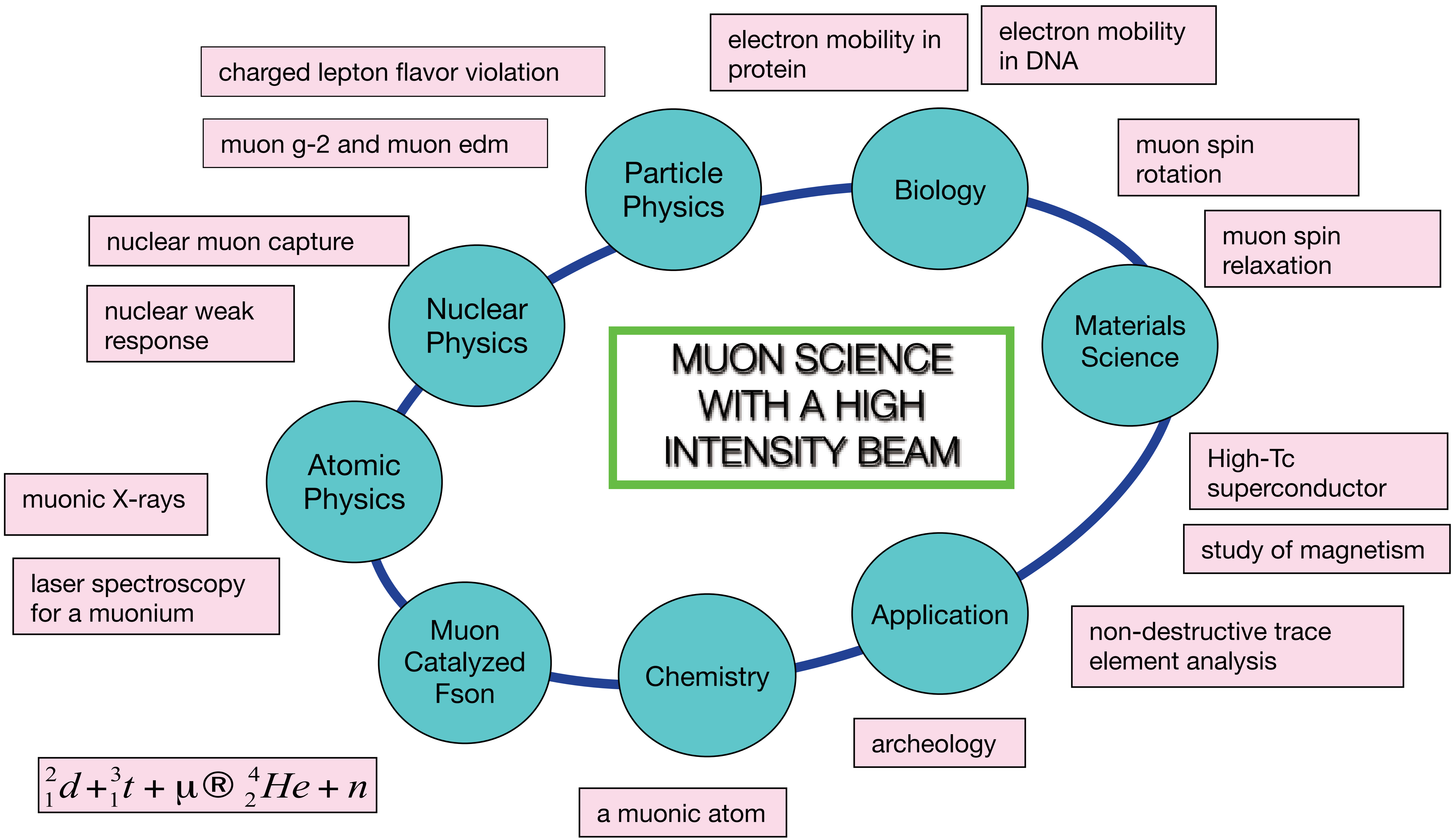
Overview of Muon Physics Worldwide

Yoshitaka Kuno
Department of Physics,
Osaka University, Japan

December 13th 2019
2nd Workshop on “EMuS Multidisciplinary Applications”
Hefei, China

Muon Science is Interdisciplinary !



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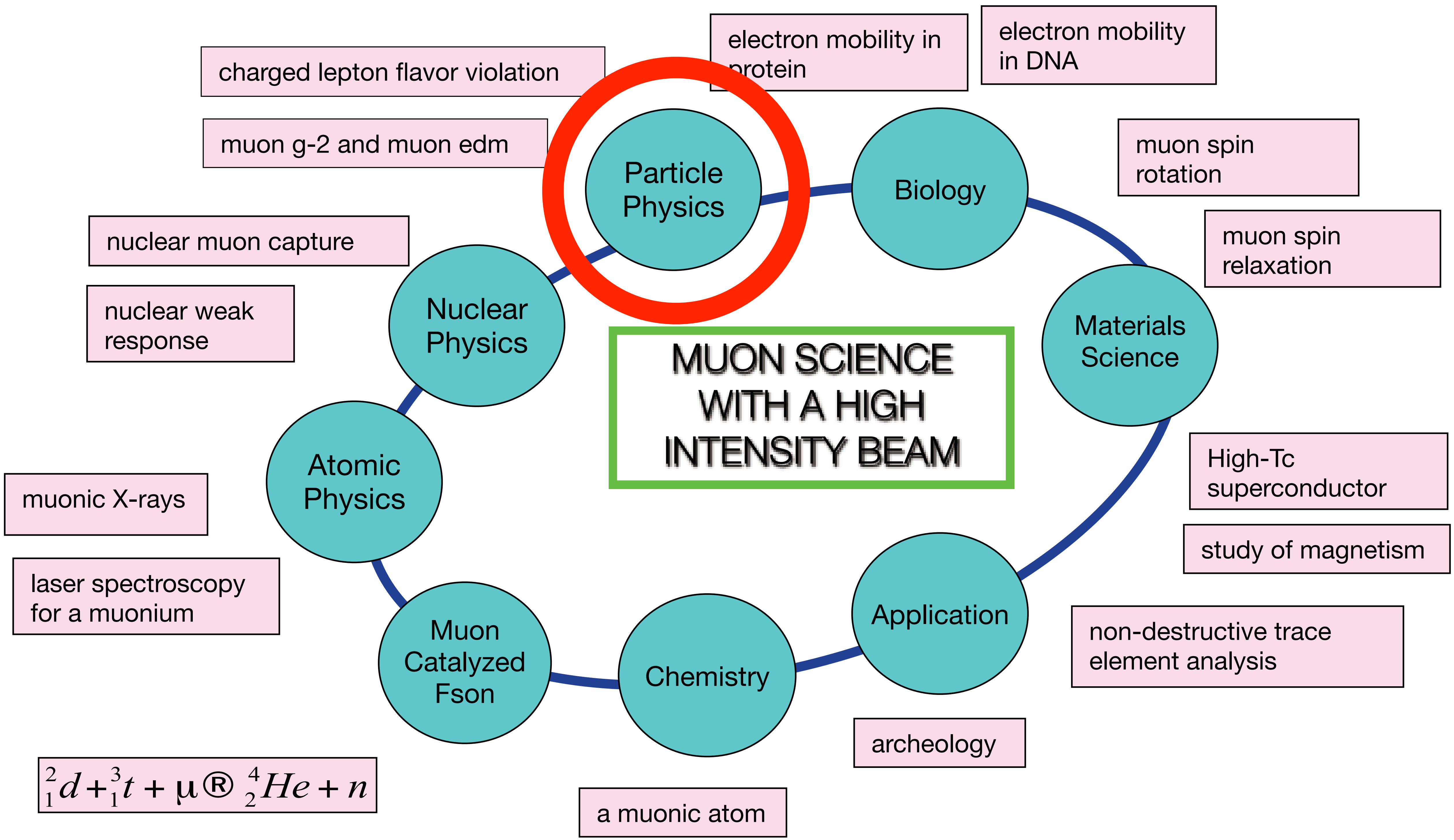

Outline

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- Introduction
- Motivation in Particle Physics
- Charged Lepton Flavour Violation (CLFV)
- Lepton Number Violation (LNV)
- Muon g-2
- Muonium
- Highly Intense Muon Sources
- Summary

Physics Motivation
- The Standard Model and Beyond

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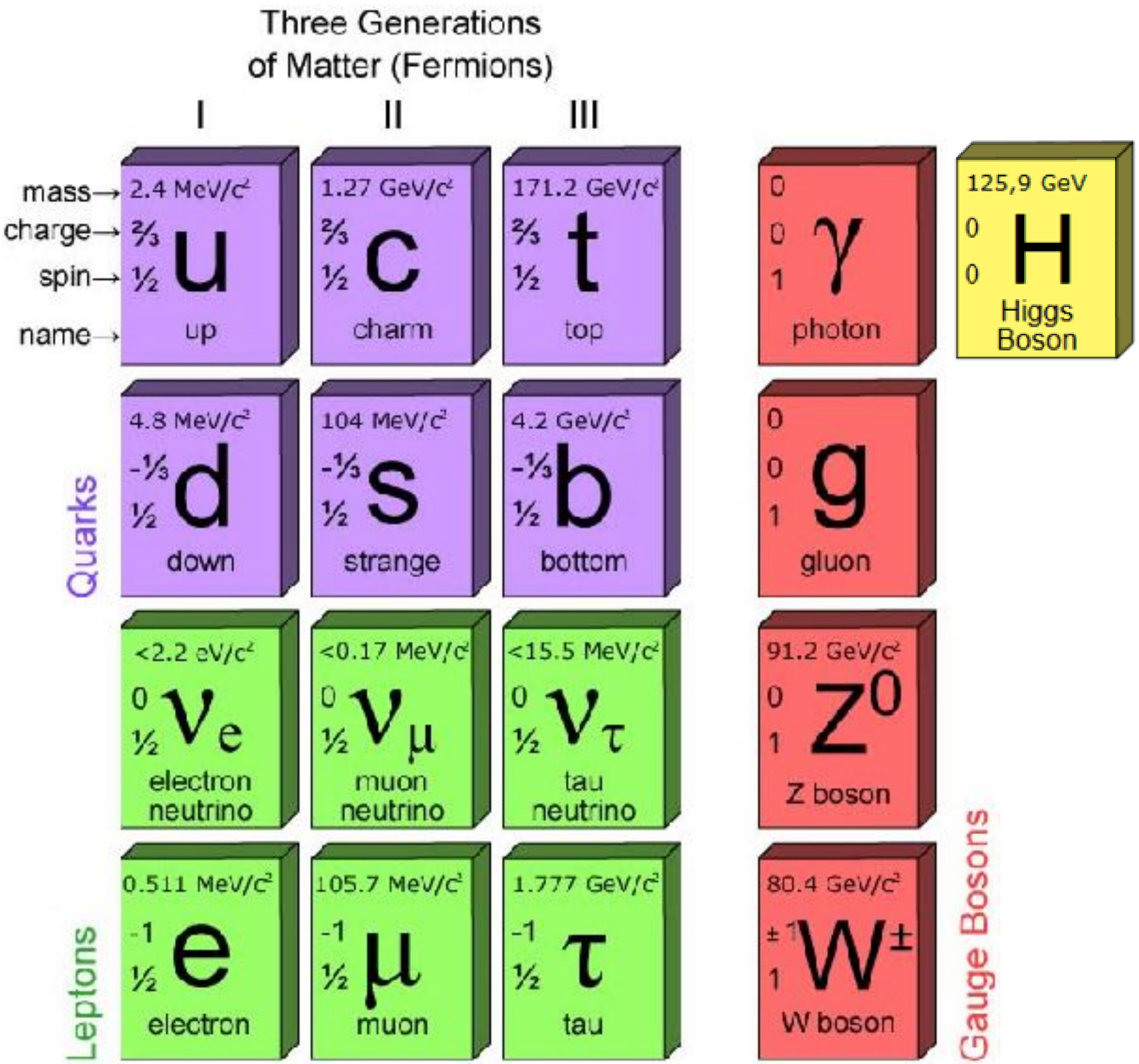
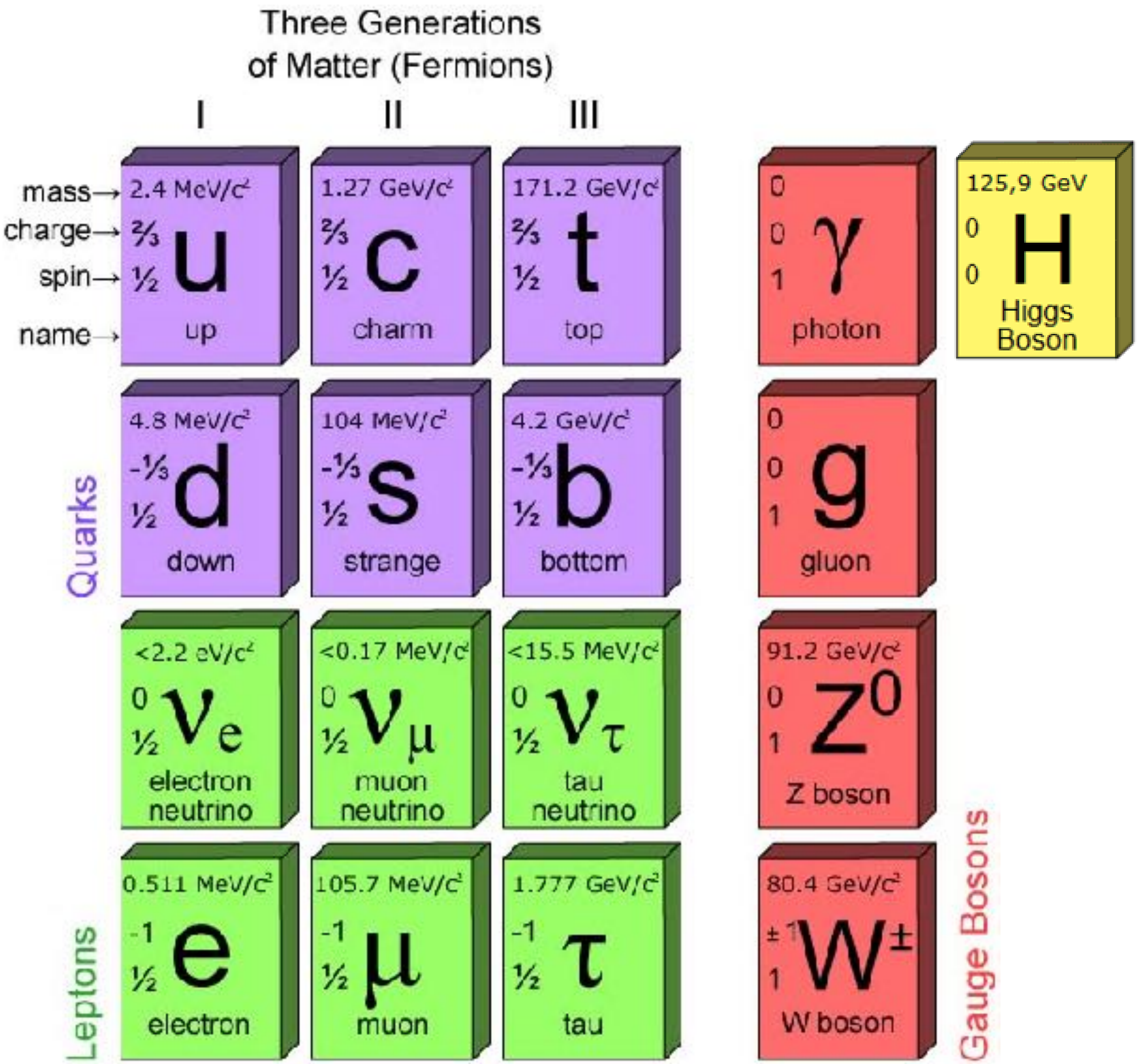


Physics Motivation
- The Standard Model and Beyond



The Standard Model is considered to be incomplete.

ex.

mass and mixing,

strong CP,

dark matter,

baryogenesis,

dark energy

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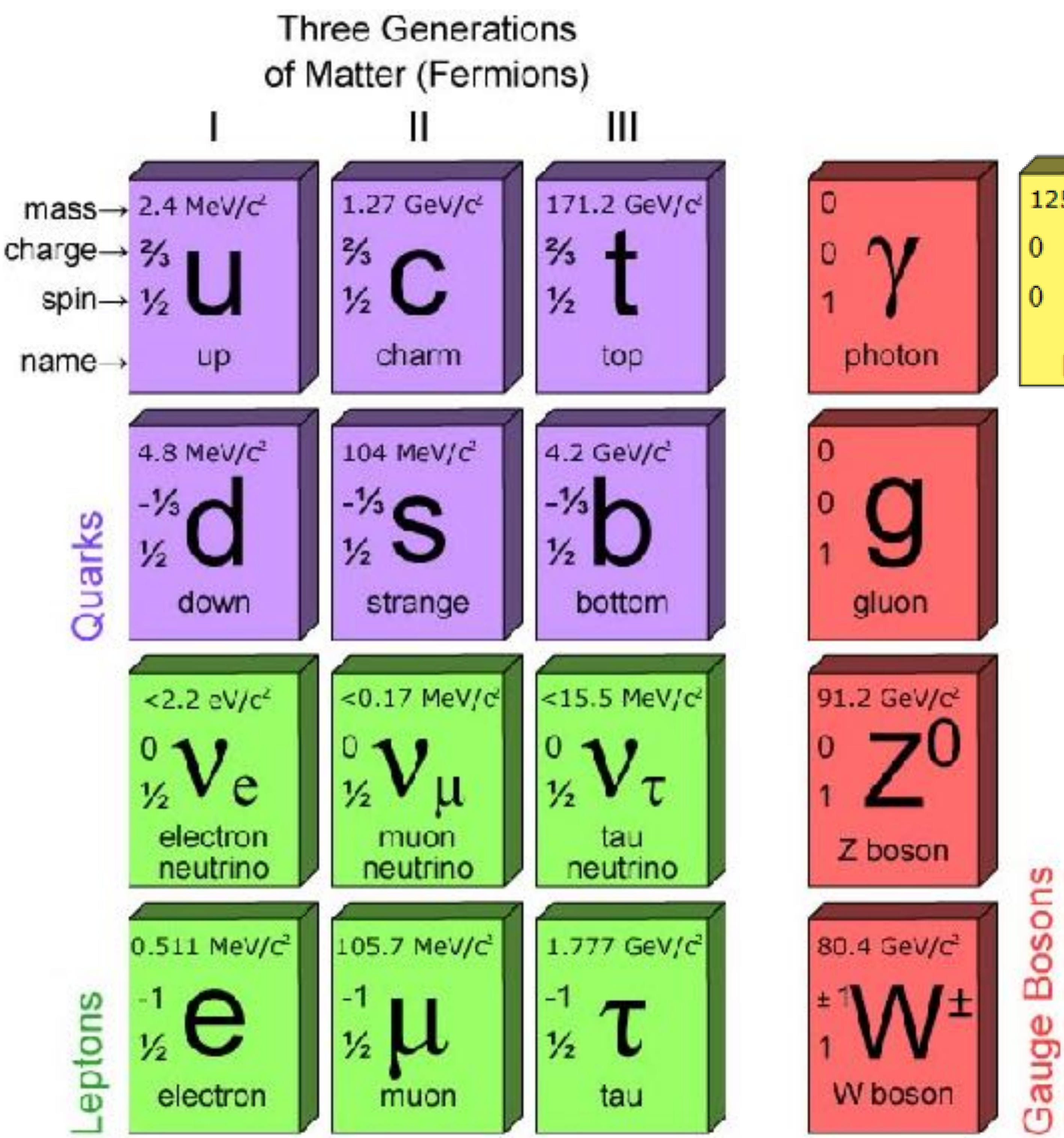

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New Physics is needed.

Charged Lepton Flavour Violation (CLFV)

Flavour Transitions : Lepton

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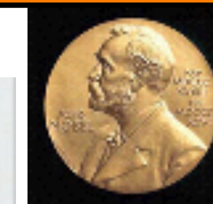
Quarks



Quark transition observed

Flavour Transitions : Lepton

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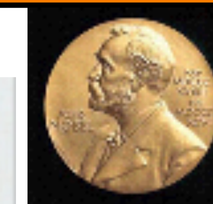

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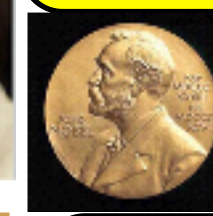
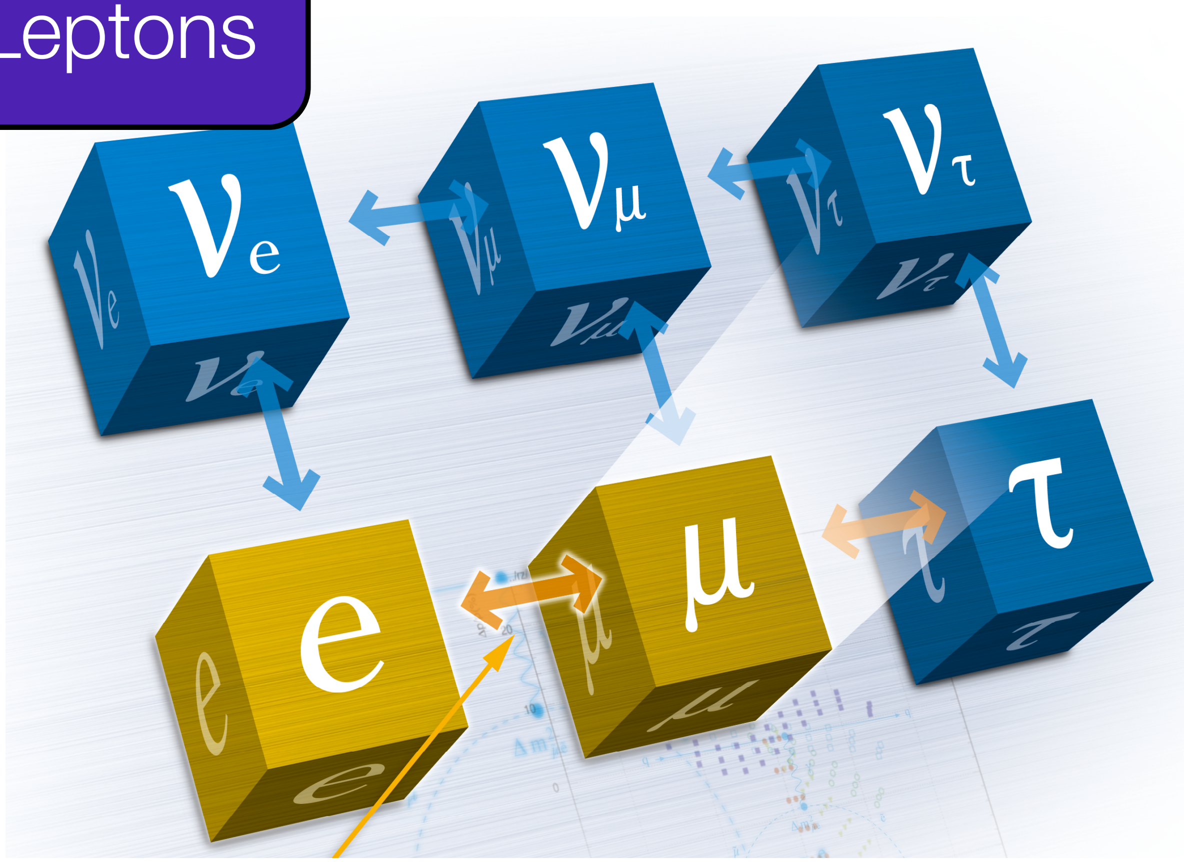


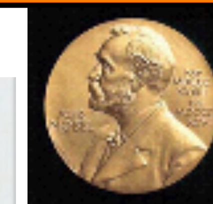
Leptons



Neutrino transition observed

Flavour Transitions : Lepton

Quarks



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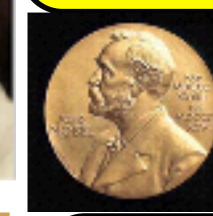

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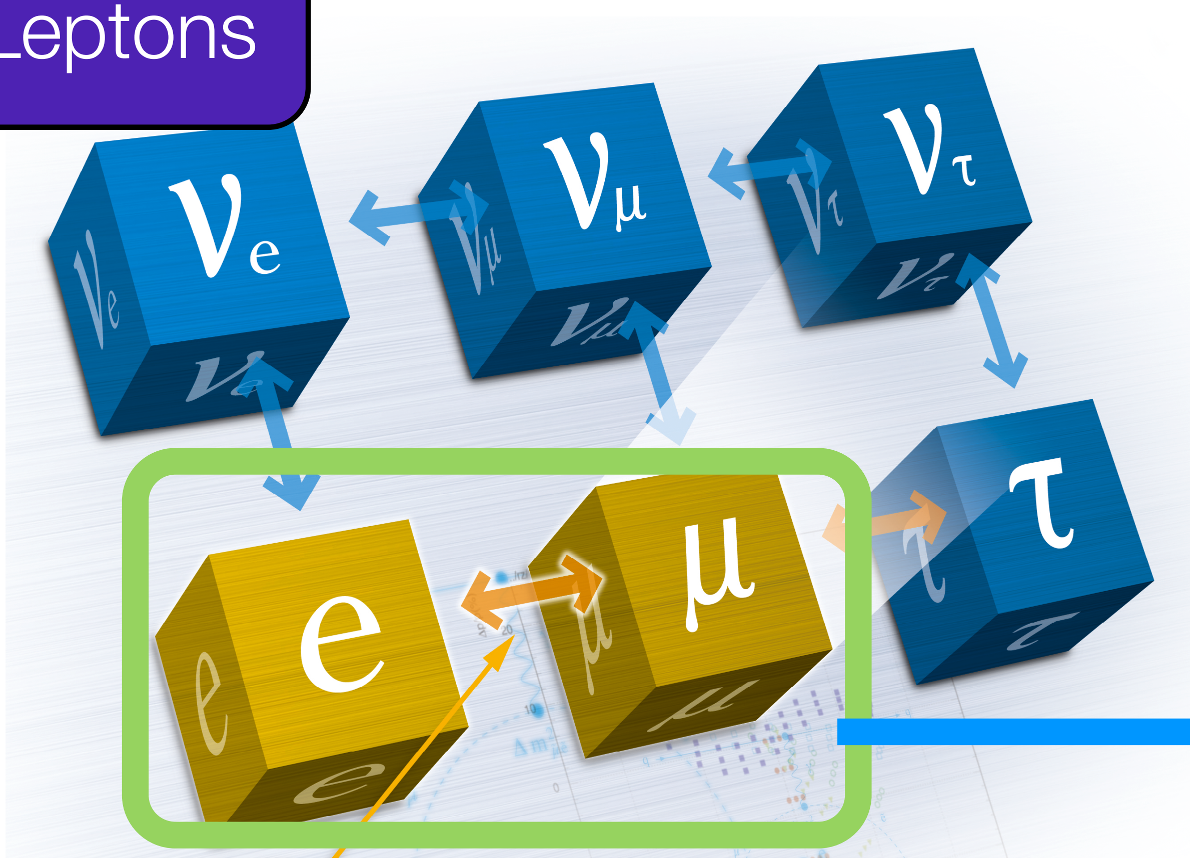
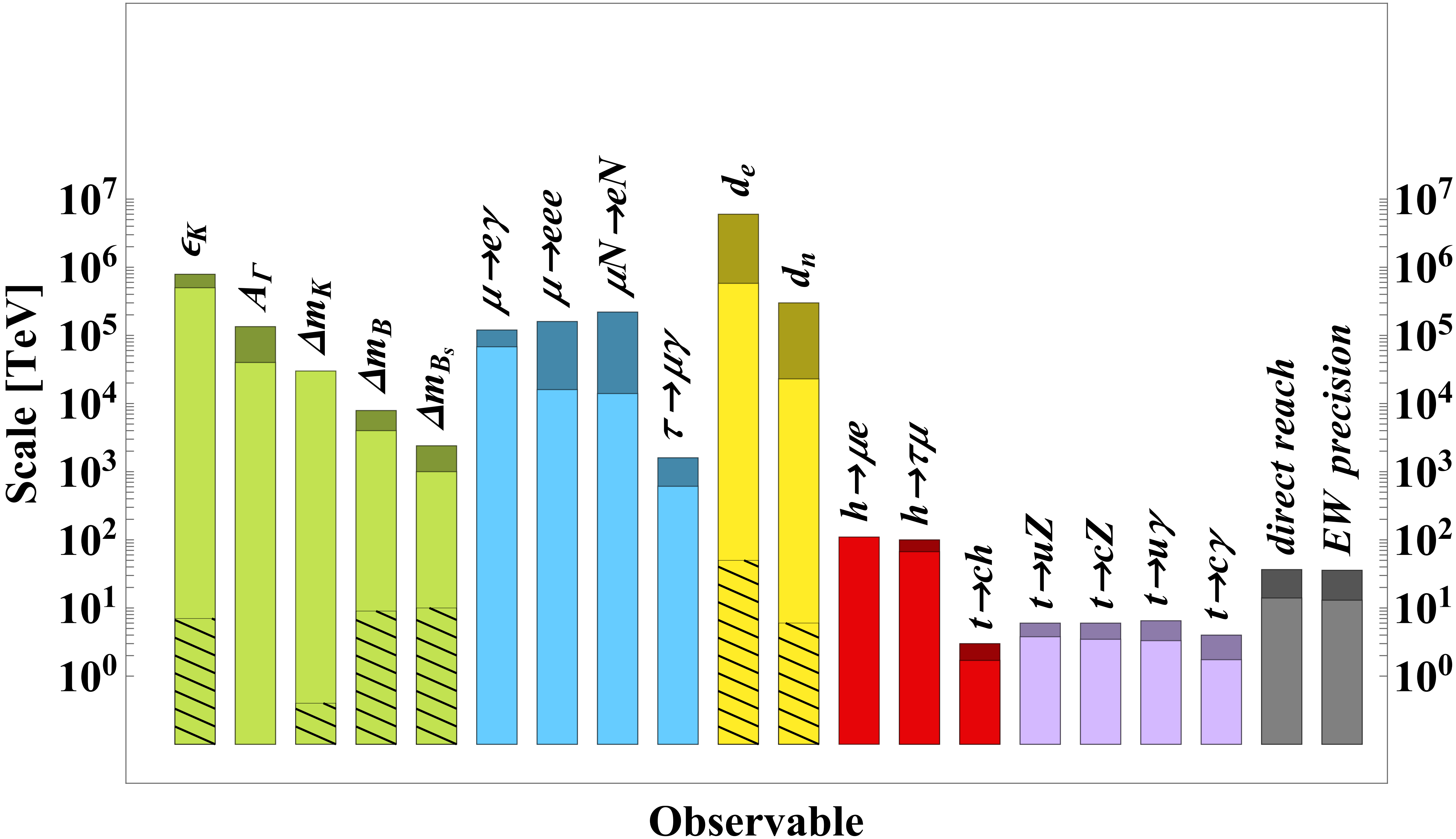


Neutrino transition observed

Charged lepton transition not observed.

Sensitivity of New Physics



shown in EPPSU2019 Physics Briefing Book

http://cds.cern.ch/record/2691414/files/Briefing_Book_Final.pdf

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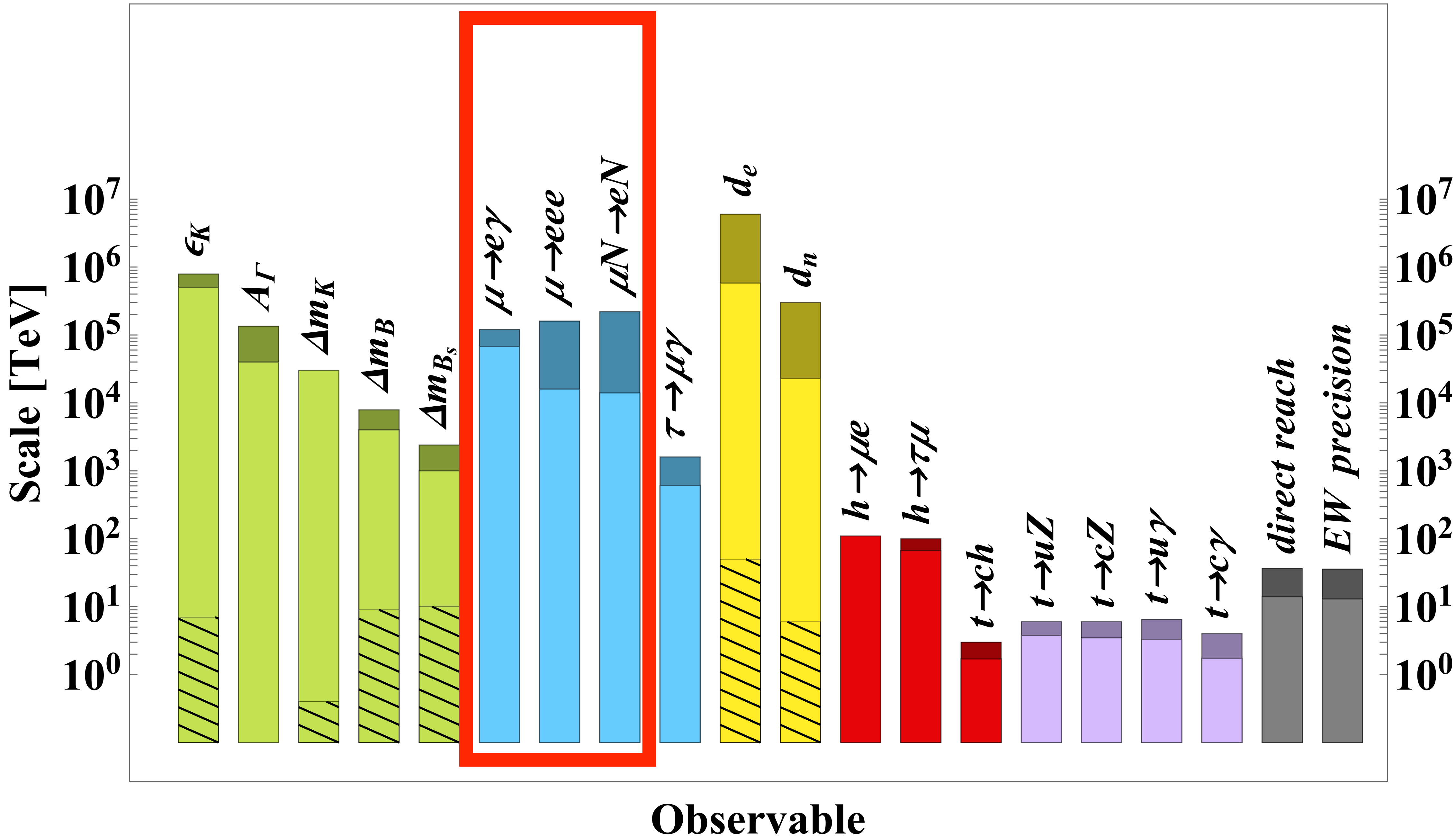

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SM Lepton Mixing to CLFV
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Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been known.

