

# J-PARCハドロン実験室における ミュオン電子転換過程探索実験

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大阪大学 大学院理学研究科 佐藤 朗

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大阪大学核物理研究センター

# 内容

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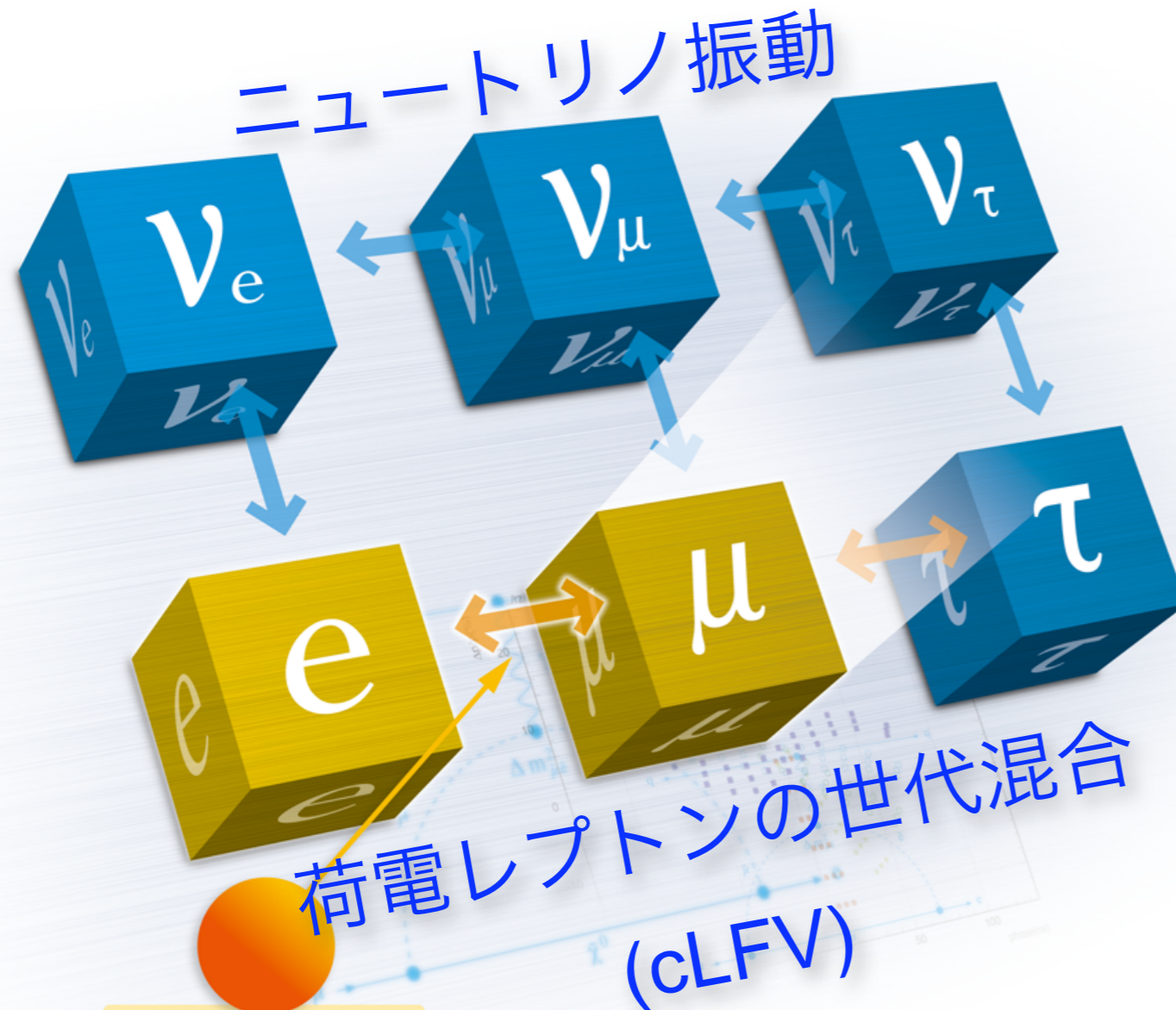
- 物理
  - 荷電レプトンにおけるレプトンフレーバー保存の破れ
- 背景
  - ミューオン電子転換過程とは
  - 探索実験の現状と将来計画
- J-PARCでの実験
- まとめ



荷電レプトンにおける  
レプトンフレーバー保存の破れ (cLFV)

# 荷電レプトンのレプトンフレーバ保存の破れ

- クォークの混合：CKM行列
- レプトンの混合：標準理論( $m_\nu=0$ )では反応の前後で世代毎のレプトン数が保存される。
  - $\nu$ 振動の発見により中性レプトンではレプトンフレーバ保存が破れた。MNS行列
  - 荷電レプトンでは未だ発見されていない。本当にないのか？



## cLFVの例

$$\mu^+ \rightarrow e^+ \gamma$$

$$L_\mu : -1 \quad 0$$

$$L_e : 0 \quad -1$$

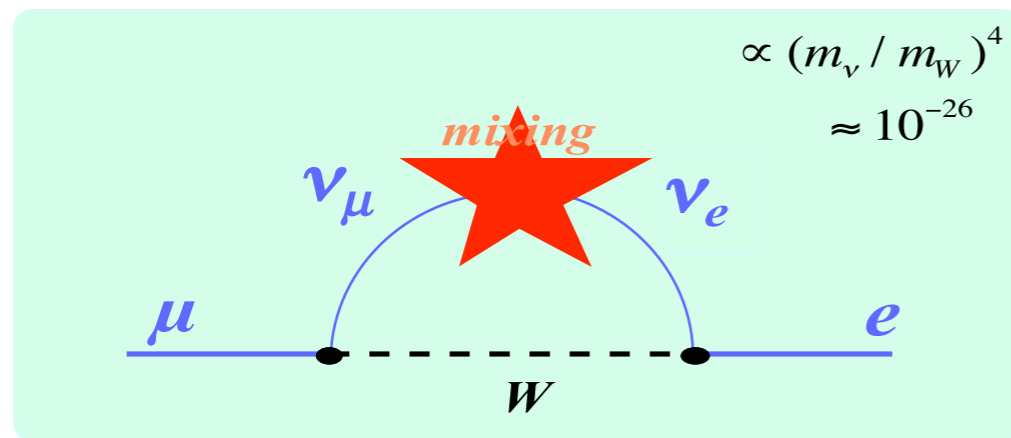
$$\mu^+ \rightarrow e^+ e^- e^+$$

$$L_\mu : -1 \quad 0 \quad 0 \quad 0$$

$$L_e : 0 \quad -1 \quad +1 \quad -1$$

# cLFV過程は起こる

- ニュートリノ振動を考慮した標準理論では、ニュートリノの世代混合により cLFV過程が起こる。



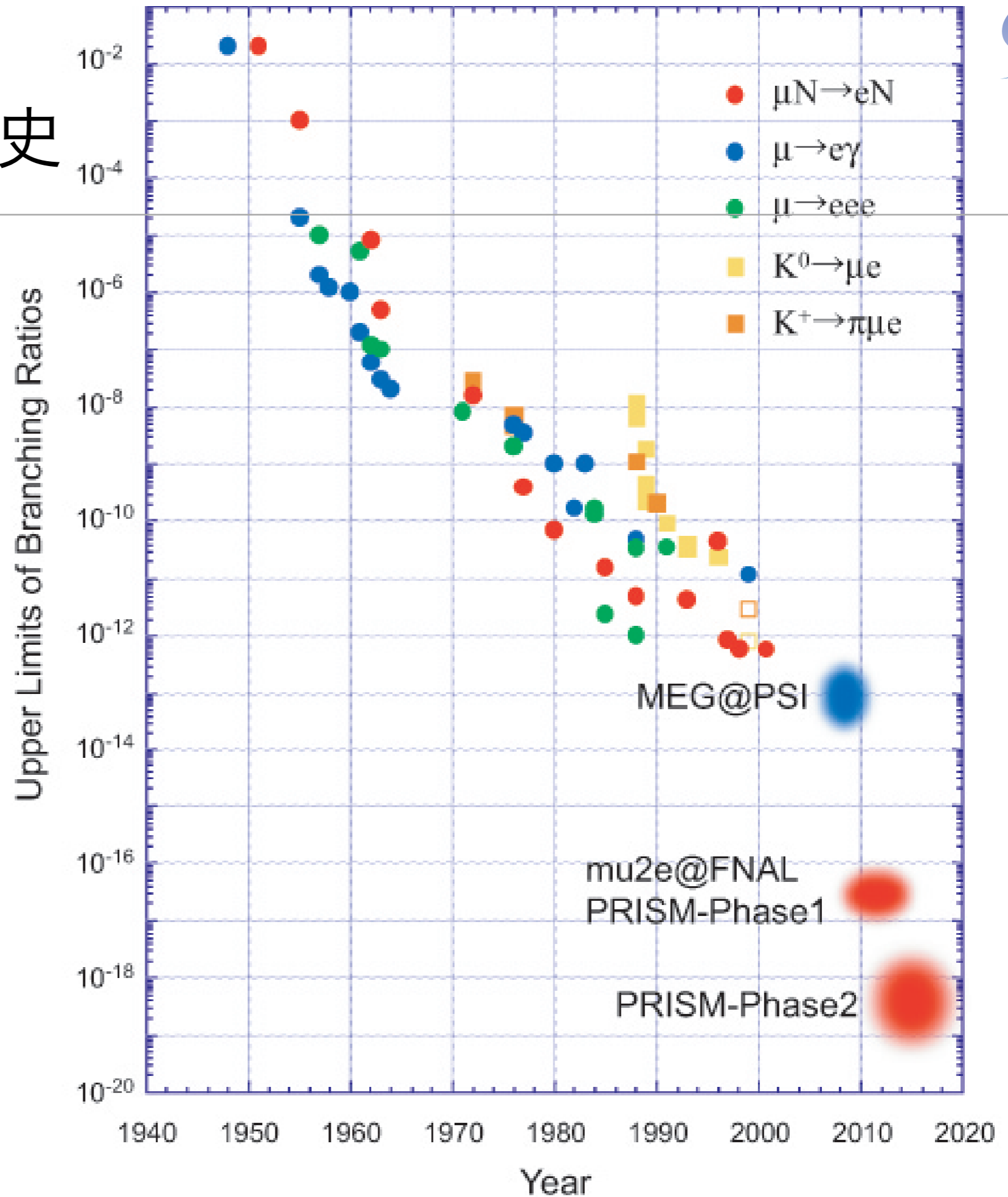
$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{ei}^* \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \simeq 10^{-60} \left( \frac{m_\nu}{10^{-2} \text{ eV}} \right)^4$$

- しかし、その分岐比の予言値は $O(10^{-50})$ と小さく実験観測にはかからない。

**cLFV過程の発見は新物理を意味する。**

多くの理論モデルが大きなcLFV分岐比を予言している。  
 実験感度を数桁向上させることで発見の可能性がある。

# cLFV探索の歴史

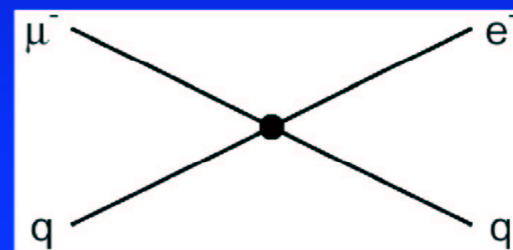
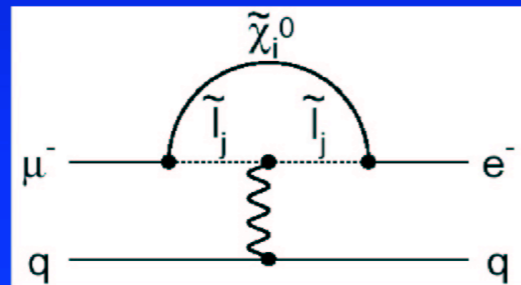


# Various Model Predict Charged Lepton Mixing

## Sensitivity to Different Muon Conversion Mechanisms

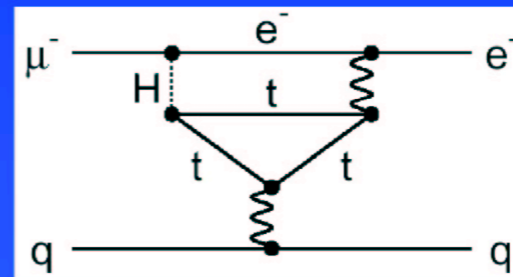
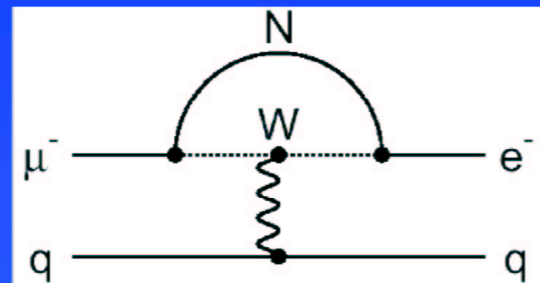


Supersymmetry  
Predictions at  $10^{-15}$



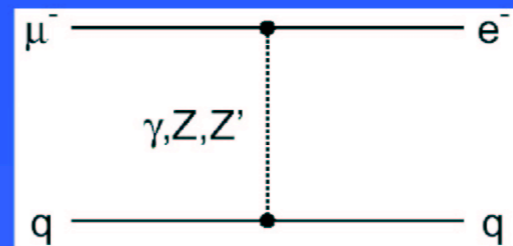
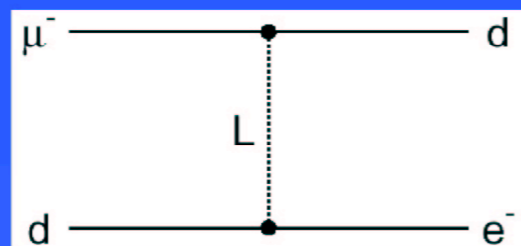
Compositeness  
 $\Lambda_c = 3000 \text{ TeV}$

Heavy Neutrinos  
 $|U_{\mu N}^* U_{eN}|^2 = 8 \times 10^{-13}$



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

Leptoquarks  
 $M_L = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$

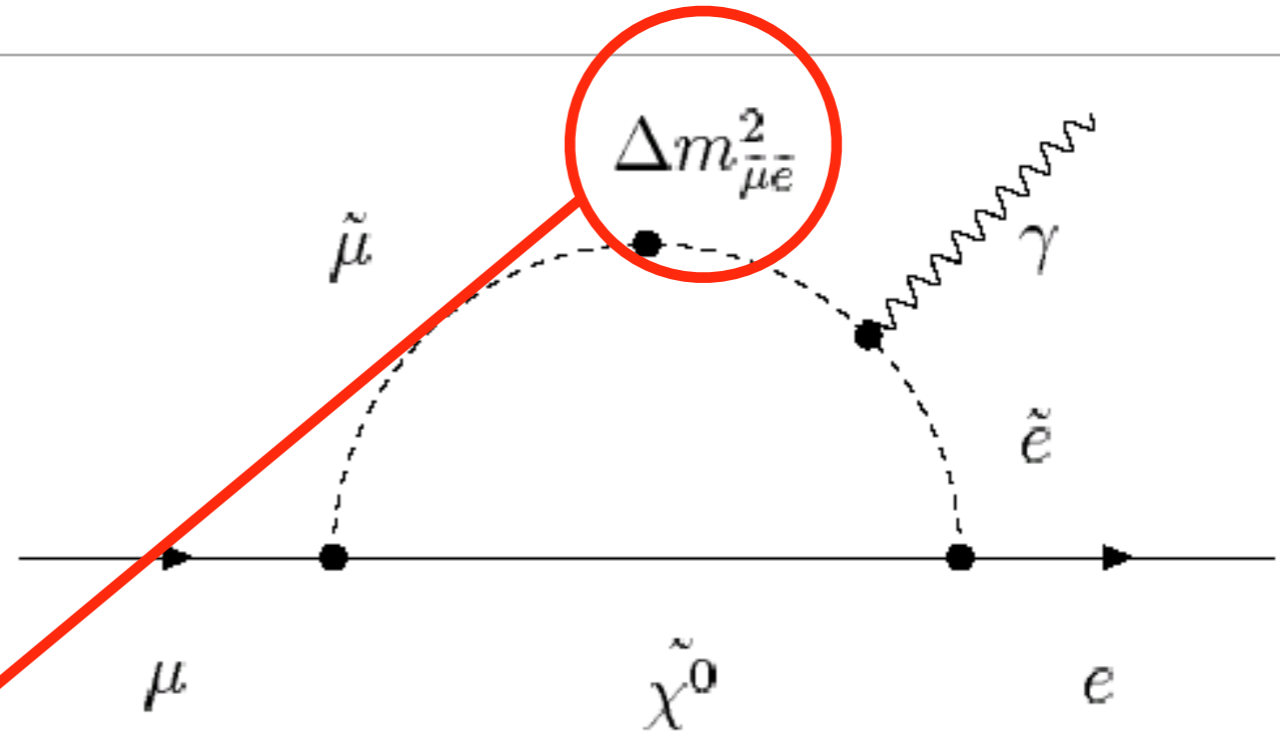


Heavy  $Z'$ ,  
Anomalous  $Z$   
coupling  
 $M_Z = 3000 \text{ TeV}/c^2$   
 $B(Z \rightarrow \mu e) < 10^{-17}$

