A Muon Facility at RISP

Dept. of Physics, Korea University
Eunil Won (원은일)
eunil@hep.korea.ac.kr

for

Muon facility working group

Muon Science

From basic science to industrial applications

Basic Science		Applications
Material Science Superconductivity Magnetism Quantum diffusion Hydrogen related phenomena	**Muon catalyzed fusion** Energy issues	**Non destructive analysis** Element analysis inside sample
Chemistry Hydrogen related chemical reaction	**Biology** Protein, DNA Electric states	**Industrial applications** Hydrogen energy Semiconductors Battery
Particle physics g-2/EDM supersymmetry rare decay	**Beam studies** Beam cooling	

Compiled from K. Nagamine, Introductory Muon Science (Cambridge)

Contents

- **Science with RISP: muon science**

  - Muon Spin Rotation/Relaxation/Resonance for condensed matter science

  - Fundamental science with Muon

  - Muon Facility at RISP

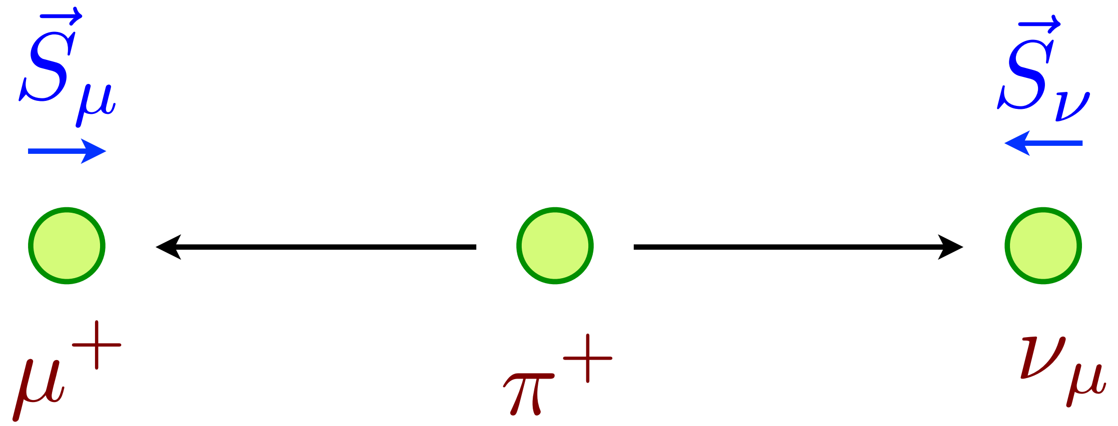
Muon

Muon (μ)

- **A spin 1/2 charged (+/-e) elementary particle**

$$m_\mu = 0.1\ m_{\text{proton}} = 200\ m_{\text{electron}}$$

- **Can be prepared to have 100% spin polarization**



- **Muon decays: mean life time 2.2 micro sec.**

$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$$

- **Large magnetic moment:** $\mu_\mu = 3.18\ \mu_{\text{proton}} = 8.89\ \mu_{\text{neutron}}$

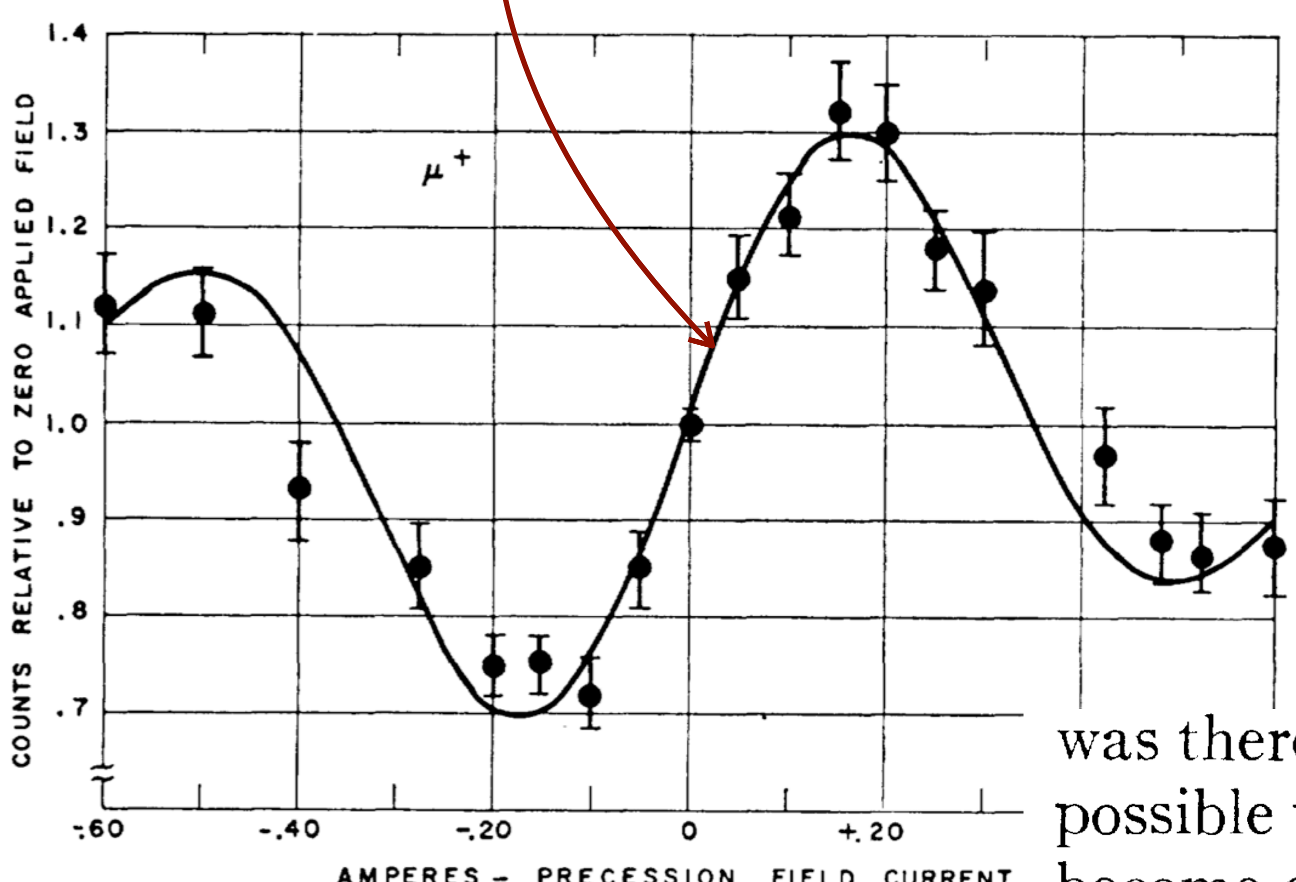
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

$1 - \frac{1}{3}\cos\theta$



Measurement of
- parity violation
- muon spin, g-factor, decay asymmetry and

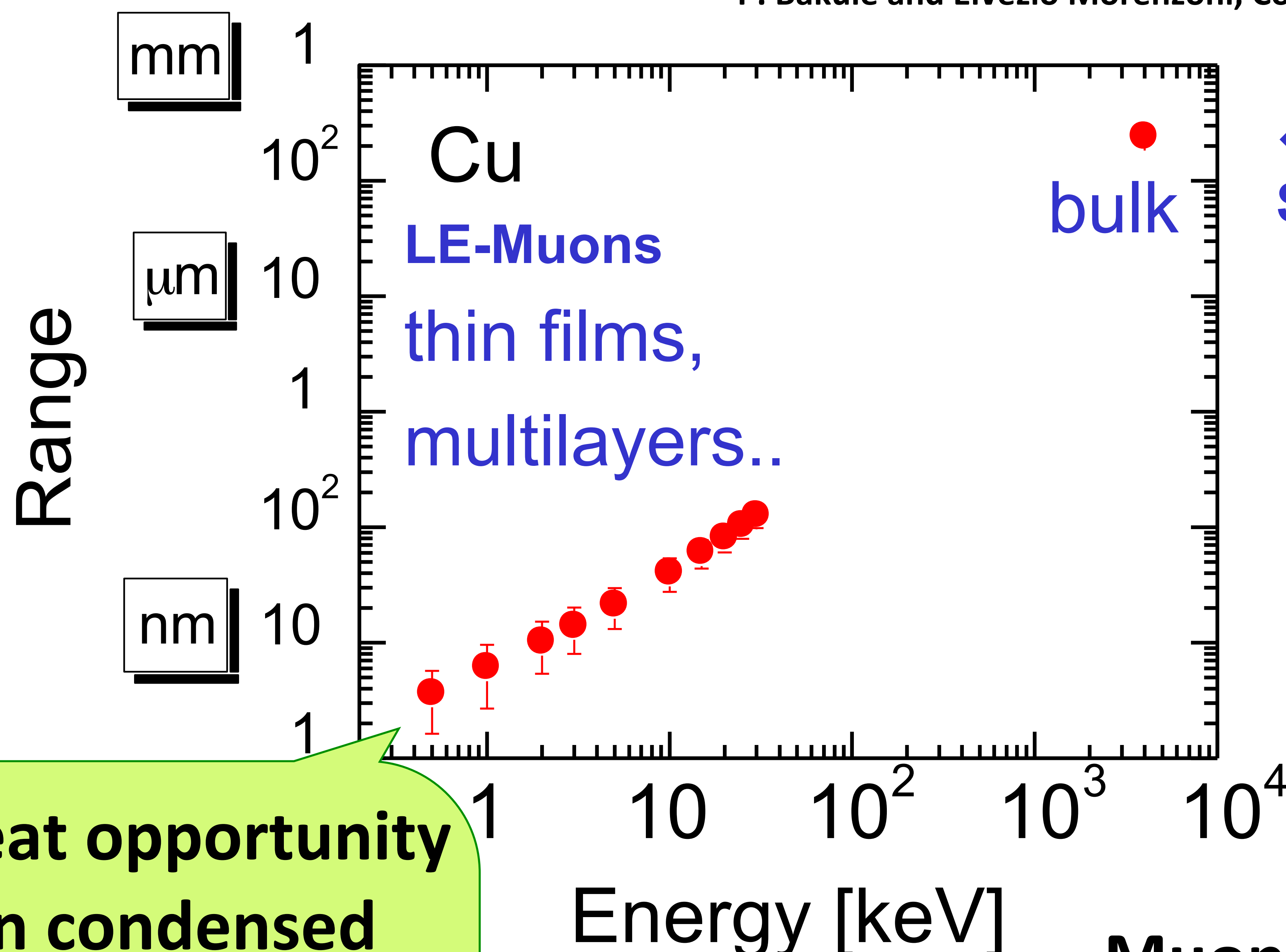
The 1st muon spin rotation spectrum

was there any evidence for an altered moment. It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

Phys. Rev. 105, 1415 (1957)

Range of muons in matter

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)



← Conventional Surface Muons

surface muon: muon from the pion that is at rest on the surface of target

Great opportunity in condensed matter science

Muons are implanted in the sample (no scattering)

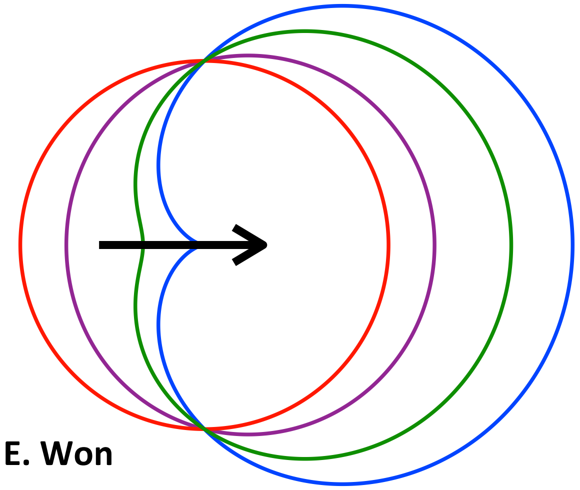
Condensed Matter Science: μSR

μSR

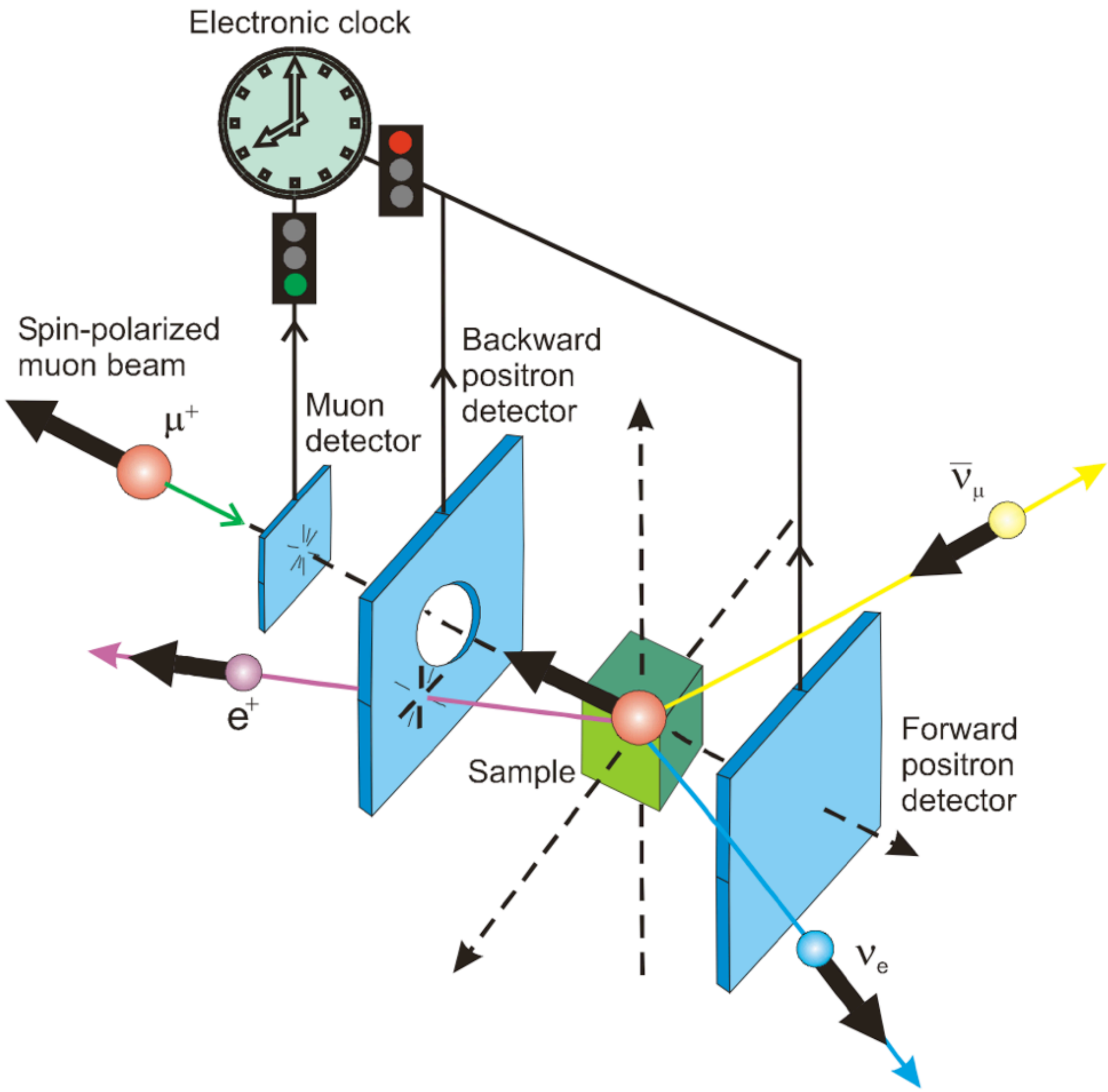
- **Muon Spin Rotation/ Relaxation/Resonance = μSR**

- Powerful tool for probing magnetic properties of matter

- Positron is emitted preferentially in the spin direction of the muon



E. Won



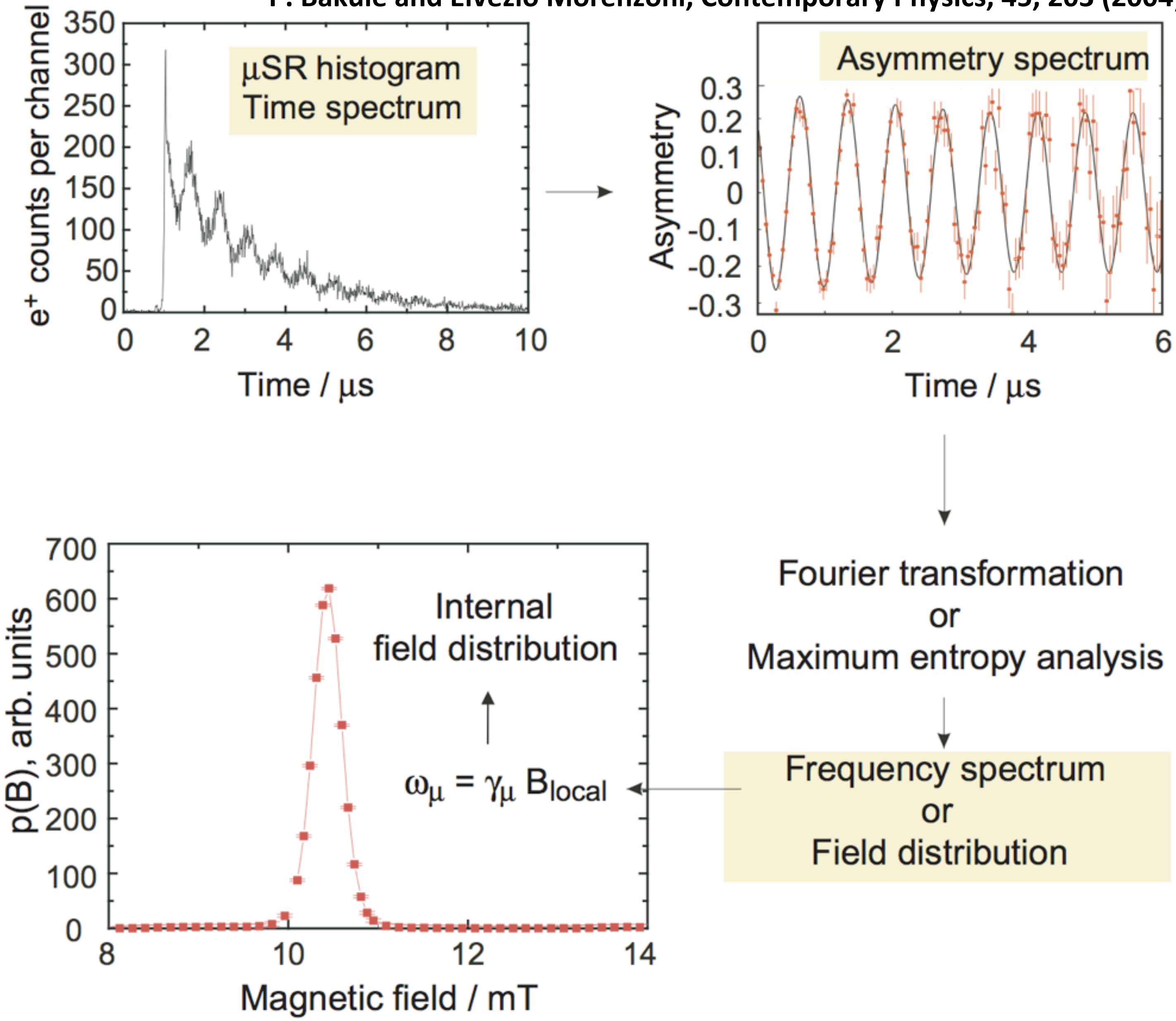
from "μSR brochure" by J.E Sonier, Simon-Fraser-Univ., Canada, 2002, http://musr.org/intro/musr/muSRBrochure.pdf

Principle of μSR

The signal corresponding the time evolution can be directly extracted by looking at the asymmetry function:

$$A(t) \equiv A_0 P(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)}$$

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)



- Asymmetry distribution contains the information about the precessing and relaxing muon spins in the total local field

- Fourier transformation to frequency domain allows measurement of the fields

$$\omega = \gamma_\mu B_{\mathrm{loc}}$$

Excellent Science with μSR

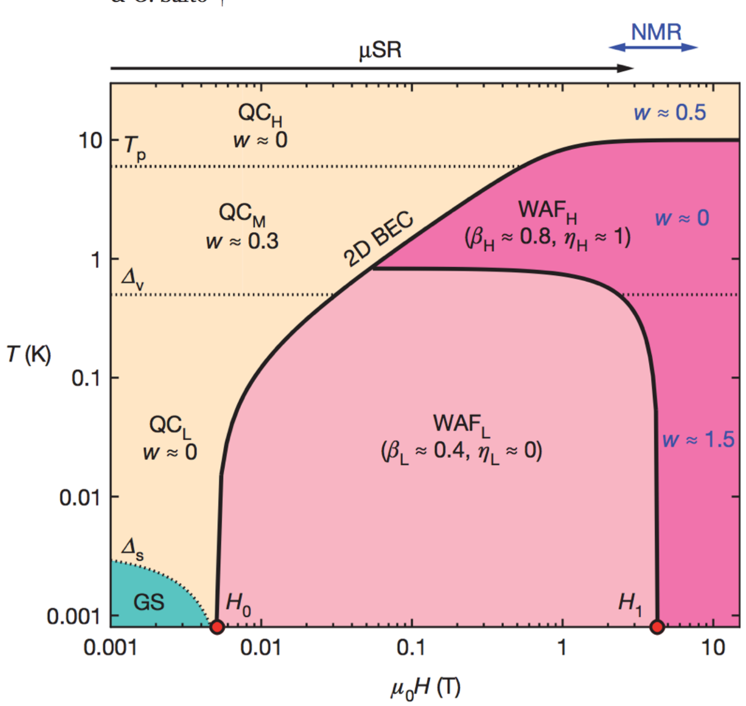
Courtesy of Byoung-Jin Suh (Catholic Univ. of Korea)

