Muon Physics in Japan

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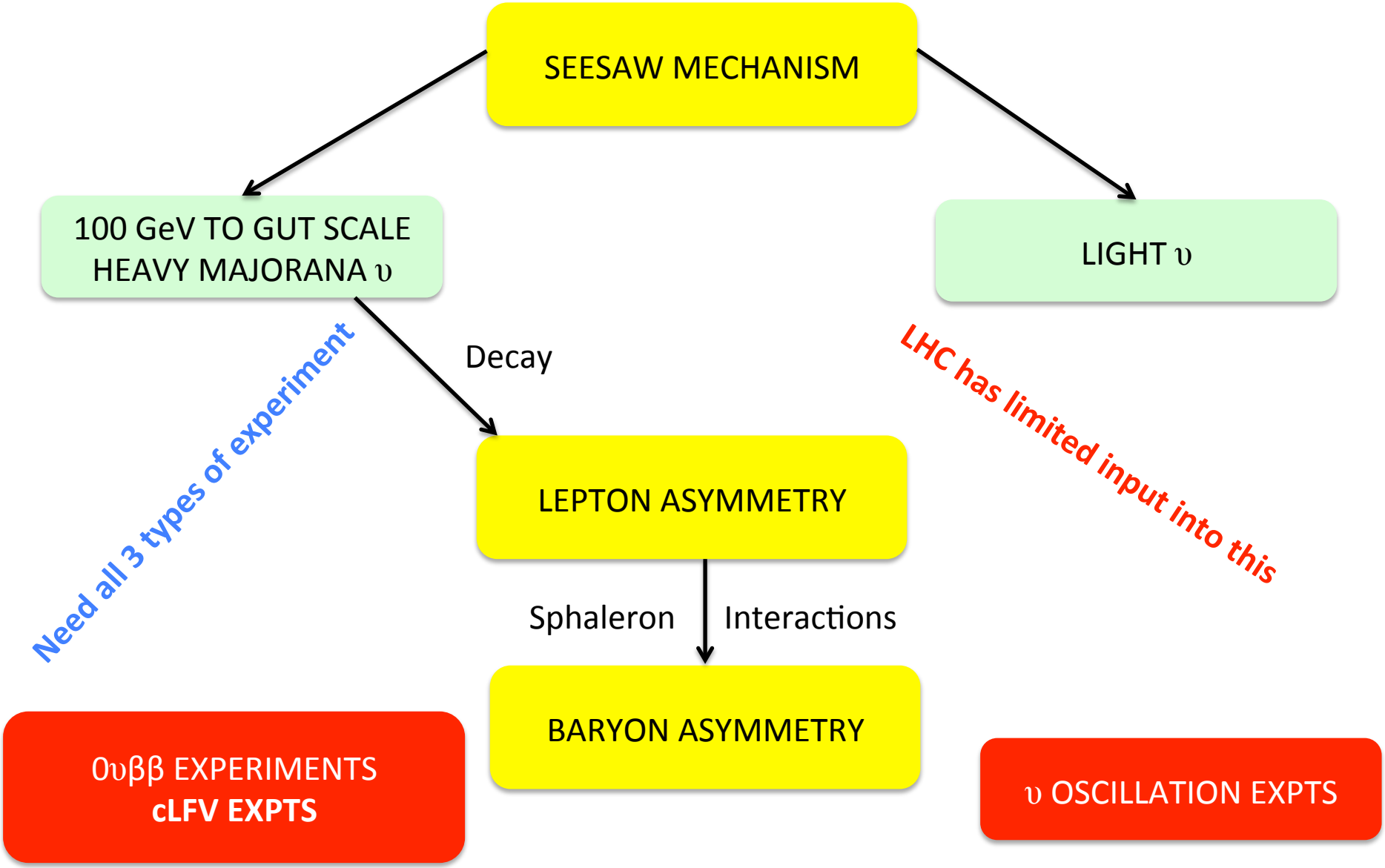
University College London

Motivation


SEESAW MECHANISM
100 GeV TO GUT SCALE HEAVY MAJORANA υ
LIGHT υ
Decay
Need all 3 types of experiment
LHC has limited input into this
LEPTON ASYMMETRY
Sphaleron
Interactions
BARYON ASYMMETRY
0υββ EXPERIMENTS
cLFV EXPTS
υ OSCILLATION EXPTS

World Status / Plans

		Funded
		$\mu^+ \to e^+\gamma$
$\mu^- N \to e^- N$	$g-2$	$\mu^+ \to e^+e^-e^+$
$g-2$	$\mu^- N \to e^- N$	
$\mu^+ \to e^+e^-e^+$	$\mu^+ \to e^+e^-e^+$	Time

The Muon Programme

Deviation from precisely known SM value

Magnetic Dipole Moment / "g-2" ~ 0.002 but predicted in SM to 0.42ppm
Present experimental uncertainty : $\Delta(a_\mu) = 0.54$ ppm

