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

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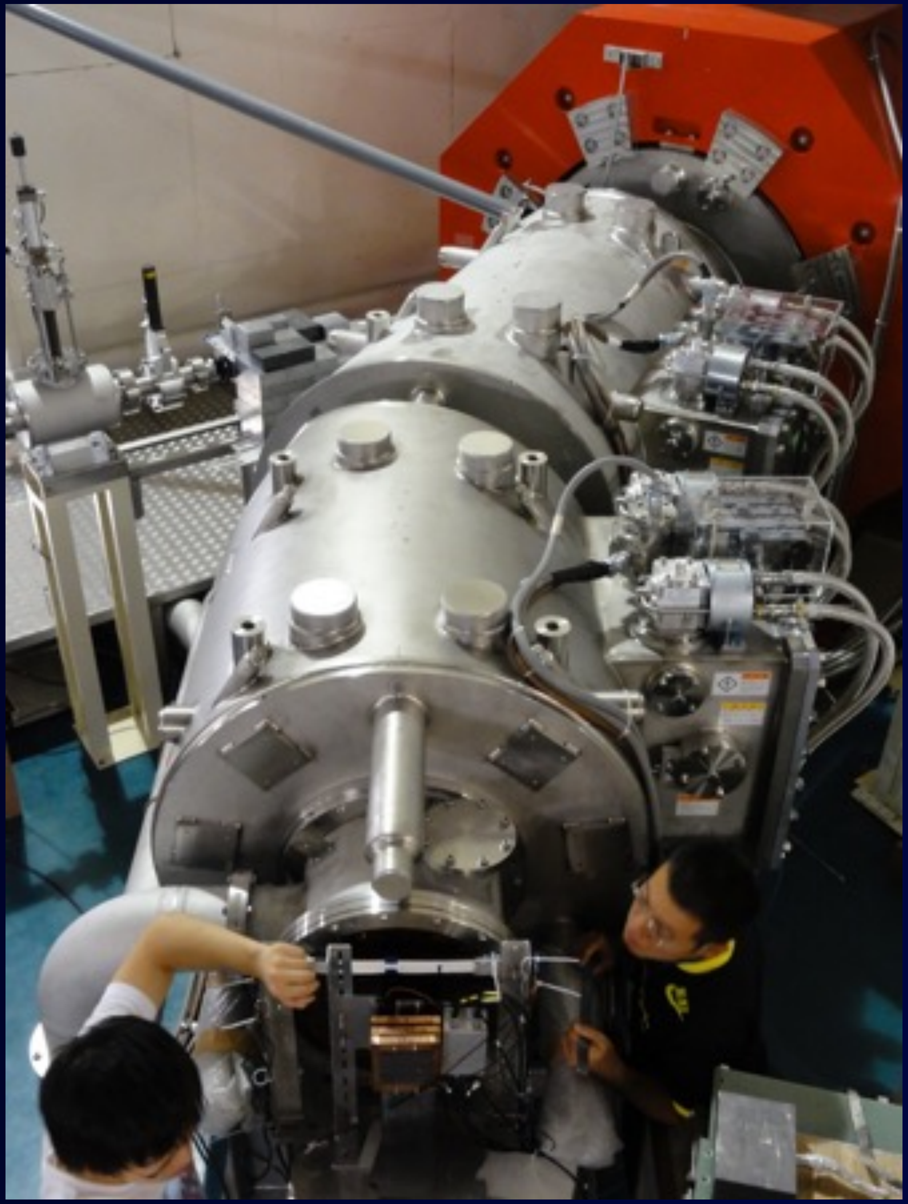
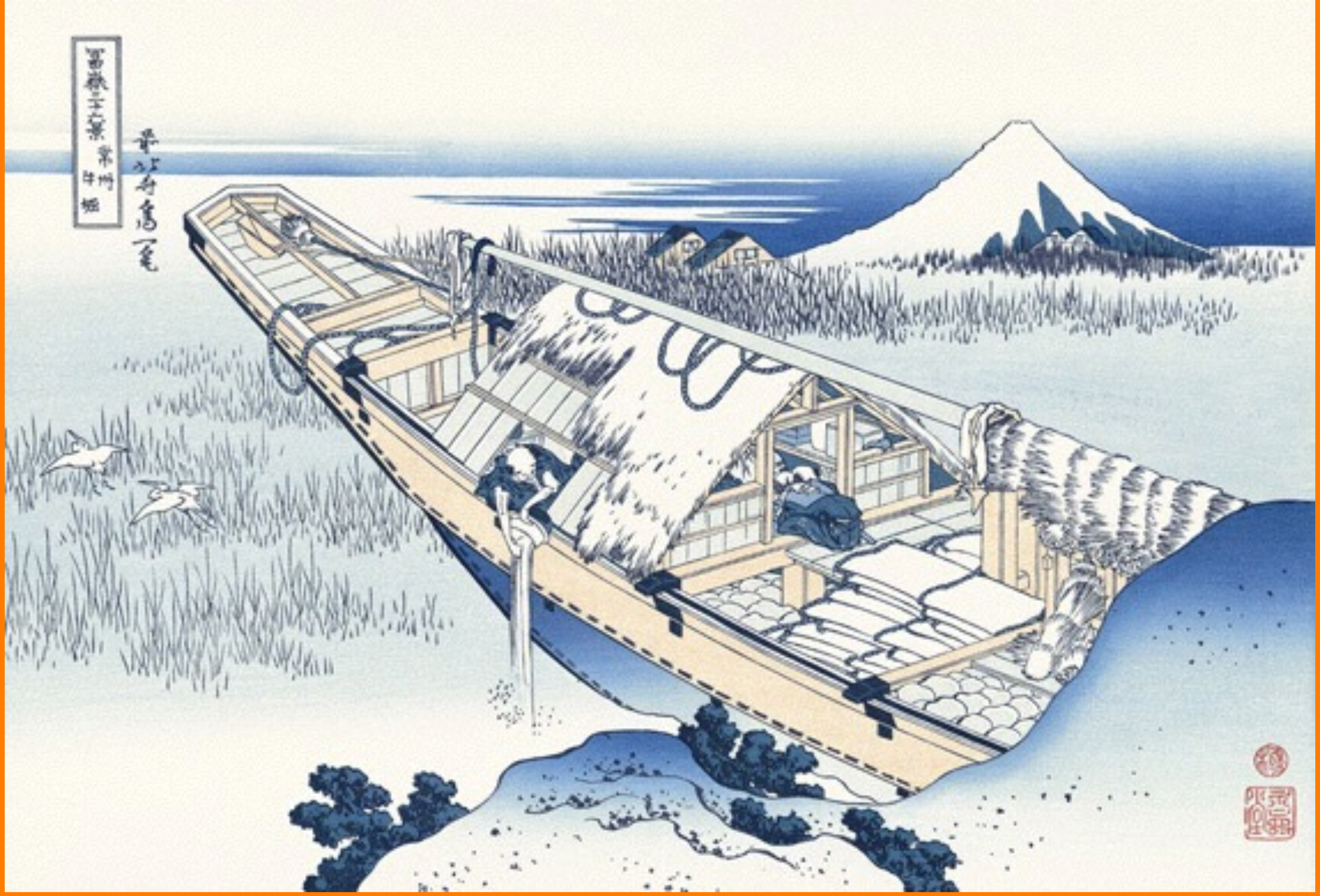
Outline

- Why Flavor Physics ?
- Why Charged Lepton Flavor Violation (CLFV) ?
- CLFV Experiments
  - Muon to electron conversion in a muonic atom
- COMET (-> COMET Phase-II)
  - for sensitivity of $7<10^{-17}$ (x10000)
- COMET Phase-I
  - for sensitivity of $7<10^{-15}$ (x100)
- Summary



Why Charged Lepton Flavor Violation ?

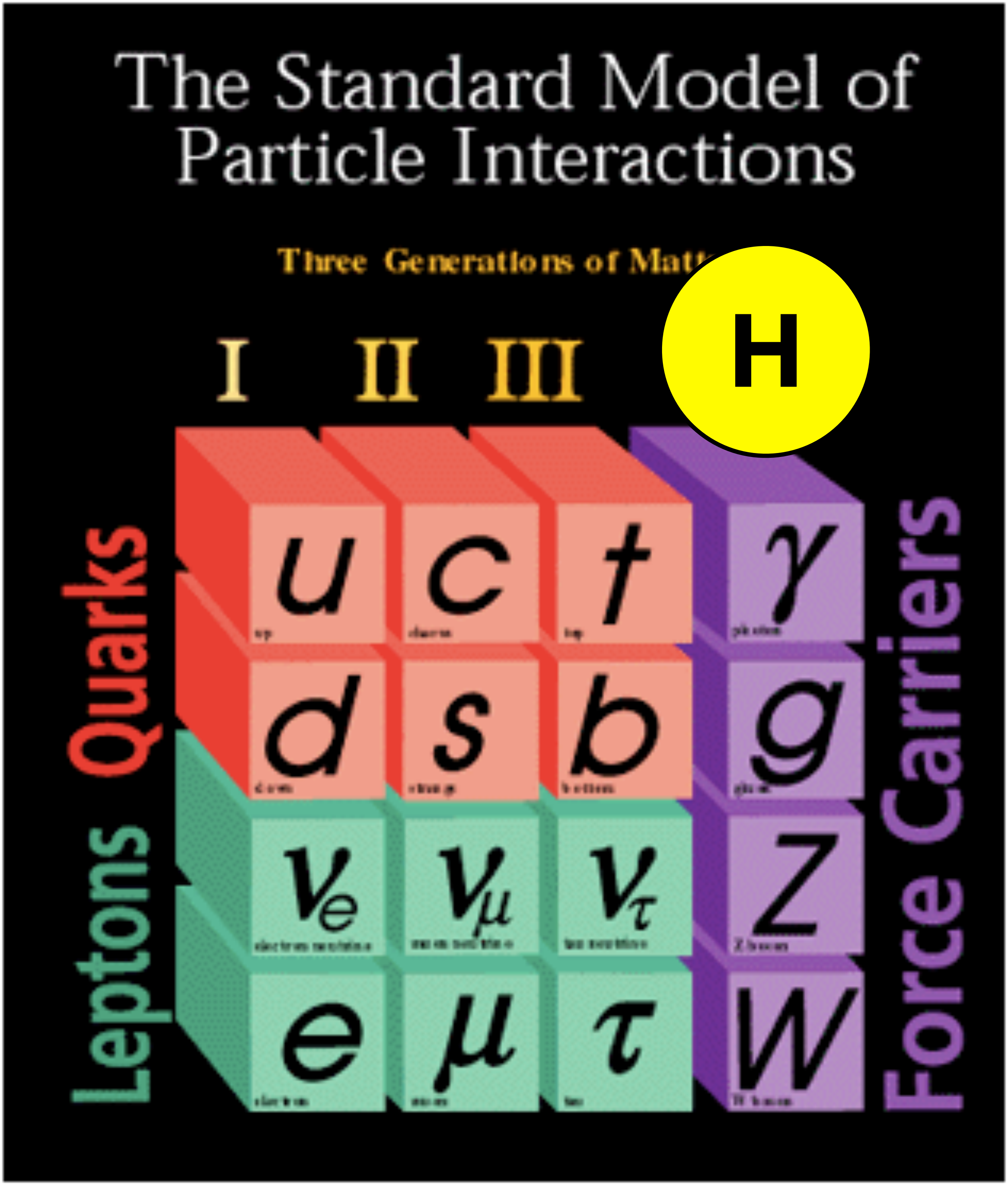


The Standard Model has the Higgs boson, but no new particles are found yet...

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.



Three Frontiers of Particle Physics

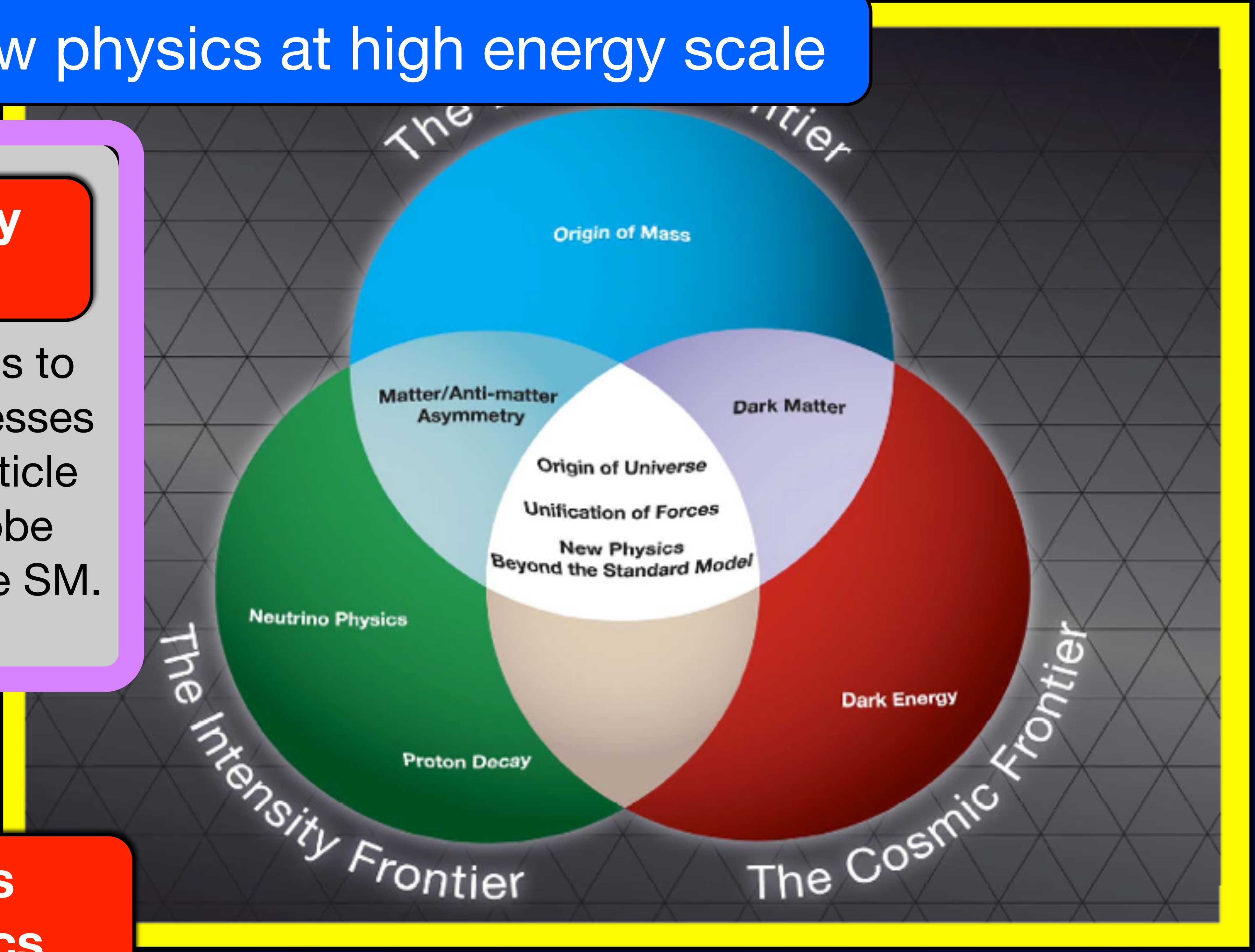
Osaka University

To explore new physics at high energy scale

The Intensity Frontier

use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.

Rare Decays
Flavor Physics



Flavor Physics and New Physics

flavor
structure

Effective Lagrangian in
the Standard Model (SM)

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

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

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 Quark Flavor

with new physics contributions

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

Λ is the energy scale of new physics

Quark Flavor

Operator	Limits on Λ (TeV) ($C_{\rm NP} = 1$)		Limits on $C_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, Φ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, Φ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\phi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\phi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

New Physics Search in Charged Lepton Flavor

with new physics contributions

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

Λ is the energy scale of new physics

Charged Lepton Flavor

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

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

$$\Lambda > 2\times10^5 \ {\rm TeV} \times (C_{\mu e})^{\frac{1}{2}} \ .$$

$\Lambda > O(10^5)$ 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 $O(10^{-54})$.

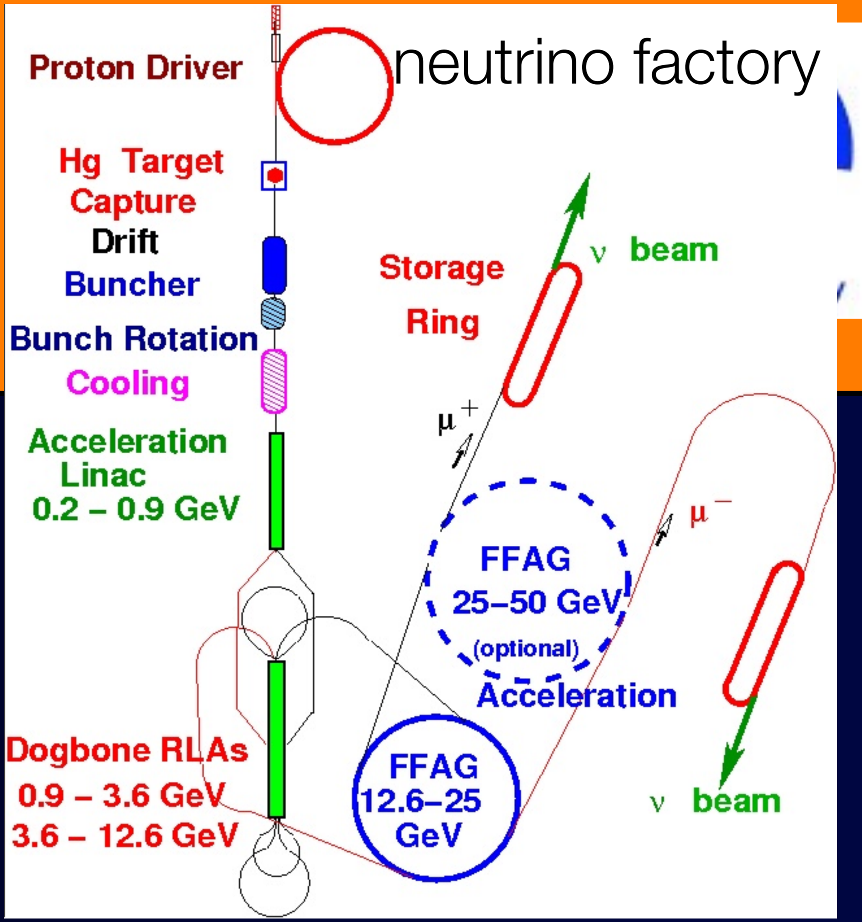
Which Rare Decays at Low Energy ?

- 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 (~10^{-50} with neutrino mixing)
  - Need to study deviations from none
    - clear signature and high sensitivity

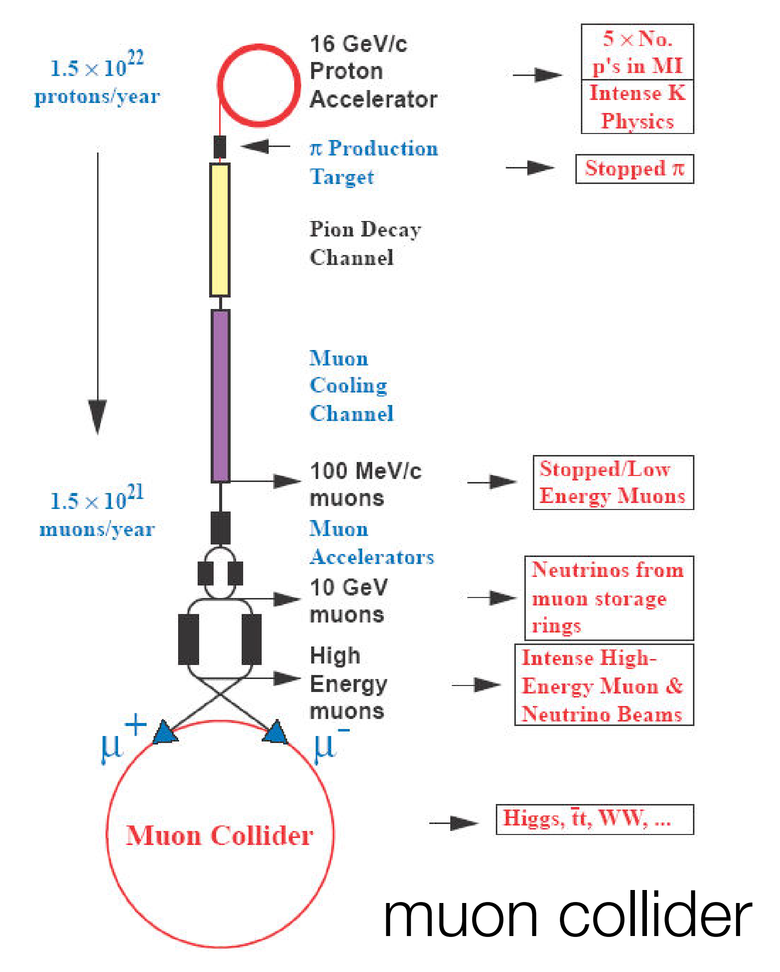
Why Muons, not Taus?

- 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



neutrino factory



muon collider

Guideline for Rare Decay Searches

SM contribution is dominant.

SM

Standard Model

New Physics

NP

👎

SM contribution is highly suppressed.

SM + NP

Uncertainty of the SM prediction limits the sensitivity.

SM contribution has to be subtracted.

SM contribution is forbidden.

+ NP

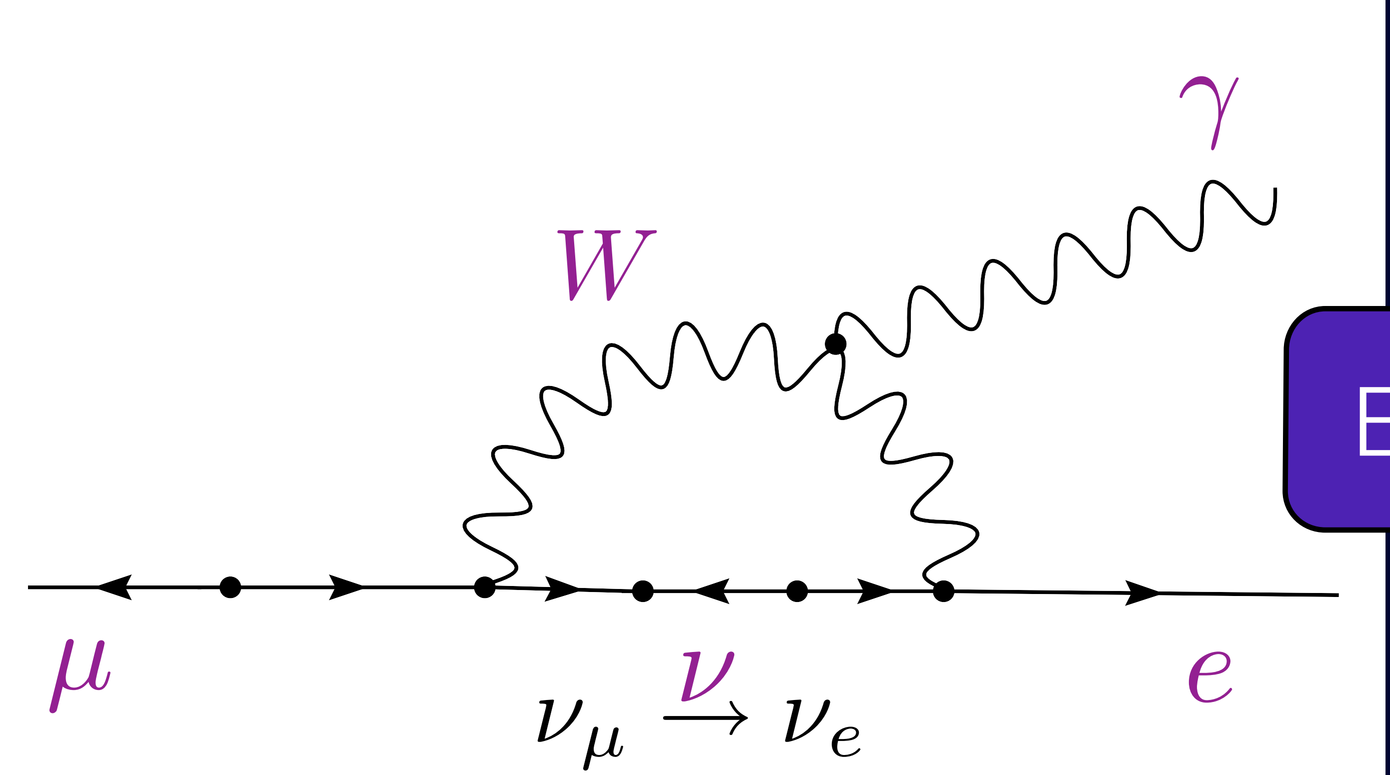
Clear signature without any subtractions

No SM contribution be subtracted.

No SM Contribution in Charged Lepton Flavor Violation (CLFV)

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

GIM suppression



BR~O(10^{-54})

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

Quark FCNC vs. Lepton FCNC

Quark (suppressed)

amplitude

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

subject to uncertainty of SM prediction

NP contribution ~ O(ε)

Lepton (forbidden)

rate

$$|A_{\mathrm{SM}}+\varepsilon_{\mathrm{NP}}|^2 \sim \cancel{|A_{\mathrm{SM}}|^2} + 2Re(\cancel{A_{\mathrm{SM}}\varepsilon_{\mathrm{NP}}}) + \underline{|\varepsilon_{\mathrm{N}}|^2}$$

could go higher energy scale

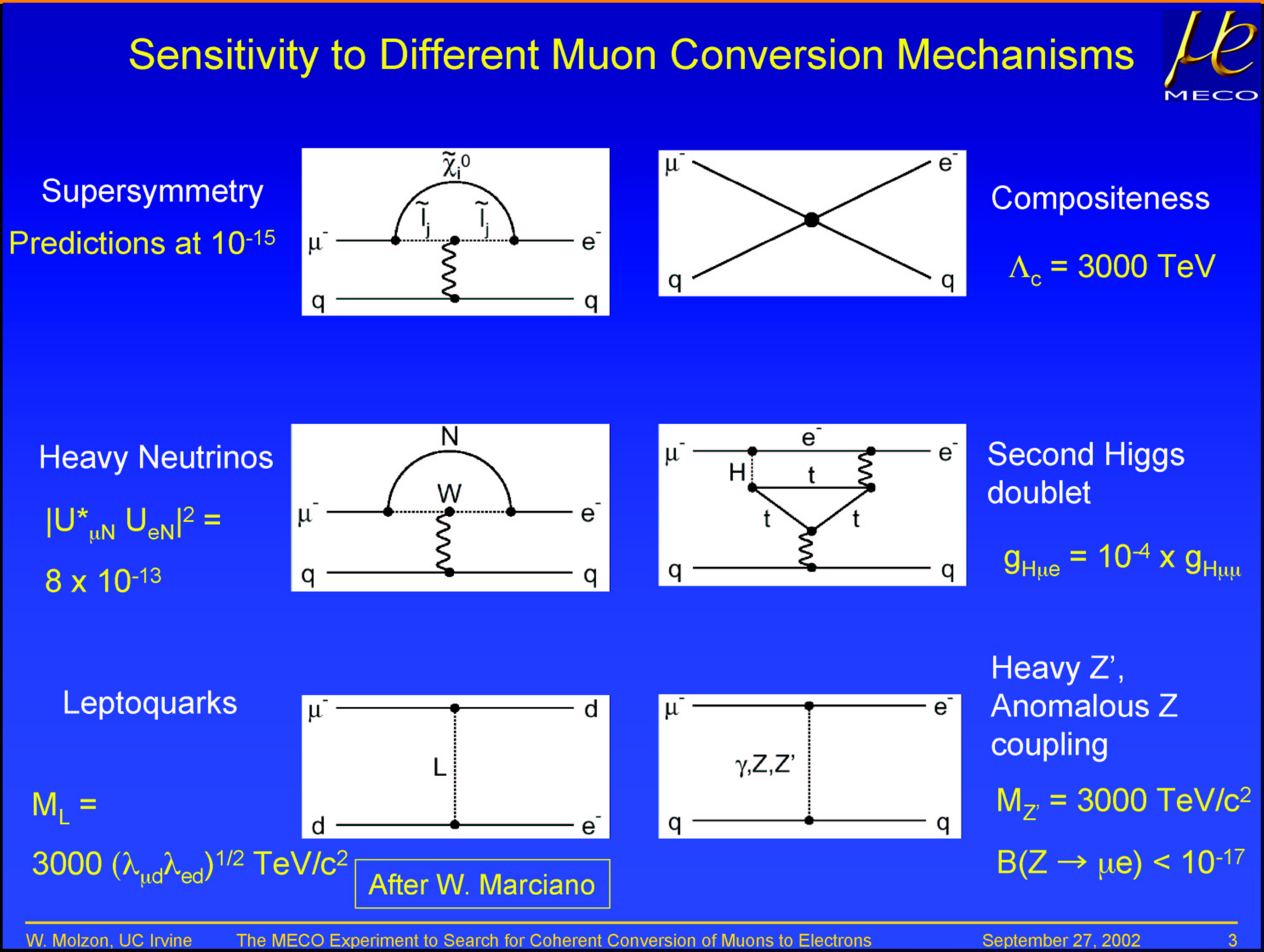
NP contribution ~ O(ε^2)

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

Quark FCNC may have limitation from SM prediction,
while lepton FCNC may need a big jump in improvement.

Lepton FCNC (CLFV) may still have better sensitivity to NP.

Various Models Predict CLFV......



Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

Compositeness

$\Lambda_c = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 =$

8×10^{-13}

Second Higgs doublet

$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

Leptoquarks

$M_L =$

$3000 (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2

After W. Marciano

Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

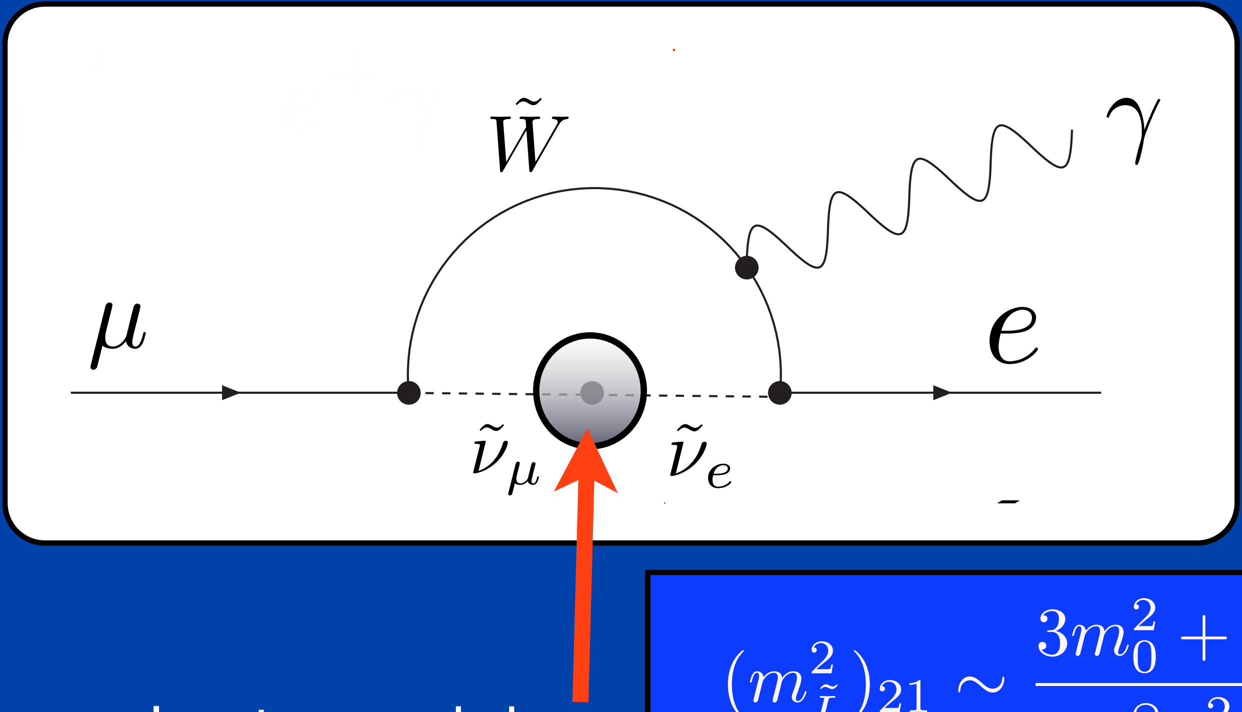
$B(Z \to \mu e) < 10^{-17}$

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

- 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

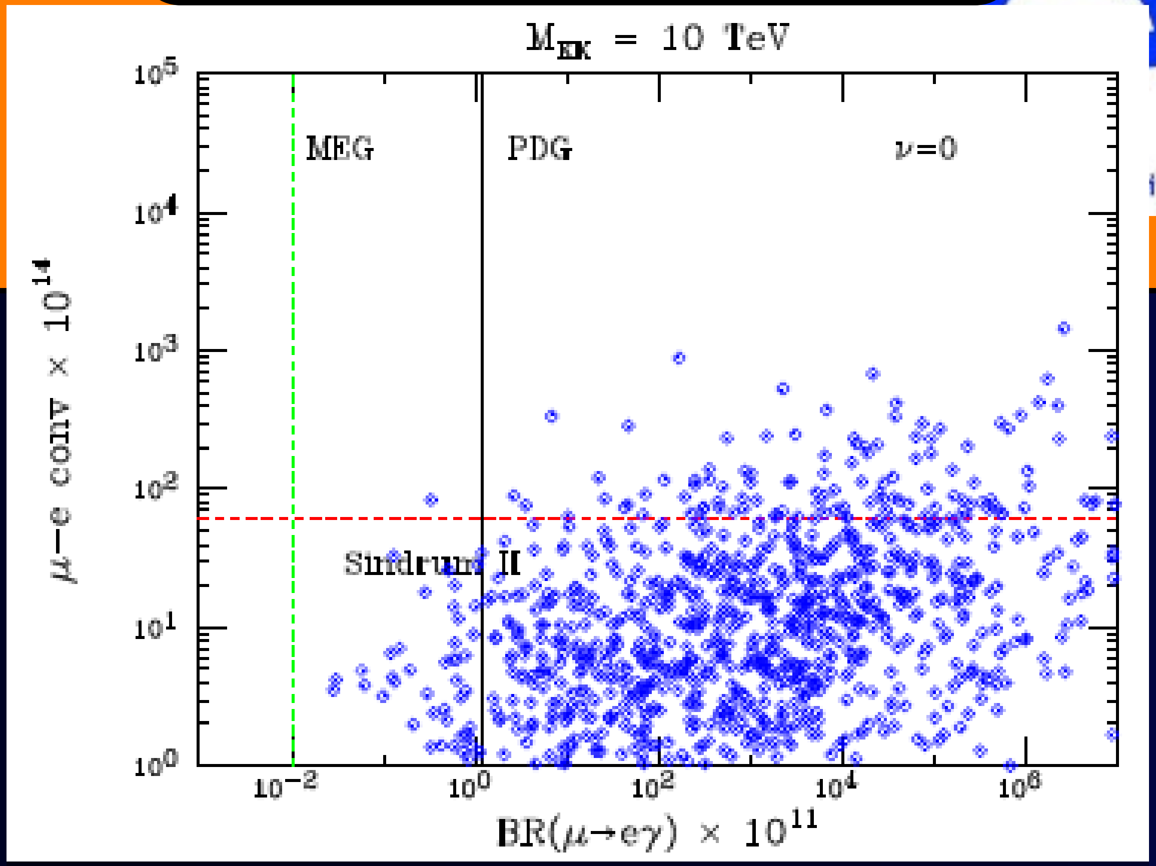
$$(m^2_{L})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln \frac{M_{GUT}}{M_R}$$

SUSY neutrino seesaw model

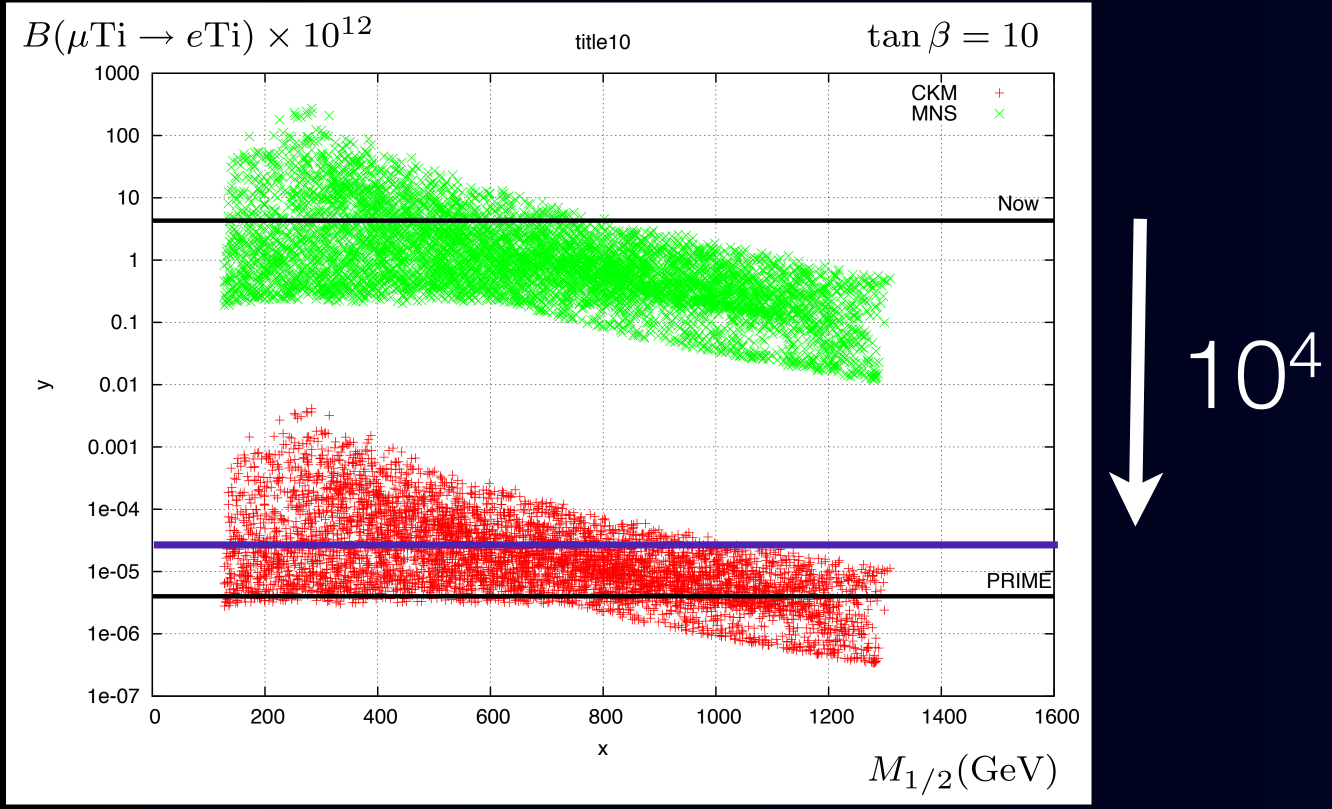
CLFV Predictions

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

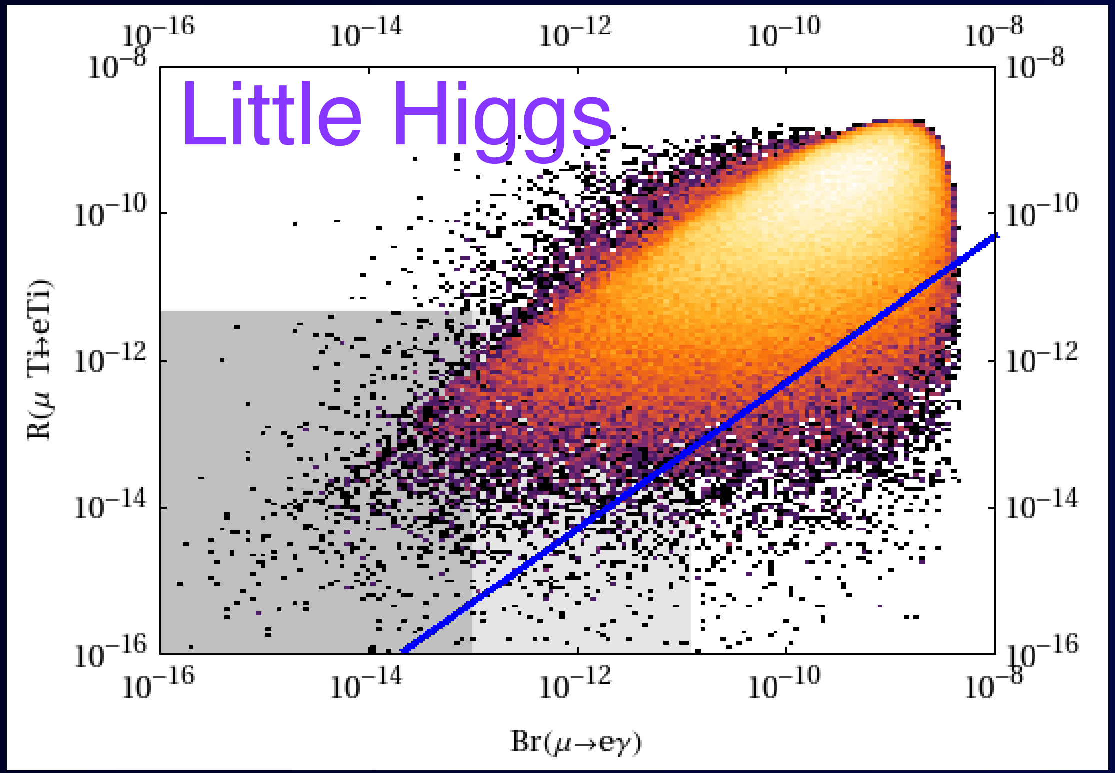
extra dimension model



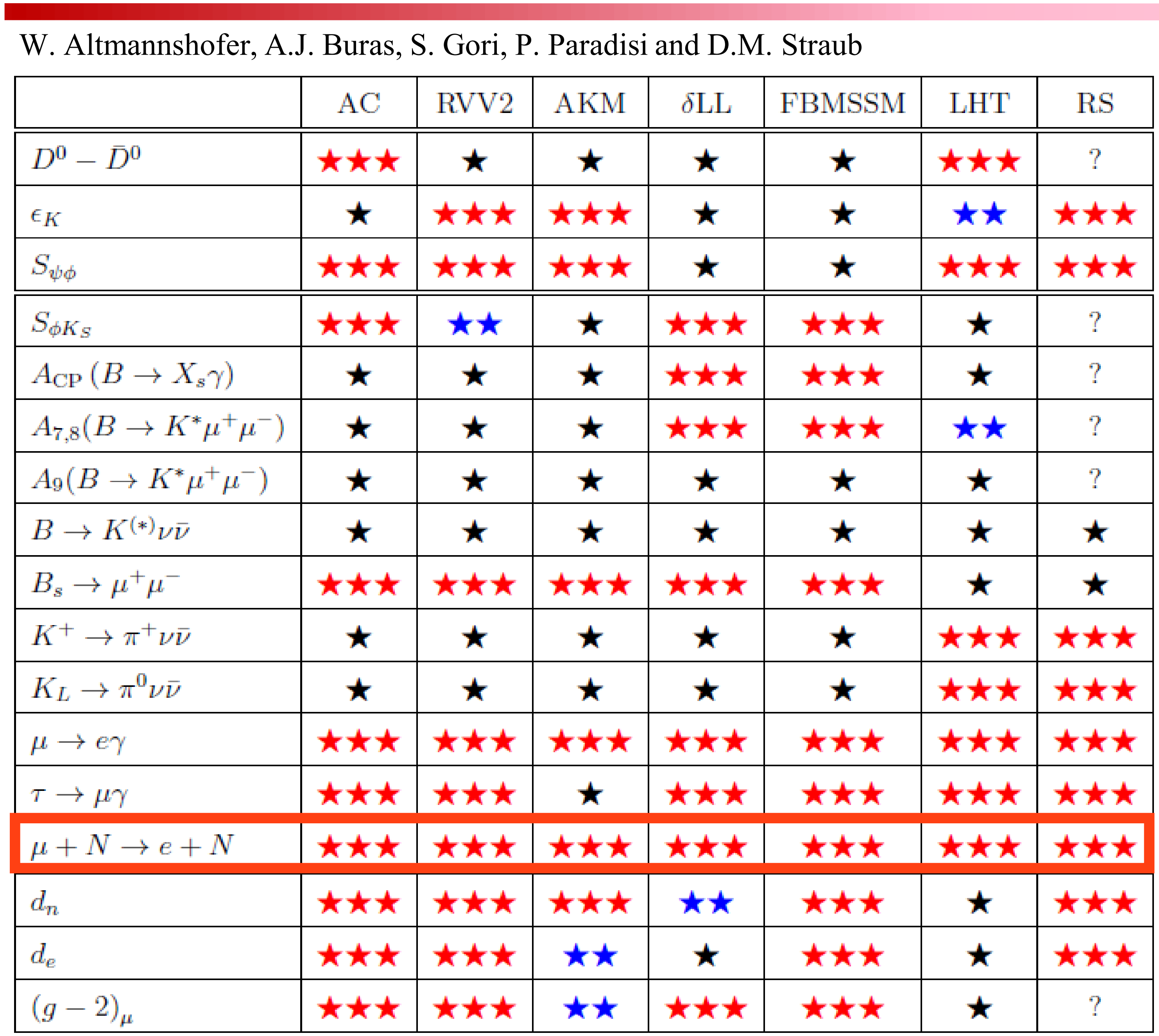
SUSY model



little Higgs model



“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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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

The pattern of measurement:

★★★ large effects

★★ visible but small effects

★ unobservable effects

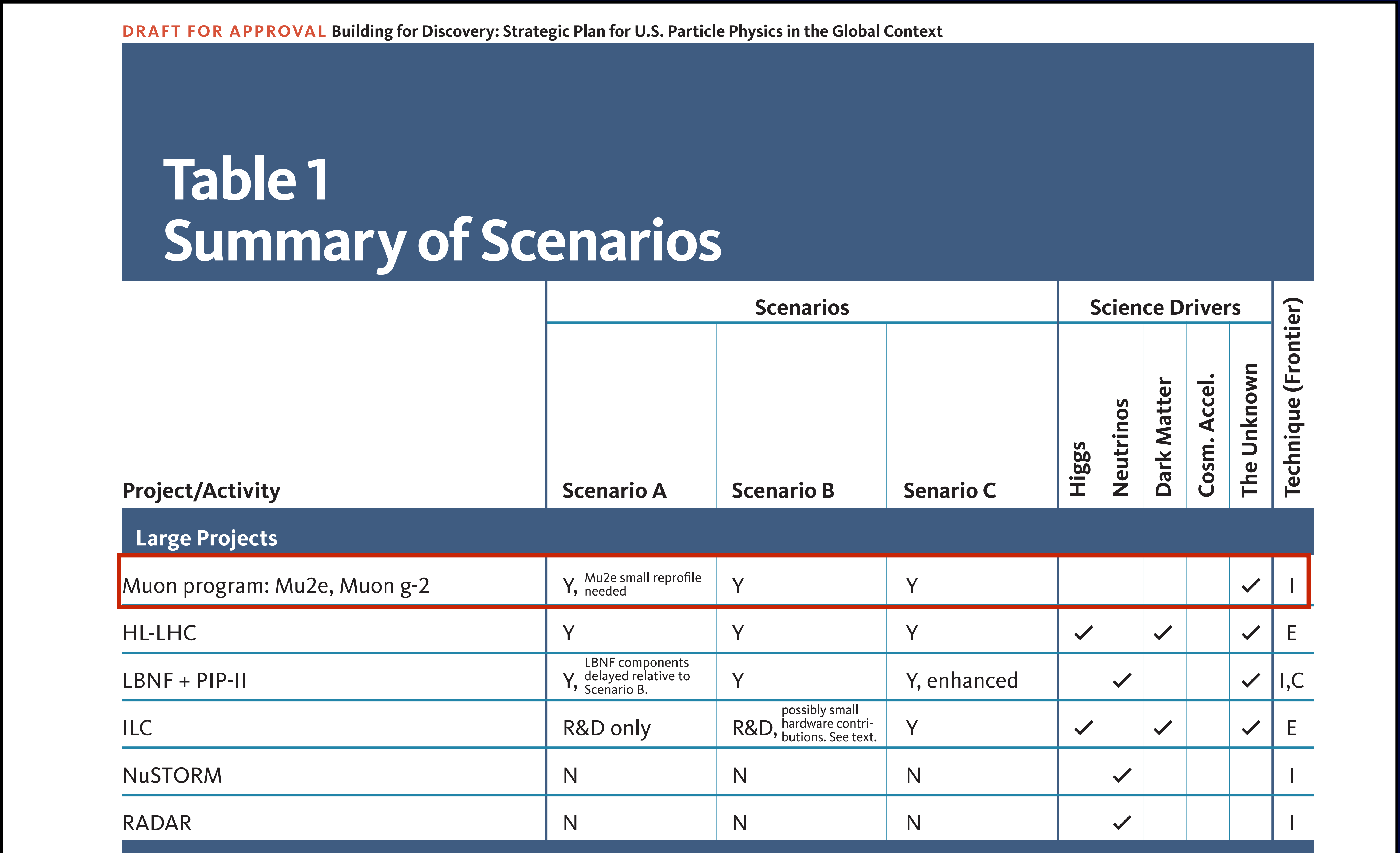
is characteristic,

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

P5 at the US



DRAFT FOR APPROVAL **Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context**

Table 1
Summary of Scenarios

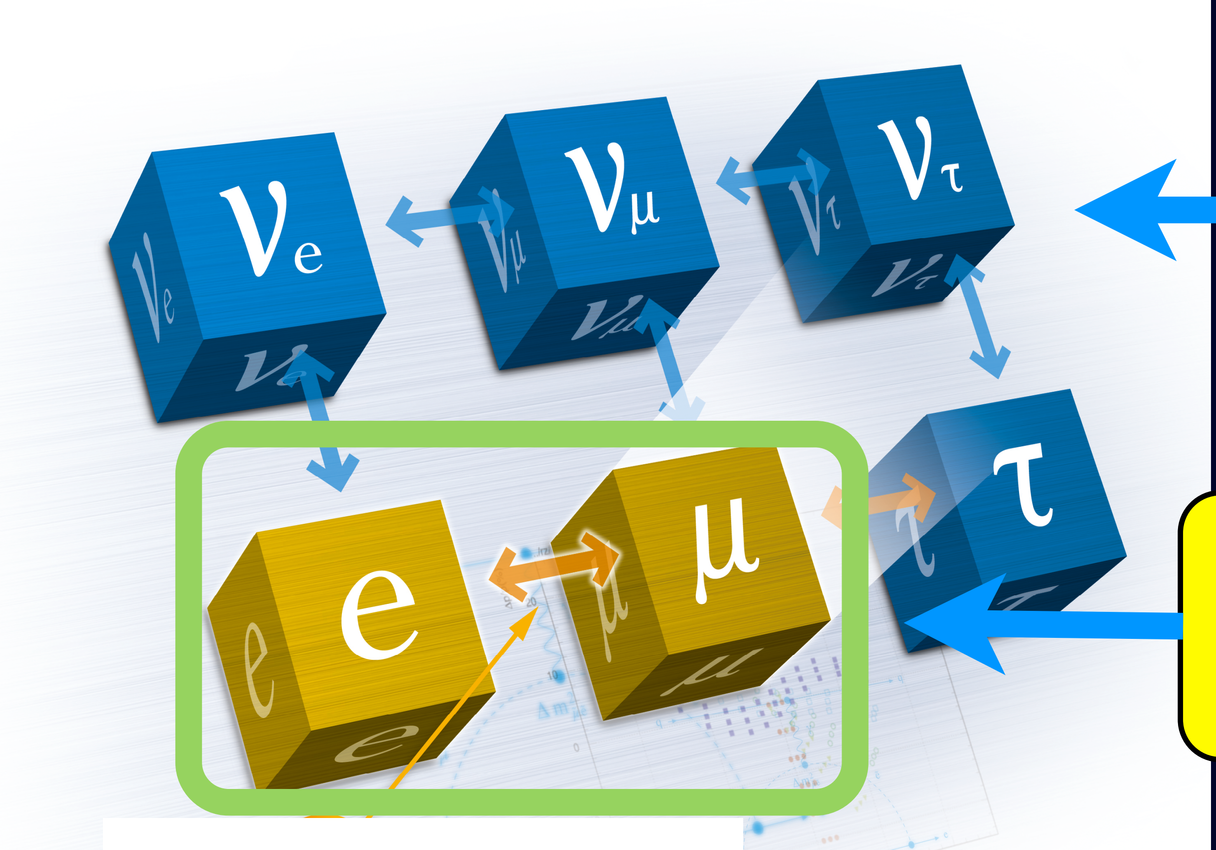
	Scenarios			Science Drivers					
Project/Activity	**Scenario A**	**Scenario B**	**Senario C**	**Higgs**	**Neutrinos**	**Dark Matter**	**Cosm. Accel.**	**The Unknown**	**Technique (Frontier)**
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

Flavour Violation on Quarks, Neutrinos, and Charged Leptons

Quarks

Quark transition observed

Lepton



Neutrino transition observed

Charged lepton transition not observed.

Charged Lepton Flavor Violation (CLFV)

CLFV Experiments

CLFV History

Osaka University

First CLFV search

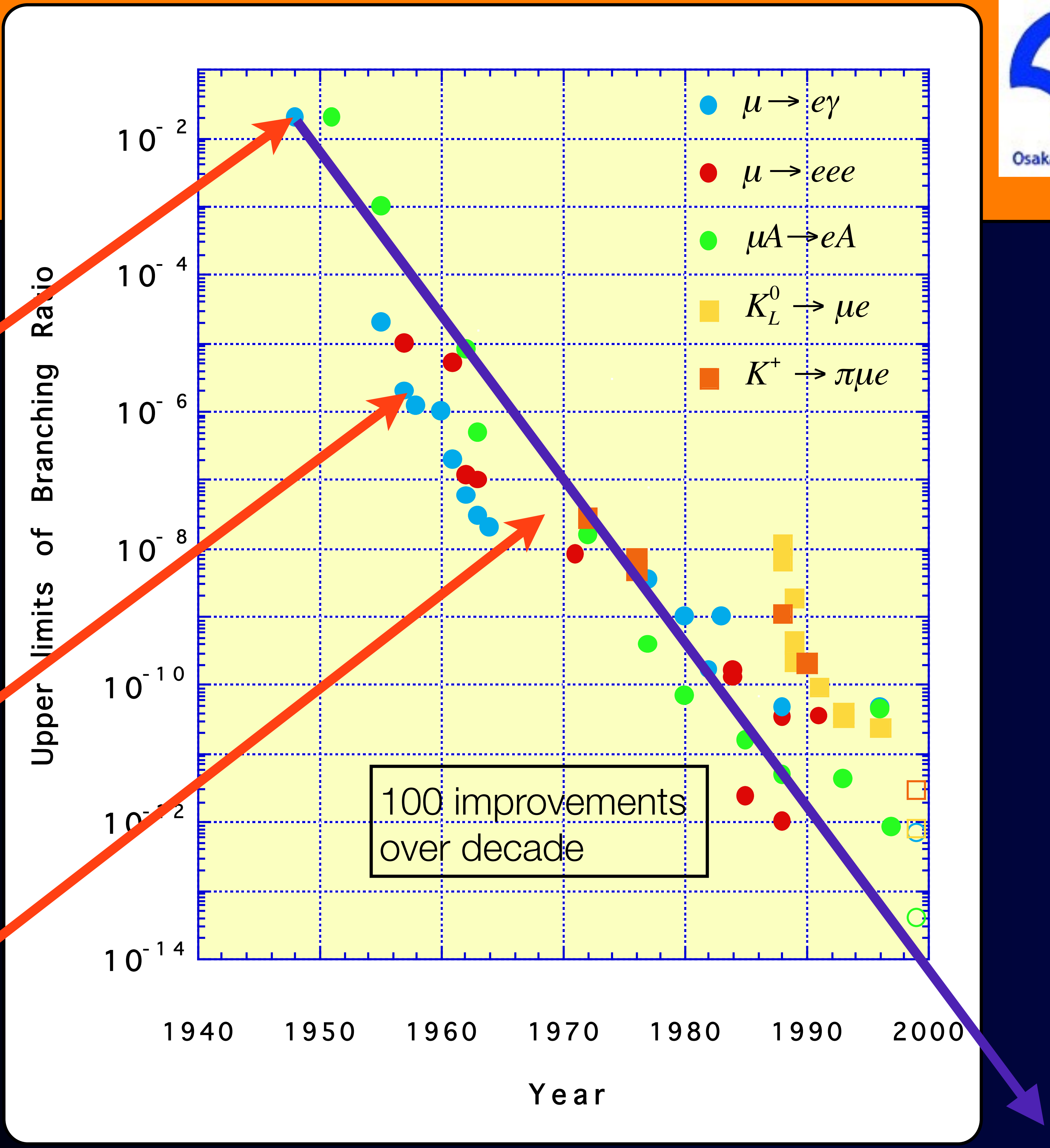
Pontecorvo in 1947

Muon Michel decay (1948)

Accelerators producing muons

Feinberg's μ→eγ crisis (1955)

Meson Factory Era



100 improvements over decade

Present Limits and Expectations in Future

process	present limit	future	
$\mu \rightarrow e\gamma$	$<5.7 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \rightarrow eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \rightarrow eN$ (in Al)	none	$<10^{-16}$	Mu2e / COMET
$\mu N \rightarrow eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-18}$	PRISM
$\tau \rightarrow e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \rightarrow eee$	$<3.6 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \rightarrow \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \rightarrow \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB/LHCb

List of cLFV Processes with Muons

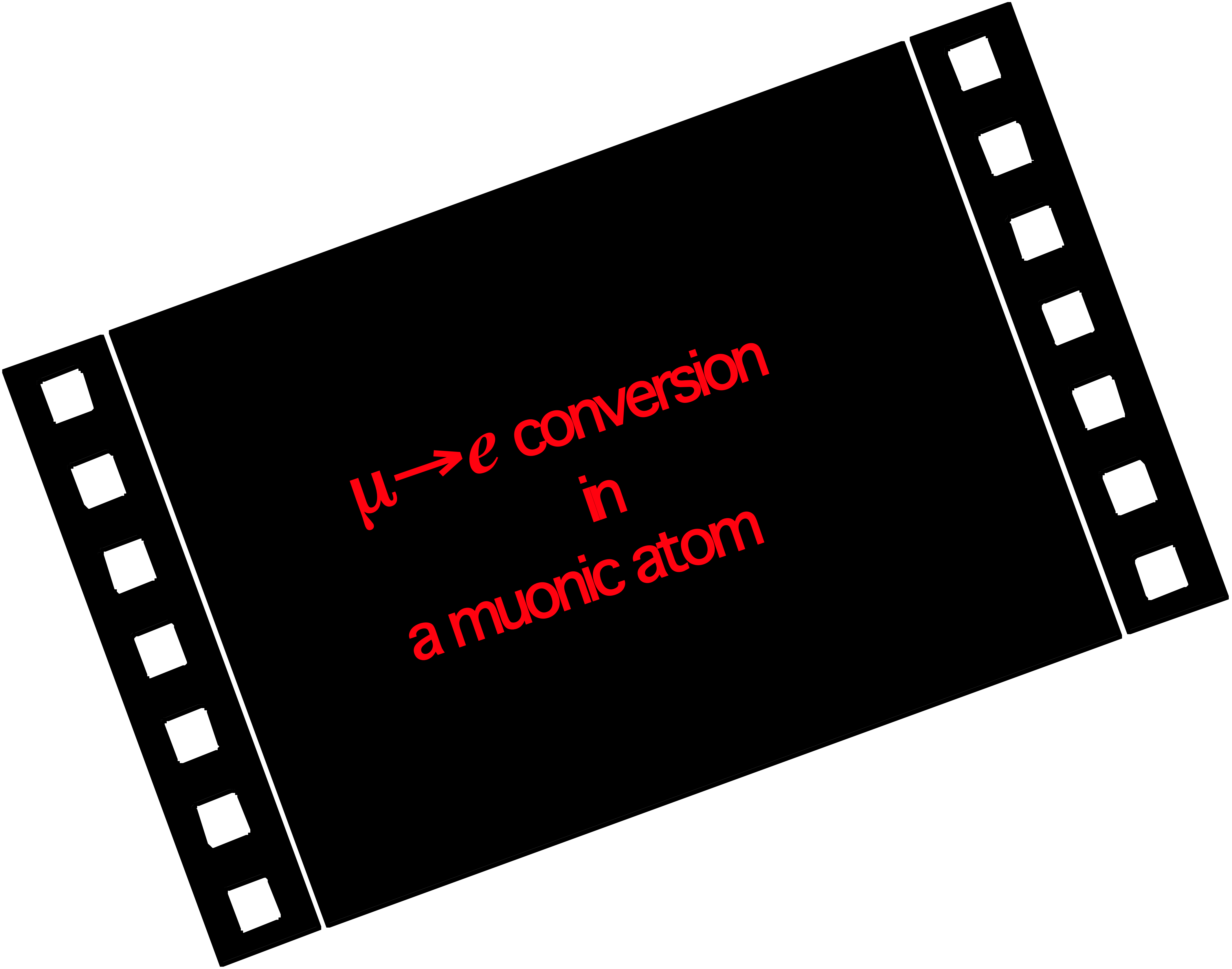
ΔL=1

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

← this talk

ΔL=2

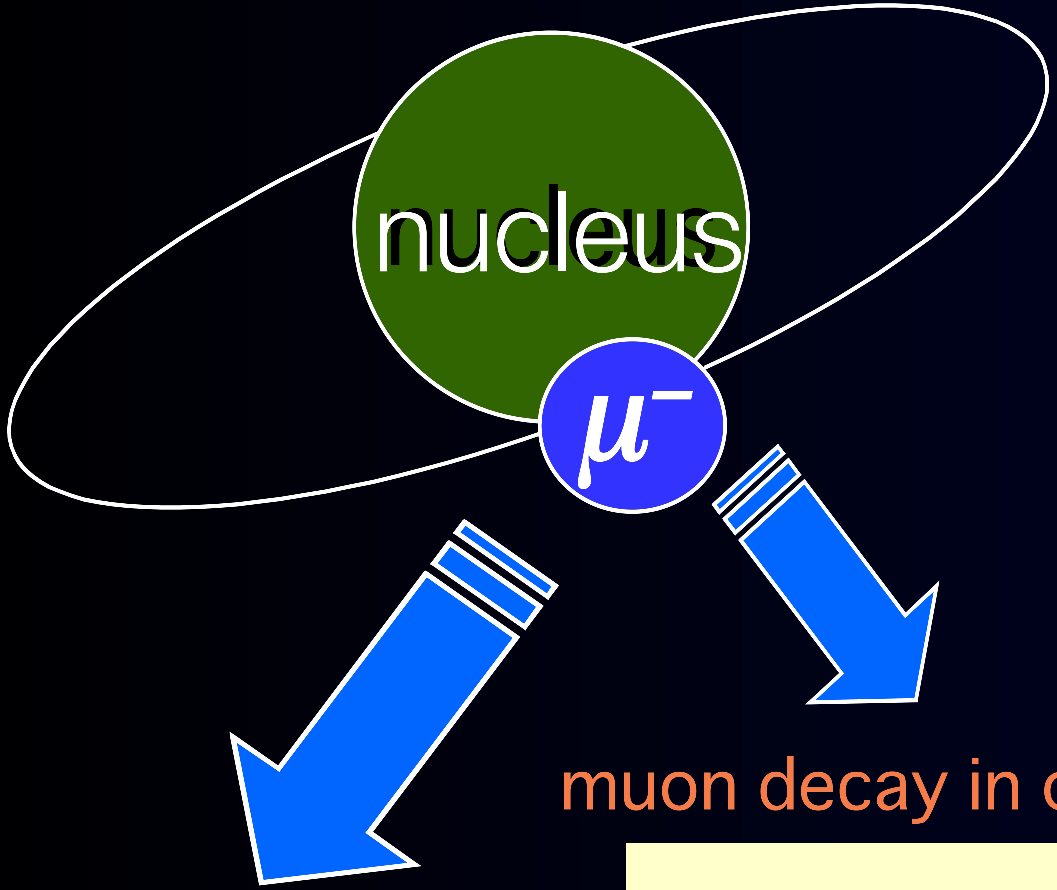
- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- + N(A,Z) \rightarrow \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+\mu^+\mu^- + N(A,Z-1)$



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

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture

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

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

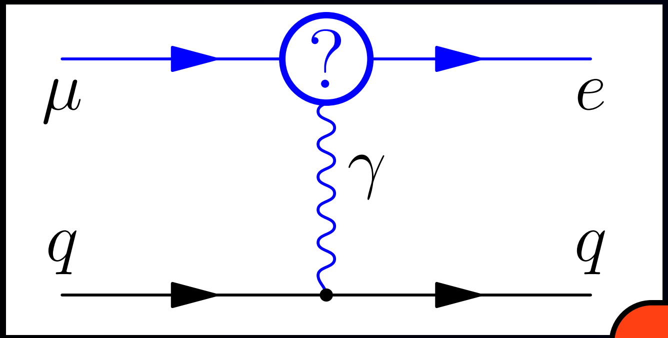
Physics Sensitivity: μ→eγ vs. μ-e conversion