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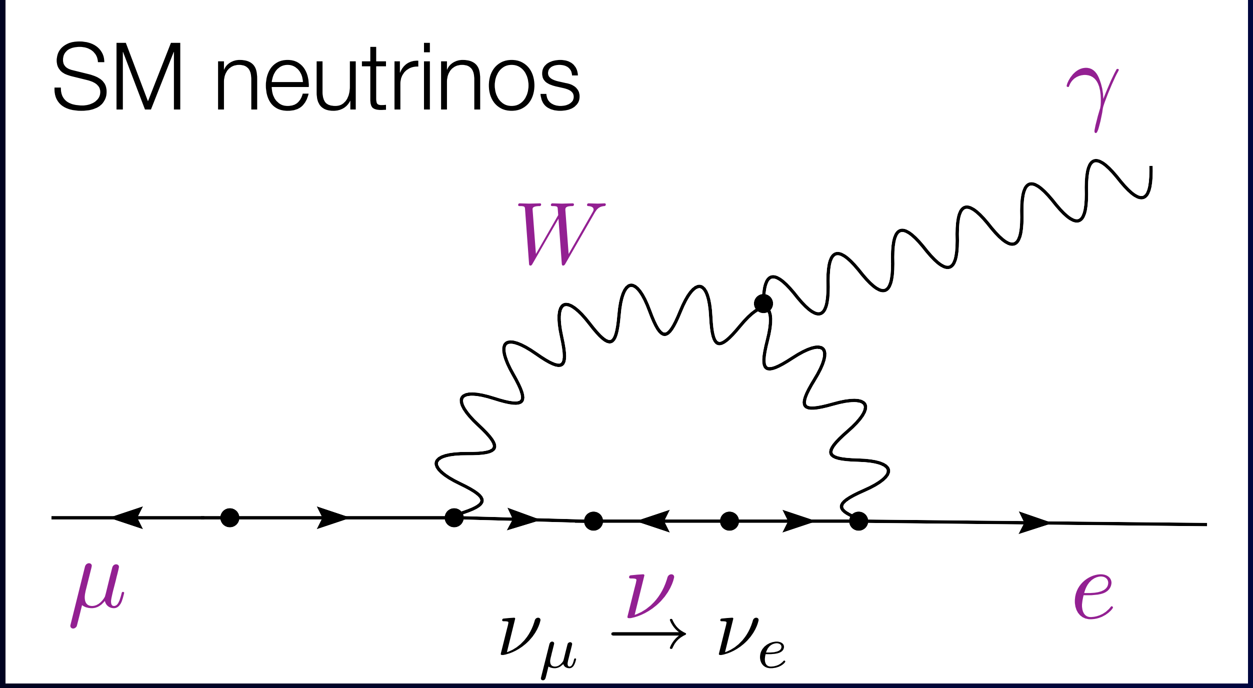

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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

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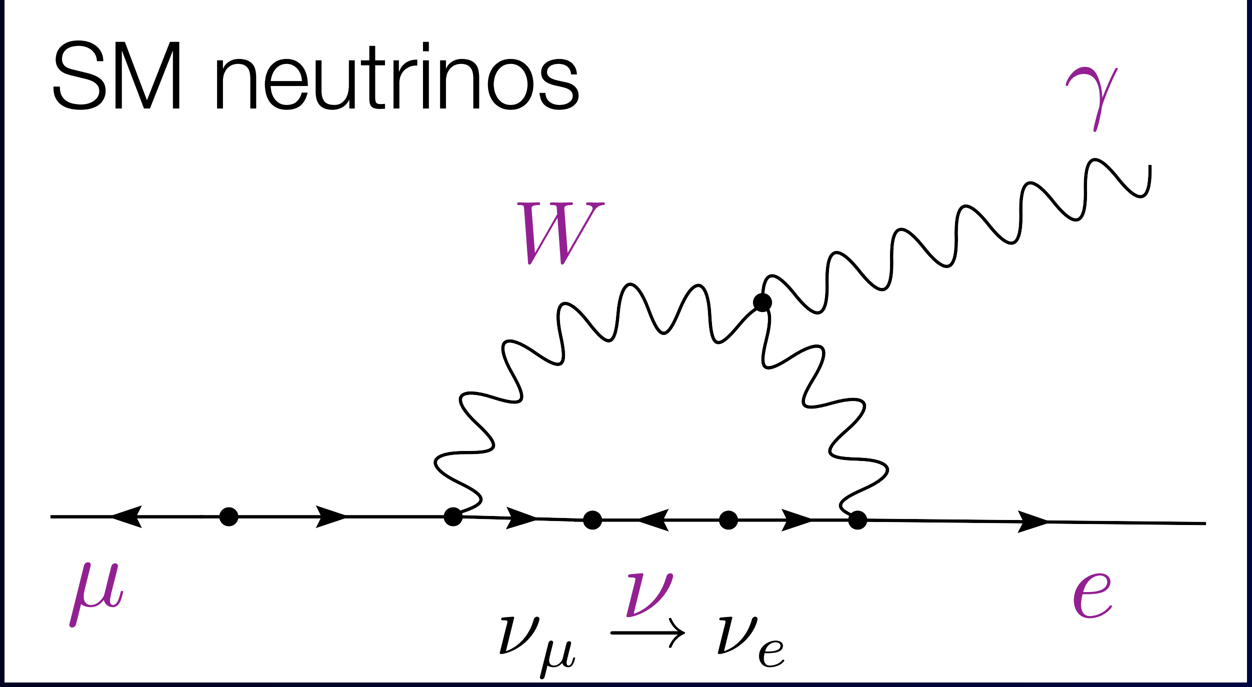

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BR~O(10^{-54})

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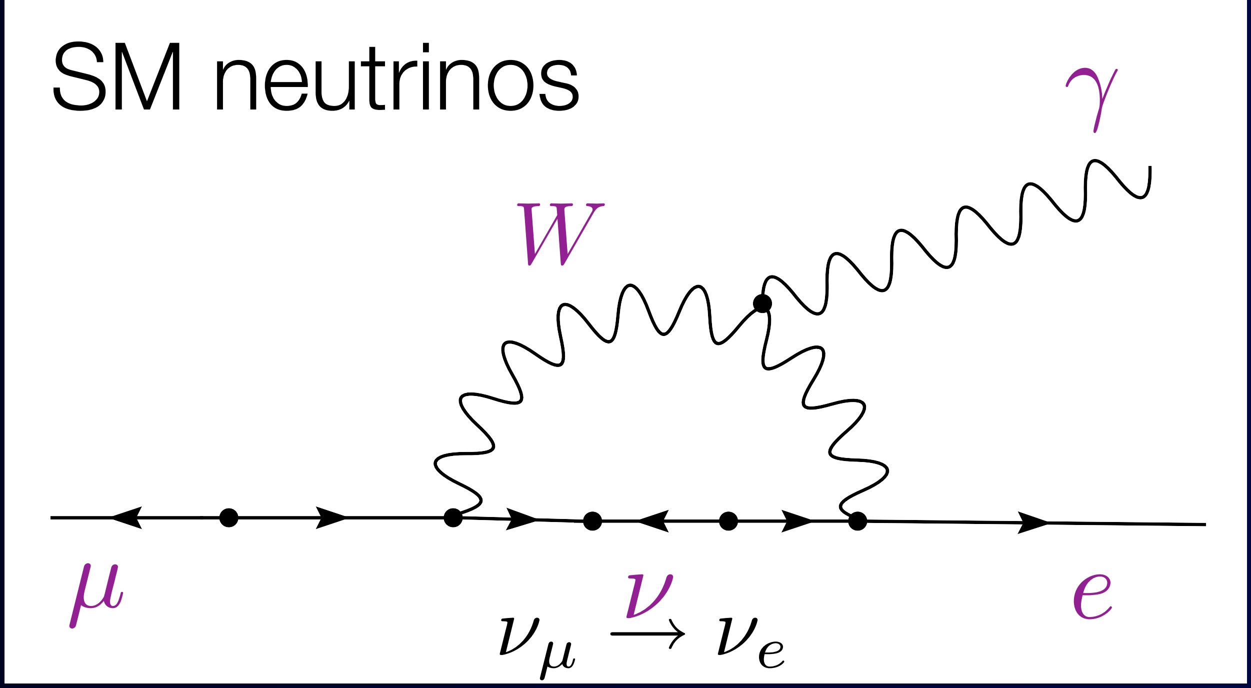

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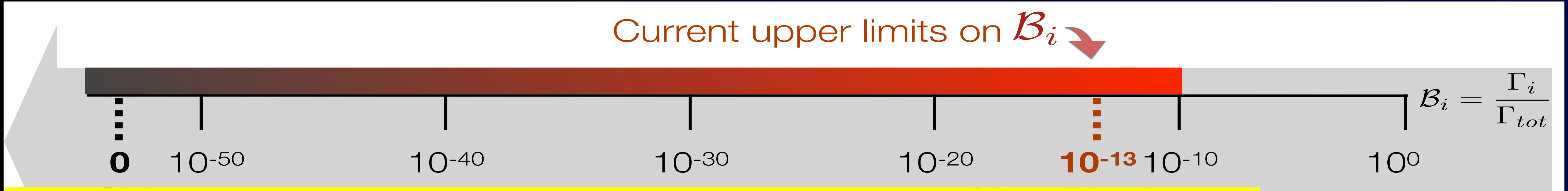


Large window for BSM search without SM backgrounds

Muon CLFV Experiments

Muon LFV
History

Muon LFV History

First CLFV search

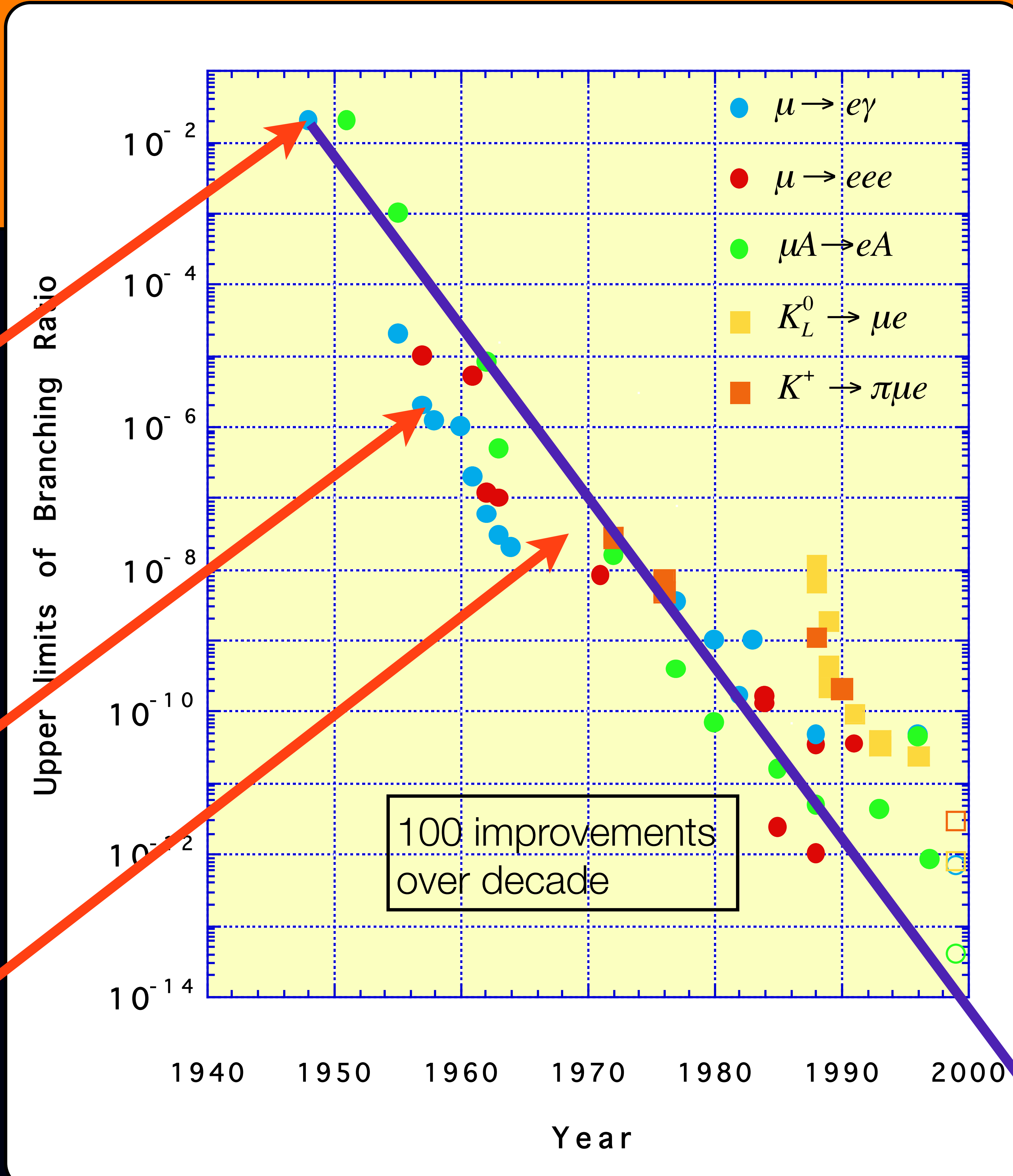
Pontecorvo in 1947

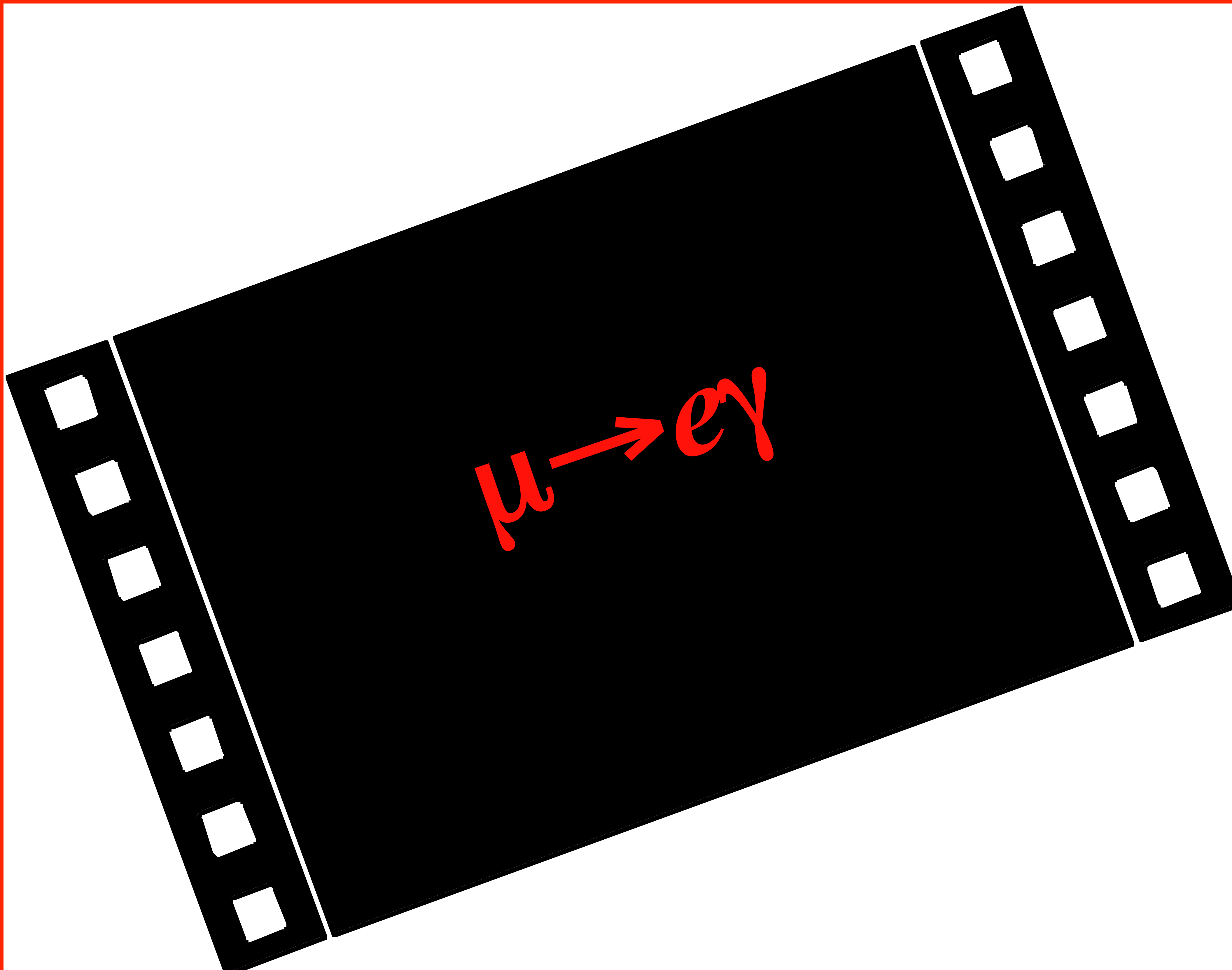
Muon Michel decay (1948)

Accelerators producing muons

Feinberg's μ→eγ crisis (1955)

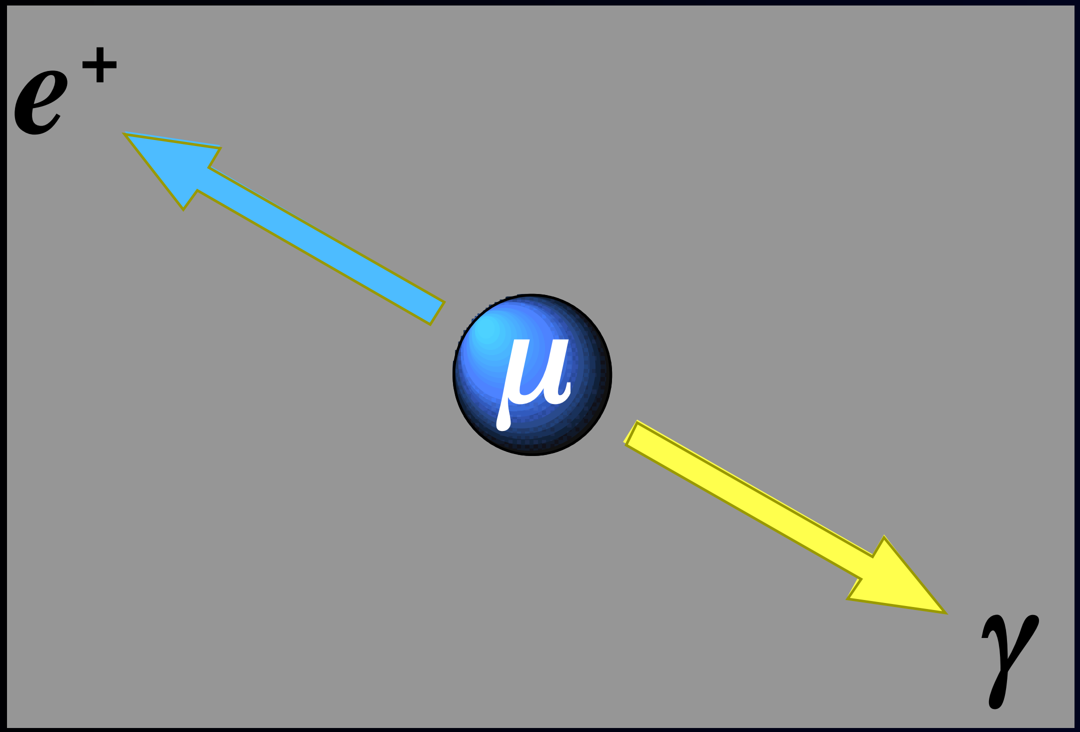
Meson Factory Era




μ→eγ

CLFV Decay of Muons : $\mu^+ \rightarrow e^+\gamma$

- Event Signature
  - $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{\mu e}$=180 degrees (back-to-back)
  - time coincidence



- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \rightarrow e\nu\nu\gamma$
  - accidental backgrounds
    - positron in $\mu \rightarrow e\nu\nu$
    - photon in $\mu \rightarrow e\nu\nu\gamma$ or photon from e^+e^- annihilation in flight.
- Current Limits
  - BR<4.2×10^{-13}
    - MEG at PSI
    - a factor 30 improvement from MEGA

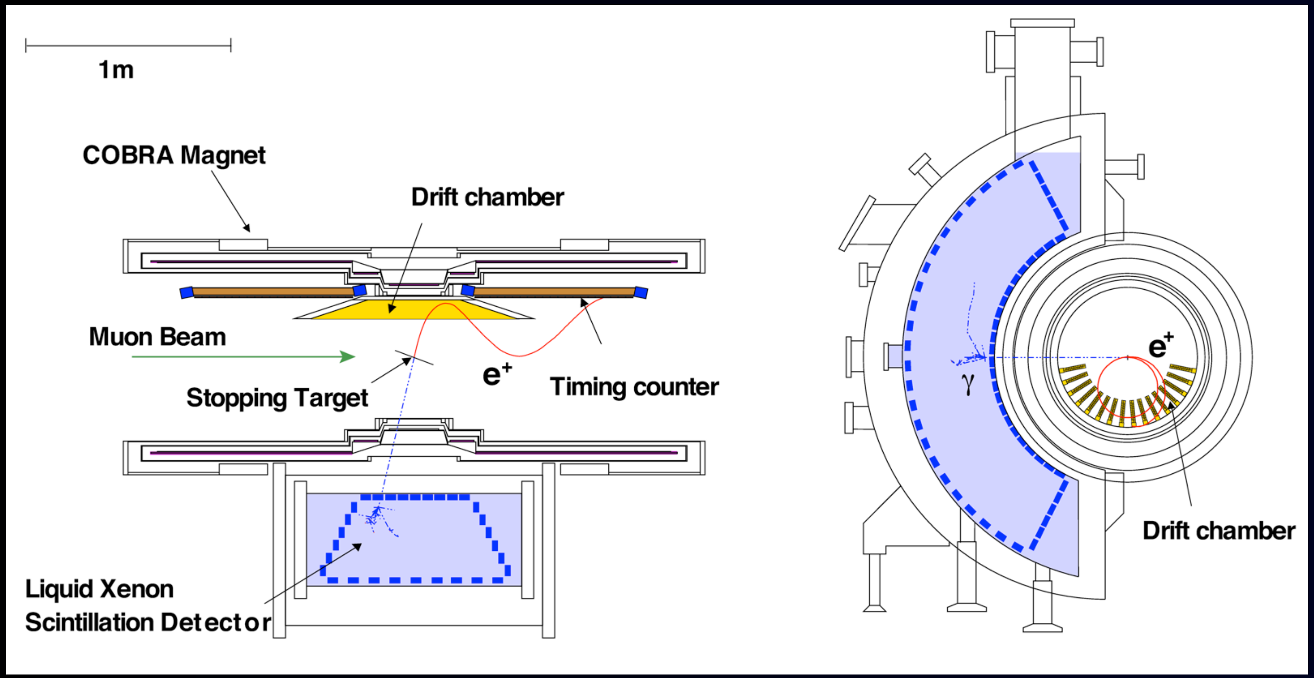
CLFV Decay of Muons : $\mu^+ \rightarrow e^+\gamma$

Osaka University

CLFV Decay of Muons : $\mu^+ \rightarrow e^+\gamma$

MEG @PSI (2016)

- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI



$$B(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$$

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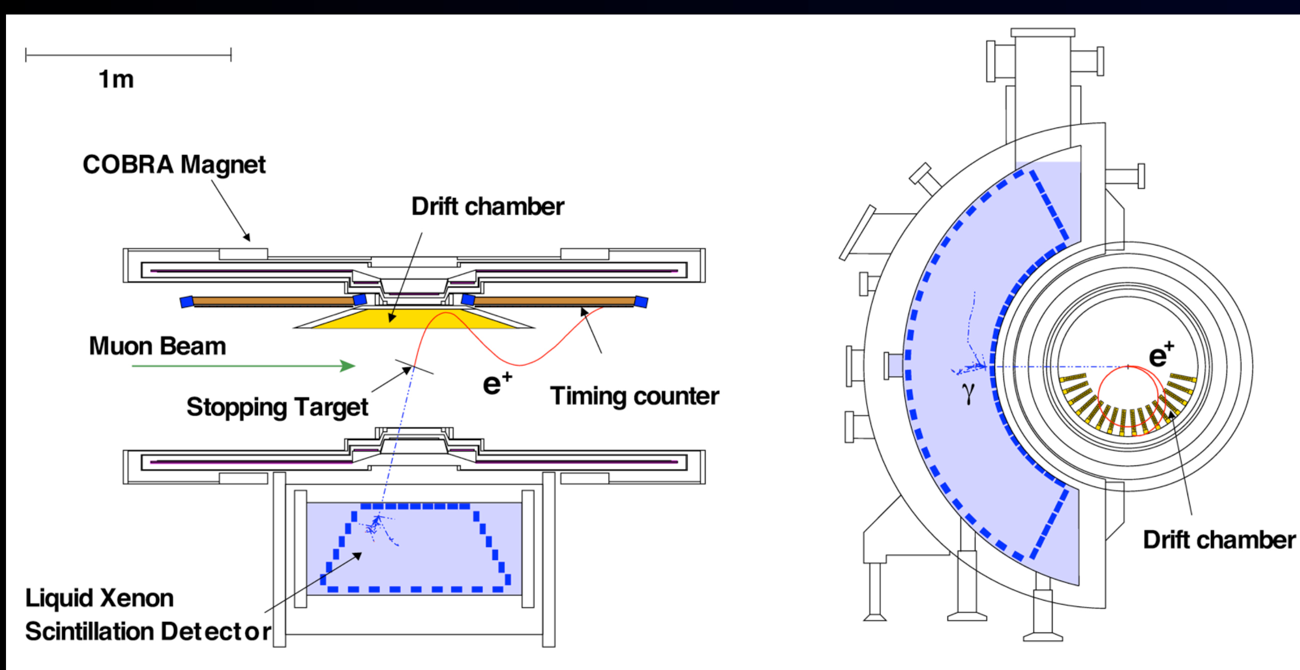
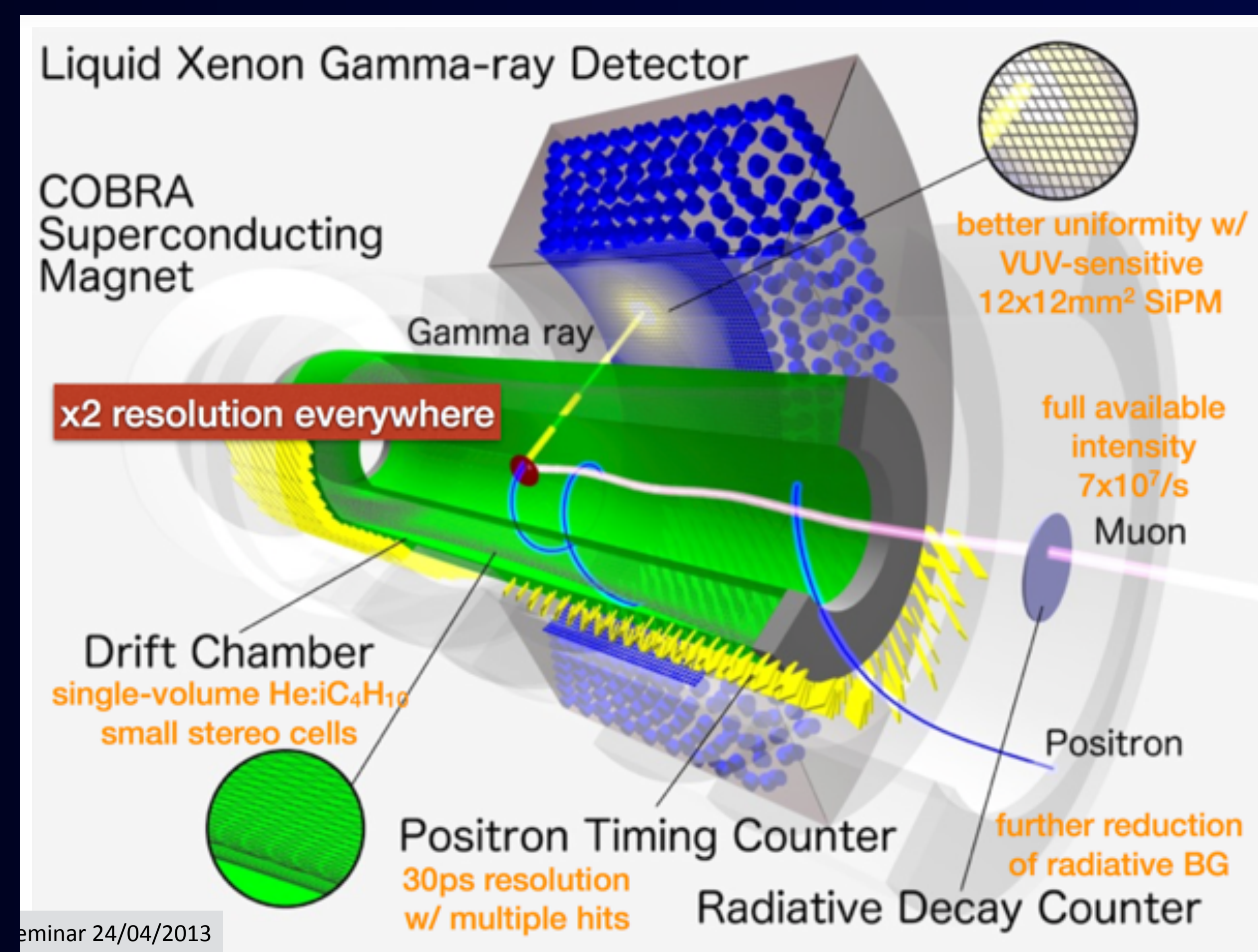


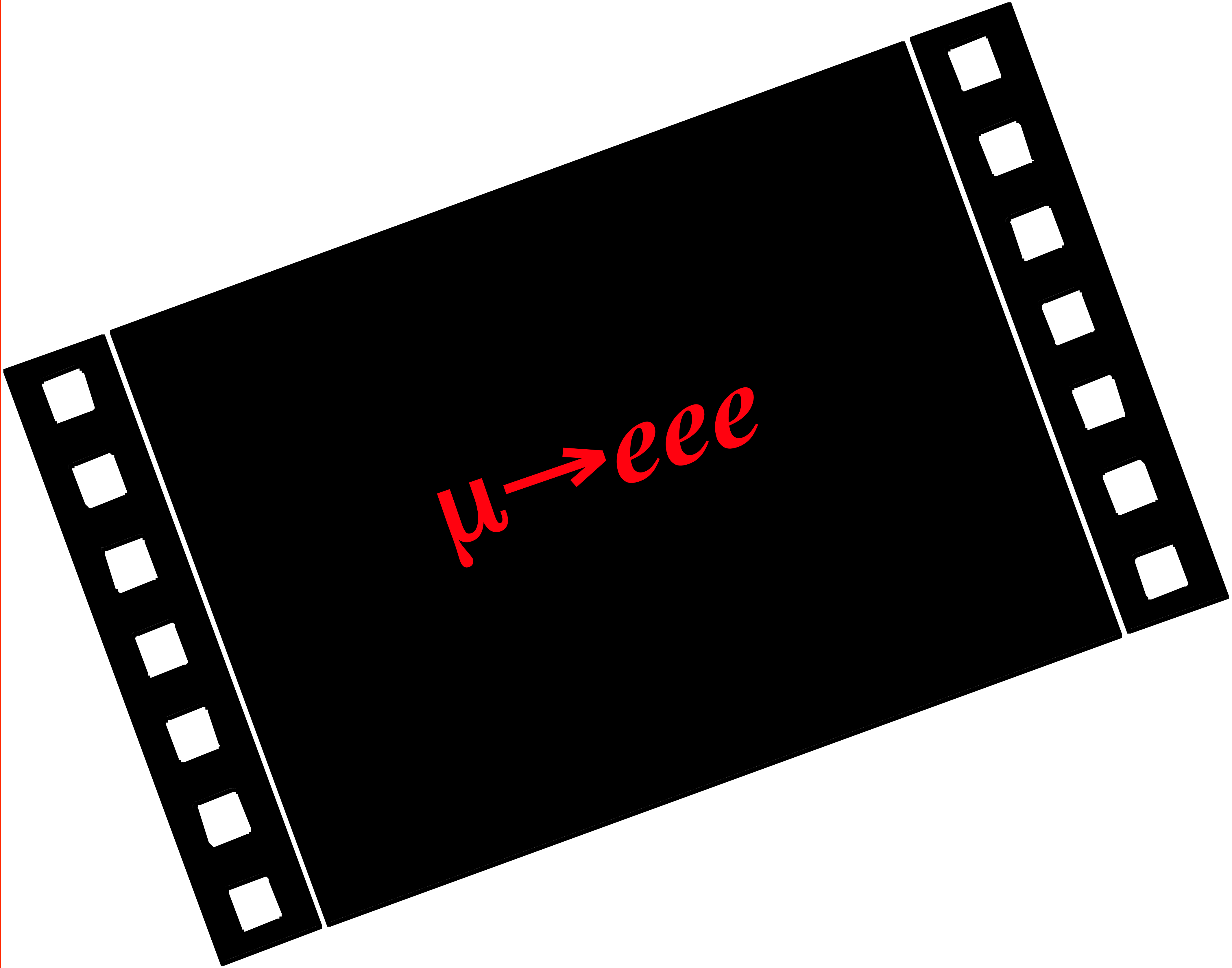
$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

- a factor of 30 improvement

MEG II

- all detectors upgraded
- full muon beam intensity
- Goal ~ $6\text{x}10^{-14}$ (2019-2021)




