J-PARCでの
μ-e転換過程探索実験
--- PRISM/Phase-1 ---

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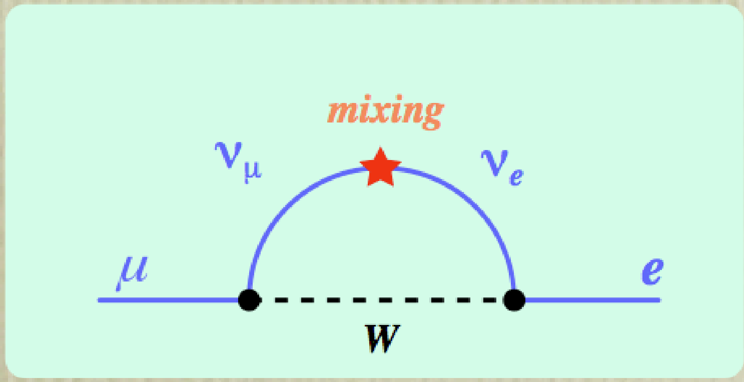
東京大学ICEPP, 2007/11/06

内容

- イントロダクション
  - Lepton Flavor Violationの理論
  - μ-LFV実験 (SIMDRUM II)
- μ-e転換過程探索実験
  - MECO, mu2e and PRISM/Phase-1
  - PRISM/Phase-1 @ J-PARC
- まとめ

Lepton Flavor Mixing

- Quark Mixing : Kobayashi-Maskawa Matrix
- Neutrino Mixing : Maki-Nakagawa-Sakata Matrix
- charged Lepton Mixing : not-yet-observed
  - charged Lepton Flavor Violation (c-LFV)
  - Neutrino-mixing predicts very small amount of c-LFV via higher order diagram; it is as small as practically impossible to observe in foreseeable future.



$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U^*_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \simeq 10^{-60} \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}} \right)^4$$

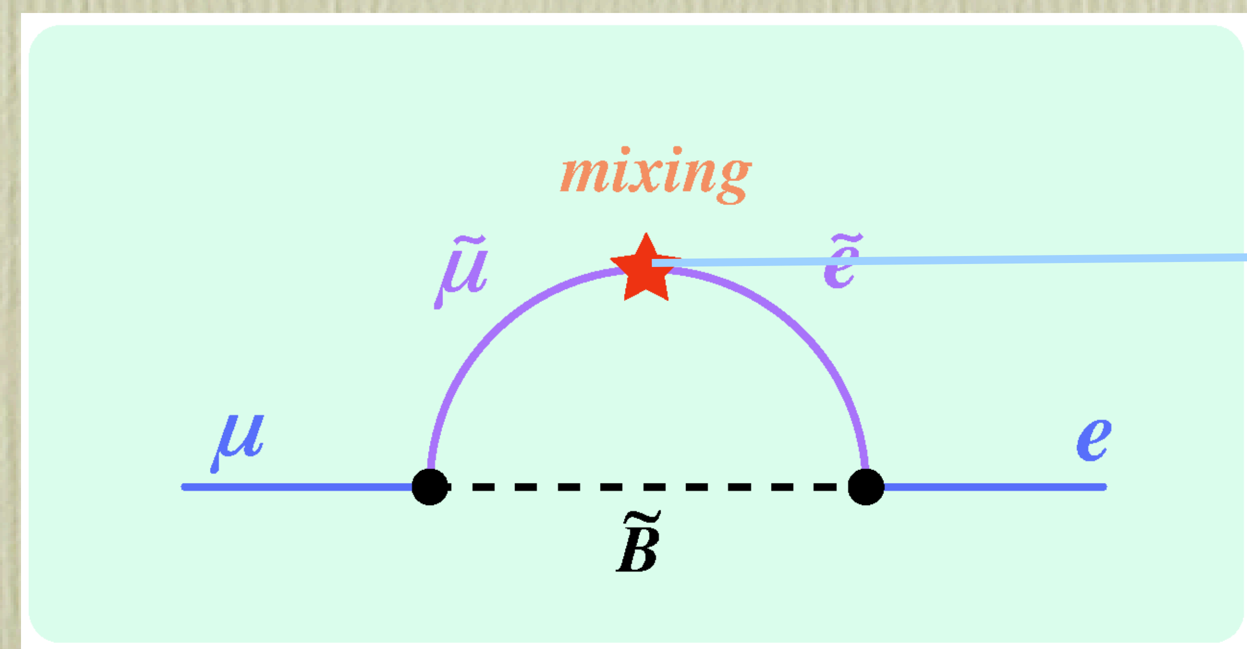
A. de Gouvea

- c-LFV = Physics beyond SM

c-LFVと超対称性

c-LFV ⟷ slepton mixing

SUSY

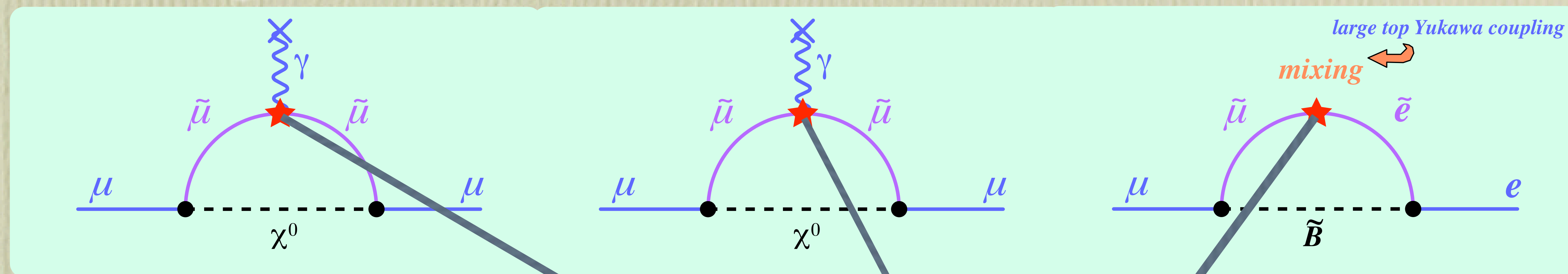


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Physics of slepton mass matrix

Golden Trio

g-2 | EDM | c−LFV



Real | Imaginary

slepton mass matrix
$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

τ-LFV

Slepton Mixing Mechanism

$$(m^2_{\tilde{l}})_{ij} = m_0^2 \delta_{ij}$$

@ Plank mass scale

SUSY-GUT

GUT Yukawa interaction

SUSY Seesaw Model

Neutrino Yukawa interaction

$$(\Delta m^2_{\tilde{l}})_{ij} \neq 0$$

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 \underline{\underline{V_{td}^* V_{ts}}} \ln \frac{M_{GUT}}{M_{R_S}}$$

Quark mixing matrix

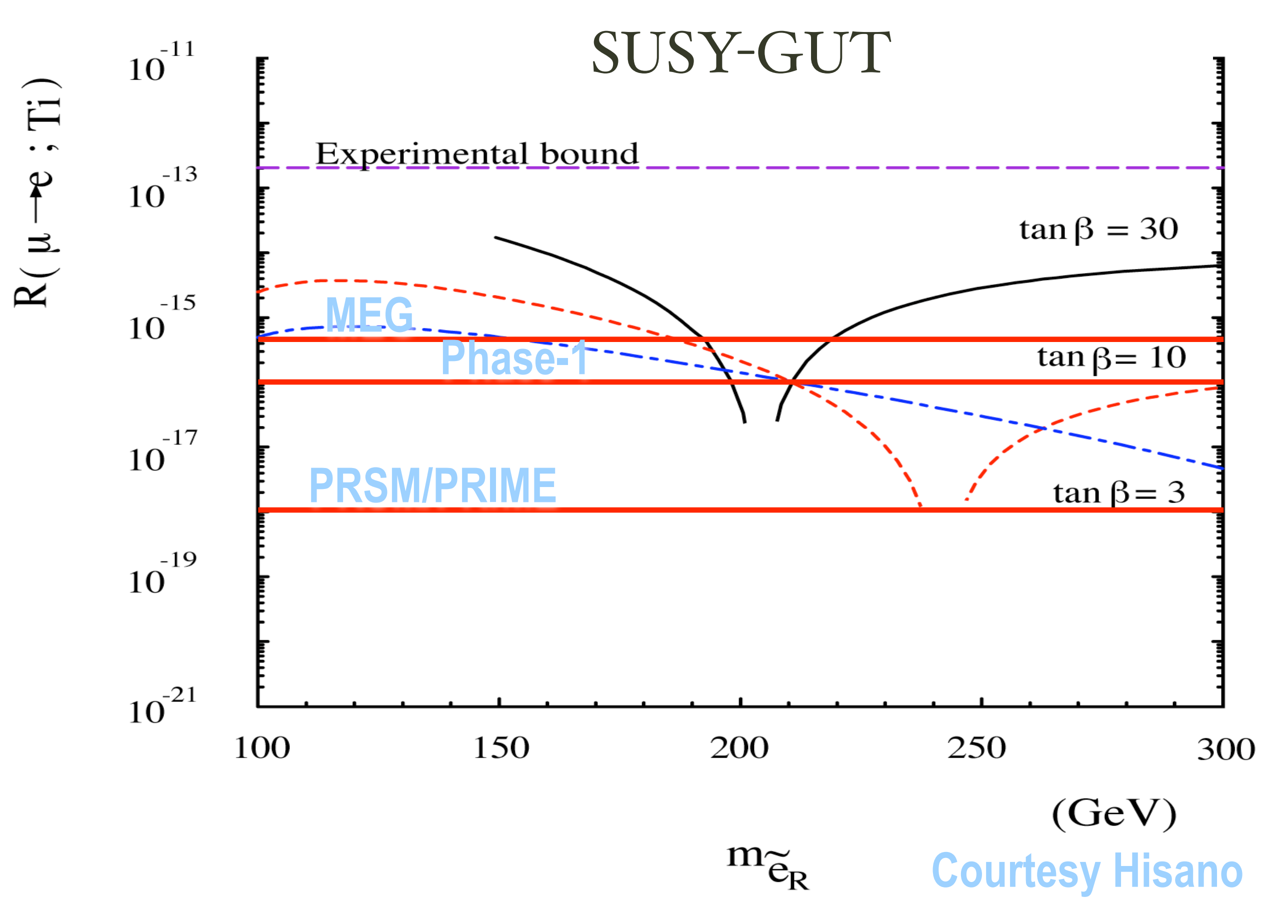
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_i^2 \underline{\underline{U_{i1}^* U_{i2}}} \ln \frac{M_{GUT}}{M_{R_S}}$$

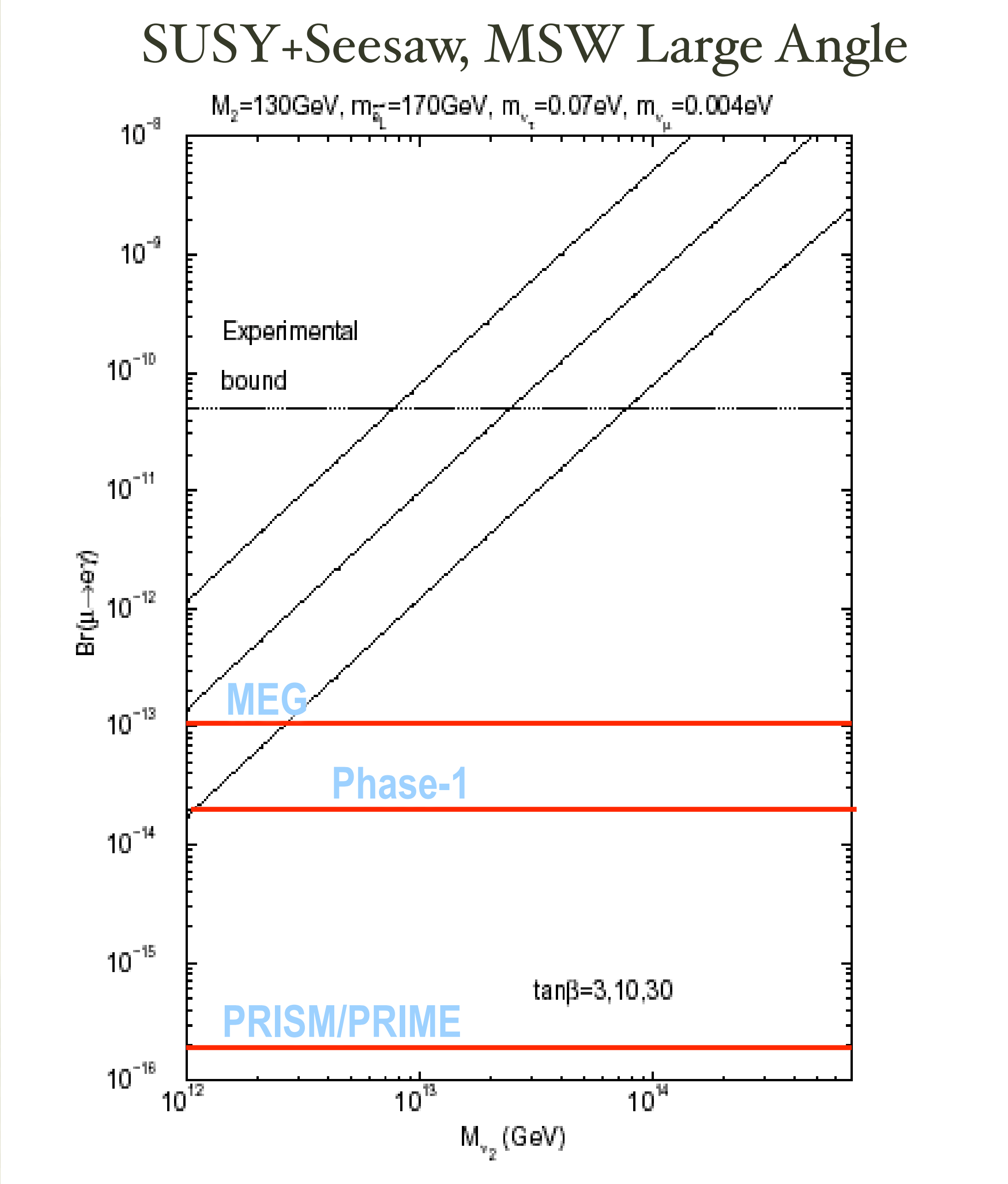
Neutrino mixing matrix

PRISM/Phase-1 LoI (2006)

Theoretical Predictions

Process	Current Limit	SUSY-GUT level	Future
$\mu N \to e N$	10^{-13}	10^{-16}	$10^{-16}, 10^{-18}$
$\mu \to e \gamma$	10^{-11}	10^{-14}	10^{-13}
$\tau \to \mu \gamma$	10^{-6}	10^{-9}	10^{-8}

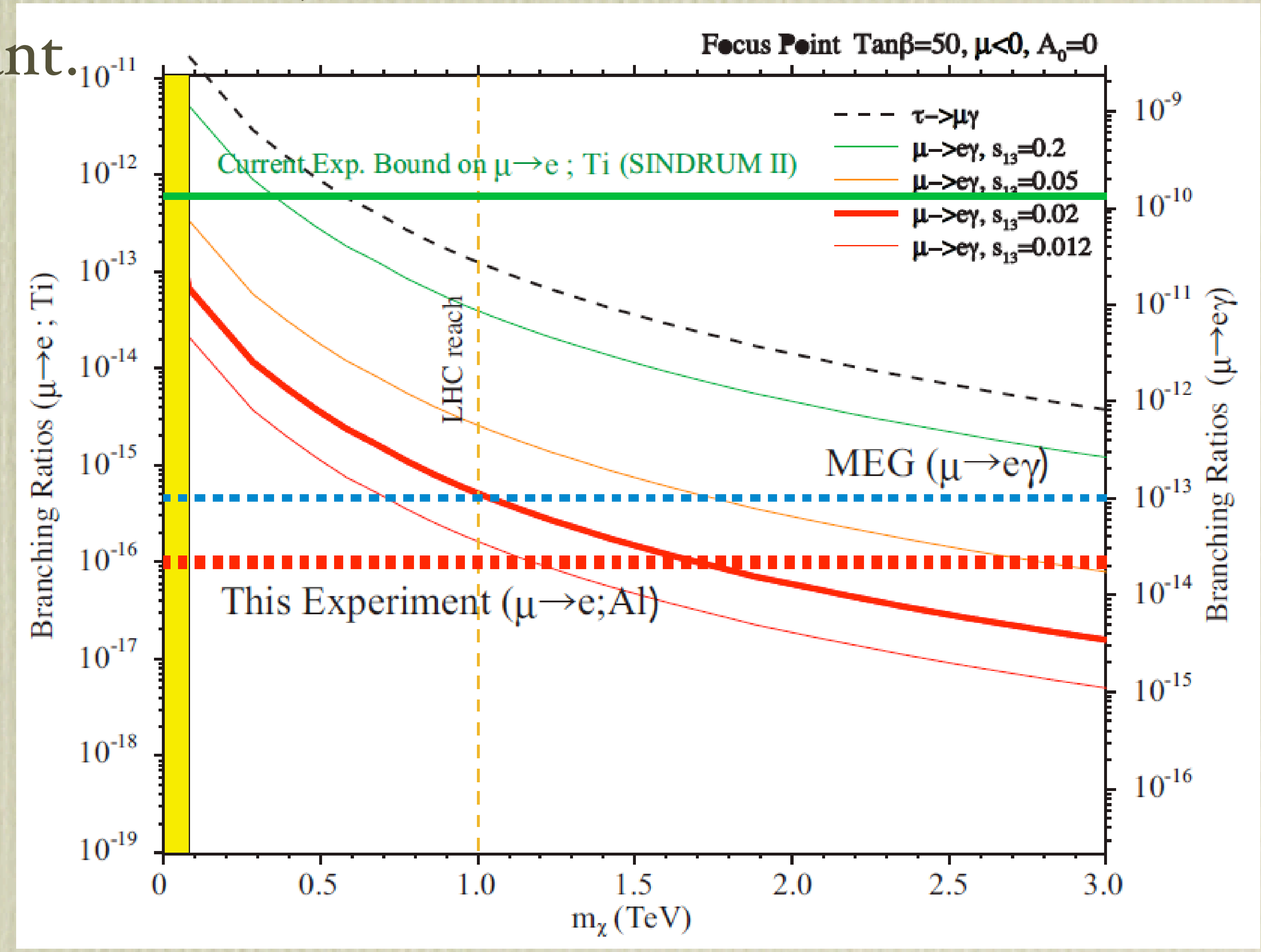




LHC and c-LFV

- if LHC finds SUSY particle
  - Physics of slepton mass matrix will be strengthened.
  - Further exploration of SUSY structure (SUSY-GUT, SUSY-Seesaw) will become more important.

- if LHC does not find SUSY particle
  - high-intensity exp. comes forefront.



L. Calibbi, A. Faccia, A. Masiero, S.K. Vempati, PRD74(2006)116002

μ-LFV

$\mu \to e\gamma$

$\mu \to eee$

$\mu N \to eN$

μ→eγ, μ→eee, μN→eN

c-LFVの一般的なラグランジアン

(A. de Gouvea, talk at Nufact'06)

photonic

$$\mathcal{L} = \frac{m_\mu}{\Lambda^2}\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{1}{\Lambda_F^2}(\overline{\mu_L}\gamma^\mu e_L)(\overline{e_L}\gamma_\mu e_L) + \frac{1}{\Lambda_F^2}(\overline{\mu_L}\gamma^\mu e_L)(\overline{q_L}\gamma_\mu q_L)$$

non-photonic

	μ→eγ	μ→eee	μN→eN
photonic	tree	×α	×α
non-photonic (e)	1-loop	tree	---
non-photonic (q)	1-loop	---	tree

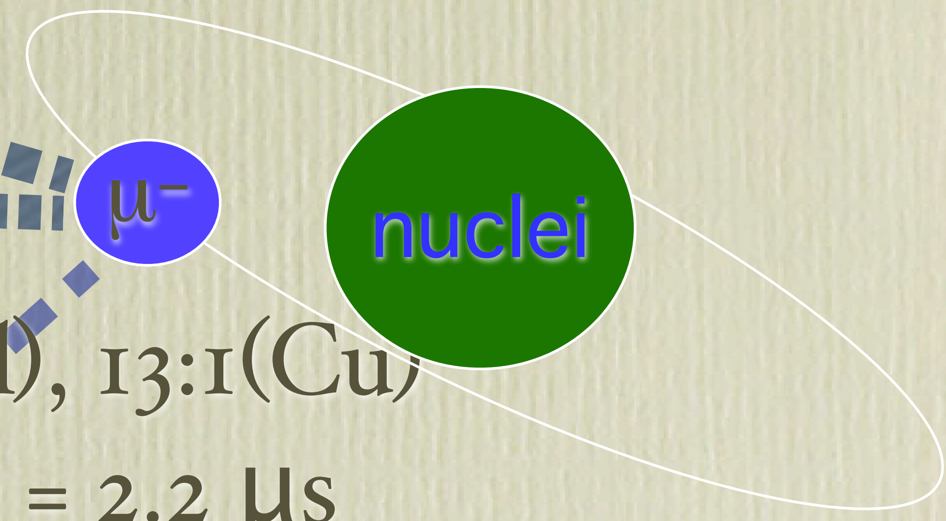
μ-e Conversion

- Muonic Atom (1S state)

Muon Capture(MC)

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

Muon Decay in Orbit (MDO) $\mu^- \to e^- \nu \bar{\nu}$



  - MC:MDO = 1:1000(H), 3:2(Al), 13:1(Cu)
  - $\tau(\mu^-;Al)$ = 0.88 μs; τ(free-μ-) = 2.2 μs

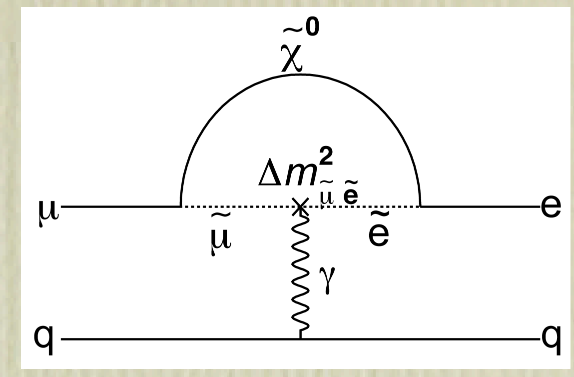
- μ-e Conversion

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

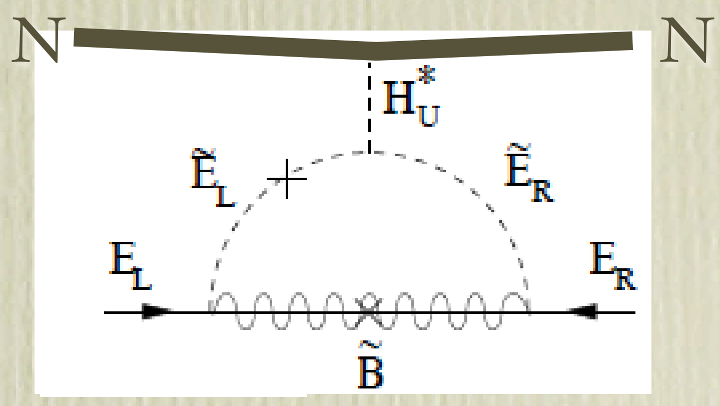
$$\mathrm{BR}[\mu^- + (A, Z) \to e^- + (A, Z)] \equiv \frac{\Gamma[\mu^- + (A, Z) \to e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)]}$$

Physics of μ-e Conversion

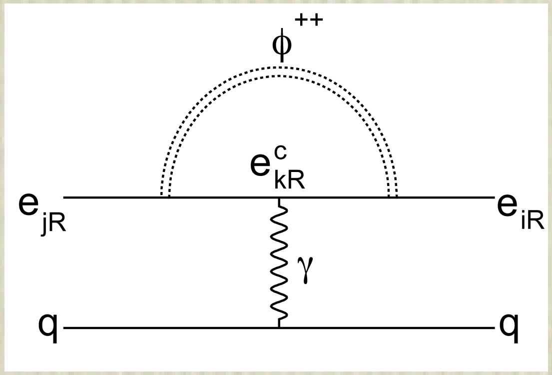
- SUSY-GUT, SUSY-seesaw (Gauge Mediated process)
  - BR = 10^{-15} = BR($\mu \to e\gamma$) × O(α)
  - $\tau \to l\gamma$



- SUSY-seesaw (Higgs Mediated process)
  - BR = 10^{-12}~10^{-15}
  - $\tau \to l\eta$



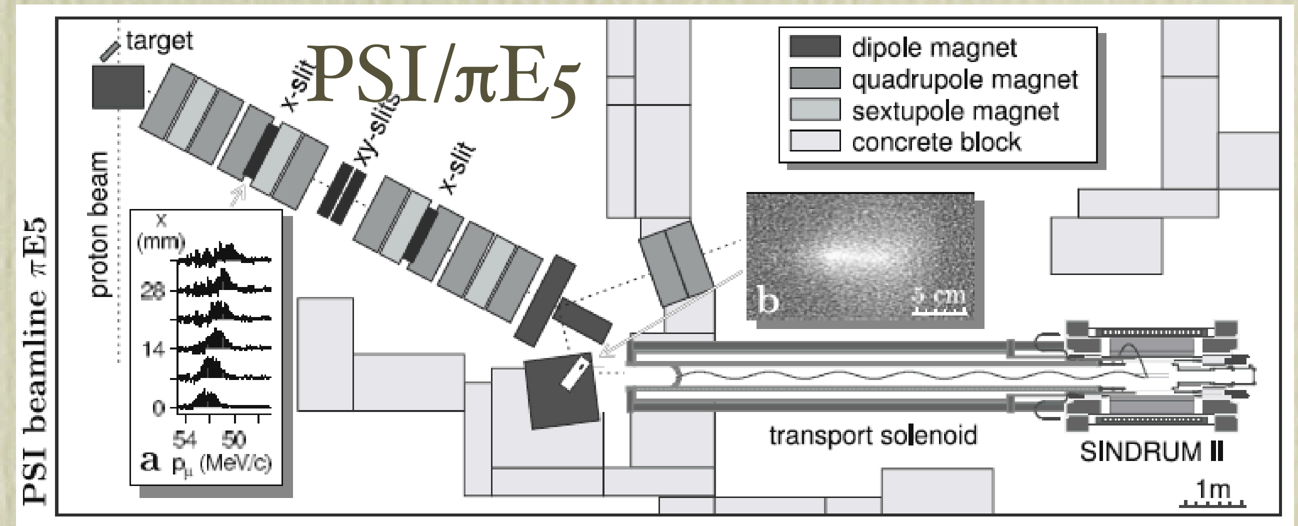
- Doubly Charged Higgs Boson (LRS *etc.*)
  - Logarithmic enhancement in a loop diagram for $\mu^- N \to e^- N$, not for $\mu \to e\gamma$
    - M. Raidal and A. Santamaria, PLB 421 (1998) 250

