Imperial College London

Intense Muon Physics: Lepton Flavour Violation

COMET Phases I & II and PRISM

18 September 2012

Yoshi Uchida

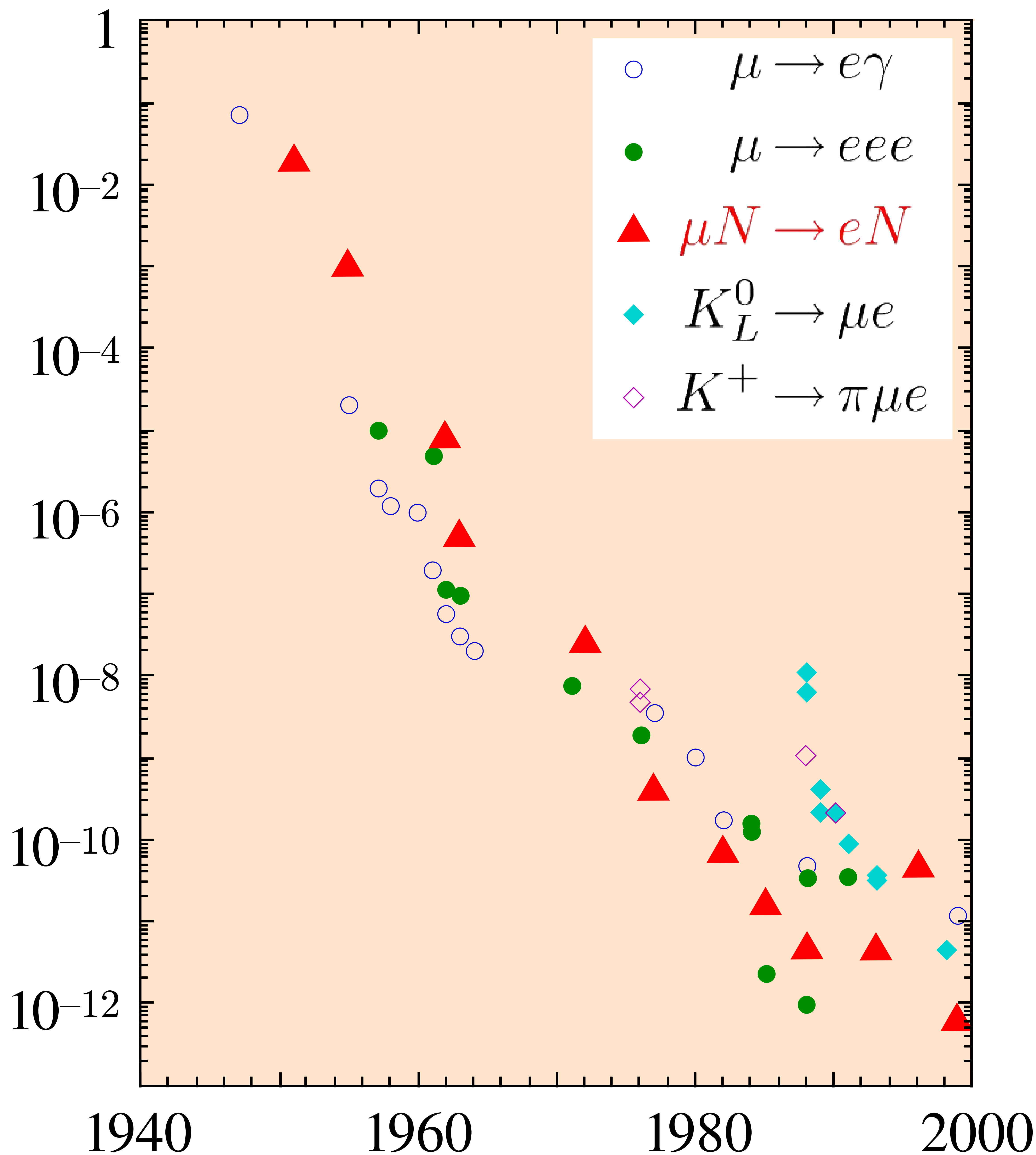
STFC Particle Physics Advisory Panel
Community Meeting at the University of Birmingham

Experimental Limits on Lepton Flavour Violation

- 90% C.L. upper limits on the branching ratio
- Will focus on muon decay channels today, which have the largest scope for improvement
- For τ leptons, improvements from future *b* factories and LHCb

Reaction	Present limit
$\mu^+ \to e^+\gamma$	$< 2.4 \times 10^{-12}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau \to \mu\mu\mu$	$< 3.2 \times 10^{-8}$
$\tau \to eee$	$< 3.6 \times 10^{-8}$
$\pi^0 \to \mu e$	$< 3.8 \times 10^{-10}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

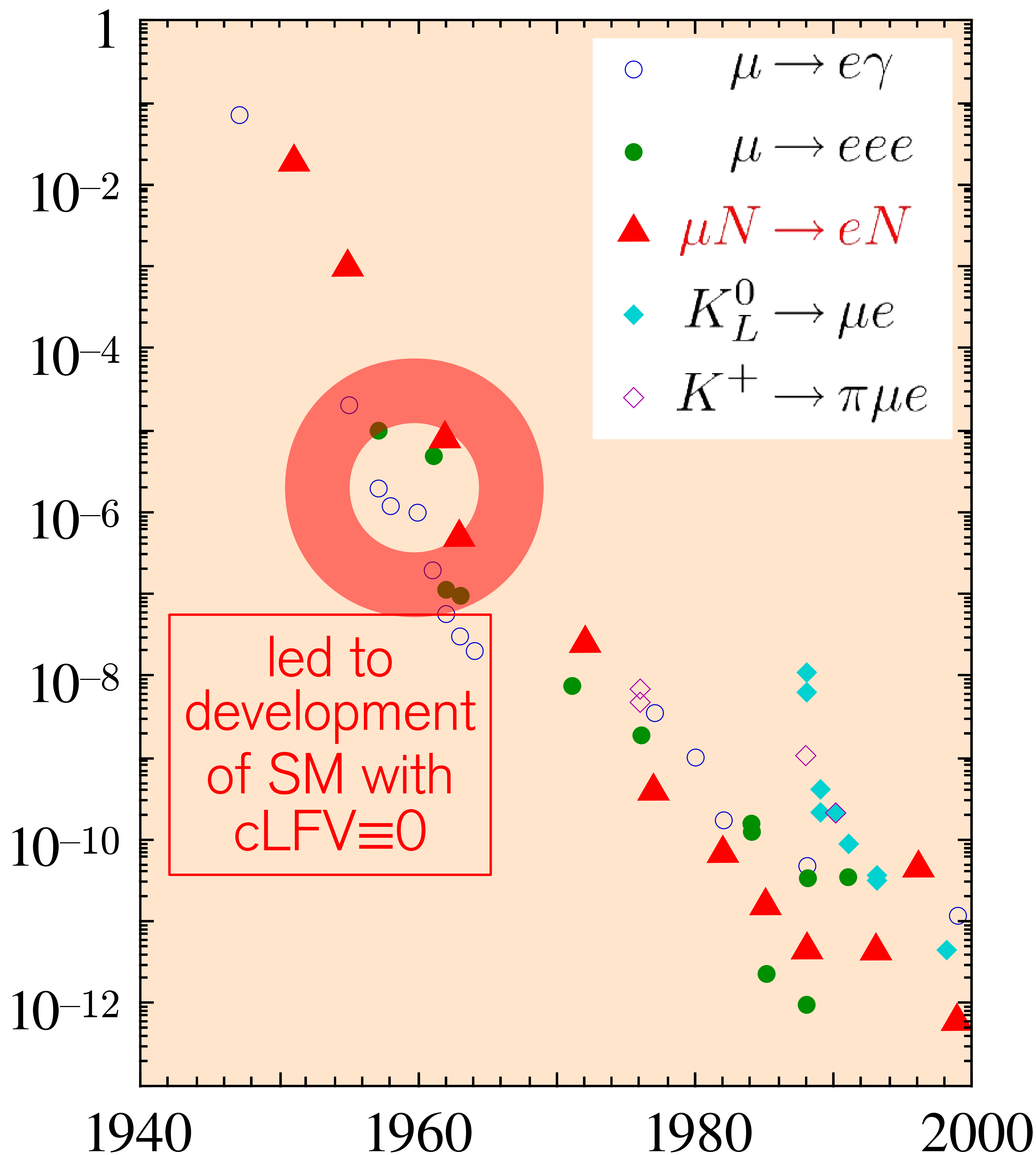
Historical Progress on Muon Flavour Violation



90% C.L.
Upper limits on branching ratios

Yoshi.Uchida@imperial.ac.uk

Historical Progress on Muon Flavour Violation



90% C.L.
Upper limits on branching ratios

Yoshi.Uchida@imperial.ac.uk

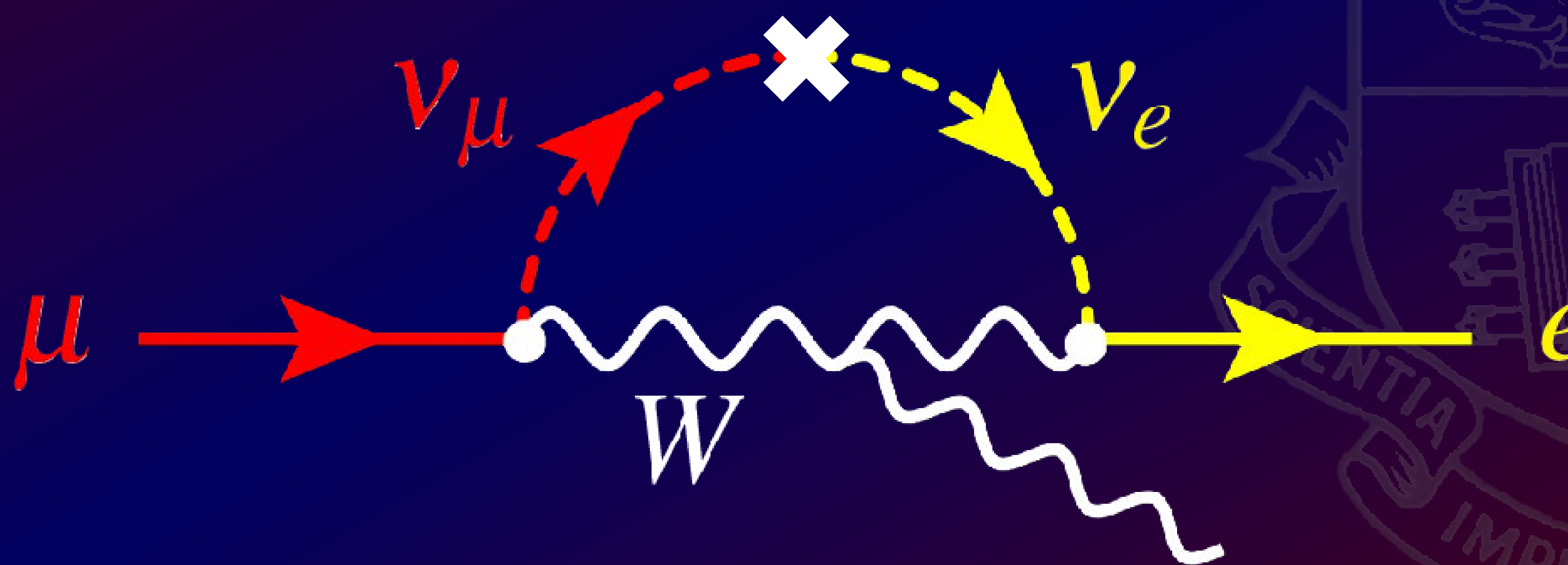
Predictions for Charged Lepton Flavour Violation

- cLFV $\equiv$ 0 in the Standard Model

Predictions for Charged Lepton Flavour Violation

- cLFV ≡ 0 in the Standard Model

- If SM is **minimally extended** by inserting neutrino masses and oscillations, for muons, for example:



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

See, e.g. Marciano, Mori, & Rony (Annu. Rev. Nucl. Part. Sci. 2008.58:315-341)

Main Muon Flavour Conversion Channels

- $\mu^+ \rightarrow e^+ + \gamma$ (MEG at PSI, running)
  - coincident, back-to-back e^+ and γ
- $\mu^+ \rightarrow e^+ e^+ e^-$ (PSI early proposal, feasibility to be demonstrated)
  - coincident particles, kinematic constraint
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
  - single electron of $E \sim m_\mu$
  - for loop dipole processes, $\sim 1/100$th of $\mu^+ \rightarrow e^+ + \gamma$ (N-dependent)
- $\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$
  - single electron of $E \sim m_\mu$
- $\mu^- + e^- \rightarrow e^- + e^-$

Predictions for Charged Lepton Flavour Violation

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

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

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

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

(For this case, O(100) smaller than $\mu \to e + \gamma$ [N-dependent])

Lepton Flavour Violation from New Physics

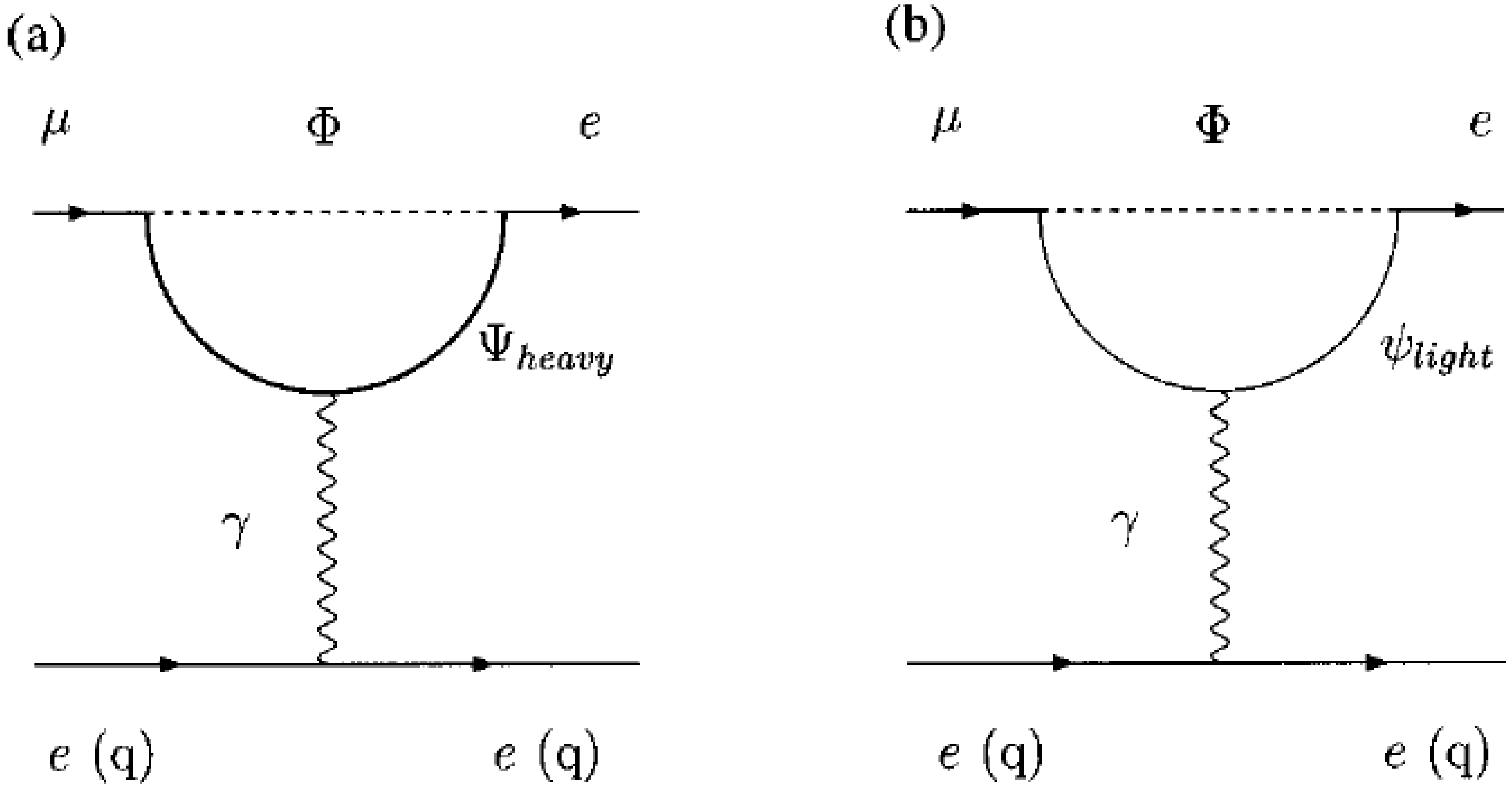


FIG. 4. Photonic penguin diagrams for $\mu-e$ transitions, such as $\mu^+\to e^+e^+e^-$ or $\mu^- - e^-$ conversion: (a) the case of a heavy particle (Ψ_{heavy}) in the loop; (b) the case of a light fermion (ψ_{light}) in the loop. Φ is a scalar field.

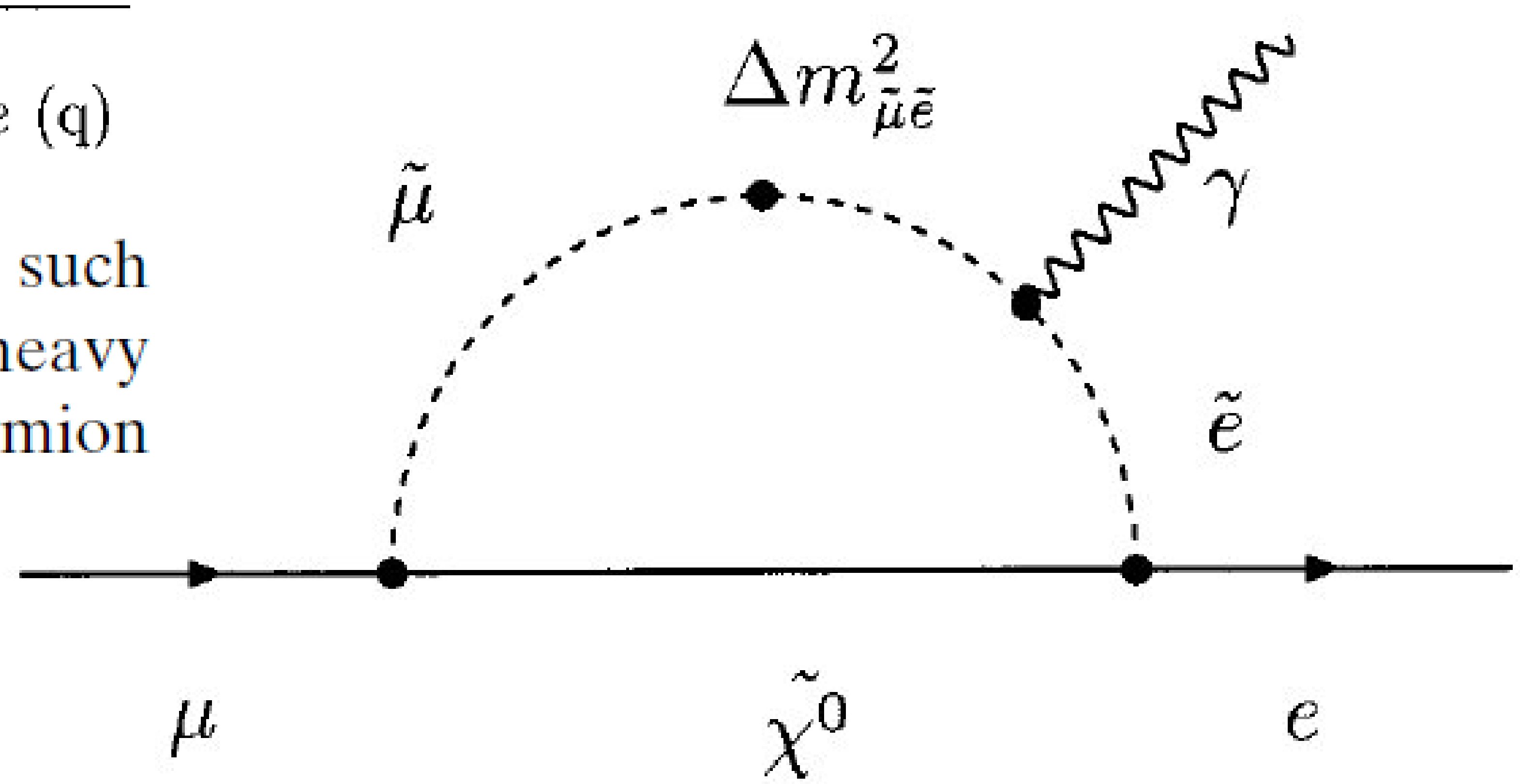


FIG. 5. Feynman diagram for $\mu^+\to e^+\gamma$ decay induced by slepton flavor mixing ($\Delta m^2_{\tilde{\mu}\tilde{e}}$).

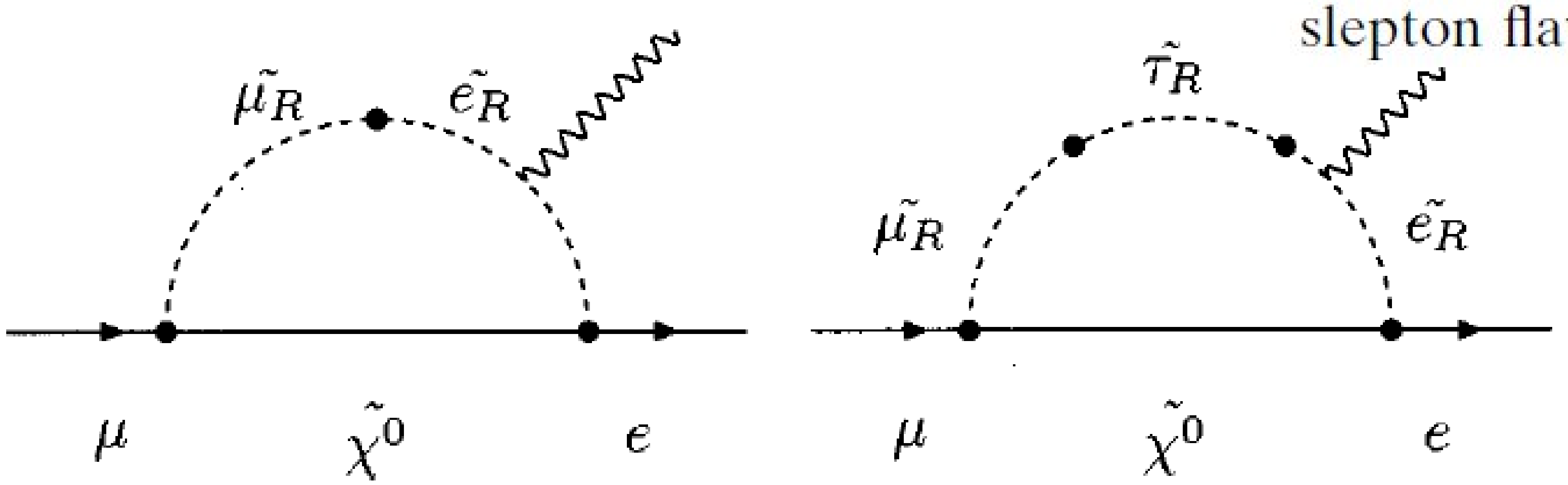
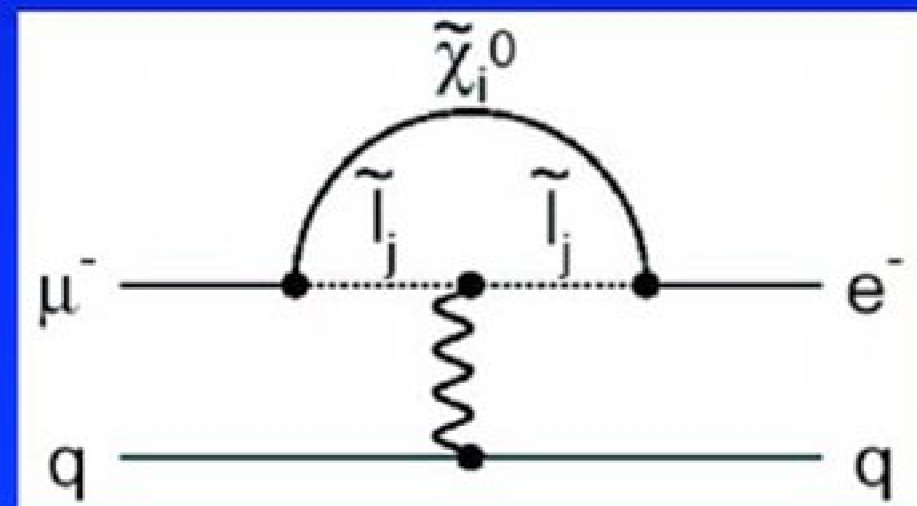


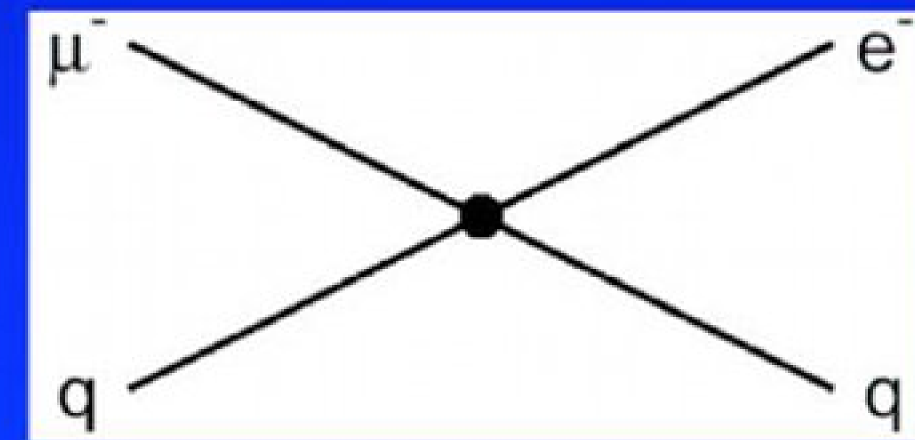
FIG. 7. Feynman diagrams for the $\mu^+\to e^+\gamma$ decay in $SU(5)$ SUSY GUT. The closed blobs represent the flavor transitions due to the off-diagonal terms of the slepton mass matrices.

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





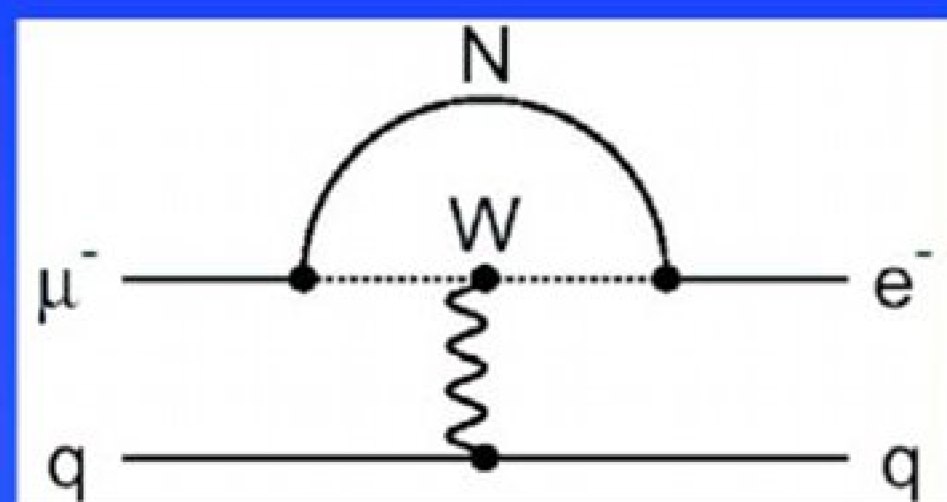
Compositeness

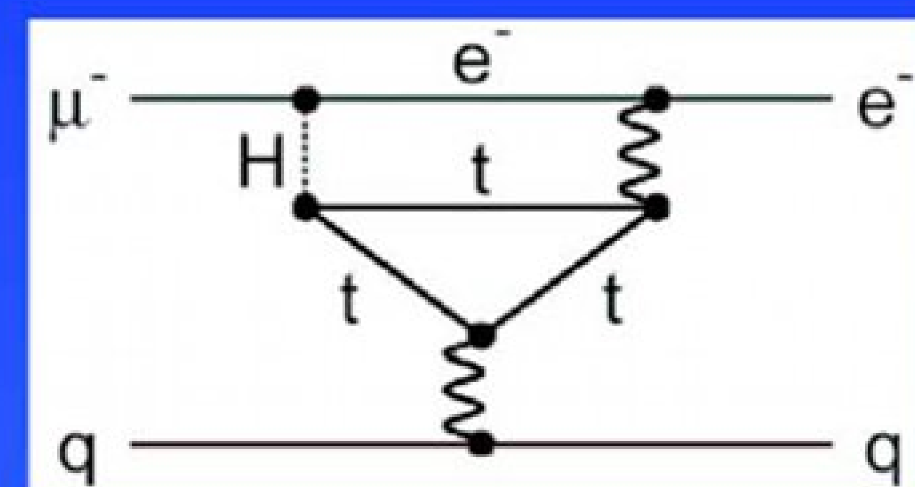
$\Lambda_c = 3000$ TeV

Heavy Neutrinos

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

8×10^{-13}





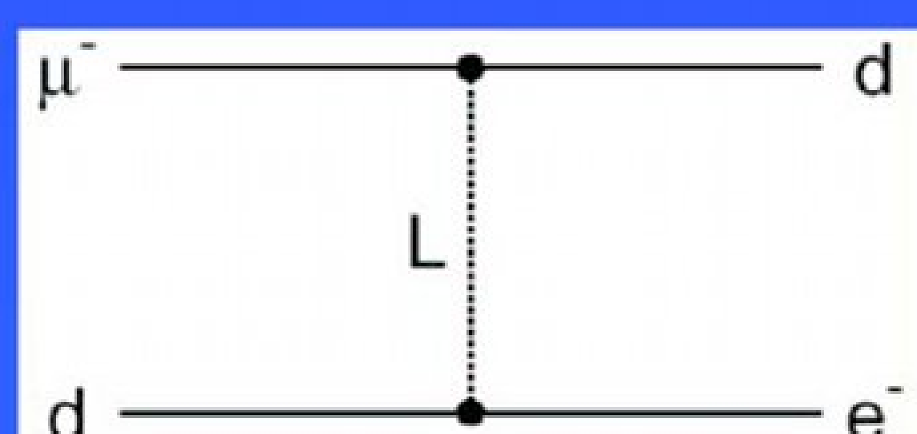
Second Higgs doublet

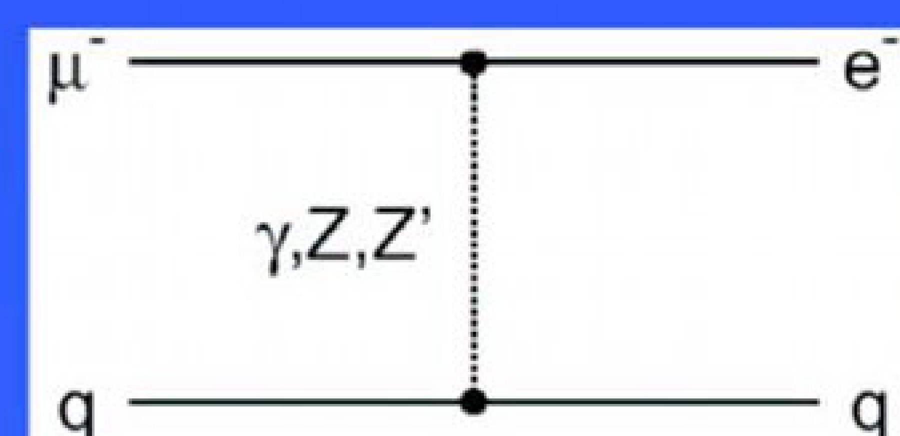
$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

Leptoquarks

$M_L =$

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





Heavy Z', Anomalous Z coupling

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

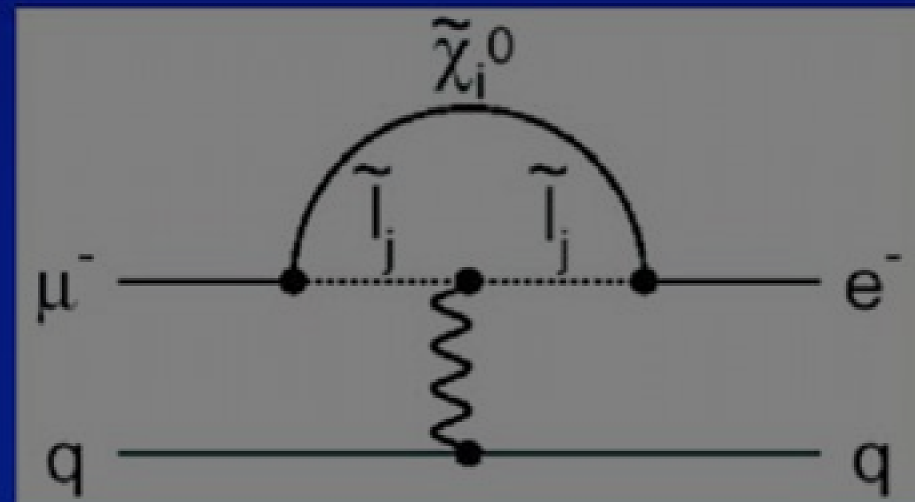
$B(Z \to \mu e) < 10^{-17}$

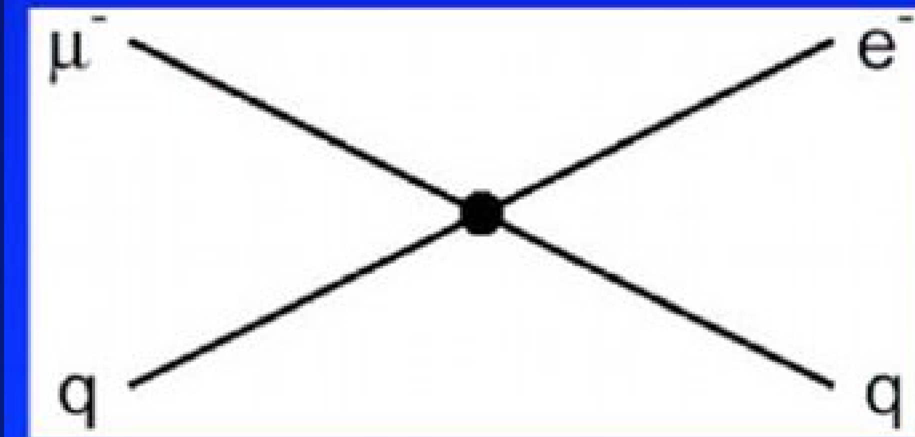
After W. Marciano

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





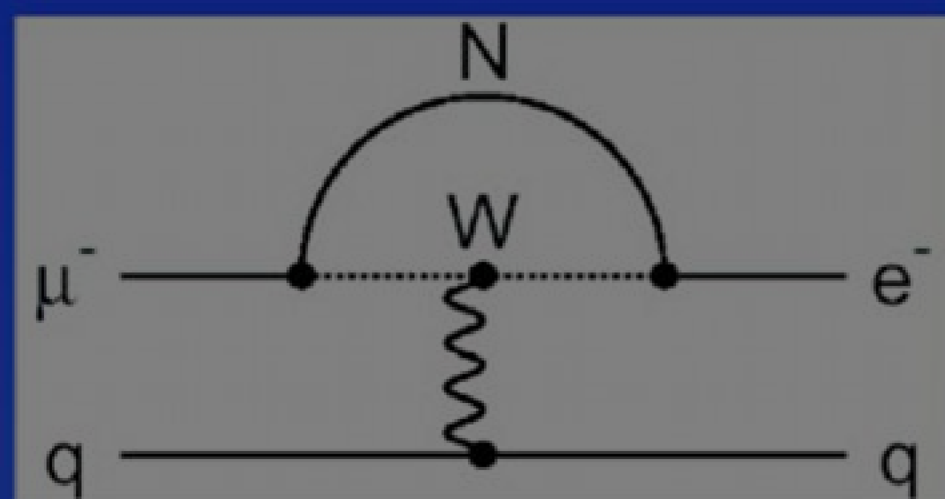
Compositeness

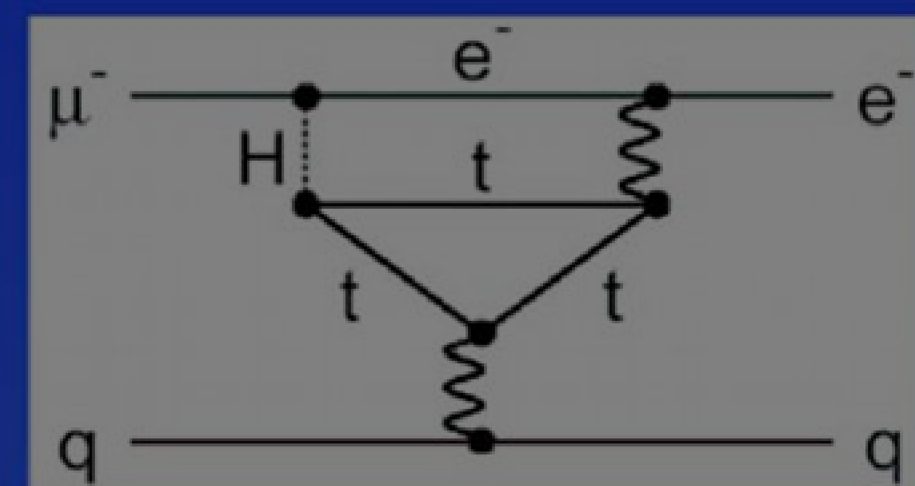
$\Lambda_c = 3000$ TeV

Heavy Neutrinos

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

8×10^{-13}





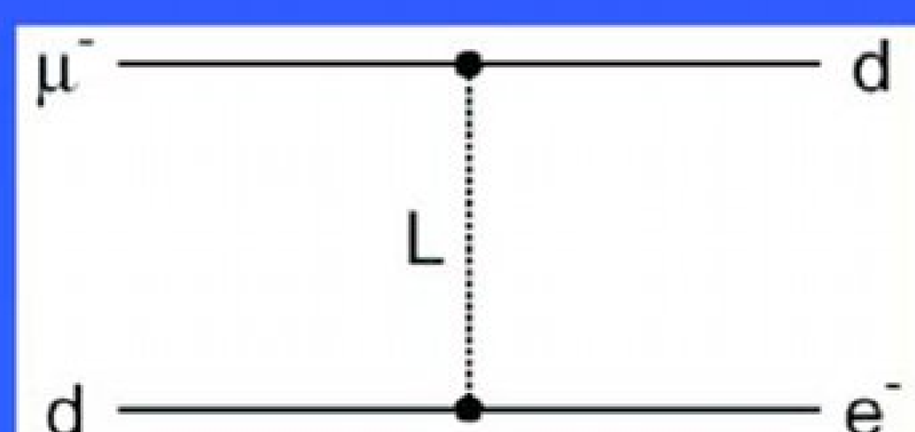
Second Higgs doublet

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

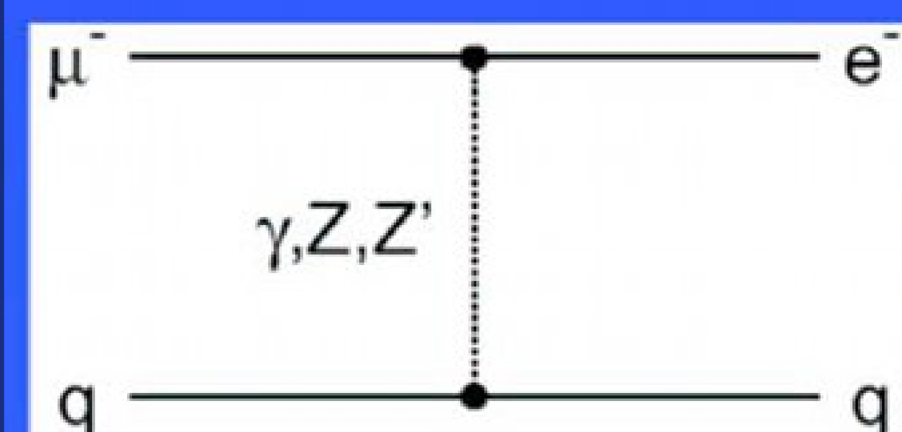
Leptoquarks

$M_L =$

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



After W. Marciano



Heavy Z', Anomalous Z coupling

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

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

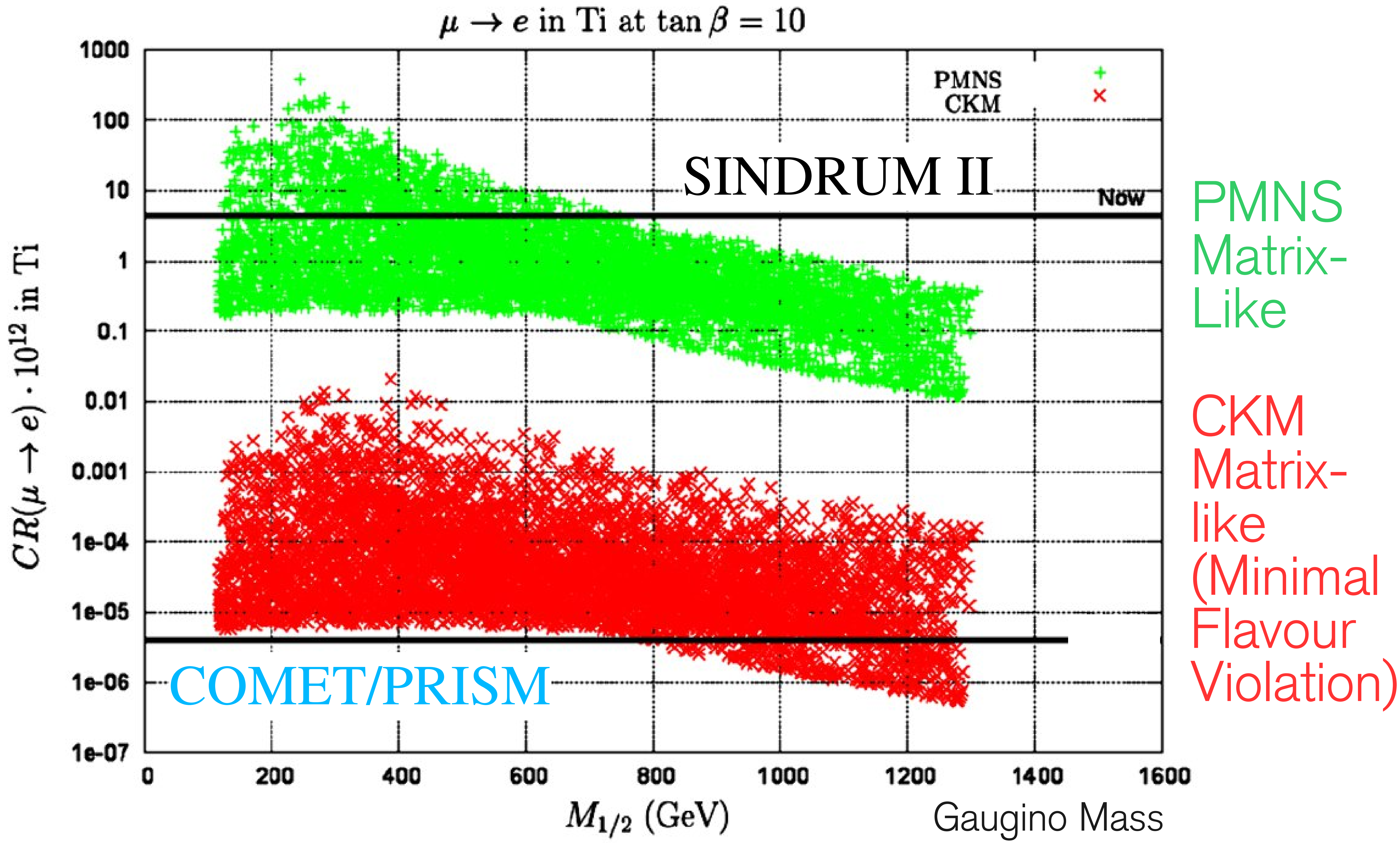
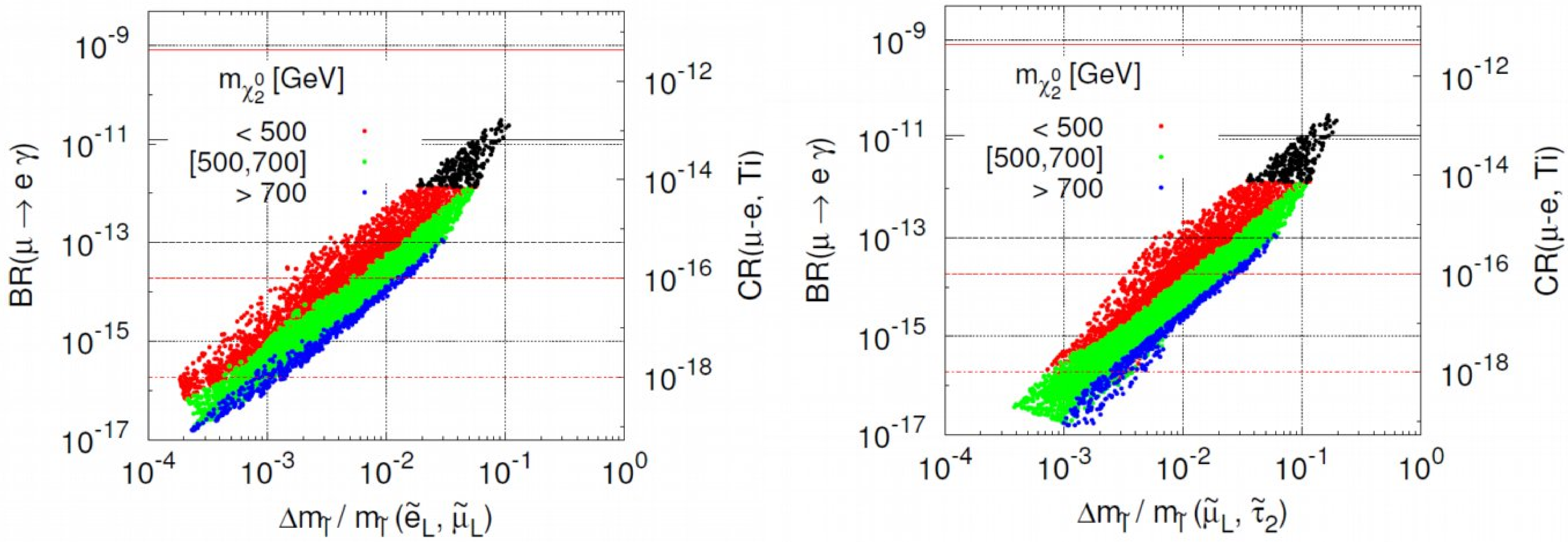
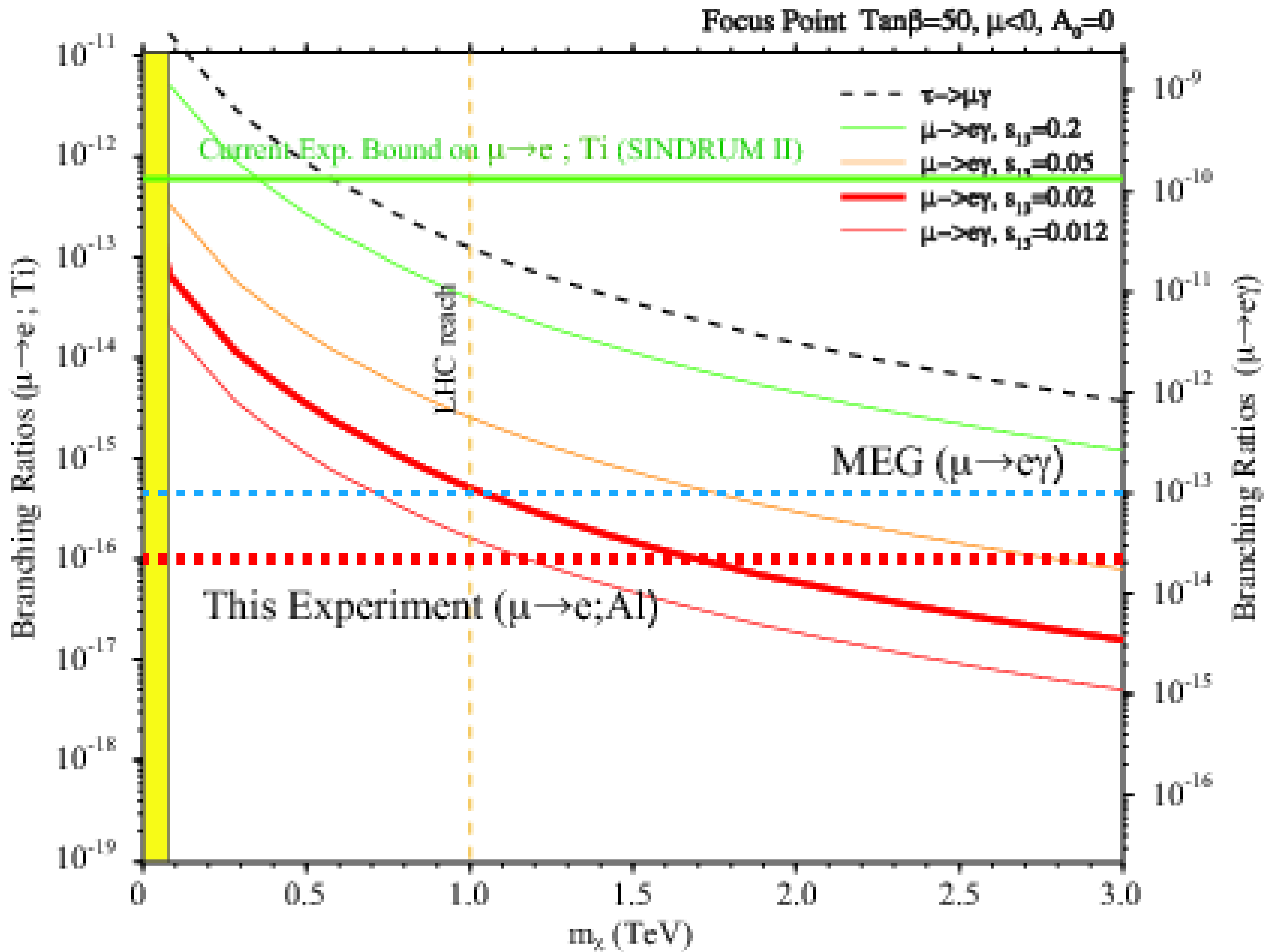


FIG. 12 $\mu \to e$ in Ti as a probe of SUSY-GUT scenarios. The plots are obtained by scanning the LHC accessible parameter space. The horizontal lines are the present (SINDRUM II) bound and the planned (PRISM/PRIME) sensitivity to the process. We see that PRIME would be able to severely constrain the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

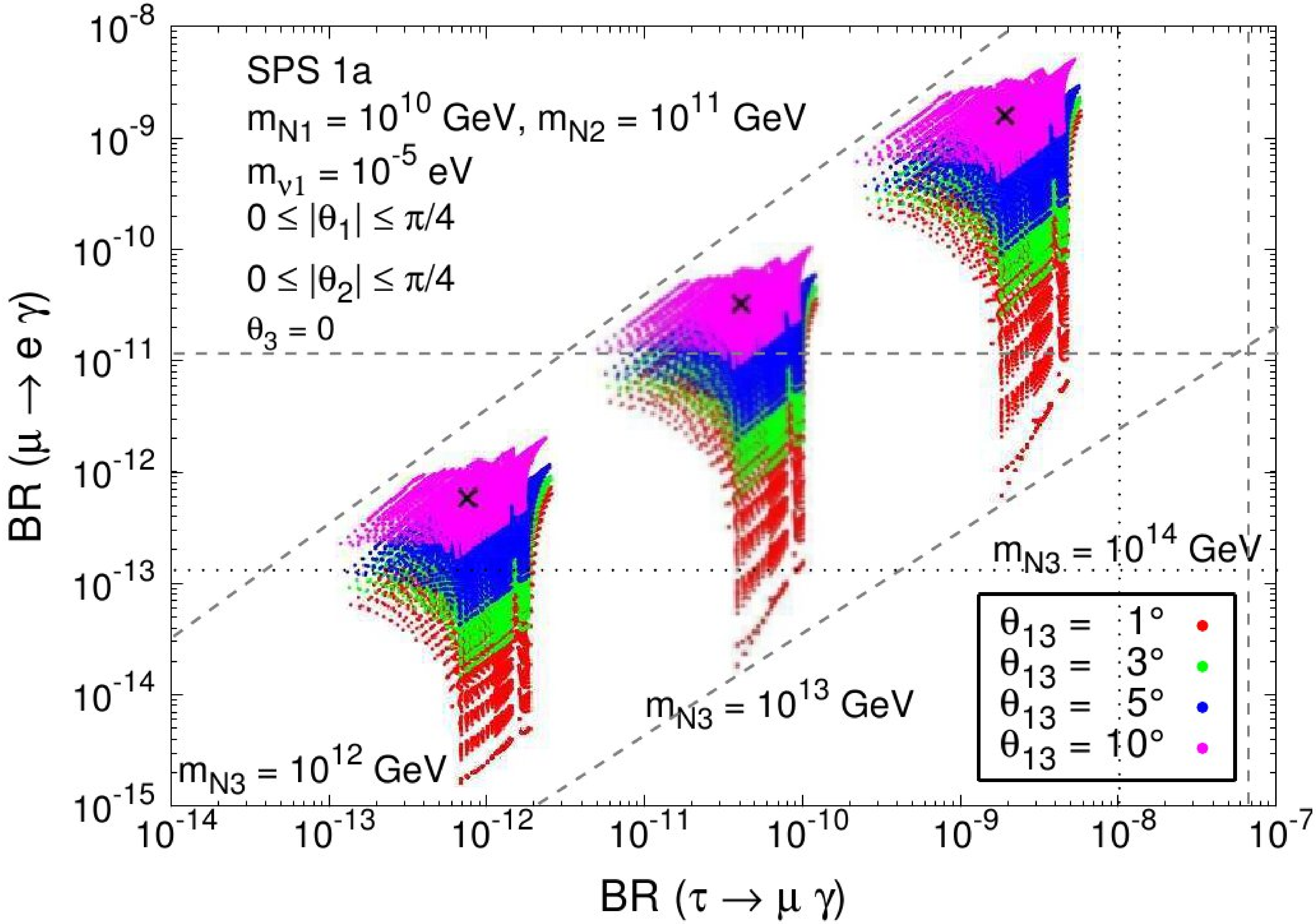


One of the most interesting results consists in the fact that almost the entire region in parameter space associated with a $\tilde{e}_L - \tilde{\mu}_L$ mass splitting $\sim \mathcal{O}(1\%)$ is also within the future sensitivity of low-energy facilities, especially for CR($\mu - e$, Ti) (even without 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.