μ→eee

CLFV Three-body Decay : $\mu^+ \rightarrow e^+ e^+ e^-$

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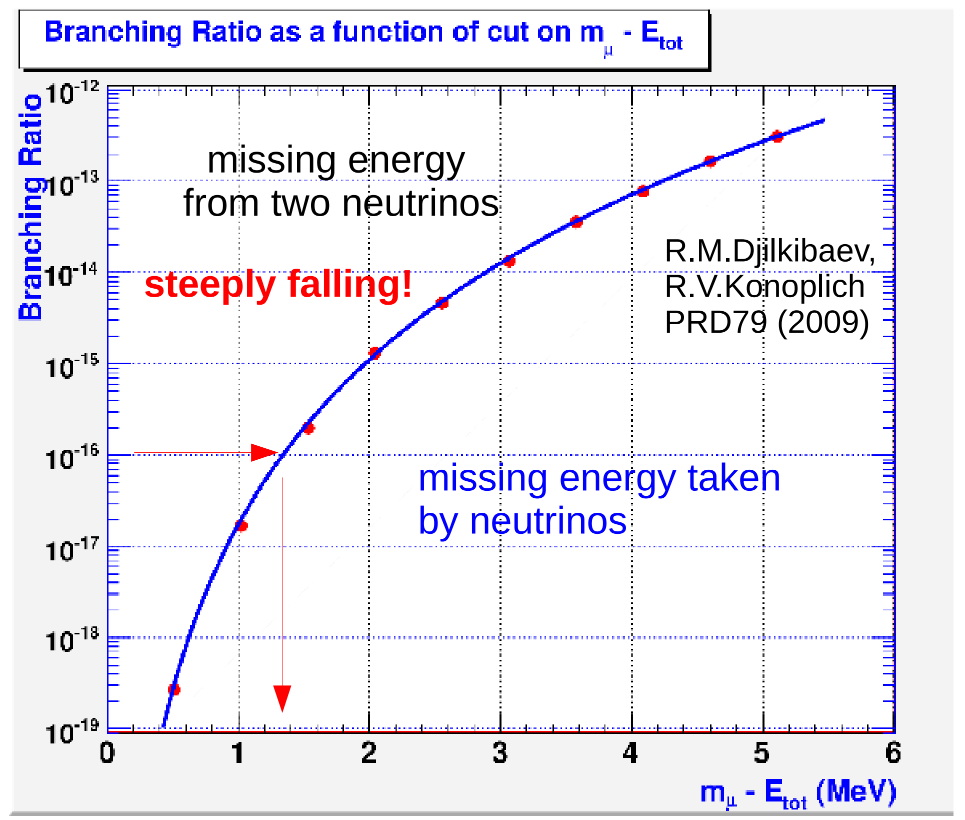
- Event Signature
  - $\Sigma E_e = m_\mu$
  - $\Sigma P_e = 0$ (vector sum)
  - common vertex
  - time coincidence
- Backgrounds
  - physics backgrounds
    - $\mu \rightarrow e\nu\nu ee$ decay ($B=3.4\times10^{-5}$)
  - accidental backgrounds
    - 2 positrons in two $\mu \rightarrow e\nu\nu$
    - 1 electrons in $\mu \rightarrow eee\nu\nu$, or $\mu \rightarrow e\nu\nu\gamma$ ($B=1.2\times10^{-2}$) with photon conversion, or Bhabha scattering

- Current Limit
  - $BR<1.0\times10^{-12}$
    - with constant matrix element.
    - SINDRUM (1988)



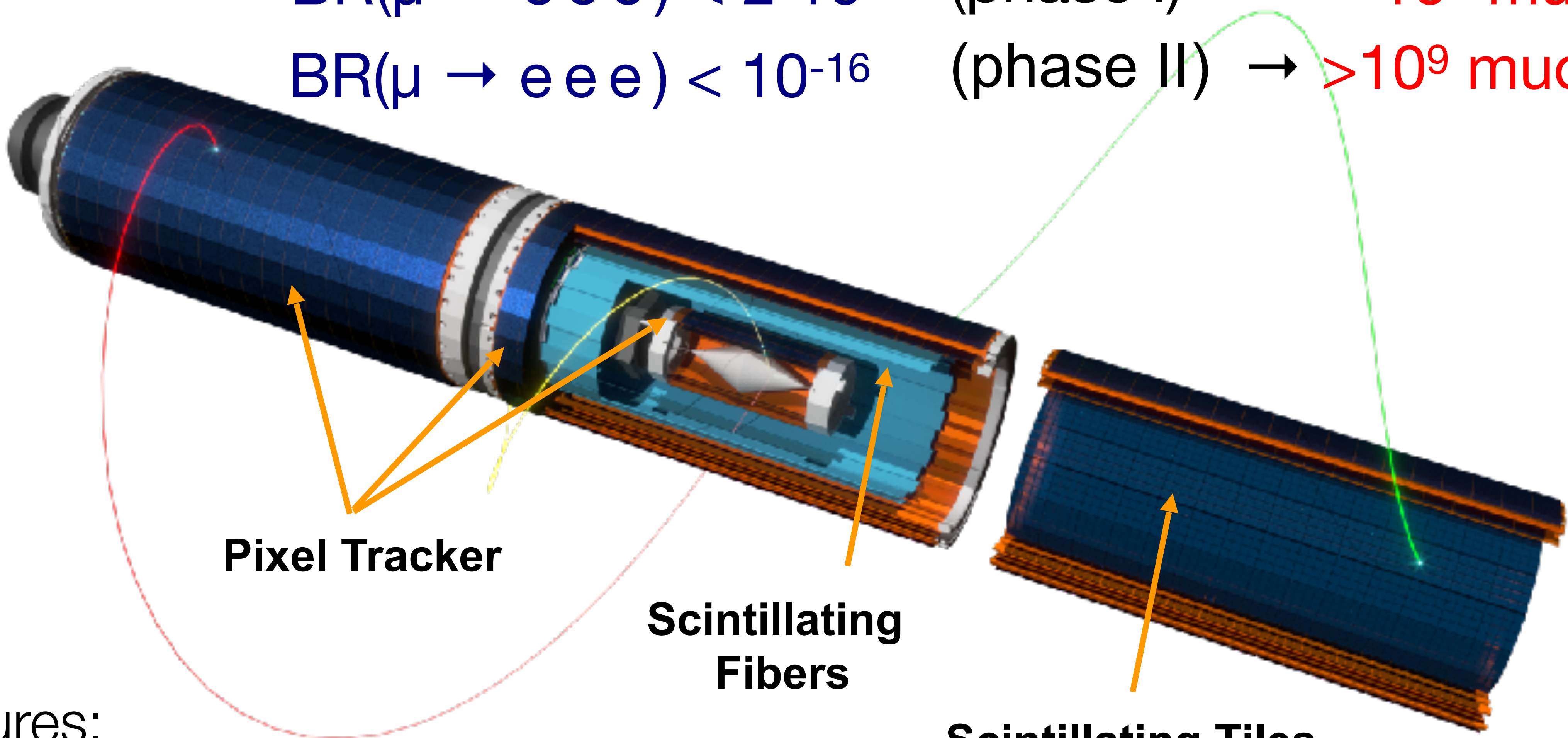
very good momentum +
total energy resolution required!

Mu3e at PSI

Mu3e at PSI

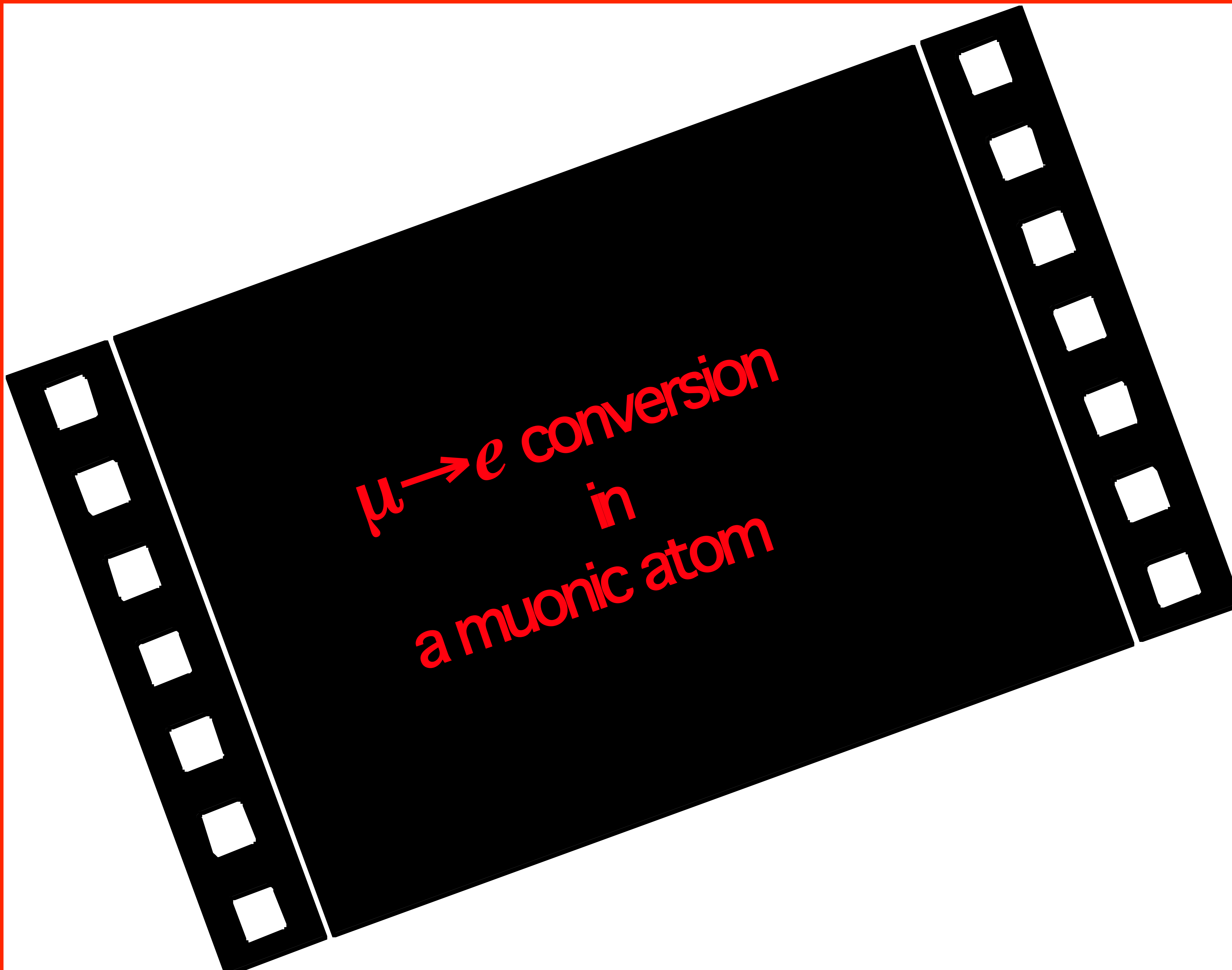
$BR(\mu \to e\,e\,e) < 2\cdot10^{-15}$ (phase I) → 10^{8} muons/s (PiE5)

$BR(\mu \to e\,e\,e) < 10^{-16}$ (phase II) → $>10^{9}$ muons/s (HiMB)



<u>Features:</u>

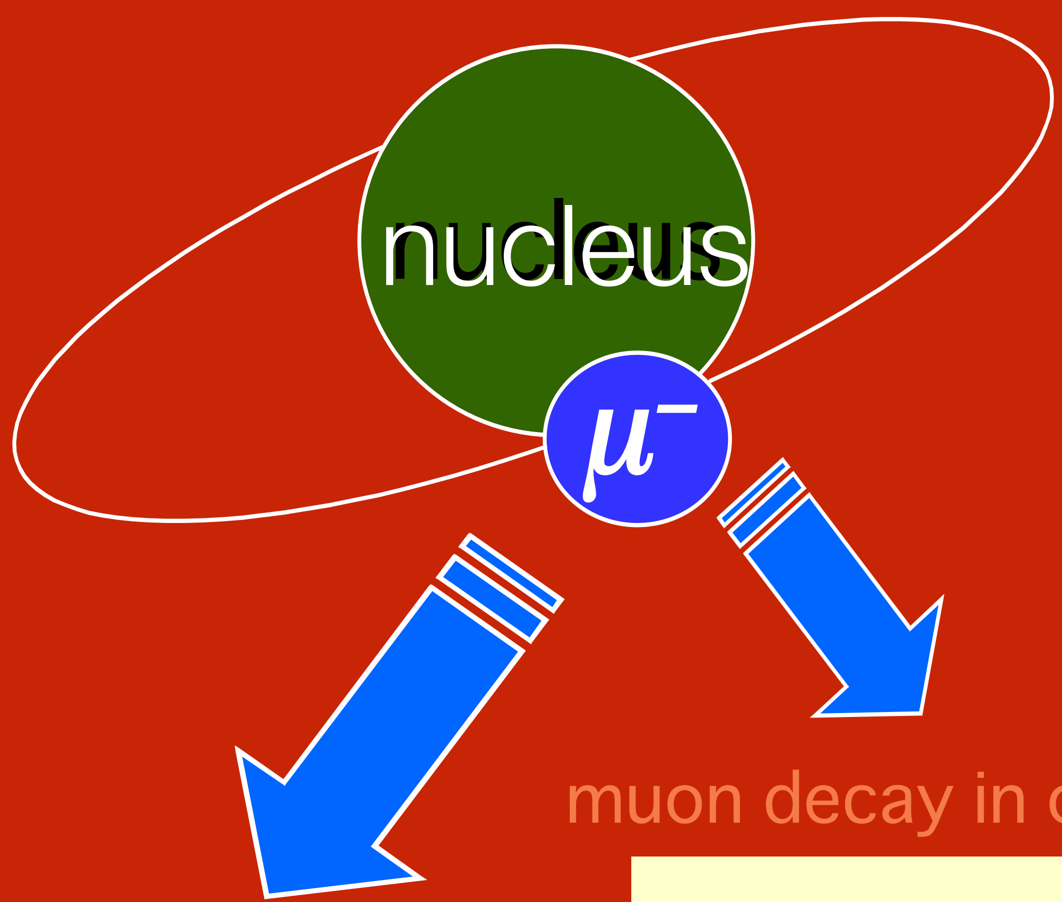
- surface muons (p=29 MeV/c, DC) stopped on target at high rate: 10^{8} - 10^{9} /s
- ultra thin silicon pixel detector (HV-MAPS) with 1 per mill radiation length / layer
- high precision tracking using recurling tracks in strong magnetic field
- fast timing detectors (scintillating fibers & tiles)
- helium gas cooling


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

μ→e Conversion in a muonic atom

μ→e Conversion in a muonic atom

1s state in a muonic atom



muon decay in orbit

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

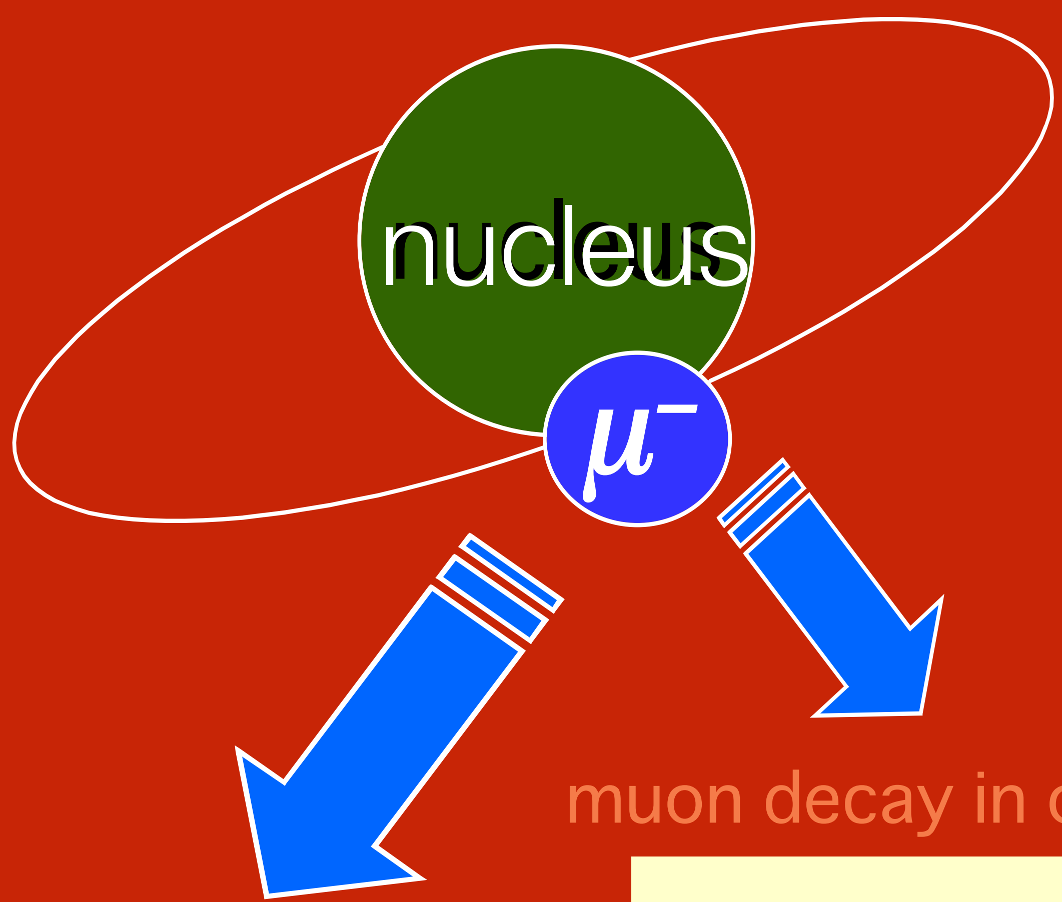
nuclear muon capture

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

$$CR(\mu^- N \rightarrow e^- N) \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \text{all})}$$

μ→e Conversion in a muonic atom

1s state in a muonic atom



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

Event Signature :

a single mono-energetic electron of 105 MeV

Backgrounds:

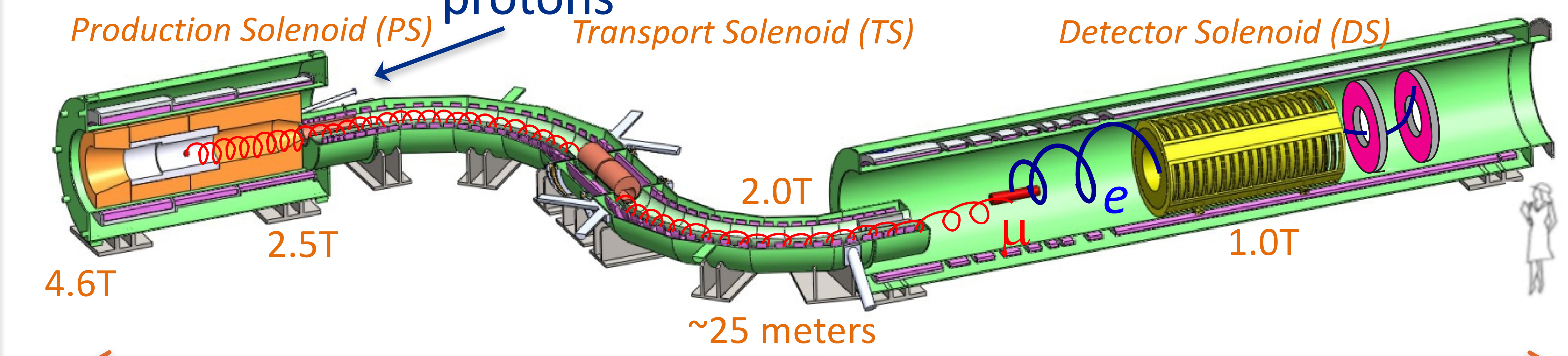
(1) physics backgrounds

(2) beam-related backgrounds

(3) cosmic rays, false tracking

	Z	CR limit
sulfur	16	$<7 \times 10^{-11}$
titanium	22	$<4.3 \times 10^{-12}$
copper	39	$<1.6 \times 10^{-8}$
gold	79	$<7 \times 10^{-13}$
lead	82	$<4.6 \times 10^{-11}$

Mu2e at Fermilab



- A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - *Discovery* sensitivity to broad swath of NP parameter space

- Experiment scope includes
  - Proton Beam line
  - Solenoid systems
  - Detector elements

    (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - Experimental hall
  - Commissioning begins in 2022

Mu2e-II - a next generation $\mu \rightarrow e$ conversion experiment at FNAL

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Mu2e-II is an upgrade that will:

- Use ~100 kW of PIP-II protons @800 MeV
- Achieve an order of magnitude improvement in sensitivity
  - probe $R_{\mu e} \sim 10^{-18}$ level,
  - extend Λ_{NP} reach by x2

- EOI Submitted to Fermilab PAC in 2018
- arXiv:1802.02599, Fermilab-FN-1052
- 130 Signatories, 36 Institutions

PAC: "physics case is compelling" "endorse request for R&D funding"
Status: Pursuing high priority R&D. Data taking ~2030 timescale.

COMET = COherent Muon to Electron Transition

COMET Phase-I : J-PARC E21

cylindrical
drift chamber

COMET = COherent Muon to Electron Transition

COMET Phase-I : J-PARC E21

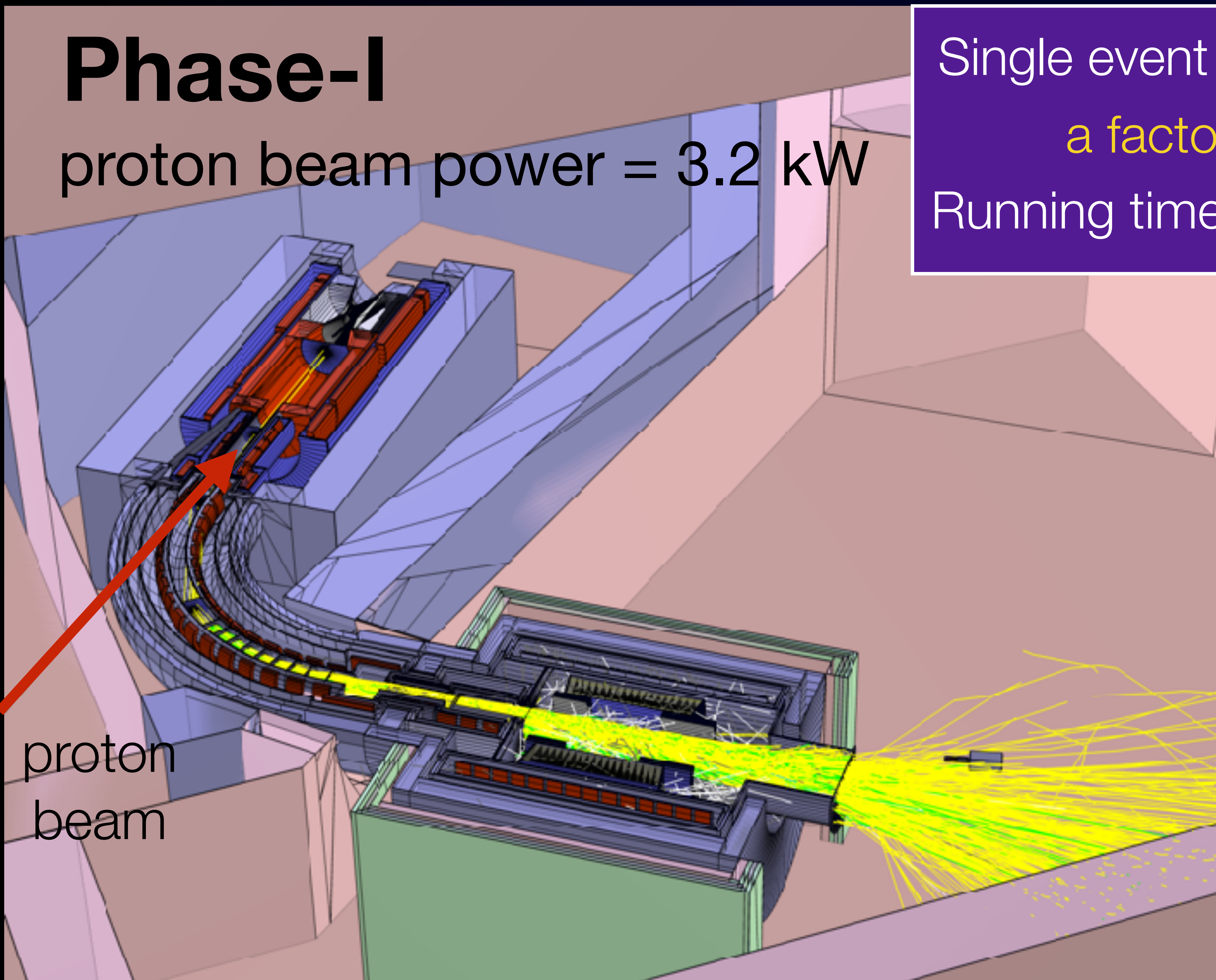
Phase-I

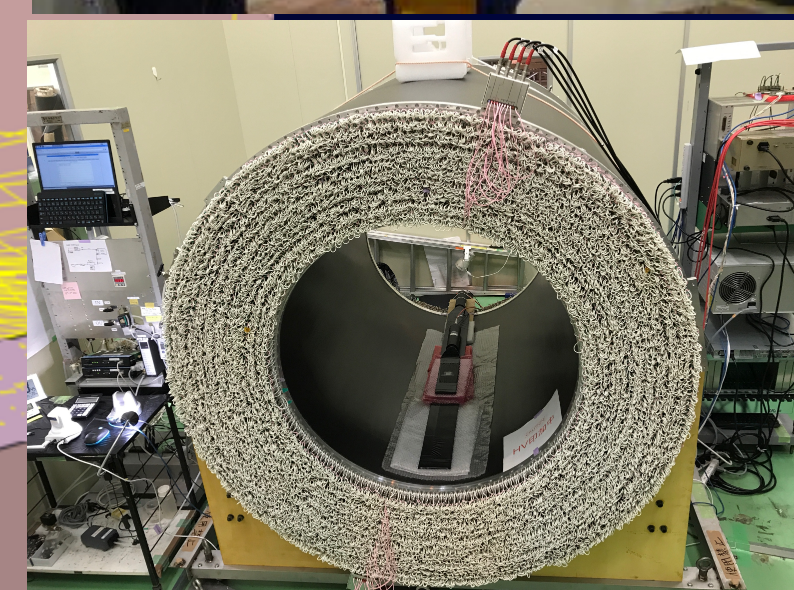
proton beam power = 3.2 kW

Single event sensitivity : 2×10^{-15}

a factor of 100 improvement

Running time: 0.4 years (1.2×10^{7}s)





COMET Phase-II : J-PARC E21

straw chamber

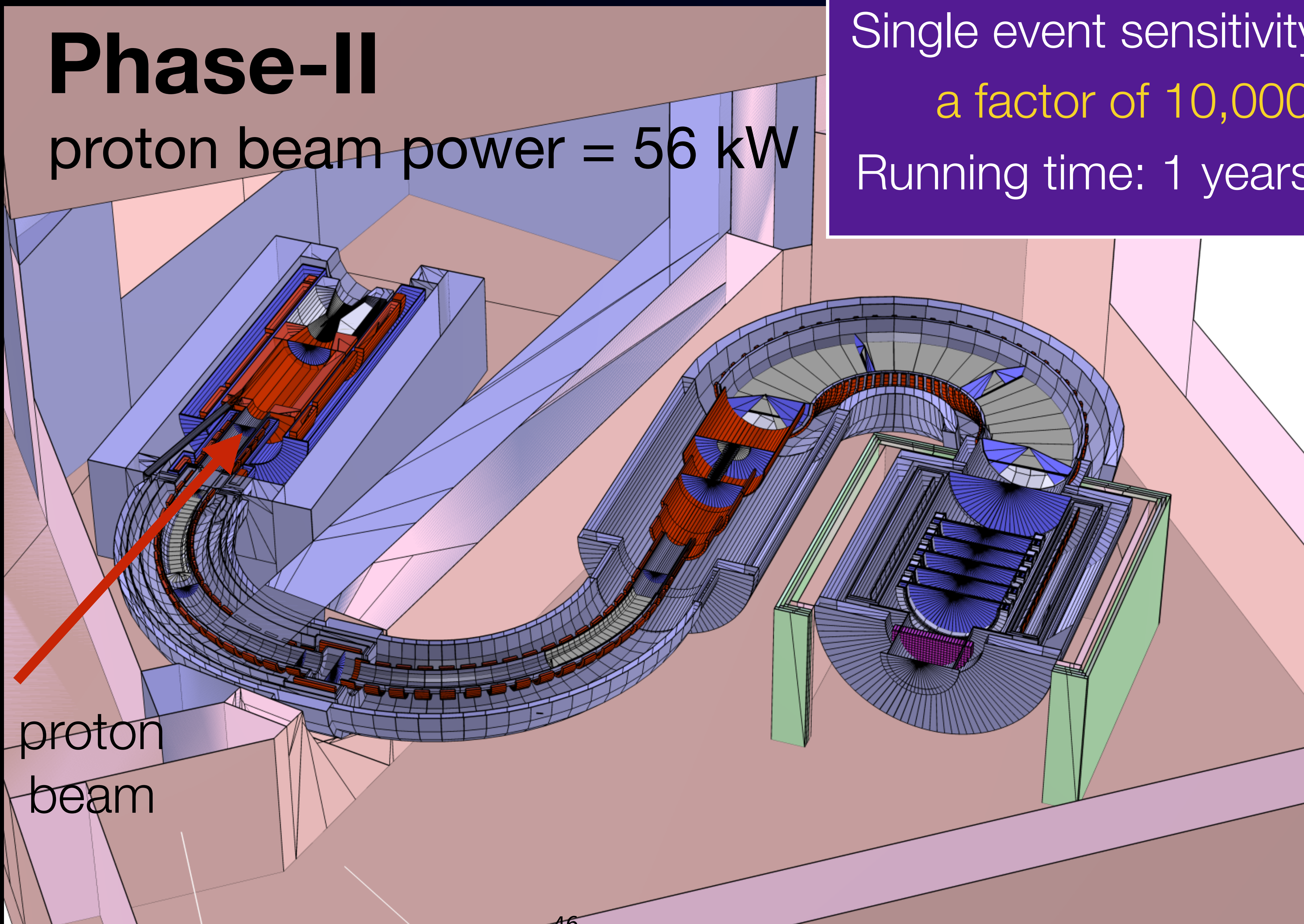
LYSO calorimeter

COMET Phase-II : J-PARC E21

Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

Running time: 1 years (2×10^{7}sec)



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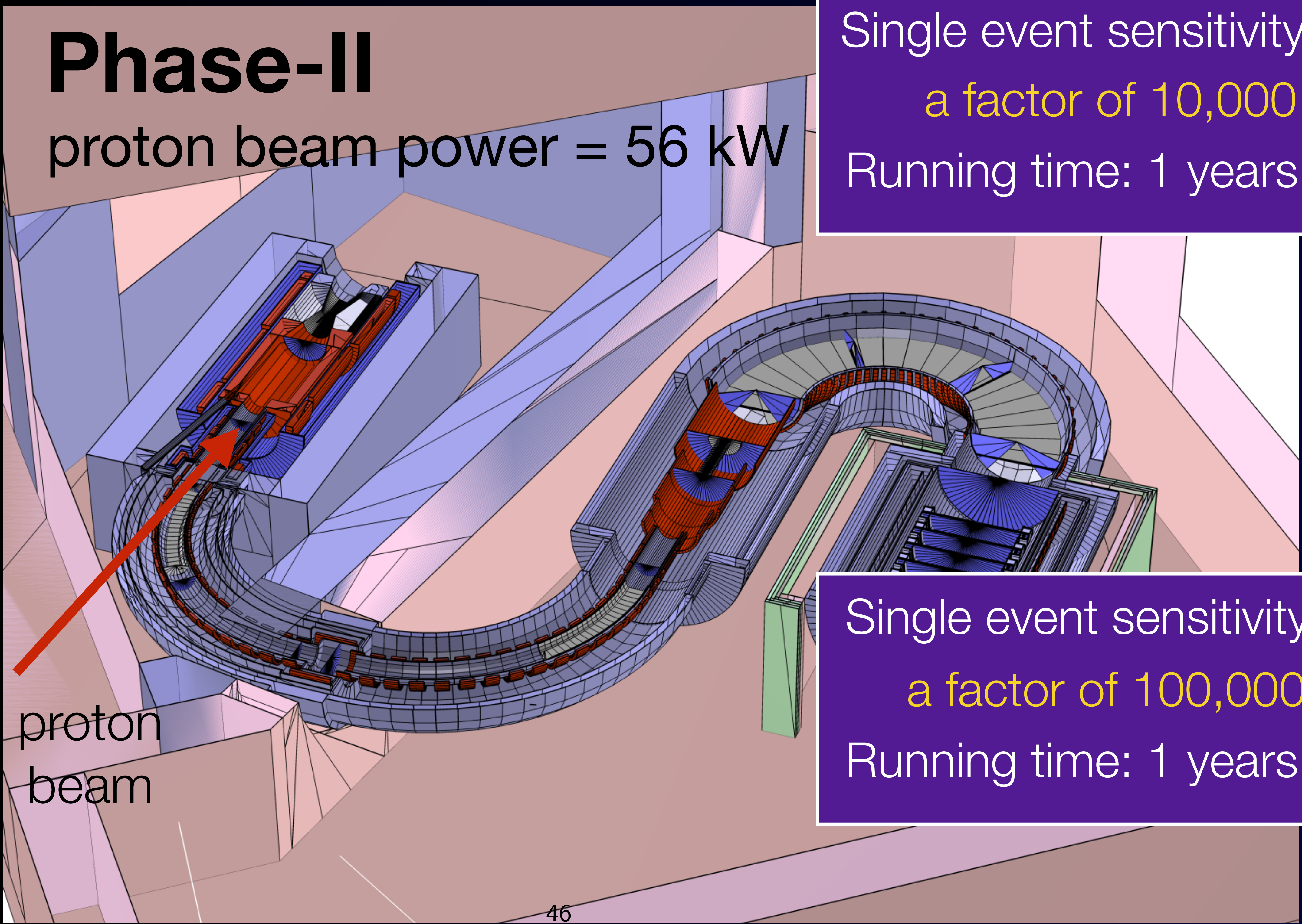


Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

Running time: 1 years (2×10^{7} sec)

Single event sensitivity : $O(10^{-18})$

a factor of 100,000 improvement

Running time: 1 years (3×10^{7} sec)

