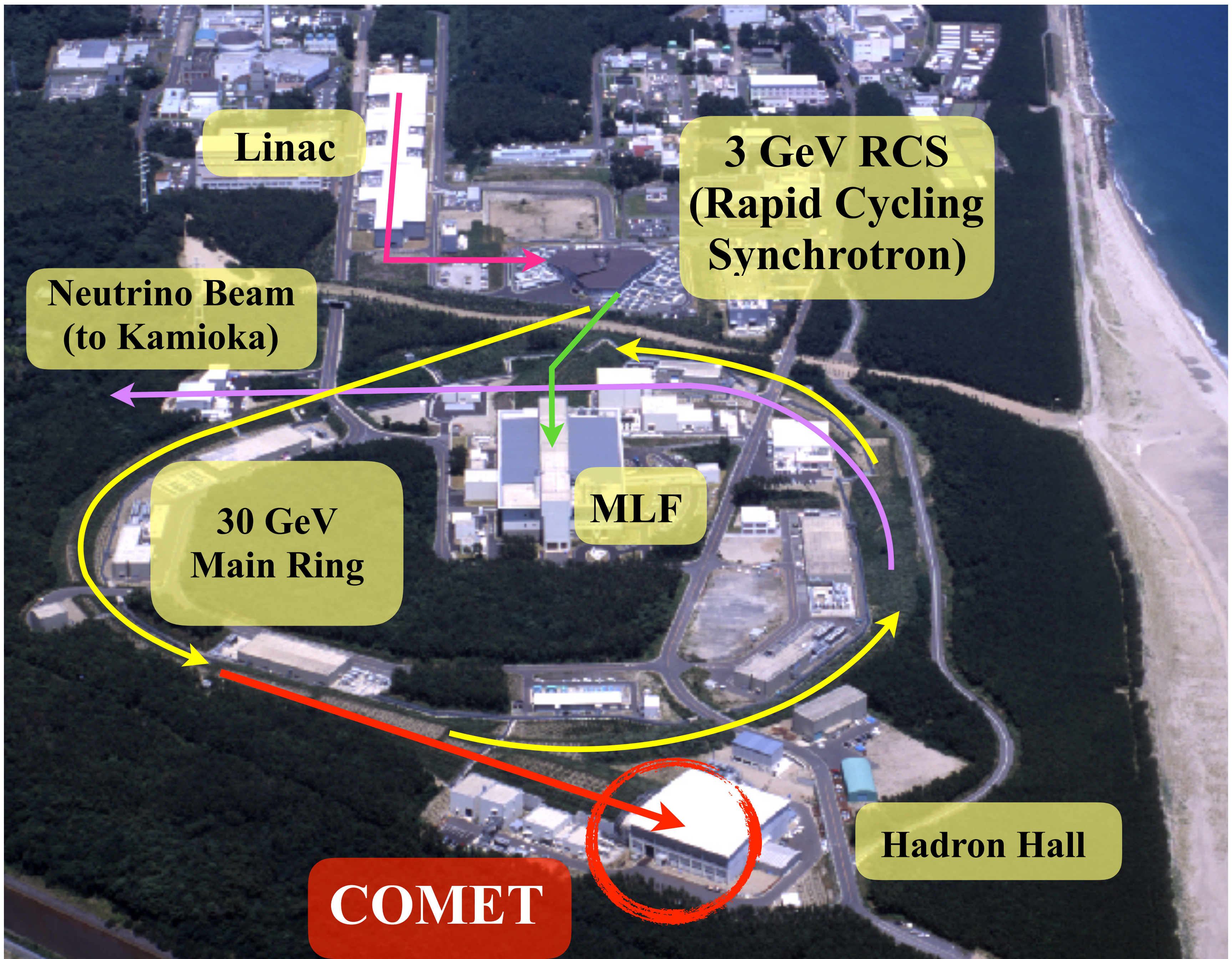
conf. MEG $\mu^+ \to e^+ \gamma$



COMET Experiment

COMET Experiment

- J-PARC (Tokai, Japan)
  extending the Hadron Hall



- Proton beam from Main Ring
  - **8 GeV**
  - **1.17 μsec** repetition
  - Beam Power

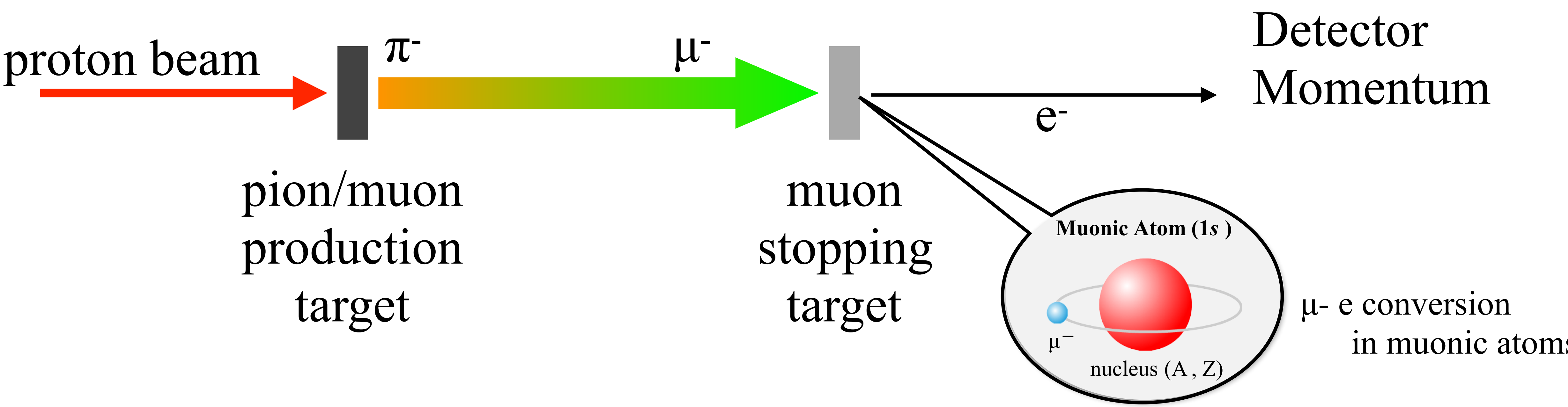
    3.2 kW for Phase-I

    56 kW for Phase-II

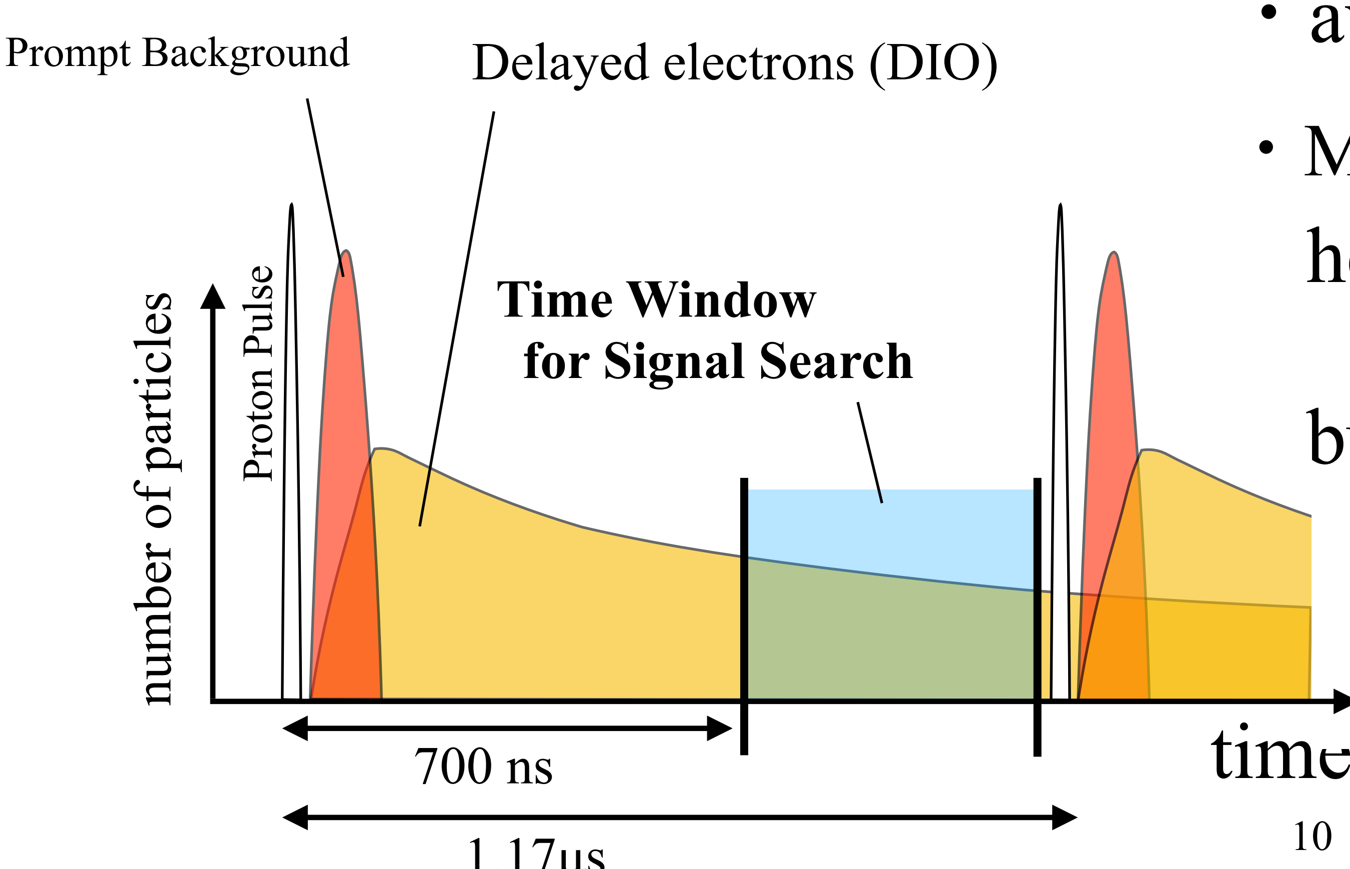
- Good Extinction factor
  - ratio of off-timing protons = (protons between buckets) / (protons in filled buckets)
  - requirement of COMET **$< 10^{-9}$**
  - measured **$< 10^{-12}$**

COMET Experiment

▶ Principle of the Experiment



▶ Utilizing the Pulsed Beam



- Delayed Time Window
  - avoid prompt beam-related backgrounds
  - Material of stopping target

    heavier nucleus …

    large overlap with muon wave function

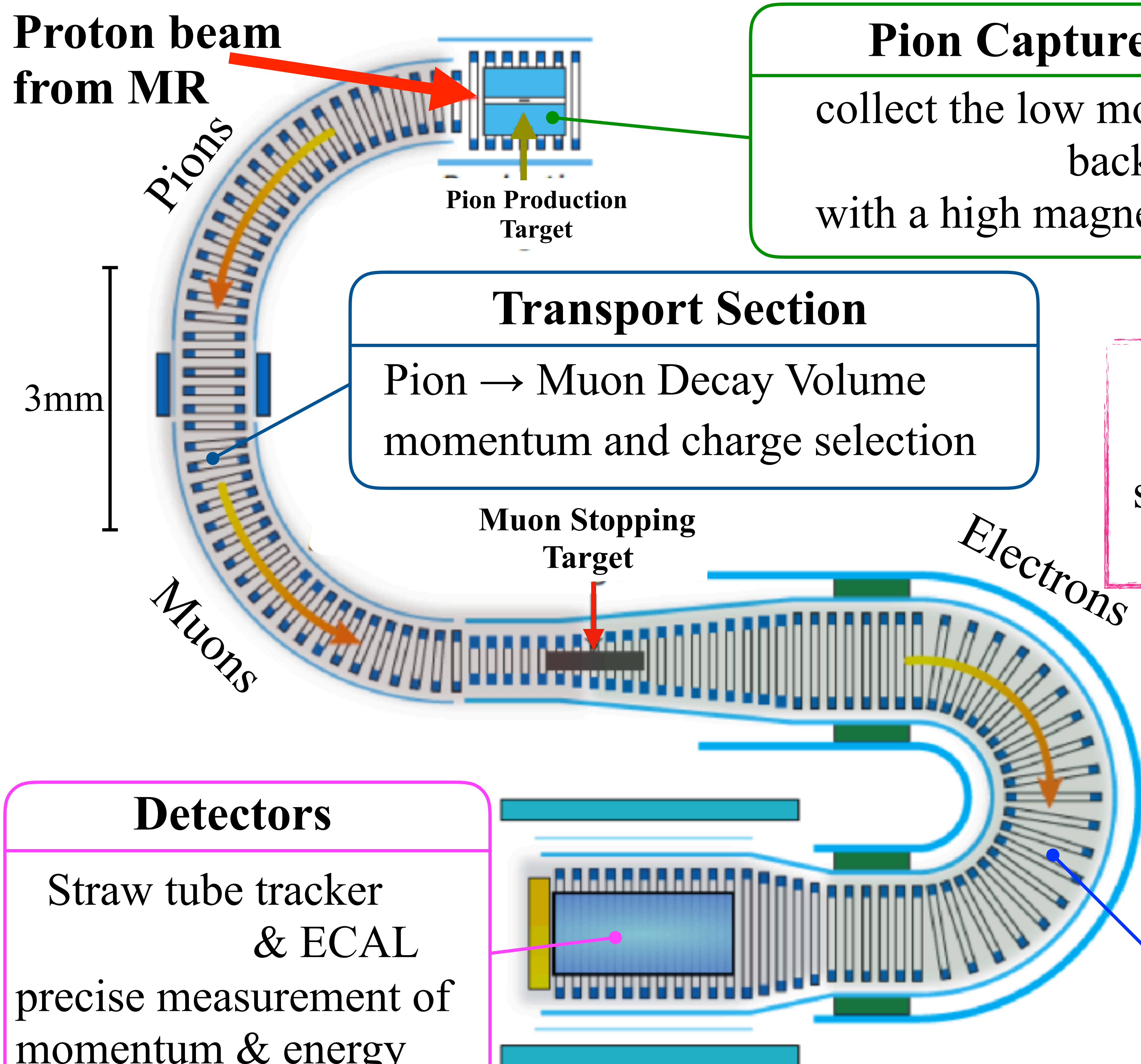
    but, short life time of muon

    - **Al** stopping target

      will be used for COMET.