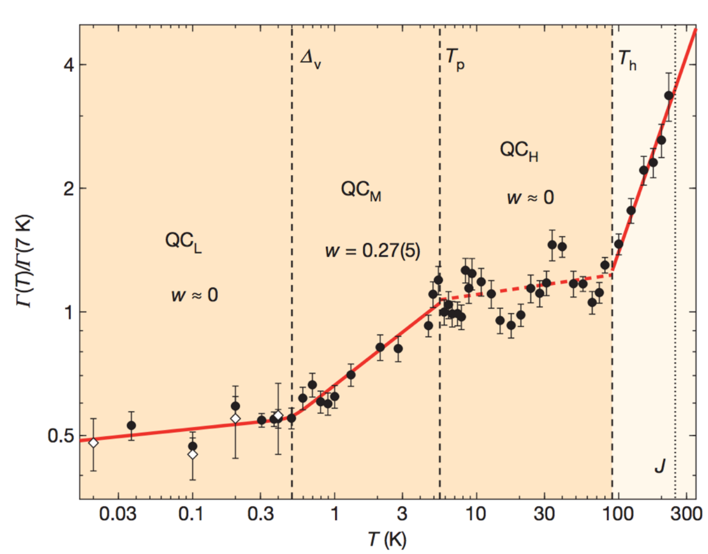
- About 15 papers per year in top class journals: PRL, Nature, Science, JACS, Angew. Chem. Int. Ed.
- More than 70 papers/year in PRB (dominated by PSI)

LETTER Nature 471 612 (2011) doi:10.1038/nature09910

Magnetic and non-magnetic phases of a quantum spin liquid

F. L. Pratt[1], P. J. Baker[1], S. J. Blundell[2], T. Lancaster[2], S. Ohira-Kawamura[3], C. Baines[4], Y. Shimizu[5], K. Kanoda[6], I. Watanabe[7] & G. Saito[8]†





Industrial Applications

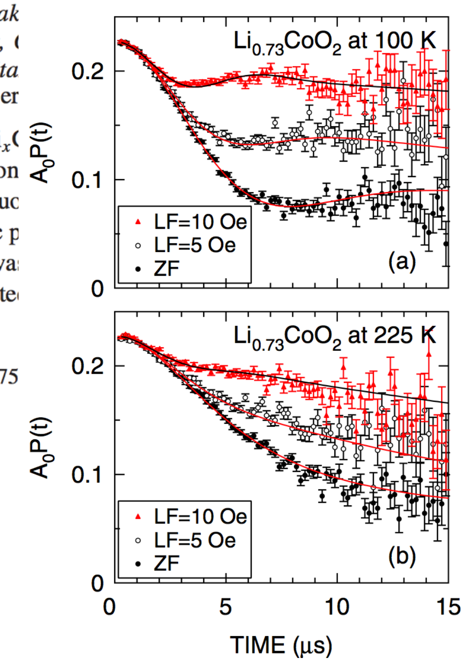
PRL 103, 147601 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

Li Diffusion in Li_xCoO_2 Probed by Muon-Spin Spectroscopy

Jun Sugiyama,[1,*] Kazuhiko Mukai,[1] Yutaka Ikedo,[1,†] Hiroshi Nozaki,[1] Martin Månsson,[2] and Isao Watanabe[3]
[1]Toyota Central Research and Development Laboratories Inc., Nagak
[2]Laboratory for Neutron Scattering, ETH Zürich and Paul Scherrer Institut, (
[3]Muon Science Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saita
(Received 16 June 2009; published 30 September

The diffusion coefficient of Li^+ ions (D_{Li}) in the battery material Li_x(muon-spin relaxation (μ^+SR). Based on experiments in zero and weak lon up to 400 K, we determined the fluctuation rate (ν) of the fields on the muc the nuclear moments. Combined with susceptibility data and electrostatic p ion diffusion was detected above ~150 K. The D_{Li} estimated from ν wa predictions from first-principles calculations, and we present the μ^+SR te detect D_{Li} for materials containing magnetic ions.

DOI: 10.1103/PhysRevLett.103.147601 PACS numbers: 76.75



Angewandte Chemie

Chiral Induction

DOI: 10.1002/anie.200904107

Chiral Induction in Lyotropic Liquid Crystals: Insights into the Role of Dopant Location and Dopant Dynamics**

*Ute C. Dawin, Herbert Dilger, Emil Roduner, Robert Scheuermann, Alexey Stoykov, and Frank Giesselmann**

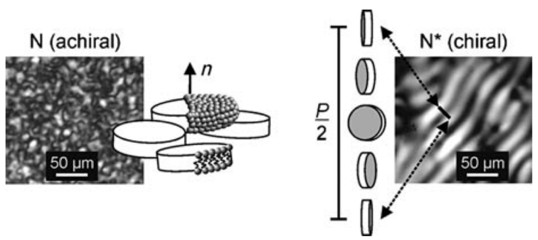
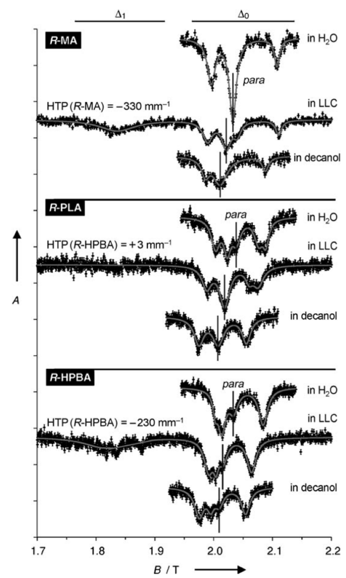


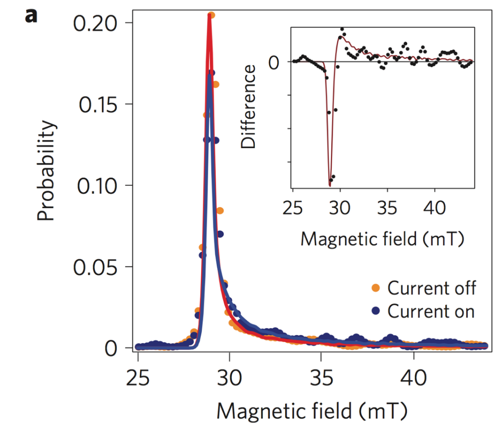
Figure 1. Schlieren texture and model of the nematic (N) LLC host phase with disk-like micelles (left). Fingerprint texture and model of the chiral nematic (N*) phase; micelles represent the helical modulation of the director **n** with pitch *P* induced by doping the host phase with 4.37% *R*-MA (right).



nature materials | ARTICLES
PUBLISHED ONLINE: 23 NOVEMBER 2008 | DOI: 10.1038/NMAT2333

Direct measurement of the electronic spin diffusion length in a fully functional organic spin valve by low-energy muon spin rotation

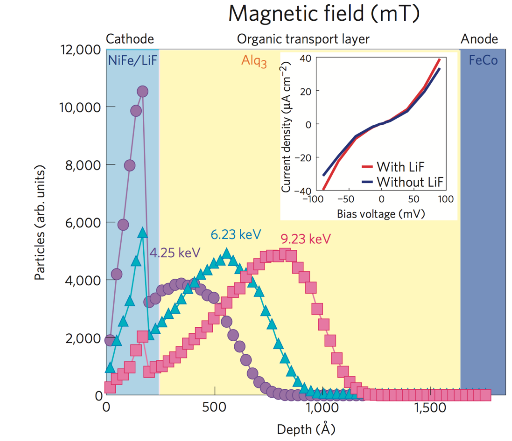
A. J. Drew[1,2]*, J. Hoppler[1,3], L. Schulz[1], F. L. Pratt[4], P. Desai[2], P. Shakya[2], T. Kreouzis[2], W. P. Gillin[2], A. Suter[5], N. A. Morley[6], V. K. Malik[1], A. Dubroka[1], K. W. Kim[1], H. Bouyanfif[1], F. Bourqui[1], C. Bernhard[1], R. Scheuermann[5], G. J. Nieuwenhuys[5], T. Prokscha[5] and E. Morenzoni[5]



nature materials | LETTERS
PUBLISHED ONLINE: 5 DECEMBER 2010 | DOI: 10.1038/NMAT2912

Engineering spin propagation across a hybrid organic/inorganic interface using a polar layer

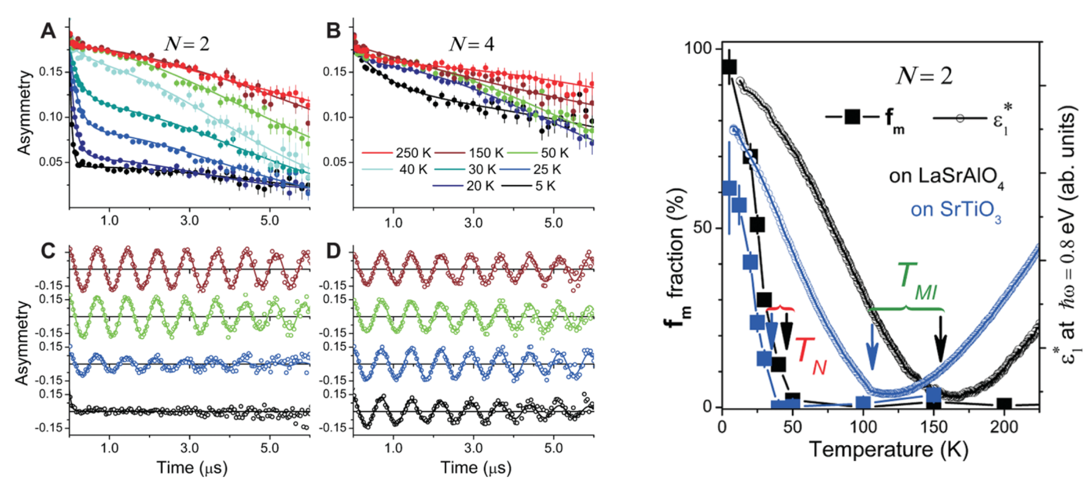
L. Schulz[1], L. Nuccio[2], M. Willis[2], P. Desai[2], P. Shakya[2], T. Kreouzis[2], V. K. Malik[1], C. Bernhard[1], F. L. Pratt[3], N. A. Morley[4], A. Suter[5], G. J. Nieuwenhuys[5], T. Prokscha[5], E. Morenzoni[5], W. P. Gillin[2]* and A. J. Drew[1,2]*



Science 332, 937 (2011)

Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices

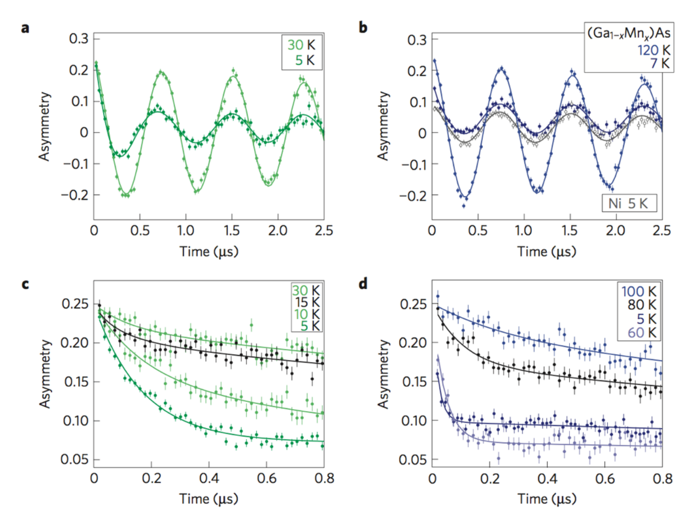
A. V. Boris,[1]* Y. Matiks,[1] E. Benckiser,[1] A. Frano,[1] P. Popovich,[1] V. Hinkov,[1] P. Wochner,[2] M. Castro-Colin,[2] E. Detemple,[2] V. K. Malik,[3] C. Bernhard,[3] T. Prokscha,[4] A. Suter,[4] Z. Salman,[4] E. Morenzoni,[4] G. Cristiani,[1] H.-U. Habermeier,[1] B. Keimer[1]*

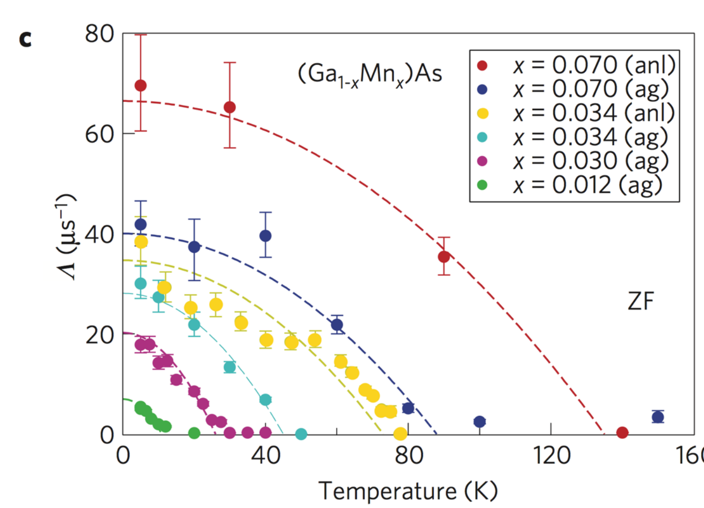


nature materials | LETTERS
PUBLISHED ONLINE: 21 MARCH 2010 | DOI: 10.1038/NMAT2715

Spatially homogeneous ferromagnetism of (Ga, Mn)As

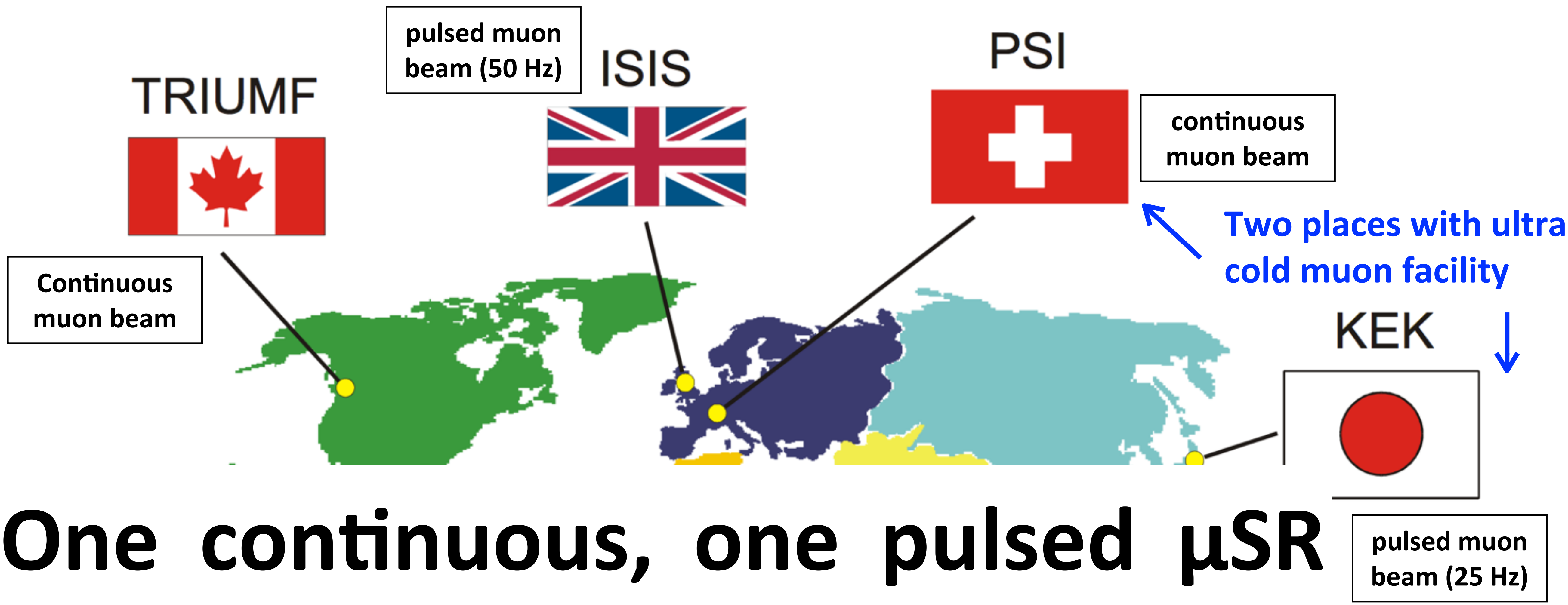
S. R. Dunsiger[1,2], J. P. Carlo[1], T. Goko[1,3], G. Nieuwenhuys[4], T. Prokscha[4], A. Suter[4], E. Morenzoni[4], D. Chiba[5,6], Y. Nishitani[6], T. Tanikawa[5,6], F. Matsukura[5,6], H. Ohno[5,6], J. Ohe[7,8], S. Maekawa[7,8] and Y. J. Uemura[1]*





World-wide μSR Facility

from "μSR brochure" by J.E Sonier, Simon-Fraser-Univ., Canada, 2002, http://musr.org/intro/musr/muSRBrochure.pdf



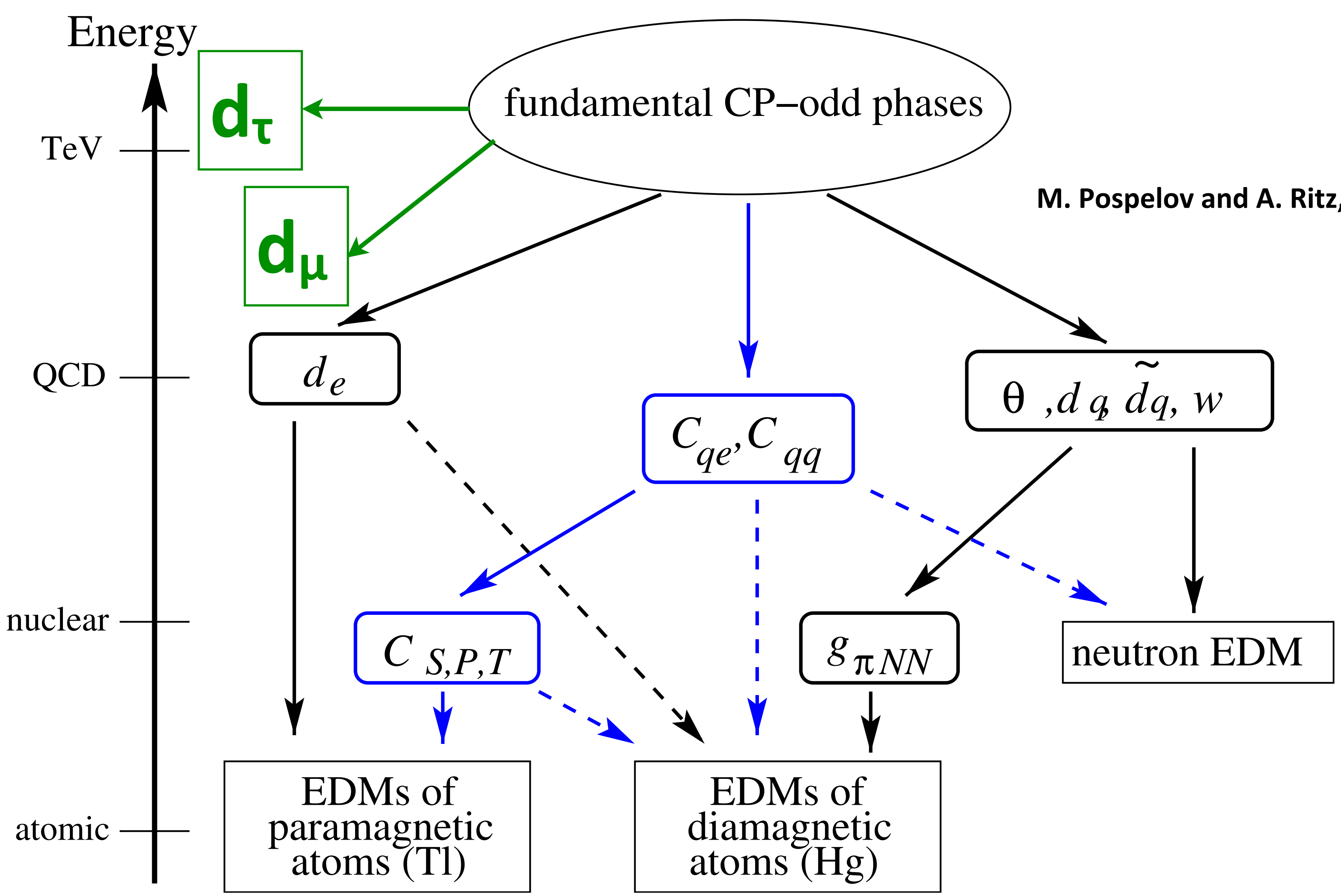
One continuous, one pulsed μSR in Asian region will be a crucial step forward (Y. Miyake: J-PARC)