COMET Collaboration

PI: Y. Kuno

The COMET Collaboration

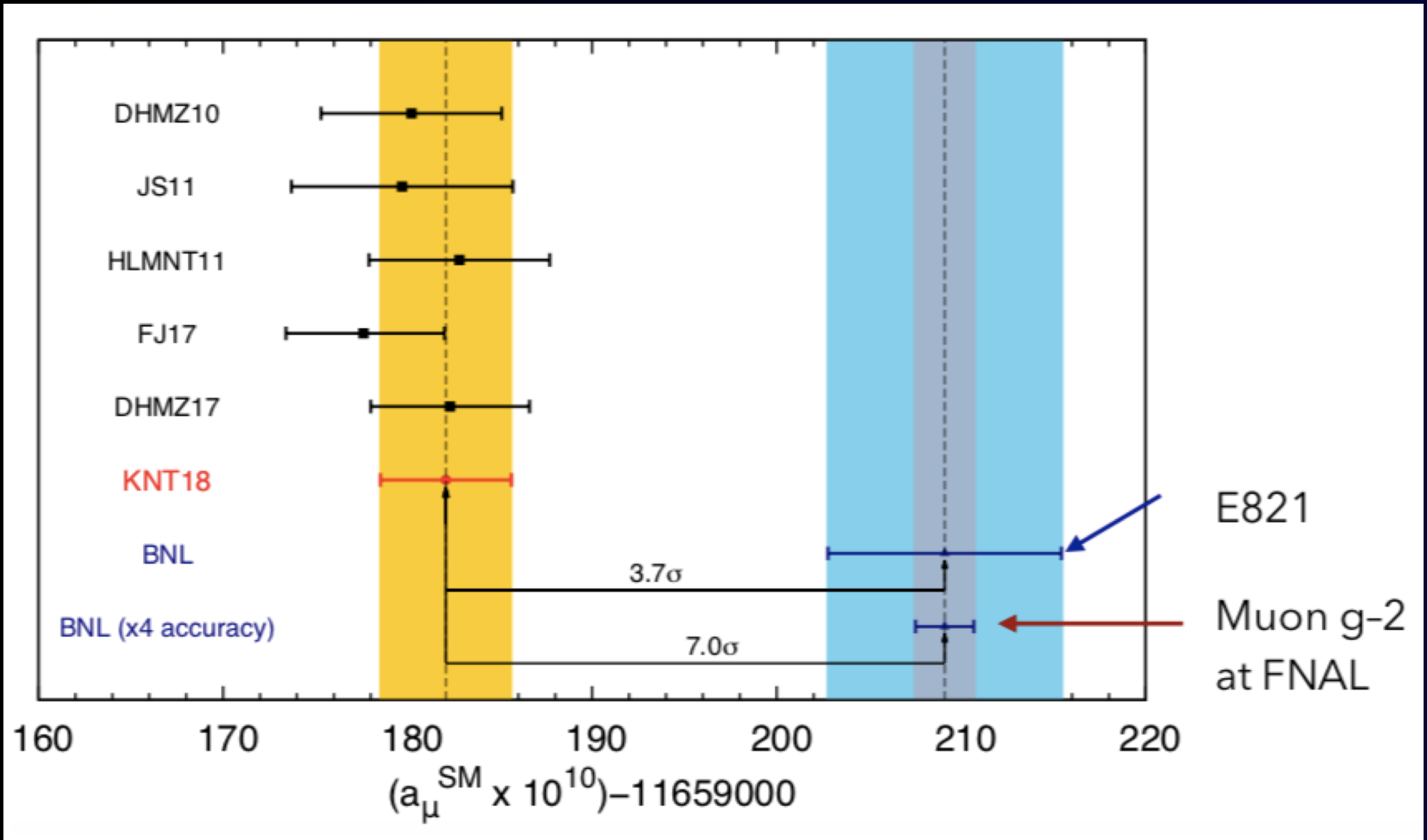
R. Abramishvili[11], G. Adamov[11], R. Akhmetshin[6,31], V. Anishchik[4], M. Aoki[32], Y. Arimoto[18], I. Bagaturia[11], Y. Ban[3], A. Bondar[6,31], Y. Calas[7], S. Canfer[33], Y. Cardenas[7], S. Chen[28], Y. E. Cheung[28], B. Chiladze[35], D. Clarke[33], M. Danilov[15,26], P. D. Dauncey[14], J. David[23], W. Da Silva[23], C. Densham[33], G. Devidze[35], P. Dornan[14], A. Drutskoy[15,26], V. Duginov[16], L. Epshteyn[6,30], P. Evtoukhovich[16], G. Fedotovich[6,31], M. Finger[8], M. Finger Jr[8], Y. Fujii[18], Y. Fukao[18], J-F. Genat[23], E. Gillies[14], D. Grigoriev[6,30,31], K. Gritsay[16], E. Hamada[18], R. Han[1], K. Hasegawa[18], I. H. Hasim[32], O. Hayashi[32], Z. A. Ibrahim[24], Y. Igarashi[18], F. Ignatov[6,31], M. Iio[18], M. Ikeno[18], K. Ishibashi[22], S. Ishimoto[18], T. Itahashi[32], S. Ito[32], T. Iwami[32], X. S. Jiang[2], P. Jonsson[14], V. Kalinnikov[16], F. Kapusta[23], H. Katayama[32], K. Kawagoe[22], N. Kazak[5], V. Kazanin[6,31], B. Khazin[6,31], A. Khvedelidze[16,11], T. K. Ki[18], M. Koike[39], G. A. Kozlov[16], B. Krikler[14], A. Kulikov[16], E. Kulish[16], … e[14,21], M. Lancast … an[29], D. Lomidze … Mao[3], O. Markin[15] … Mo-hamed Kam … kai[22], T. Nakamot … chi[18], T. Numao[36], J. O'Dell[33], T. Ogitsu[18], K. Oishi[22], K. Okamoto[32], C. Omori[18], T. Ota[34], J. Pasternak[14], C. Plostinar[33], V. Ponariadov[45], A. Popov[6,31], V. Rusinov[15,26], A. Ryzhenenkov[6,31], B. Sabirov[16], N. Saito[18], H. Sakamoto[32], P. Sarin[13], K. Sasaki[18], A. Sato[32], J. Sato[34], Y. K. Semertzidis[12,17], D. Shemyakin[6,31], N. Shigyo[22], D. Shoukavy[5], M. Slunecka[8], A. Straessner[37], D. Stöckinger[37], M. Sugano[18], Y. Takubo[18], M. Tanaka[18], S. Tanaka[22], C. V. Tao[29], E. Tarkovsky[15,26], Y. Tevzadze[35], T. Thanh[29], N. D. Thong[32], J. Tojo[22], M. Tomasek[10], M. Tomizawa[18], N. H. Tran[32], H. Trang[29], I. Trekov[35], N. M. Truong[32], Z. Tsamalaidze[16,11], N. Tsverava[16,35], T. Uchida[18], Y. Uchida[14], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[10], W. A. T. Wan Abdullah[24], M. Warren[38], M. Wing[38], T. S. Wong[32], C. Wu[2,28], H. Yamaguchi[22], A. Yamamoto[18], Y. Yang[22], W. Yao[2], Y. Yao[2], H. Yoshida[32], M. Yoshida[18], Y. Yoshii[18], T. Yoshioka[22], Y. Yuan[2], Y. Yudin[6,31], J. Zhang[2], Y. Zhang[2], K. Zuber[37]

about 200 collaborators
41 institutes, 17 countries

Muon g-2

Muon g-2

$$\frac{g-2}{2} = a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$



3.7σ deviation from the SM expectation

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Muon g-2 : Spin precession

Muon g-2 : Spin precession

Under a magnetic field

Spin vector precession

$$\omega_S = \frac{eB}{m_\mu \gamma}[1 + \frac{(g-2)}{2}\gamma]$$

Momentum vector motion

$$\omega_C = \frac{eB}{m_\mu \gamma}$$

Muon g-2 : Spin precession

Francis Farley, Hans Sens, Georges Charpak, Theo Muller, Anton with the 6-meter *g-2* magnet

Under a magnetic field

Spin vector precession

$$\omega_S = \frac{eB}{m_\mu \gamma}[1 + \frac{(g-2)}{2}\gamma]$$

Momentum vector motion

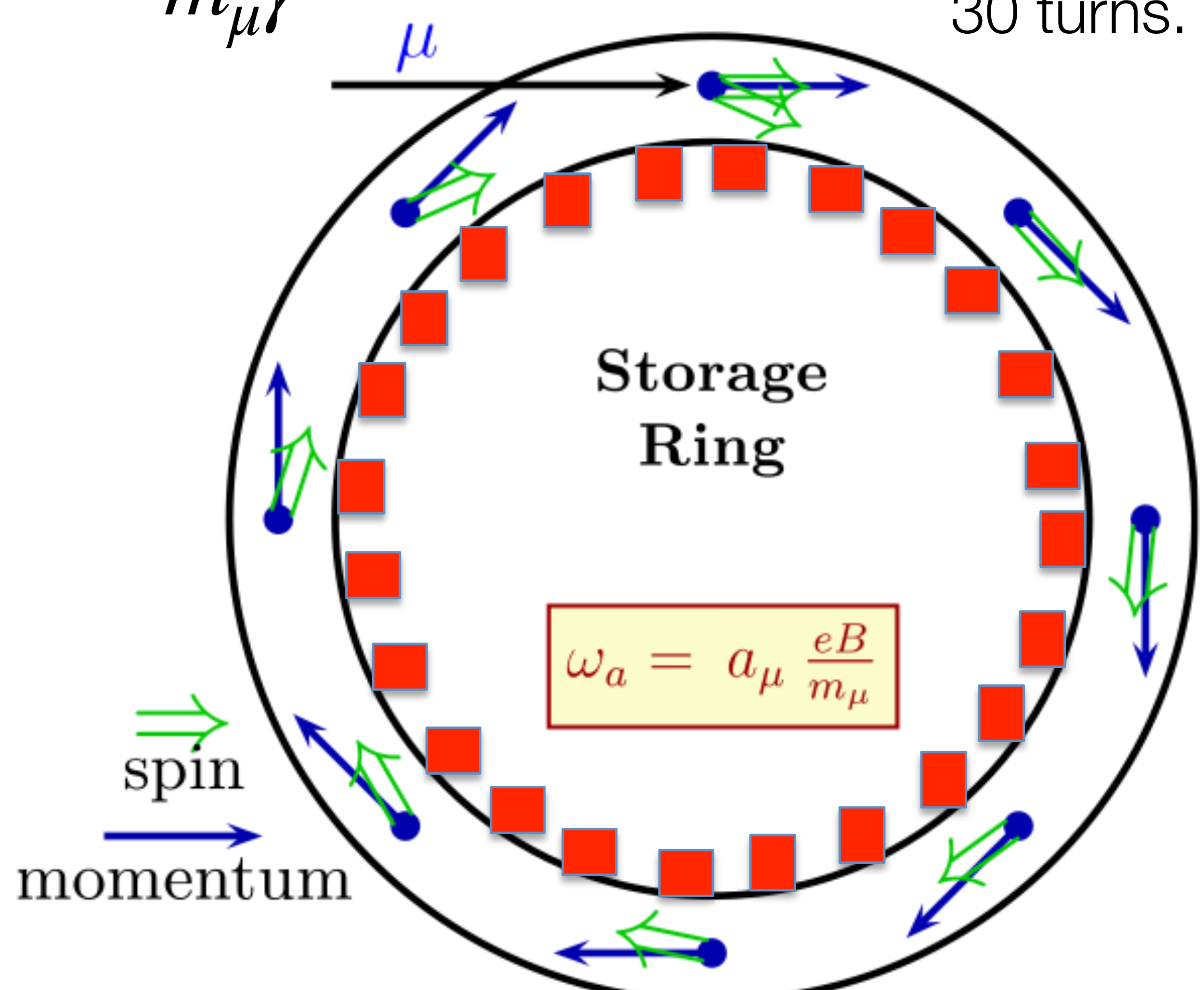
$$\omega_C = \frac{eB}{m_\mu \gamma}$$

At the BNL experiment, spin precesses around momentum once every 30 turns.

Spin precession with respect to the momentum vector

$$\omega_S - \omega_C = \omega_a = \frac{a_\mu eB}{m_\mu}$$

$$a_\mu = \frac{1}{2}(g-2)$$



Muon g-2 (E989) at FNAL

Muon g-2 (E989) at FNAL

- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year

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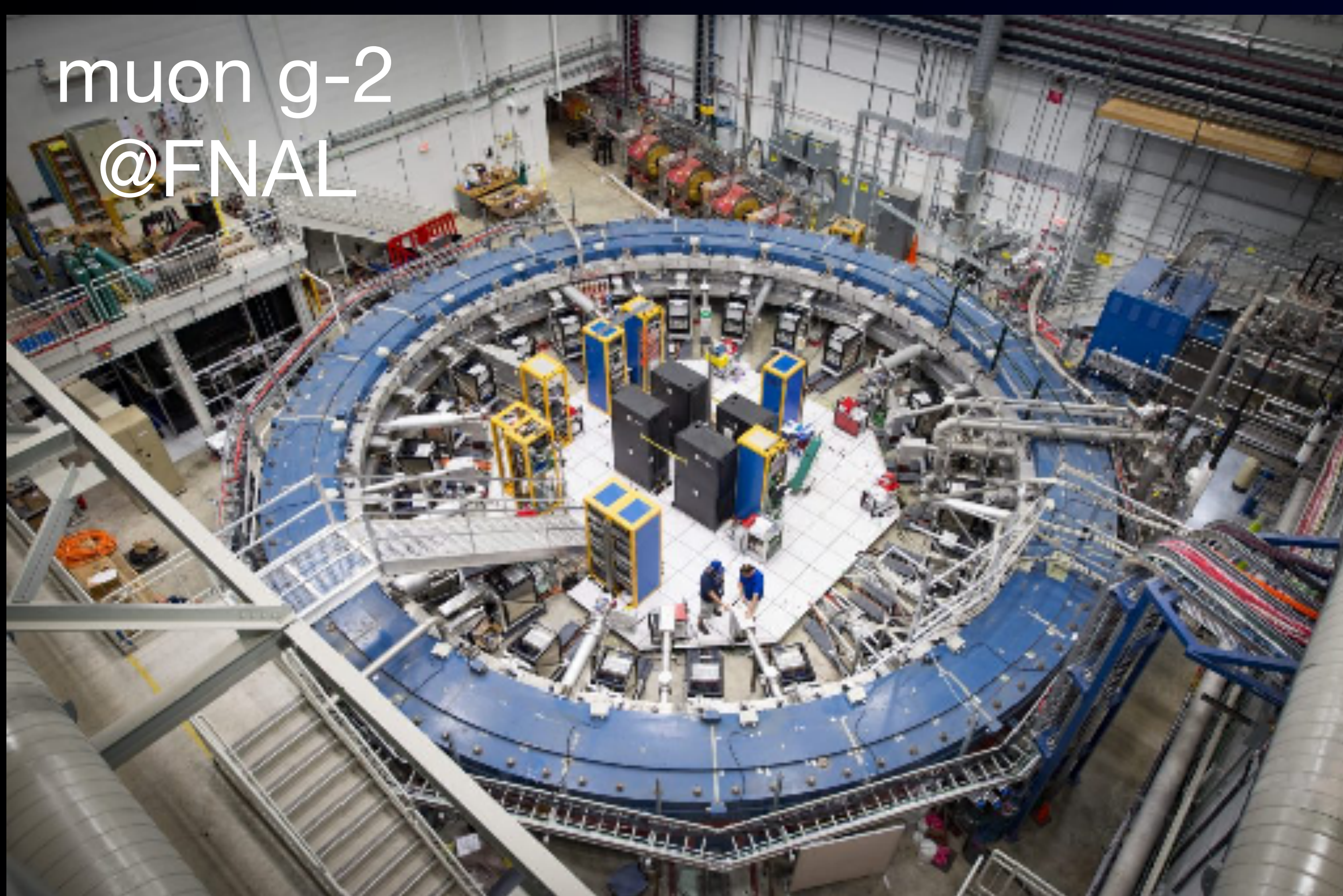
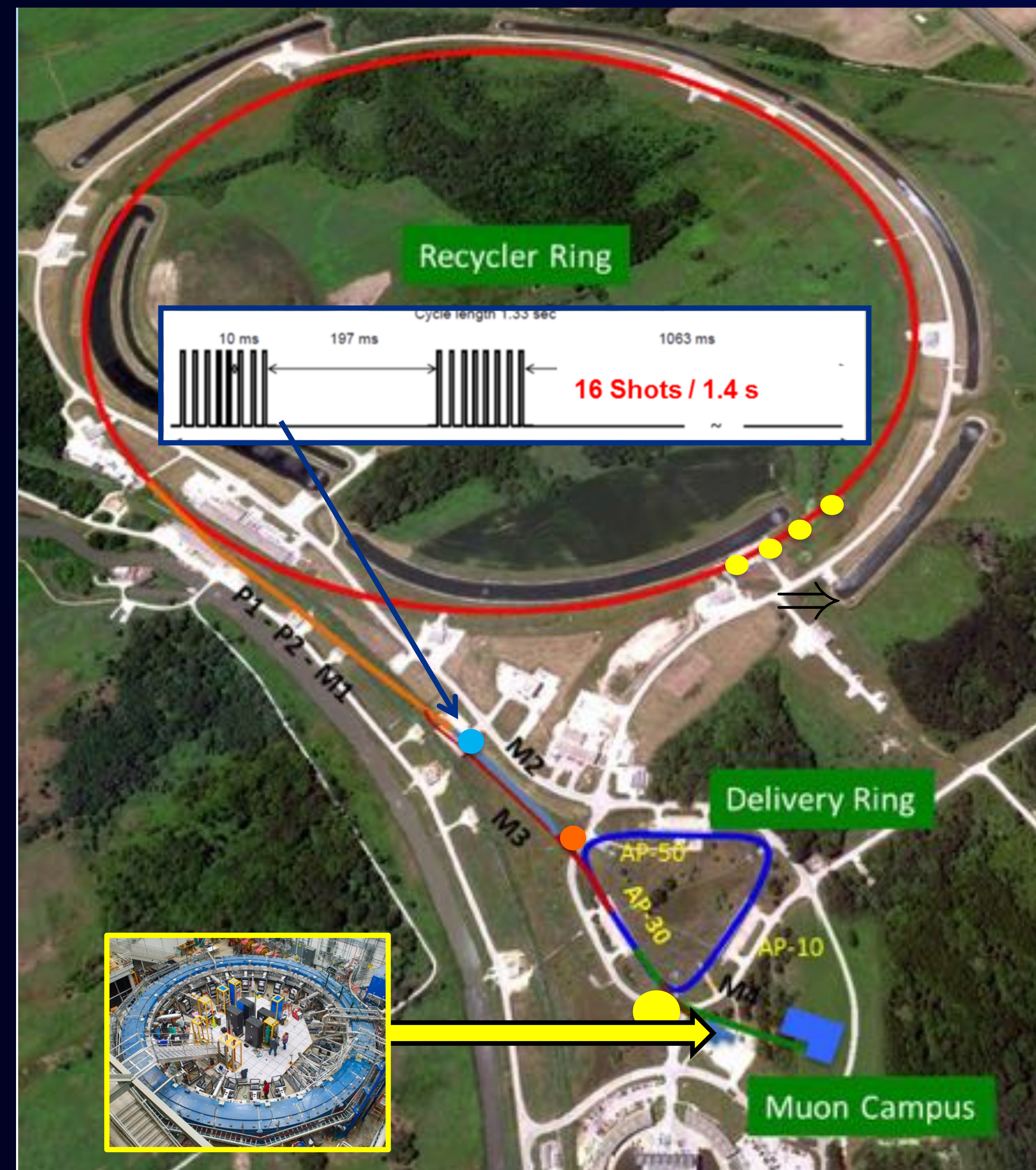
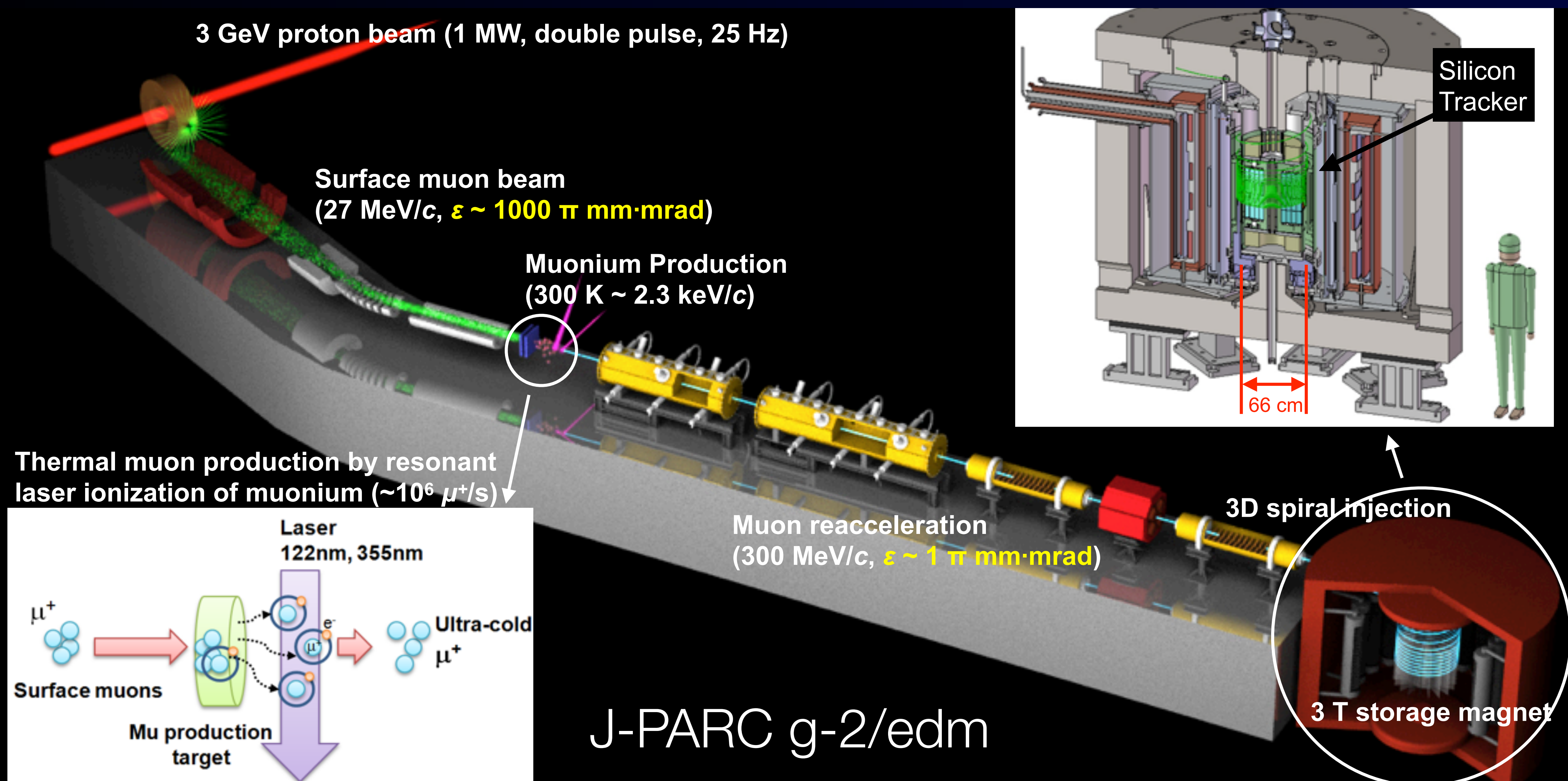




J-PARC g-2/edm

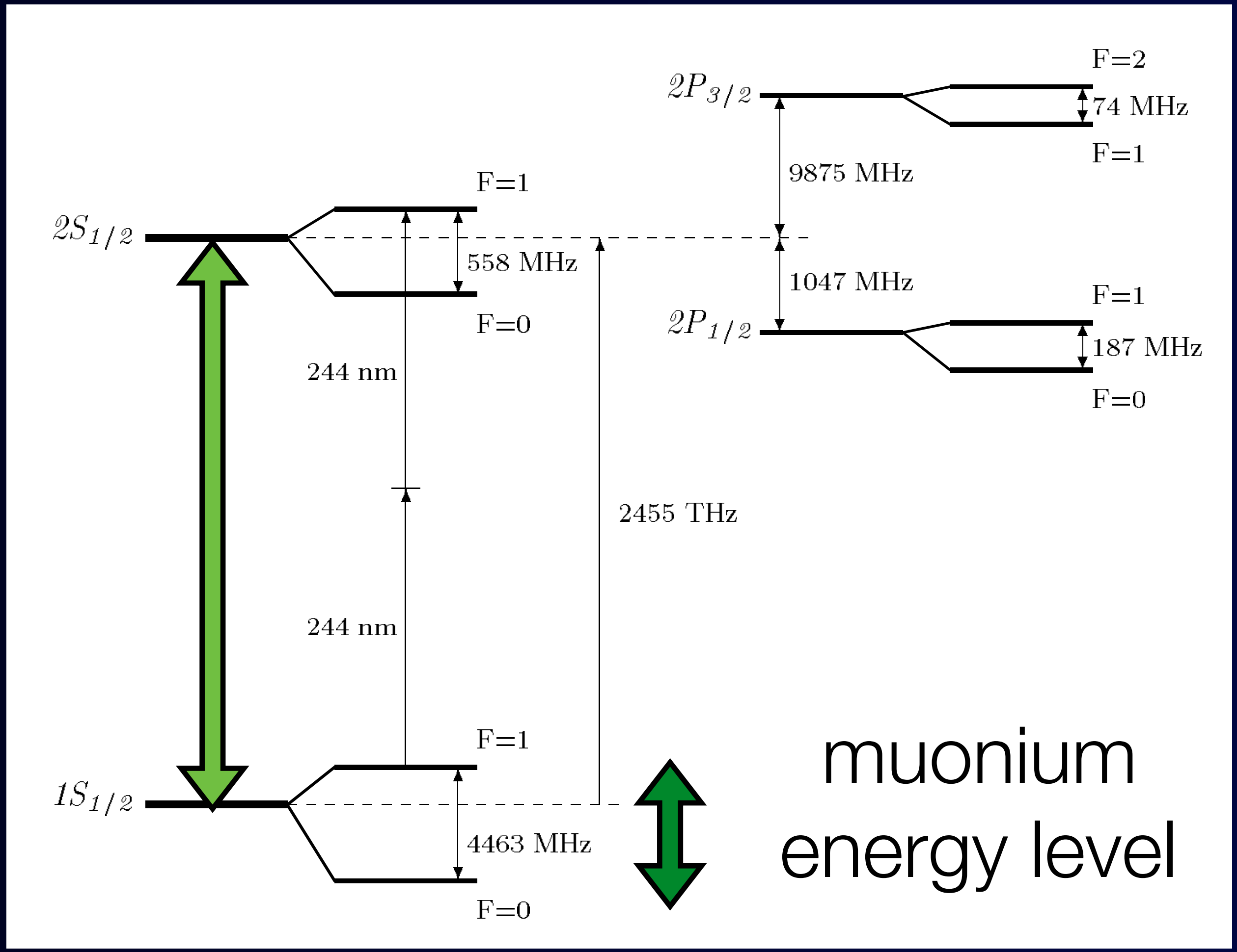
- new technique : slow muons from laser ionization of muonium.
- aim at 0.45 ppm
- different systematics



Muonium

Spectroscopy of Muon-Bound States

- Muonium spectroscopy
  - Hyperfine splitting at 1s state
    - **Museum** at J-PARC
  - 1s-2s transition splitting
    - **Mu-MASS** (MuoniuM lAser SpectroScopy) at PSI
- Muonic Hydrogen spectroscopy
  - Lamb shift
    - CREMA at PSI
    - Proton charge radius
  - Hyperfine splitting at 1s state
    - proton Zemach radius



m_μ/m_e μ_μ/μ_p

$$\nu_{HFS} = \nu_{HFS}(QED) + \nu_{HFS}(had) + \nu_{HFS}(weak) + \nu_{HFS}(BSM)$$

Muonium to Antimuonium Conversion
Mu (μ^+e^-) → anti-Mu (μ^-e^+)

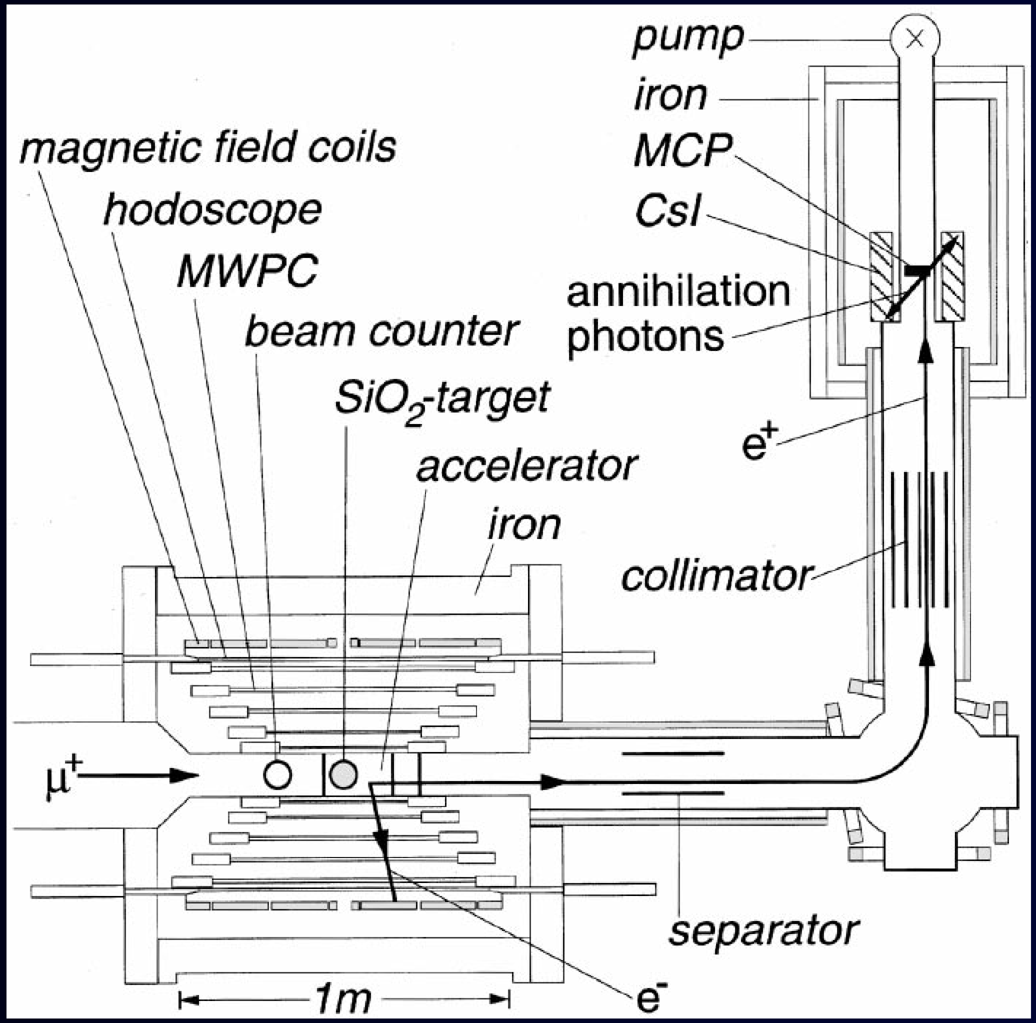
$$\mu^+ + e^- \rightarrow \mu^- + e^+$$

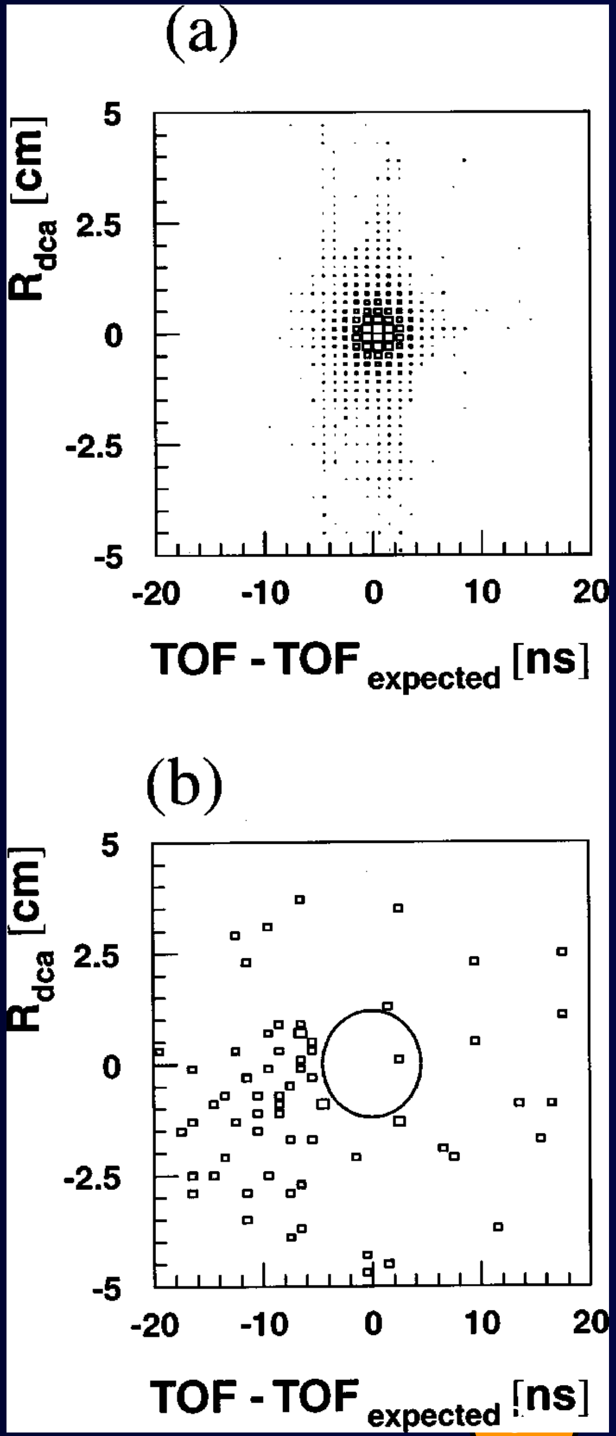
$$|\Delta L_{\mu/e}| = 2$$

- doubly-charged Higgs model etc.
- muonium production in vacuum

previous experiment at PSI (1999)

$$G_{Mu\overline{Mu}} < 3 \times 10^{-3} G_F$$





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$$\mu^+ + e^- \to \mu^- + e^+$$