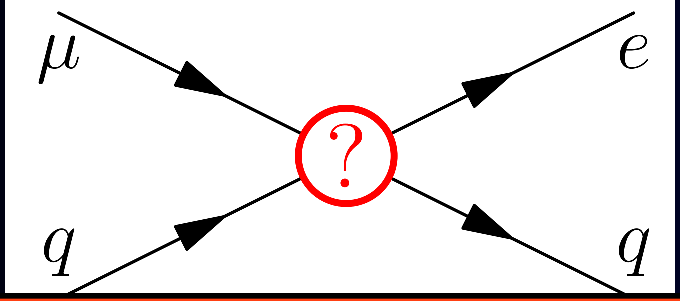
constructive

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

Photonic (dipole) interaction

Contact interaction





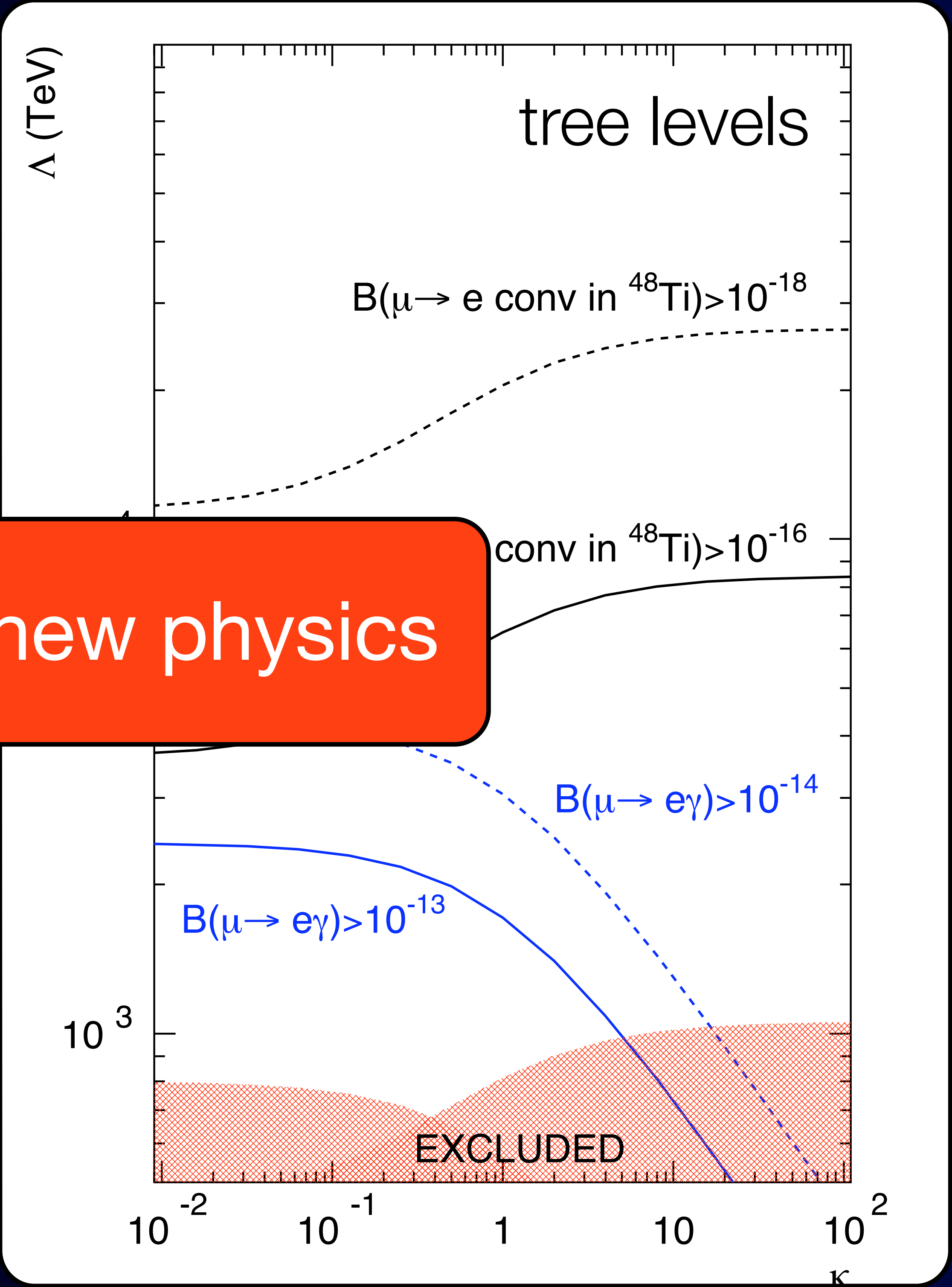
more sensitive to new physics

if photonic contri

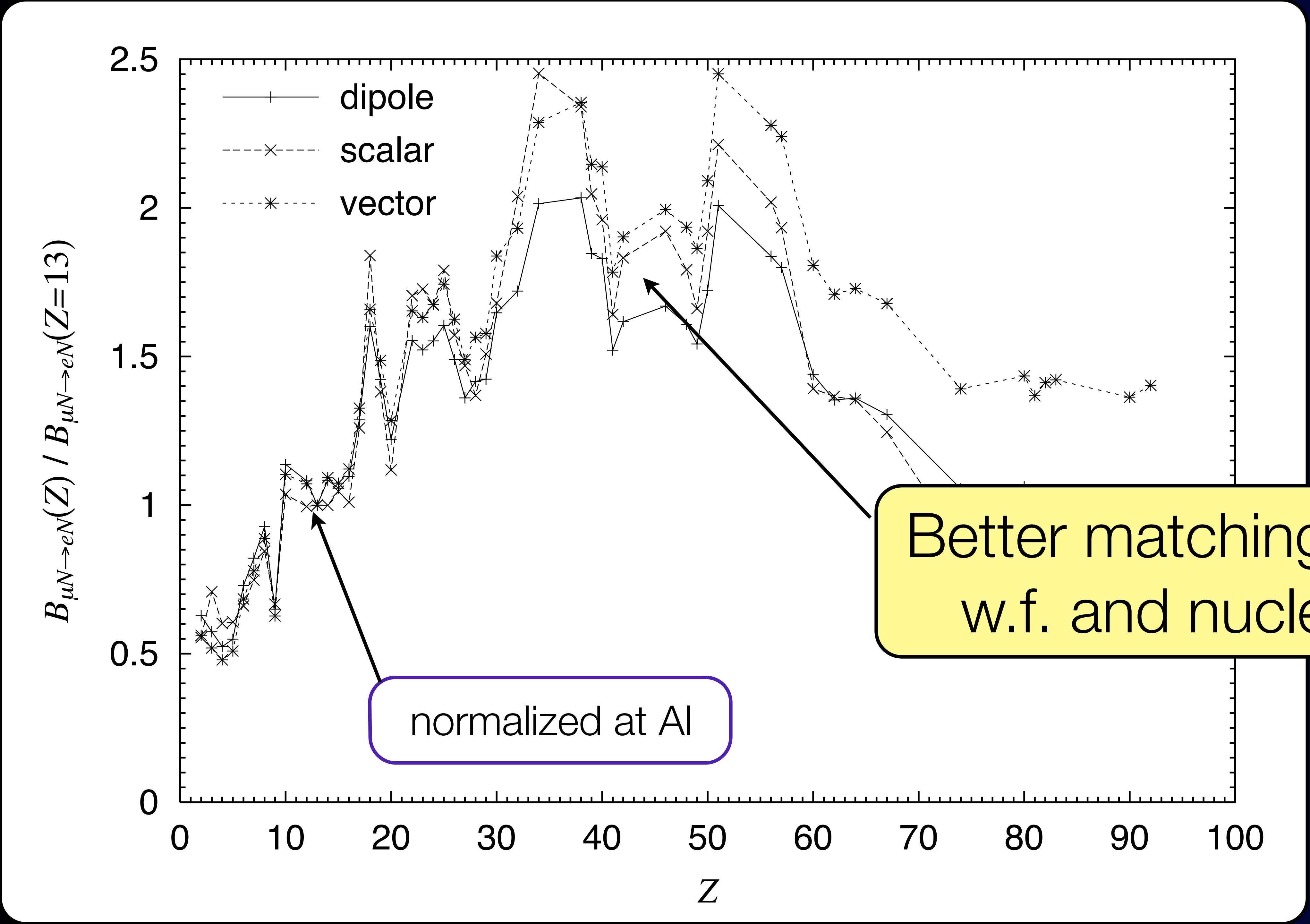
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z)$$

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

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



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



Better matching of muon w.f. and nucleus size

normalized at Al

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

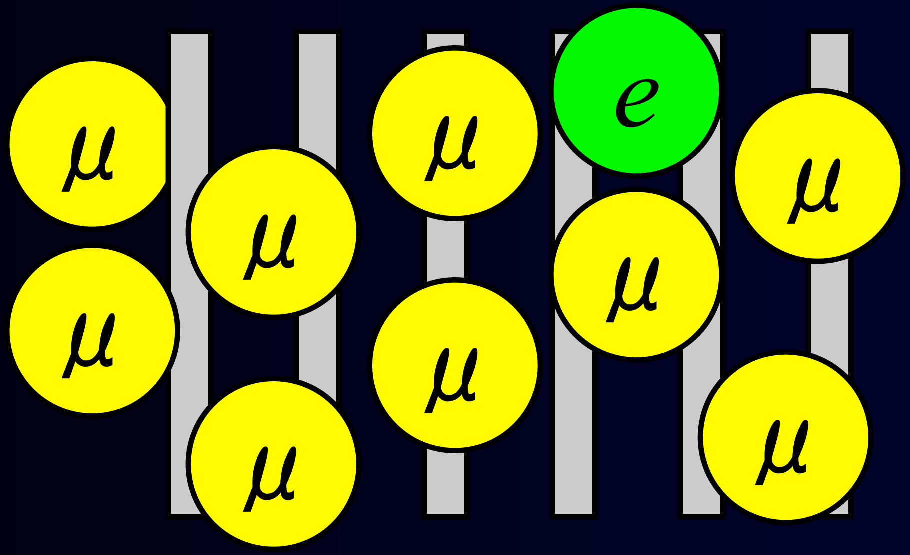
Experimental Comparison between μ→eγ and μ-e Conversion

	background	challenge	beam intensity
• μ→eγ	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

- μ→eγ :
  - Accidental background is given by (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.

μ-e conversion might be a next step.

Principle of Measurement of Measure μ-e Conversion / Meditation.....



muon stopping target

A total number of muons is the key for success.

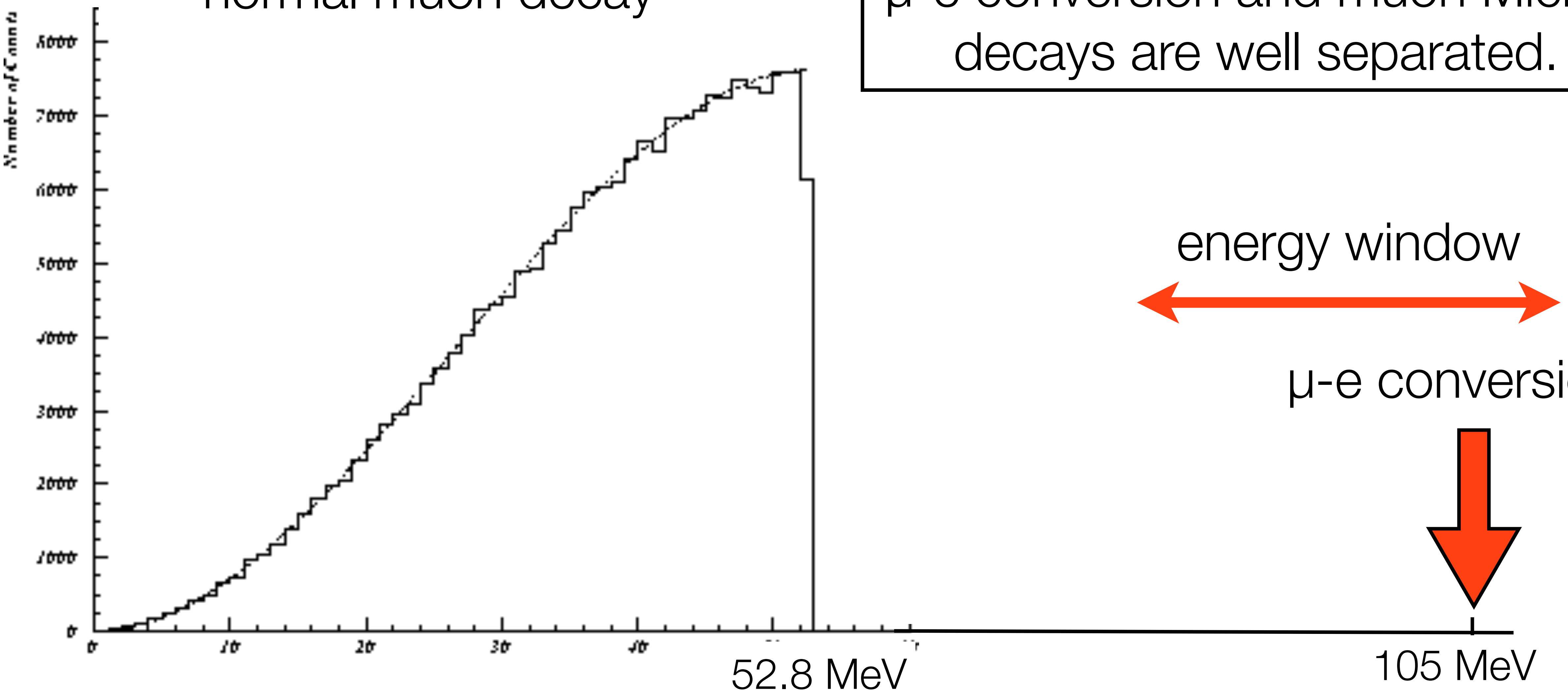
COMET：10^{18} **muons** (past exp. 10^{14} muons)

Backgrounds for Search for μ-e conversion

intrinsic physics backgrounds	Muon decay in orbit (DIO) Radiative muon decay neutrons from muon nuclear capture Protons from muon nuclear capture Antiproton induced background
beam-related backgrounds	Radiative pion capture Beam electrons Muon decay in flights Neutron background
cosmic-ray and other backgrounds	Cosmic-ray induced background False tracking

μ-e Conversion Signal and Normal Muon Decays

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



normal muon decay

energy window

μ-e conversion

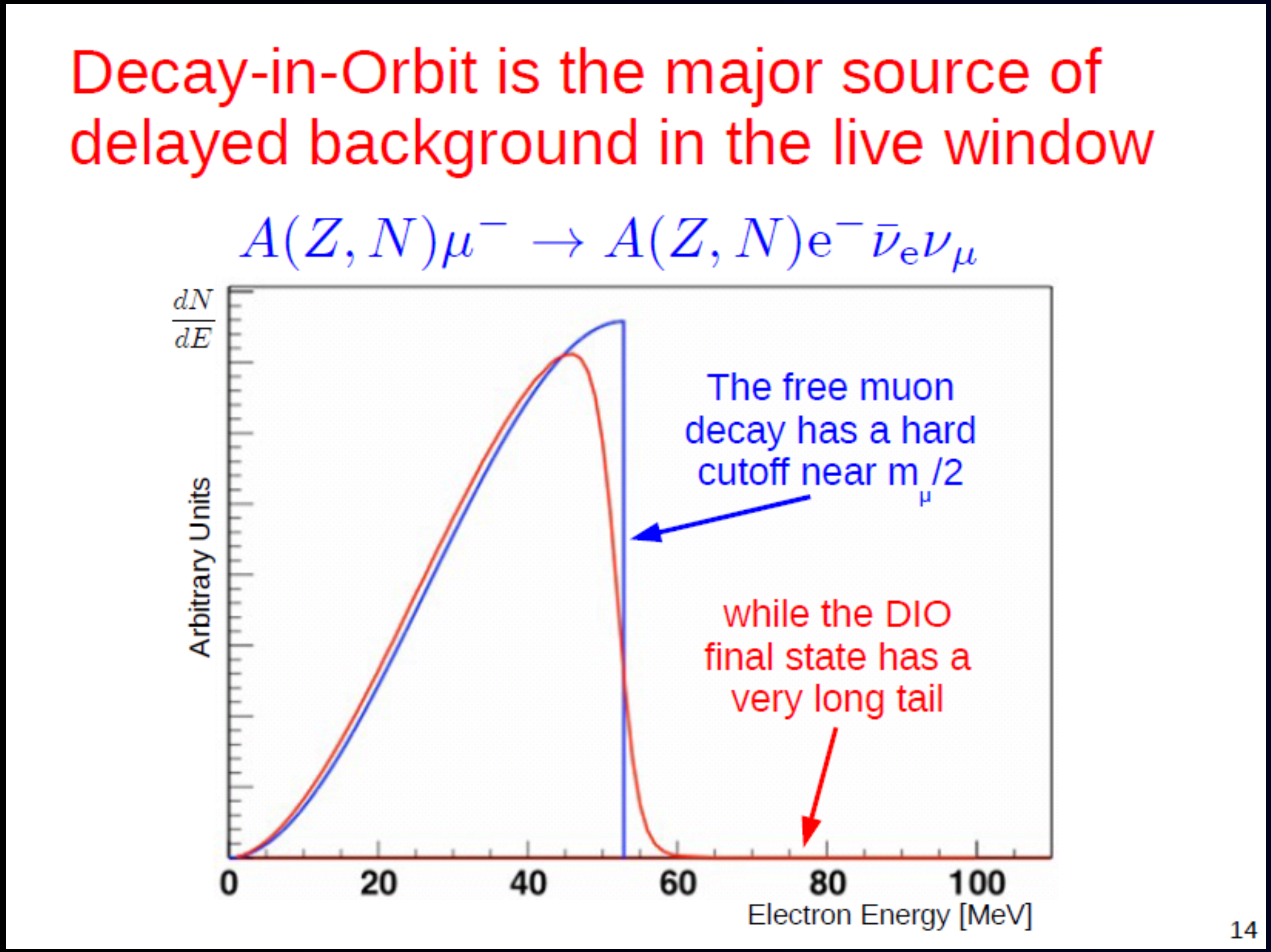
52.8 MeV

105 MeV

electron momentum spectrum

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

Intrinsic Physics Background:
Muon Decay in Orbit (DIO)

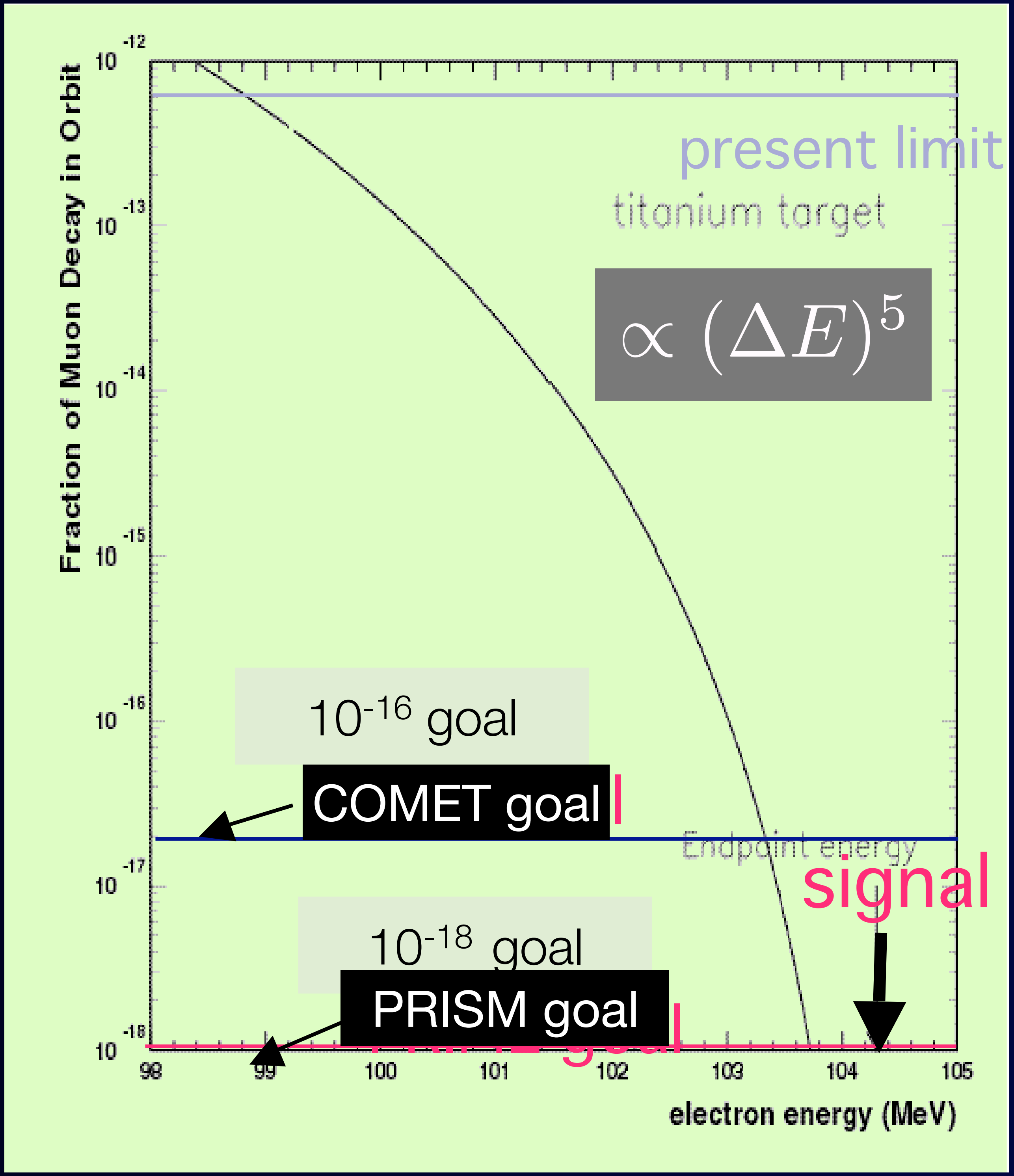


Decay-in-Orbit is the major source of delayed background in the live window

$$A(Z,N)\mu^- \to A(Z,N)e^-\bar{\nu}_e\nu_\mu$$

The free muon decay has a hard cutoff near $m_\mu/2$

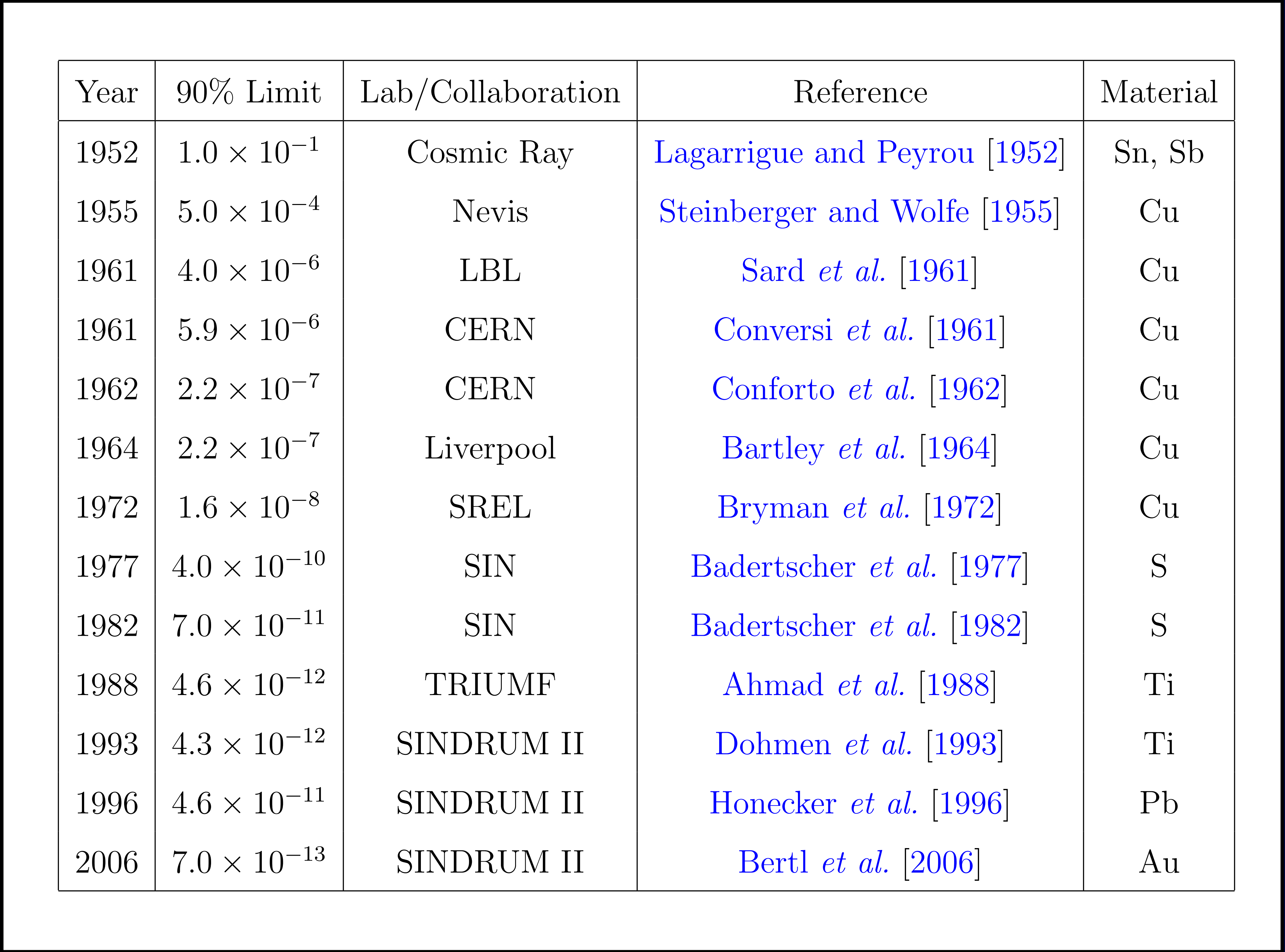
while the DIO final state has a very long tail



Good momentum resolution is needed.

Experiments

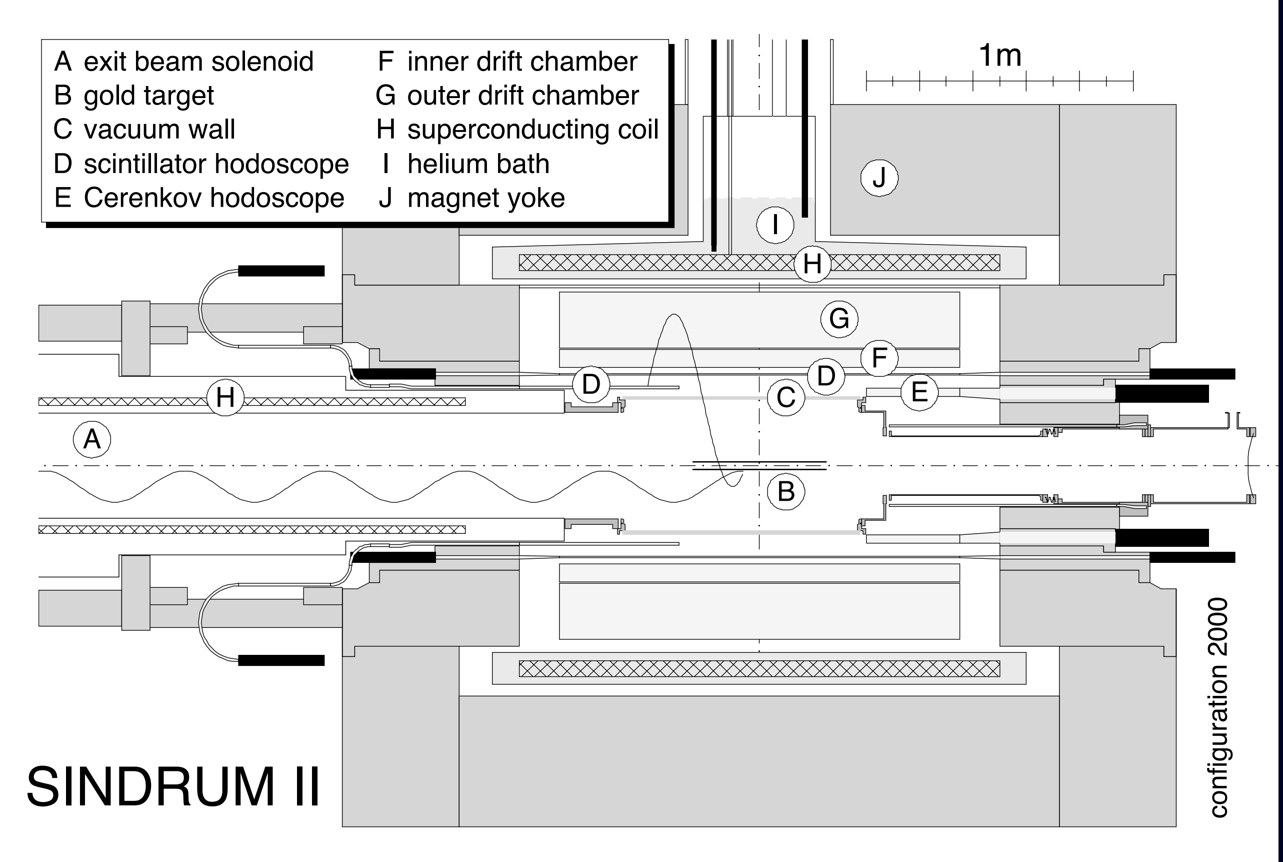
History of Search for μ-e conversion



Year	90% Limit	Lab/Collaboration	Reference	Material
1952	1.0×10^{-1}	Cosmic Ray	Lagarrigue and Peyrou [1952]	Sn, Sb
1955	5.0×10^{-4}	Nevis	Steinberger and Wolfe [1955]	Cu
1961	4.0×10^{-6}	LBL	Sard *et al.* [1961]	Cu
1961	5.9×10^{-6}	CERN	Conversi *et al.* [1961]	Cu
1962	2.2×10^{-7}	CERN	Conforto *et al.* [1962]	Cu
1964	2.2×10^{-7}	Liverpool	Bartley *et al.* [1964]	Cu
1972	1.6×10^{-8}	SREL	Bryman *et al.* [1972]	Cu
1977	4.0×10^{-10}	SIN	Badertscher *et al.* [1977]	S
1982	7.0×10^{-11}	SIN	Badertscher *et al.* [1982]	S
1988	4.6×10^{-12}	TRIUMF	Ahmad *et al.* [1988]	Ti
1993	4.3×10^{-12}	SINDRUM II	Dohmen *et al.* [1993]	Ti
1996	4.6×10^{-11}	SINDRUM II	Honecker *et al.* [1996]	Pb
2006	7.0×10^{-13}	SINDRUM II	Bertl *et al.* [2006]	Au

Previous Measurements

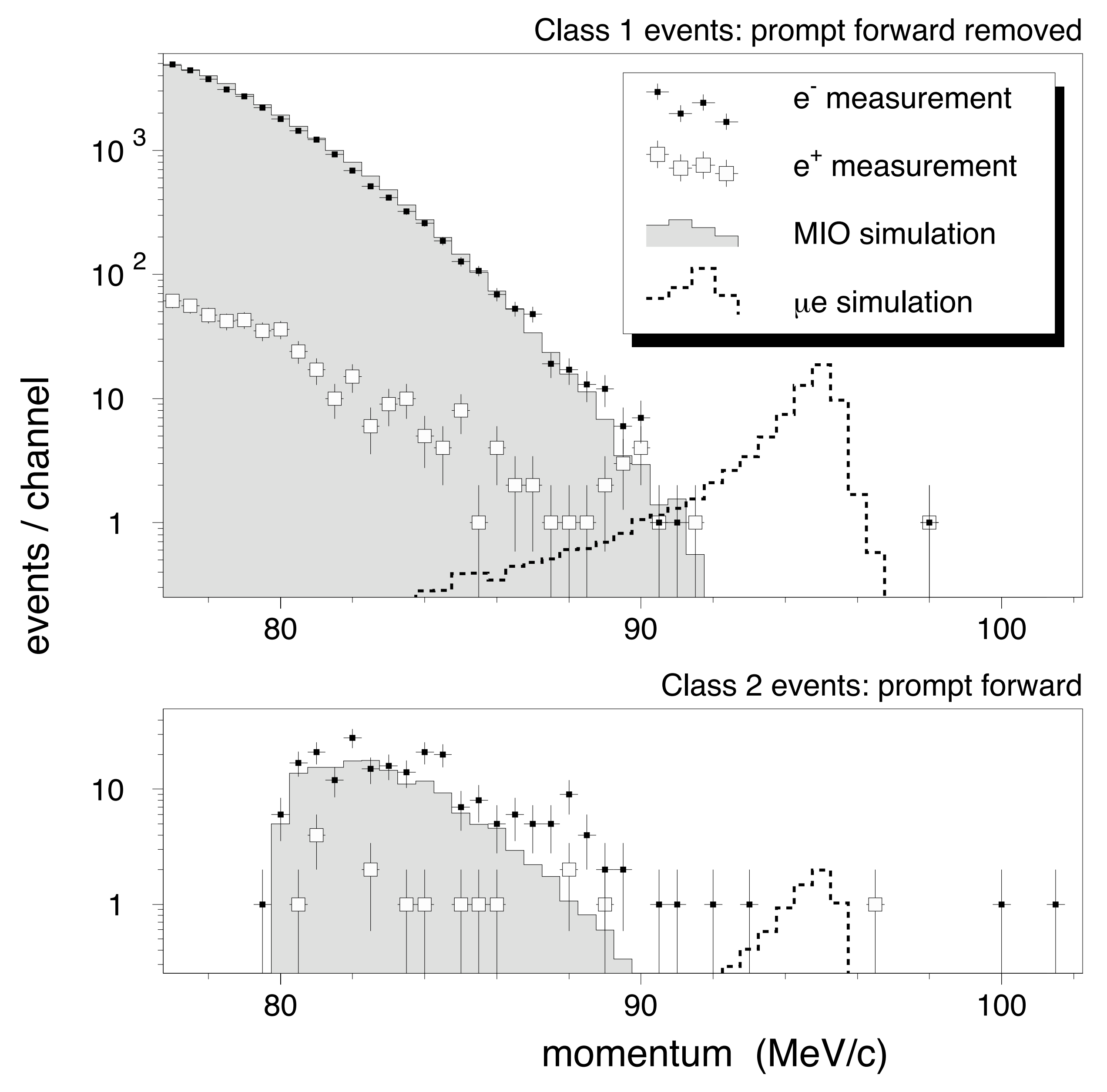
SINDRUM-II (PSI)