      τ_μ in Al ~ **0.9μsec**

COMET Experiment (Full setup, Phase-II)



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

Search for
μ - e conversion with
single event sensitivity of
2.6×10^{-17}

Electron Spectrometer

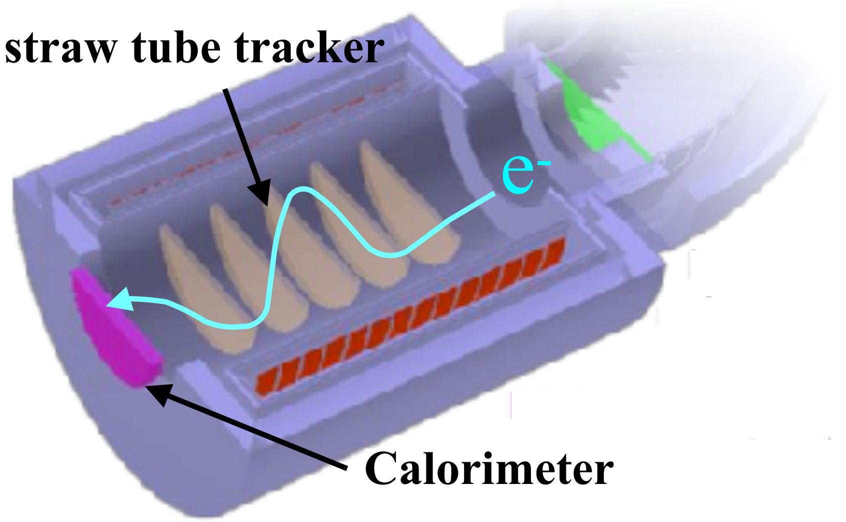
select momentum
(~105 MeV/c)
& charge

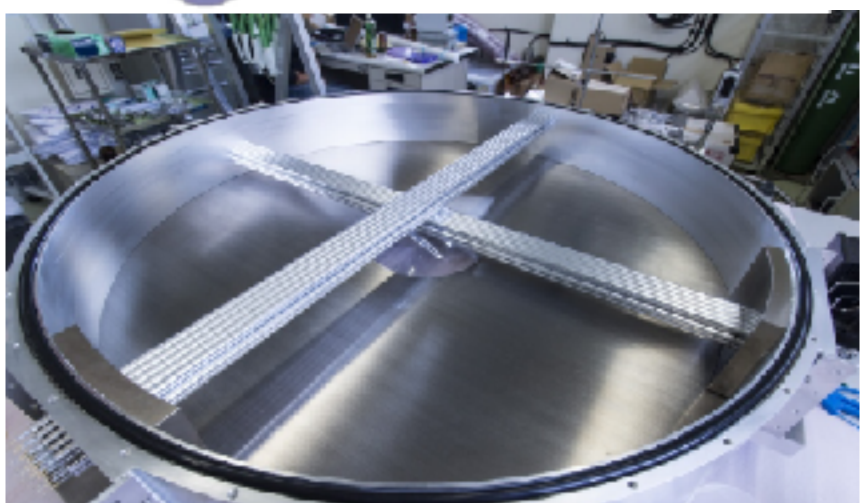
eliminate off-momentum
backgrounds

Detectors

Straw tube tracker
& ECAL
precise measurement of
momentum & energy

Phase-II Detector





prototype of Straw tube tracker

- Straw tube tracker

  4 planes × 5 Low mass … less scattering

  - Al laminated Mylar tubes (15μm thickness, 5mmφ)
  - Ar/Ethane or Ar/CO_2 gas

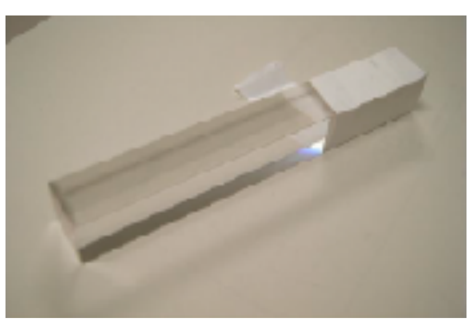
  - Position resolution **~150μm** (prototype)
  - Operation in vacuum (<**0.1Pa**)

  (achieved with prototype)

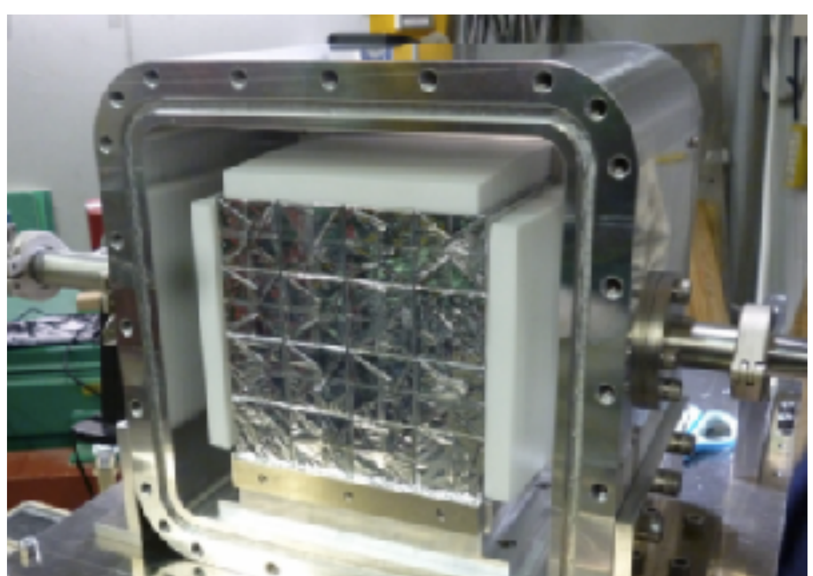
- Calorimeter

  2000 LYSO crystals

  20 × 20 × 120 mm^3 , readout = 10 × 10 mm^2 APD



LYSO crystal



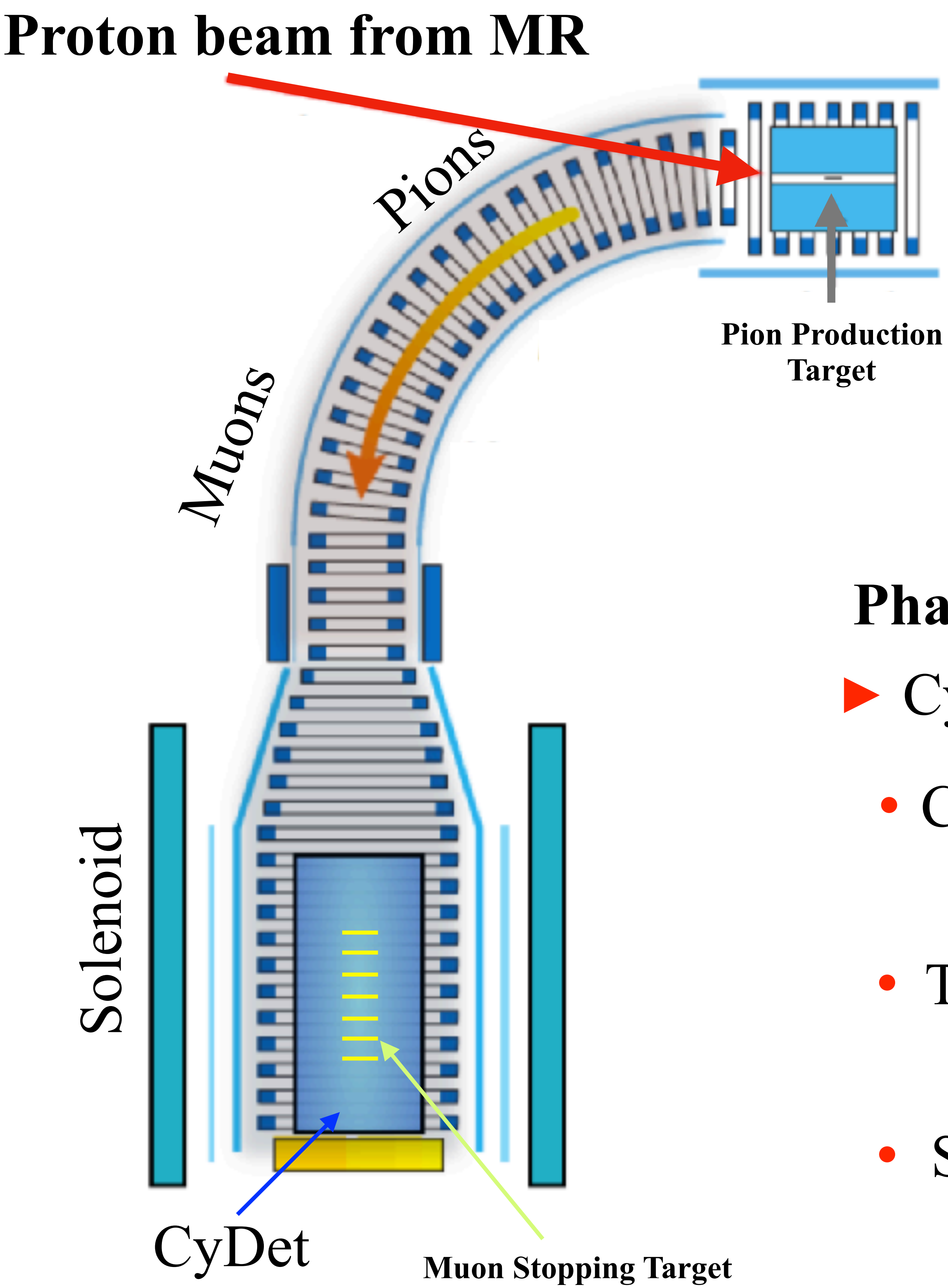
prototype of Calorimeter

performance of prototype

Energy resolution … **4.2 %**

Position resolution … **7.7 mm**

Time resolution … **0.4 ns**



Staging approach of COMET

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)
    20 Layers of stereo wires
  - Trigger Counters
    Cherenkov & Scintillator
  - Surrounding the muon stopping target
    (17 Al 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.

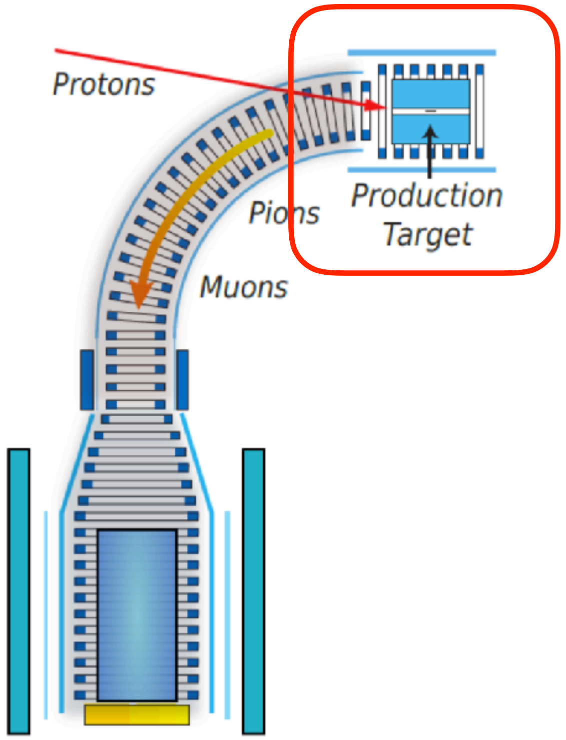
$A_{\mu e}$ = Total Acceptance for e^- from μ-e conv.

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

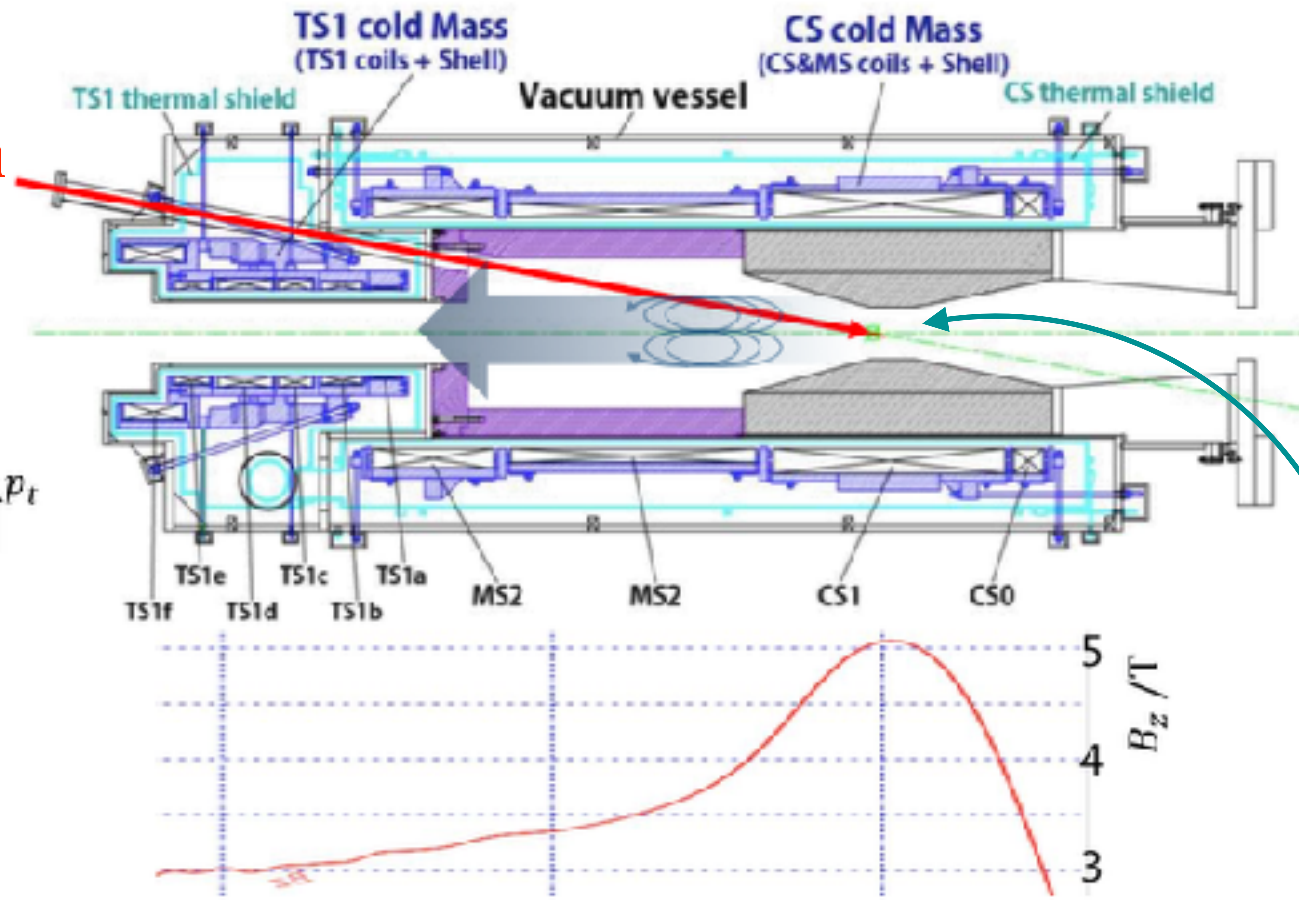
c.f. SIMDRUM-II: BR(μ^- Au→e^- Au) < $\mathbf{7 \times 10^{-13}}$

