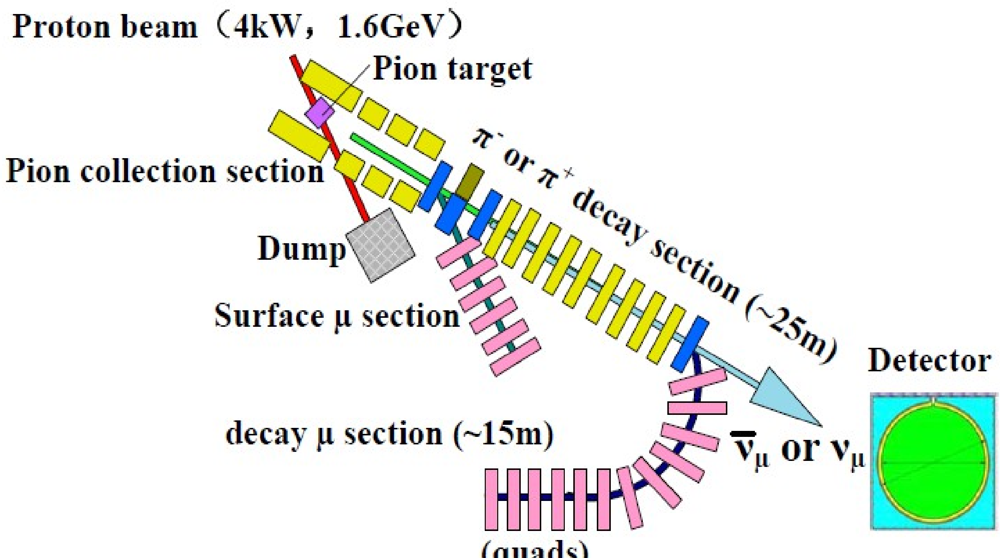
Potential of particle physics at EMuS

Jian Tang (SYSU)
Ye Yuan, Nikos Vassilopoulos (IHEP)

2018.11.21

International Review of EMuS

Dongguan, China Spallation Neutron Source.



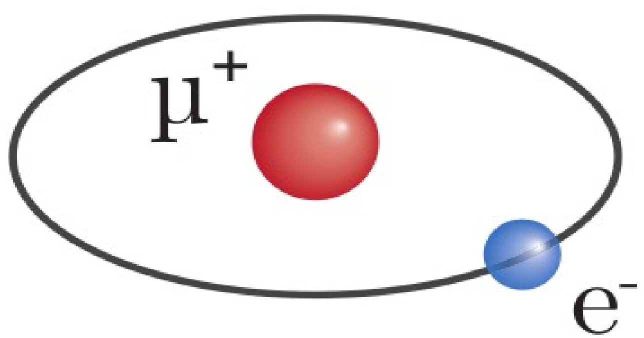


Table of contents

- Motivations
- Neutrino physics?
- Muonium physics?
- Summary.

Overview of accelerator muon sources around the world

Laboratory/Beamline	Energy/ Power	Present Muon $^{+}$/ $^{-}$ Rates [Hz]	Future estimated $^{+}$/ $^{-}$ Rate [Hz]
PSI (CH)	590 MeV, 1.3 MW DC		
LEM		$4.2\cdot10^{8}\ \mu^{+}$	
πE5		$1.3\cdot10^{8}\ \mu^{+}$	
HiMB			$O(10^{10})\ \mu^{+}$ / $O(10^{8})\ \mu^{-}$
JPARC (JP)	3 GeV, 1MW Pulsed Reached 400kW		$2\cdot10^{8}$ $^{+}$@ 1MW)
MUSE		$8\cdot10^{7}$ / $4\cdot10^{6}$	10^{7} $^{-}$@ 1MW
COMET	8 GeV, 56kW Pulsed		10^{11} $^{-}$2019/2020
FNAL (USA)			
Mu2e	8GeV, 25kW Pulsed		$5\cdot10^{10}$ $^{-}$ 2019/2020
RAON/RISP (KO)	600 MeV, 400kW DC)		$7\cdot10^{8}\ \mu^{+}$
CSNS (CN)	1.6 GeV, 100kW Pulsed		$10^{10}\ \mu^{+}$
TRIMUF (CA)	500 MeV, 75kW, DC		
M20/M9B		$2\cdot10^{6}$ / $1.4\cdot10^{6}$	
RAL ISIS (UK)	800 MeV, 160kW, Pulsed	$1.5\cdot10^{6}$/ $7\cdot10^{4}$	
RIKEN RAL			
RCNP Osaka Univ. (JP)	400 MeV, 400W DC		
MUSIC		$10^{6}/1\cdot10^{5}$	$4.2\cdot10^{8}/4.2\cdot10^{7}$