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)

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



In order to make a new-generation experiment to search for μ-e conversion …

Improvements for Signal Sensitivity

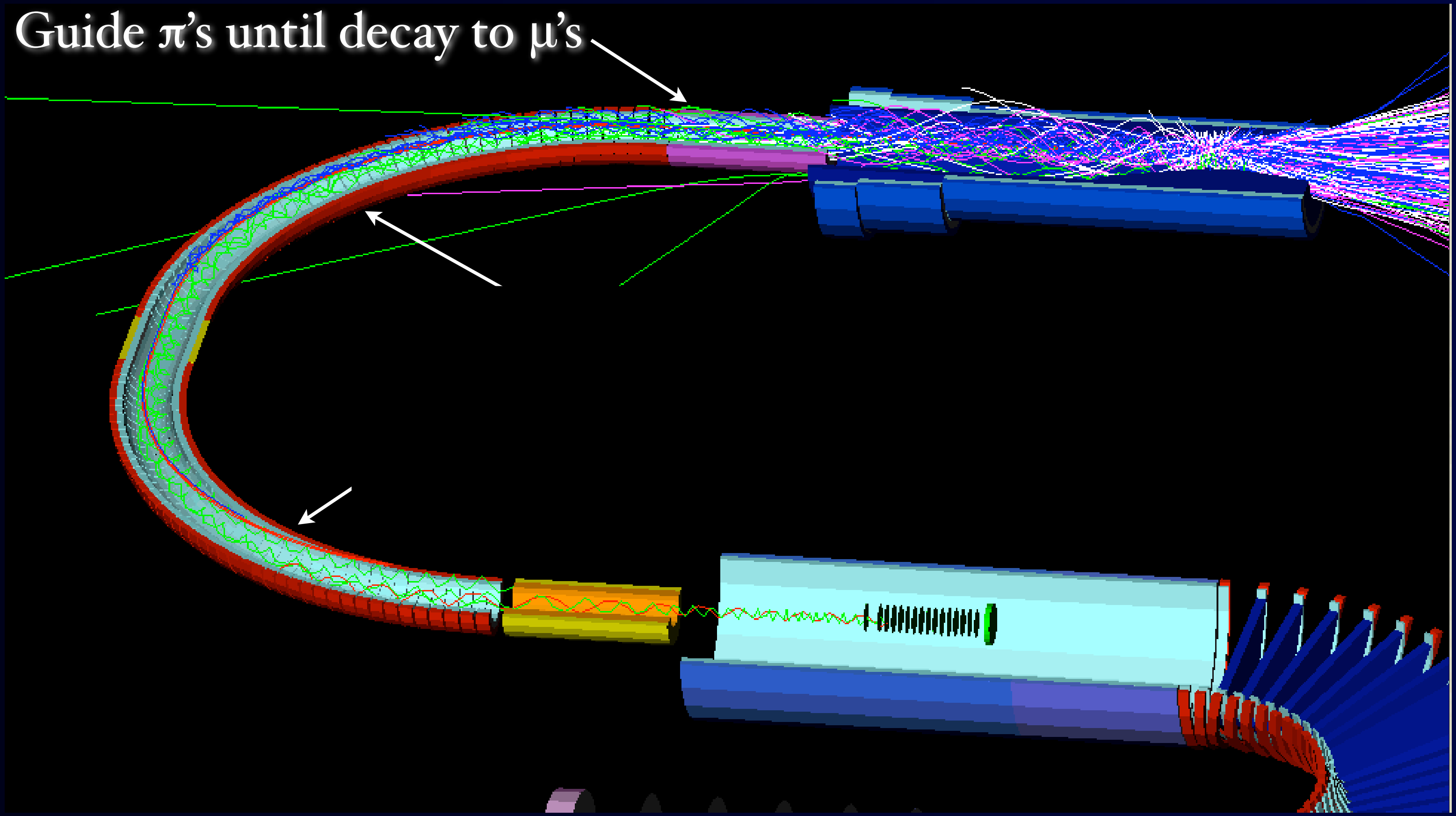
To achieve a single sensitivity of 10^{-17}, we need

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)



Guide π's until decay to μ's

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

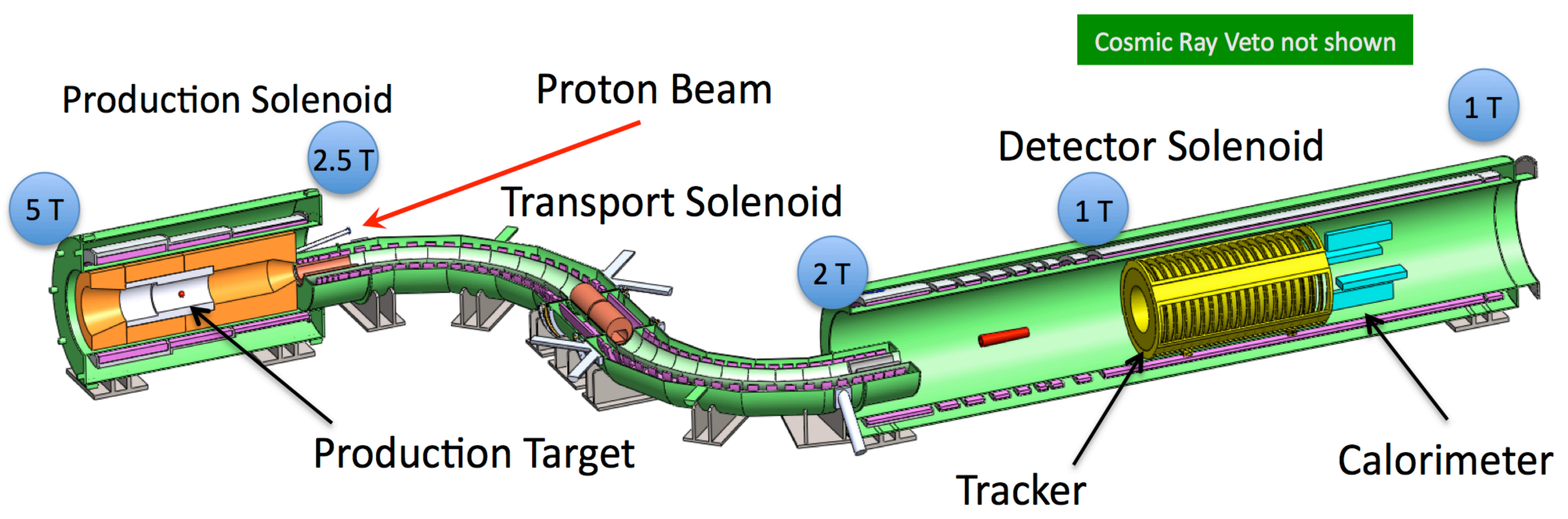
improve electron energy resolution

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

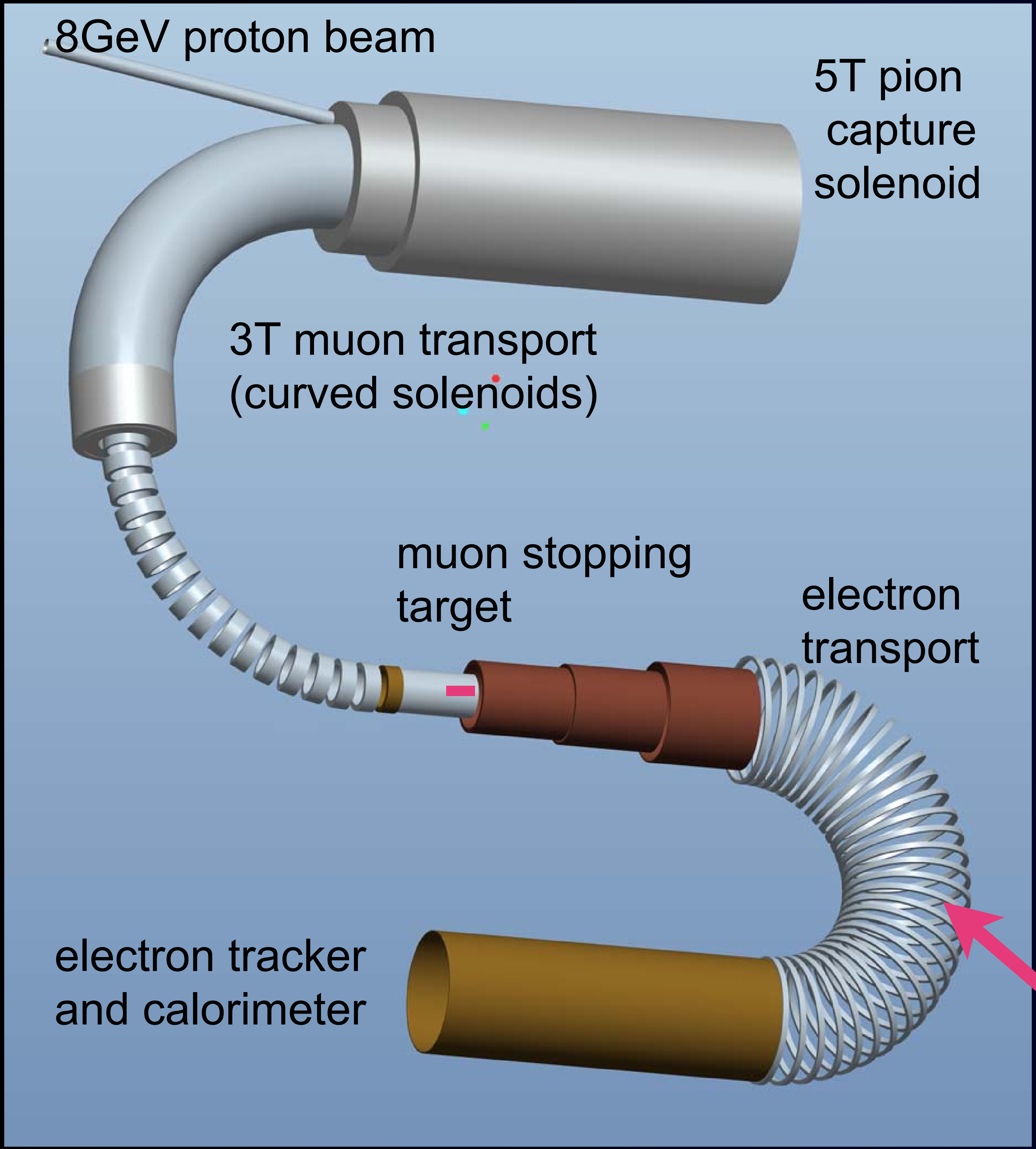


$$B(\mu^- + Al \rightarrow e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \quad (90\%\text{C.L.})$$

- Reincarnation of MECO at BNL.
- Antiproton buncher ring is used to produce a pulsed proton beam.
- Approved in 2009, CD0 in 2009, and CD1 in 2011. CD2 in 2015?
- Data taking starts in about 2019.

COMET

What is COMET (E21) at J-PARC



Experimental Goal of COMET

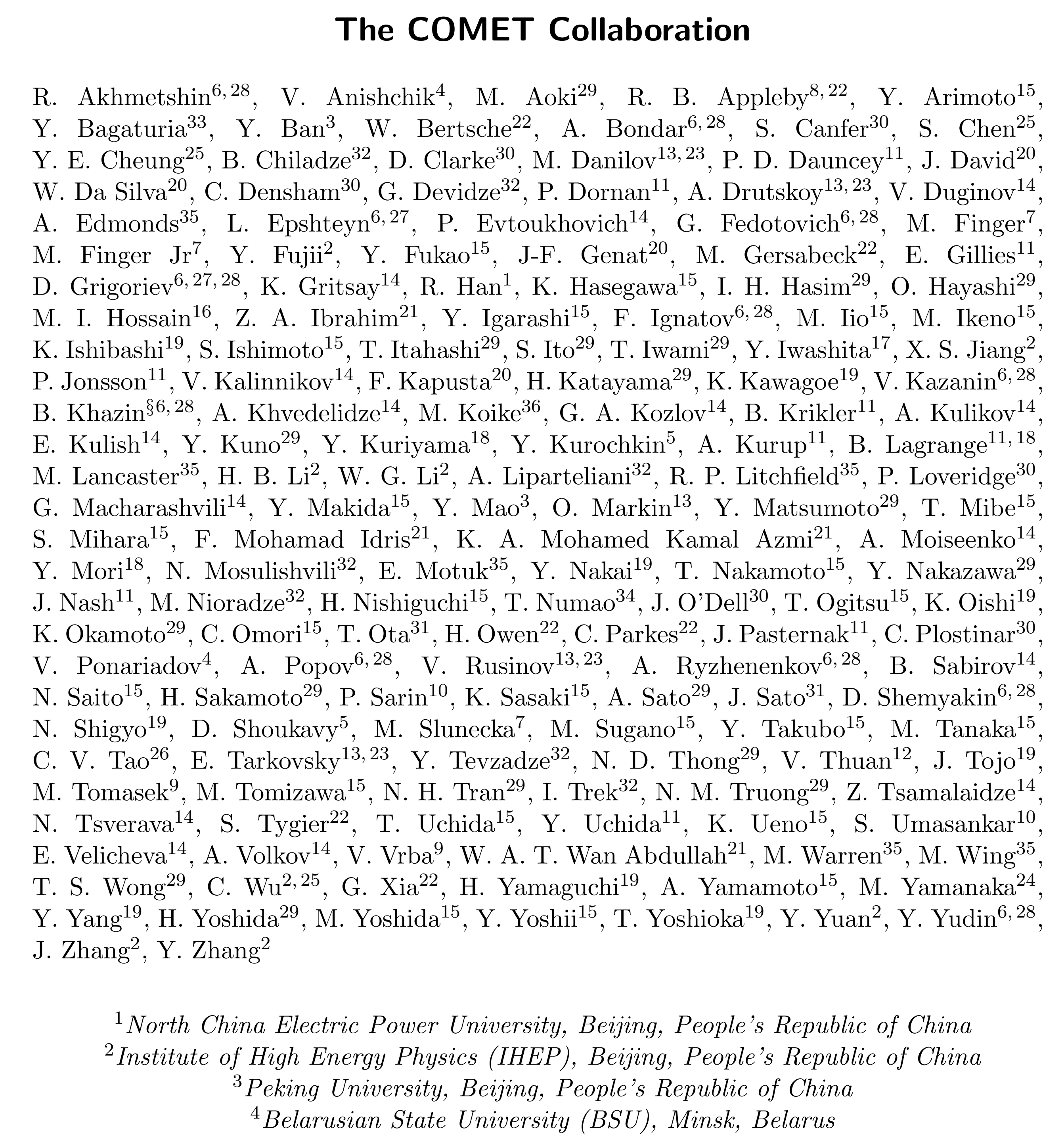
$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- $2x10^7$ 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

179 collaborators
32 institutes, 13 countries



The COMET Collaboration

R. Akhmetshin[6,28], V. Anishchik[4], M. Aoki[29], R. B. Appleby[8,22], Y. Arimoto[15], Y. Bagaturia[33], Y. Ban[3], W. Bertsche[22], A. Bondar[6,28], S. Canfer[30], S. Chen[25], Y. E. Cheung[25], B. Chiladze[32], D. Clarke[30], M. Danilov[13,23], P. D. Dauncey[11], J. David[20], W. Da Silva[20], C. Densham[30], G. Devidze[32], P. Dornan[11], A. Drutskoy[13,23], V. Duginov[14], A. Edmonds[35], L. Epshteyn[6,27], P. Evtoukhovich[14], G. Fedotovich[6,28], M. Finger[7], M. Finger Jr[7], Y. Fujii[2], Y. Fukao[15], J-F. Genat[20], M. Gersabeck[22], E. Gillies[11], D. Grigoriev[6,27,28], K. Gritsay[14], R. Han[1], K. Hasegawa[15], I. H. Hasim[29], O. Hayashi[29], M. I. Hossain[16], Z. A. Ibrahim[21], Y. Igarashi[15], F. Ignatov[6,28], M. Iio[15], M. Ikeno[15], K. Ishibashi[19], S. Ishimoto[15], T. Itahashi[29], S. Ito[29], T. Iwami[29], Y. Iwashita[17], X. S. Jiang[2], P. Jonsson[11], V. Kalinnikov[14], F. Kapusta[20], H. Katayama[29], K. Kawagoe[19], V. Kazanin[6,28], B. Khazin[§6,28], A. Khvedelidze[14], M. Koike[36], G. A. Kozlov[14], B. Krikler[11], A. Kulikov[14], E. Kulish[14], Y. Kuno[29], Y. Kuriyama[18], Y. Kurochkin[5], A. Kurup[11], B. Lagrange[11,18], M. Lancaster[35], H. B. Li[2], W. G. Li[2], A. Liparteliani[32], R. P. Litchfield[35], P. Loveridge[30], G. Macharashvili[14], Y. Makida[15], Y. Mao[3], O. Markin[13], Y. Matsumoto[29], T. Mibe[15], S. Mihara[15], F. Mohamad Idris[21], K. A. Mohamed Kamal Azmi[21], A. Moiseenko[14], Y. Mori[18], N. Mosulishvili[32], E. Motuk[35], Y. Nakai[19], T. Nakamoto[15], Y. Nakazawa[29], J. Nash[11], M. Nioradze[32], H. Nishiguchi[15], T. Numao[34], J. O'Dell[30], T. Ogitsu[15], K. Oishi[19], K. Okamoto[29], C. Omori[15], T. Ota[31], H. Owen[22], C. Parkes[22], J. Pasternak[11], C. Plostinar[30], V. Ponariadov[4], A. Popov[6,28], V. Rusinov[13,23], A. Ryzhenenkov[6,28], B. Sabirov[14], N. Saito[15], H. Sakamoto[29], P. Sarin[10], K. Sasaki[15], A. Sato[29], J. Sato[31], D. Shemyakin[6,28], N. Shigyo[19], D. Shoukavy[5], M. Slunecka[7], M. Sugano[15], Y. Takubo[15], M. Tanaka[15], C. V. Tao[26], E. Tarkovsky[13,23], Y. Tevzadze[32], N. D. Thong[29], V. Thuan[12], J. Tojo[19], M. Tomasek[9], M. Tomizawa[15], N. H. Tran[29], I. Trek[32], N. M. Truong[29], Z. Tsamalaidze[14], N. Tsverava[14], S. Tygier[22], T. Uchida[15], Y. Uchida[11], K. Ueno[15], S. Umasankar[10], E. Velicheva[14], A. Volkov[14], V. Vrba[9], W. A. T. Wan Abdullah[21], M. Warren[35], M. Wing[35], T. S. Wong[29], C. Wu[2,25], G. Xia[22], H. Yamaguchi[19], A. Yamamoto[15], M. Yamanaka[24], Y. Yang[19], H. Yoshida[29], M. Yoshida[15], Y. Yoshii[15], T. Yoshioka[19], Y. Yuan[2], Y. Yudin[6,28], J. Zhang[2], Y. Zhang[2]

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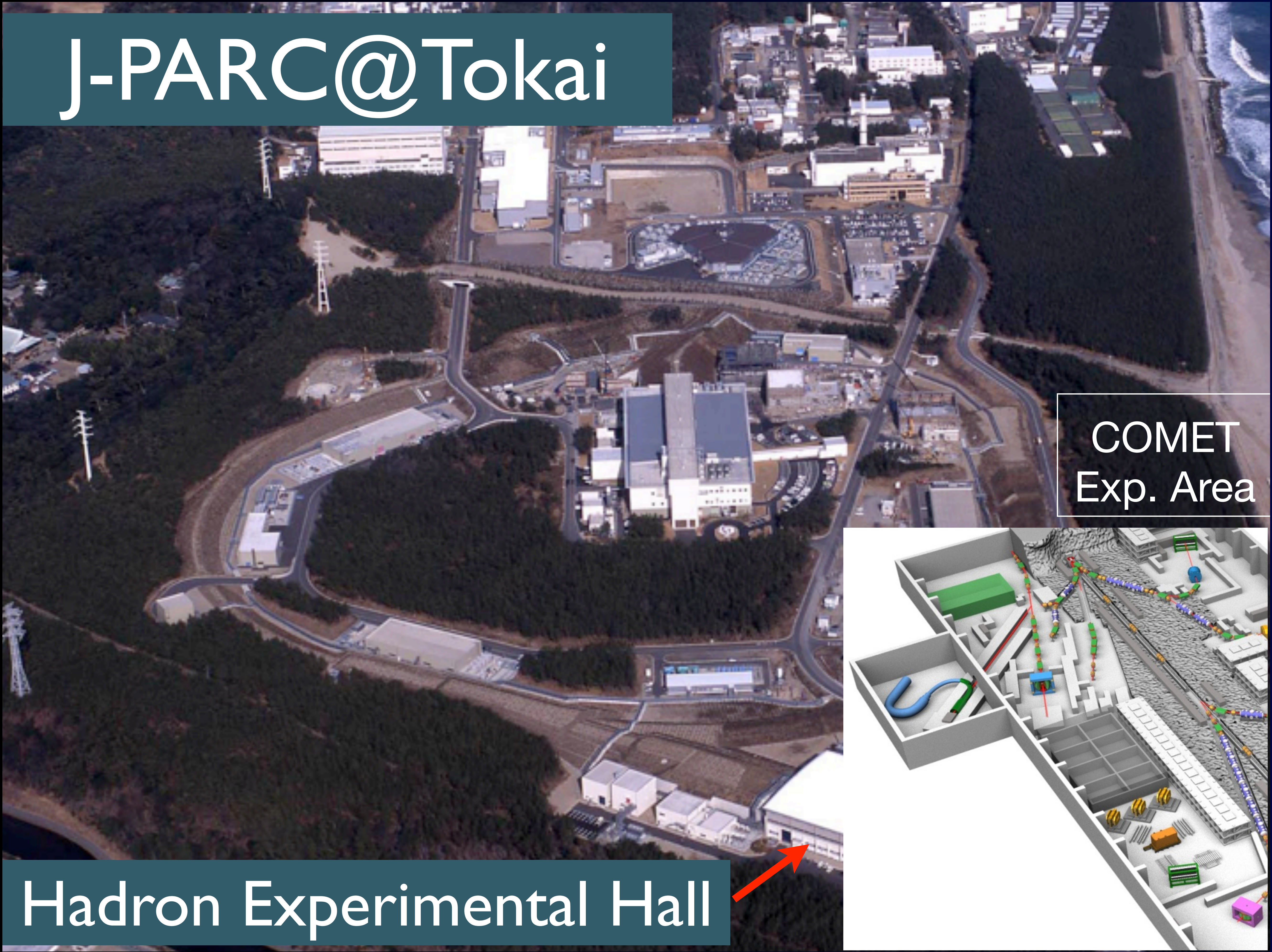
[5] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*

Proton Beam

J-PARC@Tokai

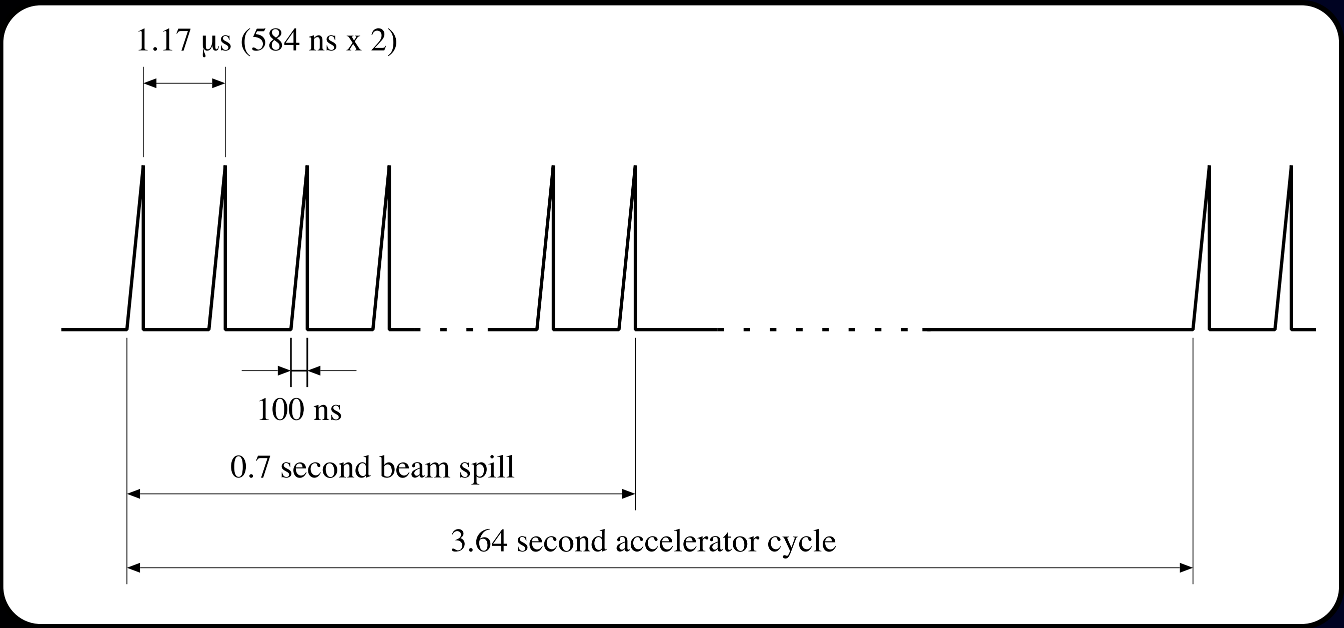


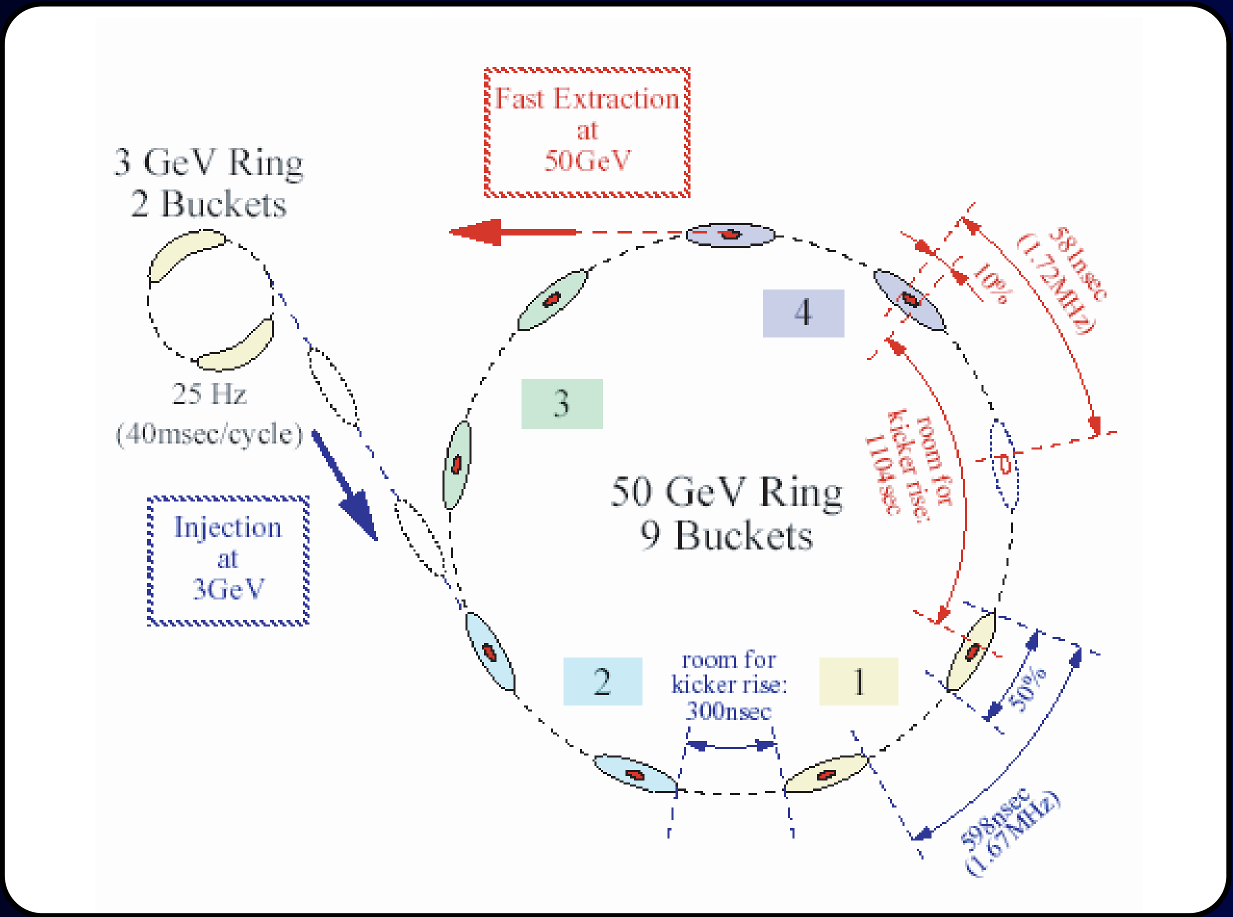
COMET
Exp. Area

Hadron Experimental Hall

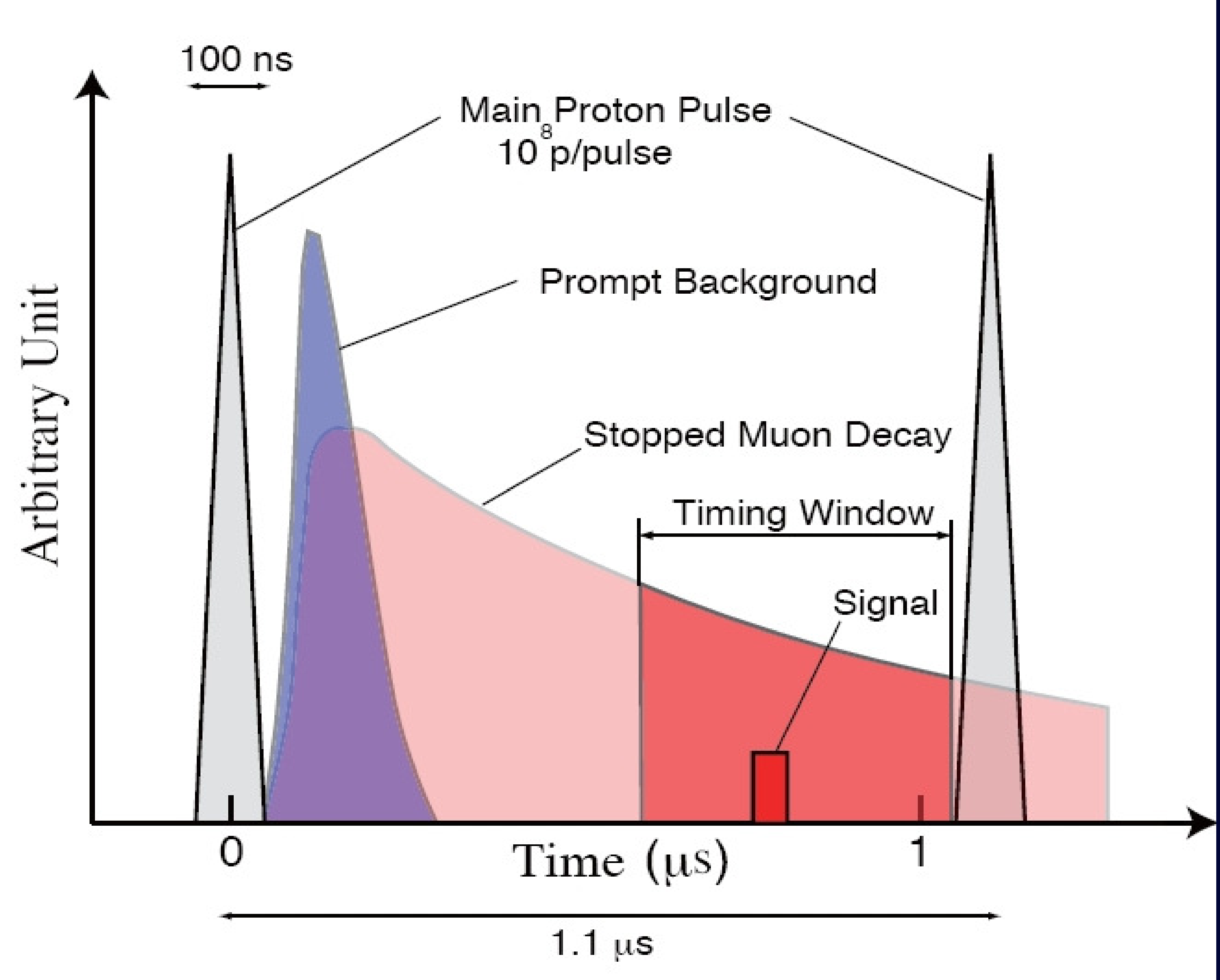
Proton Beam at J-PARC

- 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

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

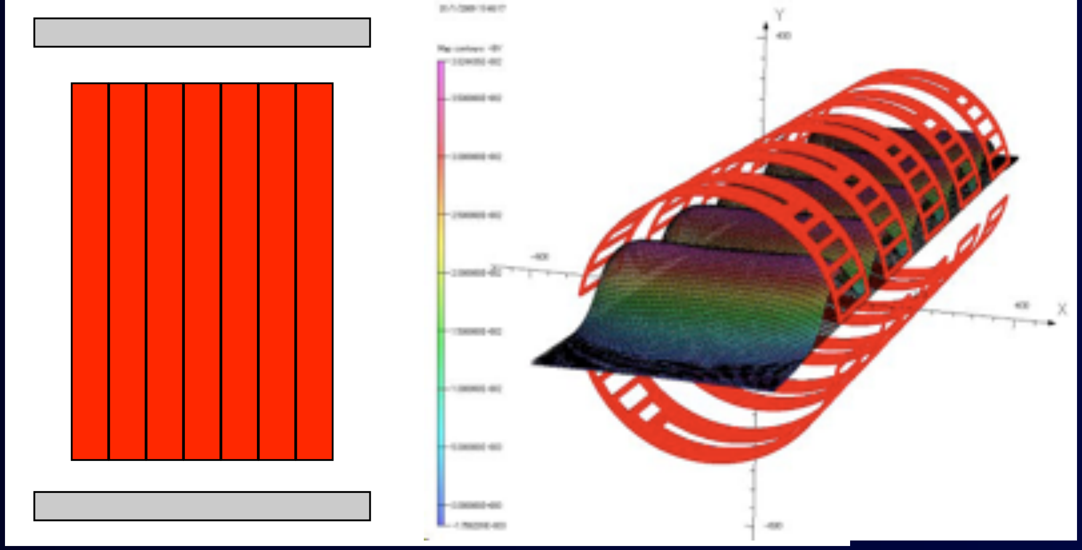
D : *drift distance*
B : *Solenoid field*
θ_{bend} : *Bending angle of the solenoid channel*
p : *Momentum of the particle*
q : *Charge of the particle*
θ : *atan*(P_T/P_L)

- This can be used for charge and momentum selection.