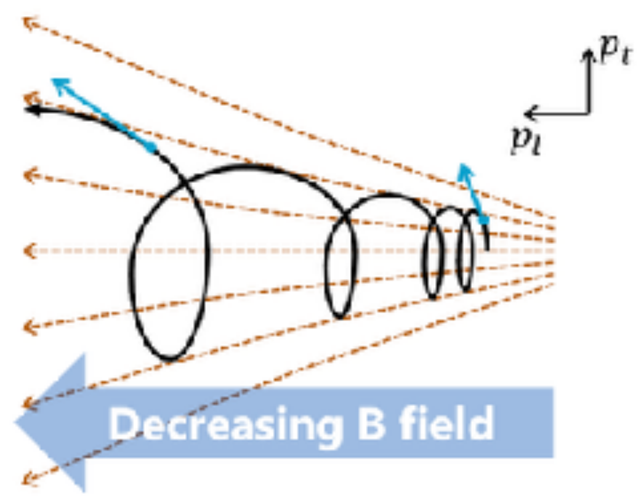
Development & Status towards Phase-I

Production Target

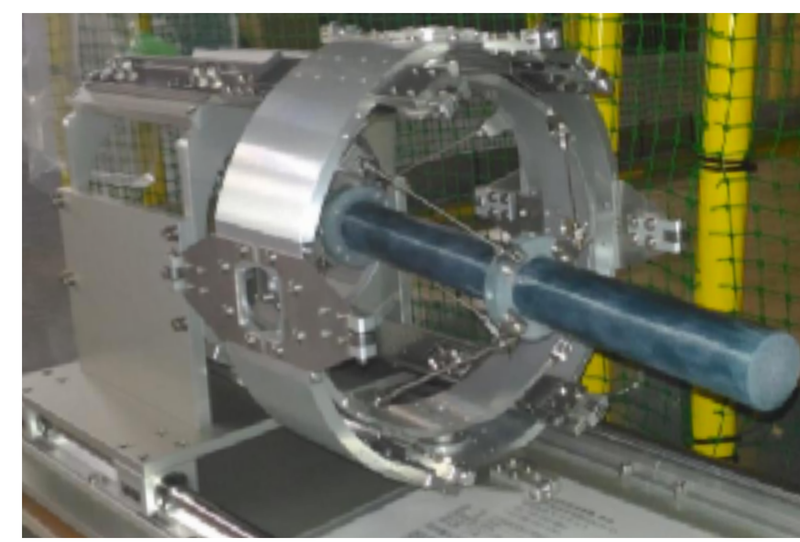


Proton beam
from
J-PARC Main Ring

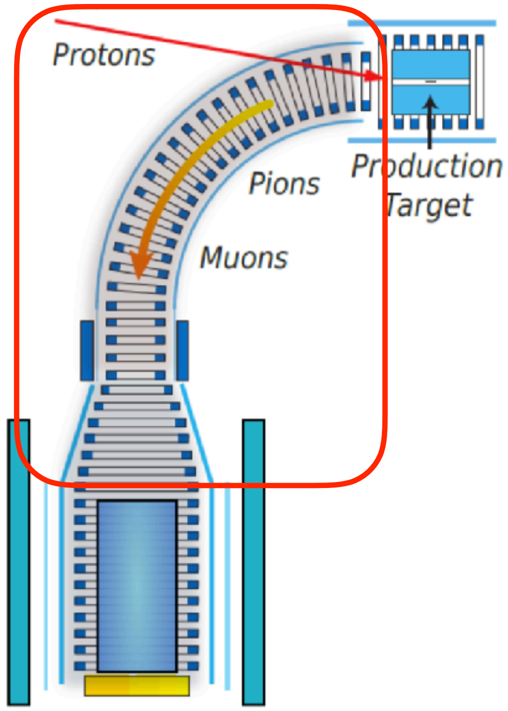




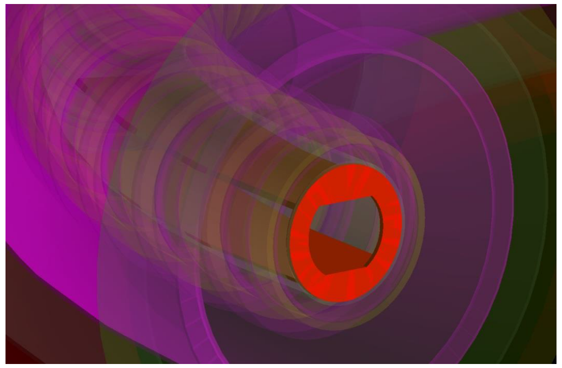
- Target rod
  - Graphite , **700 mm** length, **13 mm** radius
- Pion capture solenoid
  - collect backward pions
  - Maximize field at target (**5 T**) to give larger aperture angle



Prototype of the production target



- Curved solenoid
  - 90 degree bend
  - high transmission efficiency for **40 MeV/c μ^-**
  - collimator … block high momentum muons



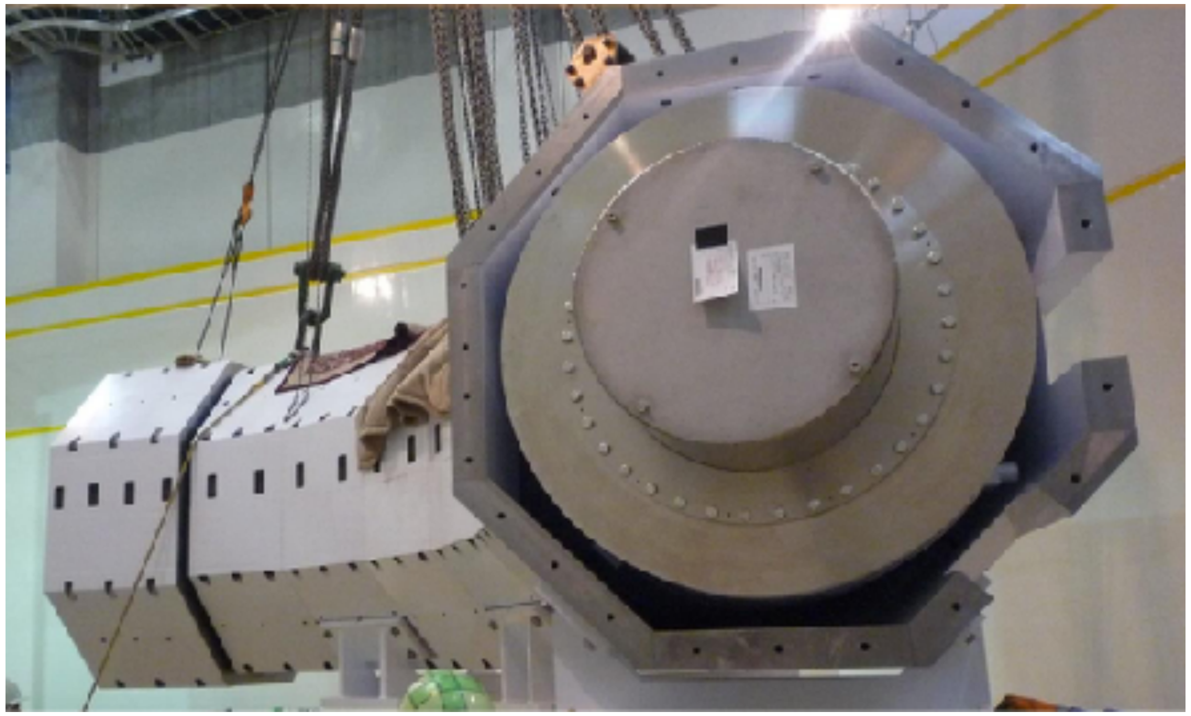
Collimator

- high stopping rate at the target
- Stopped muons in target

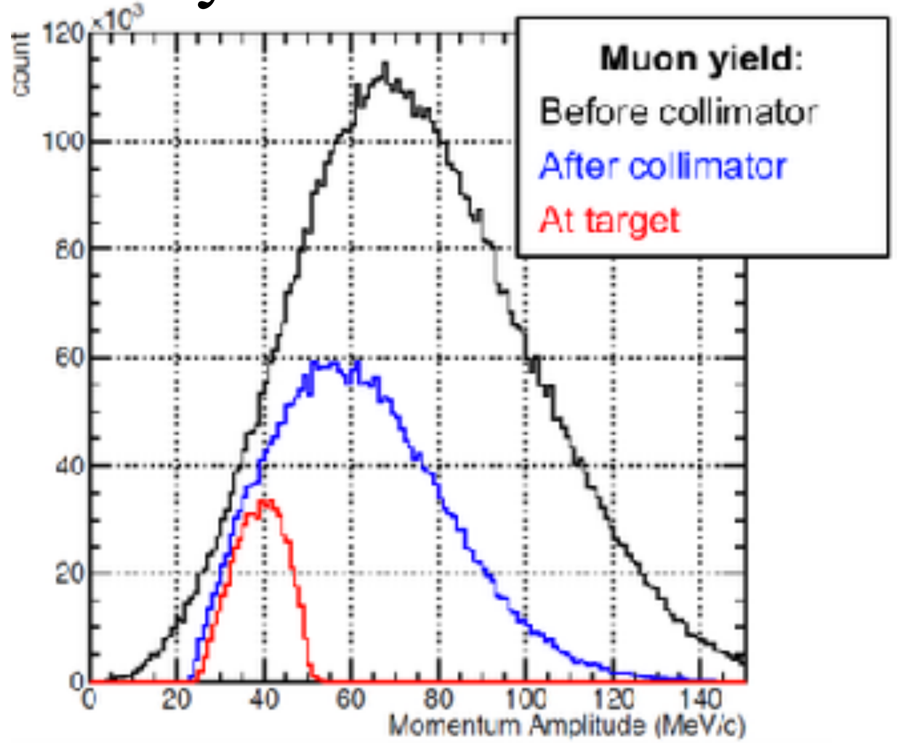
$= 4.7 \times 10^{-4}$ [1/proton]

(1.25×10^{8} [1/sec])