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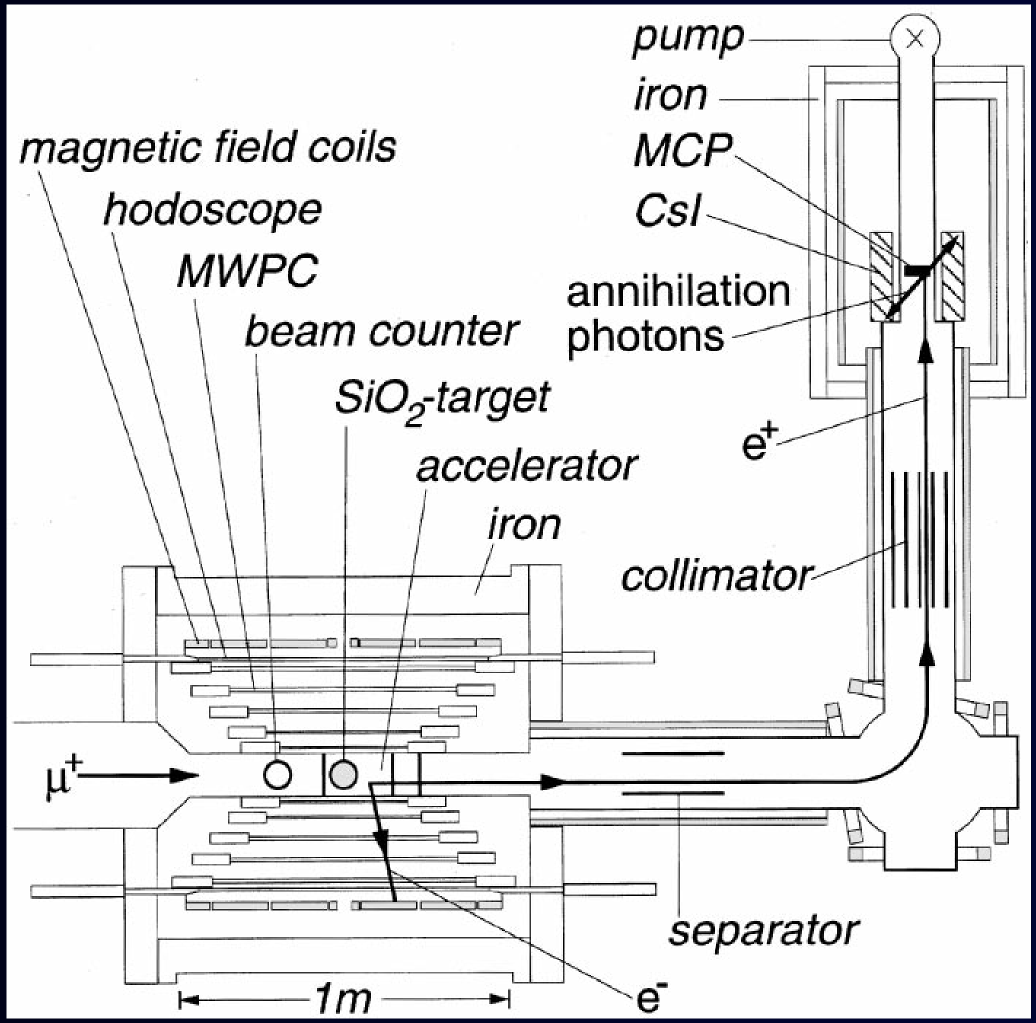
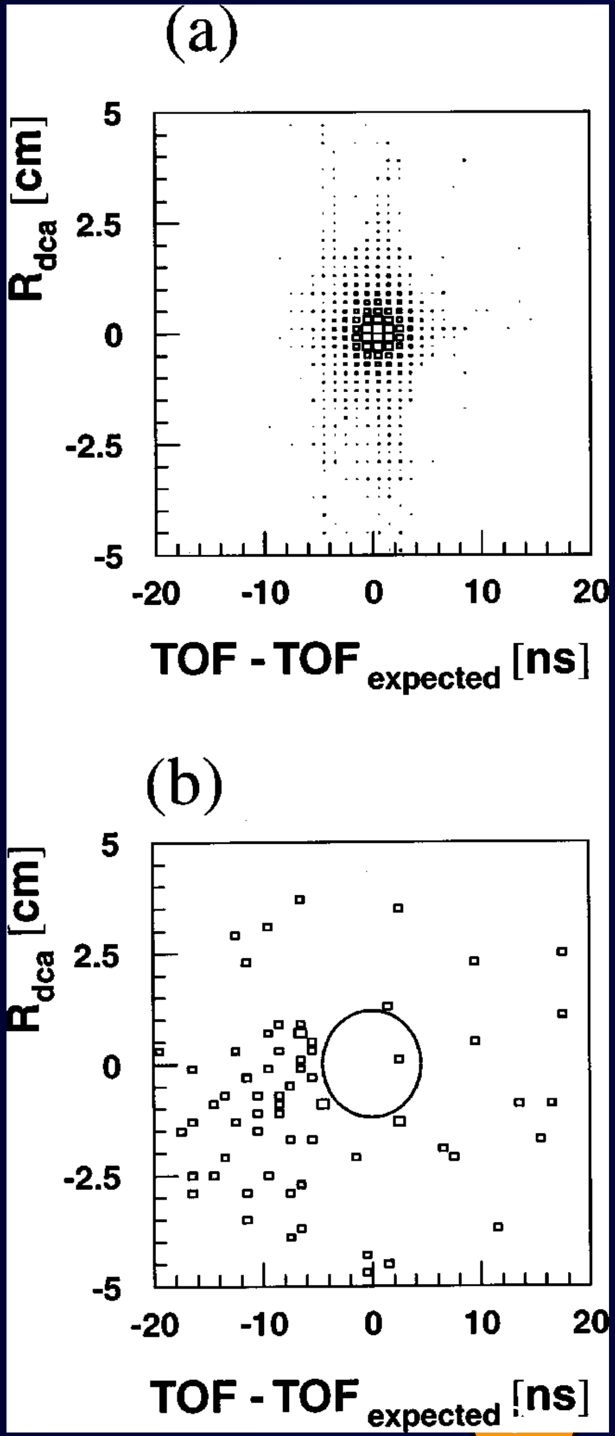


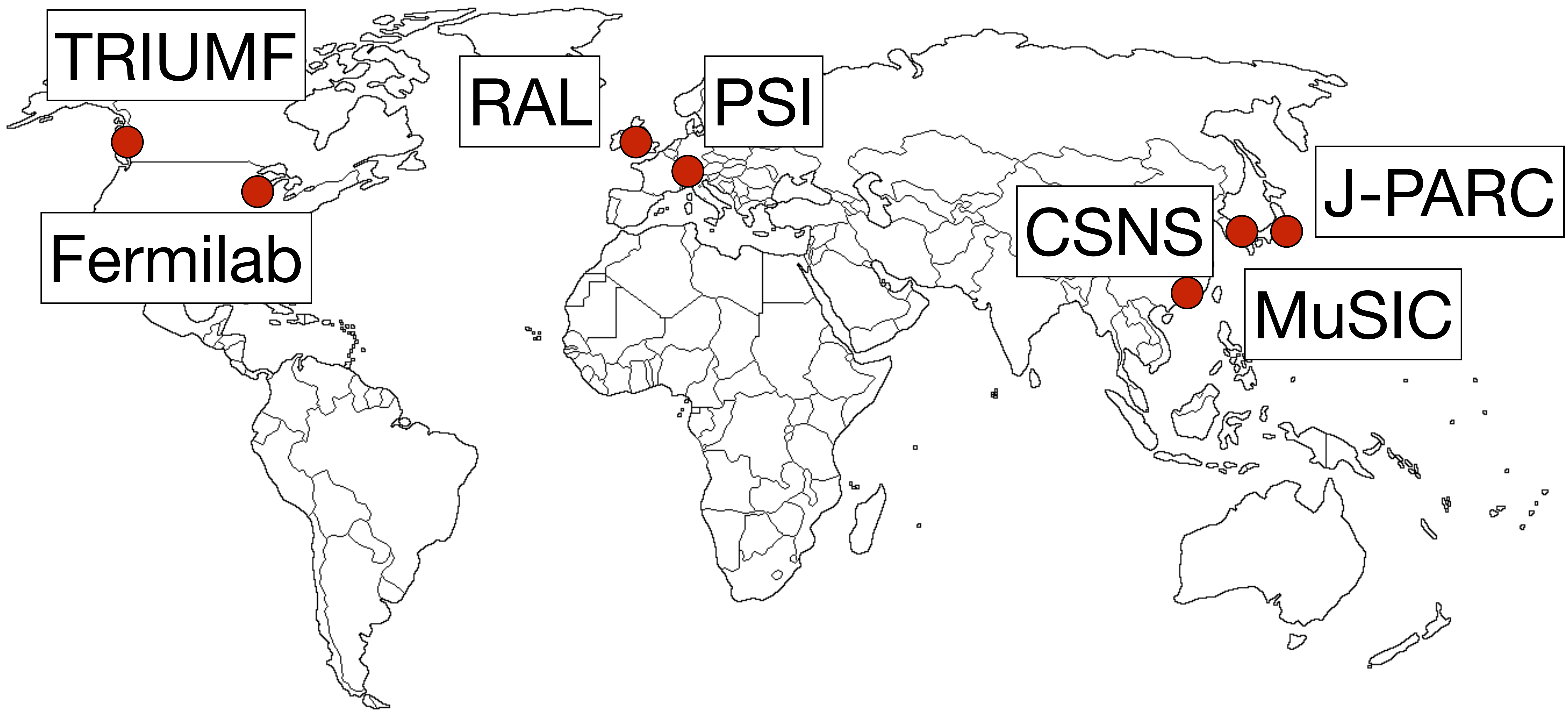


Future prospects:

- new proposal at CSNS

Highly Intense Muon Sources

World Map of Muon Particle Physics



Pulsed and DC Muon Beams

Pulsed and DC Muon Beams

Muon physics experiments and Beam time structure

Pulsed and DC Muon Beams

Muon physics experiments and Beam time structure

Pulsed muon beam

for the experiments of

- delayed measurements ($\mu \to e$ conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments (laser)

proton synchrotron
(CSNS, J-PARC, FNAL, RAL)

Pulsed and DC Muon Beams

Osaka University

Muon physics experiments and Beam time structure

Pulsed muon beam

for the experiments of

- delayed measurements (μ→e conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments (laser)

proton synchrotron
(CSNS, J-PARC, FNAL, RAL)

DC muon beam

for the experiments of

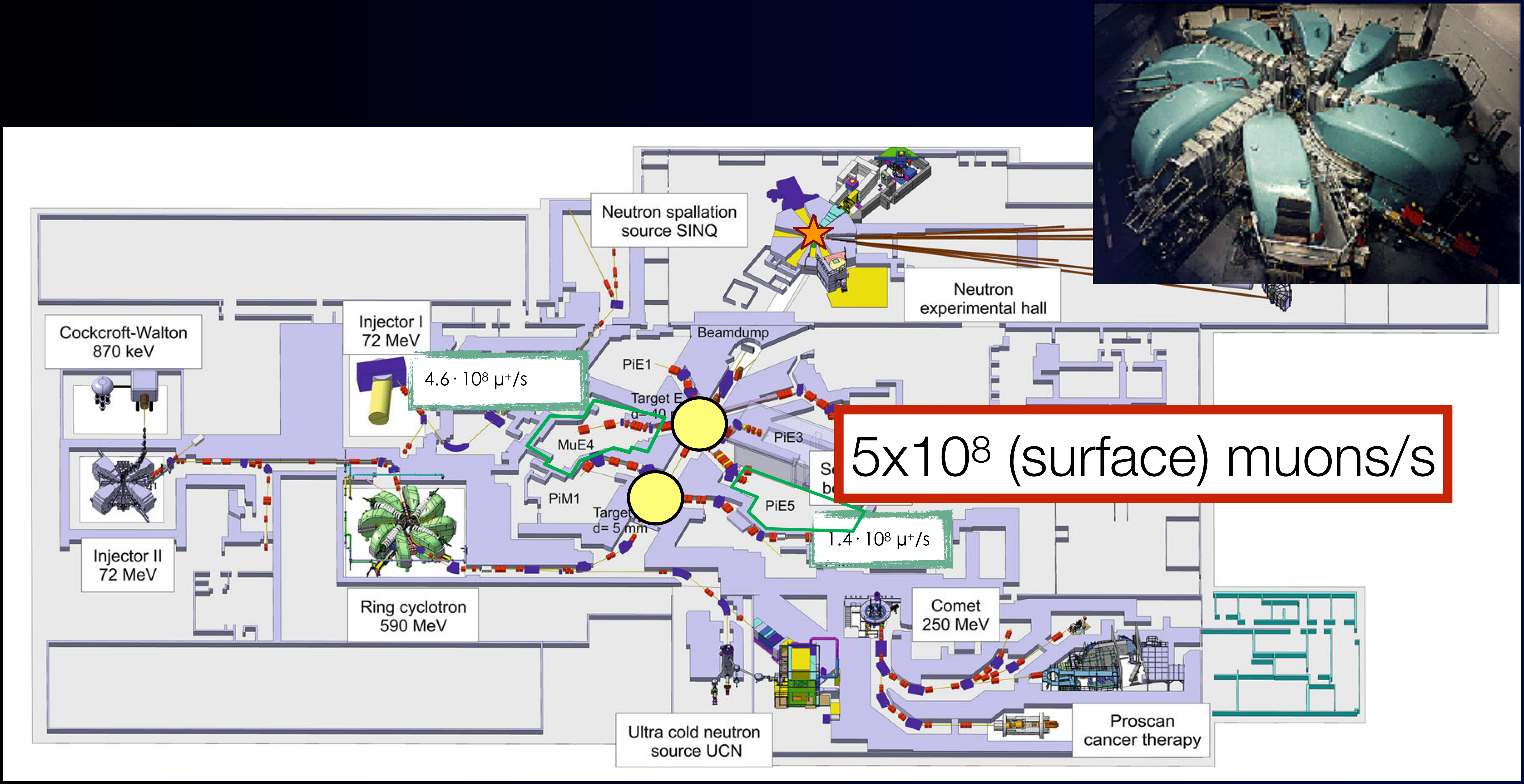
- coincidence measurements with low instantaneous intensity (μ→eγ, μ→eee)

proton cyclotron
(PSI, TRIUMF, MuSIC)

Paul Sherrer Institute (PSI)

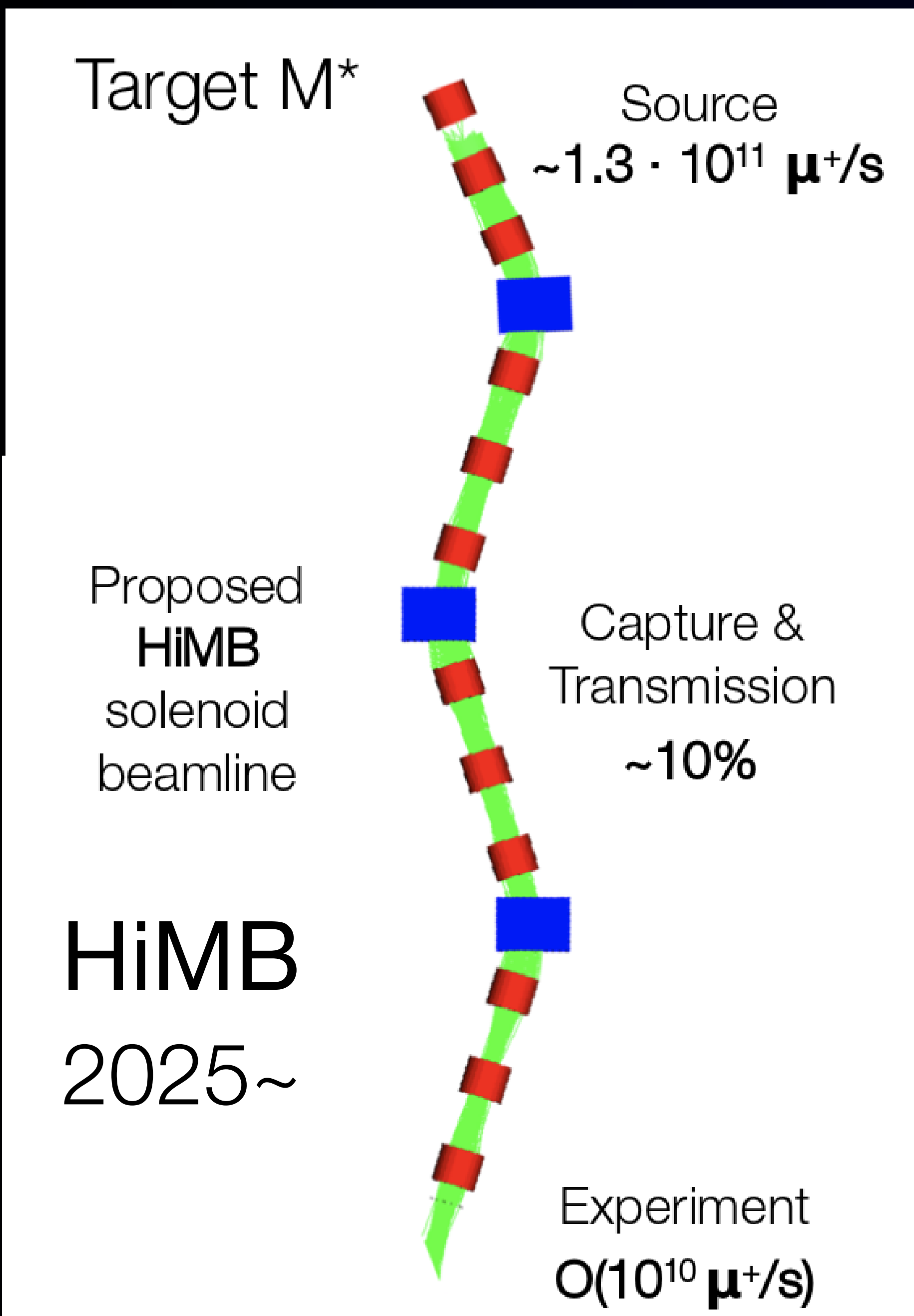
Paul Sherrer Institute (PSI)

590 MeV proton ring cyclotron 1.4MW

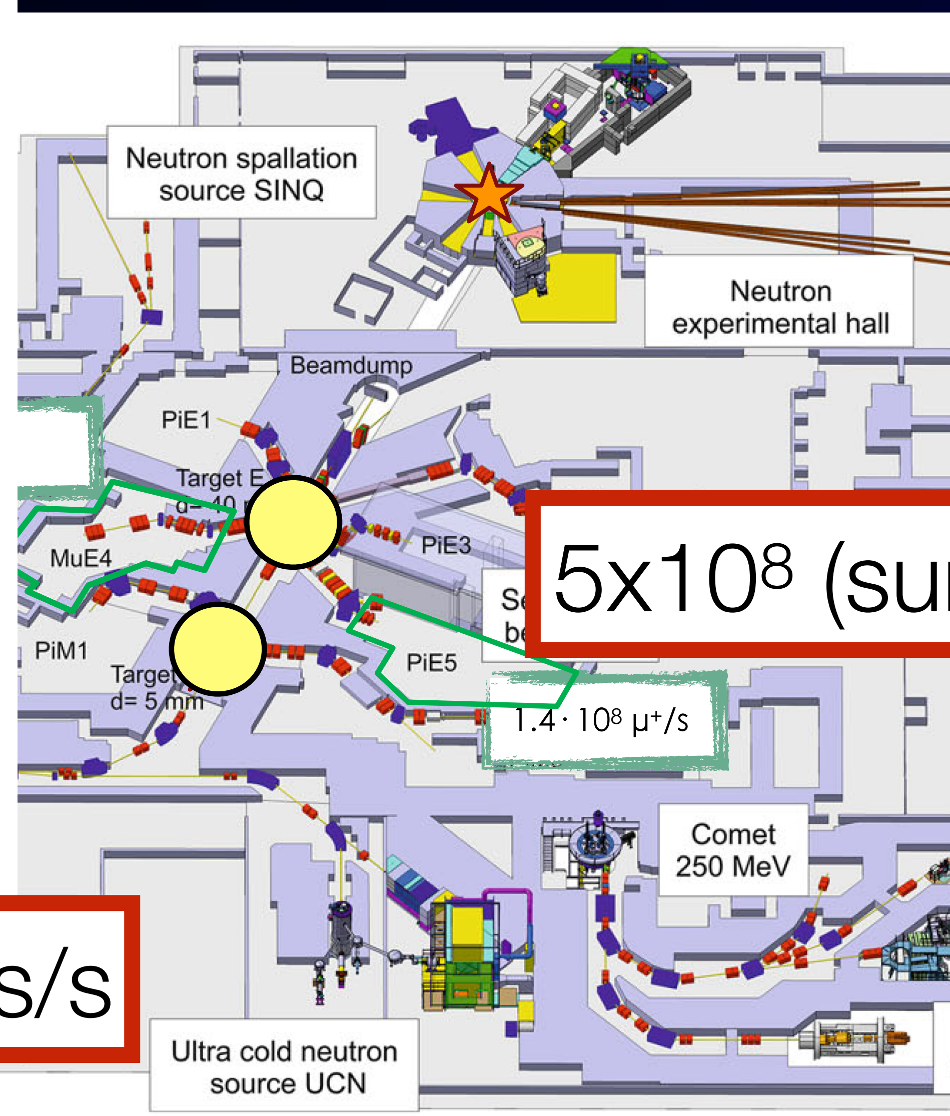


5x10⁸ (surface) muons/s

Paul Sherrer Institute (PSI)



590 MeV proton ring cyclotron 1.4MW

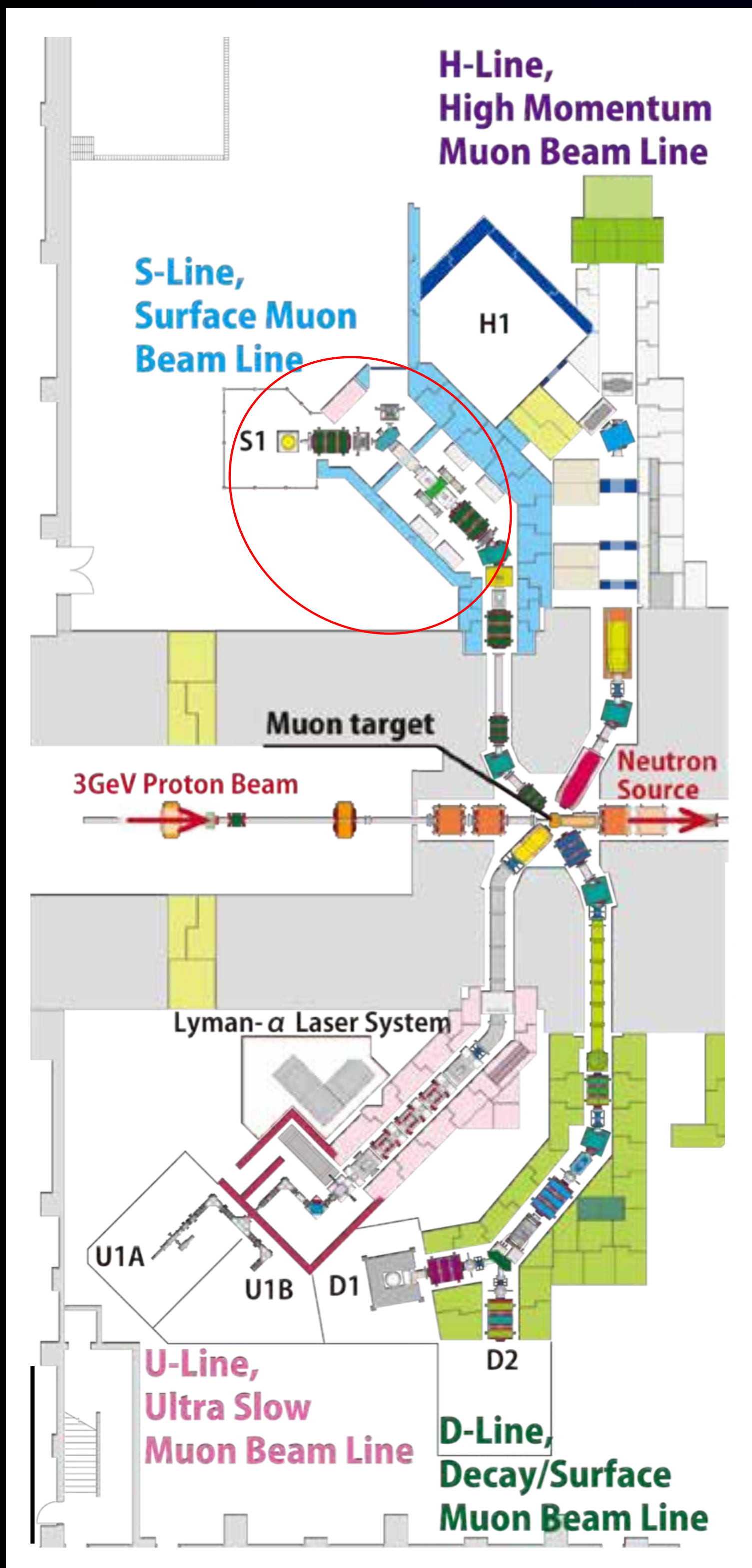


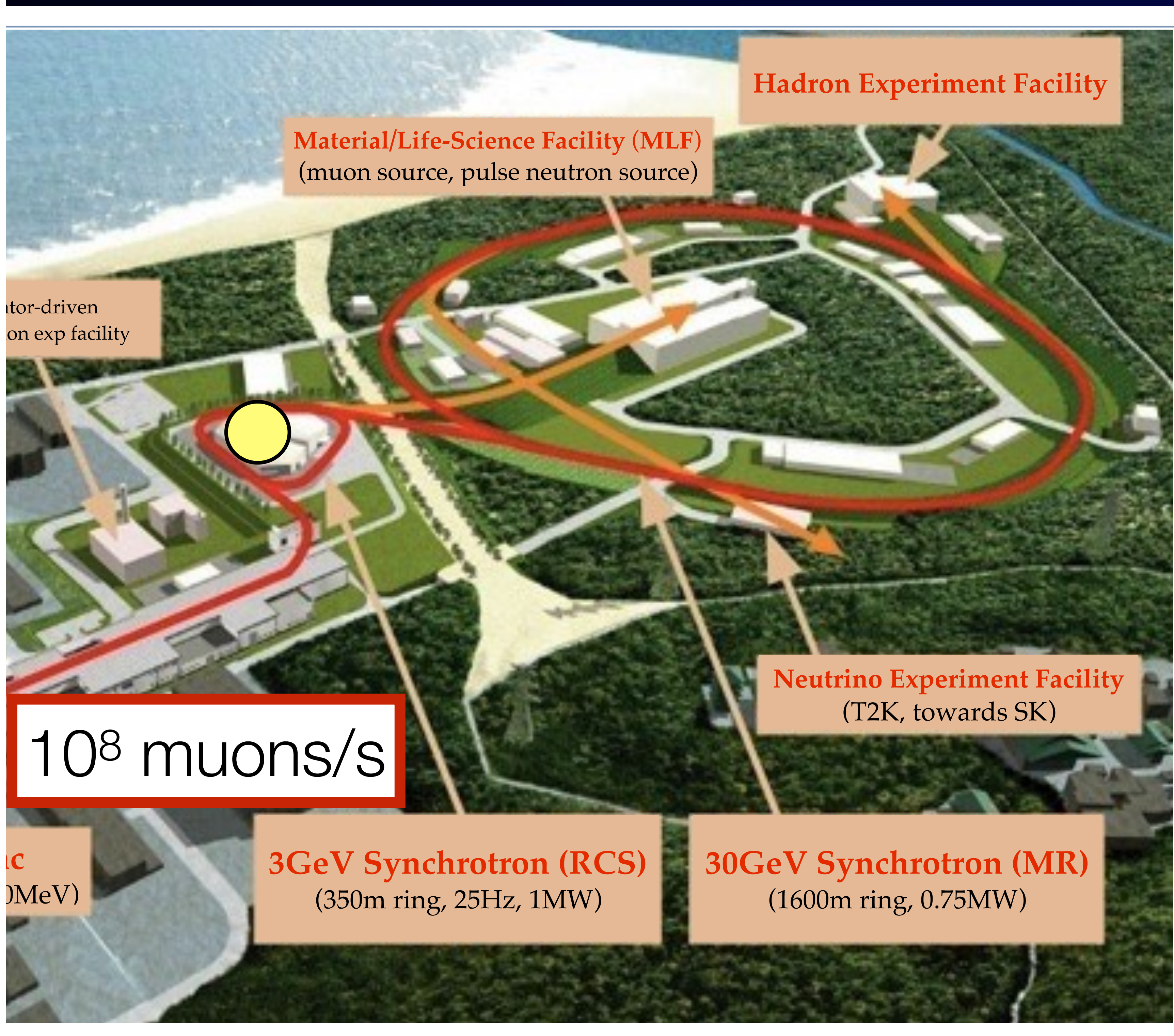
5×10^8 (surface) muons/s

$>10^{10}$ (surface) muons/s

Muon Source
J-PARC (MUSE@MLF)

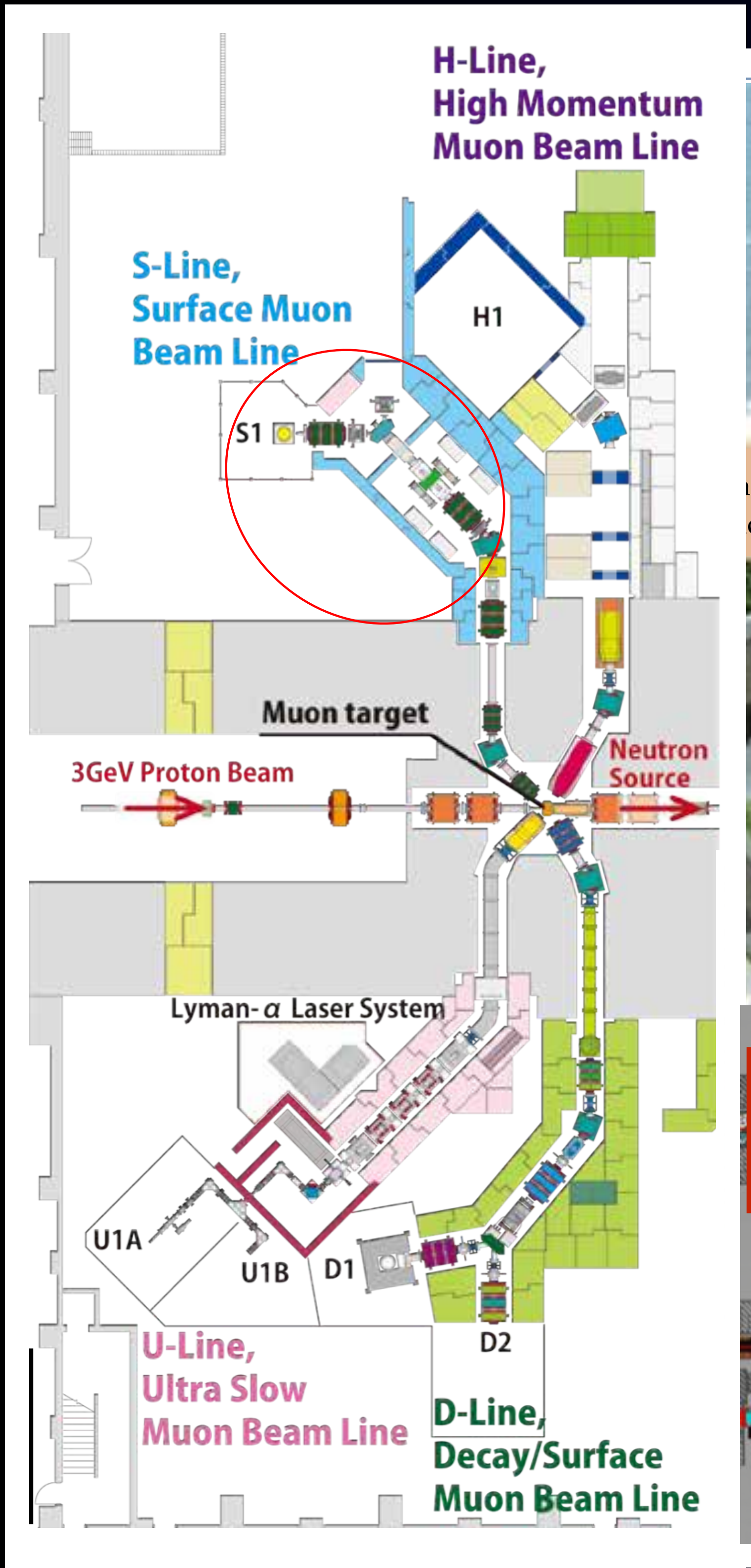
Muon Source
J-PARC (MUSE@MLF)

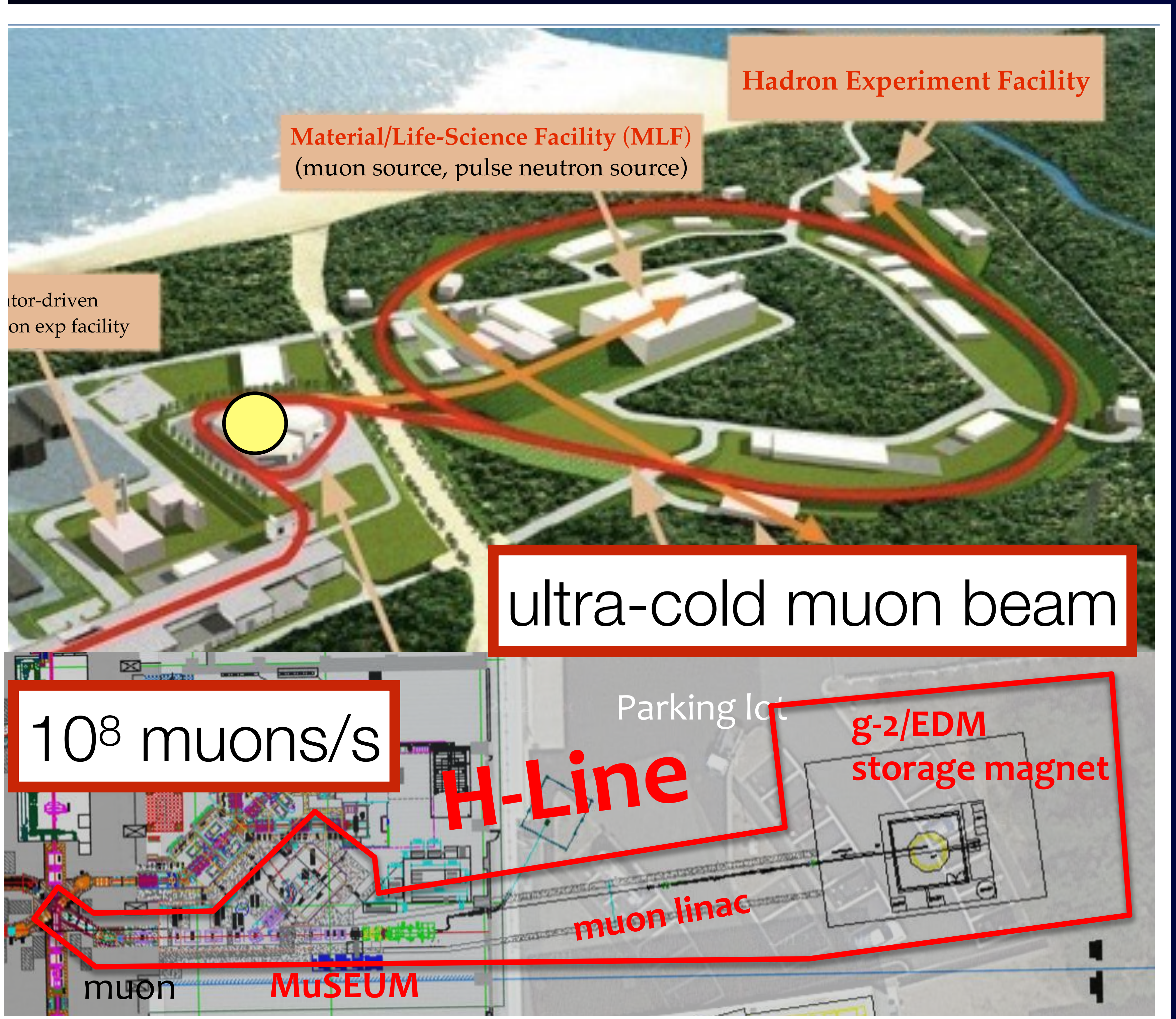




10^8 muons/s

Muon Source
J-PARC (MUSE@MLF)



