muon g-2/EDM

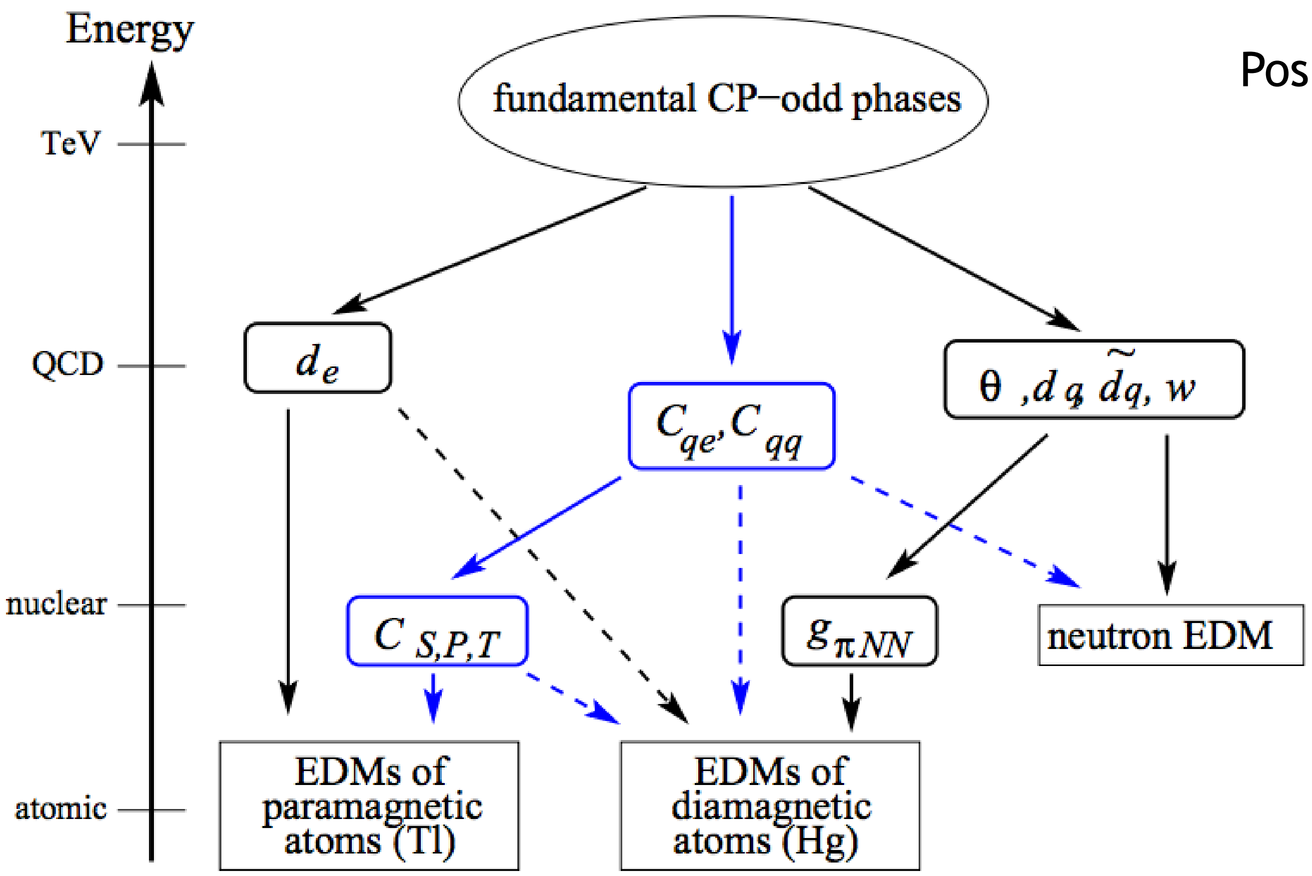
PCPV2013, February 21, 2013

Tsutomu Mibe (IPNS/KEK)

photo : Oarai Beach, Ibaraki JAPAN

Scales of CP-odd sources and EDM

Pospelov, Ritz



Scales of CP-odd sources and EDM

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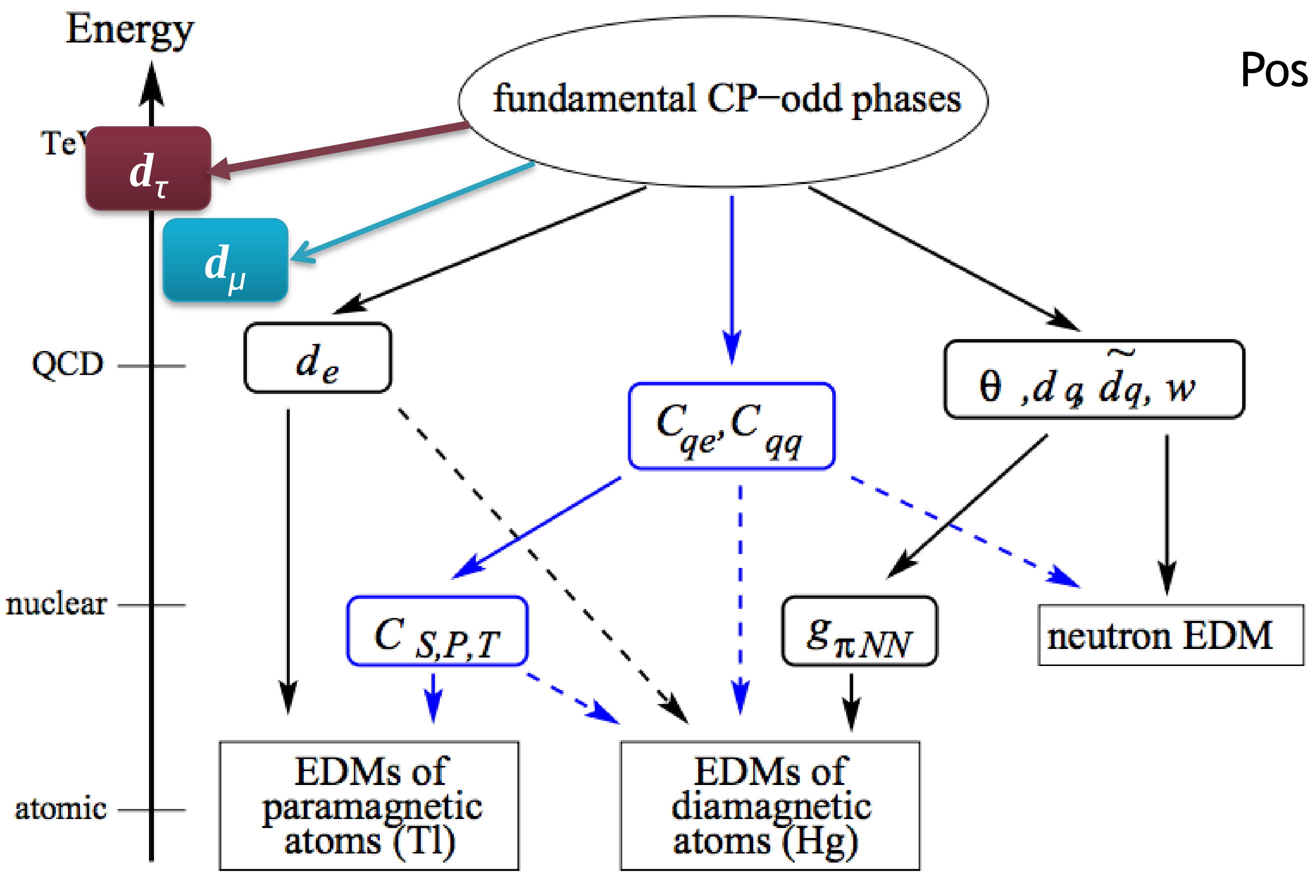


Lepton EDM directly proves CP-odd phases at TeV scale (and beyond?)

Lepton EDM limits

Particle	EDM limits (e · cm)	Standard model (e · cm)	
e	1.0×10^{-27}	$< 10^{-41}$	ICL Nature 473, 493 (2011)
μ	1.8×10^{-19}	$< 10^{-38}$	BNL E821 PR D 80, 052008 (2009)
τ	5×10^{-17}		Belle PLB 551, 16 (2003)

Lepton dipole moments

- Interactions with static B and E-fields:

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

Magnetic Dipole Moment $\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s}$

Electric Dipole Moment $\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s}$

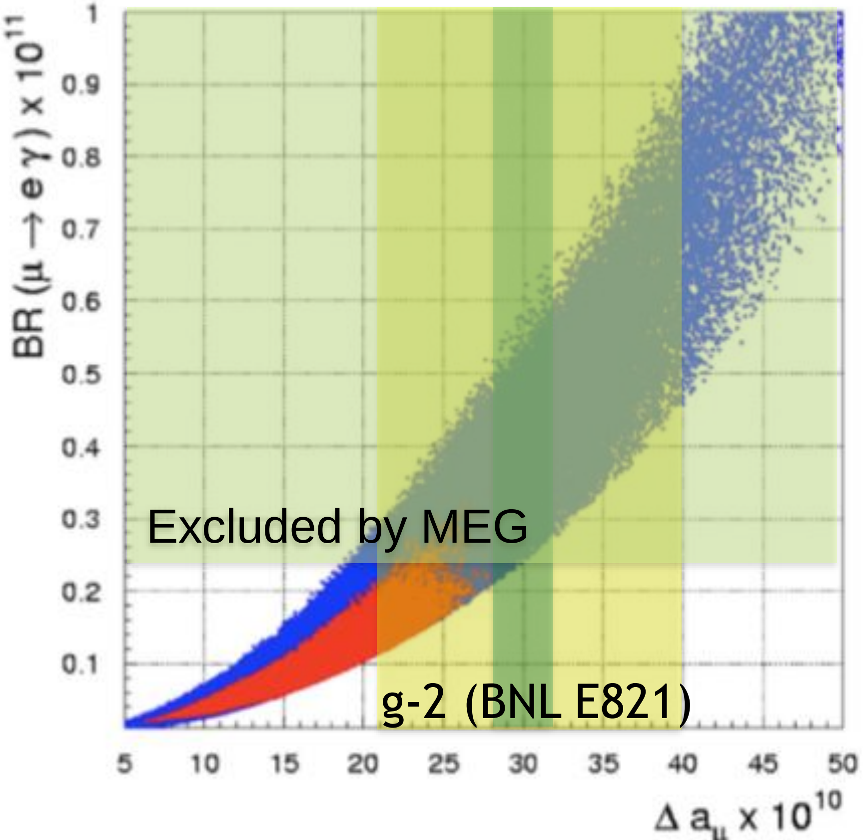
Transition Dipole Moments

cLFV process with photon radiation (e.g. $\mu \rightarrow e\gamma$)

g-2, EDM and cLFV in SUSY

- **Large g-2 → Large cLFV**

G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019

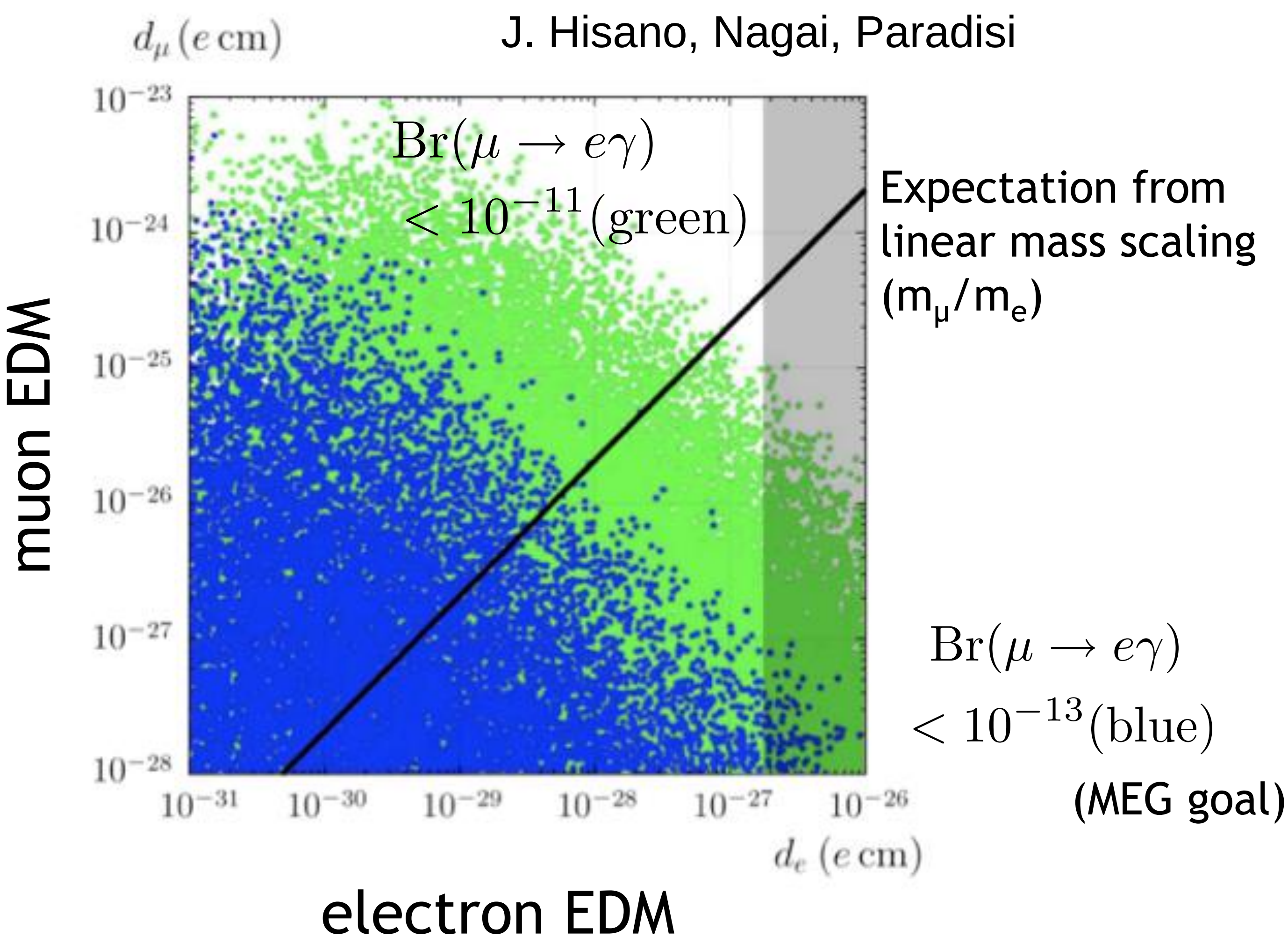


deviation from SM (g-2)

g-2, EDM and cLFV in SUSY

- **Large g-2 → Large cLFV → Large EDM**

J. Hisano, Nagai, Paradisi



Experimental status

Past - Present

Future

LFV

MEG (PSI)

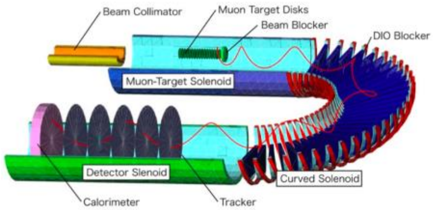
μ→eγ

Renewing upperlimit

Br < 2.4 E-12

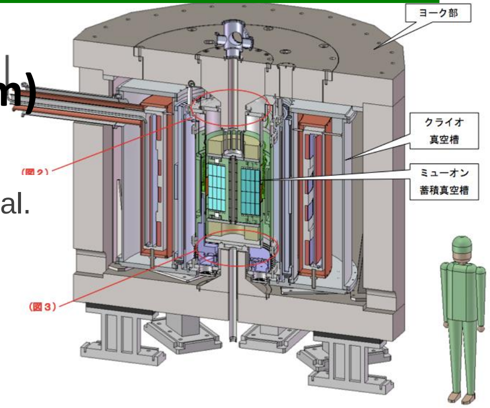
Discovery in horizon

μ-e conv :COMET(J-PARC), mu2e (FNAL)
μ→eee (PSI)



Next stage

g-2/EDM (J-PARC,FNAL)



g-2
EDM

E821 (BNL)

g-2

$\mathbf{a_\mu^{exp} = 11\ 659\ 208.9\ (6.3) \times 10^{-10}\ (0.5ppm)}$

$\mathbf{a_\mu^{SM} = 11\ 659\ 182.8\ (4.9) \times 10^{-10}}$

$\mathbf{a_\mu^{exp} - a_\mu^{SM} = +3.3\ \sigma}$

Hagiwara / Davier et al.

EDM

$\mathbf{d_\mu < 1.8\ E\text{-}19\ e\ cm\ (95\%CL)}$

Lepton dipole moments

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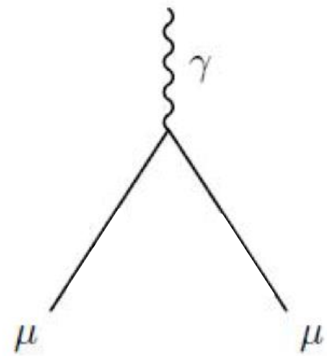
Transition Dipole Moments

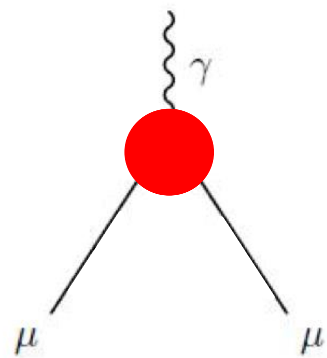
cLFV process with photon radiation (e.g. $\mu \rightarrow e\gamma$)

Anomalous magnetic moment

- The Lande's *g* factor is 2 in tree level (Dirac equation)



- In quantum field theory, *g* factor gets corrections:



Anomalous magnetic moment

$$g = 2\,(\,1 + a_\mu)$$

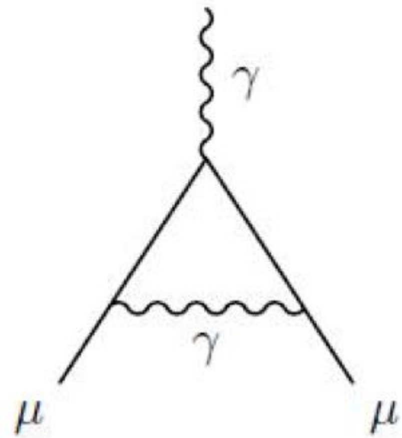
Anomalous magnetic moment

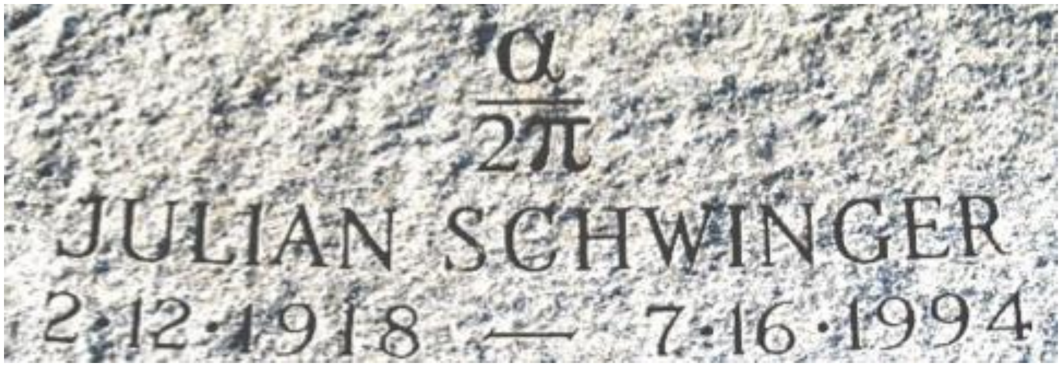
$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

All interactions, *including ones we don't know*, appear in quantum loops, and add up to contribute a_μ

QED contributions to a_μ

Leading order correction
(Schwinger term,1948)





From Lepton Moments (World Scientific, 2010)

Julian Schwinger

QED contributions to a_μ (cont.)