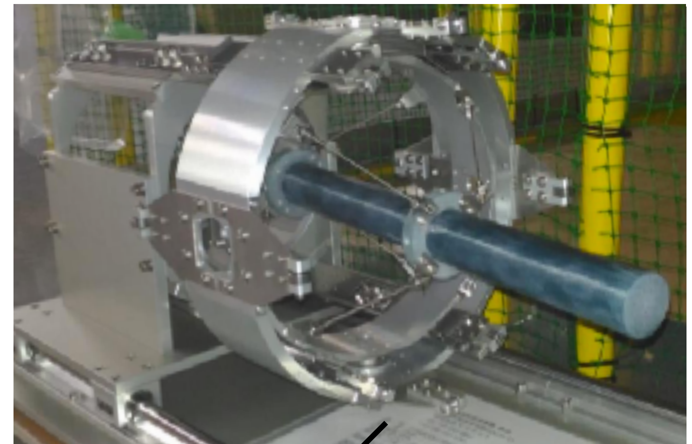
Curved solenoid



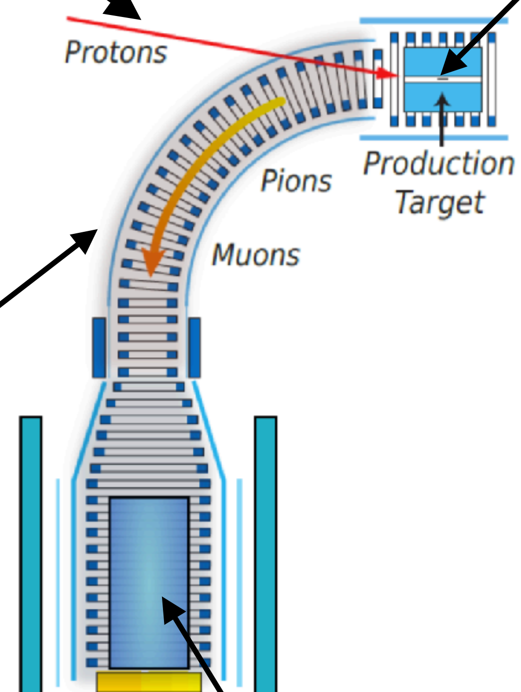
muon yield

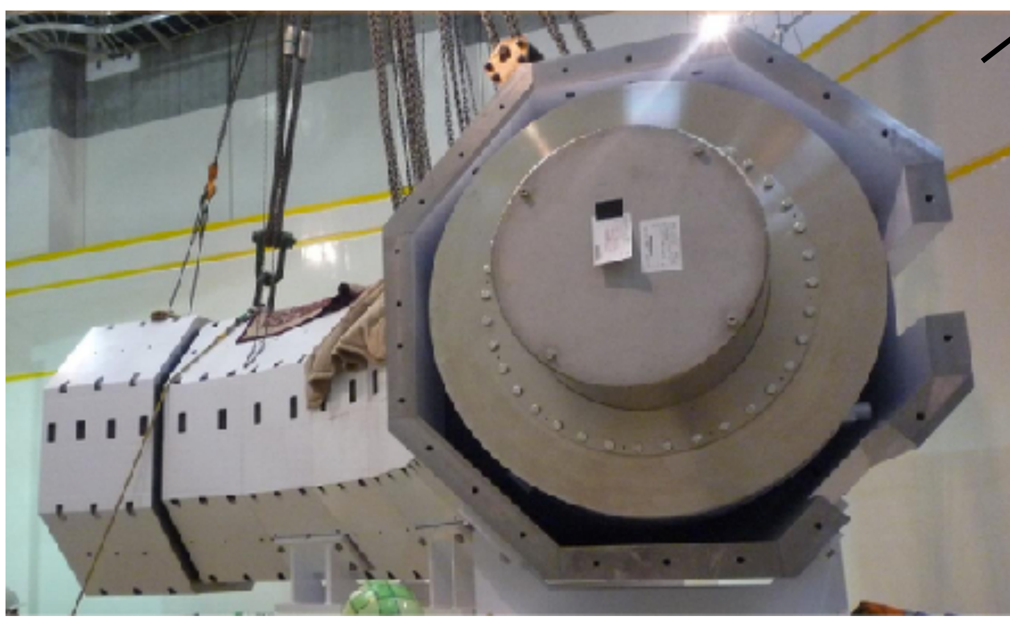


Facility Status

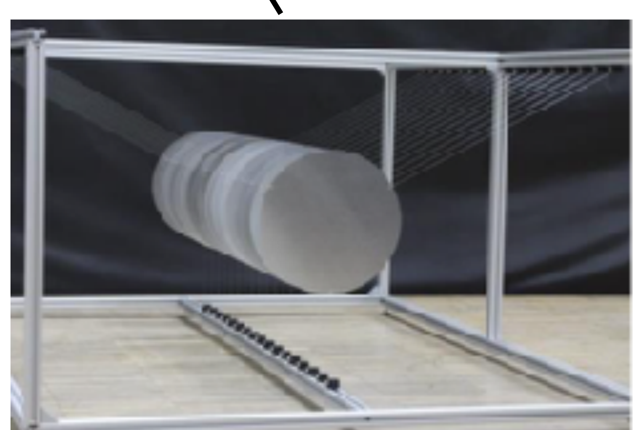


Pion Production Target Prototype





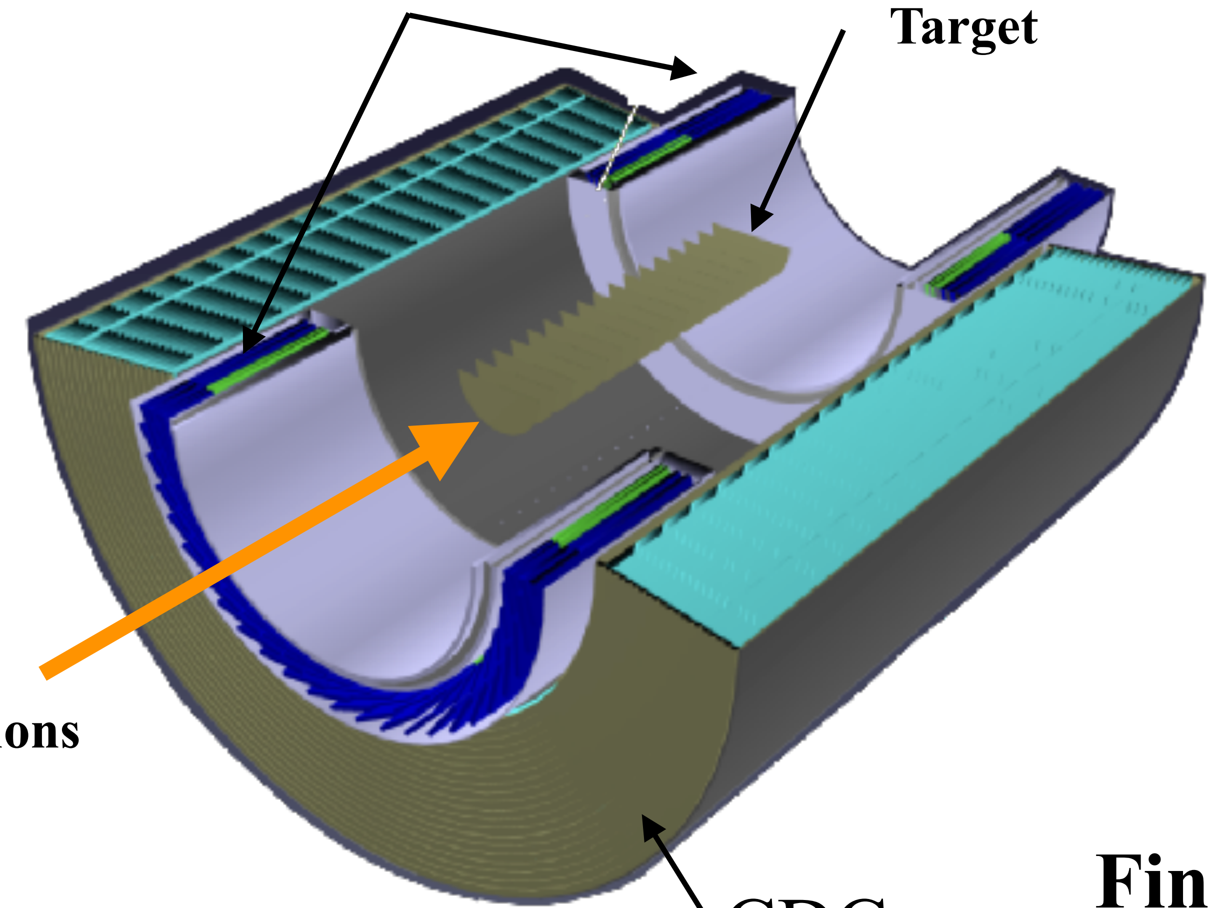
Transport Solenoid Installed



Muon Stopping Target Prototype

COMET Experimental Hall

Detector System　CyDet

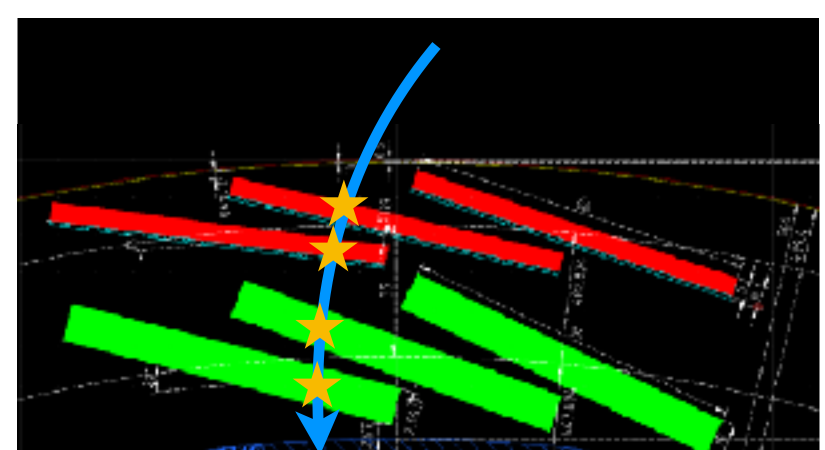


- Cylindrical Drift Chamber (CDC)
  - **20** Layers　all stereo wires
  - **4986** sense wires
  - Gas: **He/C_2H_6(50/50)** or **He/iC_4H_{10}(90/10)**
  - Magnetic Field: **1T**

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

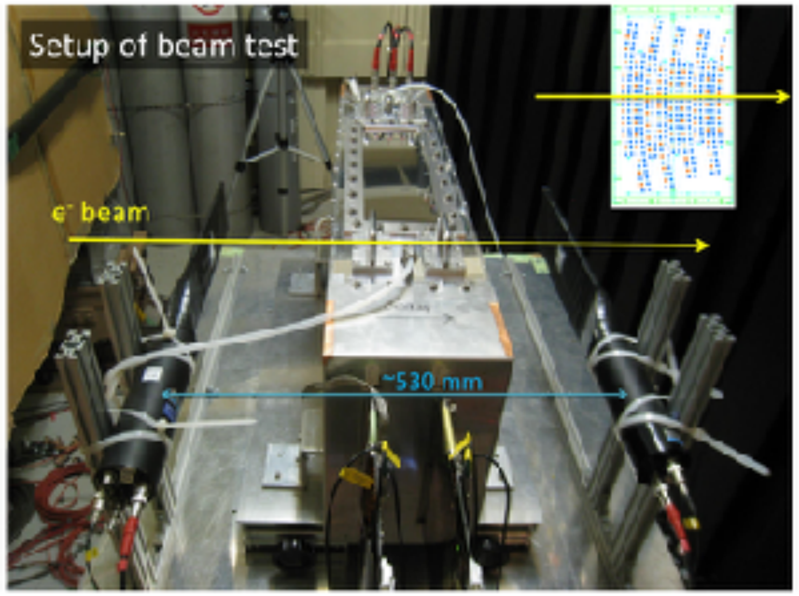
- Trigger Hodoscope
- Cherenkov counter… Acrylic, particle ID
- Scintillation counter… Plastic Scint., timing

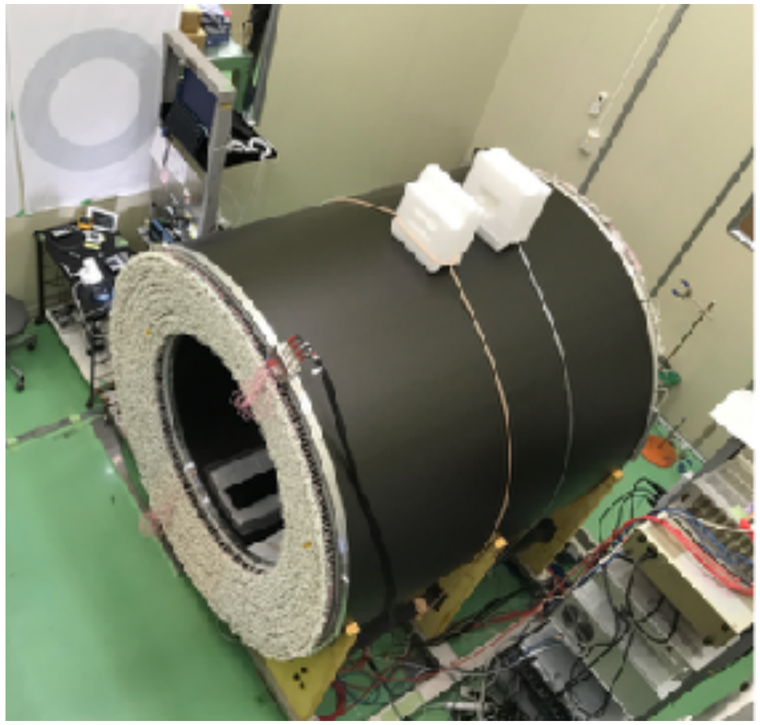
- Trigger Condition
  2 Scinti. + 2 Cherenkov



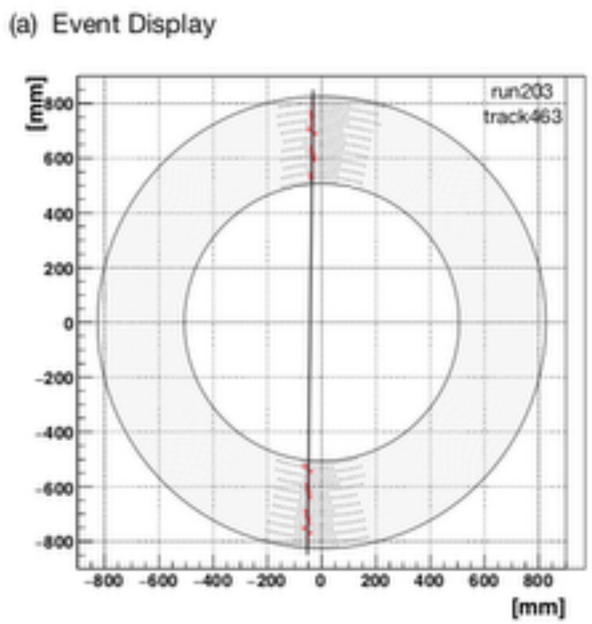
Cylindrical Drift Chamber

- Various performance test done
  - test with electron beam
  - aging test
- Cosmic ray test ongoing
  - spatial resolution ~**170 µm**
  - efficiency **95%** so far

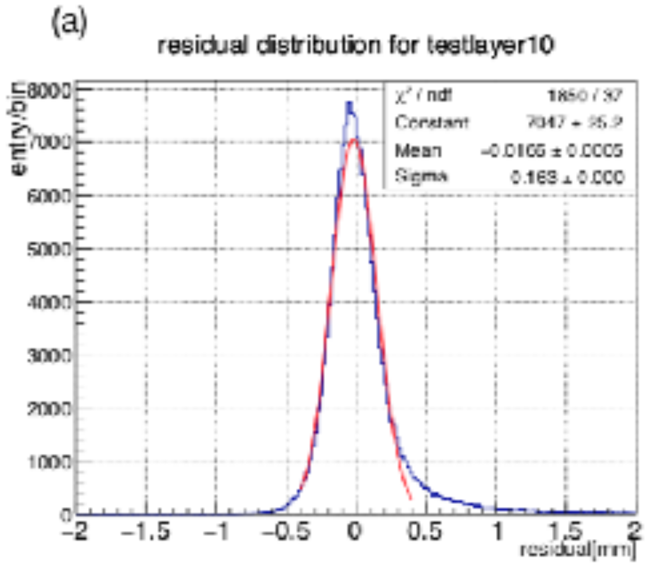




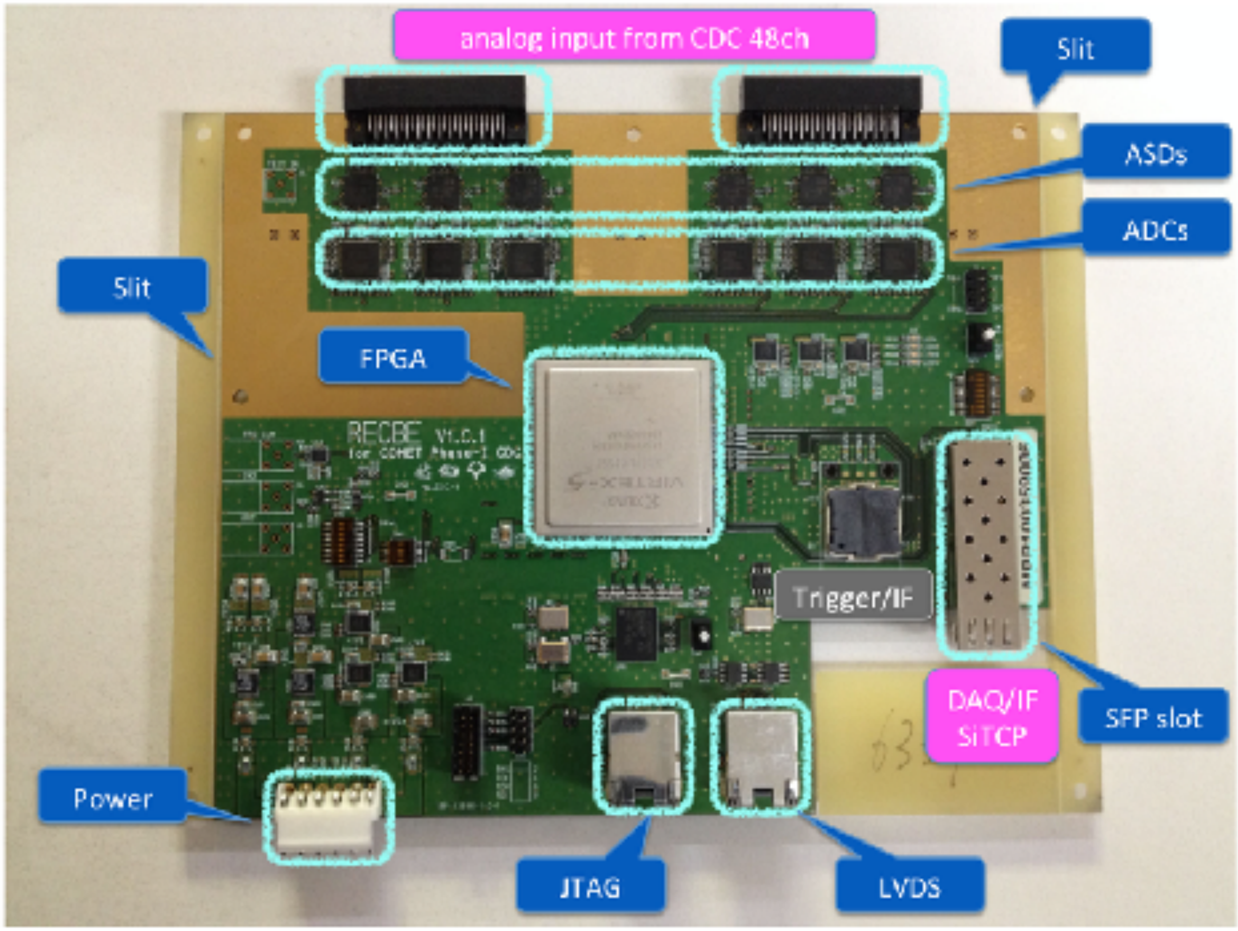
event display of cosmic ray test



residual distribution of position



▶ 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`)

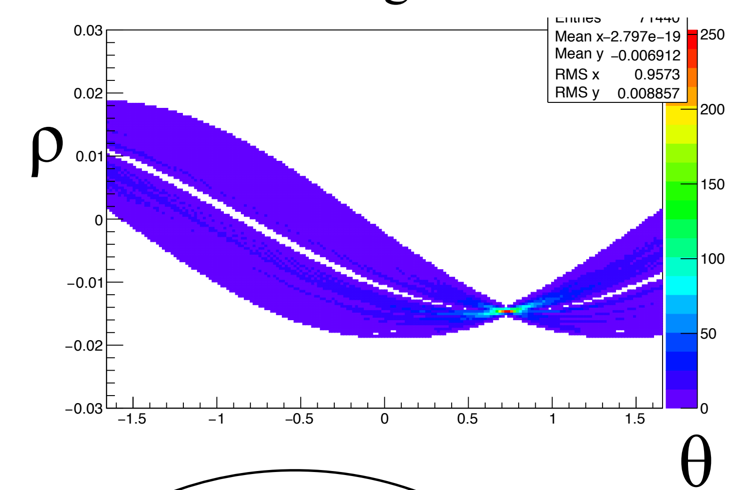
▶ Mass production already finished

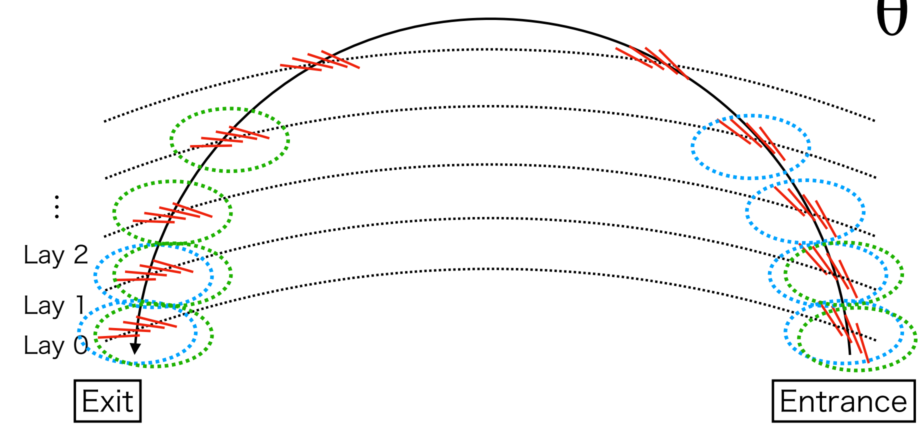
Development and Mass Production
by IHEP Electronics Group

