Application of ultra-slow muons to g–2/EDM measurements

TRIUMF
March 8, 2012

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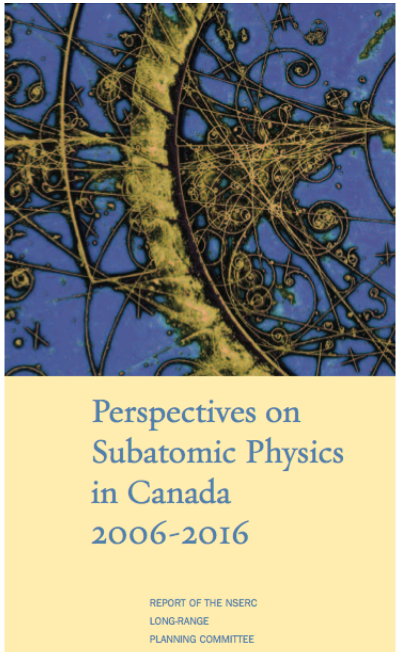
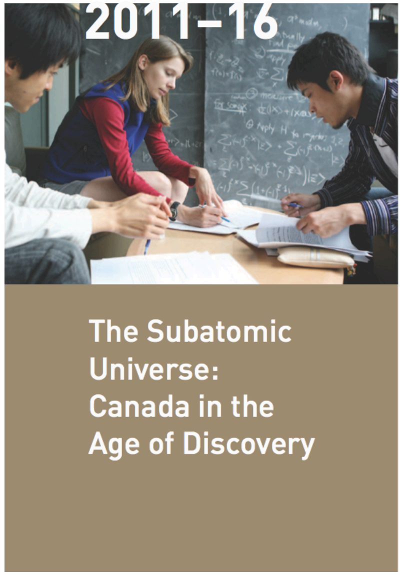
Institute of Particle and Nuclear studies, KEK

for the J-PARC muon g-2/EDM collaboration

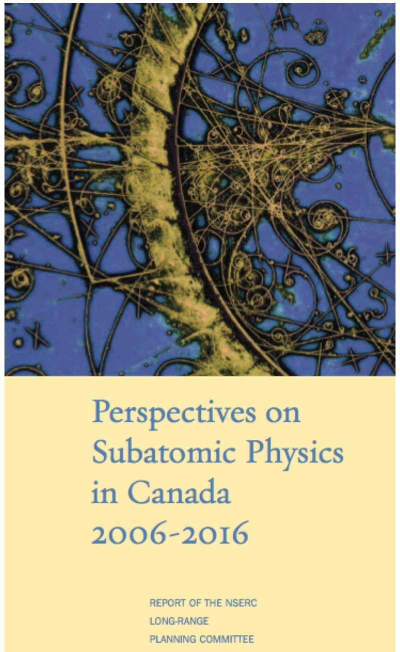
Fundamental questions of subatomic physics in Canada

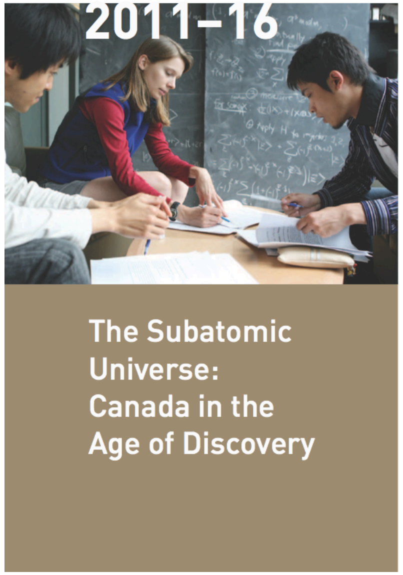




- What is the nature of new particles and physics beyond the Standard Model? Can a unified theory encompassing gravity and particles be developed?
- How do particles acquire mass? Does the Higgs particle exist and generate masses, or is new physics required?
- What is the nature of the dark matter and dark energy that comprise 95% of the Universe?
- What was the origin of the Universe? How is it evolving and what caused the asymmetry that led to a Universe dominated by matter rather than antimatter?
- What are the masses of neutrinos, and how have these particles shaped the evolution of the Universe?
- Can the theory of quark and gluon confinement quantitatively describe the detailed properties of hadrons?
- What mechanisms are responsible for the synthesis of heavy elements?

Fundamental questions of subatomic physics in Canada and the world





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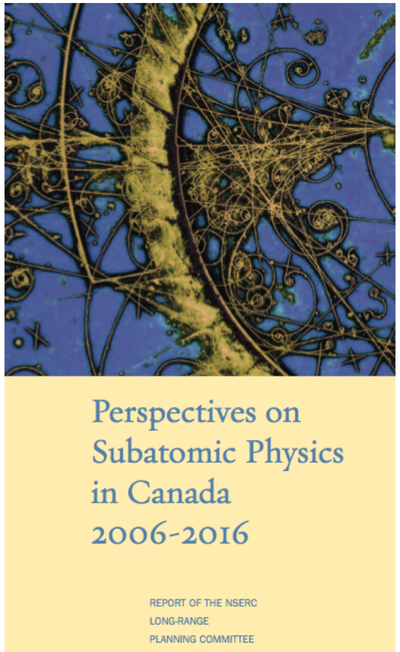

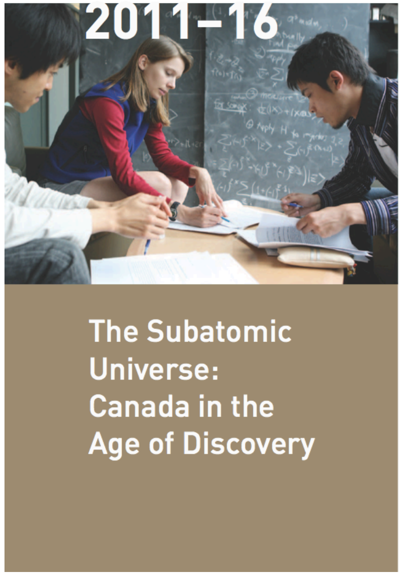

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Muon being long-lived and self-analyzing particle offers an excellent research opportunities to attack fundamental questions

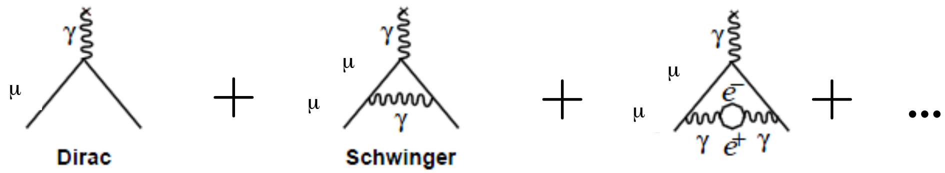
Particle dipole moments

Spin 1/2 particle in electro-magnetic field

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic dipole moment $$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s} \, ,$$

g = 2 from Dirac equation, in general g≠2 due to quantum-loop effects

$g =$ 

Electric dipole moment (EDM) $$\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s}$$

Violates Parity and Time-reversal symmetry

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

Under the CPT theorem
→CP violation

Lepton anomalous magnetic moment "g-2"

- Standard model can predict g-2 with ultra high precision

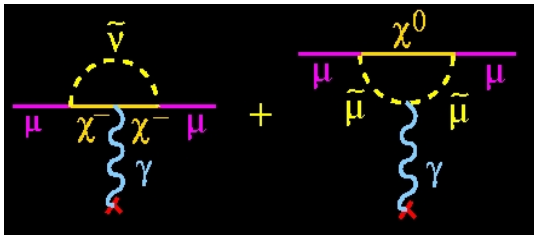
Lepton (l)	a_l	$\Delta a_l(\text{exp})/a_l$	$\Delta a_l(\text{SM})/a_l$
electron	$115\ 965\ 218\ 073(28) \times 10^{-14}$	0.24ppb	4.5 ppb
muon	$116\ 592\ 080(63) \times 10^{-11}$	0.54ppm	0.41ppm
tau	$< 2 \times 10^{-2}$		

- Sensitivity of new physics (mass scale Λ) goes with $a_l(\text{New physics}) \sim (M_l/\Lambda)^2$
  - $(M_\mu/M_e)^2 = 43000$
  - $(M_\tau/M_\mu)^2 = 300$
  - τ lepton : short life (0.3ps), limited statistics

Muon :
higher sensitivity
easier to produce

- Useful in searching for new particles and/or interactions

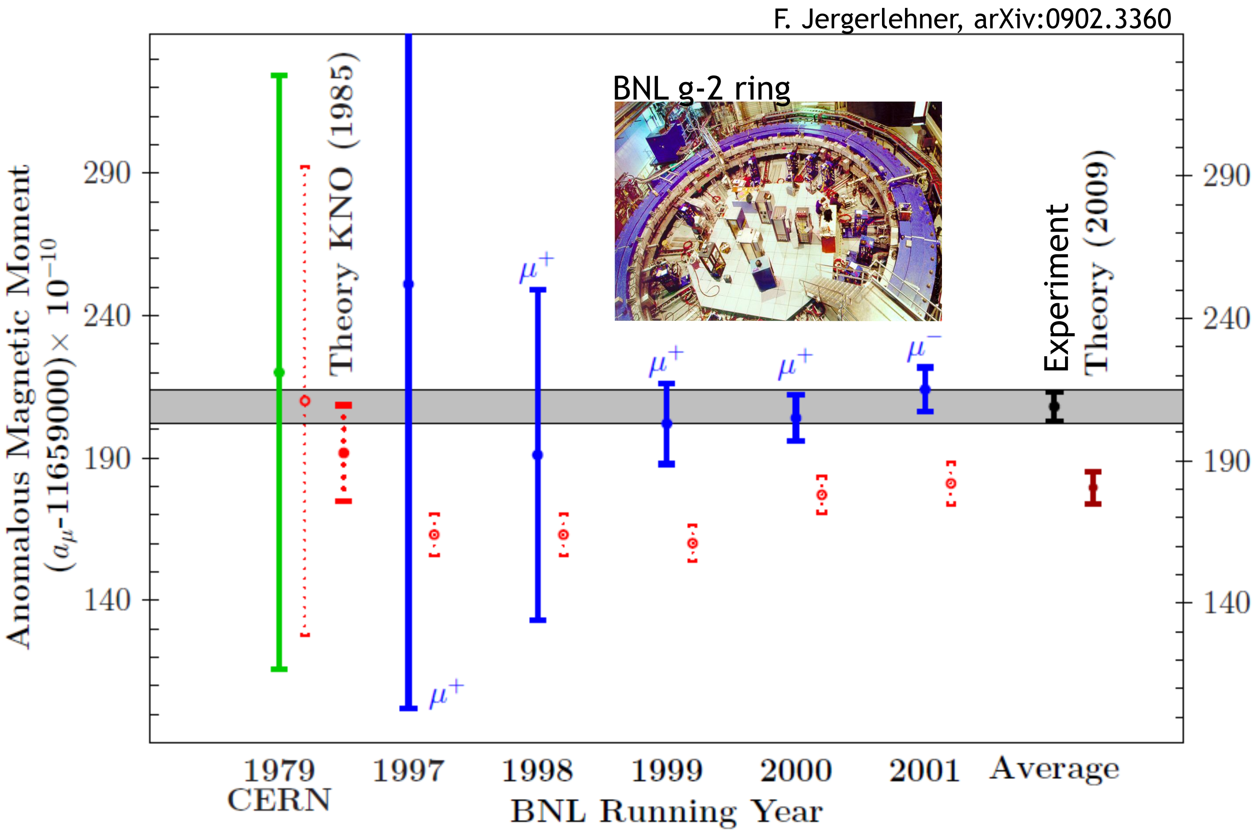
Super Symmetric particles



$$|a_\mu^{\text{SUSY}}| \simeq 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2 \tan\beta,$$

Present uncertainty : $\Delta a_\mu(\text{exp}) = 63 \times 10^{-11}$

History of muon g-2 measurements



$$a_\mu^{exp} - a_\mu^{SM} = \begin{array}{l} (261 \pm 81) \times 10^{-11} \\ (259 \pm 81) \times 10^{-11} \end{array}$$

HLMNT 2011

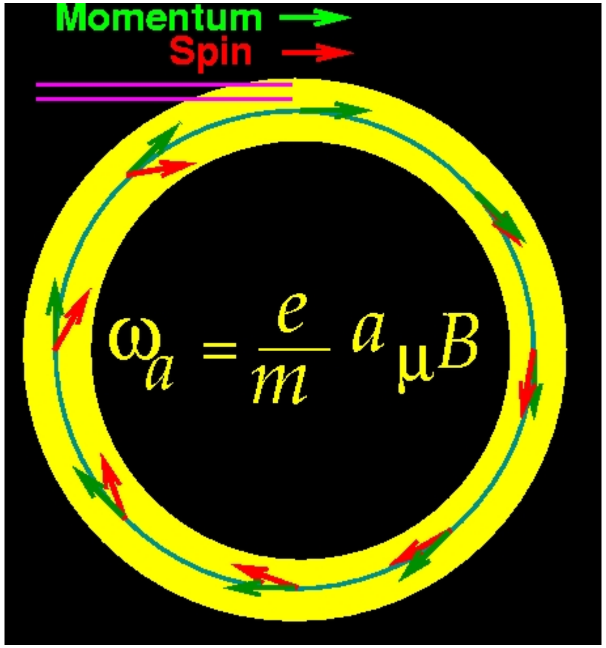
DHMZ 2010

➡ 3.3 ”standard deviations“

Muon anomalous spin precession in B and E-field

- Muon spin rotates "ahead" of momentum due to g-2 >0.
- Precession frequency

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



- BNL E821
  - Focusing **electric field** to confine muons.
  - At the **magic momentum**

    γ = 29.3, p = 3.094 GeV/c → $(a_\mu - 1/(\gamma^2-1)) = 0$

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

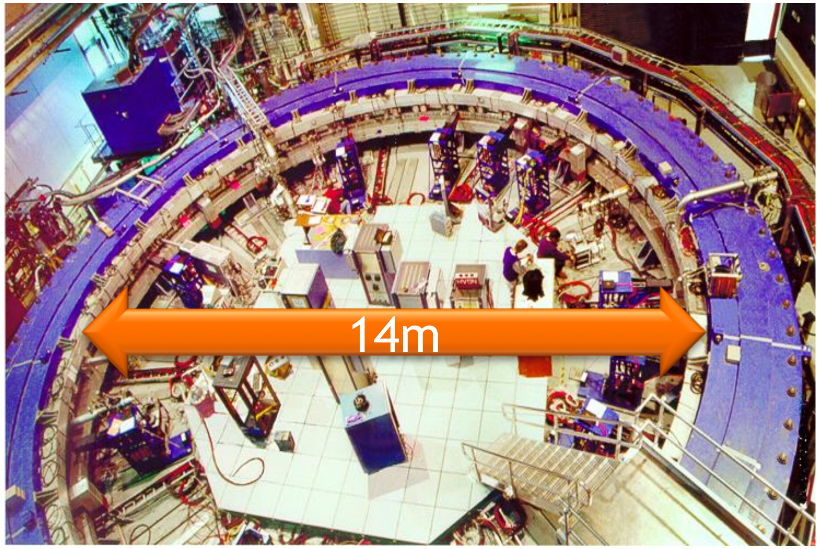
Safely be neglected with current upper limit on EDM

→ Continuation of the experiment at FNAL is planned.

Our approach

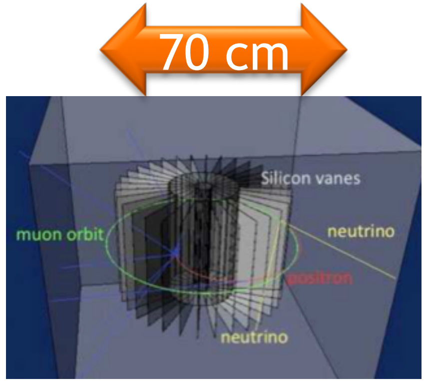
Lower energy & Compact storage ring

BNL E821 / FNAL g-2



P= 3.1 GeV/c , B=1.45 T

J-PARC g-2



P= 0.3 GeV/c , B=3.0 T

- Advantages
  - Suited for precision control of B-field
    - Example : MRI magnet , 1ppm local uniformity
  - Possibility of spin manipulation
    - Effective to cancel various systematics
  - <u>Completely different systematics than the BNL E821 or FNAL</u>

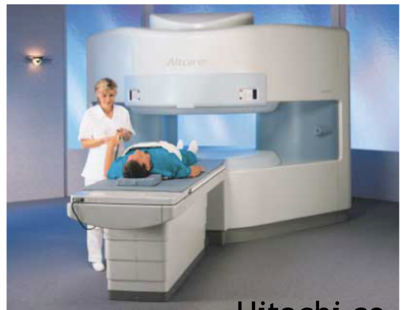


図１：オープンMRI装置の概観図

Hitachi co.

Our approach (cont')

Zero Focusing Electric field (E = 0)

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

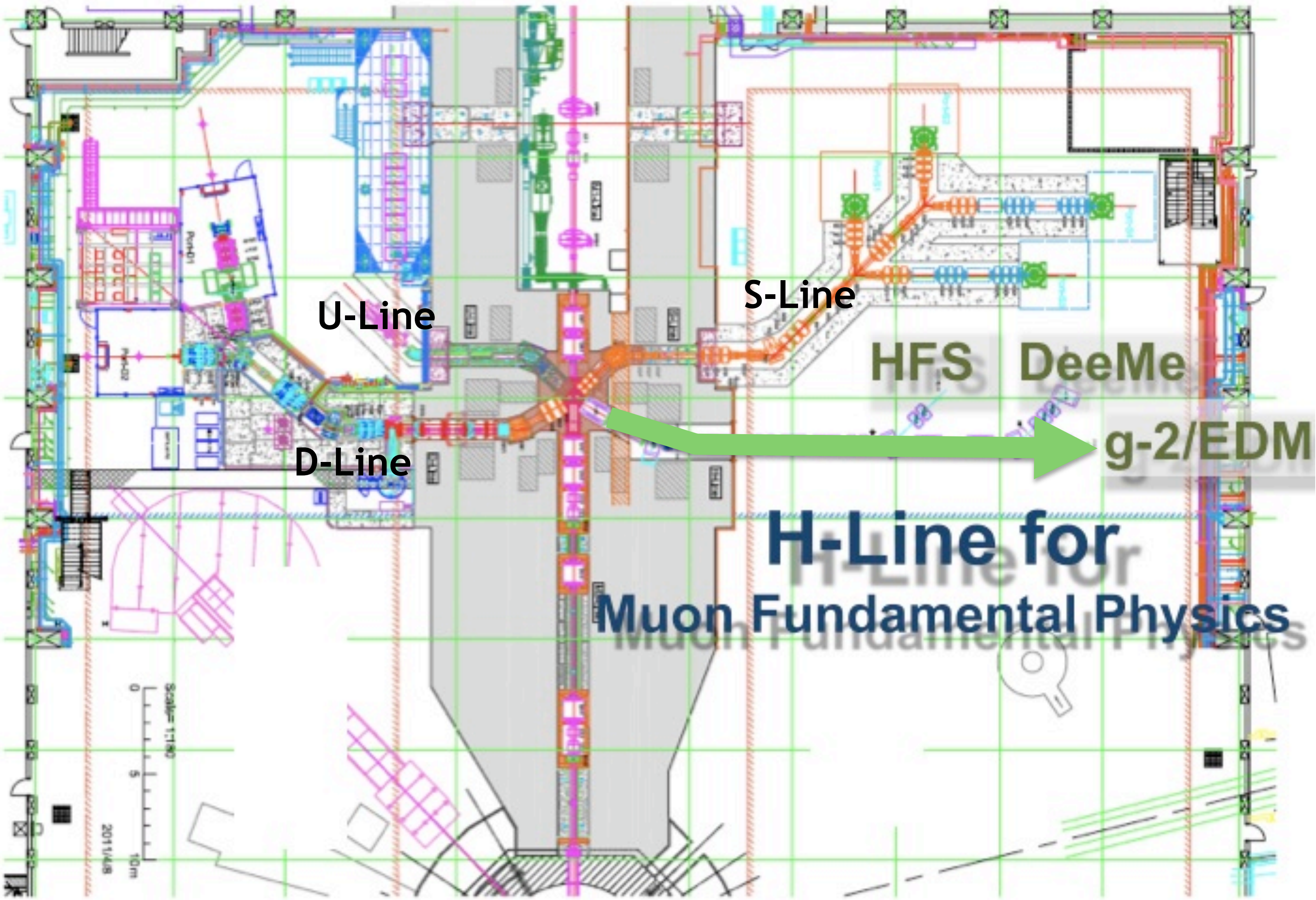
E=0

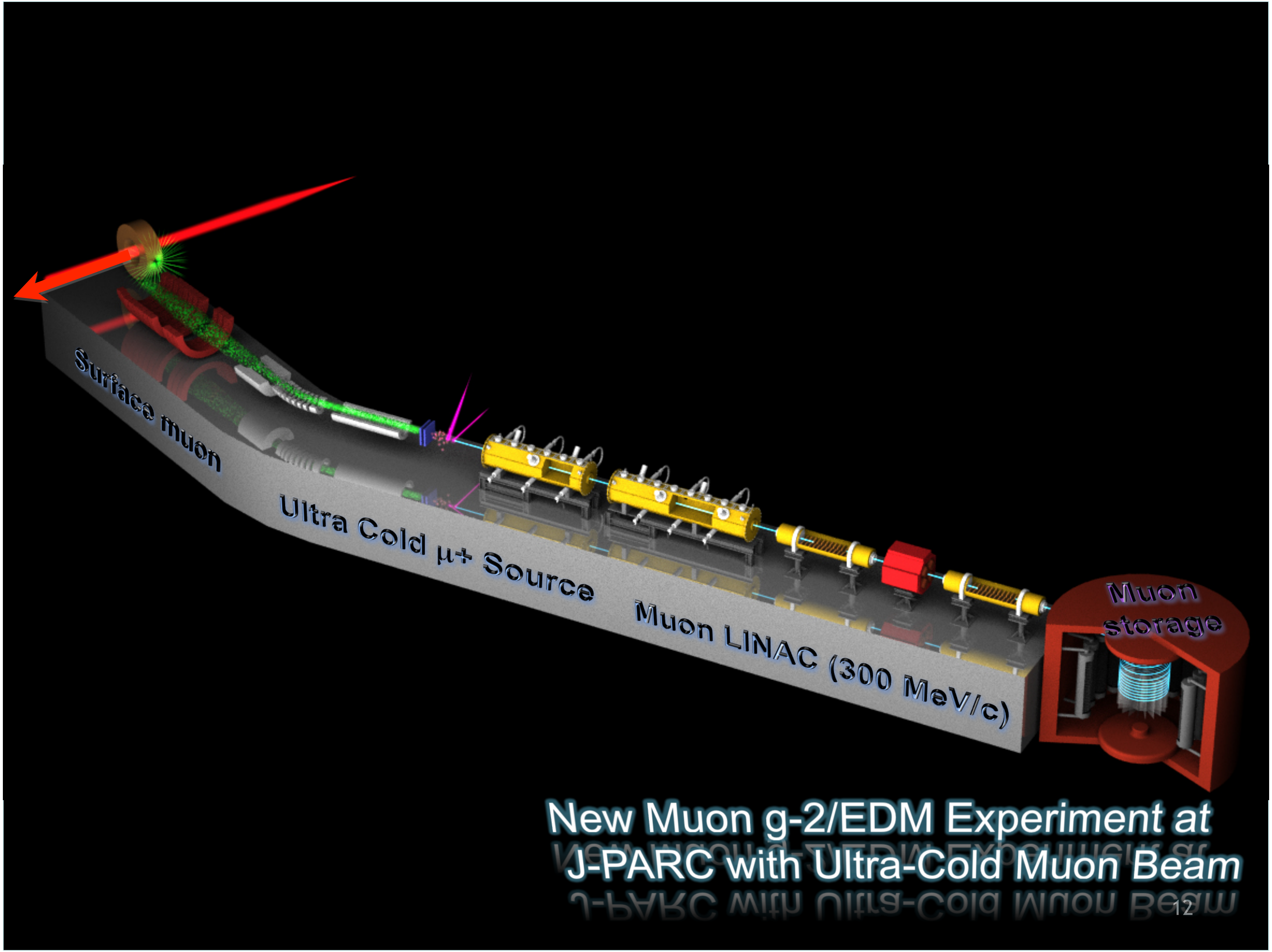
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

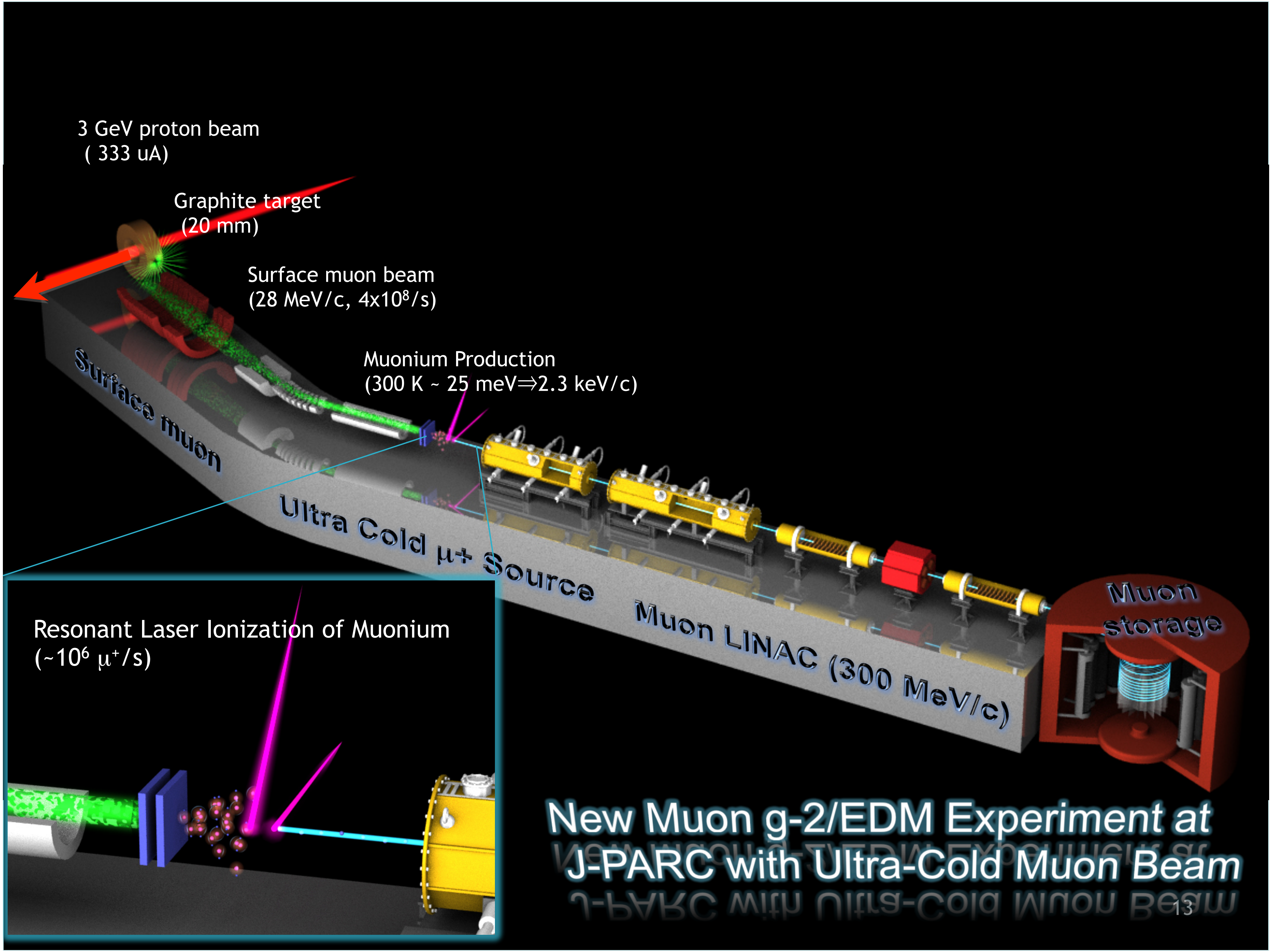
Equations of spin motion is as simple as at the magic momentum

Need a beam which never spread out during measurement:
Ultra-cold muon beam ($p_T/p < 10^{-5}$) by accelerating ultra-slow muons from 3kV/c to 300 MeV/c

J-PARC Material and Life science Facility




Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Resonant Laser Ionization of Muonium
(~10^6 μ+/s)
New Muon g-2/EDM Experiment at
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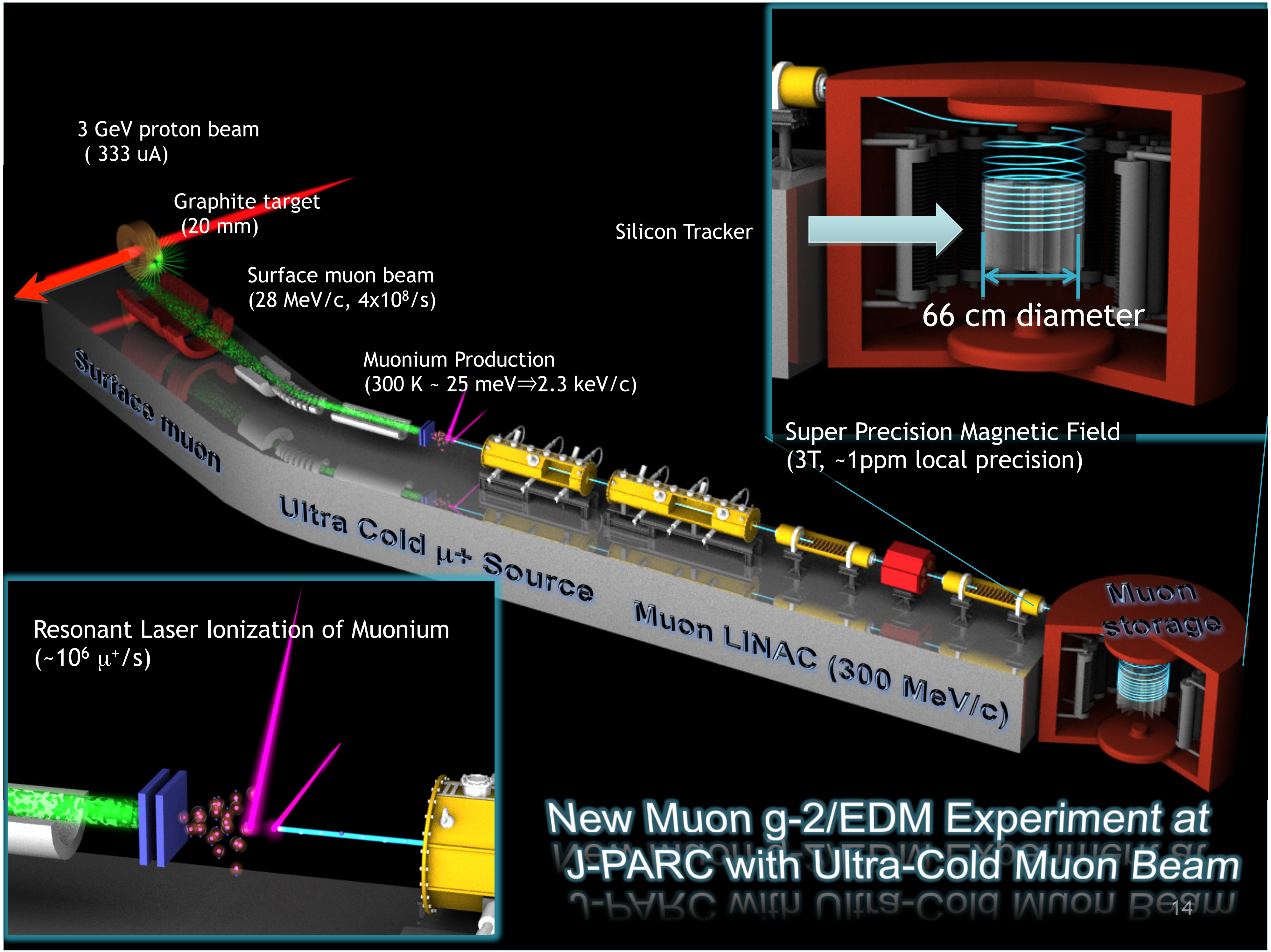


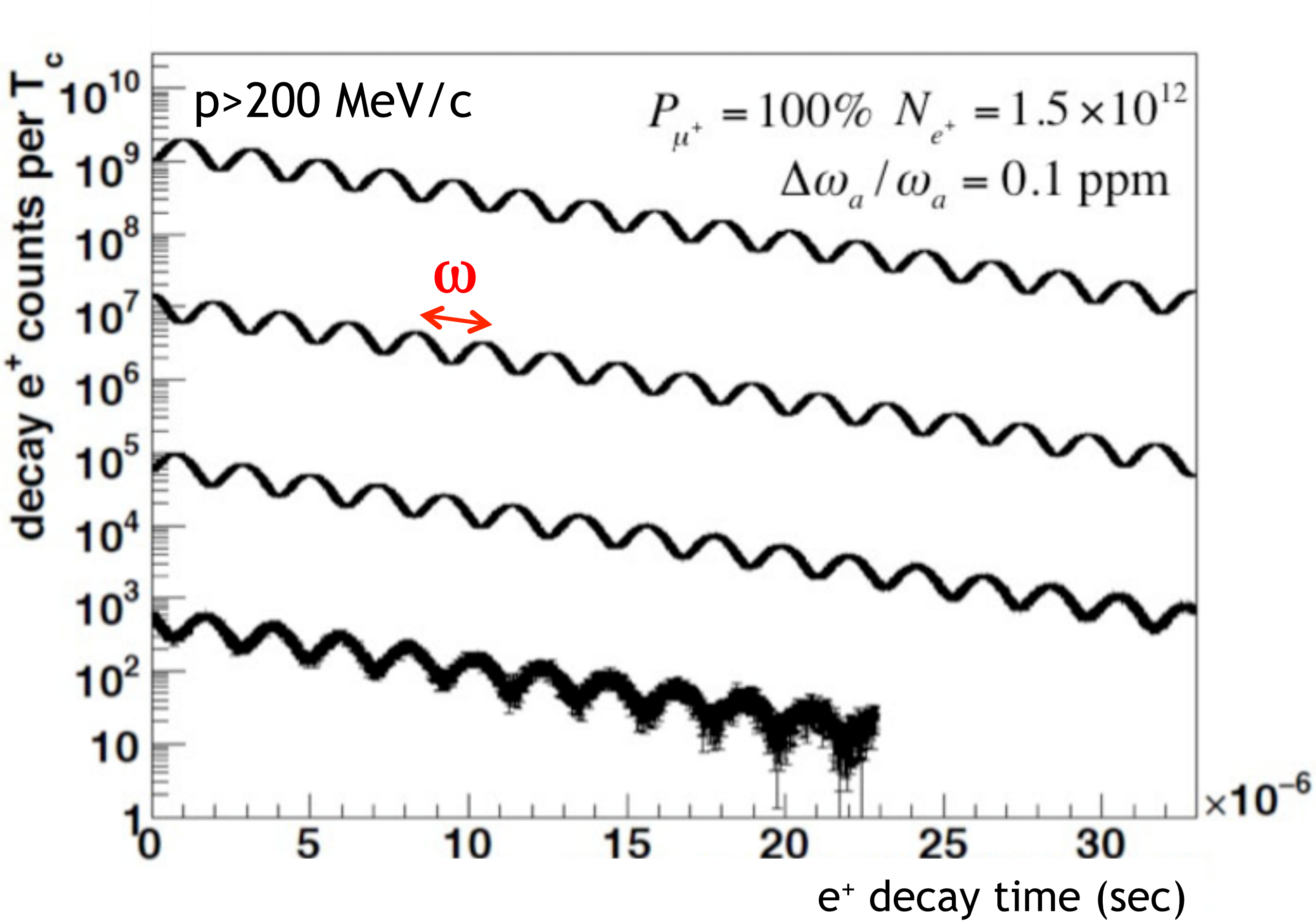
3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Resonant Laser Ionization of Muonium
(~10^6 μ$^+$/s)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

Expected time spectrum of $\mu \rightarrow e^+ \nu \bar{\nu}$ decay

Muon spin precesses with time.

→ number of high energy e⁺ changes with time by the frequency :

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

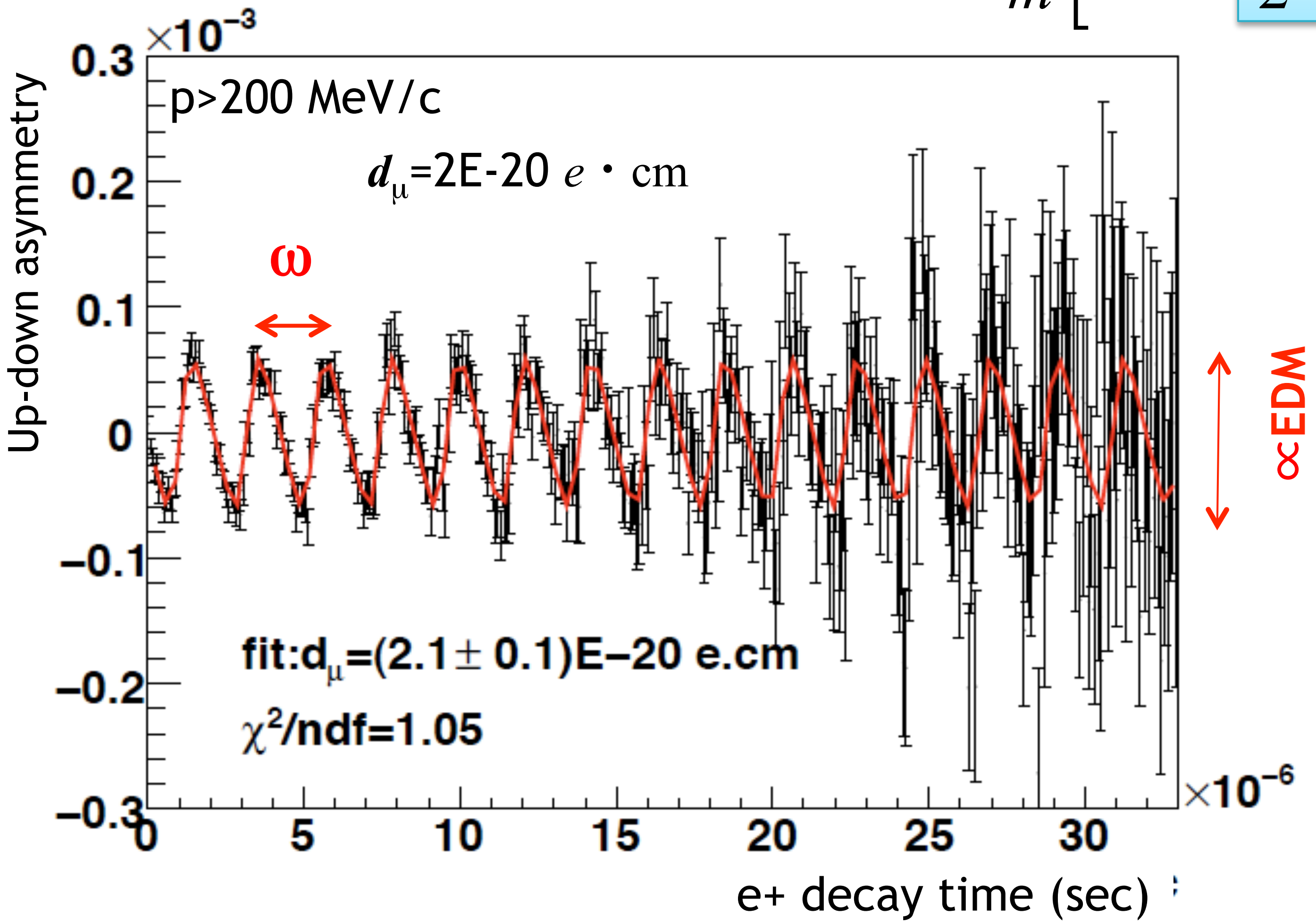


Expected time spectrum of $\mu \rightarrow e^{+}\nu\bar{\nu}$ decay

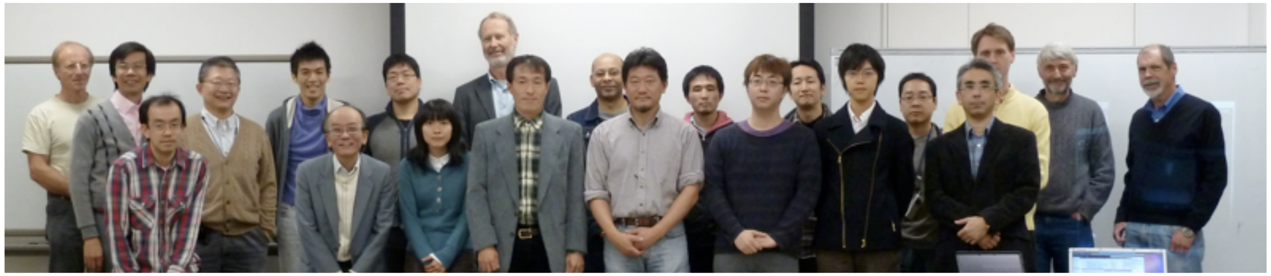
EDM tilts the precession axis.

→ This yields an up-down decay asymmetry in number of e+
(oscillates with the same frequency ω)

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



Collaboration (Contributors to CDR)



- 92 members (…still evolving)
- 25 Institutions: KEK, RIKEN, U-Tokyo, TRIUMF, BNL, PMCU, CYCRC-Tohoku, Osaka, Rikkyo, TITech, SUNYSB, RAL, UCR, UNM, Victoria
- 7 countries: Czech, USA, Russia, Japan, UK, Canada, France

Msaharu Aoki[8], Pavel Bakule[20], Bernd Bassalleck[24], George Beer[26], Gerry Bunce[27], Abhay Deshpande[19], Simon Eidelman[4], Douglas E. Fields[24], Miloslav Finger[6], Michael Finger Jr.[6], Yuya Fujiwara[17,14], Yoshinori Fukao[10], Noriyosu Hayashizaki[16], Seiko Hirota[10,14], Hiromi Iinuma[10], Masanori Ikegami[10], Masahiro Ikeno[10], Katsuhiko Ishida[17], Masa Iwasaki[17], Ryosuke Kadono[10], Takuya Kakurai[12], Takuya Kamitani[10], Yukihide Kamiya[10], Sohtaro Kanda[12], Frédéric Kapusta[5], Naritoshi Kawamura[12], Takashi Kohriki[10], Sachio Komamiya[14], Kunio Koseki[10], Yoshitaka Kuno[8], Alfredo Luccio[12], Oleg Luchev[2], Muneyoshi Maki[12], Glen Marshall[22], Mika Masuzawa[10], Yasuyuki Matsuda[9], Teijiro Matsuzaki[17], Tsutomu Mibe[10], Katsumi Midorikawa[2], Satoshi Mihara[10], Yasuhiro Miyake[10], William M. Morse[3], Jiro Murata[17,13], Ryotaro Muto[10], Kanetada Nagamine[23,10,18], Takashi Naito[10], Hisayoshi Nakayama[10], Megumi Naruki[10], Makiko Nio[21], Hajime Nishiguchi[10], Daisuke Nomura[10], Hiroyuki Noumi[15], Tomoko Ogawa[2], Toru Ogitsu[10], Kazuki. Ohishi[17], Katsunobu Oide[10], Masahiro Okamura[3], Art Olin[22,26], Norihito F. Saito[2], Naohito Saito[10,14], Yasuhiro Sakemi[7], Ken-ichi Sasaki[10], Osamu Sasaki[10], Akira Sato[12], Aurore Savoy-Navaro[5], Yannis K. Semertzidis[3], Yuri Shatunov[12], Koichiro Shimomura[10], Boris Shwartz[4], Wilfrid da Silva[25], Patrick Strasser[10], Ryuhei Sugahara[10], Michinaka Sugano[10], Ken-ichi Tanaka[10], Manobu Tanaka[10], Nobuhiro Terunuma[10], Nobukazu Toge[10], Dai Tomono[17], Eiko Torikai[12], Toshiyuki Toshito[11], Akihisa Toyoda[10], Kyo Tsukada[12], Tomohisa Uchida[10], Kazuki Ueno[17], Vlasov Vrba[1], Satoshi Wada[2], Akira Yamamoto[10], Kaoru Yokoya[10], Koji Yokoyama[17], Makoto Yoshida[10], Mitsuhiro Yoshida[10], Koji Yoshimura[10]

The stage-1 approved in IMSS PAC, and stage-1 recommended in IPNS PAC.

Ultra-slow muons for g-2/EDM

- **Pointing power**
  - No focusing field → $p_T/p < 10^{-5}$ @p=300 MeV/c
  - Momentum $p_T < 3$ keV/c
    $p = (3/2)^{1/2} p_T < 3.7$ keV/c
  - Kinetic energy $E < 0.065$ eV
  - Temperature $T < 750$ K (2000 K (hot-W)@RIKEN-RAL)
    - This condition could be relaxed if very-weak focusing is applied (hot-W would be ok too).

- **Intensity**
  - Statistical uncertainty on $a_\mu = 0.1$ ppm (goal)
    → 10^{13} muons/year
    → 10^6 ultra-slow muon /sec (25/sec @RIKEN-RAL)

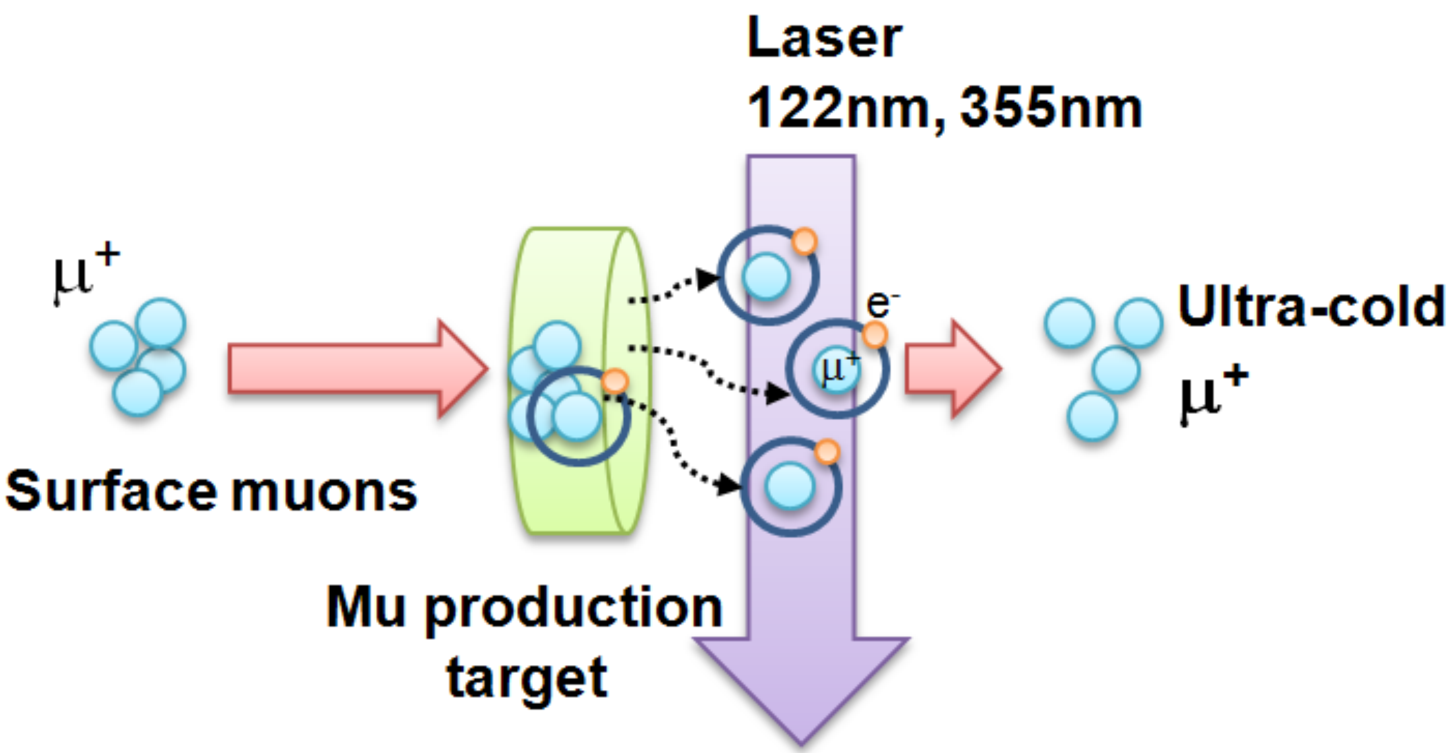
- **Polarization**
  - Figure-of-Merit = NP^2
  - 50 →100% (50% @RIKEN-RAL)

Ultra-slow muons for g-2/EDM

Requirements:

40000 times more muons, and

Cooler muon than RIKEN-RAL



Ultra-slow muons for g-2/EDM

Requirements:

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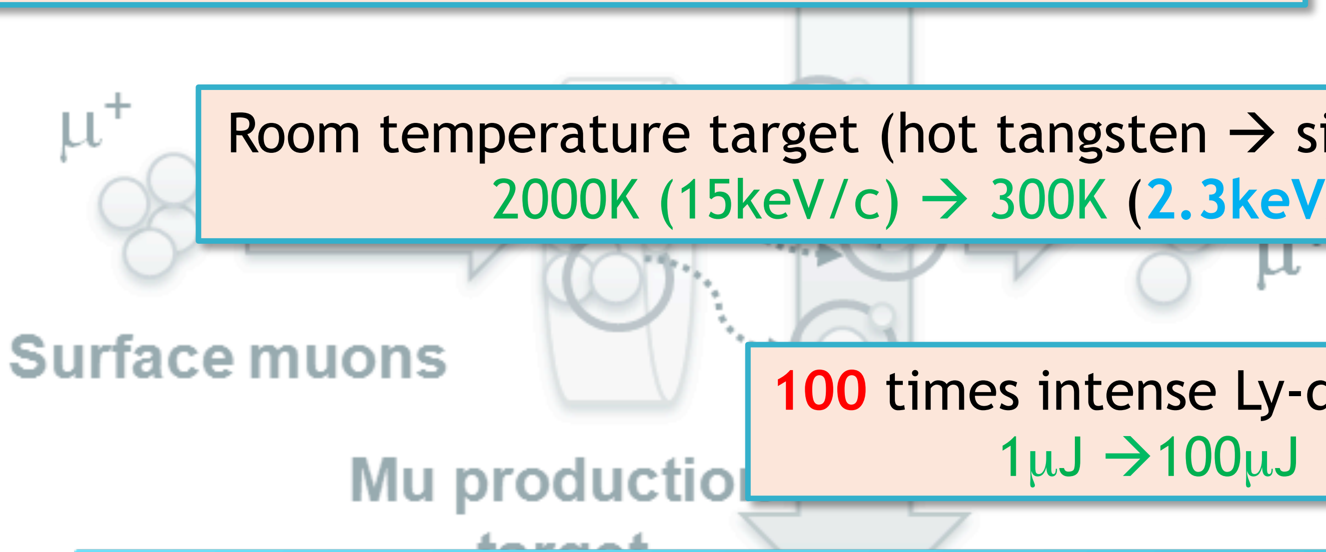
Cooler muon than RIKEN-RAL

170 times higher surface muon per spill at J-PARC H-line
2.4 x 10^4/spill → 400 x 10^4/spill (25 spill/sec)



Room temperature target (hot tangsten → silica aerogel?)
2000K (15keV/c) → 300K (**2.3keV/c**)

100 times intense Ly-α laser
1μJ →100μJ

4×10^4 ultra-cold muon/spill with p=2.3keV/c

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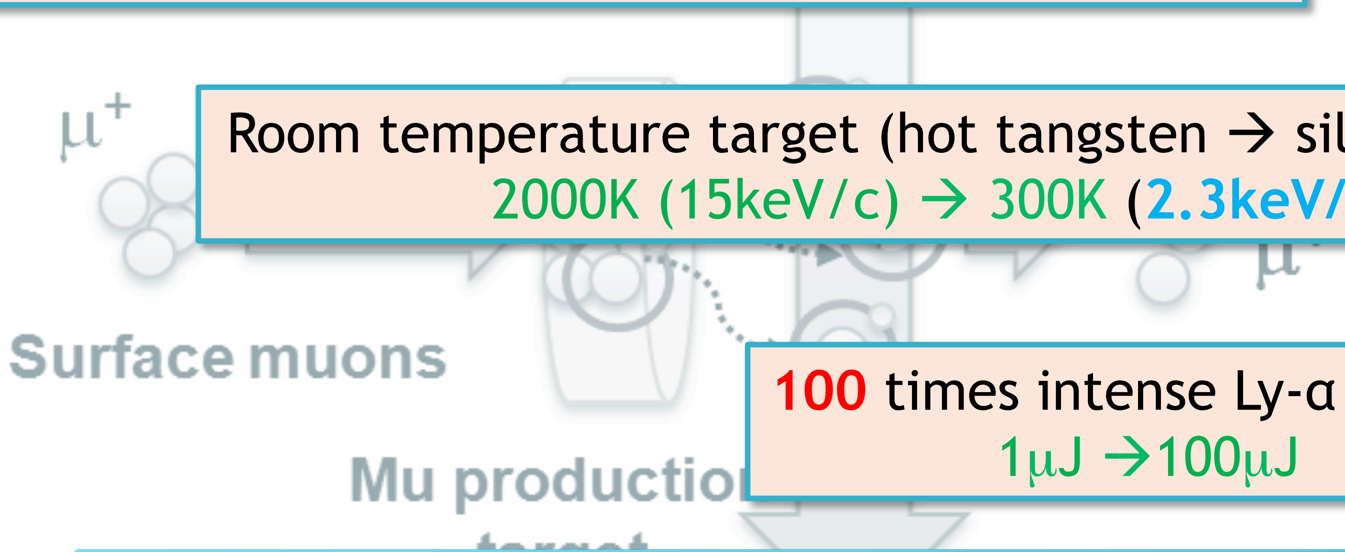

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100 times intense Ly-α laser
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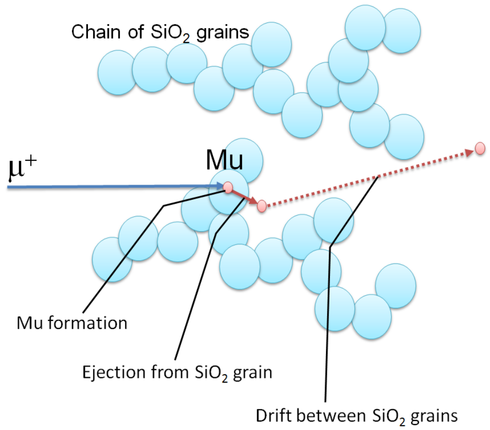
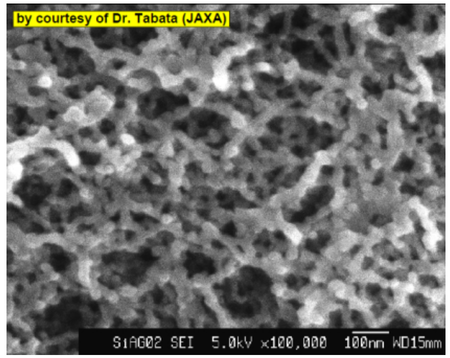
Synergy with U-line developments → Strong collaboration

Room-temperature muonium emitter

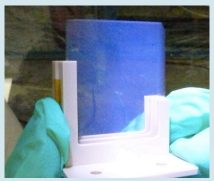
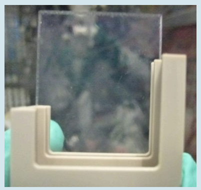
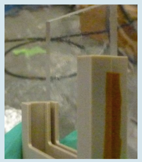
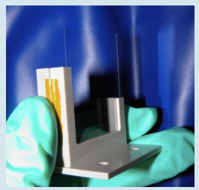
- Silica powders (SiO_2)
  - Structure : network of SiO_2 grain→ Large surface area.
  - Known to be a good Mu emitter at room temp.
  - Not self-standing → difficulty in laser ionization.



- Silica aerogel
  - Similar structure of SiO_2 grain-network.
  - Self-standing!
  - Control of density and thickness
  - Only few (and old) data available



- Vacuum yield and space-time distributions with their density dependence were measured at TRIUMF.

Material	Aerogel	Aerogel	Aerogel	Aerogel	Silica Plate
Density	27mg/cc	50mg/cc	99mg/cc	180mg/cc	2.2g/cc
Thickness	7.8mm	4.7mm	2.4mm	2.3mm	0.96mm
					

TRIUMF-S1249 group

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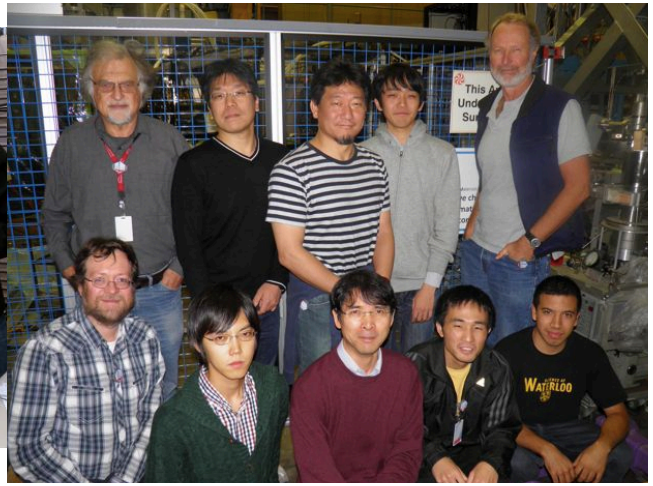

*1 RIKEN Nishina Center, Japan
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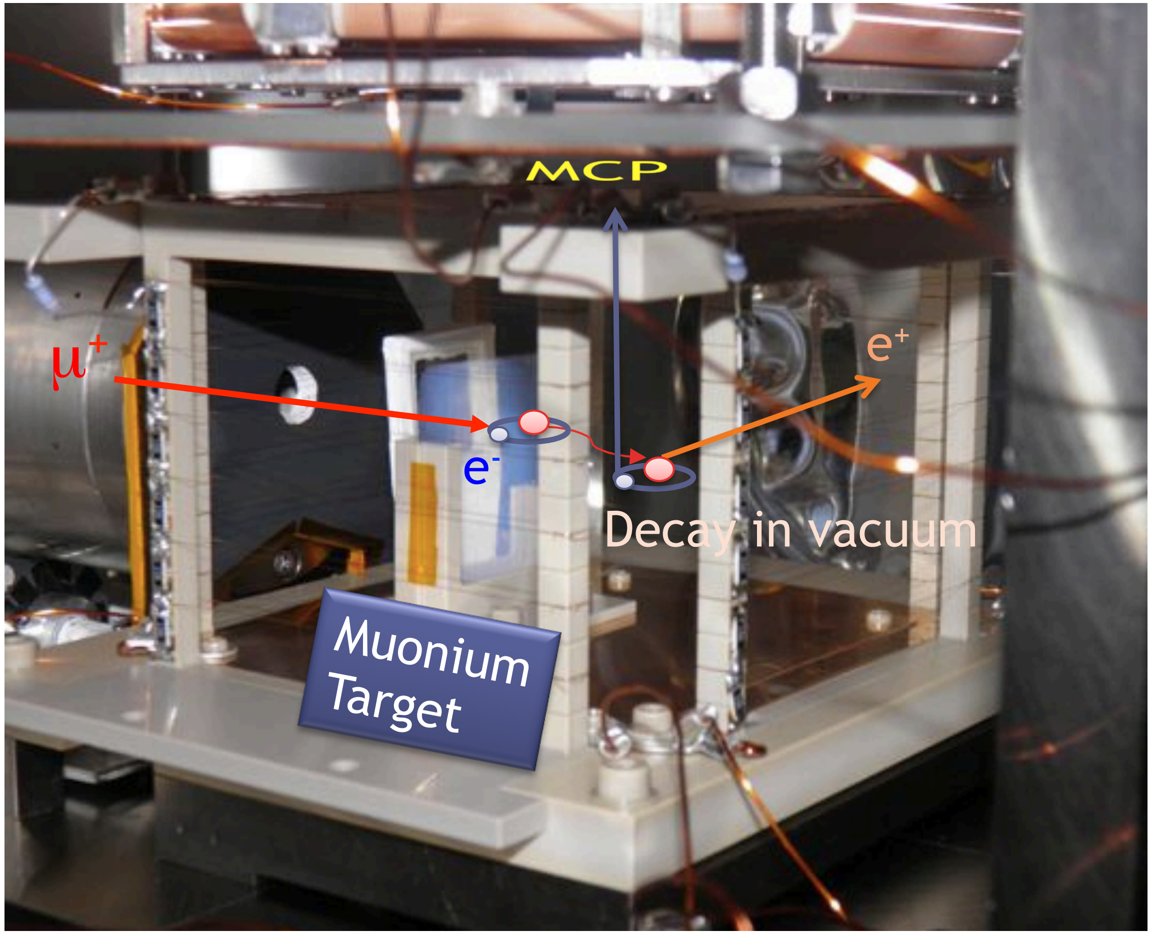
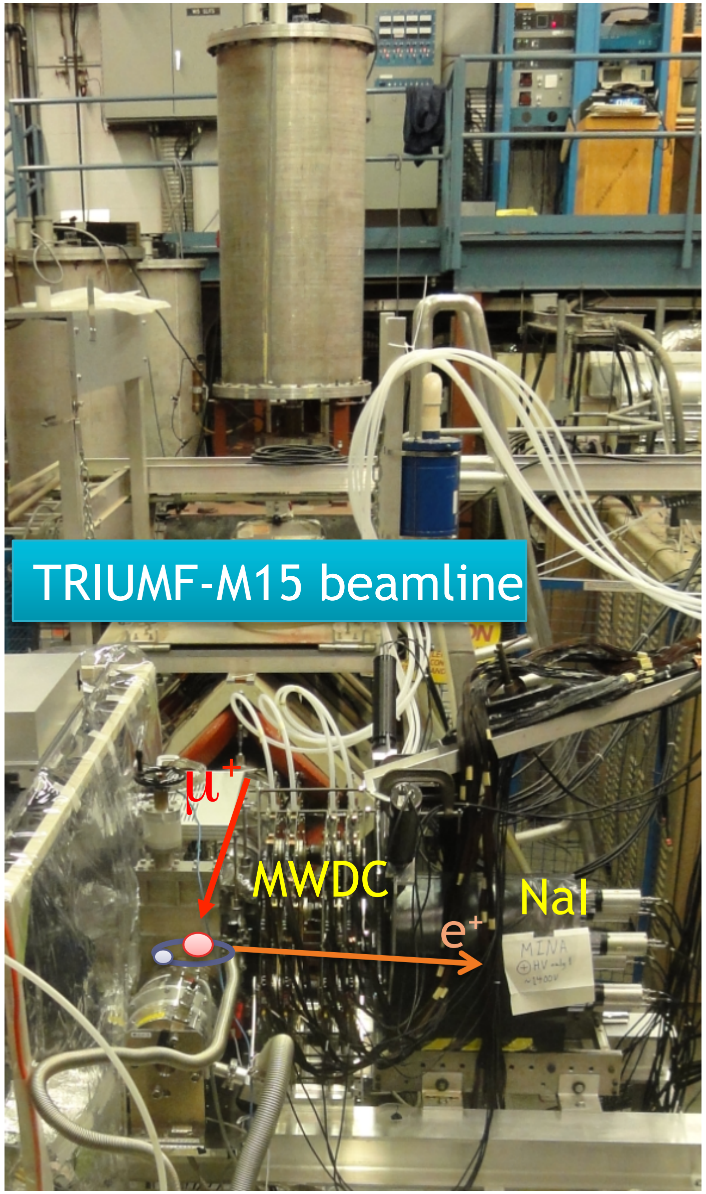
*4 High Energy Accelerator Research Organization (KEK), Japan
*5 Japan Aerospace Exploration Agency (JAXA), Japan
*6 Institute of Physics, ASCR, v. v. i, Chezk
*7 Advanced Institute for Materials Research (WPI-AIMR), Tohoku University, Japan
*8 Department of Physics, Tokyo Institute of Technology, Japan
*9 Division of Applied Chemistry, Tokyo Metropolitan University, Japan
*10 College of Arts and Sciences, The University of Tokyo, Japan
*11 Department of Physics, The University of Tokyo, Japan
*12 Department of Physics, University of Victoria, Canada

TRIUMF-S1249 : search for muonium emitting material at room temp.

Goals are to examine materials at room temp.

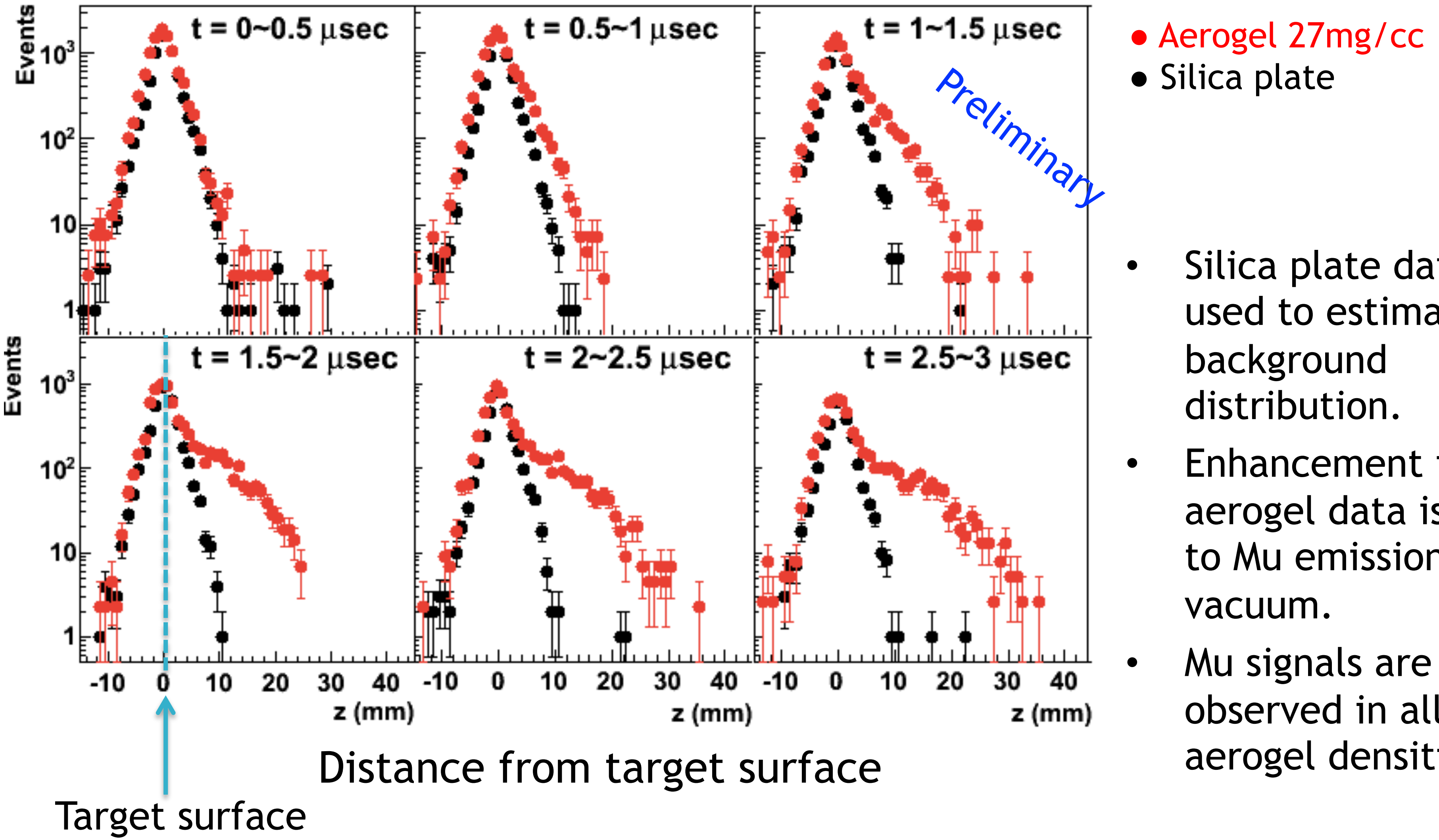
- Muonium production rate
- Muonium distribution in vacuum





Space-time distribution of Mu

Reconstructed Mu decay vertex position



- Silica plate data is used to estimate the background distribution.
- Enhancement in aerogel data is due to Mu emission in vacuum.
- Mu signals are observed in all aerogel densities.

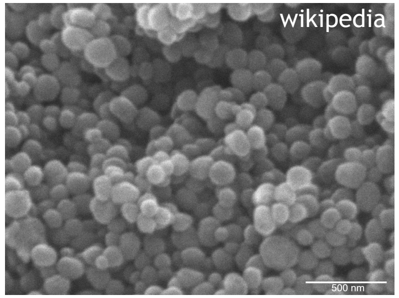
Back of envelope estimate of efficiencies from surface to ultra-cold muons

	Beer, et al. (89, TRIUMF)	Woodle, et al. (88, PSI)	S1249 (2011, TRIUMF)	Mills, et al. (86, KEK-MSL)
	Silica Powder[4]	Silica Powder[11]	Silica Aerogel (S1249)	Hot W[3]
Momentum bite (RMS)	3%(FWHM) 1.3%/5% = 0.26	7.5%(FWHM?) 3.3%/5% = 0.66	2%(RMS) 2%/5% = 0.4	5%(RMS) 5%/5% = 1.
Straggling	$(20\text{MeV}/28\text{MeV})^{3.5}$ = 0.31	$(20\text{MeV}/28\text{MeV})^{3.5}$ = 0.31	$(23\text{MeV}/28\text{MeV})^{3.5}$ = 0.50	$(23.2\text{MeV}/28\text{MeV})^{3.5}$ = 0.52
Half-stop	0.5	0.5	0.5	0.5
Mu formation	0.6	0.6	0.6	-
(total emission)/(Mu in target)	0.19	0.33	0.016 Preliminary	0.04
(Mu in laser region)/(total emission)	0.30	0.30	0.30	0.22
Ionization efficiency	0.76	0.76	0.76	0.54
Product of efficiencies	0.1E-2	0.46E-2	0.02E-2	0.12E-2
Expected Ultra-Cold Muon Yield (/s)	0.1E6	0.46E6	0.02E6	0.12E6

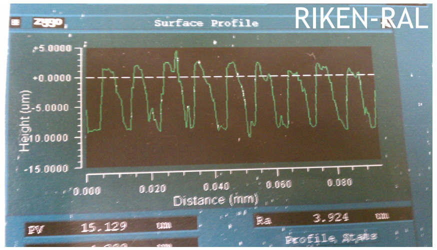
Required yield : 1.E+6/s
a factor of 8 behind ?

Prospects on Mu target developments

- **Aerogels**
  - Squeeze as much information as possible from S1249 data
    - Density dependence, space-time distributions etc…

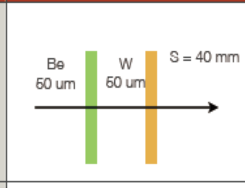
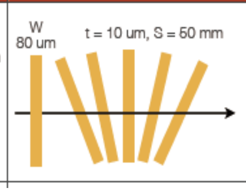
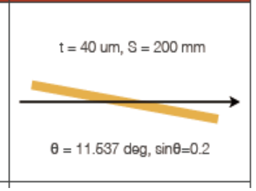


- **More surface area**
  - Porous structure?
    - New PSI work on meso-porous Silica (arXiv:1112.4887)
  - Micro-drilled W-foil
    - 10μm-pitch drilled foil was tried at RIKEN-RAL
    - Started R&D for 1μm pitch for further gain



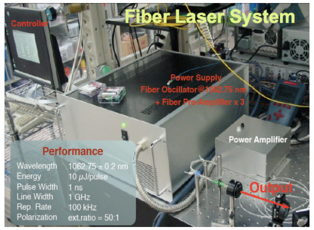
- **Surface processing**
  - W coated with alkali-metal (Na, Cs)
    - Experiment being performed at J-PARC now by Y. Miyake, Y.Nagashima et al.

- **Complex geometry**
  - Cyclotron trap
  - Slanted layer
  - Multi-layers
  - Cylinder …
  - Monte Carlo simulations have been in progress.

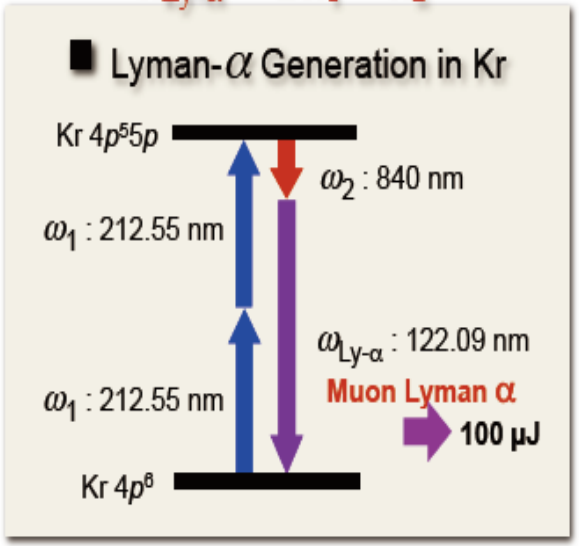
	Mills	Angled multi	Horizontal
Geometry			

Laser development and ionization test

- Laser development at RIKEN
  - Omega-1
    - Fiber Laser System ✓
    - Solid State Amplifier ✓
    - Non-linear frequency converter
  - Omega-2
    - SLM Seeder
    - 1^{st} and 2^{nd} Non-linear amplification
  - 2-photon resonant 4-wave mixing in Kr cell

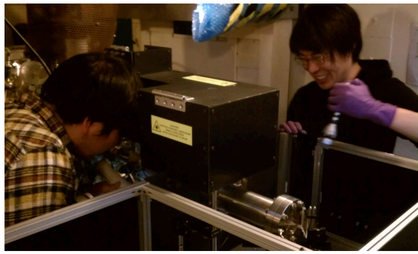


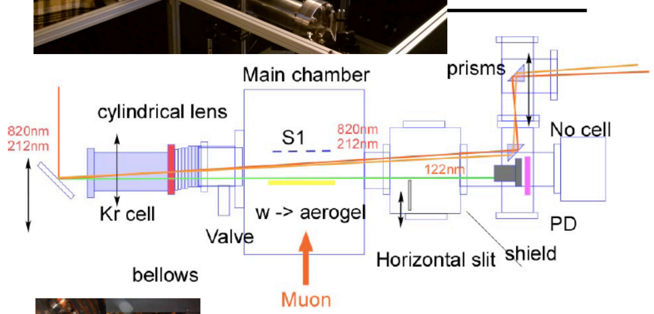
$\omega_{Ly\text{-}\alpha} = 2\omega_1 - \omega_2$

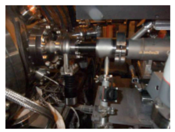


To be tested and installed to U-line in 2012

- Ionization test at RIKEN-RAL
  - Improved laser system
    - stable, more freedom of adjustments
  - New beam line controls
  - Heater system refurbished
  - **Taking data JUST NOW!**
    - Beam time : March 6-8







Summary

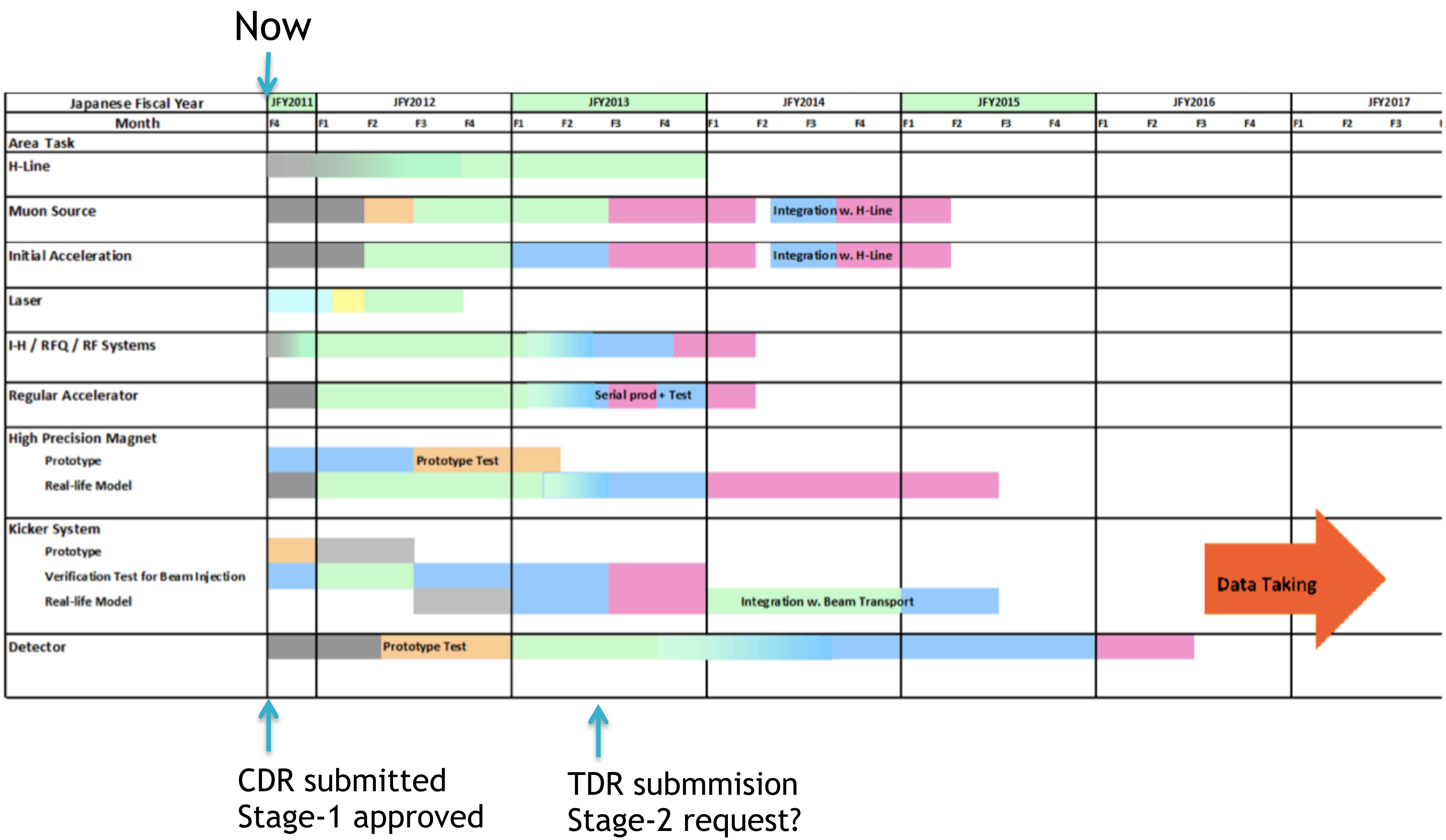
- **A new muon g-2/EDM experiment at J-PARC:**
  - Off magic momentum + compact g-2 ring
  - Complementary to FNAL g-2
  - Start in 2016
- **Ultra-slow muons**
  - The key technology to realize required beam
  - TRIUMF S1249 studies Mu emitting materials at room temp.
  - Ionization test with improved laser system is in progress at RIKEN-RAL.
  - Intense Ly-α laser being developed in close collaboration with U-line developers.

back up slides

BNL, FNAL, and J-PARC

	BNL-E821	FNAL-E989	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarization	100%		$>$ 90%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		very-weak magnetic
Cyclotron period	149 ns		7.4 ns
Anomalous spin precession period	4.37 μs		2.11 μs
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

Projected schedule



Relevant parameters of muon beam characteristics and decay properties

Section	Parameter	Value
Muon Beam	Mass	105.658 367(4) MeV/c^2
	Momentum	300.0 MeV/c
	Energy	318.1 MeV
	β	0.943
	γ	3.011
	Dilated life time	6.615 μs
	Radius of Cyclotron motion	33.33 mm
	Cyclotron period $2\pi/\omega_c$	7.387 ns
	Anomalous spin precession period $2\pi/\omega_a$	2111 ns
		285.7 turns
	Polarization	>0.9
	Intensity	1×10^6/s (4×10^4/spill)
	Pulse repetition rate	25 Hz
Positron	Mass	0.510 998 910(13) MeV/c^2
	Maximum energy (muon rest frame)	52.83 MeV
	Maximum energy (laboratory frame)	309.0 MeV
	Optimum energy threshold E^{th}_{lab}	200 MeV
	Fraction C^{th} at $E^{th}_{lab} = 200$ MeV	0.13
	Effective A at $E^{th}_{lab} = 200$ MeV	0.46
	Maximum emission angle at $E^{th}_{lab} = 200$ MeV	250 mrad (14.3 deg)
	Minimum p_{xy} at $E^{th}_{lab} = 200$ MeV	194 MeV/c

Table 7.1: *Relevant parameters of muon beam characteristics and decay properties*

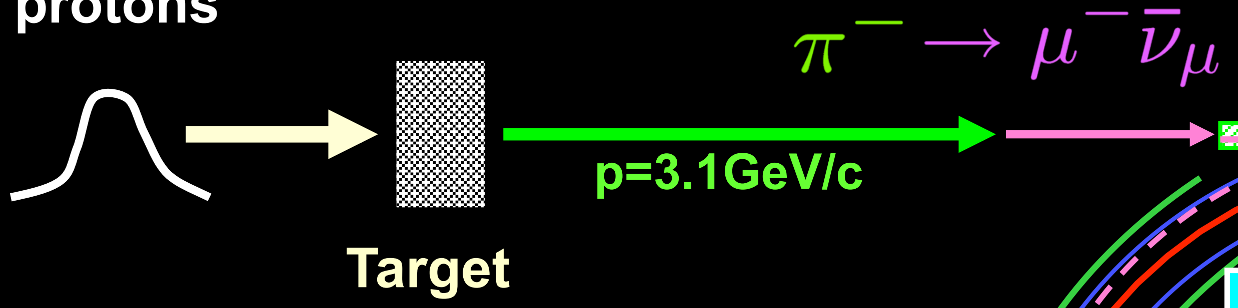
BNL E821 Experimental Technique

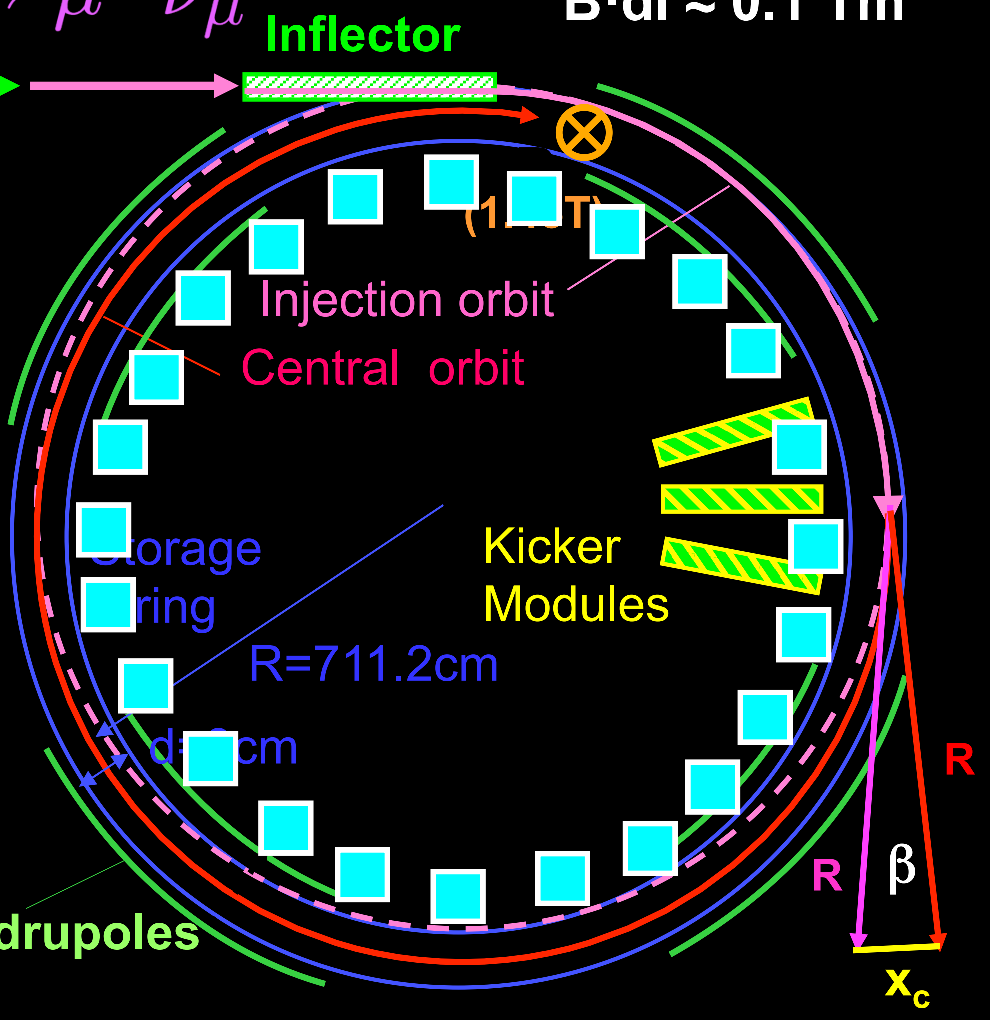
25ns bunch of
$\geqslant$ 1 X 10^{12}
protons

$x_c \approx$ 77 mm

$\beta \approx$ 10 mrad

B·dl $\approx$ 0.1 Tm

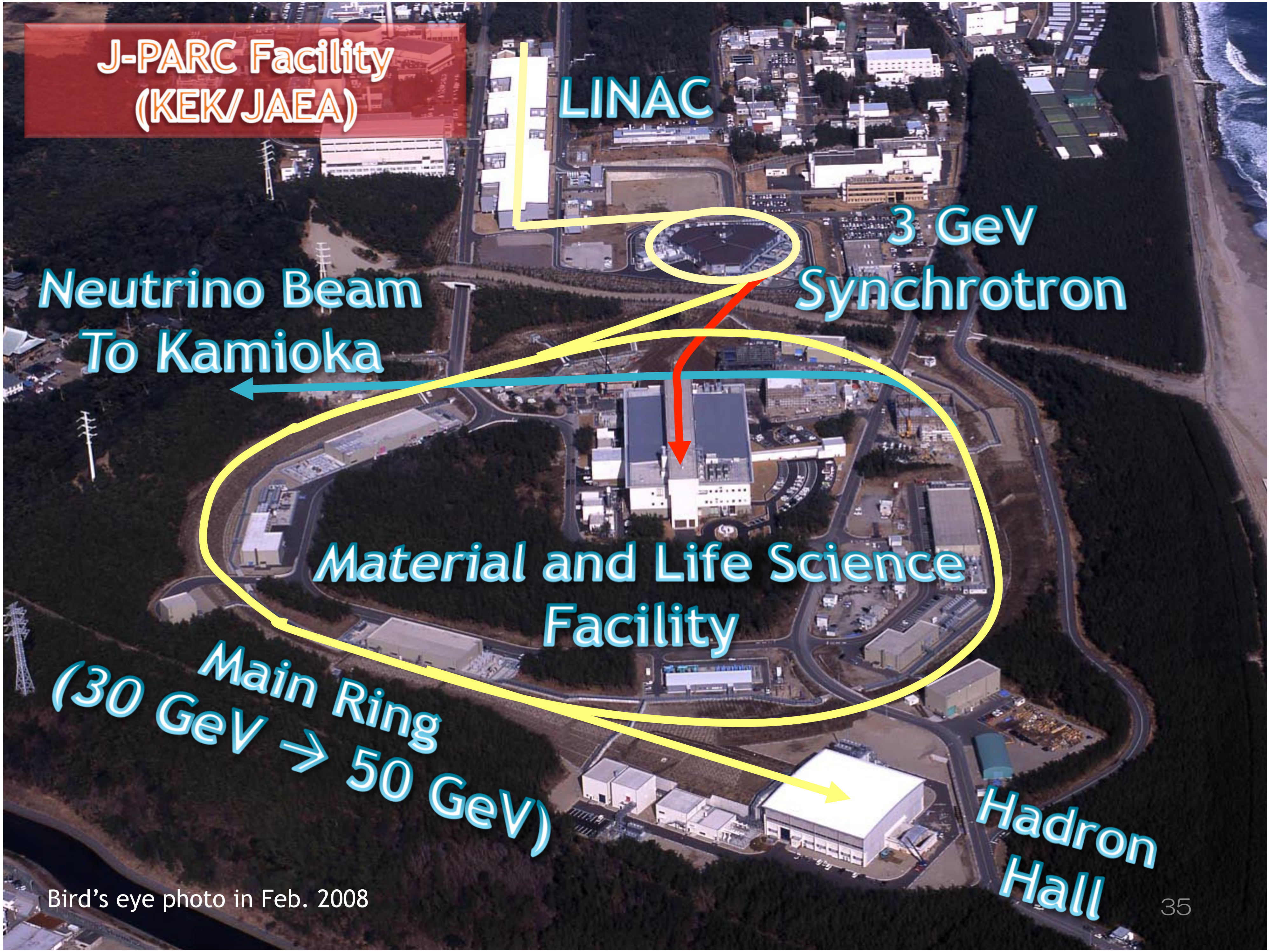




- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

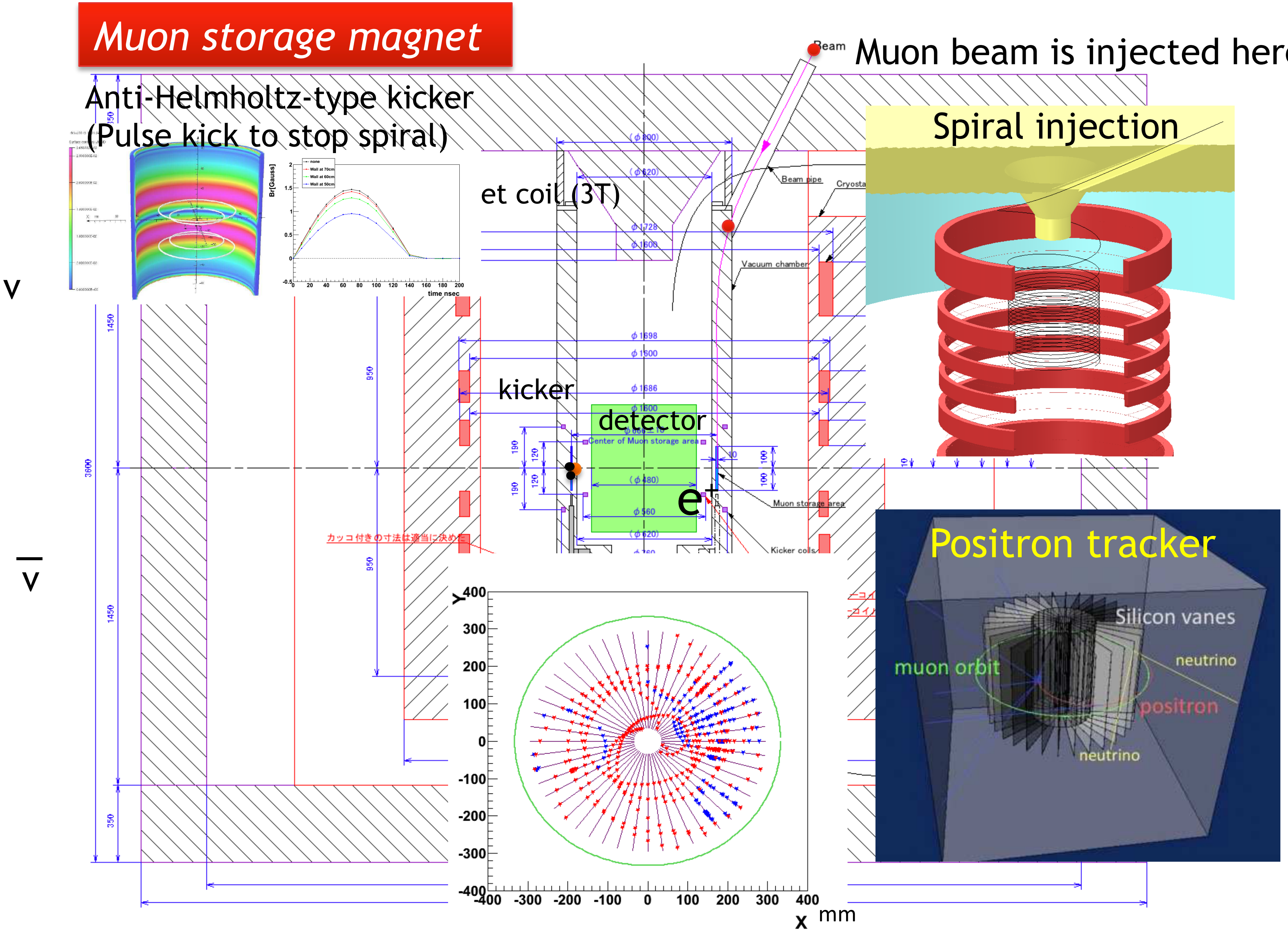
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

Slide from Lee Roberts

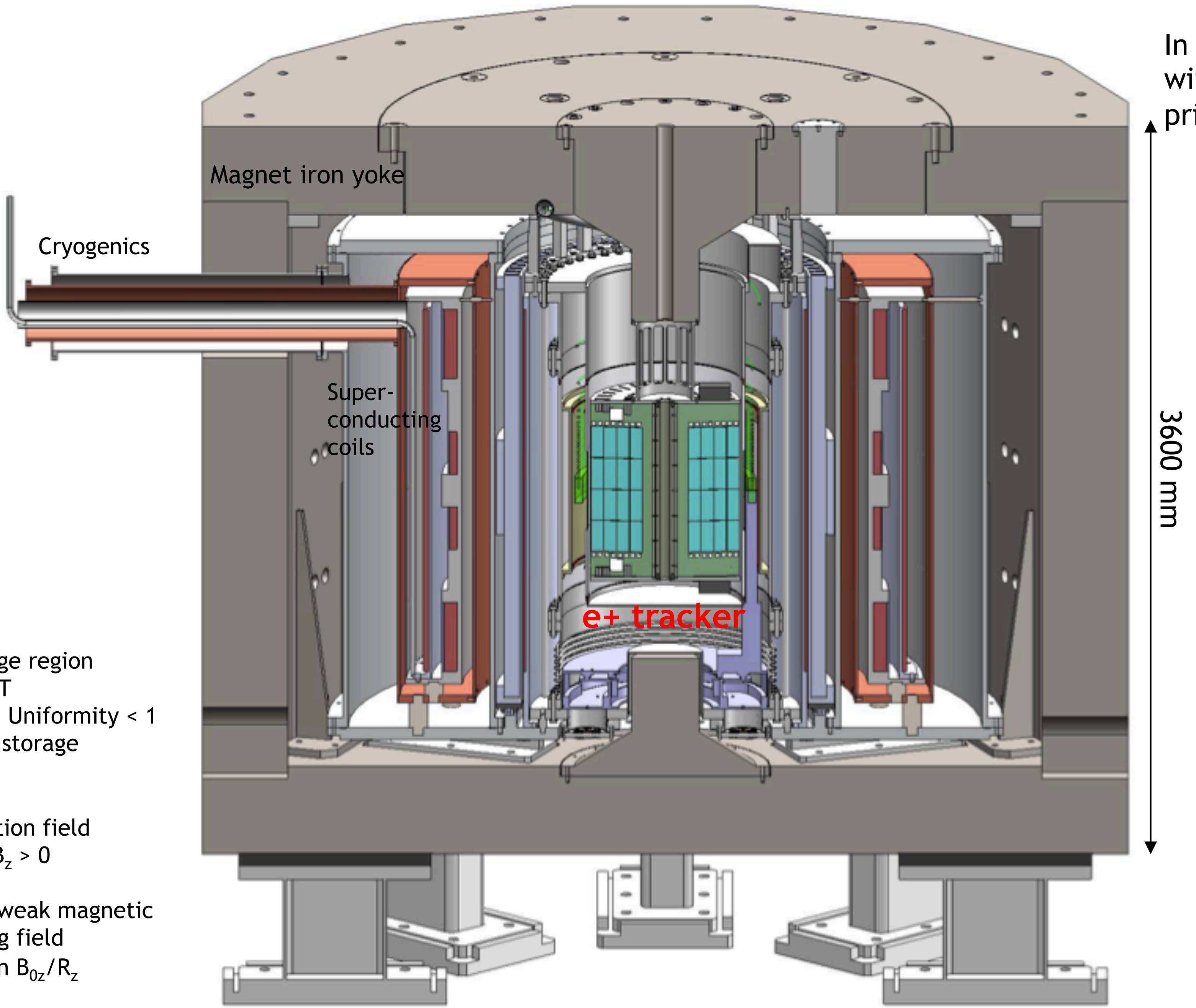


Bird's eye photo in Feb. 2008

Injection, storage, and positron detection



The muon storage magnet



In collaboration with a Japanese private company

- Storage region
  - B_z =3T
  - Local Uniformity < 1 ppm in storage Region

- Injection field
  - $B_r \times B_z > 0$

- Very-weak magnetic focusing field
  - $B_r = -n B_{0z}/R_z$

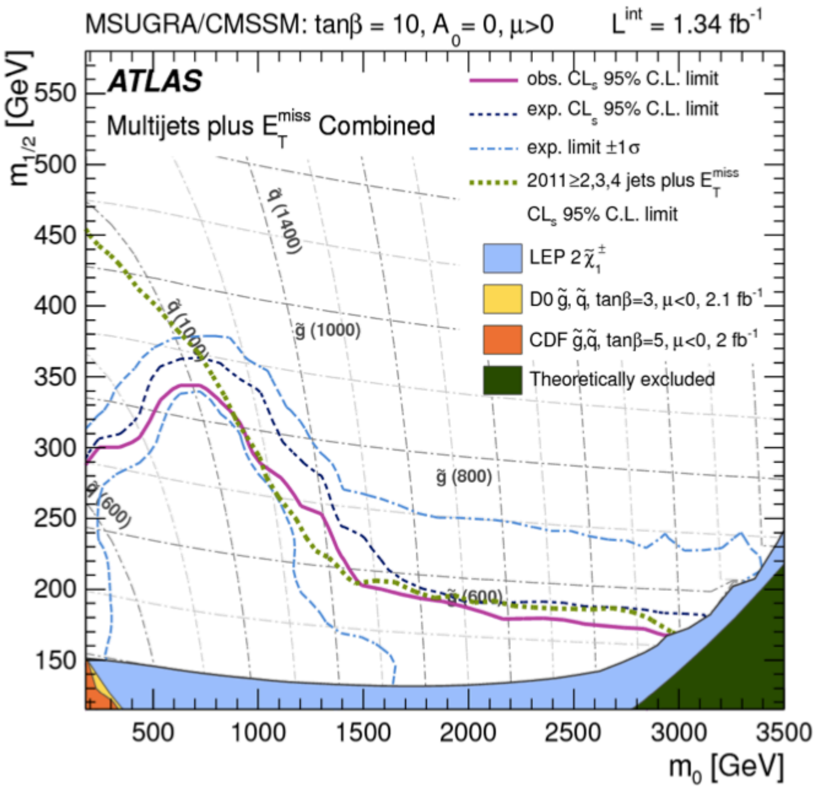
Standard model prediction

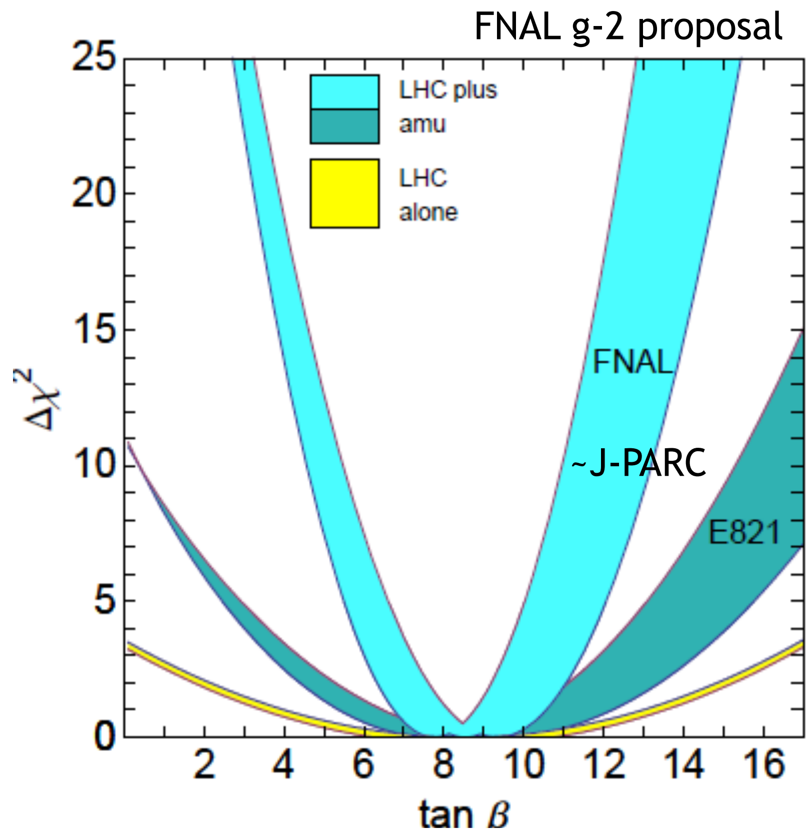
D. Nomura (PhiPsi11)

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	−9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

Hunting for SUSY (or other BSM) signature



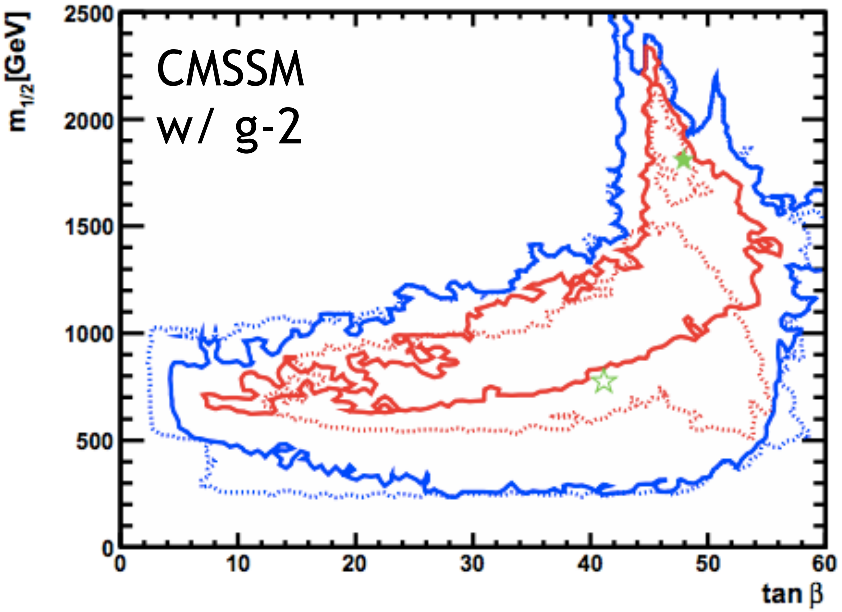


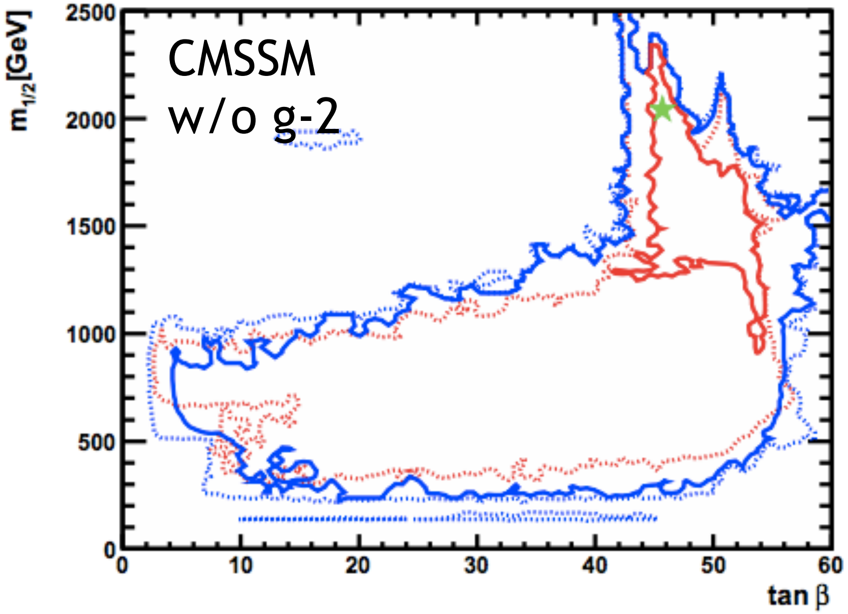
$$\left|a_{\mu}^{\rm SUSY}\right| \simeq 130 \times 10^{-11} \left(\frac{100\ {\rm GeV}}{\widetilde{m}}\right)^2 \tan\beta,$$

g-2 measurement is complementary to LHC and cLFV

Tension with LHC Higgs implications?

O. Buchmueller et al., arxiv:1112.3564

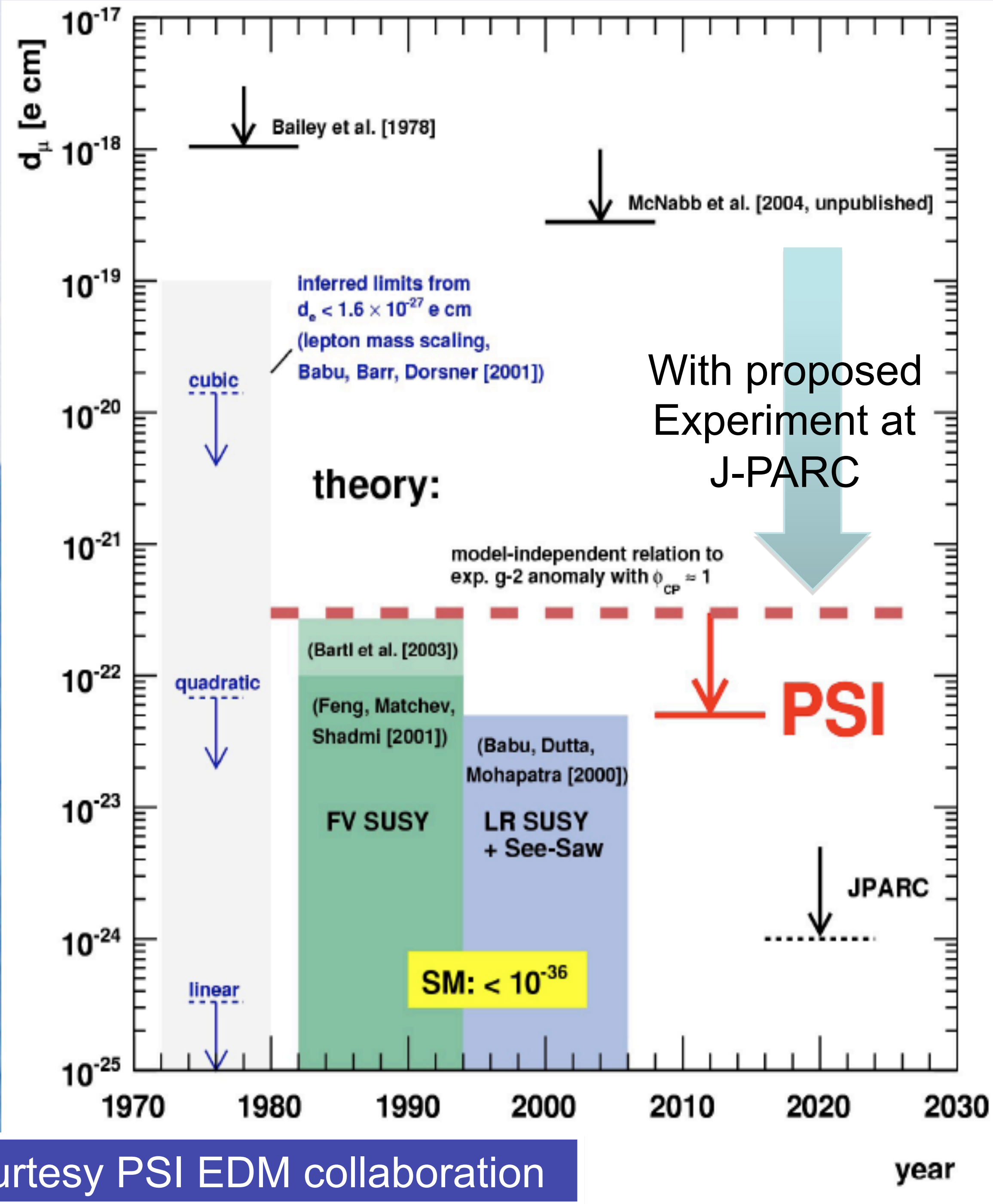




Model	Minimum χ^2/d.o.f.	Fit Probability
CMSSM		
pre-Higgs	28.8/22	15%
$M_h \simeq 125$ GeV, $(g-2)_\mu$	30.6/23	13%
$M_h \simeq 125$ GeV, no $(g-2)_\mu$	21.0/22	52%
$M_h \simeq 119$ GeV	28.8/23	19%

Muon EDM

- Direct CPV in Lepton Sector
  - CPV Required beyond KM
- Current Exp. Limit ~ 1e-19
- Potential Sensitivity of J-PARC
  - ~ 1e-22 @ MLF



Courtesy PSI EDM collaboration