Muon Particle Physics Program at J-PARC

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KEK/J-PARC

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KEK 大学共同利用機関法人 高エネルギー加速器研究機構
J-PARC

Background

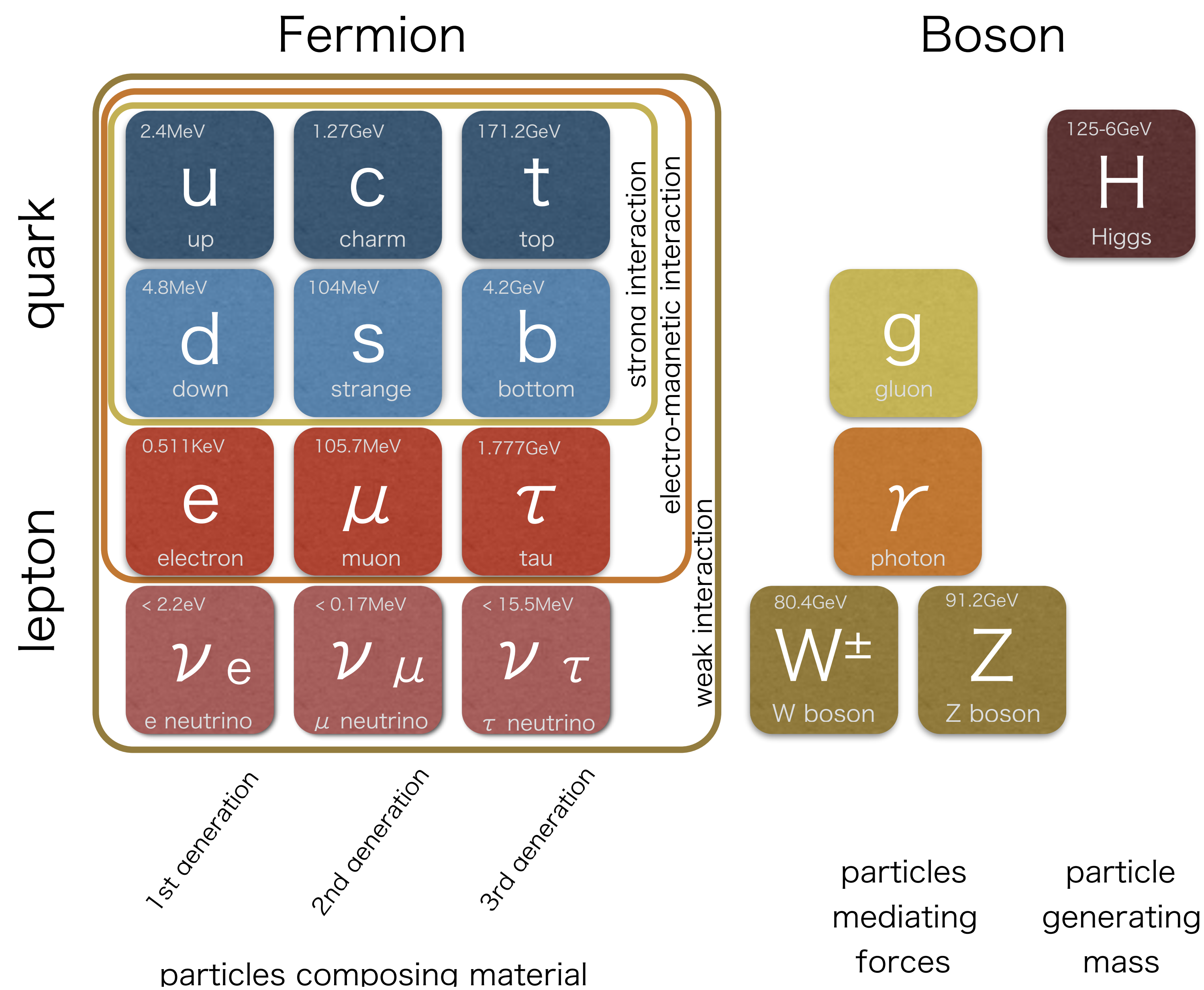
- TSU and KEK/J-PARC have been collaborating in the muon particle physics program (mu-e conversion search, COMET) at J-PARC.

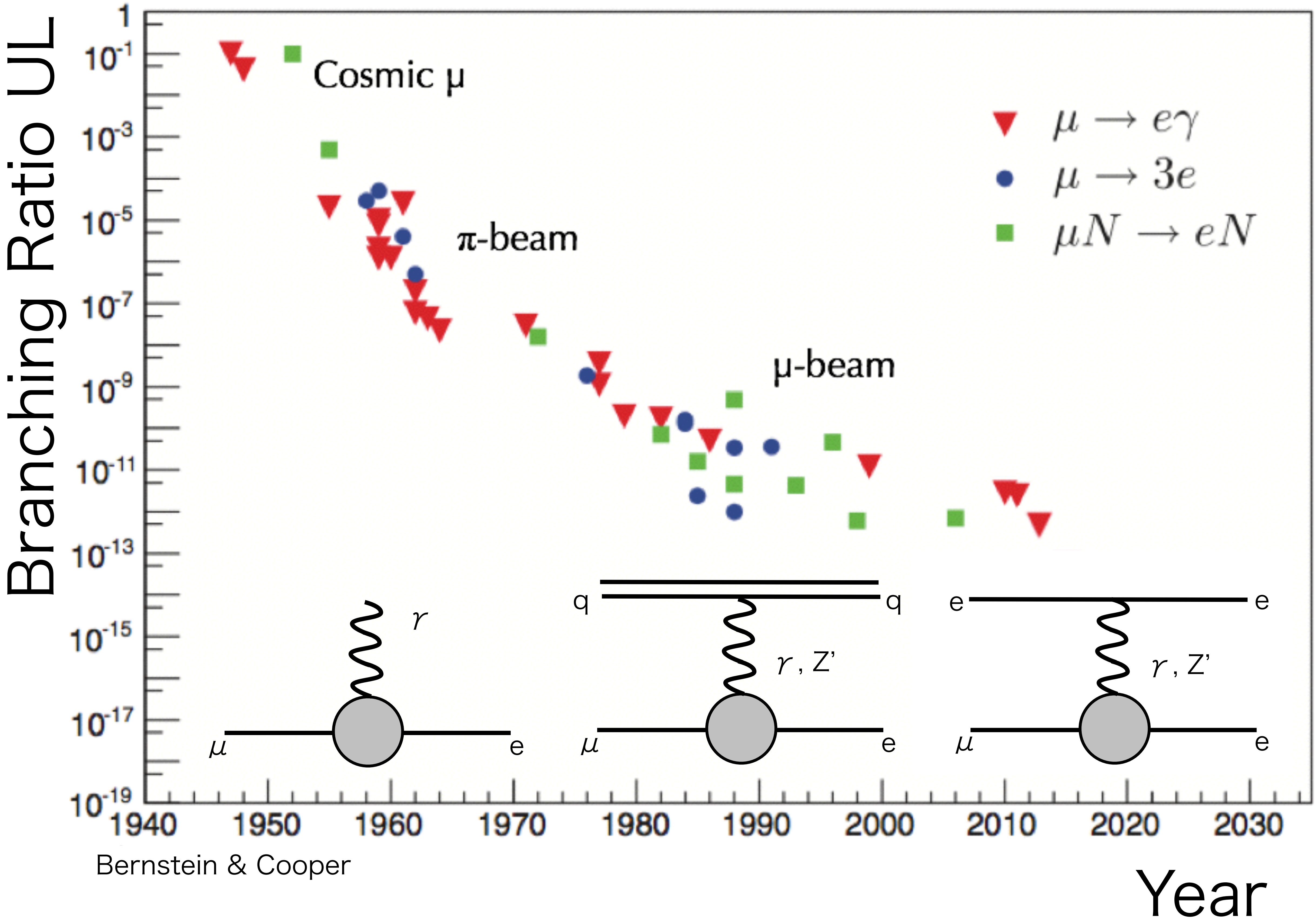
Outline

- Background
- Muon particle physics
- J-PARC & Muon particle physics experiments
- Summary

Muon Particle Physics

- Muon in the Standard Model
  - Precise measurement of muon properties
  - Establishment of SM
- Indication of BSM?
  - muon g-2, proton radius, B leptonic decay …

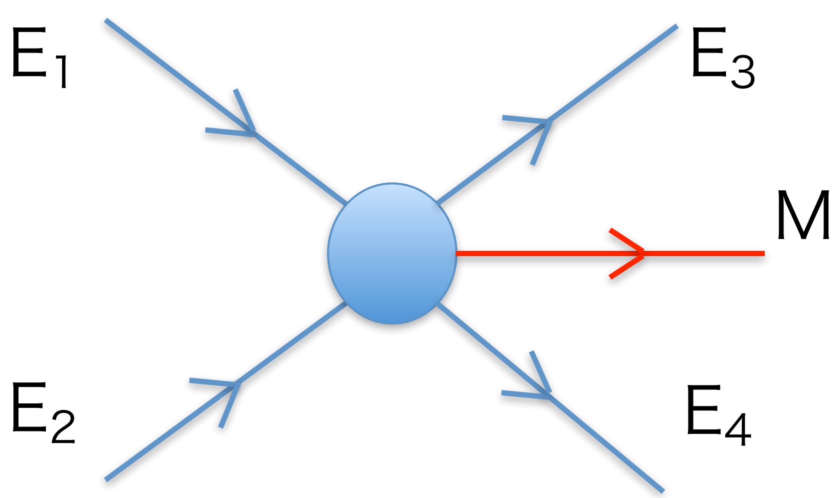



Branching Ratio UL
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year
Cosmic μ
π-beam
μ-beam
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
γ
μ
e
q
q
γ, Z'
μ
e
e
e
γ, Z'
μ
e
Bernstein & Cooper

Role of low-energy charged lepton physics in LHC/ILC era

- Direct search

  (Energy Frontier)

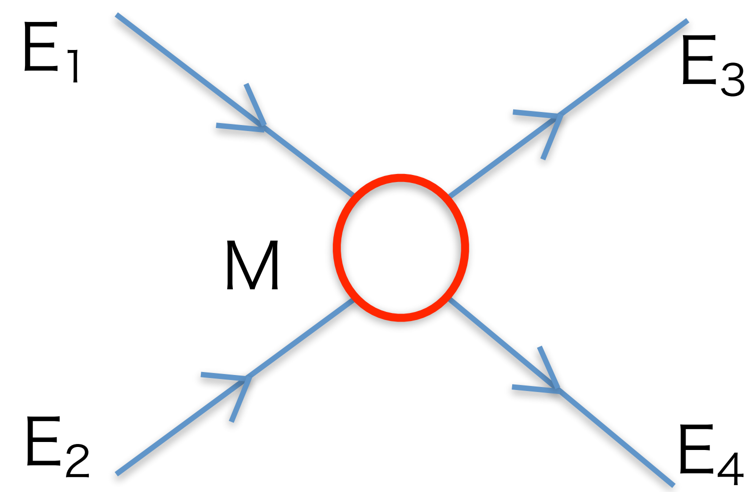


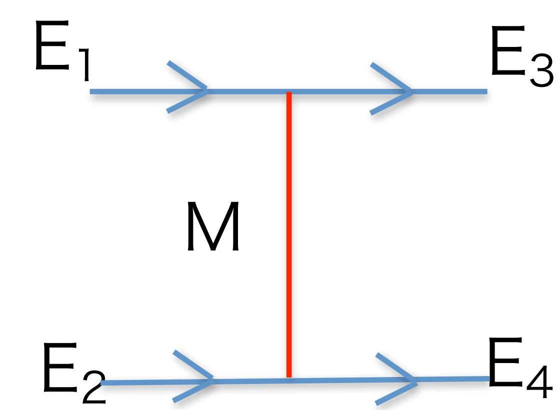
$$E_1+E_2 > M \sim O(\gg 100\,\text{GeV})$$

- LHC, ILC
  - Higher energy for heavier new particle

- Indirect search

  (Intensity Frontier)





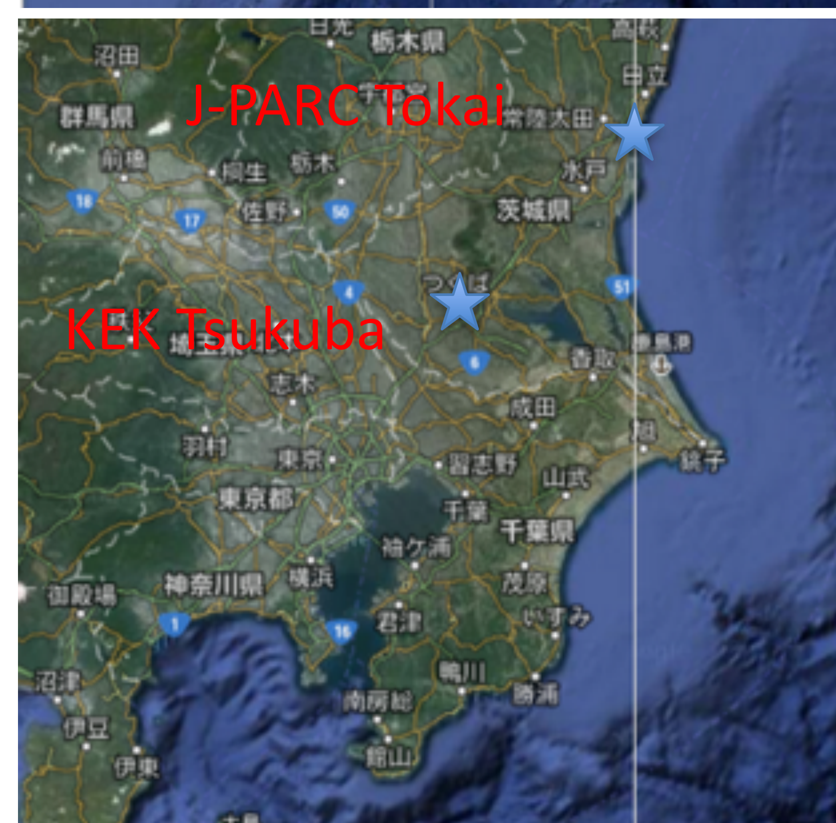
$$E_1+E_2=E_3+E_4 < M$$

- Charged LFV/g_μ-2
  - $L = L_{SM} + L_{BSM}$
  - “Slight” difference from SM prediction

J-PARC

Japan Proton acceleration research complex

- Joint project between JAEA and KEK
- **New and accelerator research facility**, using MW-class high power proton beams at both 3 GeV and 30 GeV.
- Various secondary particle beams
  - neutrons, muons, kaons, neutrinos, etc. produced in proton-nucleus reactions
- Three major scientific goals using these secondary beams
  - Particle and Nuclear physics
  - Materials and life sciences
  - R&D for nuclear transformation (in Phase 2)
- The anticipated goal is 1 MW




J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetition : 25 Hz
Design Power : 1 MW
Main Ring
Max Energy : 30 GeV
Design Power for FX : 0.75 MW
Expected Power for SX : > 0.1 MW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Muon Particle Physics Experiments at J-PARC

- Precise measurement of muon g-2/EDM
- Muon conversion search
  - DeeMe & COMET
- (Muonic atom hyper-fine spritting)

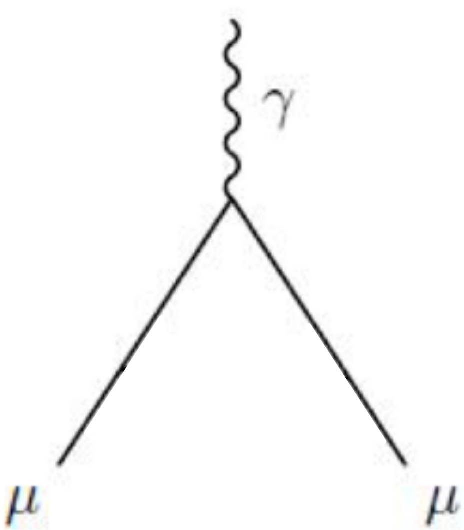
muon g-2/EDM

Magnetic Dipole Moment

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B}$$

- Spin precession in magnetic field
- Lande's g factor is 2 in tree level
- Higher order corrections in quantum field theory: $g = 2(1 + a_\mu)$



$$\vec{\omega} = -\frac{e}{m}\left[a_\mu\vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