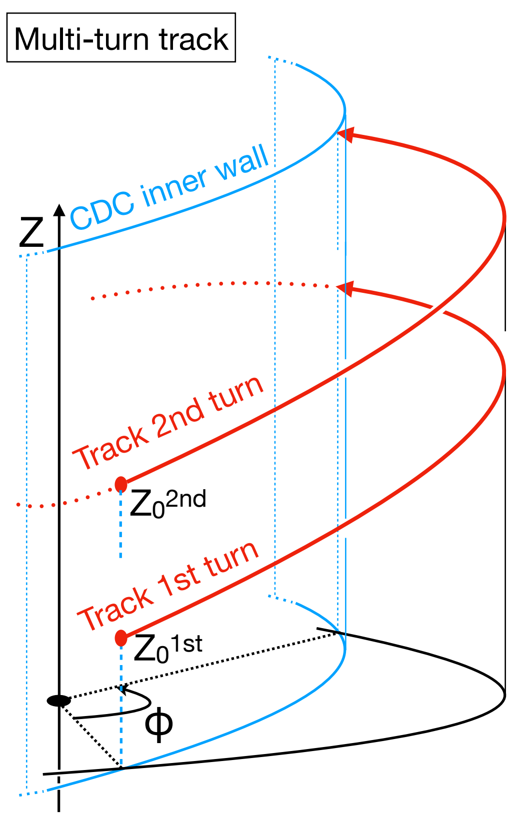
CDC Tracking

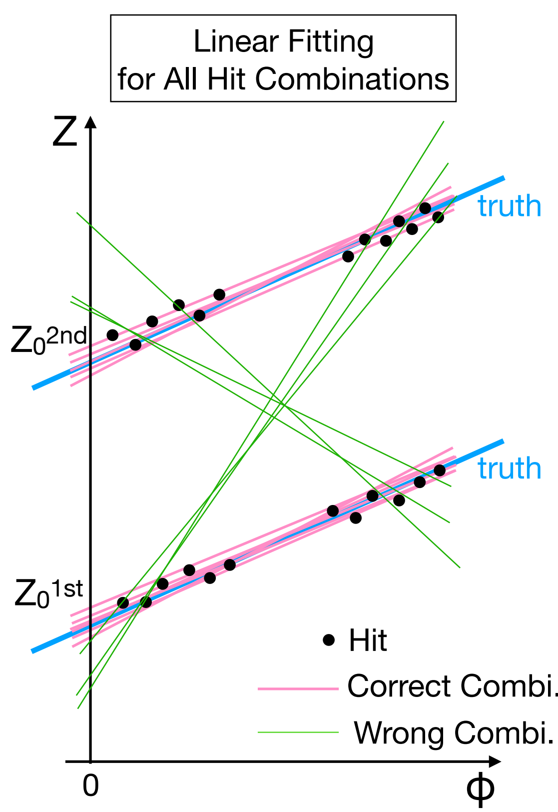
- **<u>IHEP COMET Group</u> plays leading role of CDC track reconstruction.**
- Challenge = recognition of Multi-turn track in the CDC
- Track Finding
  - Get track circle by Hough transform … initial parameter
  - Make combinations of 6 hits
  - Linear fitting on φ-Z plane
    χ^2 minimize by optimizing circle parameter
  - Peak finding in the track parameter space
    = track candidate

Hough Transform

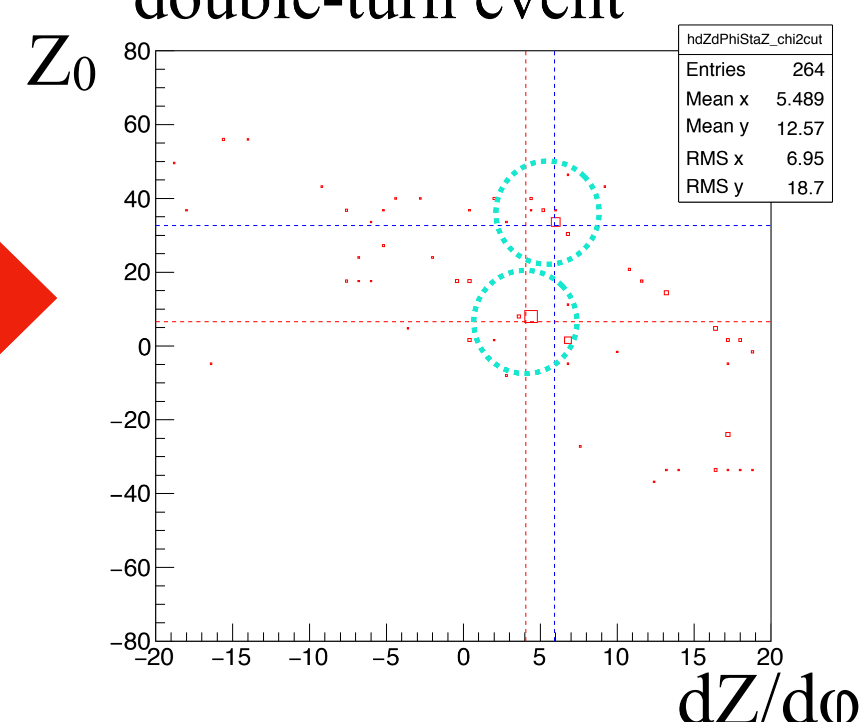








double-turn event

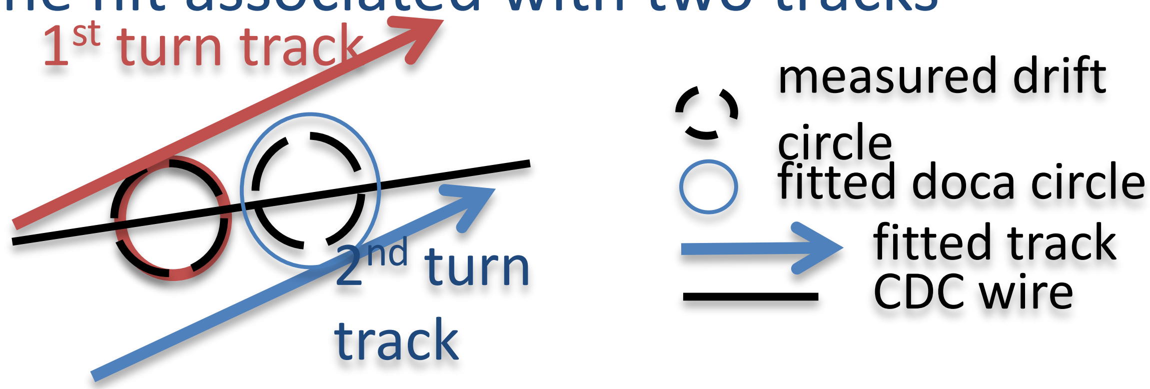


CDC Tracking

- 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



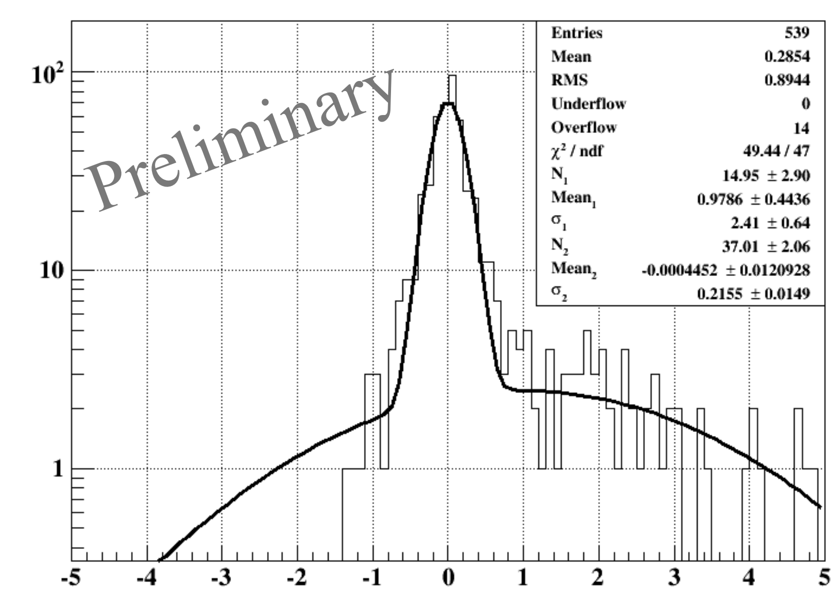
- The possibility of hit i assigned to track j

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

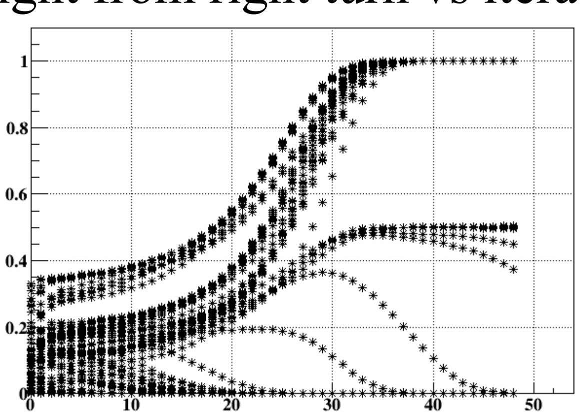
Assignment weight of hit i to track j

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

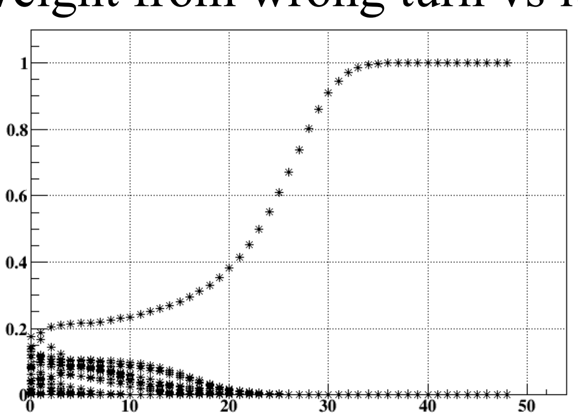
fitted result



Weight from right turn vs iteration



Weight from wrong turn vs iteration



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 $\mathbf{10^{-15}}$
    Direct measurement of background
  - Phase-II: sensitivity of $\mathbf{10^{-17}}$ with full setup

- Detector & Software development
  facility construction … ongoing!

- Schedule

  Commissioning … start at the end of 2019
  Cosmic Ray test with full set up of Phase-I … 2019
  Physics data taking for Phase-I … start at 2021 or 2022

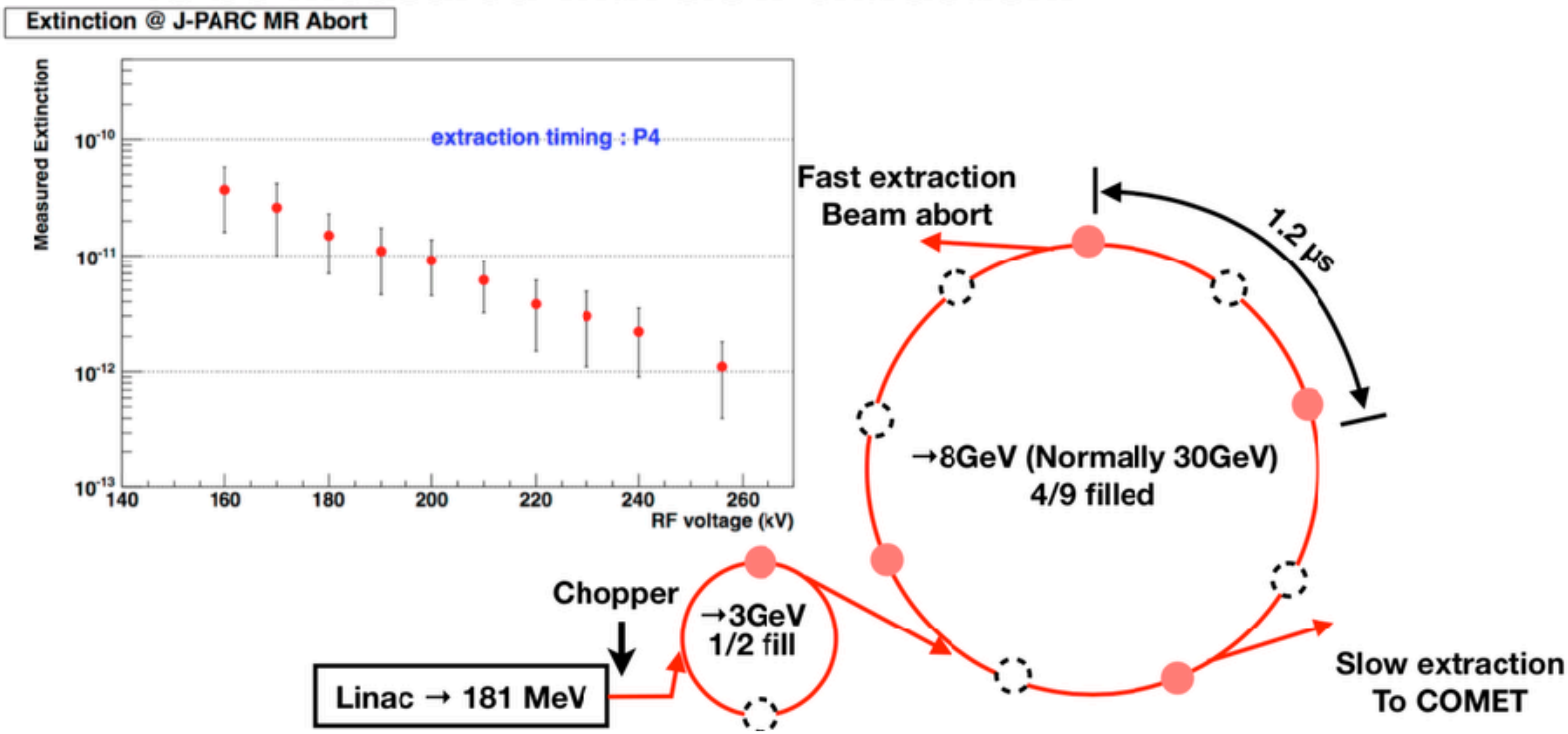
Welcome to the COMET Collaboration !

16 Counties, 40 Institutes
~200 Collaborators
... increasing!

Join us !!