M. Hayakawa (tau2012)

$$a_l(\mathrm{QED}) = a_l^{(2)} \times \frac{\alpha}{\pi} + a_l^{(4)} \times \left(\frac{\alpha}{\pi}\right)^2 + a_l^{(6)} \times \left(\frac{\alpha}{\pi}\right)^3 + a_l^{(8)} \times \left(\frac{\alpha}{\pi}\right)^4 + a_l^{(10)} \times \left(\frac{\alpha}{\pi}\right)^5 + \cdots .$$

Table: $a_\mu(\mathrm{QED})$ at each order $2n$, scaled by 10^{11}

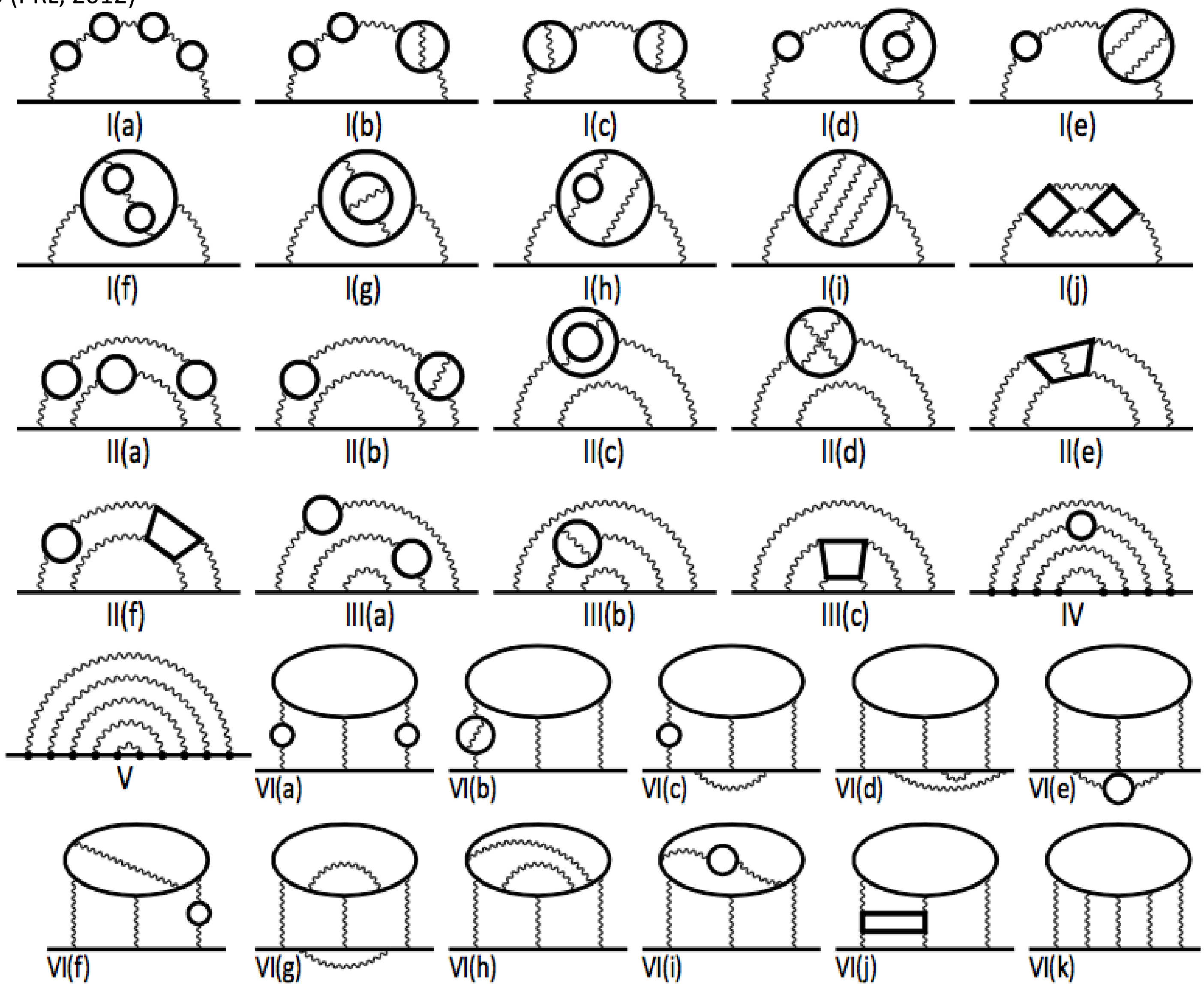
order $2n$	using $\alpha(\mathrm{Rb})$	using $\alpha(a_e)$
2	116 140 973.318 (77)	116 140 973.213 (30)
4	413 217.6291 (90)	413 217.6284 (89)
6	30 141.902 48 (41)	30 141.902 39 (40)
8	381.008 (19)	381.008 (19)
10	5.0938 (70)	5.0938 (70)
sum	116 584 718.951 (80)	116 584 718.846 (37)

NEW!

QED contributions to a_μ (cont.)

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRL, 2012)

10^{th}
12672
diagrams

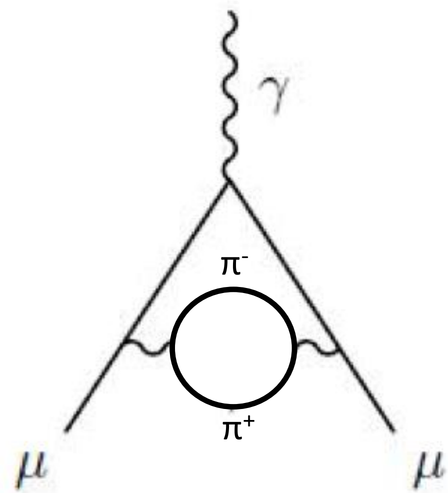


Prof. T. Kinoshita giving a lecture at KEK on 10th order QED corrections

Sohtaro Kanda (U. Tokyo, Master’s course student)
→ tomorrow’s speaker

Hadronic contributions to a_μ

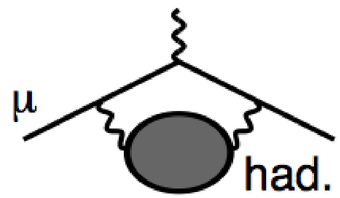
An example of
Leading order
hadronic term



Theory requires inputs to photon-hadron coupling

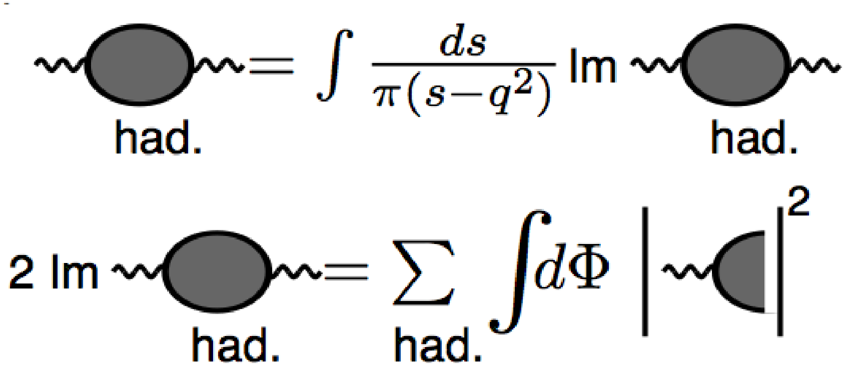
Accurate data on
"e+e- →γ^*→ hadrons" data (VEPP, BaBar, Belle, KLOE…)
has been used.

Hadronic contributions to a_μ



Coutesy
D. Nomura (tau2012)

pQCD not useful. Use the dispersion relation and the optical theorem.



$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds\, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$

- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

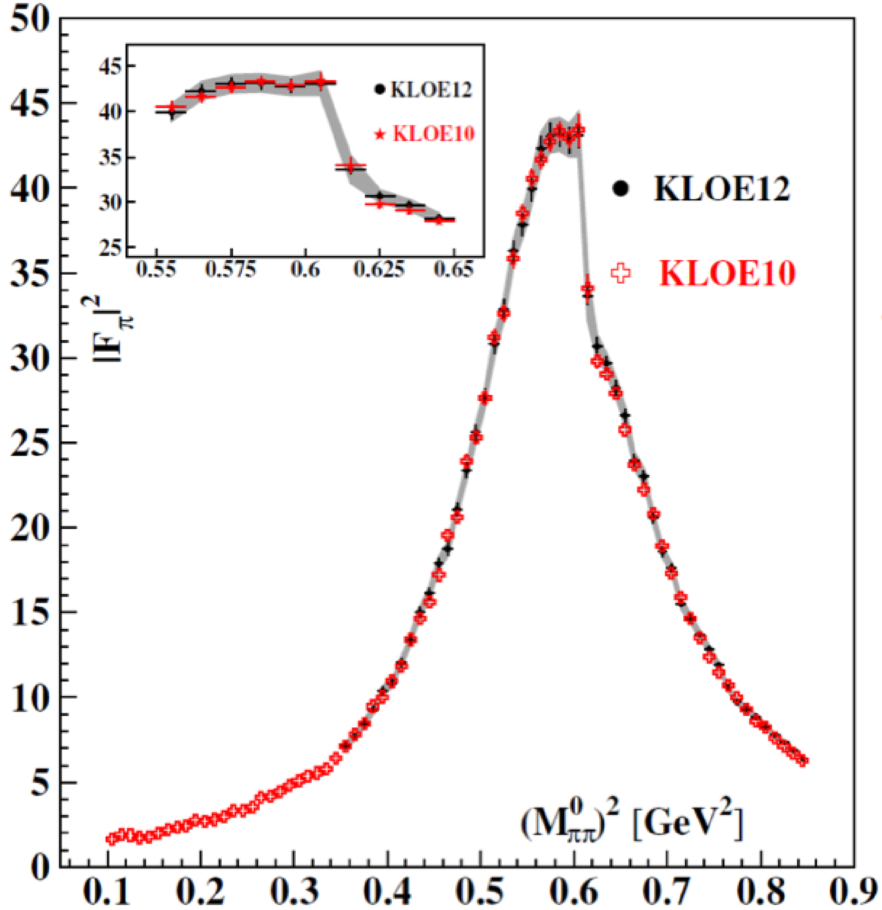
$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{had,LO}}$

Hadronic contributions to a_μ

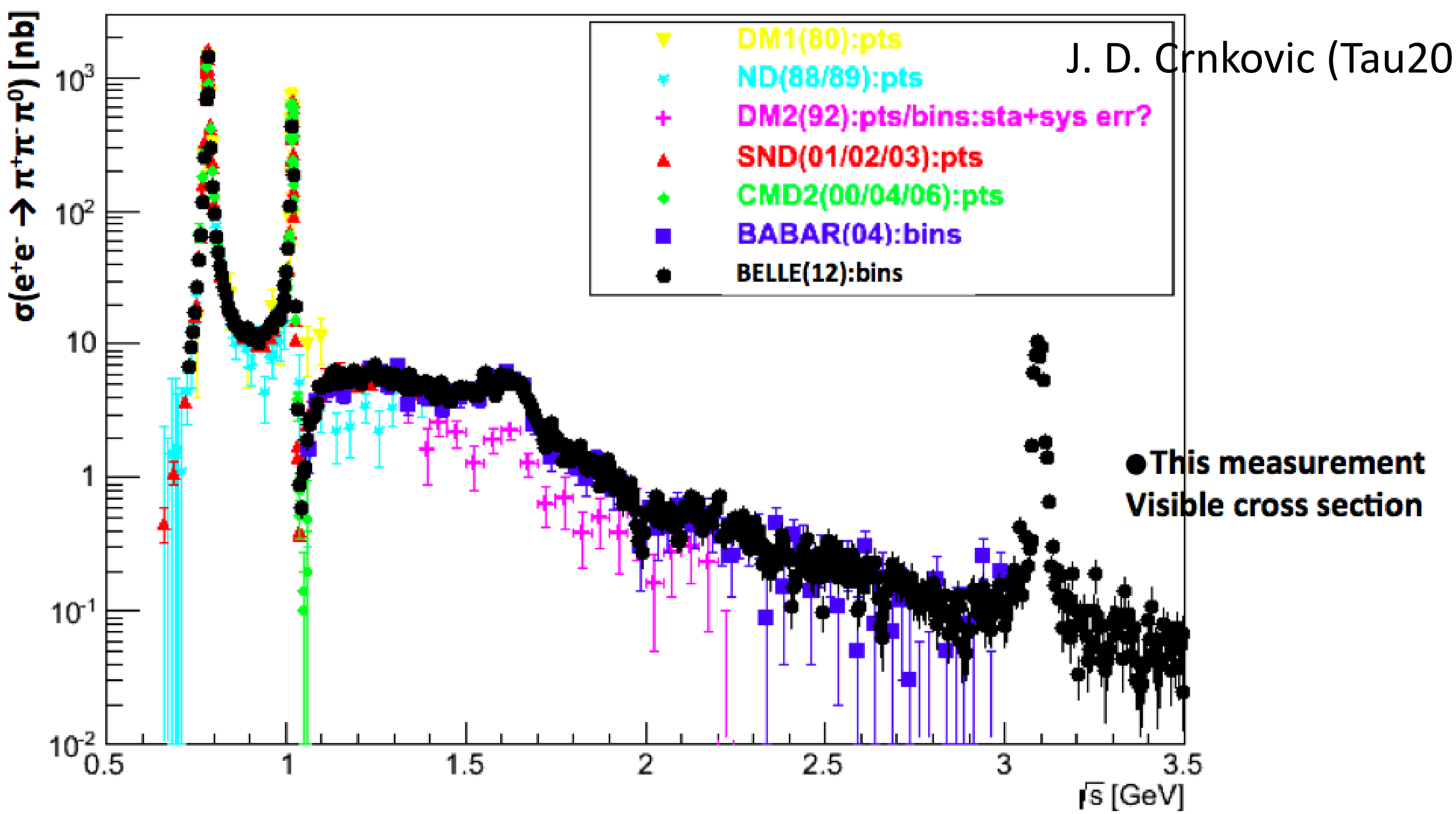
New data on $e^+e^- \rightarrow \pi^+\pi^-$ from KLOE

G. Mandaglio (tau2012)



Hadronic contributions to a_μ

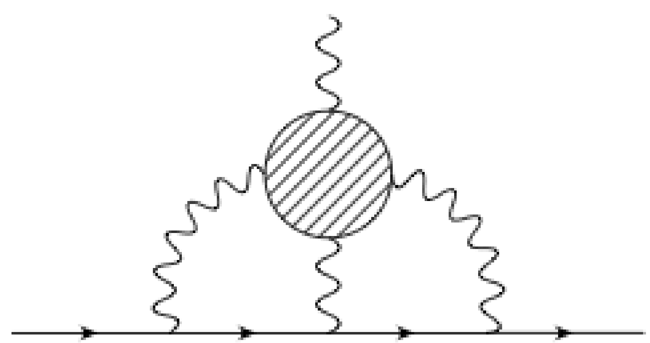
New data on $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ from Belle



J. D. Crnkovic (Tau2012)

Hadronic contributions to a_μ

- Lattice efforts making progress by Tom Blum et. al and other groups (UKQCD, ETMC, Mainz).
- Lattice is especially important for evaluation of light-by-light term, which no measurement can be done.

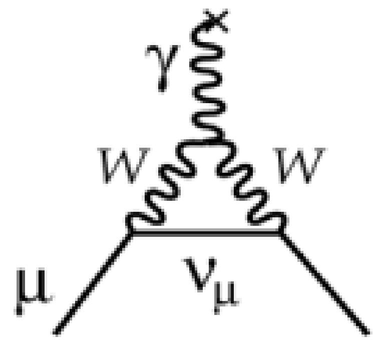


Blobs: all possible hadronic states

Courtesy Tom Blum

Electro-Weak contributions

Leading order
Electro-Weak loop



Relevant couplings have been accurately measured by the LEP experiments.

Contributions from Higgs-loop appears only in higher order.

Standard Model prediction for a_μ

D. Nomura (tau2012)

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	$\mathbf{694.9\ (4.3)} \times 10^{-10}$	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	$\mathbf{11\,659\,182.8\ (4.9)} \times 10^{-10}$	

(LO and NLO hadronic, HLMNT11:) in consistent with DHMZ10

HLMNT11 : J.Phys.G38:085003,2011

Comparison with experiments

D. Nomura (tau2012)

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	
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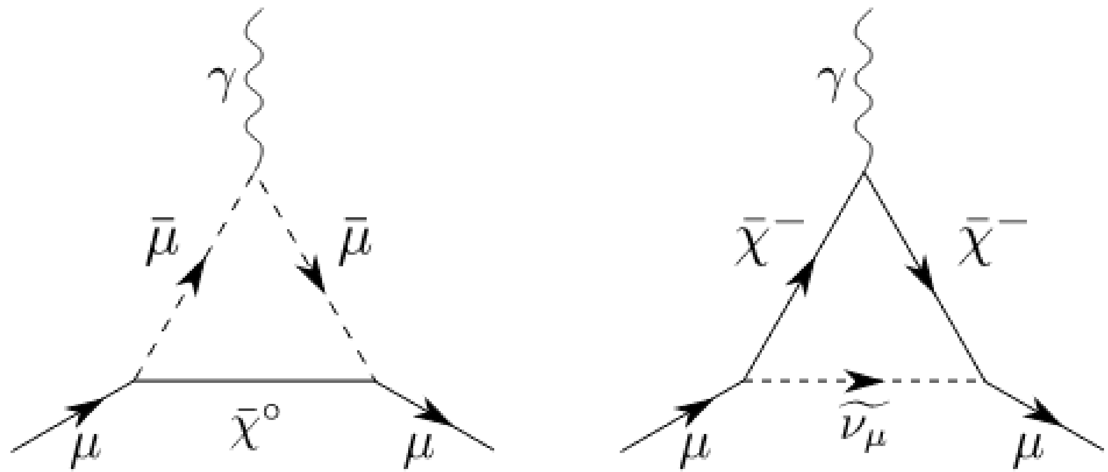
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein	
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$		
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg	**～BNL E821 (0.5ppm)**
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**	

HLMNT11 : J.Phys.G38:085003,2011

Beyond the standard model

Contributions from SUSY particles

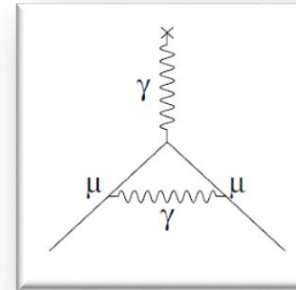


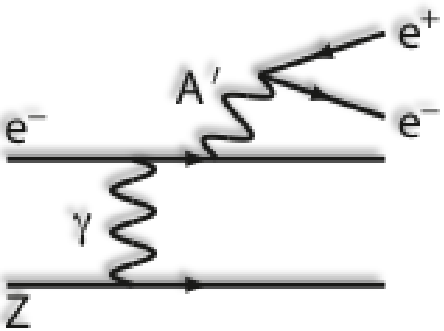
$$\left|a_\mu^{\mathrm{SUSY}}\right| \simeq 130 \times 10^{-11} \left(\frac{100\ \mathrm{GeV}}{\widetilde{m}}\right)^2 \tan\beta,$$

Present uncertainty (exp + SM) : $\Delta a_\mu = 80 \times 10^{-11}$

New Opportunity: Search for A' at Jefferson Lab

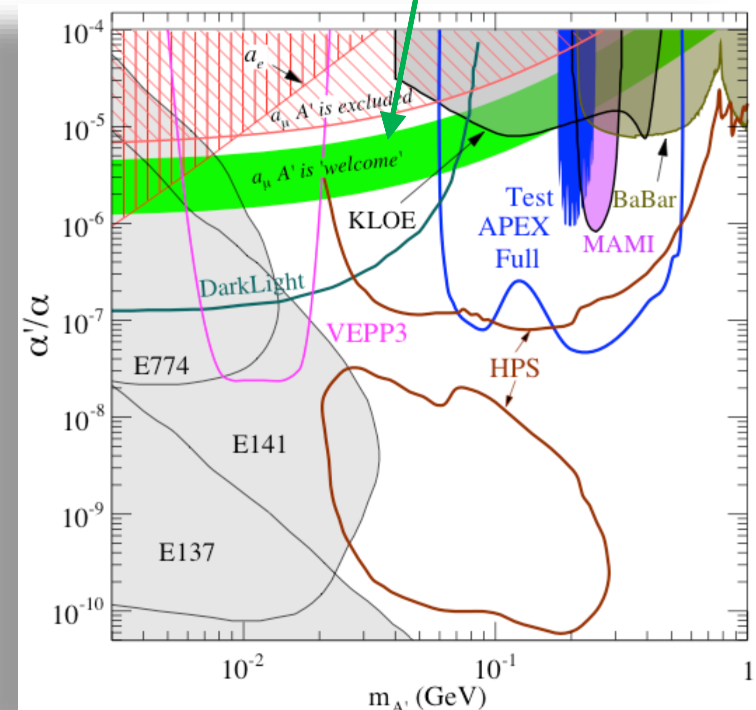
- **BNL "g-2" expt: Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)**
- **No evidence for SUSY at LHC (yet)**
- **Another solution: A', a massive neutral vector boson**





  - **also useful for dark matter models**

g – 2 preferred!