γ_{magic}=29.3

p_{magic}=3.094GeV/c

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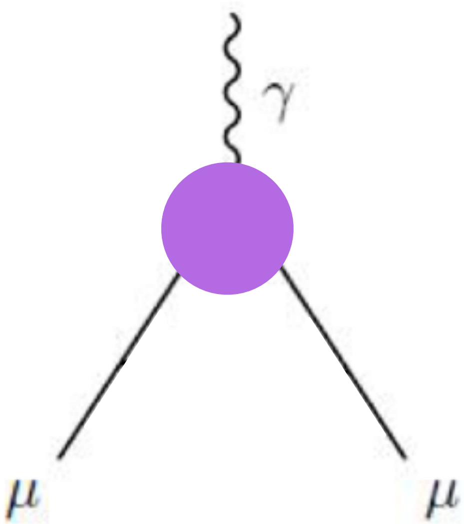

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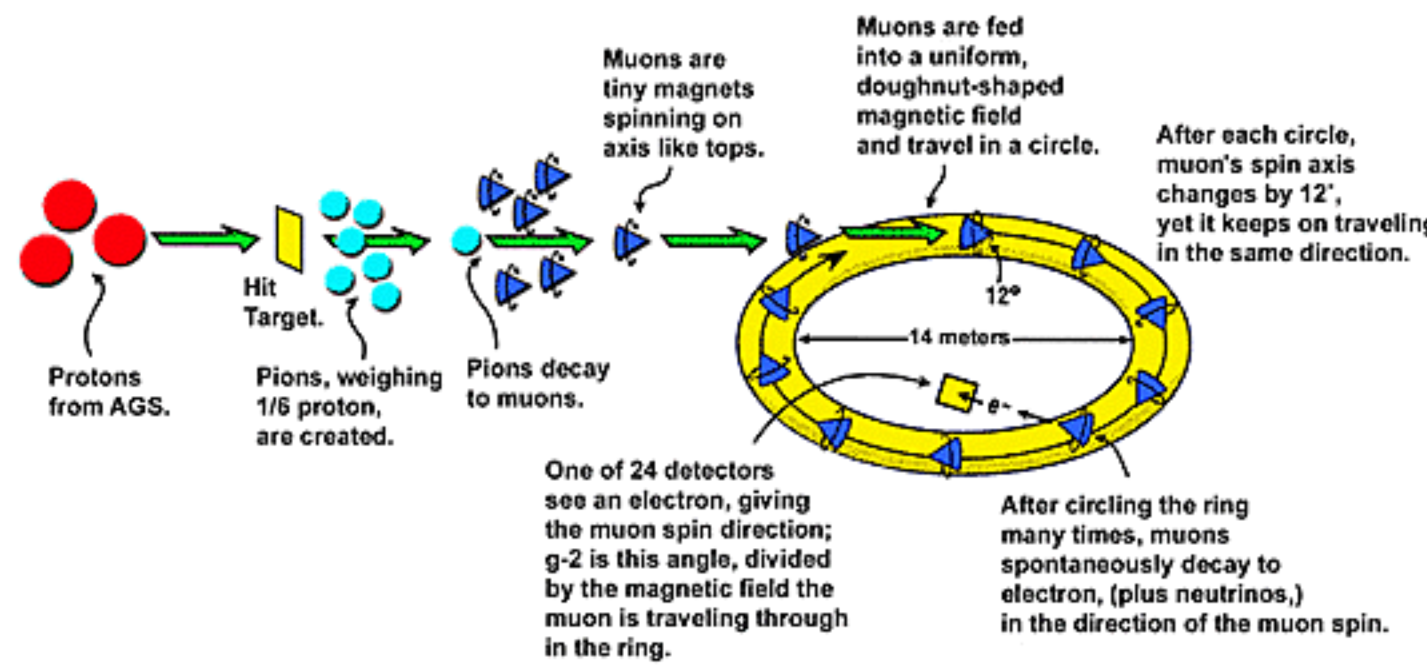
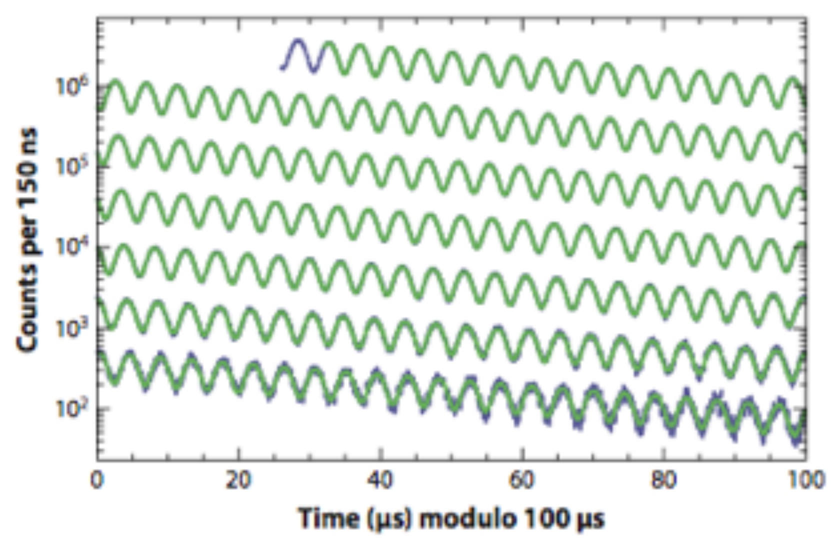
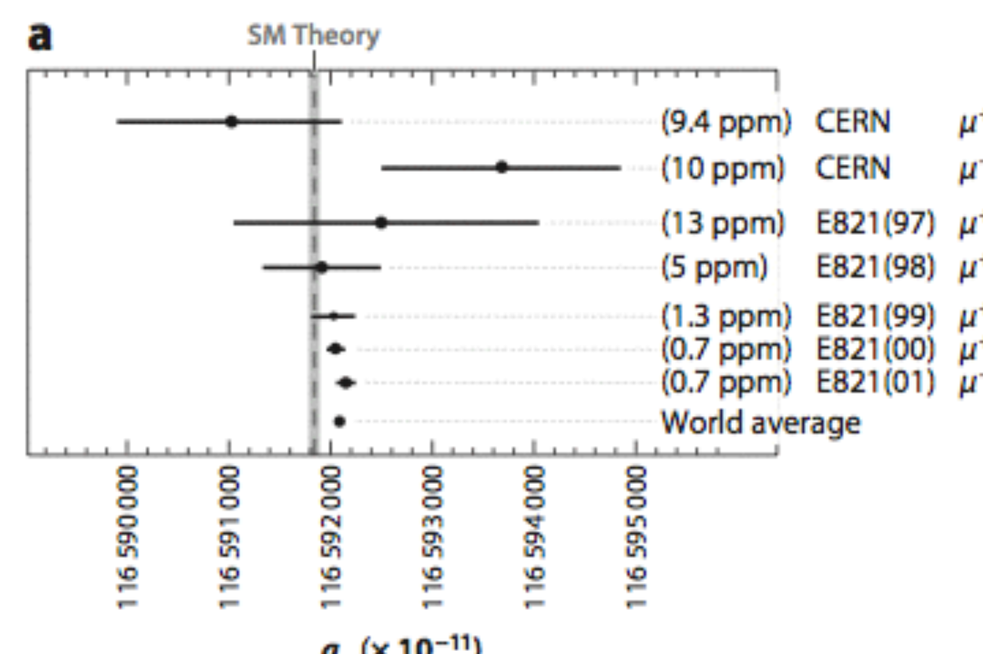
BNL E821

- Magic momentum muon
- Electron detector at inner side of the ring
- μ^+ and μ^-







> 3σ discrepancy with SM predictions

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	−9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

D. Nomura (tau2012)

Fermilab E989

- **Goal:**

$$\delta a_\mu \leq \pm 16 \times 10^{-11} \ (.14 \text{ ppm})$$

- 1.8×10^{11} detected high energy decays

beam in 2016

- systematic errors ω_a, ω_p ±0.07 ppm each

muon g-2/EDM measurements

Anomalous magnetic moment (g-2)

$a_\mu = (g-2)/2 \quad = 11\,659\,208.9\,(6.3) \times 10^{-10}$ (BNL E821 exp) **0.5 ppm**

$11\,659\,182.8\,(4.9) \times 10^{-10}$ (standard model)

$\Delta a_\mu =$ Exp - SM = $26.1\,(8.0) \times 10^{-10}$ **3σ anomaly**

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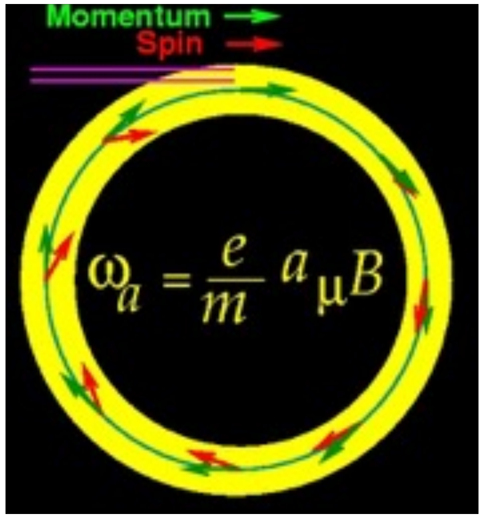
In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0

general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$



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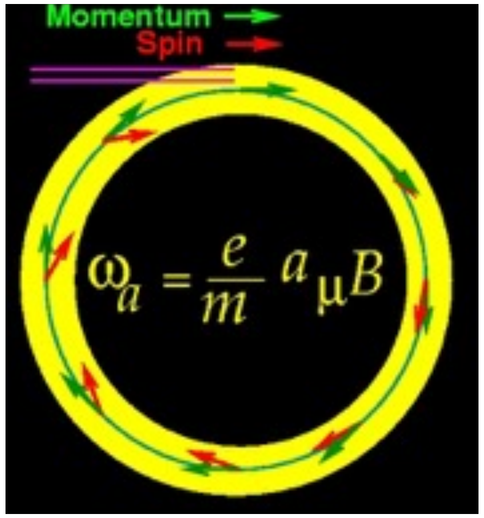
In uniform magnetic field, muon spin rotates ahead of momentum due to $g-2 \neq 0$



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BNL E821 approach
γ=30 (P=3 GeV/c)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Continuation at FNAL with 0.1ppm precision

muon g-2/EDM measurements

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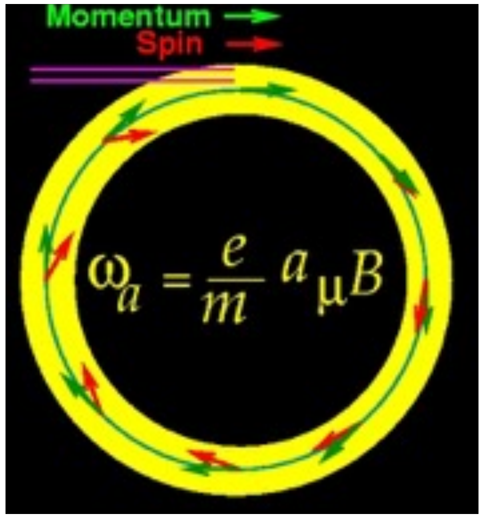

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Continuation at FNAL with 0.1ppm precision

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

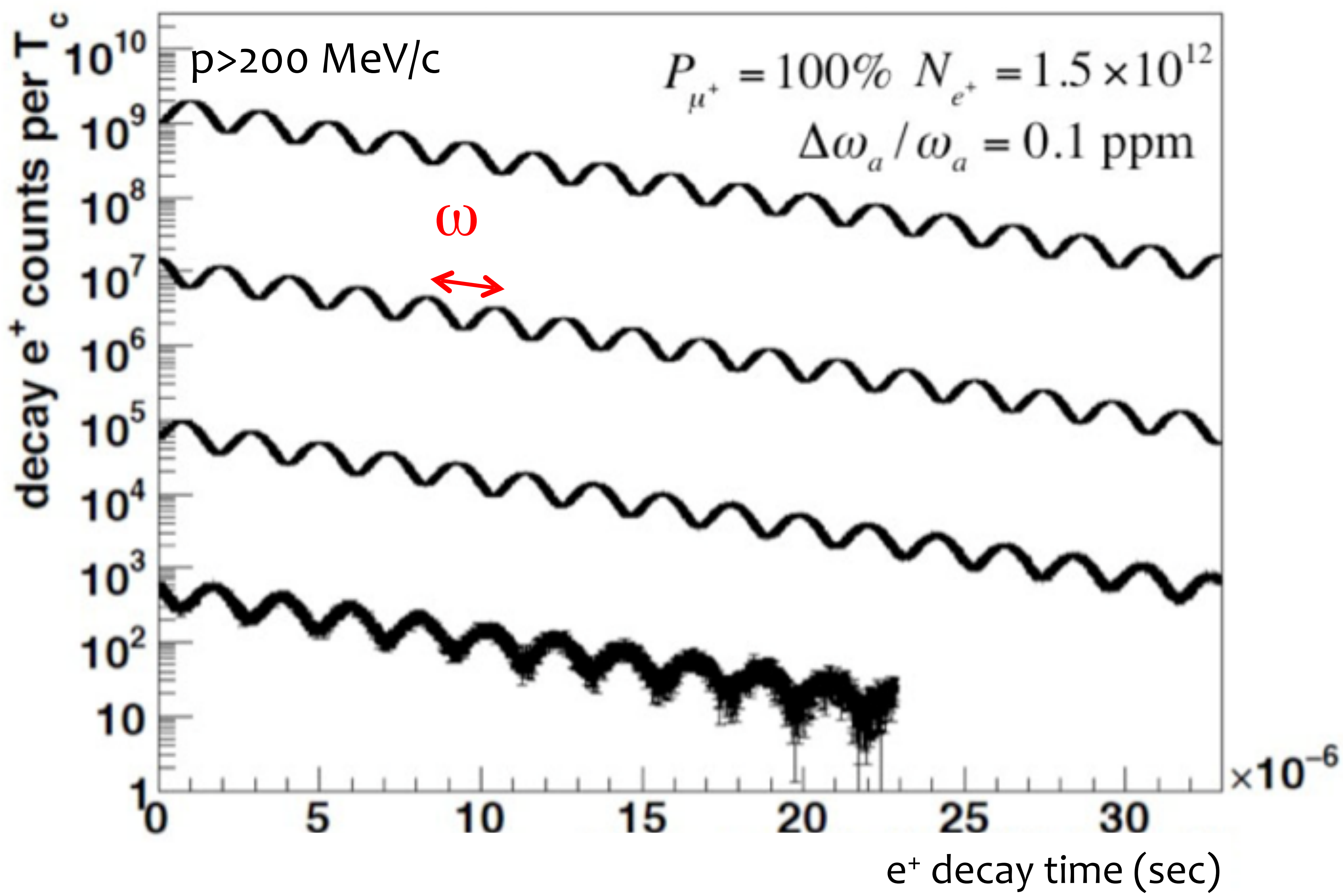
Proposed at J-PARC with 0.1ppm precision

Expected time spectrum of $\mu \rightarrow e^+\nu\nu$ decay

Muon spin precesses with time.