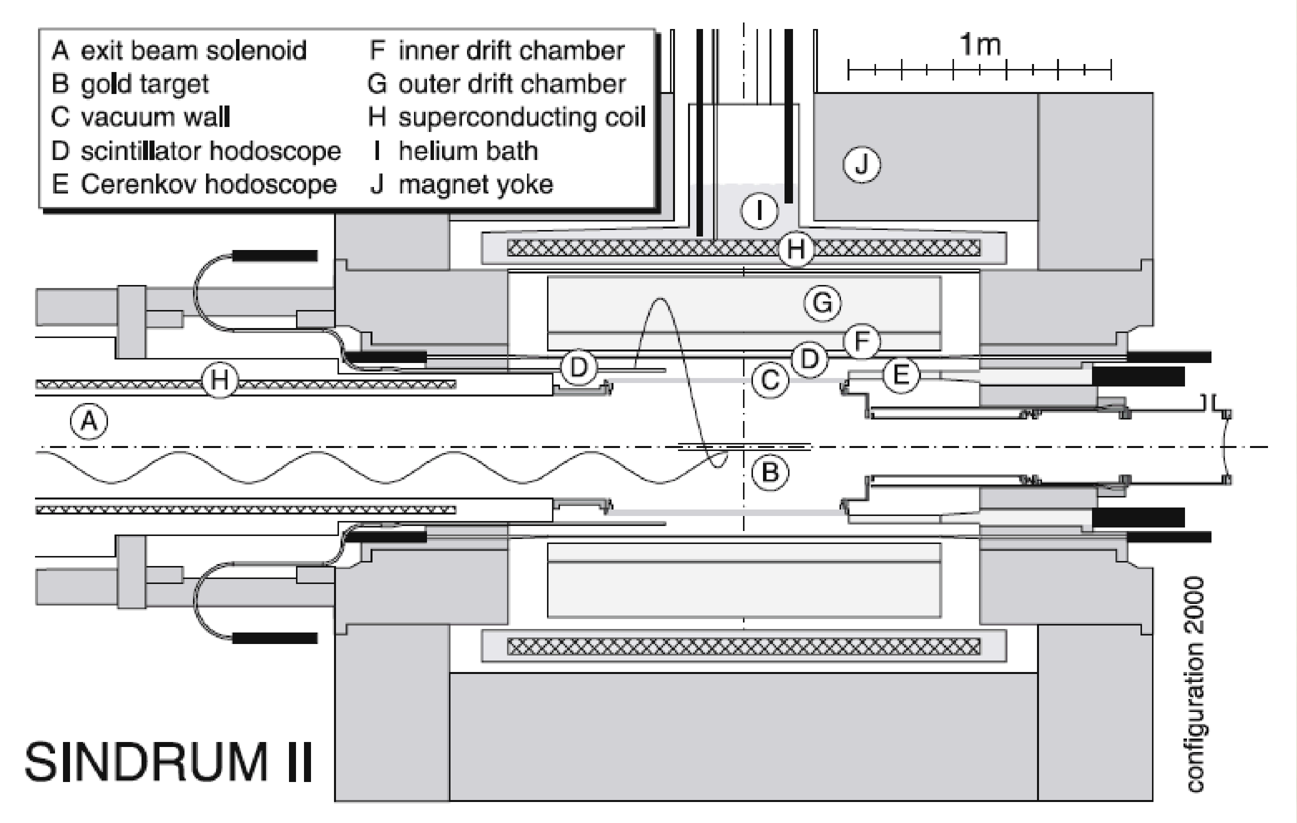


- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Compositeness
- Multi-Higgs Models

Principal of Experiment

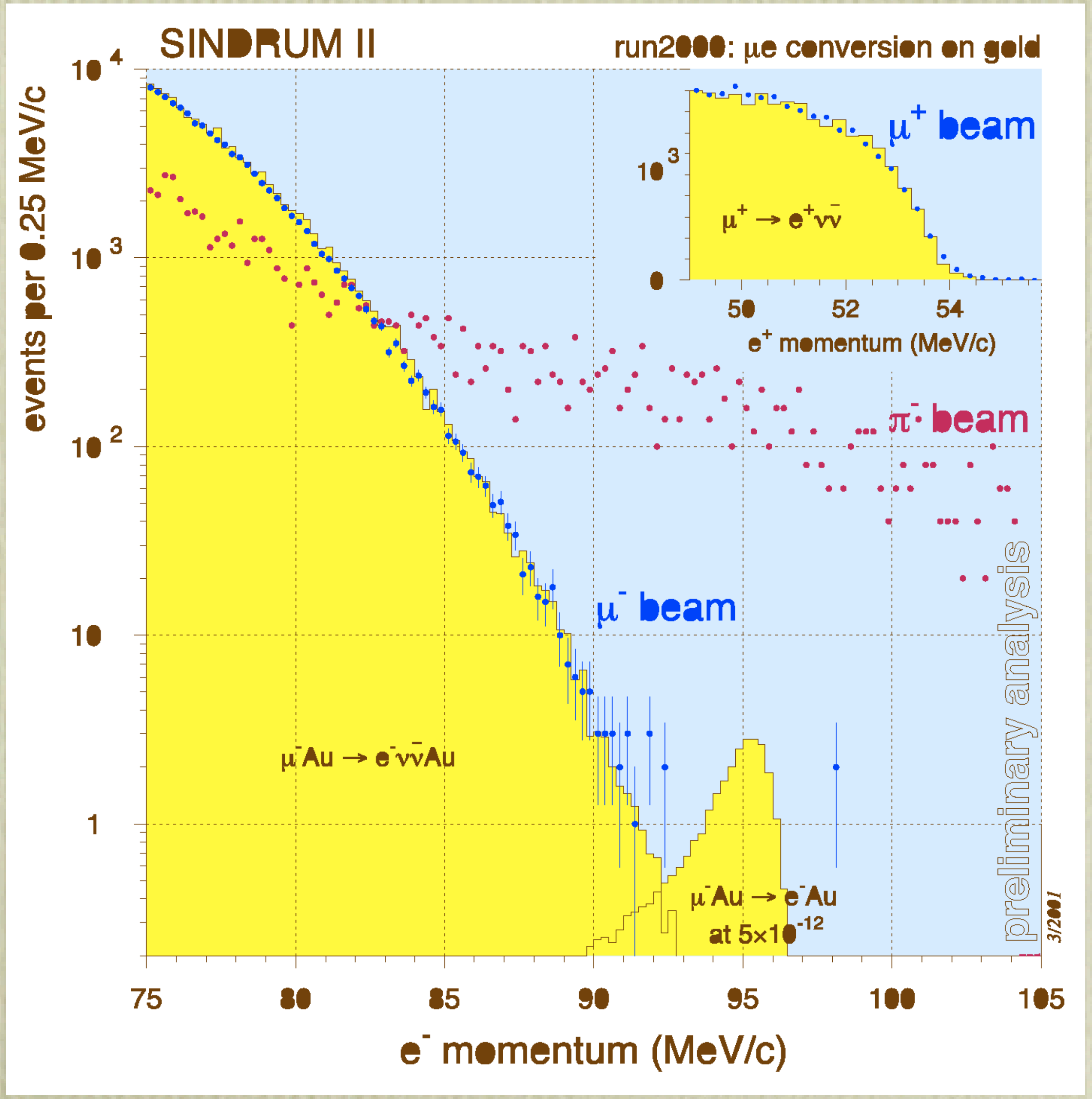
- Signal : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 100 MeV
    - Delayed : ~1μS
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (MDO)
    - ΔE_e=350 keV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Prompt timing



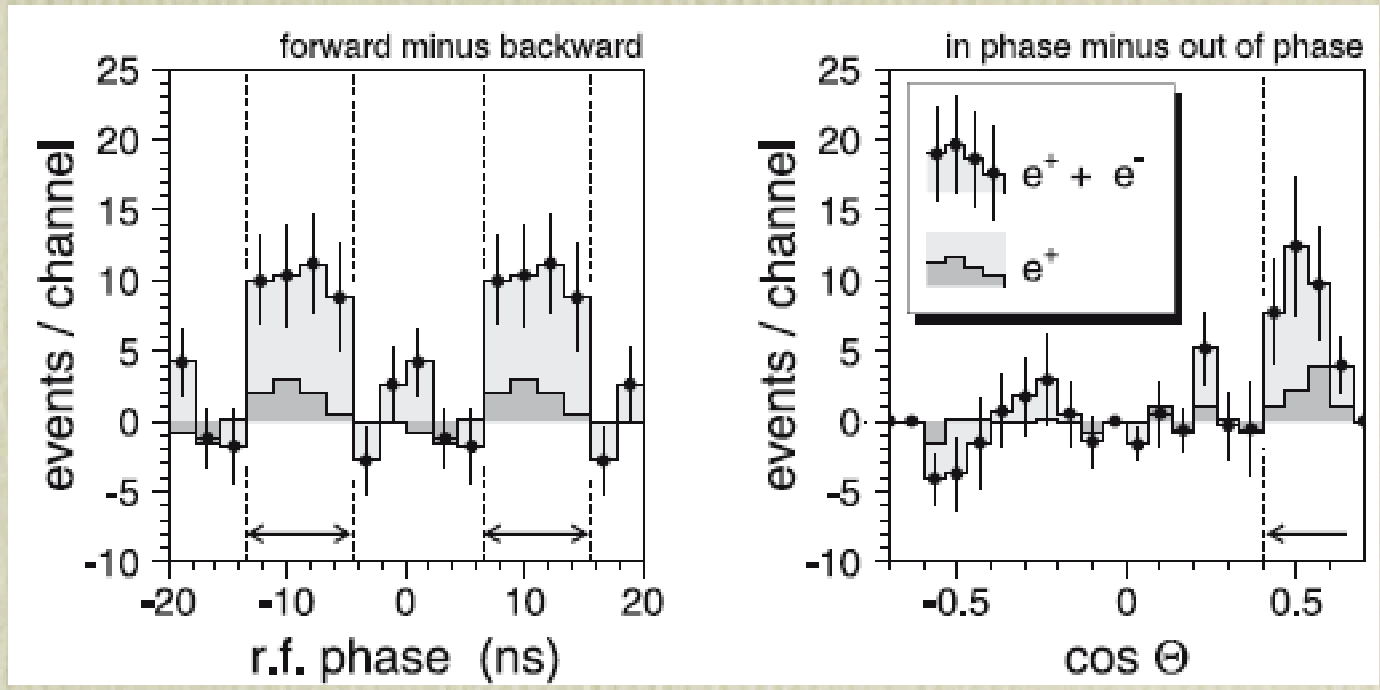


SINDRUM II

SINDRUM II



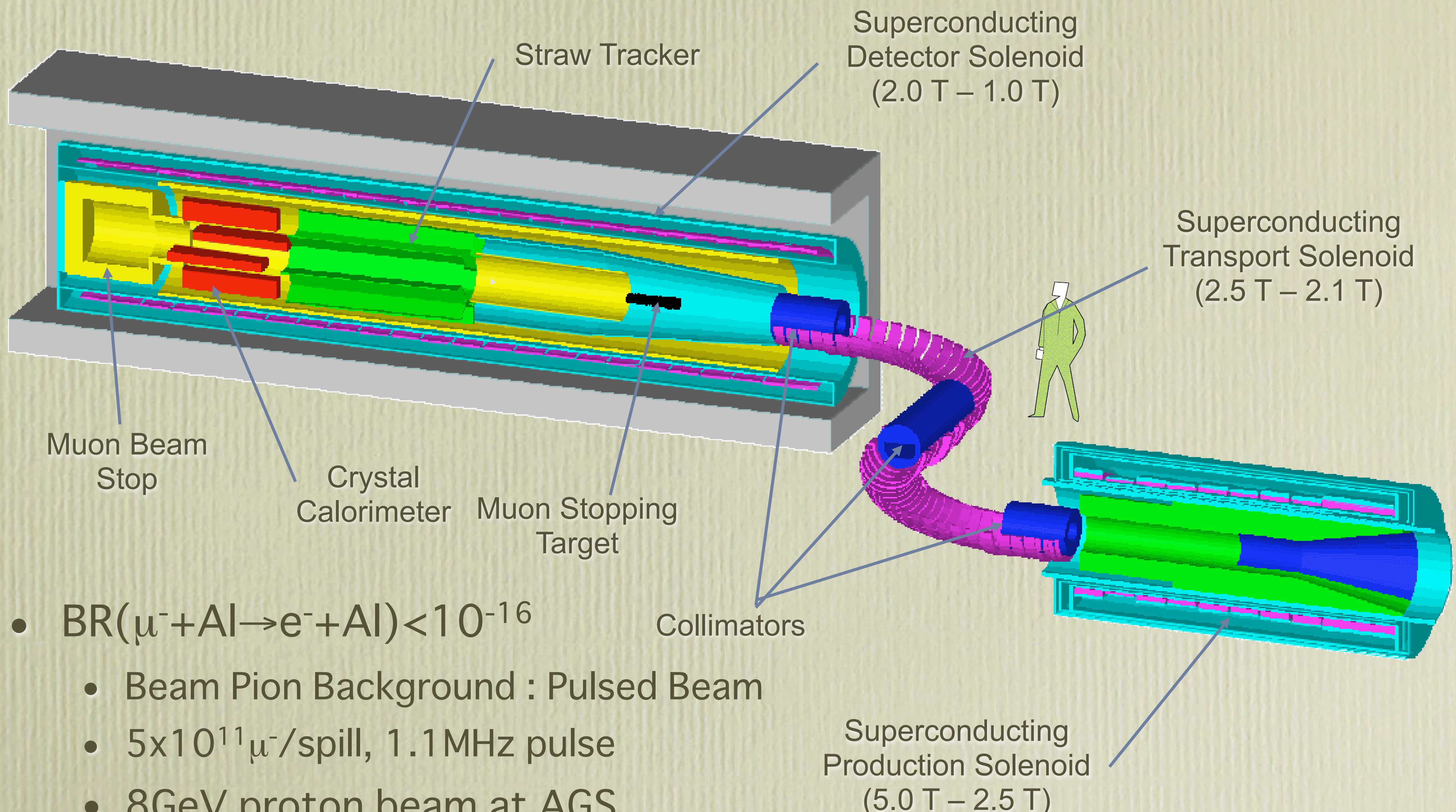
BR < 7 × 10⁻¹³



- Need more muons:
  - 10^{11} μ^-/s
  - J-PARC/MR + Solenoid π cap.
- Beam-induced prompt backgrouds:
  - Pulsed beam
  - Long Muon Beam Line
- Detector rate might be too high:
  - Curved Solenoid Detector.

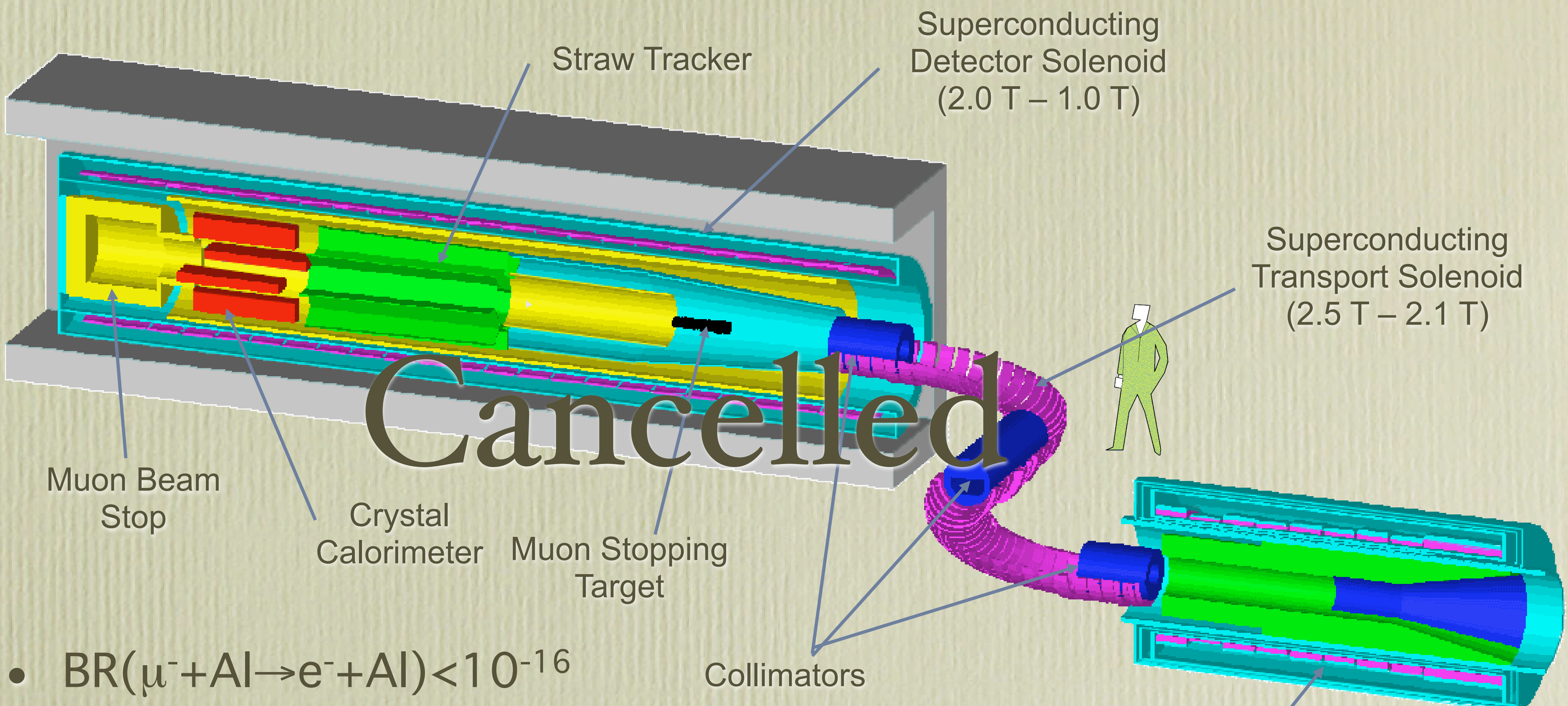
MECO, PRISM and Phase-1

MECO BNL/AGS



- $BR(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$
  - Beam Pion Background : Pulsed Beam
  - $5 \times 10^{11} \mu^-$/spill, 1.1MHz pulse
  - 8GeV proton beam at AGS
  - high field capture solenoid of 4T

MECO BNL/AGS



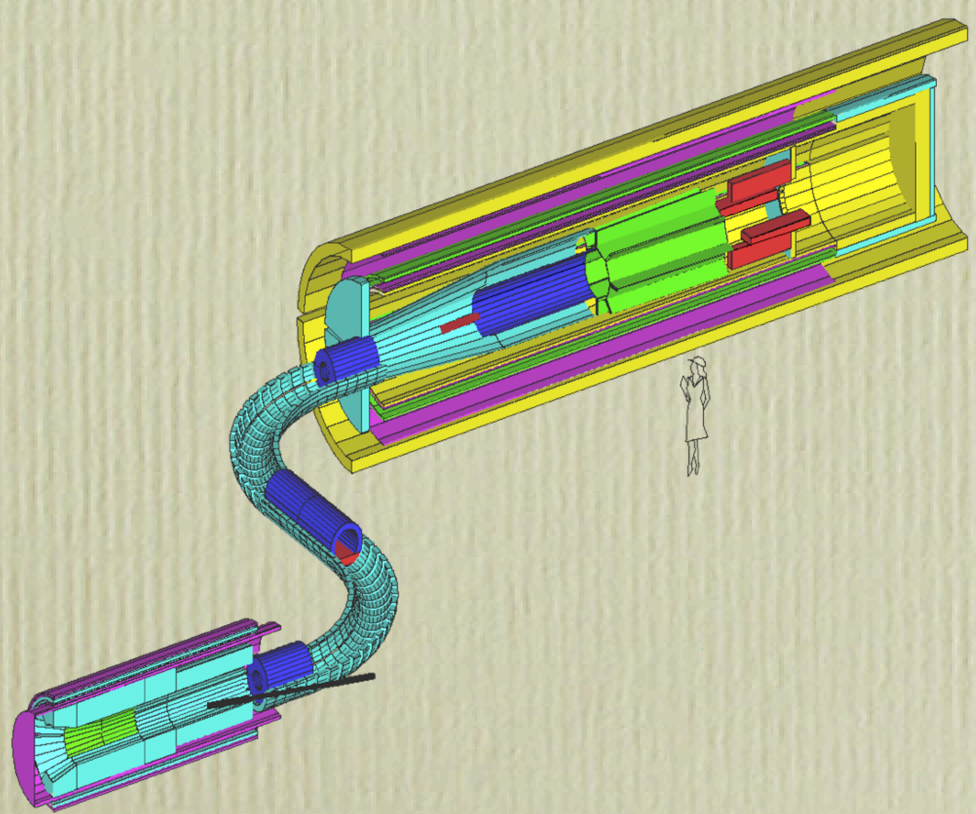
Cancelled

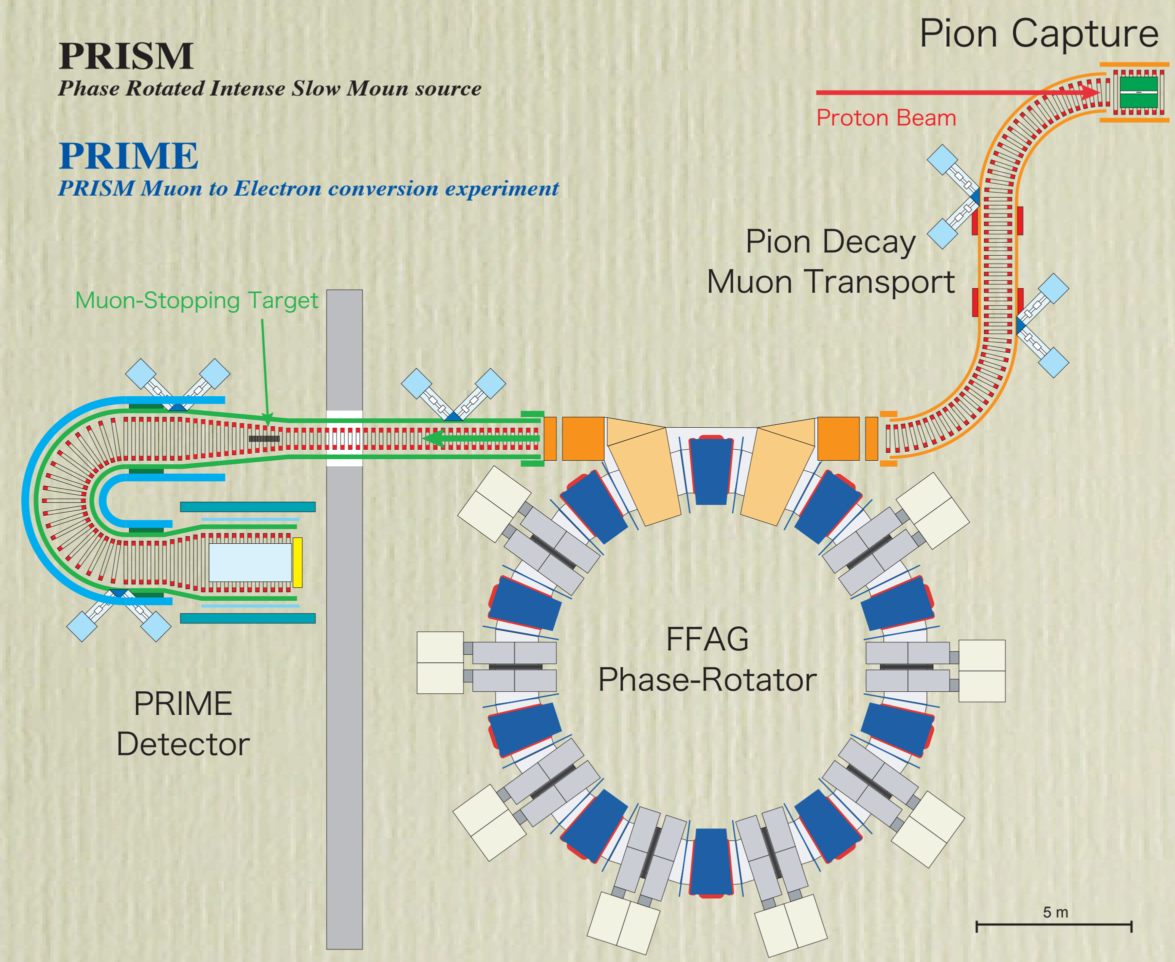
- $BR(\mu^- + Al \to e^- + Al) < 10^{-16}$
  - Beam Pion Background : Pulsed Beam
  - $5 \times 10^{11} \mu^-$/spill, 1.1MHz pulse
  - 8GeV proton beam at AGS
  - high field capture solenoid of 4T