- **3 Jefferson Lab proposals:**
  - APEX test run (Hall A) – published
  - HPS test run (Hall B) – complete
  - DarkLight test run (FEL) – July 2012

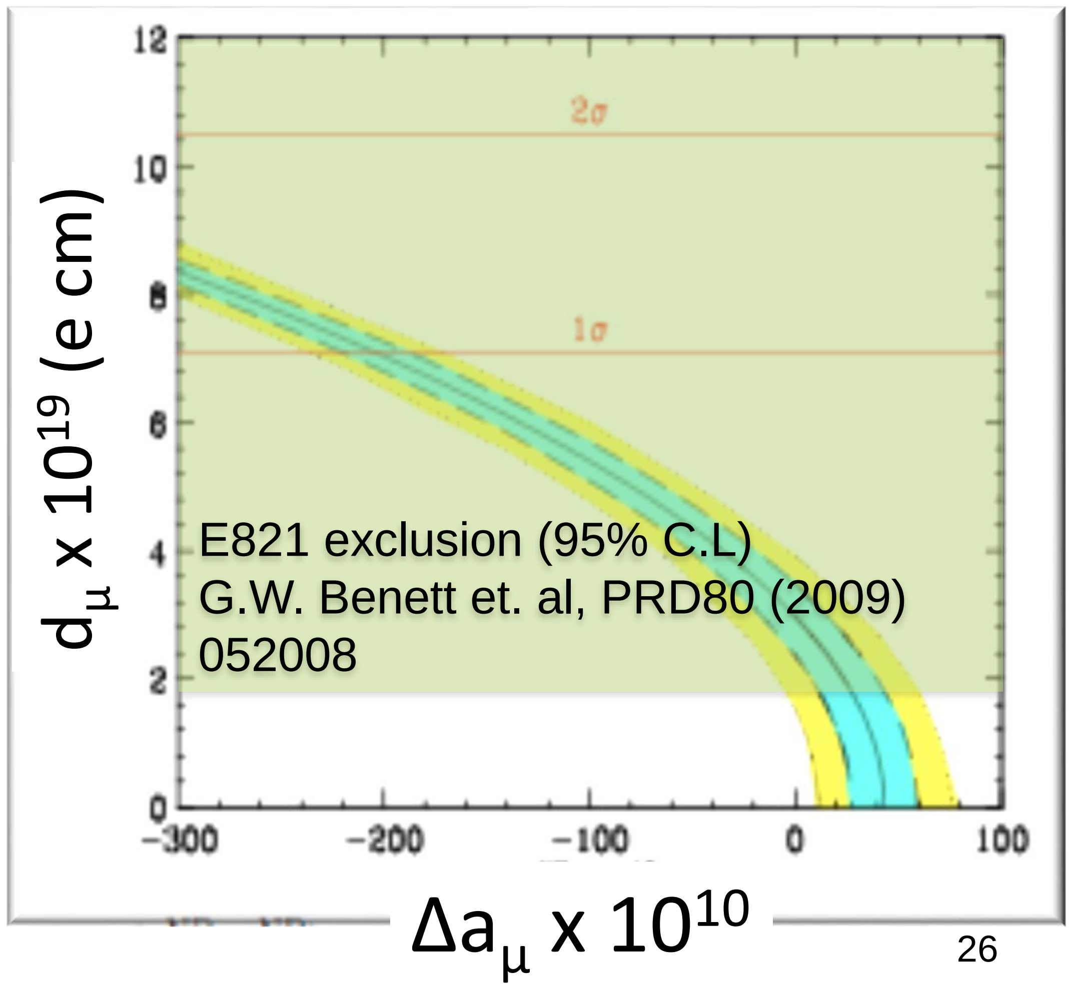
g-2 anomaly isn't?

- If the current deviation is fully from EDM?
  - J.L.Feng, K. T. Matchev, Y. Shadmi, NP B613 (2001) 366

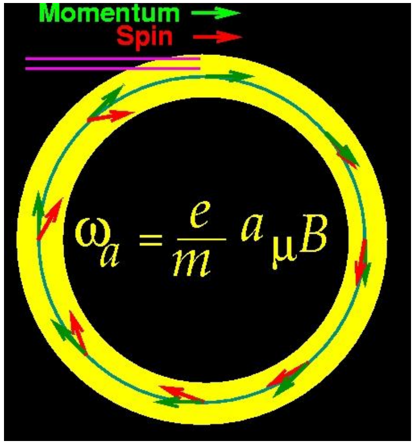
$$\vec{w} = \vec{w}_a + \vec{w}_{\mathrm{EDM}}$$

$$w = \sqrt{w_a^2 + w_{\mathrm{EDM}}^2}$$

Important to push sensitivity of EDM to test this scenario



muon g-2/EDM measurements



In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0

a_μ (= (g-2)/2) is deduced from this residual rotation (precession).
In general, spin also rotates due to $B_{eff} = \beta \times E$ and EDM.

general form of spin precession vector:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

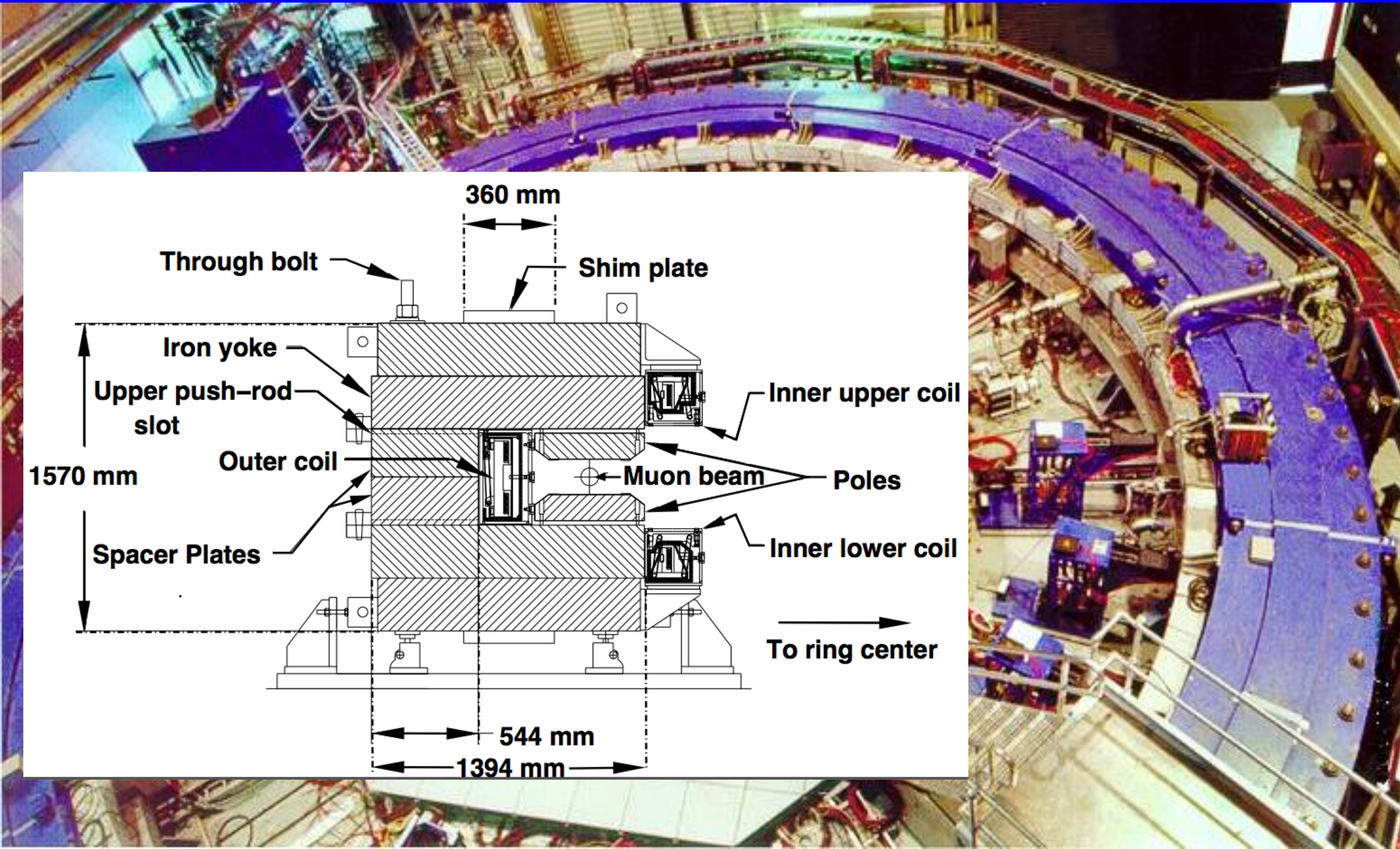
Continuation at FNAL with 0.1ppm precision

J-PARC approach
E = 0 at any γ

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

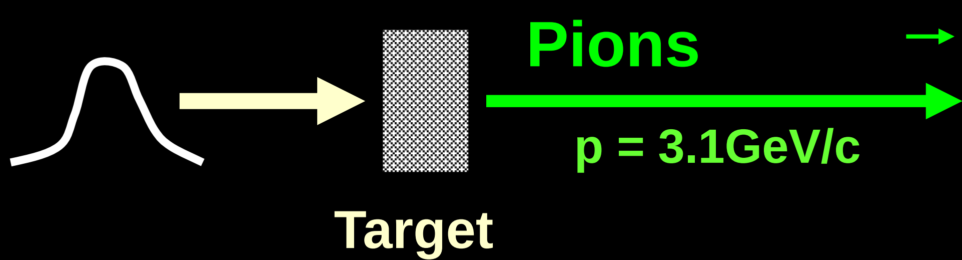
Proposed at J-PARC with 0.1ppm precision

The Experiment at BNL



E821 Experimental Technique

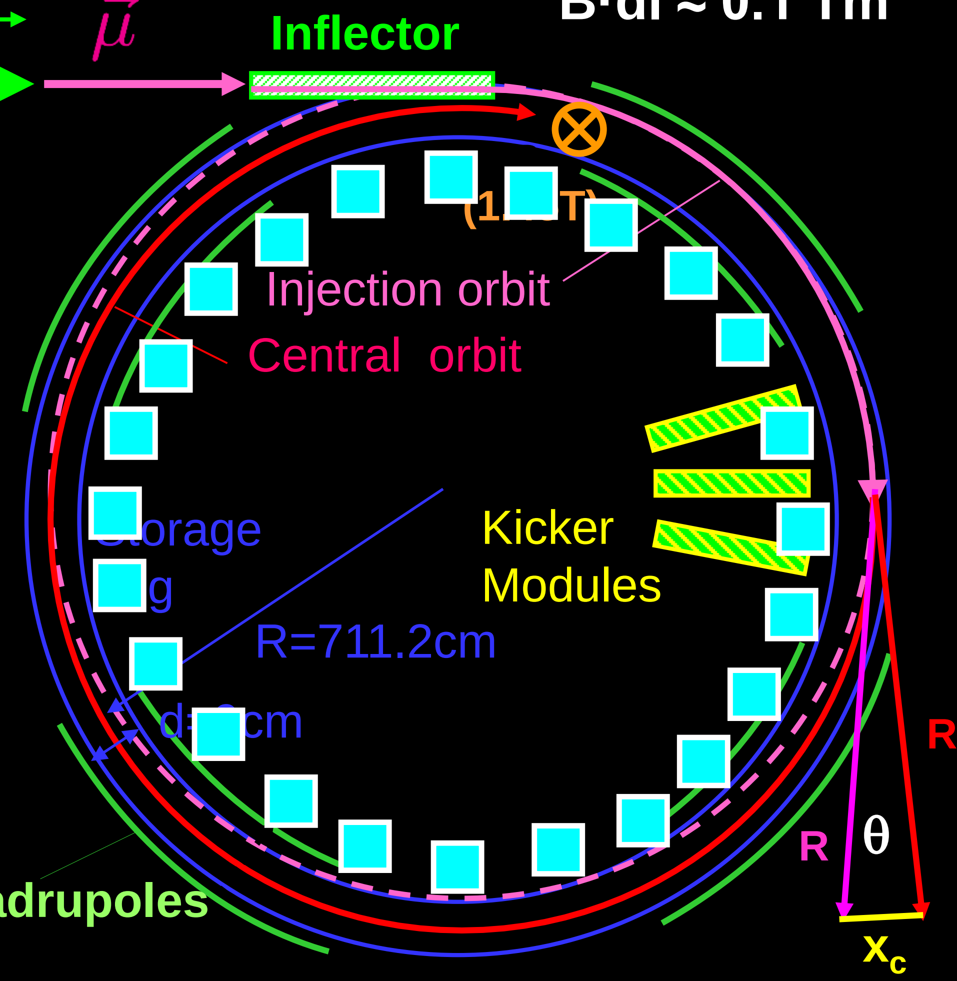
25ns bunch of
5 X 10^{12} protons
from AGS



$x_c \approx 77$ mm

$\theta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm



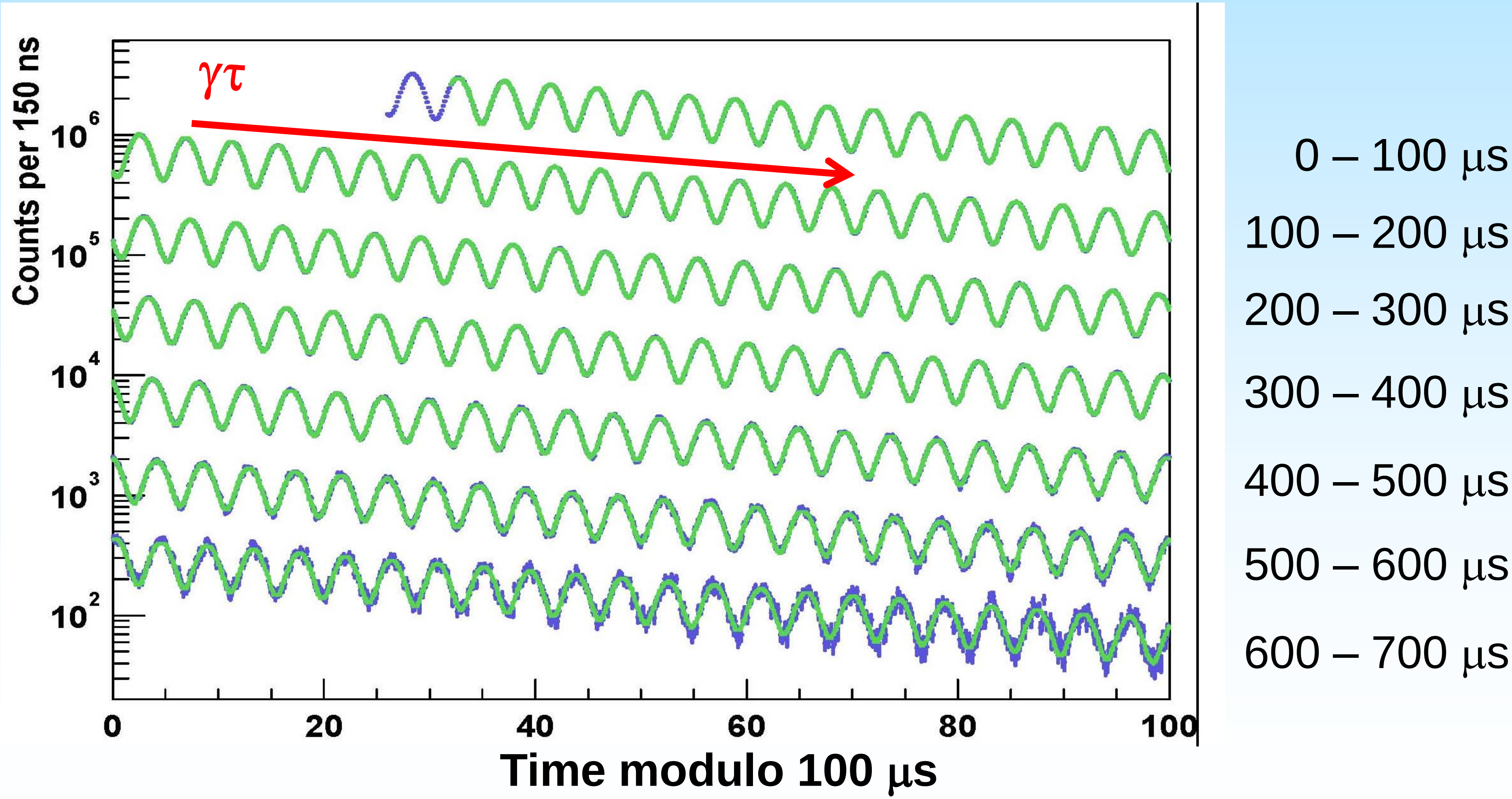
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

Arrival time spectrum

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

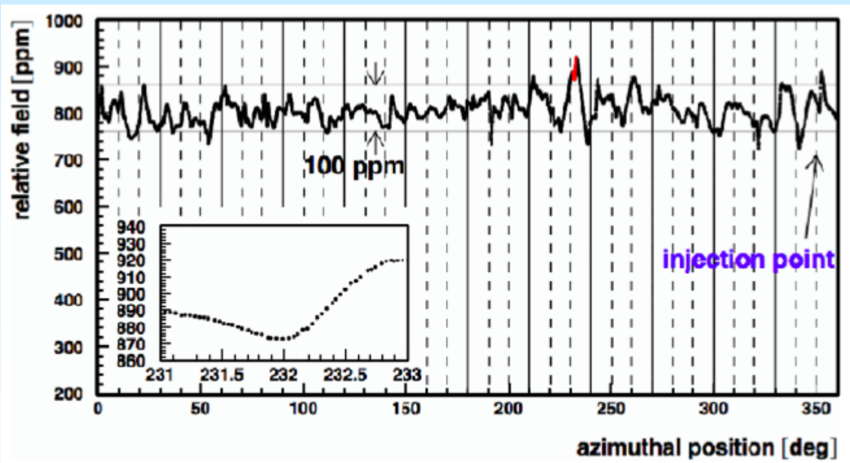
$$4 \times 10^9\ e^-,\ E_{e^-} \geq 1.8\ \mathrm{GeV}$$

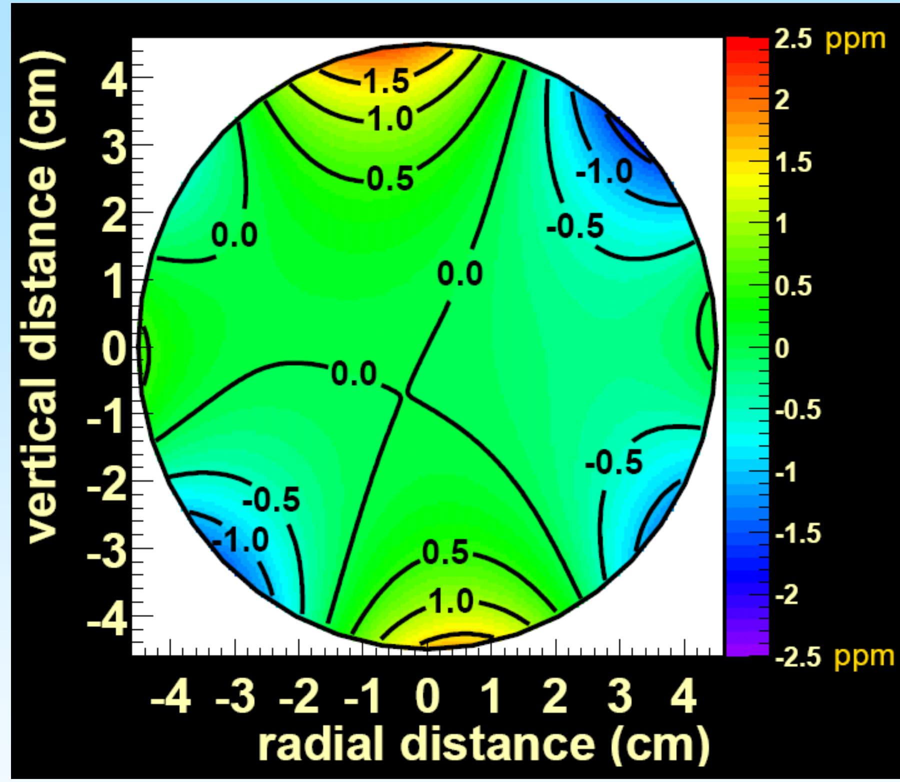


Average field uniformity ± 1 ppm

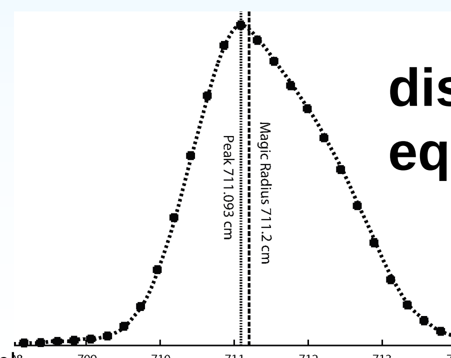
$$\langle B\rangle_{\text{azimuth}}$$

0.5 ppm contours



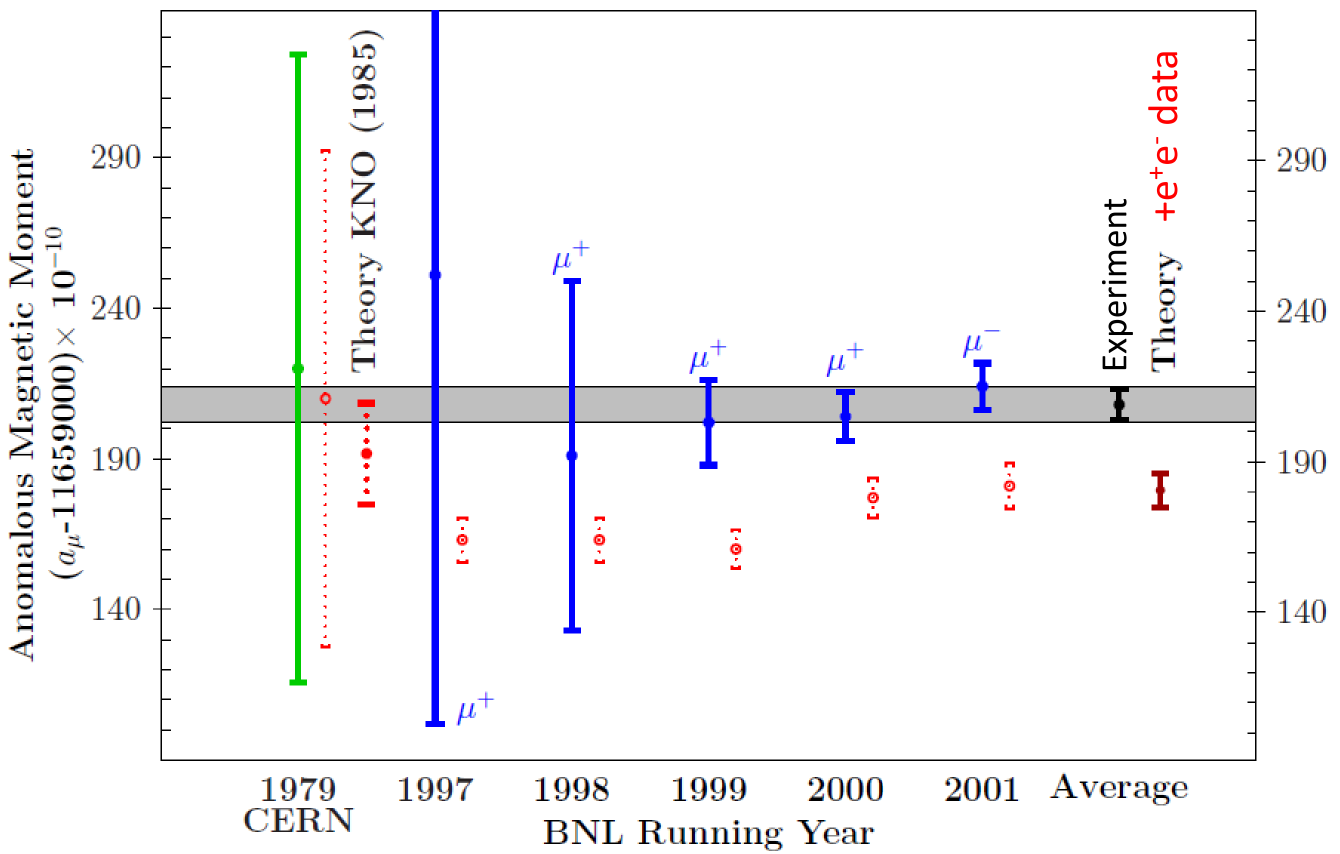


$$\sigma_{\text{syst}}\langle B\rangle_{\mu-\text{dist}} = \pm 0.03 \text{ ppm}$$



dist. of μ equil. radii

History of g-2 measurements



Courtesy F. Jergerlehner, arXiv:0902.3360

3.3 – 3.6 σ: Theory & Experiment must do better

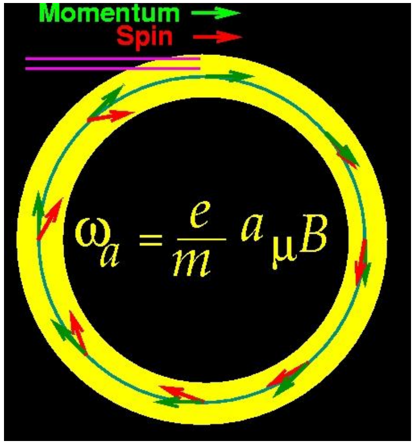
The New $g\!-\!2$ Experiment:

An experiment to Measure the Muon Anomalous Magnetic Moment

to ±0.14 ppm Precision

- Equal statistical and systematic errors of 0.1 ppm
- Experiment: E989 at Fermilab ≥ X4 better
  - relocate the storage ring to Fermilab
  - use the p-bar debuncher ring (now called the delivery ring) as a 1.9 m long decay line.
- Improve on E821 d_μ limit by factor of 100
- New detectors, electronics; improved B-field equipment muon kicker, etc
- CD0 received on September 18, 2012
- Building construction will begin in November 2012
- Ring transport in 2013 ?

muon g-2/EDM measurements



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γ=30 (P=3 GeV/c)

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Continuation at FNAL with 0.1ppm precision

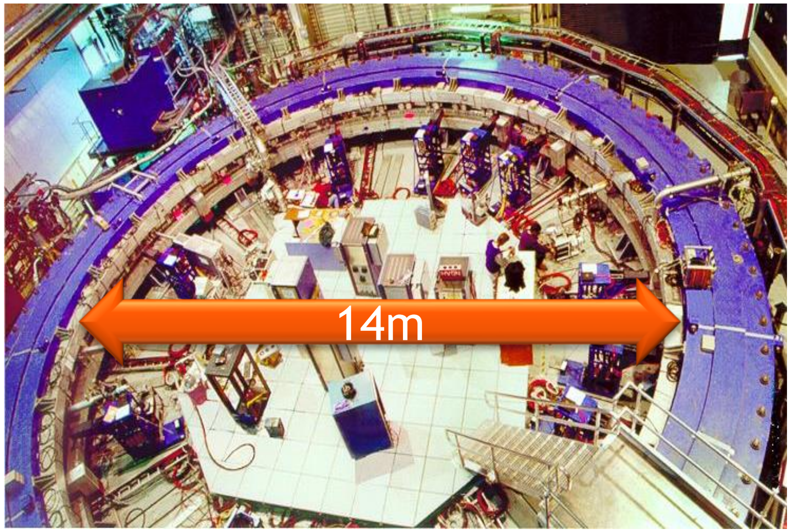
J-PARC approach
E = 0 at any γ

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

Proposed at J-PARC with 0.1ppm precision

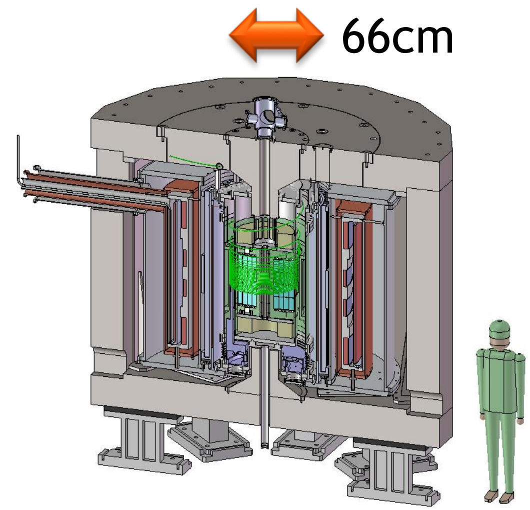
Lower energy and compact storage ring

BNL E821 / FNAL g-2



P= 3.1 GeV/c , B=1.45 T

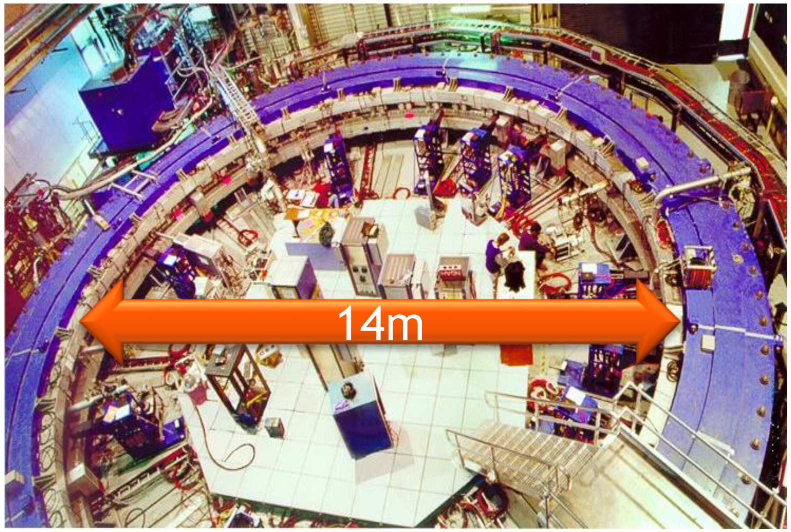
J-PARC g-2



P= 0.3 GeV/c , B=3.0 T

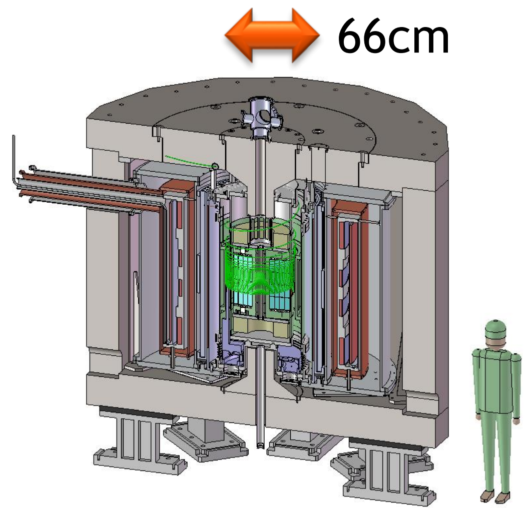
Lower energy and compact storage ring

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
  - Spin manipulation of muon beam
    - Effective to cancel various systematics
  - <u>Completely different systematics than the BNL E821 or FNAL</u>

Hitachi co.

Ultra-cold Muon

Requirement for zero E-field:

Muons should be kept stored without E-focusing

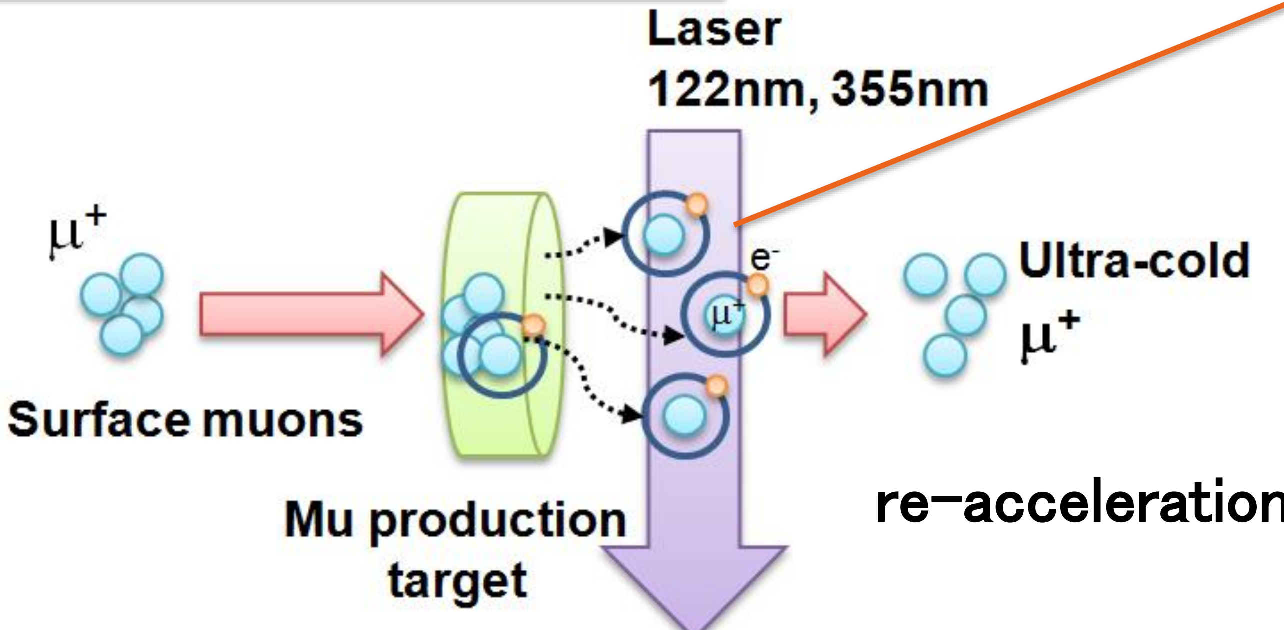
→ Beam with ultra-small transverse dispersion

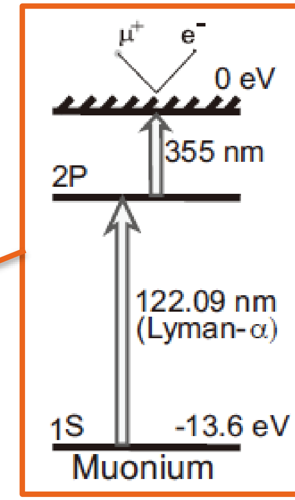
$\Delta p_T/p \sim 0$

Ultra-cold Muon

<u>Requirement for zero E-field:</u>
Muons should be kept stored without E-focusing
→ Beam with ultra-small transverse dispersion
$\Delta p_T/p \sim 0$

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



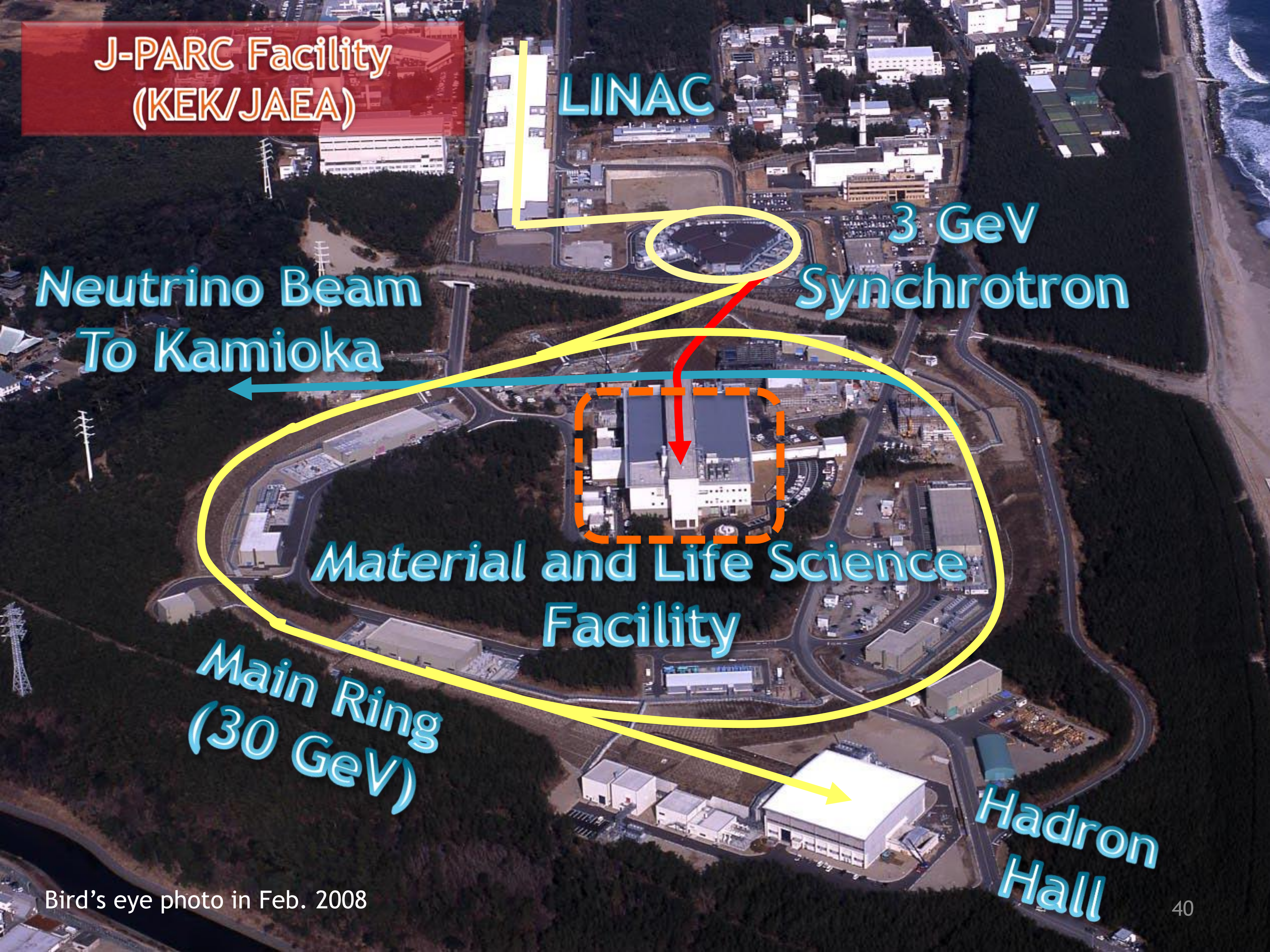


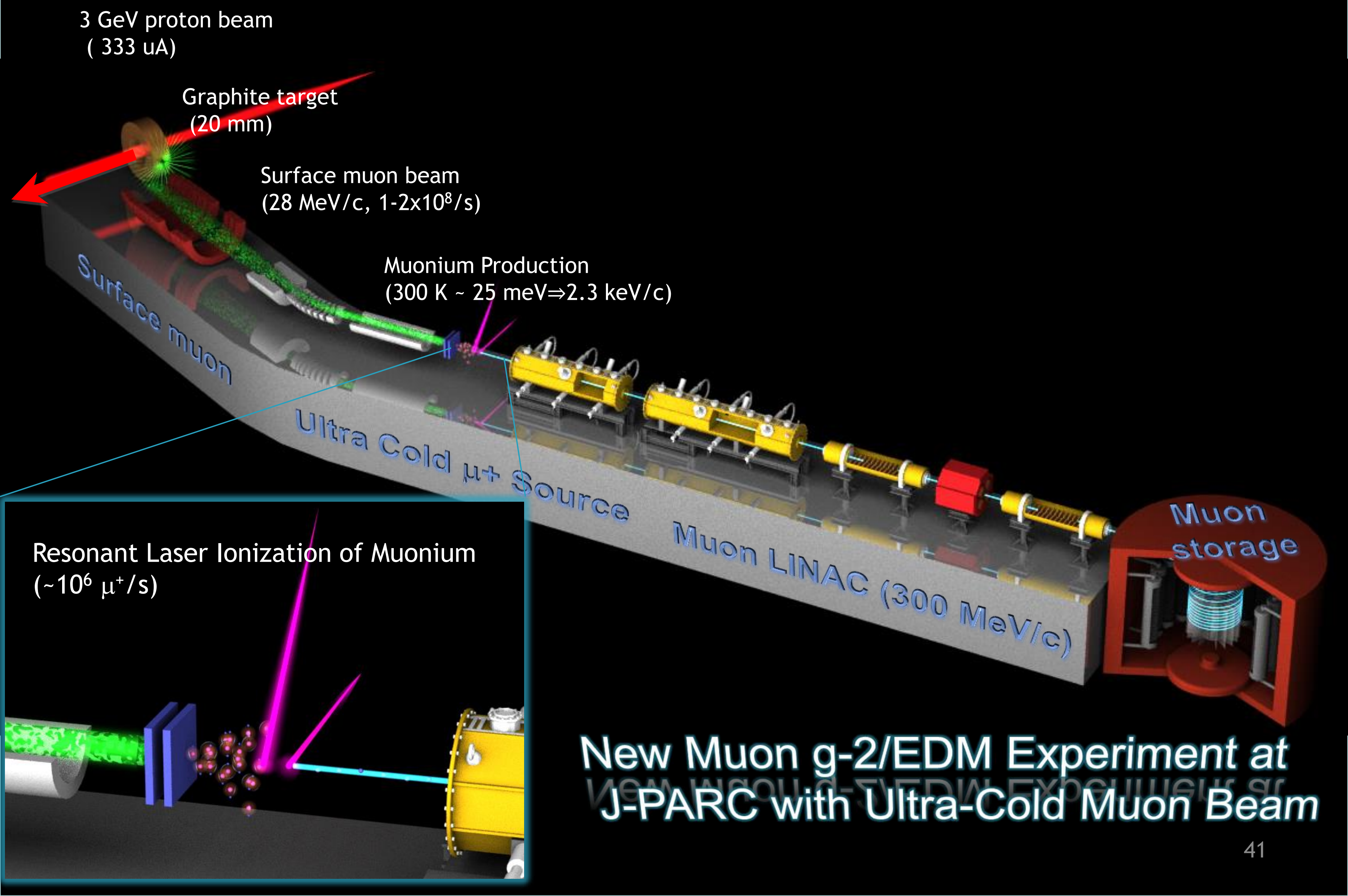
p = 28MeV/c   3 keV/c   300 MeV/c

$\Delta p_T/p \sim 3$ keV / 300 MeV =1E-5

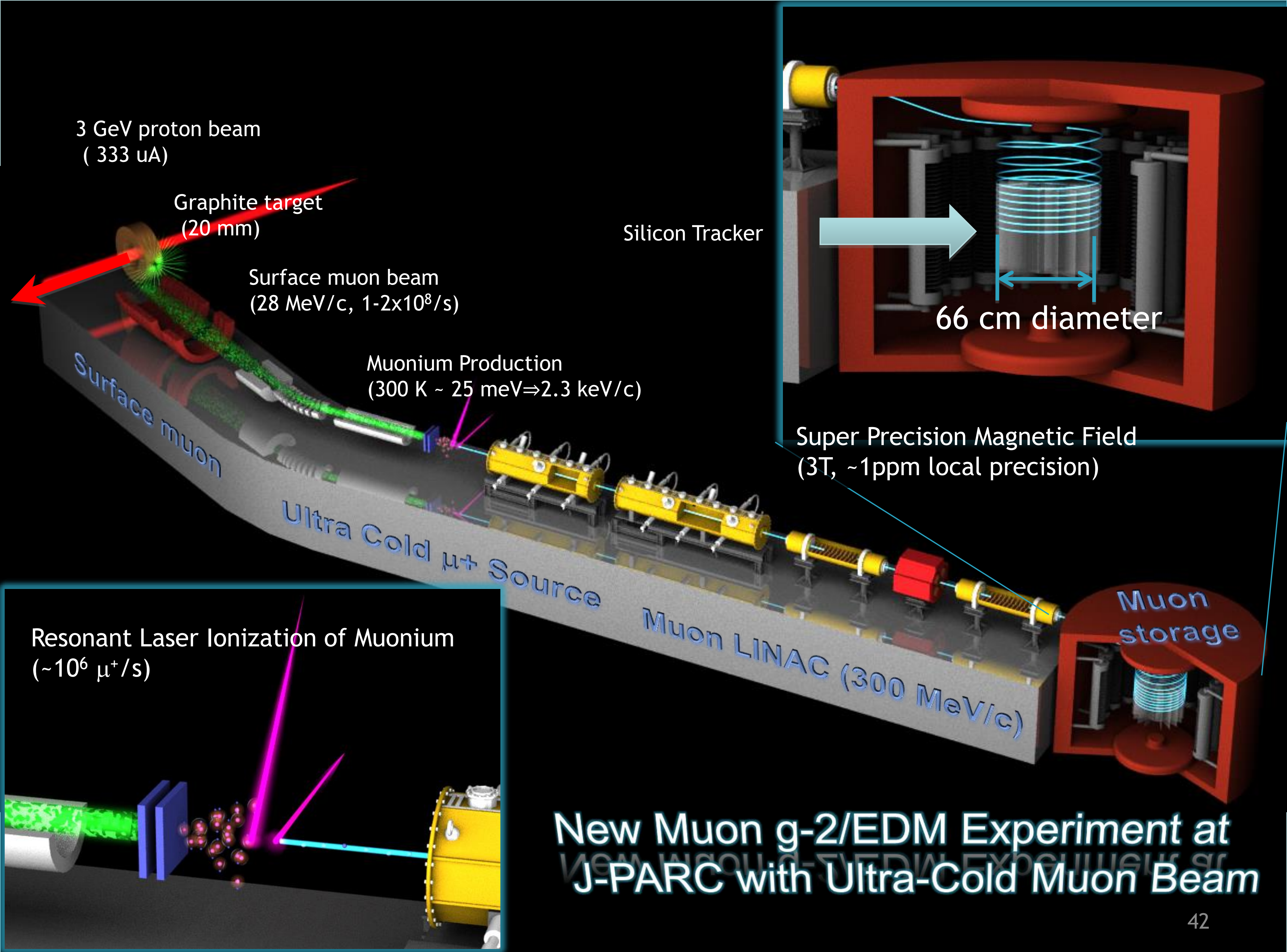
Comparison of experiments

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		Very weak magnetic
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV)
Hadron
Hall
Bird's eye photo in Feb. 2008