Fundamental Science with Muon

Electric Dipole Moment

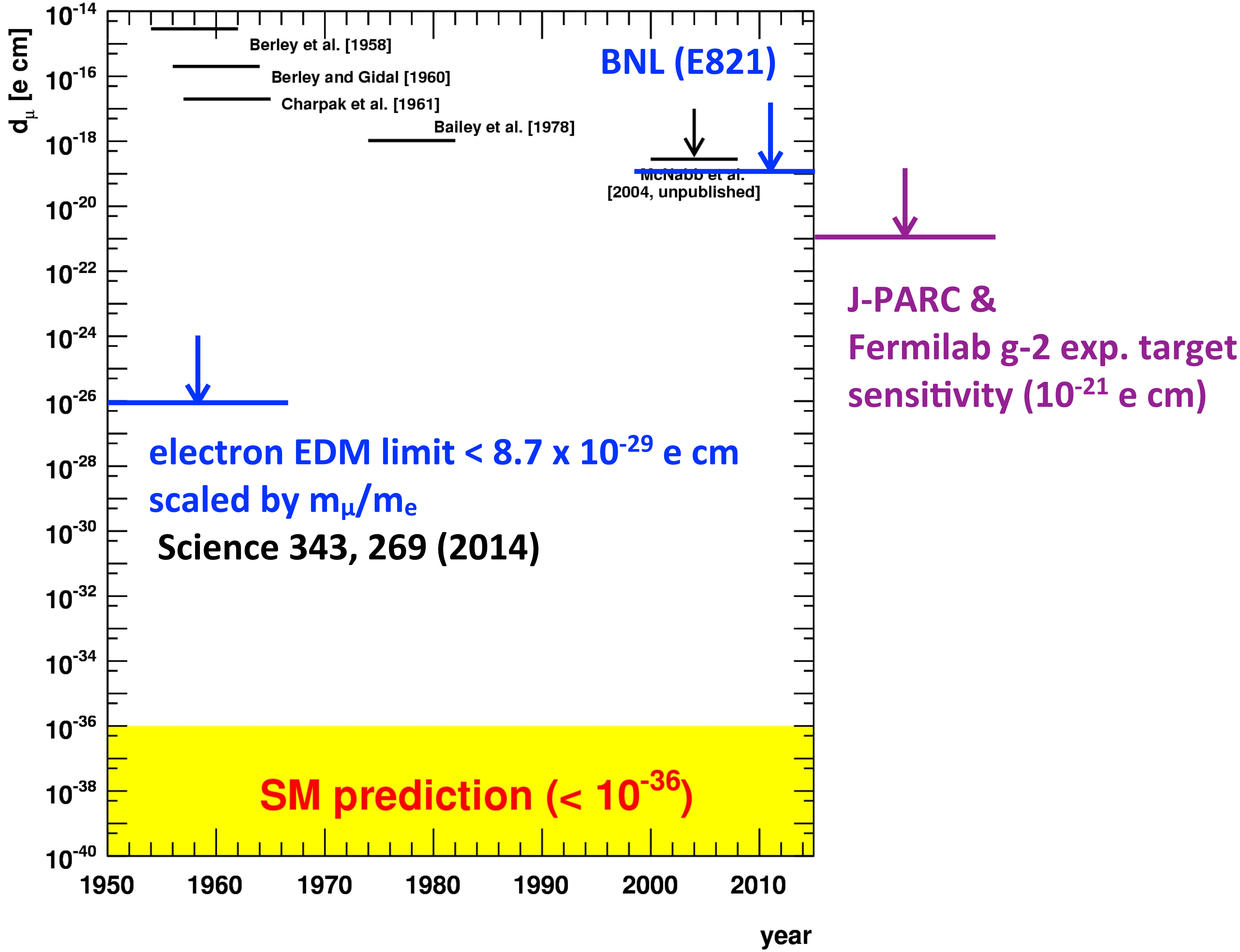
- Permanent EDM for an elementary particle: P and T violation (also CP violation under CPT invariance)

- Non-zero EDM measurement: evidence of physics beyond Standard Model



M. Pospelov and A. Ritz, Annals of Phys. 318 (2005) 119

History of EDM Searches



Muon EDM Efforts

Spin precession vector in static E and B fields with $\vec{\beta}\cdot\vec{B}=0,\ \vec{\beta}\cdot\vec{E}=0$

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

Three approaches

- **Magic momentum (g-2+EDM): BNL E821, Fermilab**

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

↕ Less sensitive to EDM (10^{-21} e cm level)

- **Zero E-field (g-2+EDM): J-PARC E34**

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

- **Spin frozen (EDM only): introduce radial E to remove g-2 term (Phys. Rev. Lett. 93, 052001 (2004))**

$$\vec{\omega}=-\frac{e}{m}\frac{\eta}{2}\left\{\vec{\beta}\times\vec{B}+\frac{\vec{E}}{c}\right\}$$

So far, only proposals exist

Muon EDM Efforts

"Spin frozen" technique: for future prospect

$$\frac{1}{\quad - 1} - a\Big)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\Big(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\Big)\Big\}$$

radial E-field to

ate this term

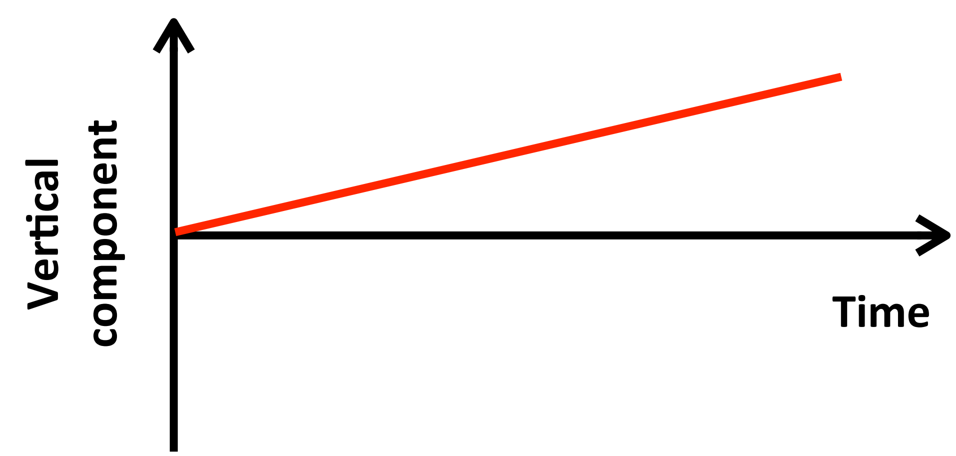
s solely by EDM: better sensitivity

y:

$$\overline{\quad AP\sqrt{N}}$$

y of electron

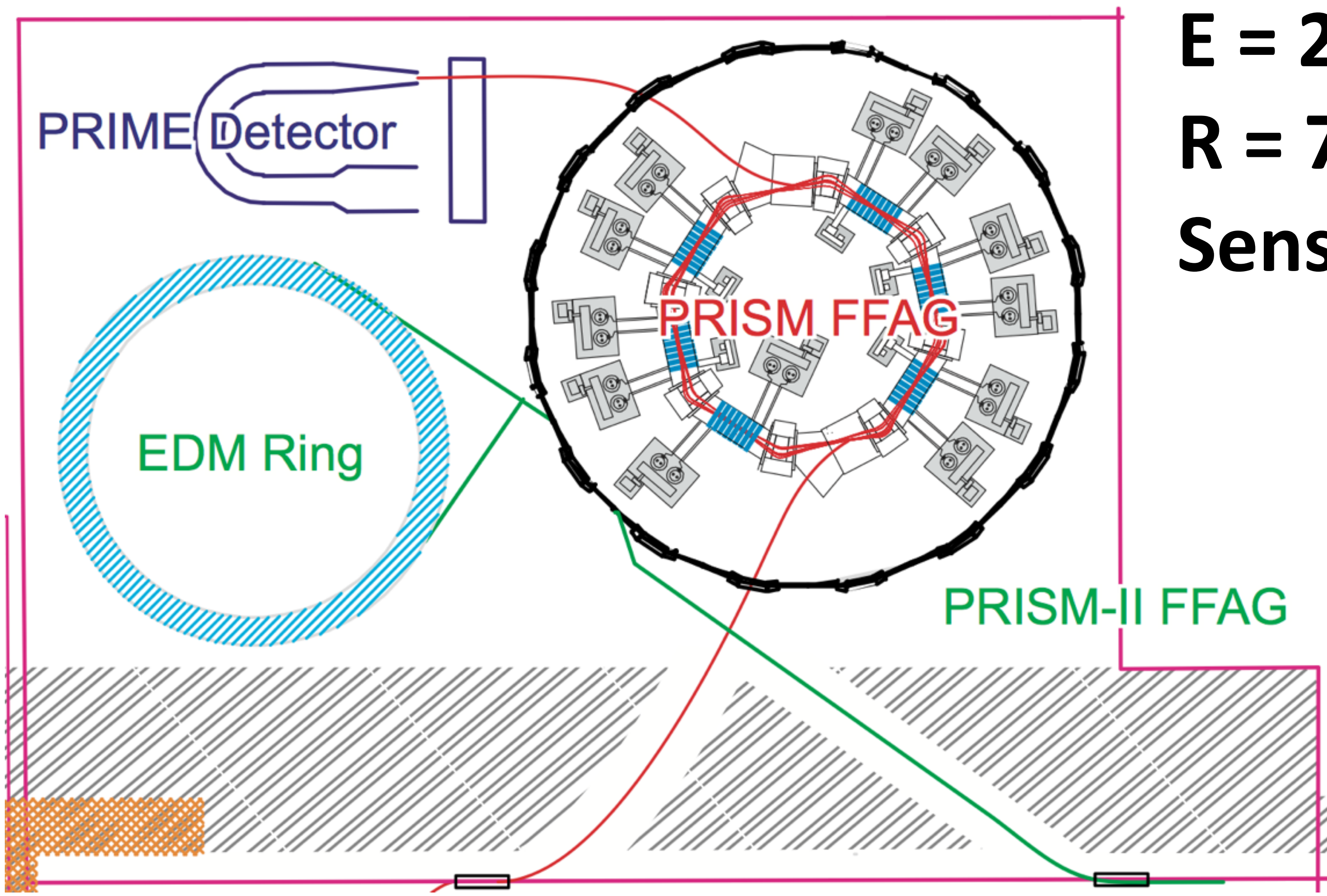
uon

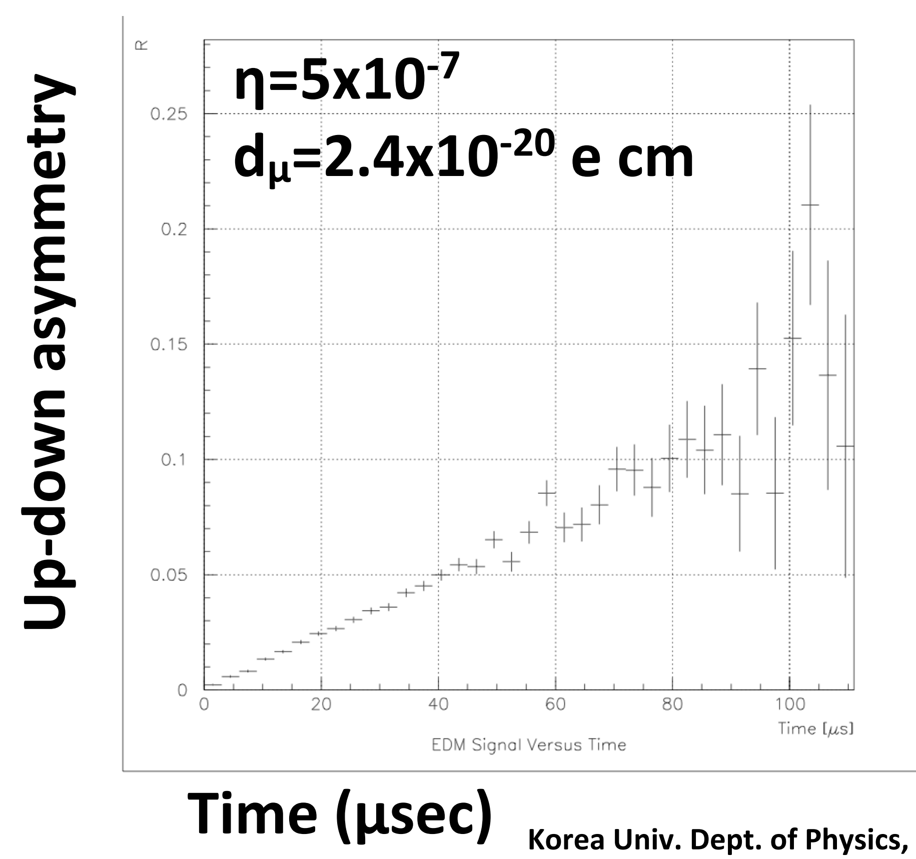


Spin frozen μ-EDM

J-PARC proposal: LOI 22, A. Silenko et al. (2003)

- p = 500, 350 MeV/c
- B = 0.25 T
- E = 2 MV/m
- R = 7 m (w/ PRISM FFAG)
- Sensitivity $\sigma(d_\mu) = 8\times10^{-25}$ e cm



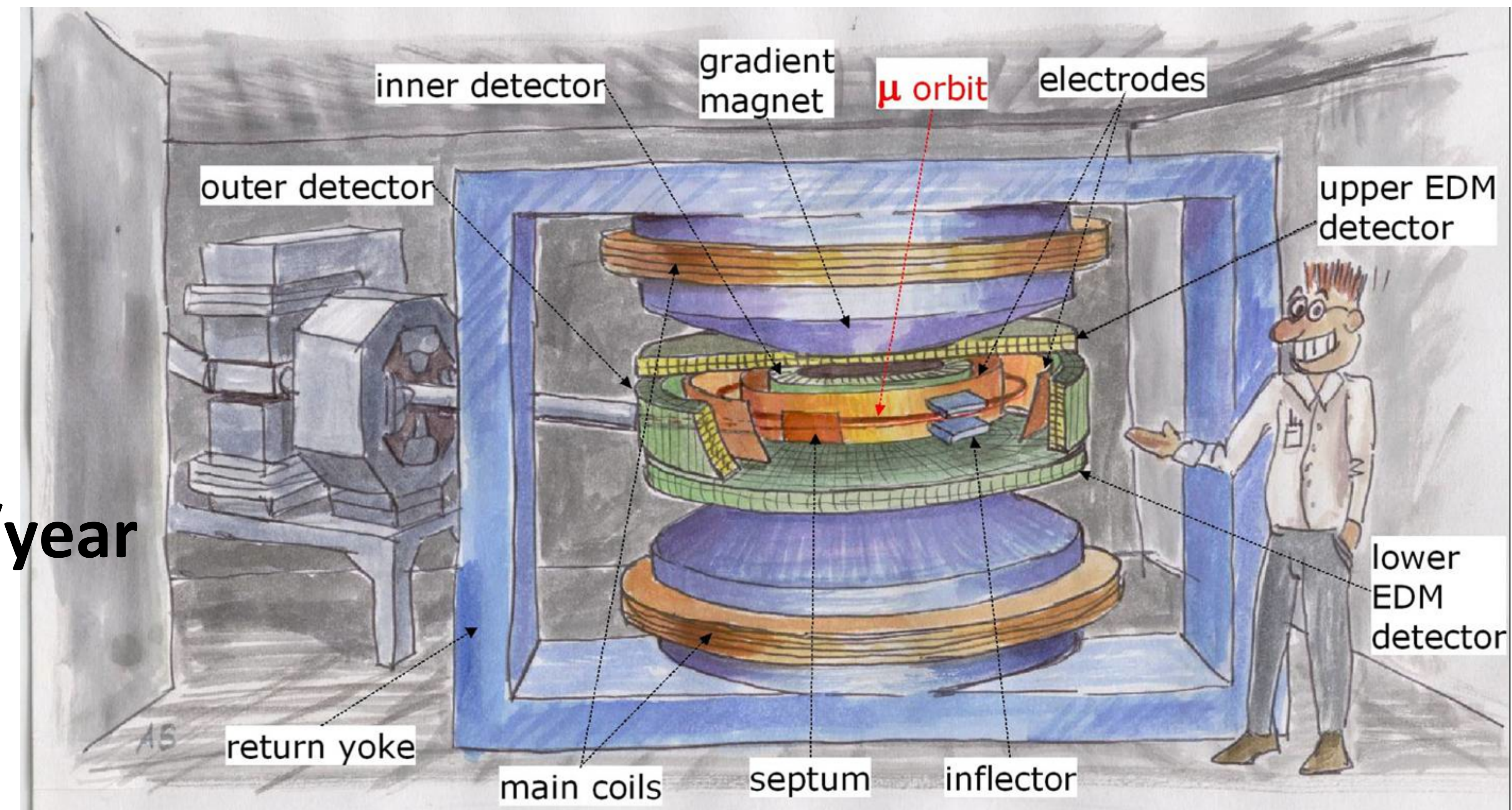


Spin frozen μ-EDM

PSI proposal: A. Adelmann, et al., J. Phys. G, 37 085001 (2010)

http://amas.web.psi.ch/projects/muonedm/
Artist's impression (A. Streun)

p = 125 MeV/c
B = 1 T
E = 0.64 MV/m
R = 0.42 m
N = 2×10^{5} /s
Sensitivity: $\sigma(d_\mu)$
= 5×10^{-23} e cm /year



A "compact storage ring" concept

Spin frozen μ-EDM

- Planned g-2 exp. (Fermilab, J-PARC) aim at sensitivity of $\sigma(d_\mu)$ ~ 10^{-21} e cm
- Spin frozen technique seems the way to go (?)
- If one sticks with linear mass scaling: $\sigma(d_\mu)$ ~ 10^{-26} e cm at least desired (?)

  - Quadratic, cubic scenarios exist
- Systematics

Muon Science @ RISP

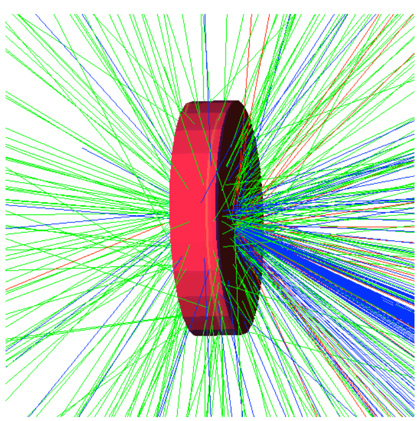
Reminder

- **RISP: 660 uA, 600 MeV for proton**
- **Note: this is slightly less than half of beam power of PSI cyclotron (1.3 MW)**

Muon yield will be less then PSI yield
- New flexible design with ideas is desired

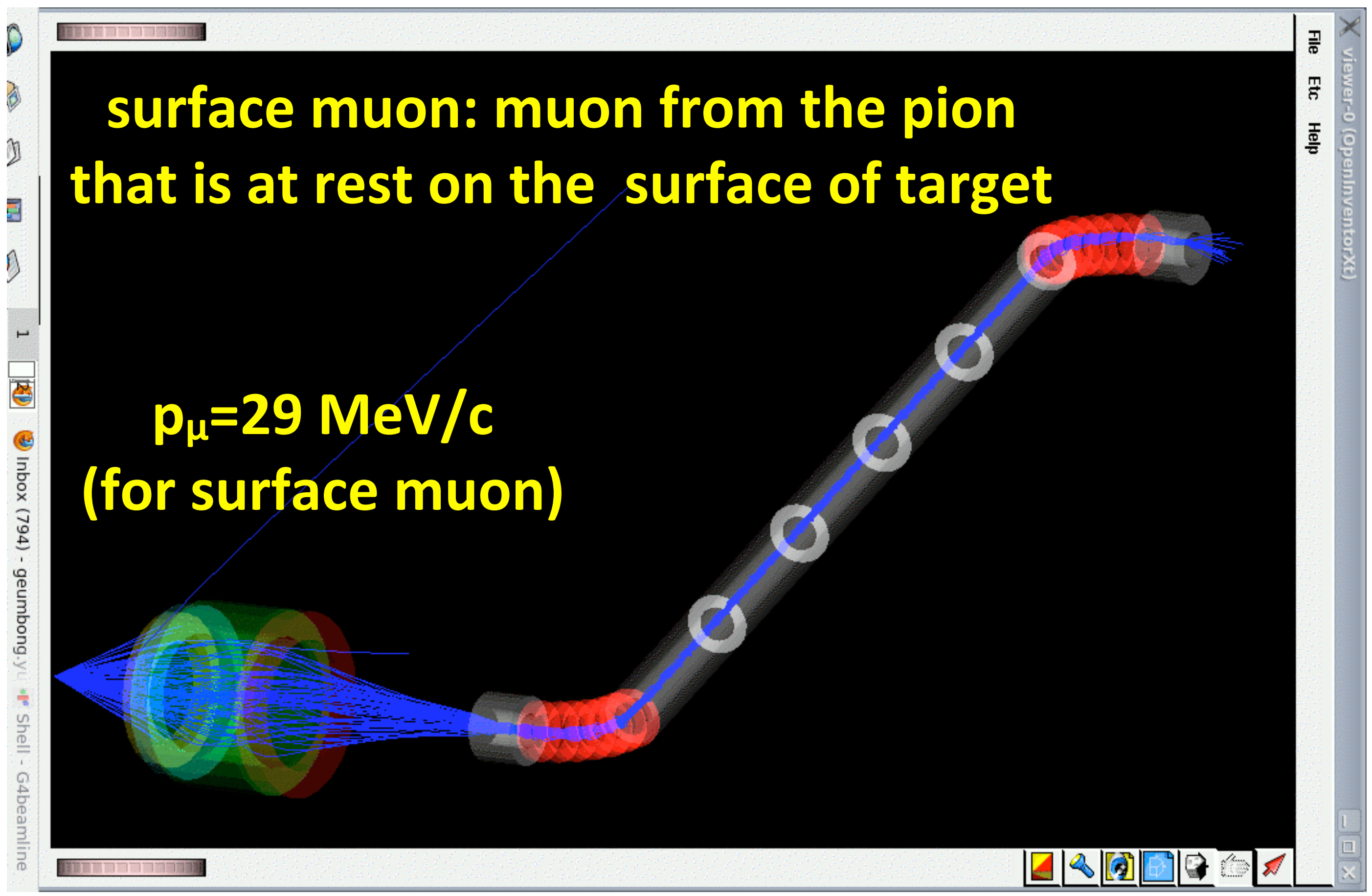
Our Simulation Shows

Muon production



~10^{-5} surface muons/proton

Muon transport

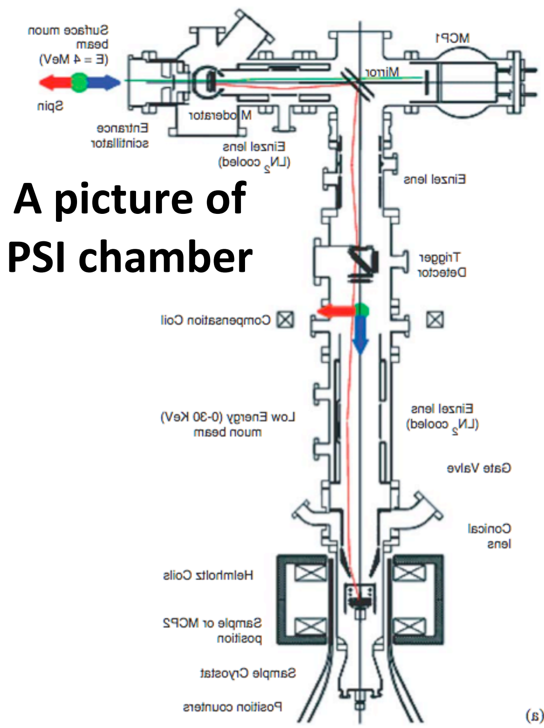


ε(collection)~O(3×10^{-2})