After W. Marciano

# Charged Lepton Mixing by SUSY

$$\mu^+ \rightarrow e^+ \gamma$$



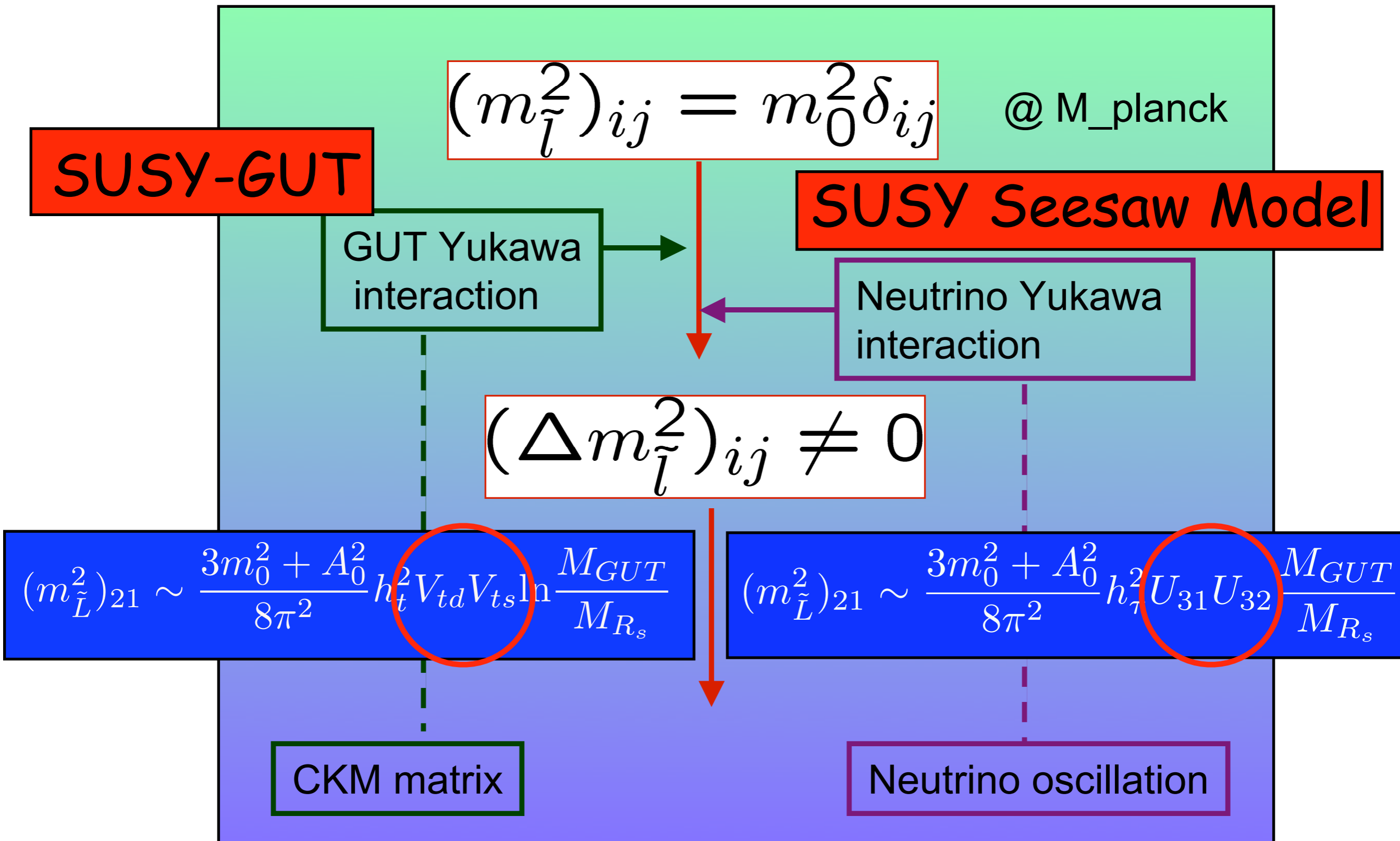
$$m_{\tilde{l}}^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

In SUSY, cLFV processes are induced by the off-diagonal terms in the slepton mass matrix. In MSSM, no off-diagonal terms exist @Planck, and **need other mechanisms.**

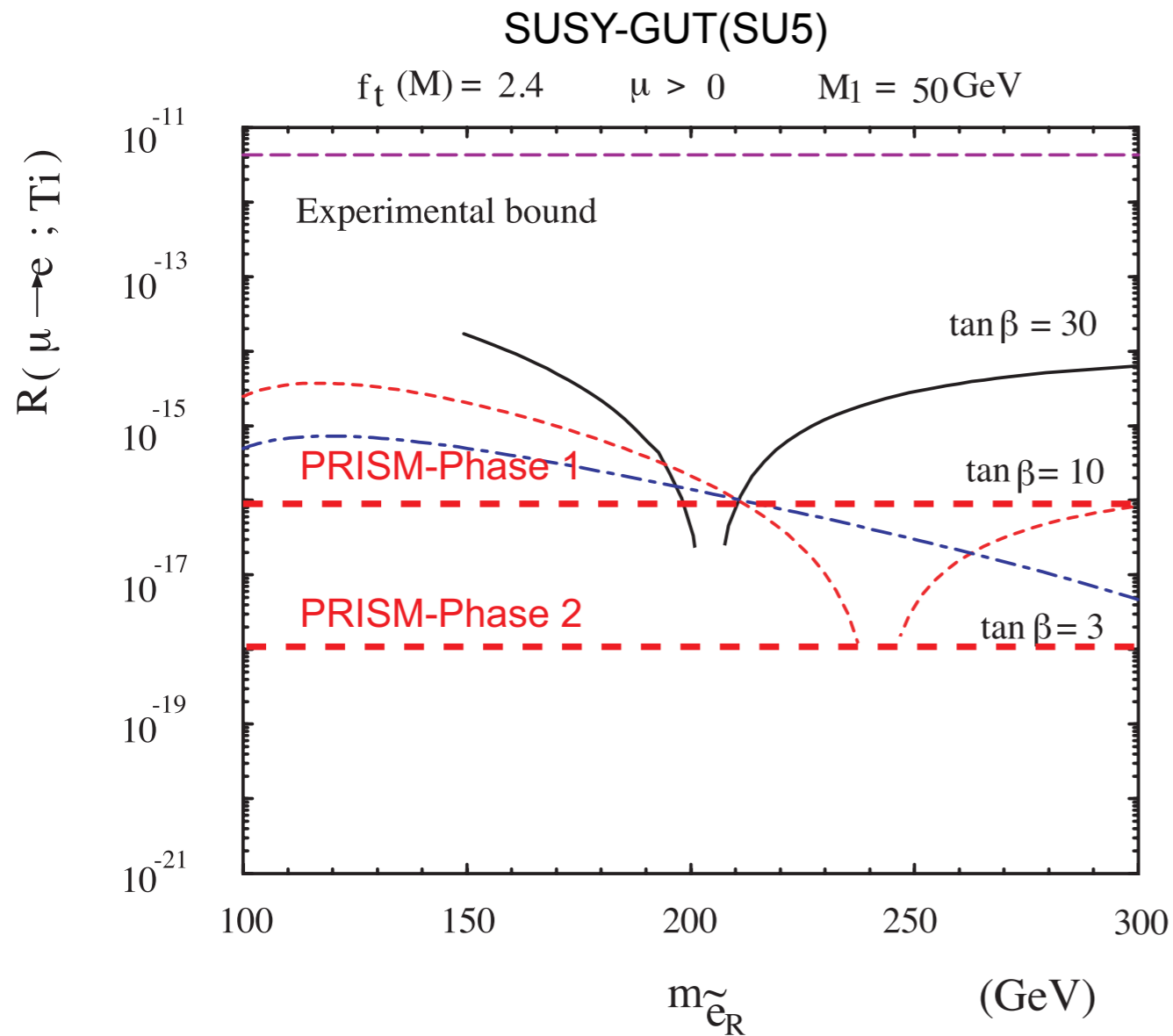
SUSY-GUT  
SUSY-Seesaw



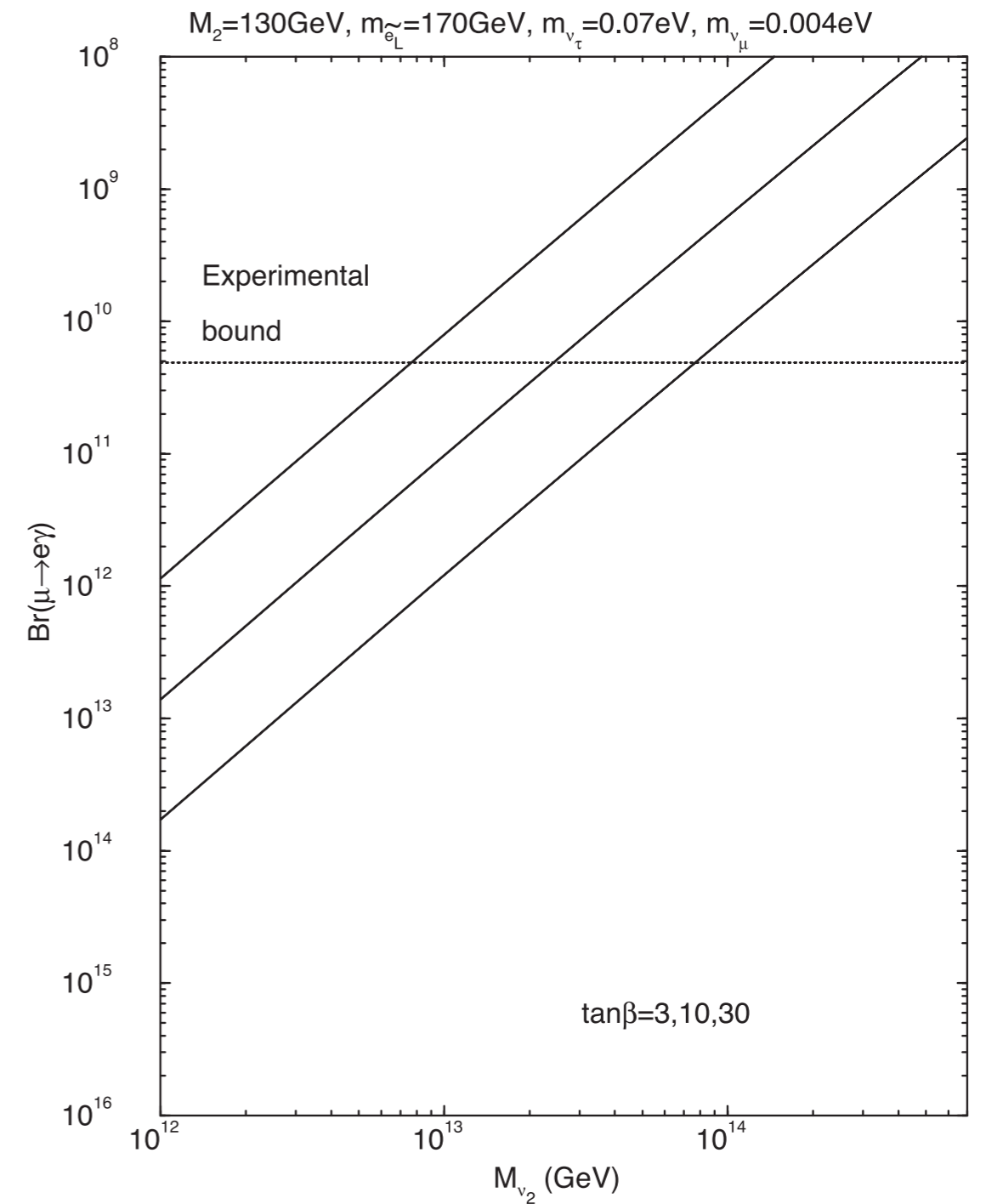
# How are Sleptons mixed ?



# SUSY Predictions



$\mu \rightarrow e \gamma$  in the MSSMRN with the MSW large angle solution

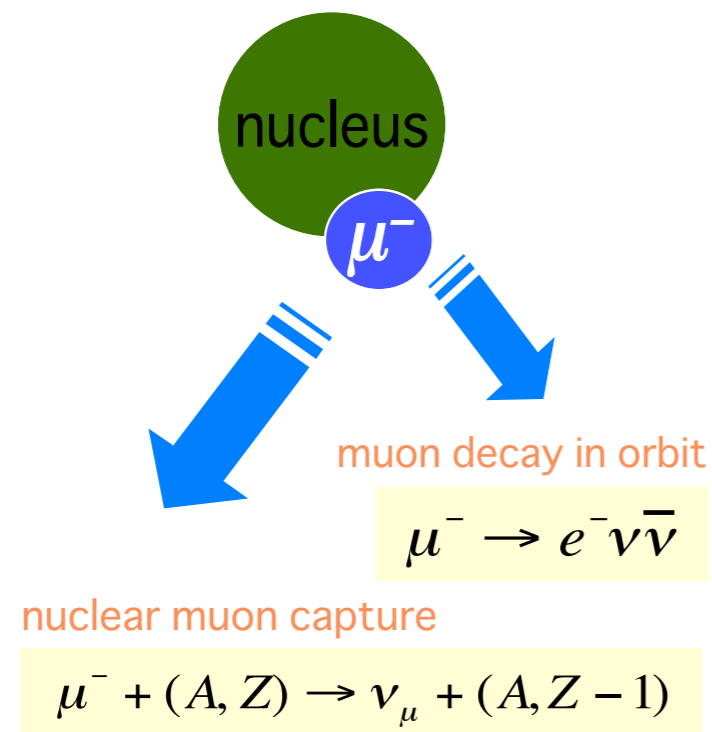




# ミューオン電子転換過程探索実験

# ミューオン電子転換事象 $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

- ミューオン原子の1s基底状態での負電荷ミューオンは？

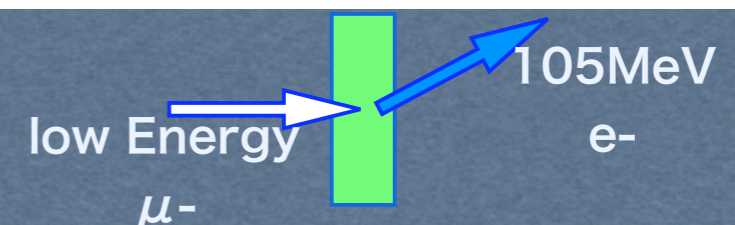


- ミューオン電子転換事象とは？
  - レプトンフレーバー保存を破る過程 ( $|\Delta L_e|=1$ ,  $|\Delta L_\mu|=1$ )

- 標準理論を超える新しい物理の探索  
 例：超対称性大統一理論や超対称性シーソー理論等。
  - 現在上限値のすぐ下に理論予言値がある。発見の可能性大。
- Signalの特徴：
  - エネルギー( $m_\mu - B_\mu$ )の単一電子
  - コヒーレント過程
- Backgroundの源：
  - muon decay in orbit、radiative pion/muon capture、muon decay in flight、cosmic rays等

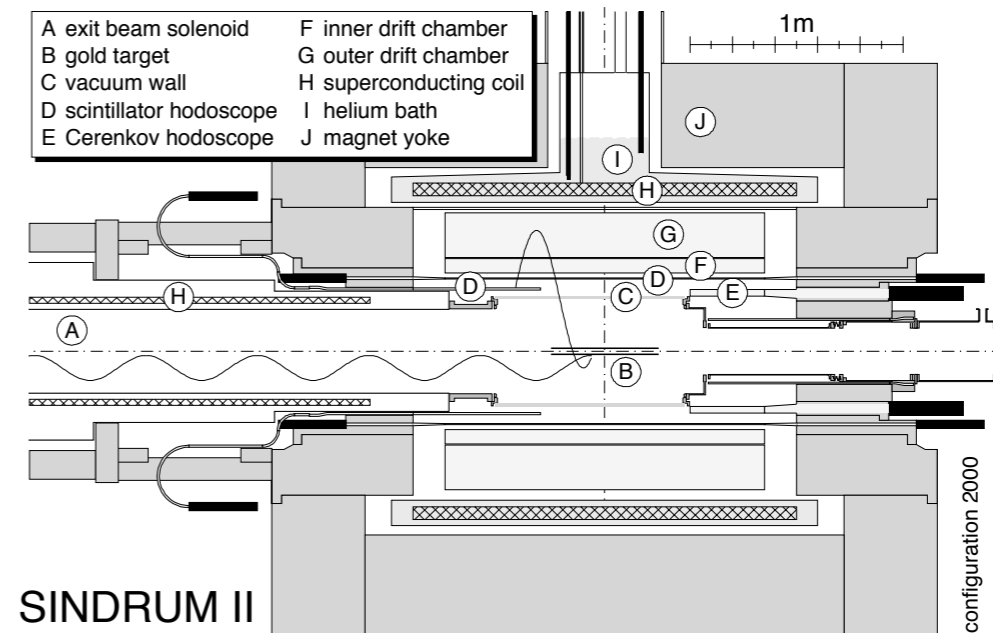
## 実験方法：

$\mu$ を物質中に停止させ、105MeVの電子を検出する。



# これまでの実験と課題

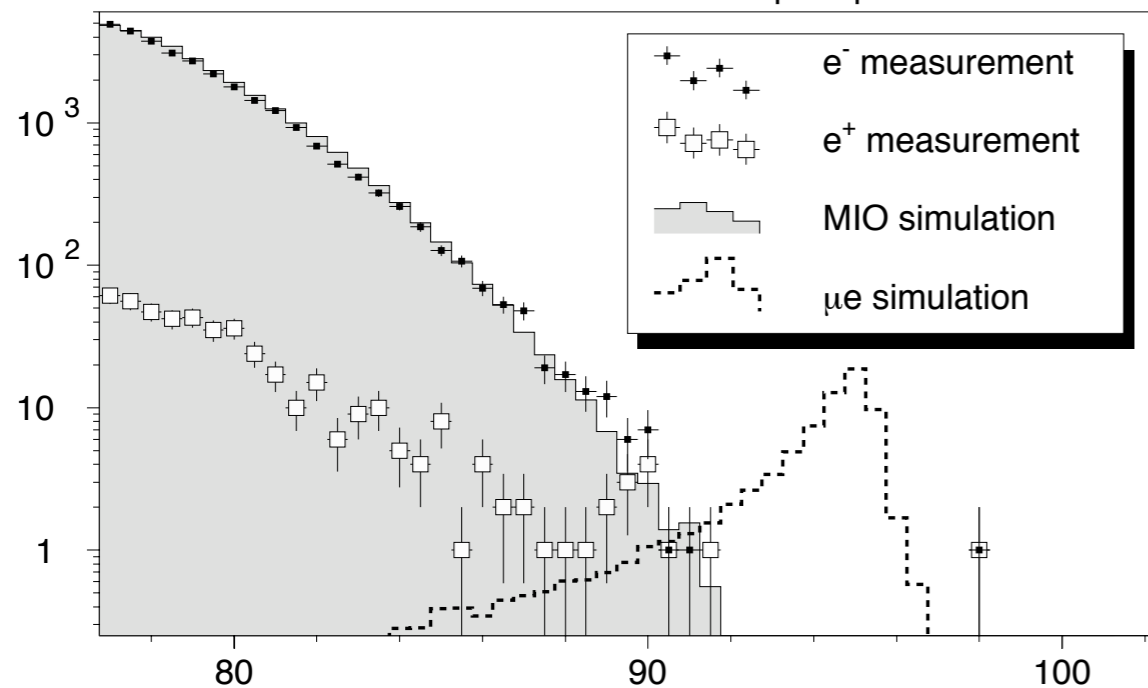
- 現在の実験上限値を決めた実験
  - SINDRUM-II (PSI)