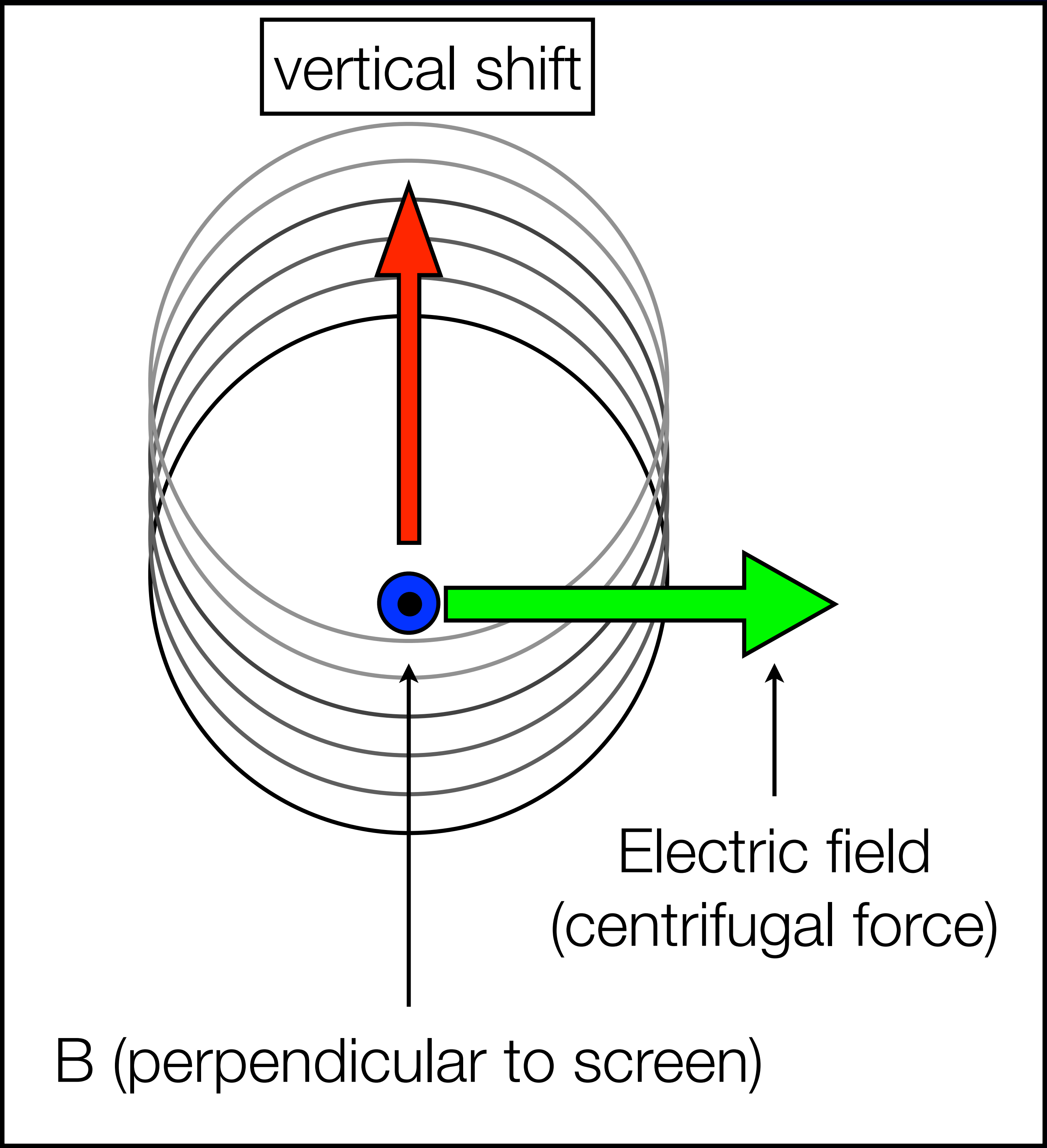
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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



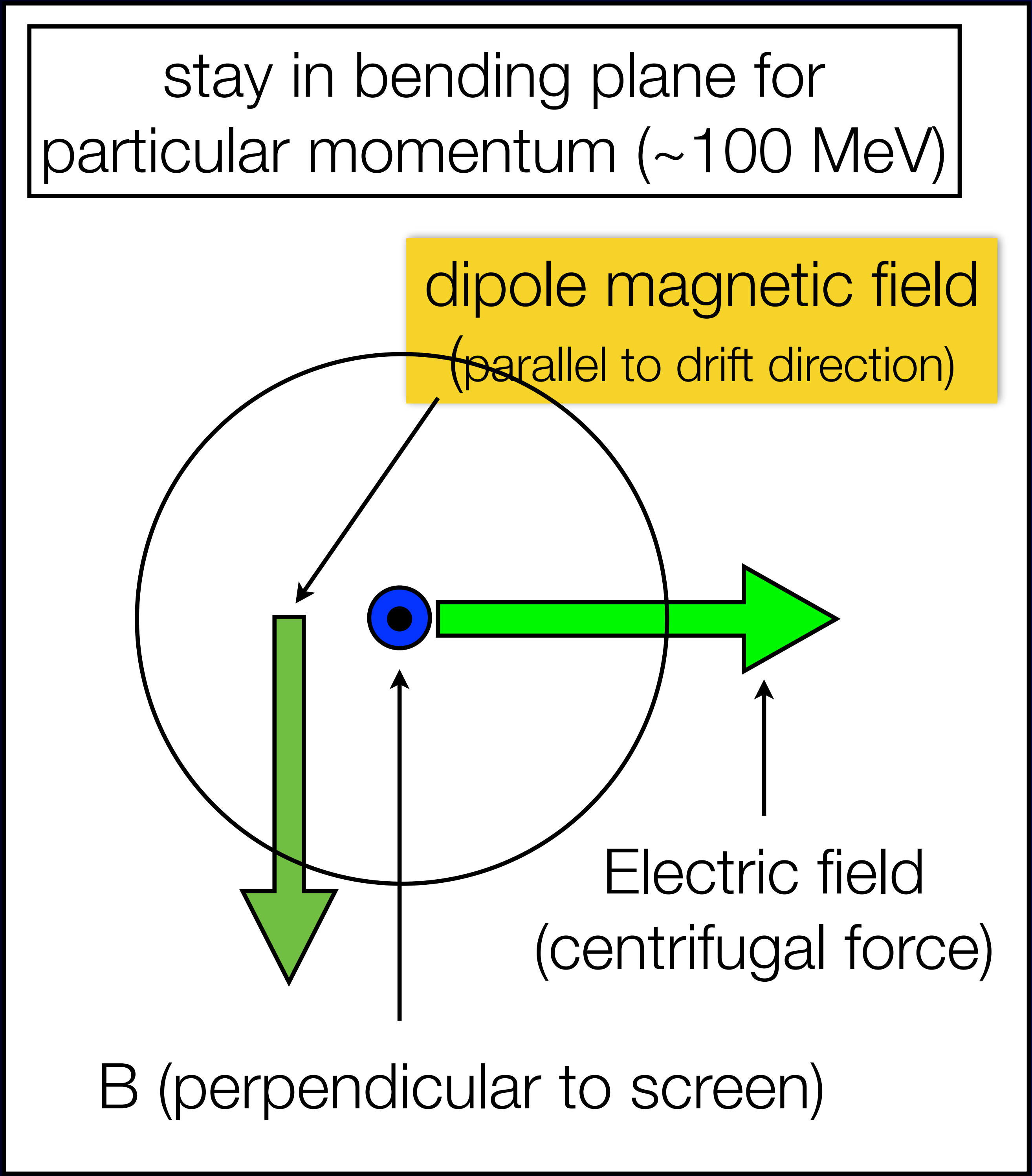
EM Physics for Particle Trajectories in Toroidal Magnetic Field



vertical shift

Electric field
(centrifugal force)

B (perpendicular to screen)



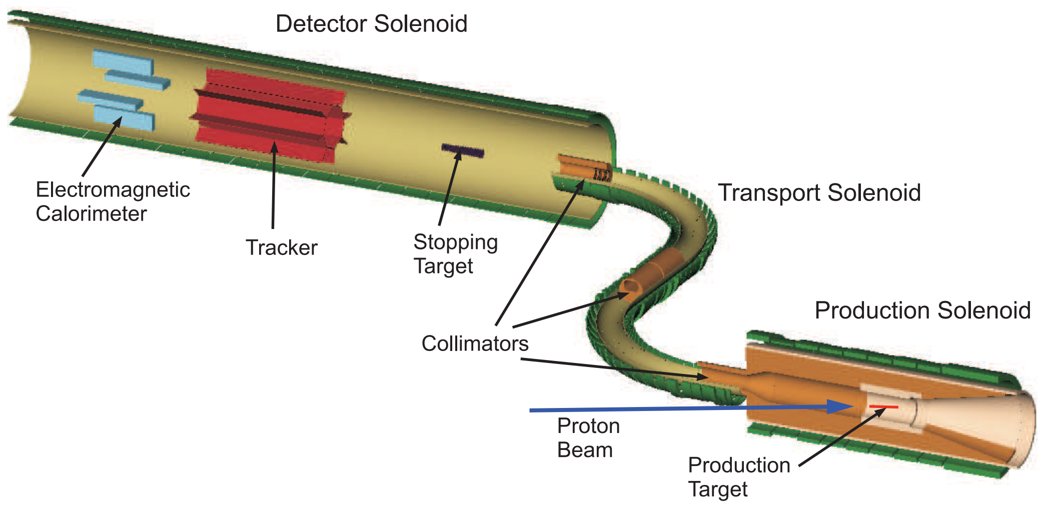
stay in bending plane for particular momentum (~100 MeV)

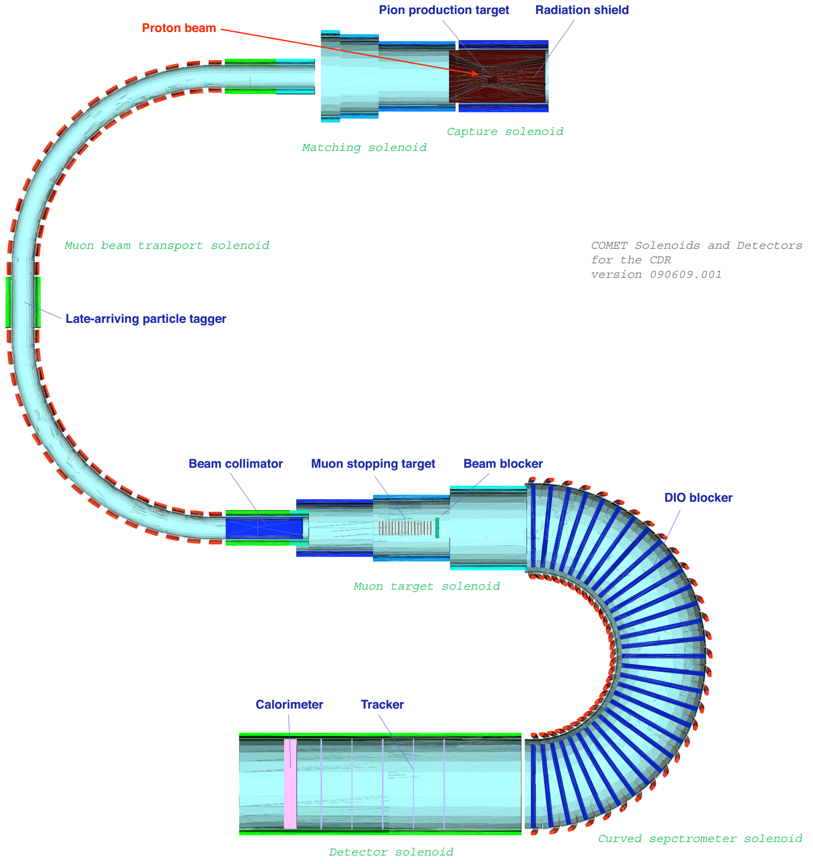
dipole magnetic field
(parallel to drift direction)

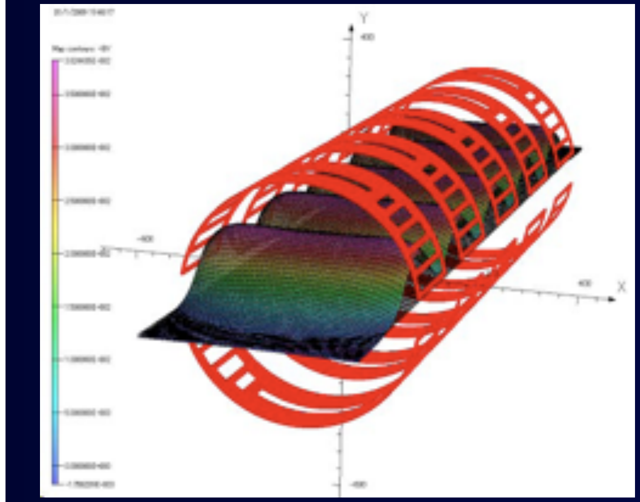
Electric field
(centrifugal force)

B (perpendicular to screen)

Mu2e vs. COMET





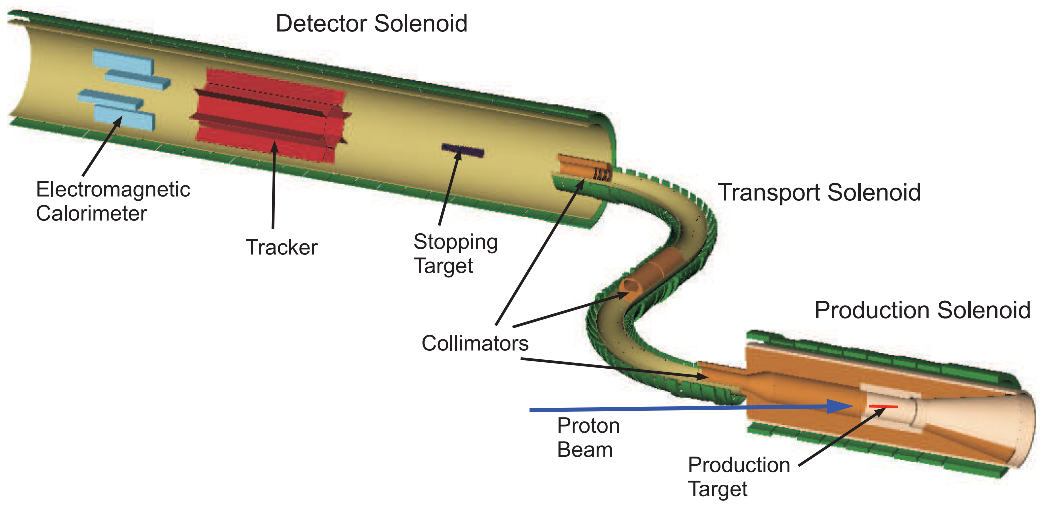


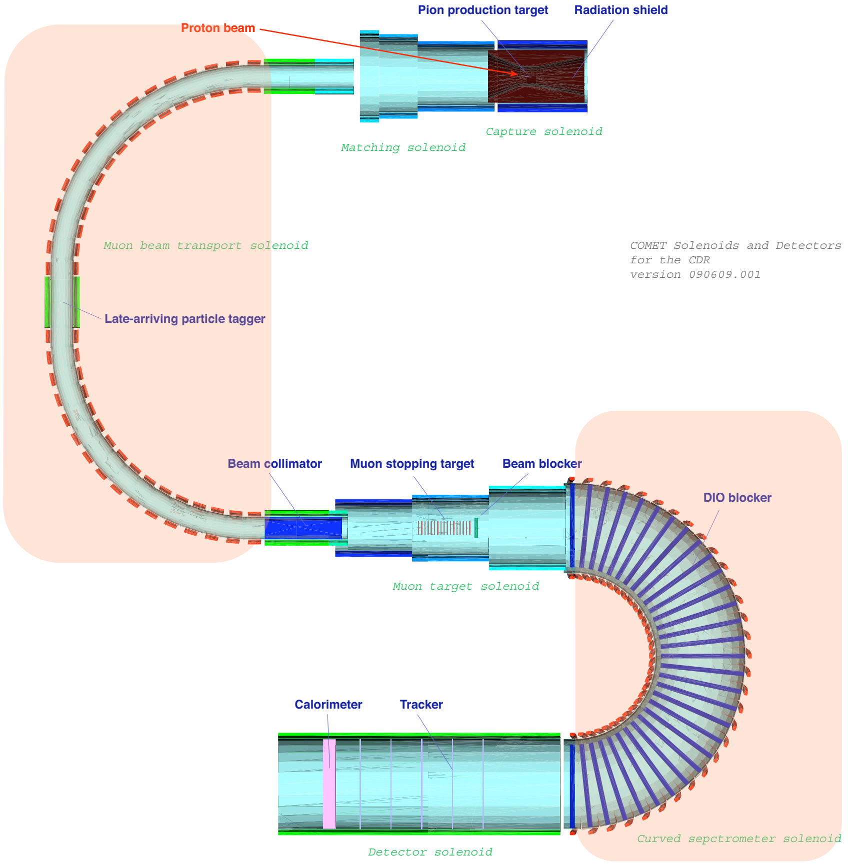
	Mu2e	COMET
muon beam line	2x 90° bends (opposite direction)	2x 90° bend (same direction)
electron spectrometer	straight solenoid	curved solenoid

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

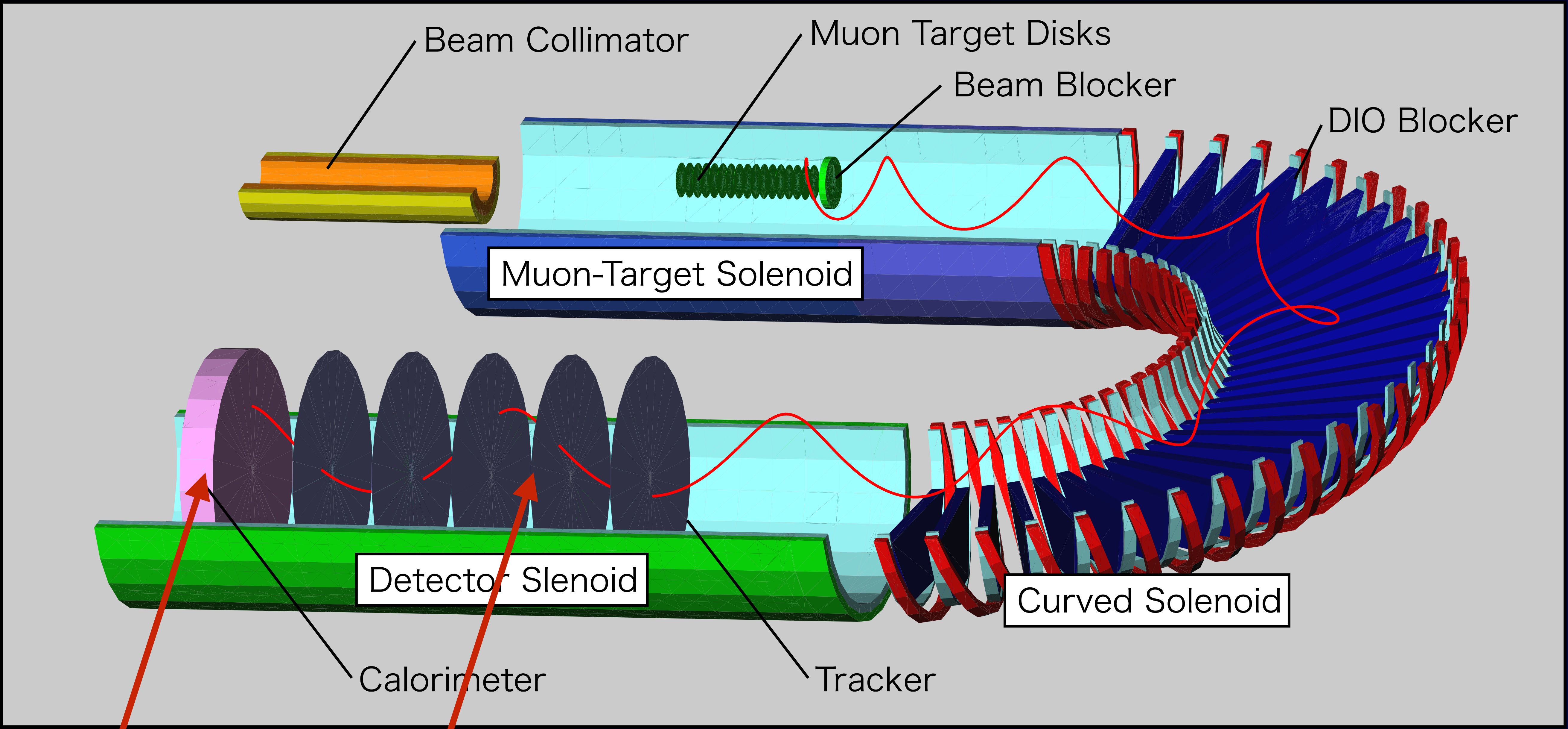
eliminate muon decay in flight

Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.

COMET Detectors



ECAL

Straw Tracker

(# of straw stations is not determined)

in vacuum under 1T magnetic field

Sensitivity and Backgrounds

Signal Sensitivity (preliminary) - 2x10^7 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 2x10^{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.

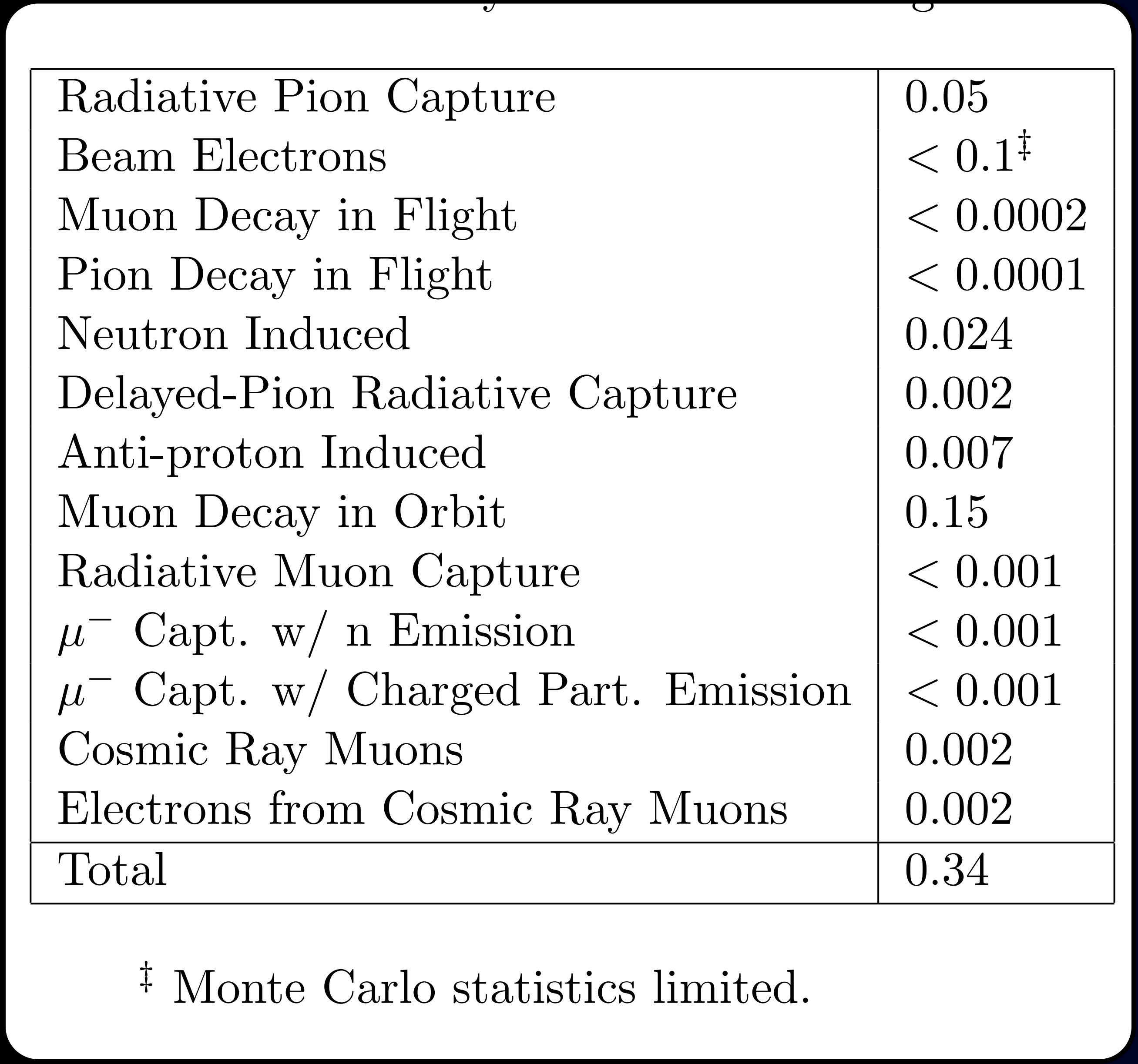
total protons muon transport efficiency muon stopping efficiency	8.5x10^{20} 0.008 0.3
# of stopped muons	2.0x10^{18}

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

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

Background Rates

Table 11.2: 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

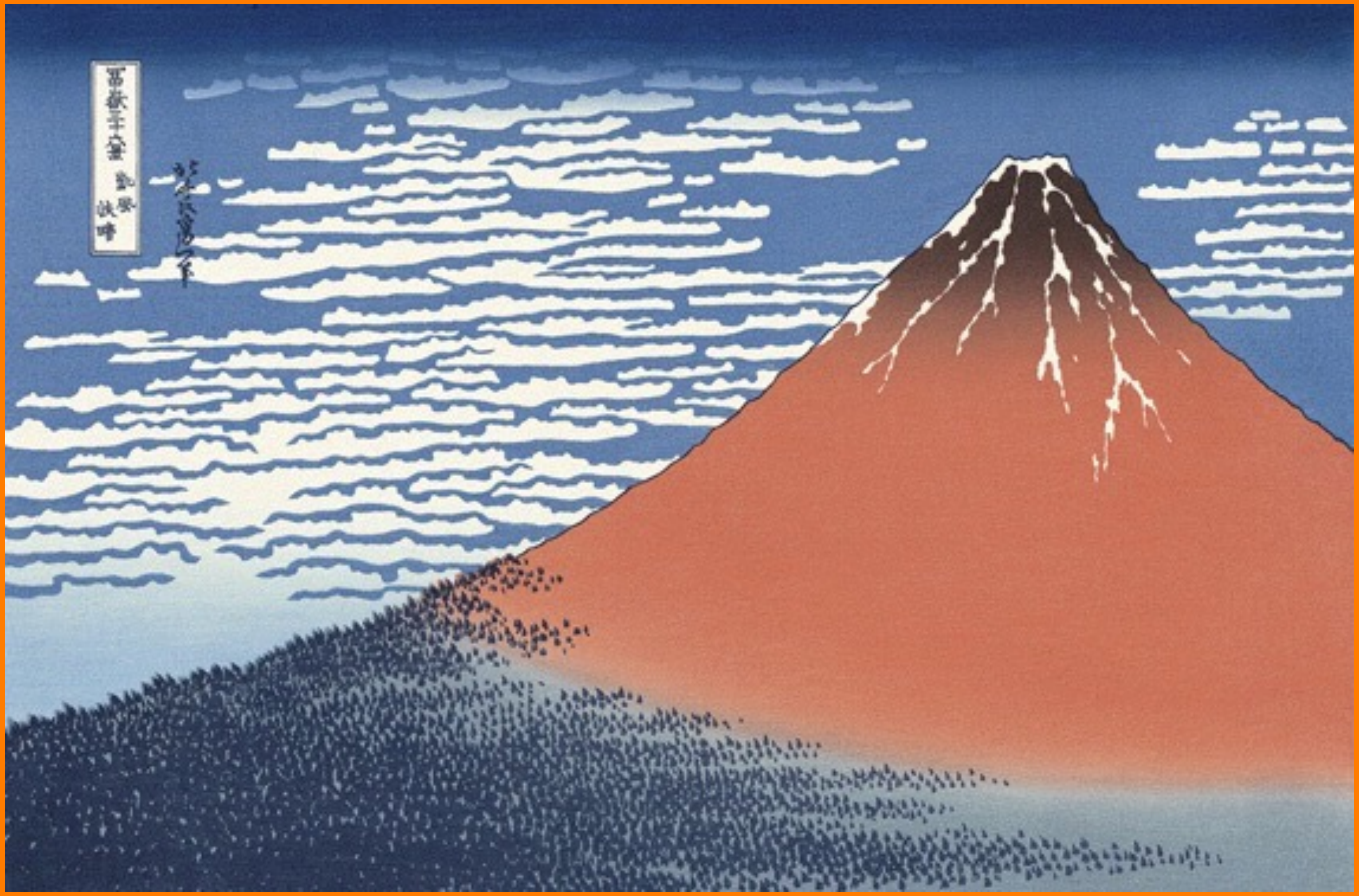
beam-related delayed backgrounds

intrinsic physics backgrounds

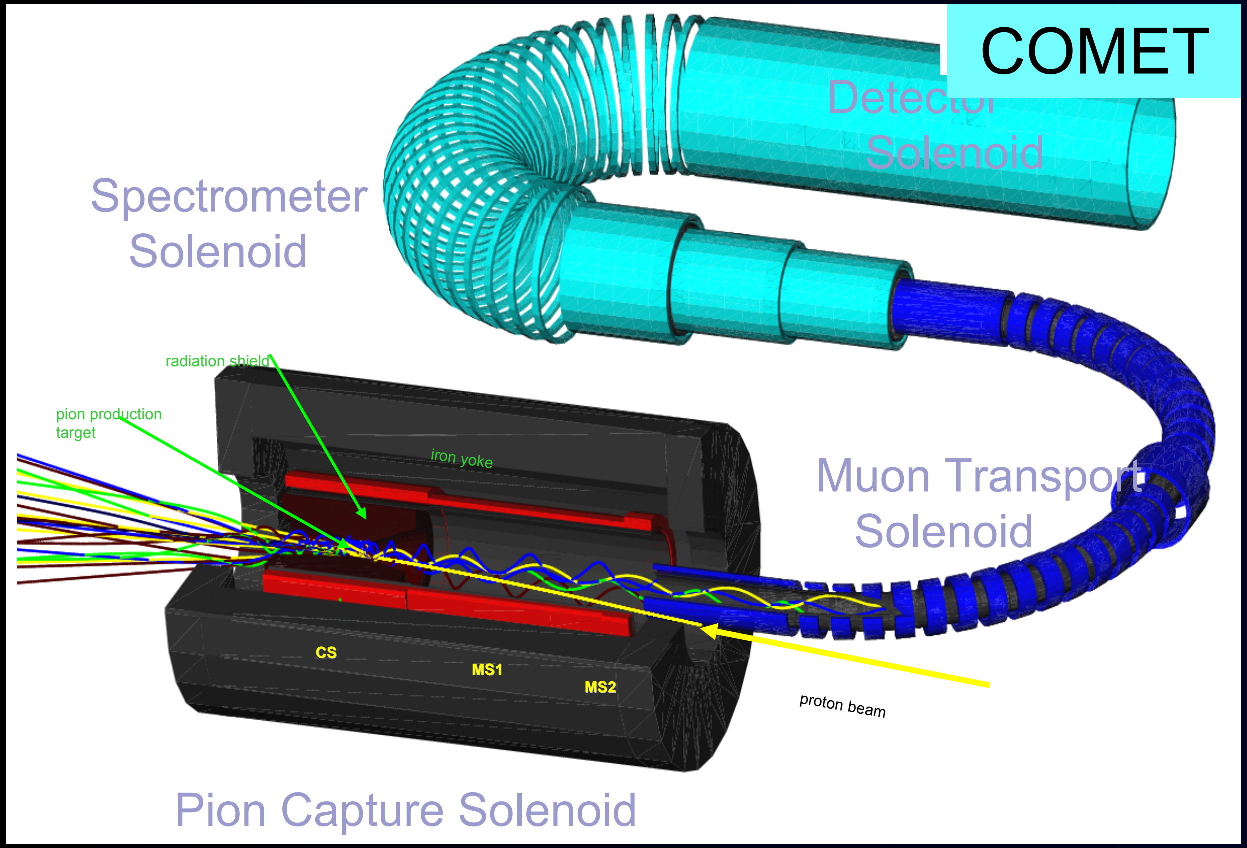
cosmic-ray and other backgrounds

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.

