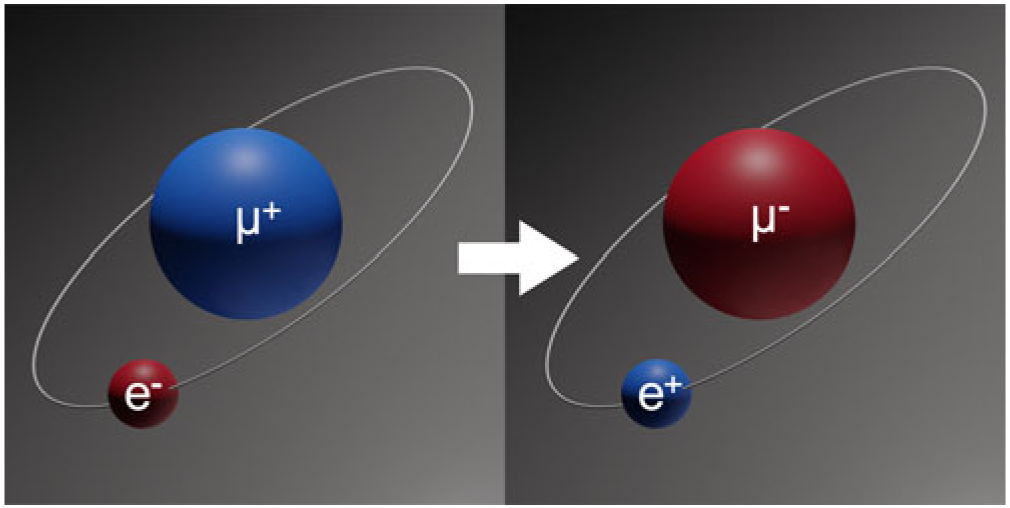
A new approach to Mu-antiMu conversion search

NEWS colloquium, 27/May/'22



Naritoshi Kawamura
Muon Sci. Sec., MLF div., J-PARC

as a counterpart of the experimental side to Y. Uesaksa's talk in the NEWS series on 20/Jan/'22

A little bit long introduction about fundamental physics using muon

Fundamental physics ≈
elementary particle physics +
ultra-high-precision measurement for QED/EW/SM

In short, we, muon fundamental physicists, are aiming for

discovery of a new physics beyond the standard model
approaching the mystery of the birth of the universe

with muons.

Is why muon?

A new physics may not be affected only on the muon.

Then, what is the reason why a muon is used?

【Technical reason】

- Easy to make
  - In the CM system, the threshold energy of muon generation is 140 MeV. (In the lab. system, 290 MeV.) A large number of muon can be generated by a middle energy accelerator.
- Easy to observe
  - A muon has a moderate life time (2.2μs), and emits a high-energy e^+/e^- that is easy to observe.
  - A spin-polarized beam and spin-directional e^+/e^- emission reflect the microscopic information of muons themselves.

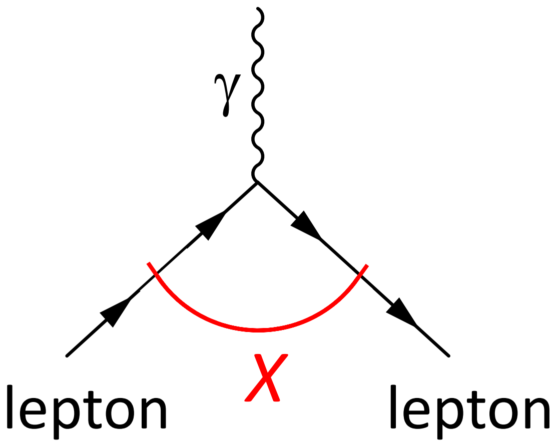
Is why muon?

【Scientific reason】

- Muon has no internal structure (in the SM).
  - Relatively easy to improve the precision of theoretical calc.
- Affected by only Electro-Week interaction
  - Strong interaction does not affect directly.
    (Only higher-order correction like vacuum polarization)
  - A muonium (μ^+e^-) is more of an ideal "hydrogen system" than a hydrogen.
- Mass scale of a new physics
  - Sensitivity to a new physics is expected to be scaled by the square of mass.
  - E.g., an electron is much easier to generate than a muon, but sensitivity is 1/42,000 ($=1/205.6^2$).

Mass scale in a new physics

In Feynman diagram



$$a_l(X) \sim C_X \left(\frac{m_l}{\Lambda_X}\right)^2$$

C_X : Coupling strength

Λ_X : Mass scale

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 43{,}000$$

A muon has much higher sensitivity than an electron

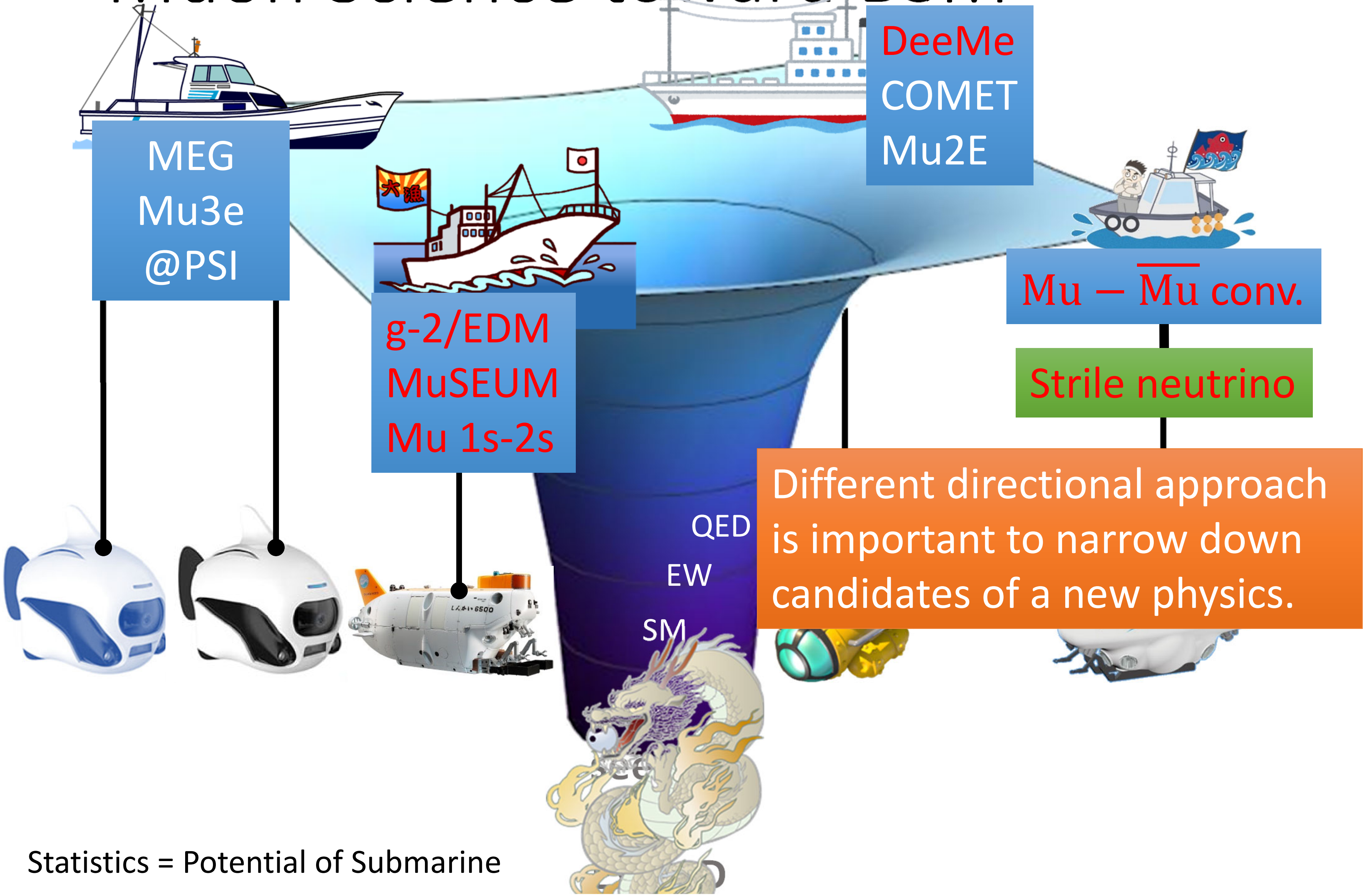
$$\left(\frac{m_\tau}{m_\mu}\right)^2 \sim 280$$

τ has higher sensitivity. But, τ is much more difficult to generate.

That’s why muon!

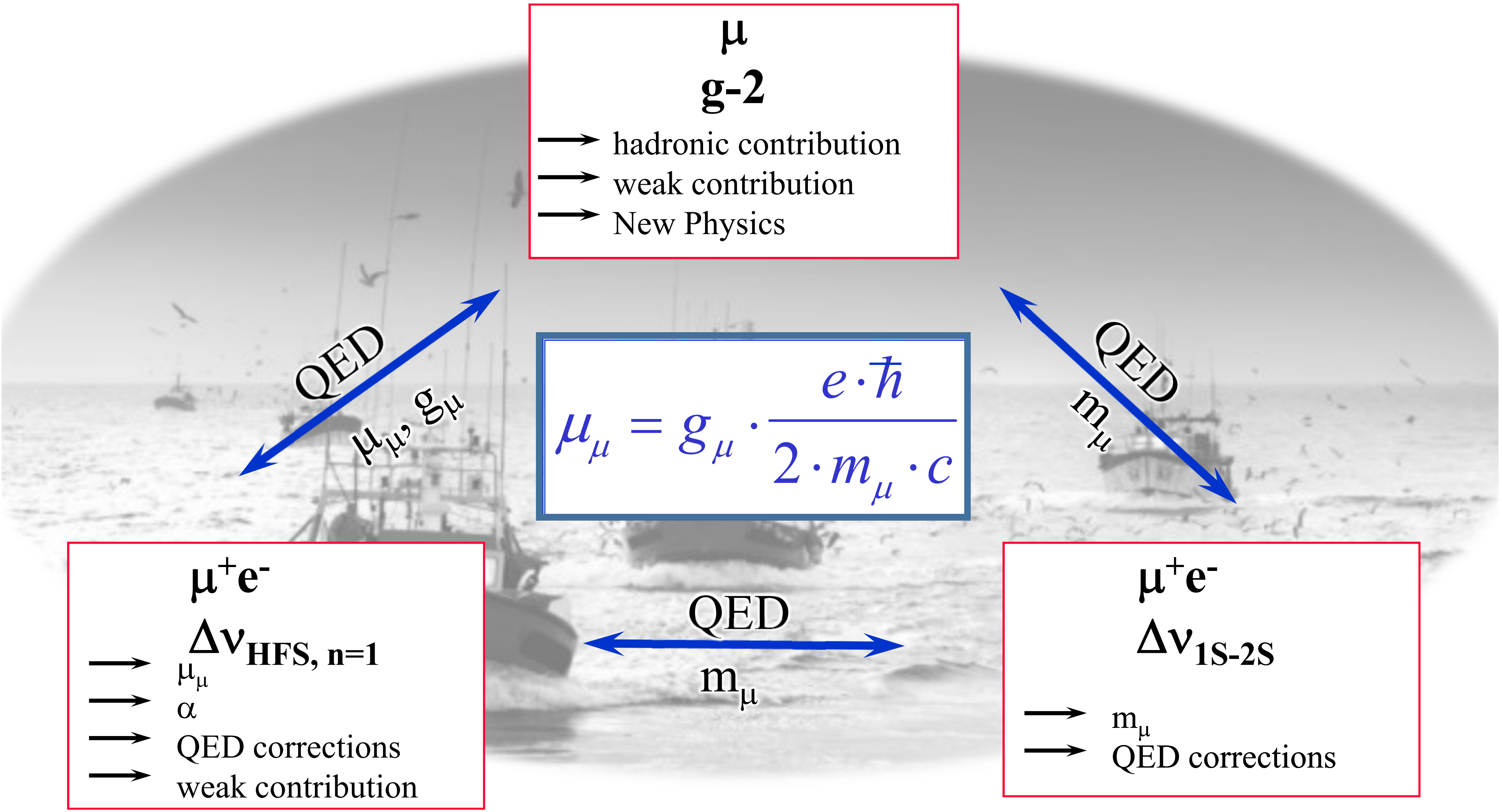
- So far, SM was completed by the discovery of Higgs. But, SM cannot answer
  - Matter dominated universe
  - Dark matter, (dark energy?)
  - Layered structure of quarks and leptons
  - Neutrino oscillation
- It is obvious SM is a part of a greater system.
- Gather and investigate a huge number of muons to find "something strange" or "abnormal character“, that can be an evidence of a new physics.
- Such studies are specialty in high intensity frontier facility like J-PARC MUSE.

Muon Science toward BSM

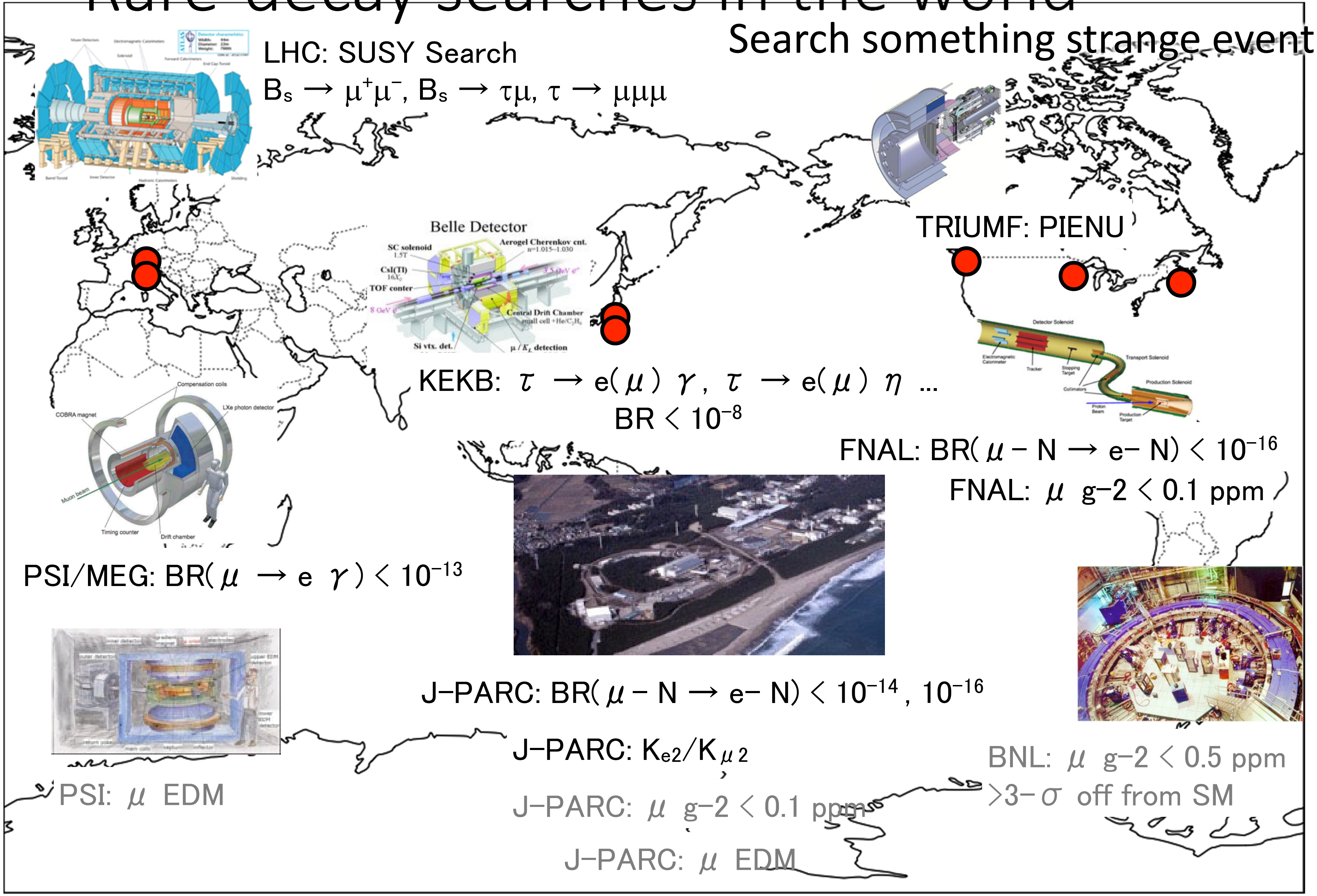


High precision studies

Search abnormal character of muon



Rare-decay searches in the world



Physics introduction

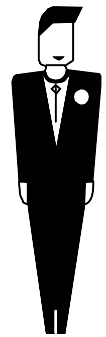
- Lepton Flavor Violation (LFV)
  - $|\Delta L_i| = 1$

$$\mu^+ \to e^+ \gamma$$

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

$$\mu^+ - e^\pm \ conversion$$

SUSY-GUT



  - $|\Delta L_i| = 2$

$$Mu - \overline{Mu} \ conversion$$

$$\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$$

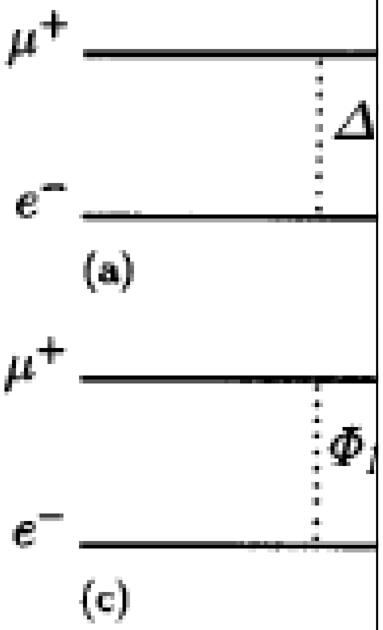
Exotic processes

$(\text{rare})^2$?

