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

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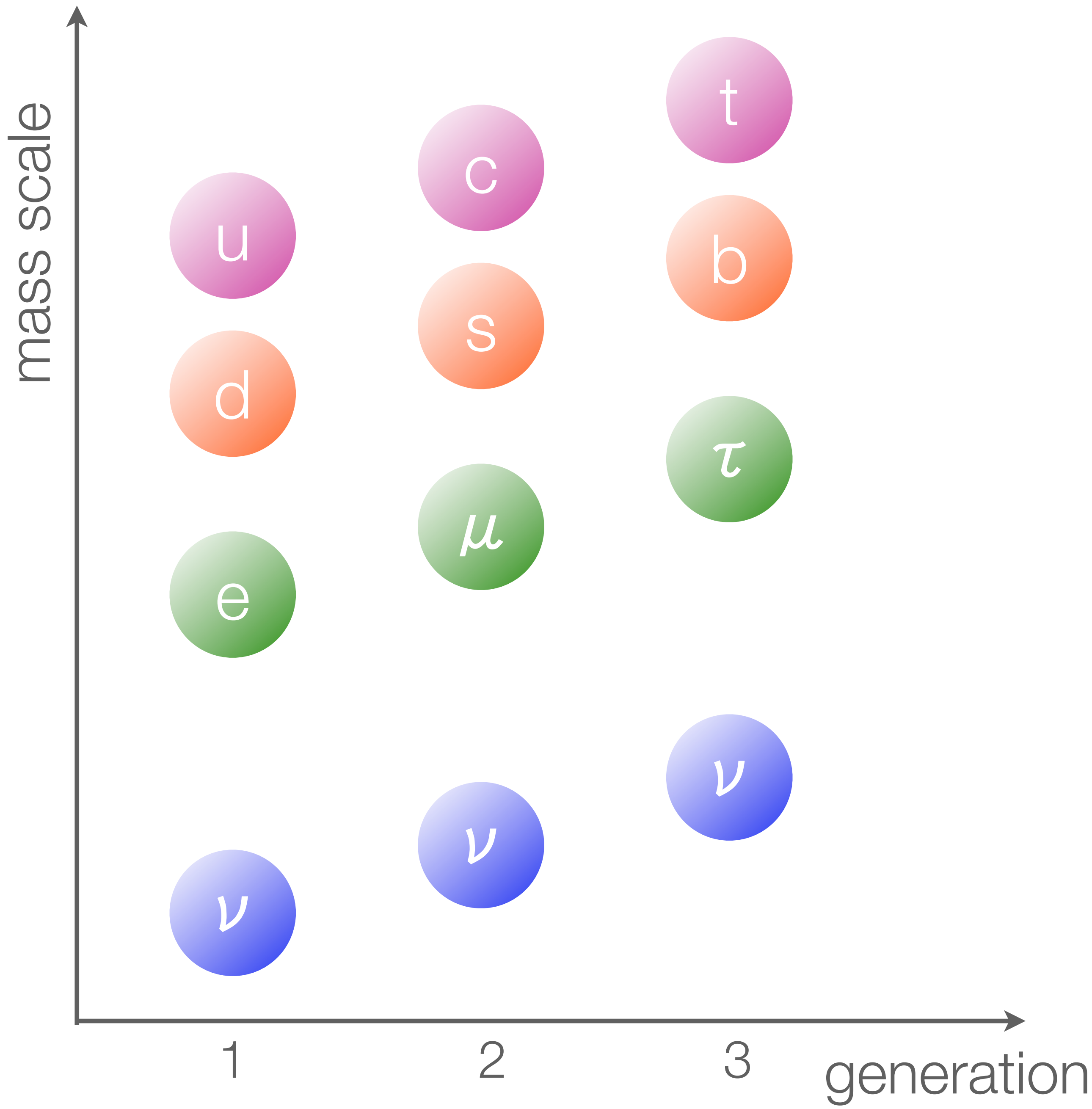
- Flavour Physics
- Charged LFV in Muon Decay
- Are You Ready ?
- R & D
- Current Status

- Flavour Physics -

in particular, charged lepton flavour violation
(so called "CLFV")

Flavour Violation



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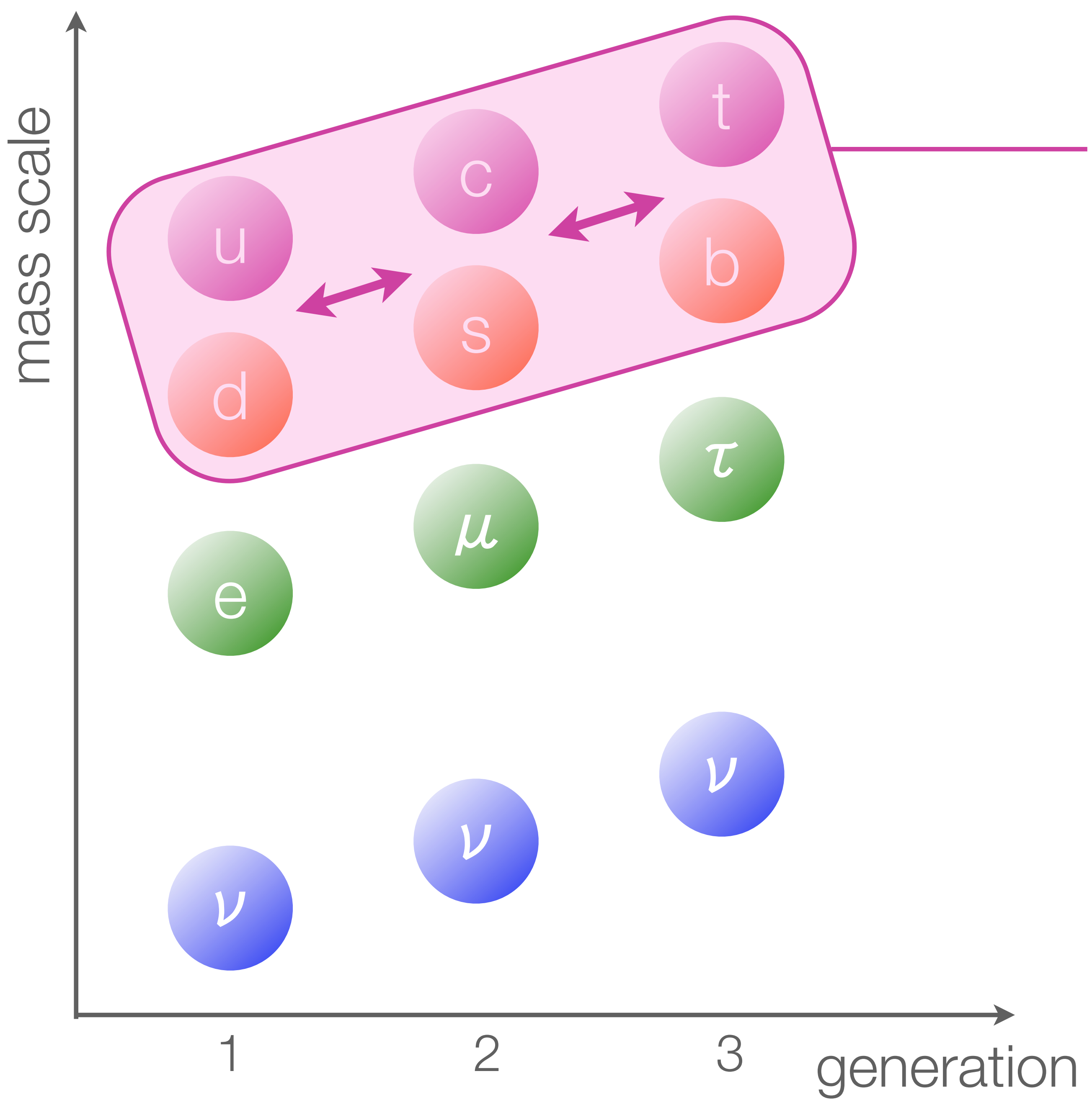
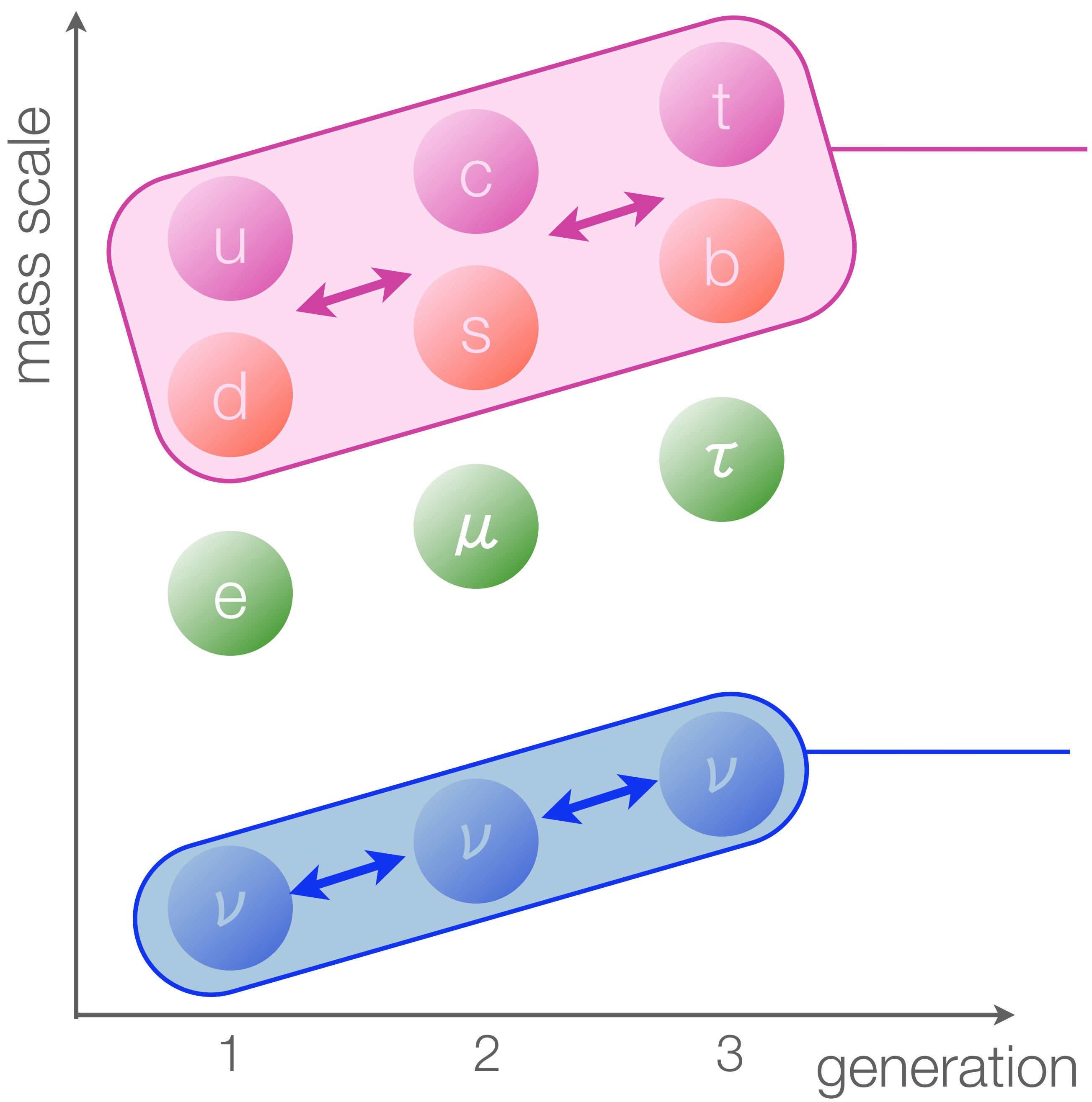


Quark Sector

- Mixed by CKM mechanism
- Experimentally Verified
  - ➡ by B-factories

Flavour Violation



Quark Sector

- Mixed by CKM mechanism
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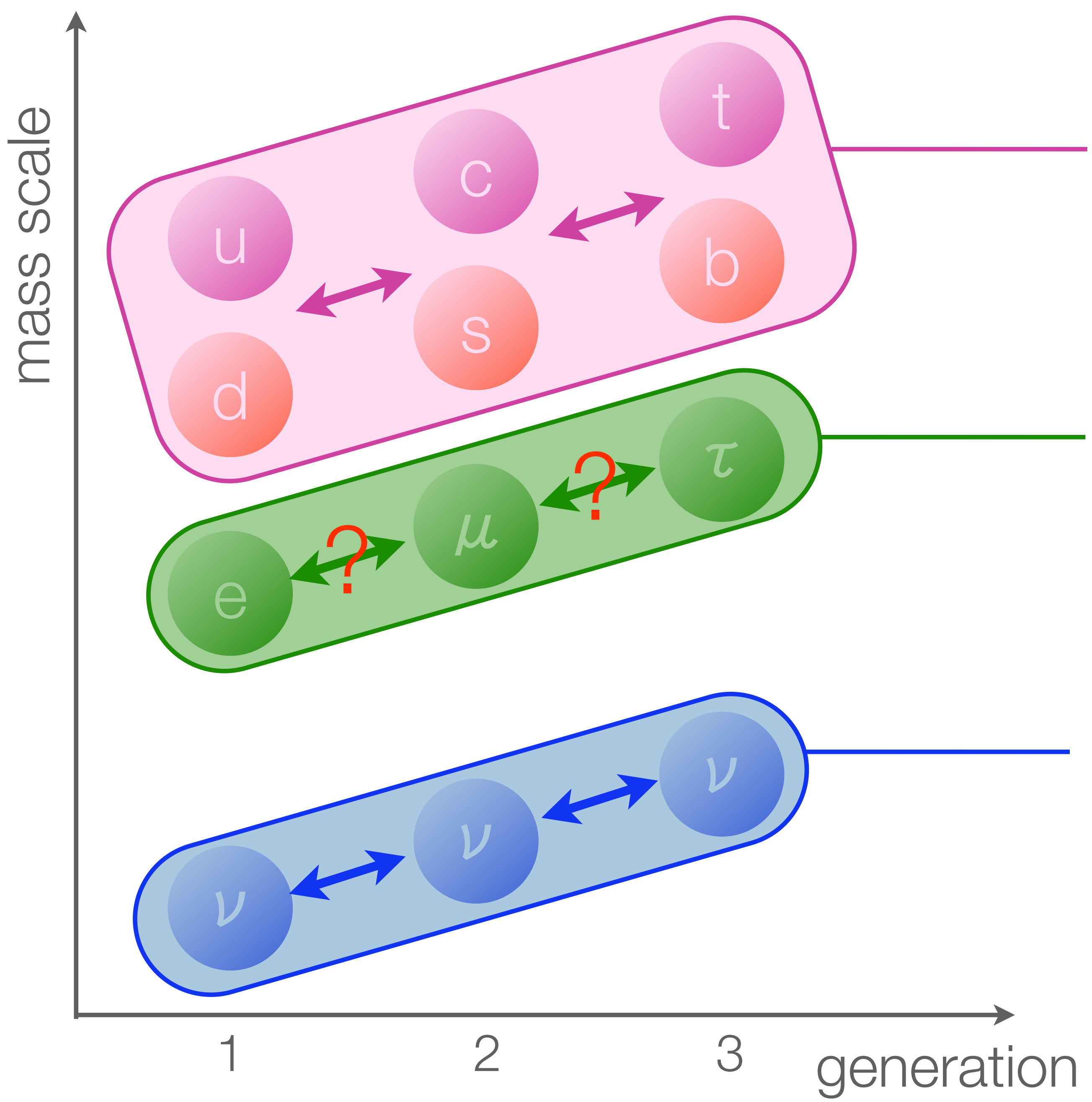
neutral Lepton Sector

- Neutrino Oscillation
- Experimentally Verified
  - ➡ by SK, KamLAND, T2K etc.

Flavour Violation



Quark Sector

- Mixed by CKM mechanism
- Experimentally Verified
  - ➡ by B-factories

charged Lepton Sector

- never observed yet !!
- source from beyond SM ??

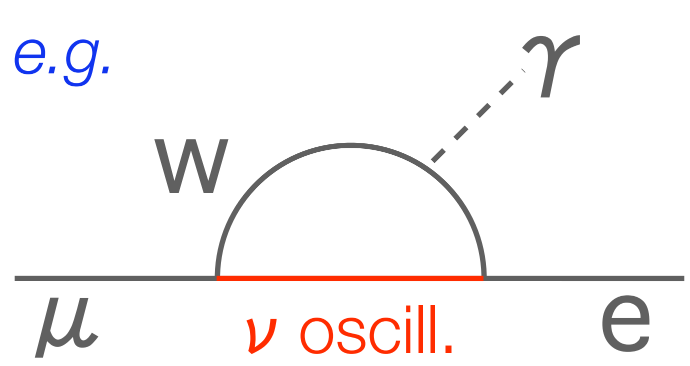
neutral Lepton Sector

- Neutrino Oscillation
- Experimentally Verified
  - ➡ by SK, KamLAND, T2K etc.

Why charged LFV has never been observed ?

SM + simple ν Oscillation

- charged LFV is possible



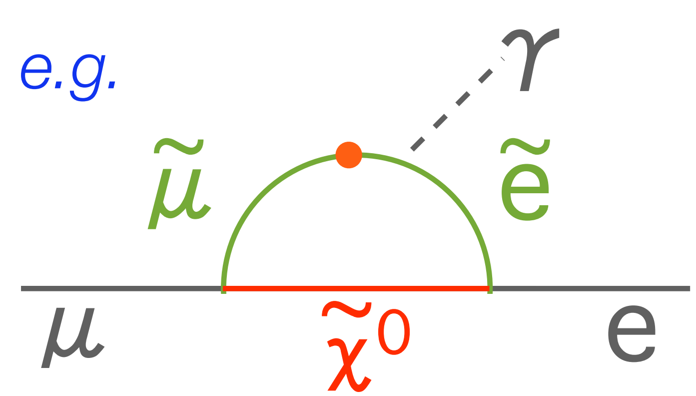
- but extremely rare (small ν)

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

- $B(\mu \to e\gamma) = 10^{-50} \sim 10^{-40}$!!!

beyond SM (SUSY-GUT etc.)

- charged LFV is largely enhanced



- still rare but observable level

$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

- $B(\mu \to e\gamma) = 10^{-15} \sim 10^{-11}$!!!

Why charged LFV is so Attractive ?

- Only charged LFV has never been observed.
- Neutrino Oscillation is possible by "SM + ν mass"
- Quark Mixing is generally contaminated by SM

→ charged LFV **is** "NEW PHYSICS"

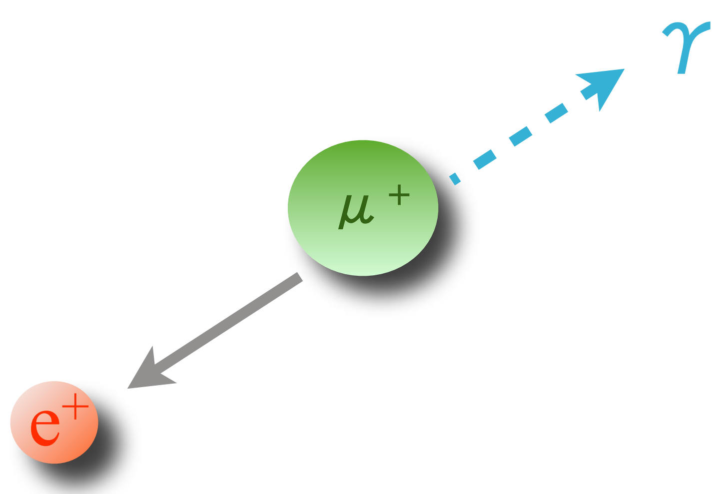
- Experimental Upper Limit is already sensitive to predicted region.
- Search for Muon Rare Decay is the most suitable.
  - Once we have a powerful proton driver, muon can be generated very easily.

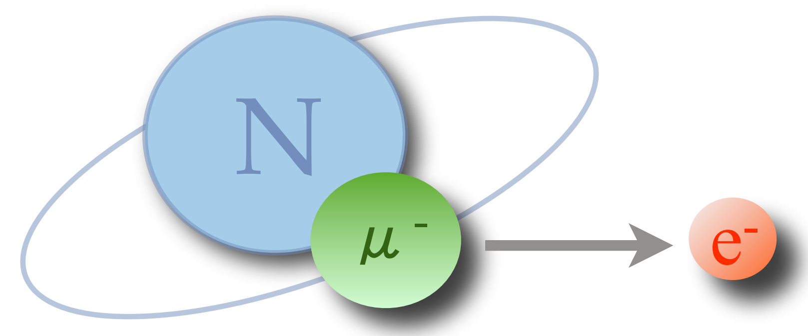
- Charged LFV in Muon Decay -

in particular, rare decay search for muon to electron conversion
(so called "μ-e conversion")

Two Muon LFV Processes

Two Muon LFV Processes

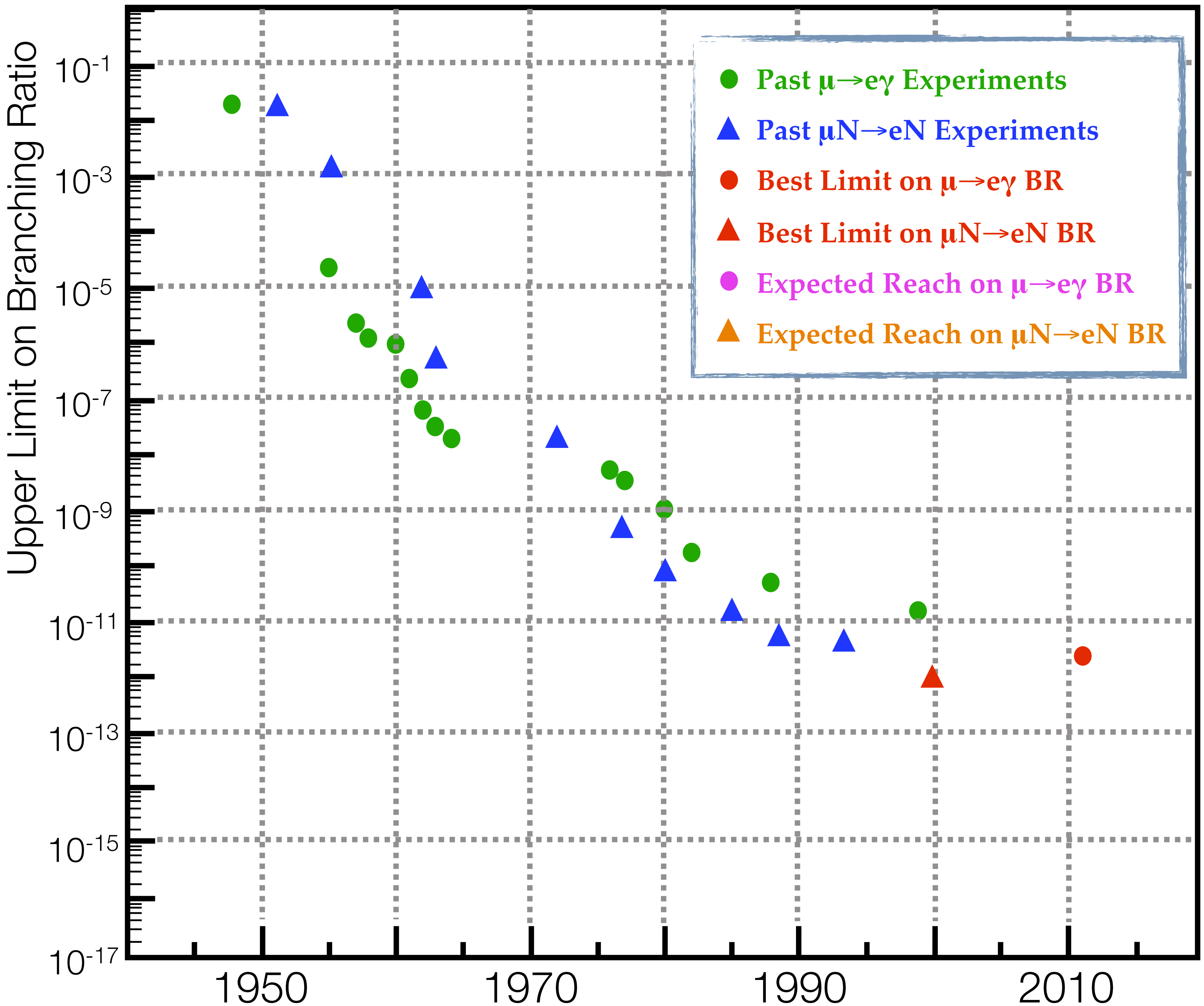




$\mu \rightarrow e\gamma$

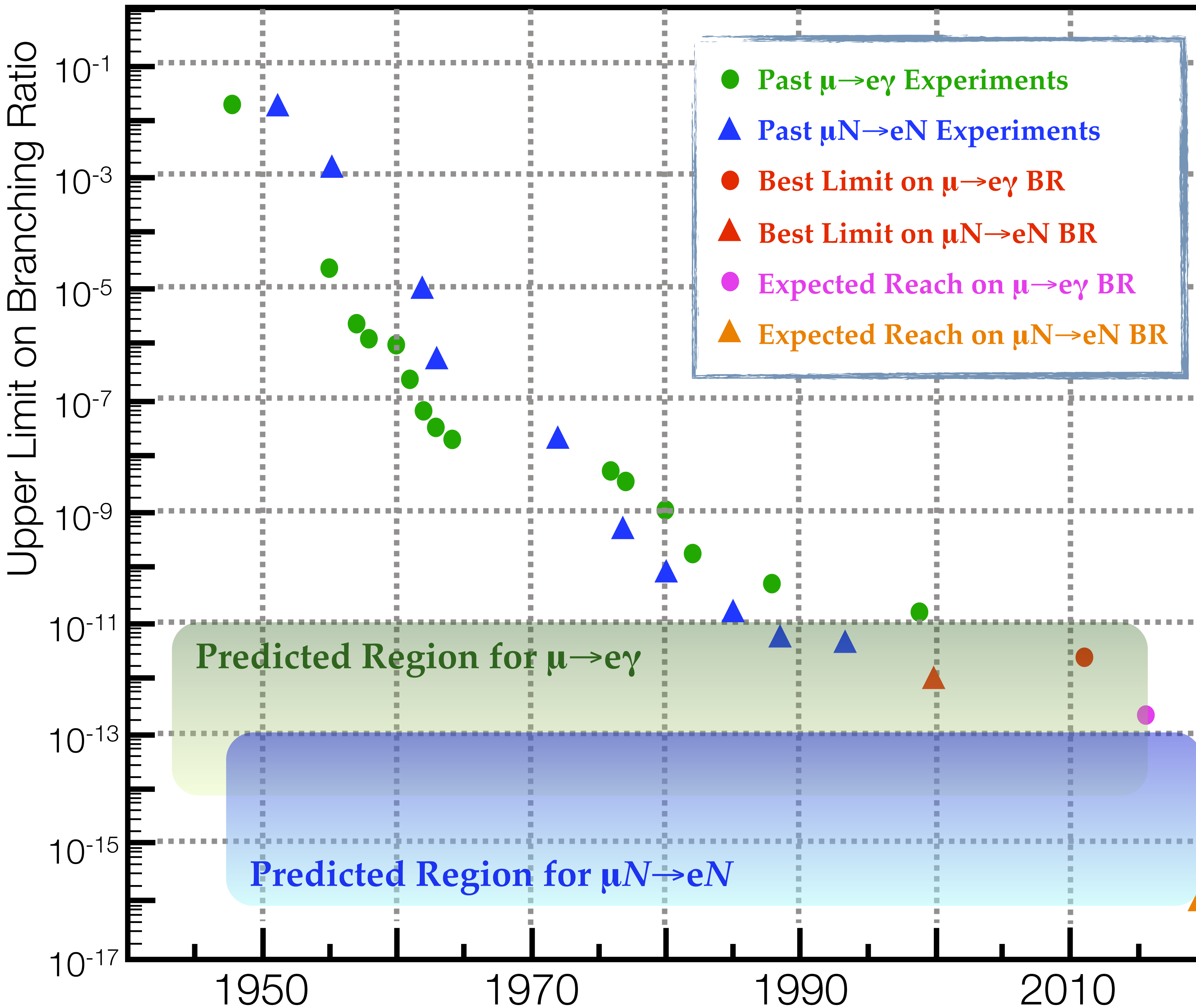
$\mu N \rightarrow eN$

History of Muon LFV Experiments



- Long Tradition on the **μ→eγ / μN→eN** Search Experiment
- Started right after the muon discovery
- **μ→eγ** has already entered the predicted region !!
- **μN→eN** is shitting at just in front of the predicted region !!
- **NOW VERY VERY ATTRACTIVE !!!!!**

History of Muon LFV Experiments



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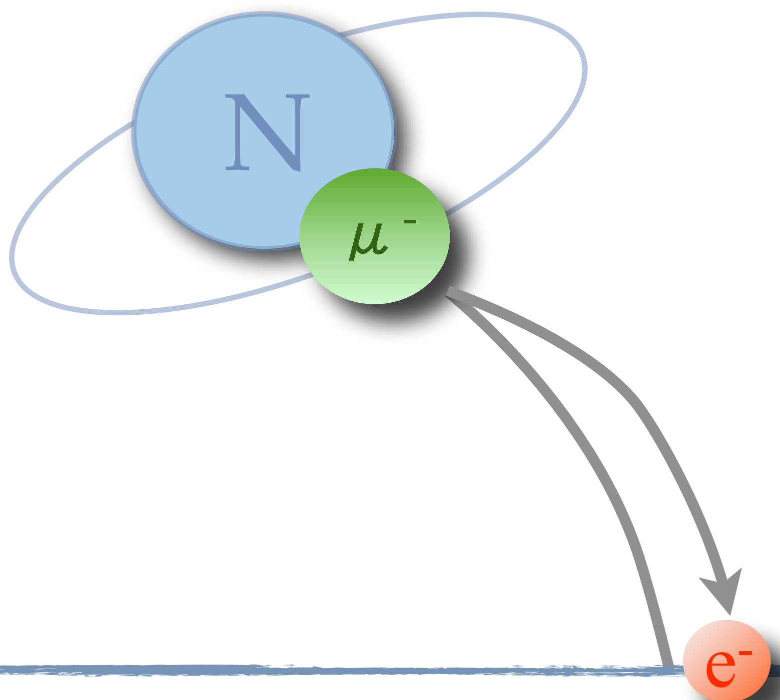
What is a Muon to Electron Conversion ?

- *1S* state in a muonic atom



Muon Decay in Orbit (DIO)

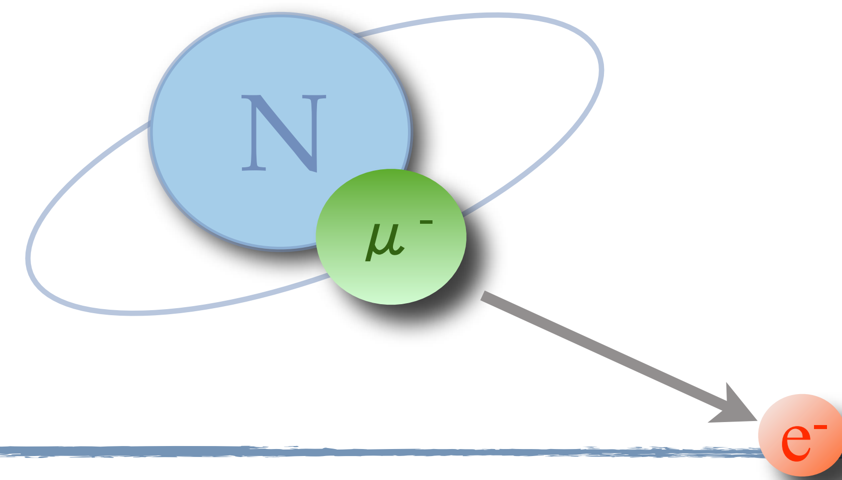
$$\mu^- \to e^- \nu_\mu \bar{\nu}_e$$

or

Nuclear Muon Capture

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

- If μ-e Conversion is Occurred ...



Neutrino-less Muon Nuclear Capture

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

- Branching Ratio is Determined as

$$\mathcal{B}(\mu^- N \to e^- N) = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu N')}$$

Experimental Signature

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

- **Signal**
  - Single Monochromatic Electron

$$m_\mu - B_\mu \sim 105\text{MeV}$$

  - Coherent Process
    - N_{initial} and N_{final} is Same

$$\propto Z^5$$

- **Backgrounds**
  - **Muon Decay in Orbit (DIO)**
    - Endpoint comes to the signal region

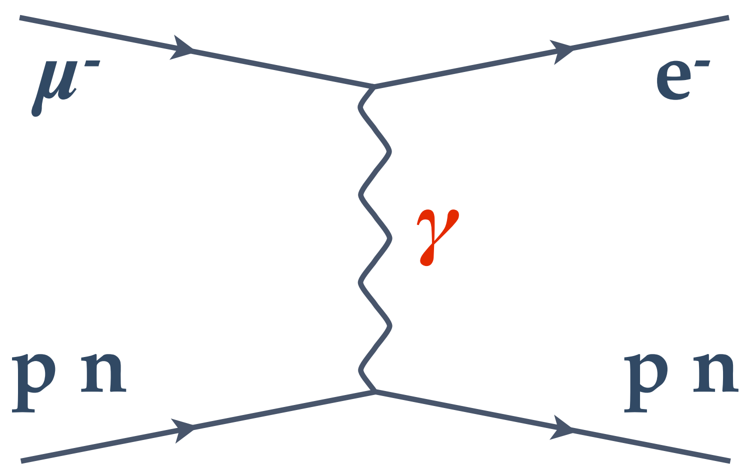
$$\propto (\Delta E)^5$$

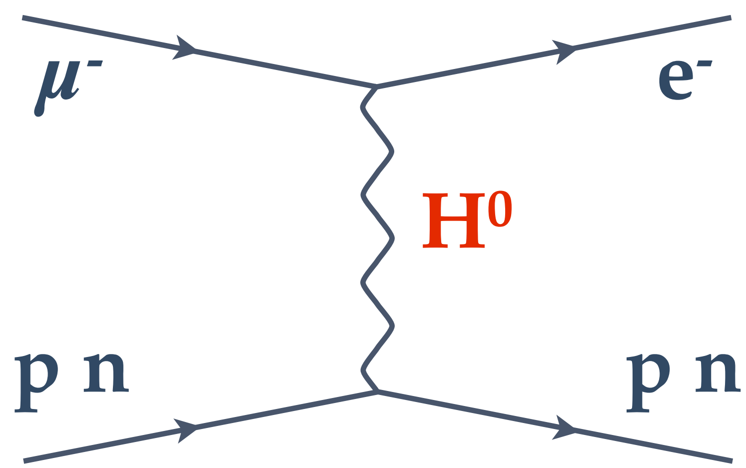
  - **Radiative Muon Capture**
  - **Radiative Pion Capture**
    - **Pulsed Beam Required**
    - **Wait until Pions Decay**
  - **Electrons from muon DIO**
  - **Cosmic Rays**
  - *etc.*

μ→eγ vs. μN→eN (*Physics* point of view)

- Sensitivity for "**photonic**" and "**non-photonic**" processes is different.

for example,
(μN→eN)





	photonic (*eg*. SUSY-base Models, *etc*.)	non-photonic (*eg*. Extra-D, Little-H, *etc*.)
μ→eγ	**YES** (on-shell)	**NO**
μN→eN	**YES** (off-shell)	**YES**

$$\frac{\mathcal{B}(\mu \to e\gamma)}{\mathcal{B}(\mu N \to eN)} \sim 100 \qquad \frac{\mathcal{B}(\mu \to e\gamma)}{\mathcal{B}(\mu N \to eN)} \sim 1$$

$\mu \to e\gamma$ vs. $\mu N \to eN$ (*Experimental* point of view)

	$\mu \to e\gamma$	$\mu N \to eN$
Dominant B.G.	Accidental	Beam related
Challenge	Detector Performance	Beam Quality
Suitable Muon Source	DC Muon Beam	Pulsed Muon Beam
Beam Intensity	(almost) Limited	No Limitation

- **$\mu \to e\gamma$** : accidental B.G. $\propto$ (rate)^2
  - MEG (and its upgrade) may be the final experiment

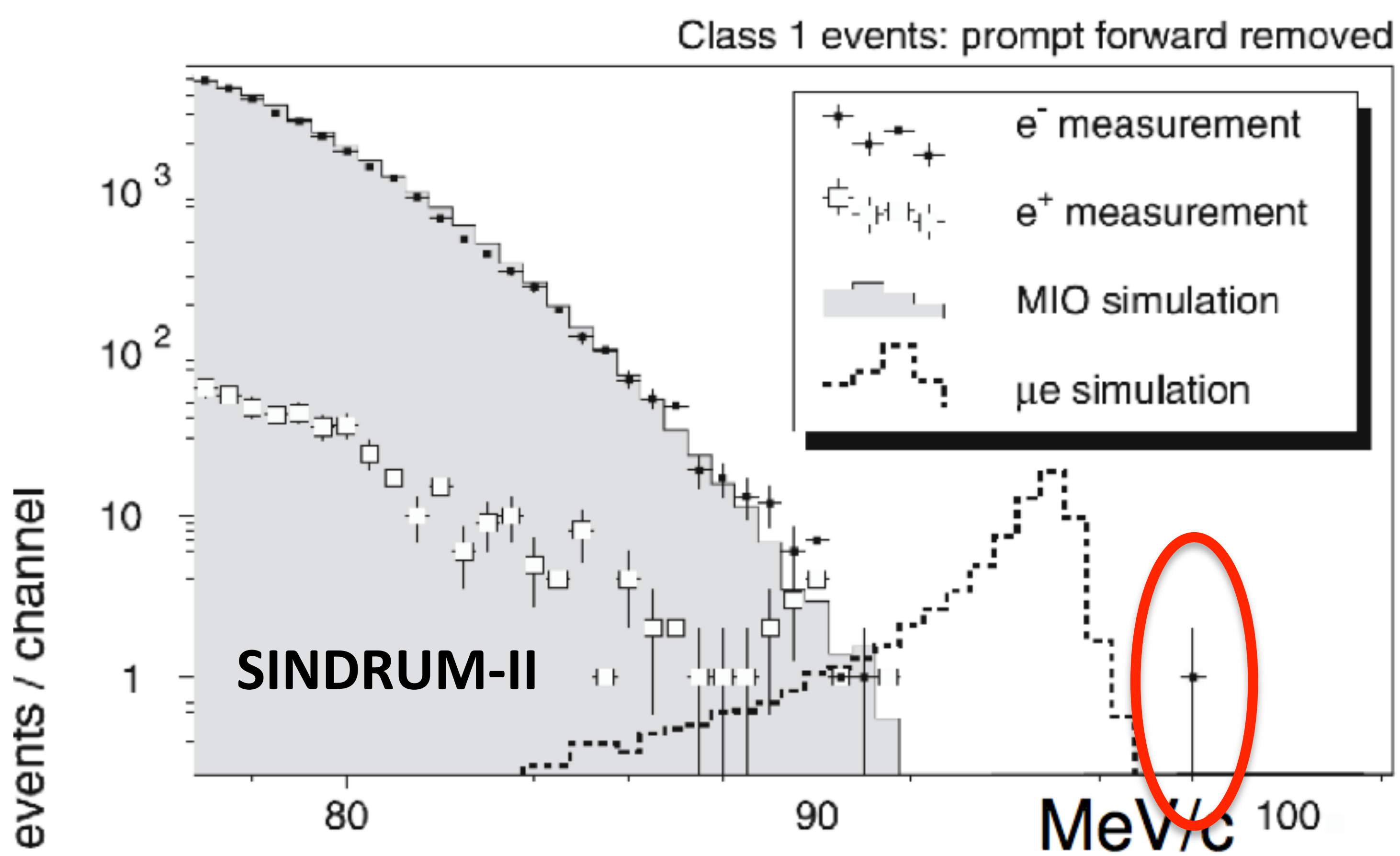
discovery

- **$\mu N \to eN$** : Required Beam is recently / finally achievable
  - Once we get a required beam, mu-e conversion might be a next step.

measurement

Present Best Limit on $\mathcal{B}(\mu N \rightarrow eN)$

- *SINDRUM-II* (present record holder)
  - 1989-1993 @ PSI
  - Continuous Beam with Beam Veto Counters



- Results -

$\mathcal{B}(\mu^- Ti \rightarrow e^- Ti) < 6.1\times10^{-13}$ (1993)

$\mathcal{B}(\mu^- Au \rightarrow e^- Au) < 7\times10^{-13}$ (2000)

(!!!)

Significant Backgrounds

Rate Limited

- **COMET** : The Next Generation Experiment
  - **Seeking to Improve Sensitivity by a factor of 10 000**

- Are You Ready ? -

YES ! J-PARC is Ready to start the R&D for “μ-e conversion”
(so called “COMET Experiment”)

Potential Improvements for Next Generation μ-e Conversion

High Intensity Muon

Pion capture and muon transport by superconducting solenoids would provide high beam intensity.

Pulsed Muon Source

Beam pulsing is very important in order to suppress prompt BG. Pulse Separation should be ~ 1μsec.

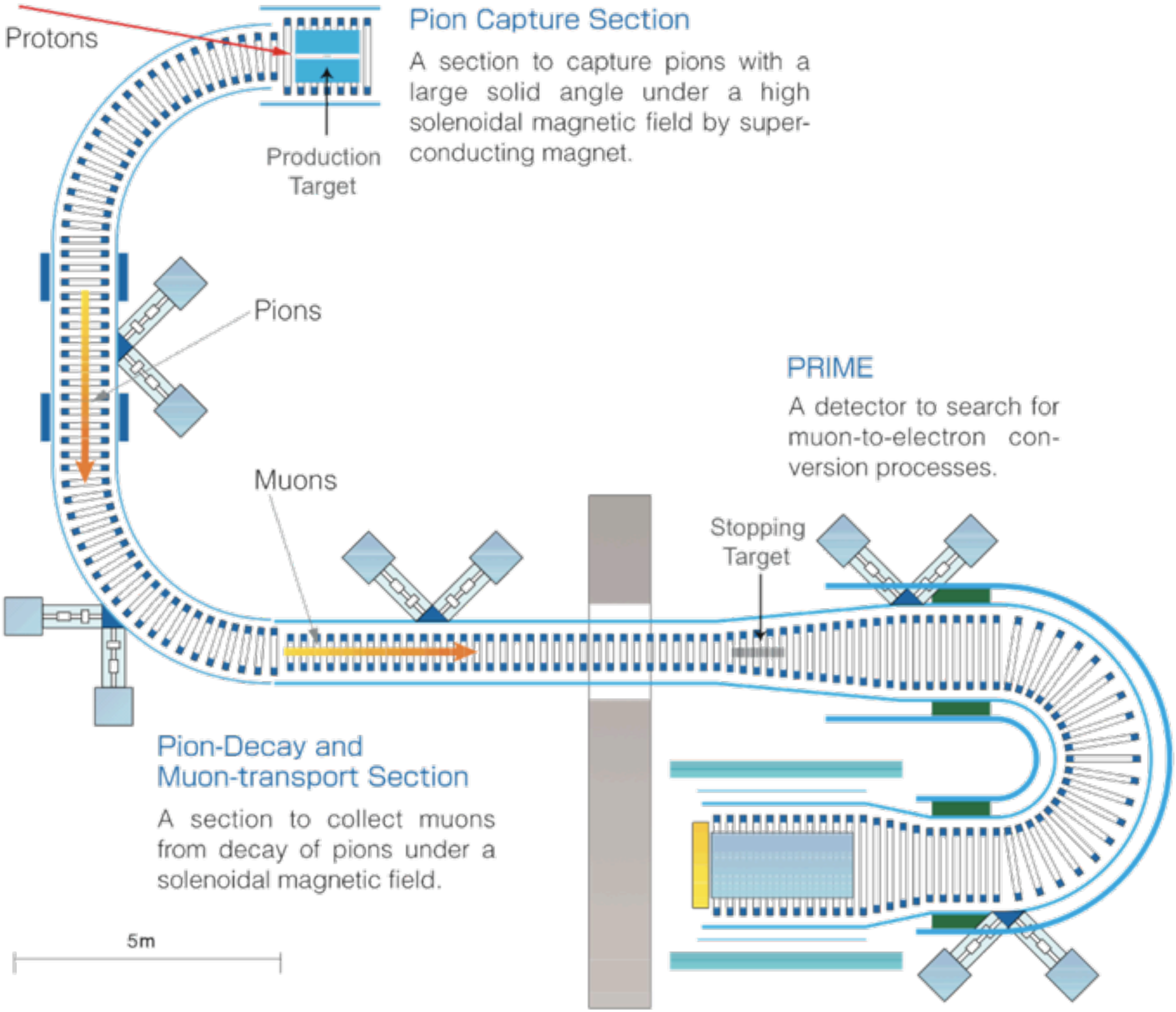
Special Muon Transport

A muon beam line should be sufficient long to eliminate pions in a muon beam, and dedicated to reject DIO electrons.

High Resolution Detectors

Endpoint of spectrum of DIO electron comes to the signal region. Good σ_E is mandatory.

The COMET Experiment



- Utilize backward pions with pion capture solenoid
- Select low-p muons (and reject high momentum pions) using C-Shaped transport solenoid
- Select high-p e- (reject low-p backgrounds) using C-shaped Detector Solenoid
- High Resolution Tracker & Calorimeter

- R & D -

R&D-1: High Intensity Muon Beam
R&D-2: Pulsed Muon Source
R&D-3: Special Muon Transport
R&D-4: Good Resolution Detectors

R&D-1: High Intensity Muon Beam

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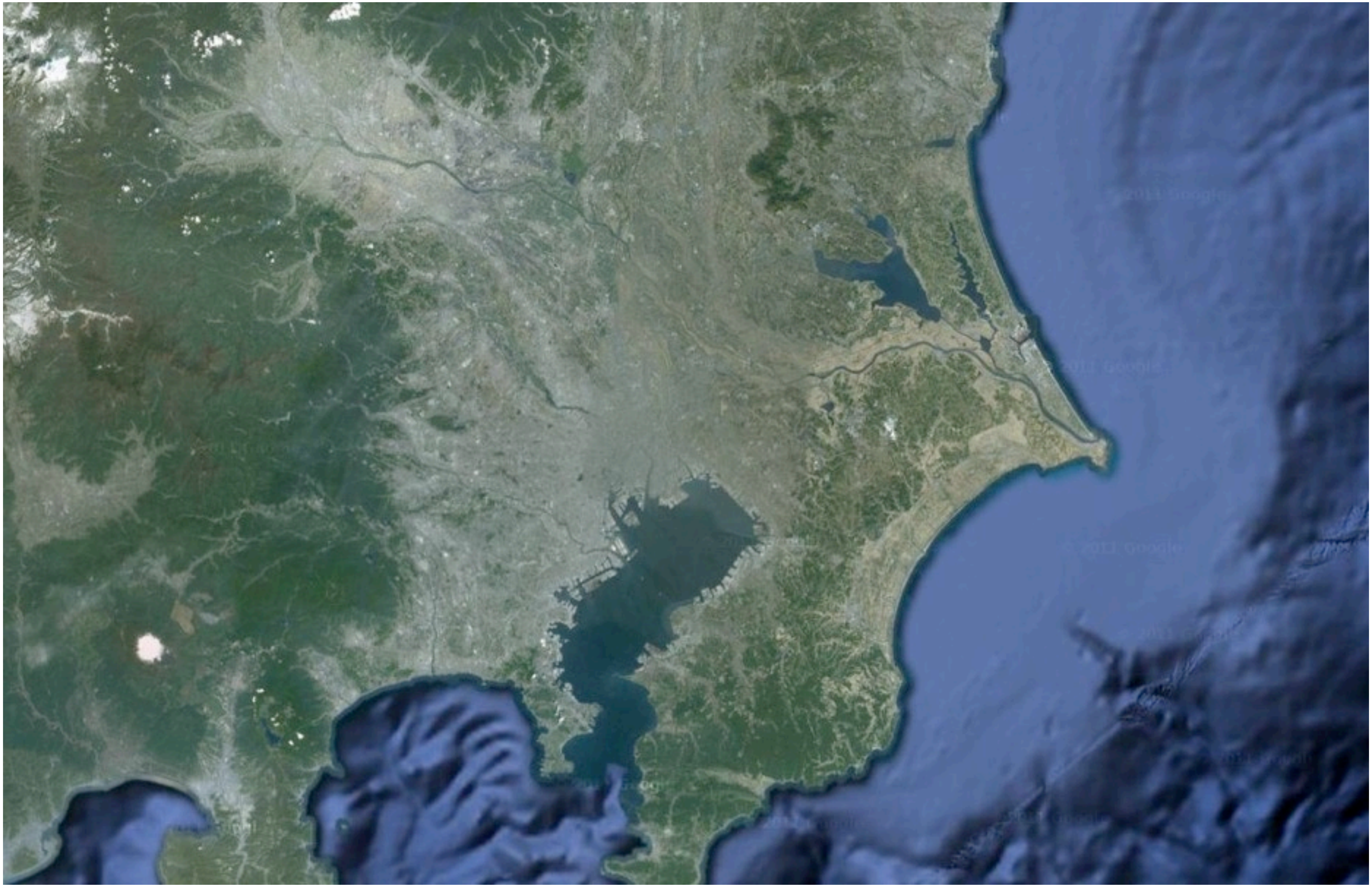
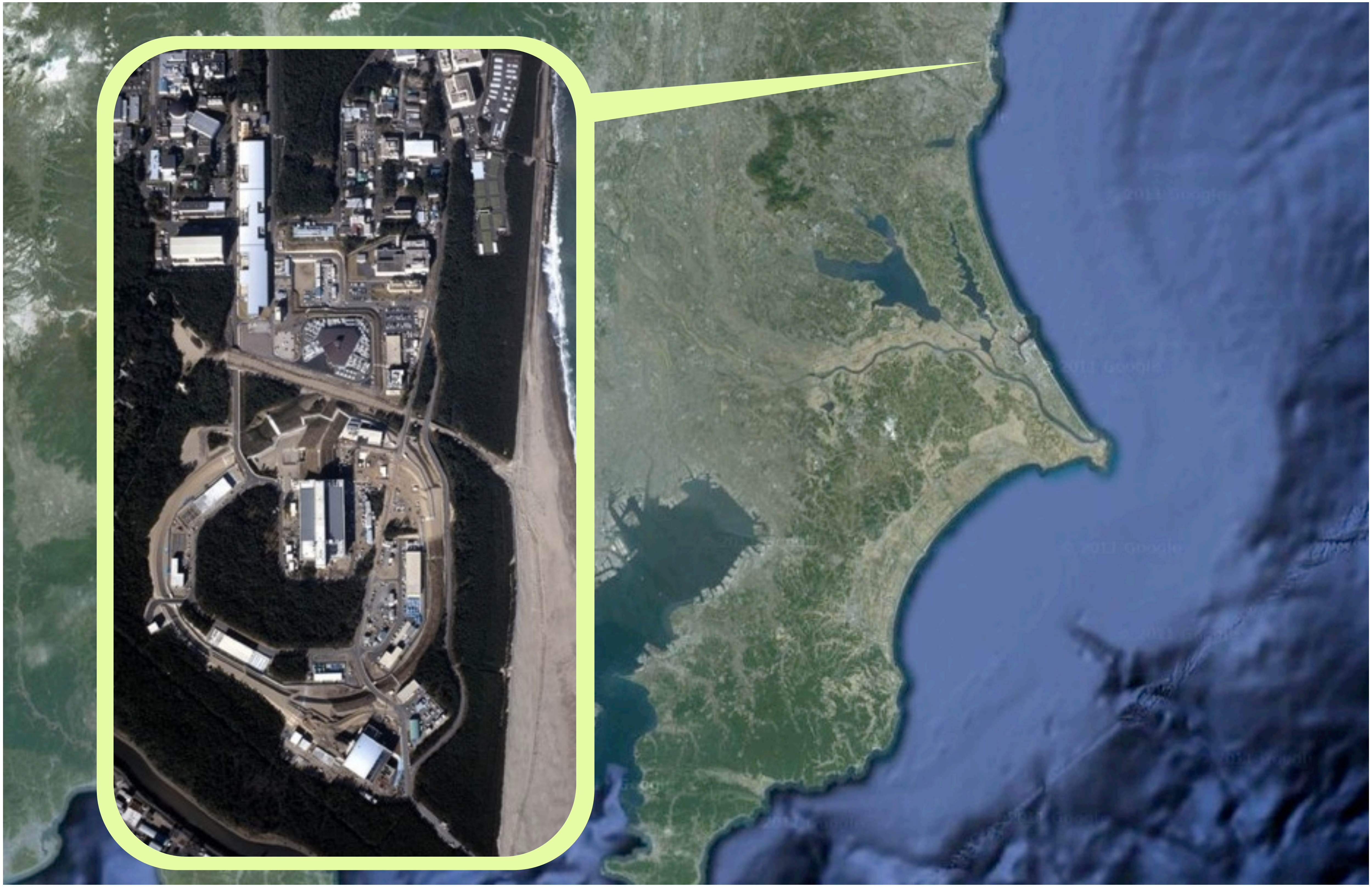
J-PARC

- J-PARC : **J**apan **P**roton **A**ccelerator **R**esearch **C**omplex
- Joint project between KEK and JAEA
- New and exciting accelerator research facility, using MW-class high power proton beams at both 3 GeV and 30 GeV (currently)
- Various secondary particle beams
  - n, μ, K, ν, etc. produced in proton-nucleus reactions
- Three major scientific goals using these secondary beams
  - Particle and Nuclear Physics
  - Material and Life Sciences
  - R&D for nuclear transmutation (in phase-2)
- The anticipated goal is 1 MW

J-PARC



J-PARC



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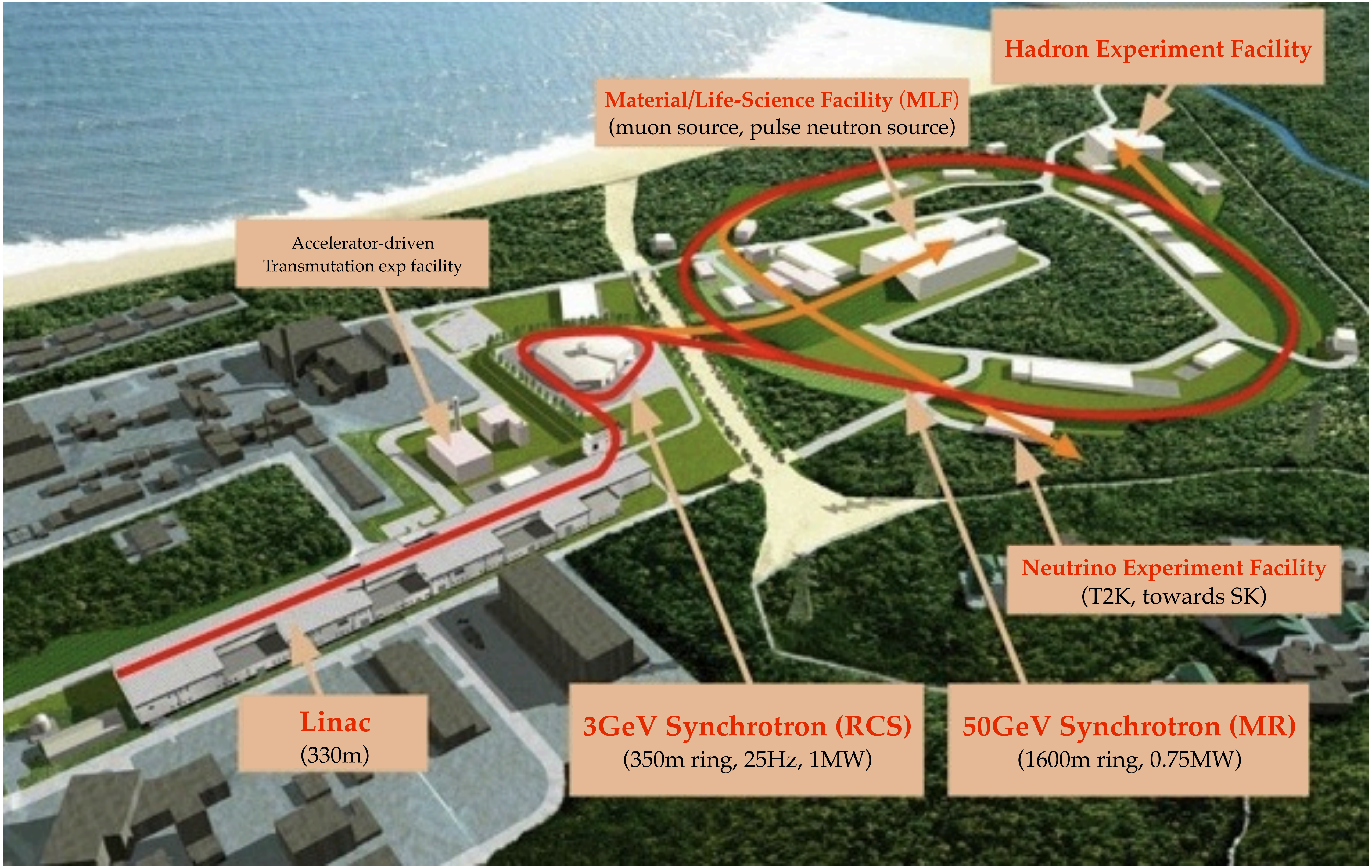
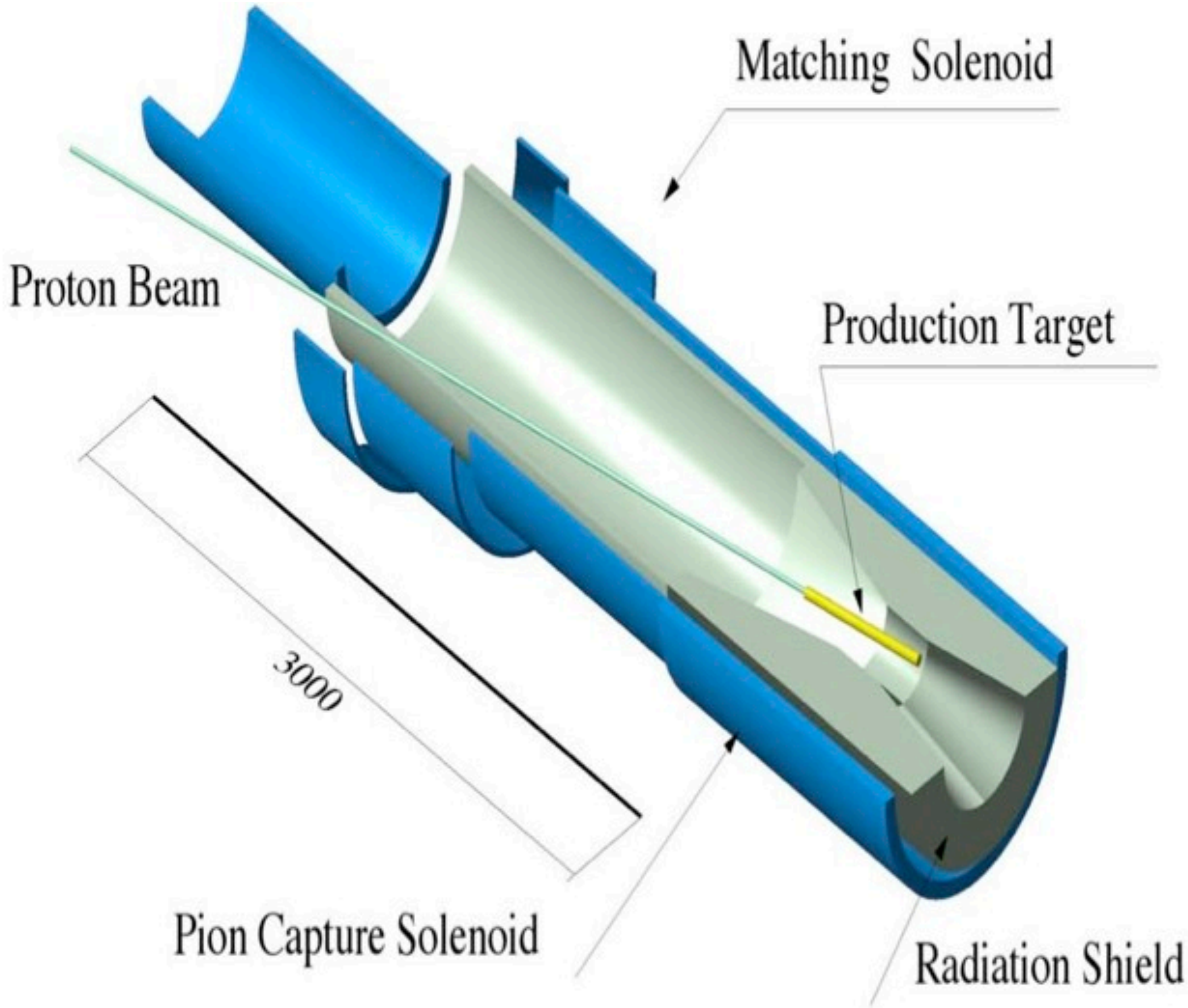

Hadron Experiment Facility
Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)
Accelerator-driven
Transmutation exp facility
Neutrino Experiment Facility
(T2K, towards SK)
Linac
(330m)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
50GeV Synchrotron (MR)
(1600m ring, 0.75MW)

