Search for Charged Lepton Flavor Violation at J-PARC - COMET Experiment -

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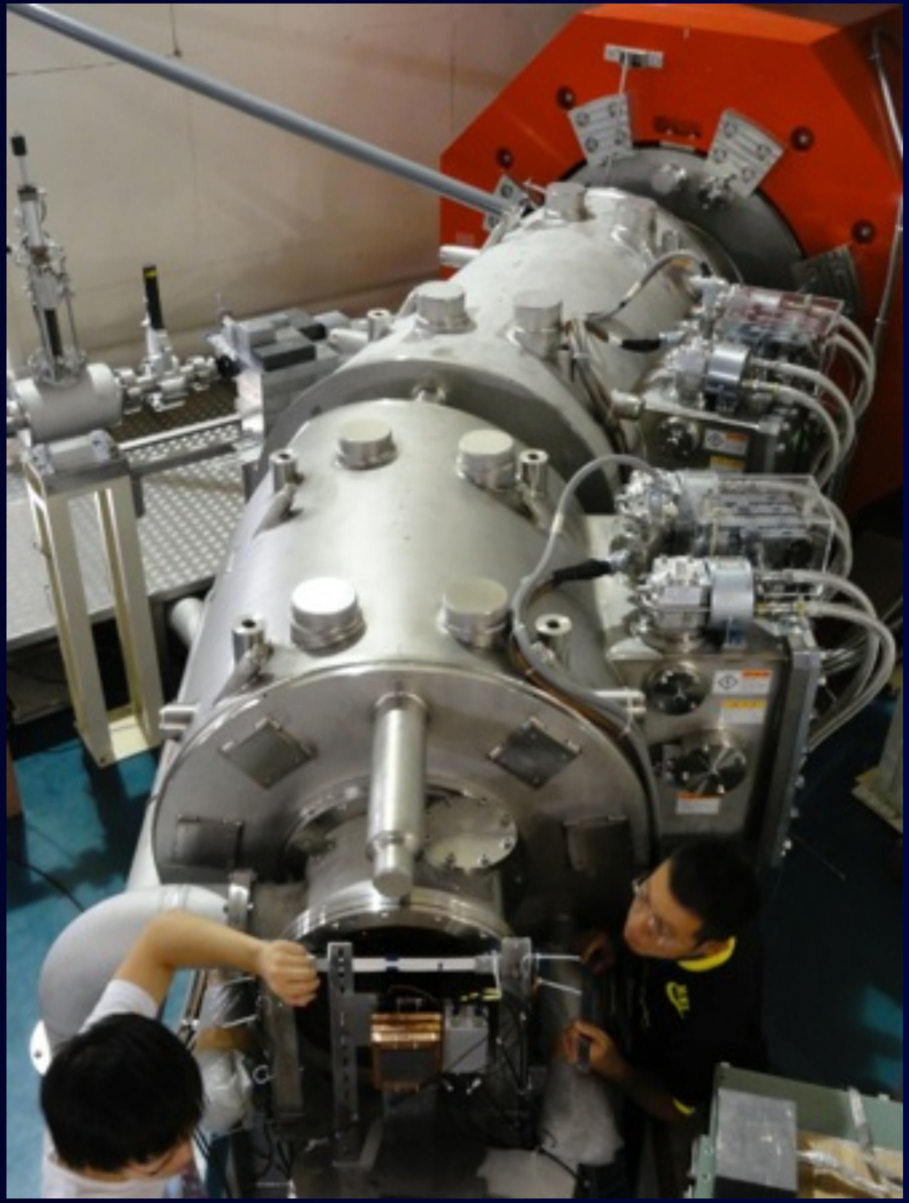
LBNL

Outline

- Why Flavor Physics ?
  Why Charged Lepton Flavor Violation (CLFV) ?
- CLFV Experiments
  - Muon to electron conversion in a muonic atom
- COMET (at J-PARC)
  - for sensitivity of $<10^{-16}$ (x10000)
- COMET Phase-I (at J-PARC)
  - for sensitivity of $<10^{-14}$ (x100)
- Summary

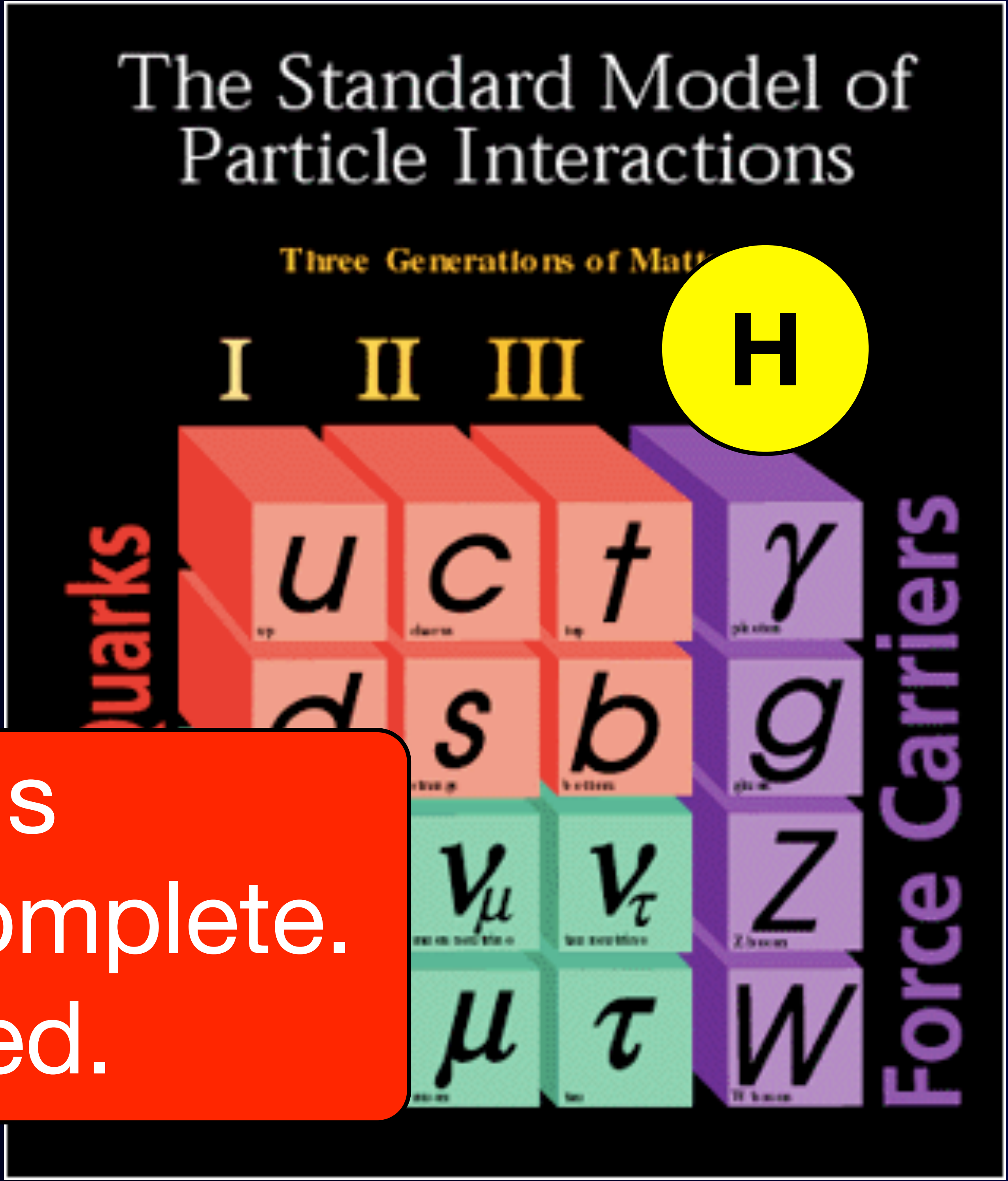


Why Flavor Physics ?
Why Charged Lepton Flavor Violation (CLFV)?

The Standard Model has the Higgs boson, but no new particles are found yet...

The discovery of the Higgs boson has been made.

The Standard Model can explain most of the experimental results. However, there are many undetermined parameters and issues.



The Standard Model is considered to be incomplete. New Physics is needed.

Flavor Physics and New Physics

flavor structure

Effective Lagrangian in the Standard Model (SM)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm sym.break.}$$

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + Y^{ij} \Psi_L^i \Psi_R^j \Phi + \frac{g_{ij}}{\Lambda} \Psi_L^i \Psi_L^{jT} \Phi \Phi^T,$$

Origin of flavor

(1) what determines the observed pattern of masses and mixing angle of quarks and leptons ?

(2) which sources of flavor symmetry breaking are accessible at low energy ?

Ques.(1) is difficult to address owing to the lack of theoretical guidance.
Ques.(2) can be answered by a series of high-precision measurements

search for new physics

New Physics Search in Charged Lepton Flavor

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with new physics contributions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{C_{\rm NP}}{\Lambda^2} O^{(6)}_{ij} ,$$

Λ is the energy scale of new physics

Charged Lepton Flavor

Charged Lepton Flavor Violation

For instance, $\mu \rightarrow e\gamma$ ($B<5.7\times10^{-13}$),

$$\frac{C_{\rm NP}}{\Lambda^2} O^{(6)}_{ij} \rightarrow \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$

$$\Lambda > 2\times 10^5 \,\text{TeV} \times (C_{\mu e})^{\frac{1}{2}} .$$

$\Lambda > O(10^5)$ TeV

The constraint in CLFV is even more severe than in the quark flavor.
The SM contribution to muon CLFV is small, of the order of $O(10^{-54})$.

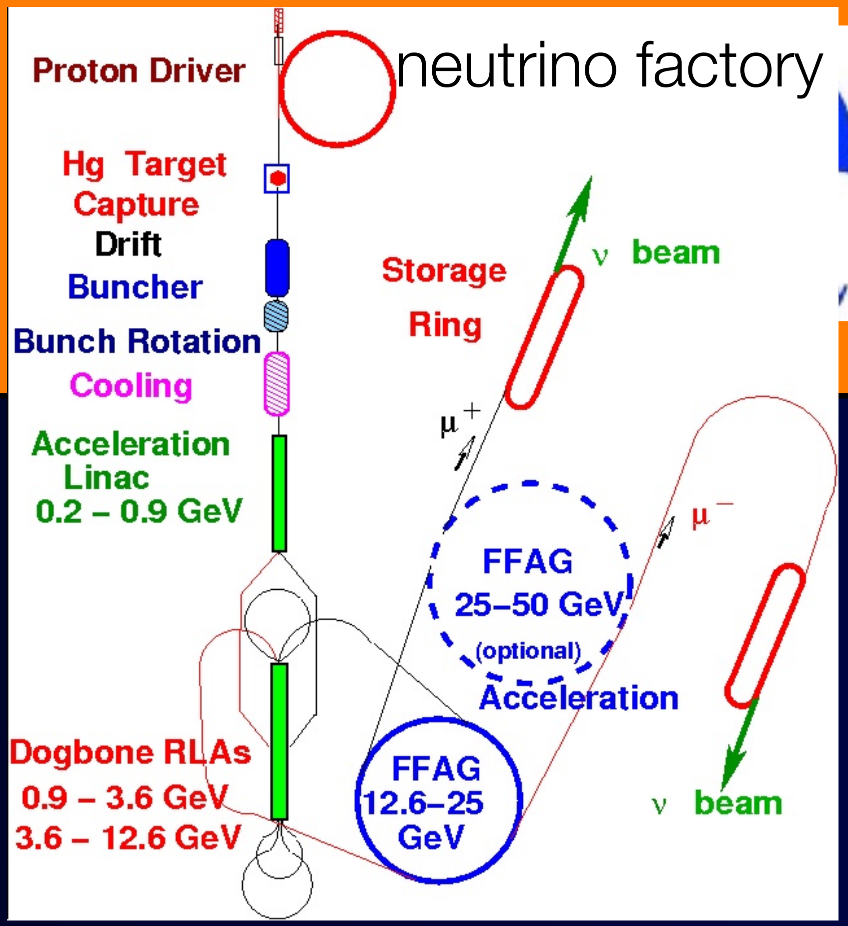
Which Rare Decays at Low Energy ?

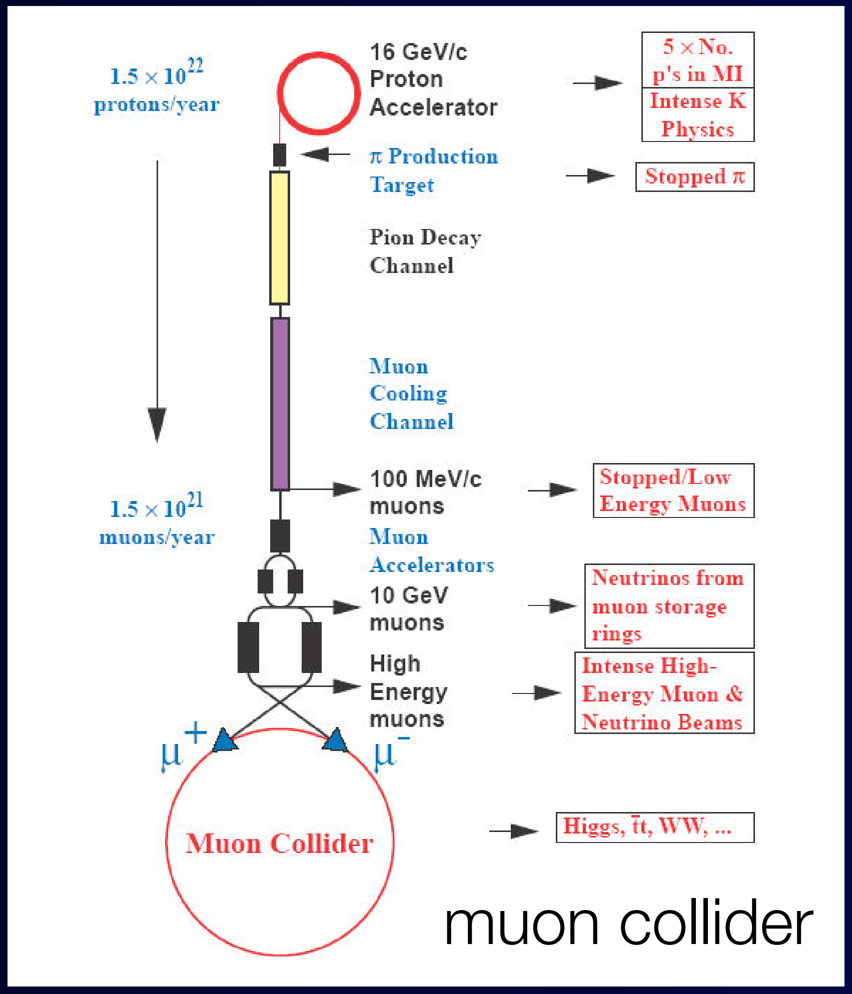
- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- Flavor Changing Neutral Current Process (FCNC)
- FCNC in the quark sector
  - $b \to s\gamma$, $K \to \pi\nu\nu$, etc.
  - Allowed in the Standard Model.
  - Need to study deviations from the SM predictions.
    - Uncertainty of more than a few % (from QCD) exists.
- FCNC in the lepton sector
  - $\mu \to e\gamma$, $\mu + N \to e + N$, etc. (lepton flavor violation =LFV)
  - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
  - Need to study deviations from none
    - clear signature and high sensitivity

Why Muons, not Taus?

- A number of taus available at B factories are about 1-10 taus/sec. At super-B factories, about 100 taus/sec are considered. Also some of the decay modes are already background-limited.
- A number of muons available now, which is about 10^8 muons/sec at PSI, is the largest. Next generation experiments aim 10^{11}-10^{12} muons/sec. With the technology of the front end of muon colliders and/or neutrino factories, about 10^{13}-10^{14} muons/sec are considered.

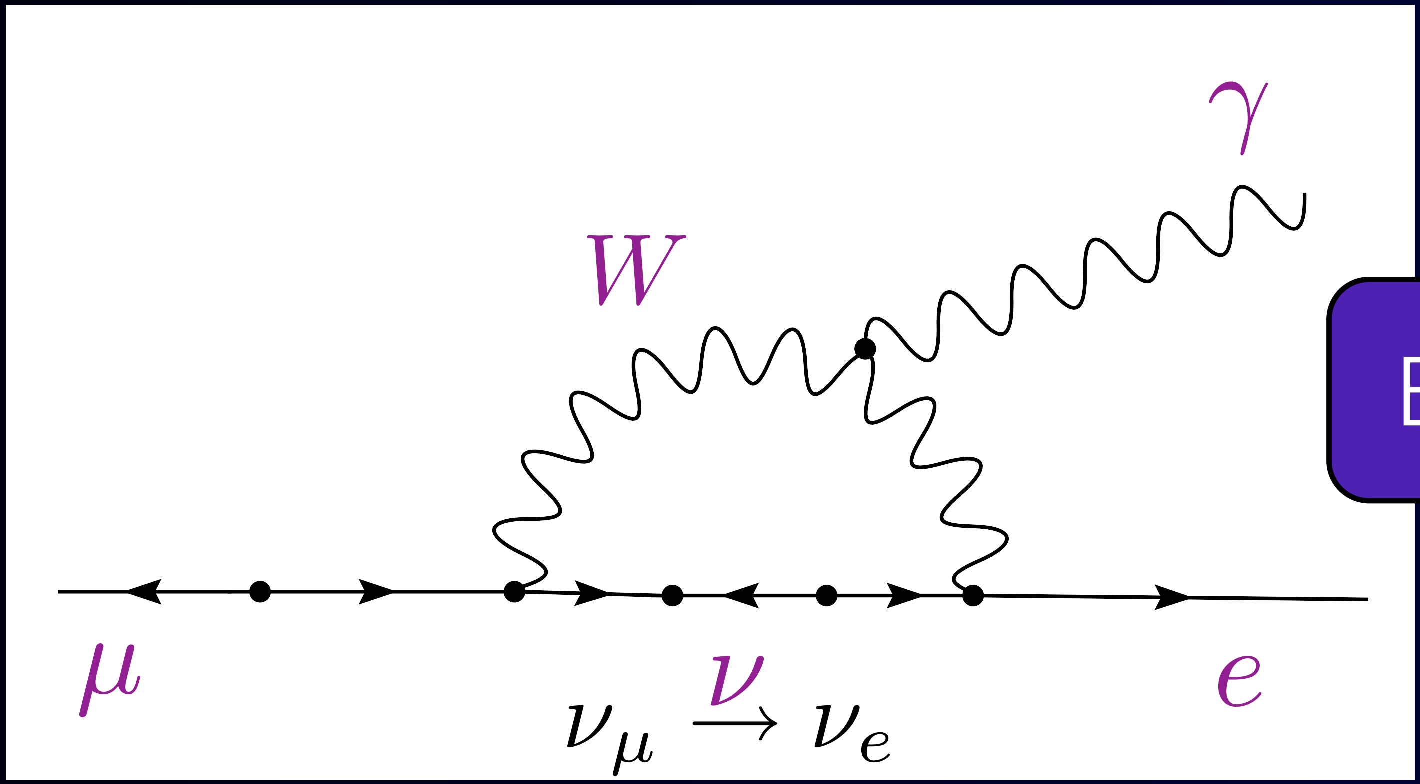
a larger window to search for new physics for muons than taus





No SM Contribution in Charged Lepton Flavor Violation (CLFV)

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



BR~O(10^{-54})

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

Sensitivity to New Physics at High Energy

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CLFV is unique and important
to find new physics beyond the SM.

CLFV is sensitive to NP at high energy scale Λ.

others

amplitude

$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_N|^2$$

subject to uncertainty of SM prediction

CLFV

rate

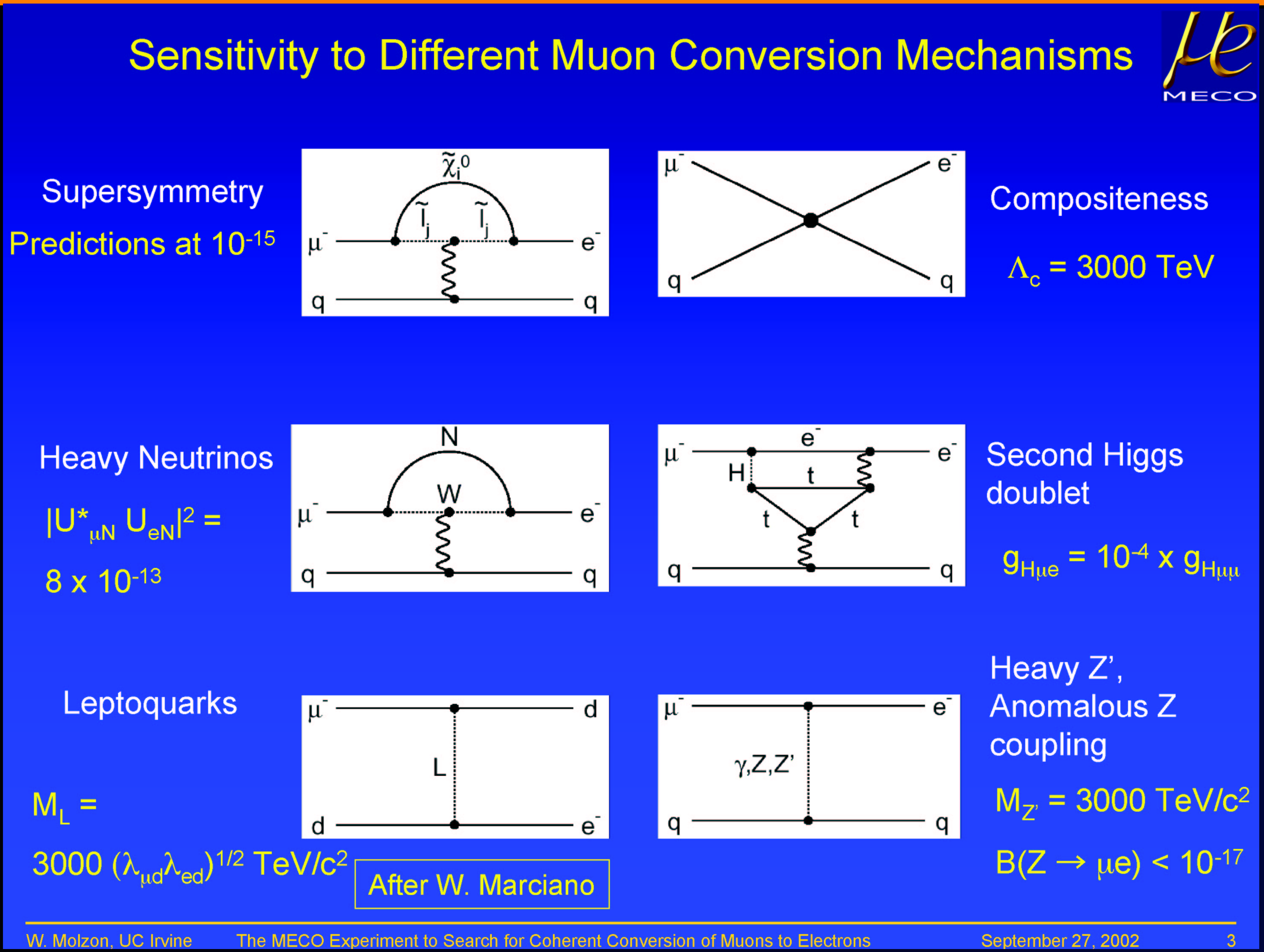
$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_N|^2$$

could go higher energy scale

$$R \propto \frac{1}{\Lambda^4}$$

CLFV for muons can be improve by a factor of 10,000 or more, implying 10 times in energy reach.

Various Models Predict CLFV......



Example of Sensitivity to NP in High Energy Scale : SUSY models

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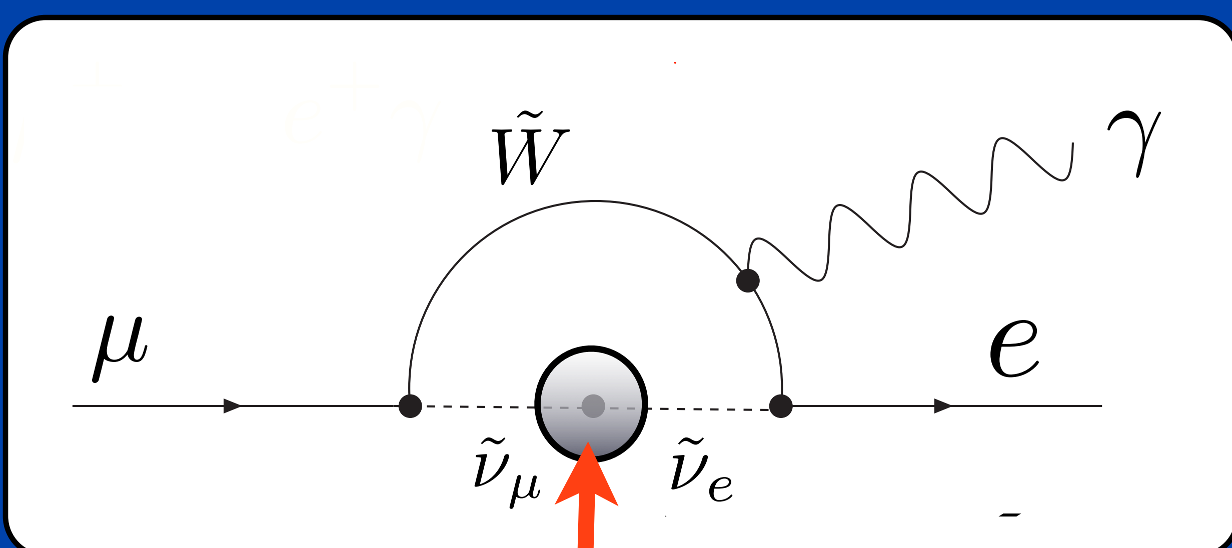
- For loop diagrams,

$$\mathrm{BR}(\mu \to e\gamma) = 1 \times 10^{-11} \times \left(\frac{2\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2 \qquad y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing



example diagram for SUSY (~TeV)

Physics at about 10^{16} GeV

slepton mixing (from RGE)

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

SUSY-GUT model

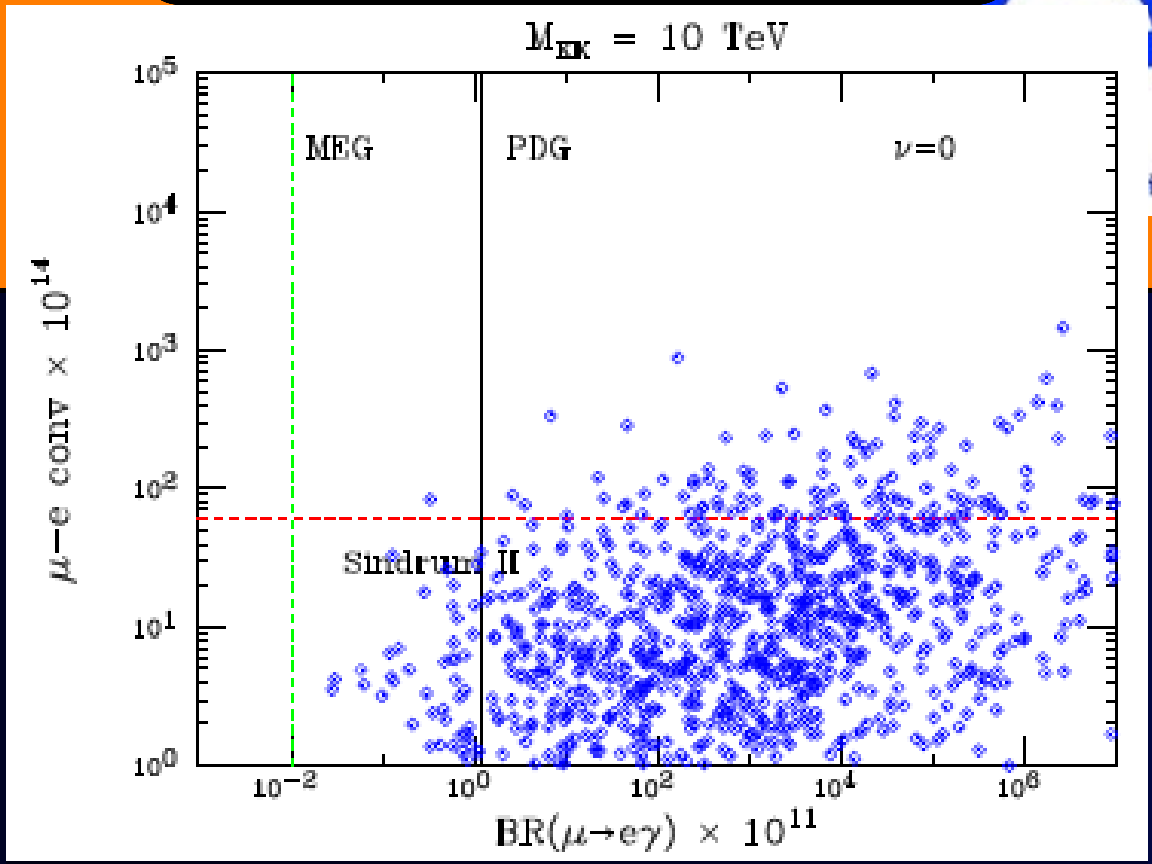
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln\frac{M_{GUT}}{M_R}$$