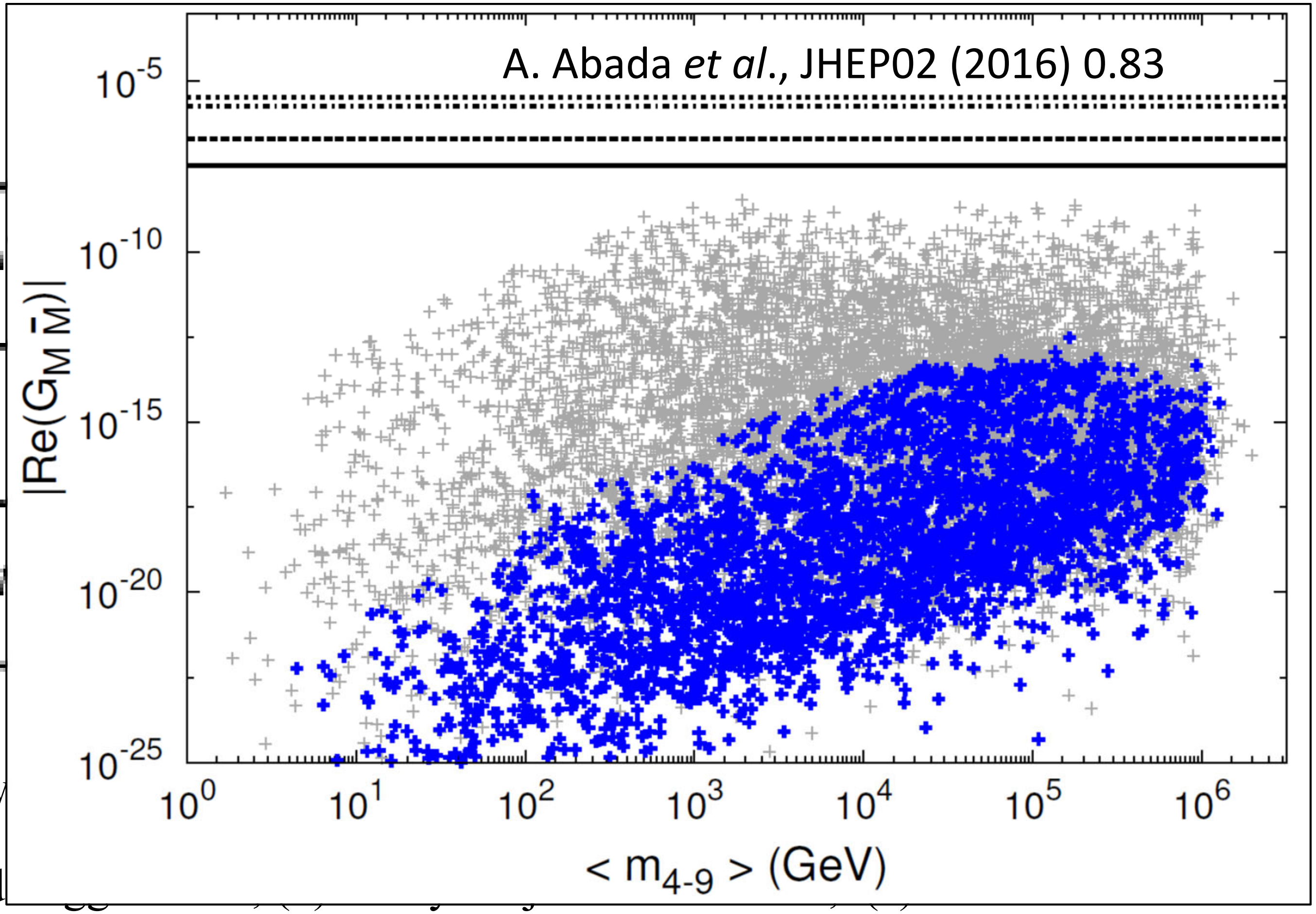
- Is the rate of "$\Delta L = 2$" is square of "$\Delta L = 1$"?
  Is there almost no hope to detect?

- No!
  They are expected in different models/mechanisms.

models



L. W



(a) doubly charged
neutral scalar, e.g., a supersymmetric τ-sneutrino, or (d) a bileptonic flavor diagonal gauge boson

History of Mu-antiMu conversion

Predicted M-M Conversion 1957- Named System "Muonium" ?

$$M \overset{?}{\Leftrightarrow} \overline{M}$$

$$\mu^+ e^- \overset{G_{M\overline{M}}}{\longleftrightarrow} \mu^- e^+$$

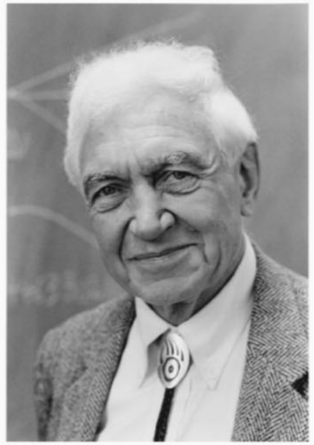
	μ^+	e^-	μ^-	e^+
L_μ:	-1		+1	
L_e:		+1		-1

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

Flavour oscillations well established in quark sector :

$$K^0 \Leftrightarrow \overline{K^0}$$

$$B^0 \Leftrightarrow \overline{B^0}$$



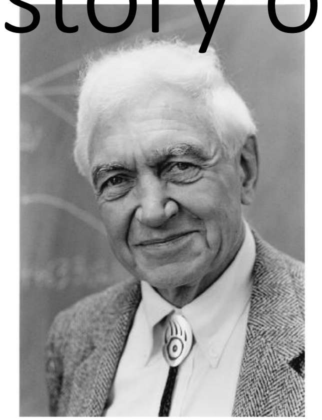
Did first Search for Conversion

Amato et al. Phys.Rev.Lett. 21, 1709 (1968)

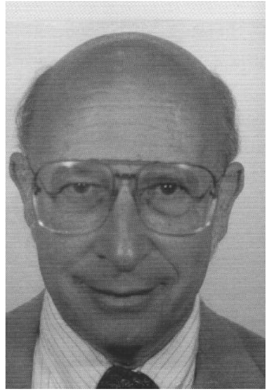
Was significant Part of many follow on experiments

from K. Jungmann's talk in *"New Developments of Muon Precision Physics"*

History of Muonium



There was stimulating competition



Discovery of Muonium 1960

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VOLUME 5, NUMBER 2 PHYSICAL REVIEW LETTERS JULY 15, 1960

FORMATION OF MUONIUM AND OBSERVATION OF ITS LARMOR PRECESSION*

V. W. Hughes, D. W. McColm, and K. Ziock
Gibbs Laboratory, Yale University, New Haven, Connecticut

and

R. Prepost
Nevis Laboratory, Columbia University, New York, New York
(Received June 17, 1960)

Hyperfine Structure addressed as an Important Quantity

211

VOLUME 8, NUMBER 3 PHYSICAL REVIEW LETTERS FEBRUARY 1, 1962

HYPERFINE STRUCTURE OF MUONIUM*

K. Ziock, V. W. Hughes, R. Prepost, J. Bailey, and W. Cleland
Yale University, New Haven, Connecticut
(Received January 5, 1962)

1956 We invented $\mu^+ e^-$ misnamed it *muonium*

1957-1958 We failed to produce it !

1960 Yale/Nevis discovered it...

1964 They got $\Delta\nu$ to 27 ppm (but...)

1969-1973 We had a couple of ideas, got $\Delta\nu$ to 0.5 ppm

1977-1982 Yale/Heidelberg/LAMPF threw us into **the dustbin of history** ($\Delta\nu$ to 0.04 ppm)

SIC TRANSIT GLORIA MUNDI!

From: V. Telegdi, in: "A Festschrift for Vernon W. Hughes", 1990

from K. Jungmann's talk in *"New Developments of Muon Precision Physics"*

2022 / 01 / 20 @ NEWS seminar

Models of the muonium to antimuonium transition

based on T. Fukuyama, Y. Mimura, & Y. Uesaka,
PRD**105**, 015026 (2022). [arXiv:2108.10736]

Contents

Yuichi Uesaka

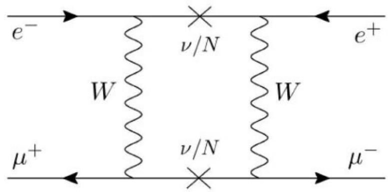
Kyushu Sangyo Univ.

from Y. Uesaka's talk in *NEW seminar*

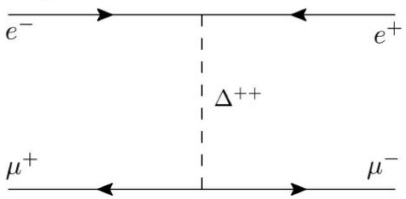
New physics to Mu-antiMu conv.

Classification of new particles & interactions to generate Mu-to-$\overline{\text{Mu}}$ transition

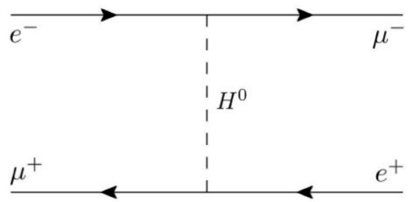
1. $\Delta L_e = \Delta L_\mu = 0$
   - mass term of SM singlet which violates lepton number
   - loop
   - e.g. Majorana ν mass



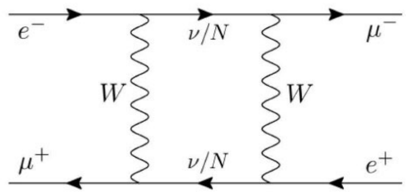
2. $(\Delta L_e, \Delta L_\mu) = (\pm 2, 0), (0, \pm 2)$
   - doubly-charged mediator
   - tree
   - LNV is not needed.
   - If mediator couples to W^+W^+, $0\nu 2\beta$ is induced.



3. $\Delta L_e = -\Delta L_\mu = \pm 1$
   - neutral mediator
   - tree
   - LNV is not needed.



4. $(\Delta L_e, \Delta L_\mu) = (\pm 1, 0), (0, \pm 1)$
   - loop
   - model-independently, strongly constrained by $\mu \to e\gamma$ or $\mu \to 3e$



from Y. Uesaka's talk in *NEW seminar*

Summary

- Mu-to-$\overline{\mathrm{Mu}}$ transition
  - ✓ rare process with $\Delta L_\mu = -\Delta L_e = 2$
  - ✓ good probe for the leptonic structure of the new physics model
  - ✓ future experiments are planned in Japan & China
  - ✓ We investigate how large impacts Mu-to-$\overline{\mathrm{Mu}}$ gives for many models.

    T. Fukuyama, Y. Mimura, & Y. Uesaka, PRD**105**, 015026 (2022).

- e.g. Zee-Babu model
  - ✓ one of radiative neutrino models (two loop)
  - ✓ Mu-to-$\overline{\mathrm{Mu}}$ rate can be the same as the current limit with reproducing neutrino masses & satisfying other LFV constraints.
  - ✓ It is interesting to cross-check τ rare decay with Mu-to-$\overline{\mathrm{Mu}}$.

from Y. Uesaka's talk in *NEW seminar*

Preceding study at PSI

➢ Setup

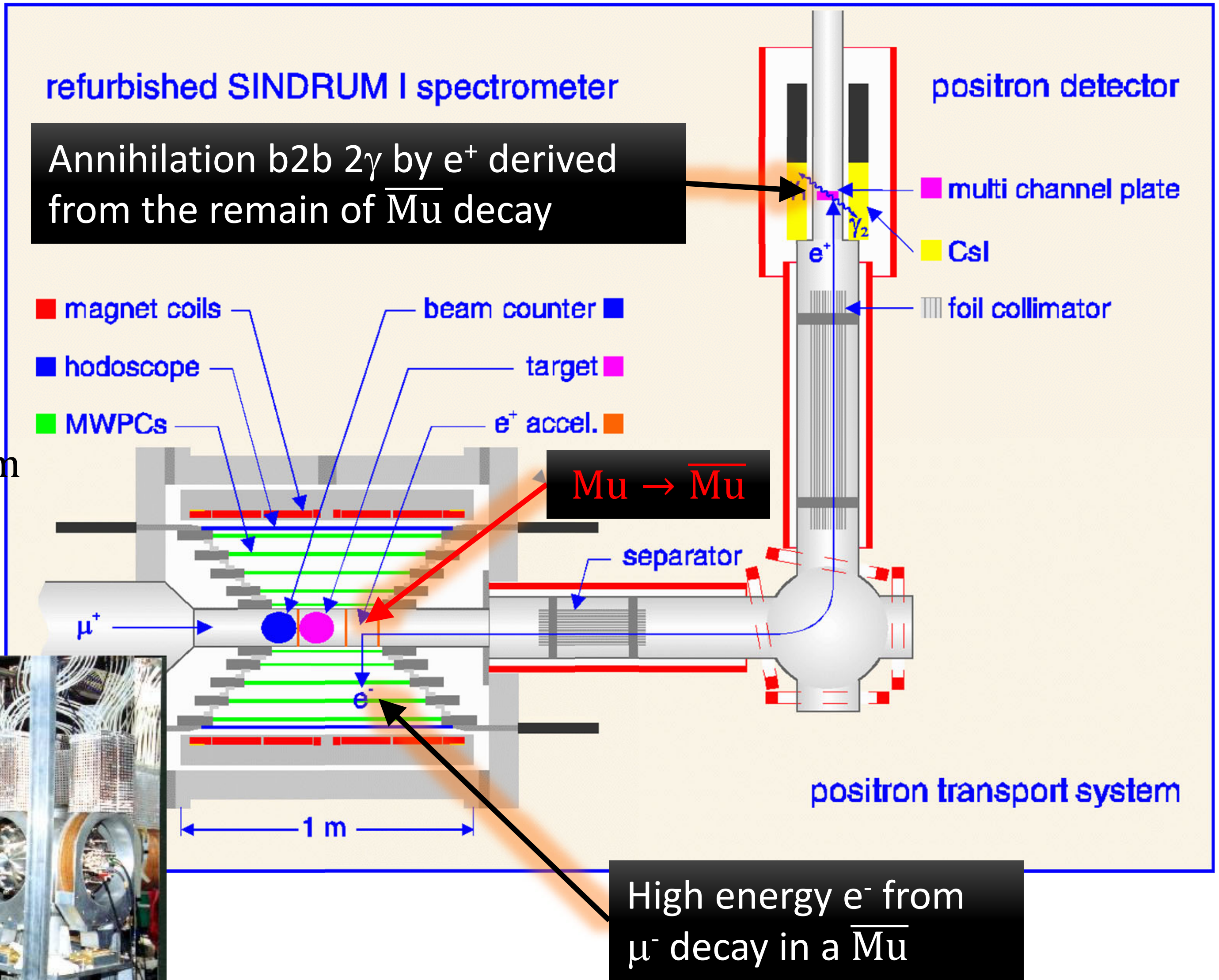
Surface muon (26 MeV/c)