Pion Capture Solenoid System



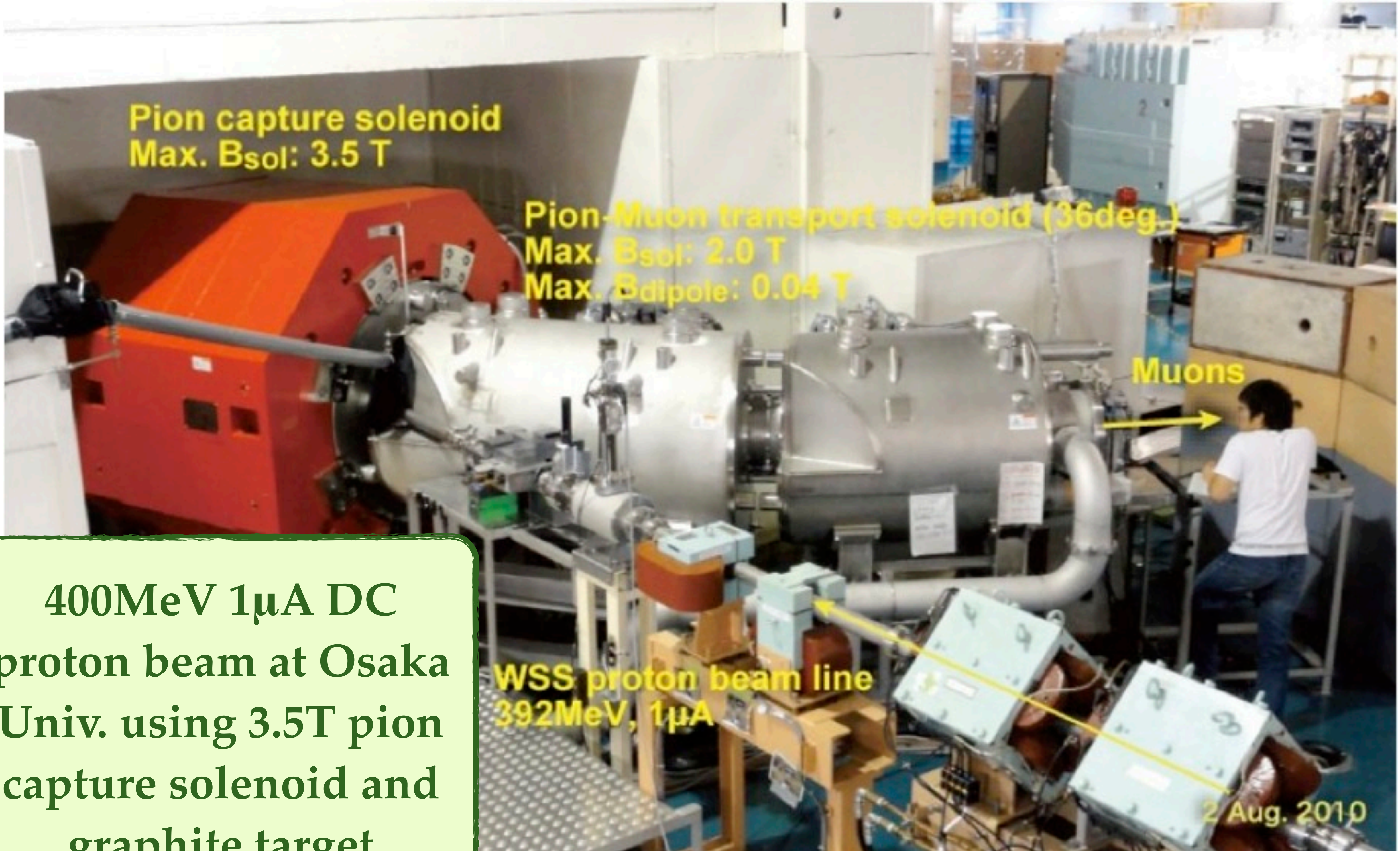
- Large muon yield by Large Solid Angle
  - Powerful Solenoid
  - Surround p target

$$P_T(\mathrm{GeV}/c) = 0.3 \times B(\mathrm{T}) \times \left[\frac{R(m)}{2}\right]$$

B=5T, R=0.2m → P_T=150MeV/c

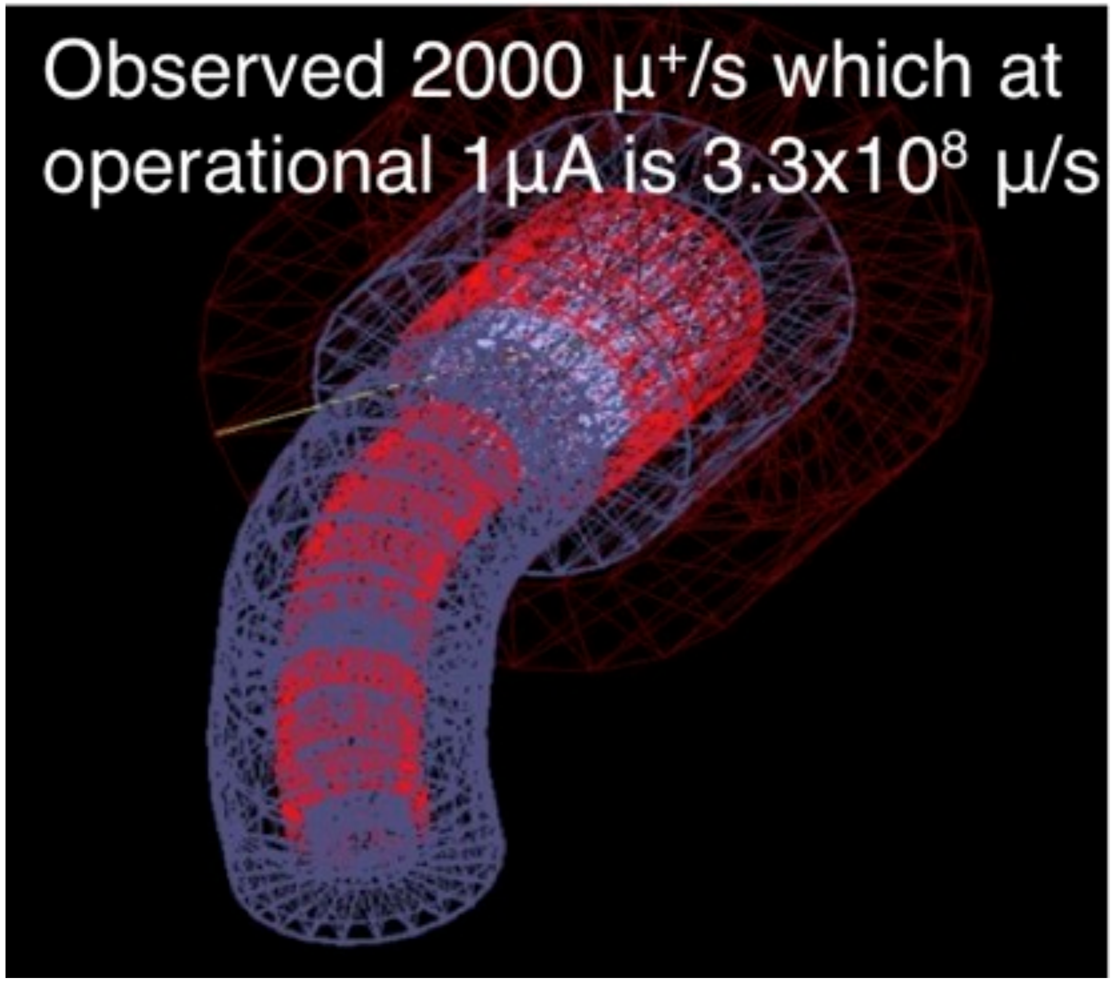
- Super-conducting solenoidal magnet
  - 15cm radium bore
  - 5T
  - 30 cm thick W shield.
- Issue : Heat Load

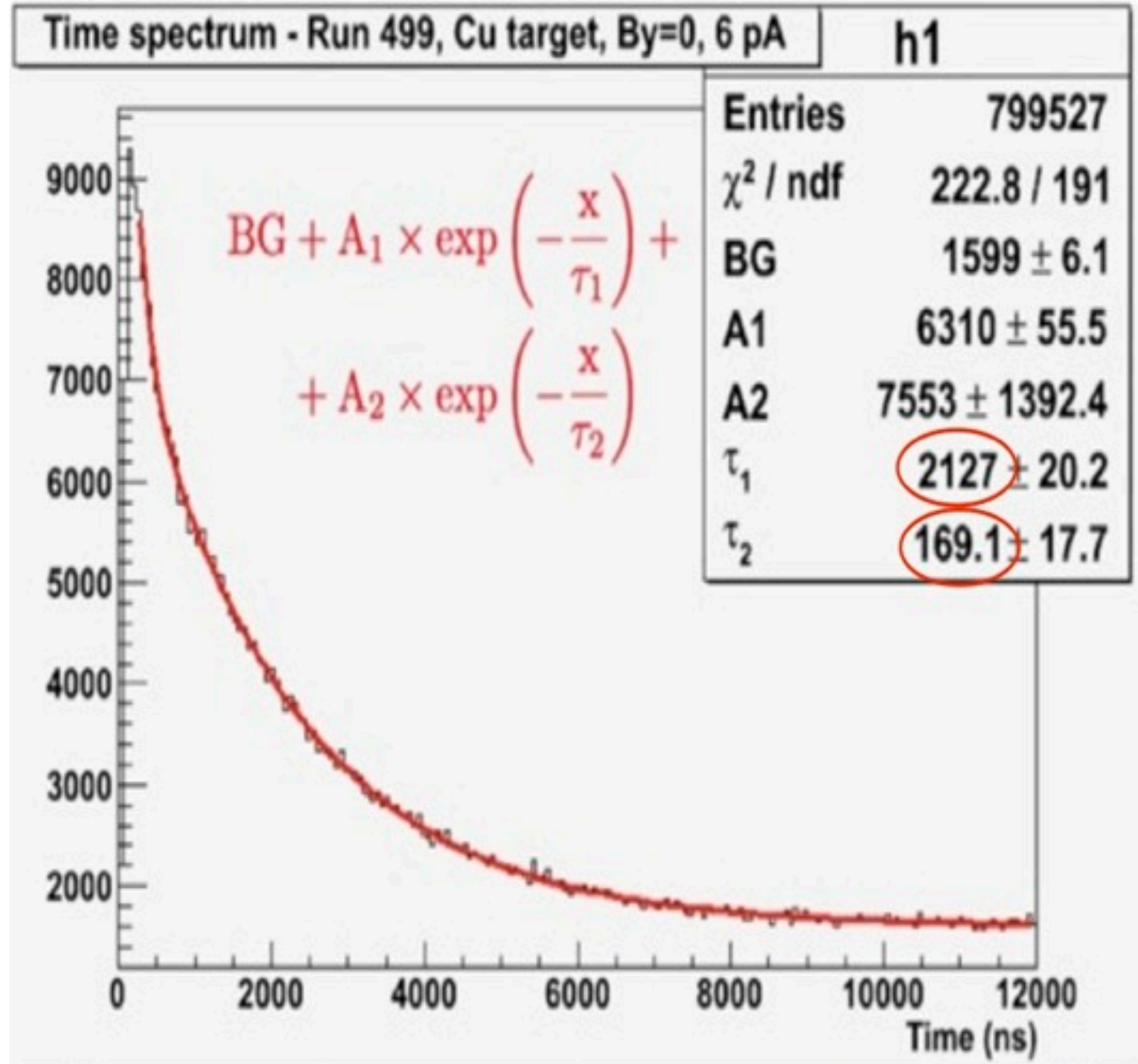
MuSIC Project at Osaka University



400MeV 1μA DC proton beam at Osaka Univ. using 3.5T pion capture solenoid and graphite target

Demonstration of Powerful Pion Capture





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

- 3 commissioning runs in 2010/11 with reduced beam I (6pA @ 2.4mW)
- Per Watt of proton power, MuSIC is producing 3000x more muon's /sec than PSI

R&D-2: Pulsed Muon Source

High Intensity Muon

Pion capture and muon transport by superconducting solenoids would provide high beam intensity.

Pulsed Muon Source

Beam pulsing is very important in order to suppress prompt BG.
Pulse Separation should be ~ 1μsec.

Special Muon Transport

A muon beam line should be sufficient long to eliminate pions in a muon beam, and dedicated to reject DIO electrons.

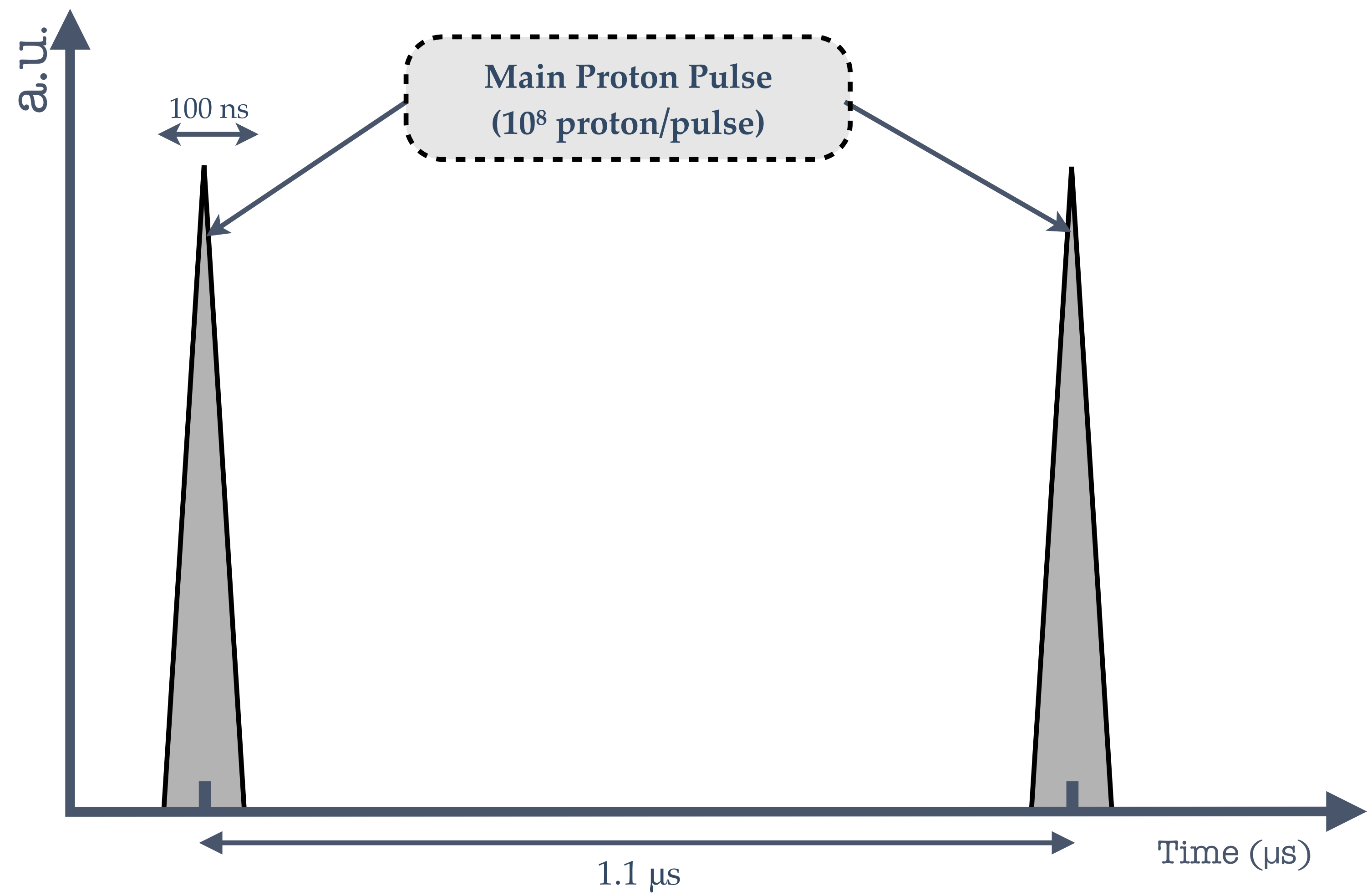
High Resolution Detectors

Endpoint of spectrum of DIO electron comes to the signal region. Good σ_E is mandatory.

Important Key : **Extinction**

- **Extinction** (= Residual protons in between the pulses)

- Dominant Backgrounds
  - Beam Pion Capture
    - π+(A,Z)→(A,Z-1)* →γ+(A,Z-1), γ→e^+e^-
    - Prompt Timing
    - *cf.* $\boldsymbol{\tau_{(\text{muonic Al})}}$**=0.88μs**
  - Muon DIO, e^- scattering



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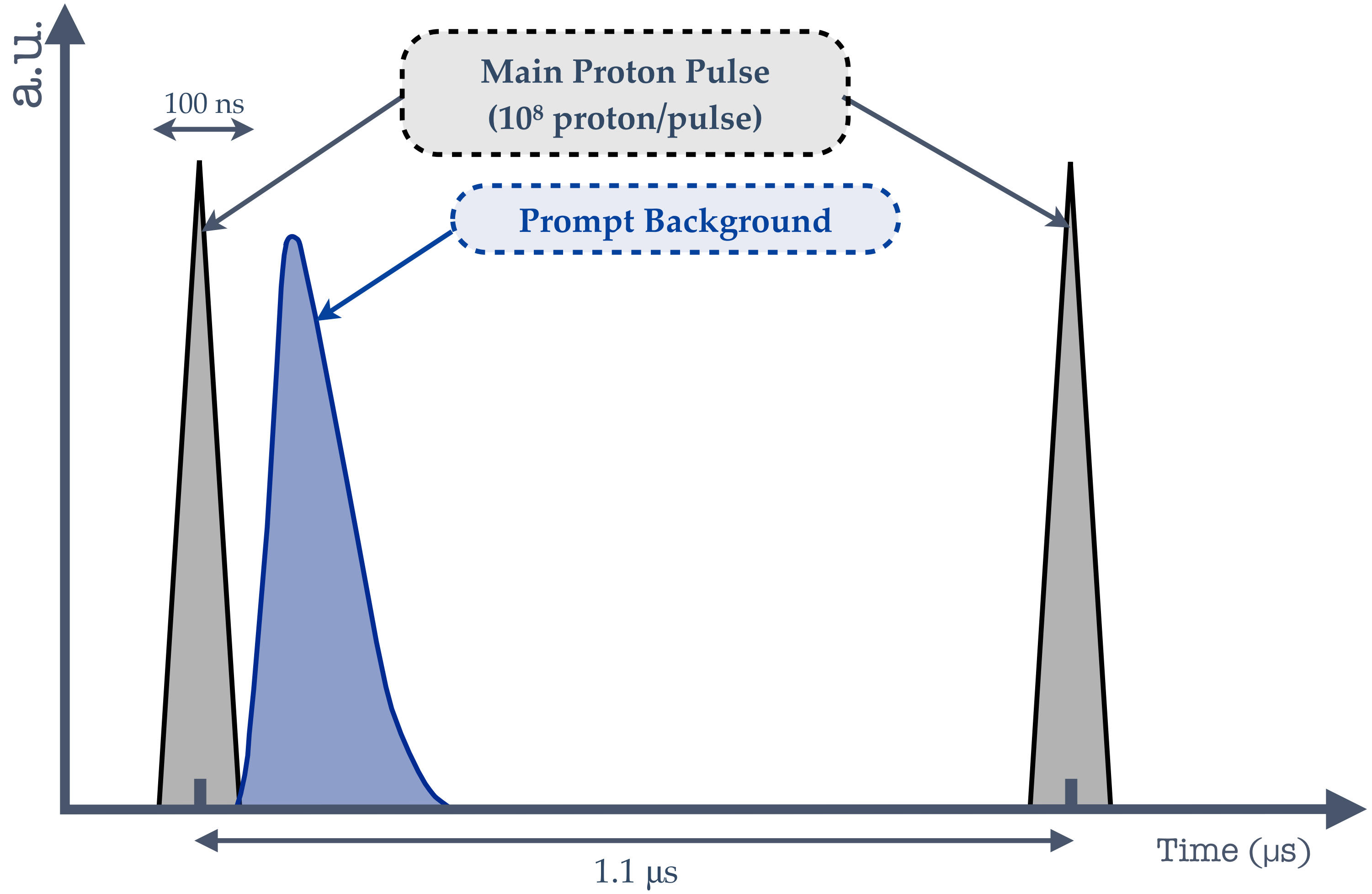