ε(transport)~O(1)

Muon thermalization

A picture of PSI chamber



ε(thermalize)~10^{-5}

4×10^{15} protons/s

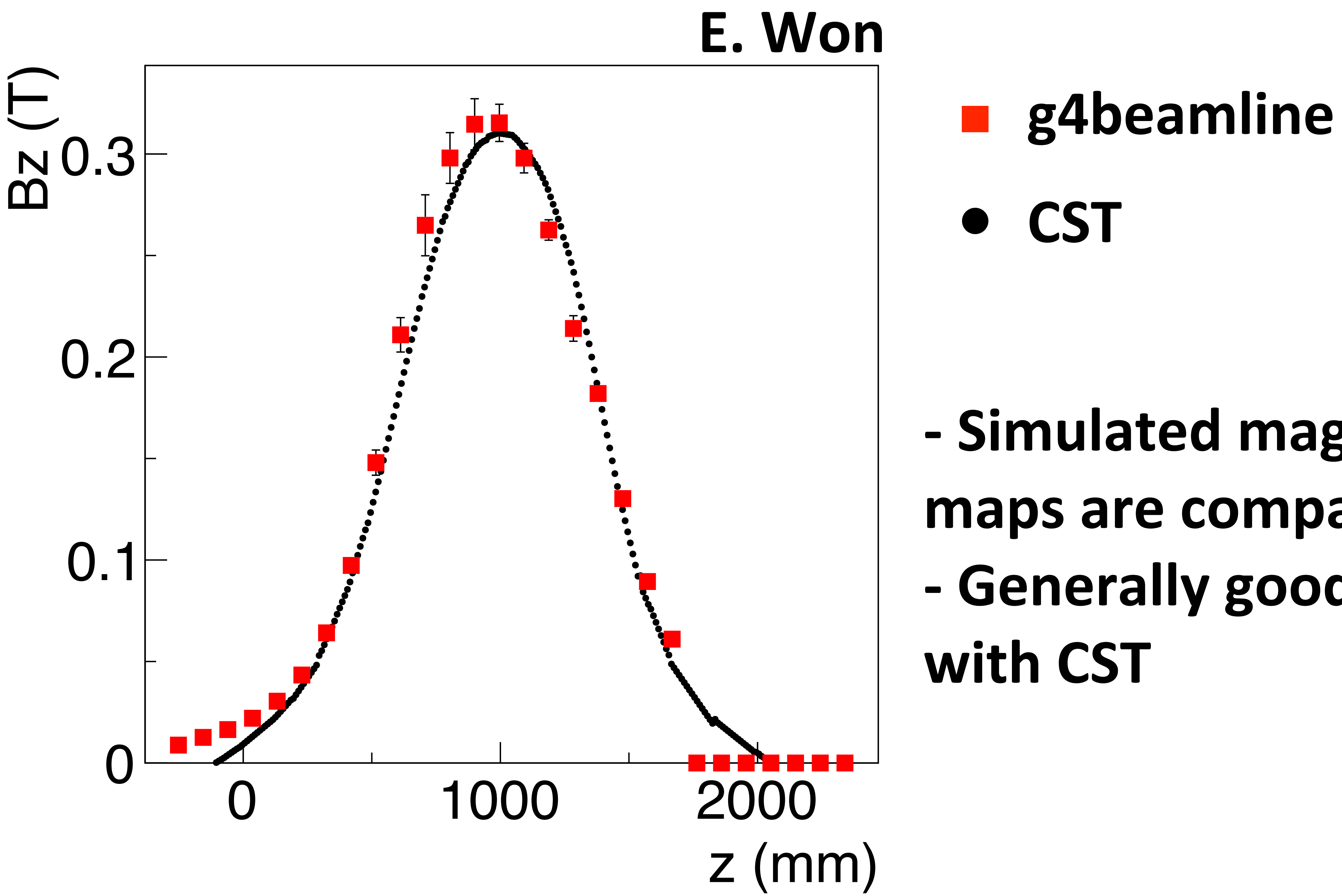
(660 uA)

10^8 surface muons/s

10^4 thermalized muons/s

?

Magnetic Field Validation

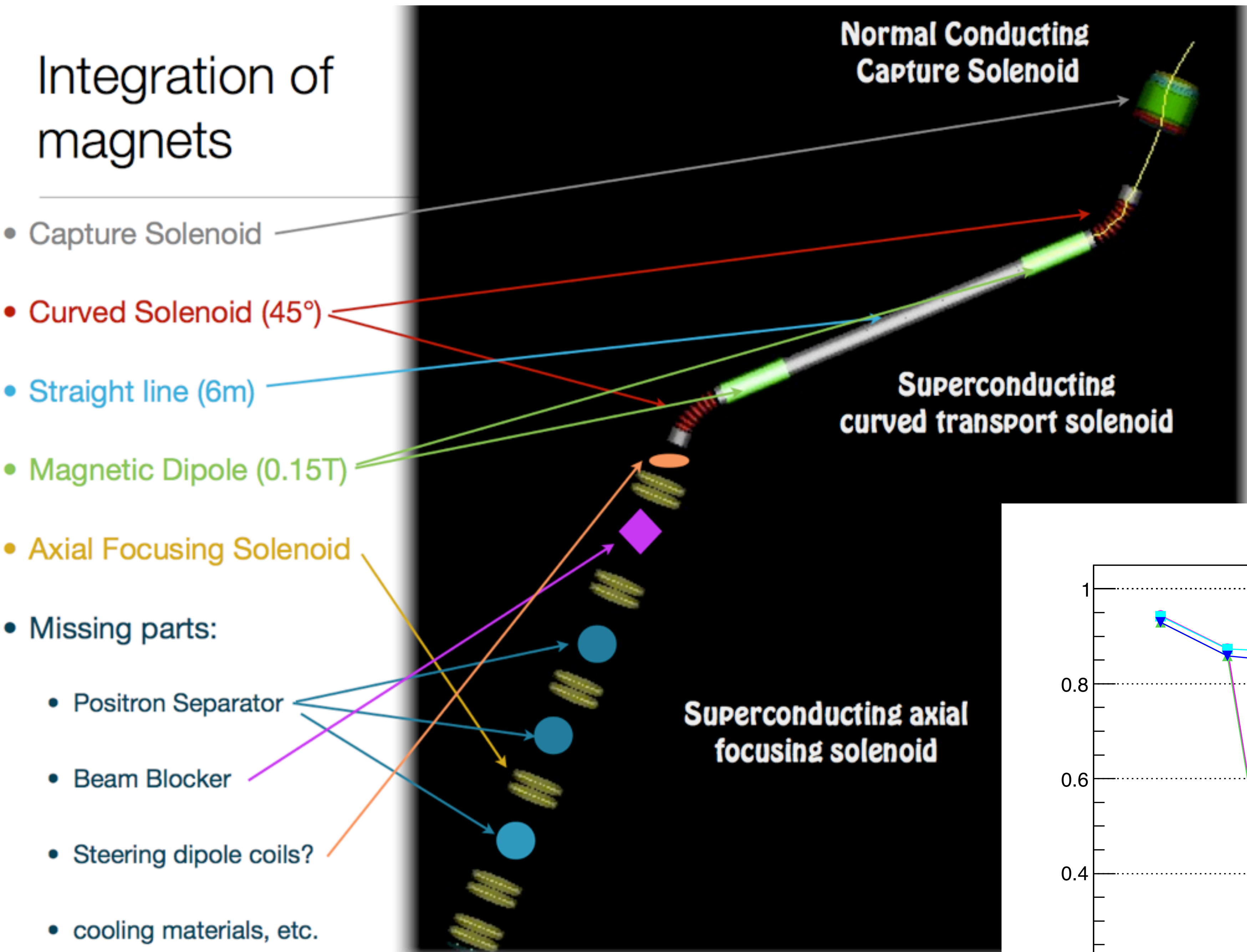


- Simulated magnetic field maps are compared
- Generally good agreement with CST

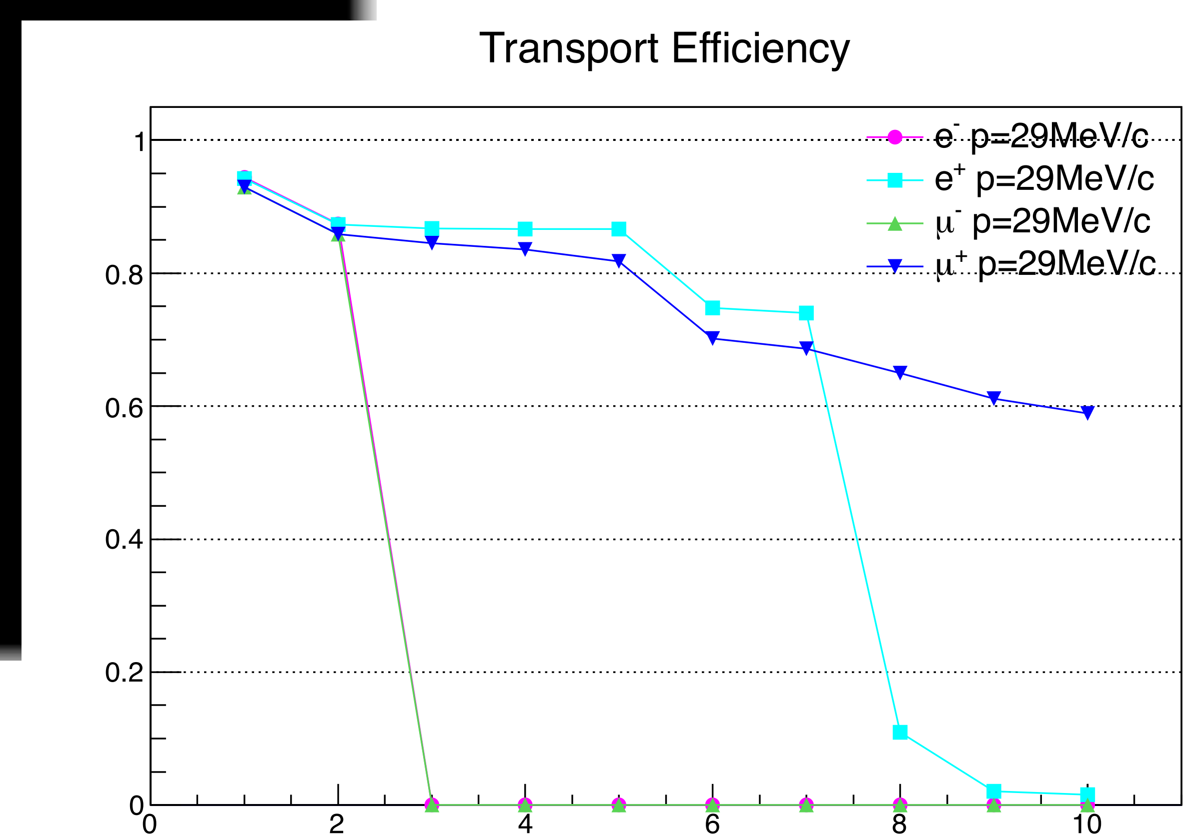
Transport in Detail

- "solenoid only" option

g4beamline / G. Yu (KU->SNU)



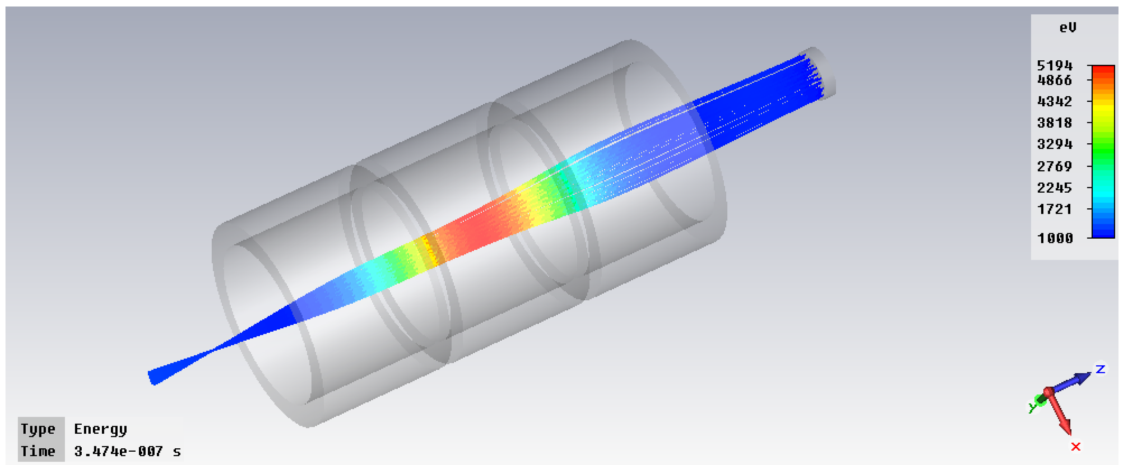
Overall surface muon transportation efficiency~60%: need further improvement

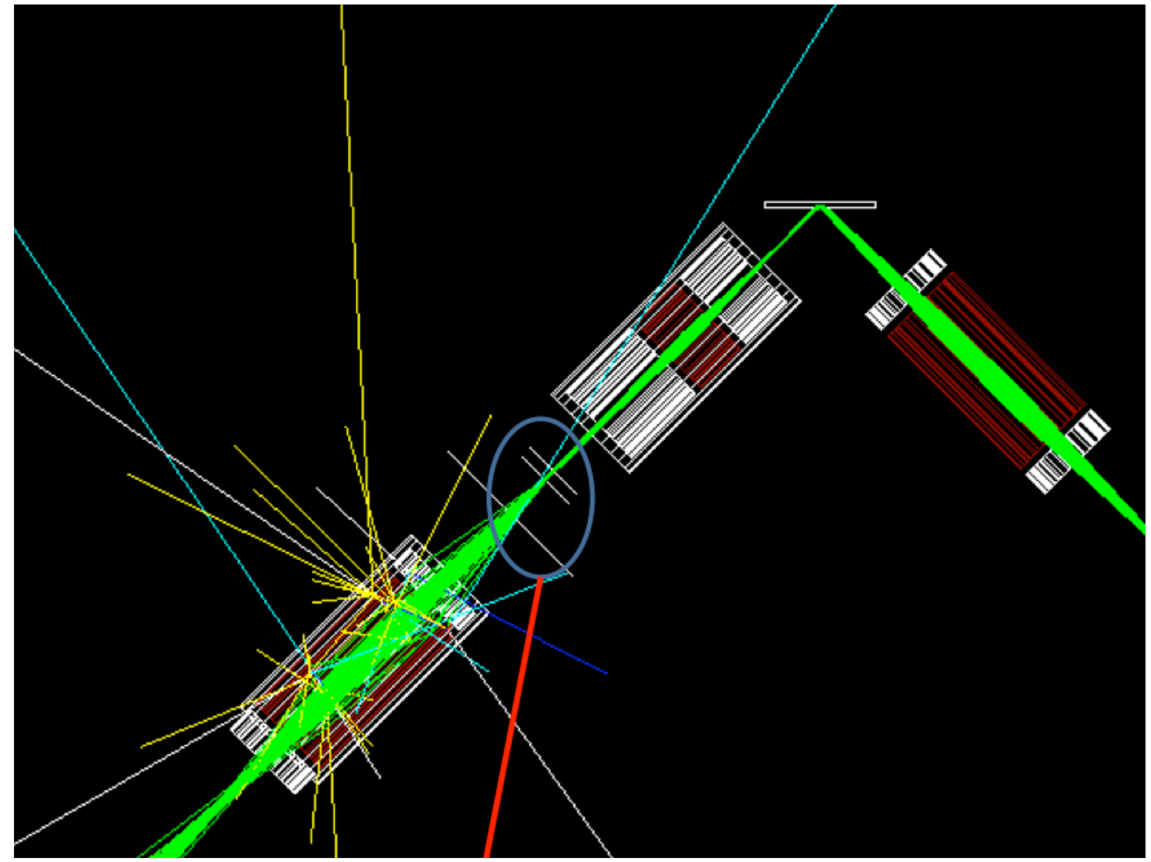


Epi-thermal Beam Line

- Einzel lens design simulation (CST)

Kyungmin Lee, Jihoon Choi/KU

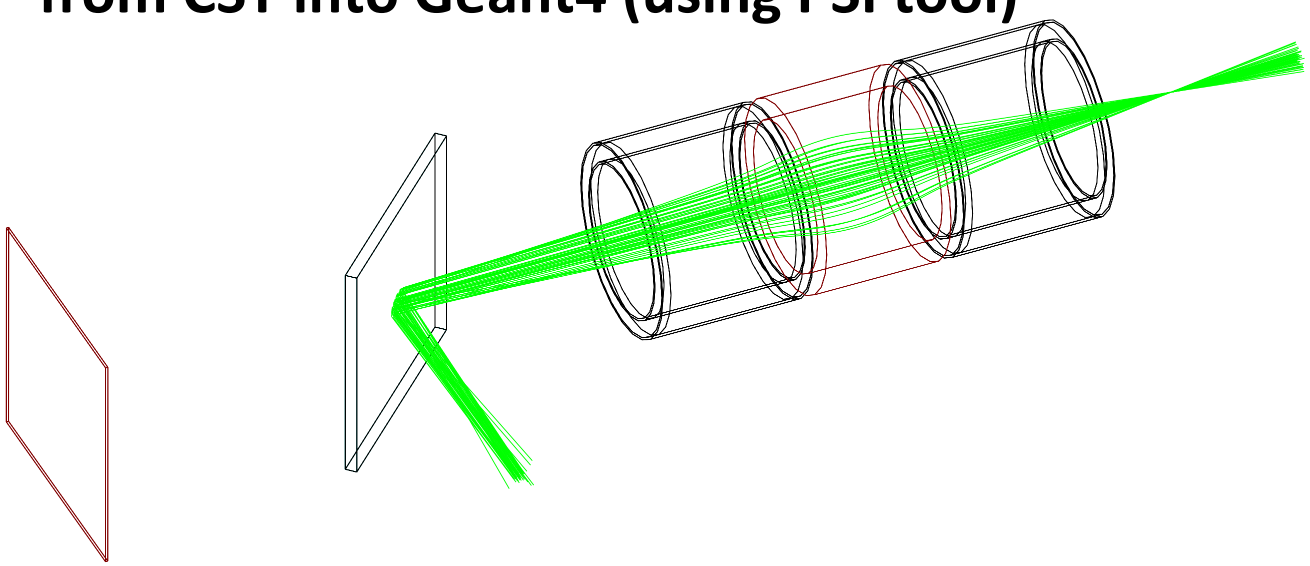




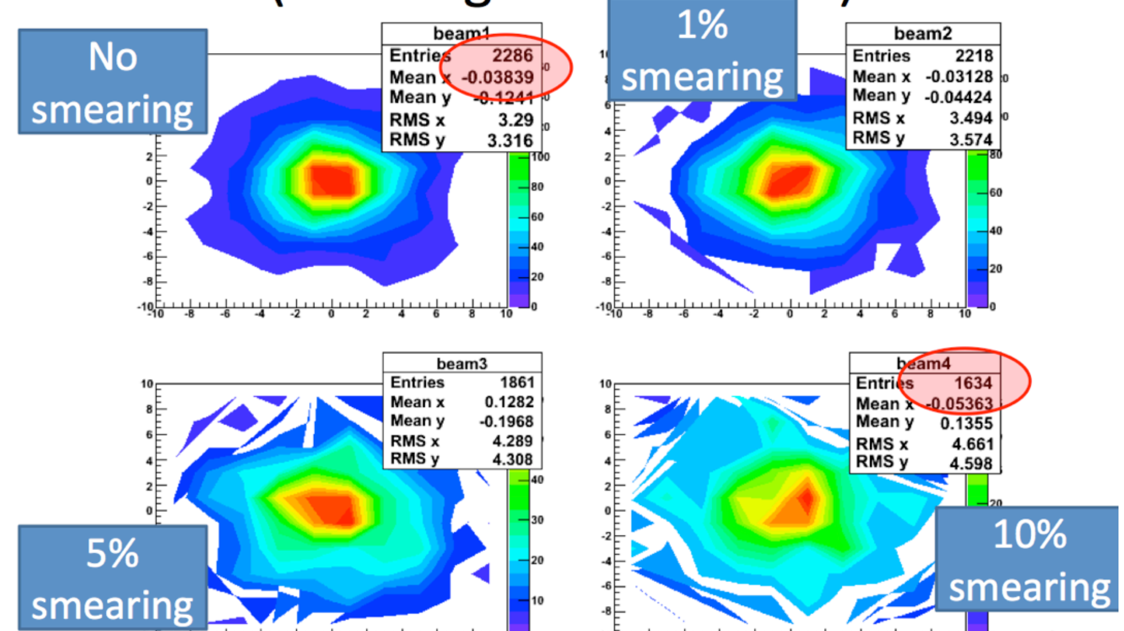
ByeongRok Ko/ KU

Moderated muons come in

- Result of simulation after field map from CST into Geant4 (using PSI tool)

