Search for Muon to Electron Conversion at J-PARC

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Tata Institute of Fundamental Research

Outline

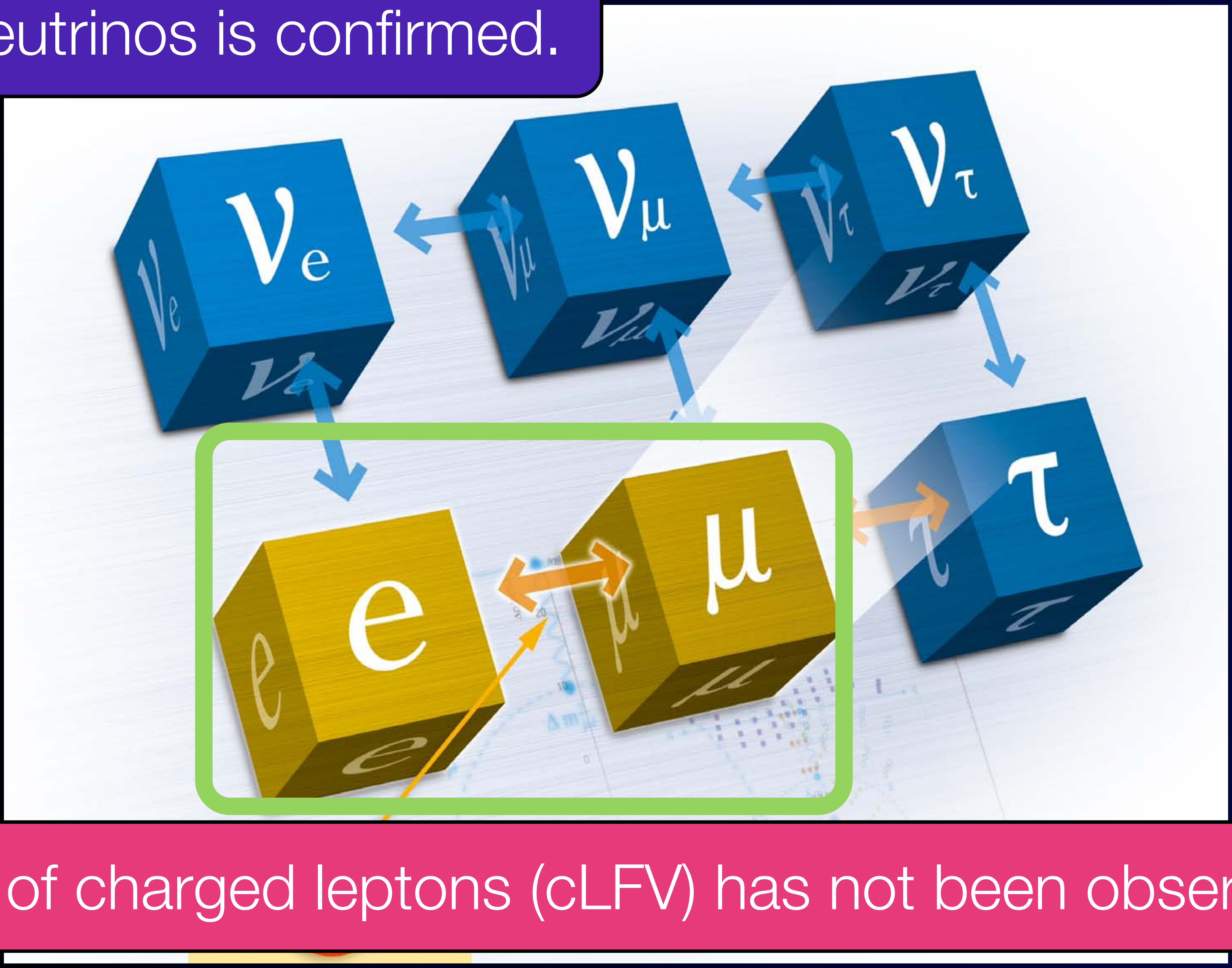
- Why Charged Lepton Flavor Violation (cLFV) ?
- COEMT experiment at J-PARC
- Summary

Why
Charged Lepton
Flavor Violation ?

Shinagawa

What is Lepton Flavor Violation of Charged Leptons (cLFV) ?

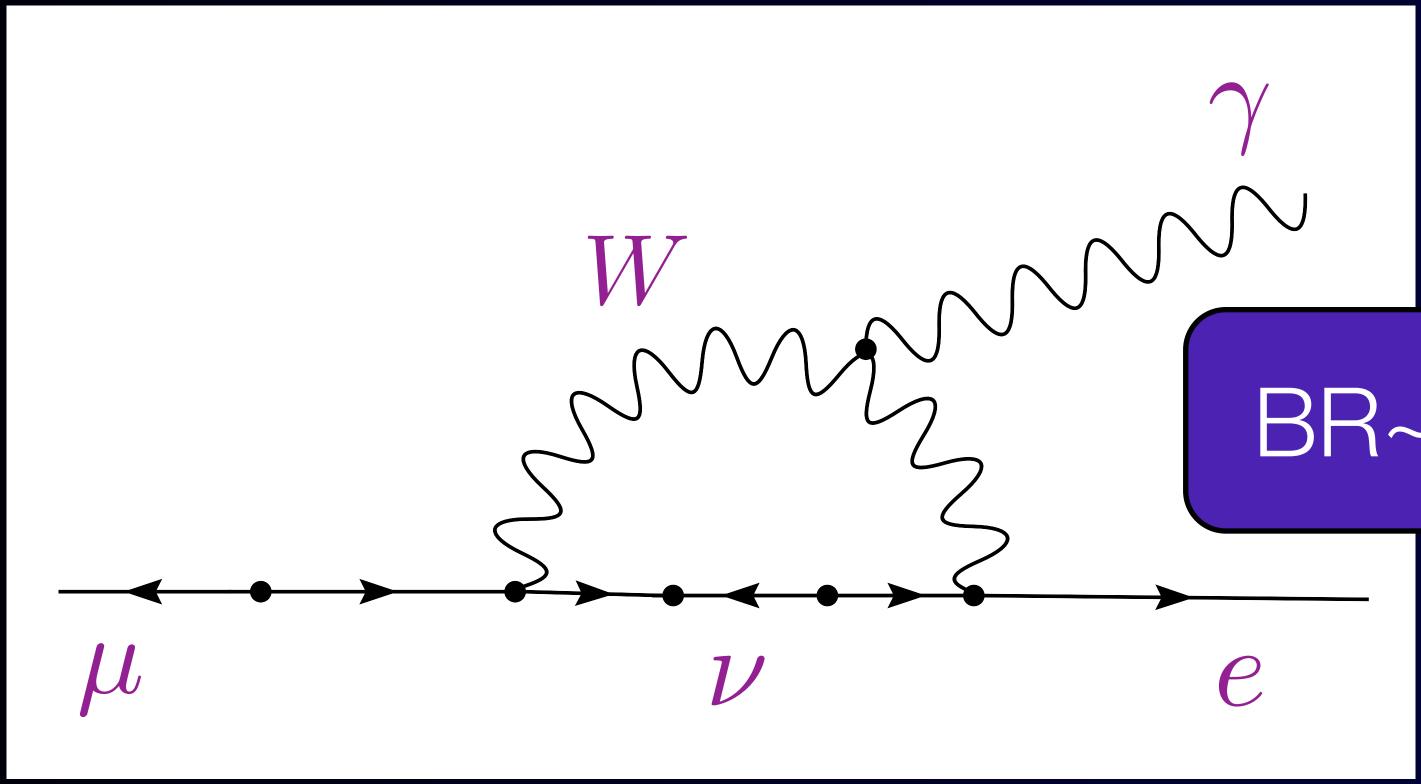
LFV of neutrinos is confirmed.



LFV of charged leptons (cLFV) has not been observed.

cLFV in the SM with massive neutrinos

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



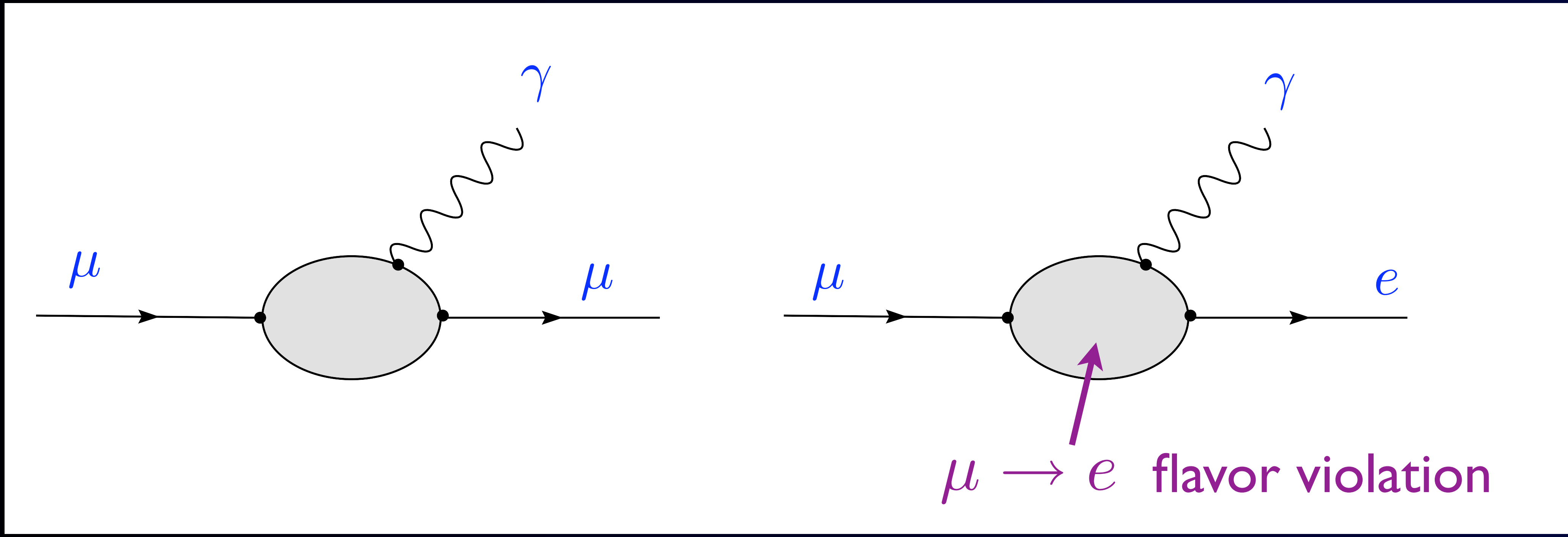
BR~O(10^{-54})

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

Relation of cLFV and muon anomalous g-2

$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (27.6 \pm 8.1) \times 10^{-10} \quad 3.4\sigma$$

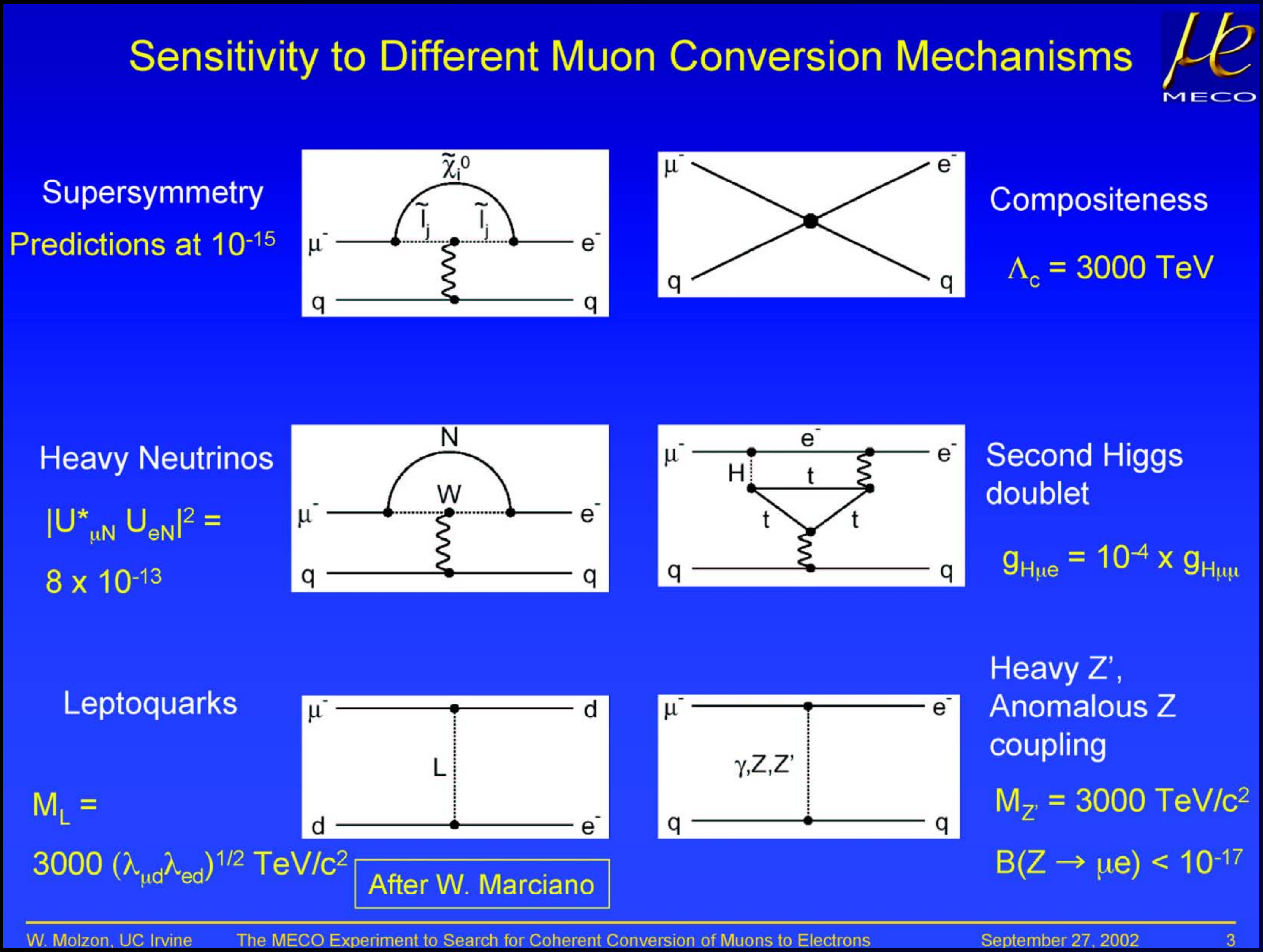
$$\delta a_\mu^{\rm EW} = (15.4 \pm 0.2) \times 10^{-10}$$



2

New physics contributing to muon g-2 would also contributes to cLFV.

Various Models Predict Charged Lepton Mixing.



New Physics Search Rating (a la Prof. Dr. A. Buras)

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, .
Nucl.Phys.B830:17-94 ,2010.

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

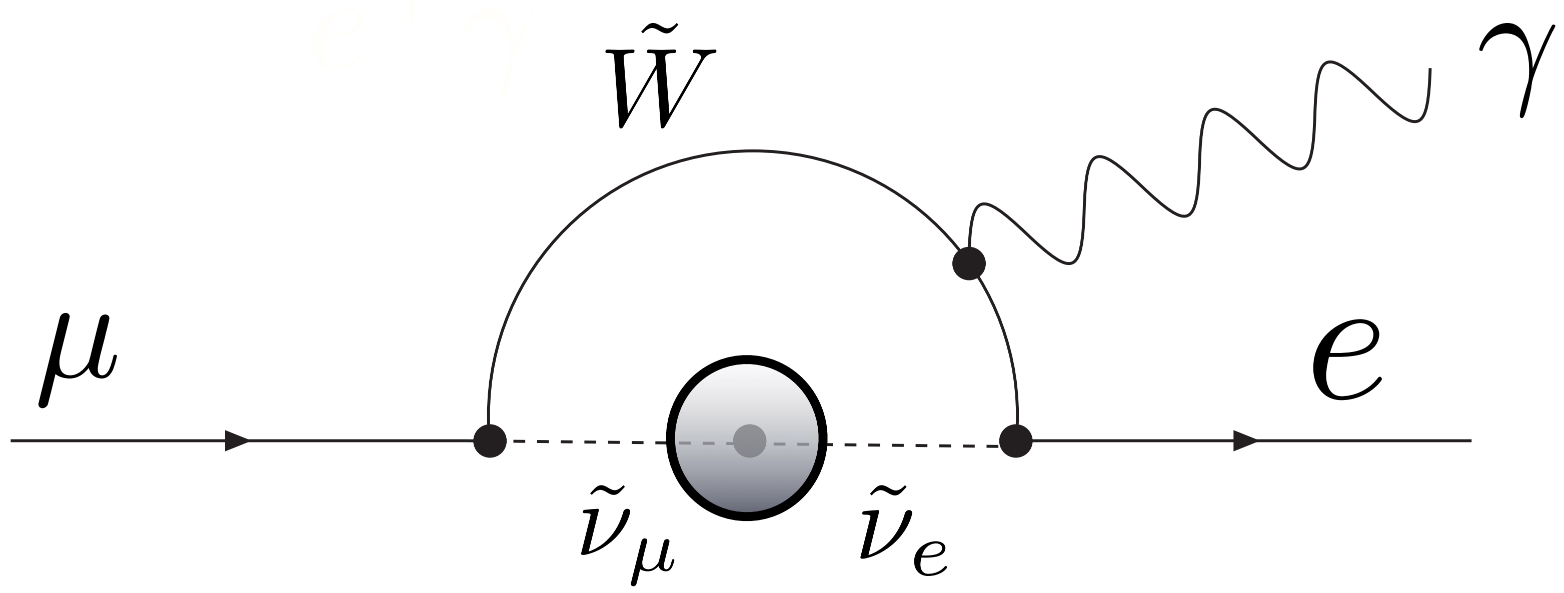
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Different theoretical models

All three stars for "muon to electron conversion"

LFV in SUSY Models

an example diagram



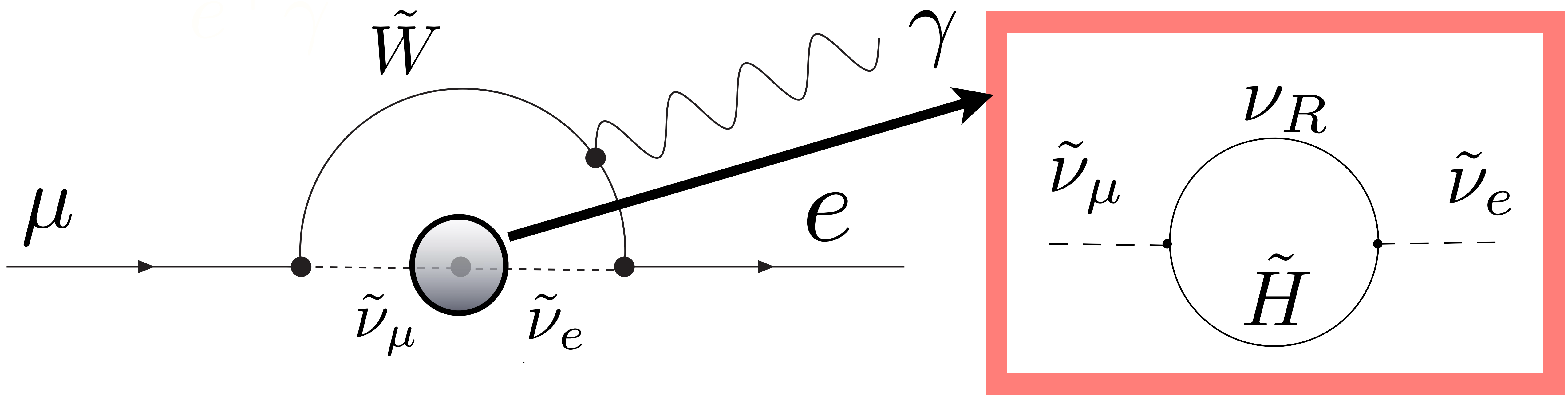
Since neutrinos are mixed & LFC is violated, sleptons can mix.

$$\mathrm{BR}(\mu \to e\gamma) \simeq 1 \times 10^{-11} \left(\frac{150\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \left(\frac{\tan\beta}{20}\right)^2 \left(\frac{\Delta_{21}}{3 \times 10^{-4}}\right)^2$$

LFV in SUSY Models

an example diagram

Slepton Mixing



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Minimal SUSY Scenario

slepton mass matrix

$$m_{\tilde{l}}^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

$\Delta m_{ij}^2 = 0$ @ Planck energy scale

New physics at high energy scale would introduce off-diagonal mass matrix elements, resulting in slepton mixing.