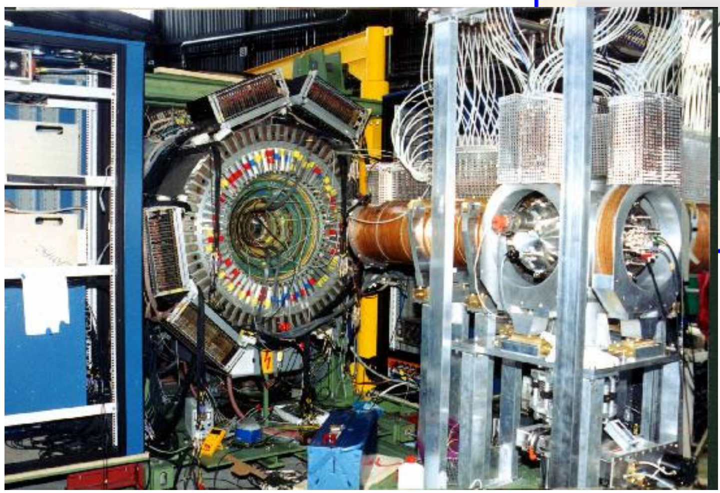
$I_{\mu^+} = 8 \times 10^6\ \mu^+/s$

Beam time: 1730 hours

A Mu formed in SiO_2 is evaporated to the vacuum

$N_{\text{Mu}} = 5.6 \times 10^{10}$





L. Willmann et al., Phys. Rev. Lett. 82 (1999) 49-52.

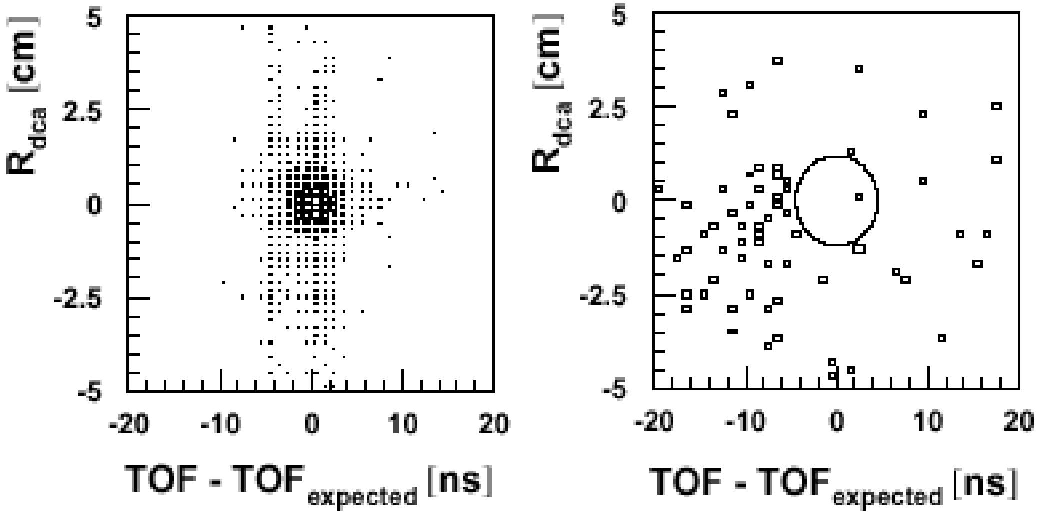
Preceding study at PSI

- Result (1730h, 5.6×10^{10} Mu)

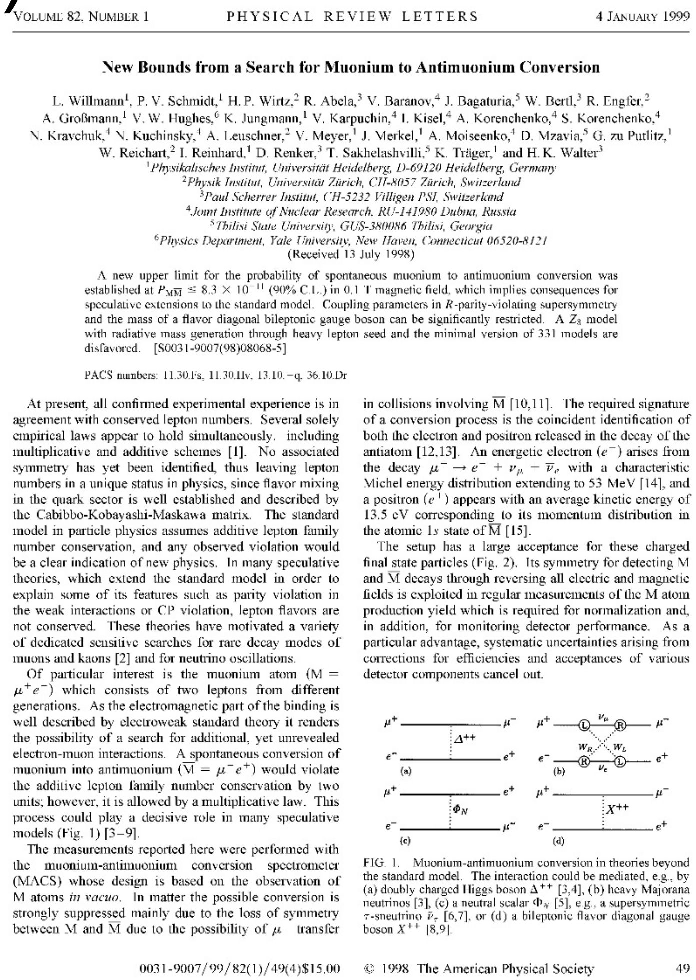
$P_{\mathrm{Mu}\overline{\mathrm{Mu}}} \leq 8.3 \times 10^{-11}$ (90% C.L.)

$N_{BG} = 1.7$

- Accidental coin. of e^- from Bhabha scattering of e^+ and scattered e^+
- $\mu^+ \rightarrow e^+ e^+ e^- \nu_e \overline{\nu_\mu}$ $(BR = 3.4 \times 10^{-5})$



The result was limited by the intrinsic BG, and there is few hope for further improvement by increasing the statistical accuracy.



VOLUME 82, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JANUARY 1999

New Bounds from a Search for Muonium to Antimuonium Conversion

L. Willmann[1], P. V. Schmidt,[1] H. P. Wirtz,[2] R. Abela,[3] V. Baranov,[4] J. Bagaturia,[5] W. Bertl,[3] R. Engfer,[2] A. Großmann,[1] V. W. Hughes,[6] K. Jungmann,[1] V. Karpuchin,[4] I. Kisel,[4] A. Korenchenko,[4] S. Korenchenko,[4] N. Kravchuk,[4] N. Kuchinsky,[4] A. Leuschner,[2] V. Meyer,[1] J. Merkel,[1] A. Moiseenko,[4] D. Mzavia,[5] G. zu Putlitz,[1] W. Reichart,[2] I. Reinhard,[1] D. Renker,[3] T. Sakhelashvilli,[5] K. Träger,[1] and H. K. Walter[3]

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[4]Joint Institute of Nuclear Research, RU-141980 Dubna, Russia
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[6]Physics Department, Yale University, New Haven, Connecticut 06520-8121

(Received 13 July 1998)

A new upper limit for the probability of spontaneous muonium to antimuonium conversion was established at $P_{M\overline{M}} \leq 8.3 \times 10^{-11}$ (90% C.L.) in 0.1 T magnetic field, which implies consequences for speculative extensions to the standard model. Coupling parameters in R-parity-violating supersymmetry and the mass of a flavor diagonal bileptonic gauge boson can be significantly restricted. A Z_8 model with radiative mass generation through heavy lepton seed and the minimal version of 331 models are disfavored. [S0031-9007(98)08068-5]

PACS numbers: 11.30.Fs, 11.30.Hv, 13.10.−q, 36.10.Dr

At present, all confirmed experimental experience is in agreement with conserved lepton numbers. Several solely empirical laws appear to hold simultaneously, including multiplicative and additive schemes [1]. No associated symmetry has yet been identified, thus leaving lepton numbers in a unique status in physics, since flavor mixing in the quark sector is well established and described by the Cabibbo-Kobayashi-Maskawa matrix. The standard model in particle physics assumes additive lepton family number conservation, and any observed violation would be a clear indication of new physics. In many speculative theories, which extend the standard model in order to explain some of its features such as parity violation in the weak interactions or CP violation, lepton flavors are not conserved. These theories have motivated a variety of dedicated sensitive searches for rare decay modes of muons and kaons [2] and for neutrino oscillations.

Of particular interest is the muonium atom ($M = \mu^+ e^-$) which consists of two leptons from different generations. As the electromagnetic part of the binding is well described by electroweak standard theory it renders the possibility of a search for additional, yet unrevealed electron-muon interactions. A spontaneous conversion of muonium into antimuonium ($\overline{M} = \mu^- e^+$) would violate the additive lepton family number conservation by two units; however, it is allowed by a multiplicative law. This process could play a decisive role in many speculative models (Fig. 1) [3–9].

The measurements reported here were performed with the muonium-antimuonium conversion spectrometer (MACS) whose design is based on the observation of M atoms *in vacuo*. In matter the possible conversion is strongly suppressed mainly due to the loss of symmetry between M and $\overline{M}$ due to the possibility of μ^- transfer in collisions involving $\overline{M}$ [10,11]. The required signature of a conversion process is the coincident identification of both the electron and positron released in the decay of the antiatom [12,13]. An energetic electron (e^-) arises from the decay $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$ with a characteristic Michel energy distribution extending to 53 MeV [14], and a positron (e^+) appears with an average kinetic energy of 13.5 eV corresponding to its momentum distribution in the atomic $1s$ state of $\overline{M}$ [15].

The setup has a large acceptance for these charged final state particles (Fig. 2). Its symmetry for detecting M and $\overline{M}$ decays through reversing all electric and magnetic fields is exploited in regular measurements of the M atom production yield which is required for normalization and, in addition, for monitoring detector performance. As a particular advantage, systematic uncertainties arising from corrections for efficiencies and acceptances of various detector components cancel out.

FIG. 1. Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated, e.g., by (a) doubly charged Higgs boson Δ^{++} [3,4], (b) heavy Majorana neutrinos [3], (c) a neutral scalar Φ_N [5], e.g., a supersymmetric τ-sneutrino $\tilde{\nu}_\tau$ [6,7], or (d) a bileptonic flavor diagonal gauge boson X^{++} [8,9].

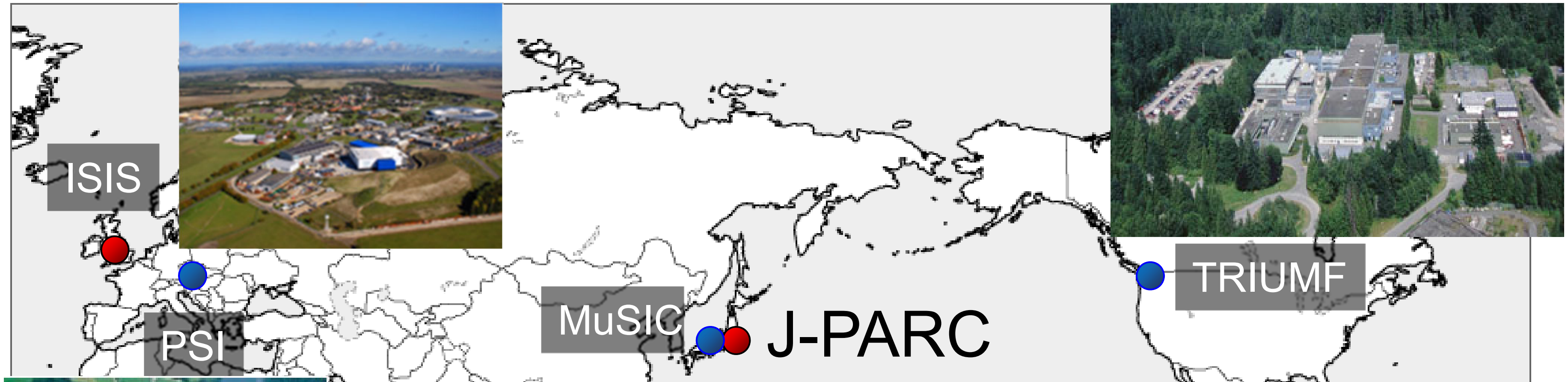
0031-9007/99/82(1)/49(4)$15.00

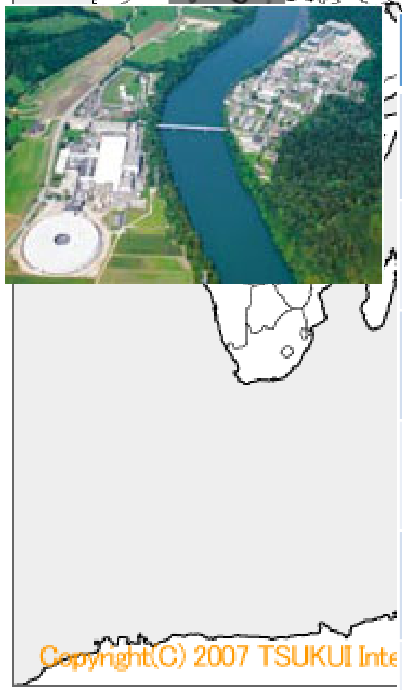
New idea

- Why don't you detect antiMu more directly?
- Assuming CPT symmetry, antiMu is the same as Mu in any internal transitions, like 1s-2p, 1s-2s, hyperfine *etc* under zero-filed.
- The only way is breaking antiMu.
  - Waiting for breaking antiMu naturally → PSI
    - Breaking antiMu = μ^- free-decay to e^- → high BG
  - Breaking antiMu artificially → present work
    - Breaking antiMu = ionization of antiMu to μ^- and e^+ → direct detection of μ^- → low BG

On another note…

Meson factories in the world





Nation	Switzerland	UK	Japan
Facility	**PSI**	**RAL ISIS**	**J-PARC MUSE**
Proton energy [GeV]	**0.59**	**0.8**	**3.0**
Proton intensity [MW]	**1.3**	**0.16**	**1.0 (design value)**
μ^+ [/s] (surface)	**2×10^8**	**6×10^5**	**2×10^8**
μ^- [/s]	**2×10^7**	**7×10^4**	**1×10^7**
Beam structure	**DC (CW)**	**Pulse (50Hz)**	**Pulse (25Hz)**

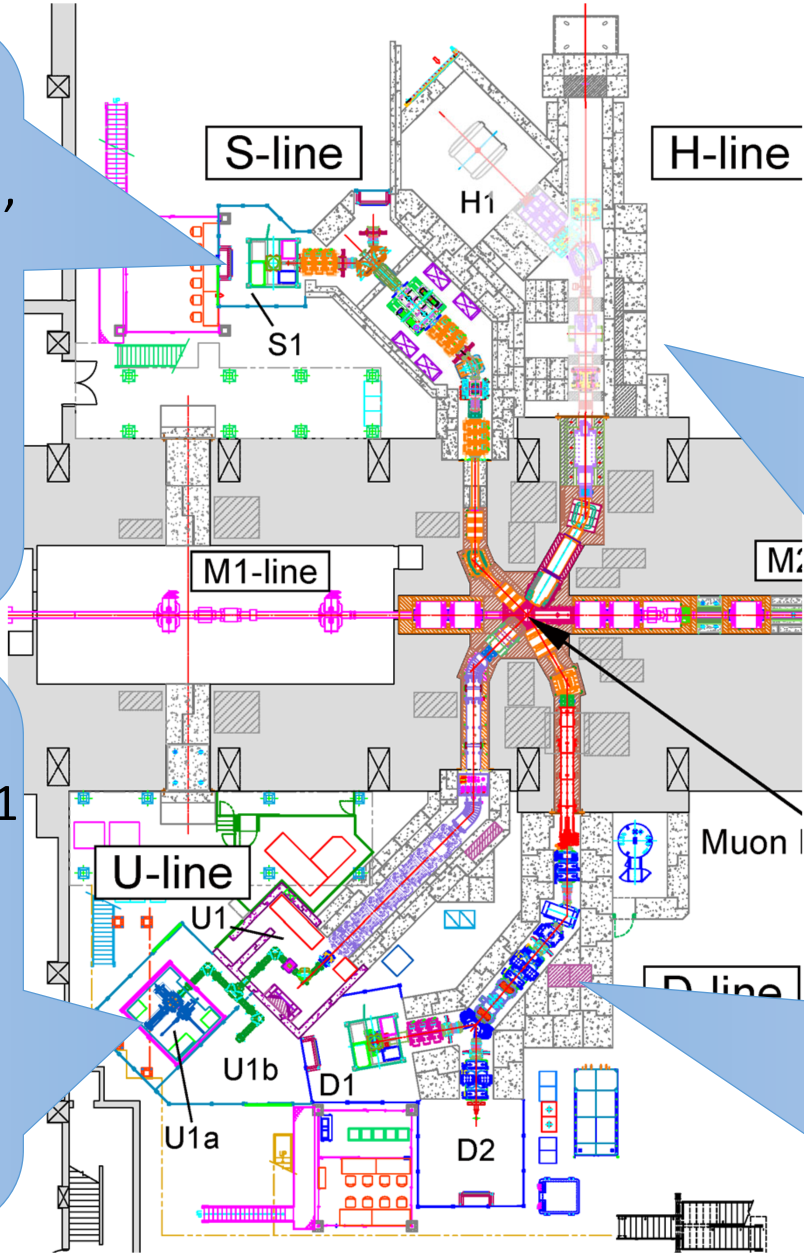
J-PARC MUSE: current status

S-line μ+

Slow beam (4 MeV), dedicated to bulk μSR ultra-low temperature/high magnetic field/ pulsed excitations.
(S1:2014~)

U-line μ+

Ultra slow beam (0.1 ~ 30 keV), near-surface, sub-micron scale condensed matter physics, chemistry, etc.
(2014~/2016~)