Staging Strategy

On the evening before the MECO cancellation

MECO	Construction	Run	Analysis
PRISM	Development	Construction	Run





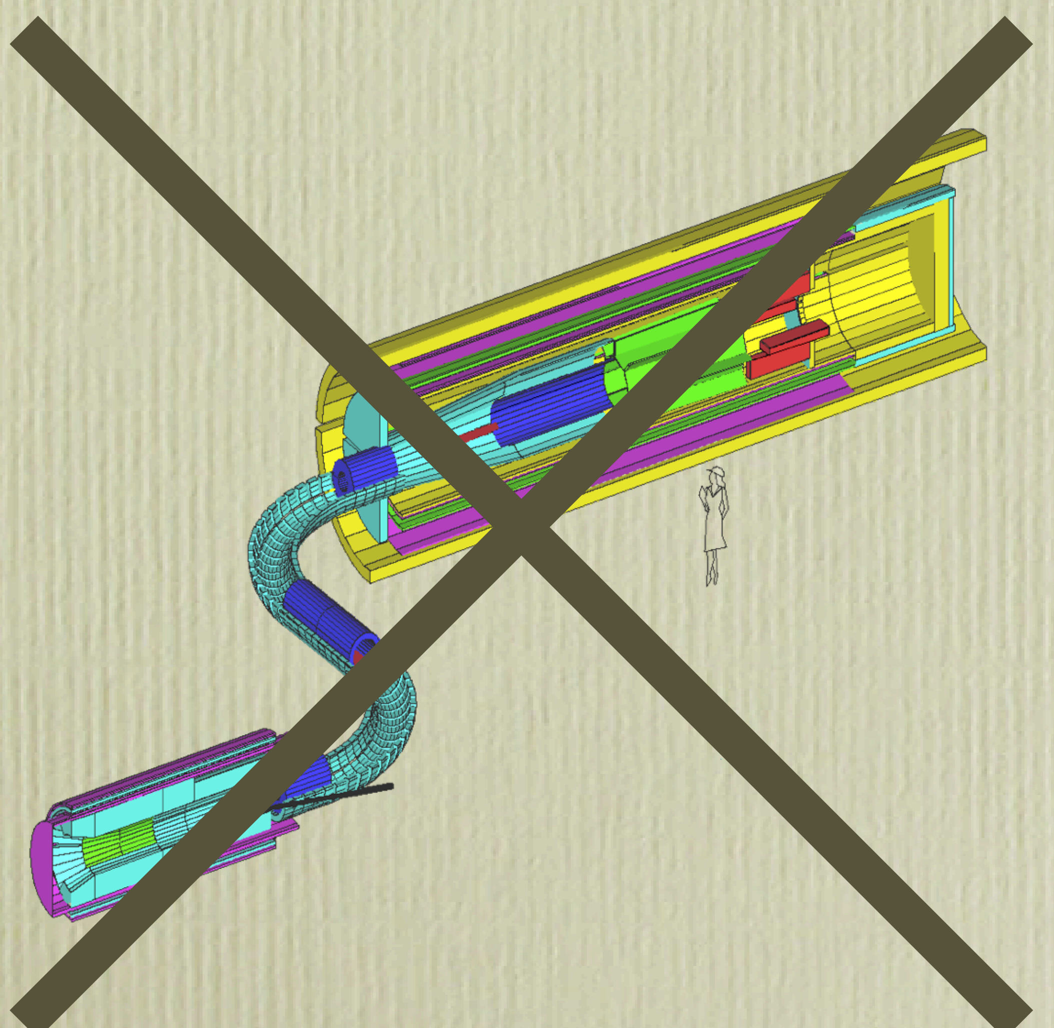
MECO:BR$<10^{-16}$

PRISM:BR$<10^{-18}$

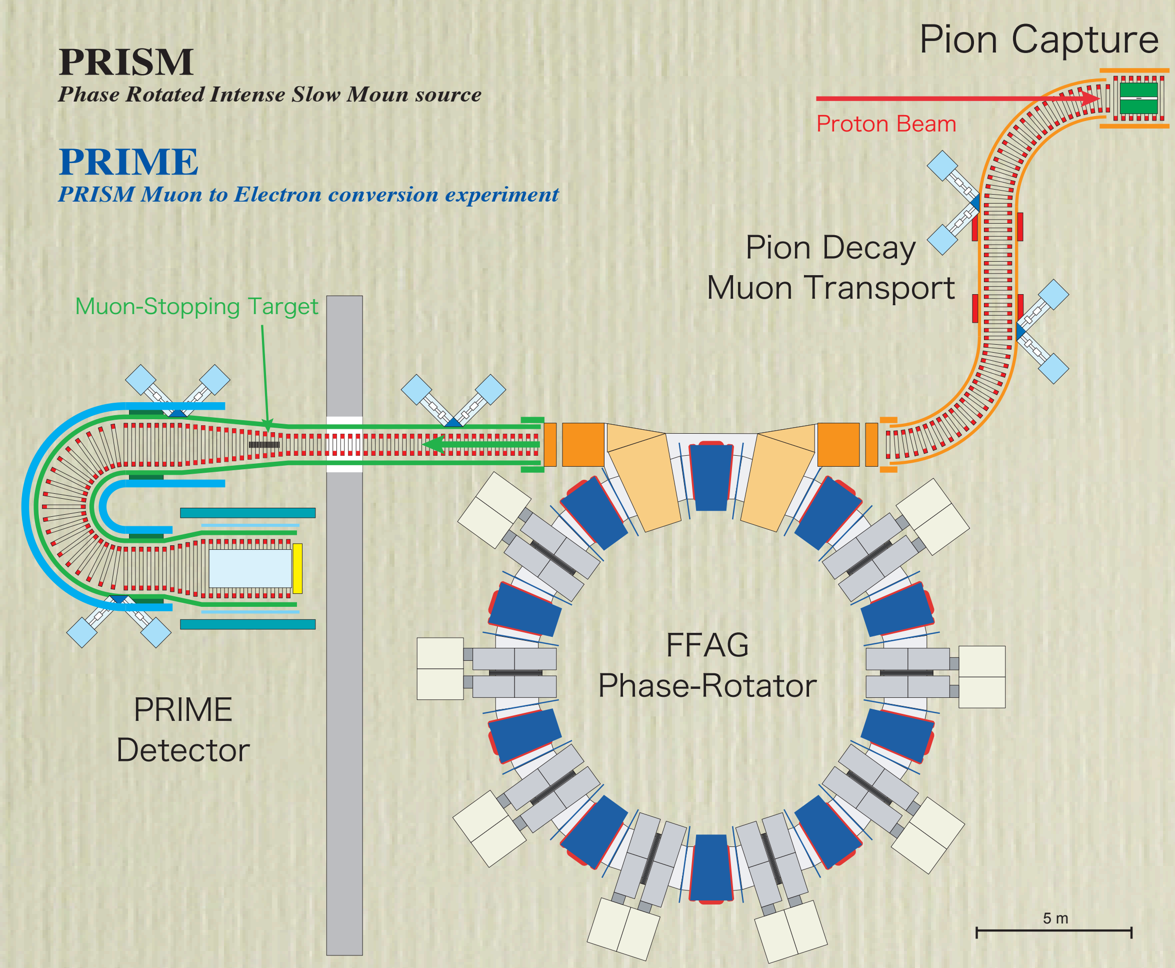
Staging Strategy

On the evening before the MECO cancellation

MECO	Construction	Run	Analysis
PRISM	Development	Construction	Run



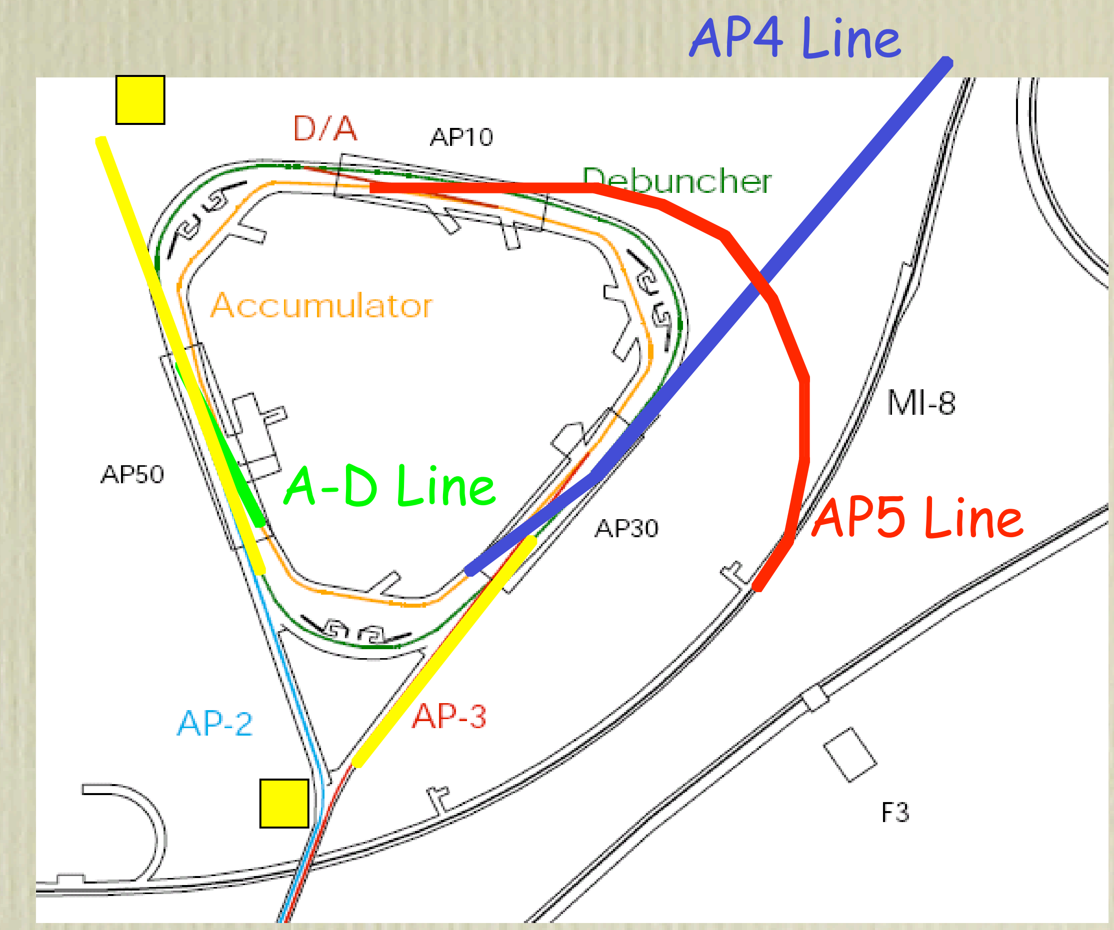
MECO:BR<10^{-16}

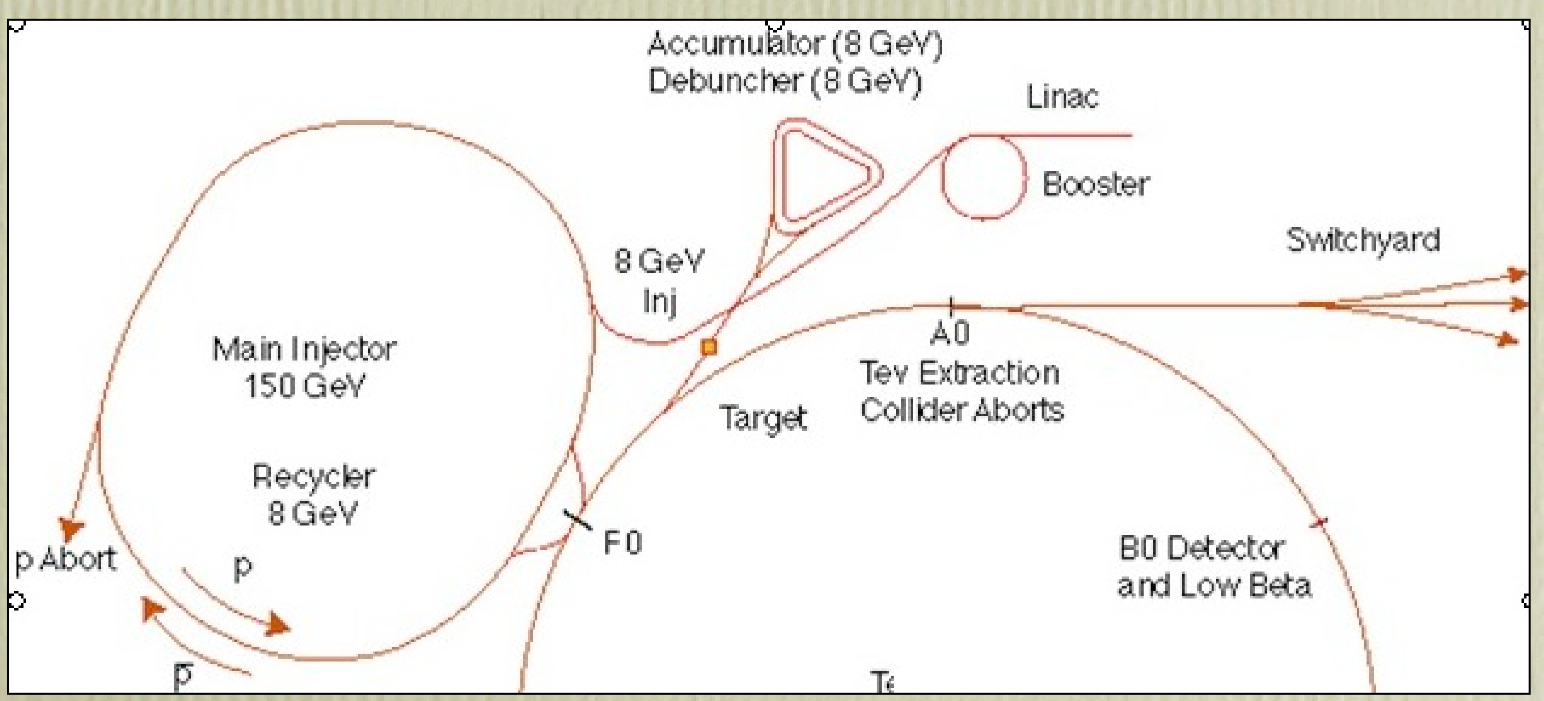


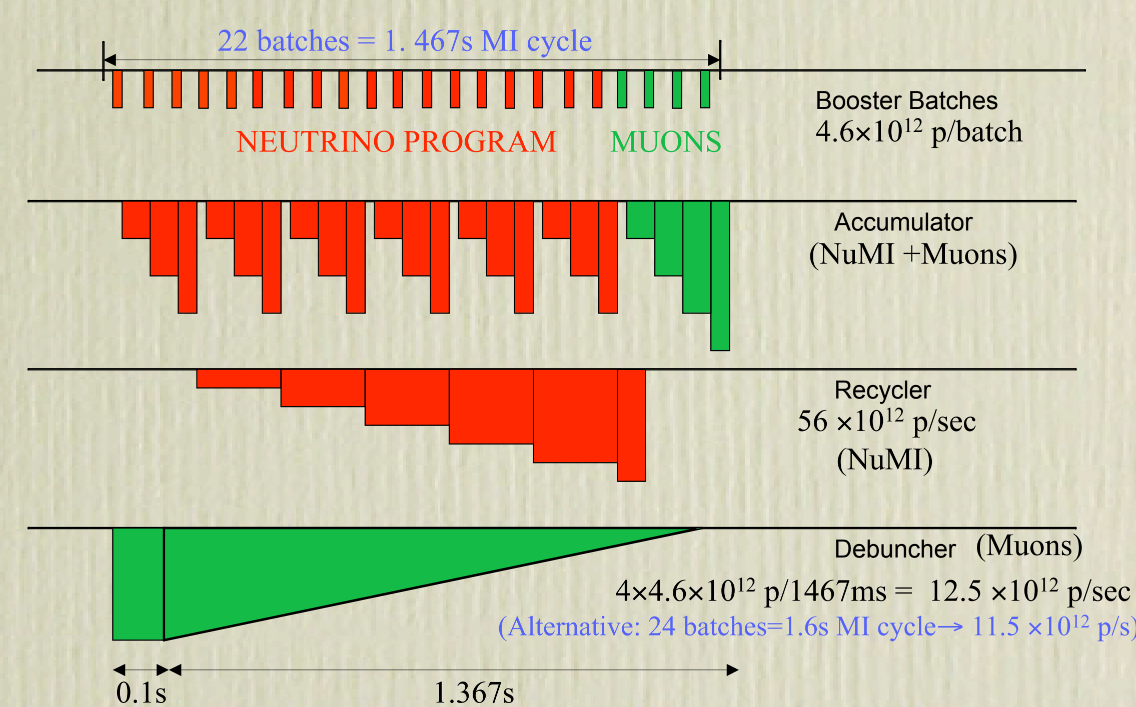
PRISM:BR<10^{-18}

After the MECO Cancellation

- mu2e(FNAL + xMECO)
  - Revive of MECO
  - After the shutdown of Tevatron
  - Parasite on SNuMI-2
    - 2012 ~
  - Renovate a Debuncher ring for beam bunching



