Imperial College London

COMET / PRISM

Beyond-the-Standard-Model Physics with Intense Muon Beams

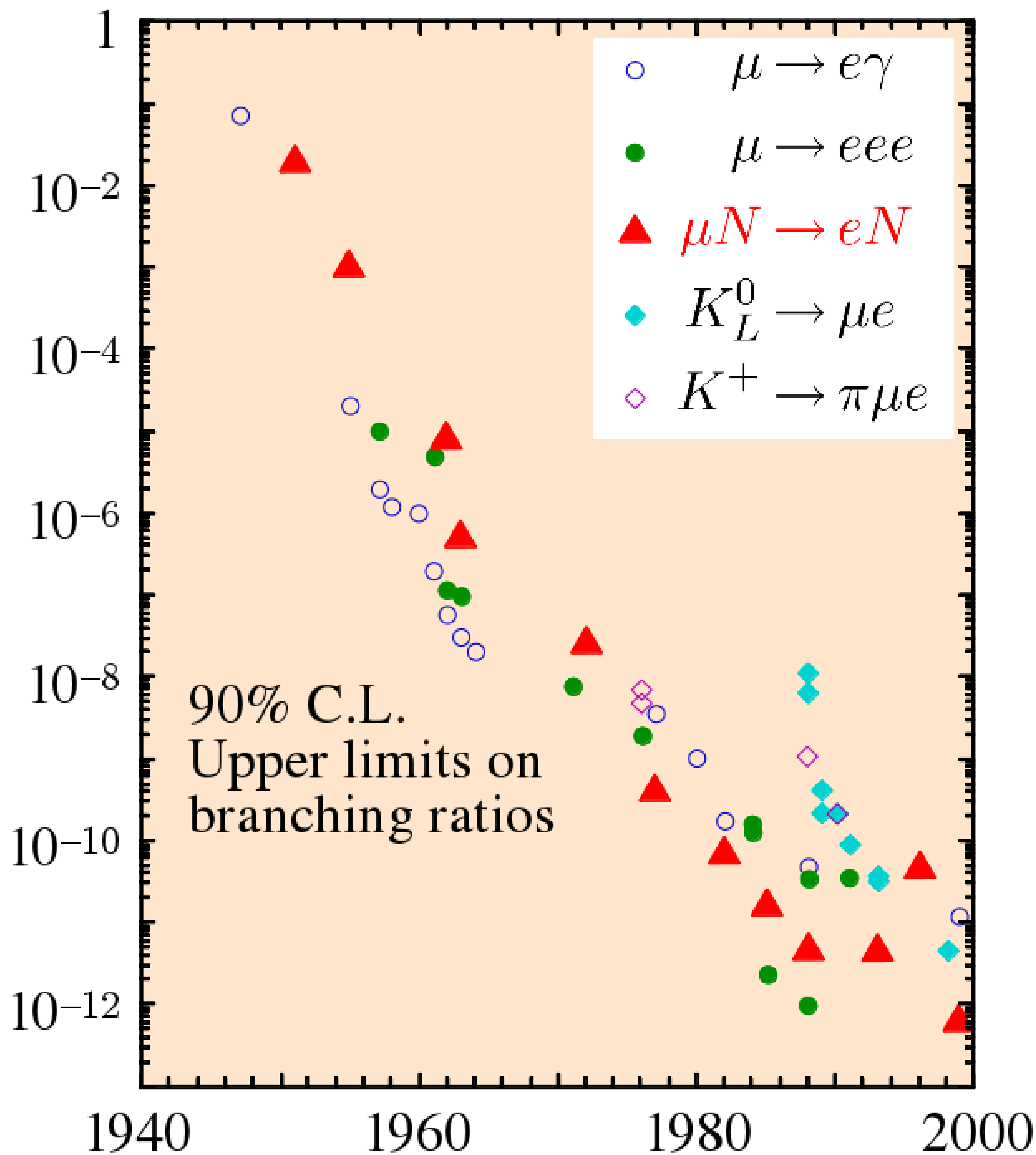
16 May 2012

The University of Birmingham

Yoshi Uchida

Flavour Violation in Leptons

Historical Progress on Muon Flavour Violation



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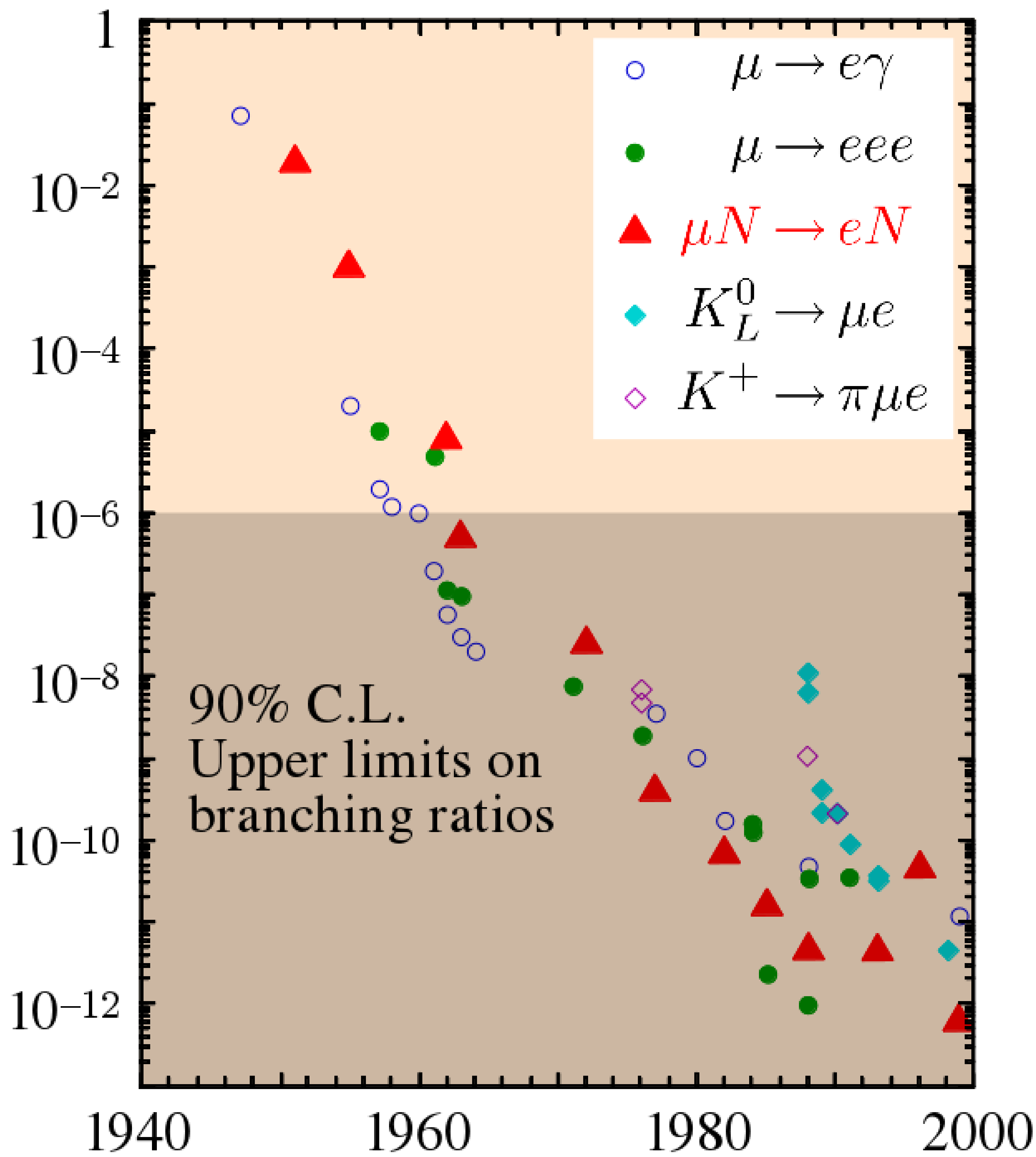
Historical Progress on Muon Flavour Violation



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LAW OF CONSERVATION OF MUONS*

G. Feinberg†
Department of Physics, Columbia University, New York, New York

and

S. Weinberg
Department of Physics, University of California, Berkeley, California
(Received February 8, 1961)

The apparent absence of muon-electron transitions without neutrinos, such as $\mu \to e + \gamma$, $\mu \to 3e$, and $\mu^- + p \to e^- + p$, leads one to suspect that there is a new conservation law forbidding them.

If we assume that μ^--e^- transitions are forbidden by a selection rule, the nature of the selection rule remains an open question. It has been suggested[3] that an additive quantum number exists which is always conserved, and which[4] is +1 for μ^- and zero for e^-. In order to make this consistent with known weak interactions, it is necessary to assume that there are two neutrinos, which are distinguished by their value of this quantum number. The conservation law forbids all reactions in which any nonzero number of muons change into electrons, without neutrinos.

This assumption of an additive conservation law is not the only possibility. All of the "missing reactions" involve odd numbers of muons and electrons. It is therefore possible to forbid them by a multiplicative conservation law. By this it

with Nishijima, Schwinger and others

The Second Neutrino Flavour

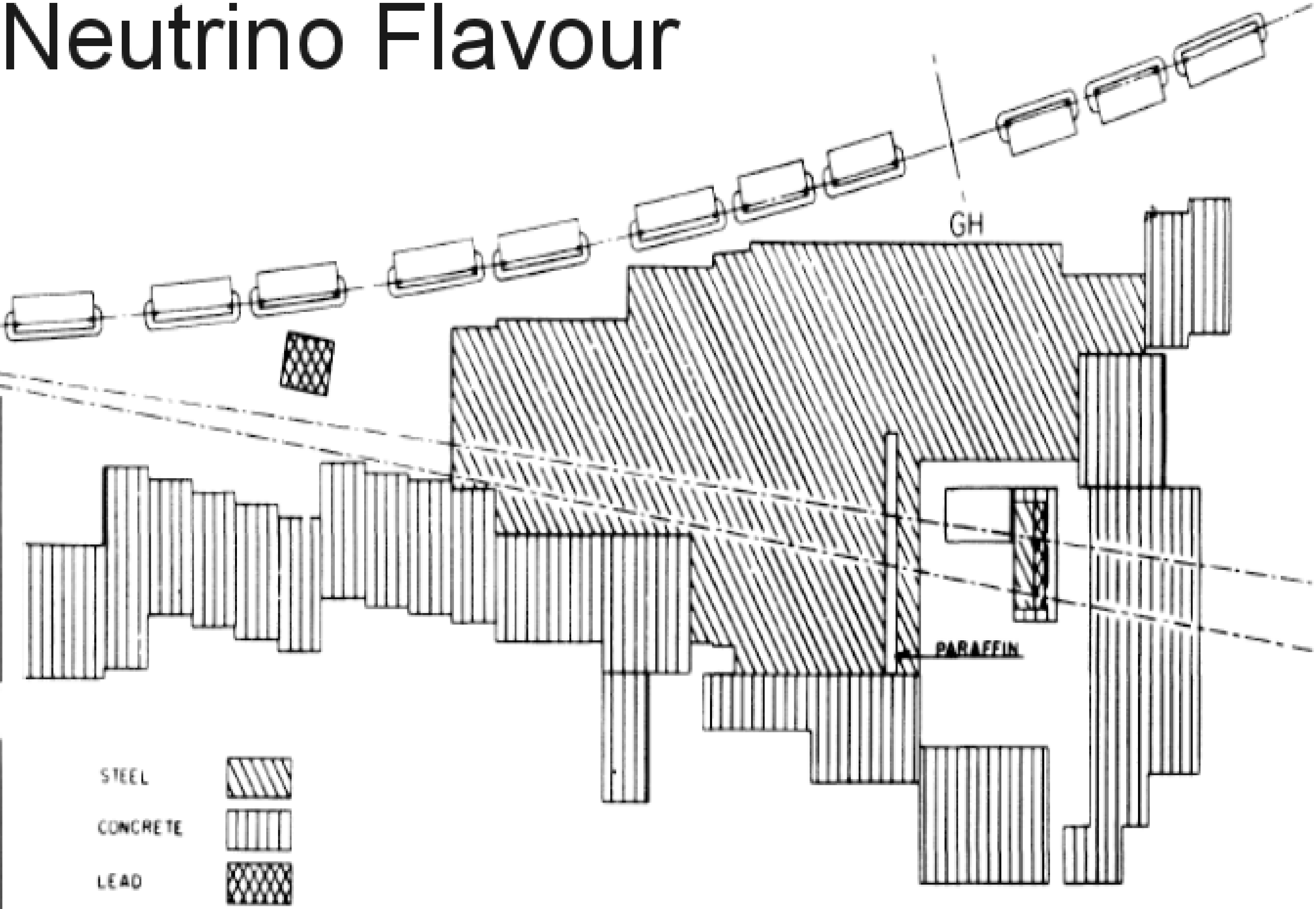
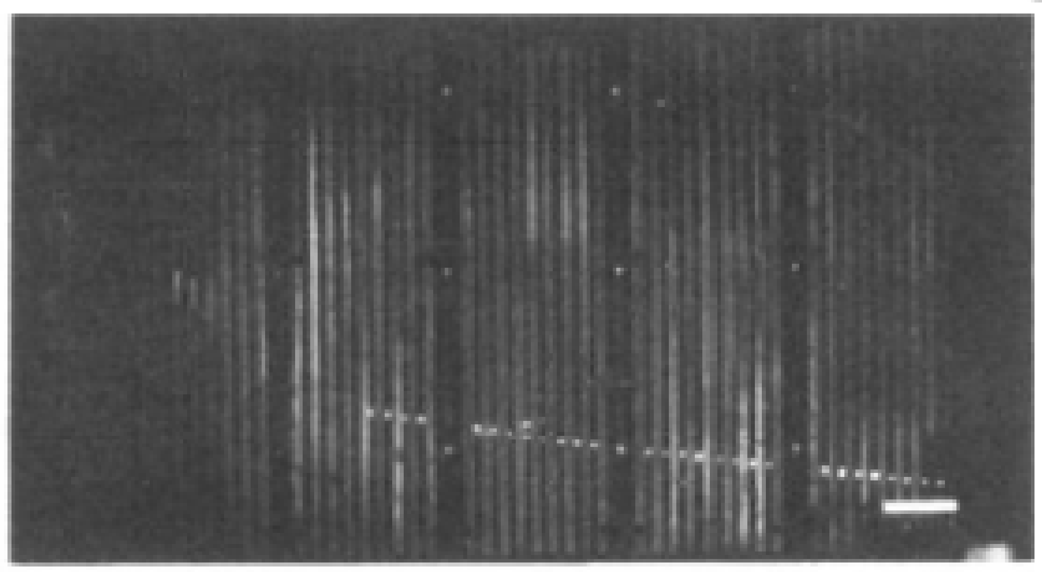
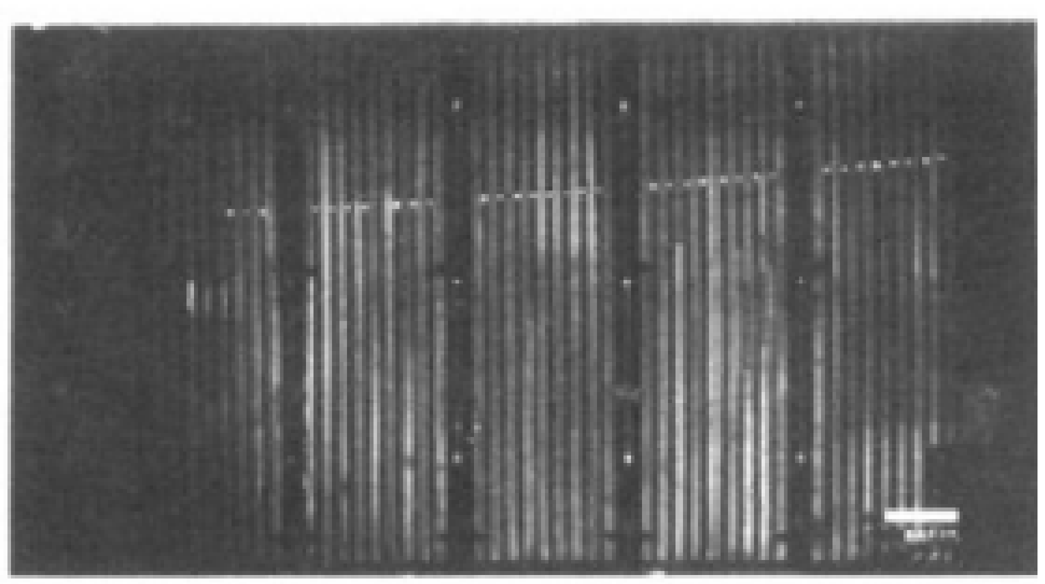
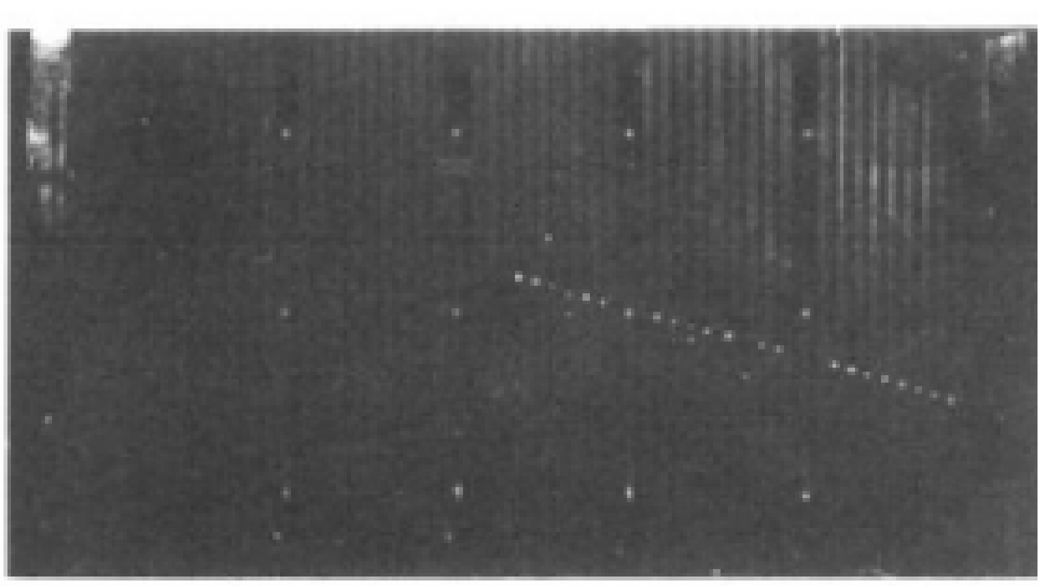


FIG. 1. Plan view of AGS neutrino experiment.

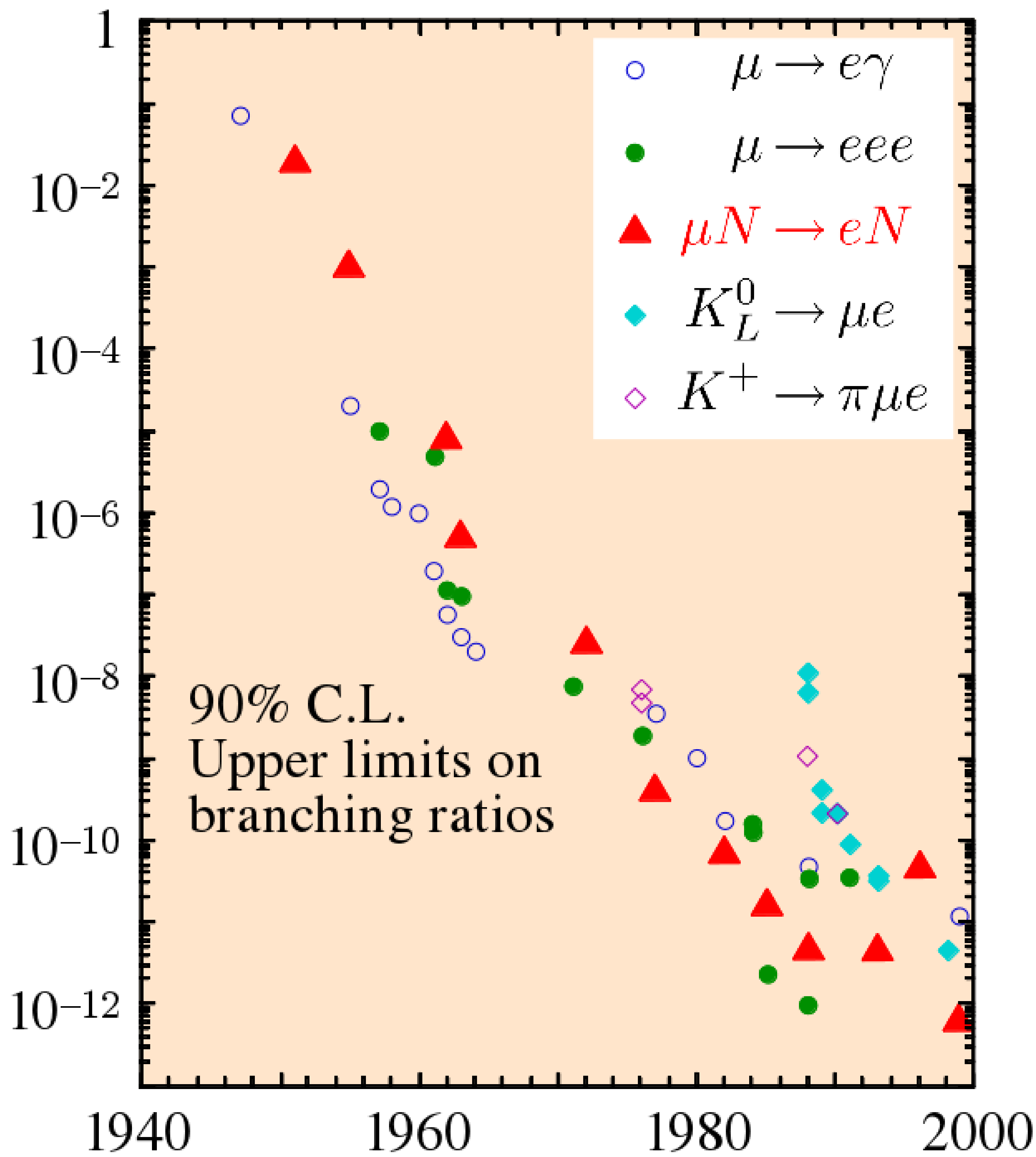






Discovery of “muon neutrinos” at Brookhaven, 1962
(Lederman, Schwartz, Steinberger)

Historical Progress on Muon Flavour Violation



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Experimental Limits on Lepton Flavour Violation

- 90% C.L. upper limits on the branching ratio

Reaction	Present limit
$\mu^+ \to e^+\gamma$	$< 1.2 \times 10^{-11}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau \to \mu\mu\mu$	$< 3.2 \times 10^{-8}$
$\tau \to eee$	$< 3.6 \times 10^{-8}$
$\pi^0 \to \mu e$	$< 3.8 \times 10^{-10}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

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$\pi^0 \to \mu e$	$< 3.8 \times 10^{-10}$
$K^0_L \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K^0_L \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

Signal selection

Event selection requires:

- events to be in ΔE, M_{ec} signal box
- signal track identified as an e (eγ) or μ (μγ)
- Signal candidates are divided in 5 categories, depending on decay in tag side and different selection is applied for each category

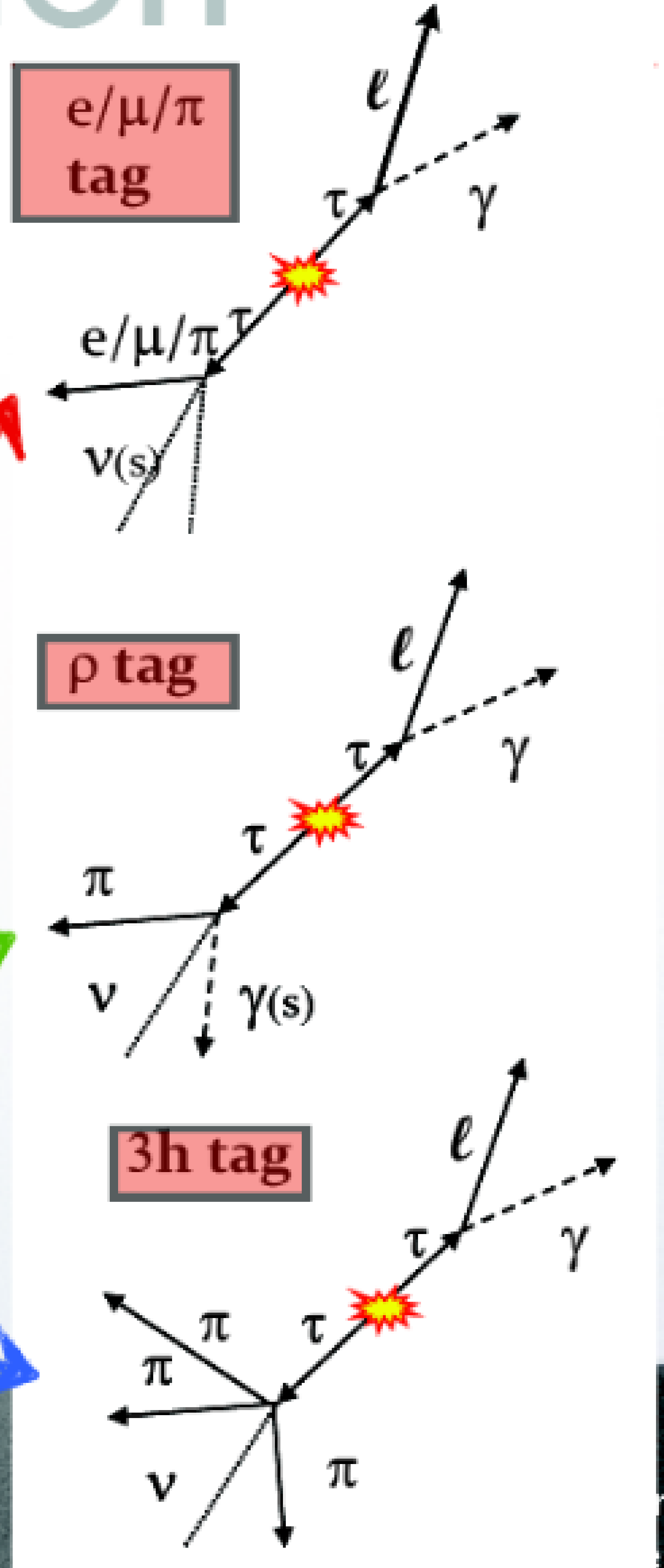
e-tag: tag track ID as electron, neutral energy in tag side < 200 MeV (e/μ)

μ-tag: tag track ID as μ, neutral energy in tag side < 200 MeV (e/μ)

π-tag: tag track ID neither e nor μ, neutral energy in tag side < 200 MeV (e/μ)

ρ-tag: tag track ID neither e nor μ, one π^0 candidate in tag side $m_\pi \in [90, 165]$ MeV

3h-tag: 3 tracks in tag side, not identified as e or μ

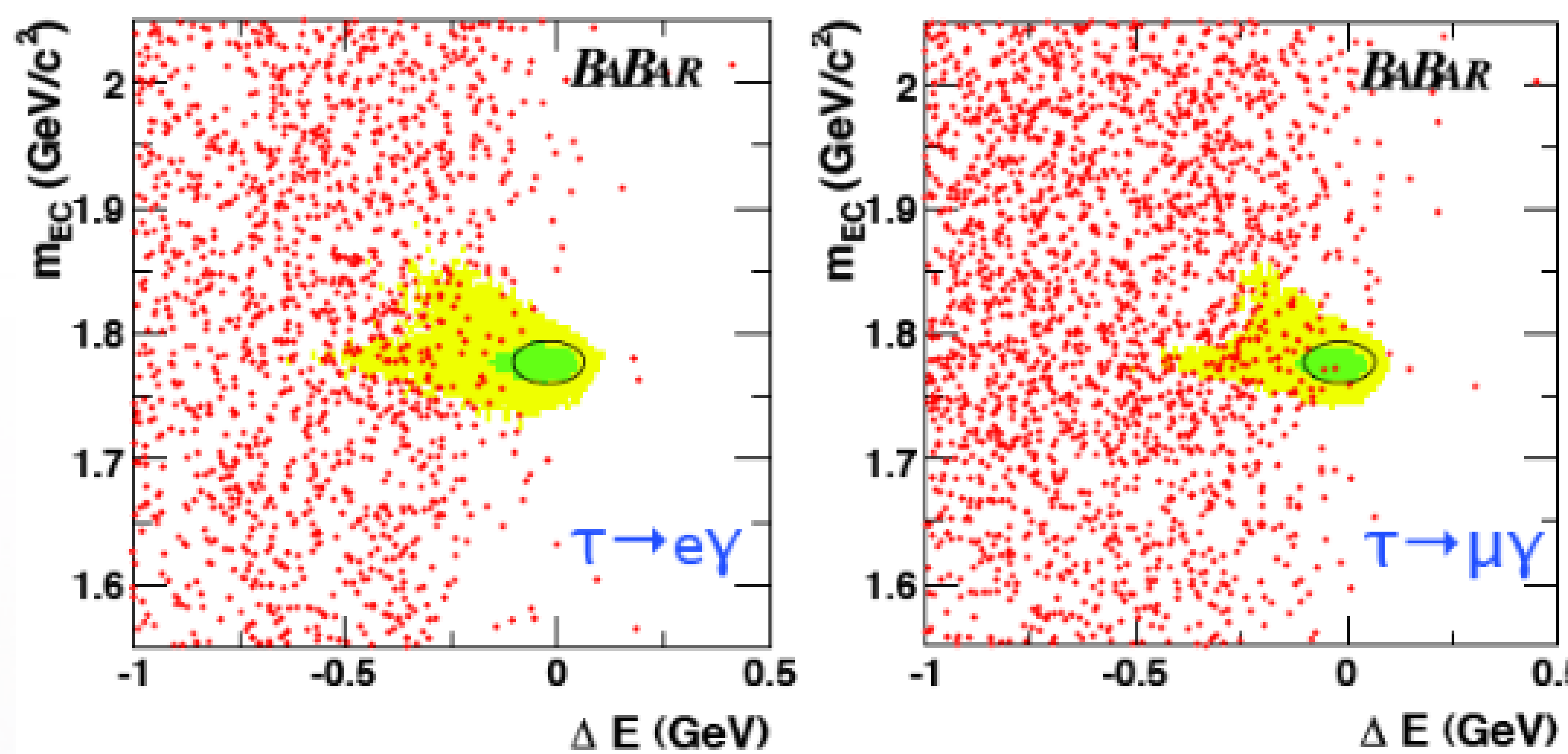


Results

N_τ = 963 ± 7 M (515 fb^{-1})

τ→eγ
- Efficiency (2σ) = 3.9 ± 0.3 %
- Expected Bkg = 1.6 ± 0.5 events
- Expected Upper Limit: 9.8 x 10^{-8}
- Observed Number of events: 0

- Previous Limits:
  - BaBar (232 fb-1): 1.1x 10^{-7}
  - Belle (535 fb-1): 1.2 x 10^{-7}



$$\mathcal{B}\ (\tau^{\pm} \to e^{\pm}\gamma) < 3.3 \times 10^{-8}$$

$$\mathcal{B}\ (\tau^{\pm} \to \mu^{\pm}\gamma) < 4.4 \times 10^{-8}$$

PRL104,021802(2010)

τ→μγ
- Efficiency (2σ) = 6.1 ± 0.5 %
- Expected Bkg = 3.6 ± 0.6 events
- Expected Upper Limit: 8.1 x 10^{-8}
- Observed Number of events: 2

- Previous Limits:
  - BaBar (232 fb-1): 6.8x 10^{-8}
  - Belle (535 fb-1): 4.5 x 10^{-8}

Belle: Phys.Lett.B666:16,2008

Results

N_τ = 963 ± 7 M (515 fb^{-1})

τ→eγ
- Efficiency (2σ) = 3.9 ± 0.3 %
- Expected Bkg = 1.6 ± 0.5 events
- Expected Upper Limit: 9.8 x 10^{-8}
- Observed Number of events: 0

- Previous Limits:
  - BaBar (232 fb^{-1}): 1.1x 10^{-7}
  - Belle (535 fb^{-1}): 1.2 x 10^{-7}

$$\mathcal{B}\,(\tau^\pm \to e^\pm\gamma) < 3.3 \times 10^{-8}$$

$$\mathcal{B}\,(\tau^\pm \to \mu^\pm\gamma) < 4.4 \times 10^{-8}$$

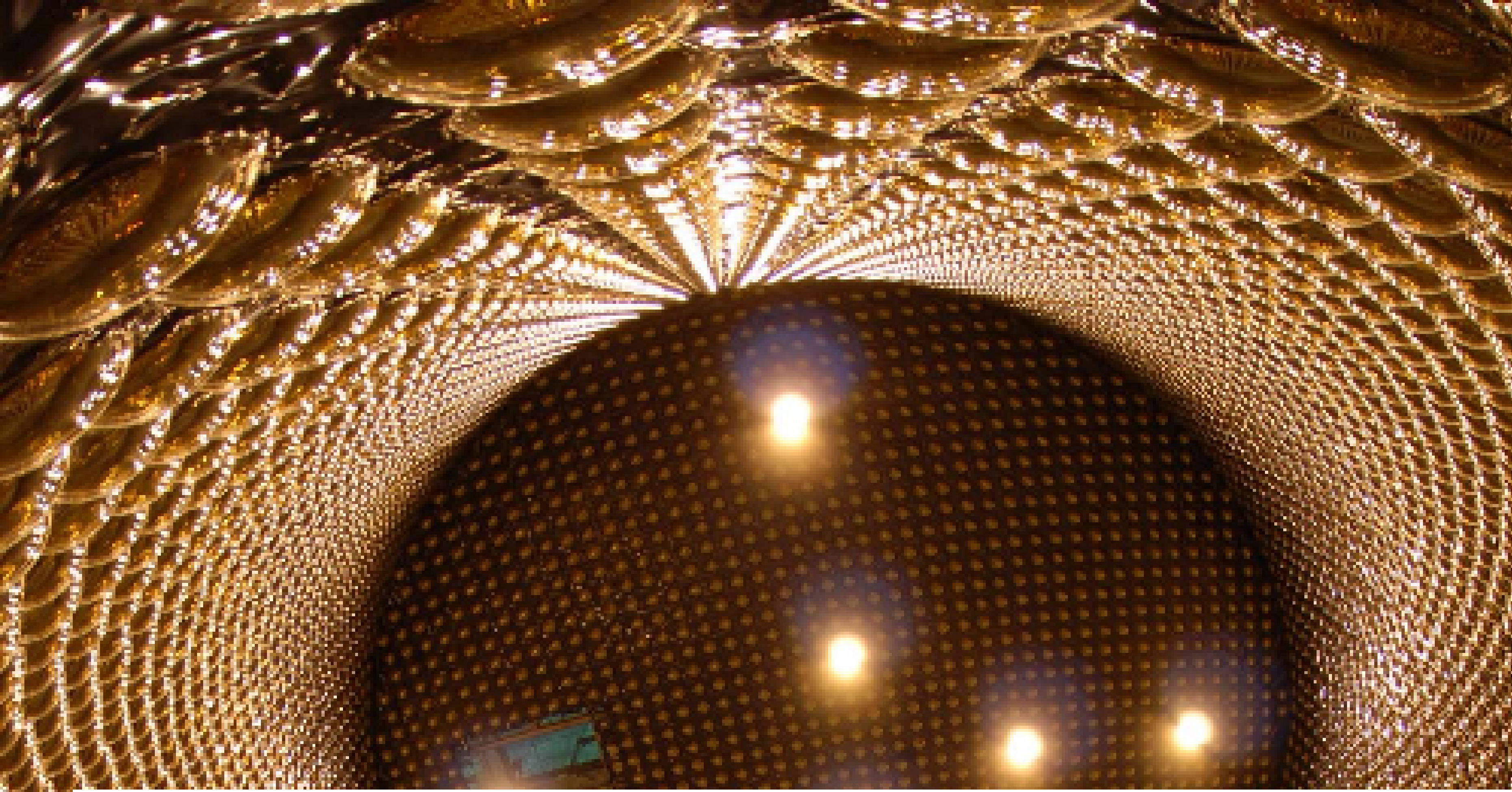
PRL104,021802(2010)

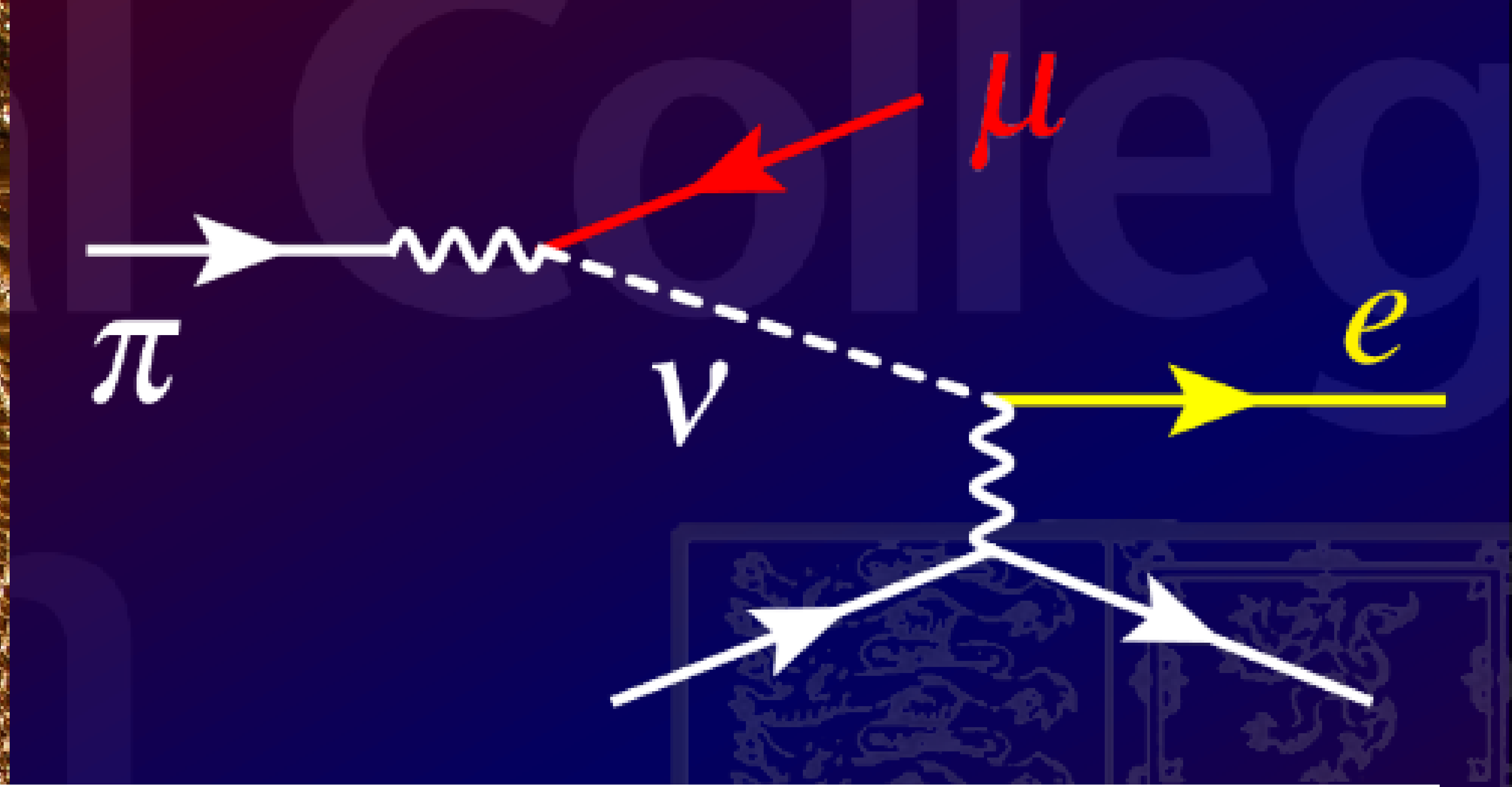
Belle: Phys.Lett.B666:16,2008

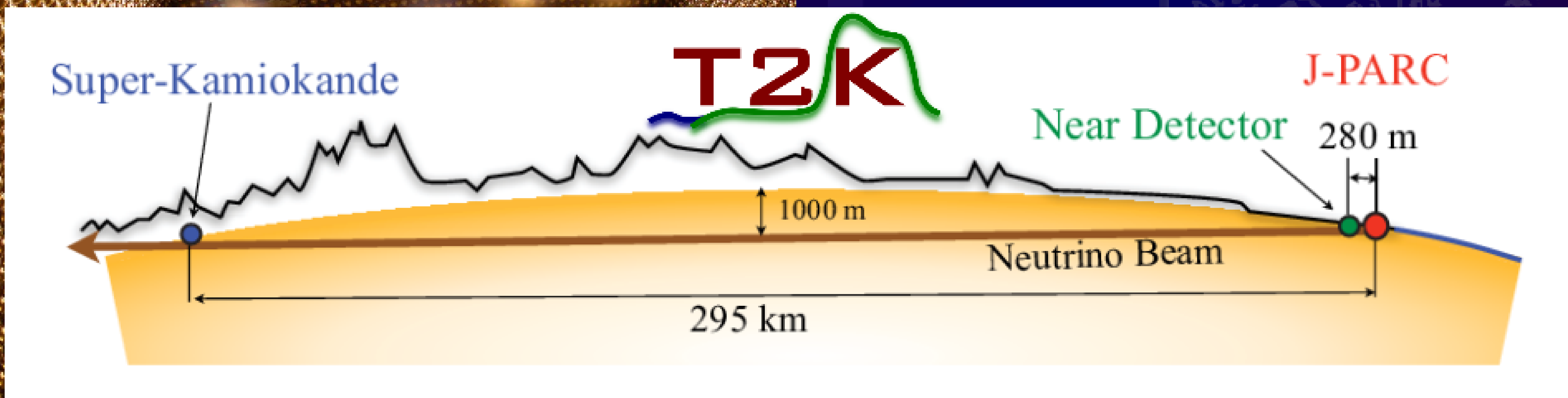
- To be improved by a factor 10 at next-generation B factories
- For new physics through loop processes, corresponds to muon-decay flavour violation at 1000 times rarer rates