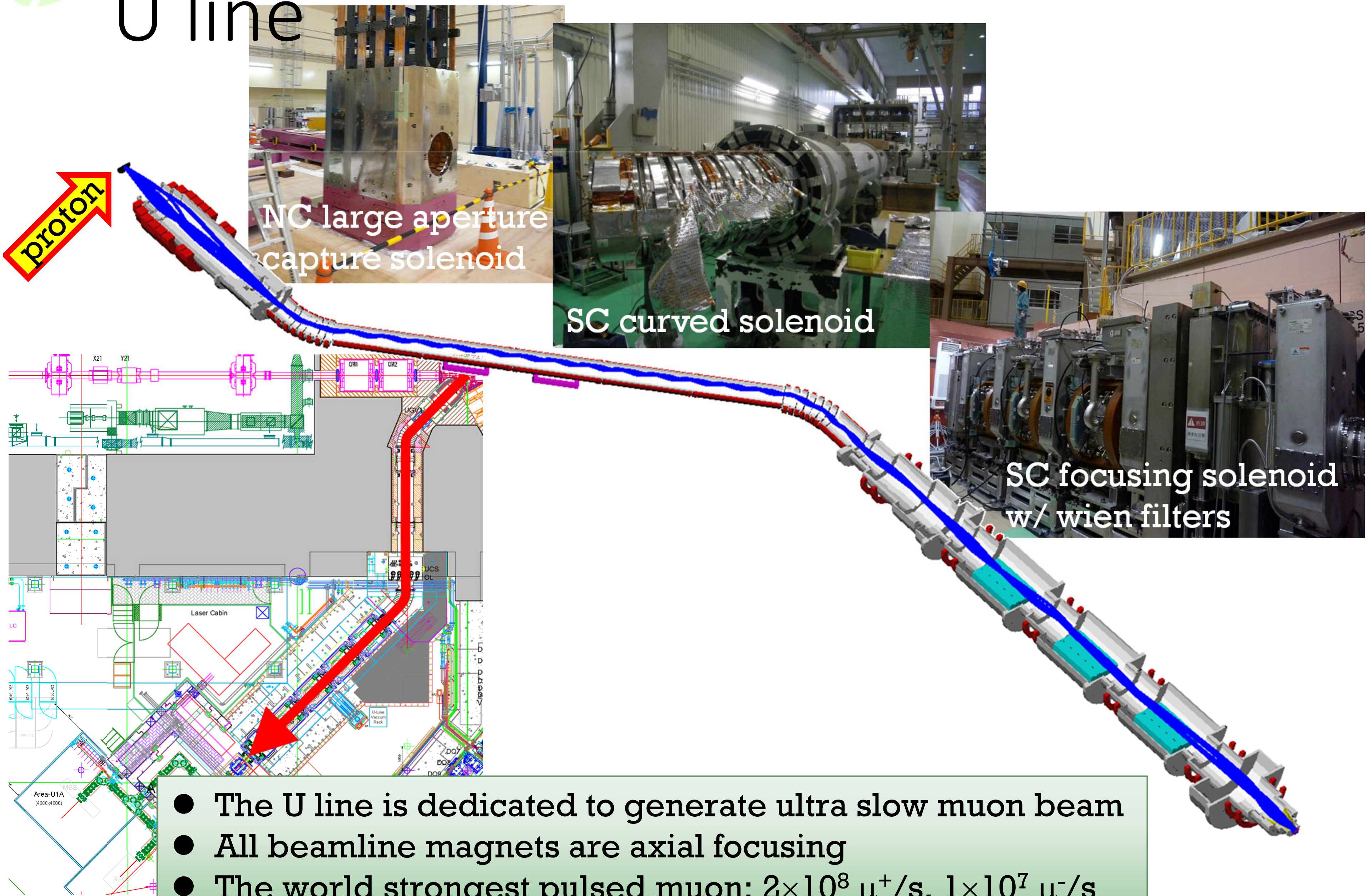
H-line μ±

Slow (4 MeV) ~ fast (50 MeV) beam, for particle physics, atomic physics "precision frontier" (under const.)

D-line μ±

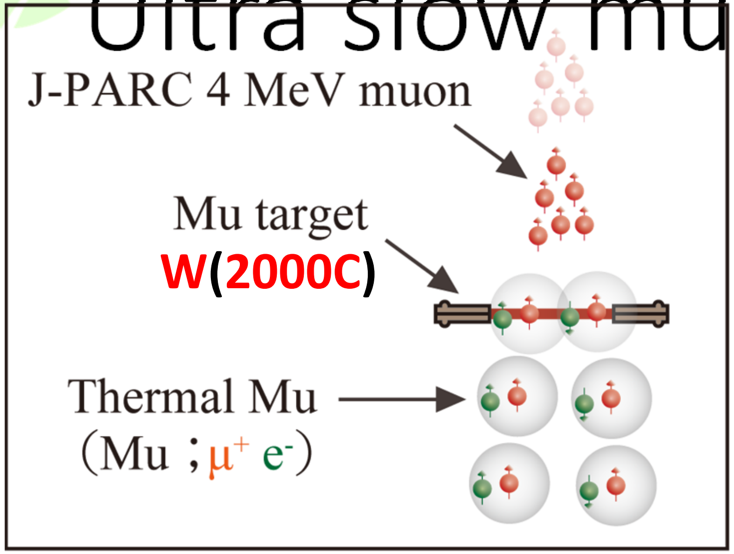
Slow (50 keV) ~ fast (50 MeV), general-purpose beamline with 2 exp. areas.
(2009~)

U line

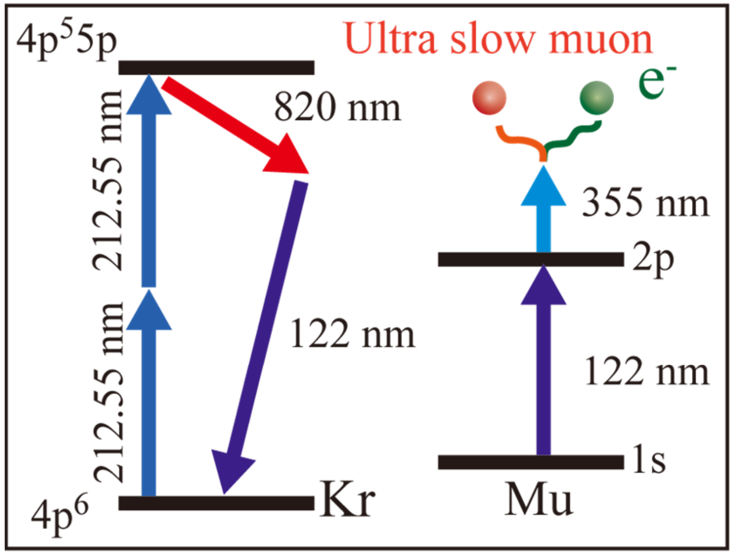


- The U line is dedicated to generate ultra slow muon beam
- All beamline magnets are axial focusing
- The world strongest pulsed muon: $2\times10^8\ \mu^+/s$, $1\times10^7\ \mu^-/s$

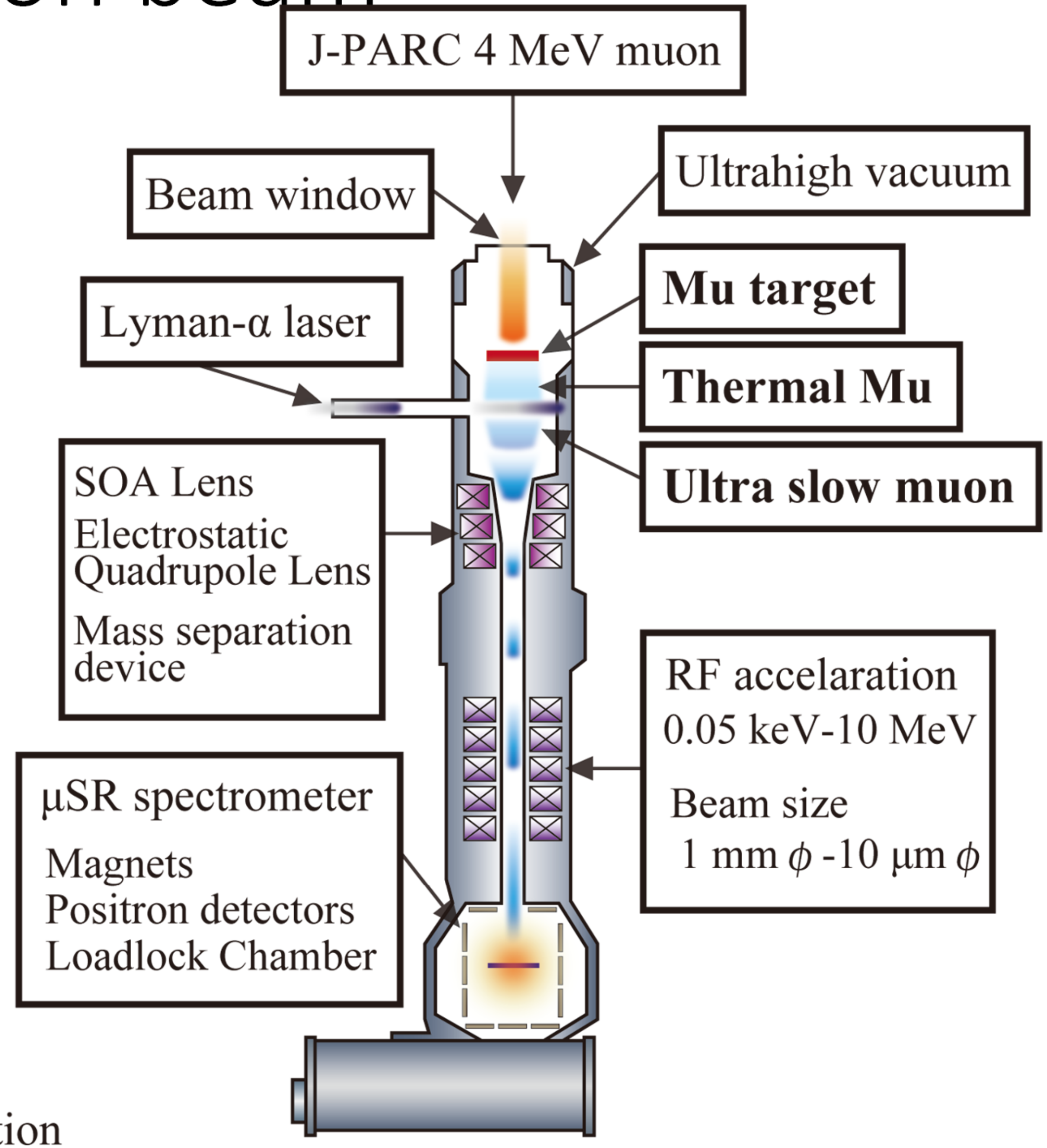
Ultra slow muon beam



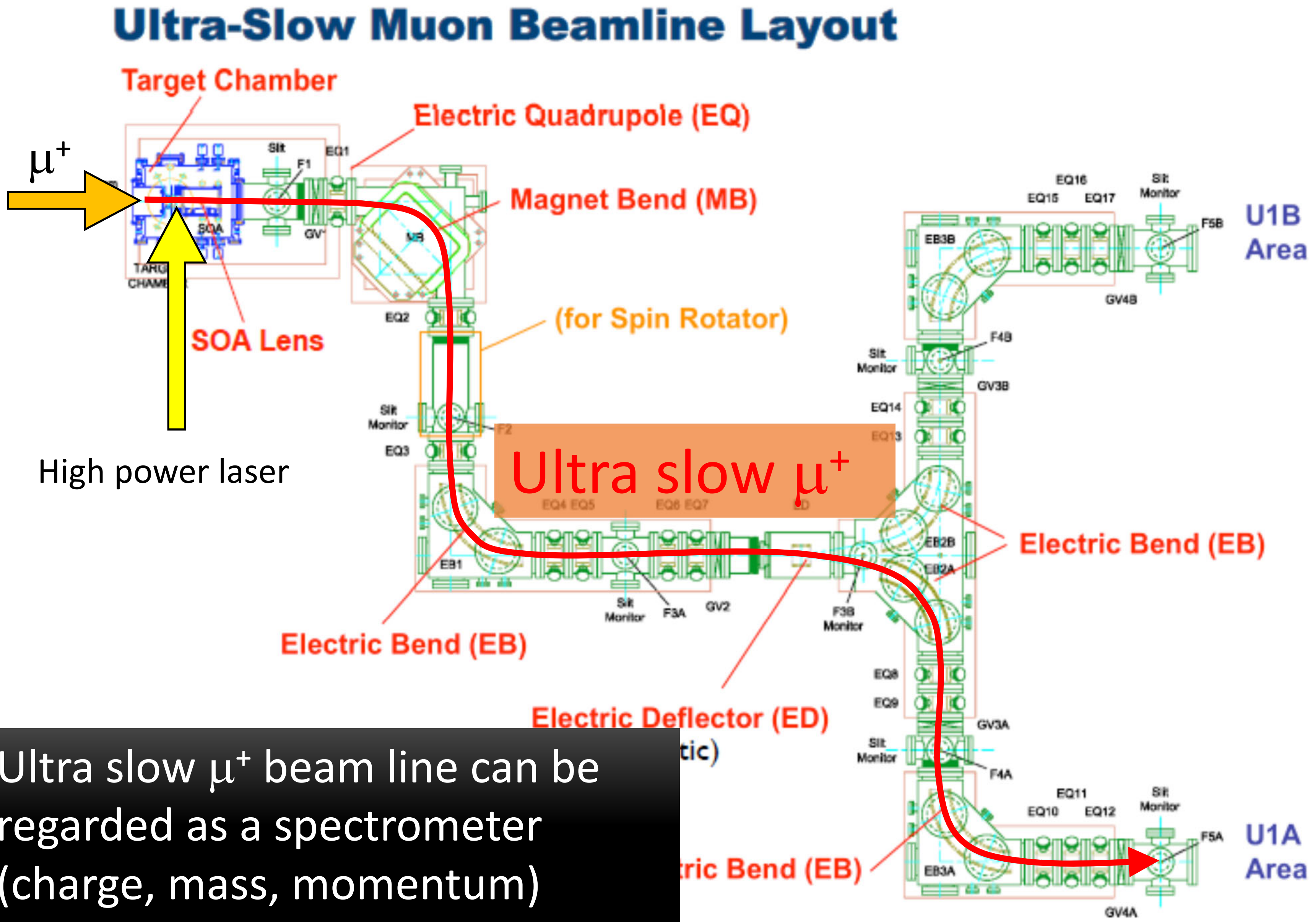
Mu generator



Lyman-α laser generation and Mu dissociation by laser resonant ionization method

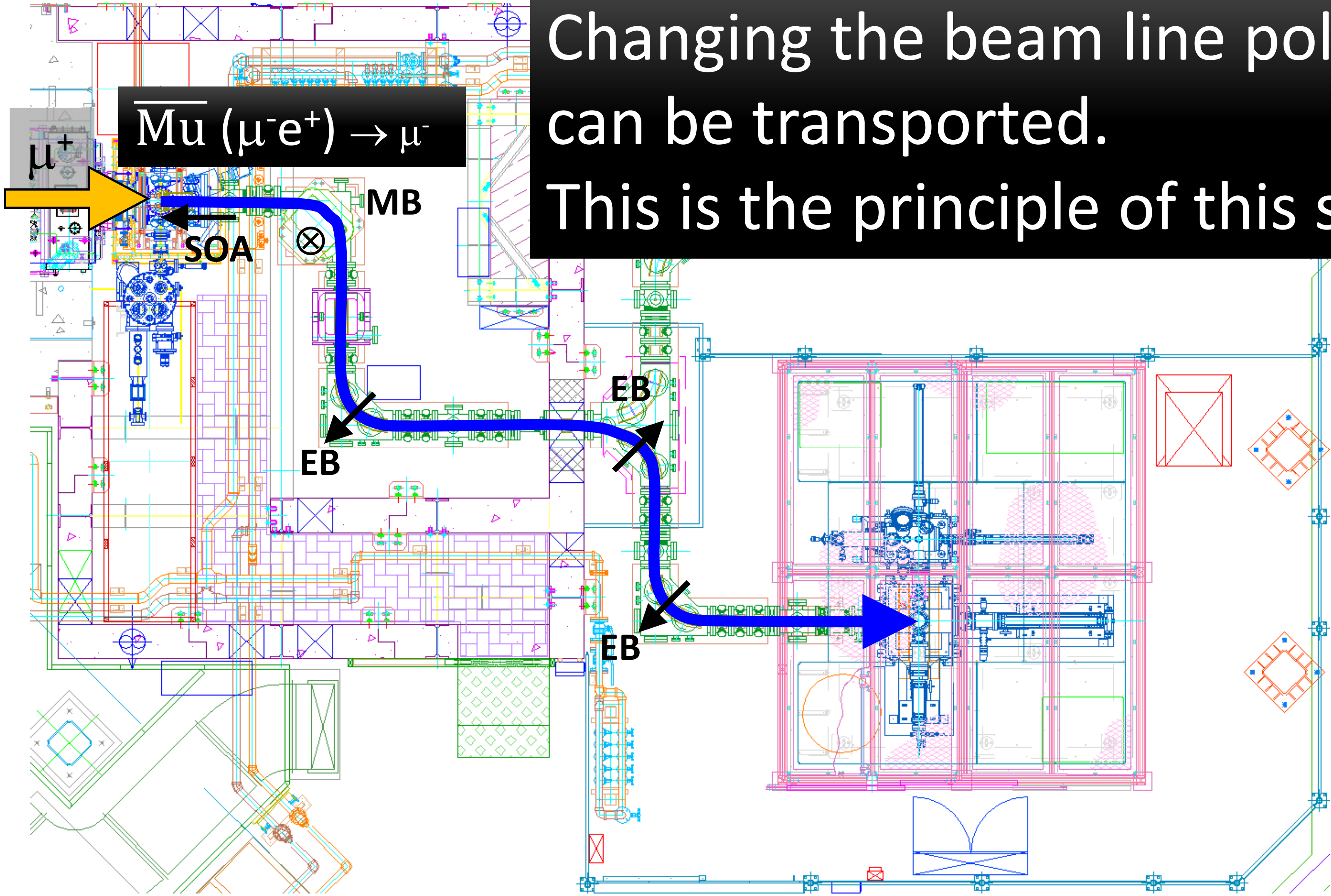


U line (cont.)