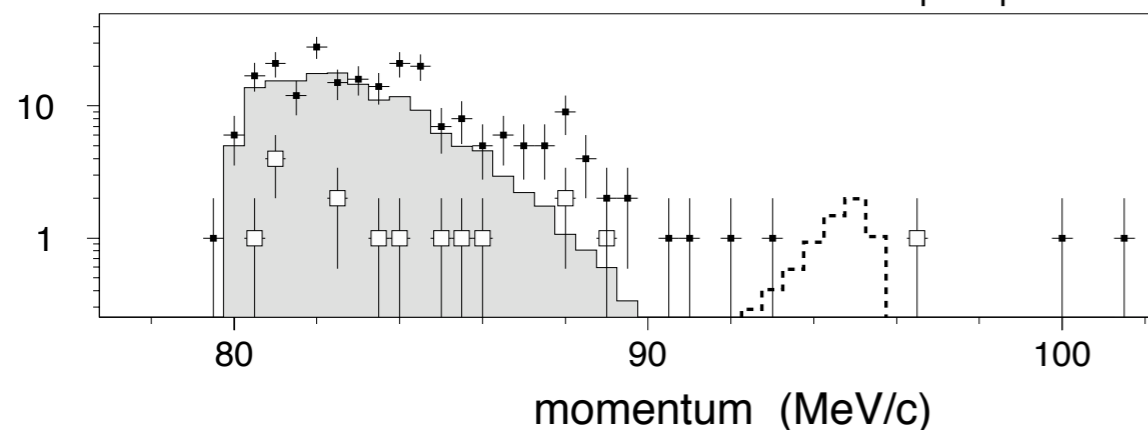
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 4.3 \times 10^{-12}$$

- 課題1：ミューオン・ビームの高強度化が必要。
- 課題2：decayed事象であるのでビームvetoが必要である。高いビーム率ではvetoが難しい。ビームのパルス化が必要。
- 課題3：ビーム中のパイオン混入を削減する必要。

Class 1 events: prompt forward removed



Class 2 events: prompt forward





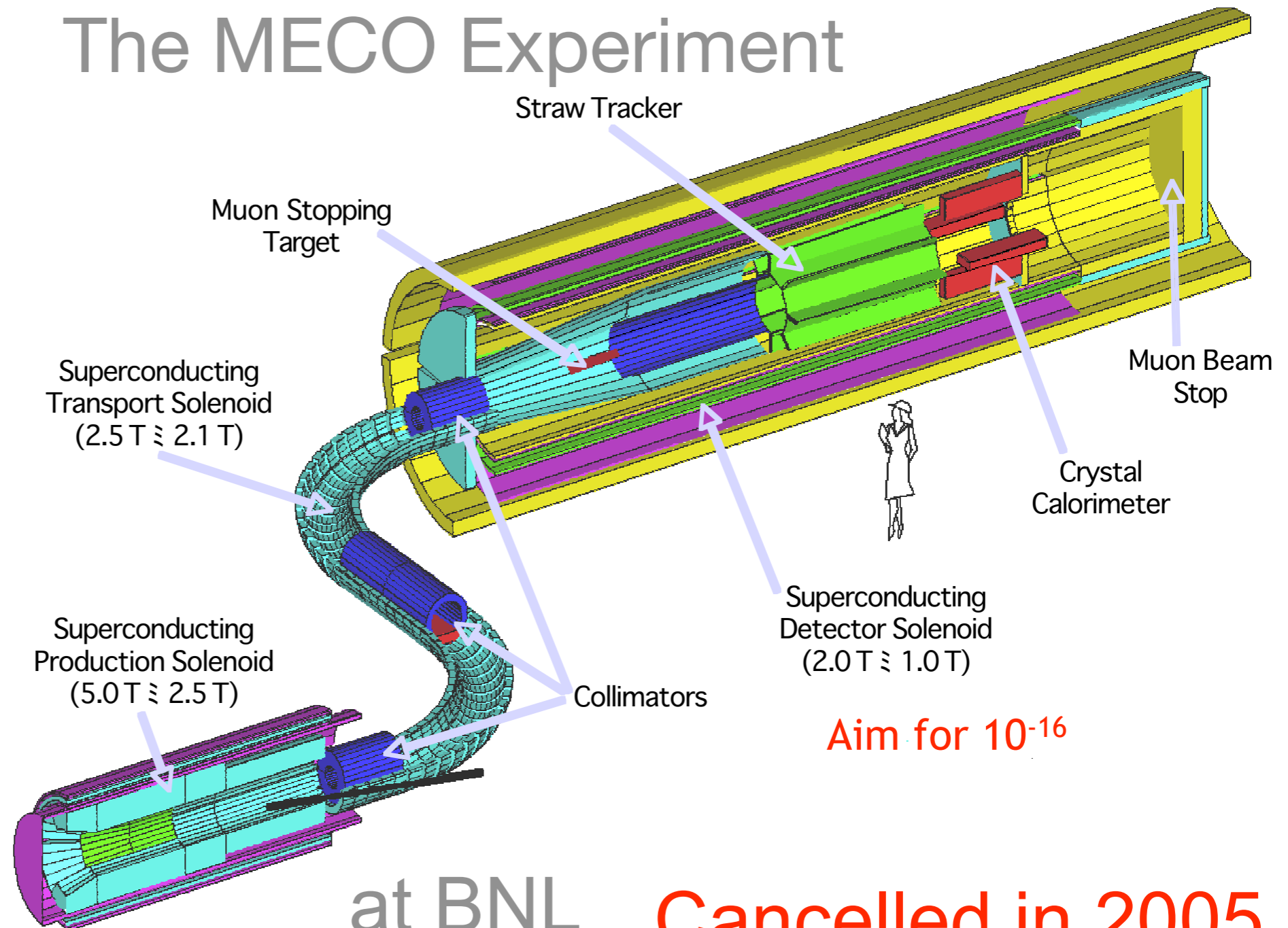
# ミューオン電子転換過程探索実験の将来計画

# MECO @ BNL/AGS

## MECO (the US)

- To eliminate beam related background, beam pulsing was adopted (with delayed measurement).
- To increase a number of muons available, pion capture with a high solenoidal field was adopted.
- For momentum selection, curved solenoid was adopted.

## The MECO Experiment



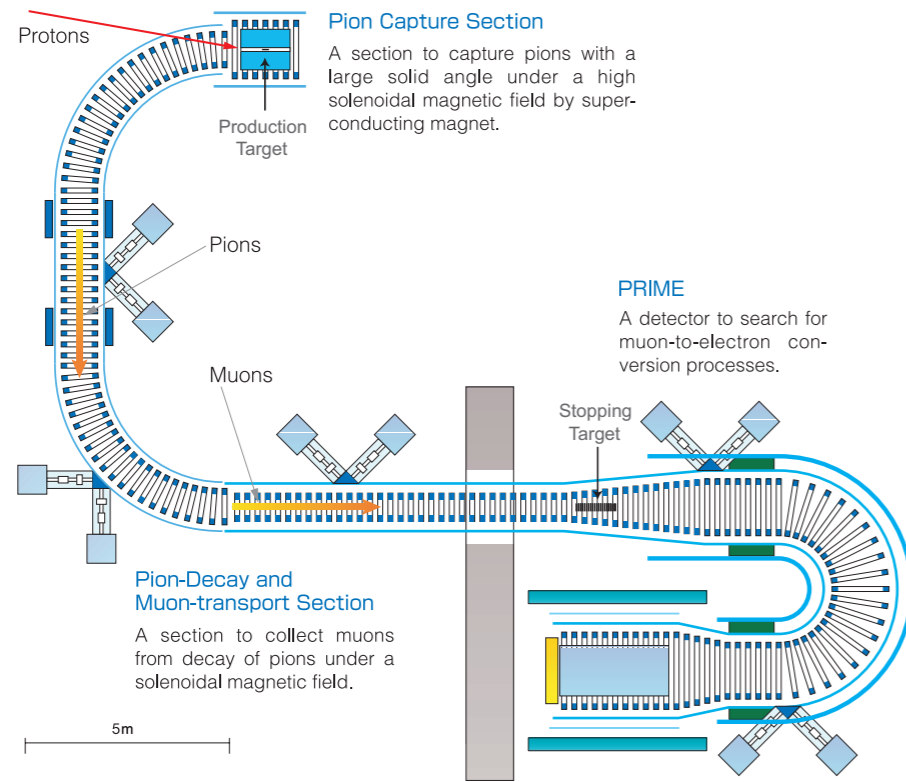
Aim for  $10^{-16}$

at BNL

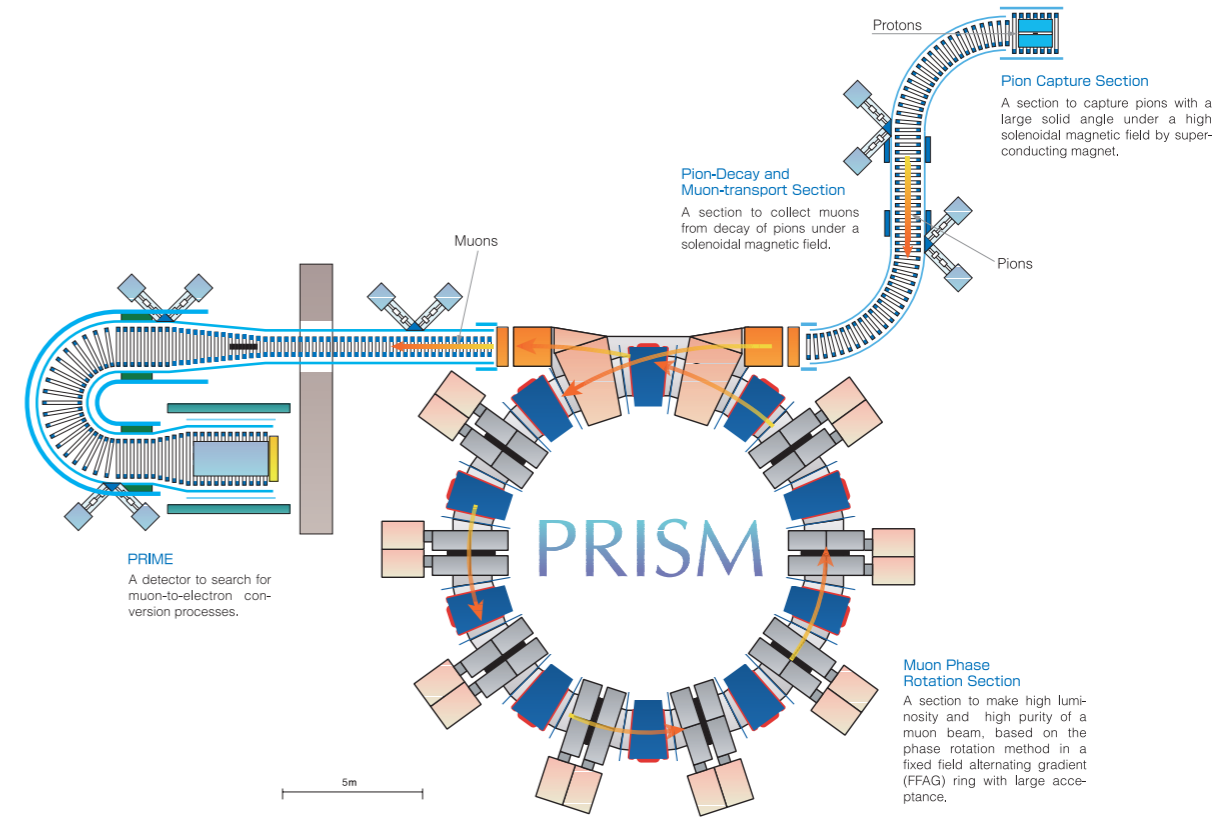
Cancelled in 2005

# J-PARCにおける $\mu$ - $e$ 転換探索実験の提案

## New Experiment



## PRISM



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

- ミューオン蓄積リングなし
- 遅い取り出しによるパルス陽子ビーム
- J-PARC ハドロン実験室を検討
- 第一段階の実験

*PRISM-Phase1*

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

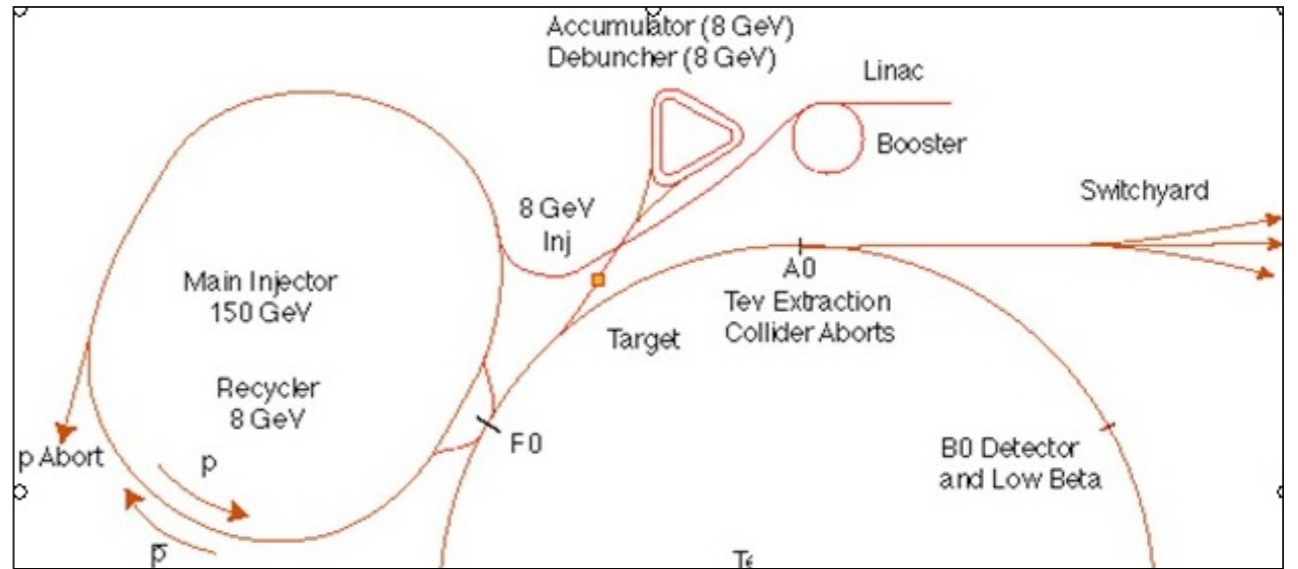
- ミューオン蓄積リングあり
- 速い取り出しによるパルス陽子ビーム
- ハドロン実験室または新しい実験室を検討
- 第二段階の実験