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)



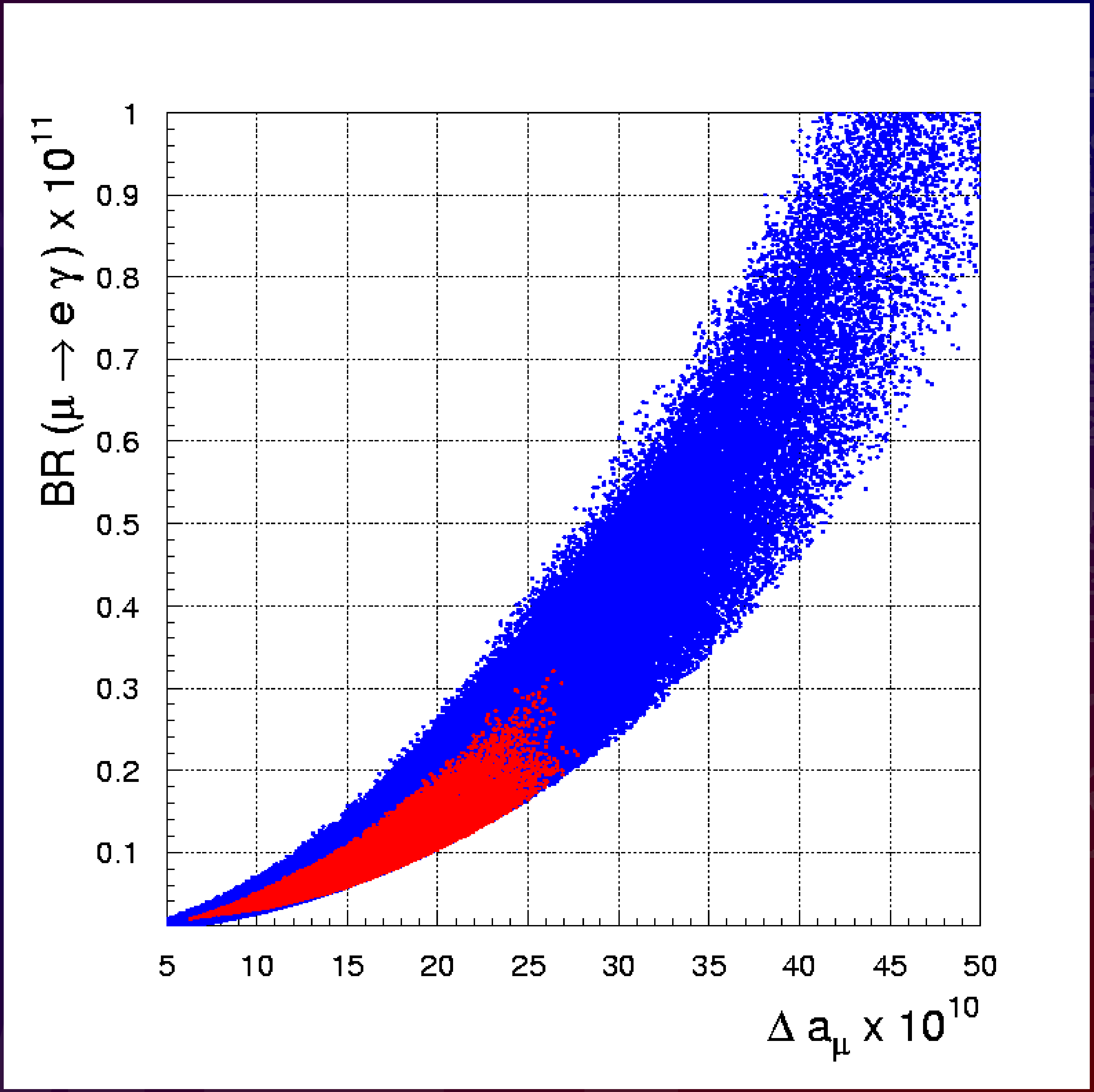
S. Antusch et al. / Nuclear Physics B (Proc. Suppl.) 169 (2007) 155–165



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

MSSM with Large $\tan\beta$ & Heavy Squarks

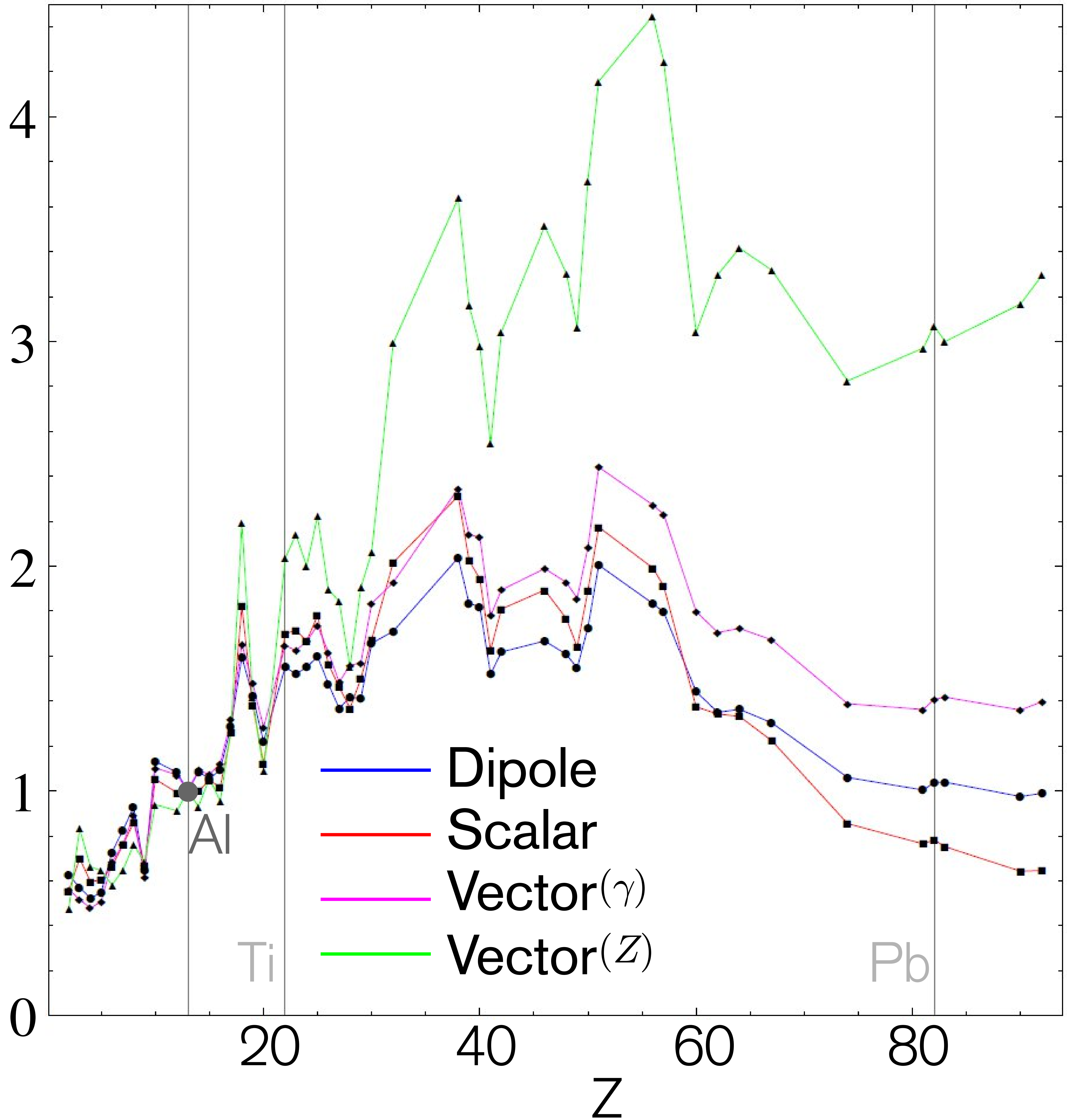
- Accommodates $g-2$ signal
- Predicts $\mu \to e + \gamma$ at 10^{-12}
  - further factor 1000 for $\mu + N \to e + N$



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

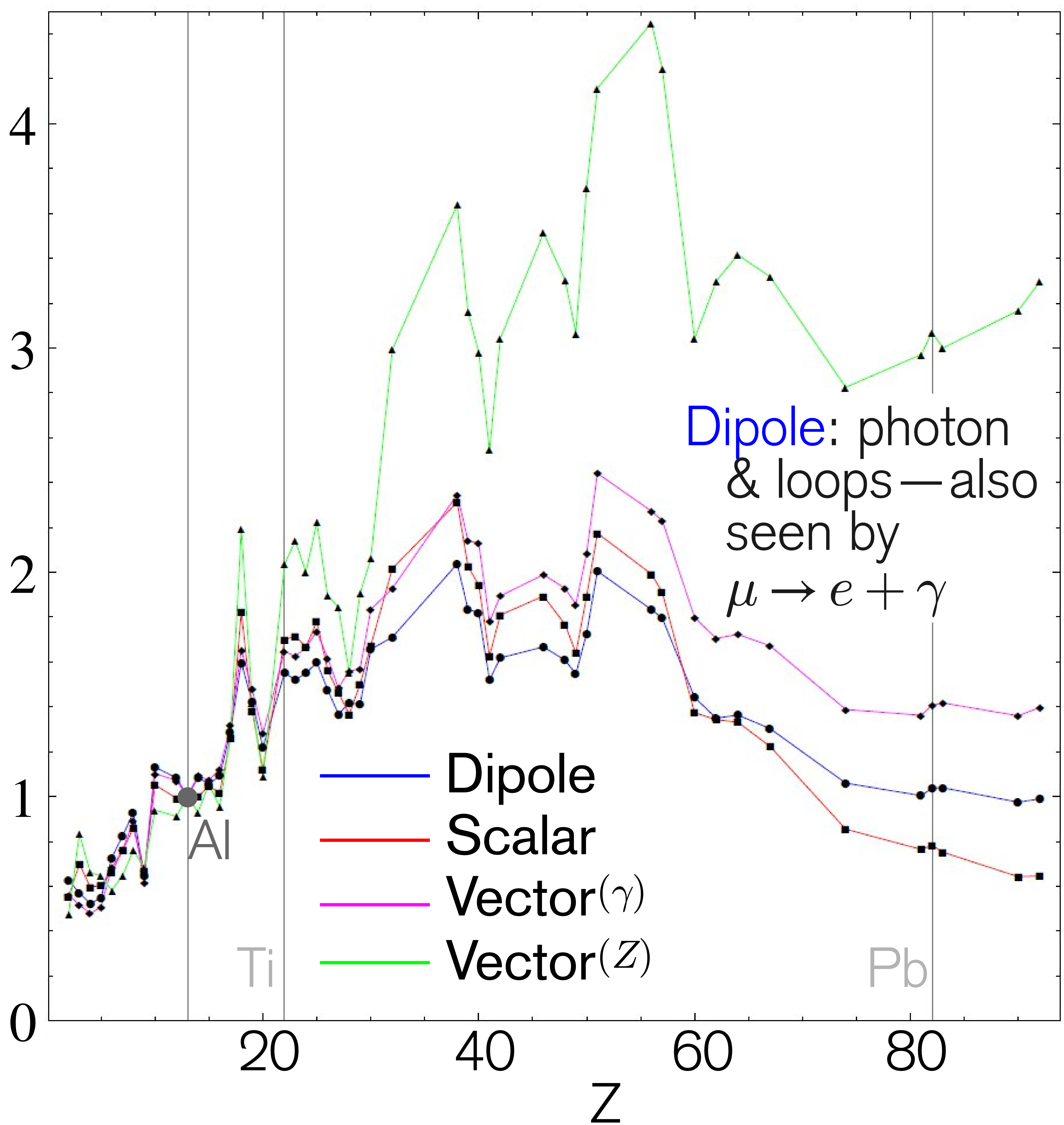
(Predictions for $\mu \to e\gamma$ also given)



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)

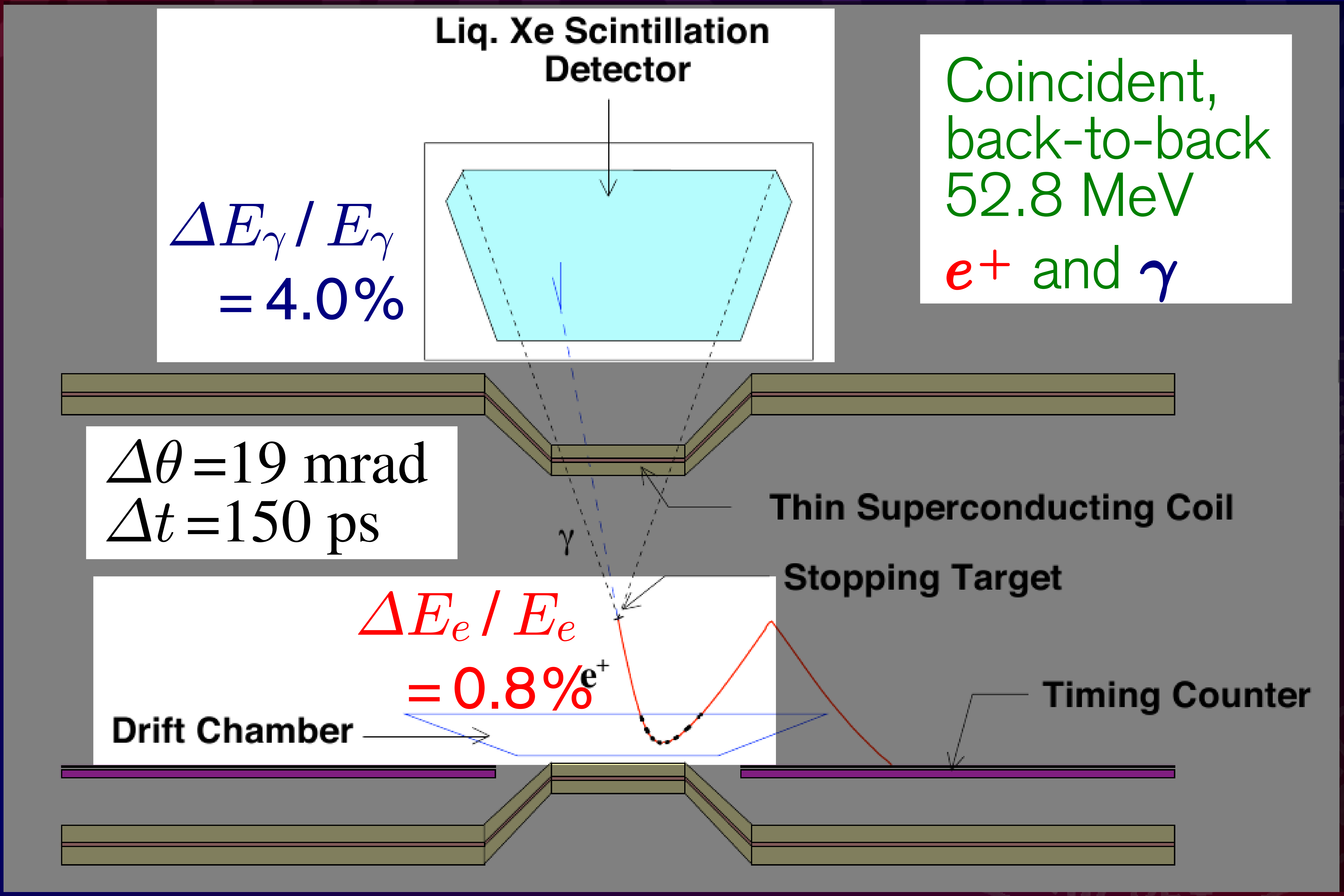


Charged Lepton Flavour Violation

- 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

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

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

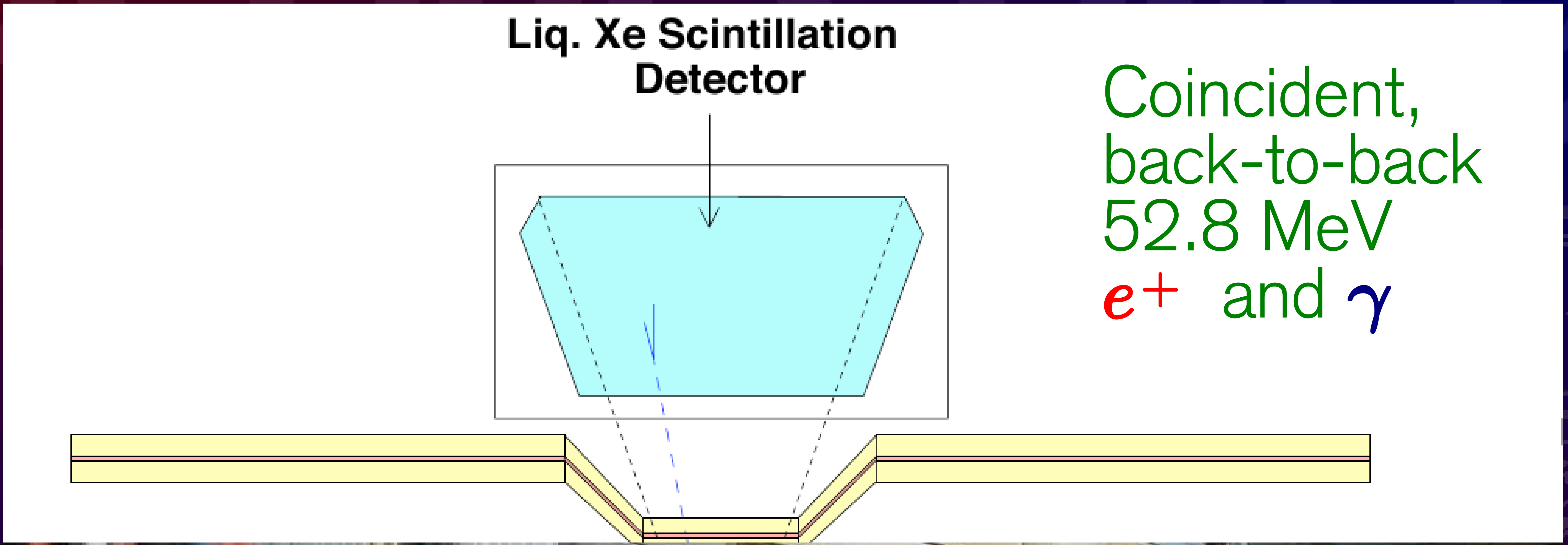


Coincidence requirement makes further improvements in sensitivity with intense beams very difficult

Latest results shown last summer

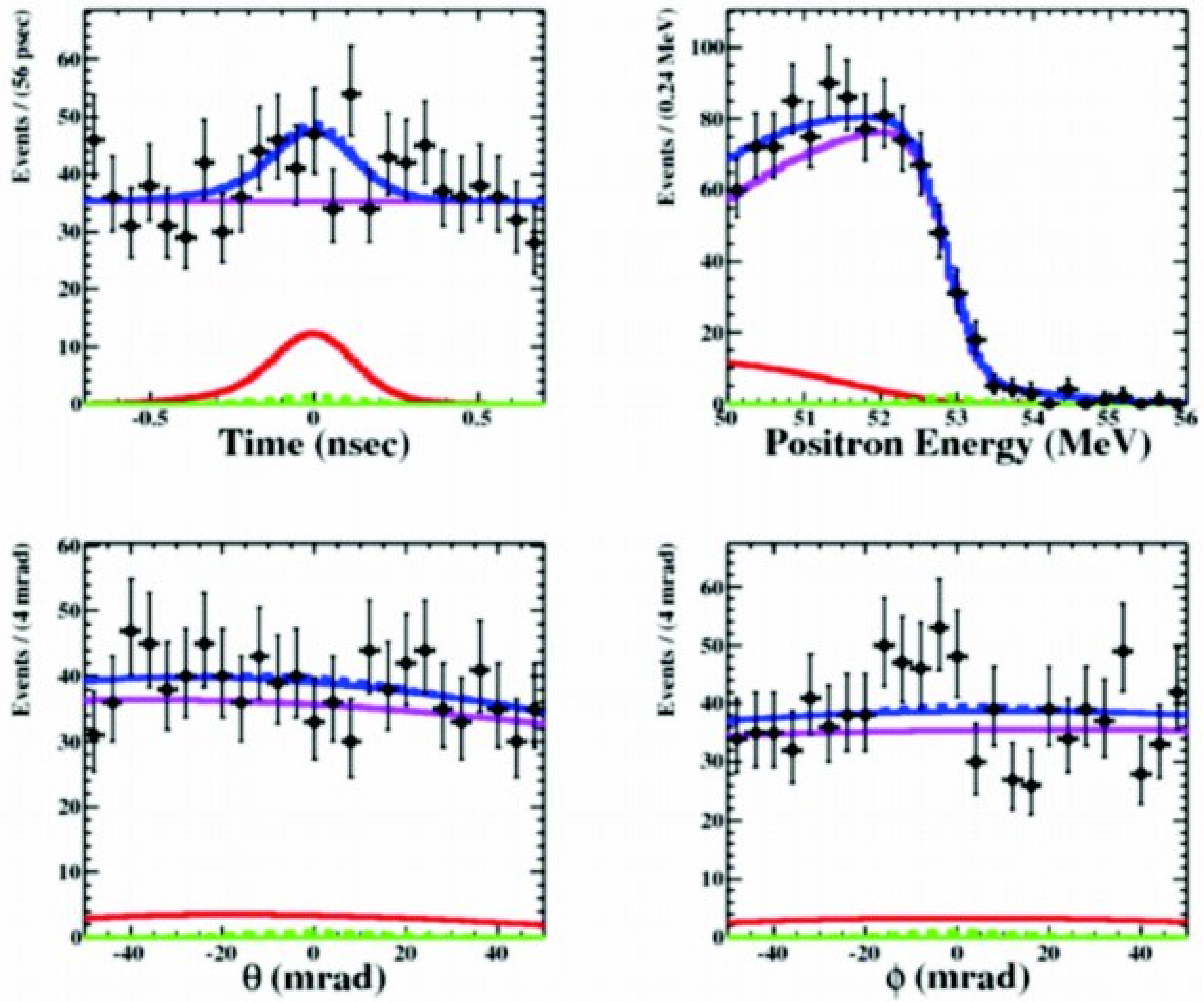
MEG ($\mu \rightarrow e\gamma$) at PSI

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



$\mu \rightarrow e\gamma$

MEG: 2009 – 2010 result



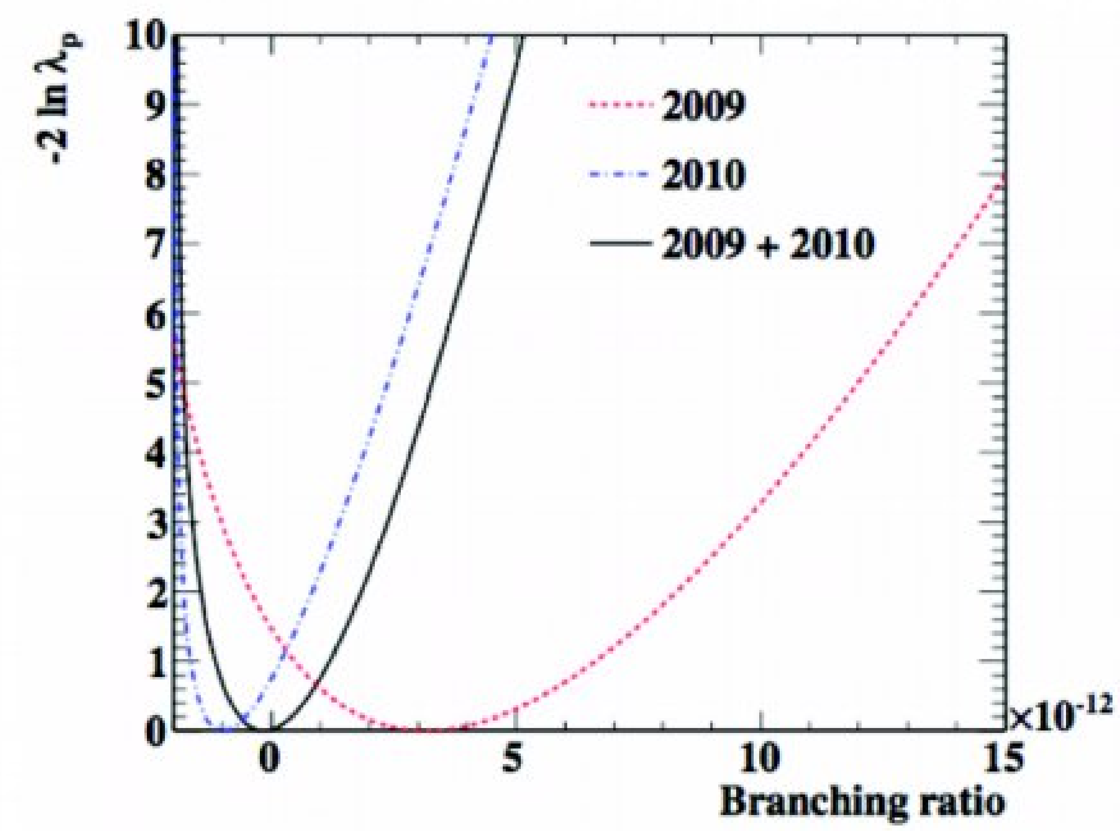
$N_{Sig} = -0.5\,^{+7.9}_{-4.7}$

$N_{RMD} = 765 \pm 12$

$N_{BG} = 88 \pm 12$

2009-2010 : $\sim 17 \times 10^{13}$ μstop on target

Espect. UL from S.B.: 1.6×10^{-12}



$BR(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12}$ (at 90% C.L.)

Phys. Rev. Lett. 107, 171801(2011)

Currently analysing 2011 data, to double the statistics

Coherent Muon-to-Electron Conversion

- Muon-to-Electron Conversion

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

muonic
atom

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

- The present limit is about

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

for the branching ratio on Gold (Sindrum II)

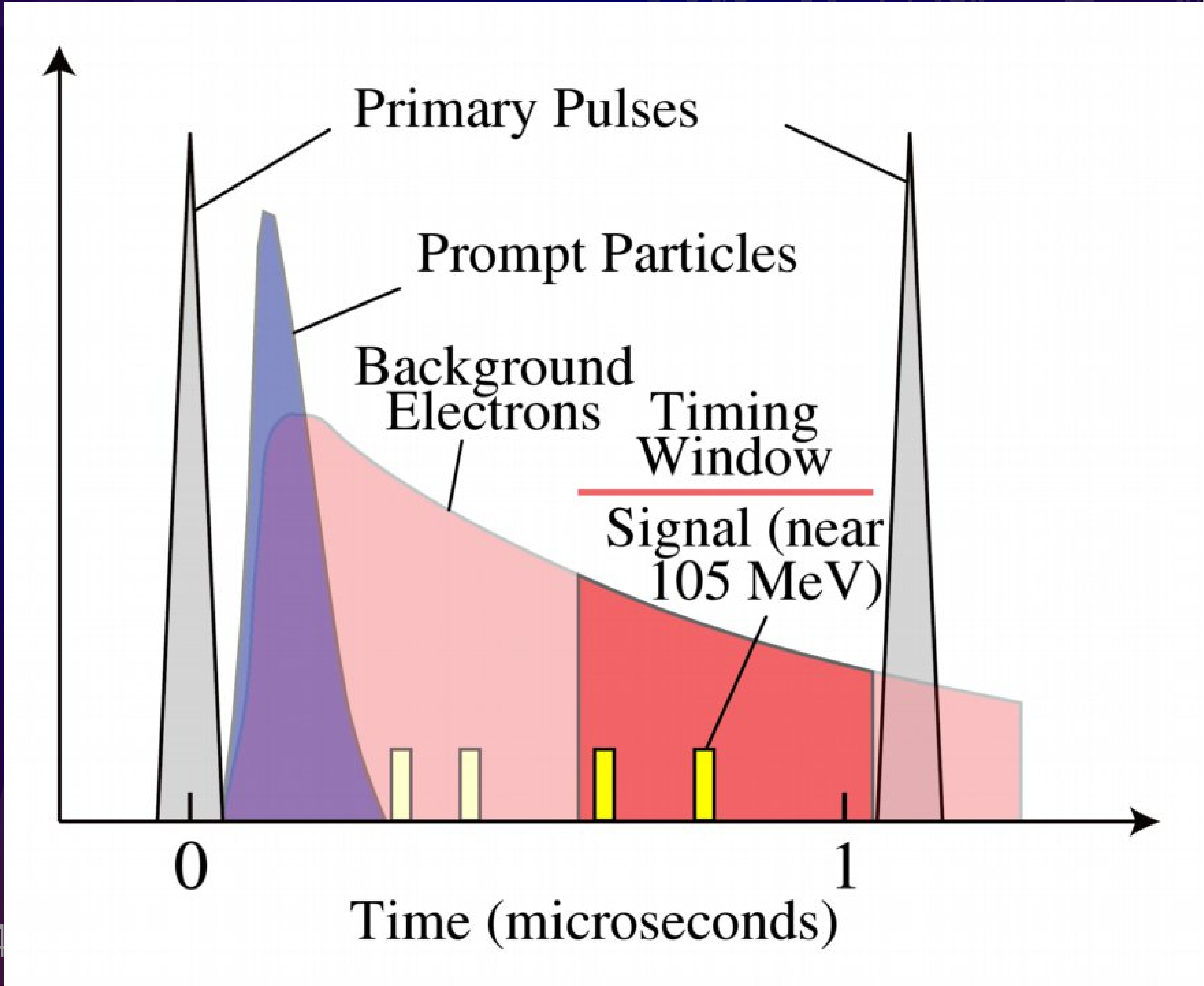
- **COMET** aims to improve sensitivity to 10^{-16}
  - **MUSIC** is a COMET prototype
    (and a muon physics facility in its own right)
- **PRISM** extends this to a sensitivity of 10^{-18}

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



Search for Lepton-Flavor-Violating Rare Muon Processes

R. M. Djilkibaev* and V. M. Lobashev**

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.

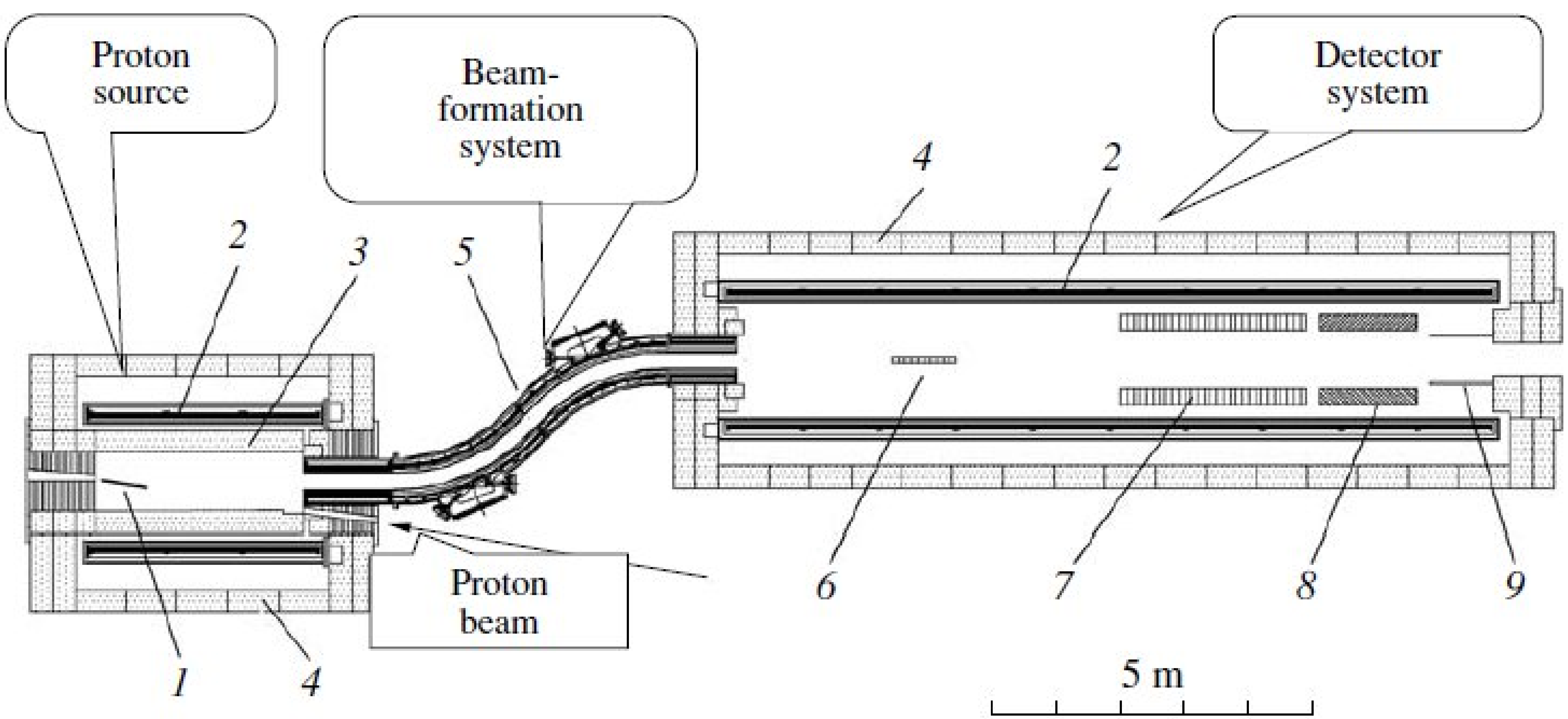


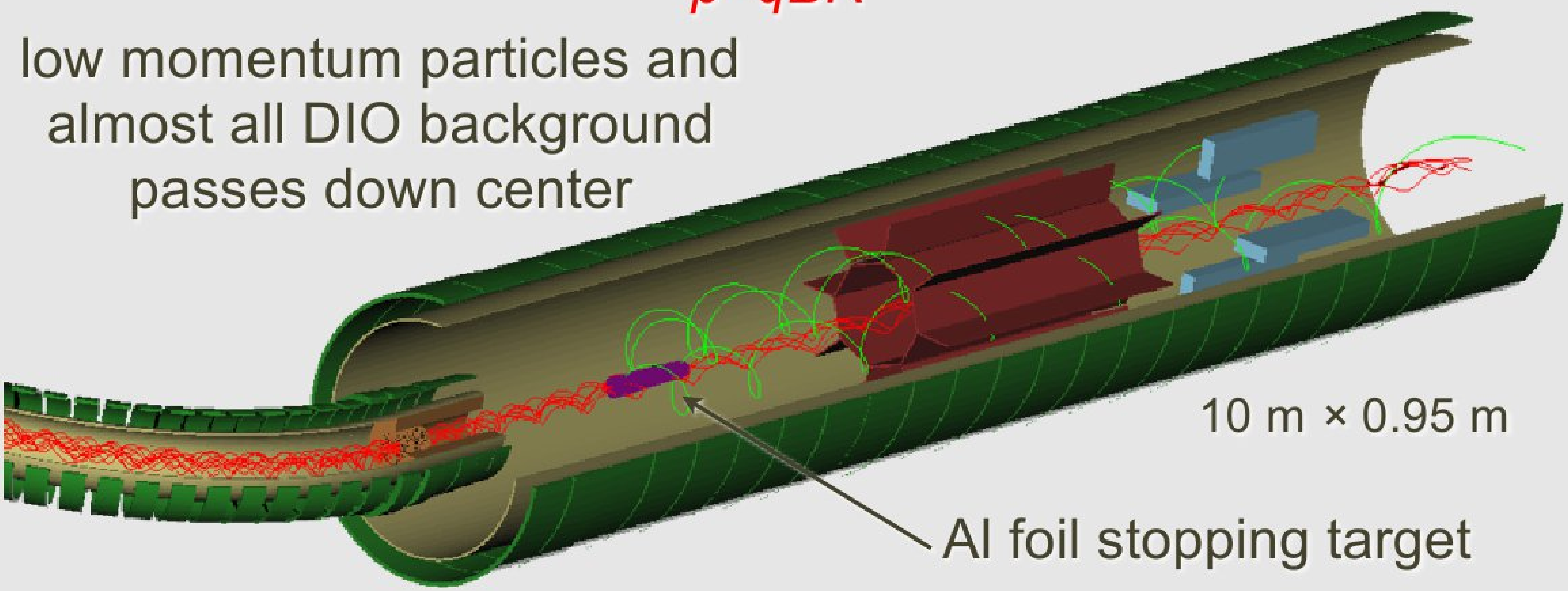
Fig. 1. Central horizontal cut of the MELC facility: (*1*) proton target, (*2*) superconductor solenoid, (*3*) shield of the solenoid, (*4*) steel yoke, (*5*) transport solenoid and collimator, (*6*) detector target, (*7*) coordinate detector, (*8*) calorimeter, and (*9*) detector shield and beam trap.

Mu2E at Fermilab

Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, $p=qBR$

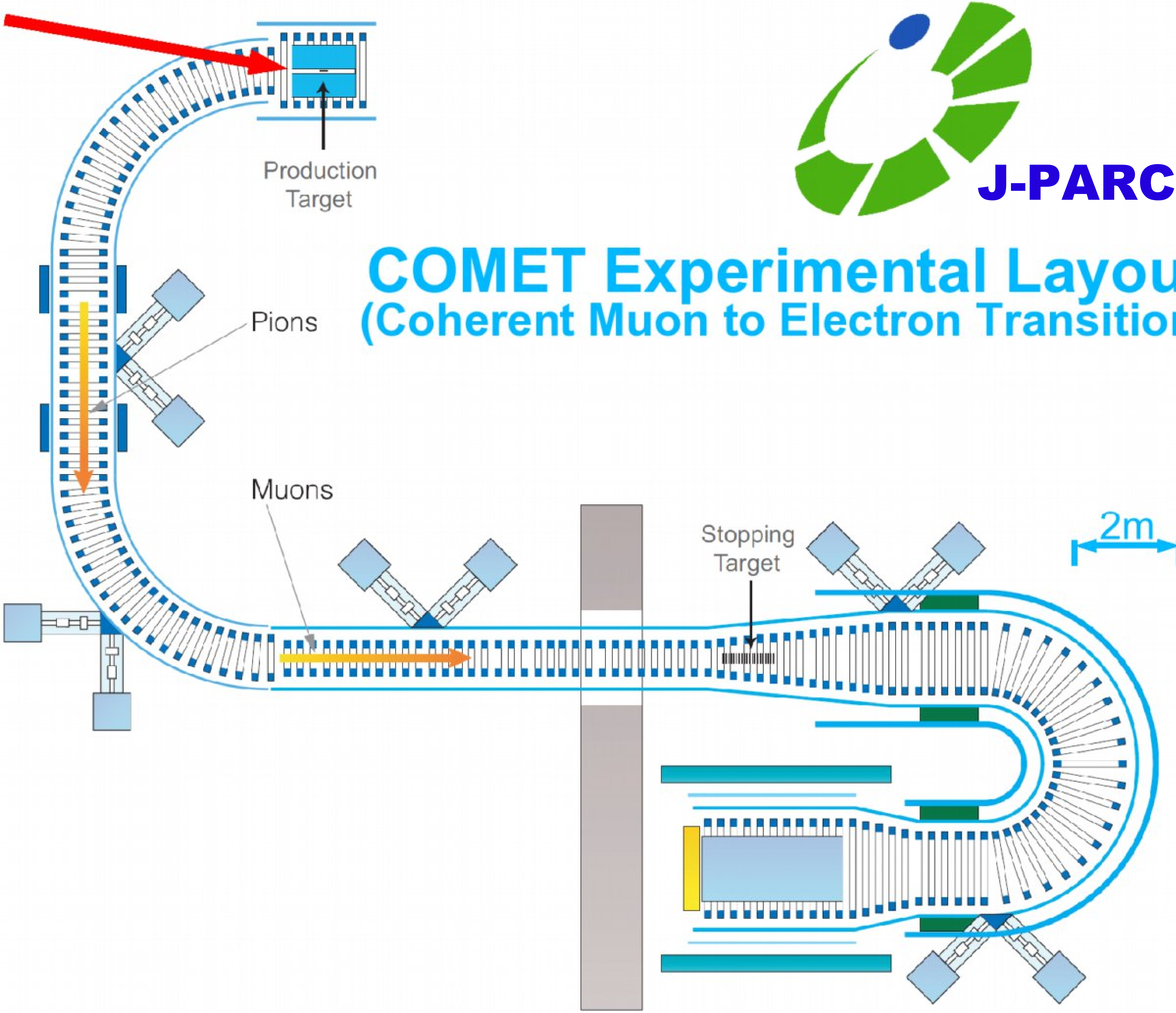
low momentum particles and almost all DIO background passes down center

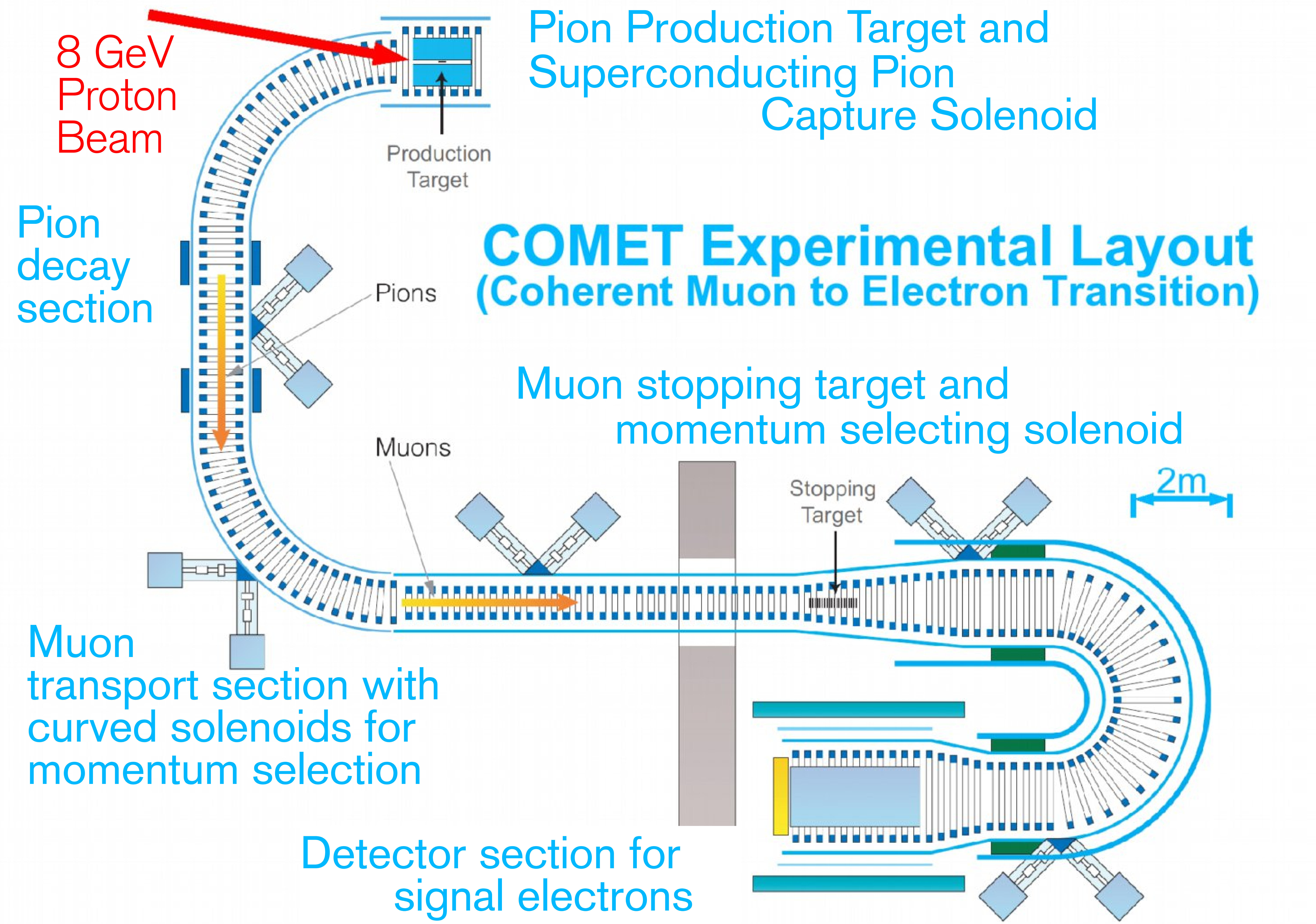


signal events pass *through* octagon of tracker and produce hits

COMET Experimental Layout
(Coherent Muon to Electron Transition)