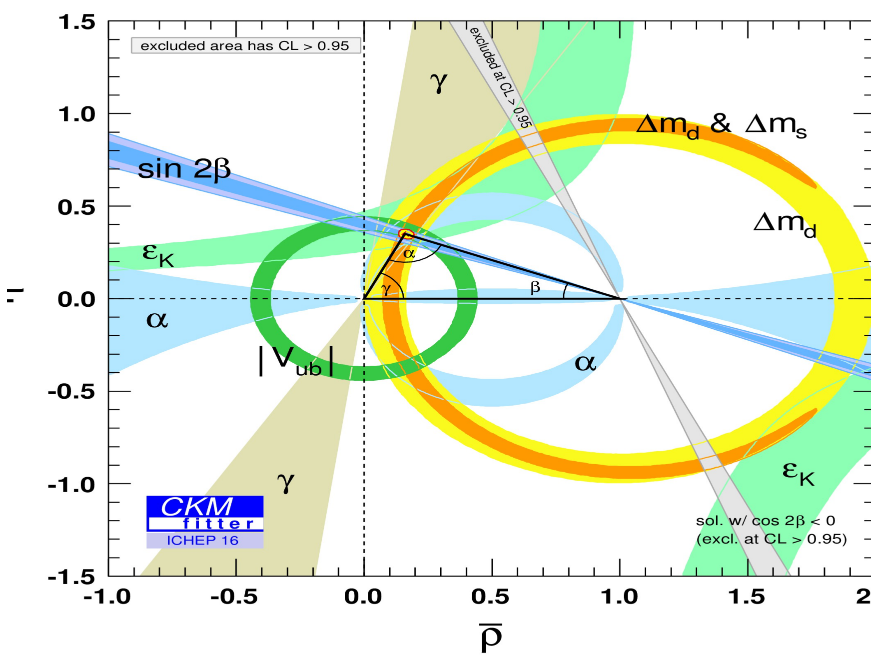
Motivation

- **EMuS is foreseen at CSNS and provides a potential platform for both muon and neutrino experiments**
- **Besides the muon science as μSR techniques in applications, can we conduct any physics study there?**
- **R&D platform for MOMENT, a future muon-decay medium-baseline neutrino beam facility**
- **High-precision cross section are requested in the next-generation accelerator neutrino oscillation experiment.**
- **EMuS is an R&D platform for the accelerator and target station design**

Parameter	Value	Precision (%)
Δm^2_{21}	$7.37\ 10^{-5}$ eV^2	2.3
θ_{12}	34°	5.8
Δm^2_{32}	$2.52\ 10^{-3}$ eV^2	1.6
θ_{23}	42°	~9
θ_{13}	8.4°	4

Capozzi et al. PRD 95, 096014 (2017)

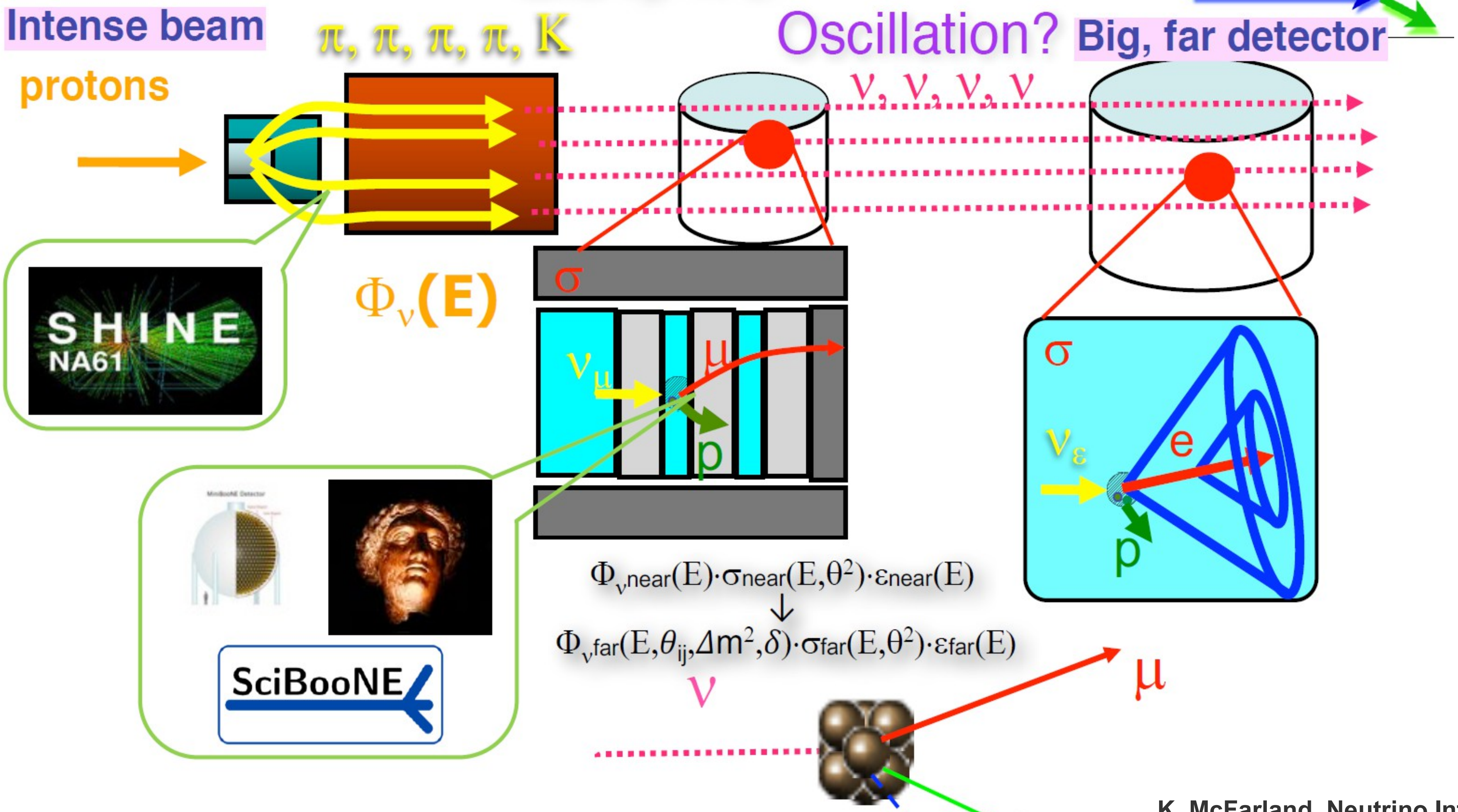
- Not precise enough!
- Can we achieve the level similar to CKM?



- Sub-percent level in CKM.

T2K experimental strategy

Search for CPV by comparing $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$.



