WG4 Summary – Muon Physics

Conveners
K. Ishida* (RIKEN)
J. Miller (Boston U.)
D. Nicolo (INFN, Pisa)

WG4 session summary

- WG4 (5 sessions, 14 talks)
- WG3-4 Joint (3 sessions, 5 talks)
  - large contributions from FNAL (8)
- Thanks to participants

- Physics with intense muon beams were discussed
  - CLFV (Charged Lepton Flavor Violation)
  - Precision Physics (g-2, Muon decay, Muon Capture)
  - New facilities and applications

- Strong motivations for muon physics
  - see Marciano's Plenary Talk
    - We now know charged lepton flavor violation is allowed
      - However, at ~10^{-50} level
    - Several New Physics models predict CLFV at accessible rate
    - g-2 to probe indication of new physics
      - consistency with others?
    - Muon applications
      - μSR probing materials, etc

Mu-to-e conversion

$\mu^- N \dashrightarrow e^- N$

Searches for single event

- High rate of muon stopping
  - Intense proton beam and pion capture solenoid
- single event sensitivity
  - proton extinction ratio

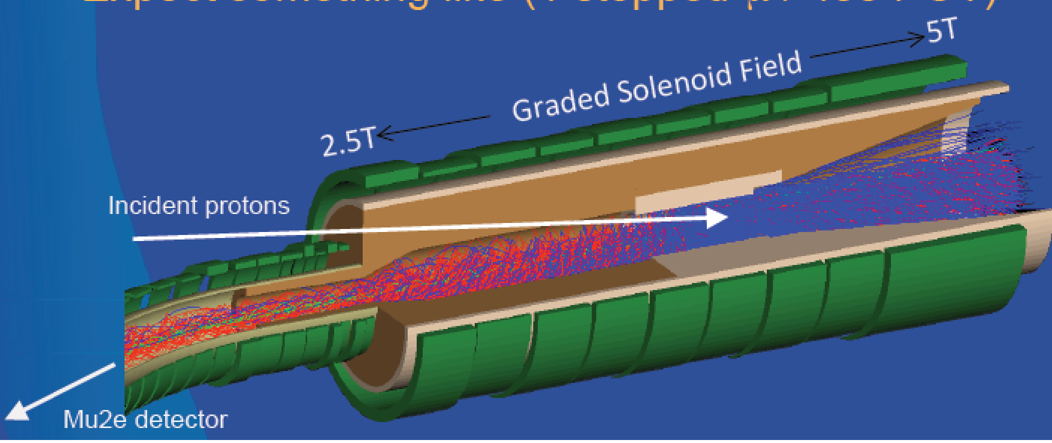
- Mu2e at Fermilab
  - Mu2e : D. Glenzinski
  - Mu2e muon beamline: R. Coleman
  - Mu2e proton beamline: M. Syphers
  - proton extinction: E. Prebys
- COMMET/PRISM at J-PARC
  - COMMET: A. Sato
  - proton extinction: N. Nakadozono
  - PRISM Development: A. Sato
  - SC Magnet for Mu2e-COMMET: T. Ogitsu

Mu2e

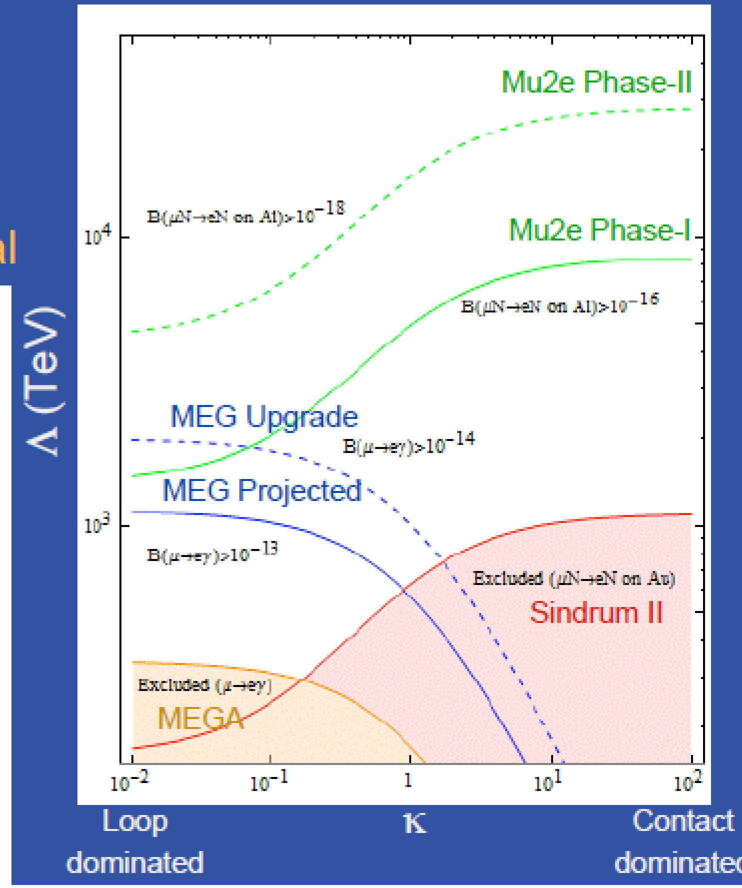
Experimental signature is an electron and nothing else

- Energy of electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
- For aluminum: E_e=104.96 MeV
- Important for discriminating background
- Signal window: 103.6-105.1 MeV accepts 62% signal

- Capture (mostly) backwards going pions
  - Eliminates backgrounds from the primary beam
  - Expect something like (1 stopped-μ / 400 POT)



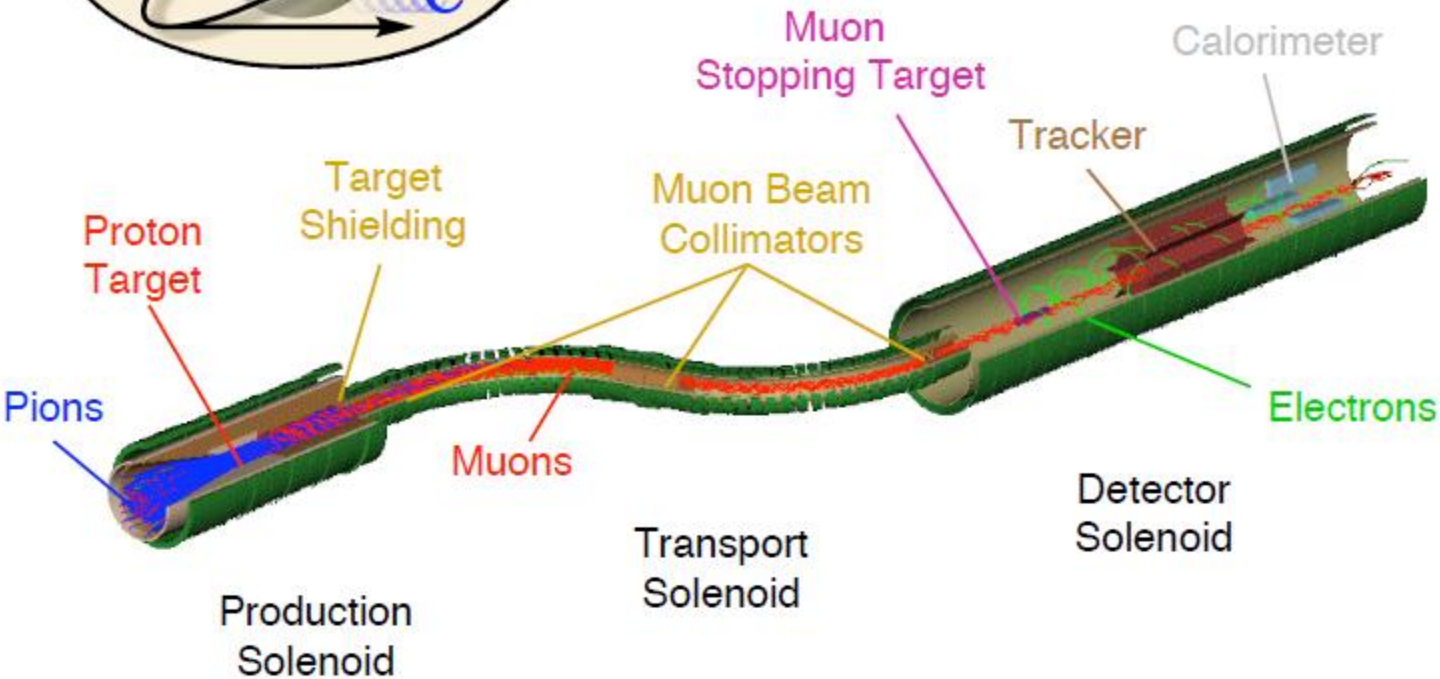
Mu2e Sensitivty



- Phase I: use Booster cycles left unused by Nova
- Phase II: use spare protons from Project-X

D. Glenzinski

Muons are collected, transported, and detected in solenoidal magnets



Mu2e Muon Beamline- follows MECO design

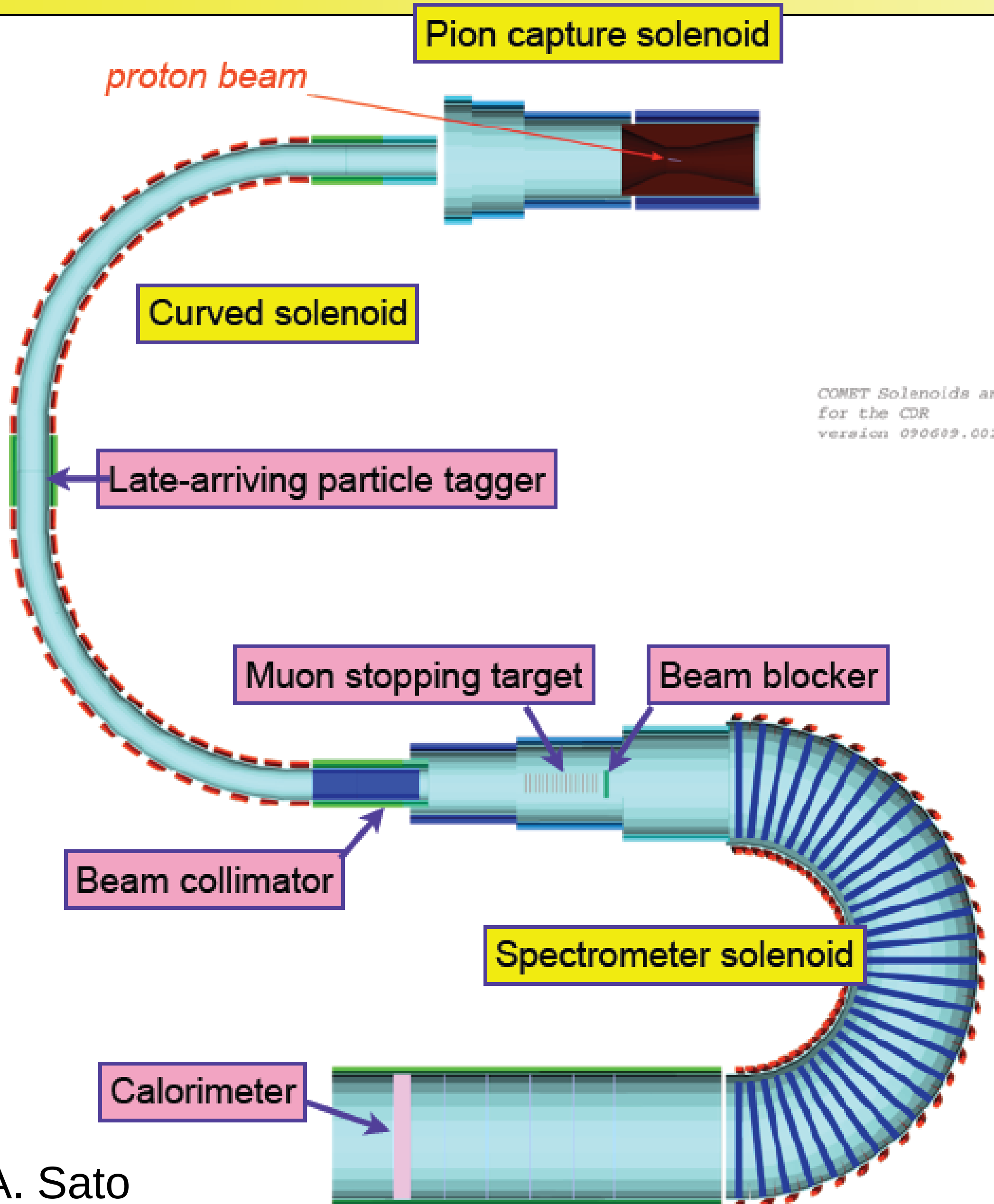
more information at http://mu2e.fnal.gov

