Imperial College London

COMET / (PRISM)

Proton Accelerators for Science and Innovation

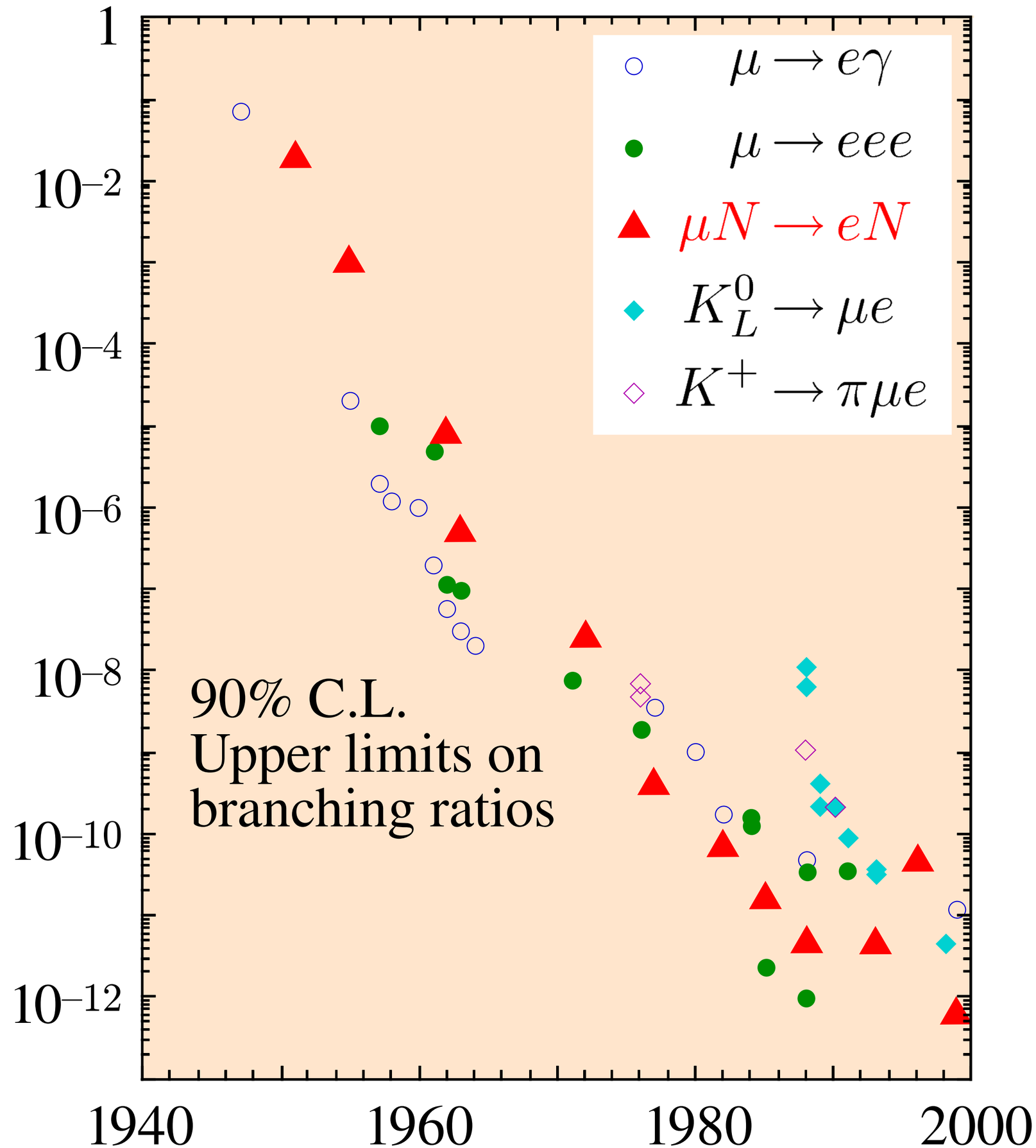
Near-Term Accelerator Physics

13 January 2012 at Fermilab

Yoshi Uchida

Flavour Violation in Leptons

Historical Progress on Muon Flavour Violation



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skipping 50 physics and motivation slides....

Charged Lepton Flavour Violation

- Probes the lepton sector, where neutrinos have given us direct evidence that the SM is incomplete, and that cLFV must happen
- Theoretically clean processes
- Complementary to the LHC
  - next generation can probe EW and TeV mass scales *and beyond*
  - sensitive to flavour physics at GUT and Seesaw scales
- Need to measure multiple channels, multiple observables
  - to disentangle flavour sector of BSM physics models
- ...but we are in the *discovery* phase
  - first observed cLFV lays down a marker for all other processes
- muon-to-electron conversion is an excellent channel
  - 4 to 6 orders of magnitude improvement feasible

COMET

Coherent Muon-to-Electron Conversion

- Muon-to-Electron Conversion

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

muonic atom

$$E_e \sim 105\mathrm{MeV}$$

- The present limit is about

$$< 7 \times 10^{-13}$$

for the branching ratio on Gold (Sindrum II)

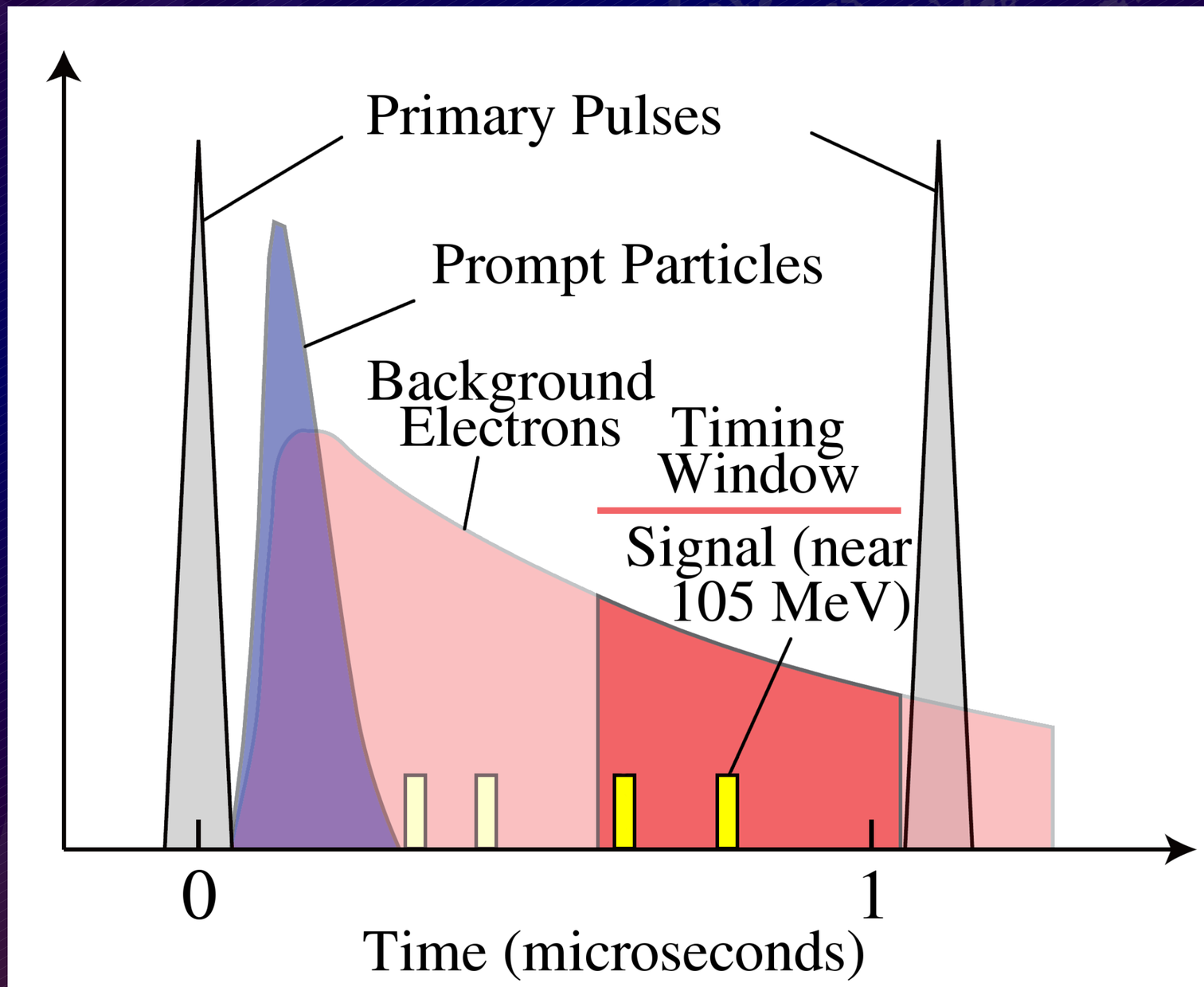
- **COMET** aims to improve sensitivity to 10^{-16}
  - **MUSIC** is a COMET prototype
    (and a muon physics facility in its own right)
- **PRISM** extends this to a sensitivity of 10^{-18}

Use of a Pulsed Primary Beam

- Large backgrounds occur promptly with incoming muons
- Signal events occur with a delay

  ⇒ Pulse primary beam to separate prompt backgrounds from signal

- Use energy and time to separate signal from backgrounds
- Muonic atom lifetimes vary due to nuclear muon capture
  - Al: 880 ns
  - Ti: 330 ns
  - Au: 73 ns



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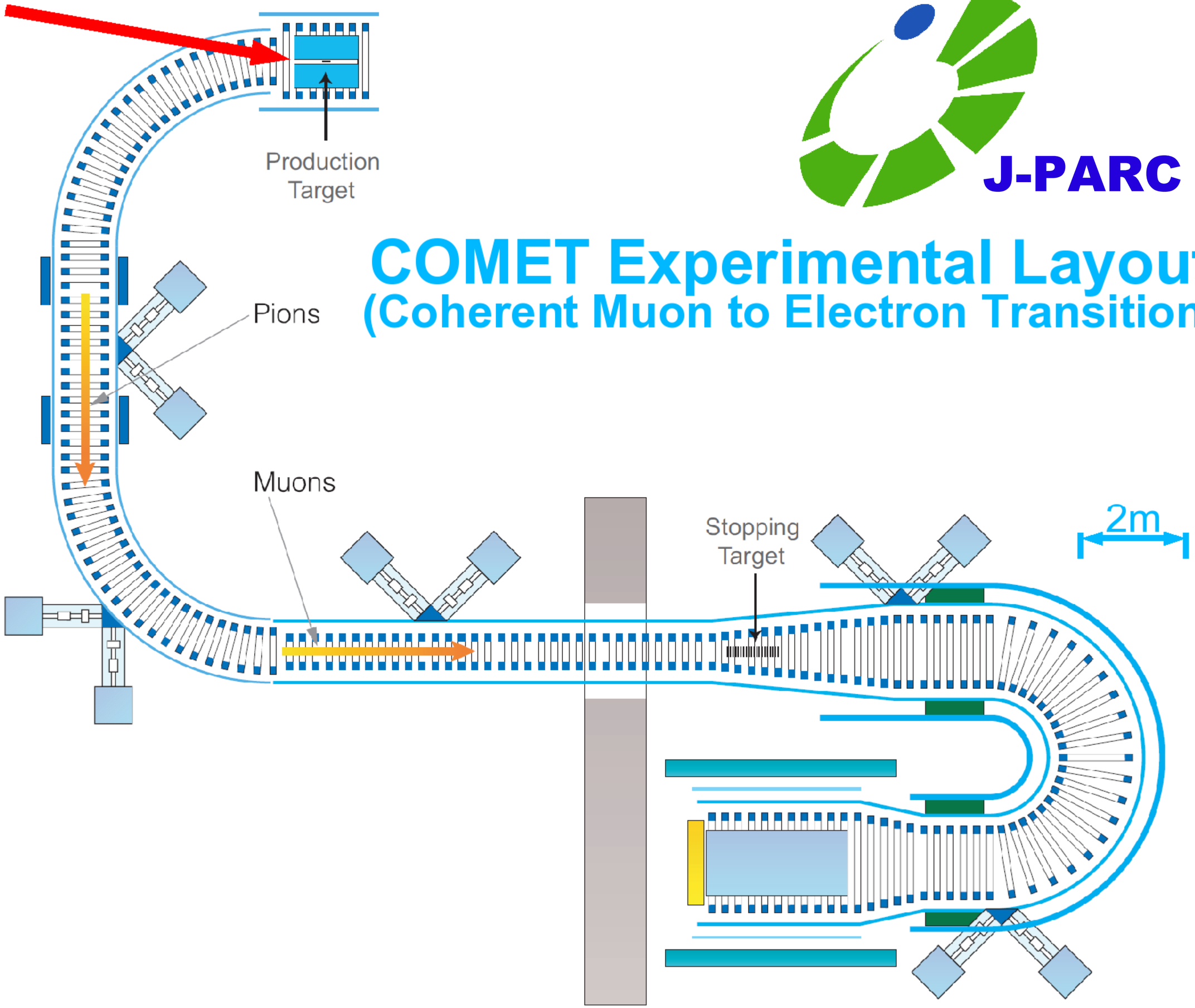
COMET Experimental Layout
(Coherent Muon to Electron Transition)



Search for Lepton-Flavor-Violating Rare Muon Processes

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Received March 26, 2010; in final form, July 12, 2010

Basic concept from 1989

Abstract—A new approach to seeking three lepton-flavor-violating rare muon processes ($\mu \to e$ conversion, $\mu \to e + \gamma$, and $\mu \to 3e$) on the basis of a single experimental facility is proposed. This approach makes it possible to improve the sensitivity level of relevant experiments by factors of 10^5, 600, and 300 for, respectively, the first, the second, and the third of the above processes in relation to the existing experimental level. The approach is based on employing a pulsed proton beam and on combining a muon source and the detector part of the facility into a unified magnetic system featuring a nonuniform field. A new detector design involving separate units and making it possible to study all three muonic processes at a single facility that admits a simple rearrangement of the detectors used is discussed.

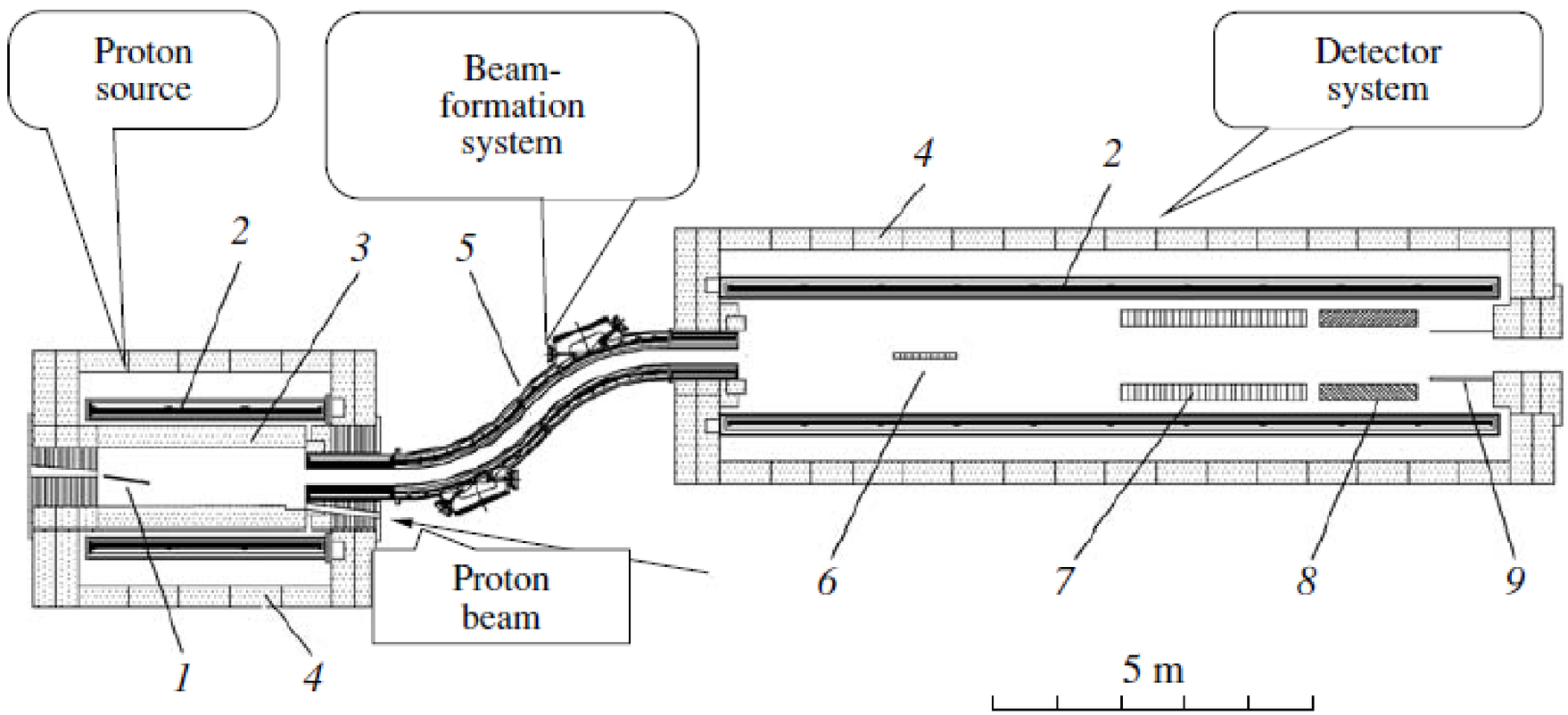
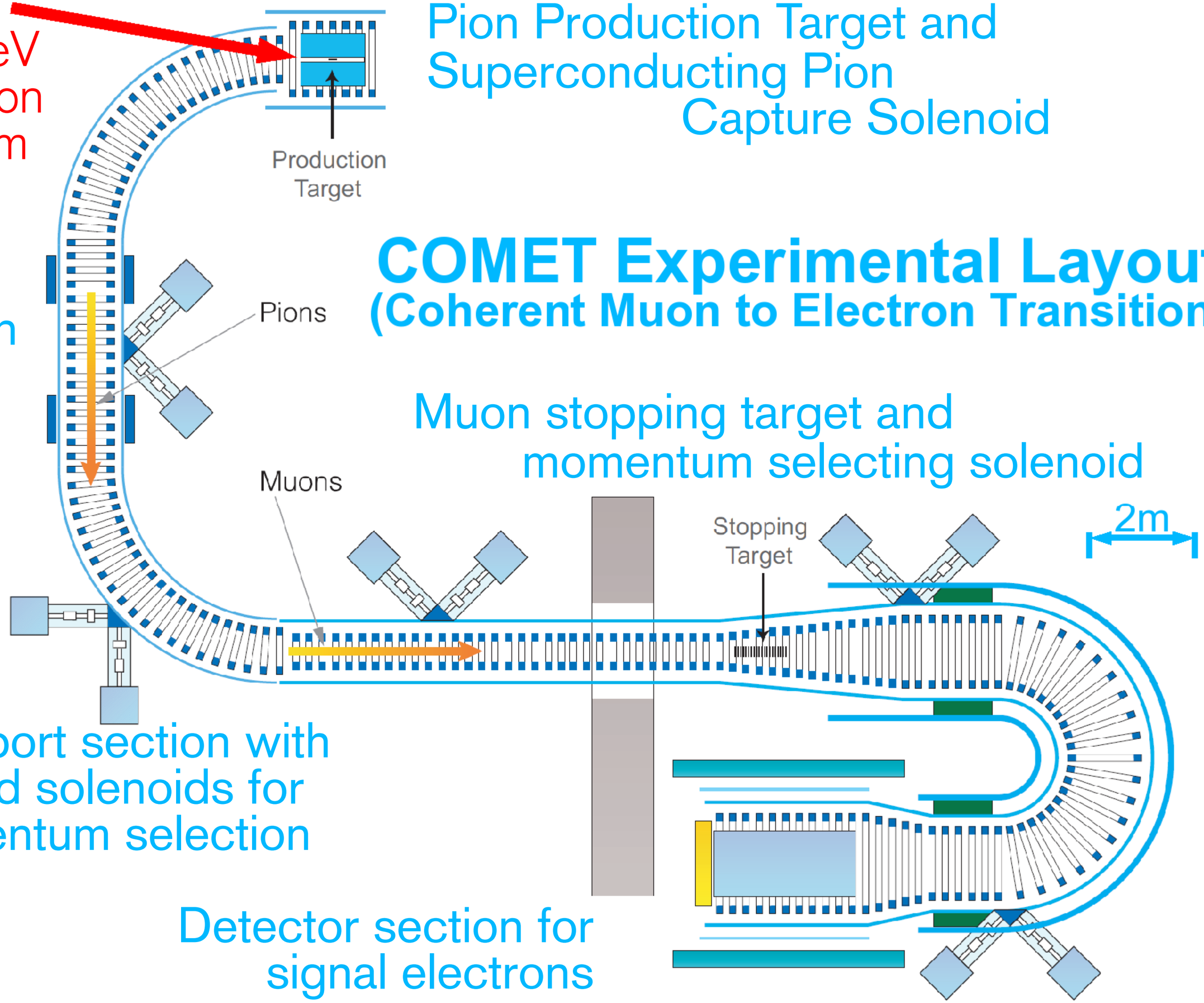


Fig. 1. Central horizontal cut of the MELC facility: (*1*) proton target, (*2*) superconductor solenoid, (*3*) shield of the solenoid, (*4*) steel yoke, (*5*) transport solenoid and collimator, (*6*) detector target, (*7*) coordinate detector, (*8*) calorimeter, and (*9*) detector shield and beam trap.