SUSY neutrino seesaw model

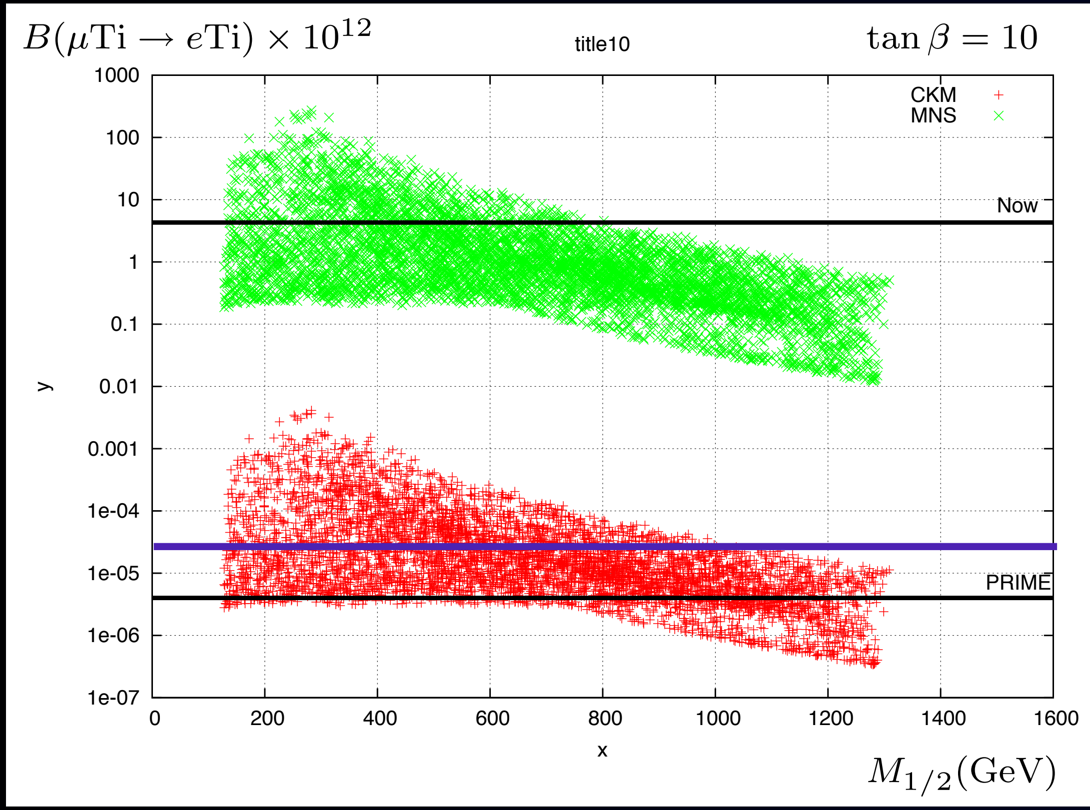
CLFV Predictions

Various BSM models predict sizable muon CLFV, as well as tau CLFV.

extra dimension model

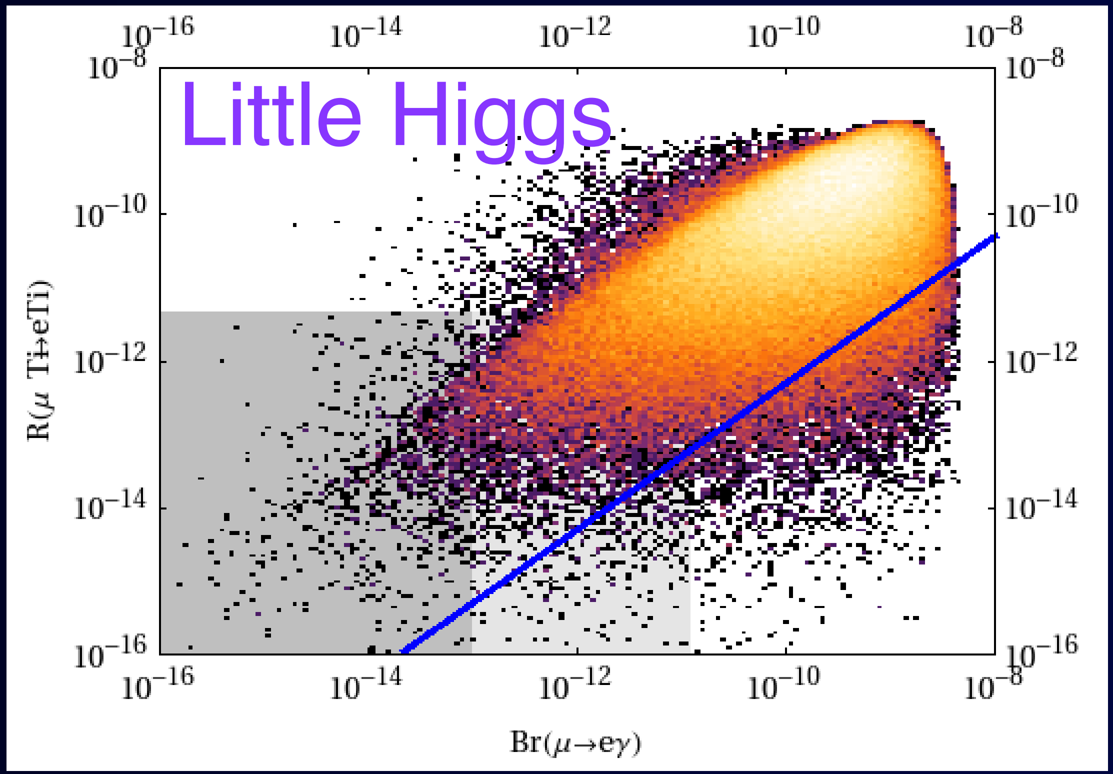


SUSY model



↓ 10^4

little Higgs model



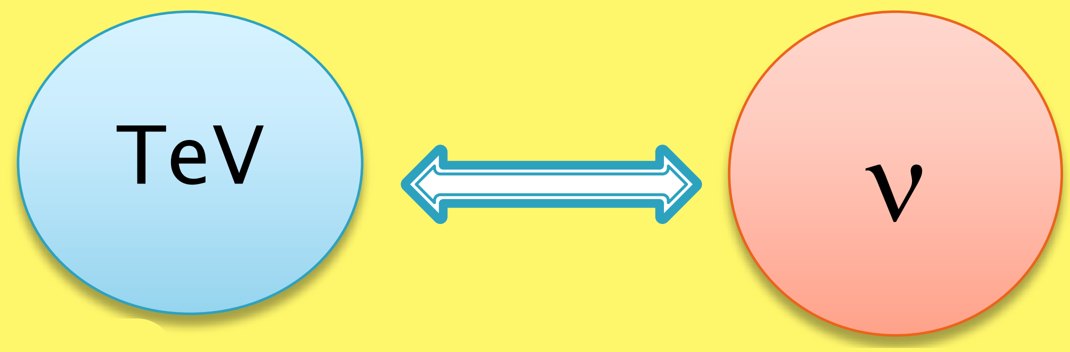
from Y. Okada san’s slide (2010)

CLFV and Neutrino Mass Generation

Scale of the electroweak symmetry breaking | Scale of the neutrino mass generation

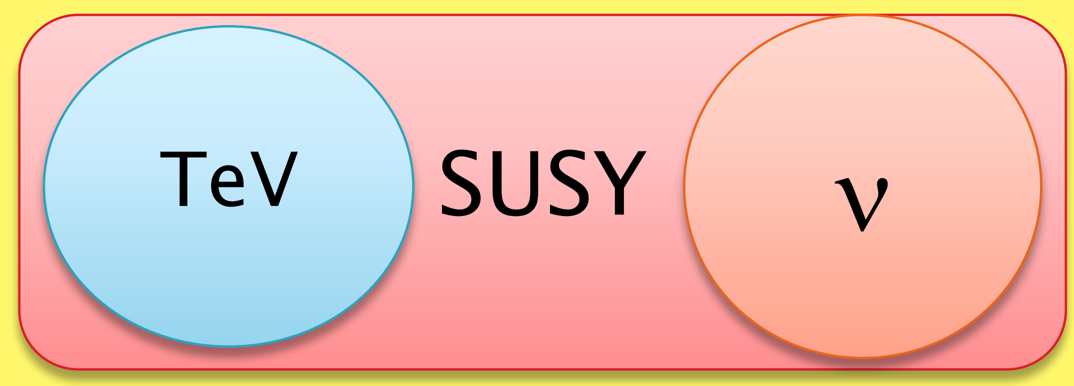
If two scales are well separated, LFVs are suppressed.

CLFV~O(10^{-54})



1

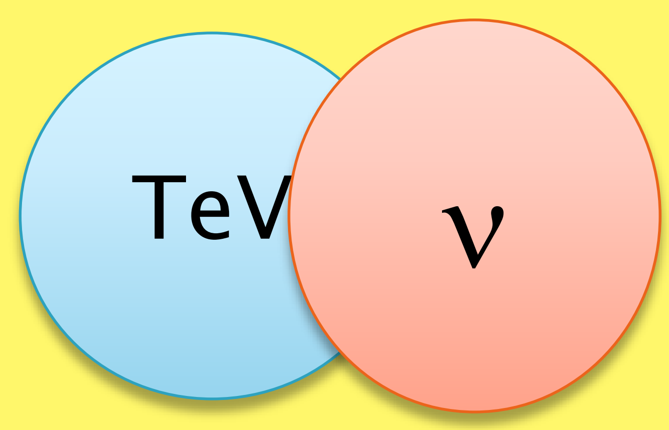
In supersymmetric models, large LFV signals are expected even if two scales are separated.



2

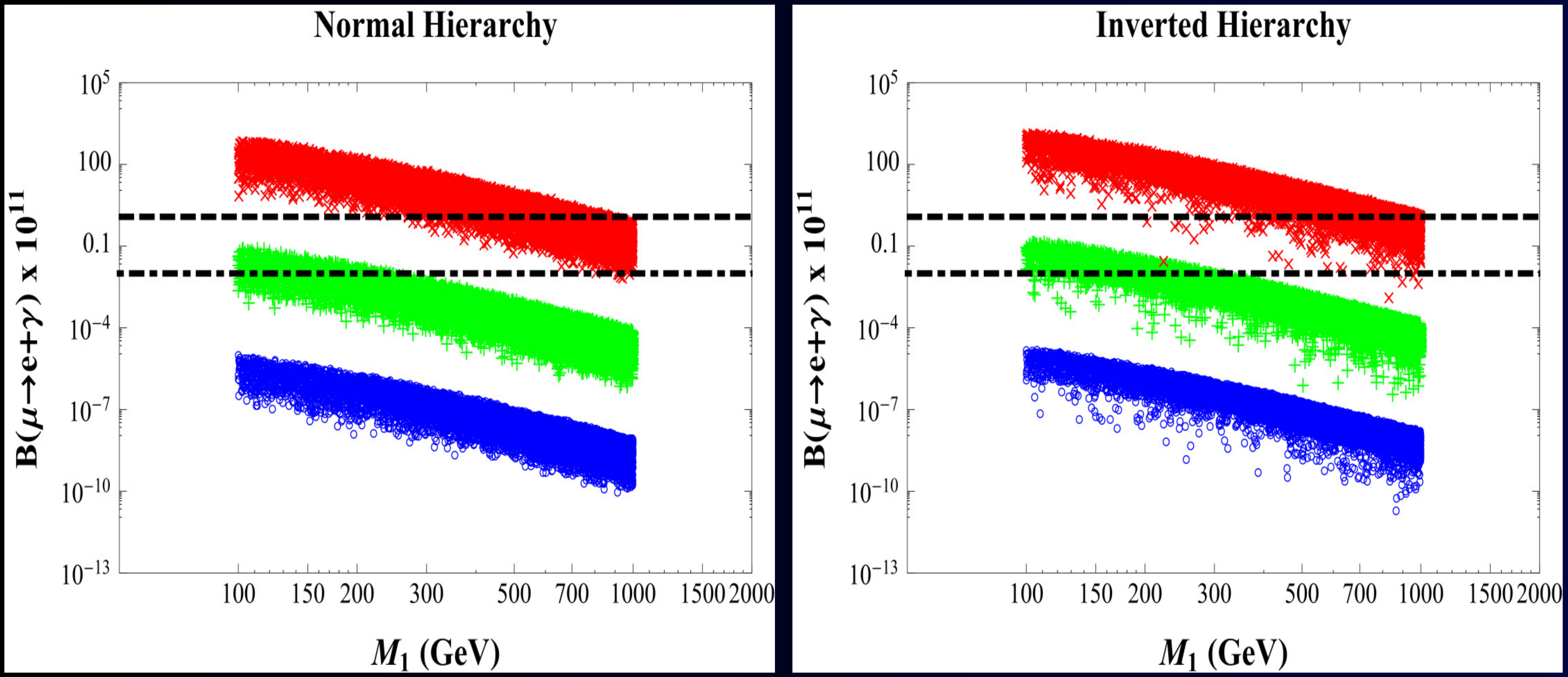
If two scales are close, large LFVs are expected.

Neutrino mass from loop
Triplet Higgs for neutrino mass
Left-right symmetric model



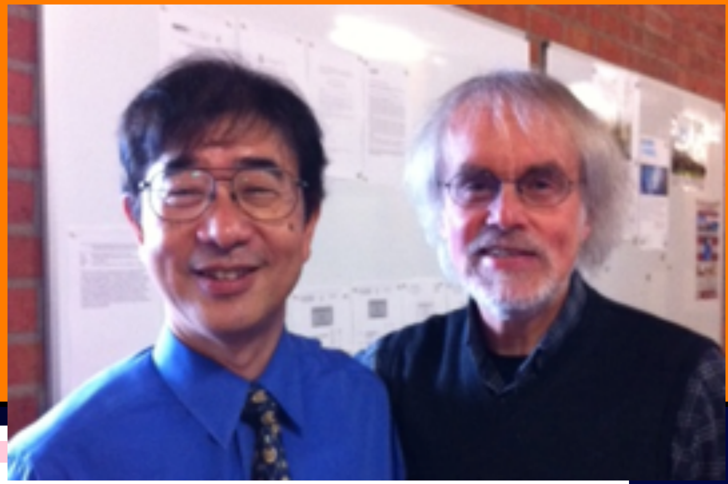
A. Ibara, E. Molinaro, S.T. Petcov, Phys. Rev. D84 (2011) 013005

CLFV with TeV Seesaw (Type-I)



TeV seesaw type-I models predict sizable branching ratio of CLFV with right-handed neutrino mass of O(TeV).

“DNA of New Physics” (a la Prof. Dr. A.J. Buras)



W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

The pattern of measurement:
★★★ large effects
★★ visible but small effects
★ unobservable effects
is characteristic,
often uniquely so,
of a particular model

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

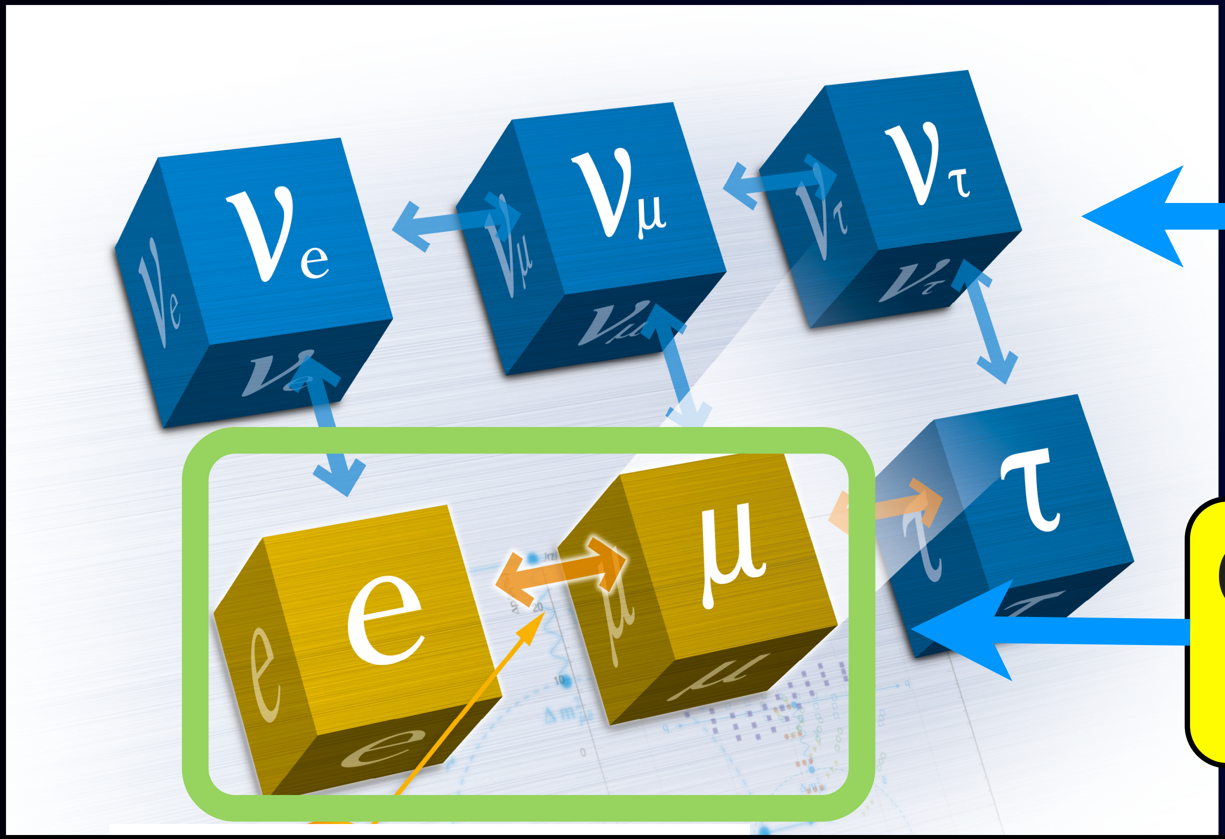
These are a subset of a subset listed by Buras and Girrbach MFV, CMFV, $2HDM_{\overline{MFV}}$, LHT, SM4, SUSY flavor. SO(10) – GUT, $SSU(5)_{HN}$, FBMSSM, RHMFV, L-R, RS_0, gauge flavor, ……….

Quarks, Neutrinos, and Charged Leptons

Quarks

Quark mixing observed

Lepton



Neutrino mixing observed

Charged lepton mixing not observed.

Charged Lepton Flavor Violation (CLFV)

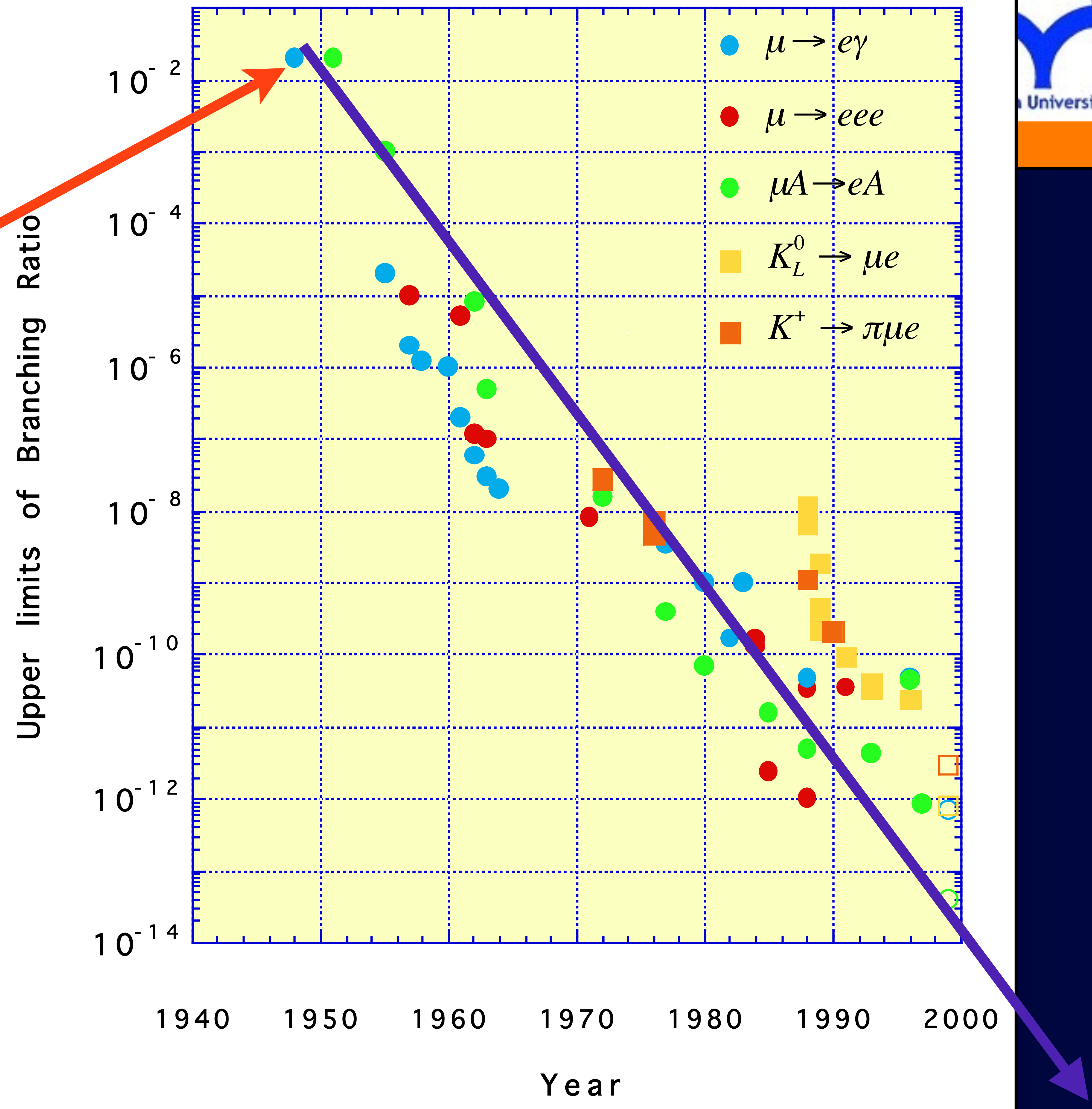
Nobel Prize-wining class research

CLFV Experiments

CLFV History

First cLFV search

Pontecorvo in 1947



Present Limits and Expectations in Future

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process	present limit	future	
$\mu \to e\gamma$	<5.7 x 10	<10	MEG at PSI
$\mu \to eee$	<1.0 x 10	<10	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	<10	Mu2e / COMET
$\mu N \to eN$ (in Ti)	<4.3 x 10	<10	PRISM
$\tau \to e\gamma$	<1.1 x 10	<10	superKEKB
$\tau \to eee$	<3.6 x 10	<10	superKEKB
$\tau \to \mu\gamma$	<4.5 x 10	<10	superKEKB
$\tau \to \mu\mu\mu$	<3.2 x 10	<10	superKEKB/LHCb

List of cLFV Processes with Muons

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ΔL=1

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$ ← this talk
- $\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$

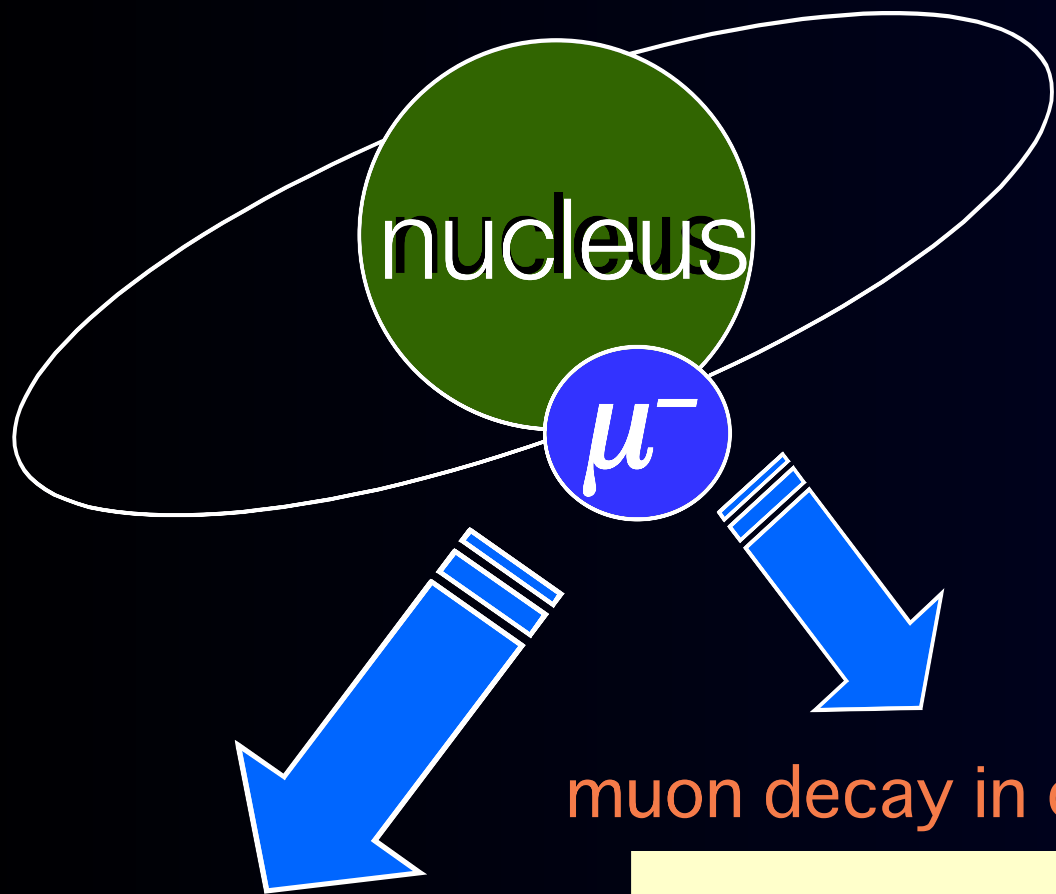
ΔL=2

- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- + N(A,Z) \rightarrow \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+\mu^+\mu^- + N(A,Z-1)$

$\mu \to e$ conversion in a muonic atom

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

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

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 105 MeV

Backgrounds:

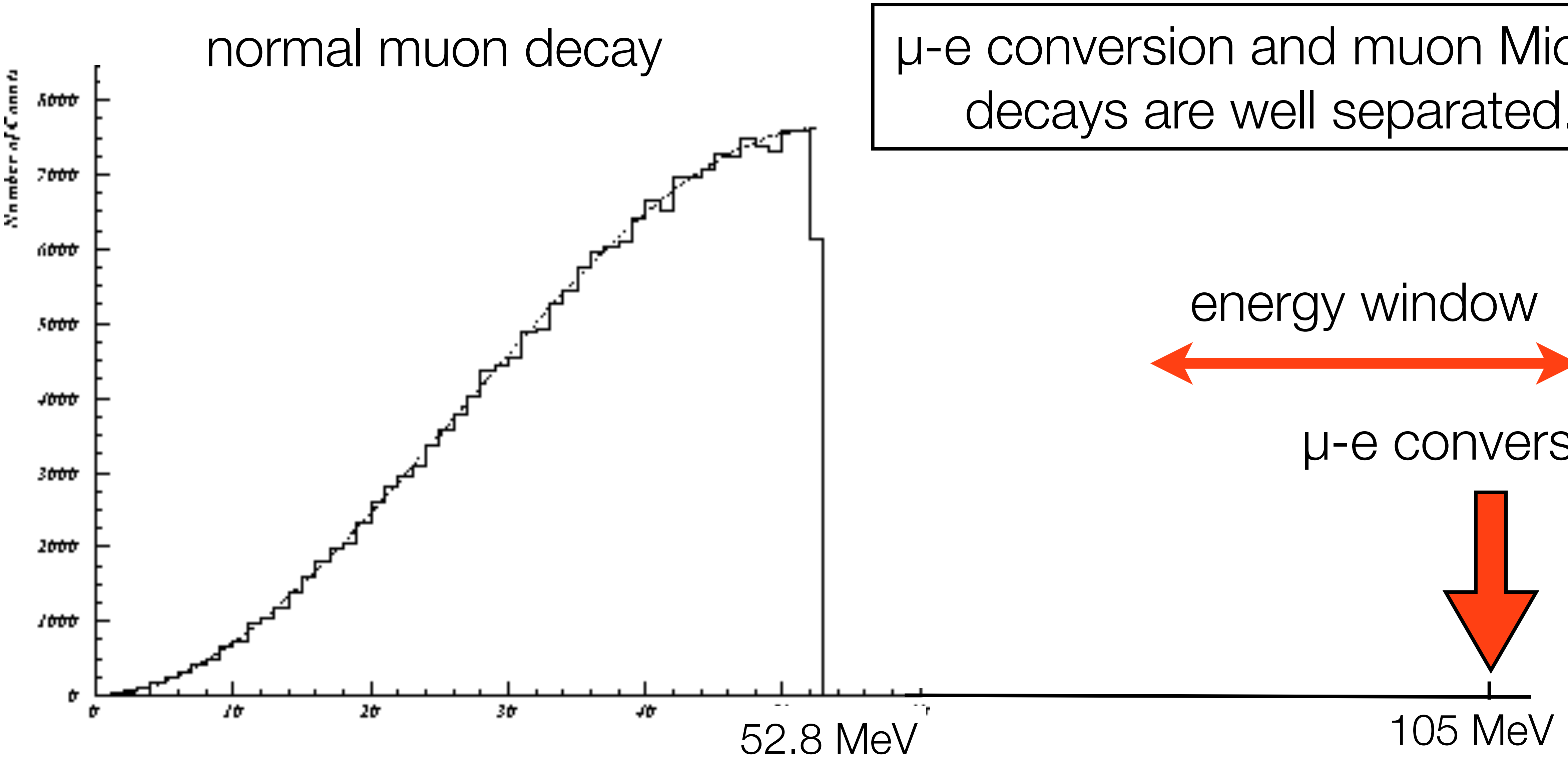
(1) physics backgrounds
  ex. muon decay in orbit (DIO)

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

(3) cosmic rays, false tracking

μ-e Conversion Signal and Normal Muon Decays

μ-e conversion and muon Michel decays are well separated.



electron momentum spectrum

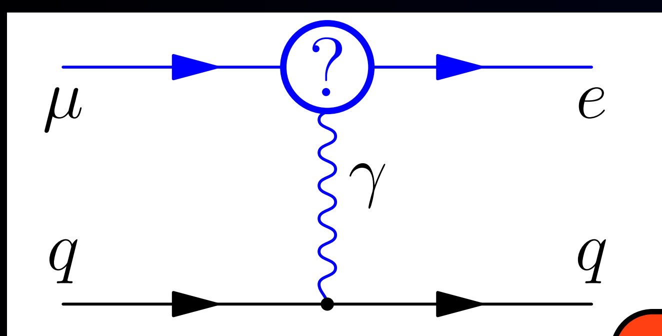
High Intensity beam can be used only for μ-e conversion

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

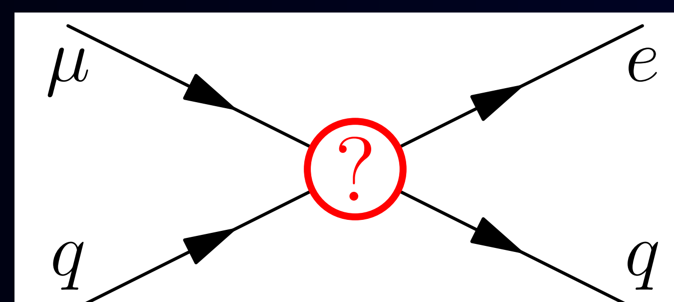
constructive

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

Photonic (dipole) interaction



Contact interaction



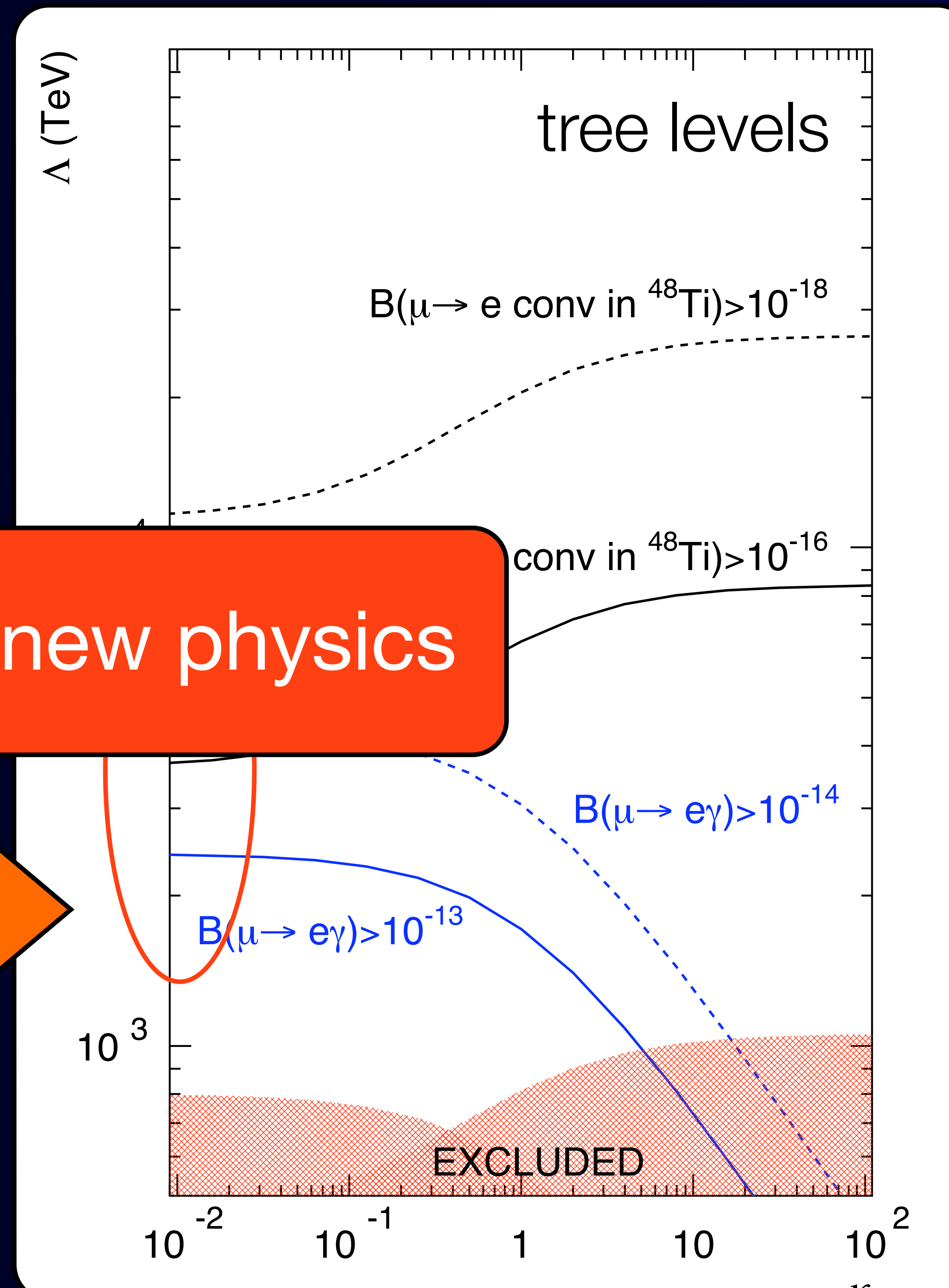
more sensitive to new physics

if photonic contri

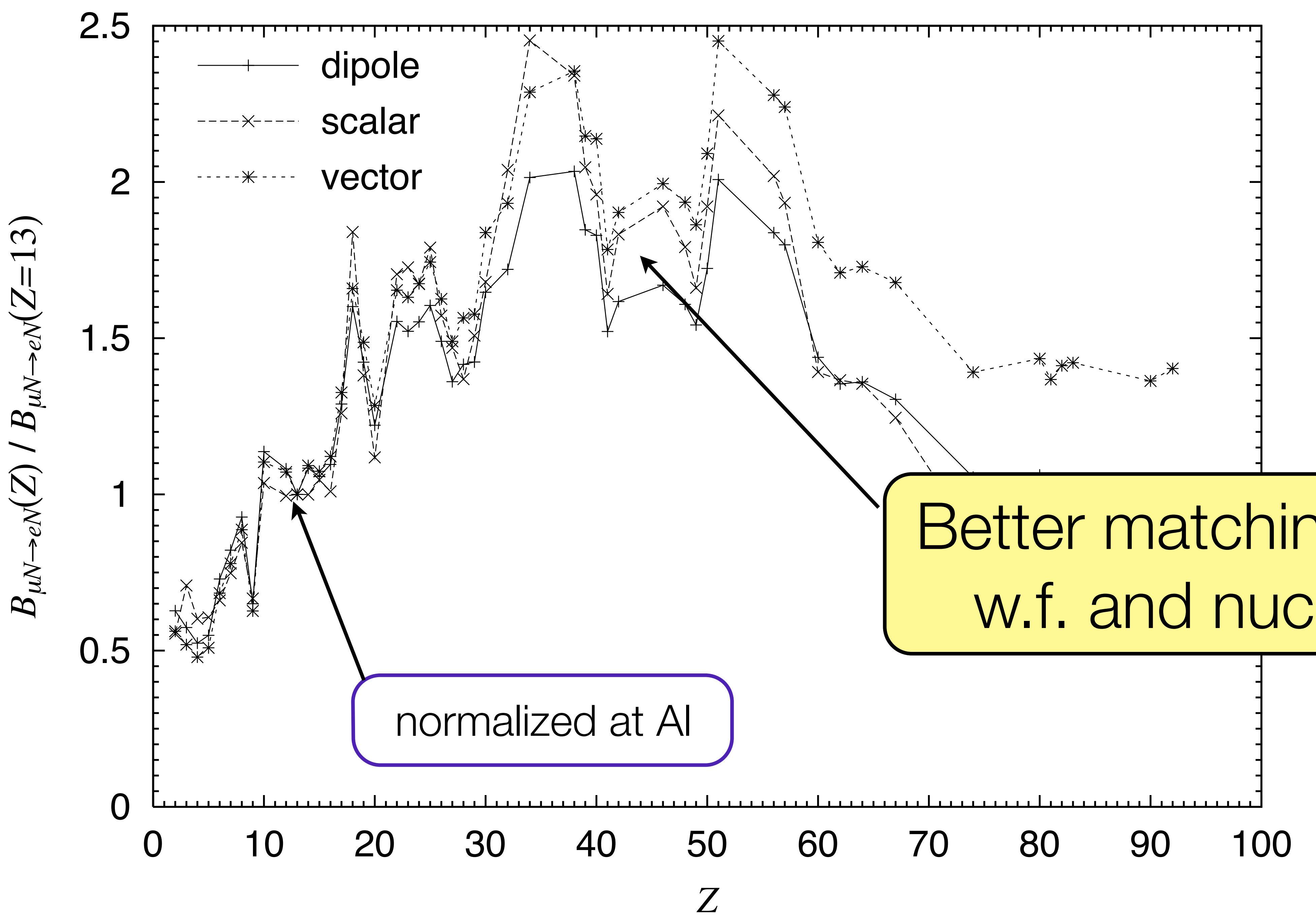
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z)$$

$$\sim \frac{B(A,Z)}{428}$$

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



μ-e Conversion : Target dependence (discriminating effective interaction)



R. Kitano, M. Koike and Y. Okada, Phys. Rev. D66, 096002 (2002)

Experimental Comparison between $\mu \rightarrow e\gamma$ and μ-e Conversion

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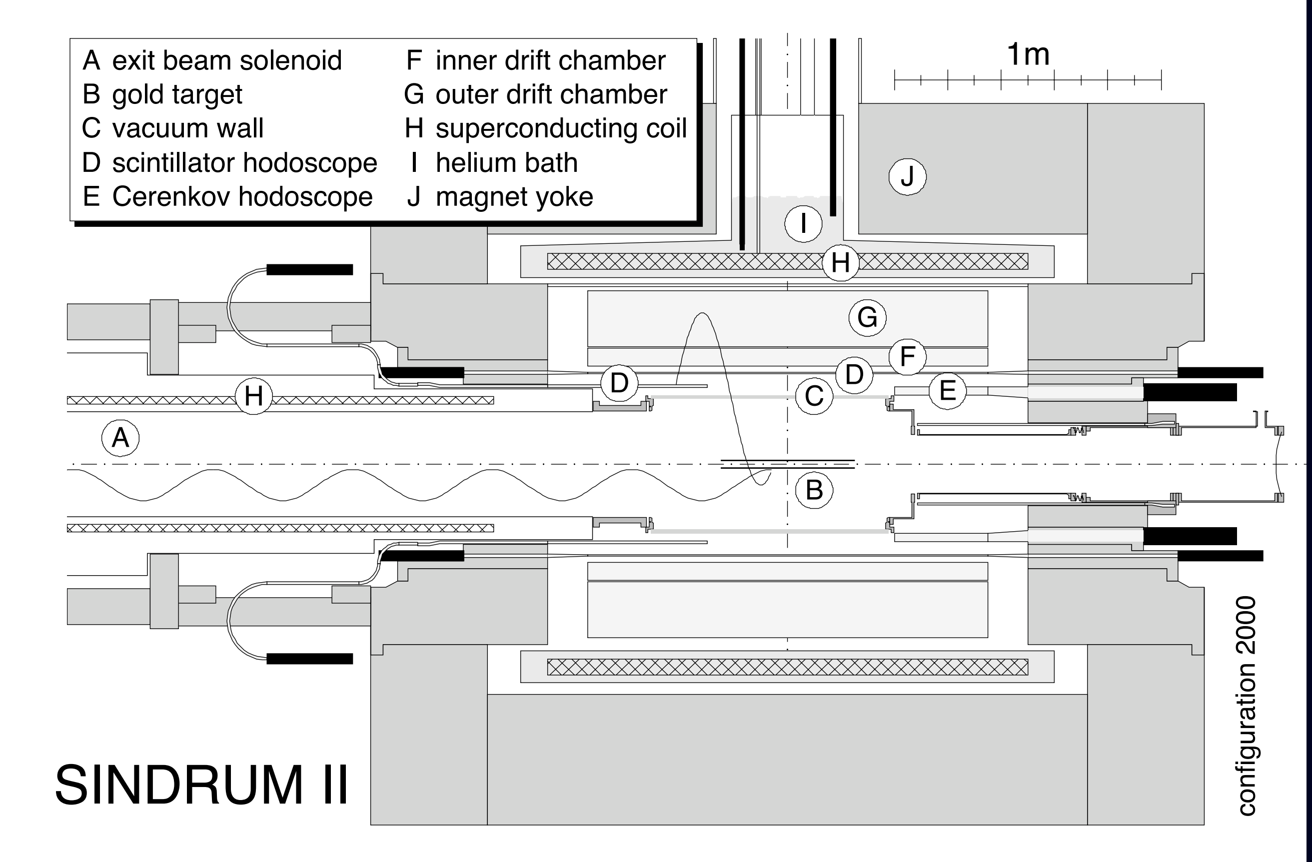
	background	challenge	beam intensity
• $\mu \rightarrow e\gamma$	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

- $\mu \rightarrow e\gamma$:
  - Accidental background is given by $(\text{rate})^2$.
  - The detector resolutions have to be improved, but difficult.
  - The ultimate sensitivity would be about 10^{-14}.
- μ-e conversion :
  - A higher beam intensity can be taken because of no accidentals.
  - Improvement of a muon beam can be possible.
    - high intensity and high purity

μ-e conversion might be a next step.

Previous Measurements

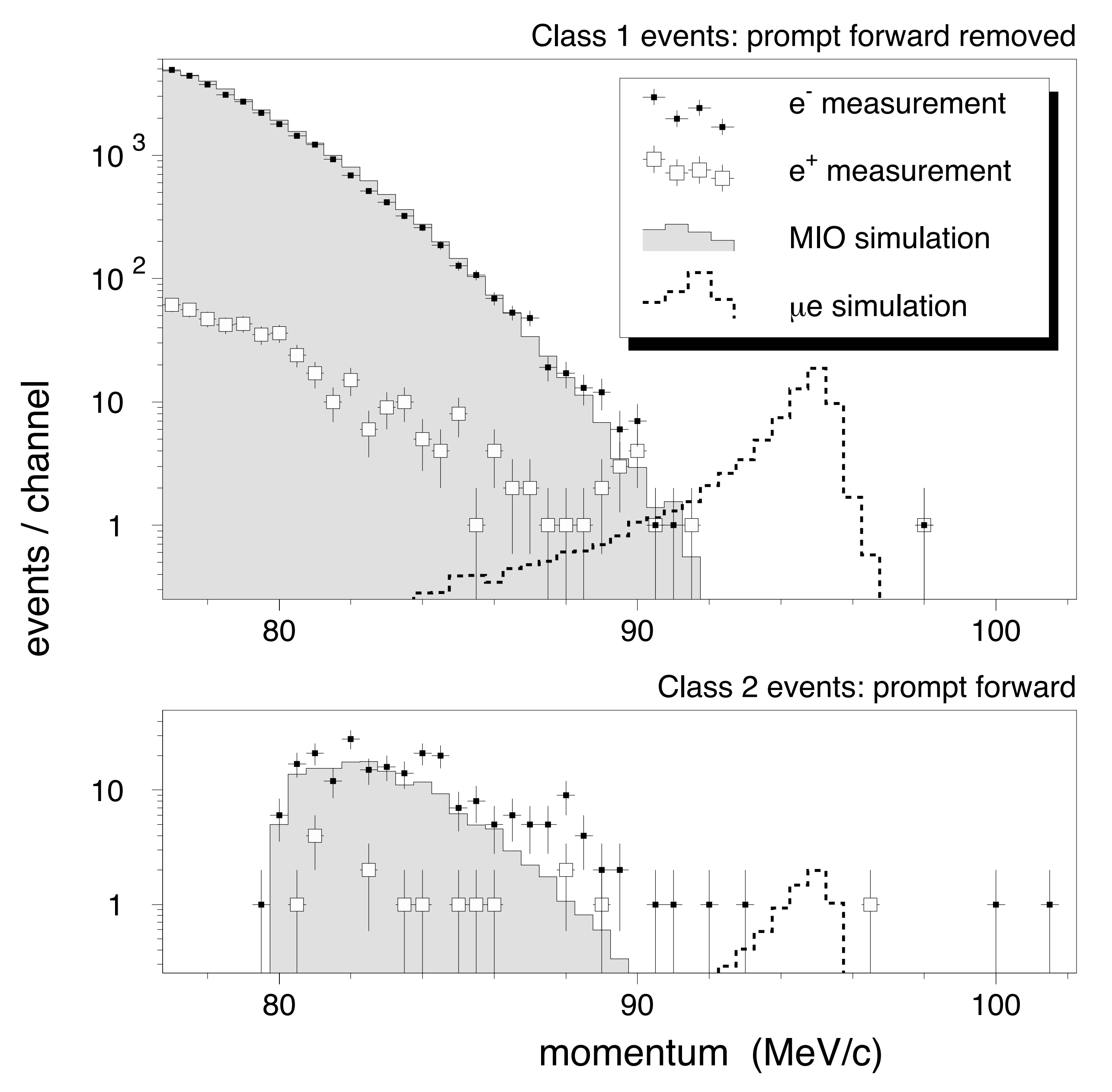
SINDRUM-II (PSI)



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

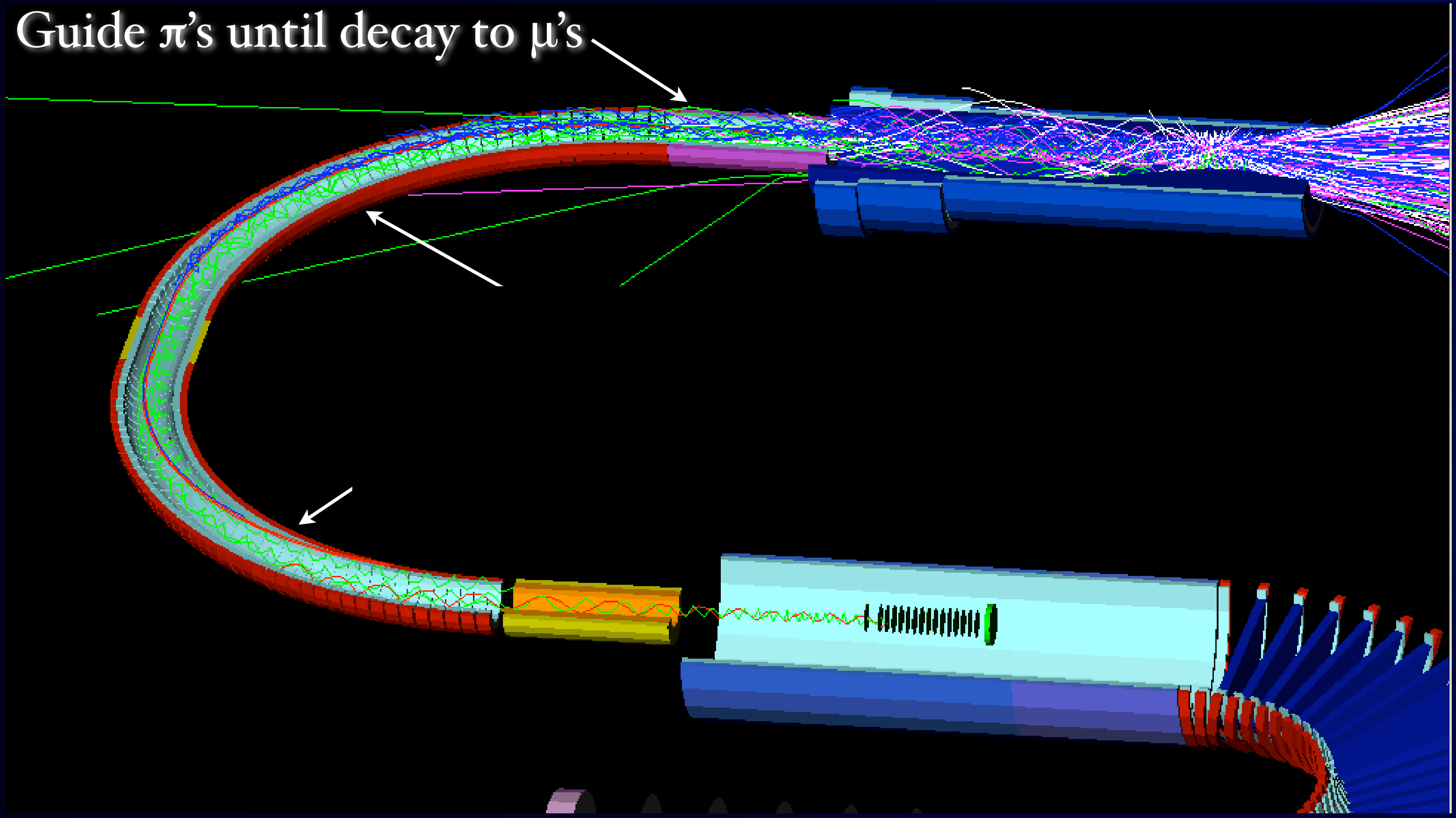
To achieve a single sensitivity of 10^{-17}, we need

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

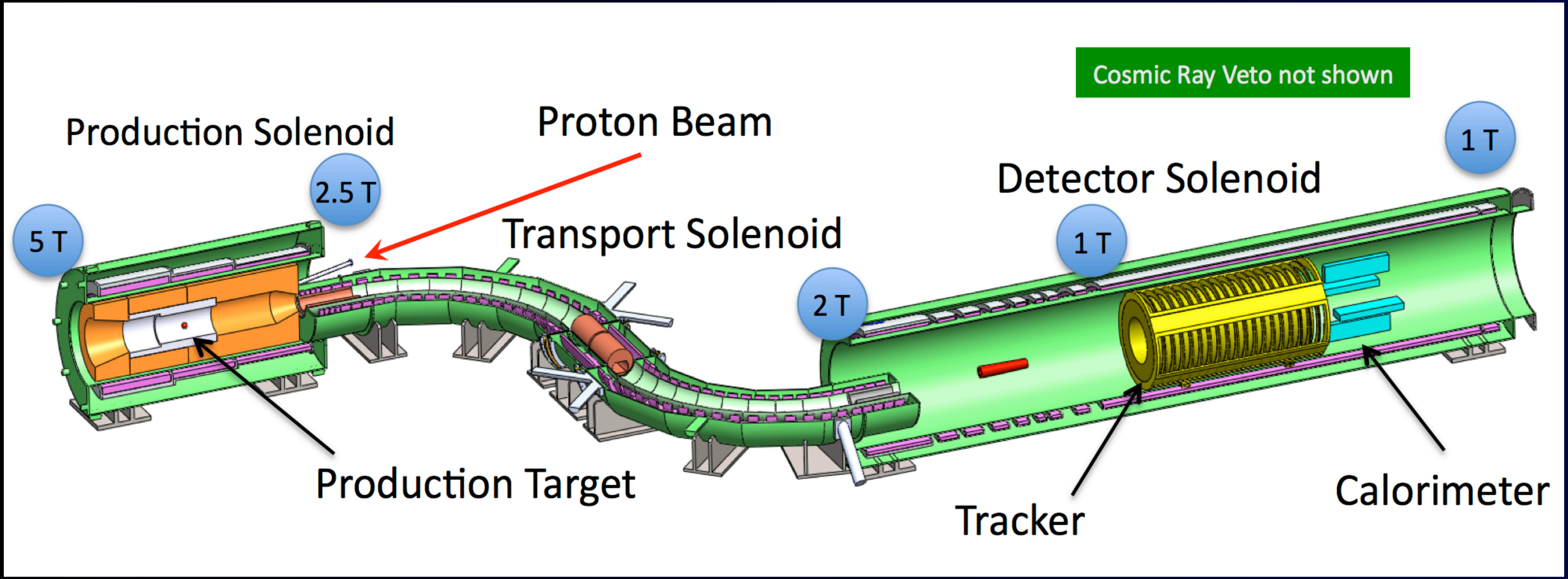
improve electron energy resolution

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 : Mu2e at Fermilab

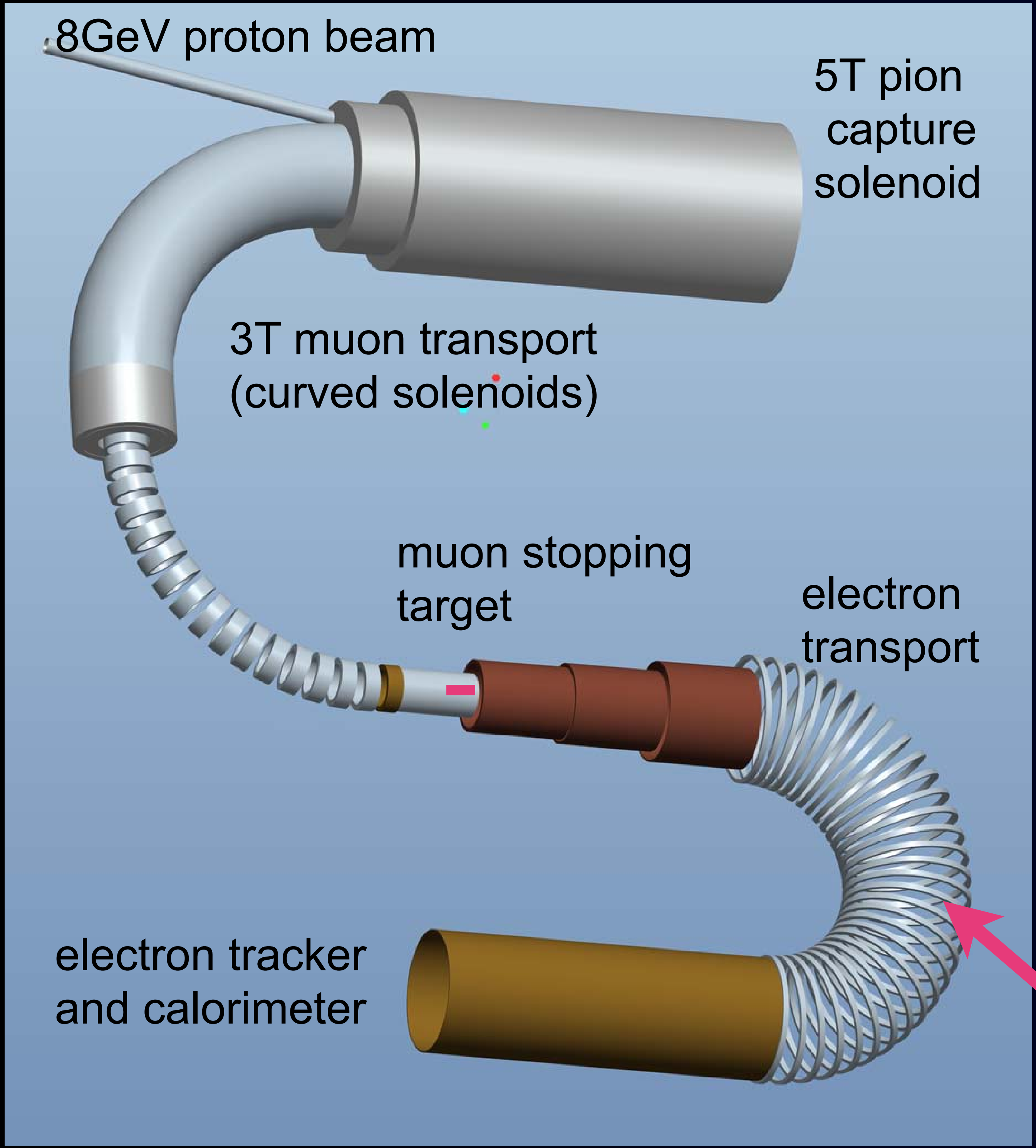


$$B(\mu^- + Al \rightarrow e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \quad \text{(90\%C.L.)}$$

- Reincarnation of MECO at BNL.
- Antiproton buncher ring is used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009, and CD1 in 2011.
- Data taking starts in about 2019.