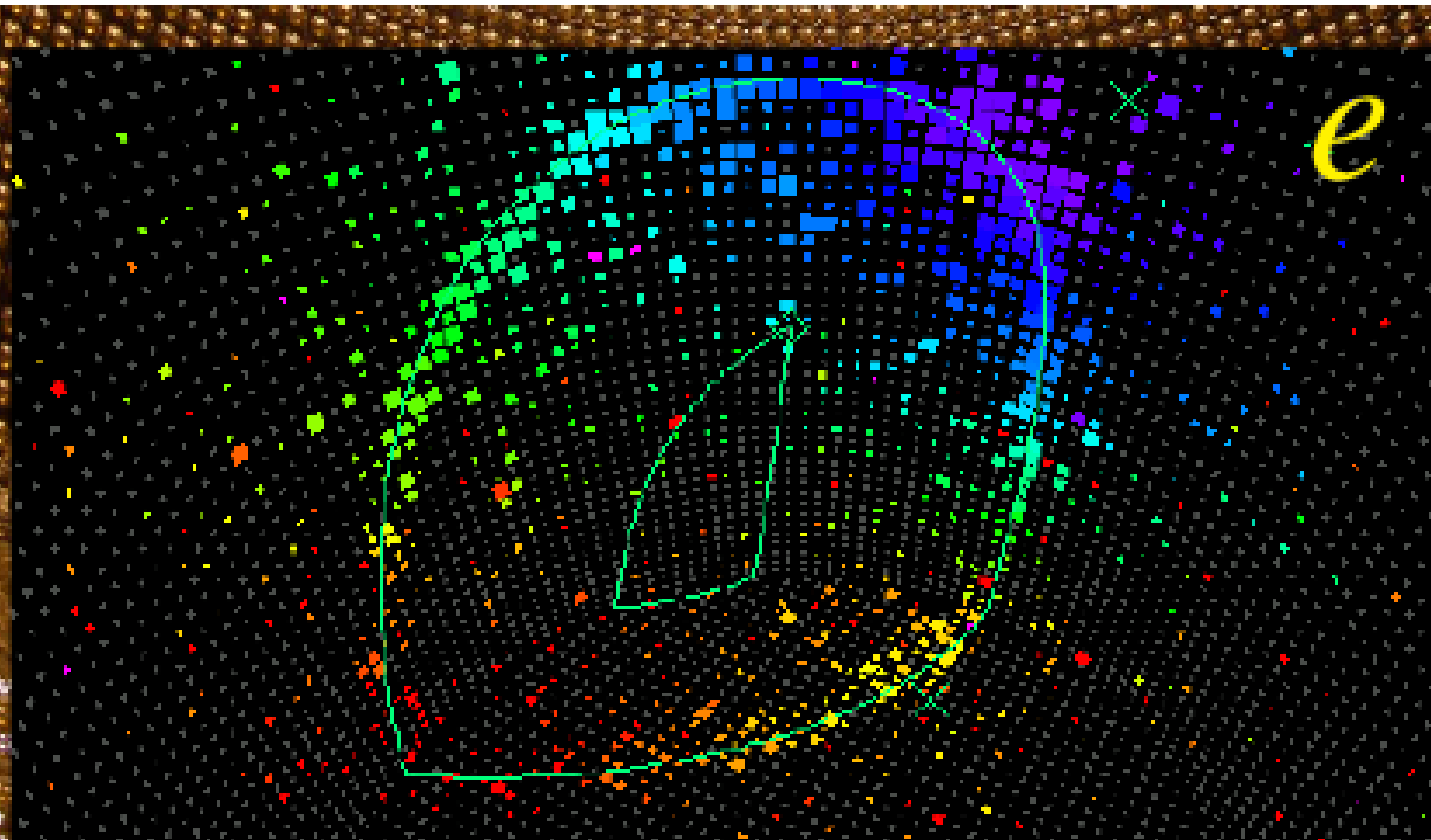
Predictions for Charged Lepton Flavour Violation

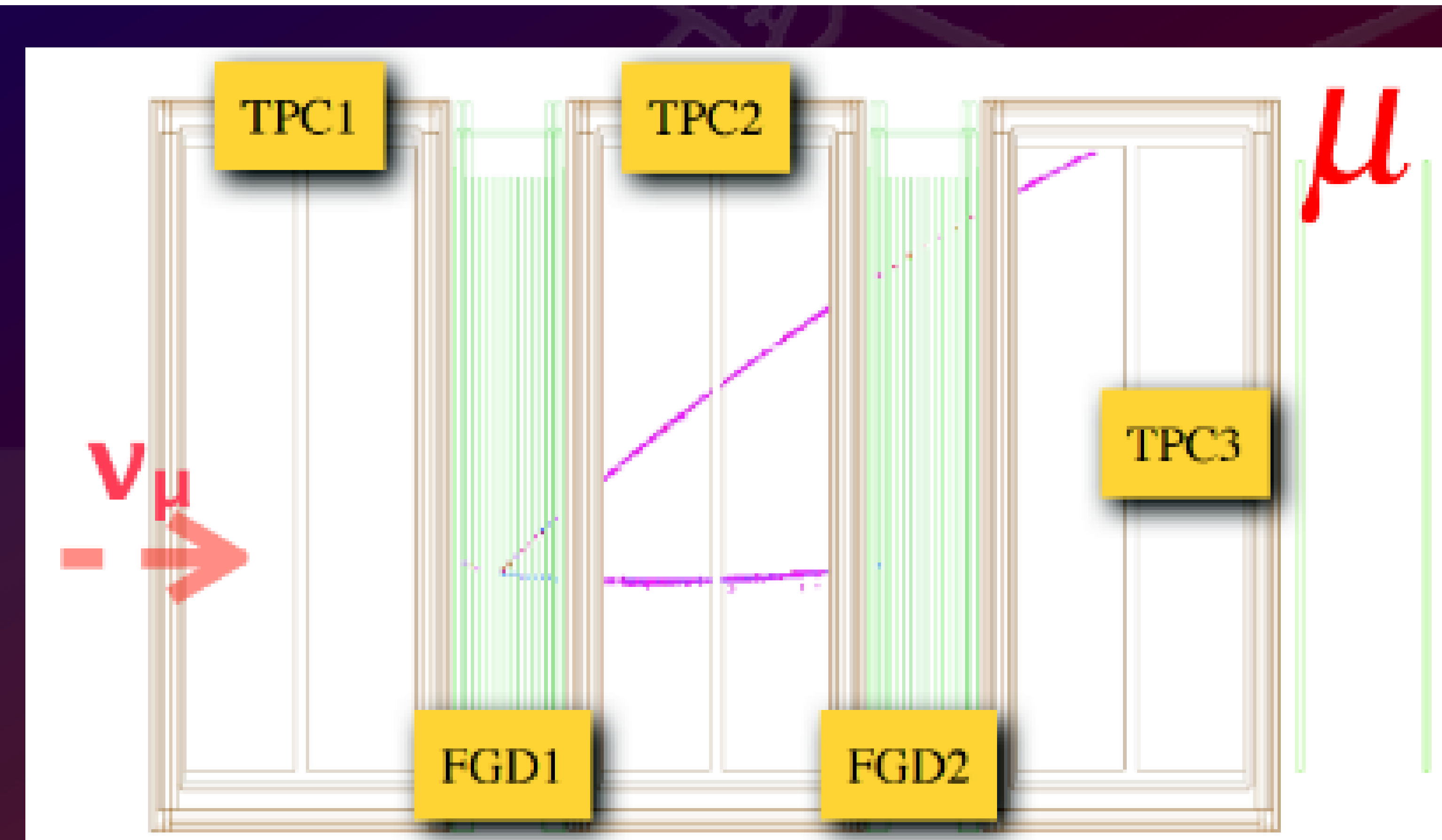
- cLFV $\equiv 0$ in the Standard Model
  - all interactions conserve lepton flavour
  - following Feinberg, Weinberg and others
- ...but the Standard Model is wrong!




μ
π
ν
e


T2K
Super-Kamiokande
J-PARC
Near Detector
280 m
1000 m
Neutrino Beam
295 km

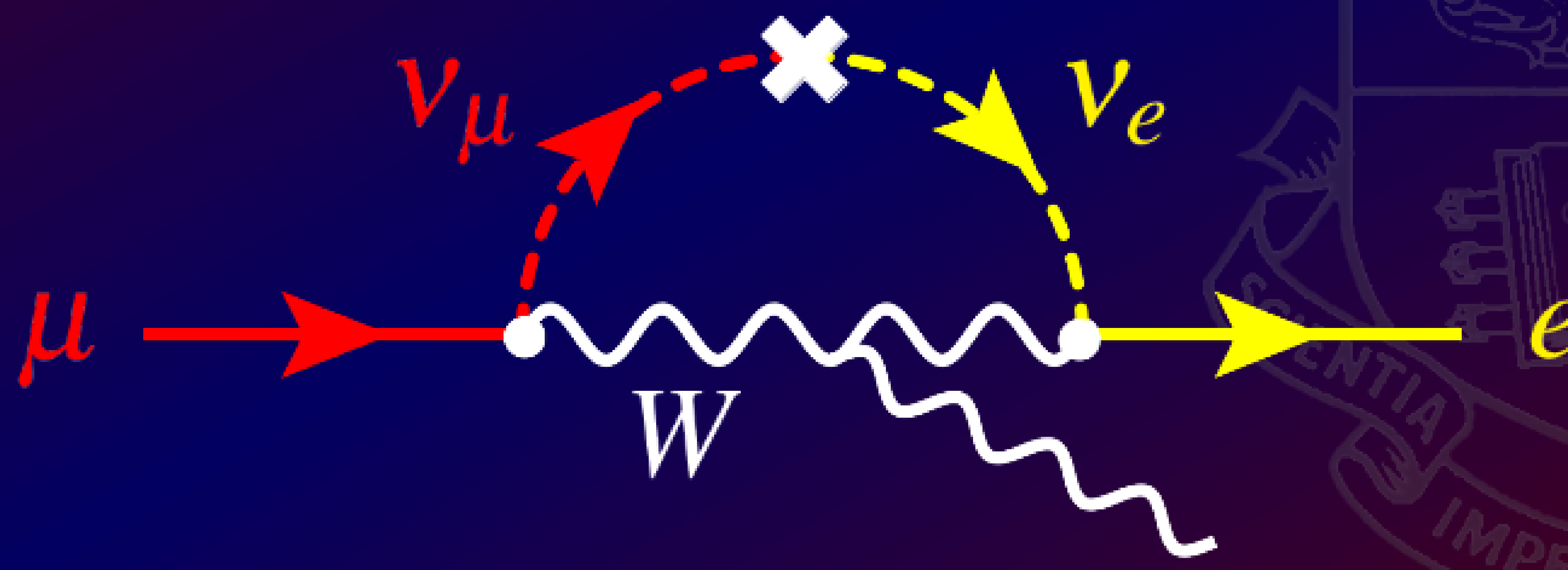

e


TPC1
TPC2
TPC3
μ
FGD1
FGD2

Predictions for Charged Lepton Flavour Violation

- cLFV ≡ 0 in the Standard Model

- If SM is **minimally extended** for neutrino masses and oscillations:



- $\mathrm{Br}(\mu \to e + \gamma) \sim 10^{-50} \Rightarrow$ **unambiguous** signal for new physics if seen

Lepton Flavour Violation from New Physics

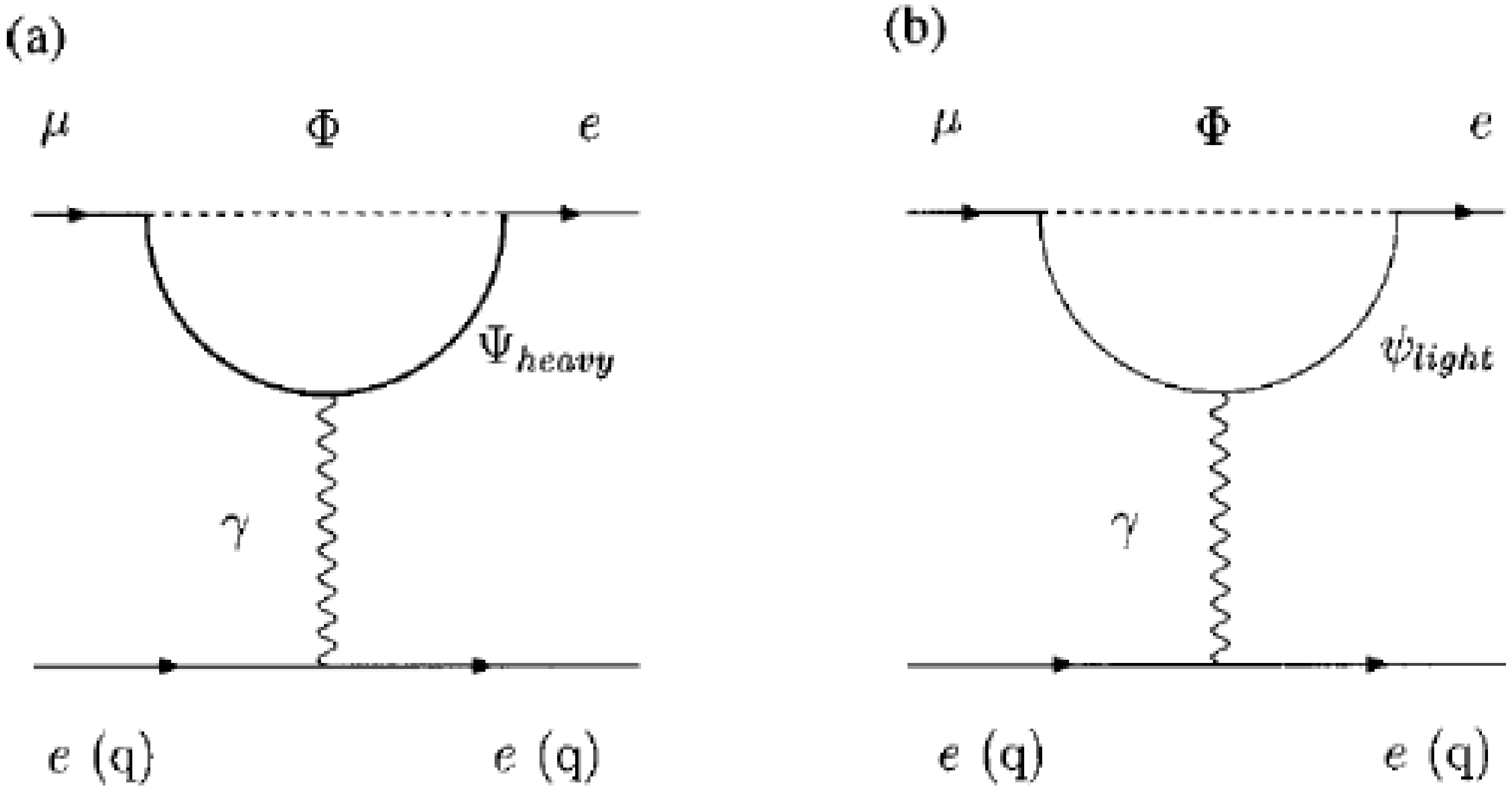


FIG. 4. Photonic penguin diagrams for $\mu - e$ transitions, such as $\mu^+ \rightarrow e^+ e^+ e^-$ or $\mu^- - e^-$ conversion: (a) the case of a heavy particle (Ψ_{heavy}) in the loop; (b) the case of a light fermion (ψ_{light}) in the loop. Φ is a scalar field.

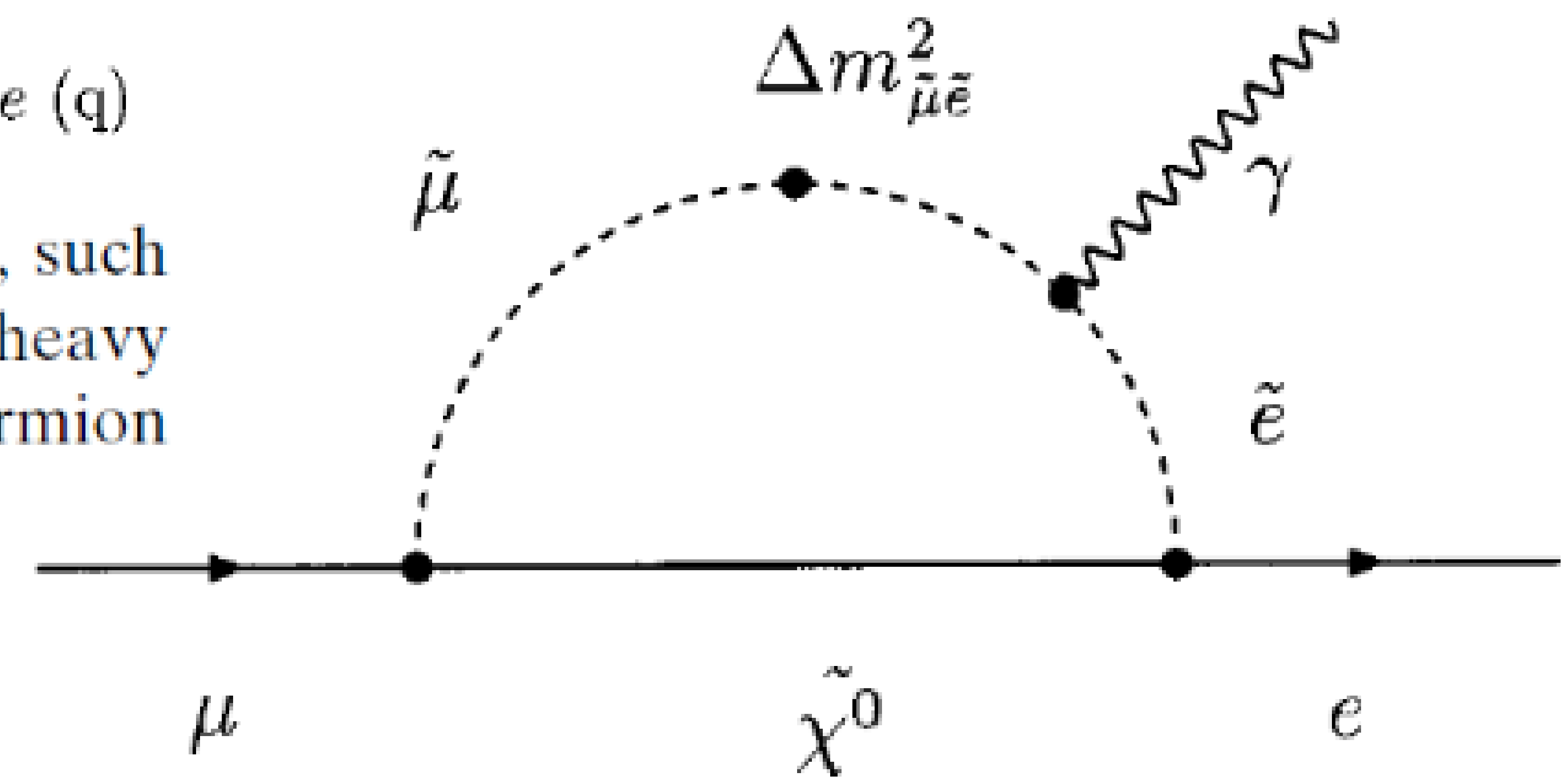


FIG. 5. Feynman diagram for $\mu^+ \rightarrow e^+ \gamma$ decay induced by slepton flavor mixing ($\Delta m^2_{\tilde{\mu}\tilde{e}}$).

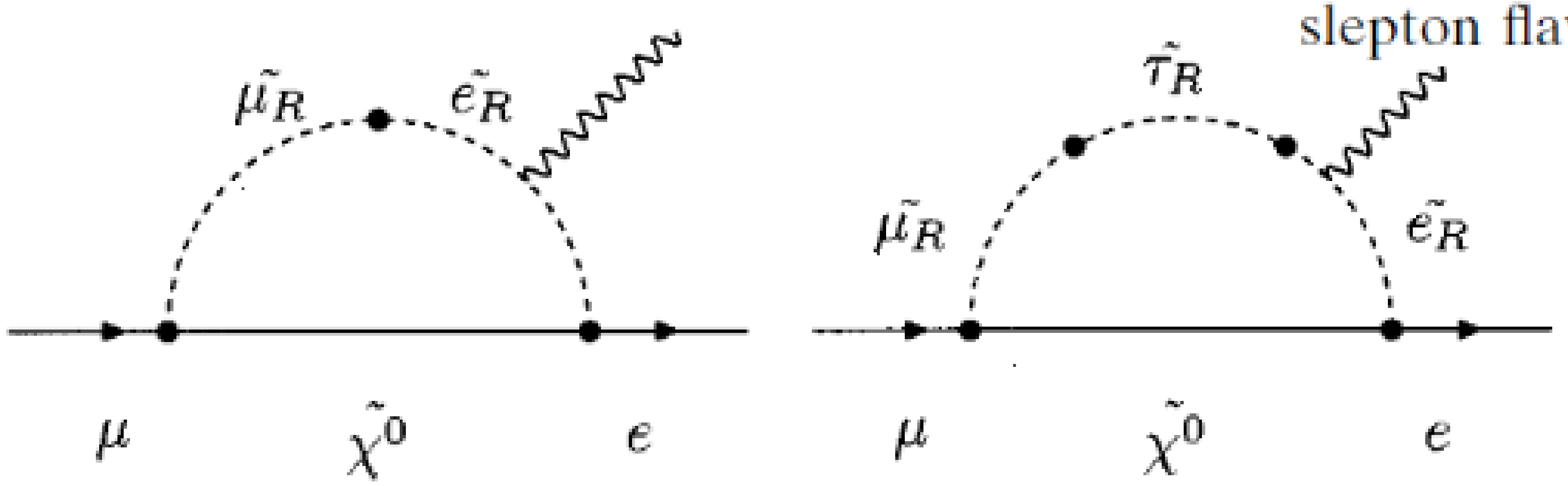


FIG. 7. Feynman diagrams for the $\mu^+ \rightarrow e^+ \gamma$ decay in $SU(5)$ SUSY GUT. The closed blobs represent the flavor transitions due to the off-diagonal terms of the slepton mass matrices.

Predictions for Charged Lepton Flavour Violation

- Beyond the Standard Model physics predicts detailed cLFV rates
  - For example, *if* new states exist at the mass scale M, and cLFV is photon mediated, effective Lagrangian via loops gives:

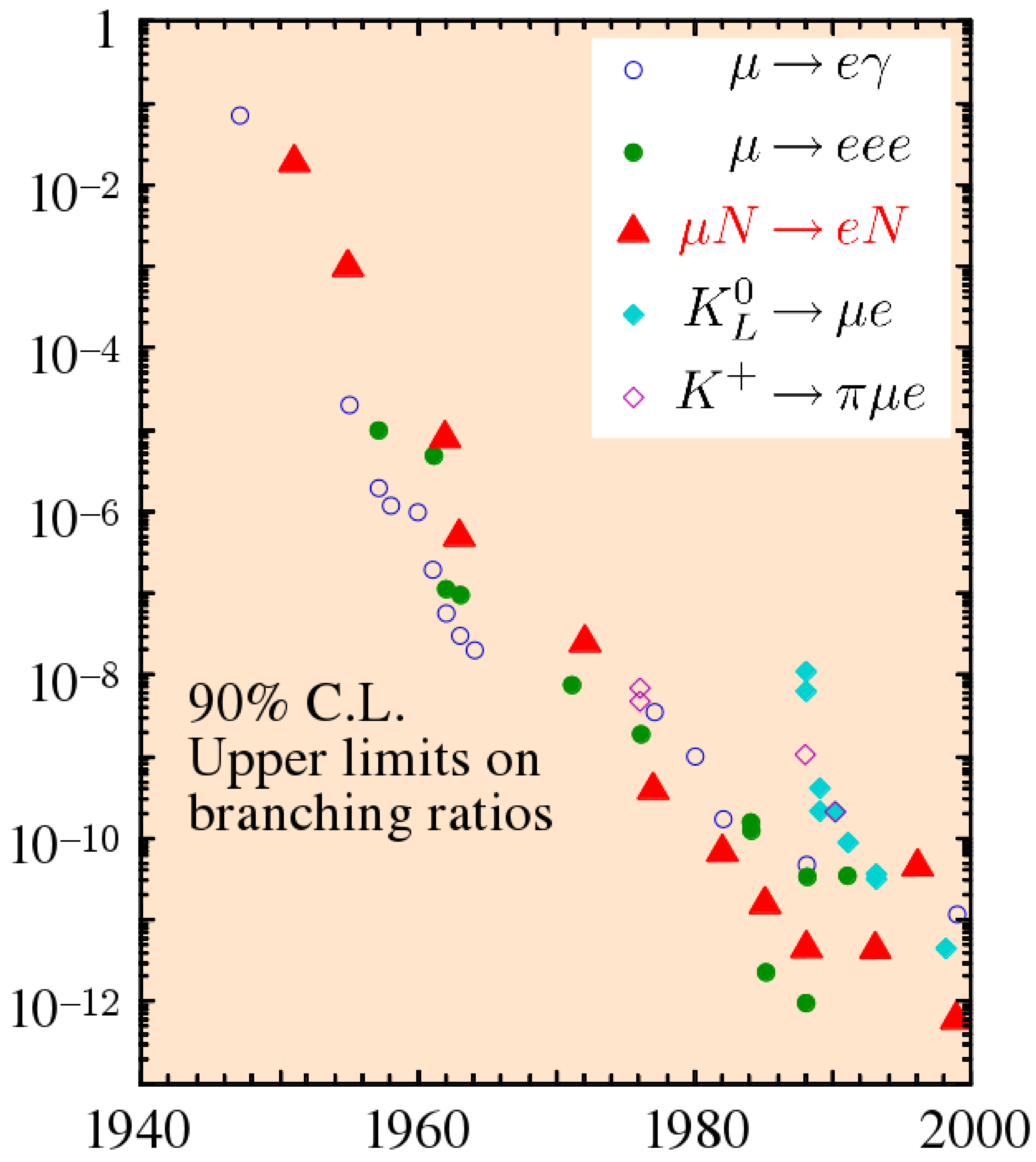
$$\mathscr{L} = e\frac{g^2}{16\pi^2}\frac{m_\ell}{M^2}\bar{\mu}\sigma^{\alpha\beta}eF_{\alpha\beta} \quad \Rightarrow$$

$$B(\mu + N \to e + N) \quad \sim \quad \left(\frac{280[\mathrm{TeV}]}{M}\right)^4 \times 10^{-18}$$

$$B(\mu \to e + \gamma) \quad \sim \quad \left(\frac{110[\mathrm{TeV}]}{M}\right)^4 \times 10^{-14}$$

(For this case, O(100) smaller than $\mu \to e + \gamma$. Dependence on lepton mass)

Historical Progress on Charged Lepton Flavour Violation



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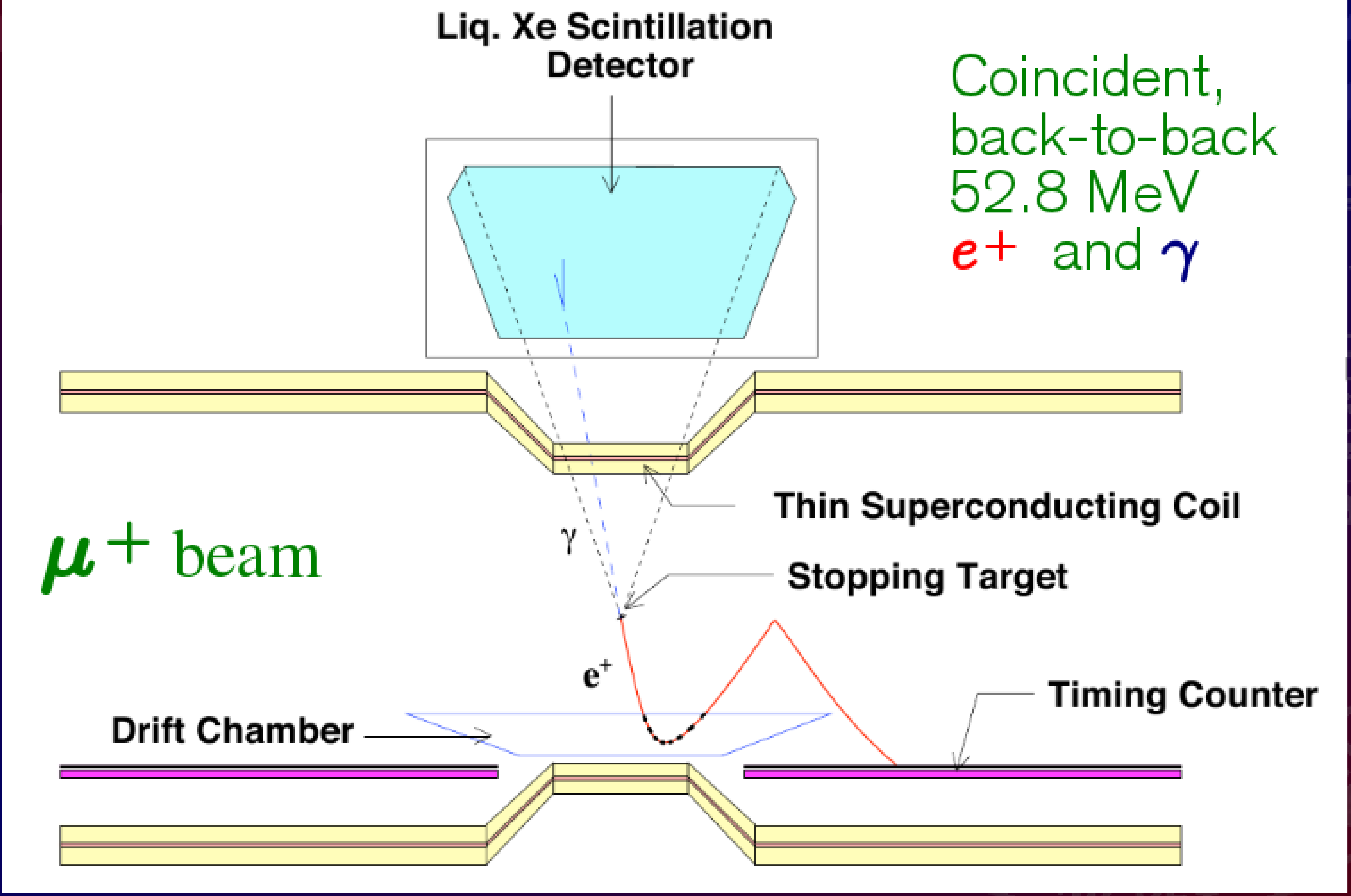
MEG ($\mu \rightarrow e\gamma$) at PSI

- Aiming for sensitivity down to branching ratio of 10^{-13}
- First Physics run from September to December 2008



MEG ($\mu \rightarrow e\gamma$) at PSI

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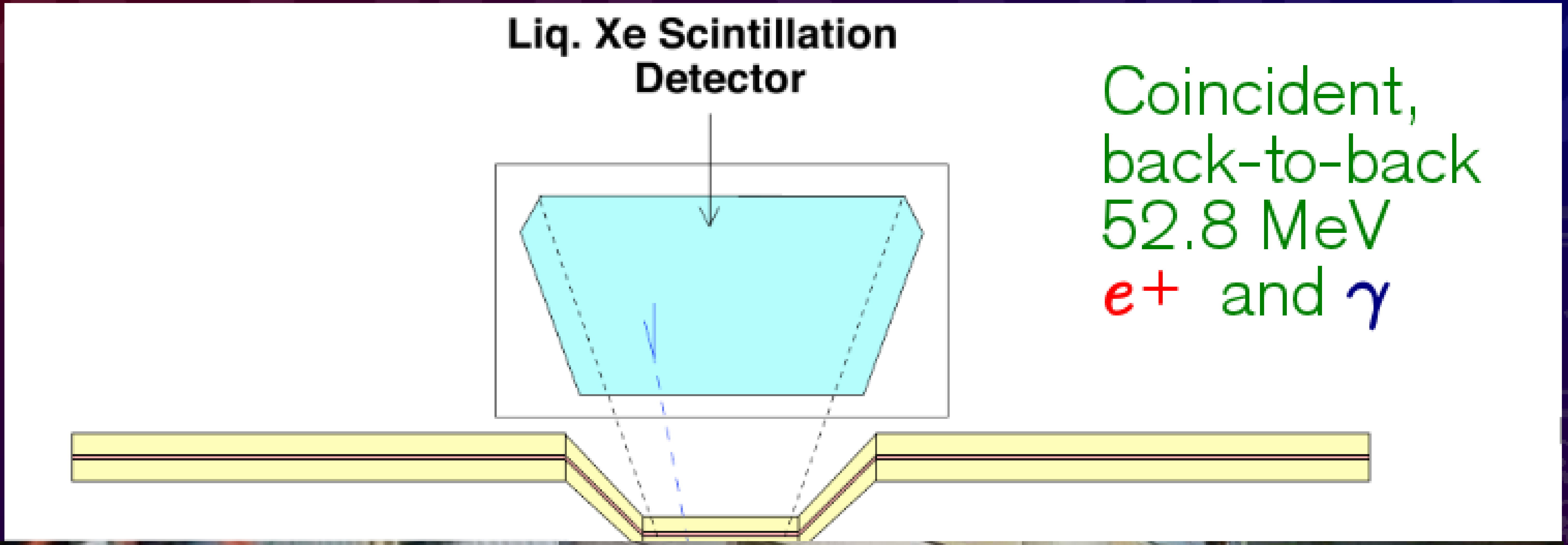
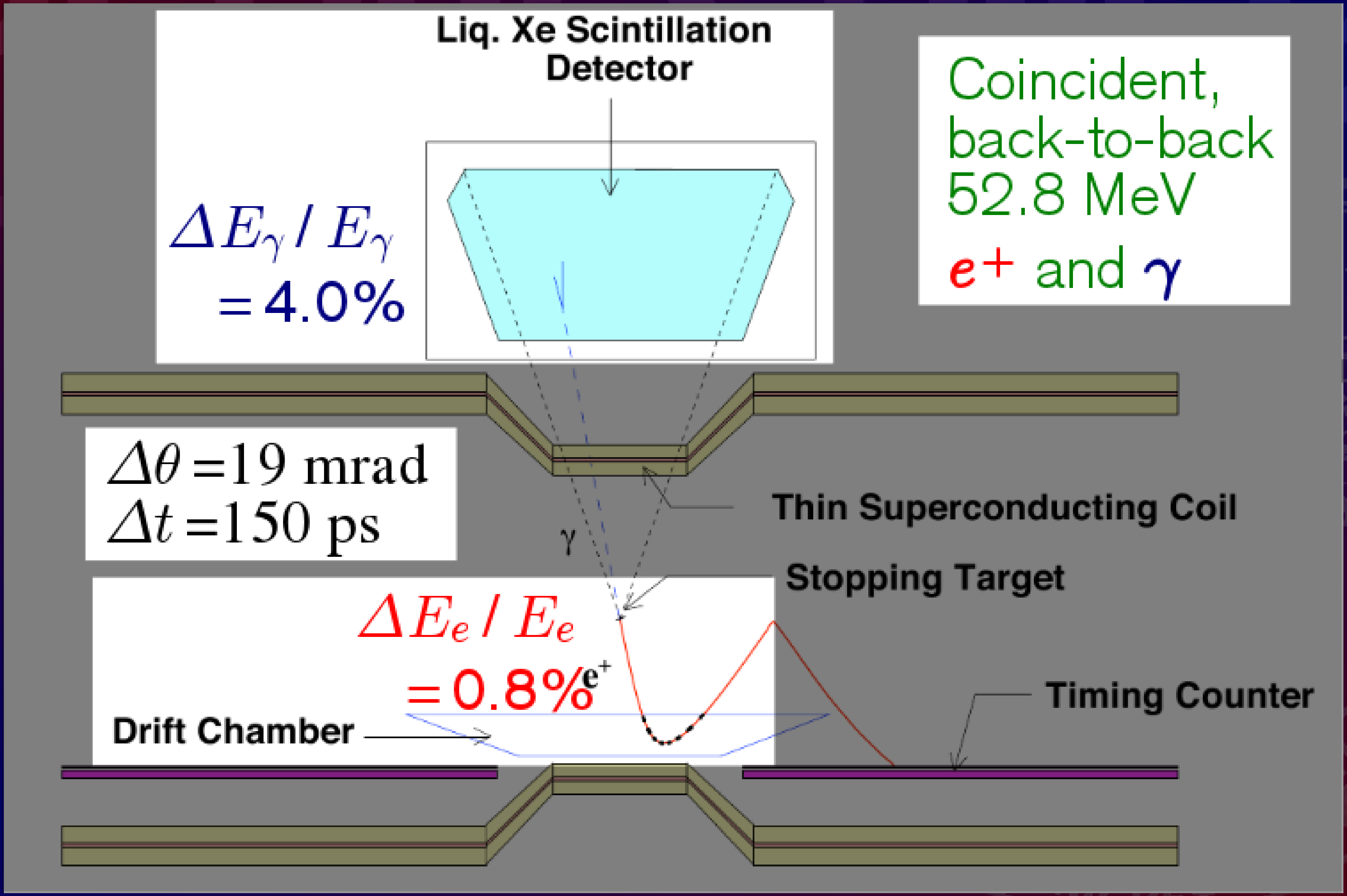


MEG ($\mu \to e\gamma$) at PSI

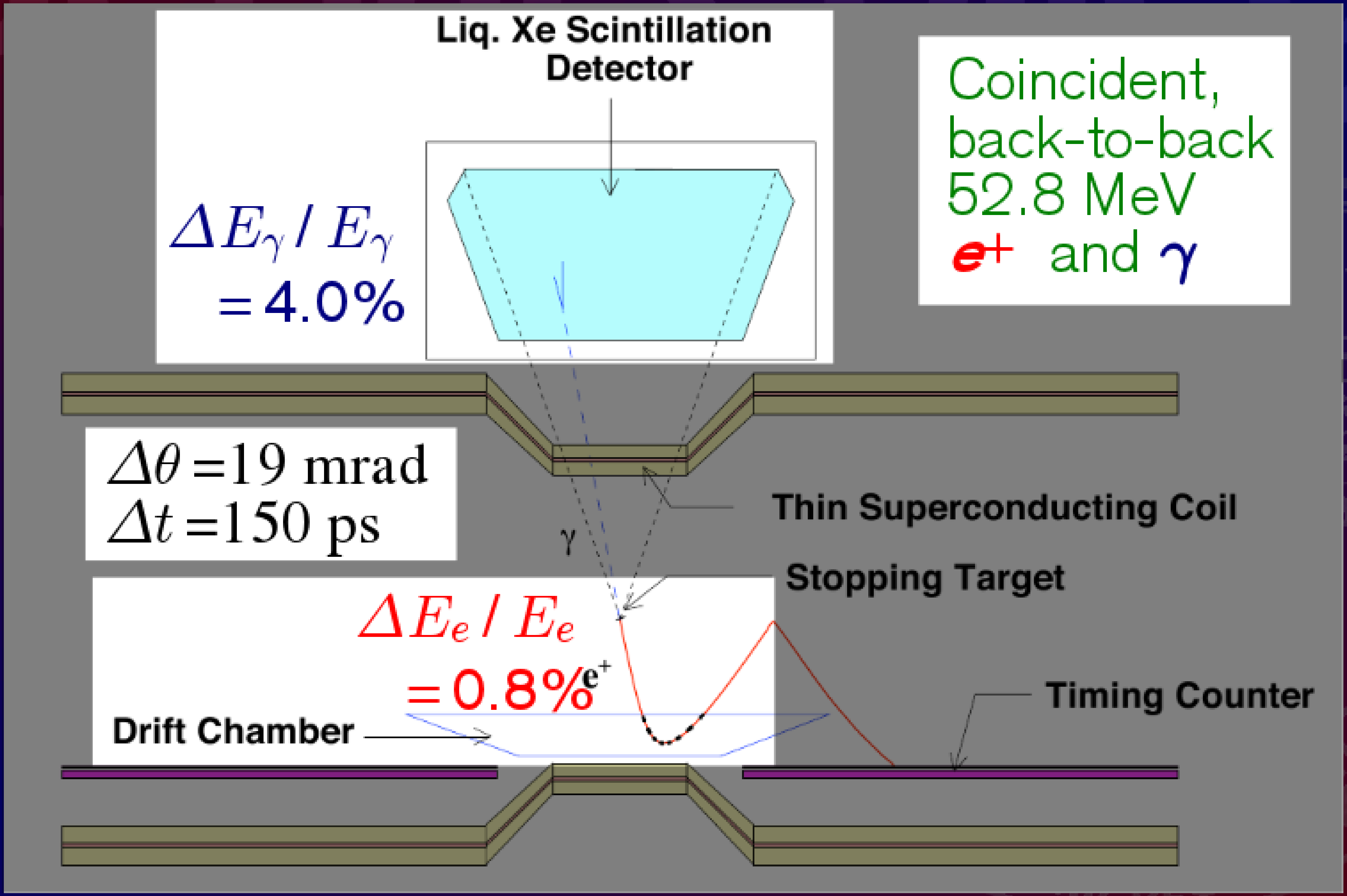
- Aiming for sensitivity down to branching ratio of 10^{-13}
- Physics runs in 2009 and 2010