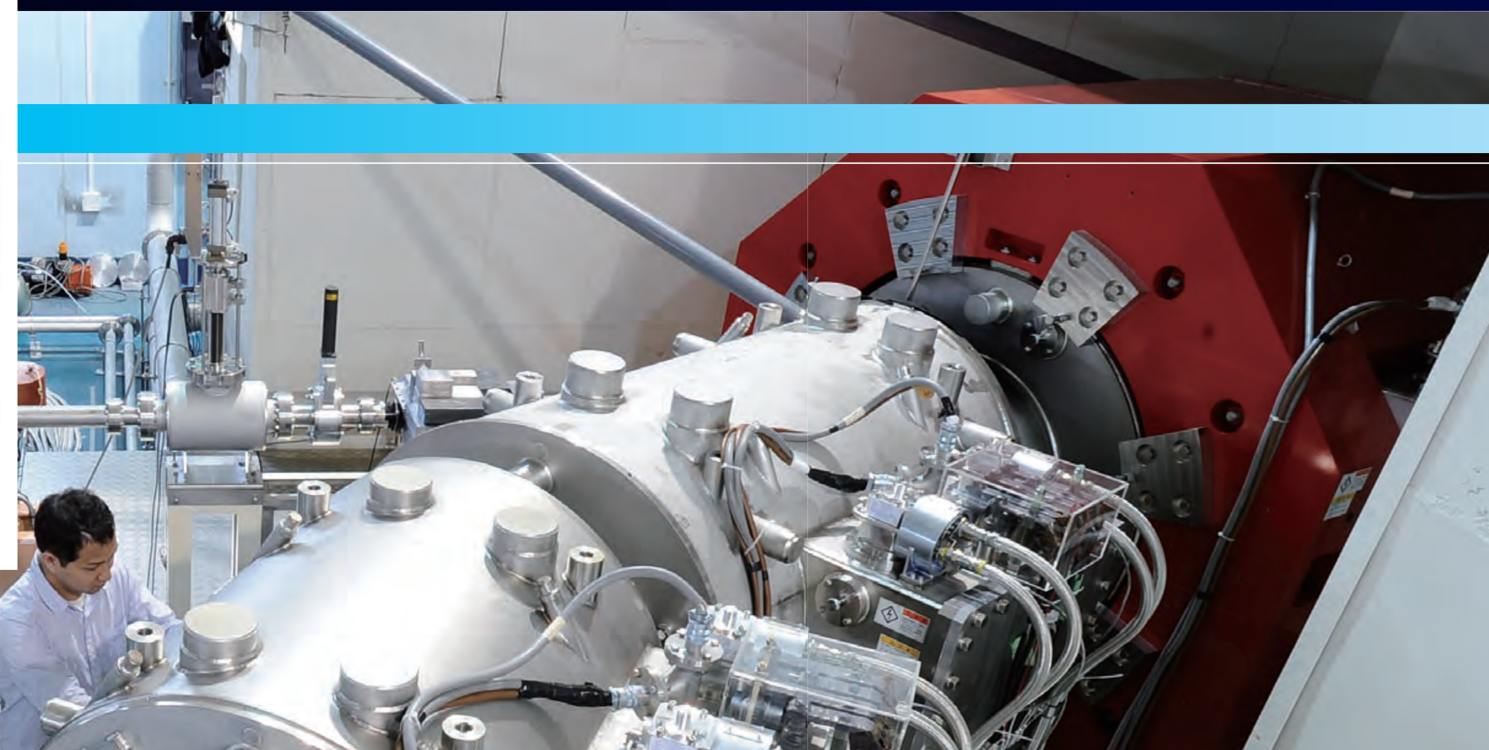


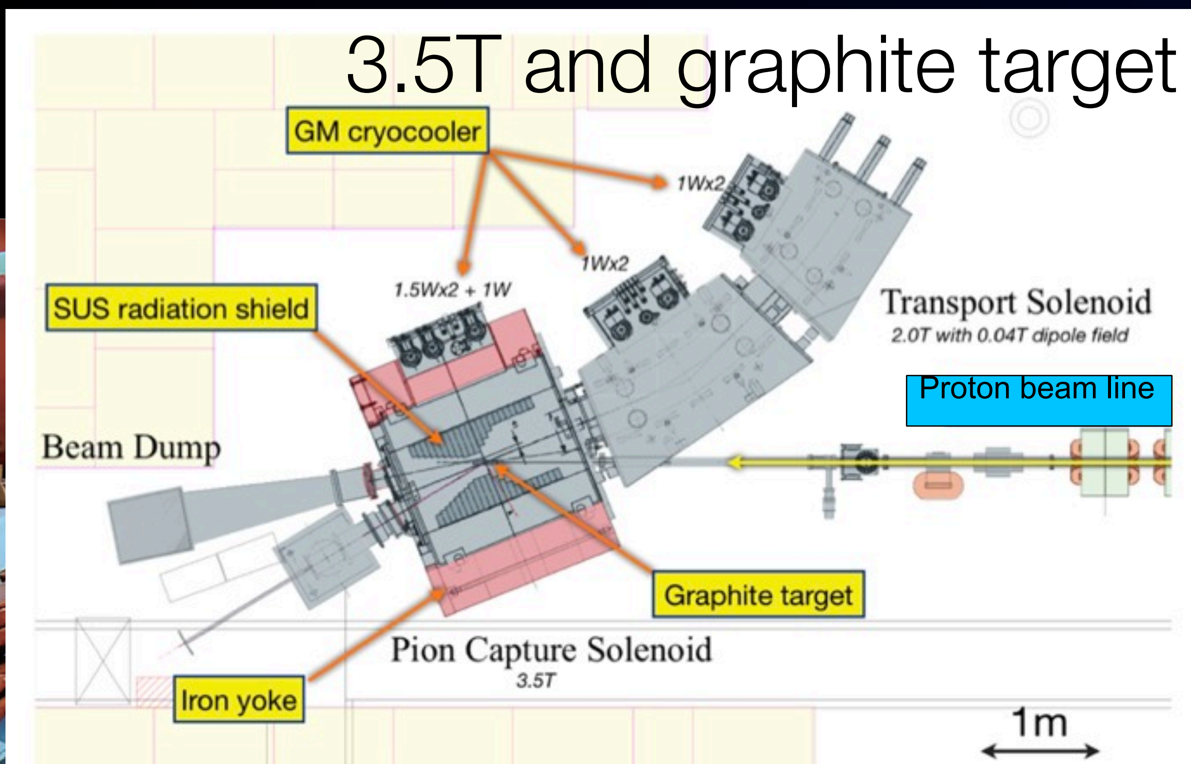
MuSIC at RCNP, Osaka University
- Highly Intense Muon Source -

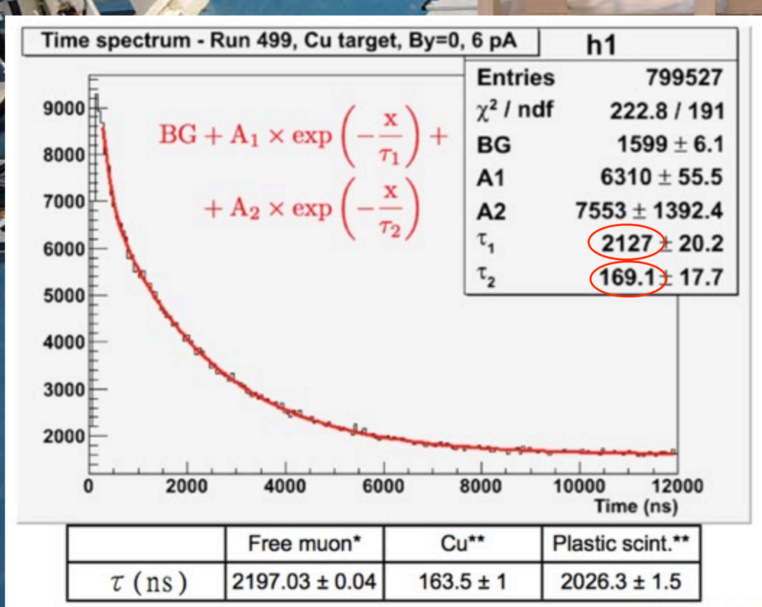
3.5T and graphite target

MuSIC at RCNP, Osaka University
- Highly Intense Muon Source -

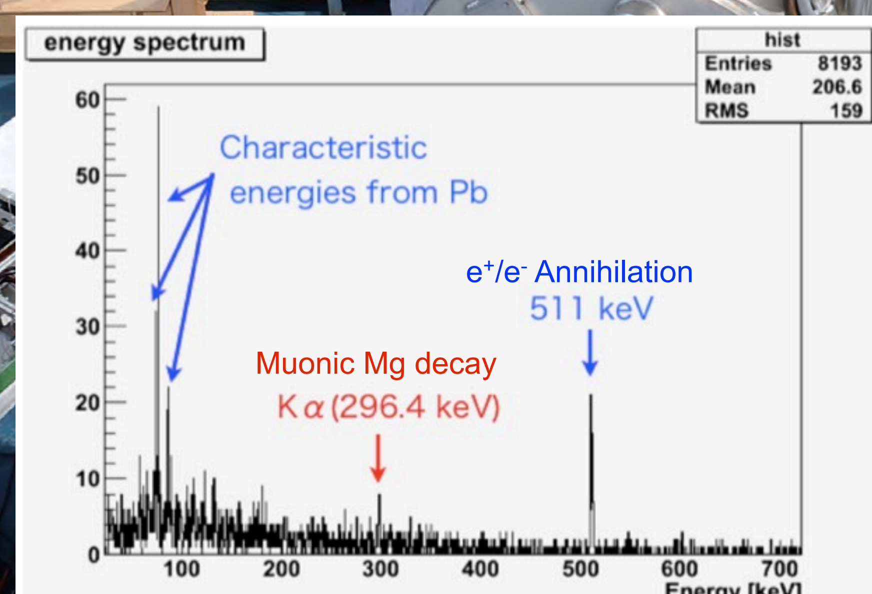
Muon Science Intense Channel (>2011)







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



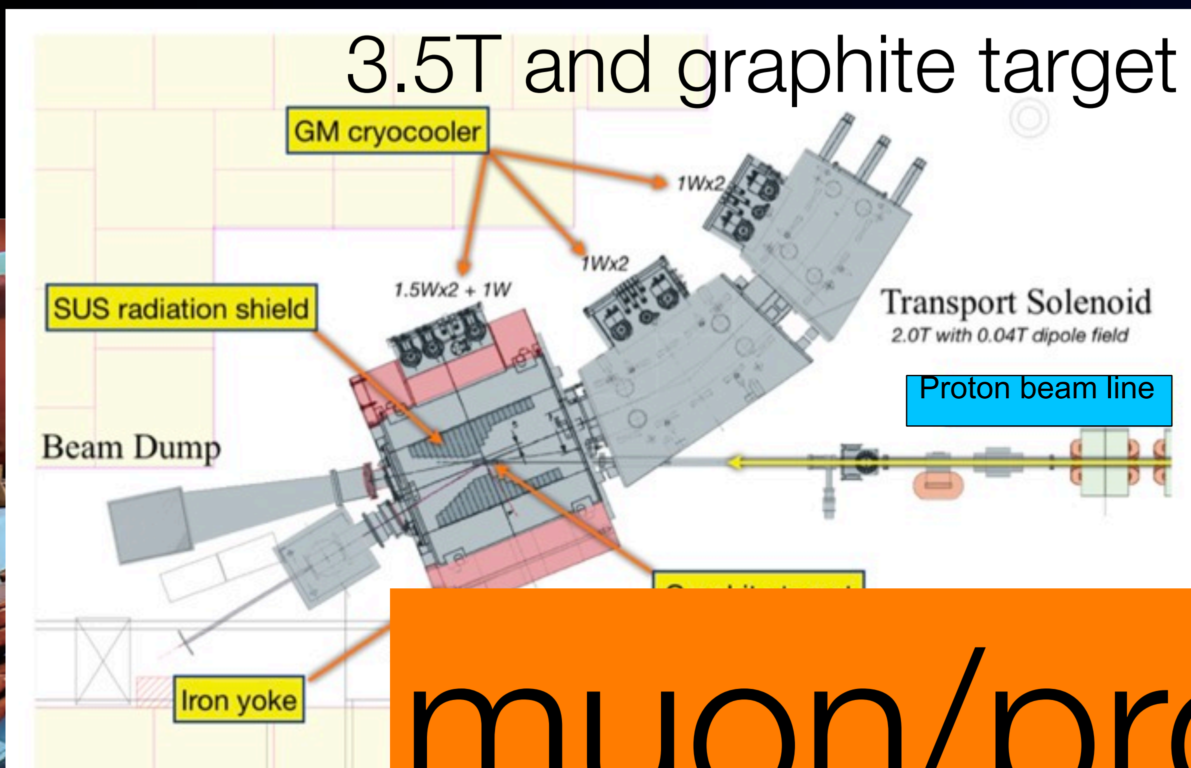
MuSIC muon yields

μ^+ : 3×10^8/s for 400W

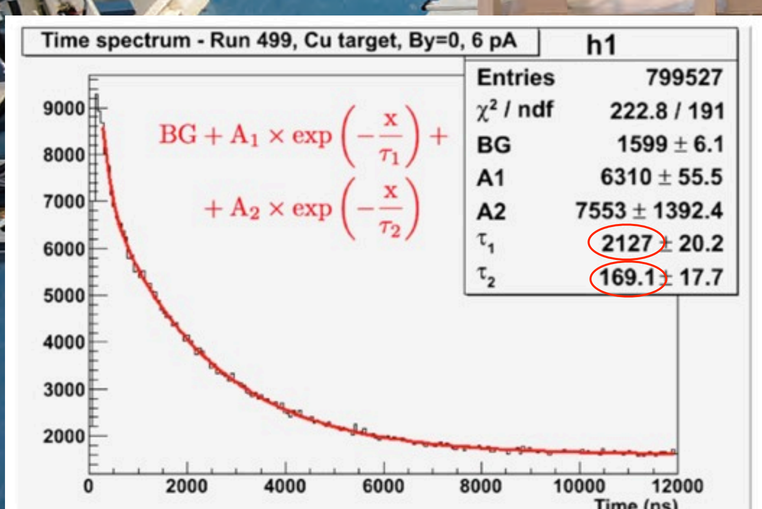
μ^- : 1×10^8/s for 400W

MuSIC at RCNP, Osaka University
- Highly Intense Muon Source -

Muon Science Intense Channel (>2011)



muon/proton~x1000



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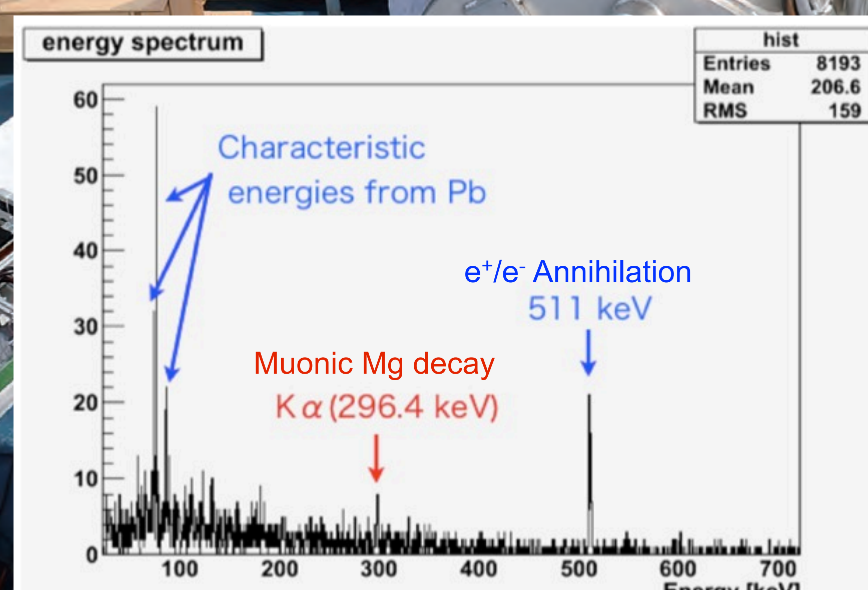


MuSIC muon yields

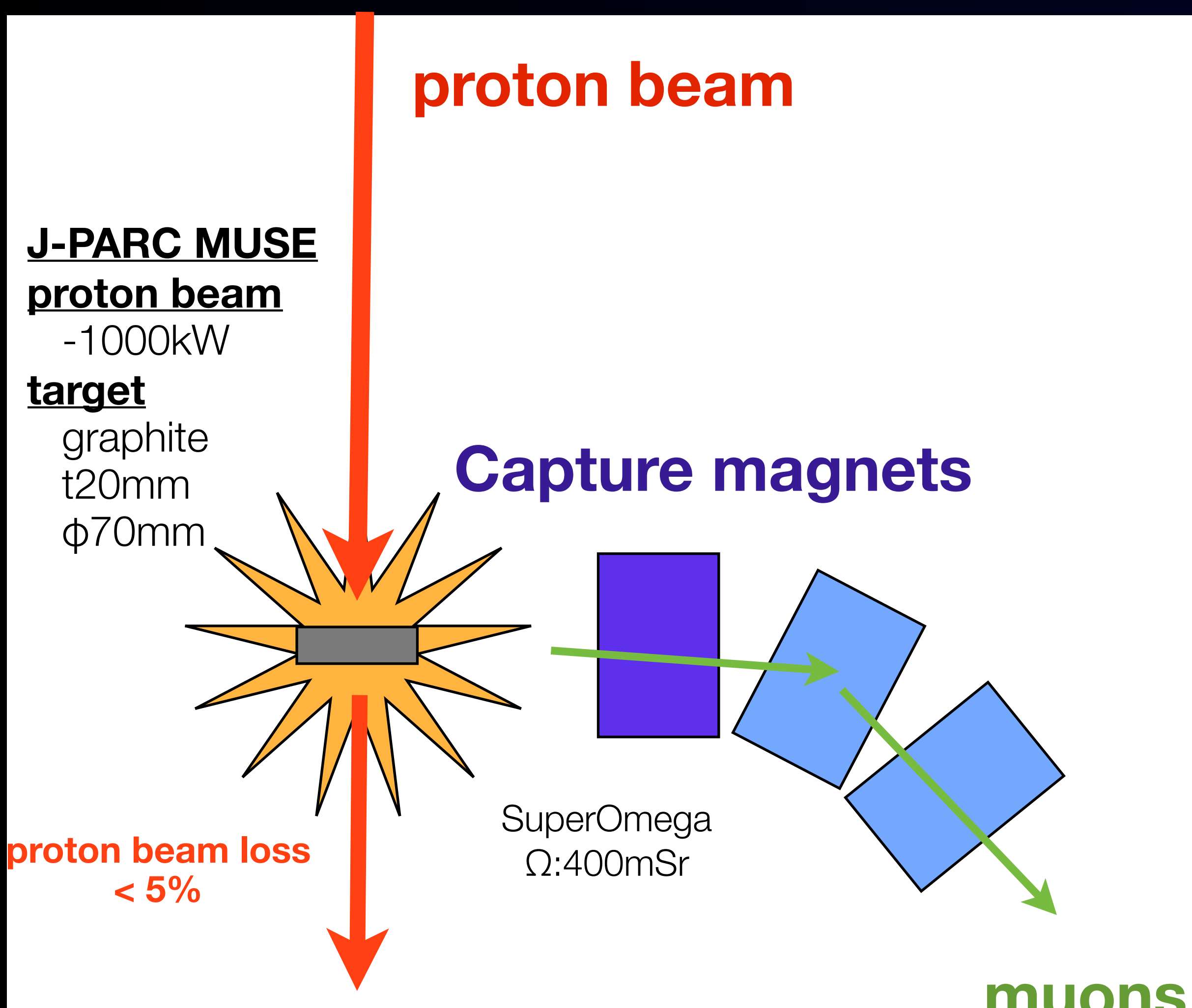
μ^+ : 3×10^8/s for 400W

μ^- : 1×10^8/s for 400W

Production and Collection of Pions and Muons

Production and Collection of Pions and Muons

Conventional muon beam line

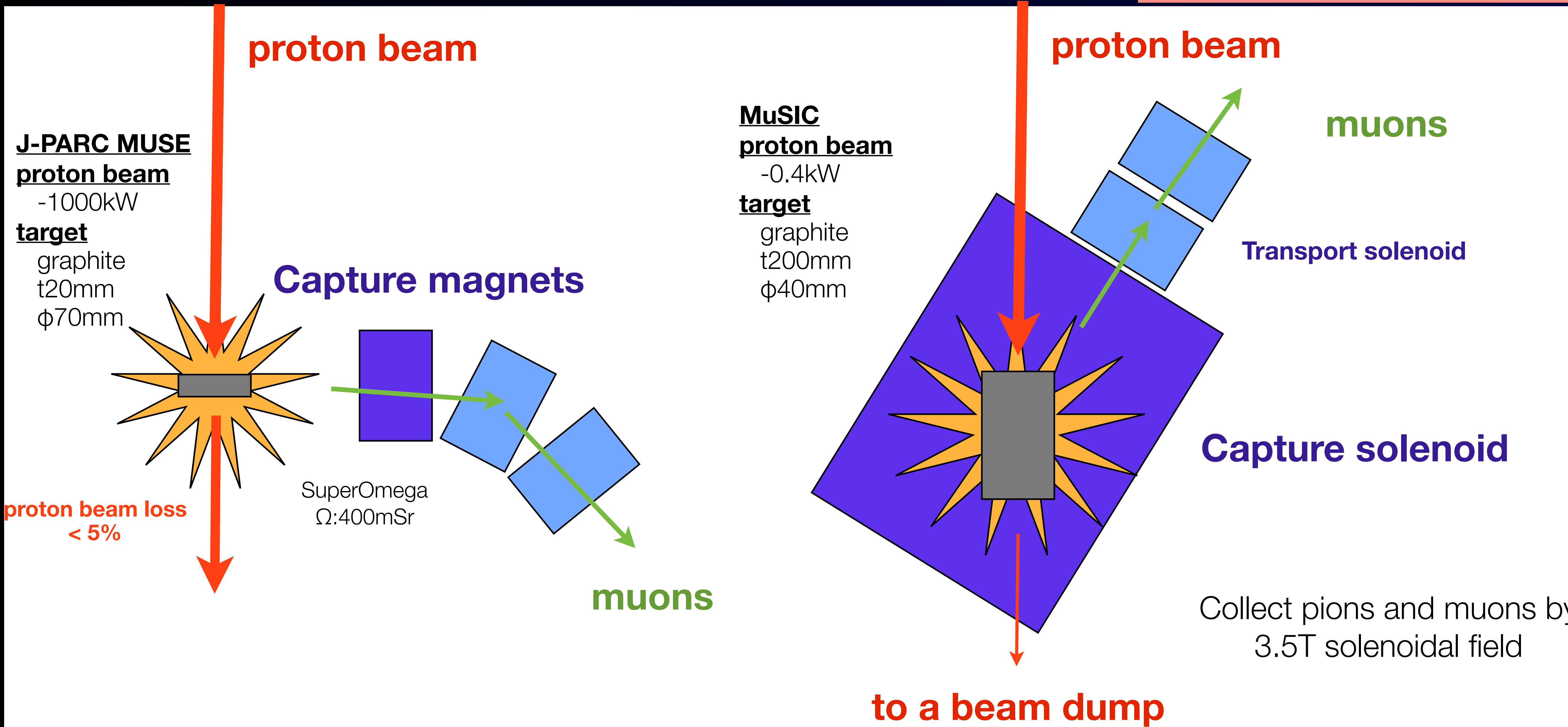


Production and Collection of Pions and Muons

Conventional muon beam line

More efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider



Large solid angle & thick target

MuSIC Publication

March, 2017, Editors Suggestions

Editors Suggestions

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 030101 (2017)

Delivering the world's most intense muon beam

S. Cook,[1] R. D'Arcy,[1] A. Edmonds,[1] M. Fukuda,[2] K. Hatanaka,[2] Y. Hino,[3] Y. Kuno,[3] M. Lancaster,[1] Y. Mori,[4] T. Ogitsu,[5] H. Sakamoto,[3] A. Sato,[3] N. H. Tran,[3] N. M. Truong,[3] M. Wing,[1,*] A. Yamamoto,[5] and M. Yoshida[5]

[1]*Department of Physics and Astronomy, UCL, Gower Street, London WC1E 6BT, United Kingdom*
[2]*Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*
[3]*Department of Physics, Graduate School of Science, Osaka University, Osaka 569-0043, Japan*
[4]*Kyoto University Reactor Research Institute (KURRI), Kyoto 590-0494, Japan*
[5]*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

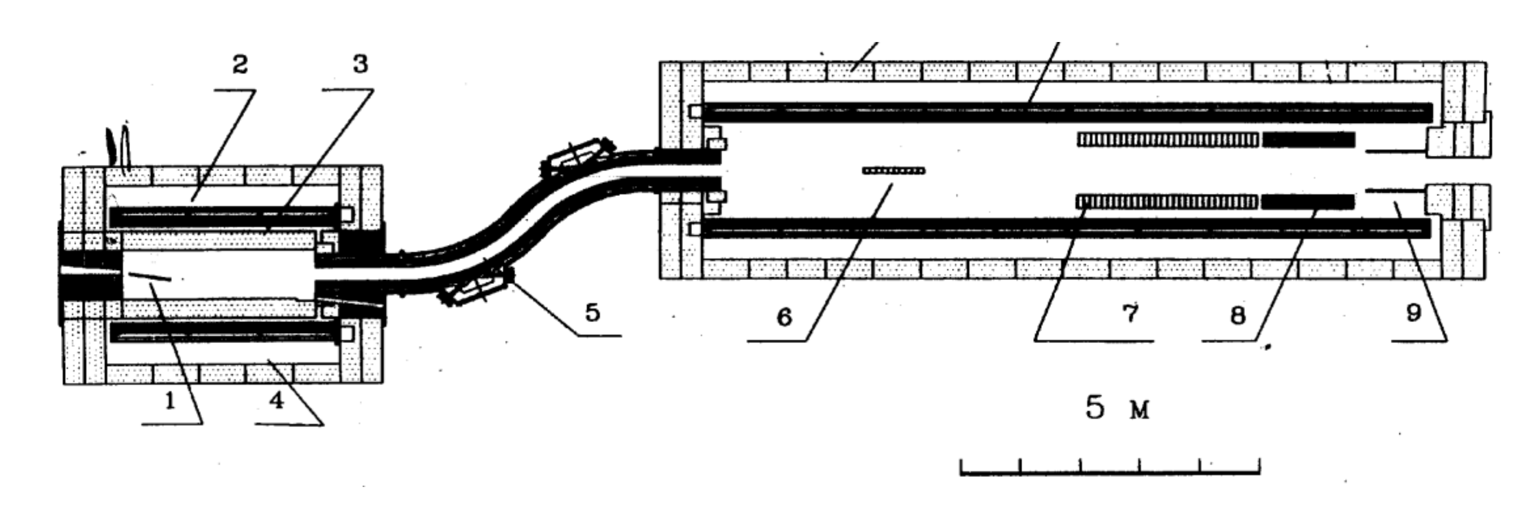
(Received 25 October 2016; published 15 March 2017)

A new muon beam line, the muon science innovative channel, was set up at the Research Center for Nuclear Physics, Osaka University, in Osaka, Japan, using the 392 MeV proton beam impinging on a target. The production of an intense muon beam relies on the efficient capture of pions, which subsequently decay to muons, using a novel superconducting solenoid magnet system. After the pion-capture solenoid, the first 36° of the curved muon transport line was commissioned and the muon flux was measured. In order to detect muons, a target of either copper or magnesium was placed to stop muons at the end of the muon

From MELC to MECO

From MELC to MECO

MELC

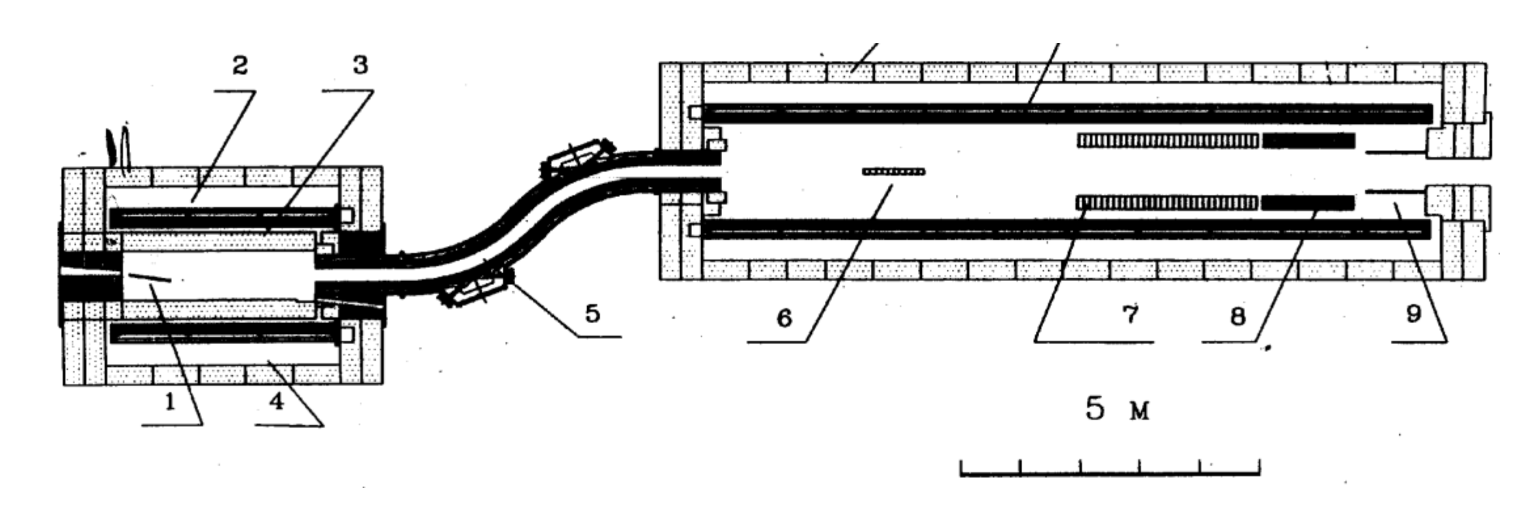


Proposal (1992) at Moscow Meson Factory

R. M. Dzhilkibaev and V. M. Lobashev, Sov. J. Nucl. Phys. 49, 384 (1989)

From MELC to MECO

MELC



Proposal (1992)
at Moscow
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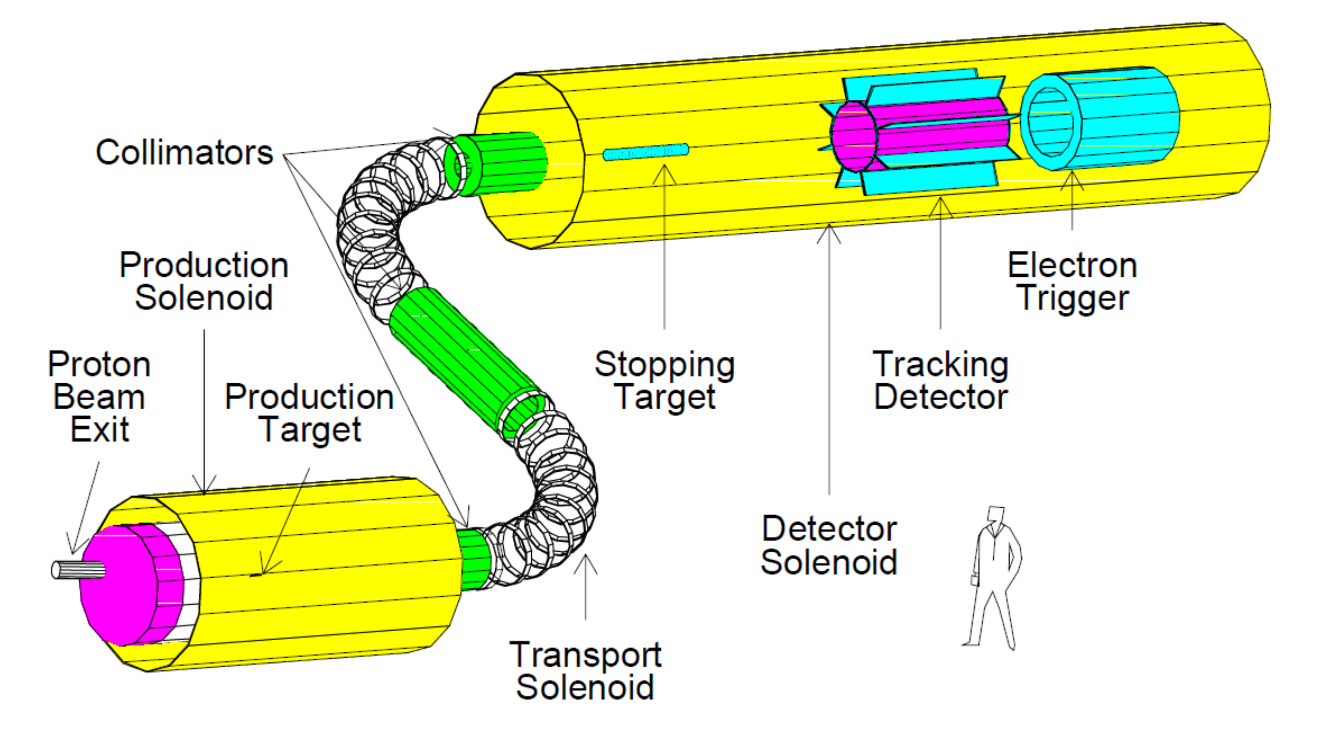
R. M. Dzhilkibaev and V. M. Lobashev, Sov. J. Nucl. Phys. 49, 384 (1989)