New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

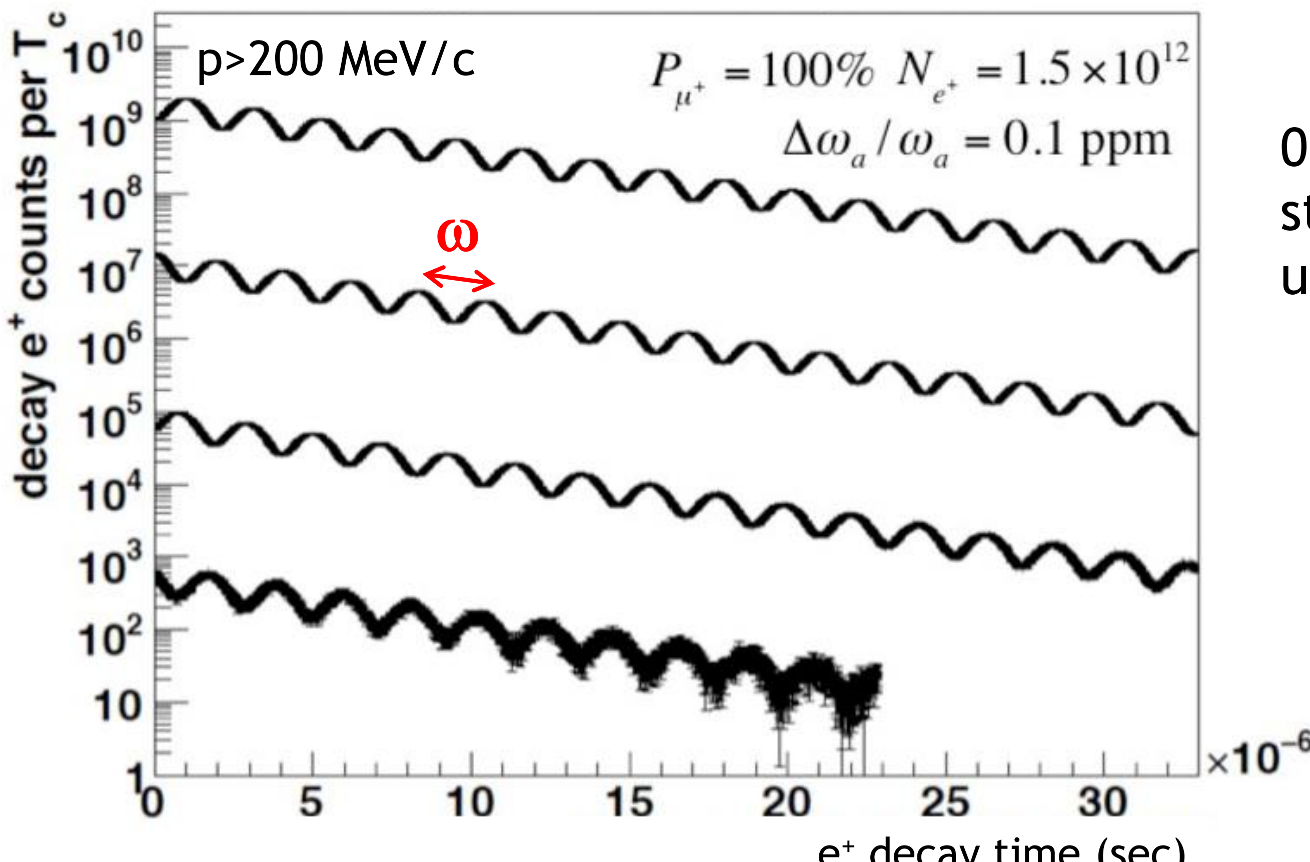

3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 1-2x10⁸/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Resonant Laser Ionization of Muonium
(~10⁶ μ⁺/s)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

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

Muon spin precesses with time.

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

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



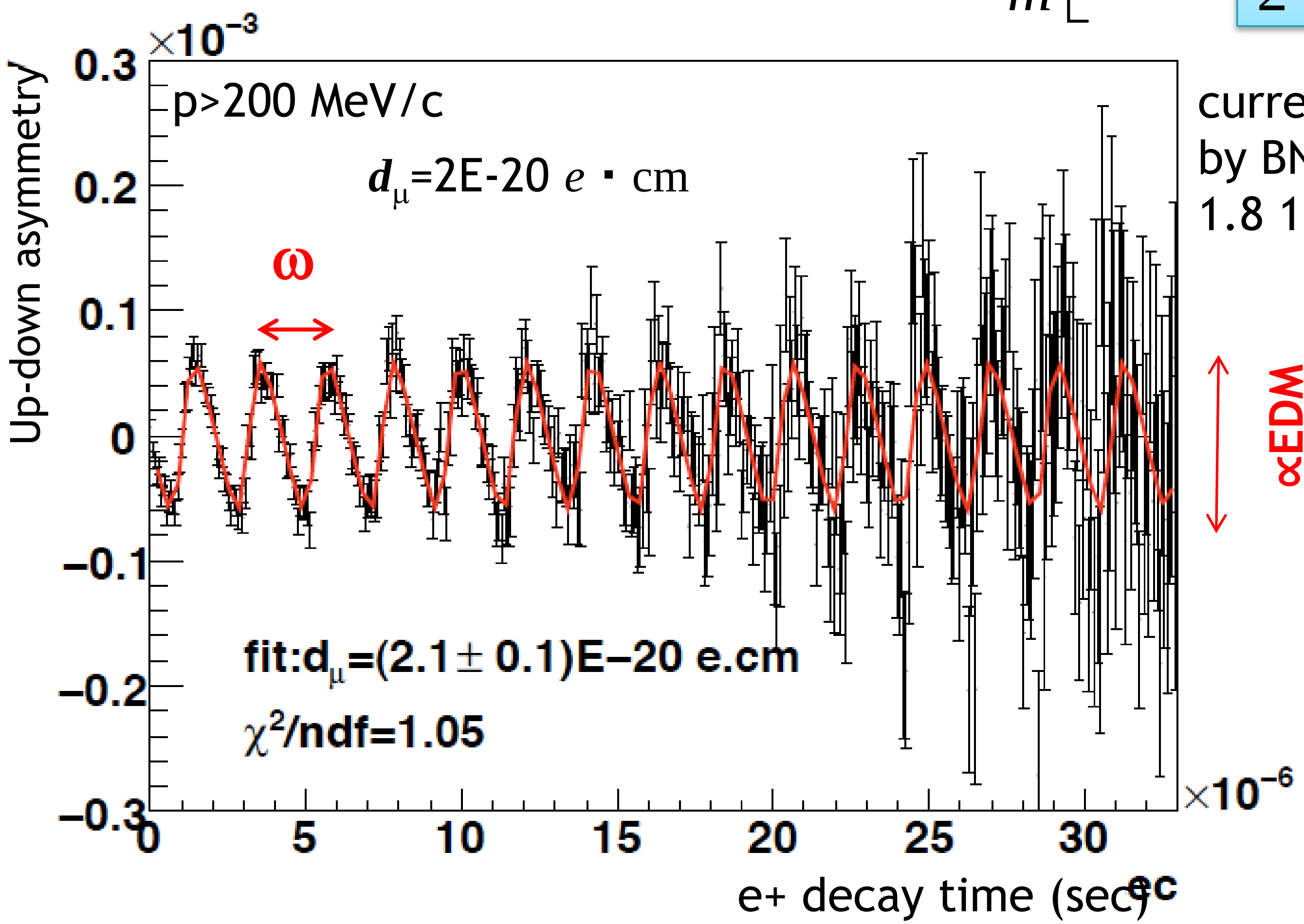
0.1ppm statistical uncertainty

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)

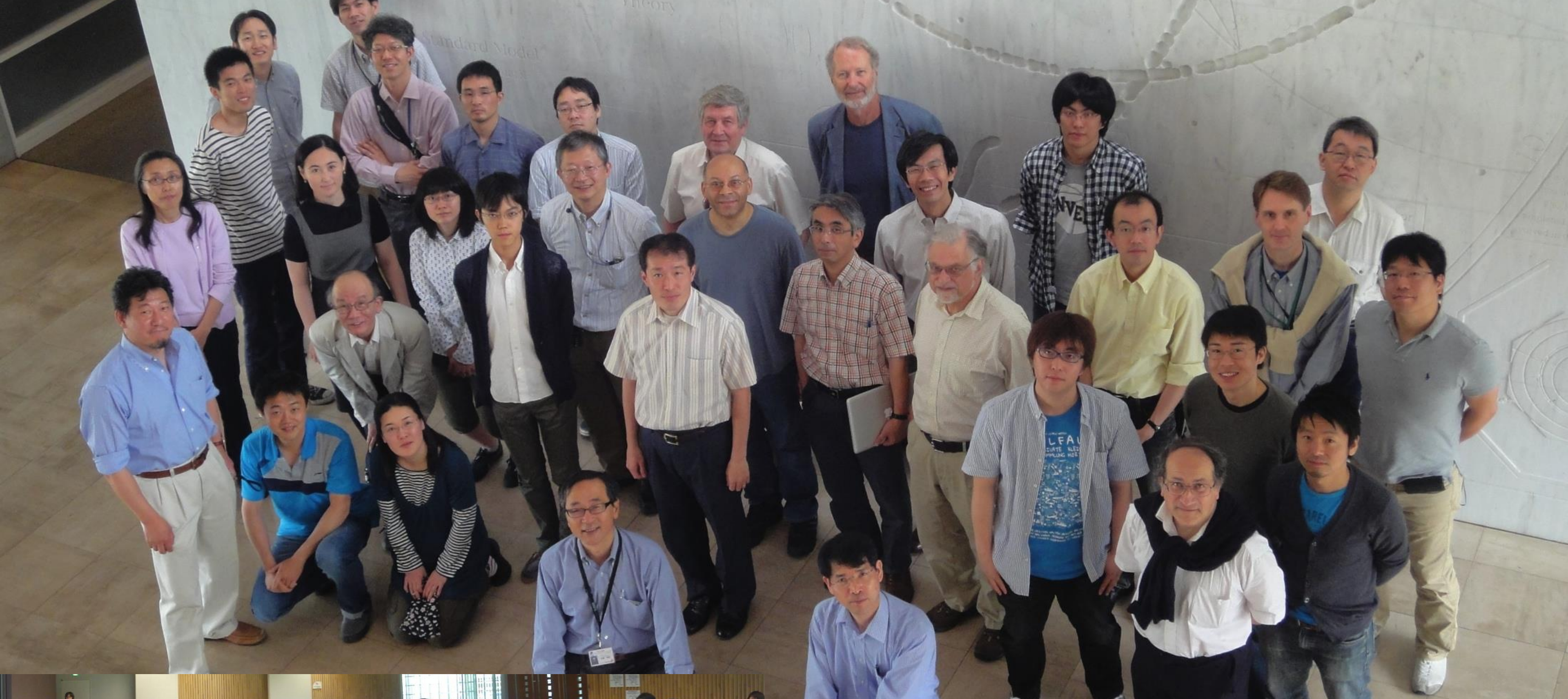
$$\vec{\omega} = -\frac{e}{m}\left[a_{\mu}\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$



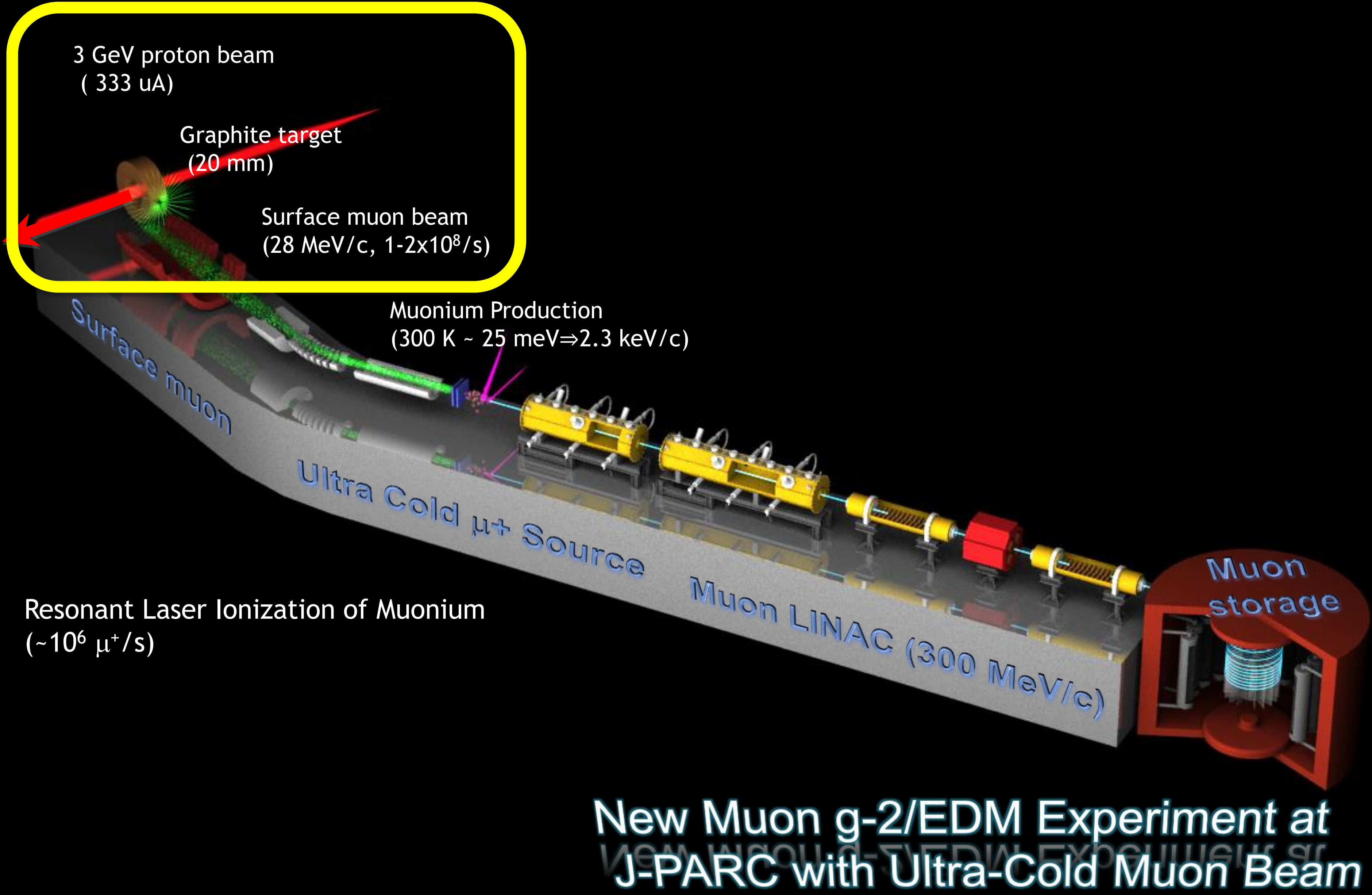
current upper limit by BNL E821 1.8 10^{-19} e · cm