COMET Experimental Layout
(Coherent Muon to Electron Transition)



Design Considerations

Background Event Categories

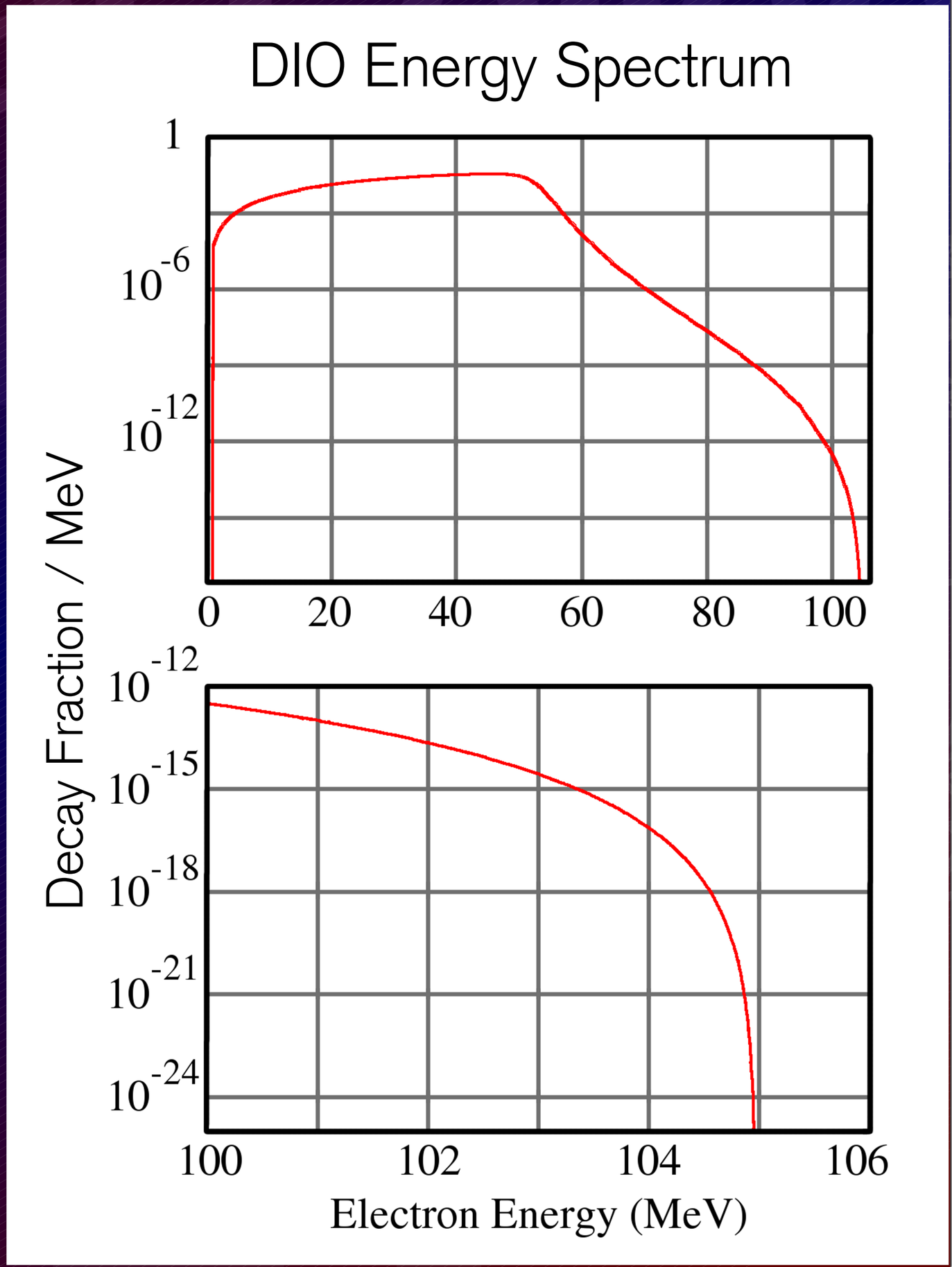
- Intrinsic physics backgrounds
  - electrons from muons stopped in the target
- Beam-related prompt backgrounds
  - due to protons which arrive outside of their beam buckets
- Beam-related delayed backgrounds
  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

Intrinsic Physics Backgrounds

- Muon Decay in Orbit (DIO)
  - $\mu + N \rightarrow N + \nu_\mu + \nu_e + e^-$
  - muon decay kinematics modified by atomic environment
- Radiative Muon Capture
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + \gamma \Rightarrow \gamma \rightarrow e^+ + e^-$
- Muon Capture with Neutron Emission
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + n \Rightarrow$ neutrons produce e^-
- Muon Capture with Charged Particle Emission
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + X \Rightarrow X$ (protons, deuterons, alphas etc) produces e^-

Decay-in-Orbit (DIO) Electrons

- For Al, 40% of muons decay "in orbit"
- Free muon decay has end-point of 52.8 MeV
- Nuclear recoil modifies the energy spectrum for DIO
- End-point can reach up to μ-e conversion energy
- $\propto (E_{\mu\text{-}e} - E)^5$ near end-point
- Crucial to understand spectrum near 105 MeV
- New calculations available (autumn 2011)



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Prompt Backgrounds

- Radiative pion capture
  - $\pi^- + N \rightarrow \gamma + N' + \ldots \Rightarrow \gamma \rightarrow e^+ + e^-$
- Beam electrons
  - e^- scattering off a muon stopping target
- Muon decay in flight
  - μ decays in flight producing e^-
- Pion decay in flight
  - π^- decays in flight producing e^-
- Neutron induced backgrounds
  - neutrons hit material producing e^-

Background Event Categories

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Beam-Related Delayed Backgrounds

- Antiproton interactions
  - interactions of p, which travel slowly, producing e^-
- Radiative capture of pions
  - very large number of pions produced – some may result in late radiative captures

Beamline design critical

Background Event Categories

- Intrinsic physics backgrounds
  - electrons from muons stopped in the target
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  - due to protons which arrive outside of their beam buckets
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  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

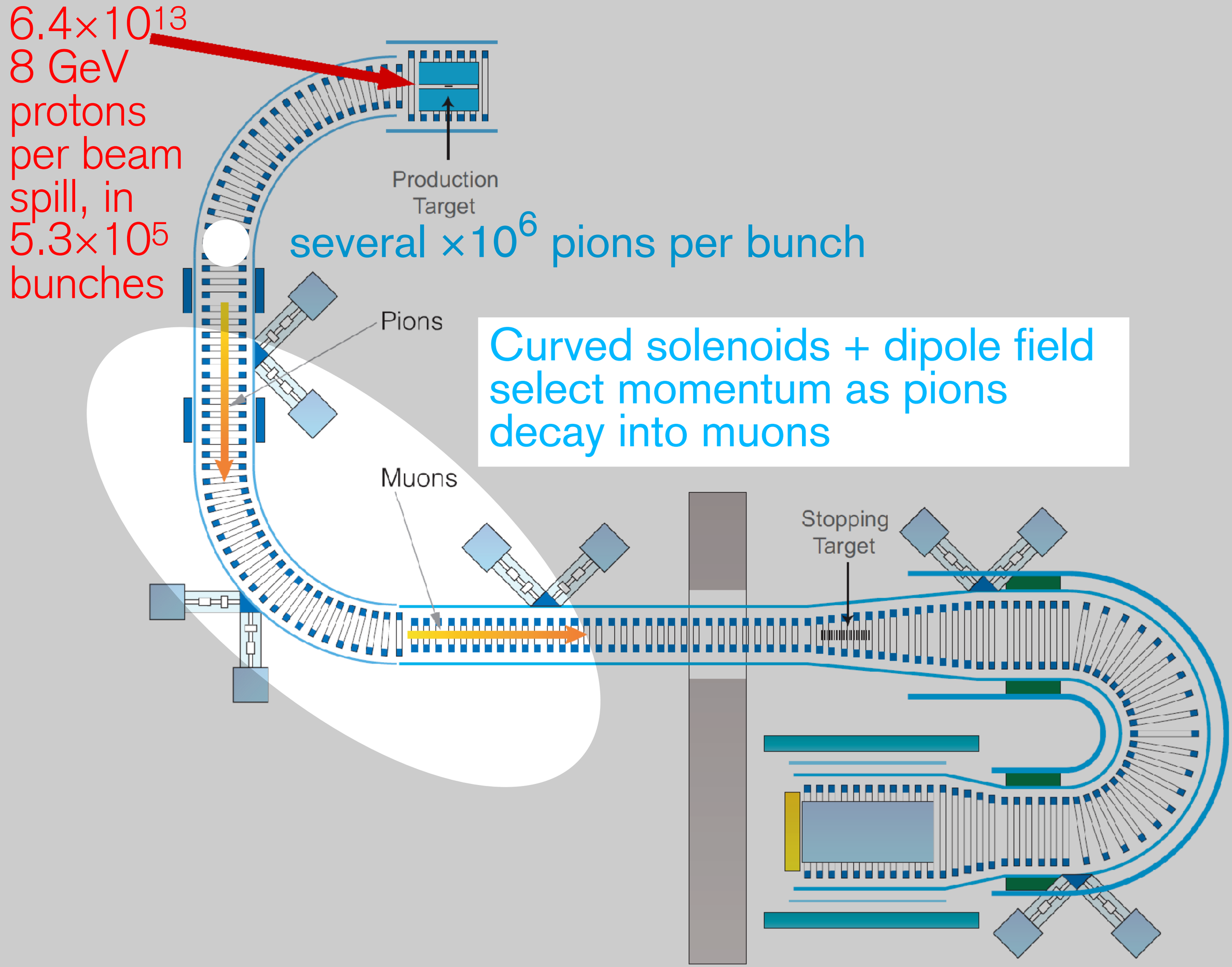
Backgrounds Strategy

- Discriminate using energy and timing, but...

- Dependent on tails of distributions of $\sim 10^{18}$ particles
- Influence experiment design and eventual analysis

- Modelling / Simulations critical
  - proton beam / target interactions
    - MARS, Geant4 QGSP, etc, external experiments
  - beamline optics (solenoidal channels)
  - experimental geometries (cosmics and neutrons etc)

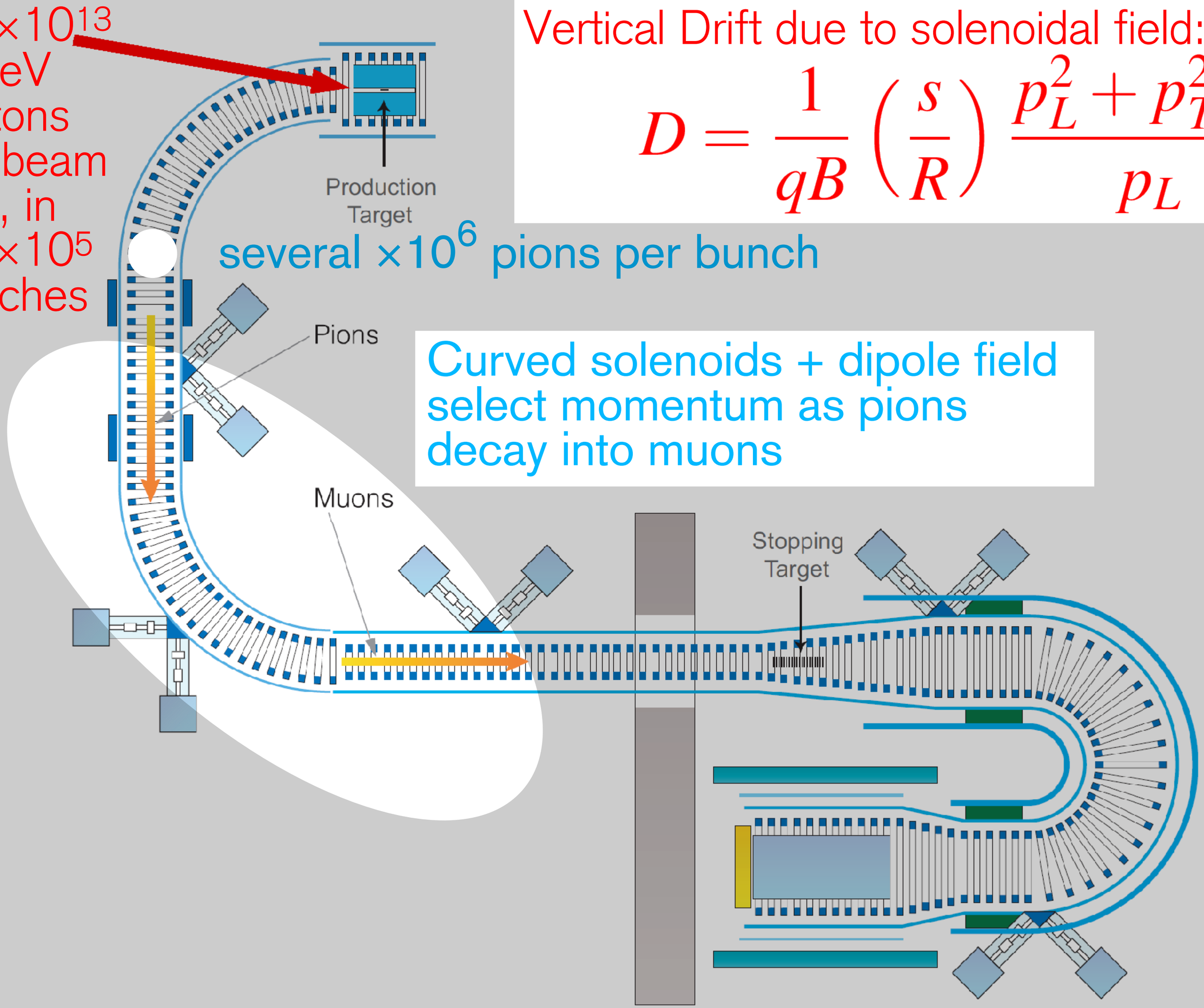
- But ultimately, the *measurement* of backgrounds will be critical


6.4×10^13
8 GeV
protons
per beam
spill, in
5.3×10^5
bunches
Production
Target
several ×10^6 pions per bunch
Pions
Curved solenoids + dipole field
select momentum as pions
decay into muons
Muons
Stopping
Target

6.4×10^{13} 8 GeV protons per beam spill, in 5.3×10^{5} bunches

Vertical Drift due to solenoidal field:

$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + p_T^2/2}{p_L}$$



several $\times10^{6}$ pions per bunch

Curved solenoids + dipole field select momentum as pions decay into muons

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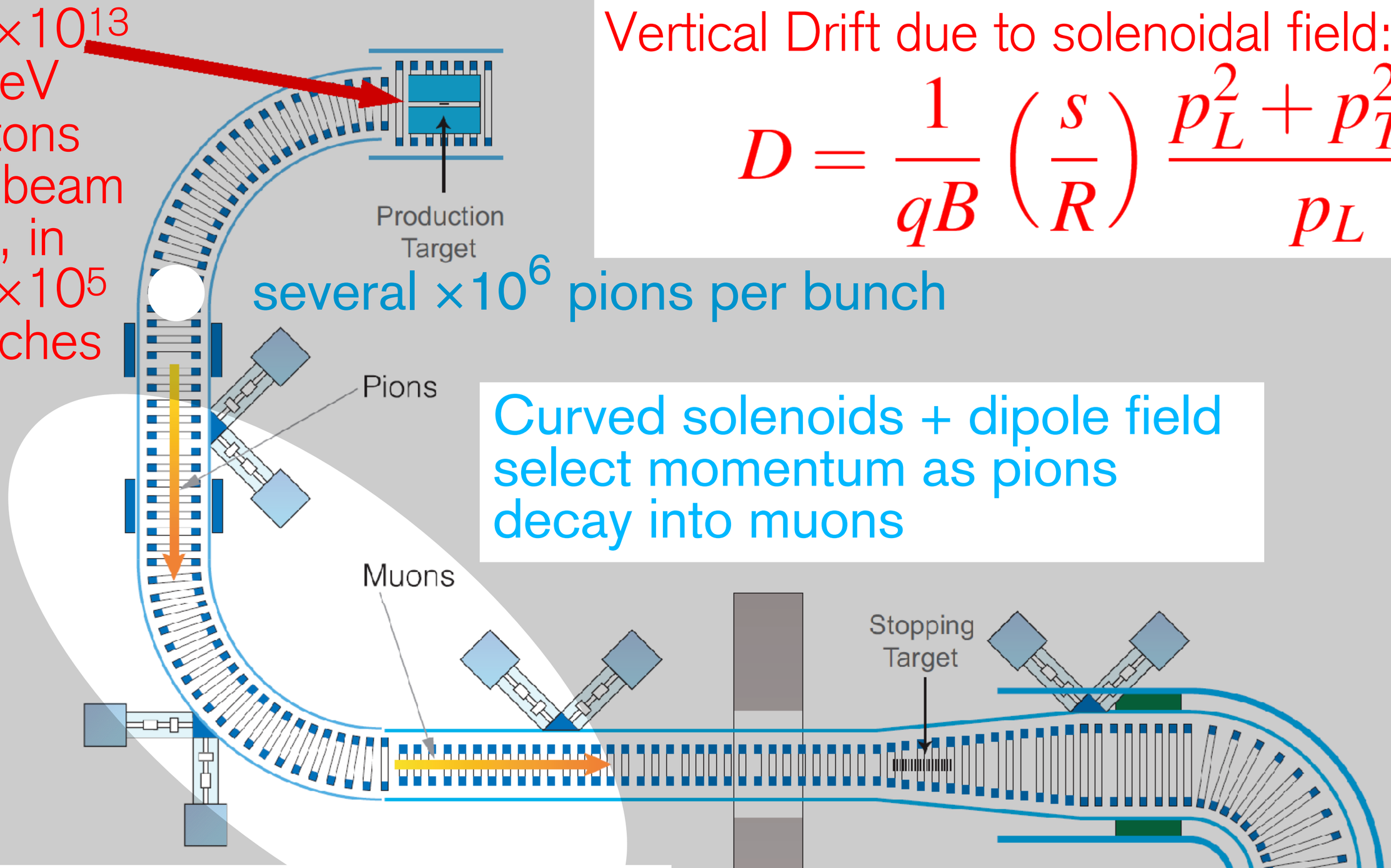


several $\times10^{6}$ pions per bunch

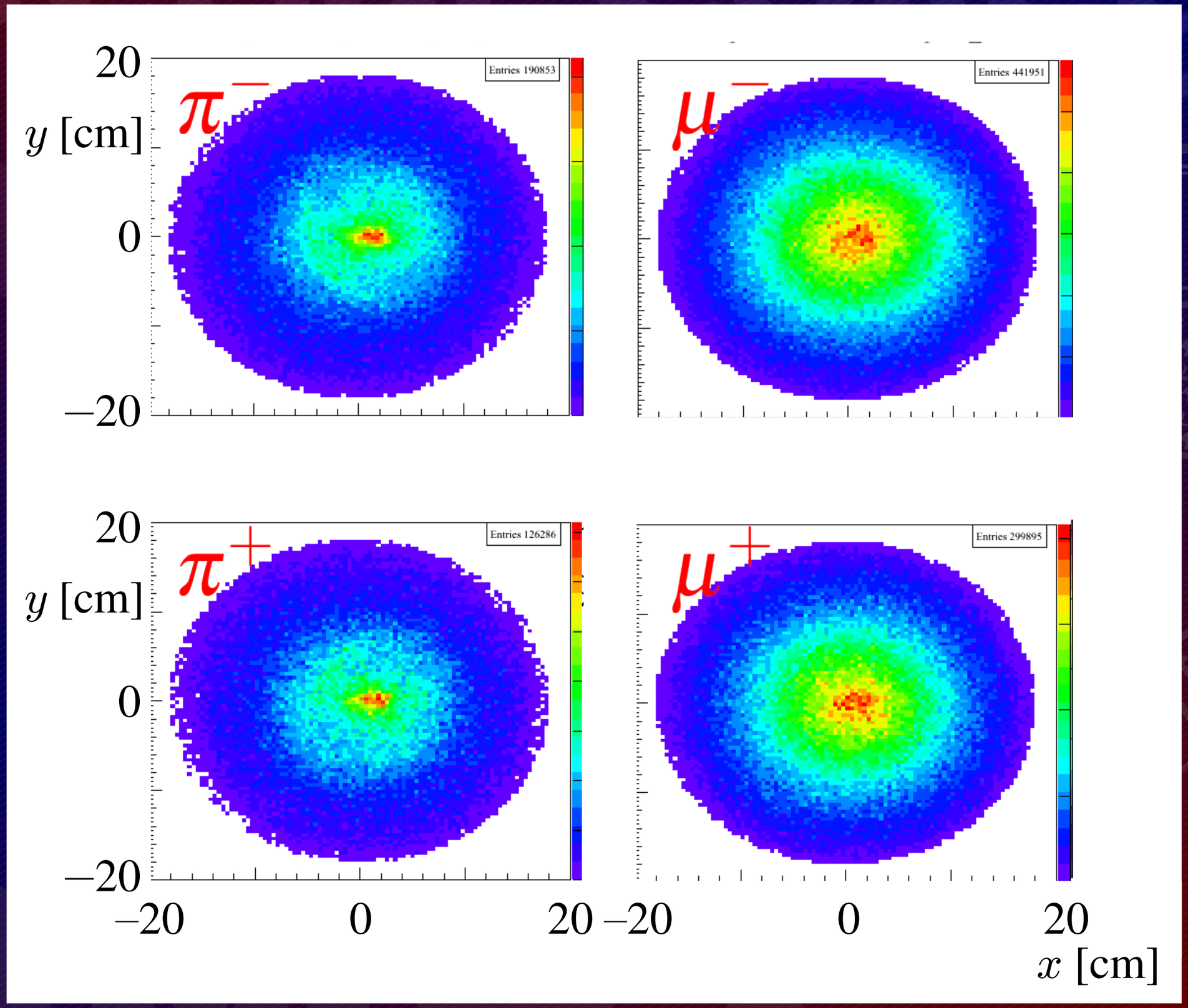
Curved solenoids + dipole field select momentum as pions decay into muons