Latest results shown last summer

MEG ($\mu \to e\gamma$) at PSI

- Aiming for sensitivity down to branching ratio of 10^{-13}



Coincidence requirement makes further improvements in sensitivity with intense beams very difficult

Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic atom

$E_e \leq 105\text{MeV}$

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

muonic atom

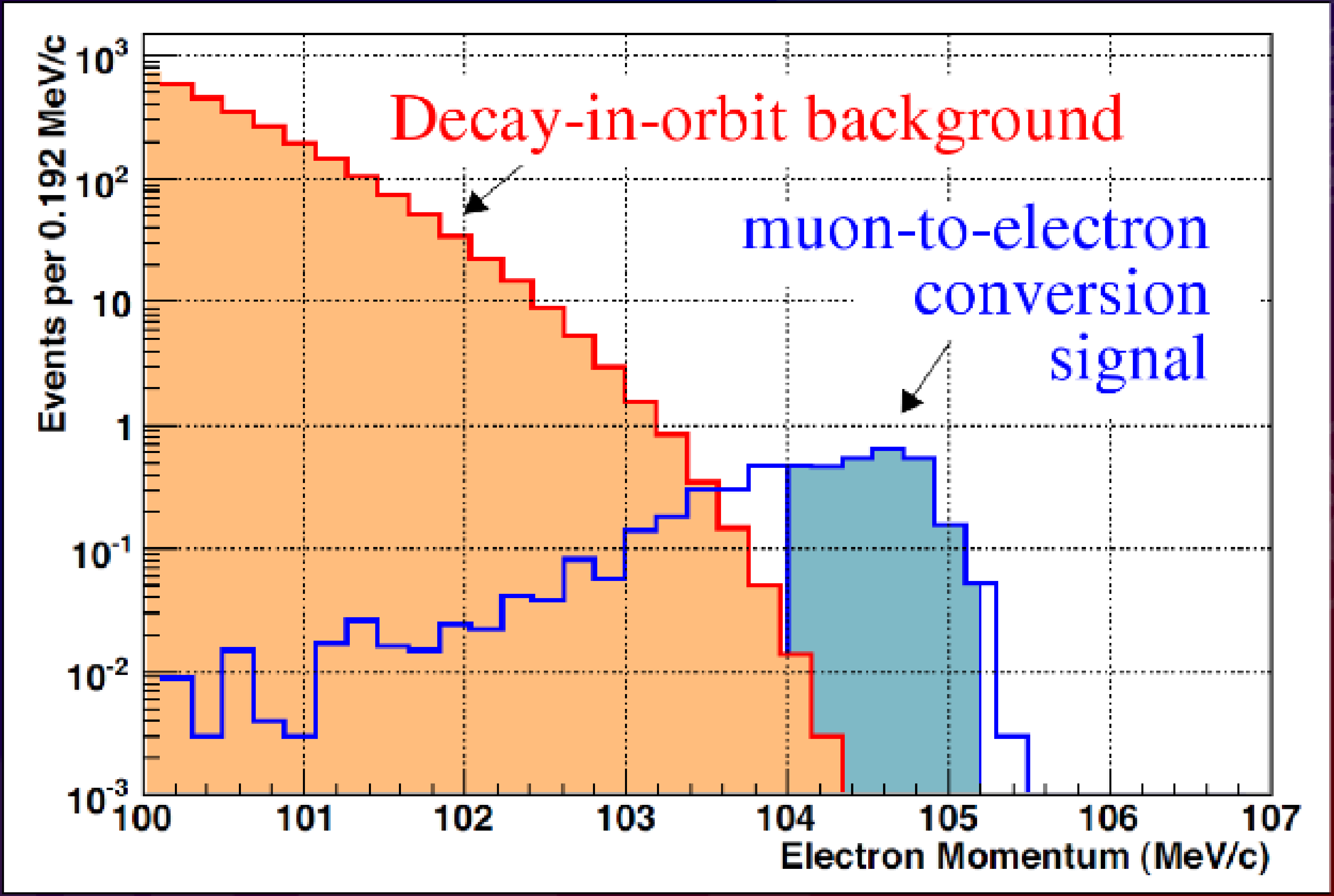
$E_e \leq 105\text{MeV}$

time available after stopping $\sim 1\mu s$ (N-dependent)

- Entirely non-existent in the Standard Model
- $\sim 10^{-52}$ when extended to include neutrino mass
- E_e is muon mass less the atomic binding and recoil energies
  - binding energy on Al: 0.5 MeV

Searching for Muon-to-Electron Conversion

- Produce muons and stop them on a target
- Muonic atoms form and cascade to 1s state and then take a microsecond or so before being captured — so watch over several hundred ns
- Observe the emitted electron spectrum over about 100 MeV/c



Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic atom

$$E_e \leq 105\text{MeV}$$

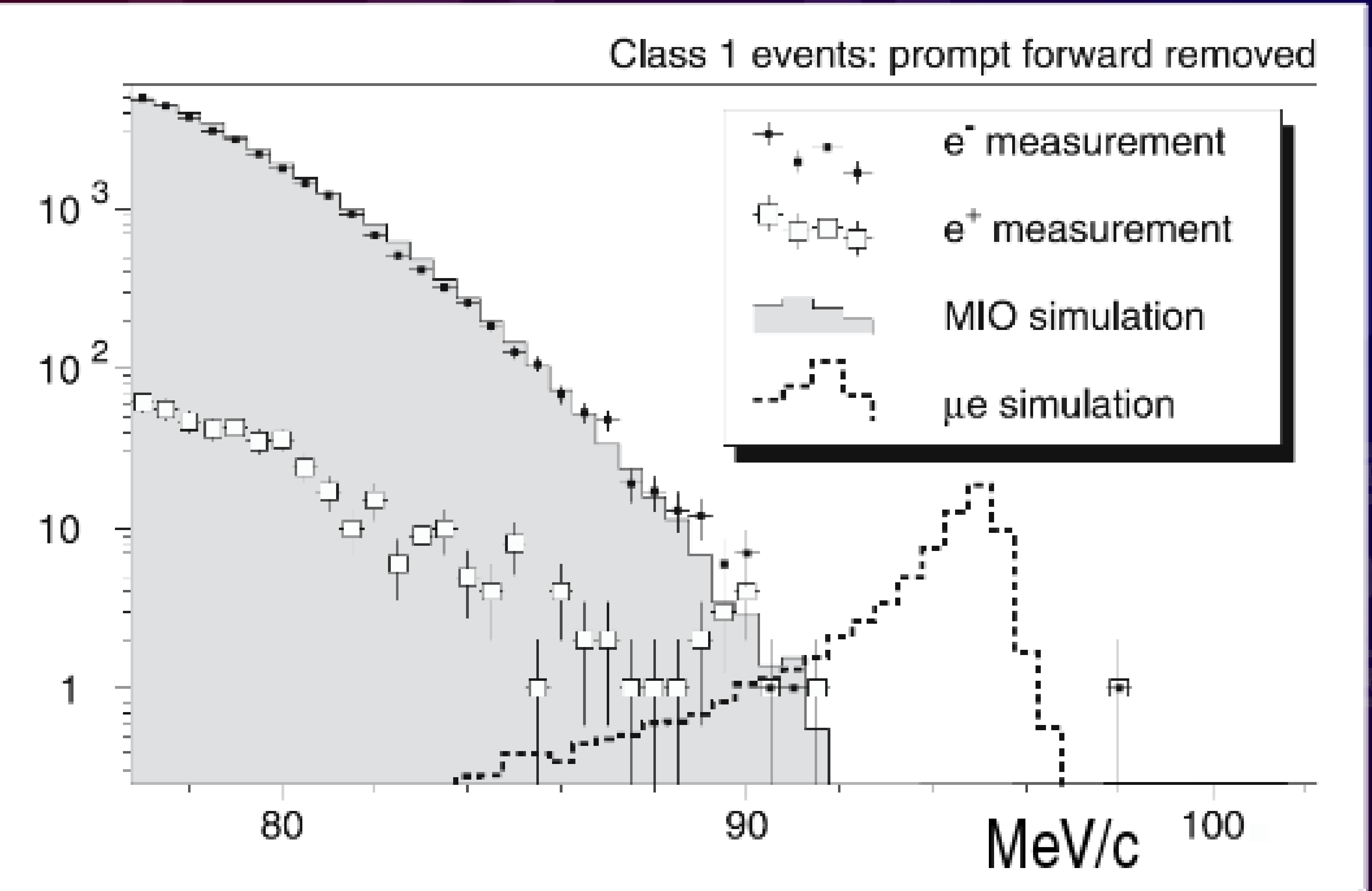
- The present limit is about

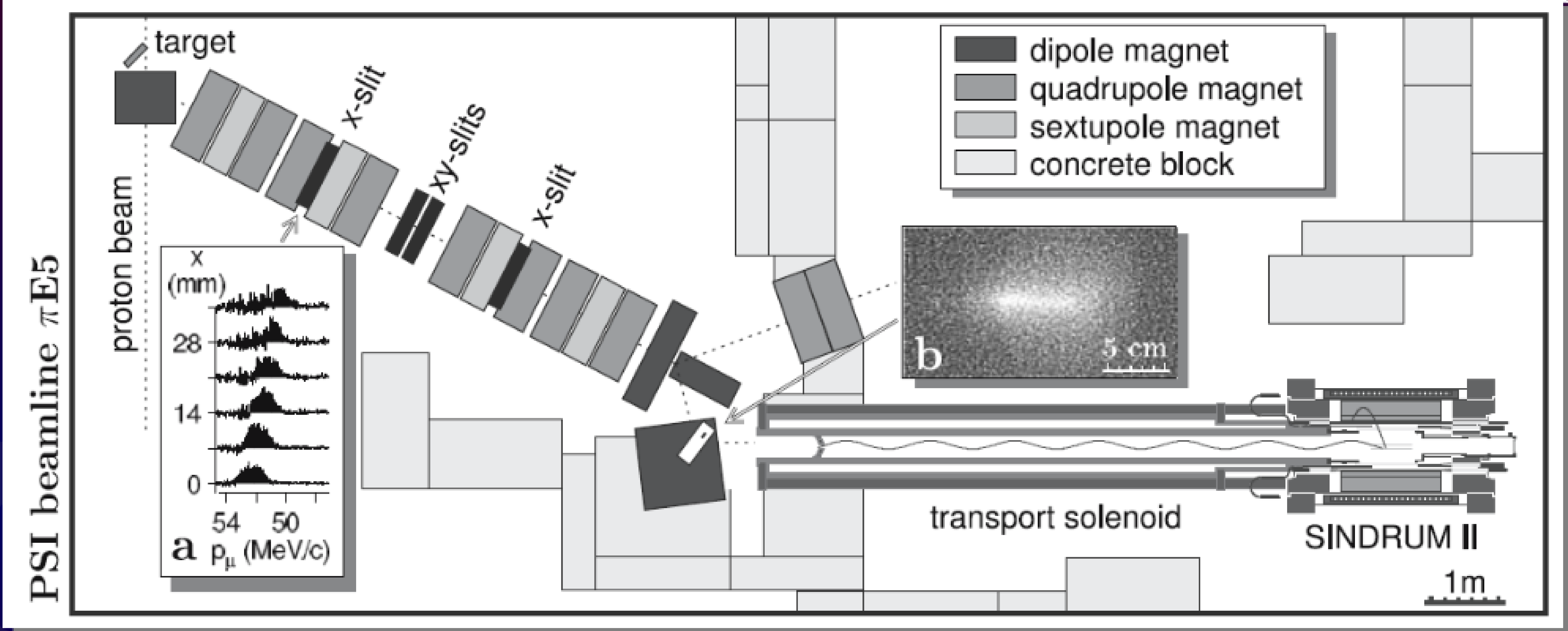
$$< 7 \times 10^{-13}$$

for the branching ratio on Gold (binding energy 10MeV)

SINDRUM II at PSI

- $10^7 - 10^8\ \mu$ /sec
- Effectively a "one-by-one" measurement
- Total rate limited by beam veto counter





Coherent Muon-to-Electron Conversion

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

muonic atom

$E_e \leq 105\text{MeV}$

- The present limit is about

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

for the branching ratio on Gold (Sindrum II)

- $\mu 2\mathrm{e}$ and **COMET** aim to improve sensitivity by ×**10,000**
- **PRISM** extends this to a factor of **1,000,000**

PHYSICAL REVIEW D **74,** 116002 (2006)

Lepton flavor violation from supersymmetric grand unified theories: Where do we stand for MEG, PRISM/PRIME, and a super flavor factory

L. Calibbi,[1] A. Faccia,[1] A. Masiero,[1] and S. K. Vempati[2,3]

(Received 29 August 2006; published 13 December 2006)

We analyze the complementarity between lepton flavor violation (LFV) and LHC experiments in probing the supersymmetric (SUSY) grand unified theories (GUT) when neutrinos get a mass via the seesaw mechanism. Our analysis is performed in an SO(10) framework, where at least one neutrino Yukawa coupling is necessarily as large as the top Yukawa coupling. Our study thoroughly takes into account the whole renormalization group running, including the GUT and the right-handed neutrino mass scales, as well as the running of the observable neutrino spectrum. We find that the upcoming (MEG, SuperKEKB) and future (PRISM/PRIME, super flavor factory) LFV experiments will be able to test such SUSY framework for SUSY masses to be explored at the LHC and, in some cases, even beyond the LHC sensitivity reach.

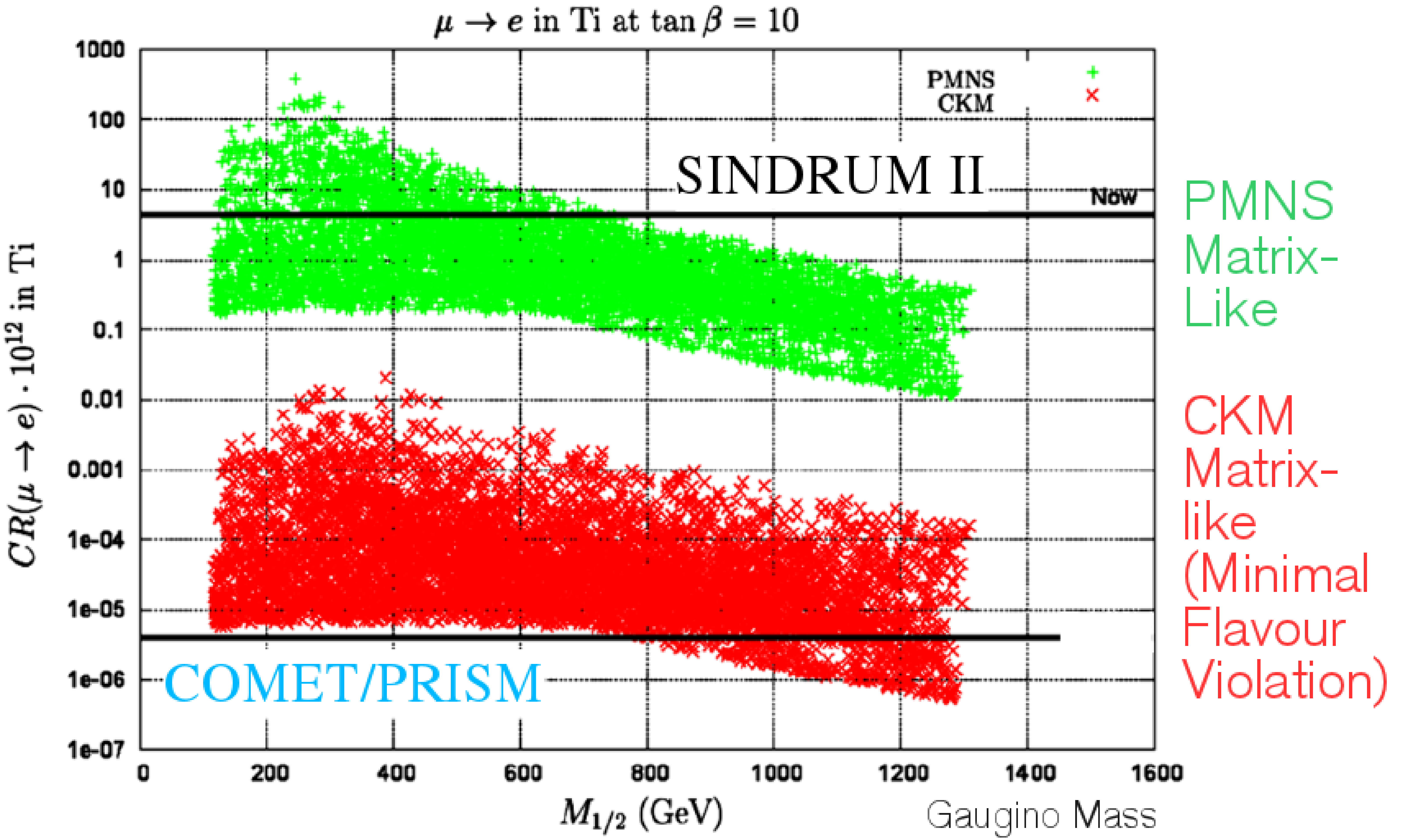
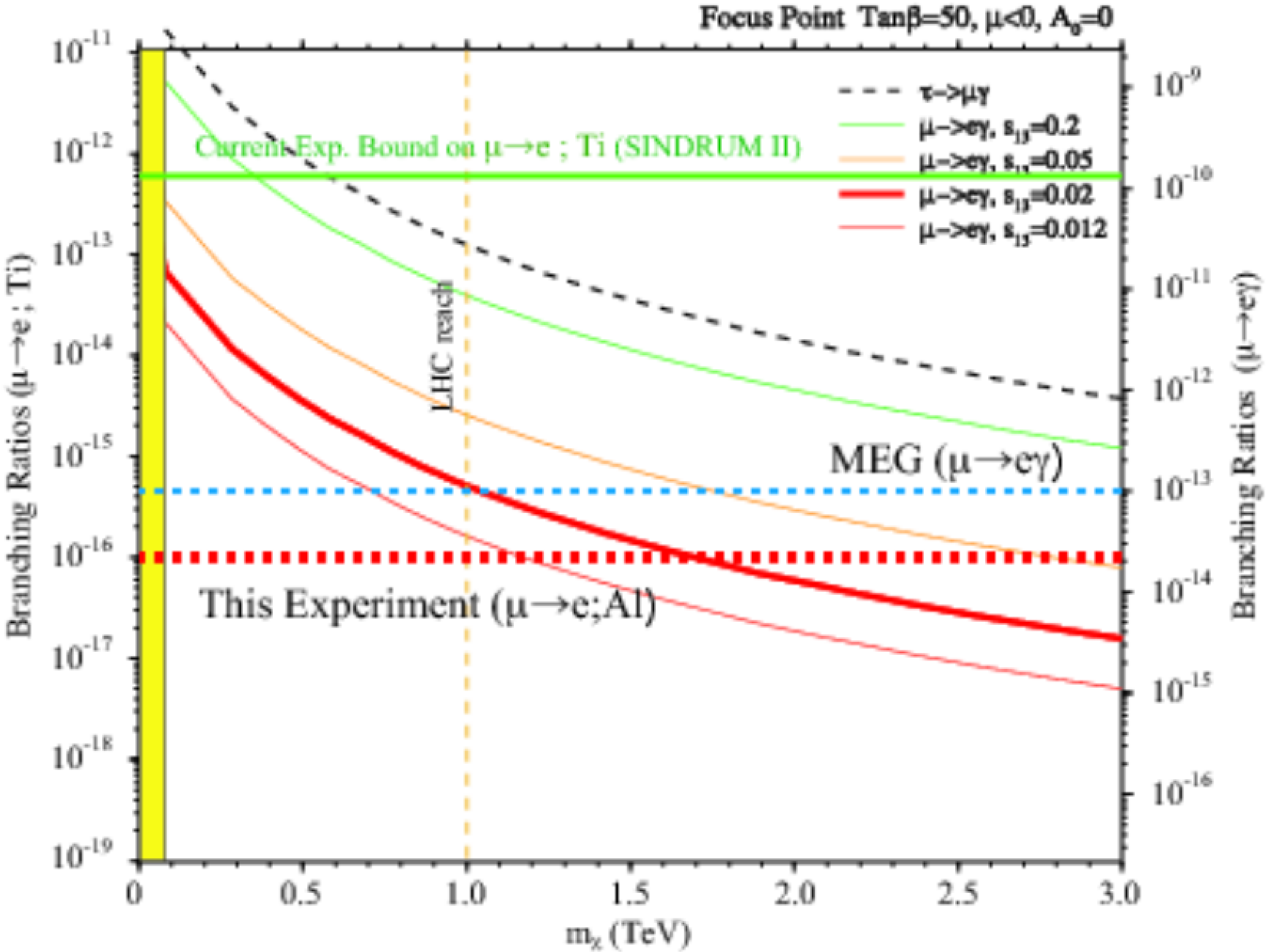


FIG. 12 $\mu \to e$ in Ti as a probe of SUSY-GUT scenarios. The plots are obtained by scanning the LHC accessible parameter space. The horizontal lines are the present (SINDRUM II) bound and the planned (PRISM/PRIME) sensitivity to the process. We see that PRIME would be able to severely constrain the low $\tan\beta$, low mixing angles case and to completely test the other scenarios.

Prediction of the muon-to-electron conversion branching ratio in the SUSY-seesaw models as a function of SUSY neutralino mass scale (Masiero, Profumo, Vempoti, and Yaguna JHEP 0403:046)

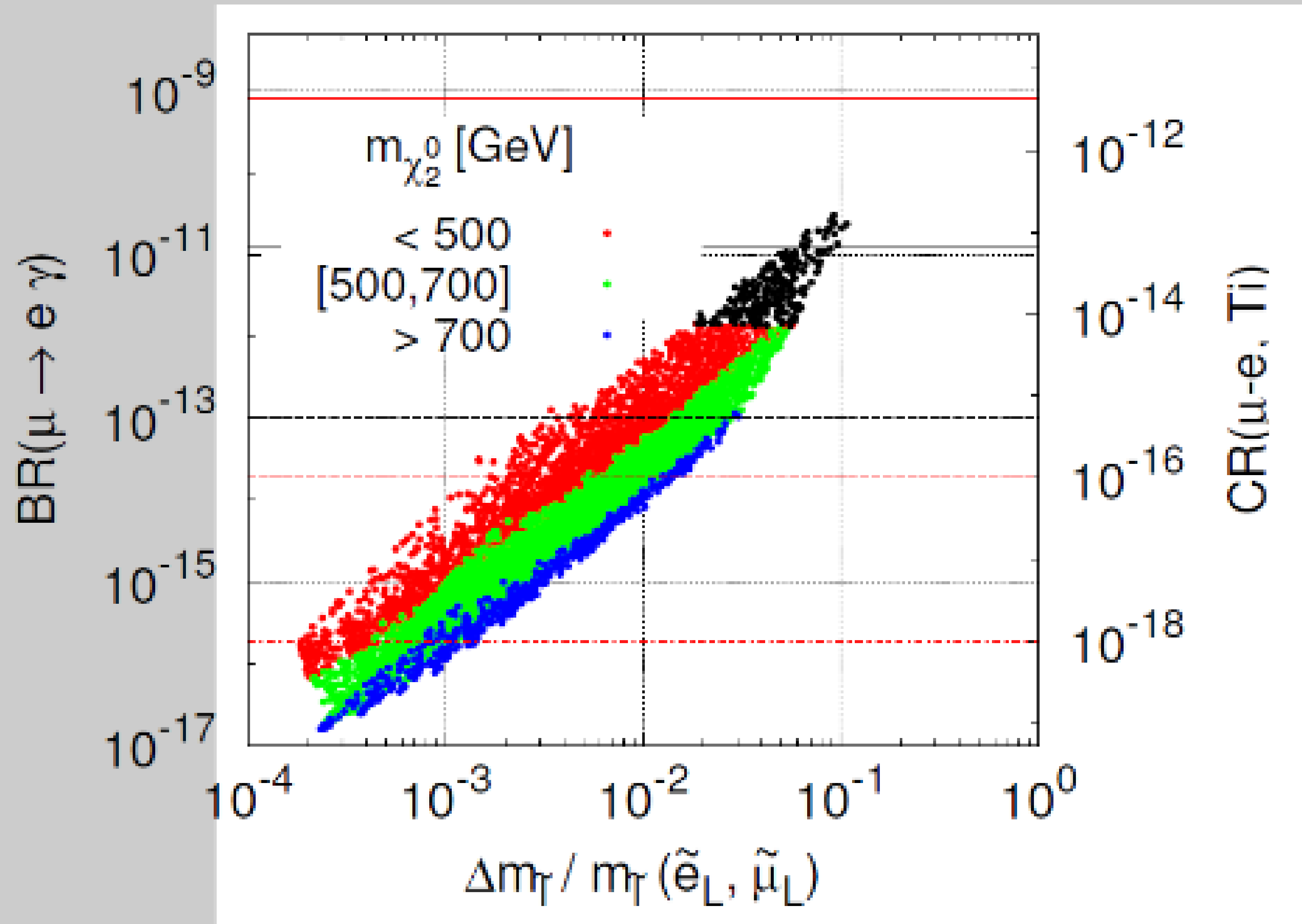


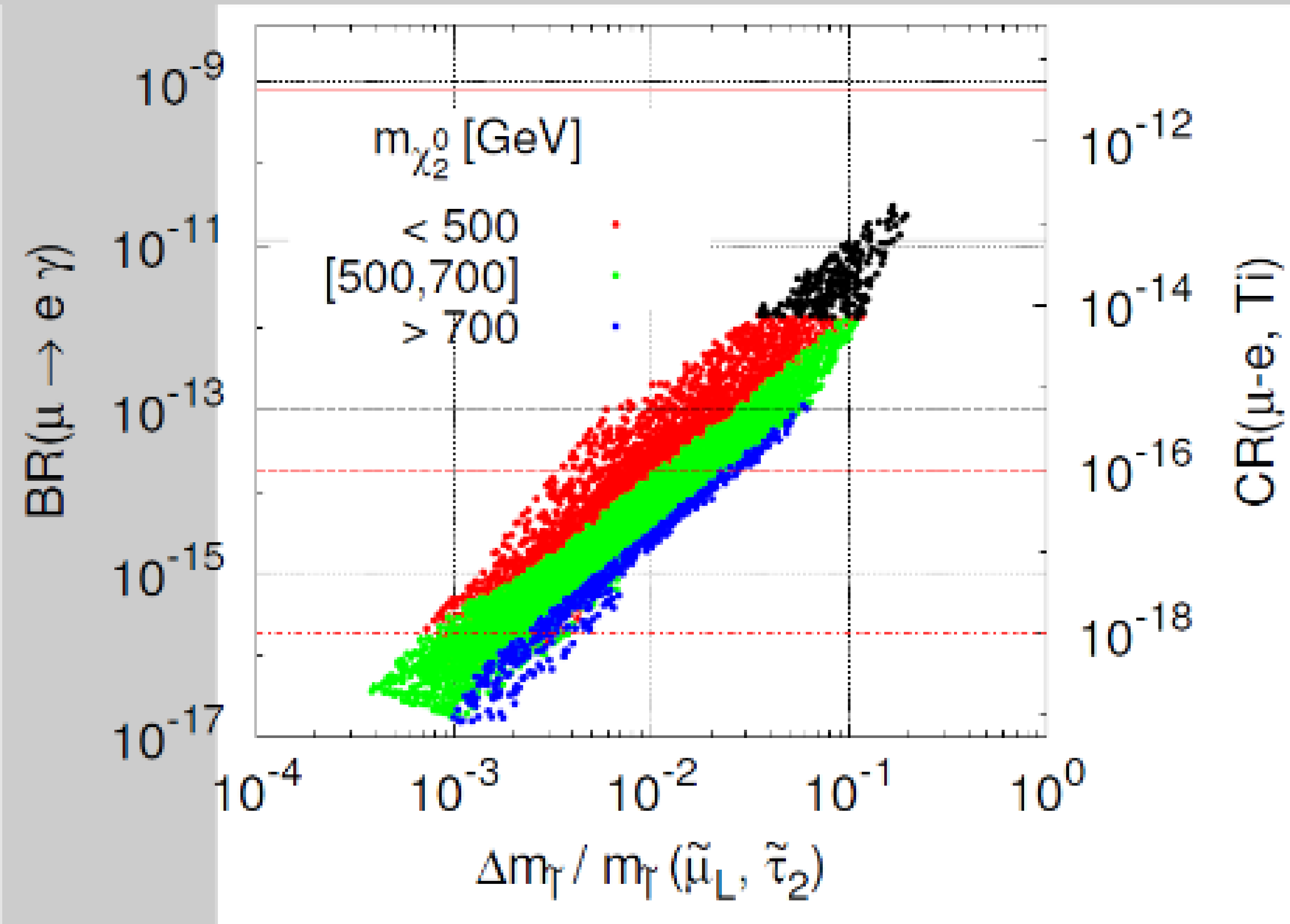
JHEP 1010:104,2010

Interplay of LFV and slepton mass splittings at the LHC as a probe of the SUSY seesaw

A. Abada[a], A. J. R. Figueiredo[b], J. C. Romão[b] and A. M. Teixeira[c]

We study the impact of a type-I SUSY seesaw concerning lepton flavour violation (LFV) both at low-energies and at the LHC. The study of the di-lepton invariant mass distribution at the LHC allows to reconstruct some of the masses of the different sparticles involved in a decay chain. In particular, the combination with other observables renders feasible the reconstruction of the masses of the intermediate sleptons involved in $\chi_2^0 \to \tilde{\ell}\,\ell \to \ell\,\ell\,\chi_1^0$ decays. Slepton mass splittings can be either interpreted as a signal of non-universality in the SUSY soft breaking-terms (signalling a deviation from constrained scenarios as the cMSSM) or as being due to the violation of lepton flavour. In the latter case, in addition to these high-energy processes, one expects further low-energy manifestations of LFV such as radiative and three-body lepton decays. Under the assumption of a type-I seesaw as the source of neutrino masses and mixings, all these LFV observables are related. Working in the framework of the cMSSM extended by three right-handed neutrino superfields, we conduct a systematic analysis addressing the simultaneous implications of the SUSY seesaw for both high- and low-energy lepton flavour violation. We discuss how the confrontation of slepton mass splittings as observed at the LHC and low-energy LFV observables may provide important information about the underlying mechanism of LFV.





One of the most interesting results consists in the fact that almost the entire region in parameter space associated with a $\tilde{e}_L - \tilde{\mu}_L$ mass splitting $\sim \mathcal{O}(1\%)$ is also within the future sensitivity of low-energy facilities, especially for CR($\mu - e$, Ti) (even without the expected upgrade to $\mathcal{O}(10^{-18})$ for PRISM/PRIME) [5]. Also, any $\tilde{e}_L - \tilde{\mu}_L$ mass splitting above 4% would also be associated with a $\mu \to e\gamma$ signal within MEG sensitivity. A similar situation (albeit not so striking) is observed for $\tilde{\mu}_L - \tilde{\tau}_2$ mass differences: as an example, mass splittings above 3%, 4% and 6% would be associated to low-energy signals of LFV within PRISM/PRIME, SuperB, and MEG reach, respectively.

PHYSICAL REVIEW D **74,** 053011 (2006)

Probing the Randall-Sundrum geometric origin of flavor with lepton flavor violation

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[1]*Department of Physics, Syracuse University, Syracuse, New York 13244, USA and School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*

[2]*Department of Physics, The Johns Hopkins University, Baltimore, Maryland 21218, USA*

[3]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*

(Received 23 June 2006; published 28 September 2006)

The anarchic Randall-Sundrum model of flavor is a low energy solution to both the electroweak hierarchy and flavor problems. Such models have a warped, compact extra dimension with the standard model fermions and gauge bosons living in the bulk, and the Higgs living on or near the TeV brane. In this paper we consider bounds on these models set by lepton flavor-violation constraints. We find that loop-induced decays of the form $l \to l'\gamma$ are ultraviolet sensitive and incalculable when the Higgs field is localized on a four-dimensional brane; this drawback does not occur when the Higgs field propagates in the full five-dimensional space-time. We find constraints at the few TeV level throughout the natural range of parameters, arising from $\mu - e$ conversion in the presence of nuclei, rare μ decays, and rare τ decays. A tension exists between loop-induced dipole decays such as $\mu \to e\gamma$ and tree-level processes such as $\mu - e$ conversion; they have opposite dependences on the five-dimensional Yukawa couplings, making it difficult to decouple flavor-violating effects. We emphasize the importance of the future experiments MEG and PRIME. These experiments will definitively test the Randall-Sundrum geometric origin of hierarchies in the lepton sector at the TeV scale.

DOI: 10.1103/PhysRevD.74.053011 PACS numbers: 13.35.−r, 11.10.Kk

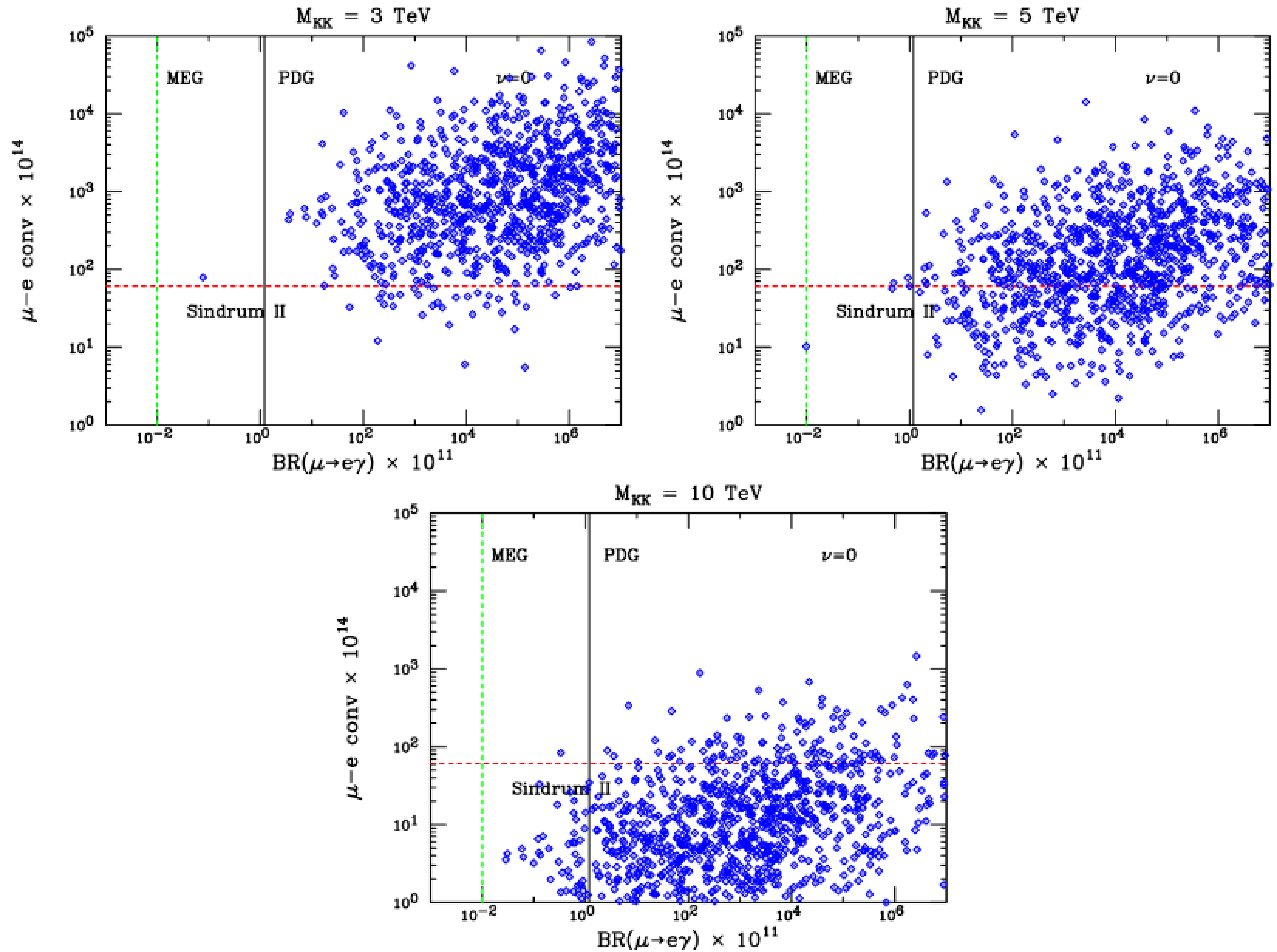

FIG. 6 Scan of the $\mu \rightarrow e\gamma$ and $\mu - e$ conversion predictions for $M_{KK} = 3$, 5, 10 TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \rightarrow e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to $BR(\mu \rightarrow e\gamma)$.

Charged lepton flavour violation and $(g-2)_\mu$ in the Littlest Higgs model with T-Parity: a clear distinction from Supersymmetry

Monika Blanke,[ab] **Andrzej J. Buras,**[a] **Björn Duling,**[a] **Anton Poschenrieder**[a] **and Cecilia Tarantino**[a]

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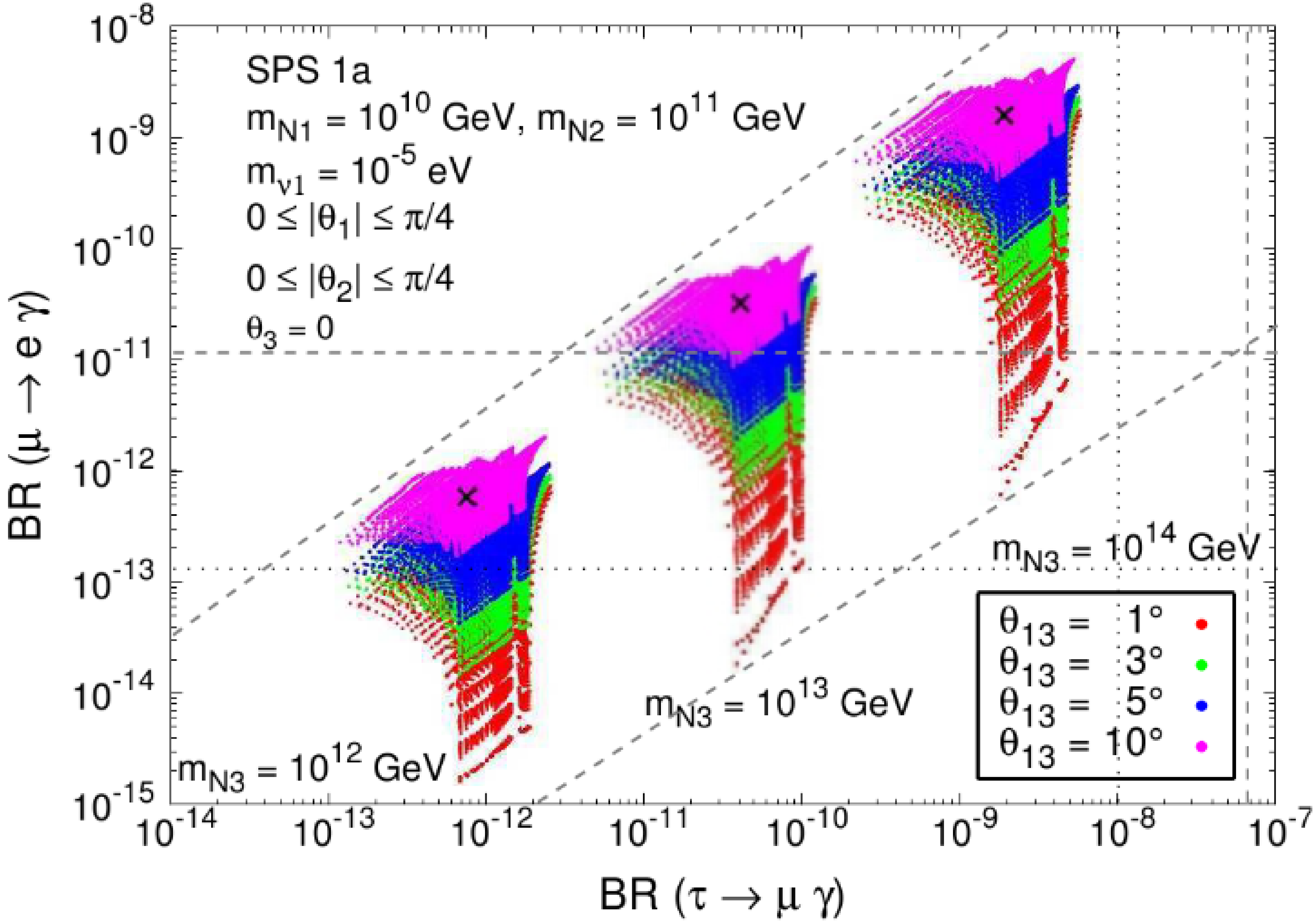
Abstract: We calculate the rates for the charged lepton flavour violating decays $\ell_i \to \ell_j \gamma$, $\tau \to \ell\pi$, $\tau \to \ell\eta$, $\tau \to \ell\eta'$, $\mu^- \to e^- e^+ e^-$, the six three body leptonic decays $\tau^- \to \ell_i^- \ell_j^+ \ell_k^-$ and the rate for $\mu - e$ conversion in nuclei in the Littlest Higgs model with T-parity (LHT). We also calculate the rates for $K_{L,S} \to \mu e$, $K_{L,S} \to \pi^0 \mu e$ and $B_{d,s} \to \ell_i \ell_j$. We find that the relative effects of mirror leptons in these transitions are by many orders of magnitude larger than analogous mirror quark effects in rare K and B decays analyzed recently. In particular, in order to suppress the $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$ decay rates and the $\mu - e$ conversion rate below the experimental upper bounds, the relevant mixing matrix in the mirror lepton sector $V_{H\ell}$ must be rather hierarchical, unless the spectrum of mirror leptons is quasi-degenerate. We find that the pattern of the LFV branching ratios in the LHT model differs significantly from the one encountered in the MSSM, allowing in a transparent manner to distinguish these two models with the help of LFV processes. We also calculate $(g-2)_\mu$ and find the new contributions to a_μ below $1 \cdot 10^{-10}$ and consequently negligible. We compare our results with those present in the literature.