The collaboration

- 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



Dec 2009 : Proposal submitted
Dec 2012 : CDR submitted
Jan 2012 : Stage-1 status granted from PAC (IMSS,IPNS)
P34 →E34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Graphite target
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(~10^6 μ+/s)
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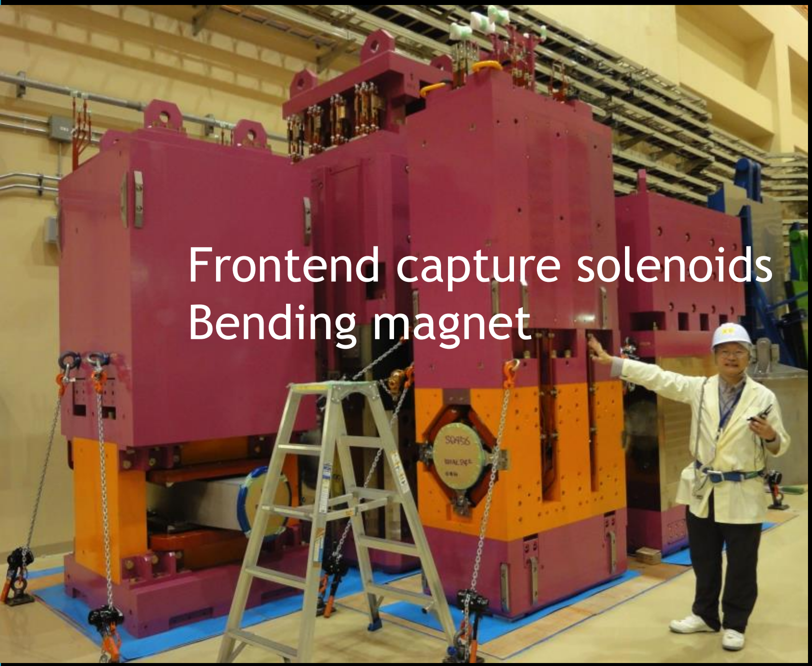
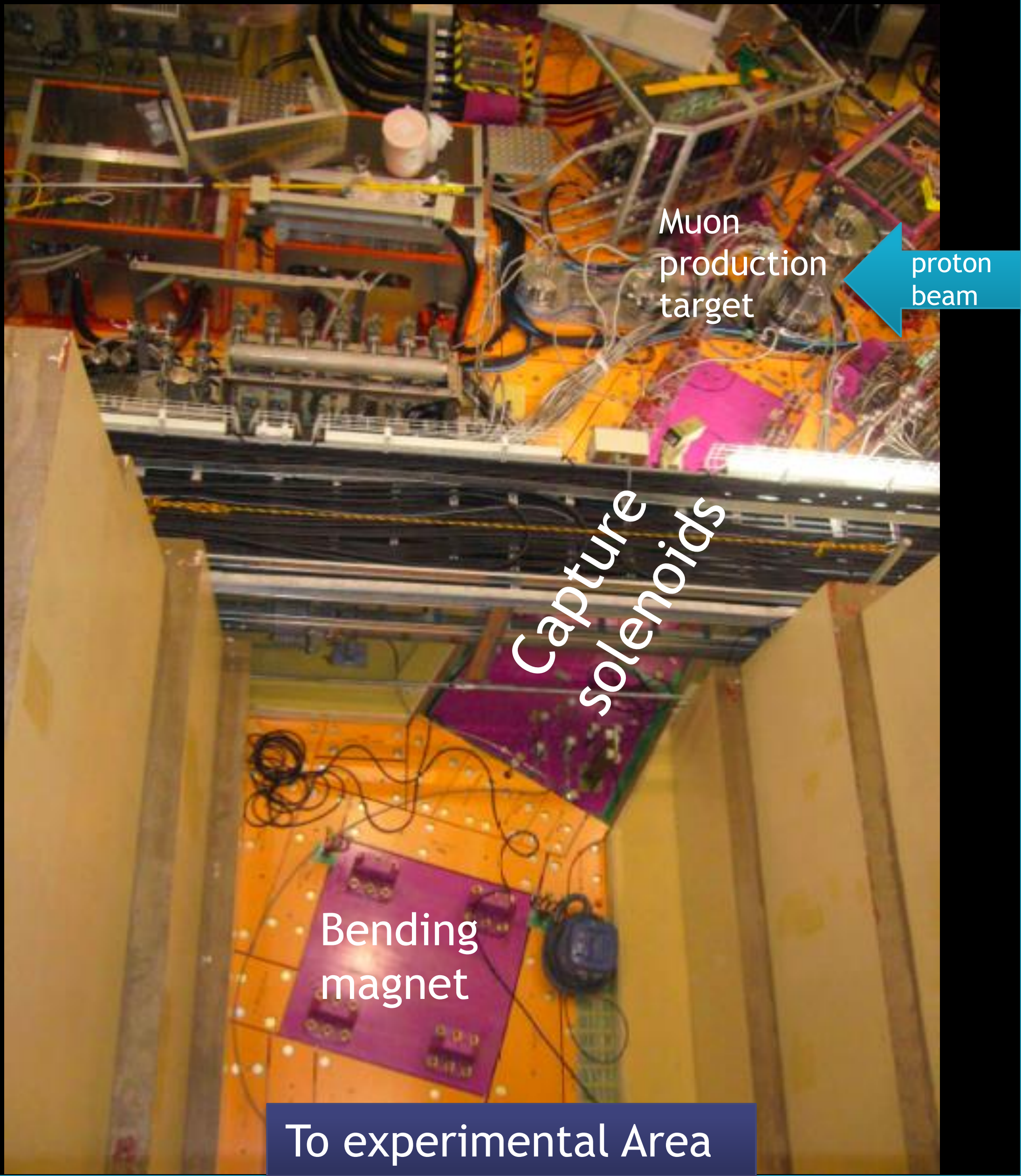
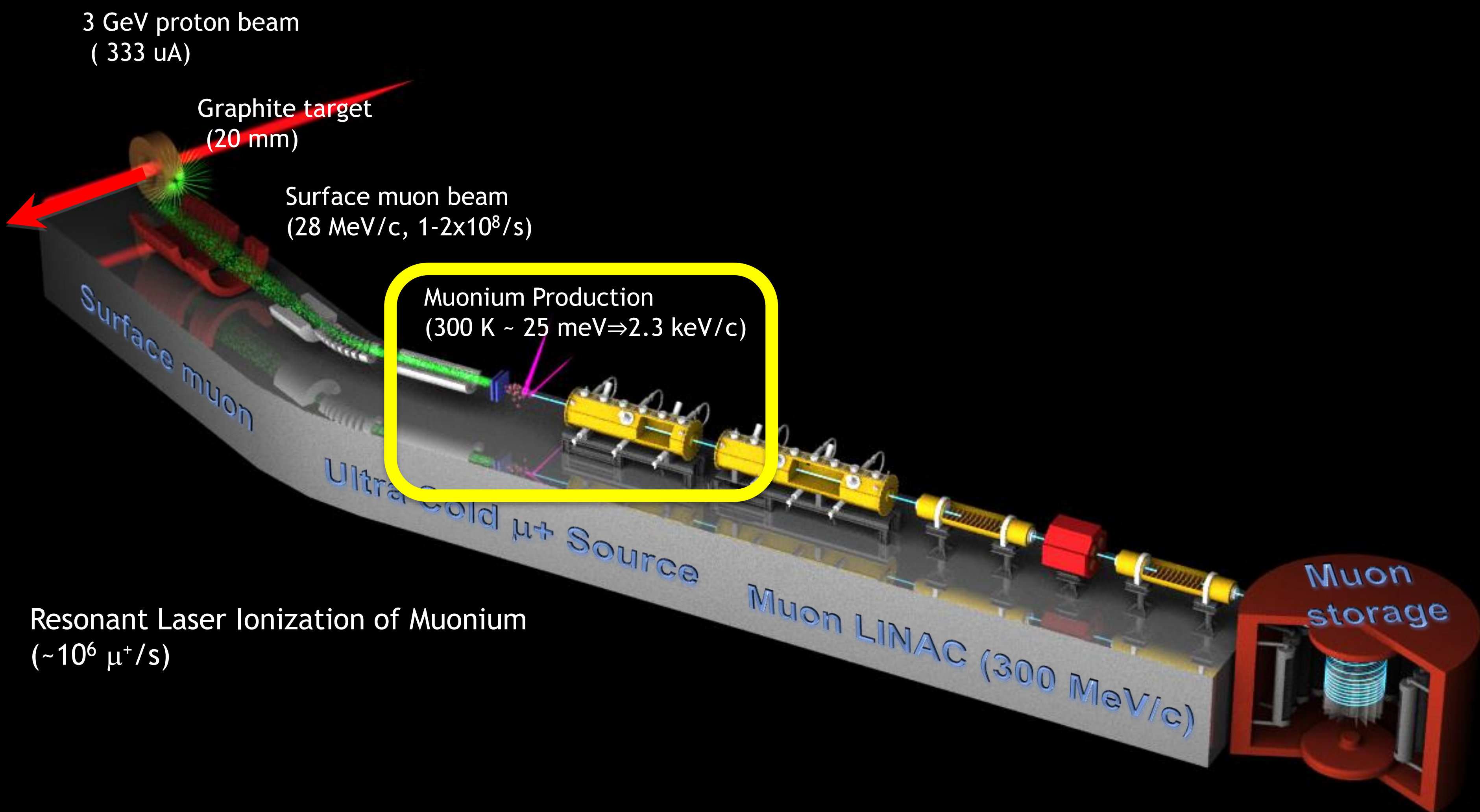
J-PARC with Ultra-Cold Muon Beam

H-Line construction at J-PARC

H-line construction at J-PARC



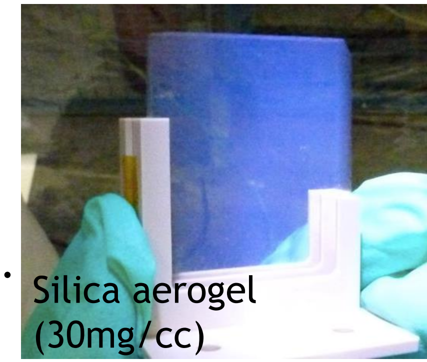


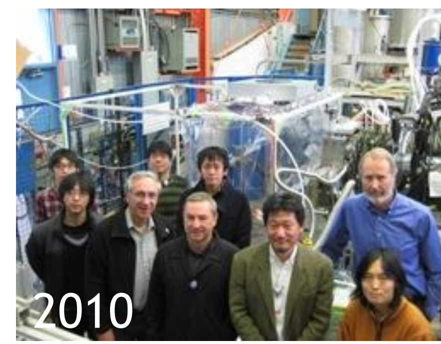


New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

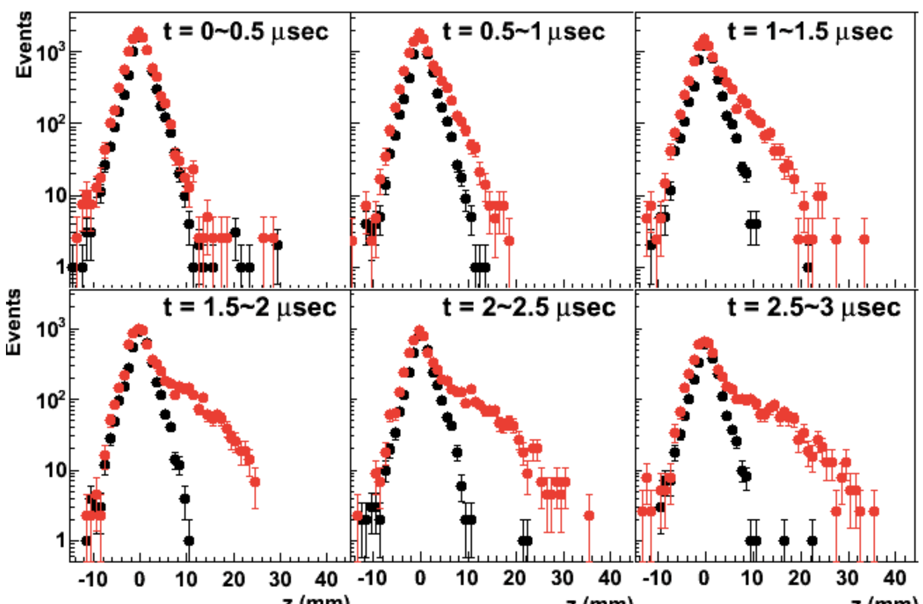
Development of Mu production target

- Silica powders (SiO_2)
  - known to be a good Mu emitter at room temp. (e.g. Used in Mu→anti-Mu conv. searches)
  - Not self-standing → difficulty in laser ionization.
- Silica aerogel
  - Similar structure of SiO_2 grain-network. Self-standing!
  - New data taken in TRIUMF S1249 experiment in 2010-2011
  - Vacuum emission confirmed. Diffusion parameters being extracted.
  - Next step → Optimization of structure (porous structure?, c.f. Antognini et al. (PRL108,143401,2012))





● Aerogel 29mg/cc
● BG



Development of Mu production target

- Metals
  - …mal emission of Mu (4%) from W at high …ture (T=2000K) (PRL, Mills et al)
  - W ha… …sed in laser ionization R&Ds at KEK-MSL and RIK…
  - Systematic s… …ith hot W in progress at RIKEN-RAL with upgra… … system (K. Yokoyama / D. Tomono et al.)

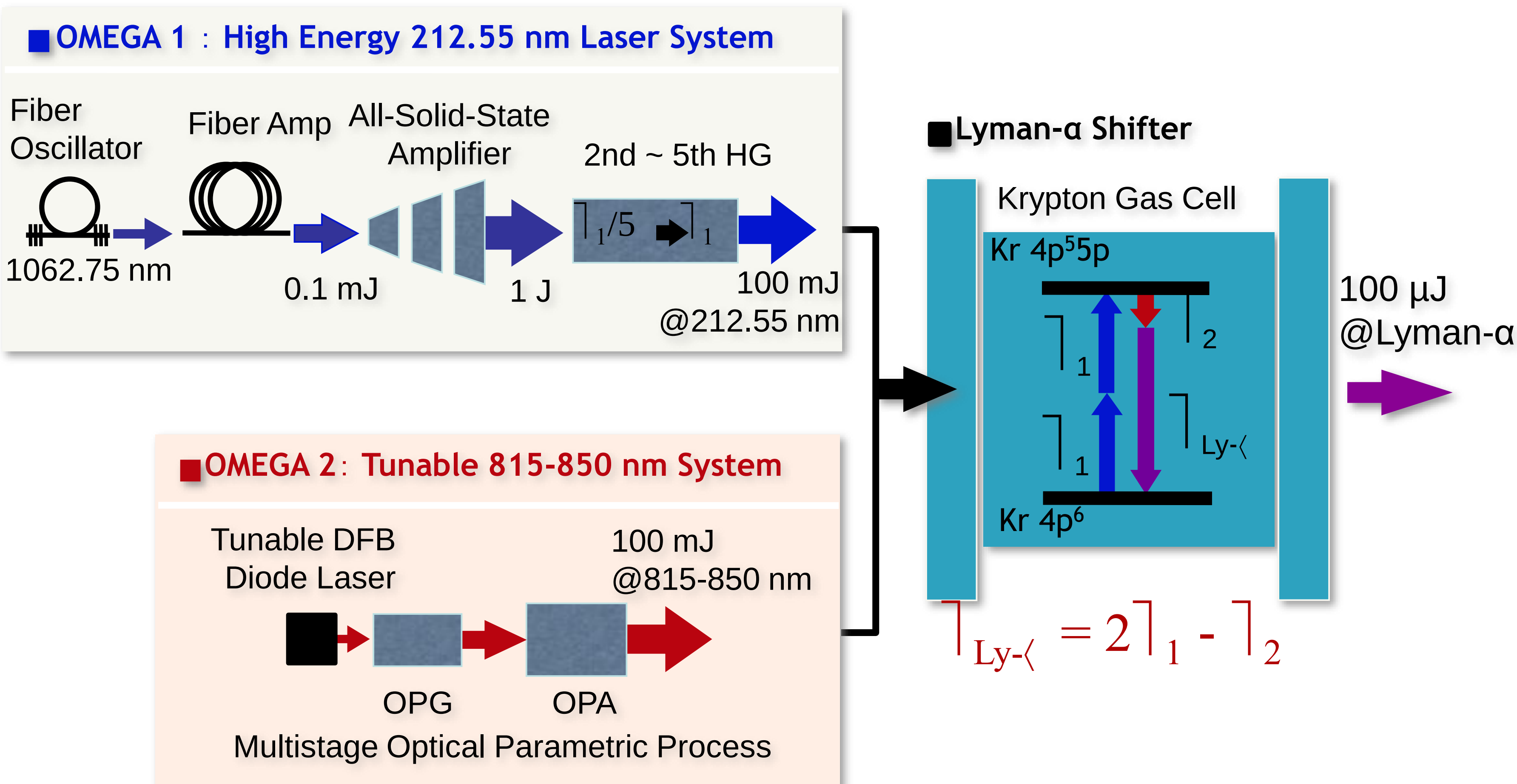
Heated W foil (RIKEN-RAL)

To be discussed tomorrow by S. Kanda

- R&D experiments at J-PARC.
  - J-PARC : The world highest pulse… …source.
  - A new apparatus to quickly study the … emission from various material is being commissi…
  - List of materials to be studied:
    - Hot W and other metals
    - Room temp W coated with alkali-metal (Na, Cs)
    - Room temp aerogel …

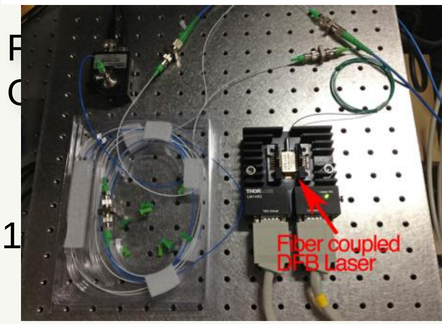
commissioning at D-Line/J-PARC

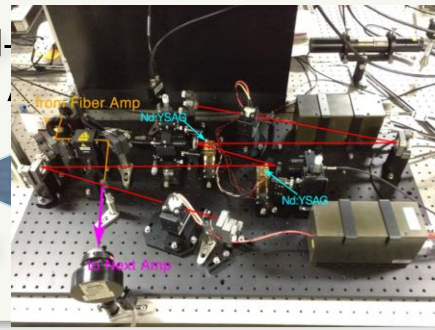
Lyman-α Generating System



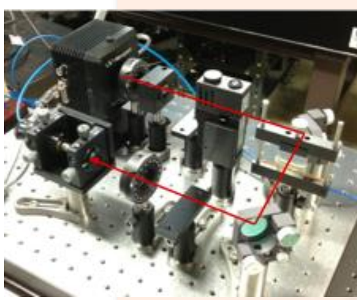
Lyman-α Generating System

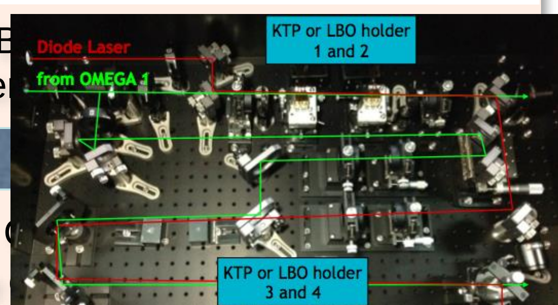
■OMEGA 1 : High Energy 212.55 nm Laser System



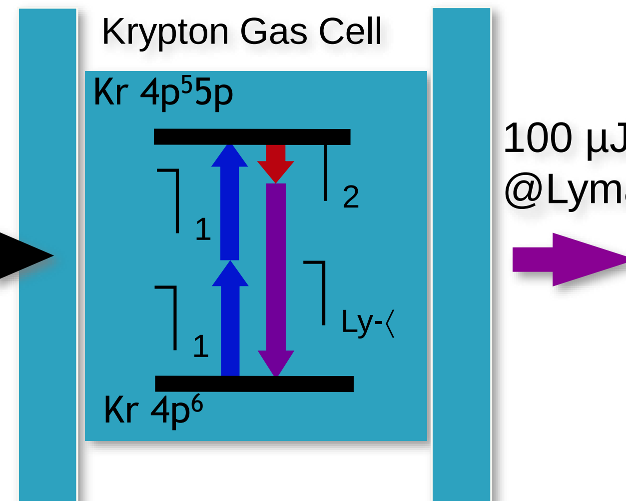


■OMEGA 2 : Tunable 815-850 nm System





■Lyman-α Shifter

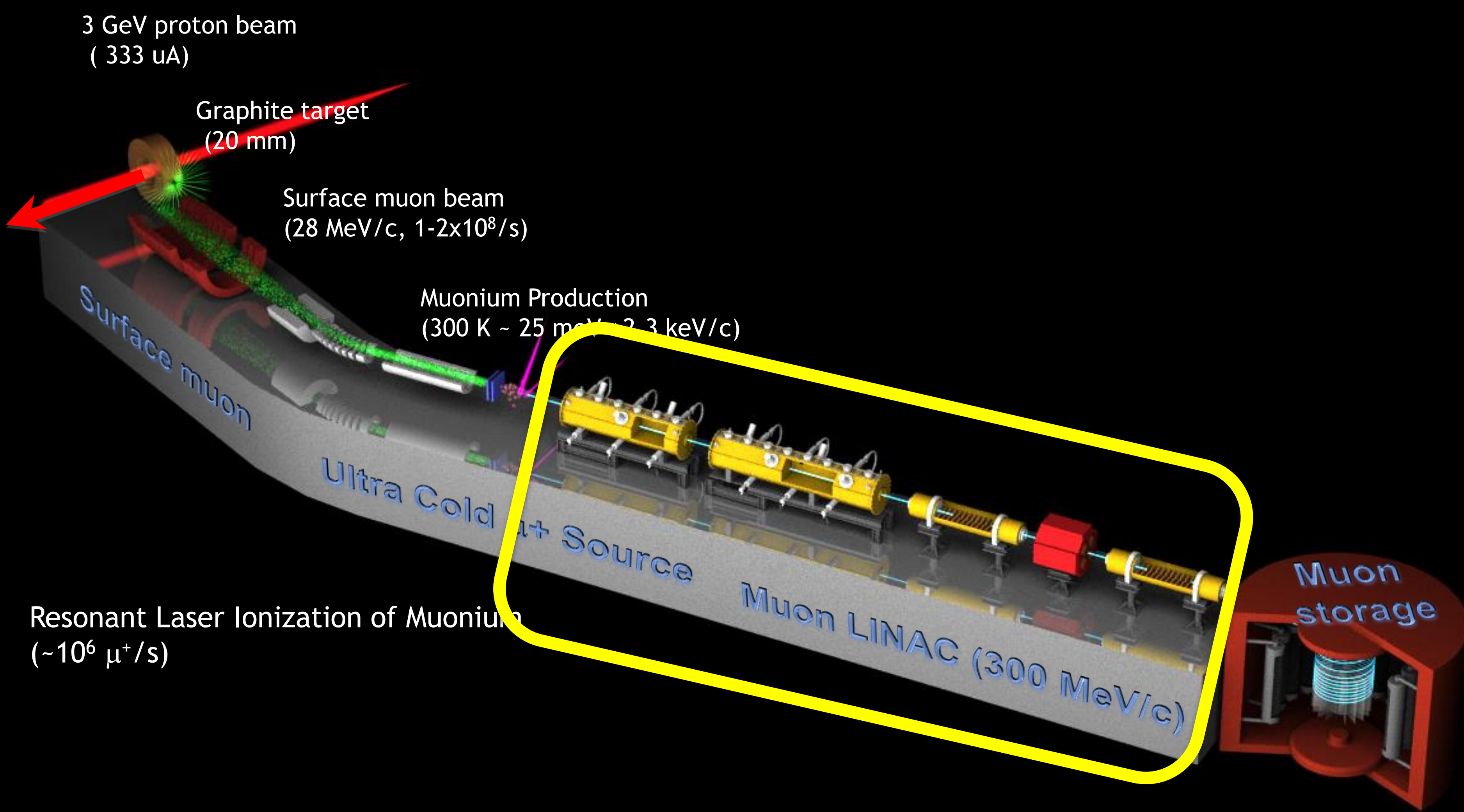


100 μJ
@Lyman-α

$$\lambda_{Ly\text{-}\alpha} = 2\lambda_1 - \lambda_2$$

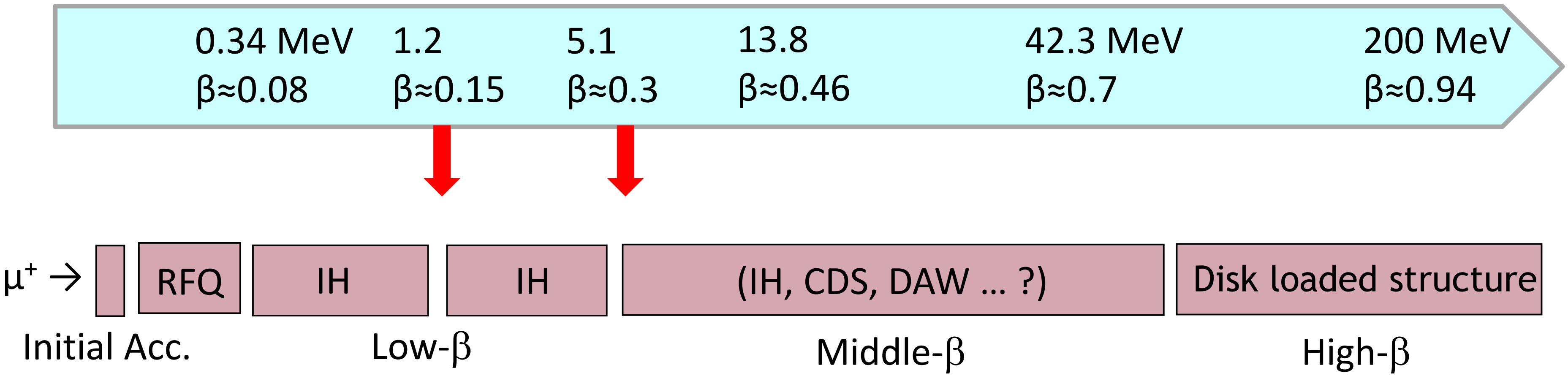
Generation of high power Lyman-α is being tested at RIKEN.
Laser ionization of Mu to be tested at U-line/J-PARC in this year.