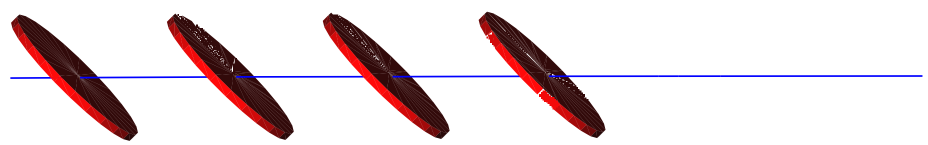


Momentum smearing (10mm gaussian beam) : unit (mm)



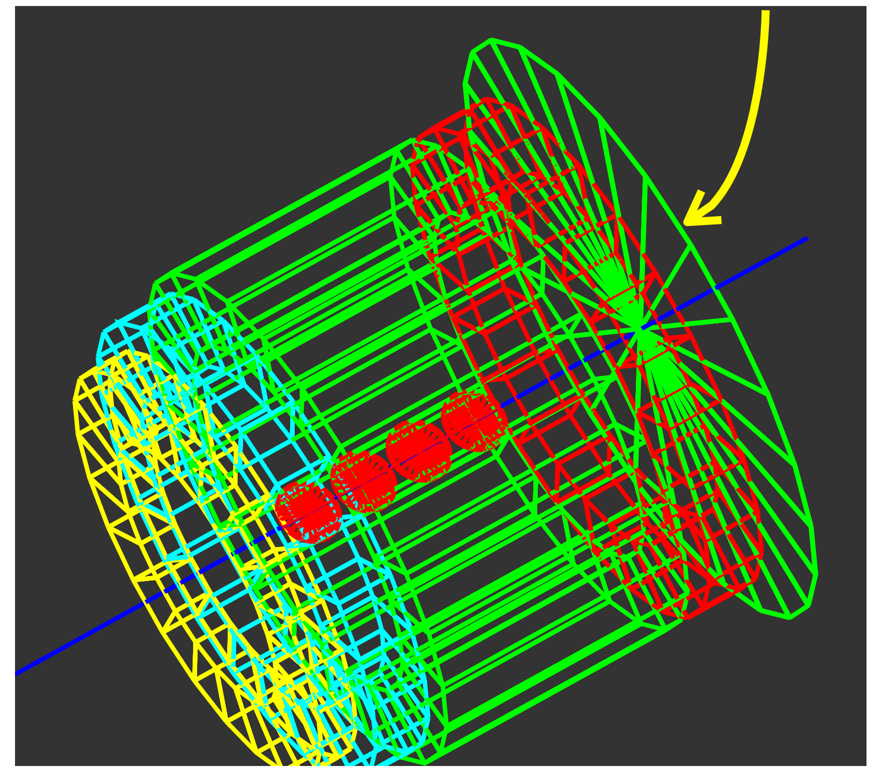
Recent Developments
(up to previous went into TDR)

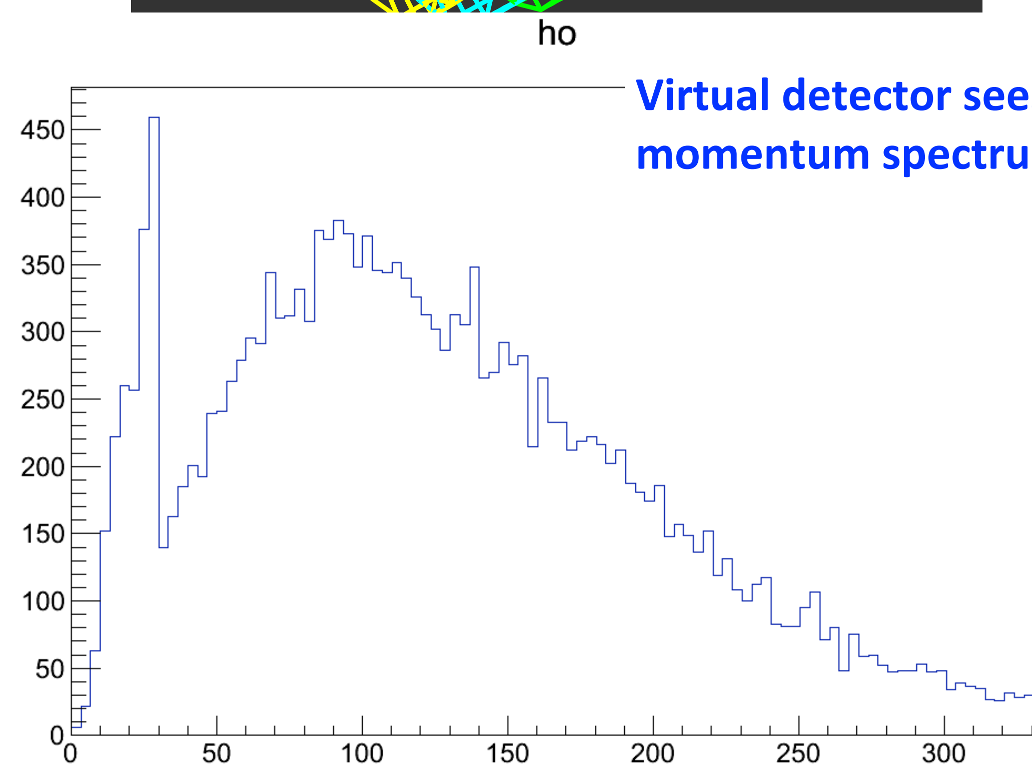
Beyond Default Design



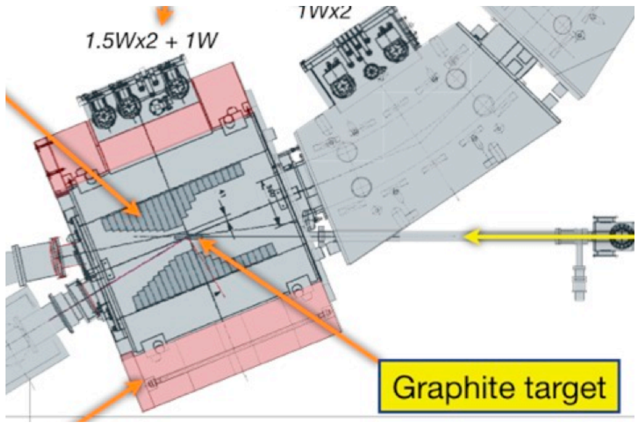
- Increase of surface μ by thinner targets: 1.6 times increase seen

- Targets in solenoid: O(20) increase seen

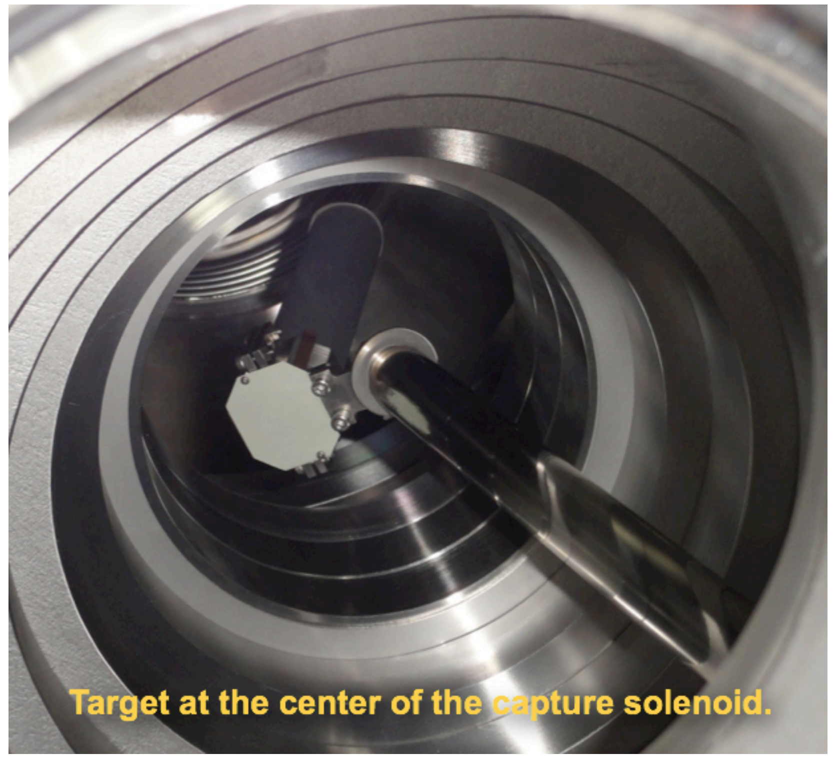


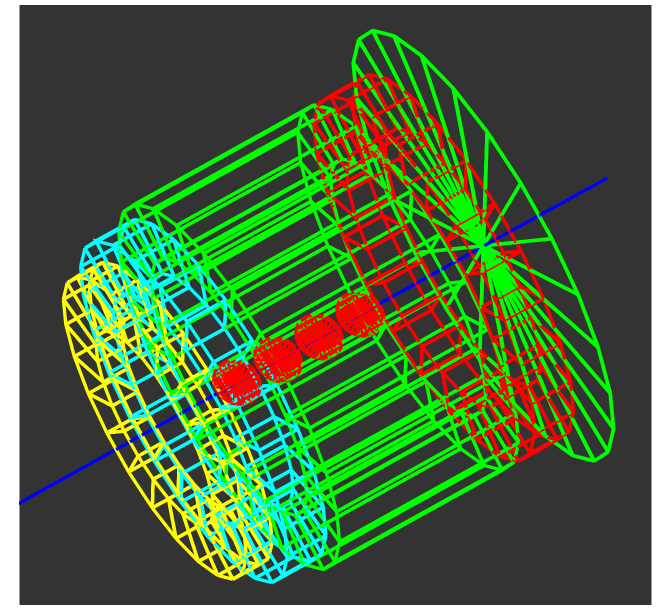


Can it work? Radiation/heat



MUSIC facility @ RCNP/Osaka
(target inside solenoid)





My Option 1
thickness (total 20 mm): 5 mm x 4

Note:	MUSIC		RISP
	1 uA	← 660 →	660 uA
	400 MeV		400 MeV
	200 mm thick	← 1/40 or 1/10 →	5 mm x 4 thick

660/40=16.5 : still O(10) higher, can we have them in the collecting solenoid?

→ **Requires serious radiation/heat study of course**

Muon Facility Working Group

- **μSR**

  Mansoo Choi, Sanghoon Lee, Jaeho Jeong (KU), W. Higemoto (TBC, JAEA/J-PARC)

- **Fundamental science**

  E. Won, ByeongRok Ko (KU), Bongho Kim, Seonho Choi (SNU), T. Mibe, N. Saito (KEK)

μSR

● Our initial studies

Critical Interfaces explored with μSR

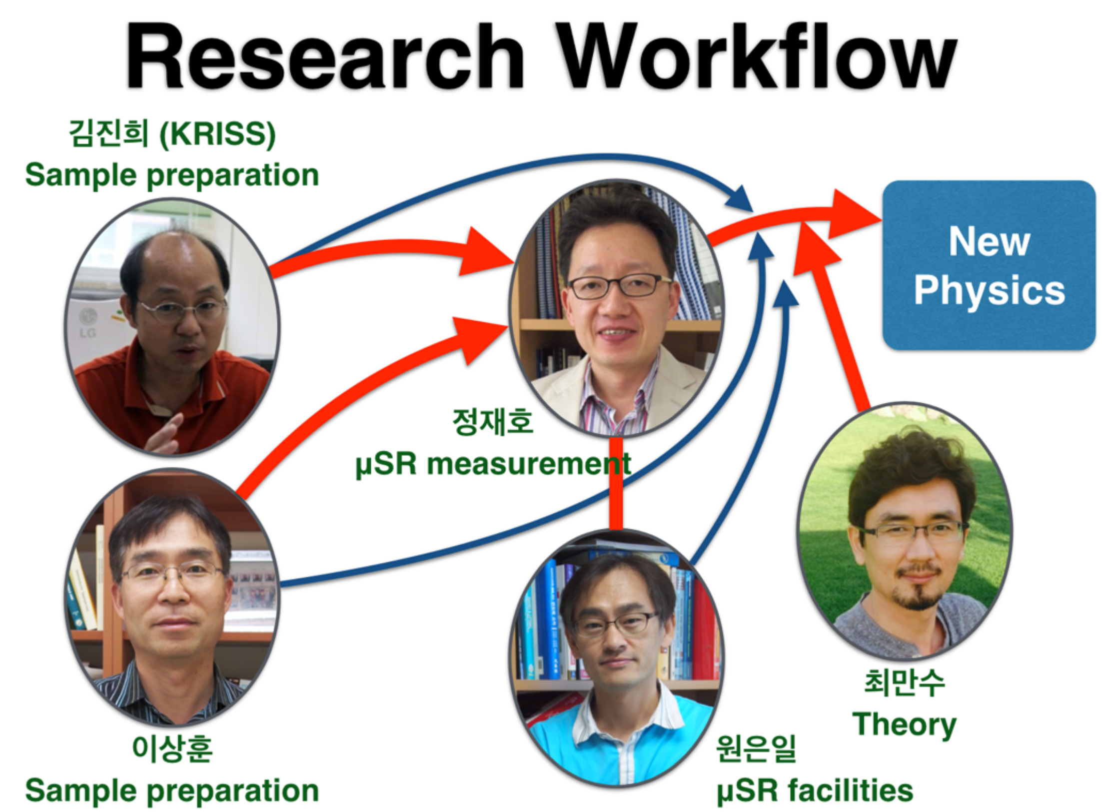
LAO/STO Interface

- Insulator + Insulator : metal
- Ferromagnetism

Topological Matter/Normal Matter

- Topological insulator /Normal superconductor
- Topological superconductor / Magnetic insulator

M. S. Choi (KU local workshop March 2014)



μSR workshop: KU+J-PARC (Apr. 18, 2014)

Mini-Workshop on MuSR Science

Friday 18 April 2014 from 09:50 to 20:20 (Asia/Seoul)
at Korea University Asan Science Building (Rm 428 (Jeongho seminar room))

Manage

Description This mini workshop is to initiate collaboration with J-PARC/JAEA and to launch a muSR program in Korea University.

Friday 18 April 2014

09:50 - 10:00	Charge of the workshop *10'* Speaker: Eunil Won Material: Slides
10:00 - 11:00	MuSR Science *1h00'* Speaker: Wataru Higemoto (J-PARC/JAEA) Material: Slides
11:00 - 11:45	Discussion on muSR science *45'*
11:45 - 11:50	Photo Session *05'* Material: pictures
11:50 - 13:30	Lunch (보문동 손만두 (Bomoondong Hand dumpling))
13:30 - 14:30	MuSR Facility at J-PARC *1h00'* Speaker: Wataru Higemoto (J-PARC/JAEA) Material: Slides
14:30 - 15:30	Discussion on muSR facility *1h00'*
15:30 - 16:00	Coffee break
16:00 - 18:00	Discussion for future plan *2h00'*
18:00 - 20:00	Dinner (타센1812, 대학로) *http://blog.naver.com/classic_1812*

To RISP: μSR

- **Ultra-slow polarized muon facility**

  It has much bigger science impact to the society than with just surface muon facility

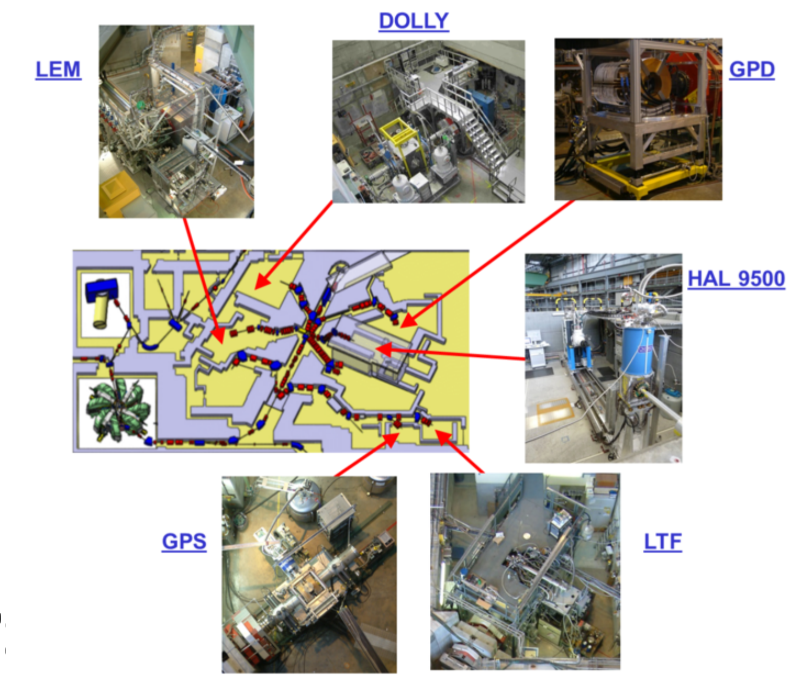
- **Design to host multiple beam lines/spectrometers (in future)**

  PSI has 6 different spectrometers for user

  Note that world-wide muon beam lines are overbooked

  : no beam at PSI in 2014 at all

  : call for beam at J-PARC for late 2014 on July 2014



Fundamental Science

- **Science case we have been developing for example**

  - Muon EDM
  - Muonium oscillation (not today)
  - We are not limited to above of course

Fundamental Science

- **Muon EDM with RISP**

  - Low emittance beam by re-acceleration of epi-thermal muons

  p = 300 MeV/c (a semi-random number from J-PARC g-2)

  - Ideal beam structure: pulsed at 1-10 kHz

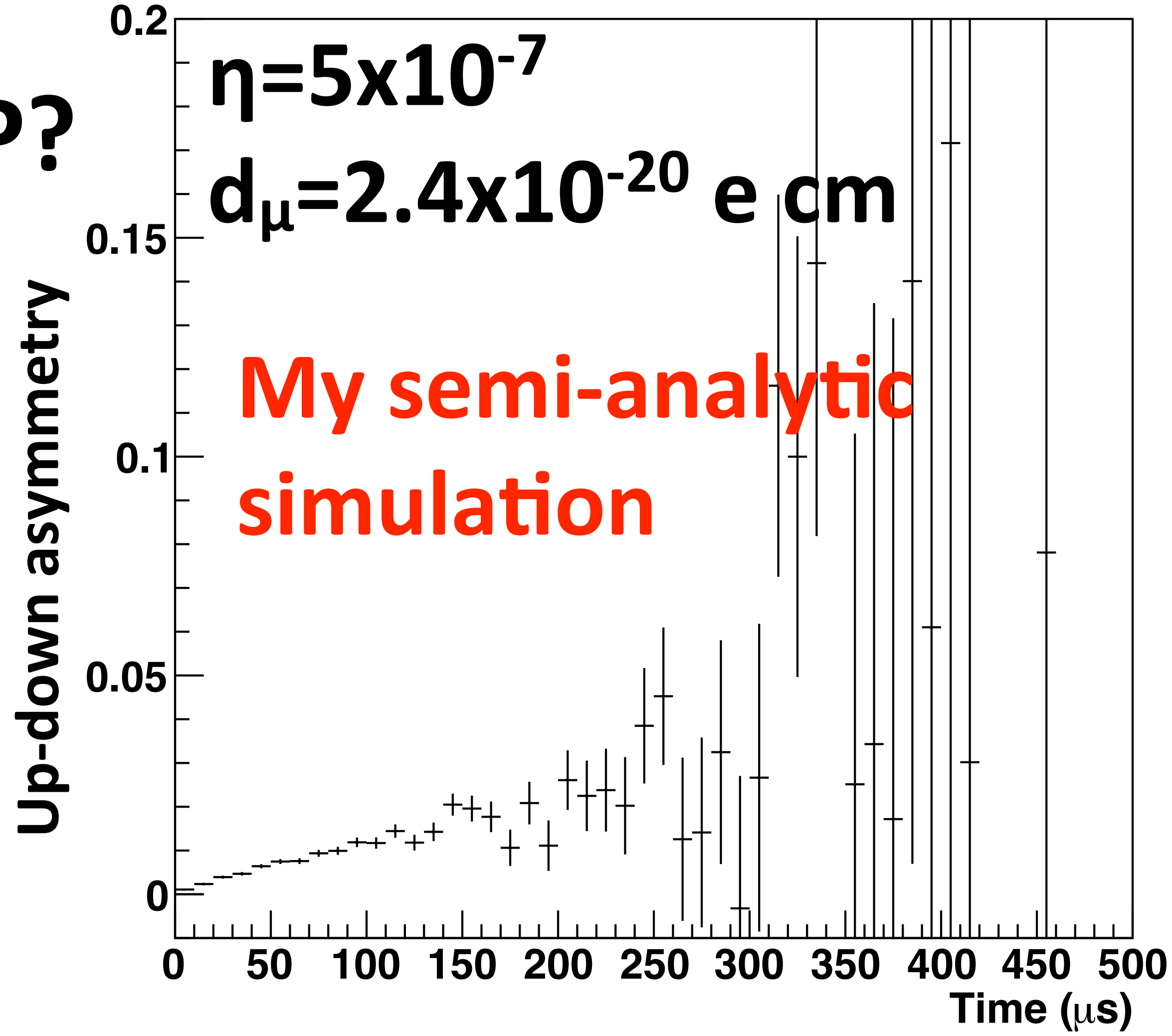
  Muon lifetime (boosted) + DAQ dead-time

  J-PARC beam is pulsed at 25 Hz and is inefficient for μEDM

Spin frozen μ-EDM

Spin frozen technique at RISP?