S. Antusch et al. / Nuclear Physics B (Proc. Suppl.) 169 (2007) 155–165



Correlation between $BR(\mu \to e\gamma)$ and $BR(\tau \to \mu\gamma)$ as a function of m_{N_3}, for SPS 1a.

"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

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

W. Altmannshofer et al. / Nuclear Physics B 830 (2010) 17–94

"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS

- AC: Abelian model by Agashe and Carone based on a U(1) flavour symmetry
- RVV2: the non-Abelian model by Ross, Velasco-Sevilla and Vives
- AKM: Antusch, King and Malinsky model based on the flavour symmetry SU(3)
- δLL: flavour models predicting pure, CKM-like, left-handed currents
- FBMSSM: flavour-blind MSSM
- LHT: Littlest Higgs Model with T-Parity
- RS: Randall–Sundrum model with custodial protection

SUSY models non-SUSY models

W. Altmannshofer et al. / Nuclear Physics B 830 (2010) 17–94

"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

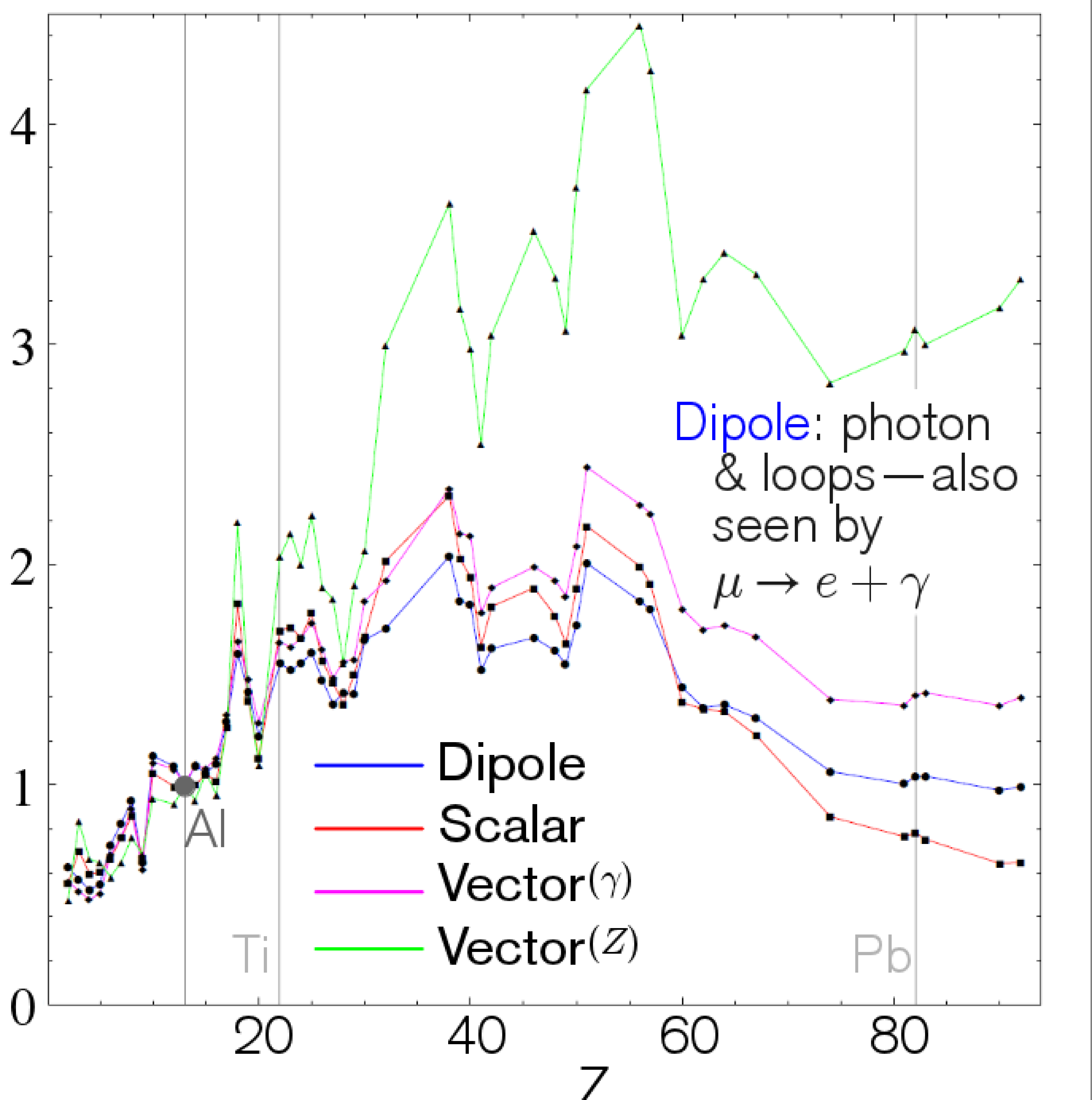
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★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

W. Altmannshofer et al. / Nuclear Physics B 830 (2010) 17–94

The relative dependences of the muon-to-electron conversion branching ratio on the target nucleus, for different models of New Physics interactions

Cirigliano, Kitano, Okada, and Tuzon, arXiv:0904.0957

(Predictions for $\mu \to e\gamma$ also given)



Coherent Muon-to-Electron Conversion

- Muon-to-Electron Conversion

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

muonic atom

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

- The present limit is about

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

for the branching ratio on Gold (Sindrum II)

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

Charged Lepton Flavour Violation

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

COMET

Coherent Muon-to-Electron Conversion

- Muon-to-Electron Conversion

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

muonic atom

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

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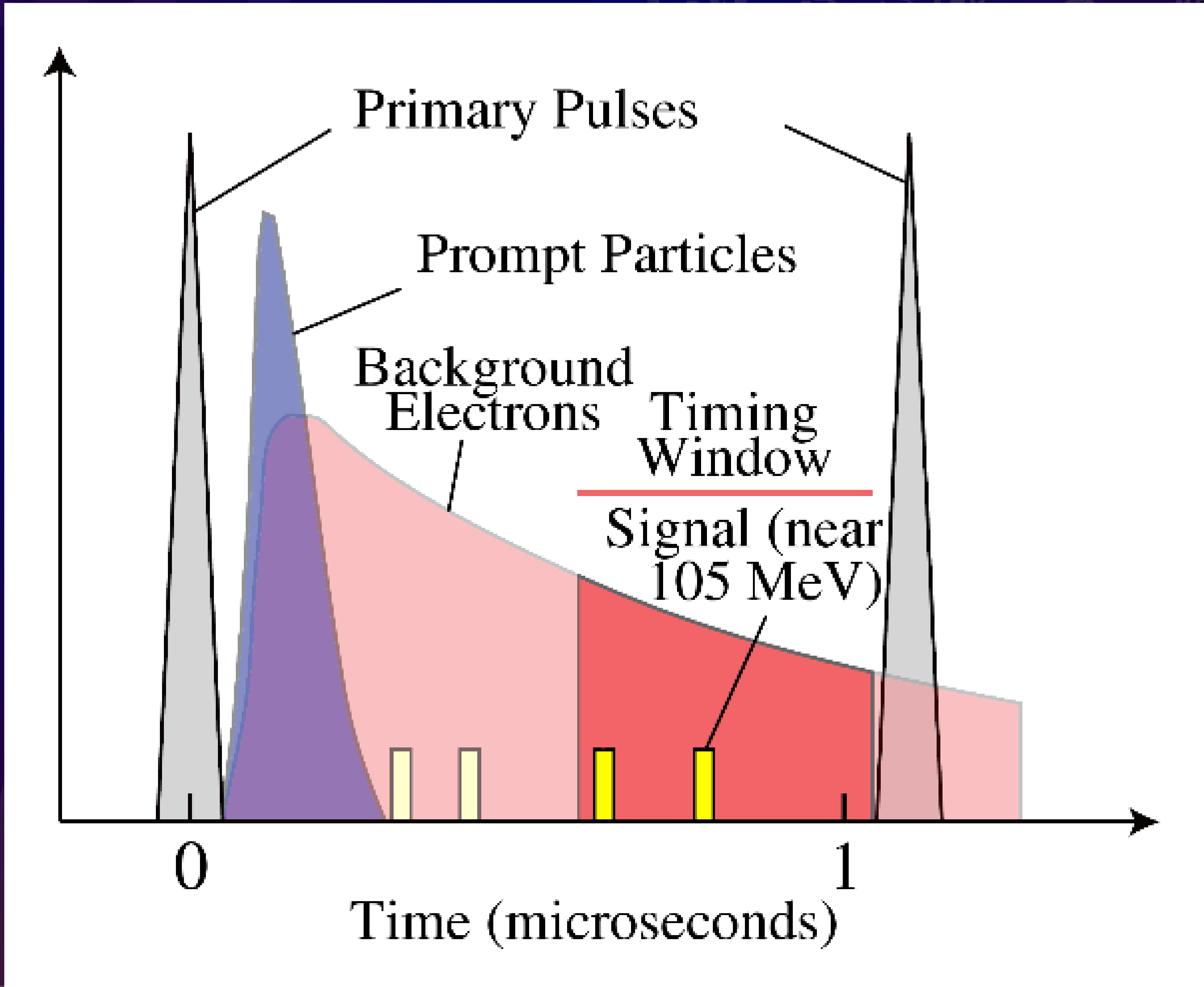
- PRISM extends this to a sensitivity of 10^{-18}

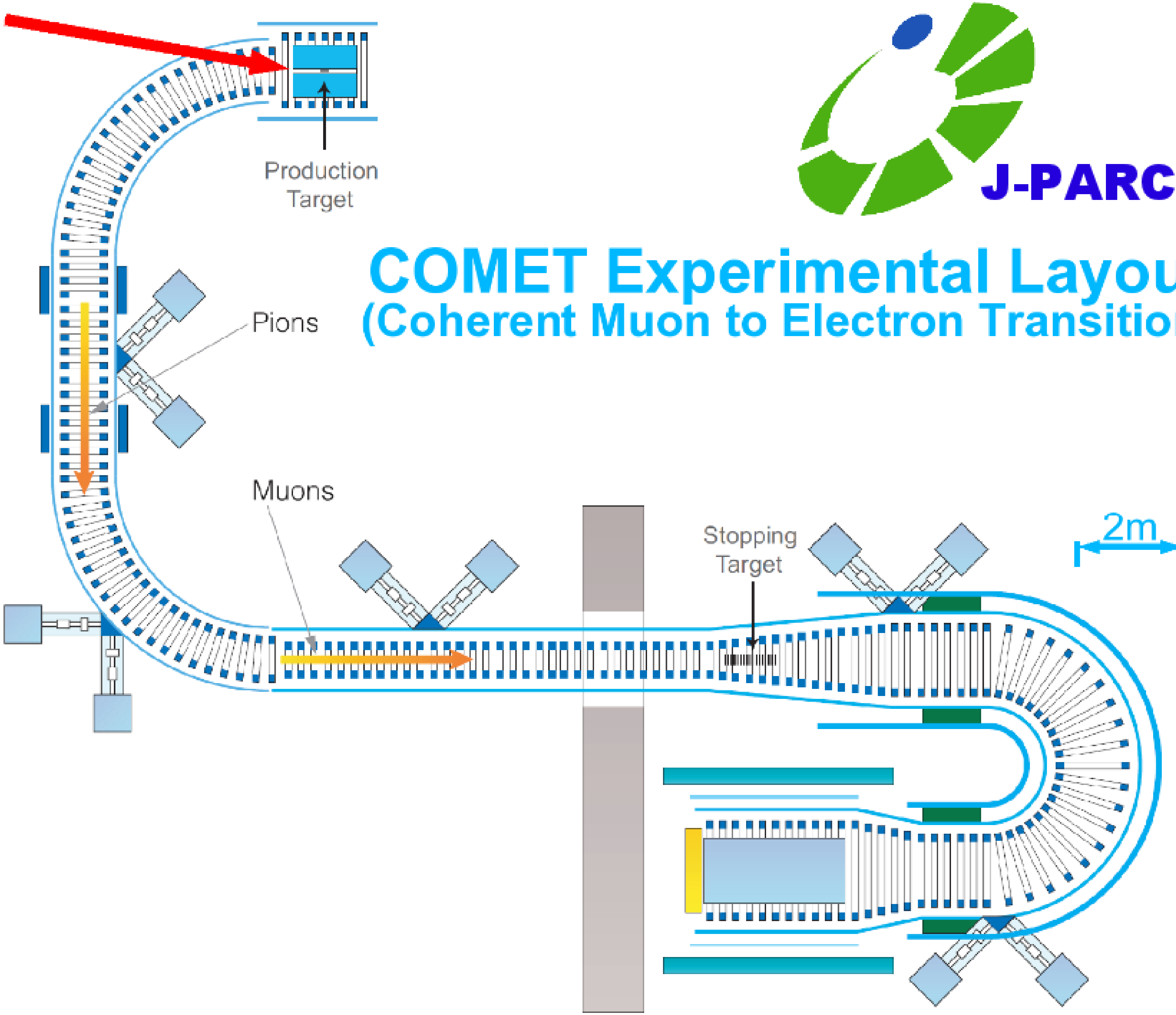
Use of a Pulsed Primary Beam

- Large backgrounds occur promptly with incoming muons
- Signal events occur with a delay
  ⇒ Pulse primary beam to separate prompt backgrounds from signal
- Use energy and time to separate signal from backgrounds
- Muonic atom lifetimes vary due to nuclear muon capture
  - Al: 880 ns
  - Ti: 330 ns
  - Au: 73 ns



Yoshi.Uchida@imperial.ac.uk

COMET Experimental Layout
(Coherent Muon to Electron Transition)



Search for Lepton-Flavor-Violating Rare Muon Processes

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Institute for Nuclear Research, Russian Academy of Sciences, pr. Shestidesyatiletiya Oktyabrya 7a, Moscow, 117312 Russia

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

Basic concept from 1989

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

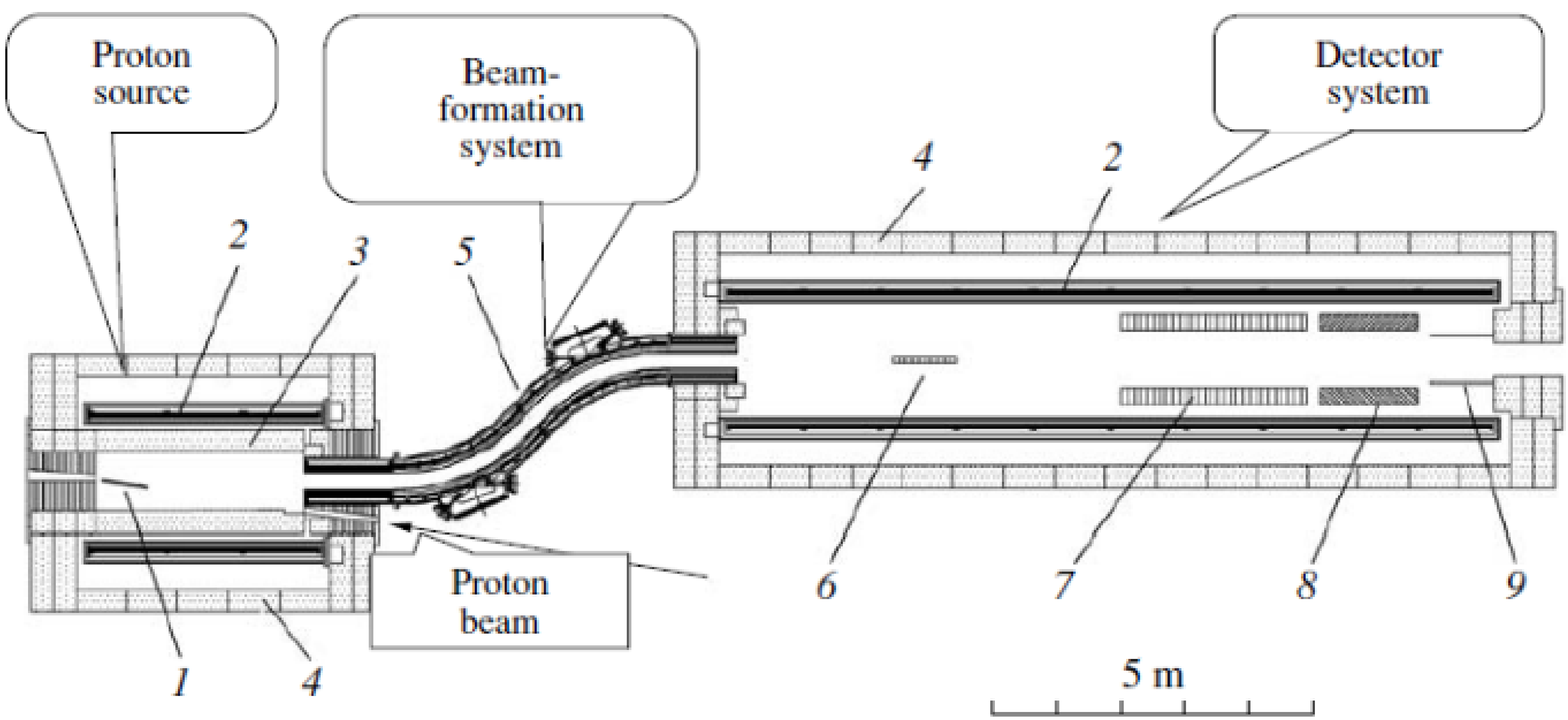
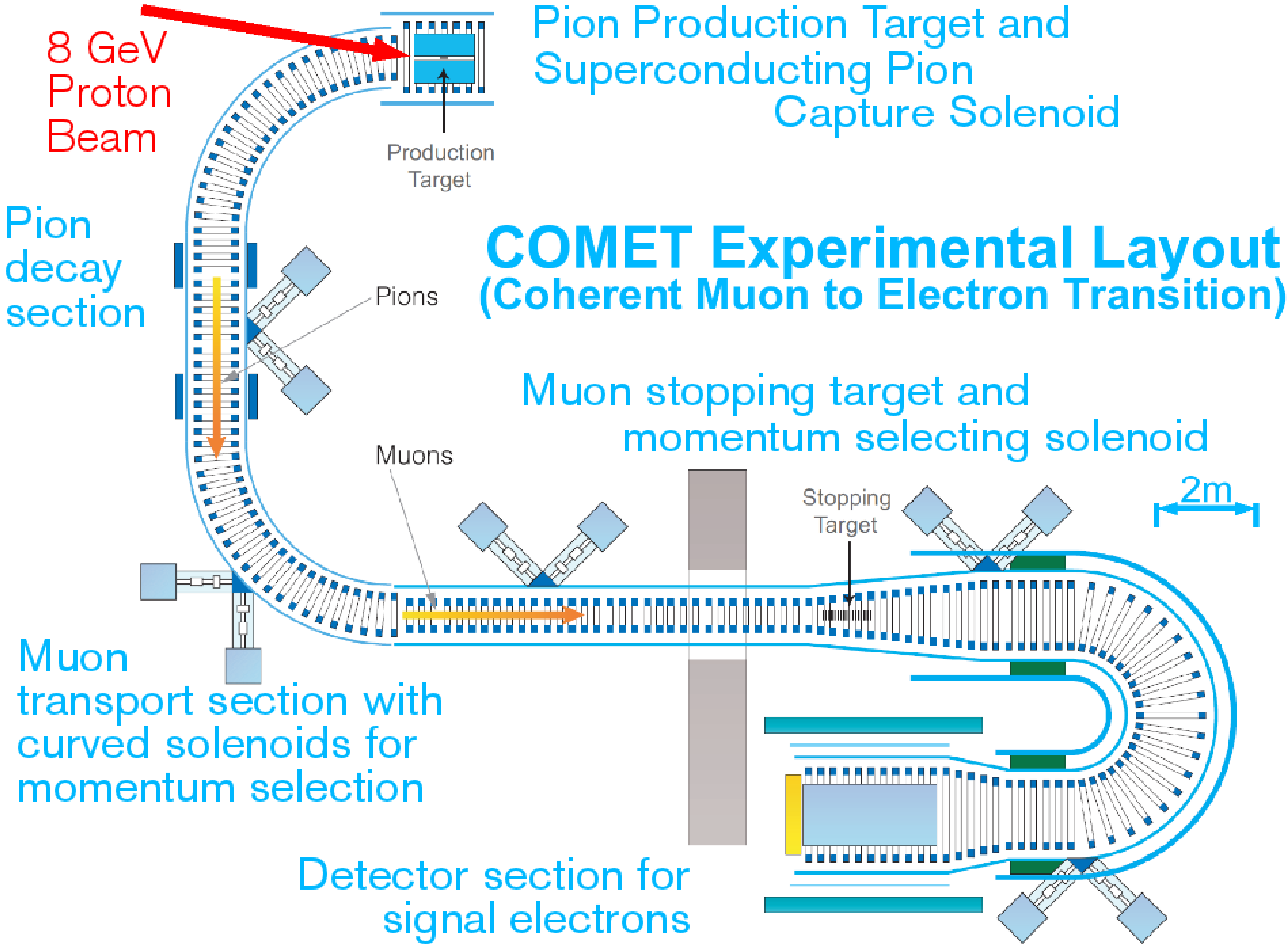


Fig. 1. Central horizontal cut of the MELC facility: (*1*) proton target, (*2*) superconductor solenoid, (*3*) shield of the solenoid, (*4*) steel yoke, (*5*) transport solenoid and collimator, (*6*) detector target, (*7*) coordinate detector, (*8*) calorimeter, and (*9*) detector shield and beam trap.


8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Pions
Muon stopping target and momentum selecting solenoid
Muons
Stopping Target
2m
Muon transport section with curved solenoids for momentum selection
Detector section for signal electrons

Design Considerations

Background Event Categories

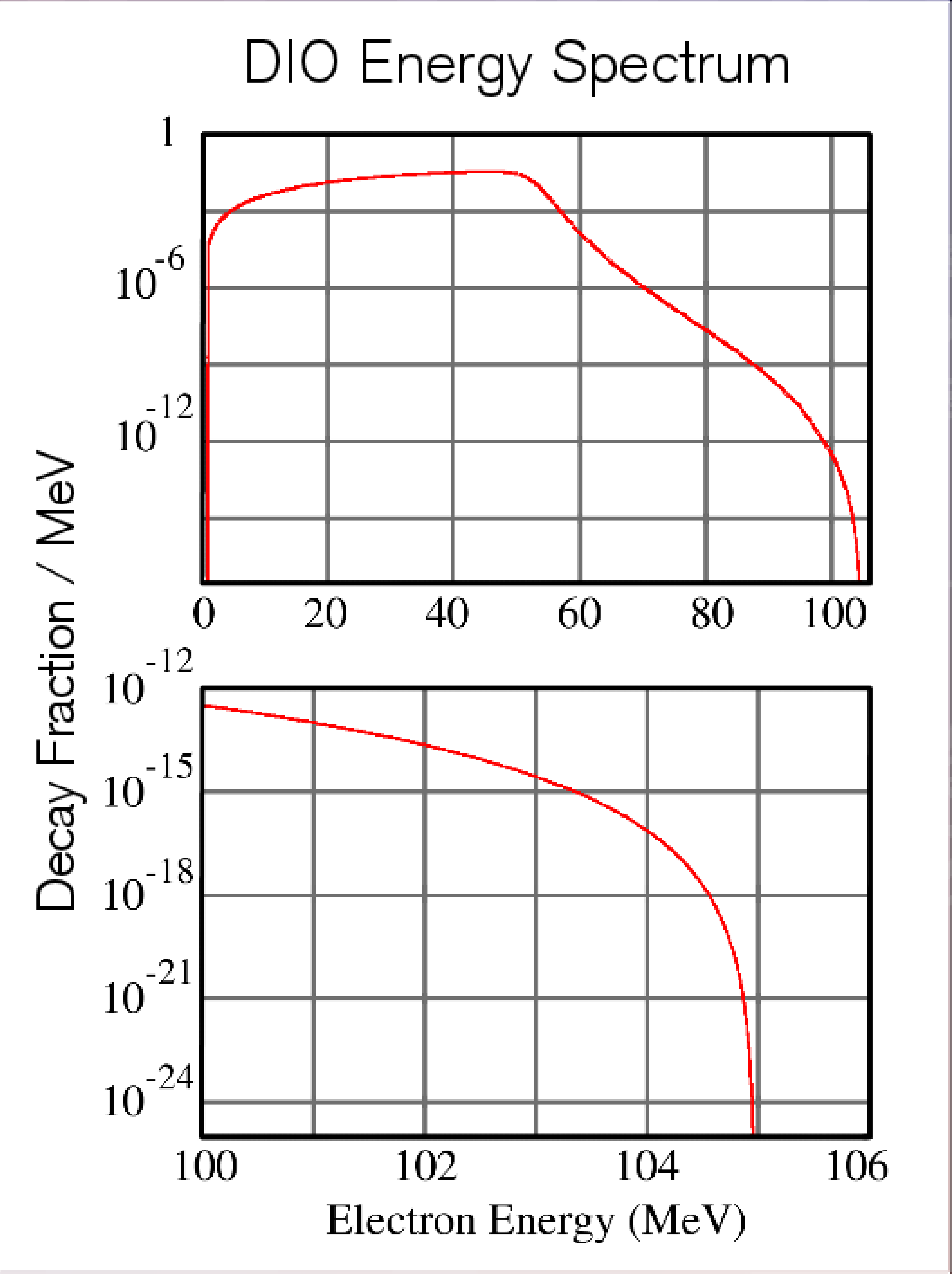
- Intrinsic physics backgrounds
  - electrons from muons stopped in the target
- Beam-related prompt backgrounds
  - due to protons which arrive outside of their beam buckets
- Beam-related delayed backgrounds
  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

Intrinsic Physics Backgrounds

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

Decay-in-Orbit (DIO) Electrons

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



Background Event Categories

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- Beam-related delayed backgrounds
  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

Prompt Backgrounds

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

Background Event Categories

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

Beam-Related Delayed Backgrounds

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

Beamline design critical

Background Event Categories

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

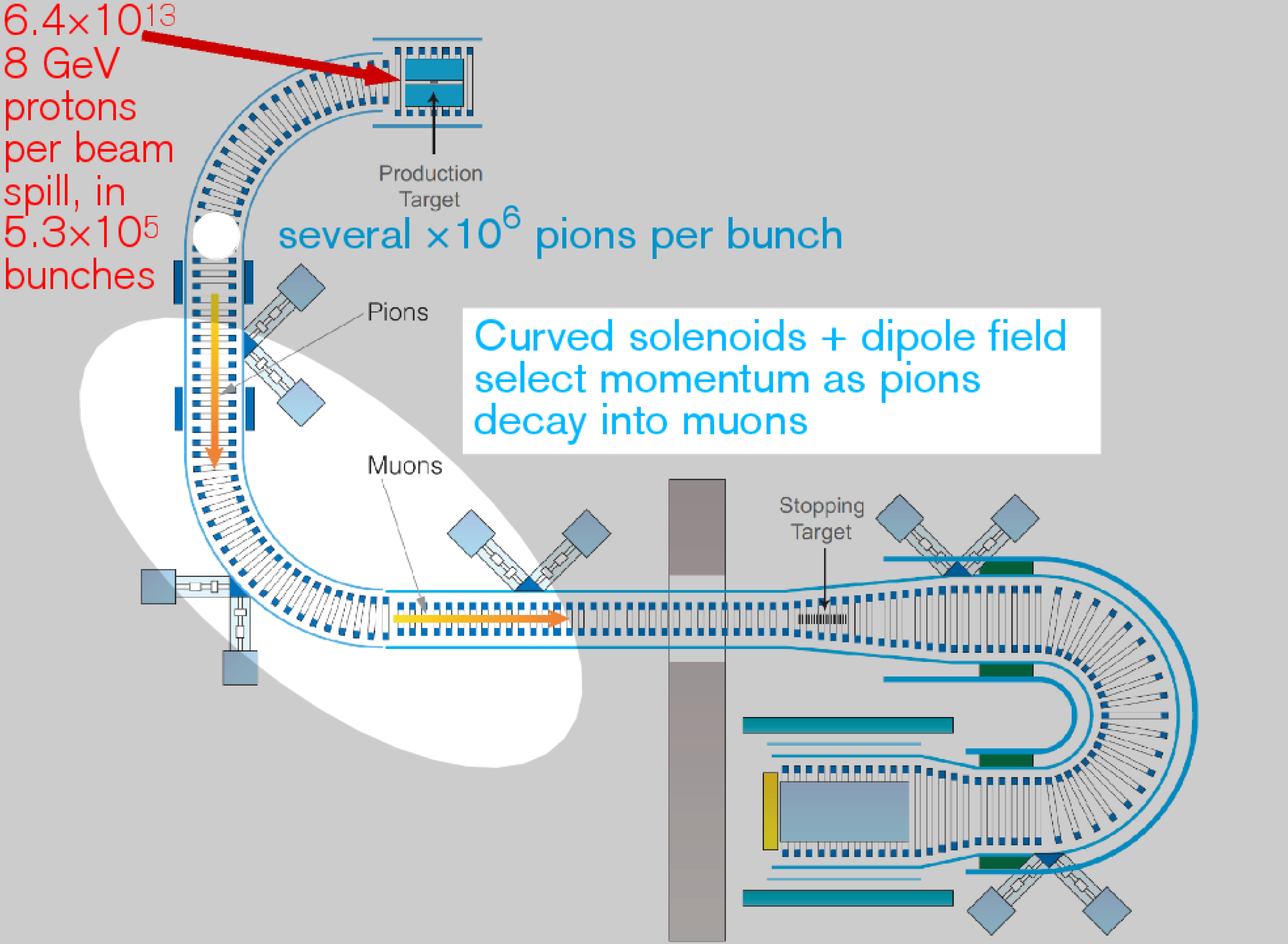
Backgrounds Strategy

- Discriminate using energy and timing, but…

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

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

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


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

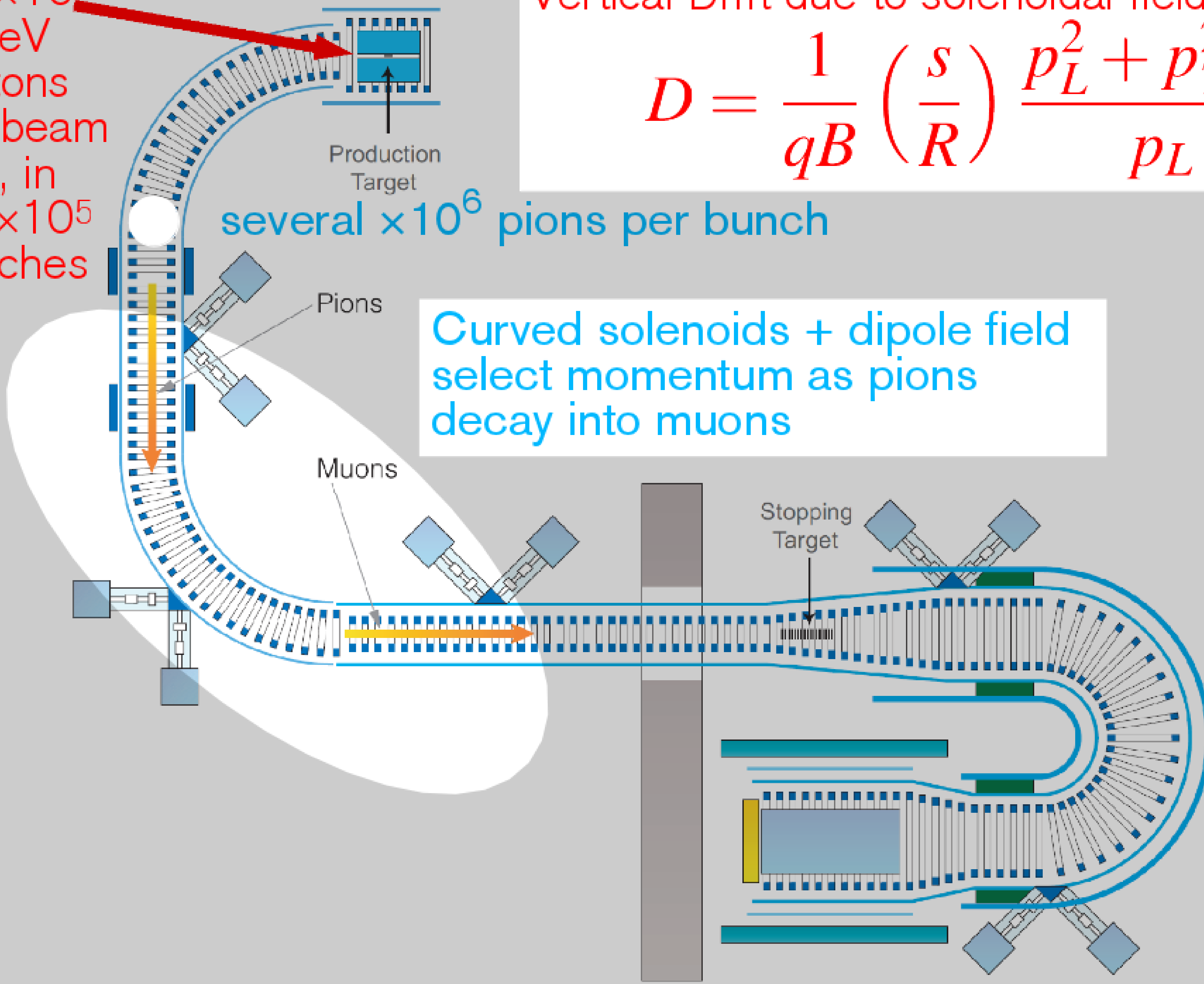
Vertical Drift due to solenoidal field:

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

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

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

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



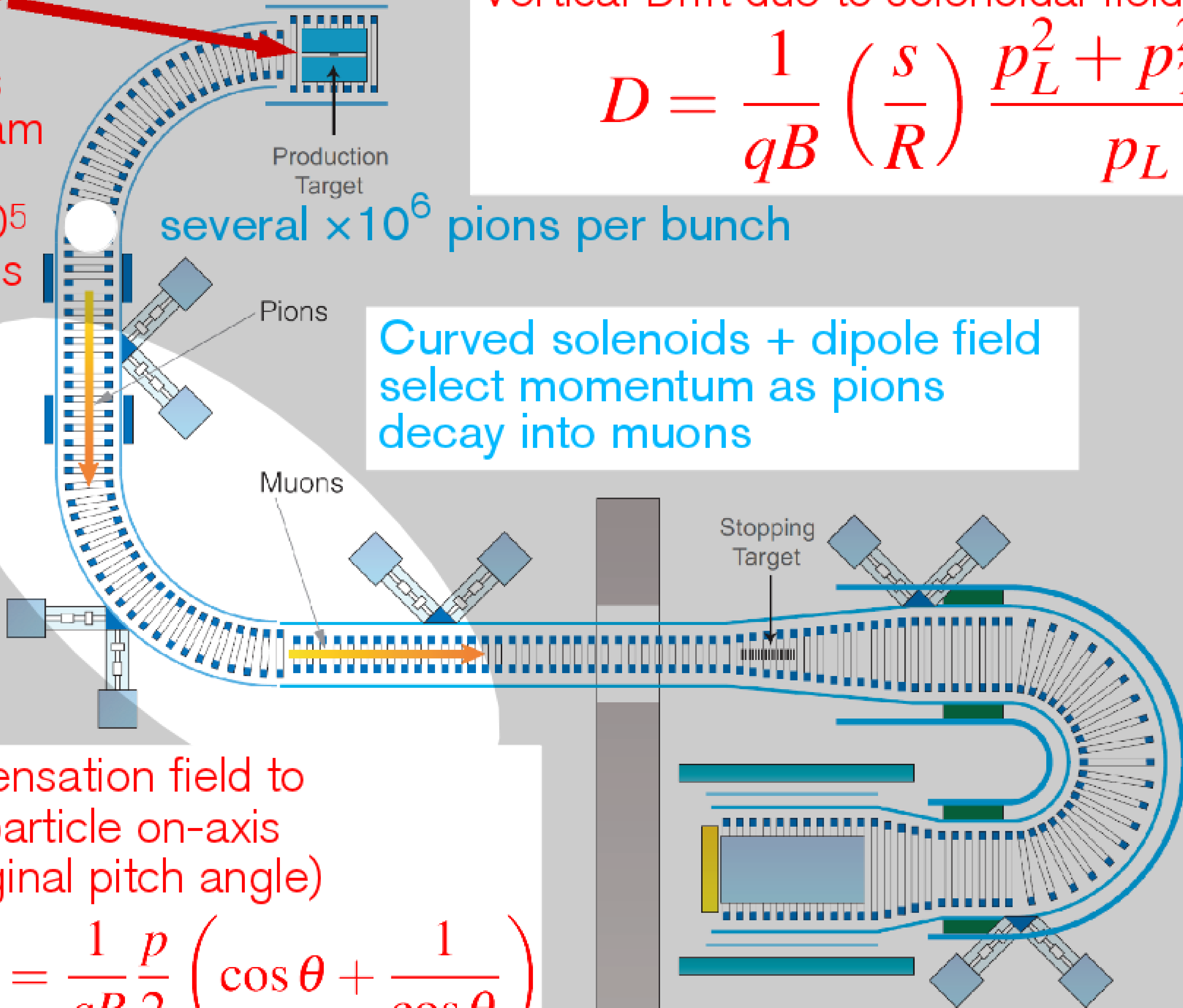
6.4×10¹³ 8 GeV protons per beam spill, in 5.3×10⁵ bunches

Vertical Drift due to solenoidal field:

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

several ×10⁶ pions per bunch

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

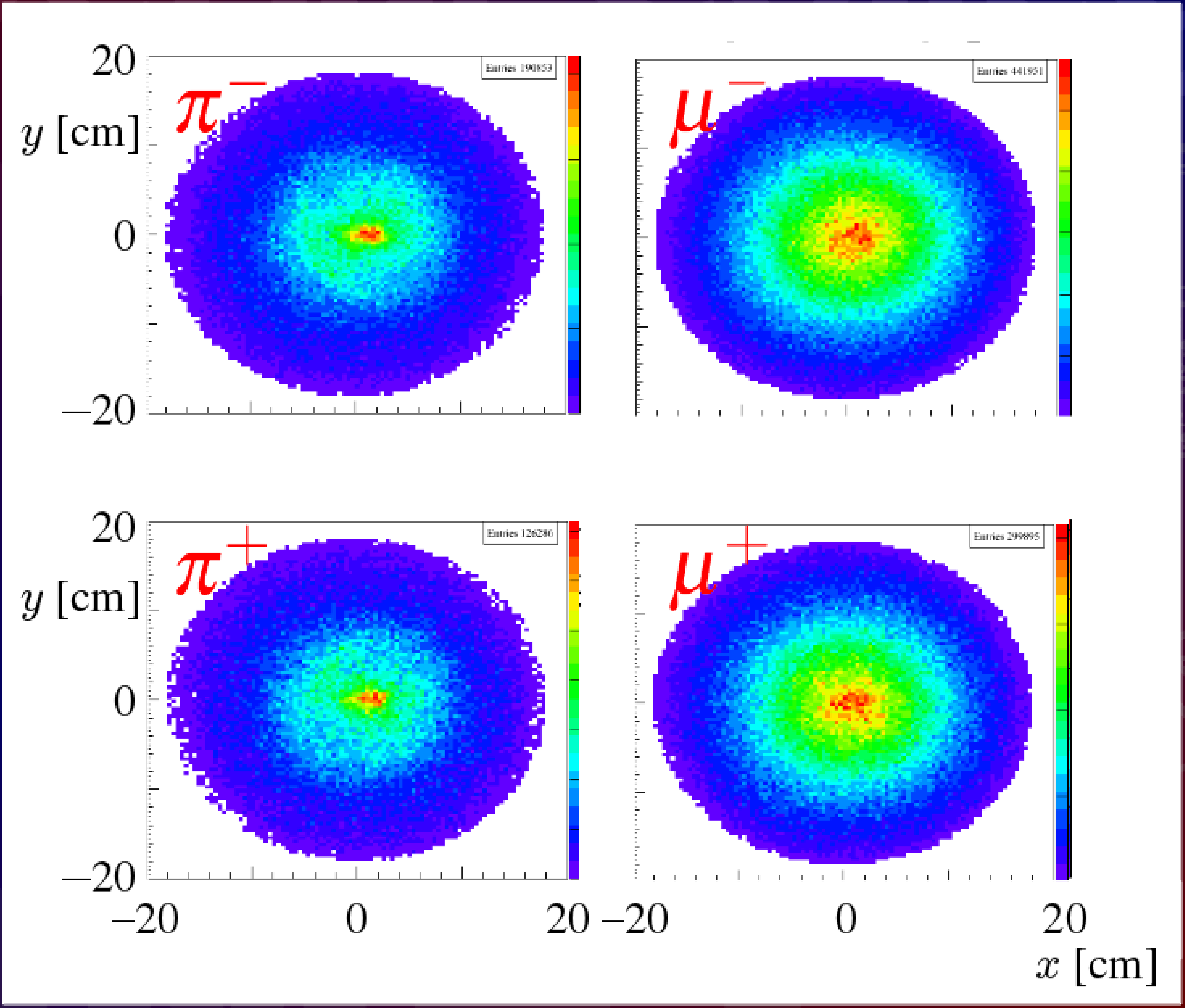


Compensation field to keep particle on-axis (θ :original pitch angle)