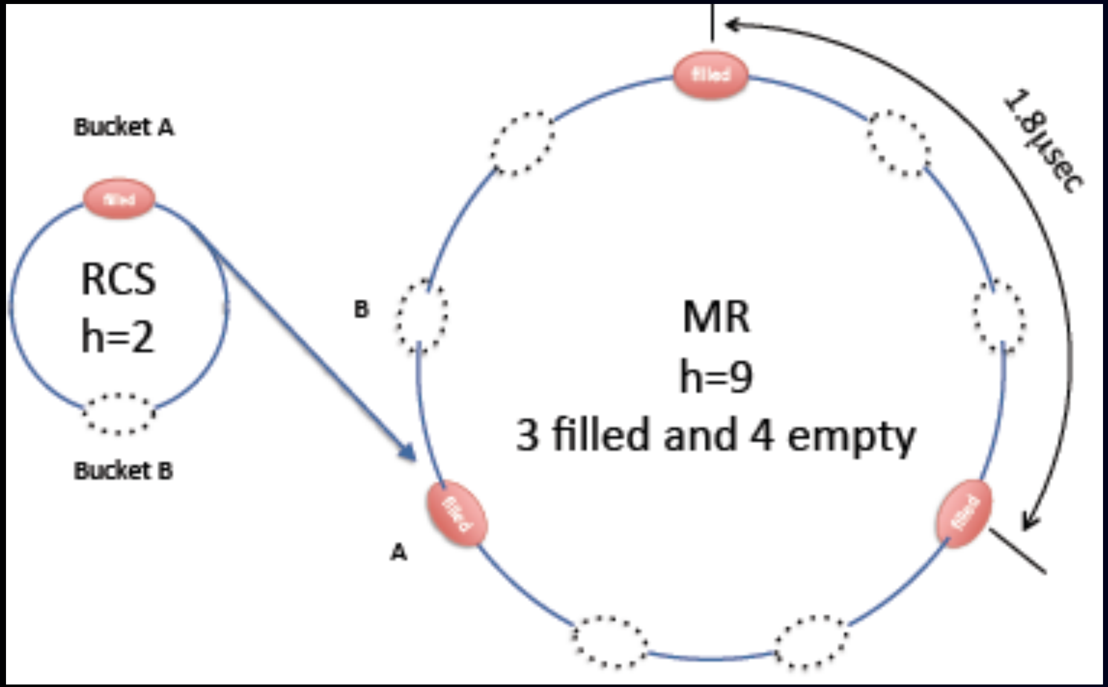
2 Increase of Muon Intensity

Pion capture system $\times10^3$

high field superconducting solenoid magnets surrounding a pion production target

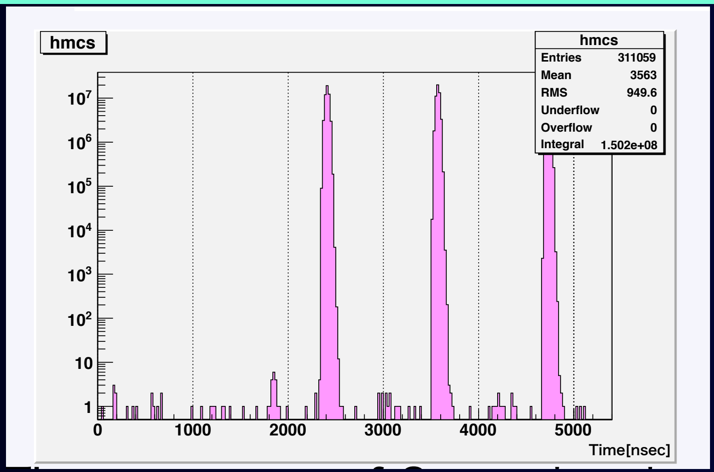
1

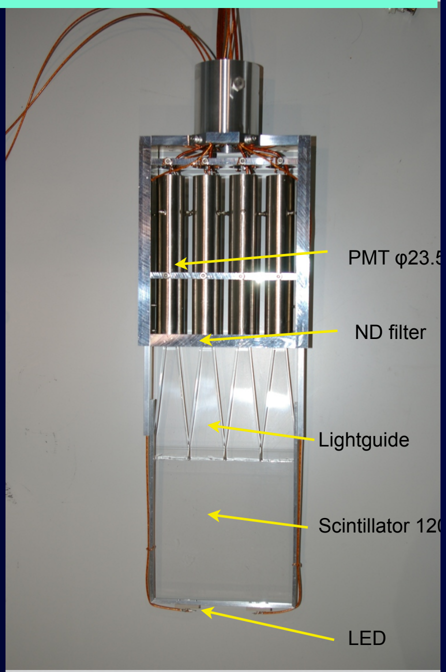
Proton Extinction Measurements at J-PARC



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





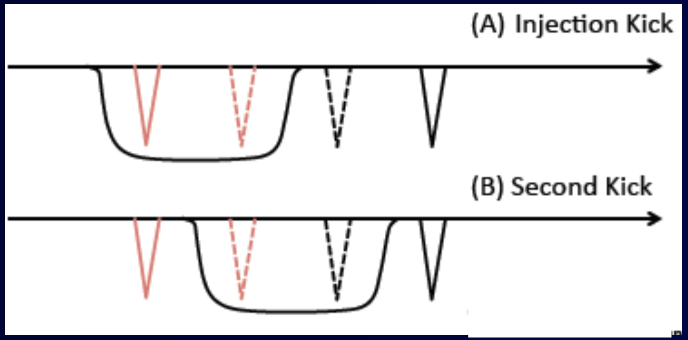
J-PARC MR proton extinction

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

Single Bunch Kicking

Tested at the abort (2010)

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

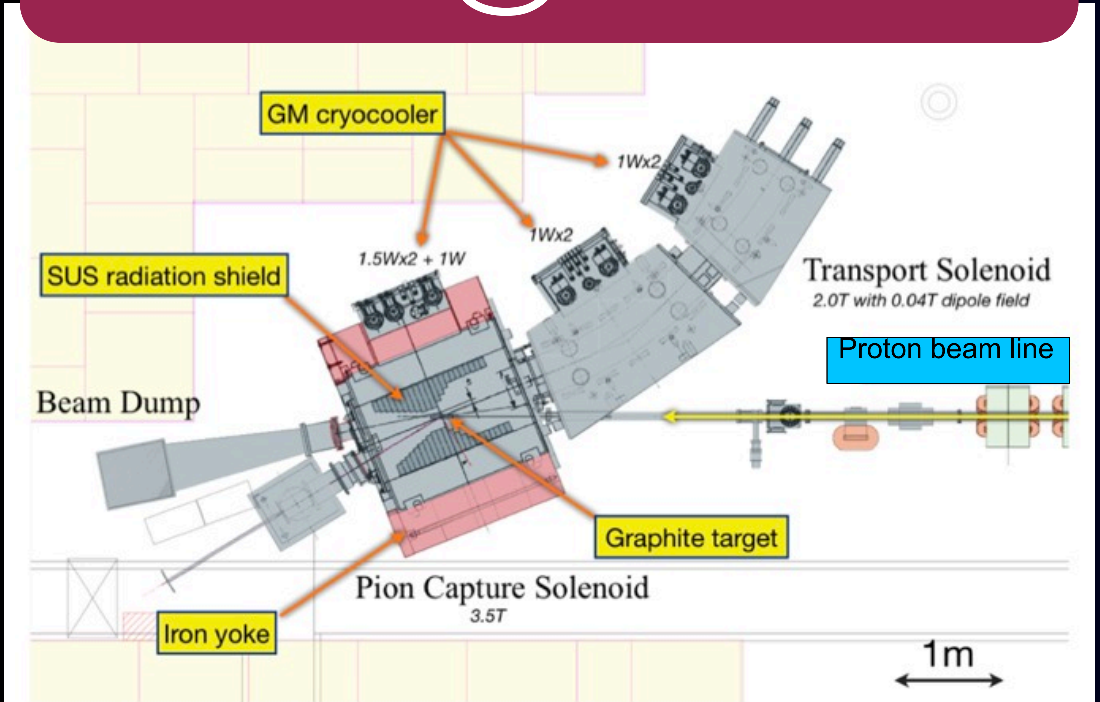


COMET is confident to achieve proton extinction of $<O(10^{-9})$.

②

Demonstration of Pion Capture System

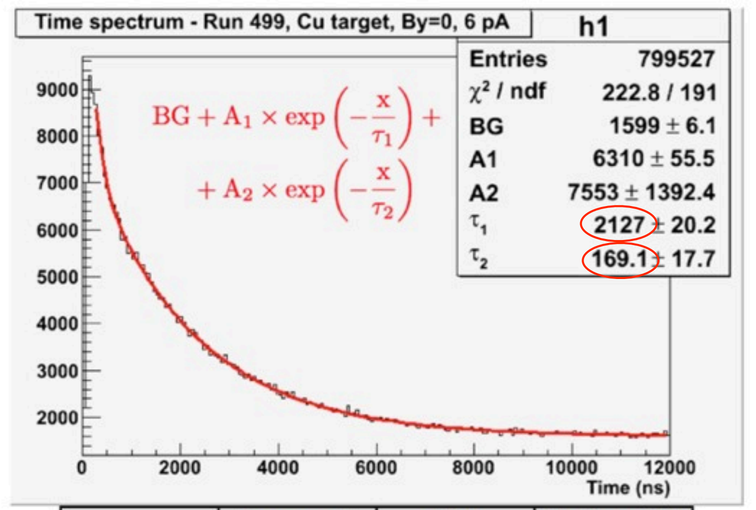
MuSIC@Osaka-U



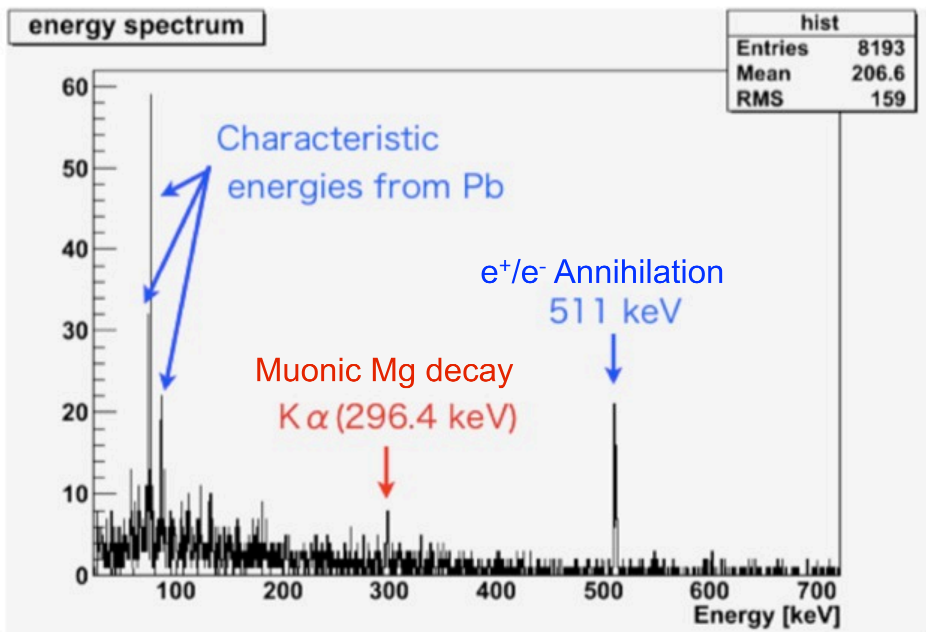
RCNP cyclotron
400 MeV, 1μA

preliminary

Measurements on June 21, 2011 (26 pA)



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



MuSIC muon yields

μ^+ : 3x10^8/s for 400W

μ^- : 1x10^8/s for 400W

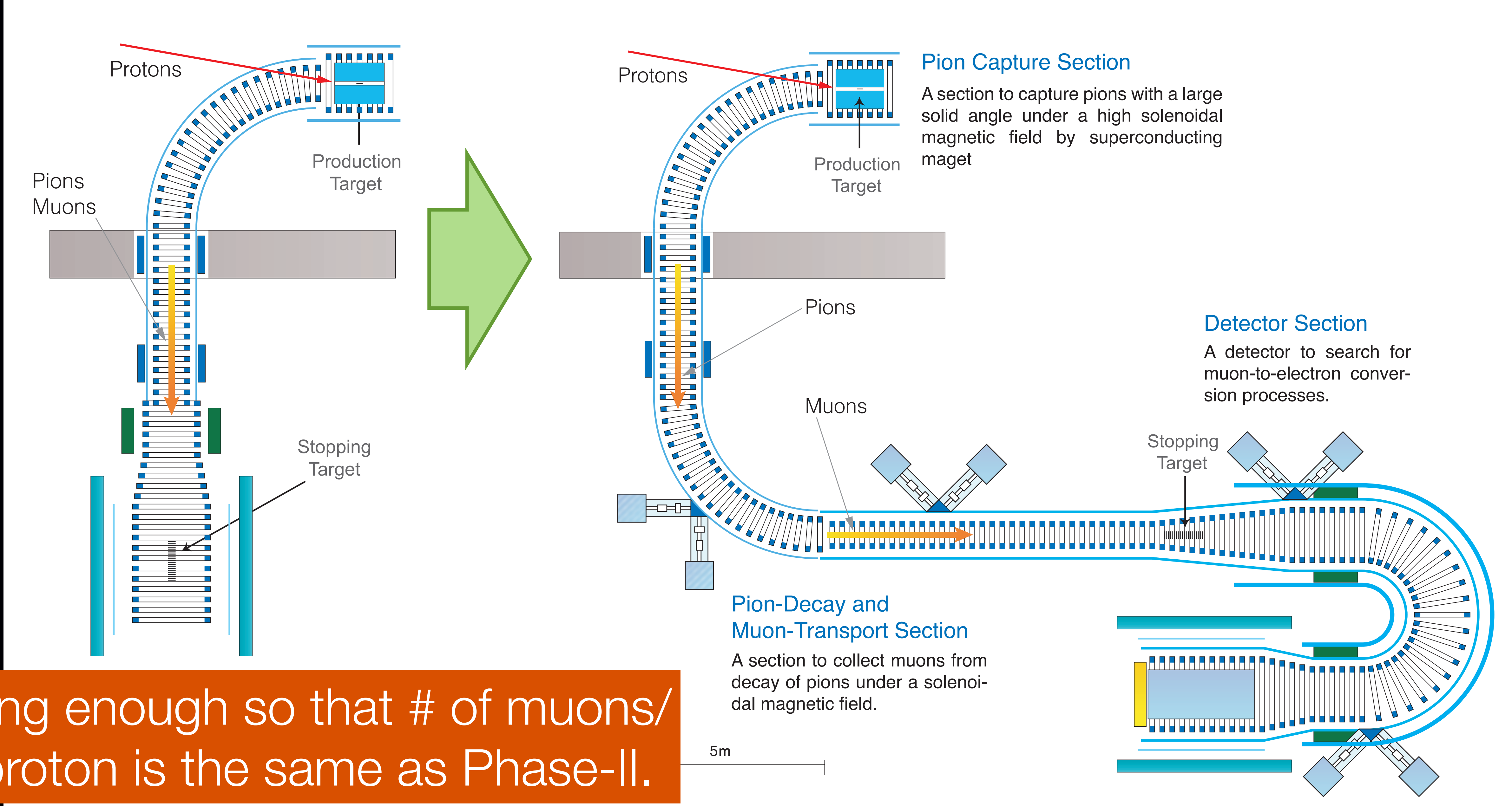
cf. 10^8/s for 1MW @PSI
Req. of x10^3 achieved...

COMET Phase-I

COMET Staged Approach (2012~)

COMET Phase-I

COMET Phase-II



Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

Detector Section

A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

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

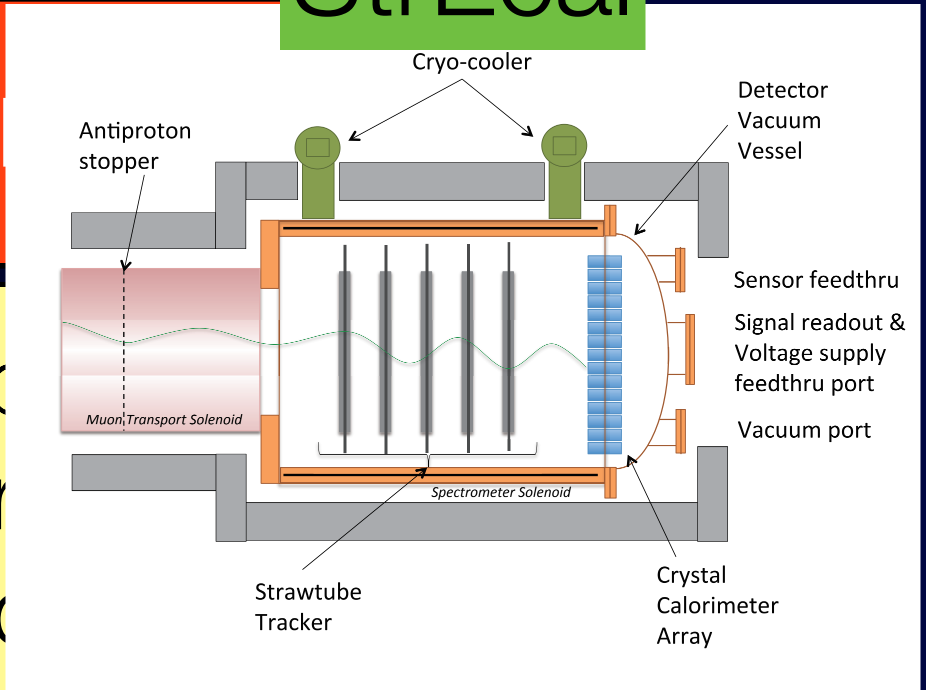
Goals of COMET Phase-I

1

Background Study for COMET P

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

StrEcal

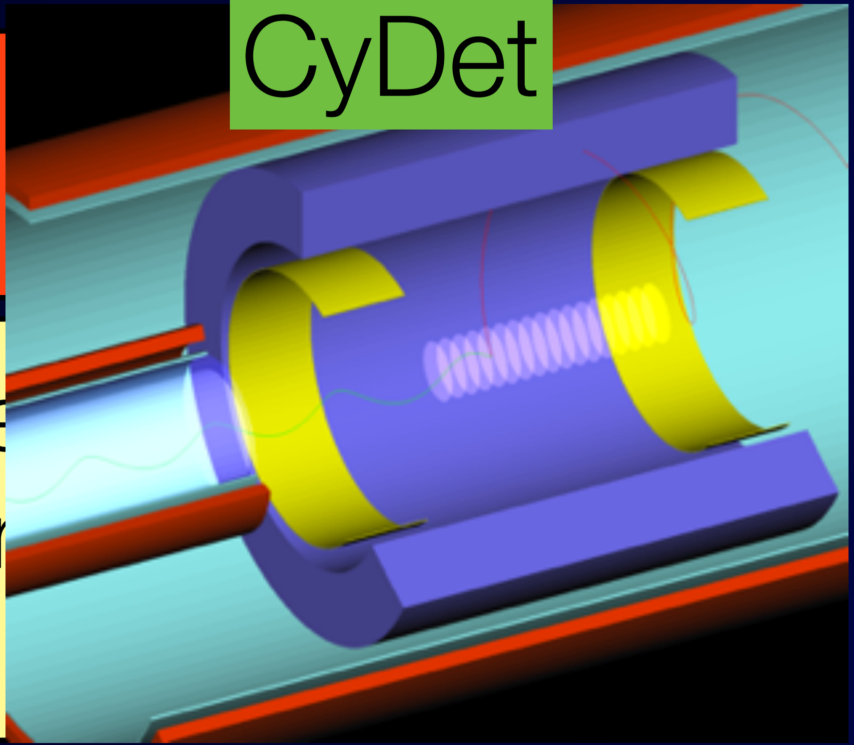


2

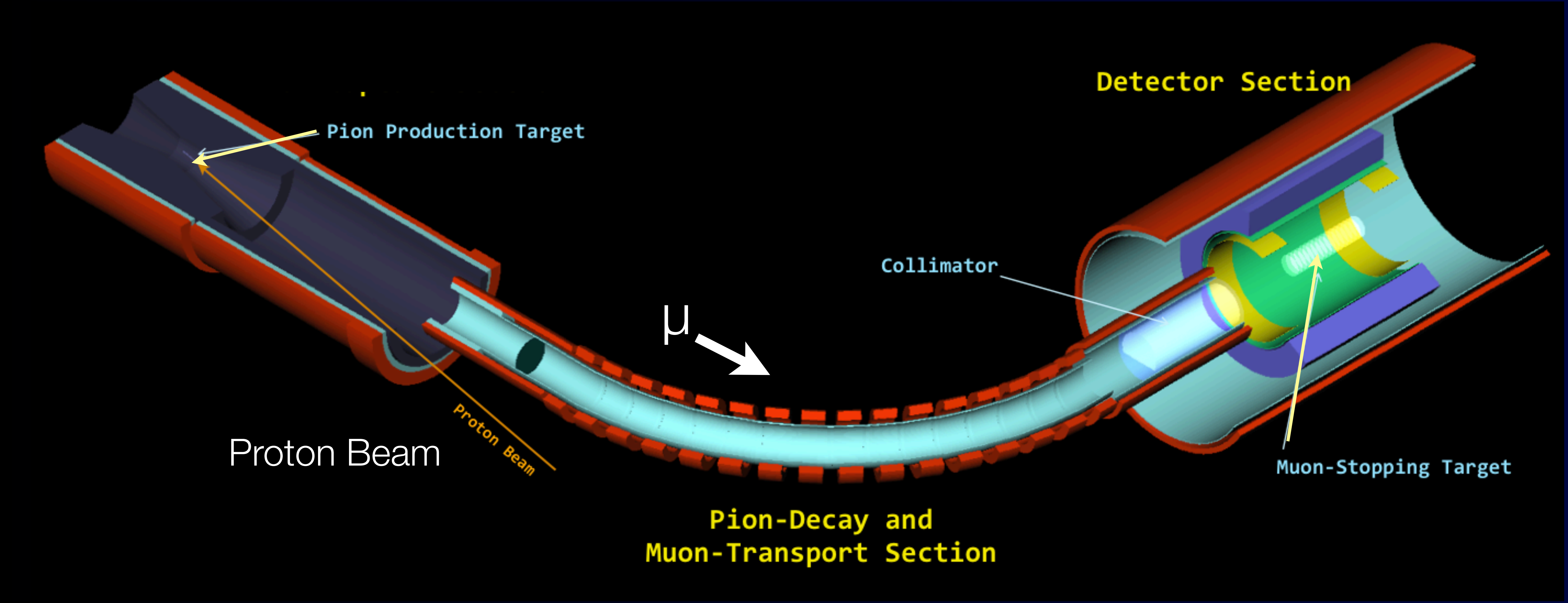
Search for μ-e conversion

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



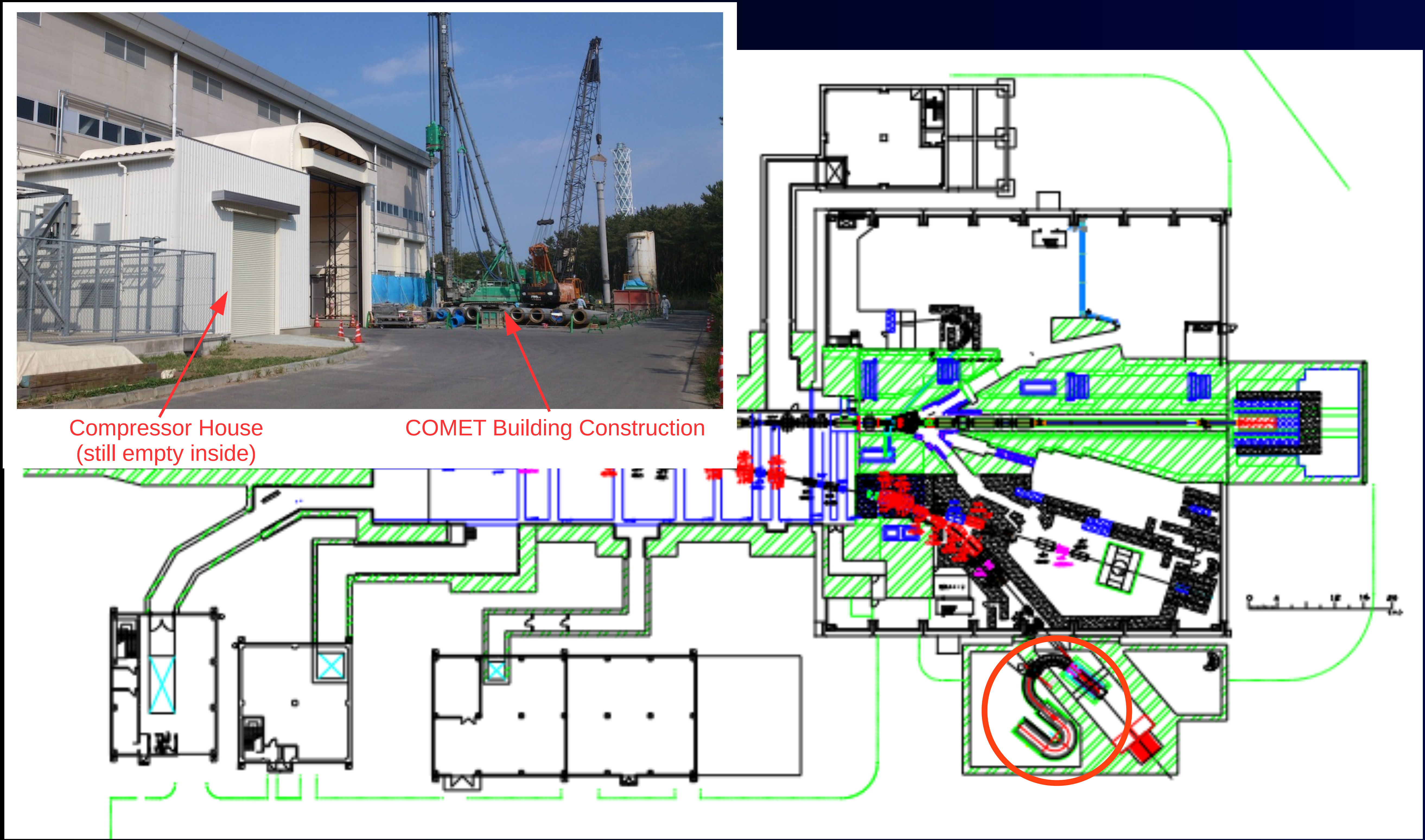
COMET muon beam-line：

6×10^9 muon/sec with 3kW beam produced. The world highest intensity.

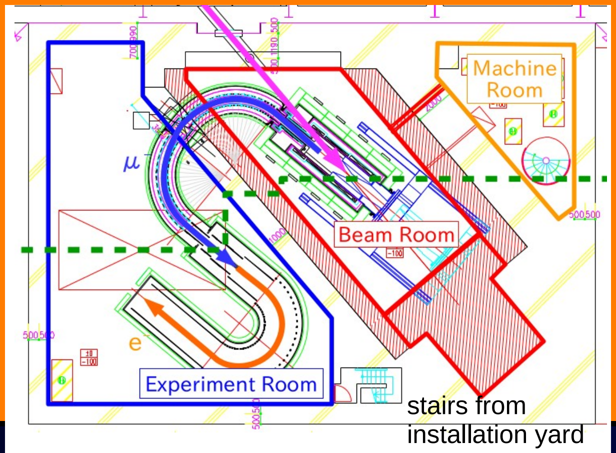
COMET Phase-I detector：

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

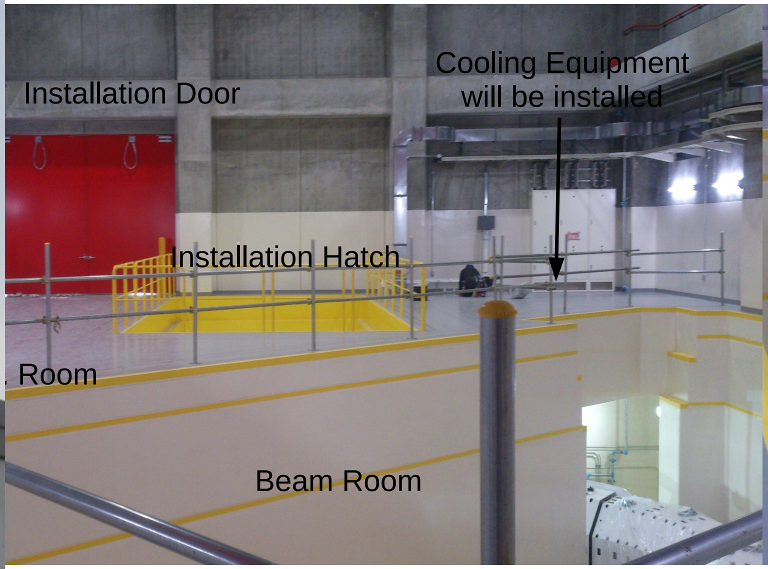
COMET Proton Beamline



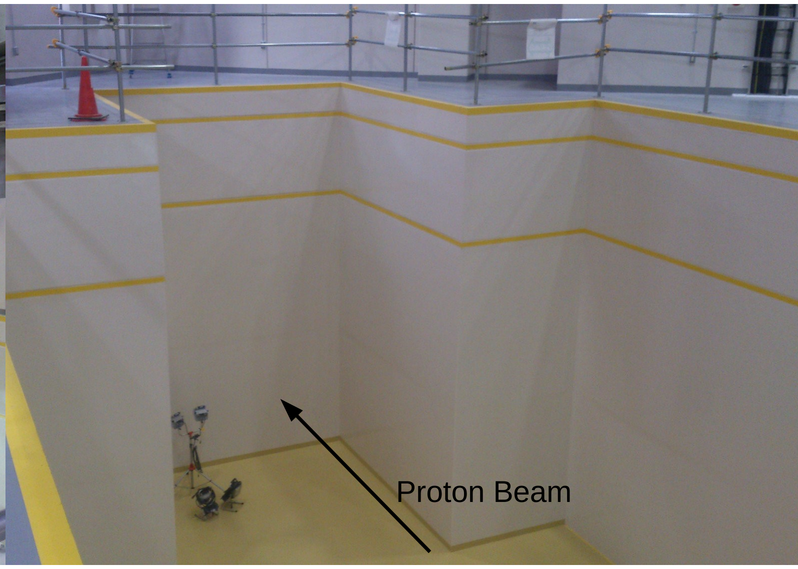
Hadron South Building (COMET Experimental Hall)



Installation Yard

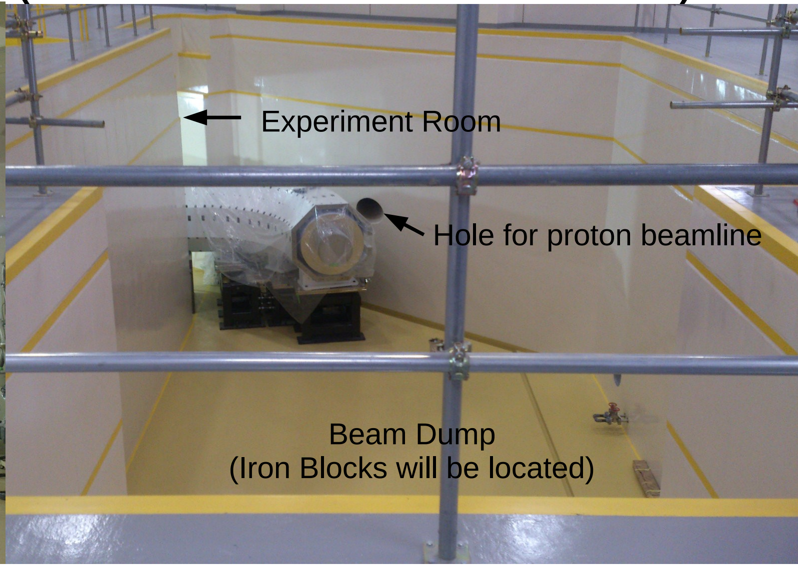


Beam Room

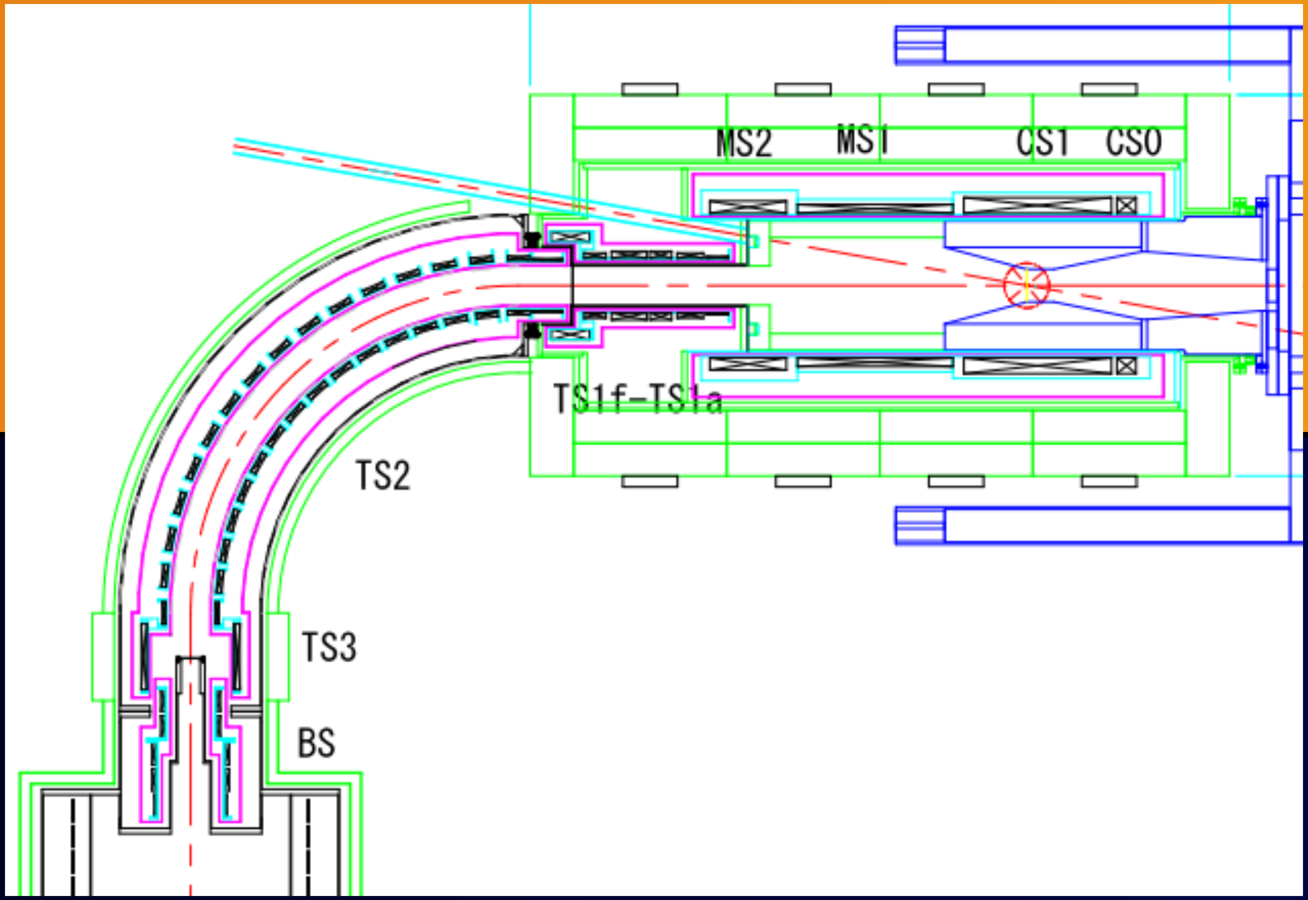


Experiment Room (View from Door)

Beam Room (view from Installation Yard)



Superconducting Solenoids



Pion capture solenoid system

- The delivery of aluminum stabilized superconductors is being made (10 km in 2013, 12 km in 2014, and 8 km in 2015).
- TS1a coil winding is made by a new winding machine.
- CS and MS coils will be made in 2015 or later.