R. Coleman

Summary Mu2e Beamline

- Reproduced many MECO results
- Production Solenoid studied in detail
  - HARP data important, working to incorporate
  - A reduced length PS (à la COMET) attractive
- Transport Solenoid studies starting
- Fermilab Technical Division has made much progress on magnets

COMET : μ-e conversion search at J-PARC

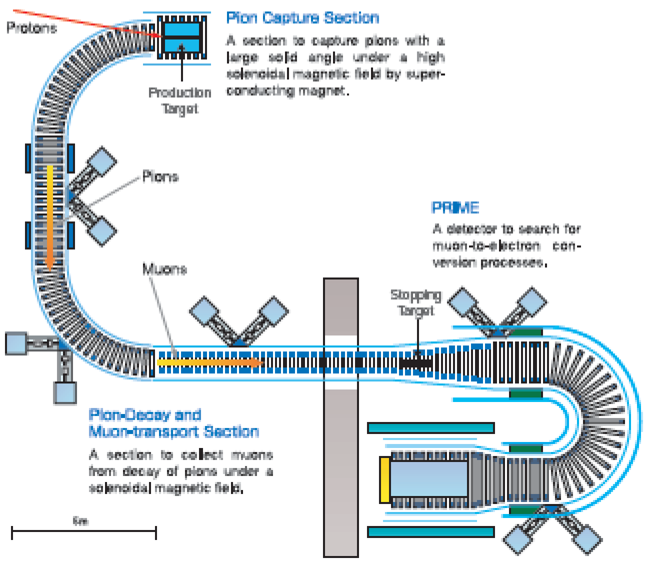


- The CDR has been submitted to the J-PARC PAC to get the stage-1 scientific approval.
- Many R&Ds and simulation studies are underway: solenoid, extinction measurement and monitor, calorimeter, silicon, and full G4 simulation ...
- The COMET collaboration is rapidly growing and many working groups are being formed.
- **Join to the collaboration!**

A. Sato

Staging Plan of μ-e Conversion in JAPAN

1st Stage : COMET

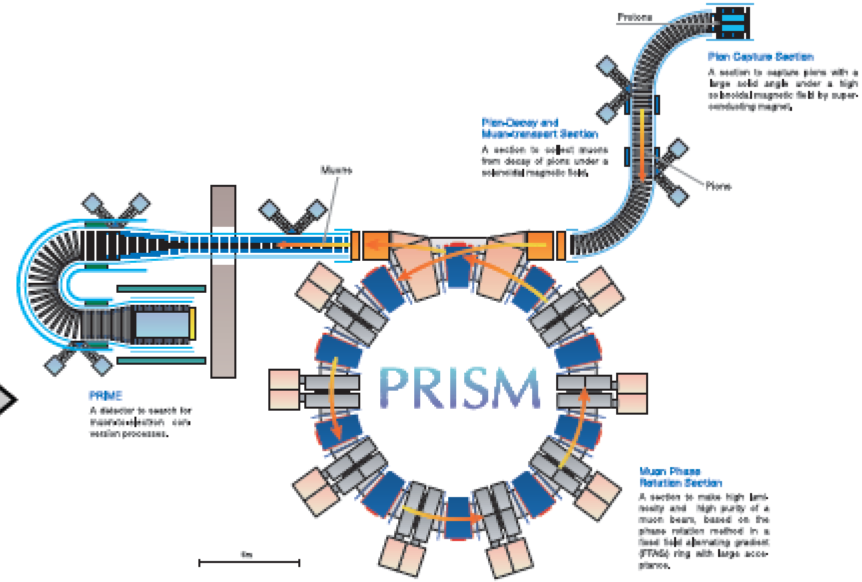


$$B(\mu^- + Al \to e^- + Al) < 10^{-16}$$

- without a muon storage ring. (MECO-type)
- with a slowly-extracted pulsed proton beam.
- at the J-PARC NP Hall.
- for early realization (~2017)

A conceptual design report has been submitted to the J-PARC PAC.

2nd Stage : PRISM/PRIME



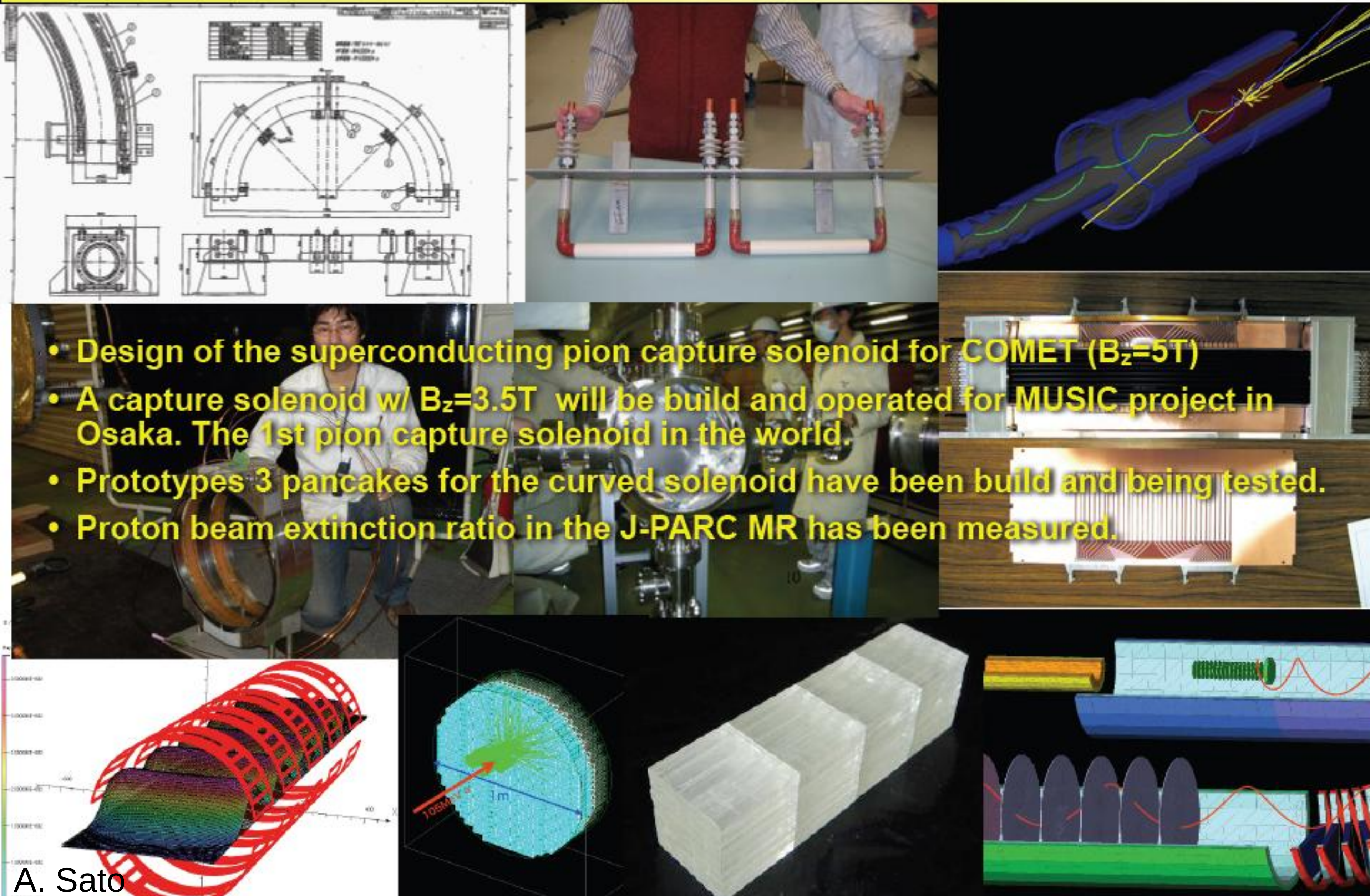
$$B(\mu^- + Ti \to e^- + Ti) < 10^{-18}$$

- with a **muon storage ring**.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- Ultimate search

R&D of PRISM-FFAG demonstrated the feasibility of the ring.

A. Sato

COMET has a lot of on going R&D programs.

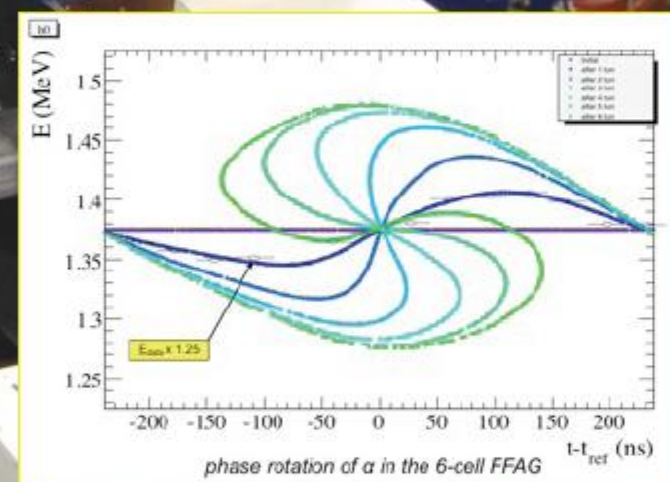


- Design of the superconducting pion capture solenoid for COMET (B_z=5T)
- A capture solenoid w/ B_z=3.5T will be build and operated for MUSIC project in Osaka. The 1st pion capture solenoid in the world.
- Prototypes 3 pancakes for the curved solenoid have been build and being tested.
- Proton beam extinction ratio in the J-PARC MR has been measured.

A. Sato

PRISM-FFAG R&D: Results and Status

- PRISM provides a solution to improve the μ-e conv. sensitivity less than 10^{-17} adopting a muon storage ring, which make mono-energetic and pure muon beam. A staging scenario of mu-e conversion experiment (COMET - PRISM) was proposed in Japan.
- The R&D program on the muon storage ring from 2003 to 2009 has produced many successful outcomes.
  - large aperture FFAG,
  - high field gardened RF system
  - 6-cell FFAG and phase rotation test.
- The collaboration and task force for the PRISM-FFAG have been proposed at the 1st PRISM-FFAG workshop in UK, and now being organized. Study and R&Ds for the PRISM-FFAG continue to realize the ultimate μ-e conv. experiment.

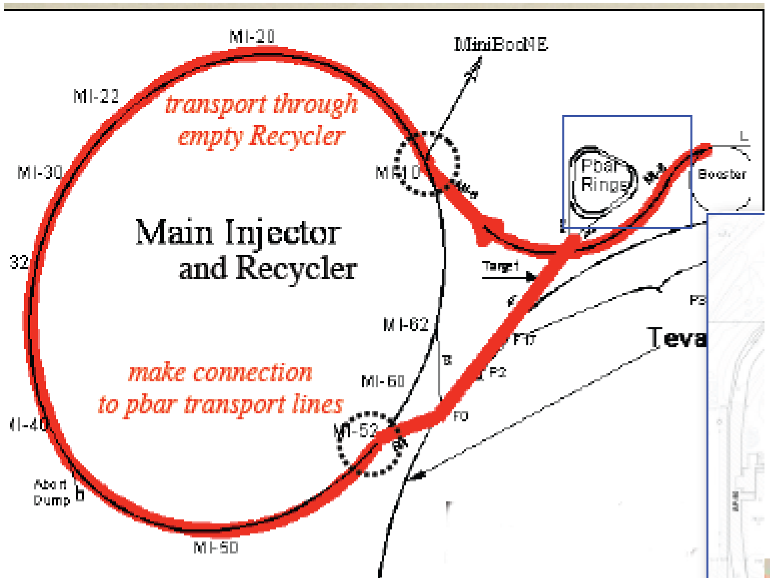


phase rotation of α in the 6-cell FFAG

6-cell PRISM-FFAG at RCNP, Osaka

A. Sato

Proton beam extinctions: Proton beamline for mu2e

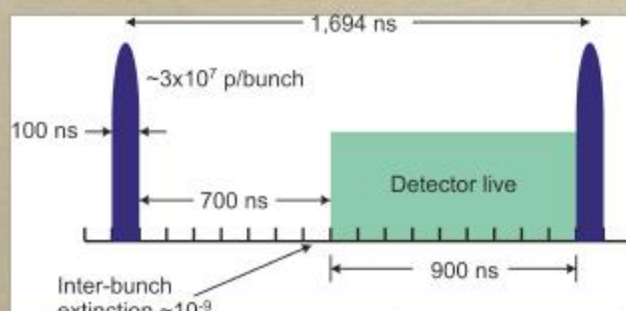


Beamline

- Narrow pulses (<100ns full width) of ~10^8 protons each, delivered every ~2*τ_μ^{Al} ~ 1700 ns
- Stringent out-of-time requirements for POT
- High duty cycle preferred

uration << τ_μ^{Al} , pulse separation ≥ τ_μ^{Al} ~ 864 ns

- FNAL ***Debuncher*** ring has circumference **1.7μs** !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse

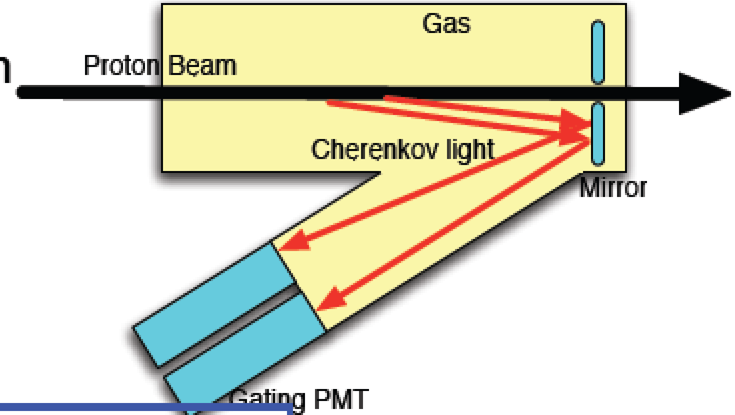


- 10^{-9} based on simulation of prompt backgrounds

M. Syphers, E. Prebys

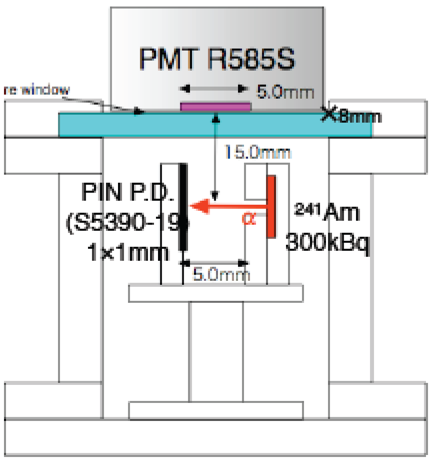
Proton extinction monitor for COMMET

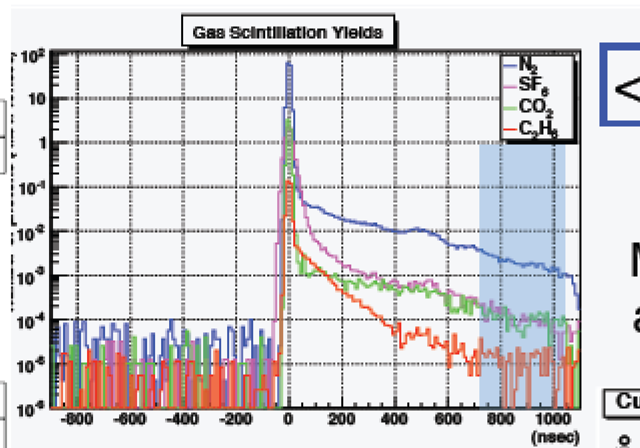
In COMET experiment searching μ-e conversion in J-PARC, Proton Extinction is important.
This Proton Extinction Monitor is gas Cherenkov counter with Gating PMT.
measure in-bunch contamination pulse-by-pulse.



<Gas selection>

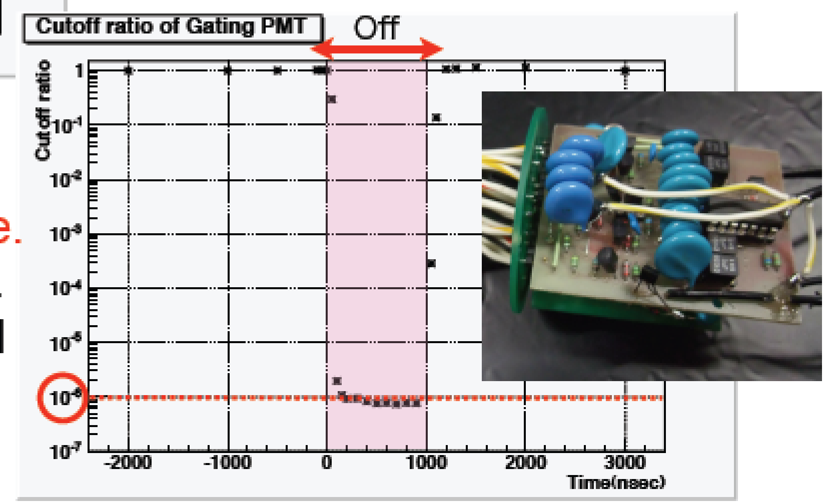
Cherenkov radiator gas must has small scintillation light.
Measurement has been done using alpha-ray, and ethane is promising.





<Gating PMT>

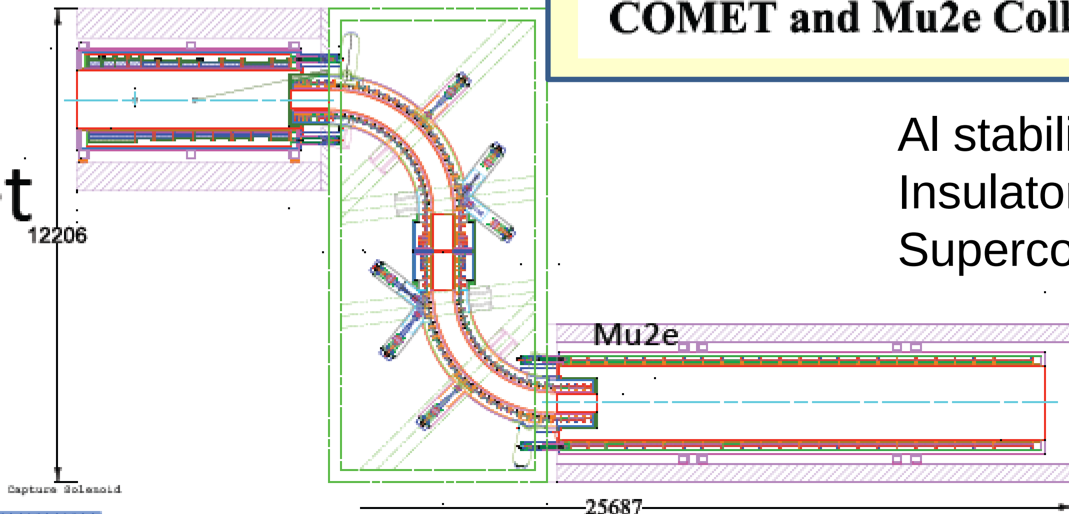
Gating PMT mask the flash by main beam pulse.
1MHz switching and 10^{-6} cutoff ratio is needed.
10kHz switching prototype has been made and tested. Cutoff ratio of 10^{-6} was achieved, but there remains problem of afterpulse.



N. Nakadozono

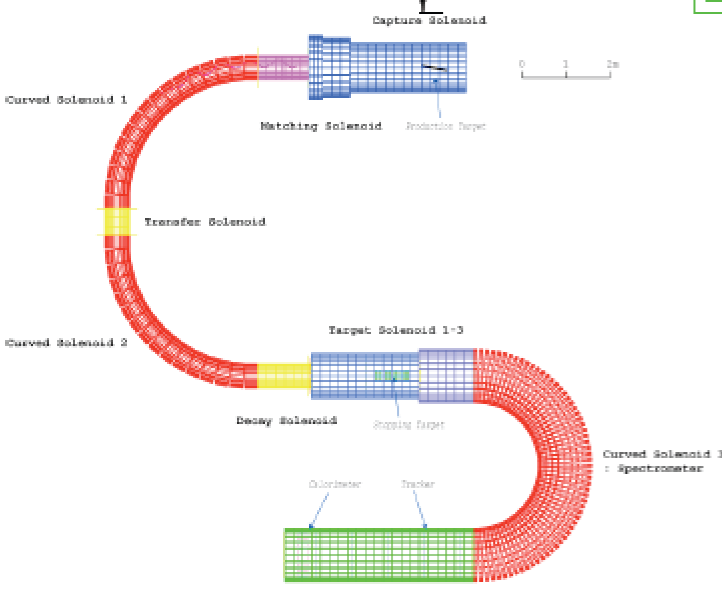
R&D for SC Magnet

Memorandum of Understanding On Joint Efforts Between the COMET and Mu2e Collaborations



Al stabilizer
Insulator
Superconductorr

COMET



Similarity in SC Magnet Specs

- Production Magnet
  - Large Aperture Solenoid (1~1.8 m)
  - Field 5~6 T
  - High Radiation
- Transport Magnet
  - Curved Solenoid (Aperture 0.4~0.8 m)
  - Field 2~2.5 T
- Detector Magnet
  - Large Aperture (1~2 m)
  - Field 1~2 T