→ number of high energy e^+ changes with time by the frequency :

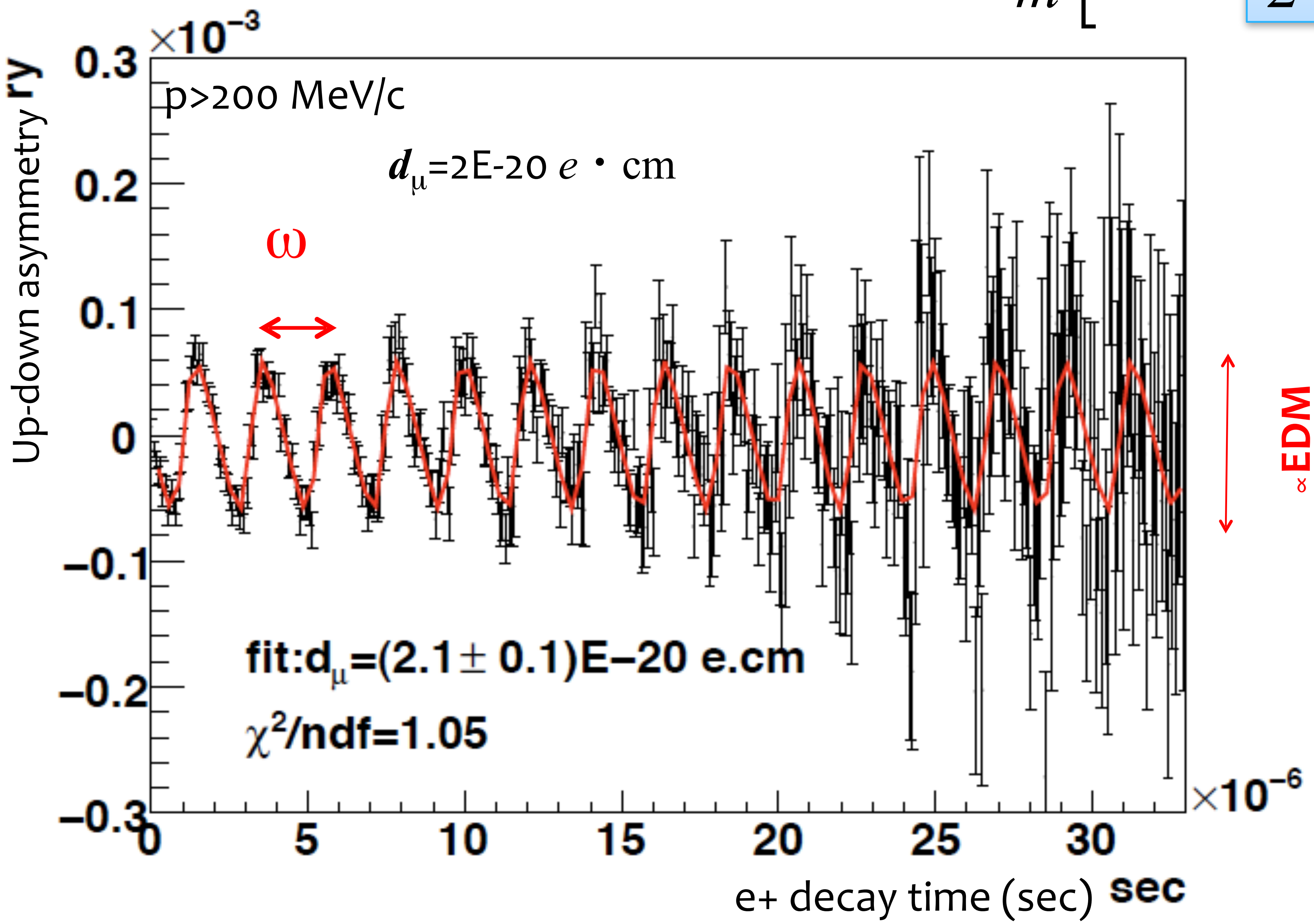
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$



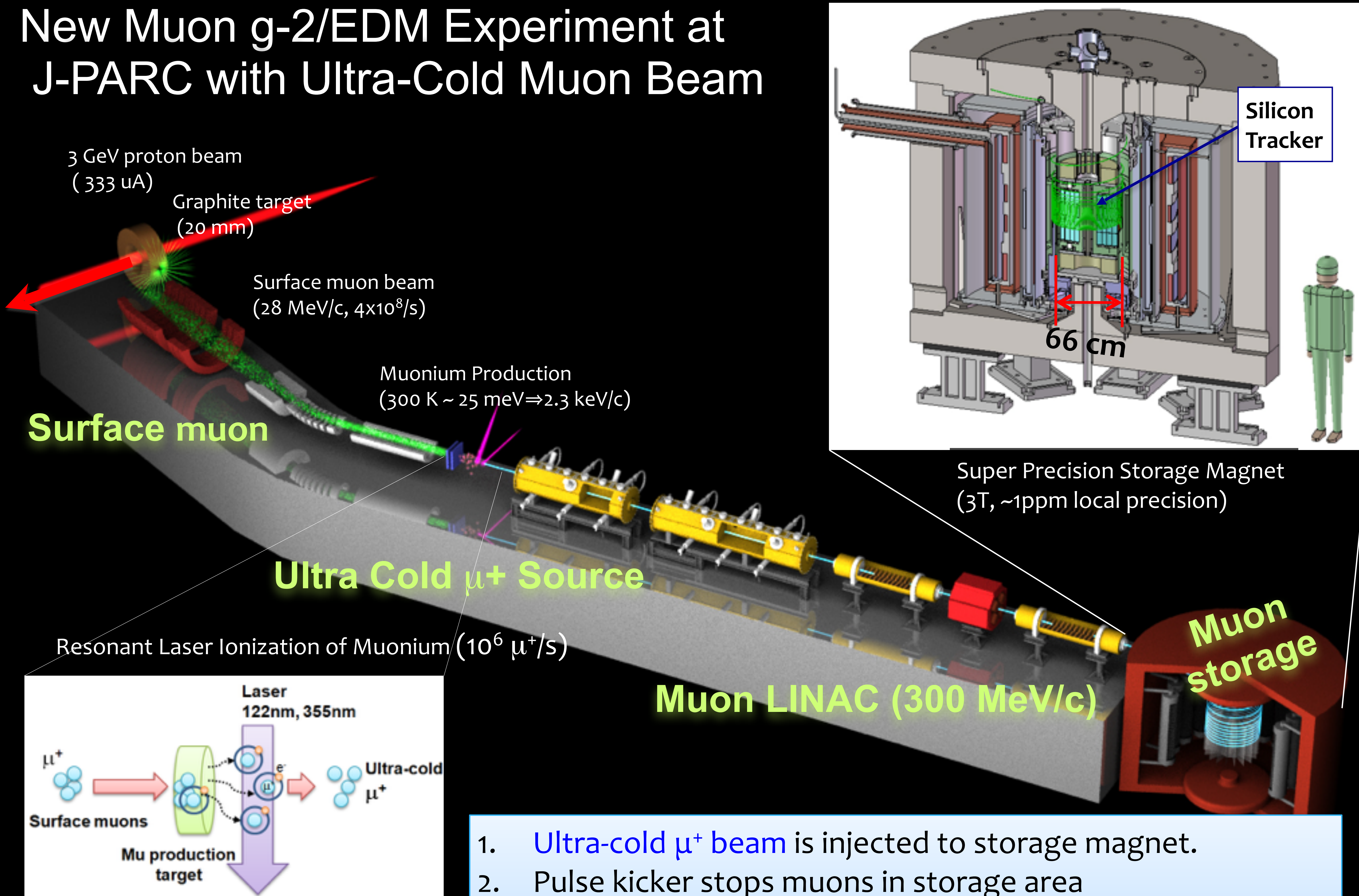
Expected time spectrum of $\mu \rightarrow e^{+}\nu\bar{\nu}$ decay

EDM tilts the precession axis.
→ This yields an up-down decay asymmetry in number of e+
(oscillates with the same frequency ω)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

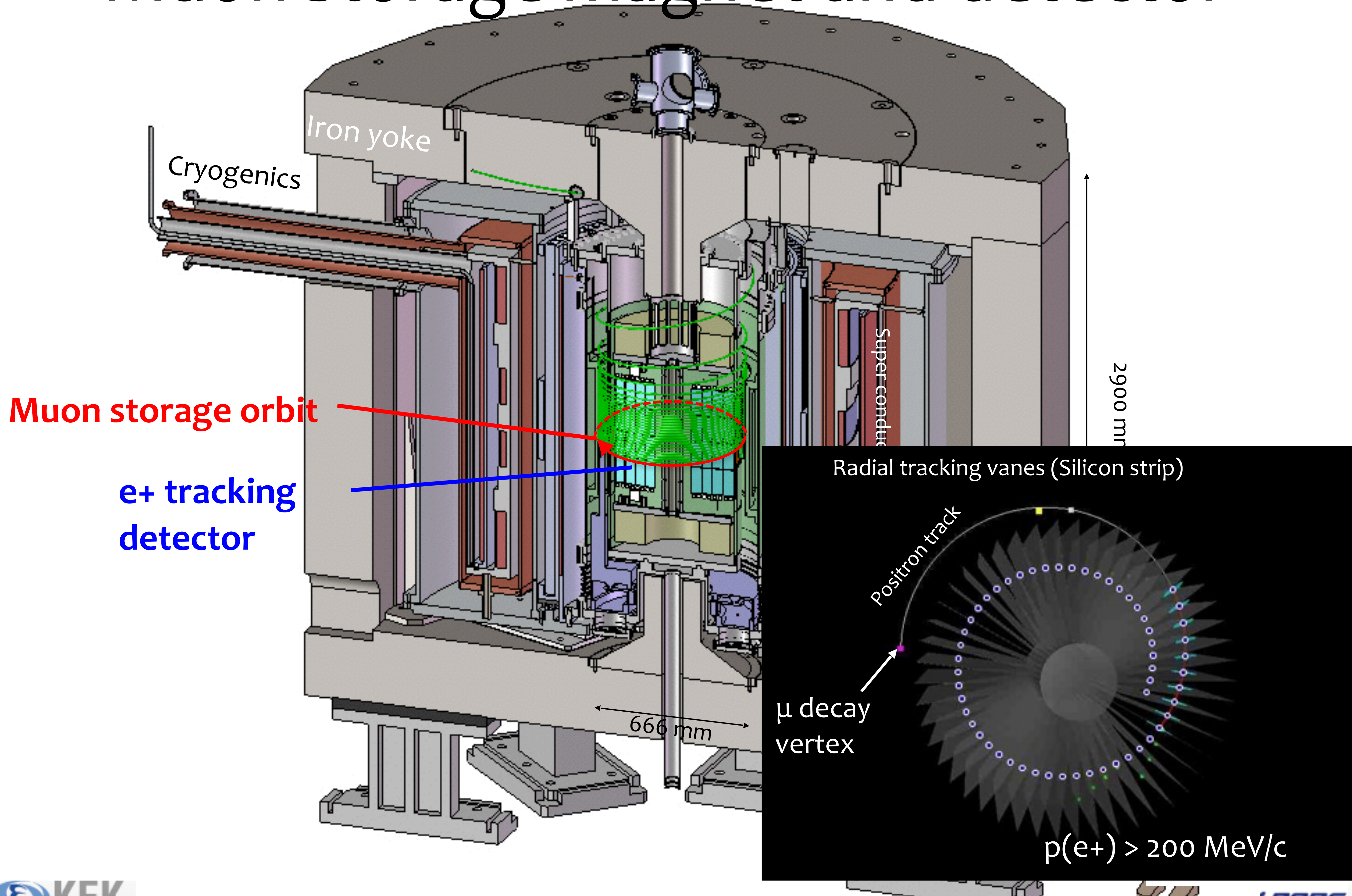


New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



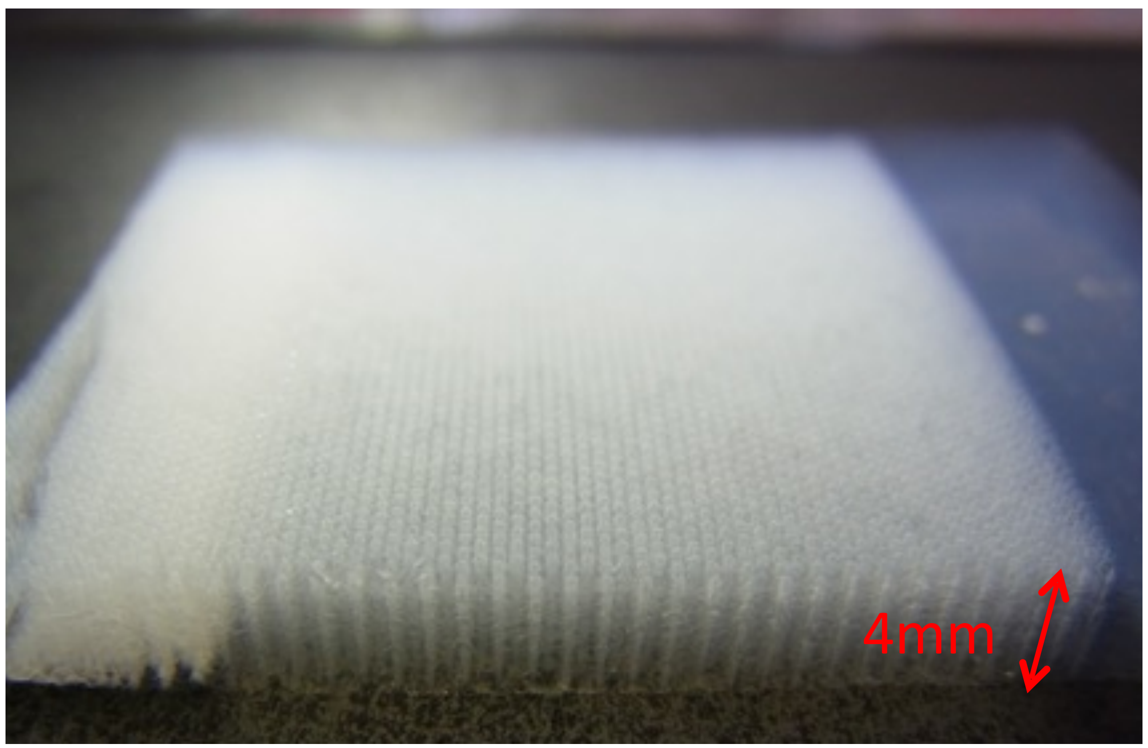
1. Ultra-cold μ^+ beam is injected to storage magnet.
2. Pulse kicker stops muons in storage area
3. Positron tracker measures e+ from $\mu^+ \rightarrow e^+\nu\nu$ decay for the period of 33μs (5 x lifetime)

Muon storage magnet and detector

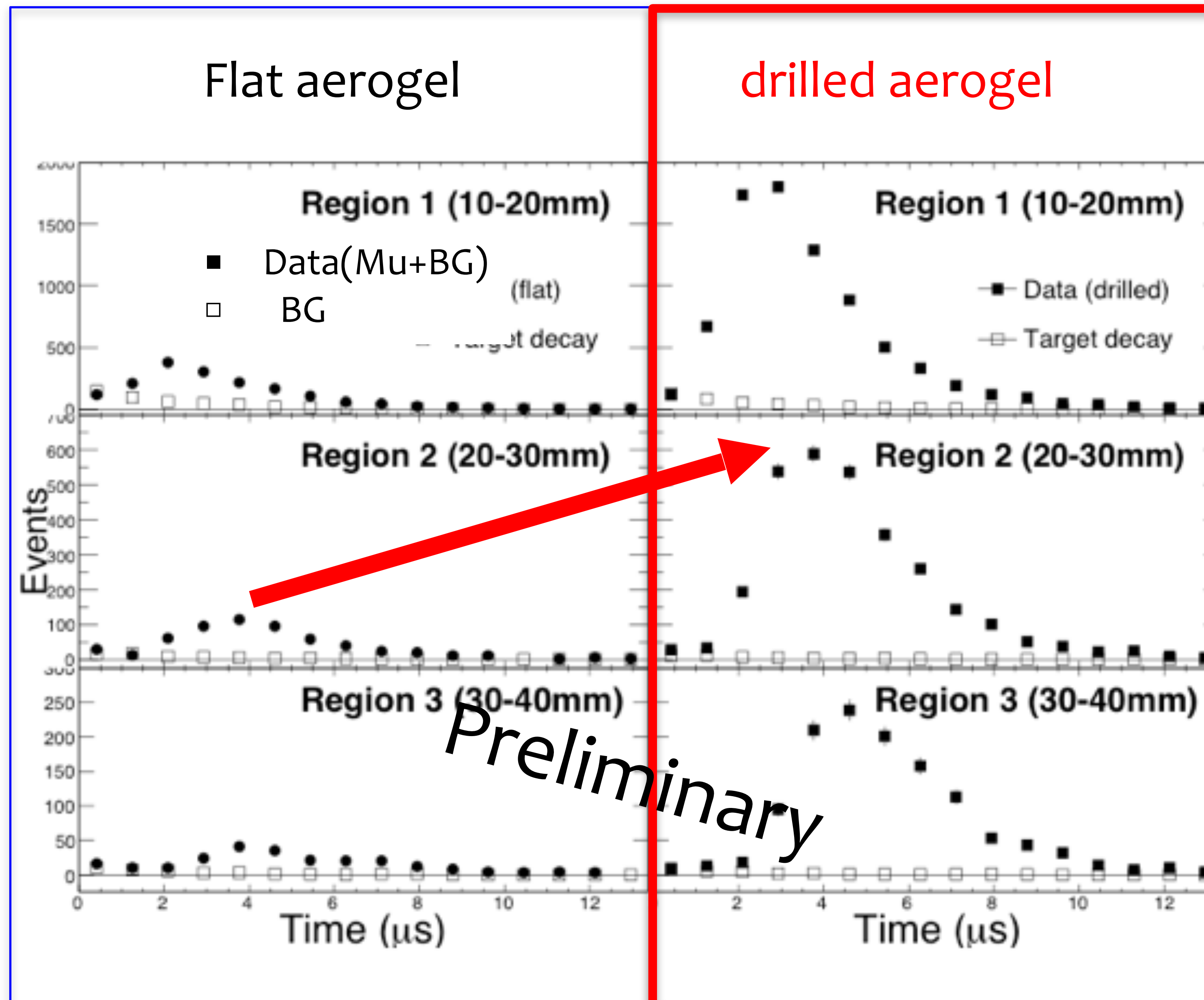


New data with drilled aerogel

Silica aerogel with holes (laser ablation)



Prepared by M. Tabata (Chiba)
and Y. Oishi (RIKEN)

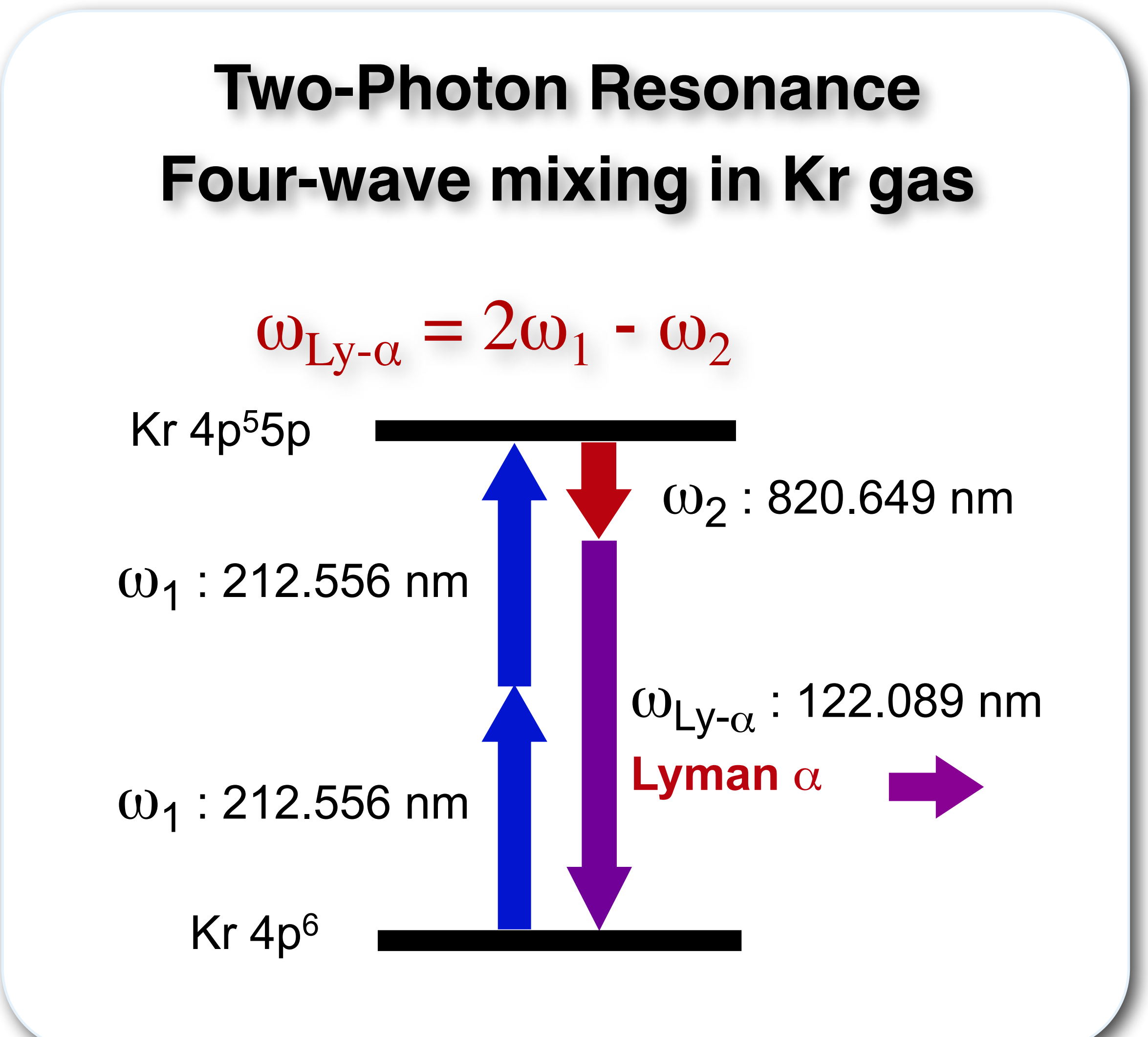


High power Ly-α laser

Center Wavelength: 122.09 nm
(= Mu Lyman-α Line)

Output Energy : 100 μJ
Pulsewidth τ : 2 ns
Bandwidth Δv : 230 GHz (for hot W)
Repetition Rate : 25 Hz

Being developed by RIKEN group



Implication to statistical sensitivity

- With drilled aerogel target, one expects
  - Ultra-cold muon rate : 0.2E+6/sec (*)
  - Running time : 1E+7 sec (120 day)

polarization 100 % 50%

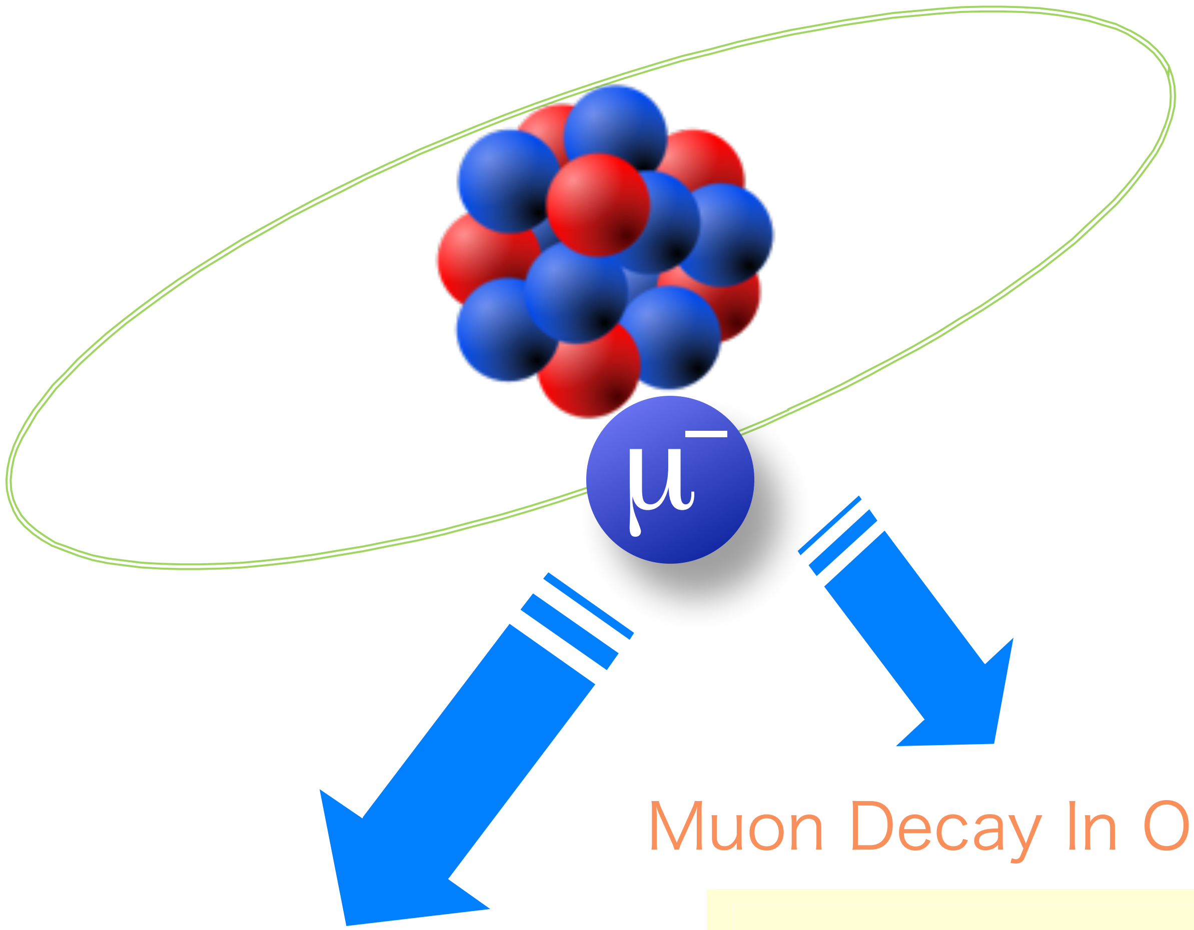
  - Statistical uncertainty on ω_a: 0.22ppm (0.44ppm)
  - Statistical uncertainty on d_μ: 4.4E-21 ecm (8.8E-21 ecm)

Good enough to test BNL E821 g-2 results

* factor of two more muons with SiC target is not included.

Mu-e conversion

mu-e Conversion



Muon Decay In Orbit

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

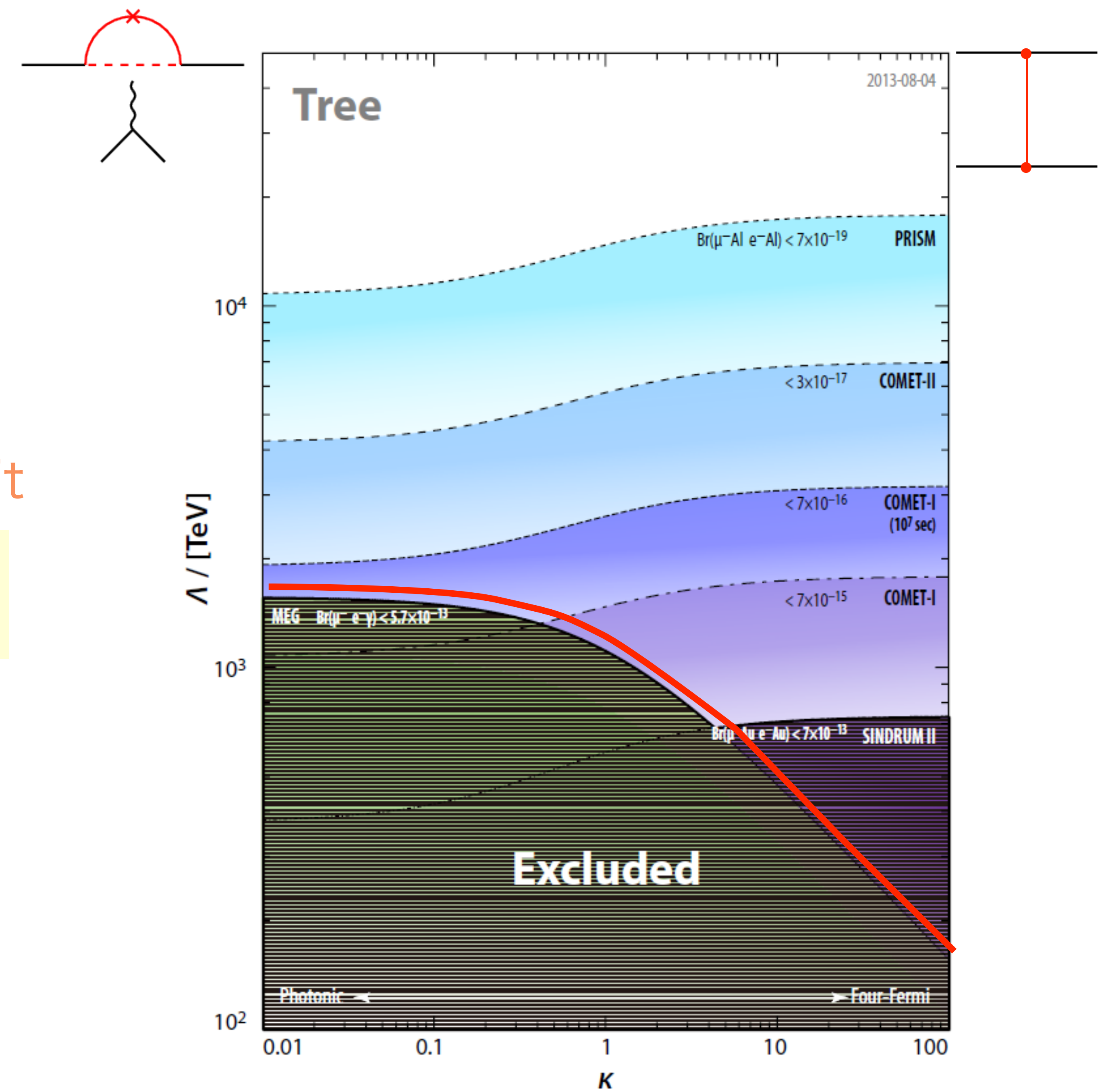
nuclear muon capture

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

μ-e conversion

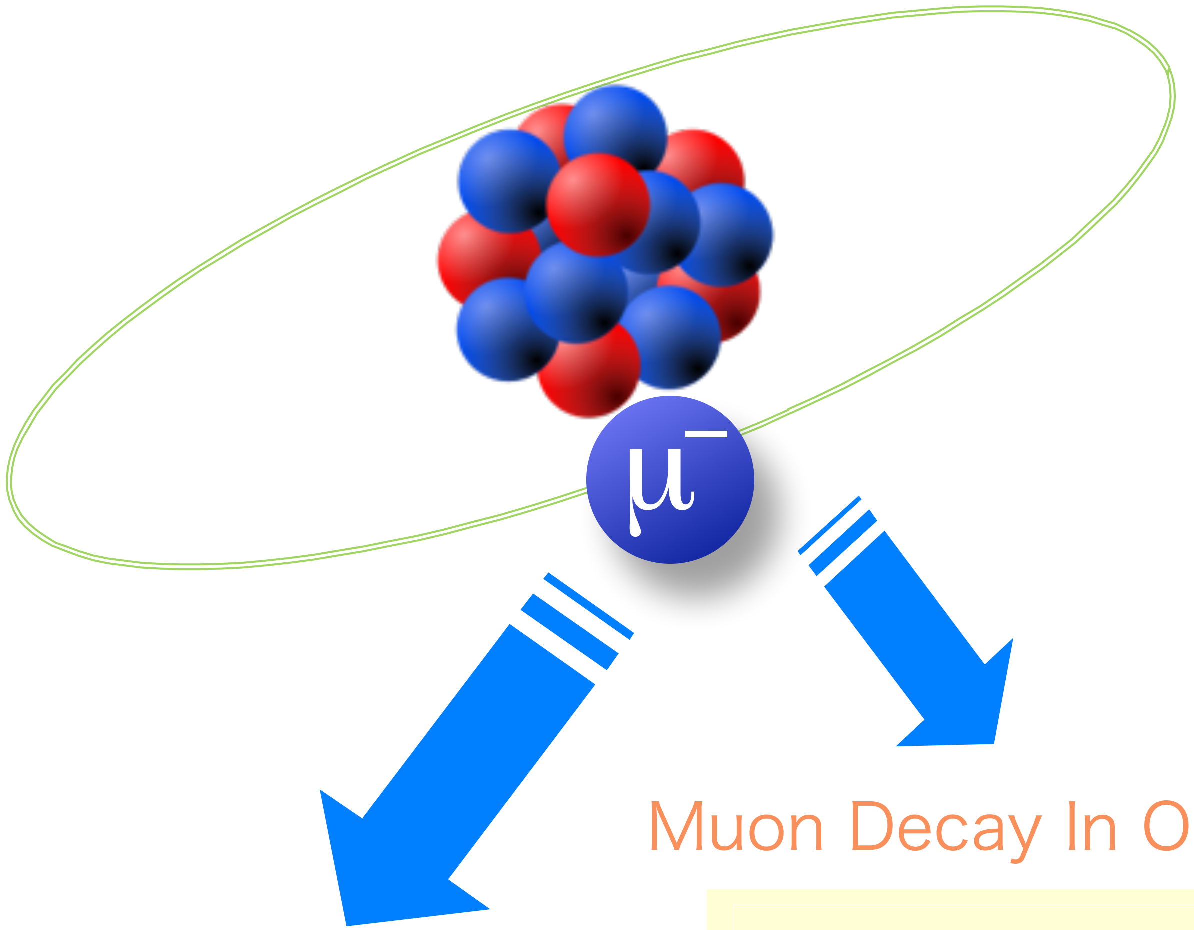
$$\mu^- + (A,Z) \to e^- + (A,Z)$$

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$



Andre de Gouvea, W. Molzon, Project-X WS (2008)