Compensation field to keep particle on-axis (θ :original pitch angle)

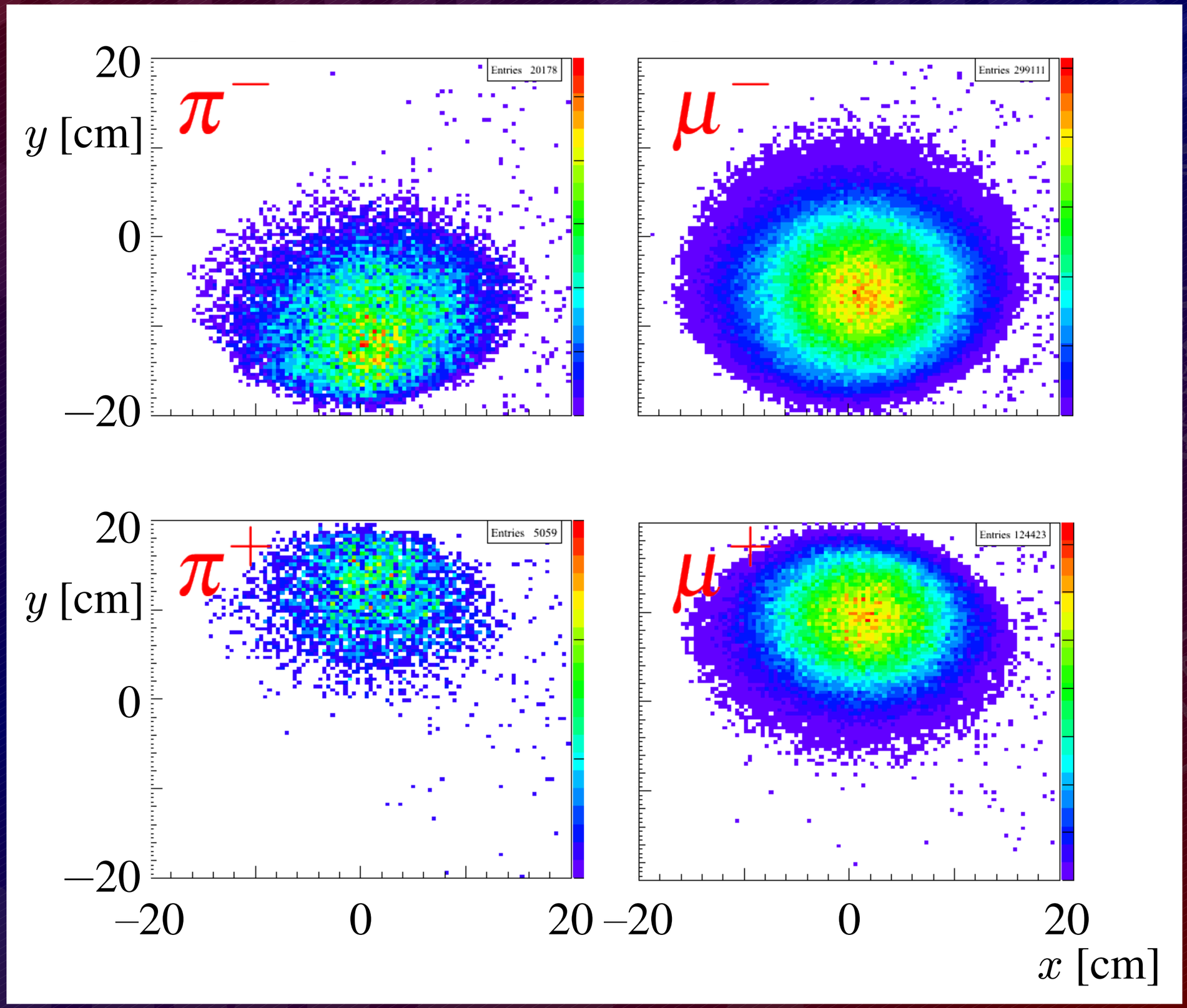
$$B_{\text{dipole}} = \frac{1}{qR}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

Ben Krikler

Fluxes at Entrance to Curved Solenoid

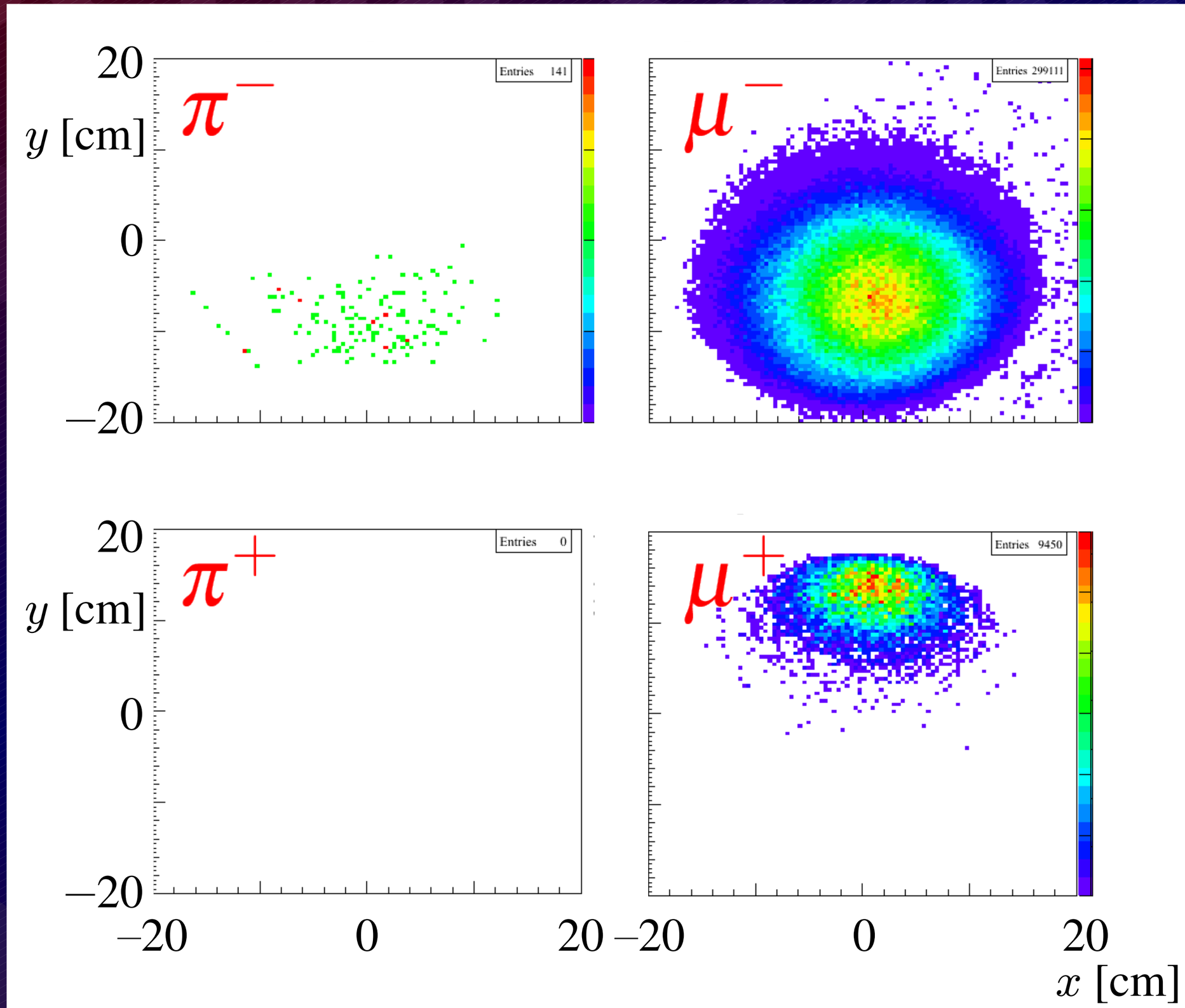


After 90 Degrees of Curved Solenoid



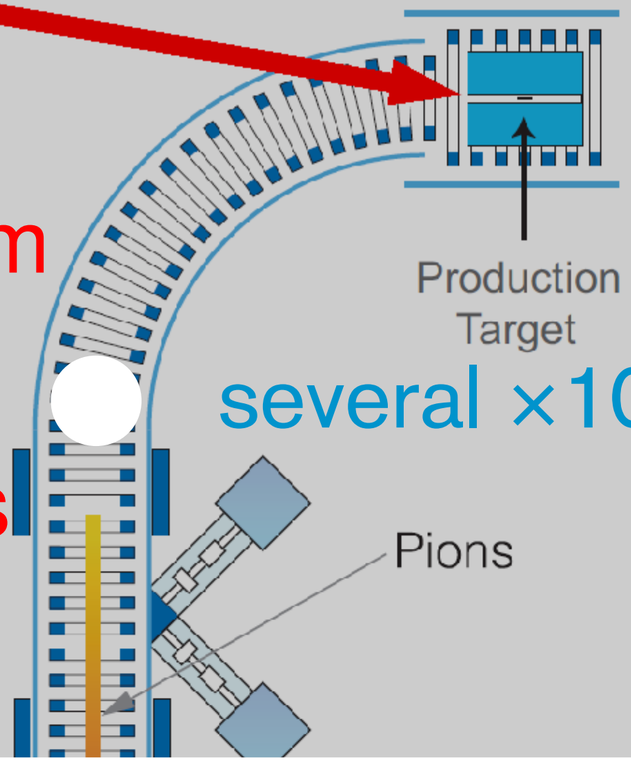
3 T solenoid field, 0.018 T dipole field (tunable)

Before Stopping Target



after collimation of high-momentum muons

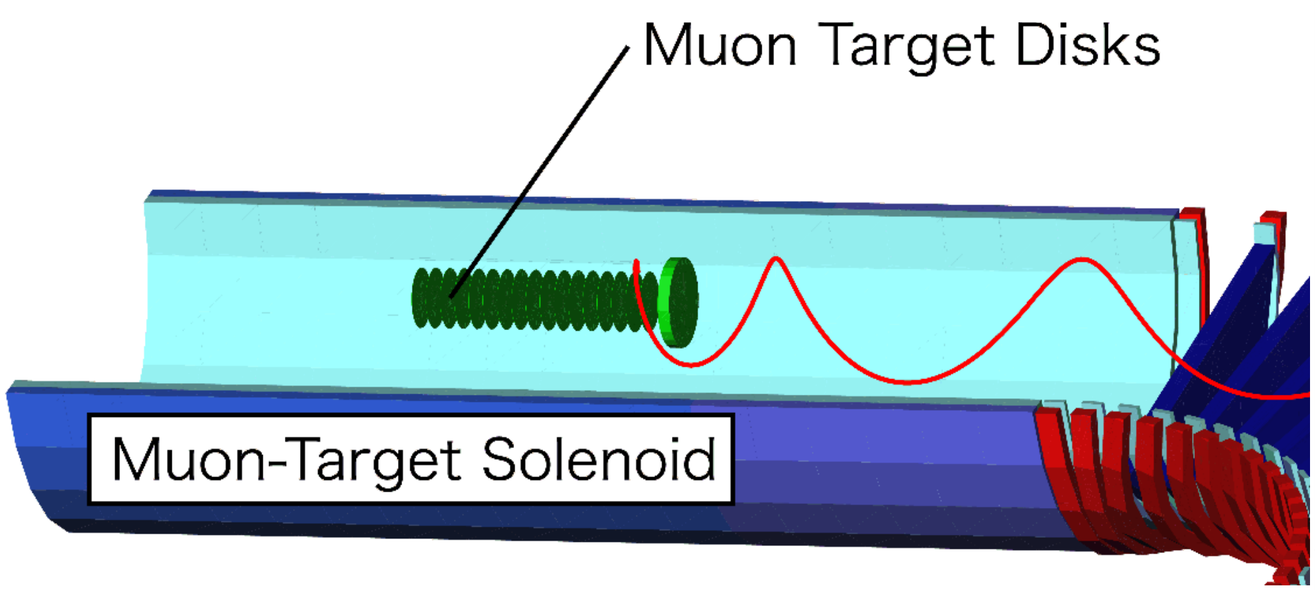
6.4×10^{13} 8 GeV protons per beam spill, in 5.3×10^{5} bunches

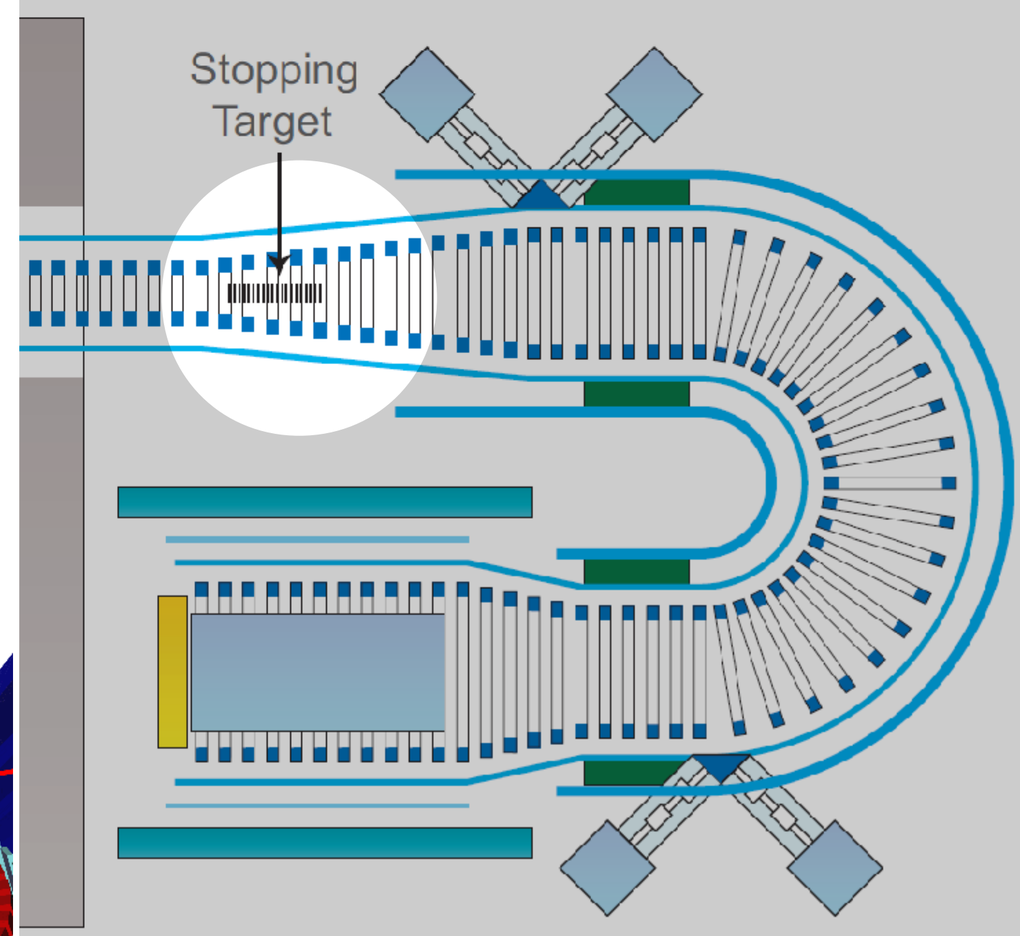


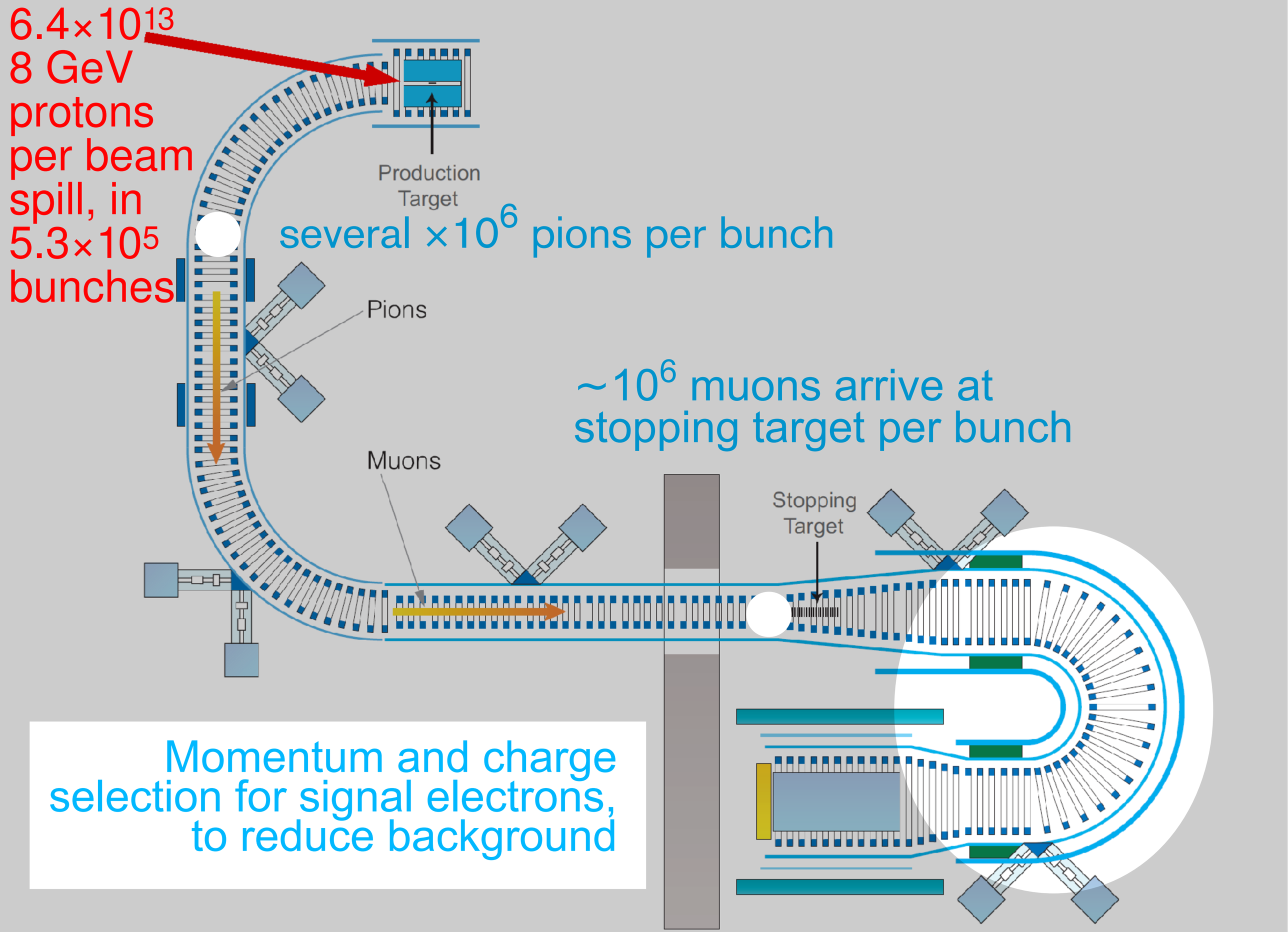
several $\times10^{6}$ pions per bunch

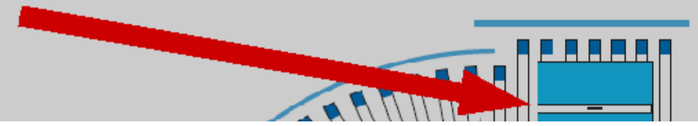
Stopping target (0.2 mm thick Aluminium discs)

about 75% geometrical acceptance for signal electrons



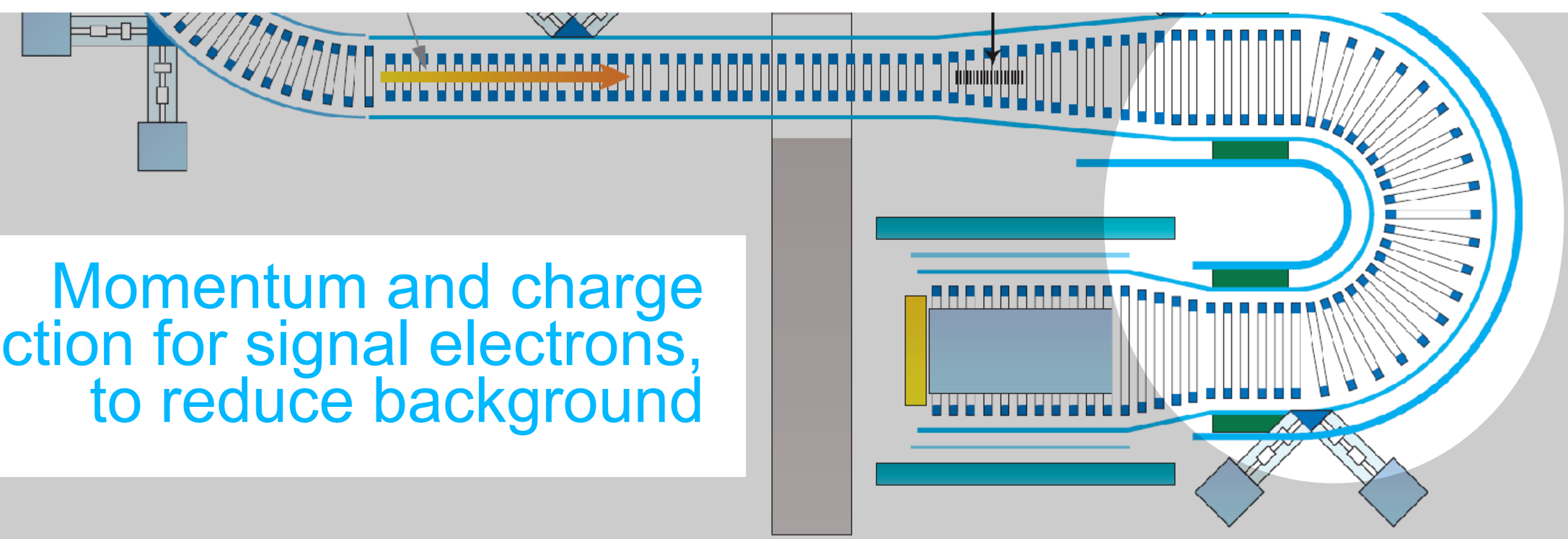



6.4×10^13
8 GeV
protons
per beam
spill, in
5.3×10^5
bunches
Production
Target
several ×10^6 pions per bunch
Pions
~10^6 muons arrive at
stopping target per bunch
Muons
Stopping
Target
Momentum and charge
selection for signal electrons,
to reduce background