*PRISM-Phase2*

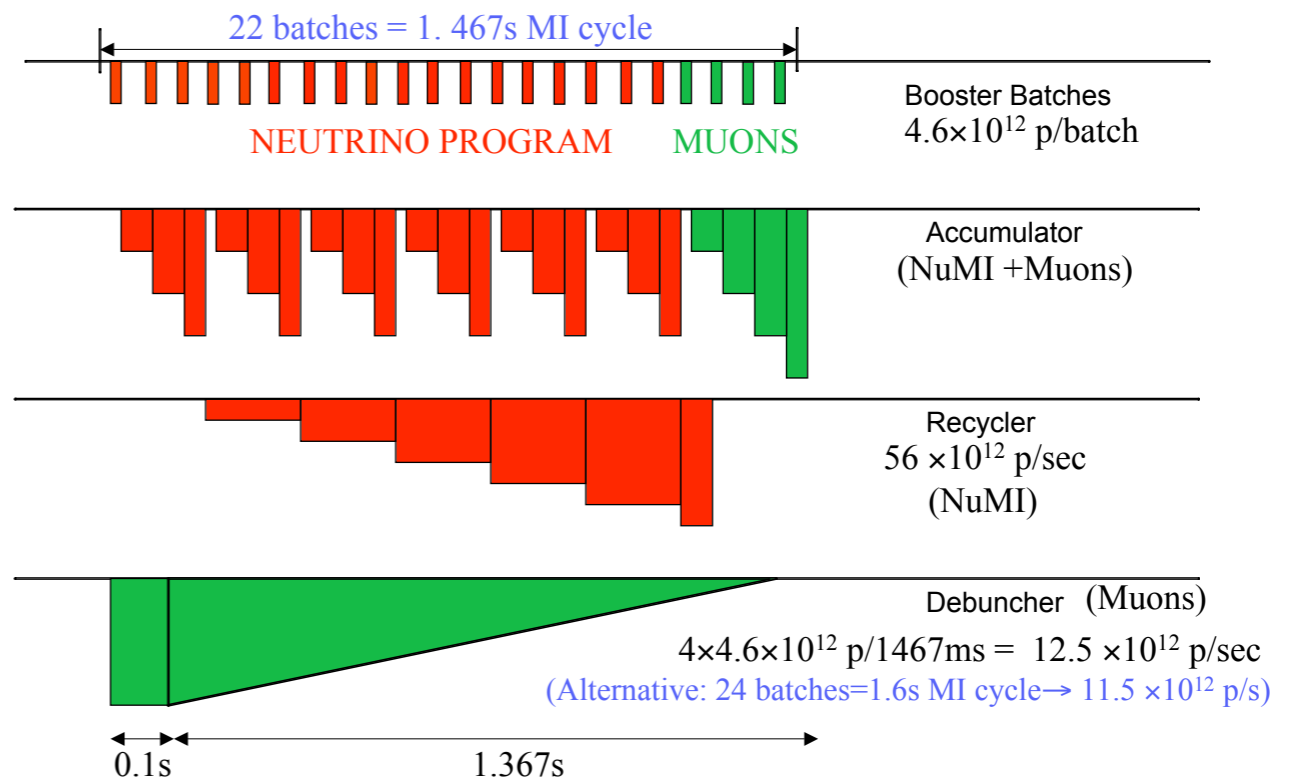
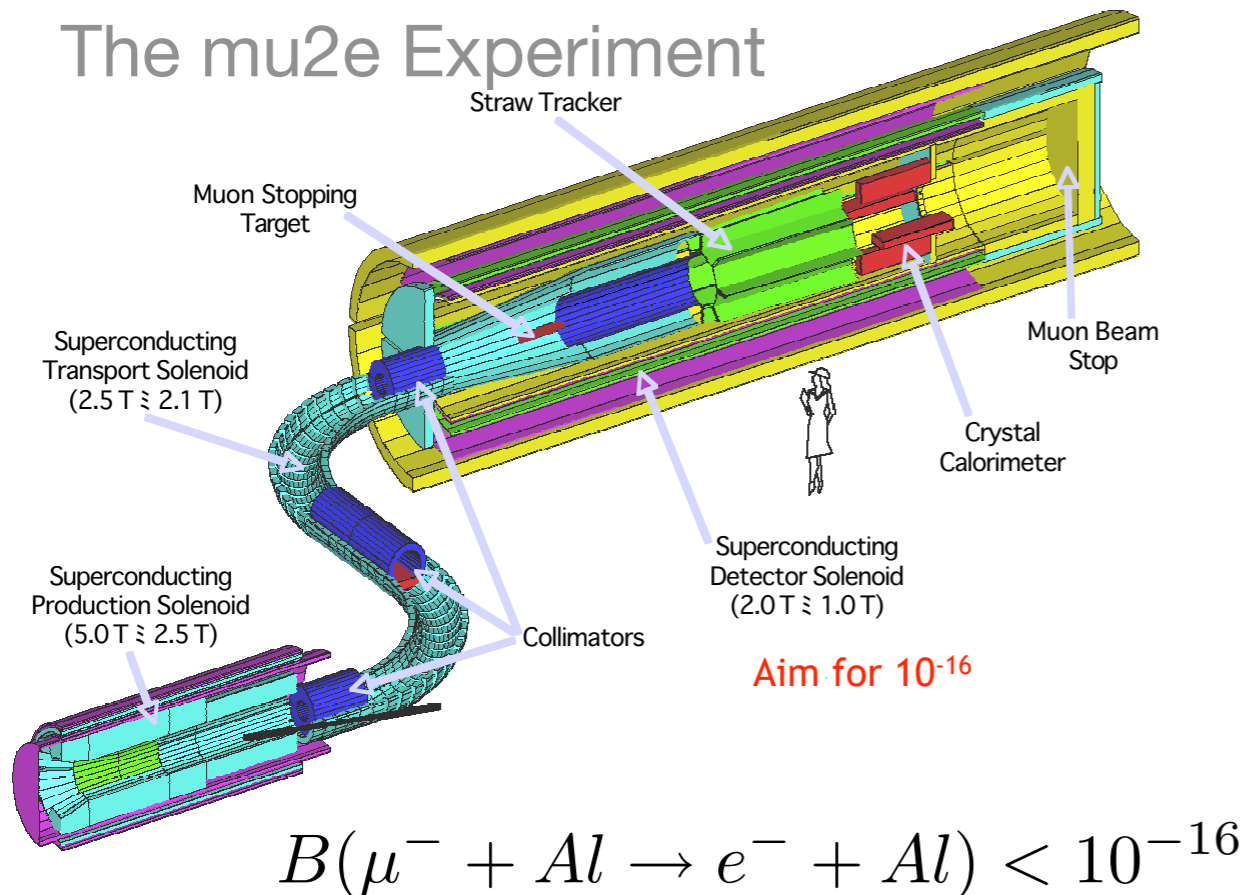


# 海外との競争

- 米国Brookhaven研究所でのMECO実験
  - 2005年夏、予算の関係でキャンセル
- 米国Fermilab研究所でのmu2e実験
  - MECO実験のリバイバル
  - 2007年6月: EoI, 2007年10月: LoI



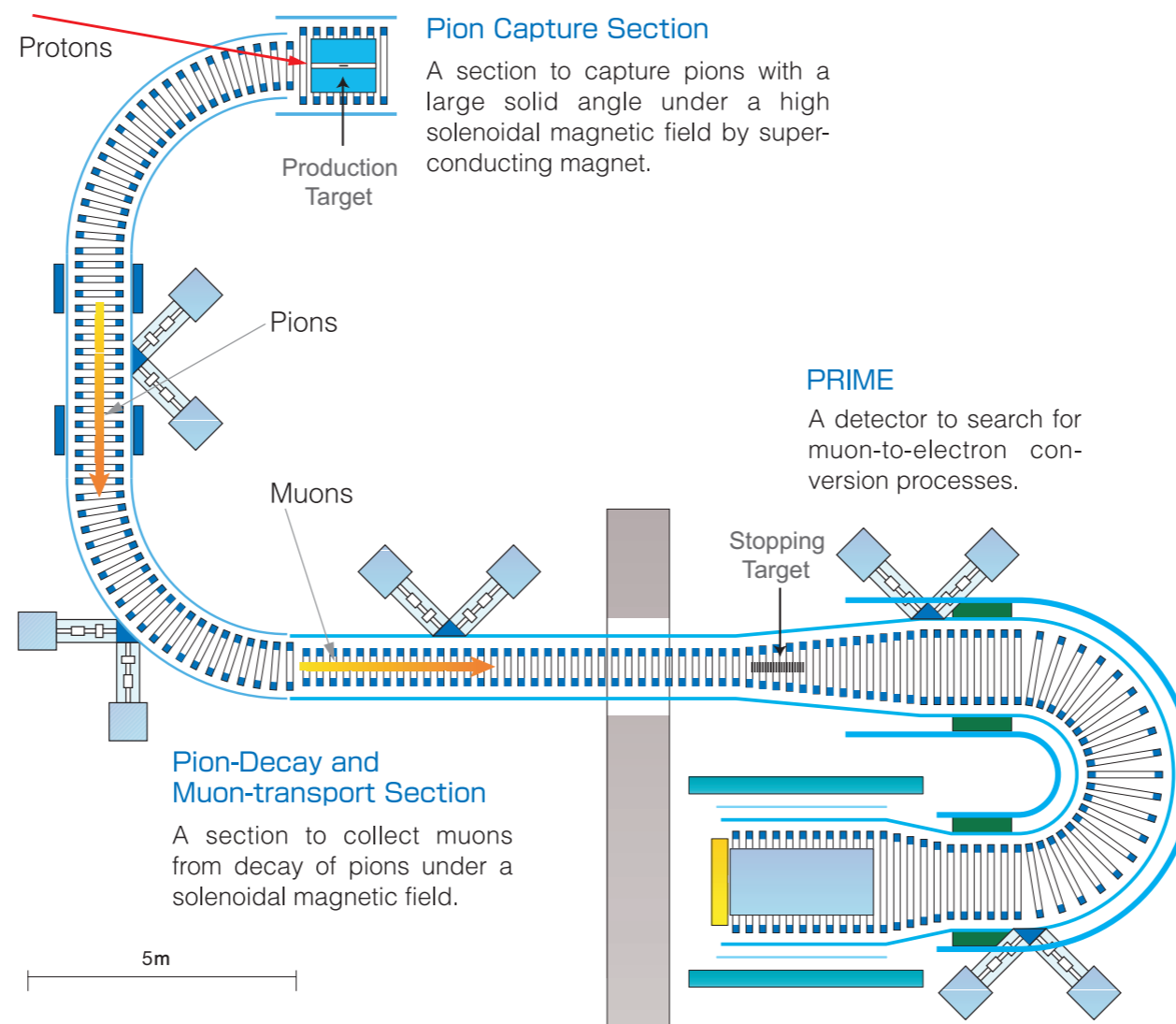
## The mu2e Experiment



# 第1段階実験(BR $\sim 10^{-16}$ )の新名称

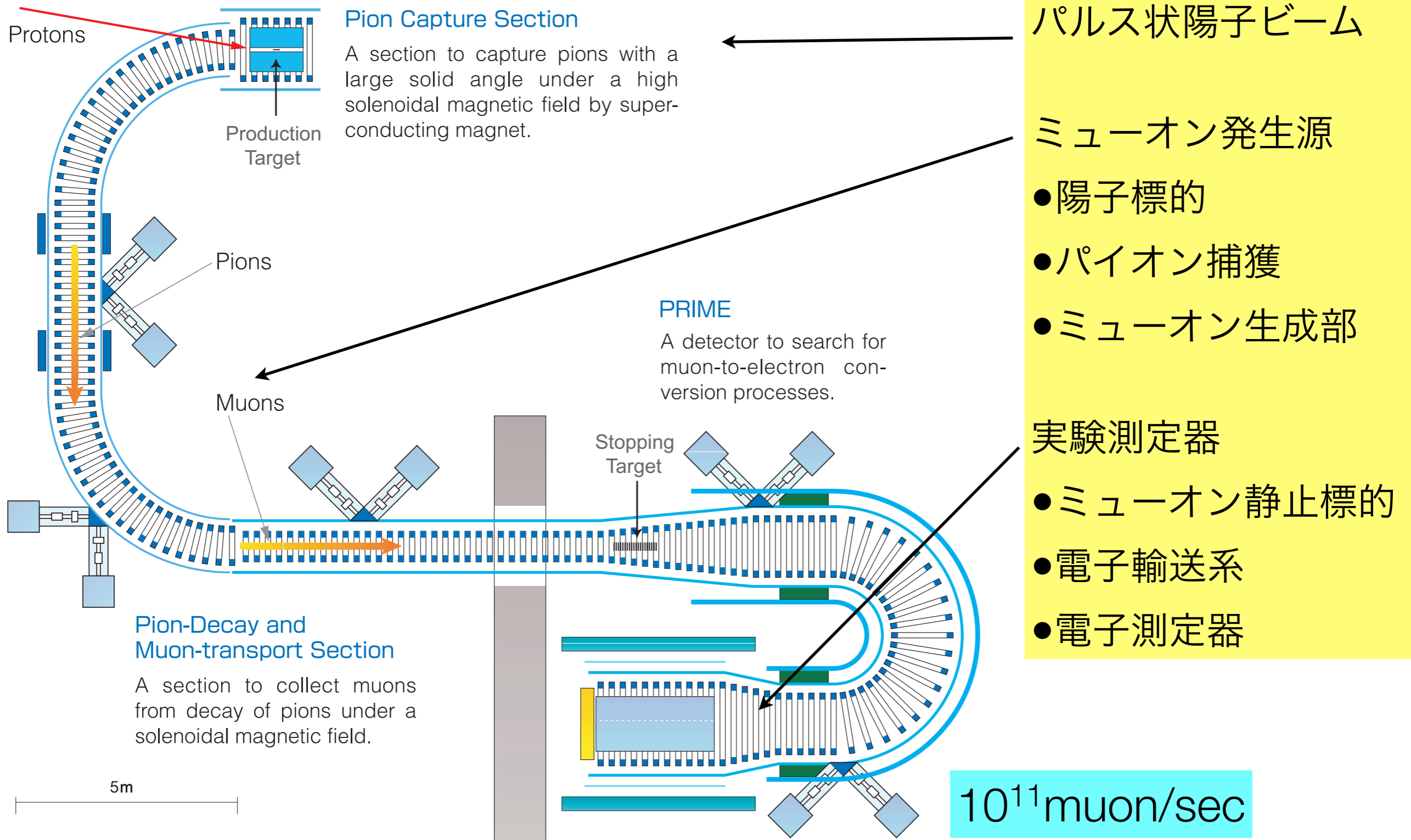
## PRISM-Phase1

# COMET (COherent Muon Electron Transition)



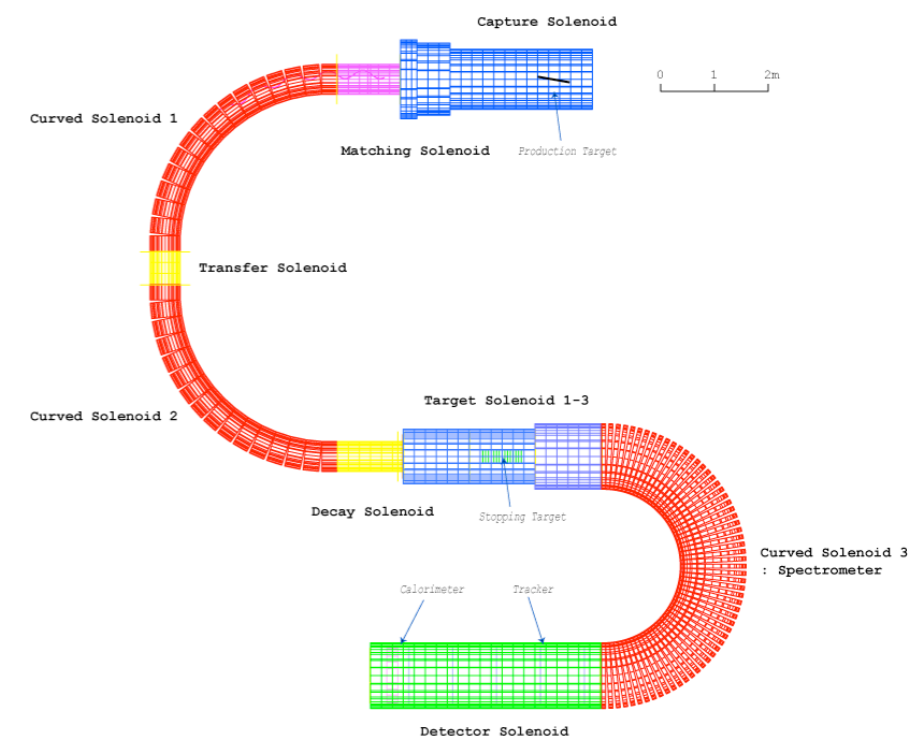
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

## ミューオン電子転換事象探索の実験レイアウト



# ミューオン・ビームへの要求

- ミューオン・ビーム強度
  - 約 $10^{11}$ 個ミューオン/秒以上。
  - 超伝導ソレノイドによるパイオン大立体角補角
- パルス状ミューオン・ビーム
  - ビームパルス間にミューオンが来ないこと。Extinction=(パルス間)/(パルス内) $\sim 10^{-9}$ 。
  - ビームパルス間隔が $\mu\text{sec}$ 程度。
  - ビームパルス幅は短く。
- ミューオン・ビームの運動量
  - 平均運動量： $P_{\mu} \sim 40 \text{ MeV}/c$
  - $P_{\mu} < 75 \text{ MeV}/c$
  - curved solenoidを用いた運動量選択
- パイオンの混入率
  - $< 2 \times 10^{-3}$ 程度 (10m以上のビームラインの長さ)



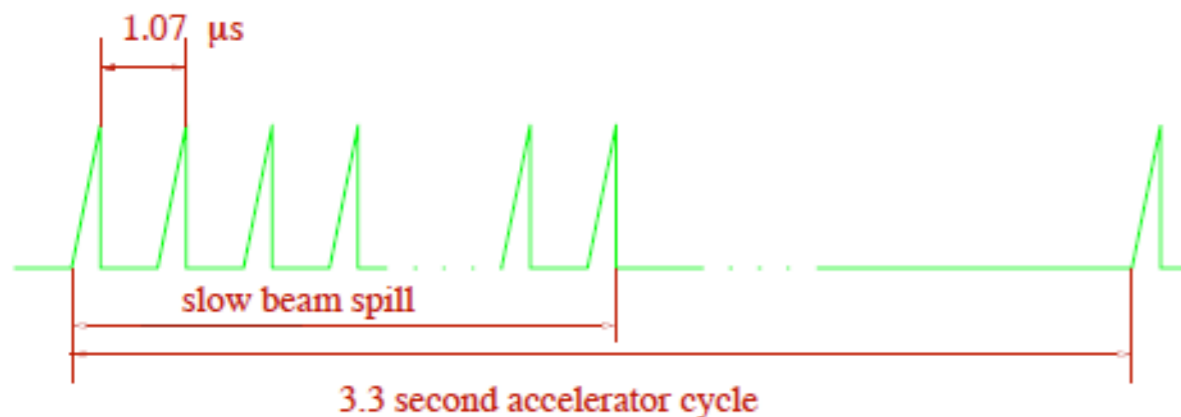
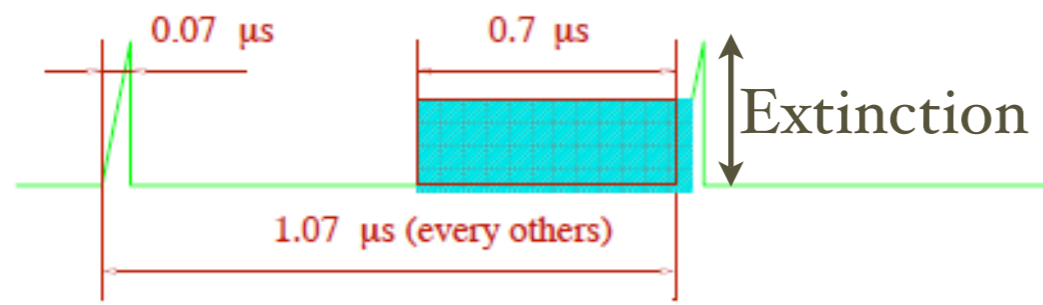
# Pulsed Proton Beam (1)