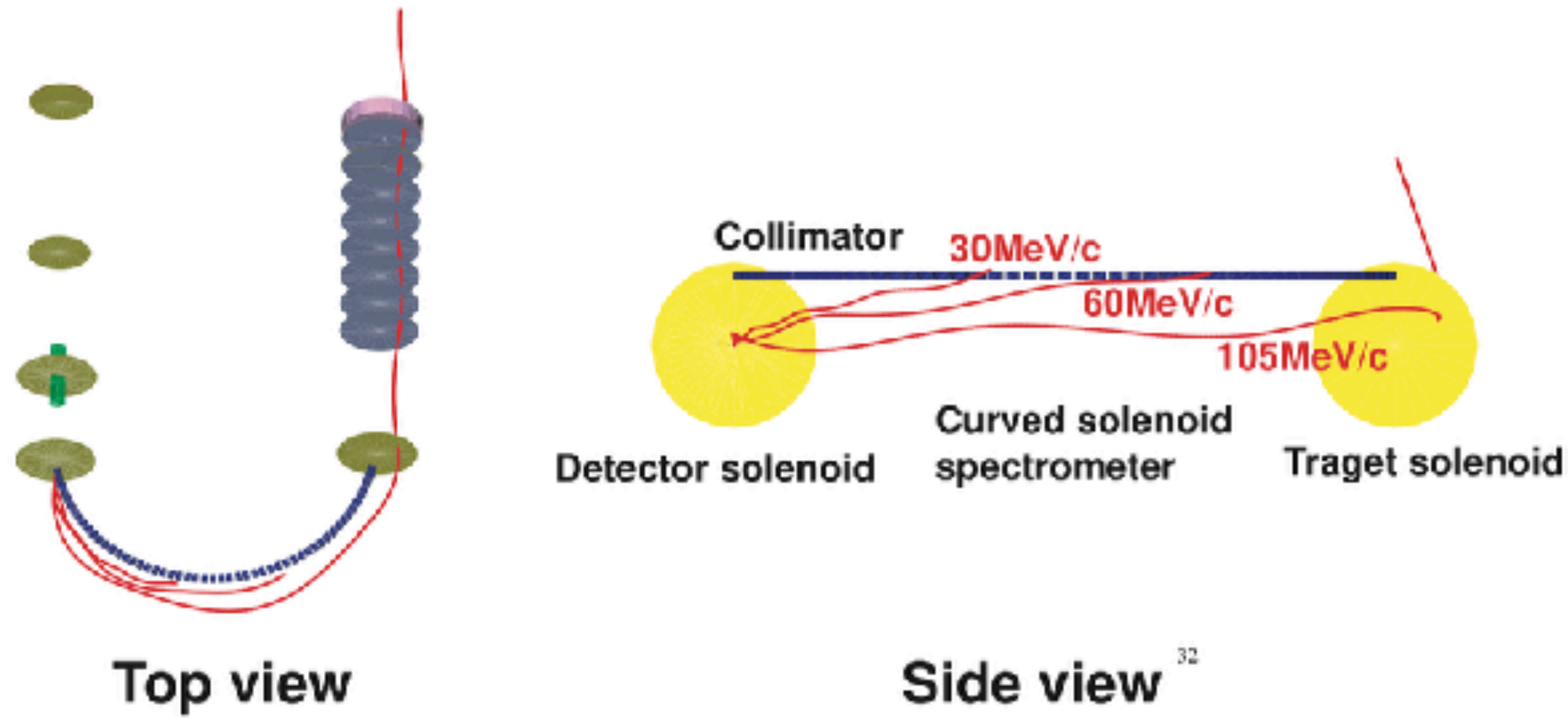
End of Slide

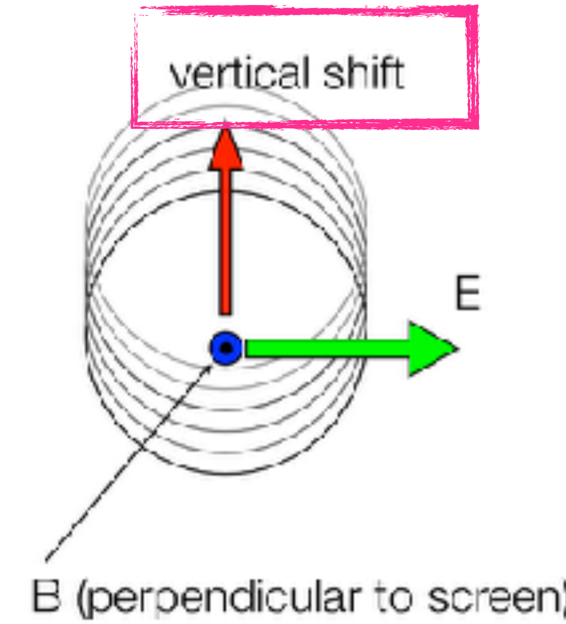
- COMET beam mode operation is already tested
- Extinction: (off-timing proton)/(proton in bunch)
  - Requirement: 10^{-9} for 10^{-17} sensitivity
  - Measured 1×10^{-12} @ FX with 8 GeV COMET operation. To be measured with slow extraction.

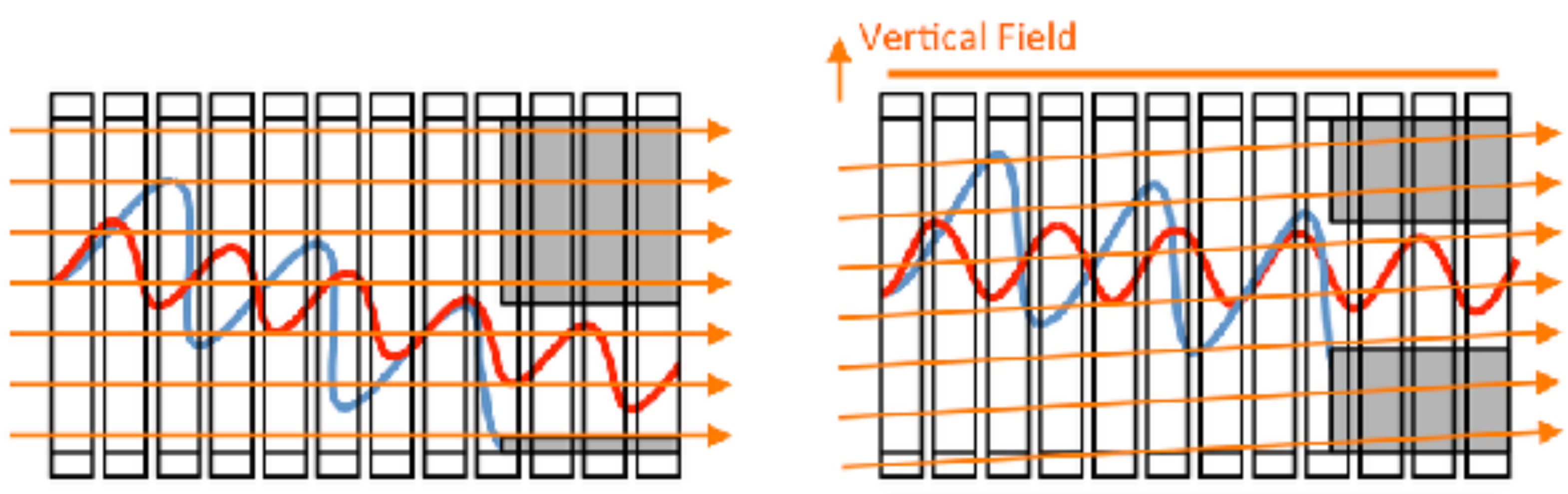


- Momentum & Charge selection in a Curved Solenoid

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







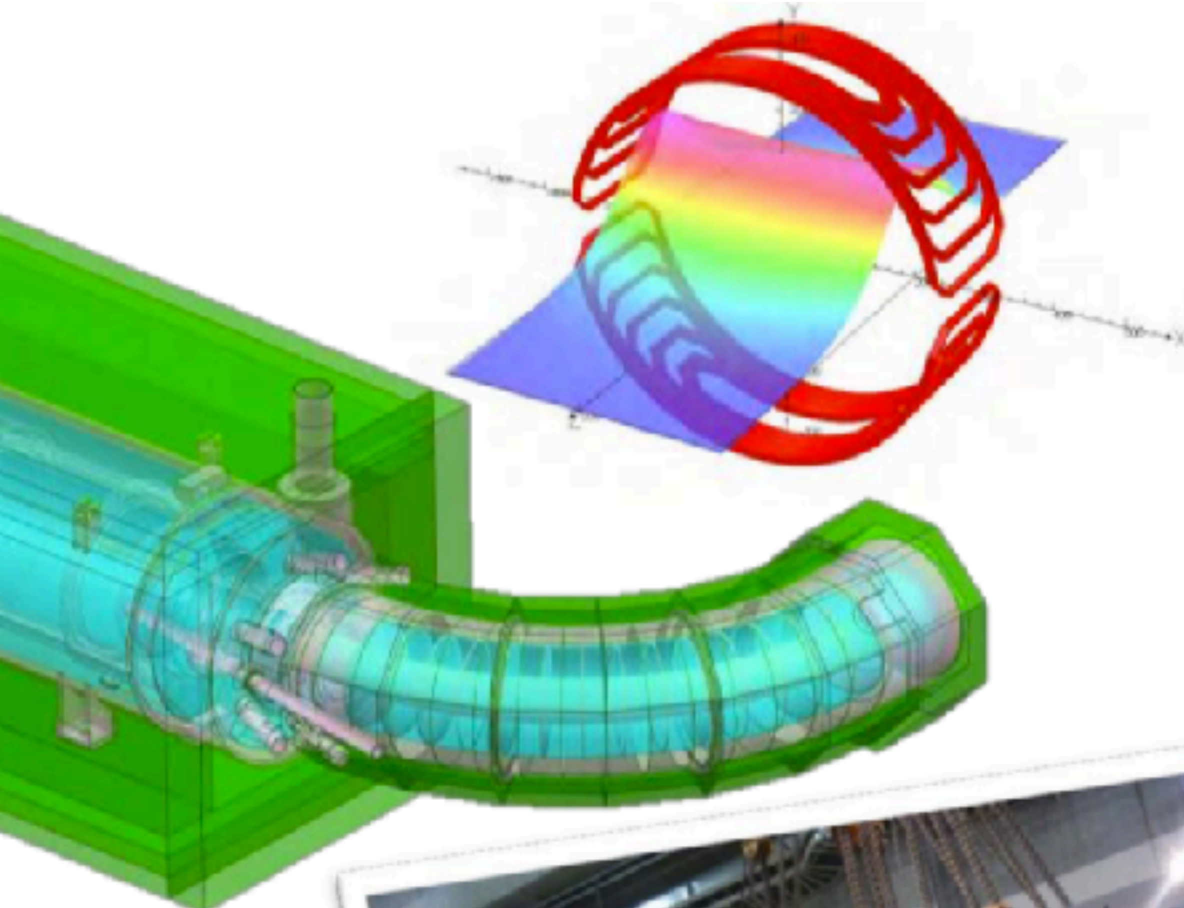
High momentum track

Low momentum track

Collimator

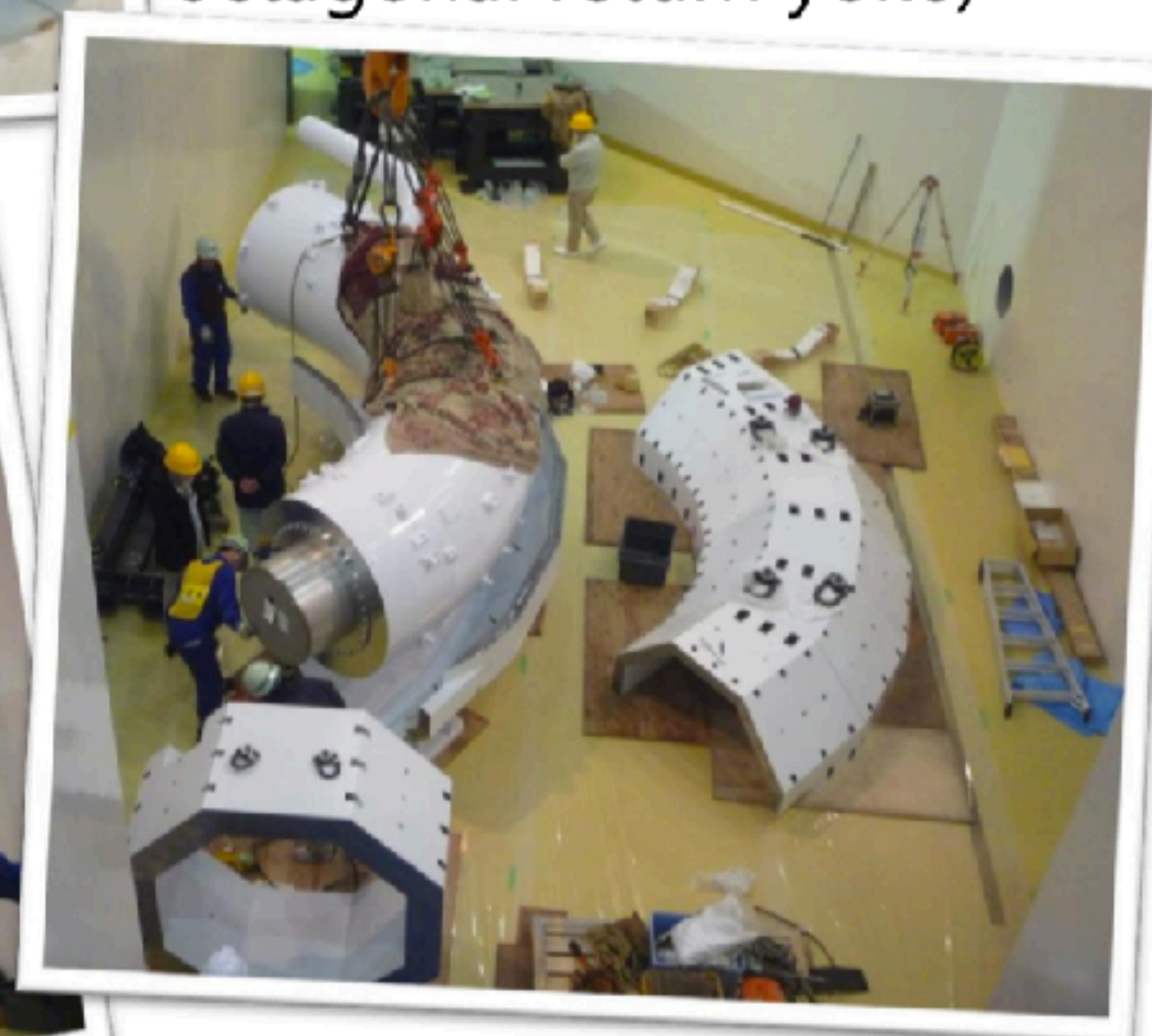
momentum selection
by applying correction field

Transport Solenoid



◀ Corrective dipoles

▼ Completed 90° muon transport arc (including octagonal return yoke)



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	$\lesssim 0.0038$
	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

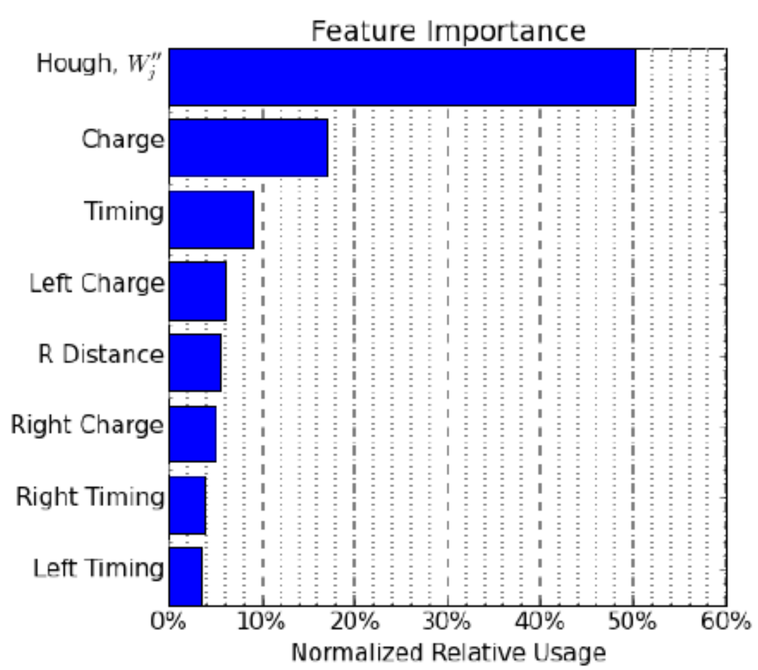
$$= \frac{1}{N_{\mu} \times f_{cap} \times f_{gnd} \times A_{\mu e}}$$