Measure non zero value where SM value ~ 0

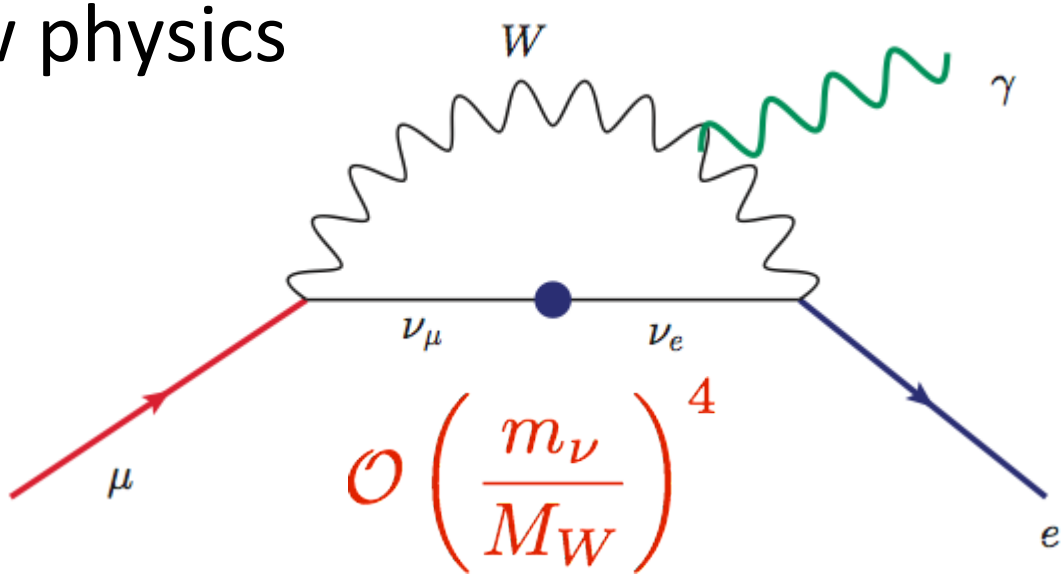
Electric Dipole Moment / EDM
Present limit (10^{-19}) is poor compared to other EDMs. SM value ~ 10^{-36}

Lepton flavour violating interactions.
Present limits $10^{-11\text{-}12}$. SM ~ 10^{-50}

Why the cLFV programme ?

1. SM is O(10^{-50})

Observation **IS** new physics



No SM theory systematic

Why the cLFV programme ?

2. BSM predictions are $O(10^{-10-20})$

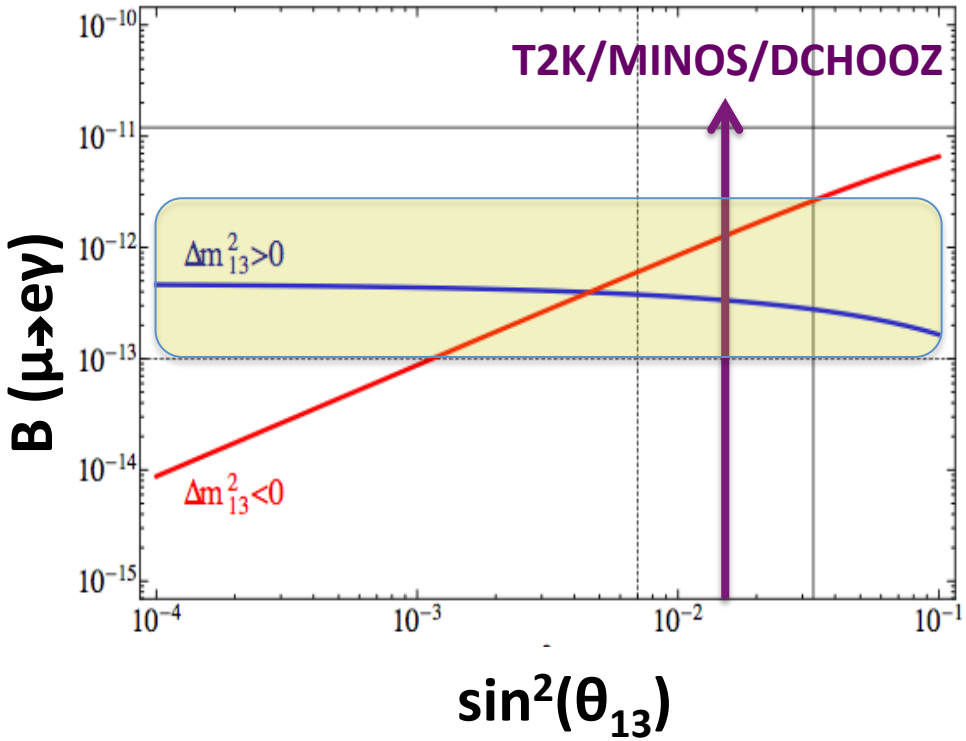
We know lepton # is not sacrosanct (υ oscillations)

How far we can probe is determined by technology

Recent advances in accelerator, s/c magnets and detectors mean $O(10^4)$ improvement in reach is readily achievable.

Why the cLFV programme ?