p = 300 MeV/c
B = 0.8 T
E = 2.5 MV/m
R = 1.3 m



RIPS: $\sigma_{d_\mu} = 8.5 \times 10^{-17}/\sqrt{N}$ e cm

PSI: $\sigma_{d_\mu} = 1.5 \times 10^{-16}/\sqrt{N}$ e cm

J-PARC: $\sigma_{d_\mu} = 2.0 \times 10^{-16}/\sqrt{N}$ e cm

10 kHz x 10^6 muons/s x 1 year:
$\sigma_{d\mu}$ ~ 10^{-25} e cm

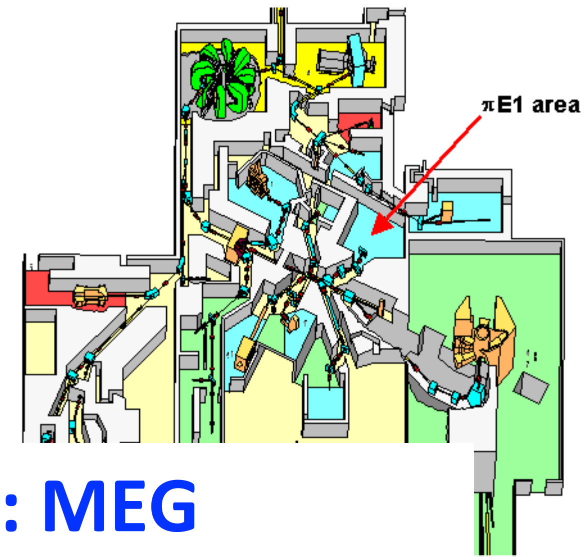
Don't get too much excited, I'm just playing with numbers

Summary

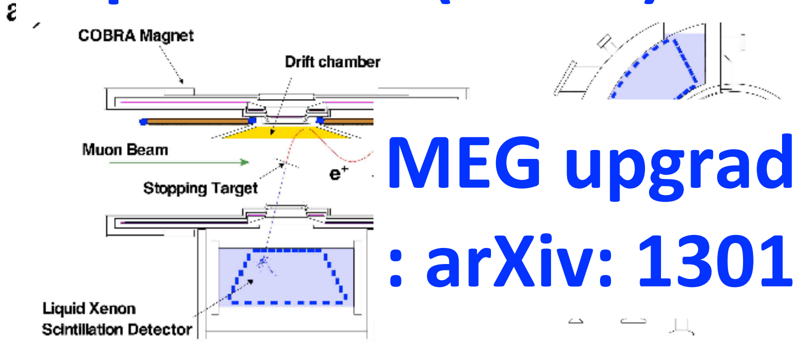
- RISP is under construction
- We are considering a muon facility for both condensed matter and fundamental science applications
- A careful design to host both μSR and fundamental science programs will be great

Particle Physics @ μ Facilities

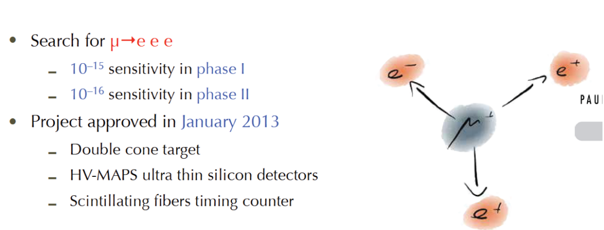
PSI (Swiss)

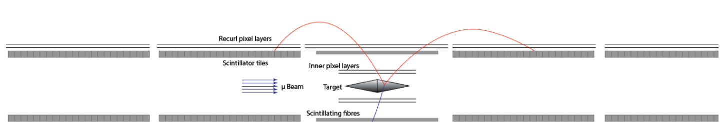


μ to eγ : MEG experiment (2009-)



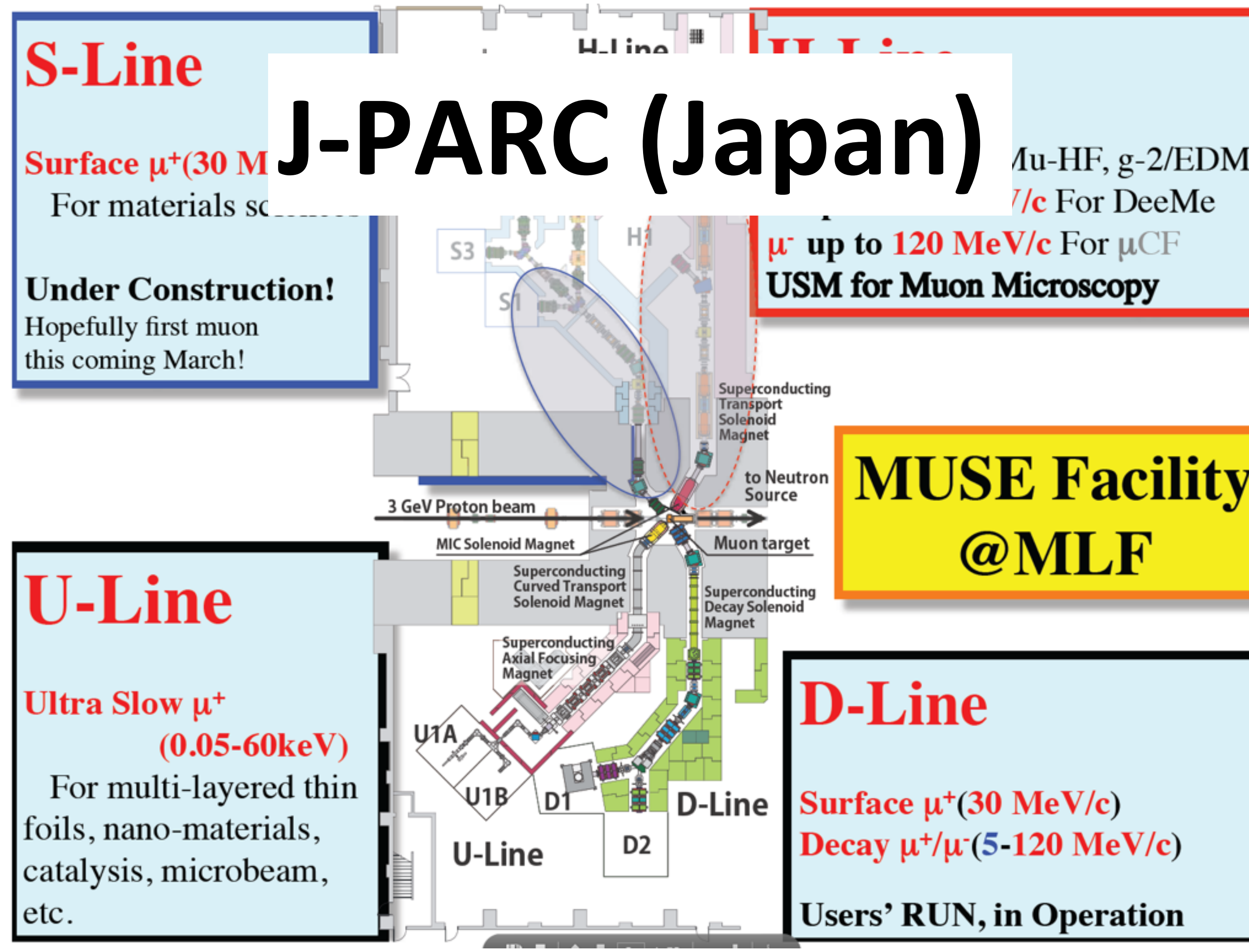
MEG upgrade (2016-2018)
: arXiv: 1301.7225





μ to eee proposal:
: arXiv: 1301.6113

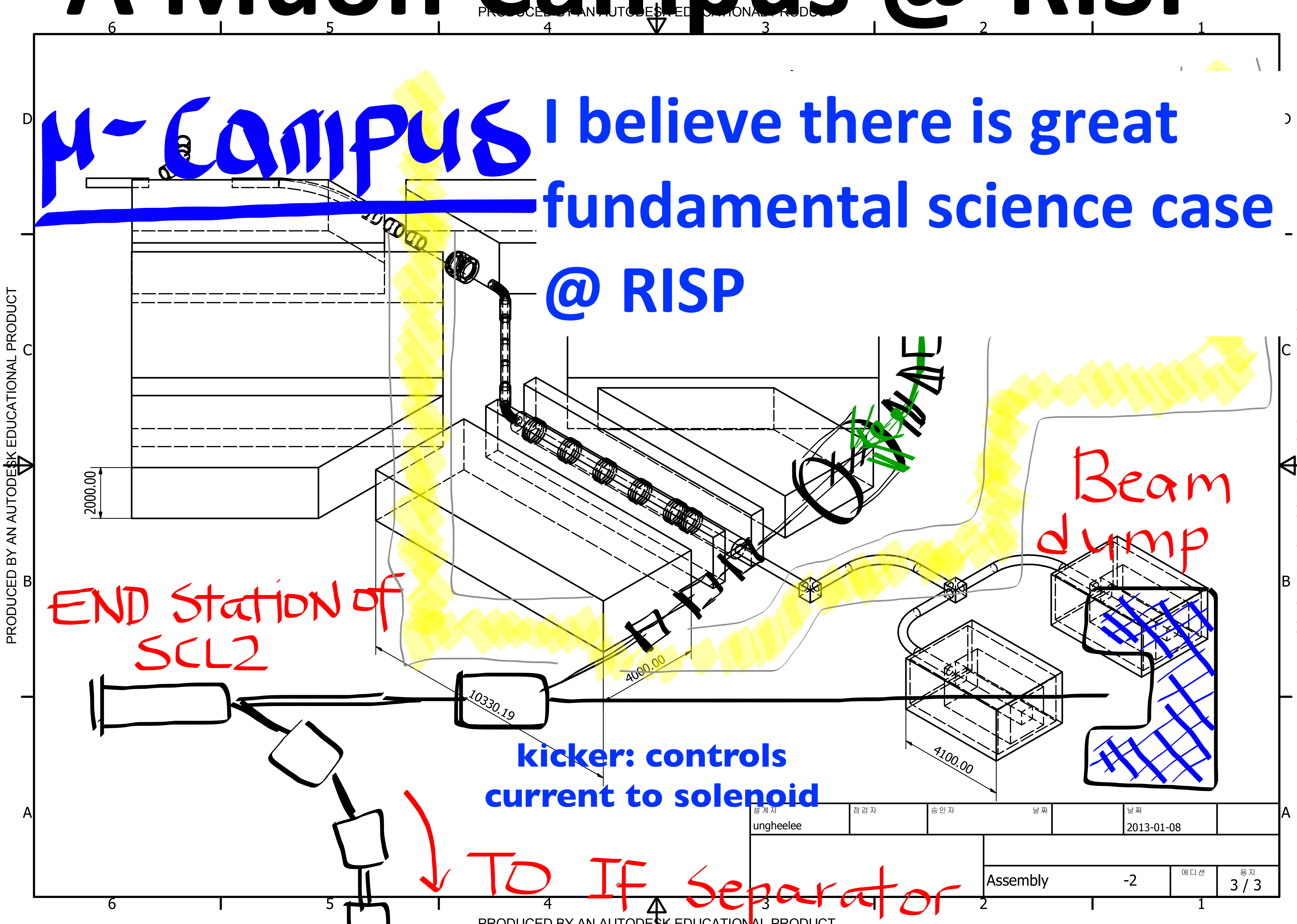
J-PARC (Japan)



J-PARC fundamental science program
- DeeMe (μ to e conversion)
- COMET (μ to e conversion)
- g-2/EDM
- (μe) hyperfine

A Muon Campus @ RISP

I believe there is great fundamental science case @ RISP

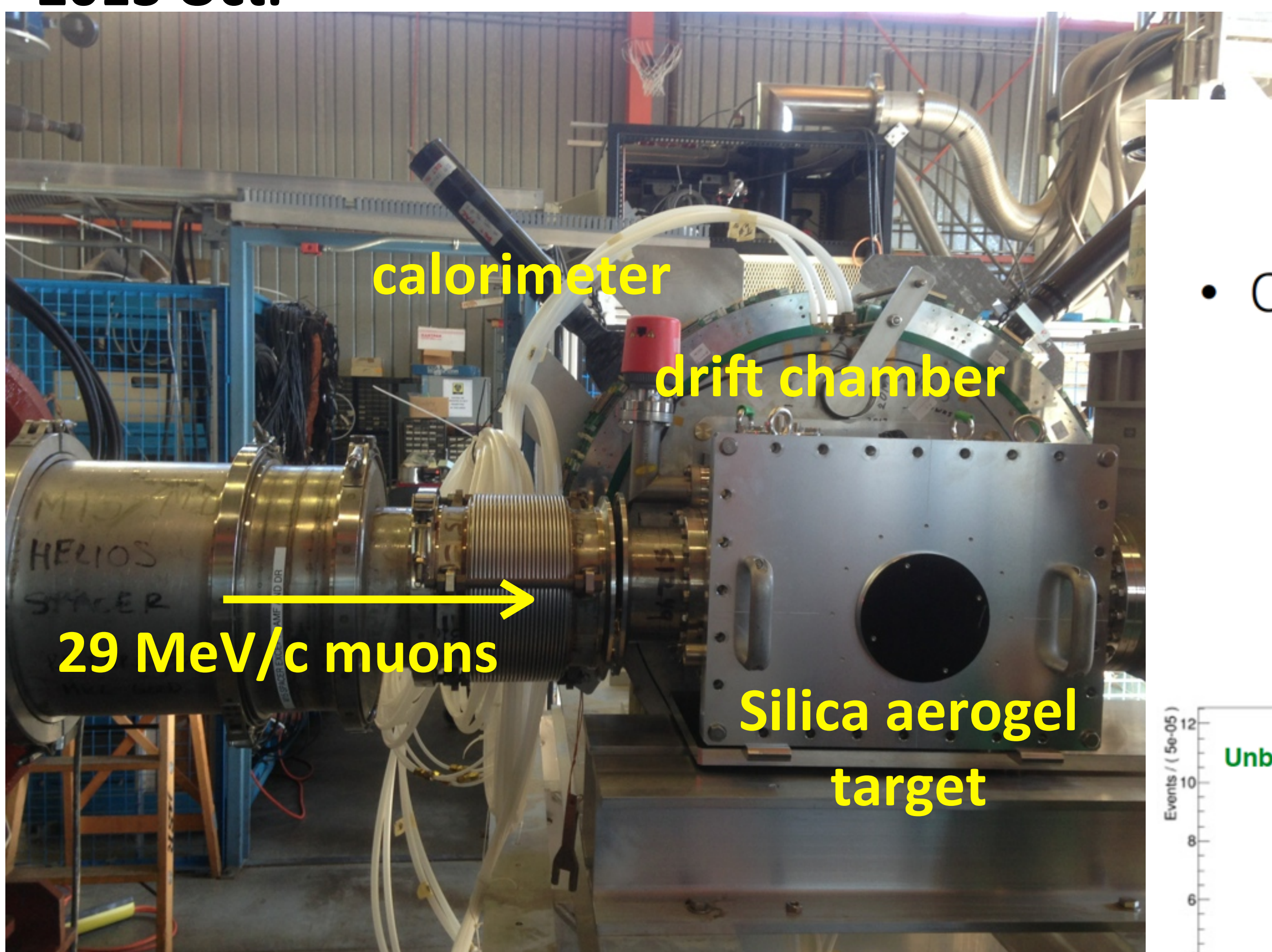


Extra Slides

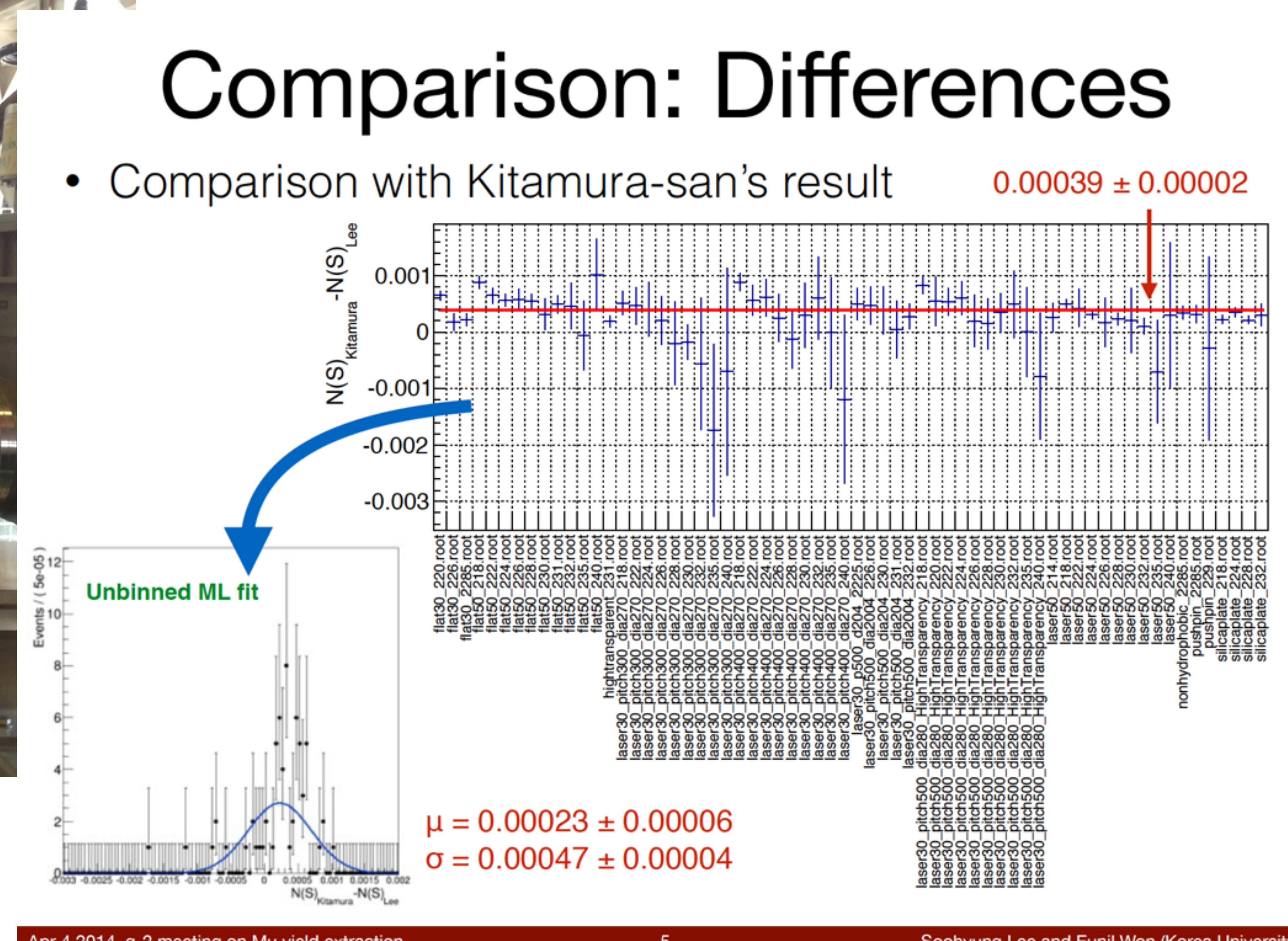
Ultra-slow Muon Generation

Beam test at TRIUMF: Muonium yield estimation

KEK+RIKEN+TRIUMF + E. Won, W. Lee (KU): 2013 Oct.



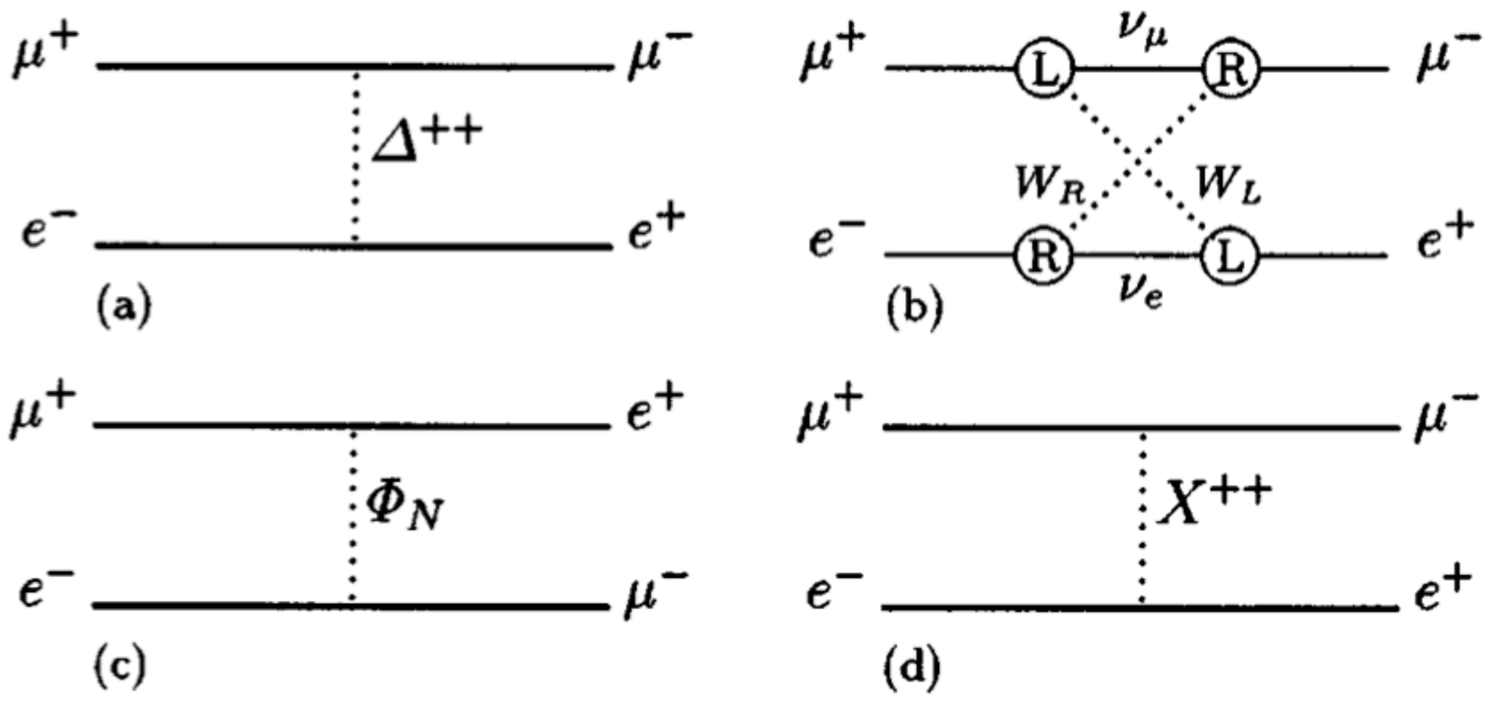
Analysis being done by KEK + S. H. Lee (KU)



Muonium Oscillation Exp.

- Some of us have been looking at a **muonium oscillation** experiment (**but not limited to it**)

Phys. Rev. Lett. 82, 49 (1999)



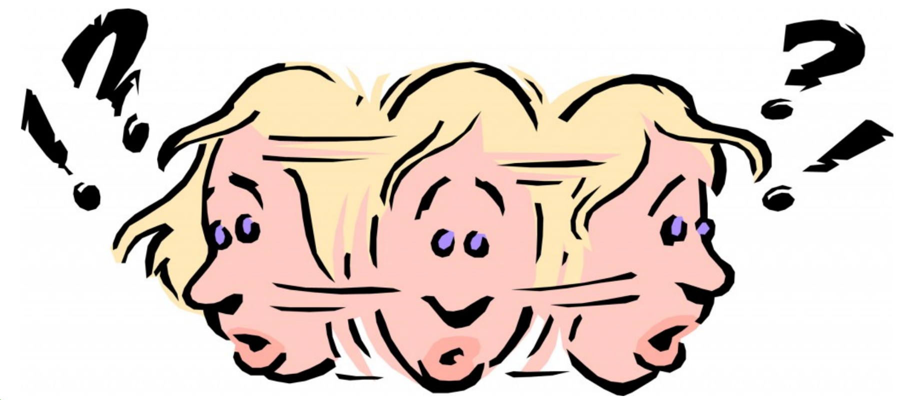
- Various new fundamental interaction can cause Mu to anti-Mu transition

- Not updated since 1999

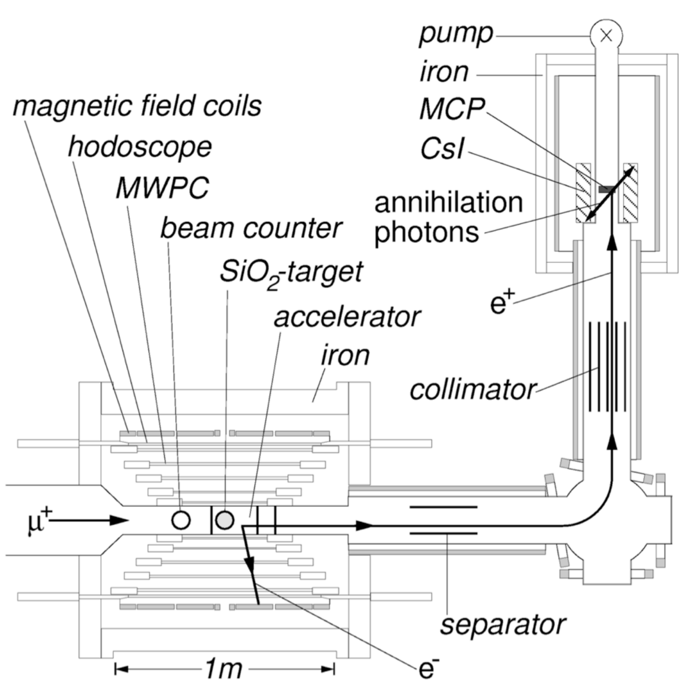
- A new technique to reject accidental and irreducible backgrounds more effectively needed

Muonium Oscillation Exp.

arXiv:1307.5787 "*Charged Lepton Flavor Violation: An Experimenter's Guide*"
- by R. Bernstein and P. Cooper (Fermilab)
- excellent review of cLFV experiments



Latest limit: Phys. Rev. Lett. 82, 49 (1999)
- typical counter type
- suffer from rate-dependent background
- $< 3\times10^{-3}$ G_F was achieved



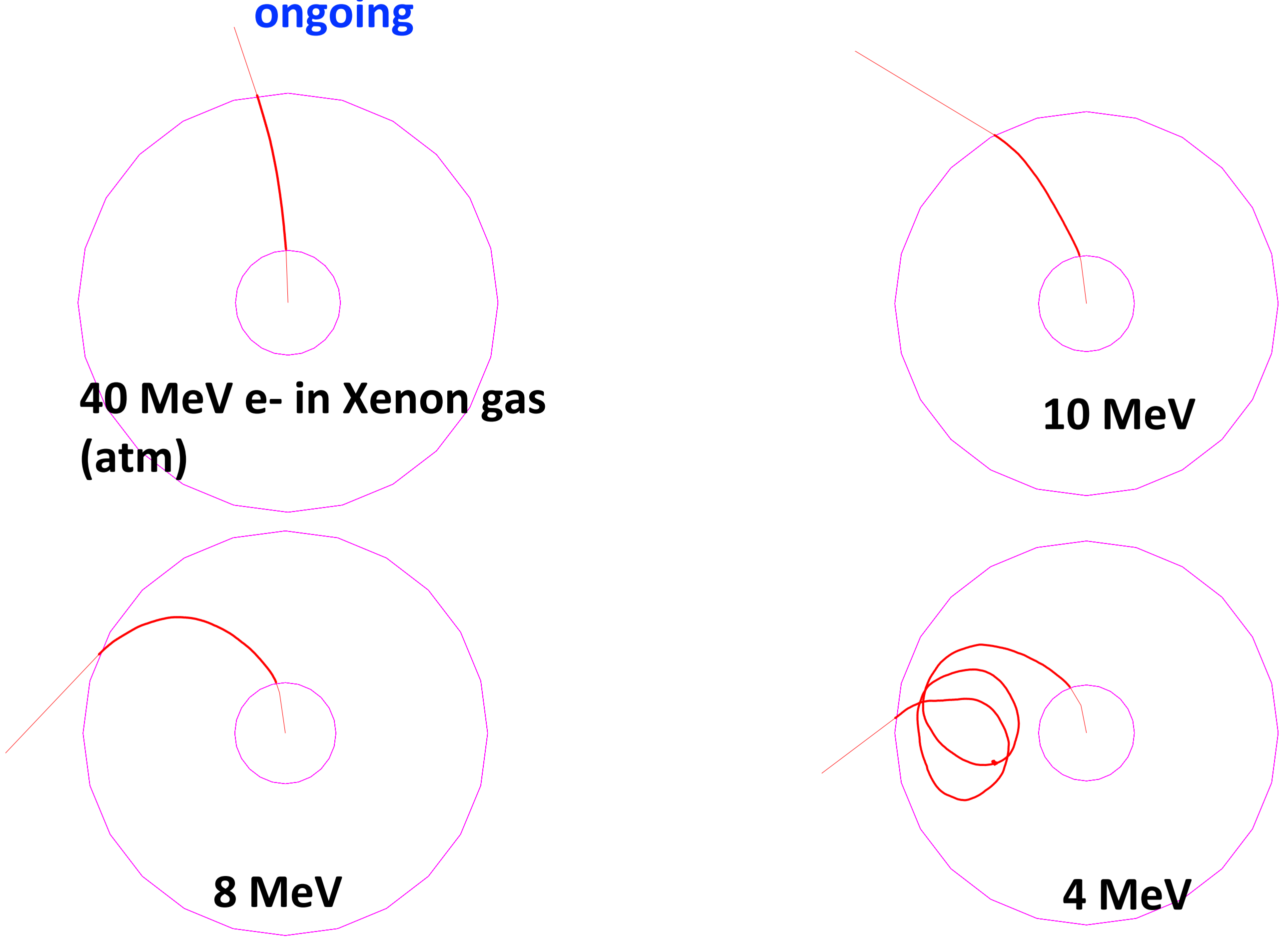
M. Aoki, NIM A 503, 258 (2003)
- a radiochemical approach
- antimuonium absorbed in tungsten nucleus (μ^- W $\rightarrow \nu_\mu$ ^{184}Ta)
- $< 10^{-4}$ G_F can be possible

arXiv:1307.5787
- improve counter type experiment
- use modern technology
- could reduce limit by 10^{-2} (but with pulsed beam)

Muonium Oscillation Exp.

One slide R&D status

Geant4 study for tracker is ongoing



- ✓ Muonium production R&D is starting with J-PARC people
- ✓ Improvement from MWPC
- ✓ Improvement from CsI and faster timing
- ✓ Active target ?

Continuous vs. Pulsed

Continuous

- At RISP the accelerator structure (80 MHz microstructure) and the pion lifetime (26 ns) leads to a practically continuous surface muon beam

http://people.web.psi.ch/morenzoni/FS-2012/Chapter5-MuonSpinRotation-1.pdf

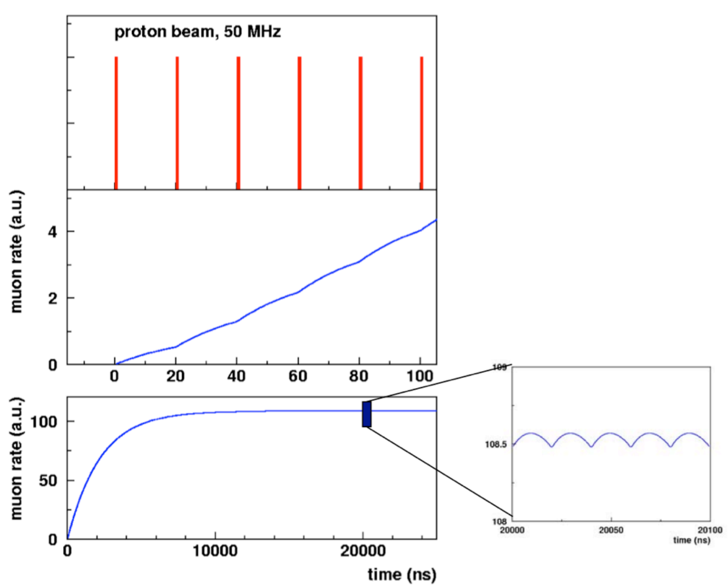


Fig. 5-3: Build up of the muon rate at PSI.

- one muon at a time
(otherwise it is background)

Pulsed

- At a pulsed machine all the muons are contained in a pulse (50-100 ns wide) with low repetition rate (25-50 Hz)

- This allows a higher rate (all the decay positrons of a pulse are measured at once)

- But only one positron in a detector or in the case of more than one, you have to get the time stamp on them

This requires a high segmentation of the positron spectrometer (HEP knows how to do it)

Generation of Slow Muons

1) By moderation in thin layers of cryosolids

- More suitable for "continuous" accelerator such as RISP and PSI

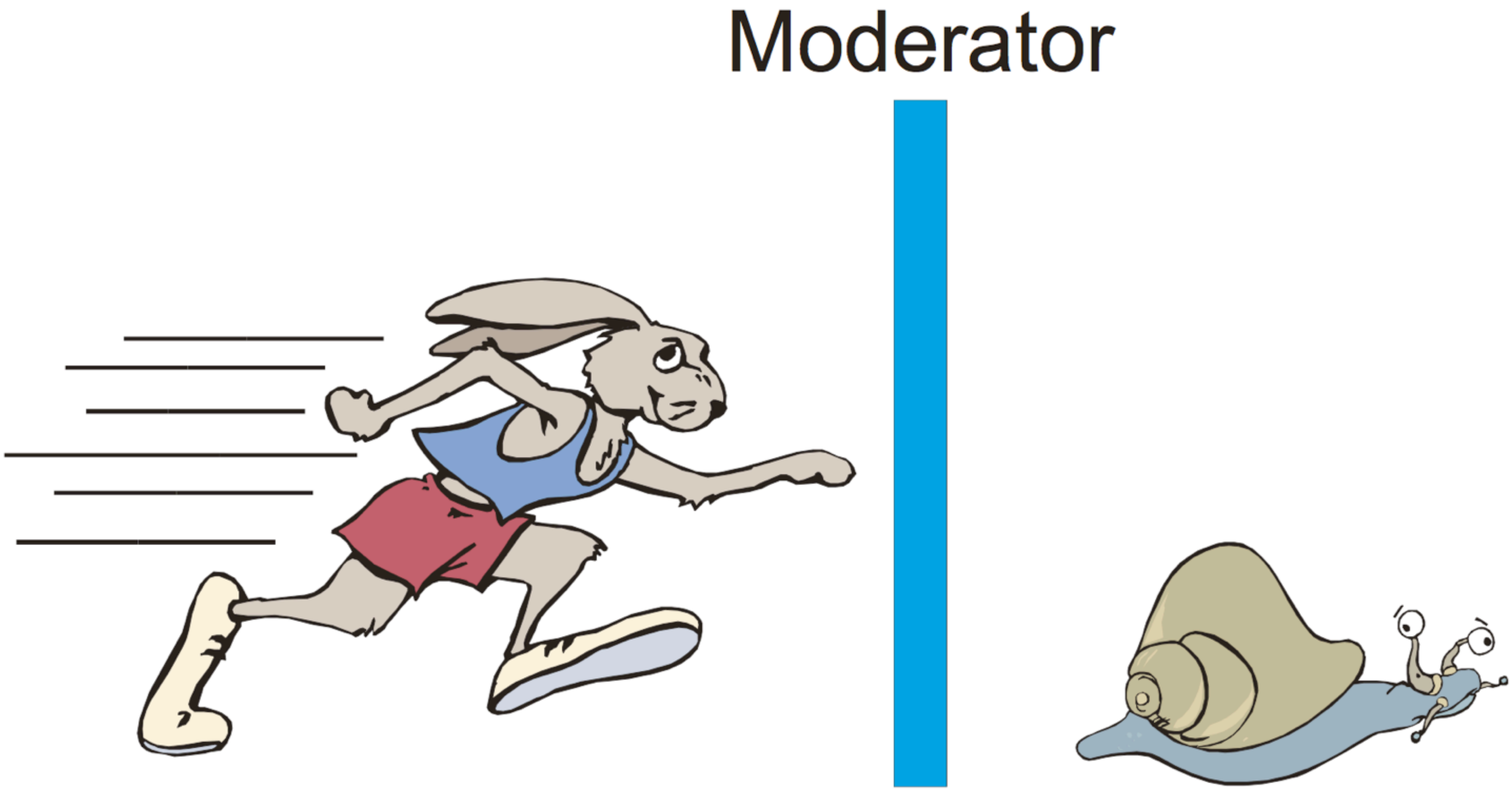
Muonium is a bound state of μ^+e^- and called Mu

2) By laser resonant ionization of muonium

- More suitable for "pulsed" accelerator such as J-PARC and Project X

Generation of Slow Muons

1) By moderation in thin layers of cryosolids

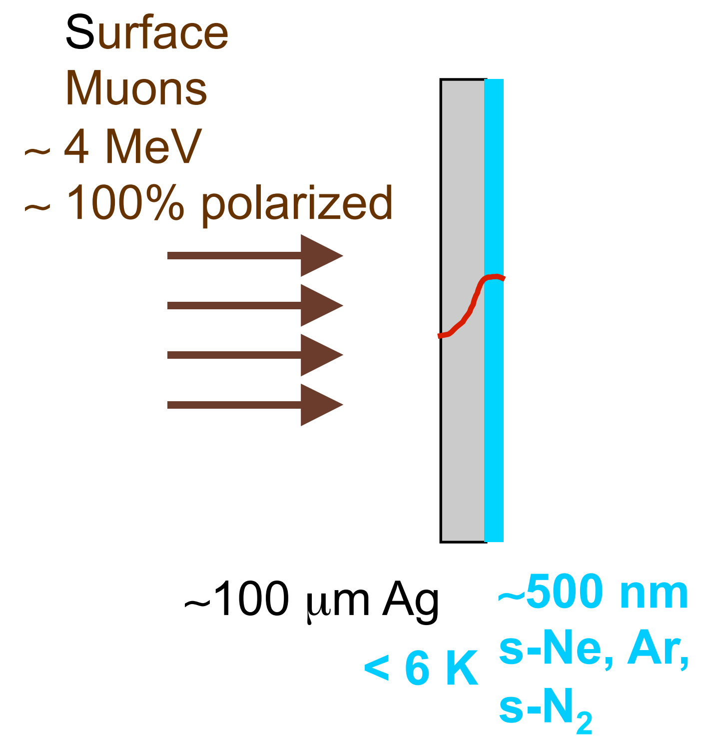


Generation of Slow Muons

1) By moderation in thin layers of cryosolids

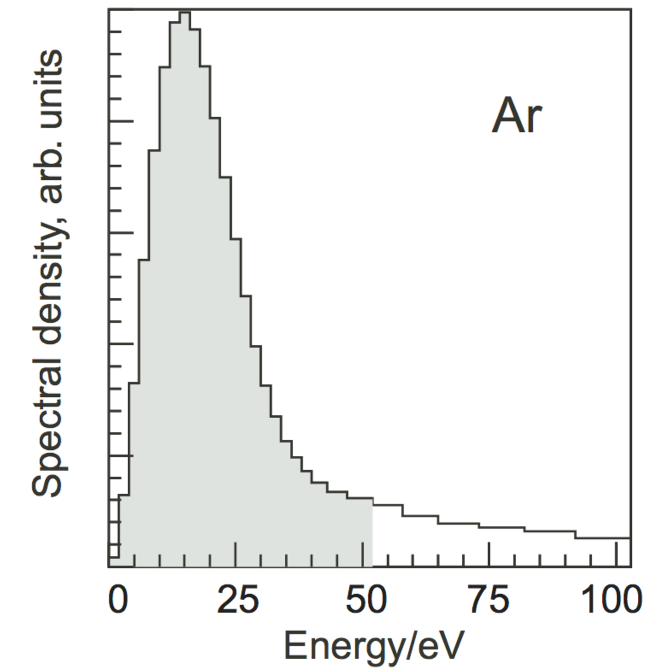
This is a 2-step process

i) Put a foil (O(100) µm thick) in the muon's flight path: this will slow down the muon but the energy spectrum of muons exiting the foil is very broad



P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)

Coulomb collisions with target atoms (e-h pair, excitation creation)



ii) Then place some well-selected materials (moderator, usually < 1 µm thick) and it will lead to a preferential emission of muons at energies of a few eV

Generation of Slow Muons

2) By laser resonant ionization of muonium

What is muonium? (a μ+μ- bound state? NO) : muonium = μ+e-

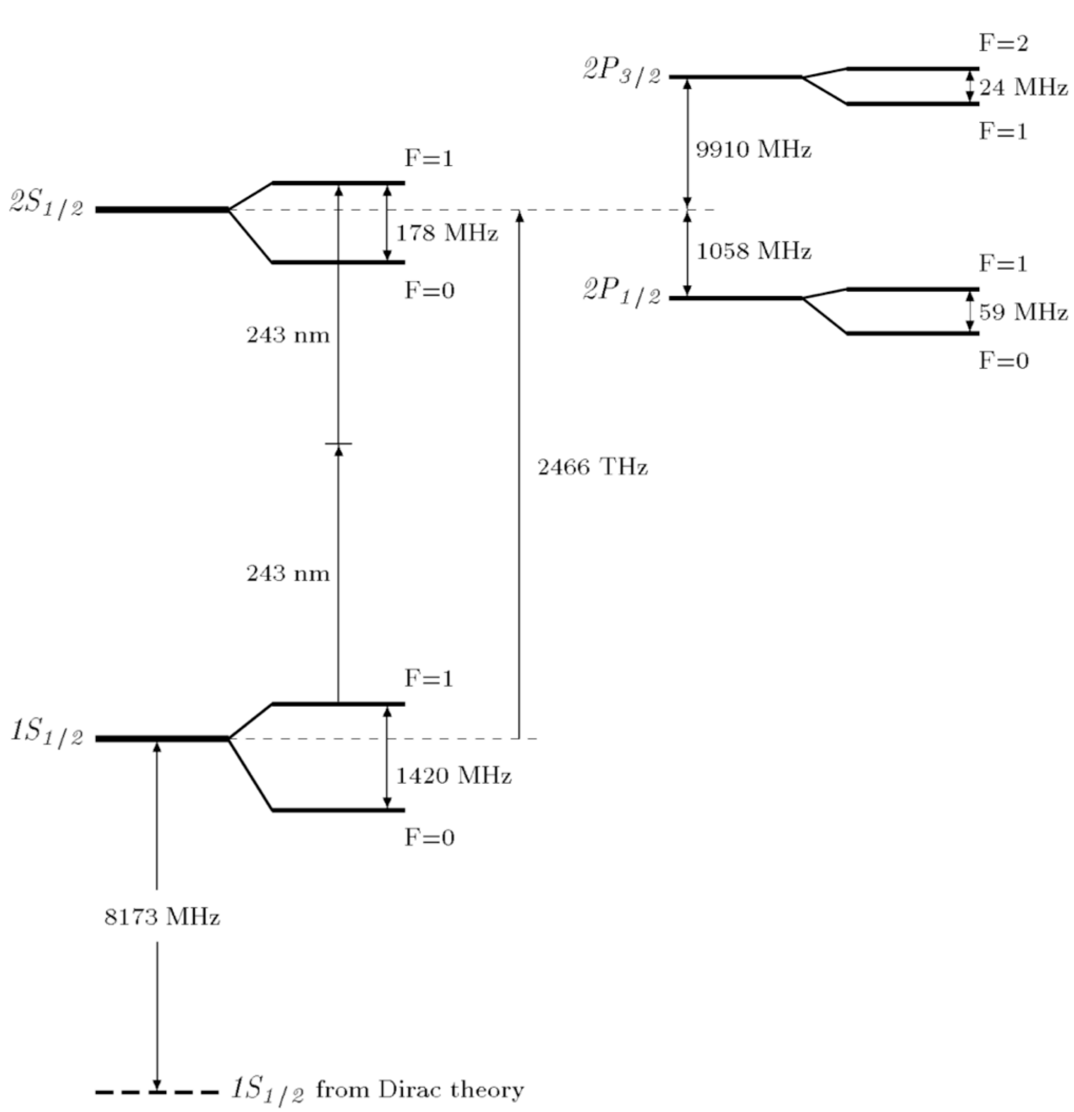


Fig. 1. Hydrogen energy levels.

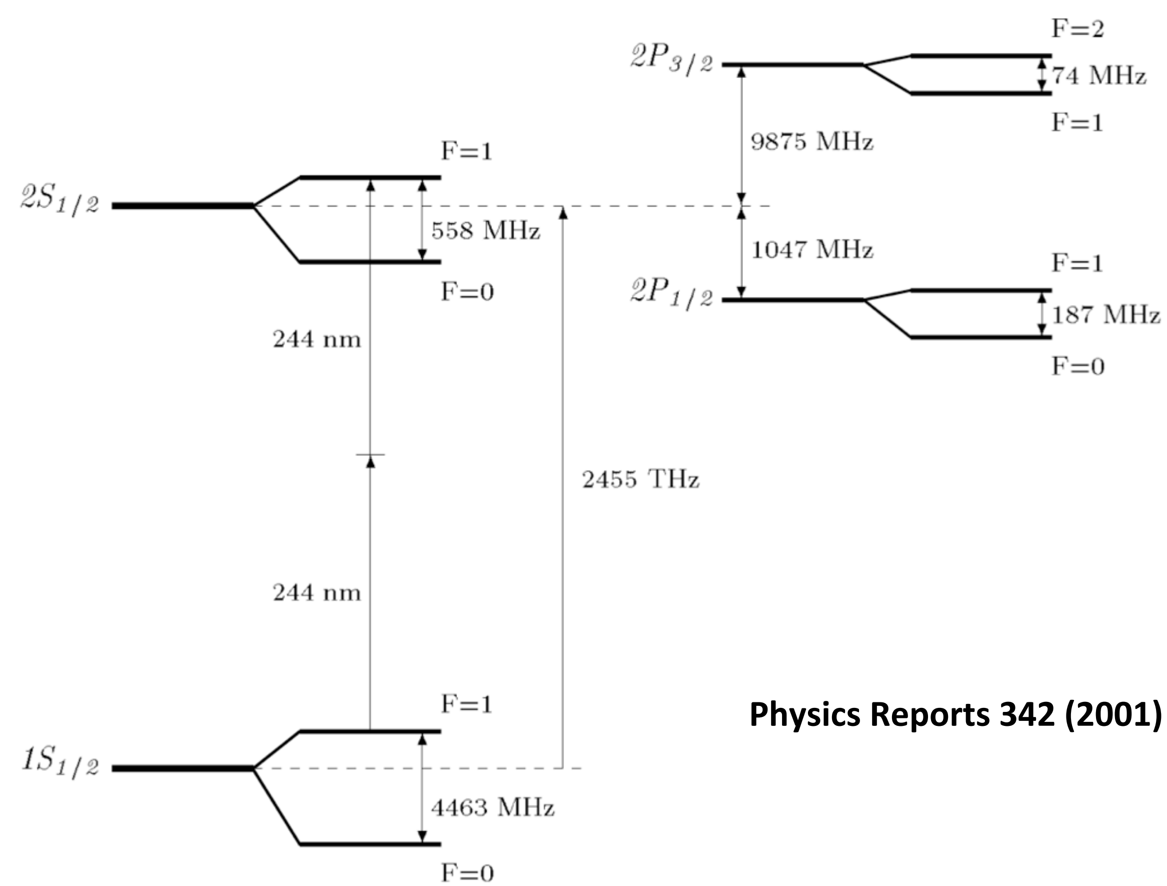


Fig. 2. Muonium energy levels.

Physics Reports 342 (2001) 63-261

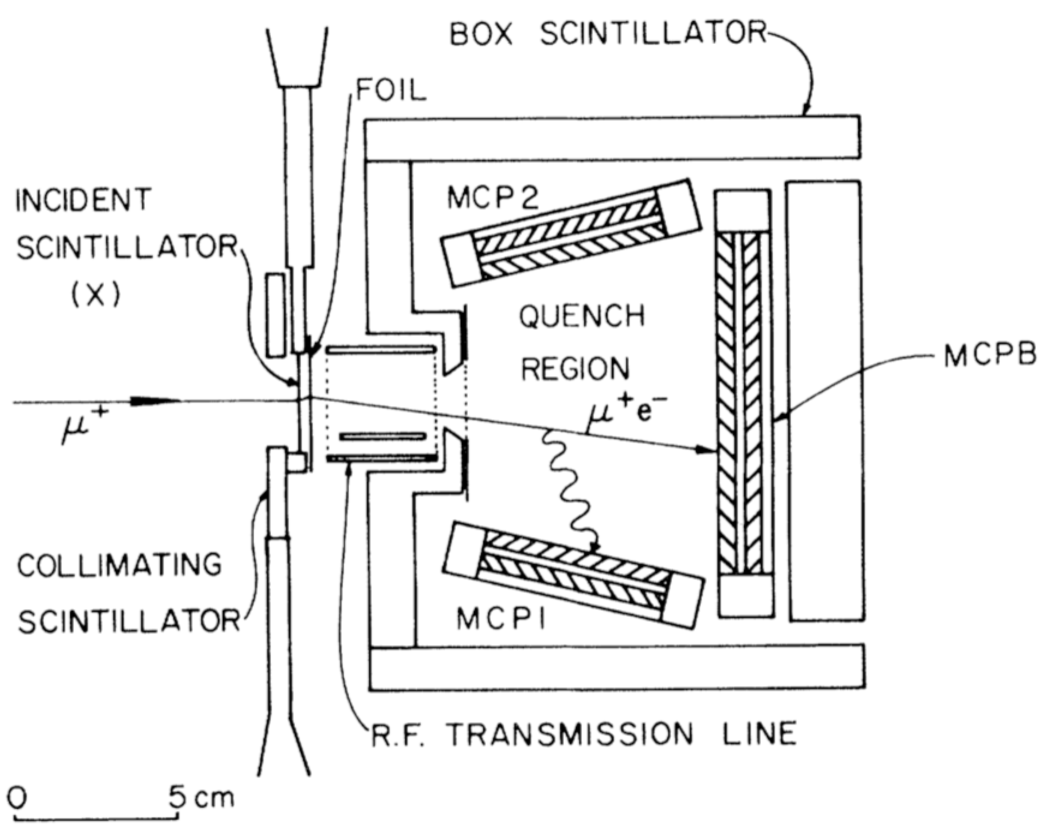
Muonium energy levels are somewhat similar to those of hydrogen

Generation of Slow Muons

2) By laser resonant ionization of muonium

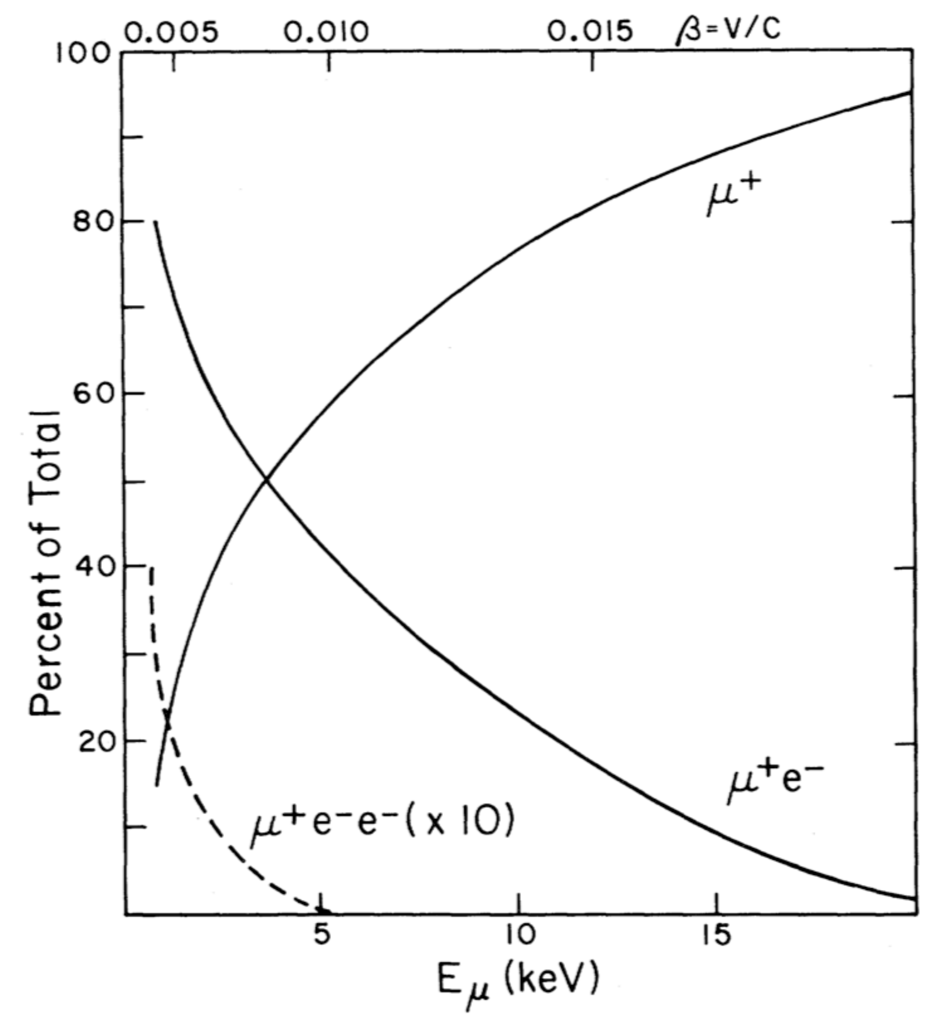
Generation of muonium:

PRL 52, 910 (1984)



Observation of Muonium in Vacuum

PRL 47, 1441 (1981)



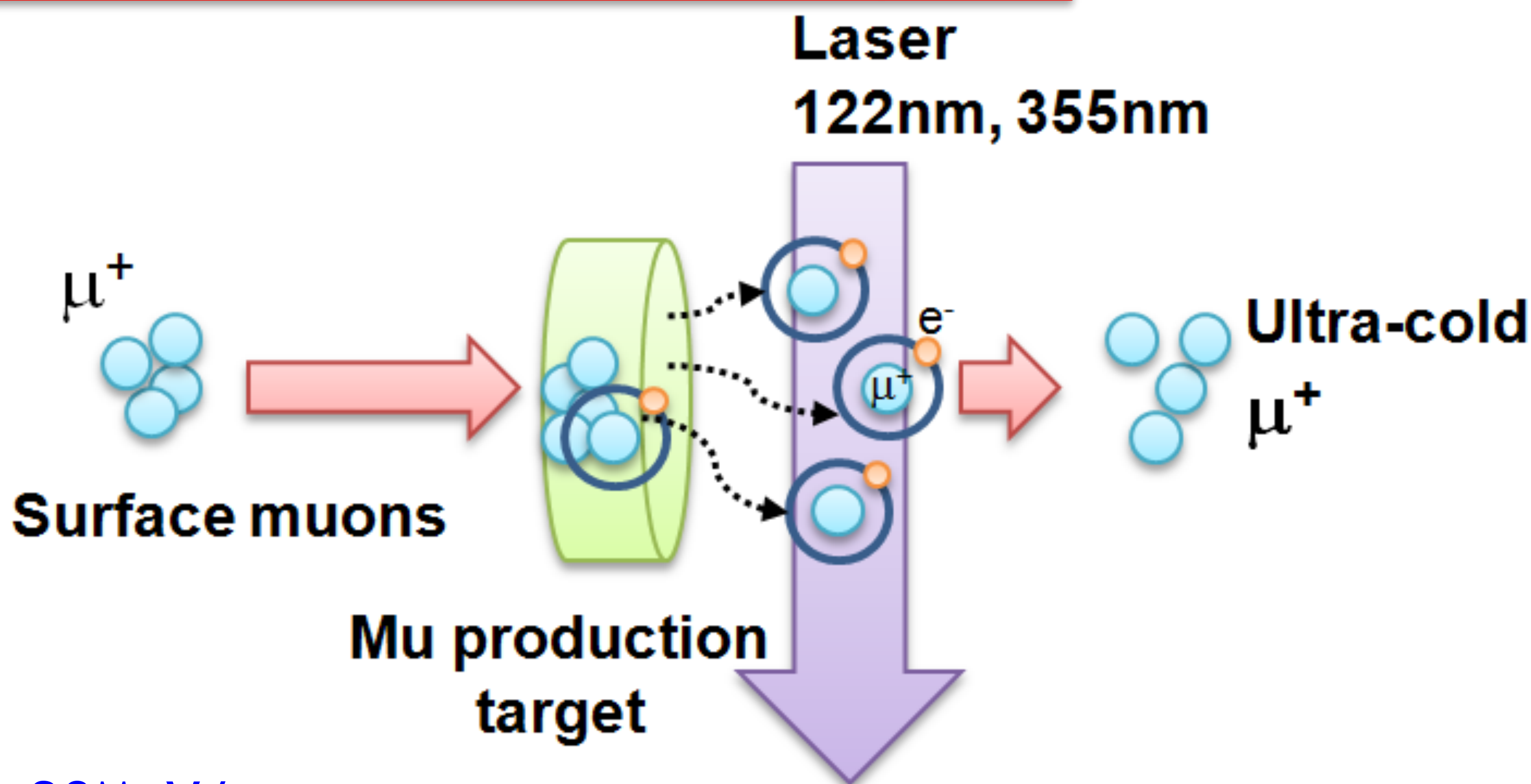
Incident surface muons to a target generate slower muons and muonium atoms

Ultra-slow Muon Generation

2) By laser resonant ionization of muonium

Laser resonant ionization of Muonium (μ^+e^-)

T. Mibe, KPS Fall (2012)

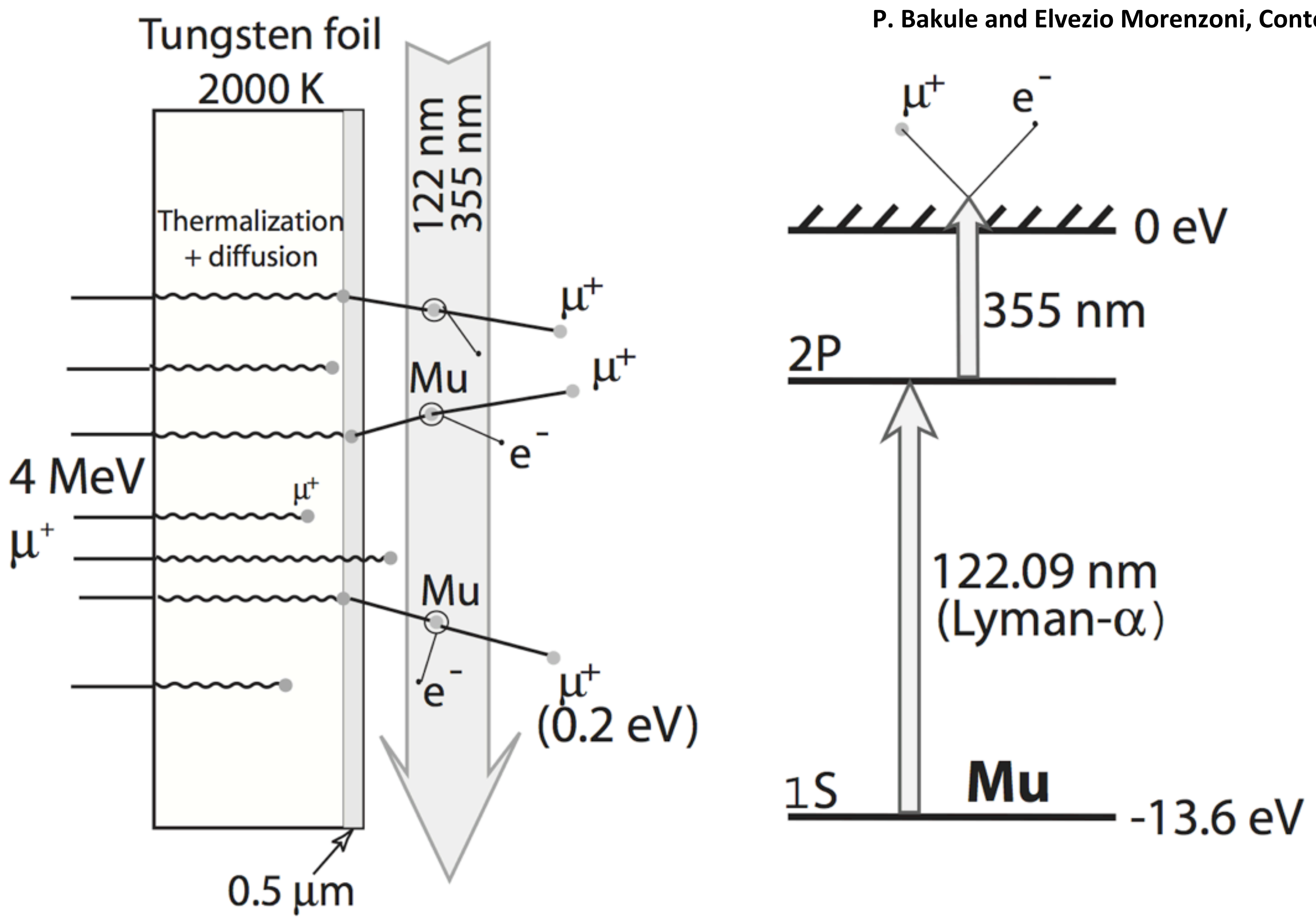


p = 28MeV/c 3 keV/c

Ultra-slow Muon Generation

2) By laser resonant ionization of muonium

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)



Moderator vs. Laser

Kazutaka Nakahara (UMD, JLAB seminar 8/28/2009)

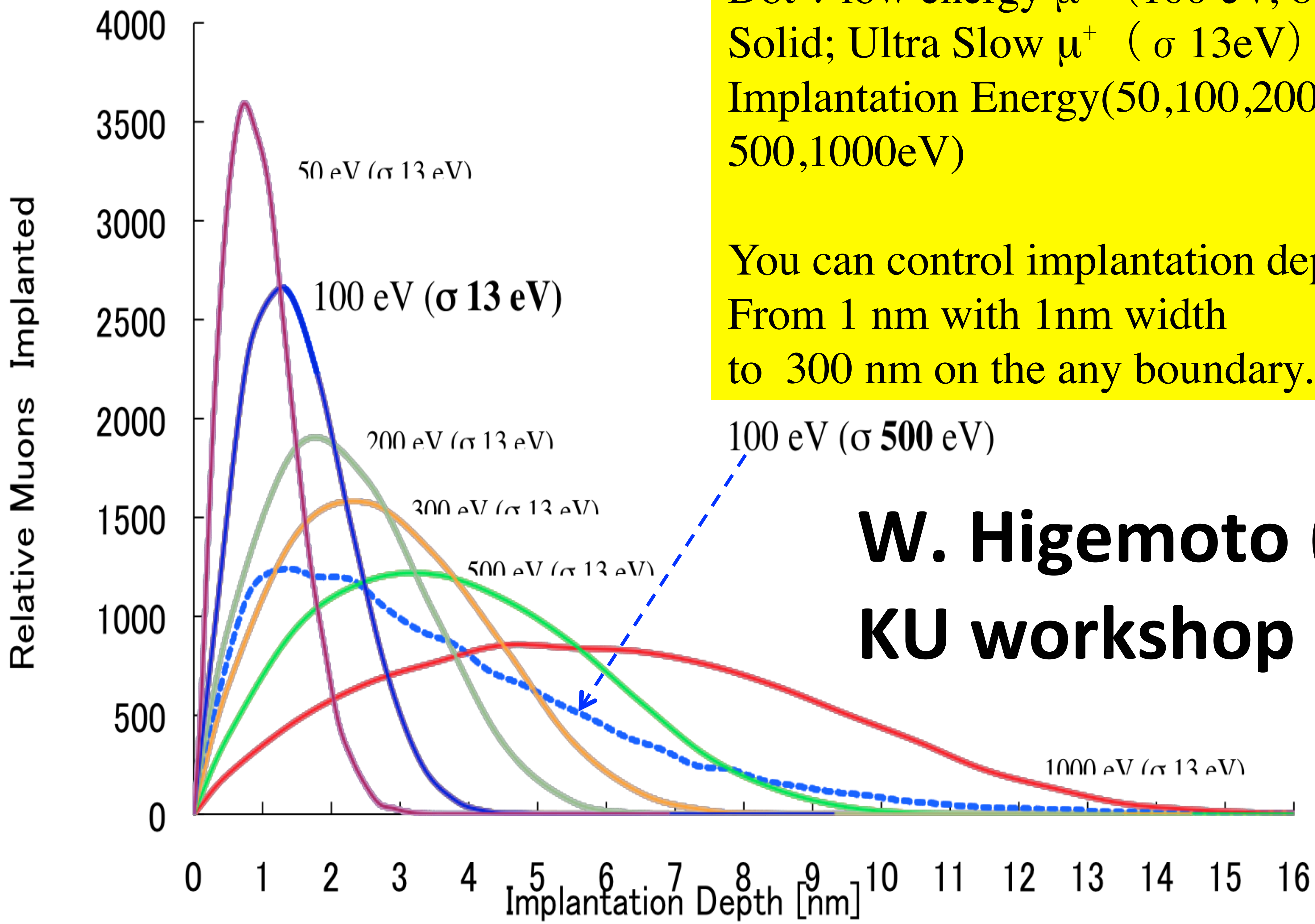
	Laser Resonant Ionization	Moderator
Location	J-PARC, RIKEN/RAL	PSI, TRIUMF
Beam Energy	0-30 keV	0-30 keV
Energy Spread	0.2 eV	10 - 100 eV
Beam Size	0.5-1 mm	10 - 15 mm
Temporal Resolution	100 ps - ~ ns	10 ns

U-Line

Stopping Range of Ultra Slow μ^+ Generated by Laser Resonant Ionization of Mu

Dot : low energy μ^+ (100 eV, σ500 eV)
Solid; Ultra Slow μ^+ (σ 13eV)
Implantation Energy(50,100,200,300, 500,1000eV)

You can control implantation depth
From 1 nm with 1nm width
to 300 nm on the any boundary.



W. Higemoto (J-PARC)
KU workshop