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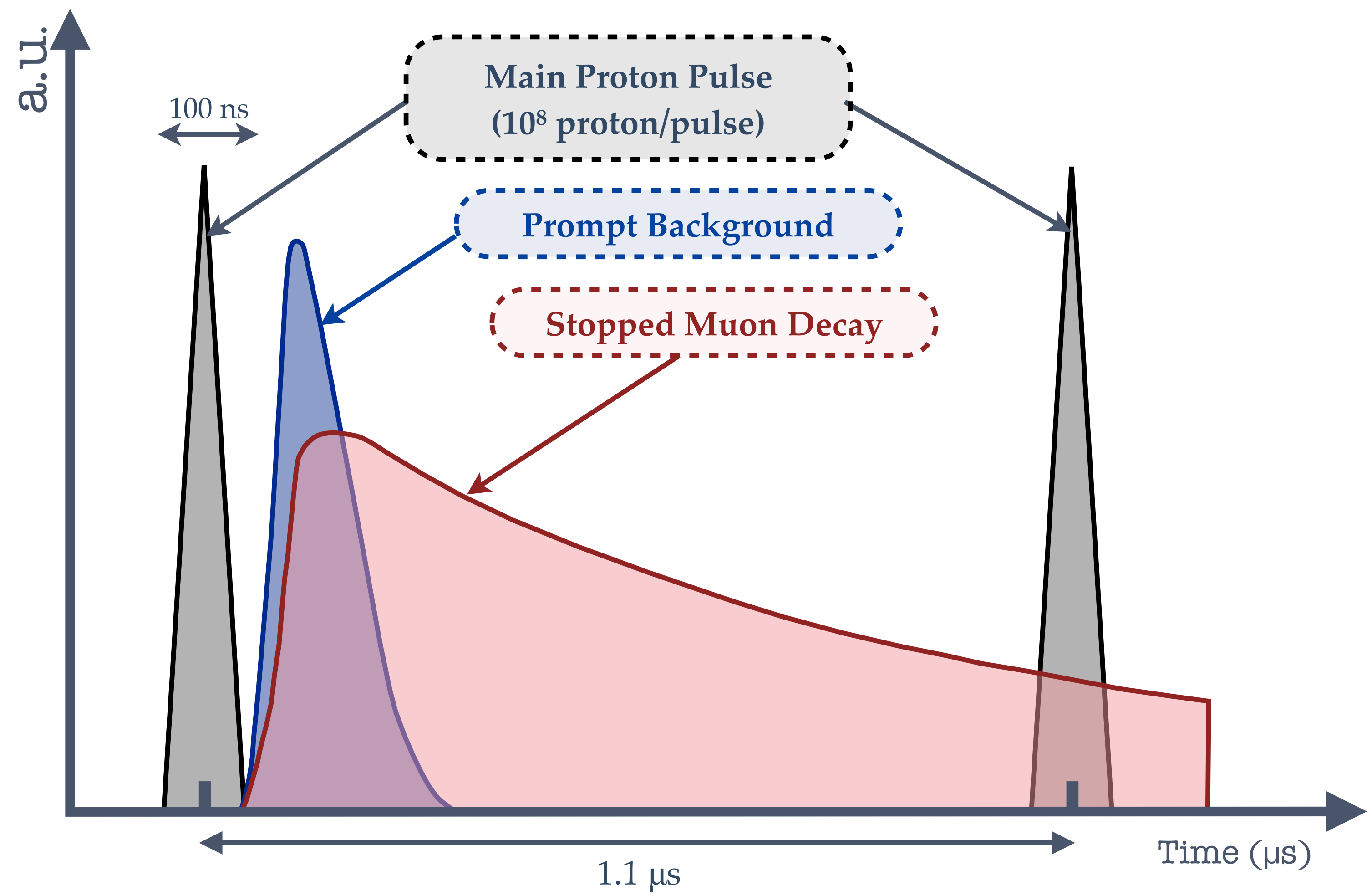

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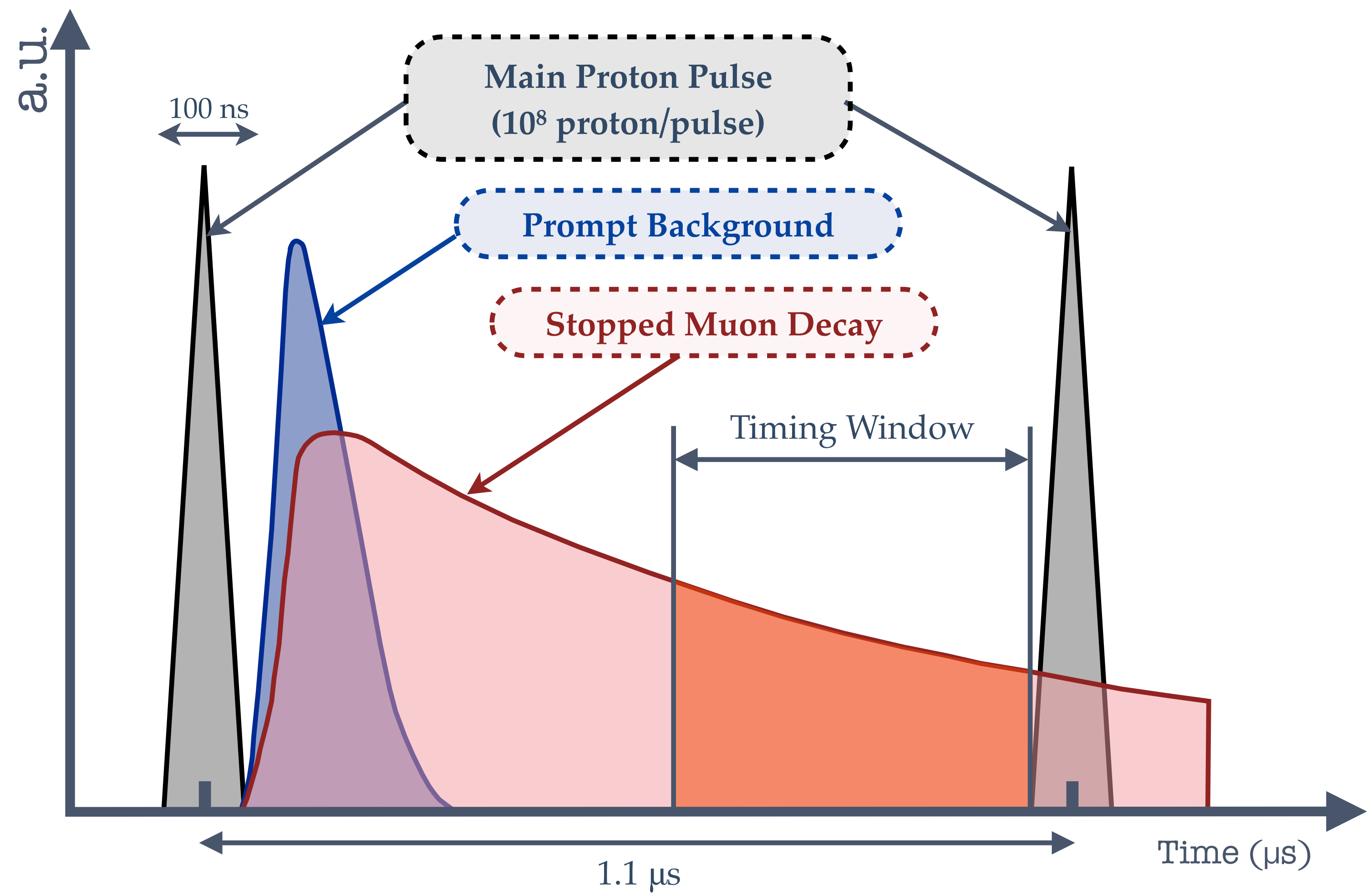

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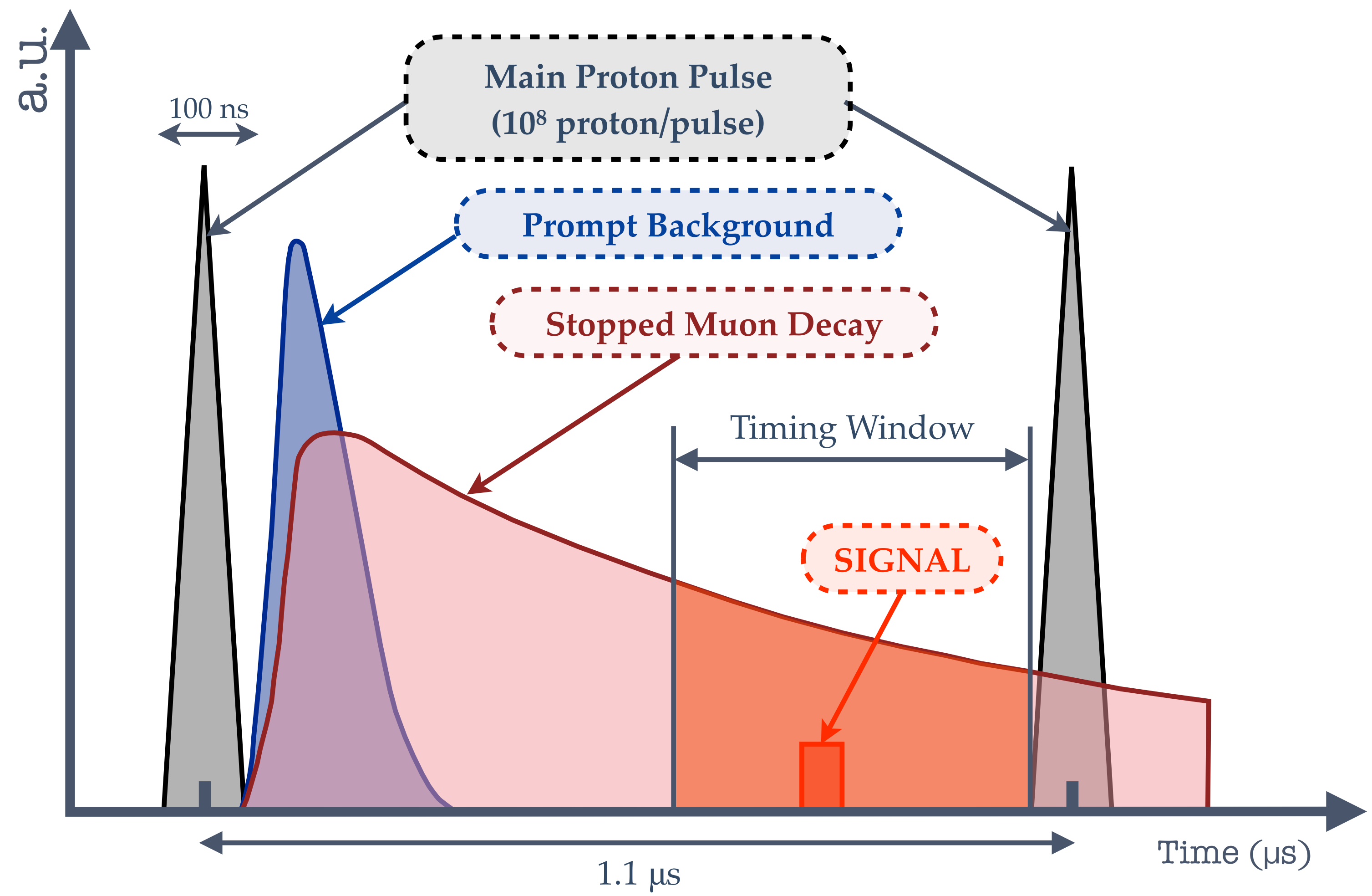

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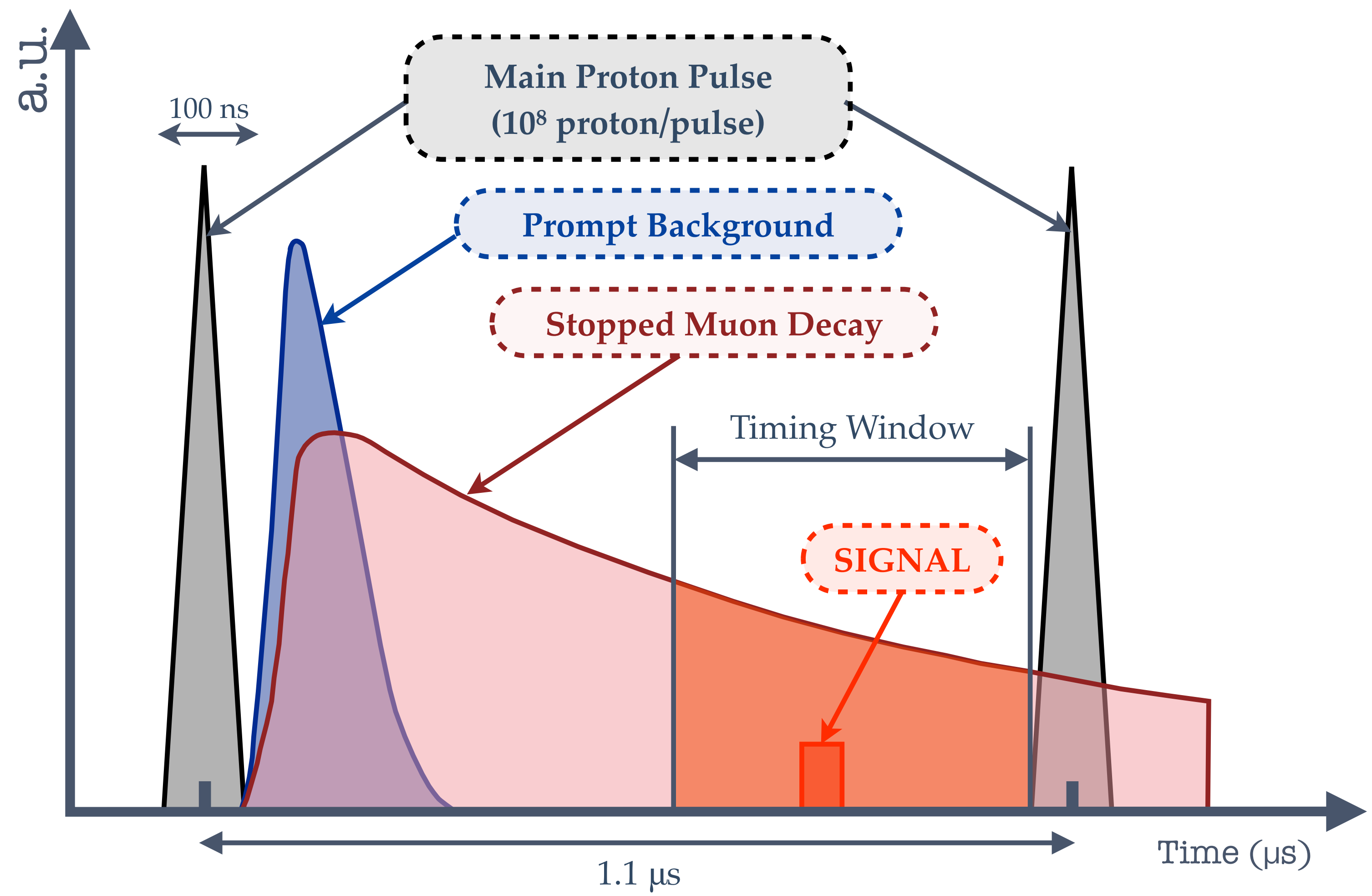
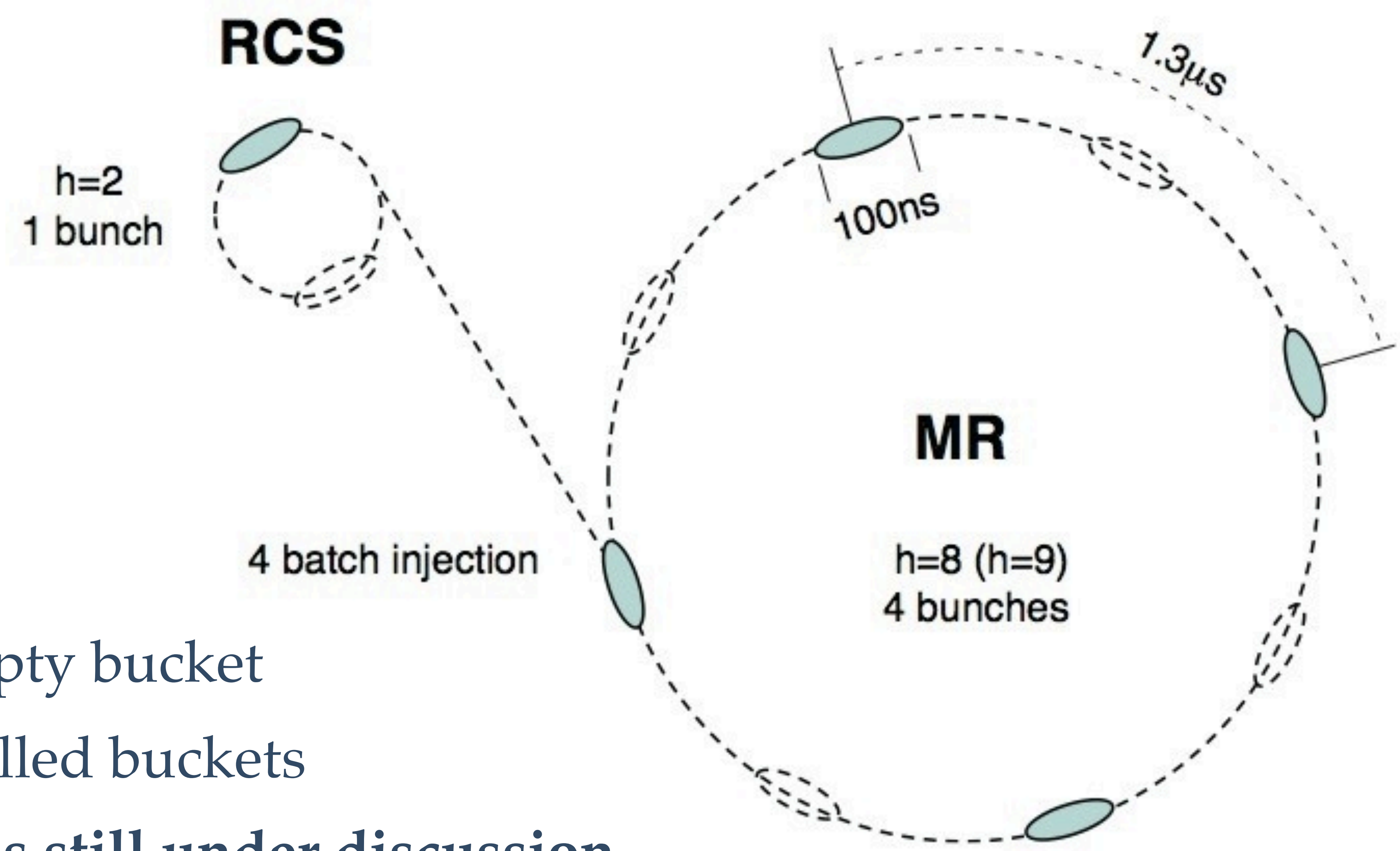


Extinction should be <10^{-9} : To achieve 10^{-16} Single Event Sensitivity

J-PARC Proton Acceleration for COMET

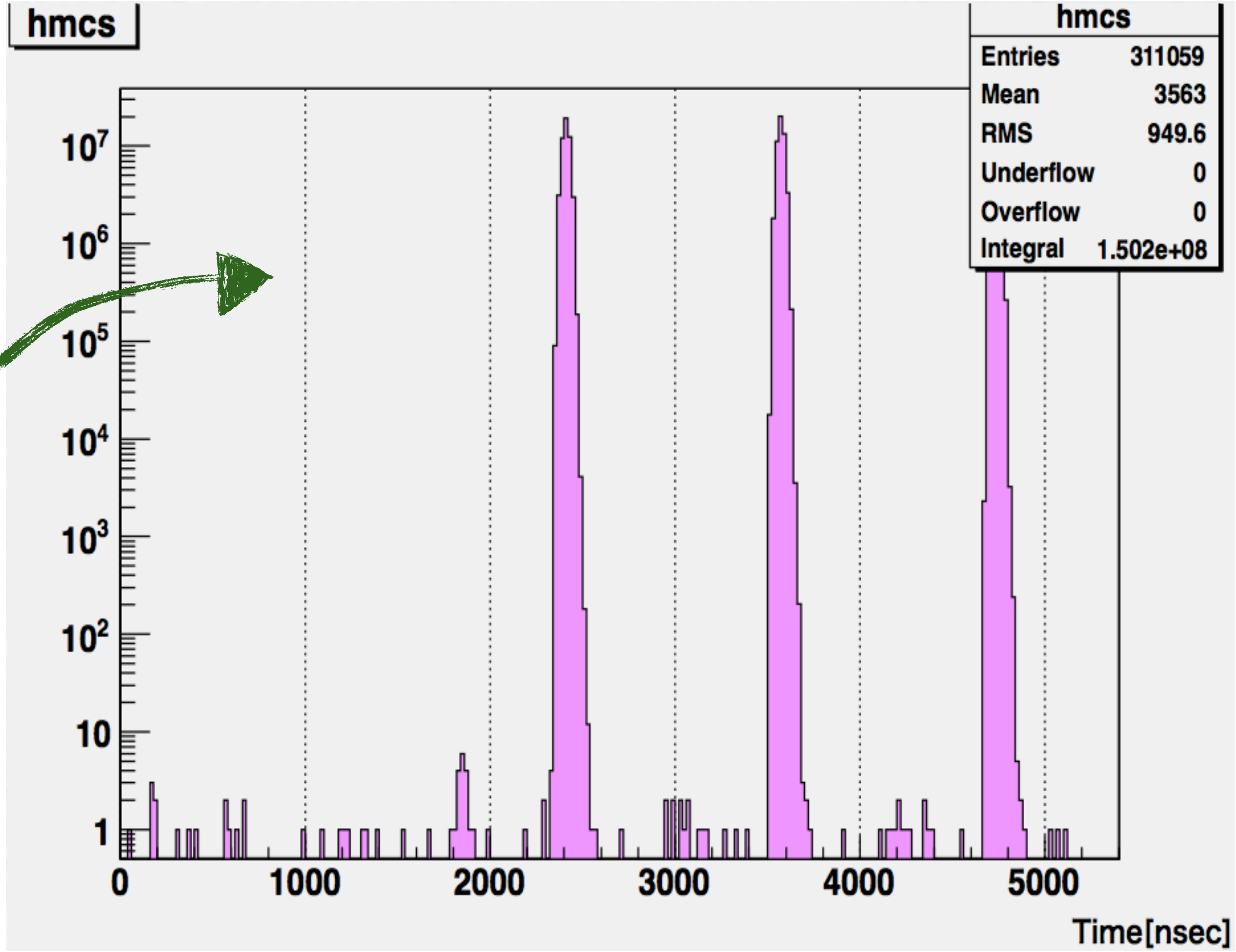


- RCS : h=2 with 1 empty bucket
- MR : h=8(9) with 4 filled buckets
  - **Operation Mode is still under discussion**
- Very Simple Solution
  - No need of hardware modification
- Two Issues
  - Heavier heat load in the scraper
  - Possible leakage of chopped beam in empty buckets

Extinction Measurements

- Pilot Measurement 2010
  - At Secondary Beam line of hadron experiment facility
  - At Abort line of MR

$O(10^{-7})$ level of extinction confirmed (at worst)



- Further Improvement is Required (at least 2 orders more)
  - **AC-dipole devices** before proton target (3 orders improvement is expected)
  - **Double Kicking** Injection into the MR (6 orders improvement is expected)

R&D-3: Special Muon Transport

High Intensity Muon

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Pulsed Muon Source

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High Resolution Detectors

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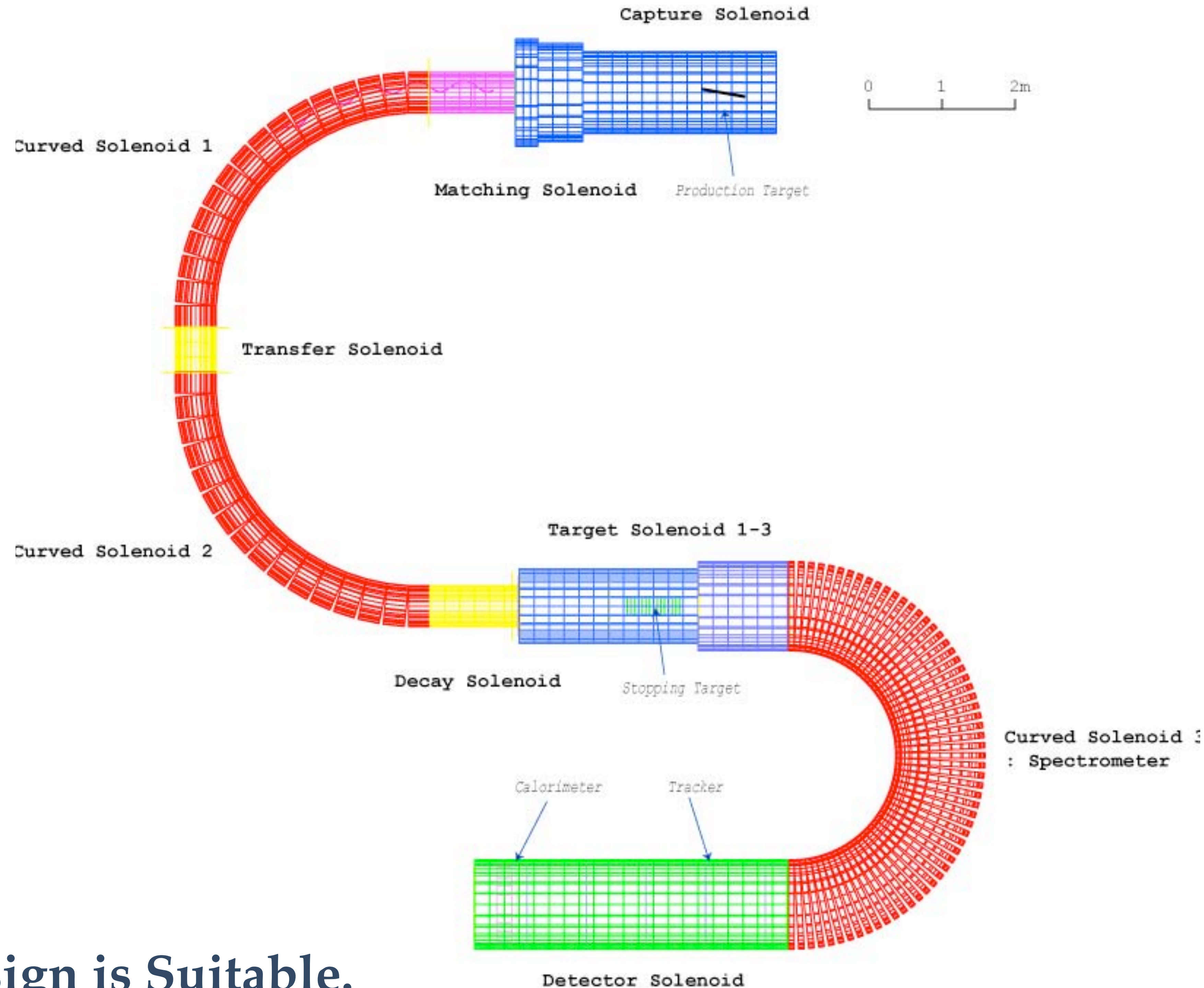
Design of Transport Solenoid

- Requirements:
  - Long enough for pions to decay to muons (>20m)
  - High transport efficiency (P_μ~40MeV/c)
  - Negative charge selection
  - Low momentum selection (P_μ<75MeV/c)



- **Curved Solenoid Design is Suitable.**

Charged Particle Trajectory in Curved Solenoids

- In a curved solenoidal field, a centre of helical trajectory of charged particles is drifted by

$$D = \frac{P}{qB}\theta_{bend}\frac{1}{2}\left[\cos\theta + \frac{1}{\cos\theta}\right],$$

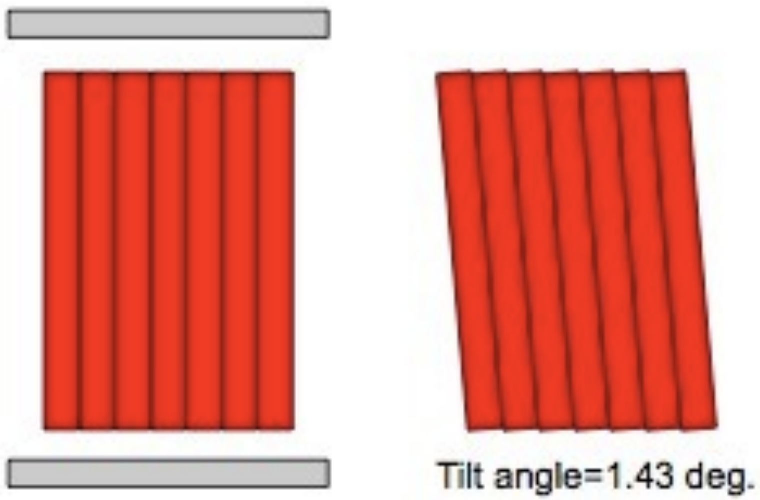
where D is drift distance and $\theta = \tan^{-1}(P_T/P_L)$.

- This effect is suitable for charge and momentum selection.

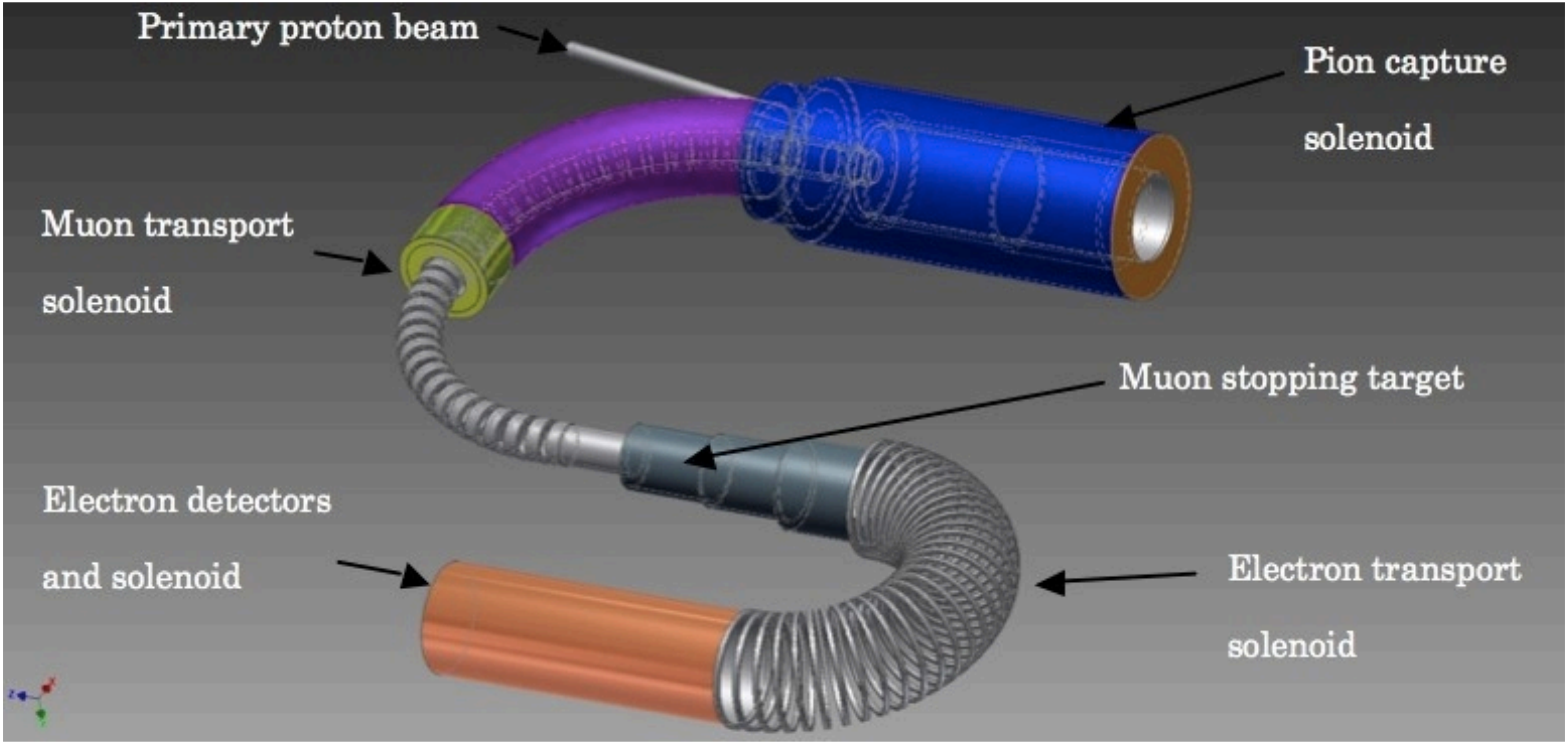
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{\rm comp} = \frac{P}{qr}\frac{1}{2}\left[\cos\theta + \frac{1}{\cos\theta}\right],$$

where $B_{\rm comp}$ is a compensation field and r is a major radius of the solenoid



Engineering Design Work



- Still ongoing
  - Optimization, Cost reduction *etc*. (with companies)

R&D-4: High Resolution Detectors

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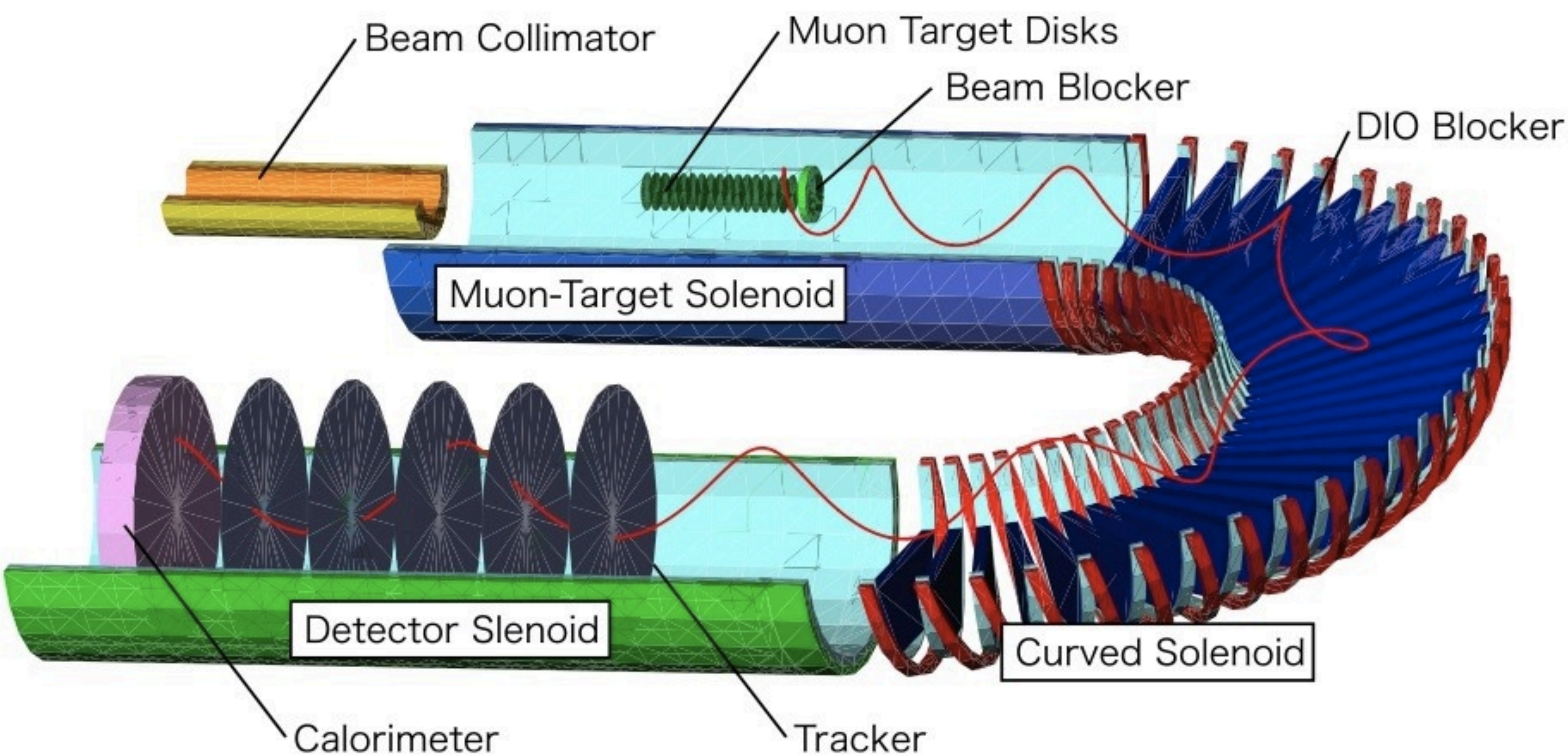
High Resolution Detectors

Endpoint of spectrum of DIO electron comes to the signal region. Good σ_E is mandatory.

COMET Detector Apparatus



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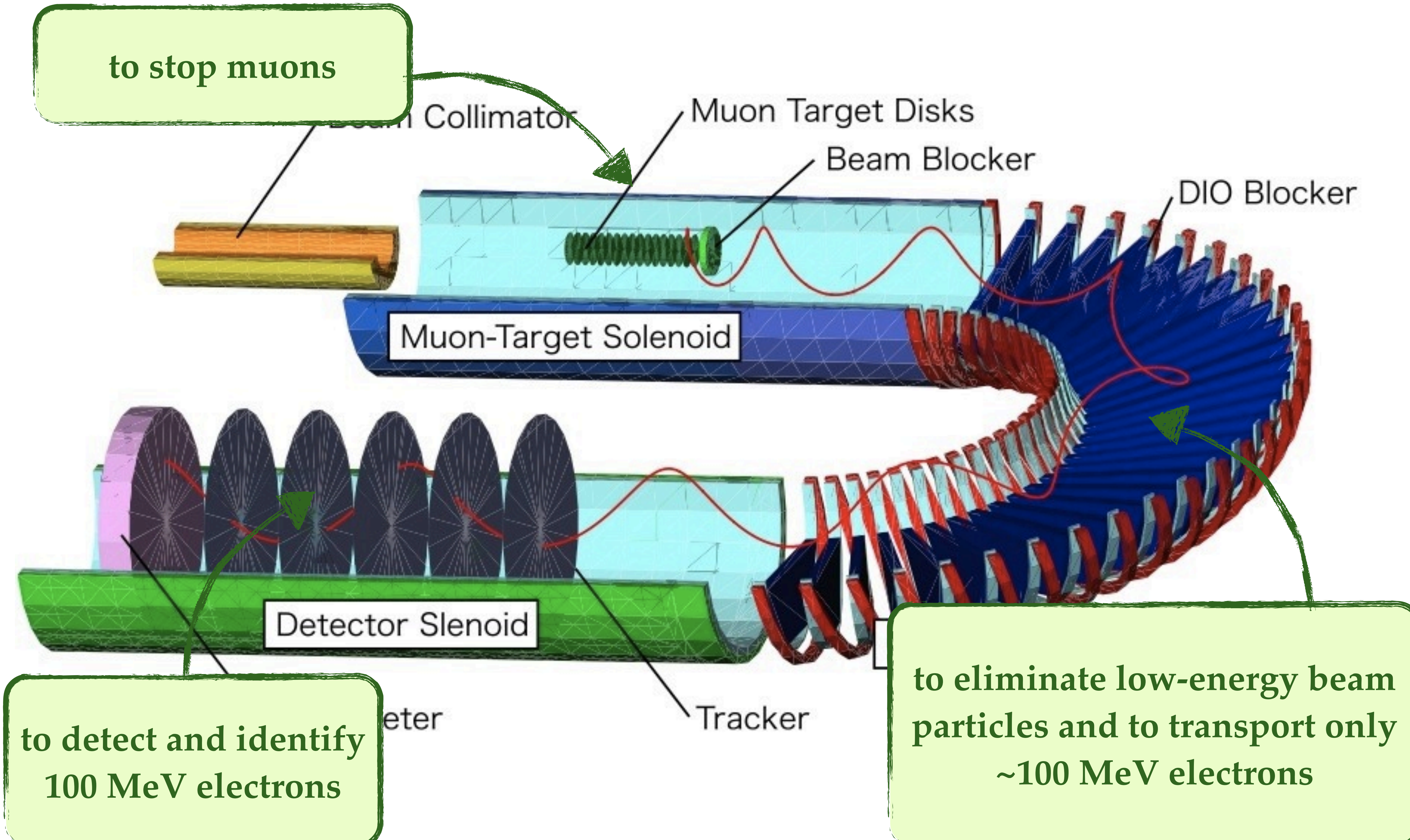
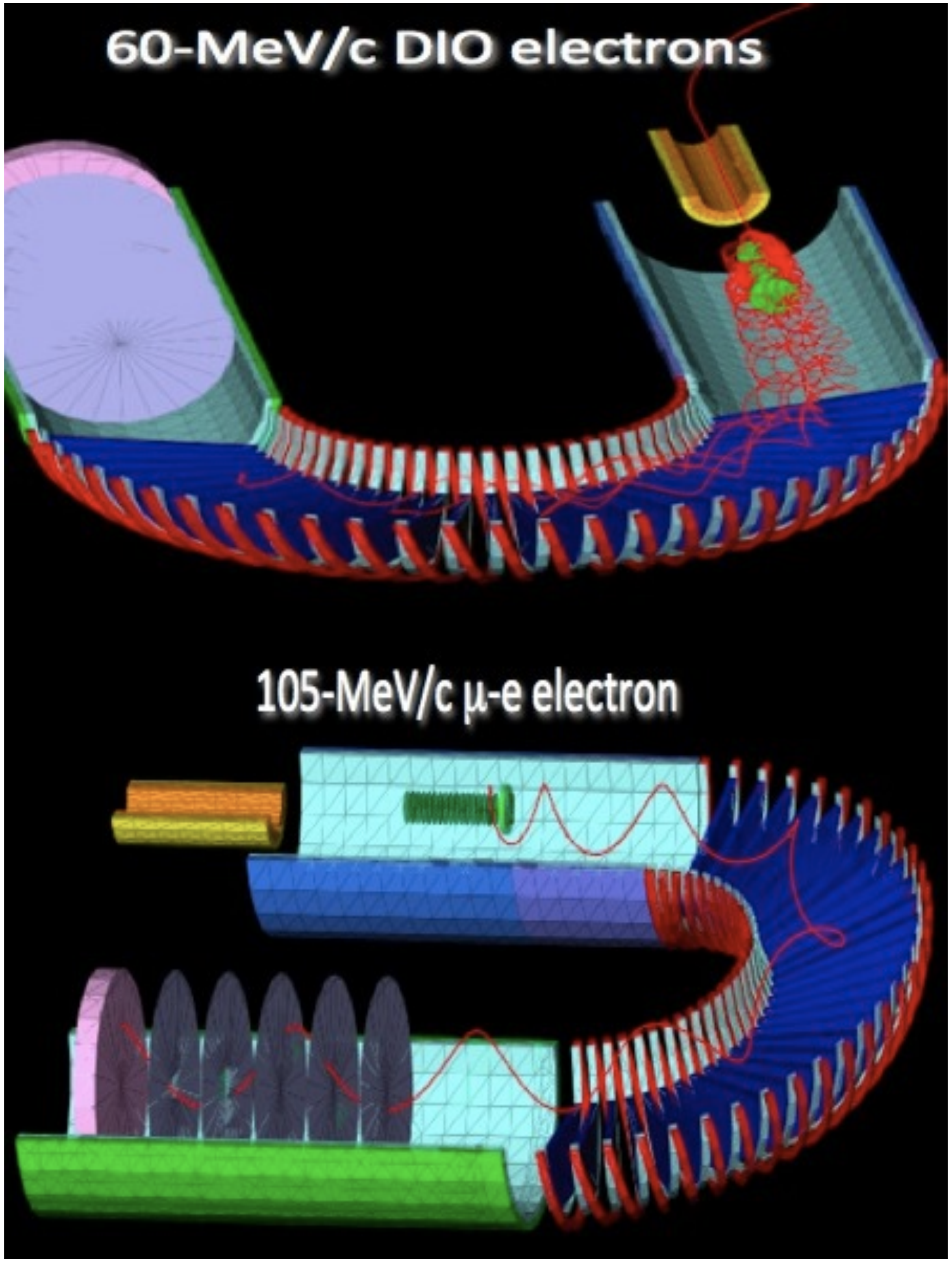


Curved Solenoid Spectrometer

- Torus drift for rejecting low energy DIO electrons.

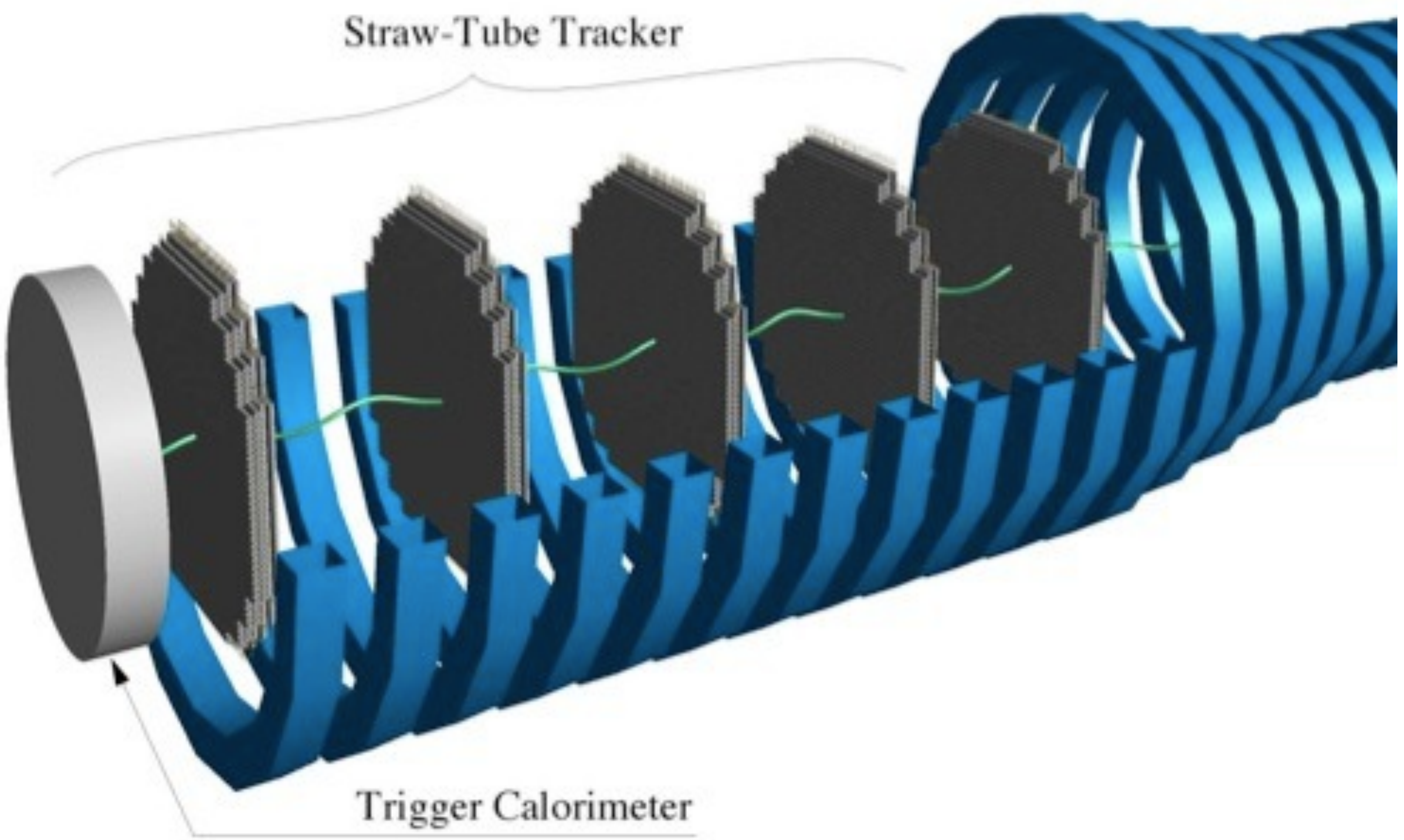
$$D(m) = \frac{1}{0.3 \times B(T)} \times \frac{s}{R} \times \frac{P_L^2 + \frac{1}{2}P_T^2}{P_L}$$

- Rejection Power : ~10^{-6}
- Good Acceptance for signal electrons (w/o including event selection and trigger acceptance)
  - ~20%



Electron Detector (Tracker+Crystal)

- Rate < 800 kHz
- **Straw-tube tracker to measure electron mom.**
  - 5 planes with 48cm spacing
  - σ_P=230 keV/c
    - 4 layers / plane
    - 5mm diam. straw-tube with 25 μm thick
  - **should be operational in vacuum**
  - <500μm spacial resolution



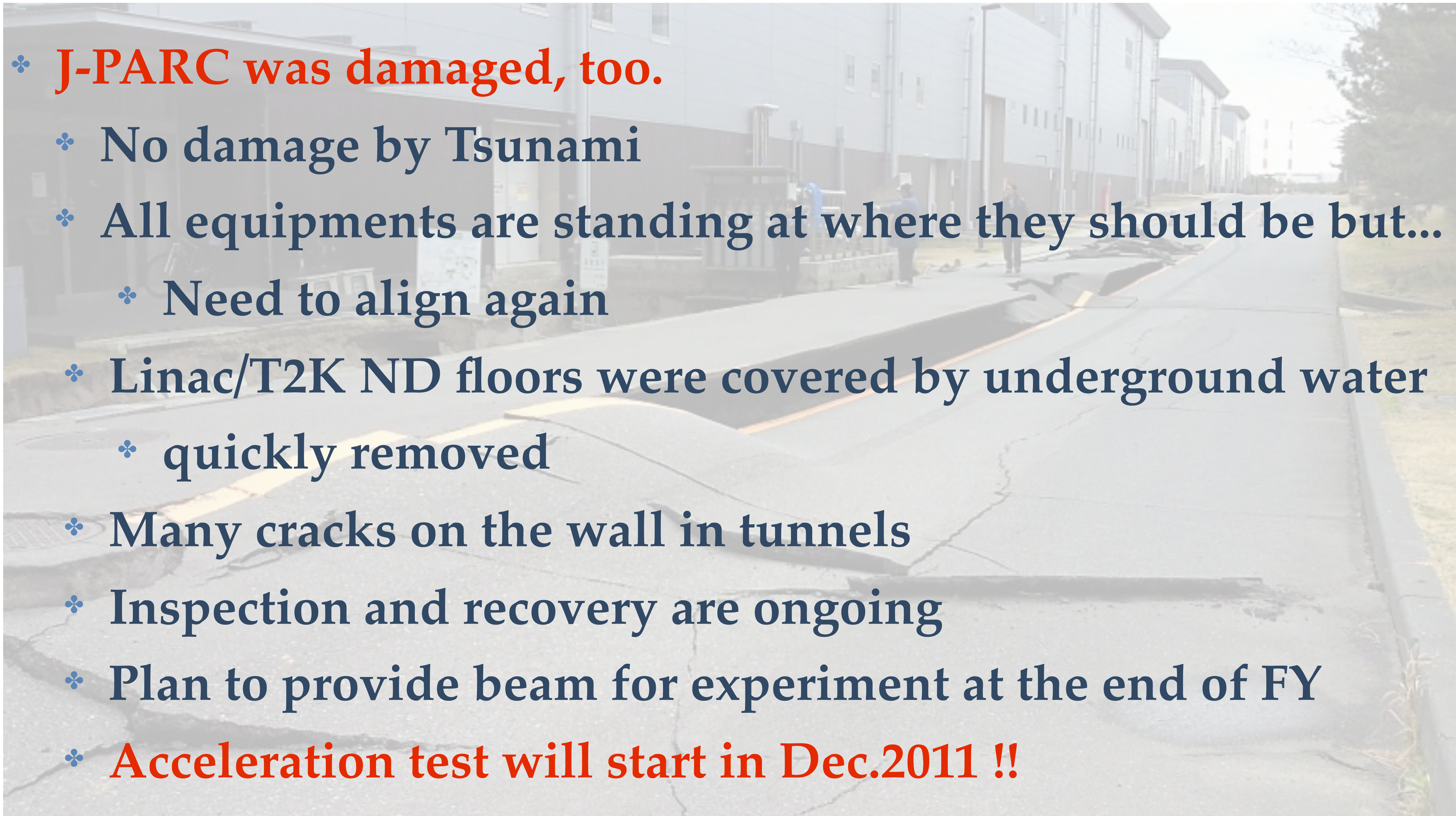
- **Crystal calorimeter for trigger**
  - BGO, PWO, LYSO, or new crystals...

- Current **Status** -

after the big disaster ...

Earthquake attacked

Earthquake attacked



- J-PARC was damaged, too.
  - No damage by Tsunami
  - All equipments are standing at where they should be but...
    - Need to align again
  - Linac/T2K ND floors were covered by underground water
    - quickly removed
  - Many cracks on the wall in tunnels
  - Inspection and recovery are ongoing
  - Plan to provide beam for experiment at the end of FY
  - Acceleration test will start in Dec.2011 !!

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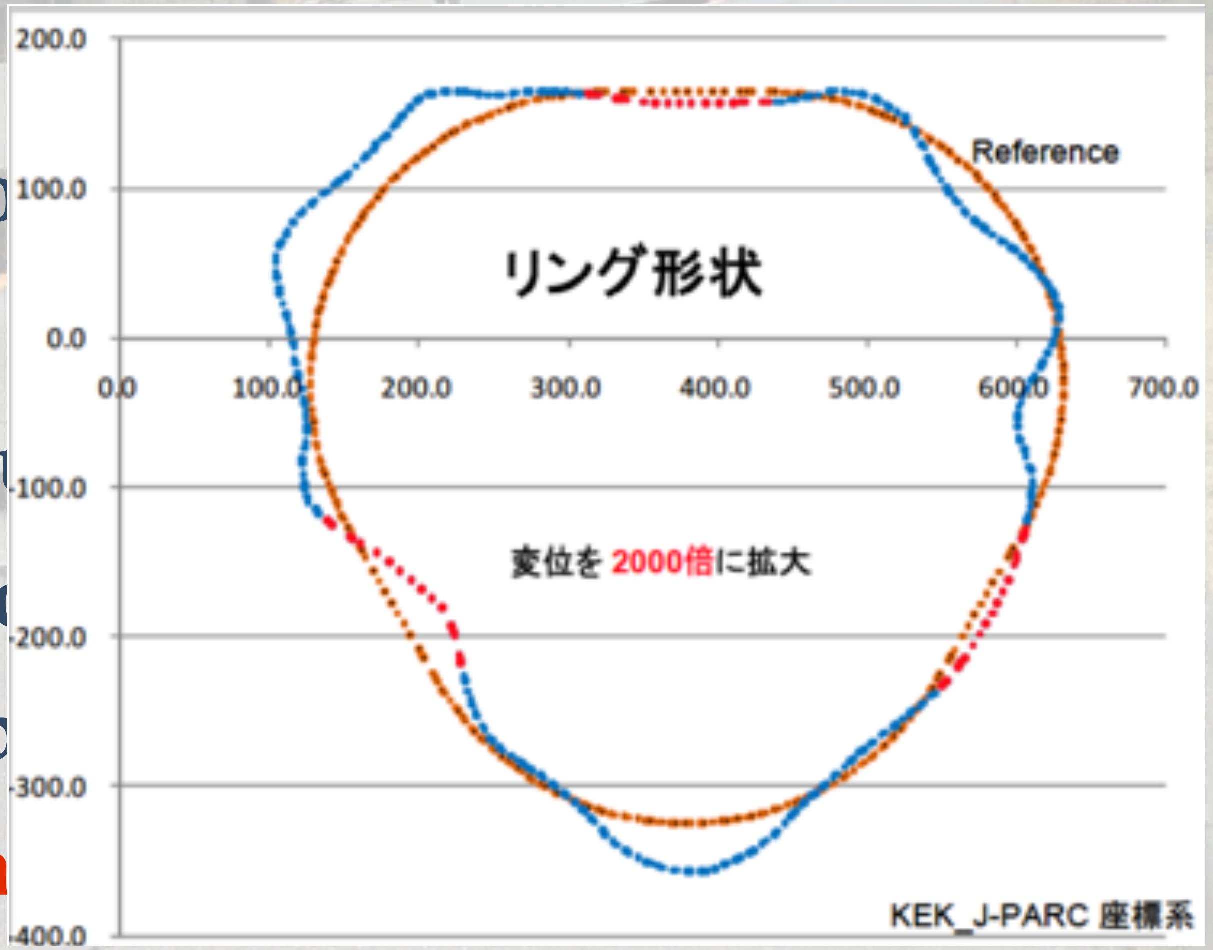

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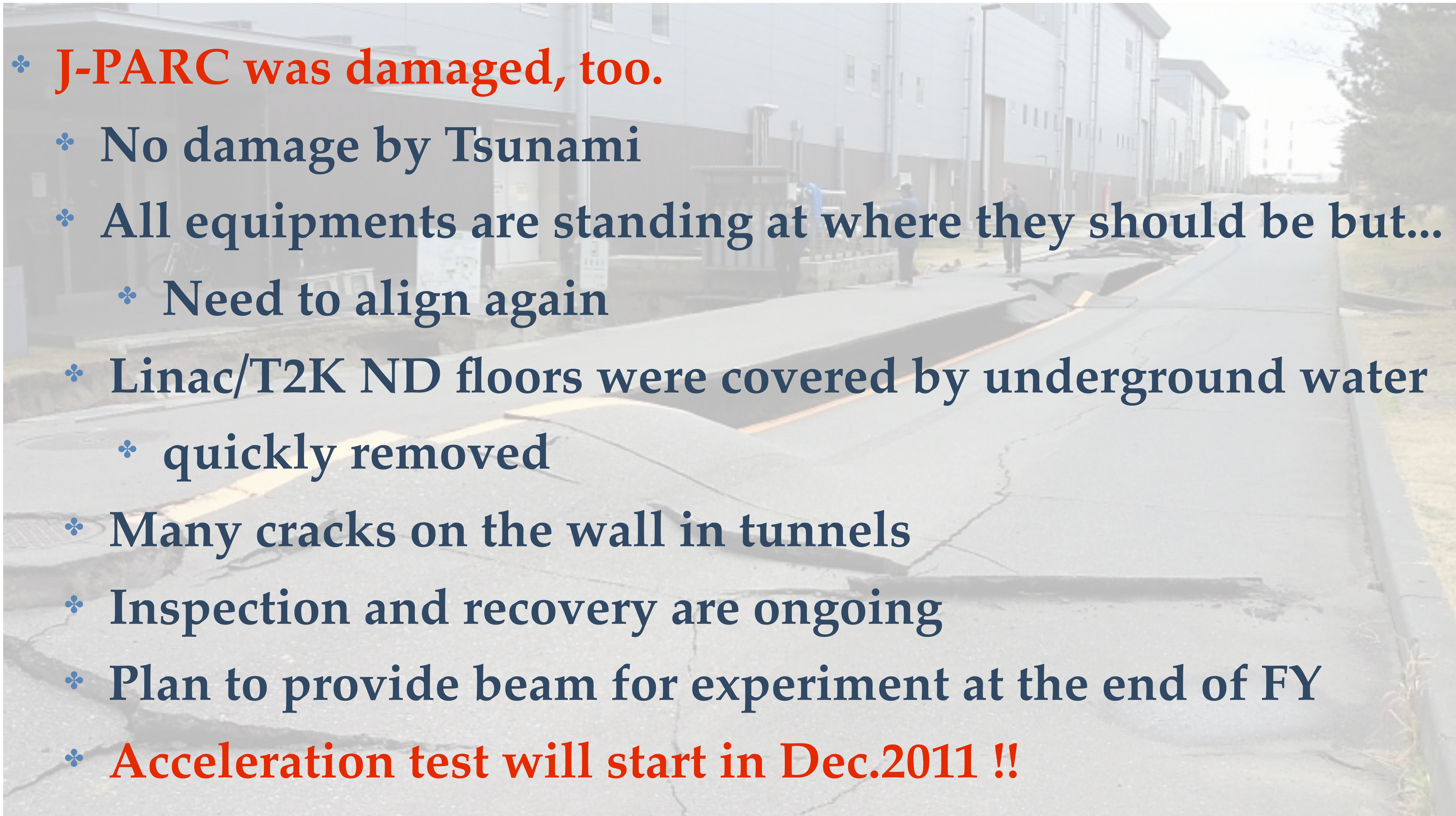

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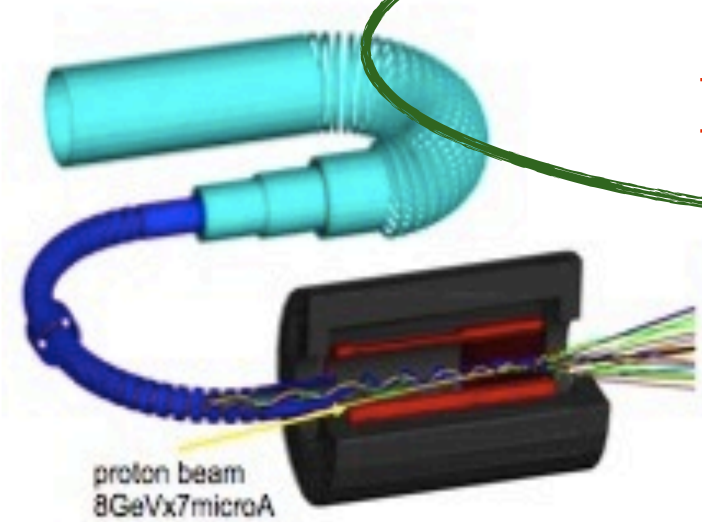
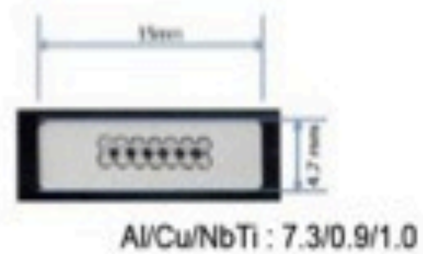
COMET R&D

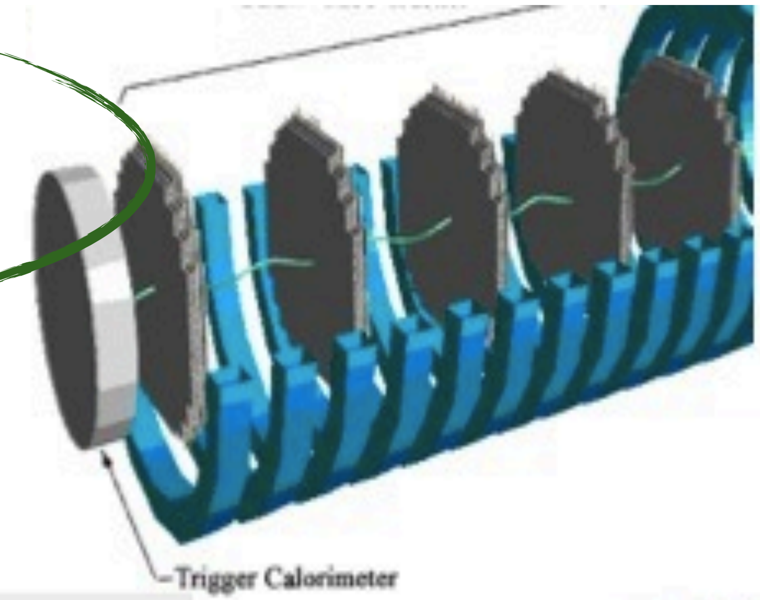
Many Activities are Progressing in Parallel

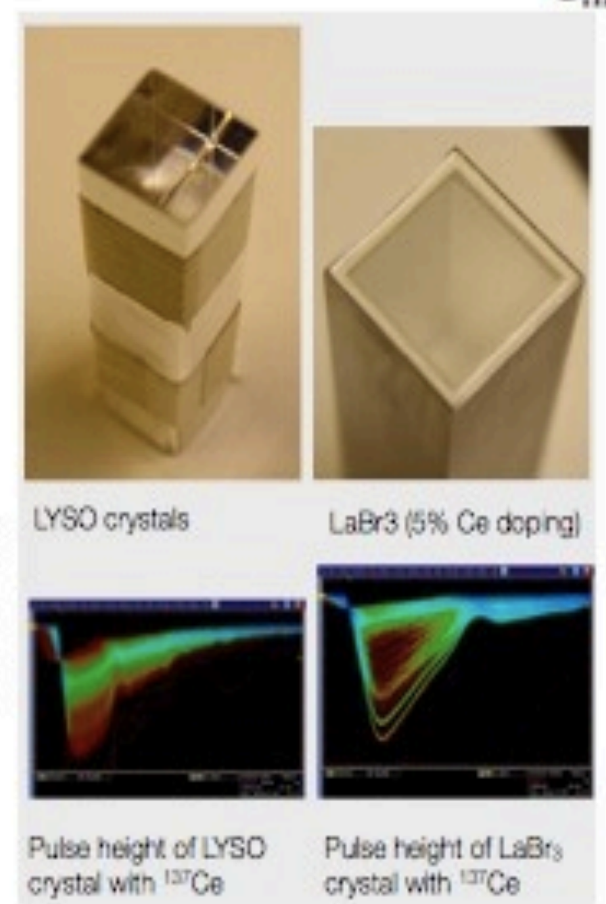


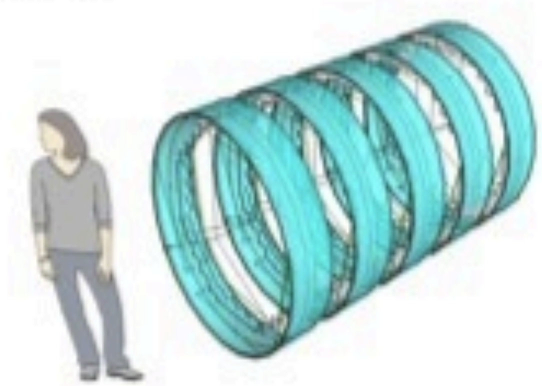
Al stabilized conductor

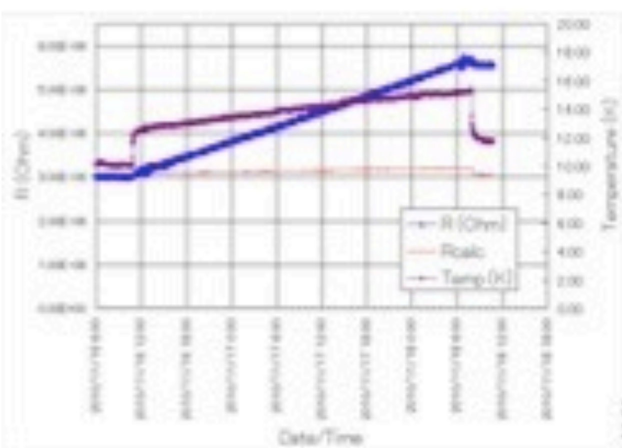


Crystal development

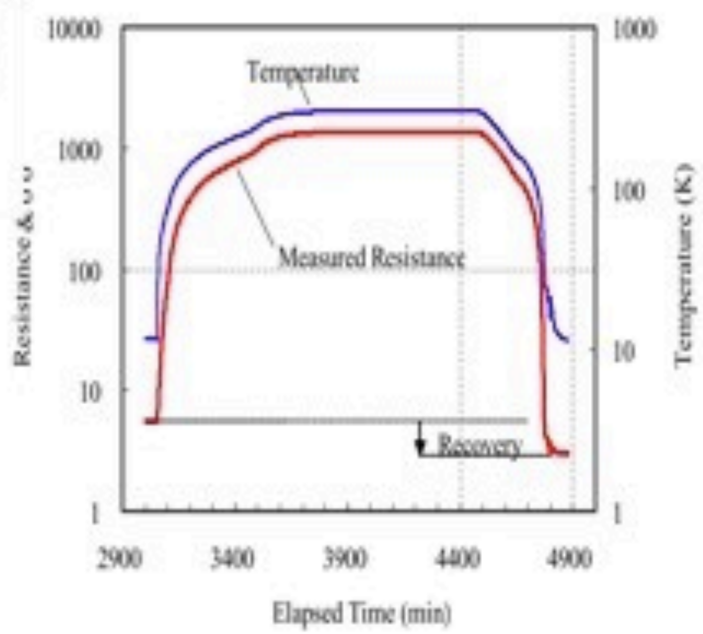


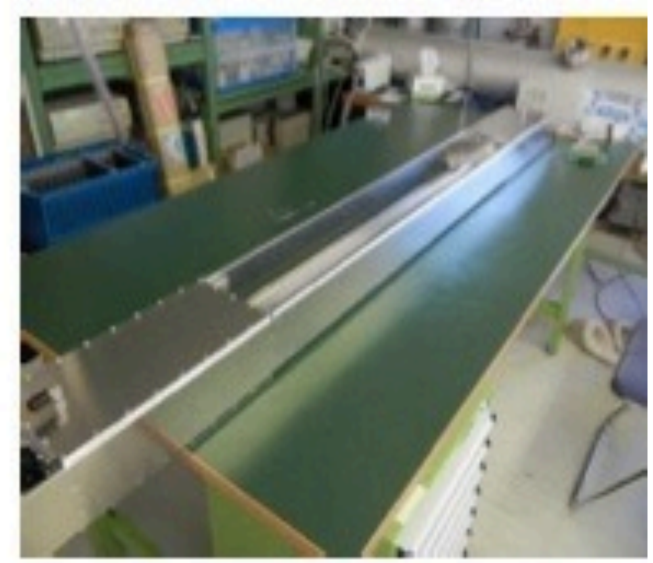




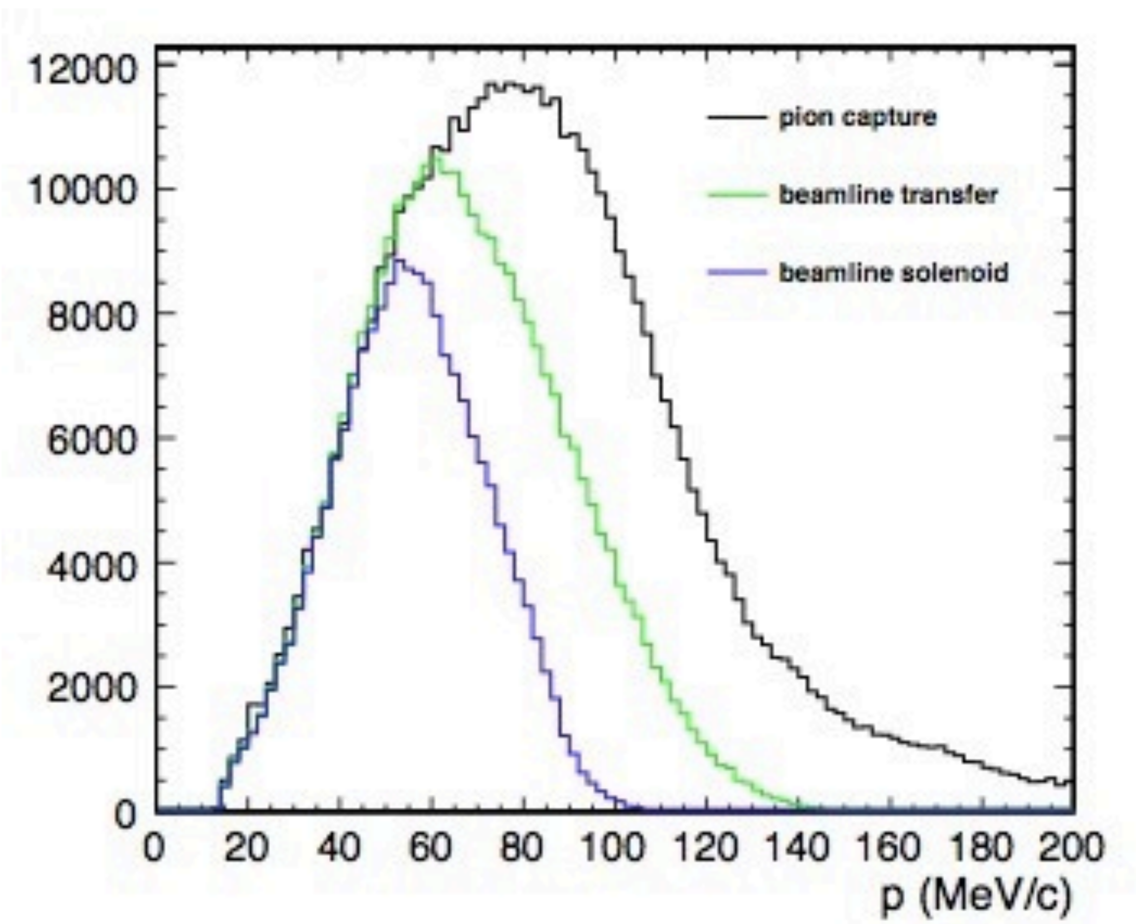


Neutron irradiation at a research reactor

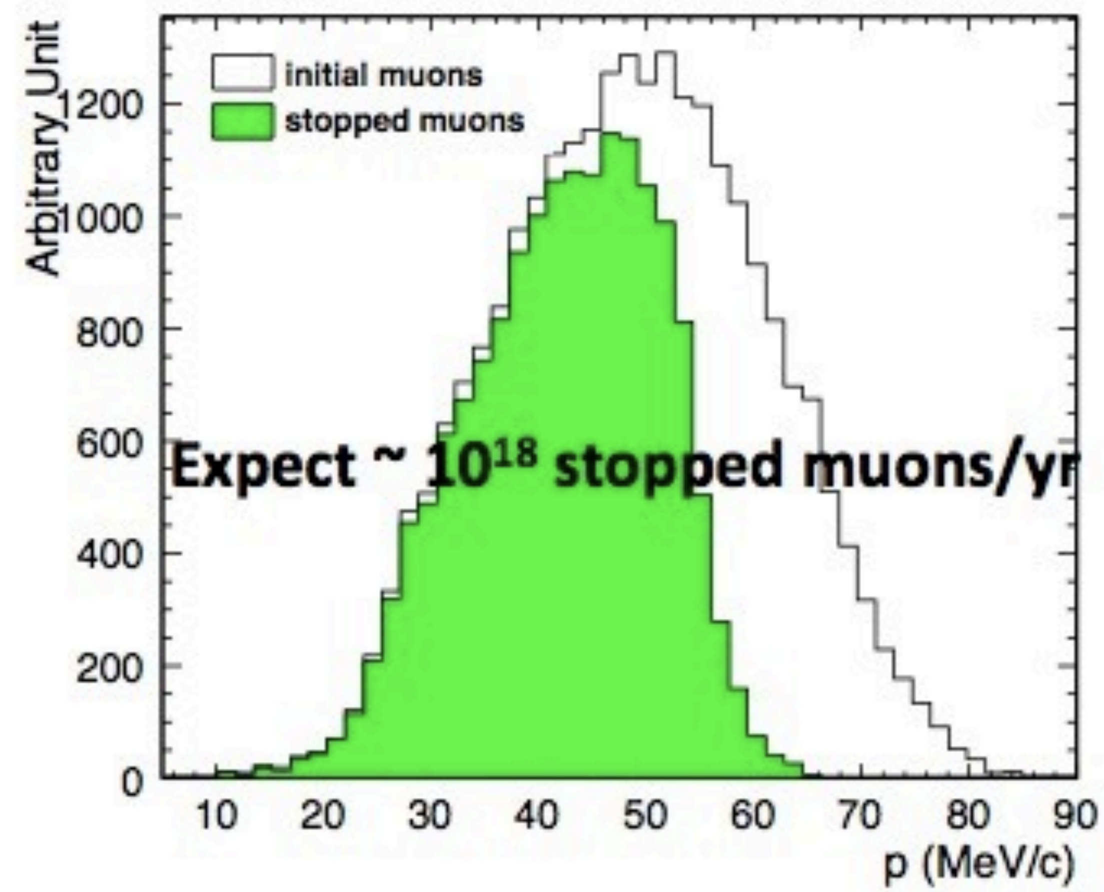




Sensitivity Studies



Momentum selection of μ as passes down transport beamline



Momentum distributions of muons stopped in Al target

- Using MARS / G4Beamline and Geant4
  - **Still much to do in terms of optimizing collimators / beam blockers / target *etc*.**

Sensitivity Estimation

- Single Event Sensitivity (2×10^7 sec running):

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

- N_μ is a # of stopped muons
  - 2.0×10^{18} muons
- f_{cap} is a fraction of muon capture
  - 0.6 for aluminum
- A_e is the detector acceptance
  - 0.031

total # of p's	**8.5×10^{20}**
μ yield / p	**0.0035**
μ stopping ε	**0.66**
# of stopped μ's	**2.0×10^{18}**

Single Event Sensitivity
2.6×10^{-17}

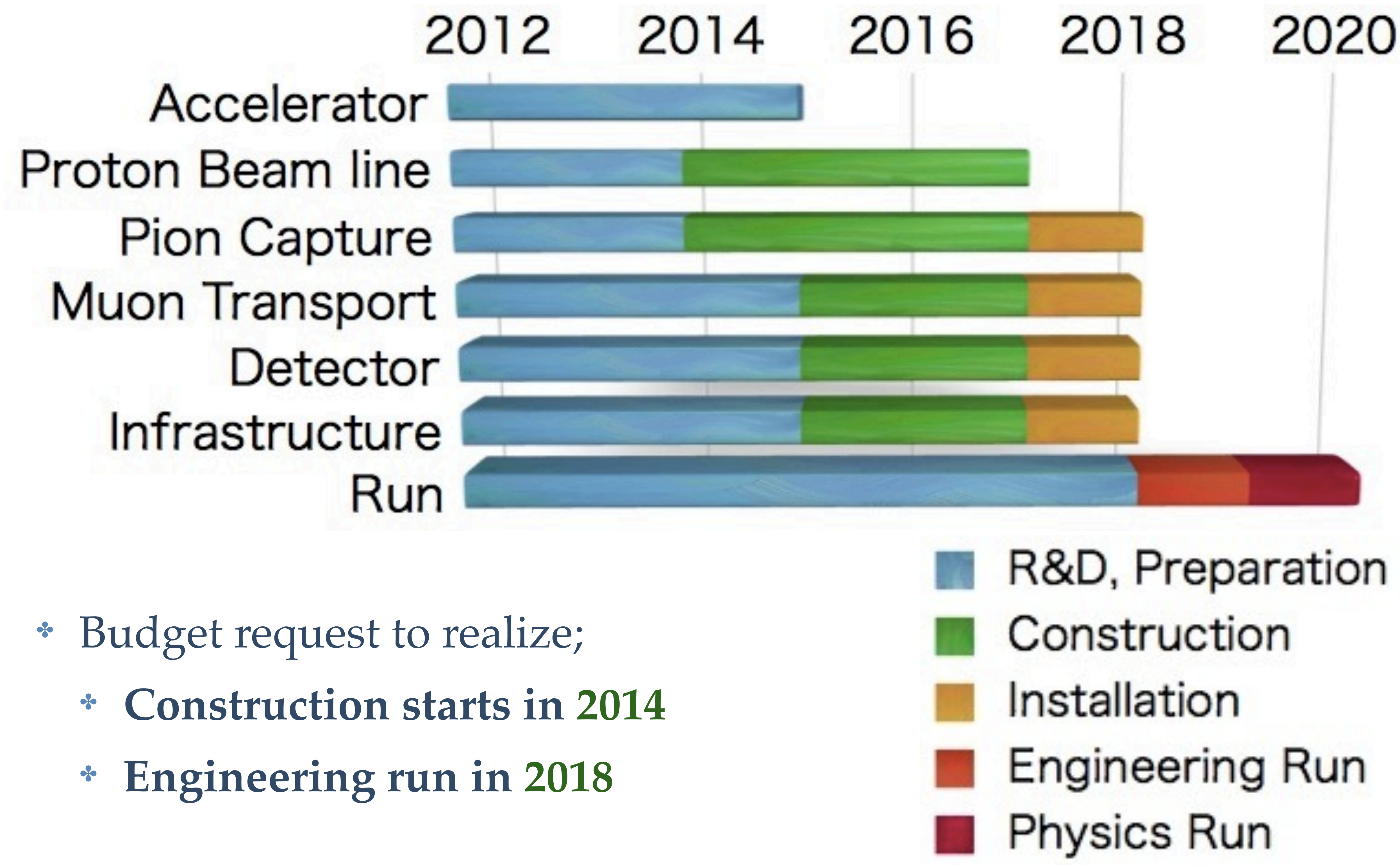
Upper Limit (CL.90)
6.0×10^{-17}

Background Estimation

(10^{-9} extinction is assumed)

	Events	Comments
Radiative Pion Capture	0.05	
Beam Electrons	<0.1	MC stat. limited
Muon Decay in Flight	<0.0002	
Pion Decay in Flight	<0.0001	
Neutron Induced	0.024	for high E neutron
Delayed-Pion Radiative Capture	0.002	
Anti-Proton Induced	0.007	for 8 GeV proton
Muon Decay in Orbit	0.15	
Radiative Muon Capture	<0.001	
Muon Capture with neutron Emission	<0.001	
Muon Capture with Charged Particle Emission	<0.001	
Cosmic-Ray Muons	0.002	
Electrons from Cosmic-Ray Muons	0.002	
Total	**0.34**	

Schedule



- Budget request to realize;
  - **Construction starts in 2014**
  - **Engineering run in 2018**

The COMET Collaboration

Summary

- **Charged Lepton Flavour Violation** is very attractive to explore the new physics.
- Charged Lepton Flavour Violation have no observable SM rate and not withstanding backgrounds etc. are excellent probes of beyond SM.
- In particular, muon decay is the most sensitive probe. (**$\mu \rightarrow e\gamma$** and **$\mu N \rightarrow eN$**)
  - **$\mu \rightarrow e\gamma$** : MEG experiment (PSI) is ongoing
  - **$\mu N \rightarrow eN$** : COMET experiment was proposed (J-PARC)
    - CDR completed in 2009 and secured stage-1 (of 2 stages) approval from J-PARC PAC. Expect to complete TDR ASAP in readiness of 2nd stage of approval
    - Significant Milestones have already been reached in Proton Extinction, S/C magnet design and Pion Capture System
    - Mu2E (FNAL) is aiming the same goal with similar schedule, competitive.
- Even we were damaged severely by the earthquake, COMET is not delayed so much.
  - J-PARC recovery is progressing, and acceleration test will start soon.
  - COMET R&D is also progressing
  - Aiming to start construction in 2014, engineering run in 2018