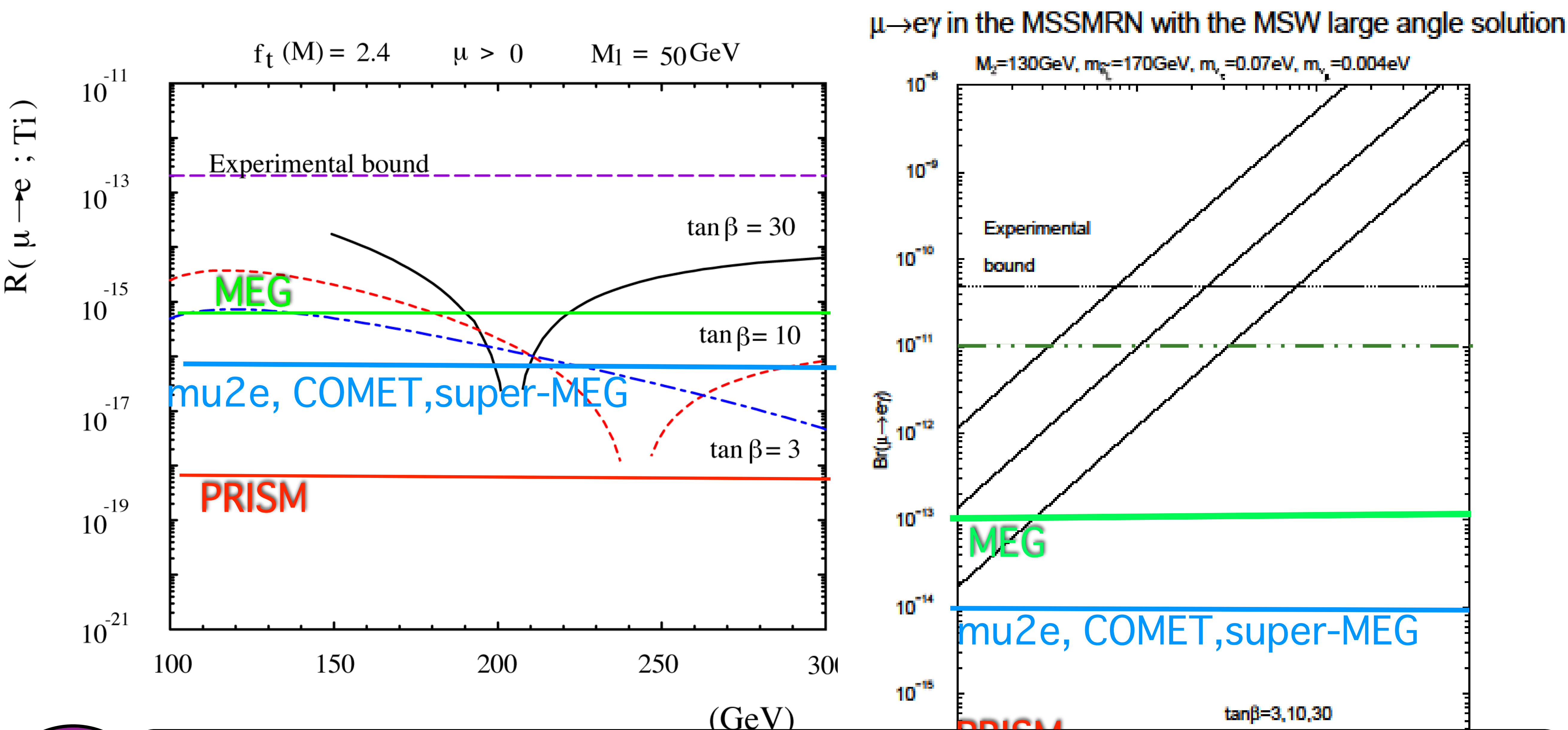
neutrino seesaw mechanism (~10^{15}GeV)

grand unification (GUT) (~10^{16}GeV)

$\Delta m_{ij}^2 \neq 0$ @ Weak energy scale (100 GeV)

4 cLFV have potential to study physics at very high energy scale like 10^{16} GeV.

SUSY Predictions for cLFV



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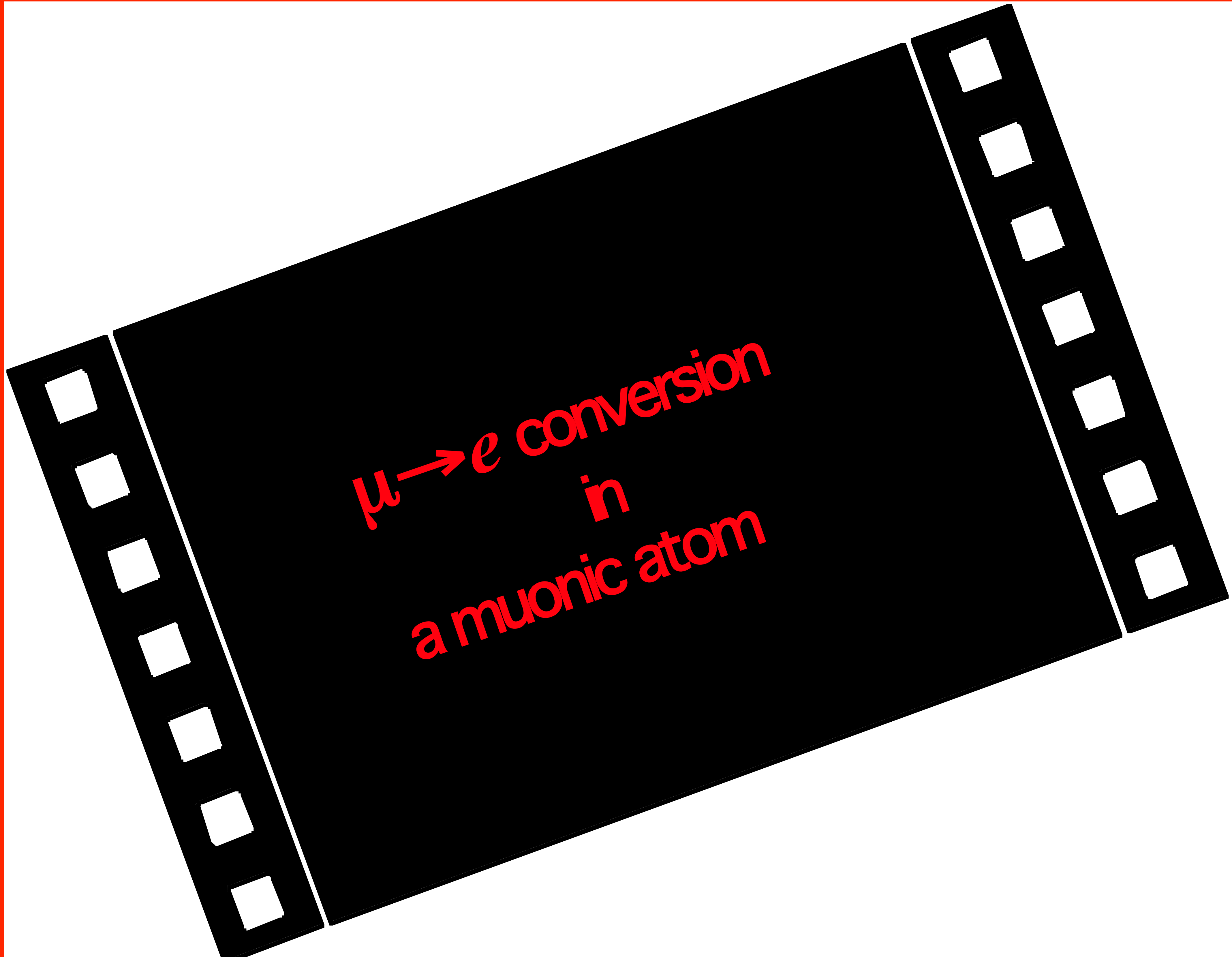
Theoretical predictions are just below the present experimental bound.

cLFV Physics Motivation Summary

1. Observation of cLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.
2. New physics contributing to muon g-2 would also contributes to cLFV.
3. The physics of cLFV is complementary to that of LHC and neutrino physics.
4. cLFV have potential to study physics at very high energy scale like 10^{16} GeV.
5. Theoretical predictions are just below the present experimental bound.

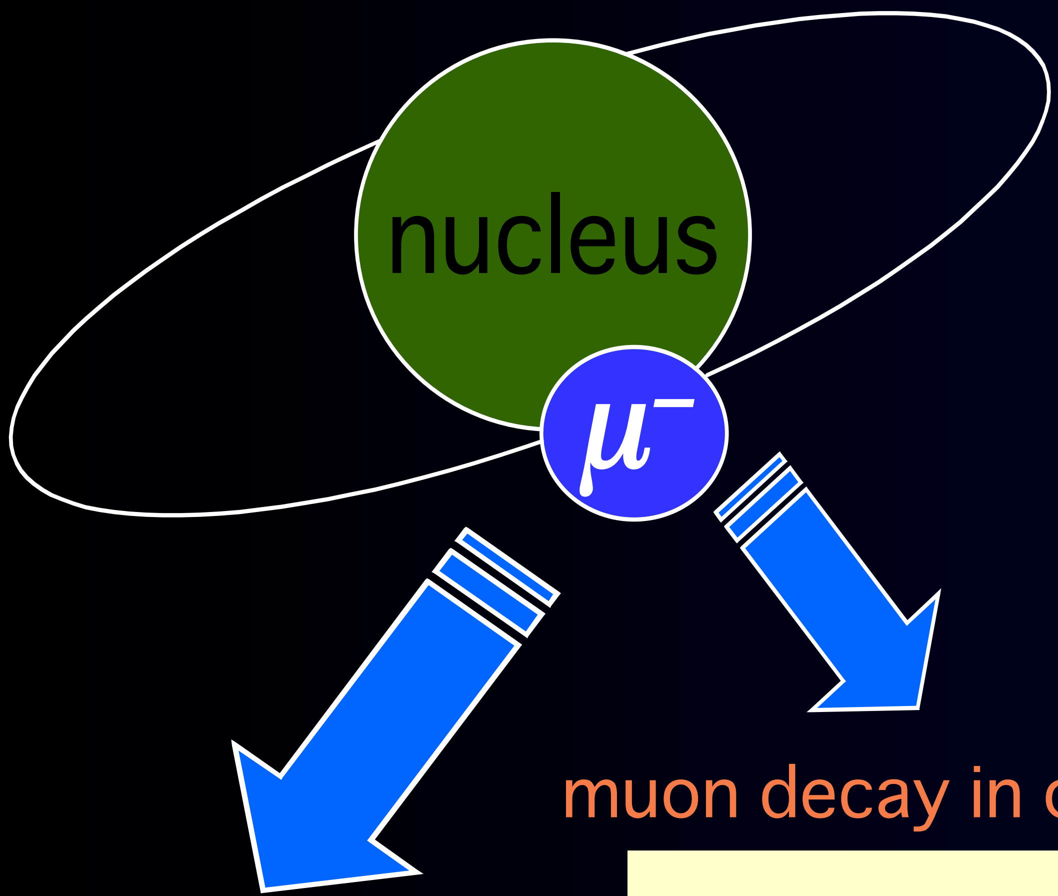
cLFV Experiments

at Kawasaki


μ→e conversion
in
a muonic atom

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture (=μ-e conversion)

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

lepton flavors changes by one unit.

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

μ-e Conversion Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

$$m_\mu - B_\mu \sim 105MeV$$

- The transition to the ground state is a coherent process, and enhanced by a number of nucleus.

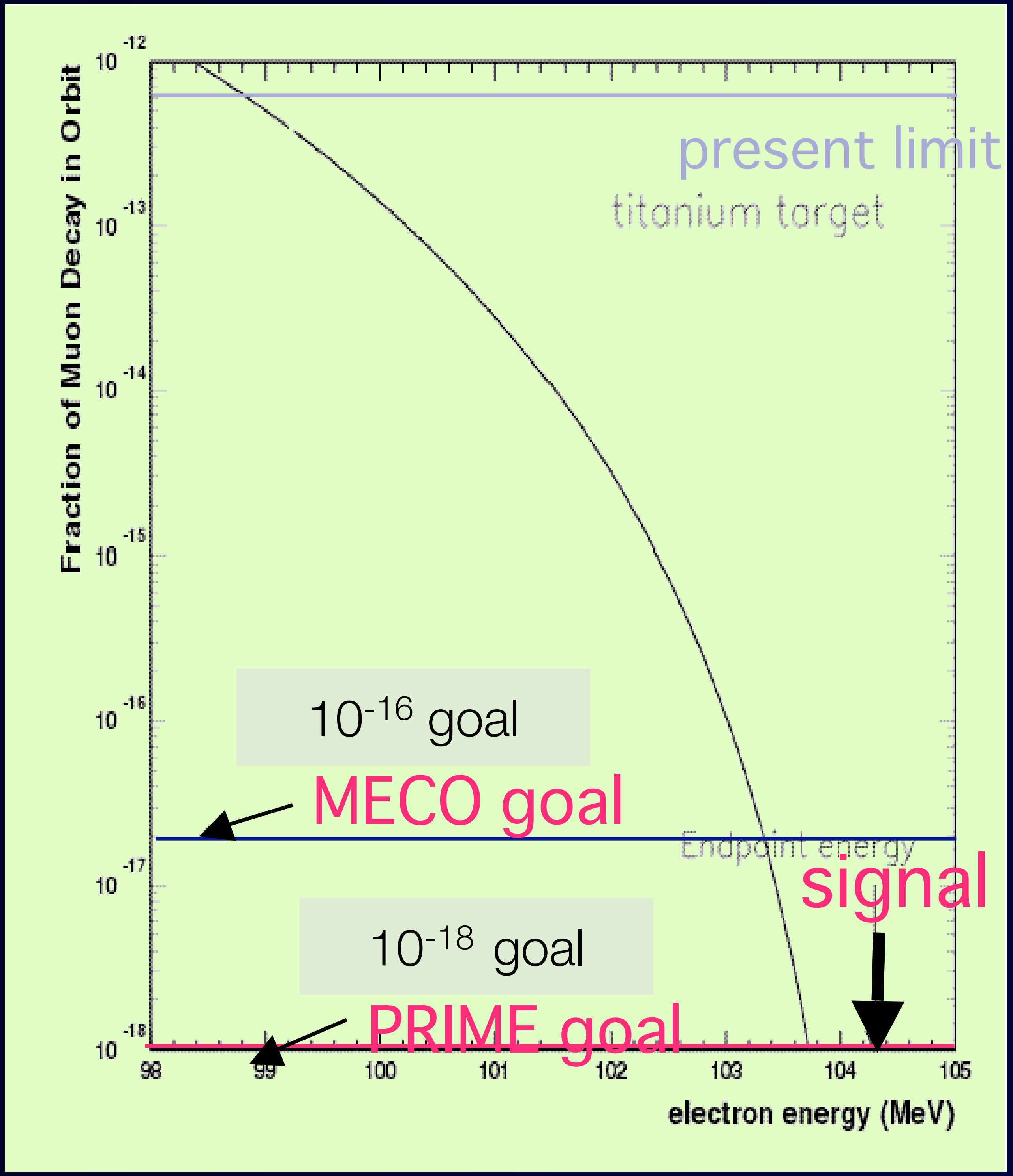
$$\propto Z^5$$

- Backgrounds
  - Intrinsic physics background
    - muon decay in orbit (DIO)
  - beam-related background
    - radiative pion capture
    - muon decay in flight (DIF)
  - cosmic-ray background
  - tracking failure
  - etc....