- バックグラウンド

- $\pi^+(A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma^+(A,Z-1), \gamma \rightarrow e^+ e^-$  : 一次陽子ビームに同期

- 信号

- $\mu^+(A,Z) \rightarrow e^+(A,Z)$  : 遅延 ( $\sim 1\mu s$ )



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

$N_P$  : total # of protons ( $\sim 10^{21}$ )  
 $Y_{\pi/P}$  :  $\pi$  yield per proton (0.015)  
 $A_{\pi}$  :  $\pi$  acceptance ( $1.5 \times 10^{-6}$ )  
 $R_{ext}$  : Extinction Ratio ( $10^{-9}$ )  
 $P_{\gamma}$  : Probability of  $\gamma$  from  $\pi$  ( $3.5 \times 10^{-5}$ )  
 $A$  : detector acceptance (0.18)

$$N_{bg} < 0.22 \Leftrightarrow \text{Extinction} < 10^{-9}$$

Extinction:  $< 10^{-9}$

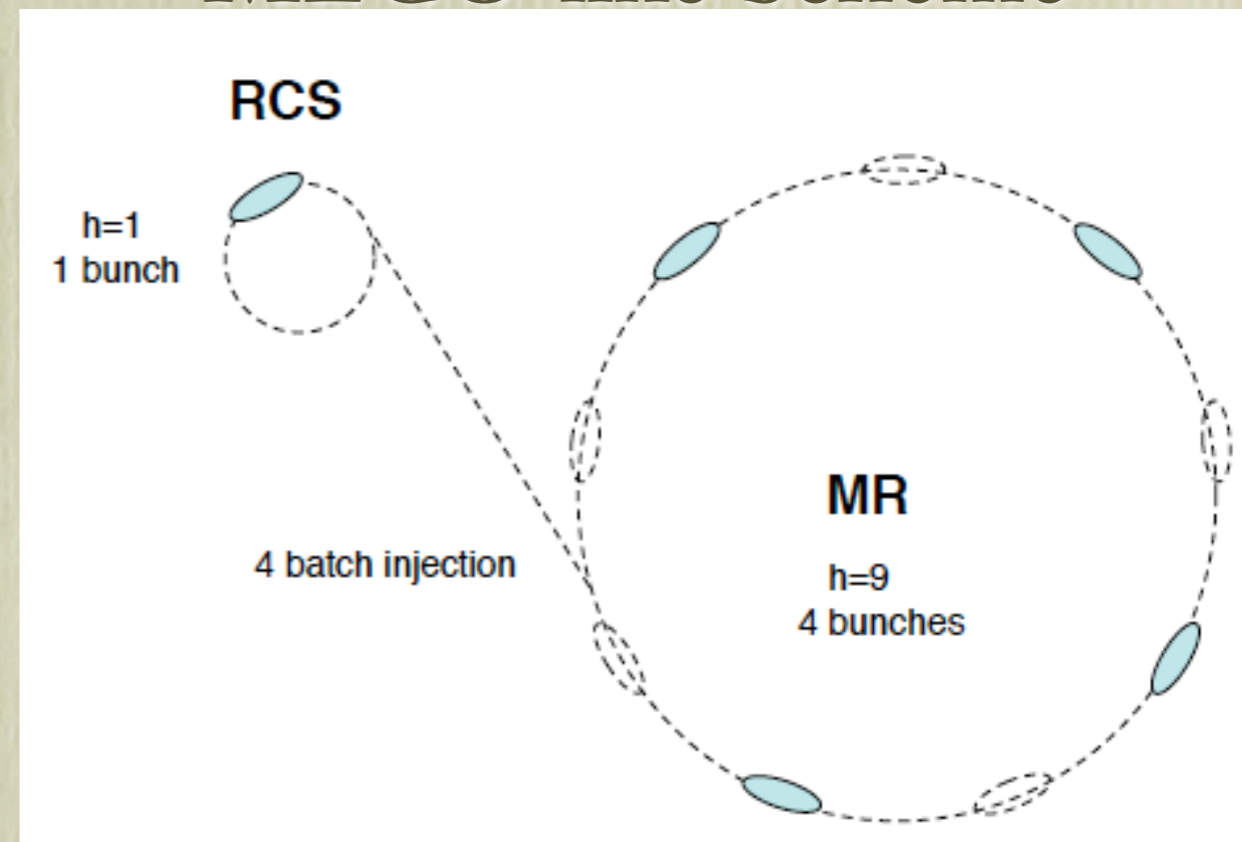
Power: 60 kW ( $4 \times 10^{13}$  pps@8 GeV)

# Pulsed Proton Beam (2) : Bunching Scheme

## J-PARC Accelerator Complex

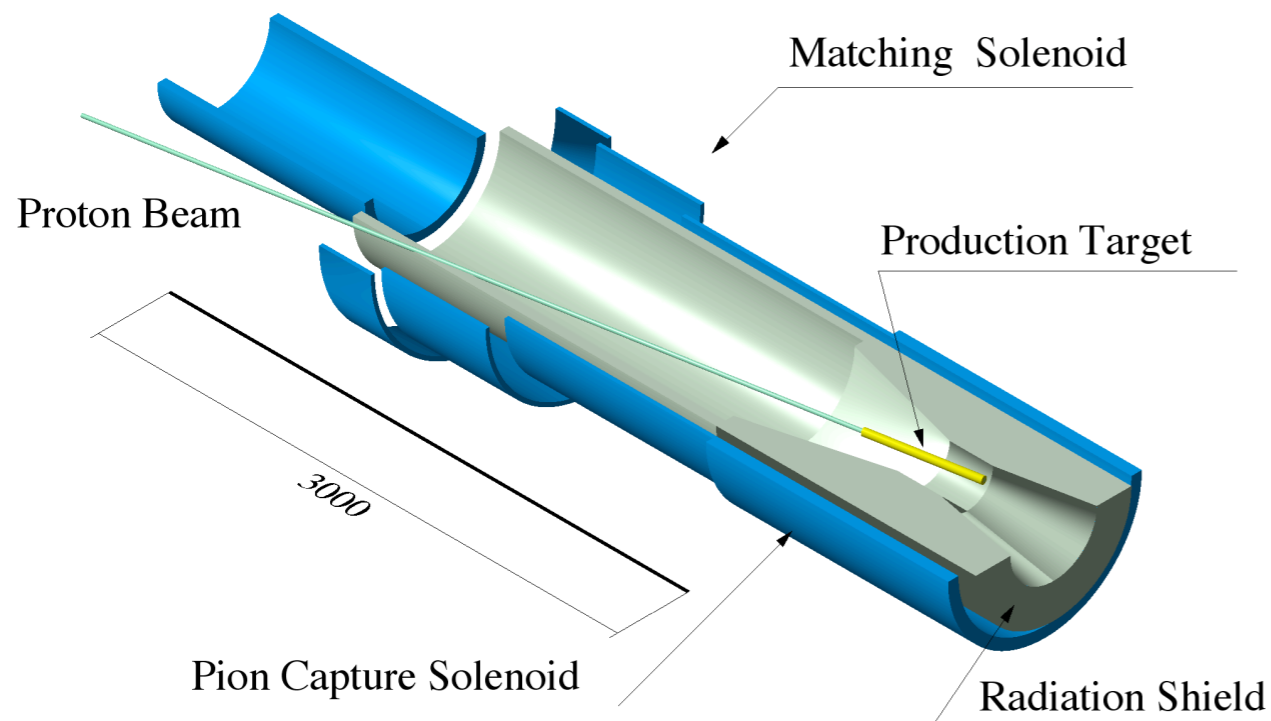
- RCS : 1 bunch operation
  - $h=1$  or  $h=2$  w/ empty bucket
- MR : Empty bucket Scheme
  - $h=9$  or  $h=8$
- Adiabatic dumping : small
  - $30 \text{ GeV} \rightarrow 8 \text{ GeV}$
  - Reduce RCS painting area
  - Smaller 3-50BT collimator
- $8 \text{ GeV}$ ,  $7 \mu\text{A}$  ;  $56 \text{ kW}$  to NP-Hall

## MECO-like Scheme



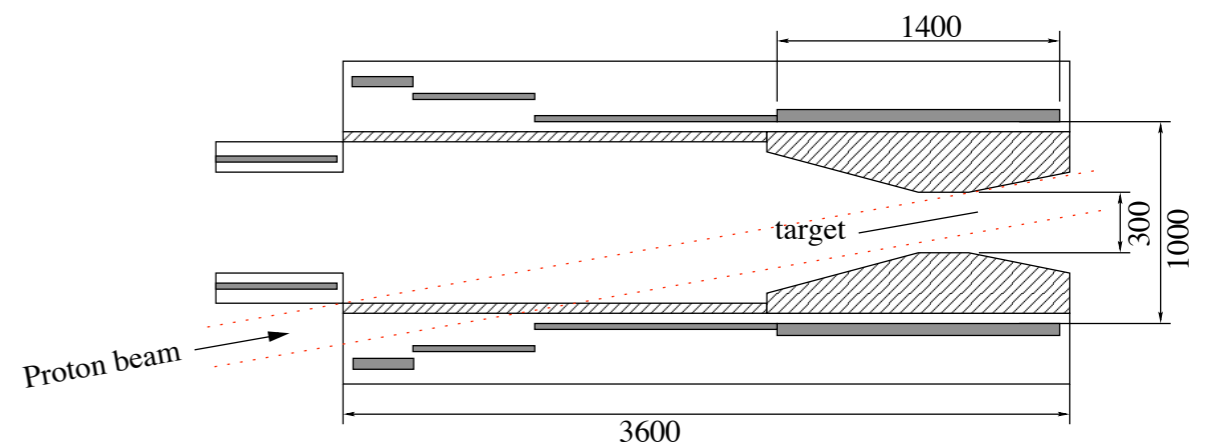
# Pion Capture

- A large muon yield can be achieved by large solid angle pion capture by a high solenoid field, which is produced by solenoid magnets surrounding the proton target.



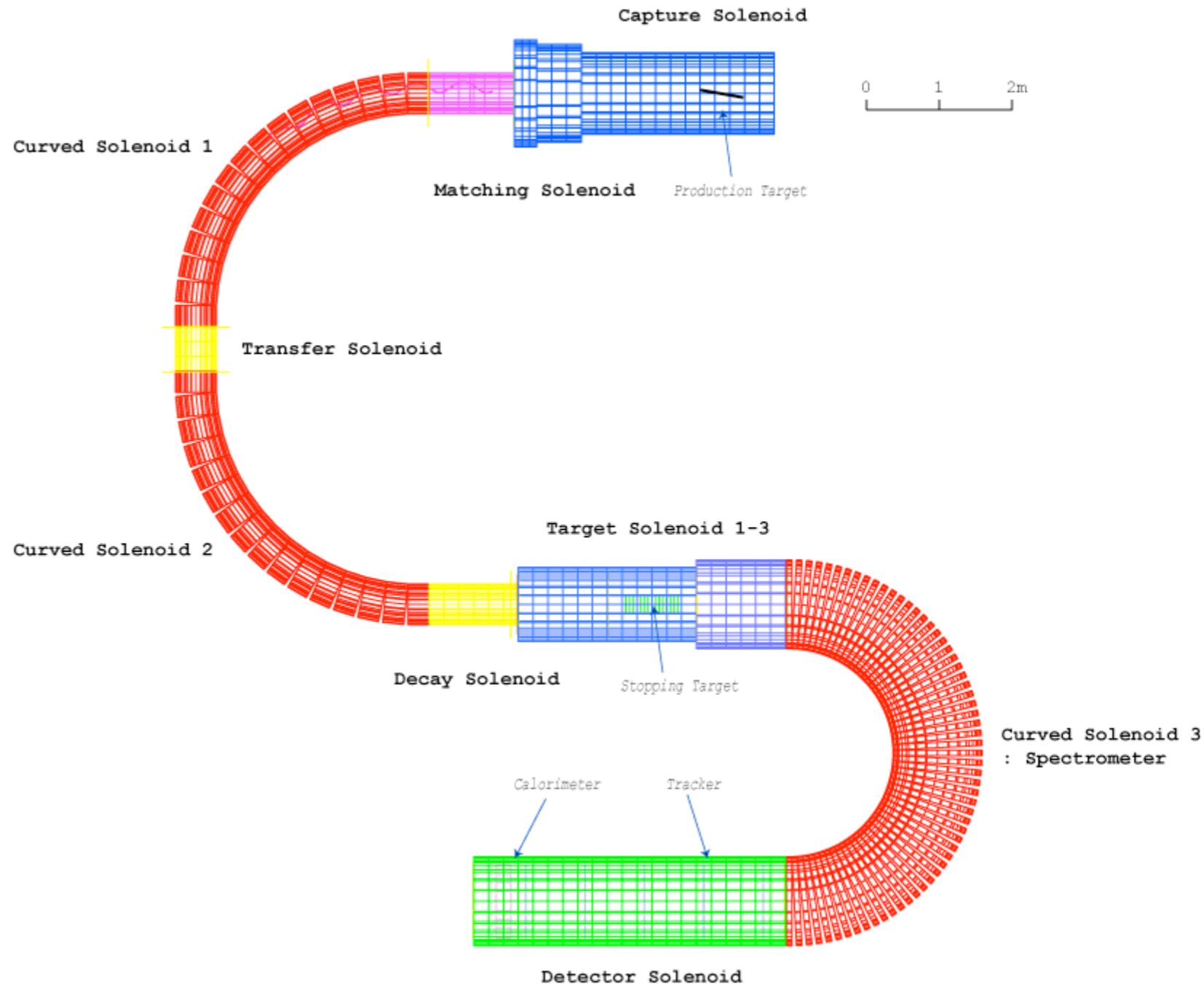
$$P_T(\text{GeV}/c) = 0.3 \times B(\text{T}) \times \left(\frac{R(\text{m})}{2}\right)$$

- B=5T, R=0.2m,  $P_T=150\text{MeV}/c$ .
- Superconducting Solenoid Magnet for pion capture
  - 15 cm radius bore
  - a 5 tesla solenoidal field
  - 30 cm thick tungsten radiation shield
  - heat load from radiation
  - a large stored energy



# Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- Requirements :
  - long enough for pions to decay to muons ( $> 20$  meters  $\approx 2 \times 10^{-3}$ ).
  - high transport efficiency ( $P_{\mu} \sim 40$  MeV/c)
  - negative charge selection
  - low momentum selection ( $P_{\mu} < 75$  MeV/c)
- Straight + curved solenoid transport system is adopted.





# Charged Particle Trajectory in Curved Solenoids

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- 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

$\theta_{bend}$  : Bending angle of the solenoid channel

$p$  : Momentum of the particle

$q$  : Charge of the particle

$\theta$  :  $\text{atan}(P_T/P_L)$

- This effect can be used for charge and momentum selection.

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

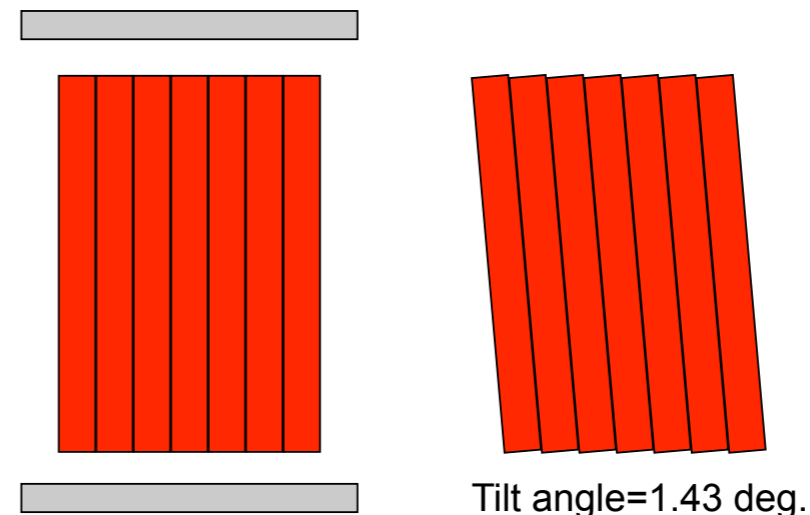
$$B_{comp} = \frac{p}{qr} \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right)$$