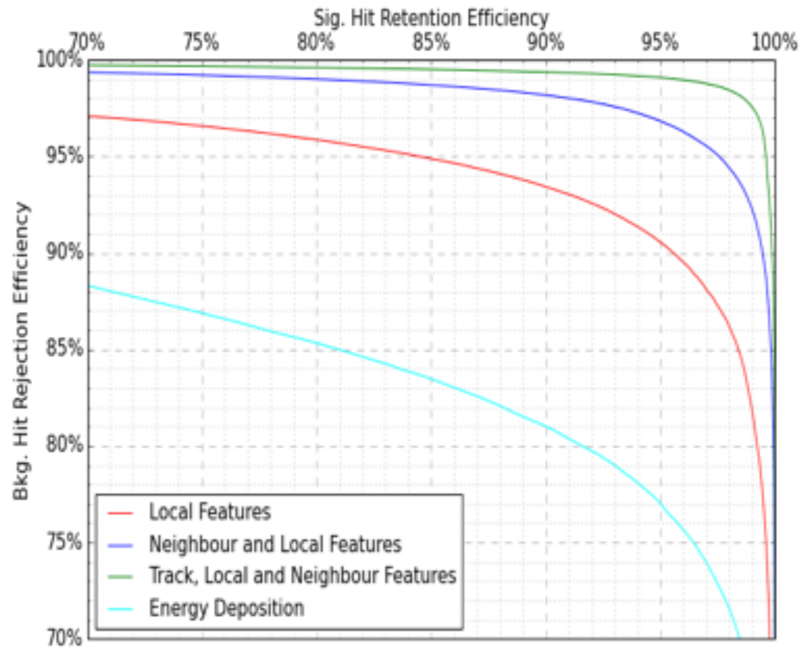
$$= \mathbf{3 \times 10^{-15}}$$

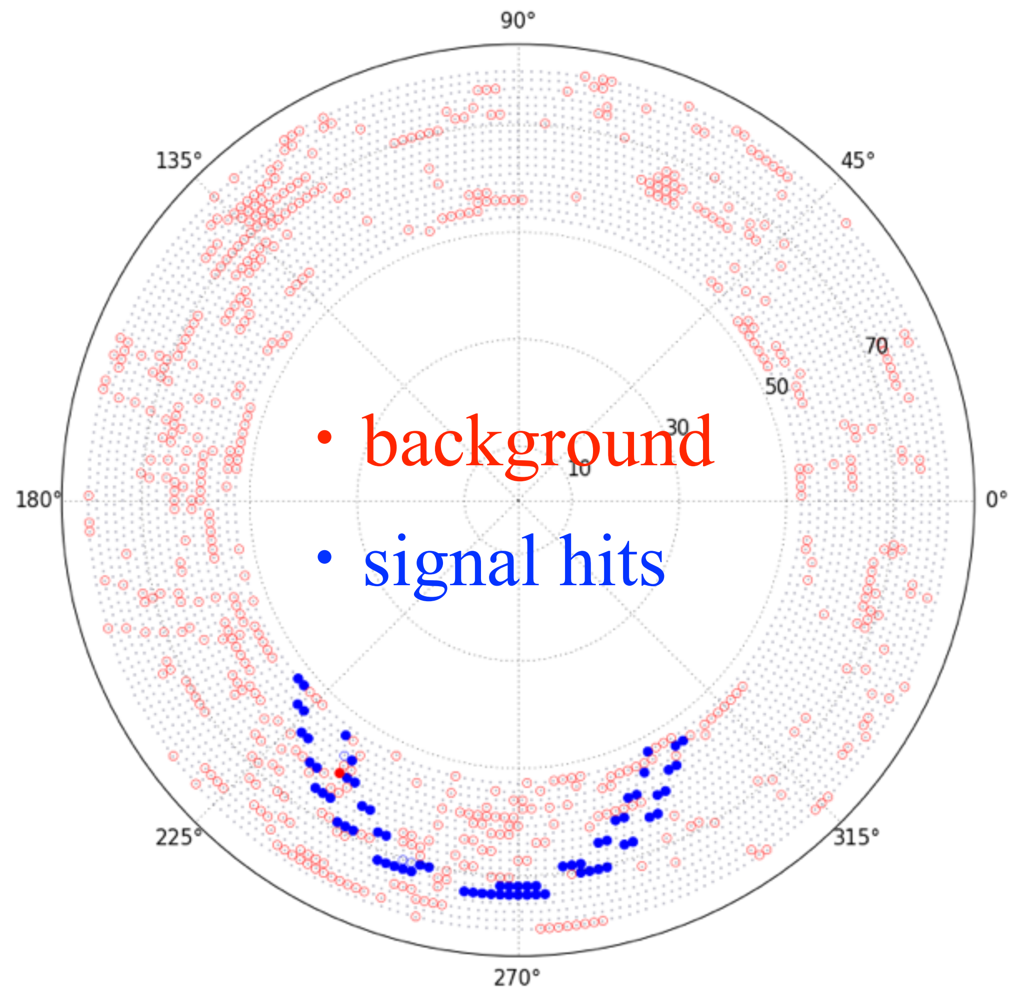
N_{μ}(number of muons stopping on the target)	= **1.5×10^{16}**
f_{cap}(fraction of muon capture)	= **0.61**
f_{gnd}(fraction of nucleus which is not excited by μ-e conv.)	= **0.9**
$A_{\mu e}$(Total Acceptance for e^- from μ-e conv.)	= **0.041**

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

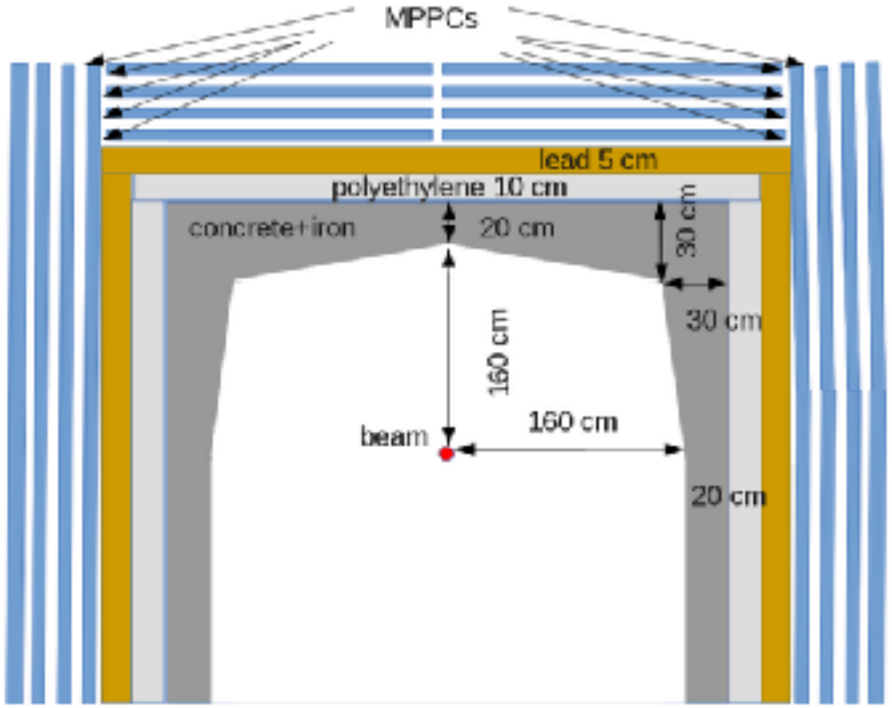
- Hit selection using Gradient Boosted Decision Trees (GBDT) and Reweighted Inverse Hough Transform
- Background hits are rejected based on timing, charge & local features
- **99%** of background rejected & keeping **99%** of signal hits

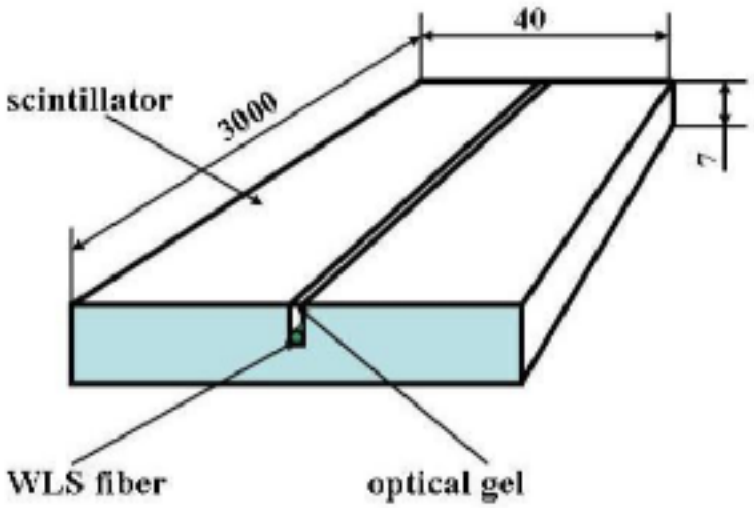


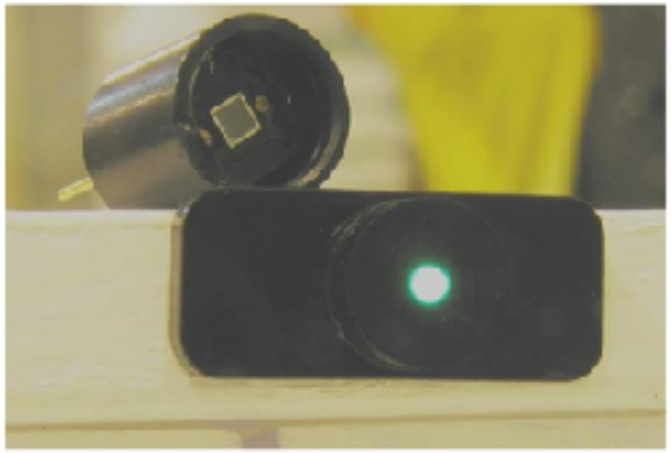


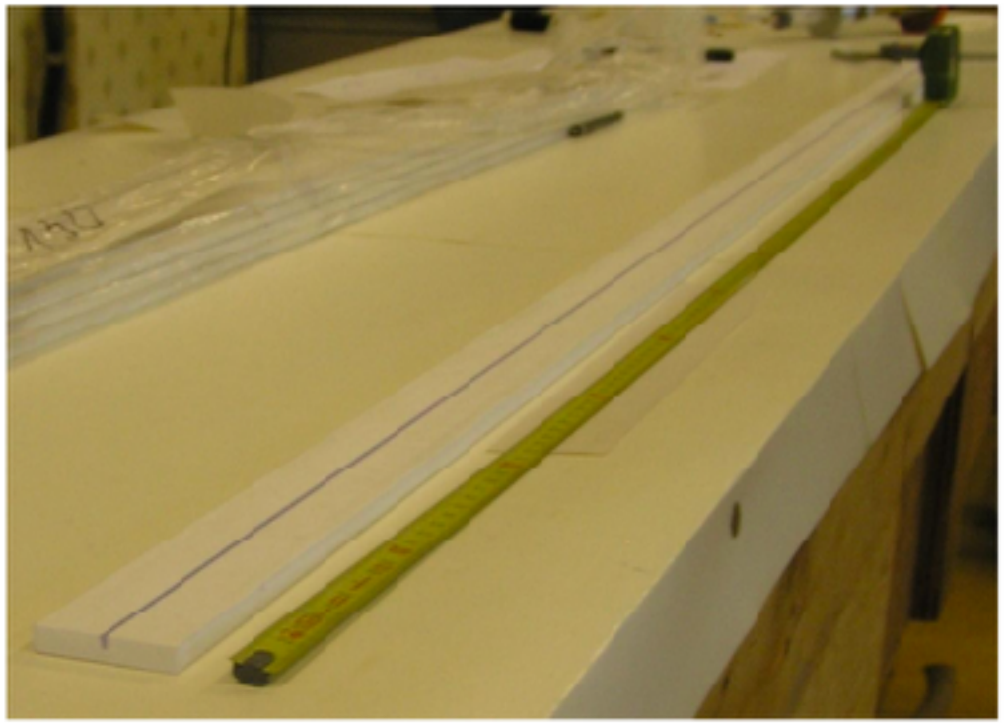


Cosmic Ray Veto







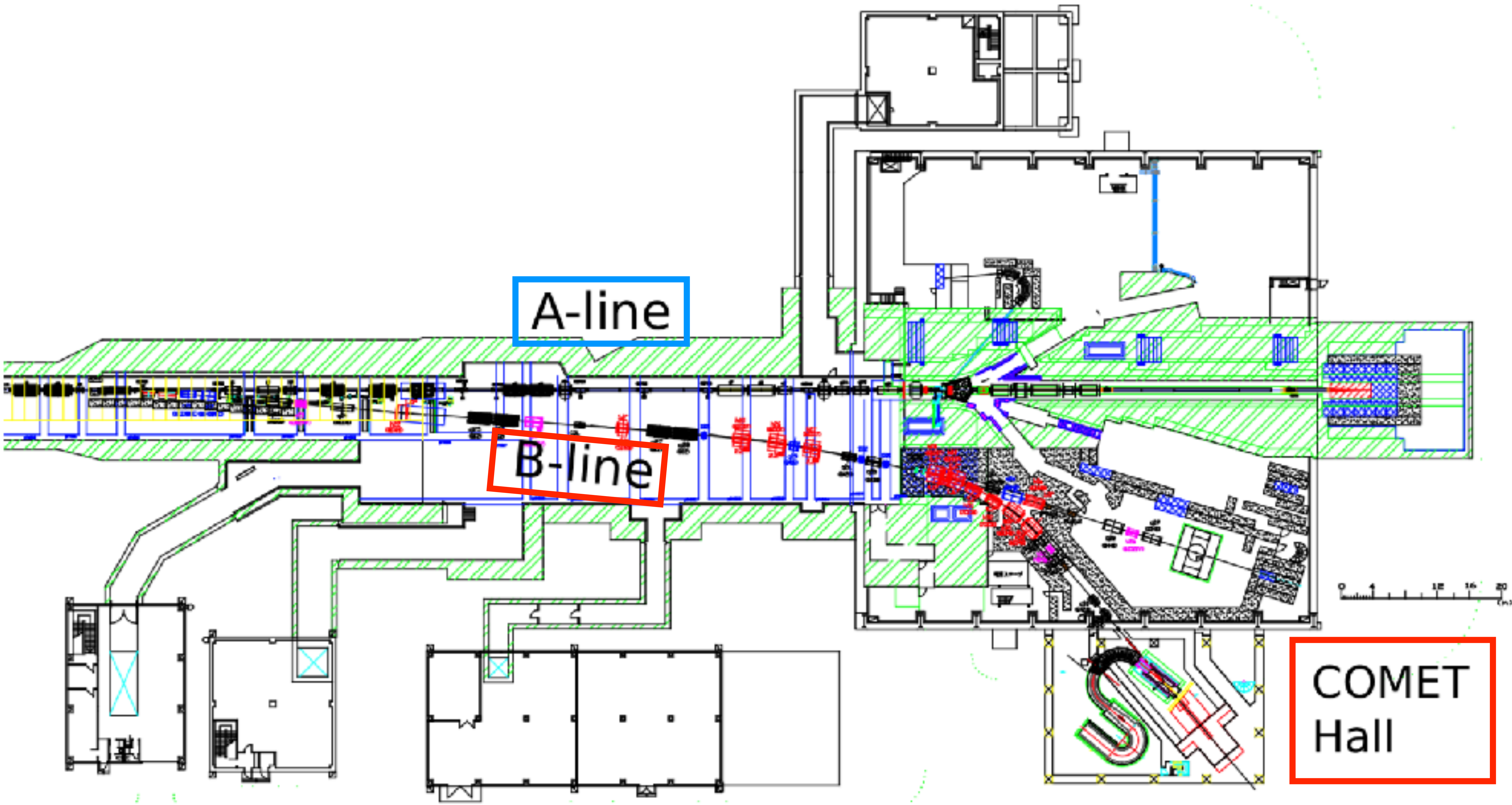


- requirement … inefficiency < 10^{-4}
- Based on BELLE-II design:

  Plastic scintillator readout with WLS+SiPM
- The design in progress

  (dependes on overall final design of the magnets, detector and infrastructure)