Muon Decay In Orbit (DIO) in a Muonic Atom

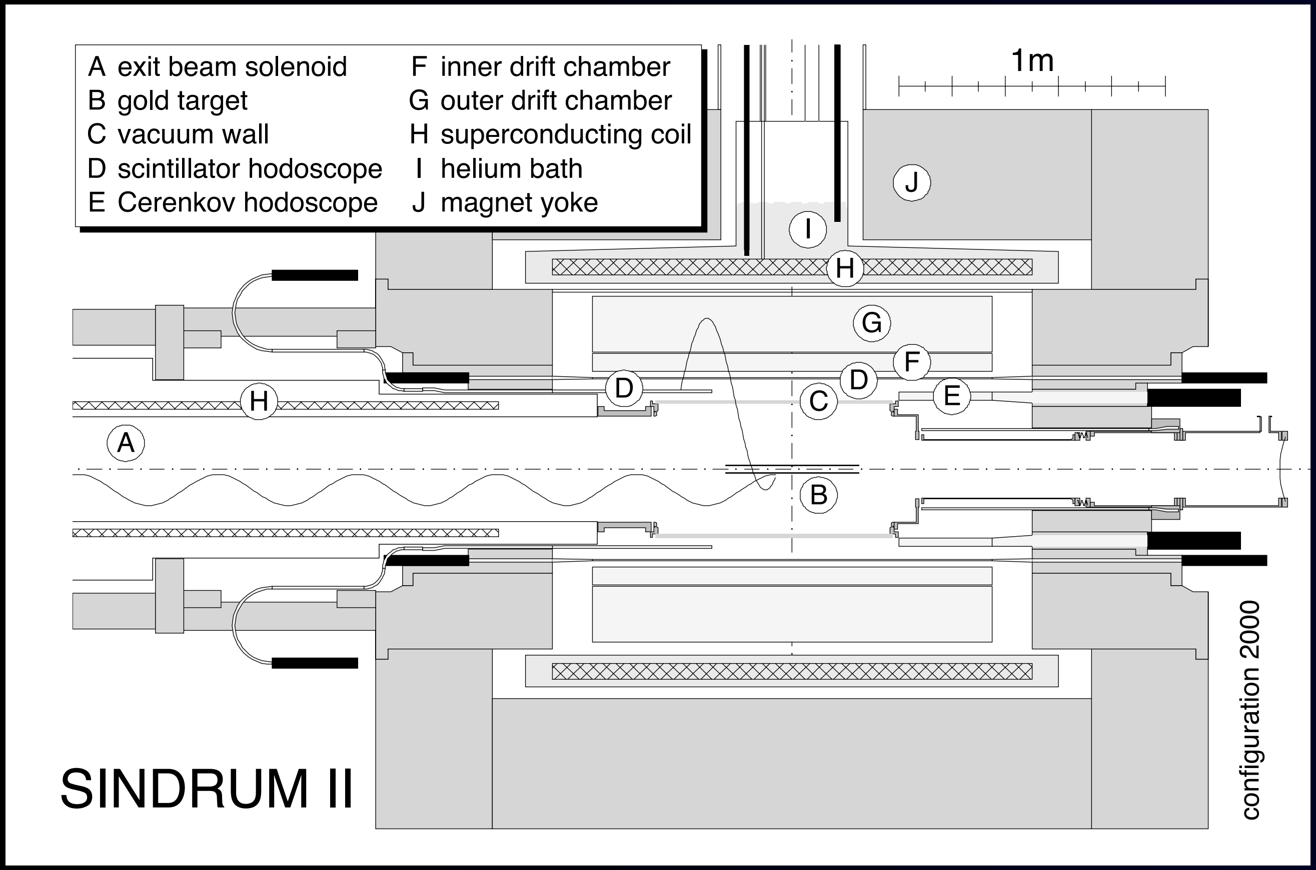
- Normal muon decay has an endpoint of 52.8 MeV, whereas the end point of muon decay in orbit comes to the signal region.
- good resolution of electron energy (momentum) is needed.

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



Previous Measurements

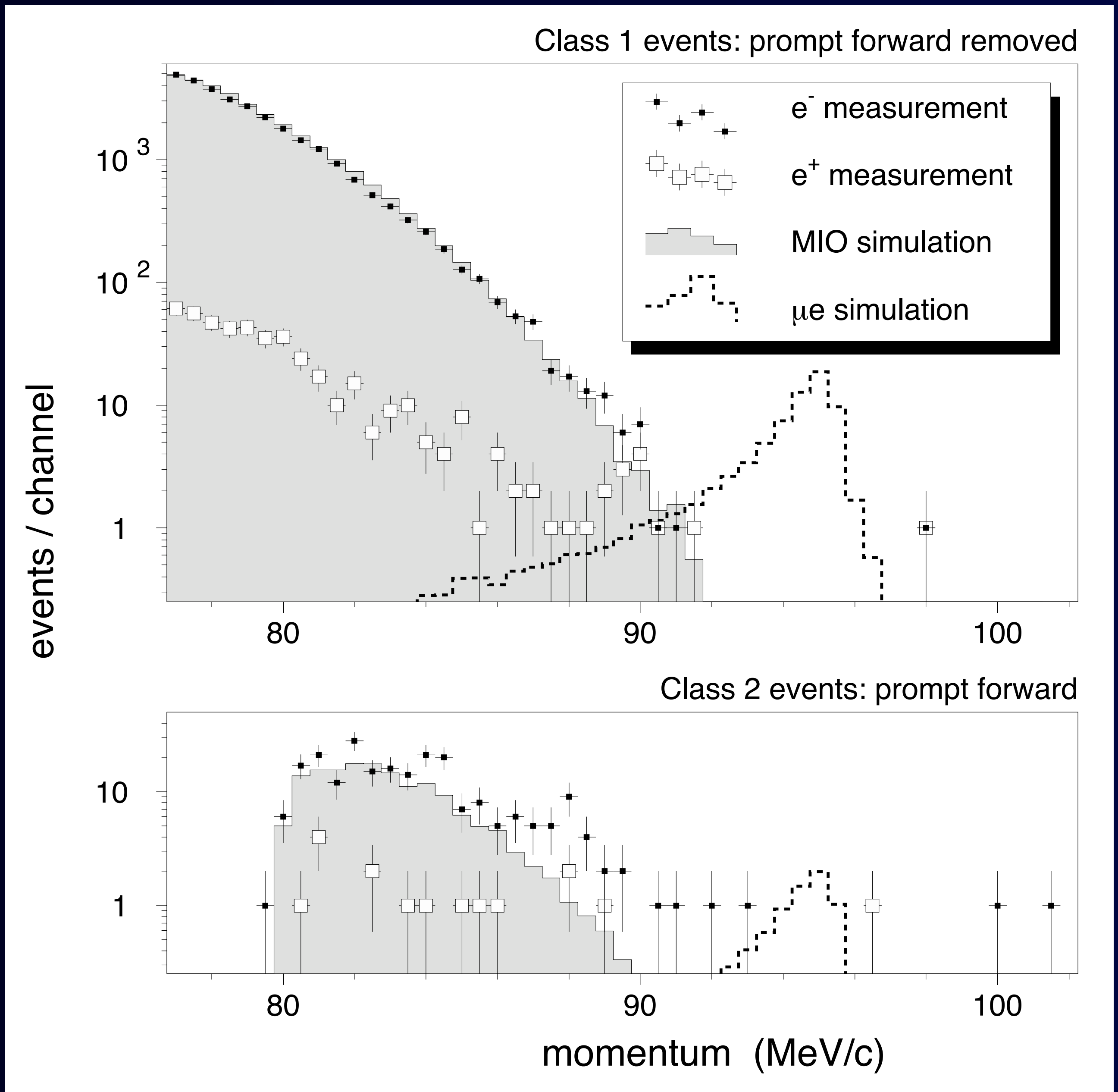
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

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



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

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

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

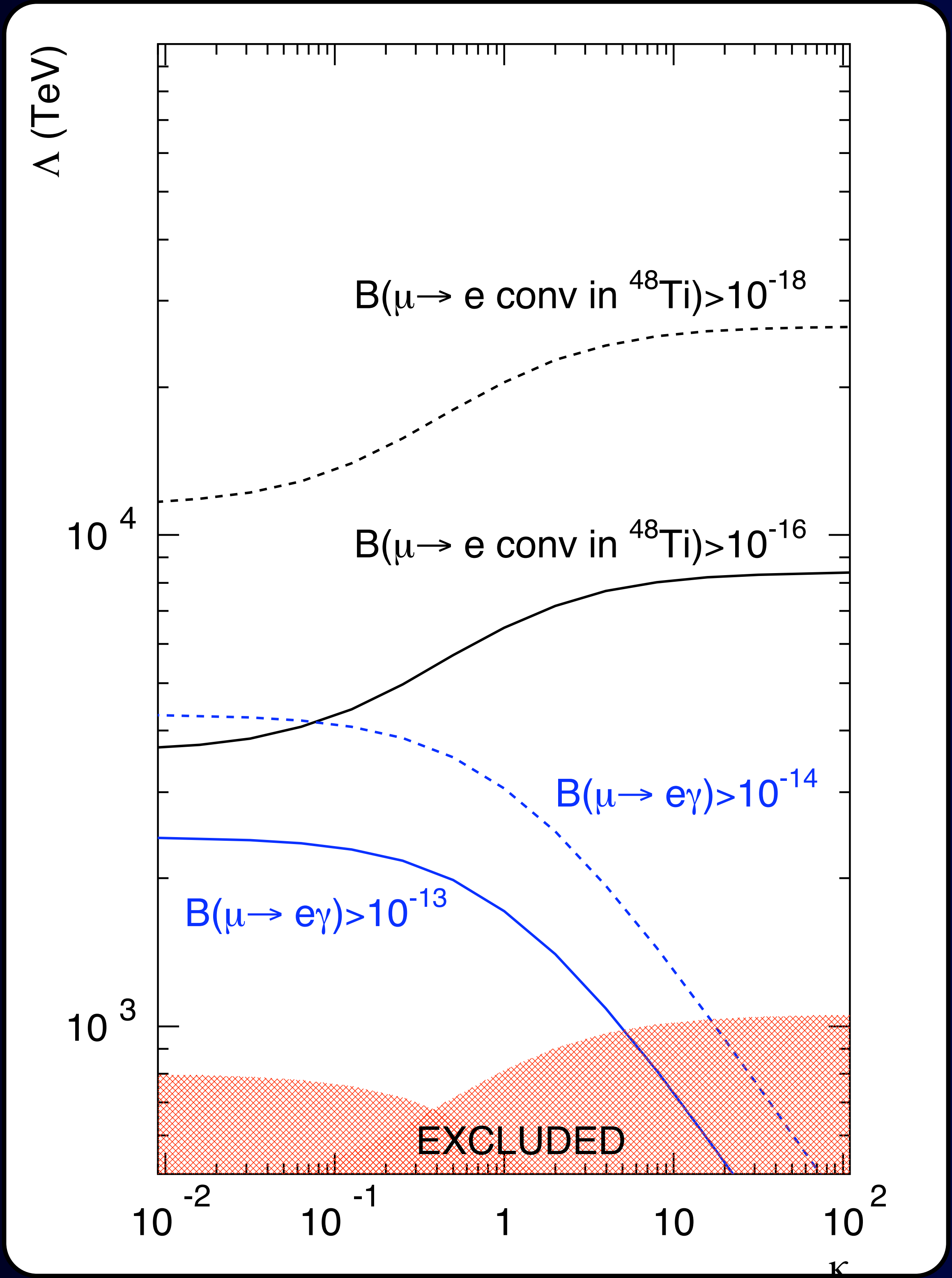
μ-e conversion might be a next step.

Physics Sensitivity Comparison between μ→eγ and μ-e Conversion

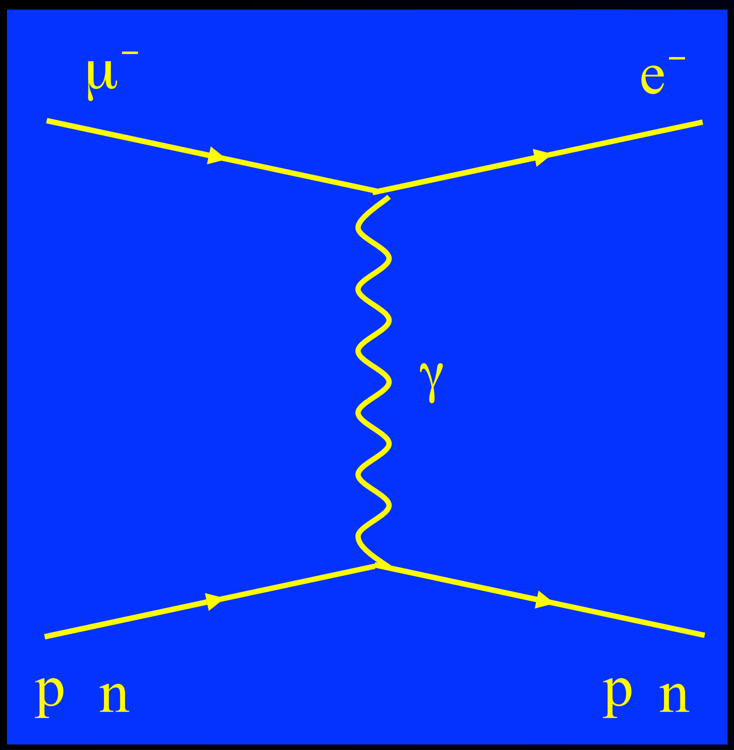
Photonic (dipole) and non-photonic contributions

	photonic (dipole)	non-photonic
μ→eγ	yes (on-shell)	no
μ-e conversion	yes (off-shell)	yes

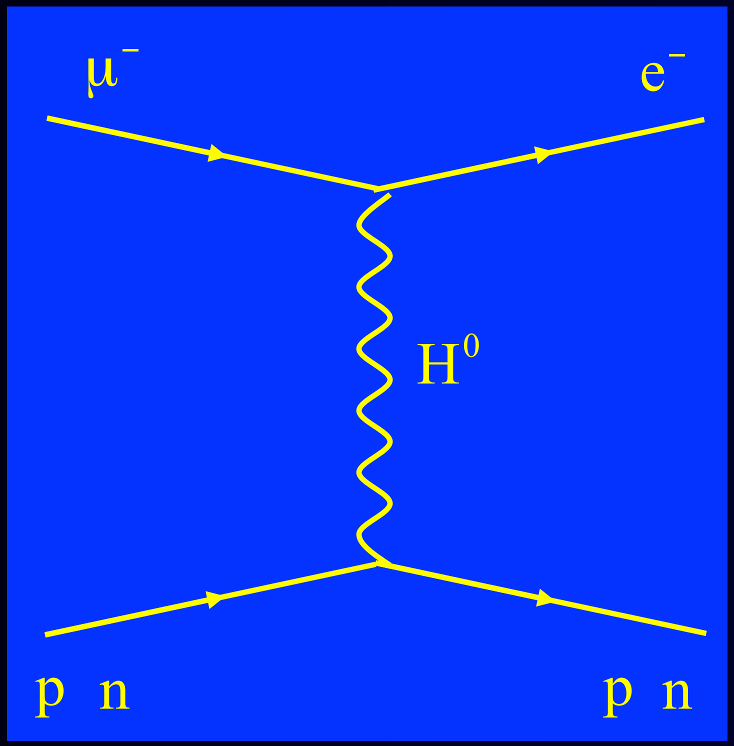
more sensitive to new physics



SUSY Higgs Mediated Contribution (large tanβ)