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

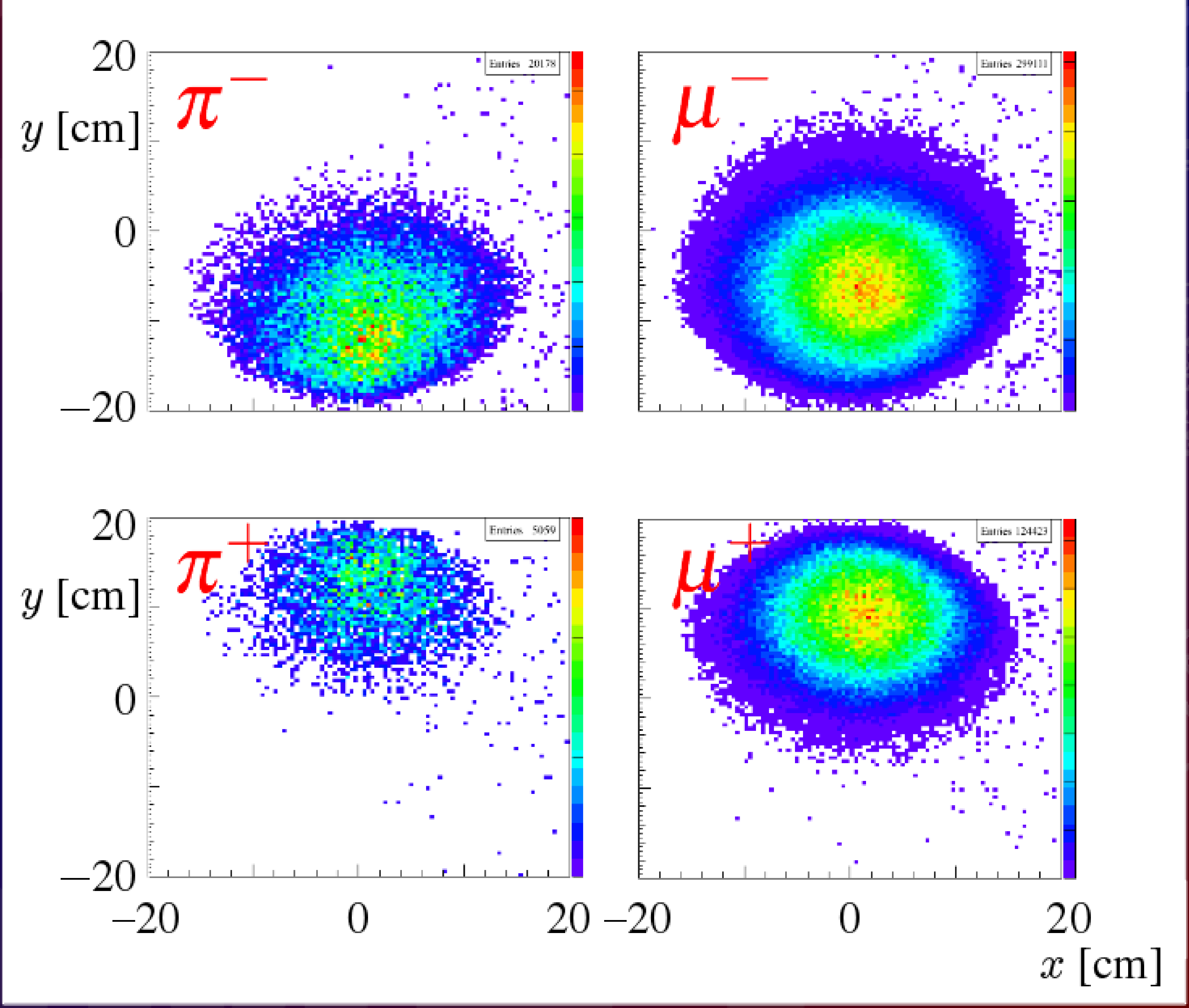
Ben Krikler

Fluxes at Entrance to Curved Solenoid



Ben Krikler

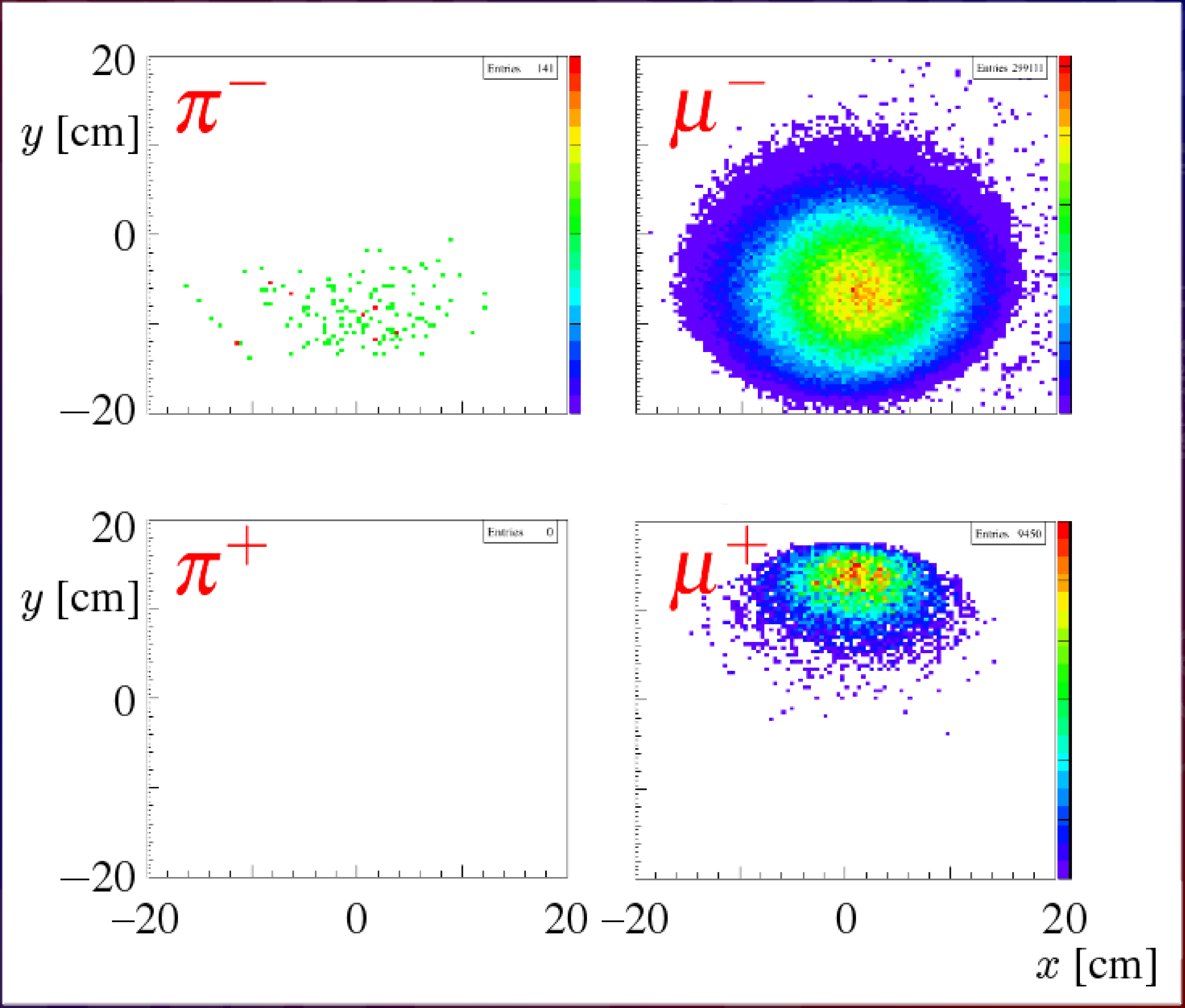
After 90 Degrees of Curved Solenoid



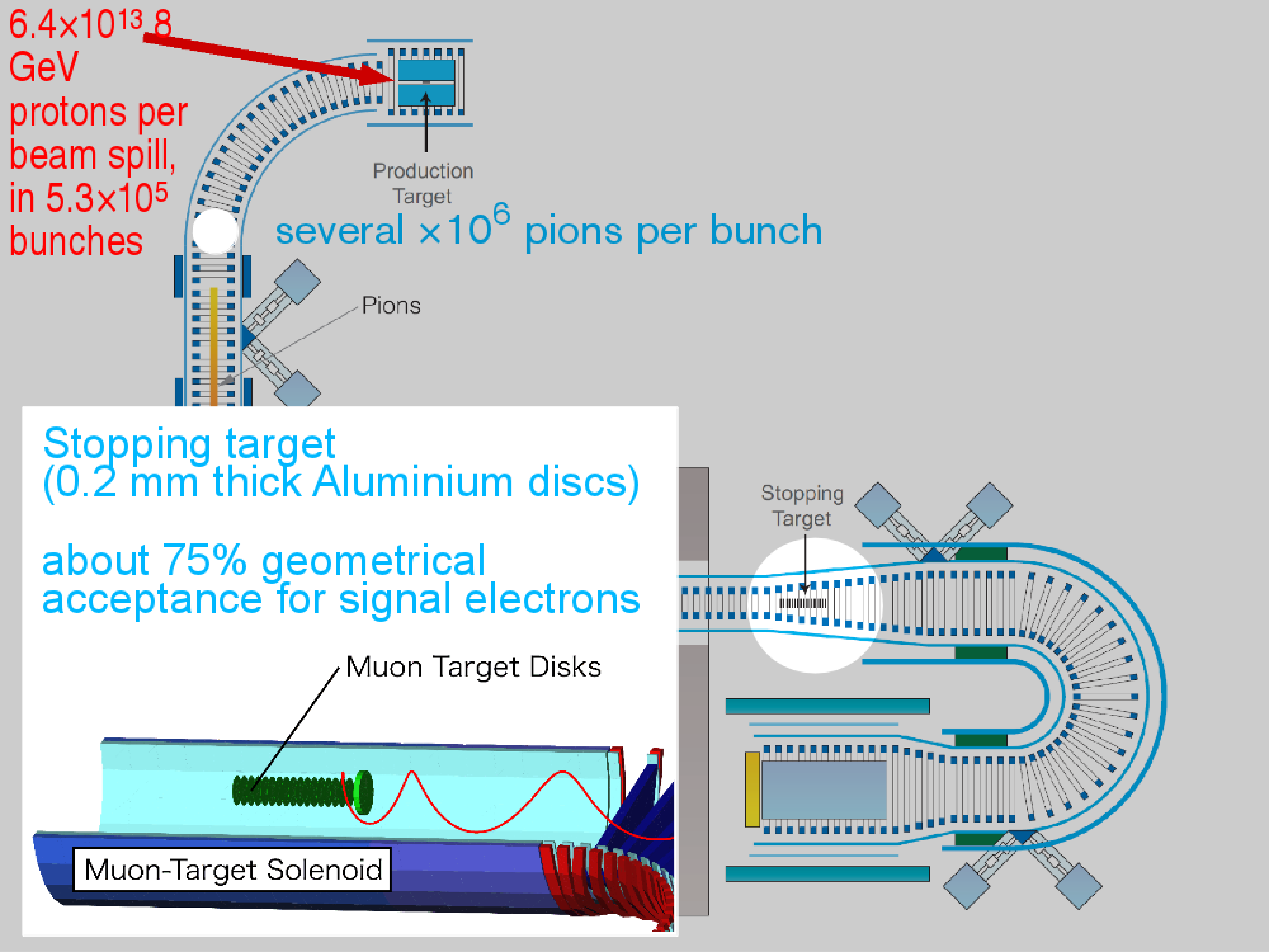
3 T solenoid field, 0.018 T dipole field (tunable)

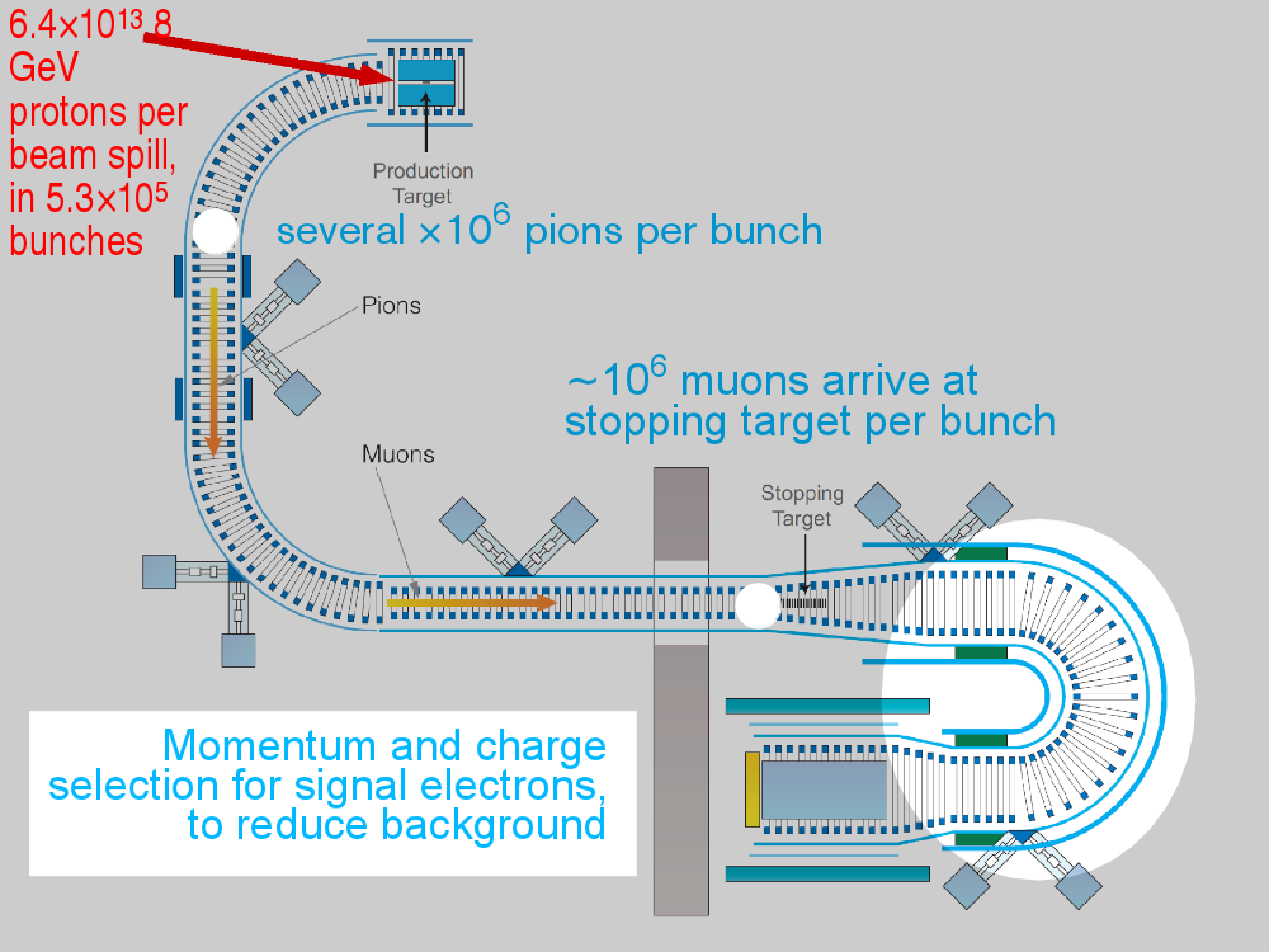
Ben Krikler

Before Stopping Target



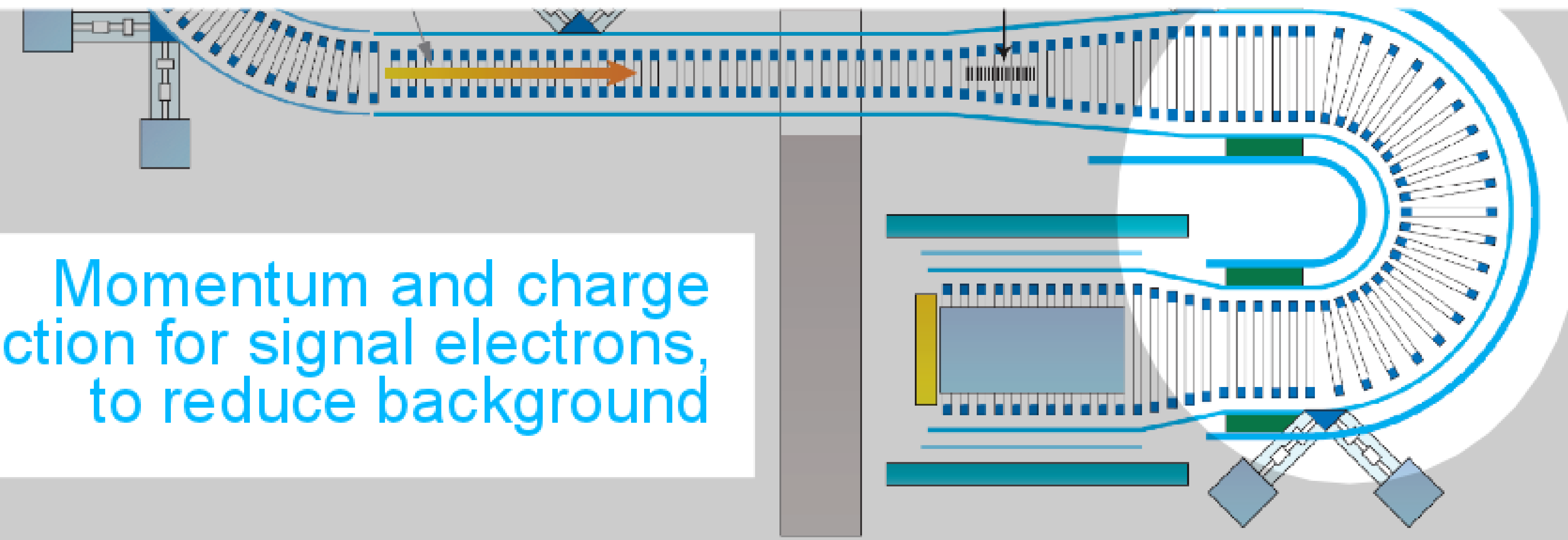
after collimation of high-momentum muons


6.4x10^13 8 GeV protons per beam spill, in 5.3x10^5 bunches
Production Target
several ×10^6 pions per bunch
Pions
Stopping target
(0.2 mm thick Aluminium discs)
about 75% geometrical
acceptance for signal electrons
Muon Target Disks
Muon-Target Solenoid
Stopping Target


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

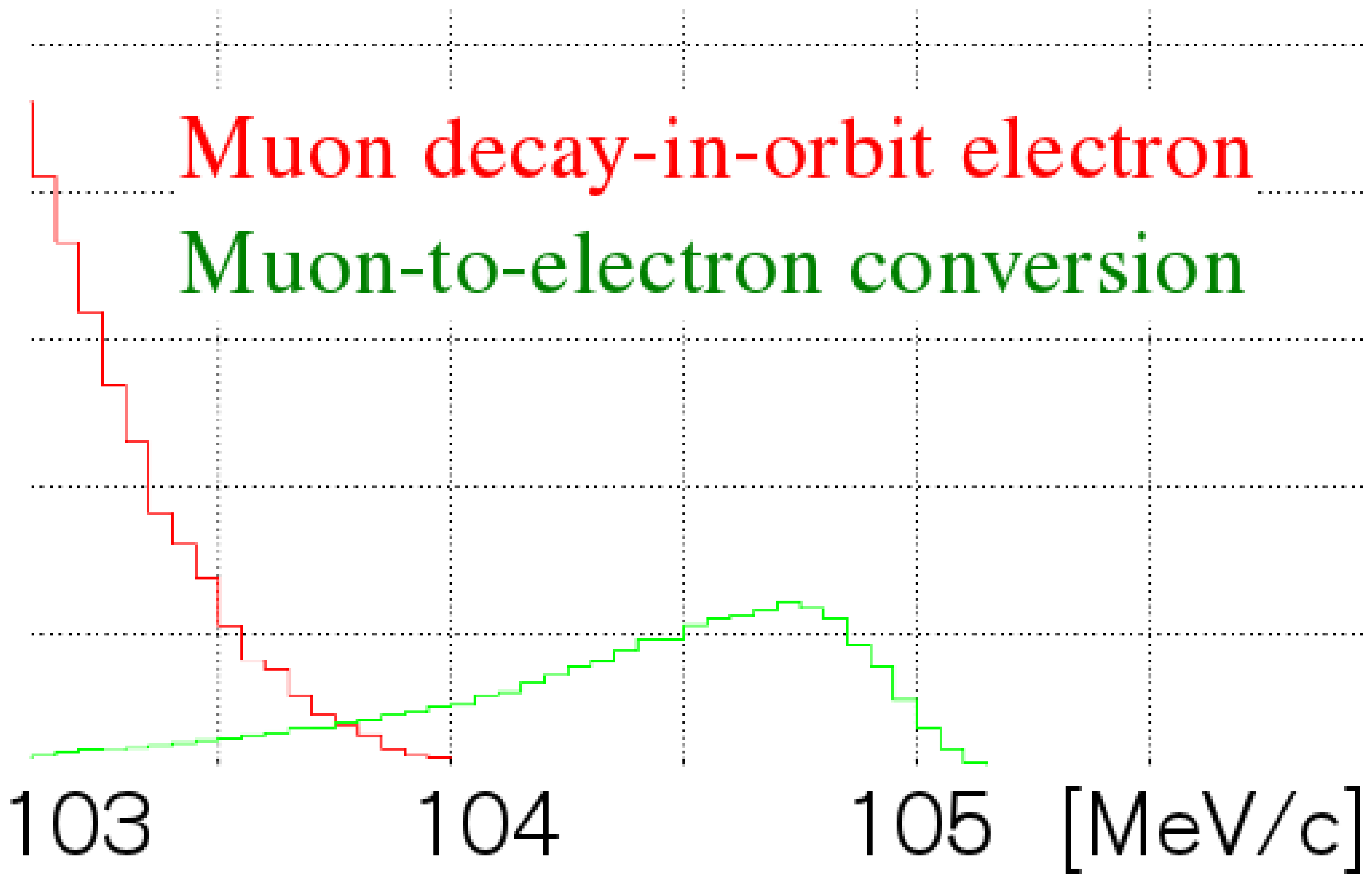
Particles seen after the curved solenoid

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

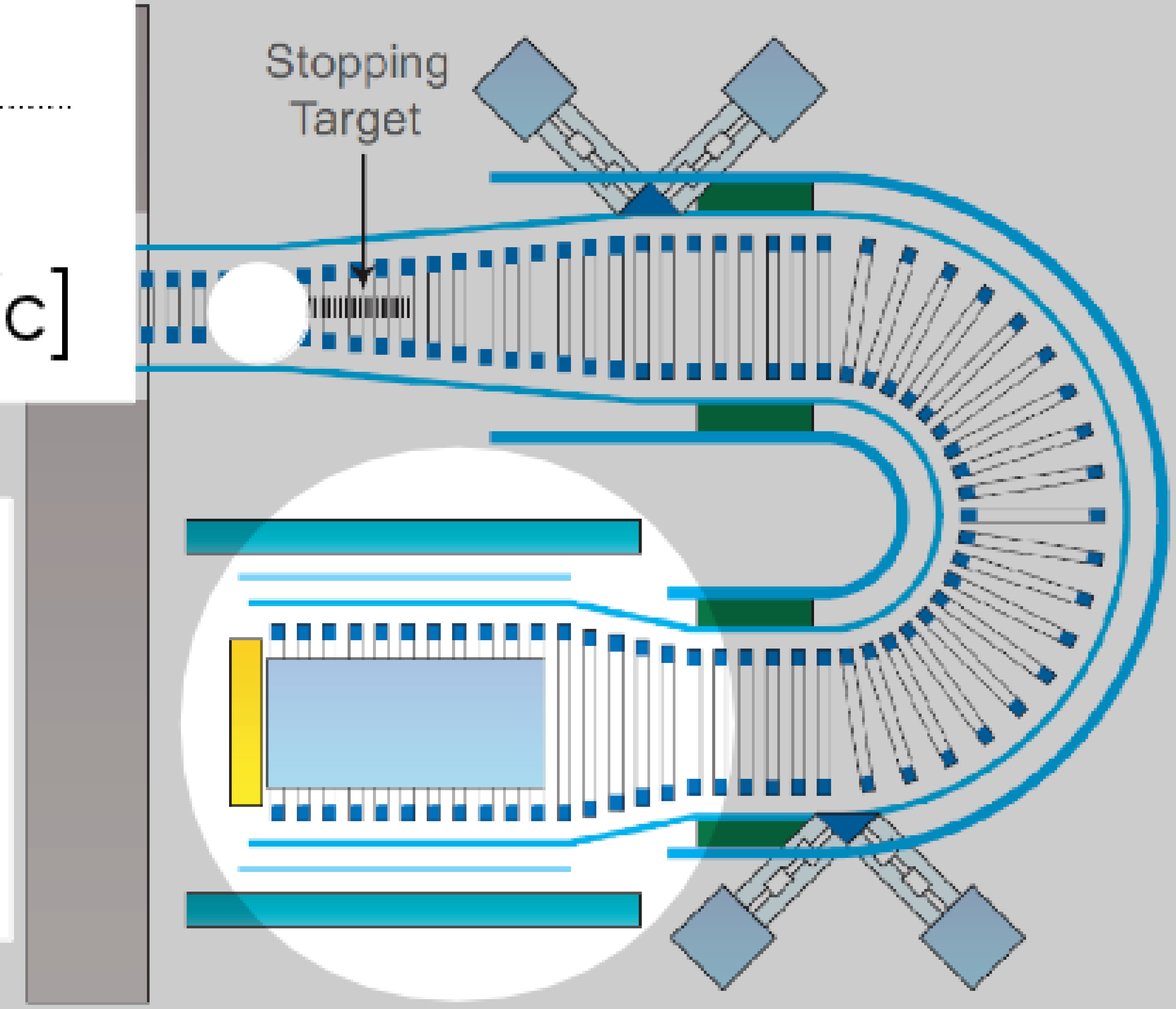


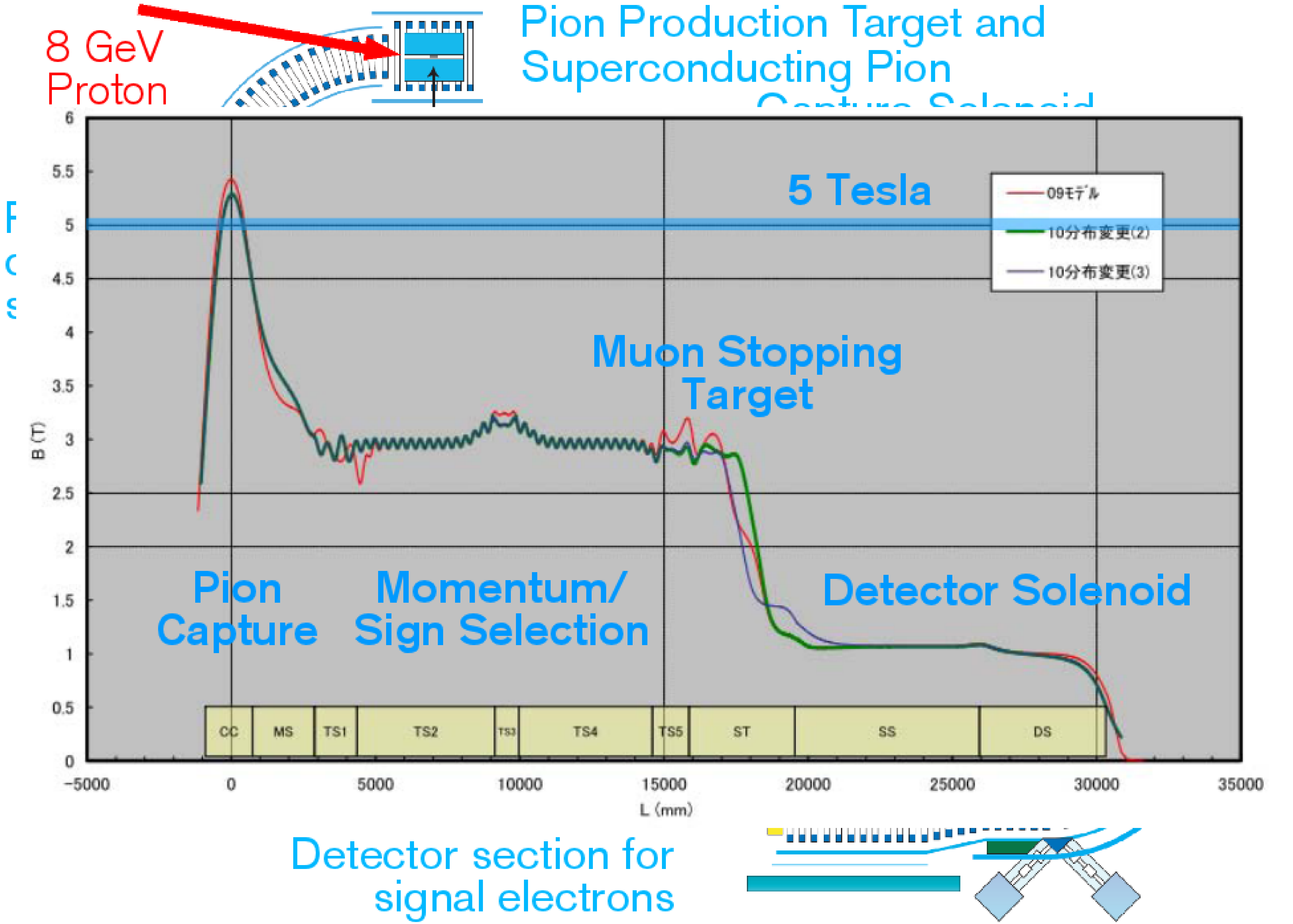
Momentum and charge selection for signal electrons, to reduce background

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



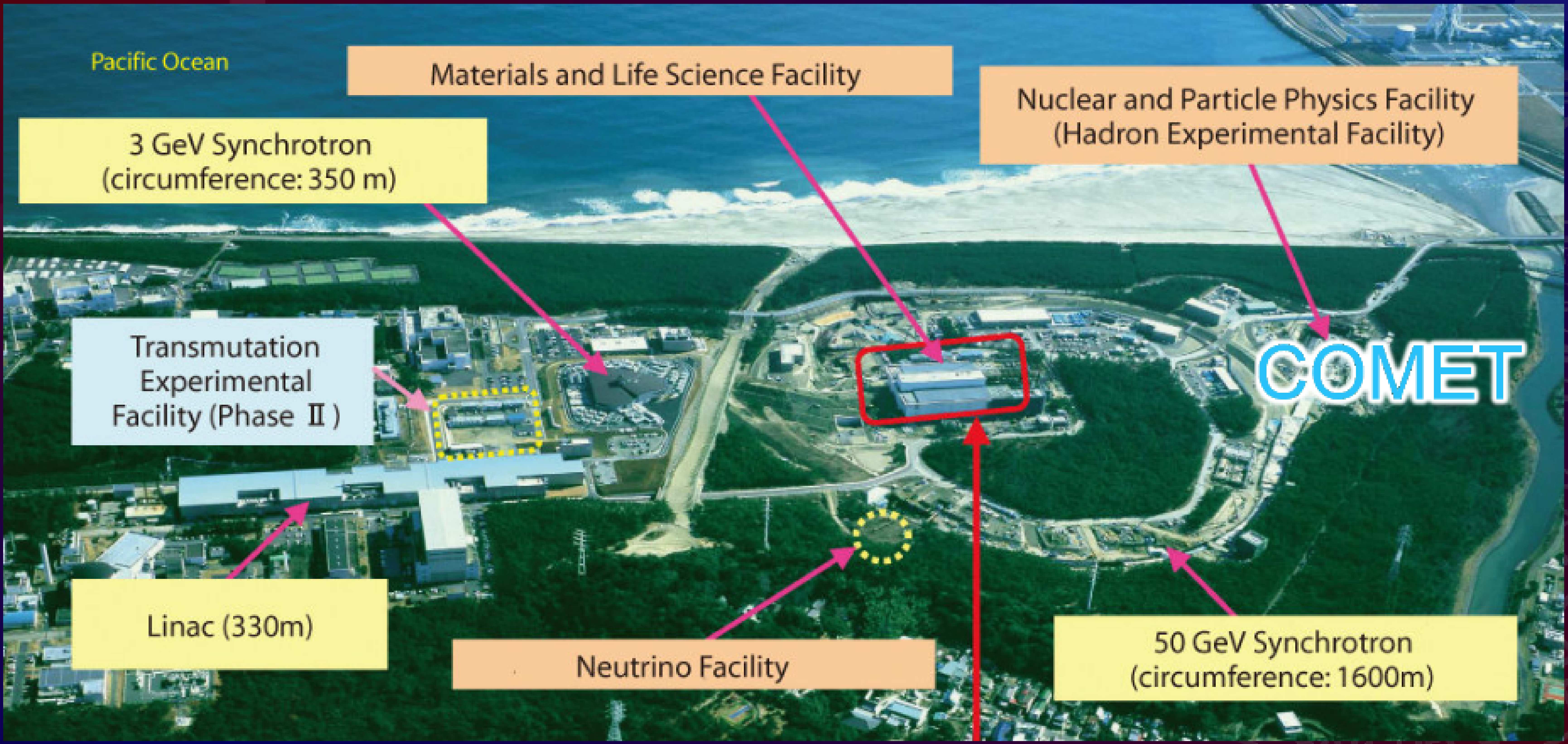
Tracking detector for momentum measurement, calorimeter for energy and triggering redundancy





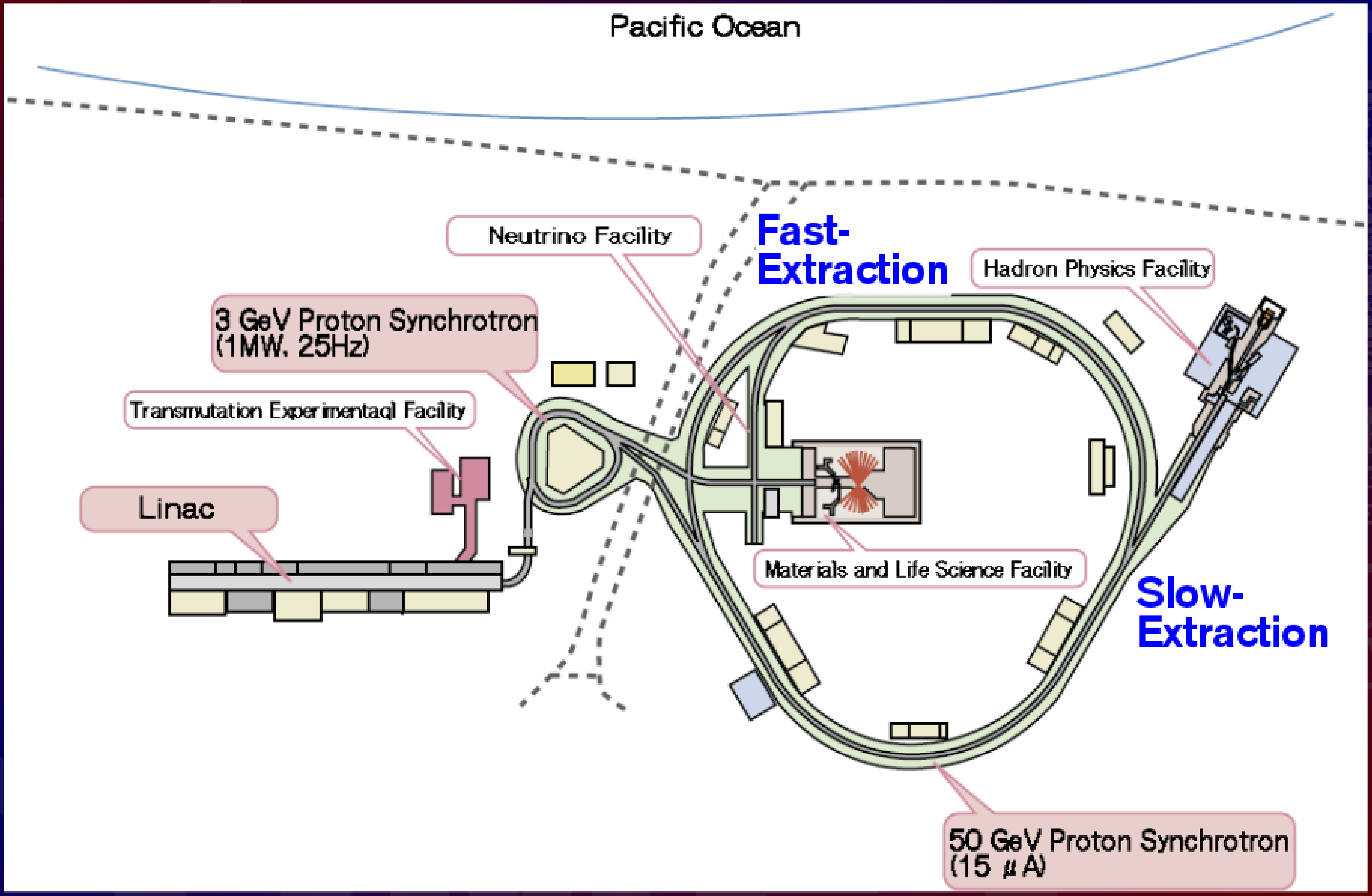
8 GeV
Proton
Pion Production Target and
Superconducting Pion
5 Tesla
09モデル
10分布変更(2)
10分布変更(3)
Muon Stopping
Target
Pion
Capture
Momentum/
Sign Selection
Detector Solenoid
B (T)
L (mm)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-5000
0
5000
10000
15000
20000
25000
30000
35000
CC
MS
TS1
TS2
TS3
TS4
TS5
ST
SS
DS
Detector section for
signal electrons

J-PARC



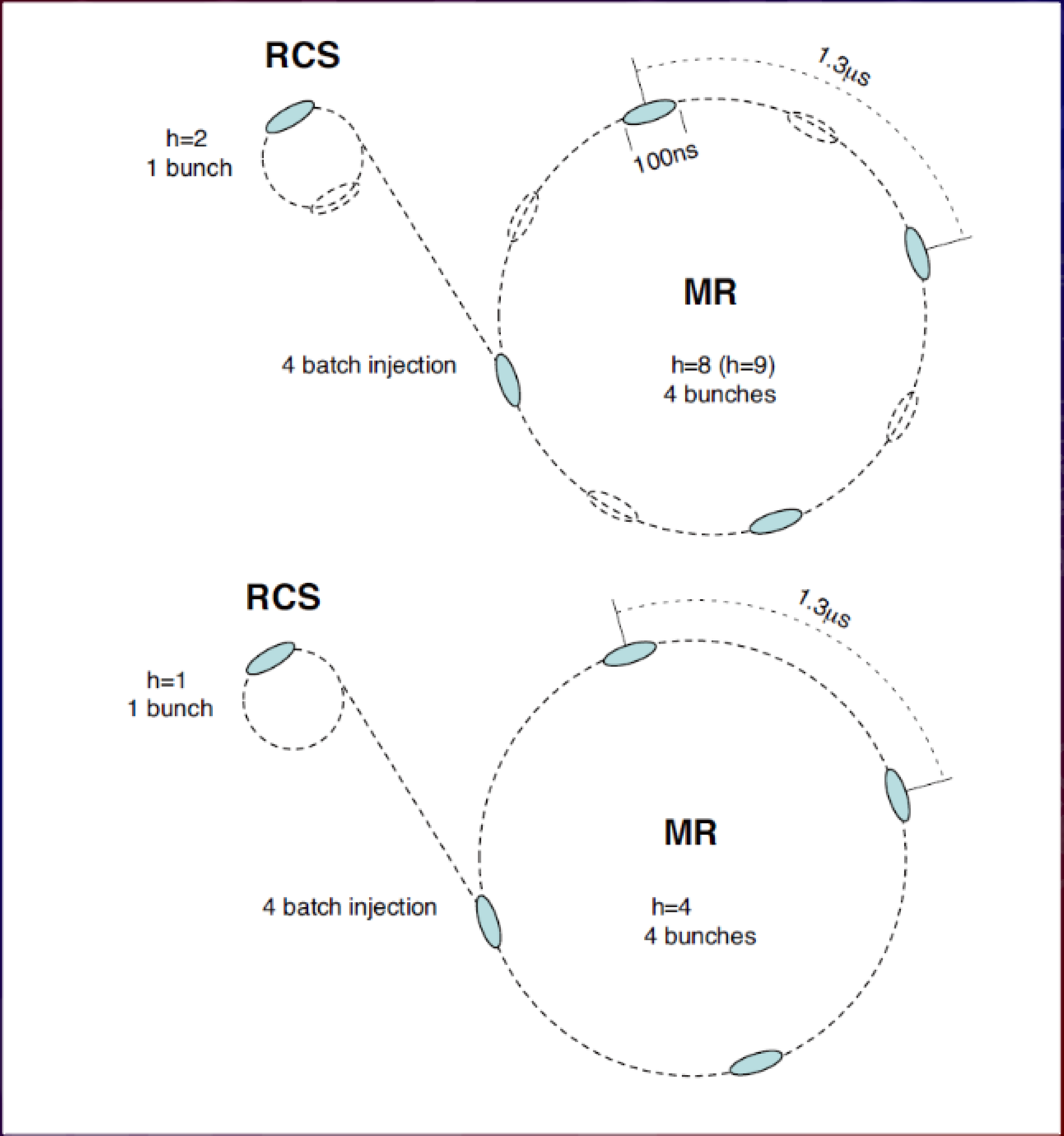
Pacific Ocean
Materials and Life Science Facility
Nuclear and Particle Physics Facility
(Hadron Experimental Facility)
3 GeV Synchrotron
(circumference: 350 m)
COMET
Transmutation
Experimental
Facility (Phase Ⅱ)
Linac (330m)
Neutrino Facility
50 GeV Synchrotron
(circumference: 1600m)