$p$  : Momentum of the particle

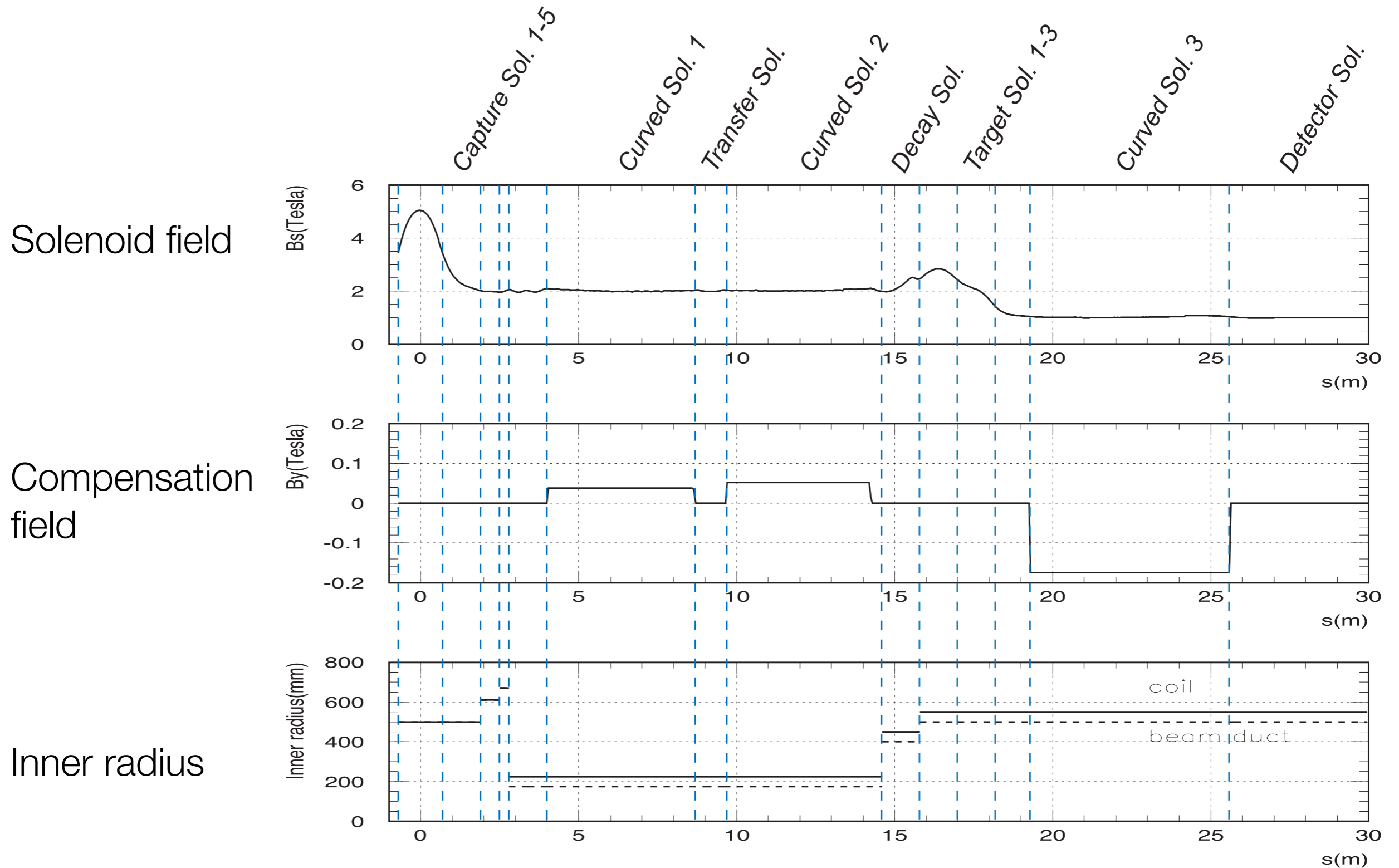
$q$  : Charge of the particle

$r$  : Major radius of the solenoid

$\theta$  :  $\text{atan}(P_T/P_L)$



# Design of Muon Transport Beamline (preliminary)



# Spectra at the End of the Muon Transport

- Preliminary beamline design
  - main magnetic field
  - compensation field
  - radius of magnets (175 mm)
- Transport Efficiency

|  |                    |
|--|--------------------|
| # of muons /proton                       | 0.0024             |
| # of stopped muons /proton               | 0.0007             |
| # of muons of $p_\mu > 75$ MeV/c /proton | $2 \times 10^{-4}$ |

## Spectra at the end of the beamline

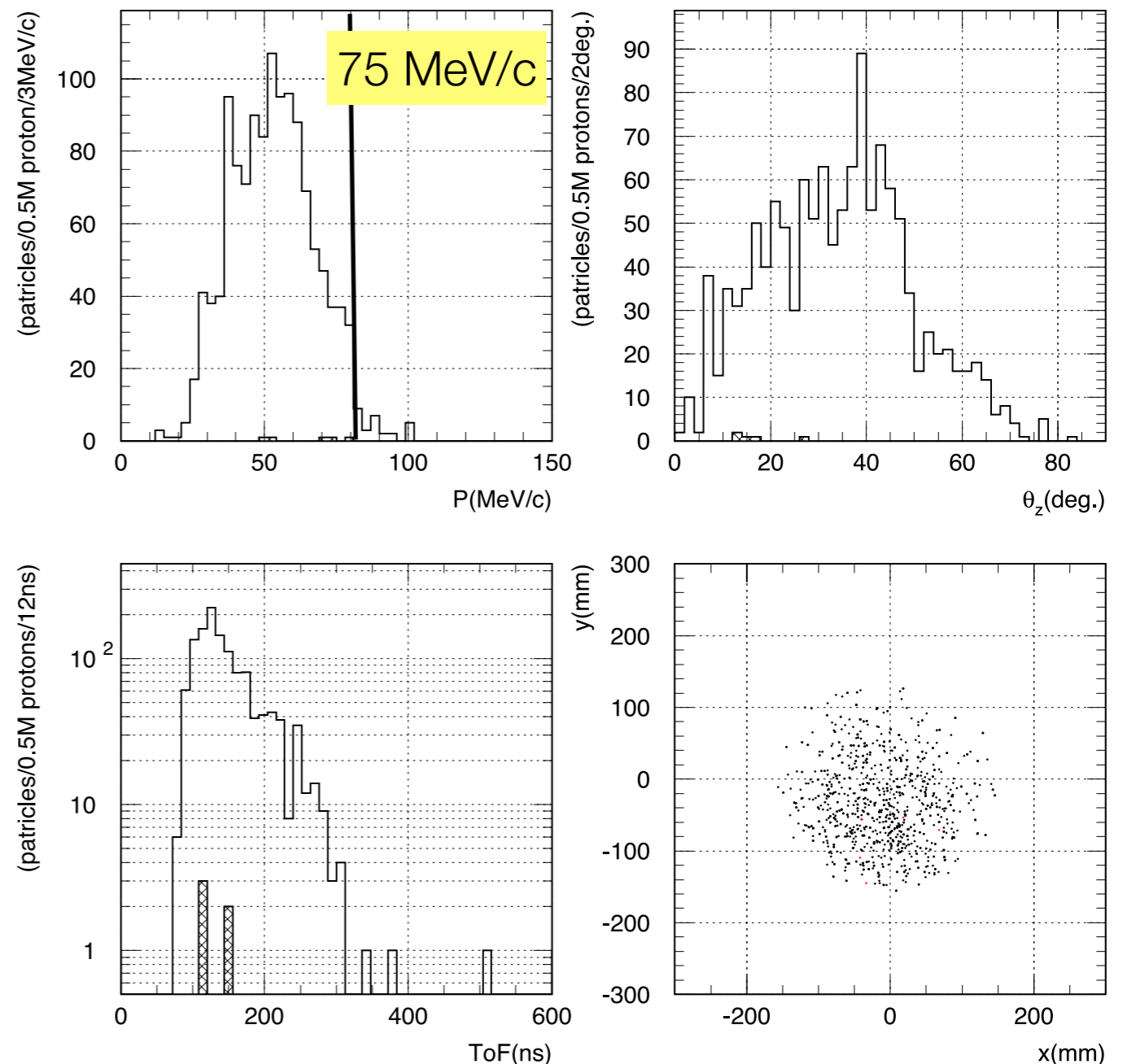
(top left) total momentum

(top right) direction angles to beam axis

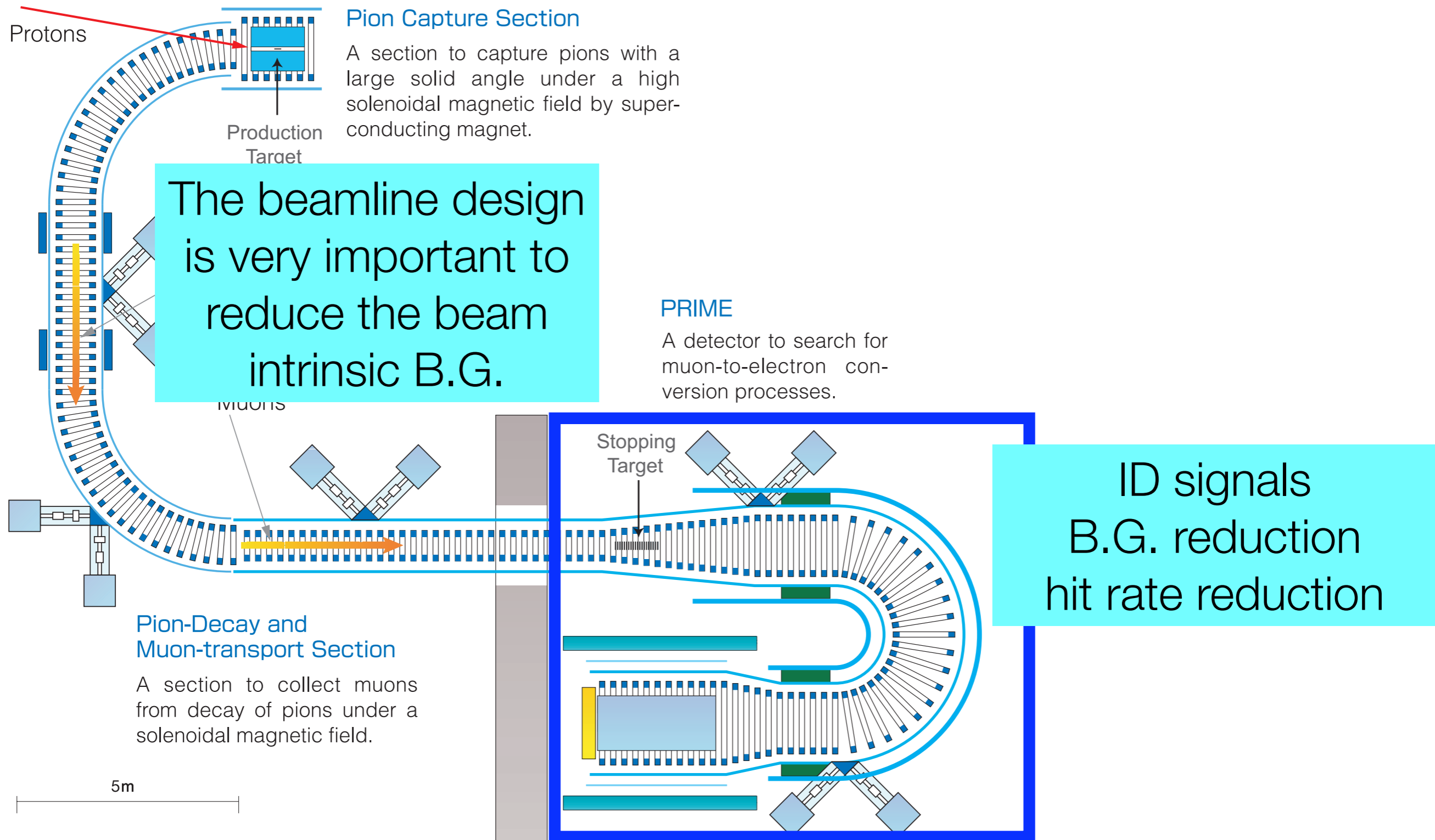
(bottom left) time of flight

(bottom right) beam profile

muons for open histograms, pions for hatched histograms.



# Overview of the New Experiment : COMET



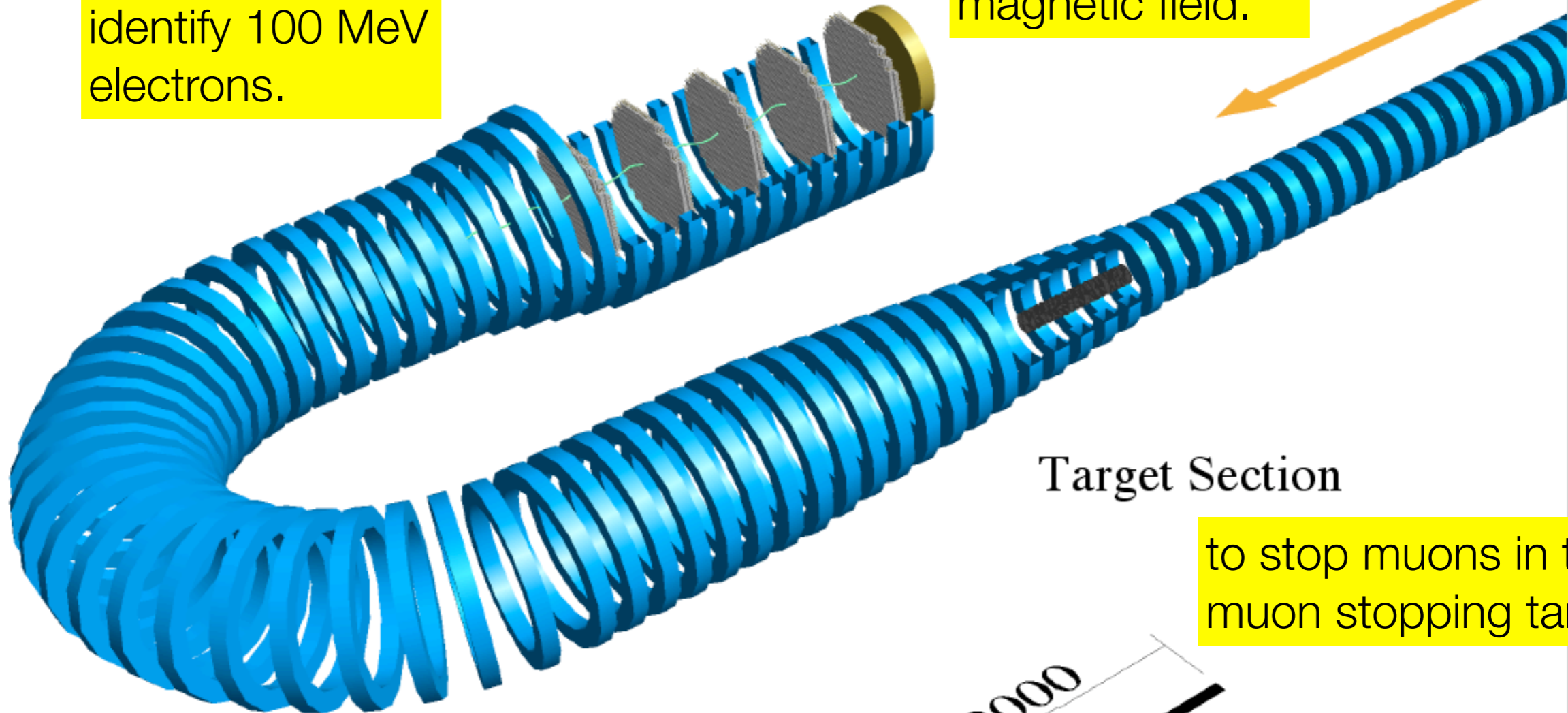
# COMETの検出器



to detect and identify 100 MeV electrons.

Detector Section

under a solenoid magnetic field.



Curved Solenoid

Target Section

to stop muons in the muon stopping target.

2000

to eliminate low-energy beam particles and to transport only ~100 MeV electrons.

## Detector Components

a muon stopping target, curved solenoid, tracking chambers, and a calorimeter/trigger and cosmic-ray shields.

# Detector and Spectrometer

- To identify the genuine mu-e conv. events from a huge number of B.G. events.
  - signal : a 105MeV electron from the stopping targets.
  - background : muon decay in orbit etc.
- Muon Decay in Orbit (DIO)
  - Main B.G. source
  - Electron spectrum from muon decay in orbit