mu-e Conversion



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

Muon Decay In Orbit

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nuclear muon capture

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μ-e conversion

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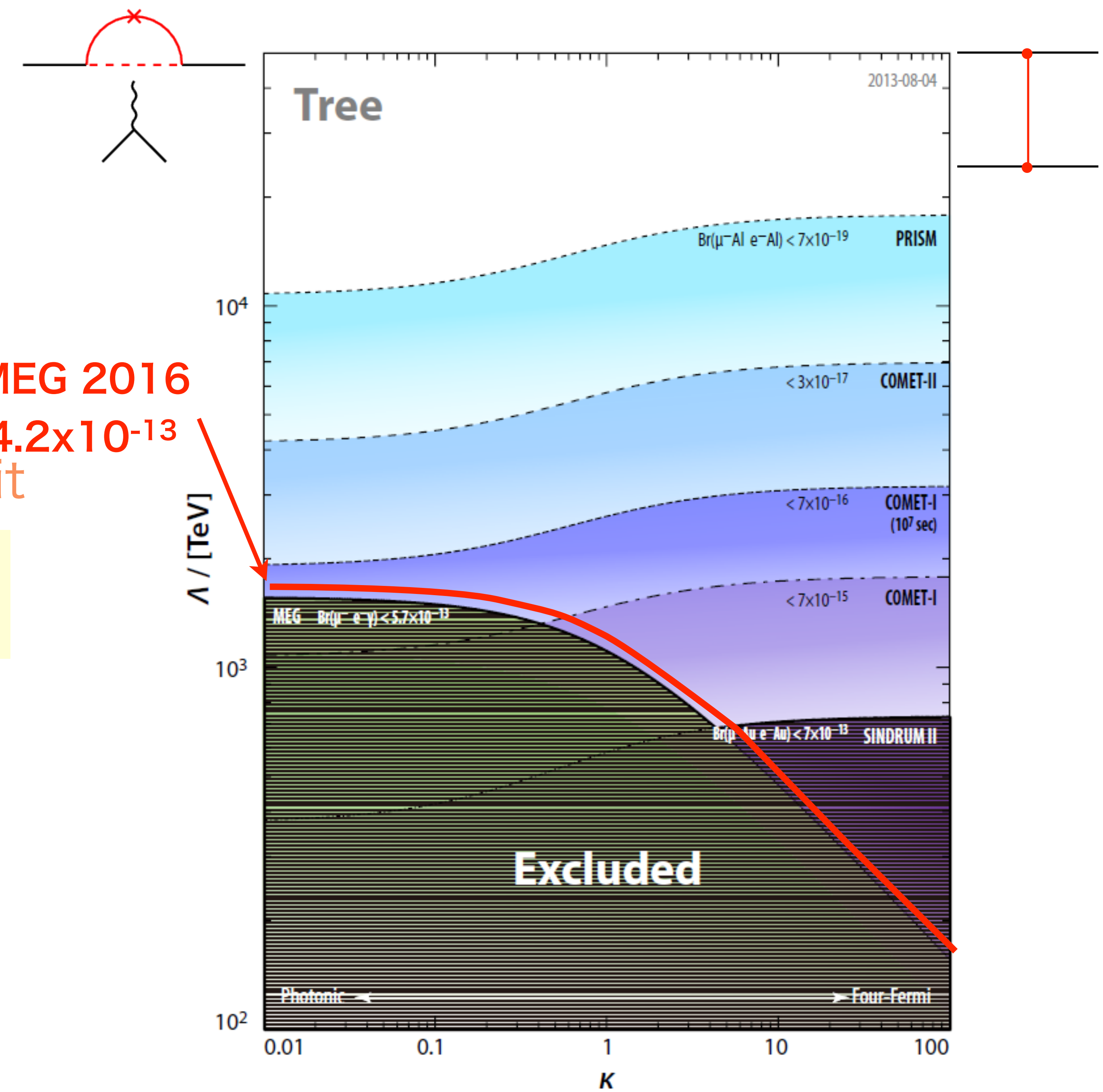
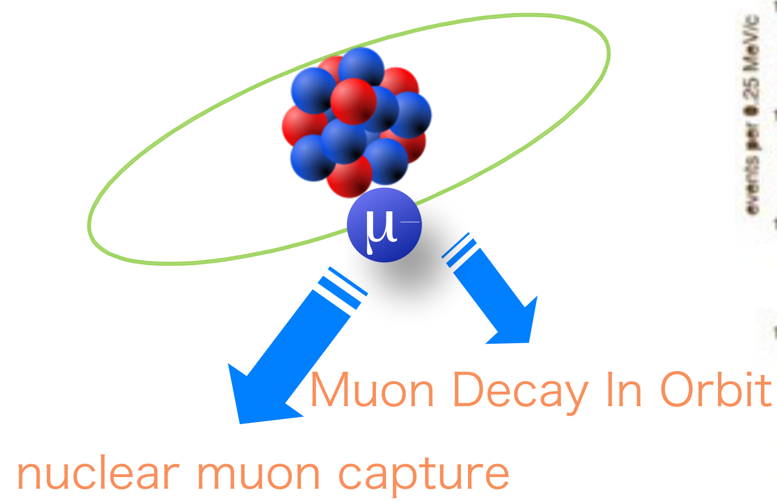
MEG 2016 4.2×10^{-13}



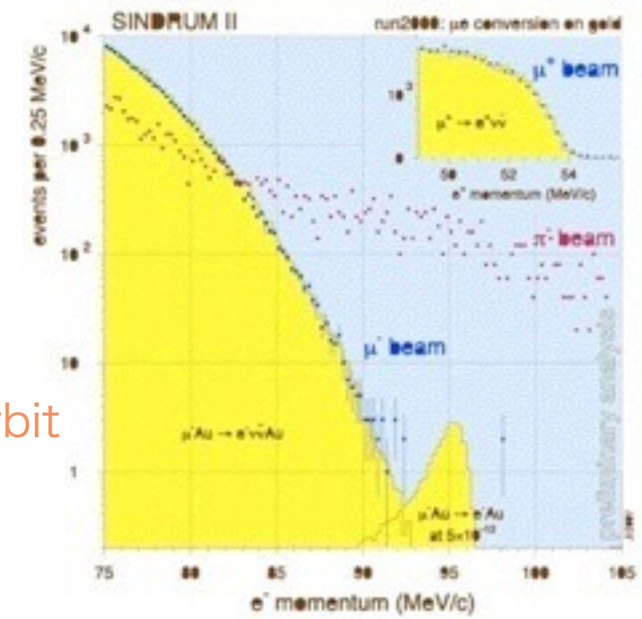
Andre de Gouvea, W. Molzon, Project-X WS (2008)

Experimental Techniques

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - $E_{\mu e} \sim m_\mu - B_\mu$:105 MeV for Al
  - Delayed : ~1 μS
  - No accidental backgrounds

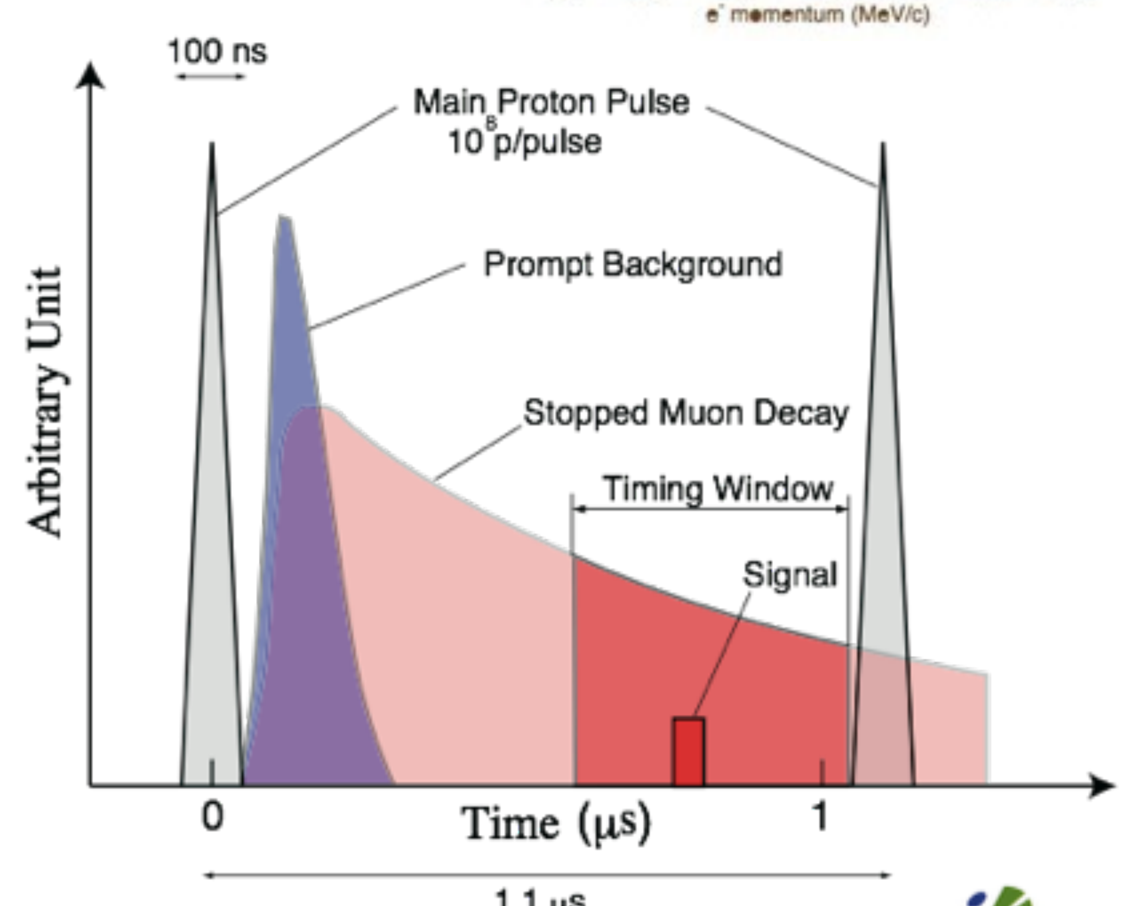


SINDRUM II



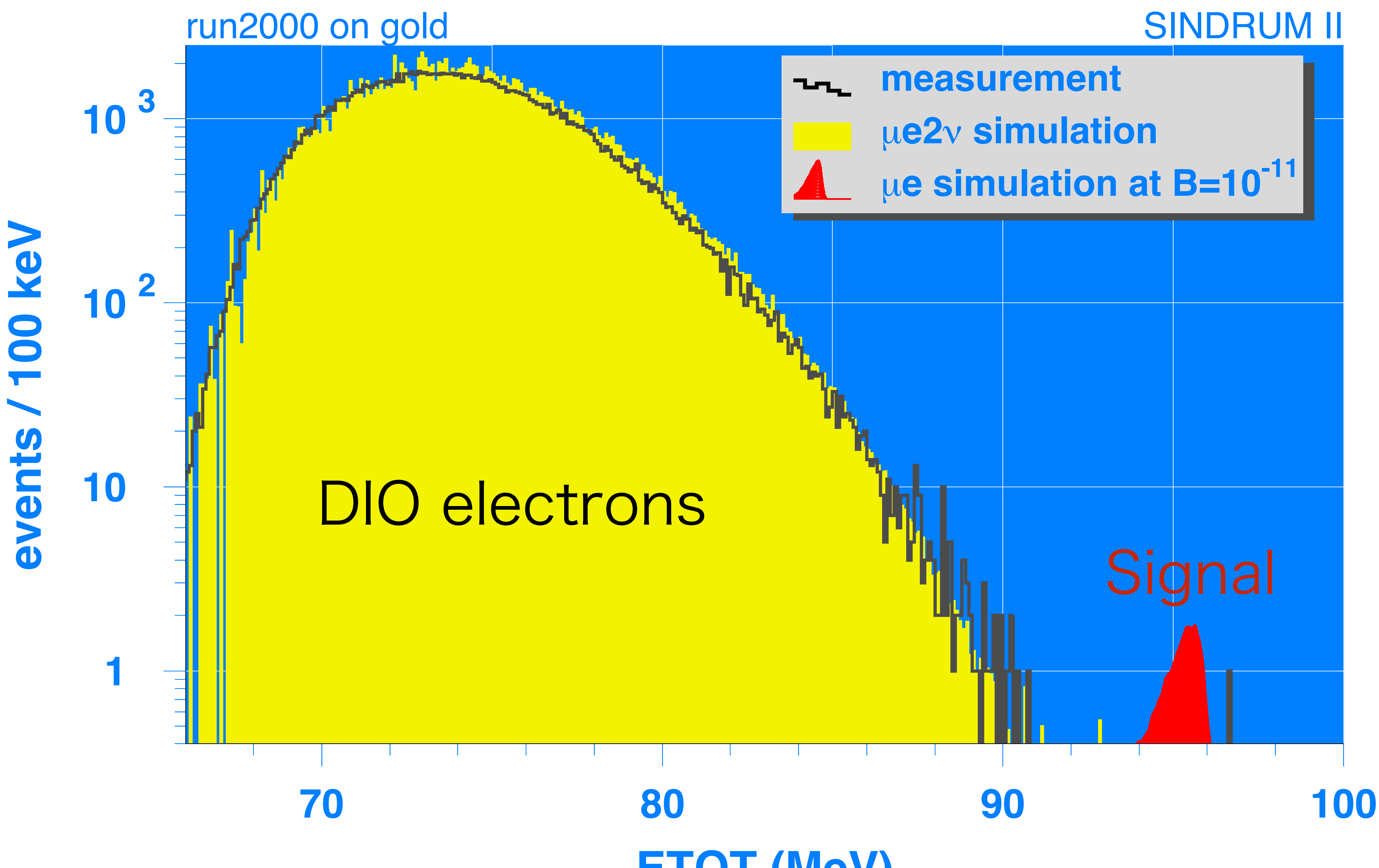
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - E_e > 102.5 MeV (BR:10^{-14})
    - E_e > 103.5 MeV (BR:10^{-16})
  - Beam Pion Capture
  - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$

    $\gamma \rightarrow e^+ e^-$



$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

Electron Energy

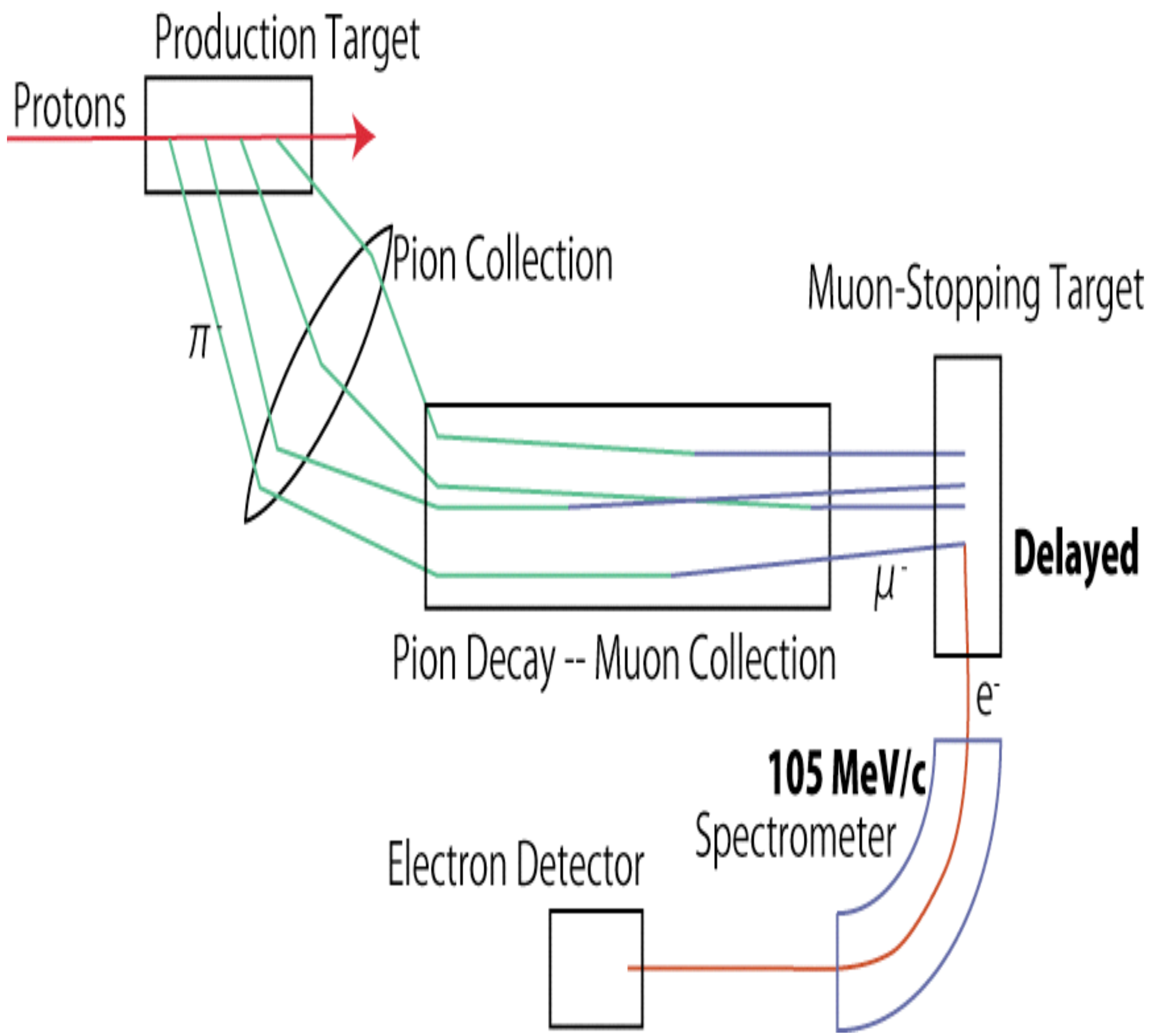


mu-e Conversion Searches at J-PARC

- **DeeMe**
- Intermediate sensitivity : $< 10^{-13}$
- Pion production target as a muon stopping target
- Beam line as a spectrometer

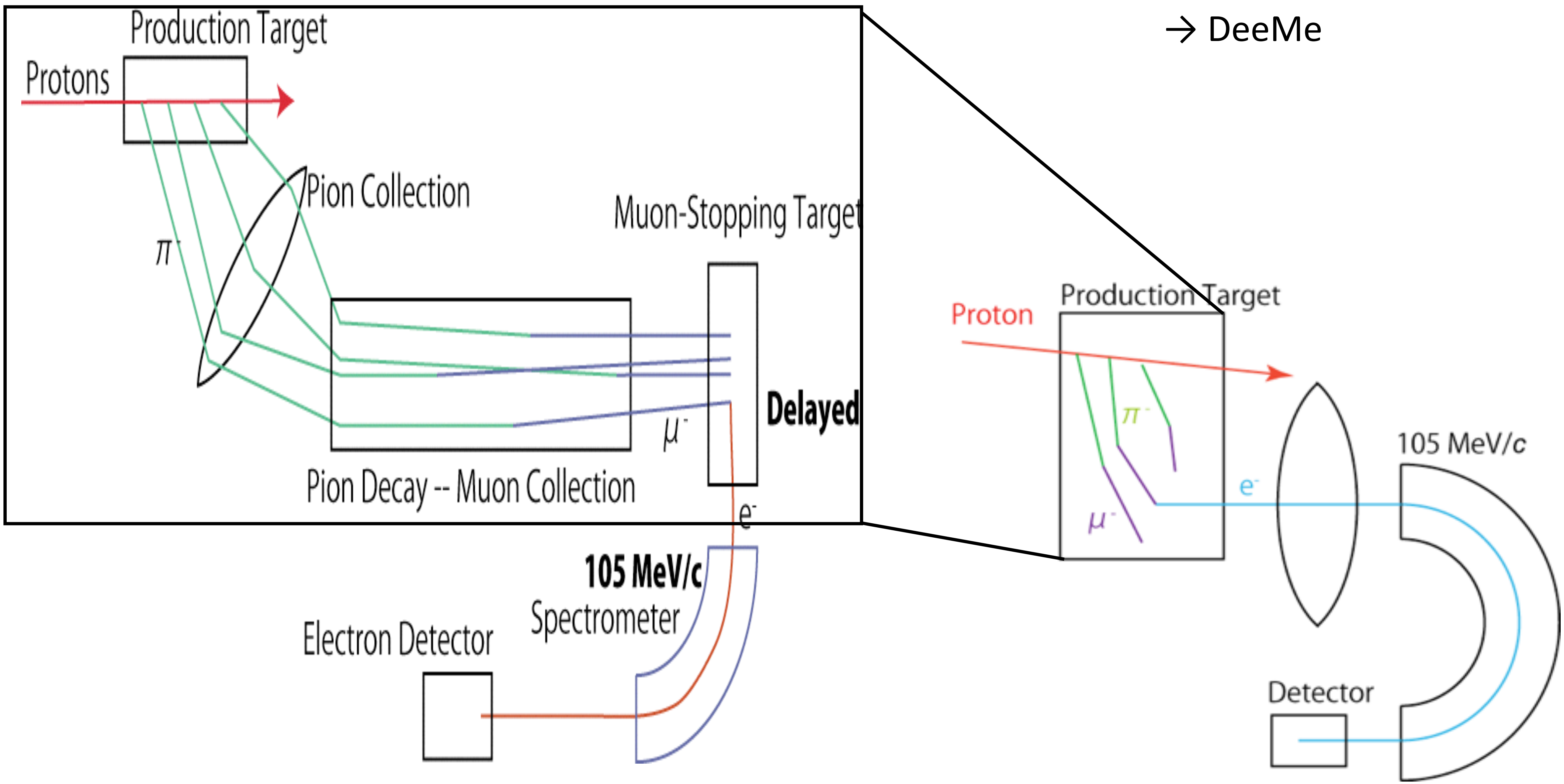
- **COMET**
- Staged approach to reach $< 10^{-16}$ sensitivity
- Phase I : $< 10^{-14}$
- Phase II : $< 10^{-16}$
- Large SC magnet for pion collection, muon transport & electron measurement

Principle of DeeMe



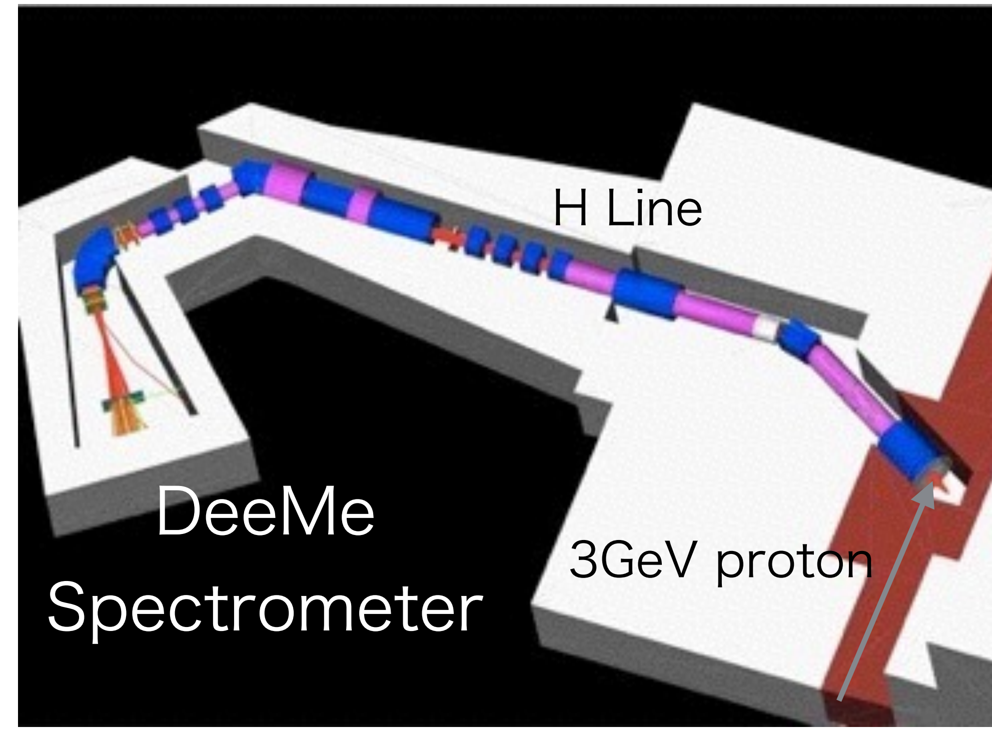
Principle of DeeMe

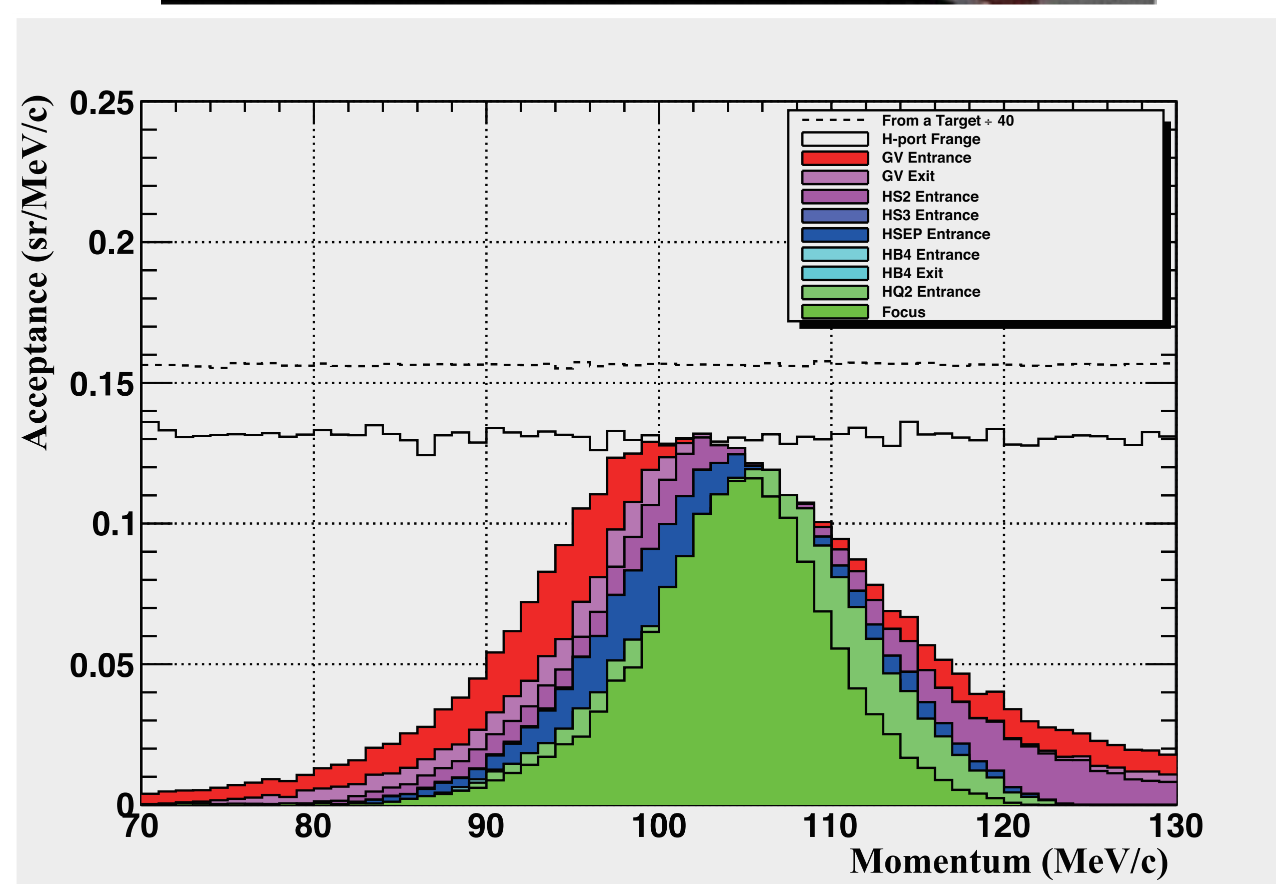
→ DeeMe



DeeMe at J-PARC

- **mu-e conversion search at J-PARC with a S.E.S. of 10^{-14}**
  - Primary proton beam from RCS
    - 3GeV, 1MW
  - Pion production target as a muon stopping target
  - Beam line as a spectrometer
    - Kicker magnets to remove prompt background
  - Multi-purpose beam line for DeeMe, HFS, g-2/EDM is under construction
  - **Engineering run in JFY 2016**

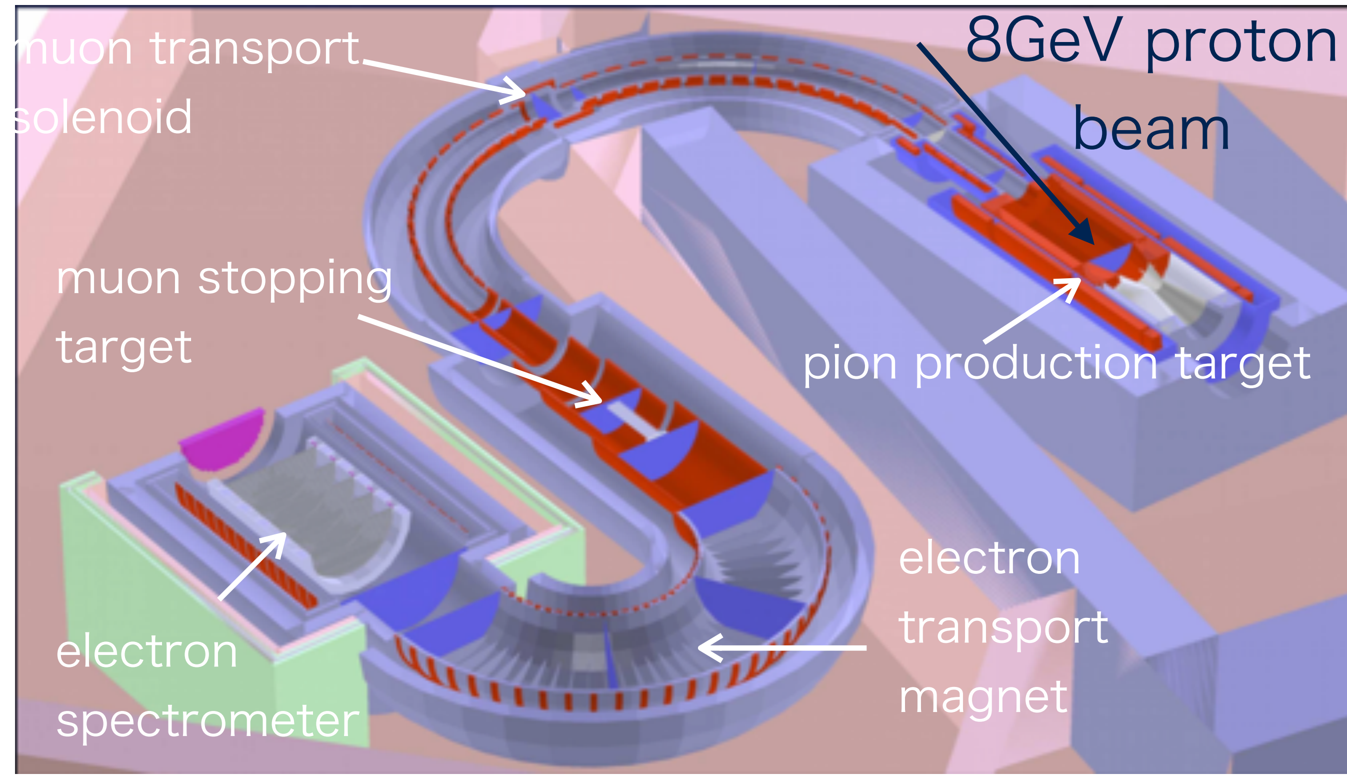


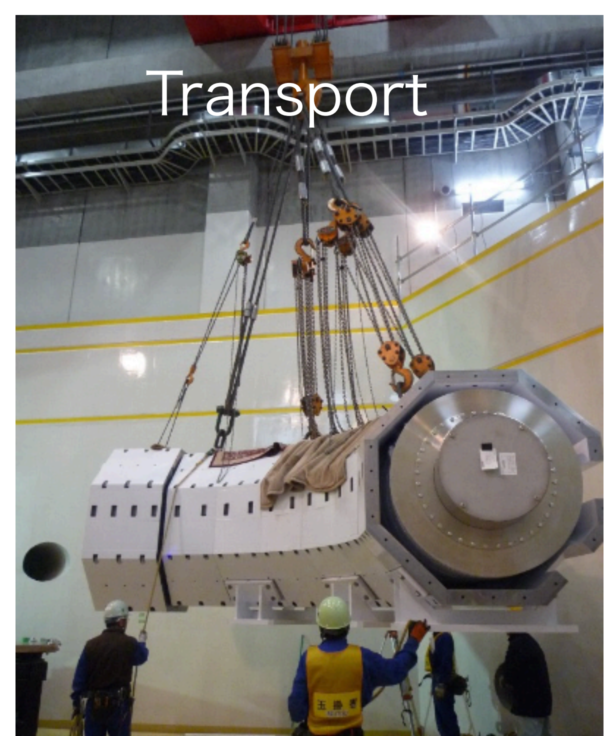


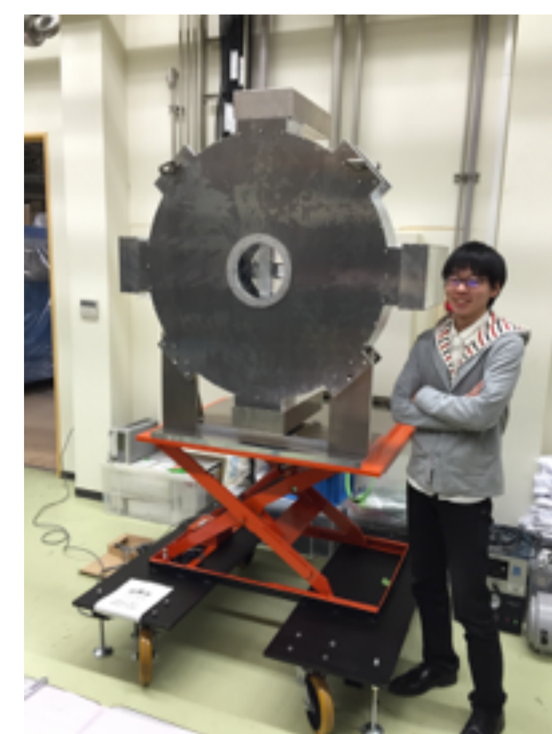
COMET at J-PARC

- **Target S.E.S. 2.6×10^{-17}**

- Pulsed proton beam at J-PARC
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- pion production target in a solenoid magnet
- Muon transport & electron momentum analysis using C-shape solenoids
  - smaller detector hit rate
  - need compensating vertical field
- Tracker and calorimeter to measure electrons
- Recently staging plan showed up. The collaboration is making an effort to start physics DAQ as early as possible under this.

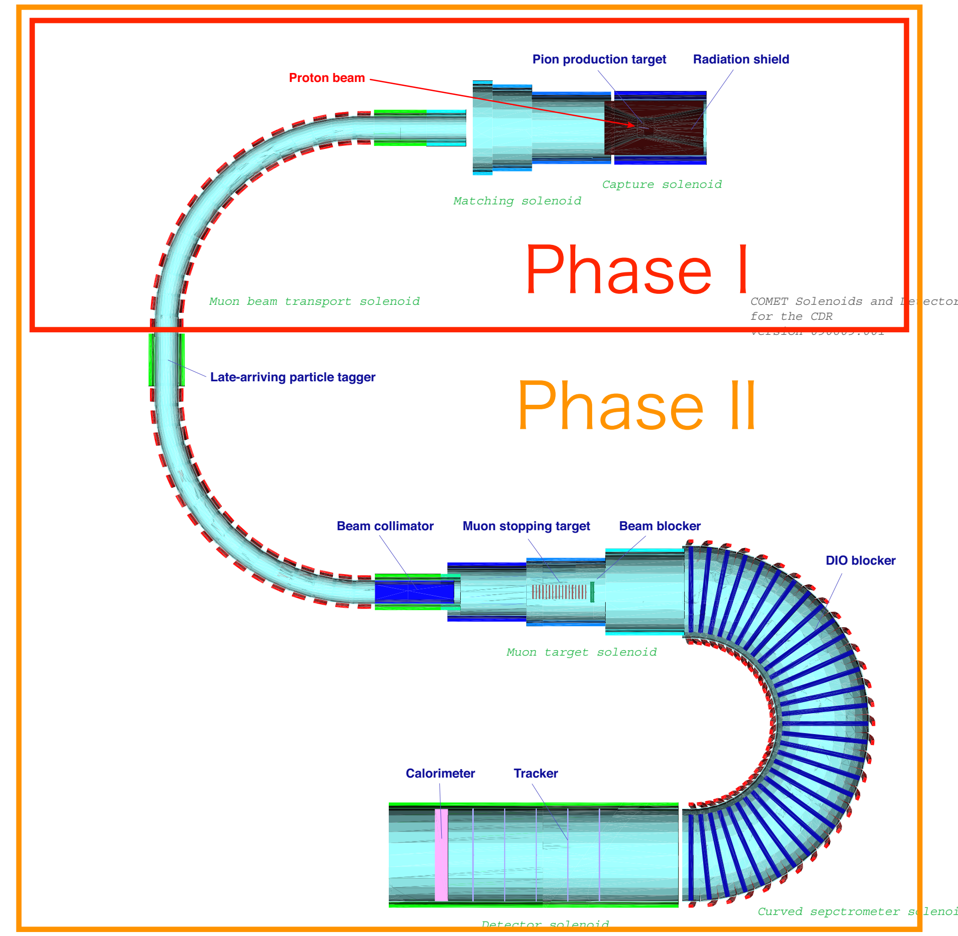






COMET Phase I & II

- Phase I
  - Beam background study, achieve an intermediate sensitivity of < 10^{-14}
  - 8GeV, 3.2kW, 110 days of DAQ
- Phase II
  - 8GeV, 56kW, 1 year DAQ to achieve the COMET final goal of < 10^{-16} sensitivity



<u>Phase I</u>

2013-2018

Facility construction

2013-2019

Magnet construction & installation

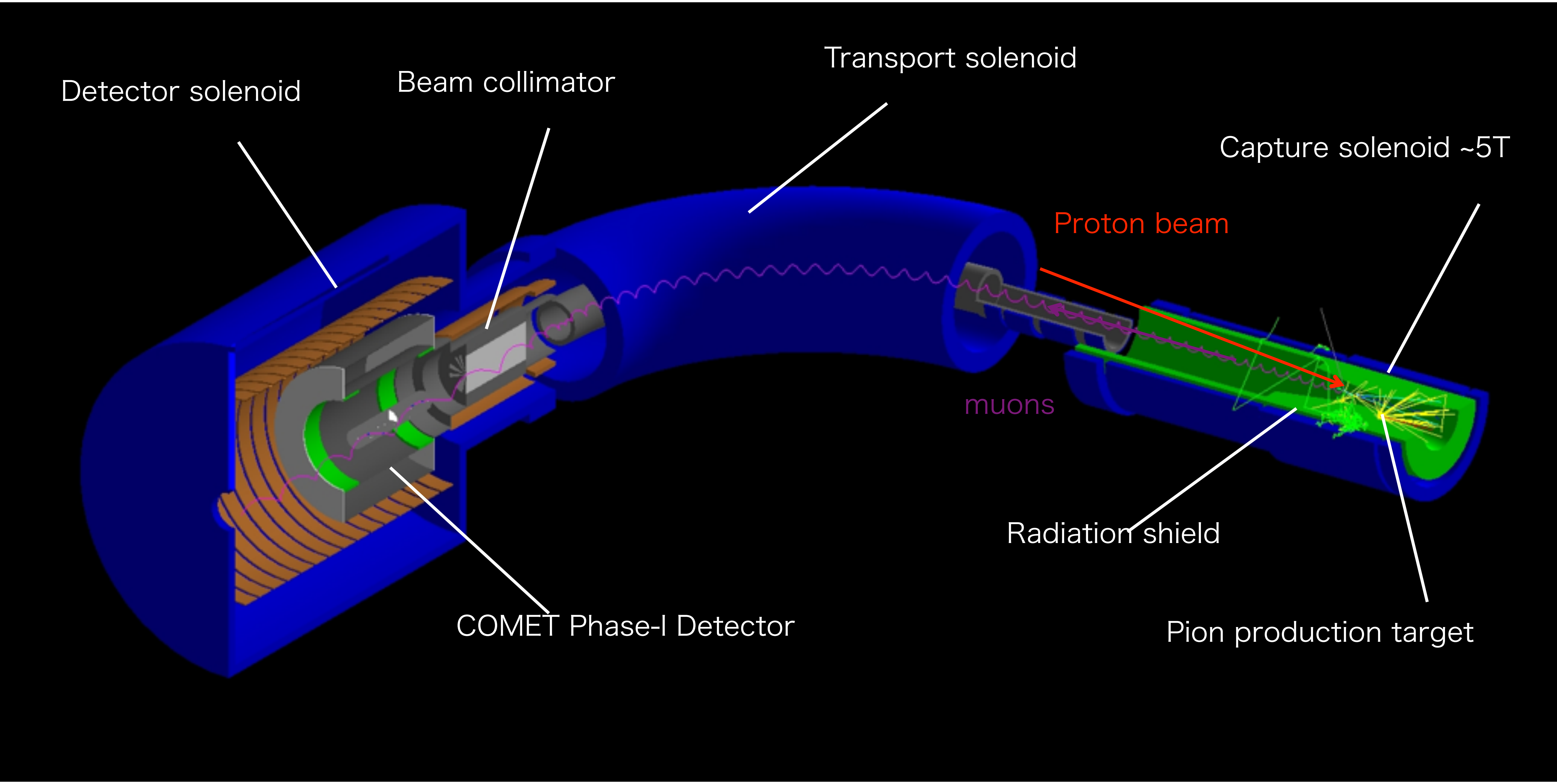
2018-2020

Eng. run & Physics run

<u>Phase II</u>

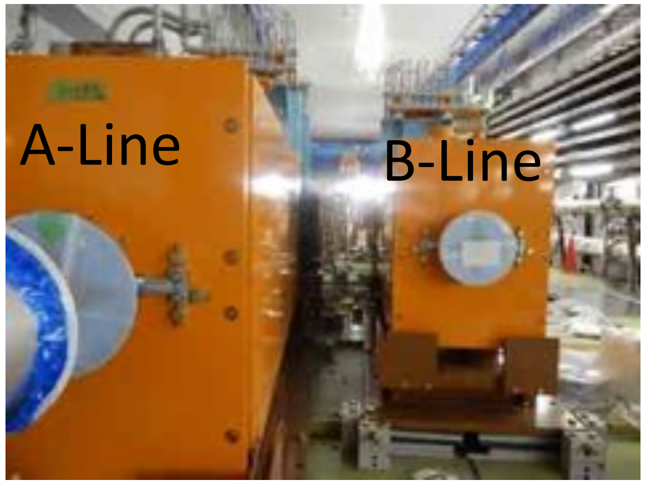
Eng. run in 2022(?)

COMET Phase I

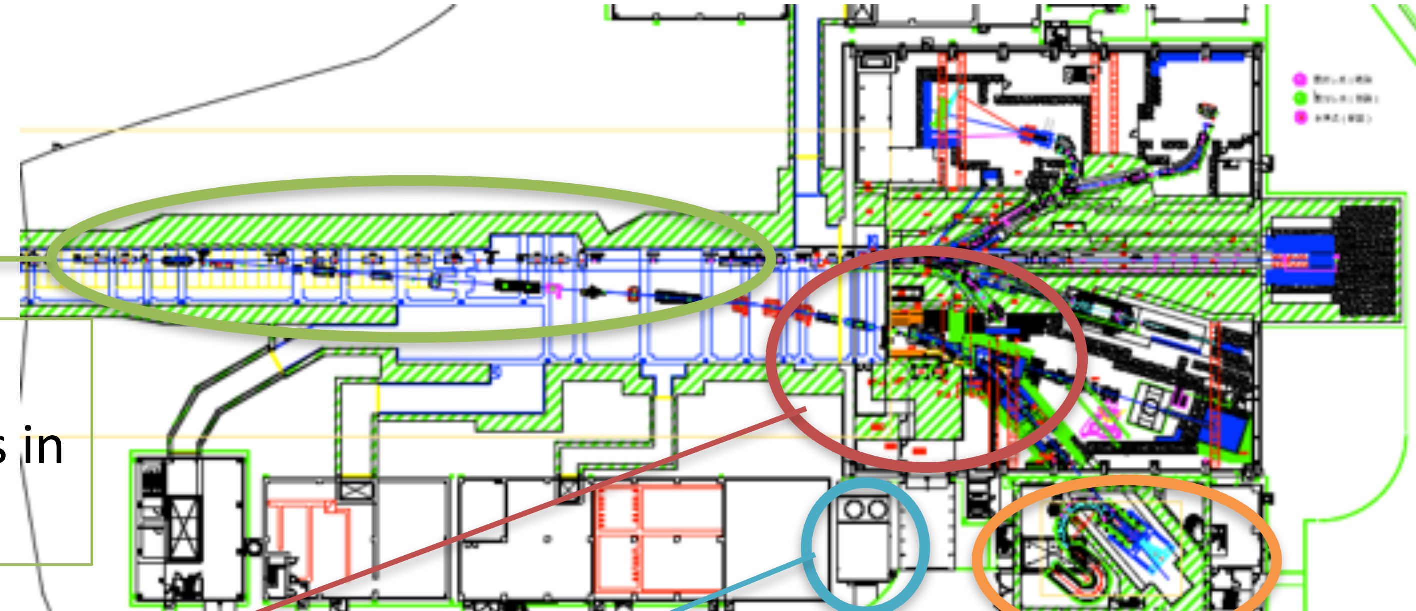


Status of COMET Experiment Facility

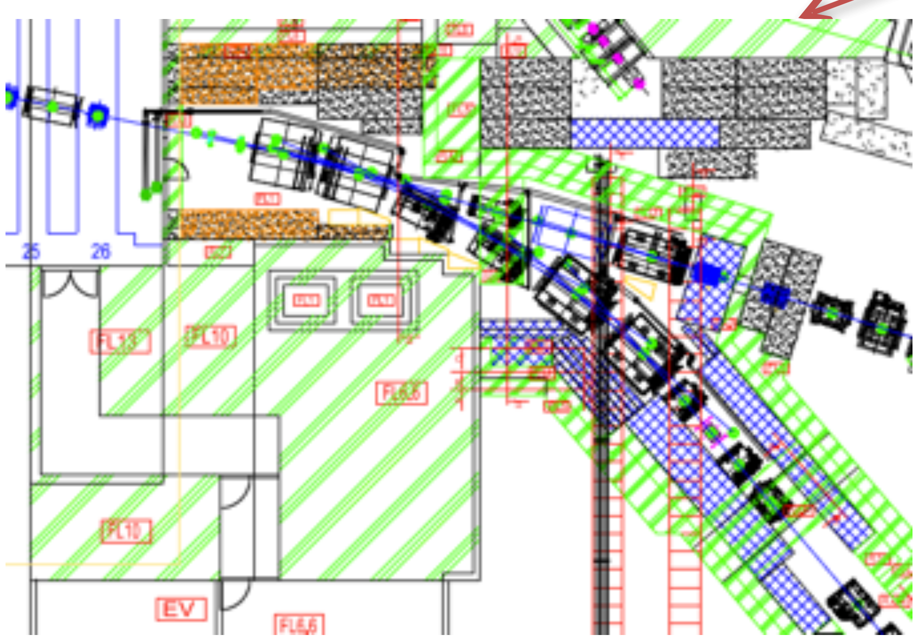
Switch Yard Beamline Elements



Beam line component installation in progress in SY since 2014



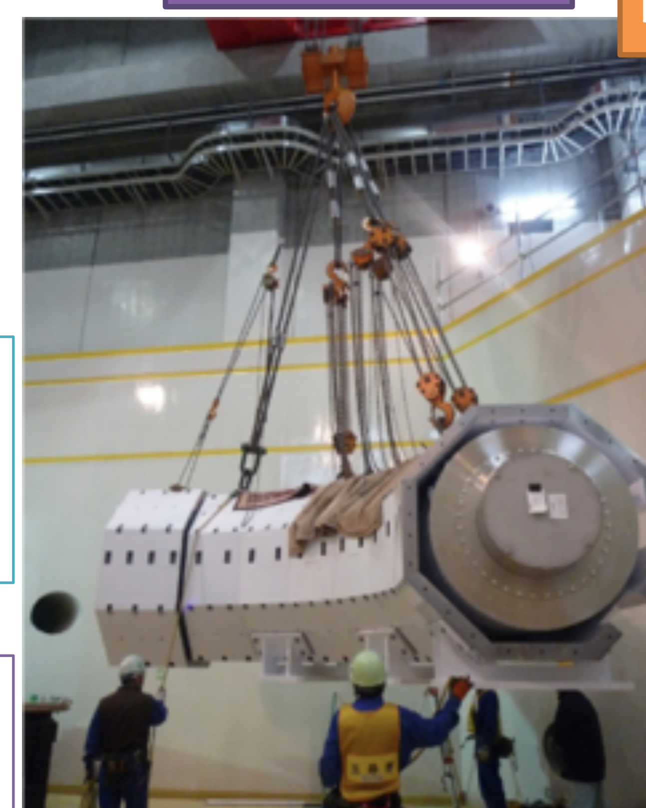
Beam transport line in HD hall



Significant construction work 2016 Summer to connect SY and Hall along the B-Line

He compressor used for E36 will be reused for COMET

SC magnets



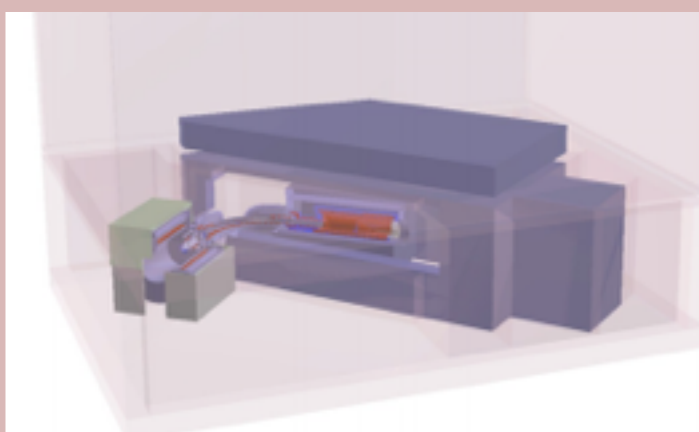
90 deg. Transport Solenoid installed in Spring 2015

Hall construction

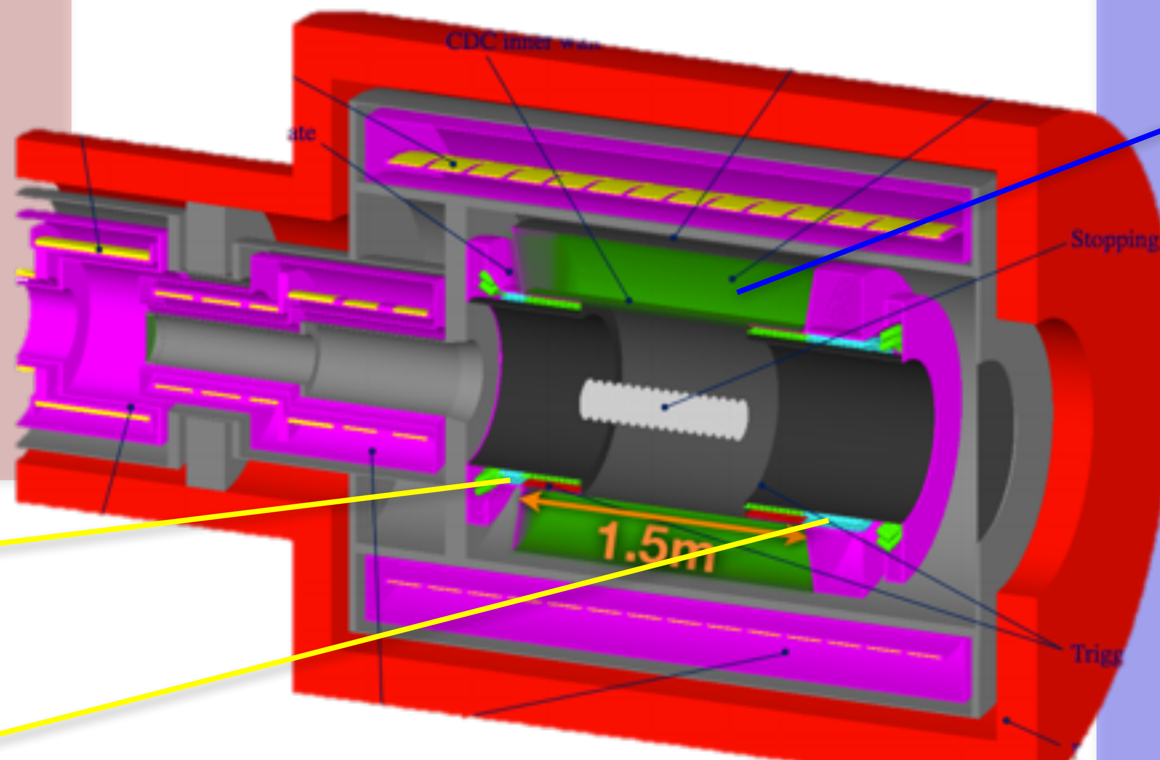
COMET Hall ready in Spring 2015

COMET:Status of Detector Preparation

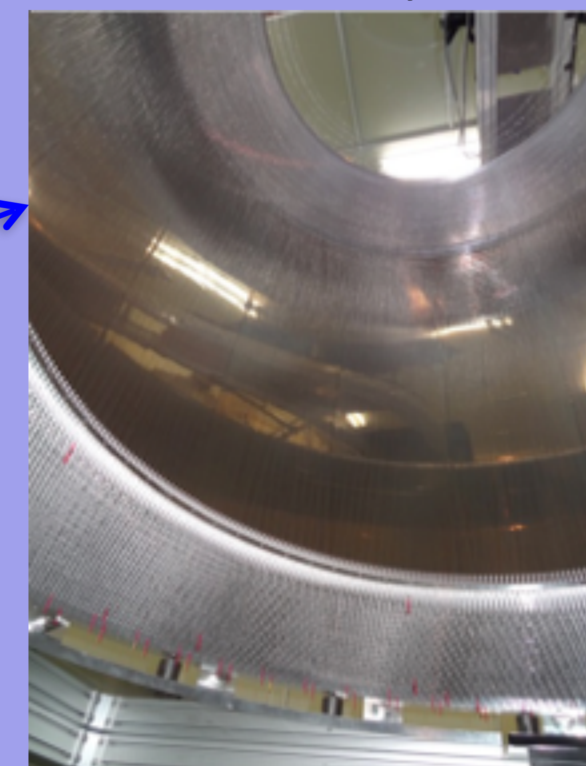
All geometry implemented in the full simulation: ICEDUST



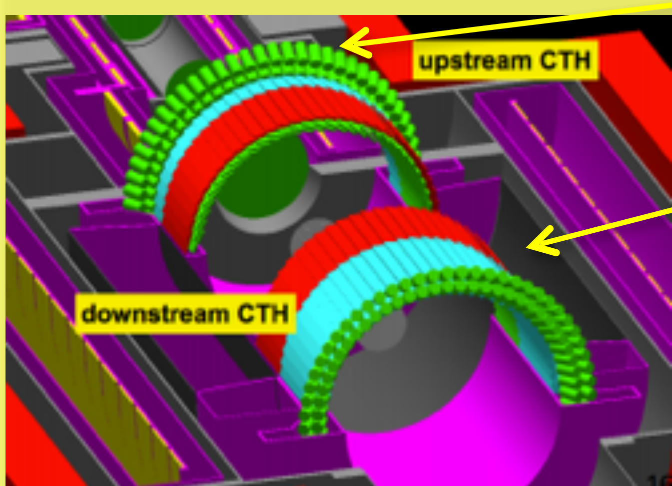
Detector for physics measurement in Phase I

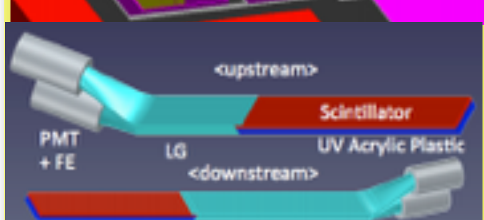


CDC : the main detector of COMET Phase-I Physics



Total ~20,000 wire stringing completed in Nov. 2015 at KEK



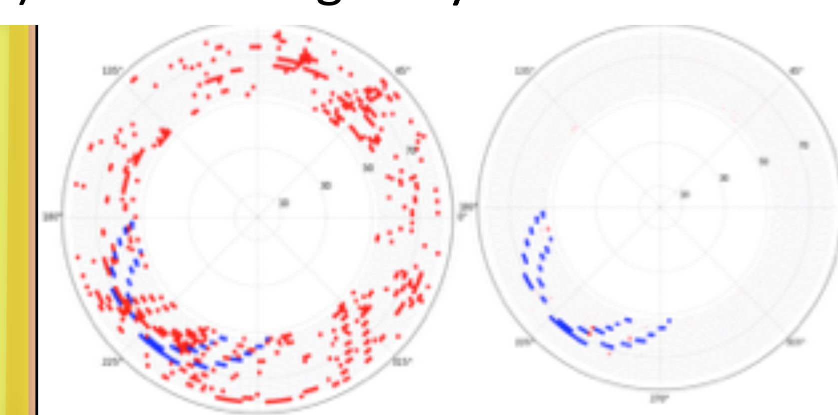


Beam test @ PSI 2015

Trigger Hodoscope Counter

Scintillator + Cerenkov

Analysis algorithm development in progress using simulation data.
ex) track finding in CyDET

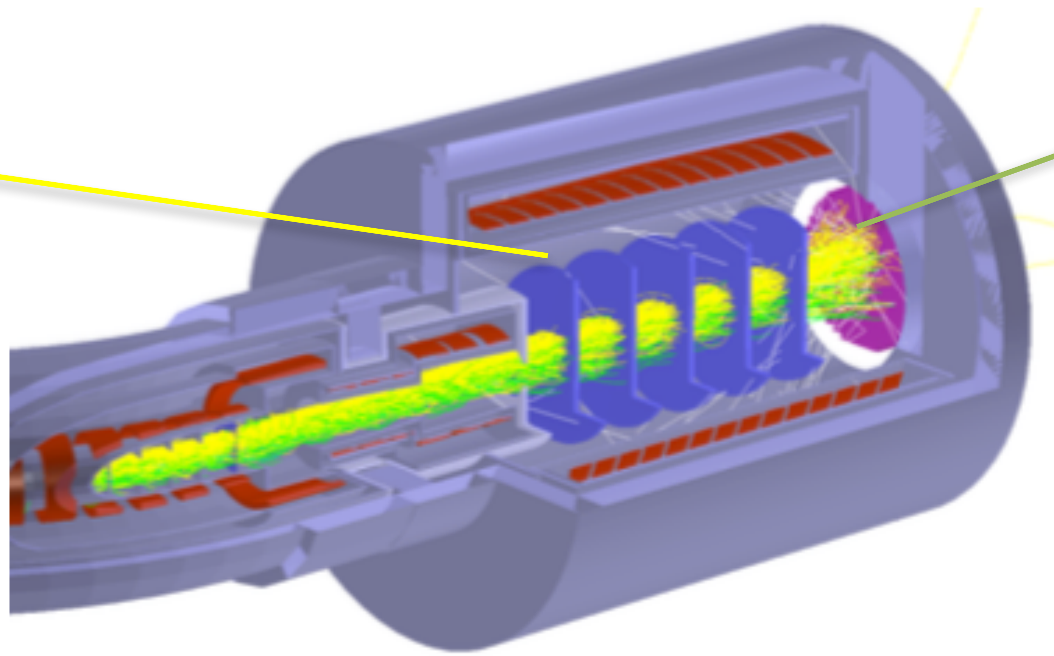


CDC Read Out Electronics RECBE production at IHEP

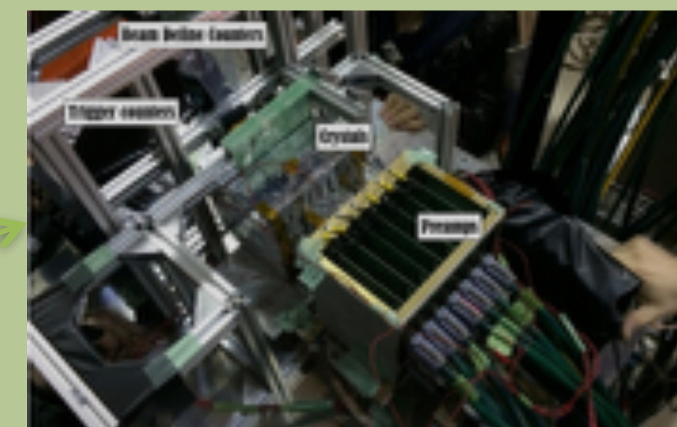
COMET: Detector Preparation Cont'd

Straw tracker (operational in vacuum) prototype

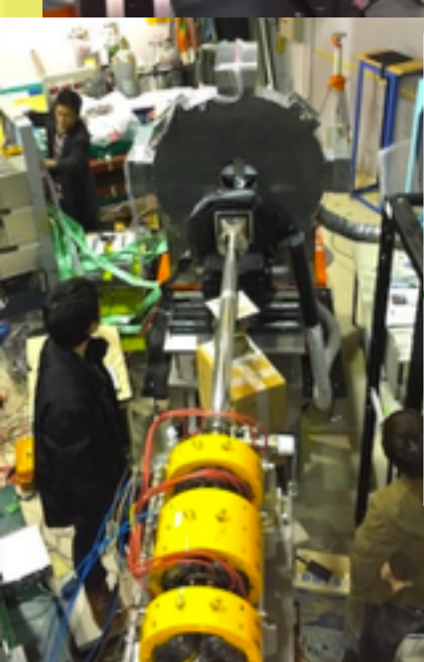
Detector for beam BG measurement in Phase I and physics measurement in Phase II

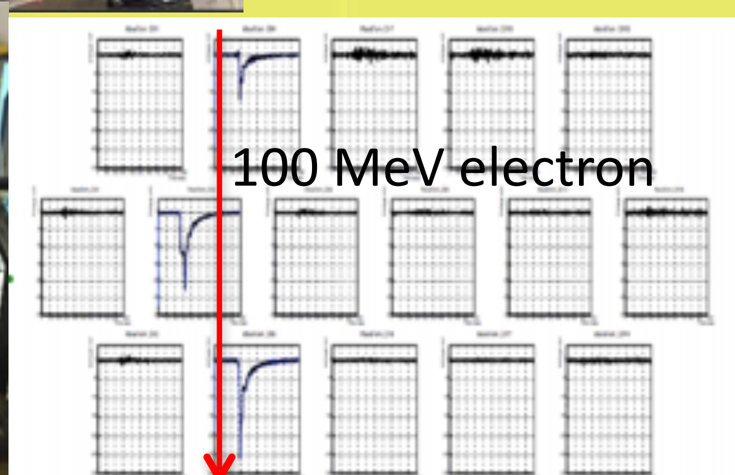


ECal (LYSO) R&D using prototypes



Crystal quality test bench at JINR

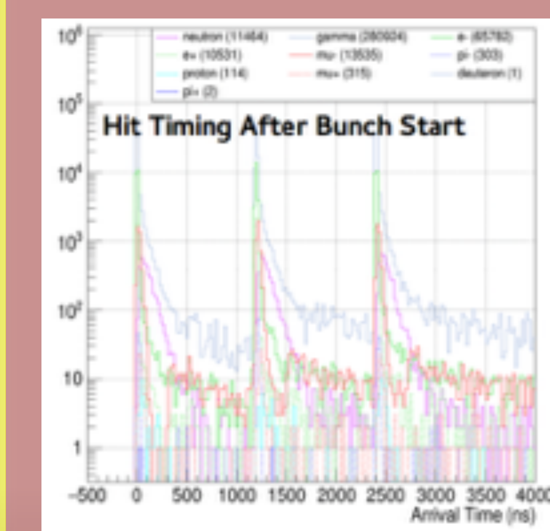


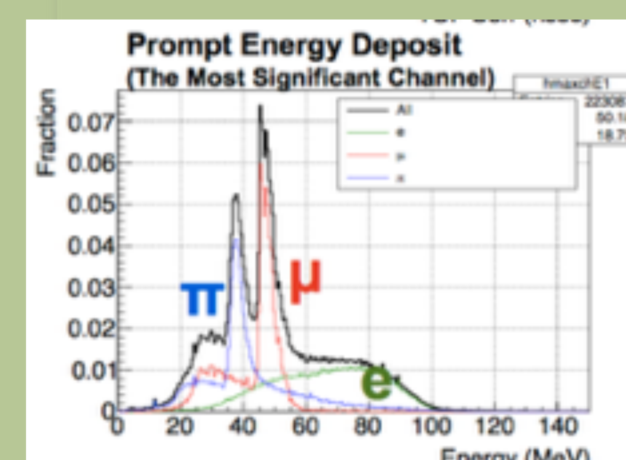


↑Wave form taken in the test

← Electron beam test at ELPH

Ecal Pile-up study using simulation data





Ecal PID performance evaluation at PSI 2015

Summary

- Muon as a tool to investigate physics beyond the Standard Model
- High power proton accelerator at J-PARC
  - High intensity muon beam
- Muon physics program at J-PARC
  - New measurement of muon g-2/EDM
  - mu-e conversion experiments