TS1a coil winding

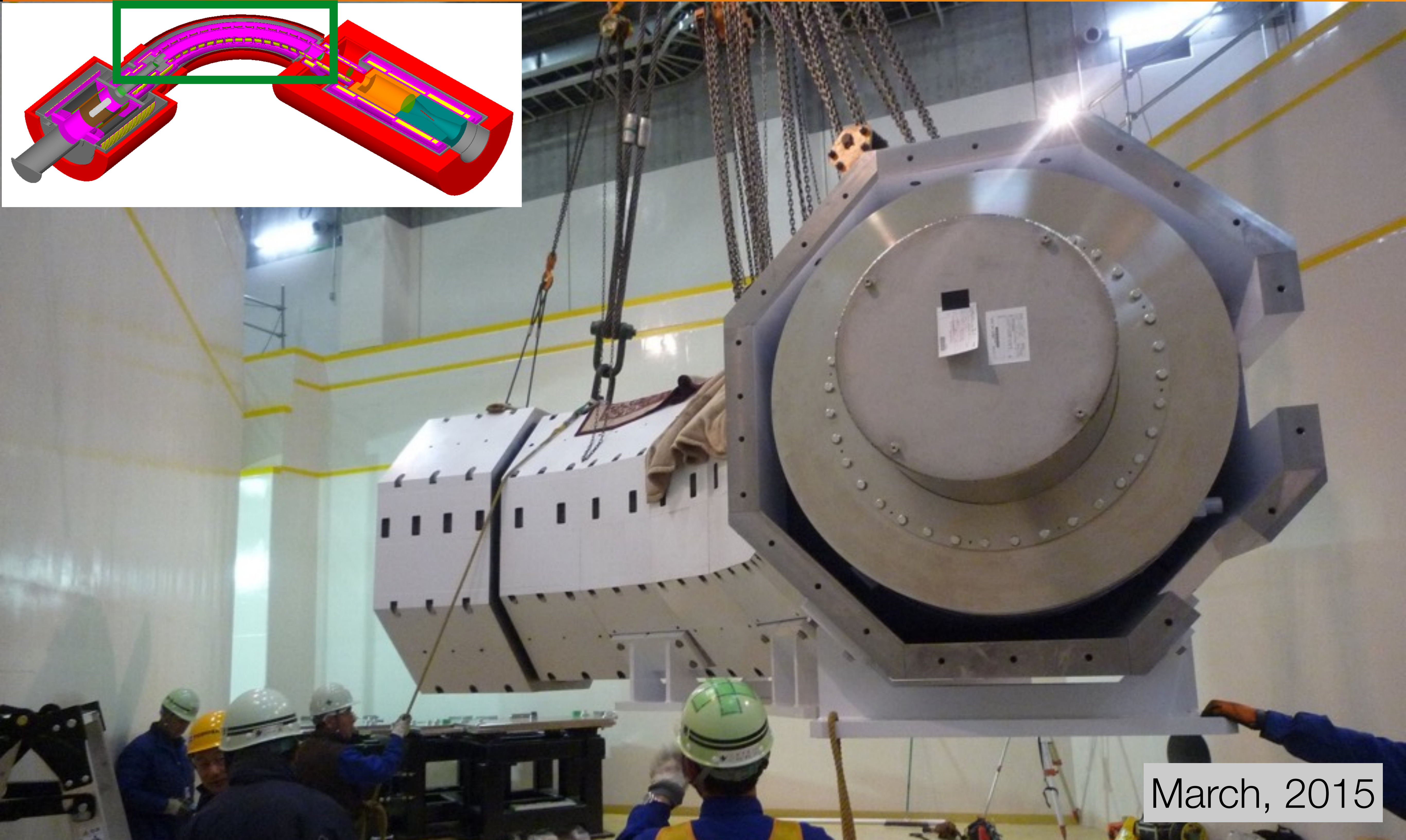
Muon transport solenoid system

- The construction of the muon transport system (TS2-TS3) has been delivered by Toshiba Co.

The review of radiation safety and design of the COMET magnet was made in January, 2014.

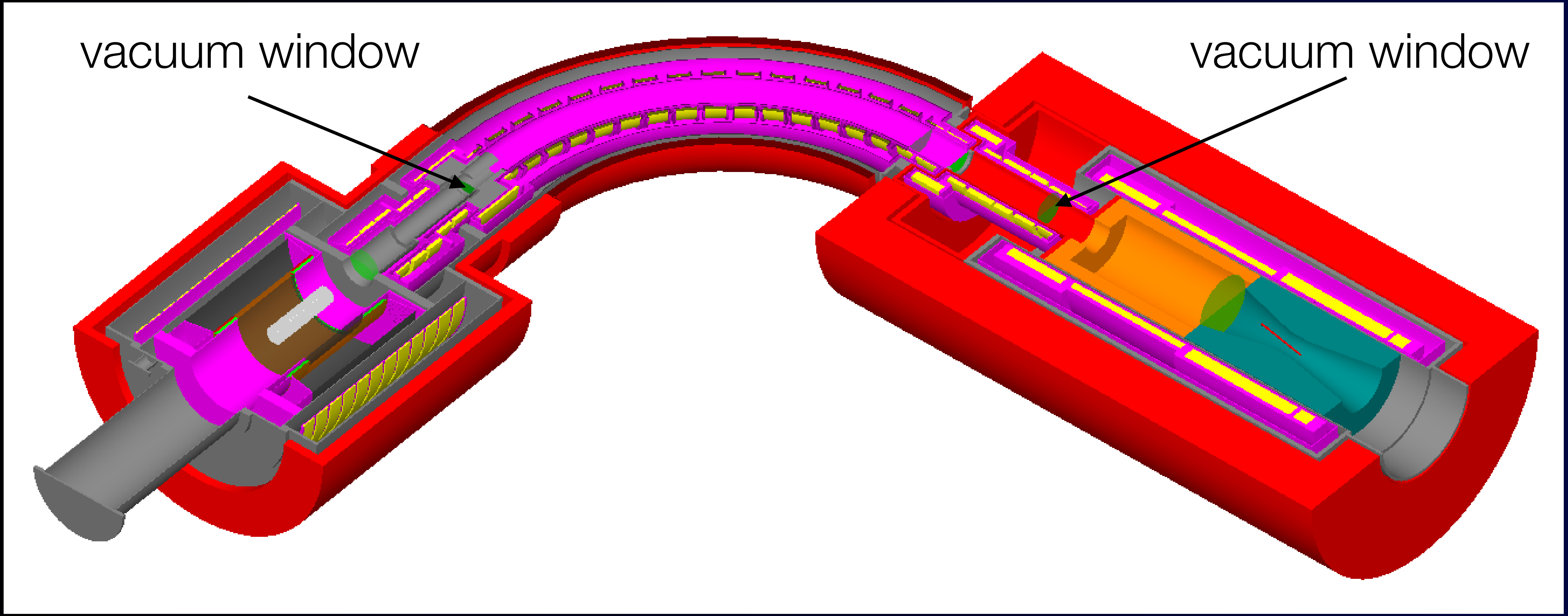
Curved Solenoids for Muon Transport Completed and Delivered!

Osaka University



March, 2015

COMET Phase-I Muon Beam Line

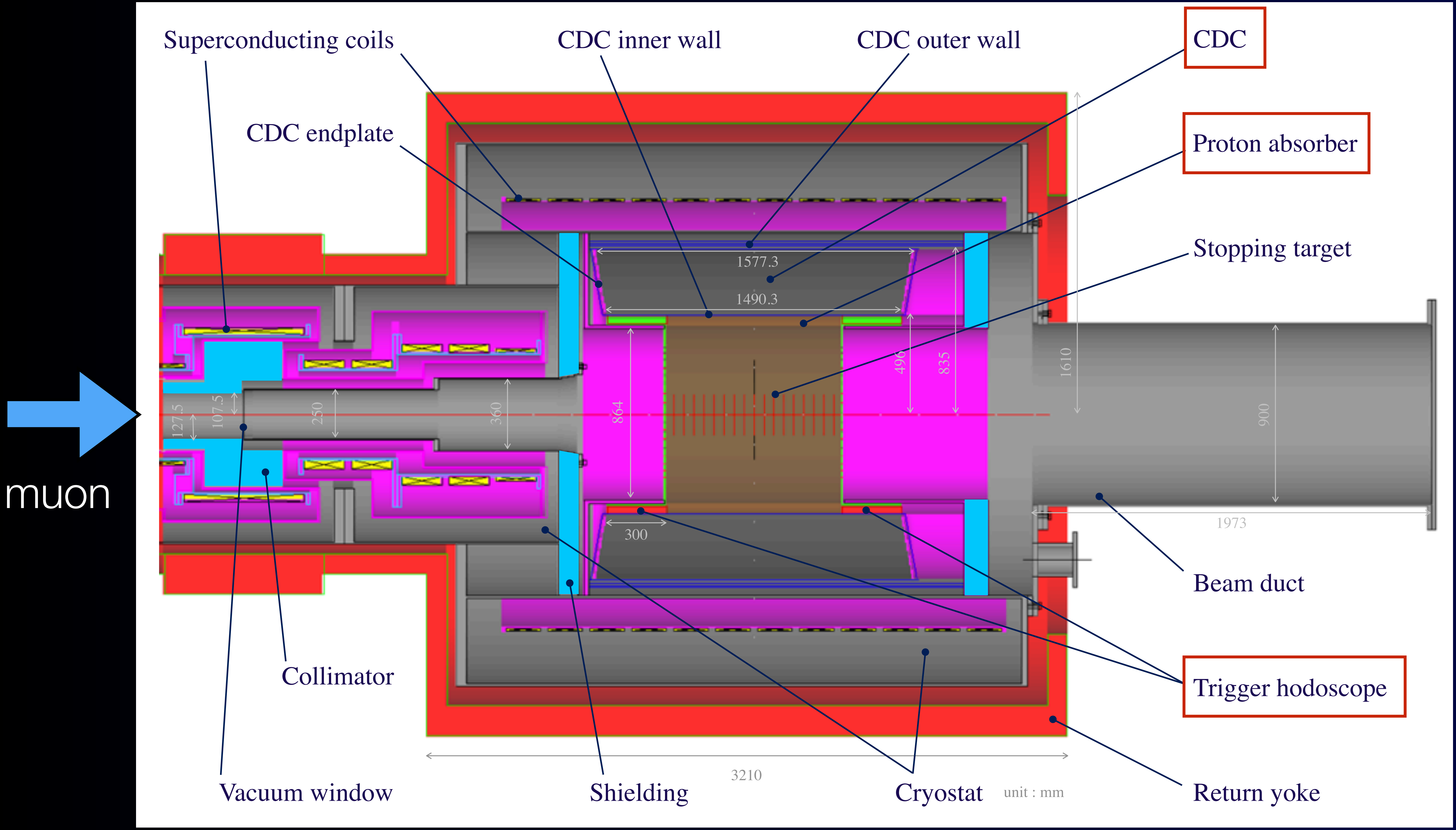


detector system

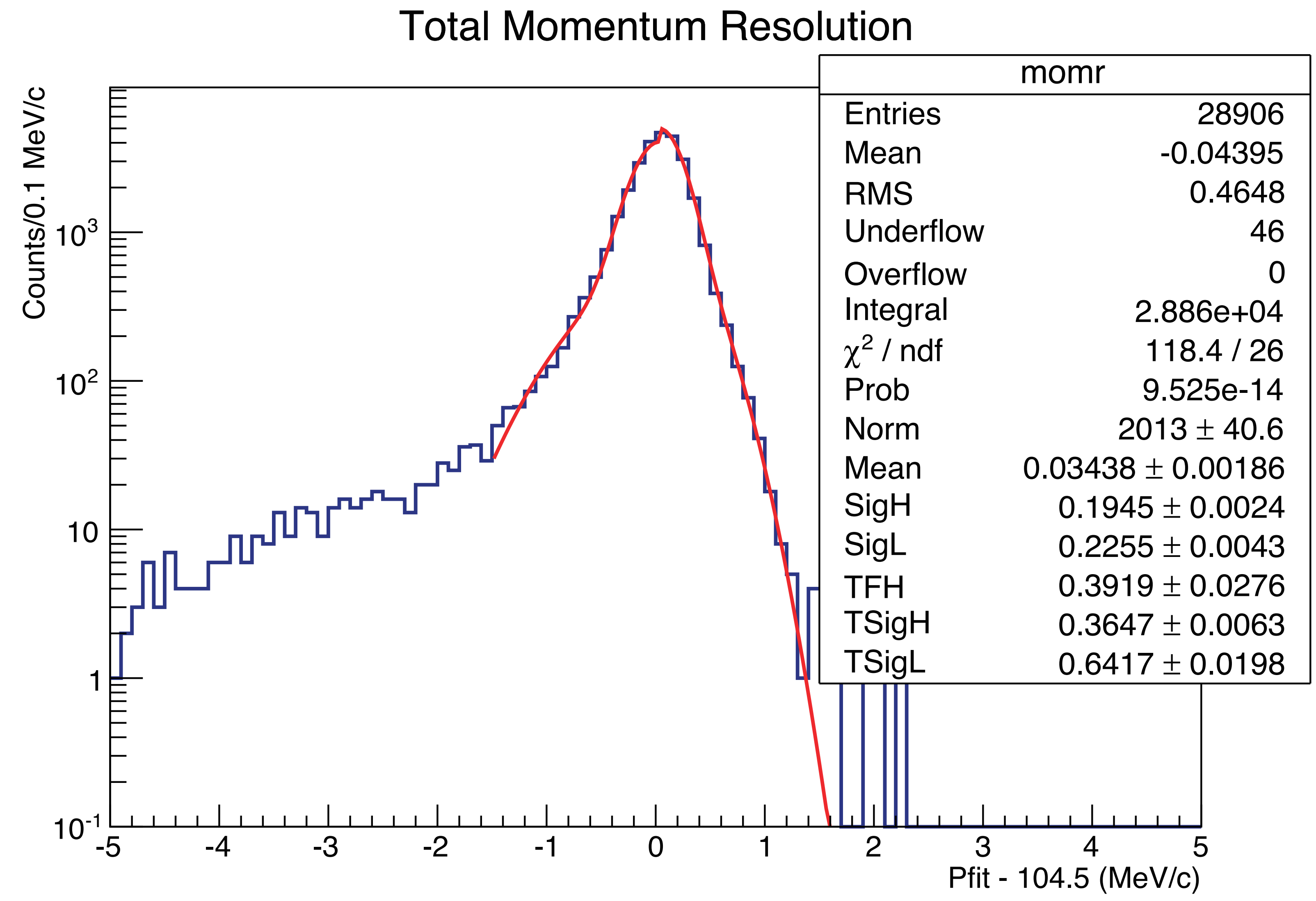
muon transport system

pion production system

CyDet (Cylindrical Detector): Layout



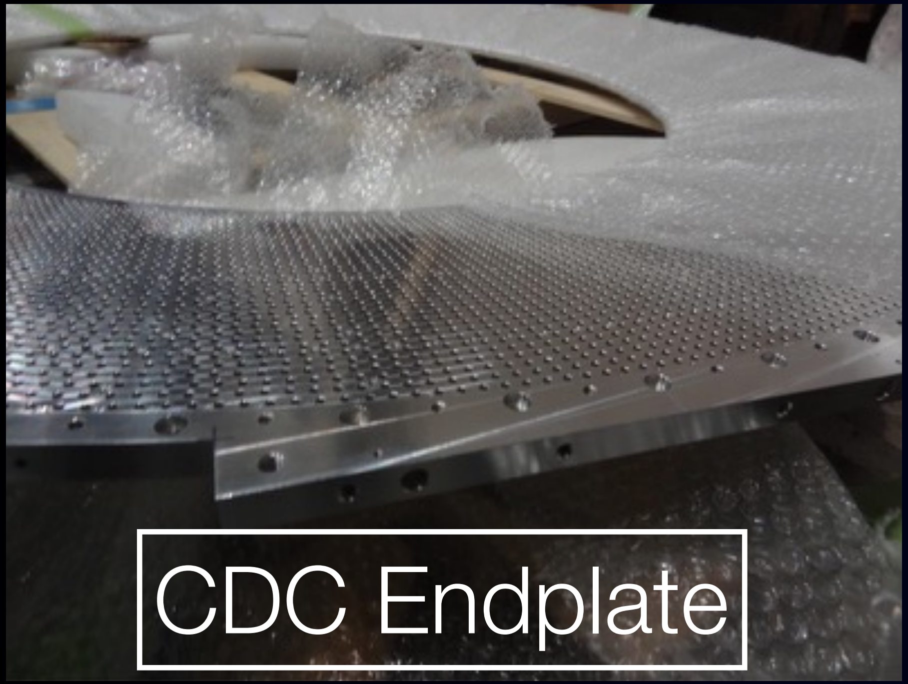
CDC Momentum Resolution (simulation)



σ of the core Gaussian at the high momentum side `SigH`	195 keV$/c$
σ of the core Gaussian at the high momentum side `SigL`	226 keV$/c$
Fraction in the tail distribution `TFH`	39%
σ of the tail Gaussian at the high momentum side `TSigH`	365 keV$/c$
σ of the tail Gaussian at the low momentum side `TSigL`	642 keV$/c$

about 200 keV/c achieved.

CDC Construction



CDC Endplate

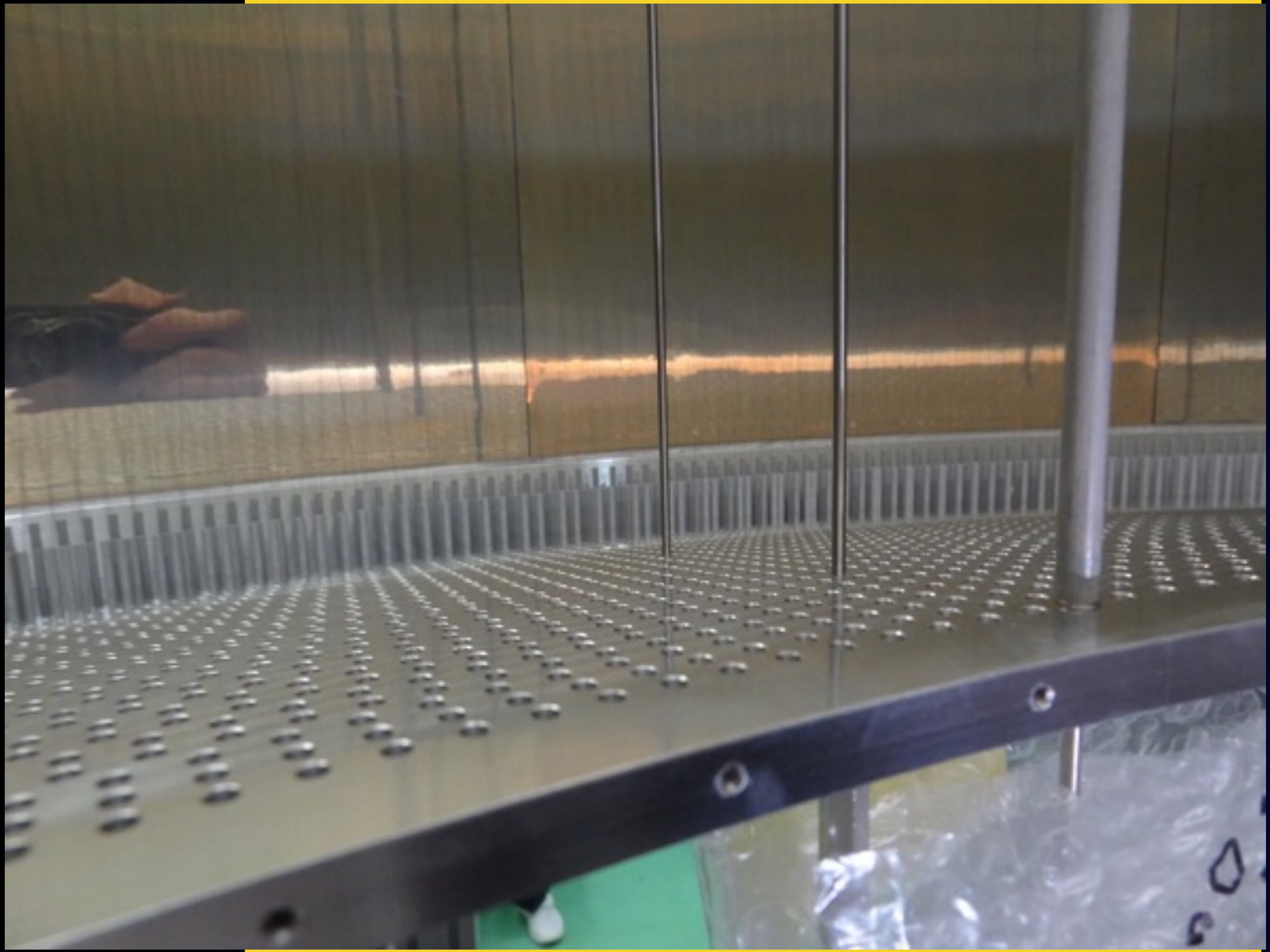
CDC Outer wall

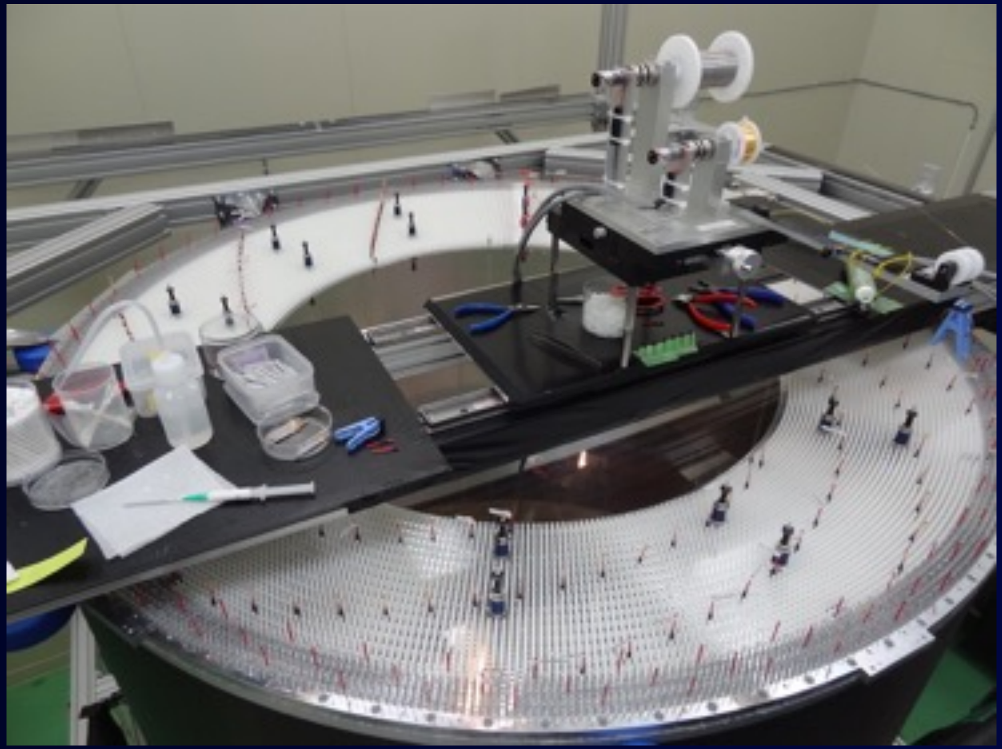
CDC assembly

CDC on wire stringing assembly

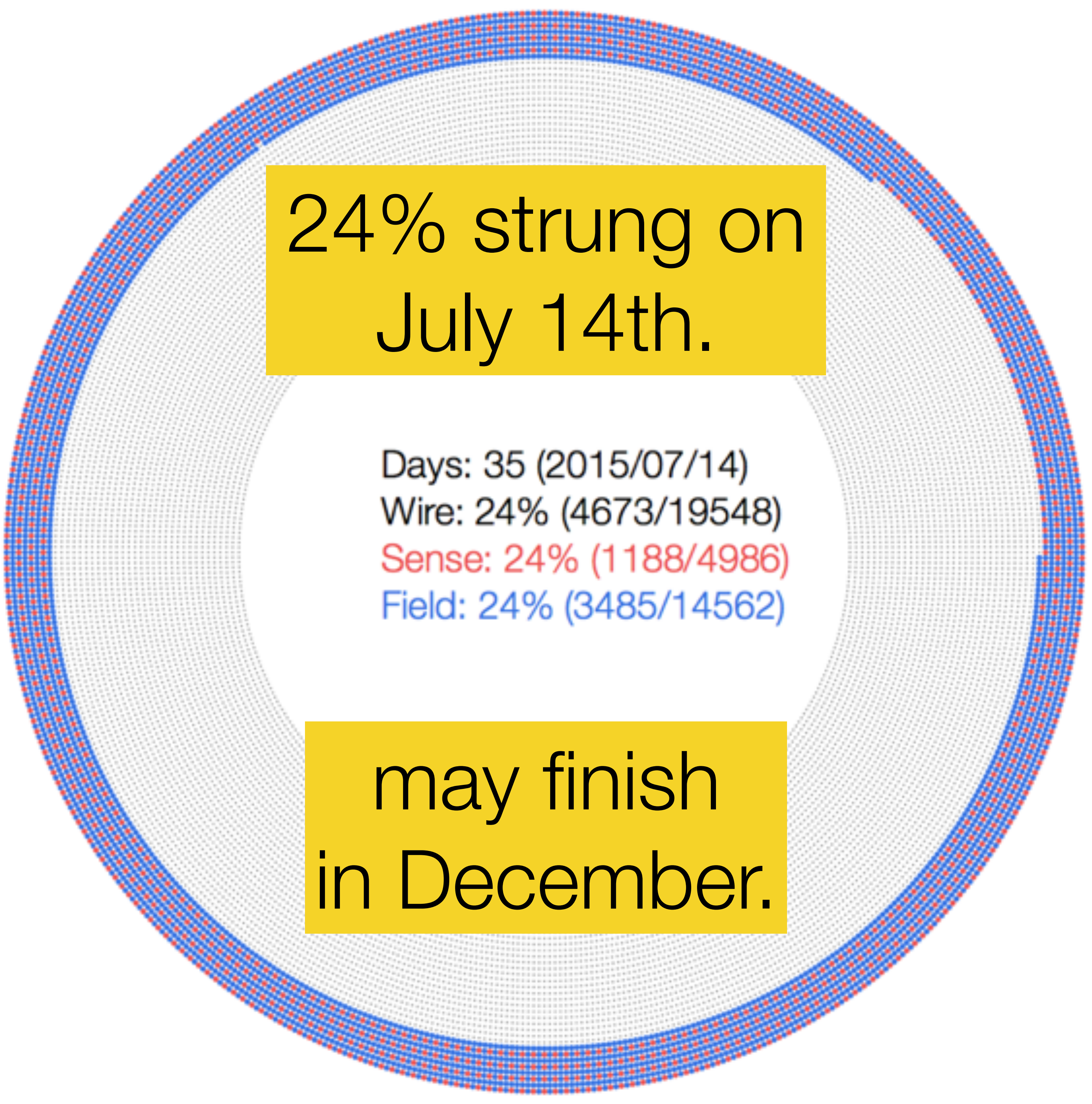
Wire Stringing for the CDC Started !

Wire stringing started in May at the Fuji hall.





Status of Wire Stringing at July 14th, 2015

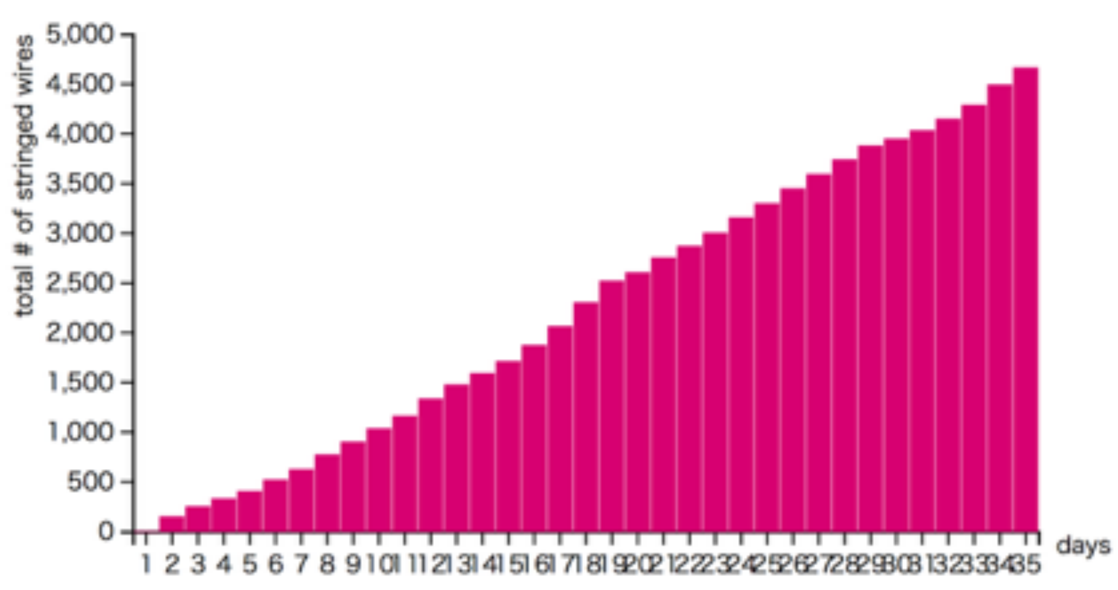


24% strung on July 14th.