K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

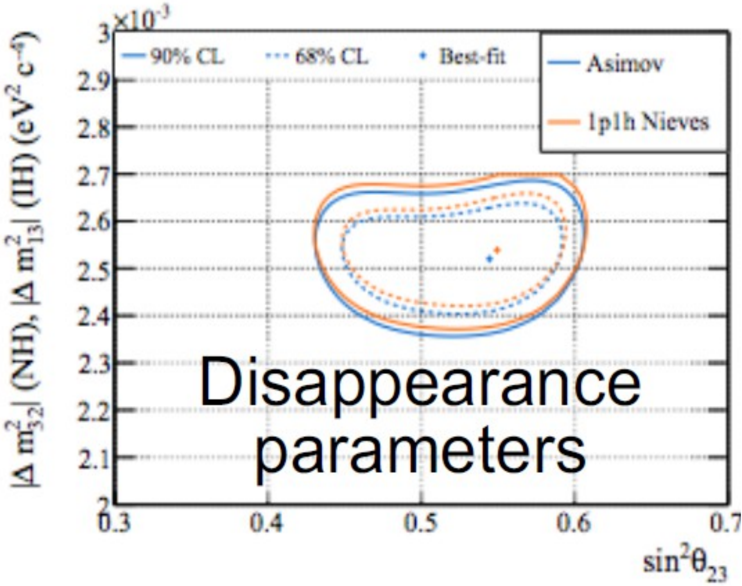
The largest uncertainty from the neutrino interactions

- **It is a major goal of near detectors in T2HK/DUNE to pin down uncertainties in neutrino interaction cross sections.**
- **Different neutrino interaction cross sections change fitting neutrino mixing parameters dramastically.**

Extracting neutrino mixing parameters in T2K analysis

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

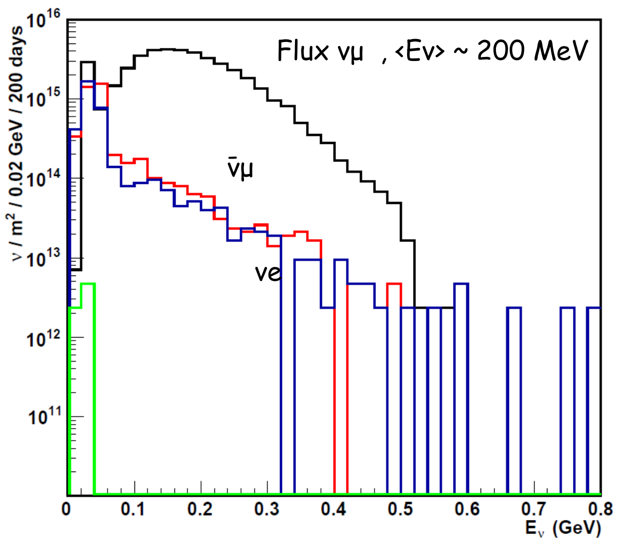
Fractional uncertainties (%)

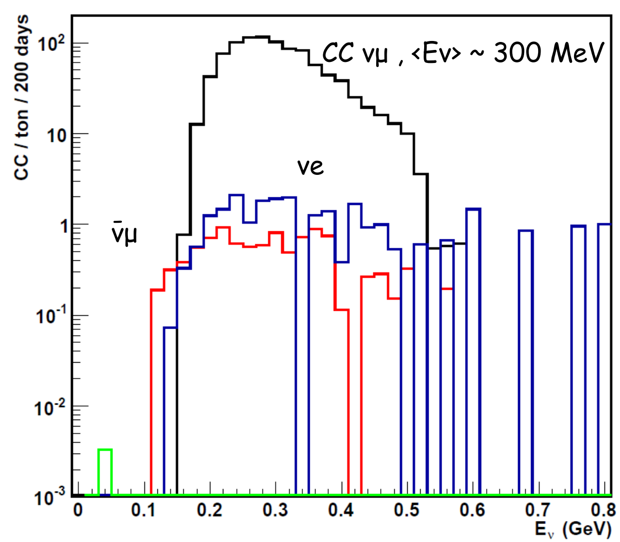


K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

Measurements of low-energy neutrino interactions

- CC ν_μ at $\langle E_\nu \rangle$ = 300 MeV at EMuS
- ~ 1000 CC events / ton / year at CSNS – I
- x 50 with capture system and decay channel upgrades at CSNS-II



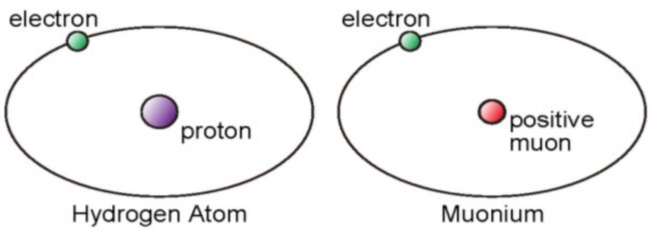


Detector performance analysis needed in order to investigate its value

1-8% stat. error, FLUKA	N ν ($\times 10^{16}$) / m2 / 200 days		CC / ton / 200 days	
	> 53 MeV	%		%
Muon anti-neutrino	3.78	94.5	959	96.5
Muon neutrino	0.13	3.2	10	1
Electron anti-neutrino	0.09	2.3	25	2.5
Electron neutrino	-	-	0.004	-

Why Muonium?

- **Muon: elementary particle, 200 times heavier than an electron, lifetime of 2.2 μs.**



- **Muonium:**
  - **Bound state of μ^+ and e^- governed by QED.**
  - **Similar to Hydrogen but free from the finite size of proton.**
  - **Hyperfine structure splittings.**

- **Muonium 1s-2s and HFS spectroscopy:**

  → test of bound-state QED

  → fundamental constants: m_μ , R_∞ , m_μ/m_p , q_μ/q_e ...