J-PARC

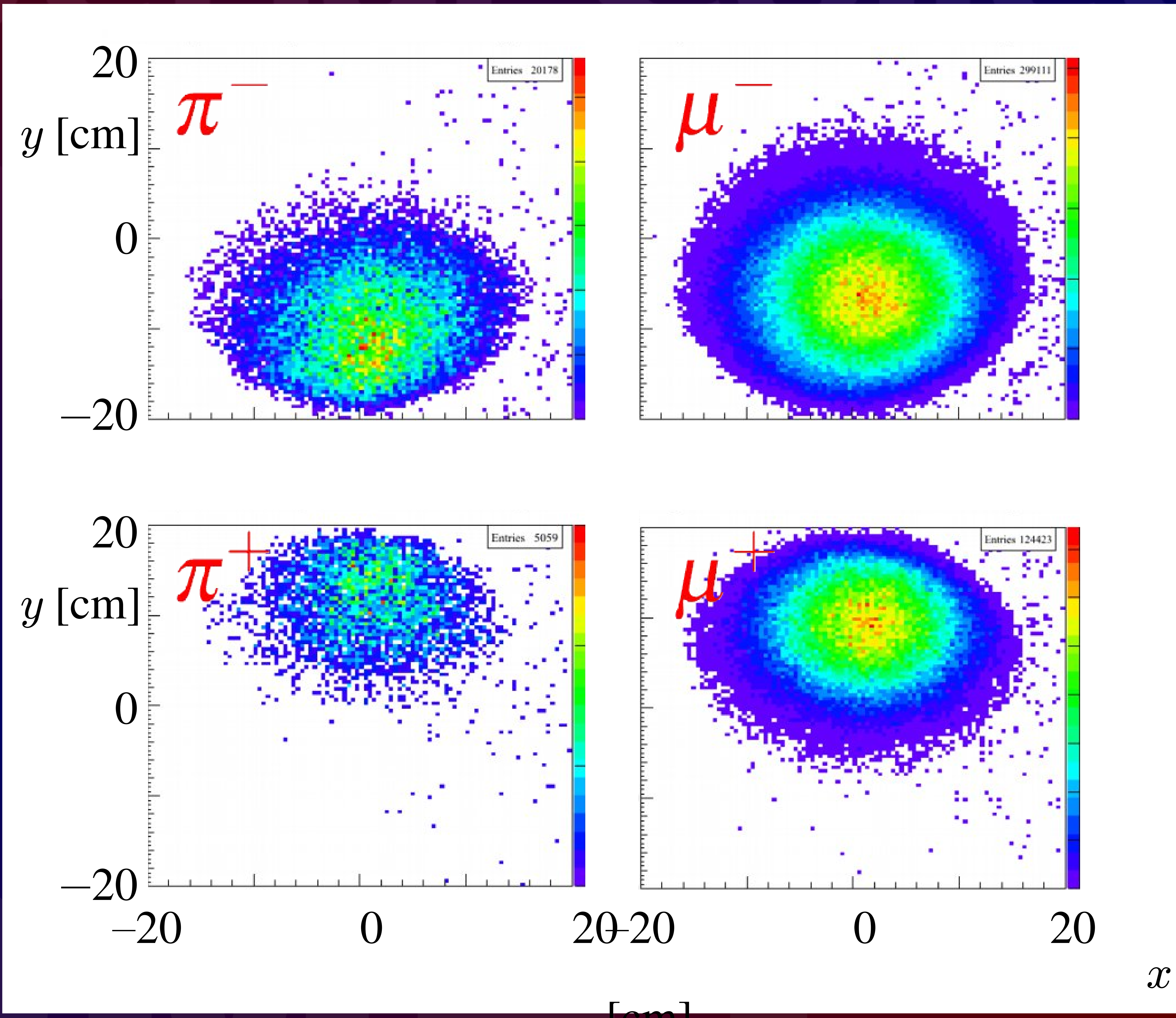




8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Pions
Muon stopping target and momentum selecting solenoid
Muons
Stopping Target
2m
Muon transport section with curved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

J-PARC

After 90 Degrees of Curved Solenoid



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

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

Y.G. Cui, R. Palmer
Department of Physics, Brookhaven National Laboratory, USA

Y. Arimoto, Y. Igarashi, S. Ishimoto, S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, N. Saito, M. Tomizawa, A. Yamamoto, K. Yoshimura
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

P. Dornan, P. Dauncey, U. Egede, A. Kurup, J. Pasternak, Y. Uchida,
Imperial College London, UK

Y. Iwashita
Institute for Chemical Research, Kyoto University, Kyoto, Japan

V. Kalinnikov, A. Moiseenko, D. Mzhavia, J. Pontecorvo, B. Sabirov, Z. Tsamaiaidze, and P. Evtukhouvich
Joint Institute for Nuclear Research (JINR), Dubna, Russia

M. Aoki, Md.I. Hossain, T. Itahashi, Y. Kuno*, E. Matsushita, N. Nakadozono, A. Sato, S. Takahashi, T. Tachimoto, M. Yoshida,
Department of Physics, Osaka University, Osaka, Japan

M. Koike, J. Sato, M. Yamanaka
Department of Physics, Saitama University, Japan

Y. Takubo
Department of Physics, Tohoku University, Japan

D. Bryman
Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada

R. D'Arcy, M. Lancaster, M. Wing
Department of Physics and Astronomy, University College London, UK

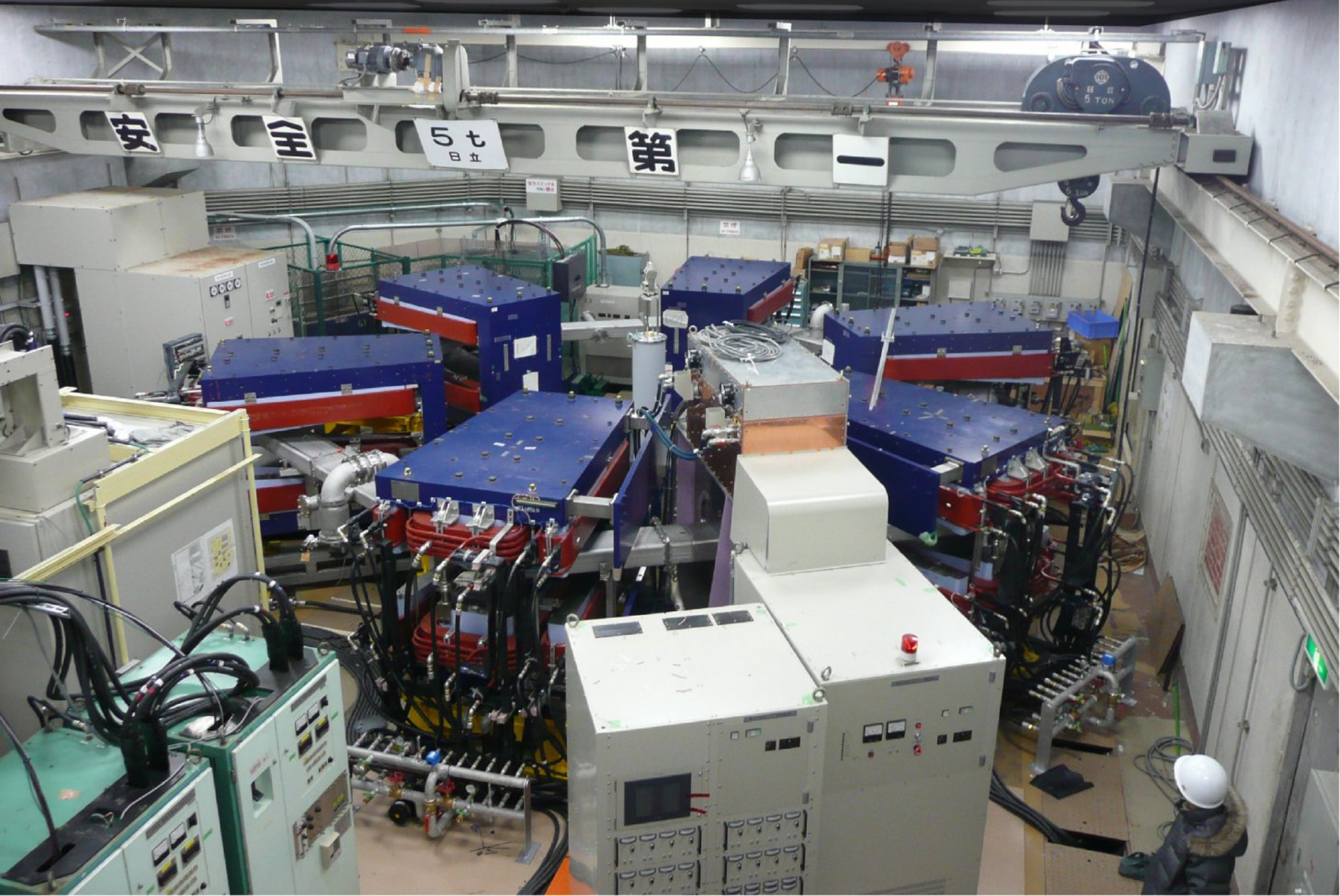
E. Hungerford
Department of Physics, University of Houston, USA

T. Numao
TRIUMF, Canada

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

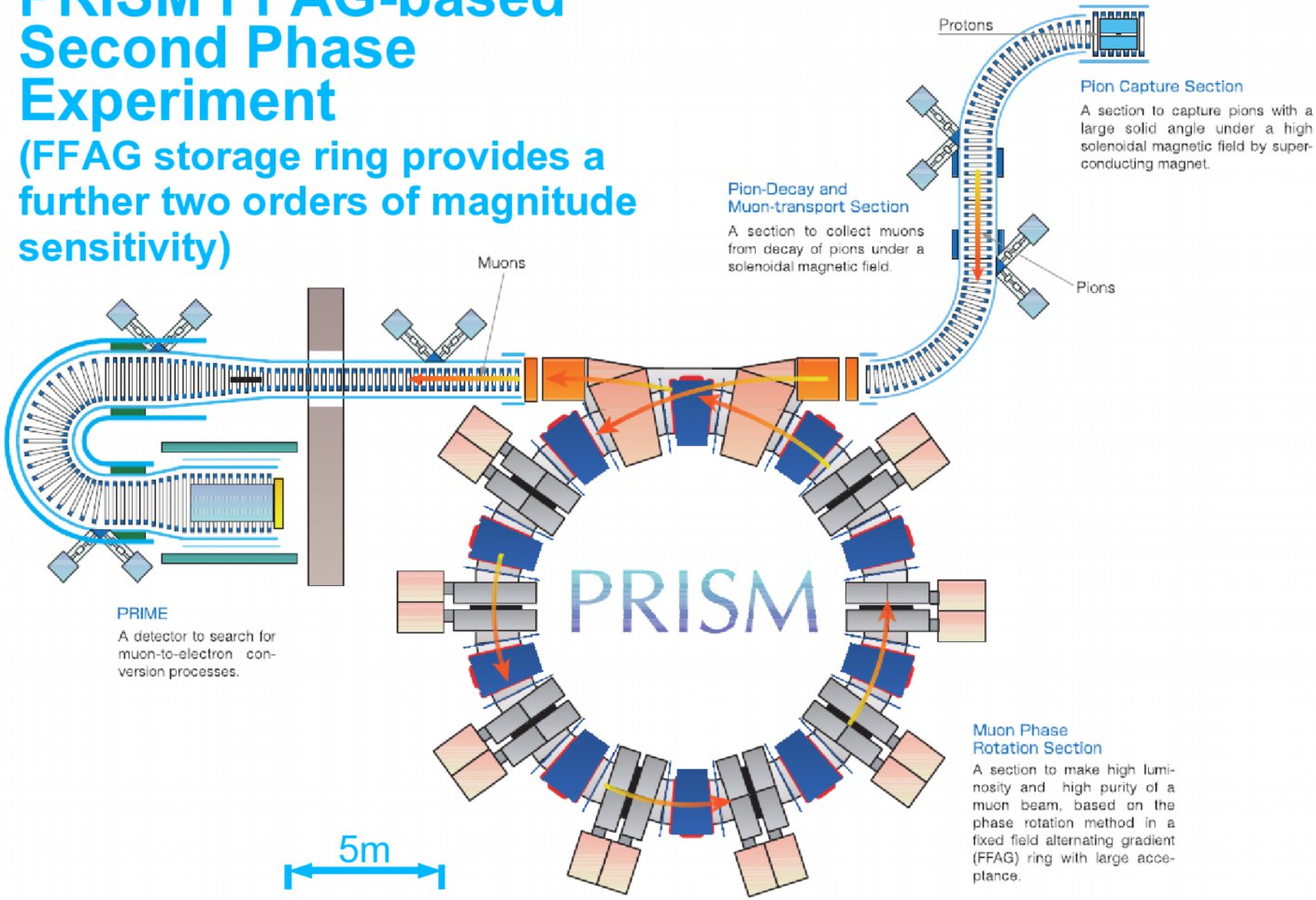
The PRISM FFAG Ring for Muon-to-Electron Conversion

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**

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

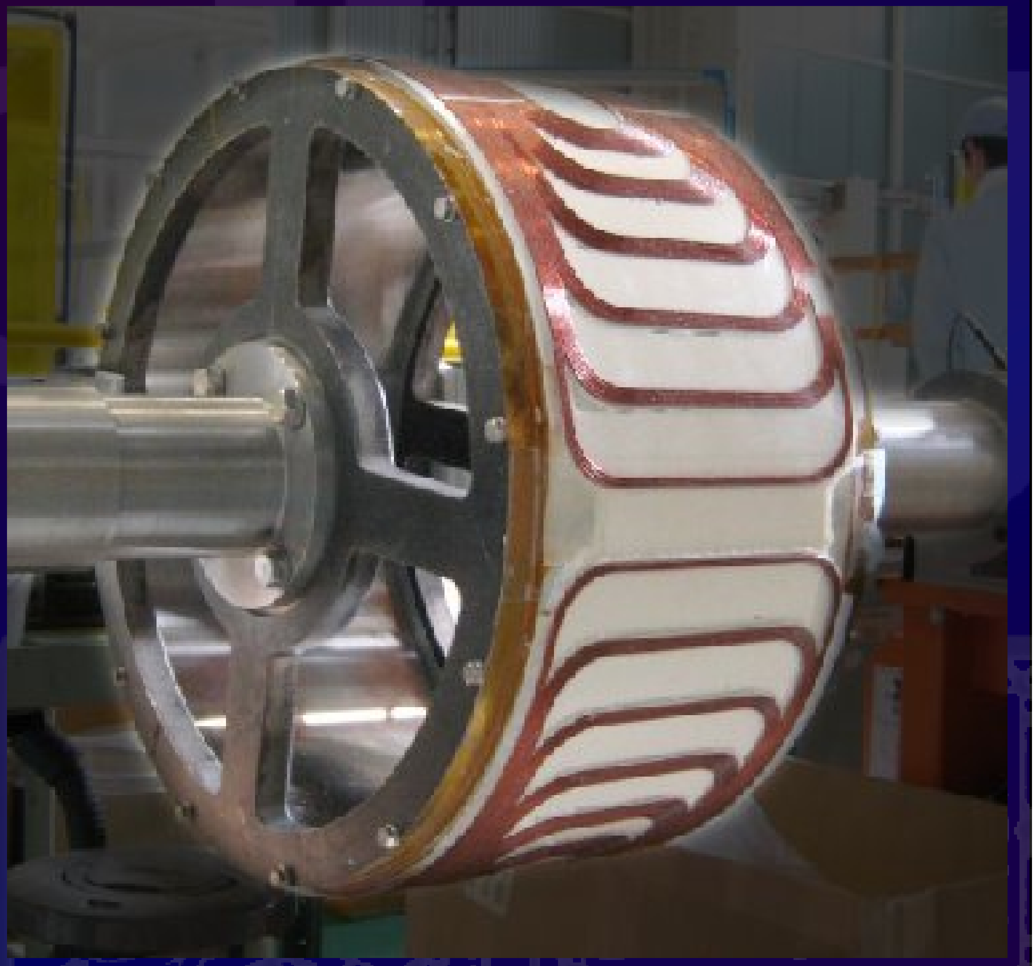
PRISM Task Force

Recent PRISM/FFAG Workshop

- 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
- 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)

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

New Since January 2012: COMET Phase-I

- Decision to **"phase" the construction of COMET**
- Start with the proton beamline from the J-PARC MR Synchrotron, pion production target & solenoid, full experimental hall, and first half of pion/muon transport solenoid
- Experimental & funding benefits
  - Will allow for a full evaluation of the novel pion production solenoid + curved solenoids with dipole momentum selection, physics processes and backgrounds
  - Also allows for cLFV measurements
    - $\times$100 previous for $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
    - and other channels

R. Akhmetshin, A. Bondar, L. Epshteyn, G. Fedotovich, D. Grigoriev, V. Kazanin, A. Ryzhenenkov, D. Shemyakin, Yu. Yudin
Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Y.G. Cui, R. Palmer
Department of Physics, Brookhaven National Laboratory, USA

Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto, Y. Makida, S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, N. Saito, K. Sasaki, M. Sugano, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida, A. Yamamoto, M. Yamanaka, M. Yoshida, Y. Yoshii, K. Yoshimura
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Yu. Bagaturia
Ilia State University (ISU), Tbilisi, Georgia

P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. Pasternak, Y. Uchida
Imperial College London, UK

P. Sarin, S. Umasankar
Indian Institute of Technology Bonbay, India

Y. Iwashita
Institute for Chemical Research, Kyoto University, Kyoto, Japan

V.V. Thuan
Institute for Nuclear Science and Technology, Vietnam

H.-B. Li, C. Wu, Y. Yuan
Institute of High Energy Physics (IHEP), China

A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trekov, N. Tsverava
Institute of High Energy Physics of I.Javakhishvili State University (HEPI TSU), Tbilisi, Georgia

S. Dymov, P. Evtoukhovich, V. Kalinnikov, A. Khvedelidze, A. Kulikov, G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsmalaidze
Joint Institute for Nuclear Research (JINR), Dubna, Russia

M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky
Institute for Theoretical and Experimental Physics (ITEP), Russia

T. Ota
Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), Munchen, Germany

Y. Mori, Y. Kuriyama, J.B. Lagrange
Kyoto University Research Reactor Institute, Kyoto, Japan

C.V. Tao
College of Natural Science, National Vietnam University, Vietnam

M. Aoki, T. Hiasa, I.H. Hasim T. Hayashi, Y. Hino, S. Hikida, T. Itahashi, S. Ito, Y. Kuno*, T.H. Nam, H. Nakai, H. Sakamoto, A. Sato, N.D. Thong, N.M. Truong
Osaka University, Osaka, Japan

M. Koike, J. Sato
Saitama University, Japan

D. Bryman
University of British Columbia, Vancouver, Canada

S. Cook, R. D'Arcy, A. Edmonds, M. Lancaster, M. Wing
University College London, UK

E. Hungerford
University of Houston, USA

W.A. Tajuddin
University of Malaya, Malaysia

R.B. Appleby, W. Bertsche, M. Gersabeck, H. Owen, C. Parkes
University of Manchester, UK

F. Azfar
University of Oxford, UK

Md. Imam Hossain
University Technology Malaysia

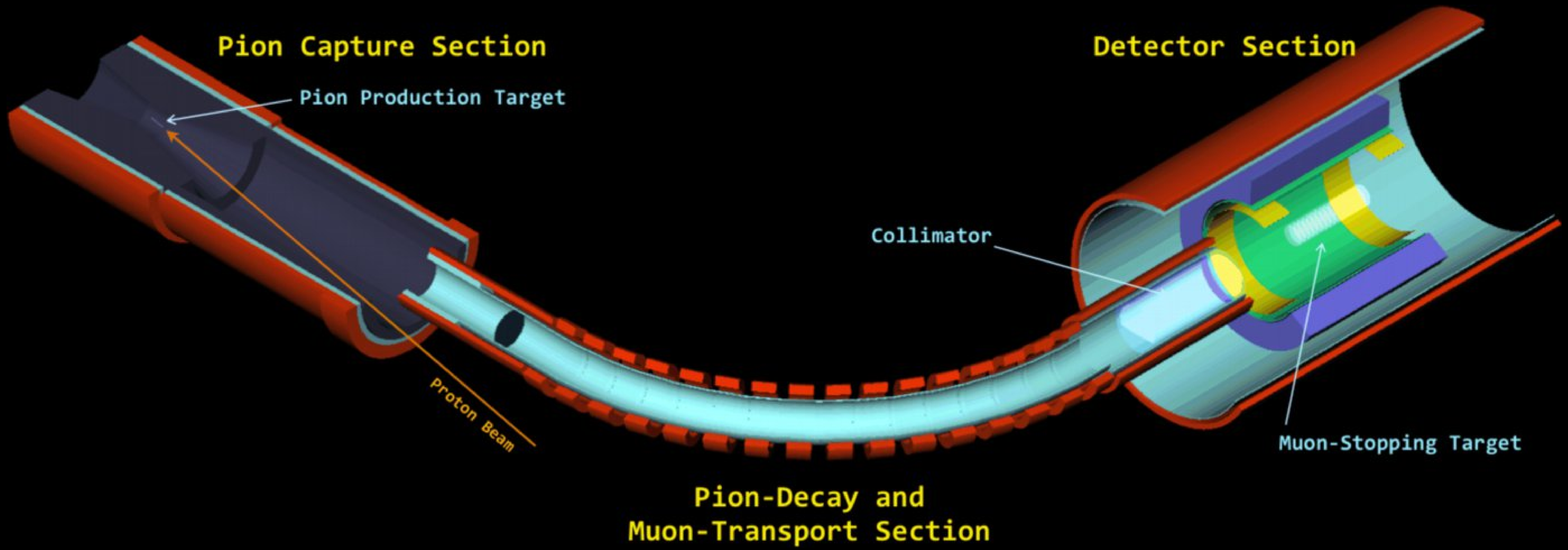
T. Numao
TRIUMF, Canada

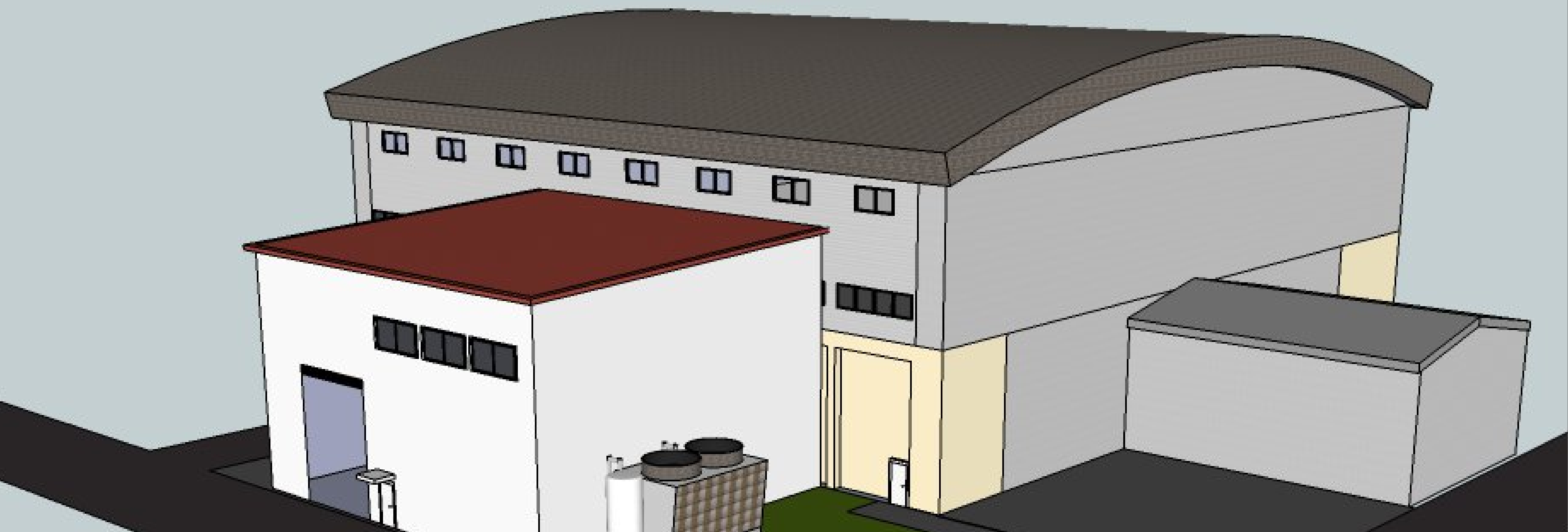
Letter of Intent for Phase-I of the COMET Experiment at J-PARC

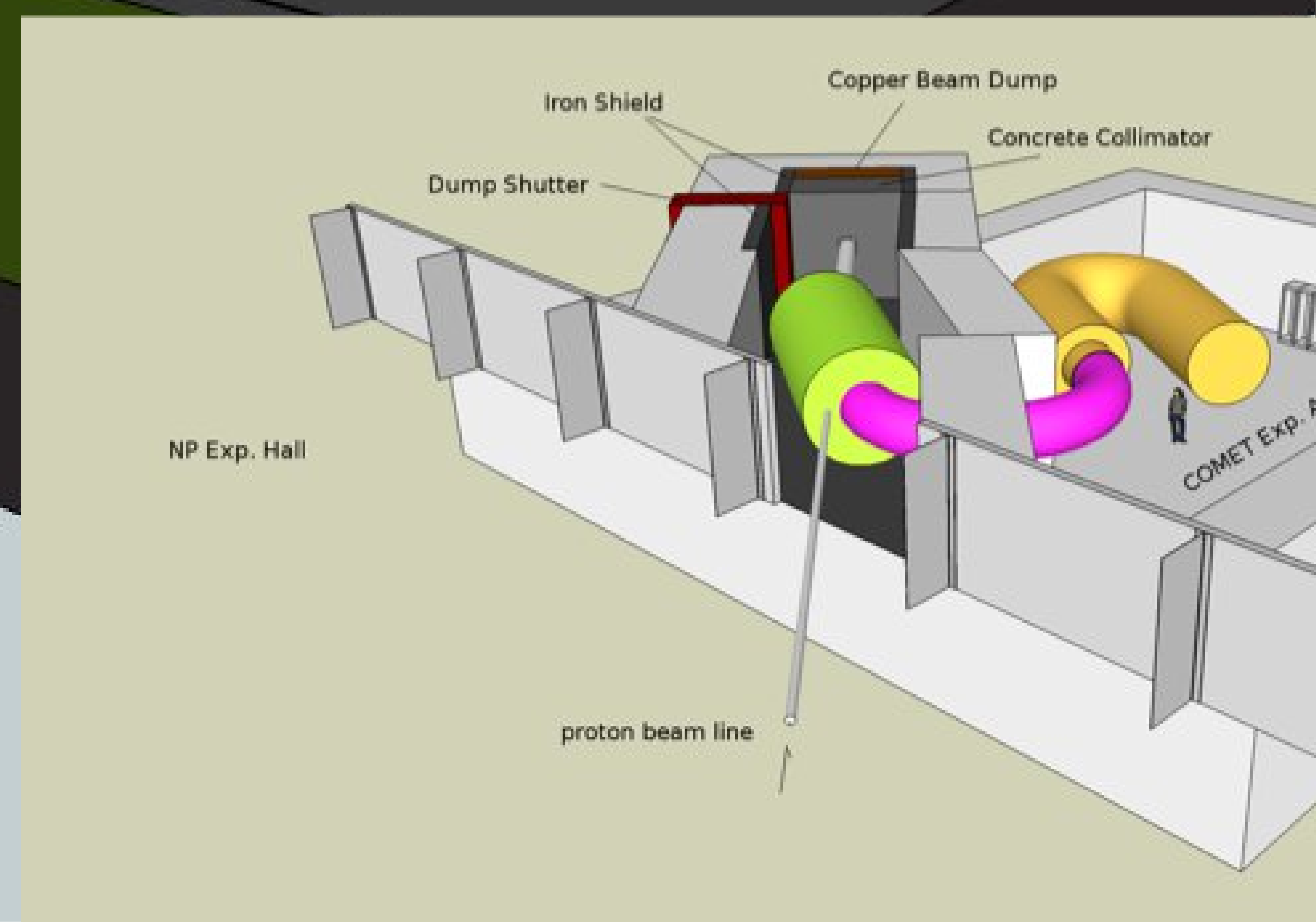
March 21, 2012

Now approved: construction effort under way

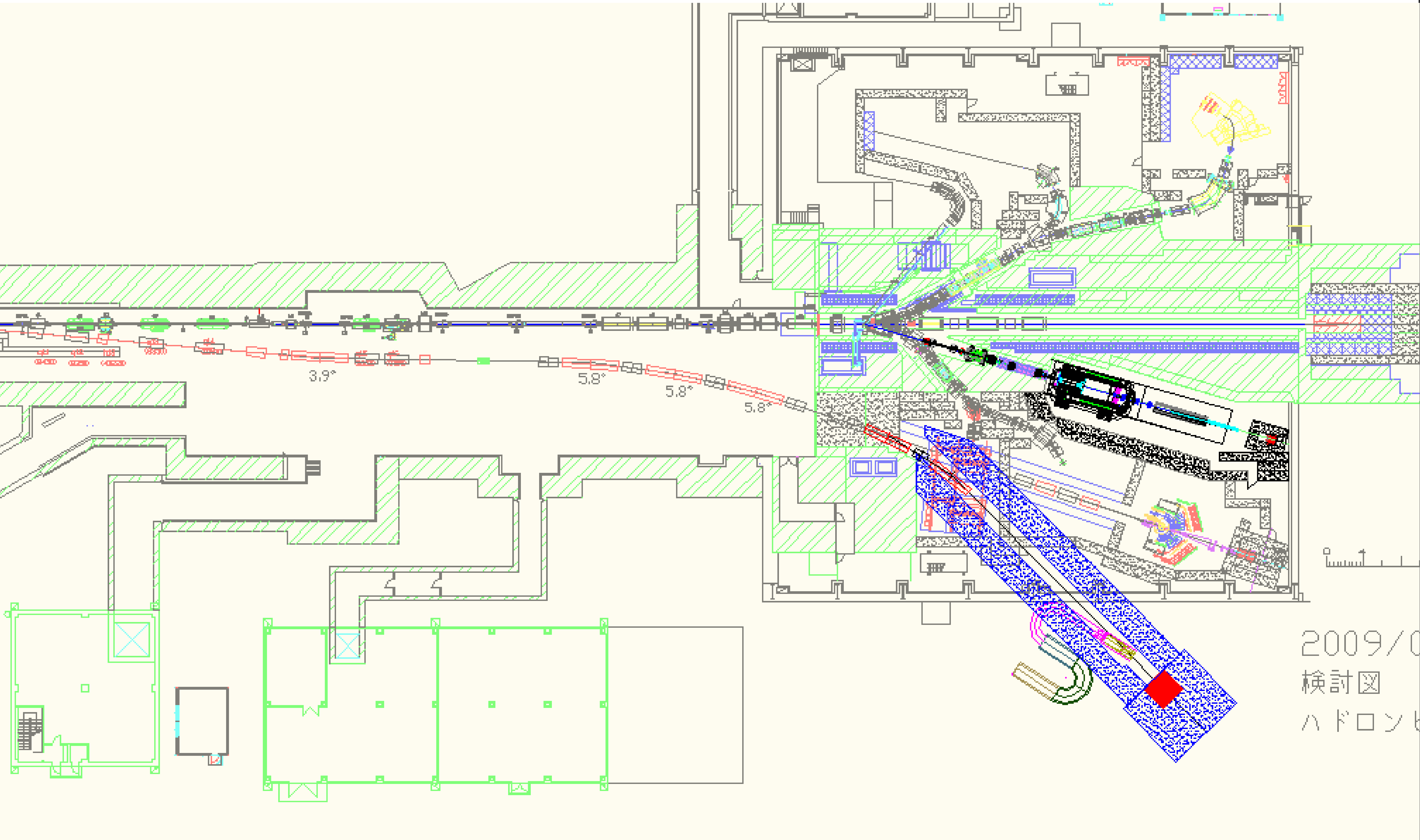
COMET Phase-I



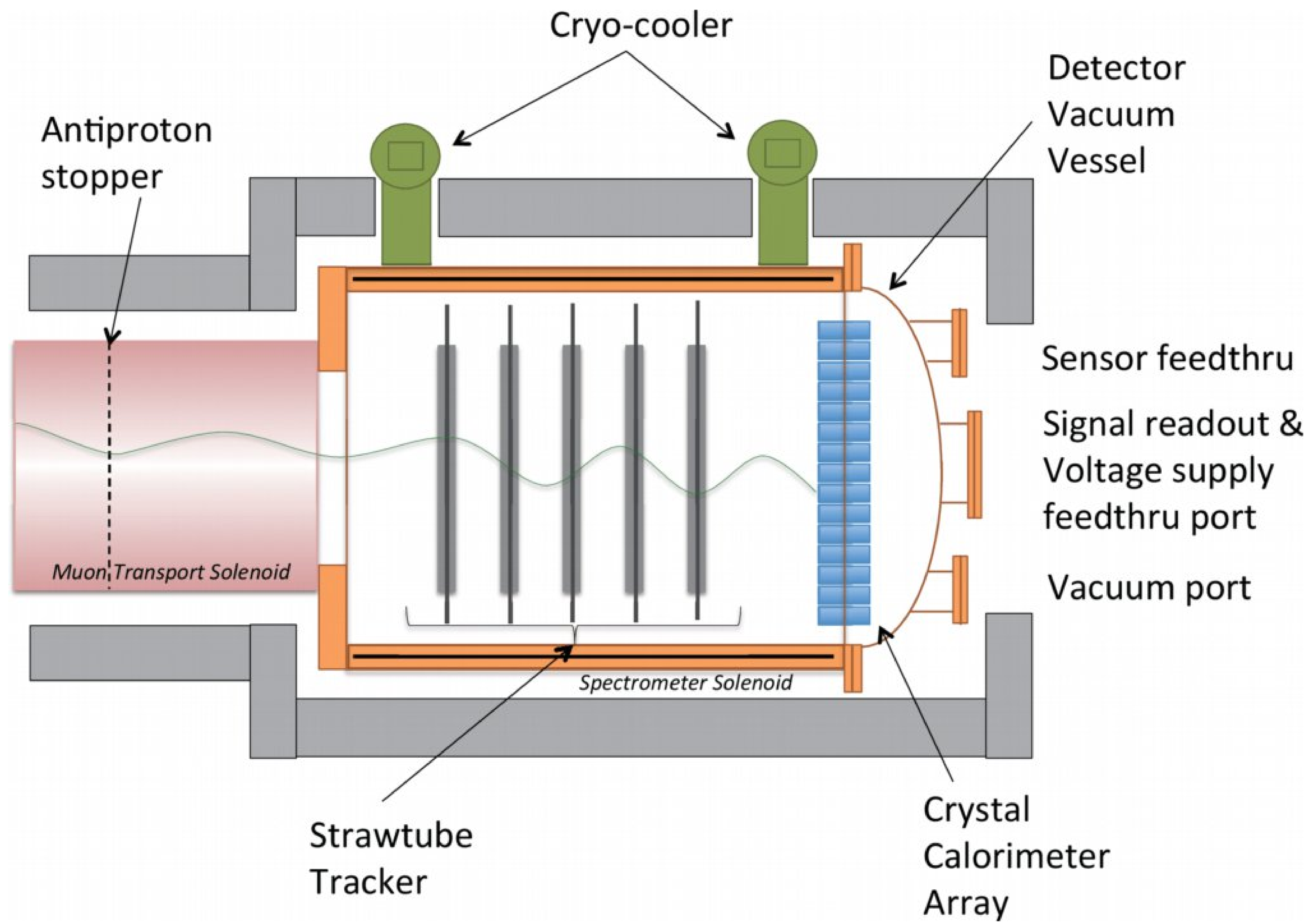




COMET Phase-I
to include construction
of underground experimental
hall and counting rooms

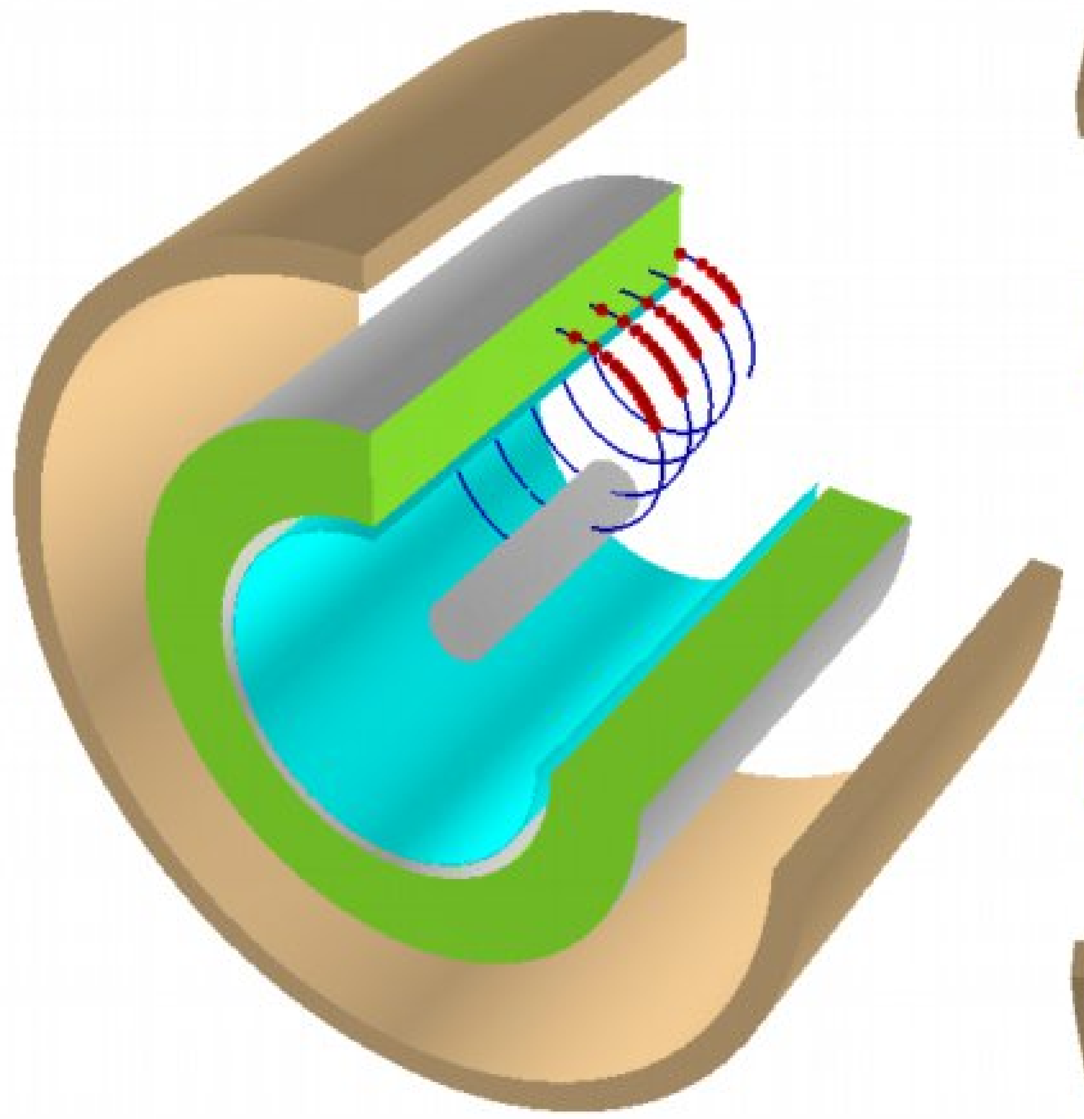
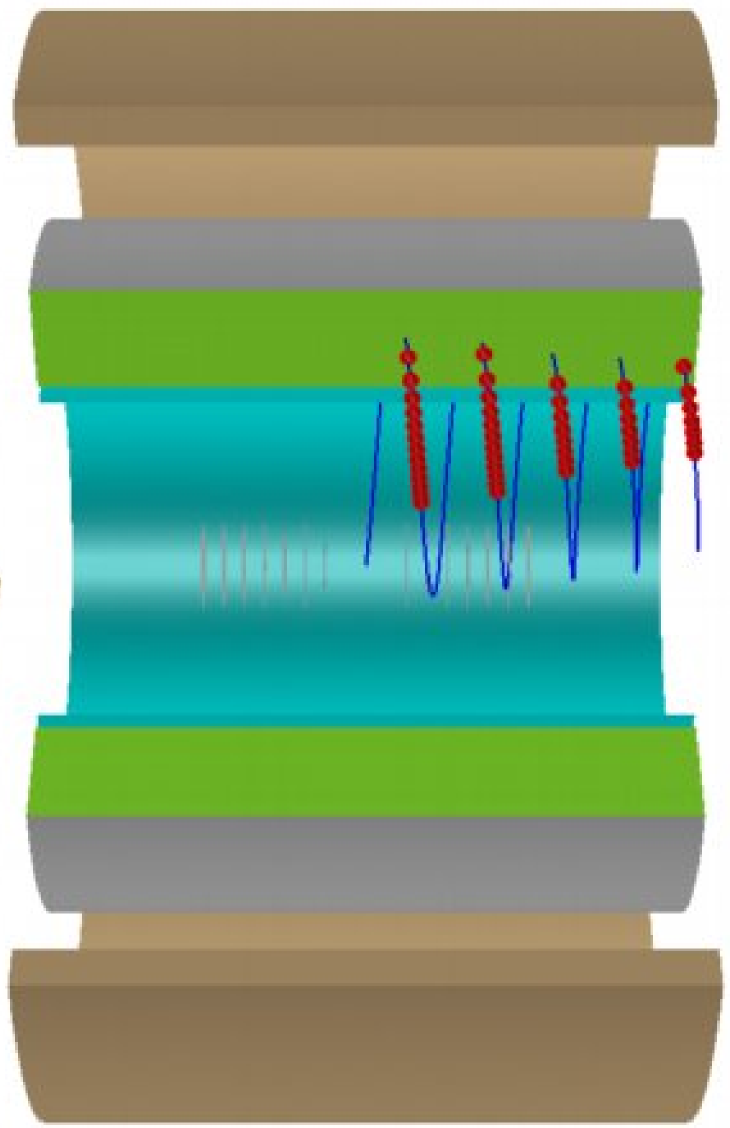
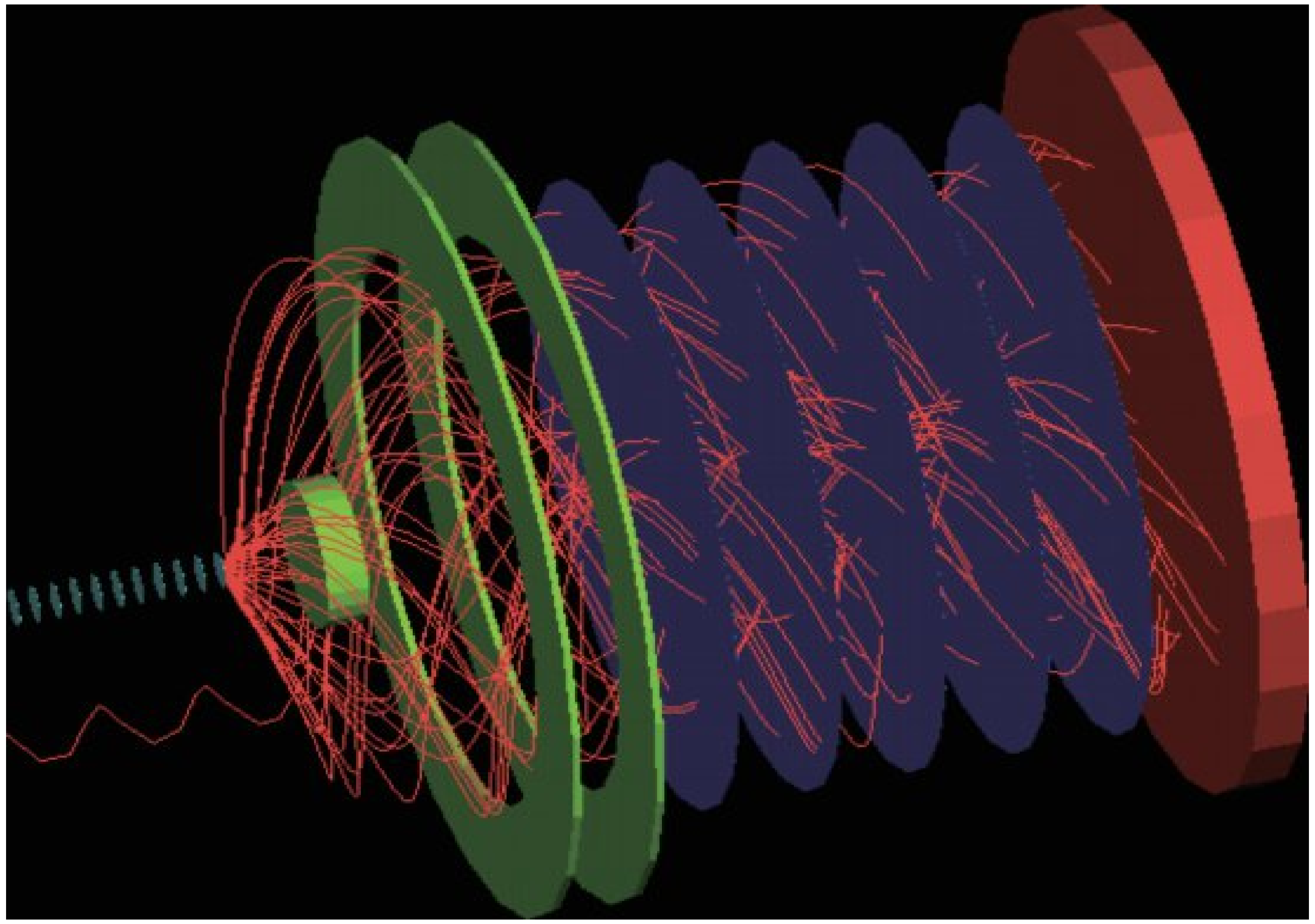

3.9°
5.8°
5.8°
5.8°
2009/0
検討図
ハドロンビ

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

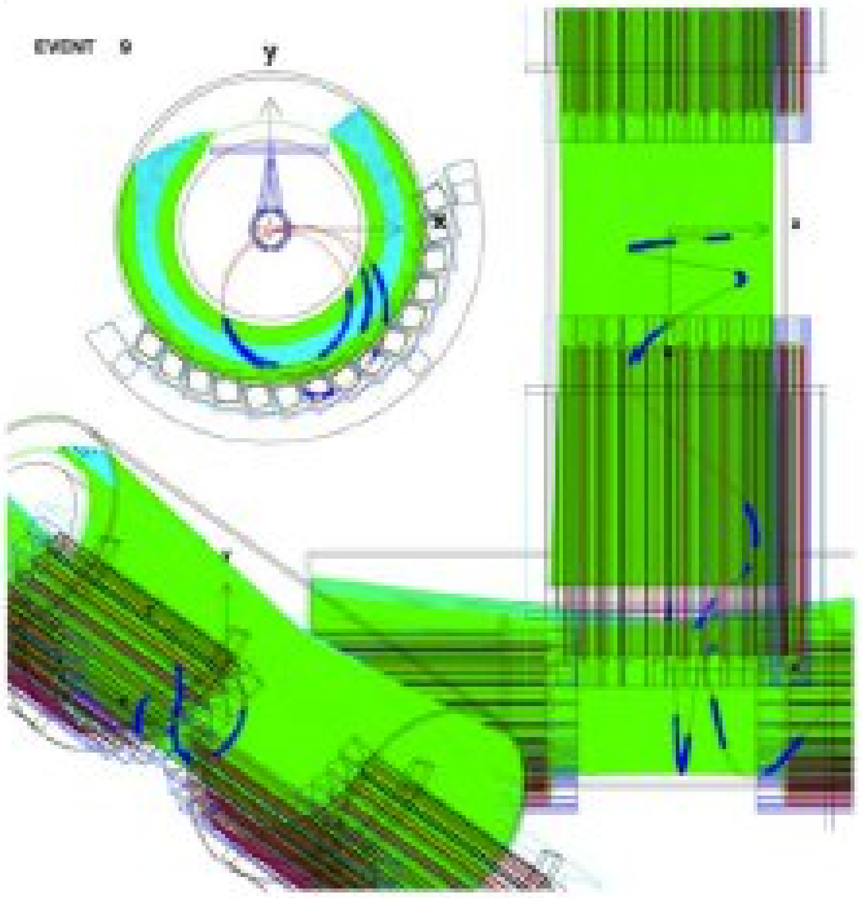
an updated SINDRUM-style design
(currently undergoing simulation studies and optimisation)

COMET Phase-I Timeline

- [2012—] Test beams for calorimeter, tracker prototypes
  - also DAQ vertical slice tests
- [2012—] Civil construction at J-PARC
- [2013—] Superconducting magnet cable production
- **[2014] Campaign at DeeMe (secondary beam experiment at J-PARC 3 GeV hall) for measurements supporting COMET, followed by analysis and publication**
- [2015—] Integration in detector hall
- [2016—] Data-taking