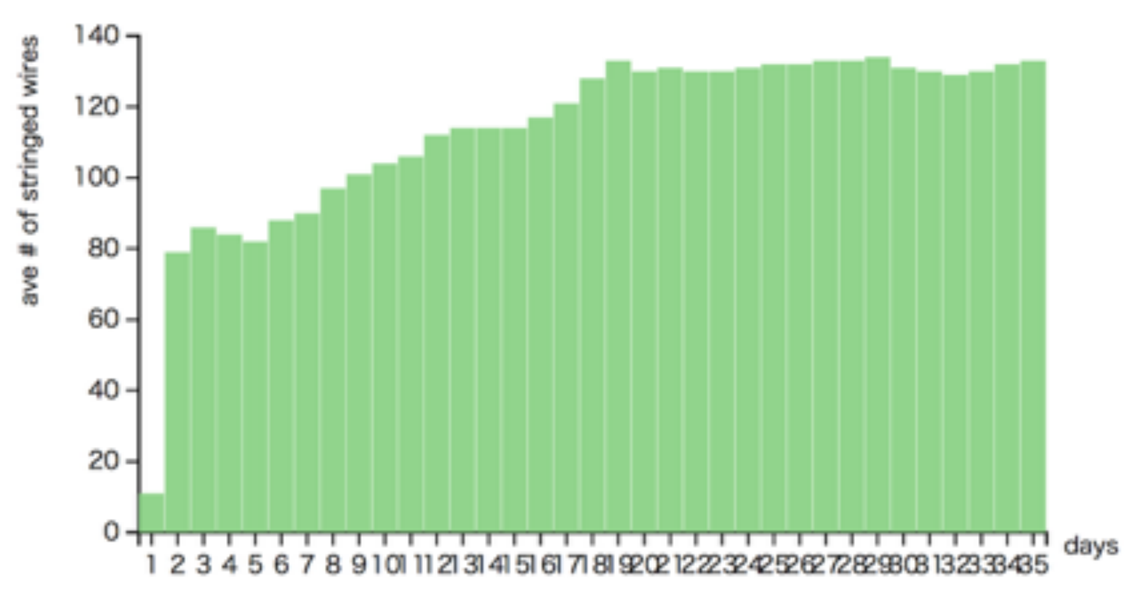
Days: 35 (2015/07/14)
Wire: 24% (4673/19548)
Sense: 24% (1188/4986)
Field: 24% (3485/14562)

may finish in December.

of total strung wires



of strung wires per day



Signal Sensitivity with CyDet

Signal Acceptance

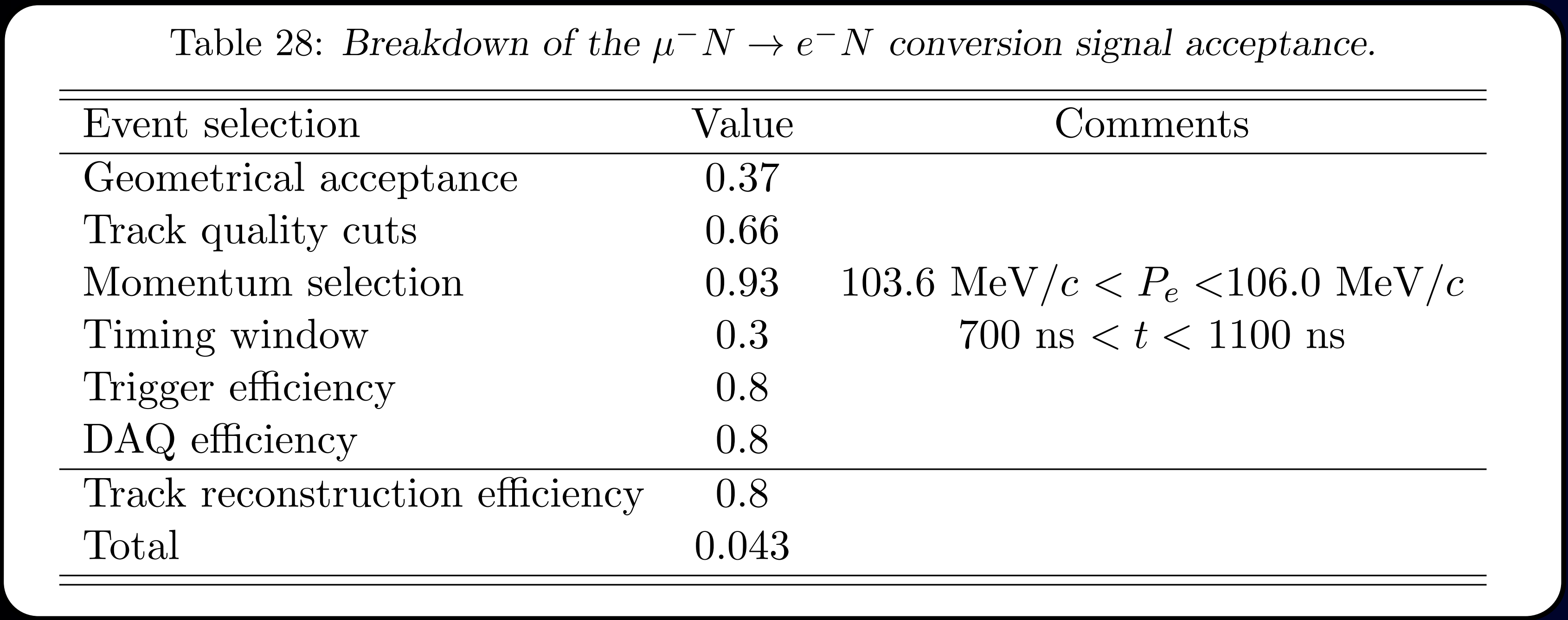
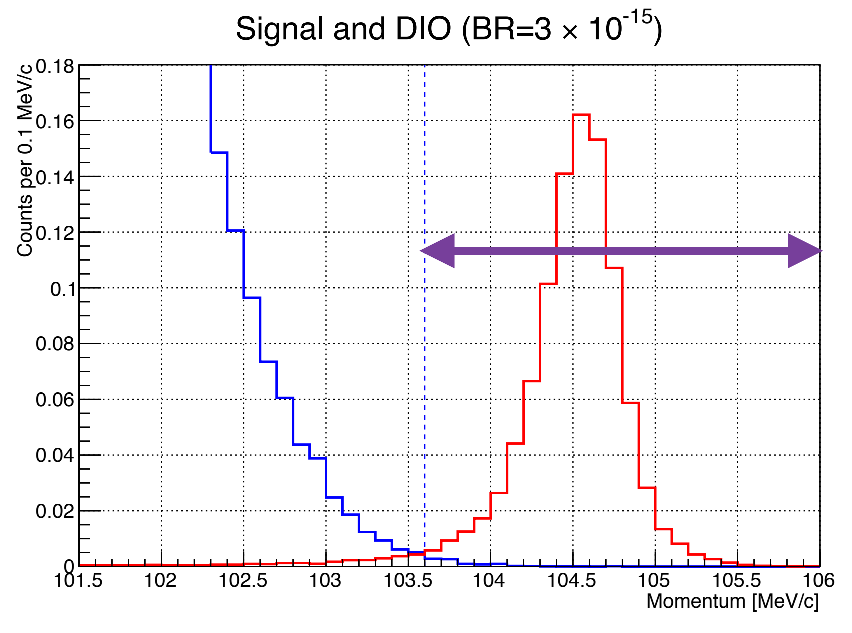


Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	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

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

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23\times10^{16}$ muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$

$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

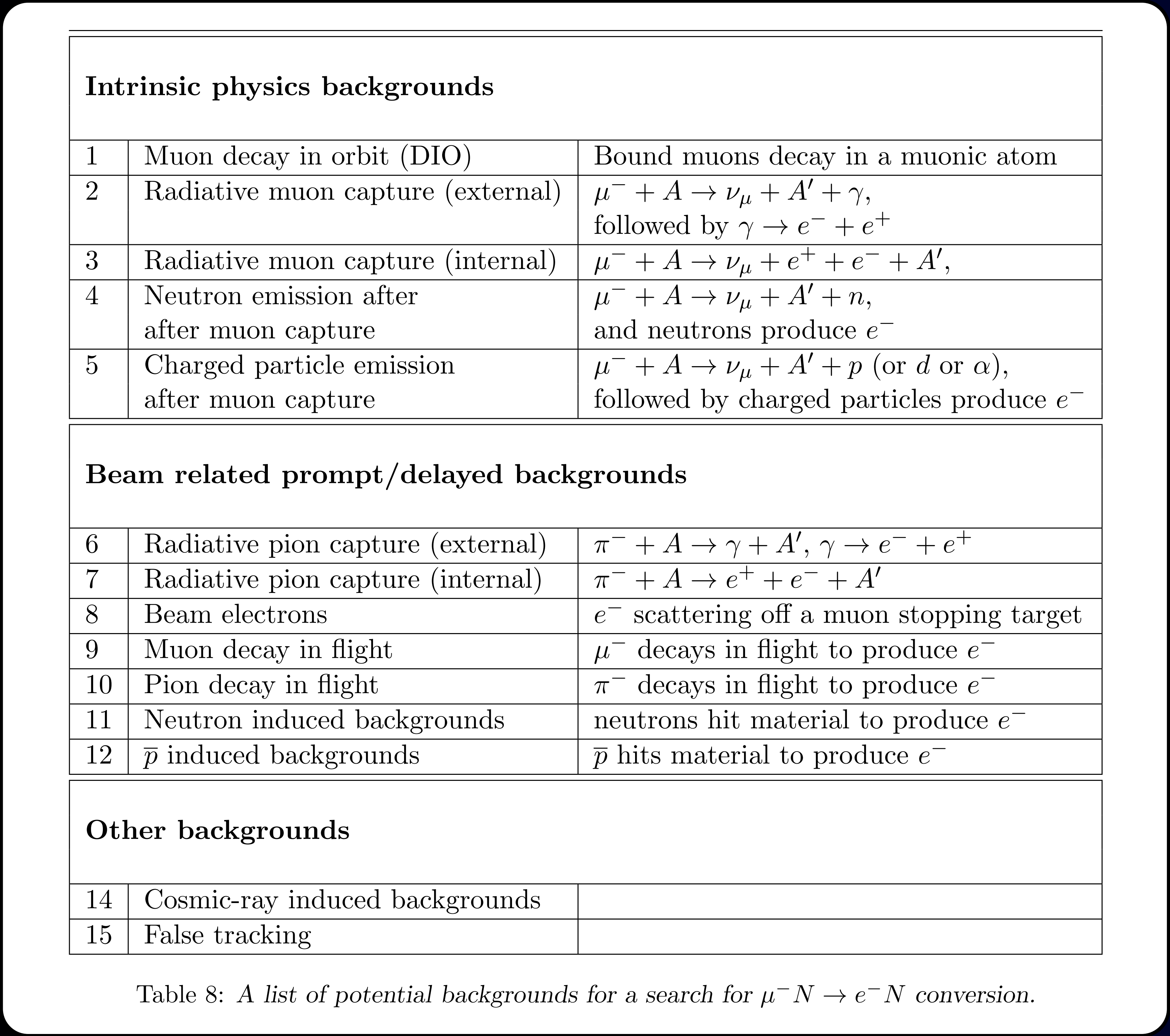
Muon intensity

about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 110 days is needed.

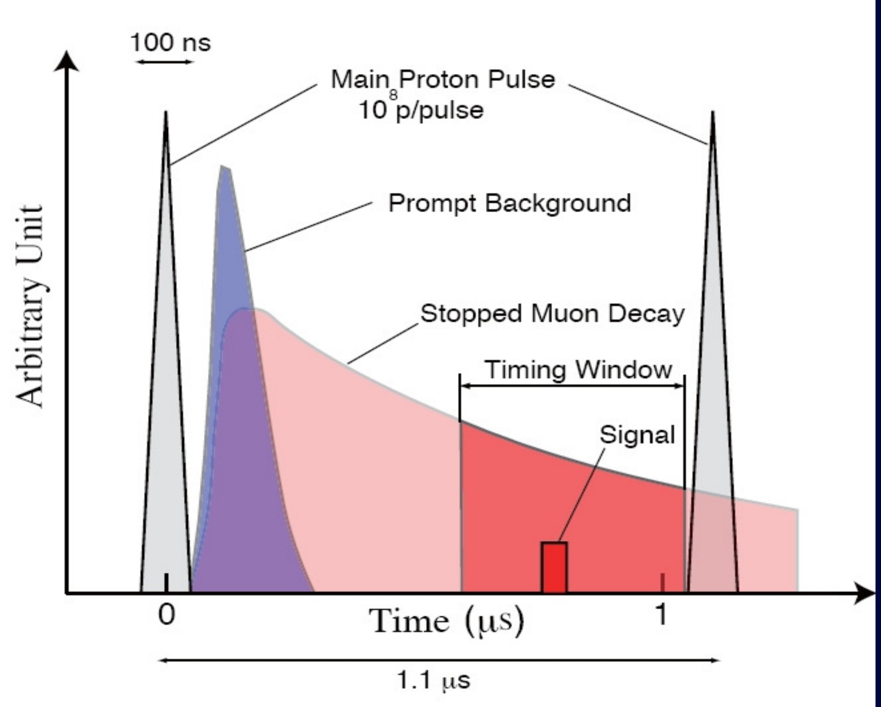
Energy

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	$\overline{p}$ induced backgrounds	$\overline{p}$ hits material to produce e^-
Other backgrounds		
14	Cosmic-ray induced backgrounds	
15	False tracking	

Table 8: *A list of potential backgrounds for a search for $\mu^- N \to e^- N$ conversion.*



prompt and delayed backgrounds

Background Estimate for μ-e conversion Search

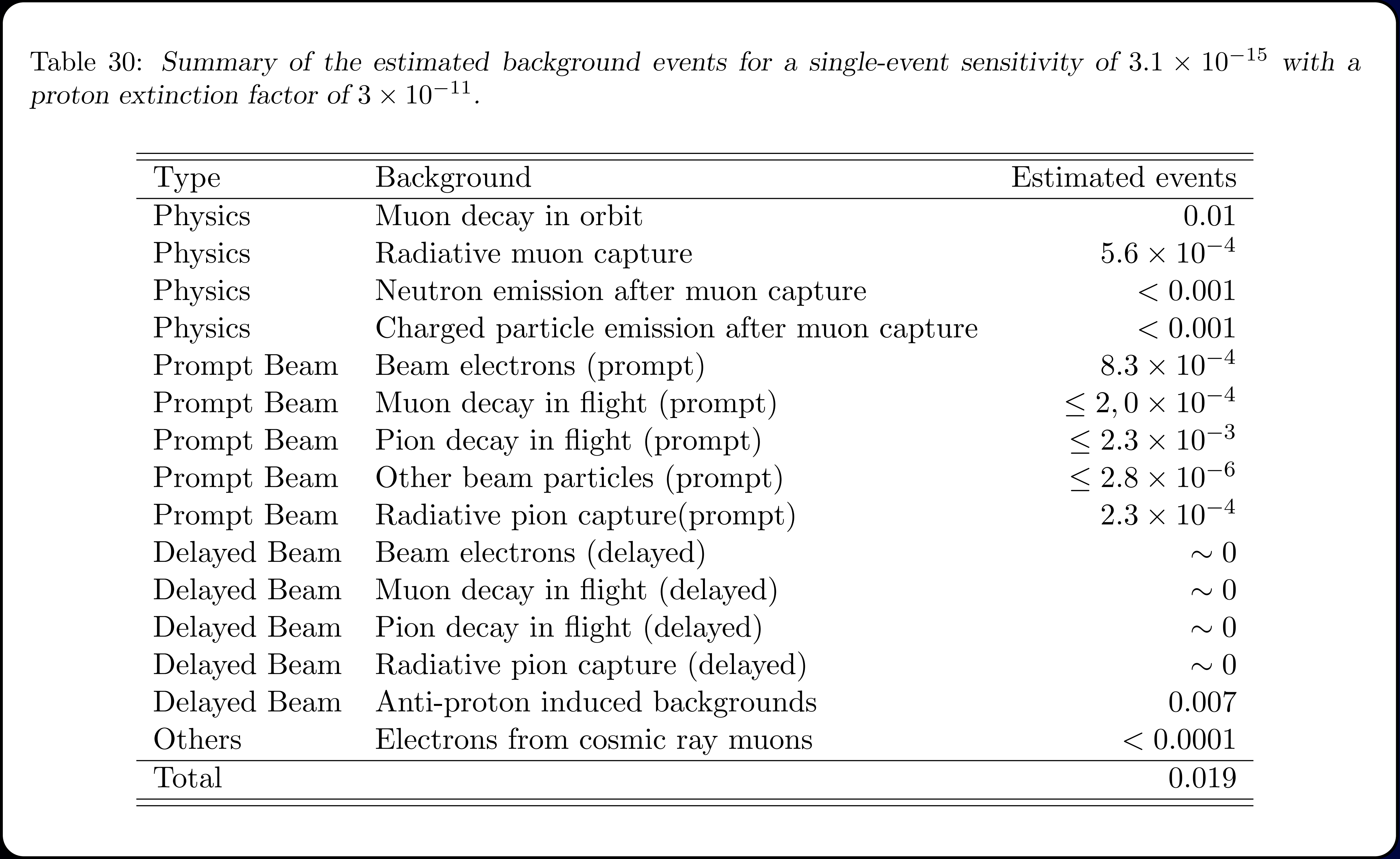
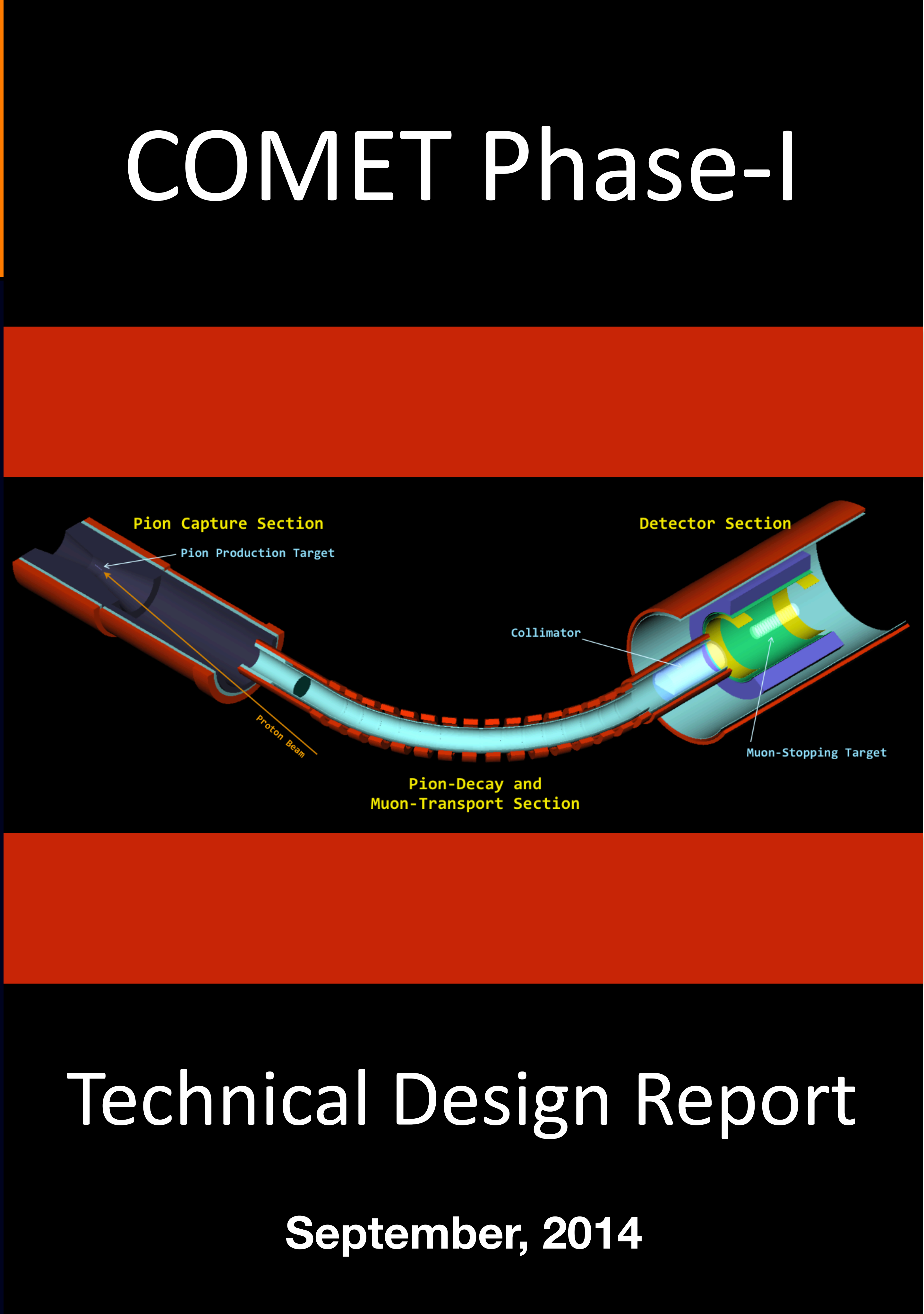


Table 30: *Summary of the estimated background events for a single-event sensitivity of* 3.1×10^{-15} *with a proton extinction factor of* 3×10^{-11}.

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)	8.3×10^{-4}
Prompt Beam	Muon decay in flight (prompt)	$\leq 2,0 \times 10^{-4}$
Prompt Beam	Pion decay in flight (prompt)	$\leq 2.3 \times 10^{-3}$
Prompt Beam	Other beam particles (prompt)	$\leq 2.8 \times 10^{-6}$
Prompt Beam	Radiative pion capture(prompt)	2.3×10^{-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

COMET TDR
September 2014

- The Technical Design Report (TDR) on COMET Phase-I (version September 2014) was submitted to the J-PARC PAC.
- It is a single document of 170 pages.
- The note of the COMET response to the KEK/IPNS Technical Review has been submitted to the PAC.

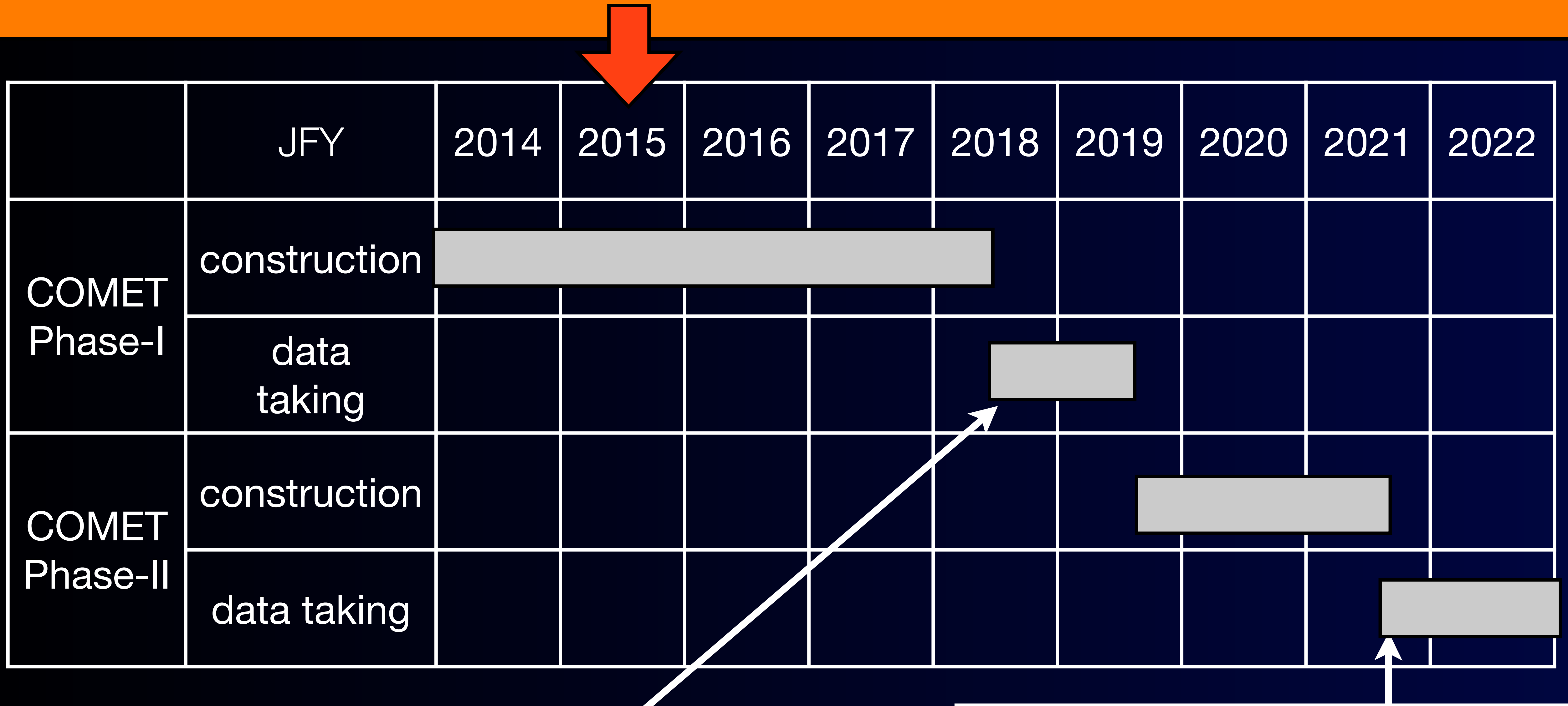


COMET Phase-I

Technical Design Report

September, 2014

Schedule of COMET Phase-I and Phase-II



COMET Phase-I :
2017 ~
S.E.S. ~ 3×10^{-15}
(for 110 days
with 3.2 kW proton beam)

COMET Phase-II :
2021~
S.E.S. ~ 3×10^{-17}
(for 2×10^{7} sec
with 56 kW proton beam)

Comparison of COMET Phase-I / Phase-II and Mu2e

90% C.L. upper limit is 7×10^{-13} (SINDRUM)

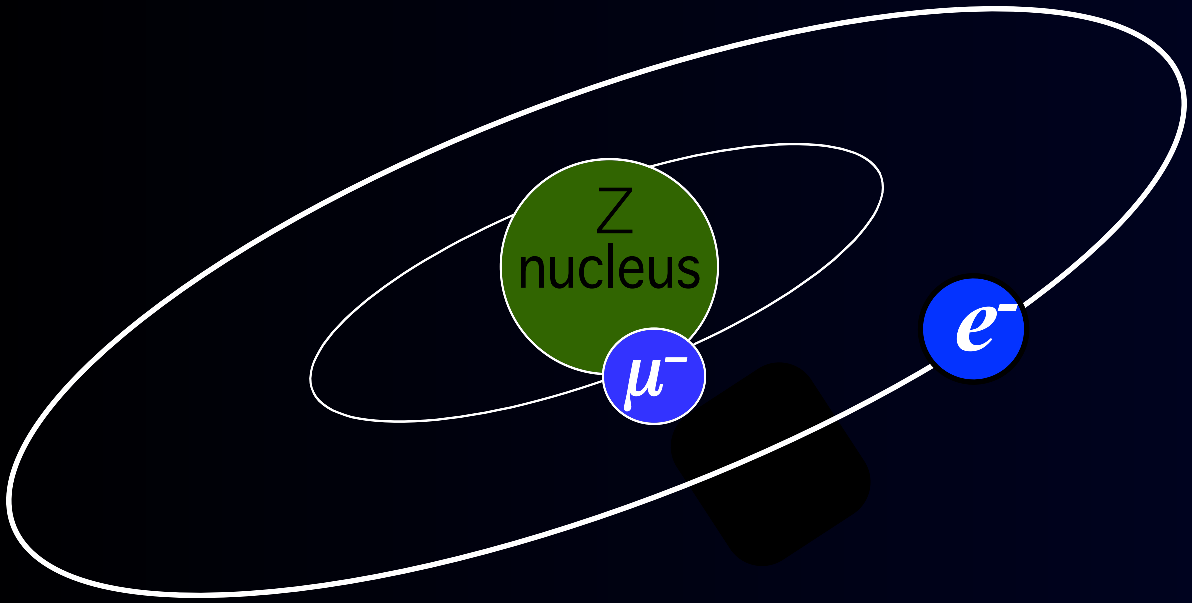
	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	3×10^{-15}	0.02	1.5×10^{6}	2018 -2019	Proposal (2012)
COMET Phase-II	3×10^{-17}	0.34	2×10^{7}	~2021	CDR (2009)
Mu2e	3×10^{-17}	0.37	3x (2×10^{7})	~2021	3 years

Other CLFV

Other CLFV Physics at COMET Phase-I

$\boxed{\mu^- + N(Z) \rightarrow e^+ + N(Z-2)}$

$\boxed{\mu^- + e^- \rightarrow e^- + e^-}$

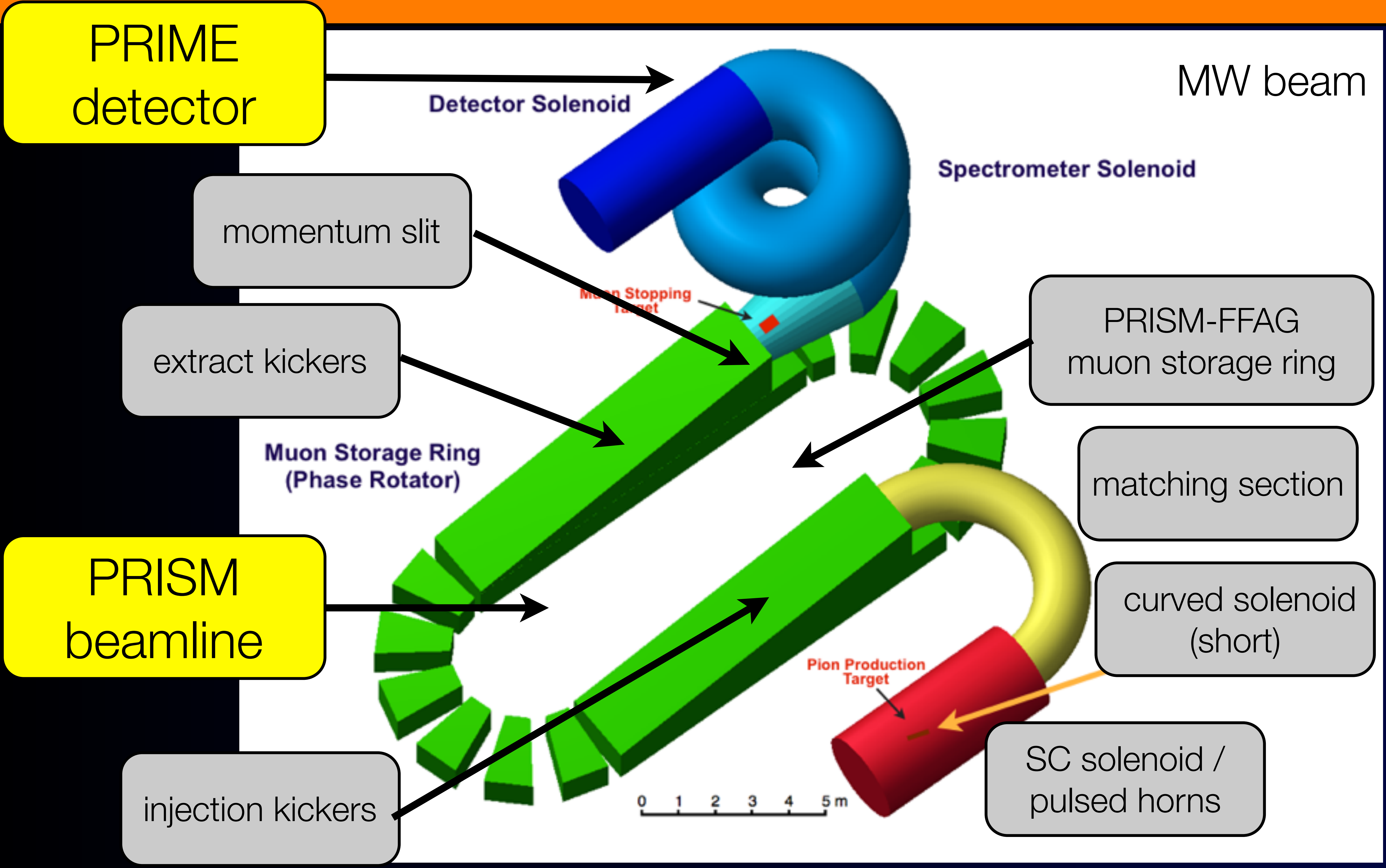


- $\mu^- e^- \rightarrow e^- e^-$ has two-body final state, although $\mu^+ \rightarrow e^+ e^+ e^-$ is a 3-body decay.
- A muonium CLFV decay such as $\mu^+ e^- \rightarrow e^+ e^+$ is a 2-body decay having a larger phase space, but the overwrap of μ^+ and e^- is small.

The overwrap between μ^- and e^- is proportional to Z^3. For Z=82 (Pb), the overwrap increases by a factor of 5×10^5 over the muonium. The rate is 10^{-17} to 10^{-18}.

PRISM (~10^{-19})

PRISM/PRIME : Future Search with S.E. sensitivity of 3×10^{-19}



MW beam

PRIME detector

momentum slit

extract kickers

PRISM beamline

injection kickers

PRISM-FFAG muon storage ring

matching section

curved solenoid (short)

SC solenoid / pulsed horns

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.
- COMET (Phase-II) at J-PARC is aiming at S.E. sensitivity of $3x10^{-17}$.
- COMET Phase-I is aiming at S.E. sensitivity of $3x10^{-15}$.
  - The construction of the beam line started at KEK in 2013.
  - The measurement will start in early 2018-2019.

New collaborators are welcome.