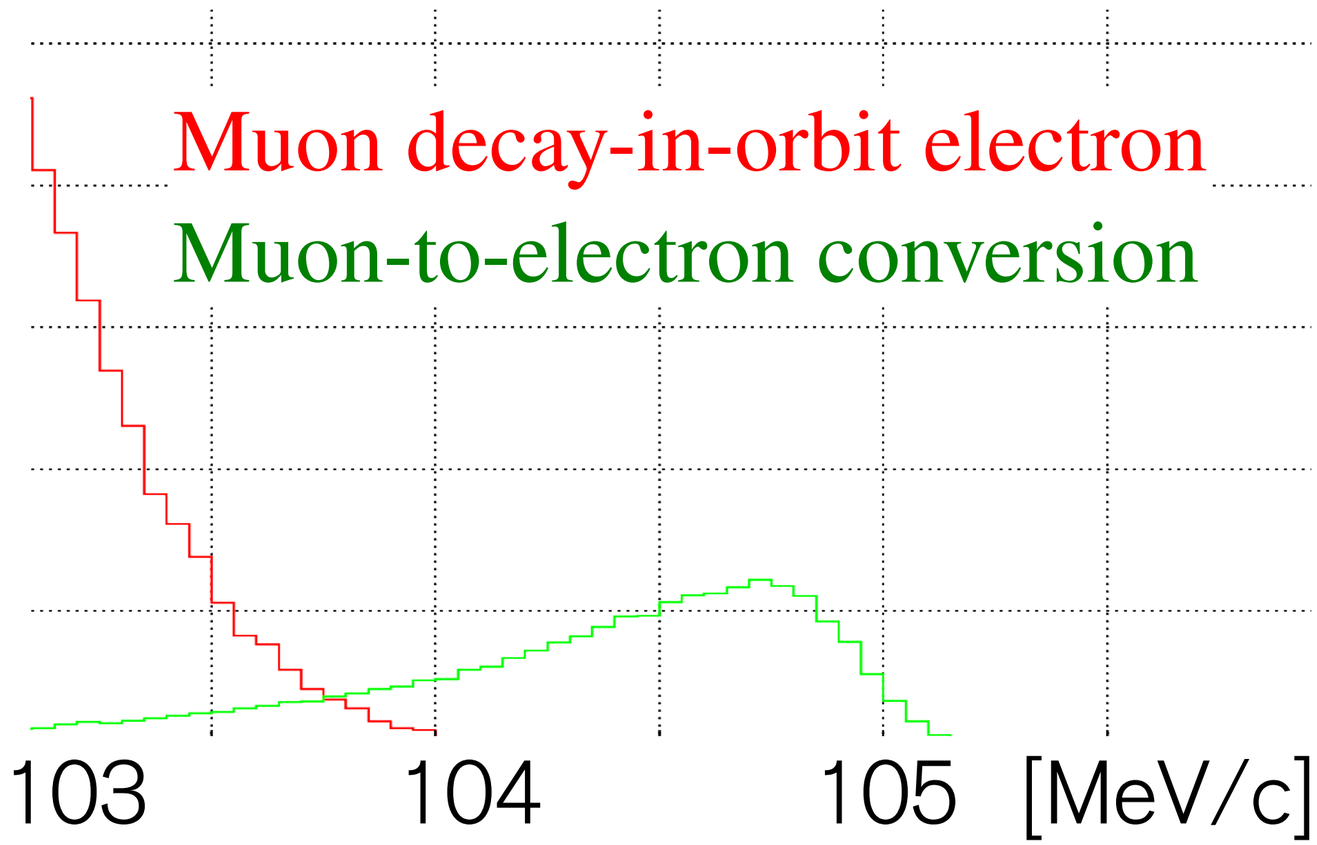
Particles seen after the curved solenoid

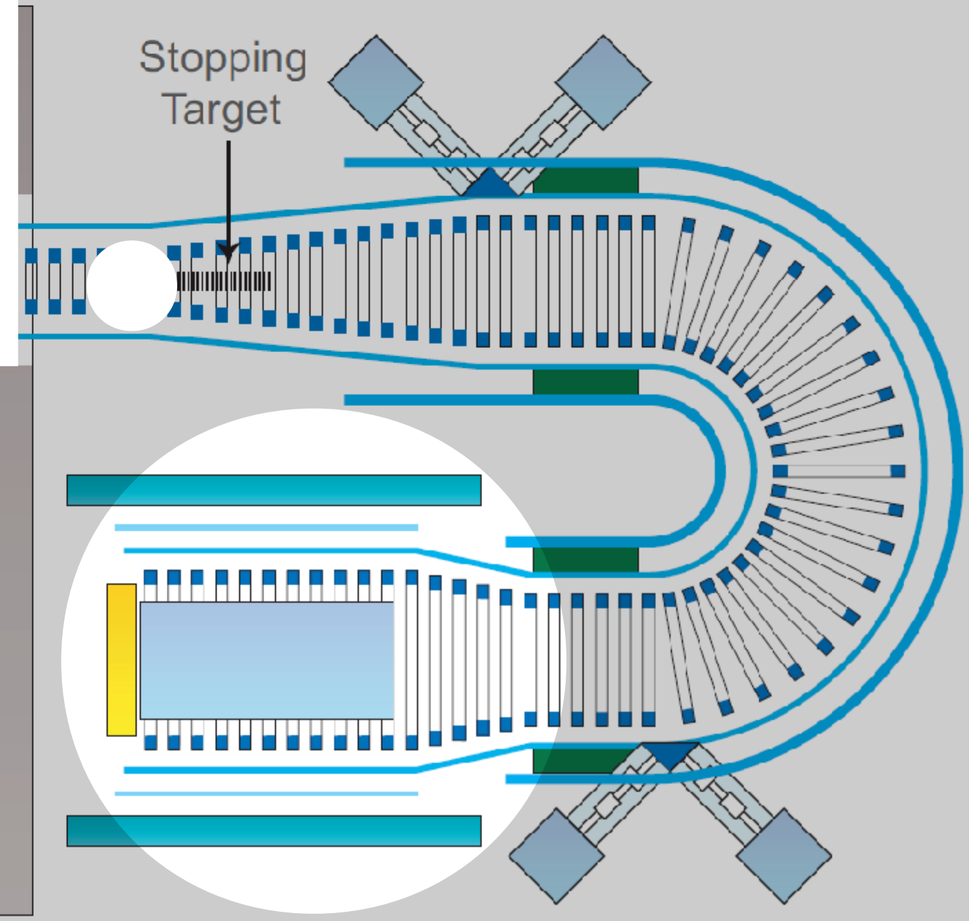
	Timing	Tracker (kHz)	Calorimeter (kHz)	Energy (MeV)
DIO electrons	Delayed	10	10	50–60
Back-scattering electrons	Delayed	15	200	< 40
Beam flash muons	Prompt	$< 150^{\ddagger}$	$< 150^{\ddagger}$	15–35
Muon decay in calorimeter	Delayed	—	$< 150^{\ddagger}$	< 55
DIO from outside of target	Delayed	< 300	< 300	< 50
Proton from muon capture	Delayed	—	—	—
Neutron from muon capture	Delayed	—	10	~ 1
Photons from DIO e^- scattering	Delayed	150	9000	$\langle E \rangle = 1$



Momentum and charge selection for signal electrons, to reduce background

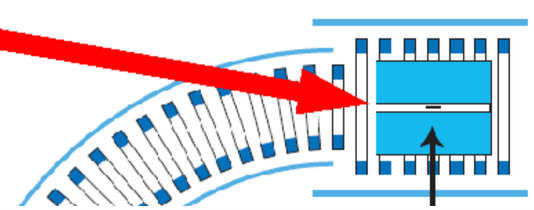
Relative signal and background spectra for branching ratio of 10^{-16} statistics ×100 (including energy loss and tracker resolution)



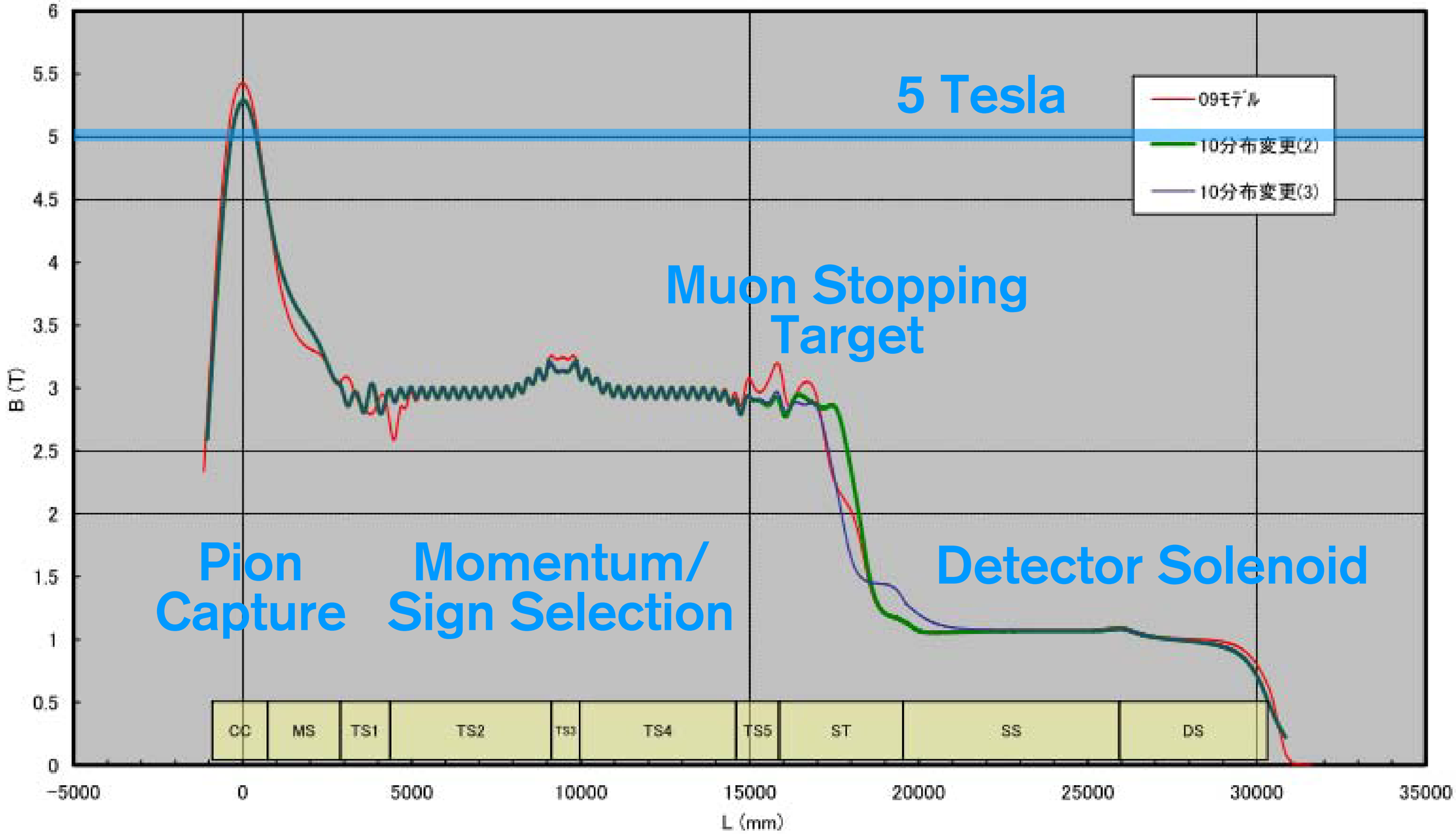


Tracking detector for momentum measurement, calorimeter for energy and triggering redundancy

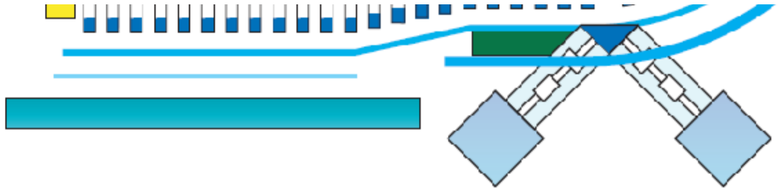
8 GeV
Proton



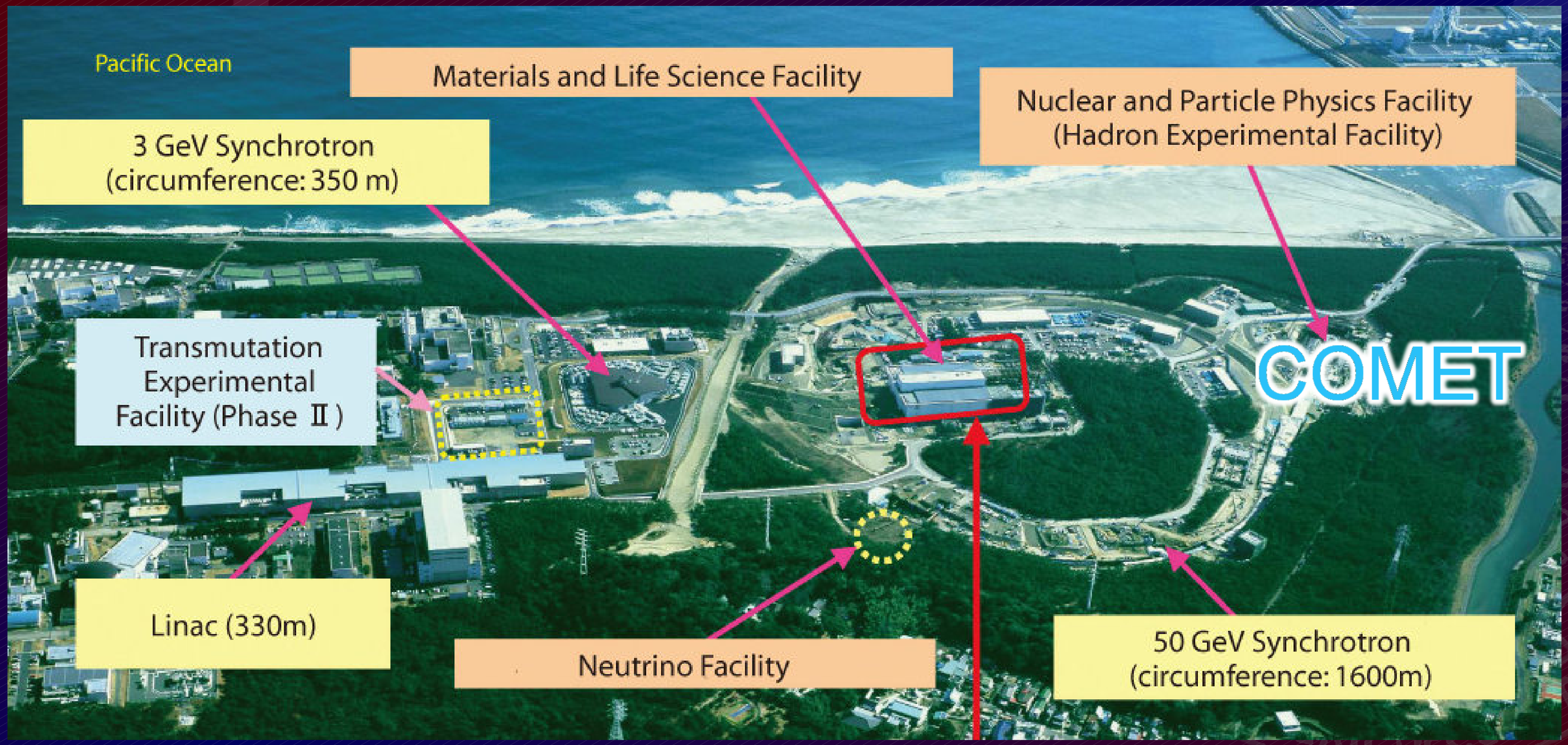
Pion Production Target and
Superconducting Pion
Capture Solenoid



Detector section for
signal electrons

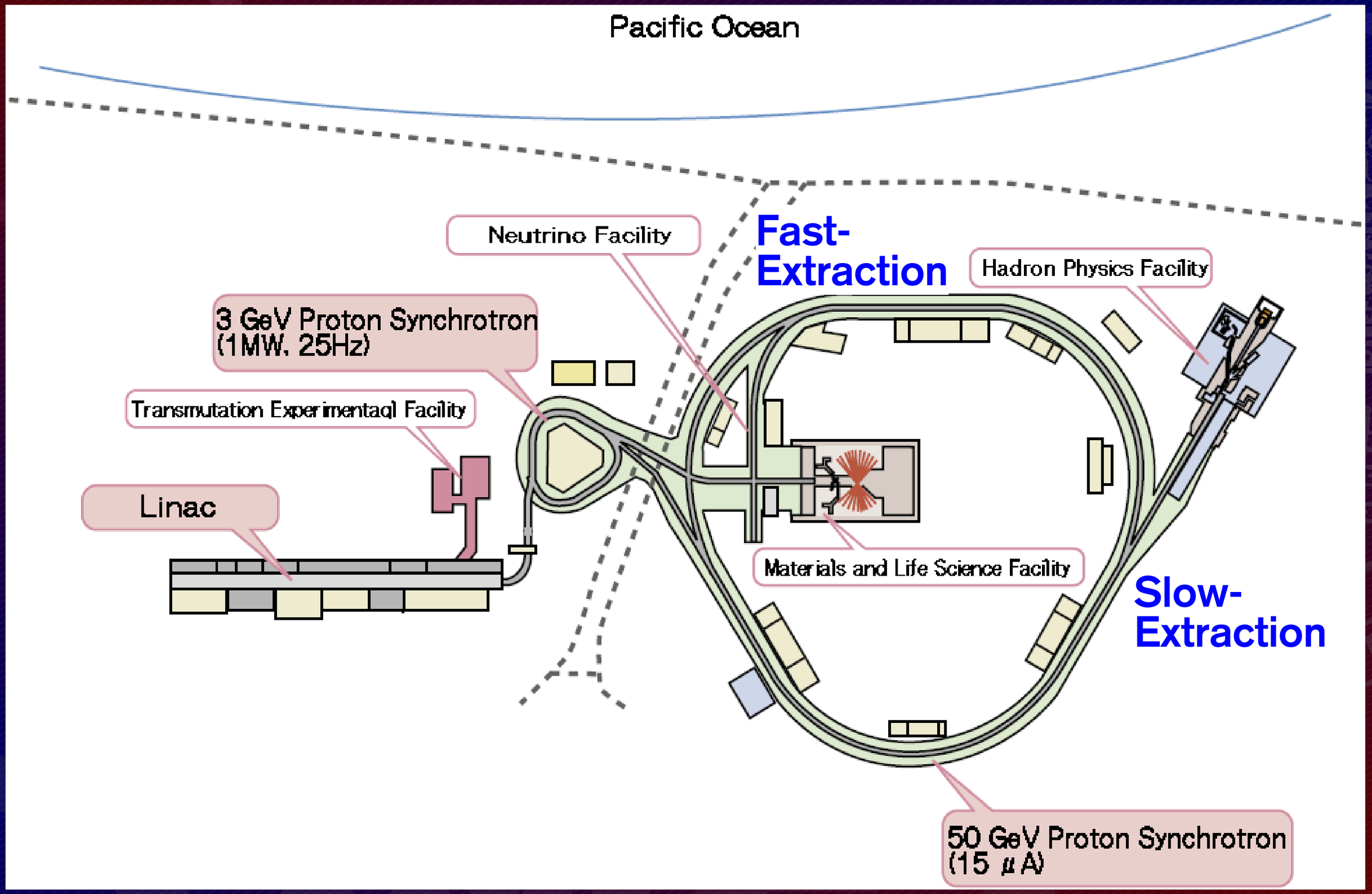


J-PARC


Pacific Ocean
Materials and Life Science Facility
Nuclear and Particle Physics Facility
(Hadron Experimental Facility)
3 GeV Synchrotron
(circumference: 350 m)
Transmutation
Experimental
Facility (Phase Ⅱ)
COMET
Linac (330m)
Neutrino Facility
50 GeV Synchrotron
(circumference: 1600m)