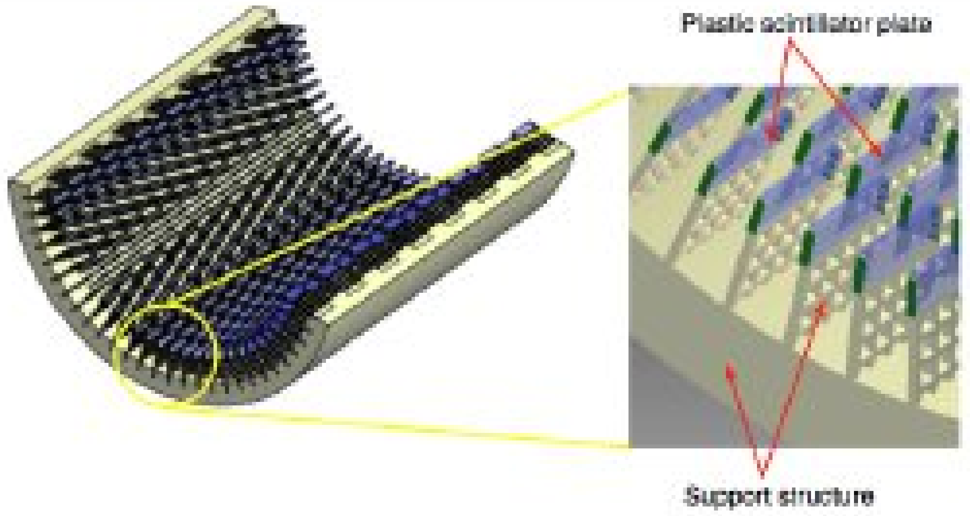
$\mu \to e\gamma$

MEG: upgrade



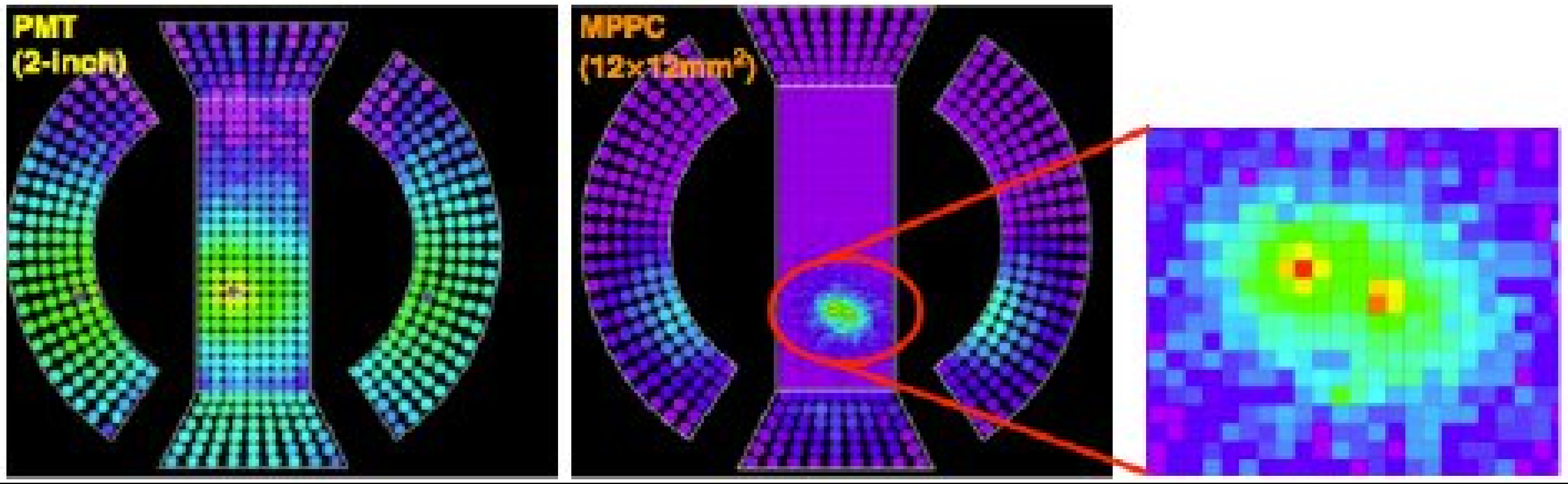
Unique volume tracker

- 3 times more hits
- tracking up to TC
- lower MS



Segmented TC with scintillator bricks and SiPM

- reduced pile up
- multiple hit information



SiPM instead of PMT in inner face

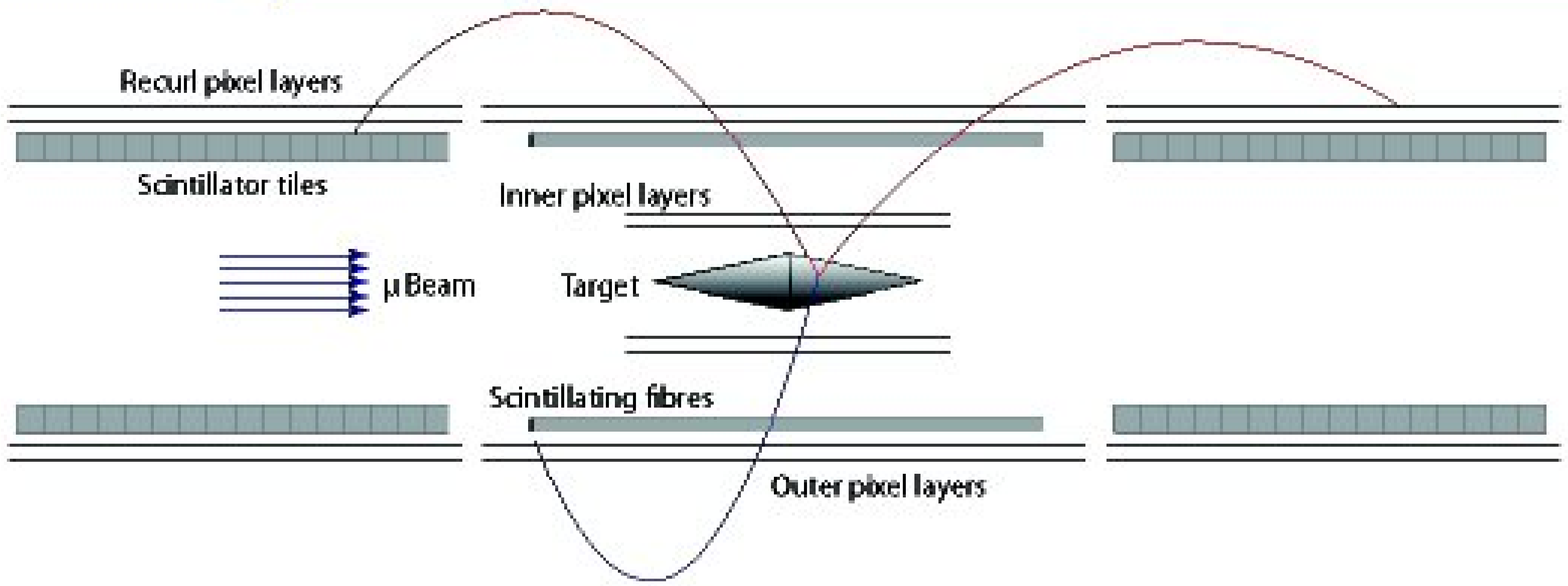
- increased sensitive area
- Better pileup rejection
- Improved photon reconstruction

Goal: sensitivity to BR($\mu \to e\gamma$) ~ 5×10^{-14} after 3 years of data starting in 2015

Longer-term potential for UK

μ→3e

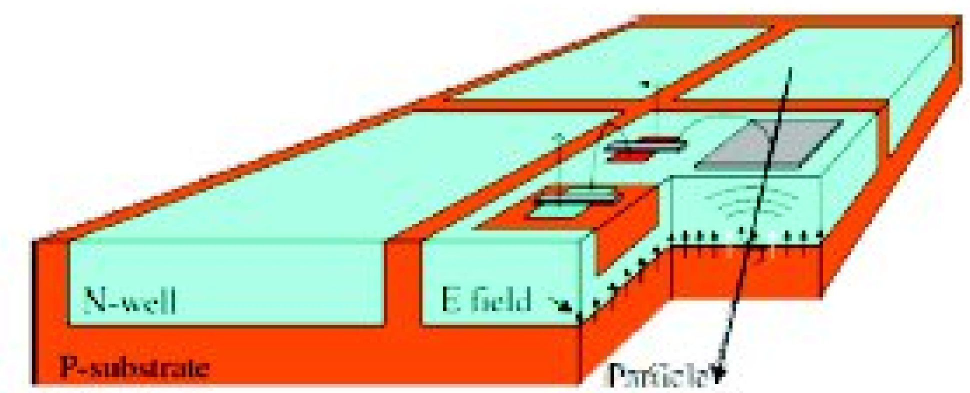
Mu3e detector challenges



Aggressive schedule:
start data taking in 2014

Needs momentum and timing with excellent resolutions

- Tracker with HV-MAPS (275 million of channels)
  - fast 100 ns timing
  - Low Xo (thinned to 50 μm)
  - No cooling (low power constraint)
  - Light support structure
- Timing measurement with scintillating fibers and high resolution hodoscope
  - Fibers for track selection (1 ns resolution)
  - Scintillating tiles (100 ps on on each particle)



HV Monolithic Active Pixel Sensors

Longer-term potential for UK

Collaborations

- SINDRUM II (2000)
  - **12 members**, 3 institutions: Aachen, PSI, Zurich
- Brookhaven $(g-2)_\mu$ Collaboration (2001)
  - **68 members**, 11 institutions: US, JP, RU, DE
- MEG (2009)
  - **69 members**, 13 institutions: IT, JP, CH, US, RU

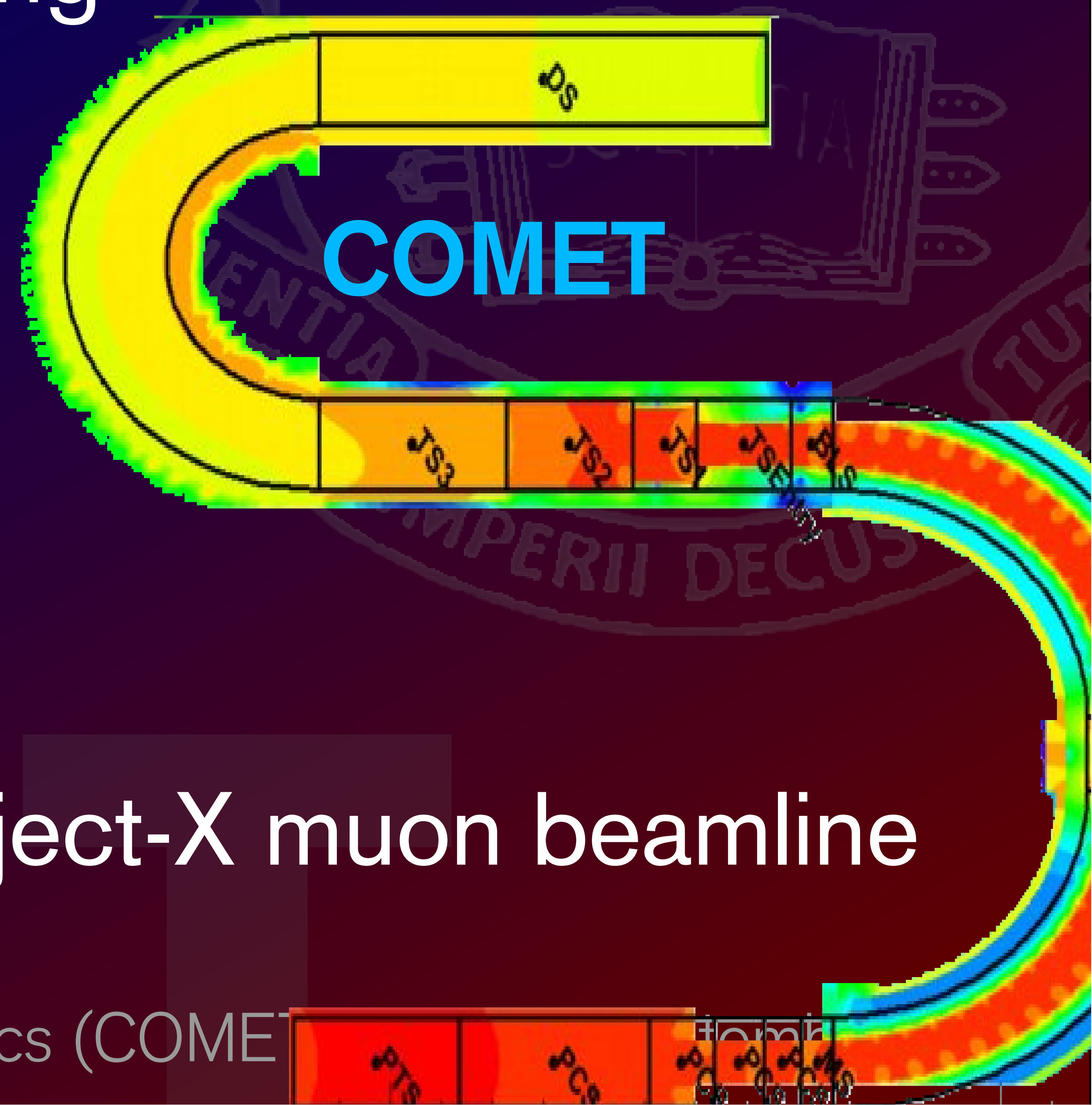
- **MECO** (1999, proposal)
  - **26 members**, 9 institutions: US, RU
- **COMET** (2012—*proto*-collaboration)
  - **109 members**, 23 institutions, JP, RU, UK, GA, CN, DE, CN, VN, MY
- **Mu2E** (2012, CD1)
  - **138 members**, 25 institutions: US, RU, IT

Some Comments

- MEG is the only running μFV experiment, since 2009
  - the previous SINDRUM experiment last took data in 2000
    - $\mu + N \rightarrow e + N$, using very different principles to COMET
- New experiments use larger, custom-built beamlines
  - no-one has actual experience with these
- We can become a leader in this newly-reinvigorated field by participating now
  - as well as leadership in individual projects
  - many UK technical strengths to be utilised
- Internationally, individuals frequently work on multiple projects (e.g. $\mu \rightarrow e + \gamma$ & $\mu + N \rightarrow e + N$,or $(g-2)_\mu$ & $\mu + N \rightarrow e + N$ etc) simultaneously

Current COMET/PRISM Work in the UK

- Active work on leading simulation development, design optimisation of overall experiment, and the Technical Design Report and MUSIC beam studies
- Implementation and testing of realistic solenoidal field maps from manufacturer
- Design studies for an in-situ late-arriving particle monitor detector
- Leading DAQ and Software requirements specification
- High-power proton beam targetry
- Next-generation experiment work
  - PRISM FFAG design / Fermilab Project-X muon beamline



Some Applicable UK Strengths

- Accelerators
  - FFAGs (EMMA, NF)
  - solenoidal channels (MICE)
  - muon beam dynamics / diagnostics (Neutrino Factory, PASI etc)
- Proton beam targetry / high radiation engineering (T2K, NF, Mu2E etc)
- Detectors (tracking, calorimetry, silicon....)
- Software & analysis (expect very intense analysis efforts)
- Electronics and DAQ
- Integration engineering (J-PARC experience with T2K)

COMET / PRISM : UK Status

- Participating in the programme since 2007
  - COMET CDR (2009, obtained Stage-I PAC approval)
  - Phase-I EOI & LOI (2012, approved and in construction)
  - Leadership in several areas within COMET
- SOI submitted to STFC (2012, as “Muon Physics in UK”)
  - “a strategic fit with the STFC Science Roadmap”
- COMET:
  - academic and technical support at **Imperial, Manchester, Oxford and UCL**
  - STFC RAs and PhD students at **Imperial and UCL**
- PRISM:
  - PRISM Task Force exploiting synergies with UK accelerator R&D

Conclusions

- Intense muon physics, especially flavour violation, is highly promising as a probe into Beyond-the-Standard-Model physics, which is complementary to the LHC
- 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, starting with Phase-I in 2016/17
- A positive discovery will be one of the most significant in the history of particle physics, and open up an entire new field of precision cLFV measurements across many channels
  - c.f. neutrinos pre-1980s and now
- Modest UK support now will ensure we stay one of the leaders in the field


Comet
California
CPFC

End of Talk—Spare Slides Follow

τ LV at LHCb

$\tau \to lll$

LHCb

Data sample: 80 mb^{-1} at 7 TeV

7.9 x 10^{10} τ produced

Production channel: $D_s \to \tau\nu$

Analysis strategy:

likelihood analysis on

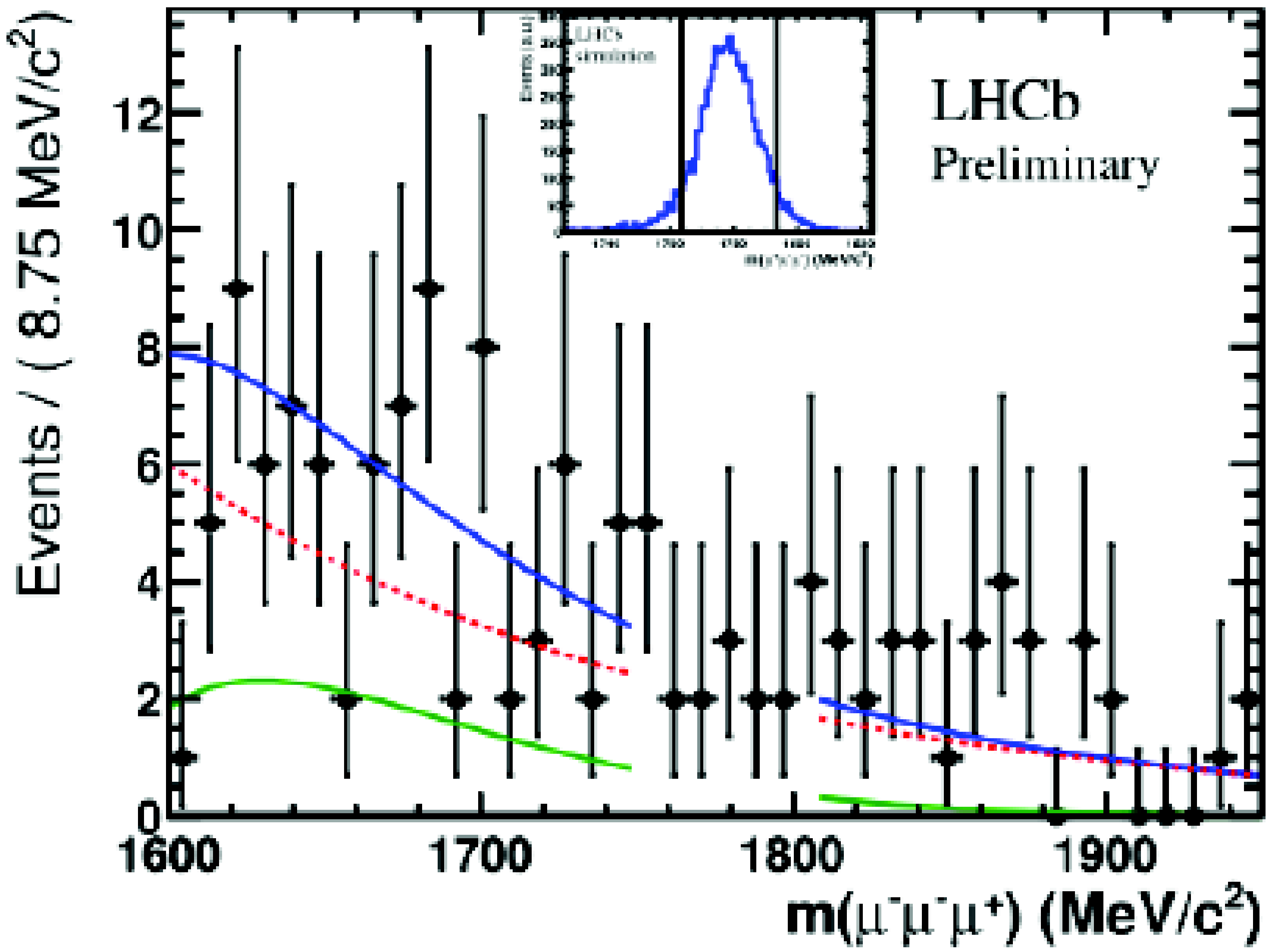
- Invariant mass
- Decay topology
- Particle id

Efficiency on signal: 11%

Result: BR < 6.3 x 10^{-8} (90% C.L.)

Competitive with future B factories !!

Paul Seyfert at NuFact 2012



Background

Red combinatorial

Green $D_s^+ \to \eta(\mu^-\mu^+\gamma)\mu^+\nu_\mu$

Blue total

Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic
atom

$E_e \leq 105\mathrm{MeV}$

Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic
atom

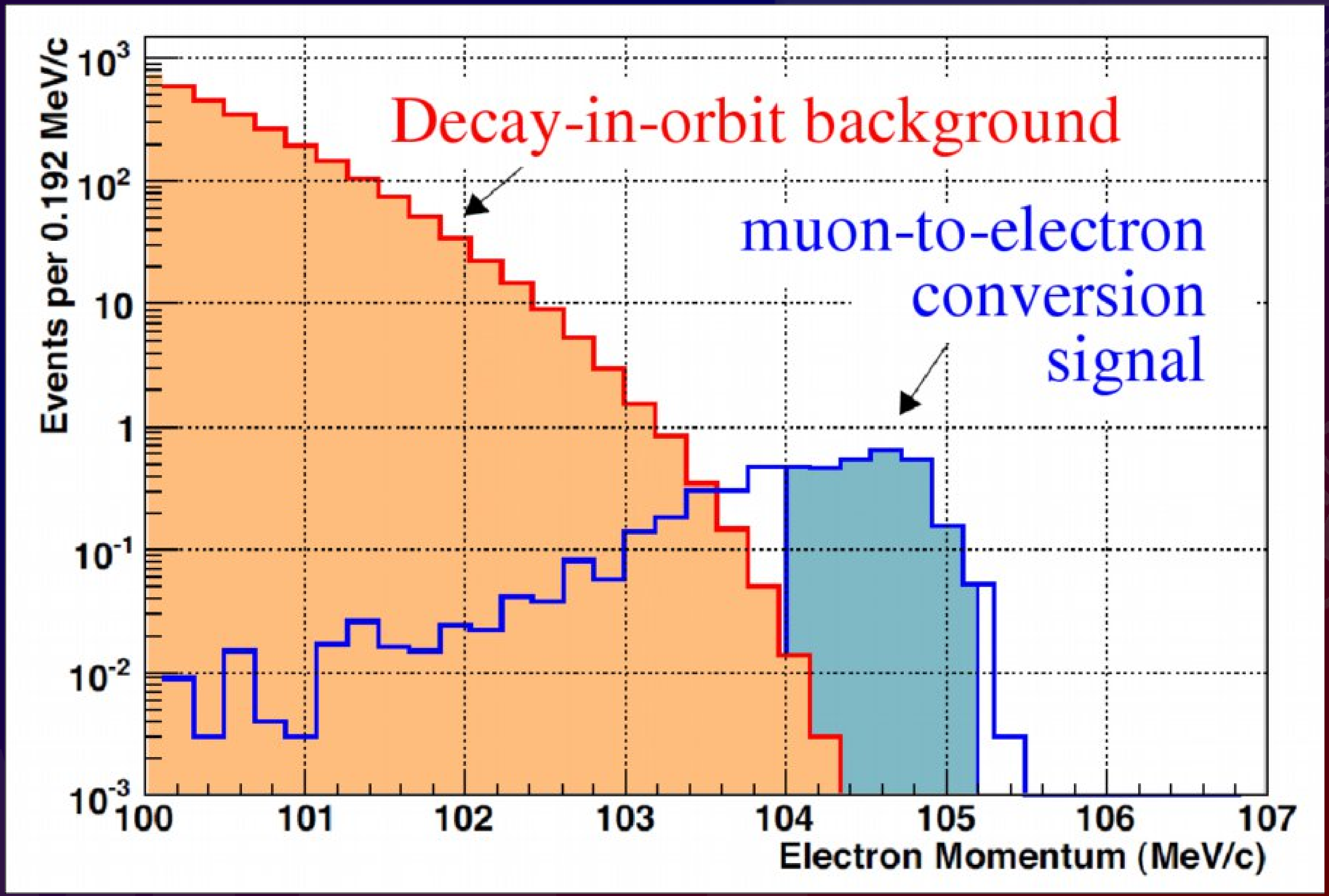
$E_e \leq 105\mathrm{MeV}$

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

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

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)

- μ2e and **COMET** aim to improve sensitivity by ×**10,000**
- **PRISM** extends this to a factor of **1,000,000**

Muon Flavour Conversion Channels

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

Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic atom

$E_e \leq 105\text{MeV}$

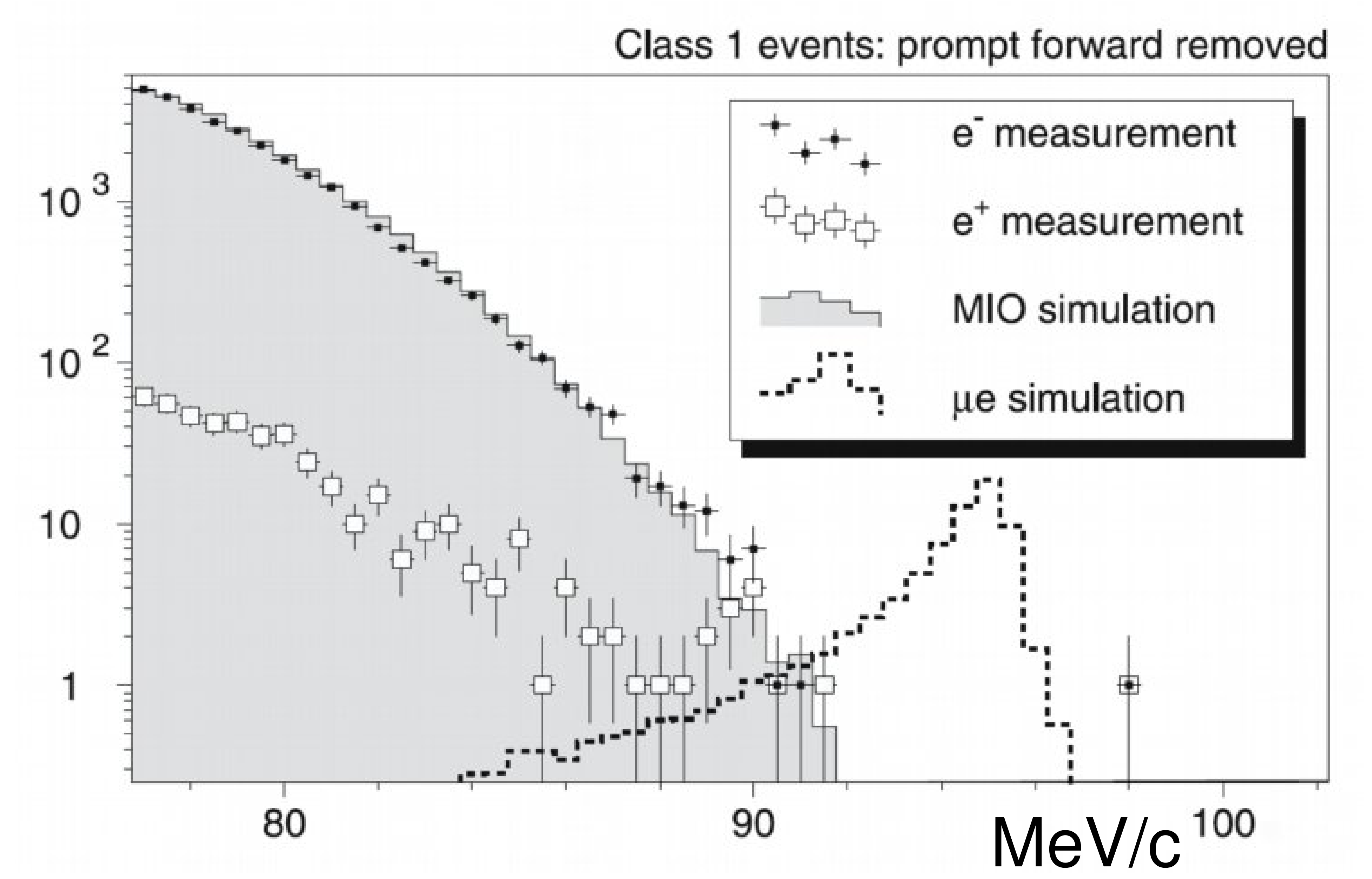
- The present limit is about

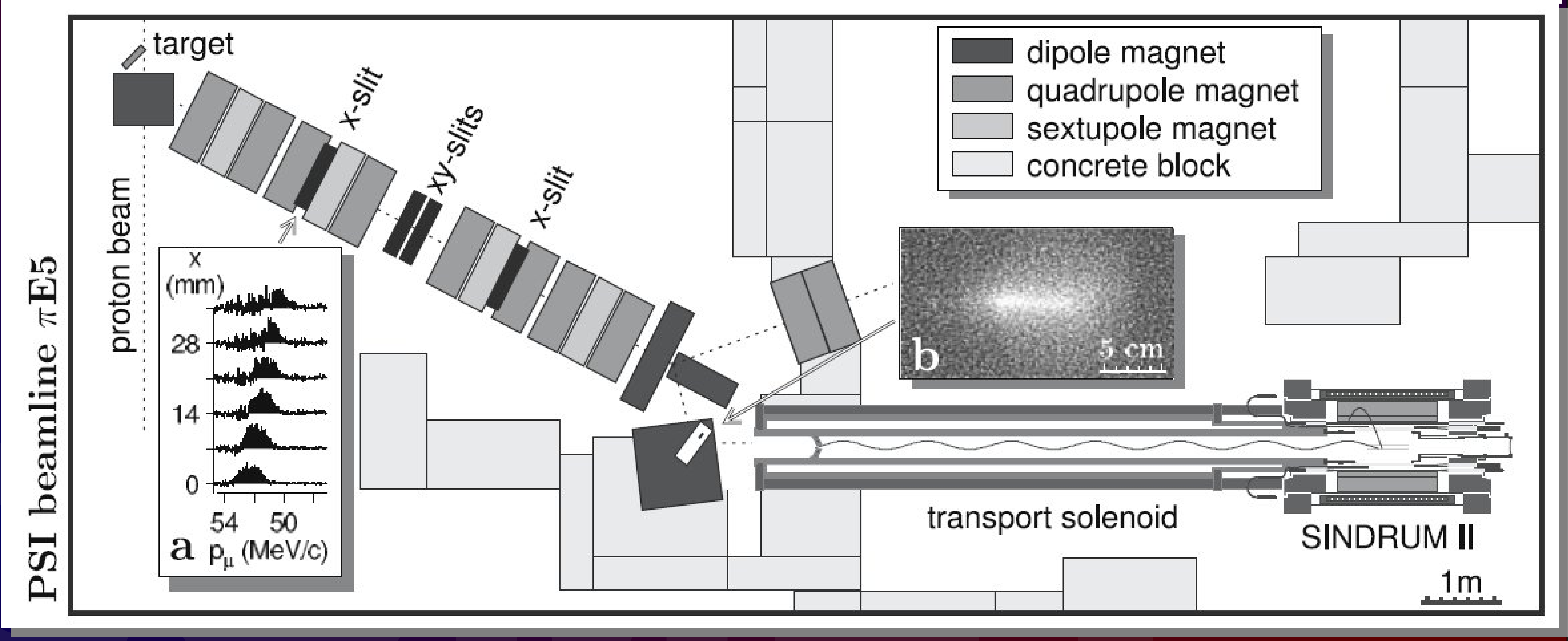
$$< 7 \times 10^{-13}$$

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

SINDRUM II at PSI

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





Coherent Muon-to-Electron Conversion

- Muon-to-Electron Conversion

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

muonic atom

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

- 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}

Design Considerations

Background Event Categories

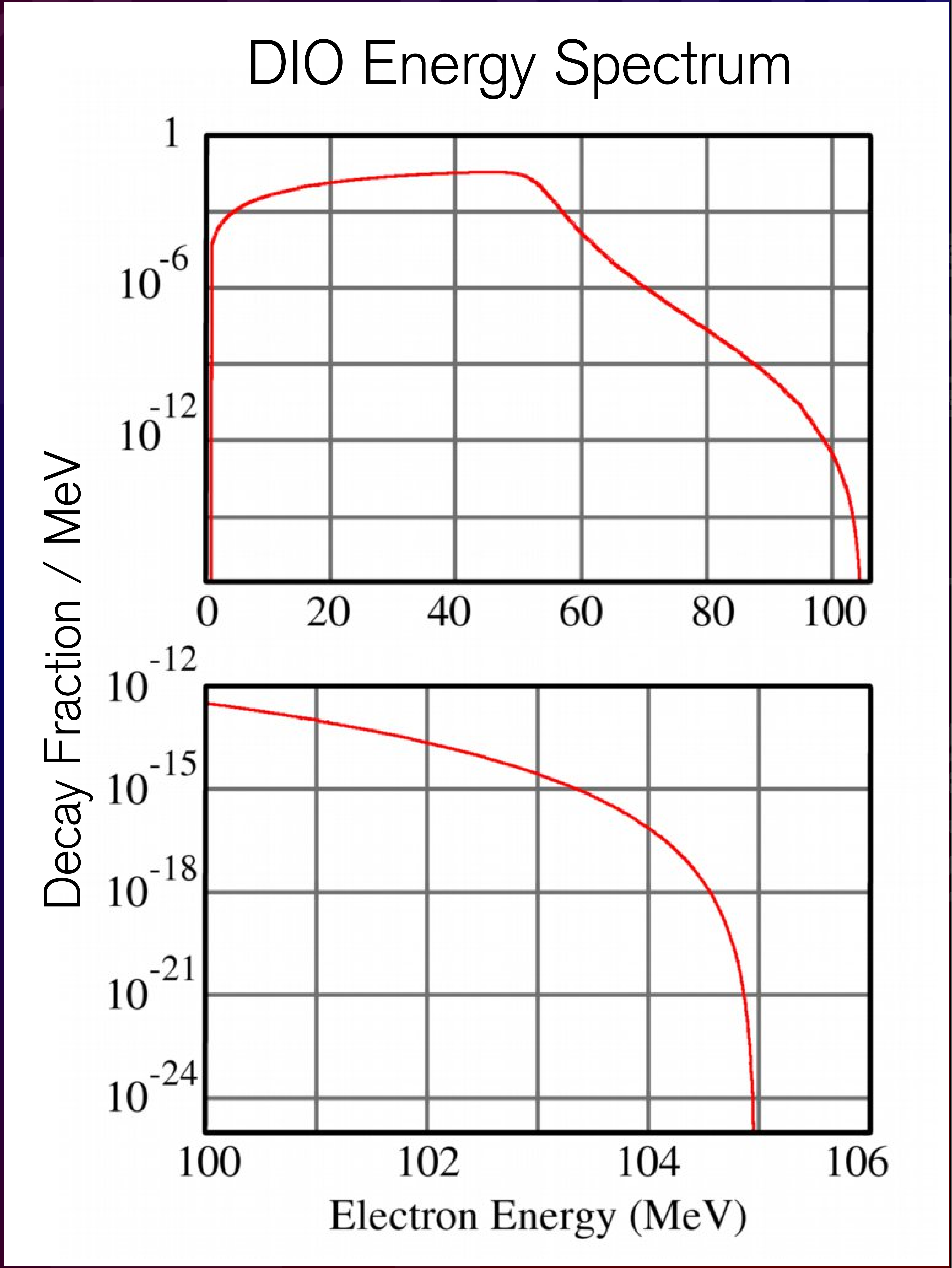
- Intrinsic physics backgrounds
  - electrons from muons stopped in the target
- Beam-related prompt backgrounds
  - due to protons which arrive outside of their beam buckets
- Beam-related delayed backgrounds
  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

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

- 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

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

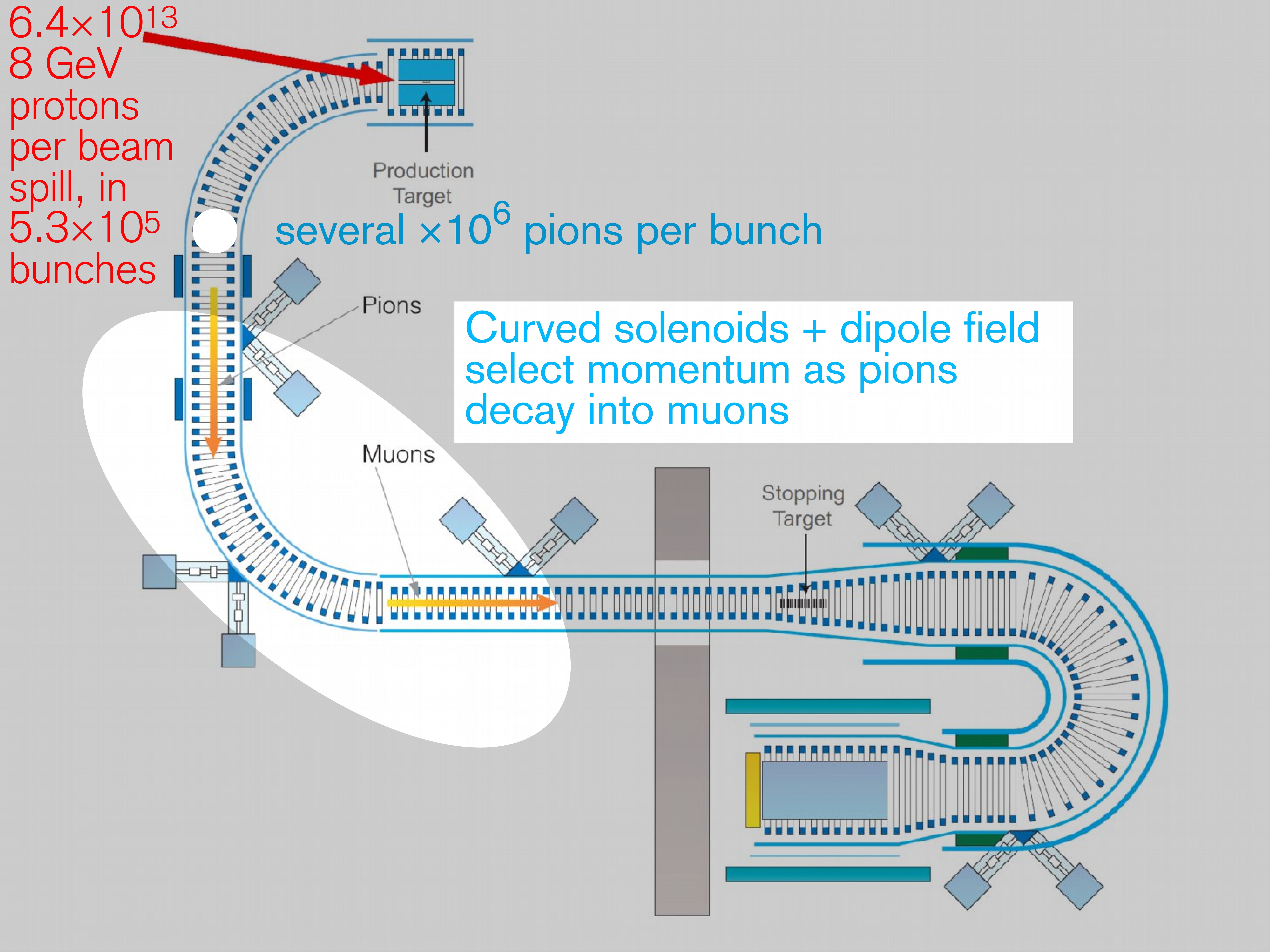
Backgrounds Strategy

- 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



6.4×10¹³ 8 GeV protons per beam spill, in 5.3×10⁵ bunches
Production Target
several ×10⁶ pions per bunch
Pions
Curved solenoids + dipole field select momentum as pions decay into muons
Muons
Stopping Target

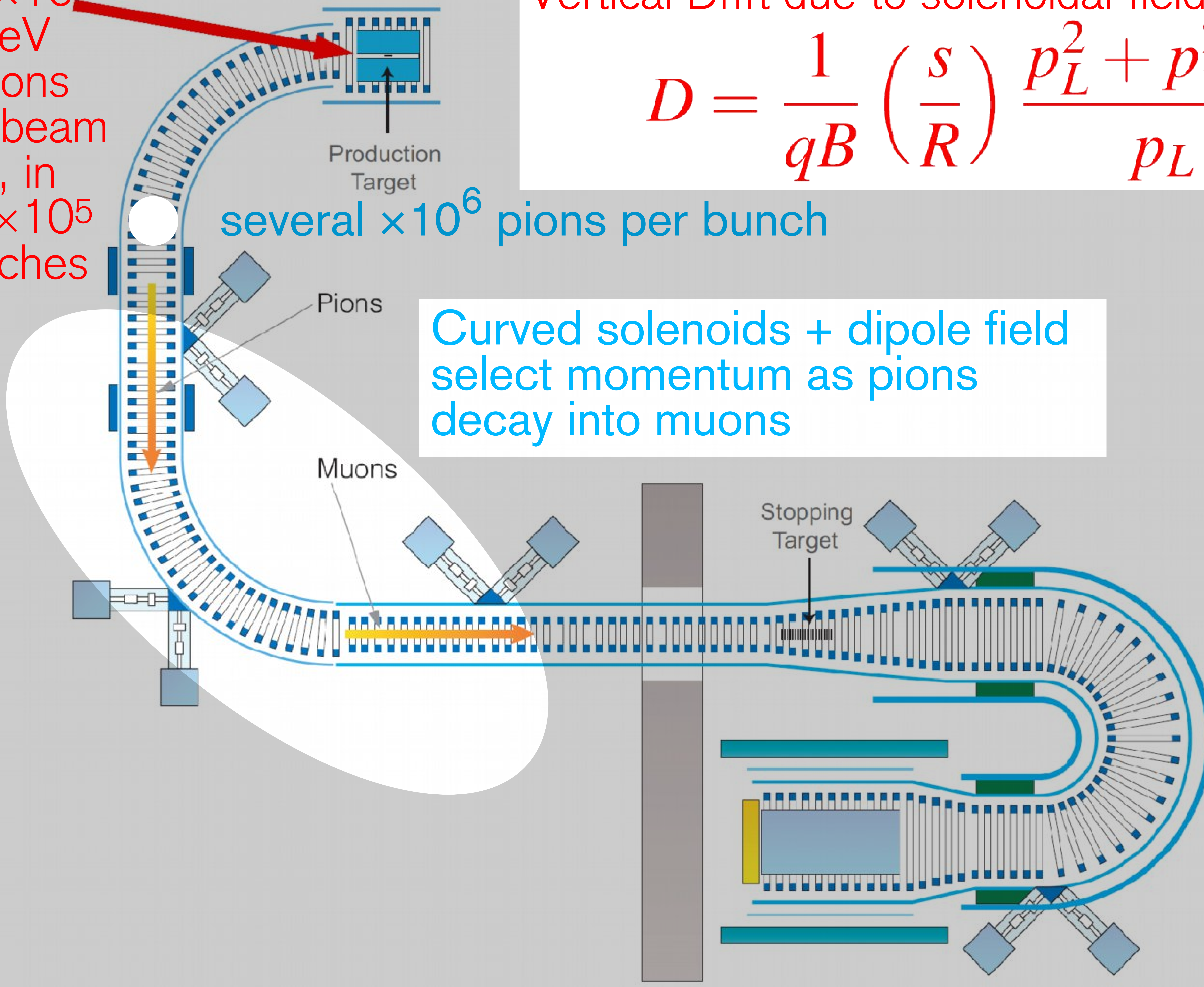
6.4×10^13 8 GeV protons per beam spill, in 5.3×10^5 bunches

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 ×10^6 pions per bunch

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

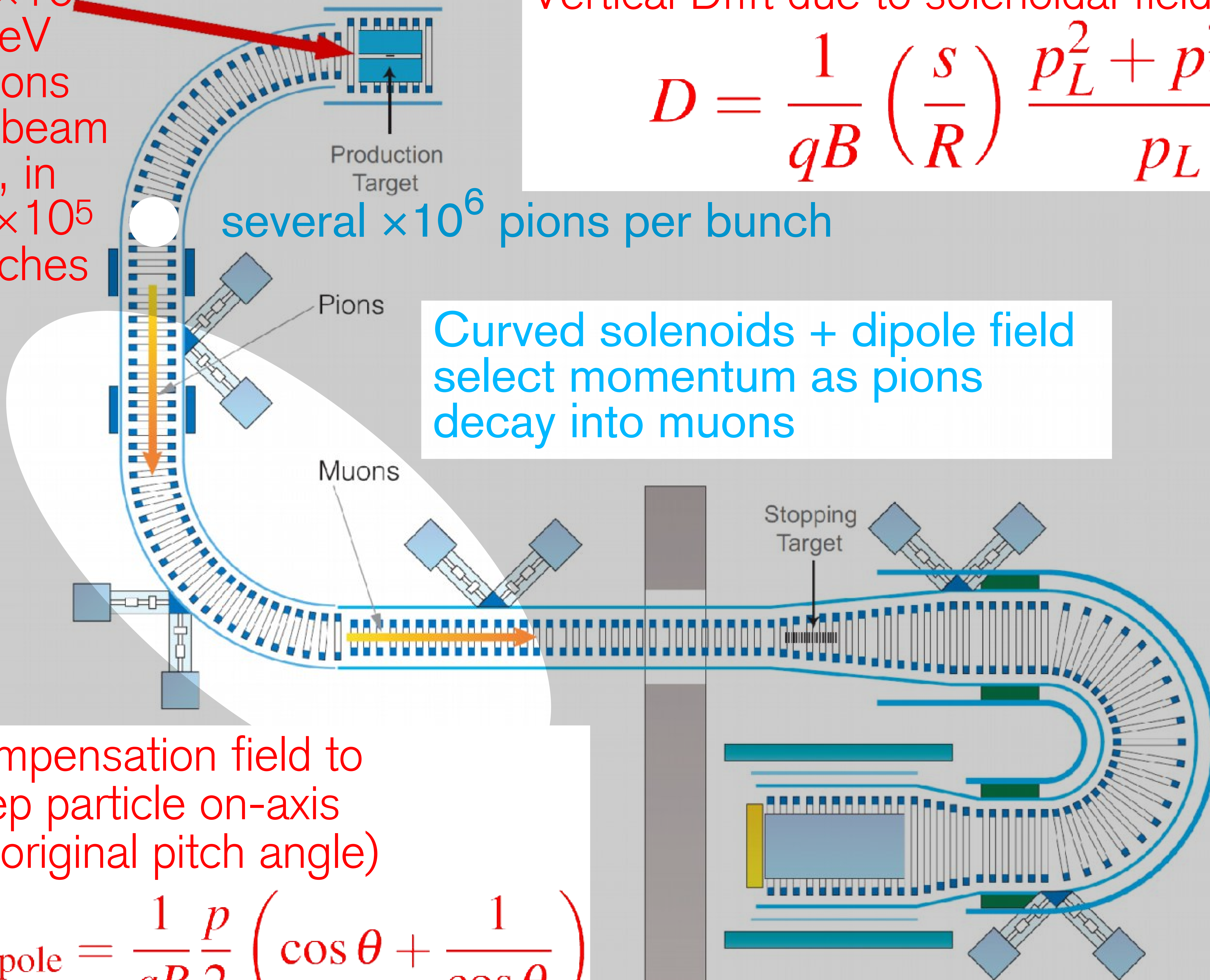


6.4×10^{13} 8 GeV protons per beam spill, in 5.3×10^{5} bunches

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 $\times10^{6}$ pions per bunch



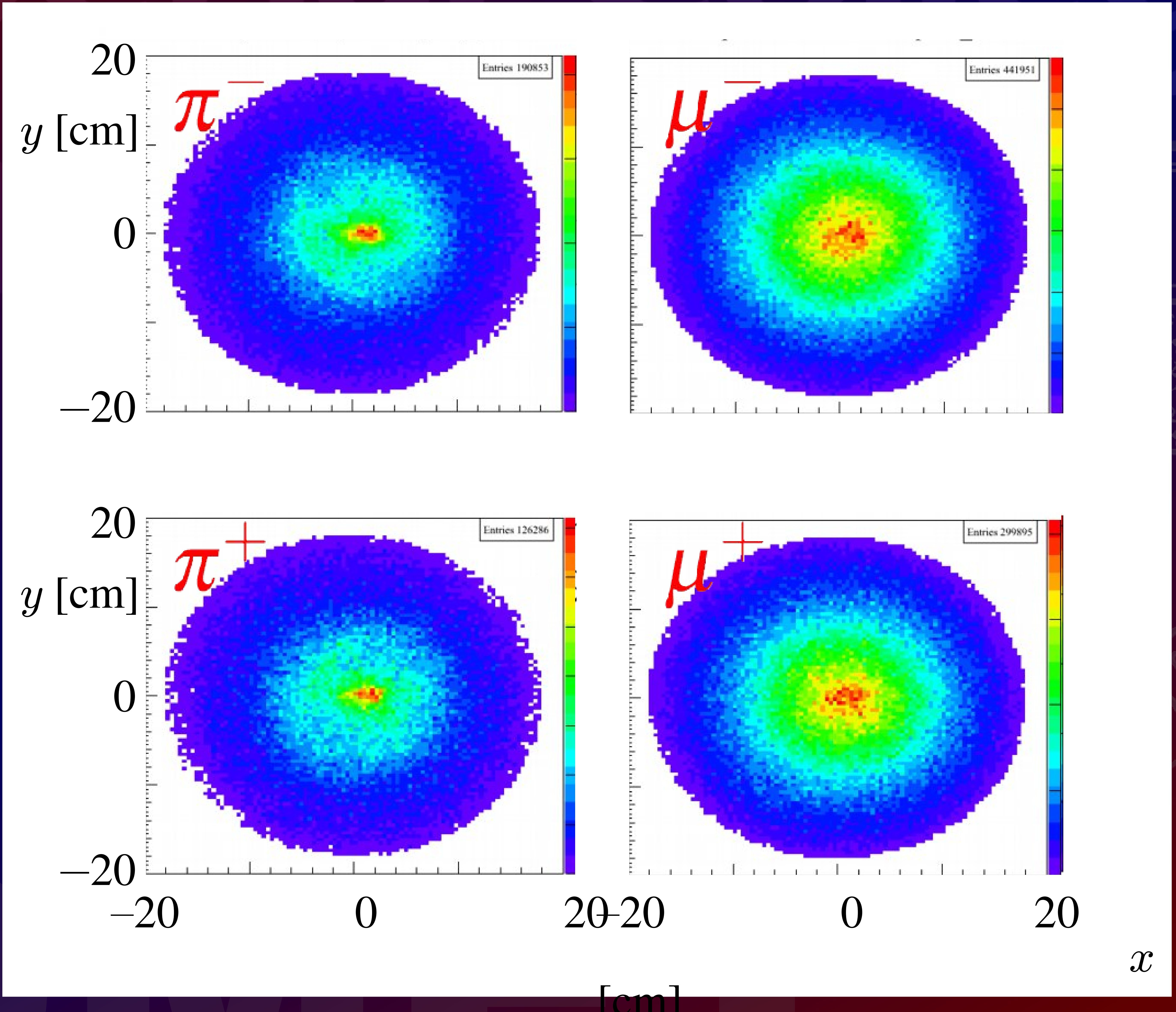
Curved solenoids + dipole field select momentum as pions decay into muons

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



The COMET / PRISM Programme

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

J. Pasternak, Imperial College London, UK/RAL STFC, UK
L. J. Jenner, A. Kurup, Imperial College London, UK/Fermilab, USA
Y. Uchida, Imperial College London, UK
B. Muratori, S. L. Smith, Cockcroft Institute, Warrington, UK/STFC-DL-ASTeC, Warrington, UK
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

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 $\mu \rightarrow e+\gamma$, $\mu \rightarrow 3e$, and $\mu^- + p \rightarrow e^- + p$, 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

New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \rightarrow e^+\gamma$

J. Adam,[1,2] X. Bai,[3] A. M. Baldini,[4a] E. Baracchini,[5] C. Bemporad,[4a,4b] G. Boca,[6a,6b] P. W. Cattaneo,[6a] G. Cavoto,[7] F. Cei,[4a,4b] C. Cerri,[4a] A. de Bari,[6a,6b] M. De Gerone,[8a,8b] T. Doke,[9] S. Dussoni,[8a,8b] J. Egger,[1] K. Fratini,[8a,8b] Y. Fujii,[3] L. Galli,[4a,4b] G. Gallucci,[4a,4b] F. Gatti,[8a,8b] B. Golden,[5] M. Grassi,[4a] D. N. Grigoriev,[10] T. Haruyama,[11] M. Hildebrandt,[1] Y. Hisamatsu,[3] F. Ignatov,[10] T. Iwamoto,[3] P.-R. Kettle,[1] B. I. Khazin,[10] O. Kiselev,[1] A. Korenchenko,[12] N. Kravchuk,[12] A. Maki,[11] S. Mihara,[11] W. Molzon,[5] T. Mori,[3] D. Mzavia,[12,*] H. Natori,[3,1] D. Nicolò,[4a,4b] H. Nishiguchi,[11] Y. Nishimura,[3,†] W. Ootani,[3] M. Panareo,[13a,13b] A. Papa,[1] R. Pazzi,[4a,4b,*] G. Piredda,[7] A. Popov,[10] F. Renga,[7,1] S. Ritt,[1] M. Rossella,[6a] R. Sawada,[3] F. Sergiampietri,[4a] G. Signorelli,[4a] S. Suzuki,[9] F. Tenchini,[4a,4b] C. Topchyan,[5] Y. Uchiyama,[3,1] R. Valle,[8a,8b,‡] C. Voena,[7] F. Xiao,[5] S. Yamada,[11] A. Yamamoto,[11] S. Yamashita,[3] Yu. V. Yudin,[10] and D. Zanello[7]

(MEG Collaboration)

We present a new result based on an analysis of the data collected by the MEG detector at the Paul Scherrer Institut in 2009 and 2010, in search of the lepton-flavor-violating decay $\mu^+ \rightarrow e^+\gamma$. The likelihood analysis of the combined data sample, which corresponds to a total of 1.8×10^{14} muon decays, gives a 90% C.L. upper limit of 2.4×10^{-12} on the branching ratio of the $\mu^+ \rightarrow e^+\gamma$ decay, constituting the most stringent limit on the existence of this decay to date.