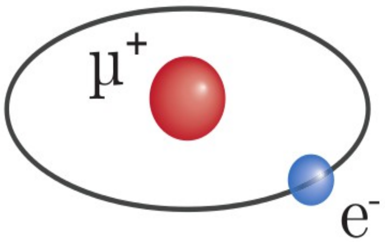
  → fundamental symmetries

- **Muonium – antimuonium:**

  → put limits on the charged LNV

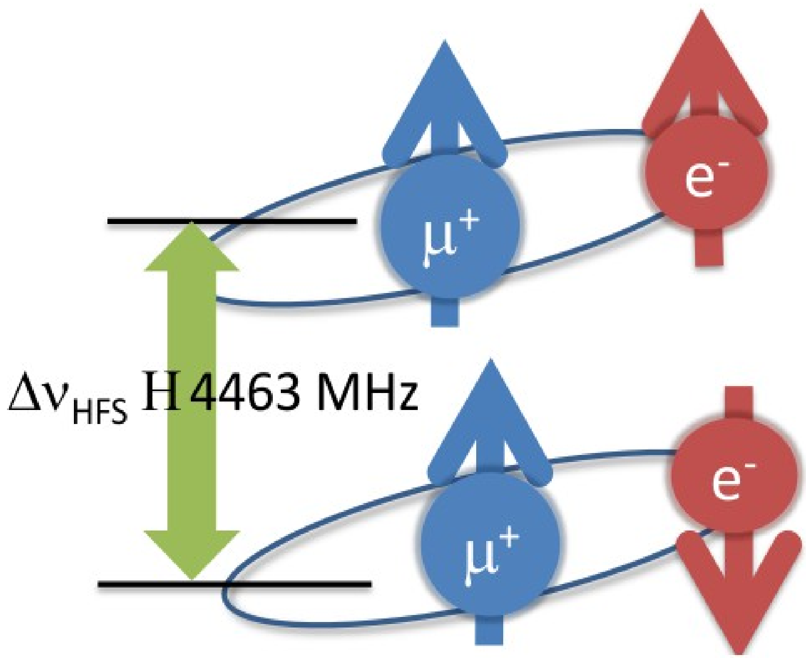
Muonium HFS

$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

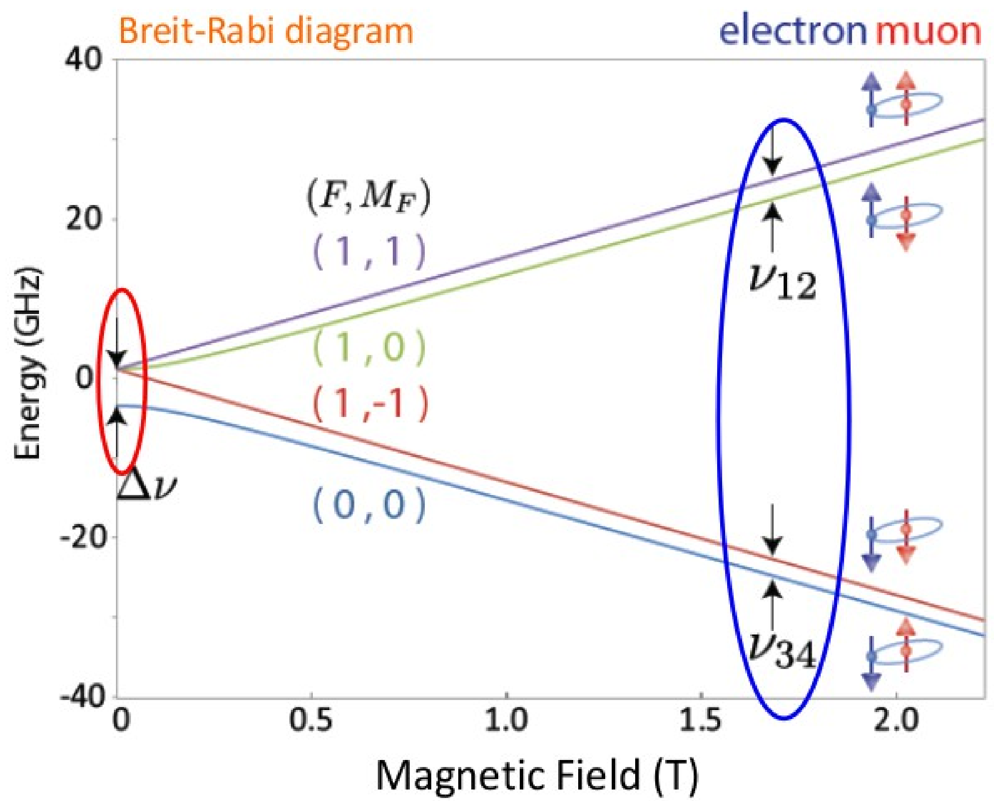


$\Delta\nu_{HFS}$: Mu Hyperfine Structure

Zeeman Splitting



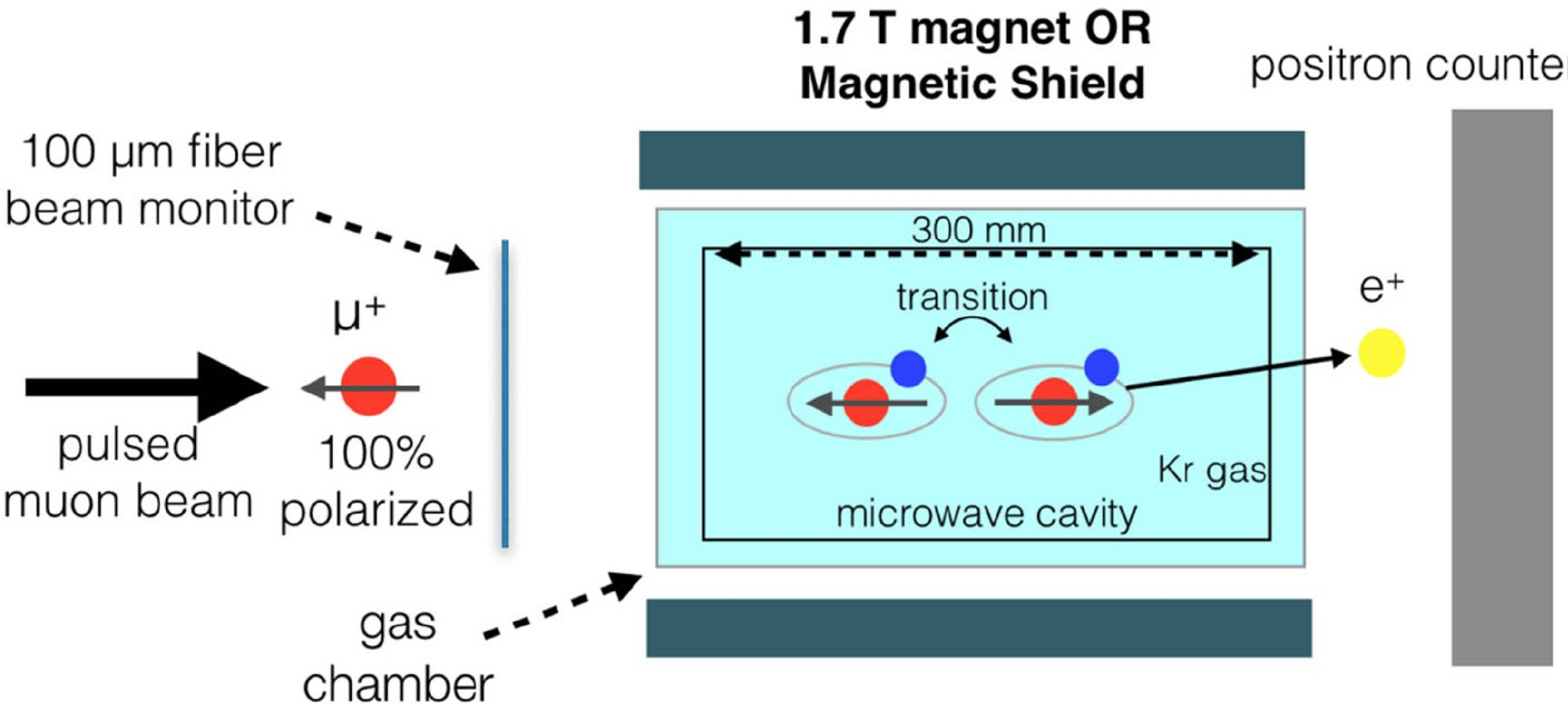
Pure lepton
= point particle



$\nu_{12}+\nu_{34} = \Delta\nu_{HFS}$ $\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p \propto m_\mu/m_p$

Ref: K. Shimomura, see the MuSEUM project in Japan.

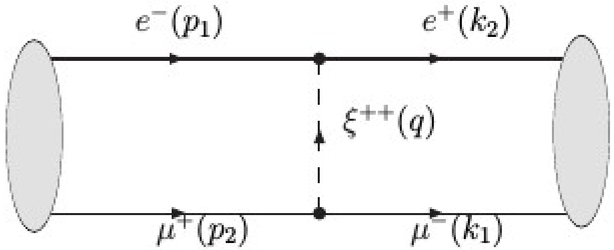
Muonium HFS



Ref: The MuSEUM project in J-PARC.
Hyperfine Interact (2017) 238: 14