COMET

What is 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.
- $2\text{x}10^7$ running time (~1 year)
- C-shape muon beam line
- 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 is international.

129 collaborators
28 institutes, 11 countries

The COMET Japan group funded.	The COMET China group funded.	The COMET JINR group funding underway.

The COMET Collaboration

R. Akhmetshin[3], K. Akuma[17], M. Aoki[22], R. B. Appleby[19], Y. Arimoto[12], Y. Bagaturia[7], W. Bertsche[19], A. Bondar[3], D. Bryman[2], B. Chiladze[5], M. Danilov[10], W. daSilva[16], P. Dauncey[8], G. Devidze[5], P. Dornan[8], A. Drutskoy[10], S. Dymov[11], A. Edmonds[25], L. Epshteyn[3], P. Evtoukhovich[11], G. Fedotovich[3], Y. Fukao[12], M. Gersabeck[19], D. Grigoriev[3], K. Hasegawa[12], I. H. Hasim[22], O. Hayashi[22], M. I. Hossain[18], Z. Ibrahim[17], F. Idris[17], Y. Igarashi[12], F. Ignatov[3], M. Ikeno[12], S. Ishimoto[12], T. Itahashi[22], S. Ito[22], T. Iwami[22], Y. Iwashita[13], X. Jiang[4], P. Jonsson[8], V. Kalinnikov[11], F. Kapusta[16], H. Katayama[22], K. Kawagoe[15], V. Kazanin[3], B. Khazin[3], A. Khvedelidze[11], M. Koike[26], G. Kozlov[11], B. Krikler[8], A. Kulikov[11], Y. Kuno[22], Y. Kuriyama[14], A. Kurup[8], B. Lagrange[14], M. Lancaster[25], H. B. Li[4], W. Li[4], A. Liparteliani[5], G. Macharashvili[11], Y. Makida[12], Y. Matsumoto[22], T. Mibe[12], S. Mihara[12], A. Moiseenko[11], Y. Mori[14], N. Mosulishvili[5], E. Motuk[25], Y. Nakai[15], T. Nakamoto[12], T. H. Nam[22], J. Nash[8], M. Nioradze[5], H. Nishiguchi[12], T. Numao[24], T. Ogitsu[12], K. Okamoto[22], C. Omori[12], K. Ooishi[15], T. Ota[23], H. Owen[19], R. Palmer[1], C. Parkes[19], J. Pasternak[8], A. Popov[3], V. Rusinov[10], A. Ryzhenenkov[3], B. Sabirov[11], N. Saito[12], H. Sakamoto[22], P. Sarin[6], K. Sasaki[12], A. Sato[22], J. Sato[23], D. Shemyakin[3], V. Shmakova[11], M. Sugano[12], W. Tajudeen[17], Y. Takubo[12], M. Tanaka[12], C. V. Tao[21], E. Tarkovsky[10], Y. Tevzadze[5], N. D. Thong[22], V. Thuan[9], J. Tojo[15], M. Tomizawa[12], I. Trekov[5], N. M. Truong[22], Z. Tsmalaidze[11], N. Tsverava[11], S. Tygier[19], T. Uchida[12], Y. Uchida[8], K. Ueno[12], S. Umasankar[6], E. Velicheva[11], A. Volkov[11], M. Warren[25], M. Wing[25], C. Wu[4], G. Xia[19], K. Yai[22], A. Yamamoto[12], M. Yamanaka[20], M. Yoshida[12], Y. Yoshii[12], K. Yoshimura[12], T. Yoshioka[15], Y. Yuan[4], Y. Yudin[3], Y. Zhang[4]

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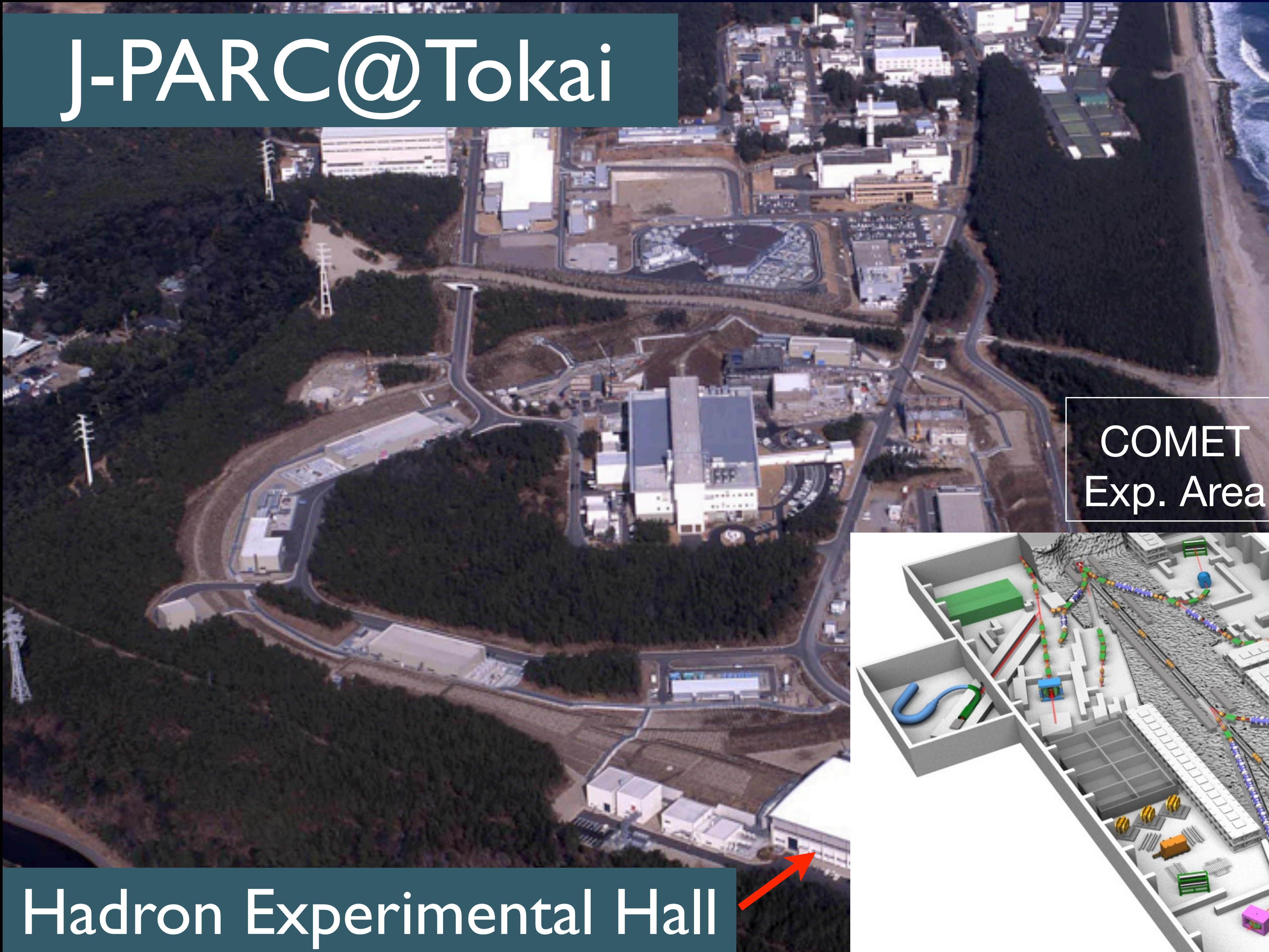
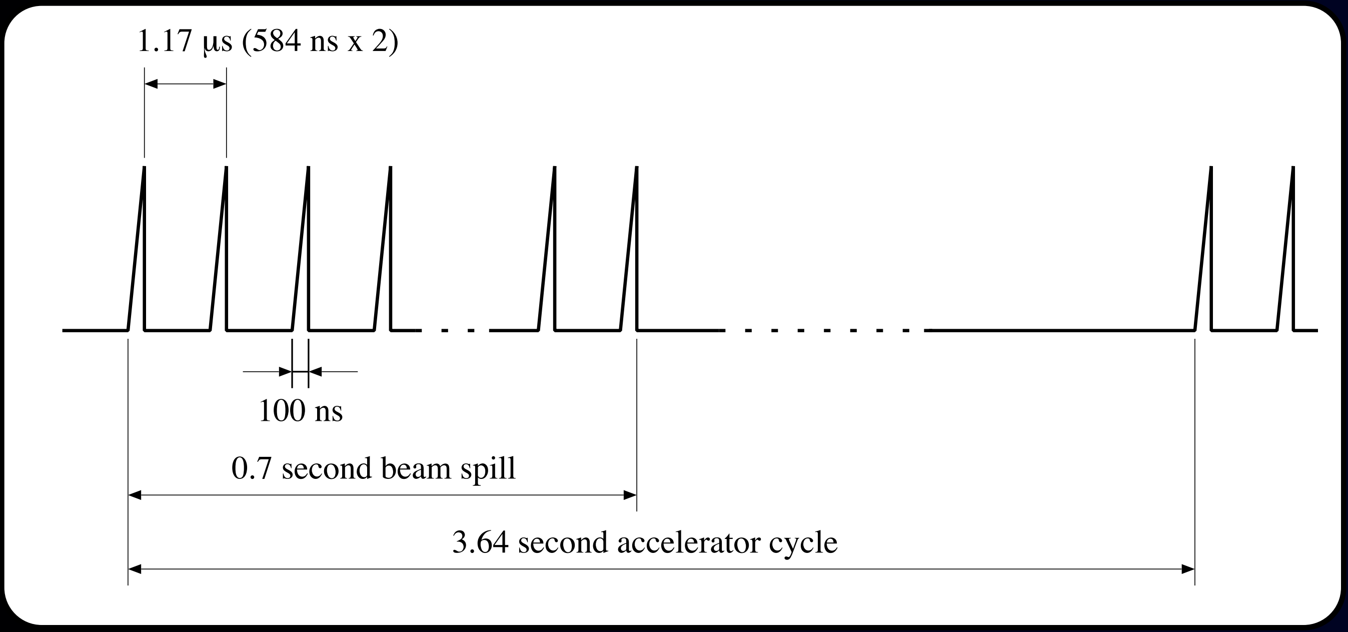
Proton Beam

J-PARC@Tokai

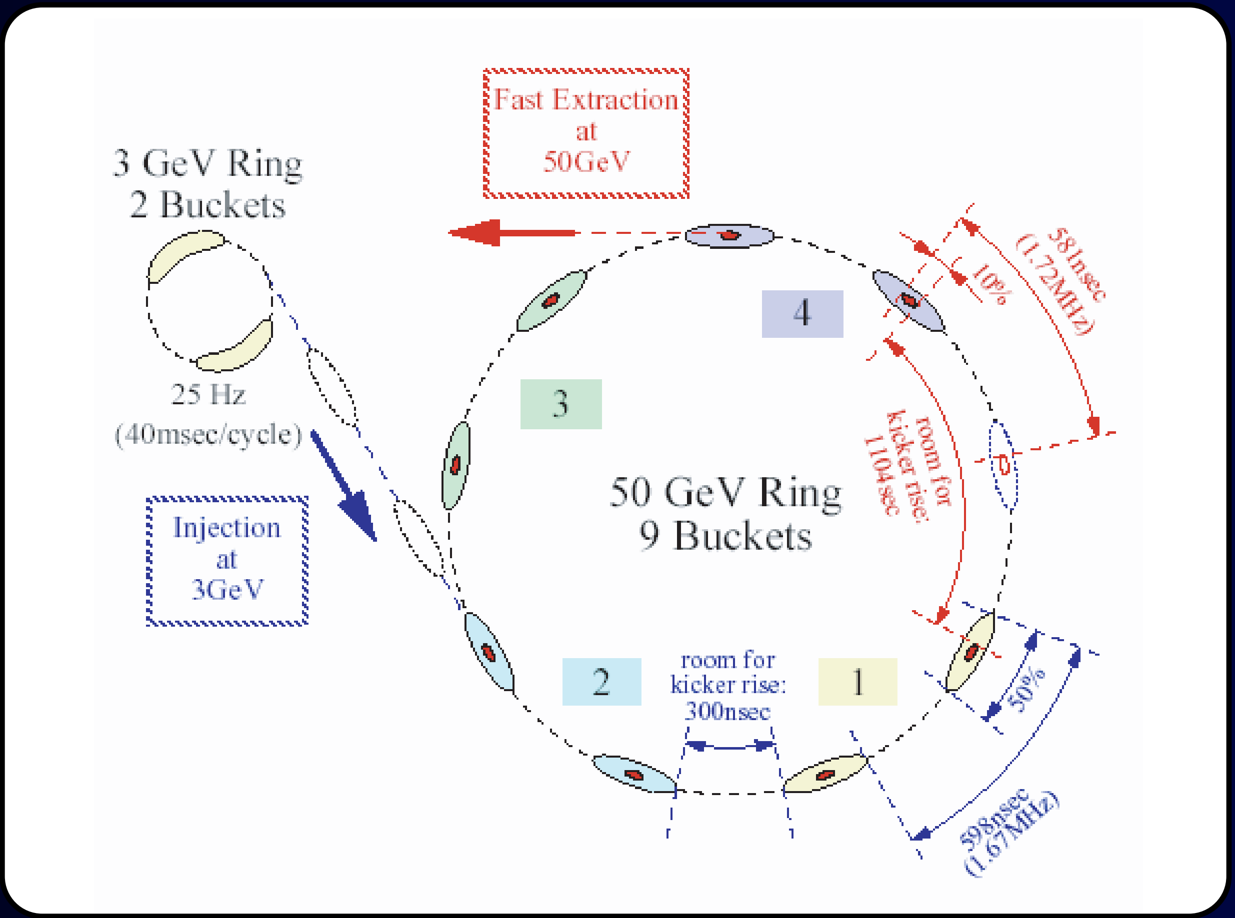


Proton Beam at J-PARC

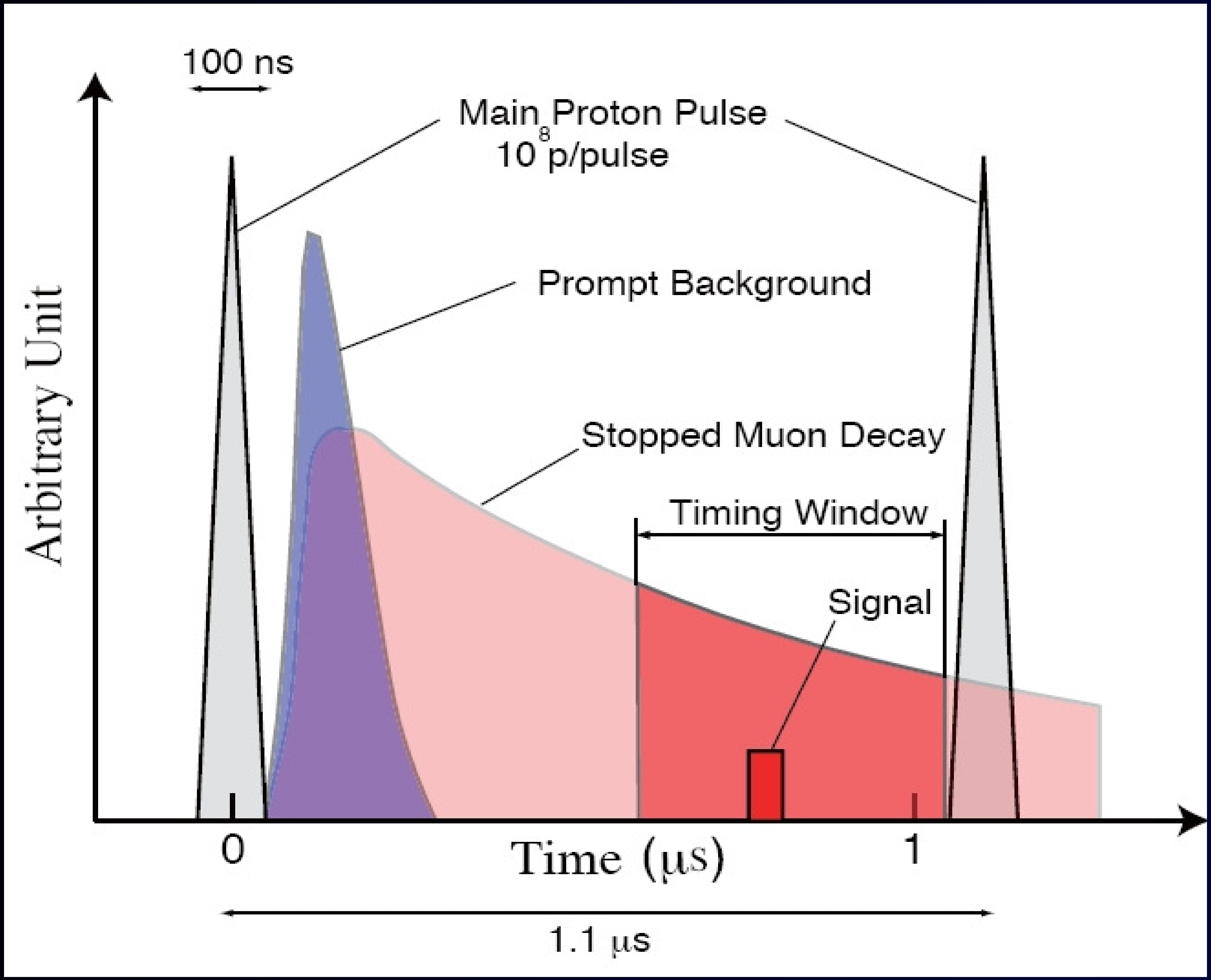
- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)



- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7



Proton Beam for COMET



Muon Beam

Charged Particle Trajectory in Curved Solenoids

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

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

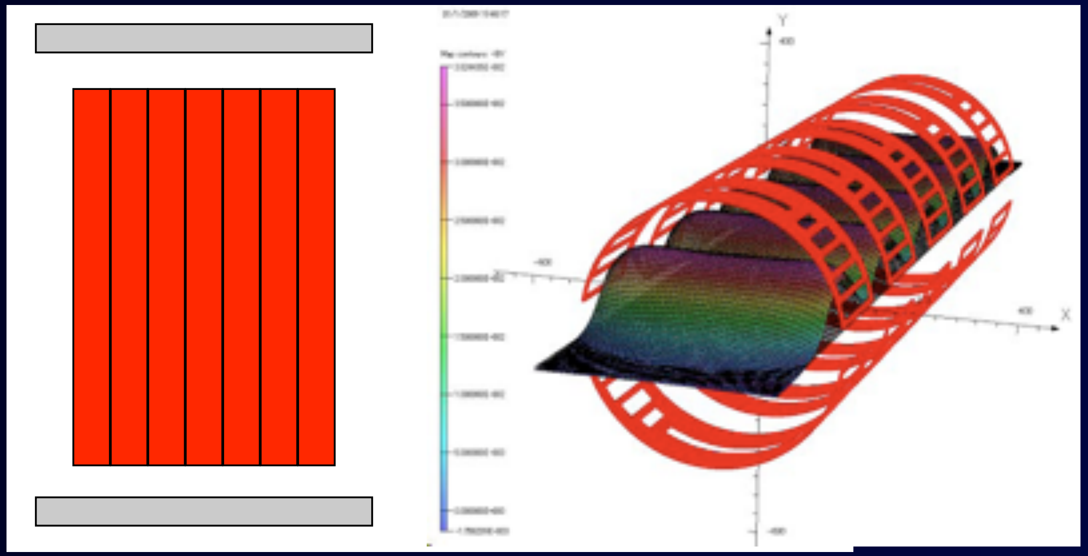
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This can be used for charge and momentum selection.

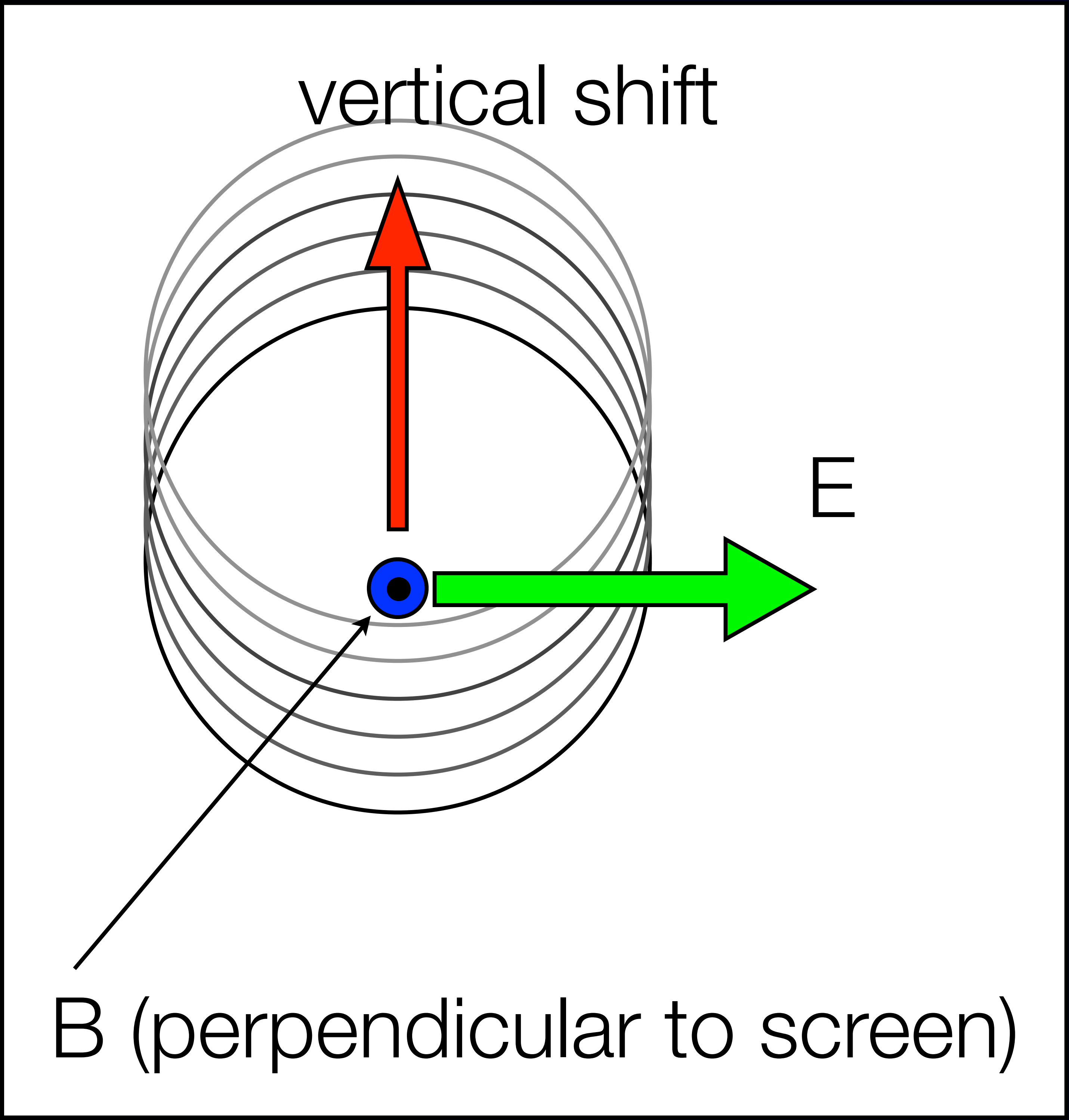
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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

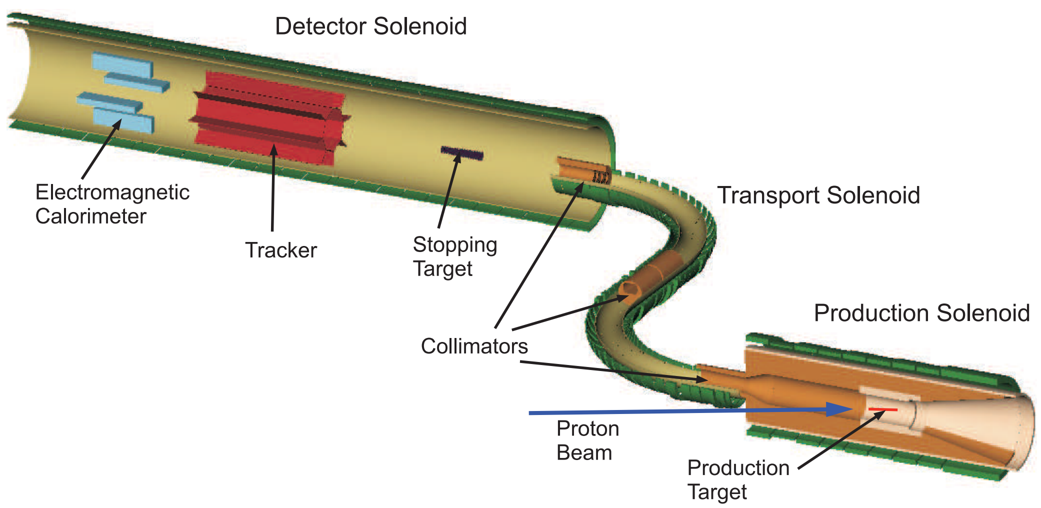


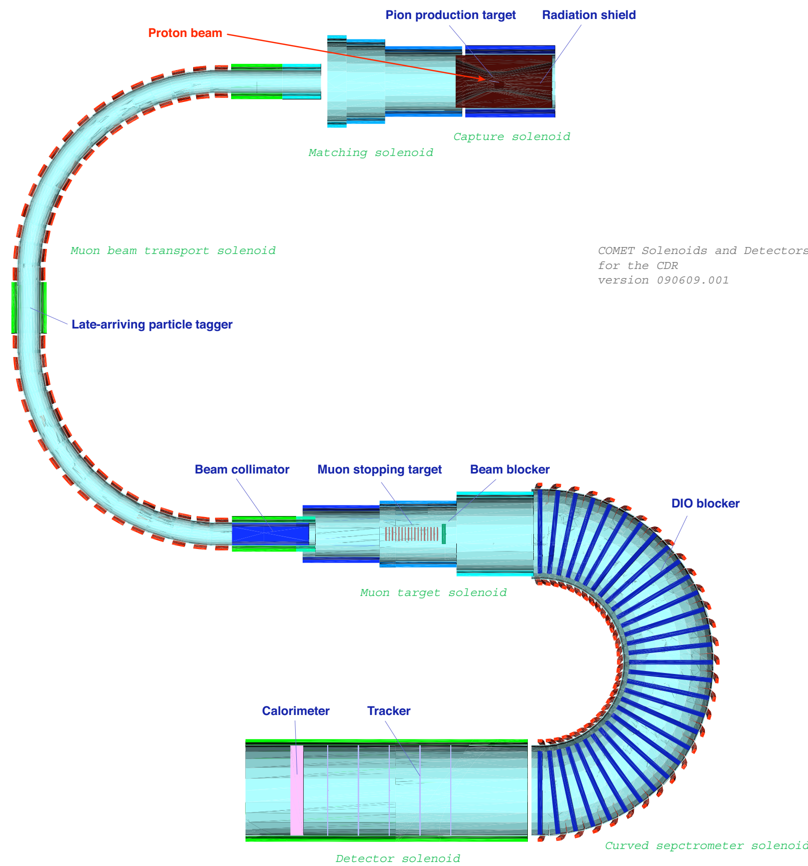
EM Physics for Particle Trajectories in Toroidal Magnetic Field



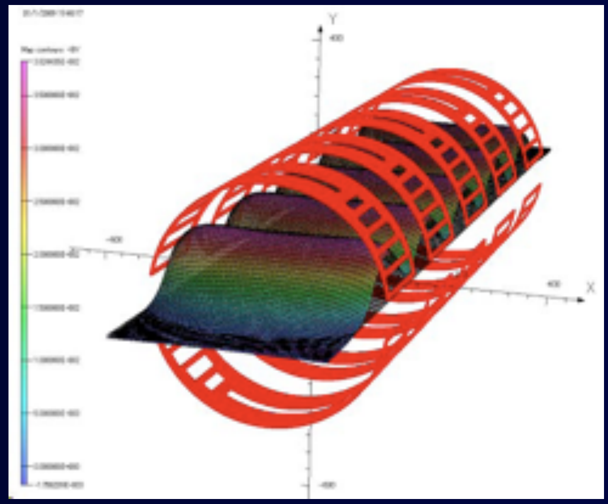
- For helical trajectory in a curved mag. field, a centrifugal force gives E in the radial direction.
- To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by v x B, can be applied.