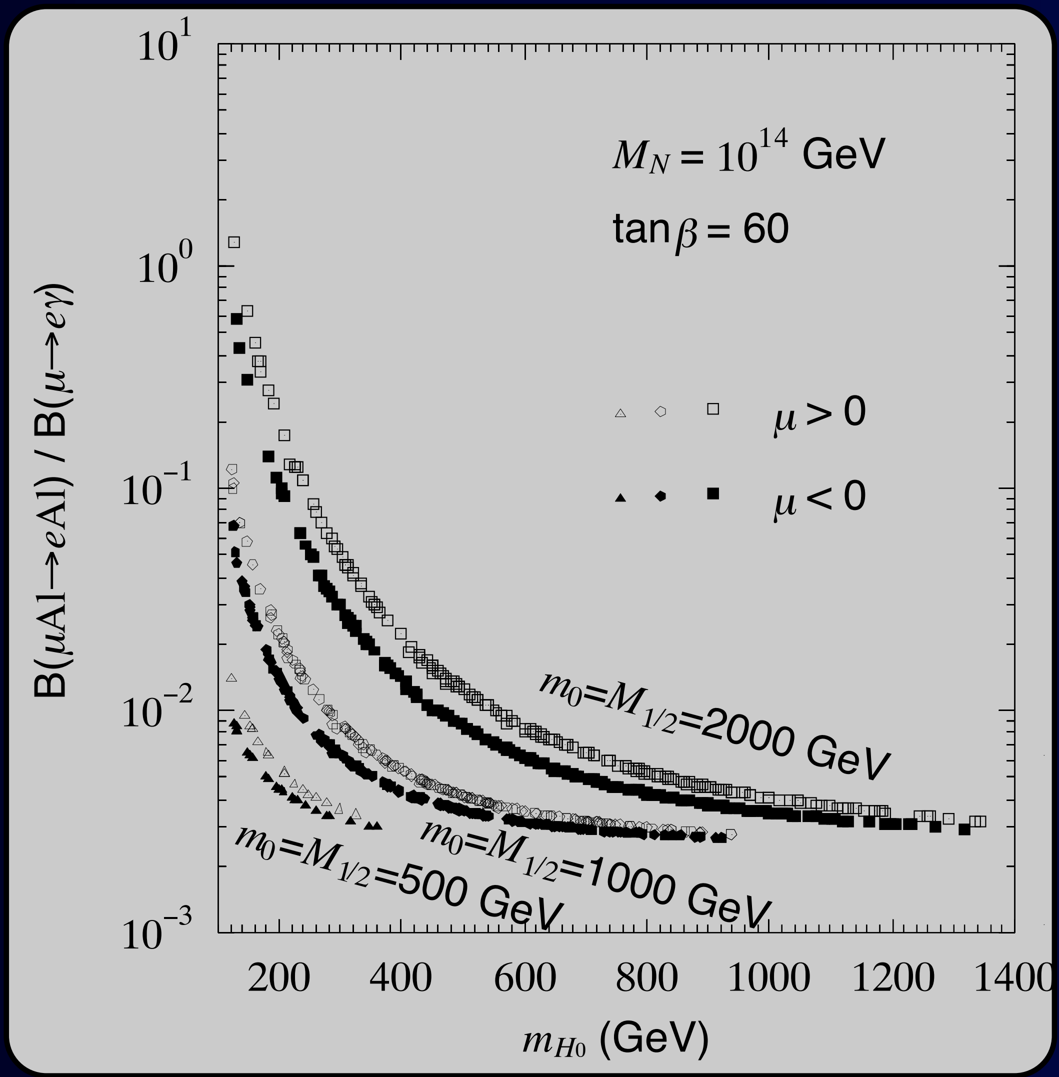


$$\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \sim \frac{1}{100}$$

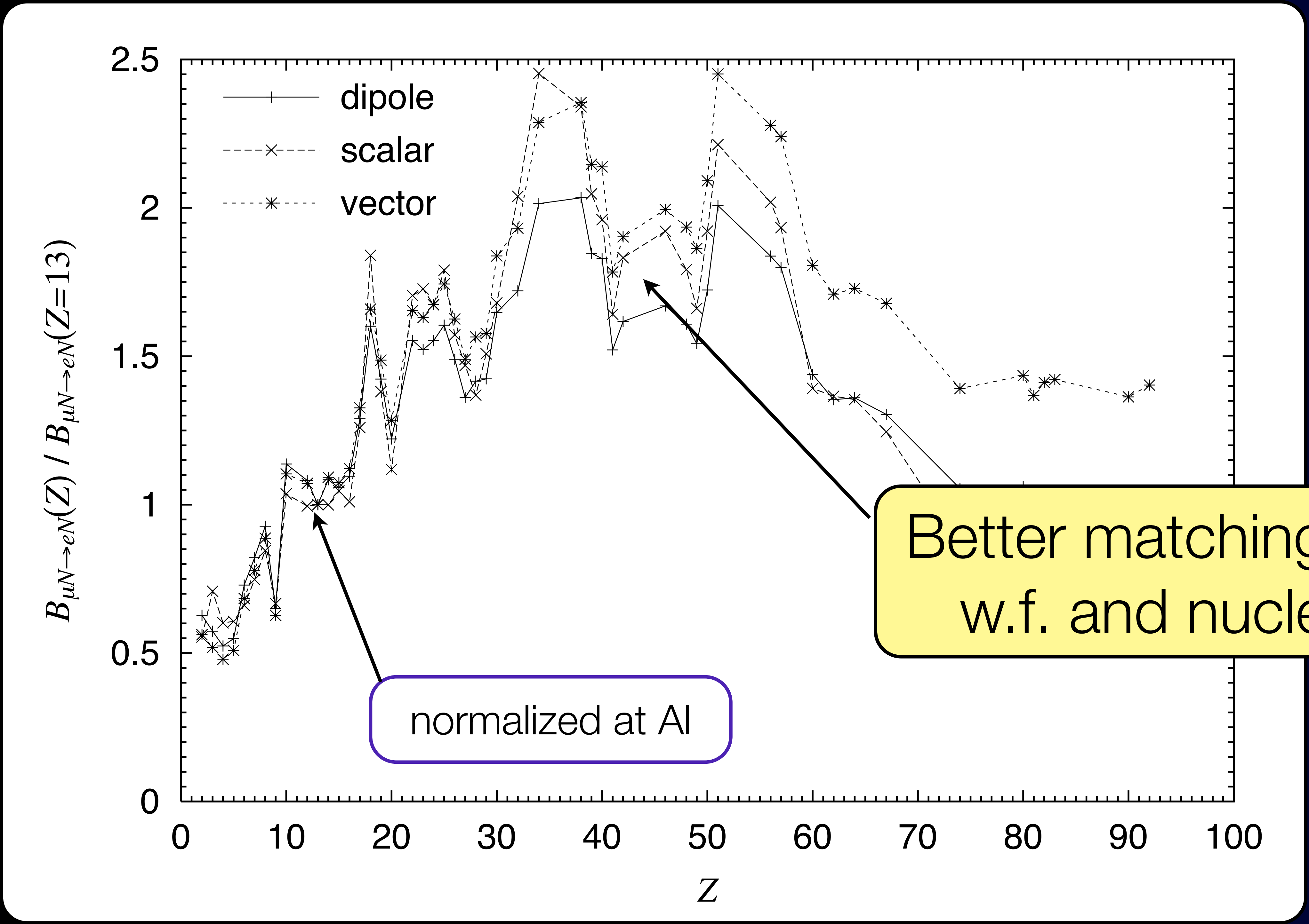


$$\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \sim O(1)$$

R. Kitano, M. Koike, S. Komine and Y. Okada, Phys. Lett. B575, 300 (2003)



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



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

Experimental Design for Muon to Electron Conversion

at Tenryu river, Shizuoka

Improvements for Signal Sensitivity

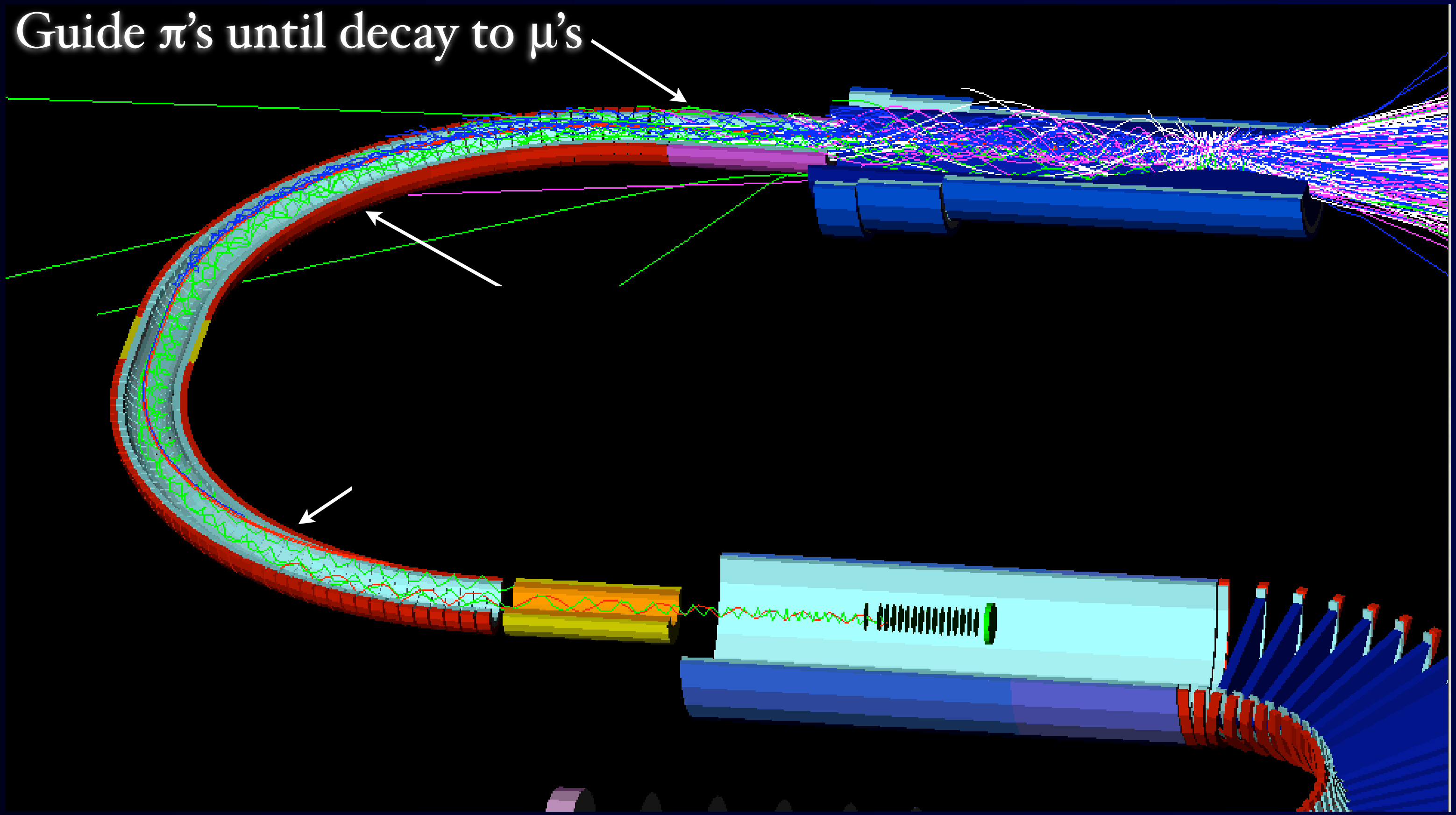
To achieve a single sensitivity of 10^{-16}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10^{11} muons for 50 kW beam power)



Improvements for Background Rejection

Beam-related backgrounds → Beam pulsing with separation of 1μsec

measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse < 10^{-9}

Muon DIO background → low-mass trackers in vacuum & thin target

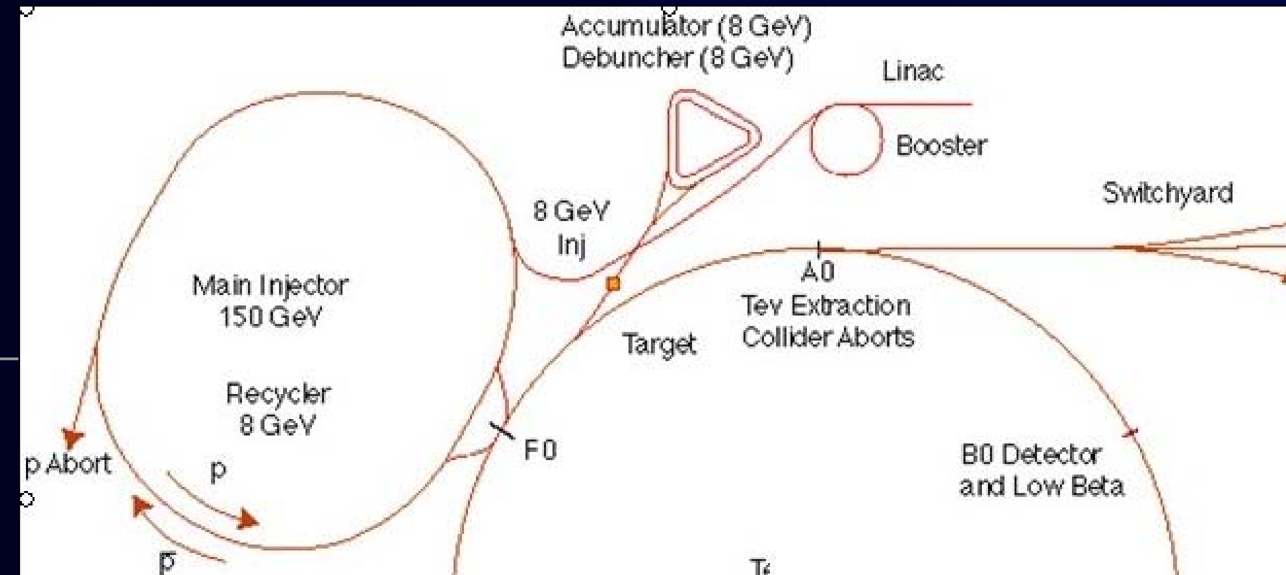
improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection

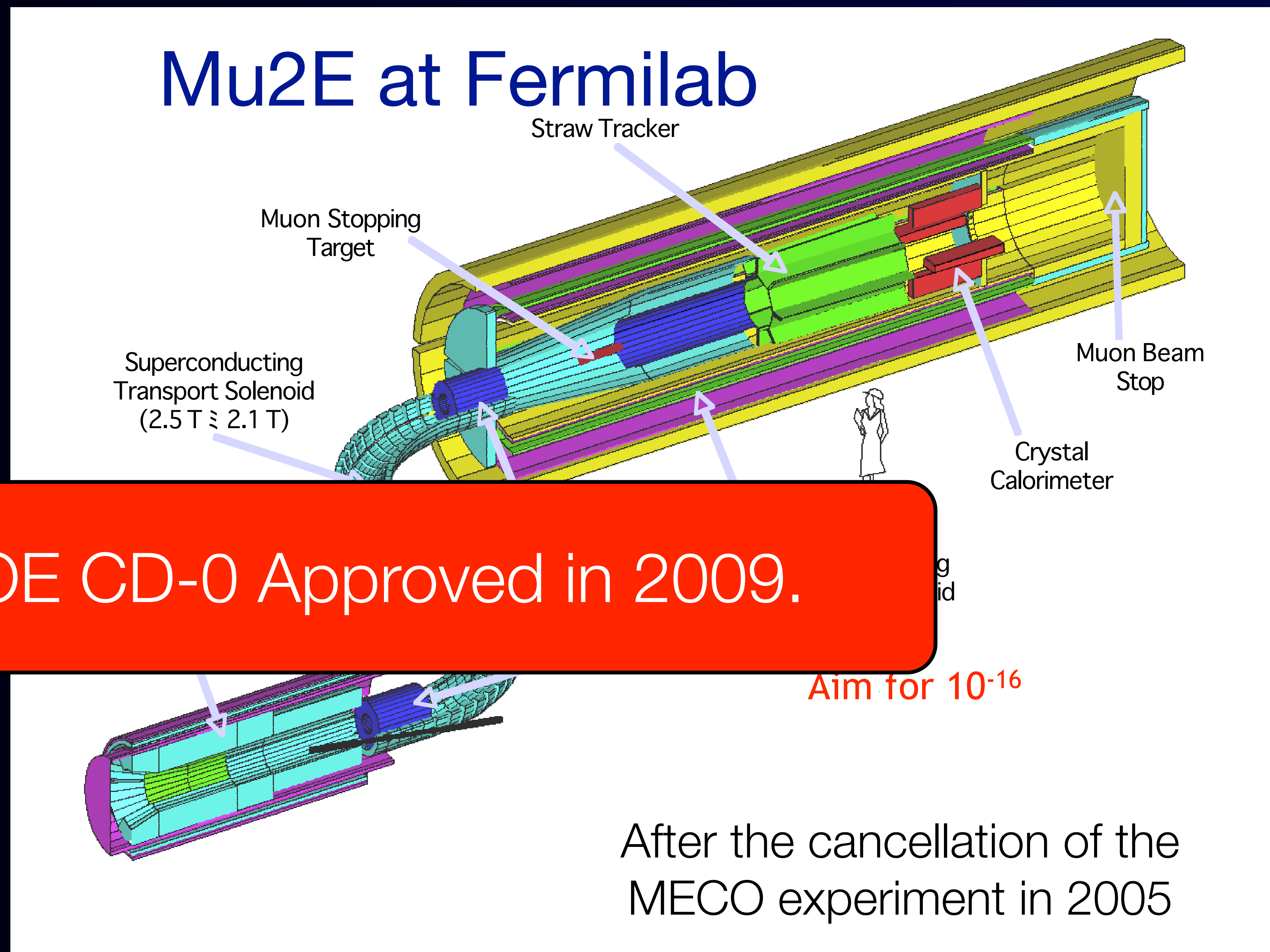
eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

Mu2E
at Fermilab



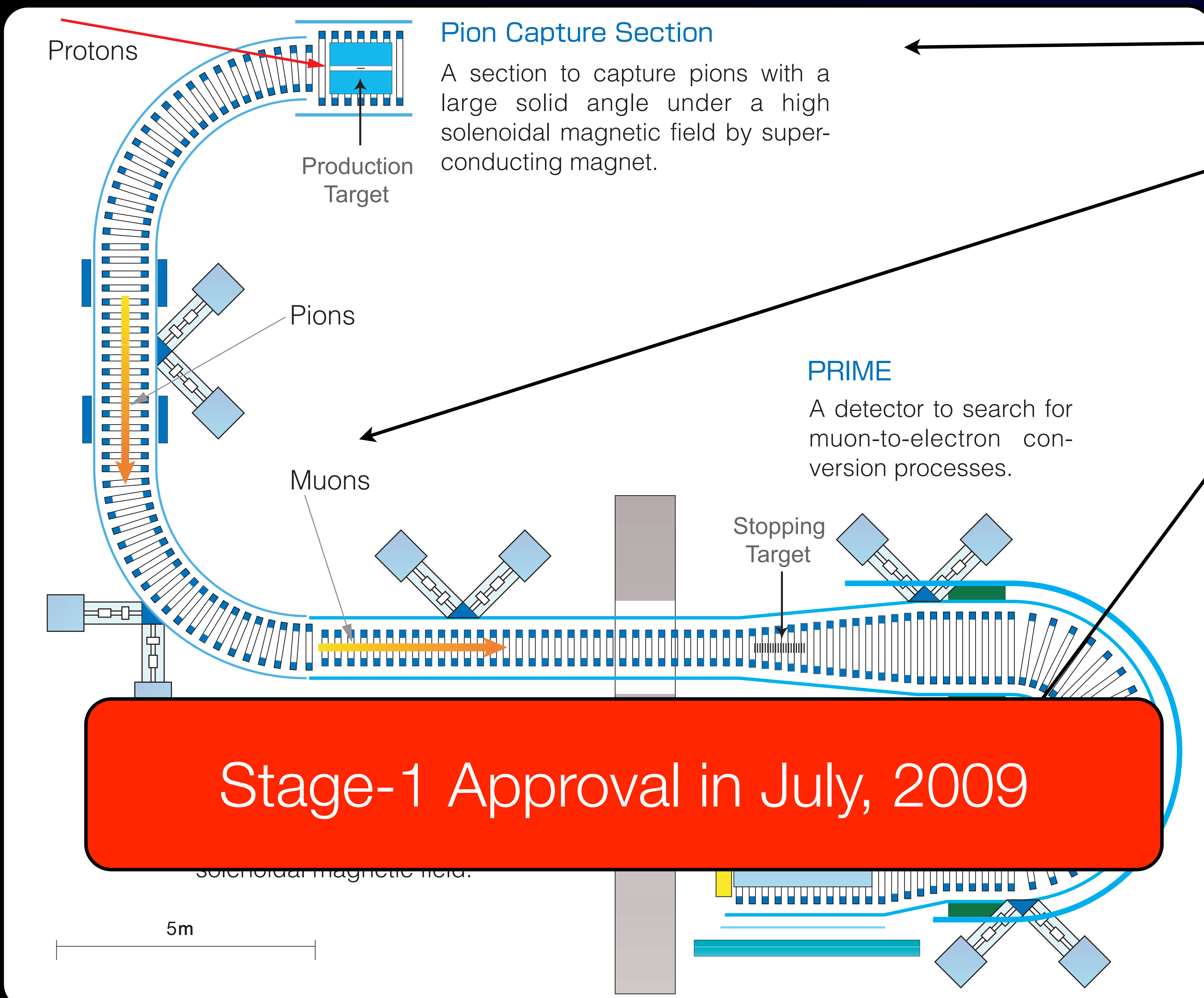
- After Tevatron shutdown, use the antiproton accumulator ring and debuncher ring for beam pulsing.
- Proton beam power is 20 and >200 k pre and post Project-X, respectively.



DOE CD-0 Approved in 2009.

COMET (COherent Muon to Electron Transition) in Japan

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$



Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

Stage-1 Approval in July, 2009

proposed to J-PARC

COMET Collaboration List

49 people from 14 institutes (September 2010)

Imperial College London, UK
A. Kurup, J. Pasternak, Y. Uchida,
P. Dauncey, U. Egede, P. Dornan
University College London, UK
M. Wing, M. Lancaster, R. D'Arcy
University of Glasgow
P. Soler

JINR, Dubna, Russia
V. Kalinnikov, A. Moiseenko,
D. Mzhavia, J. Pontecorvo,
B. Sabirov, Z. Tsamaiaidze,
and P. Evtukhouvich
BINP, Novosibirsk, Russia
D. Grigorev

Department of physics and astronomy, University of British Columbia, Vancouver, Canada
D. Bryman
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T. Numao, I. Sekachev

Department of Physics, Brookhaven National Laboratory, USA
R. Palmer, Y. Cui
Department of Physics, University of Houston, USA
E. Hungerford, K. Lau

IUniversity of Malaya
Wan Ahmad Tajuddin

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Y. Iwashita, Y, Mori
Department of Physics, Osaka University, Japan
M. Aoki, T. Hiasa, Md.I. Hossain, T. Itahashi, Y. Kuno, H. Nakai,
H. Sakamoto, A. Sato
Department of Physics, Saitama University, Japan
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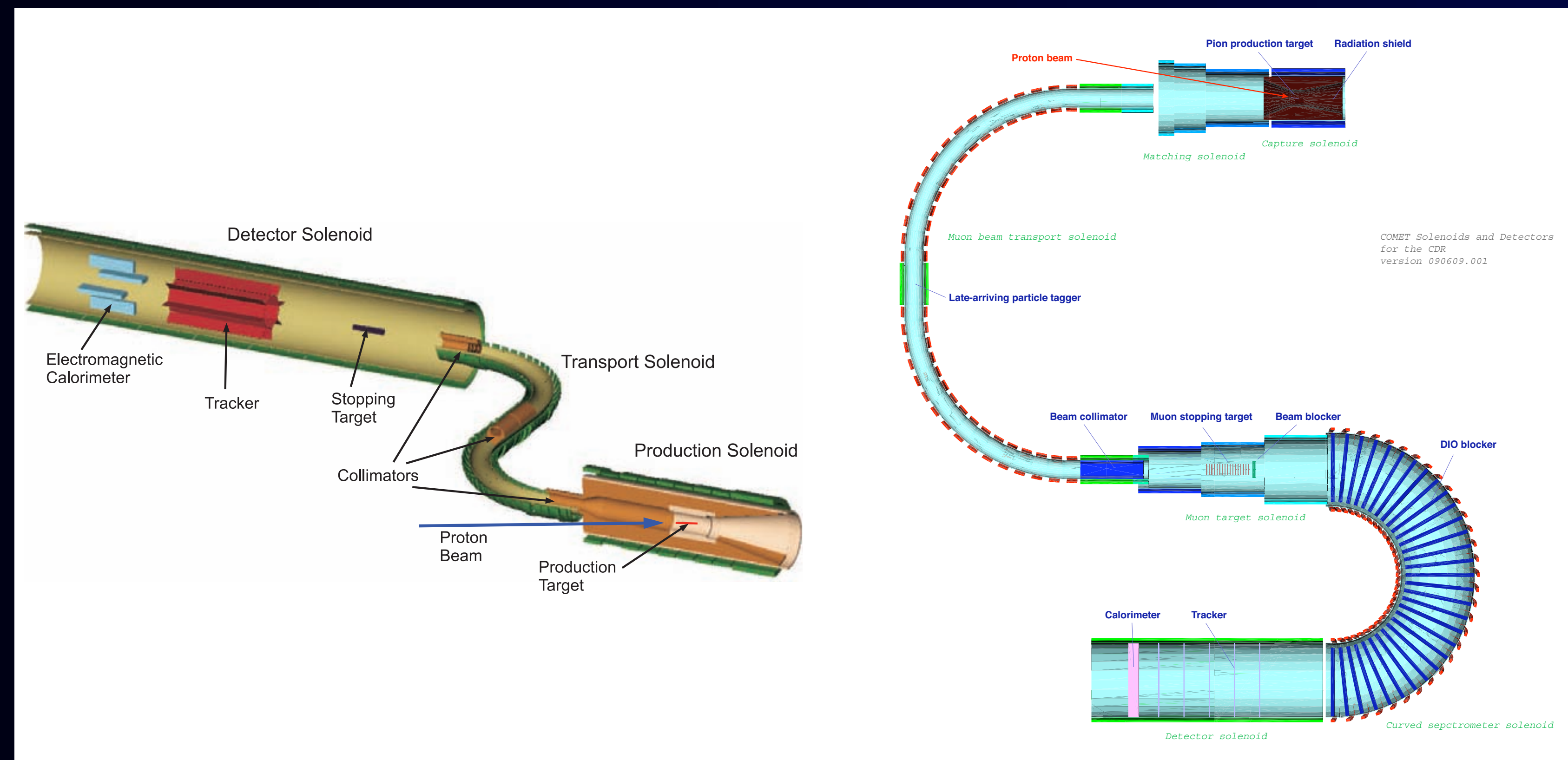
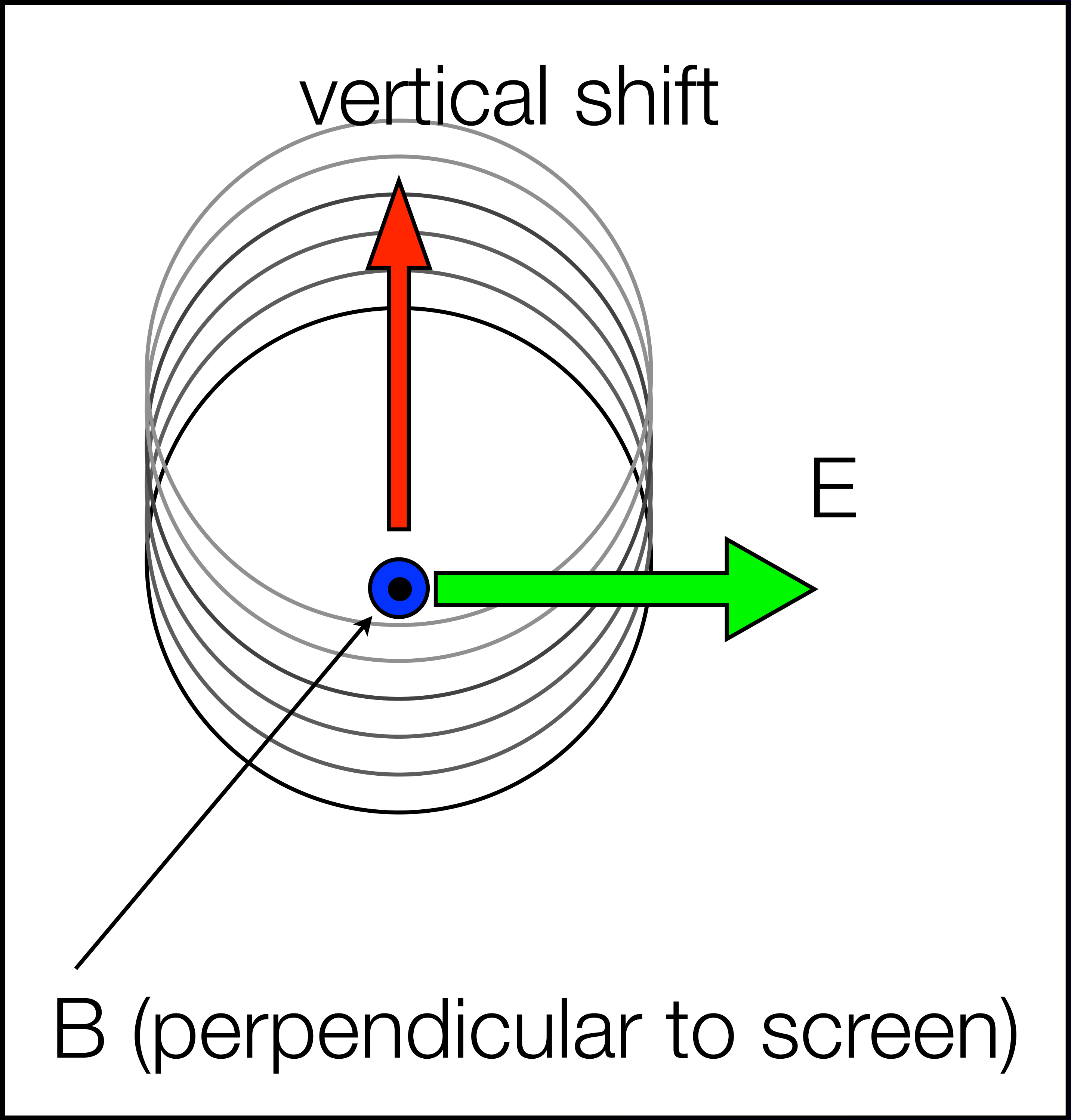
Department of Physics, Tohoku University, Japan
Y. Takubo,
High Energy Accelerator Research Organization (KEK), Japan
Y. Arimoto, Y. Igarashi, S. Ishimoto, S. Mihara, H. Nishiguchi,
T. Ogitsu, M. Tomizawa, A. Yamamoto, M. Yoshida and K. Yoshimura

Design Difference Between Mu2e and COMET



	Mu2e	COMET
Muon Beam-line	S-shape	C-shape
Electron Spectrometer	Straight solenoid	Curved solenoid

EM Physics for Particle Trajectories in Toroidal Magnetic Field



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

Charged Particle Trajectory in Curved Solenoids

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

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

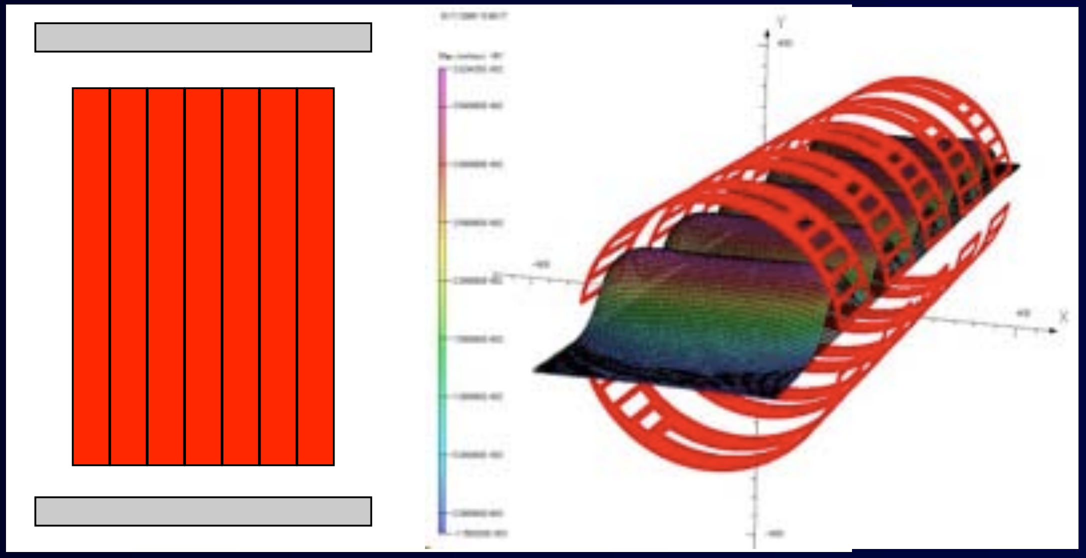
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

  - This can be used for charge and momentum selection.

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

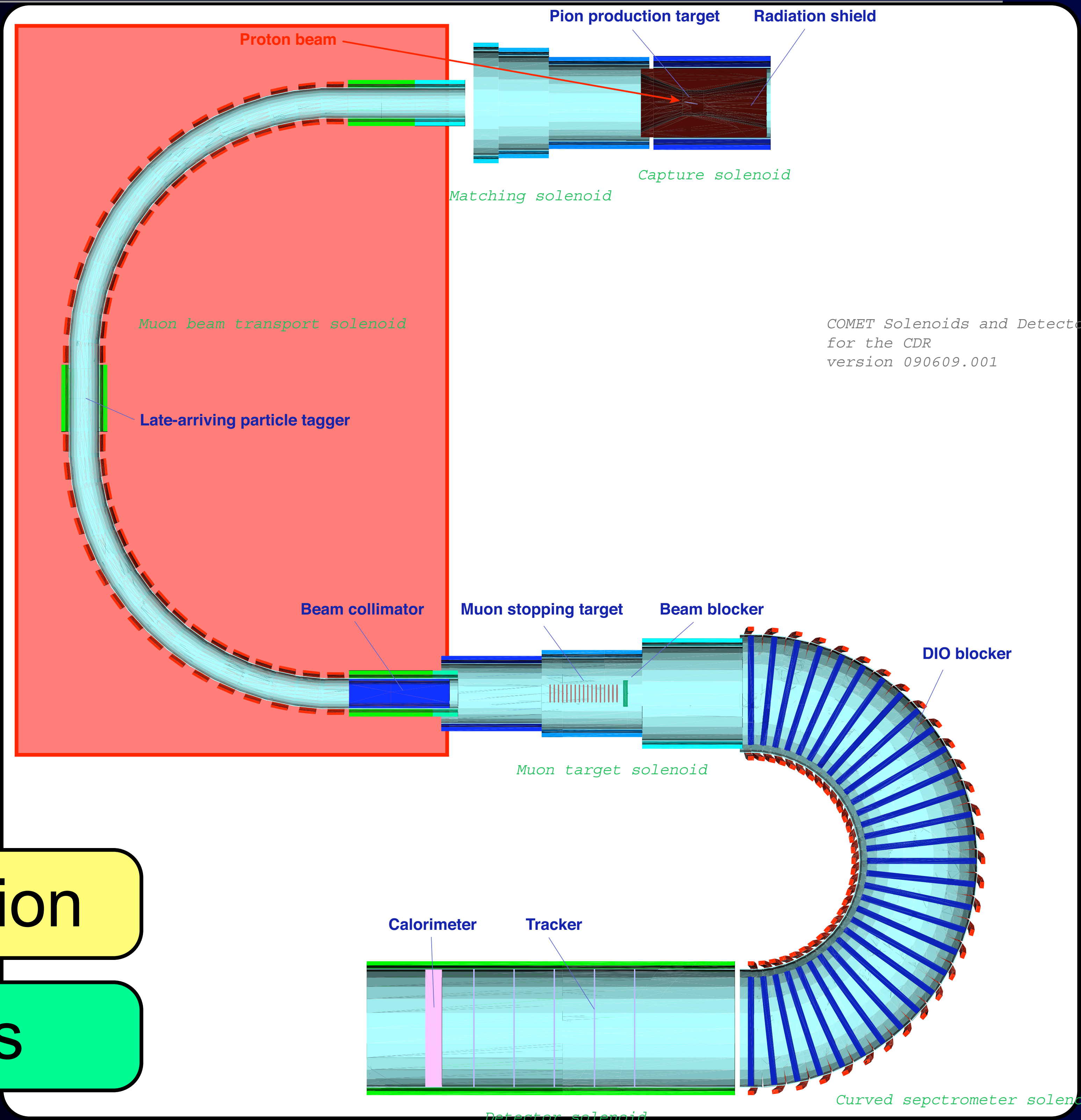
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

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



Muon Transport System for COMET

- The muon transport system consists of curved solenoids.
  - bore radius : 175 mm
  - magnetic field : 2 T
  - bending angle : 180 degrees
  - radius of curvature : 3 m
- Dispersion is proportional to a bending angle.
- muon collimator after 180 degree bending.
- Elimination of muon momentum > 70 MeV/c

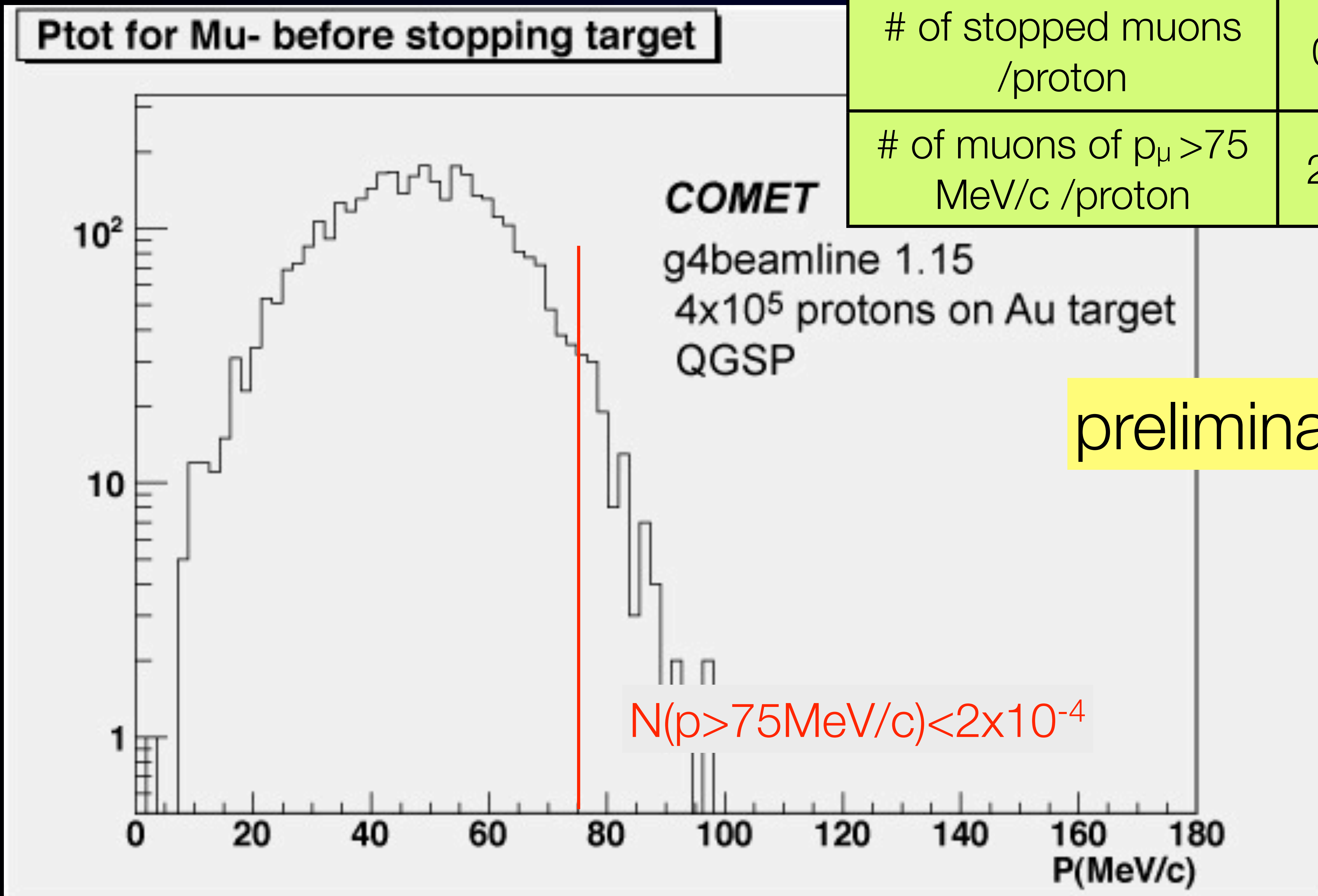


good momentum selection

no high-energy muons

Muon Momentum Spectrum at the End of the Transport Beam Line

# of muons /proton	0.009
# of stopped muons /proton	0.003
# of muons of p_μ >75 MeV/c /proton	2×10^{-4}



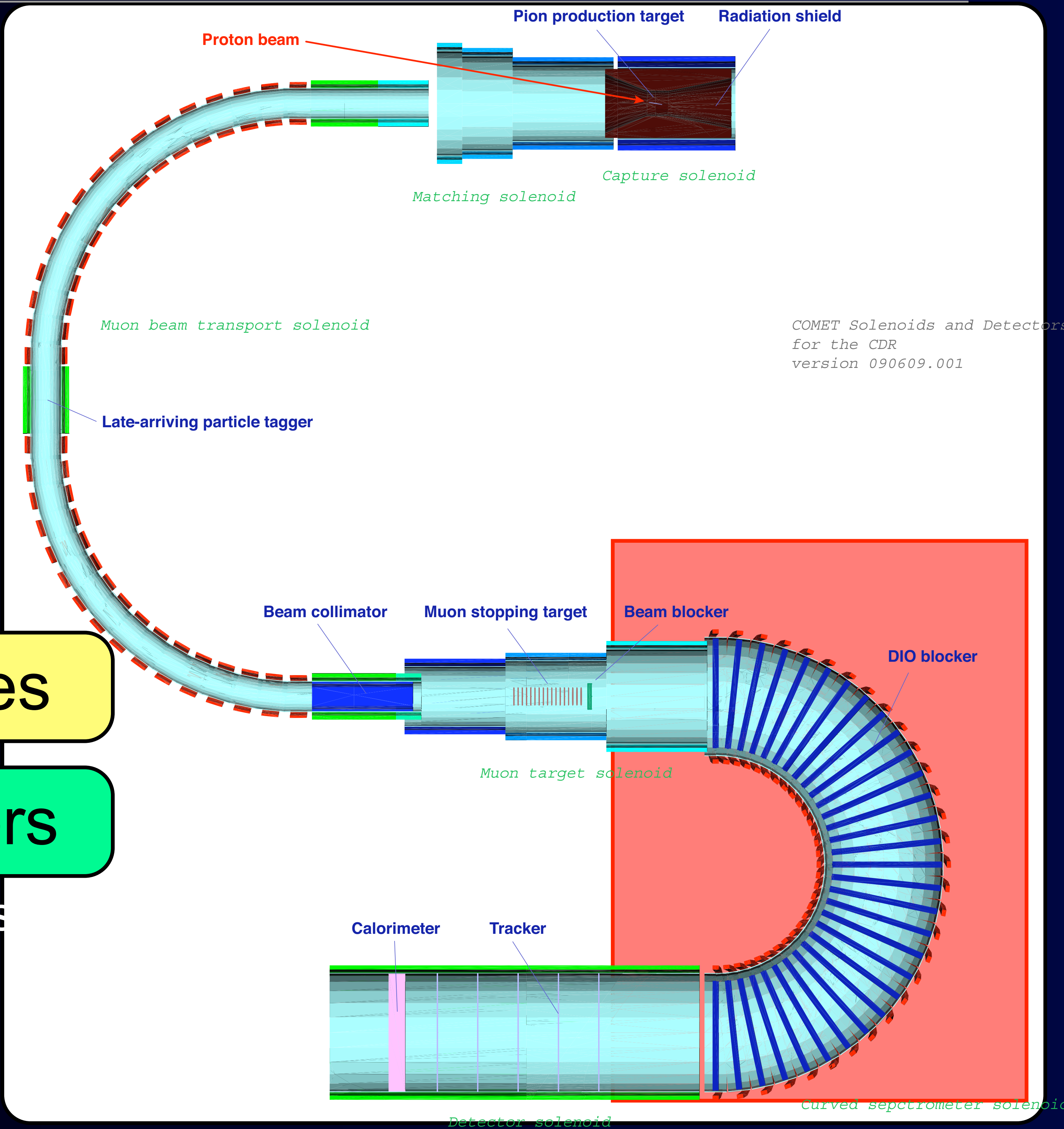
Electron Transport System for COMET

- The electron transport
  - bore : 700 mm
  - magnetic field : 1T
  - bending angle : 180 degrees
- Electron momentum ~ 104 MeV/c
- Elimination of negatively-charged particles less than 80 MeV/c
- Elimination of positively-charged particles (like protons from muon capture)

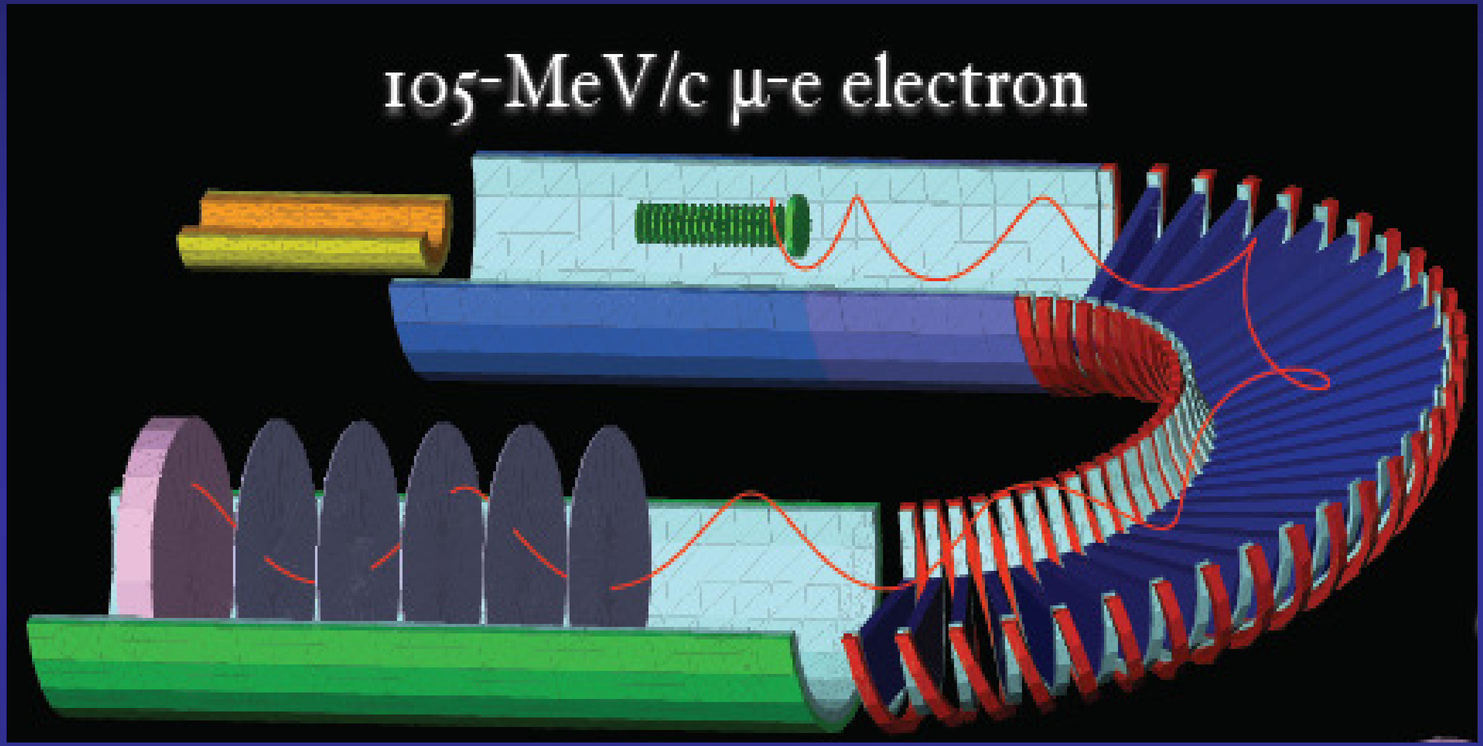
reduction of detector rates

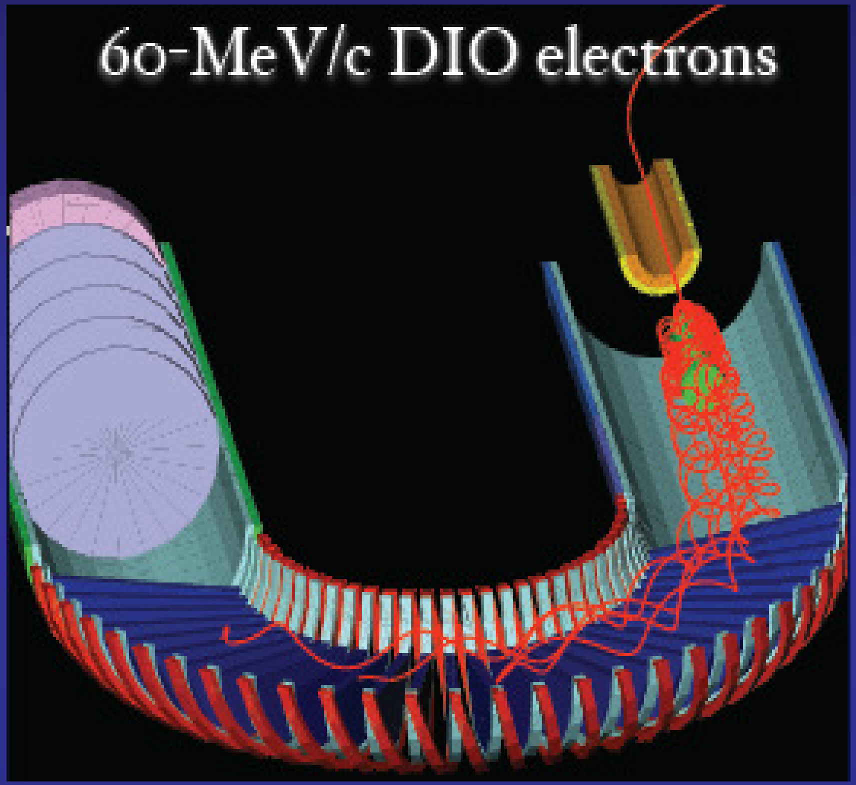
no protons in the detectors

- a straight solenoid where detectors are placed follows the curved spectrometer.



Electron Spectrometer

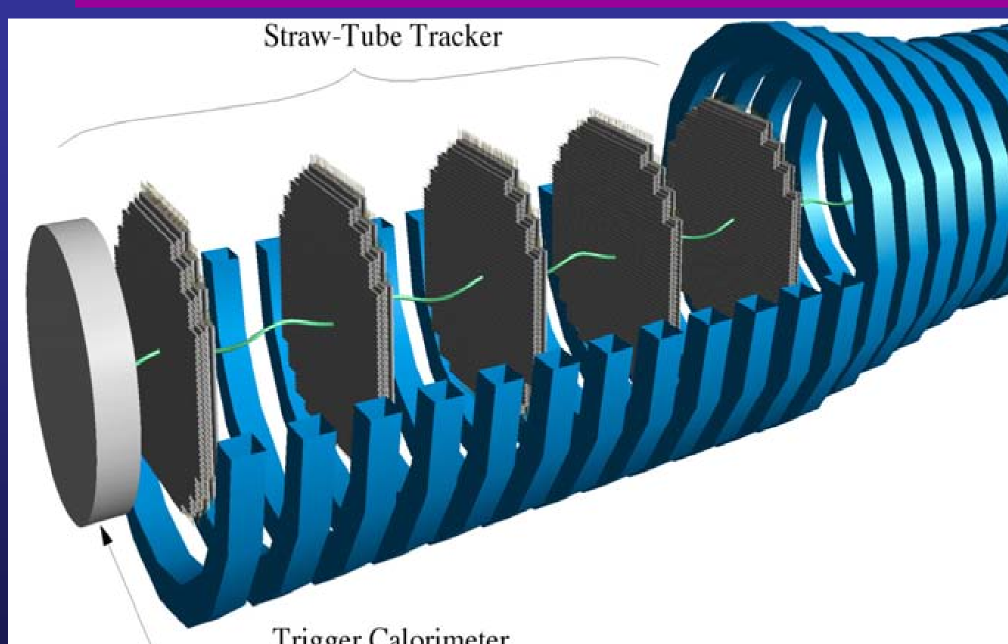


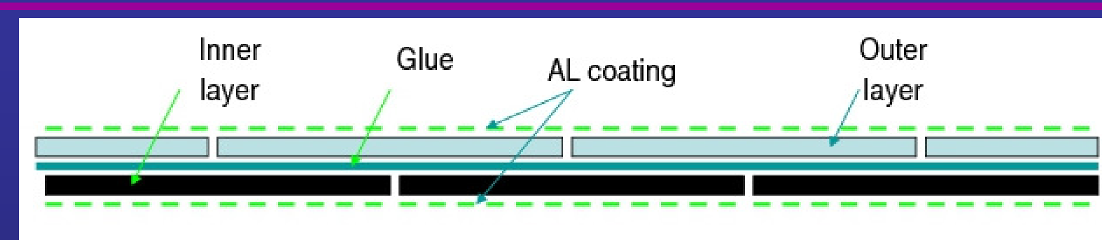


- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~ 1kHz.

COMET Electron Tracker

- Requirements
  - operate in a 1T solenoid field.
  - operate in vacuum (to reduce multiple scattering of electrons).
  - [redacted]
  - 0.4% momentum and 700μm spatial resolution.
- Current design utilises straw tube chambers
  - Straw tubes 5mm in diameter. Wall composed of two layers of 12μm thick metalized Kapton glued together.
- 5 planes 48cm apart with 2 views (x and y) per plane and 2 layers per view (rotated by 45° to each other).



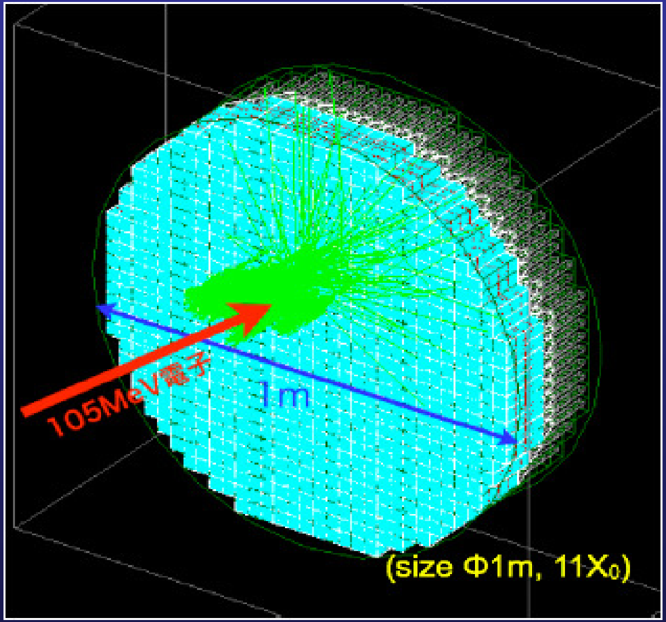


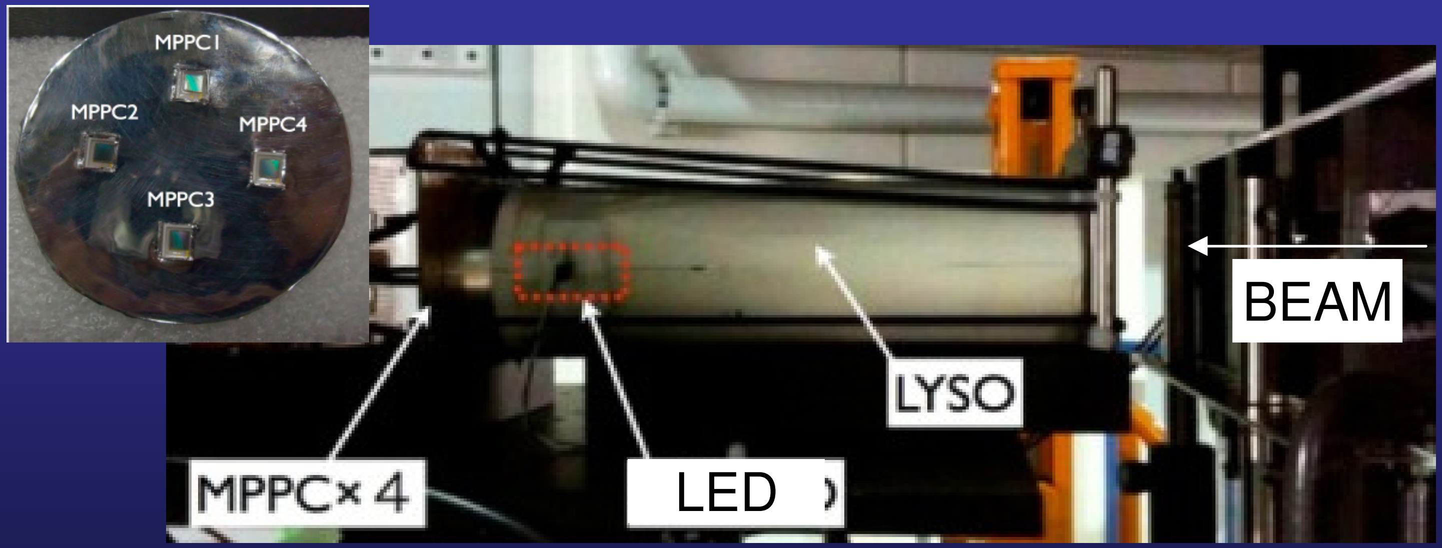
Straw wall cross-section.

350mm long seamless straw tube prototype.

COMET Electron Calorimeter

- Measure energy, PID and give additional position information. Can be used to make a trigger decision.
- 5% energy and 1cm spatial resolution at 100MeV
  - High segmentation (3x3x15 cm^3 crystals)
- Candidate inorganic scintillator materials are Cerium-doped Lutetium Yttrium Orthoscilicate (LYSO) or Cerium-doped Gd_2SiO_5 (GSO).
- Favoured read out technology is multi–pixel photon counters (MPPC).
  - high gains, fast response times and can operate in magnetic fields.
- R&D by Osaka group. Further beam tests planned for November.





100 MeV electron beam tests at Tohoku University

Other Detector Elements

- Proton extinction monitor in a proton beamline
  - off at the beam prompt
  - gas Cherenkov
- Cosmic ray veto counters
  - large area
  - inefficiency 10^{-4}
- Muon intensity monitor
  - muonic X-ray measurement from muon-stopping target
- Calibration system for electron momentum and energy detection
  - use pions ?
  - electron linac ?
- Delay particle tagger in a muon beamline
  - off at the beam prompt
  - detect late-arriving particles (PID)

Signal Sensitivity (preliminary) - 2×10^7 sec

- Single event sensitivity

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

  - N_μ is a number of stopping muons in the muon stopping target. It is 2×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons	8.5×10^{20}
muon transport efficiency	0.008
muon stopping efficiency	0.3
# of stopped muons	2.0×10^{18}

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

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

Background Rates

Radiative Pion Capture	0.05
Beam Electrons	$< 0.1^{\ddagger}$
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

‡ Monte Carlo statistics limited.

beam-related prompt backgrounds

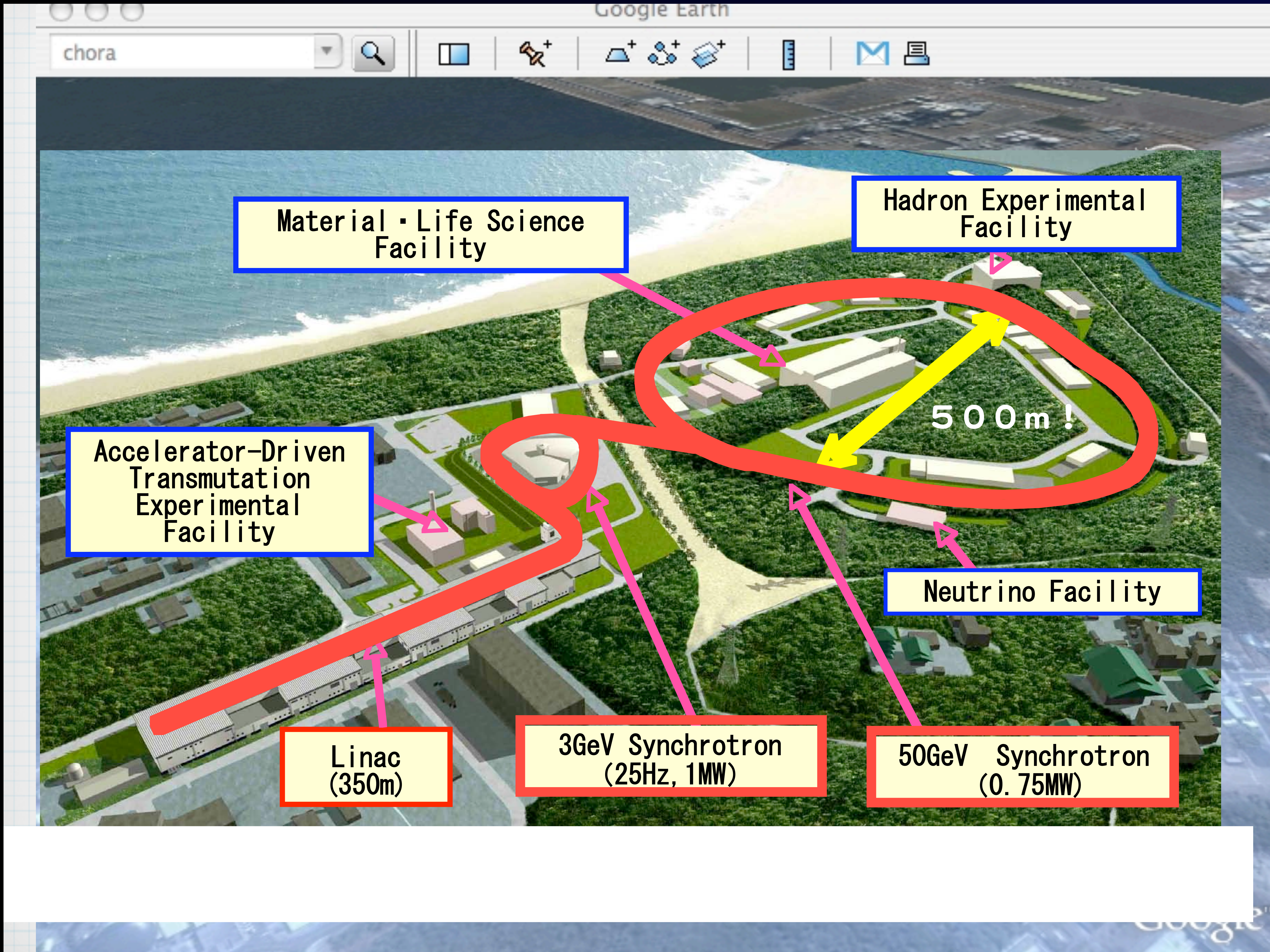
beam-related delayed backgrounds

intrinsic physics backgrounds

cosmic-ray and other backgrounds

Expected background events are about 0.34.

J-PARC at Tokai, Japan

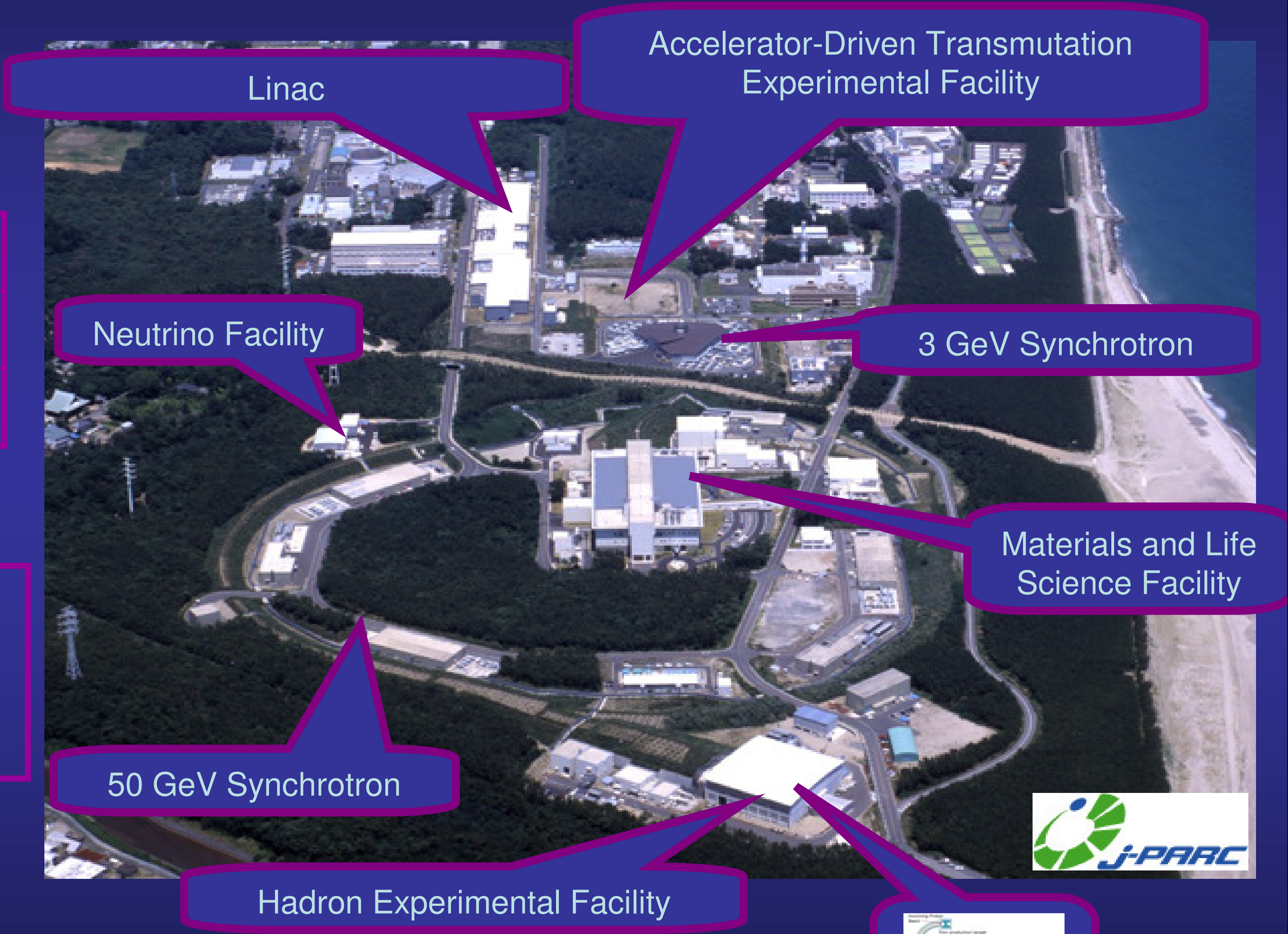


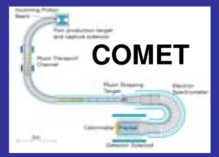
COMET at J-PARC

Proton beam parameters

Beam Power	56 kW
Beam Energy	8 GeV
Average Current	7μA

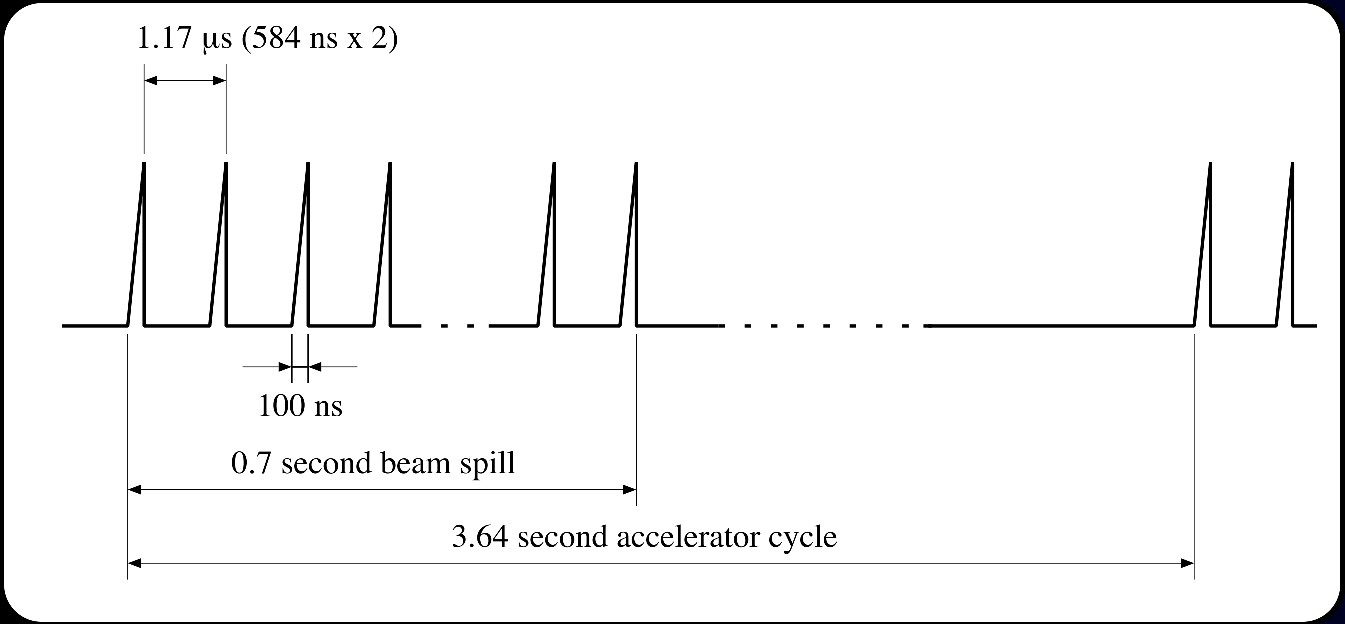
- Slow-extracted proton beam.
- 8 GeV to suppress anti-proton production.



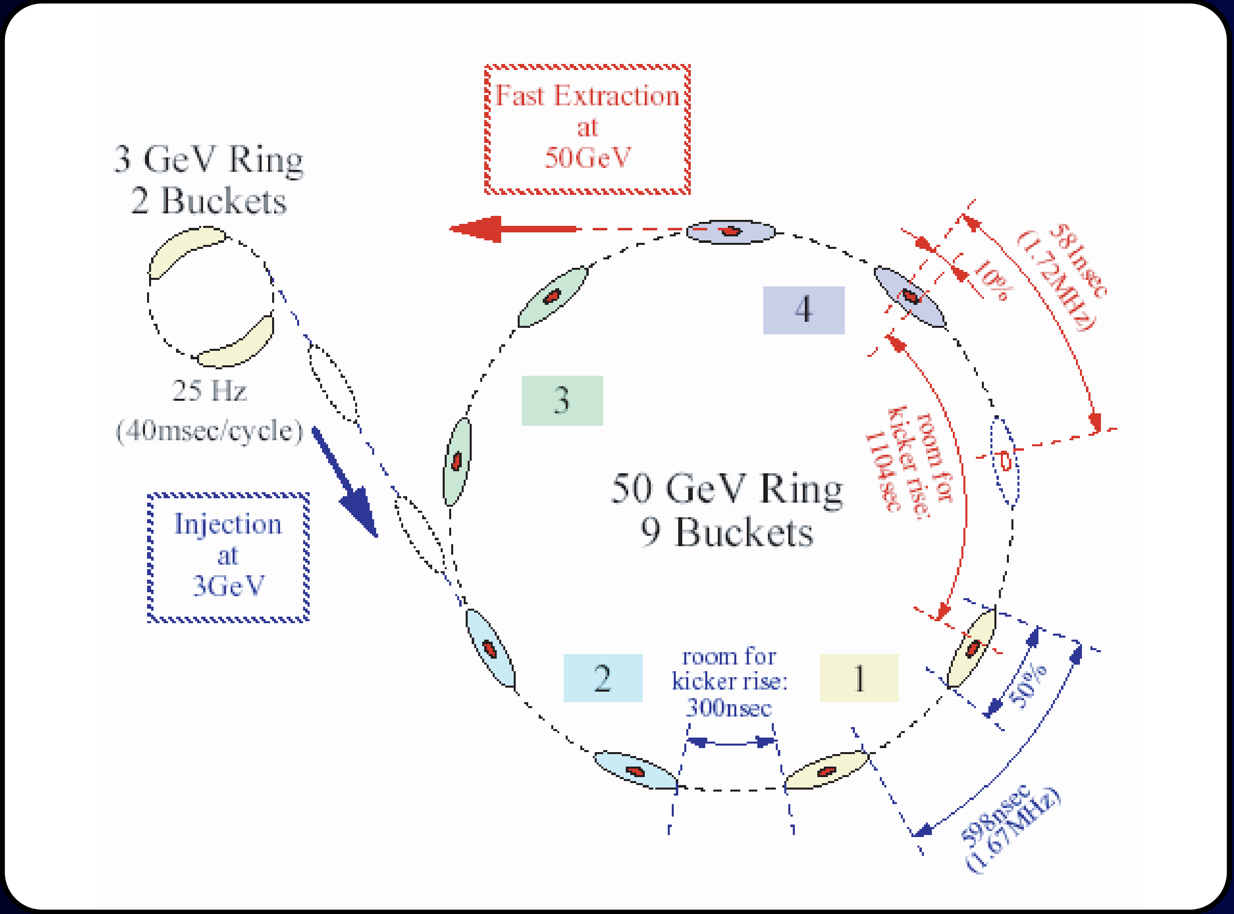


Proton Beam at J-PARC

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



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



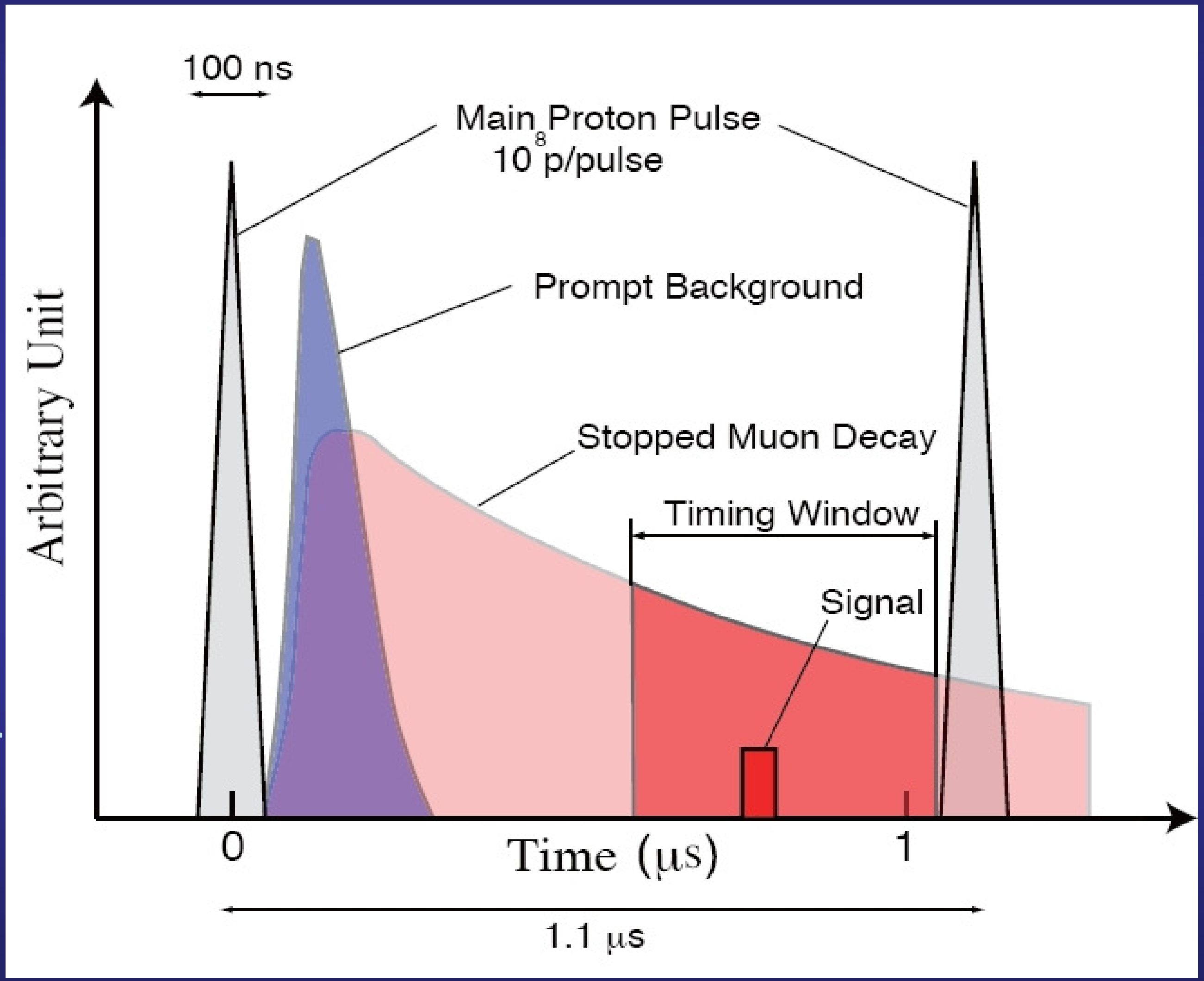
Proton Beam for COMET

- Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

Bunch Structure

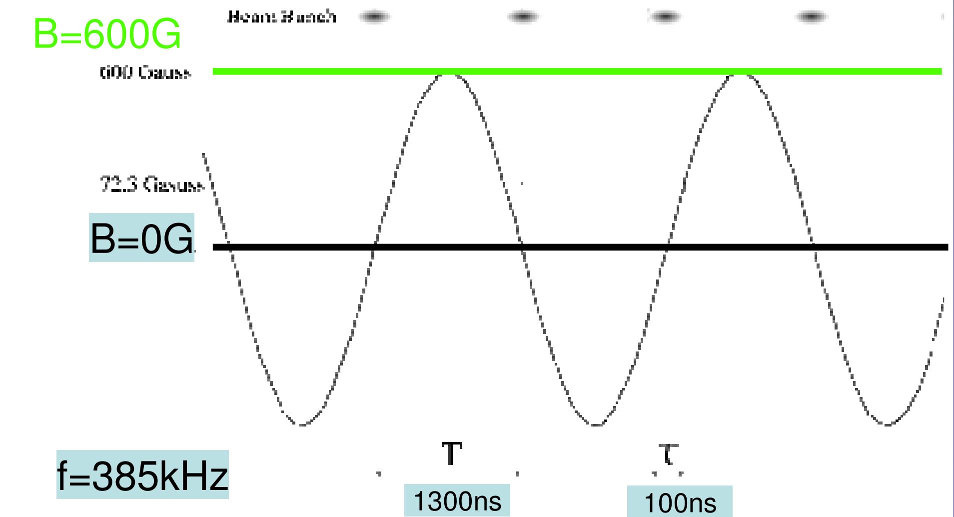
Bunch Separation	1.3 µs
Bunch Length	100ns
Protons per Bunch	1.2×10^8
Bunches per Spill	5.3×10^5
Spill time	0.7s
Extinction	10^{-9}

- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important.
  – Without sufficient extinction, all processes in prompt background category could become a problem.



Proton Extinction at J-PARC

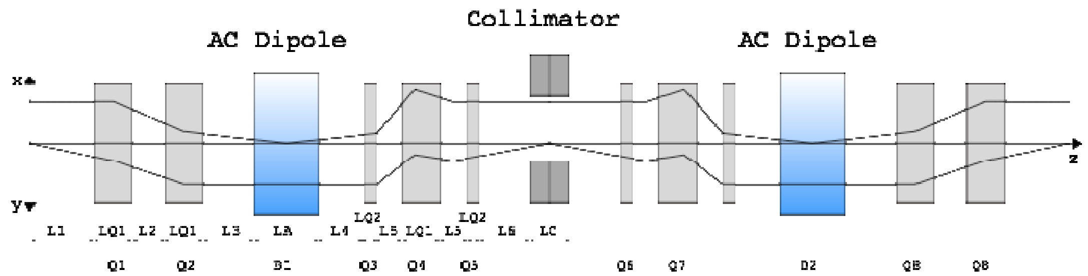
- Intrinsic extinction from the J-PARC main ring is expected to be around 10^{-7}.
  - Need additional extinction device to give additional factor 10^{-2}.
- One possible solution is to use an AC dipole
  - Collaboration between COMET and Mu2e

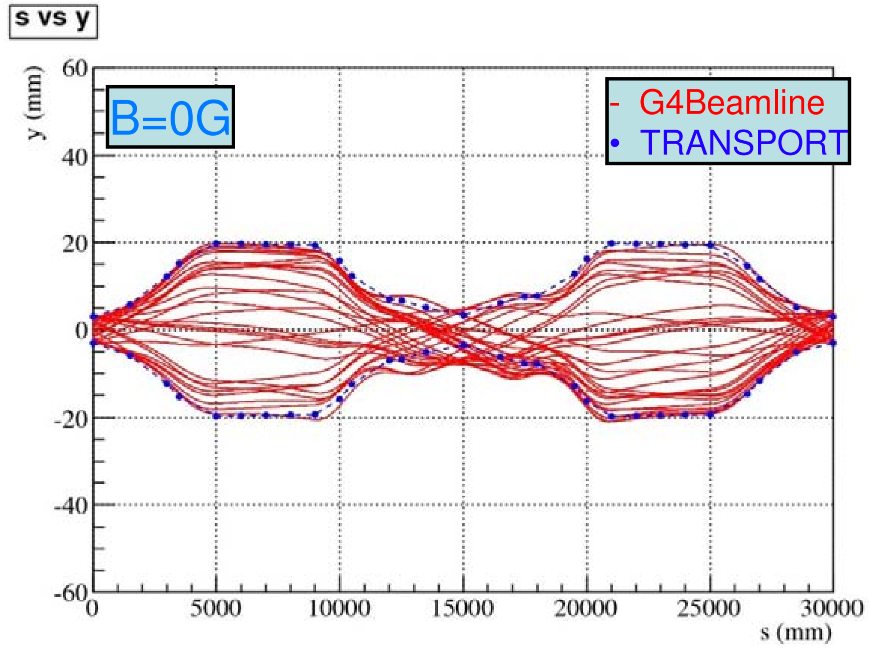


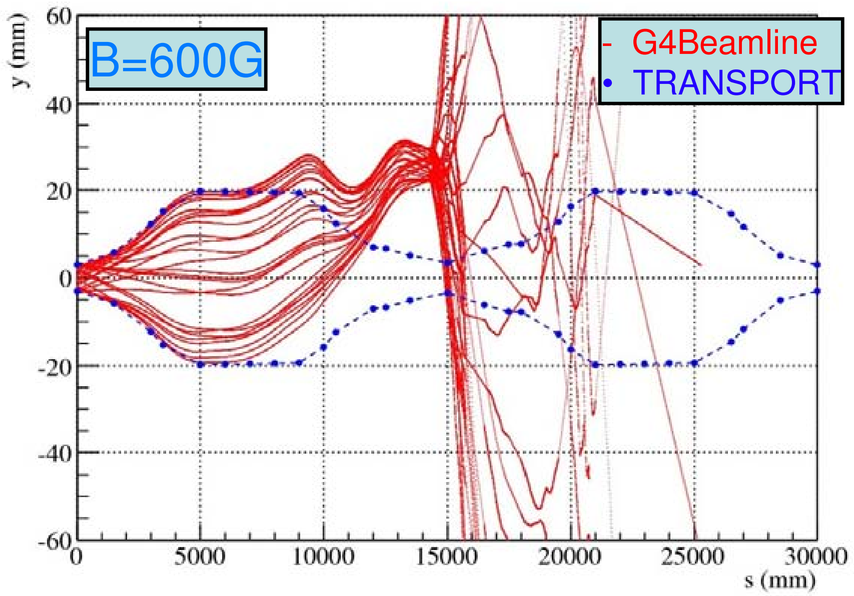
Transmission [-100:100ns] = 100%

$R_{extinction}$ [<-300ns, >300ns] < 1/1000

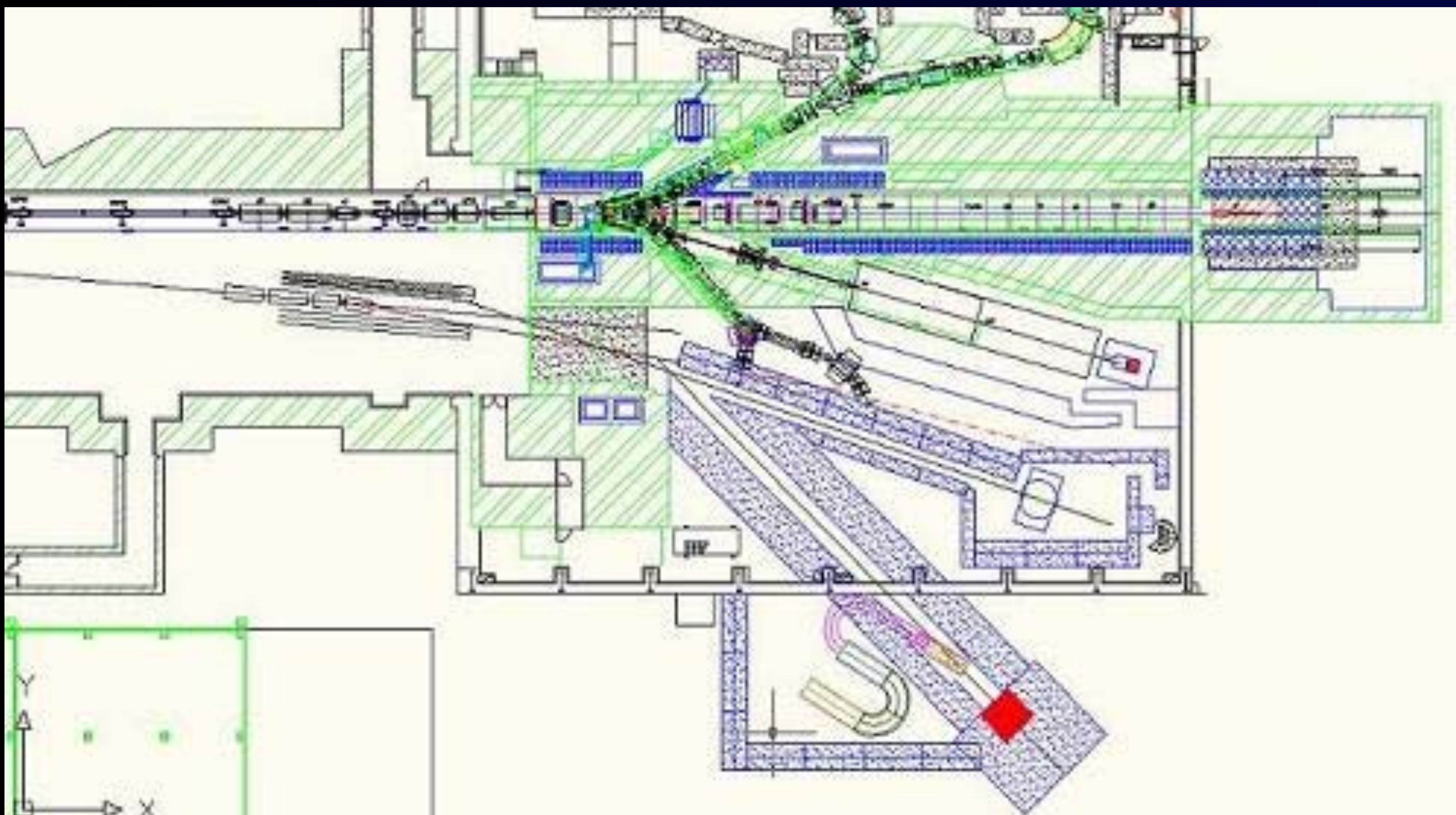
$R_{extinction}$ [<-200ns, >200ns] < 1/100



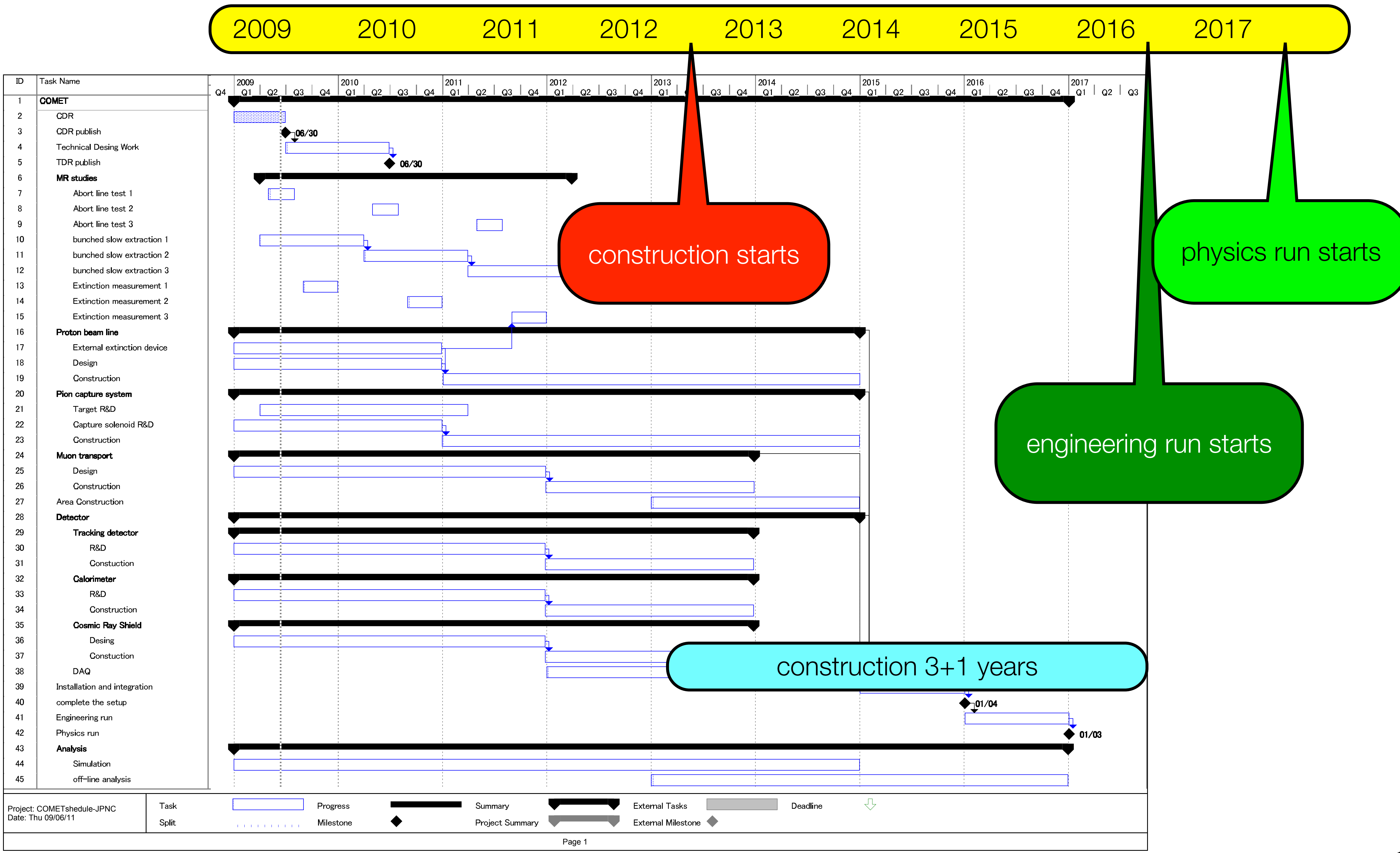




Possible Layout of COMET in the J-PARC Hadron Hall



Wishful Timeline for COMET



The COMET Conceptual Design Report is available at http://comet.phys.sci.osaka-u.ac.jp/internal/publications/comet-cdr-v1.0.pdf/view

Summary

- Physics motivation of cLFV processes would be significant and robust in 10-15 years from now.
- Among various muon cLFV processes, μ-e conversion might be the next step.
- The COMET experiment at J-PARC is aiming at a search for μ-e conversion for 2.6×10^{-17} single event sensitivity. The COMET has received stage-1 approval at the J-PARC PAC, aiming its start in around 2015.

New Collaborators to the COMET is highly welcomed.