Muonium to anti-muonium conversion beyond SM

- **Lepton number violating process beyond SM.**
- **For example, prediction in the type-II seesaw model.**



$\mathcal{P}(M \to \bar{M})$	$G_{M\bar{M}}/G_F$	Experiment
$< 2.1 \times 10^{-6}$	< 0.29	Huber et al. (1990)
$< 6.5 \times 10^{-7}$	< 0.16	Matthias et al. (1991)
$< 8.0 \times 10^{-9}$	$< 1.8 \times 10^{-2}$	Abela et al. (1996)
$< 8.3 \times 10^{-11}$	$< 3 \times 10^{-3}$	Willmann et al. (1999)

The best limit!

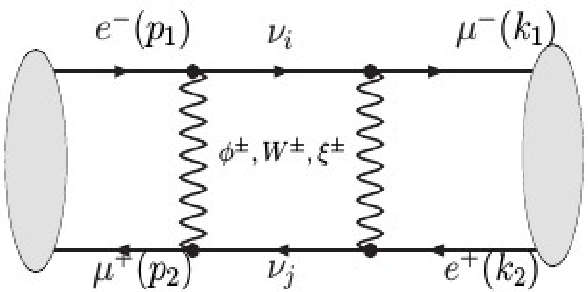


Figure 2.3: Dirac-Box (a)

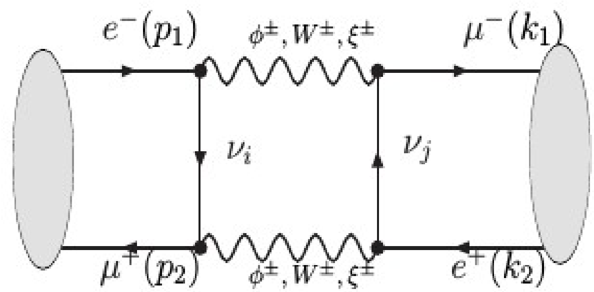


Figure 2.4: Dirac-Box (b)

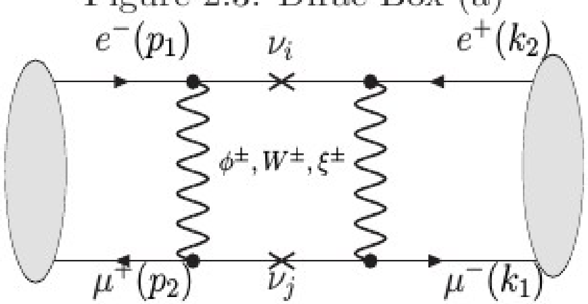


Figure 2.5: Majorana-Box (c)