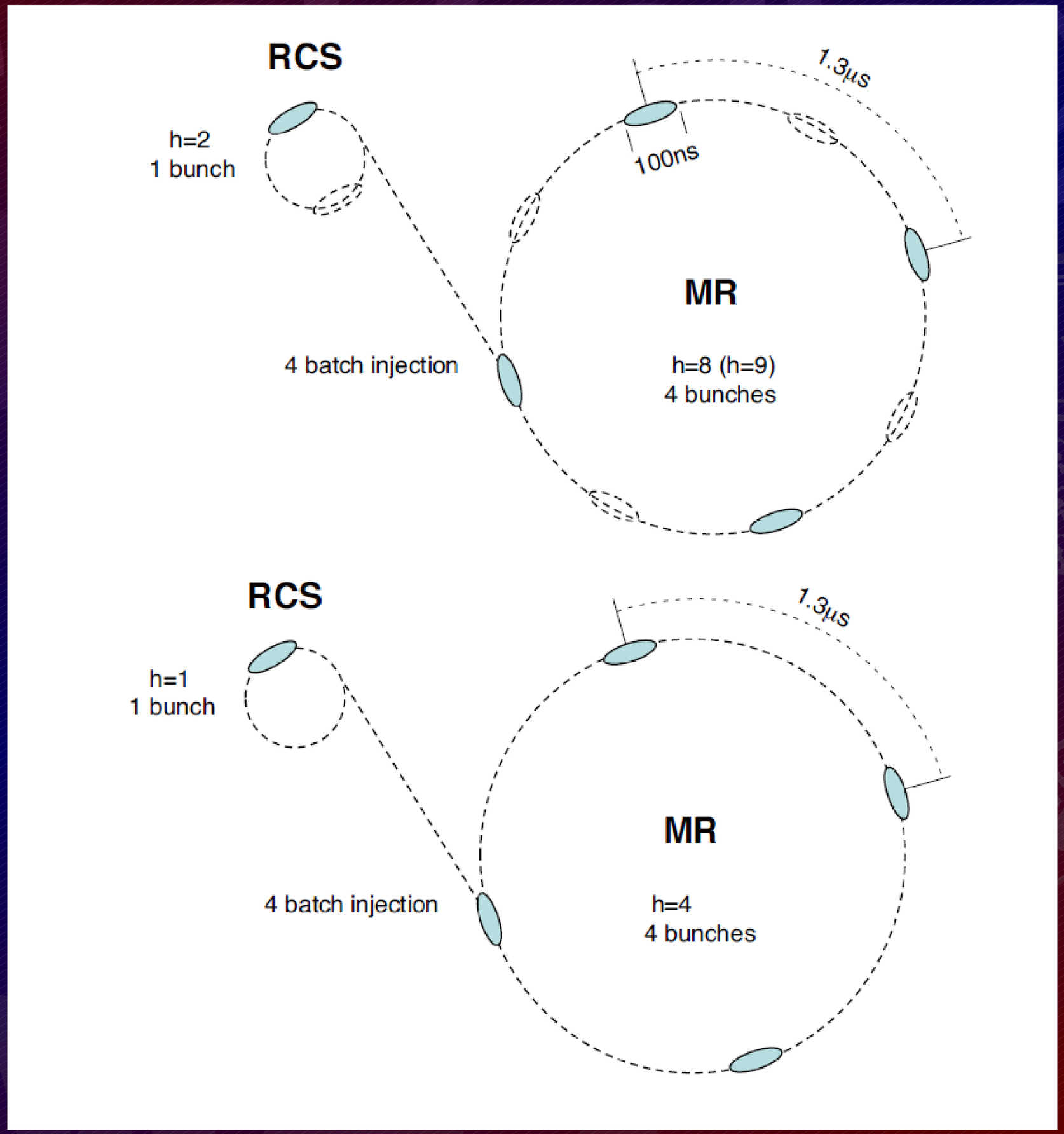
J-PARC

J-PARC


Pacific Ocean
Neutrino Facility
Fast-Extraction
Hadron Physics Facility
3 GeV Proton Synchrotron (1MW, 25Hz)
Transmutation Experimentaql Facility
Linac
Materials and Life Science Facility
Slow-Extraction
50 GeV Proton Synchrotron (15 μA)

J-PARC

Possible Acceleration Schemes



T2K operates at h=9, with 8 bunches filled

R&D Status

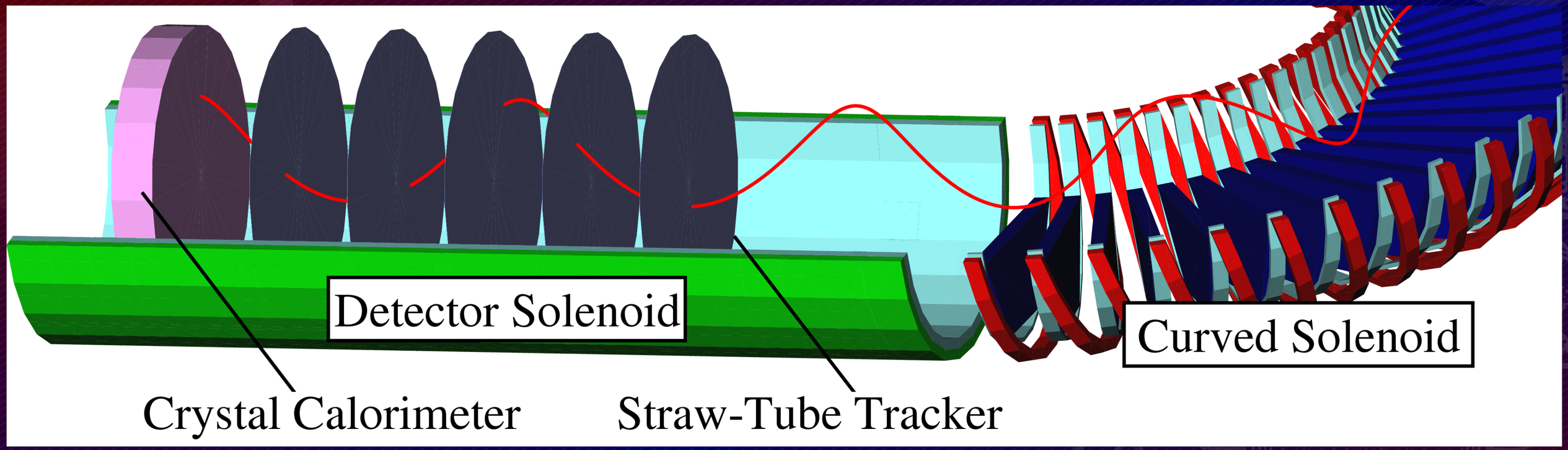
Beam Extinction

- Very high beam extinction performance necessary between proton pulses
- 10^{-9} extinction needed
- Methods undergoing R&D
- Internal extinction
  - remove off-pulse protons during circulation
- External extinction
  - AC dipole on proton beamline to experiment
    - joint Mu2E / COMET R&D

Beam Monitor for Beam Extinction Tests and Measurements at J-PARC

(2010 preliminary result 10^{-7} ⇒ 10^{-9} goal or better achievable with internal and external extinction)

COMET Detector Section



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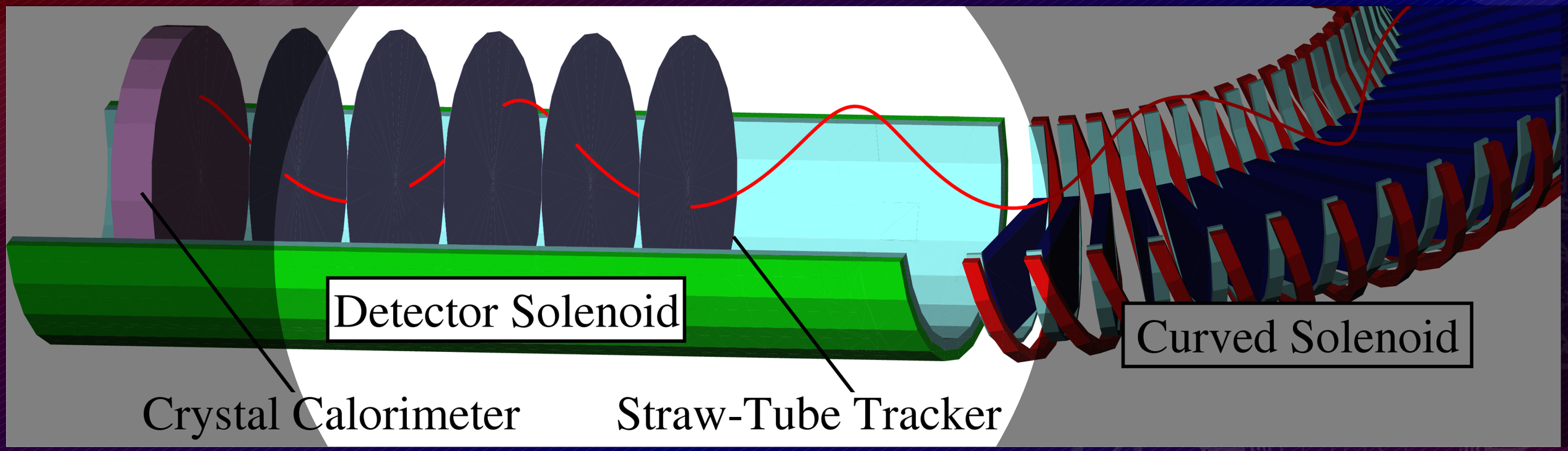
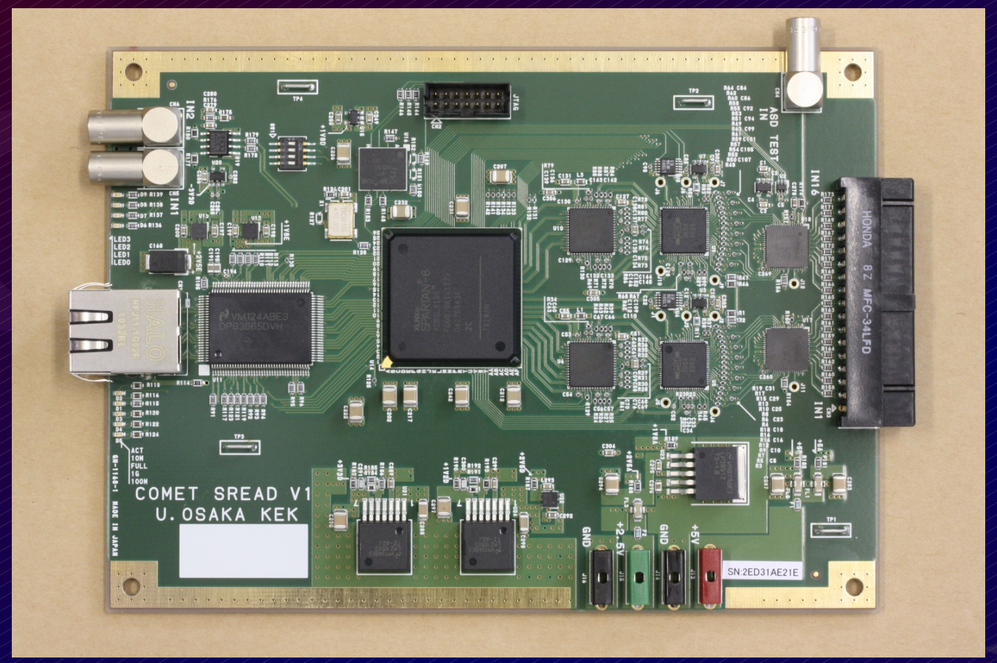
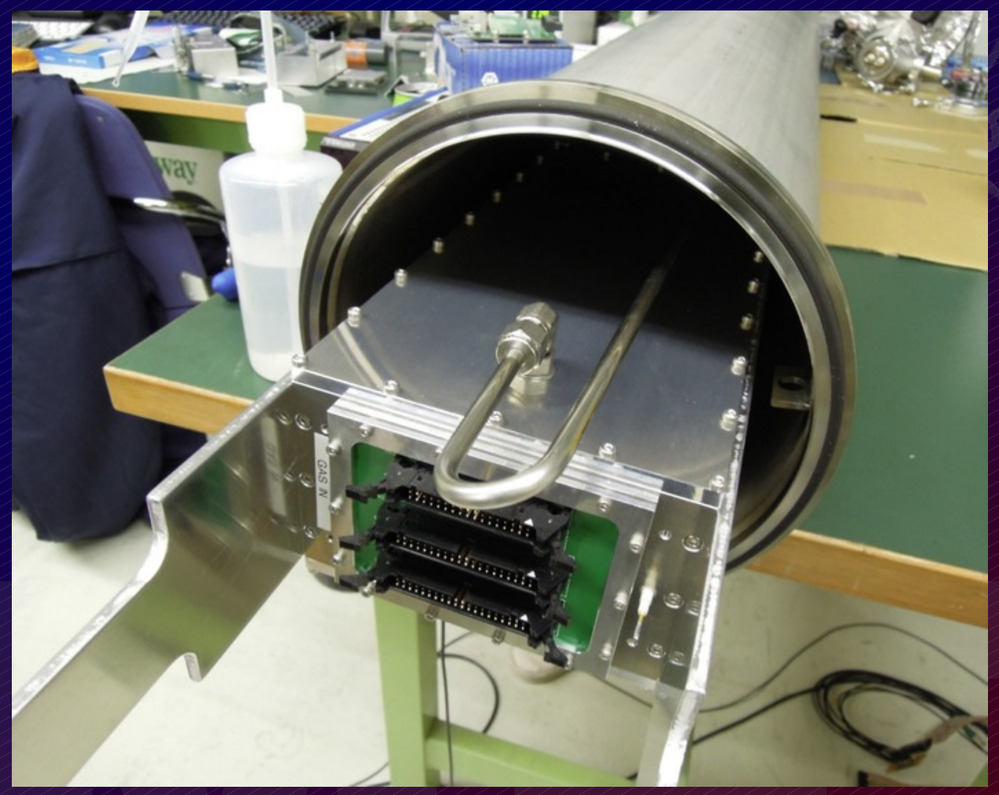


- Straw-tube electron tracker in 1 Tesla field
  - 800 kHz charged particle and 8 MHz gamma rates
  - 0.4% momentum and 700 micron spatial resolution required

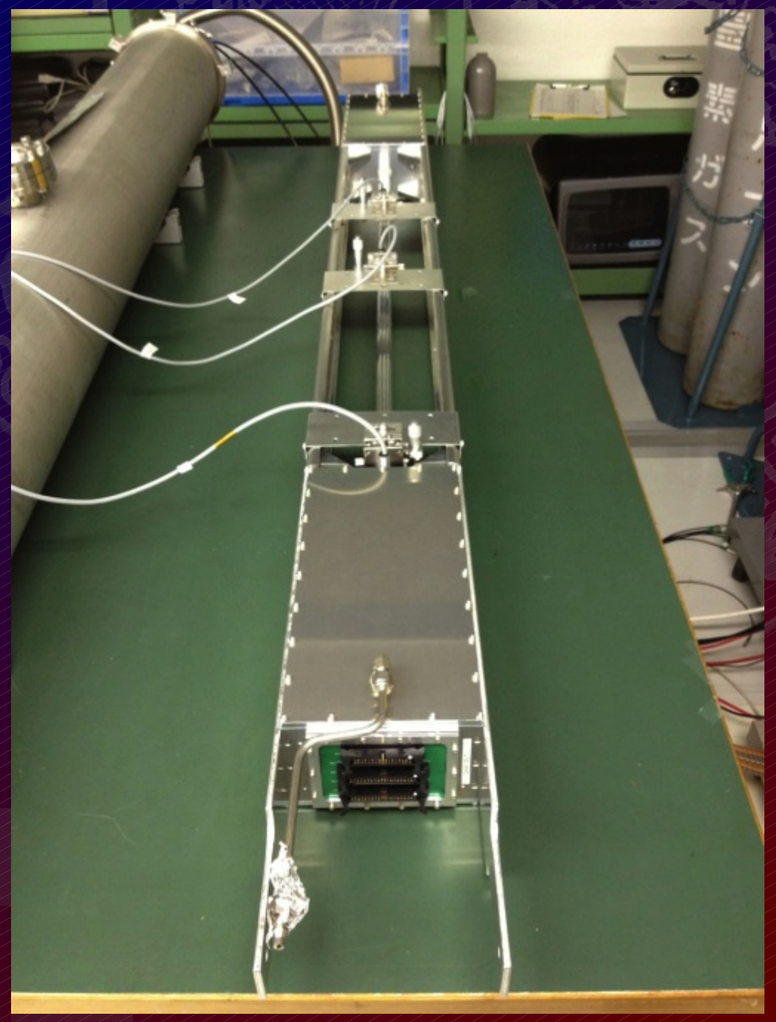
Straw Tube Tracker R&D

Prototype at KEK (7 straw tubes)

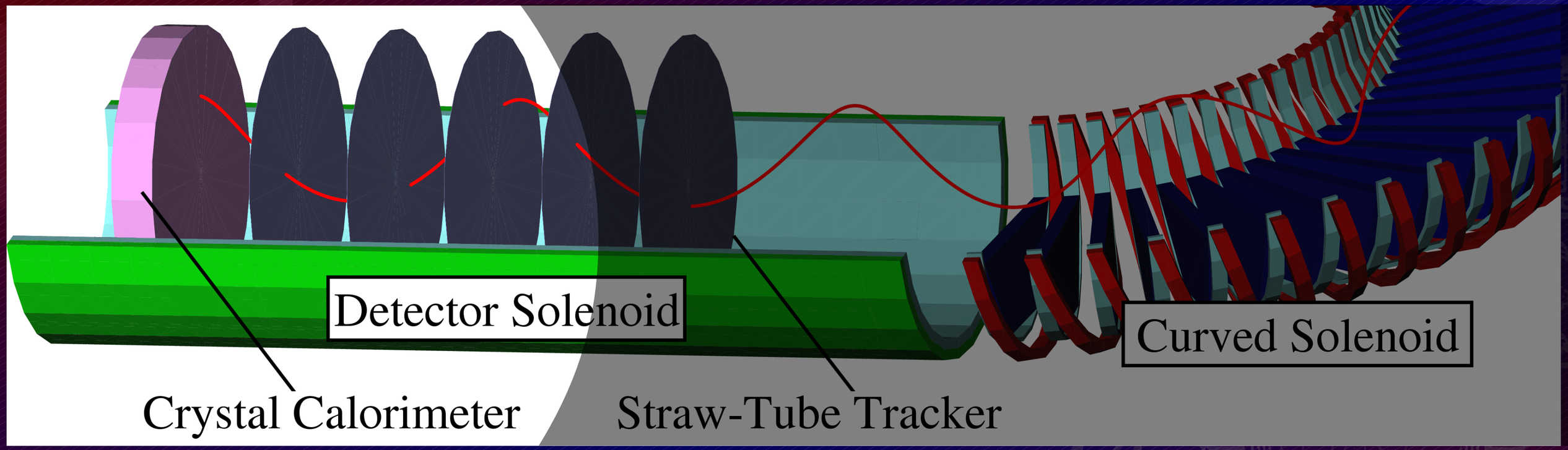




Front-end electronics R&D, leak, deformation, gain and timing tests



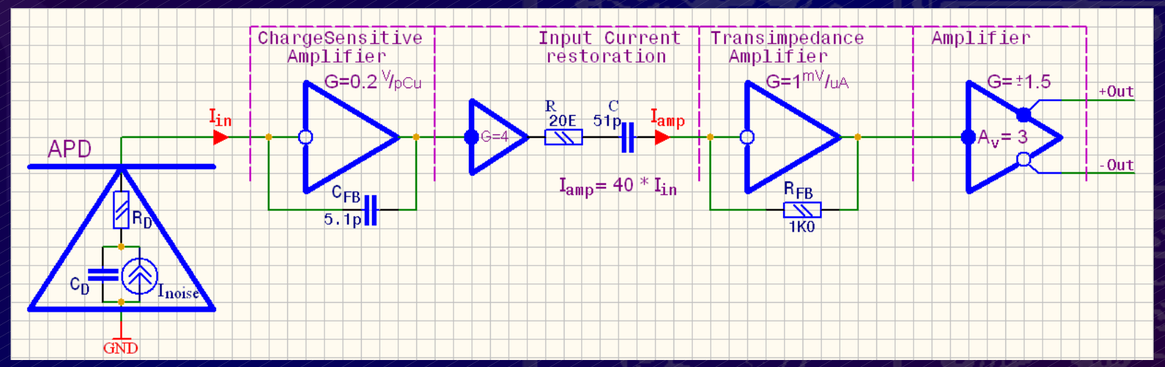
COMET Detector Section



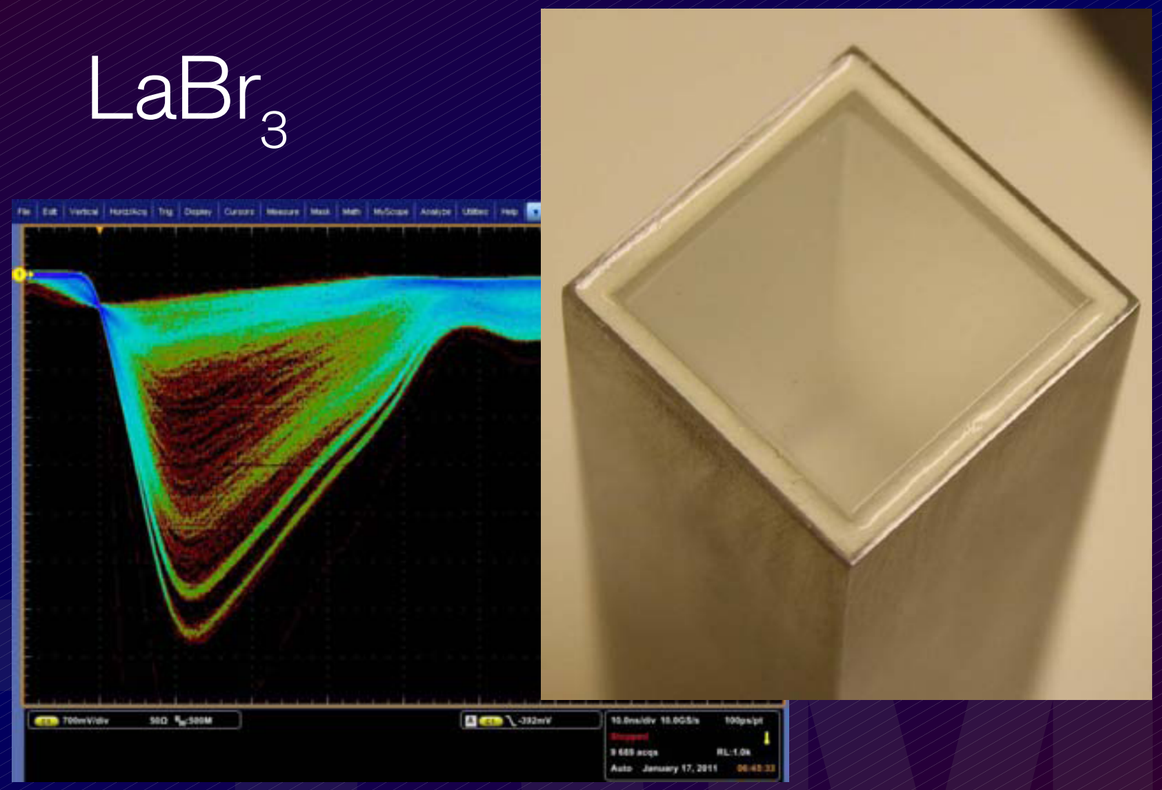
- Crystal calorimeter
  - for energy and position measurement, PID, trigger signal
  - 5% energy and 1cm spatial resolution at 100 MeV