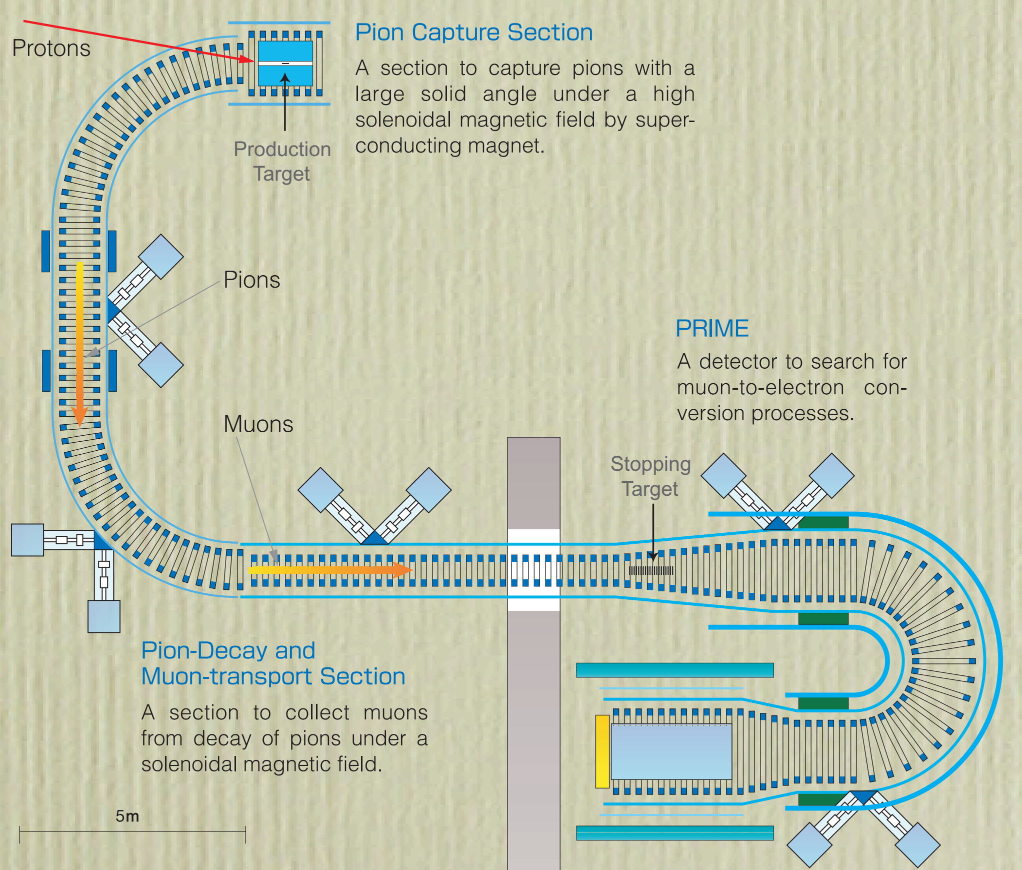




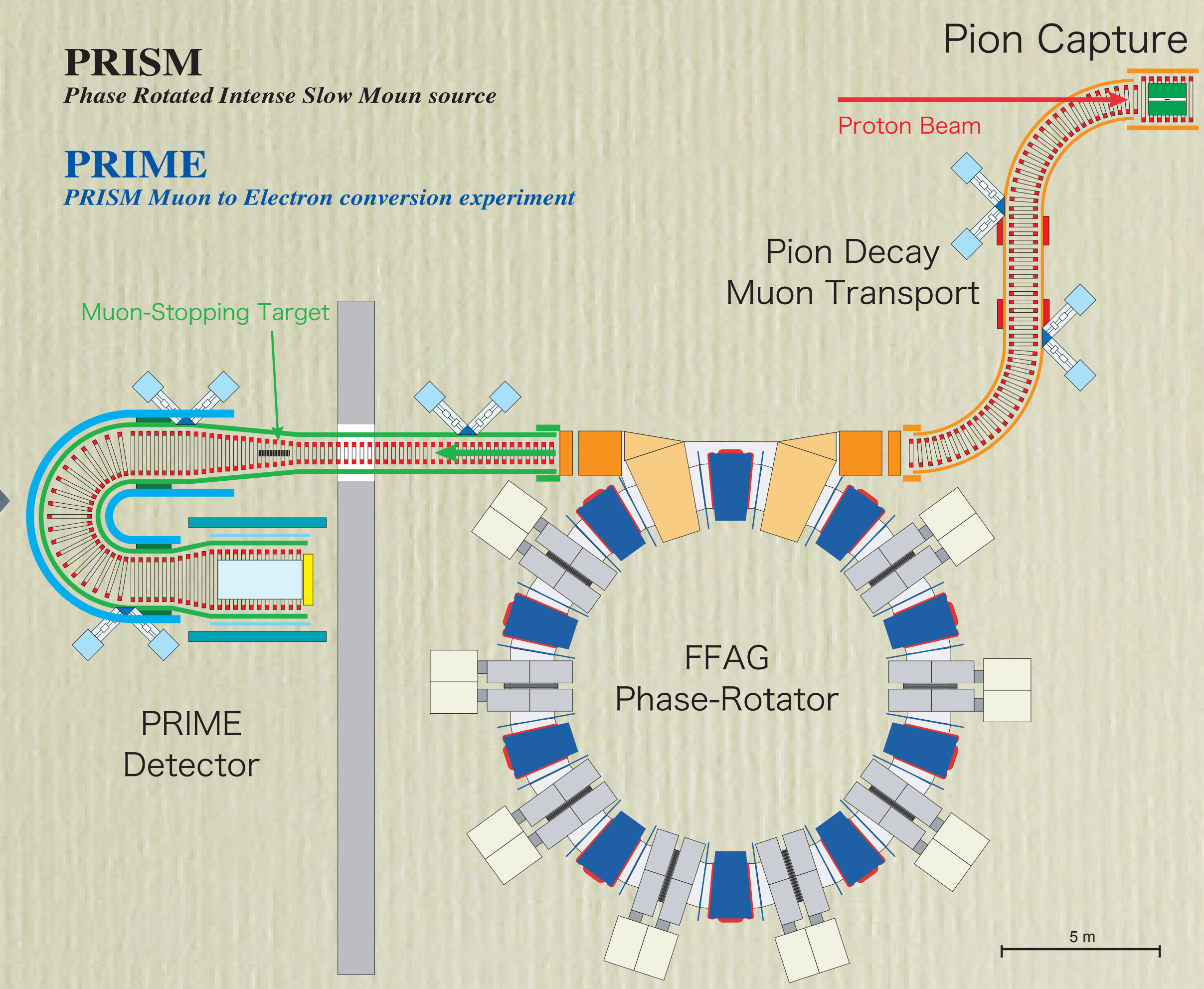
Staging of PRISM

~10 years

Phase-1	R&D	Construction	Run	Analysis
PRISM	Development	Construction	Run	

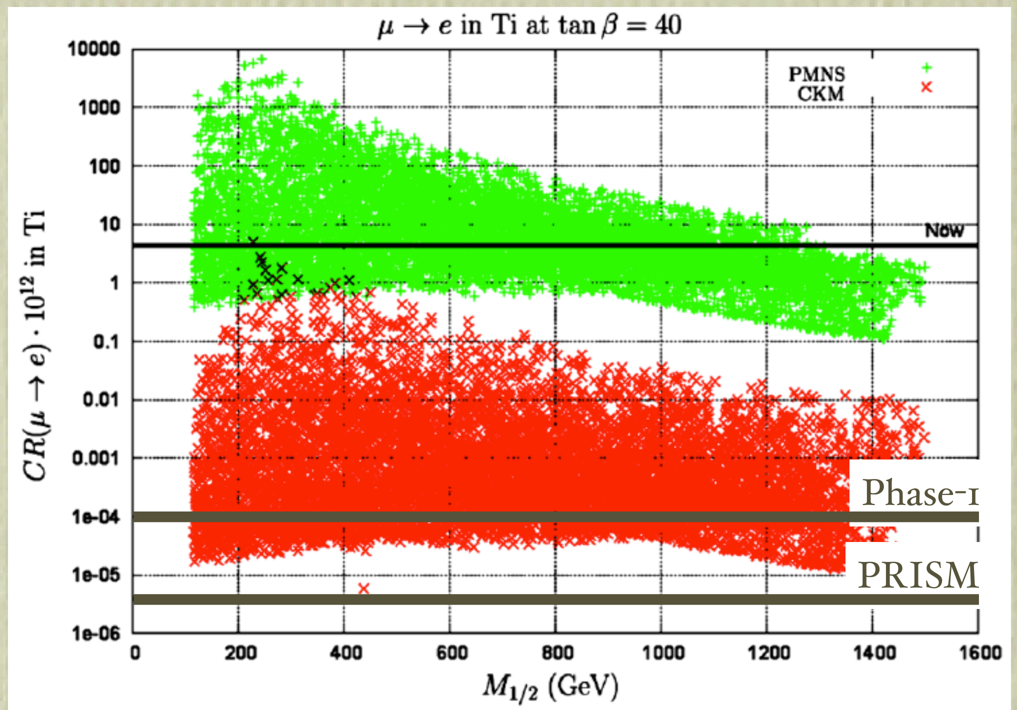


Phase-1: $BR<10^{-16}$

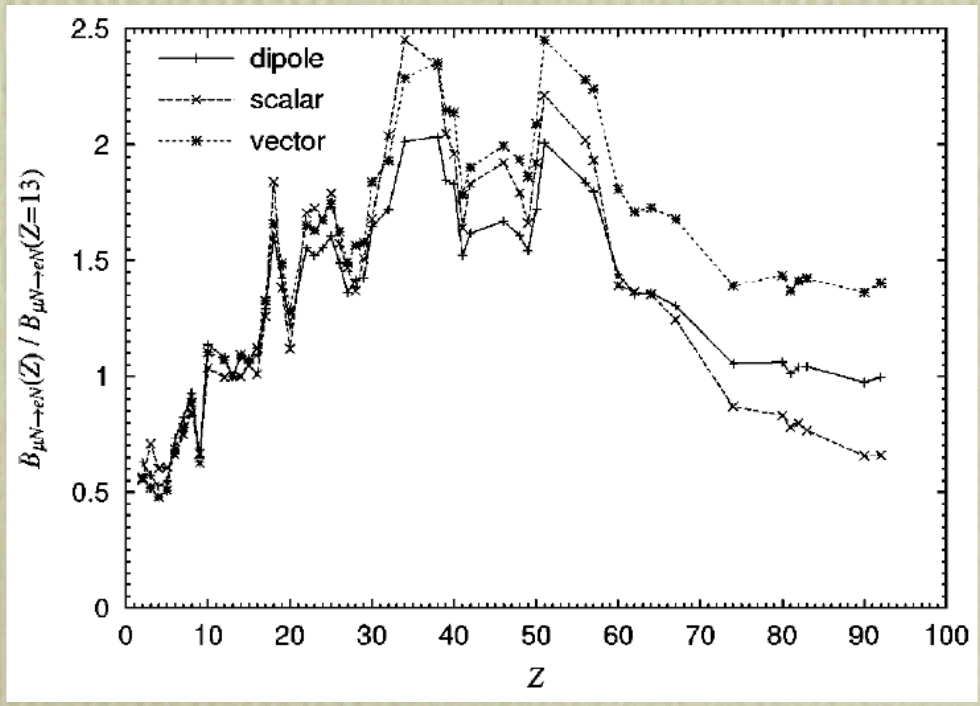


Full PRISM: $BR<10^{-18}$

Why Staging, why 10^{-18}



L. Calibbi, A. Faccia, A. Masiero and S.K. Vempati PRD 74(2006) 116002

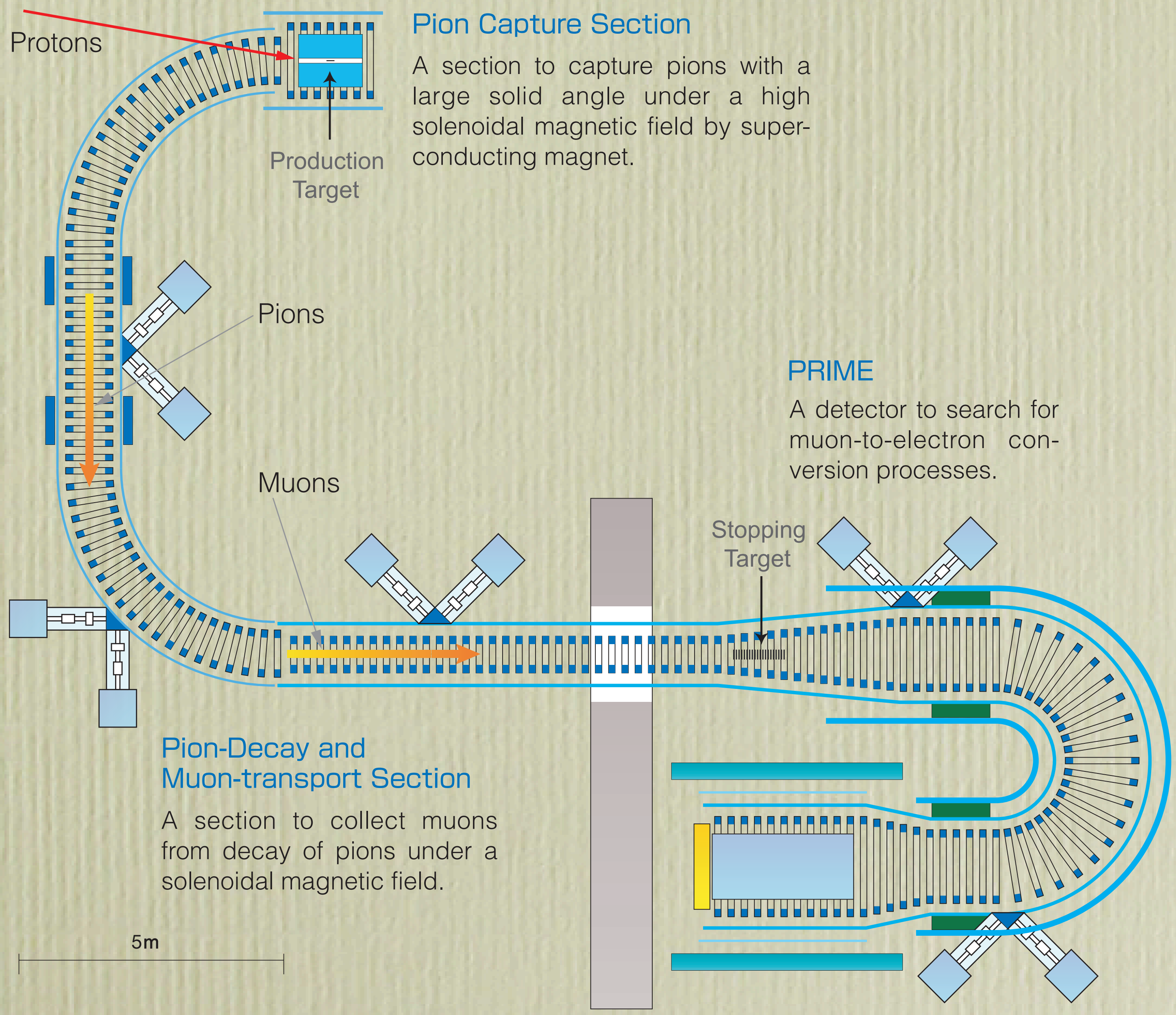


R. Kitano, M. Koike, Y. Okada PRD 66(2002) 096002

- Staging
  - Early Realization, Discovery
  - Understand the phenomena in a real-world step by step; we may see something new in every step of factor 10 improvements
- Why 10^{-18}, why full-PRISM
  - Covering almost entire parameter space
  - Study of interaction types
    - $\tau_{\mu^- Al}$ = 880 ns, $\tau_{\mu^- Pb}$ = 82 ns

Phase-1

Phase-1 Overview

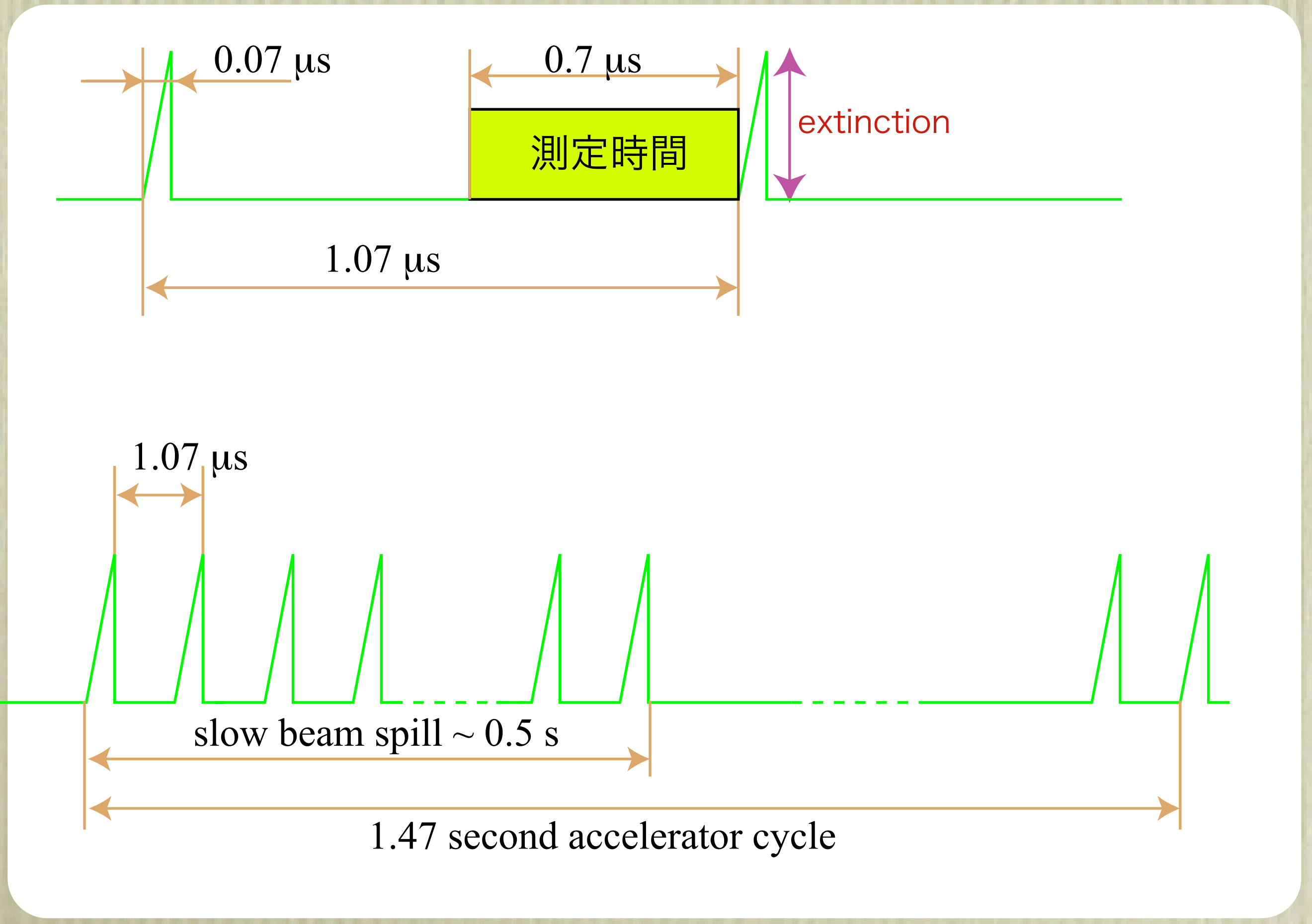


- Large μ yields
  - J-PARC/MR
    only 60 kW out of 450kW
  - π-capture SC-solenoid
  - 10^{11} μ/s (PSI:10^{8} μ/s)
- Pulsed Proton Beam
  - π-b.g. suppression
- Curved-solenoid detector
  - Lower detector rate
- Upgradability to PRISM
  - add Phase-Rotator-Ring

Pulsed Proton Beam

パルス陽子ビーム

- バックグランド
  - $\pi^- + (A,Z) \to (A,Z-1)^* \to \gamma + (A,Z-1)$, $\gamma \to e^+ e^-$ ：一次陽子ビームに同期
  - μ^- decay-in-flight, e^- scattering, neutron streaming
- 信号
  - $\mu^- + (A,Z) \to e^- + (A,Z)$ ：遅延 (~1μs)



$N_{bg} = N_P \times R_{ext} \times Y_{\pi/P} \times A_\pi \times P_\gamma \times A$

N_P : total # of protons (~10^{21})

R_{ext} : Extinction Ratio (10^{-9})

$Y_{\pi/P}$: π yield per proton (0.015)

A_π : π acceptance (1.5×10^{-6})

P_γ : Probability of γ from π (3.5×10^{-5})

A : detector acceptance (0.18)

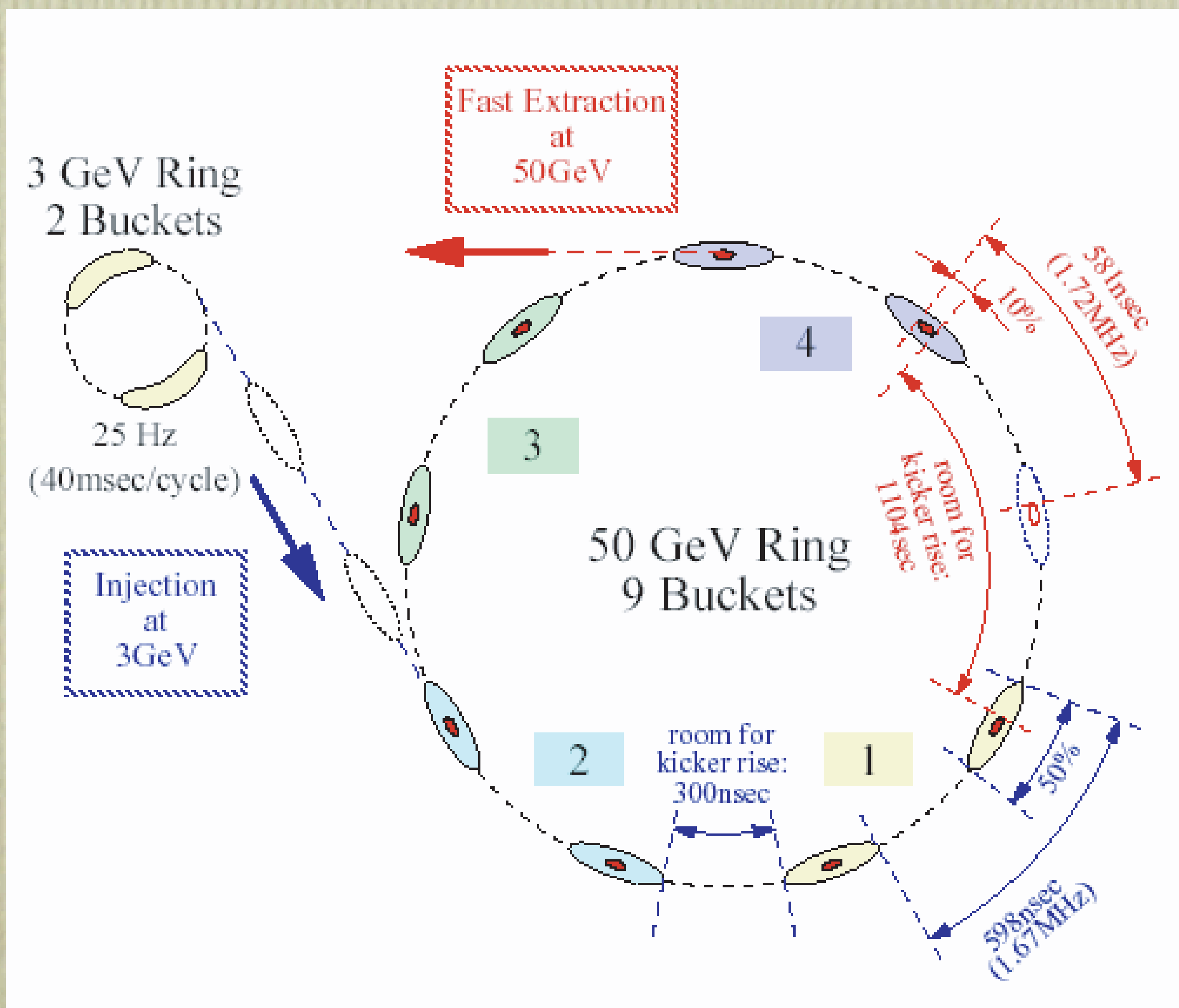
BR=10^{-16}, $N_{bg} < 0.12$

⇔ Extinction < 10^{-9}

Extinction: < 10^{-9}

Power: 60 kW (4×10^{13} pps@8 GeV)

J-PARC

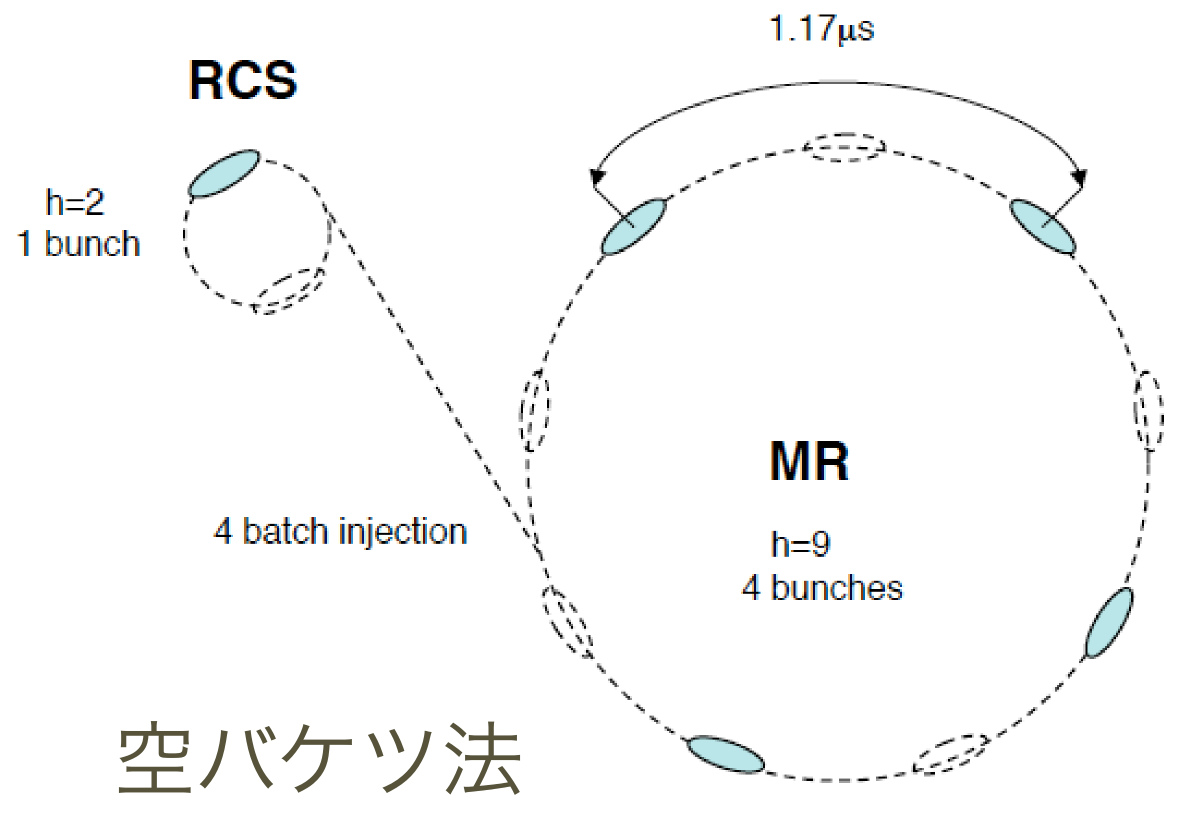


- LINAC
  - 0.4 GeV
  - 4π mm.mrad
- RCS
  - Painting: 300 times 144π mm.mrad
  - Extraction: <81π mm.mrad
- MR
  - Injection: 81π mm.mrad
  - Extraction: 10π mm.mrad @ 30 GeV

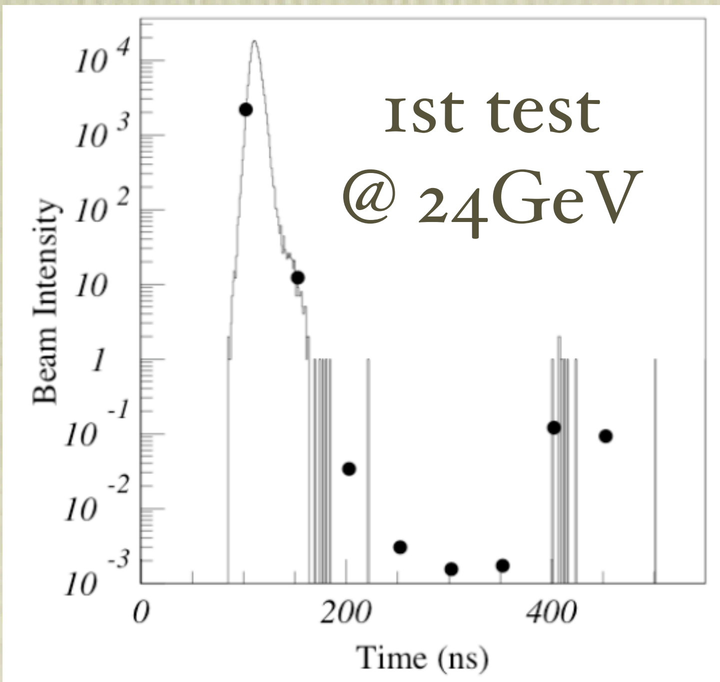
adiabatic dumping

Bunching Scheme @ J-PARC

- Tomizawa Scheme
- RCS : h=2 w/ empty bucket
- MR : Empty bucket Scheme
  - h=9 or h=8
- Bunched Slow Extraction



MECO @AGS



Extinction (1st test)
- Inter buchet: 10-6
- Empty bucket: 10-3

2nd test (7.4GeV) : 10-7

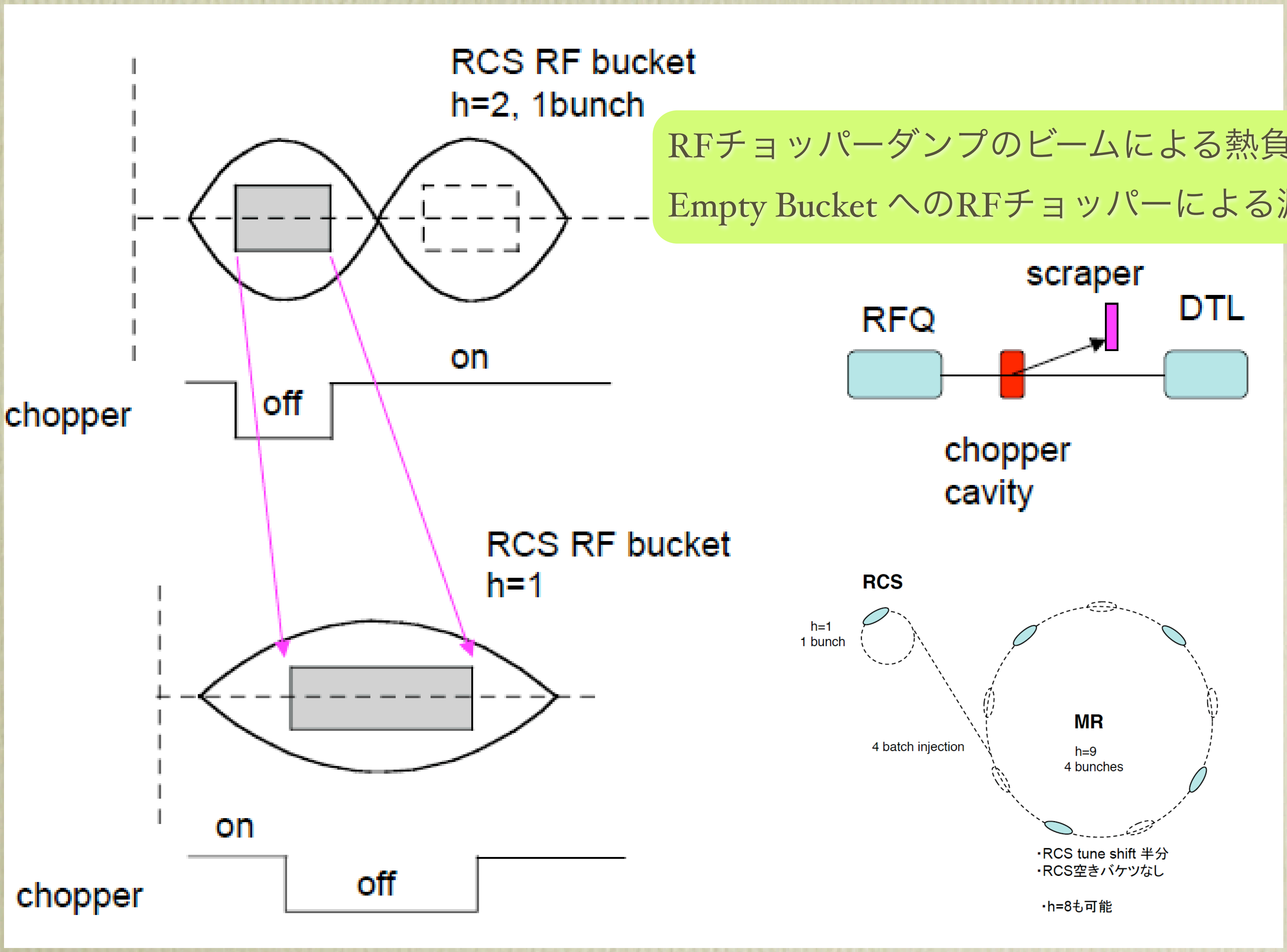
Transitionによる悪化？

J-PARC/MR: Transition 無

空バケツの作り方

RFチョッパーダンプのビームによる熱負荷

Empty Bucket へのRFチョッパーによる漏れ込み



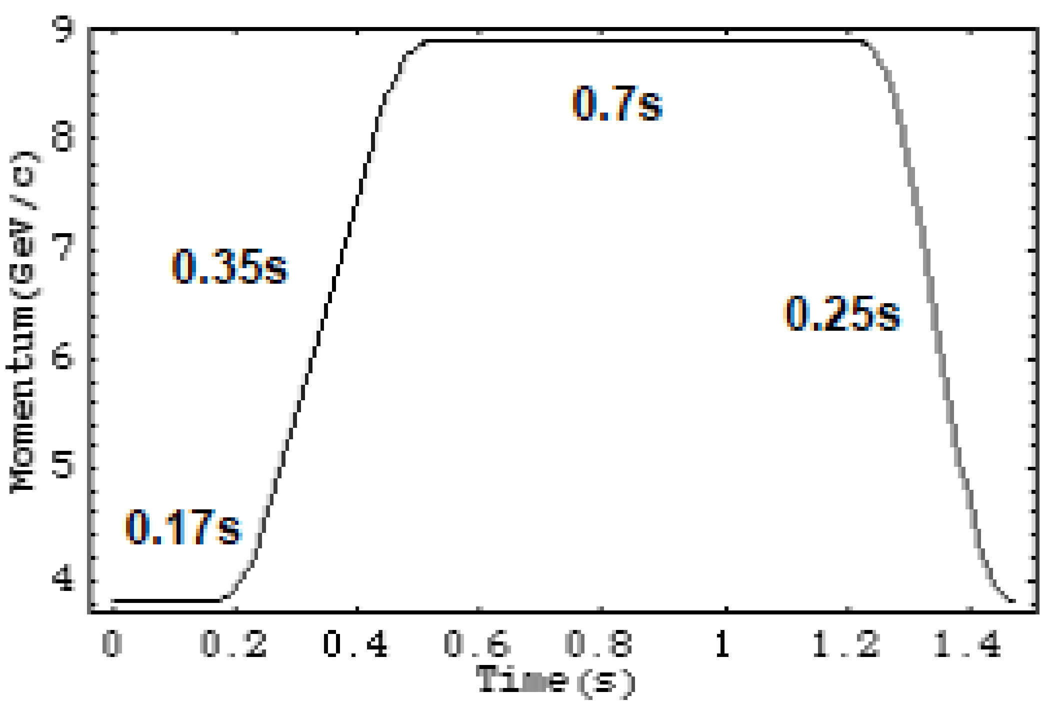
Emittance Control

- Adiabatic dumping ∝ 1/βγ
  - NP-Hall Acceptance: 10π(24π) mm.mrad
    - 30 GeV : 10π → 8 GeV : 34π!!??
  - Vertical: Reduce RCS painting area
  - Horizontal: 遅い取り出しならば < 5π mm.mrad
- in Tomizawa Scheme
  - 高加速繰返し
  - 低バンチ当たり粒子数: 低 space charge
  - 小 RCS painting area、小3-50BT・MR コリメータ