T. Ogitsu

High precision muon physics

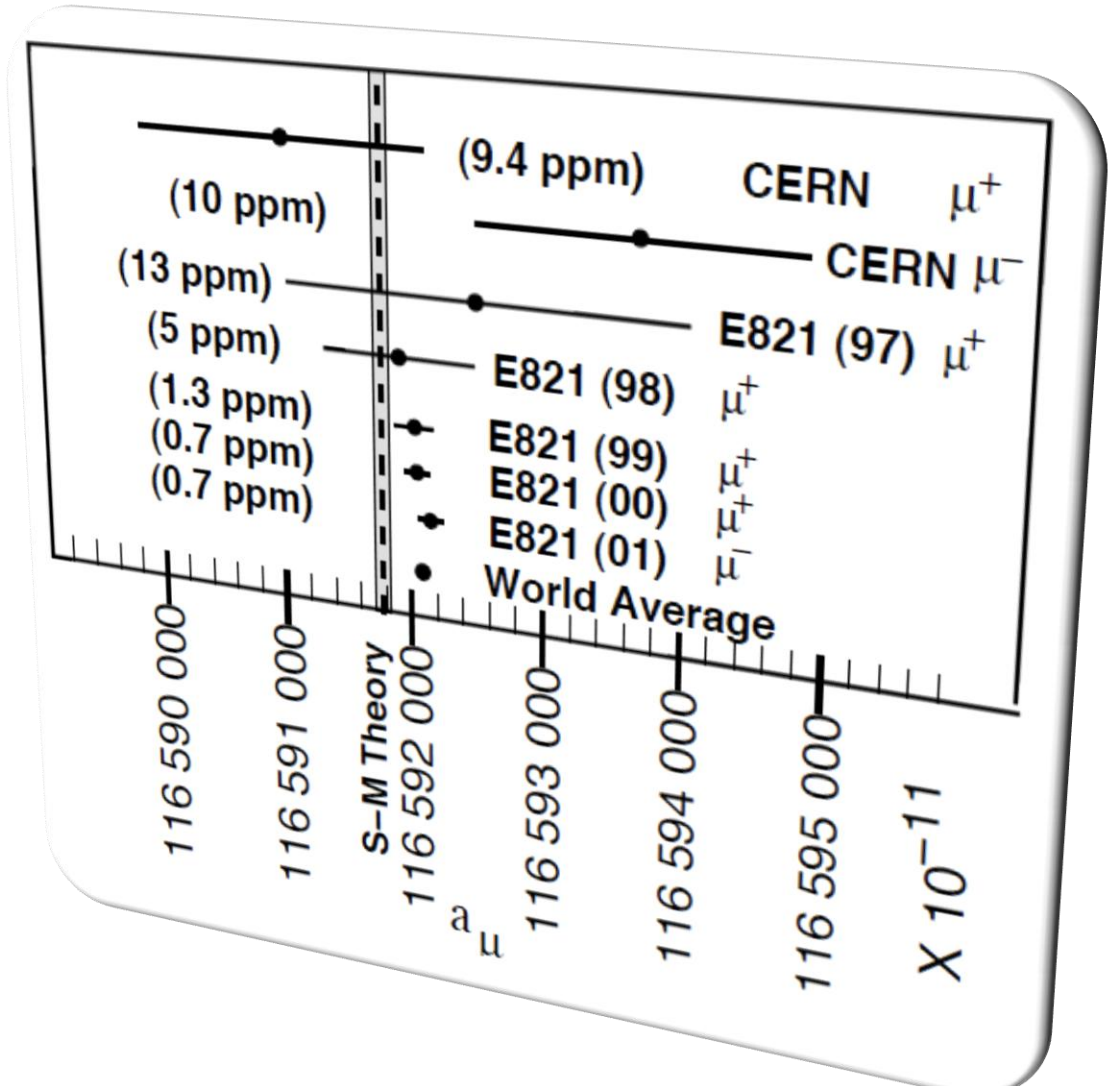
- muon g-2
  - g-2 at Fermilab

    C. Polly
  - g-2 at J-PARC
    - g-2: N. Saito
    - ultra slow muon source: K. Ishida

muon g-2: Current Precision

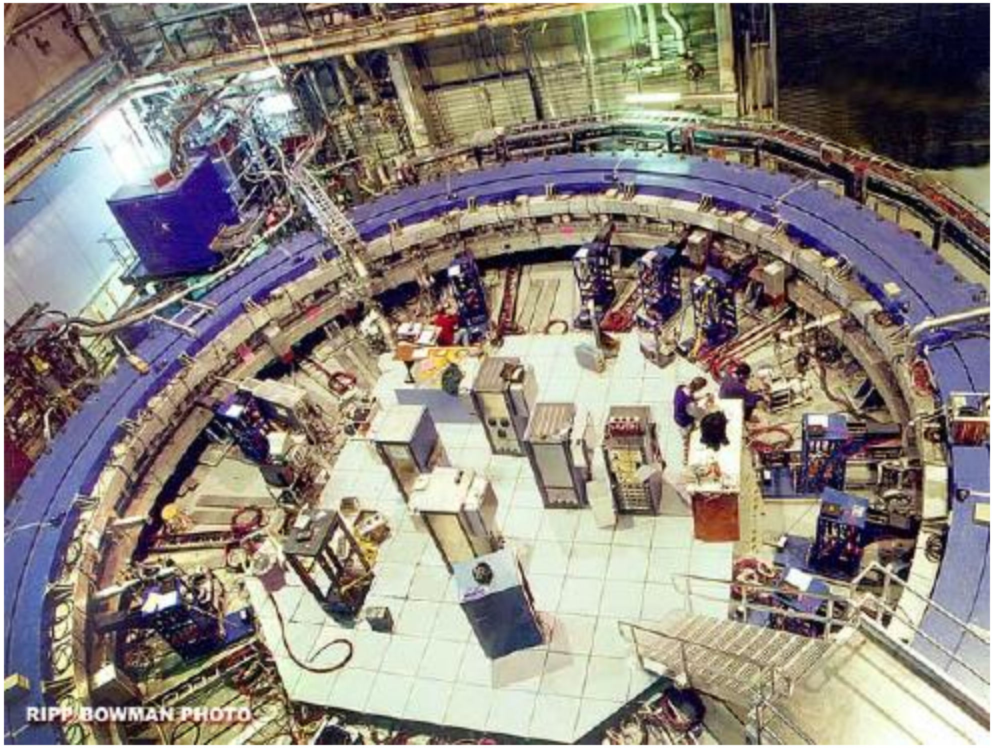
$$\Delta a_\mu^{(\text{today})} = a_\mu^{(\text{Exp})} - a_\mu^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$

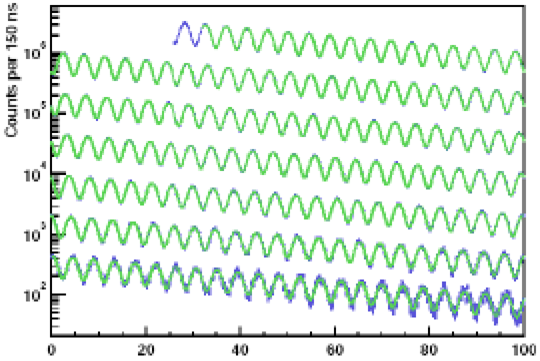
- E821 at BNL-AGS measured down to 0.7 ppm for both μ+ and μ−
- 3.4 sigma deviation from the SM
  - SM prediction OK?
  - New Physics?
- Need to explore further



N. Saito

g-2 at FNAL





BNL g-2 ended with 3.3σ discrepancy Δa_μ(exp-thy)
– statistics limited

moving g-2 ring to FNAL -> x20 muon luminosity

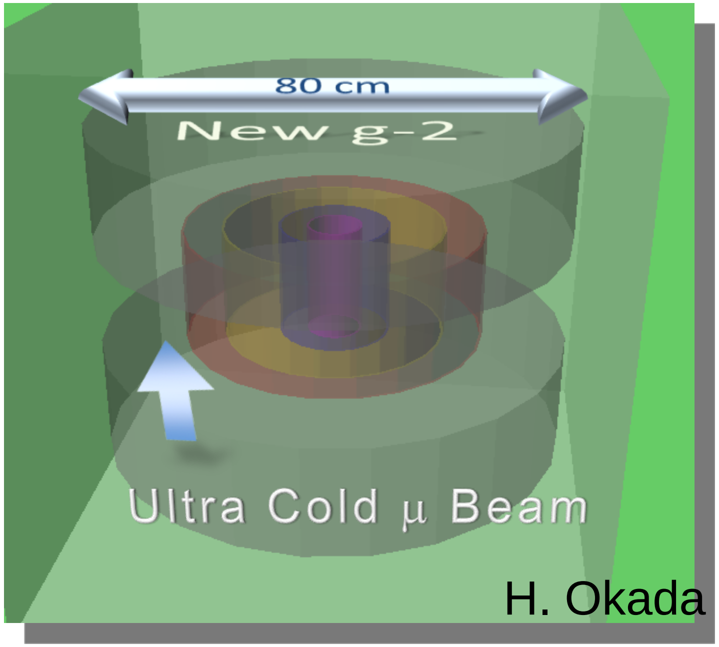
reduce δa_μ (exp) from 0.56 ppm to 0.14ppm

C. Polly

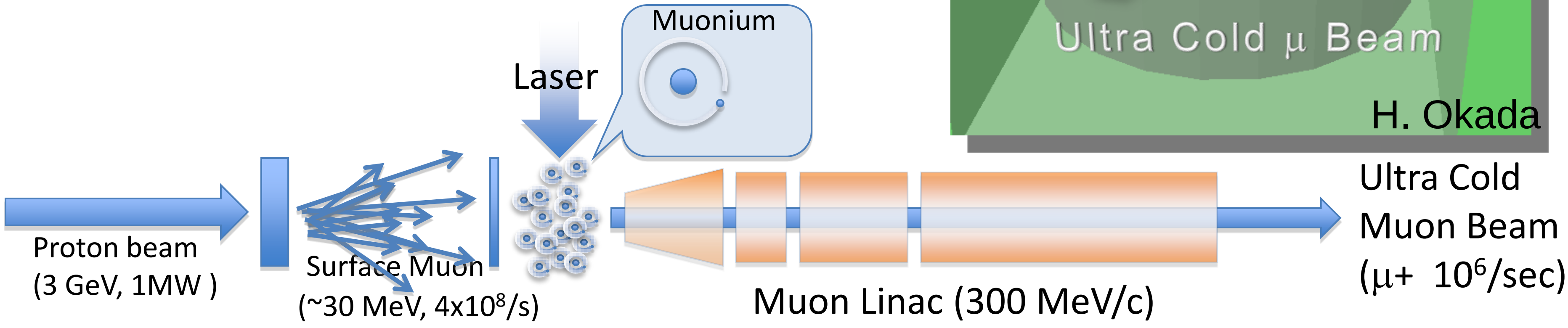
New Generation of Muon g-2@J-PARC

Proposal in preparation

- New generation of muon g-2 experiment is being explored at J-PARC
- With completely new technique
  - Off magic momentum with ultra-cold muon beam at 300 MeV/c
  - Stored in ultra-precision B field without E-field so that the β x E term drops



H. Okada



N. Saito

BNL, FNAL, and J-PARC

- complimentary

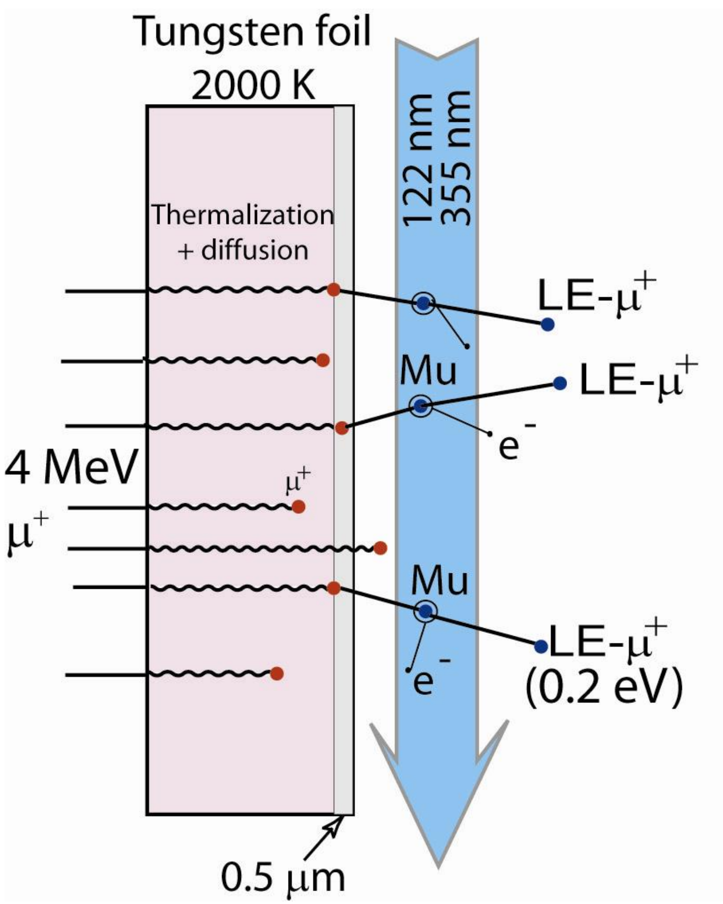
	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.11 ppm

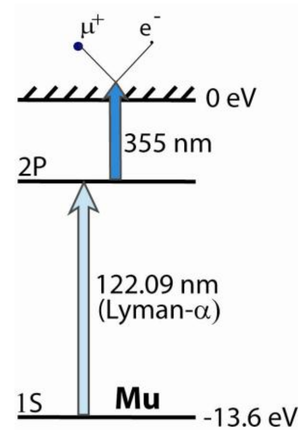
N. Saito

generating ultra-cold muons at high density for g-2

good cooling required!

4 MeV muons —2%→ 0.2 eV thermal Mu → 0.2 eV μ^+





122.09 nm (Mu)
121.57 nm (H)
121.53 nm (D)

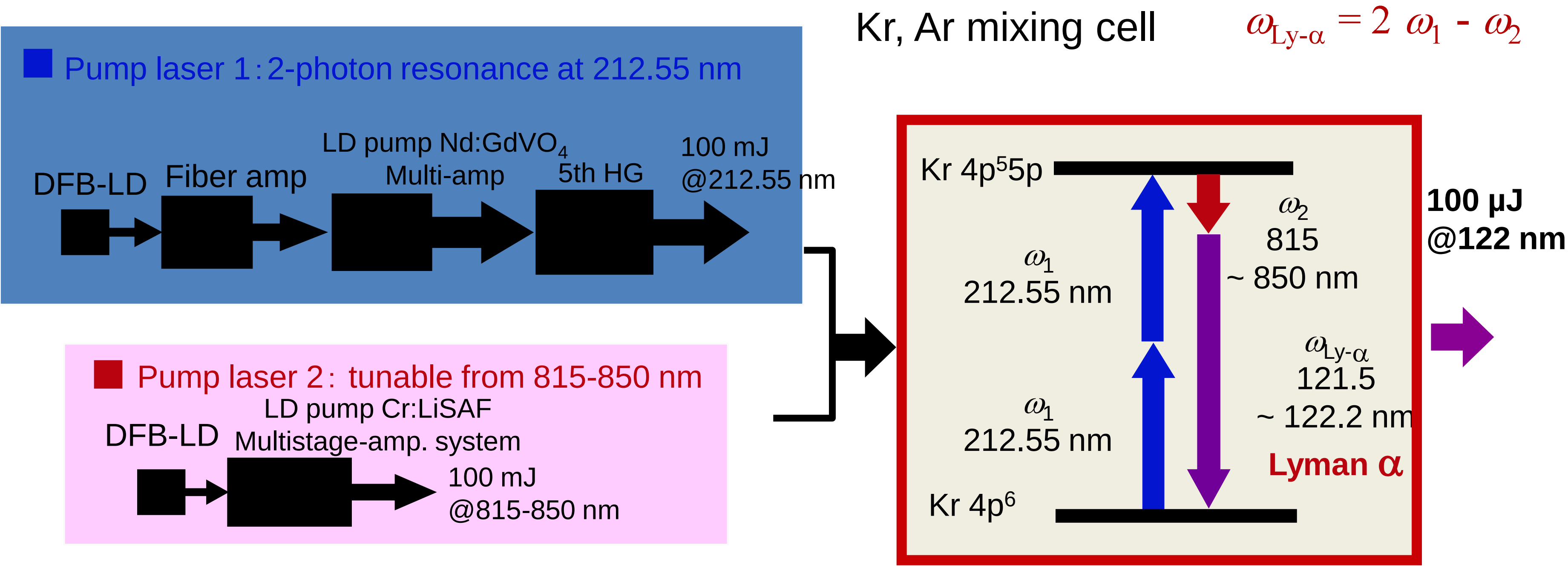
- **two** laser beams necessary for resonant ionization
- required very broad laser bandwidth due to thermal movement of atoms

1S-2P saturation intensity

I_{sat}=2.3 W/cm^2 monochromatic<100MHz ⇒ I_{sat}=4.6 kW/cm^2 (Doppler 200GHz)

Main challenge: to generate VUV @ 122 nm and with 200 GHz (+ 1 ns jitter rel. to ext. trig.)

K. Ishida



To improve present intensity ~20/s by 2 orders

ionizing Lyman-alpha laser

another 2 orders by RIKEN -> J-PARC Dedicated muon channel

To achieve g-2 muon storage requirement

K. Ishida

Exciting recent progress - understanding muons

- MEG (Muon to eγ) another CLFV
  - D. Nicolo
- TWIST (Precision measurement of Michel parameters)
  - G. Marshall
- MuCAP (Muon nuclear capture to hydrogen)
  - S. Clayton

MEG (μ->eγ)

back to back decay signal of mono-energetic e+ and γ

The PSI beam

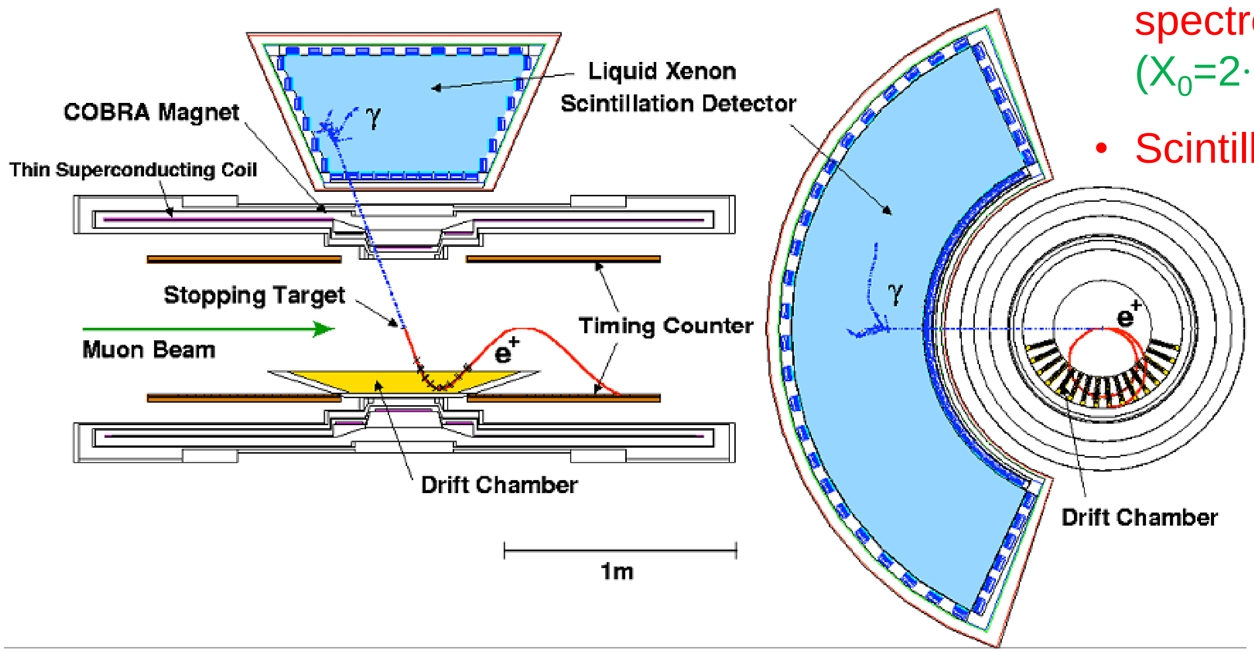
The worldwide most intense DC beam (>10^8m/s)

of surface muons (28 MeV/c)

→ stopped on a thin target

The detector

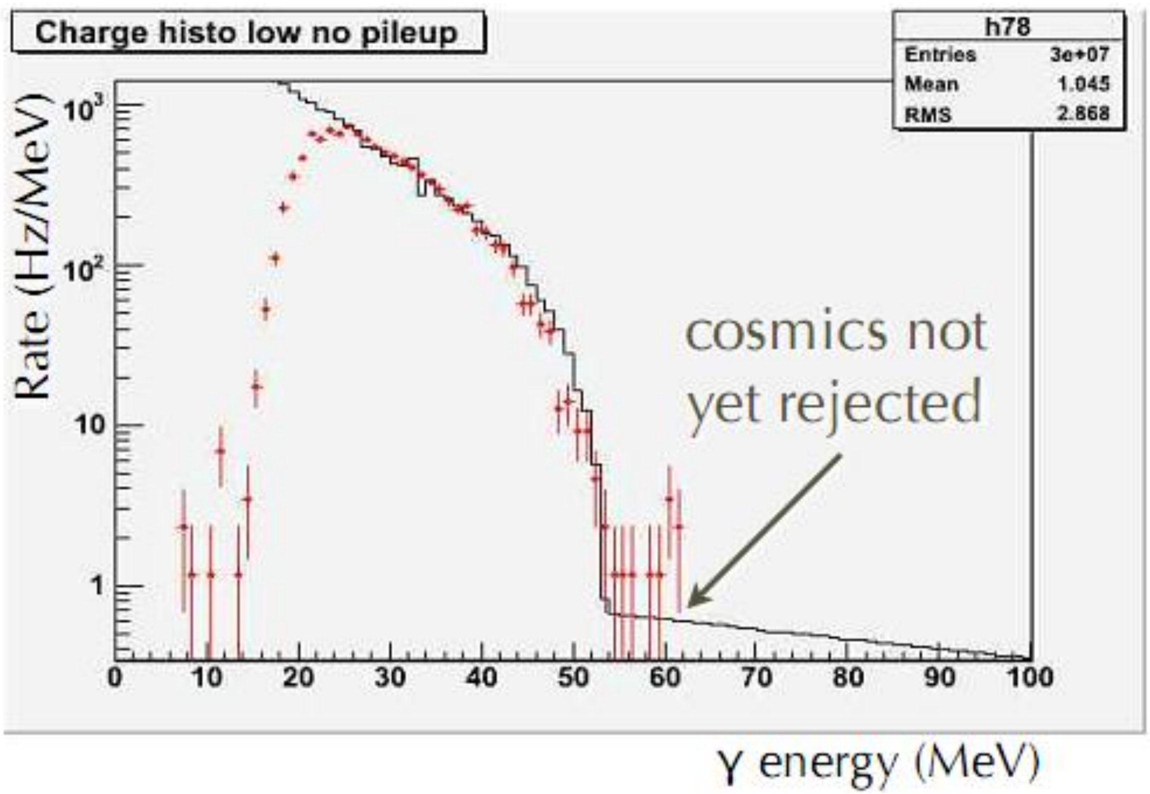
- Liquid Xenon calorimeter for γ detection (scintillation)
  - fast ($\tau \sim 20 \div 40$ ns)
  - high light yield (70% NaI)
- Thin wall quasi-solenoidal spectrometer & drift chambers ($X_0=2\cdot10^{-3}$) for e^+ momentum
- Scintillation counters for e^+ timing



Matter effects must be minimized in order not to spoil the resolution

D. Nicolo

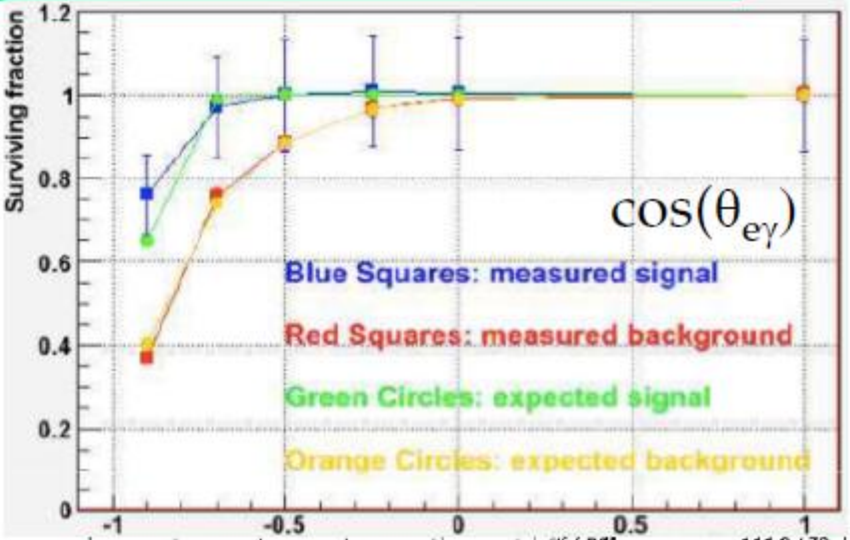
LXe-alone energy spectrum exhibits no difference with expectations both in absolute rate and spectral shape
➔ detection efficiency and background are under control



D. Nicolo

Radiative decays

- The number of observed events is compatible with estimated efficiencies
- also the angular distribution agrees with expectations



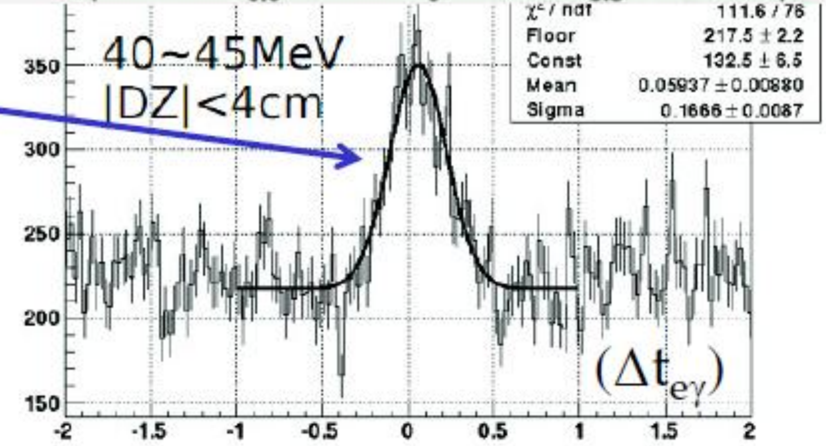
- also seen in normal data (with kinematical cuts applied)

$\sigma(\Delta t_{e\gamma}) = (159 \pm 9)$ ps

(extrapolated to 143 ps @52.8 MeV)

- contribution from tracking

➔ e^+ time-of-flight uncertainty



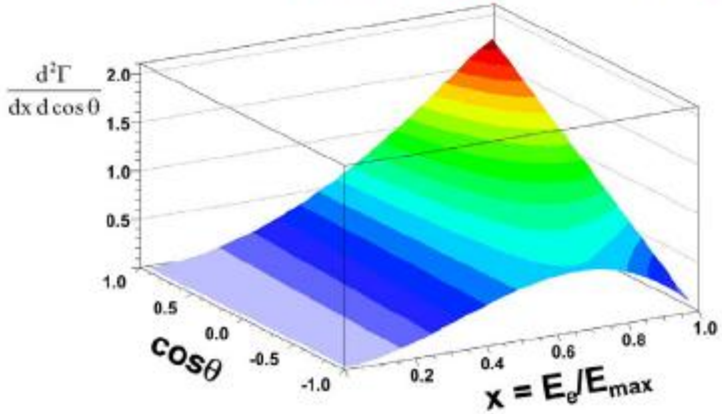
Run 2008 analysis about to finish
Results to appear in middle August

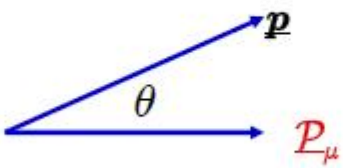
D. Nicolo

TWIST at TRIUMF

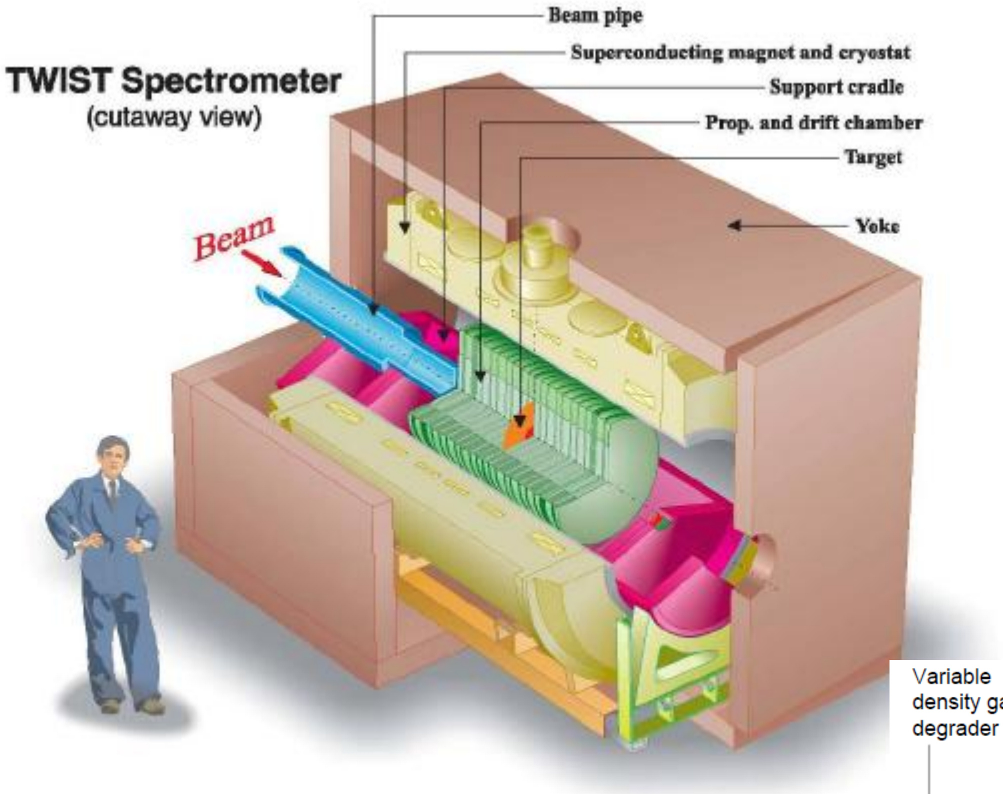
- Muon decay parameters ρ, η, $\mathcal{P}_\mu\xi$, δ
  - muon differential decay rate *vs.* energy and angle:

$$\frac{d^2\Gamma}{dx\ d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x,\rho,\eta) + \cos\theta \cdot \mathcal{P}_\mu \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

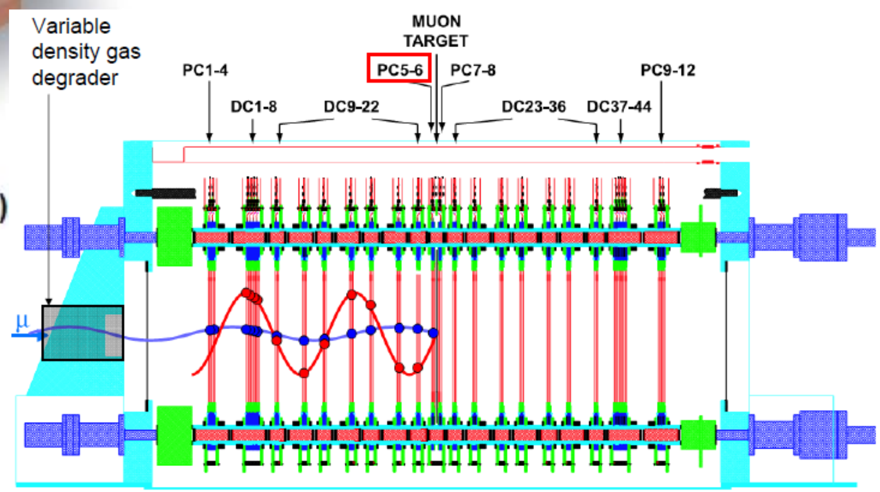




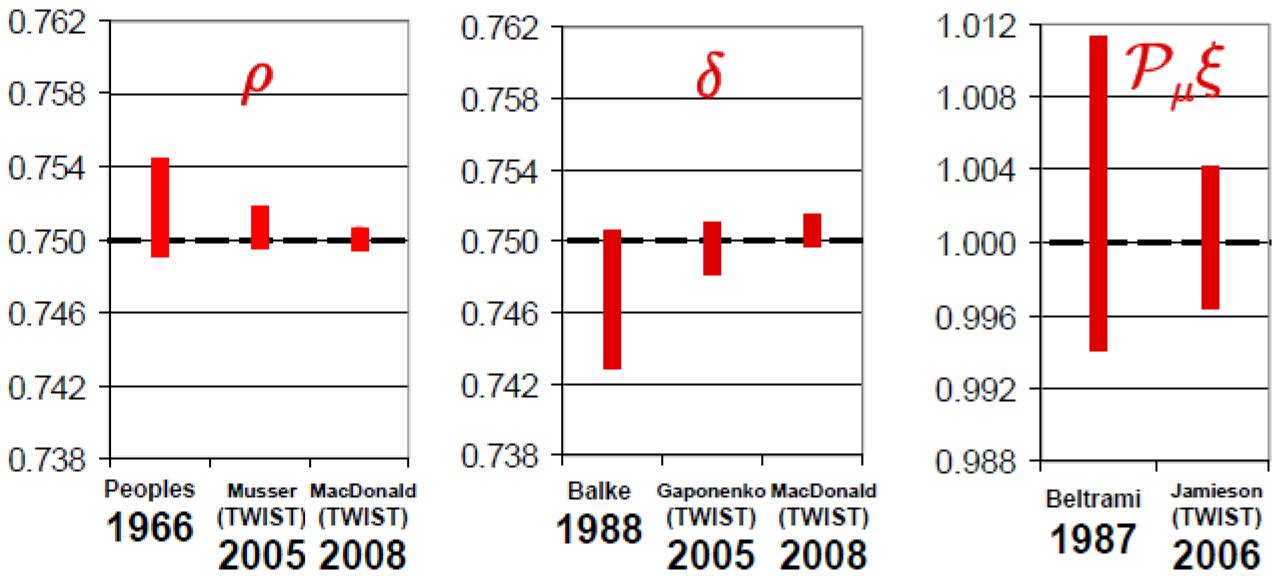
TWIST
Precision measurement of Michel parameters



R. Henderson et al., Nucl. Instr. and Meth. A548 (2005)



G. Marshall



$\rho = 0.75014 \pm 0.00017(\text{stat}) \pm 0.00046(\text{syst}) \pm 0.00011(\eta)$

$\delta = 0.75068 \pm 0.00030(\text{stat}) \pm 0.00067(\text{syst})$

$\mathcal{P}_\mu\xi = 1.0003 \pm 0.0006(\text{stat}) \pm 0.0038(\text{syst})$

Also $\mathcal{P}_\mu\xi\delta/\rho > 0.99682$ from Jodidio et al, 1986

Data taking ended
Analysis in progress
Further improvement (x2-4) by NuFact10

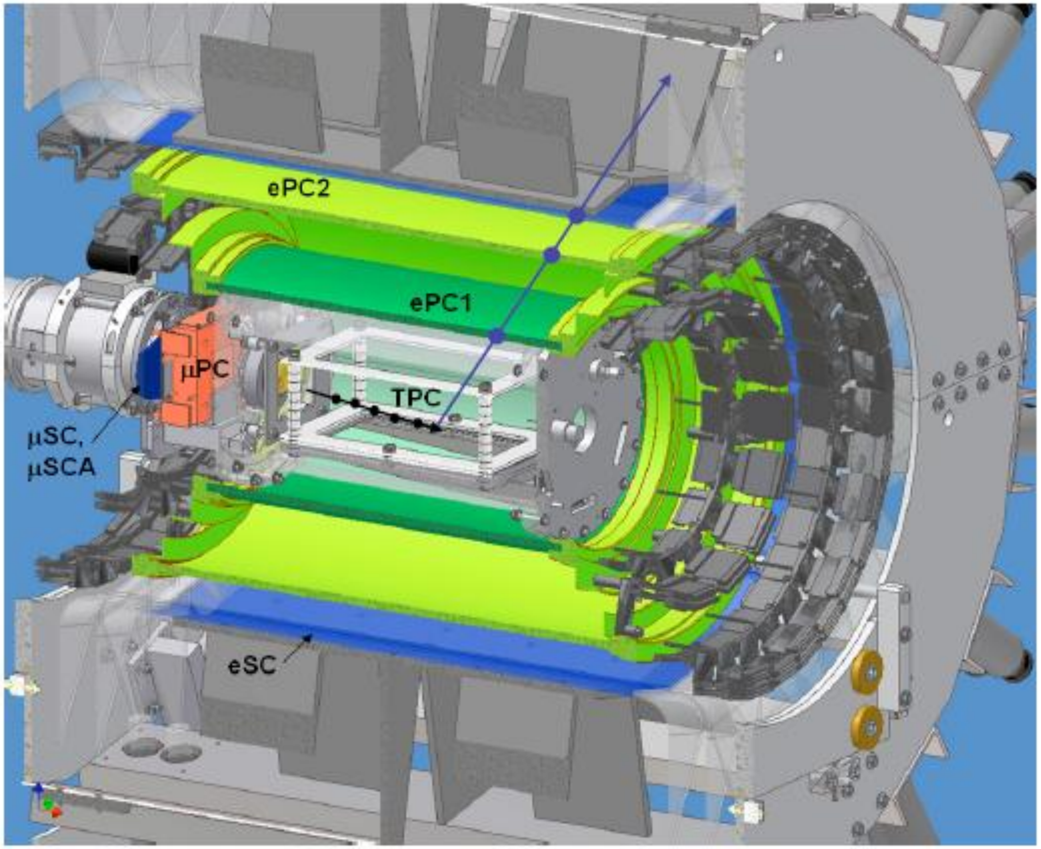
G. Marshall

MuCap

$\mu + p \rightarrow n + \nu_\mu$

μCap Detailed Diagram

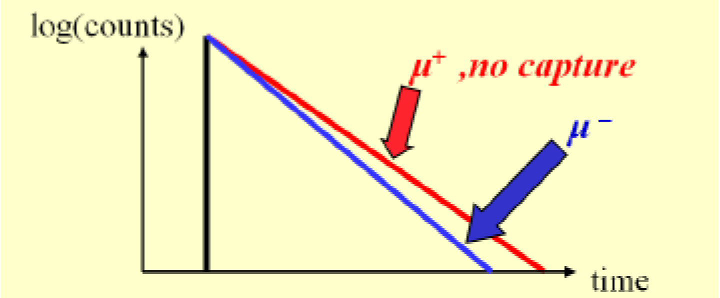
- Tracking of Muon to Stop Position in Ultrapure H_2 Gas
- Tracking of Decay Electron



S. Clayton

μCap Experimental Strategy

- Unambiguous interpretation
  - capture mostly from F=0 μp state at 1% LH_2 density
- Lifetime method
  - 10^{10} $\mu^- \to e\nu\nu$ decays
  - measure $\tau_{\mu-}$ to 10ppm
  - $\to \Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$ to 1%



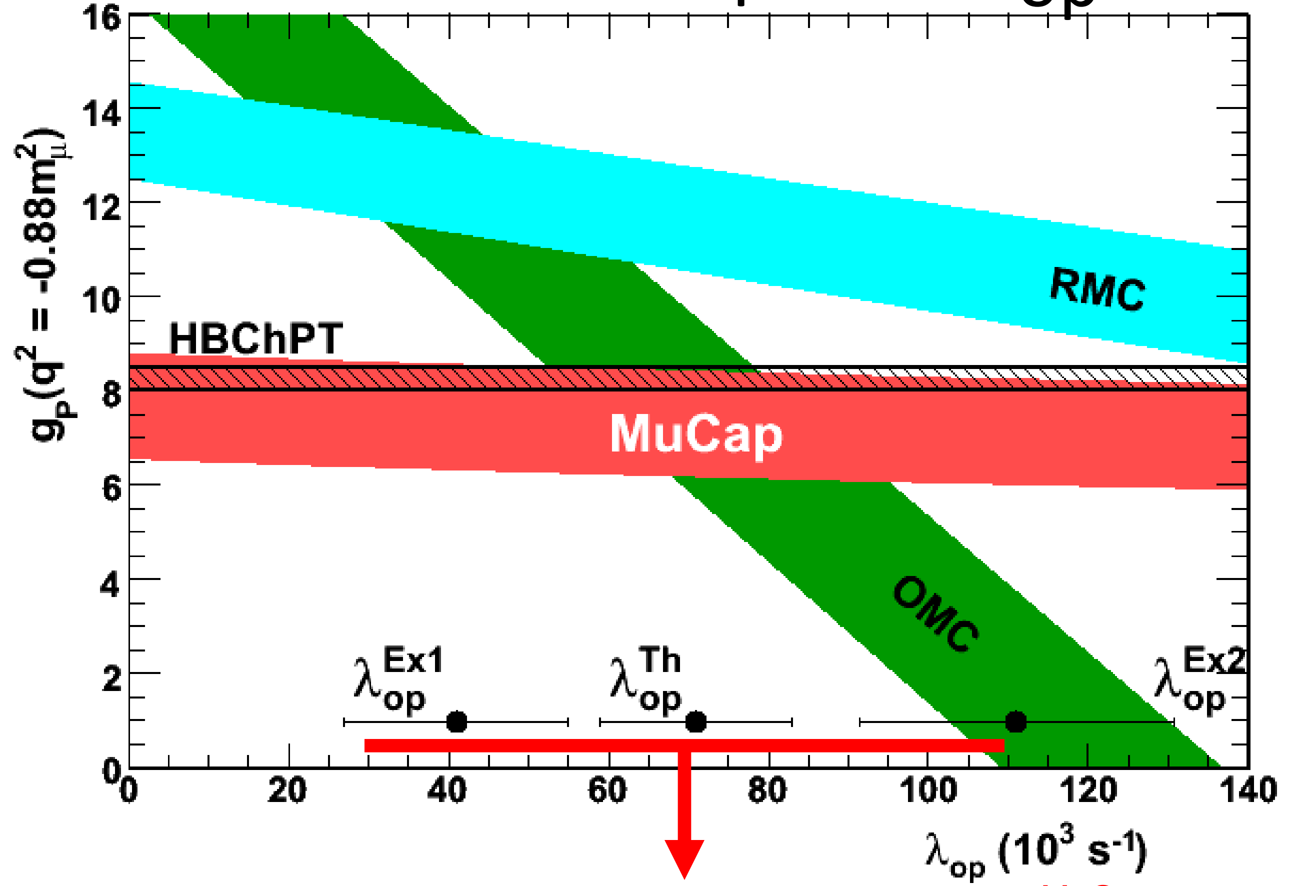
- Clean μ stop definition in active target (TPC) to avoid μZ capture, 10 ppm level
- Ultra-pure gas system and purity monitoring to avoid: μp + Z → μZ + p, ~10 ppb impurities
- Isotopically pure "protium" to avoid μp + d → μd + p, ~1 ppm deuterium

diffusion range ~cm

fulfill all requirements simultaneously
unique μCap capabilities

S. Clayton

Updated g_P vs. λ_{op}



(contributes 3% uncertainty to g_p^{MuCap})

- MuCap 2007 result (with g_P to 15%) is consistent with theory.
- This is the first precise, unambiguous experimental determination of g_P
- Further factor of 2.5 improvement in g_P expected with final MuCap result

S. Clayton

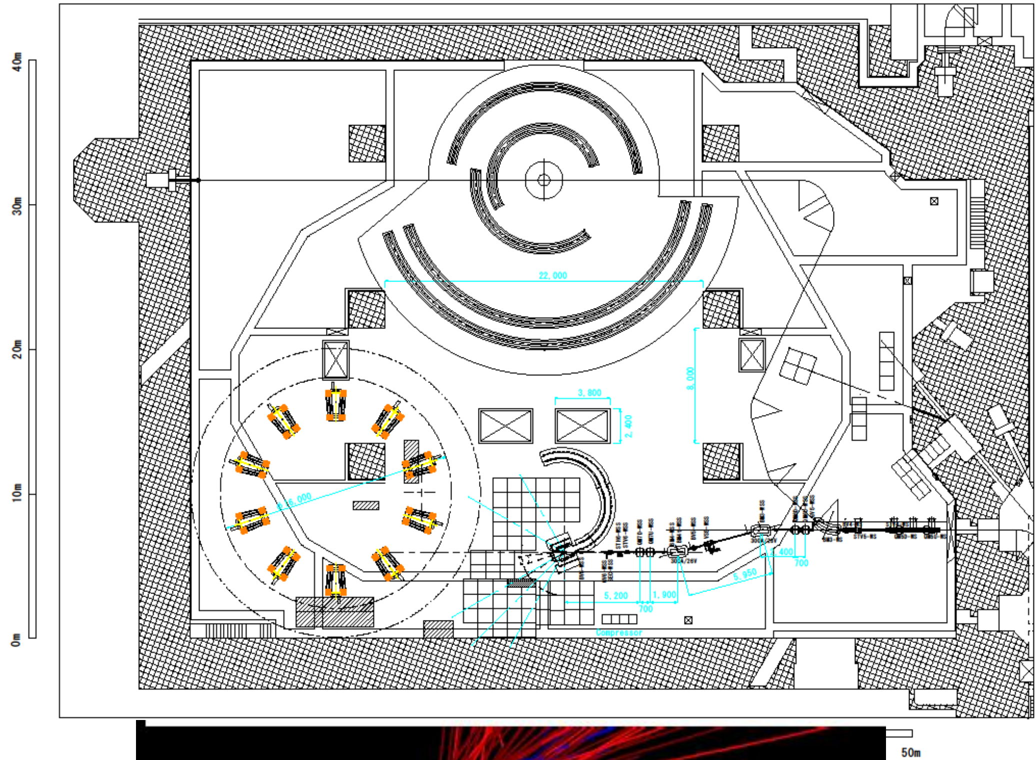
Facilities for the Future

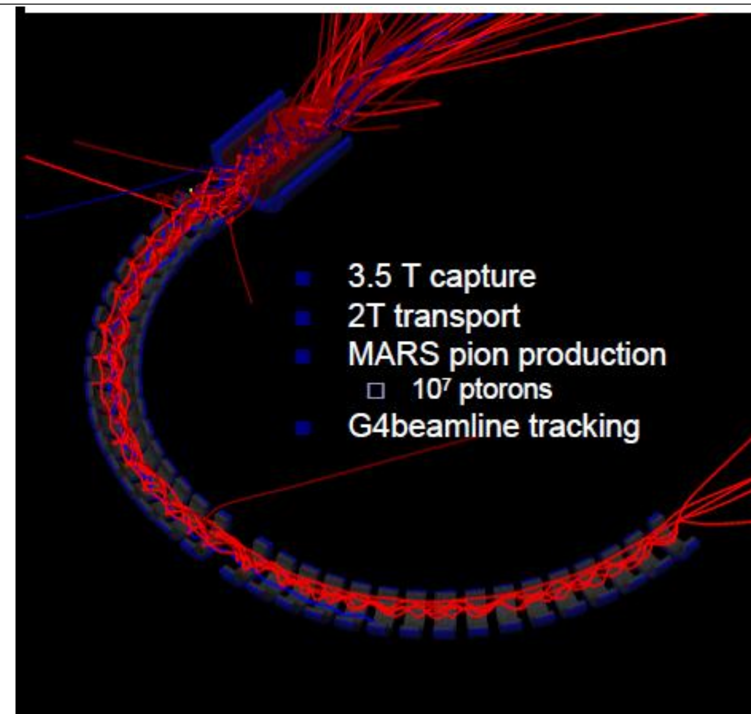
- MUSIC at RCNP
  - M. Yoshida (Osaka)

- J-PARC/MLF/MUSE and Super Omega
  - K. Nakahara (Maryland)

The MUSIC project at RCNP

- MUon Science Innovative Commission
- Muon channel at RCNP, Osaka Univ.
- Science using muons
  - Material science
  - Muon physics
  - R&D on muon accelerator
- Cyclotron proton beam produce pions in graphite target
  - Target size: 40mm dia. x 200mm len.
- Large pion-capture solenoid surrounding target can collect pions in large solid angle
- Long bent transport solenoid All the superconducting solenoid magnets are cooled by cyocooler





tem
from the
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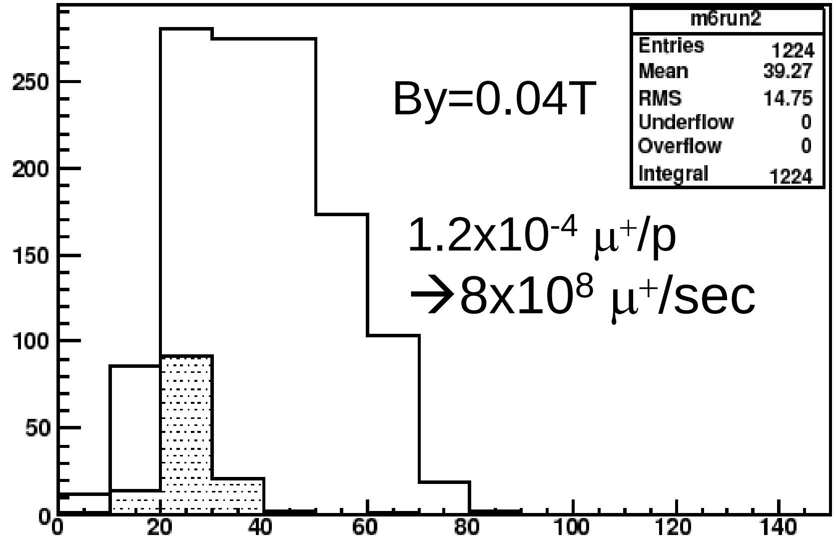
M. Yoshida

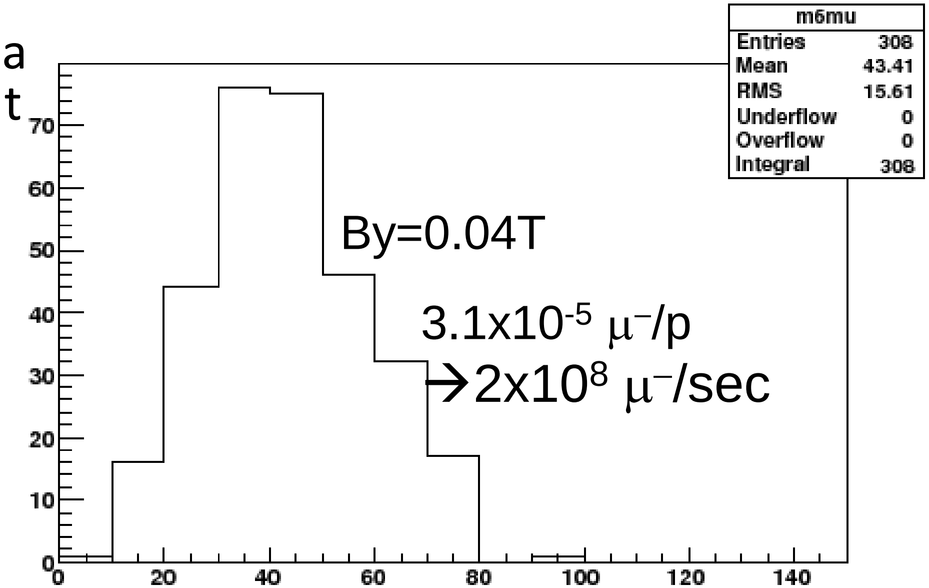
Muon beam at MUSIC

- 8×10^8 μ^+/sec with By=0.04T
- 2×10^8 μ^+/sec with By=0

- 2×10^8 μ^-/sec with By=0.04T
- 5×10^7 μ^-/sec with By=0

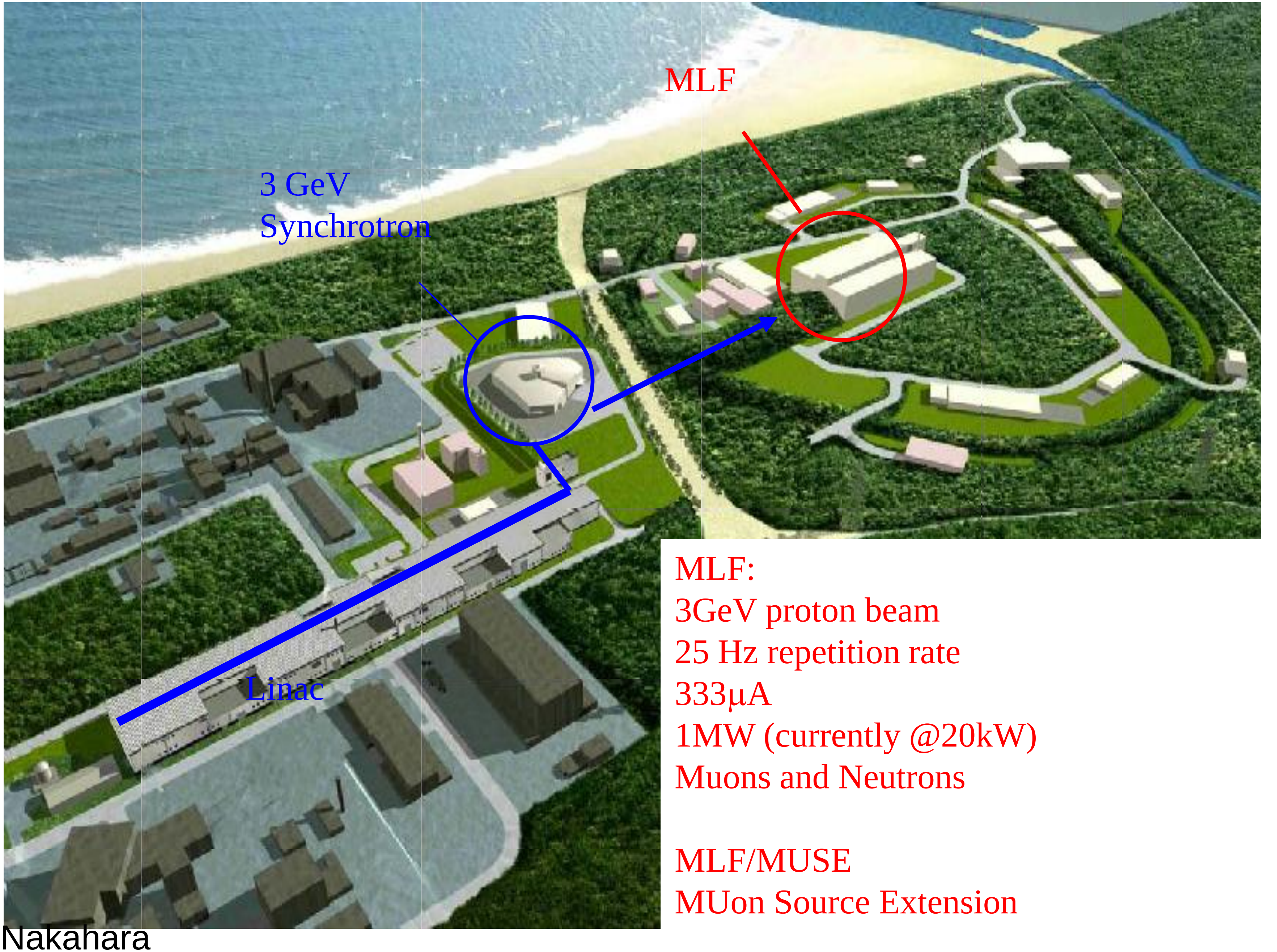
- Pion Capture System for MUSIC with a few meter transport solenoid is about to be constructed at RCNP in FY2009
- Commissioning will start with proton beam next year





M. Yoshida

J-PARC/MLF

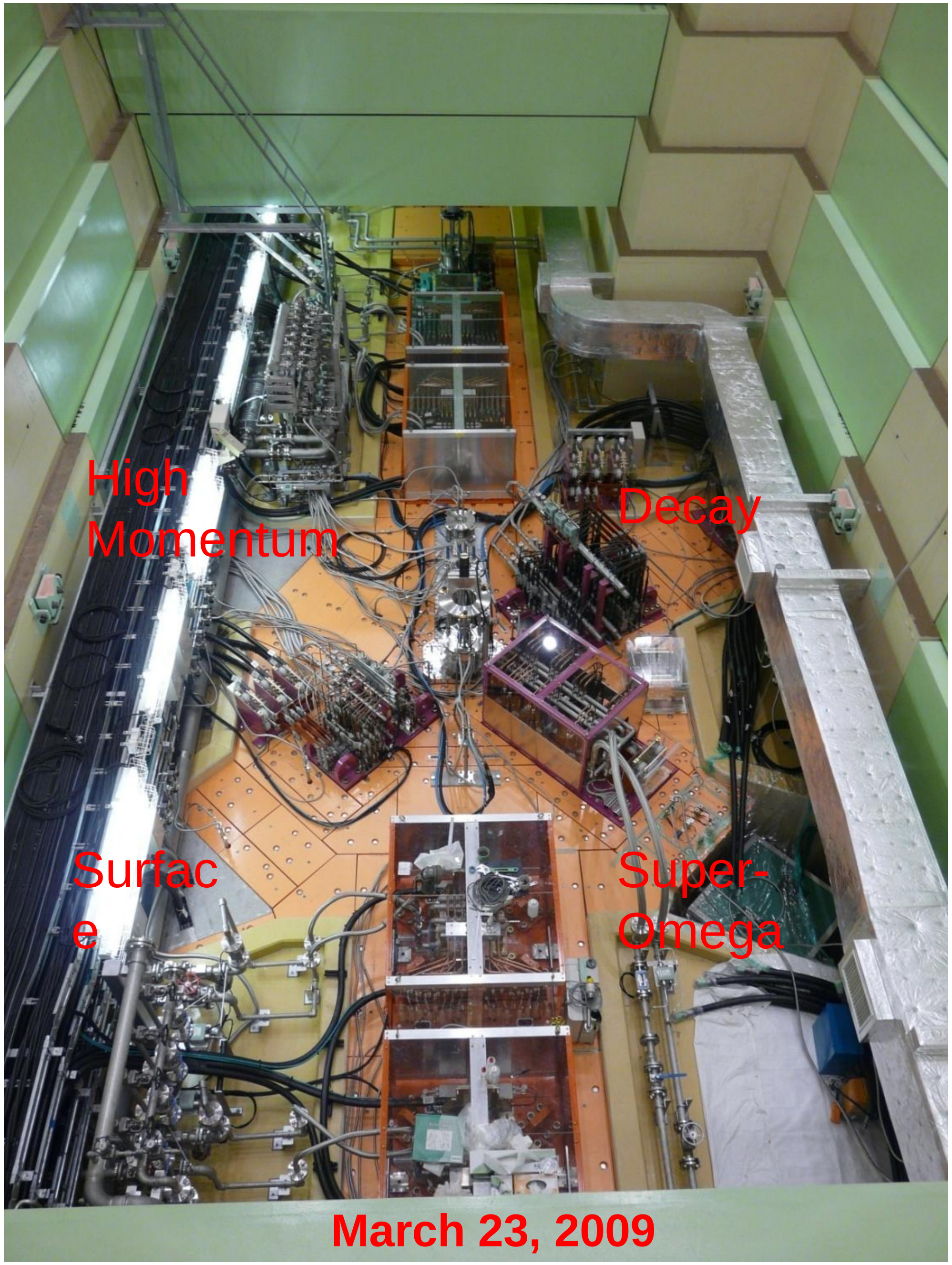


MLF:
3GeV proton beam
25 Hz repetition rate
333μA
1MW (currently @20kW)
Muons and Neutrons

MLF/MUSE
MUon Source Extension

K. Nakahara


June 29, 2006


High
Momentum
Decay
Surfac
e
Super-
Omega
March 23, 2009

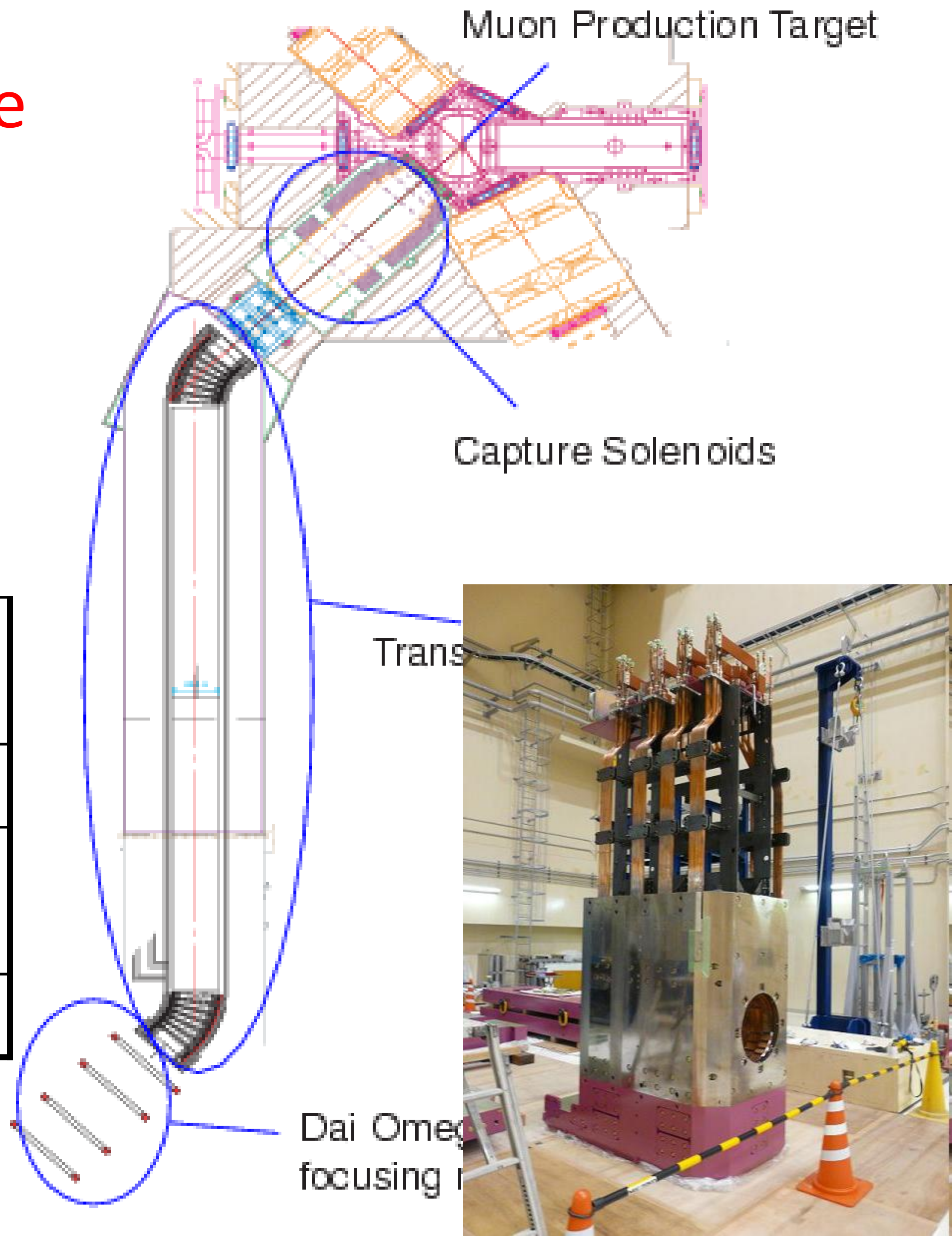
K. Nakahara

The Super Omega Muon Beamline

Build the highest intensity pulsed muon beamline in the world

Capture μ^+ and μ^- simultaneously

Conventional beamlines	Super-Omega
30-40 msr	400 msr
Quadrupole triplets (capture)	Large acceptance solenoid
Bending magnet	Curved solenoid



K. Nakahara

Summary

Progress on new measurement – design and R&D

μe conversion, g-2, …

Several experiments produce new results of high quality

Synergy of neutrino factory and muon physics?

Common Facilities

high intensity proton driver

some requires severe proton time structure

solenoid capture of pions and muons

most new experiments need such beam

most muons physics requires low energy muons

- backward pion collection

Good future for muon and neutrino physics!