Primary Proton Beam Line



Optimization of COMET beamline

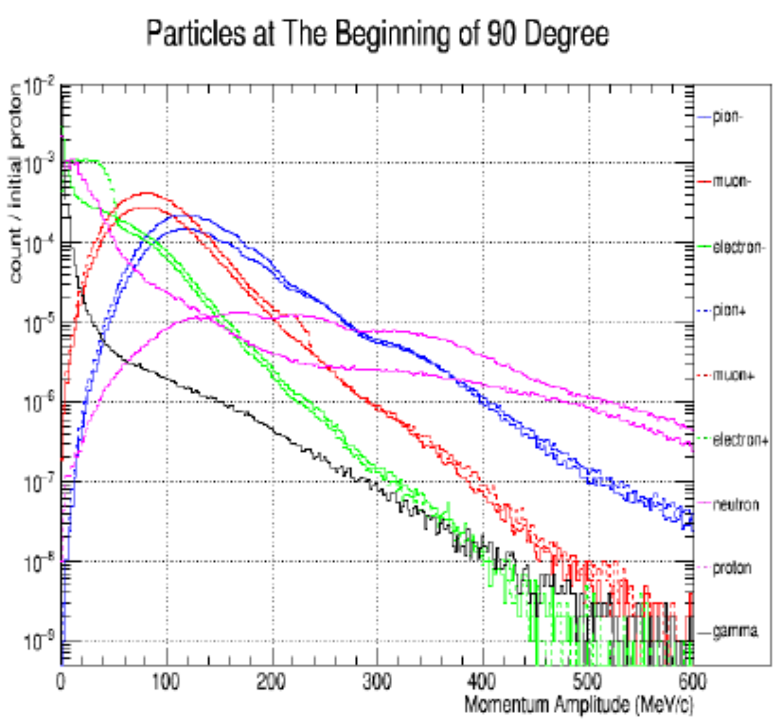
Based on various simulation studies

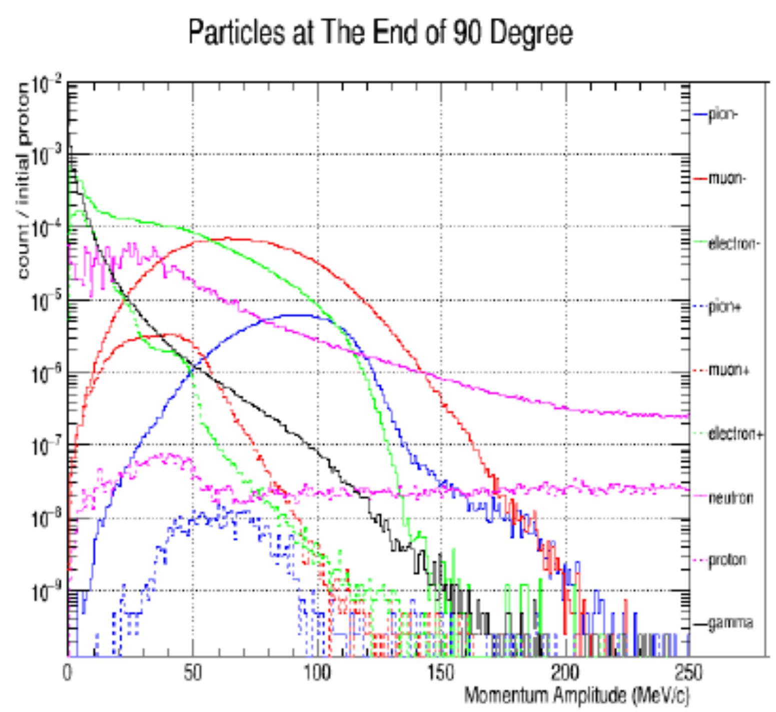
optimizing target dimension … maximum pion yield at the production target

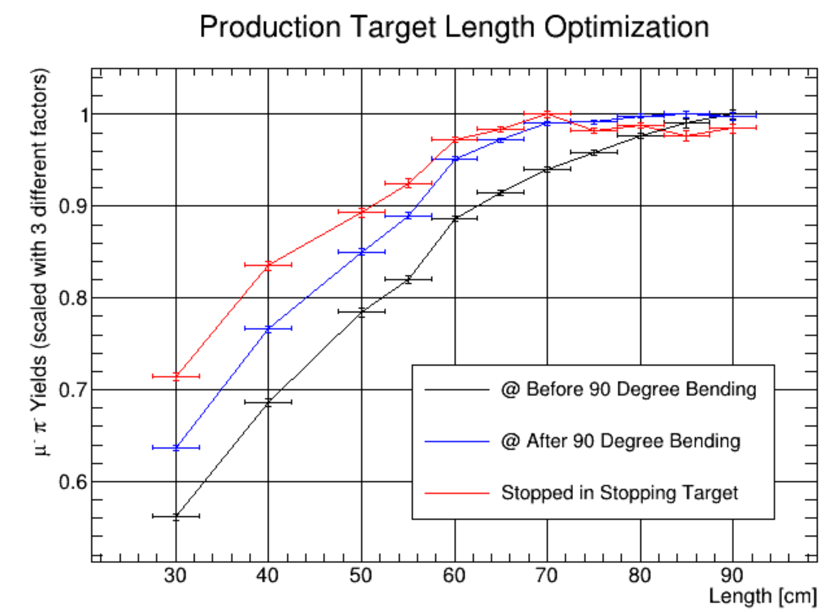
field strength … efficient transport of muons

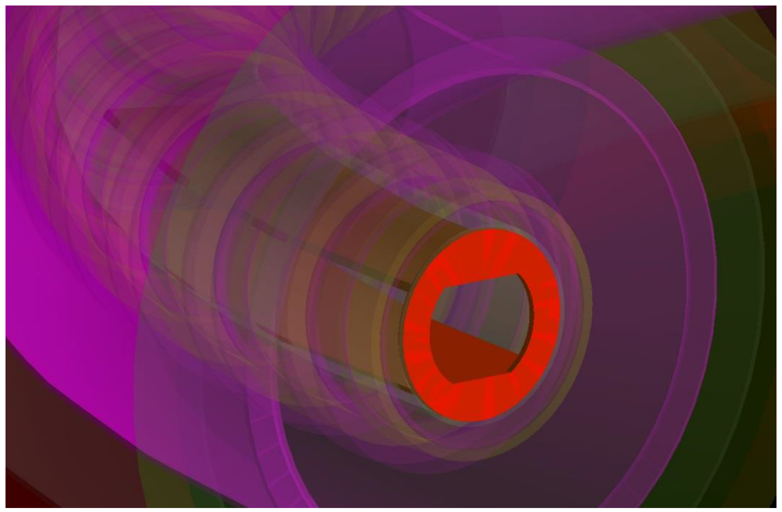
collimator size … rejection of off-momentum particles

… etc



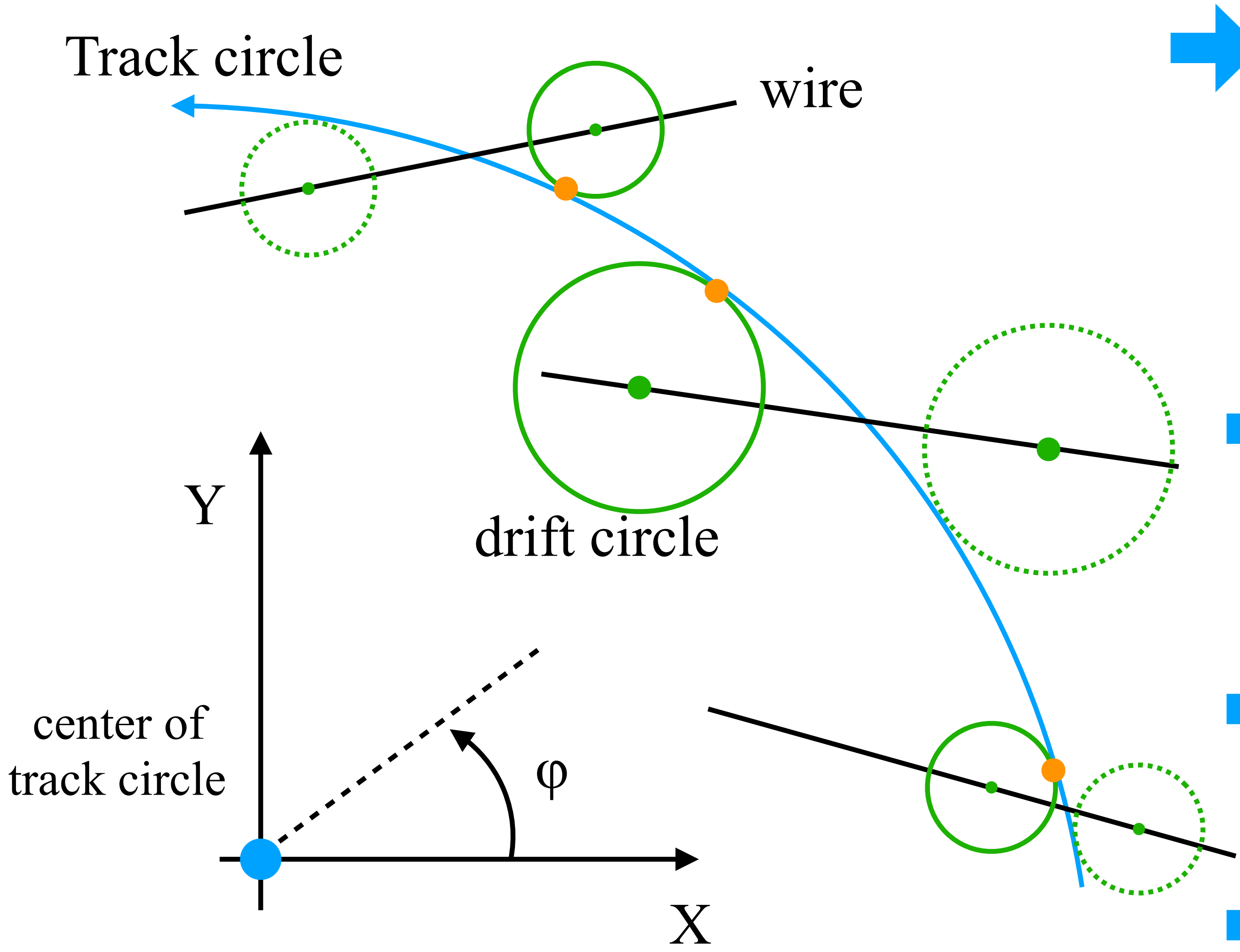


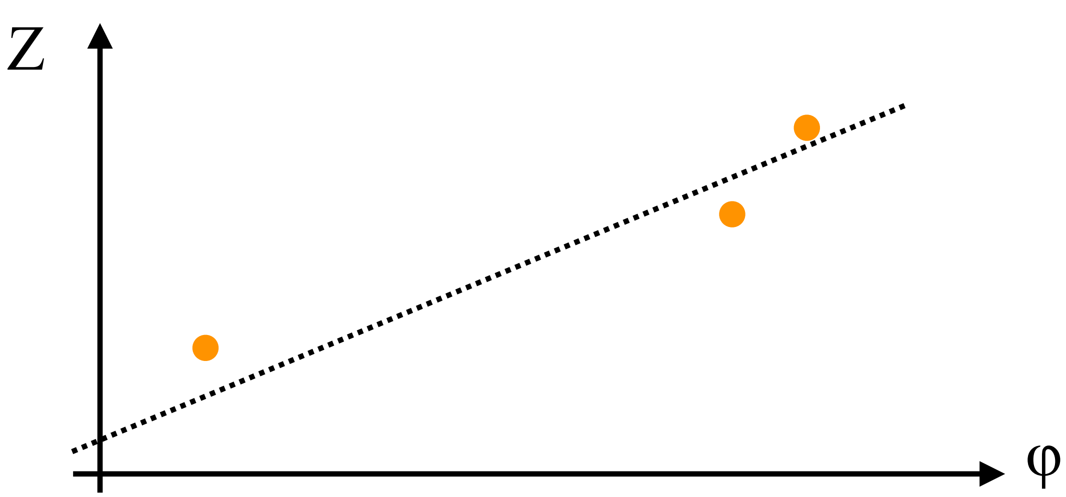




Linear Fitting in ϕ-Z plane

Assuming Track is Helix



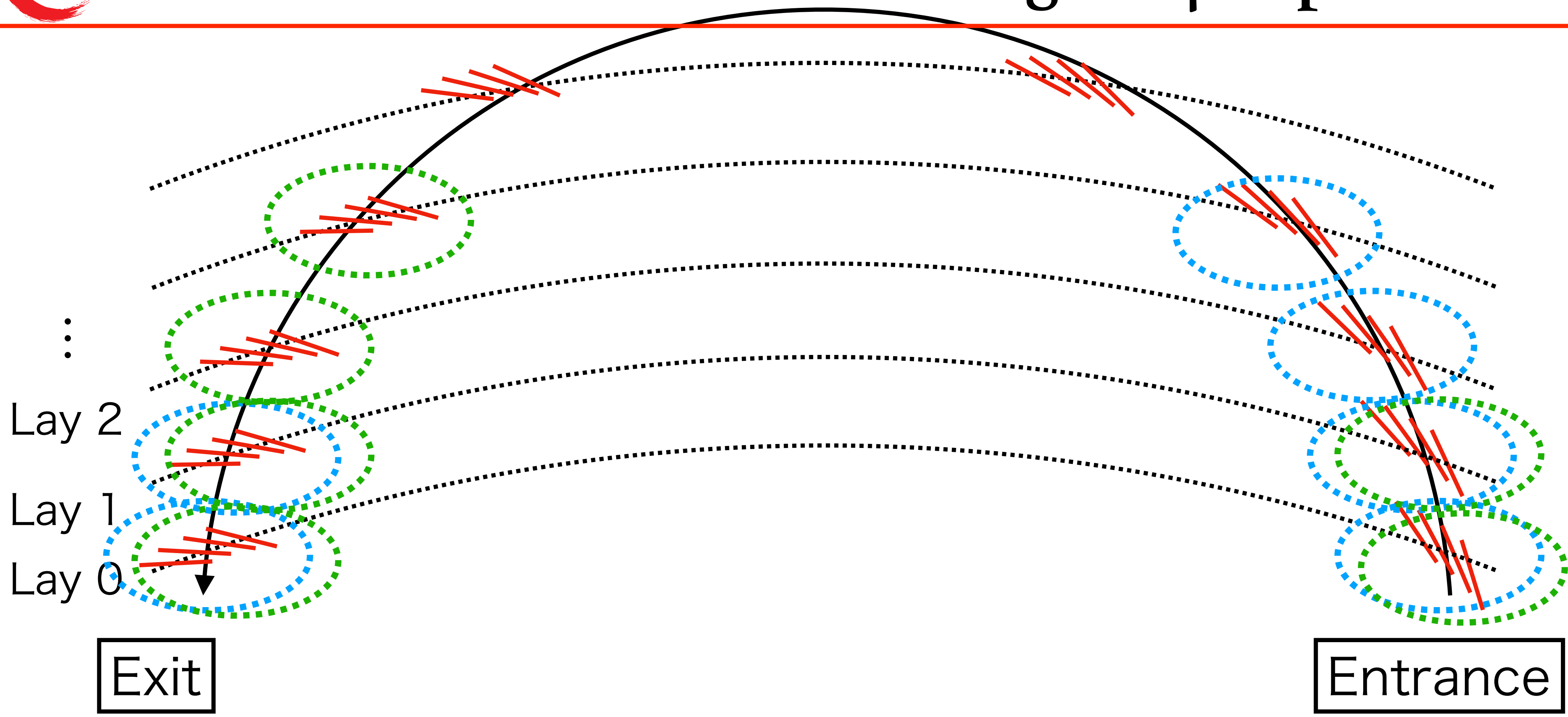


Once circle parameters are geven…

- Contact point between track and drift circle (sliding the center of drift circle along wire) <u>for fixed Left-Right assignment</u>
- Position of drift circle on wire → Z coordinate
- φ - Z coordinate
- Linear Fitting in φ-Z plane

Minimize chi square of linear fitting
by
<u>optimizing circle parameters</u>

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}

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.