Tomizawa Scheme

8GeV extraction
7μA, 56kW
RCS: h=1, 1banch
MR: h=9, 4batch, 4banch

total time(s)=1.47

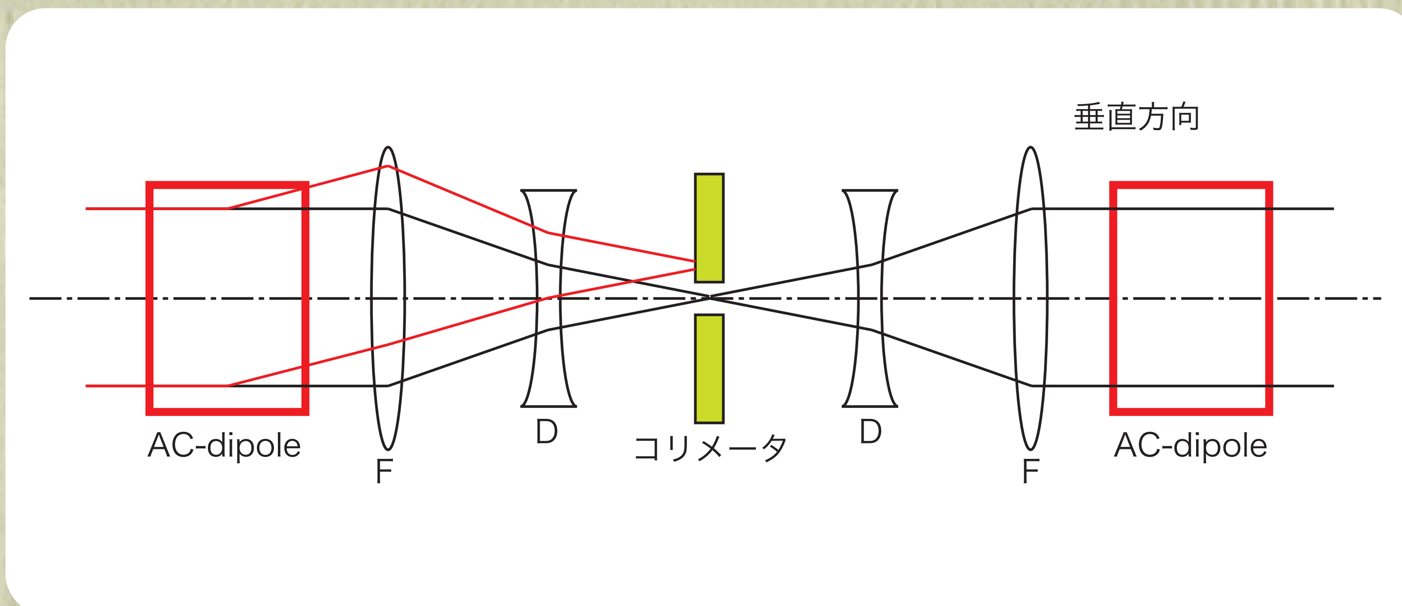


Slow Extraction

0.16×10^{14} ppb (1/2.6 of designed 0.4125×10^{14} ppb)

- 144π (0.4GeV) -> 36π (3GeV) –>15π (8GeV)
  RCS tune shift -0.046
- 93π (0.4GeV) -> 23π (3GeV) –>10π (8GeV)
  RCS tune shift -0.072

Extra Extinction Devices



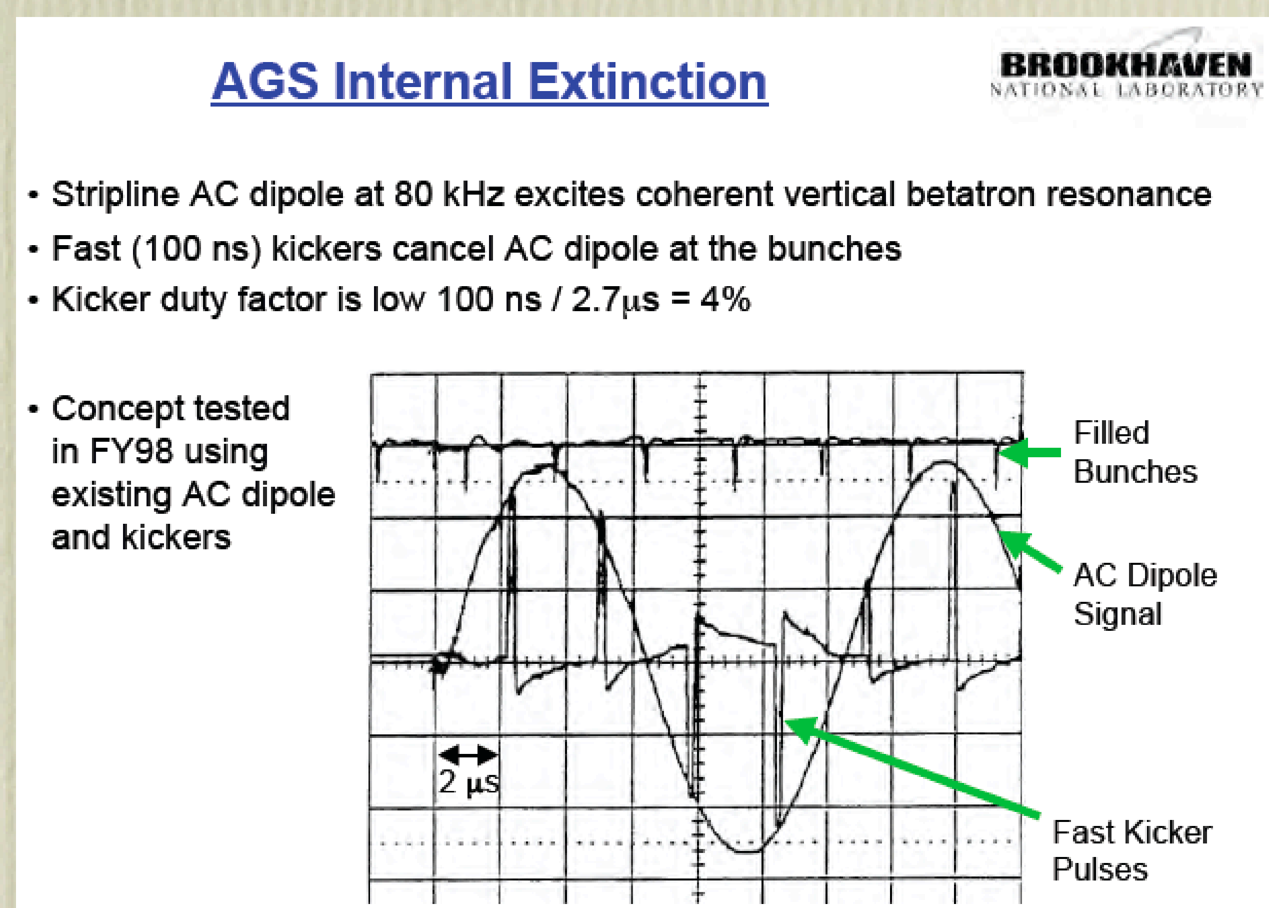
External Extinction Dev.

- AC-dipole
- $f_{extinction}$ ~ 1/100

Bunch Cleaner

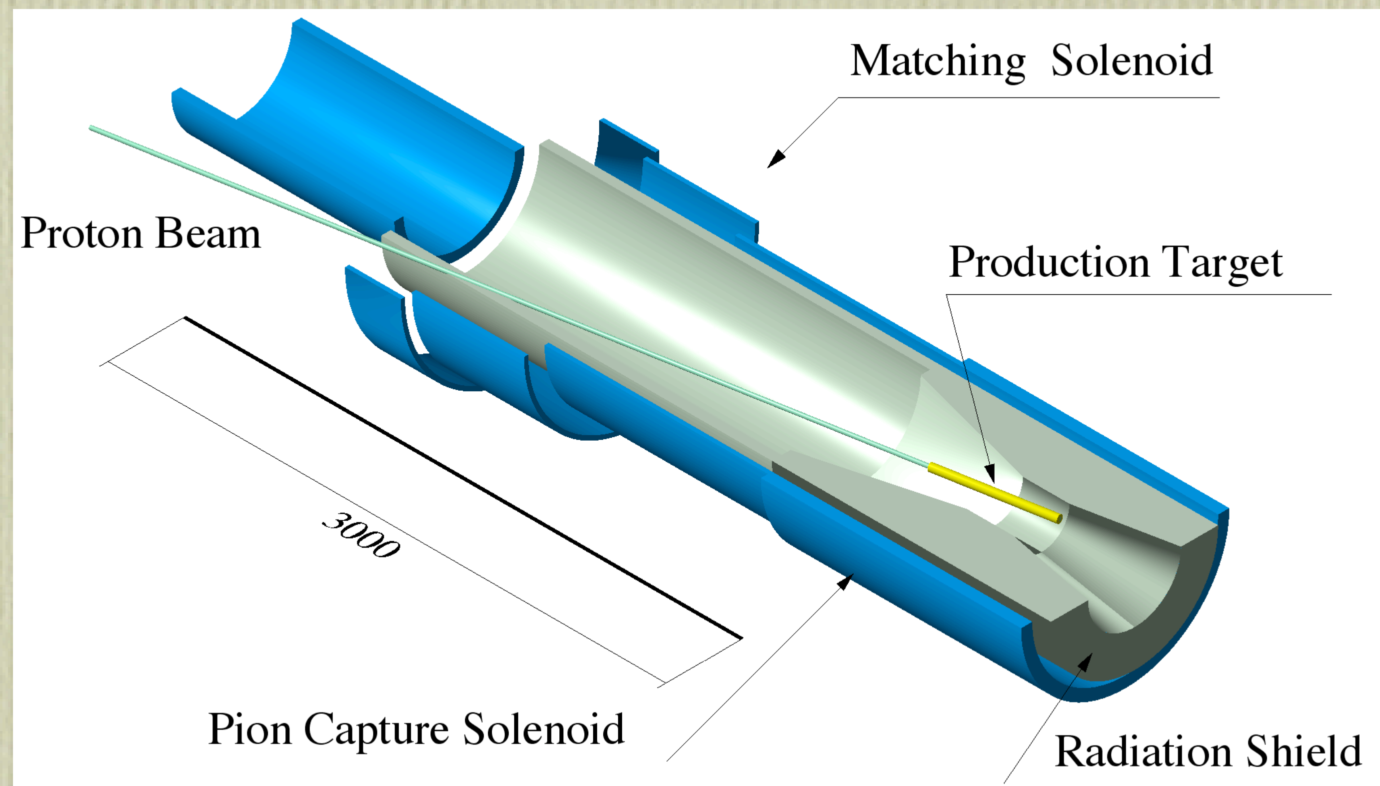
- AC-dipole
- Fast Kicker

場所はある@J-PARC/MR

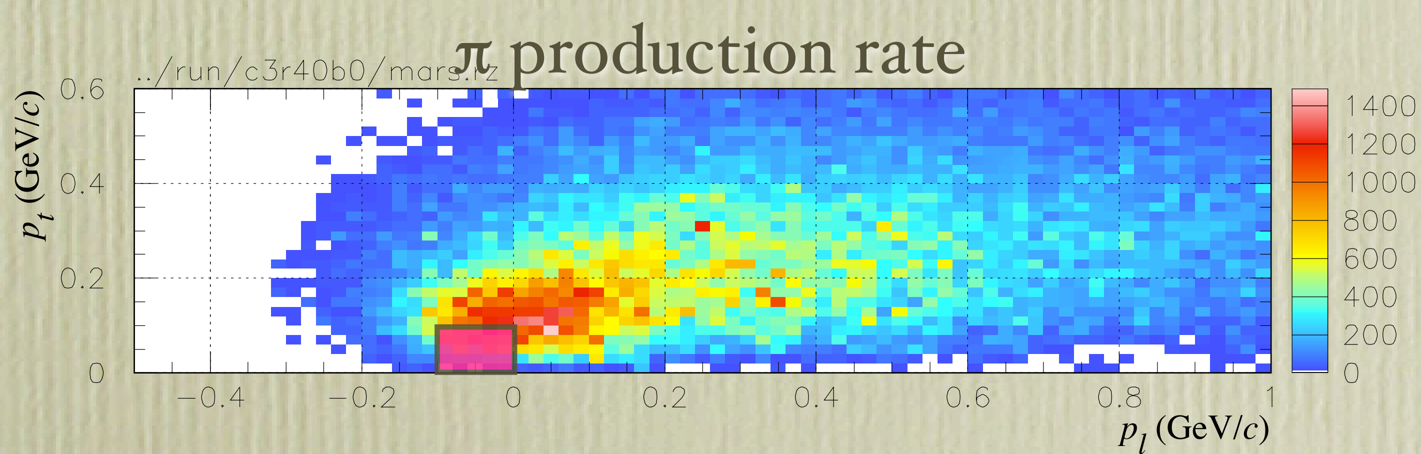


Muon Beam Line

Pion Production



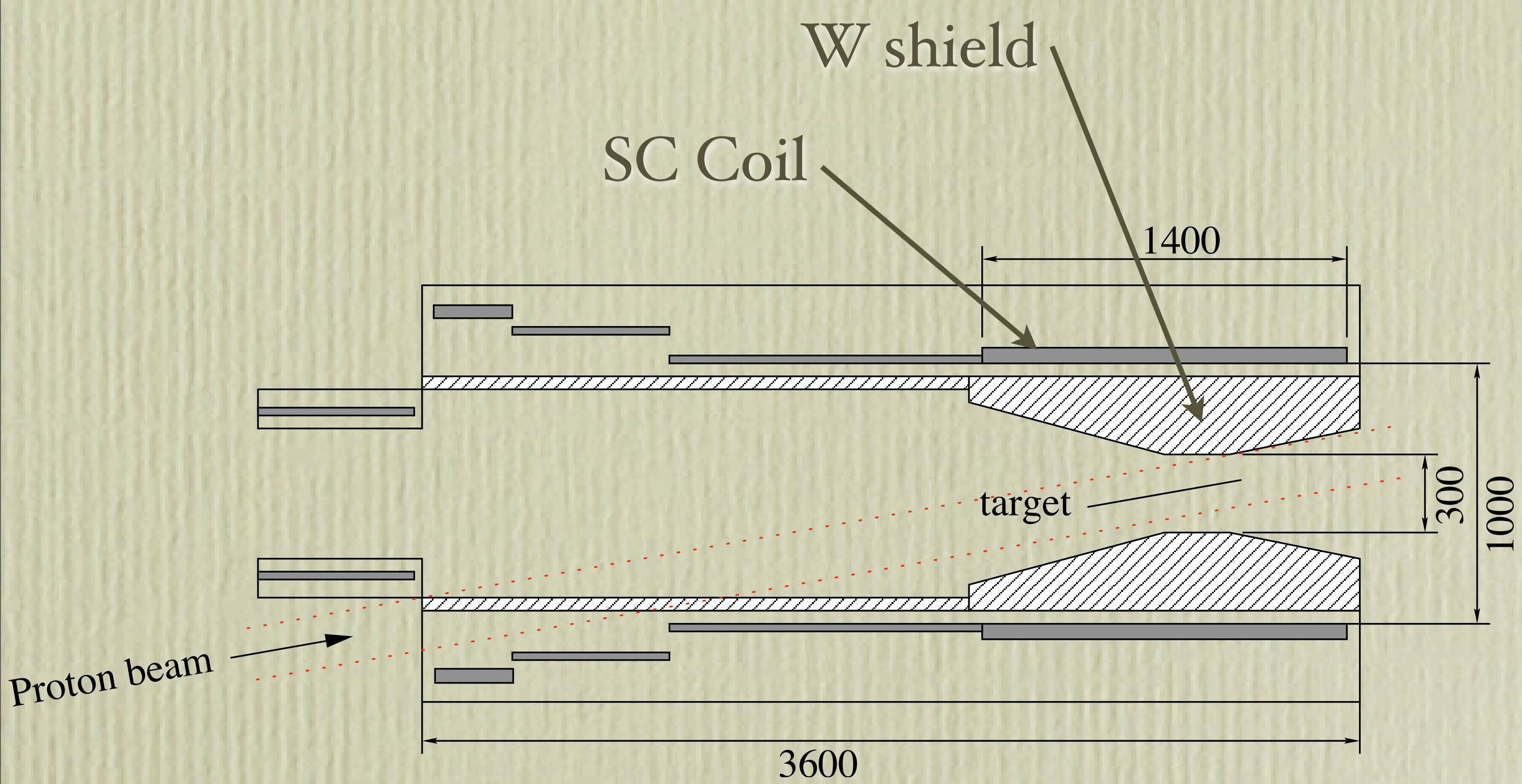
- Pion Production Target
  - Graphite : 60cm^{L}, 4cm$^{\phi}$
  - 2 kW energy dissipation for 56 kW
  - He gas cool

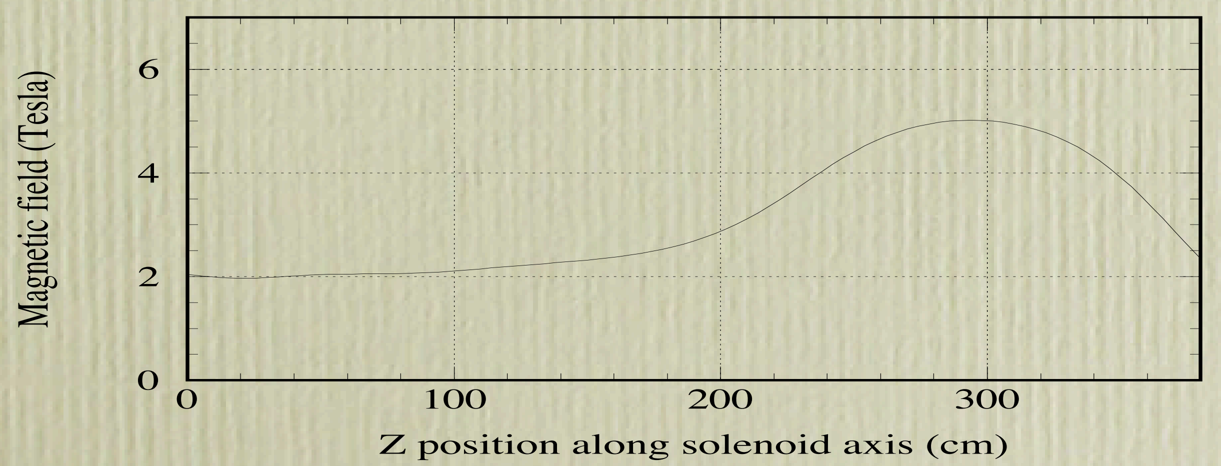


- Backward Extraction
  - Reduce high-p π-b.g.
  - Reduce heat-load to solenoids

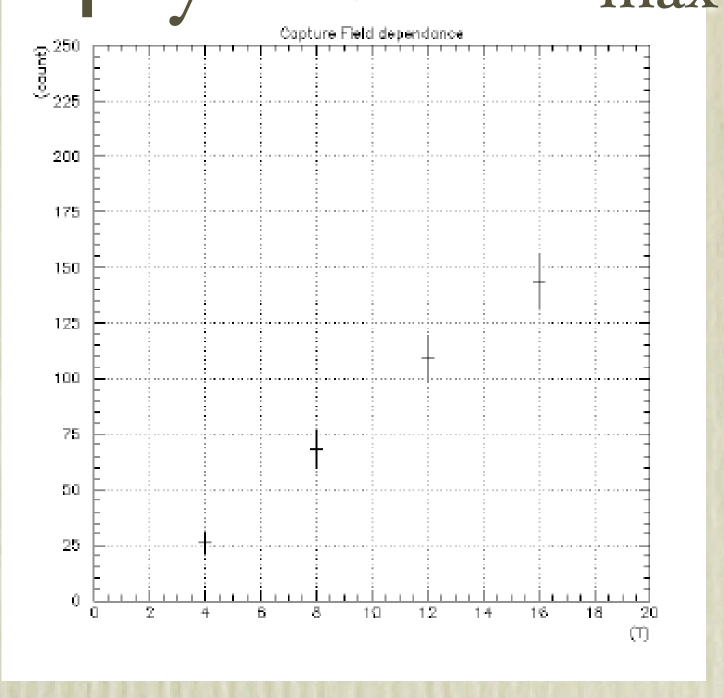
MELC, MECO idea

Pion Capture





μ-yield vs. B_{max}

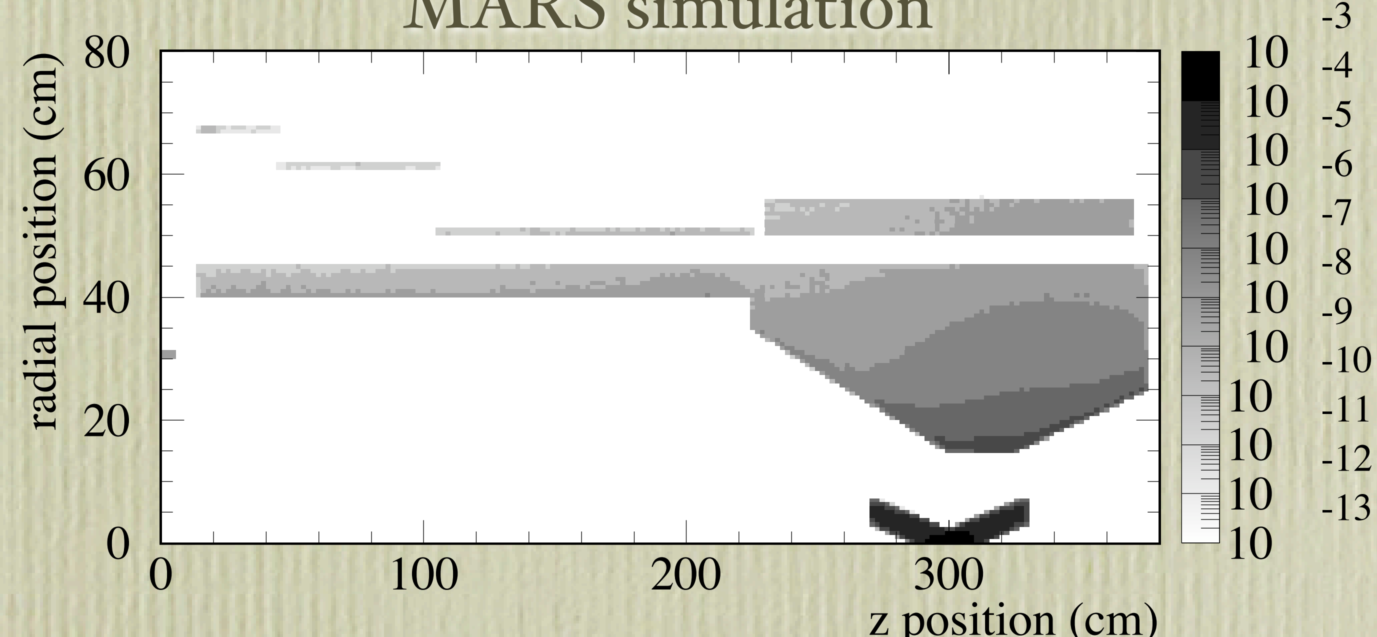


- $p_t \rightarrow p_l$
  - Parallel beam for p selection downstream
- yields : 0.05 (π+μ)/proton