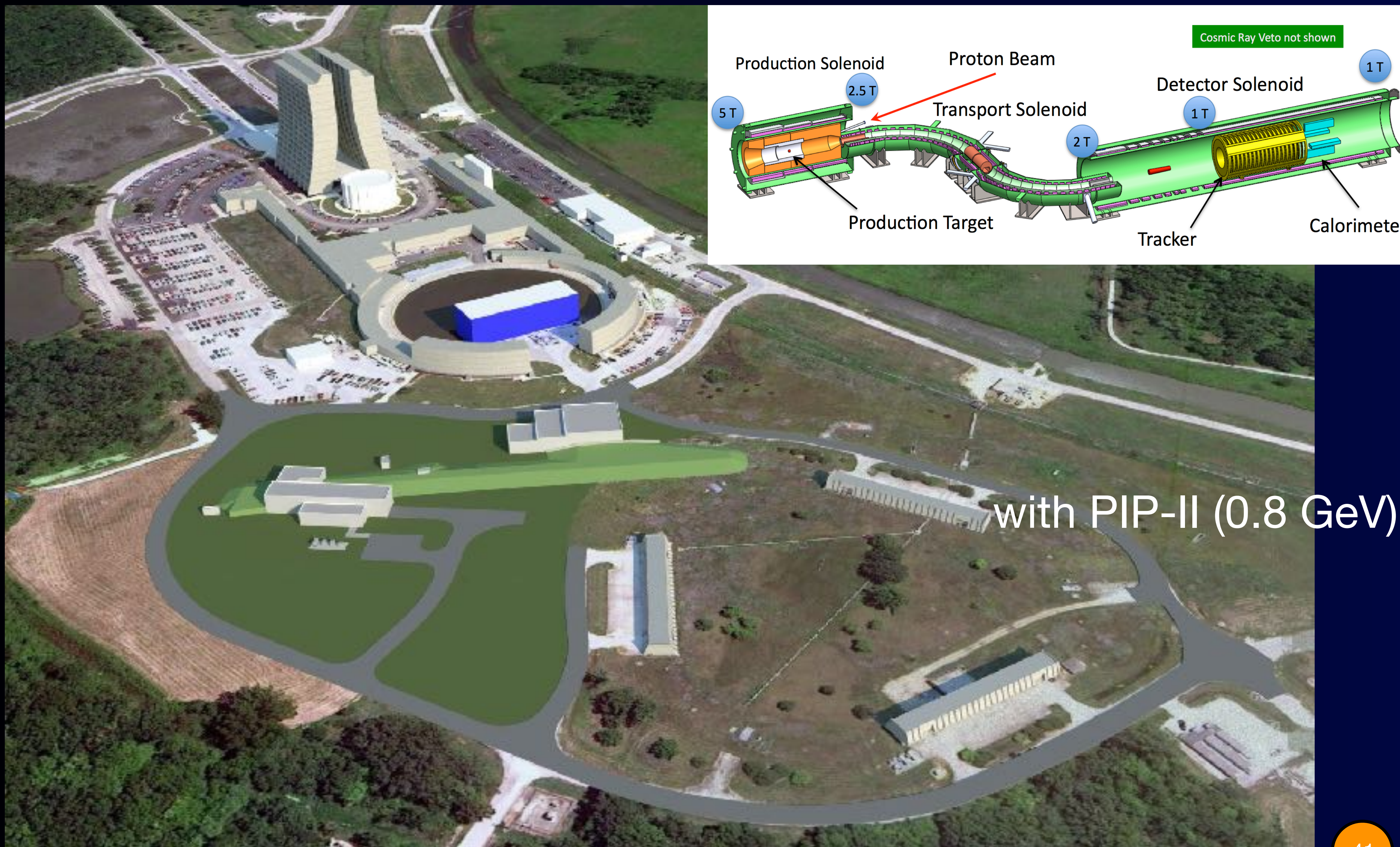
MECO



BNL E940 (1997)
one of the RSVP (rare symmetry violating processes with KOPIO)

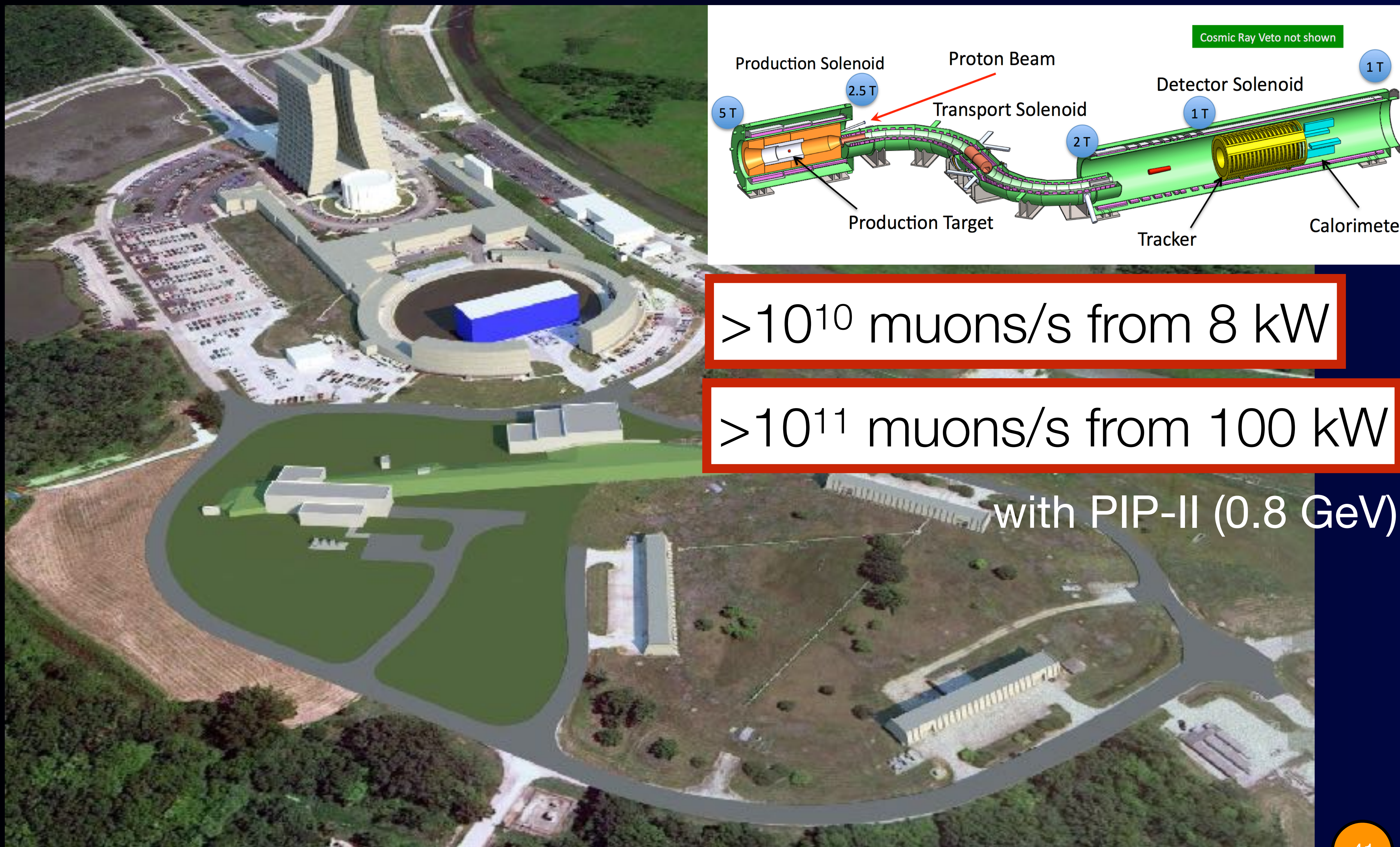
terminated in 2005

Fermilab Muon Campus



with PIP-II (0.8 GeV)

Fermilab Muon Campus



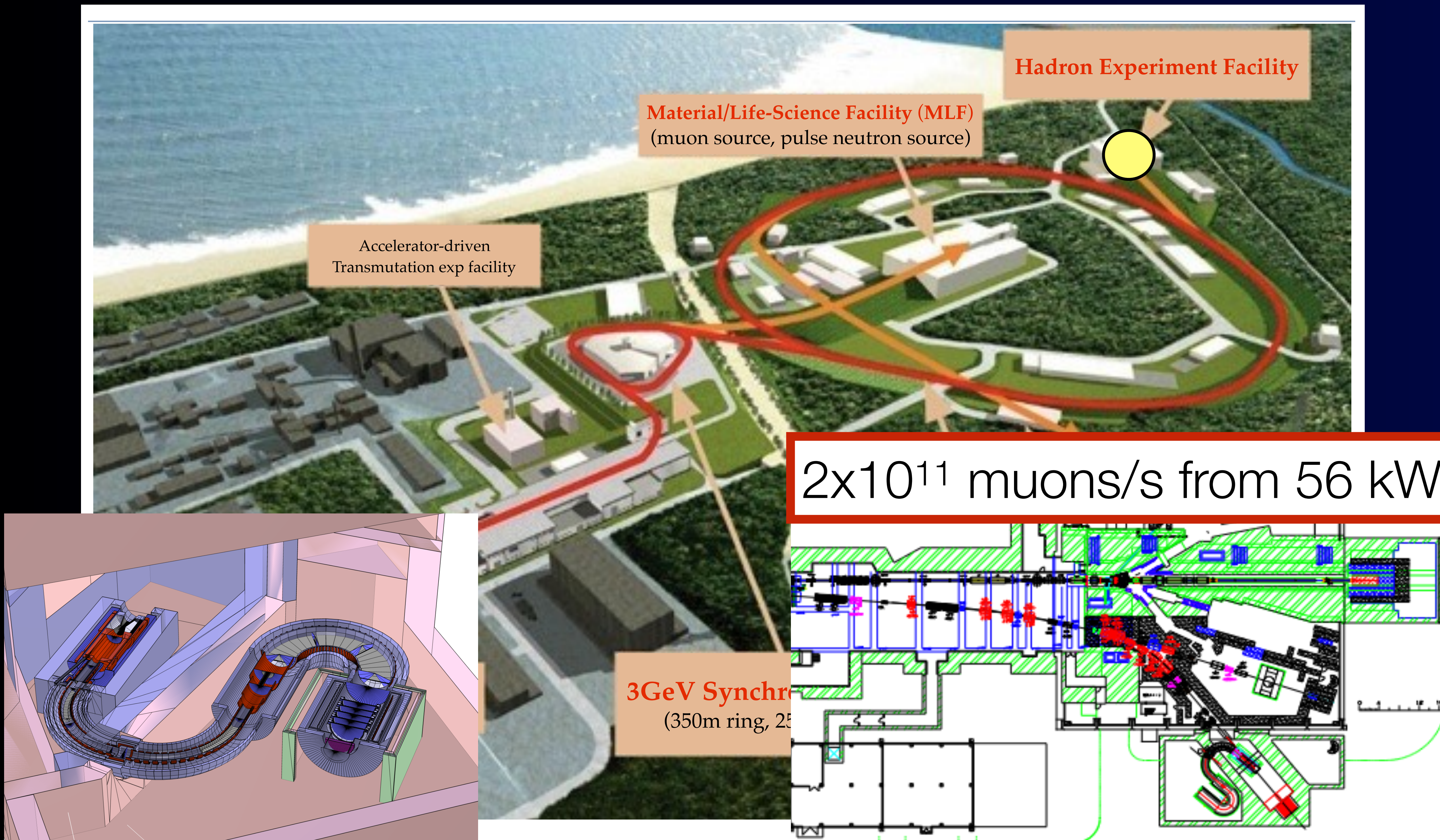
$>10^{10}$ muons/s from 8 kW

$>10^{11}$ muons/s from 100 kW

with PIP-II (0.8 GeV)

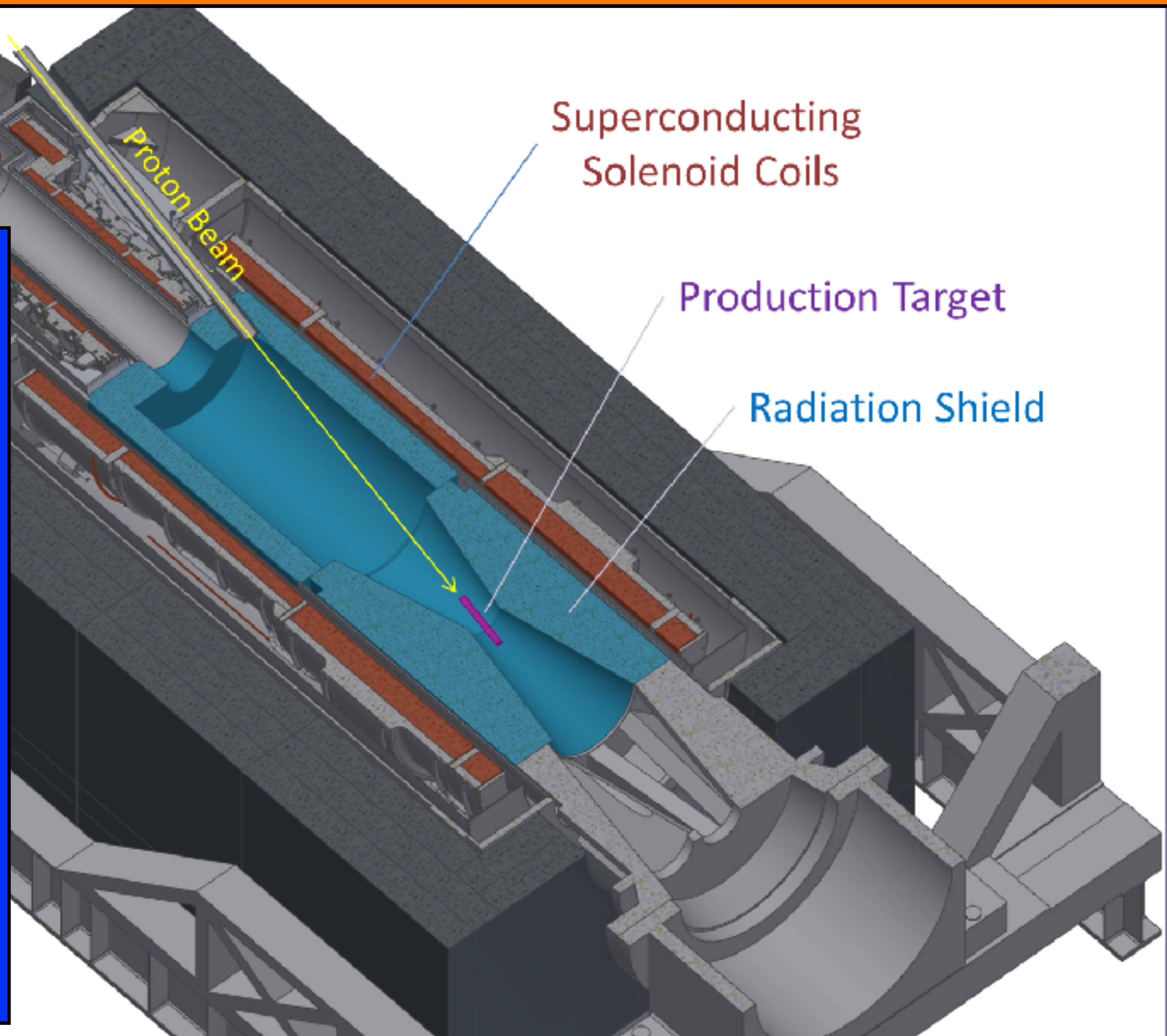
High Intensity Muon Source
J-PARC Main Ring

High Intensity Muon Source
J-PARC Main Ring



2×10^{11} muons/s from 56 kW

Improvement of Signal Sensitivity - More Muons



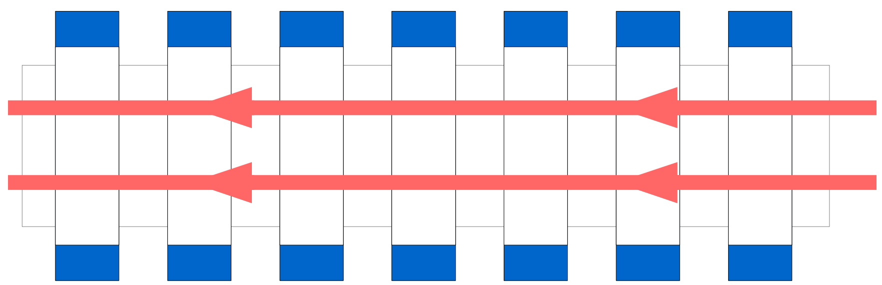
proton target in a solenoidal field (~5 T)

a long proton target (1.5~2 interaction length) of heavy material)

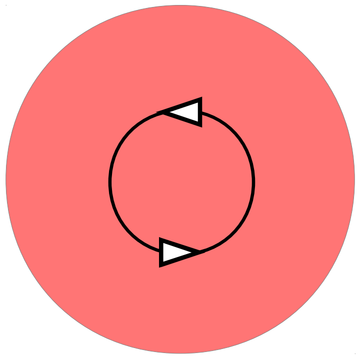
O(>10^{11}) stopped μ^-/sec
for 56 kW protons

Momentum Selection of Muons and Signal Electrons

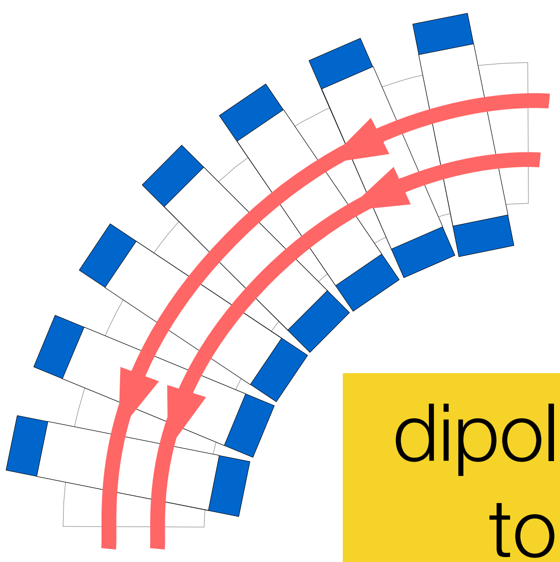
curved solenoid and drifts



- Uniform B field
- Linear field lines

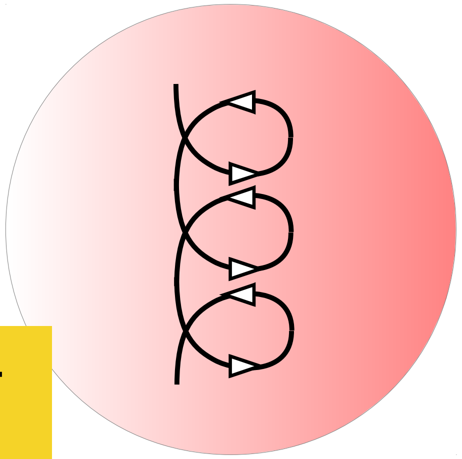


Circular motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines

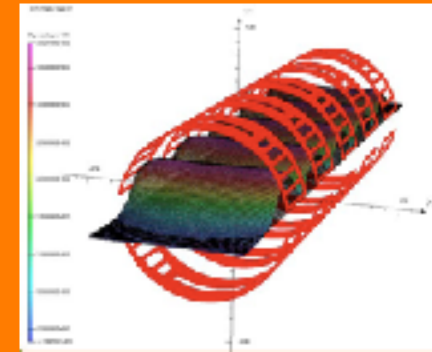
dipole field perpendicular to the solenoid field

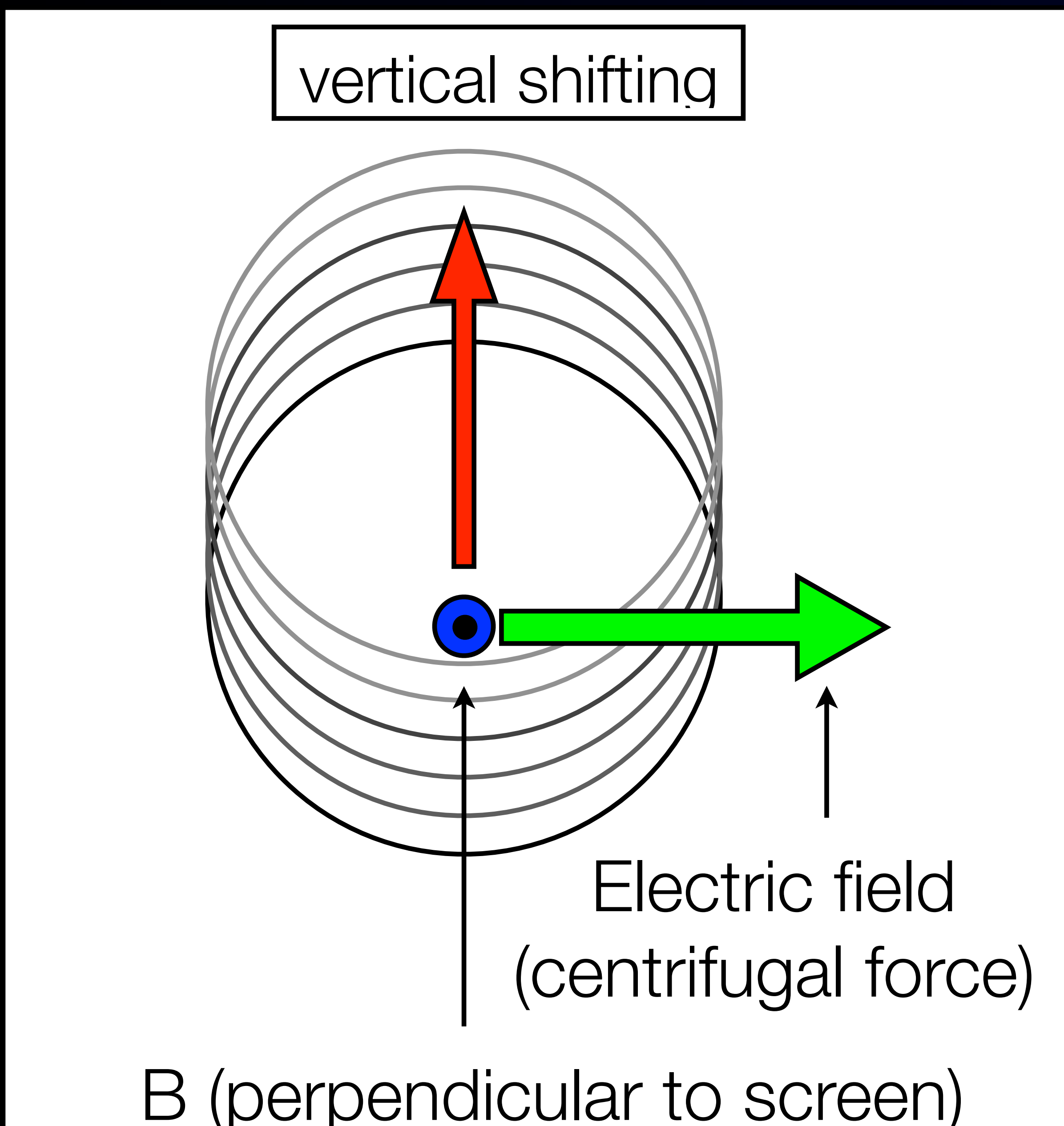


Circular motion about a drifting centre:

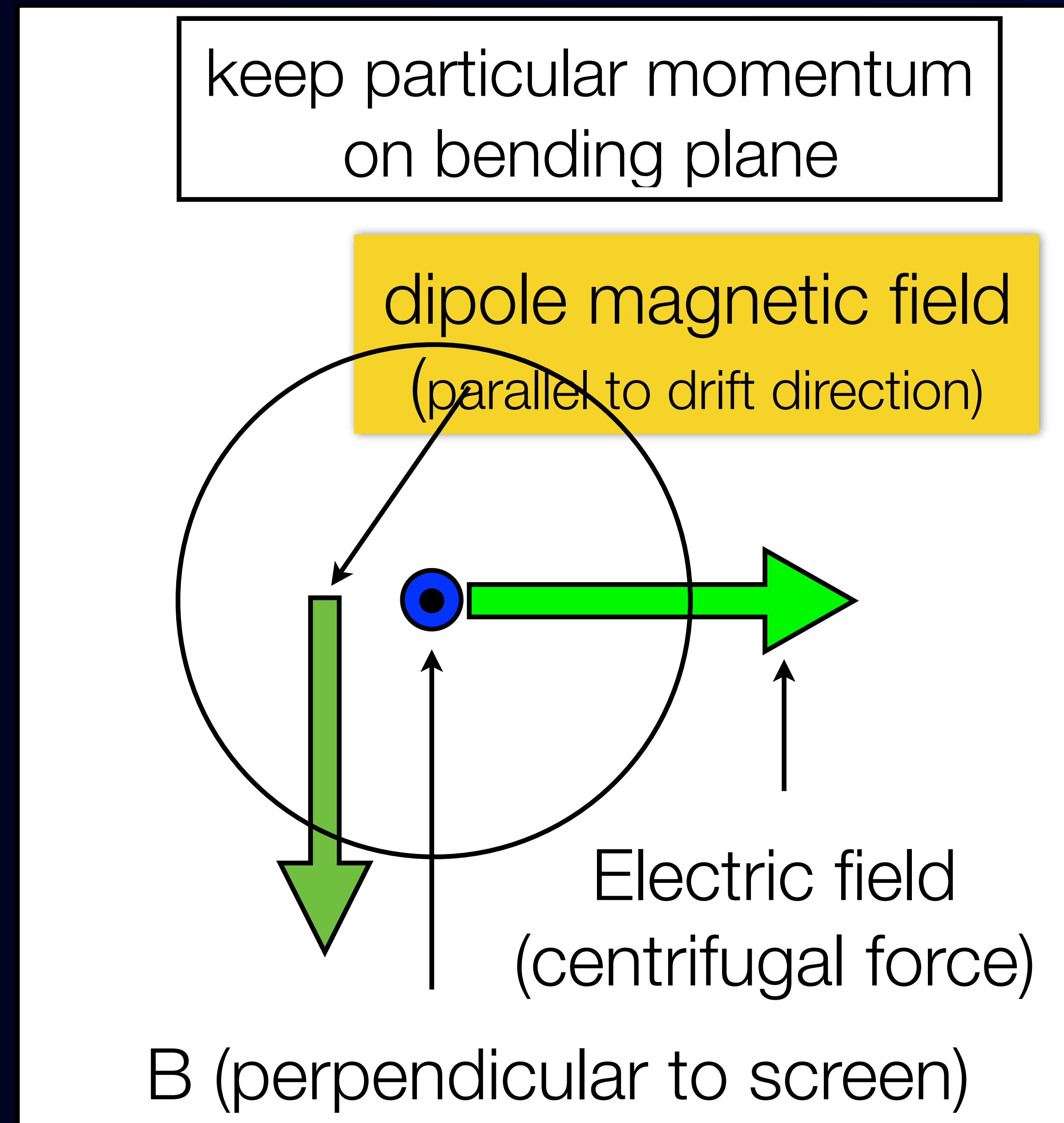
$$D \propto \frac{p}{qB} f(\theta)$$

Particle Trajectories in Curved Solenoid



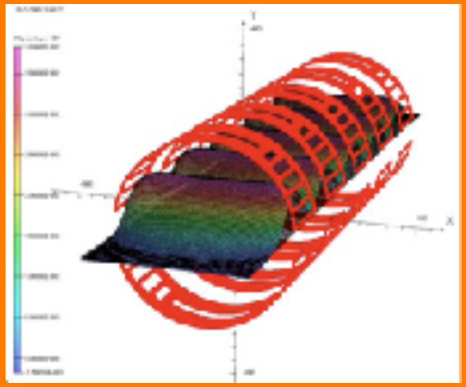


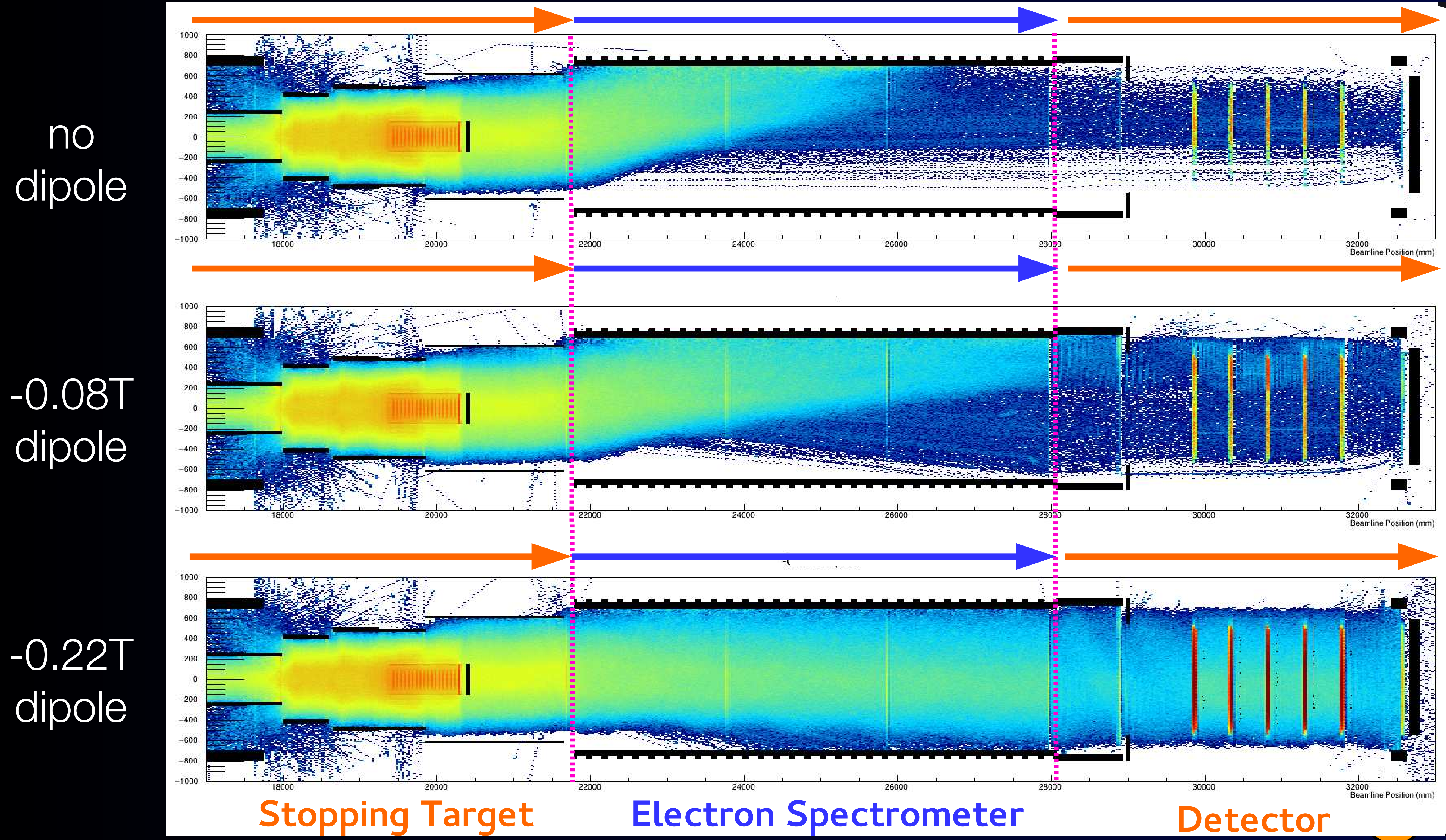
$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}(\cos\theta + \frac{1}{\cos\theta})$$



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

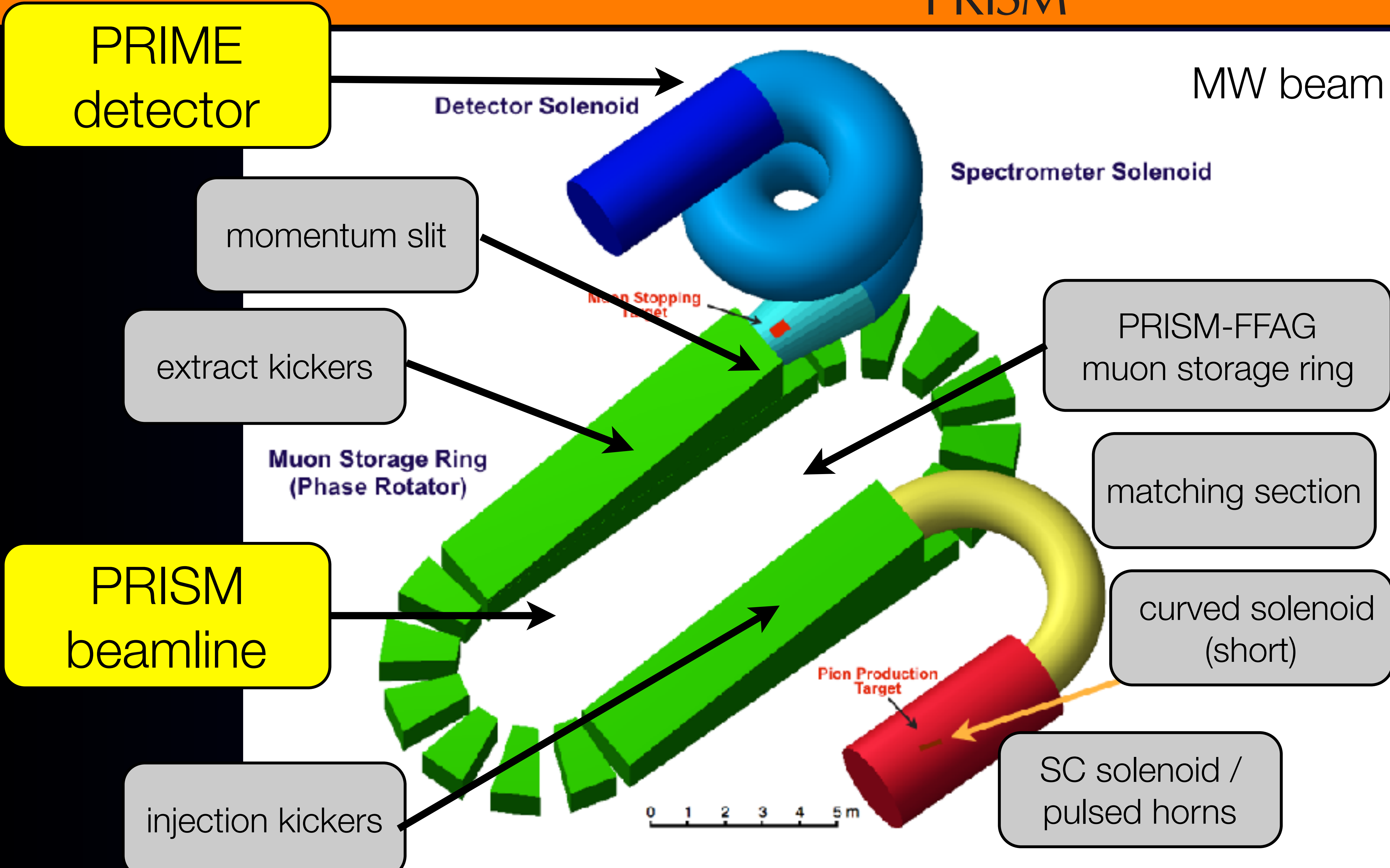
Curved Solenoid + Dipole Magnetic Field





Curved Solenoid for COMET

PRISM/PRIME : Future Search with Sensitivity of $O(10^{-19})$



Phase Rotation

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narrow energy spread of muon beam