Calorimeter R&D

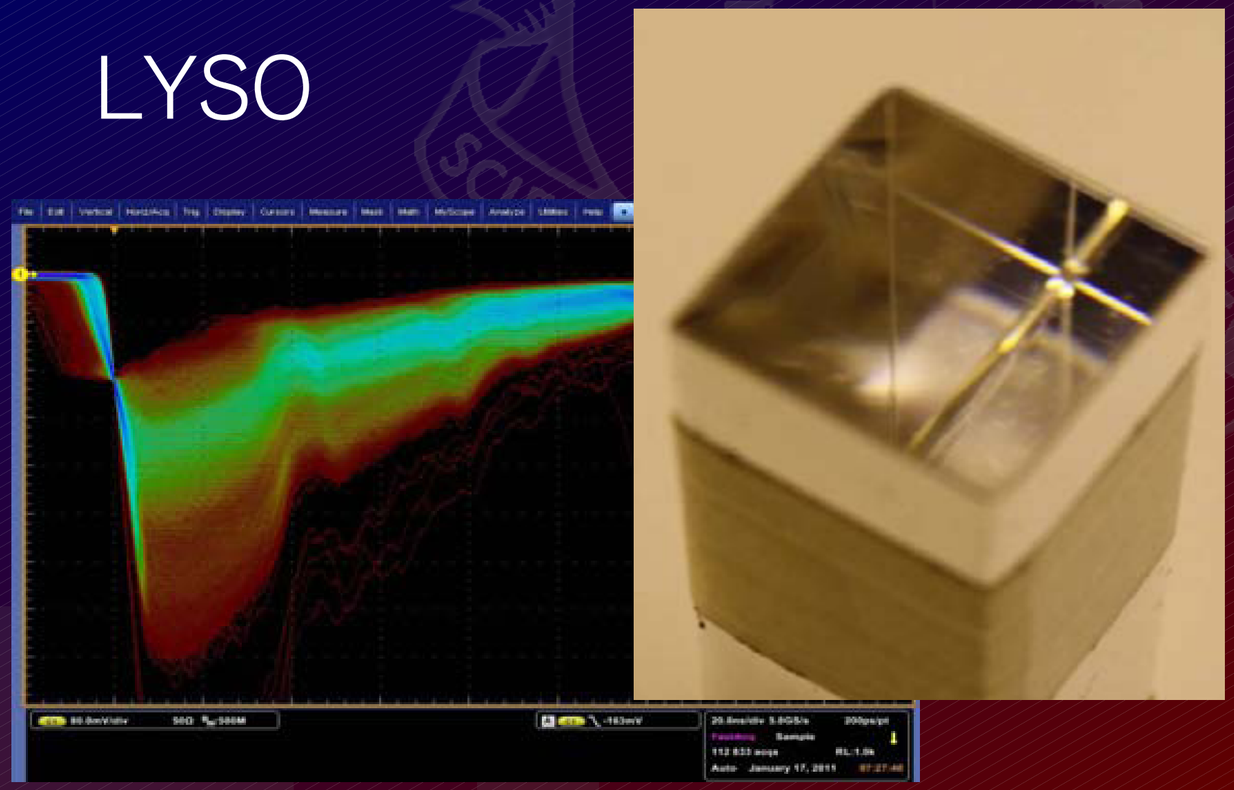
- GSO / LYSO crystals with APDs tested 2011
  - Vertical slice tests this year
- Design being finalised for 50-crystal / APD prototype
  - beam tests later this year at BINP Novisibirsk



$LaBr_3$

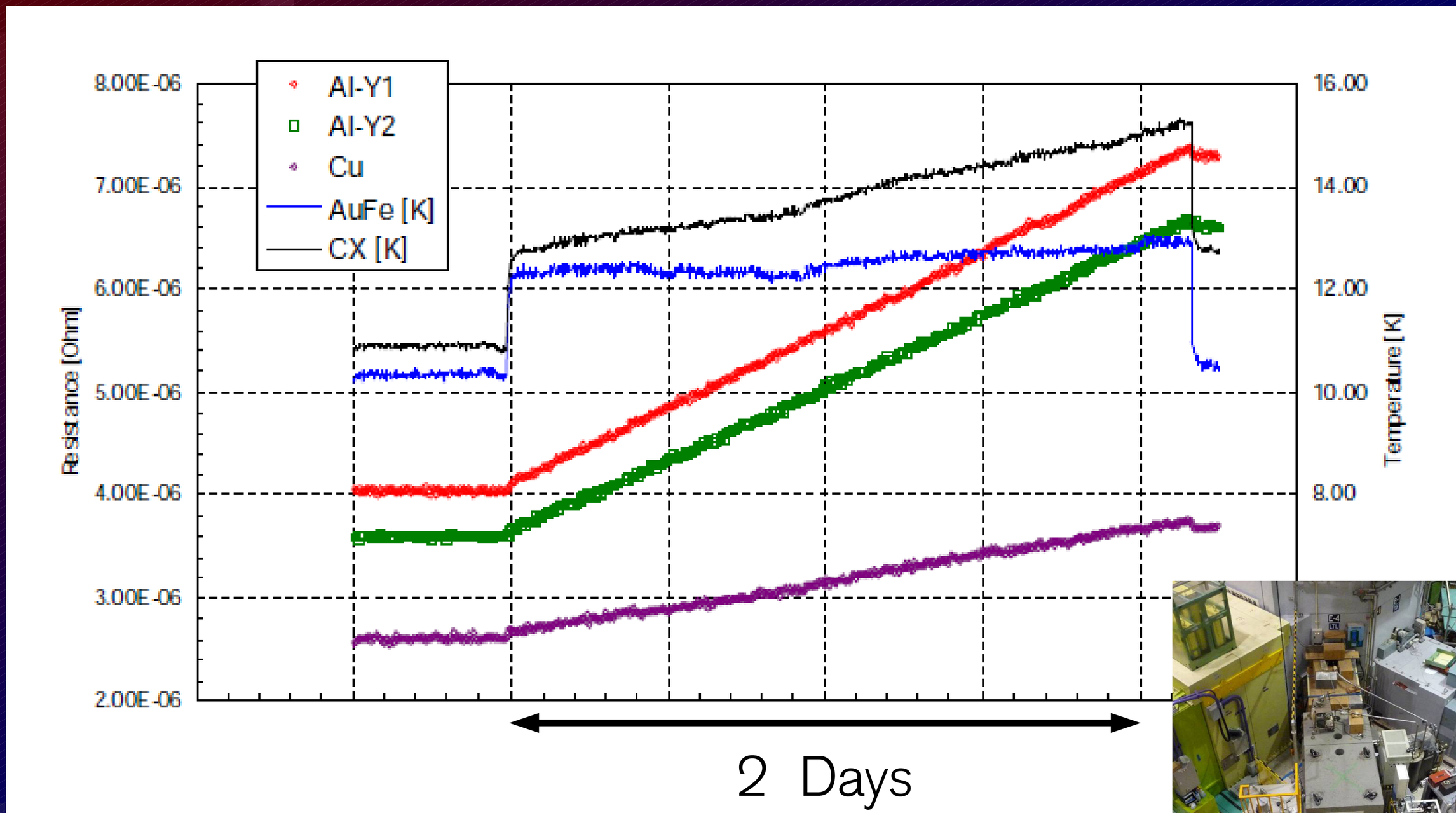


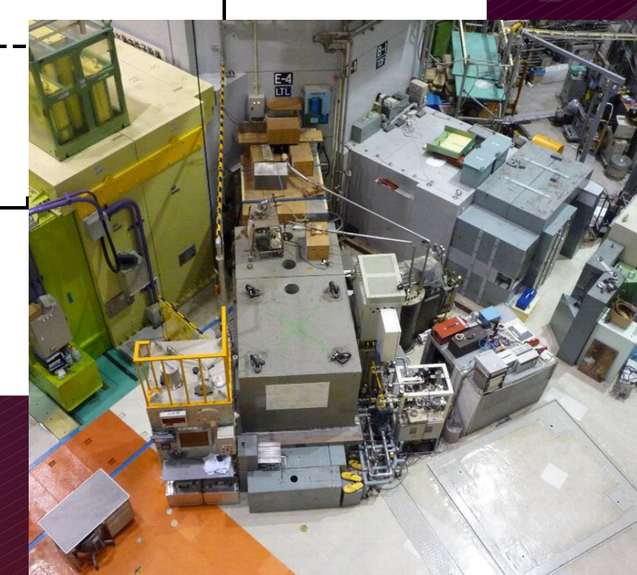
LYSO



Superconducting Solenoid R&D

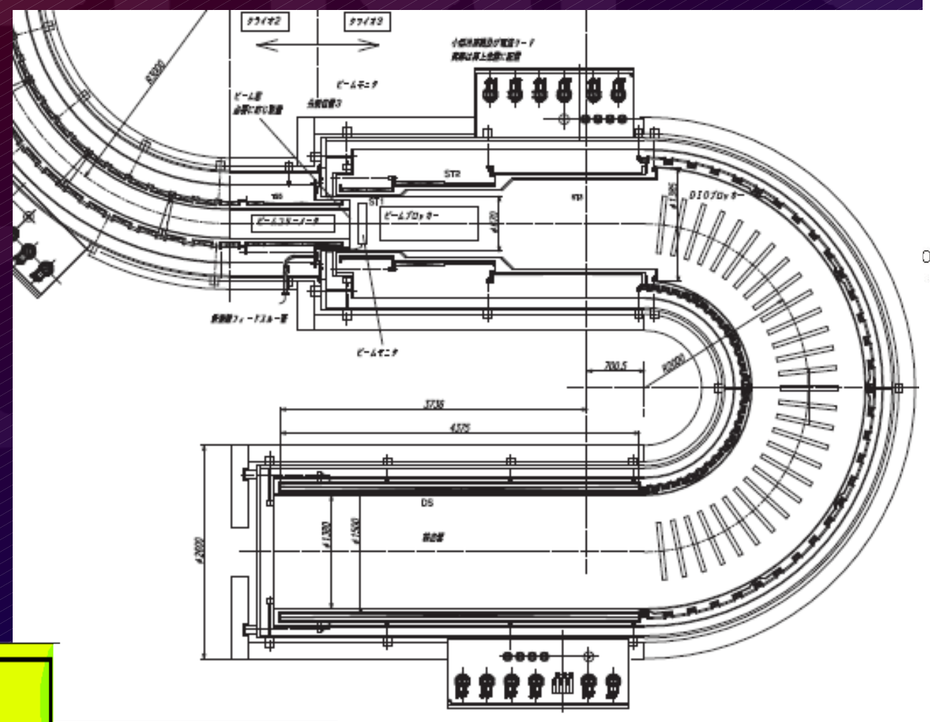
Neutron irradiation tests performed at KURRI reactor, Kyoto University