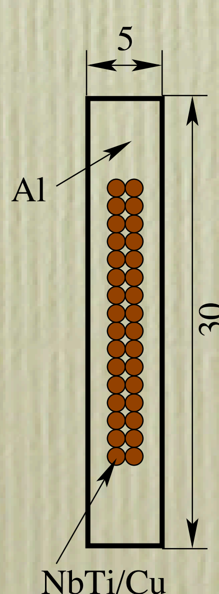
π-Solenoid

- Heat Load
  - 2 kW @ target
  - 35 kW @ W Shield
- ΔE density : 2×10^{-5} W/g behind W shield
  - 20cm-Cu SC coil : 1 kW MECO design
- Design goal < 100 W
  - 2 × 3cm-Al SC coil : 10 W
    - B = 5T, D = 300mm
    - 12.3 MJ, 12.5 kJ/kg

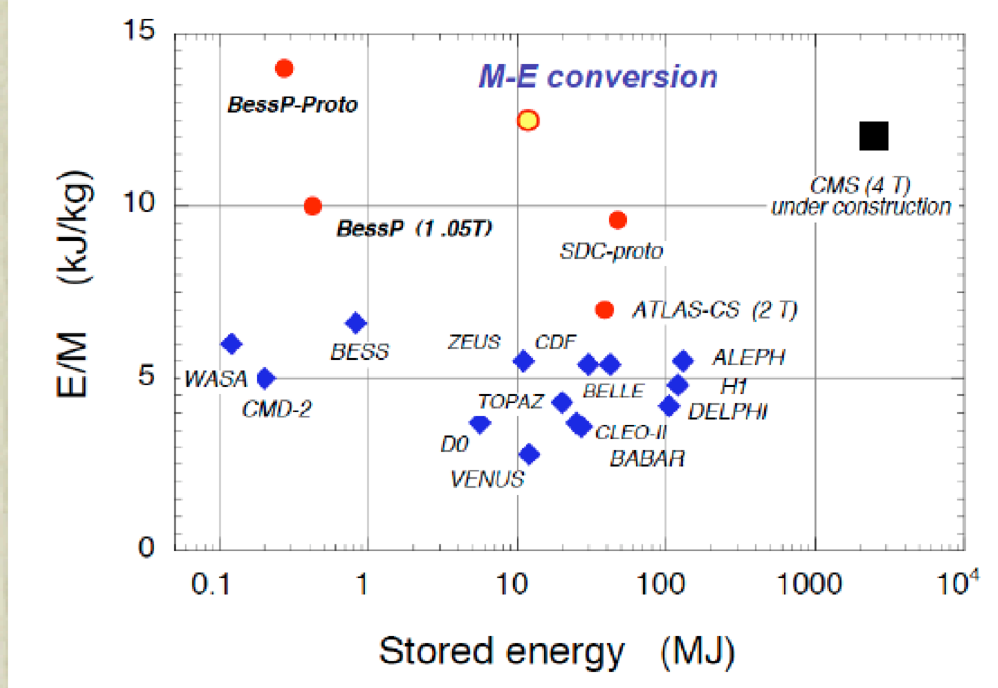
MARS simulation



Energy deposition (GeV/g/1ppp)



30 mm × 5 mm
NbTi
1.28 mm diameter
32 strands
NbTi: Cu: Al = 19%: 34%: 46%
density: 4.0 g/cm^3

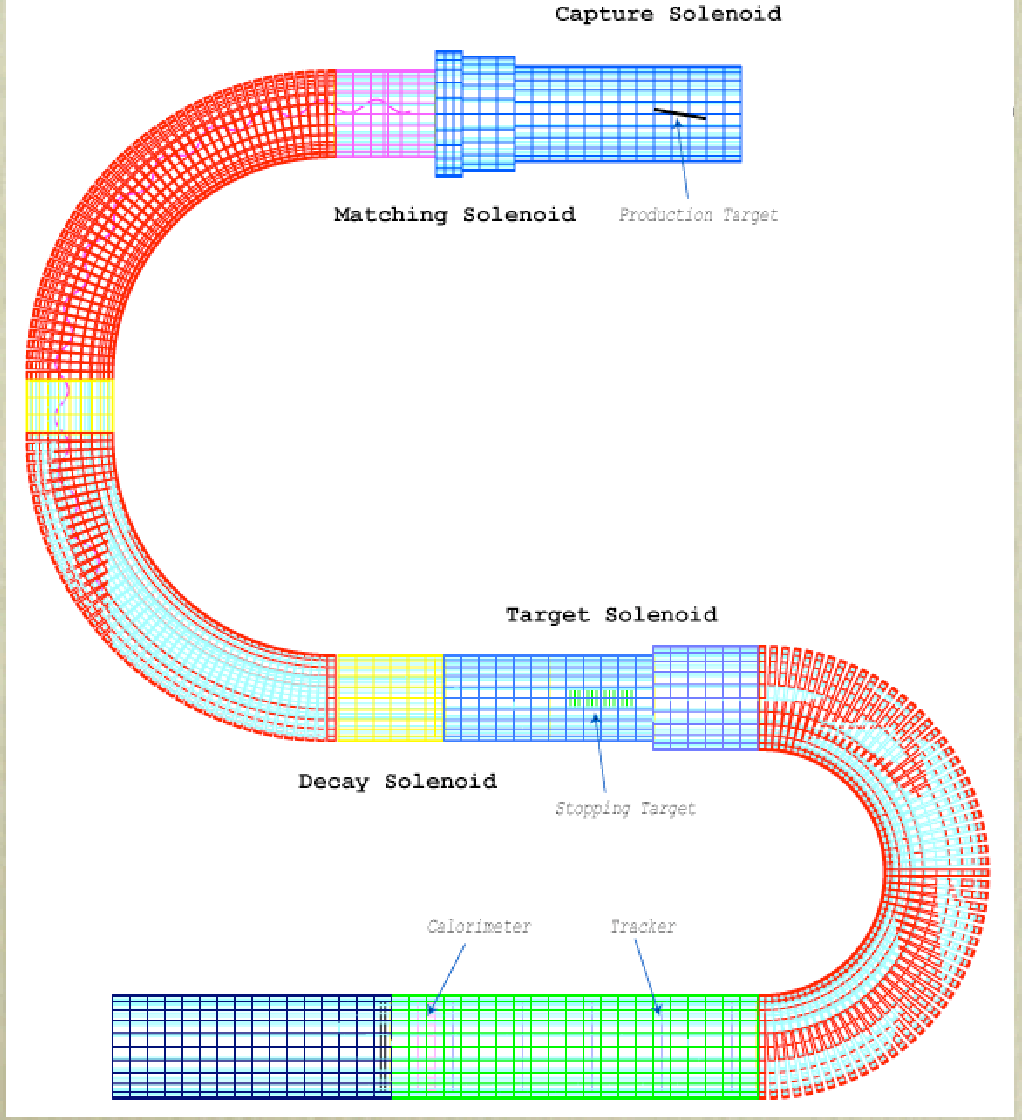


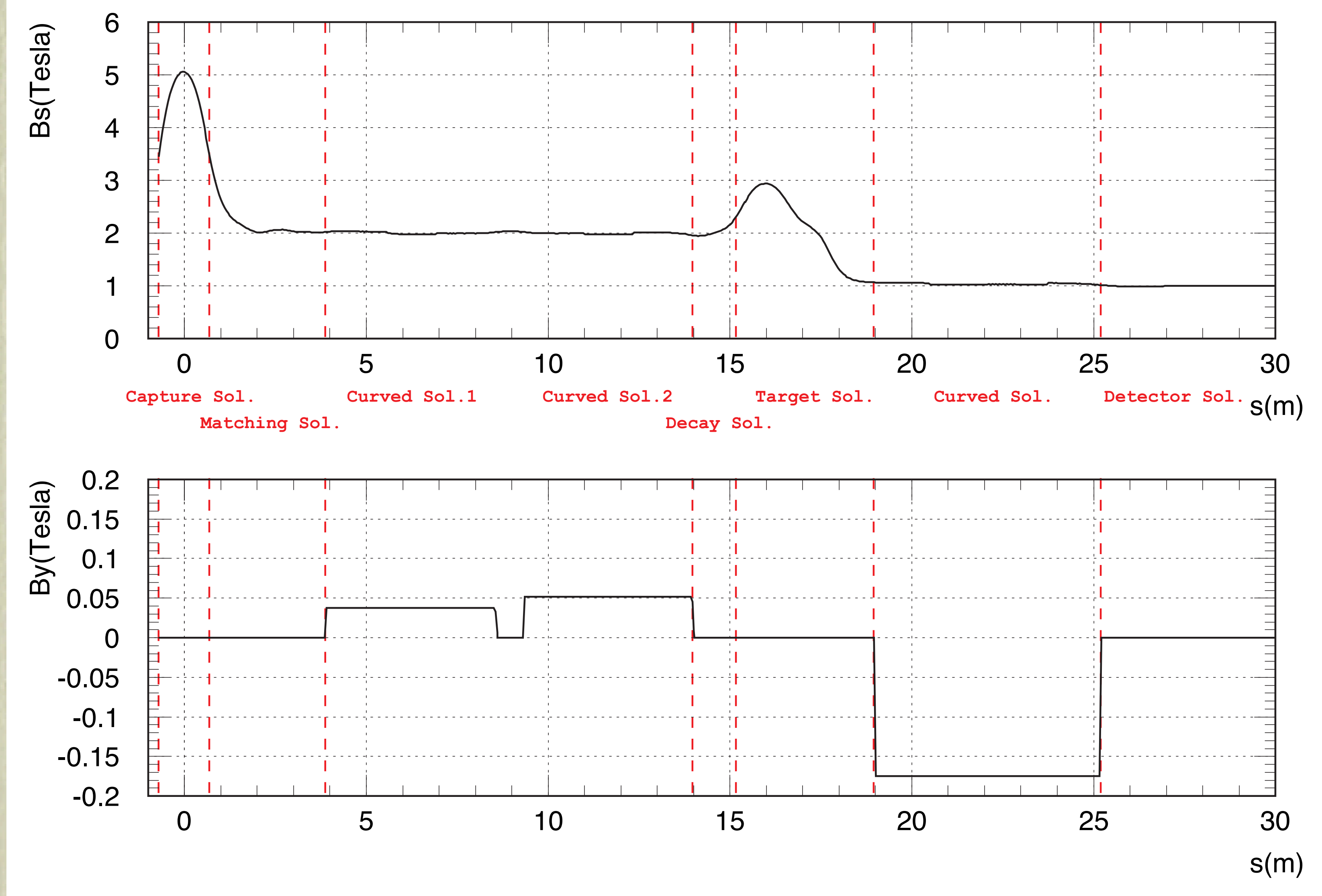
Muon Beamline

- Guide π's until decay to μ's
- Suppress unwanted particles
  - μ's : $p_\mu < 75$ MeV/*c*
  - e's : $p_e < 100$ MeV/*c*

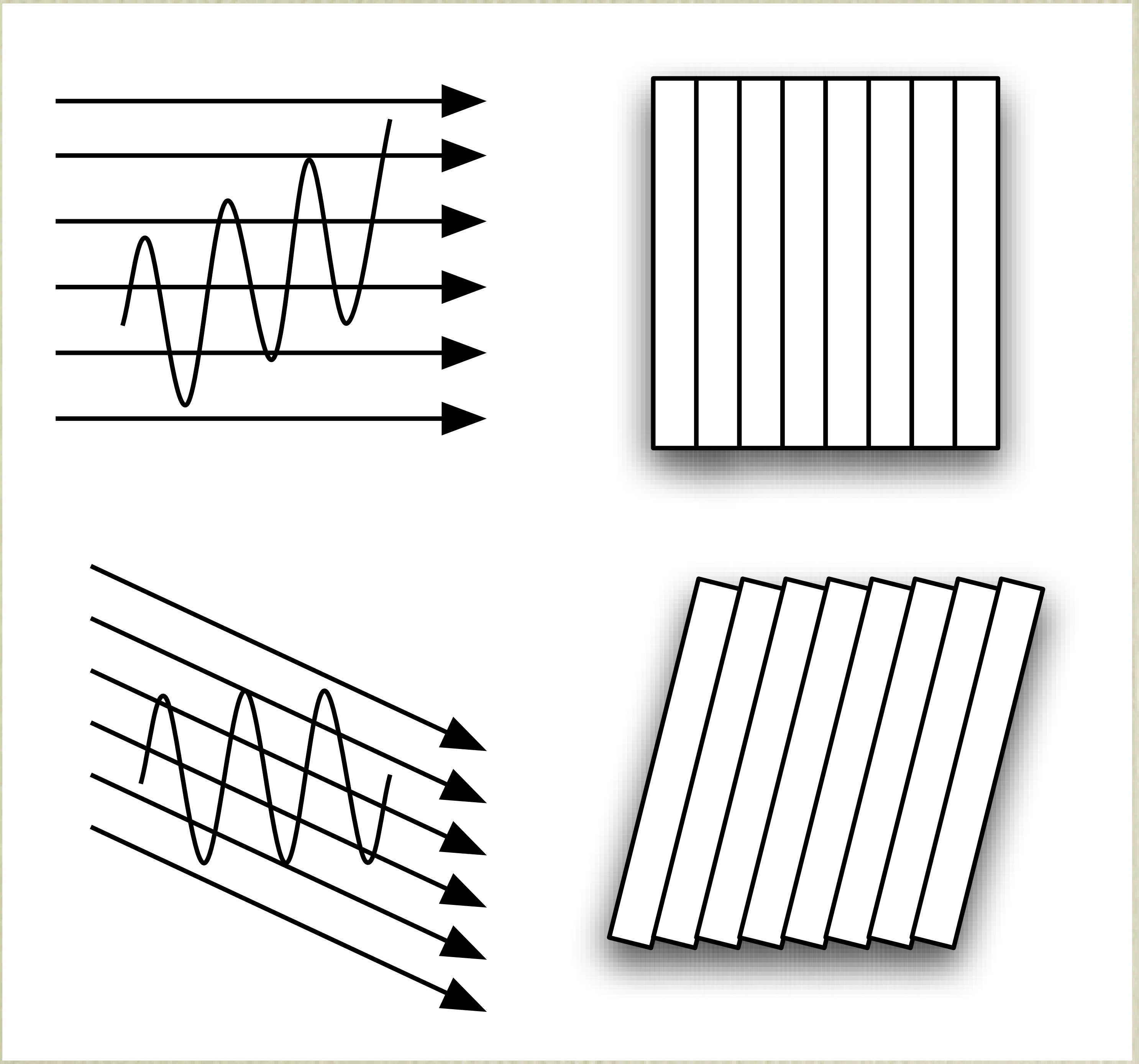
Vertical Drift in Torus

$$D[m] = \frac{1}{0.3 \times B[T]} \times \frac{s}{R} \times \frac{p_l^2 + \frac{1}{2} p_t^2}{p_l}$$

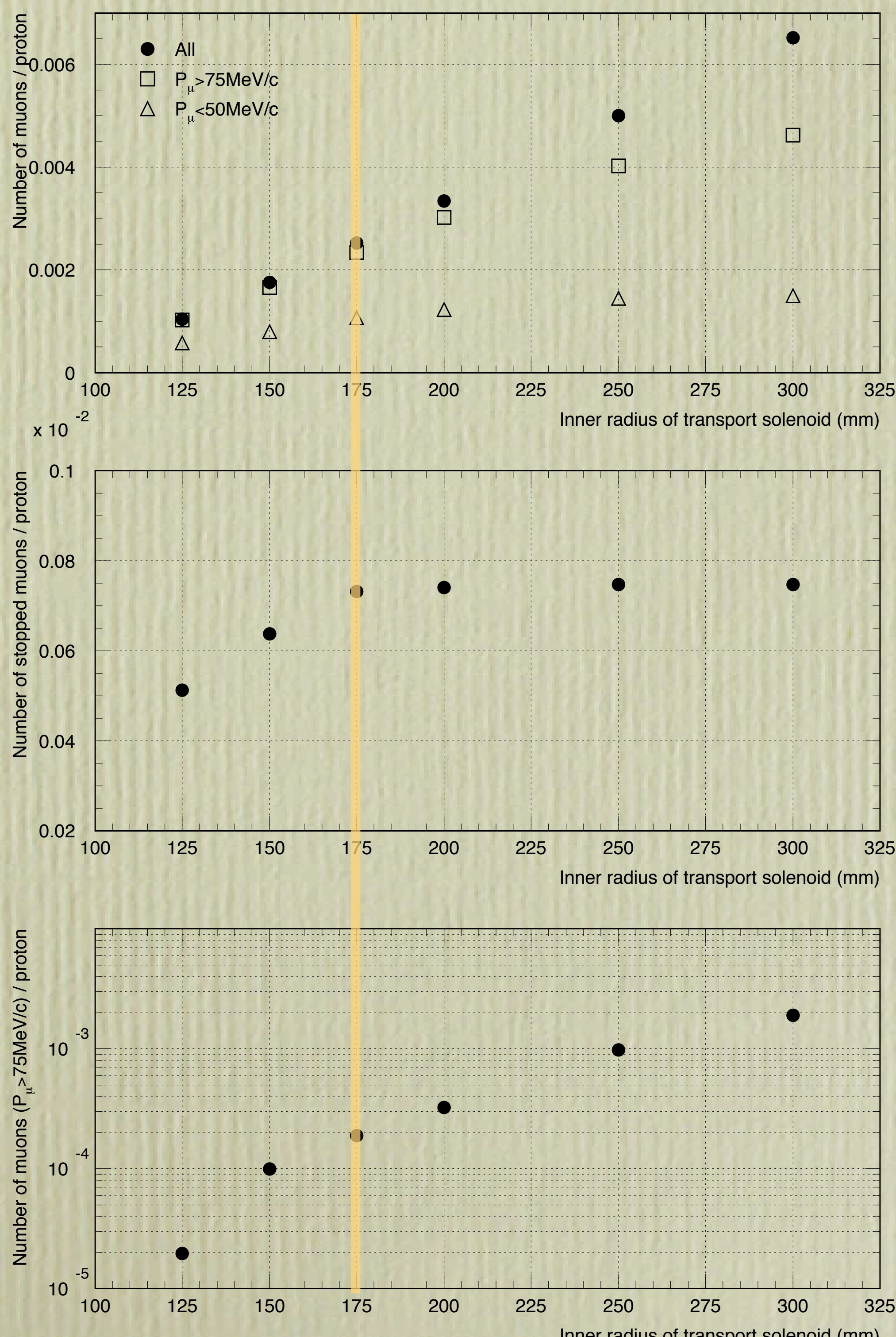




Compensative Vertical B

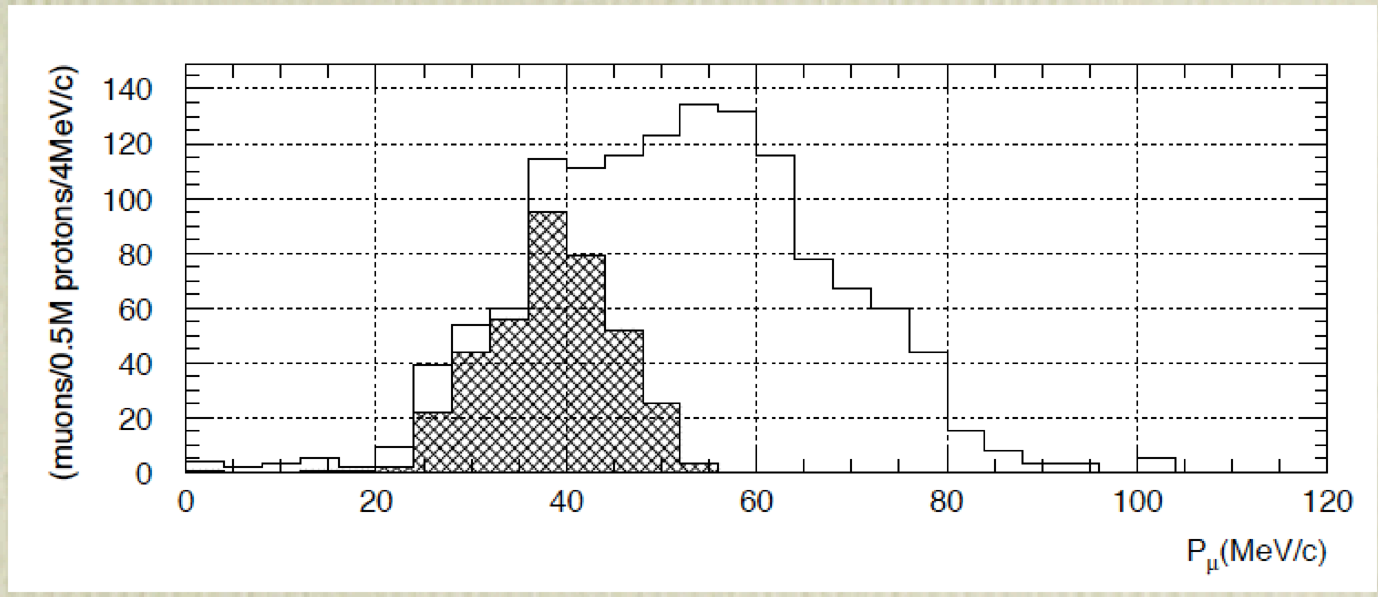


Muon Beamline Optimization



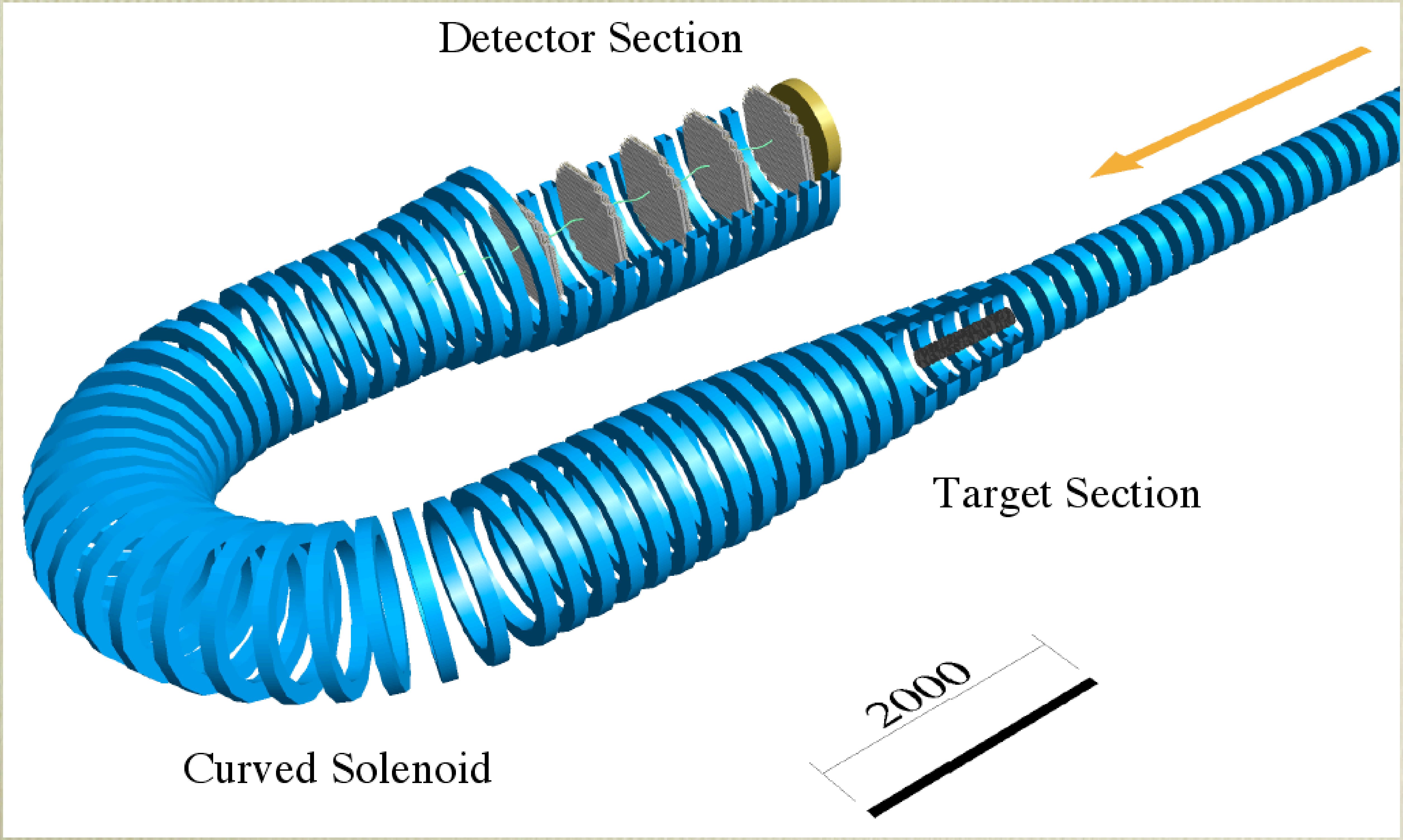
- Compensative Vertical B
  - 0.038 T and 0.052 T
- R = 175 mm
- L = 15 m (baseline)

- <u>yields : 0.002 μ's/proton</u>
  - 0.0002 (p_μ > 75 MeV/*c*)
  - 10^{-5} π's/proton