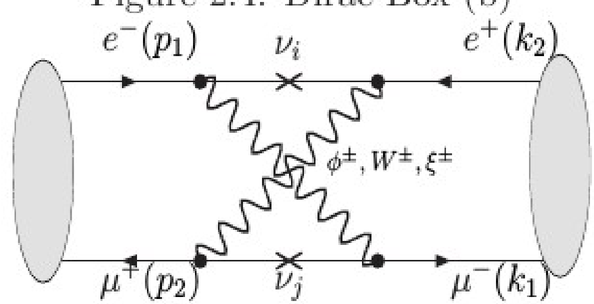
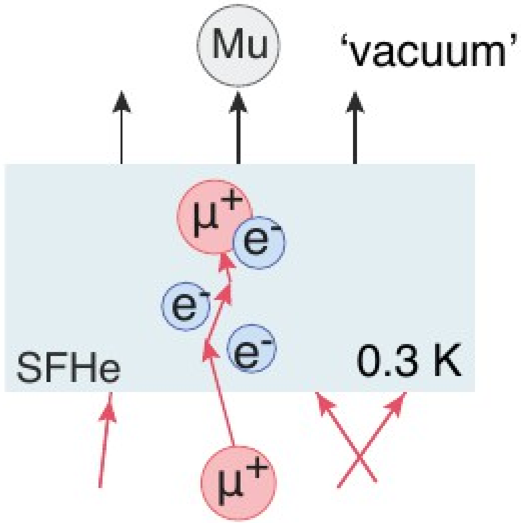


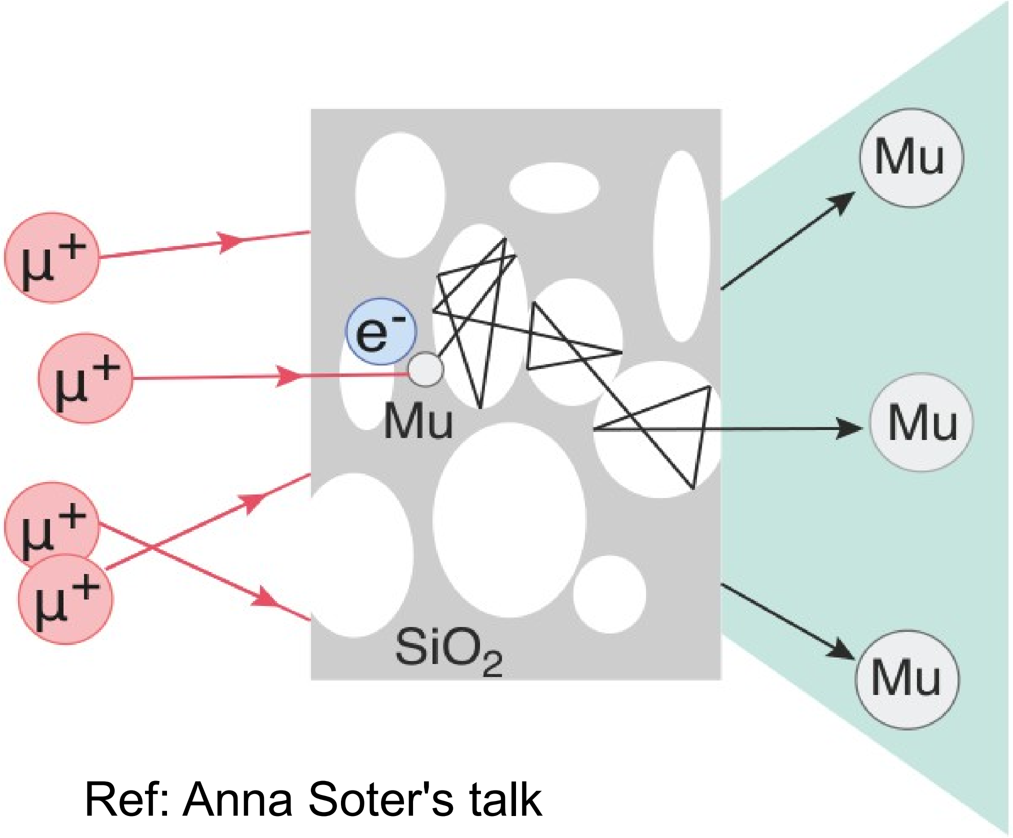
Figure 2.6: Majorana-Box (d)