J-PARC


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

J-PARC

Possible Acceleration Schemes



T2K operates at h=9, with 8 bunches filled

R&D Status

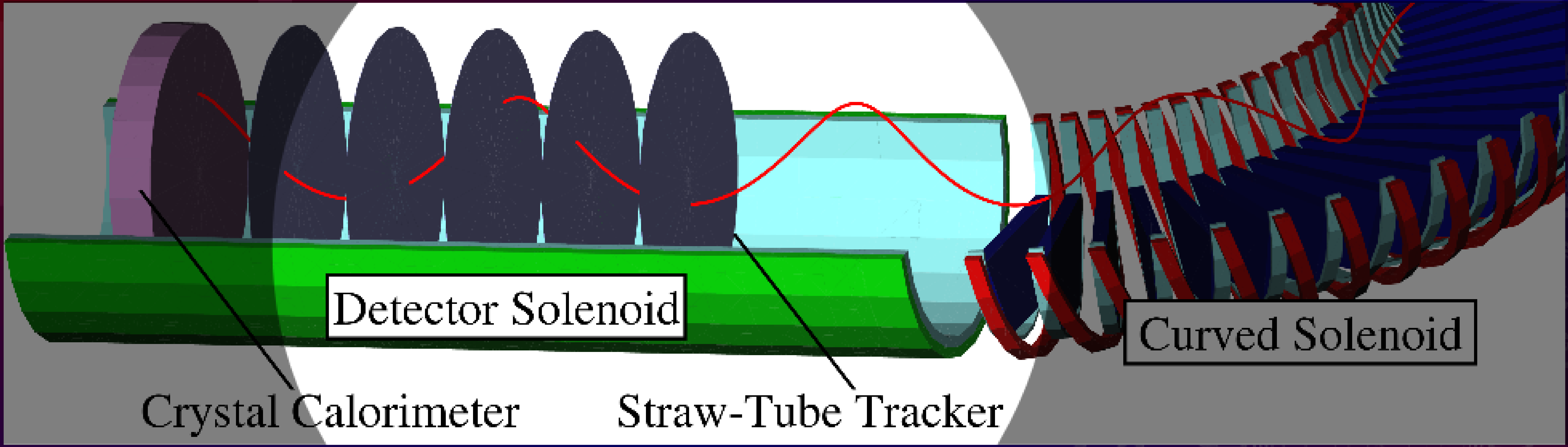
Beam Extinction

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

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

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

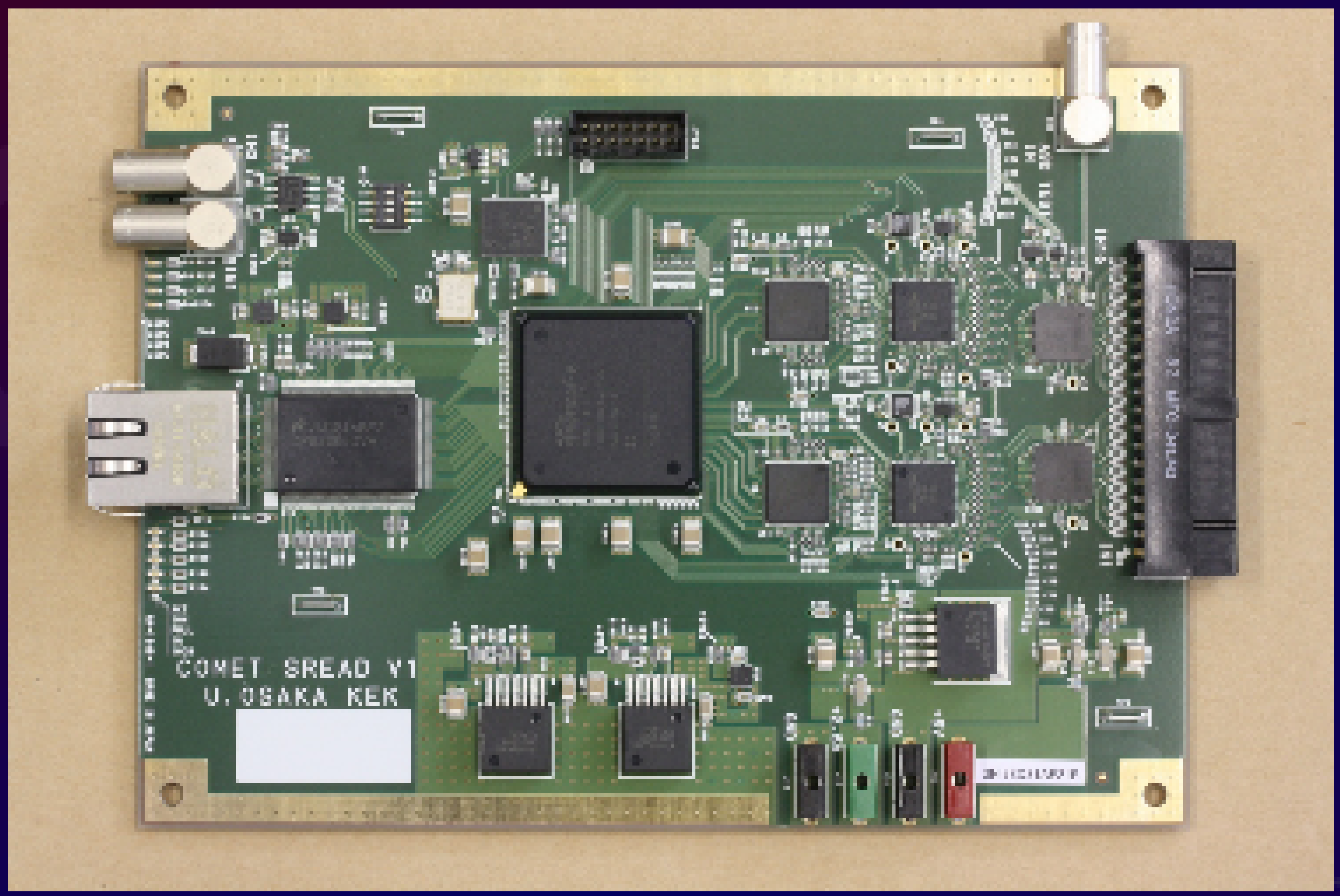
COMET Detector Section

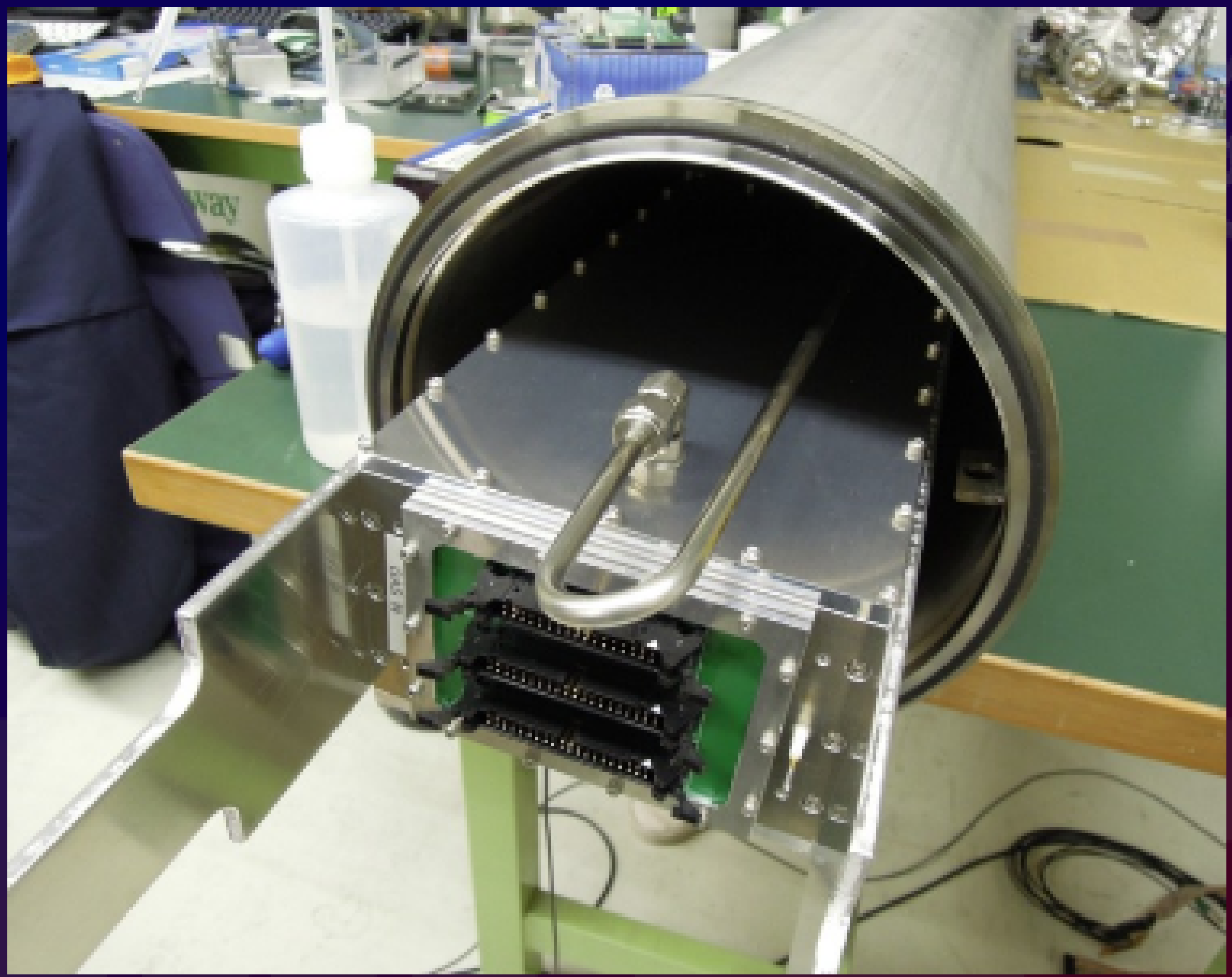


- Straw-tube electron tracker in 1 Tesla field
  - 800 kHz charged particle and 8 MHz gamma rates
  - 0.4% momentum and 700 micron spatial resolution required

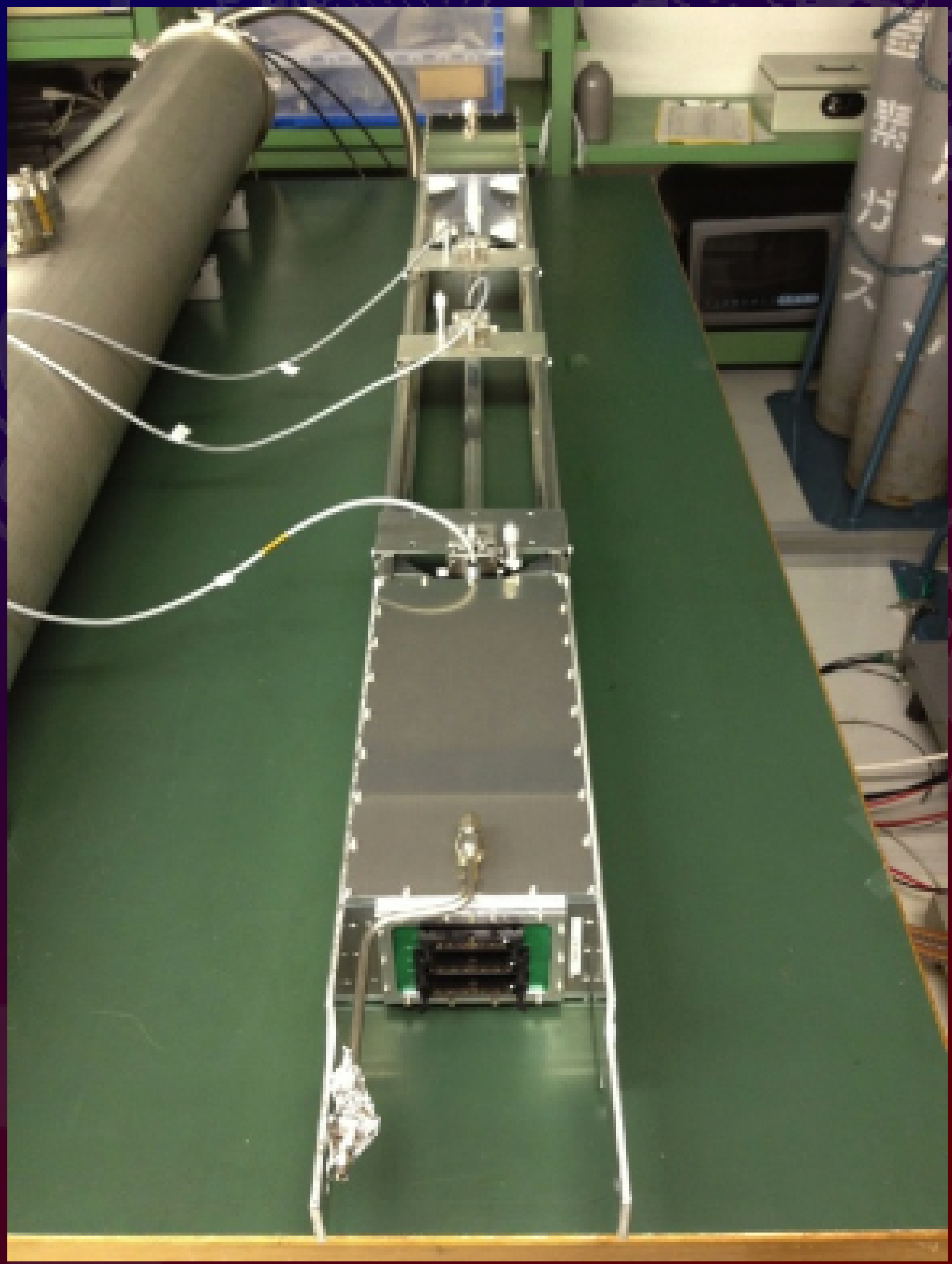
Straw Tube Tracker R&D

Prototype at KEK (7 straw tubes)

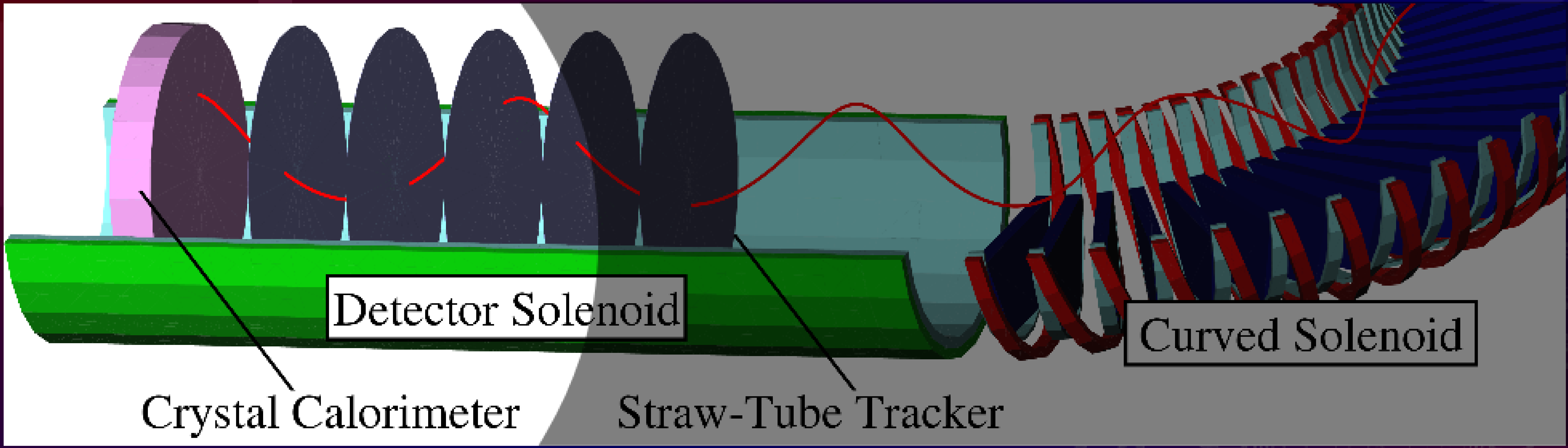




Front-end electronics R&D, leak, deformation, gain and timing tests



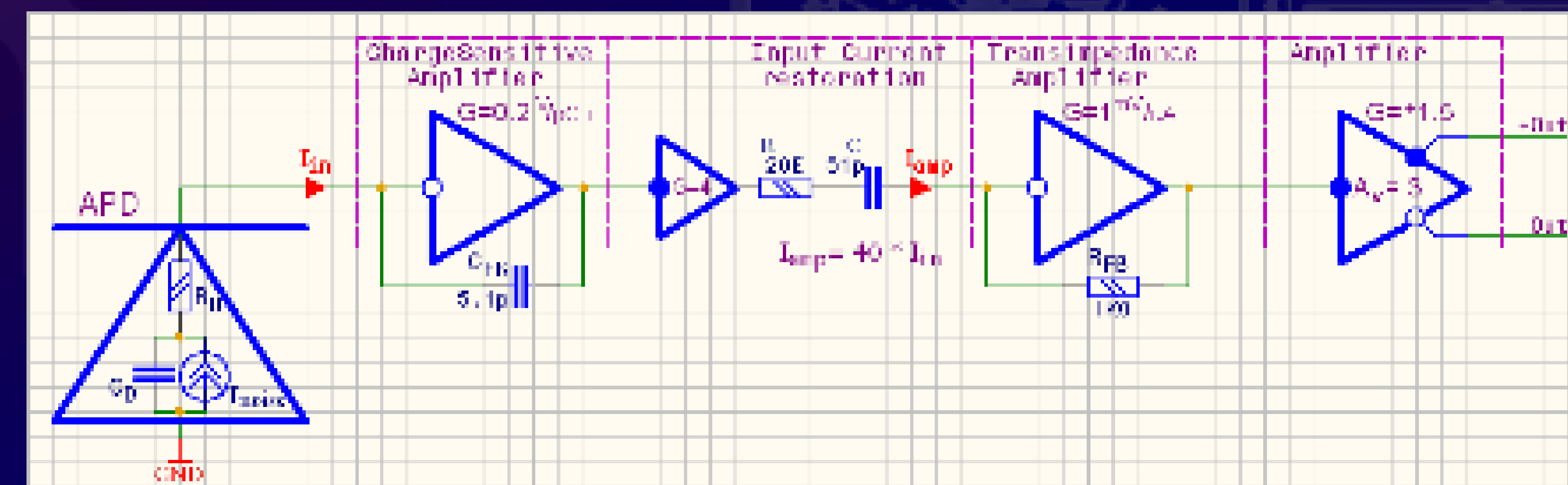
COMET Detector Section



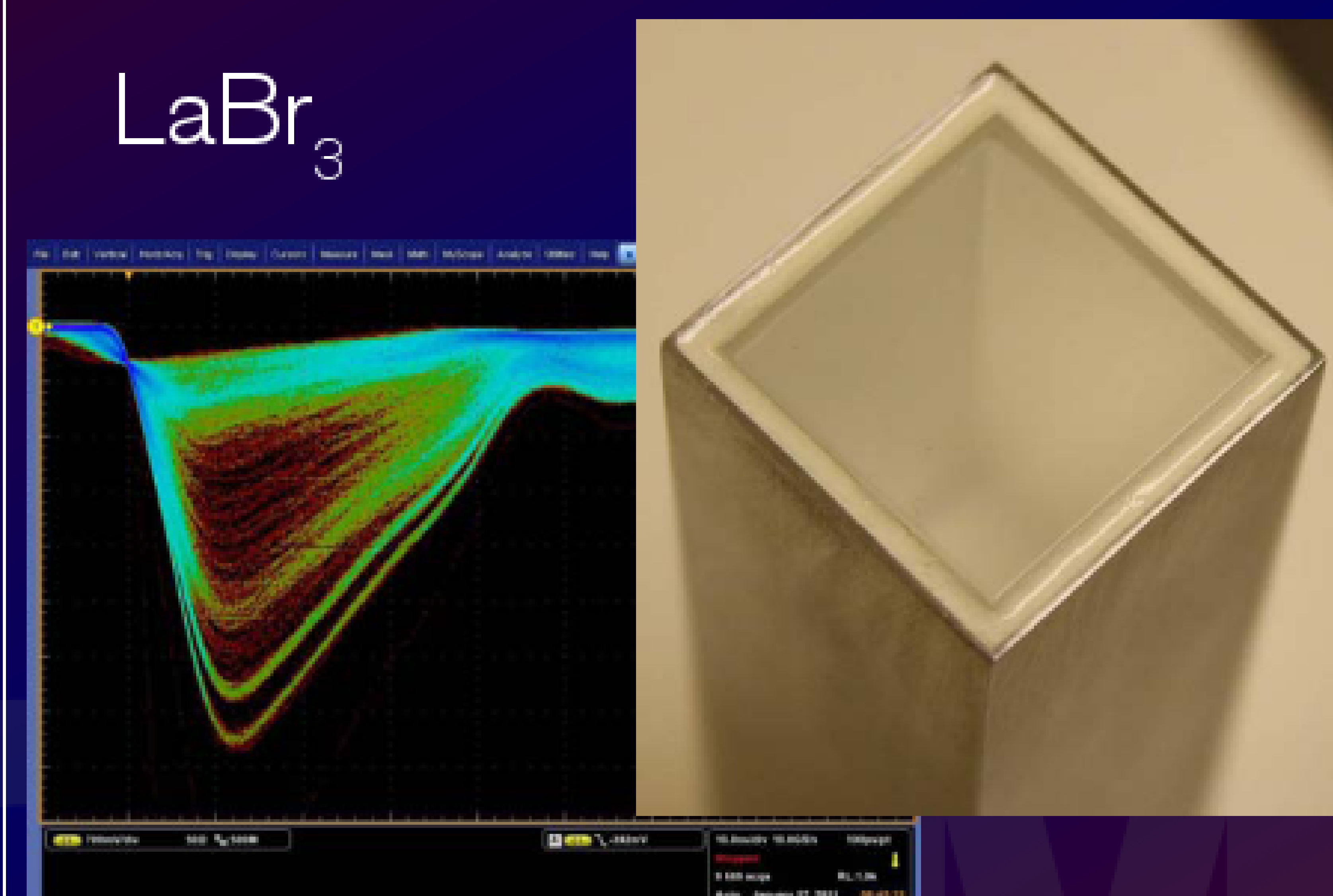
- Crystal calorimeter
  - for energy and position measurement, PID, trigger signal
  - 5% energy and 1cm spatial resolution at 100 MeV

Calorimeter R&D

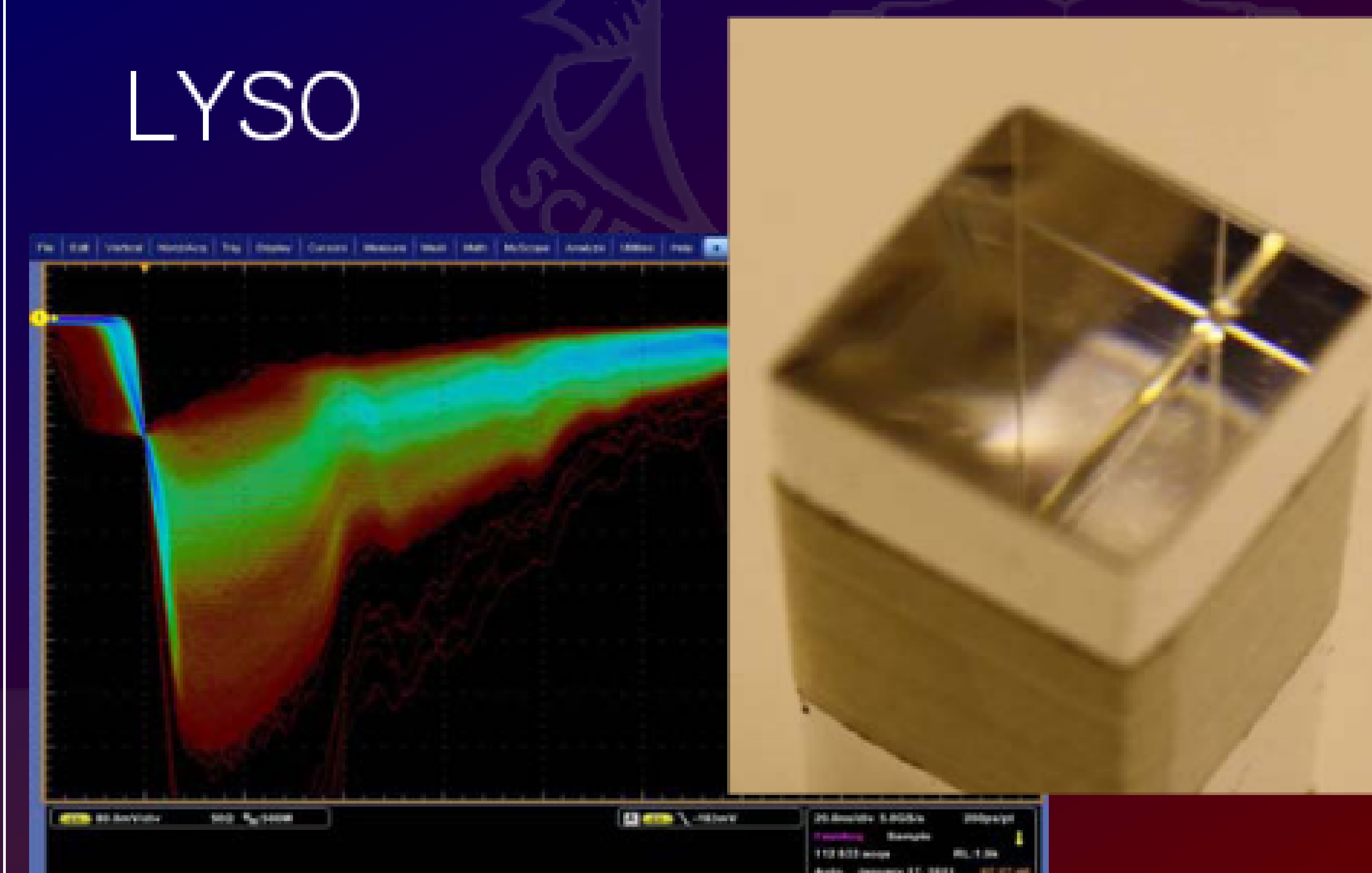
- GSO / LYSO crystals with APDs tested 2011
  - Vertical slice tests this year
- Design being finalised for 50-crystal / APD prototype
  - beam tests later this year at BINP Novisibirsk



$LaBr_3$

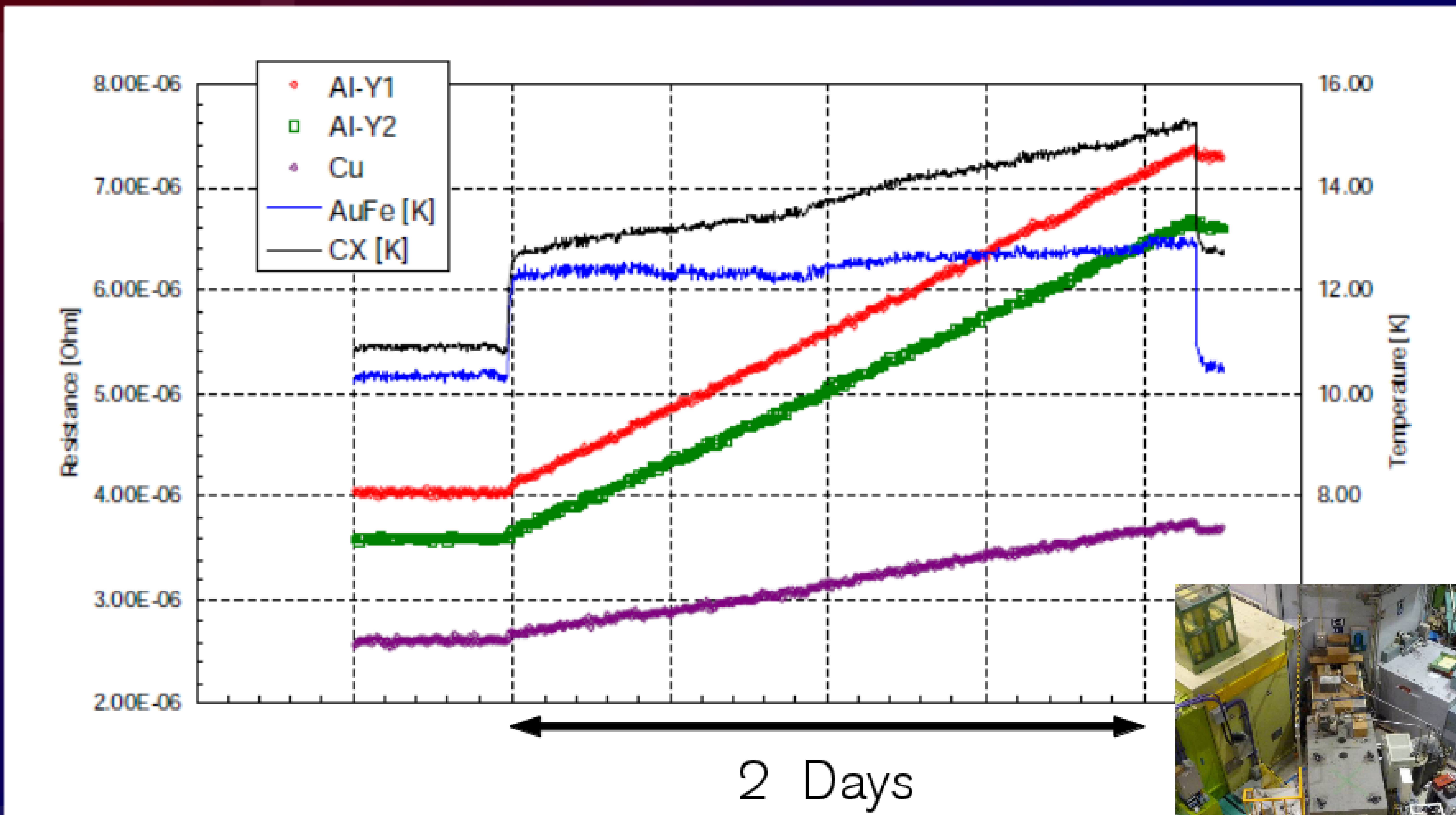


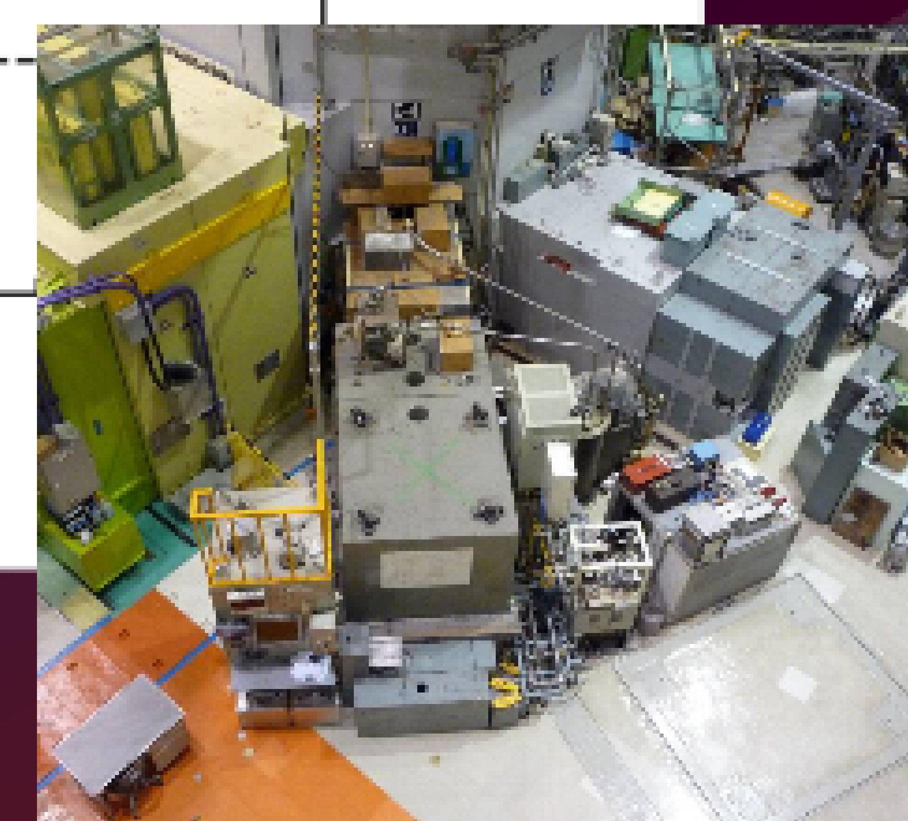
LYSO



Superconducting Solenoid R&D

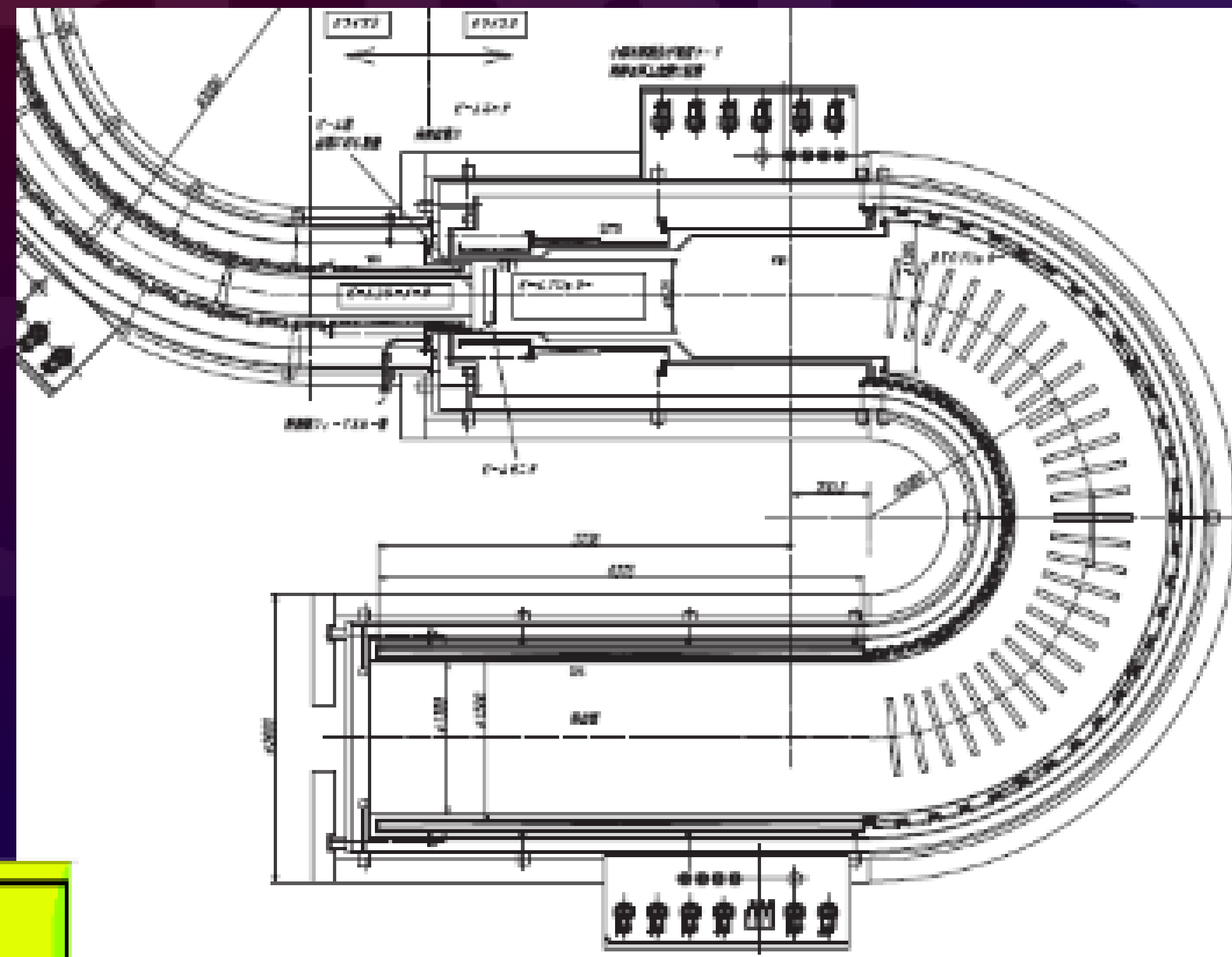
Neutron irradiation tests performed at KURRI reactor, Kyoto University