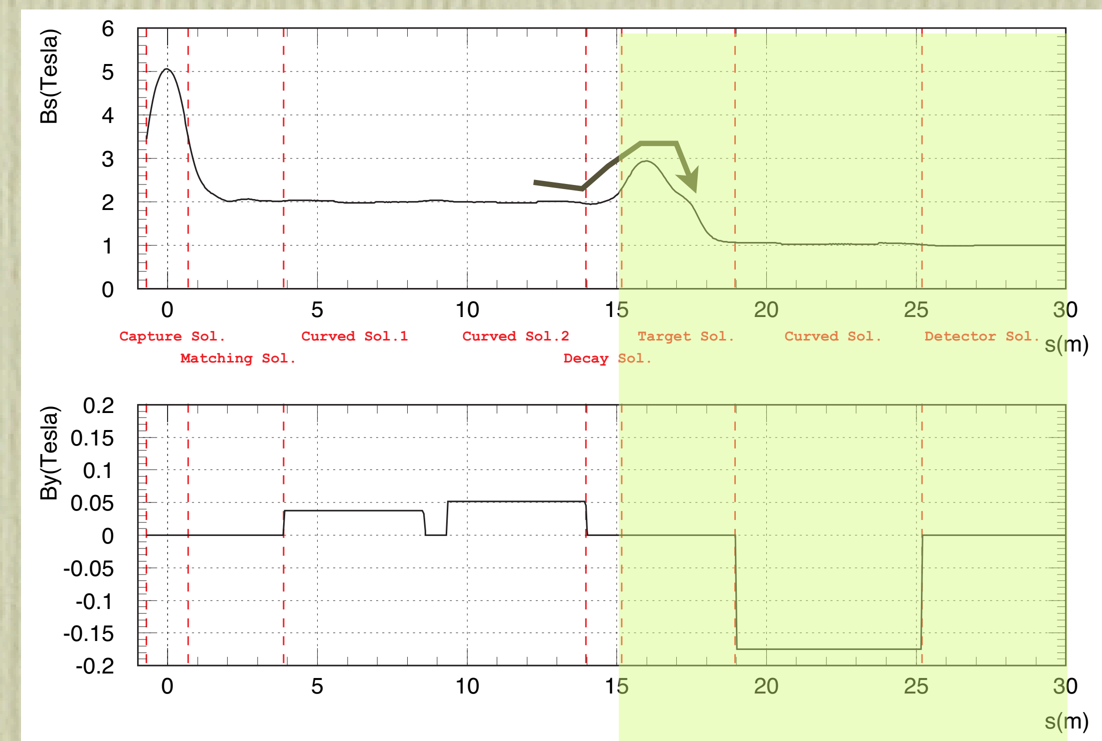


Detector

Curved Solenoid Spectrometer

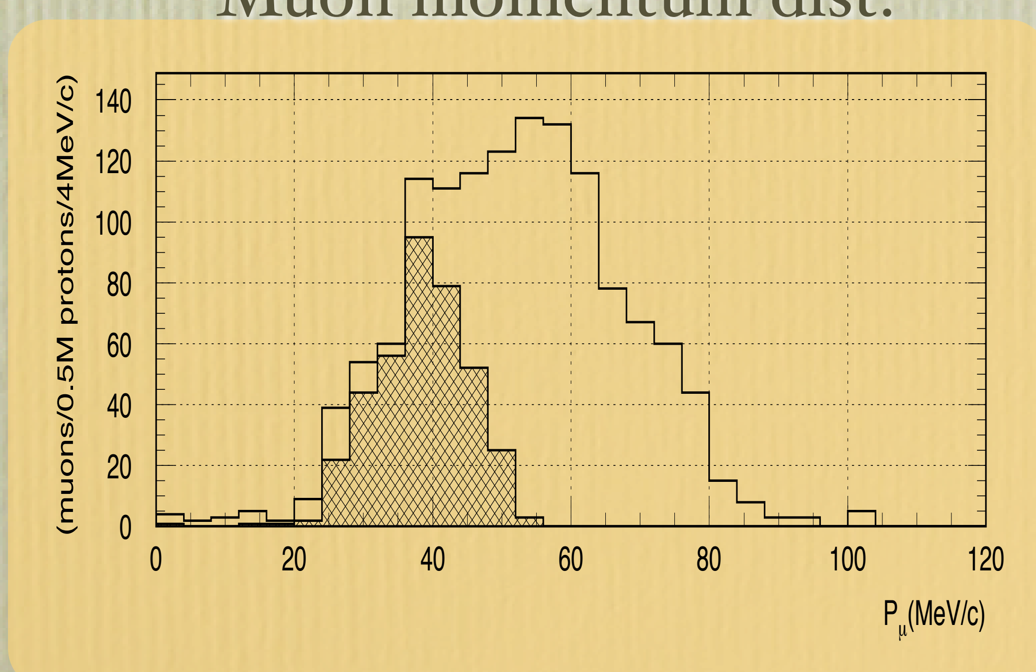


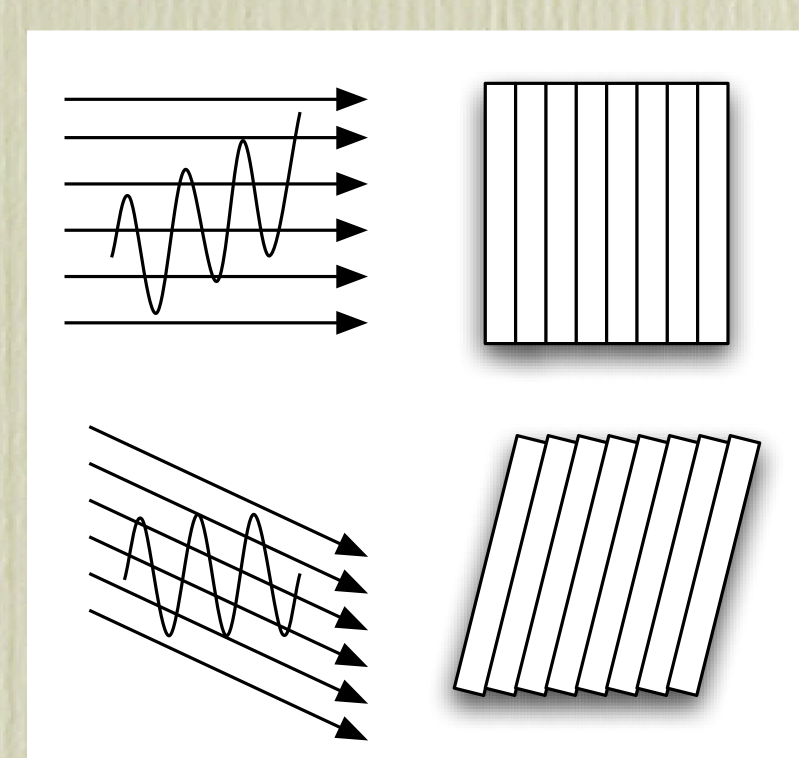
Curved Solenoid Spectrometer



- Moderate μ-Stopping ϵ
  - ϵ=0.29 (Geant4 MC)
  - 0.0007 μ-stops/proton
- Compensative vertical B
  - Select 105 MeV e^-

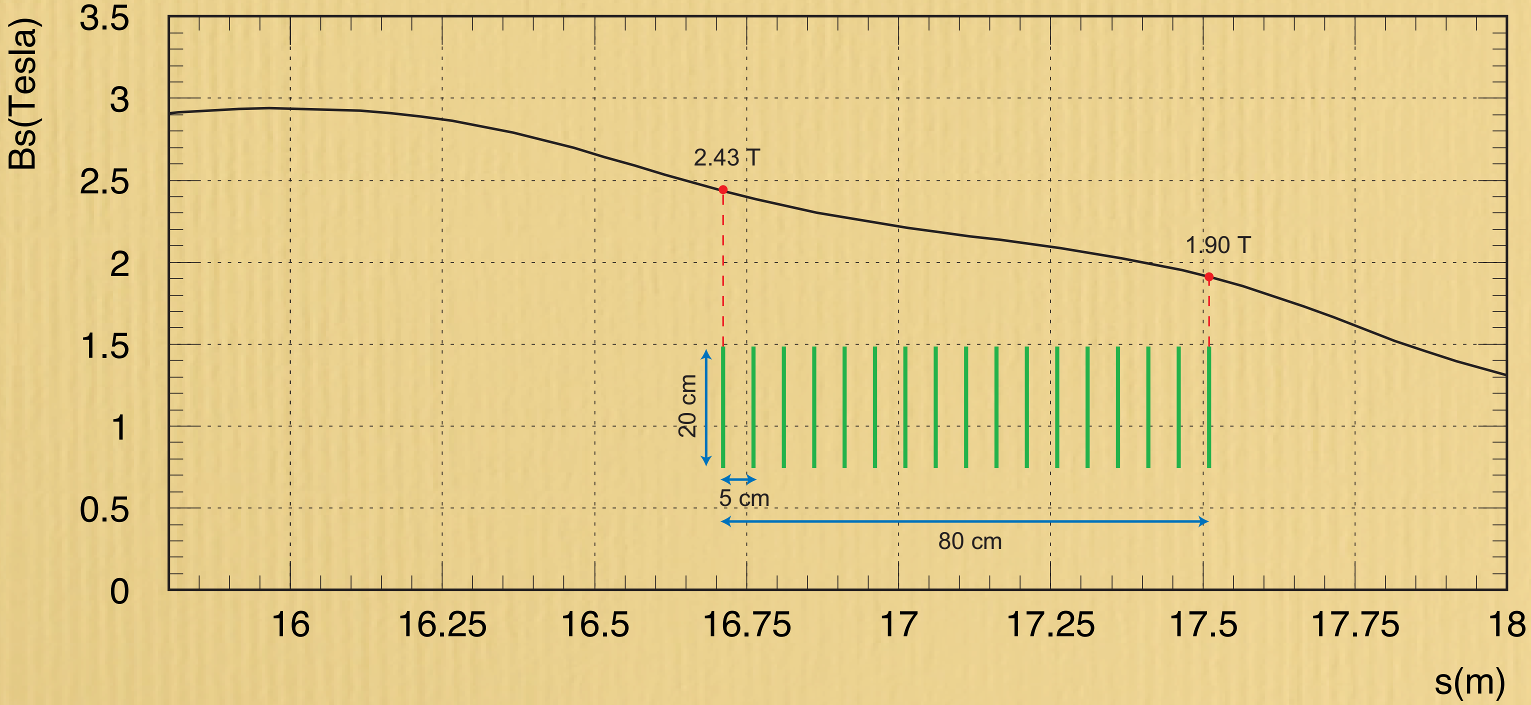
Muon momentum dist.

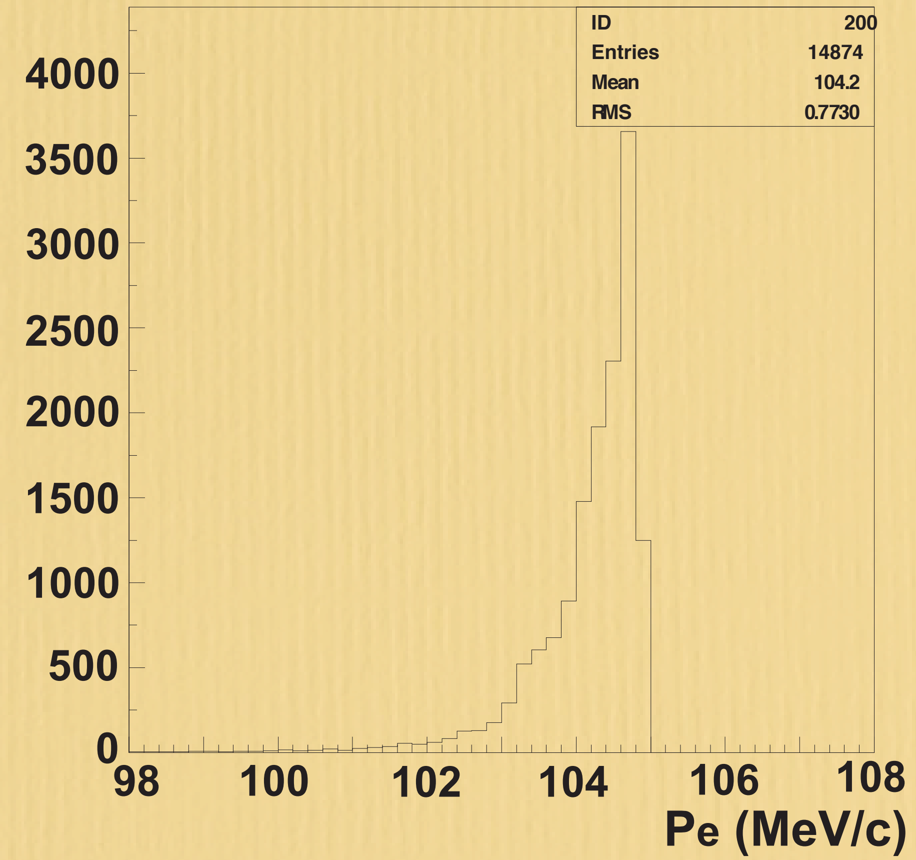




Muon Stopping Target

- Light material for delayed measurement
  - Aluminum : $\tau_{\mu^-} = 0.88\ \mu s$
- Thin disks to minimize energy loss in the target
  - R = 100 mm, 200μm^t, 17 disks, 50 mm spacing
- Graded B field for a good transmission in the downstream curved section.

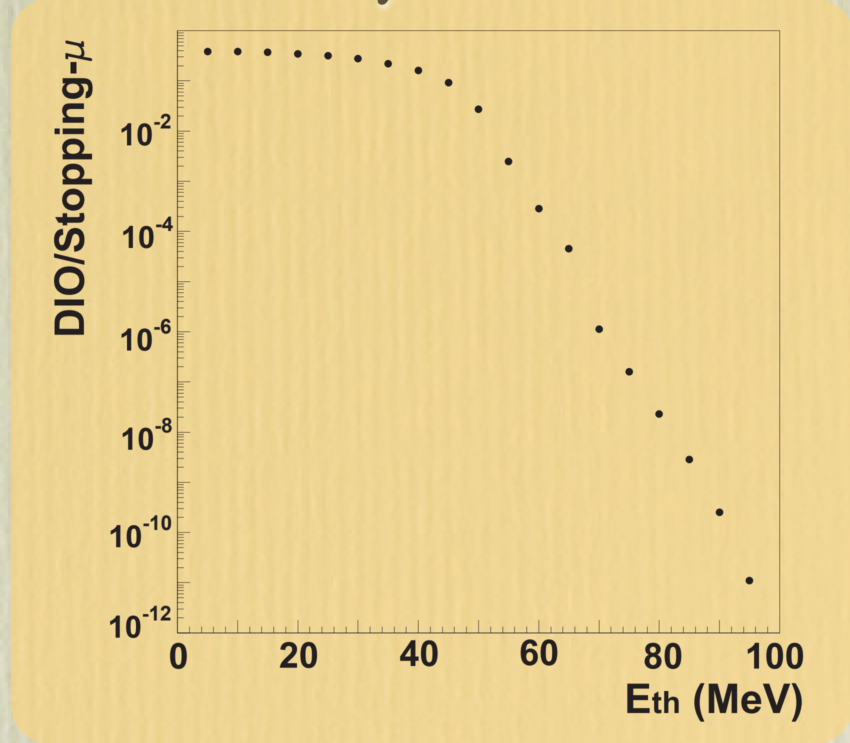


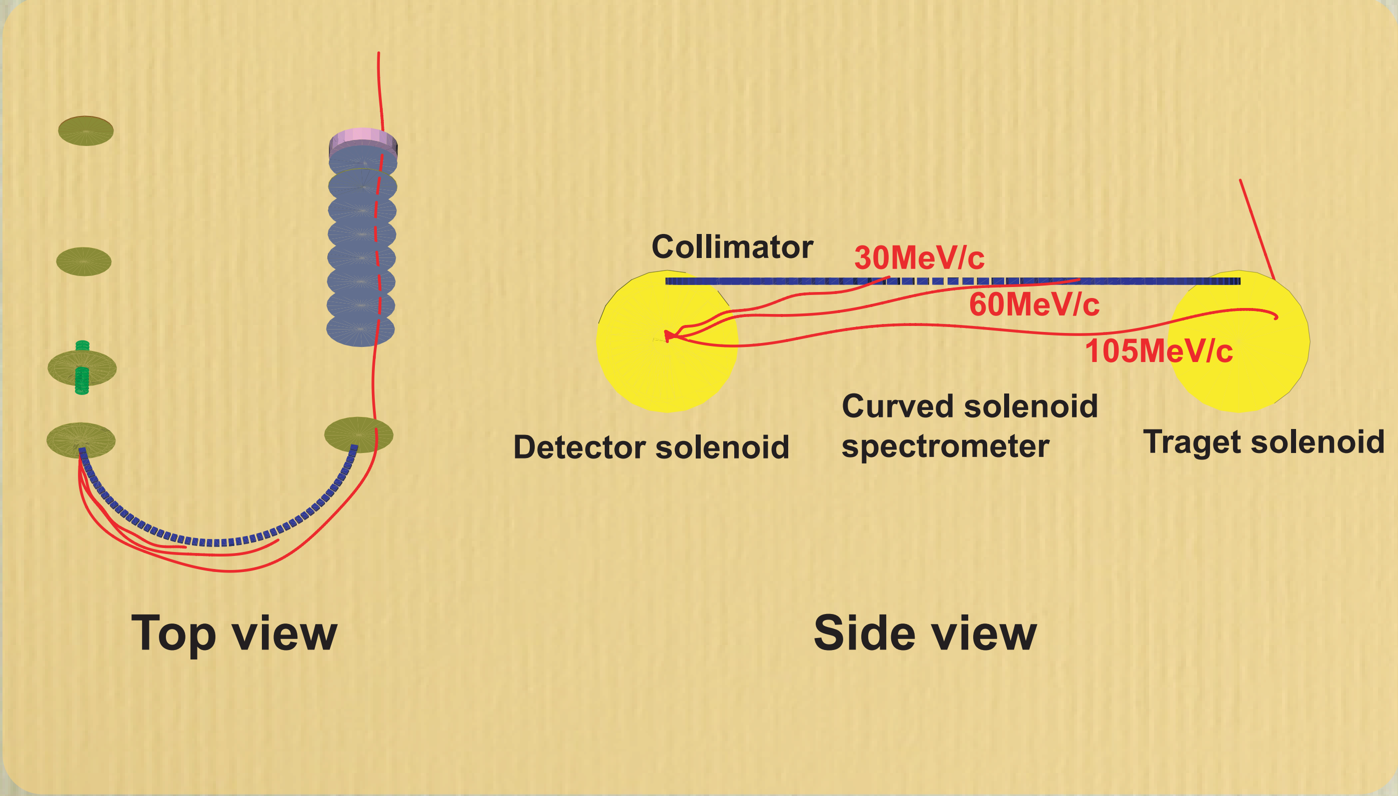


Electron Transmission

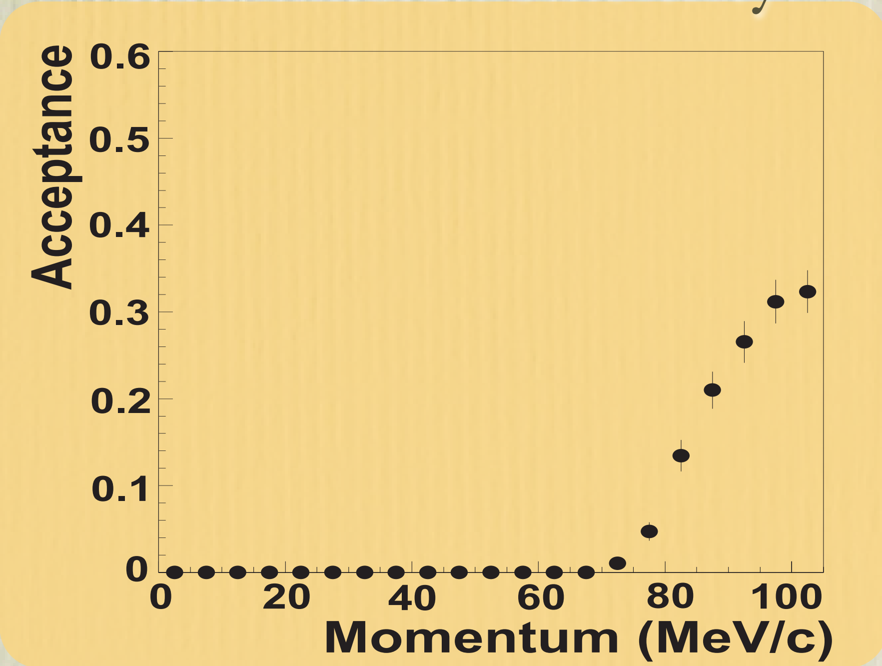
- Use torus drift for rejecting low energy DIO electrons.
  - rejection : 10^{-7}-10^{-8}, < 1kHz
- Good acceptance for signal e's
  - 30-40%

Decay-in-Orbit



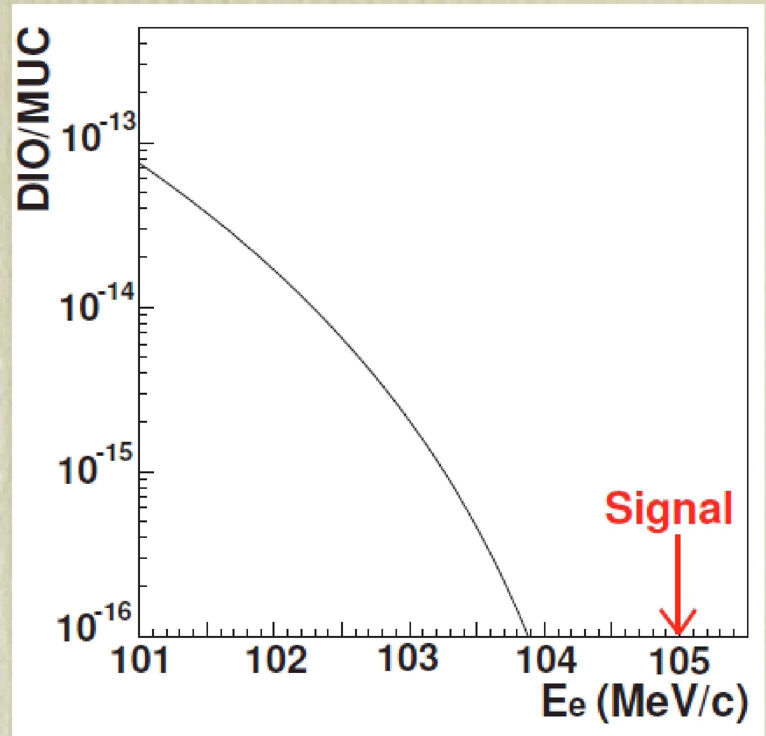


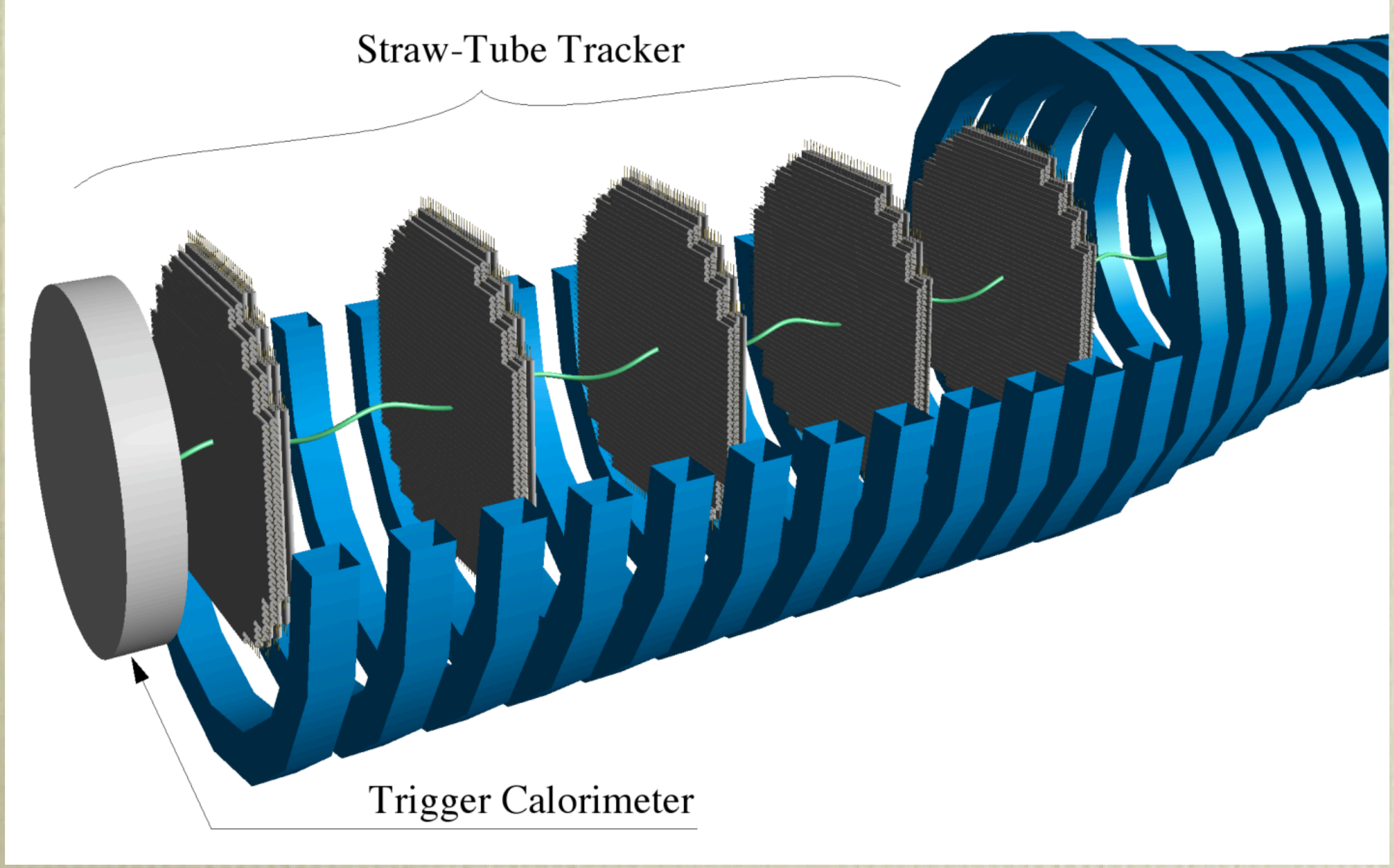
Transmission efficiency

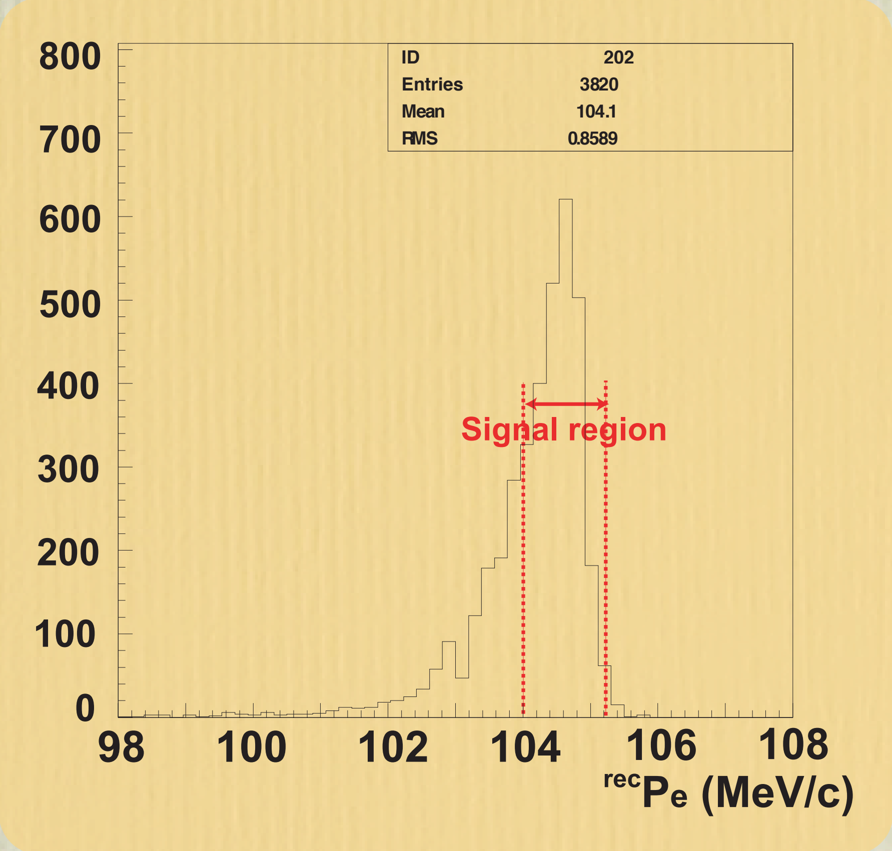


Electron Detector

- Rate < 1 kHz
- Straw-tube tracker layers
  - σp = 230 keV/c
- Trigger calorimeter