3. Complementary to & probes scales > LHC



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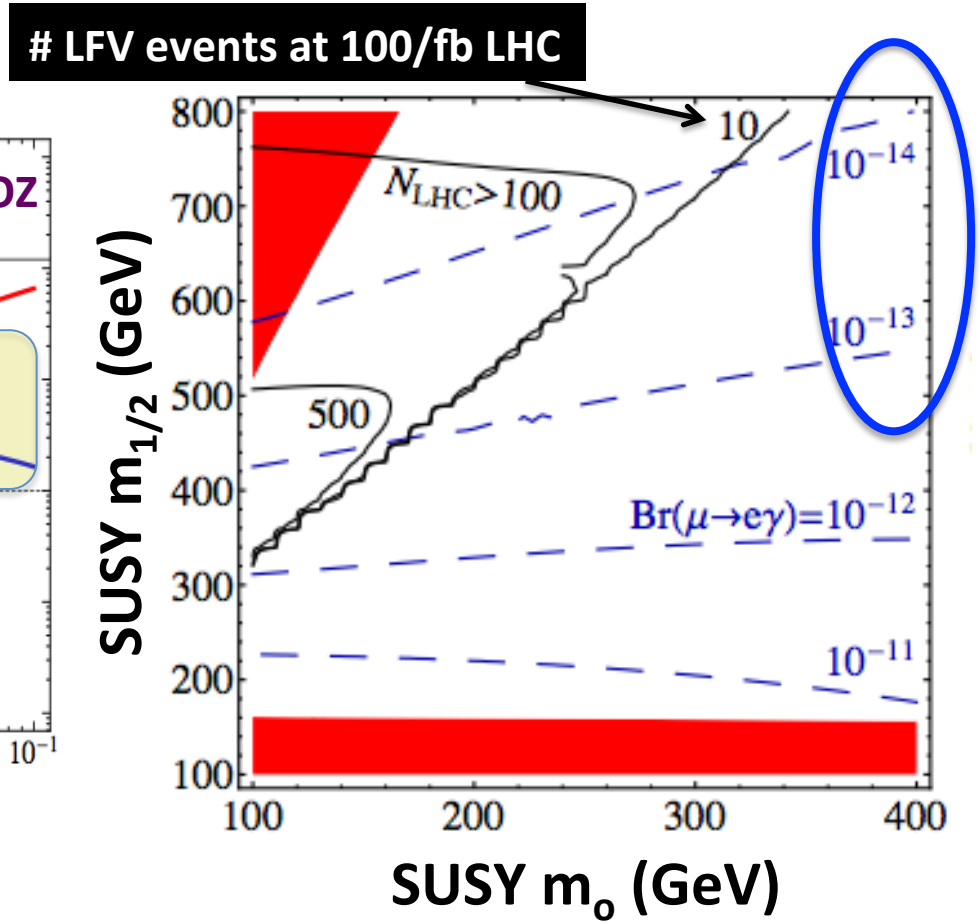


arxiV:1011.1404

Flavor Physics Observables

4.Sensitivity to widest variety of BSM models.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Different **SUSY** and **non-SUSY** BSM models.