Ultra slow μ^+ beam line can be regarded as a spectrometer (charge, mass, momentum)

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



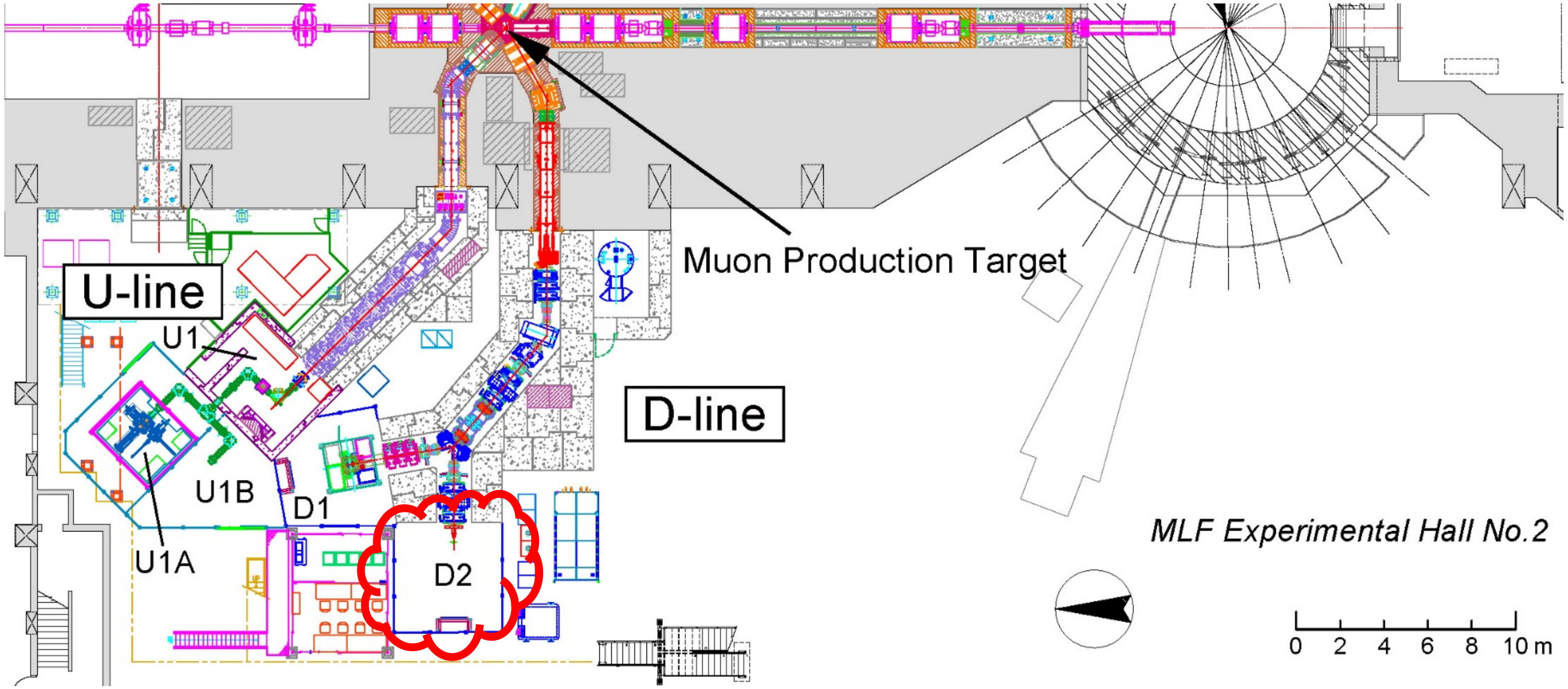
Changing the beam line polarity, μ^- can be transported.
This is the principle of this study.

Is it feasible?

- You may feel that the idea sounds interesting but is it feasible.

- Good question!
- First of all, we should check …
  - Unexpected background source
  - Data taking rate

Background study



U line

Surface muon（4MeV）2×10^8 /s @1MW

Ultra slow muon beam (eV ~ keV)

U1A : Surface and interface study
for material science

U1B : micro beam
by re-acceleration of USM

D line

Surface muon 1×10^7 /s

Decay muon（μ^+/μ^-： 50 keV ~ 50 MeV）

D1 : permanent μSR spectrometer

D2 : open area for versatile use

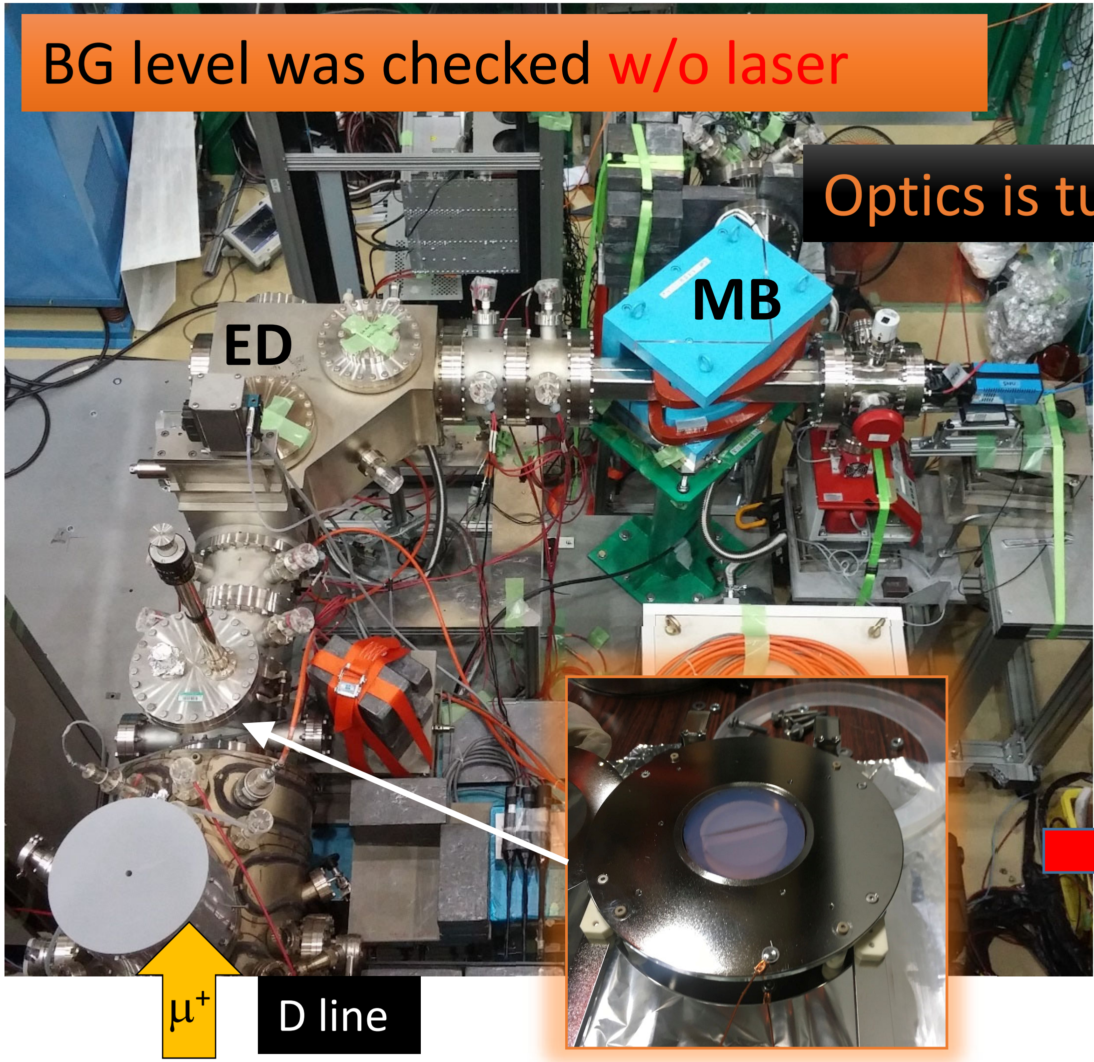
Feasibility check (BG measurement) was performed in D2 area in Dec/'16 and Feb/'19.

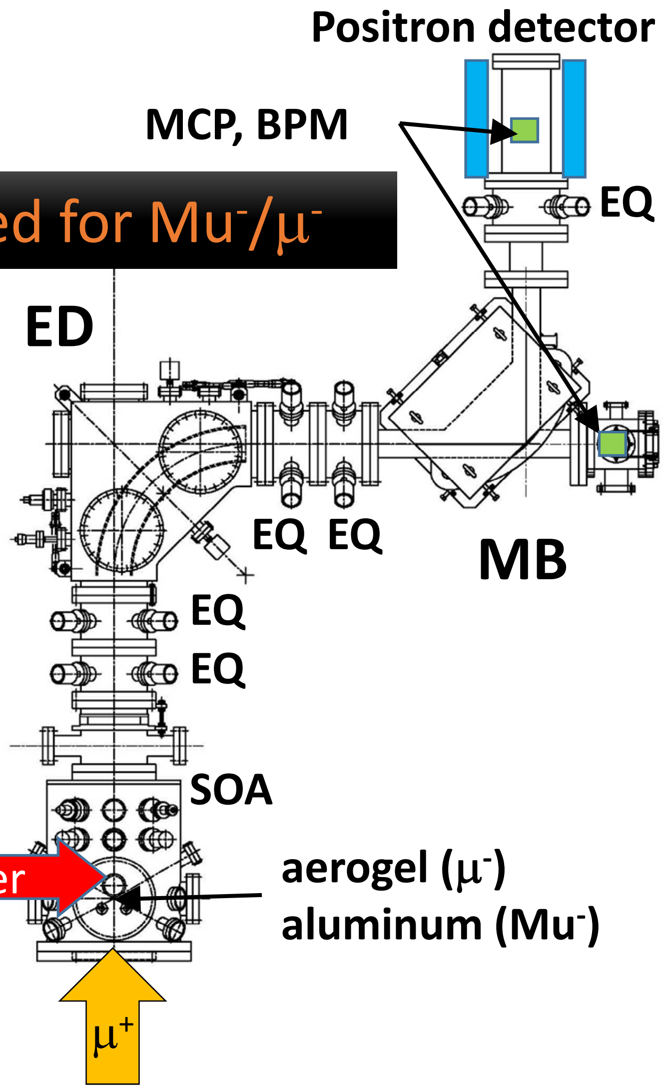
Background study cont.

Apparatus of Mu$^-$ study for g-2/EDM was applied.

BG level was checked w/o laser

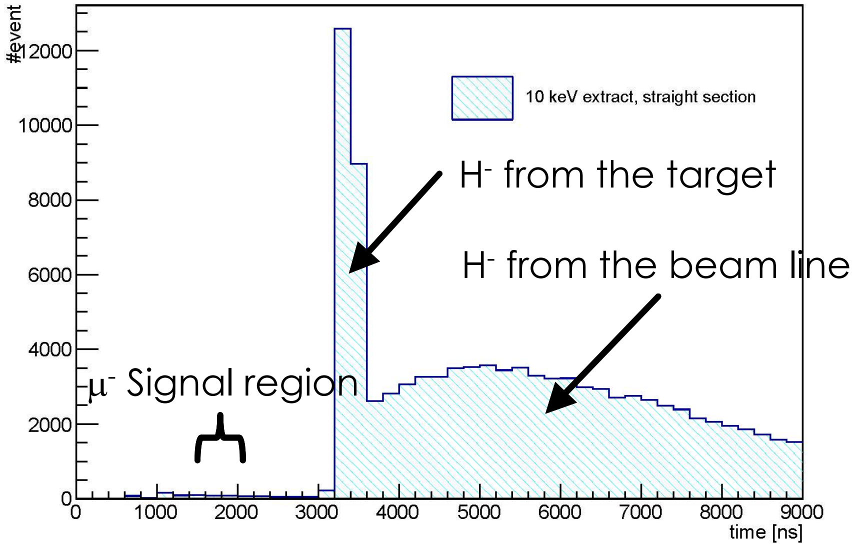
Optics is tuned for Mu$^-$/μ^-



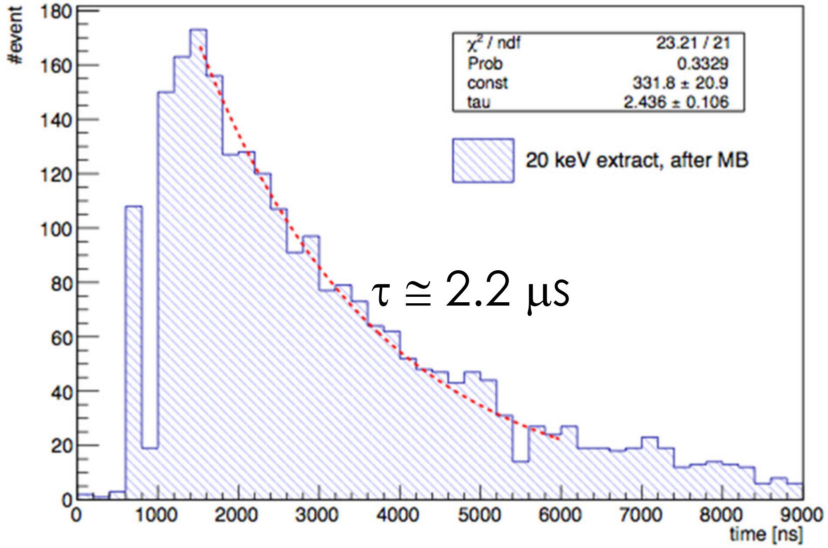


Preliminary analysis

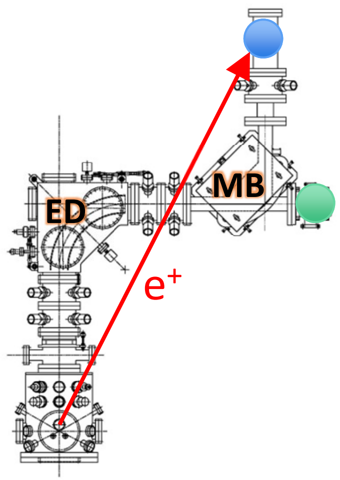
Time spectrum passing the ED



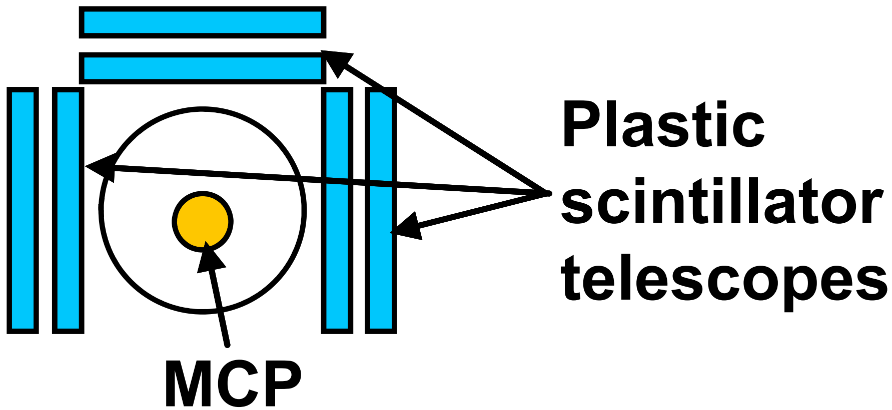
Time spectrum passing EB+MB

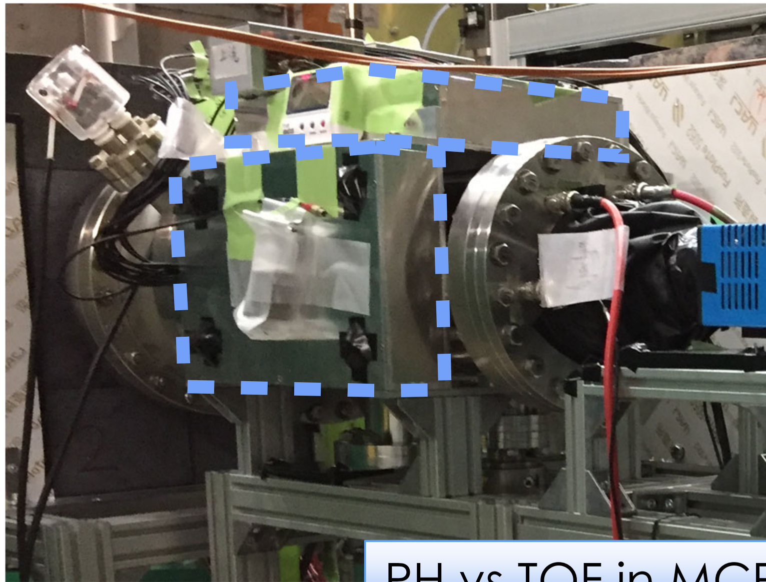


- Main BG is H^-s, and they are reduced by below 1/10000 with the pair of ED and MB.
- A component with the muon life time remains.
- The origin of muon-life BG
  - Direct Michel e^+ from μ^+ stopping around the target
  - e^- by Michel e^+ Bhabha scattering around/after ED
    - They reach at MCP directly / through the beamline components.