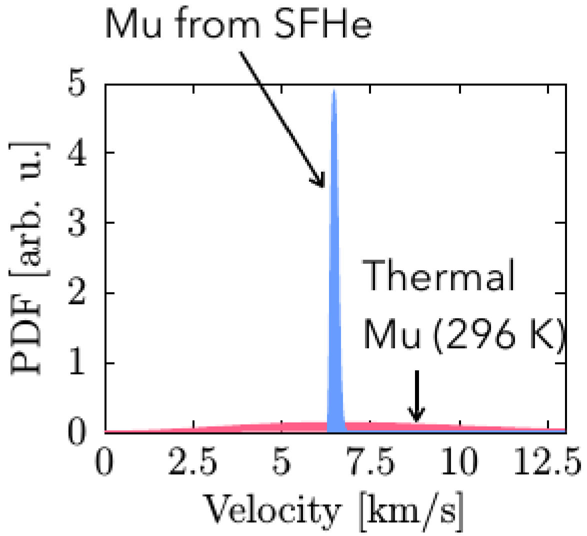
Muonium productions

- **Latest progress made by PSI.**
- **From chemical potential E/k_B~270 K:**

Mu atoms are ejected from bulk Super Fluid Helium with v = 6.3 mm/μs



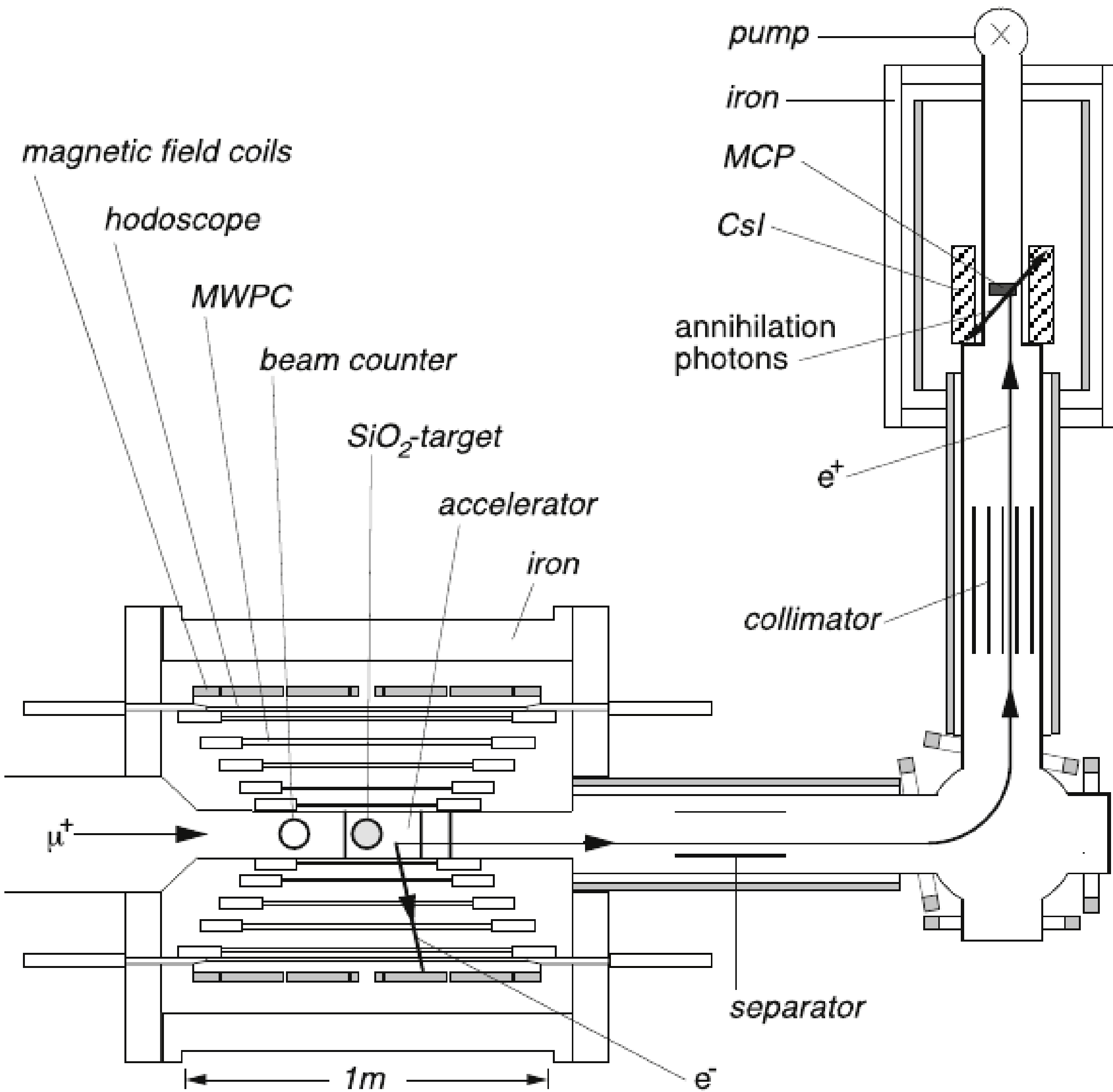




Ref: Anna Soter's talk

Detections of muonium to anti-muonium conversions

- **Follow the apparatus at PSI built more than 20 years ago.**
- **Continous muon source: 8×10⁶ μ⁺/s, p=26 MeV with 5% spread.**



- Magnetic spectrometer to study the anti-muonium
- Signal one: energetic e^- from μ^- decay
- Signal two: atomic shell e^+, accelerated and guided onto a MCP
- Coincident signals: time and position.

$\mathcal{P}(M \to \bar{M})$	$G_{M\bar{M}}/G_F$	Experiment
$< 2.1 \times 10^{-6}$	< 0.29	Huber et al. (1990)
$< 6.5 \times 10^{-7}$	< 0.16	Matthias et al. (1991)
$< 8.0 \times 10^{-9}$	$< 1.8 \times 10^{-2}$	Abela et al. (1996)
$< 8.3 \times 10^{-11}$	$< 3 \times 10^{-3}$	Willmann et al. (1999)

Major sources of background in the latest measurement

- **Accidental coincidence between an energetic e^- produced by Bhabha scattering of e^+ from μ^+ decay in a muonium and a scattered e^+.**
- **Physics background from μ^+ decay (pulsed muon source helps):**