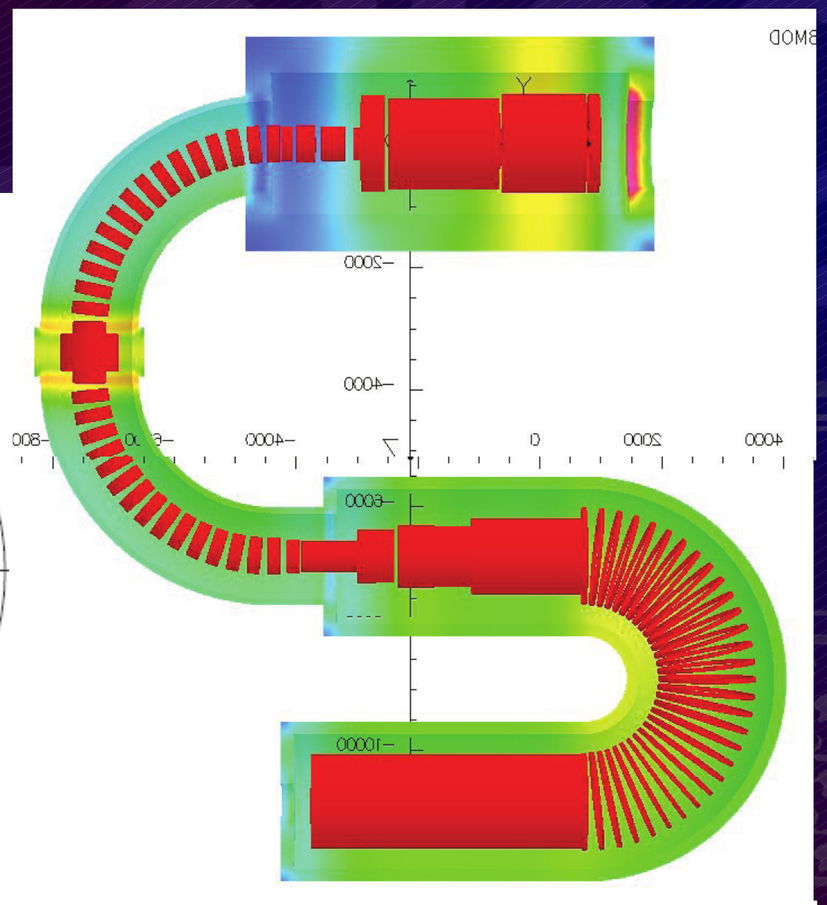


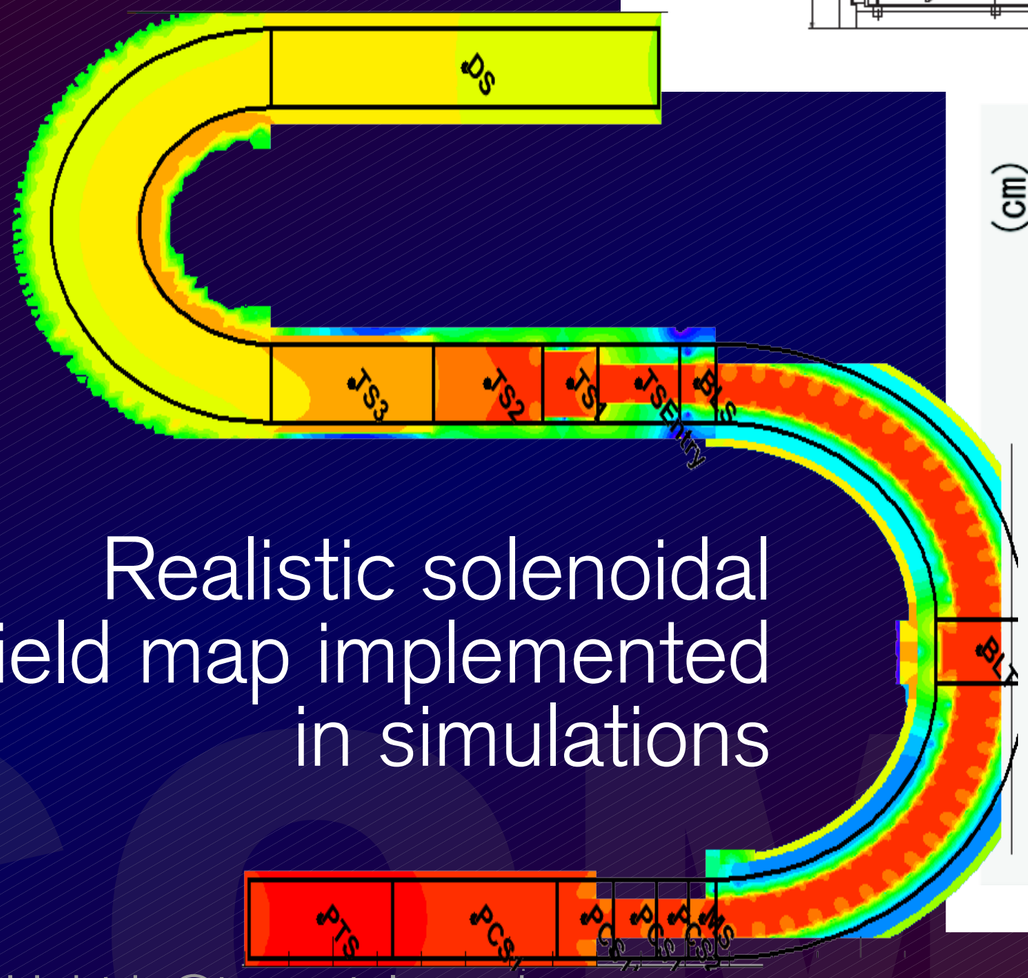


Demonstrated that Al stabiliser tolerates COMET radiation environment

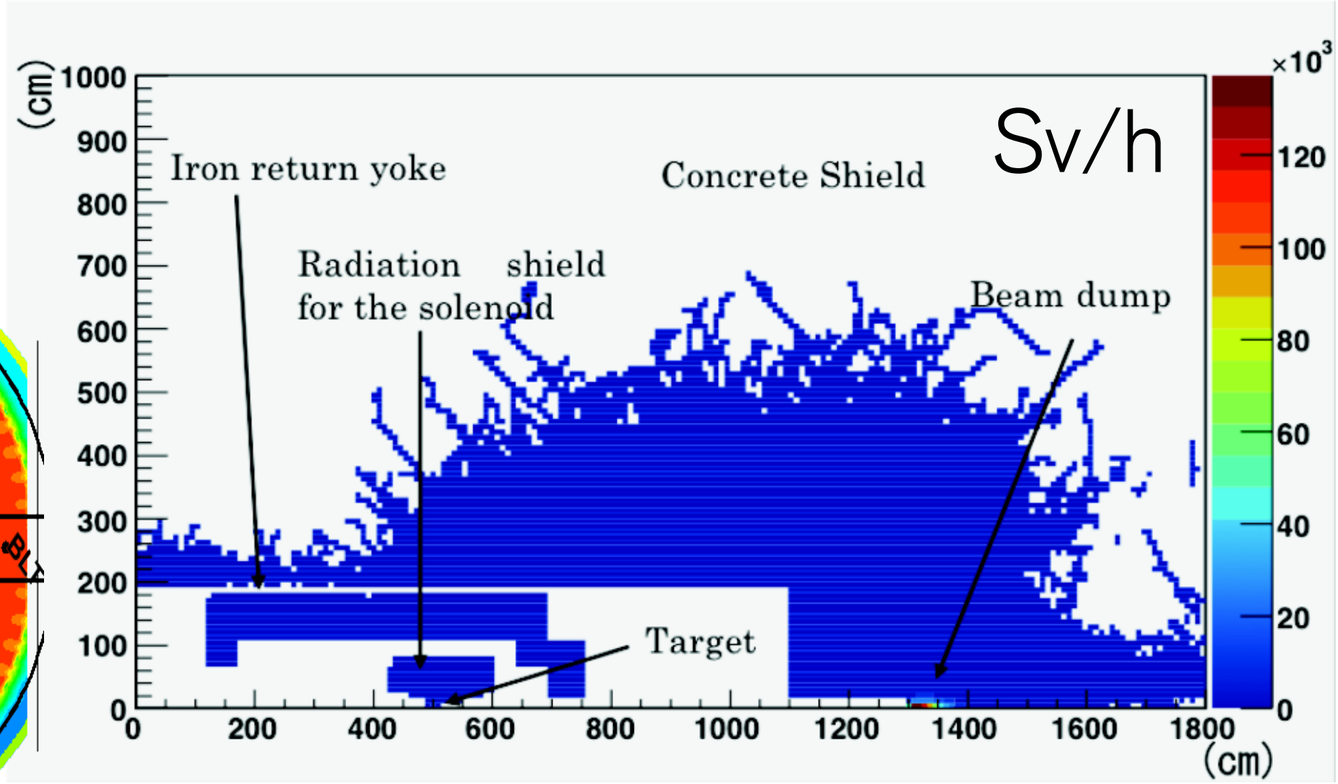
Industrial Design Studies







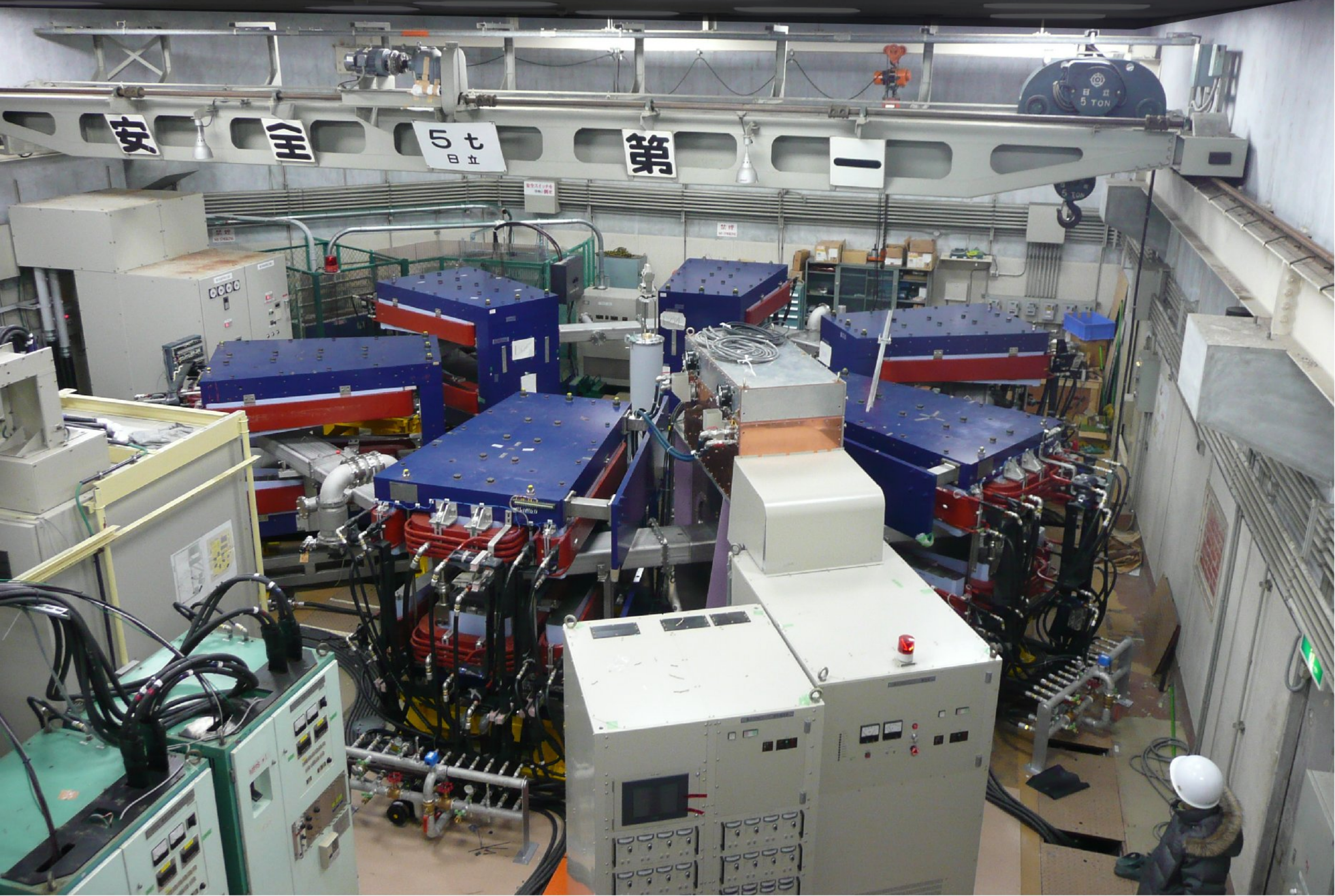
Realistic solenoidal field map implemented in simulations



PRISM

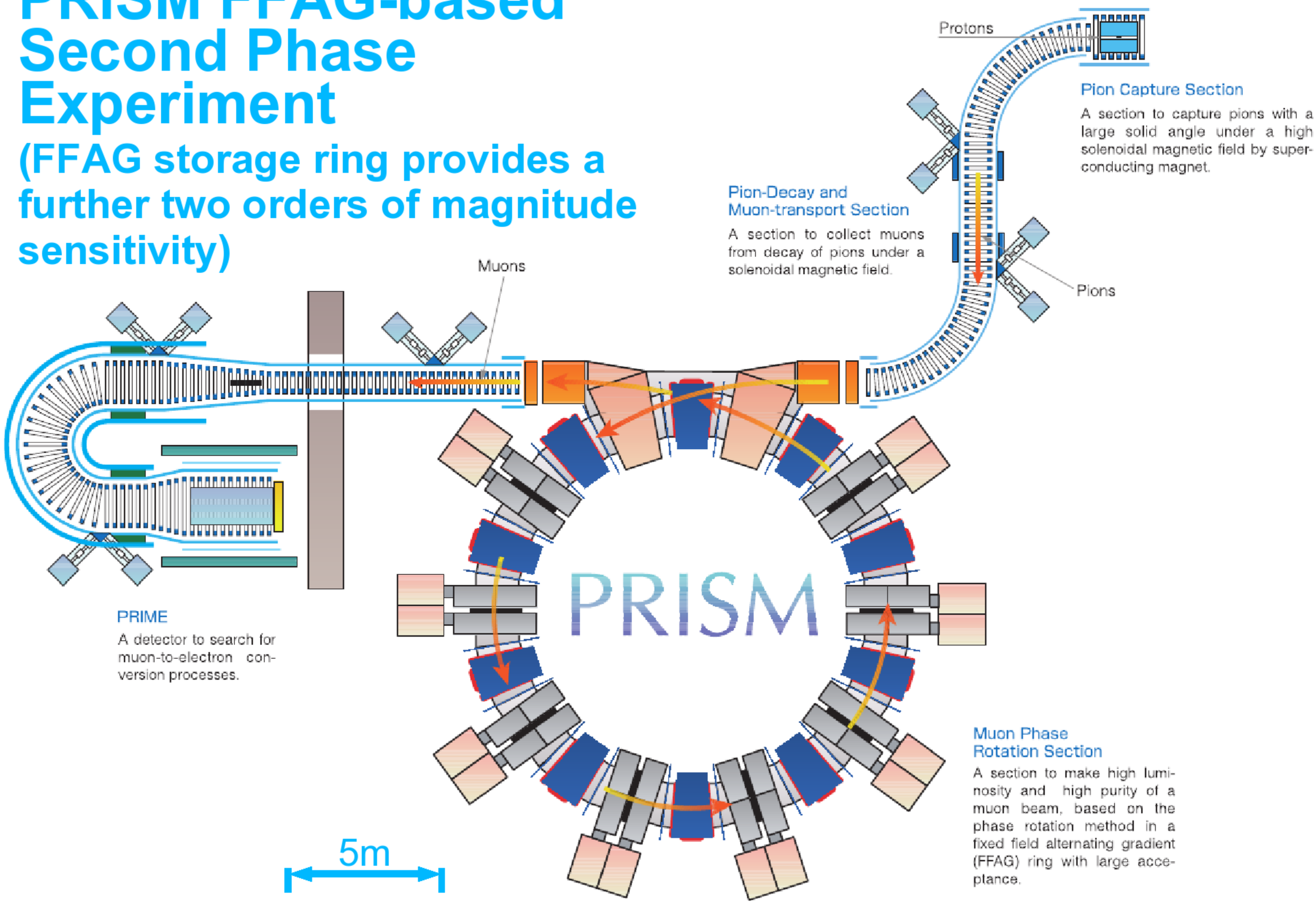
The PRISM FFAG Ring for Muon-to-Electron Conversion

Prototype ring at Osaka University



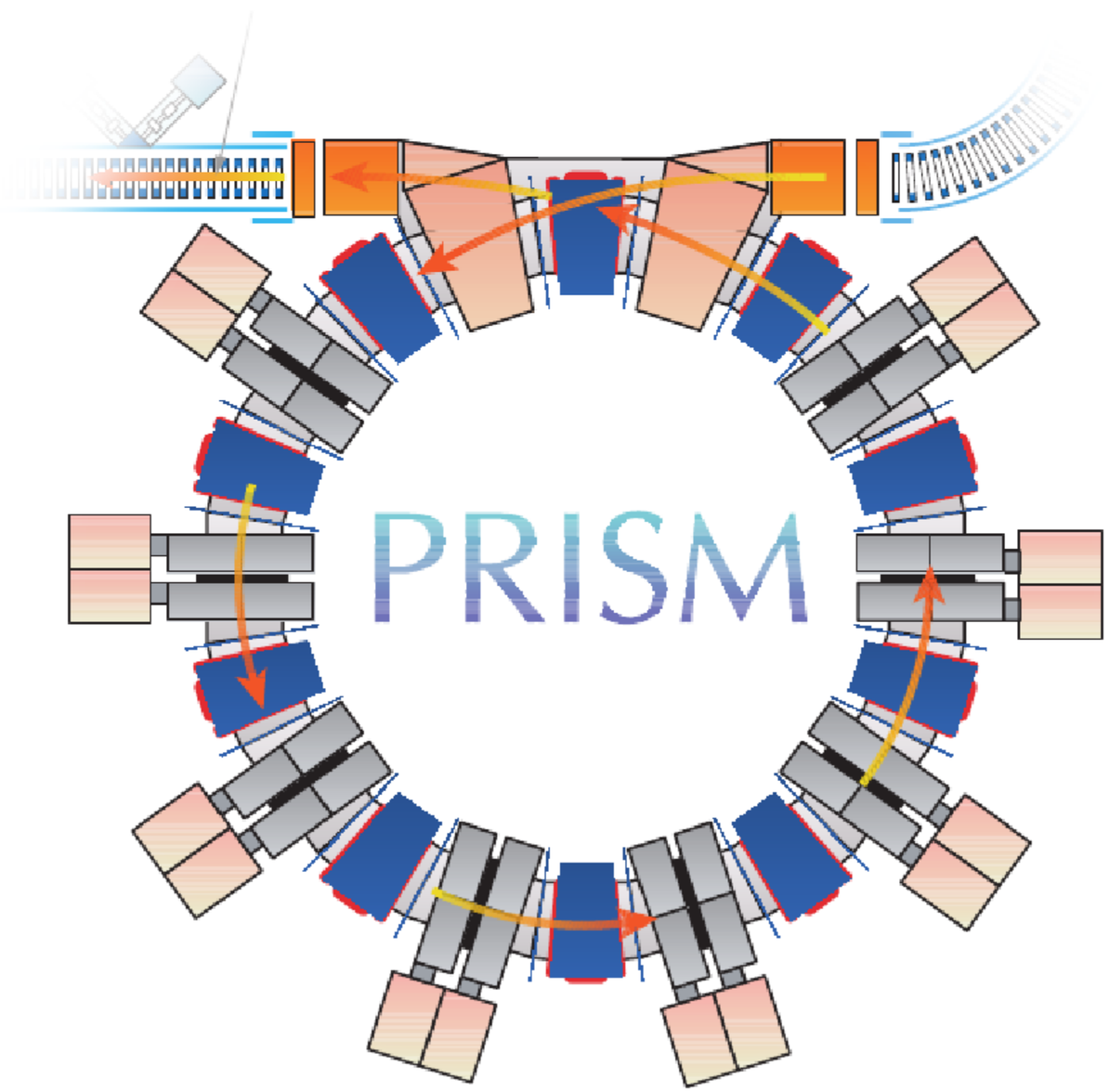
PRISM FFAG-based Second Phase Experiment

(FFAG storage ring provides a further two orders of magnitude sensitivity)



PRISM/FFAG
Muon Storage Ring

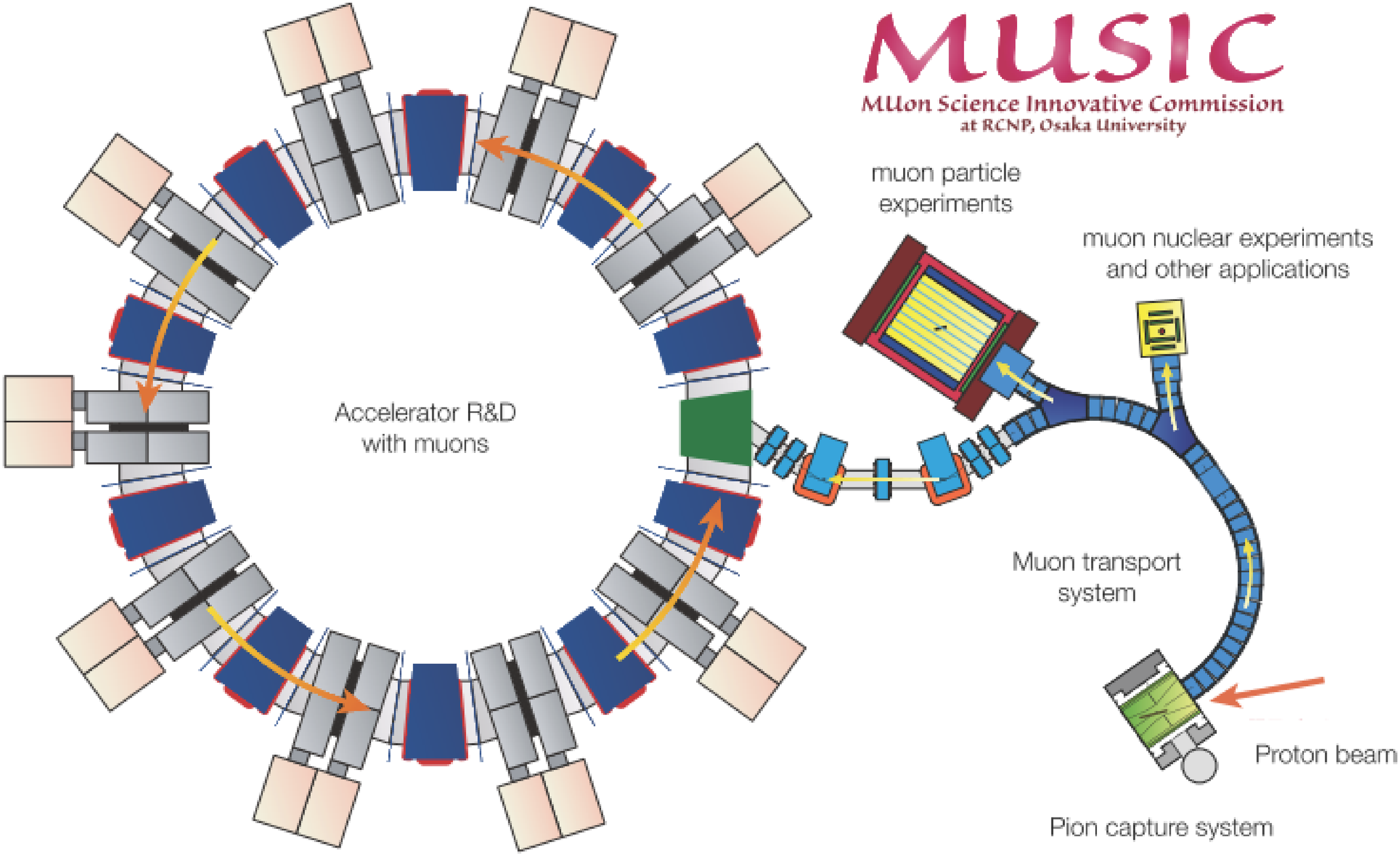
See Jaroslaw Pasternak's talk later this morning

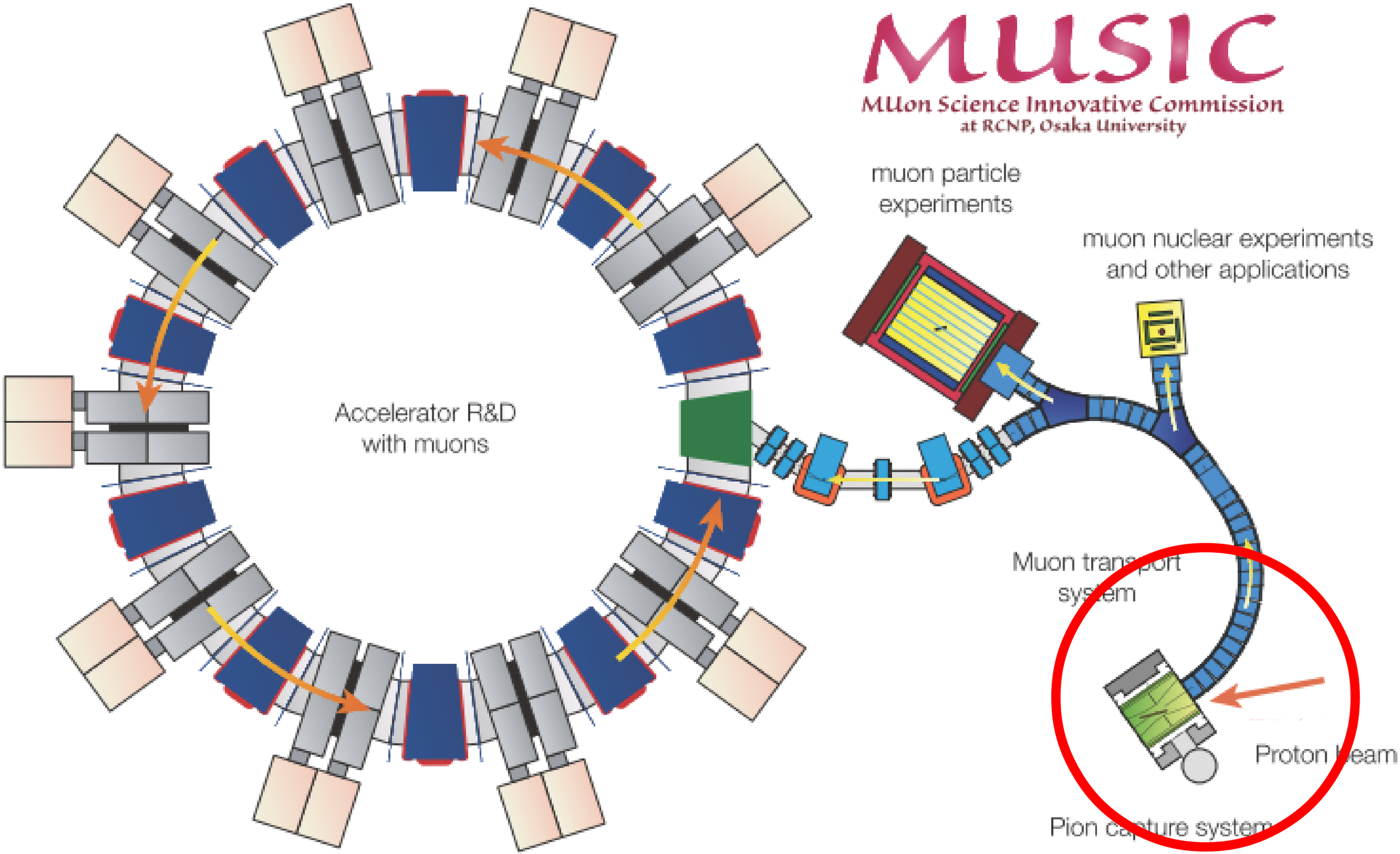


MUSIC

MUSIC

MUon Science Innovative Commission
at RCNP, Osaka University





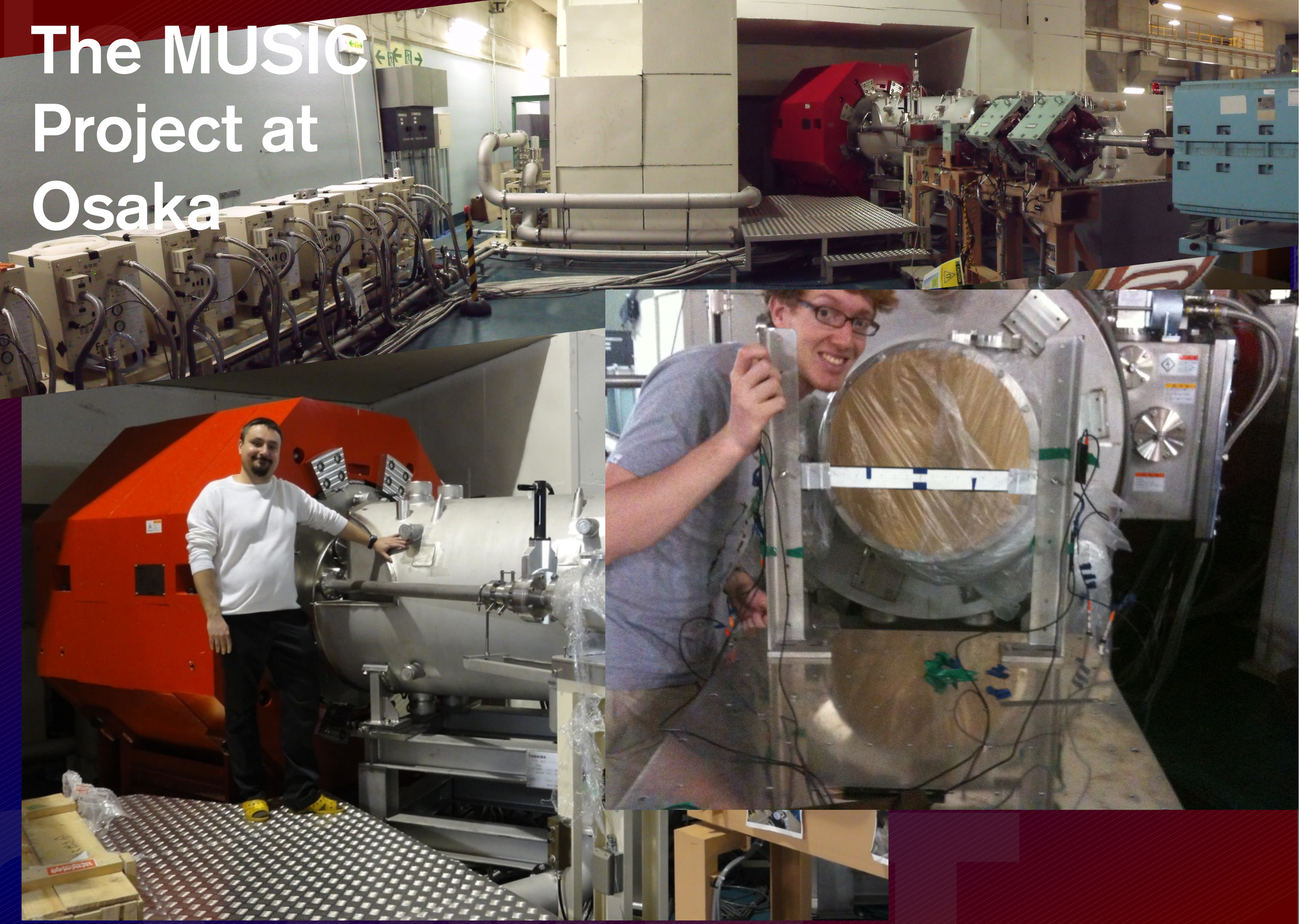
Commissioned April 2010—
The world's first superconducting pion capture solenoid