Mu2e vs. COMET





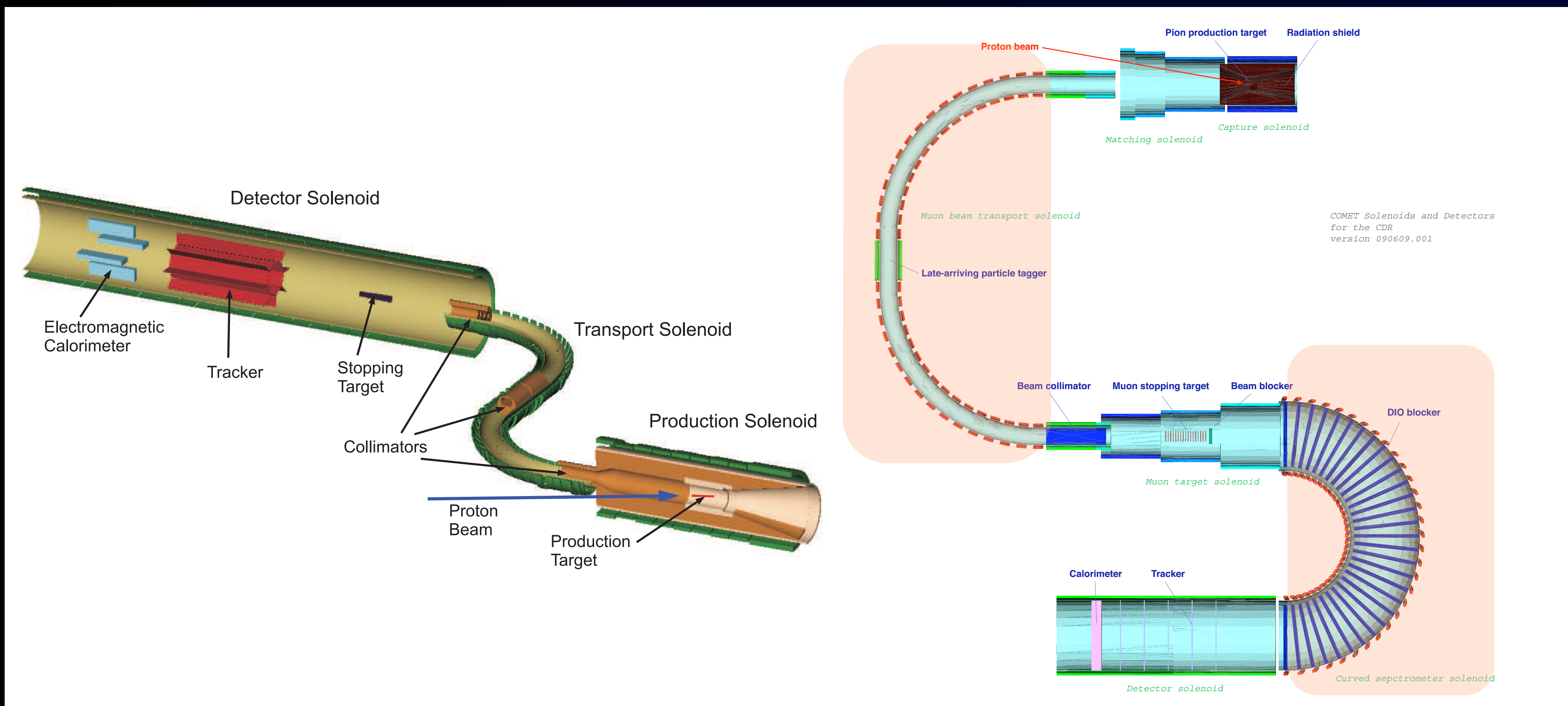
	Mu2e	COMET
muon beam line	2x 90° bends (opposite direction)	2x 90° bend (same direction)
electron spectrometer	straight solenoid	curved solenoid



Dipole Coils

COMET curved solenoids have dipole coils on top of the solenoids, to keep muons with momentum of interest in the bending plane.

Mu2e vs. COMET



	Mu2e	COMET
muon beam line	2x 90° bends (opposite direction)	2x 90° bend (same direction)
electron spectrometer	straight solenoid	curved solenoid

Select low momentum muons

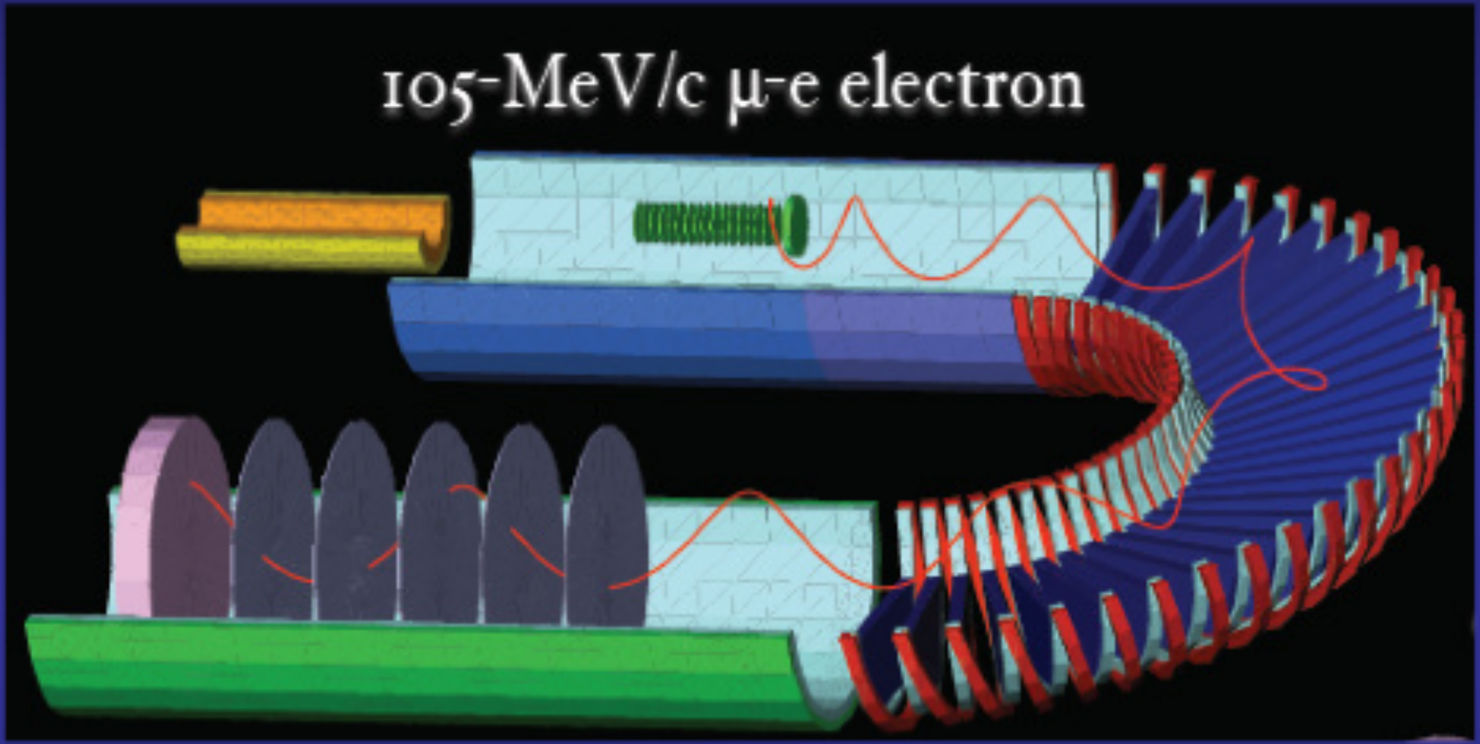
eliminate muon decay in flight

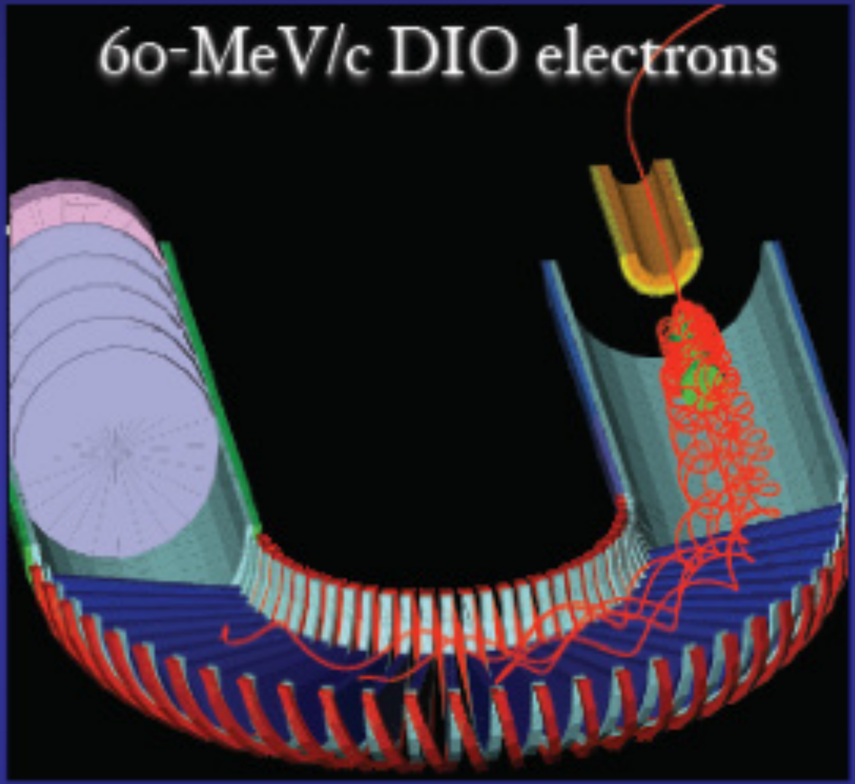
Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.

Electron Spectrometer





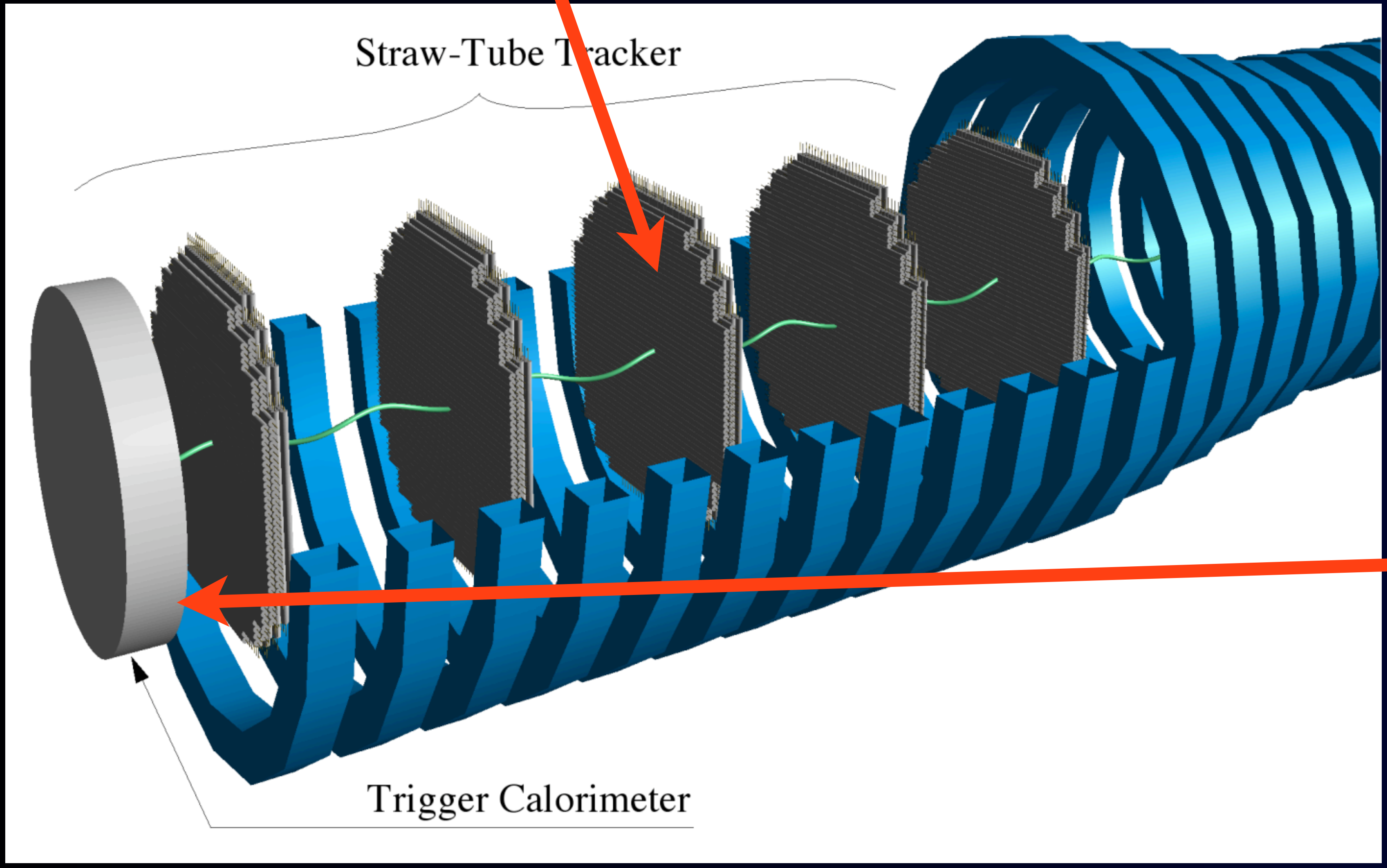
- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~ 1kHz.

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

Sensitivity and Backgrounds

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	8.5x10
muon transport efficiency	0.008
muon stopping efficiency	0.3
# of stopped muons	2.0x10

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

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

Background Rates

Table 11.9: Summary of Estimated Backgrounds.

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

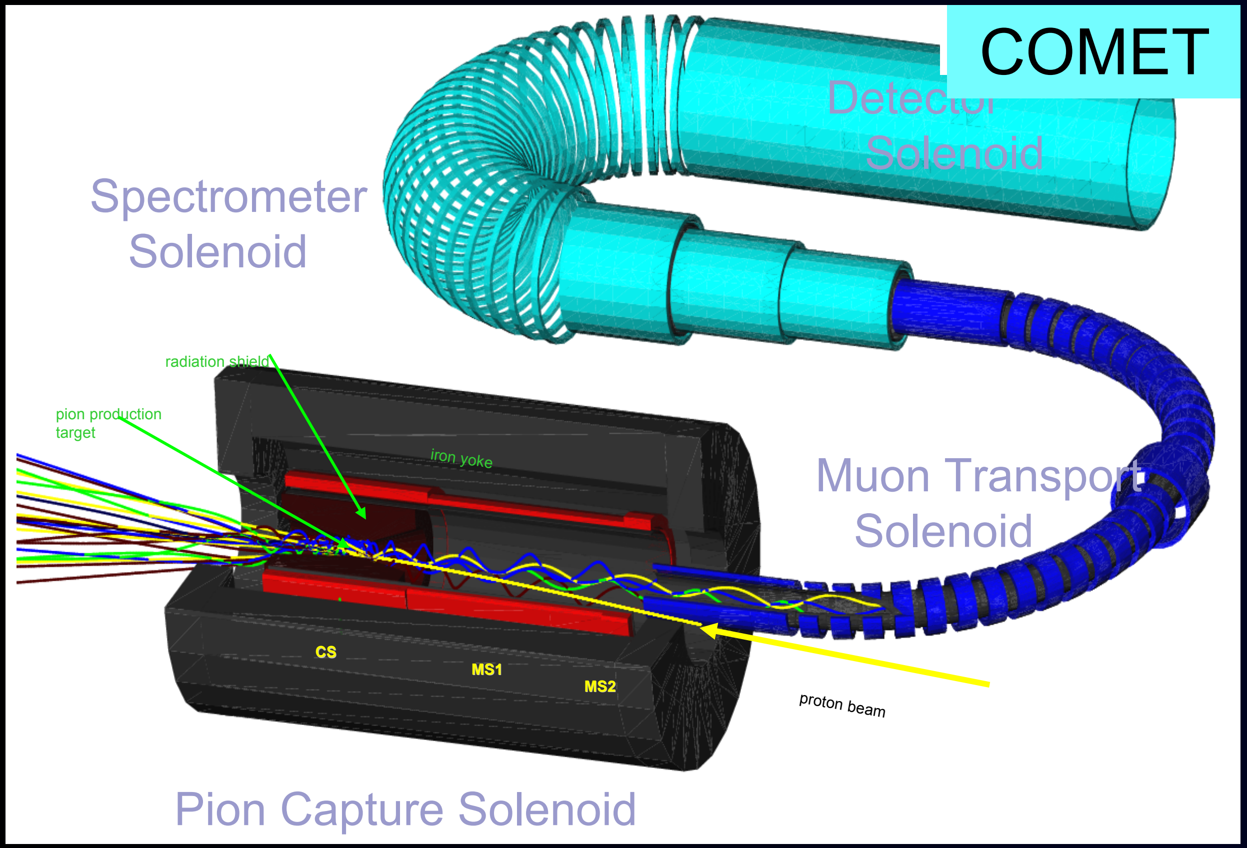
‡ Monte Carlo statistics limited.

- beam-related prompt backgrounds
- beam-related delayed backgrounds
- intrinsic physics backgrounds
- cosmic-ray and other backgrounds

Expected background events are about 0.34.

COMET 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.

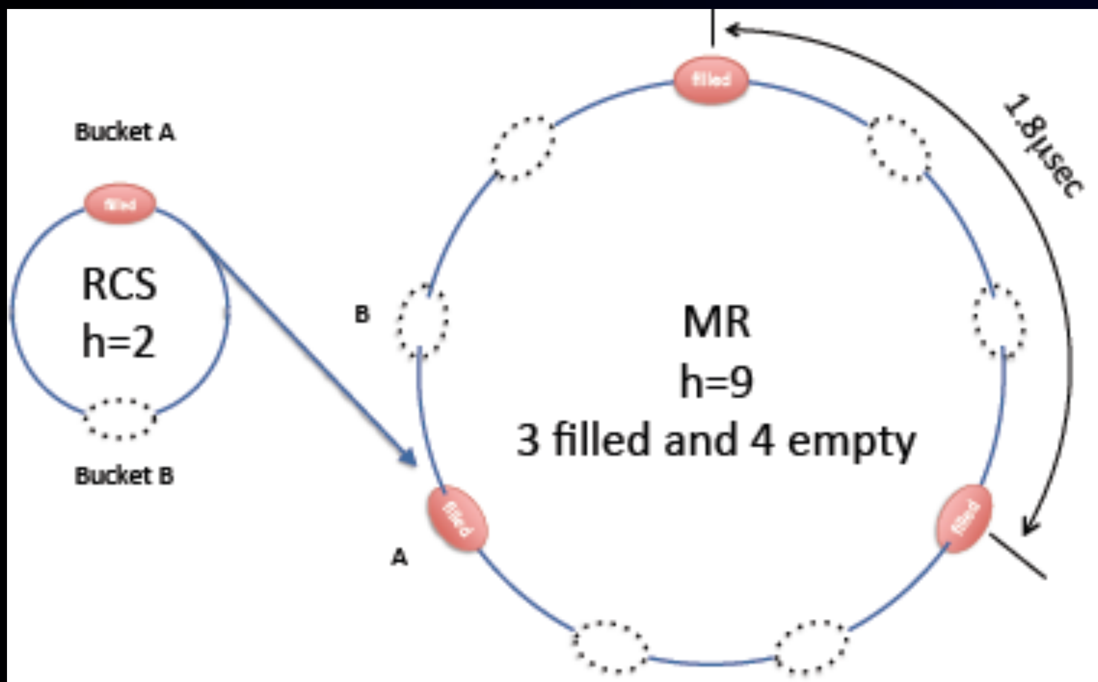
2 Increase of Muon Intensity

Pion capture system

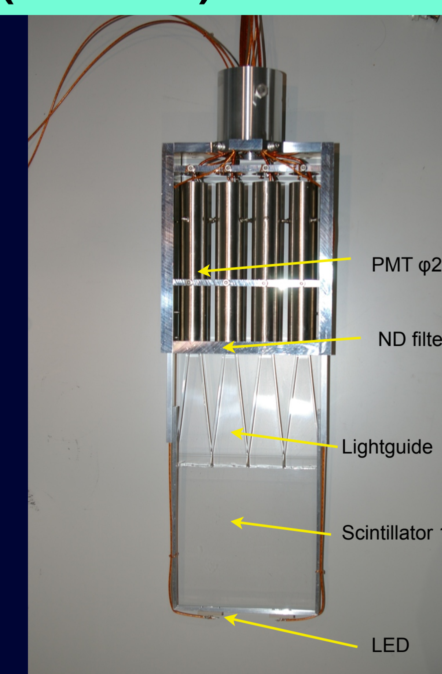
$\times 10^3$

high field superconducting solenoid magnets surrounding a pion production target

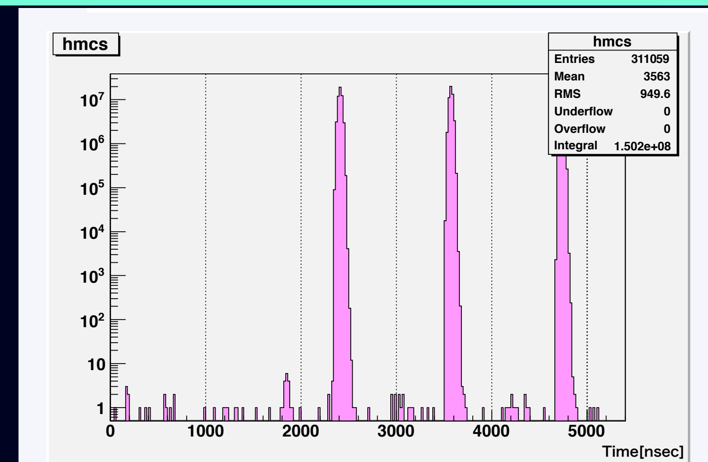
1 Proton Extinction Measurements at J-PARC



Measured at abort beamline (2010)



Measured at secondary beamline (2010)



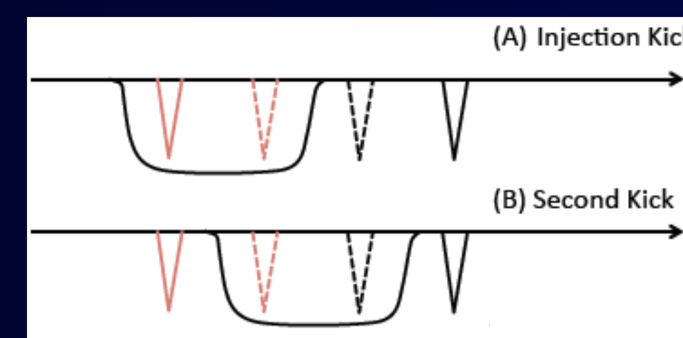
J-PARC MR proton extinction

~ $O(10^{-7})$

Single Bunch Kicking

Tested at the abort (2010)

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



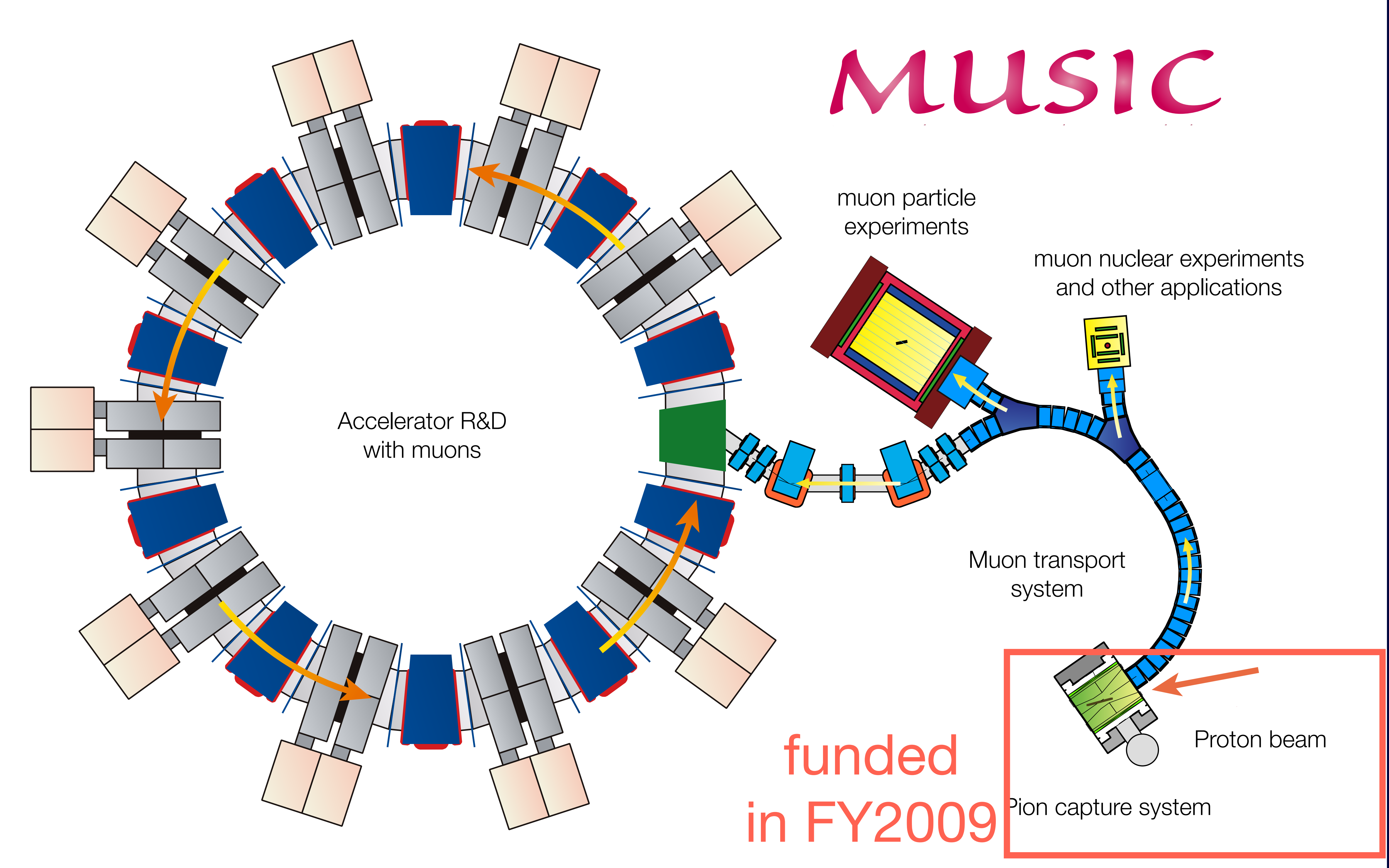
COMET is confident to achieve proton extinction of $<O(10^{-9})$.

2 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.

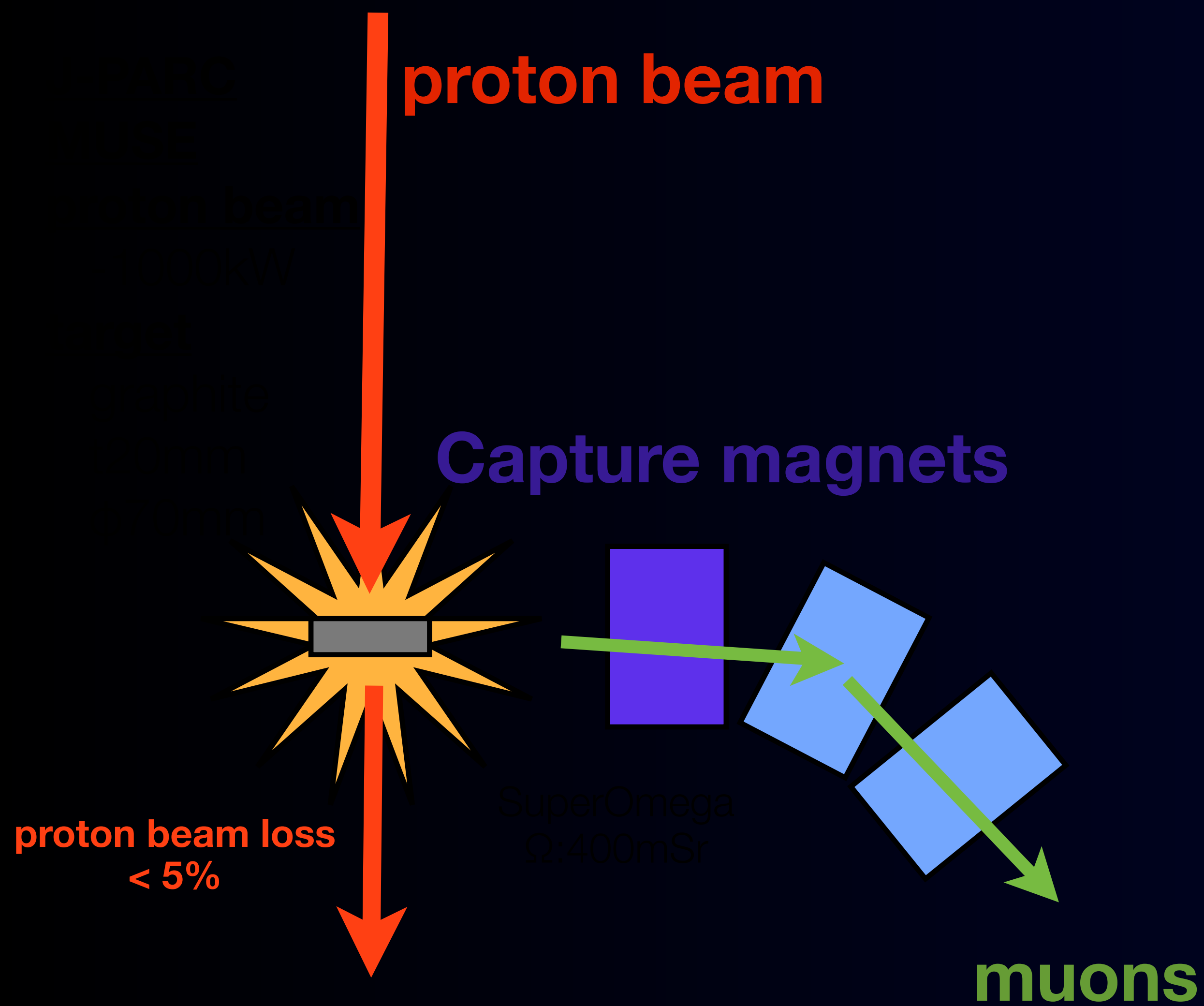
Muon Source with low proton power at Osaka U.?

MuSIC (=Muon Science Innovative Channel)



Production and Collection of Pions and Muons

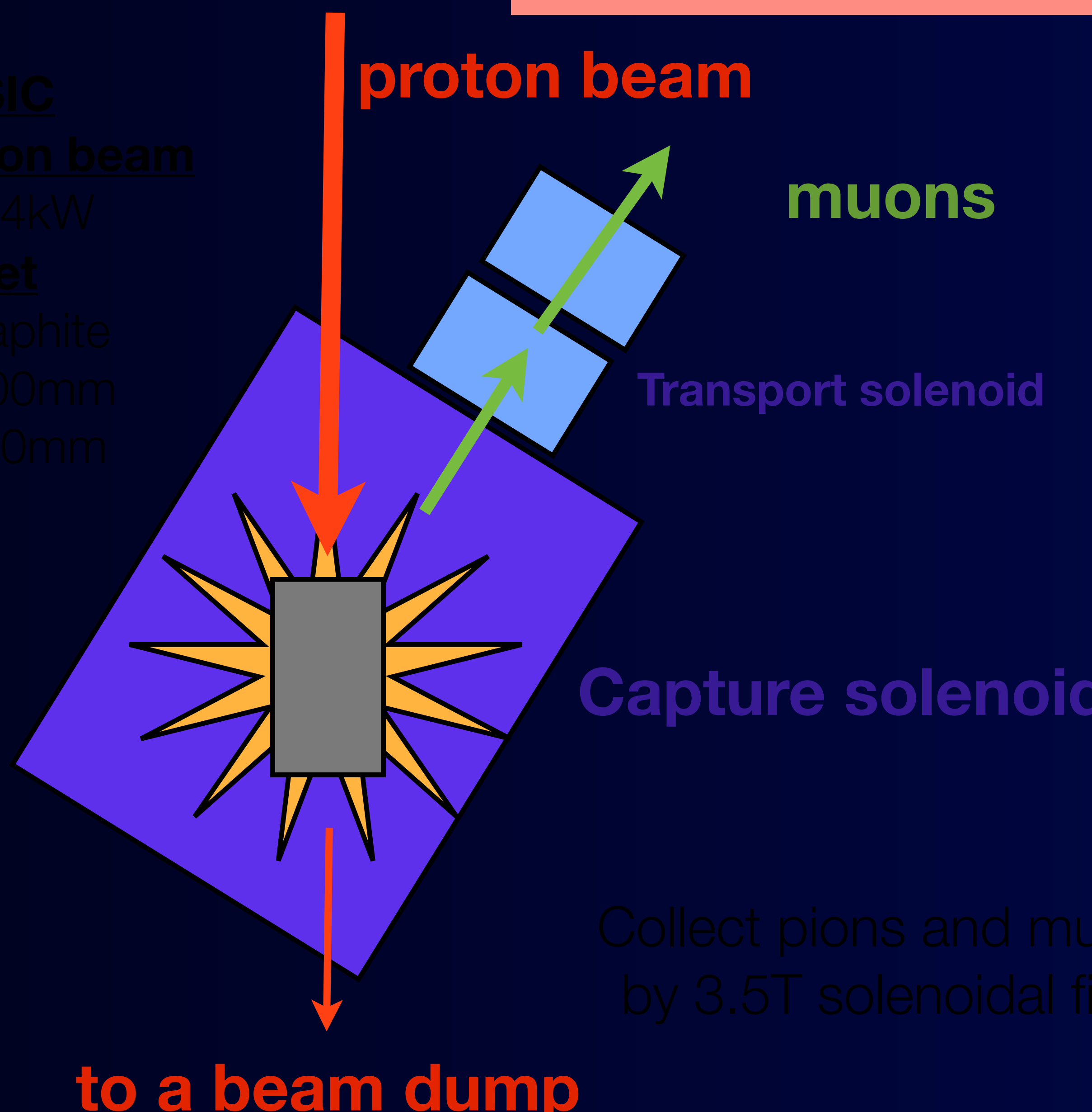
Conventional muon beam line



Much efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider

MuSIC
proton beam
~0.4kW
target
graphite
t200mm
φ40mm

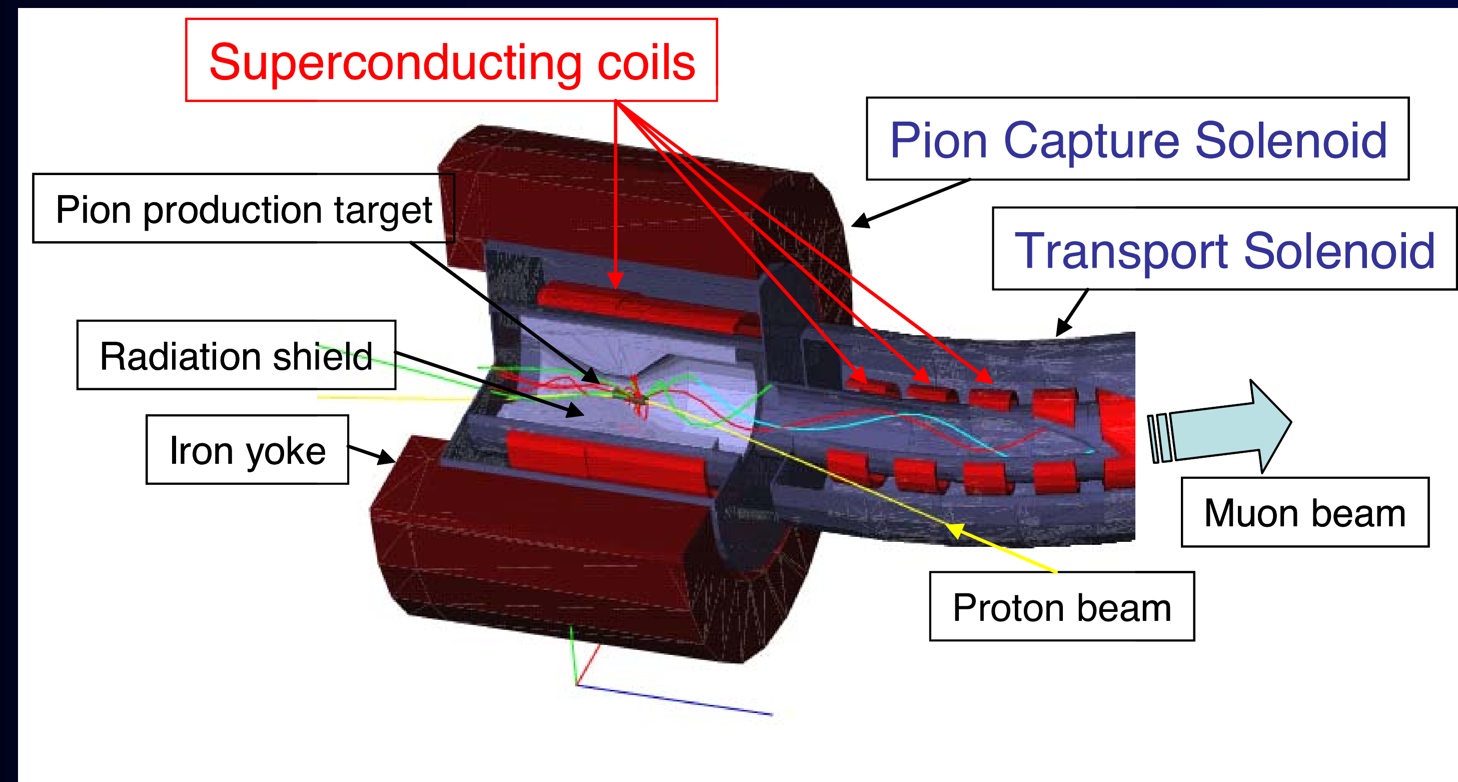


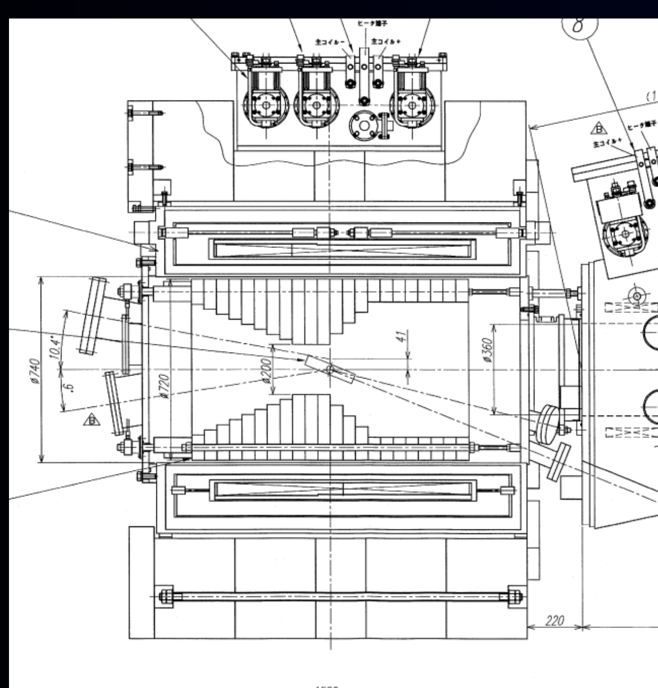
Collect pions and muons
by 3.5T solenoidal field

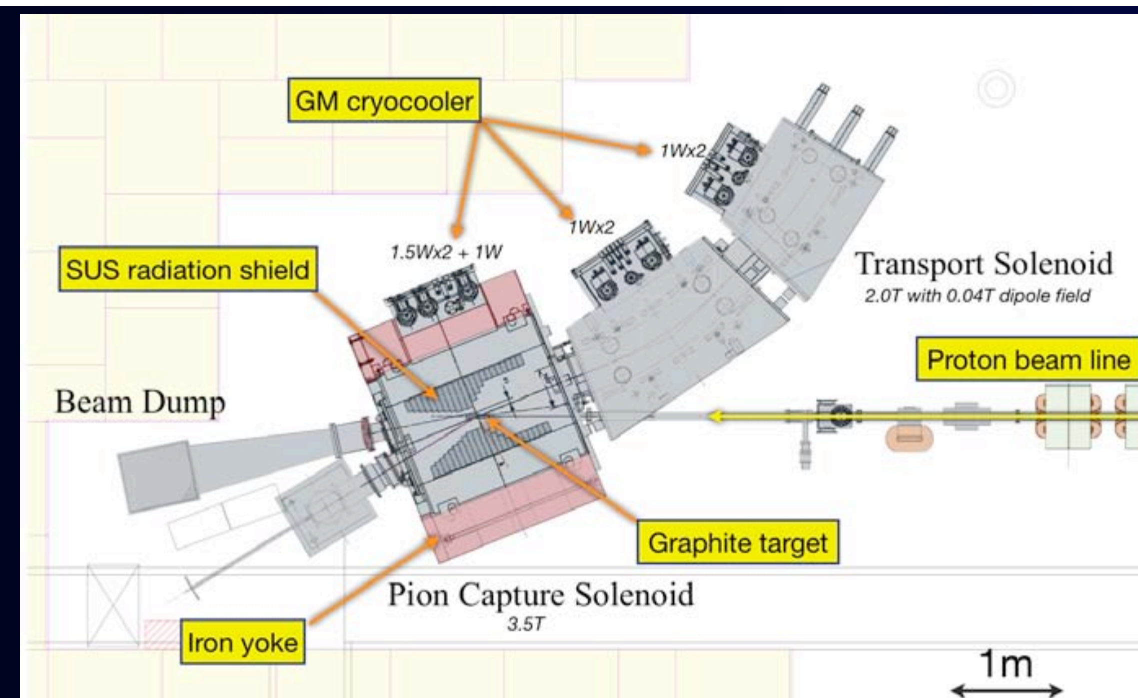
Large solid angle & thick target

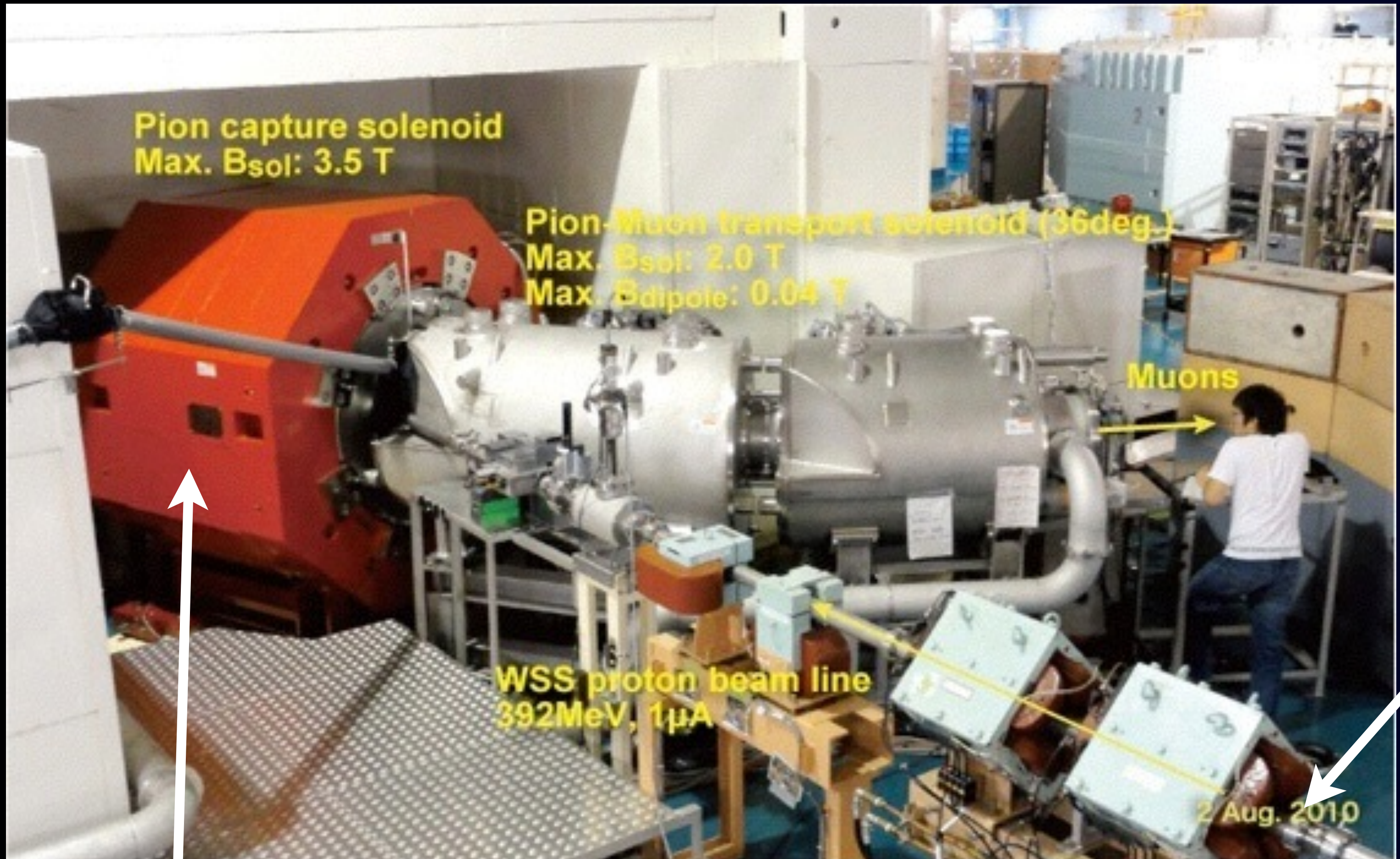
Pion Capture System at MuSIC@Osaka-U

- 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



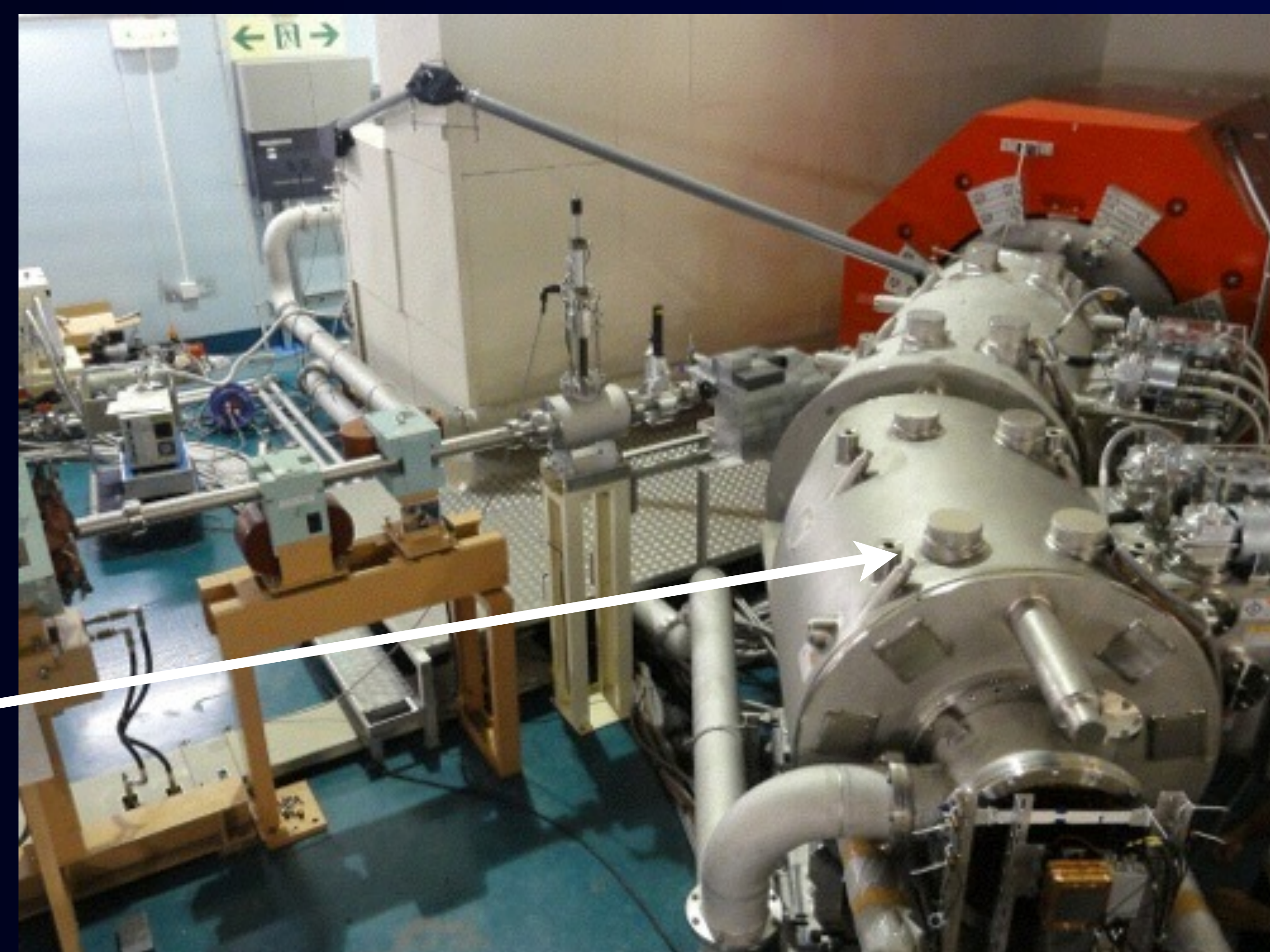






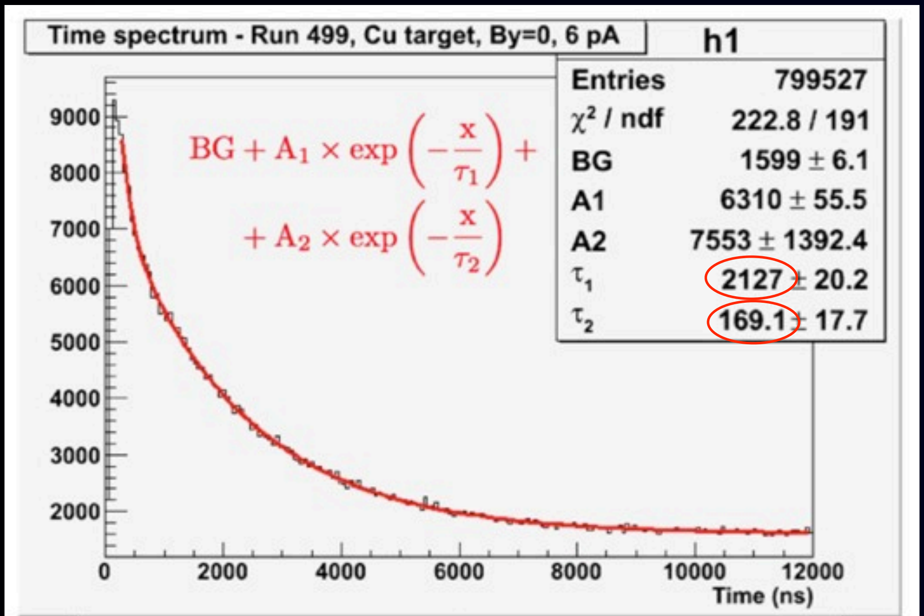
proton beam line

pion capture superconducting solenoid

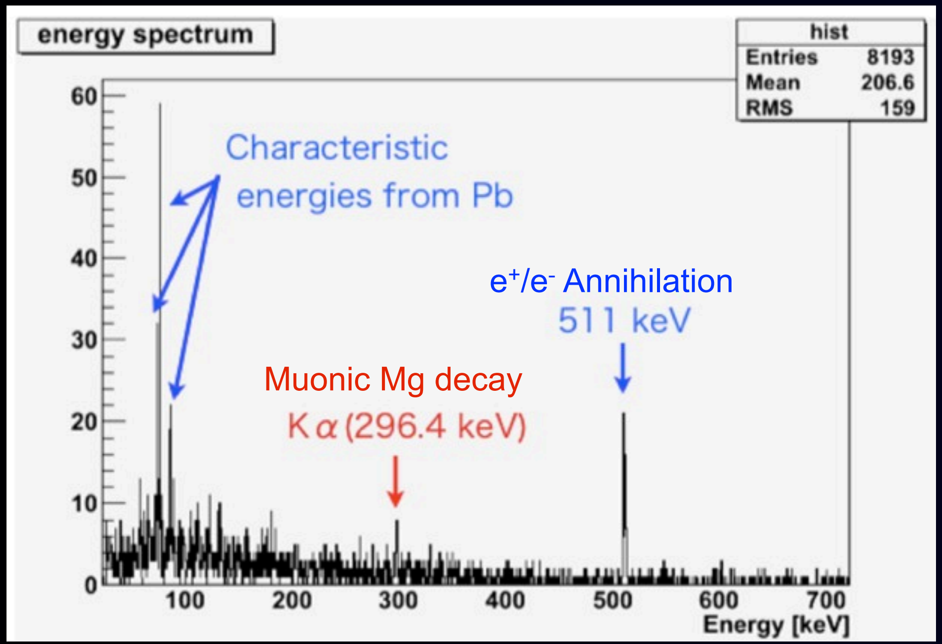


muon transport superconducting solenoid

MuSIC Beam Test in 2011



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



preliminary

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 $\times 10^3$ achieved...

Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (62 pA)

Common R&D with COMET and Mu2e

Superconducting Magnet R&D (2010~)

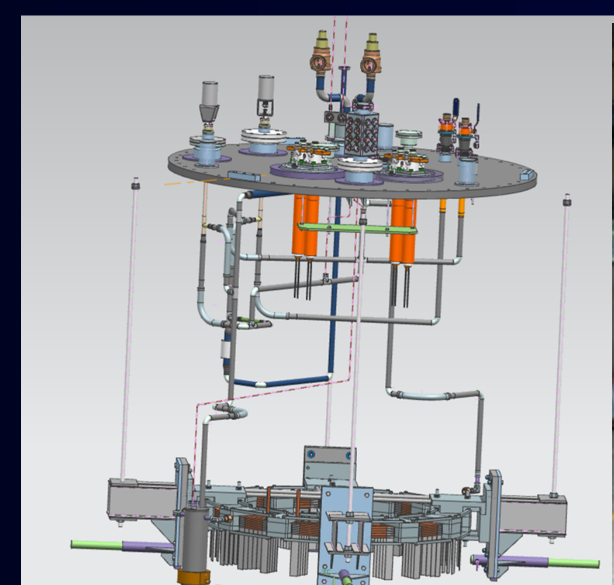
...through the US-Japan Program

R&D of solenoid coils with aluminum-stalibized superconductors

Japan

Prototype coil of aluminum-stabilied superconductors were wound in Japan and sent to FNAL (2010-2012).

U.S.



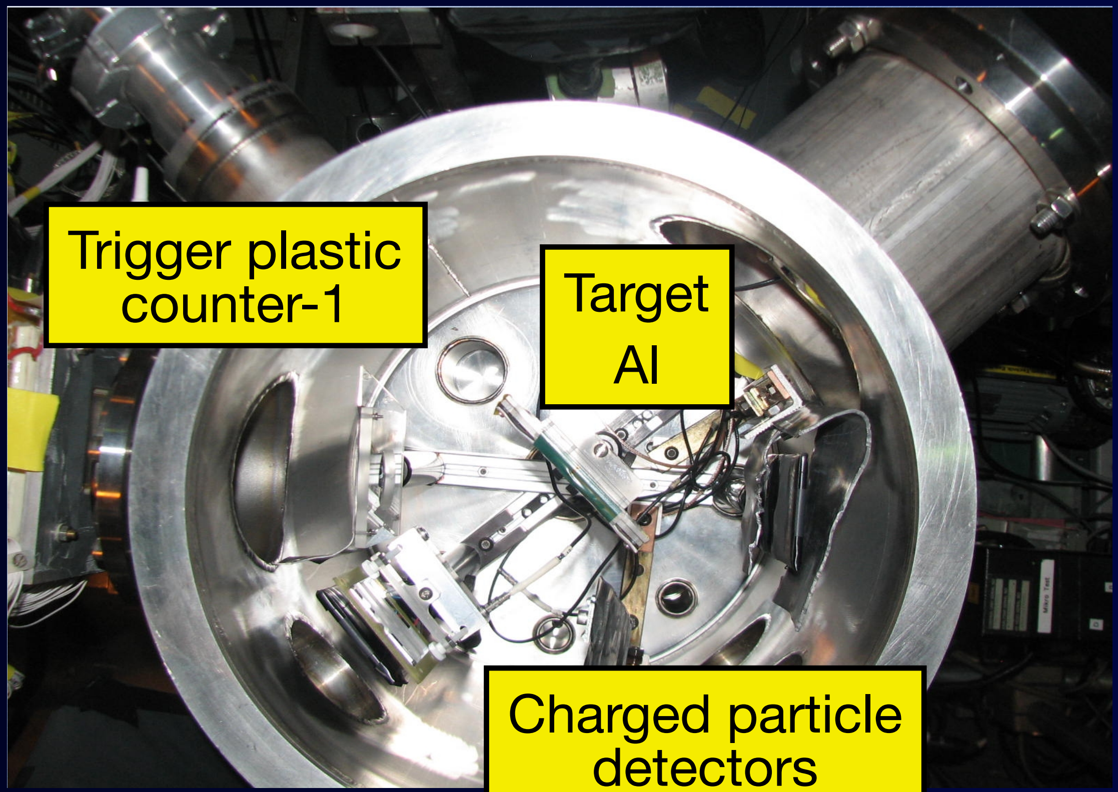
Indirect cooling test bench was prepared at FNAL to test the prototype coil (2013~, not yet?)

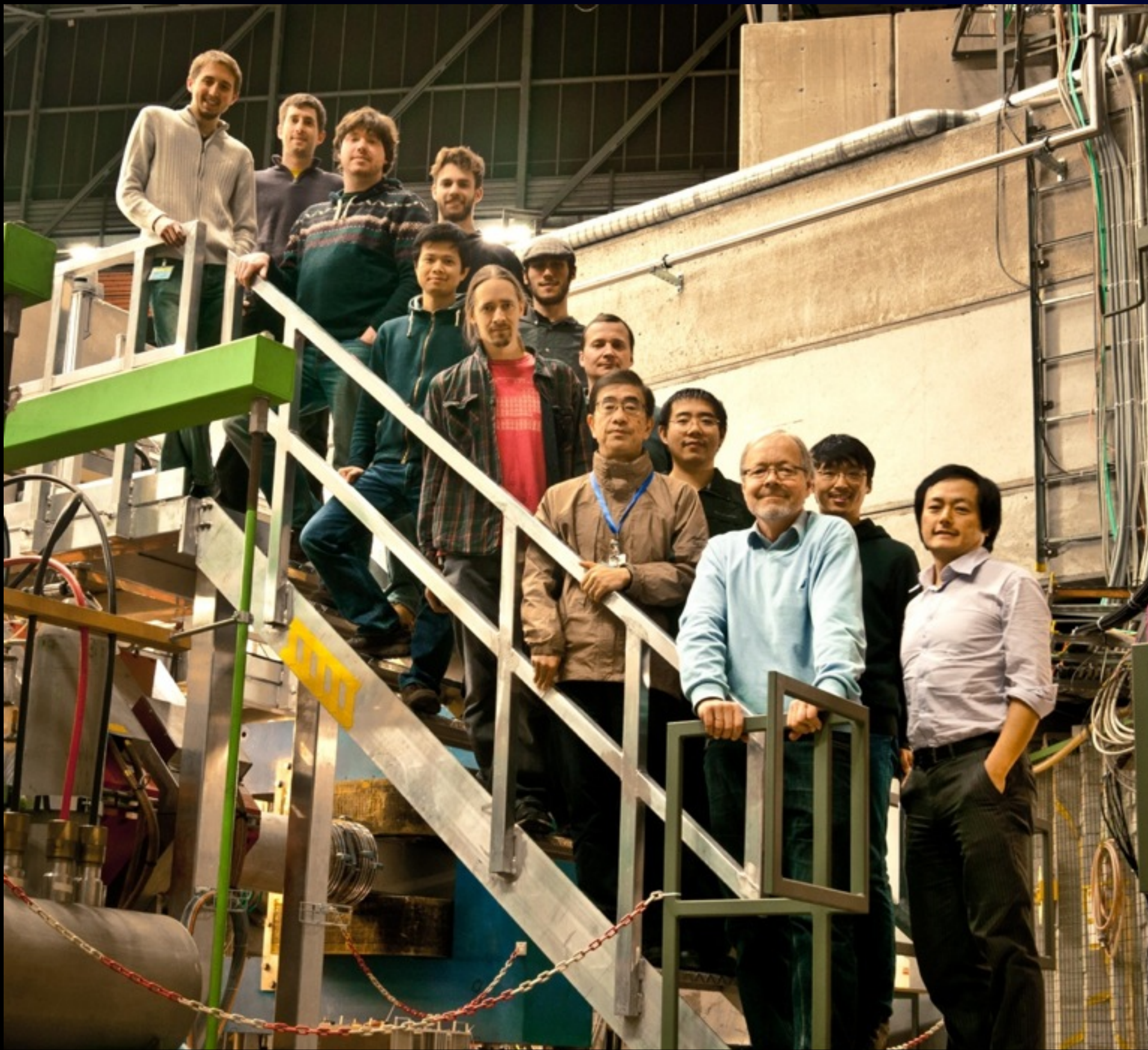
AlCap Experiment at PSI (2013~)

...through the US-Japan Program

Measurements of particle (proton) production after muon capture on Al.

- Proton emission rate after muon capture is important, since it determines single rates of tracking chambers if no charge selection is made before detection.
- That rate for aluminum has not been measured.
- As a joint effort of Mu2e and COMET, the AlCap experiment (P. Kammel (UW) and YK (Osaka), co-spokespersons) is being done at PSI in December, 2013.
- The measurements of neutron emission will be done in 2014?





AlCap@PSI

Dec. 13

AlCap@PSI

Dec. 13

C COMET

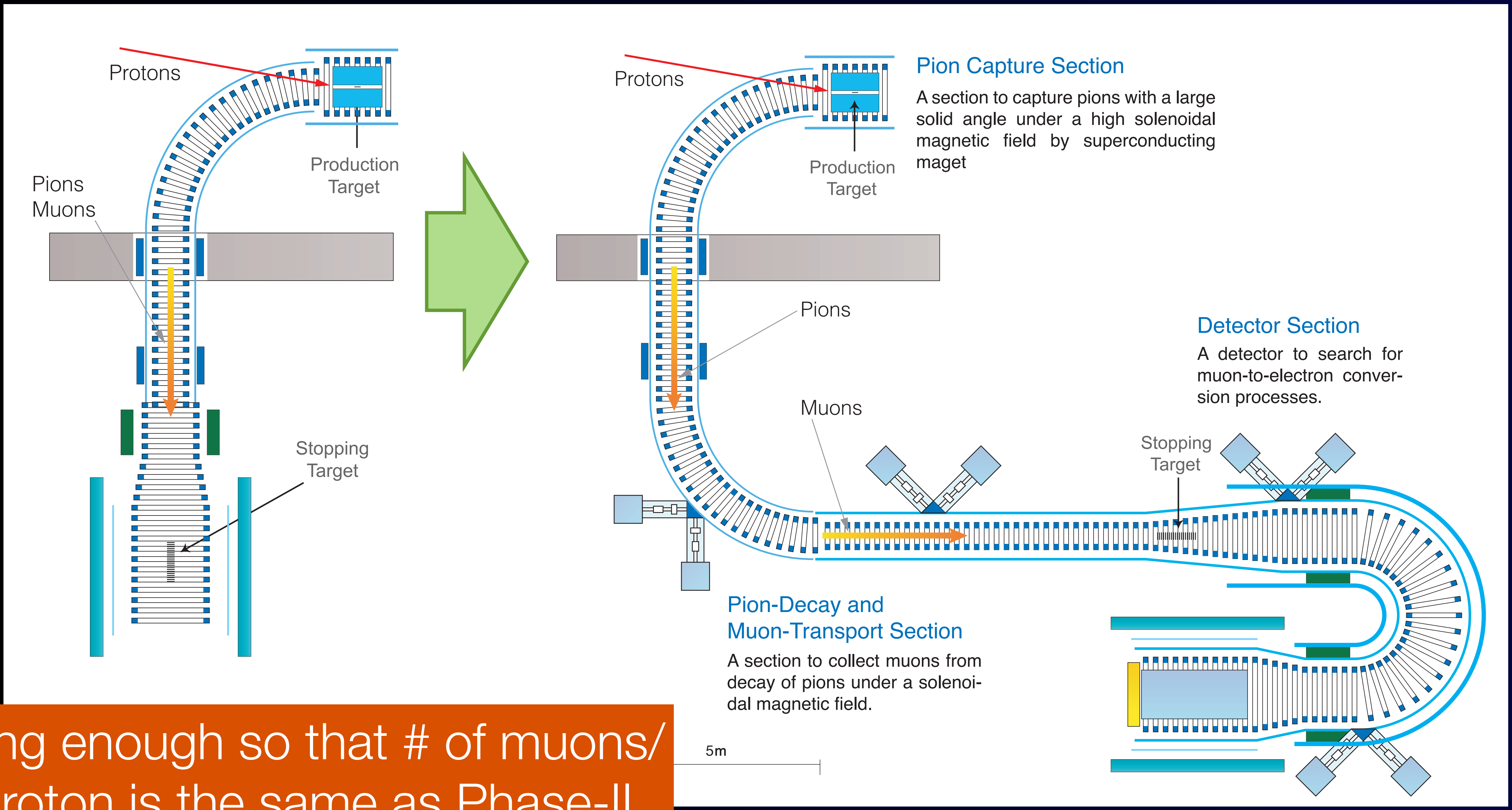
M Mu2e

COMET Phase-I

COMET Staged Approach (2012~)

COMET Phase-I

COMET Phase-II



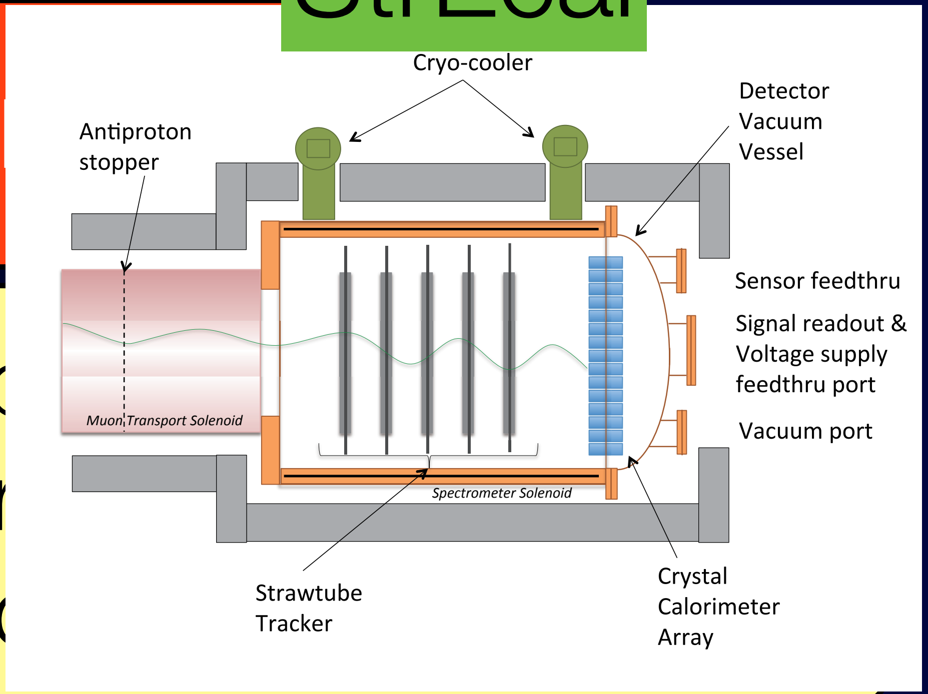
long enough so that # of muons/ proton is the same as Phase-II.

Goals of COMET Phase-I

1 Background Study for COMET P

direct measurement of potential b
sources for the full COMET exper
actual COMET beamline construc

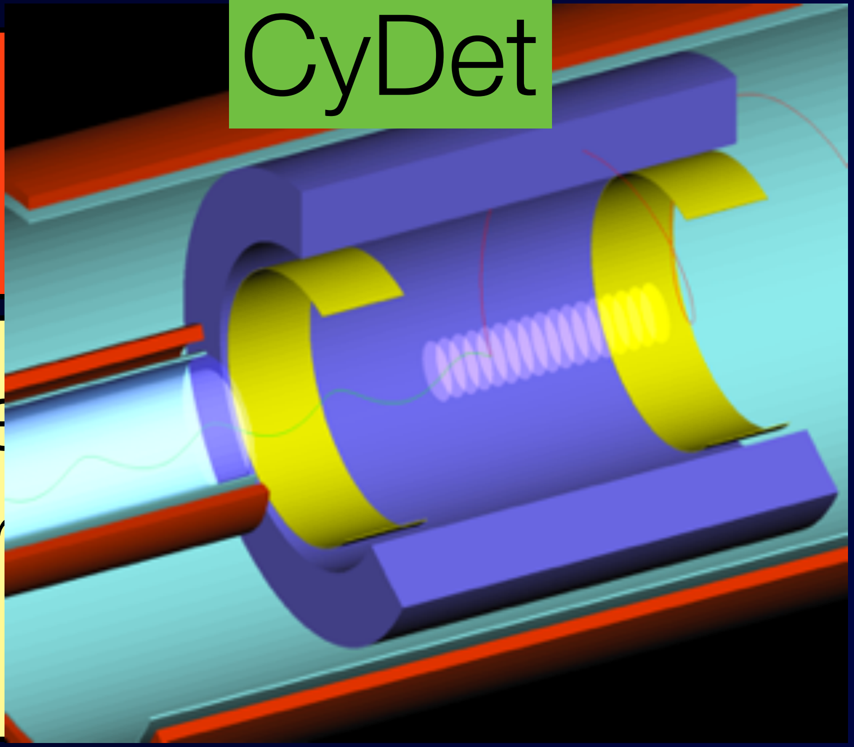
StrEcal



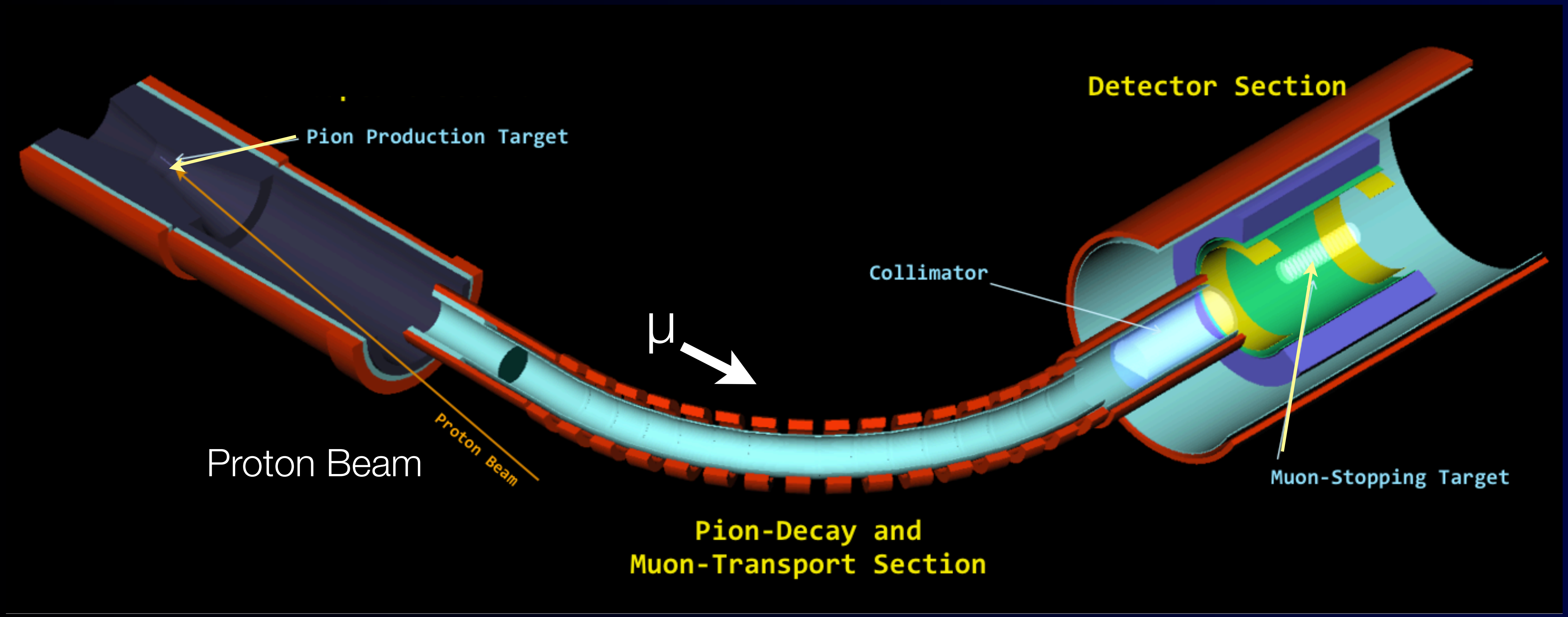
2 Search for μ-e conversion

a search for μ^-–e^- conversion at inte
sensitivity which would be more thar
than the SINDRUM-II limit

CyDet



COMET Phase-I Experimental Layout



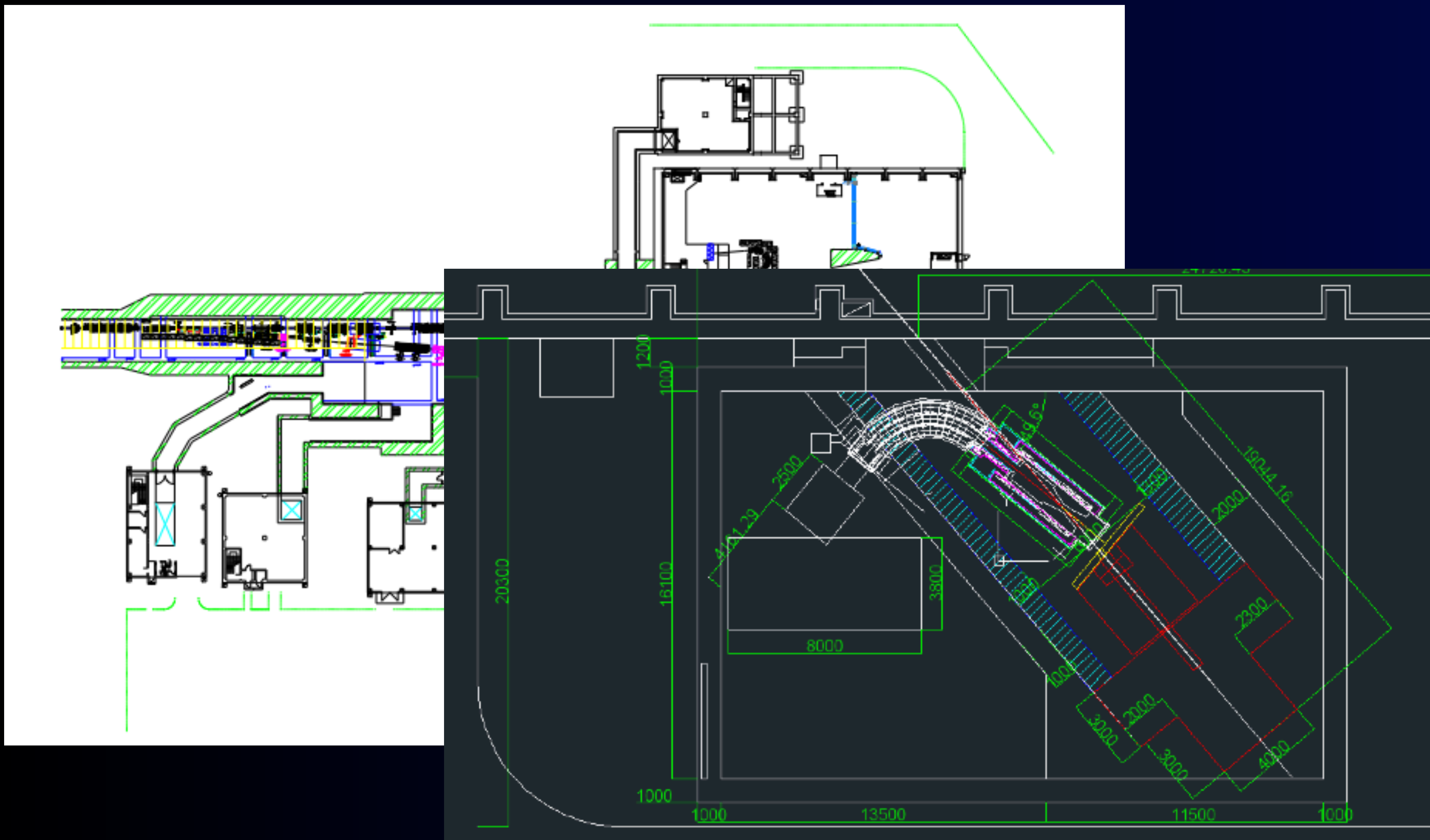
COMET muon beam-line：

$6x10^9$ muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector：

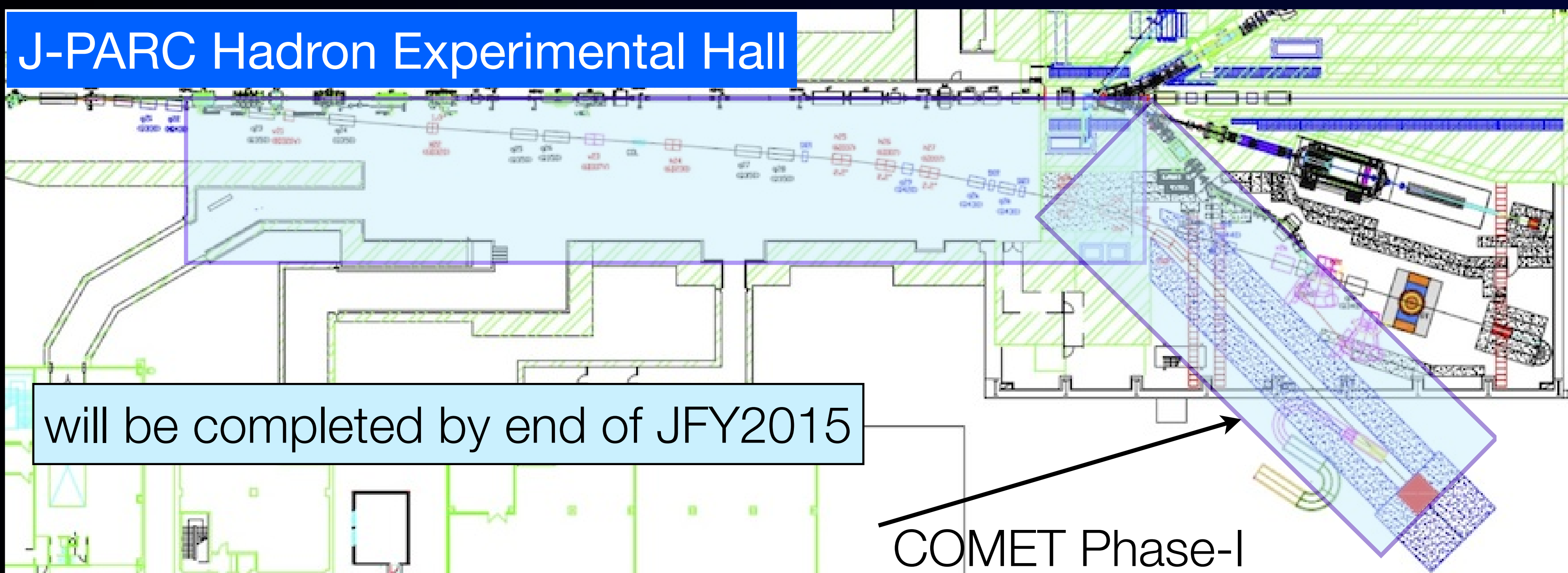
About 10^{16} muons are stopped in the target. Electron from μ-e conversion will be measured

COMET Beam line



Funds for Phase-I is secured.....

Budget for COMET Phase-I has been approved.



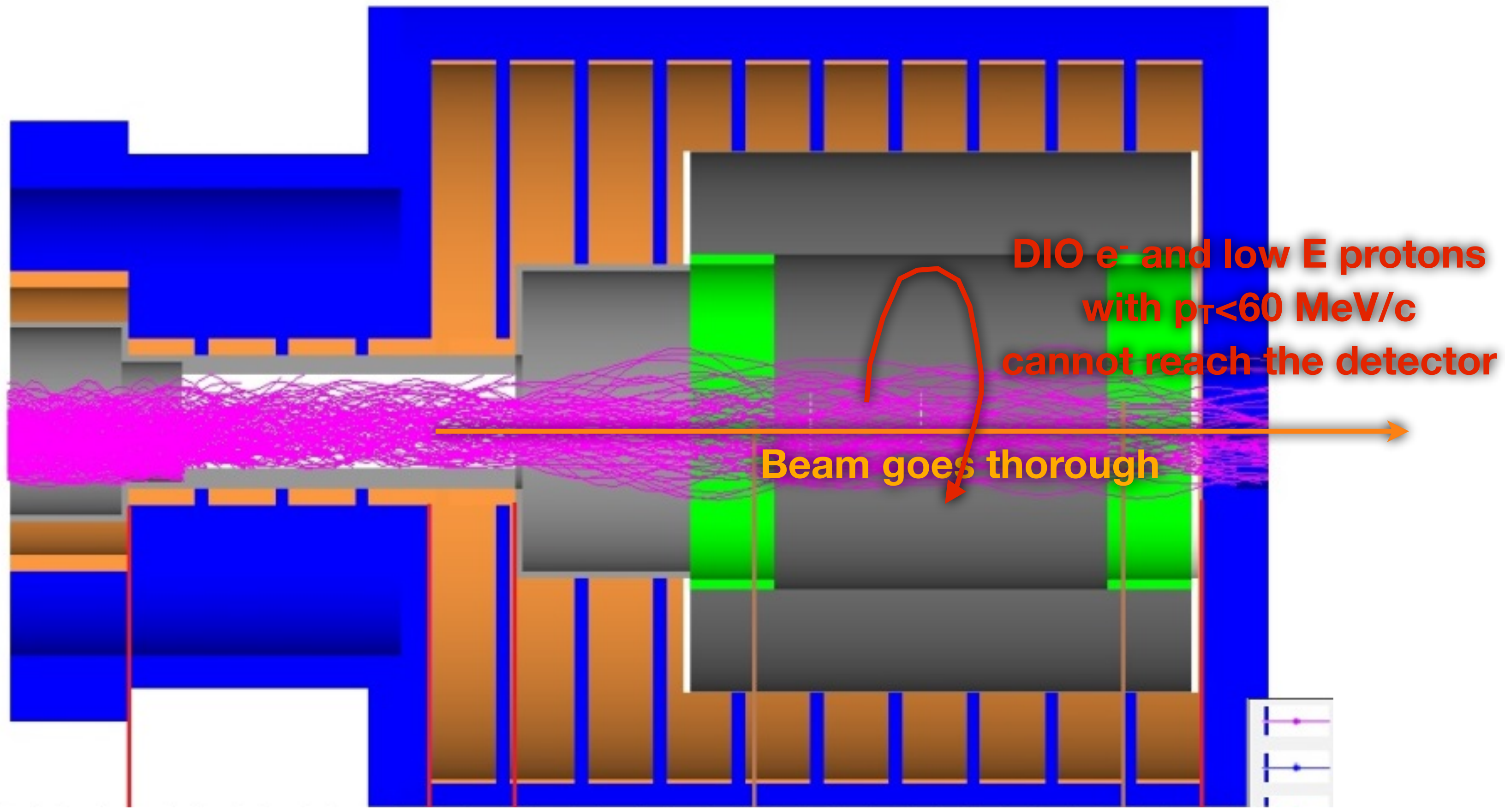
JFY2012 Supplemental budget

High momentum proton beam line for nuclear physics

Items		done by
proton beam-line	general use	KEK
muon beam-line		
COMET detector	exp. proper	COMET collaboration

Detector budget (CDC and detector solenoid) has been secured.

Cylindrical Drift Chamber Detector (CyDet)

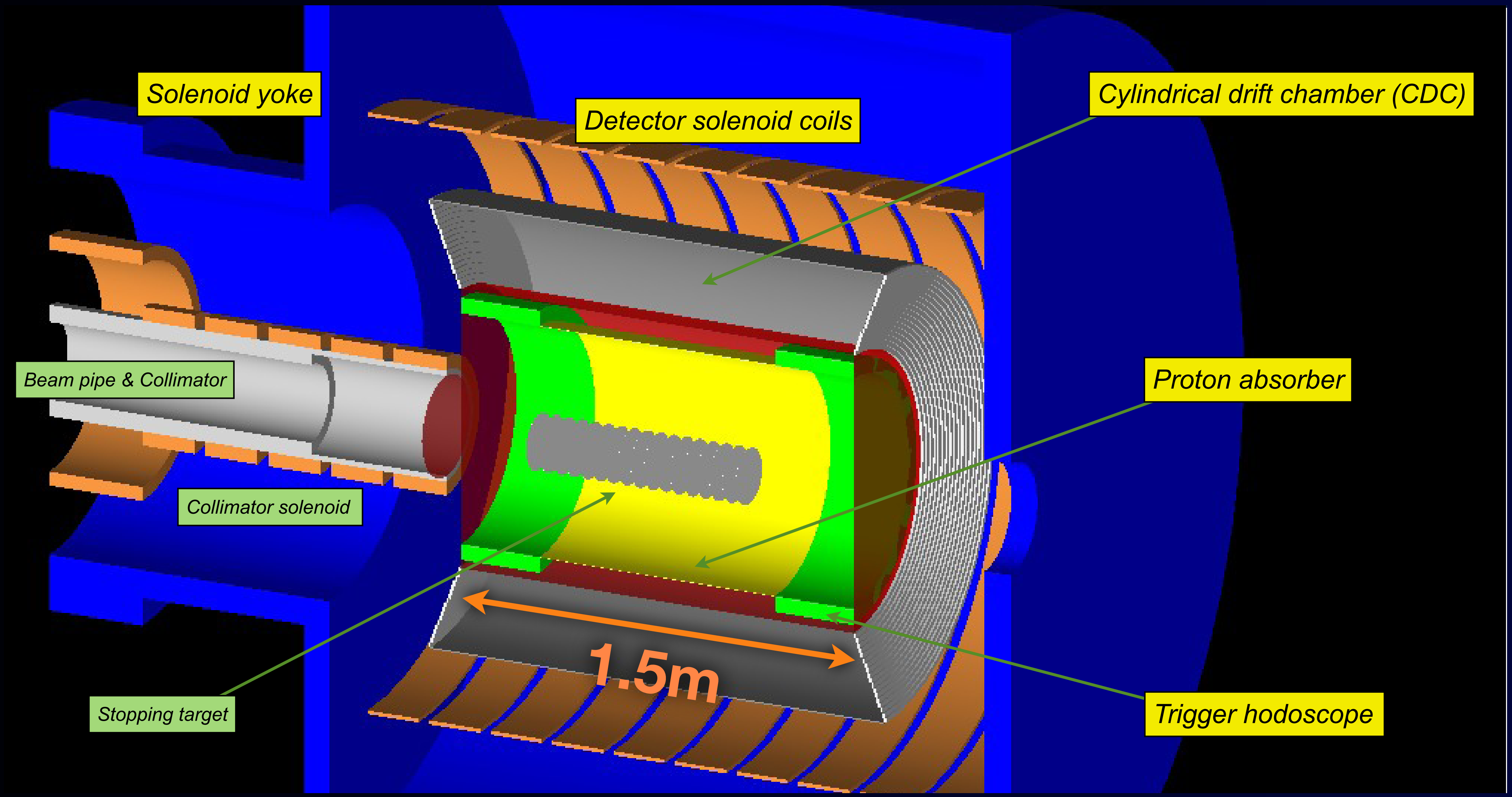


- to avoid hits of beam particles, DIO e^-, and low energy protons

Why CyDet ?

For Phase-I, no curved solenoid electron transport to momentum and charge select the particles is available. In the CyDet geometry, no beam particles hit the detector, and low momentum tracks do not reach the detector.

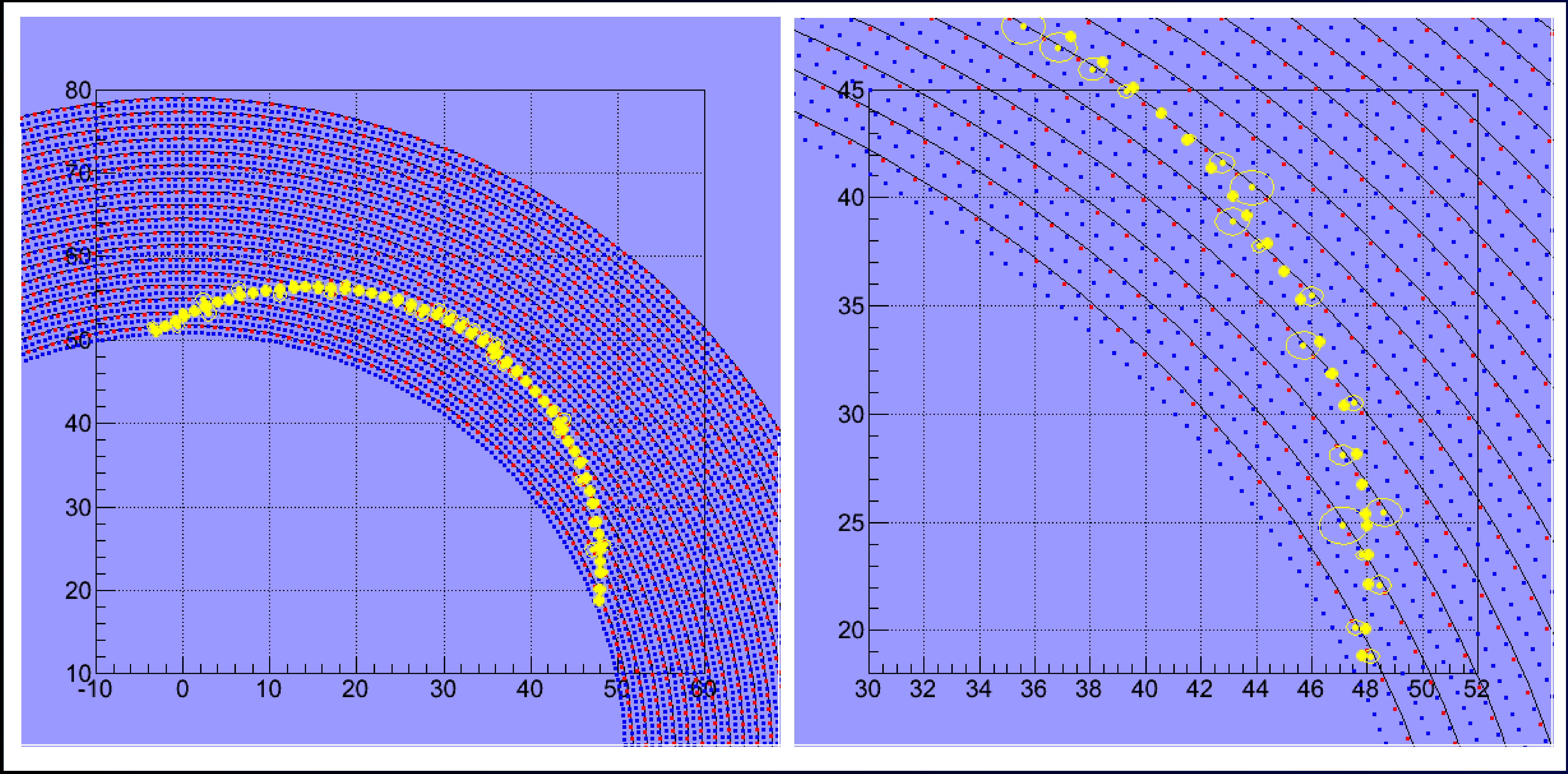
Cylindrical Drift Chamber Detector (CyDet)



CDC design

- z hit position by stereo layers (all stereo layers)
- reduction of multiple scattering by helium based gas mixture
- large inner radius to reduce DIO electron hits. (rate)
- proton absorber of CFRP to reduce protons from muon capture

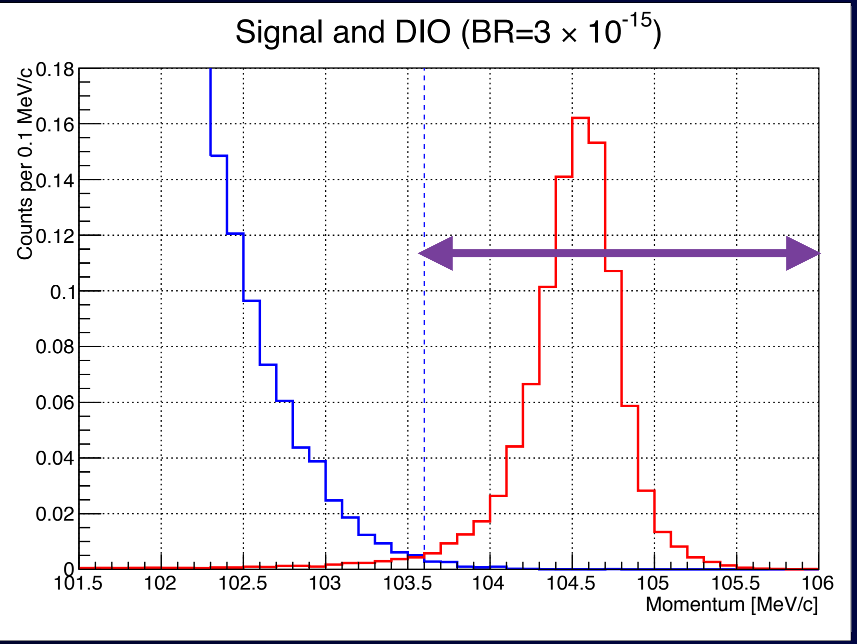
Cylindrical Drift Chamber Detector (CyDet)



Signal Sensitivity with CyDet

Signal Acceptance

Event selection	Value	Comments
Geometrical acceptance and tracking cuts	0.29	
Momentum selection	0.97	103.6 MeV/c < P_e <106.0 MeV/c
Timing window	0.3	700 ns < t < 1100 ns
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	



Signal Sensitivity

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

- f_{cap} = 0.6
- A_e = 0.056
- N_μ = 9.4x10^{15} muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-17}$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-17} \quad (90\% C.L.)$$

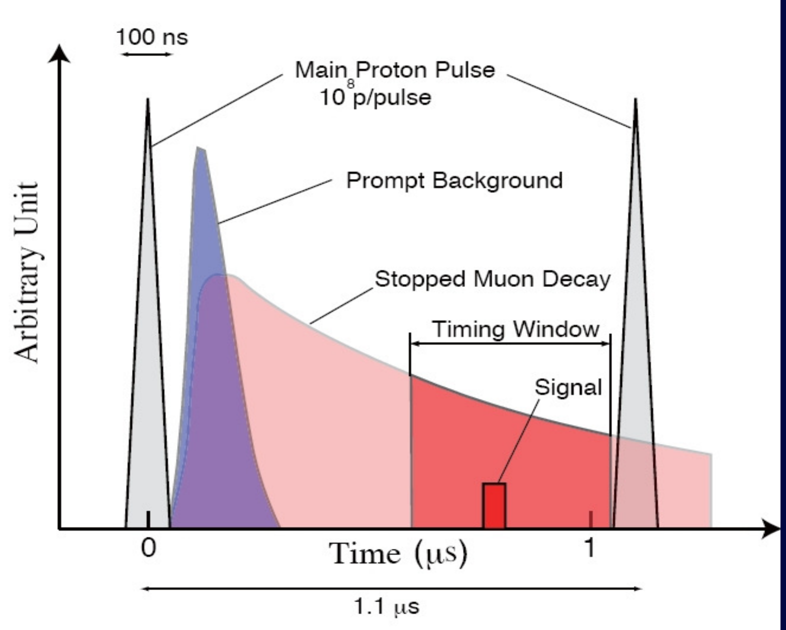
Muon intensity

about 0.00064 muons stopped/proton

With 0.4 μA, a running time of about 90 days is needed.

Background List

Intrinsic physics backgrounds		
1	Muon decay in orbit (DIO)	Bound muons decay in a muonic atom
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,
4	Neutron emission after after muon capture	$\mu^- + A \to \nu_\mu + A' + n$, and neutrons produce e^-
5	Charged particle emission after muon capture	$\mu^- + A \to \nu_\mu + A' + p$ (or d or α), followed by charged particles produce e^-
Beam related prompt/delayed backgrounds		
6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$, $\gamma \to e^- + e^+$
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$
8	Beam electrons	e^- scattering off a muon stopping target
9	Muon decay in flight	μ^- decays in flight to produce e^-
10	Pion decay in flight	π^- decays in flight to produce e^-
11	Neutron induced backgrounds	neutrons hit material to produce e^-
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits material to produce e^-
Other backgrounds		
14	Cosmic-ray induced backgrounds	
15	Room neutron induced backgrounds	
16	False tracking	



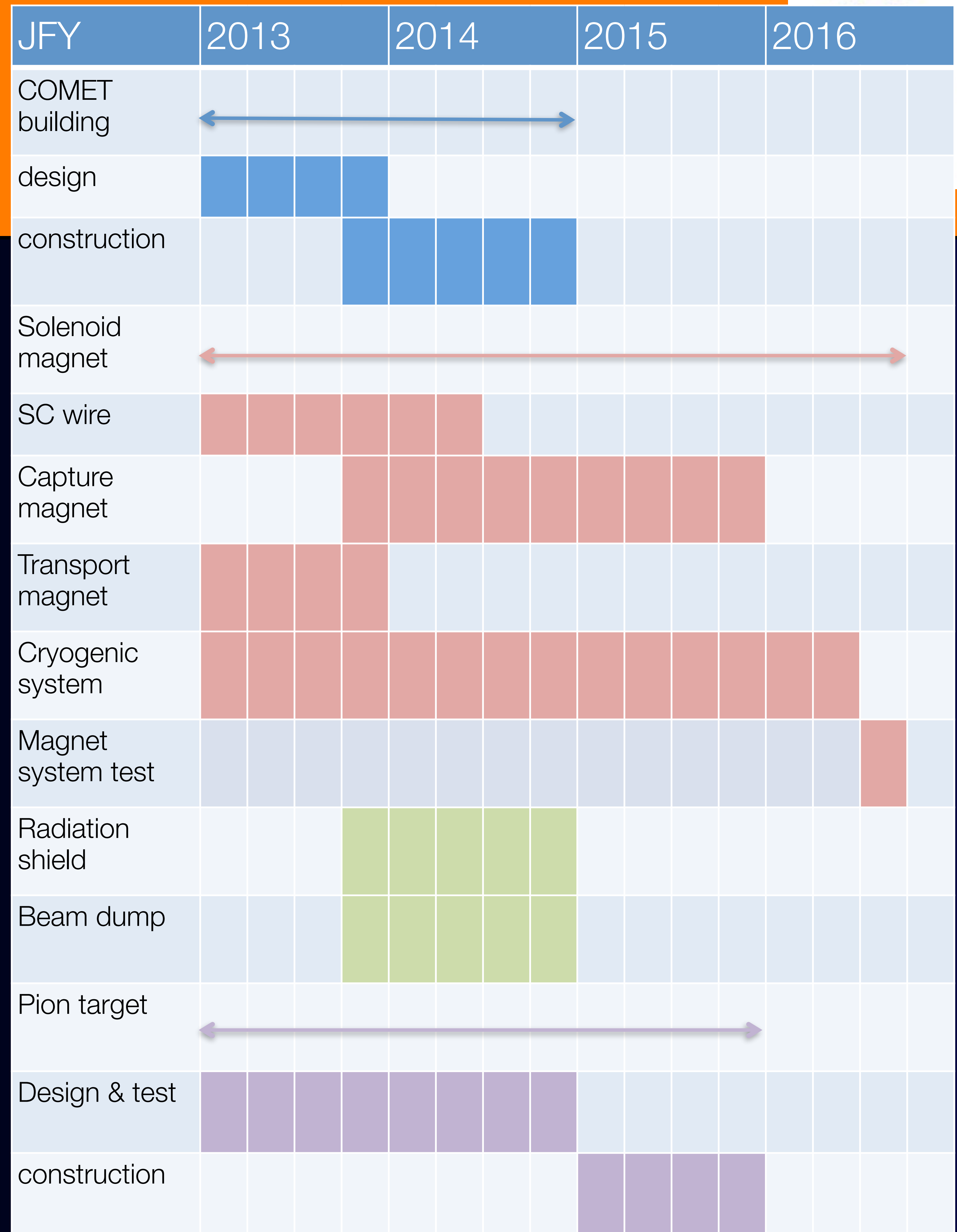
prompt and delayed backgrounds

Background Estimate with CyDet

Table 26: *Summary of the estimated background events for a single-event sensitivity of* 3.1×10^{-15} *with a proton extinction factor of* 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
Physics	Radiative muon capture	5.6×10^{-4}
Physics	Neutron emission after muon capture	< 0.001
Physics	Charged particle emission after muon capture	< 0.001
Prompt Beam	Beam electrons (prompt)	7.1×10^{-4}
Prompt Beam	Muon decay in flight (prompt)	$\leq 1.7 \times 10^{-4}$
Prompt Beam	Pion decay in flight (prompt)	$\leq 2.0 \times 10^{-3}$
Prompt Beam	Other beam particles	$\leq 2.4 \times 10^{-6}$
Prompt Beam	Radiative pion capture(prompt)	4.24×10^{-4}
Delayed Beam	Beam electrons (delayed)	~ 0
Delayed Beam	Muon decay in flight (delayed)	~ 0
Delayed Beam	Pion decay in flight (delayed)	~ 0
Delayed Beam	Radiative pion capture (delayed)	~ 0
Delayed Beam	Anti-proton induced backgrounds	0.007
Others	Electrons from cosmic ray muons	< 0.0001
Total		0.019

Schedule (Facility)



- 2013
  - Design of the building & beam line
    - Bid tendering and start construction
  - Design of superconducting solenoid magnets and start of construction
    - Production of SC wires as well
  - Design of the pion production target
- 2014
  - Completion of the building
  - Construction of superconducting solenoid magnets
  - Start magnet and radiation shielding (and beam dump) installation
    - Transport solenoid
  - Start preparation of cryogenic system
  - Tests of the target production target
- 2015
  - Construction of superconducting solenoid magnets
  - Preparation of cryogenic system
  - Construction of the pion production target
- 2016
  - Installation of the capture solenoid
  - Completion of the cryogenic system
    - Tests of the magnet system
  - Installation of the target
  - Ready to accept the 8GeV beam

Schedule (Detector)

Osaka University

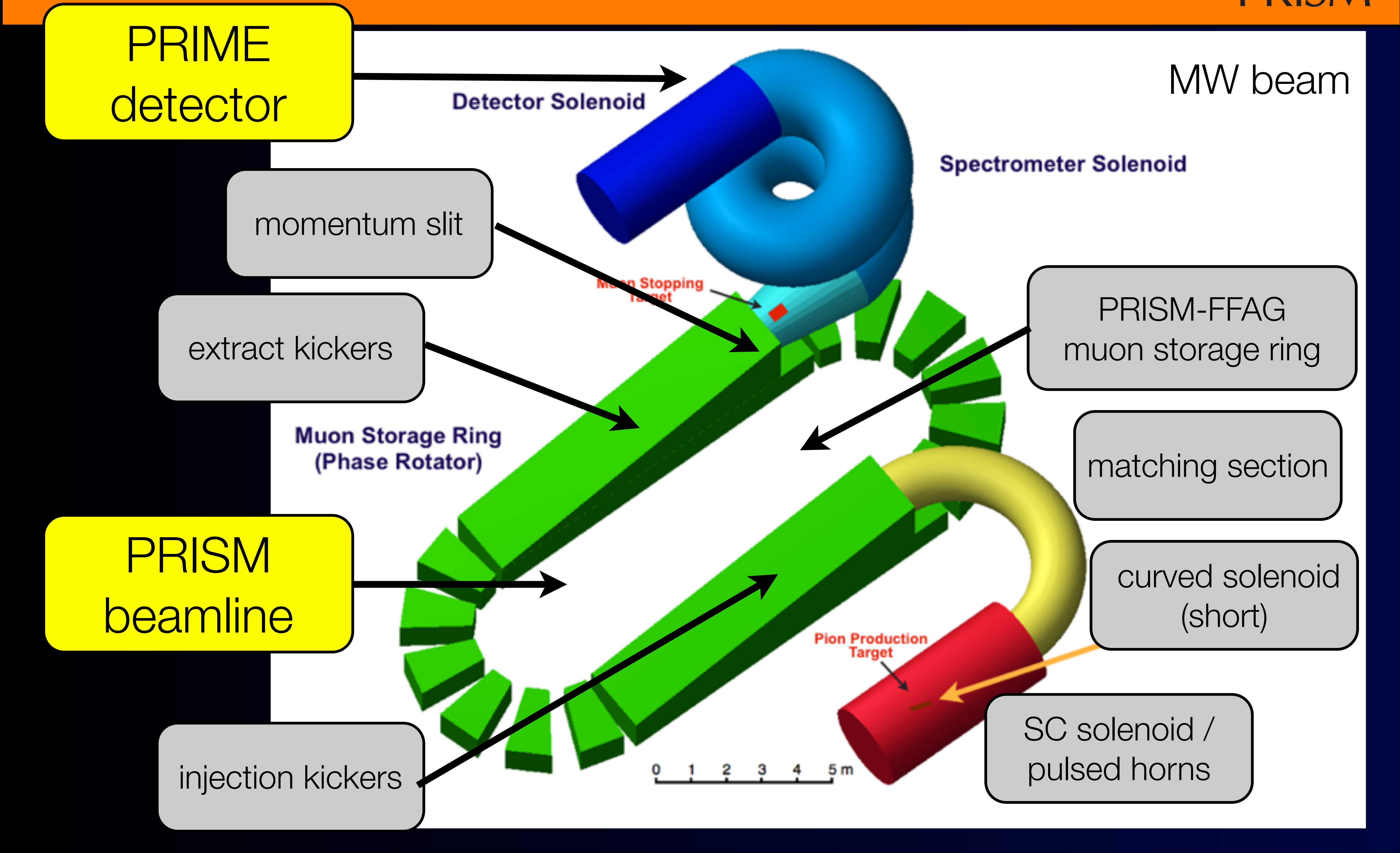
Detector construction

System	Works	2013	2014	2015	2016
CDC	Prototype construction				
	Endplate construction				
	Inner & outer wall construction				
	wire stringing & assembly				
	readout electronics				
	gas system construction				
	cosmic test				
CDC trigger counter	counter construction				
	readout electronics				
Detector Solenoid	design				
	superconductor fabrication				
	coil winding				
	cryostat construction				
	iron yoke production				
	power supply				
Collimator Solenoid	design				
	superconductor fabrication				
	coil winding				
	cryostat construction				
	iiron yoke construcution				
	power supply				
Muon Target	construction				

System	Works	2013	2014	2015	2016
Straw Chamber	straw construction				
	ROESTI prototype				
	ROESTI production				
	vacuum chamber				
	gas system construction				
ECAL	crystal construction				
	ROESTI prototype				
	ROESTI production				
	assembly				
Cosmic Veto	counter construction				
	SiPM production				
	installation				
Muon Target	construction				
DAQ	trigger prototype				
	trigger production				
	DAQ development				
Muon collimator	beam measurement				
	construction				
X-ray detector	procurement				
Experiment	Transportation				
	Installation				
	Engineering run				
	Physics run				

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

μ-e conversion at S.E. sensitivity of $3x10^{-19}$ 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.

Summary

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- Muon to electron conversion could be one of the important CLFV processes in terms of theoretical and experimental points of view.
- COMET (Phase-II) at J-PARC is aiming at S.E. sensitivity of 3×10^{-17}.
- After the staged approach, COMET Phase-I is aiming at S.E. sensitivity of 3×10^{-15}. The beam line construction has been funded at KEK and the construction will start in 2013. Hope to do a measurement in 2016.

IKU (go ahead)