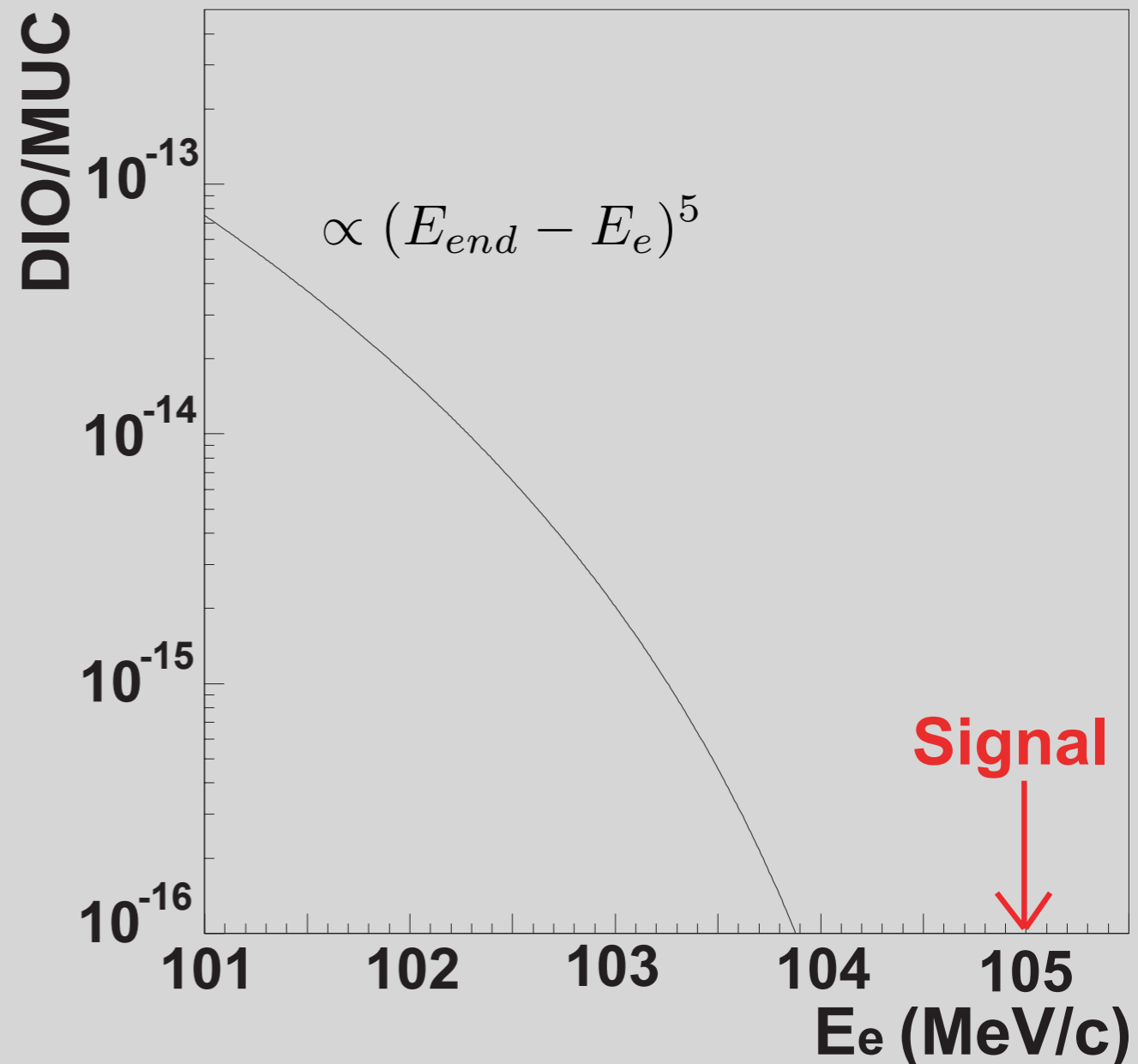
energy

timing

as precisely as possible

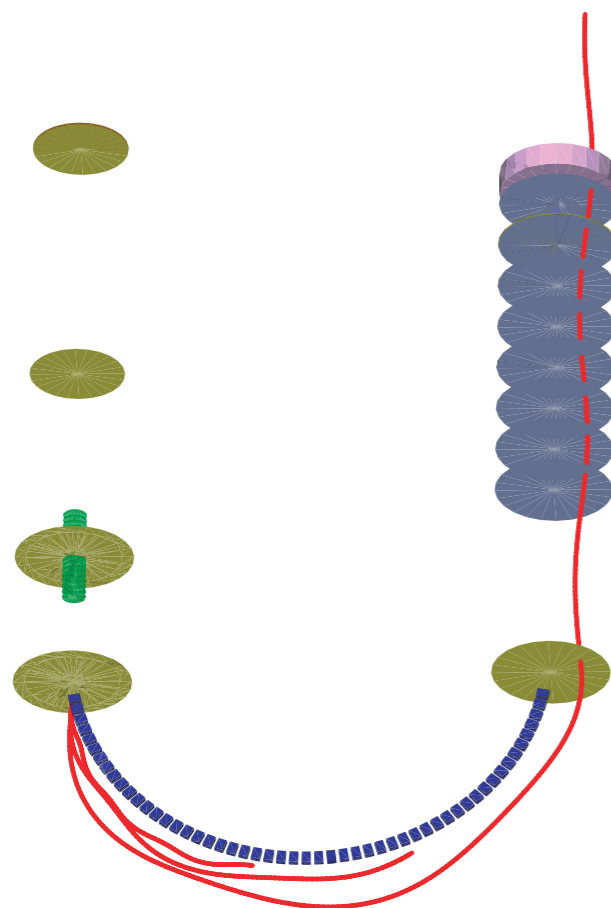
Reject using a curved solenoid spectrometer

Energy spectrum of electrons from decays in orbit in a muonic atom of aluminum, as a function of electron energy. The vertical axis shows the effective branching ratio of  $\mu$ -e conversion.

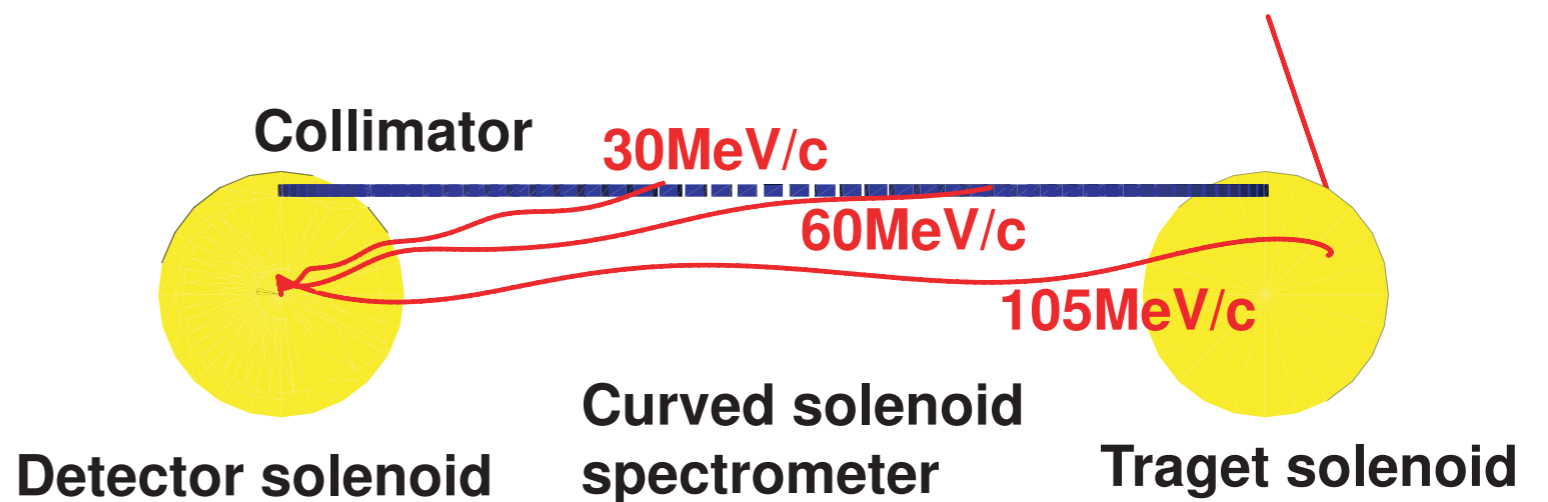


# Mom. Selection in a Curved Solenoid

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



Top view



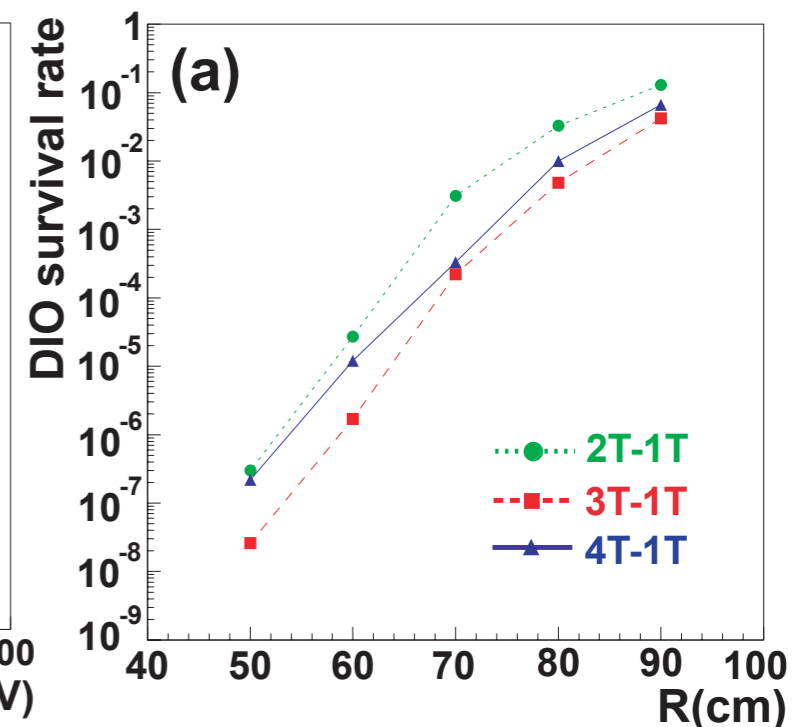
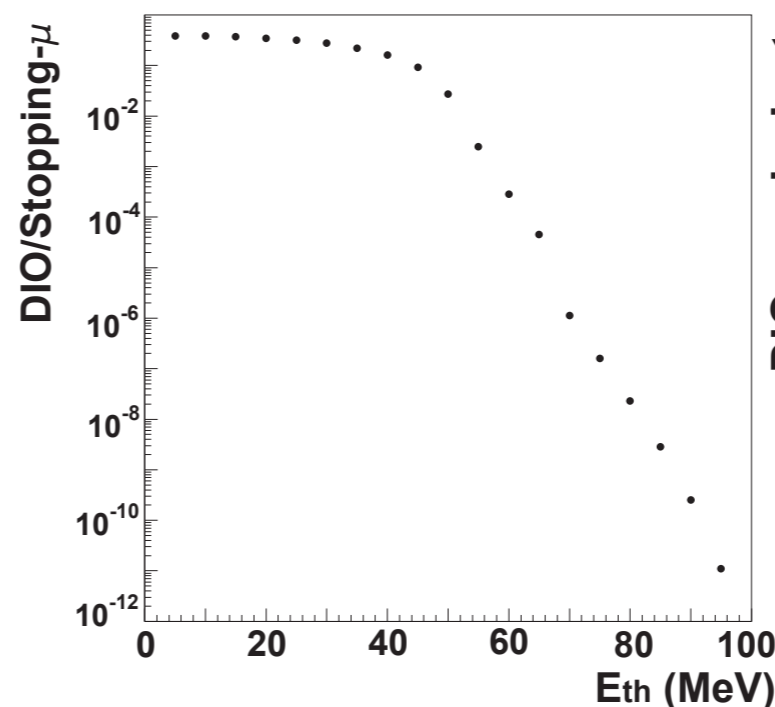
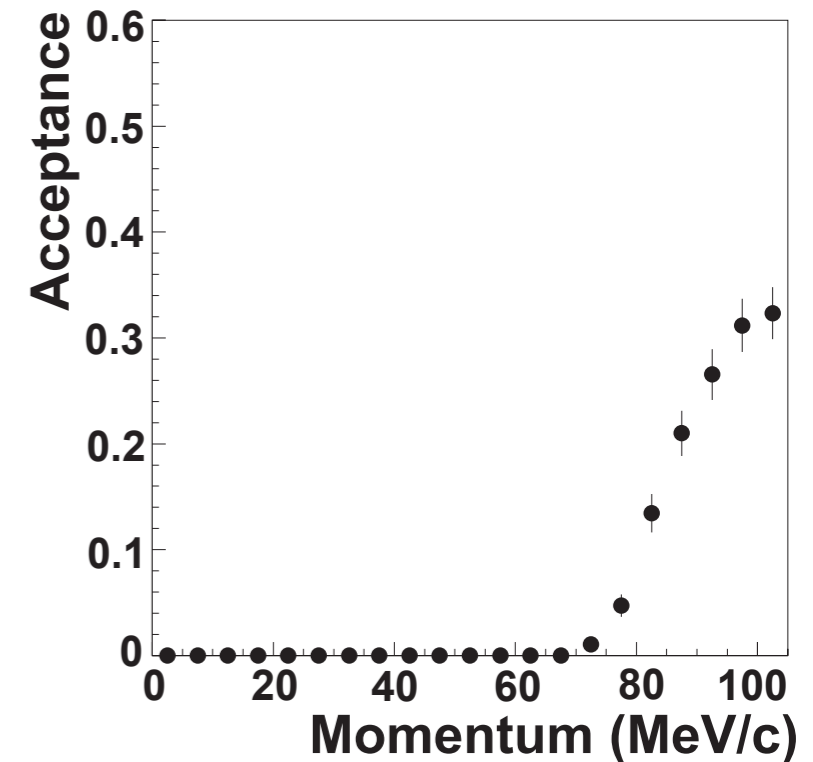
Side view <sup>32</sup>



# Transmission of the Electron Transport (CS)

- Electron Transport System Parameters (preliminary)
  - Radius : 50 cm
  - Magnetic field : 1 Tesla
  - Bending angle : 180 degrees
- Geometrical Acceptance
  - Solid angle at the target : 0.73
    - mirror effect at a graded field
  - Transport efficiency : 0.44
  - Total : 0.32
- Suppression of electrons from decay in orbit.
  - about  $10^{-8}$  suppression
  - about **1000 tracks** / sec for  $10^{11}$  stopping muons.

Ratio of a number of electrons reaching the end of transport to all electrons emitted in  $4\pi$ .



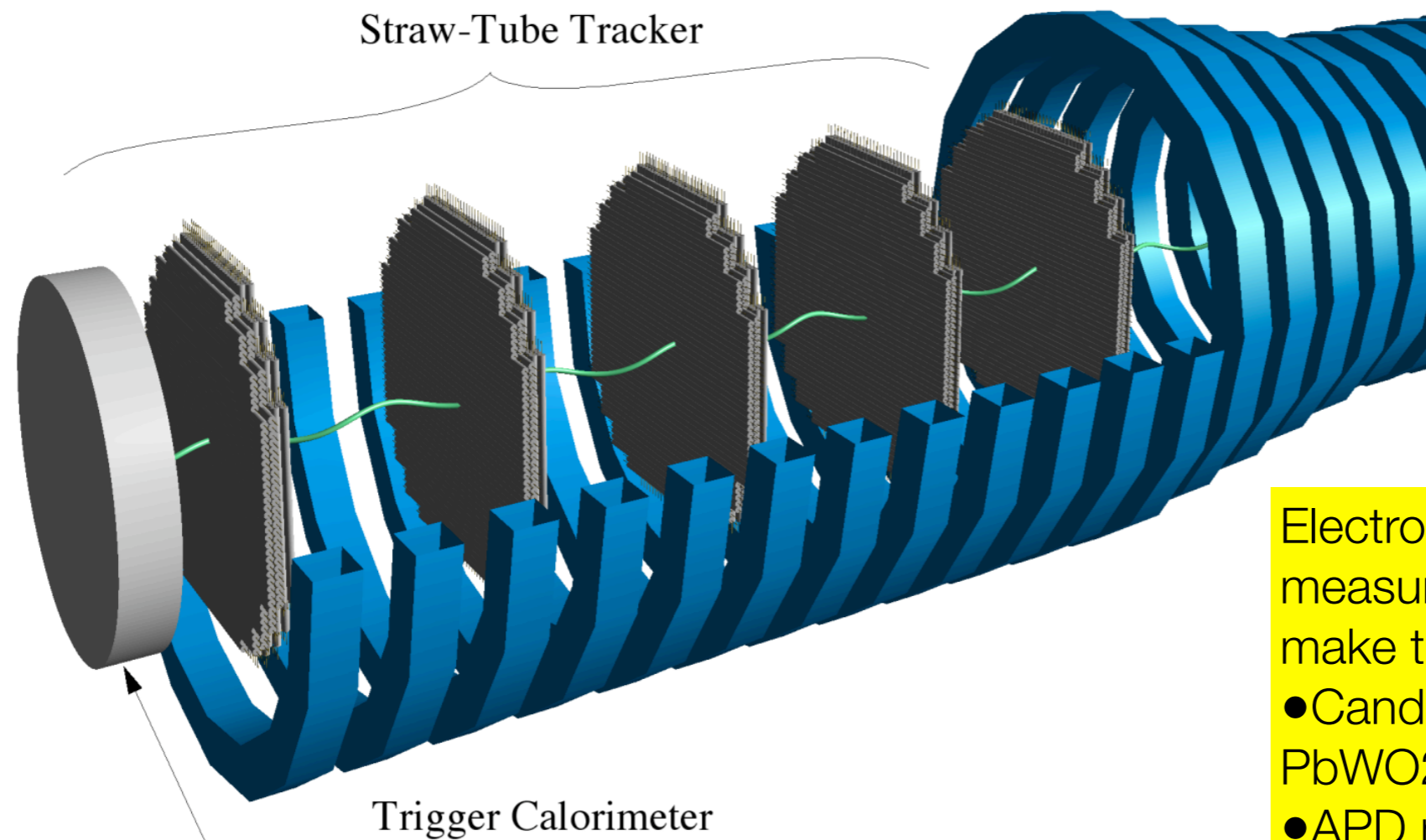
# Electron Detection (preliminary)

Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.

Straw-tube Trackers to measure electron momentum.

- should work in vacuum and under a magnetic field.
- A straw tube has  $25\mu\text{m}$  thick, 5 mm diameter.
- One plane has 2 views (x and y) with 2 layers per view.
- Five planes are placed with 48 cm distance.
- $250\mu\text{m}$  position resolution.



Electron calorimeter to measure electron energy and make triggers.