DOI: 10.1103/PhysRevLett.107.171801 PACS numbers: 13.35.Bv, 11.30.Hv, 12.10.Dm, 12.60.Jv

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.

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.

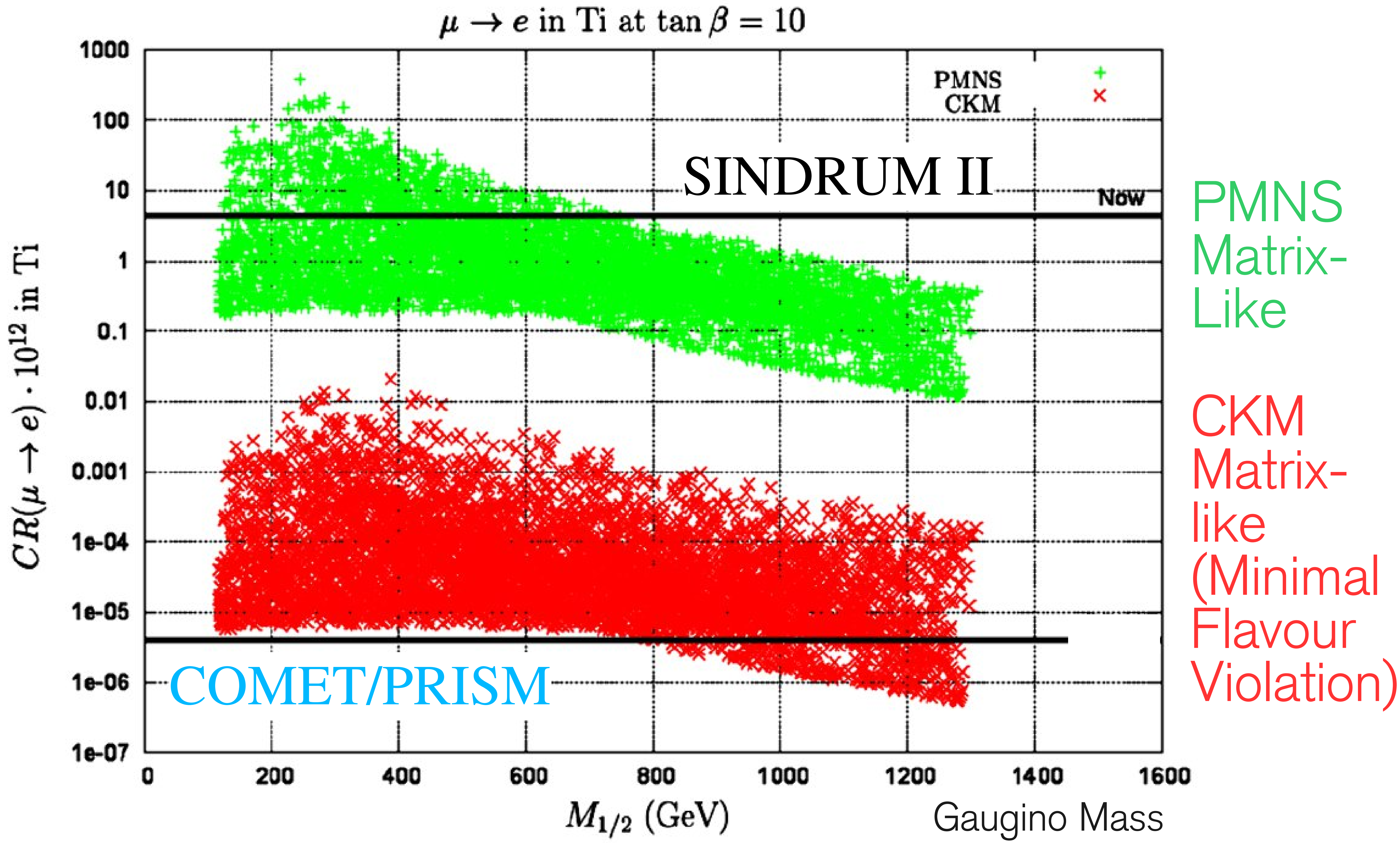
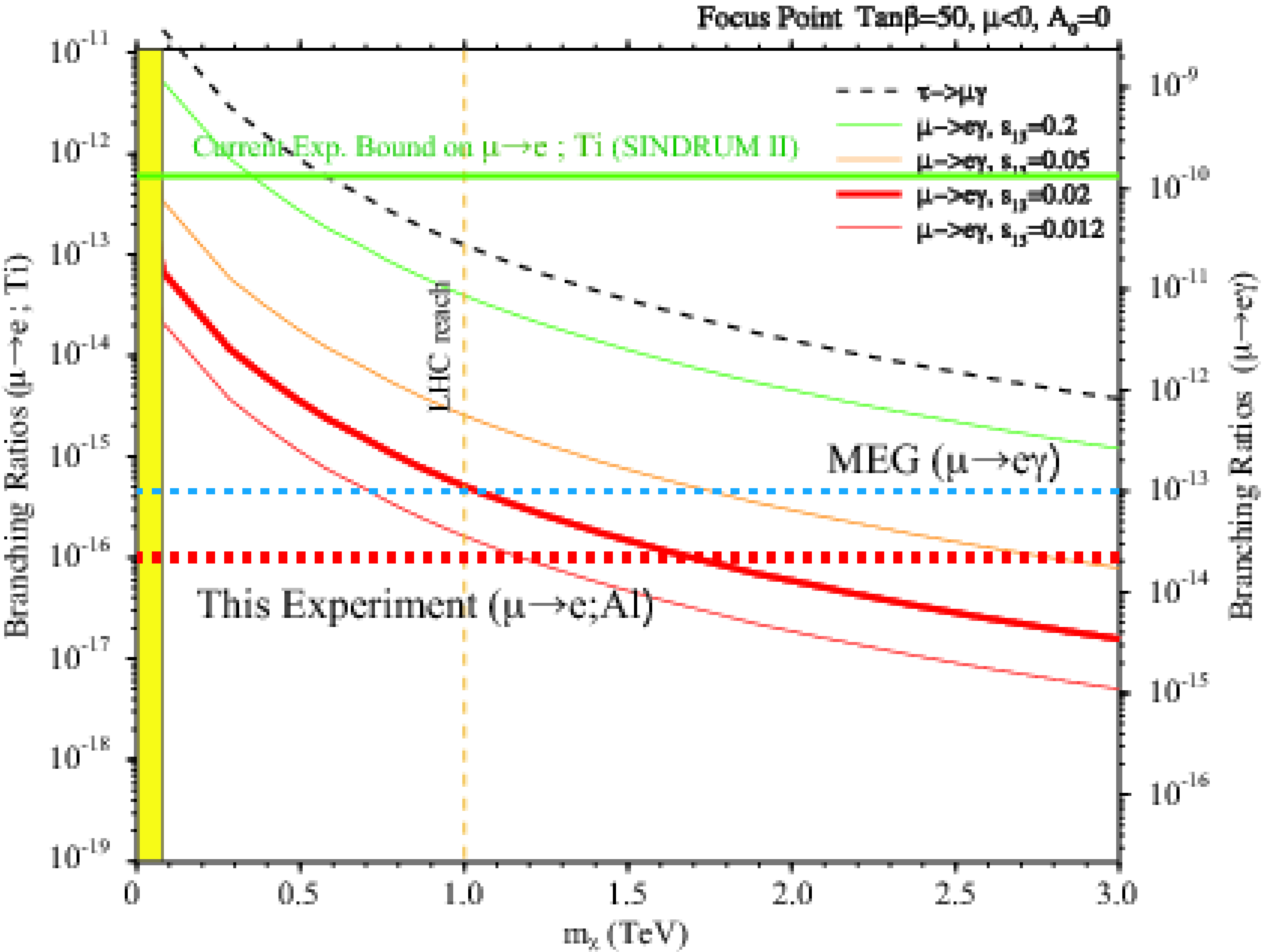


FIG. 12 $\mu \to e$ in Ti as a probe of SUSY-GUT scenarios. The plots are obtained by scanning the LHC accessible parameter space. The horizontal lines are the present (SINDRUM II) bound and the planned (PRISM/PRIME) sensitivity to the process. We see that PRIME would be able to severely constrain the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

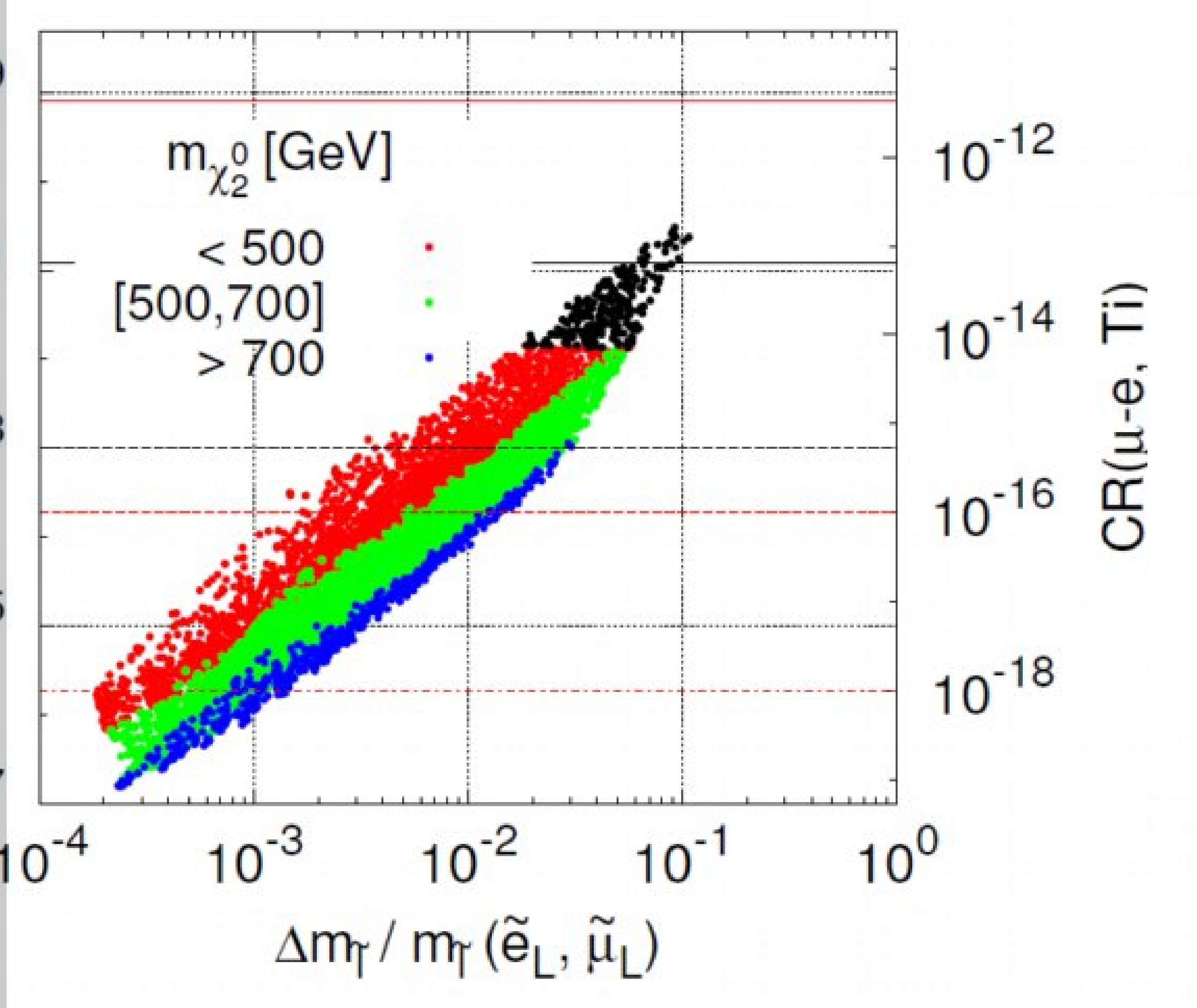


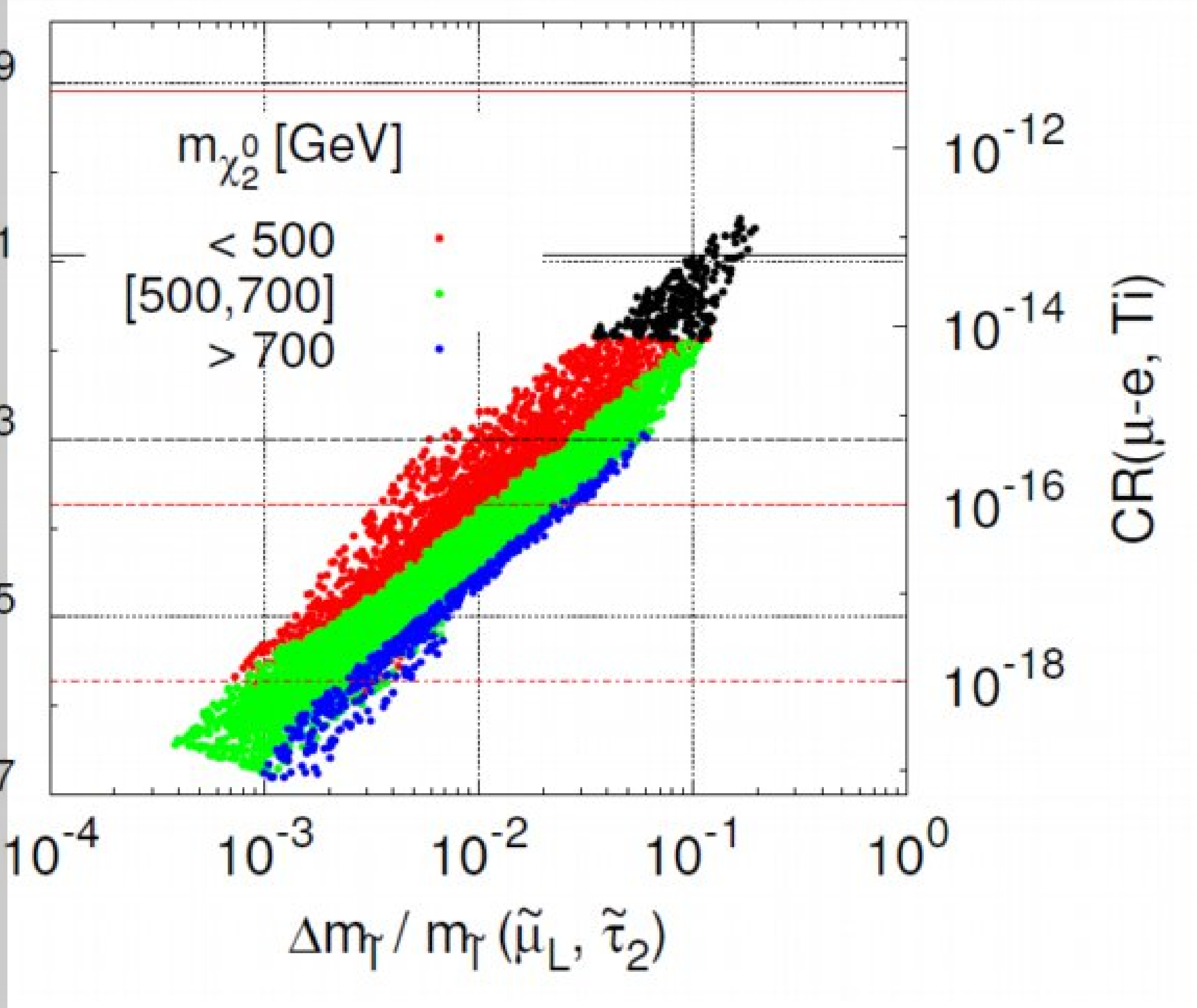
JHEP 1010:104,2010

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

Kaustubh Agashe,[1] Andrew E. Blechman,[2] and Frank Petriello[3]

[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 $l \rightarrow l'\gamma$ 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 $\mu \rightarrow e\gamma$ 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

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

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

Kaustubh Agashe,[1] Andrew E. Blechman,[2] and Frank Petriello[3]

[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 $l \rightarrow l'\gamma$ 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 $\mu \rightarrow e\gamma$ 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

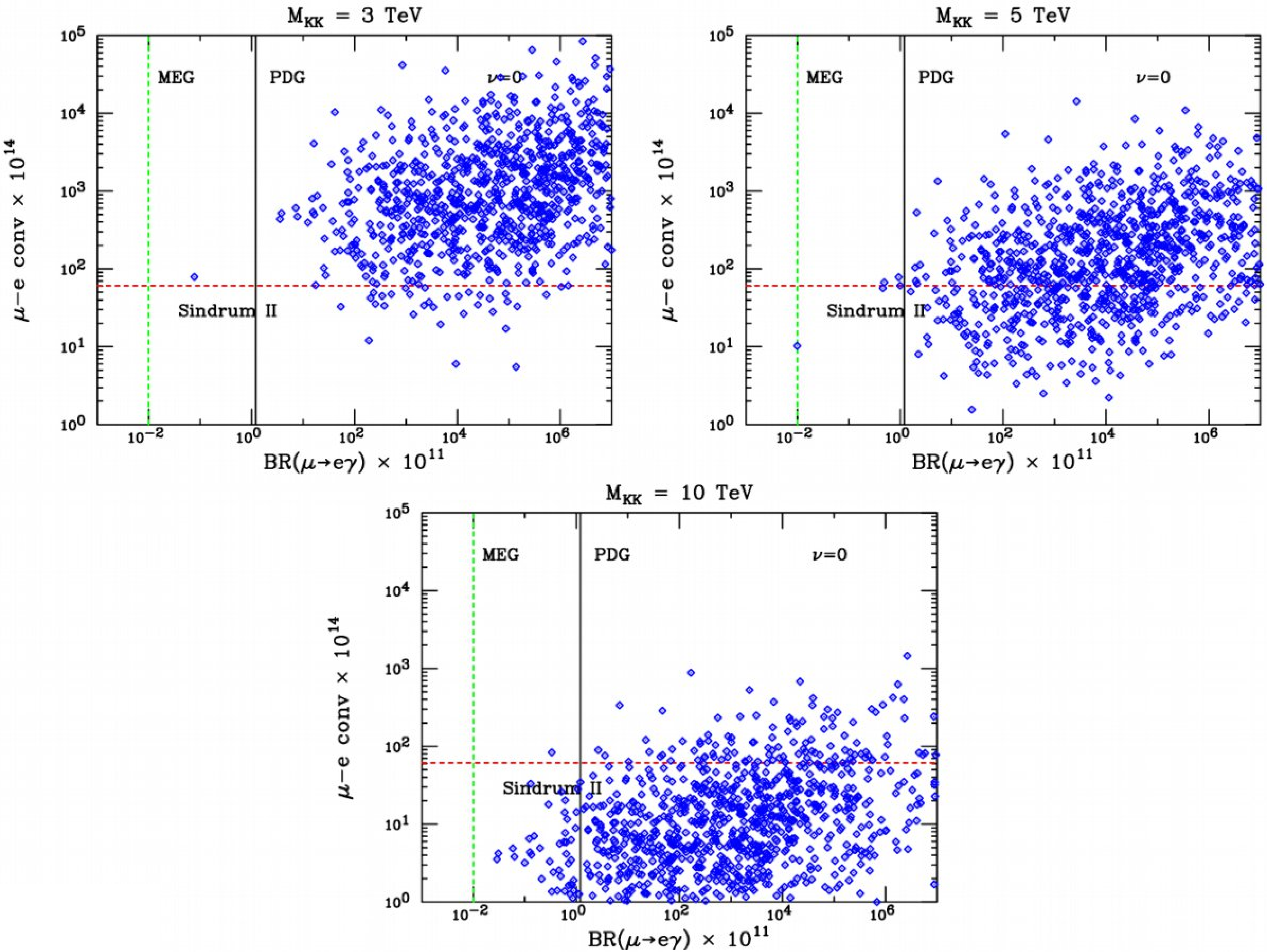


FIG. 6 Scan of the $\mu \to e\gamma$ and $\mu - e$ conversion predictions for $M_{\mathrm{KK}} = 3, 5, 10$ TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \to e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to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

JHEP

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]

[a] *Physik Department, Technische Universität München D-85748 Garching, Germany*

[b] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut) D-80805 München, Germany*

E-mail: mblanke@ph.tum.de, aburas@ph.tum.de, bduling@ph.tum.de, aposchen@ph.tum.de, ctaranti@ph.tum.de

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.

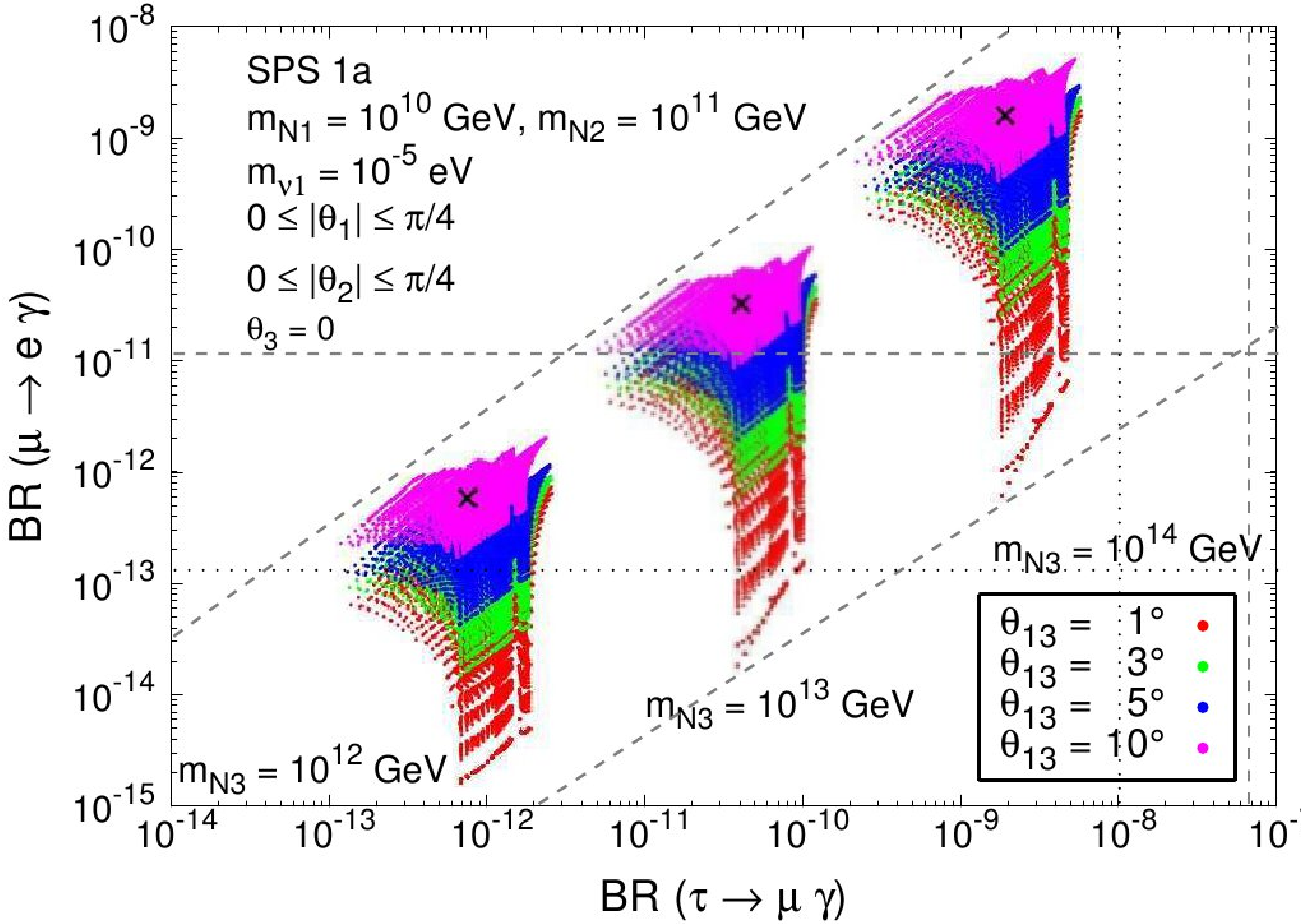
Charged lepton flavour violation and $(g-2)_\mu$ in the Littlest Higgs model with T-Parity: a clear distinction from Supersymmetry

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

[a] *Physik Department, Technische Universität München*
D-85748 Garching, Germany
[b] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)*
D-80805 München, Germany
E-mail: mblanke@ph.tum.de, aburas@ph.tum.de, bduling@ph.tum.de, aposchen@ph.tum.de, ctaranti@ph.tum.de

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

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

"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

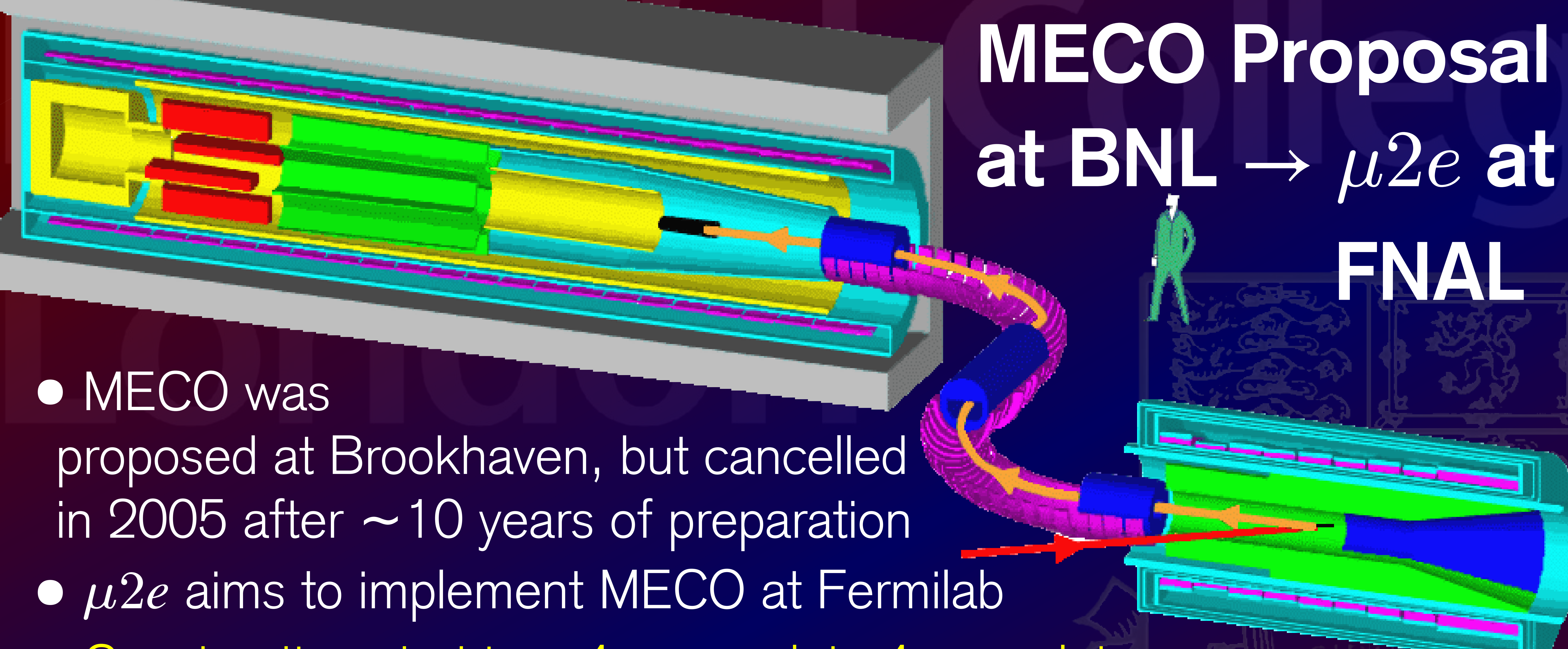
"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

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

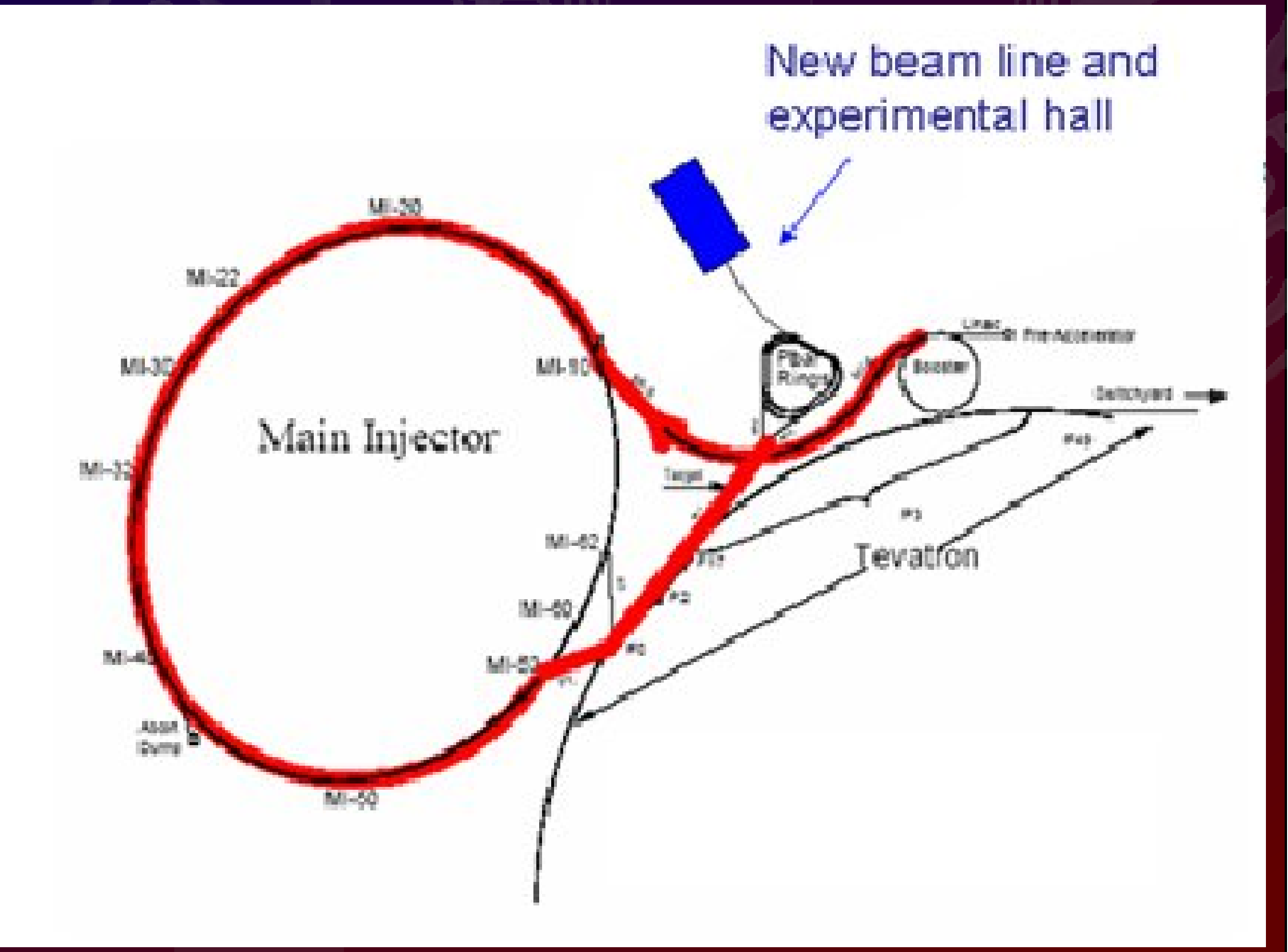
W. Altmannshofer et al. / Nuclear Physics B 830 (2010) 17–94

MELC / MECO / $\mu 2e$

MECO Proposal at BNL → $\mu 2e$ at FNAL



- MECO was proposed at Brookhaven, but cancelled in 2005 after ~10 years of preparation
- $\mu 2e$ aims to implement MECO at Fermilab
- Construction start in ~4 years, data 4 years later
- $\mu 2e$ and COMET* share basic principles, but some significant design differences
  - muon sign/momentum selection through collimation ("S-shaped" solenoid)
  - no sign/momentum selection after stopping target

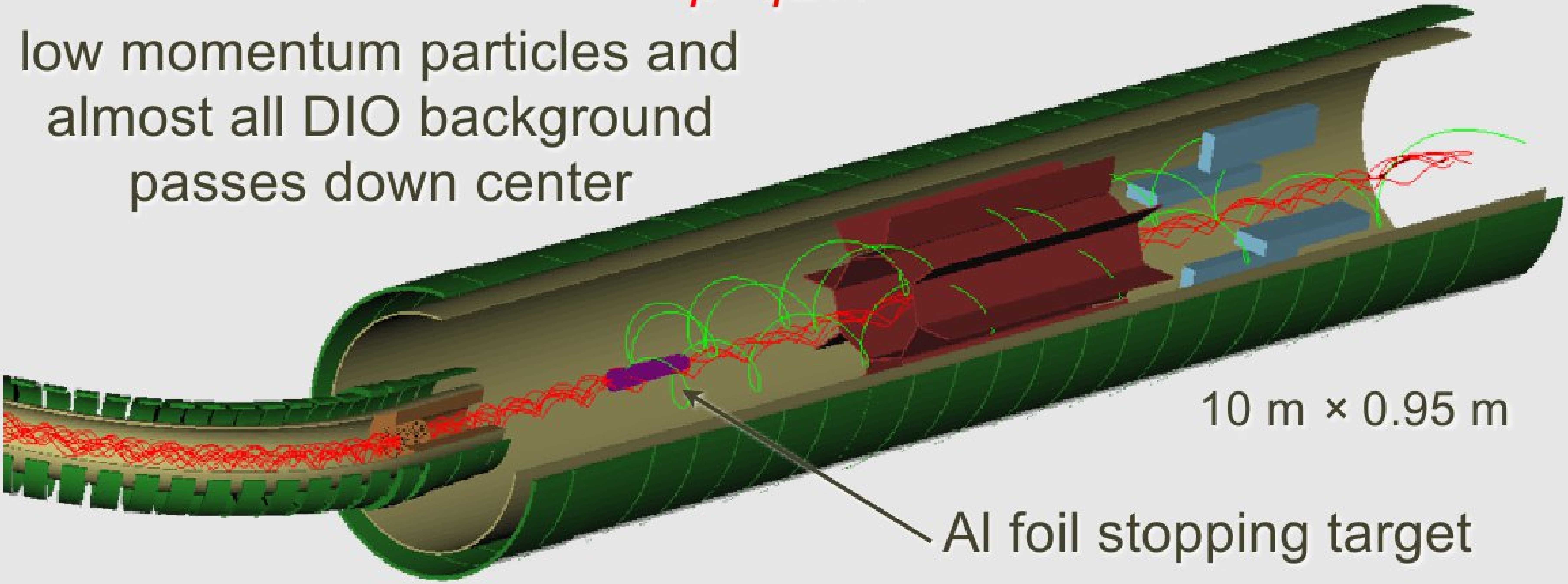


*MOU signed in 2009

Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center



10 m × 0.95 m

Al foil stopping target

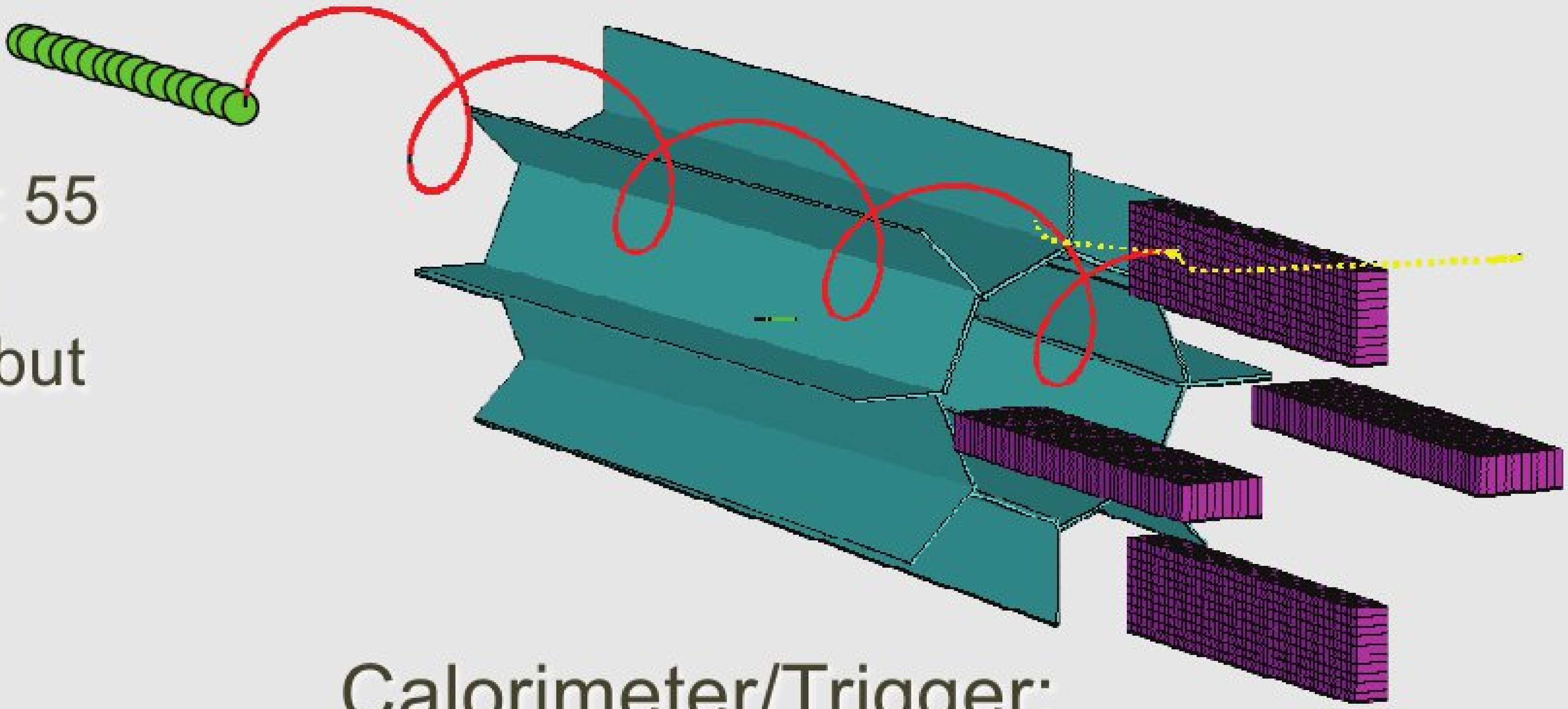
signal events pass *through* octagon of tracker and produce hits

Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center
- Followed by Calorimeter

$\sigma = 200\ \mu$ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick



Calorimeter/Trigger:

σ/E = 5%, 1024 3.5 × 3.5 × 12 cm $PbWO_4$

- Of the Imperial HEP programme, muon physics offers a unique combination of hardware, software, analysis and phenomenology that will help shape future cutting-edge particle physics experiments
- The broad range of topics and nature of the work provides extra flexibility for students to find the perfect contributions to their training and PhD study
- This will lead to highly diverse training as a PhD studentship, an authorship on an impressive range of refereed papers
- We work with several smaller groups of highly committed physicists, who have been extremely welcoming to young colleagues — (arguably) leading to greater research impact, juicier research topics, and less large-collaboration distractions
- The Imperial group is in a position to provide top-quality guidance and support

Next Generation Muon-to-Electron Conversion Experiments

- Brief historical background
- Theoretical implications
- The next-generation
  - making the most of modern high-power beams
- COMET and Mu2E
- Signal and Backgrounds
- Technologies
- The COMET/PRISM Programme

Lepton Flavour Conversion and COMET/PRISM

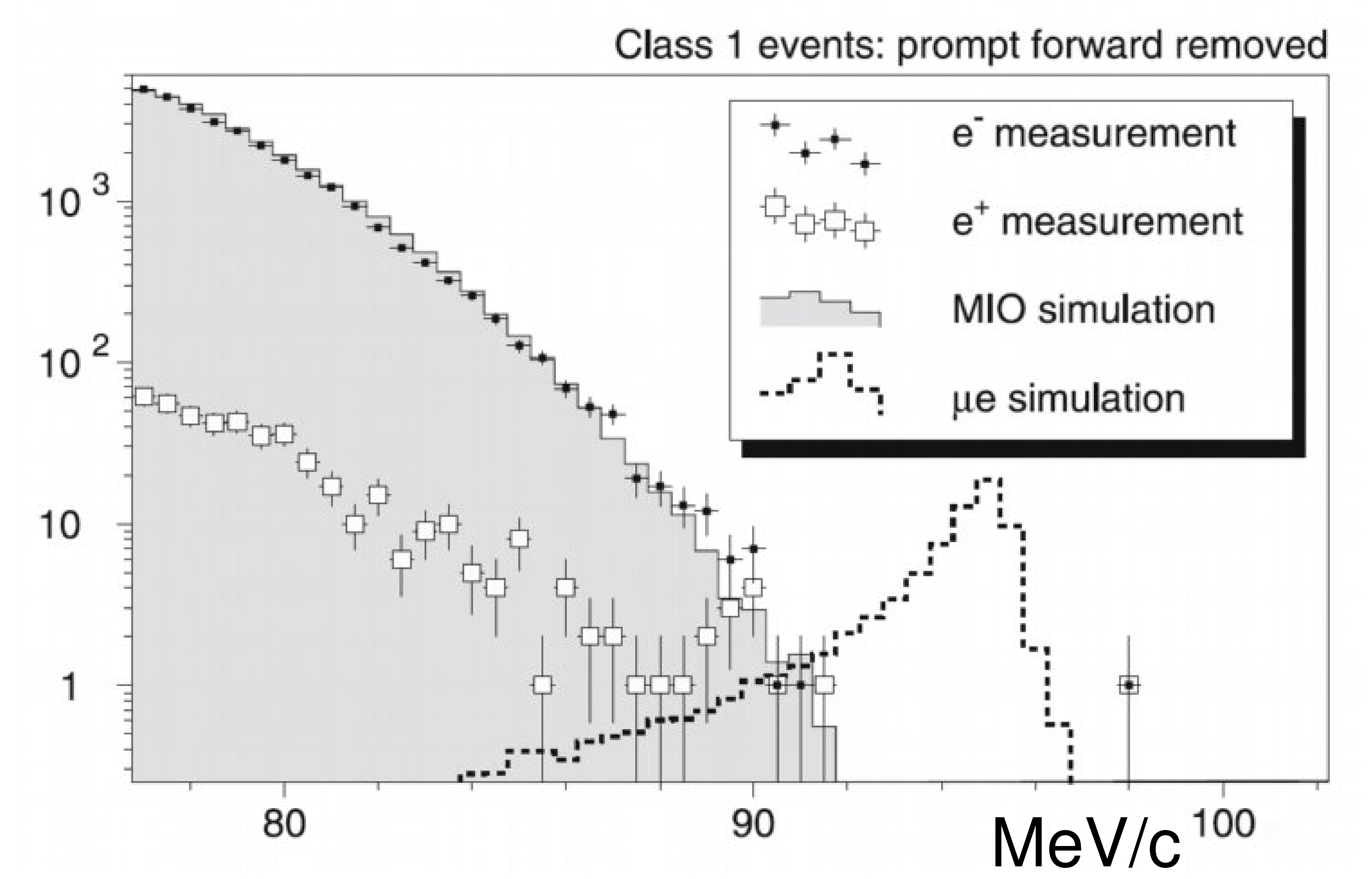
Sussex University

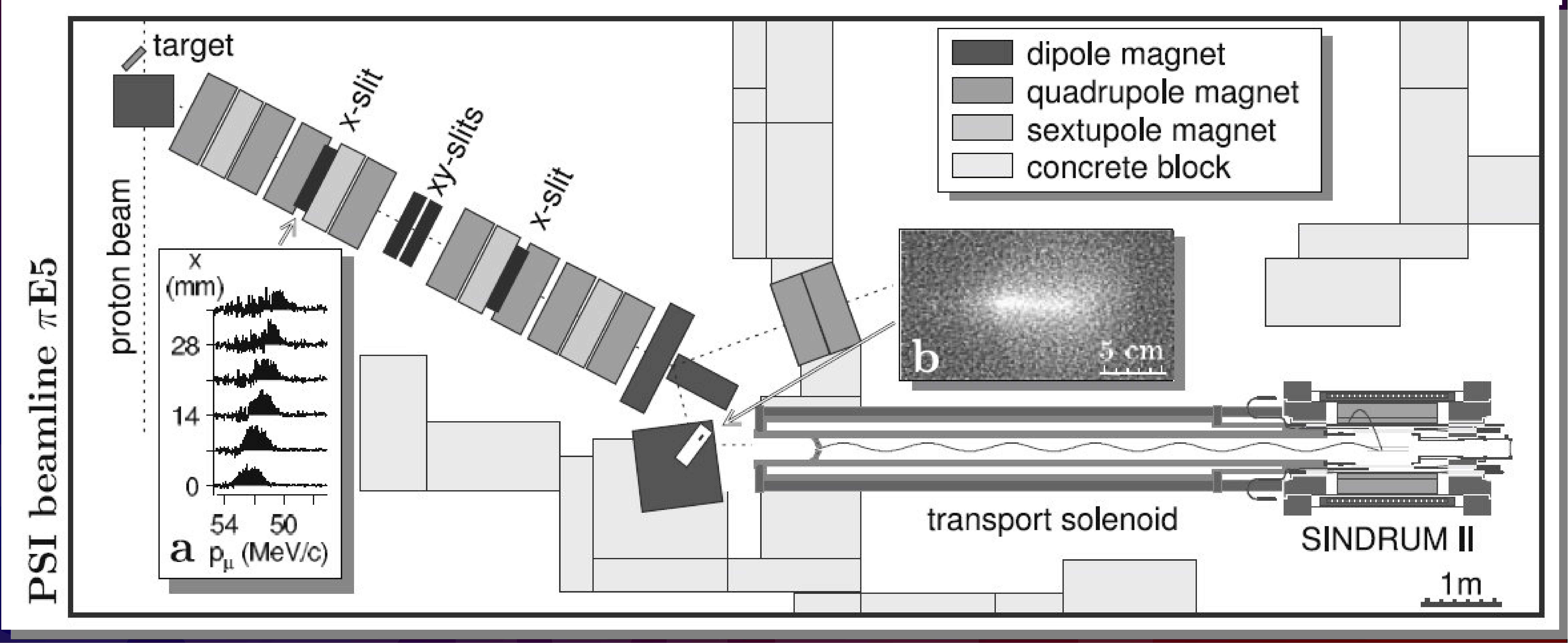
11 November 2010

Yoshi Uchida

SINDRUM II at PSI

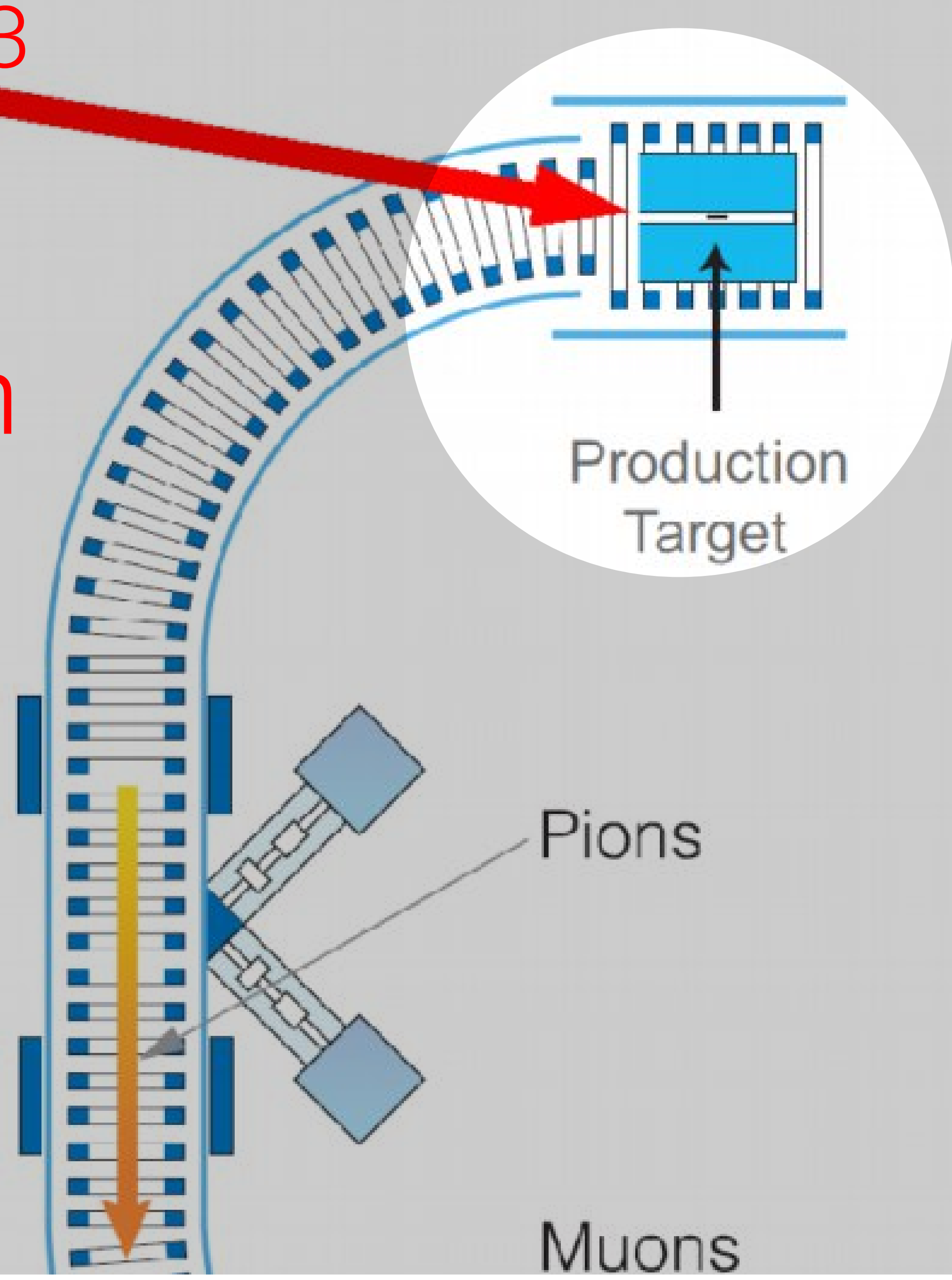
- $10^7 - 10^8\ \mu$/sec
- Effectively a "one-by-one" measurement
- Total rate limited by beam veto counter