Y. Oishi 29 Jun. 2012



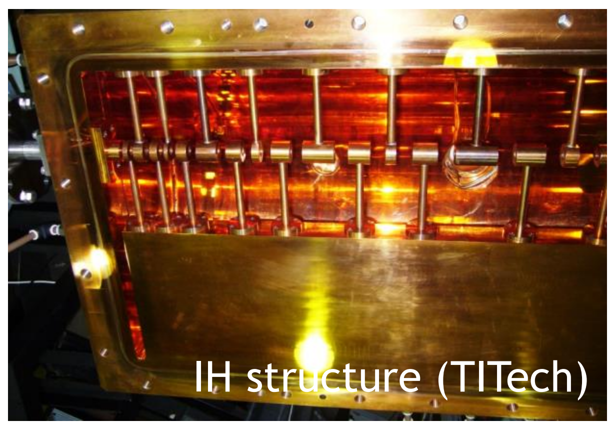
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

Muon acceleration

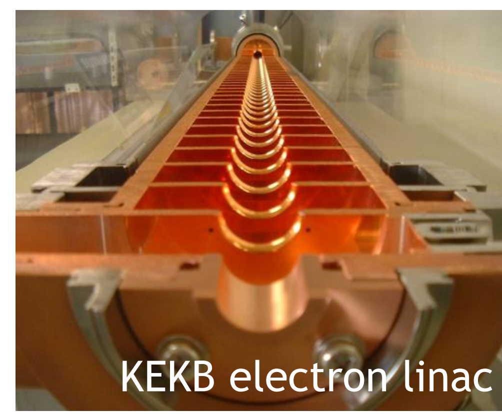


RFQ

IH linac

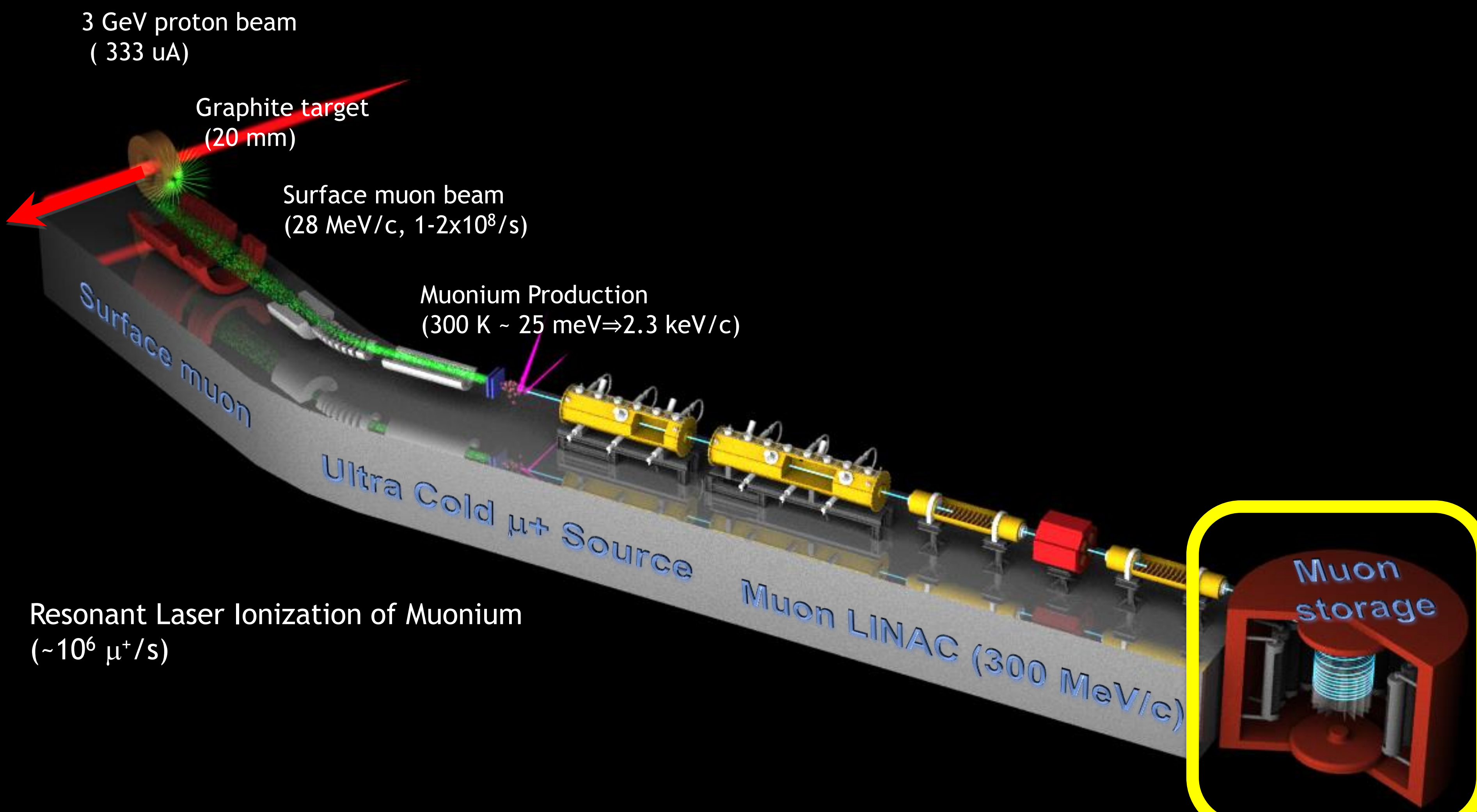


Disk loaded structure



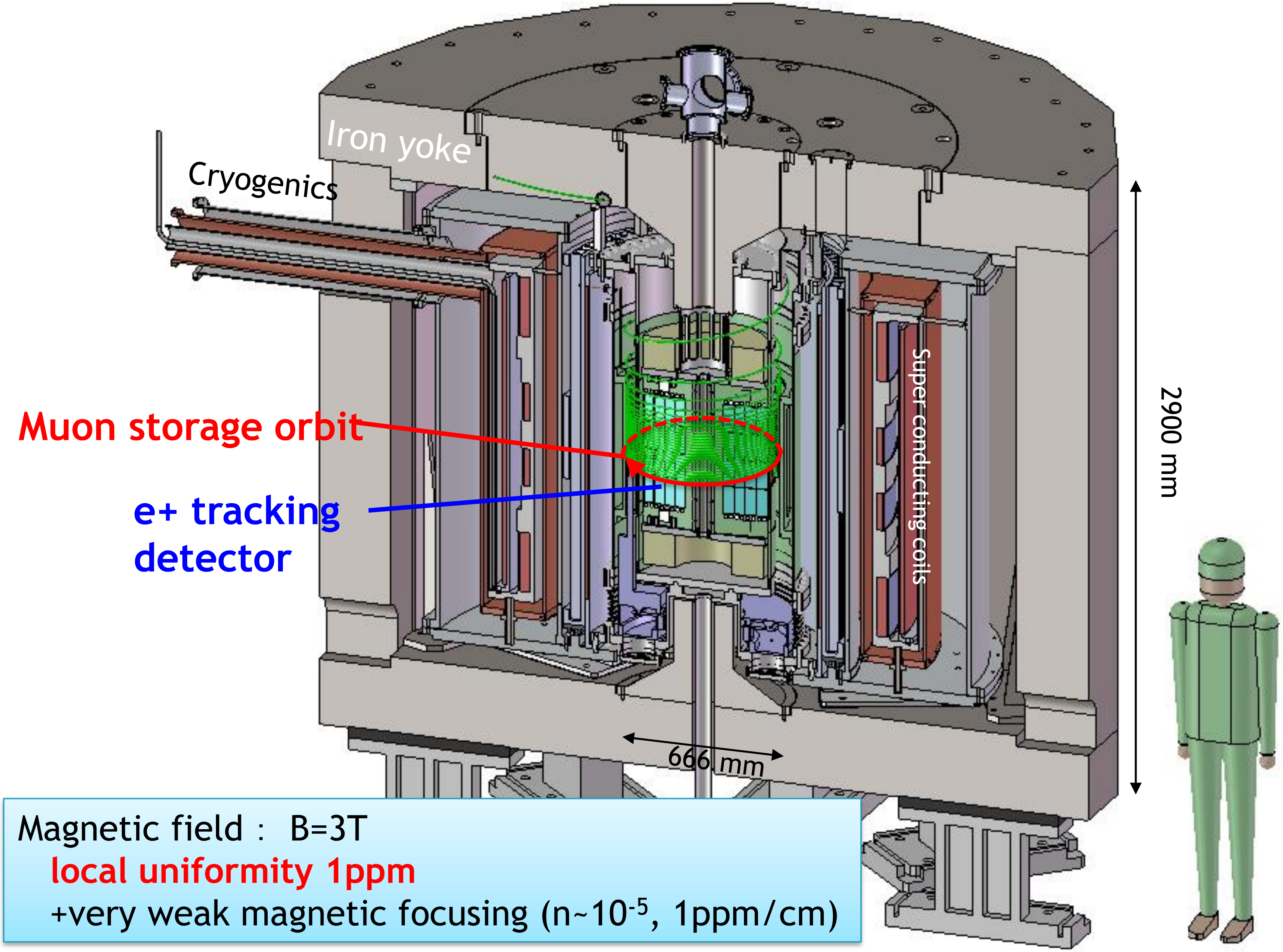
KEKB/J-PARC accelerator group + TITech + Kyoto

Beam simulations in progress. Muon acceleration test being planned at J-PARC



New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

Muon storage magnet and detector

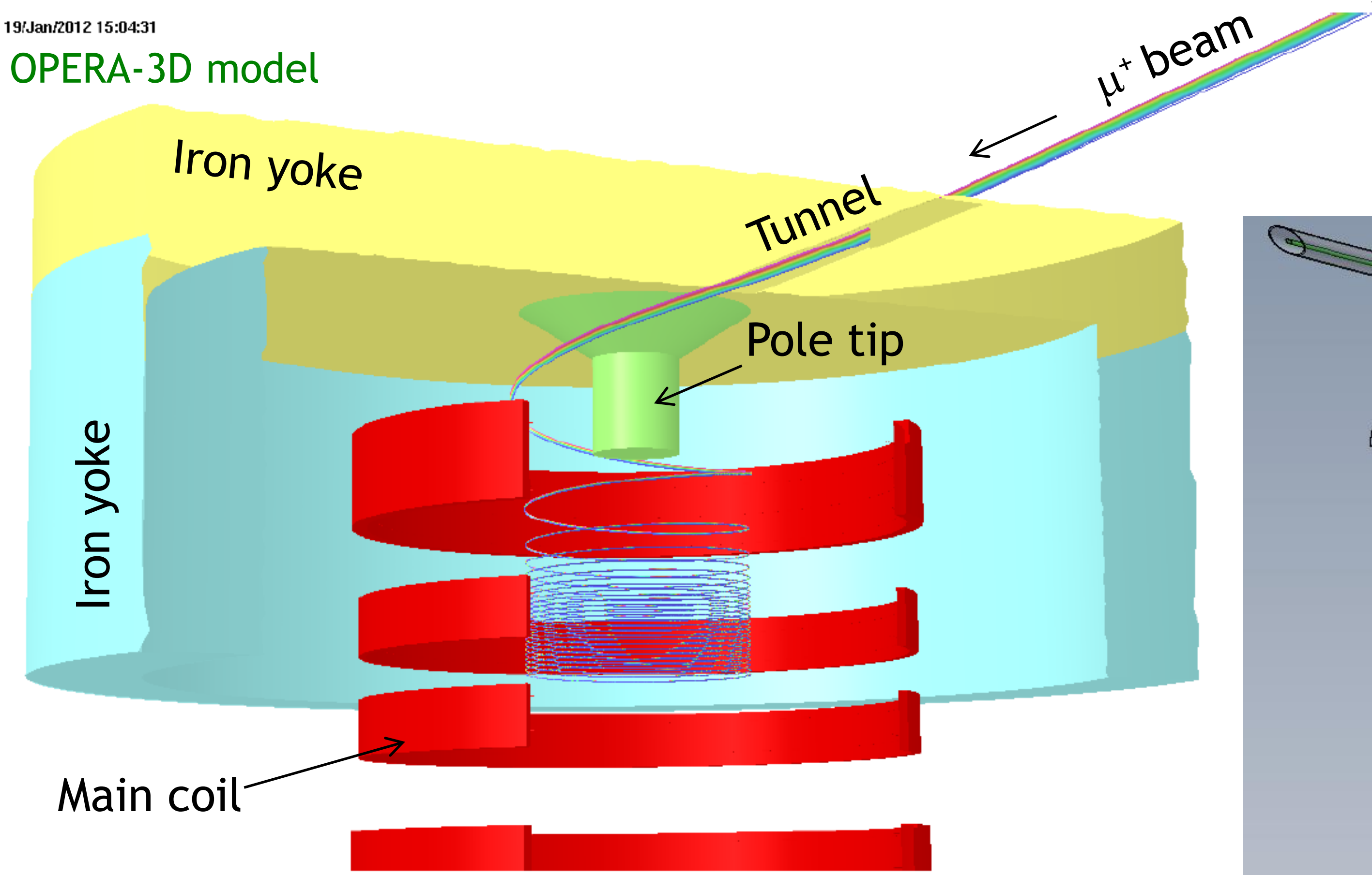


Magnetic field : B=3T

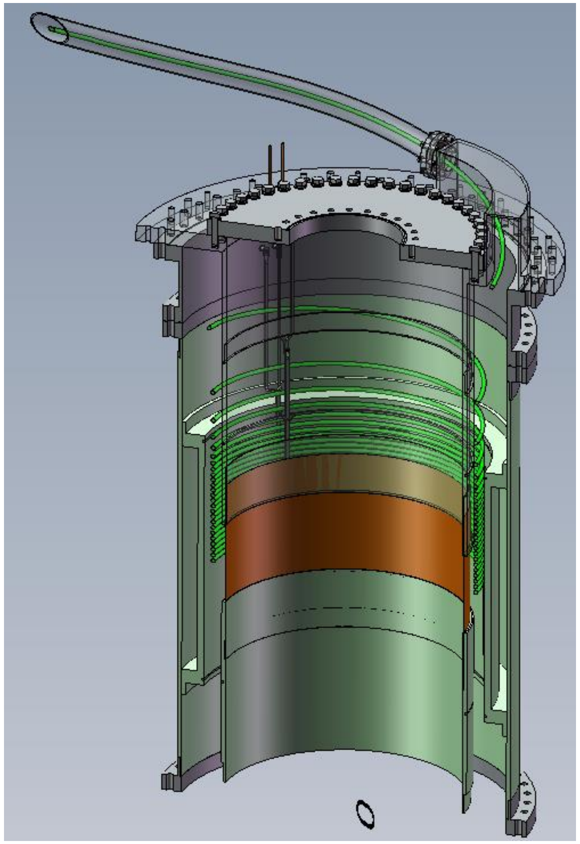
local uniformity 1ppm

+very weak magnetic focusing ($n \sim 10^{-5}$, 1ppm/cm)

Spiral injection



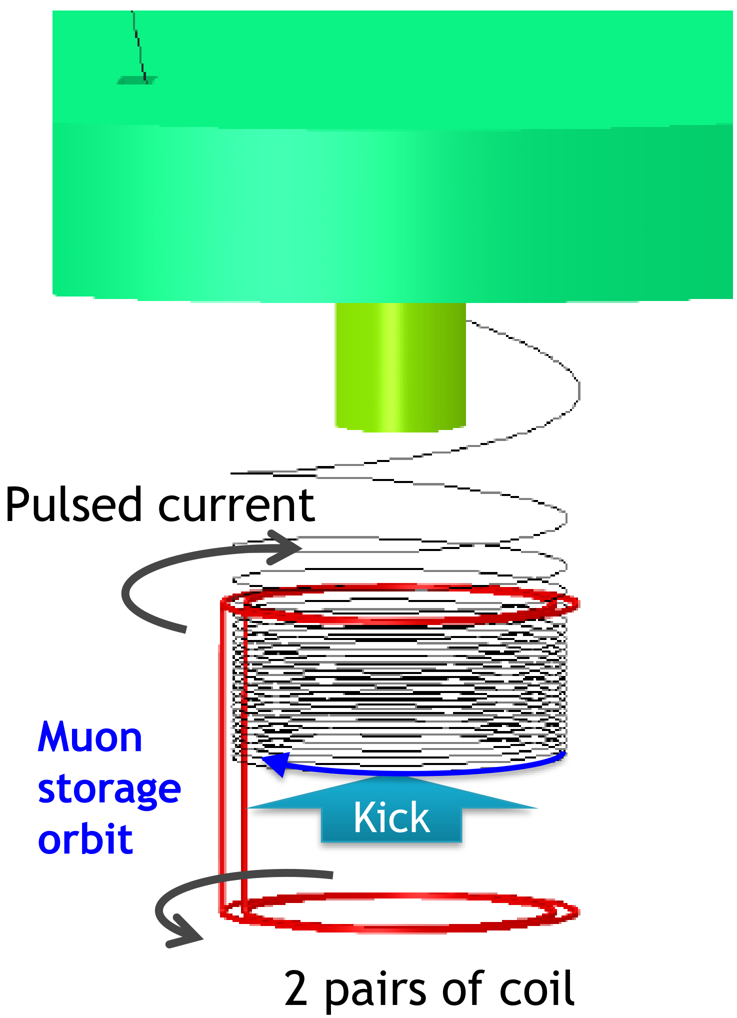
Ray-tracing with G4 and magnet design in progress.
Acceptance has been evaluated with 3D B-field map.