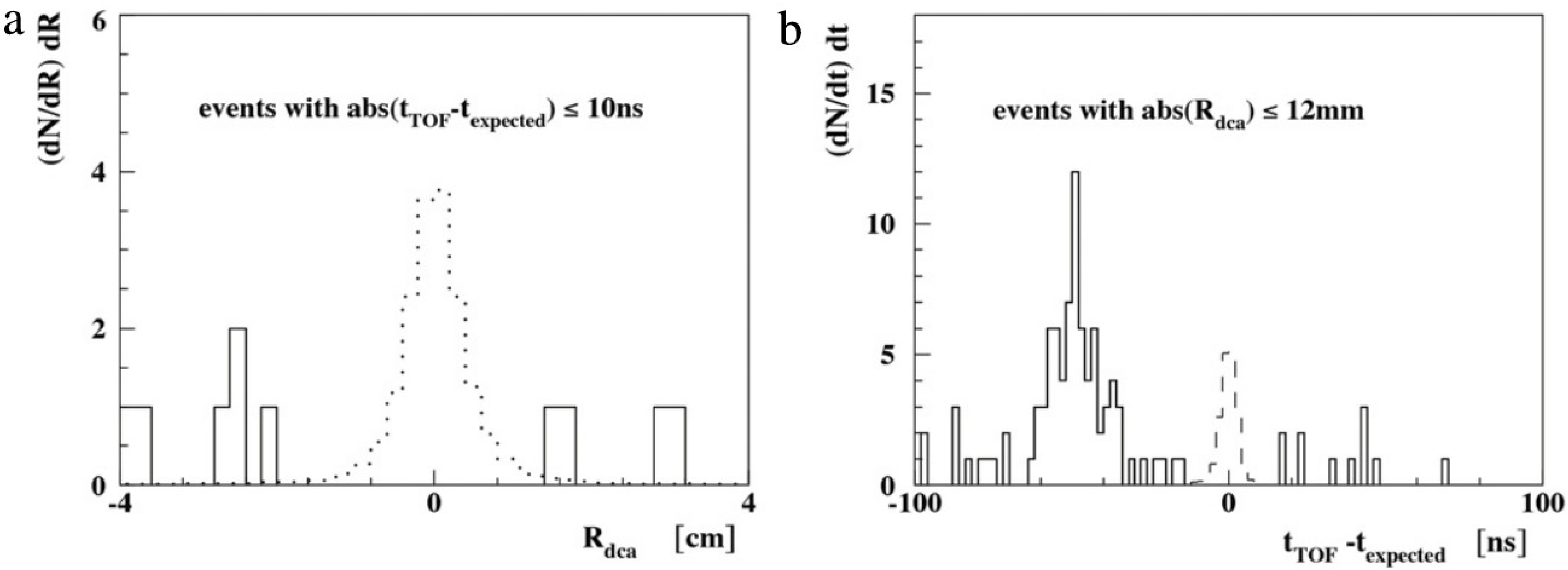
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu} e^+ e^-$$

Branch ratio = 3.4×10^{-5}.

- **How pin down these backgrounds?**
  - **MCP-based TOF system with a FWHM of 3.3 ns. => modern TOF system improved by a factor of 10.**
  - **Cathod strip hadoscope in a 0.1 T field to measure e^-.**
  - **e^+ accelerated to 7 keV and measured by a CsI calorimeter with 350 keV resolution.**
- **Detected muonium: $5\times10^{-3}/\mu^+$**

Latest results in PSI 20 years ago

- **Chamber/counter techniques**
- **Search for an energetic electron from normal muon decay in coincidence with an ~13.5 keV kinematic energy positron.**



Rough estimates of physics prospects in EMuS

- **Pulsed muon source: 10^6 => 10^8 μ^+/s**
- **Muonium efficiency: 1.8% => 5% ???**
- **Total accumulation: 5×10^{10} muonium.**
- **Detected muonium: 5×10^{-3} /μ^+.**
- **The same chamber/counter technique with a better timing TOF to suppress the backgrounds: =>10.**
- **Expect a factor of >100 improvement of the current limit!**

Summary

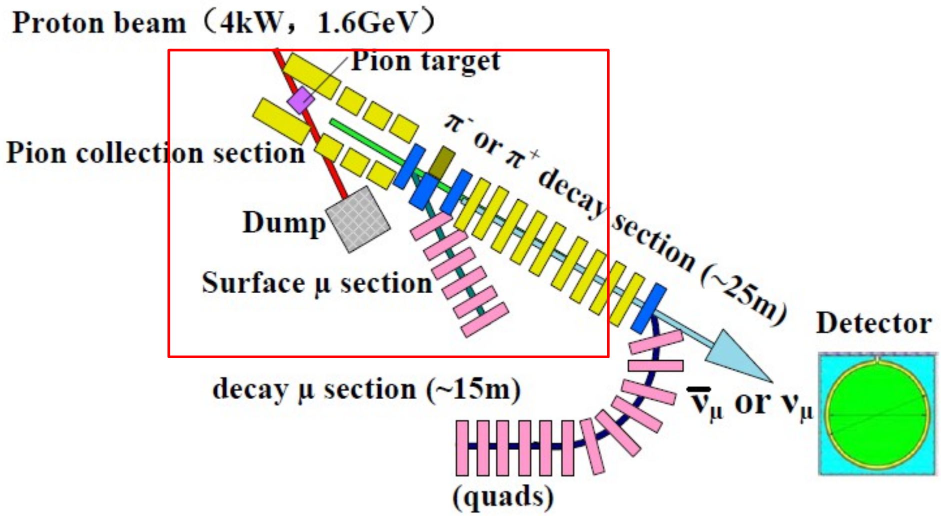
- **EMuS offers a chance to measure the cross section of neutrino interactions, which helps precision measurements of neutrino mixing parameters like T2HK and DUNE.**
- **EMuS provides a good testbed for Muonium physics, including precision measurements of hyper-fine structure splittings, muonium to anti-muonium conversions.**
- **A bunch of new models predict the existence of muonium to anti-muonium conversions.**
- **The latest experimental results achieved 20 years ago.**
- **Current limits can be significantly improved with modern technology and the advent of new and intense muon sources.**
- **Welcome to working together to pursue Muonium physics.**

Thank you for your attention.

Backup

EMuS full scheme:

Baseline experimental scheme



Schematics of the 5 T adiabatic capture SC solenoid: