WG4 Answers and Questions

K. Ishida
for WG4 conveners

Muon Physics

- At its heart a Neutrino Factory is also a Muon Factory

$$p + Target \to \pi, K \to \mu\nu$$

- Producing these intense neutrino beams will require new high intensity muon beam lines

- This will greatly increase the number of μ's available to probe for hints of physics beyond the standard Model

Muon Physics

- Enables new searches for CLFV in the μ sector
- Enables new generations of precision g-2/EDM measurements

But…

- Is there a deeper connection between muon physics and neutrino physics?
  - Fundamental questions of lepton flavor

Questions posed for 2014

- Three "Big" questions we wanted to address at this year's workshop:
  - Expt:
    What is the ultimate $\mu \to e\gamma$ and $\mu \to eee$ reach once $\mu N \to eN$ has set the limit.
    - What are the roles of the ratios of cLFV processes and other precision experiments at this point?
  - Beams:
    What are the beam specifications for muon physics?
    (our requirements)
    - Are these compatible with the NuFact?
    - Are there other options?
  - Theory:
    What else besides cLFV? EDMs?
    - What does theory tell us once we observe cLFV?
    - How do we relate our results to the models?

Plenary Talks — Friday 29th

Expt:

Lepton Flavour Violation Experiments

Ajit Kurup, Imperial College London

Beams:

Muon Facilities for Precision Experiments

Naohito Saito, KEK

Theory:

Lepton Flavour Violation Theory

Lorenzo Calibbi, University of Brussels

The Week to Come:

- Charged Lepton Flavor — 11 talks
  - $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$, $\tau \to$ cLFV
  - Connections to theory
- Precision Measurements — 7 talks
  - muon g-2
  - μ hyperfine spliting
  - proton radius
  - μ capture
- Muon Facilities — 7 talks
  - Progress on mu cooling
  - New methods for intense mu beams

Questions posed 1

Expt:

What is the ultimate $\mu \to e\gamma$ and $\mu \to eee$ reach once $\mu N \to eN$ has set the limit.

- What are the roles of the ratios of cLFV processes and other precision experiments at this point?

cLFV

Many presentations in WG4

μe conversion (μN→eN)

COMET Phase-I: P. Litchfield
COMET Phase-II: A. Kurup
PRISM Design: J. Pasternak

ALCap P. Litchfield

Mu2e at Fermilab : Y. Kolomensky

DeeMe: Y. Nakatsugawa

μ→eγ

MEG and MEG II: F. Tenchini

μ→eee: M. Kiehn

tau-decay : G. Onderwater

They are well summarized in Plenary Talk
So I will not repeat here

Expt:

Lepton Flavour Violation Experiments

Ajit Kurup, Imperial College London

A. Kurup, in plenary

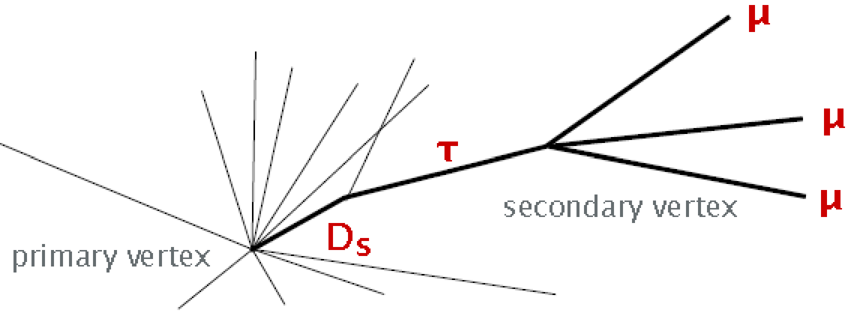
Summary

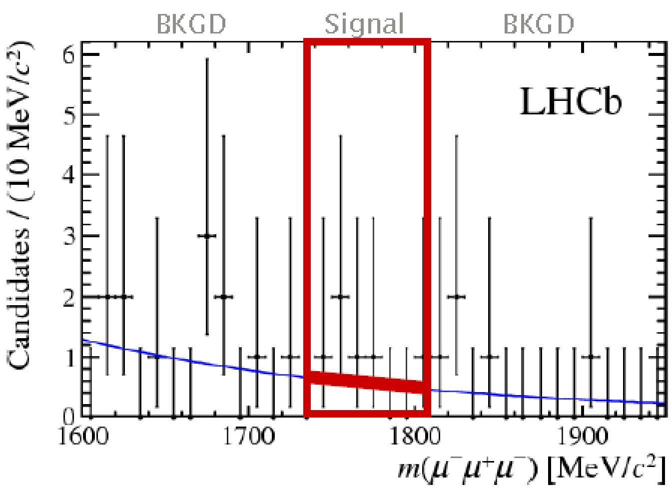
- Upcoming experiments will have significant improvements in sensitivity.
  - $\mu^+ \rightarrow e^+\gamma$: 10, MEG→MEG-II.
  - $\mu^+ \rightarrow e^+e^+e^-$: 10^3 for Mu3e.
  - $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$: 10^4 for COMET and Mu2e.
- Future experiments such as PRISM can make use of advances in accelerator technology to deliver intense muon beams with a small energy spread.
  - Sensitivity $<10^{-18}$ for muon to electron conversion.
- Synergies with neutrino factory accelerator complex.
- Very exciting potential for discovering new physics!

cLFV in tau-decay

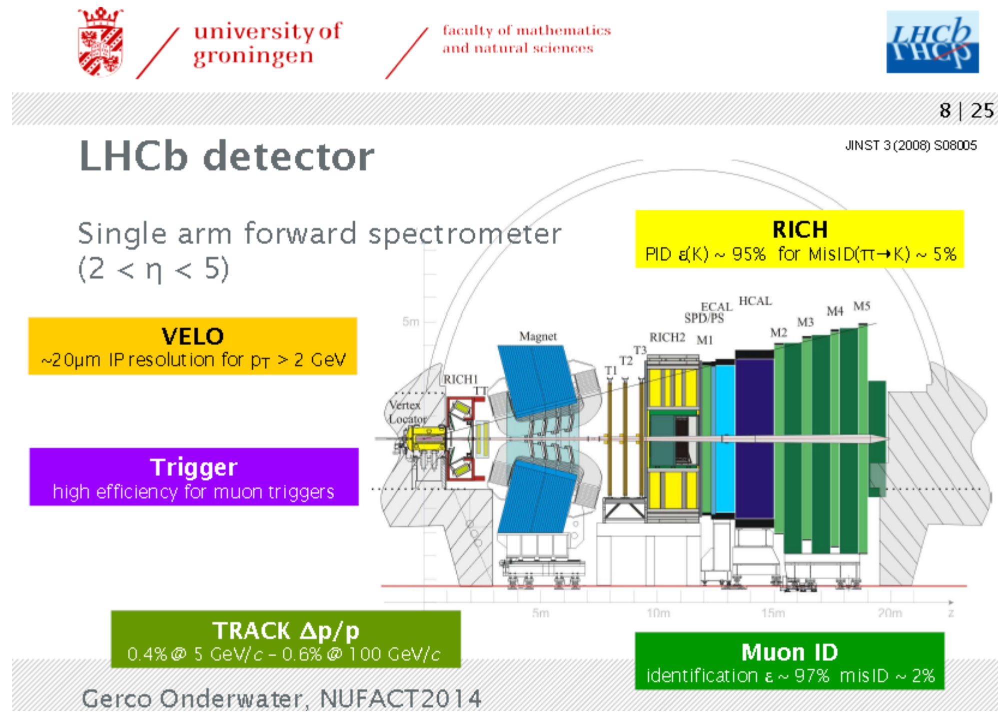
G. Onderwater

Large mass → many possible LFV final states
→ closer to high-mass new physics





$B(\tau^- \to \mu^-\mu^+\mu^-) < 8.0\ (9.8) \times 10^{-8}$



cLFV with LNV & BNV

$B(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3\times10^{-7}$

$B(\tau^- \to p\mu^-\mu^-) < 4.4\times10^{-7}$

Other Muon Precision Measurements

muon g-2/EDM : deviation from theory(SM)?

MuHFS: precision QED

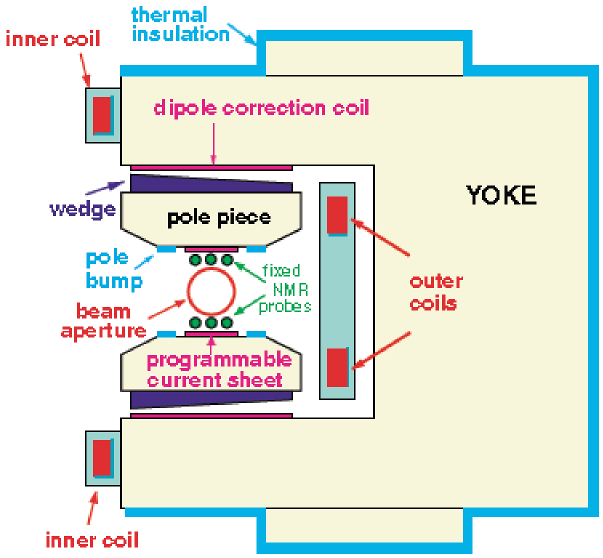
MUSUN (μ^-+d nuclear capture):
also relation to ν

Proton radius puzzle:
μ+p and e+p scattering
μp hyperfine splitting

muon g-2 at Fermilab

P. Paradisi

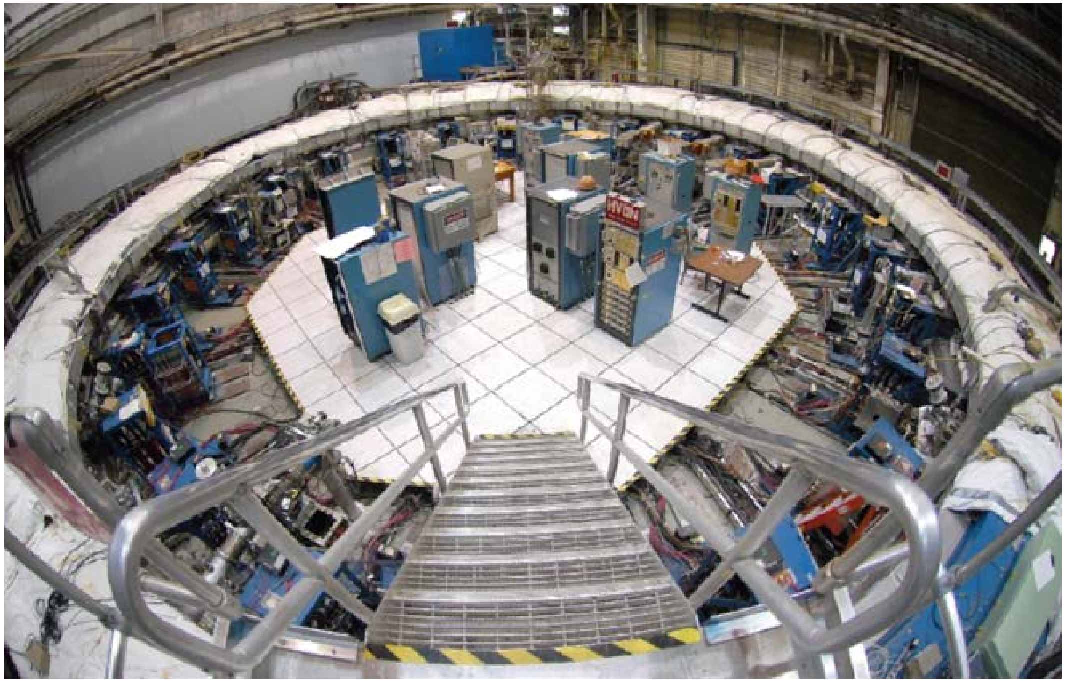
Present g-2 measurement precision (BNL E821) is 0.5 ppm
Discrepancy with theory(SM) by 3~3.5σ
Need of new physics?



x21 statistics at Fermilab
and reduce systematics errors

magnet transport from BNL completed
and to be tested at Fermilab

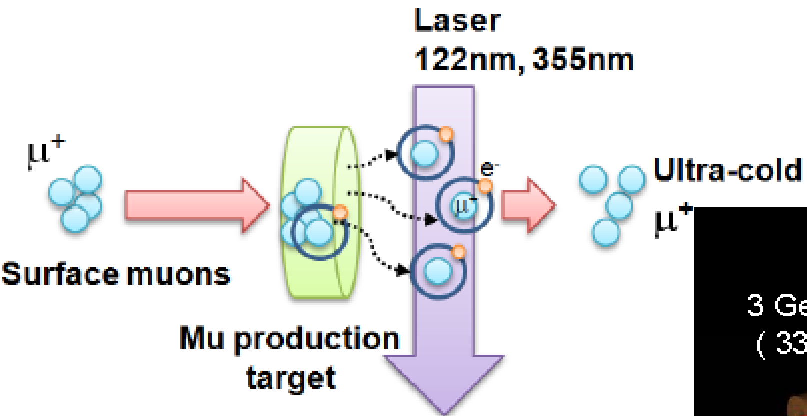
Expect data run in ~2017

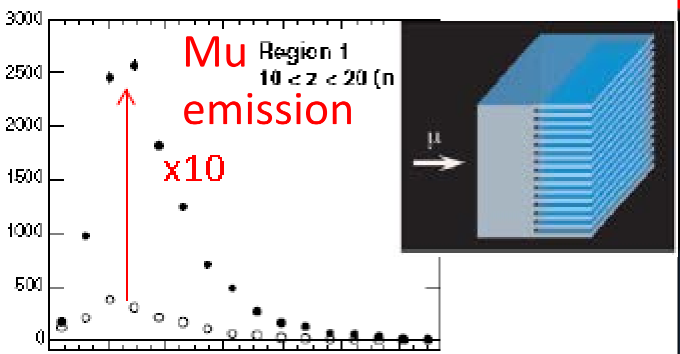


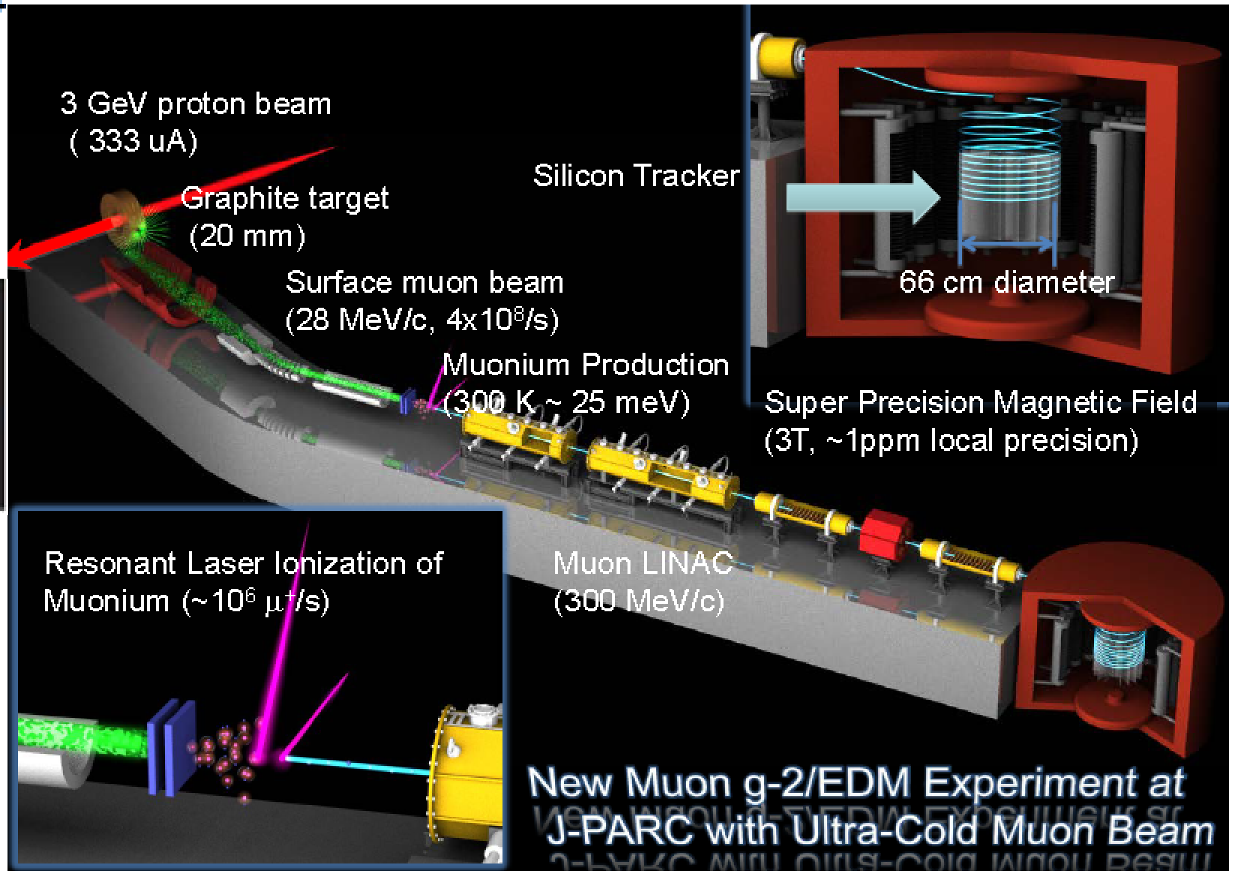
muon g-2/EDM@J-PARC

K. Ishida

A new measurement of g-2/EDM planned at J-PARC
based on "ultra-cold muon beam" and MRI-type storage ring.
10 times increase of Mu emission achieved by laser ablation of silica aerogel surface.
=> coming close to beam intensity requirement





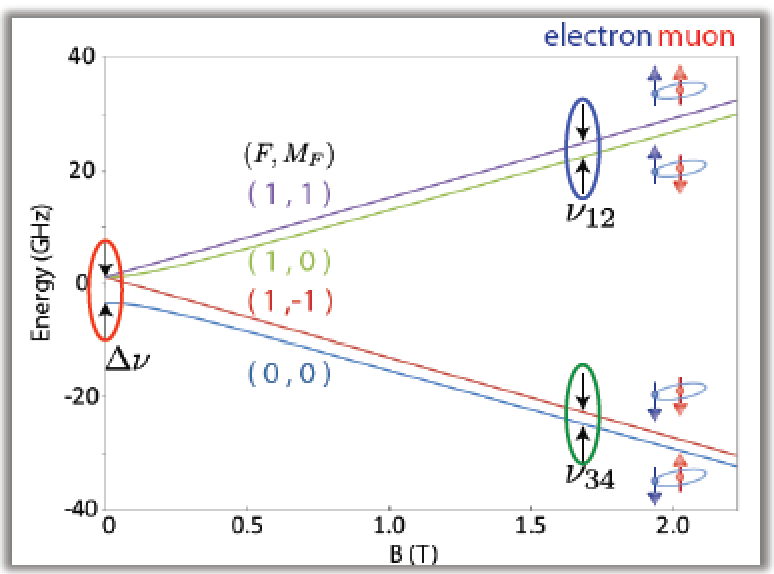


Mu HFS (MUSEUM)

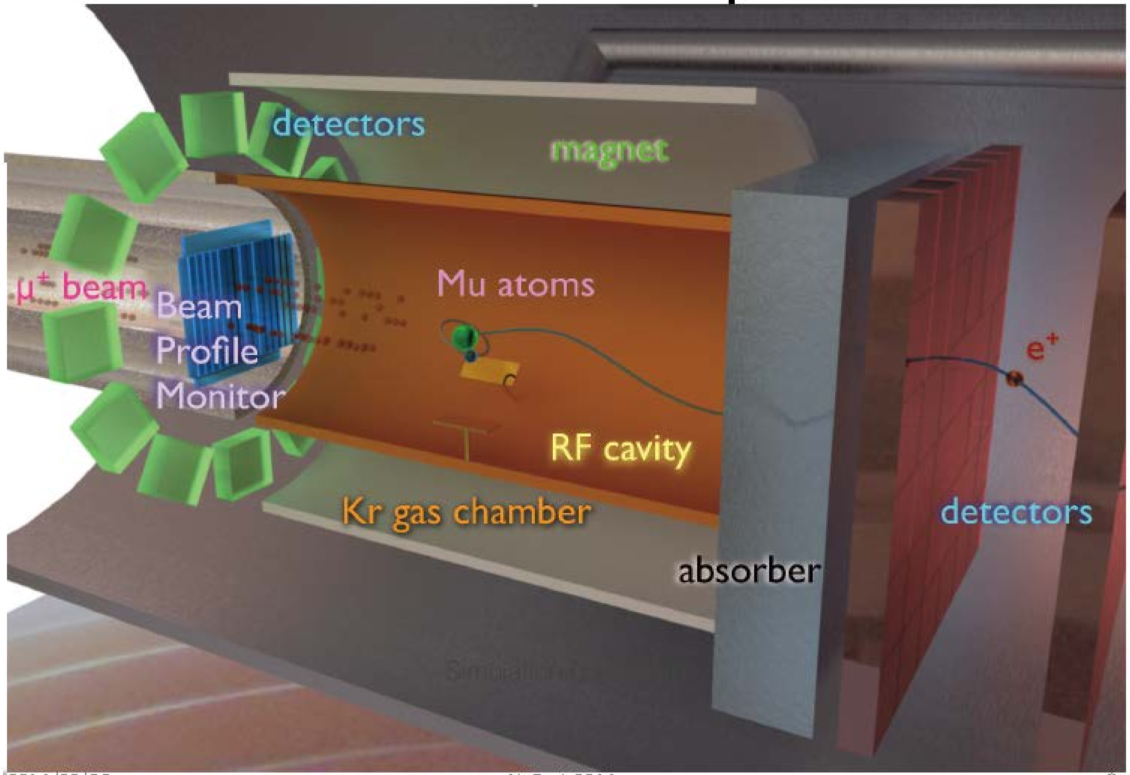
P. Strasser

Precision measurement of Muonium ground state HyperFine Structure
→Precise test of QED
→ Muon magnetic moment (relative to proton) (used as input for muon g-2)

Aim to improve previous LAMPF measurement precision by x10



Schematic of the Experiment



$\nu_{12}+\nu_{34} = \Delta\nu_{HFS}$

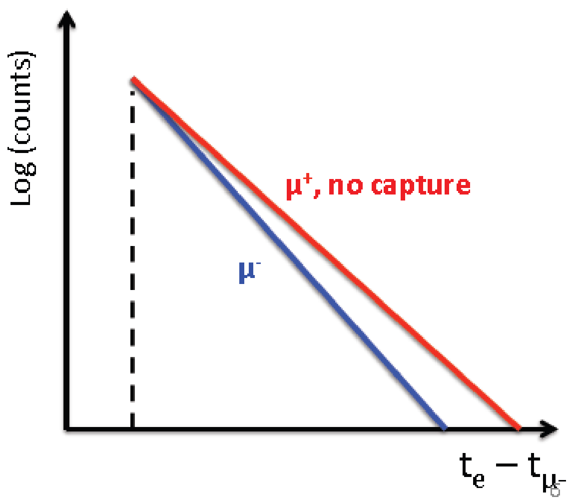
$\nu_{12}-\nu_{34} \propto \mu_{\mu}/\mu_{p} \propto m_{\mu}/m_{p}$

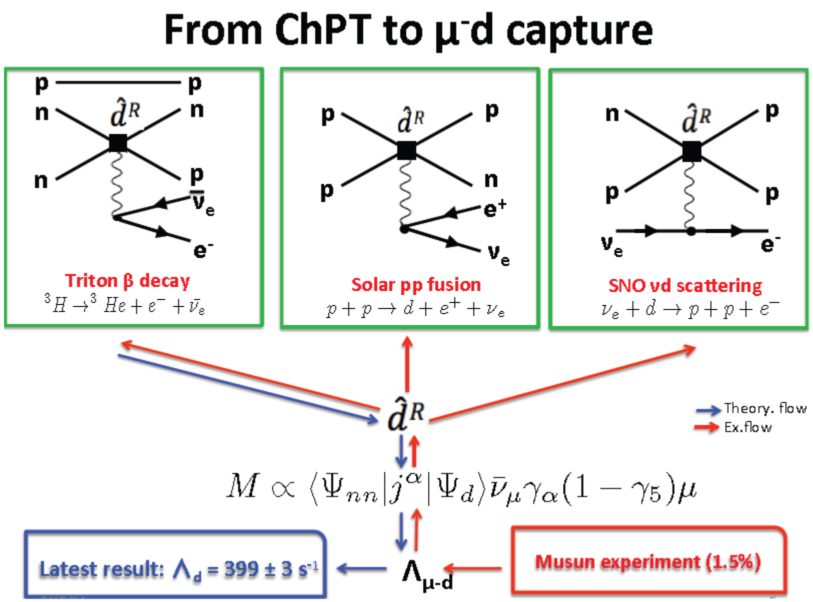
MuSun: Muon capture on deuteron

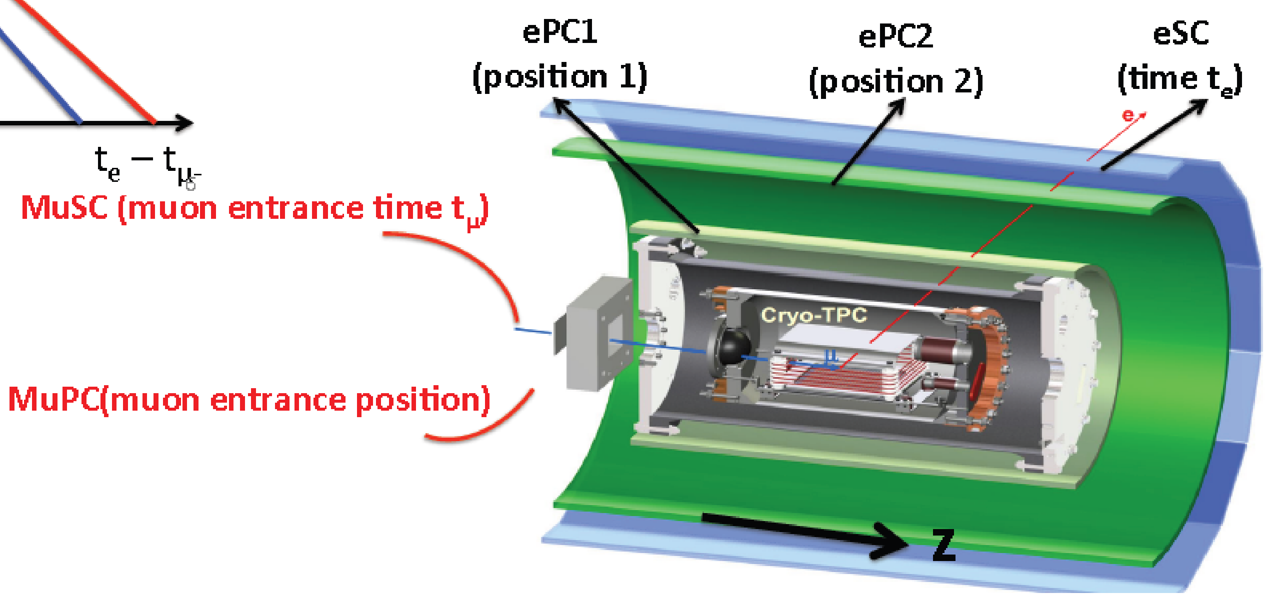
X. Luo

$\mu^- + d \rightarrow \nu_\mu + n + n$

Data collected 2011, 2013, 2014
Systematics study ongoing
Expect first result in 2015







MUSE (μp scattering)

K. Mesick

Proton Radius Puzzle:
7.9σ discrepancy between the more precise muonic-H spectroscopy results and electronic results.

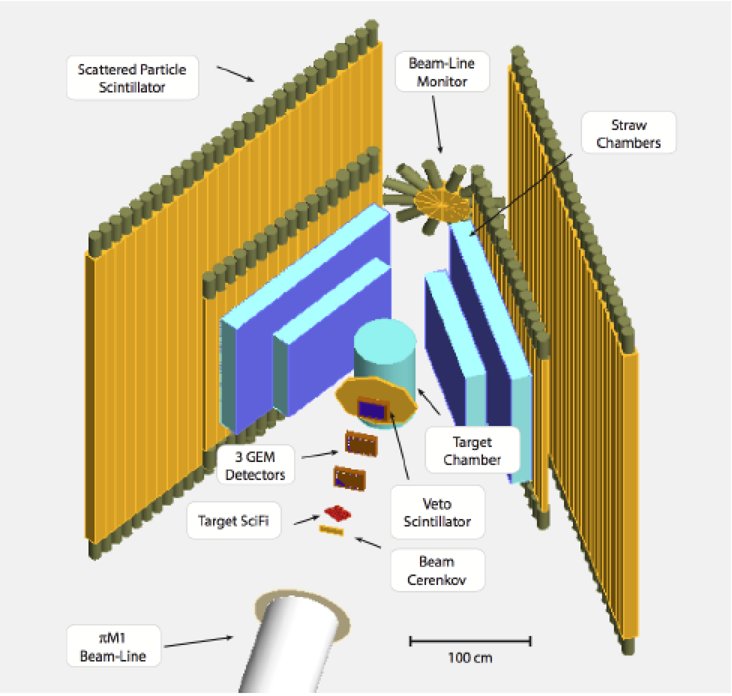
Muonic hydrogen 2S→2P Lamb shift measurement

r_p (fm)	electrons	muons
atom	0.8758 ± 0.0077	0.8409 ± 0.0004
scattering	0.8770 ± 0.0060	???

ep and μp scattering with the same apparatus

production runs expected in 2017-2018

Detector Overview in Simulation



- Measure ep and μp cross sections

p = 115, 158, and 210 MeV/c
θ = 20° – 100°
Q^2 = 0.002 – 0.07 GeV^2
ε = 0.256 - 0.94

- Measure both + and – polarity

- Challenges include

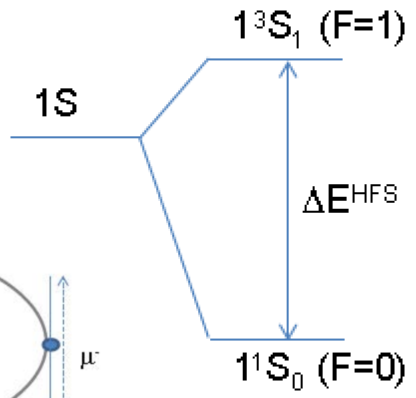
Need high pion rejection efficiency
Good particle ID
Precise timing

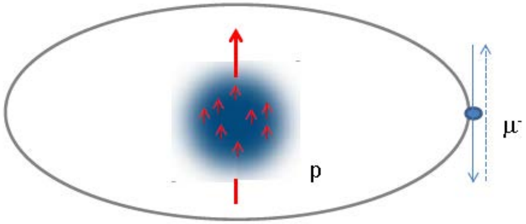
μp HFS

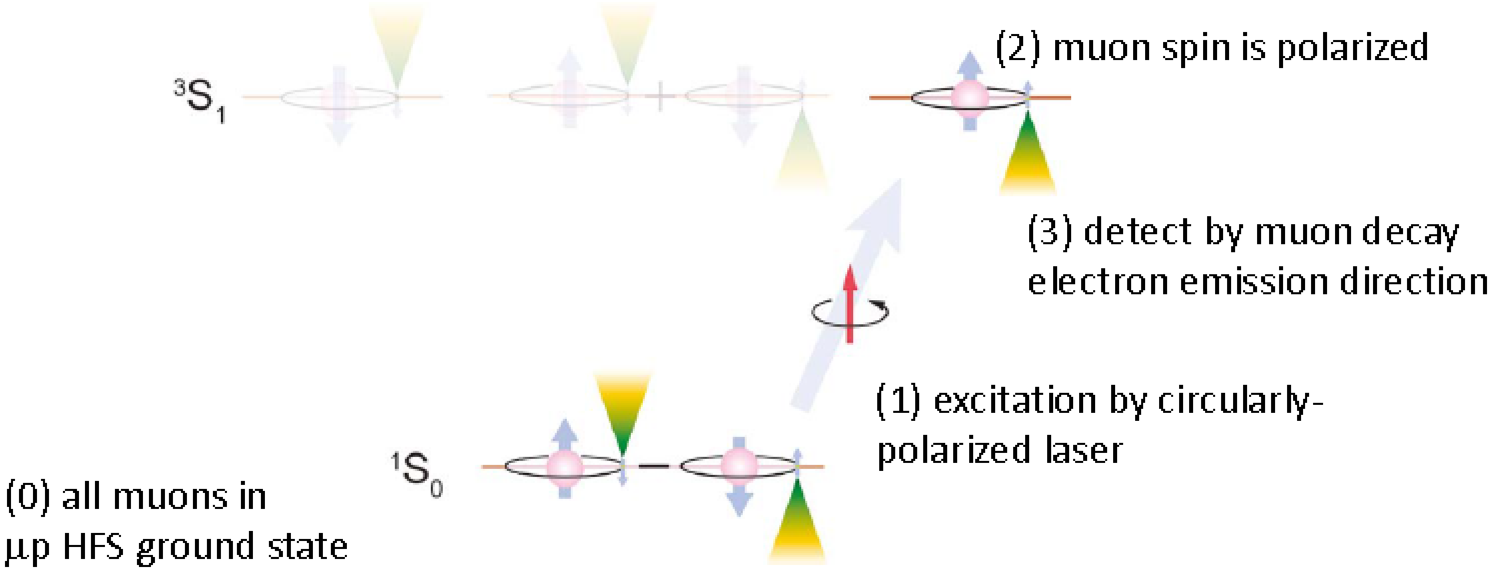
K. Ishida

First measurement of the 1S HFS energy of muonic hydrogen
Gives magnetic radius of proton (Zemach Radius)
- clue to Proton Radius Puzzle

Infra-red laser and target design in progress







Questions posed 2:

- Beams:
  What are the beam specifications for muon physics?
  (our requirements)
  - Are these compatible with the NuFact?
  - Are there other options?

Muon Facilities for Precision Experiments

Naohito Saito, KEK

WG3/WG4 Joint Session Discussion

J-PARC MUSE Facility
  Y. Miyake
Ultra-slow muon beam line
  K. Adachi
MUSIC
  Y. Matsumoto

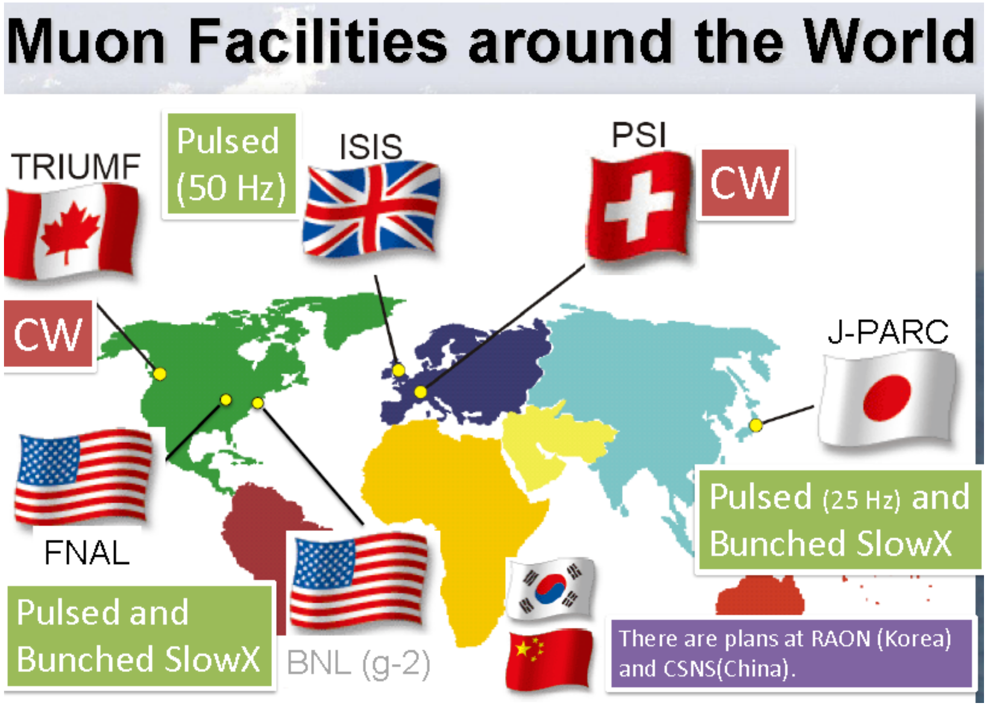
Muon Facilities for Precision Experiments

N. Saito
in Plenary

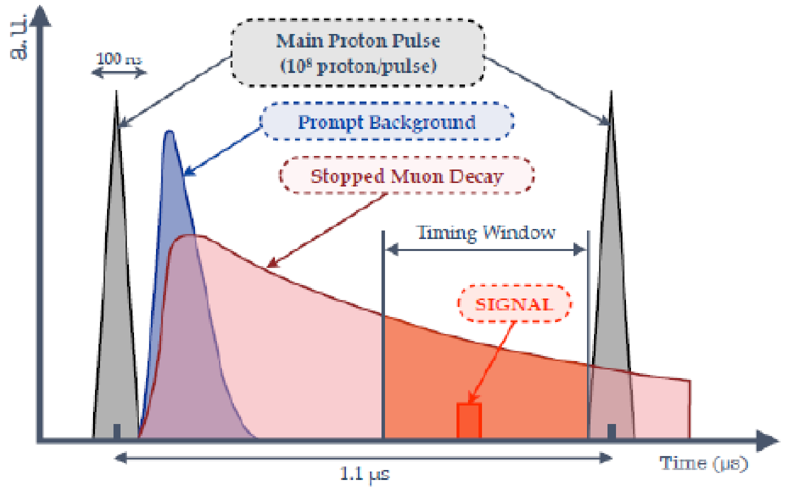
Time structure matters for
muon precision measurements

MEG&MEG II: CW to minimize pileup

COMET: proton distinction



proton distinction



Facilities

J-PARC MUSE

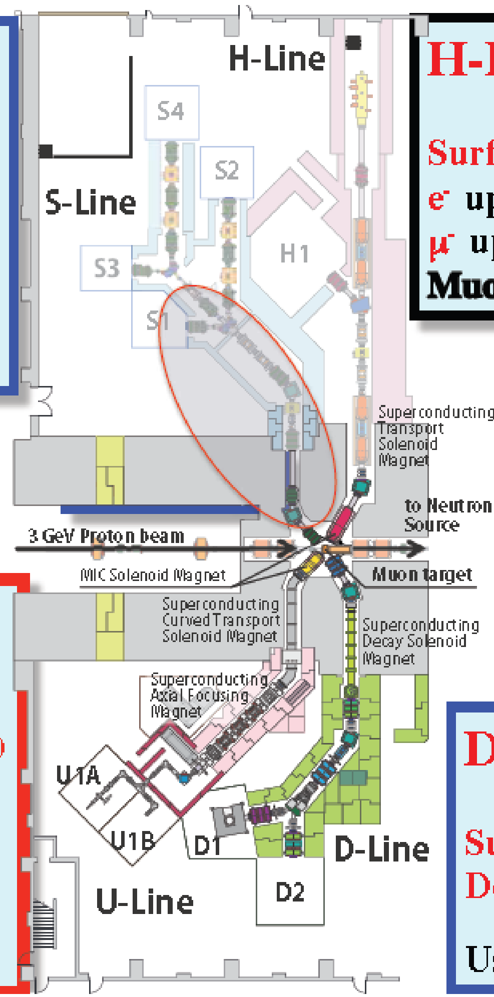
Y. Miyake

Muons @ 1 MW J-PARC MLF (3 GeV, 333 μA)
Home for muon g-2/EDM, DeeMe, MUSEUM(MuHFS)
and various muon applications (μSR, Ultra Slow Muon, analysis)
D-Line: operational, U-Line: construction completed,
S-Line: to be completed, H-Line: under construction

S-Line

Surface μ^+(30 MeV/c)
For materials sciences

Under Construction!
Hopefully first muon
this coming March!



H-Line

Surface μ^+ For Mu-HF, g-2/EDM
e^- up to 120 MeV/c For DeeMe
μ^- up to 120 MeV/c For μCF
Muon Microscopy

MUSE Facility @MLF

U-Line

Ultra Slow μ^+ (0.05-60keV)
For multi-layered thin foils, nano-materials, catalysis, microbeam, etc.

D-Line

Surface μ^+(30 MeV/c)
Decay μ^+/μ^-(5-120 MeV/c)

Users' RUN, in Operation

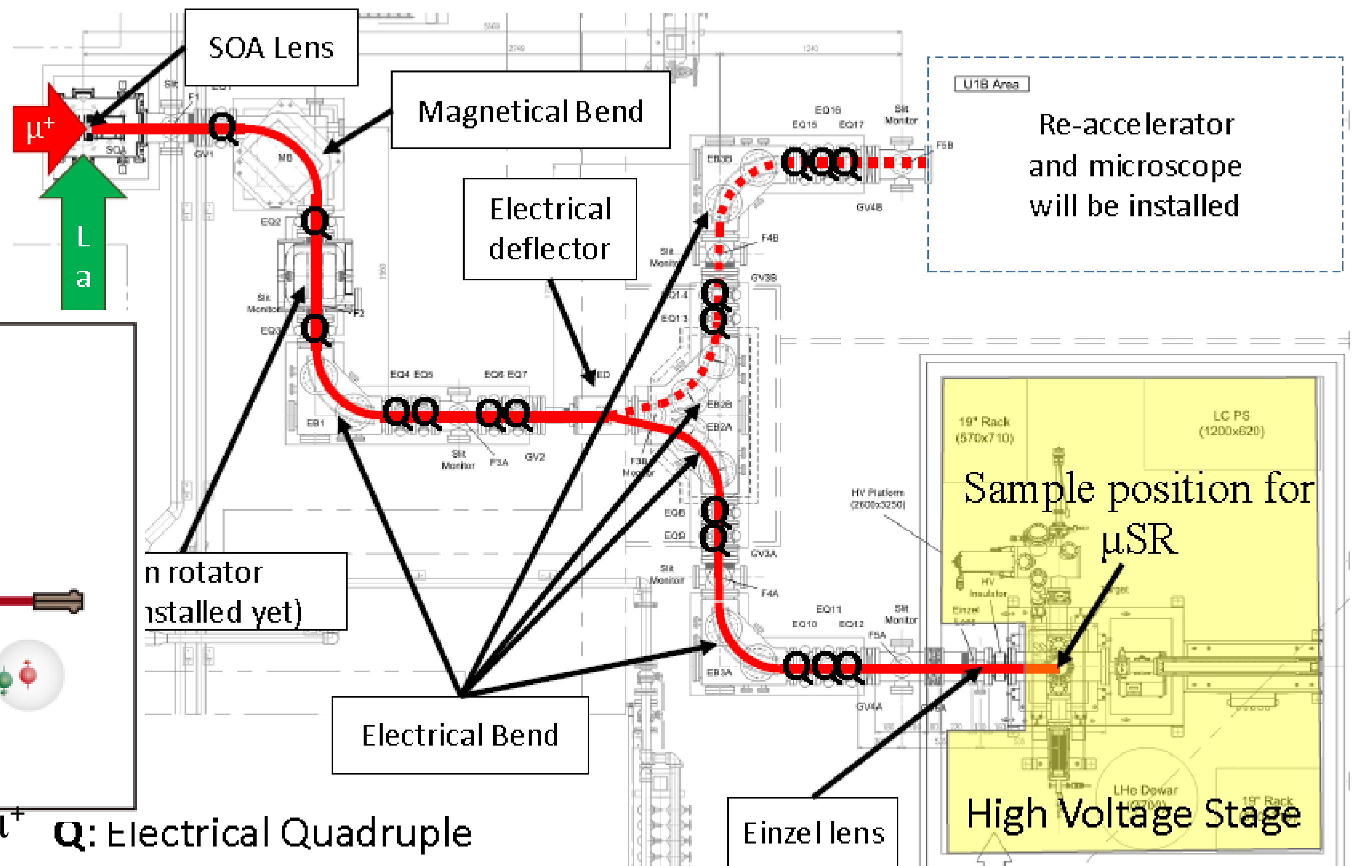
Facilities

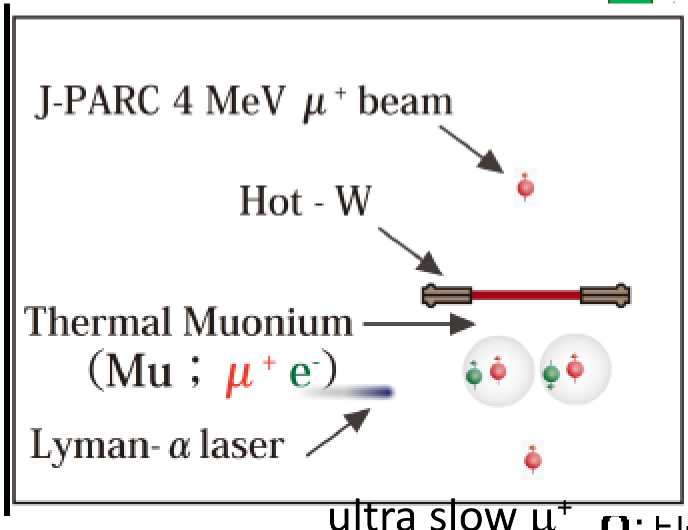
Ultra slow muon beamline

A. Taihei

Very low energy muon beam for materials study
at J-PARC MUSE U-Line
Commissioning with H^+ in progress
Ultra slow muon beam expected in Nov

Overview of the Ultra slow muon transport system





Q: Electrical Quadruple

Facilities

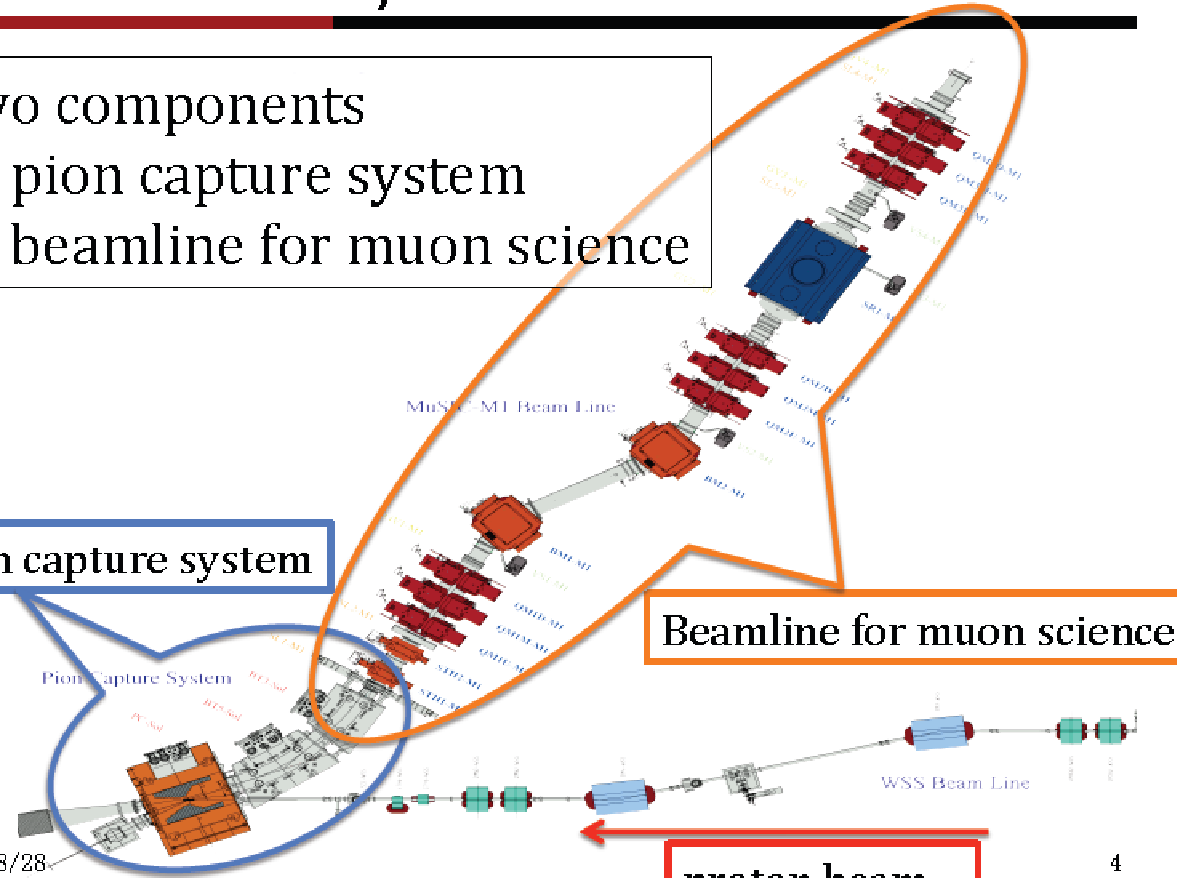
MUSIC @RCNP(Osaka)

Y. Matsumoto

0.4 kW 392 MeV proton beam
3.5T pion capture solenoid
muon beamline added in 2013FY
beam tuning in progress
use of DC muon beam 2015~

Layout of MuSIC

two components
- pion capture system
- beamline for muon science



	simulation	measurement
mu+ [μ^+/sec/μA]	2×10^8	3×10^8
mu− [μ^-/sec/μA]	1.4×10^8	$(1.7 \pm 0.3) \times 10^8$

Questions posed 3:

- Theory:
  What else besides cLFV? EDMs?
  - What does theory tell us once we observe cLFV?
  - How do we relate our results to the models?

Theory overview on Lepton Flavour Violation

L. Calibbi in Plenary

Concluding remarks

There is New Physics out there
but we don't know the scale!

LFV processes are a unique laboratory
to search for New Physics beyond the LHC reach

LFV and LHC highly complementary in testing
TeV-scale New Physics

Exploring different channels is crucial
to cover the full 'theory space'

also about muon g-2 theory in WG1/WG4: SM by M. Passera, NP by P. paradisi

Probing high-energy scales

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{C_{ij}^{(d)}}{\Lambda_{NP}^{d-4}} \, O_{ij}^{(d)}$$

BR($\mu \to e\gamma$) $< 5 \times 10^{-14}$

Process	Relevant operators	Present Bound on Λ (TeV)		Future Bound on Λ (TeV)	
		$C = 1/16\pi^2$	$C = 1$	$C = 1/16\pi^2$	$C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	50	—	90	—
$\mu \to eee$	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17	210	170	2100
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10	120	100	1200
$\mu \to e$ in Ti	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	30	420	580	7300
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	60	750	1000	13000

updated from LC Lalak Pokorski Ziegler '12

BR($\mu \to eee$) $< 10^{-16}$

CR($\mu \to e$ in Ti) $< 5 \times 10^{-17}$

Questions and WG4 discussion

"What is the situation and what do we expect by next workshop"
(request to conveners and participants)

What is the ultimate μ->eγ, μ->eee or others?

MEG II is planned as short term upgrade

μ->eee 10^9/sec is set by detector limit (10^{16}/year)

-> Further improvement by orders yet seems difficult. We will see.

What do we do once cLFV observed?

-> muon polarization

-> target dependence

Good use of ultra-cold muon beam (quality rather than intensity) for LFV physics?

or "cooled" muon at ν-fact/collider

10^6/s for muon g-2, still low for ν-factory (10^9/s)?

Discussion in WG4 (continued)

Accelerator parameter for muon physics?

- for example, time structure, energy

Muons more involvement in accelerator parameters?

The requirement varies much depending on physics

10 kHz~100 kHz suitable for muon decay measurement (μSR, g-2,,,)

DC muon beam to avoid signal overlap (rare decay)

Pulsed beam (various) for proton distinction, pulse laser, ...

Muon physics possibility at new accelerators

NuSTORM, MOMENT, ...

Watch our family members

tau decay, g-2

electron g-2 and EDM (very high precision)

Summary (WG4 muon physics)

New precision measurements are under preparation or in progress.
Good possibility to observe cLFV in a few years - new physics.

We wish good progress in data run, preparation, R&D, new facilities.