mechanical structure of
vacuum chamber

H. Iinuma, H. Nakayama

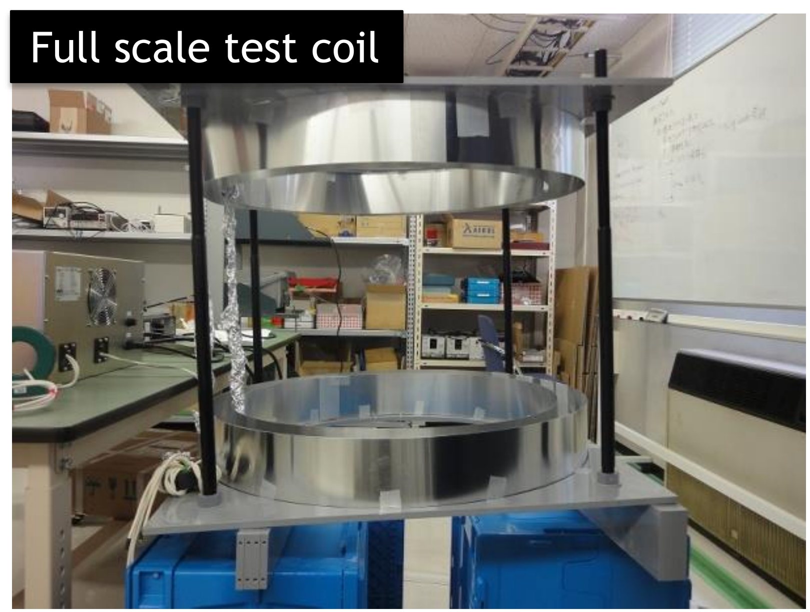
Vertical kicker



Vertical kicker is to stop muon beam in the muon storage area

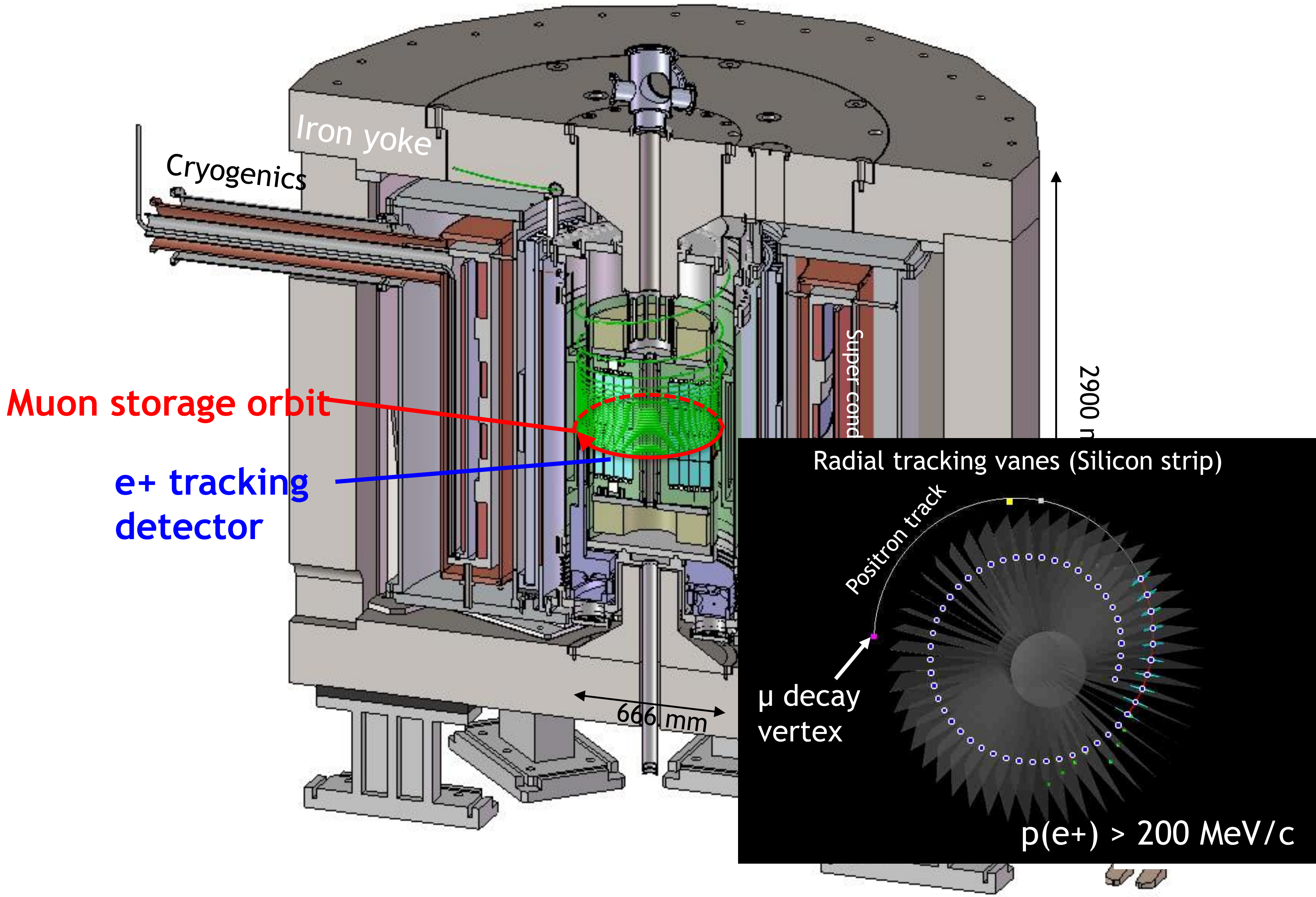
$$B_{kick}(t)=B_{peak}\times\sin(\omega t)$$
$$\omega=\pi/T_{kick}$$

✓Stop beam vertical motion 7~9mrad
✓B_{peak} =1~10 gauss
✓T_{kick}=150 nsec (~20 turns of muon)
✓Uniformity ~1%


Full scale test coil

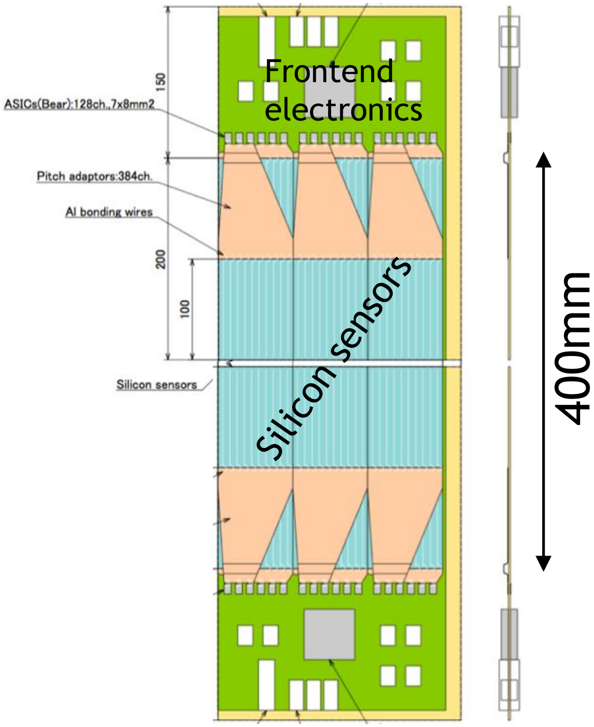
H. Iinuma, H. Nakayama

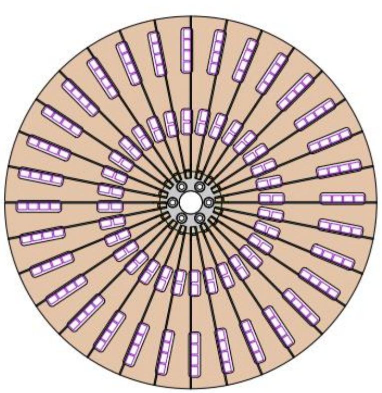
Muon storage magnet and detector



Silicon strip tracker

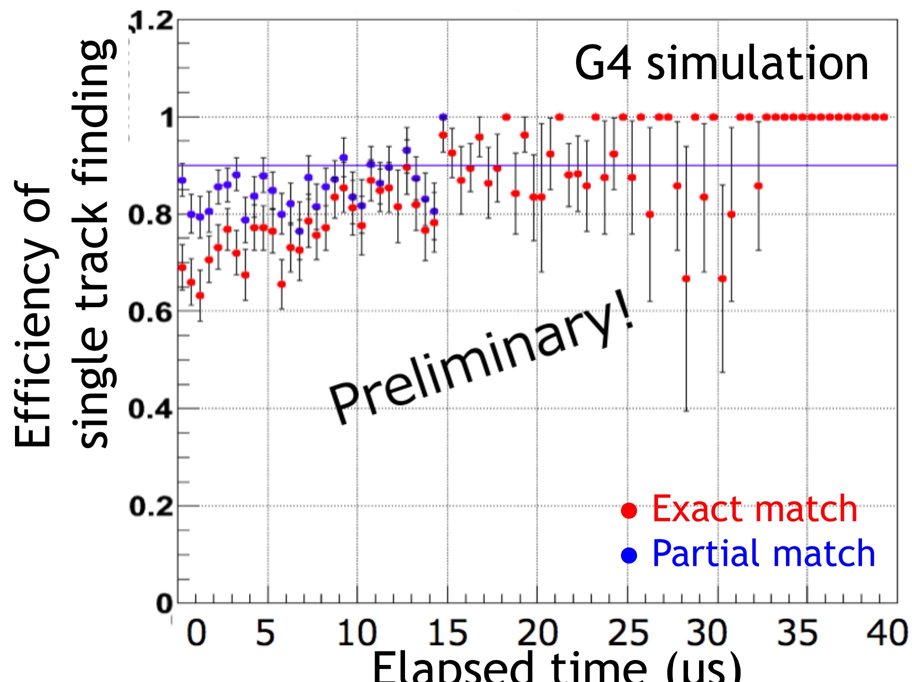
Detector module





Number of vanes: 24-48

- Tracking e+ from muon decay (p = 200-300 MeV/c)
- No contamination of B-field (< 1ppm) and E-field (<10mV/cm) in the muon storage region.
- Efficient and stable over ~5 lifetime (33μs)
  - Instantaneous rate changes by two orders of magnitude.
  - Flipping spin of muon will cancel rate effect in the leading order.



K. Ueno

Silicon-strip detector development

- Test detector module (KEK)
  - Studies on rate effects
  - Impact to precision B-field
- Frontend ASICs under development (KEK)
- Software development (KEK-RIKEN-LPNHE)

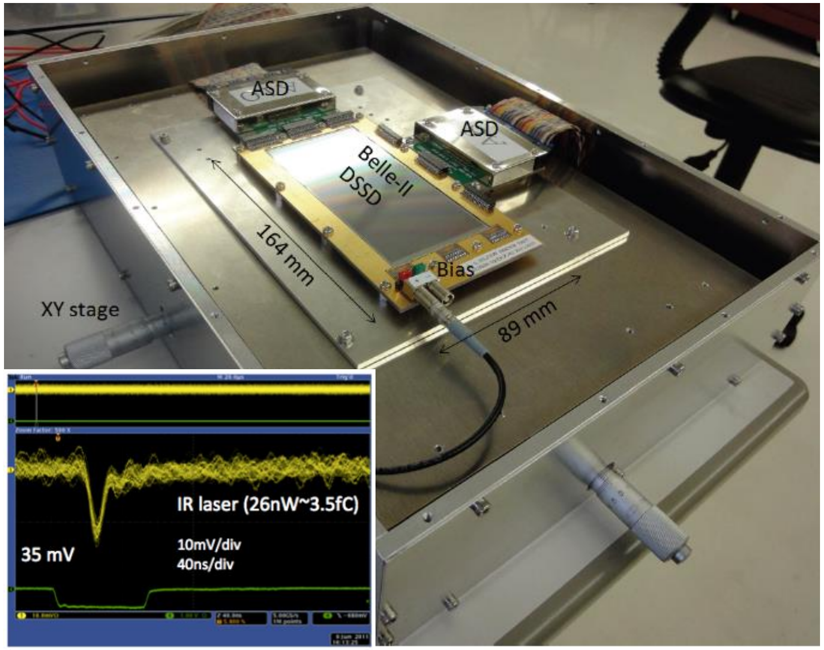
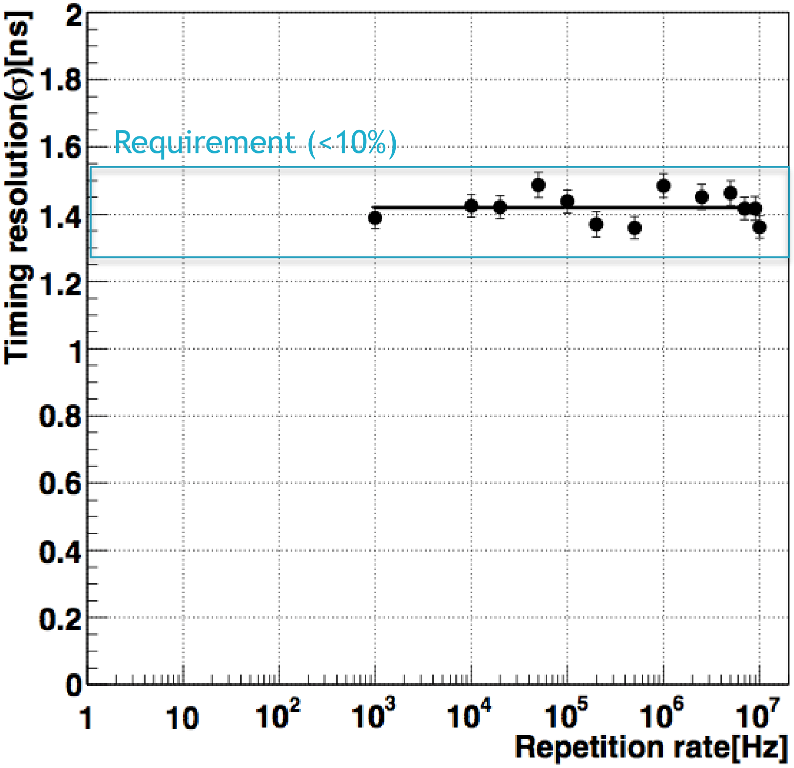


Figure 7.29: The DSSD test module on the support box

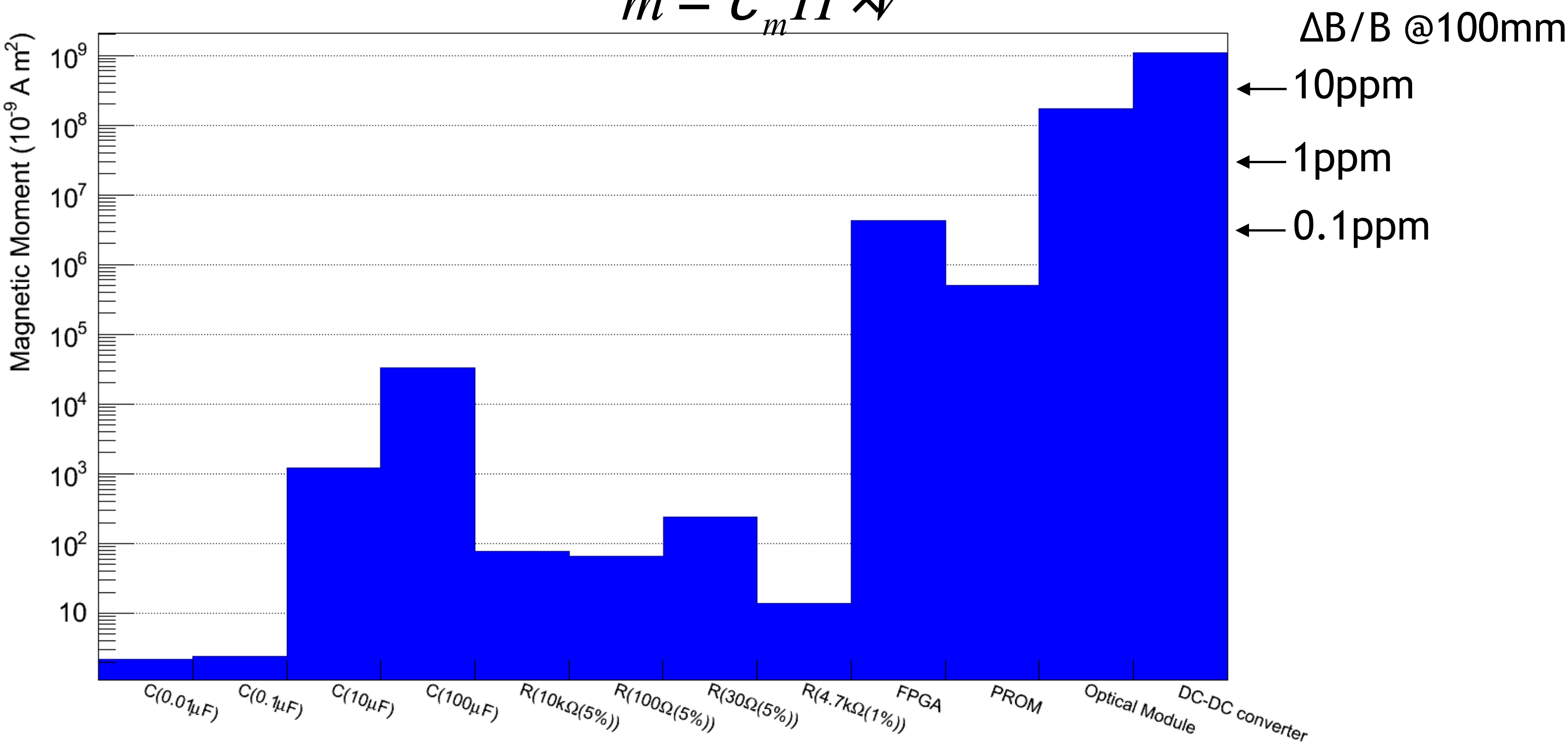
Timing resolution Rate dependence

T. Kakurai

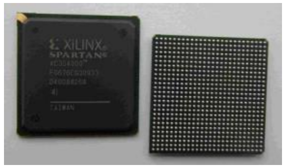


Measured magnetic moment of detector components

$$\vec{m} = c_m \vec{H} \times V$$







Milestones

M1) Demonstration of the ultra-cold muon production with the required conversion efficiency leading to an intensity of $1\times10^6\mu^+/s$.

M2) Muon acceleration tests with the baseline configuration of low-β muon LINAC, i.e. RFQ, and IH LINAC.

M3) Tests of the spiral injection scheme.

M4) Production of a prototype magnet and development of the field monitor with the required precision.

M5) Demonstration of rate capability of the detector system for decay positron detection.

Summary

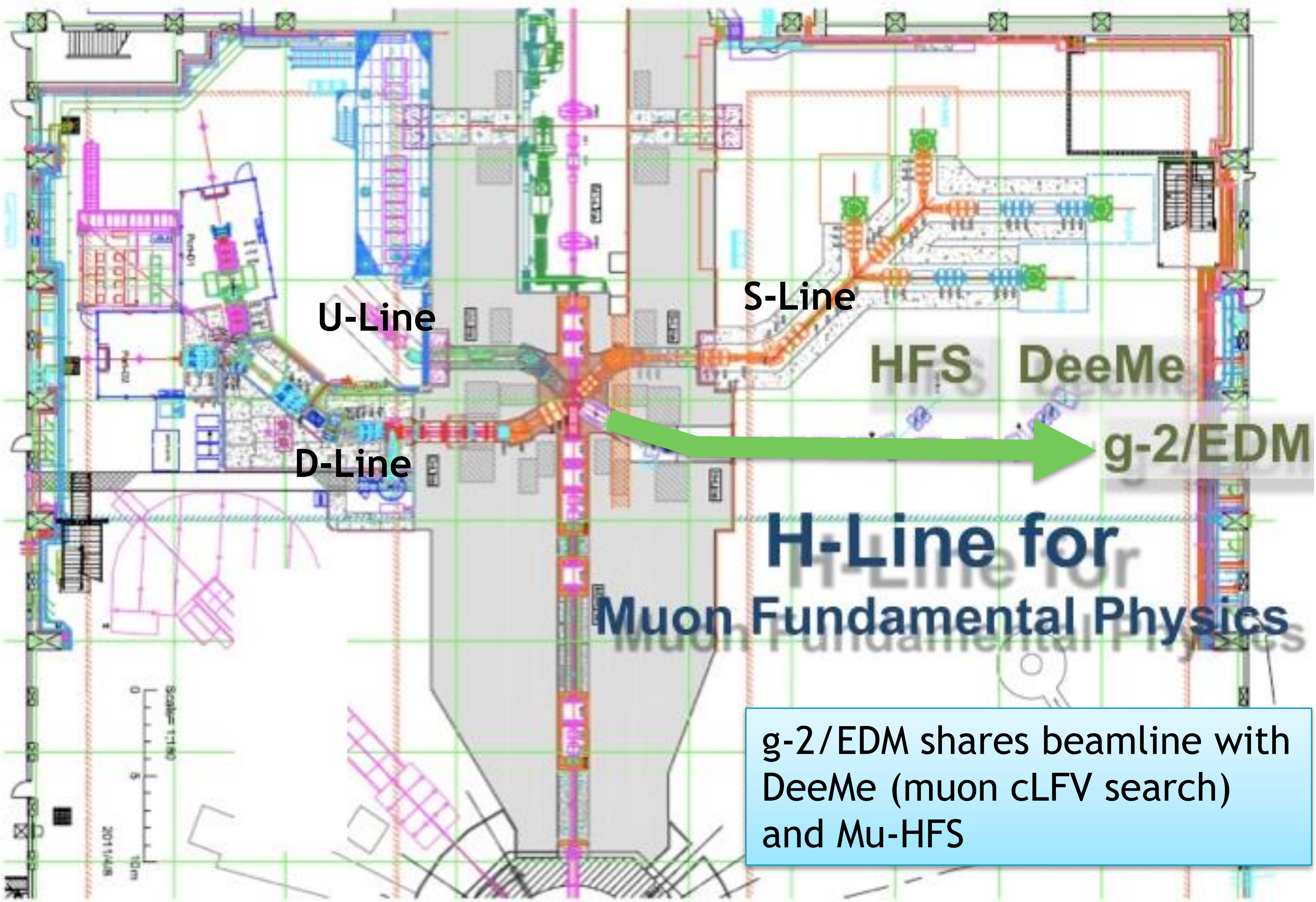
- **J-PARC muon g-2/EDM experiment**
  - Precision measurement of muon g-2 (0.1ppm)
  - Search for muon EDM (sensitivity< 10^{-20} e・cm)

- **Project status**
  - Conceptual Design Report was released.
  - Stage-1 status granted from PAC (IMSS, IPNS)

  - H-Line construction has started.
  - R&Ds in progress for all areas of the project

  - Experiment can be started in 5 years (technically driven schedule)

J-PARC Material and Life science Facility



g-2/EDM shares beamline with DeeMe (muon cLFV search) and Mu-HFS