★★★ **Large effects**

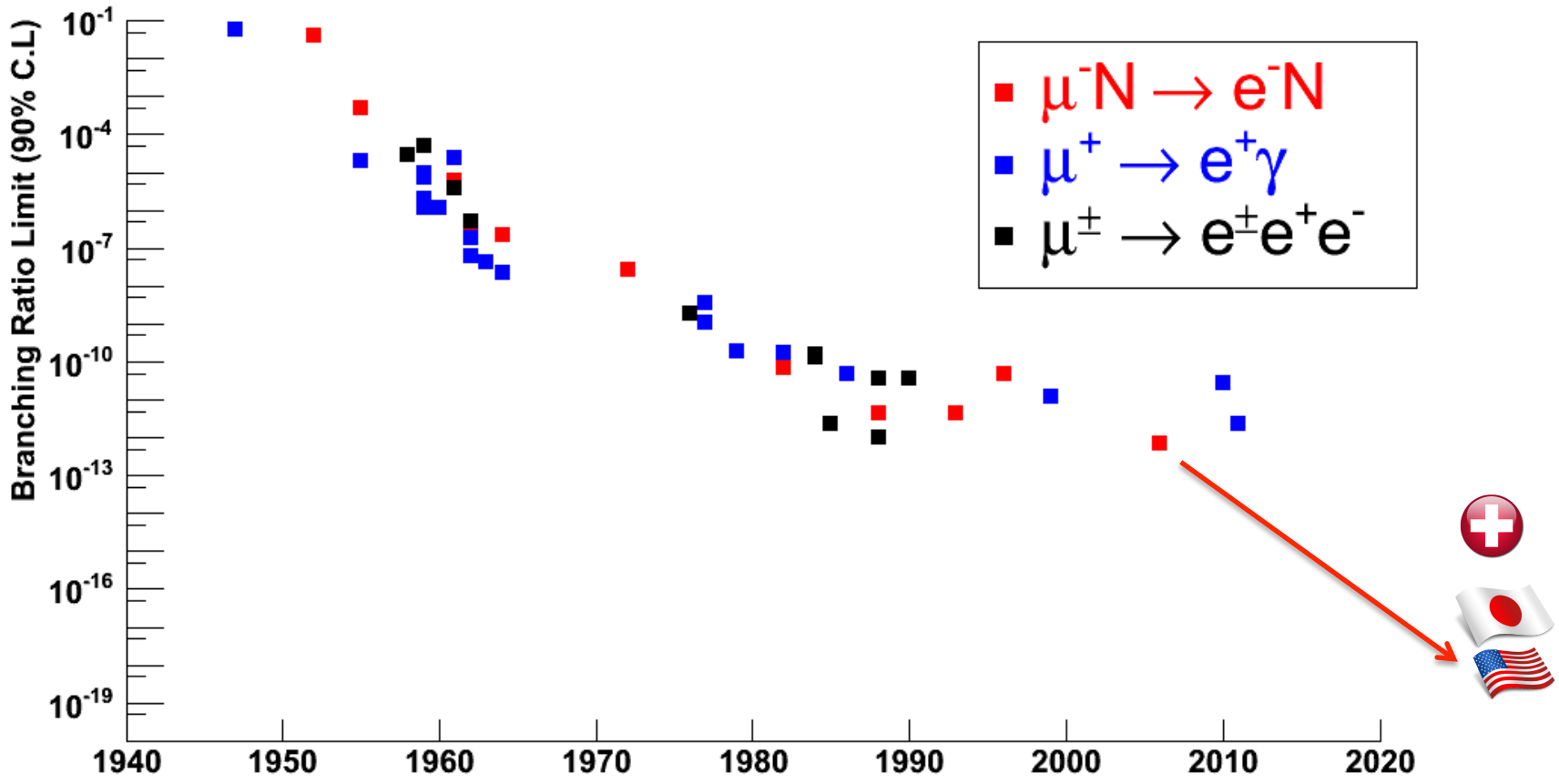
★★ **Visible but small**

★ **No sizeable effect**

W. Altmannshofer, et al Nucl. Phys. B 830 17 (2010)

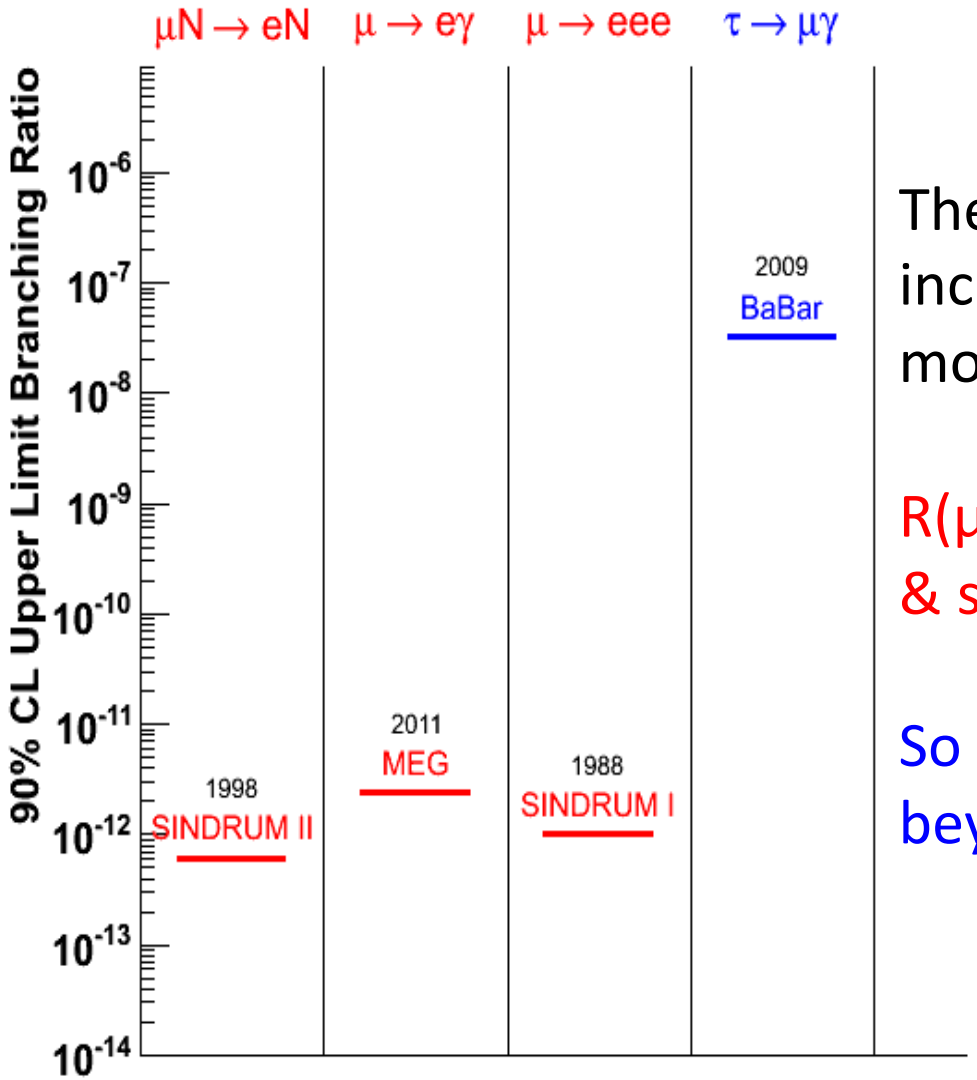
Where are we now ?

Limits improved O(10^{10}) for **three muon LFV processes** over 50 years



and ΔL=2 decays of muonic (μ^+e^-) atoms have placed limits on G_F'

Where are we now ?



The present eγ limit is more incisive since typically in BSM models:

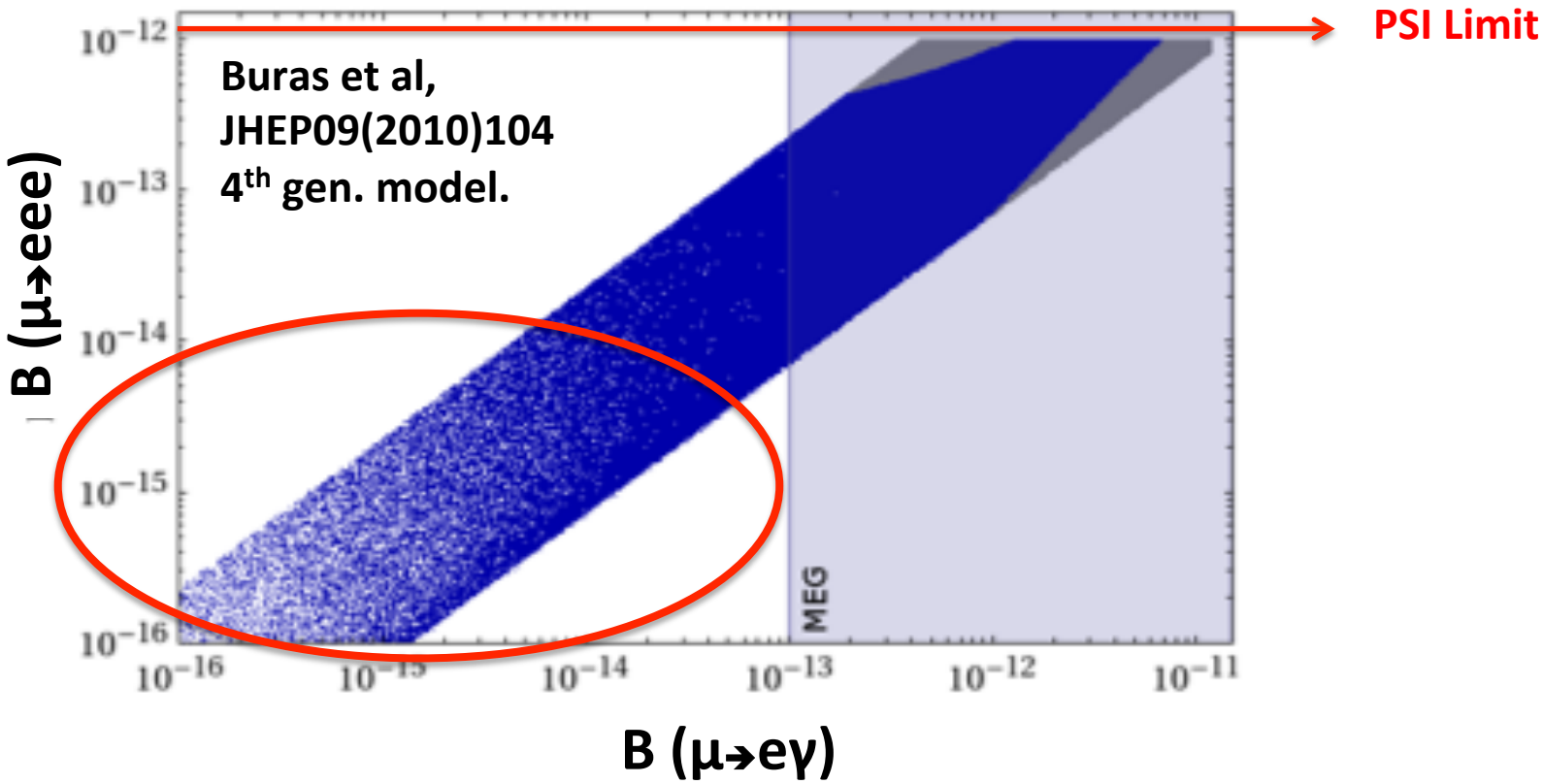
$R(\mu N \to eN)/R(\mu \to e\gamma) \sim O(\alpha_{EM})$
& similarly for $\mu \to 3e$

So present MEG/PSI limit is ~ 10 beyond the two SINDRUM/PSI limits.

Where do we want to be ?

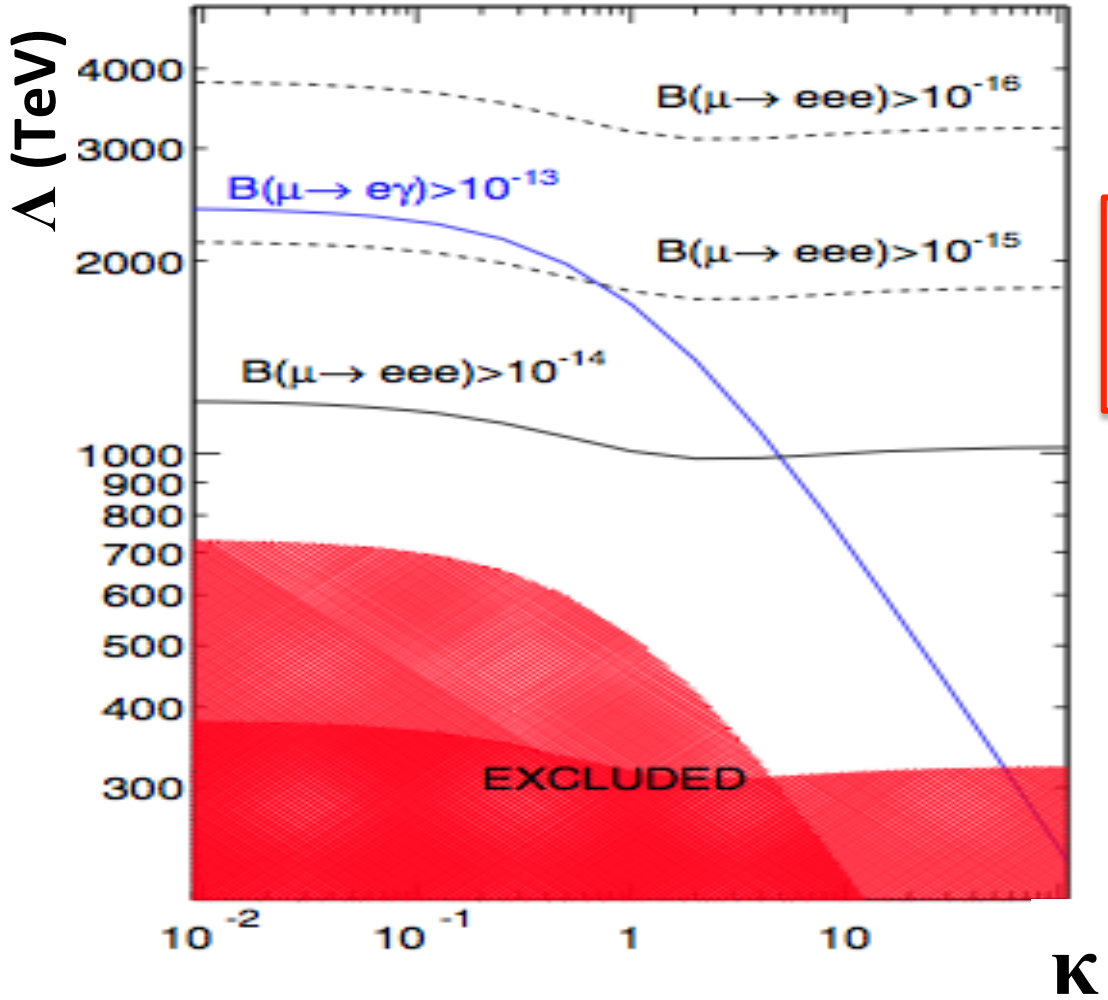
Measurements of all 3 processes (& τ) with commensurate sensitivity.

- μN→eN & μ→3e : need O(100) improvement to eclipse present μ→eγ(MEG).



Ideally need μ→3e at 10^{-16} and beyond

BSM dipole interaction ⟷ **BSM 4-fermion interaction**



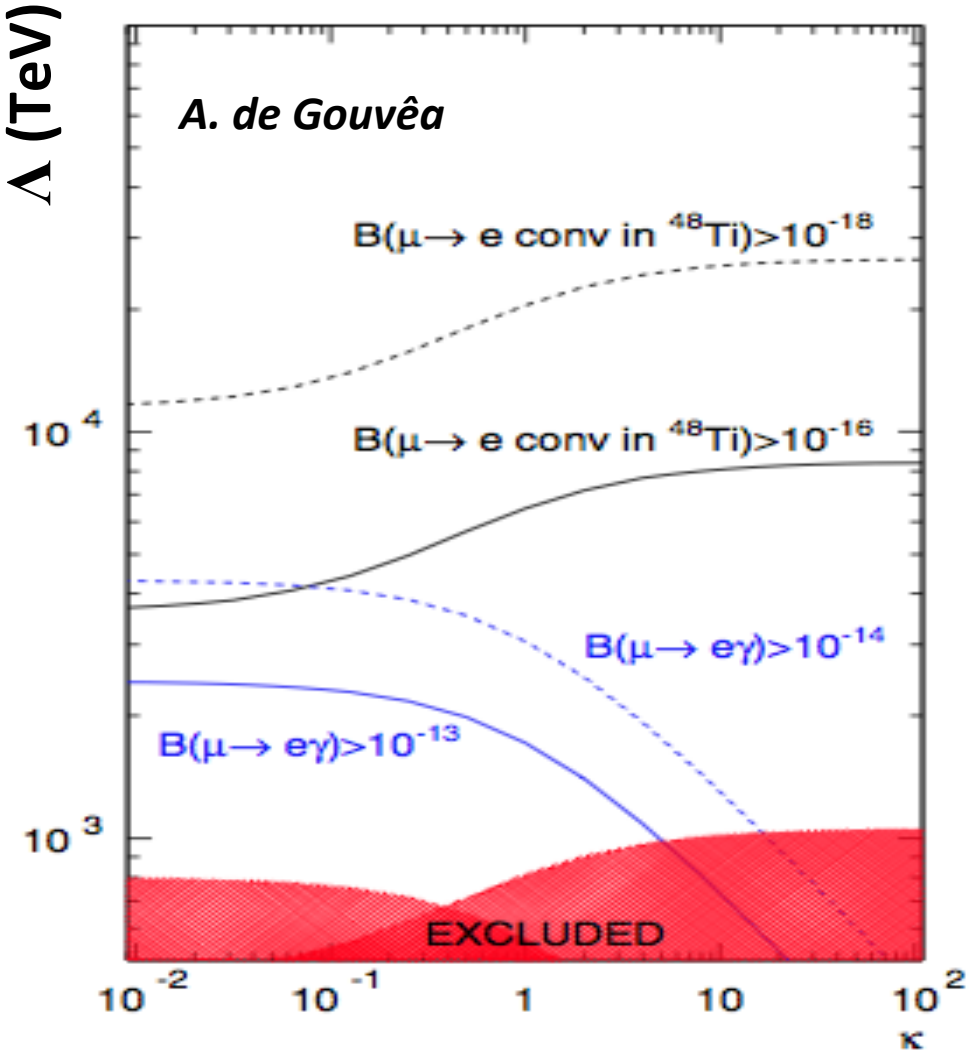
Generic Lagrangian with BSM dipole (low κ) and BSM 4-fermion (high κ) interactions at scale Λ

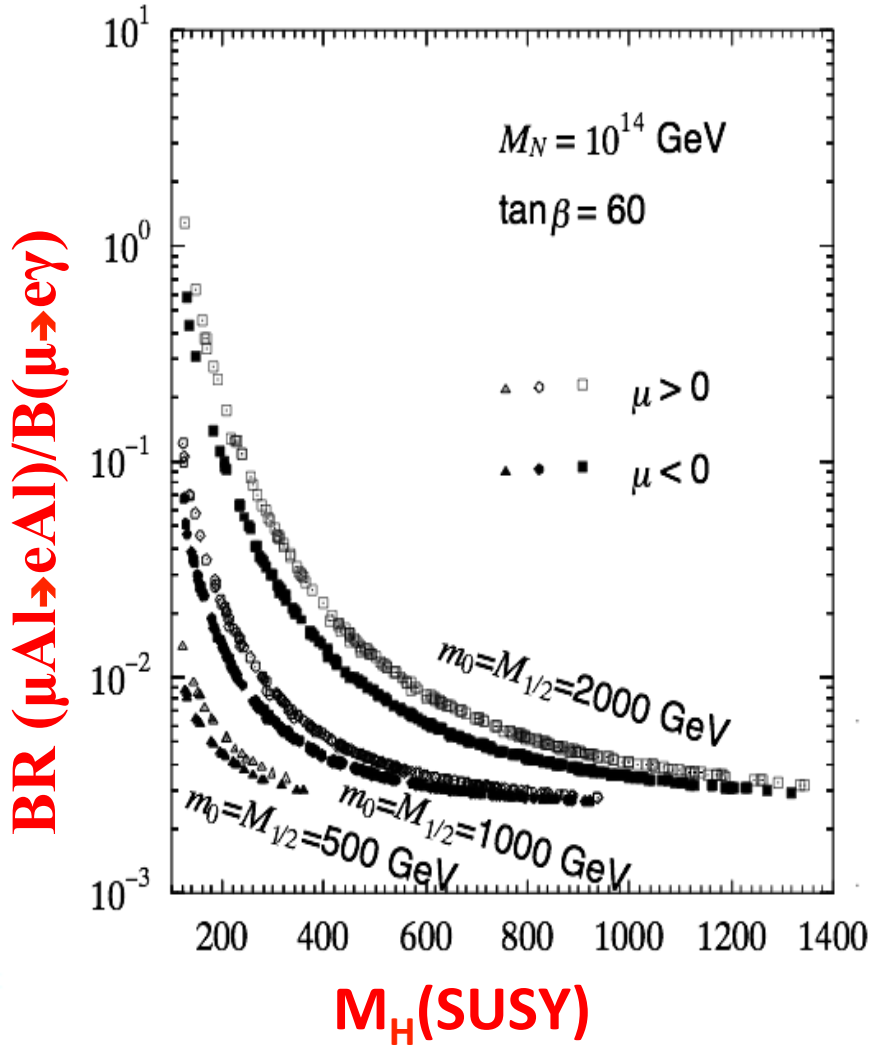
$$\frac{1}{\Lambda^2} \approx \frac{g^2 \theta_{e\mu}}{M_{\rm SUSY}^2}$$

Note scale is O(1000) TeV …

A. de Gouvêa, Nuclear Physics B (Proc. Suppl.) 188 (2009) 303–308

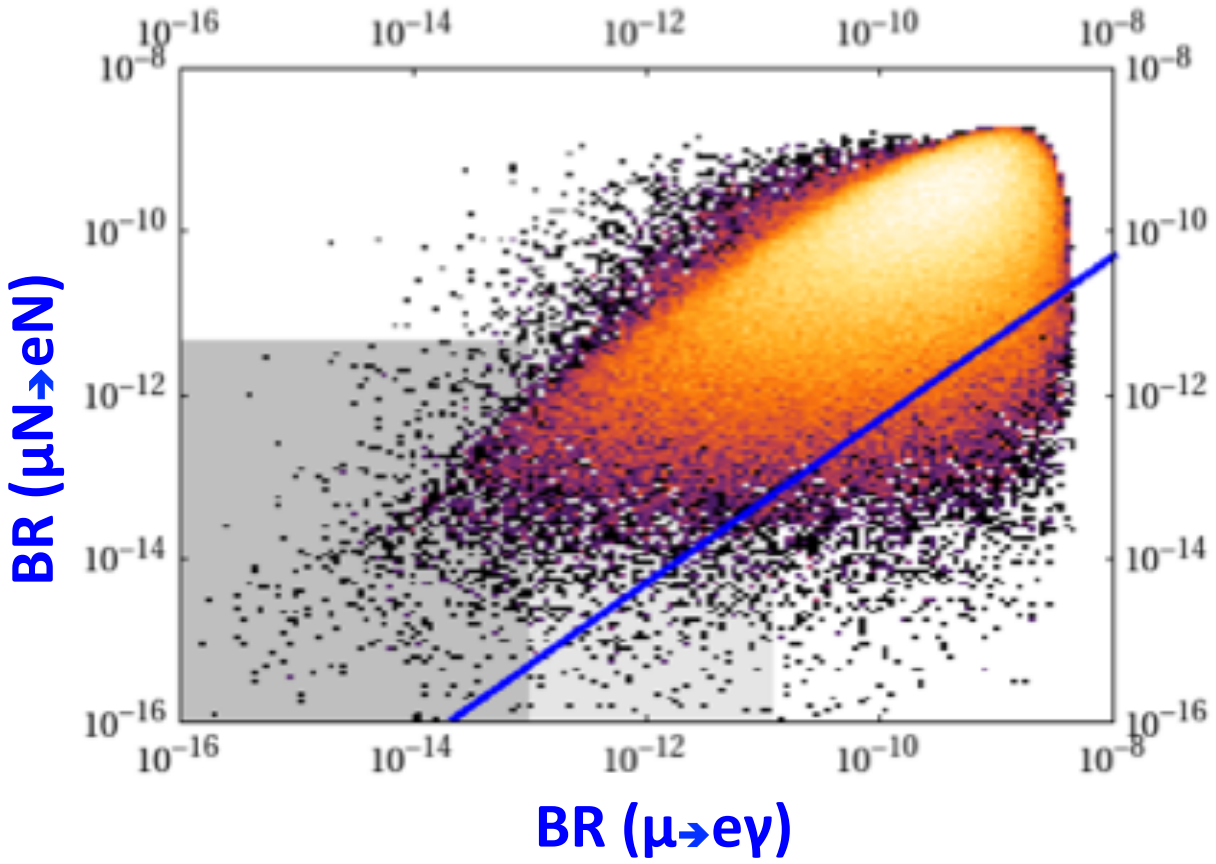
Need μN→eN at 10^{-16} and beyond





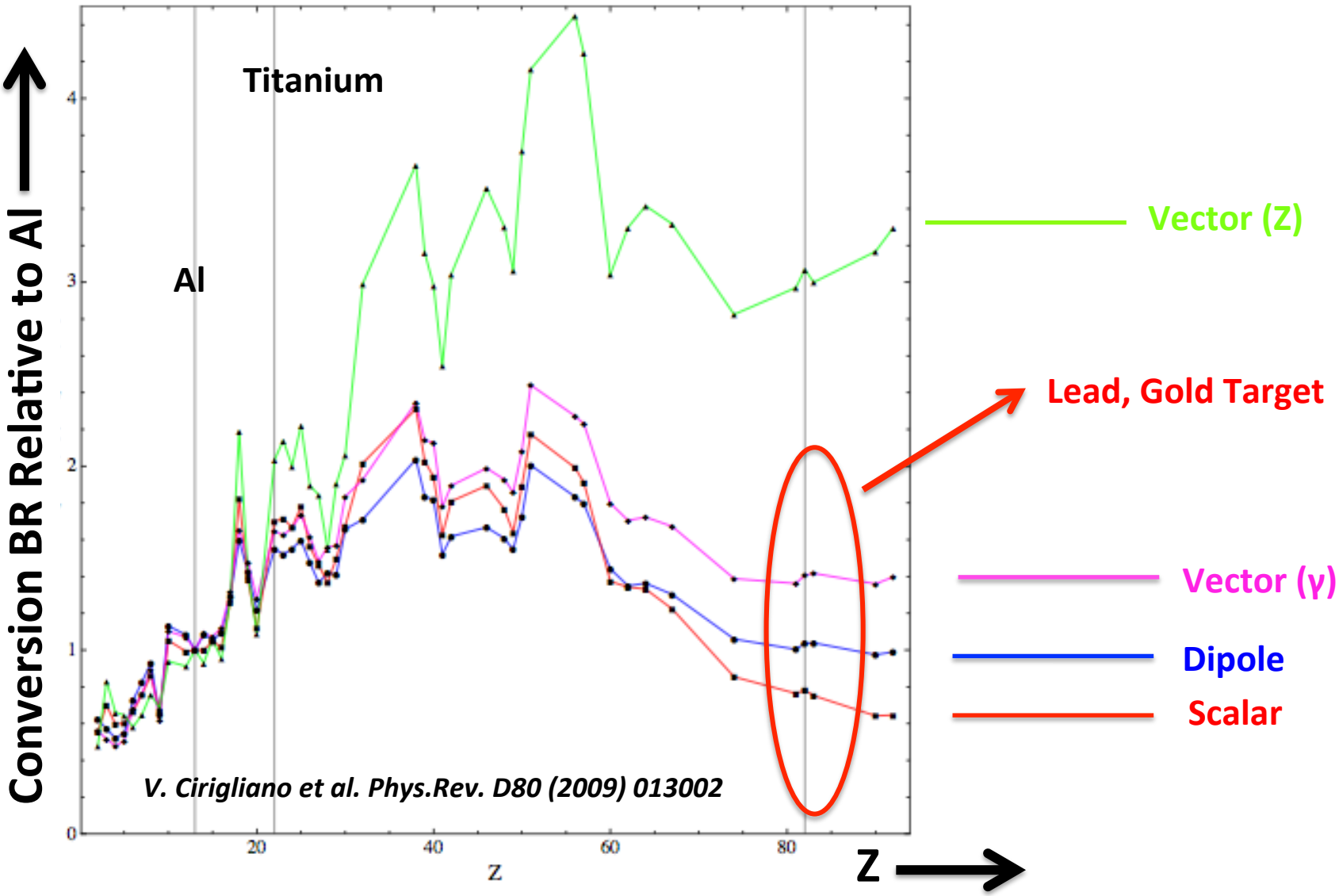
Process Ratios are Model Dependent

e.g. In Littlest Higgs model with T-parity (LHT): $R(\mu N \to eN)/R(\mu \to e\gamma) \sim 1$



Blanke et al, Acta Phys.Polon.B41:657,2010