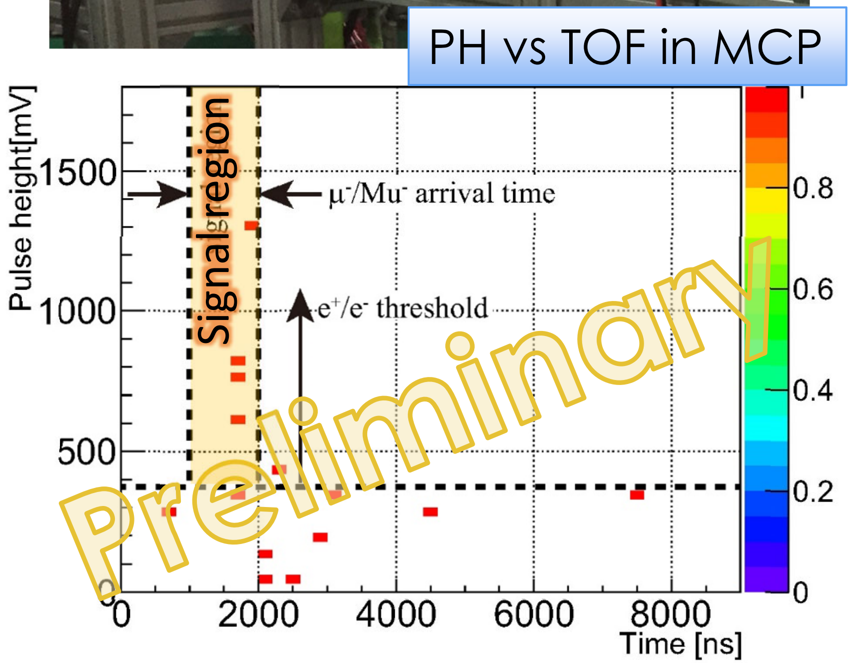


Preliminary analysis (cont.)

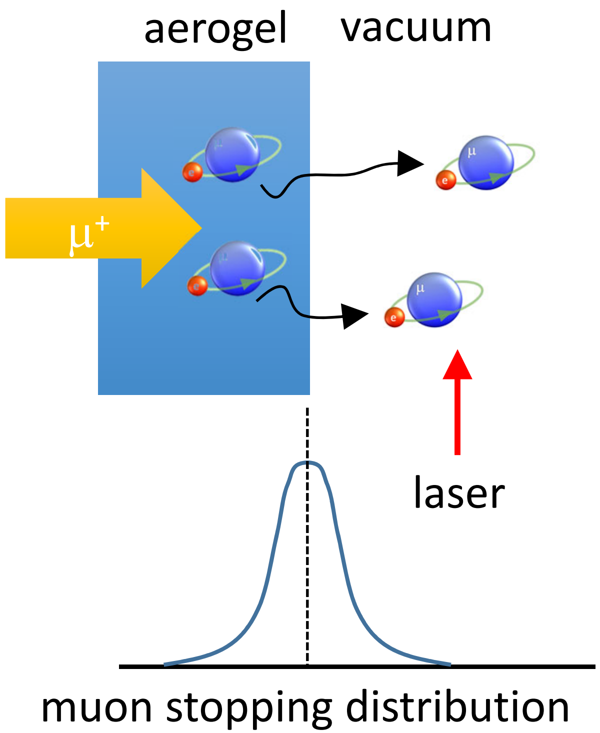




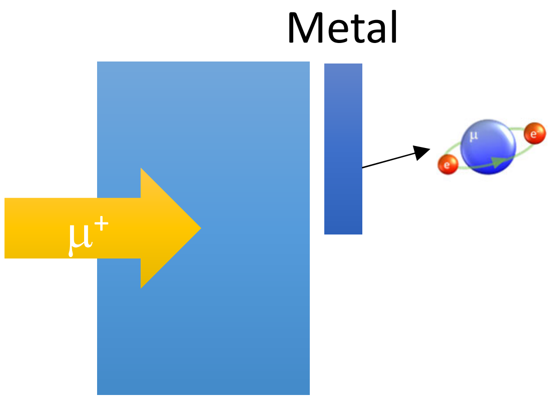
- Half-a-day run, ~10^{10} μ incident
- 4 events remain by applying
  - Coincident signal in surrounding PS telescopes
  - time window μ^- arrival to MCP
  - Pulse height threshold higher than e^-/e^+ events
- The origin of 4 events could be due to Mu⁻ from the metallic parts around the aerogel target.



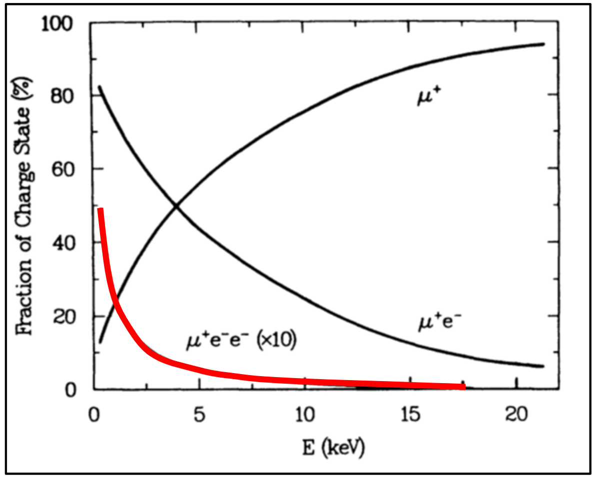
Mu$^-$



Mu is generated and diffused in the aerogel, and then evaporated from the surface.
Half stop condition (the peak of the stopping distribution is at the rear surface) is the best to maximize the Mu yield in the vacuum region.



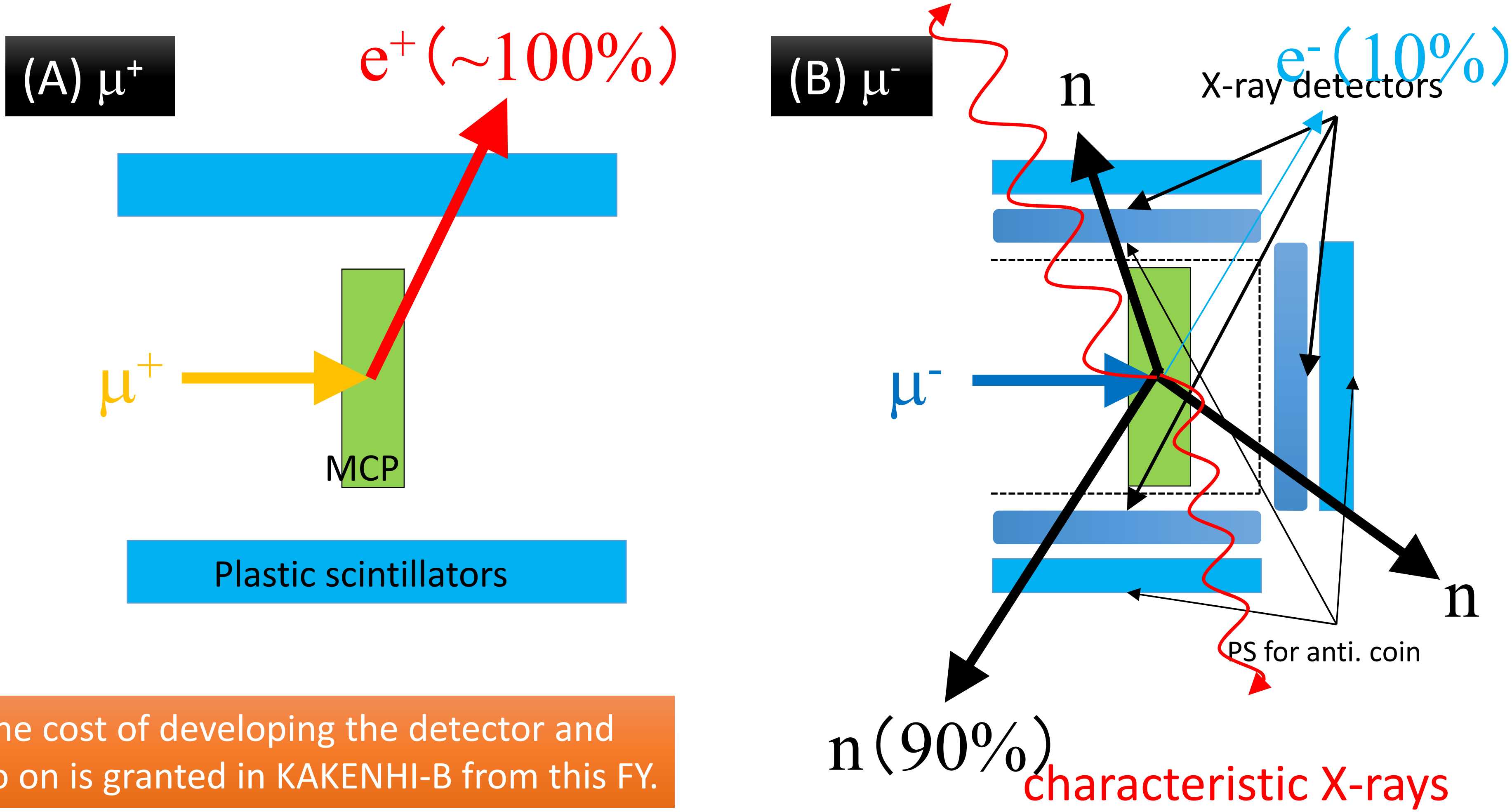
It is known that Mu$^-$ ($\mu^+ e^- e^-$) is emitted from the metal surface, similar to H$^-$.
Y. Kuang *et al*, PRA 39 (1989) 6109.



Mu$^-$ is hard to distinguish from μ^- because the charge and the mass are almost the same.
In addition, Mu$^-$ emits e^+ with the lifetime of 2.2 μs.

μ^- detection

- If μ^- is reached at MCP, how to detect.



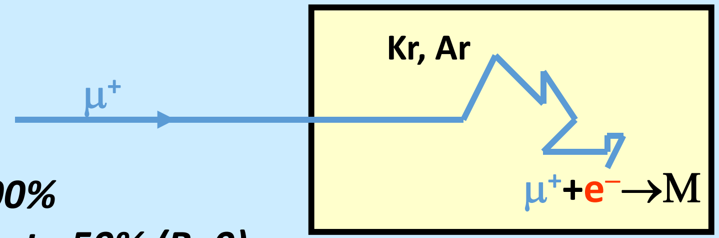
The cost of developing the detector and so on is granted in KAKENHI-B from this FY.

Details about Mu Production

Methods of Muonium Production

• Gas Stop

MuSEUM

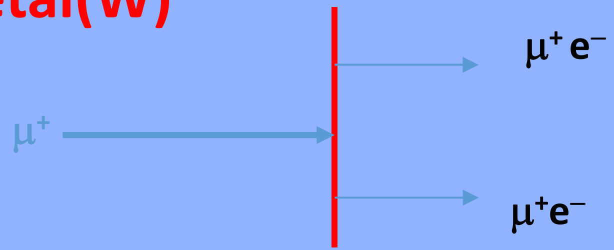


Yields up to 100%
Polarization up to 50% (B=0)
100% (B>>1T)

foreign gas effects

• Hot Metal(W)

U line

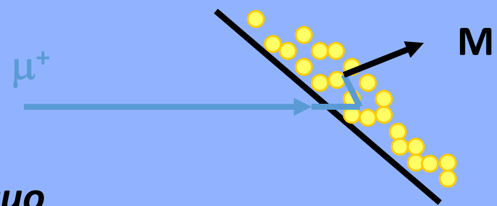


Muonium in Vacuo

thermal energy (2000K)

• SiO_2 Aerogel

g-2/EDM
Mu 1s-2s

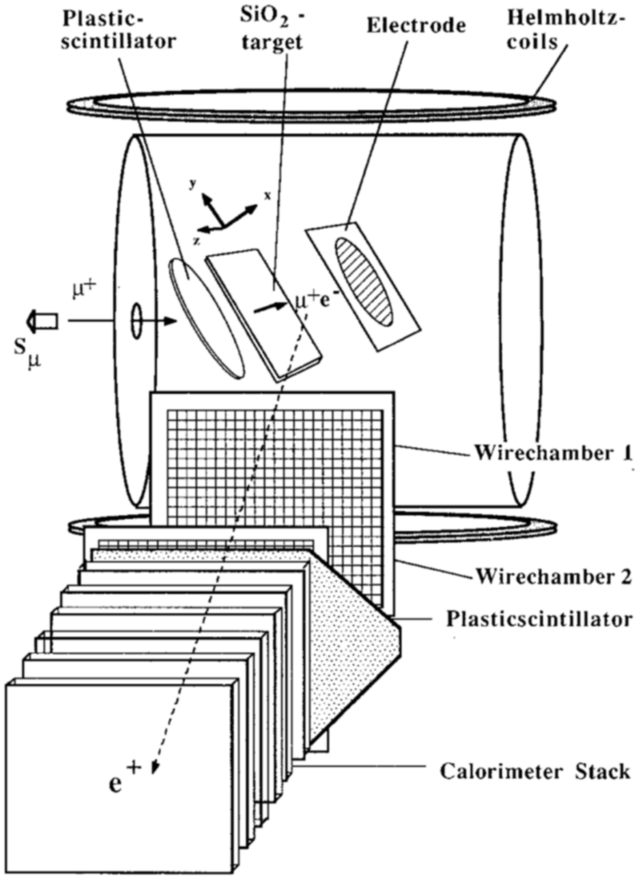


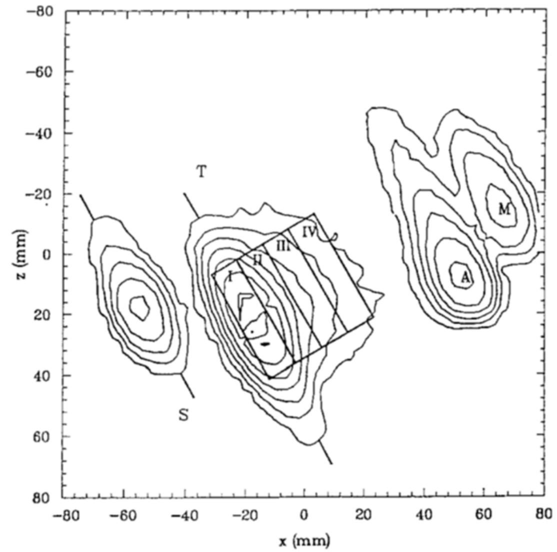
Thermal Muonium in Vacuo
Yields up to < 1 %
Polarization 30(10)%

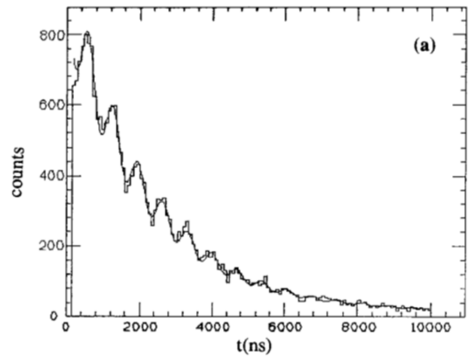
velocity 1.5 cm/ τ_μ
less fragile targets

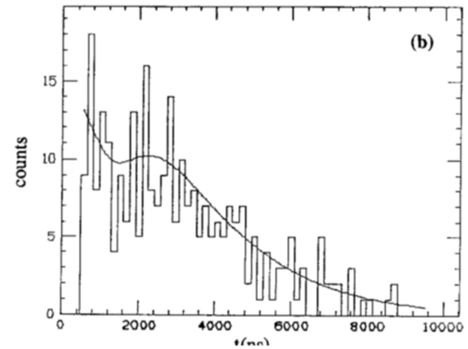
from K. Jungmann's talk in *"New Developments of Muon Precision Physics"*

Muonium in Vacuo from SiO_2 AEROGELS









W. Schwarz, V. Ebert, H. Geerds, K. Jungmann, S. Kirches, S. Koppe, F. Maas, H.-J. Mundinger 1, G. zu Putlitz, J. Rosenkranz 2, W. Sch~ifer 3, G. Schiff and Z. Zhang
Journal of Non-Crystalline Solids 145 (1992) 244