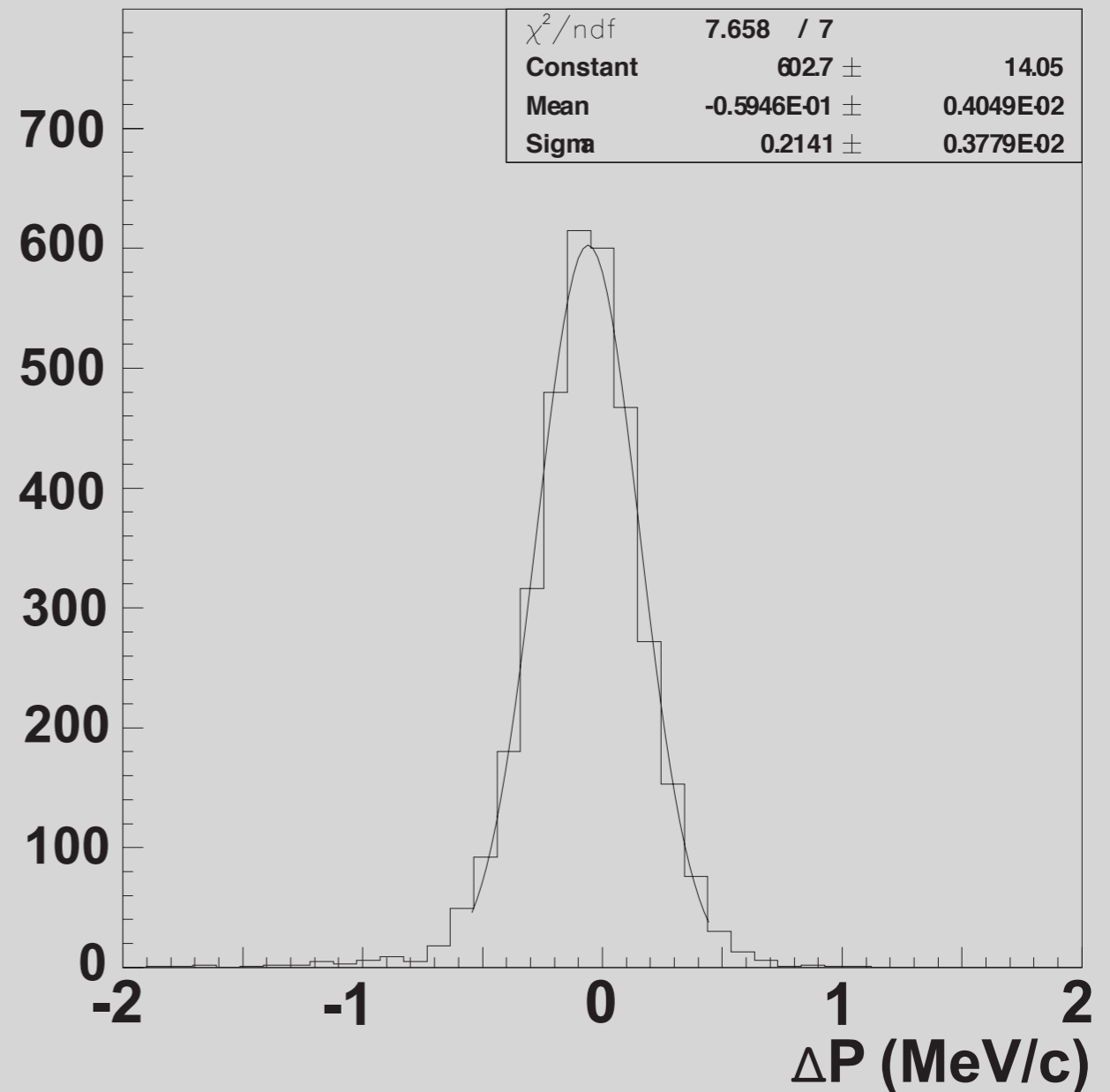
- Candidate are GSO or  $\text{PbWO}_2$ .
- APD readout (no PMT).

# Momentum Resolution

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- 5 stations in vacuum
  - One station has two views (x and y).
  - One view has two layers.
  - Straw tube has 25 $\mu$ m thickness.
- Position resolution : 250  $\mu$ m
- 230 keV/c in sigma (multiple scattering dominated.)

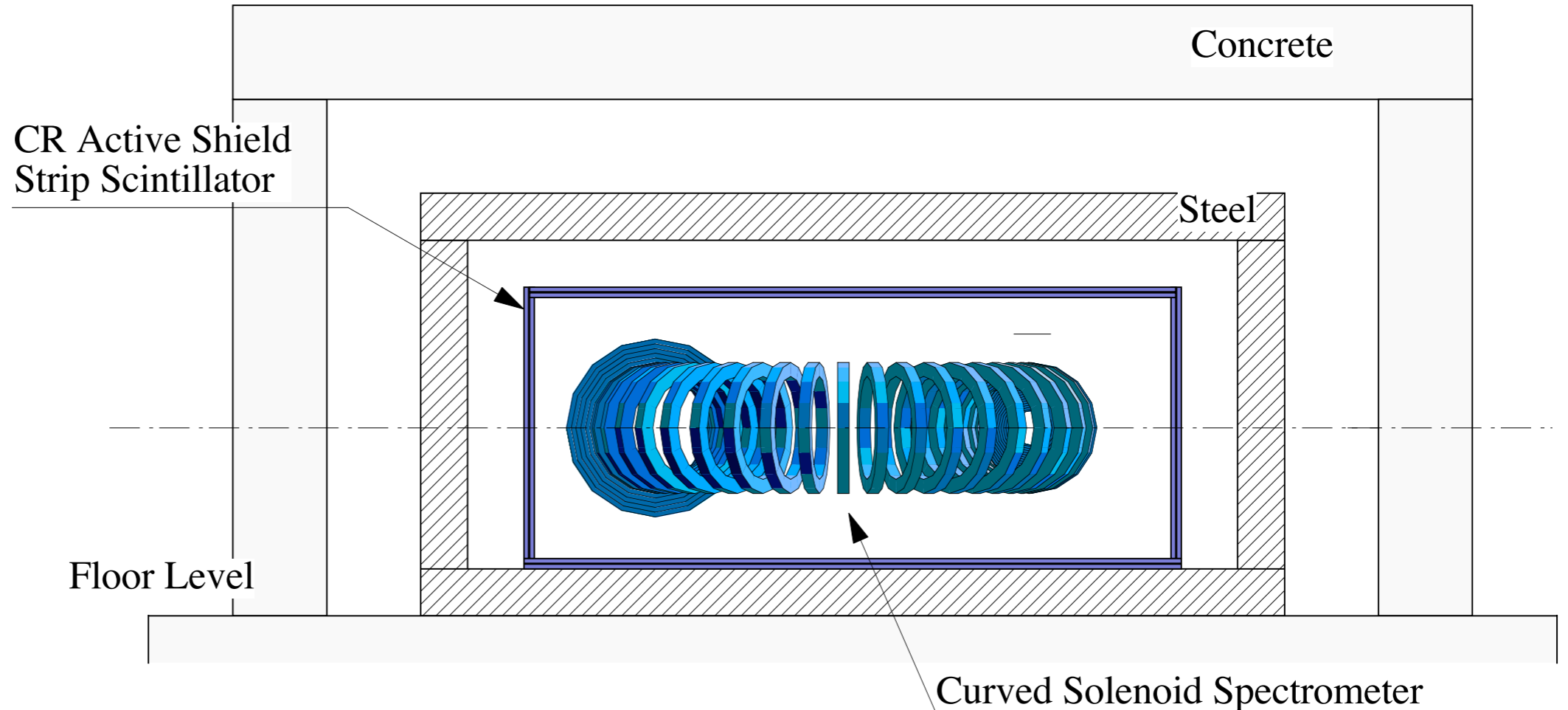
Residual distribution between reconstructed and true momenta.



# Cosmic Ray Shields

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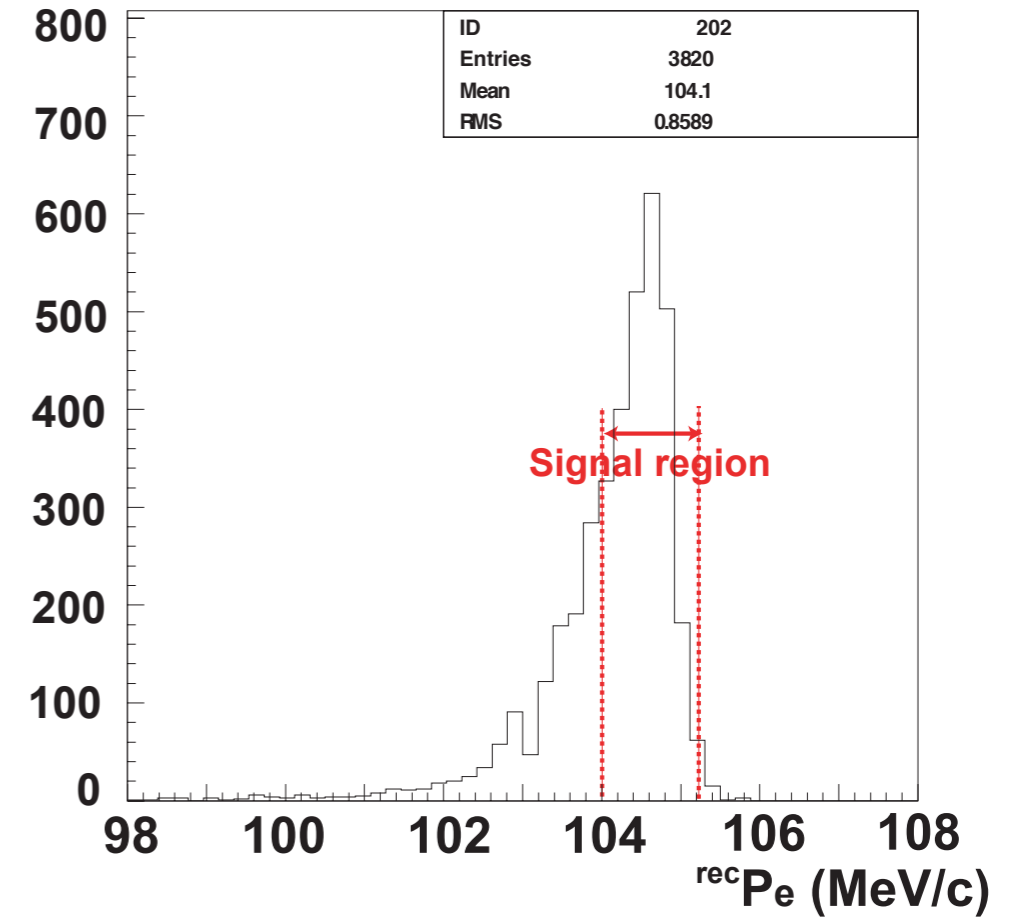
- Both passive and active shields are used.
- Passive shields
  - 2 meter of concrete and 0.5 m of steel
- Active shields
  - layers of scintillator veto counters ( $\sim 1\%$  inefficiency)



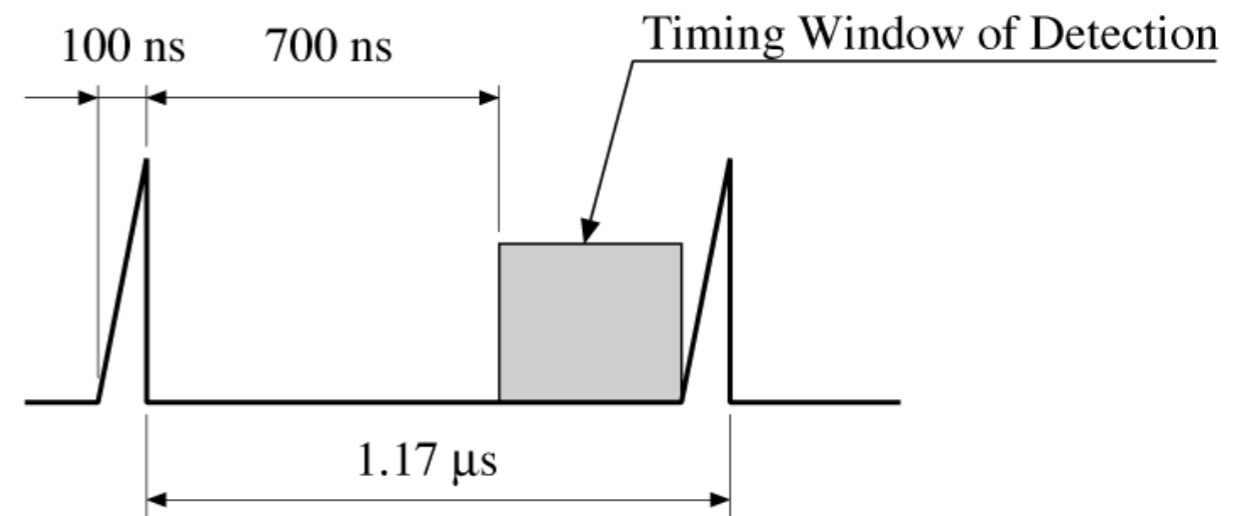
# Signal Acceptance

- The signal acceptance is given by the geometrical acceptance of the detector and the analysis (cut) acceptance.

| Items                 | Acceptance |
|-----------------------|------------|
| geometrical           |            |
| solid angle at target | 0.73       |
| transport efficiency  | 0.44       |
| analysis              |            |
| energy cut            | 0.68       |
| $p_t > 52$ MeV/c cut  | 0.82       |
| time window cut       | 0.38       |
| total                 | 0.07       |



signal energy window (104.0-105.2 MeV in uncorrected energy scale)



# 実験感度の評価

- 実験感度 (single event sen.)

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

- $N_\mu$  は静止したミューオンの総数で、 $6 \times 10^{17}$  muons.
- $f_{cap}$  はミューオン捕獲確率で、アルミニウムの場合は**0.6**。
- $A_e$  は測定器のacceptanceで、**0.07**である。

|             |                    |
|-------------|--------------------|
| 必要な8GeV陽子総数 | $8 \times 10^{20}$ |
| ミューオン生成率/陽子 | 0.0024             |
| ミューオン静止率    | 0.29               |
| 静止ミューオン総数   | $6 \times 10^{17}$ |

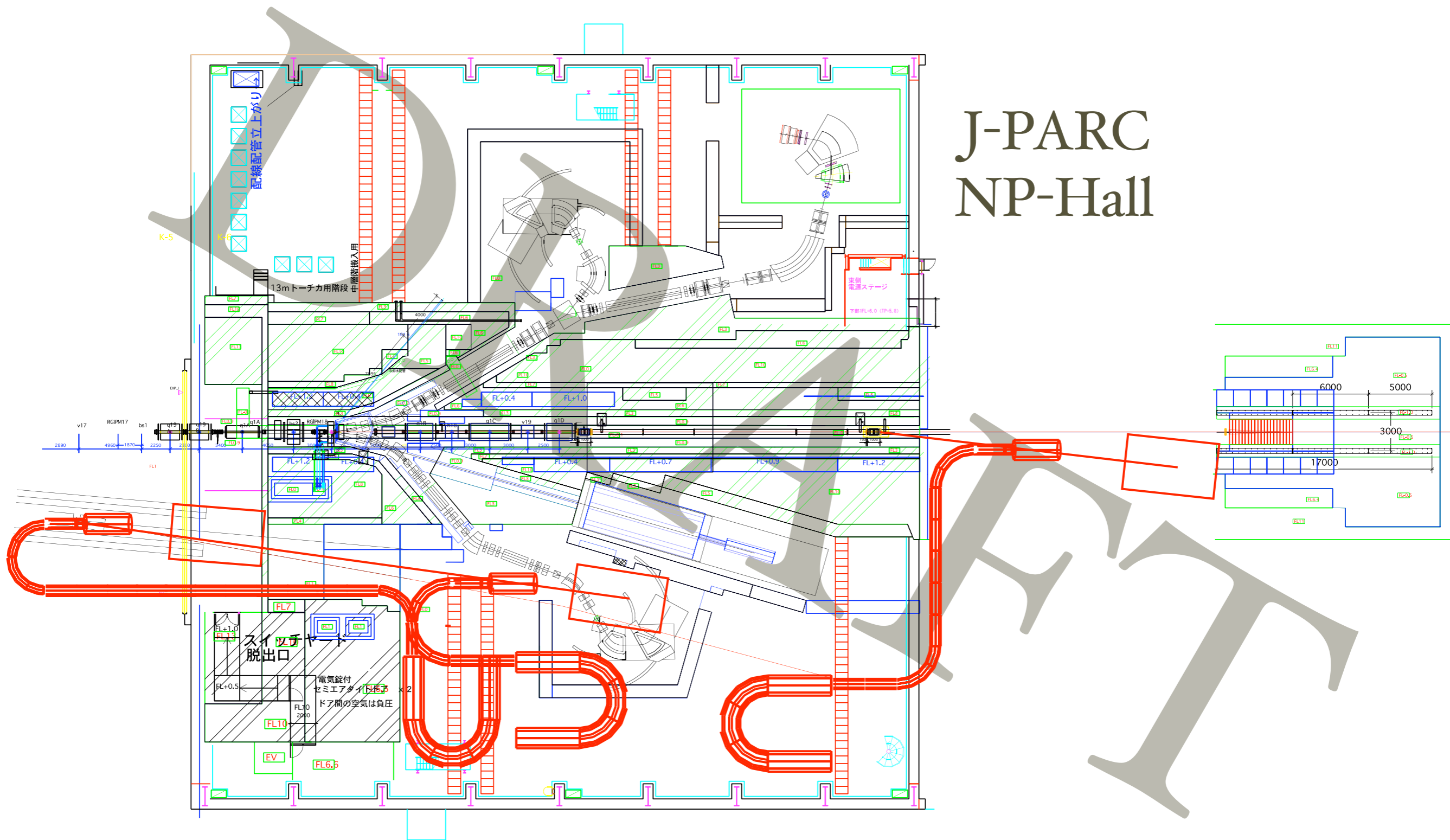
$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{6 \times 10^{17} \times 0.6 \times 0.07} = 4 \times 10^{-17}$$

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \quad (90\% \text{ C.L.})$$

# Backgroundの評価

|                    | Backgrounds                                 | Events            | Comments                  |
|--------------------|---|-------------------|---------------------------|
| (1)                | Muon decay in orbit                         | 0.05              | 230 keV resolution        |
|                    | Radiative muon capture                      | <0.001            |                           |
|                    | Muon capture with neutron emission          | <0.001            |                           |
|                    | Muon capture with charged particle emission | <0.001            |                           |
| (2)                | Radiative pion capture*                     | 0.12              | prompt                    |
|                    | Radiative pion capture                      | 0.002             | 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 |                           |
| (3)                | Cosmic-ray induced                          | 0.04              | $10^{-4}$ veto efficiency |
|                    | Pattern recognition errors                  | <0.001            |                           |
|                    | Total                                       | 0.34              |                           |

# ハドロン実験室へのCOMET配置可能性





# まとめ

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- ミューオン電子転換事象はレプトンフレーバー保存を破る過程であり、標準理論では強く抑制されてるおり、素粒子標準理論を超える新しい物理(超対称性大統一理論や超対称性シーソー理論)などの探索に適している。
- J-PARCハドロン実験室で検討している実験では、 $B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) < 10^{-16}$ を目標にしている。実験レイアウト、実験感度、Background評価を行い、装置開発など準備を進めている。
- 2006年12月にJ-PARCへPRISM-Phase1のLoIを提出した。
- 2007年11月末にJ-PARCへCOMETのプロポーザルを提出する予定。
- **現在、コラボレーターを大募集中。**