Search for Charged Lepton Flavor Violation with Muons at J-PARC

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Department of Physics
Osaka University

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Groningen

Outline

- Why Charged Lepton Flavor Violation (CLFV)?
- COMET@J-PARC
- MuSIC@Osaka University
- COMET Phase-I@J-PARC
- Summary

Why Charged Lepton Flavor Violation (CLFV)?

What is Charged Lepton Flavor Violation (CLFV) ?

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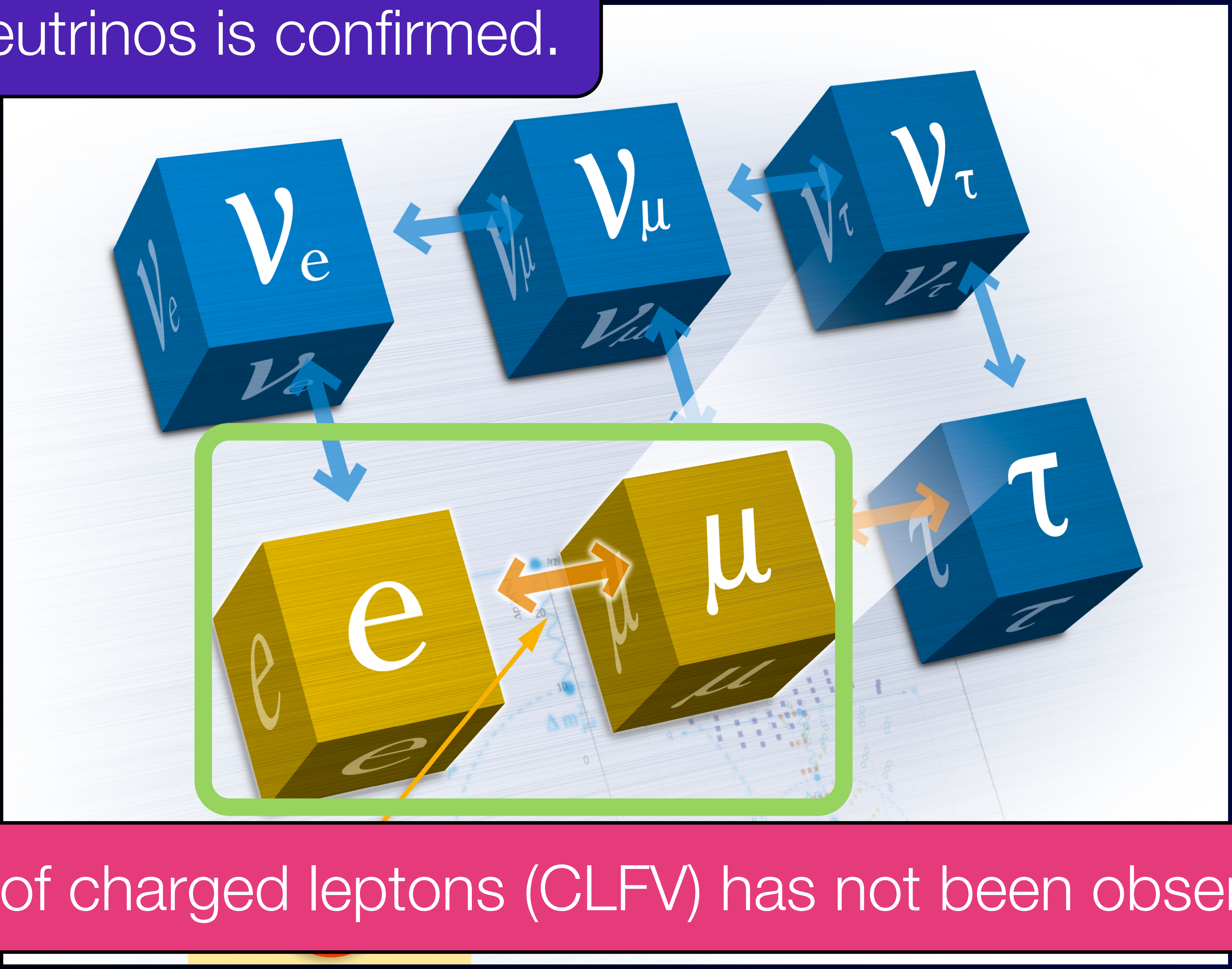
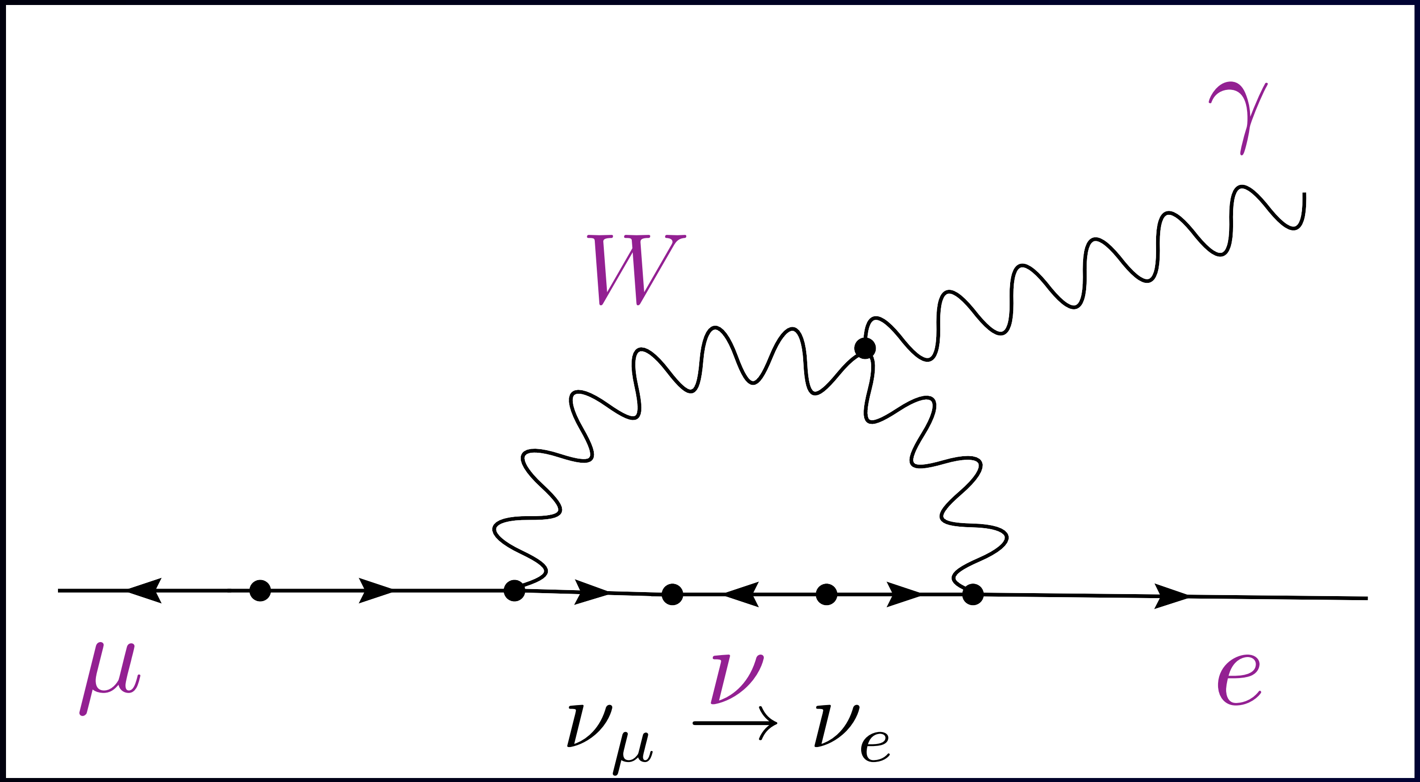
LFV of neutrinos is confirmed.



LFV of charged leptons (CLFV) has not been observed.

CLFV in the SM with Massive Neutrinos

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$



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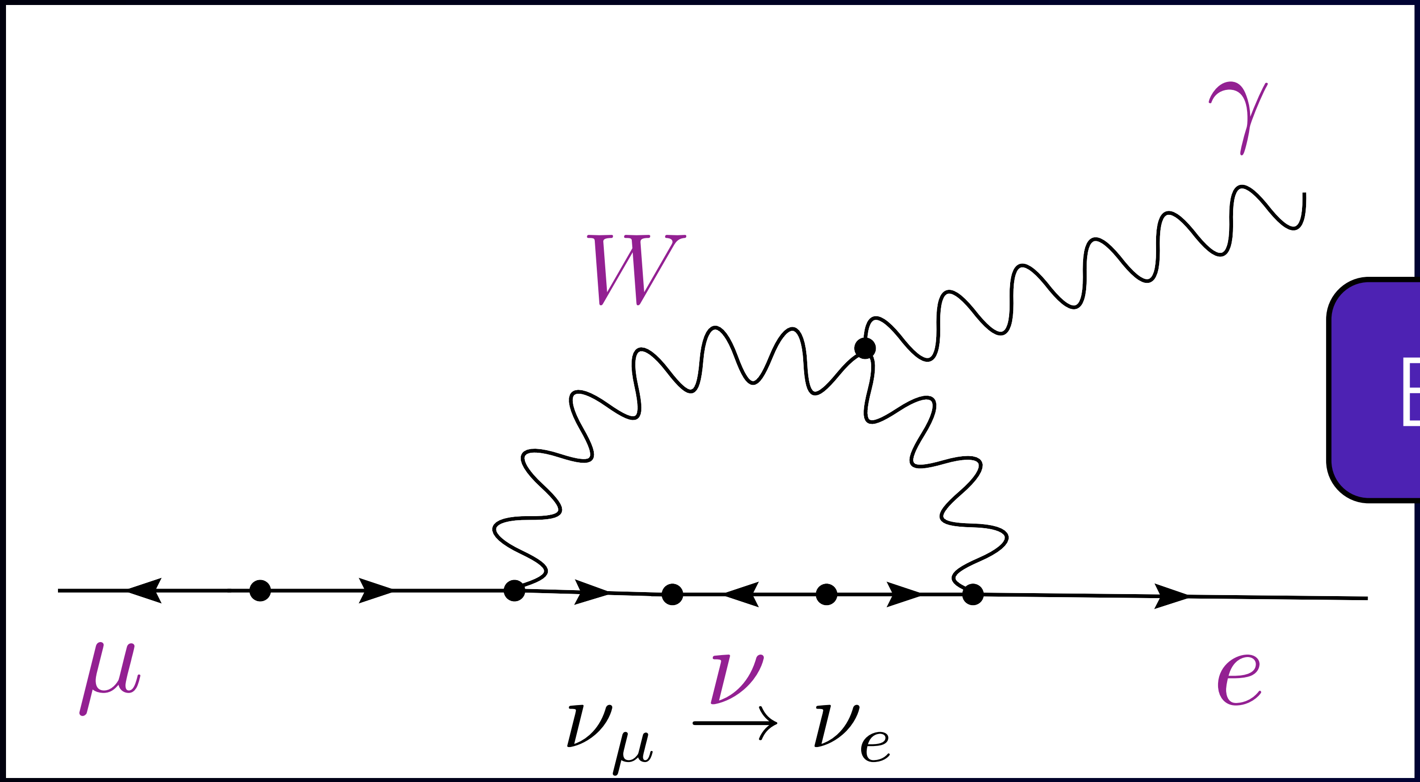

BR~O(10^{-54})

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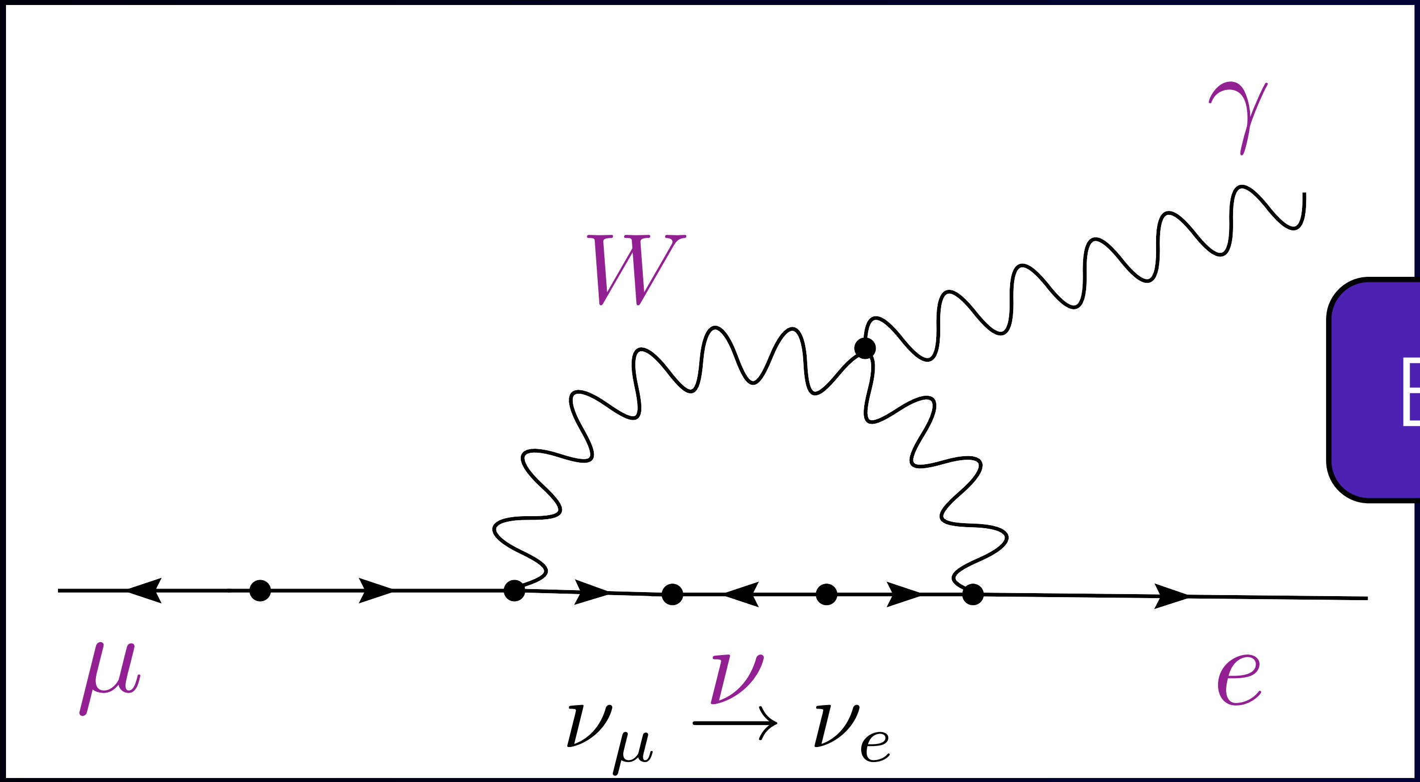

BR~O(10^{-54})

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

Sensitivity to High Energy Scale Physics
Exercise (1) : Tree Level

A. de Gouvea's effective interaction

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

Λ: energy scale of new physics

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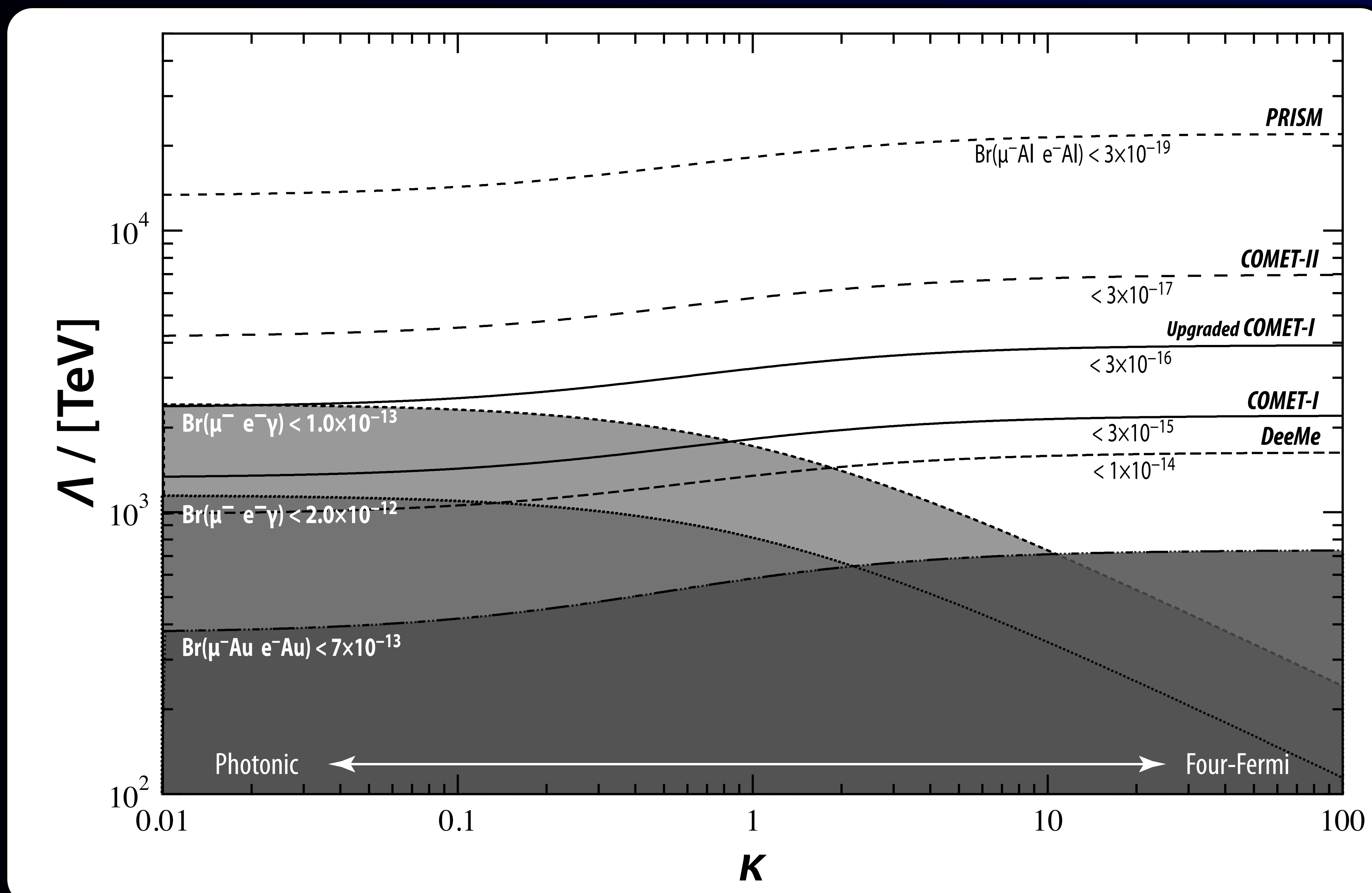

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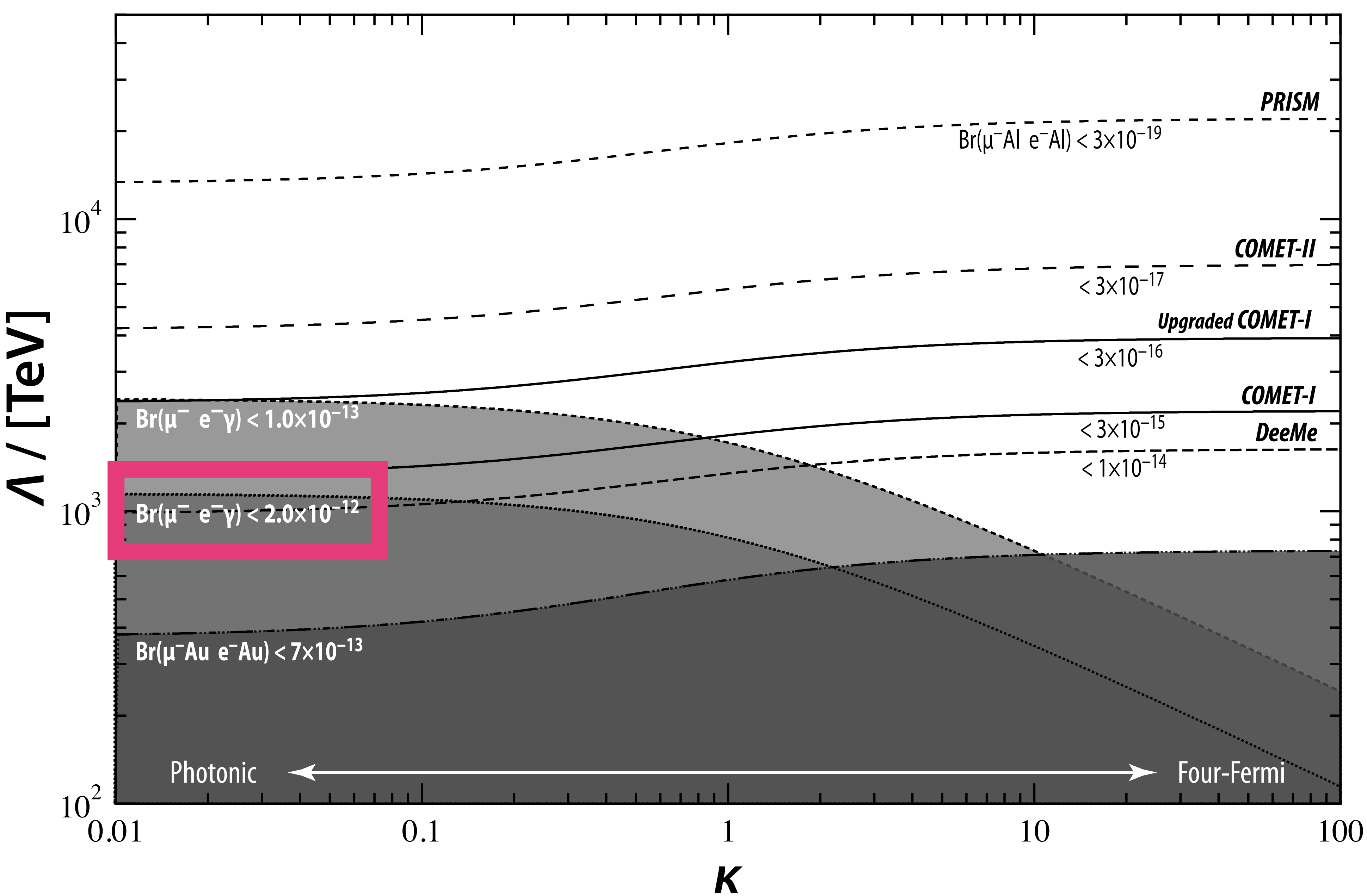
$O(10^3)$TeV



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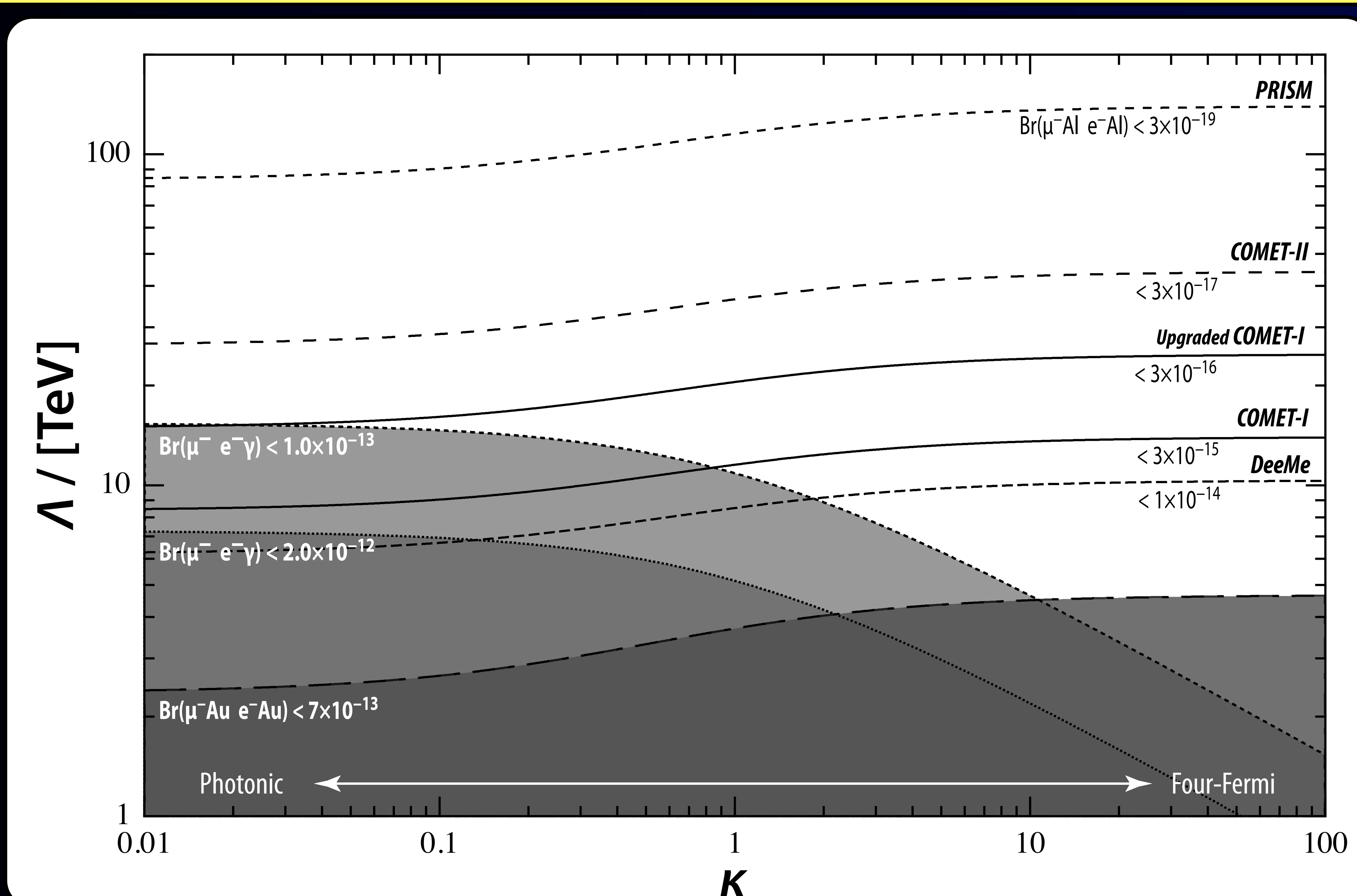

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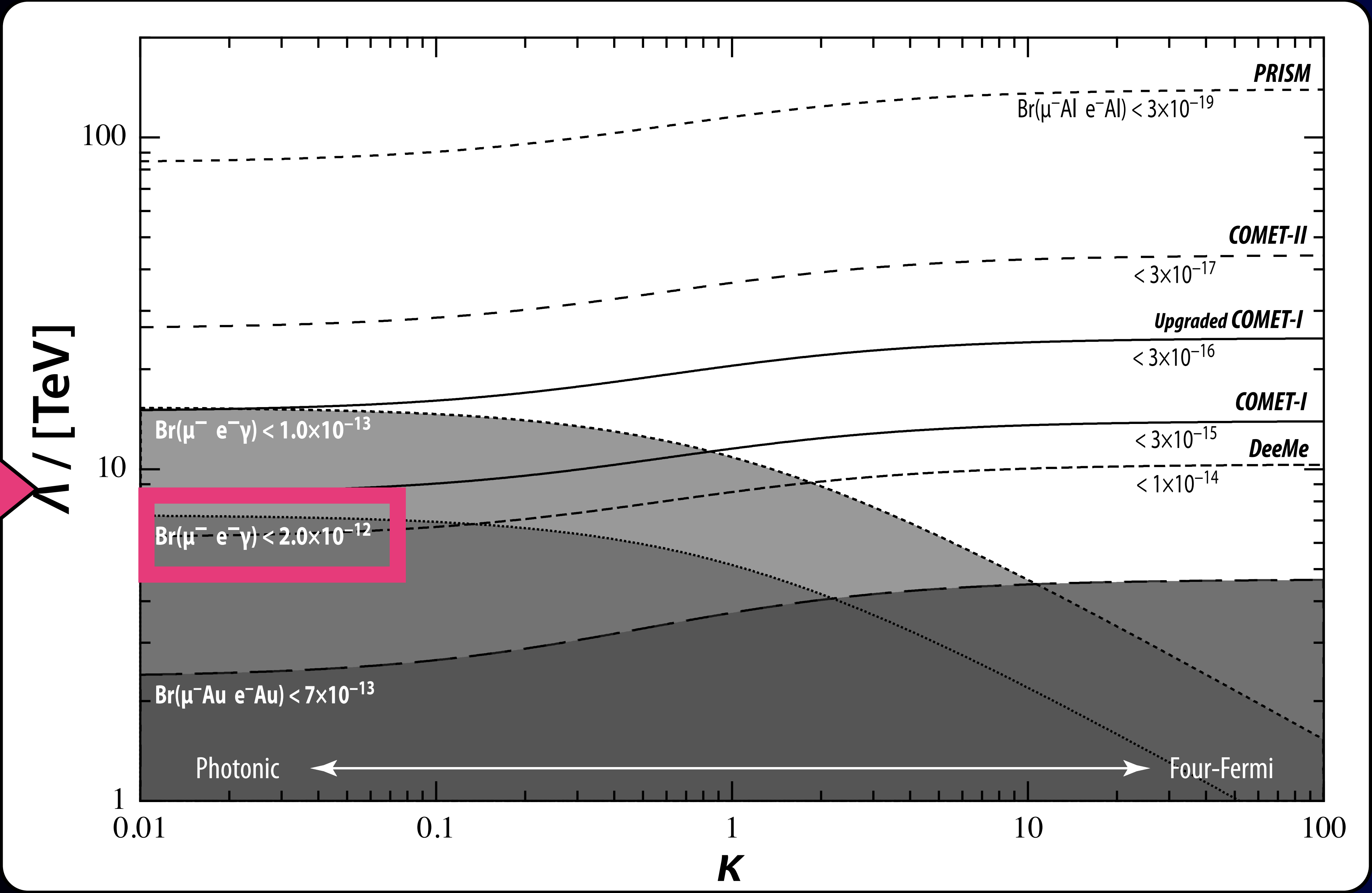

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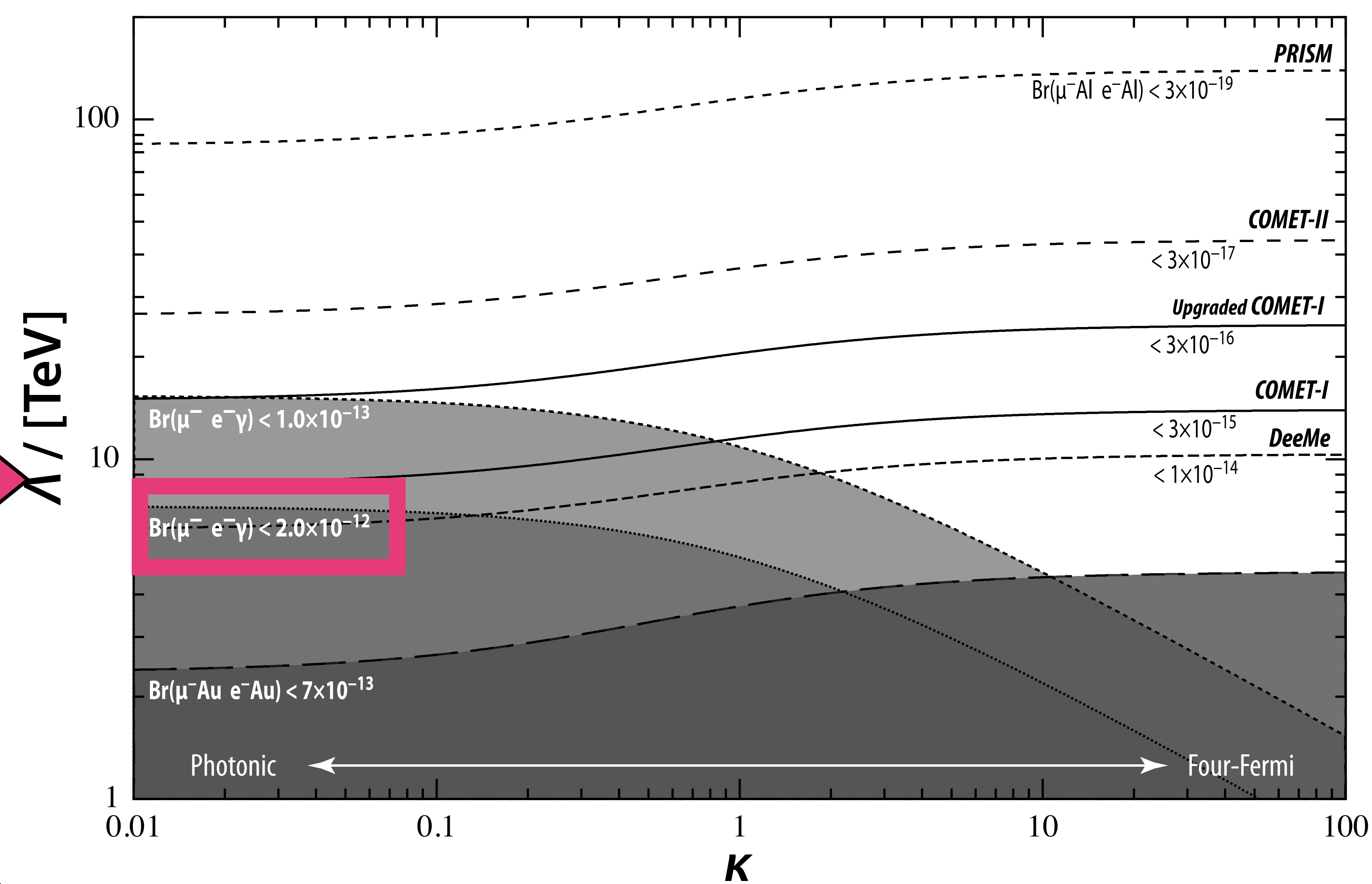
O(1)TeV

Flavor mixing couplings gives additional reduction on the Λ reach.



Sensitivity to High Energy Scale Physics
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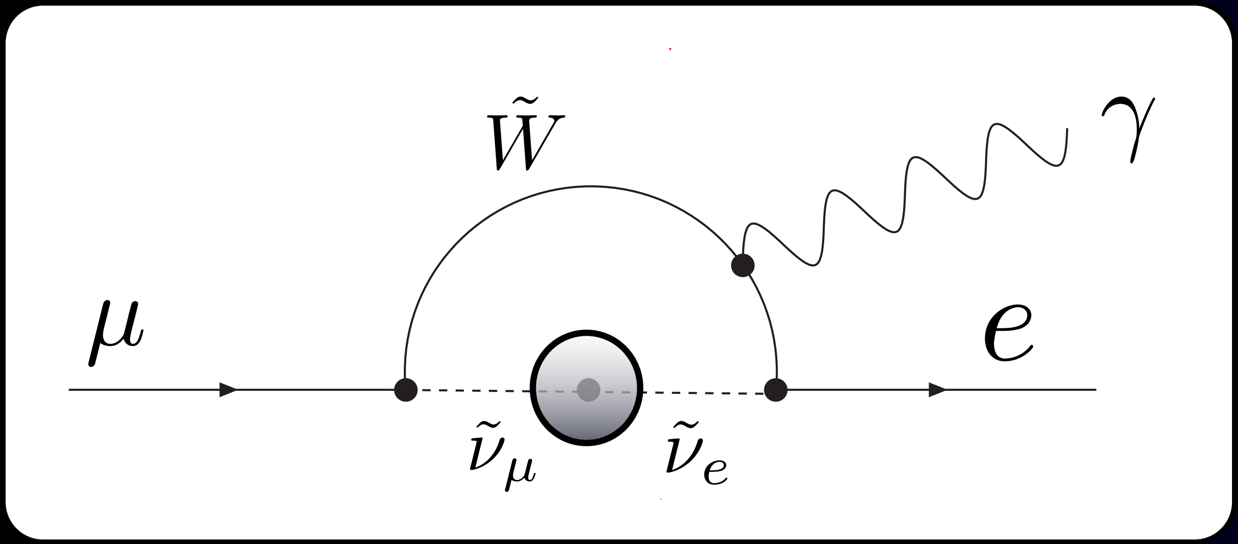
- For loop diagrams,

$$\mathrm{BR}(\mu \to e\gamma) = 1 \times 10^{-11} \times \left(\frac{2\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2$$

$$y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing



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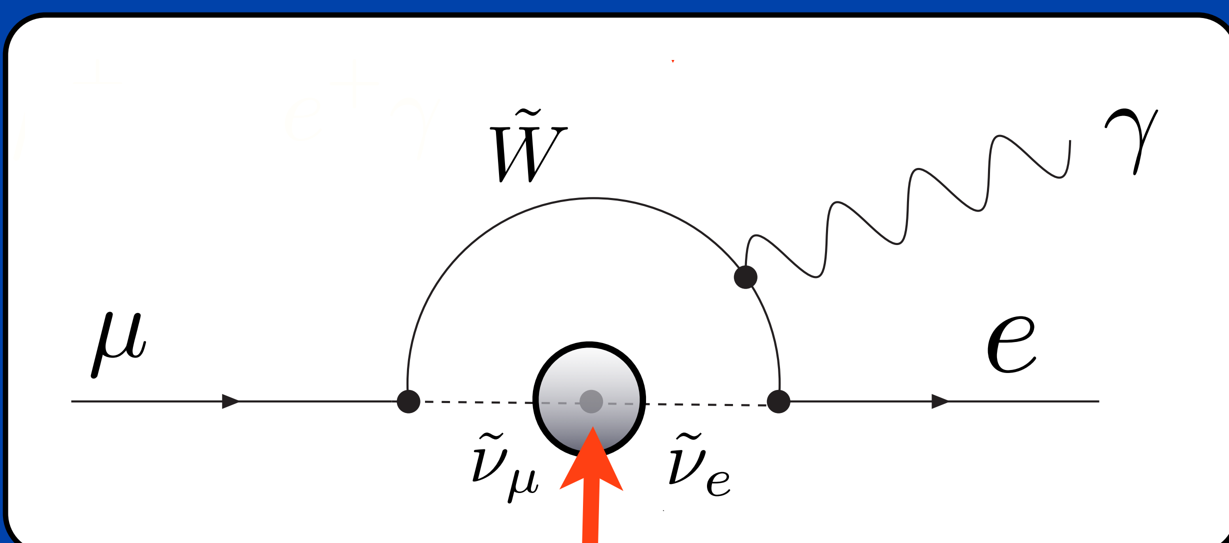
example diagram for SUSY (~TeV)



Physics at about 10^{16} GeV

slepton mixing (from RGE)

SUSY-GUT model:

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$$

SUSY neutrino seesaw model:

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \frac{M_{GUT}}{M_{R_s}}$$

Scales of Electroweak Symmetry Breaking, and Neutrino Mass Generation, and CLFV

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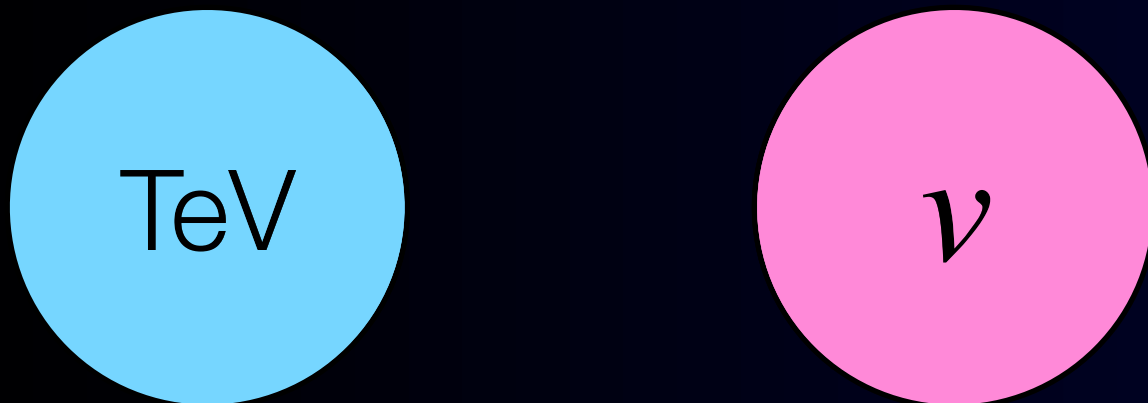
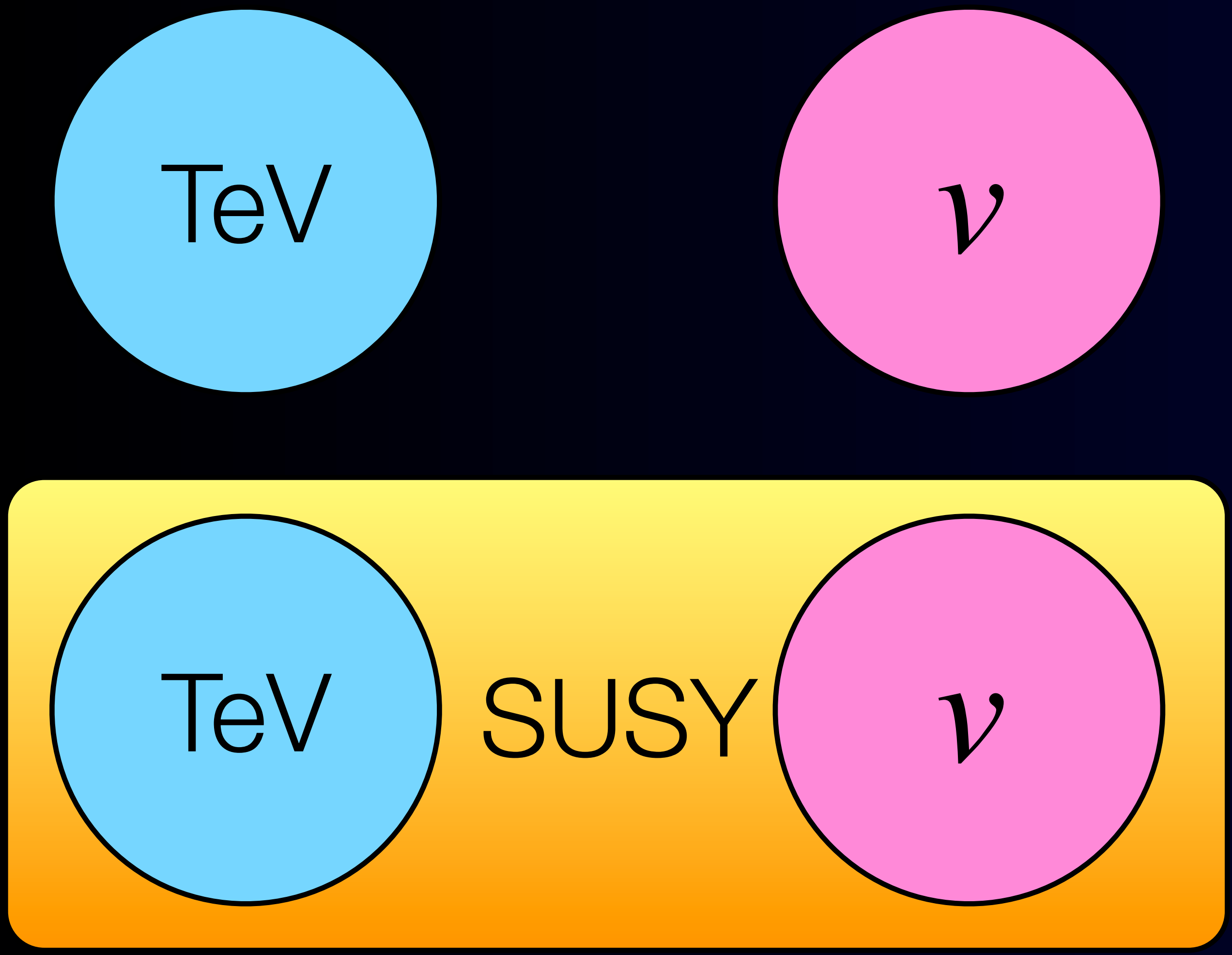


if the two scales are well separated, CLFV is small. ~O(10^{-54})

Scales of Electroweak Symmetry Breaking, and Neutrino Mass Generation, and CLFV



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In supersymmetric models, even if the two scales are well separated, large CLFV is expected.

Scales of Electroweak Symmetry Breaking, and Neutrino Mass Generation, and CLFV

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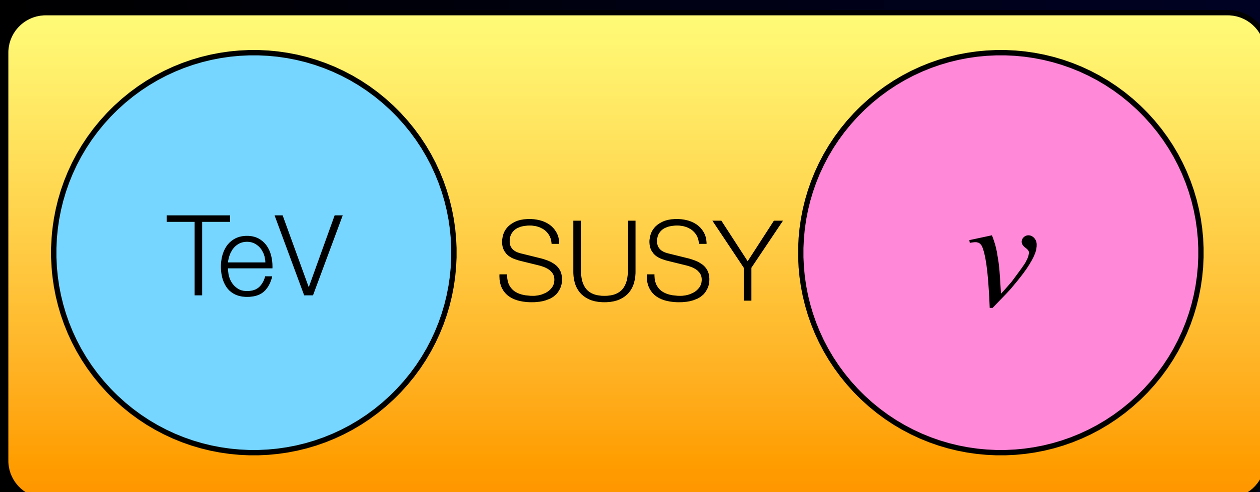

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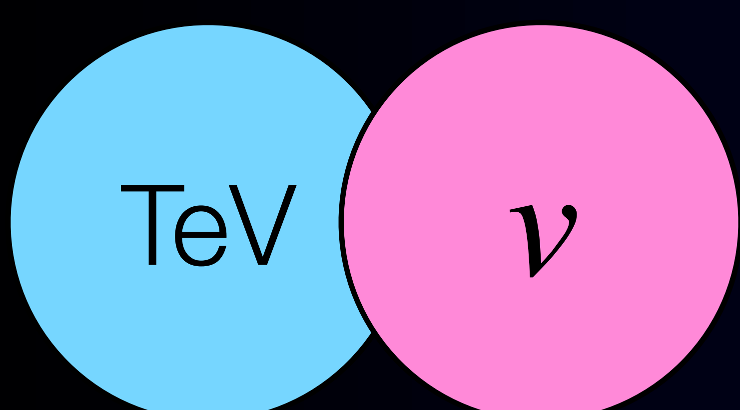
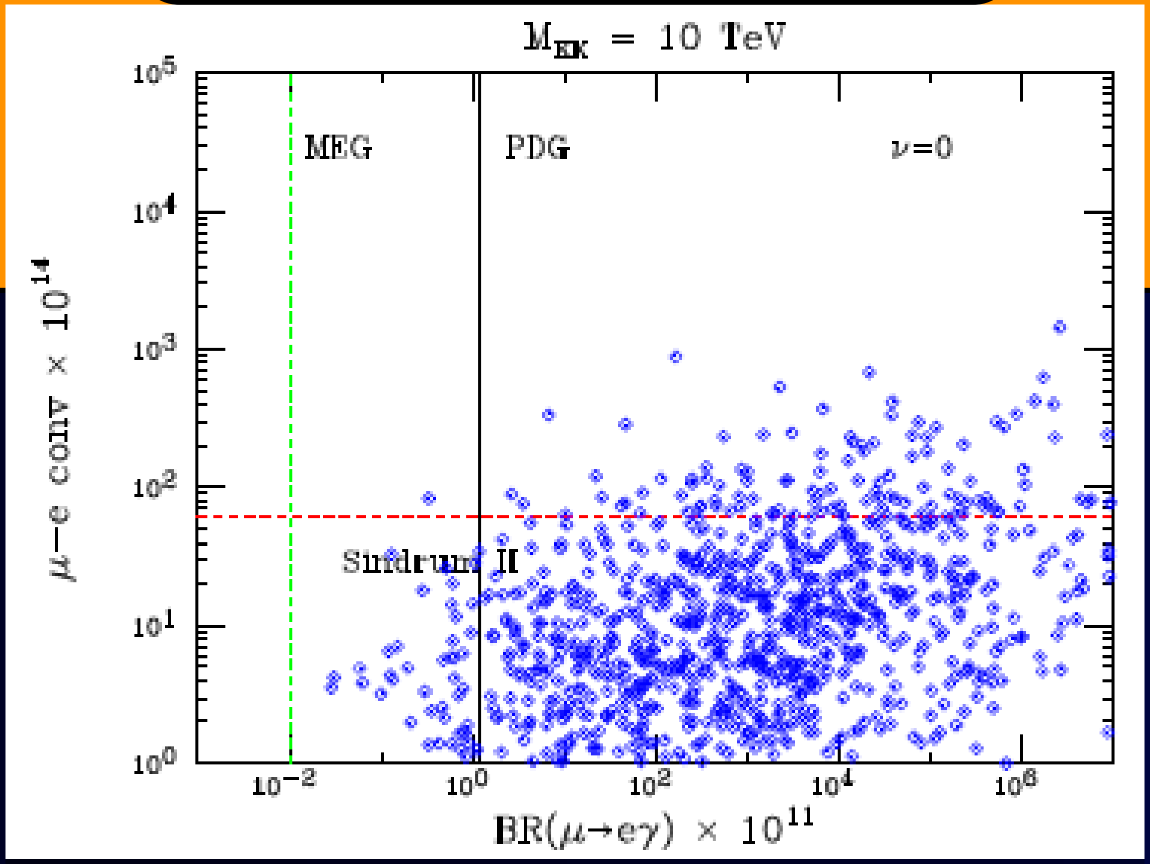


Even without supersymmetric models, the two scales are close, large CLFV is expected.

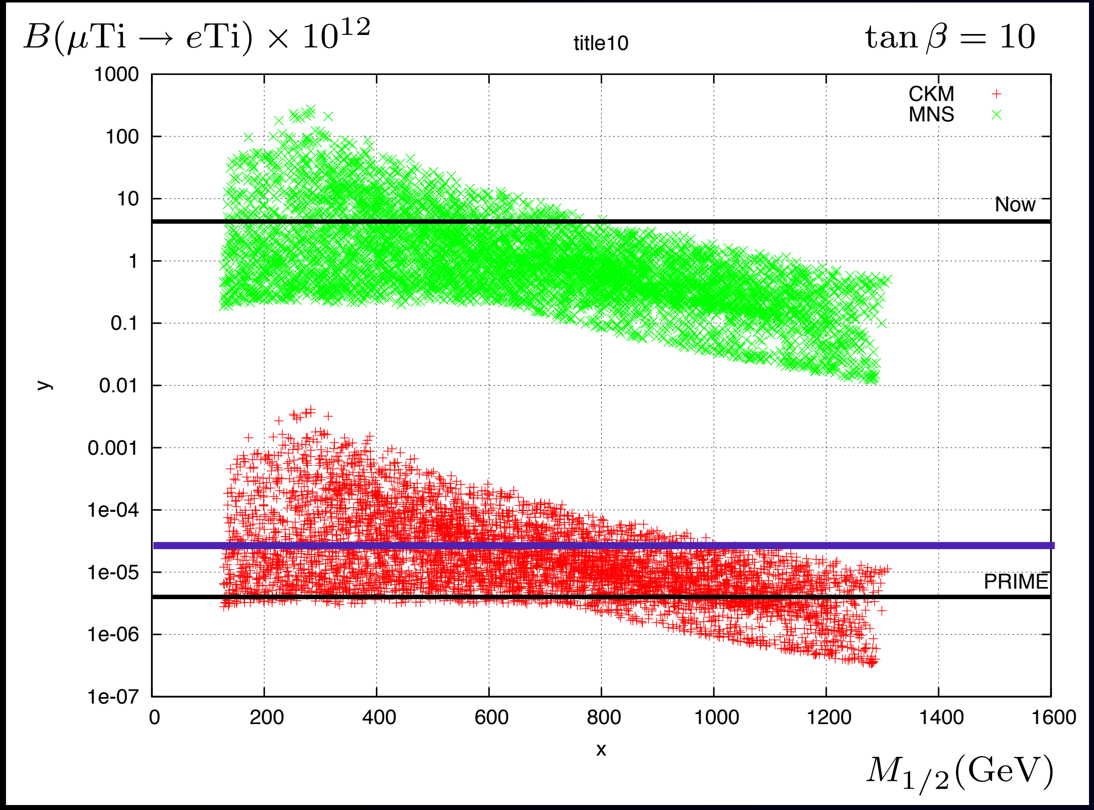
CLFV Predictions

Various BSM models predict sizable CLFV.

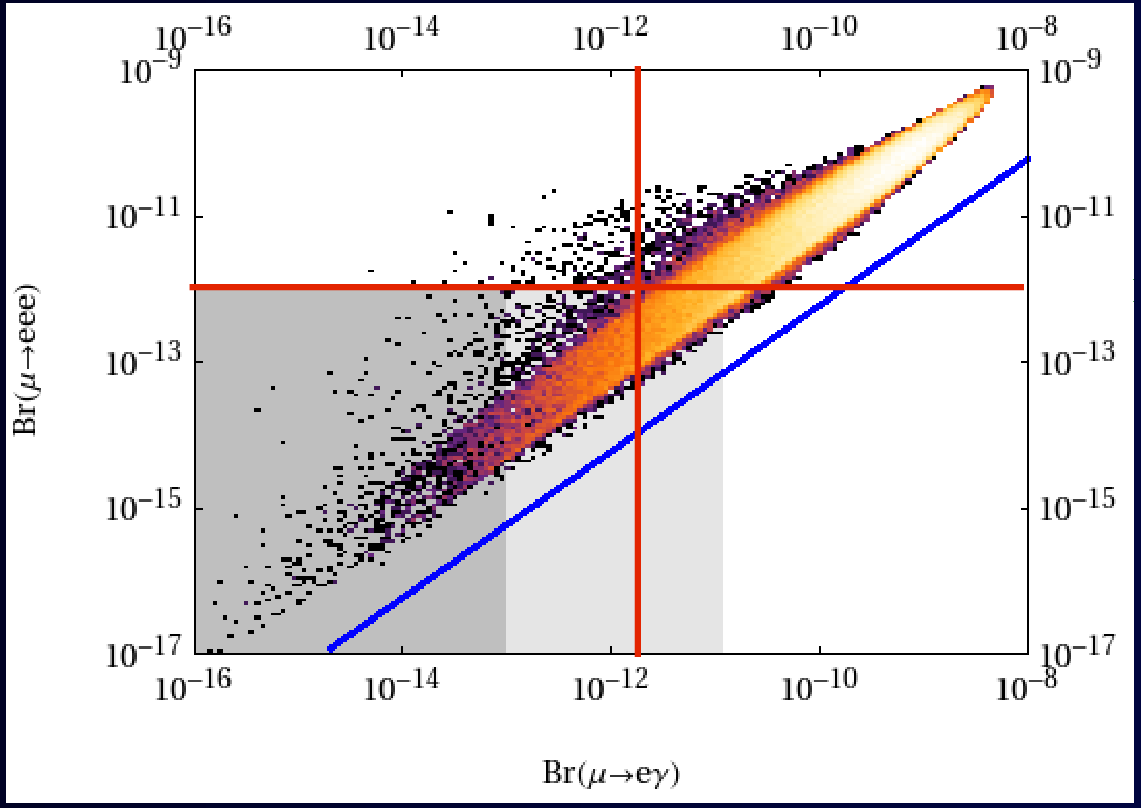
extra dimension model



SUSY model



little Higgs model



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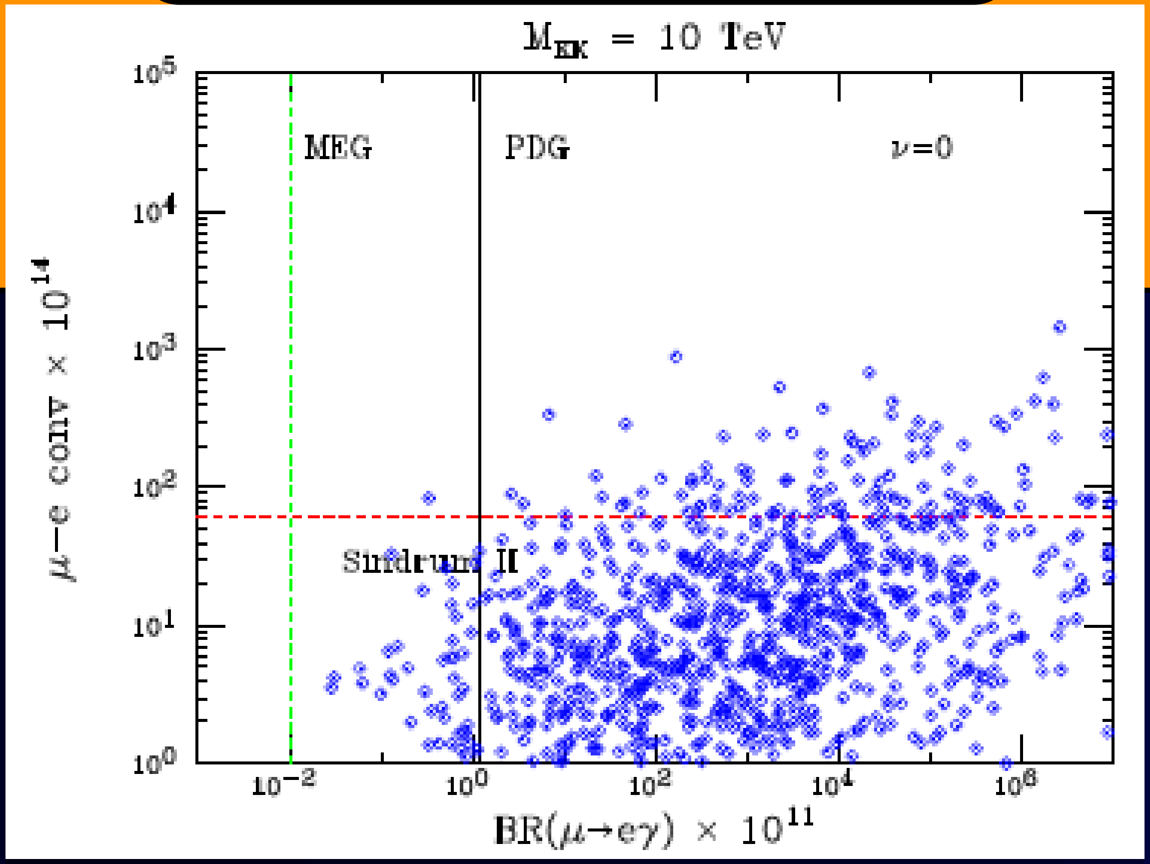

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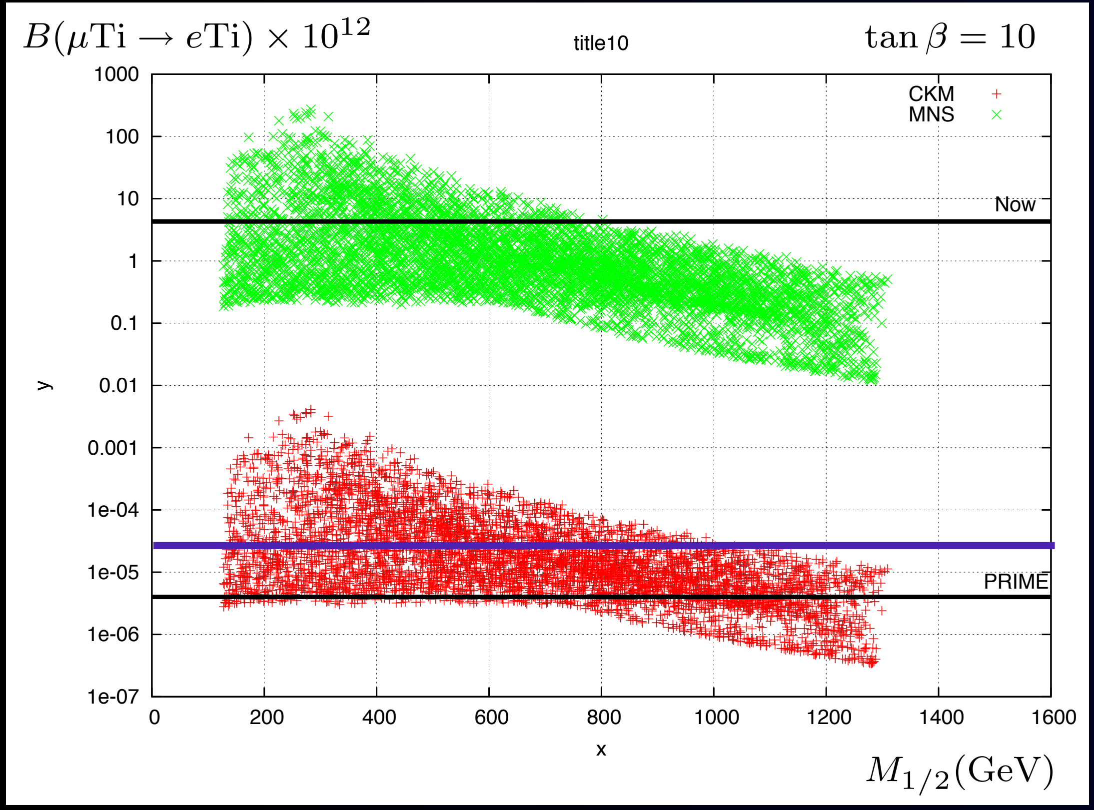
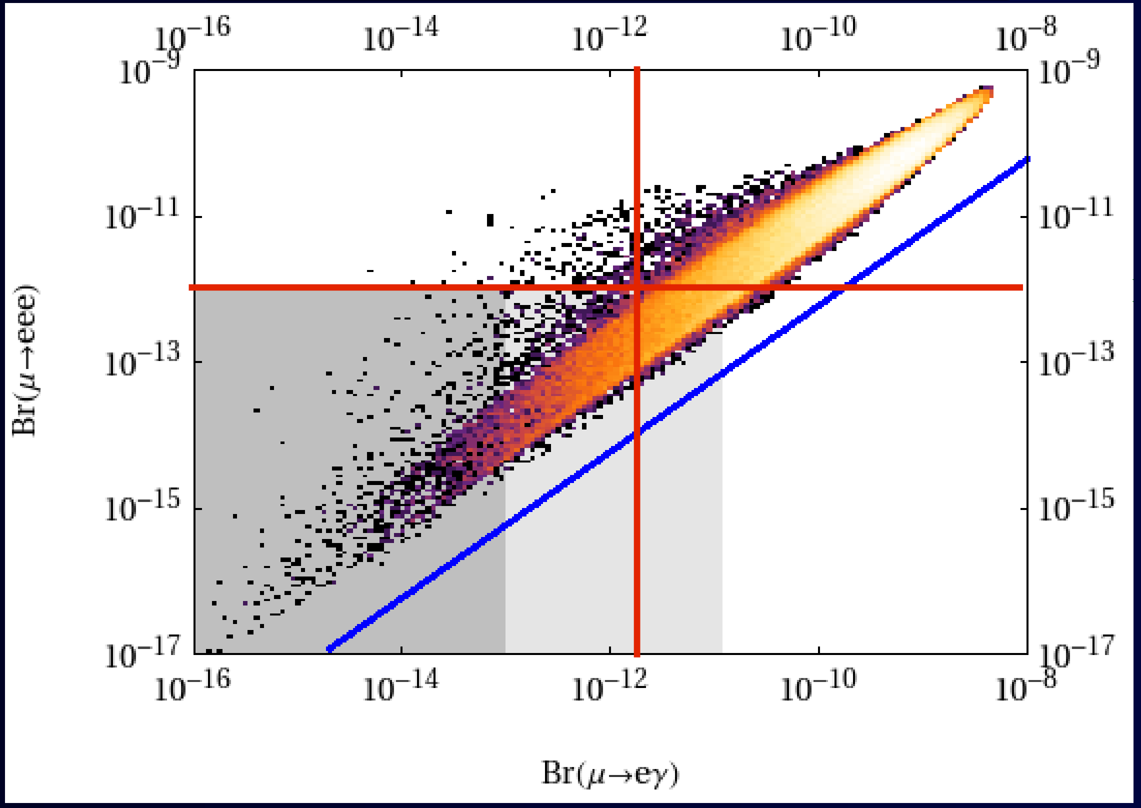


↓ 10^4

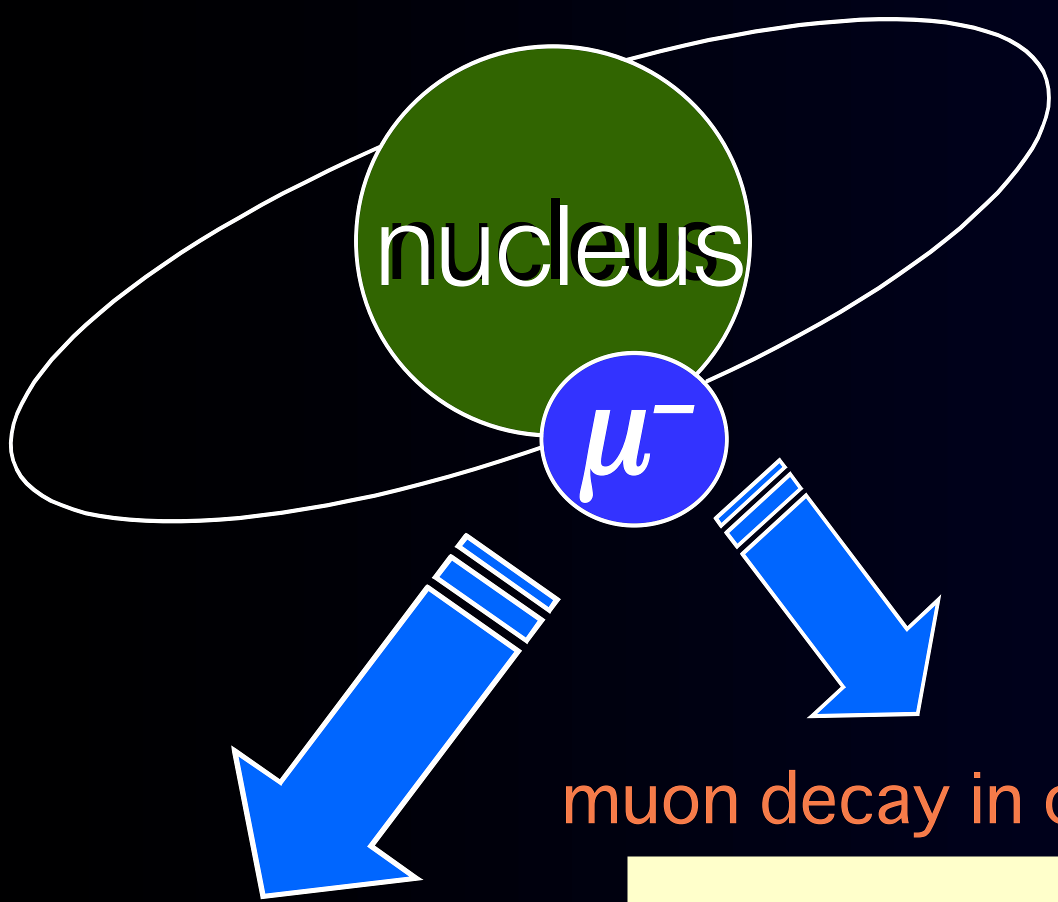
little Higgs model



μ-e Conversion in a Muonic Atom

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture

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

Event Signature :

a single mono-energetic electron of 100 MeV

Backgrounds:

(1) physics backgrounds
 ex. muon decay in orbit (DIO)

(2) beam-related backgrounds
 ex. radiative pion capture,
 muon decay in flight,

(3) cosmic rays, false tracking

Physics Sensitivity: μ→eγ vs. μ-e conversion

constructive

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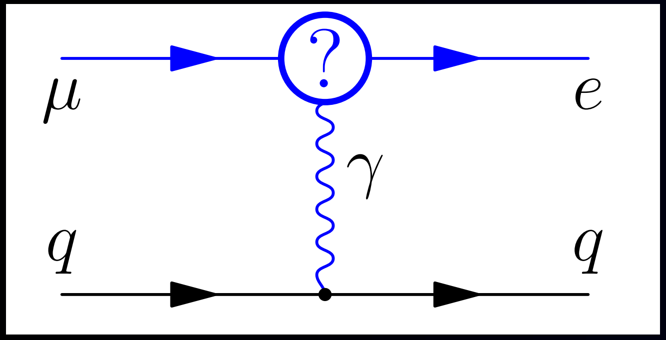
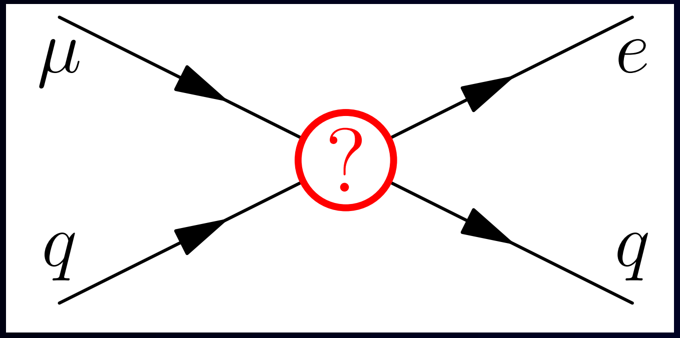
Photonic (dipole) interaction



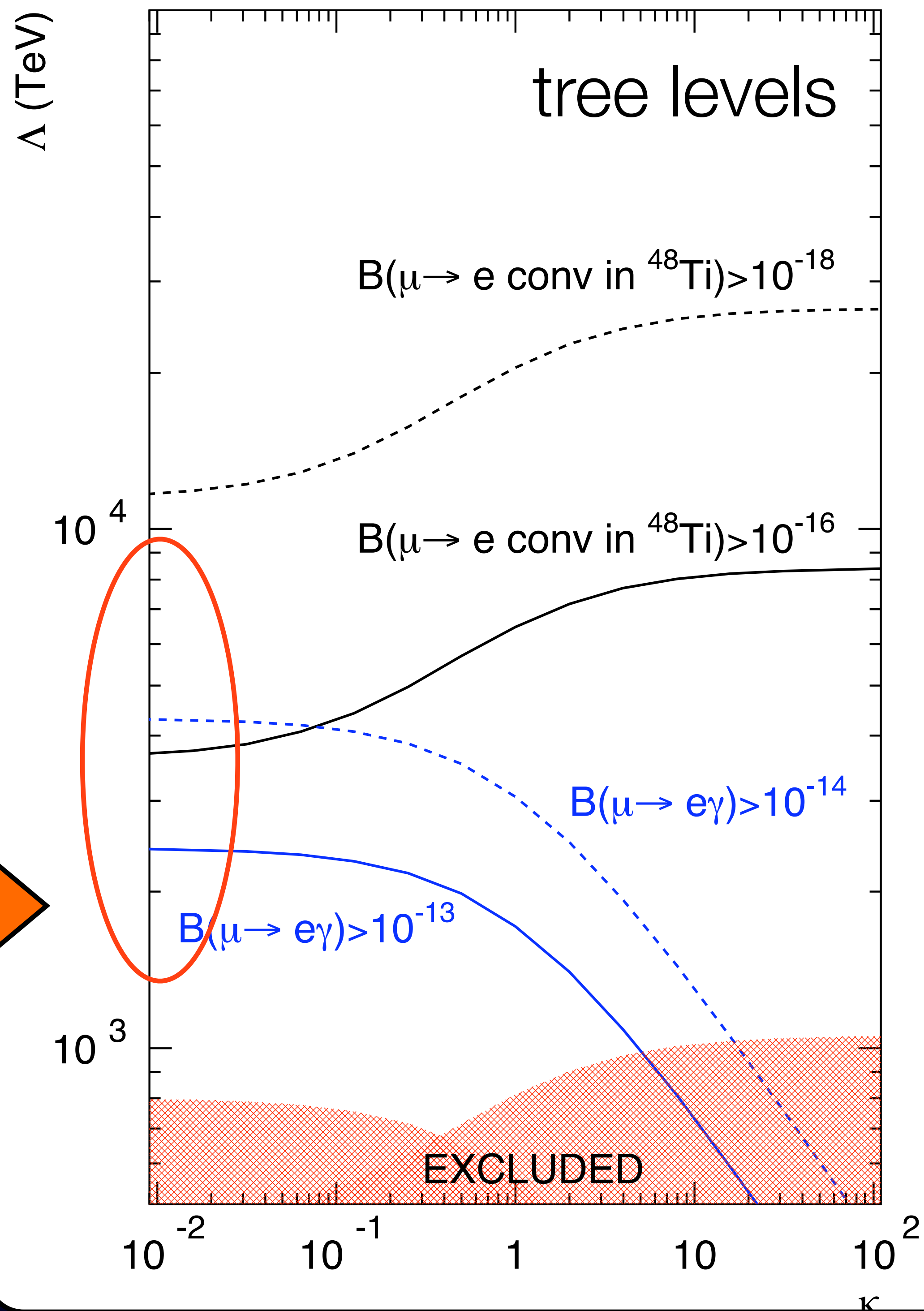
Contact interaction



if photonic contribution dominates,

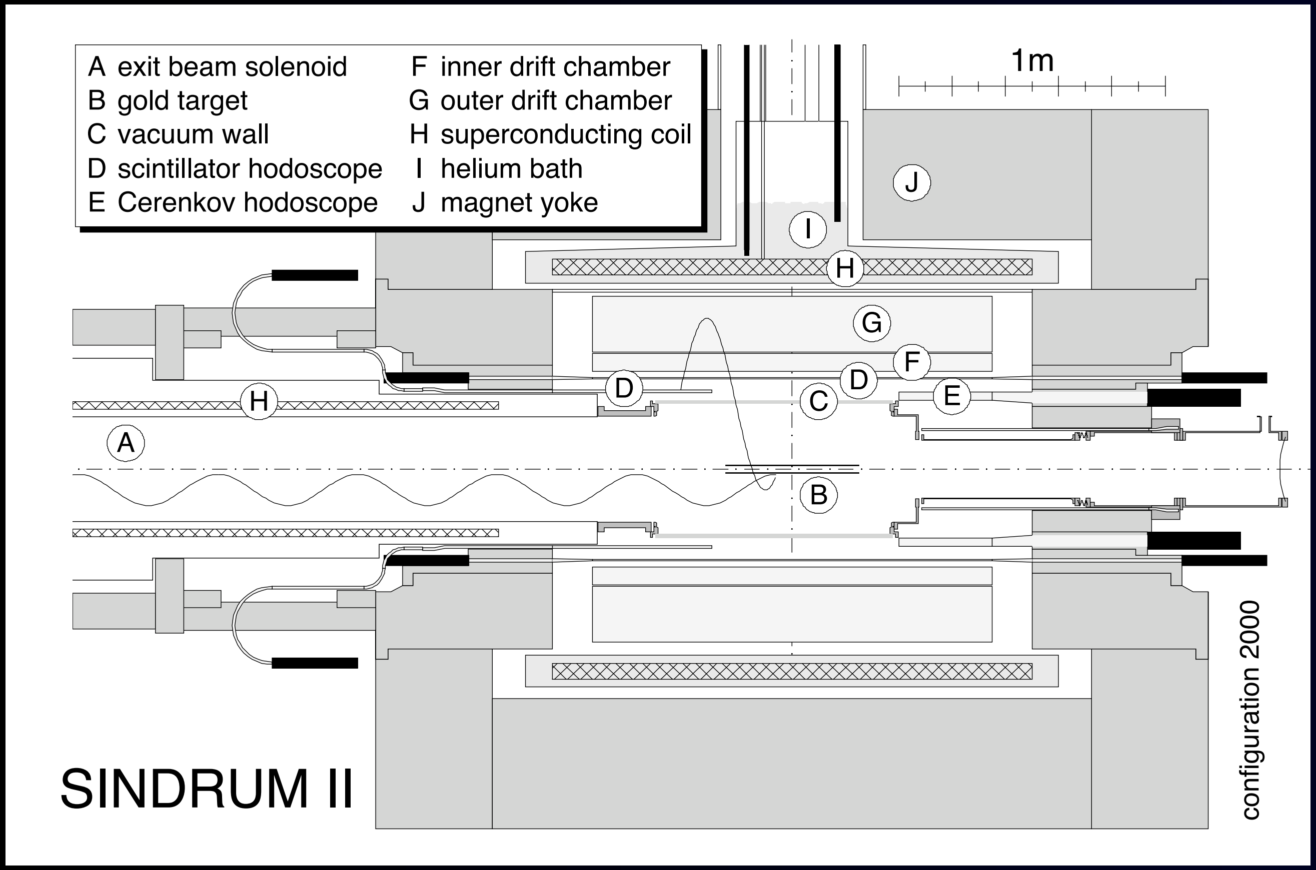
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z) \sim \frac{B(A,Z)}{428}$$

- for aluminum, about 1/390~0.003
- for titanium, about 1/230



Previous Measurements

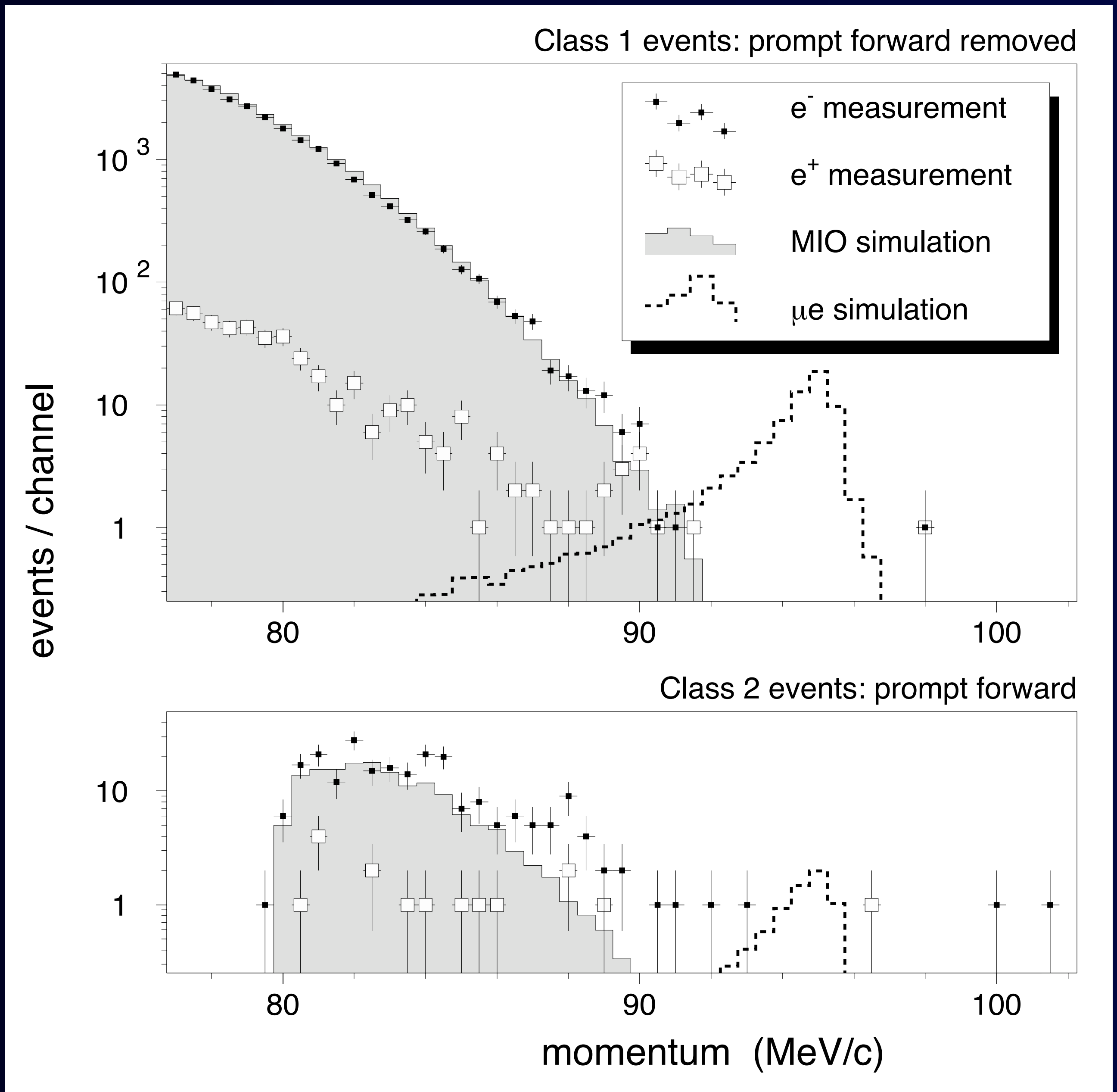
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

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



Improvements for Signal Sensitivity

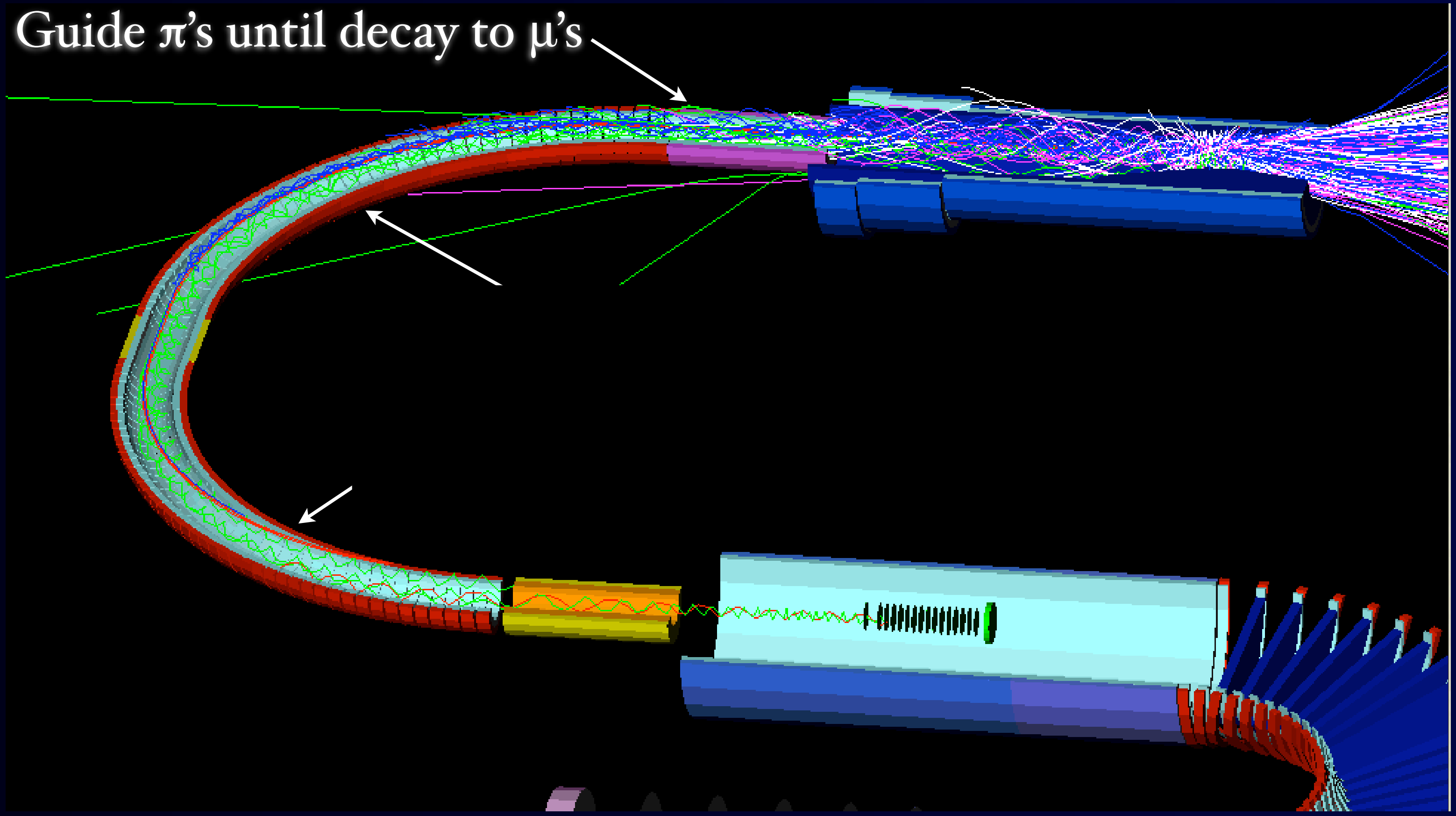
To achieve a single sensitivity of 10^{-17}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10^{11} muons for 50 kW beam power)



Improvements for Background Rejection

Beam-related backgrounds → Beam pulsing with separation of 1μsec — measured between beam pulses

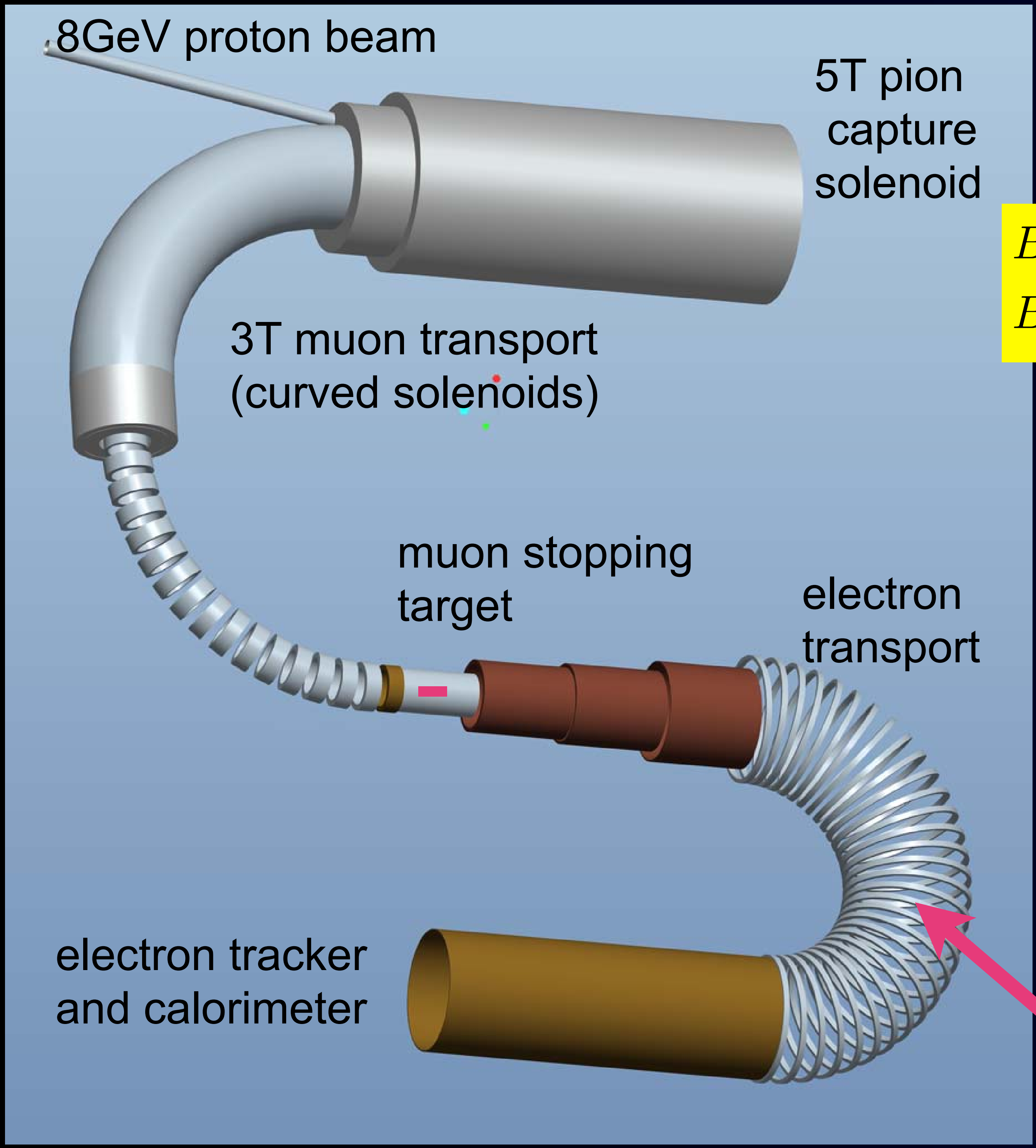
proton extinction = #protons between pulses/#protons in a pulse < 10^{-9}

Muon DIO background → low-mass trackers in vacuum & thin target — improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

μ-e conversion : COMET (E21) at J-PARC



Experimental Goal of COMET

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

COMET Collaboration

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University Technology Malaysia

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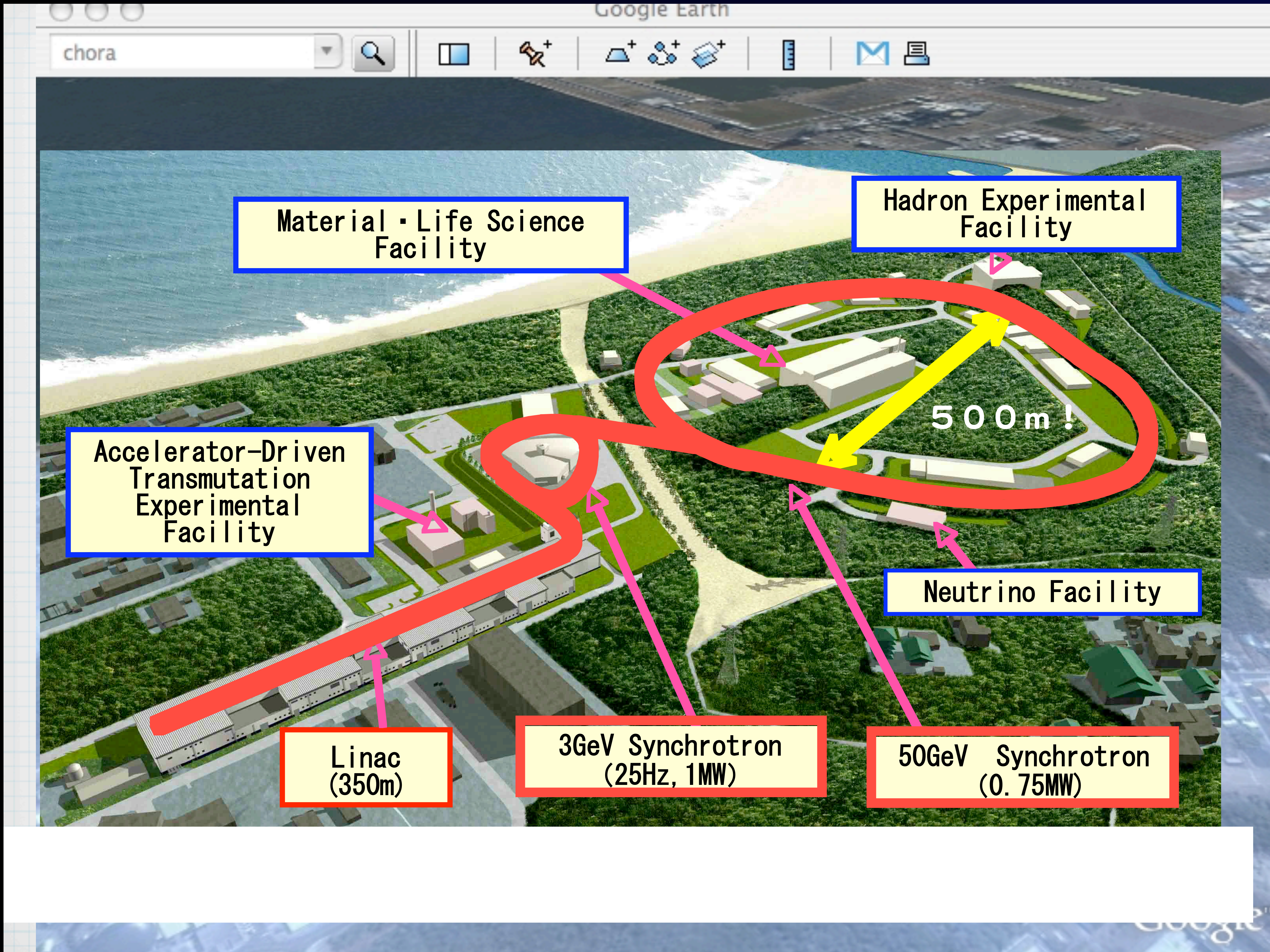
TRIUMF, Canada

- 107 collaborators
- 25 institutes
- 11 countries

Proton Beam

J-PARC at Tokai, Japan

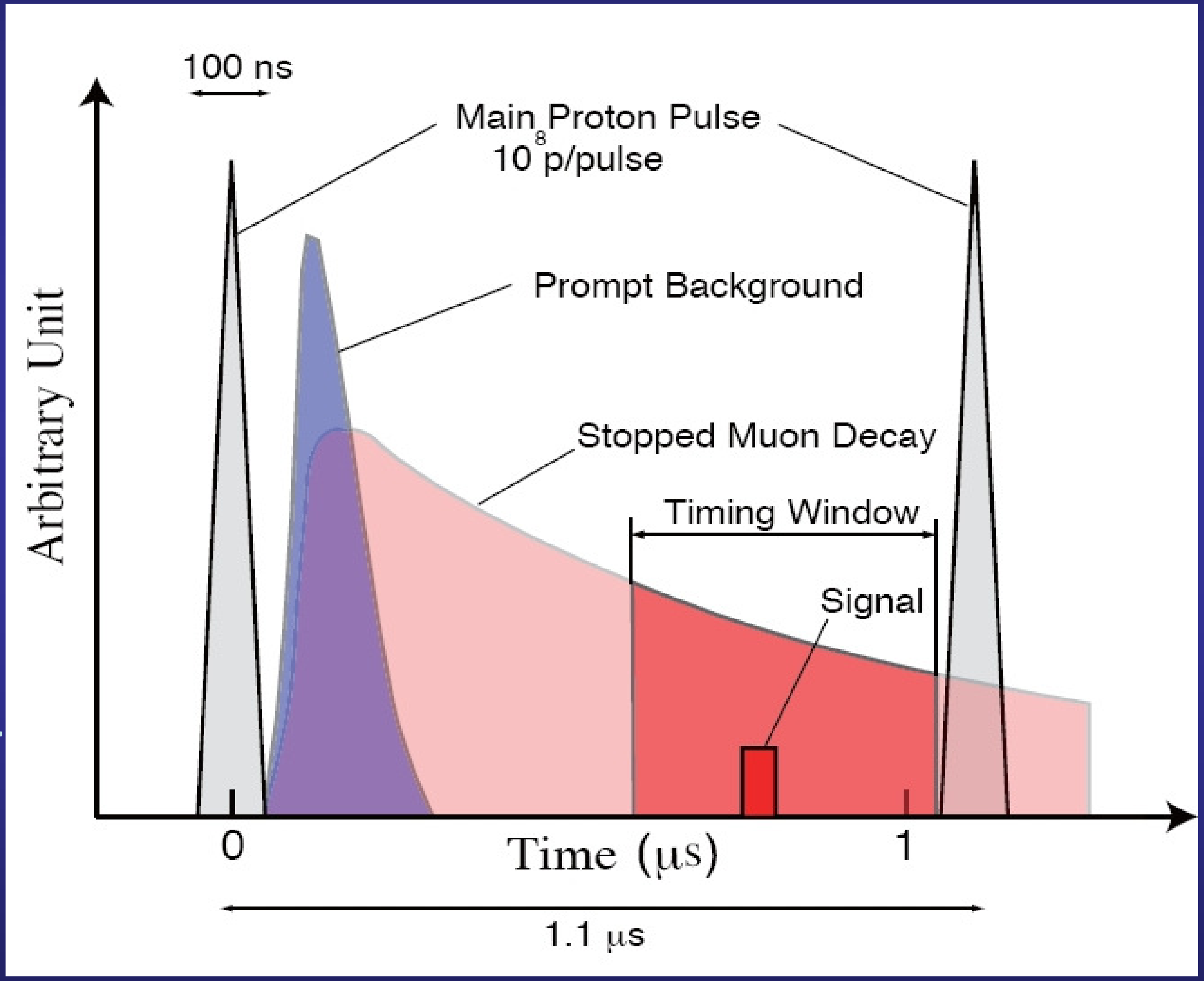


Proton Beam for COMET

- Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

Bunch Structure

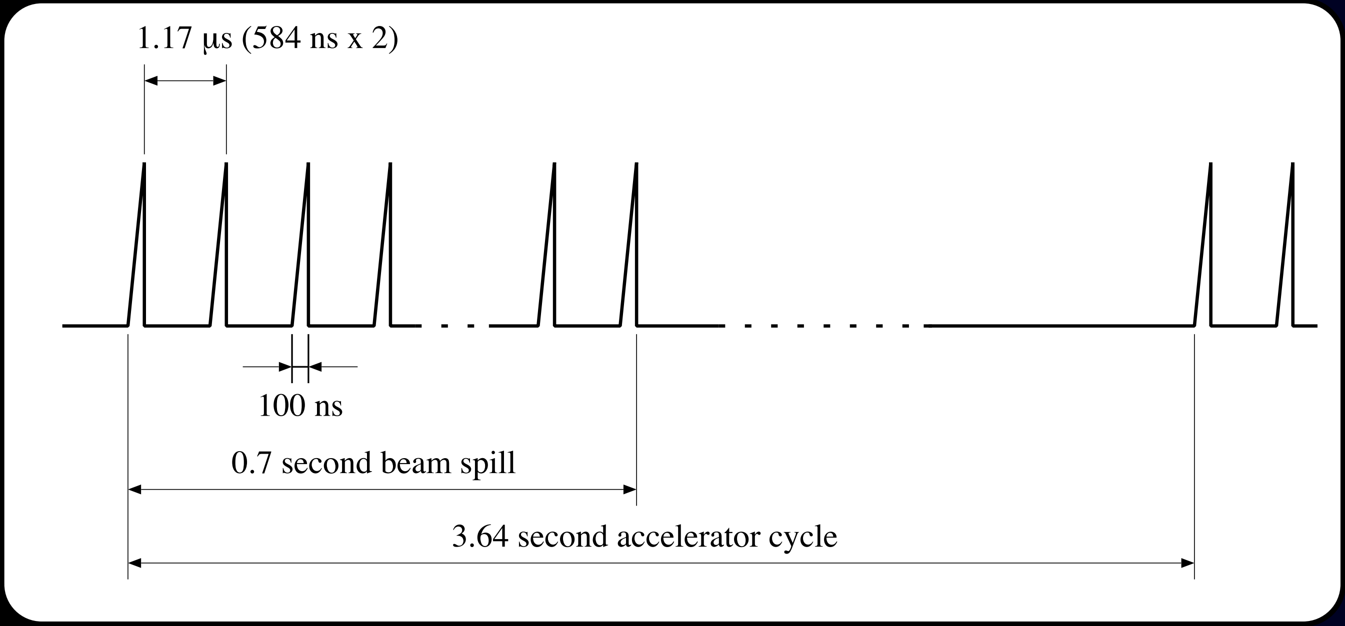
Bunch Separation	1.3 μs
Bunch Length	100ns
Protons per Bunch	1.2×10^8
Bunches per Spill	5.3×10^5
Spill time	0.7s
Extinction	10^{-9}

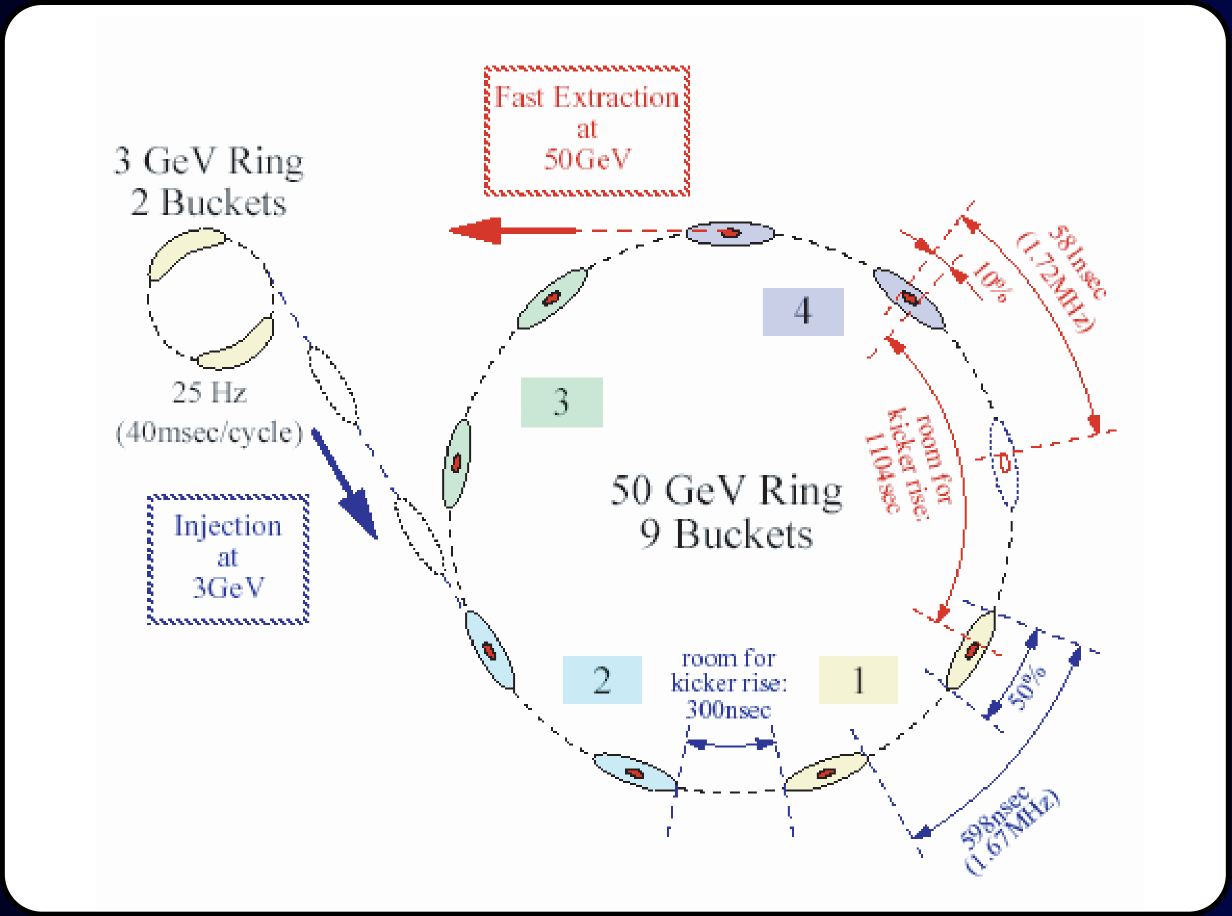


- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important.
  - Without sufficient extinction, all processes in prompt background category could become a problem.

Proton Beam at J-PARC

- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7





Proton Extinction Measruements at J-PARC

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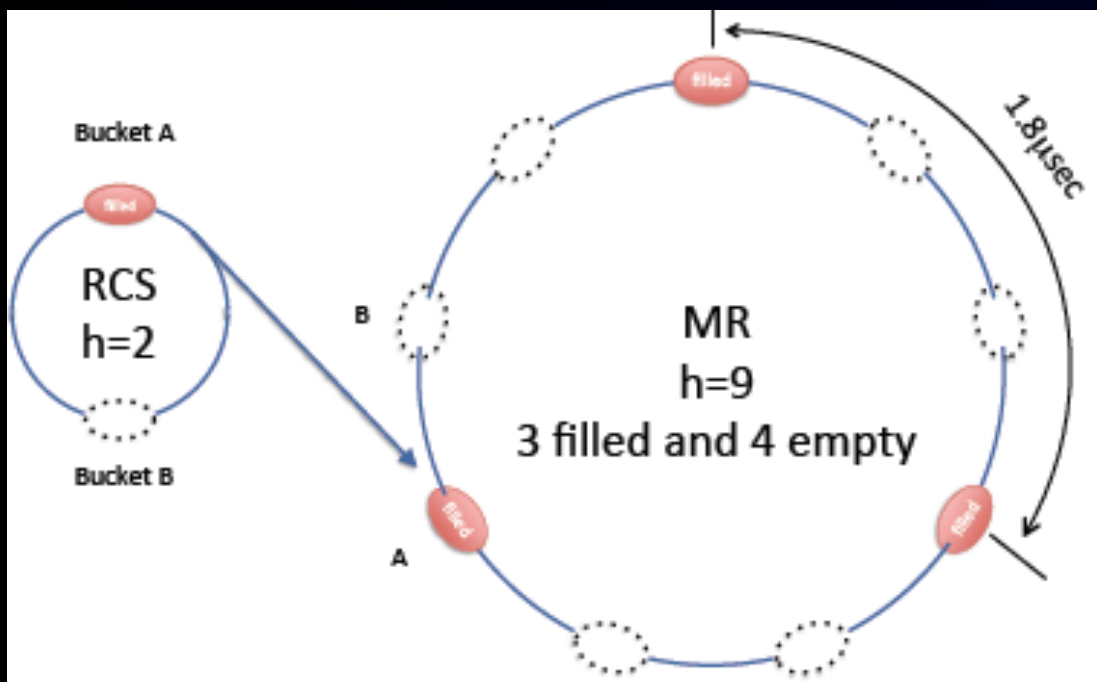
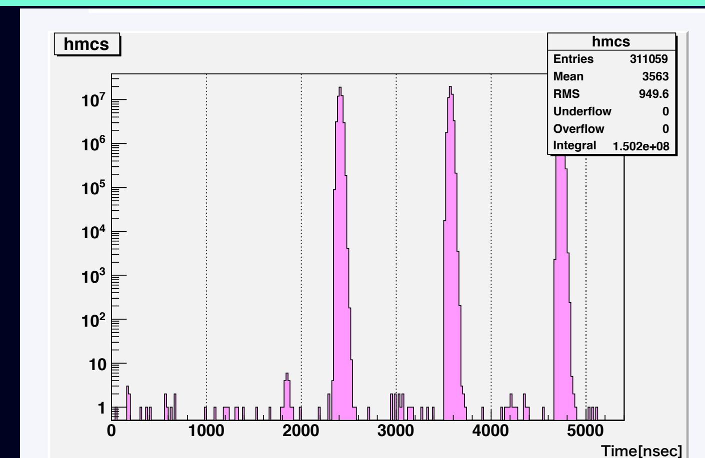
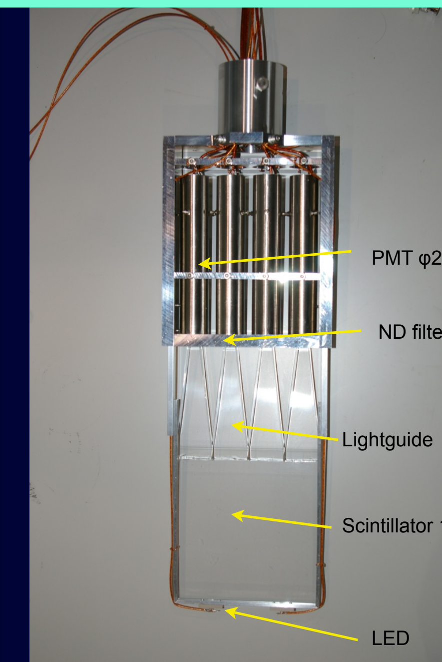


Measured at abort beamline (2010)

Measured at secondary beamline (2010)

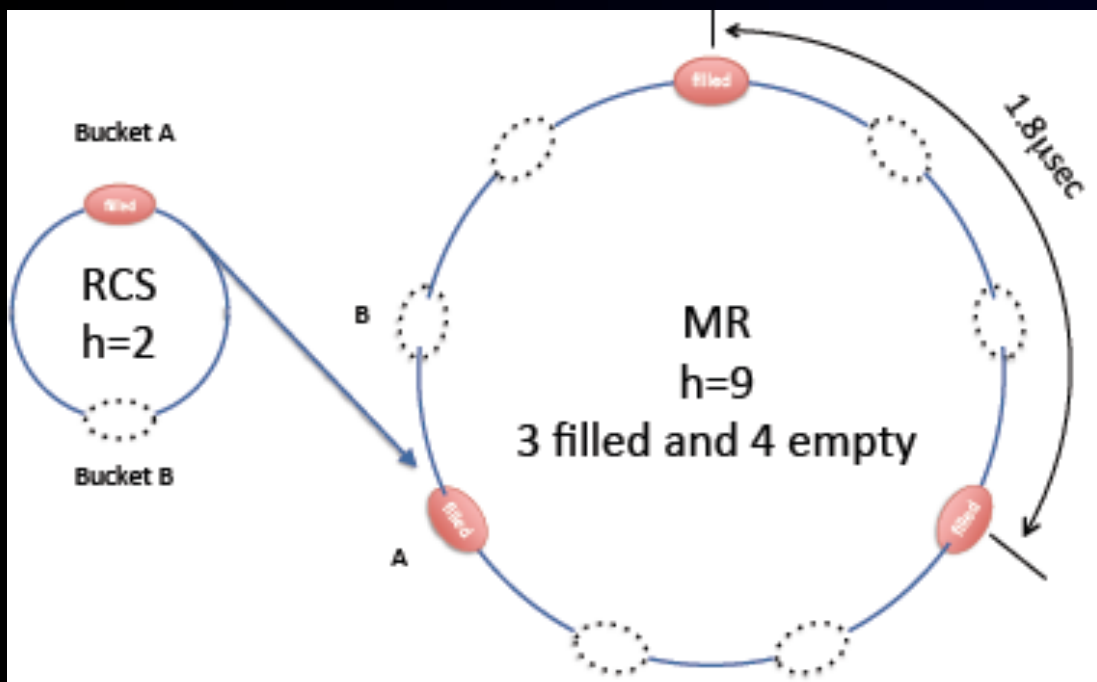




J-PARC MR proton extinction

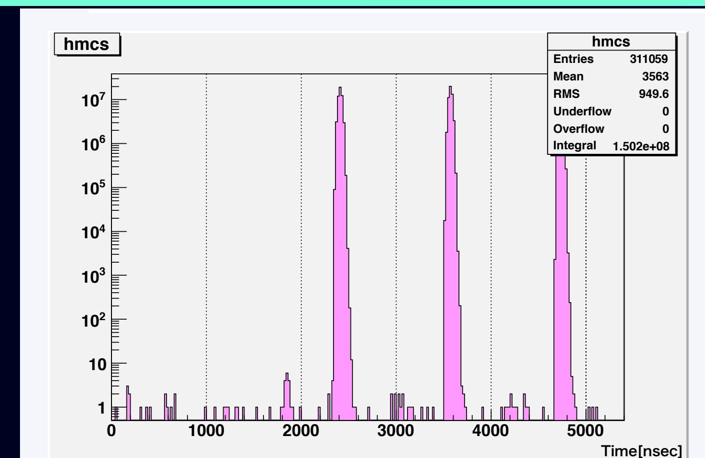
~ O(10^{-7})

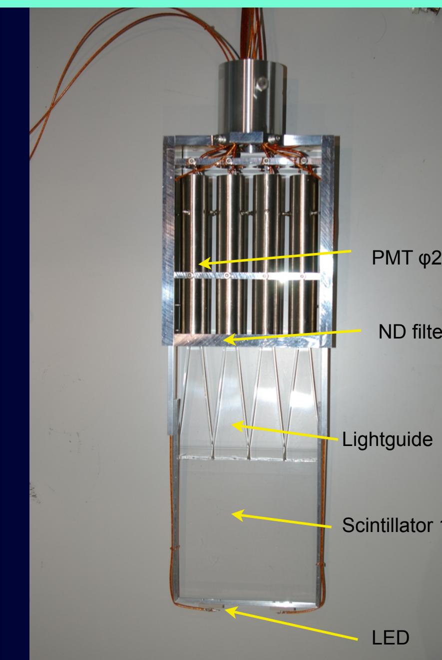
Proton Extinction Measruements at J-PARC



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





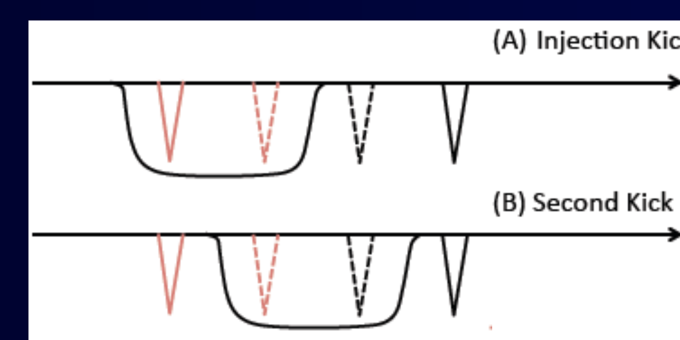
J-PARC MR proton extinction

~ O(10^{-7})

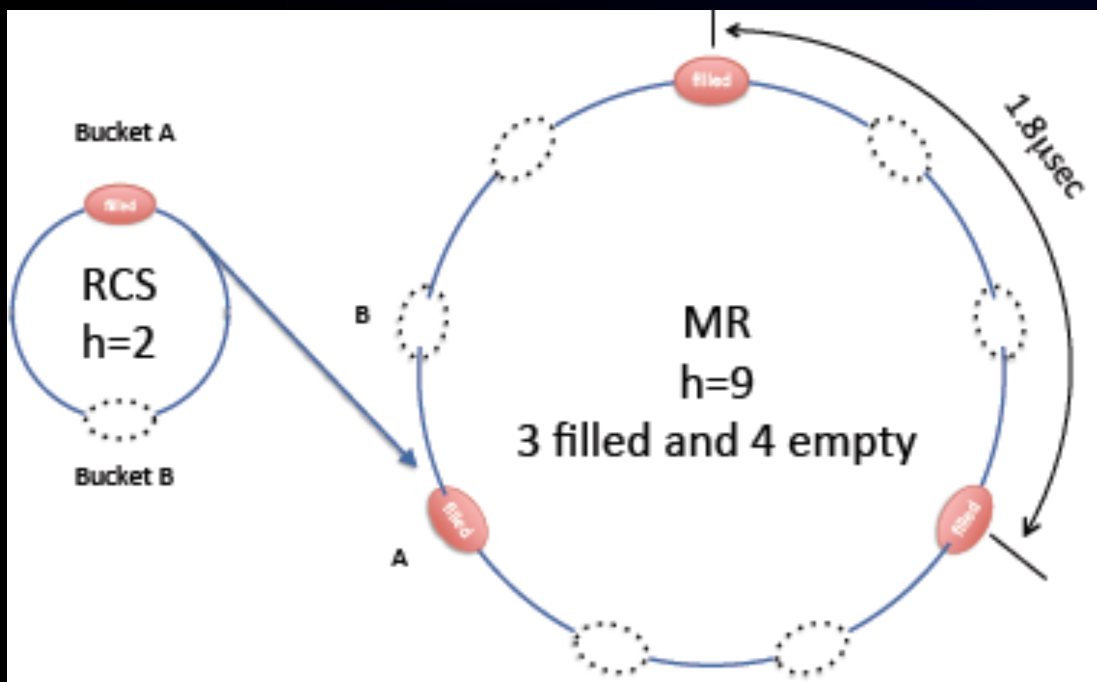
Double Injection Kicking

Tested at the abort (2010)

x additional O(10^{-6})

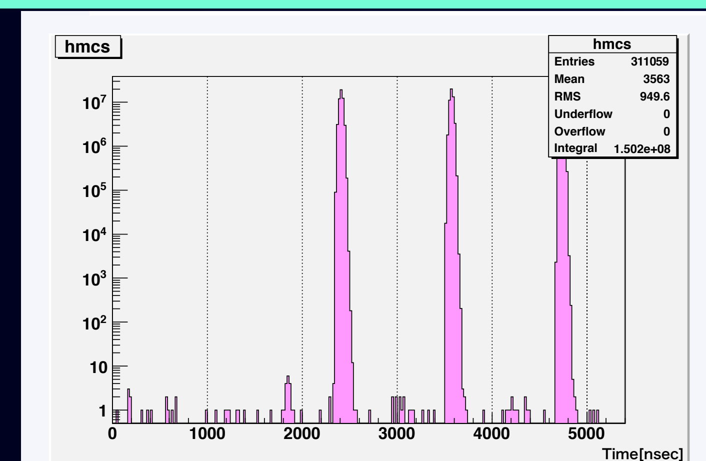


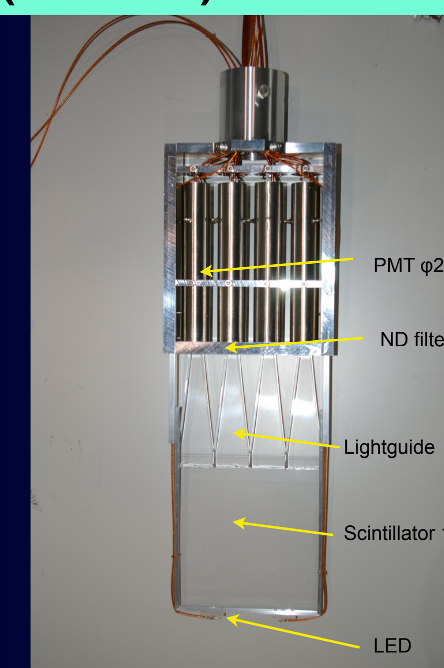
Proton Extinction Measruements at J-PARC



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





J-PARC MR proton extinction

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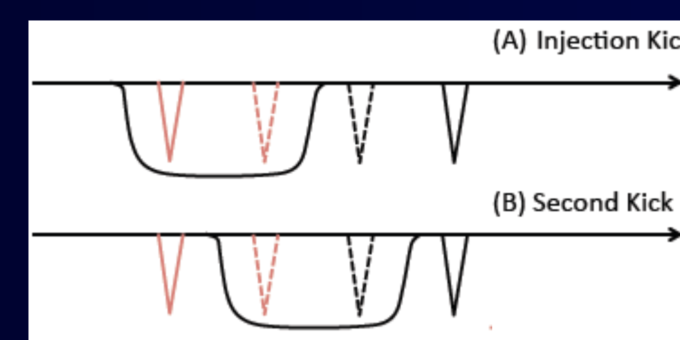
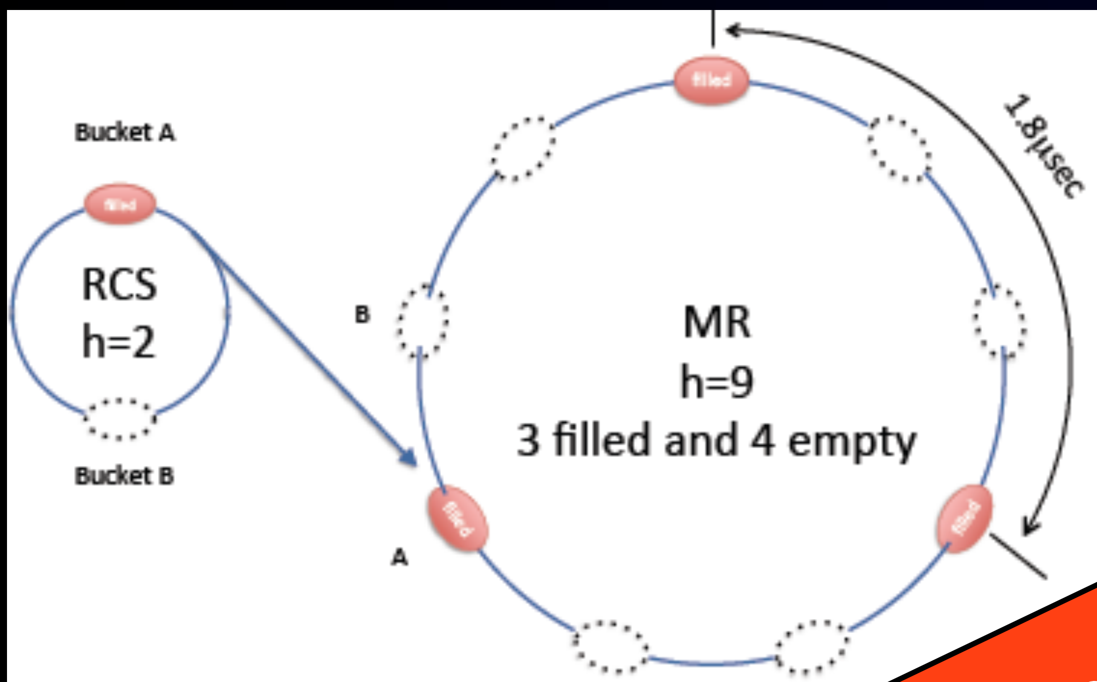


External Extinction Device

AC dipole magnet R&D

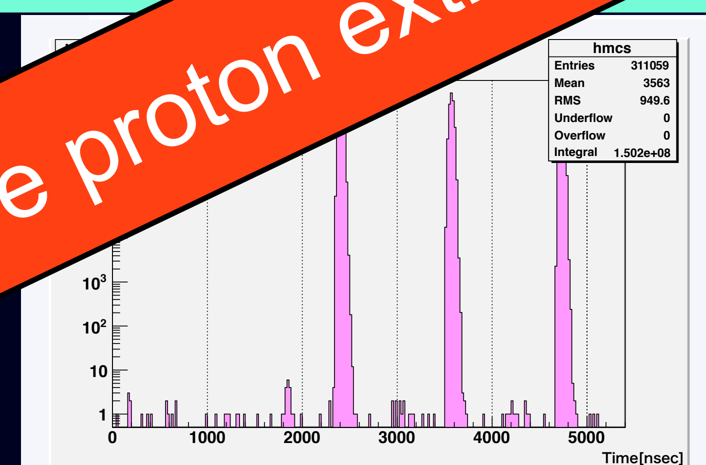
x additional O(10^{-3})

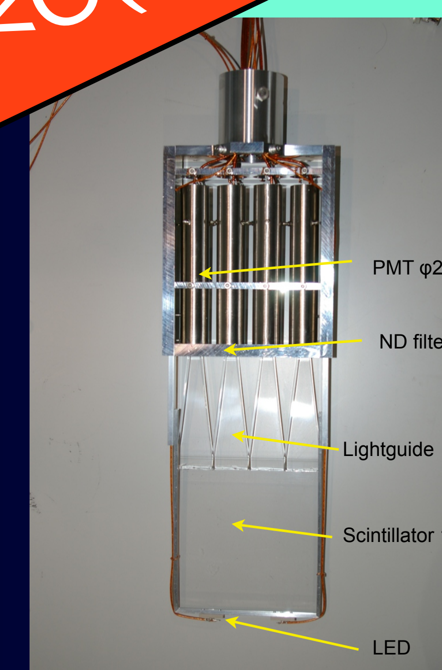
Proton Extinction Measruements at J-PARC



Measured at ...
beamli...

Measured at se...
beamline (...





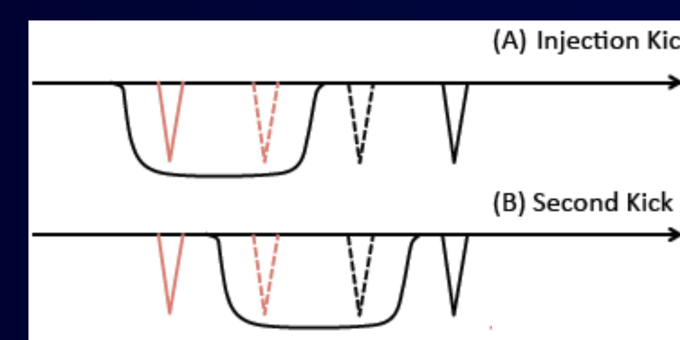
J-PARC MR pr...
extinc...

$O(10^{-7})$

...jection
Kicking

Tested at the abort (2010)

x additional $O(10^{-6})$



External Extinction Device

AC dipole magnet R&D

x additional $O(10^{-3})$

COMET is confident to achieve proton extinction of $<O(10^{-9})$.

Muon Beam

Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

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

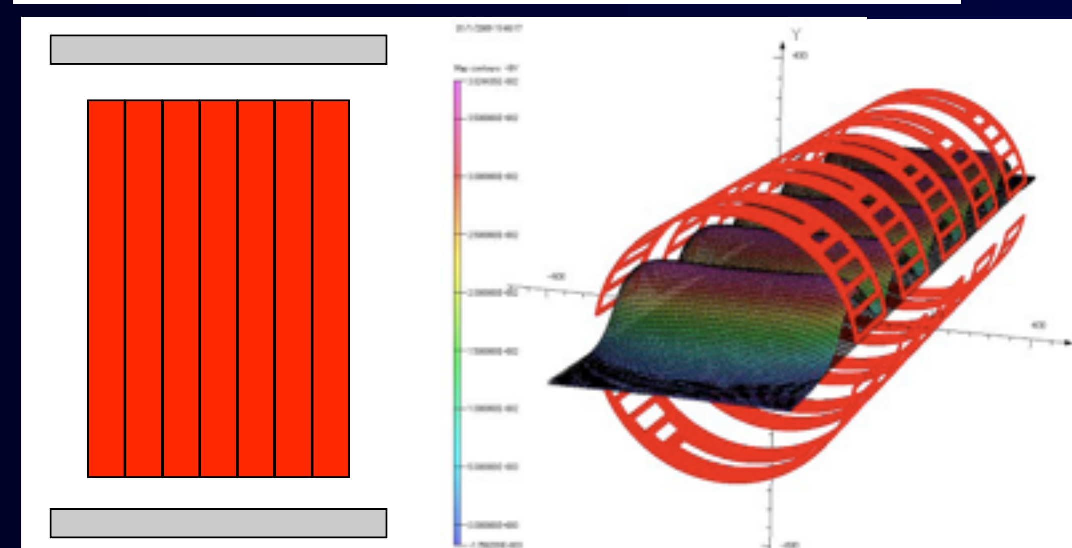
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This can be used for charge and momentum selection.

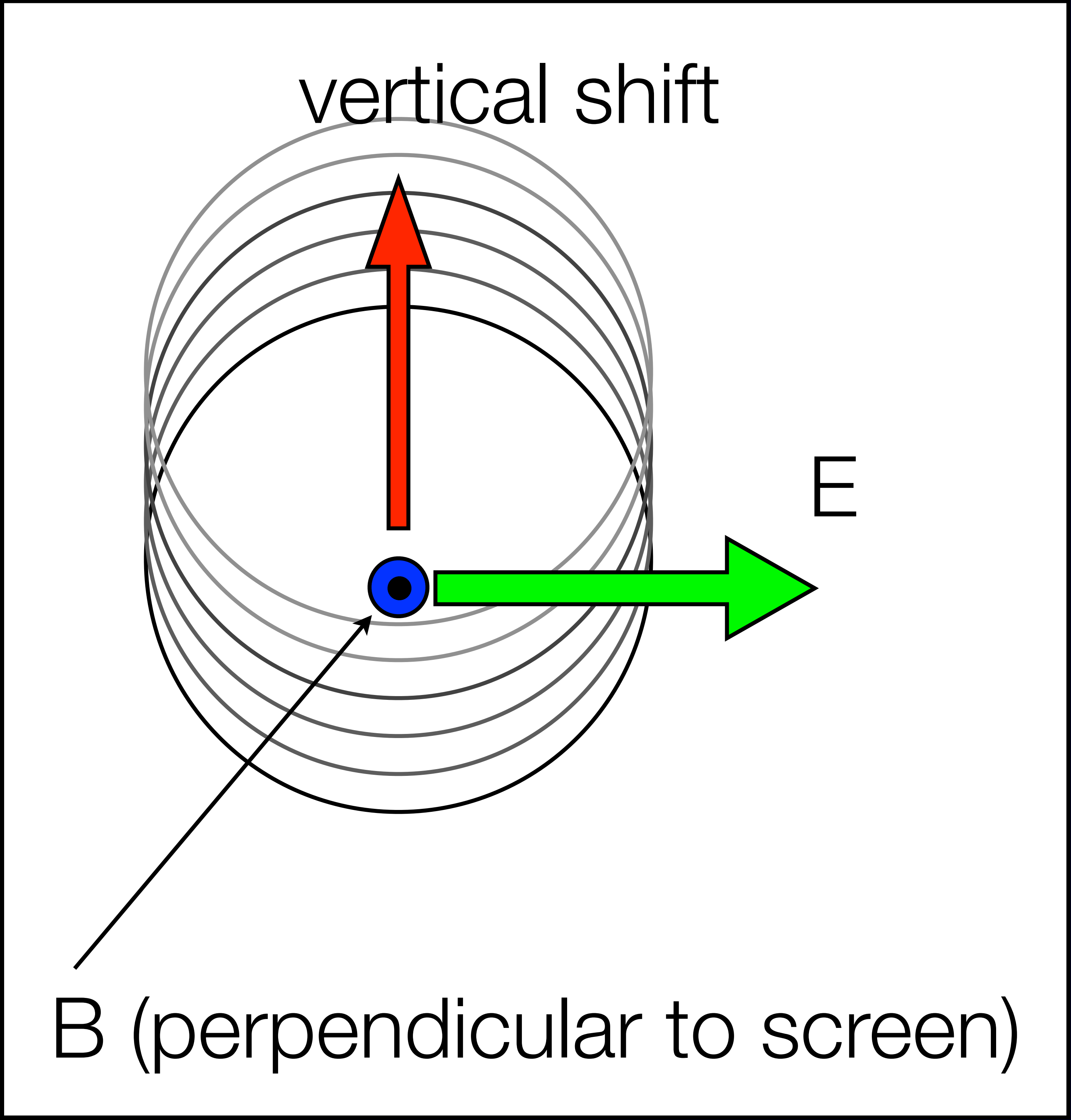
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ *: atan(*P_T/P_L*)*



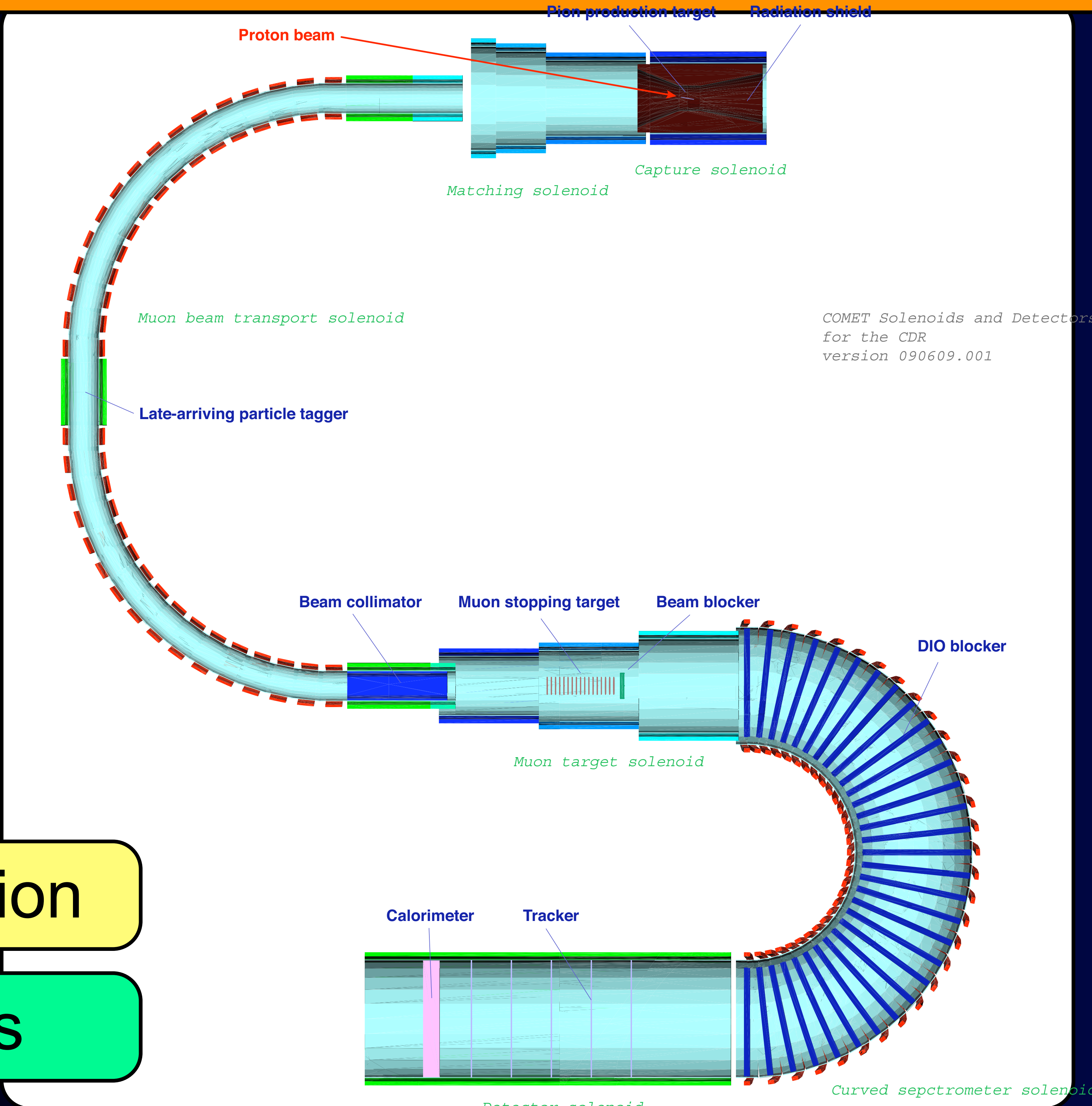
EM Physics for Particle Trajectories in Toroidal Magnetic Field



- For helical trajectory in a curved mag. field, a centrifugal force gives E in the radial direction.
- To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by v x B, can be applied.

Muon Transport System for COMET

- The muon transport system consists of curved solenoids.
  - bore radius : 175 mm
  - magnetic field : 2 T
  - bending angle : 180 degrees
  - radius of curvature : 3 m
- Dispersion is proportional to a bending angle.
- muon collimator after 180 degree bending.
- Elimination of muon momentum > 70 MeV/c



good momentum selection

no high-energy muons

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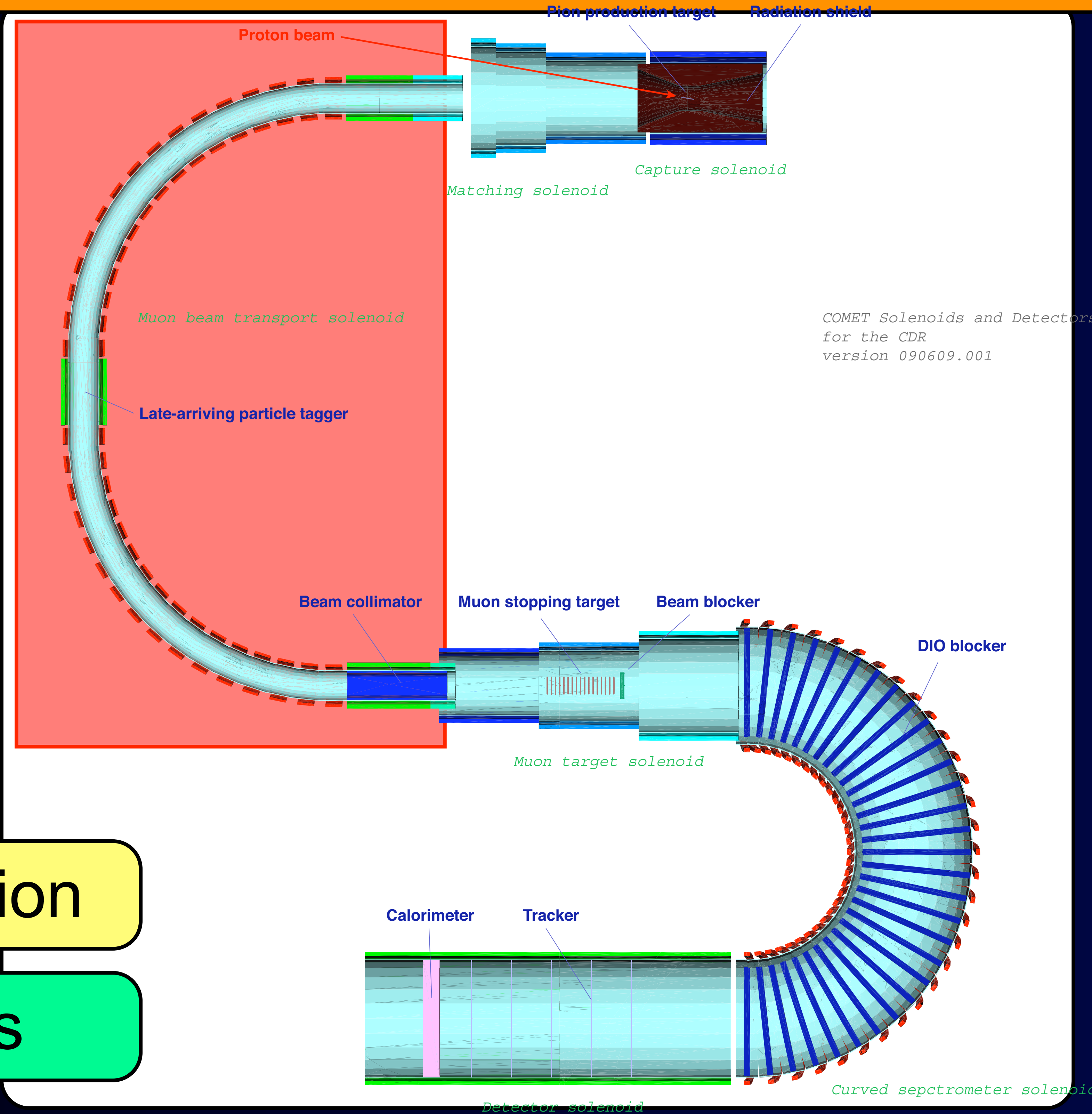
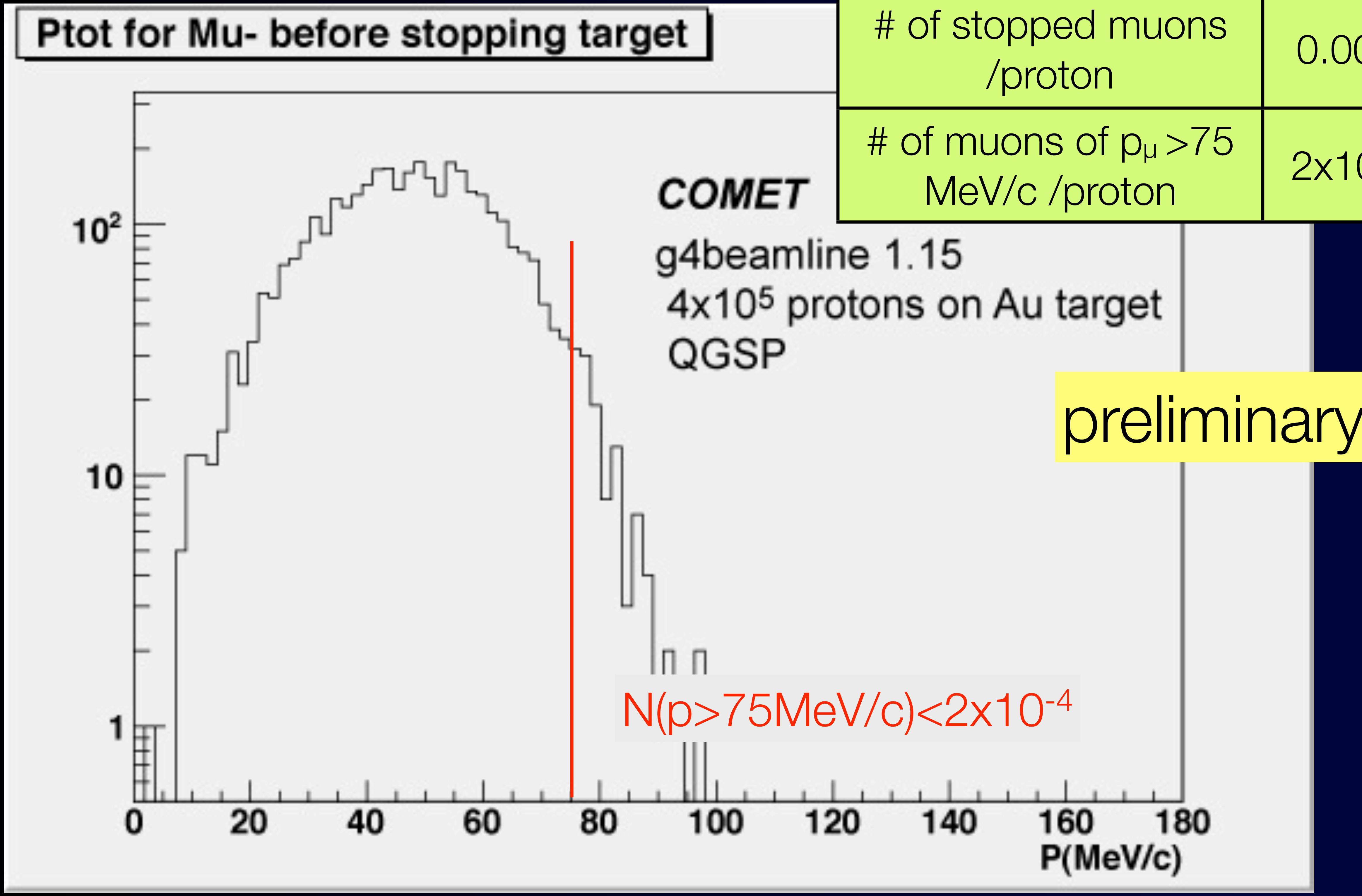


good momentum selection

no high-energy muons

Muon Momentum Spectrum at the End of the Transport Beam Line

# of muons /proton	0.009
# of stopped muons /proton	0.003
# of muons of $p_{\mu} > 75$ MeV/c /proton	2×10^{-4}



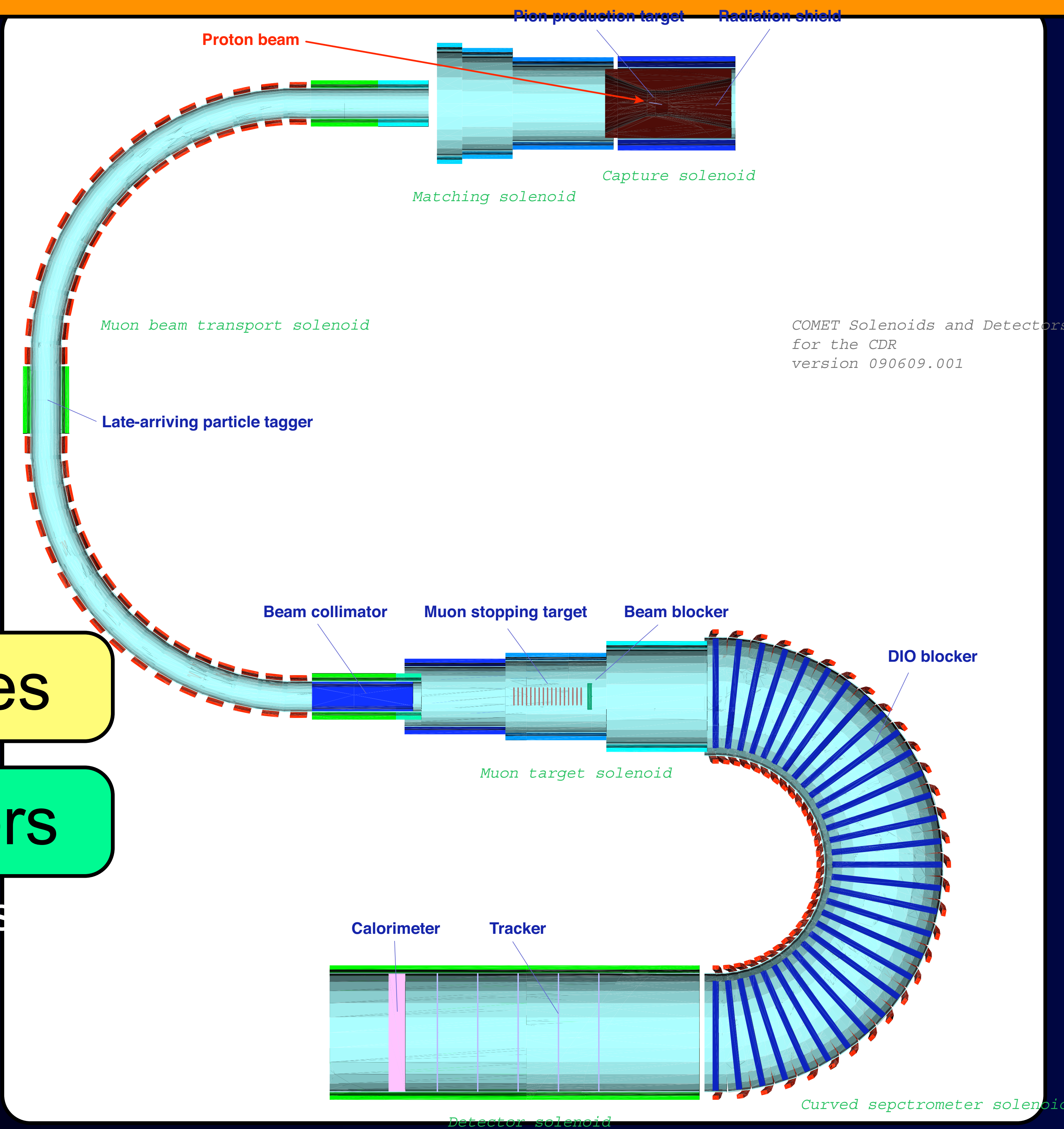
Electron Transport System for COMET

- The electron transport
  - bore : 700 mm
  - magnetic field : 1T
  - bending angle : 180 degrees
- Electron momentum ~ 104 MeV/c
- Elimination of negatively-charged particles less than 80 MeV/c
- Elimination of positively-charged particles (like protons from muon capture)

reduction of detector rates

no protons in the detectors

- a straight solenoid where detectors are placed follows the curved spectrometer.



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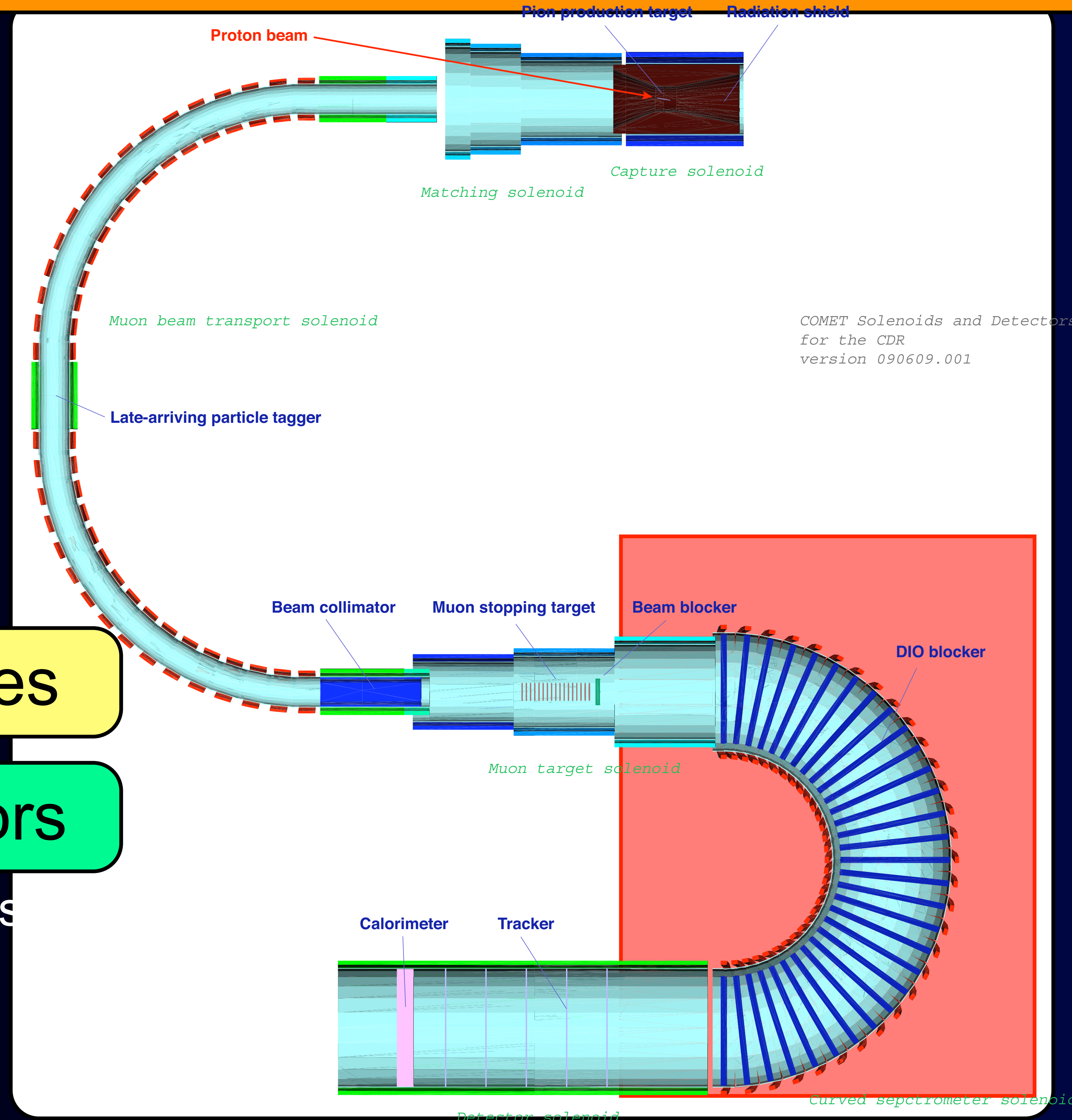
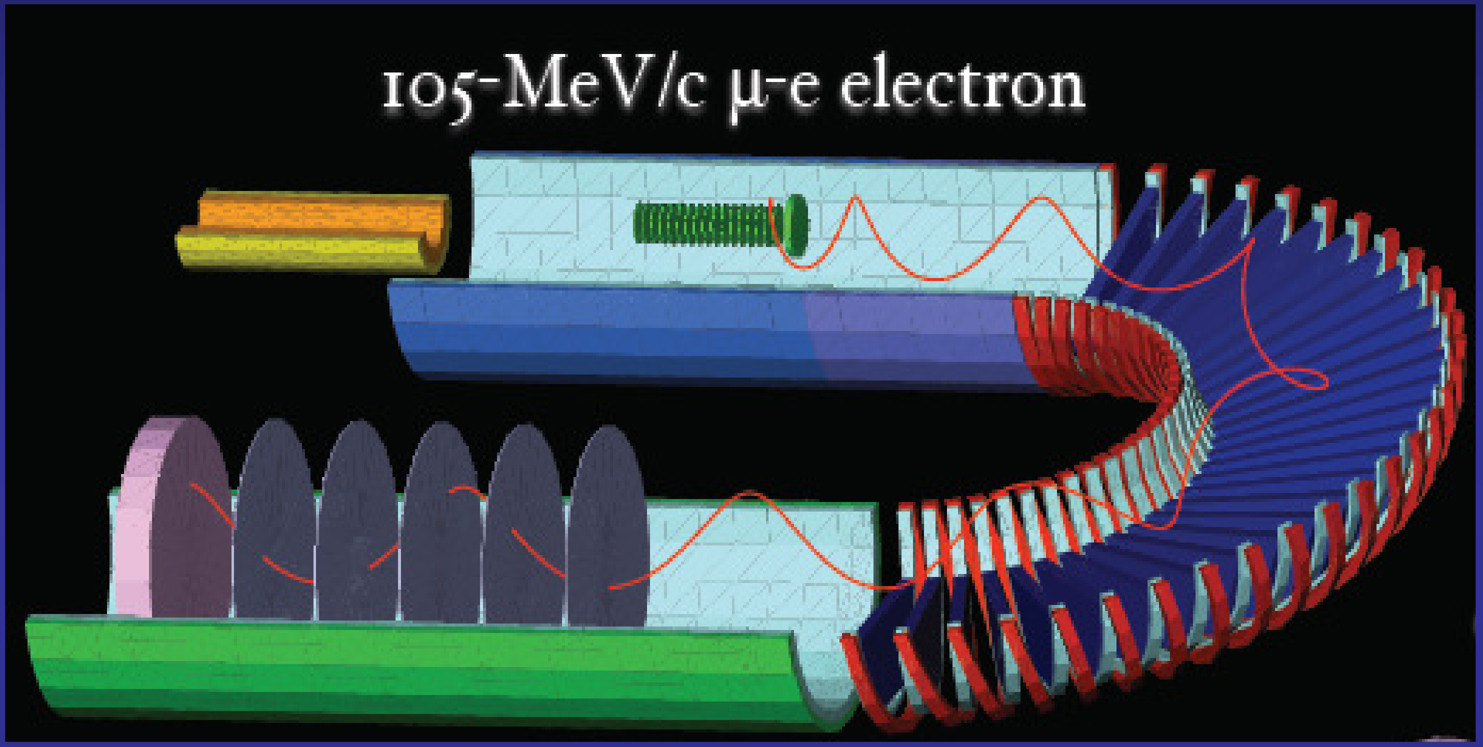
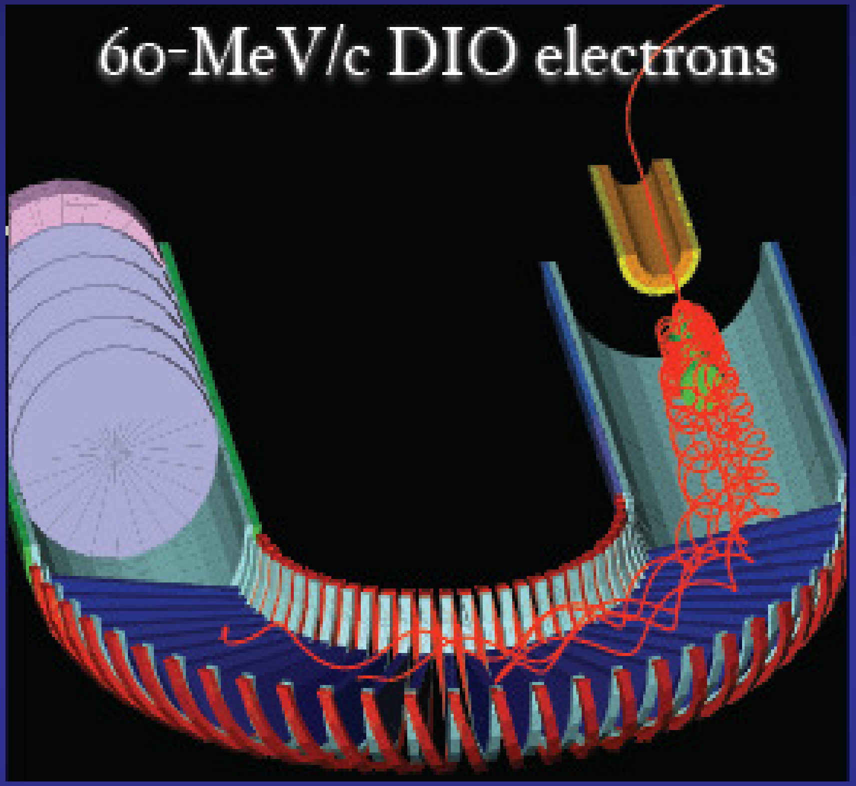


Electron Spectrometer





- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~ 1kHz.

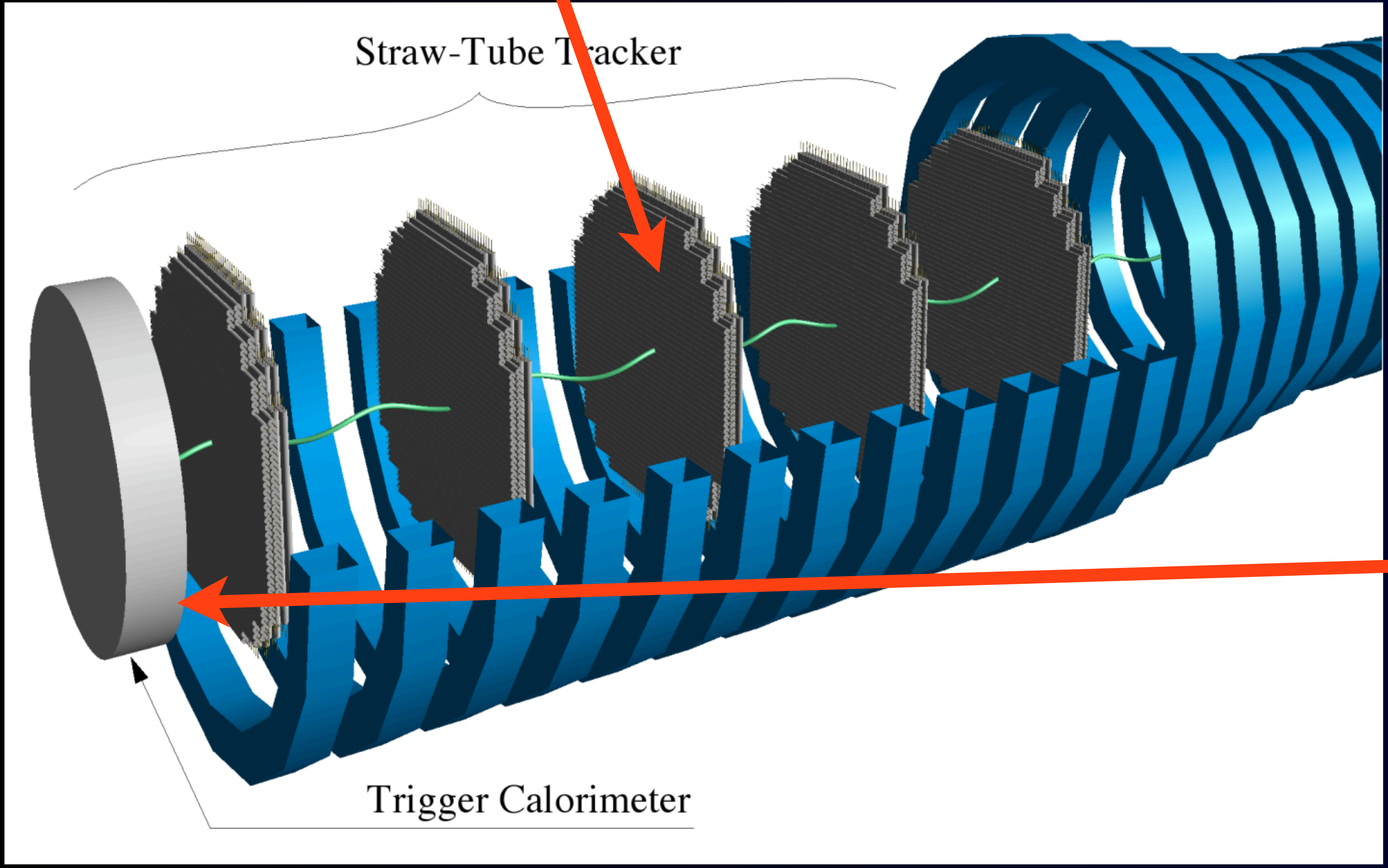
Detector

Electron Detection

Electron Tracker to measure electron momentum
- work in vacuum and under a magnetic field.
- Straw tube chambers
  - Straw tubes of 25μm thick, 5 mm diameter.
  - five plane has 2 views (x and y) with 2 layers per view.
- Planar drift chambers

Under a solenoidal magnetic field of 1 Tesla.

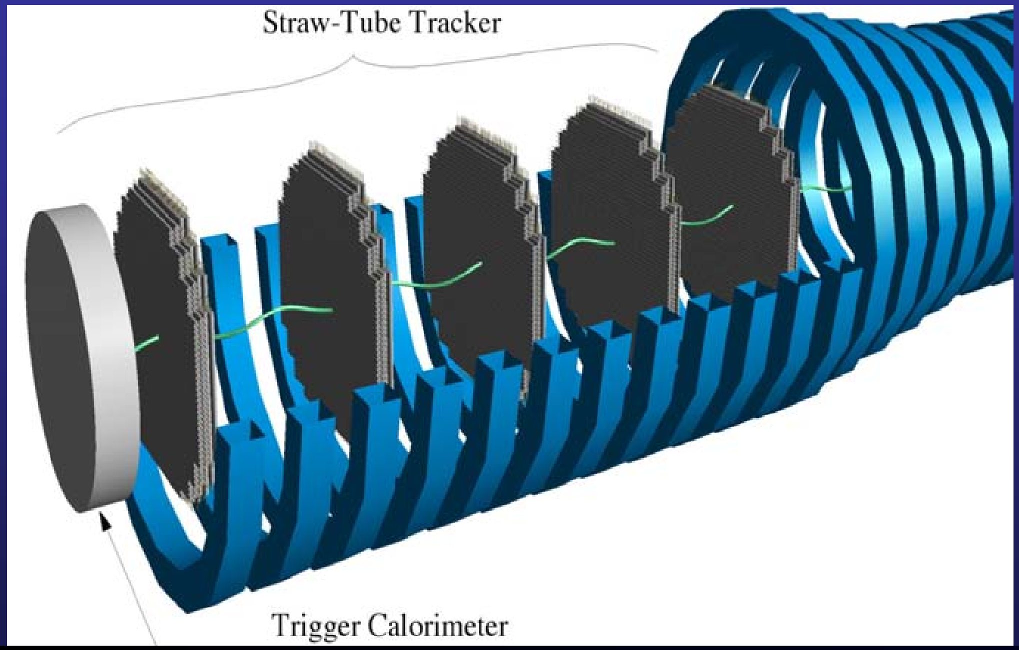
In vacuum to reduce multiple scattering.

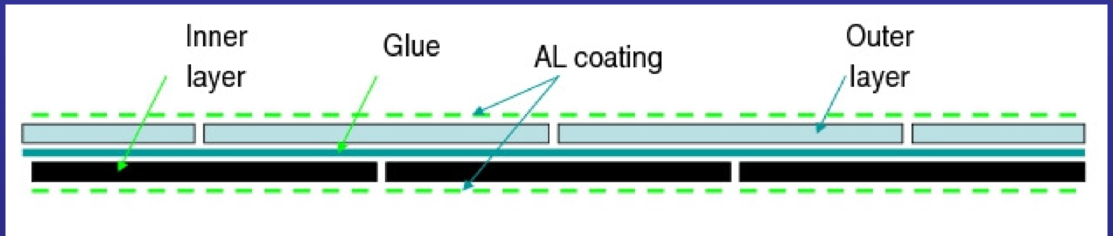


Electron calorimeter to measure electron energy, make triggers and give additional hit position.
- Candidate are LYSO, GSO
- MPPC or APD readout

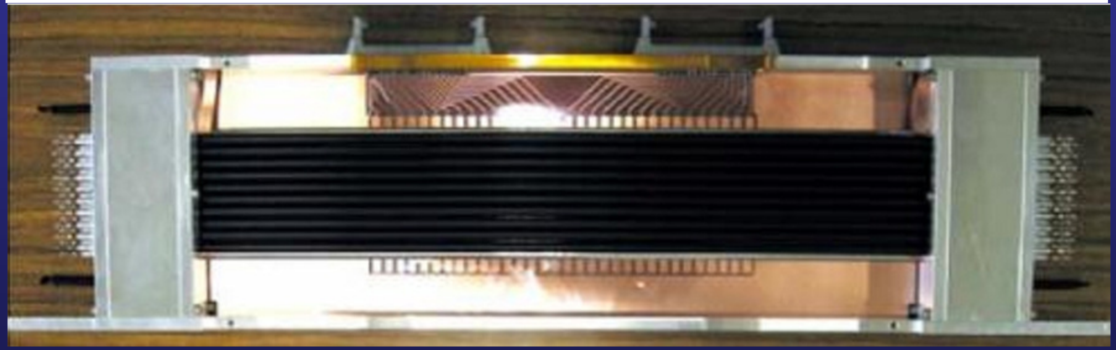
COMET Electron Tracker

- Requirements
  - operate in a 1T solenoid field.
  - operate in vacuum (to reduce multiple scattering of electrons).
  - 800kHz charged particle rate and 8MHz gamma rates
  - 0.4% momentum and 700µm spatial resolution.
- Current design utilises straw tube chambers
  - Straw tubes 5mm in diameter. Wall composed of two layers of 12µm thick metalized Kapton glued together.
- 5 planes 48cm apart with 2 views (x and y) per plane and 2 layers per view (rotated by 45° to each other).





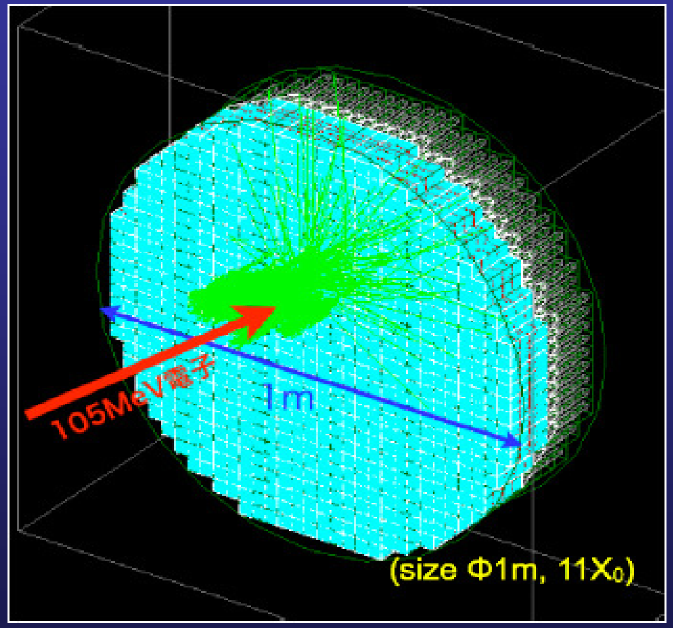
Straw wall cross-section.

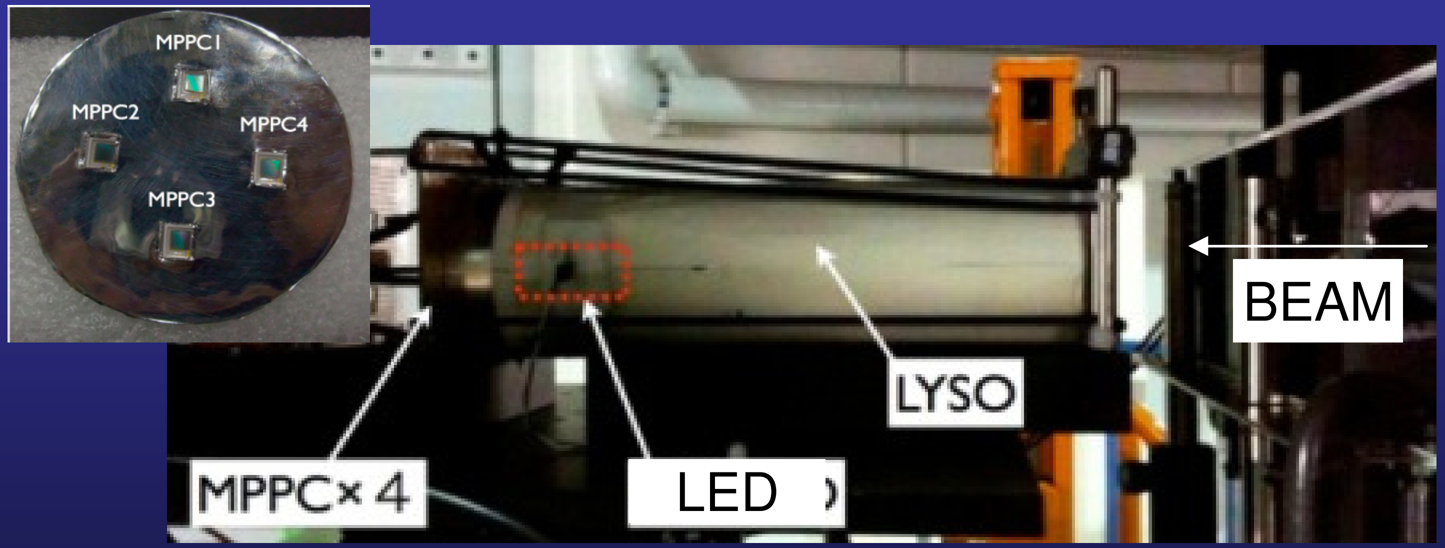


350mm long seamless straw tube prototype.

COMET Electron Calorimeter

- Measure energy, PID and give additional position information. Can be used to make a trigger decision.
- 5% energy and 1cm spatial resolution at 100MeV
  - High segmentation (3x3x15 cm^3 crystals)
- Candidate inorganic scintillator materials are Cerium-doped Lutetium Yttrium Orthoscilicate (LYSO) or Cerium-doped Gd_2SiO_5 (GSO).
- Favoured read out technology is multi–pixel photon counters (MPPC).
  - high gains, fast response times and can operate in magnetic fields.
- R&D by Osaka group. Further beam tests planned for November.

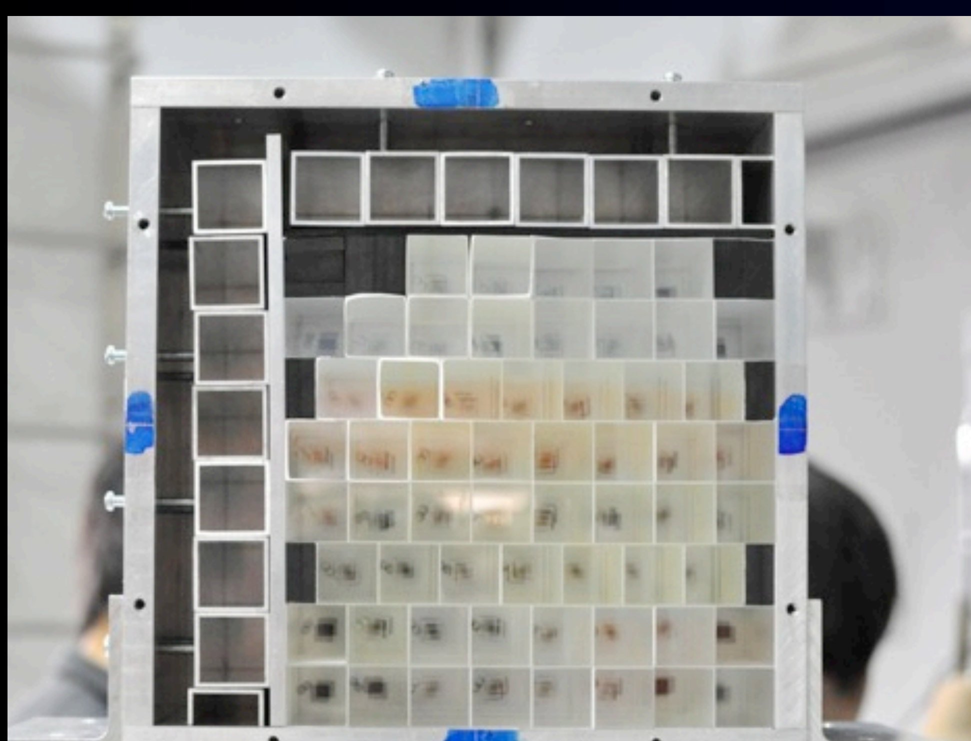




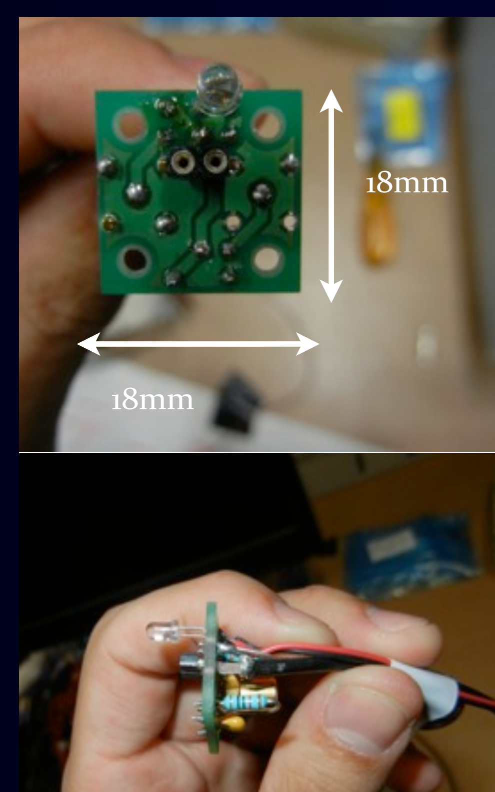
100 MeV electron beam tests at Tohoku University

R&D on Electron Calorimeter

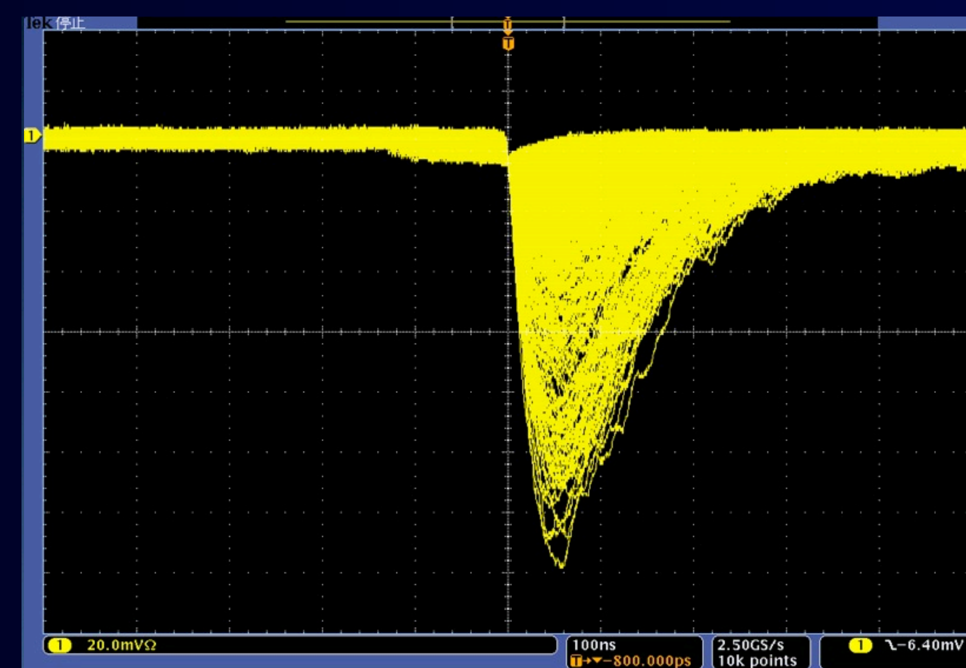
- Candidates of scintillating crystals are GSO(Ce), LYSO, $LaBr_3$ and others.
- Candidates of Calorimeter readout of MPPC and APD.
- The beam test of GSO with either MPPC and APD was done with electron beam at Tohoku Univ. in 2009 and 2010.
- Data analysis goes underway.



GSO(Ce) Crystals



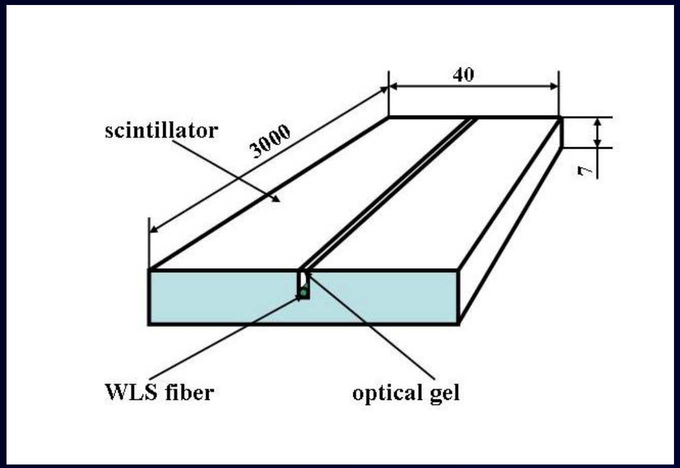
MPPC and readout

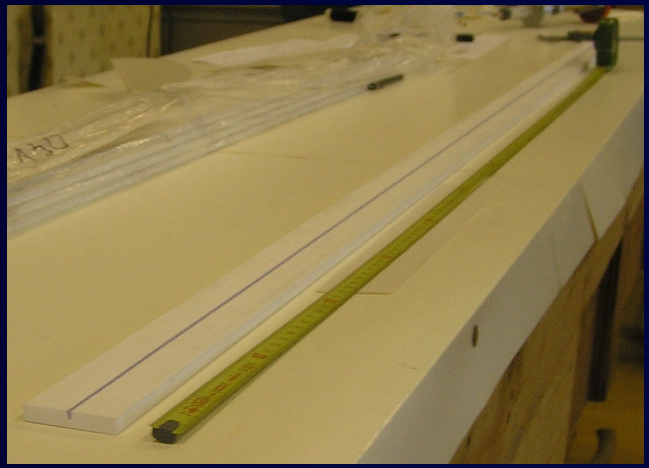


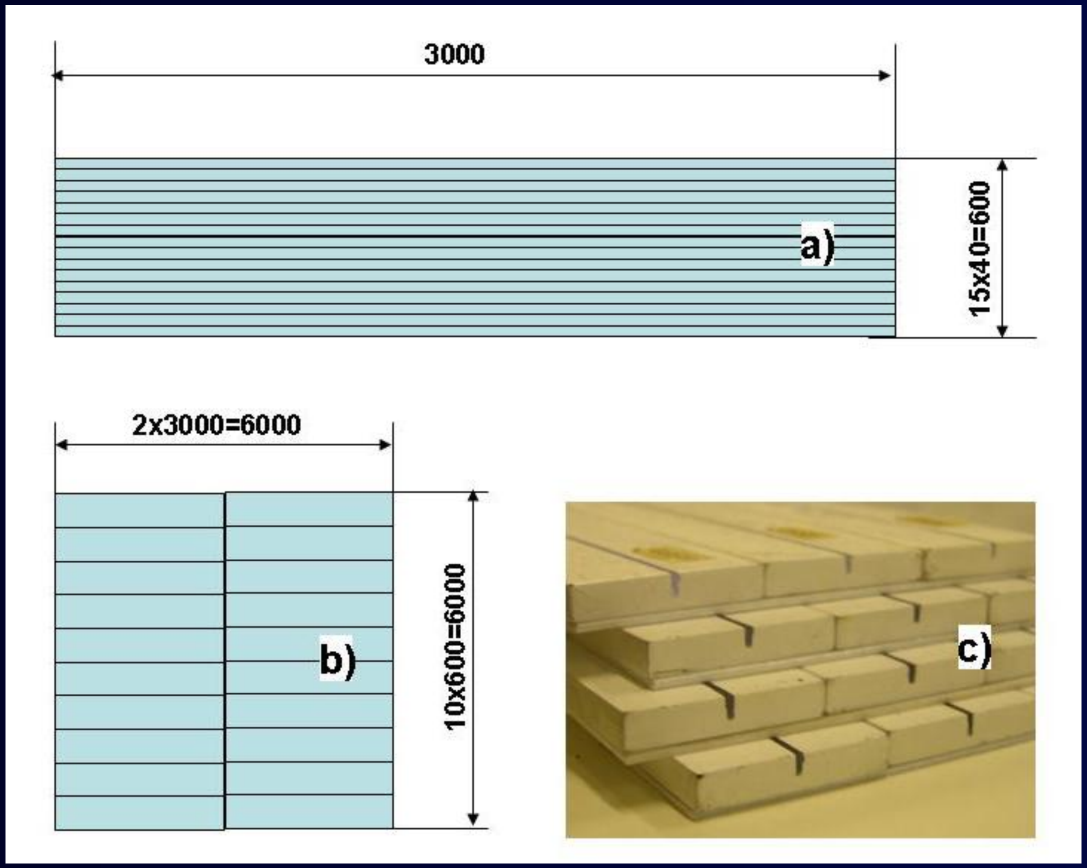
signal from MPPC for GSO(Ce)

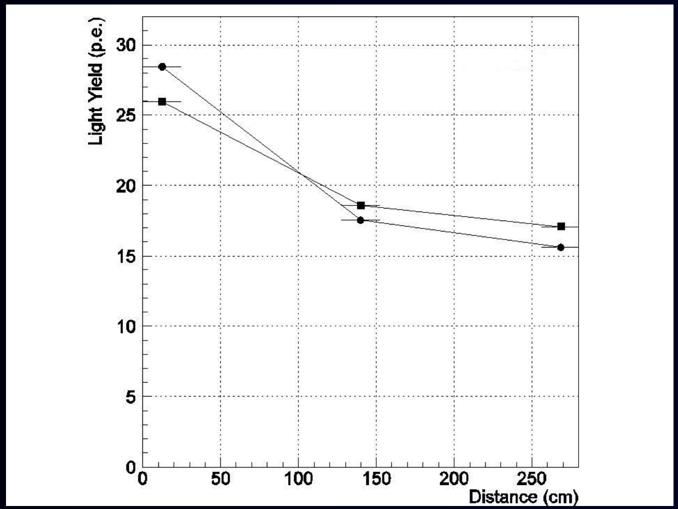
R&D on Cosmic Ray Veto

- The active cosmic ray veto system has been designed and tested by the BINP (Novosibirsk) and ITEP (Moscow) group.
- Plastic scintillators with fiber readout by SiPM or APD.
- The light yield at a far end is even 15 pe. The counter efficiency for MIP is 99.7% with 55 pixel threshold.









Plastic scintillators with fiber readout (basic module).

R&D on Stopping Muon Monitor System

- To monitor a number of stopping muons, muonic X-rays from the muon stopping target (made of aluminum) is to be measured.

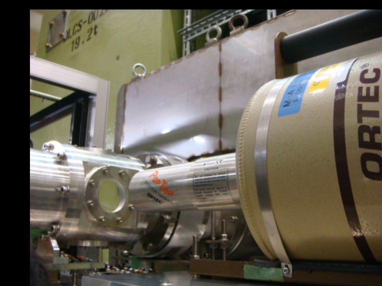
Al	**347keV**	413keV	436keV	**66keV**	89keV	100keV
	(0.811)	(0.058)	(0.019)	(0.422)	(0.072)	(0.031)

- Two different detectors, Ge and CdTe were tested at the J-PARC MLF muon facilities in fall, 2010.
- Detector efficiencies and transition rates are studied.
- R&D on Multi-pixel detectors is being done.
- Location of the muonic X-ray detectors at COMET is being studied.

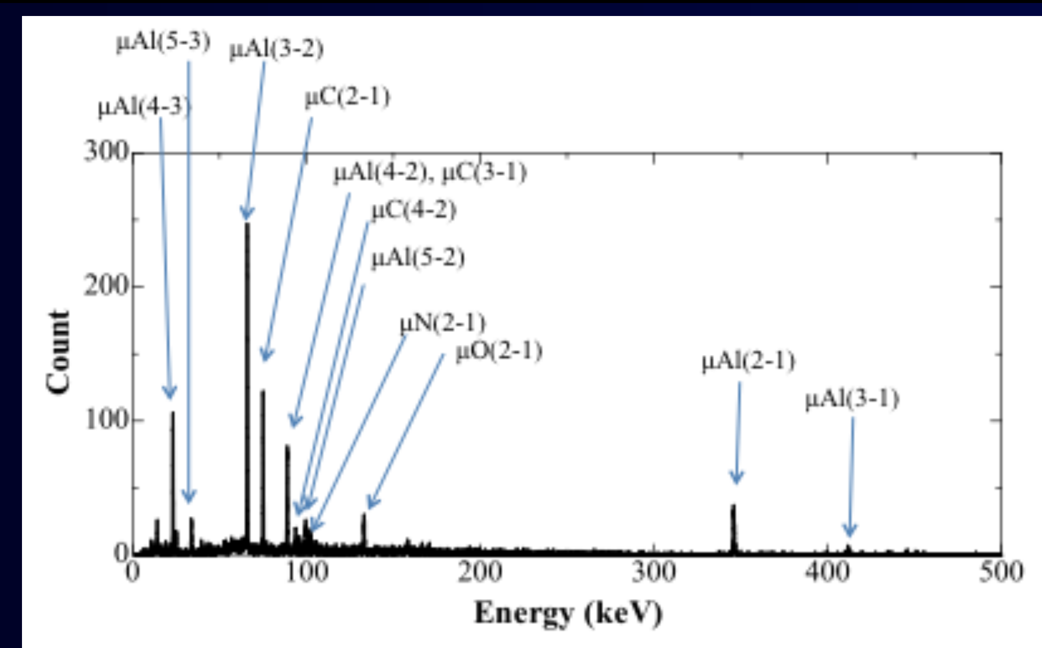
CdTe detector

EURORAD,Ohmic type
10mm×10mm×3mm

Ge detector



Ortec,POPTOPtype,GMX
ϕ=50mm,length=50mm



Measured muonic X-rays from aluminum

Sensitivity and Backgrounds

Signal Sensitivity (preliminary) - 2×10^7 sec

Signal Sensitivity (preliminary) - 2×10^7 sec

- Single event sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is 2×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons	8.5×10^{20}
muon transport efficiency	0.008
muon stopping efficiency	0.3
# of stopped muons	2.0×10^{18}

$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

Background Rates

Radiative Pion Capture	0.05
Beam Electrons	$< 0.1^{\ddagger}$
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

‡ Monte Carlo statistics limited.

beam-related prompt backgrounds

beam-related delayed backgrounds

intrinsic physics backgrounds

cosmic-ray and other backgrounds

Expected background events are about 0.34.

BG with asterisk needs beam extinction.

Background Rejection Summary (preliminary)

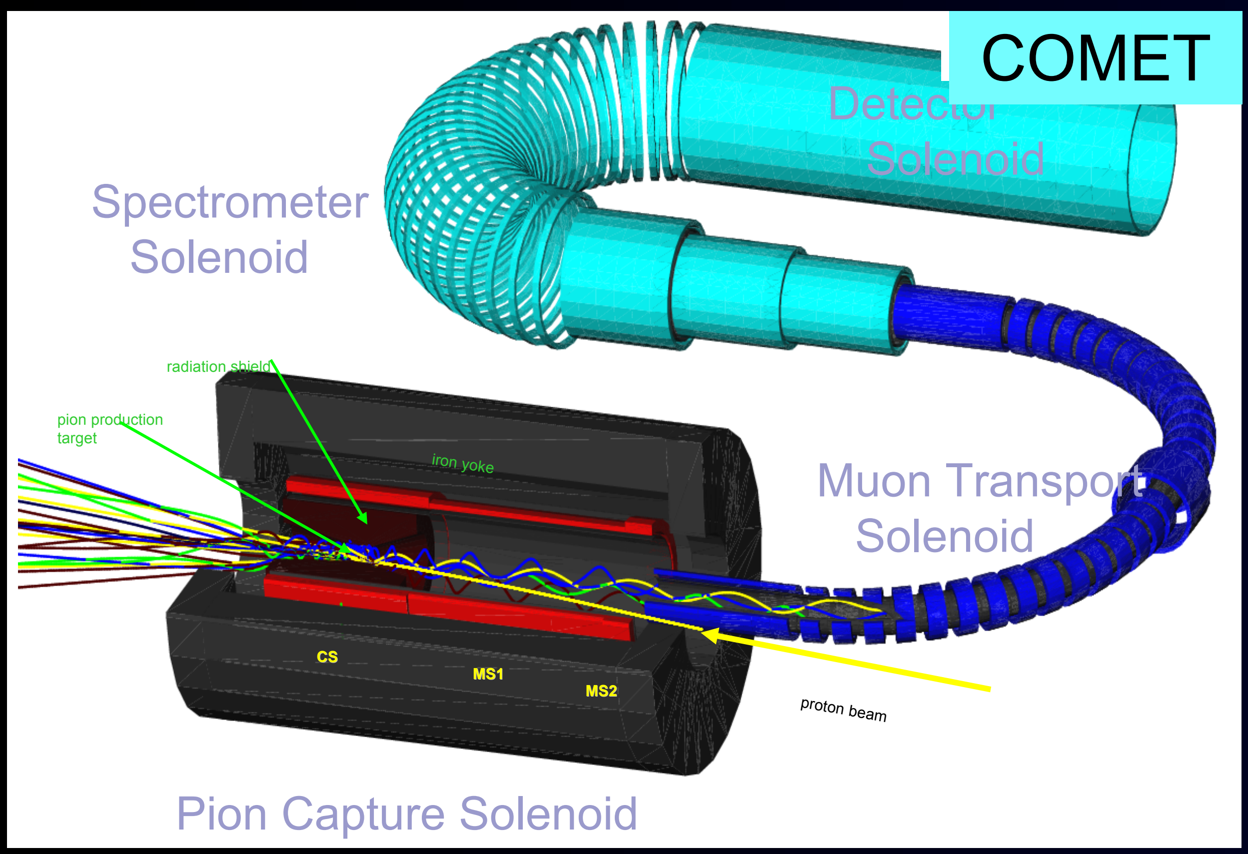
BG with asterisk needs beam extinction.

Background Rejection Summary (preliminary)

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.10	10^{-4} veto & 2×10^{7} sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

R&D Milestones

R&D Milestones for μ-e conversion



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

single event sensitivity: 2.6×10^{-17}

1 Reduction of Backgrounds

Beam pulsing

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

2 Increase of Muon Intensity

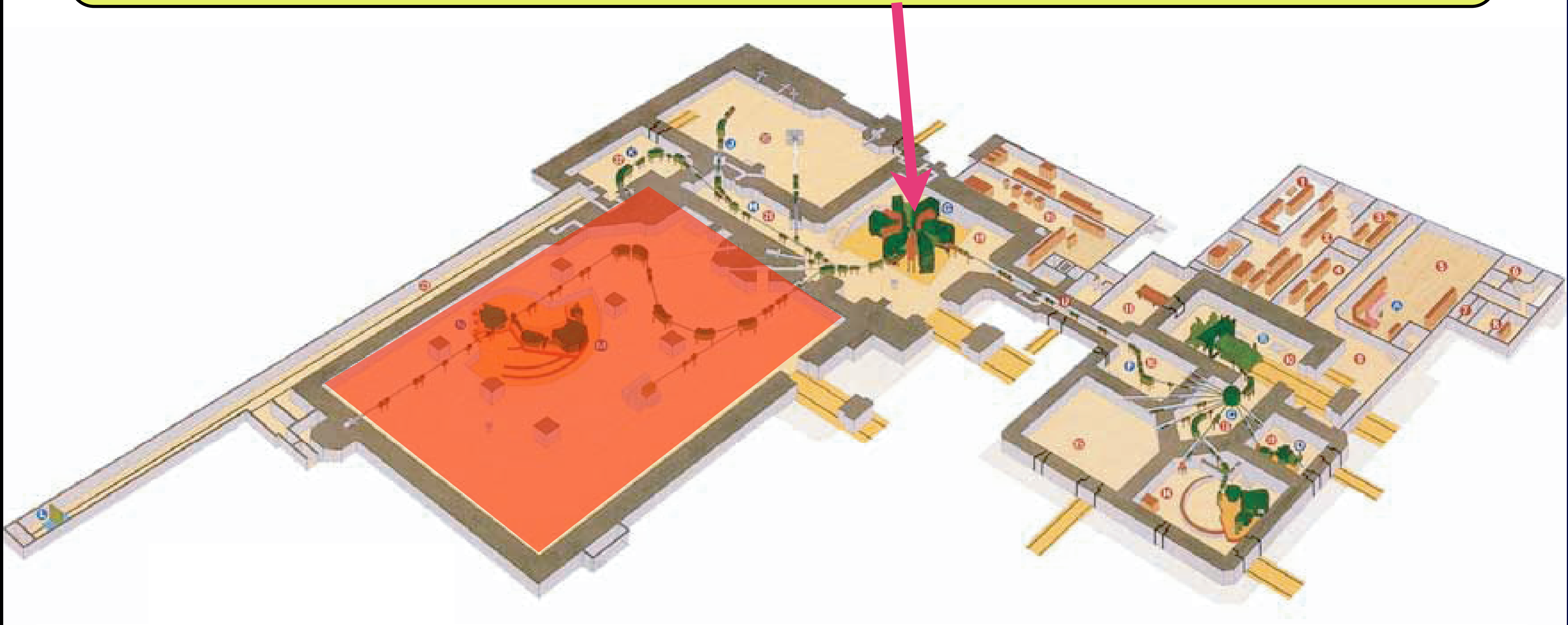
Pion capture system $\times 10^3$

high field superconducting solenoid magnets surrounding a pion production target

Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



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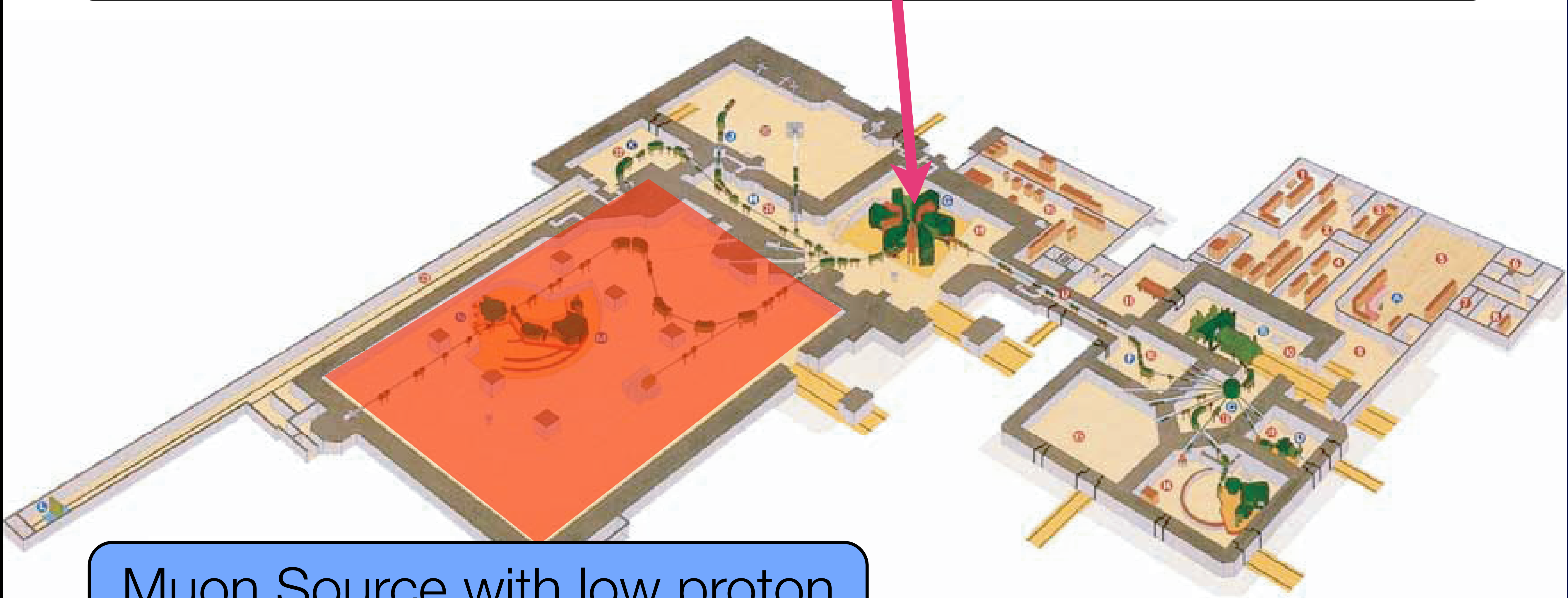
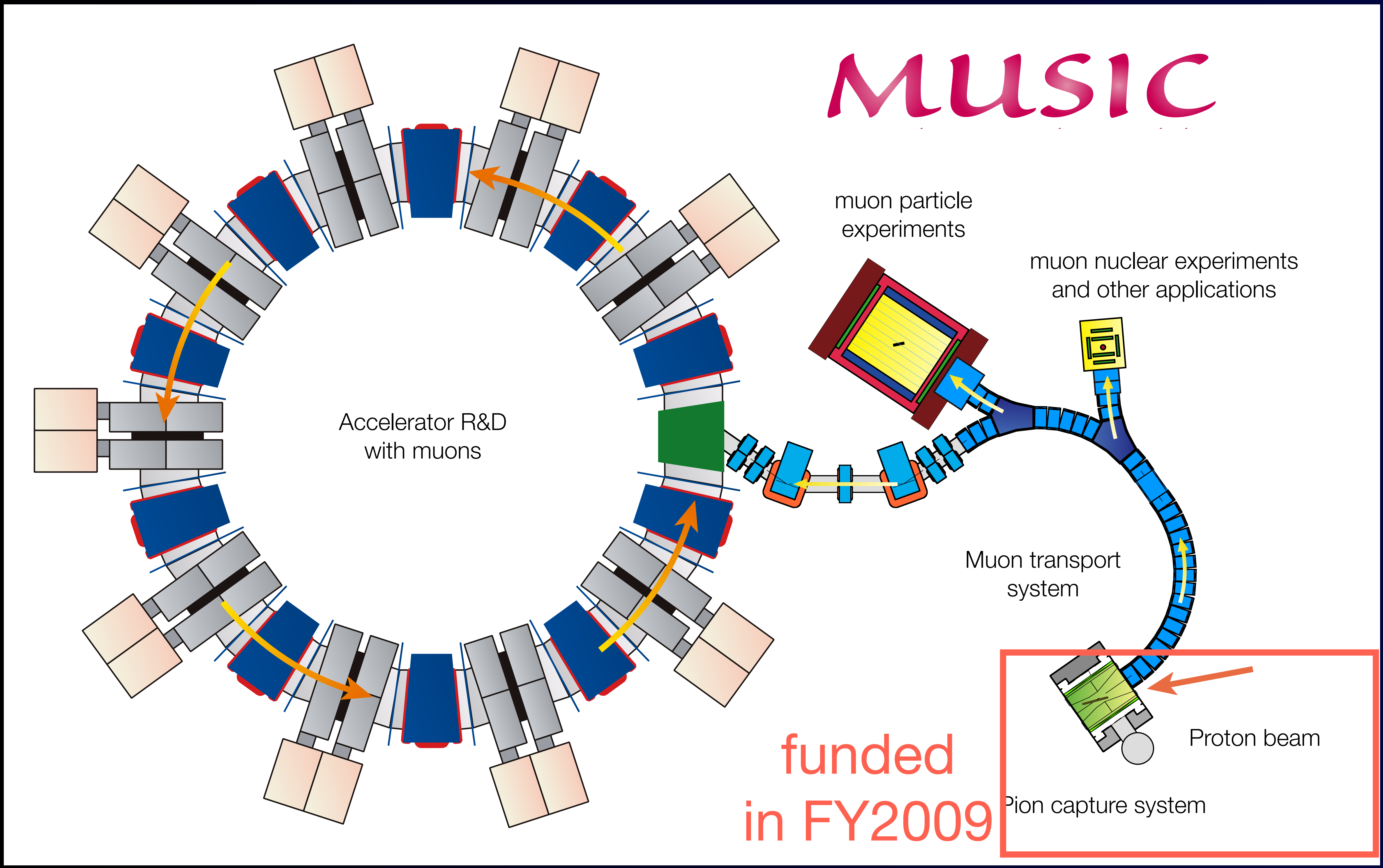


Muon Source with low proton power at Osaka U.?

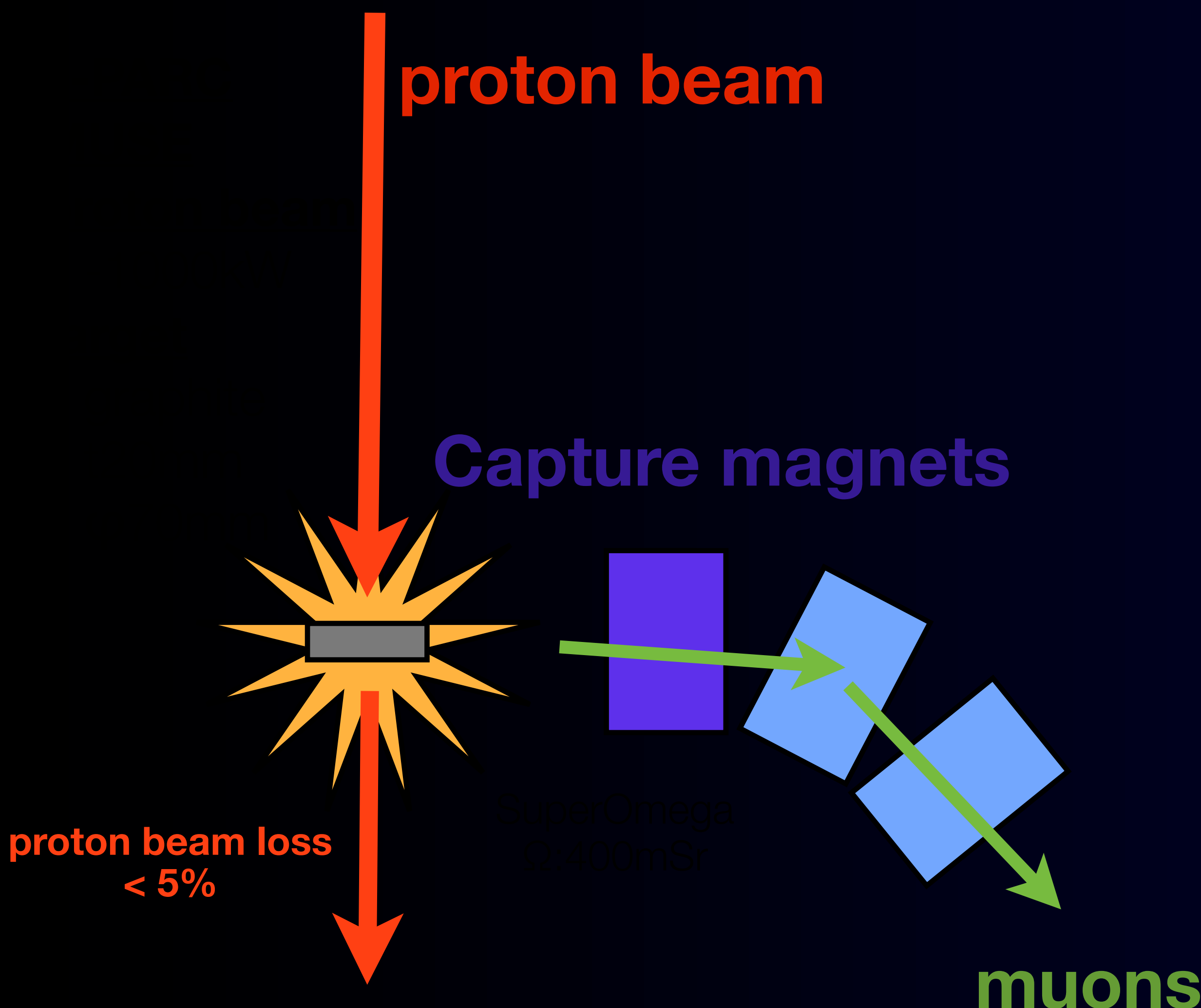
MuSIC (=Muon Science Innovative Channel)



Production and Collection of Pions and Muons

Production and Collection of Pions and Muons

Conventional muon beam line



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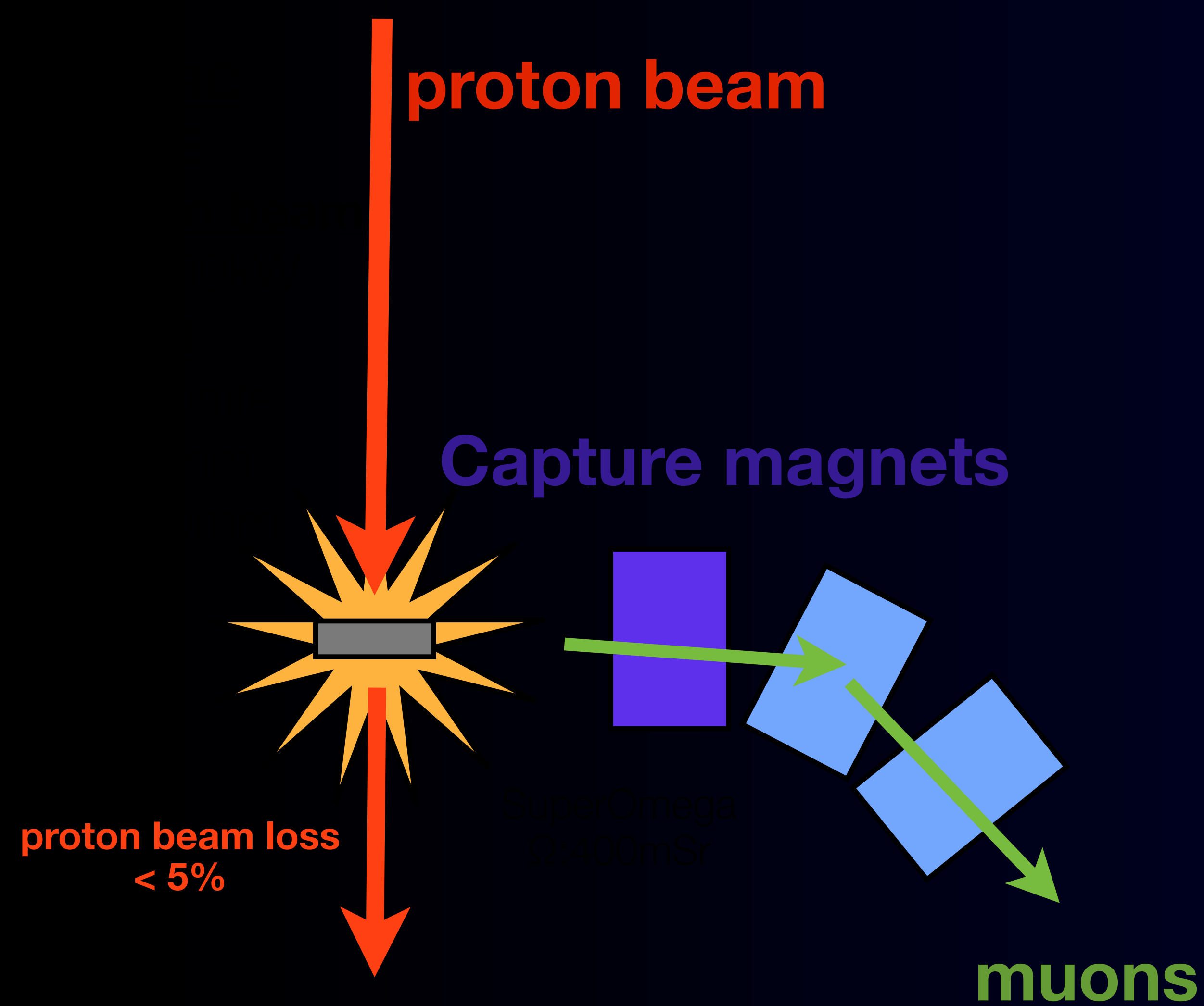
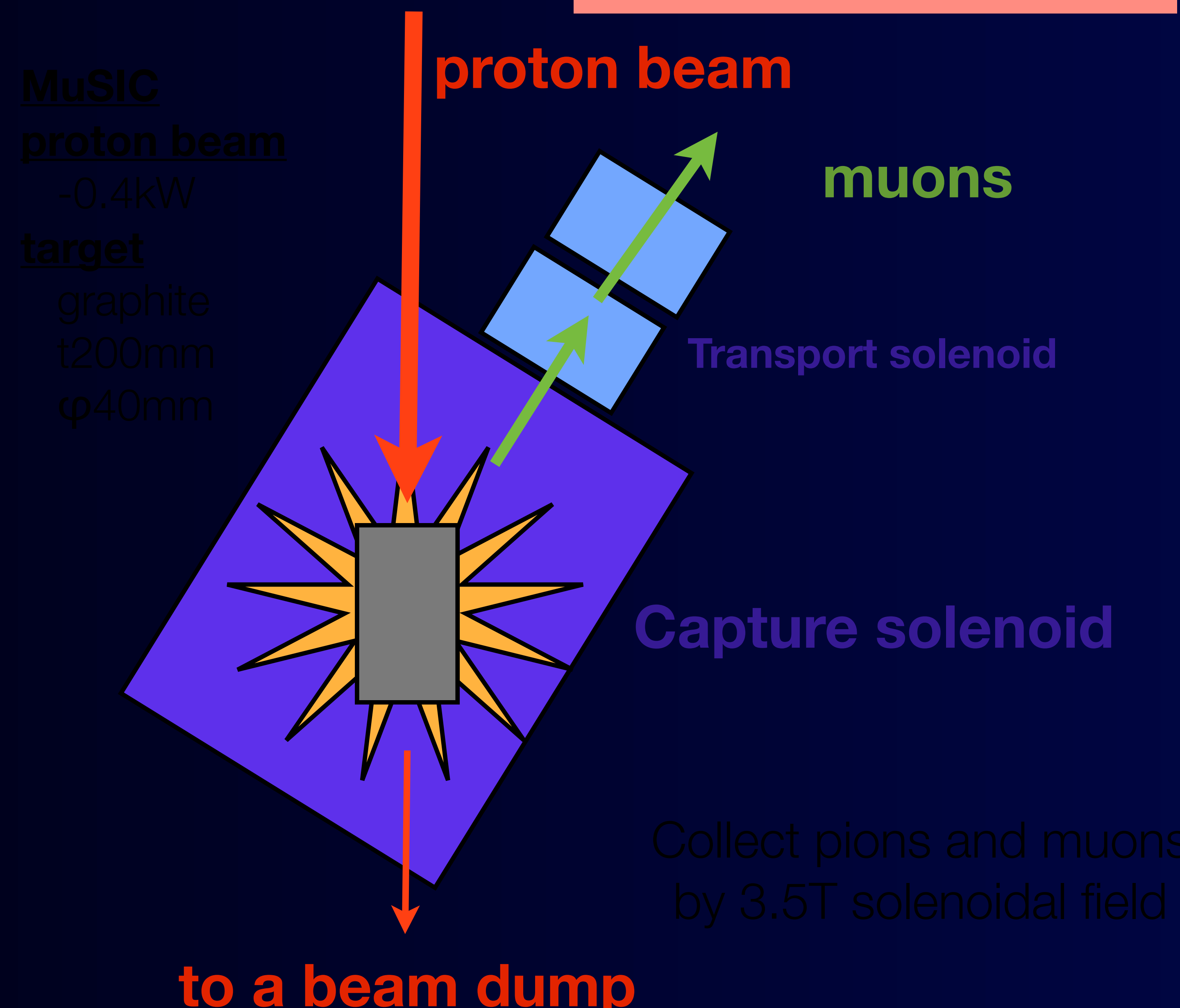


Much efficient

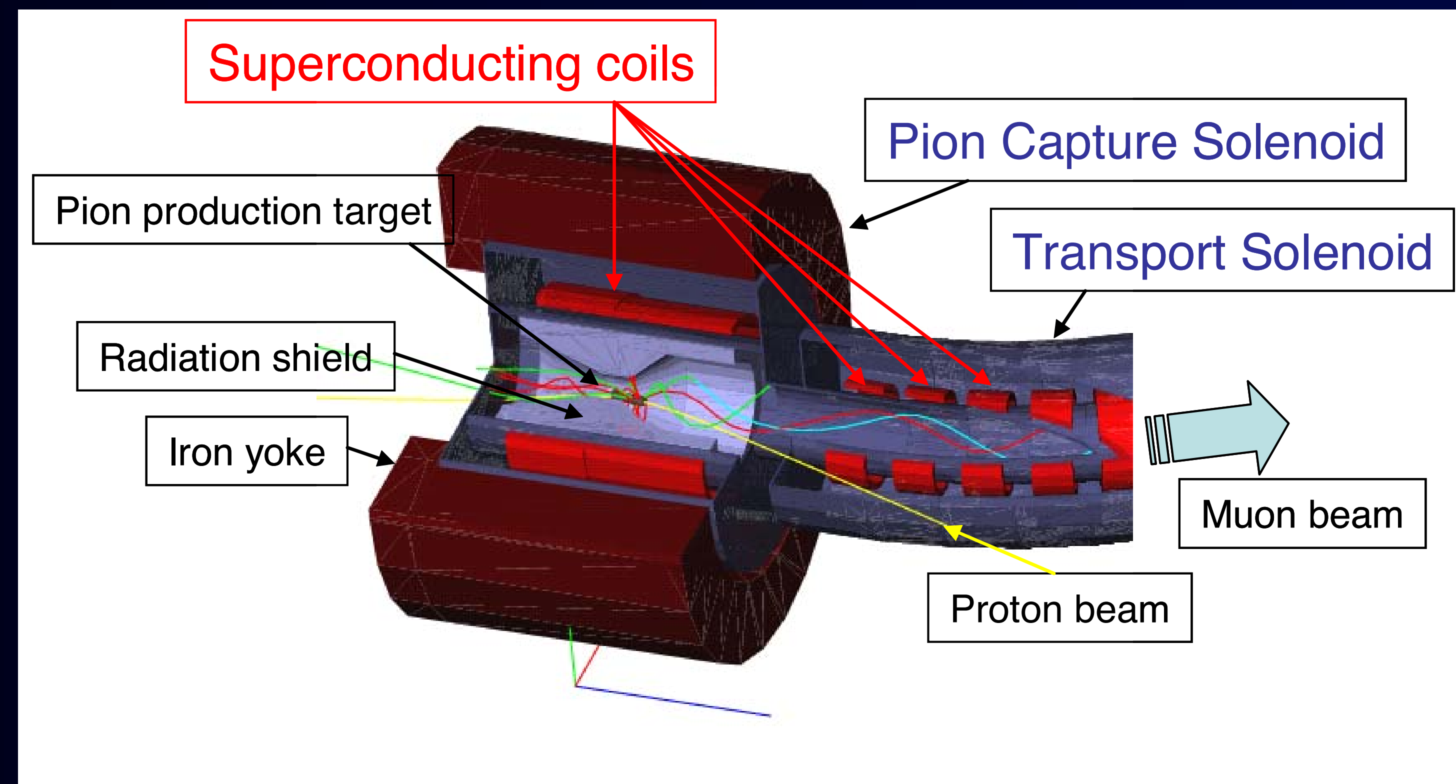
MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider

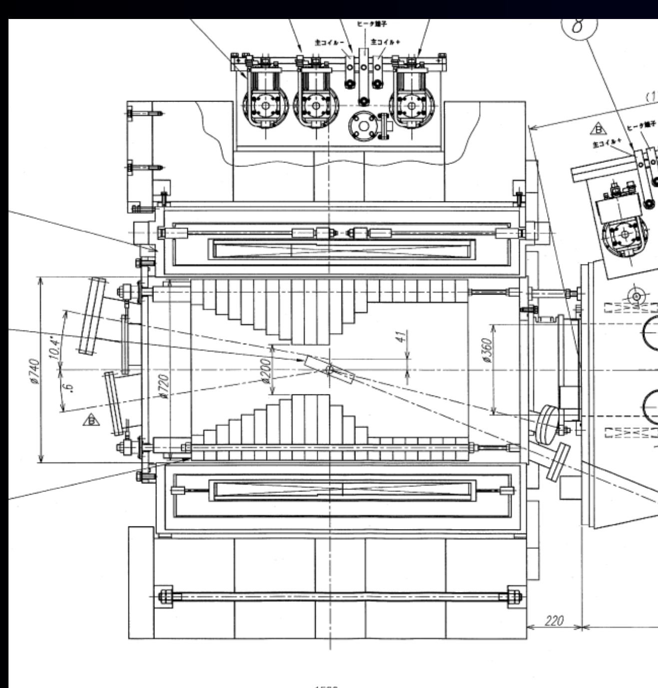


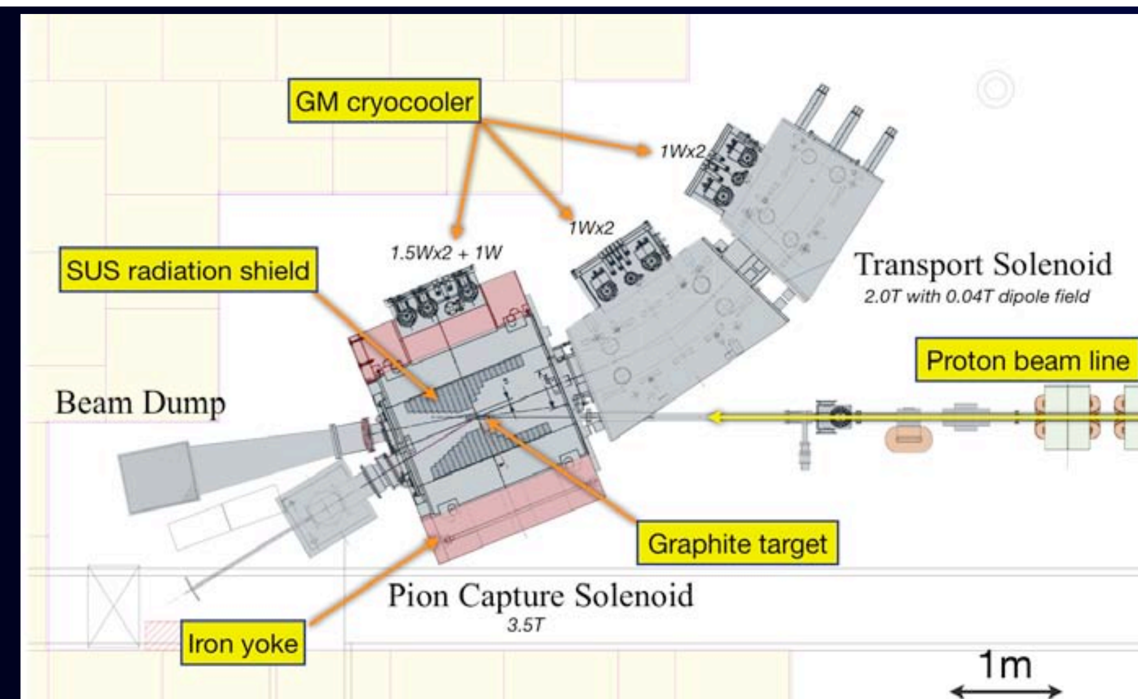
Large solid angle & thick target

Pion Capture System at MuSIC@Osaka-U

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

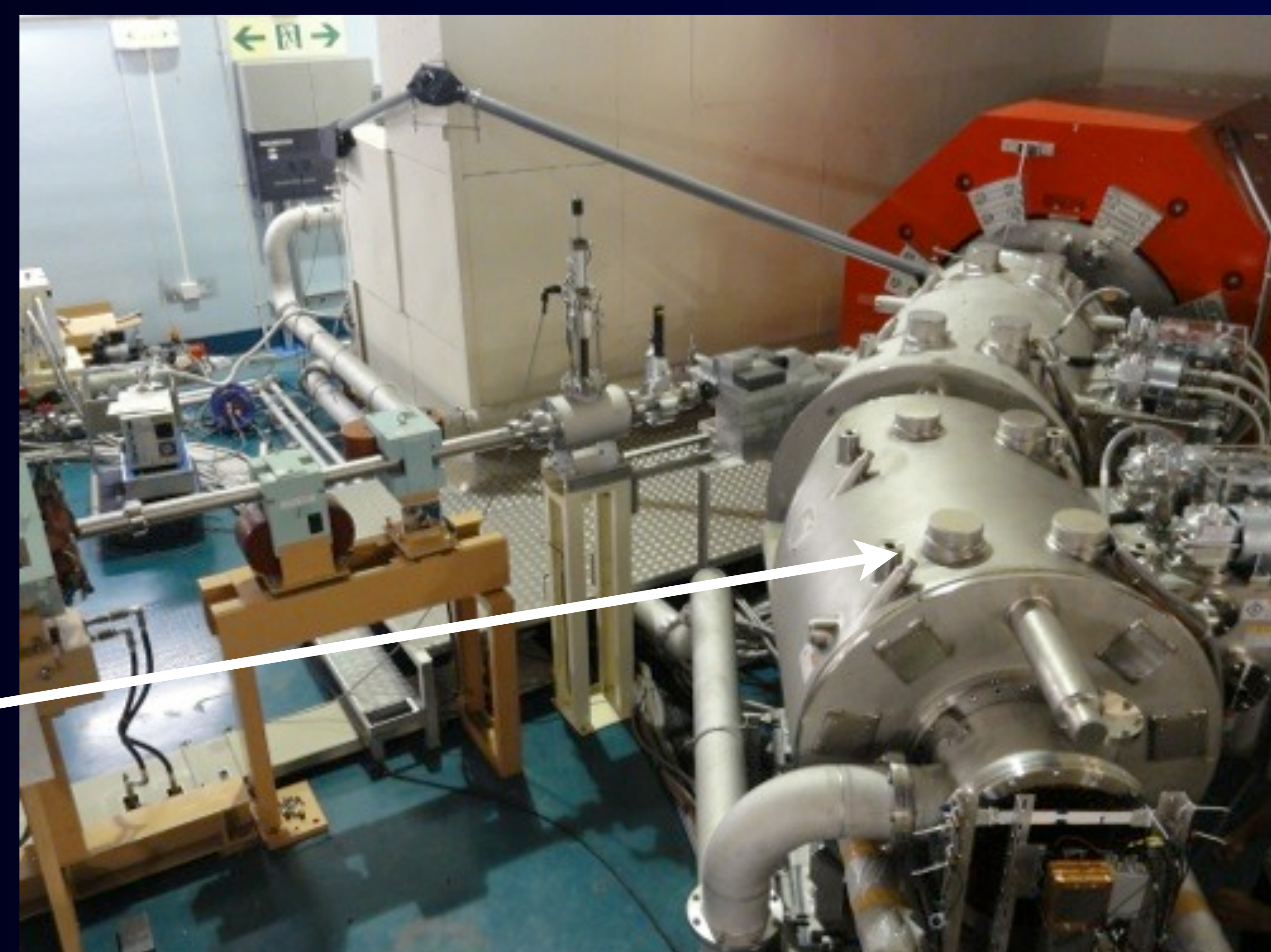






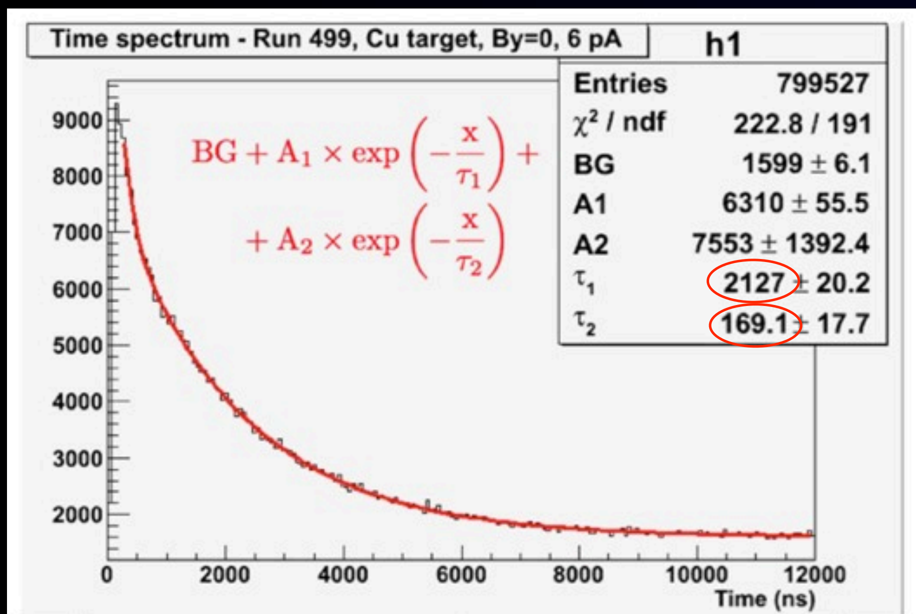
proton beam line

pion capture superconducting solenoid



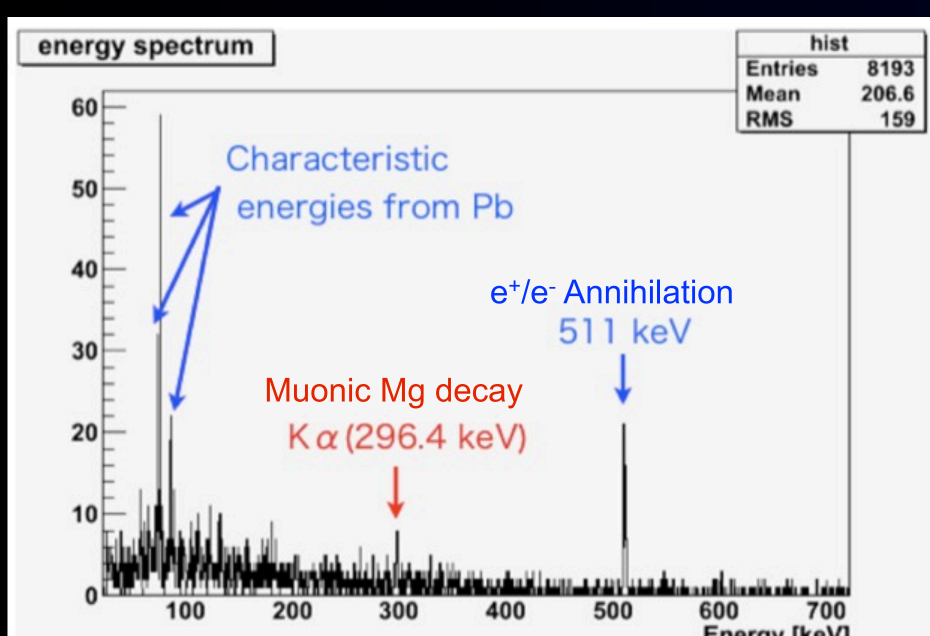
muon transport superconducting solenoid

MuSIC Beam Test in 2011



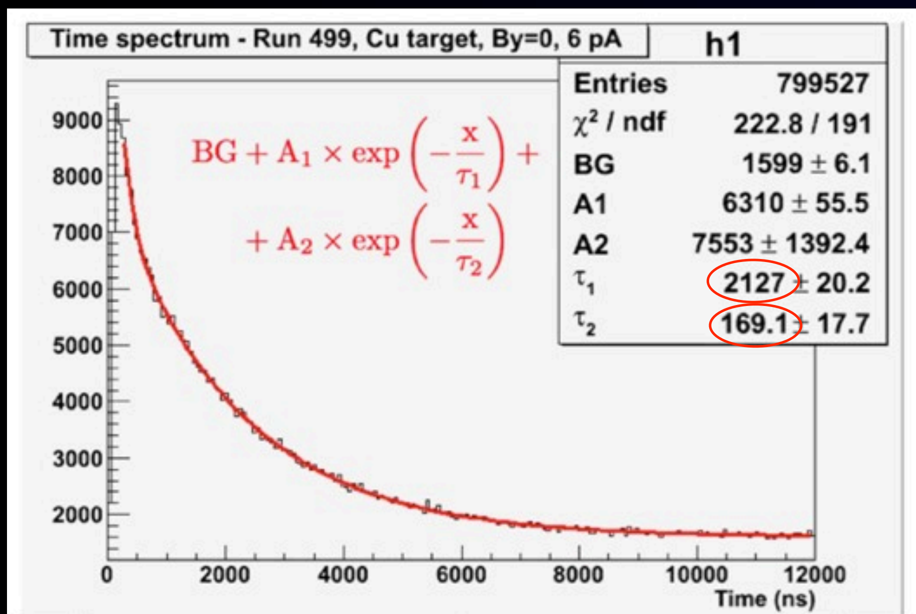
	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5

preliminary



Measurements on June 21, 2011 (6 pA)

MuSIC Beam Test in 2011



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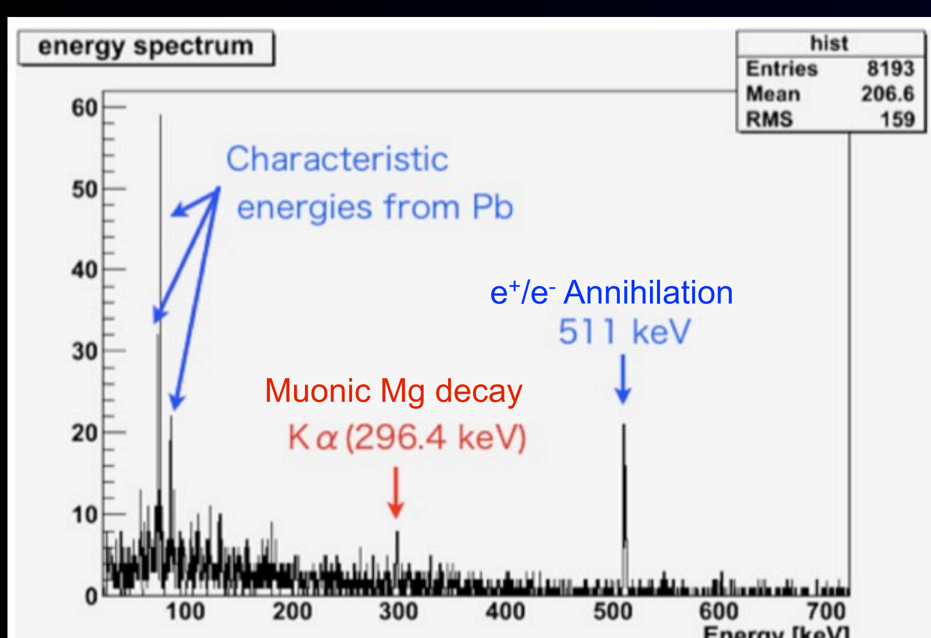


preliminary

MuSIC muon yields

μ^+ : 3×10^8/s for 400W

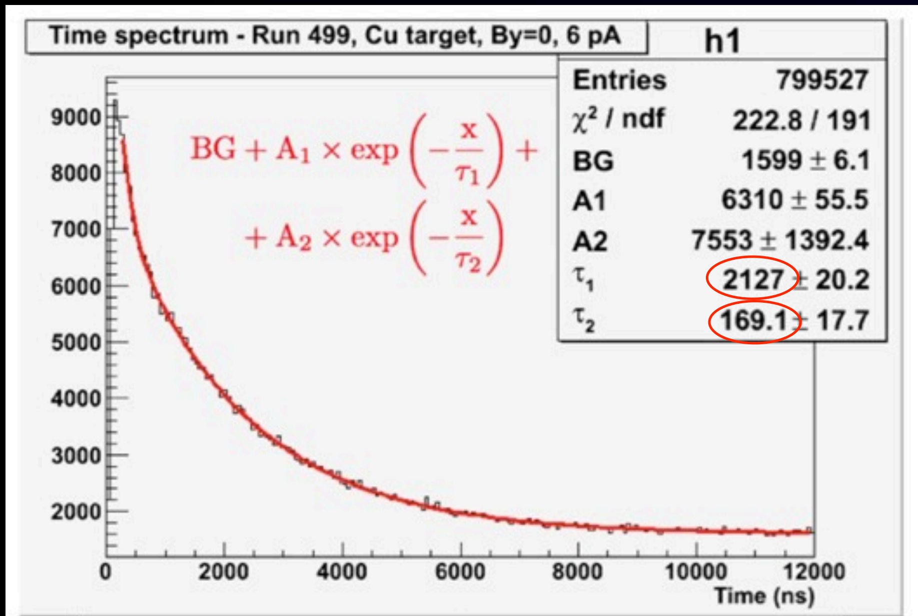
μ^- : 1×10^8/s for 400W

cf. 10^8/s for 1MW @PSI

Req. of $\times10^3$ achieved...

Measurements on June 21, 2011 (6 pA)

MuSIC Beam Test in 2011



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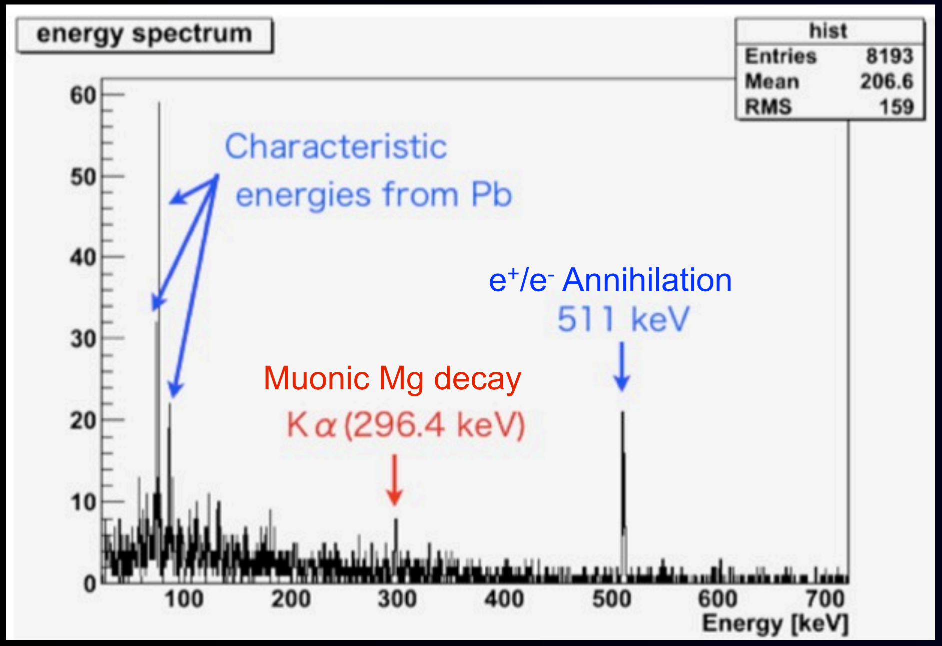
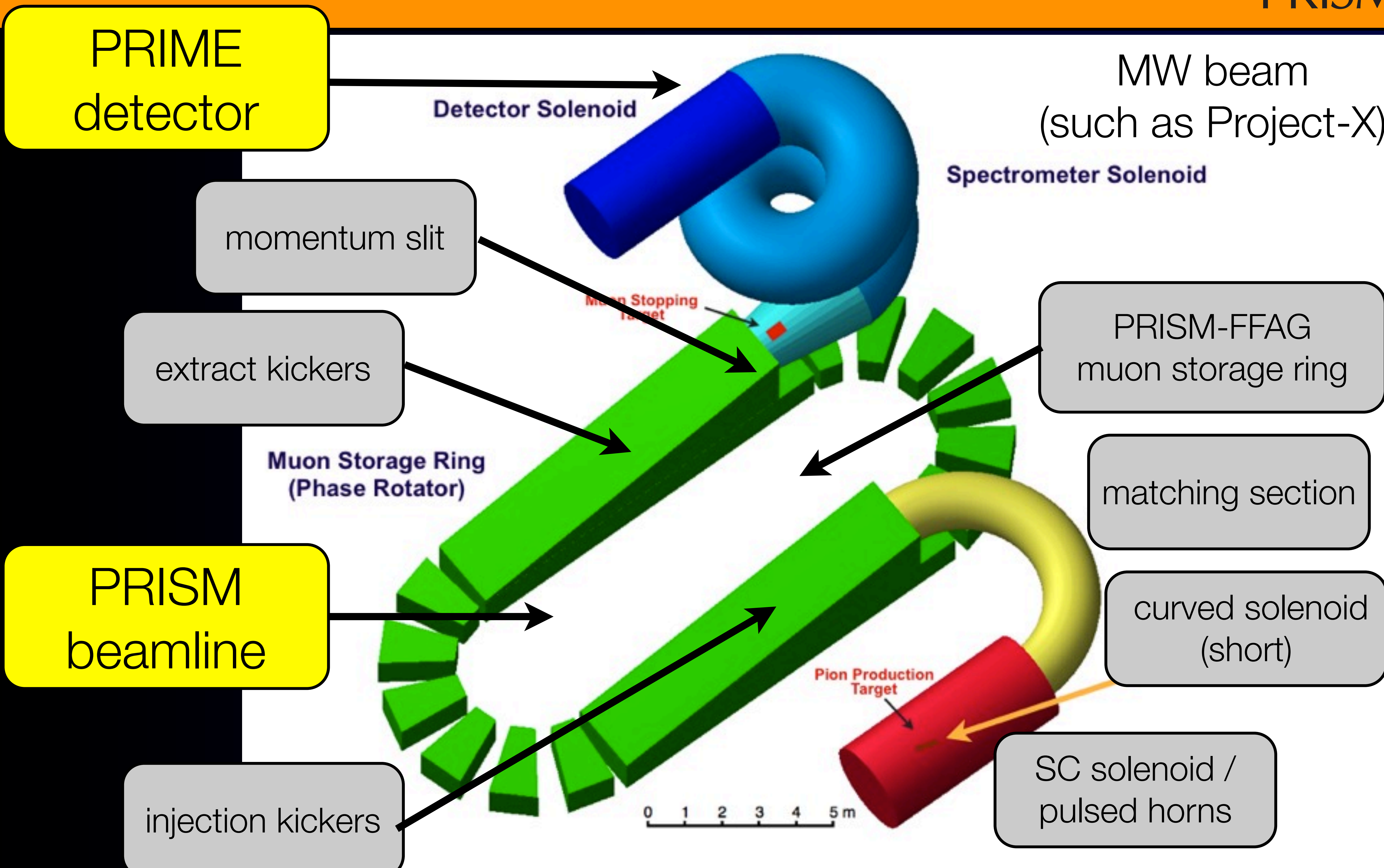


Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (6 pA)

Future Future Prospects
of μ-e conversion of 3×10^{-19}

μ-e conversion at S.E. sensitivity of 3×10^{-19} PRISM/PRIME (with muon storage ring)



R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

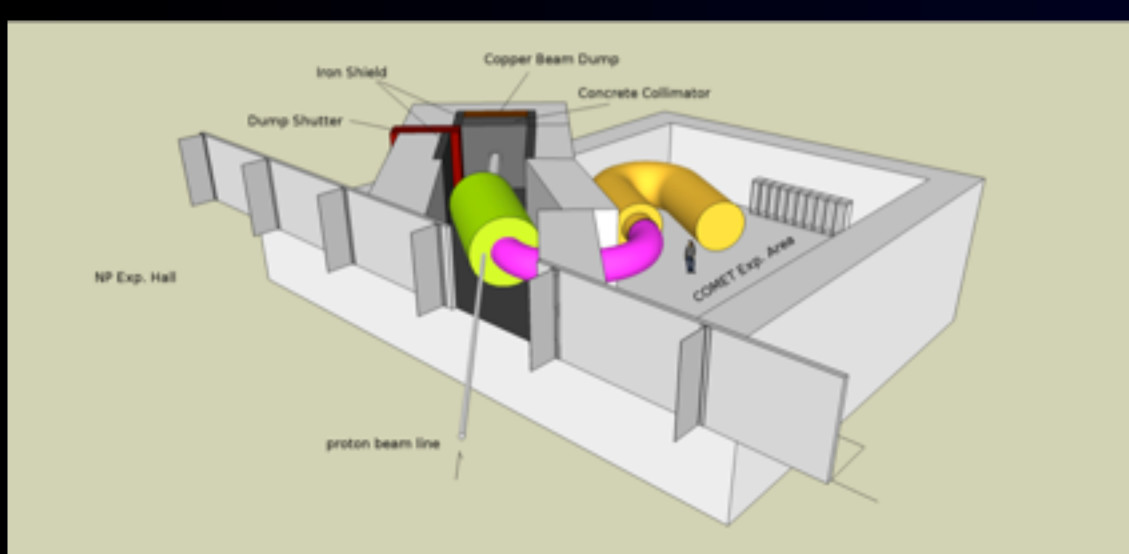
demonstration of phase rotation has been done.

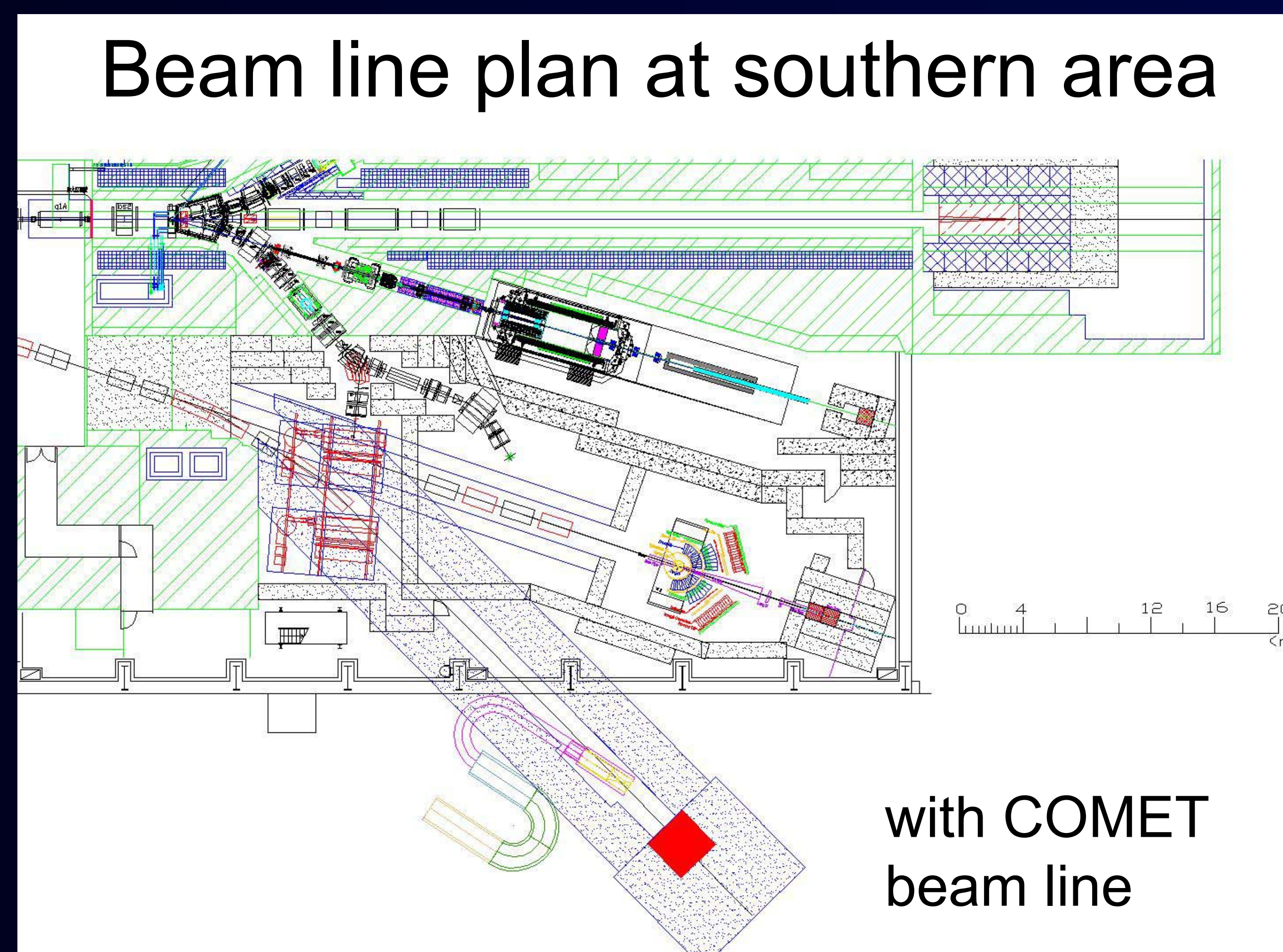
COMET Phase-I

COMET Phase-I (staged scenario)

New

- IPNS/KEK determined
  - COMET Phase-I as one of the J-PARC mid-term projects from JFY2013.
  - The other is the high-P proton beam line, which is the upstream line of the COMET.

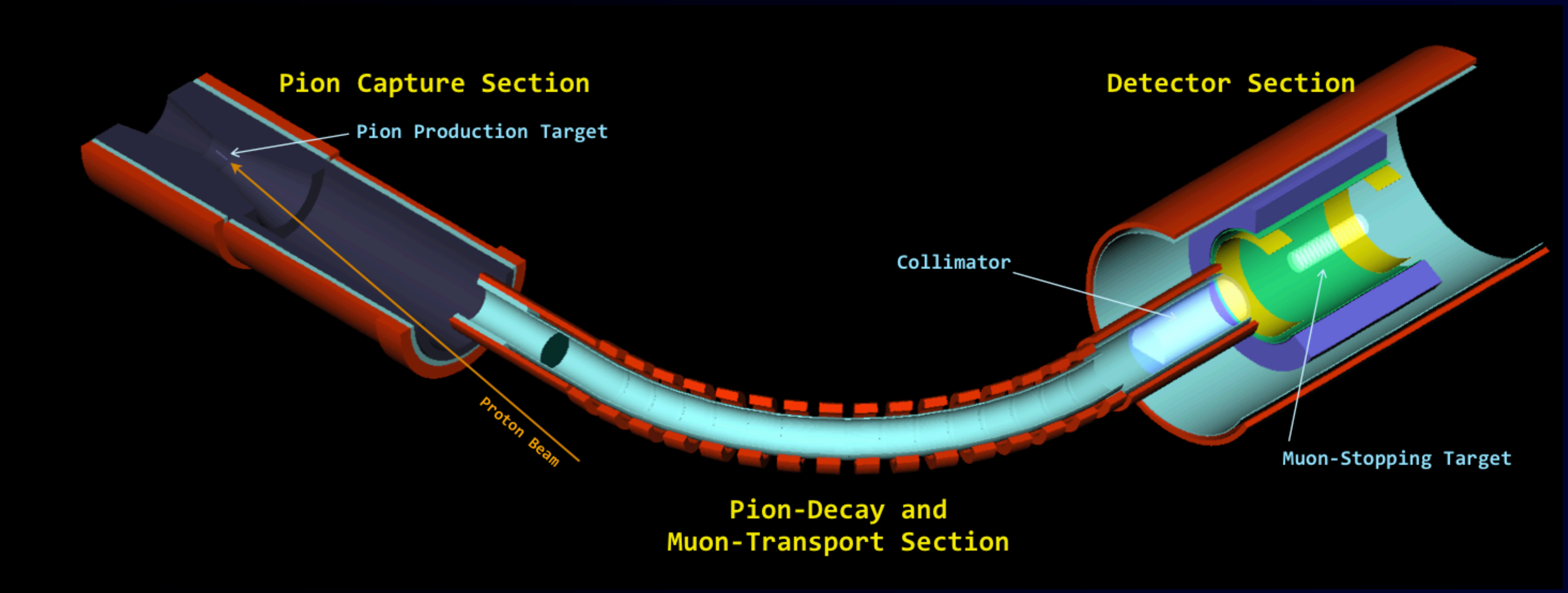


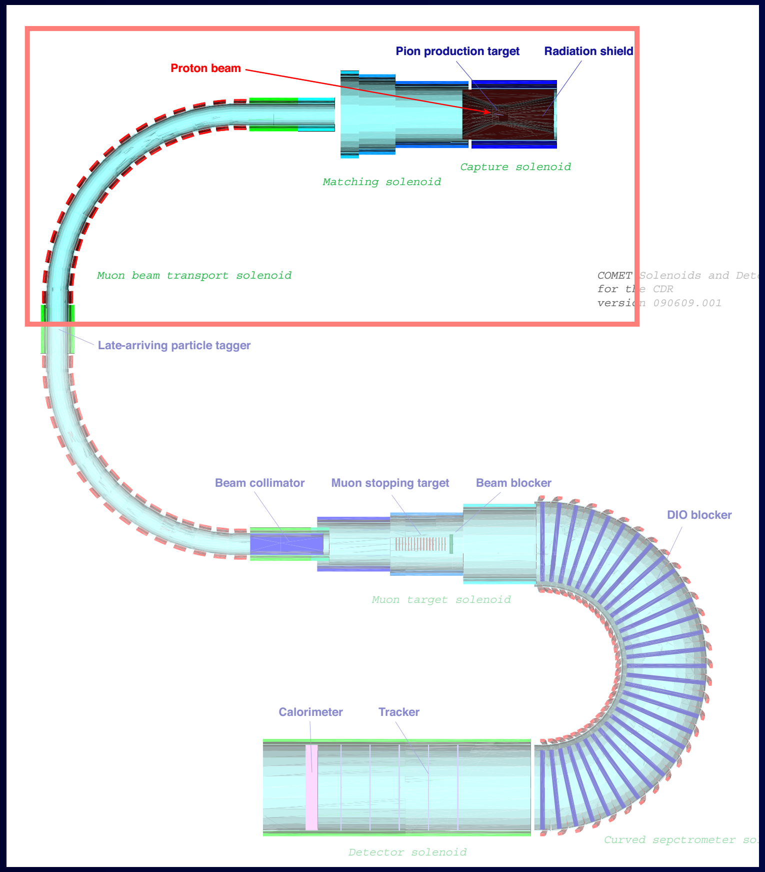


COMET Phase-I (staged scenario)

New

- Phase-I would cover ....
  - proton beam line
  - muon beam line up to the end of the first 90° bend
  - no detector
- Funding starts in JFY2013
- Experiment may start in JFY2016/17?

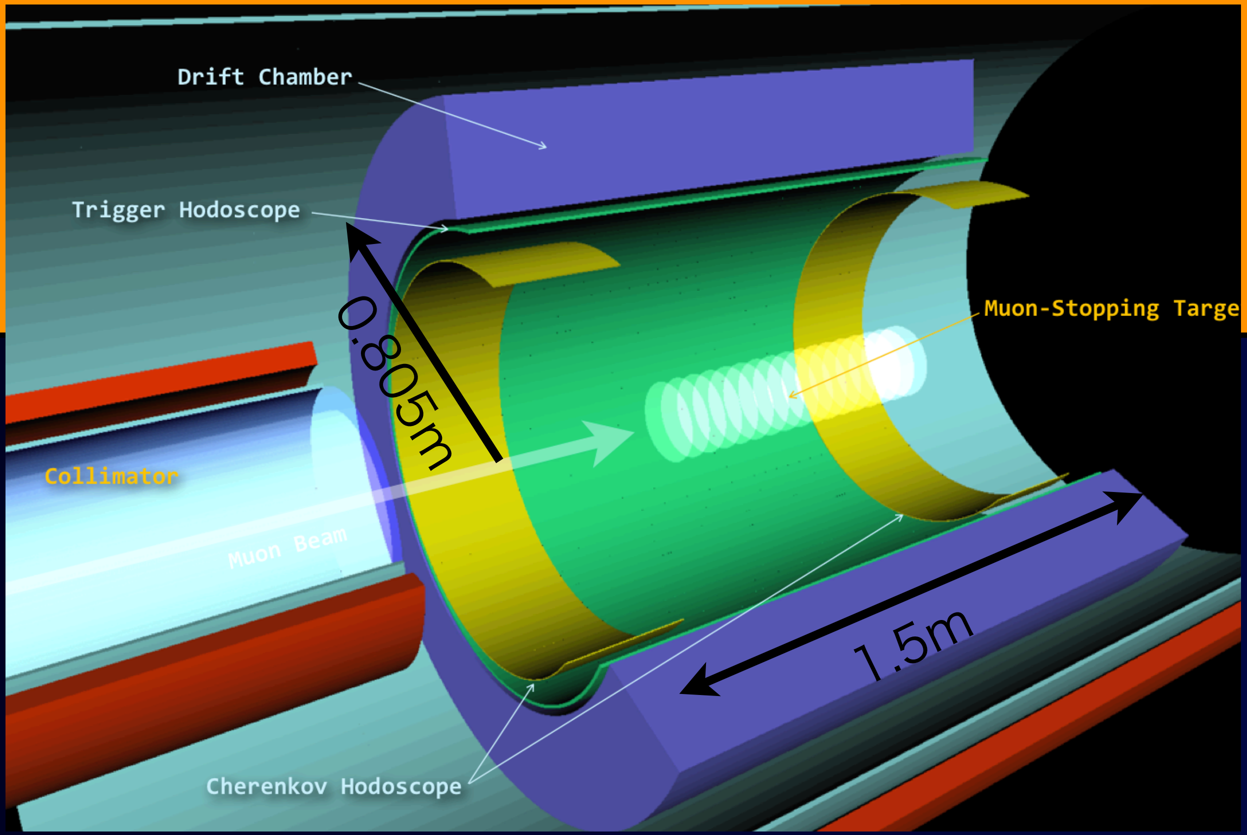


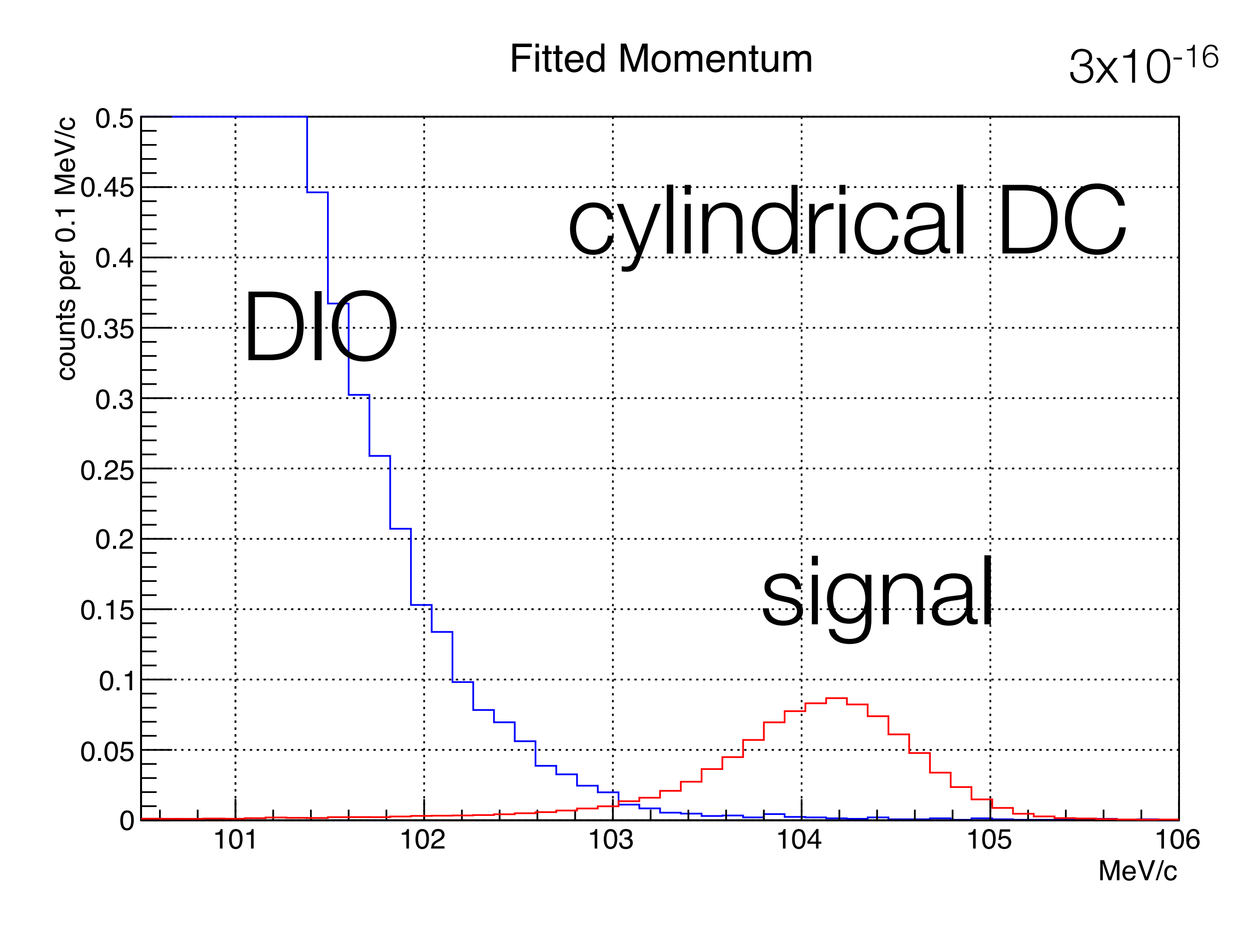


COMET Phase-I

New

- COMET Phase-I (LOI) aims ....
  - BG studies for Phase-II
    - mini Full COMET detector
    - extinction measurement
  - intermediate sensitivity
    - cylindrical drift chamber (copy of BESS-II CDC)
    - SE sensitivity~3×10^{-15} for 10^6 s (12 days) with 3 kW proton beam power (with 5×10^9 stopped μ/s).
  - if no BG, keep running for 10^7 s.
- Detector cost should be covered by the collaboration.
- The proposal submitted soon.





Summary

Summary

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- The field of CLFV gets important and exciting.
- COMET at J-PARC is aiming at S.E. sensitivity of 3×10^{-17}.
- The COMET Phase-I is aiming at S.E. sensitivity of 3×10^{-15} and hopefully the construction will start in 2013.
- R&D on PRISM/PRIME for S.E.3×10^{-19} is going.
- and ... MuSIC@Osaka ~10^{8} μ/s with 400 W.

- New collaborators are welcome....