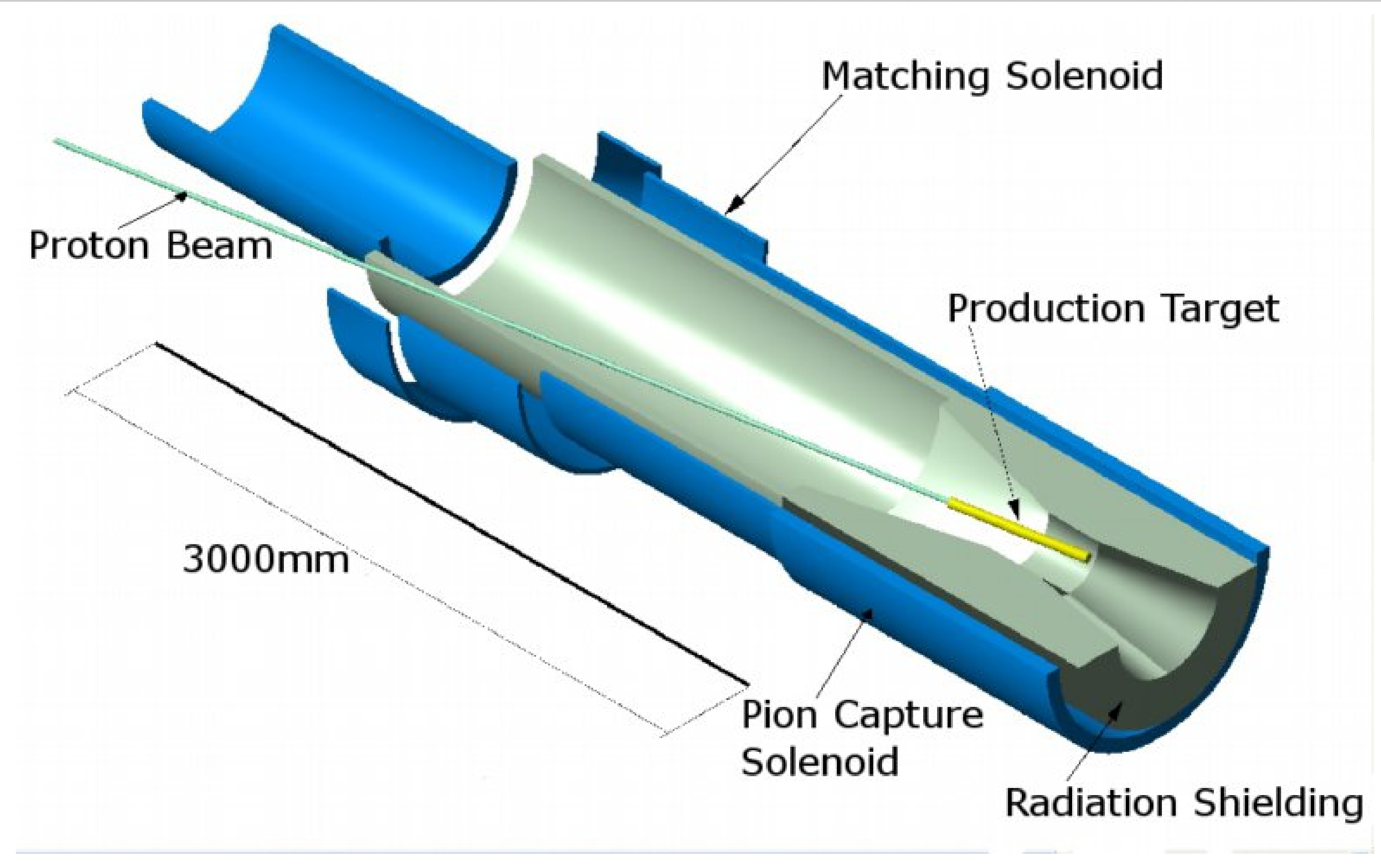




COMET

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





Heavy metal (W, Au, Pt....) target

5 Tesla superconducting pion capture solenoid

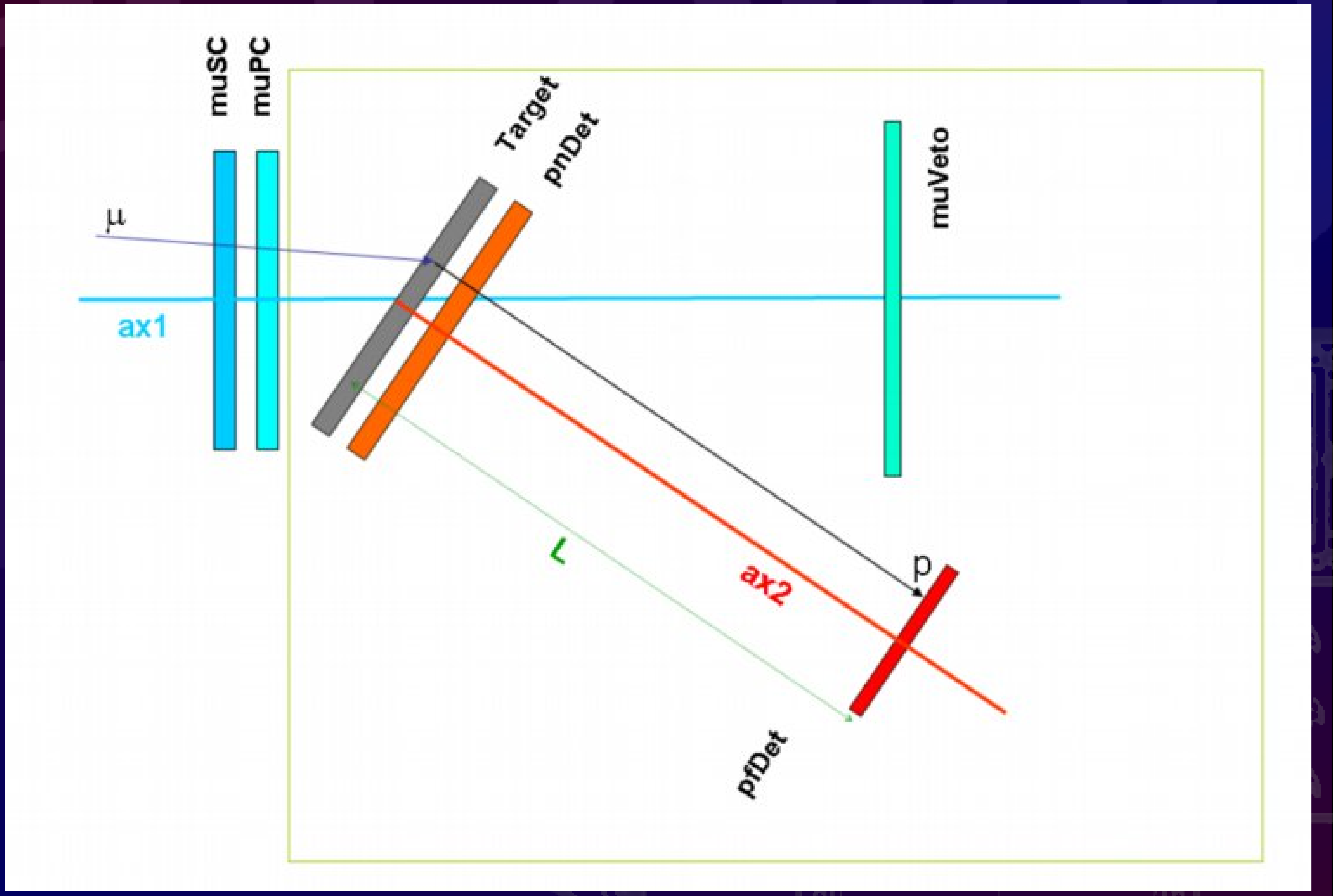
R&D for Aluminium-stabilised superconducting coils ongoing (Manufactured by Hitachi, winding at Fermilab)

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^-

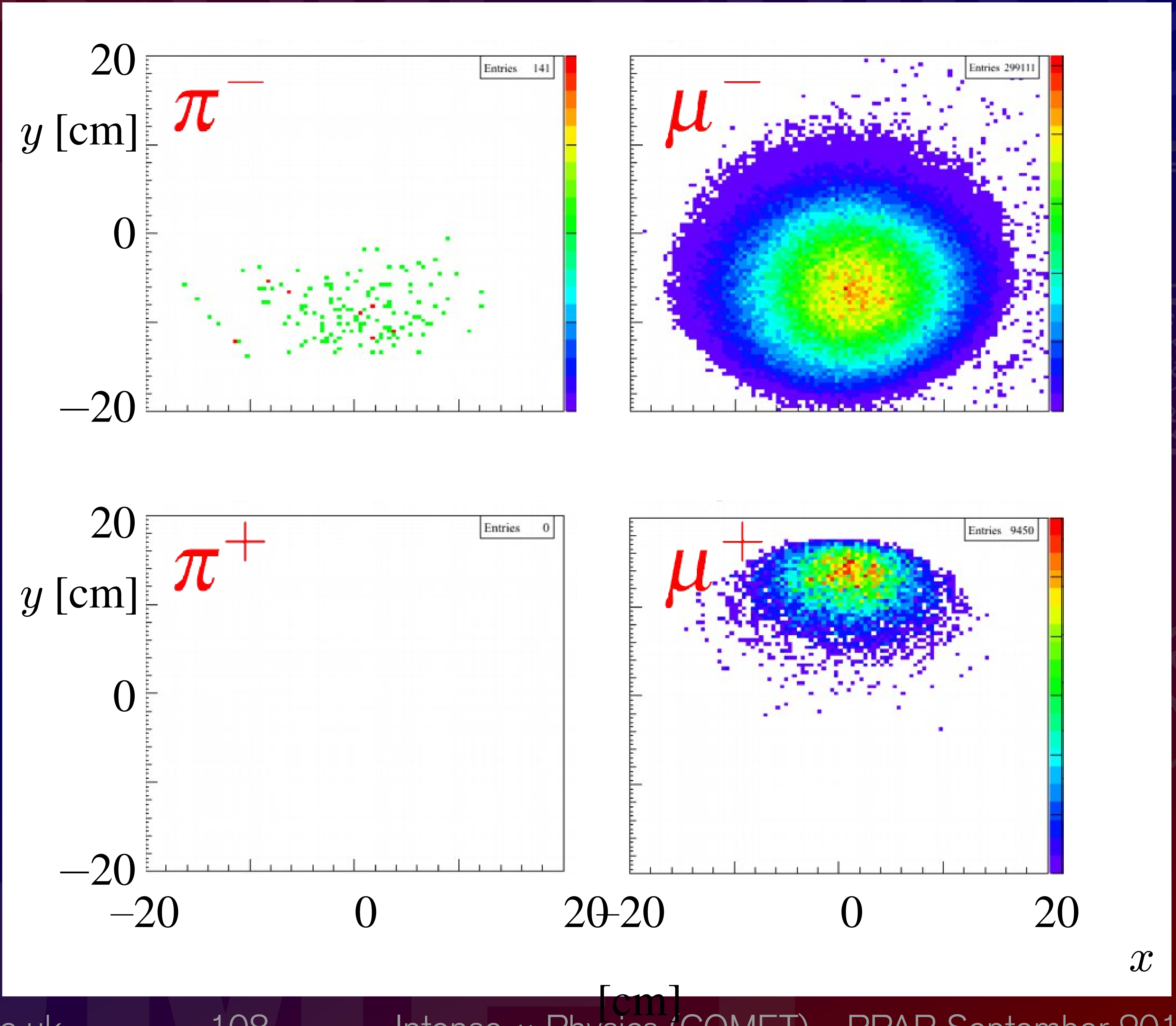
Background Production Studies at PSI

- Measurement programme at PSI πE3 muon beam, led by $\mu 2e$ group
- To directly observe charged particle emissions from stopping target materials
- First runs conducted this past summer, with some UK student participation
- Initial focus mainly protons

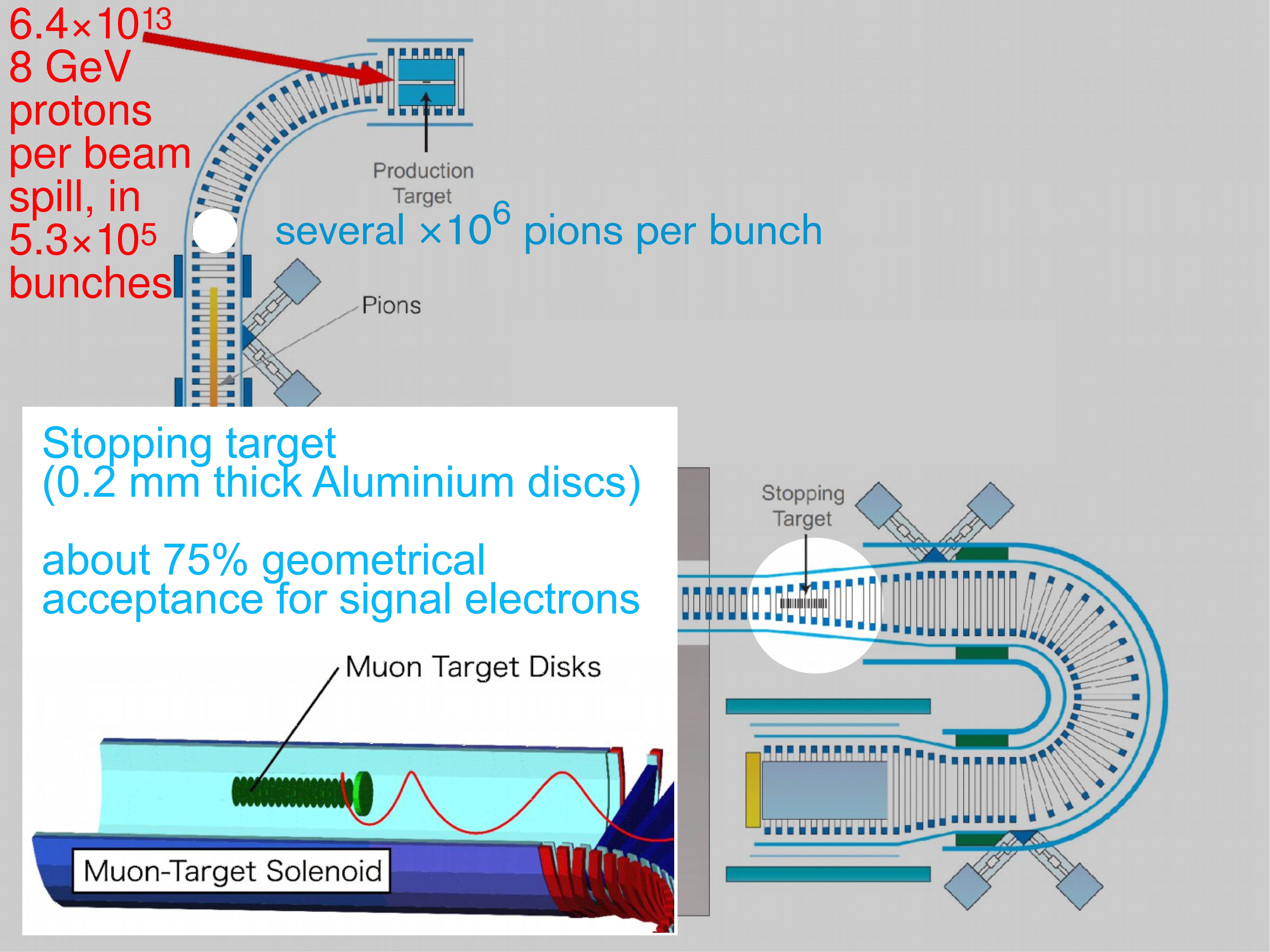


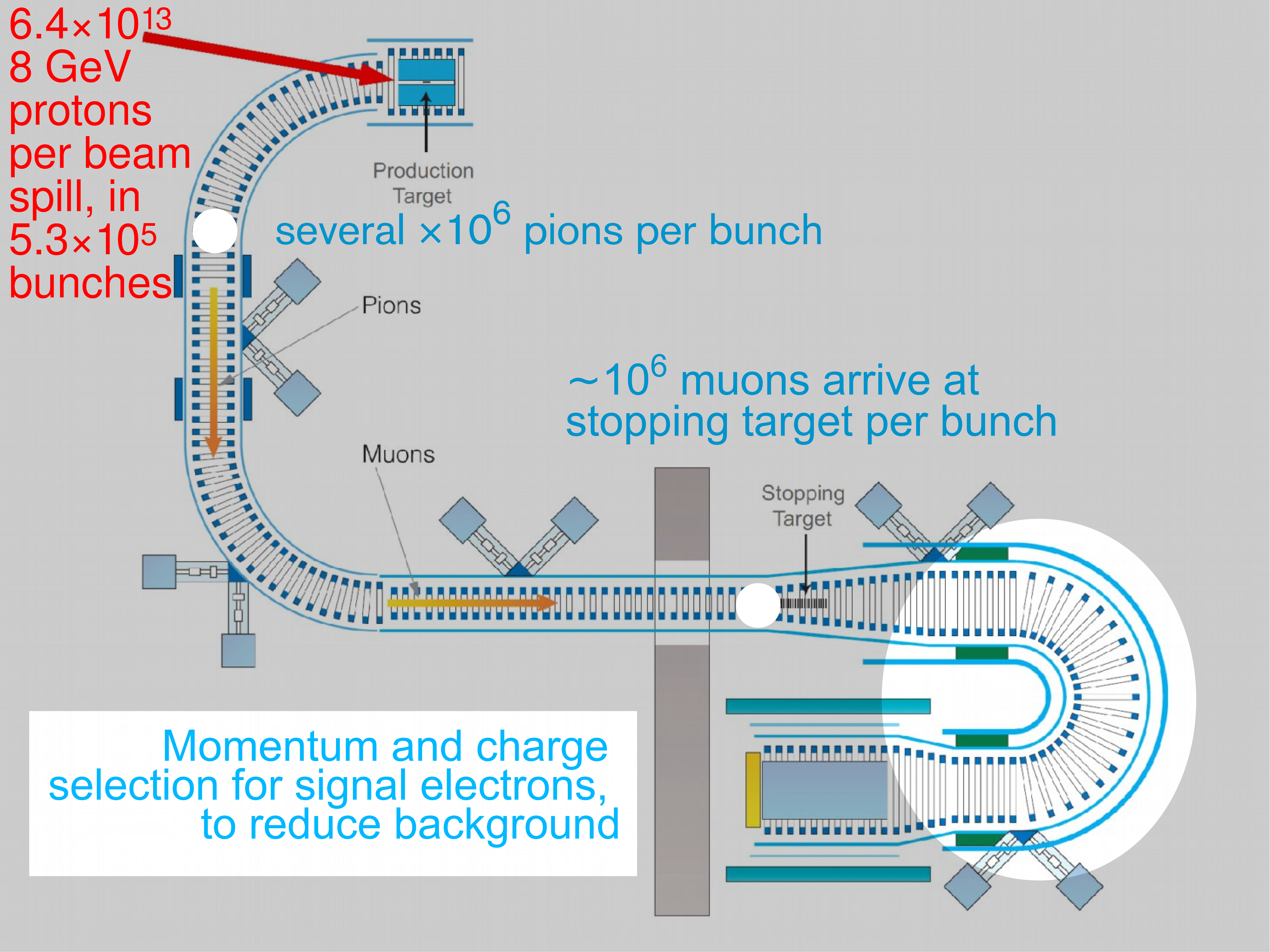
Ben Krikler

Before Stopping Target



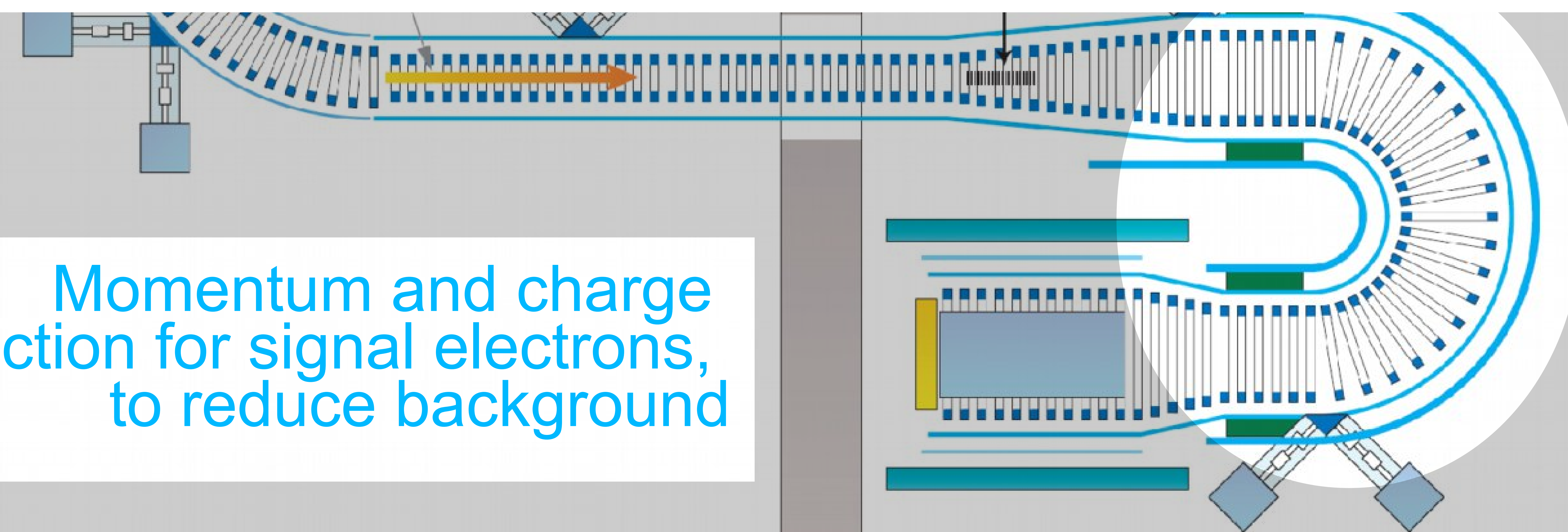
after collimation of high-momentum muons


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
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

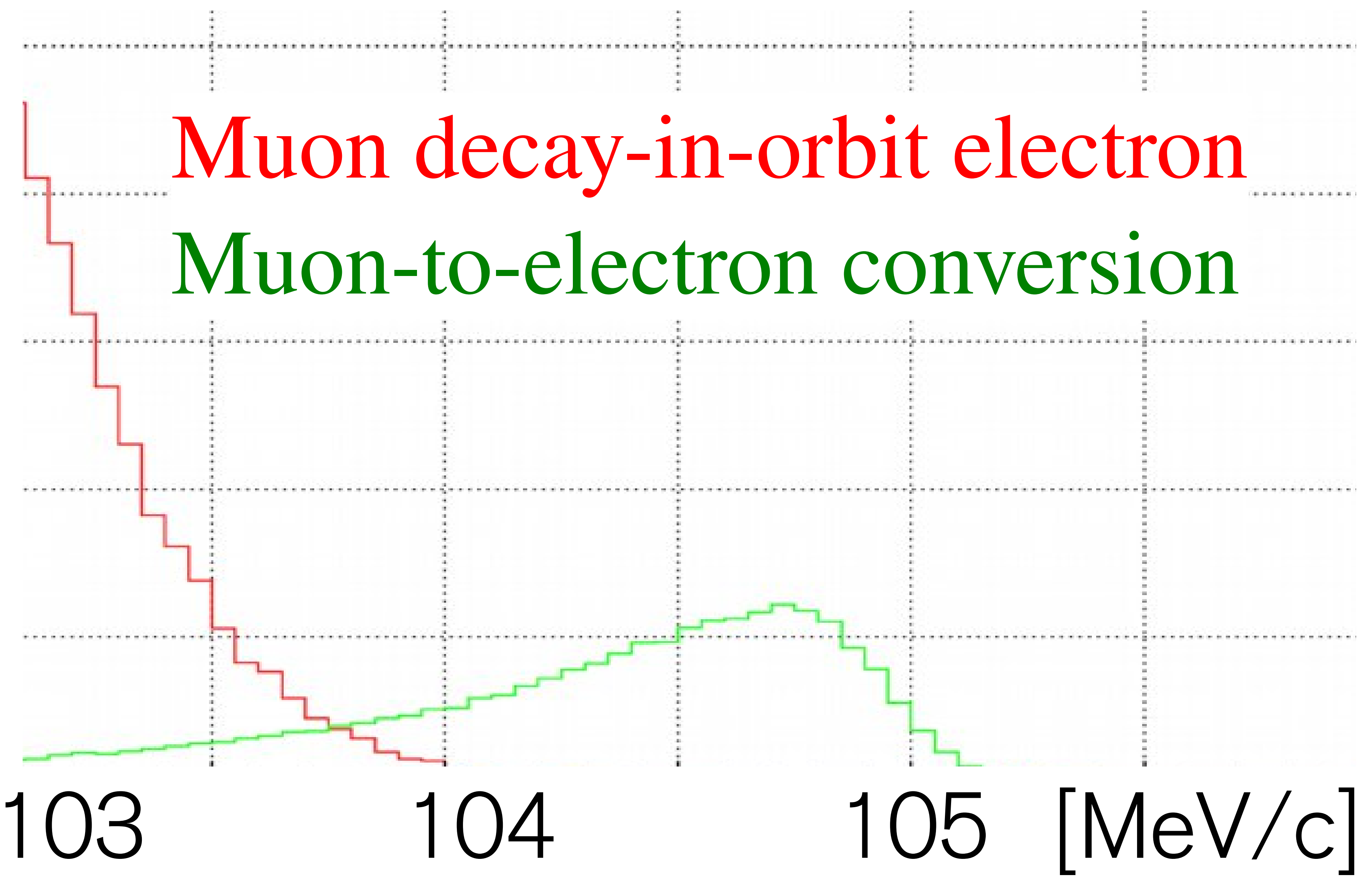
Particles seen after the curved solenoid

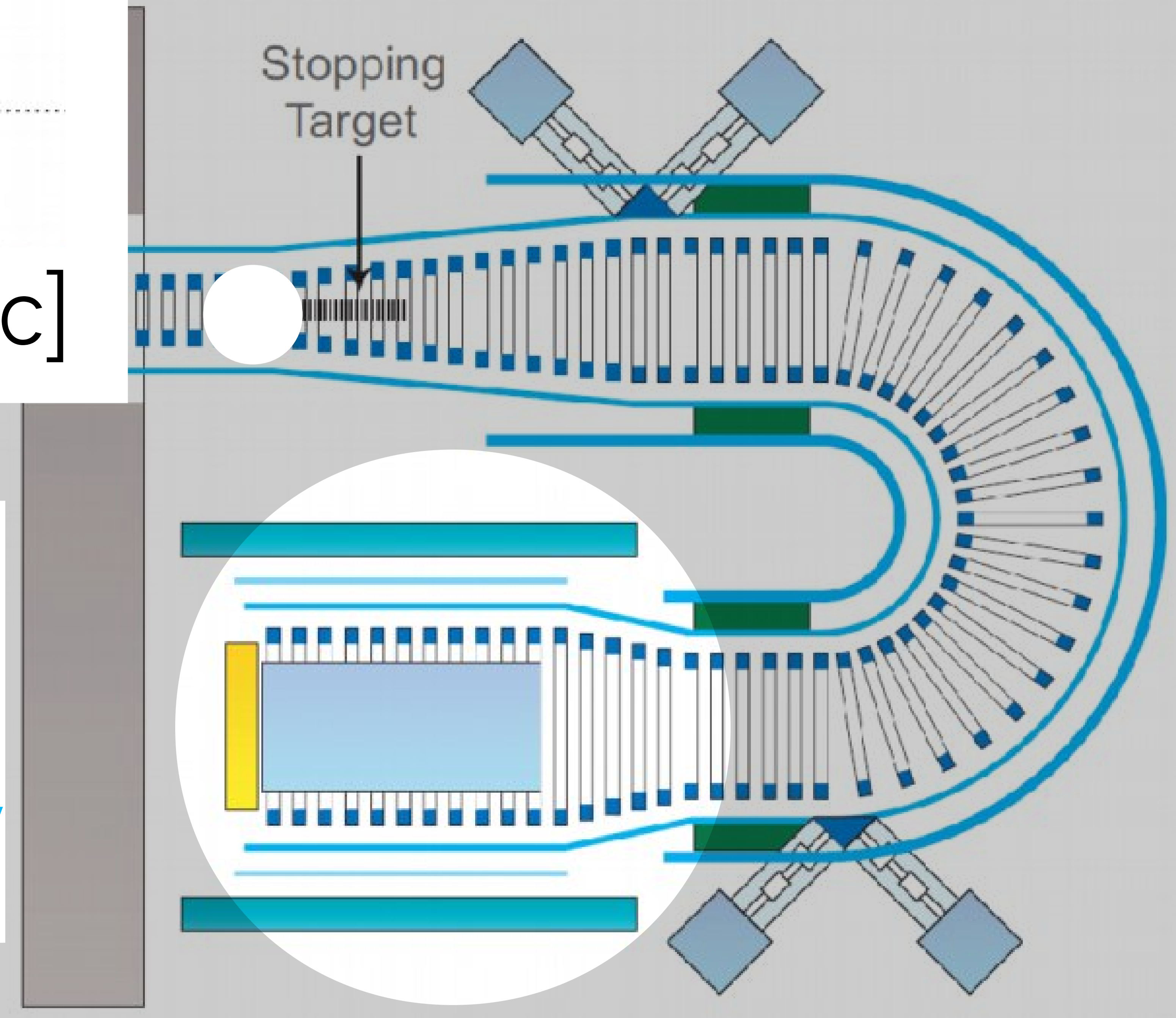
	Timing	Tracker (kHz)	Calorimeter (kHz)	Energy (MeV)
DIO electrons	Delayed	10	10	50–60
Back-scattering electrons	Delayed	15	200	< 40
Beam flash muons	Prompt	$< 150^{\ddagger}$	$< 150^{\ddagger}$	15–35
Muon decay in calorimeter	Delayed	—	$< 150^{\ddagger}$	< 55
DIO from outside of target	Delayed	< 300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



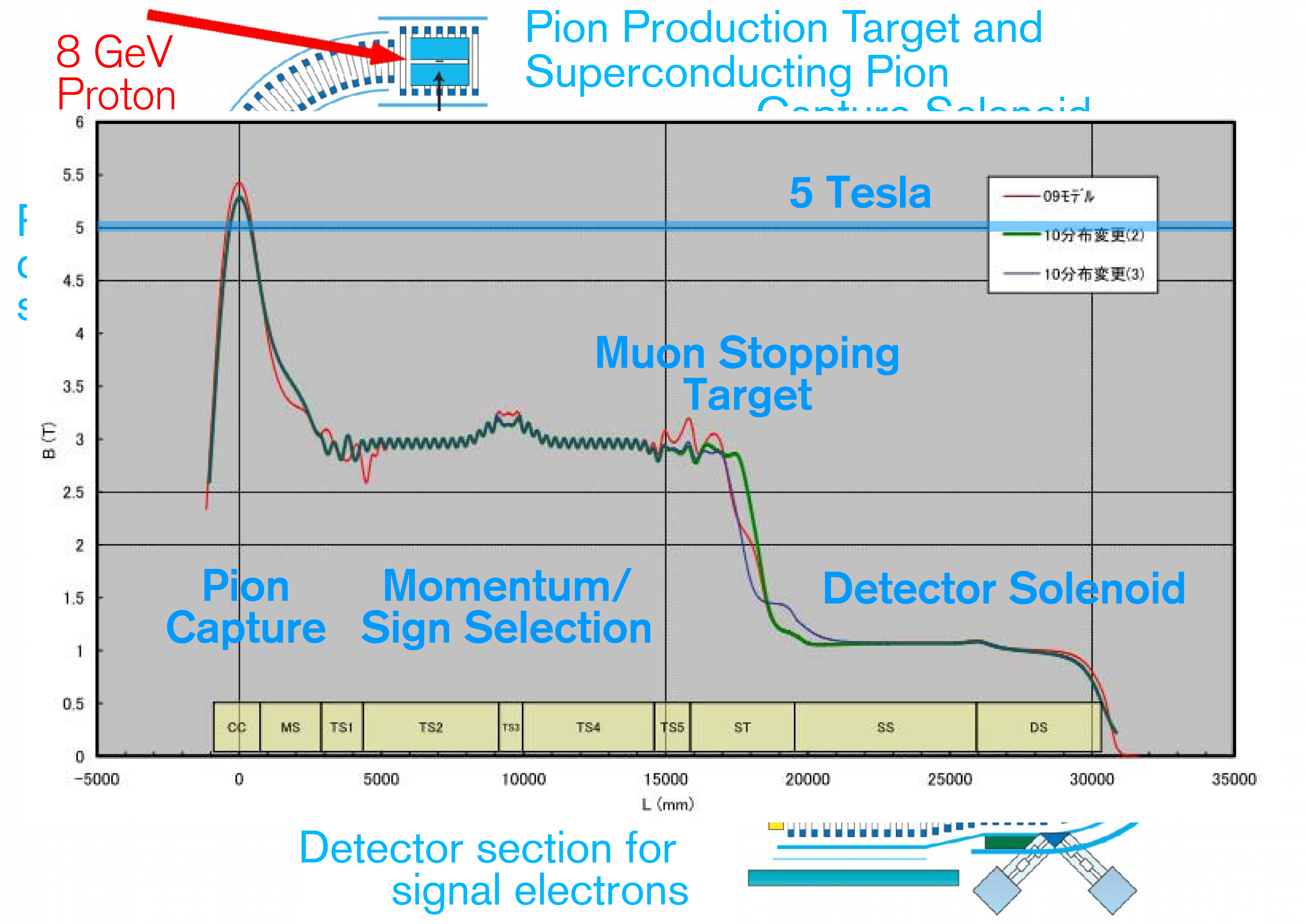
Momentum and charge selection for signal electrons, to reduce background

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

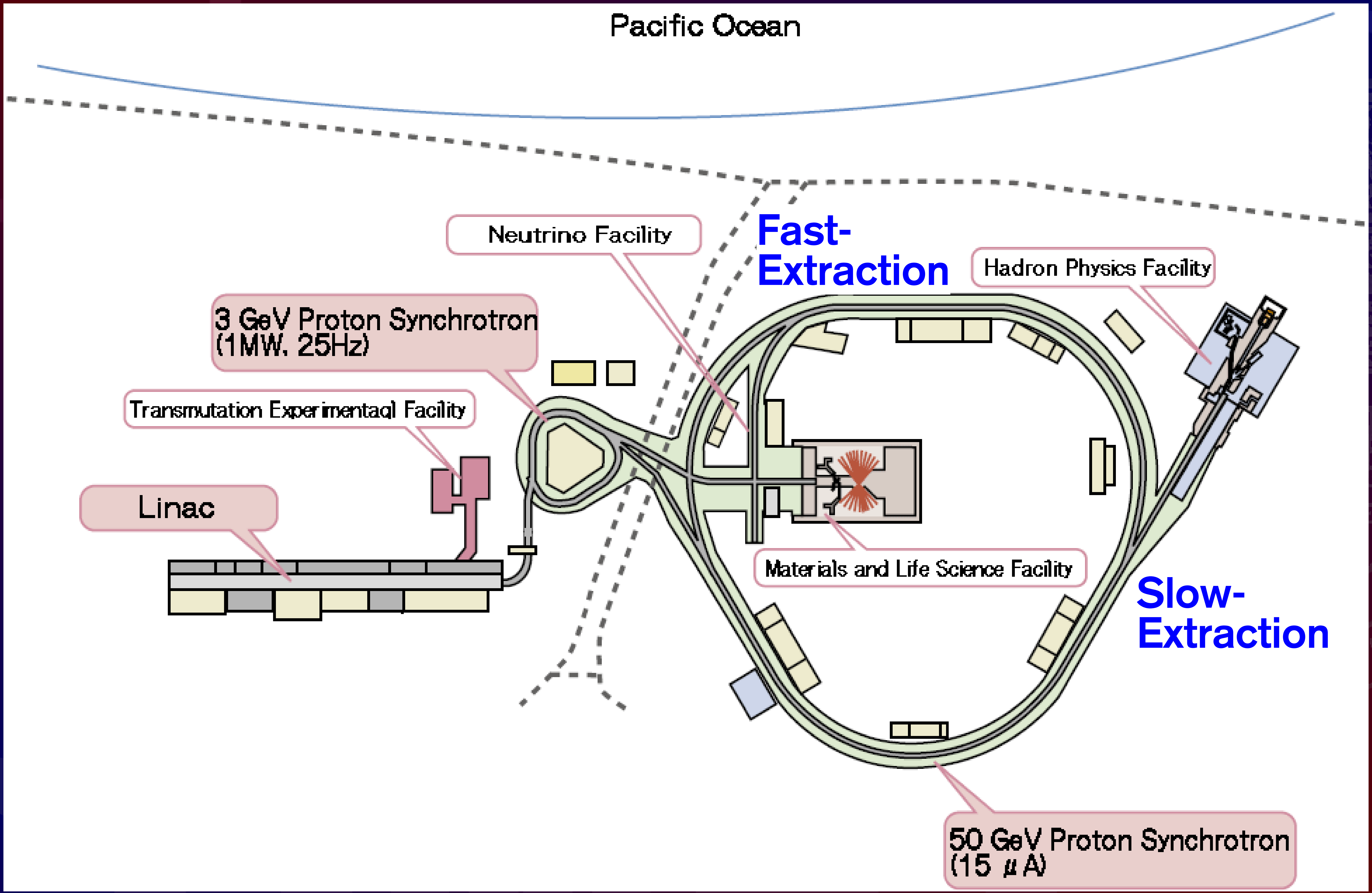




Tracking detector for momentum measurement, calorimeter for energy and triggering redundancy

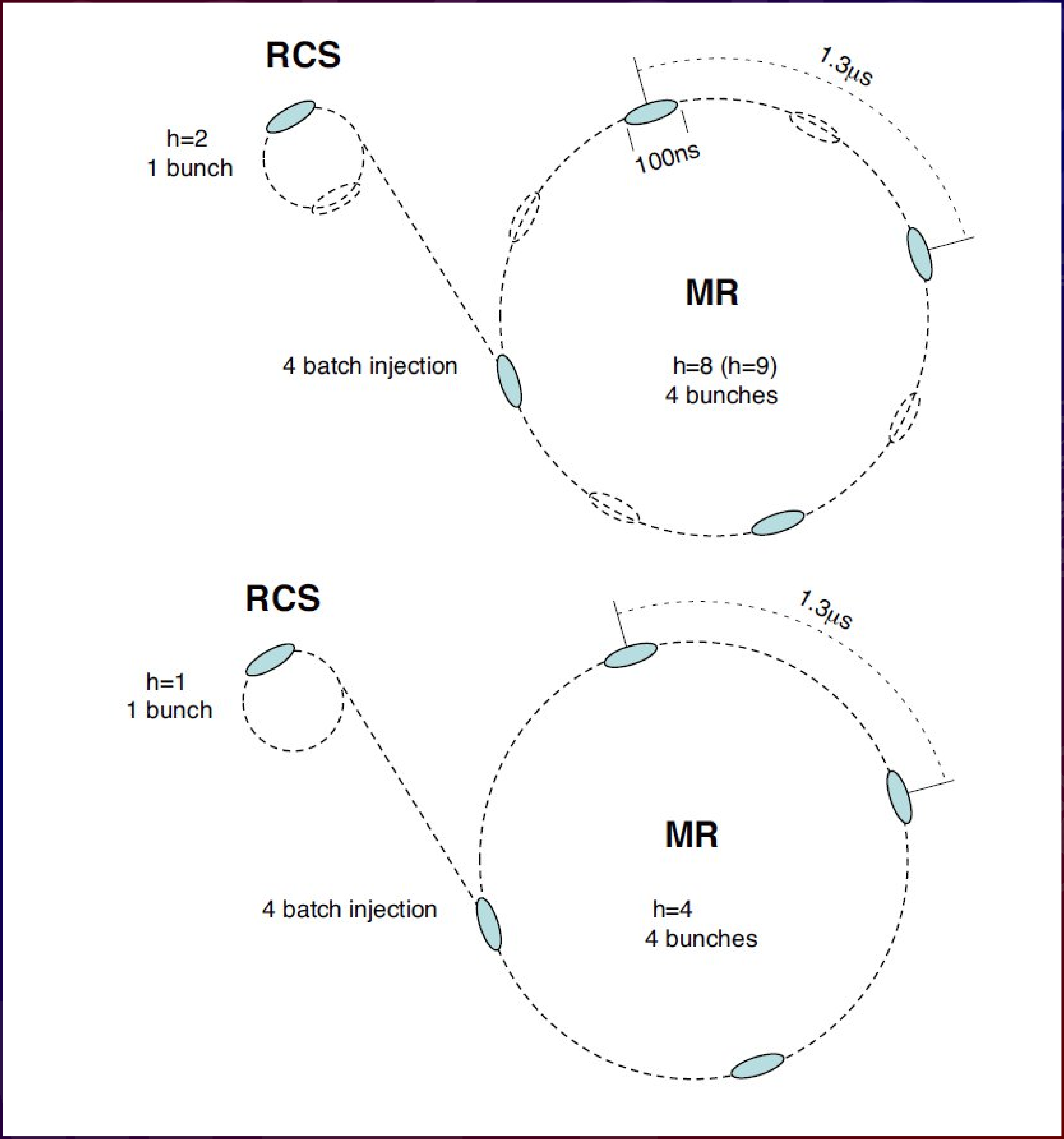

8 GeV Proton
Pion Production Target and Superconducting Pion Capture Solenoid
5 Tesla
09モデル
10分布変更(2)
10分布変更(3)
Muon Stopping Target
Pion Capture
Momentum/ Sign Selection
Detector Solenoid
B (T)
L (mm)
CC
MS
TS1
TS2
TS3
TS4
TS5
ST
SS
DS
Detector section for signal electrons

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

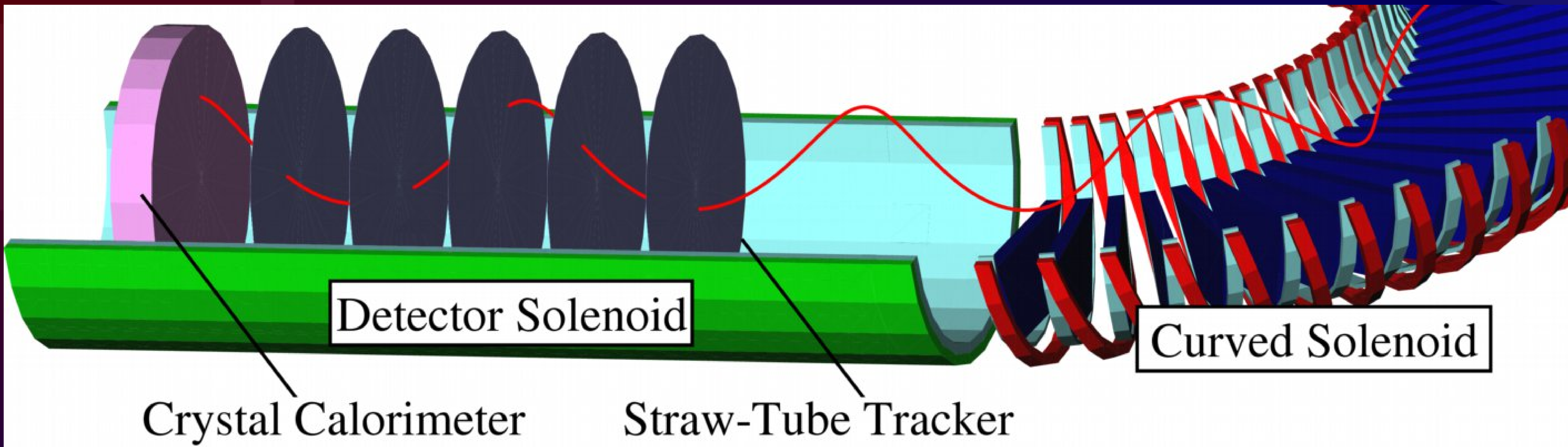
Beam Extinction

- 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

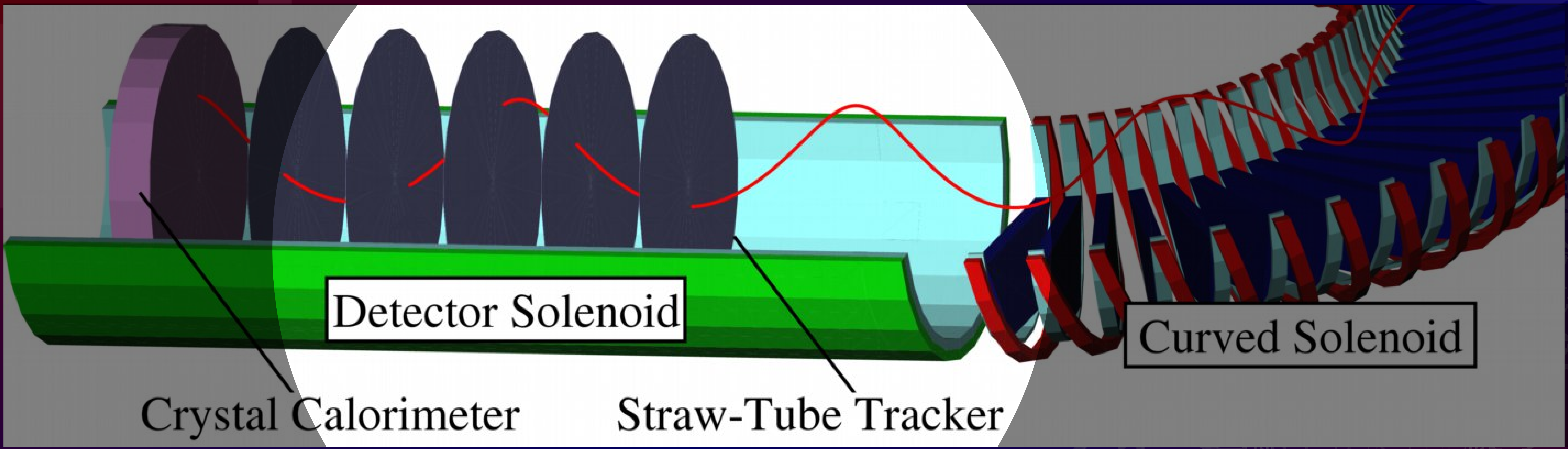
Beam Monitor for Beam Extinction Tests and Measurements at J-PARC