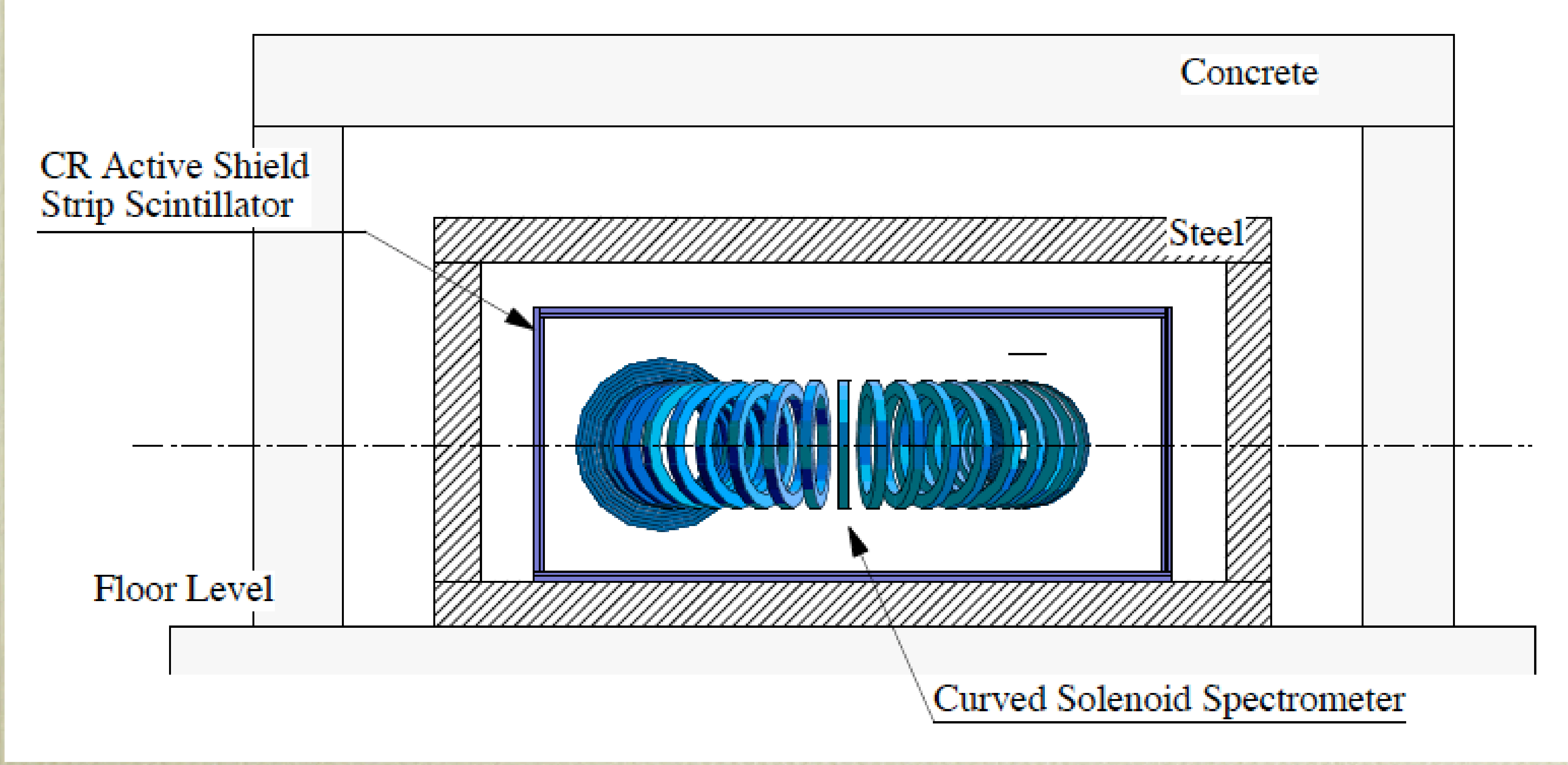






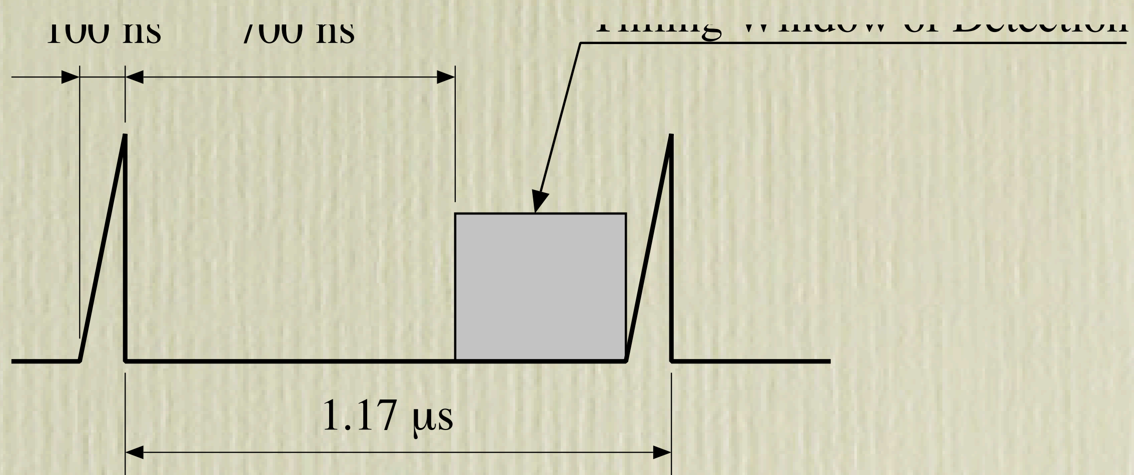
Cosmic Ray Veto

- Passive Shield
- Active Shield
  - Double layers of scintillator: 99% each
- 計測時間に比例
  - やばくなったらスピル長を縮める。



Detector Acceptance & Signal Sensitivity

	Acceptance
Geometrical Acc.	0.73
Electron Transport	0.44
Energy Selection	0.68
$p_t > 90$ MeV/c	0.82
Timing cut	0.38
Total	0.07



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

Proton Intensity	4×10^{13} Hz
Running Time	2×10^{7} sec
μ's yields per proton	0.0024
μ-stopping efficiency	0.29
Total	5.6×10^{17} stopped μ's

- $N_\mu = 5.6 \times 10^{17}$
- $f_{cap} = 0.6$ for Aluminum
- $A_e = 0.07$
- $B(\mu^- + Al \rightarrow e^- + Al) = 4 \times 10^{-17}$
  $< 10^{-16}$ (90% C.L.)

Background

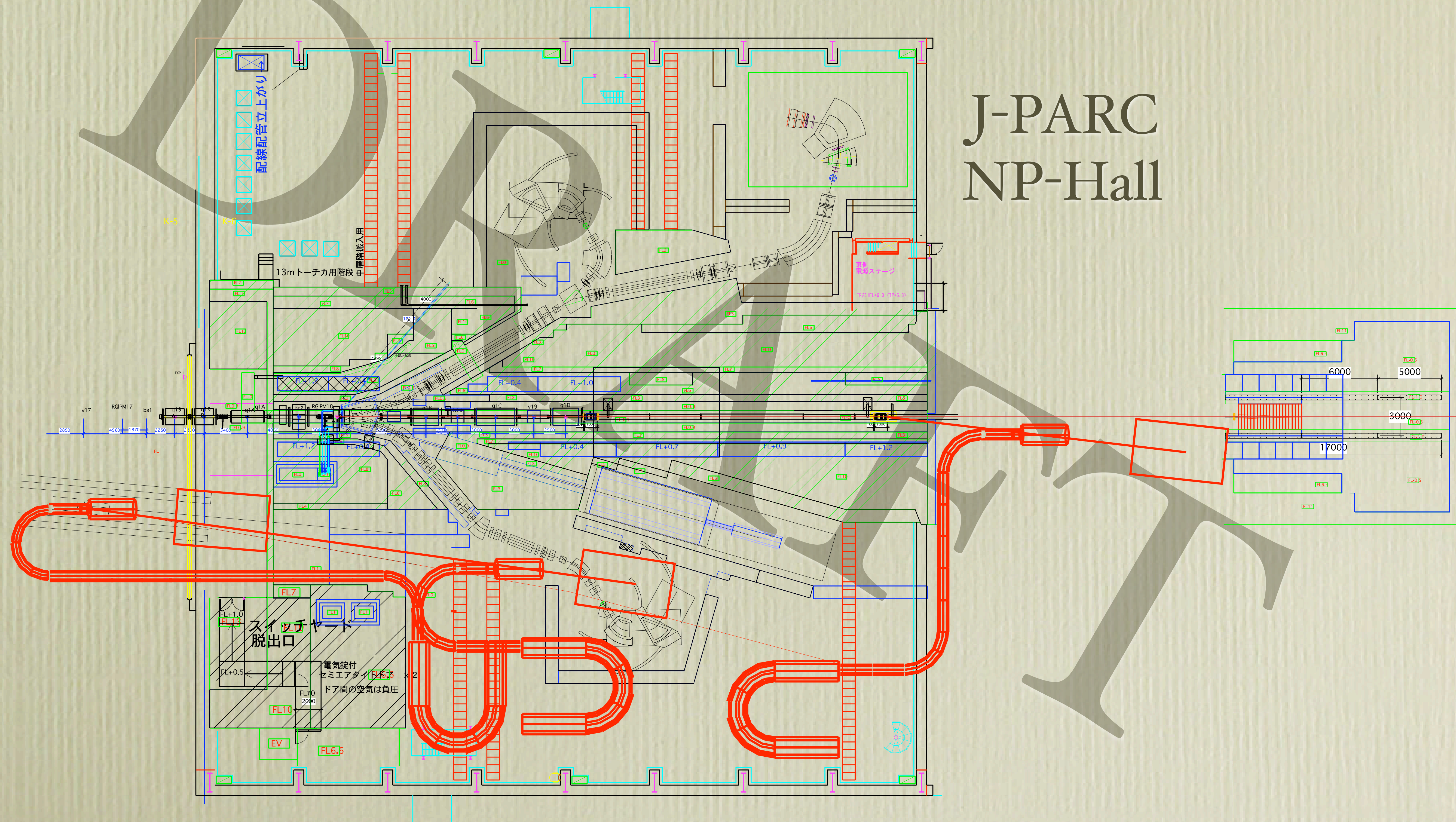
Background estimates for 10^{-16}

*: assuming the extinction 10^{-9}

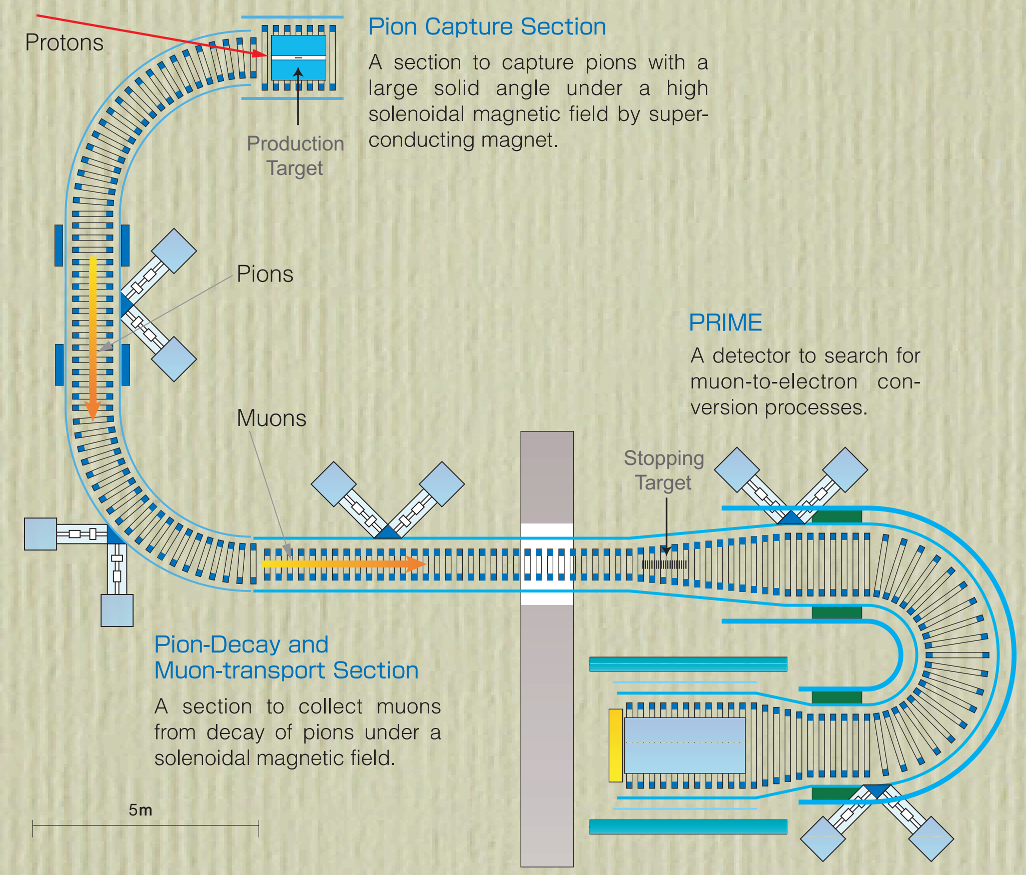
Background	Events	Comments
Muon decay in orbit	0.05	230 keV (sigma) assumed
Pattern recognition rrrors	<0.001	
Radiative muon capture	<0.001	
Muon capture with neutron emission	<0.001	
Muon capture with charged particle emission	<0.001	
Radiative pion capture*	0.12	prompt pions
Radiative pion capture	0.002	due to late arriving pions
Muon decay in flight*	< 0.02	
Pion decay in flight*	< 0.001	
Beam electrons*	0.08	
Neutron induced*	0.024	for high energy neutrons
Antiproton induced	0.007	for 8 GeV protons
Cosmic rays induced	0.04	with 10^{-4} veto inefficiency
Total	0.34	

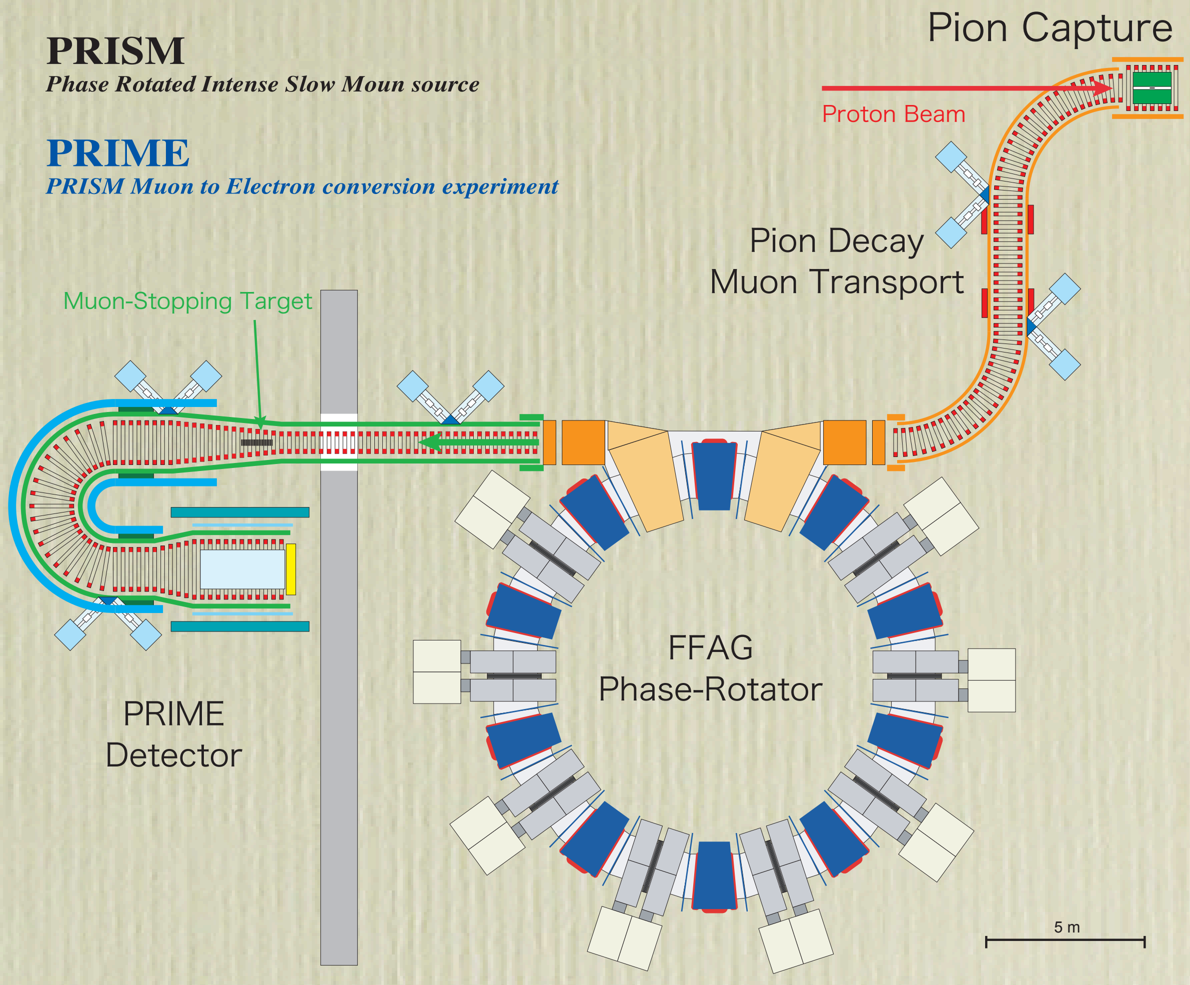
Straw-man's Layouts

J-PARC
NP-Hall



Toward full PRISM





Phase-1: $R<10^{-16}$

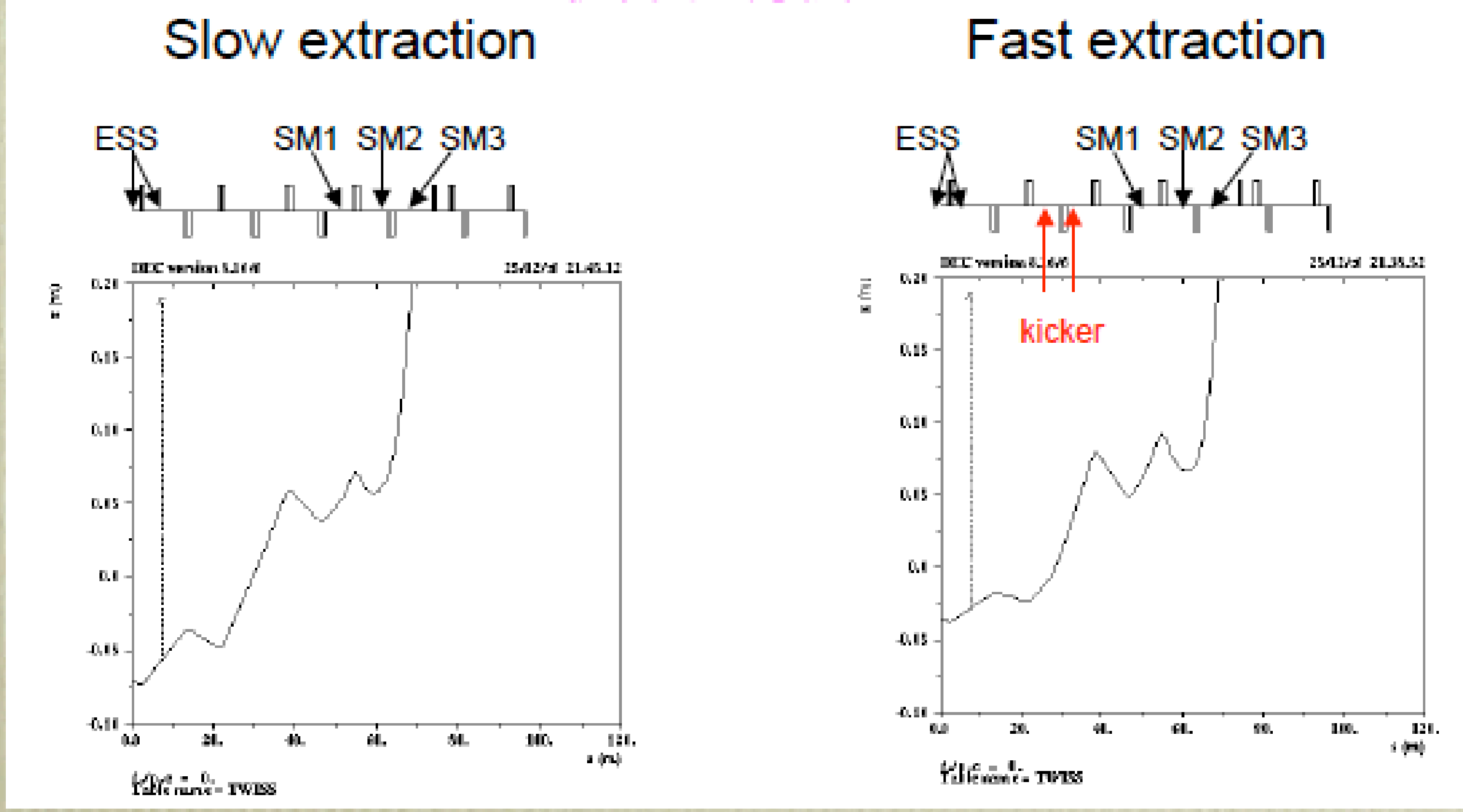
Full PRISM: $R<10^{-18}$

- Same Beam line, Detector
- Replace Target & π-Cap. Solenoid
- Add FFAG Phase -Rotator
- Fast-Extracted Proton Pulse

Full PRISM at NP-Hall

Fast Extraction (to NP-Hall) Scheme exist

- Add 2 kickers
- Slow bump ON, E Septum OFF, M Septum all ON
- Need more study, but promising.



- Precise measurement
- Target A dependency
  - Interaction type
- By-products

MECO,mu2e and Phase-1

	MECO	mu2e	Phase-1
Machine	BNL/AGS	FNAL/Debuncher	J-PARC/MR
Energy	7.5 GeV/c	8 GeV/c	8 GeV/c
Pulse	1.4 μs	1.7 μs	1.1 μs
Extraction	Bunched Slow	←	←
Target	Tungsten	←	Graphite
Muon Beamline	Curved Solenoid	←	Curved Solenoid + Vertical Field
μ stop	10^{11} muons/s	←	10^{11} muons/s
Detector	Straight	←	Curved
Rate	500 kHz/wire	←	300 DIO tracks/s
Sensitivity	10^{-16}	←	←
Upgradability	NO	Project-X	PRISM(10^{-18})

Japan & Fermilab:
Collaboration work on pulsed-proton beam
AC-dipole, Extinction Monitor, etc.

まとめ

- μ-e電子転換過程はc-LFVの一つであり、μ→eγやμ→eeeと共に重要なテーマである。
- LHCの後でもその重要に違いは無い。
- BR=10^{-16} での μN→eN をJ-PARCで実行するべく準備中である。
    - LoI提出済み:P21
    - 現在プロポーザル準備中
    - web page: http://nasubi.hep.sci.osaka-u.ac.jp:8080/prime/
- コラボレーターを募集しています。一緒にμN→eNをやりませんか。

End of Slides