Target	Surface	Thickness (mg/cm^2)	μ^+ beam momentum, p (MeV/c)	$\Delta p/p$ (%)	M/μ_{stop} (%)
powder M5	fluffy	7.5	19.5 (RAL)	5	8.2(1.0)
	compressed	7.8	18.5 (PSI)	3	2.5(5)
aerogel No. 3	untreated	42	26.5 (PSI)	3	1.0(2)
	ethanol treated	42	26.5 (PSI)	3	1.5(2)
aerogel No. 4	enlarged				
	+ ethanol treated	60	26.7 (RAL)	5	2.3(3)

from K. Jungmann's talk in *"New Developments of Muon Precision Physics"*

Muonium i… Vacuo from Si… …OGELS

- …sis)
- …3)
- …erogel
- …t of surface
- …ory of aerogel
- μ^+ beam $\Delta p/p$
- Similar to SiO_2 powder after grinding of aerogel to powder
- Aging not studied, yet

(measurements in old μE4 area of PSI)

Tgt Nr.	Eigenschaften	p $[\frac{MeV}{c}]$	d_F $[\frac{mg}{cm^2}]$	ρ $[\frac{mg}{cm^3}]$	F $[cm^2]$	$C_{M_{stop}}$ $\frac{M}{\mu_{stop}}[\%]$	$C_{M_{free}}$ $\frac{M}{\mu_{free}}[\%]$
#1	Aluminiumfolie Dicke $\simeq 20\mu m$	n.a.	5.4	$\simeq 2700$	154	0	0
#2	SiO_2 - Pulver	23	9	32	154	8.27 ± 0.31	4.60 ± 0.20
#3	Aerogel, längere Zeit der Luft ausgesetzt	24	7.5	5	40	2.32 ± 0.13	1.74 ± 0.11
#4	Aerogel, neu	24.5	12.8	16	10	0.99 ± 0.12	0.[illegible]
#5	Aerogel, neu	26	27.5	55	16	$0.67 \pm$ [illegible]	[illegible]
#5a	Aerogel, Oberfläche aufgerauht	26	27.5	55	16	[illegible]	[illegible]
#6	Aerogel, 1.5min Mikrowelle	26	27.5	55	[illegible]	[illegible]	[illegible]
#7	Aeorgel, 6min Mikrowelle	26	27.5	[illegible]	[illegible]	[illegible]	[illegible]
#8	Aerogel, mit Alkohol behandelt	24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
#9	Aerogel, neu	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
#10	Aerogel, al[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± 0.22
#11	A[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]3	1.20 ± 0.14
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.85 ± 0.23	0.55 ± 0.07
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	154	2.25 ± 0.46	0.70 ± 0.14
#14	[illegible]	[illegible]	[illegible]	17	154	11.43 ± 0.31	1.86 ± 0.19
#15	D[illegible]	[illegible]	$\simeq 400$	$\simeq 2000$	20	2.44 ± 0.34	1.11 ± 0.11
#16	M[illegible] SiO_2 [illegible]	28	$\simeq 400$	$\simeq 2000$	20	1.99 ± 0.23	0.81 ± 0.10
#17	Tgt #4 [illegible]zer-rieben a[illegible] Watte	24	7.1	20	154	3.59 ± 0.26	1.68 ± 0.13

page from M. Springer, Diplomarbeit, Heidelberg (1992)

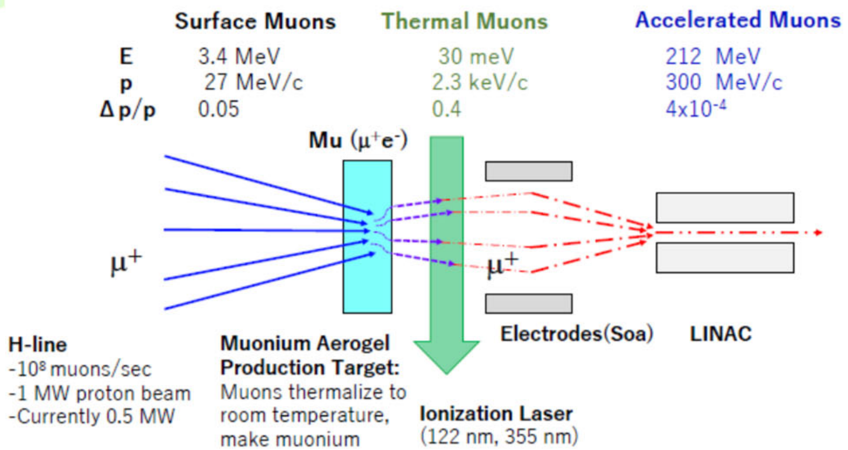
Thermal muonium yield M/μ_{stop} in vacuum from SiO_2 powder and aerogel targets with different surface conditions

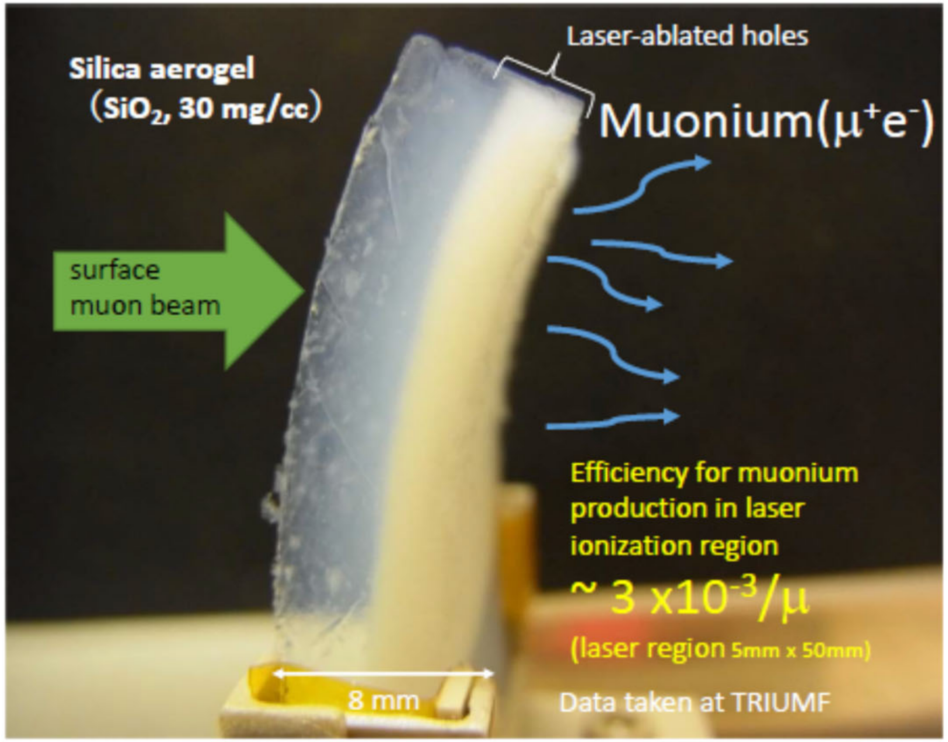
Target	Surface	Thickness (mg/cm²)	μ^+ beam momentum, p (MeV/c)	$\Delta p/p$ (%)	M/μ_{stop} (%)
powder M5	fluffy	7.5	19.5 (RAL)	5	8.2(1.0)
	compressed	7.8	18.5 (PSI)	3	2.5(5)
aerogel No. 3	untreated	42	26.5 (PSI)	3	1.0(2)
	ethanol treated	42	26.5 (PSI)	3	1.5(2)
aerogel No. 4	enlarged + ethanol treated	60	26.7 (RAL)	5	2.3(3)

Aerogel target No. 4 is supplied by M.J. van Bommel (density 160 mg/cm³).

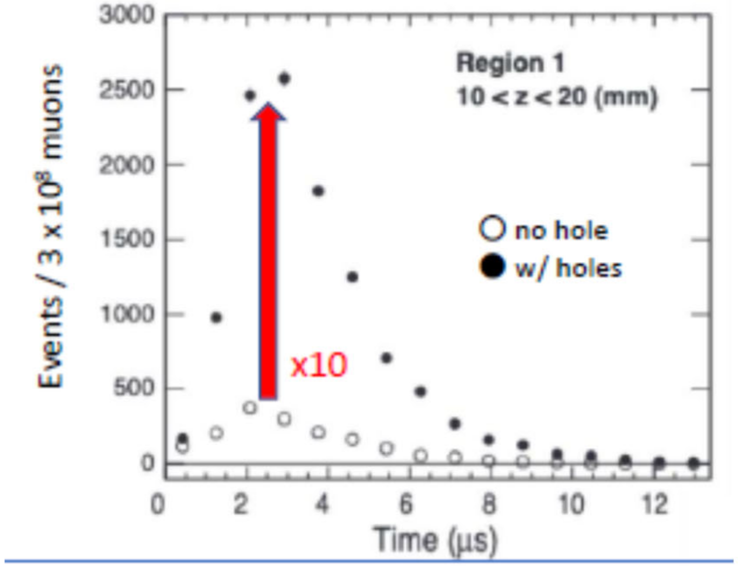
from K. Jungmann's talk in "New Developments of Muon Precision Physics"

Muonium from Drilled Aerogels





P. Bakule et al., PTEP 103C0 (2013), G. Beer et al., PTEP 091C01 (2014)

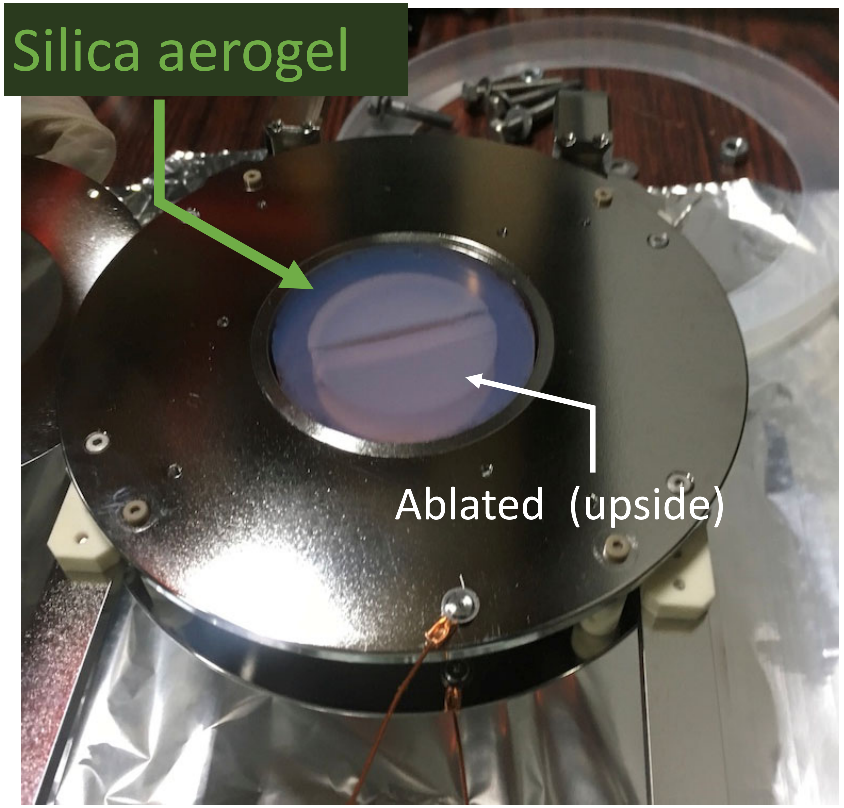


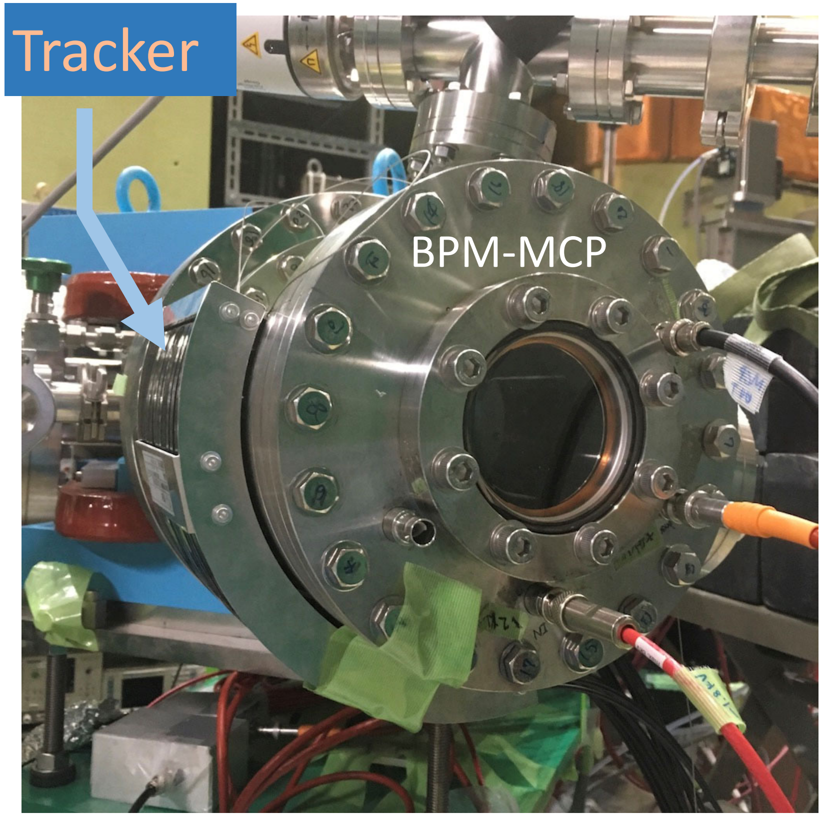
Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [7])	none	2.74 ± 0.11
Laser ablated	500 μm	16.0 ± 0.2
Laser ablated	400 μm	20.9 ± 0.7
Laser ablated	300 μm	30.5 ± 0.3

slides compiled from
J-PARC Muon g-2/EDM and Muonium, D. Kawall
Muon g-2 Elba Physics Week, May 27-June 1, 2019

- **curious to learn about long term stability**
- **SiO_2 powder targets known to degrade within one week**

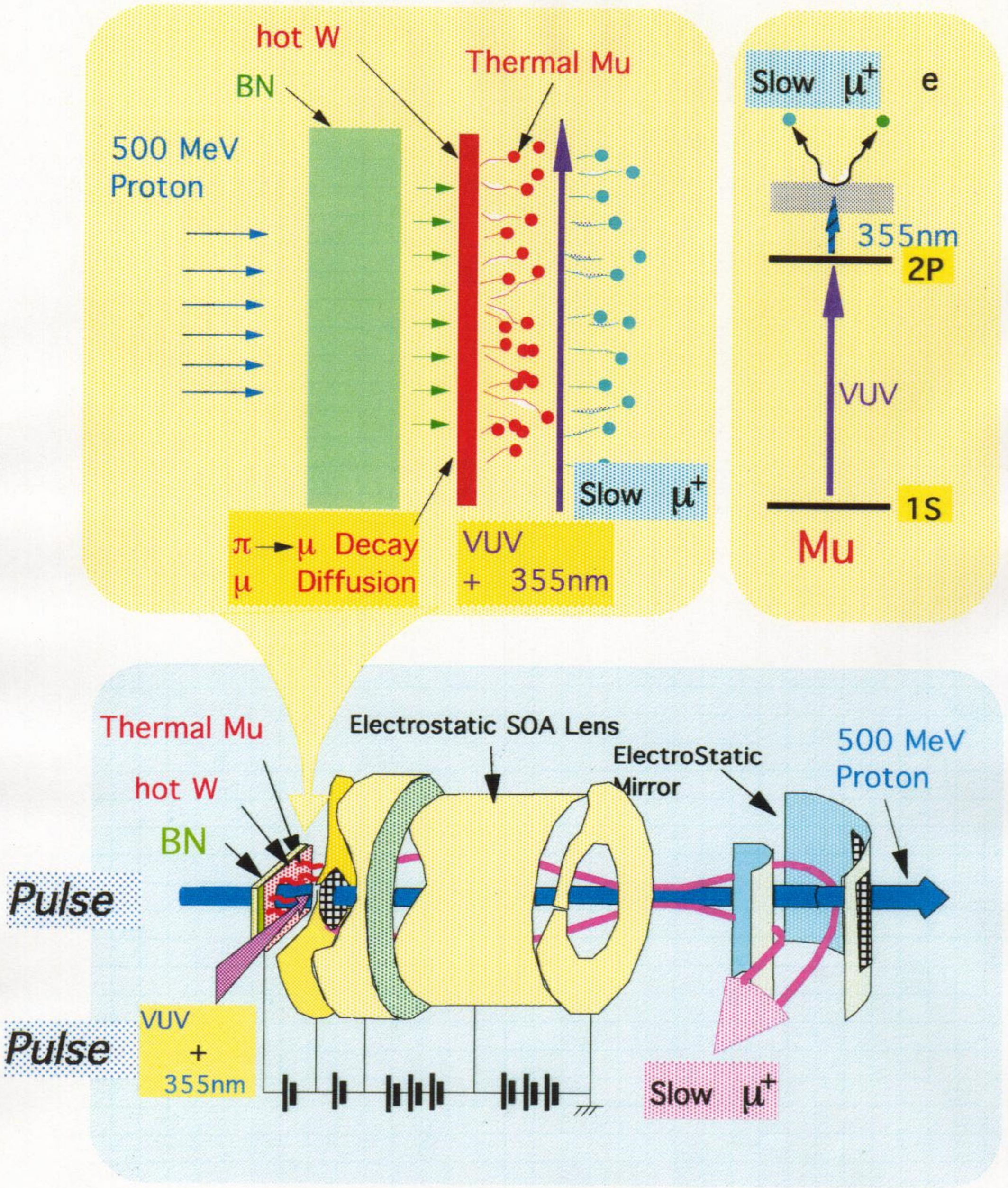
Target and Tracker Install





PS telescopes can not distinguish the positron from the target region.
To solve this problem, we developed the tracker to identify the electron signal from MCP.