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

COMET Detector Section



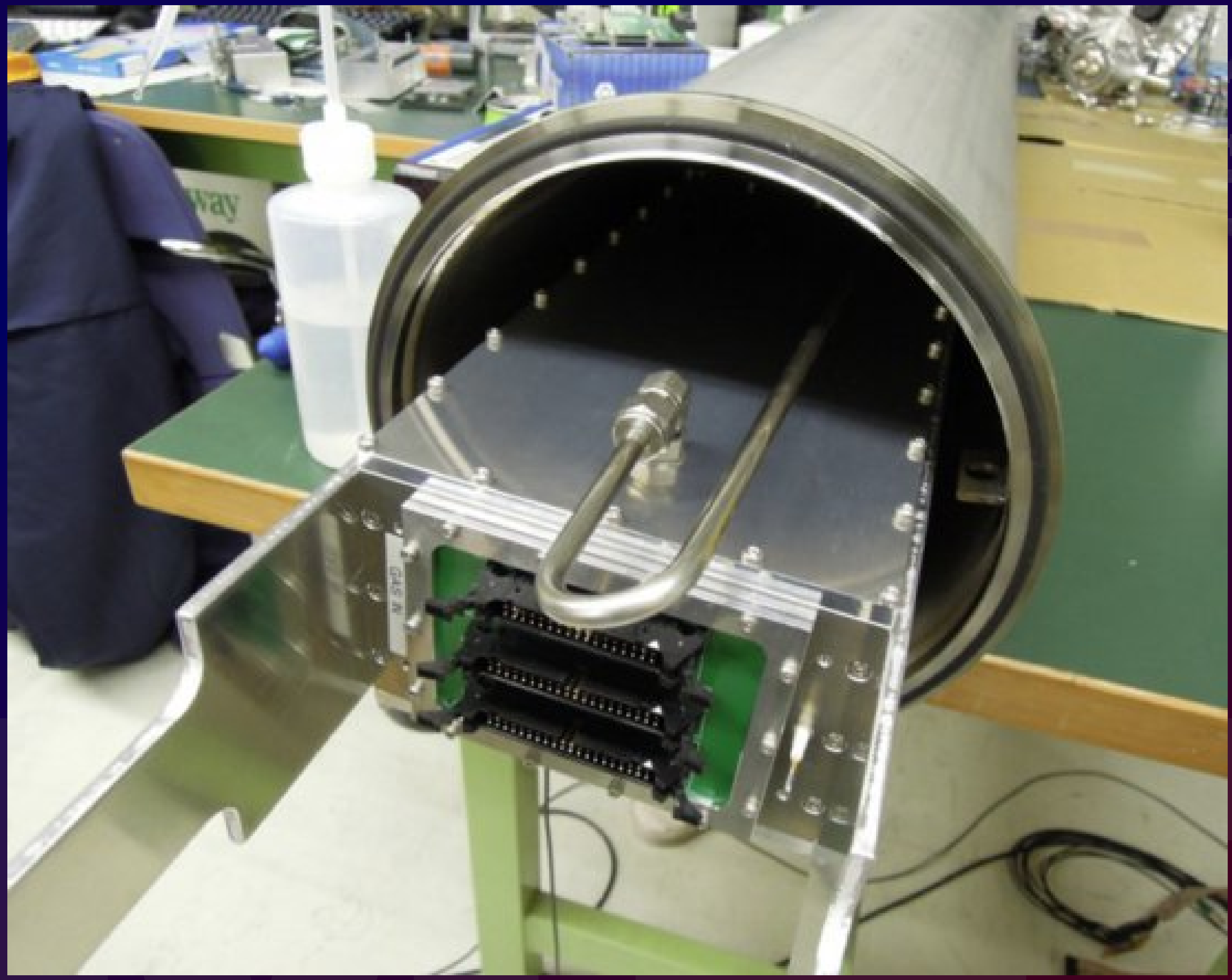
COMET Detector Section



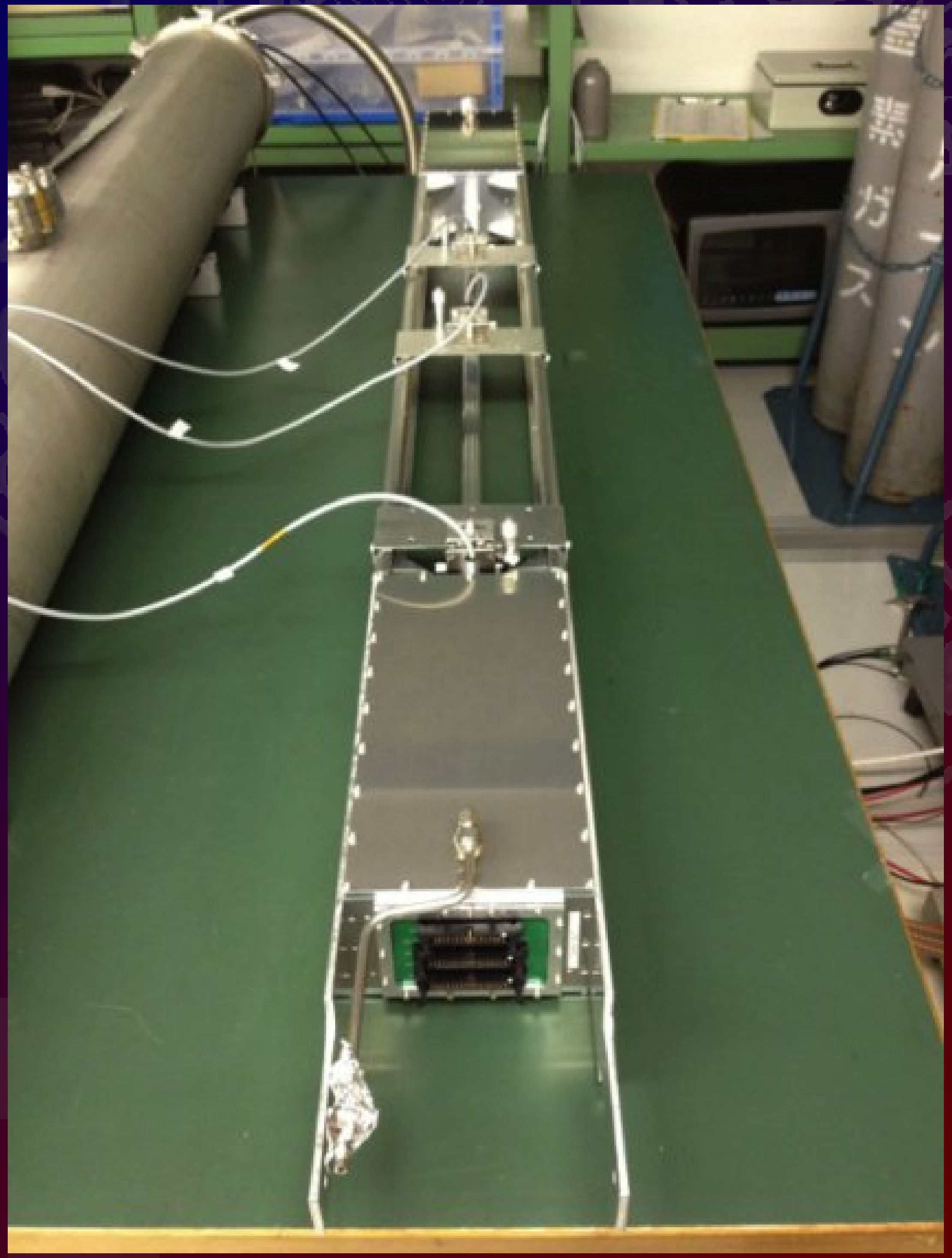
- Straw-tube electron tracker in 1 Tesla field
  - 800 kHz charged particle and 8 MHz gamma rates
  - 0.4% momentum and 700 micron spatial resolution required

Straw Tube Tracker R&D

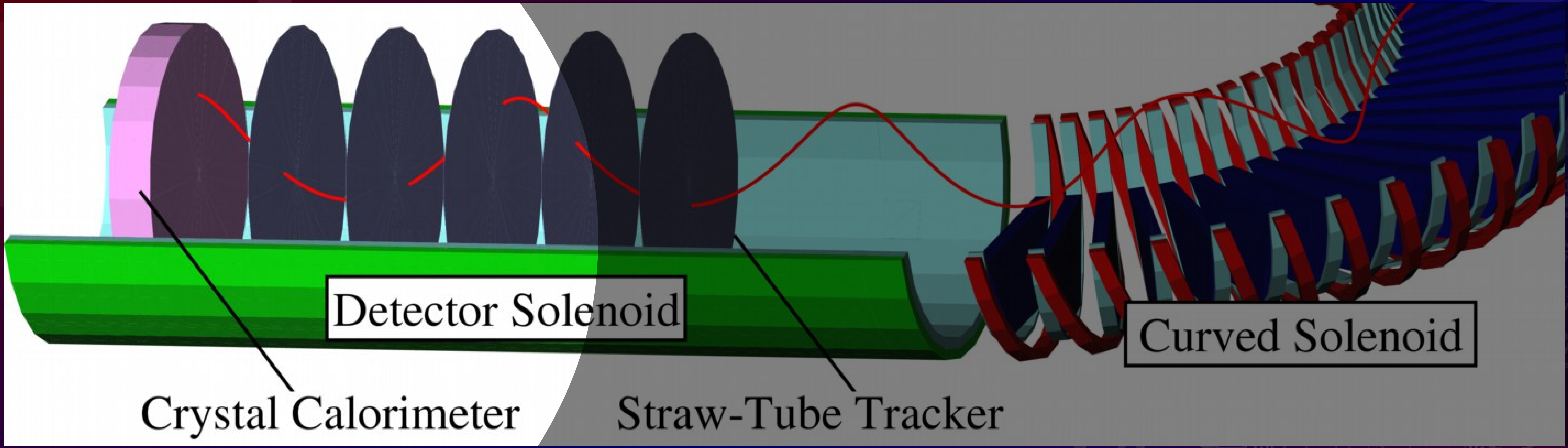
Prototype at KEK (7 straw tubes)



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



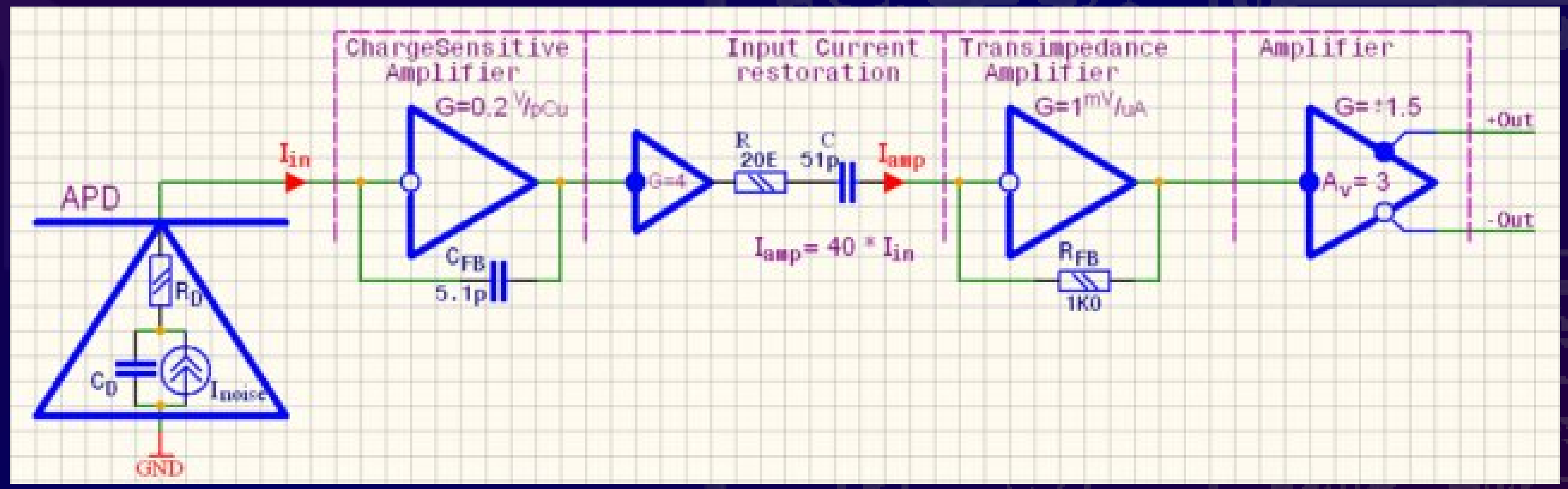
COMET Detector Section



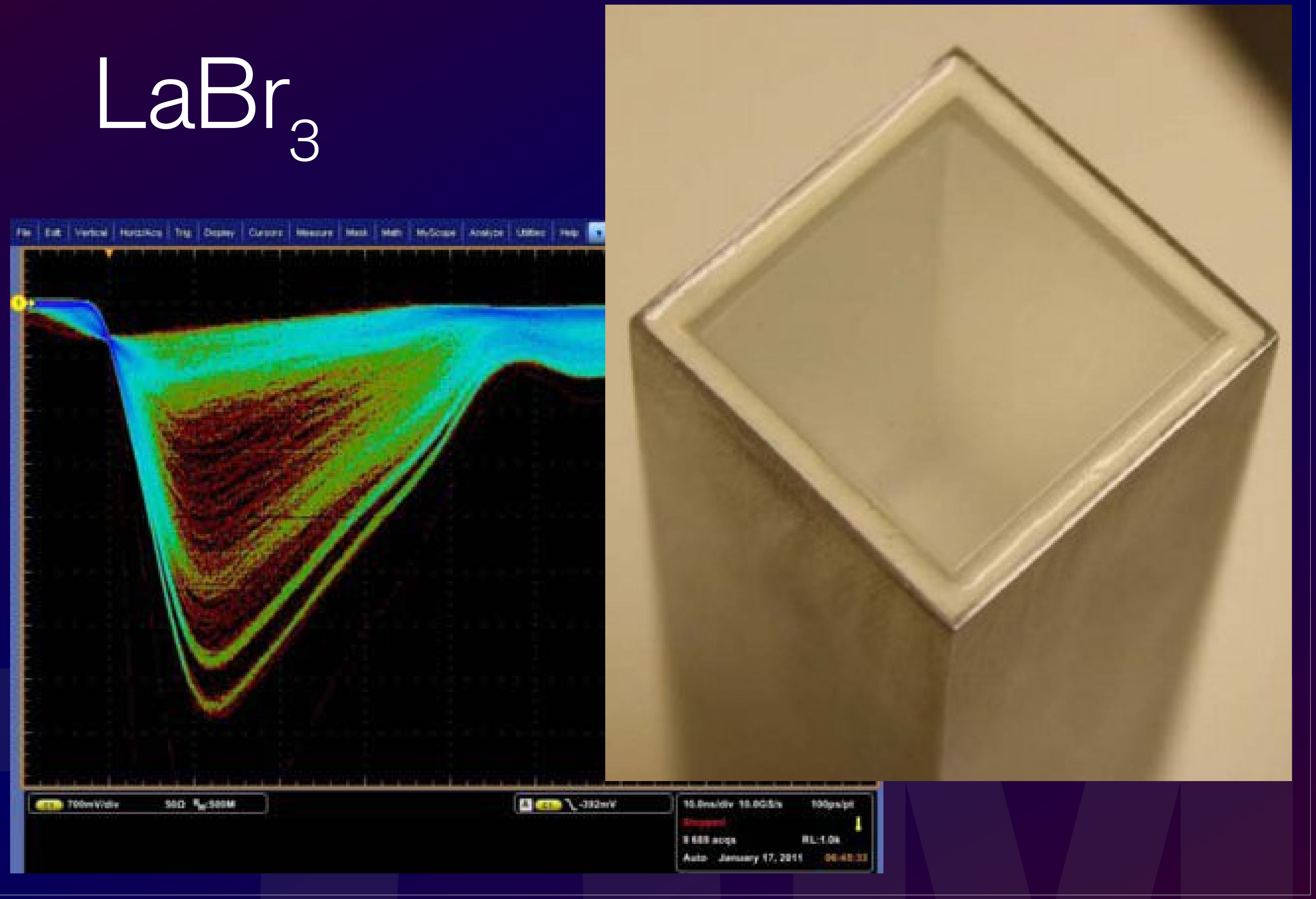
- Crystal calorimeter
  - for energy and position measurement, PID, trigger signal
  - 5% energy and 1cm spatial resolution at 100 MeV

Calorimeter R&D

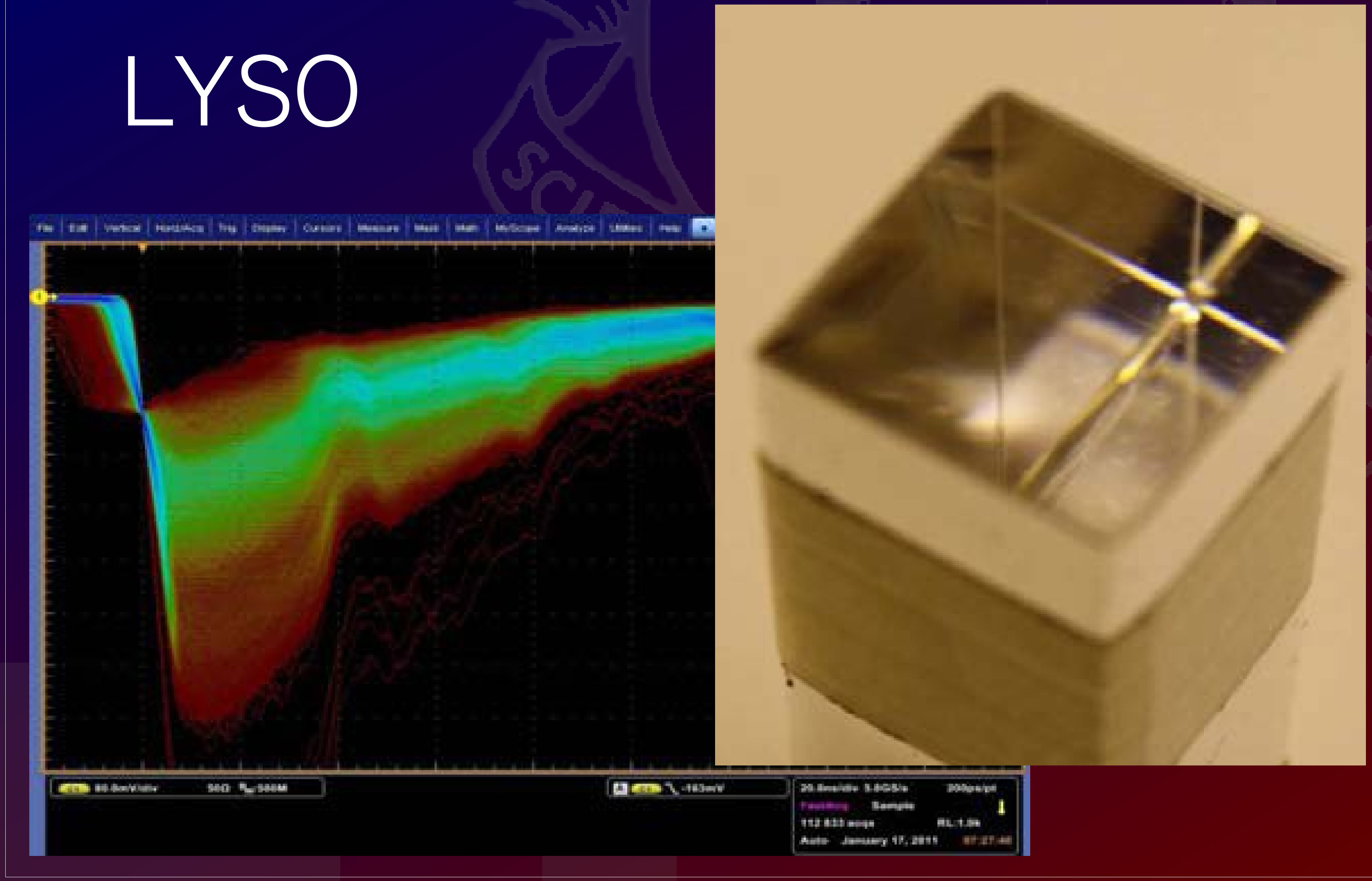
- GSO / LYSO crystals with APDs tested 2011
  - Vertical slice tests this year
- Design being finalised for 50-crystal / APD prototype
  - beam tests later this year at BINP Novisibirsk



LaBr$_3$

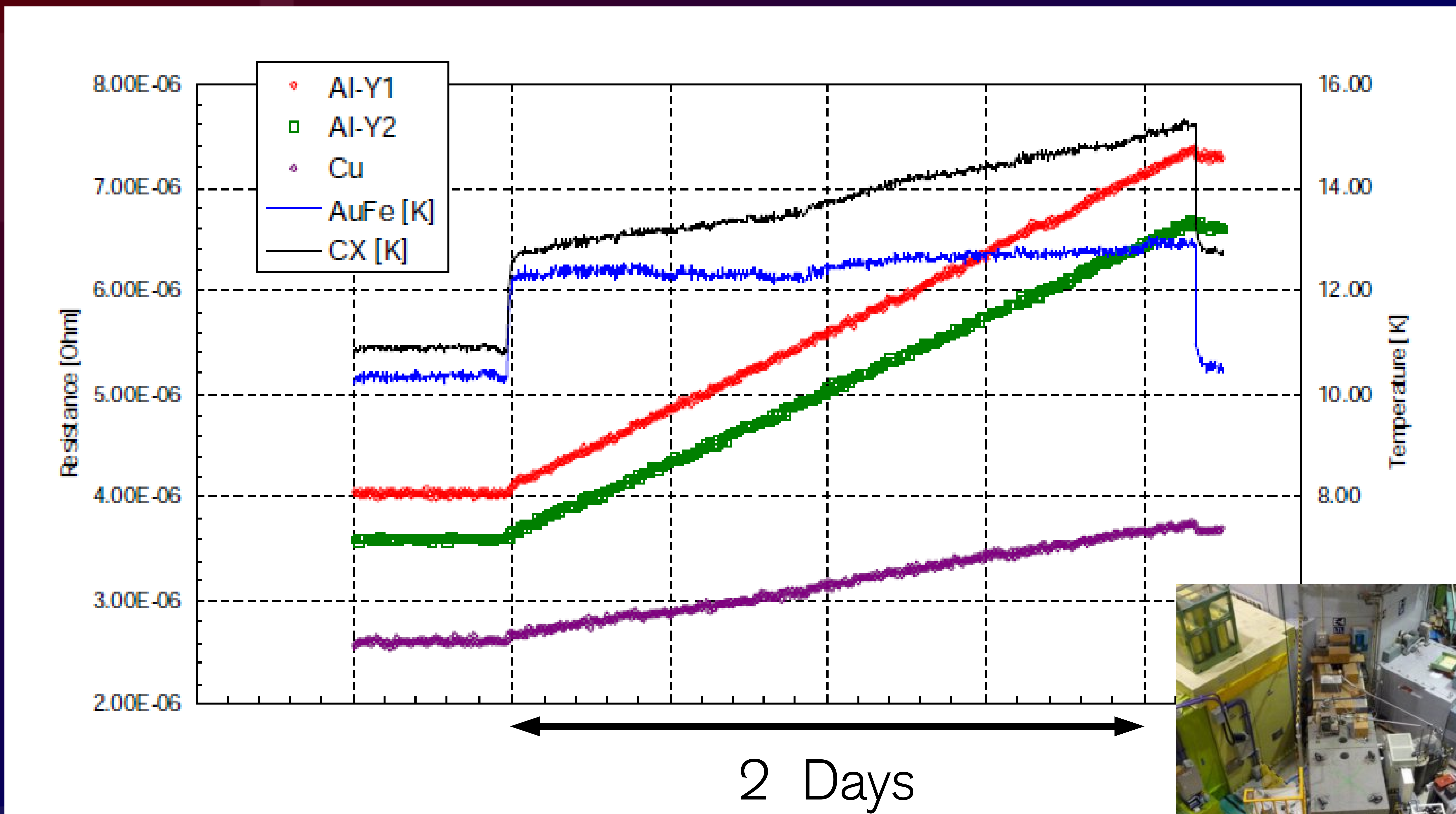


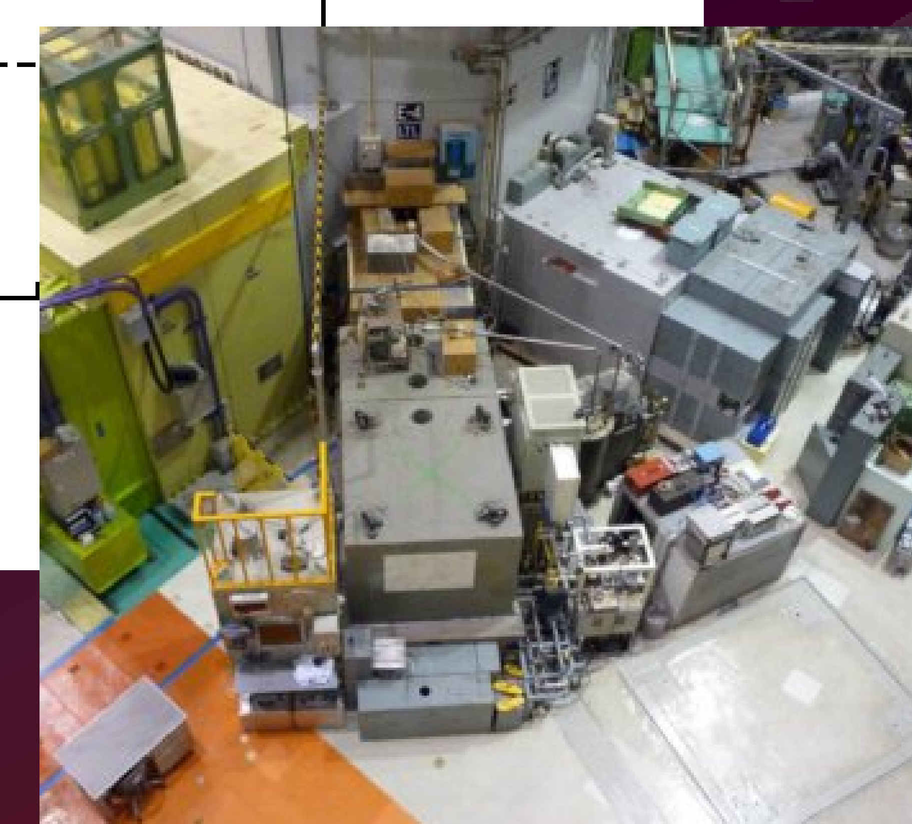
LYSO



Superconducting Solenoid R&D

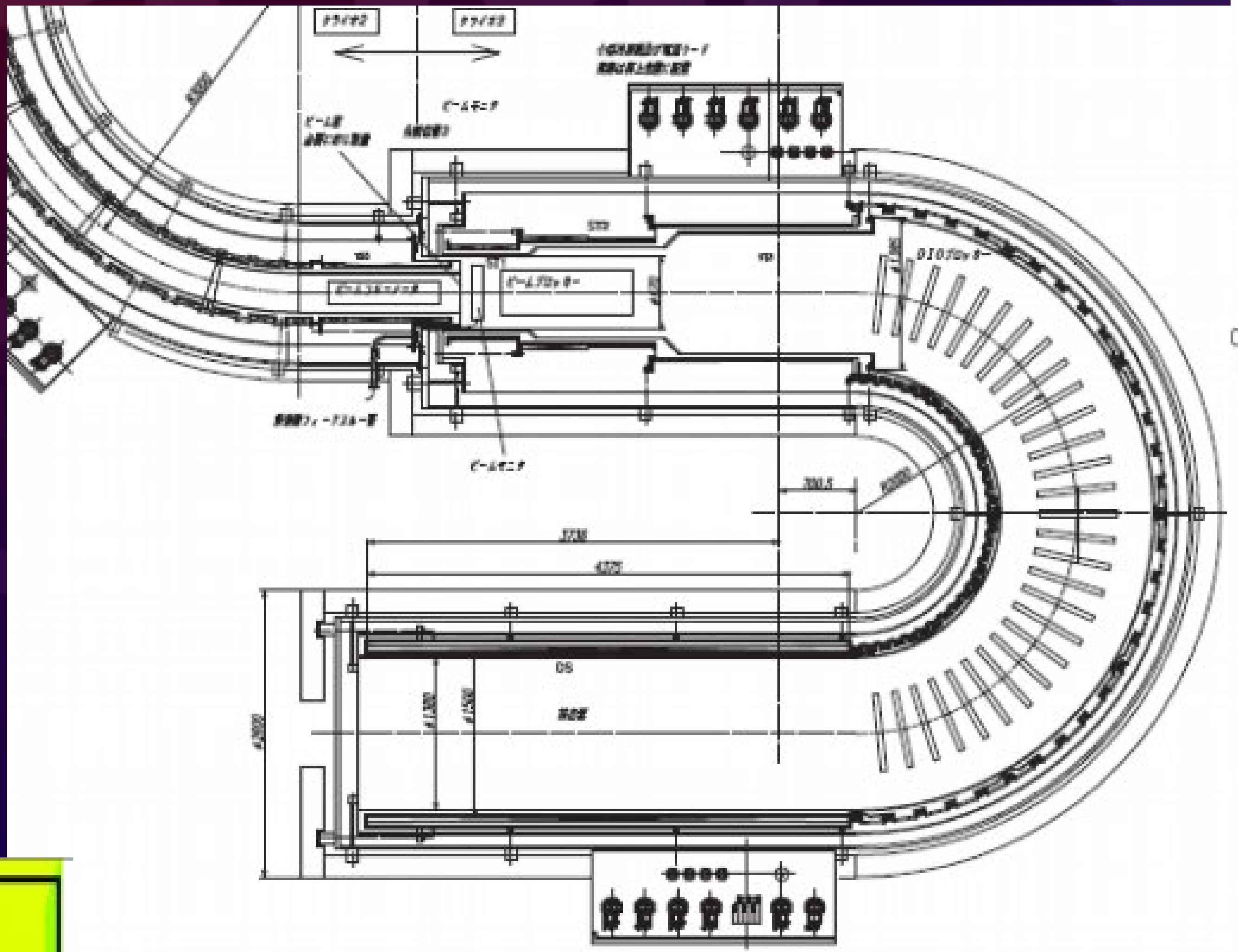
Neutron irradiation tests performed at KURRI reactor, Kyoto University

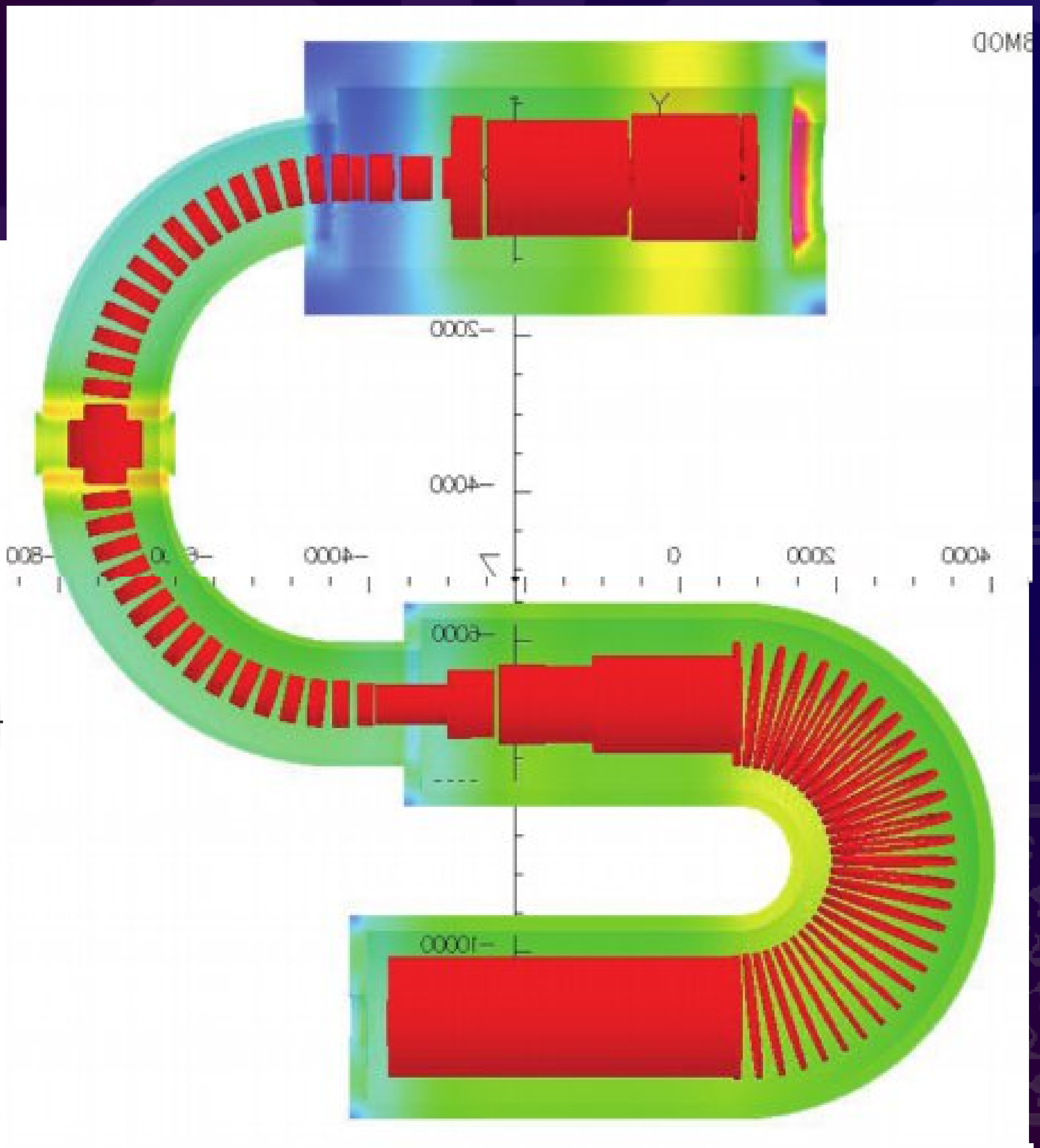


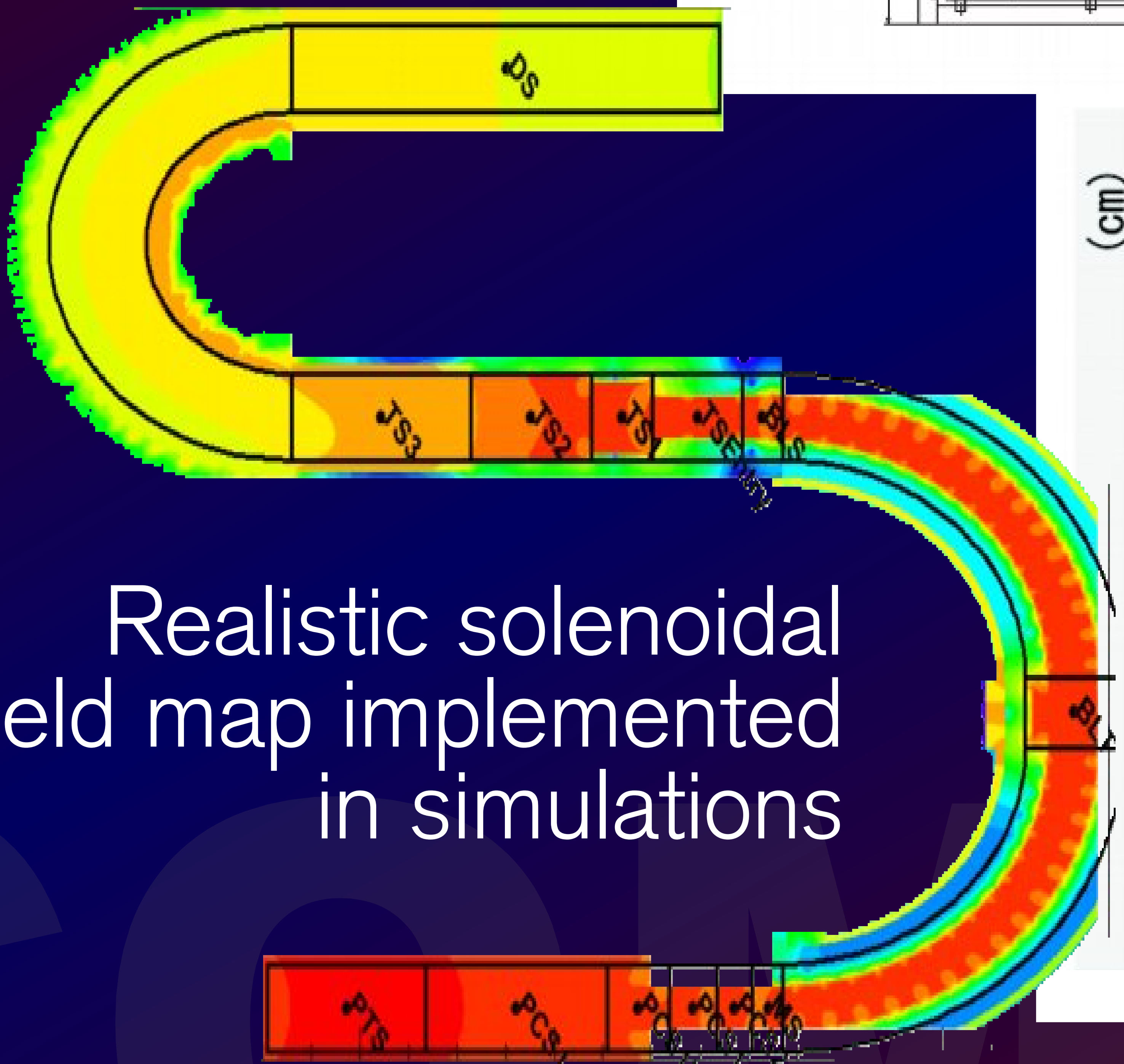


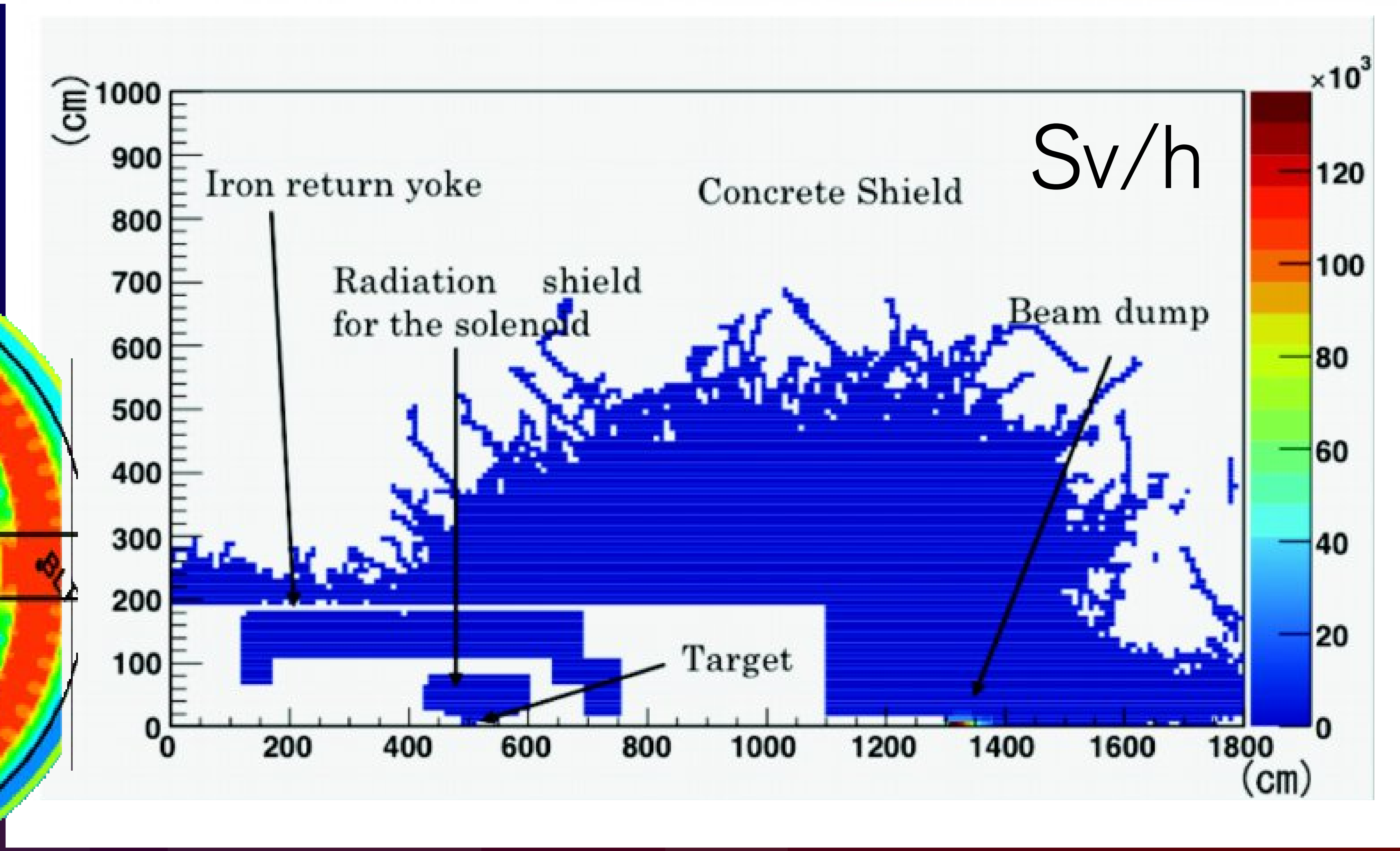
Demonstrated that Al stabiliser tolerates COMET radiation environment

Industrial Design Studies

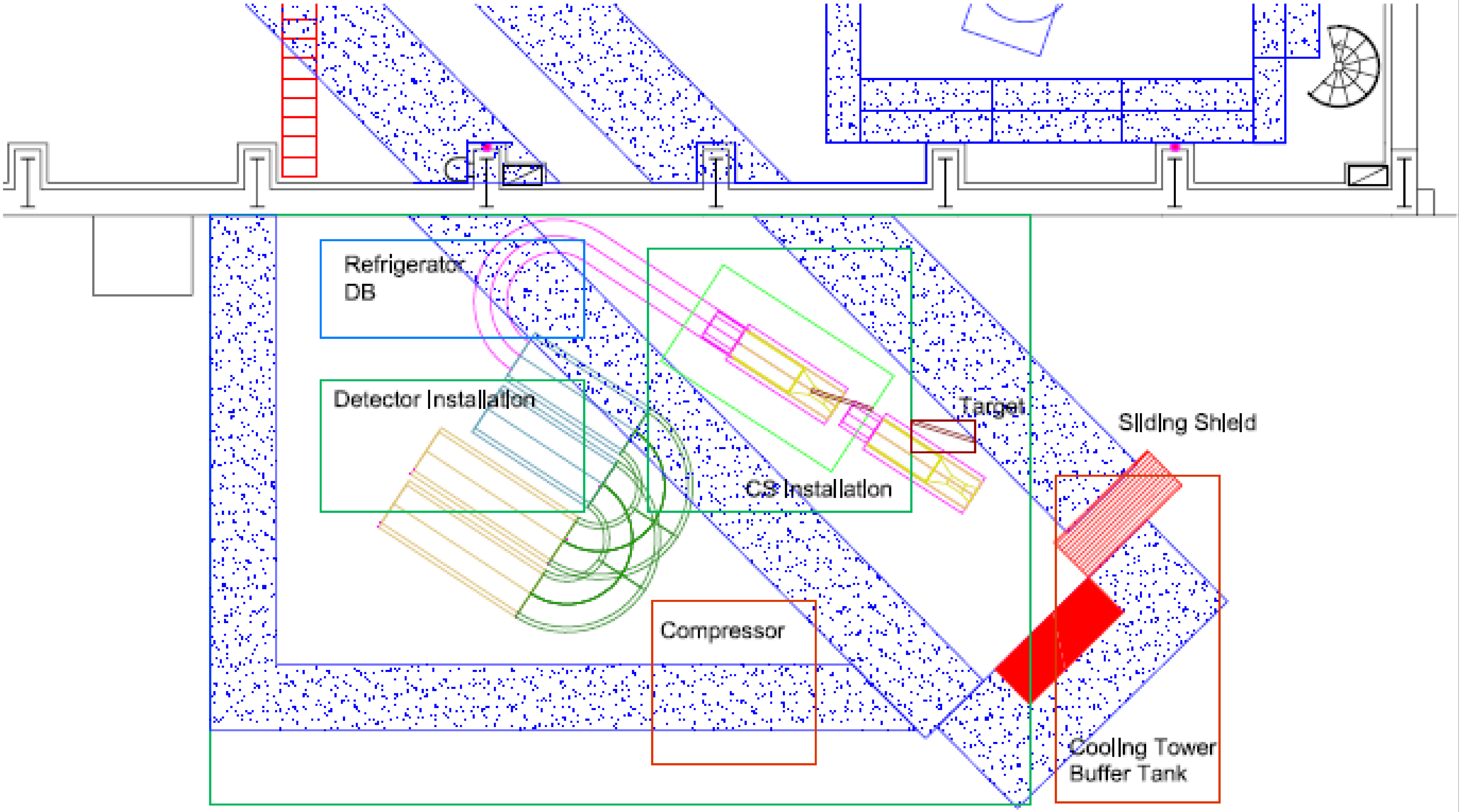








Realistic solenoidal field map implemented in simulations

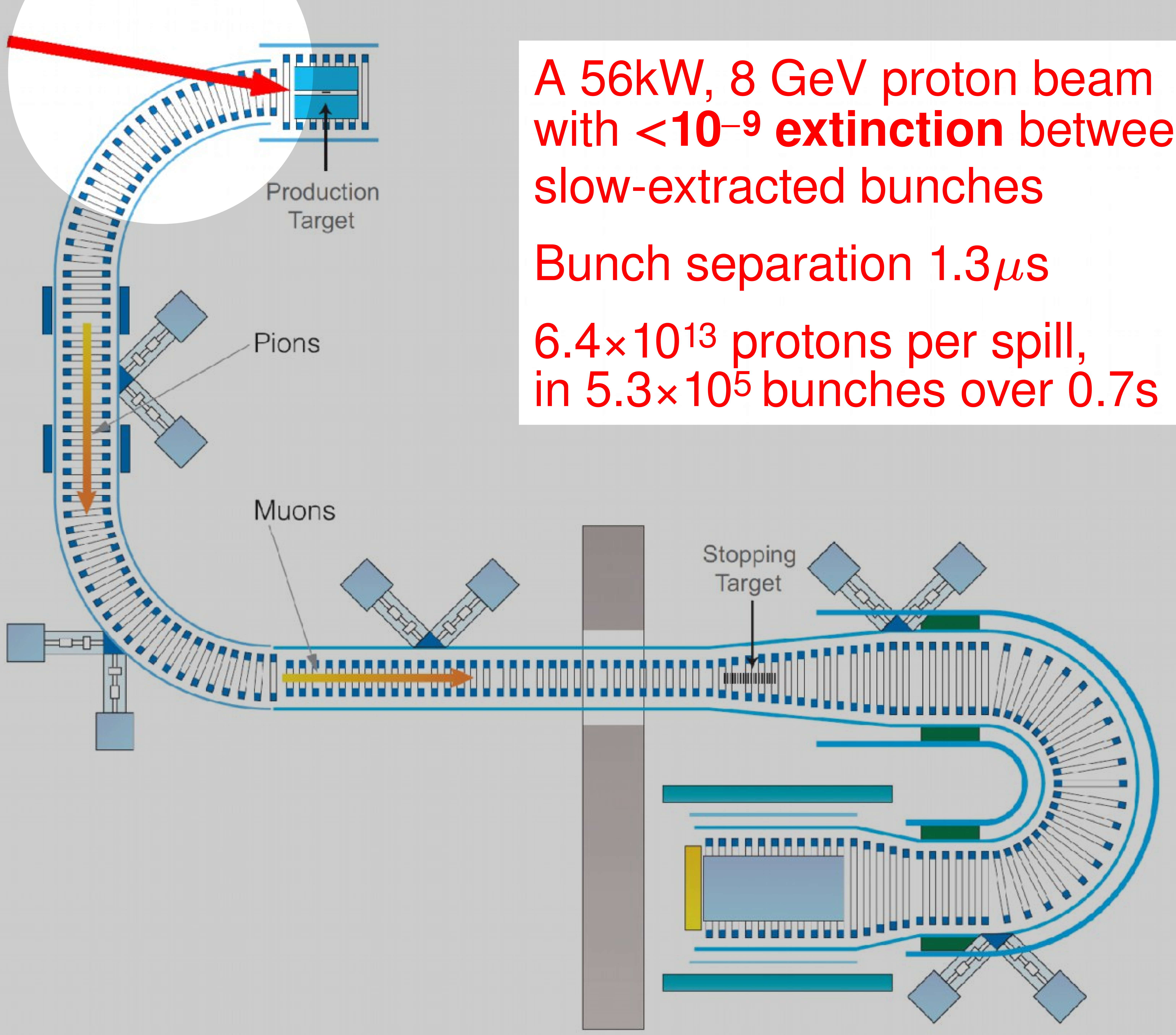


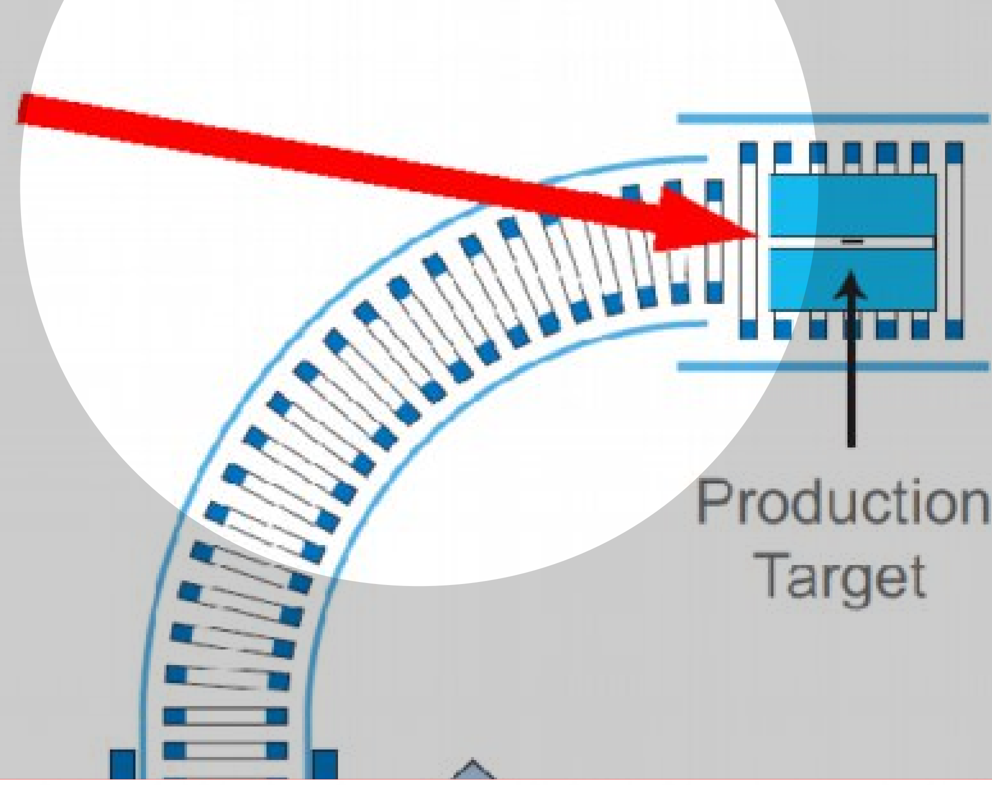
Refrigerator
DB
Detector Installation
CS Installation
Target
Sliding Shield
Compressor
Cooling Tower
Buffer Tank

A 56kW, 8 GeV proton beam with <10^{-9} **extinction** between slow-extracted bunches

Bunch separation 1.3μs

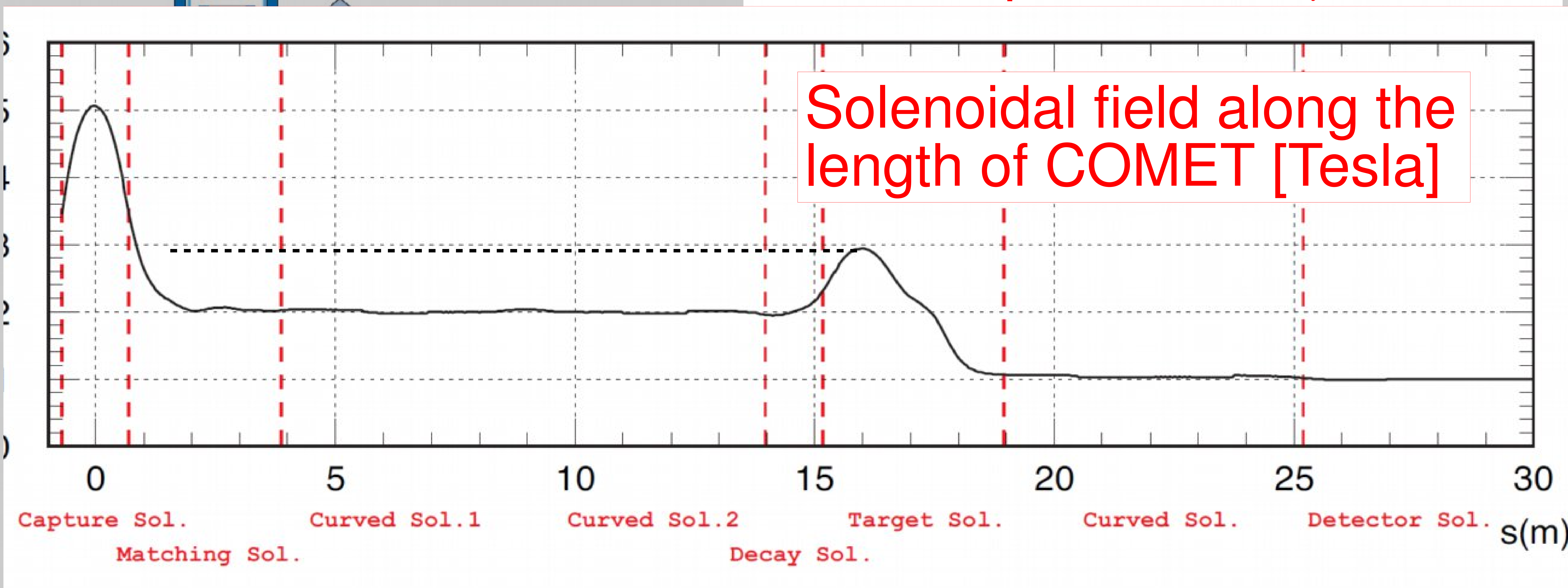
6.4×10^{13} protons per spill, in 5.3×10^{5} bunches over 0.7s

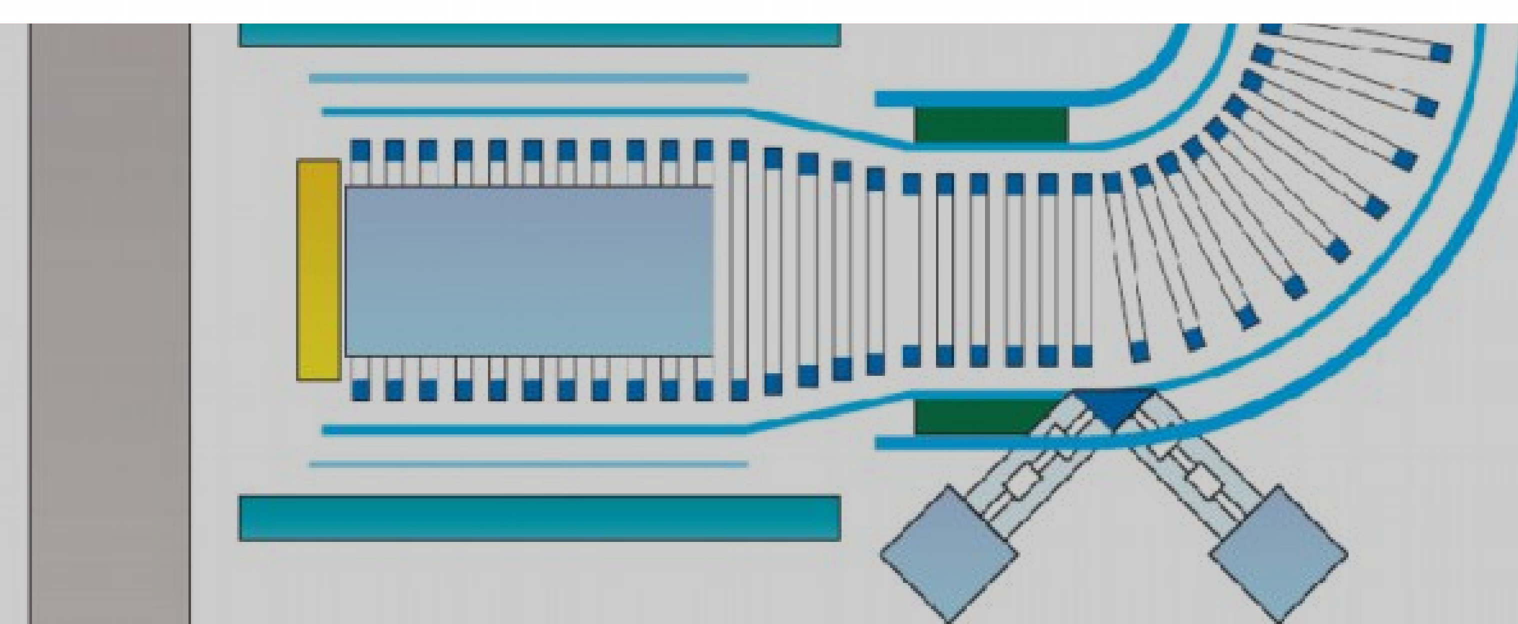




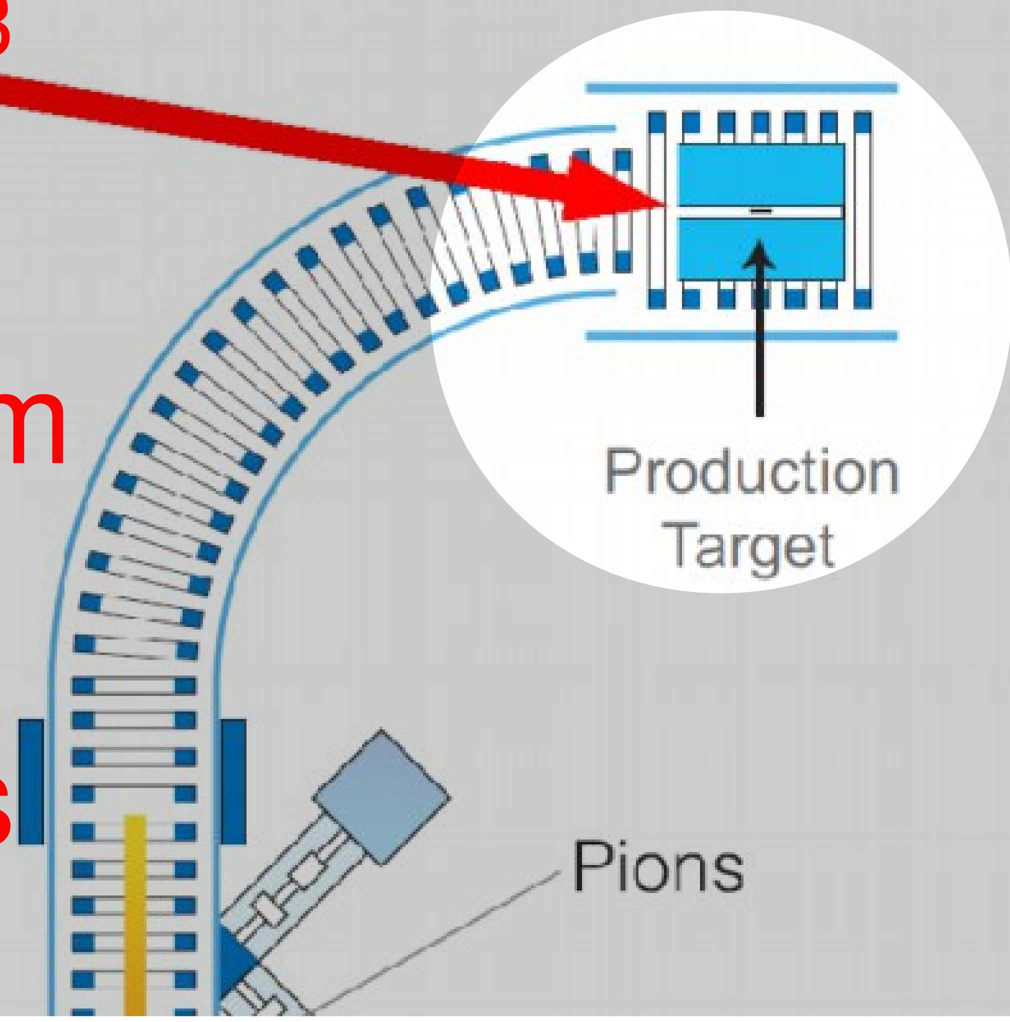
A 56kW, 8 GeV proton beam with <**10^{-9} extinction** between slow-extracted bunches

Bunch separation 1.3μs



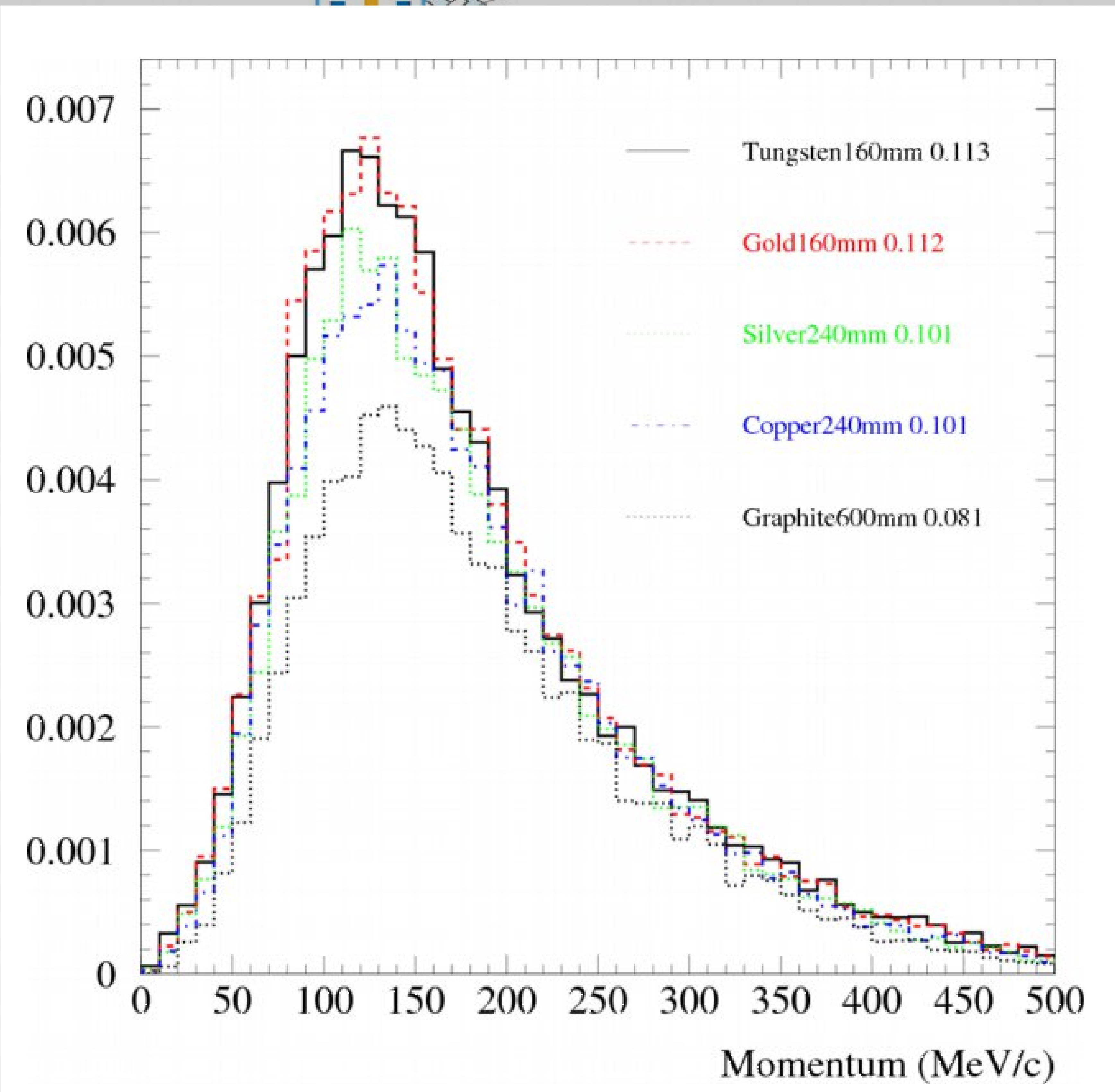


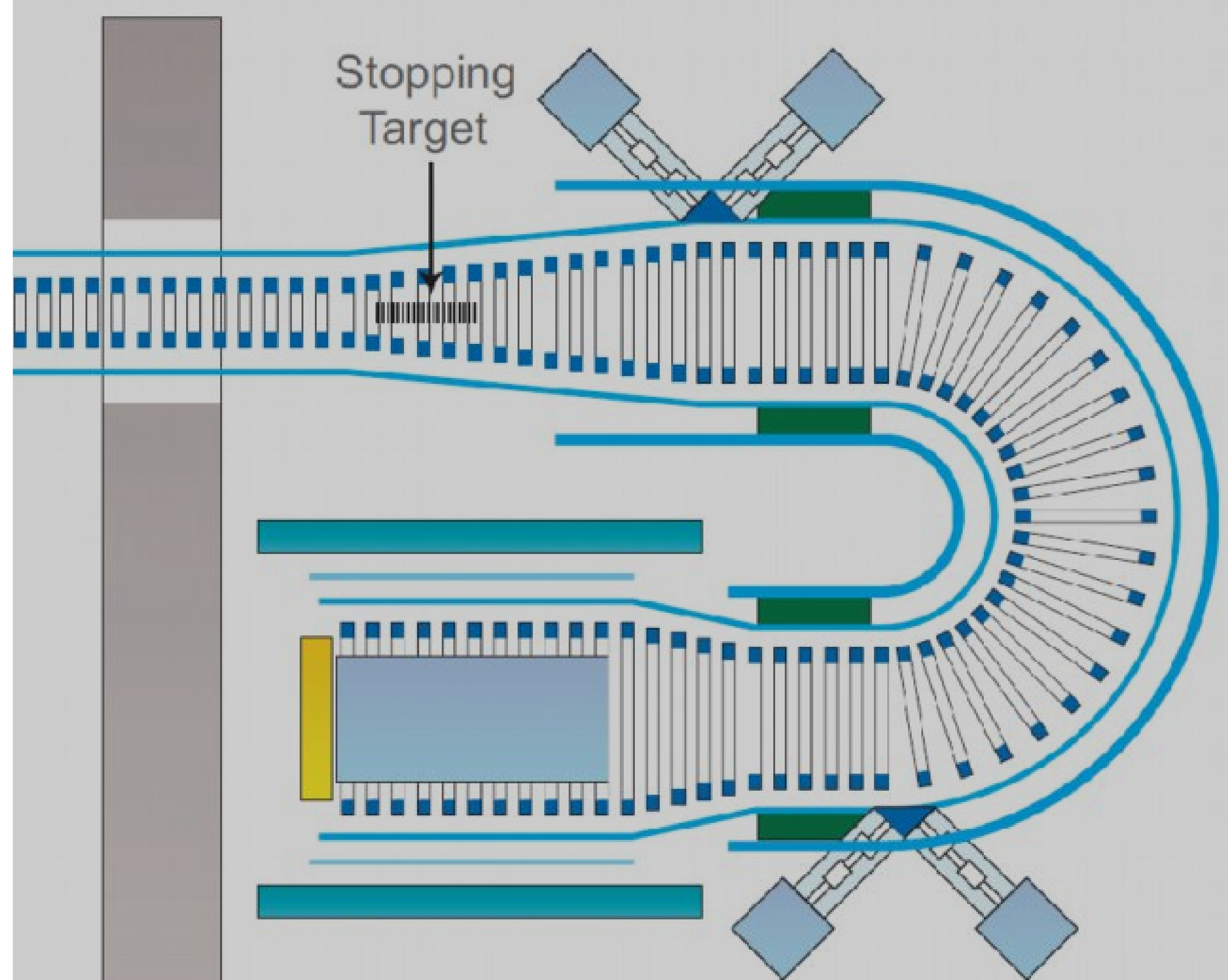
6.4×10^{13}
8 GeV
protons
per beam
spill, in
5.3×10^{5}
bunches

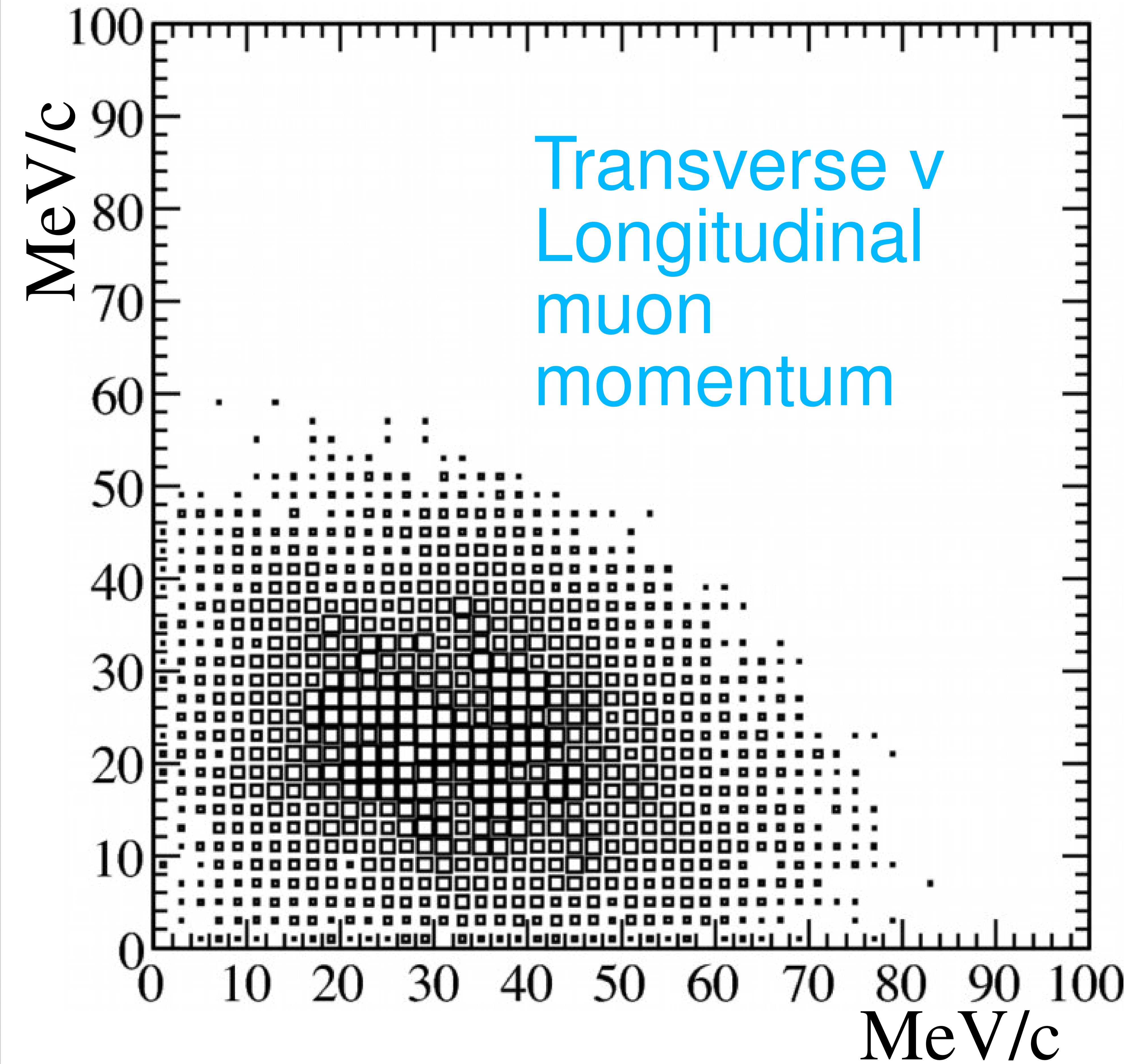


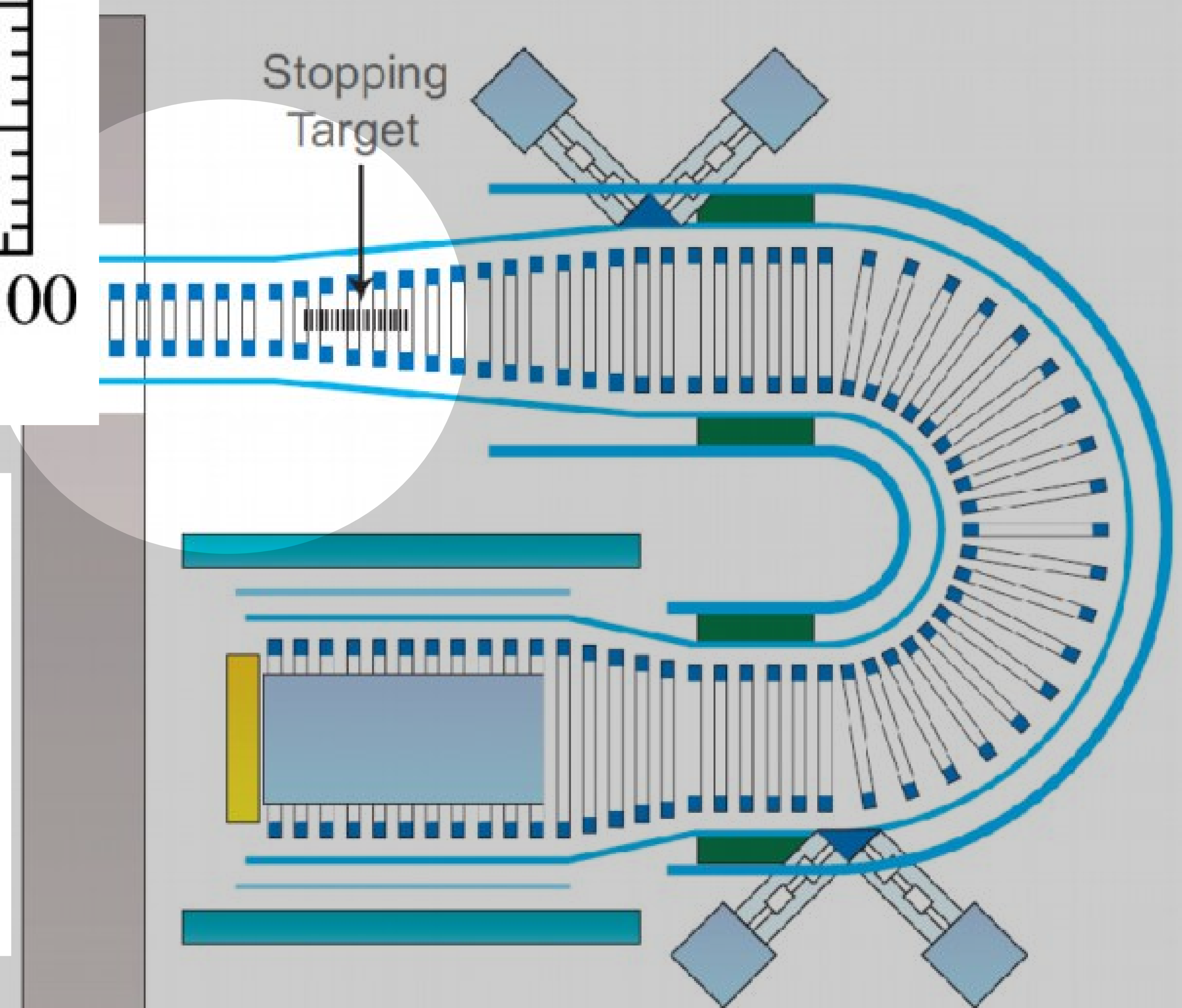
A few $\times10^{12}$ pions produced per spill (some physics uncertainty)

lower-energy, backward pions captured and sent to transfer solenoid





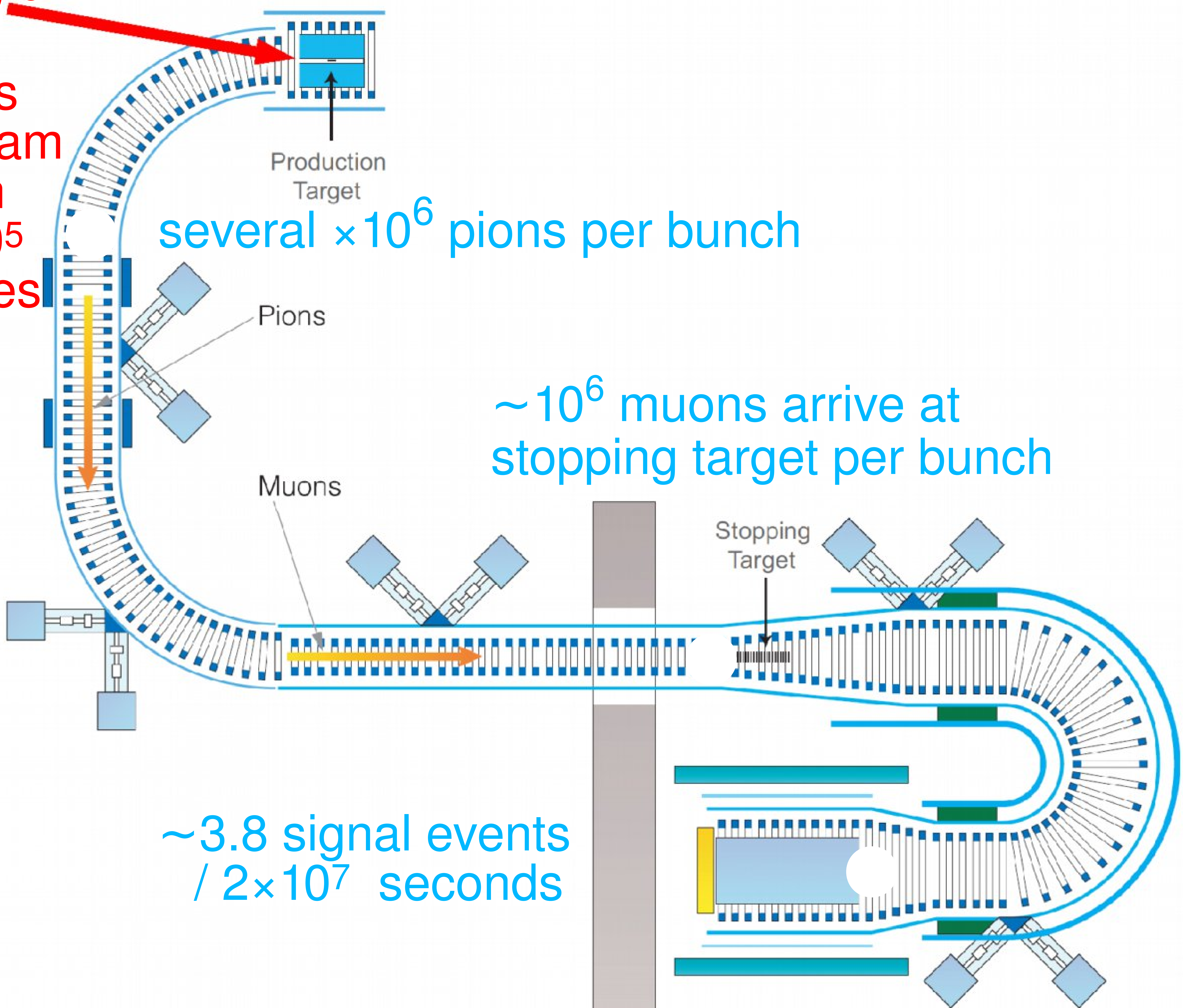




10^{10} to 10^{11} muons below 85 MeV/c arrive at stopping target per spill (current best is 10^8/sec at PSI)

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

several $\times 10^{6}$ pions per bunch

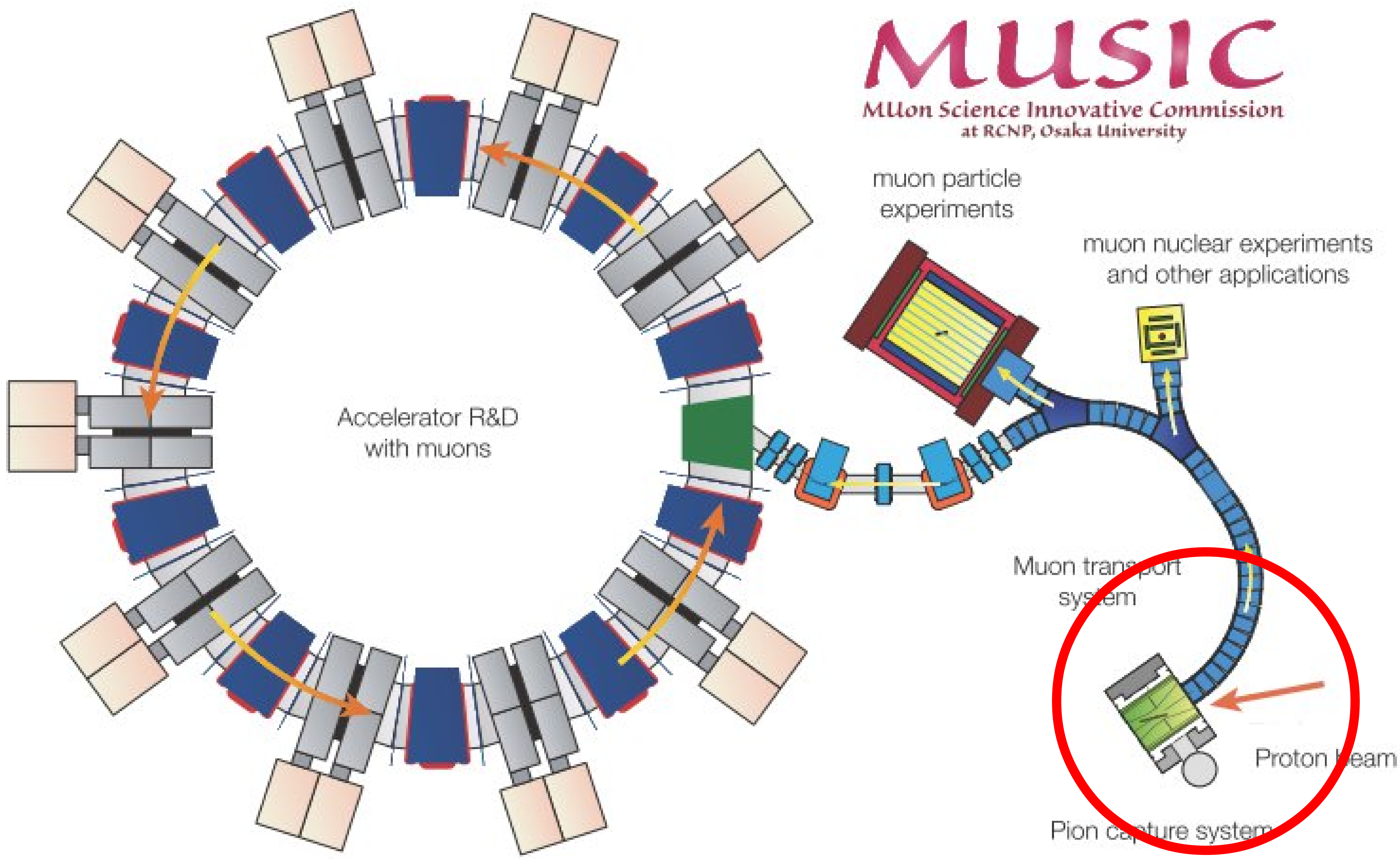


$\sim 10^{6}$ muons arrive at
stopping target per bunch

$\sim$3.8 signal events
/ $2{\times}10^{7}$ seconds

Background Breakdown from COMET CDR (July 2009)

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



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

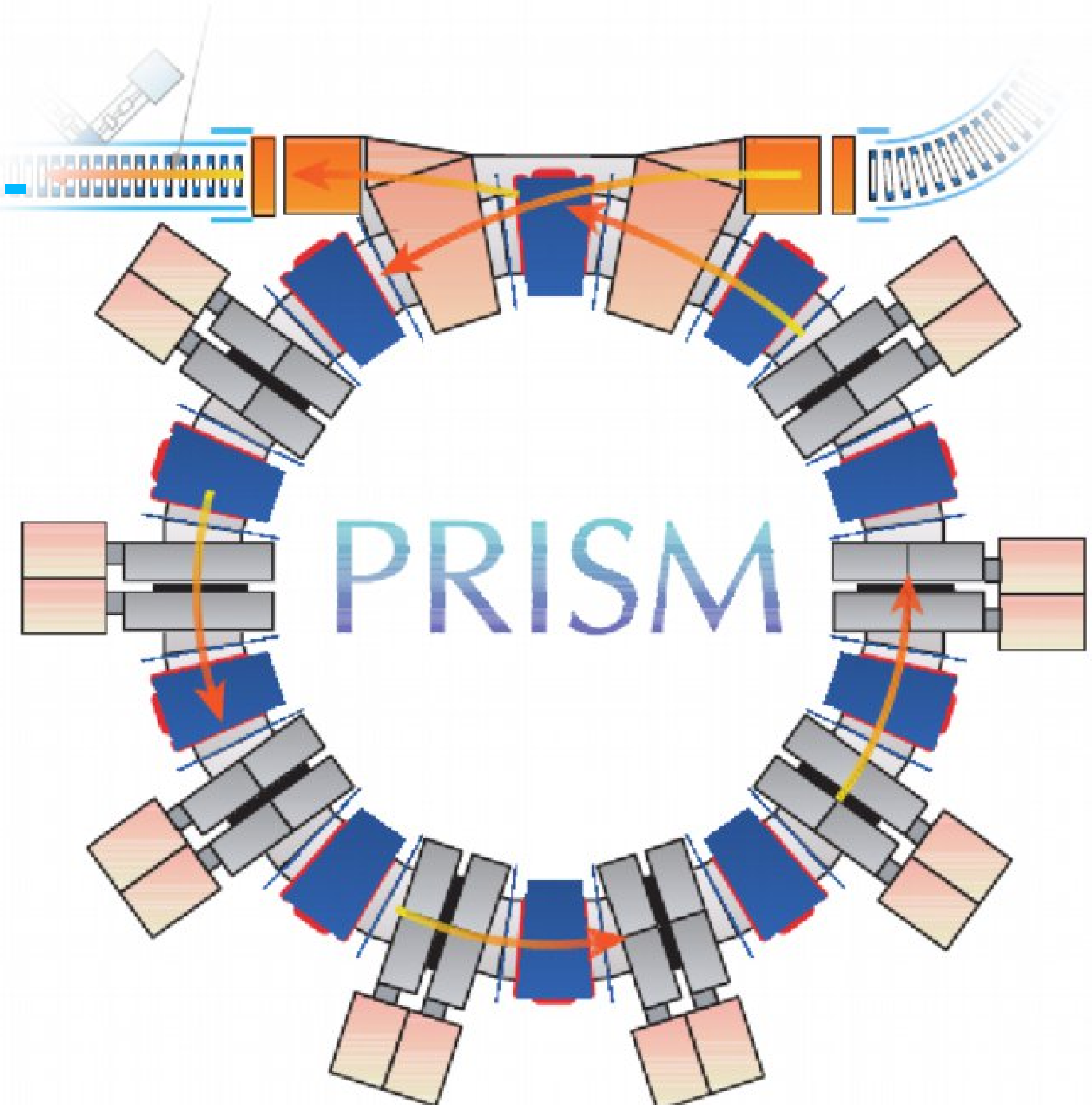
PRISM/FFAG

Muon Storage Ring

- **high acceptance**
  H: 40000 mm mrad
  V: 6500 mm mrad

- **phase-rotation produces mono-energetic beam**

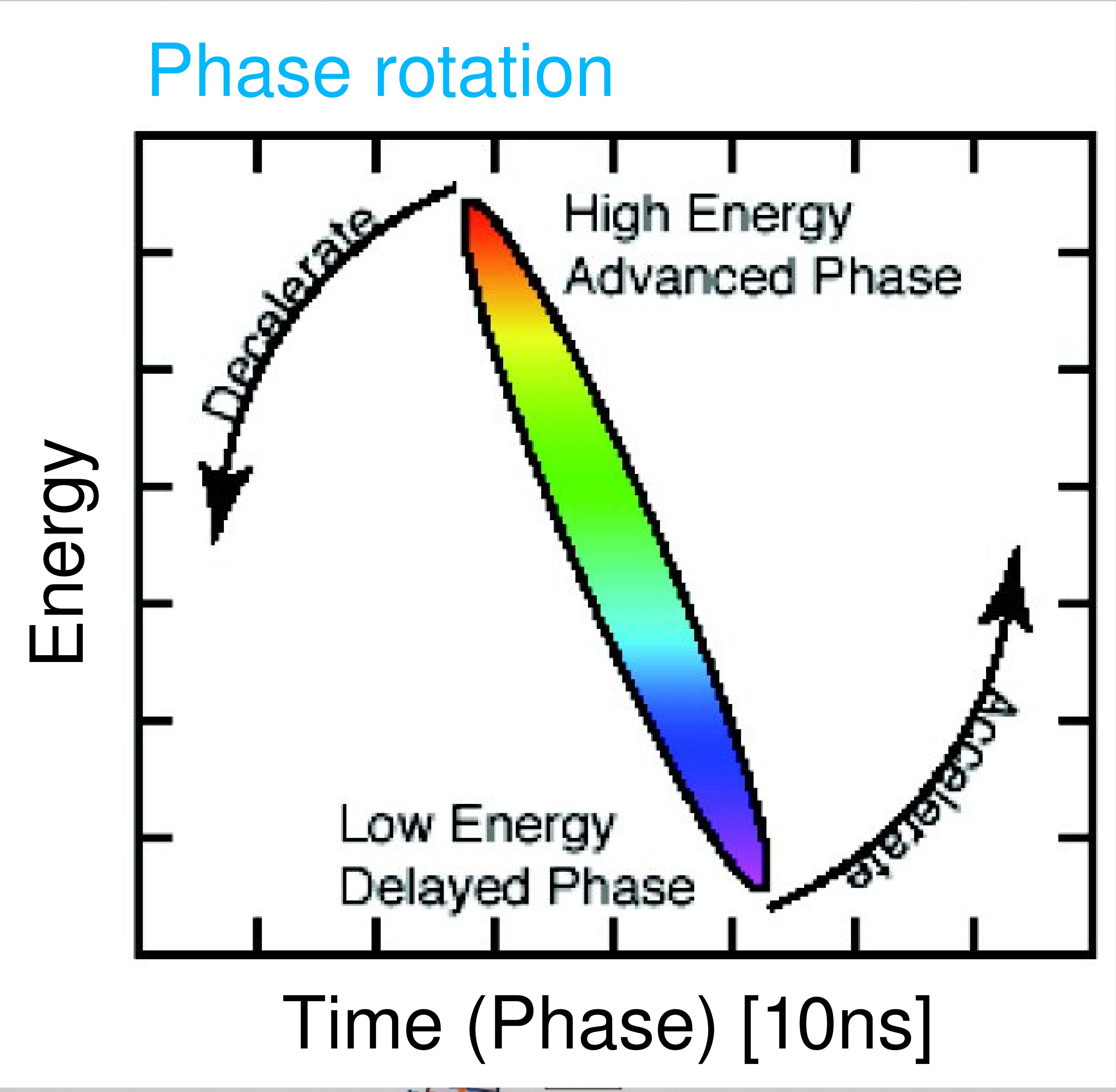
- **8 turns gives a 150m path length**

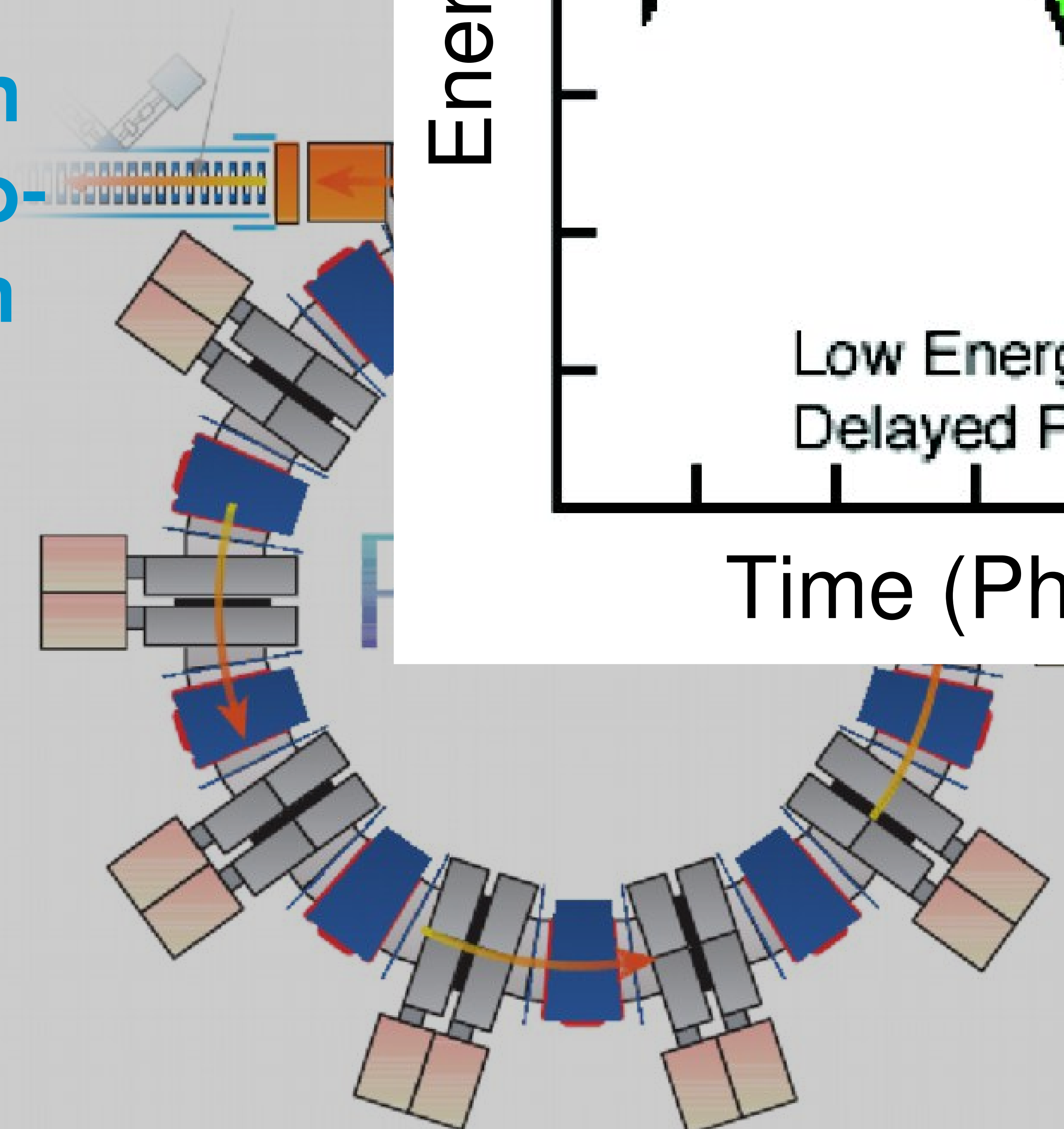


PRISM/FFAG

Muon Storage Ring

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

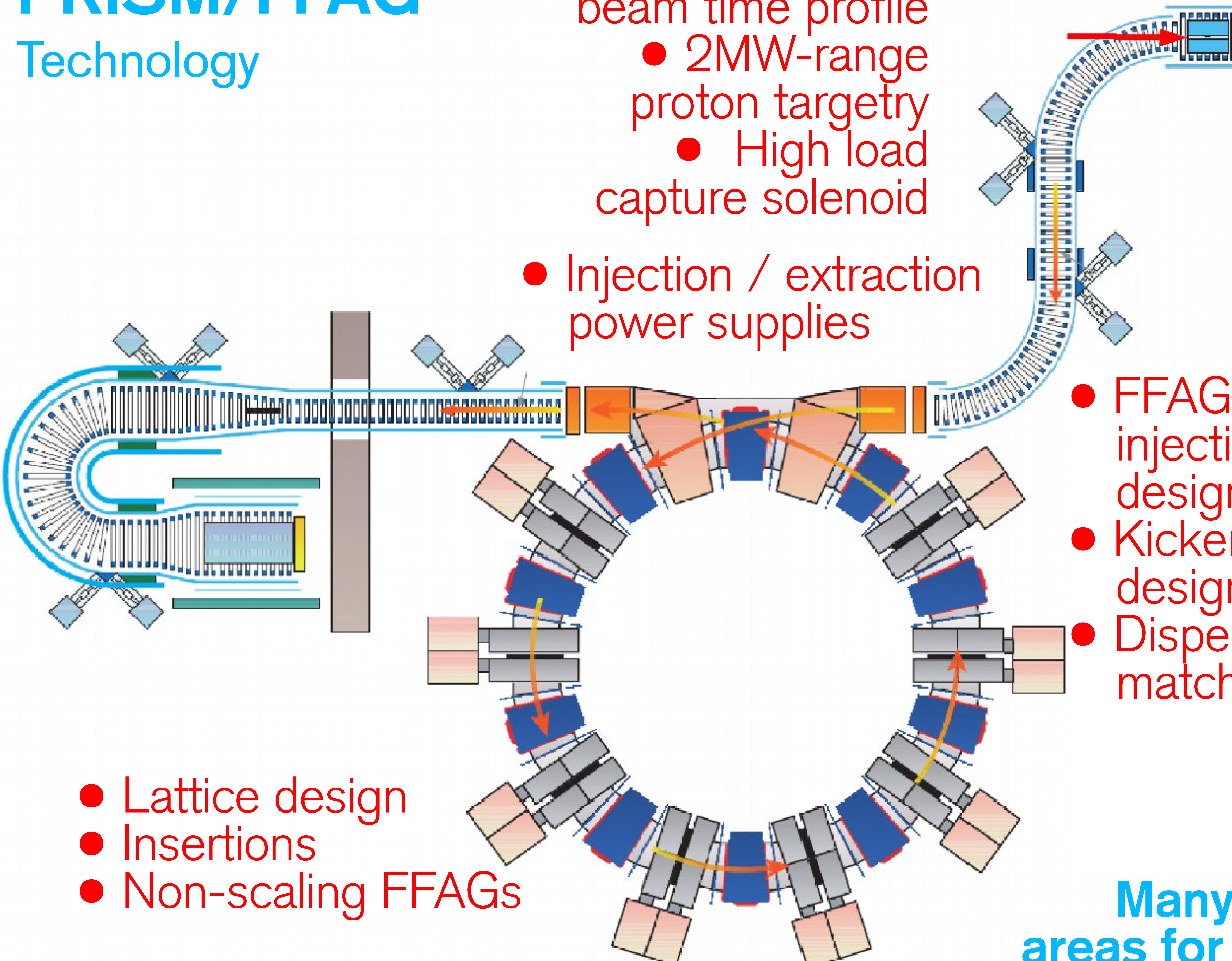




PRISM/FFAG

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