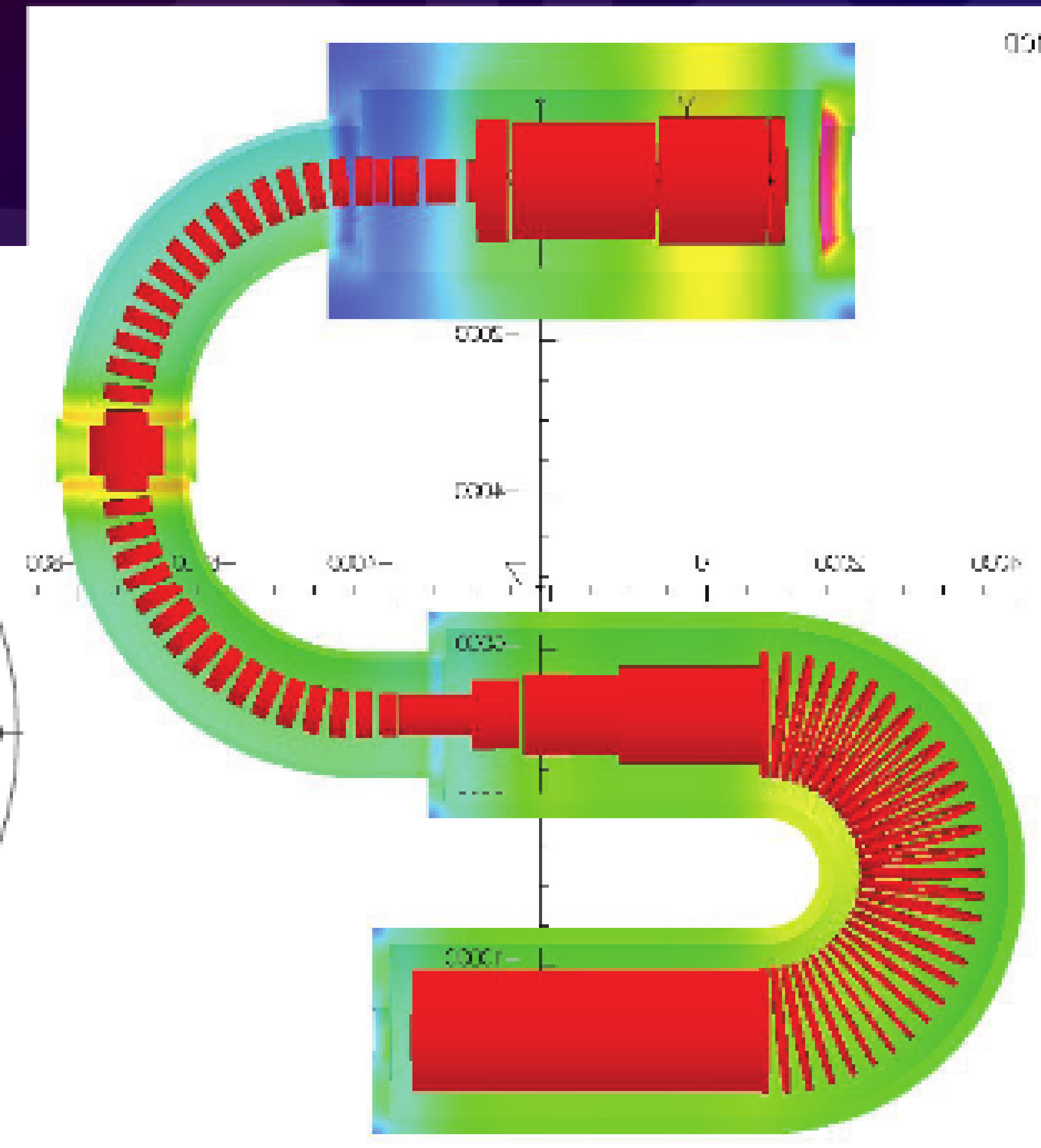


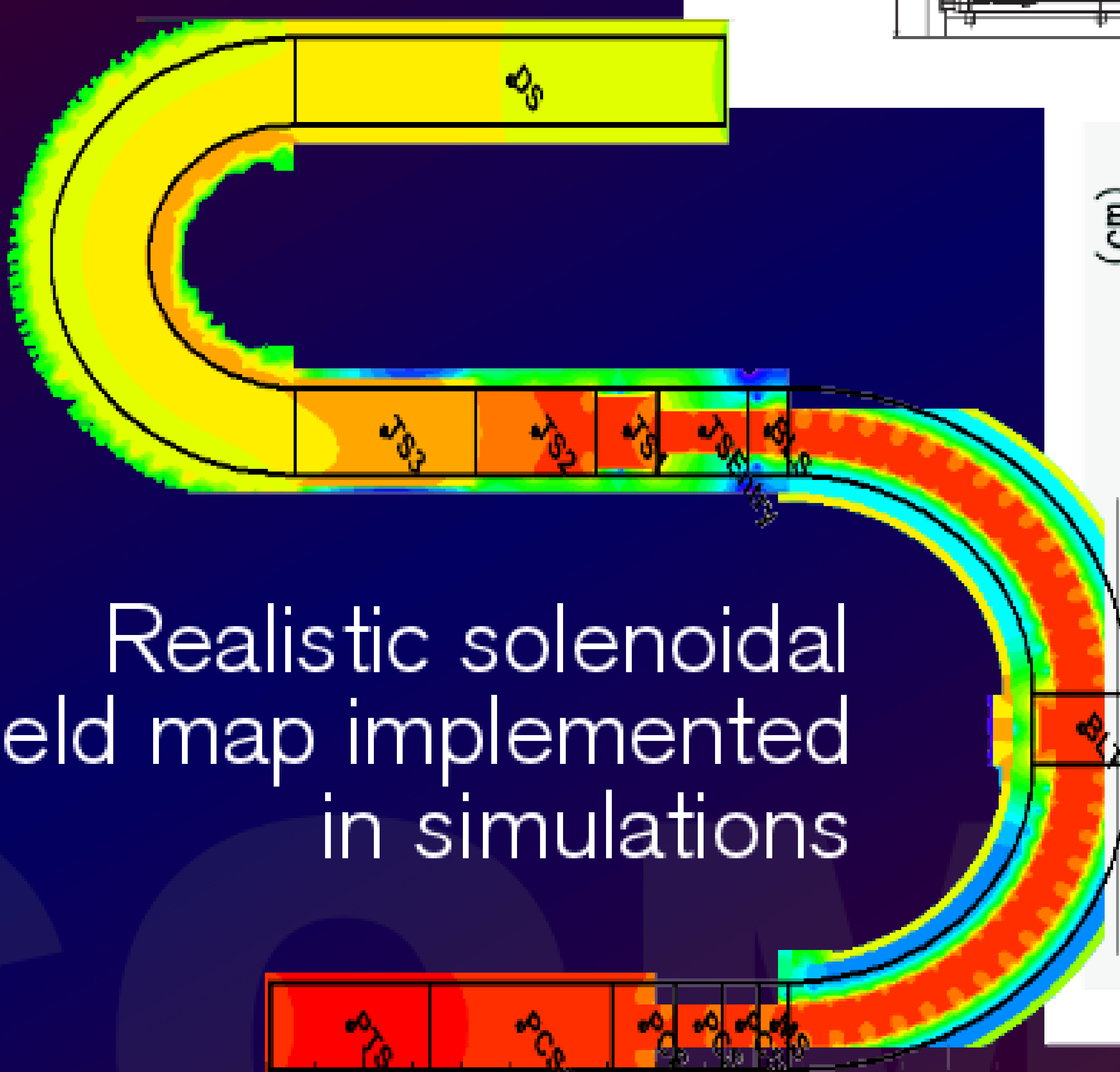


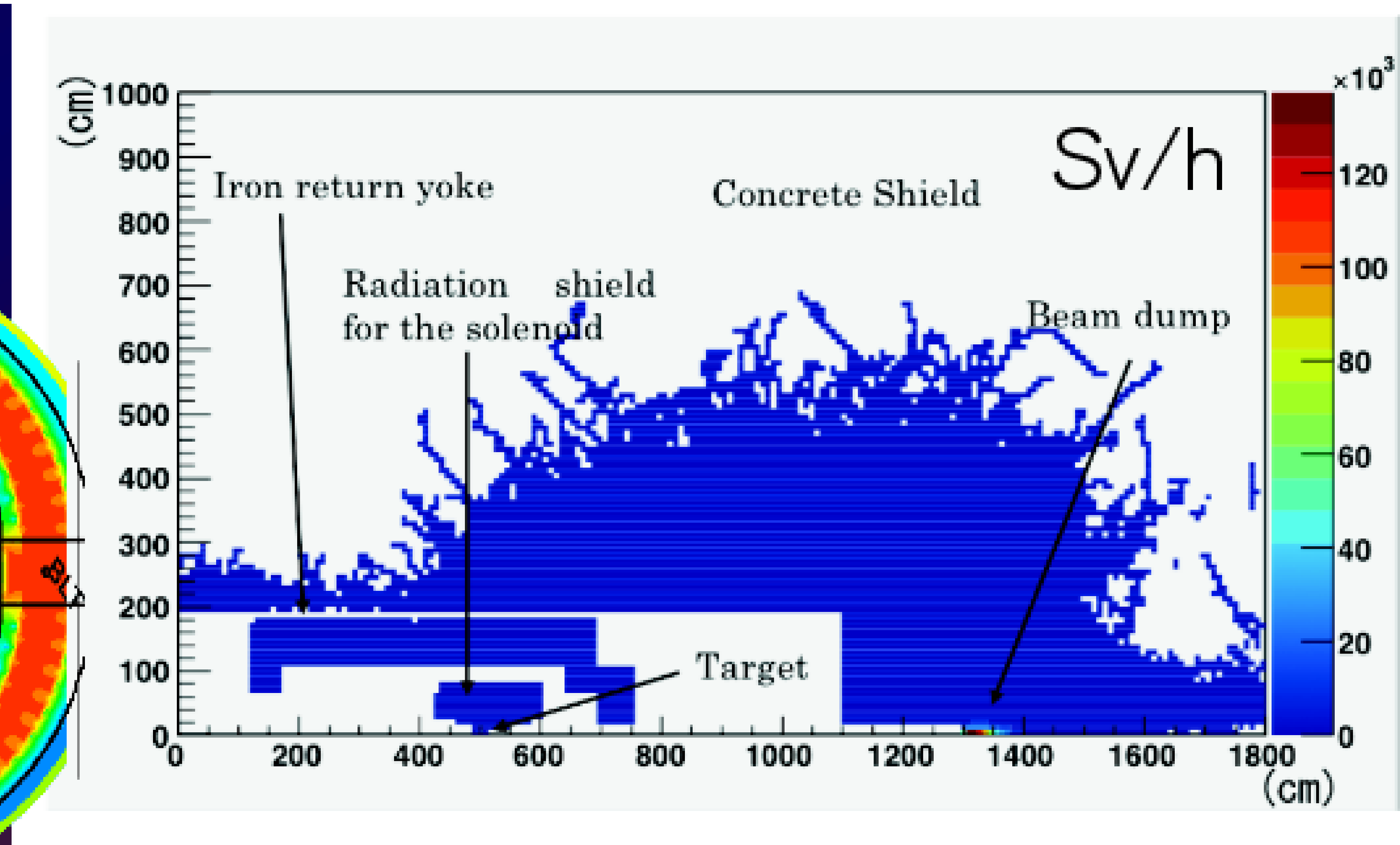
Demonstrated that Al stabiliser tolerates COMET radiation environment

Industrial Design Studies

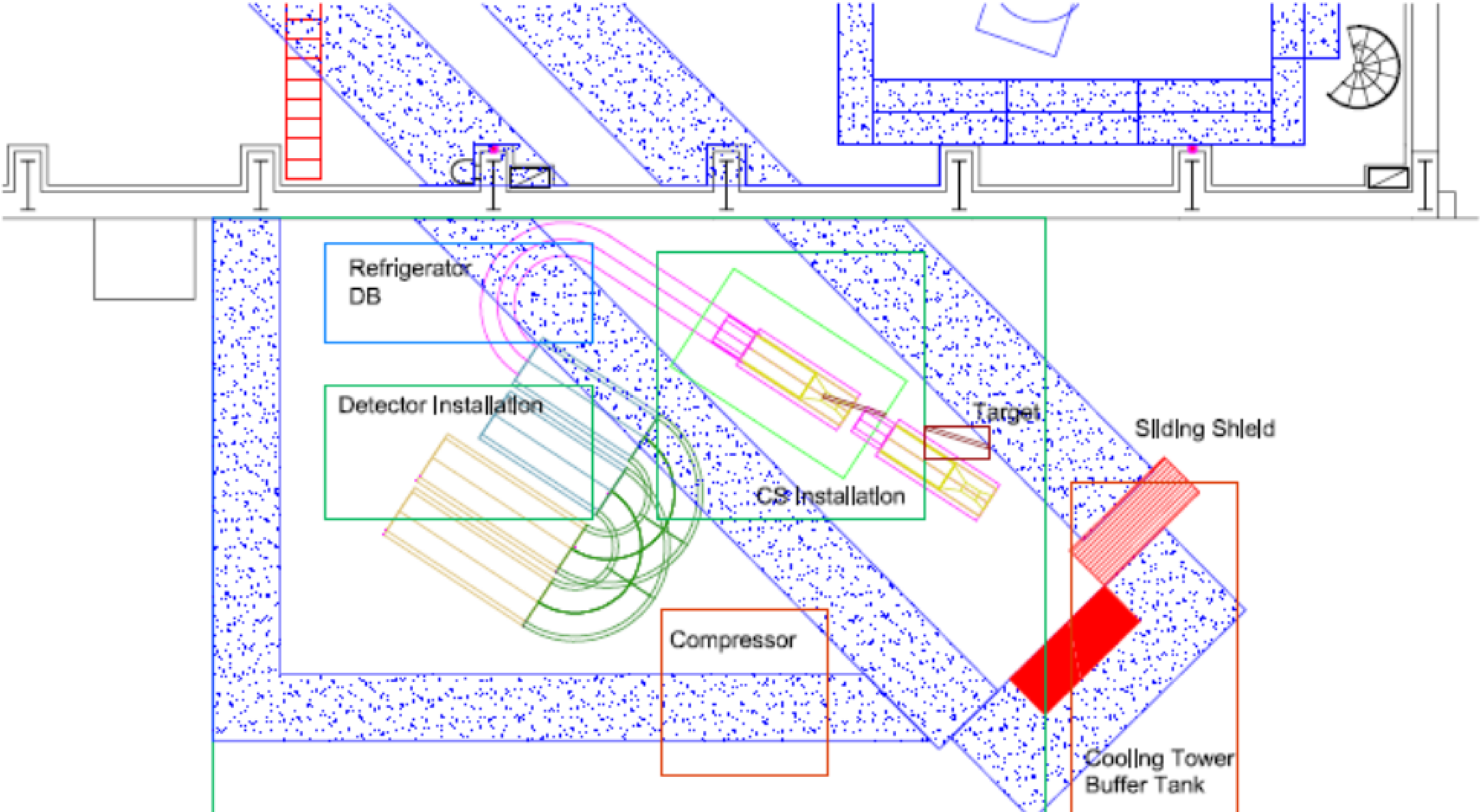








Realistic solenoidal field map implemented in simulations


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

CDR submitted to
J-PARC PAC in June 2009

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

The COMET Collaboration

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E. Hungerford
Department of Physics, University of Houston, USA

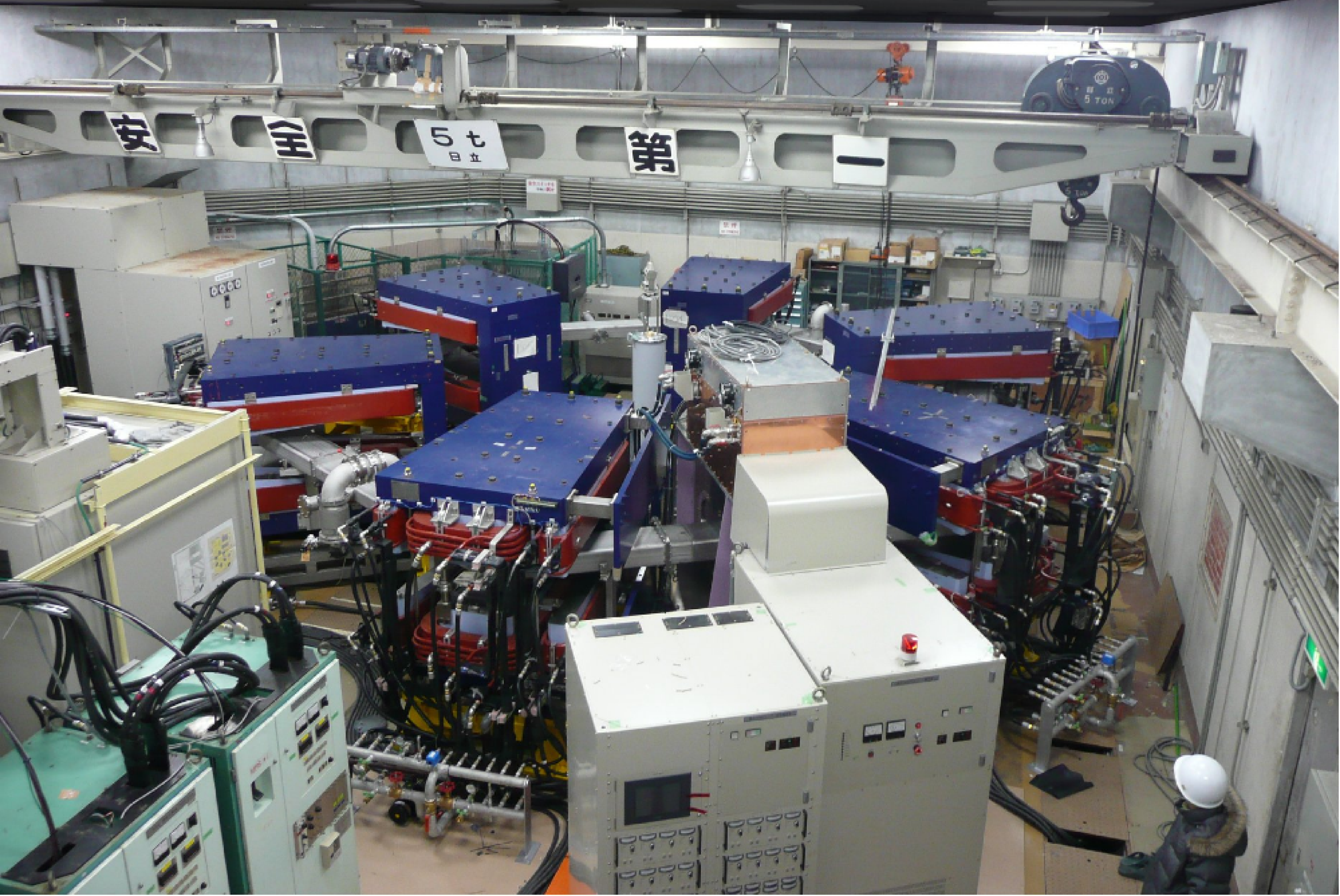
T. Numao
TRIUMF, Canada

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

PRISM

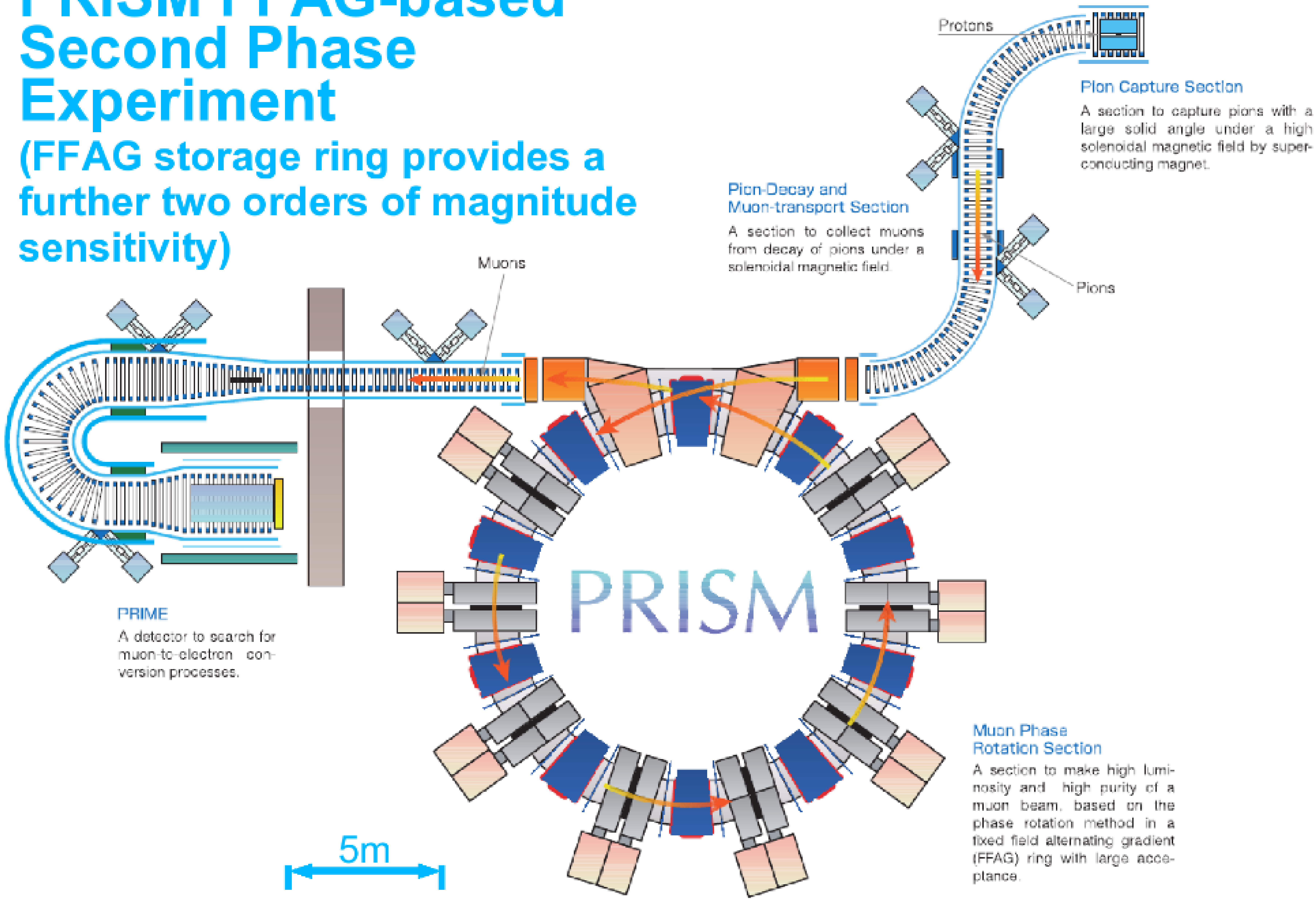
The PRISM FFAG Ring for Muon-to-Electron Conversion

Prototype ring at Osaka University



PRISM FFAG-based Second Phase Experiment

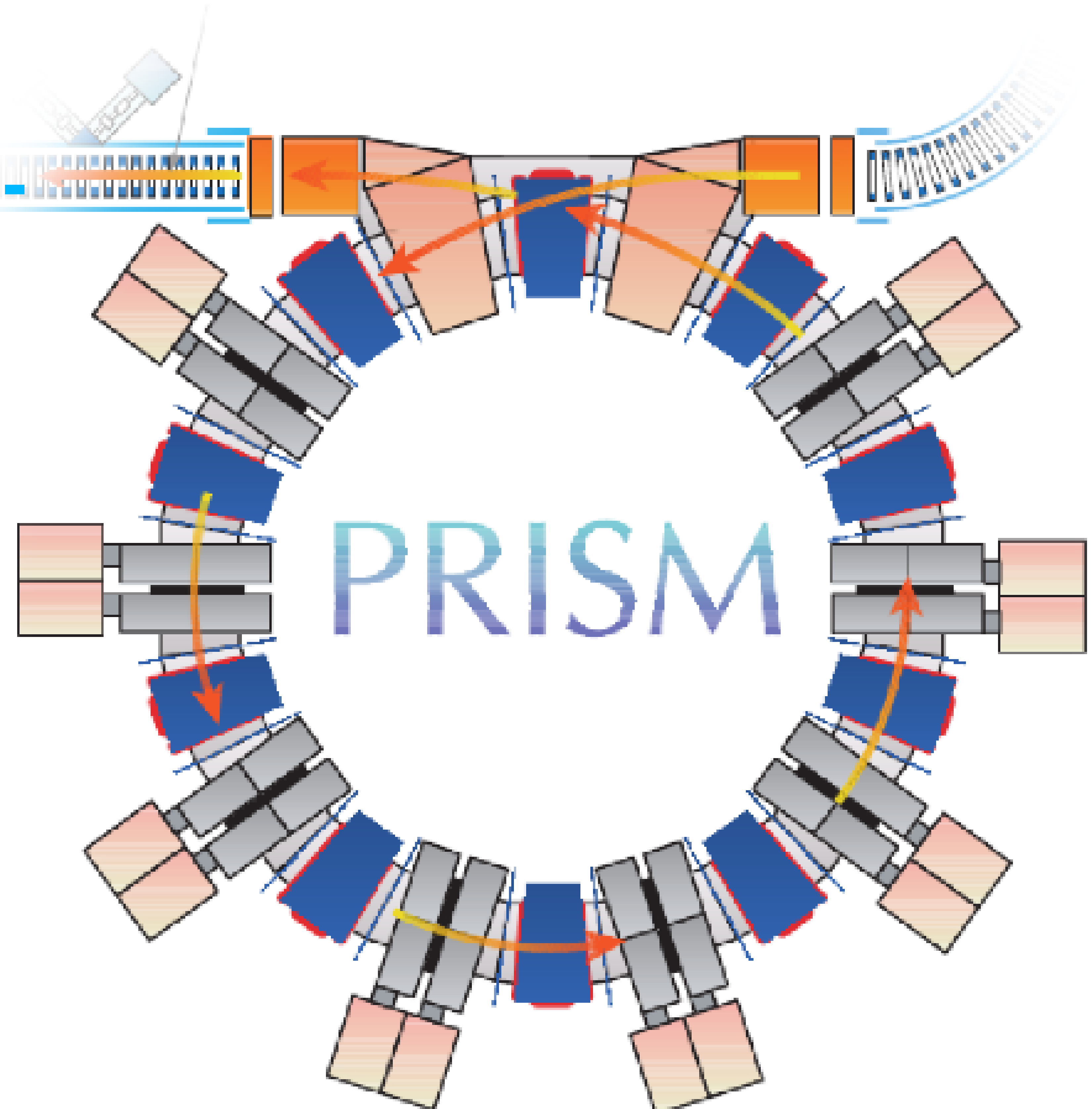
(FFAG storage ring provides a further two orders of magnitude sensitivity)



PRISM/FFAG

Muon Storage Ring

- high acceptance
  H: 40000 mm mrad
  V: 6500 mm mrad
- phase-rotation produces mono-energetic beam
- 8 turns gives a 150m path length



PRISM/FFAG

Muon Storage Ring

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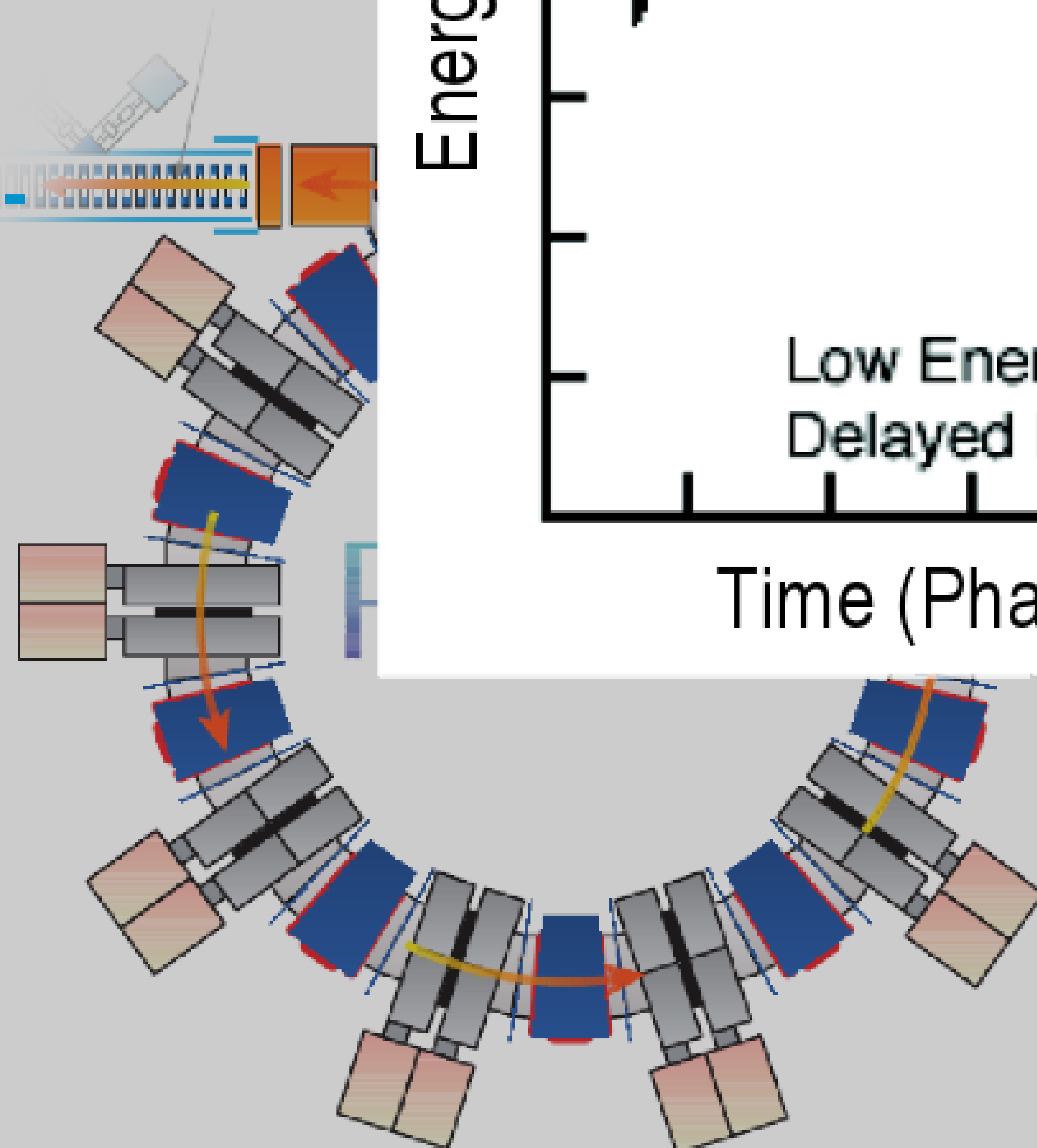
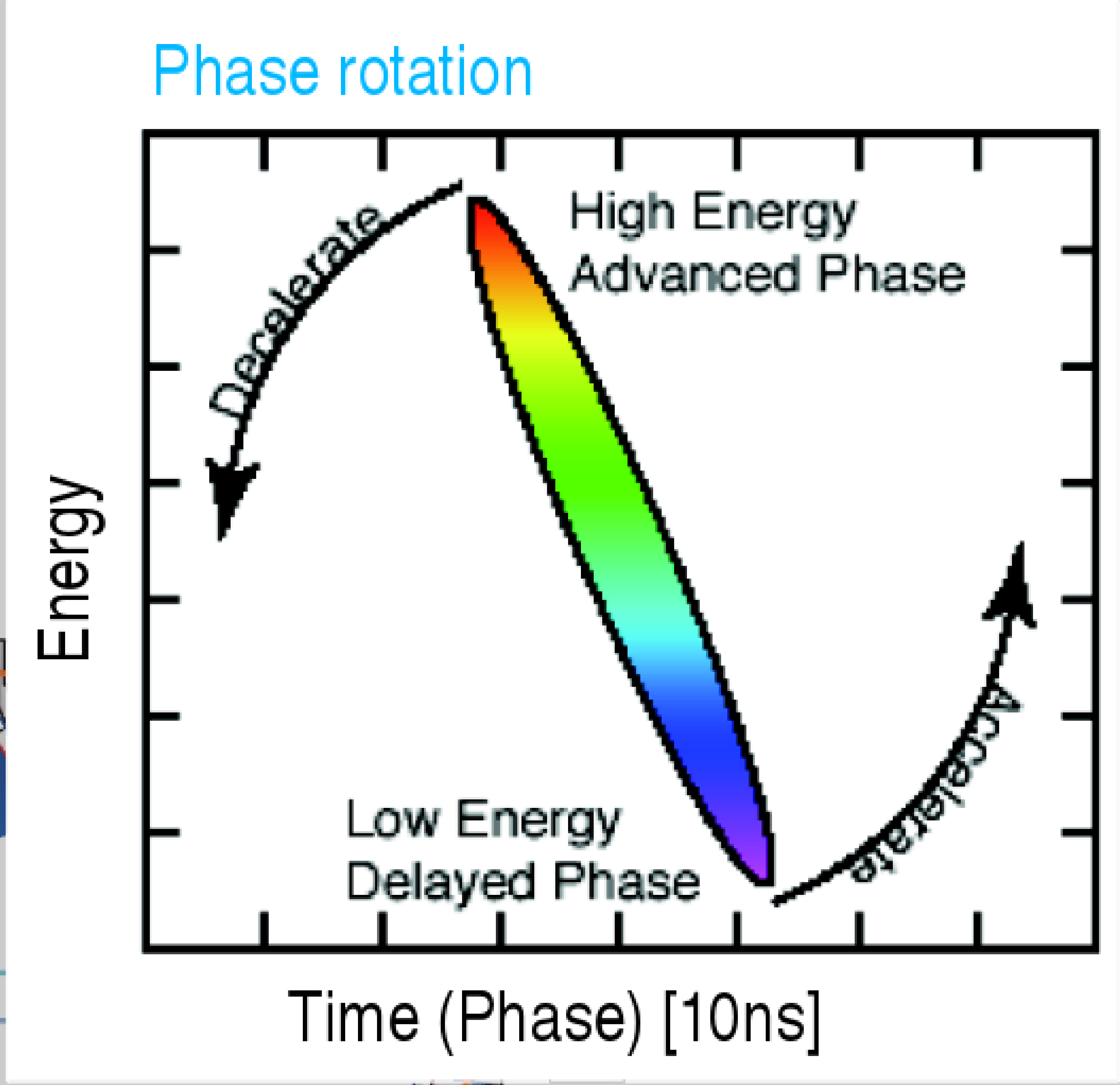




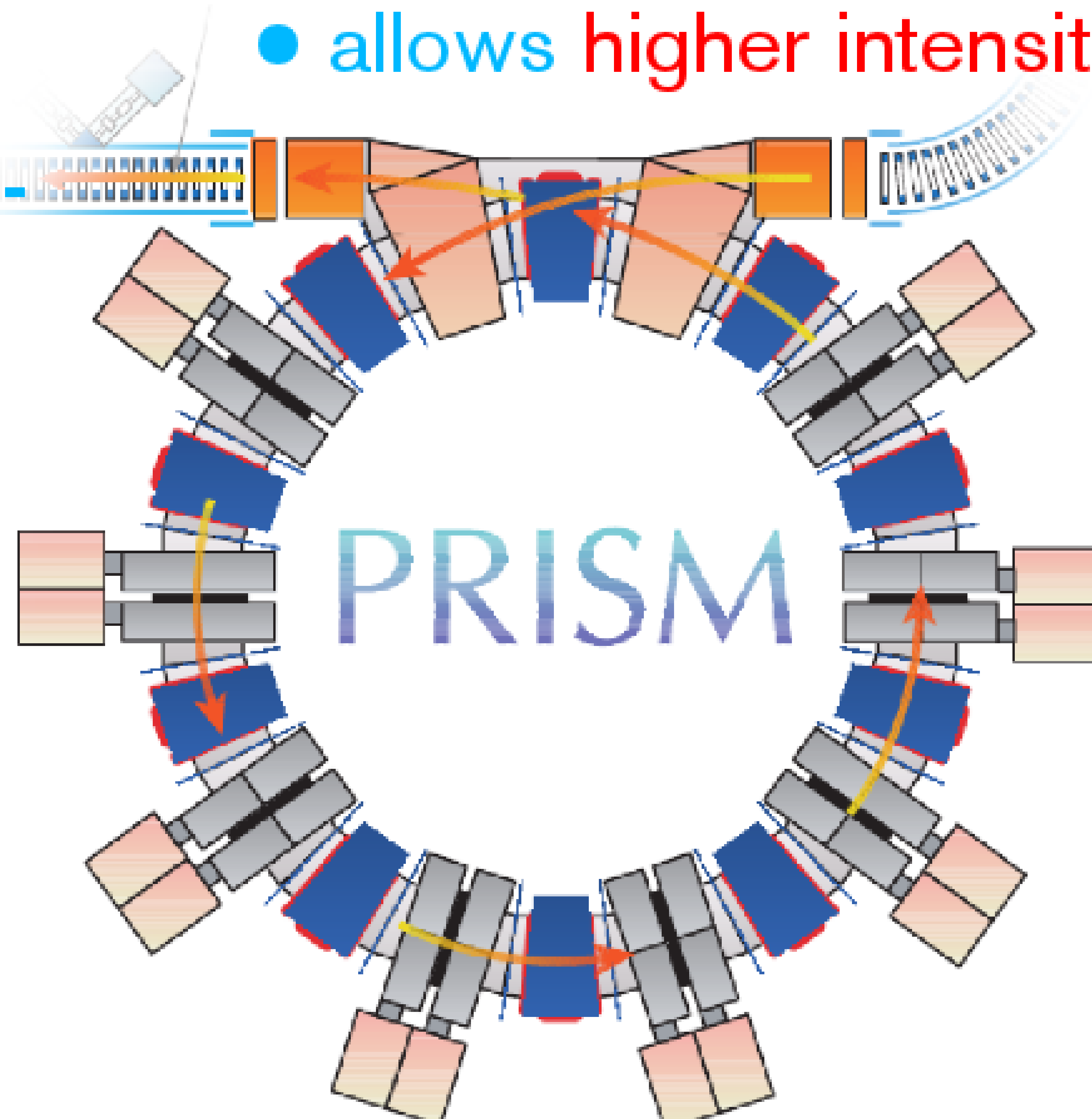
PRISM/FFAG

Muon Storage Ring

- **high acceptance**
  H: 40000 mm mrad
  V: 6500 mm mrad
- **phase-rotation produces mono-energetic beam**
- **8 turns gives a 150m path length**

Benefits:

- narrow momentum spread allows for thinner, optimised stopping target
- long path length makes residual pions negligible ($<10^{-20}$)
- muon beam inter-bucket extinction
- allows higher intensity running
- lower duty cycle to reduce cosmic backgrounds
- stopping target materials with larger Z



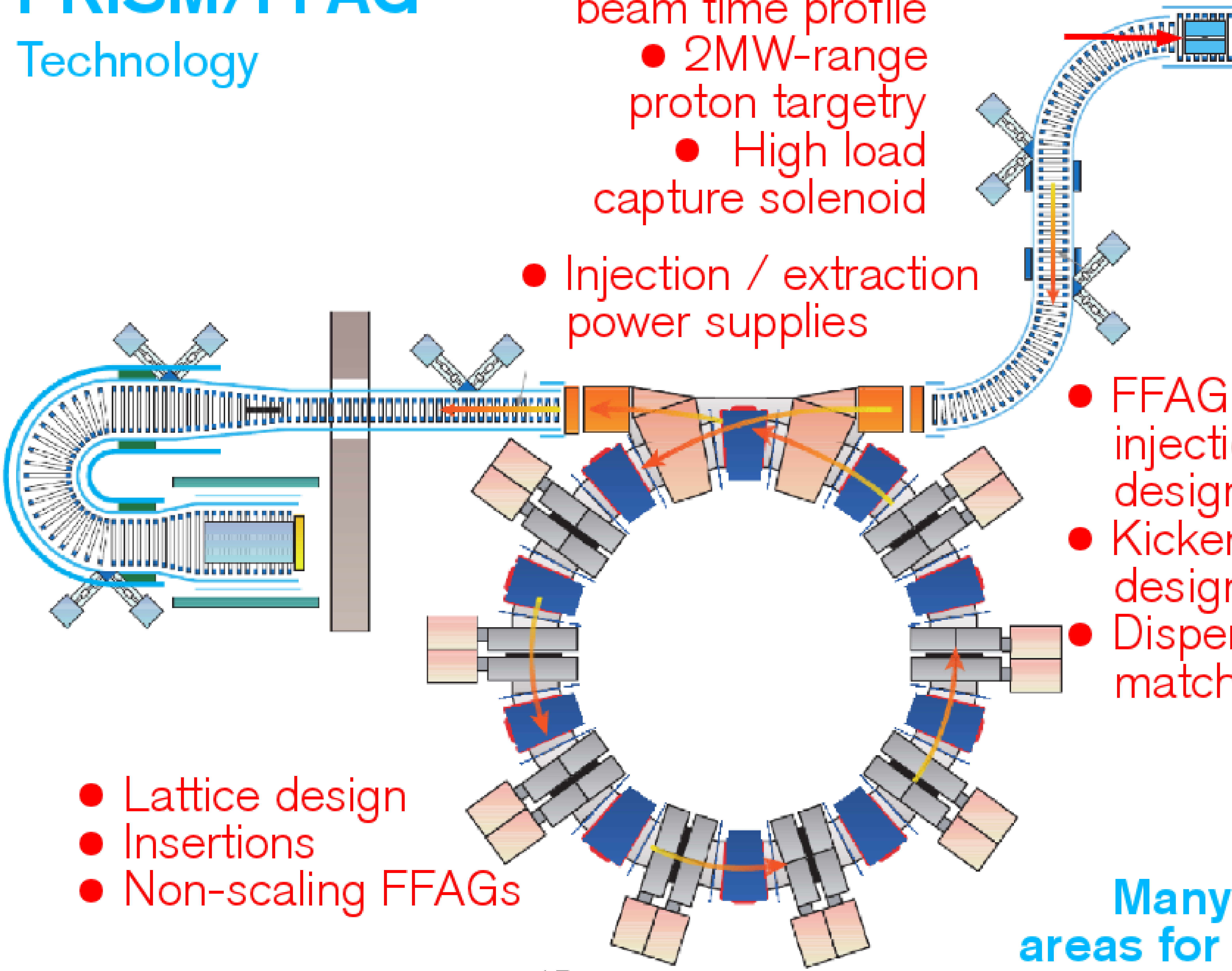
PRISM/FFAG

Technology

- 10 ns proton beam time profile
- 2MW-range proton targetry
- High load capture solenoid

- Injection / extraction power supplies

- FFAG beam injection design
- Kicker magnet design
- Dispersion matching



- Lattice design
- Insertions
- Non-scaling FFAGs

Many strong areas for the UK

PRISM Task Force

- Formed in 2009 to tackle outstanding issues
  - Targetry, pion capture, superconducting solenoids
  - FFAG ring design, injection and kicker design
  - Potential for non-scaling FFAG use etc

Recent PRISM/FFAG Workshop

- International membership with participants from:
  - UK: Currently RAL and Daresbury labs, ASTeC, Cockcroft Institute, the John Adams Institute, Imperial and UCL
  - Osaka, Kyoto, KEK & possibly the US, France etc
- Led by Jaroslaw Pasternak
- Report from Task Force could bring forward plans for PRISM
- Also being considered as option for muon beamline at Project-X (Fermilab)

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

To be updated for IPAC 2012

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

Abstract

The next generation of lepton flavour violation experiments will use high intensity and high quality muon beams. Such beams can be produced by sending a short proton pulse to the pion production target, capturing pions and performing RF phase rotation on the resulting muon beam in an FFAG ring, which was proposed for the PRISM project. A PRISM task force was created to address the accelerator and detector issues that need to be solved in order to realise the PRISM experiment. The parameters of the initial proton beam required and the PRISM experiment are reviewed. Alternative designs of the PRISM FFAG ring are presented and compared with the reference design. The ring injection/extraction system, matching with the solenoid channel and progress on the ring's main hardware systems like RF and kicker magnet are discussed. The progress and future directions of the study are presented in this paper.