Ultra-Cold Positive Muon Beams by Laser Ionization of Muonium



⇒ K. Nagamine and colleagues have been pioneering Ultra-Cold μ^+ beams, see e.g.
K. Nagamine Z. Phys. C56, 215 (1992)

⇒ Constant progress ever since

Mu ionization Laser

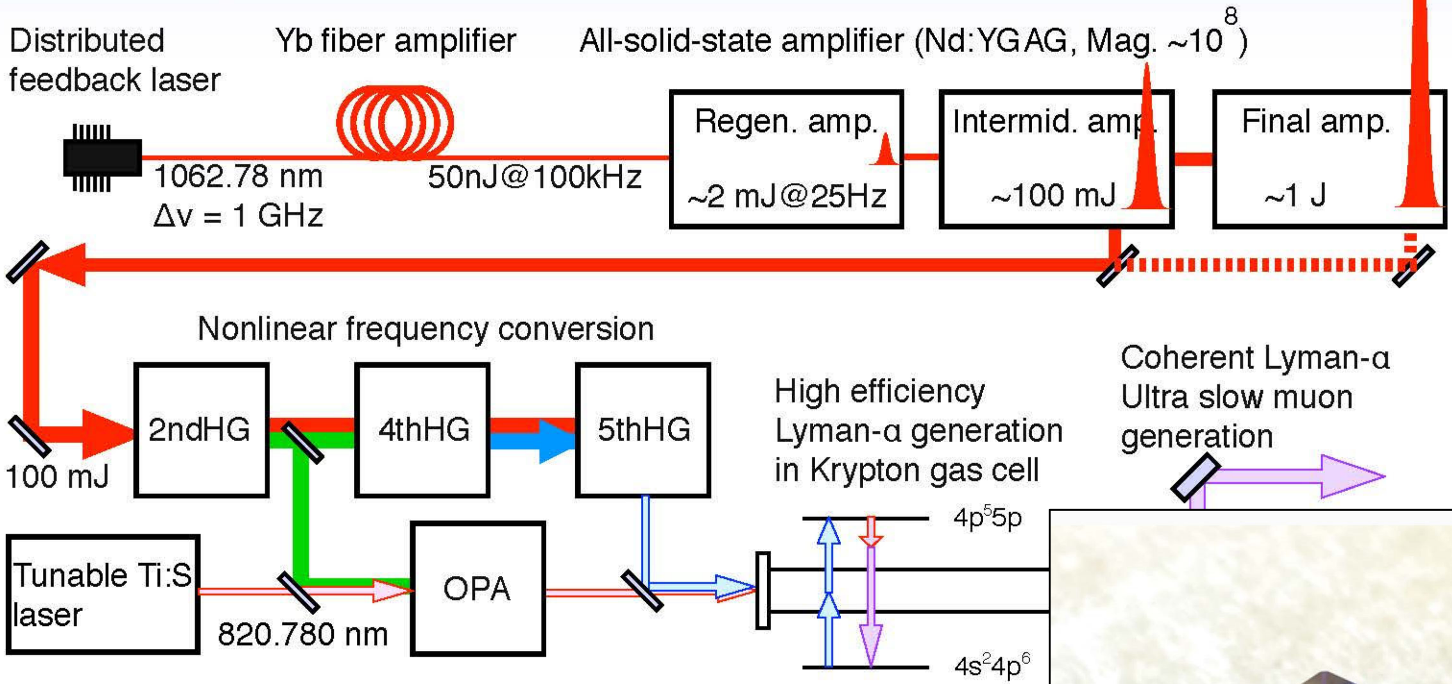
- At present we are considering two options

- Lyman a laser developed in the U line
  1s $\rightarrow$ 2p $\rightarrow$ unbound

- Two photon absorption developed for high precision measurement of Mu 1s-2s by Okaya-U group

U-line Laser

Progress and updates in 2021



Establishment of a multi-institutional collaboration for laser

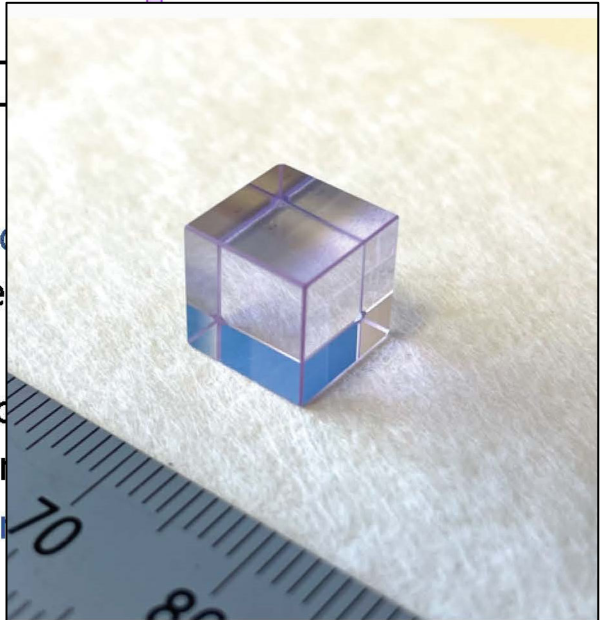
- A new team to collaborate on the ionization laser improve

Improvements for higher pulse energy of Lyman-α

- Phase compensation in the laser gain medium using a defo
- Preparation for a new pumping scheme using Nd:YSAG cer

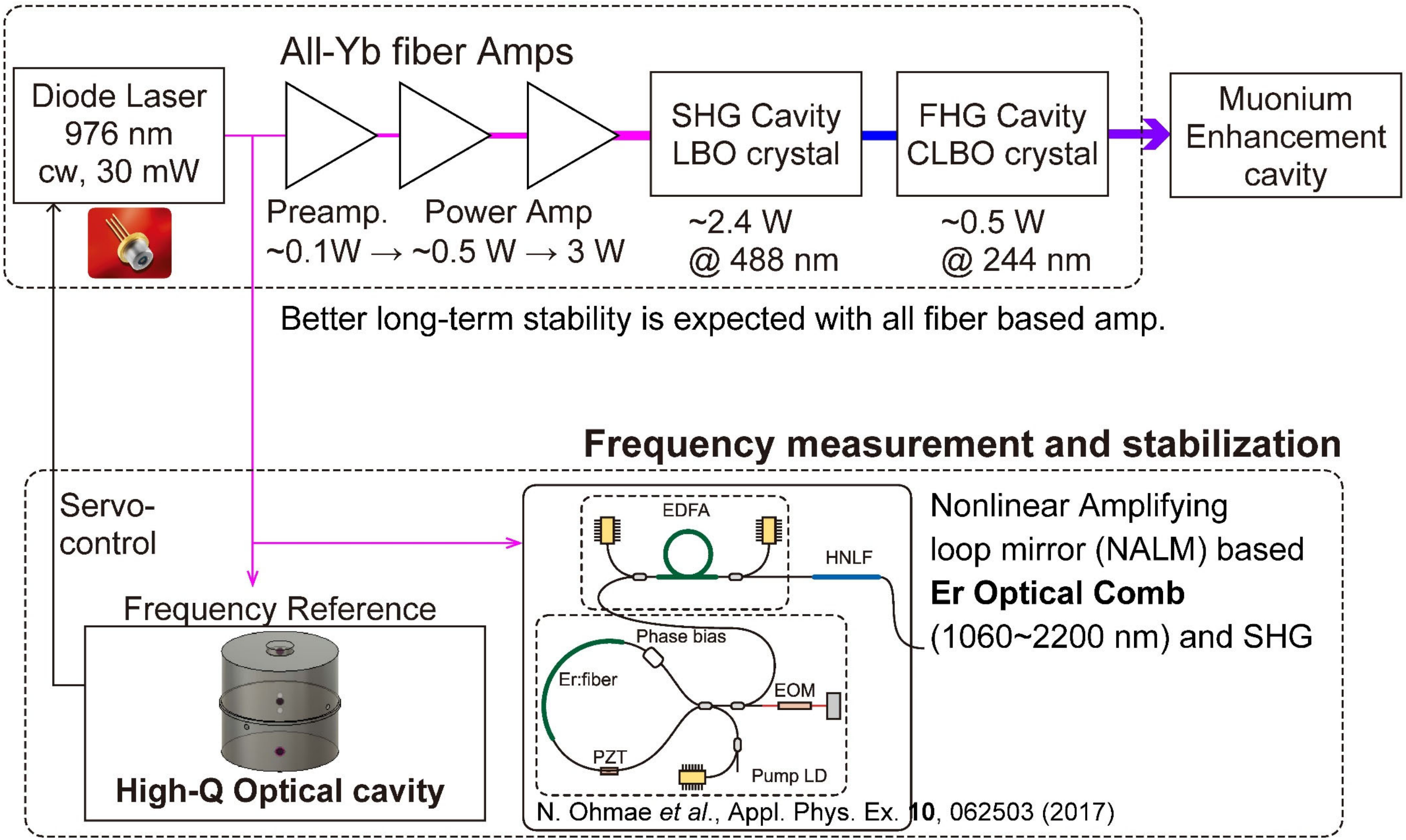
Improvements for stable and efficient operation of the syste

- Automatic, remote alignment of the laser beams
- Remote control of the steering mirrors for Lyman-α to exte



A new ceramic sample

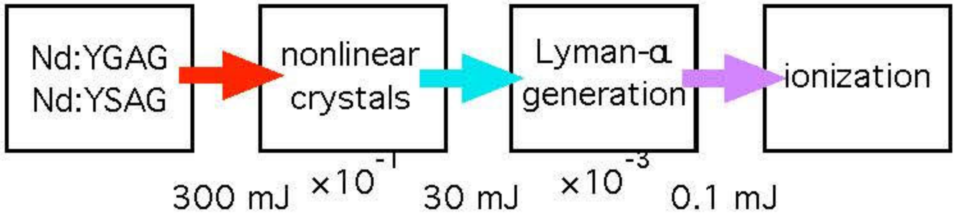
Design of Laser for 1S-2S Spectroscopy @J-PARC



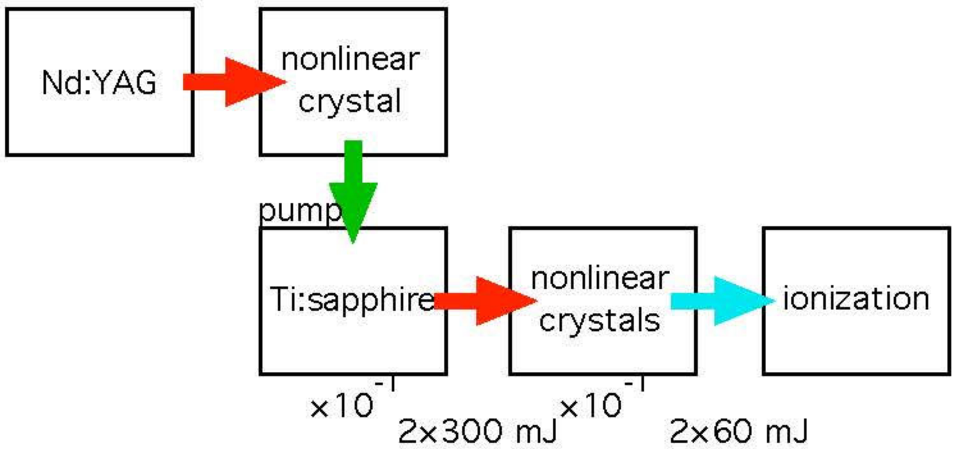
U-line Laser

Development of an alternative ionization scheme through collaboration

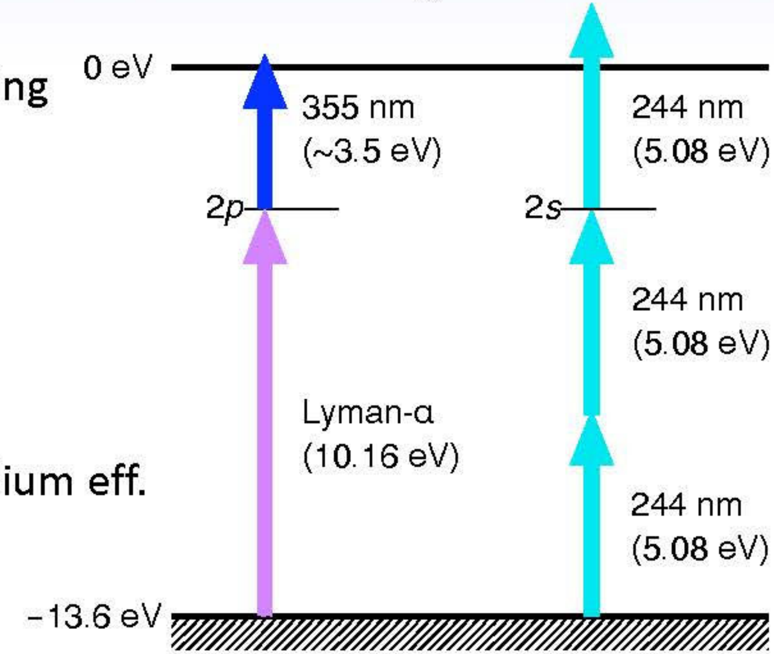
- The original scheme: Highly efficient but challenging
1s-2p (VUV one-photon excitation)



- An alternative scheme: Well established with medium eff.
1s-2s (UV two-photon excitation)



- The alternative system has been developed by the group of Okayama Univ. and to be tested in muonium 1S-2S spectroscopy at MLF MUSE S2.



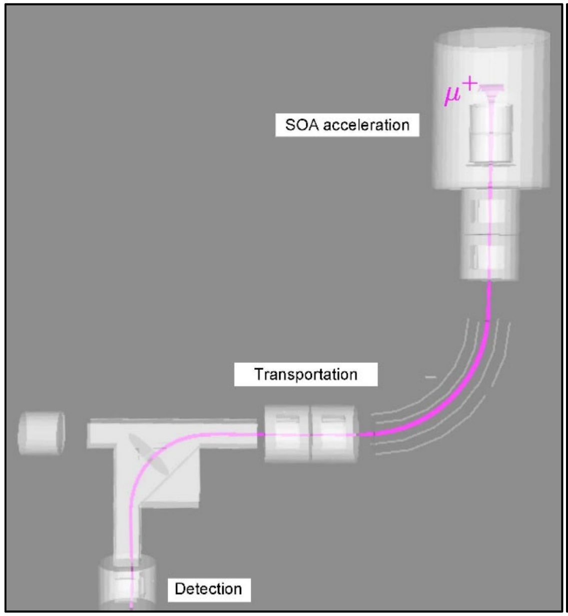
Summary

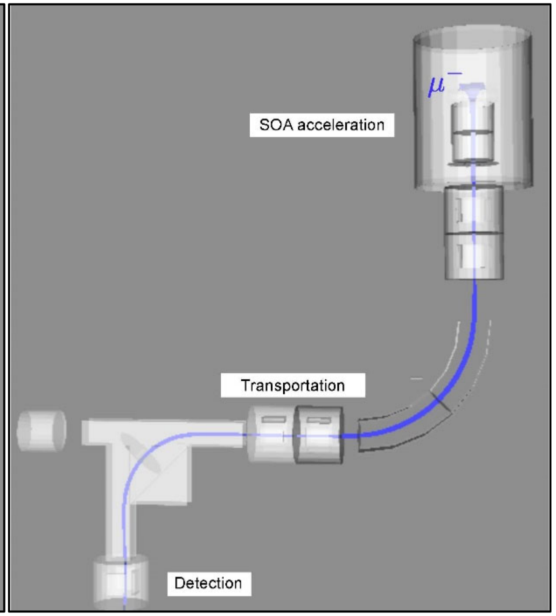
- $\mathrm{Mu}\text{-}\overline{\mathrm{Mu}}$ conversion search is a global trend (PSI, CSNS)
- Possibility of the low BG measurement was demonstrated in the feasibility study in the D line.
- We can reach the sensitivity of the preceding study at PSI, $O(10^{-11})$, by 1-year data acquisition.
  - Surface muon: 10^7 /s (in the S line)
  - $\mathrm{Mu}/\overline{\mathrm{Mu}}$ ionization: 0.2% (laser: under development)
  - Transmission eff. through the slow optics: 10%
  - Detection efficiency: 20% (under development)

- Next (Next) prospect
  - Surface muon: 10^8 /s (in the H line)
  - Realization of cold Mu target and multi-path laser: $\times 10$

Current situation

- The cost of developing the detector and so on is granted in KAKENHI-B from this FY.
- Some other parts are also granted.
- GAKUSHIN PD is joined. He is working hard to maximize the detection efficiency.
- You are always welcome! Let's reveal new physics!





Many thanks