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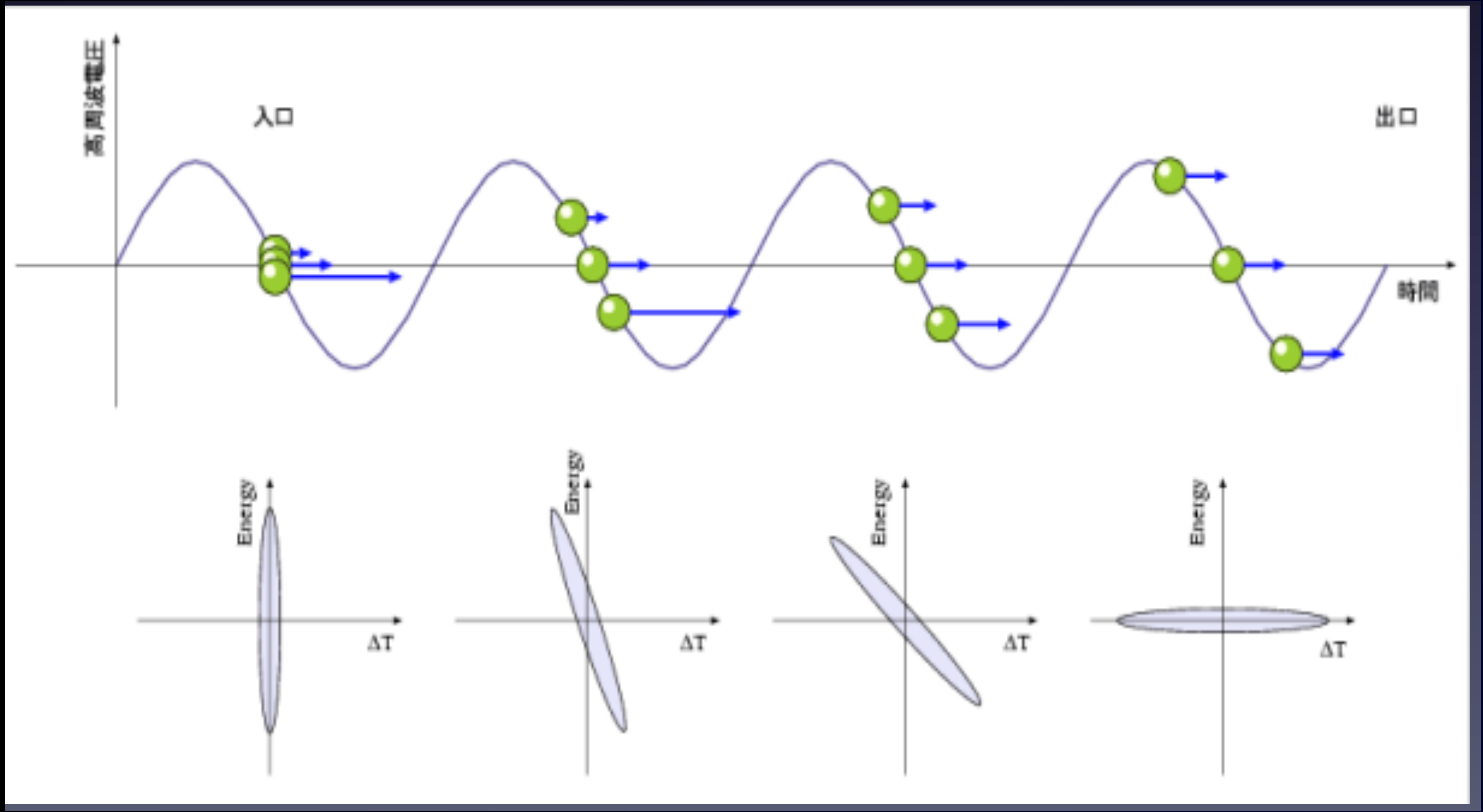
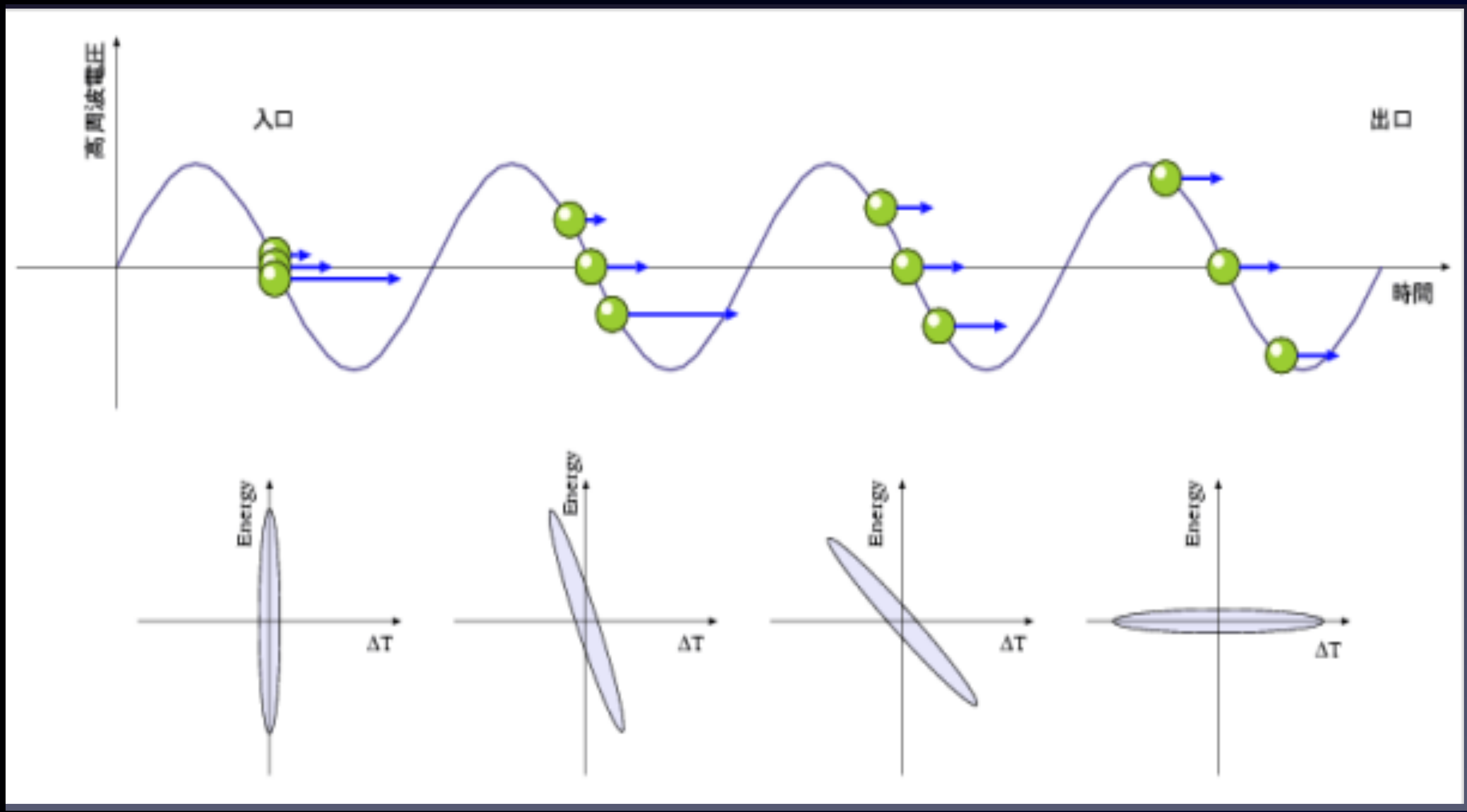


Phase Rotation

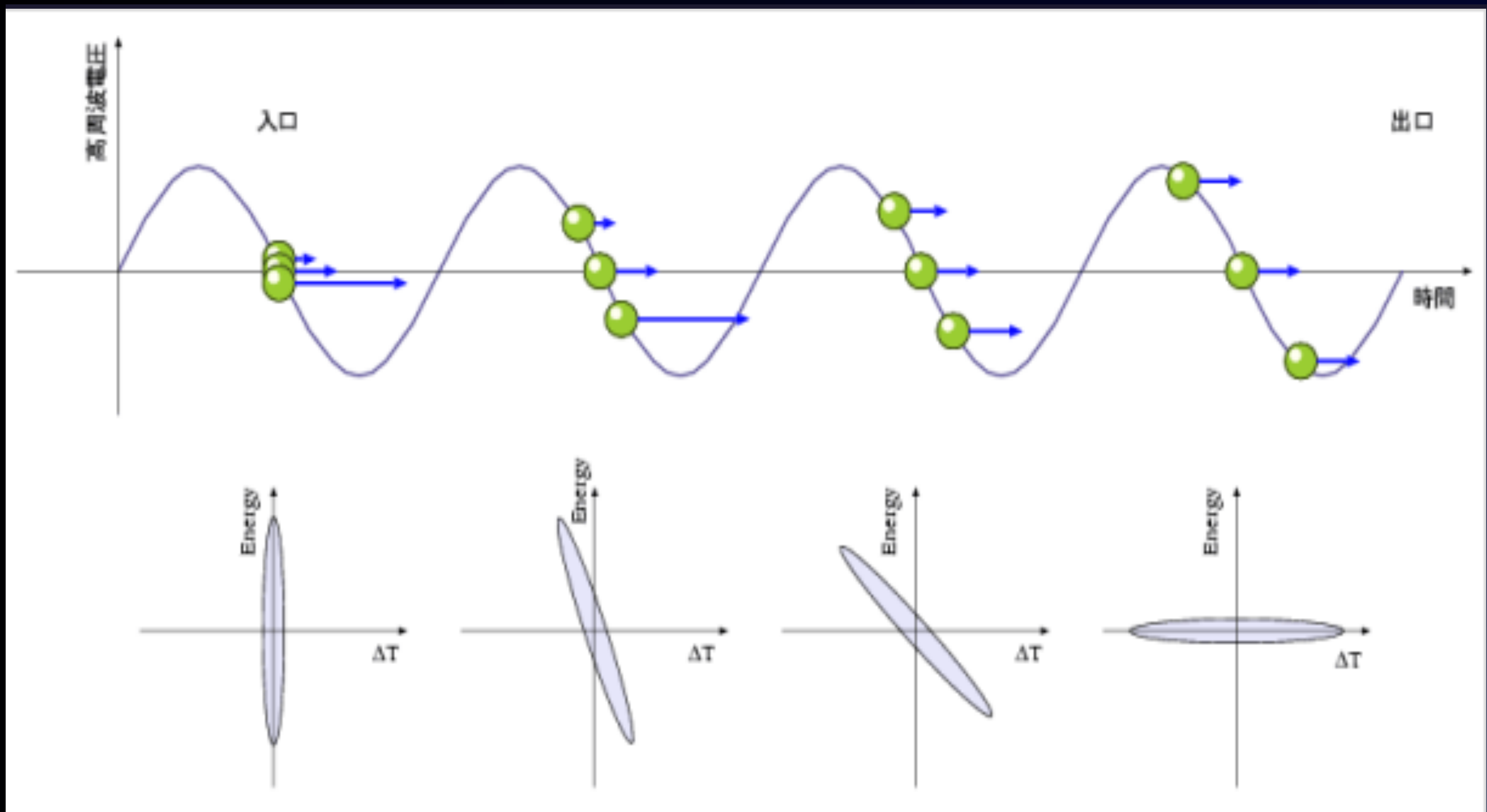
narrow energy spread of muon beam



allows a thinner muon stopping target

Phase Rotation

narrow energy spread of muon beam

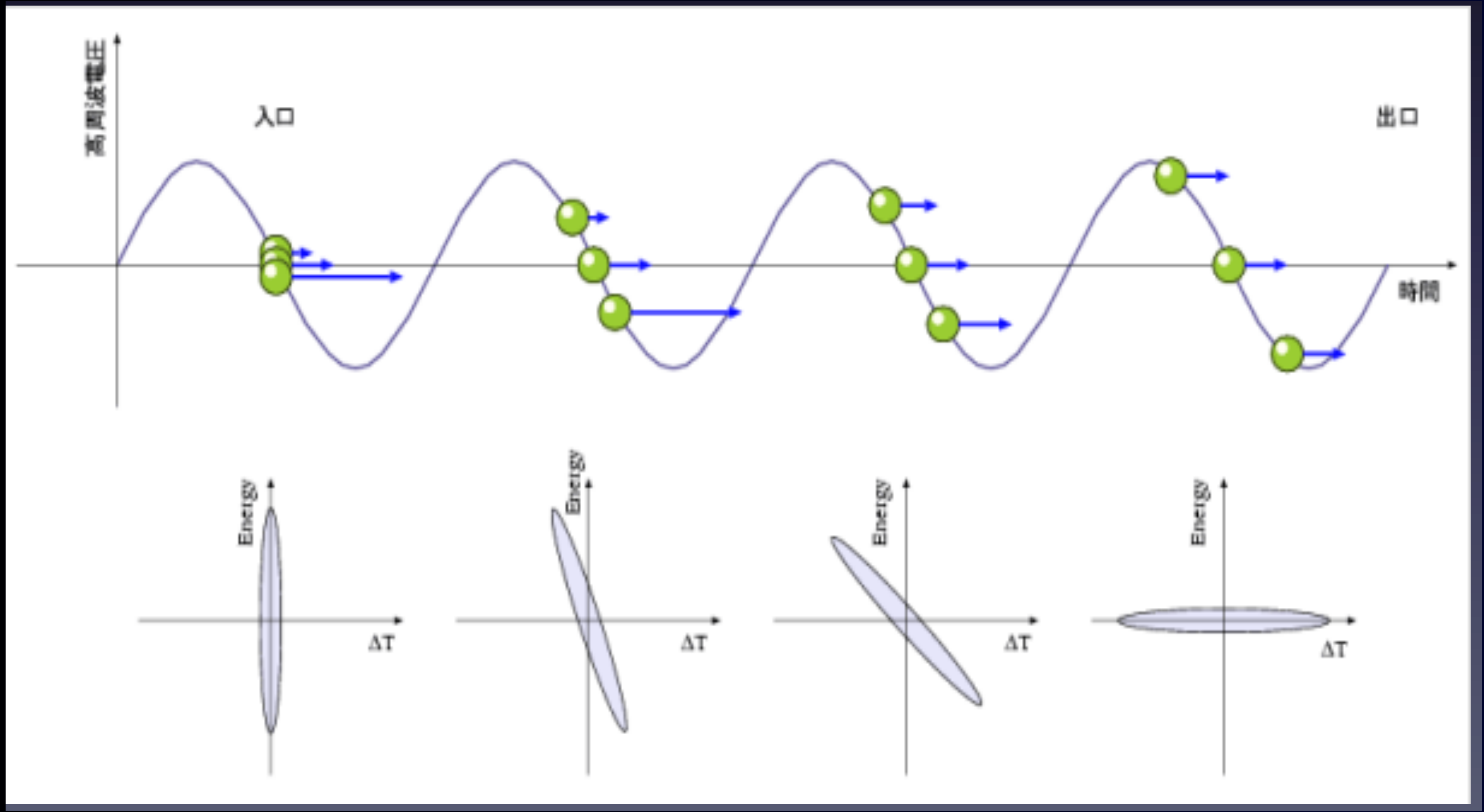


allows a thinner muon stopping target

decelerate fast muons (coming earlier) and accelerate slow muons (coming late) by RF with a narrow proton beam.

Phase Rotation

narrow energy spread of muon beam



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pure muon beam (pion< 10^{-20})

PRISM FFAG R&D

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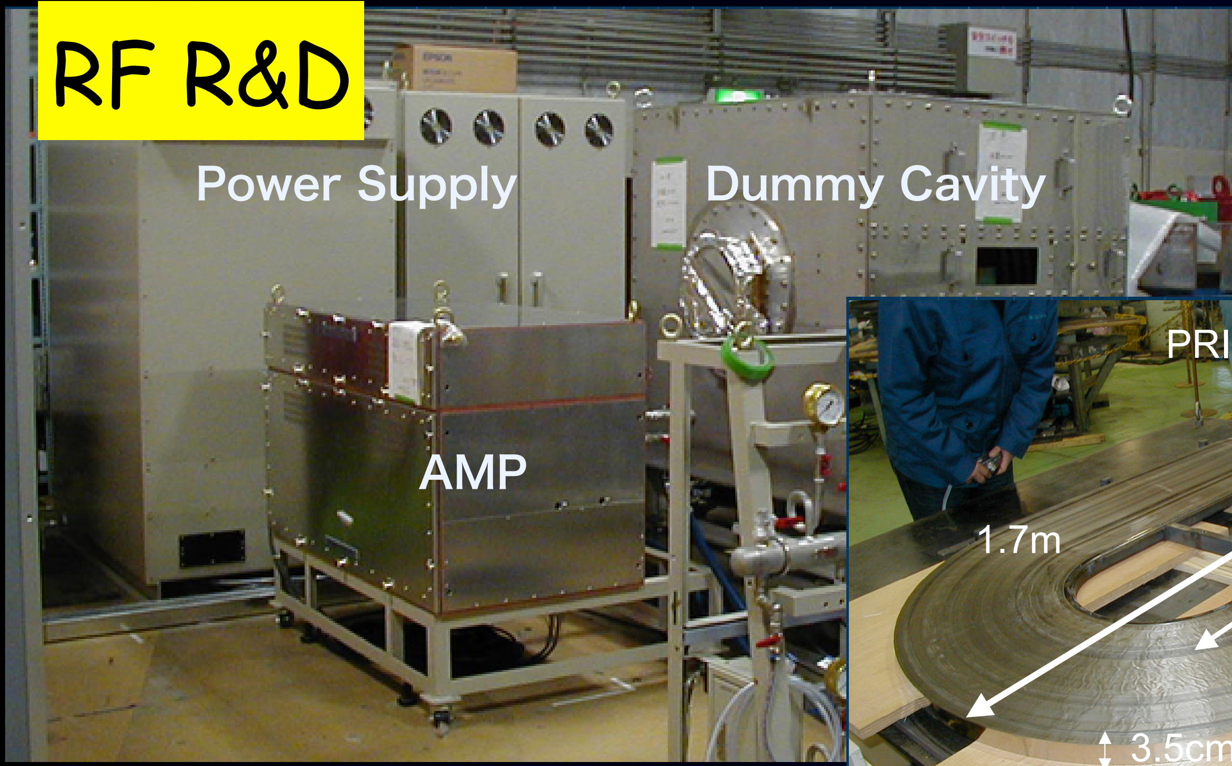
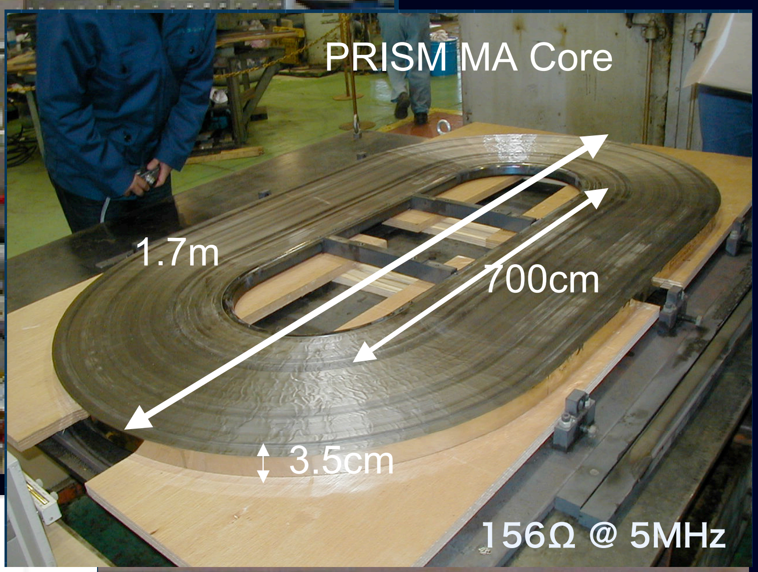
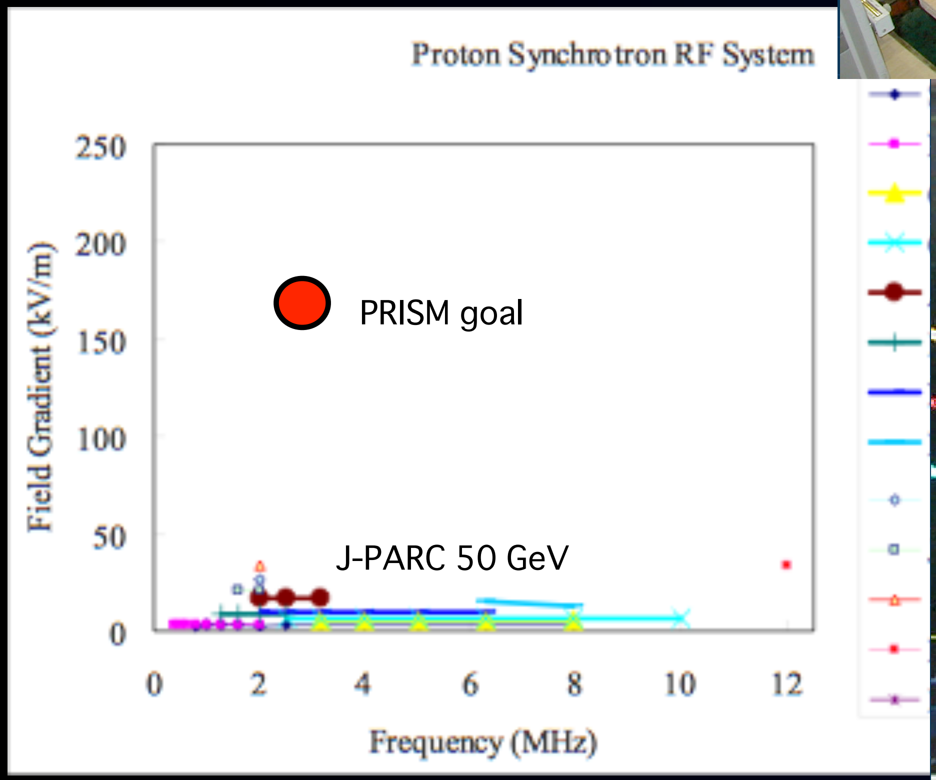
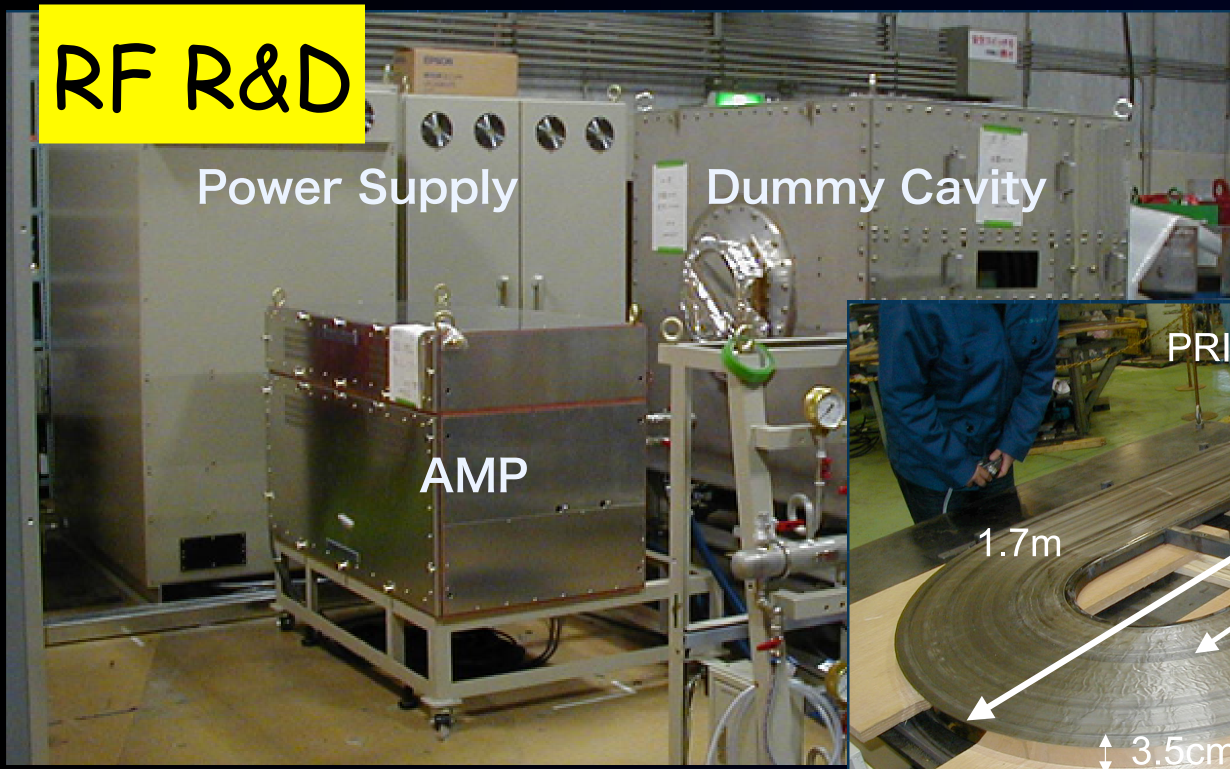
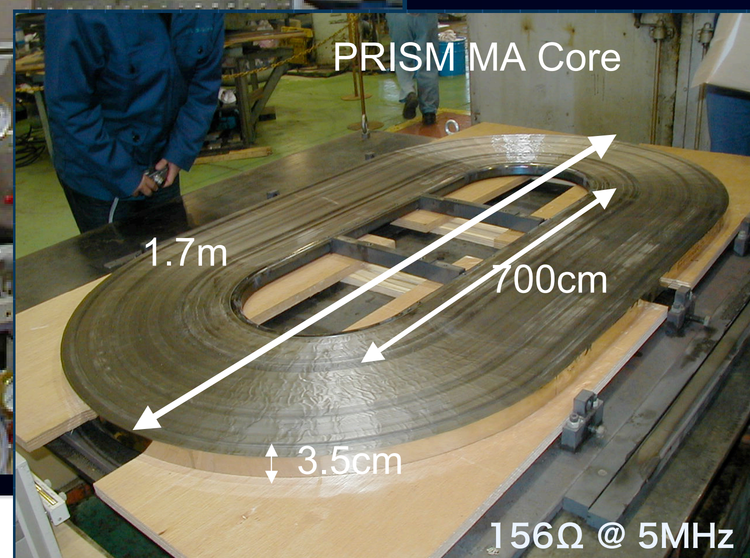


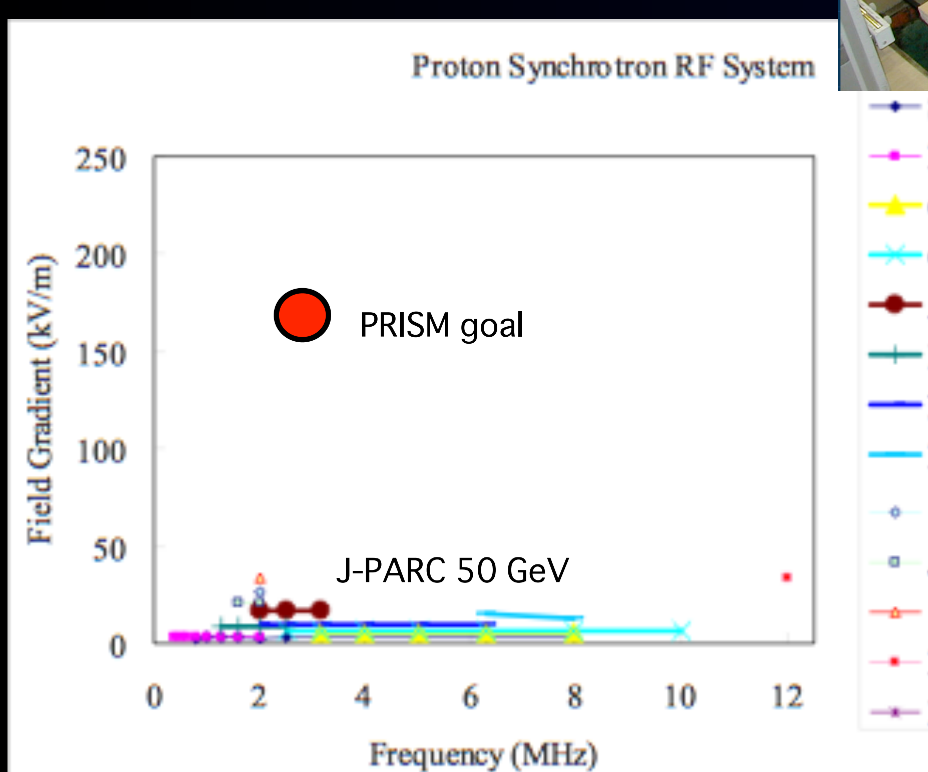


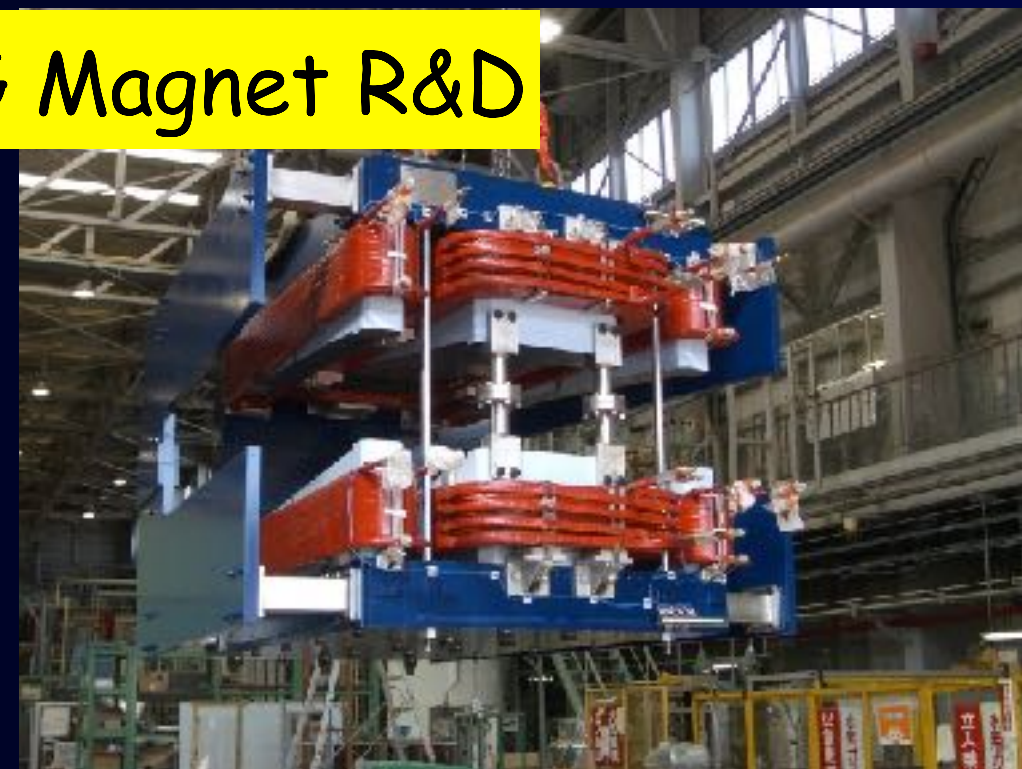


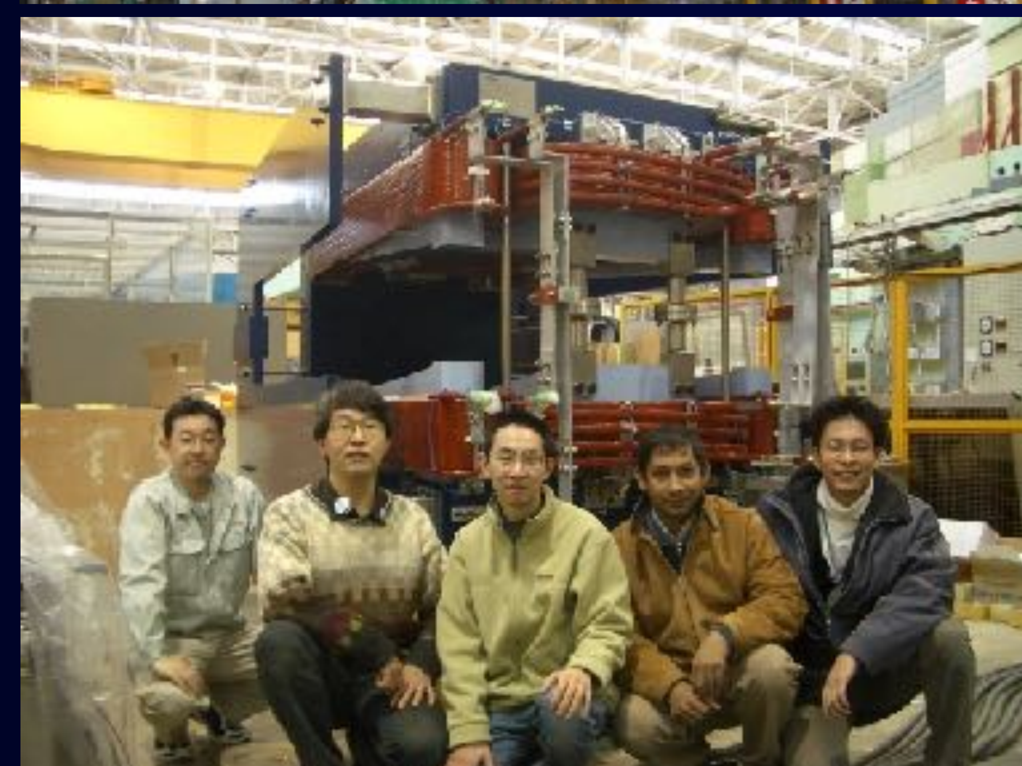
PRISM FFAG R&D











R&D on the PRISM-FFAG Ring at Osaka University

demonstration of phase rotation has been done.

Summary

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my dog, IKU

Thank you for your attention!

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Thank you!

谢谢

ありがとう!

Thank you for your attention!