The MUSIC Project at Osaka

- Identical physics principles as upstream parts of COMET
- Much lower power
- High muon intensity

- Prototype studies for COMET
- Pion-capture solenoid/muon transport line studies
- Muon physics
- UK on-site activity at MUSIC since 2009

The MUSIC Project at Osaka



CDR submitted to
J-PARC PAC in June 2009

Stage-1 Approval (of two stages) granted July 2009
as a potential flagship experiment at J-PARC

Collaboration in process of growing (Imperial, UCL and Glasgow in the UK, China, India, Vietnam etc)

TDR studies in progress to satisfy PAC requests towards Stage-2 Approval

The COMET Collaboration

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Department of Physics, University of Houston, USA

T. Numao
TRIUMF, Canada

Available at http://www.hep.ph.ic.ac.uk/muec

COMET Collaboration List

80 people from 20 institutes (March 2011)

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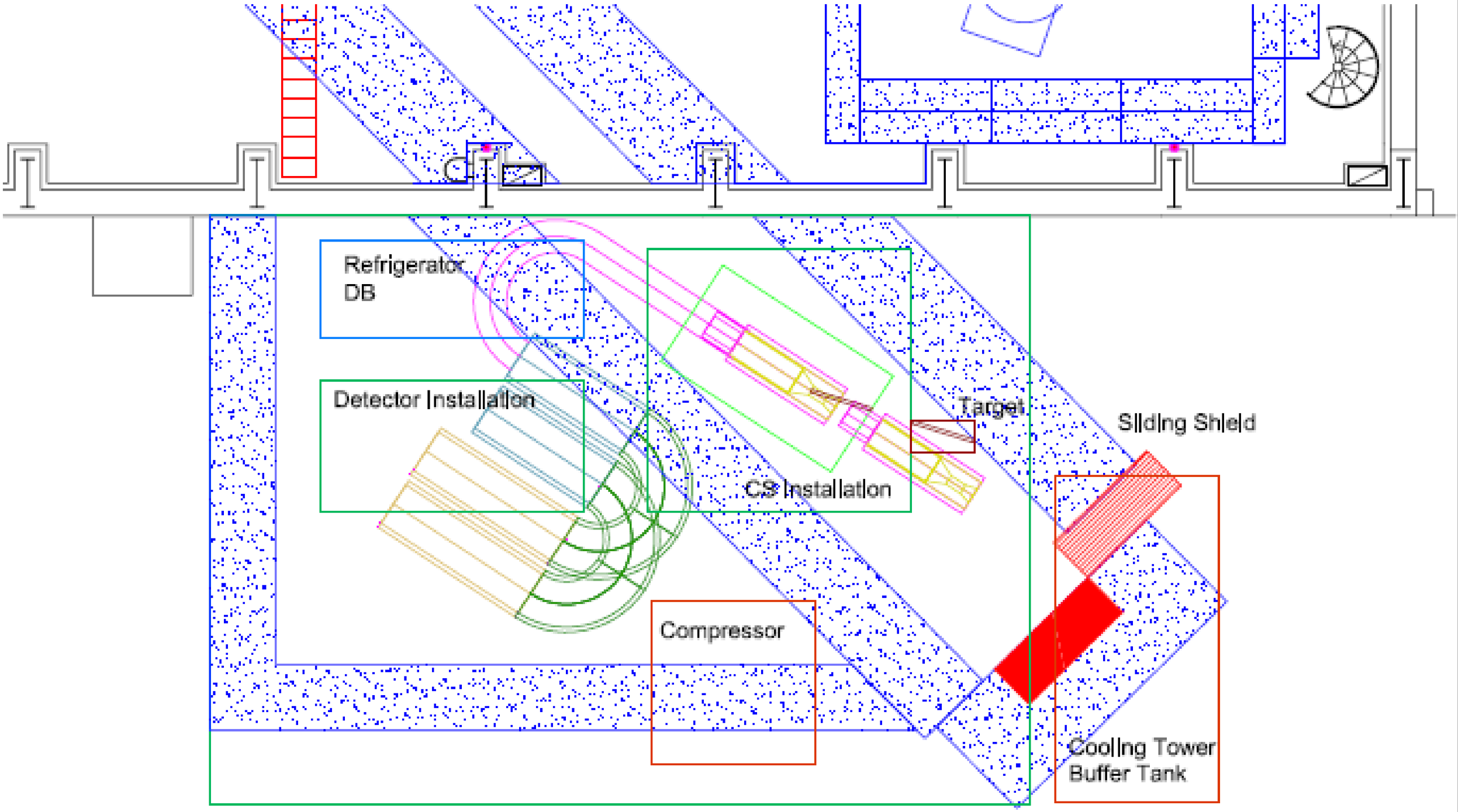
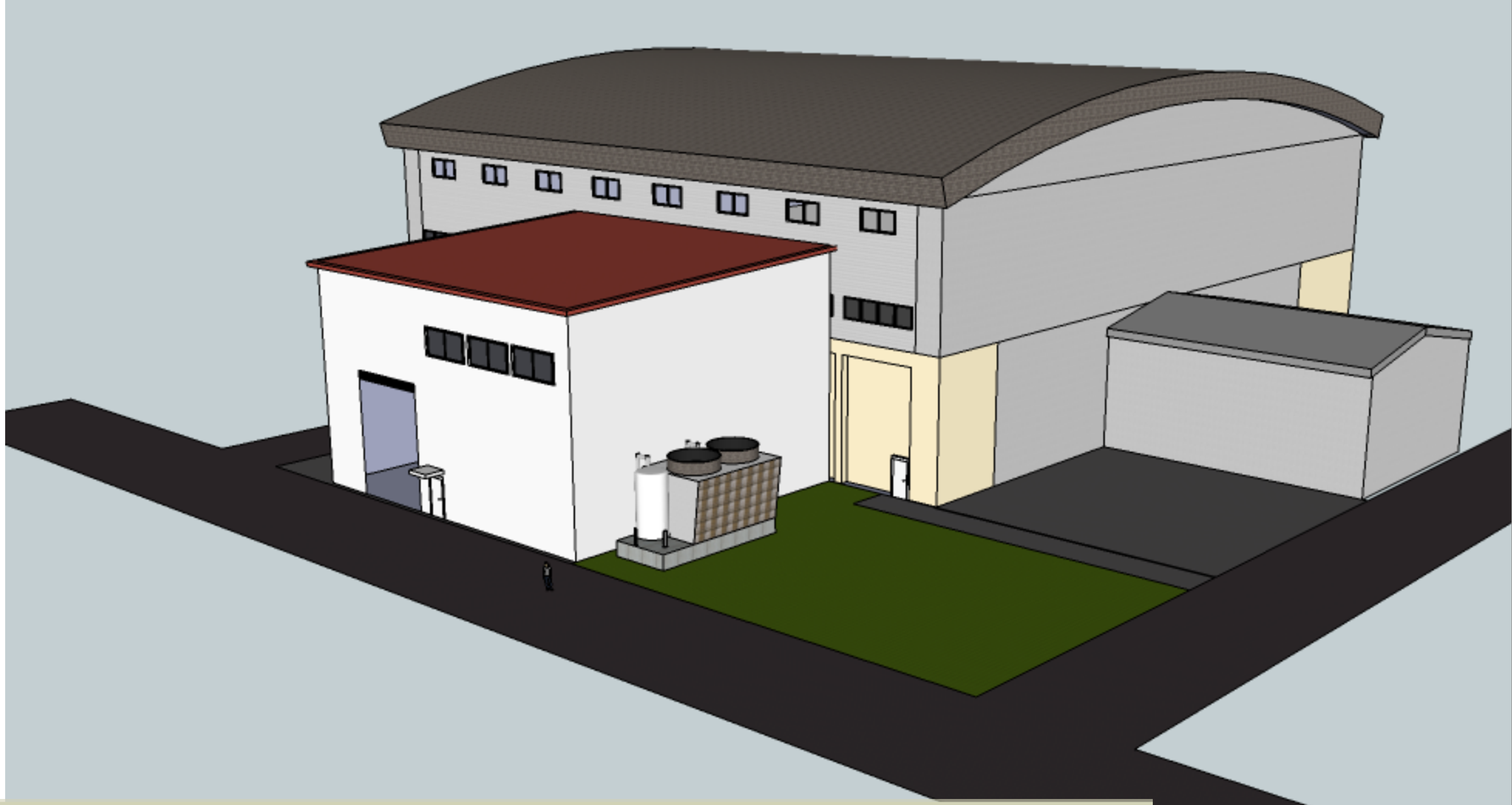
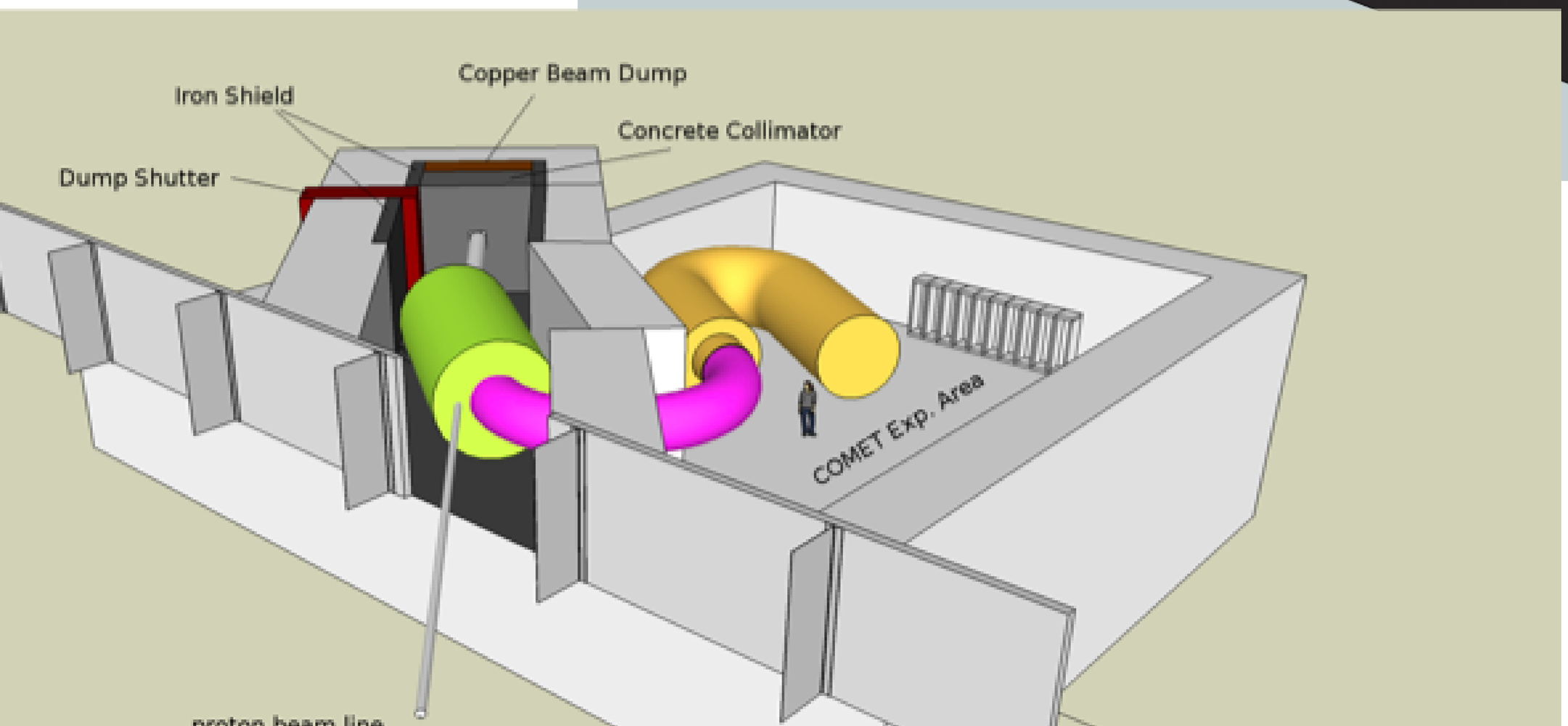
Further recent participation by institutes from China and India

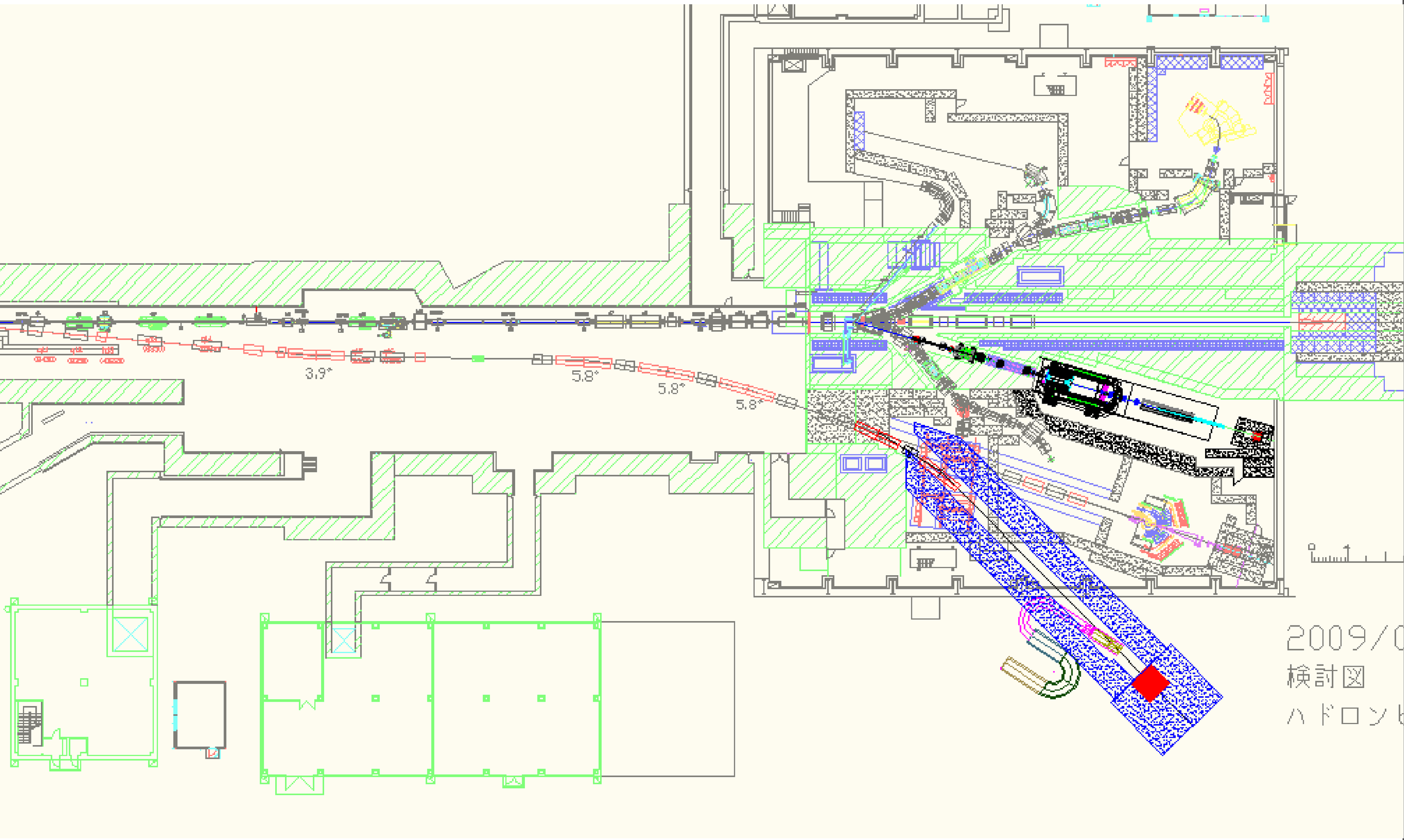

Refrigerator
DB
Detector Installation
CS Installation
Target
Sliding Shield
Compressor
Cooling Tower
Buffer Tank




Copper Beam Dump
Iron Shield
Concrete Collimator
Dump Shutter
COMET Exp. Area
proton beam line

Staging Plan

- Construction start in April 2013
  - as KEK facility construction (experimental hall, proton beamline + upstream parts of COMET)
  - about 1/3 of COMET (in cost terms)
- 5-year plan
- Data-taking in 2017 (COMET Phase-I)
  - first 90 degrees of the muon transport curved solenoid
  - rich programme of study
    - particle production and transport and secondary particle production, optics and field tuning, neutron production etc
    - lepton flavour violating processes
- A fast reliable path towards Phase-II (full experiment)
- Plan being presented to J-PARC PAC 14 January 2012


3.9°
5.8°
5.8°
5.8°
2009/0
検討図
ハドロン

UK / US Synergies

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[illegible]
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Tbilisi State University
M. Nioradze,
Ni. Tsverava
Y. Tevxadze

The COMET / PRISM Programme

Proceedings of IPAC'10, Kyoto, Japan WEPE056

ACCELERATOR AND PARTICLE PHYSICS RESEARCH FOR THE NEXT GENERATION MUON TO ELECTRON CONVERSION EXPERIMENT - THE PRISM TASK FORCE

J. Pasternak, Imperial College London, UK/RAL STFC, UK
L. J. Jenner, A. Kurup, Imperial College London, UK/Fermilab, USA
Y. Uchida, Imperial College London, UK
B. Muratori, S. L. Smith, Cockcroft Institute, Warrington, UK/STFC-DL-ASTeC, Warrington, UK
K. M. Hock, Cockcroft Institute, Warrington, UK/University of Liverpool, UK
R. J. Barlow, Cockcroft Institute, Warrington, UK/University of Manchester, UK
C. Ohmori, KEK/JAEA, Ibaraki-ken, Japan
H. Witte, T. Yokoi, JAI, Oxford University , UK
J-B. Lagrange, Y. Mori, Kyoto University, KURRI, Osaka, Japan
Y. Kuno, A. Sato, Osaka University, Osaka, Japan
D. Kelliher, S. Machida, C. Prior, STFC-RAL-ASTeC, Harwell, UK
M. Lancaster, UCL, London, UK

UK / US Synergies

- COMET/PRISM programme & Mu2E programme
  - see talks by J. Pasternak, and E. Prebys and V. Lebedev
- Pursuing physics at the 10^{-16}, 10^{-18} level using novel methods (in terms of implementation)
  - highly non-trivial measurements (not turn-on-and-wait!)
- Complimentary near-term programmes
  - highly valuable to have multiple independent efforts
  - allows both groups to find solutions and gain expertise
- Longer-term programme involves further advances in accelerator technologies
  - cooperation in R&D and design studies
  - aided by experience from the near-term programme
  - technologies applicable to other muon-related activities

Conclusions

- COMET to probe muon-to-electron conversion at the 10^{-16} level
- Staged construction: data-taking for Phase-I physics by 2017
  - detailed particle flux studies for Phase-II
  - lepton flavour violation physics
- Strong synergies with US programme
  - long-term muon-to-electron conversion physics
    - PRISM, Project-X
  - intense muon beam technologies
    - targetry, pion capture solenoids, muon transport channels etc