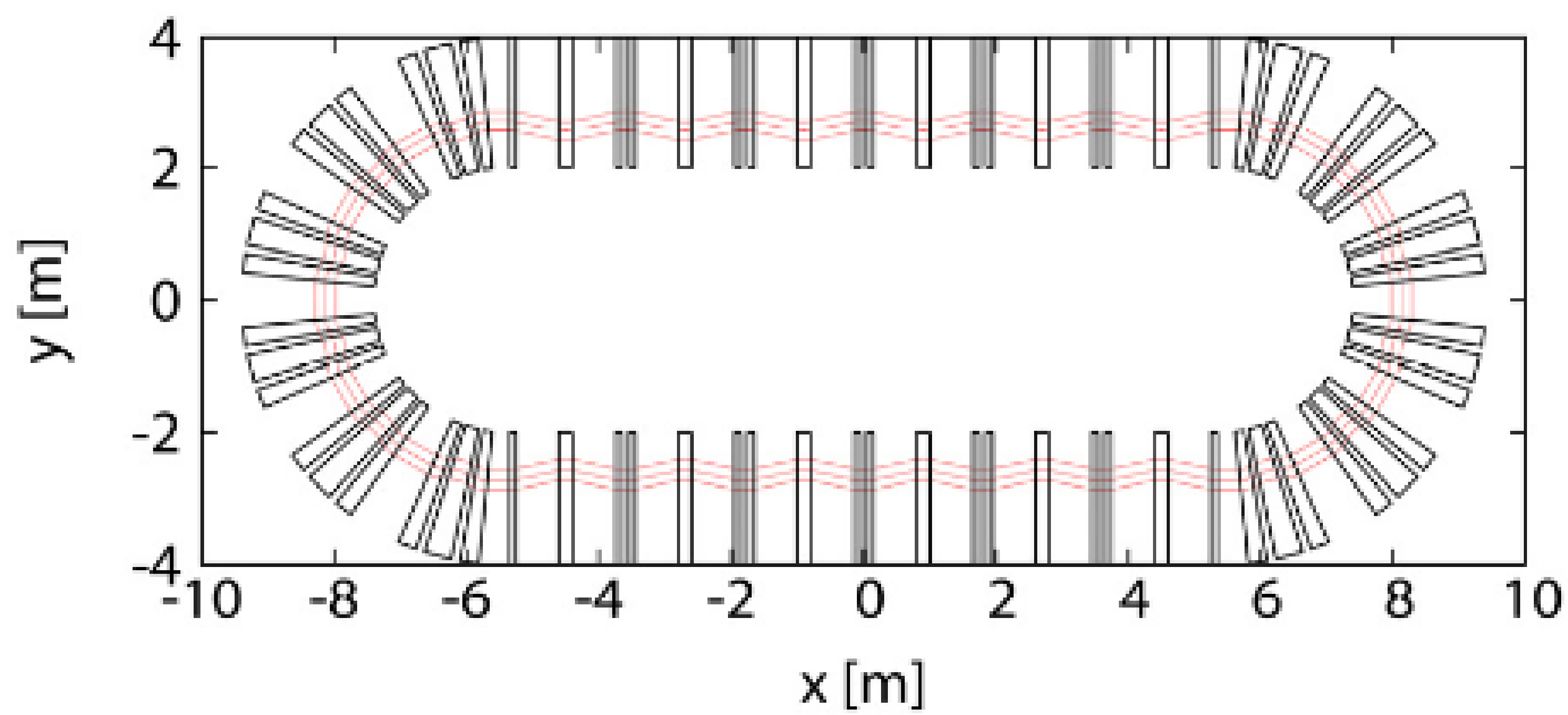
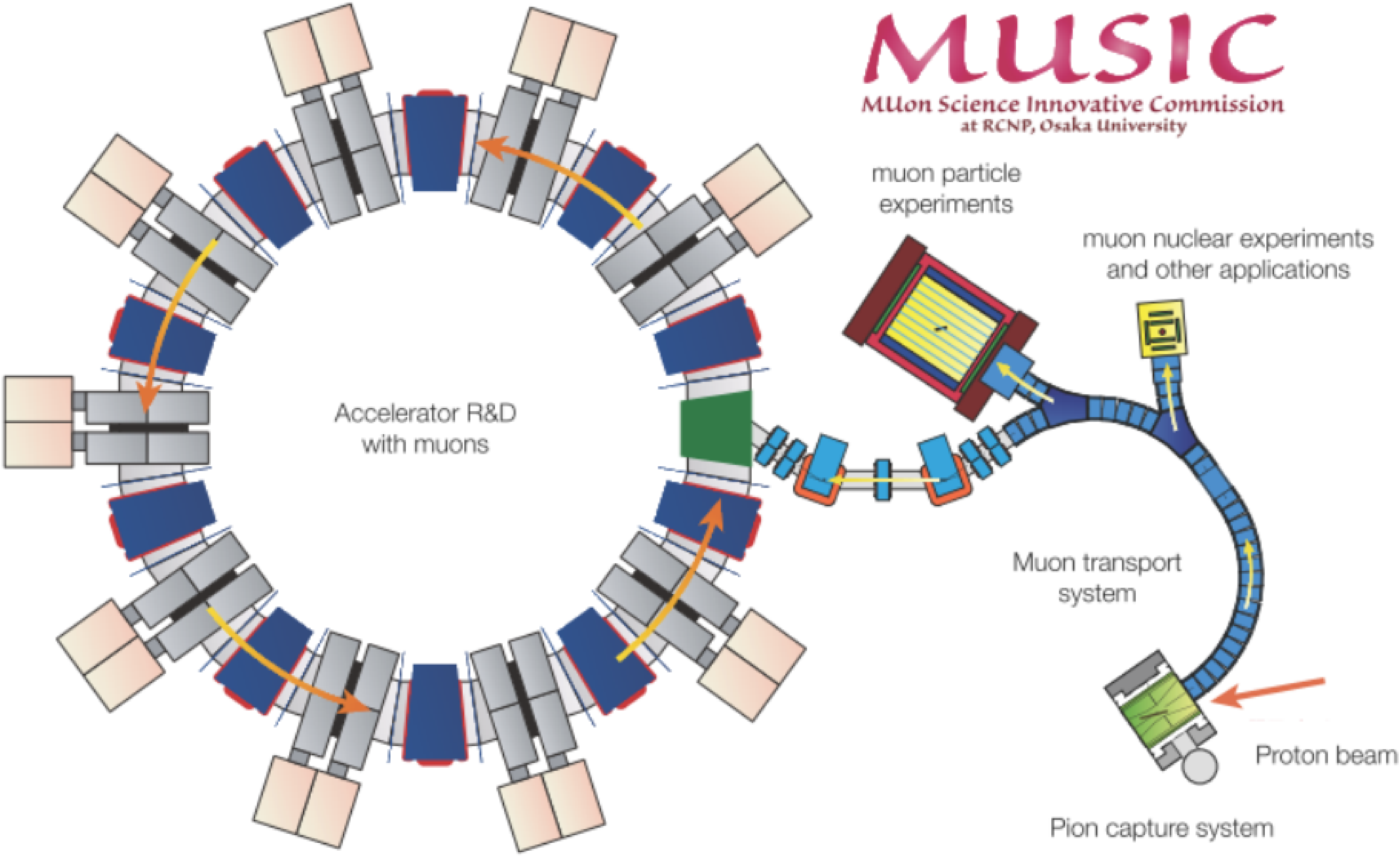


Figure 1: Layout of the advanced FFAG solution for the PRISM ring. Closed orbits of 55 MeV/c, 68 MeV/c and 82 MeV/c muons are shown.

MUSIC

MUSIC

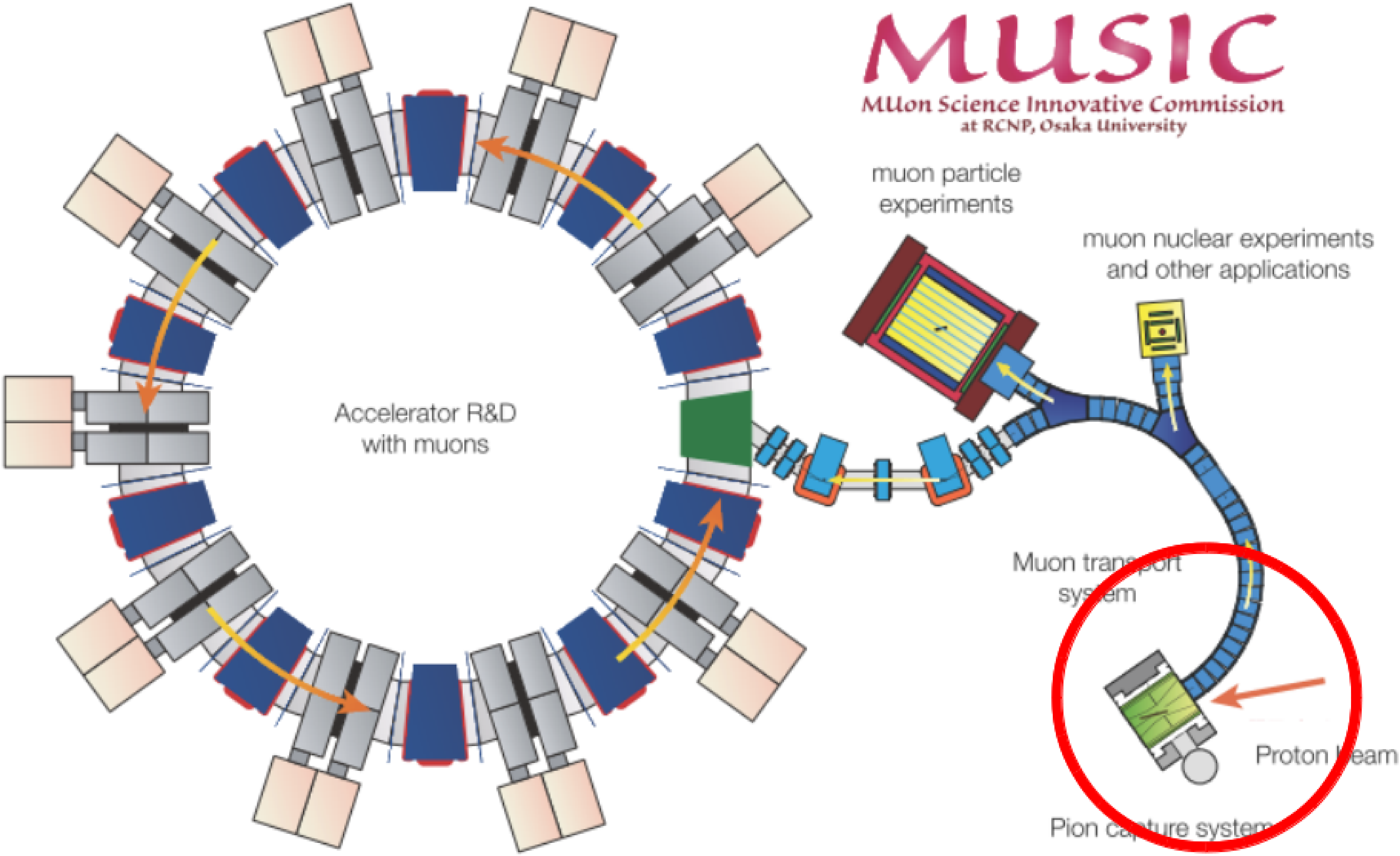
MUon Science Innovative Commission
at RCNP, Osaka University



MUSIC

MUon Science Innovative Commission

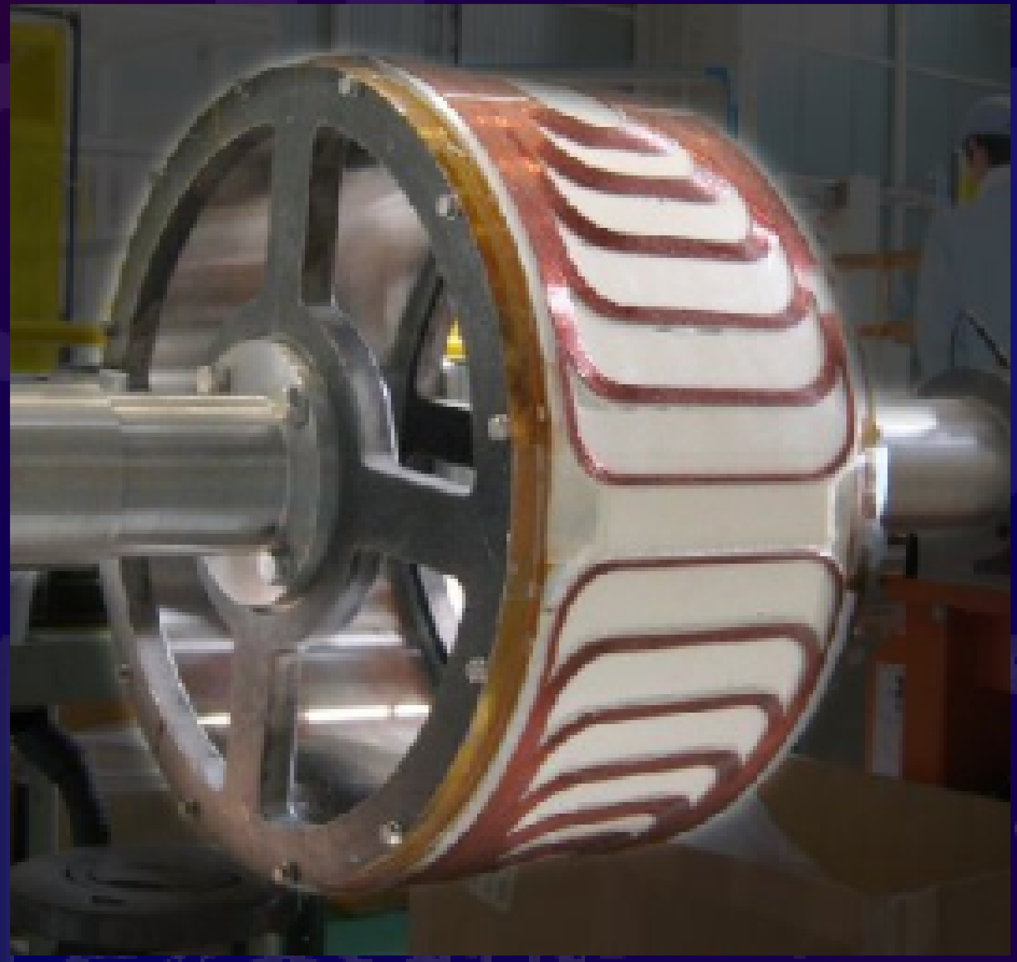
at RCNP, Osaka University



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

The MUSIC Project at Osaka

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



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

Staging Plan (New as of late 2011)

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

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University of Manchester, UK

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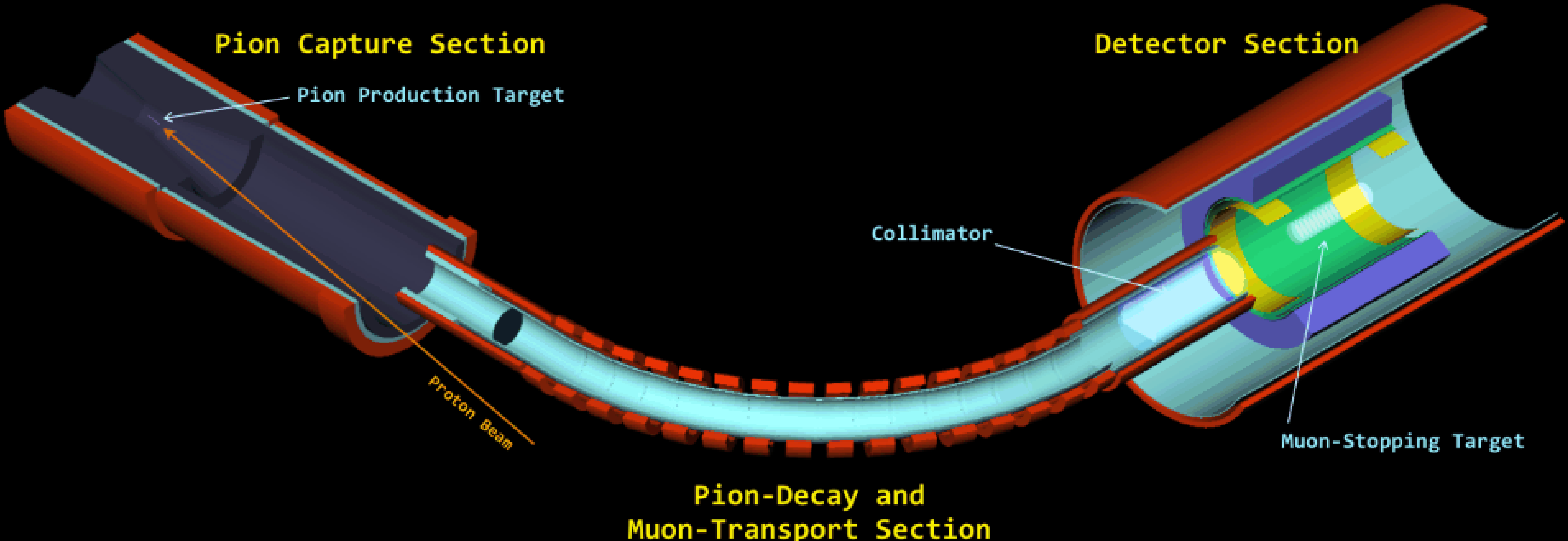
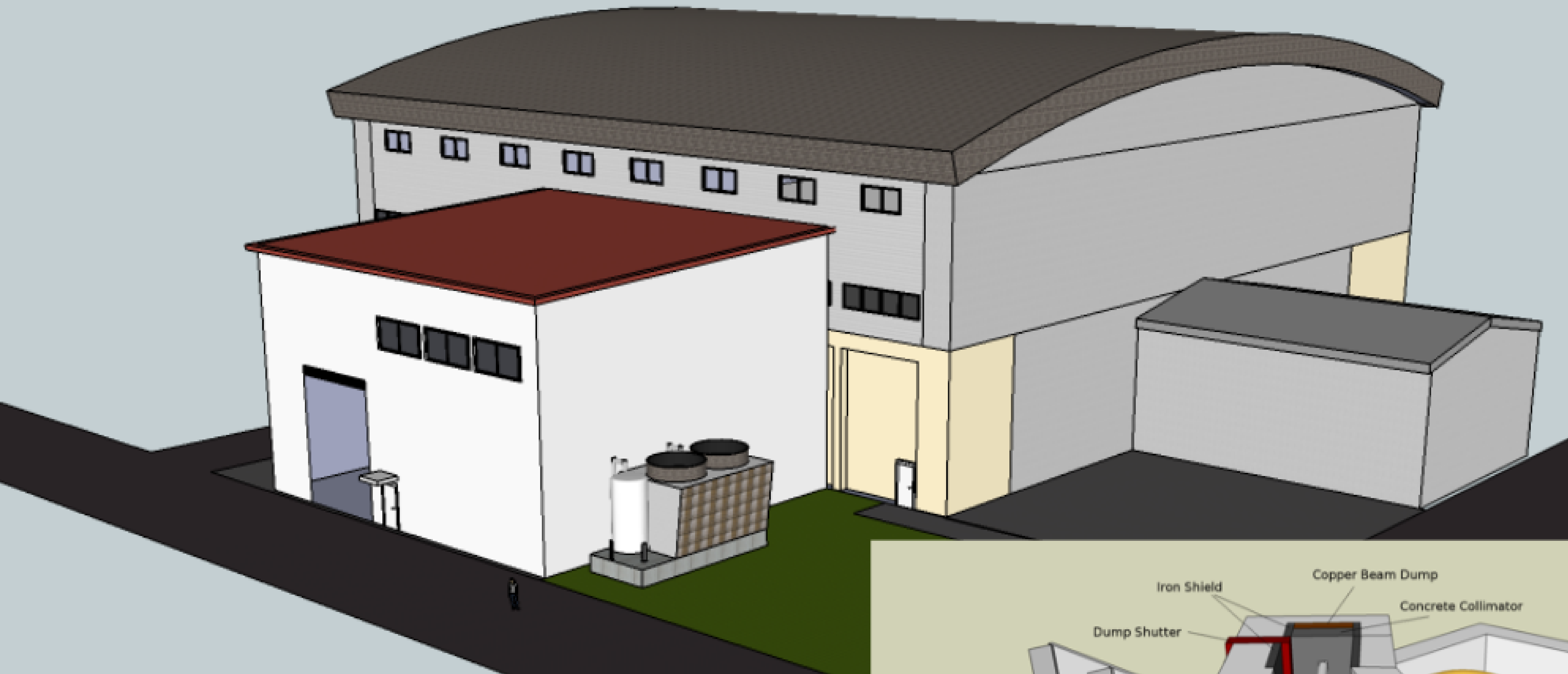
TRIUMF, Canada

Letter of Intent for Phase-I of the COMET Experiment at J-PARC

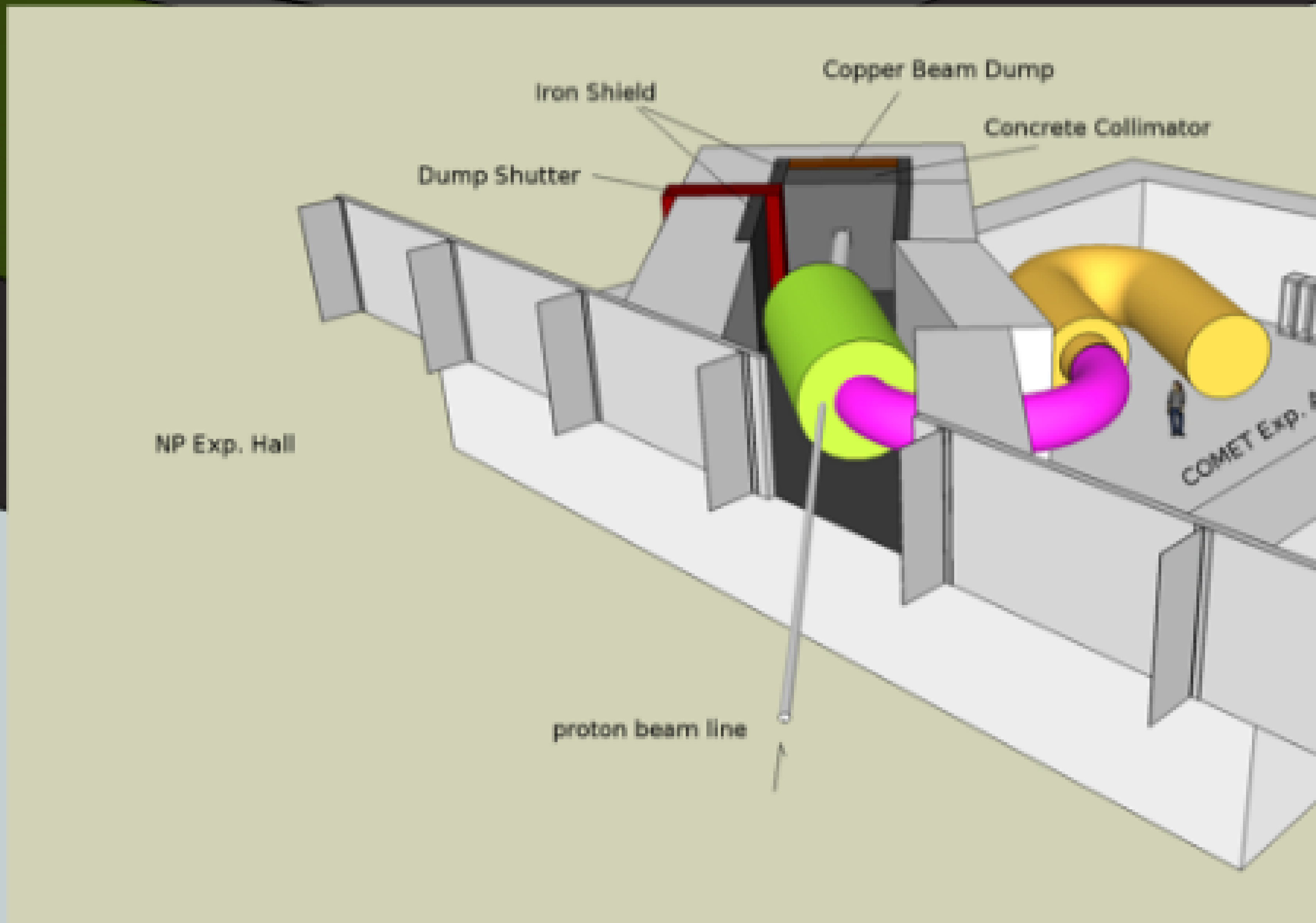
March 21, 2012

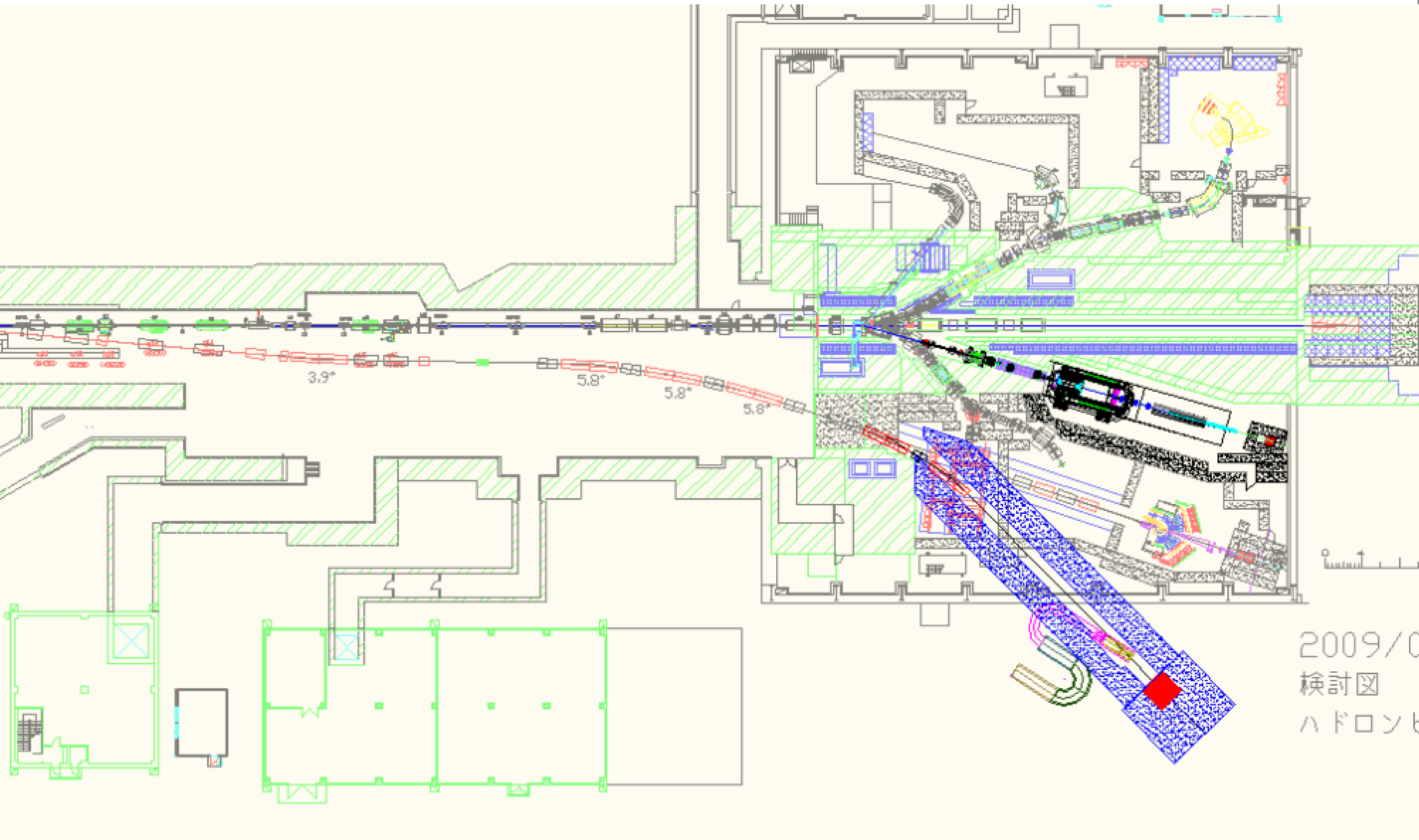
COMET Phase-I





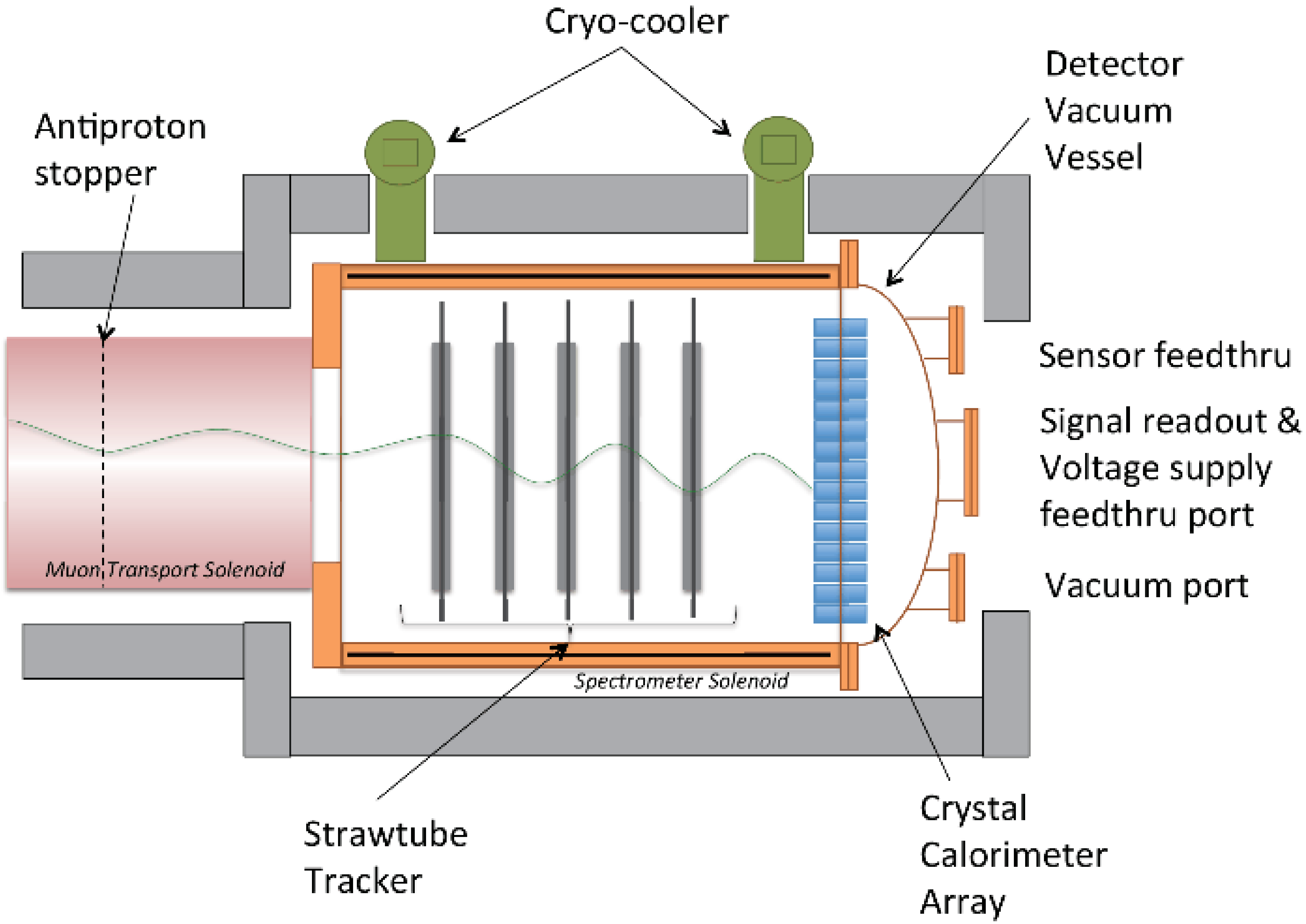
COMET Phase-I
to include construction
of underground experimental
hall and counting rooms





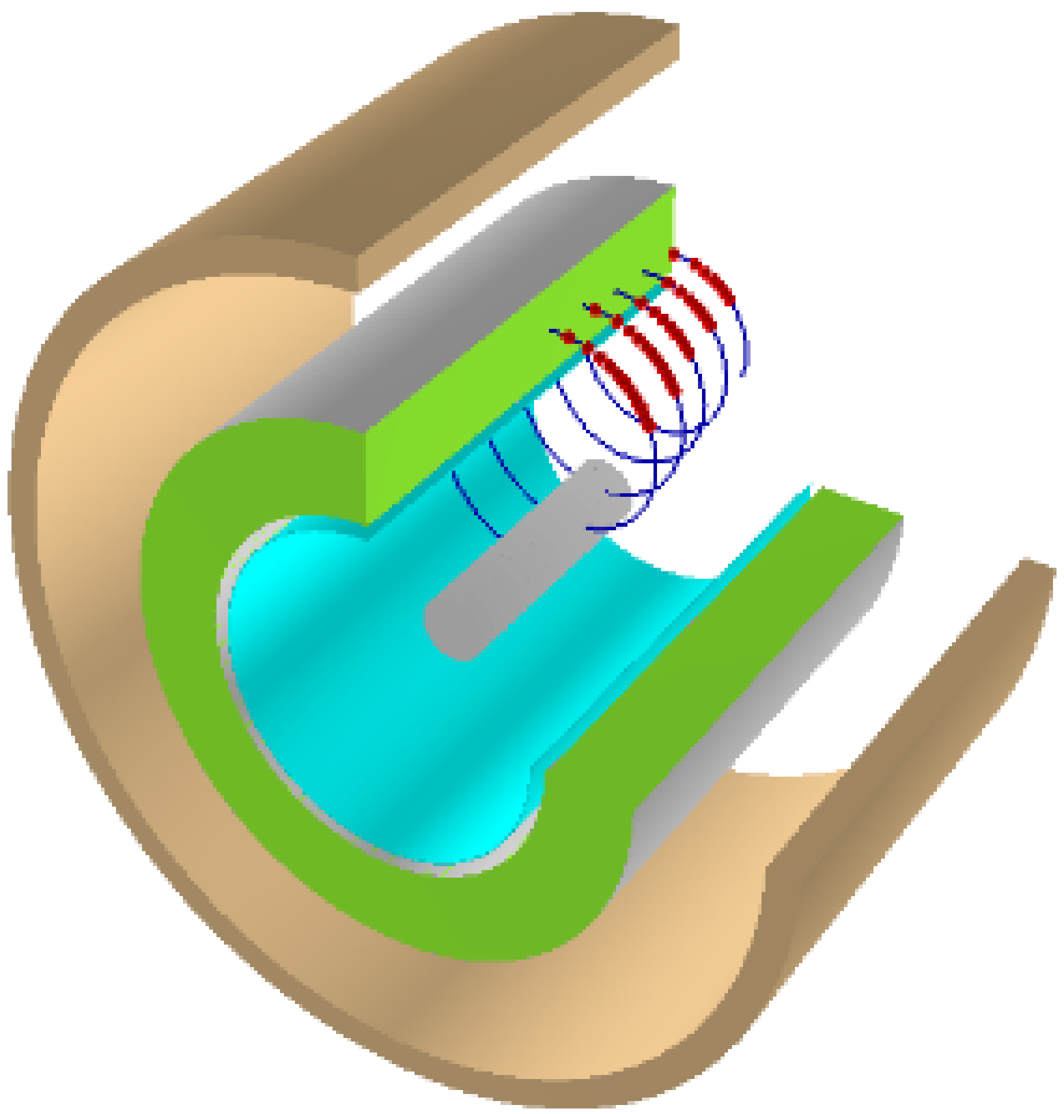
3.9°
5.8°
5.8°
5.8°
2009/0
検討図
ハドロンヒ

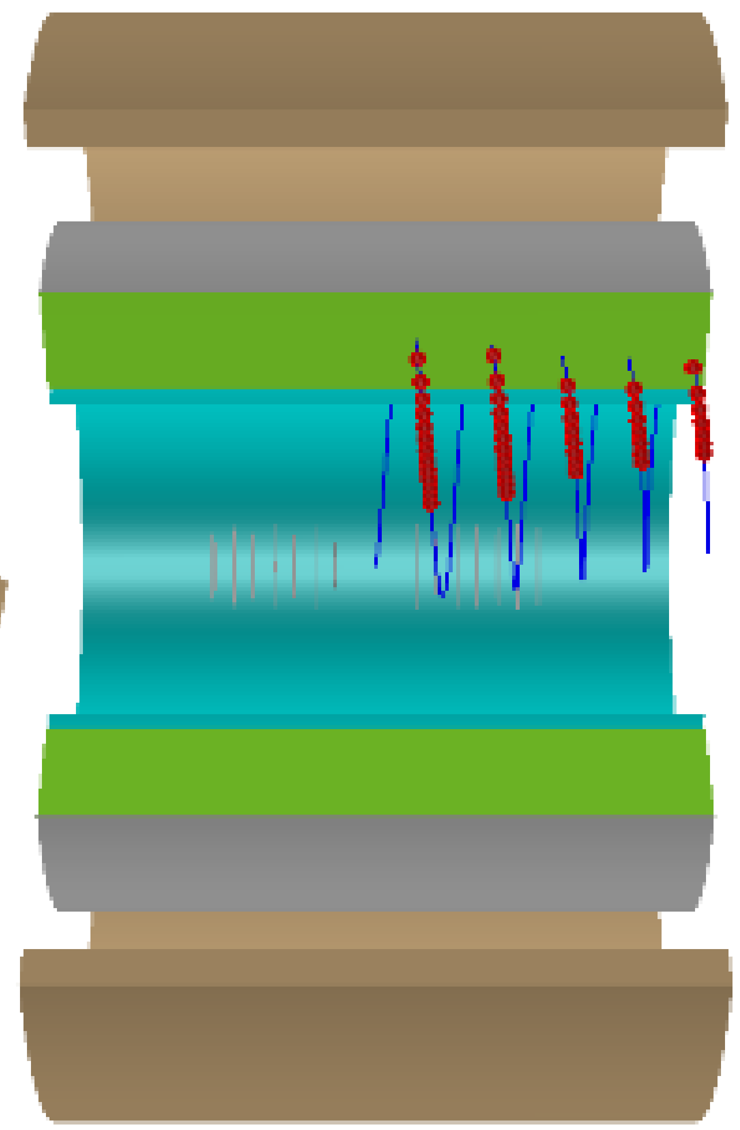
COMET Phase-I Detector for Beam Physics and Backgrounds Studies

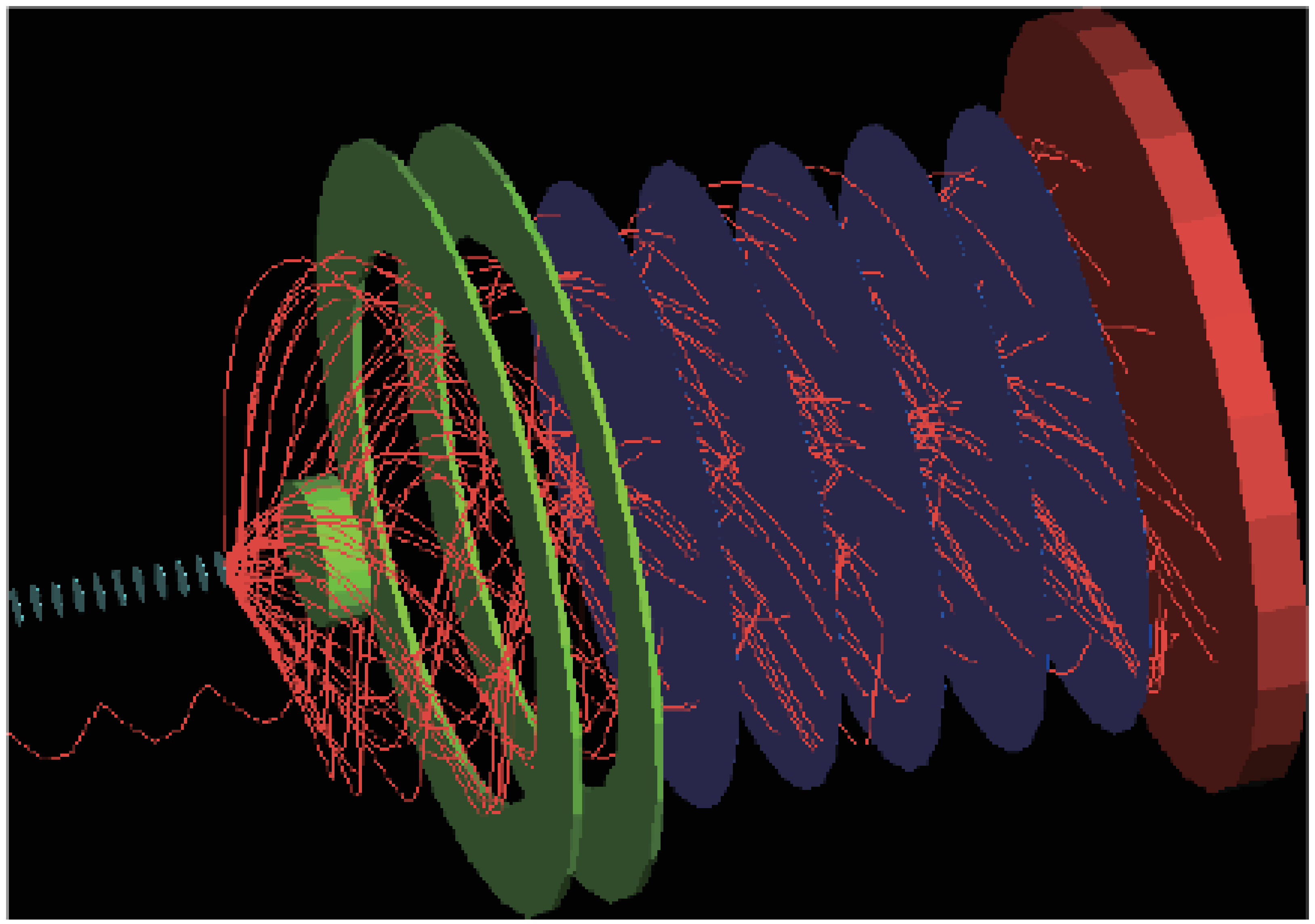


also a prototype for detector section for the full COMET experiment

COMET Phase-I Detector For Lepton Flavour Physics Studies







an updated SINDRUM-style design
(currently undergoing simulation studies and optimisation)

Conclusions

- Intense muon physics is highly promising as a probe into Beyond-the-Standard-Model physics
- Currently a gap in the UK physics programme
- Strong synergies with UK strengths
- COMET/PRISM to probe muon-to-electron conversion to the 10^{-18} level
- Staged construction: data-taking for Phase-I physics by 2017
  - detailed particle flux studies for full COMET
  - lepton flavour violation physics
- As part of a new area of intense muon physics
  - muon


Comet
California
CPFC