We also want to measure Z dependence



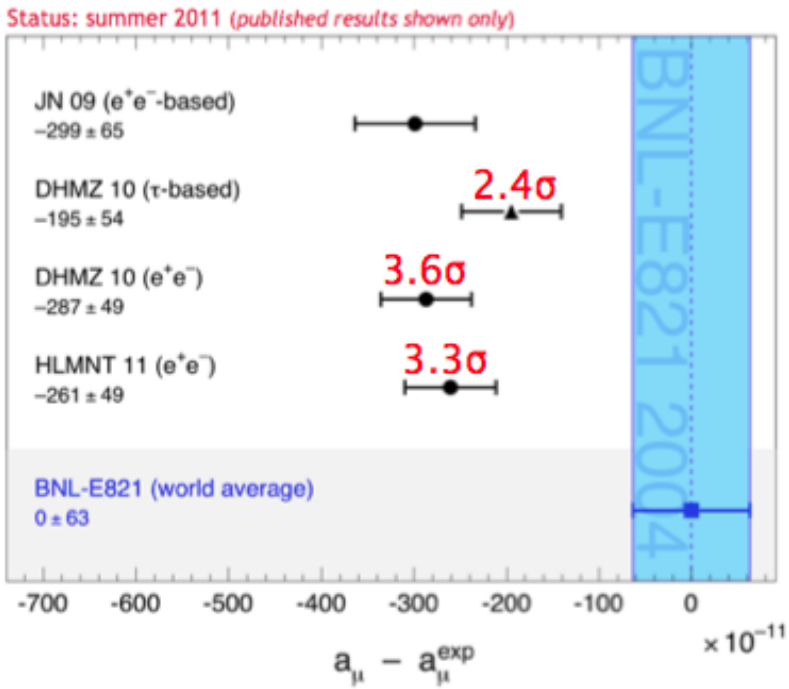
g-2

$a_\mu^{exp} = 116\ 592\ 089\ (63) \times 10^{-11}$

$a_\mu^{thy} = 116\ 591\ 802\ (49) \times 10^{-11}$

$a_\mu^{exp} - a_\mu^{thy} = 287\ (80) \times 10^{-11}$

$$a_\mu = \frac{g-2}{2}$$



3.6σ

M. Davier - Oct 2011 ICFA Seminar

g-2

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

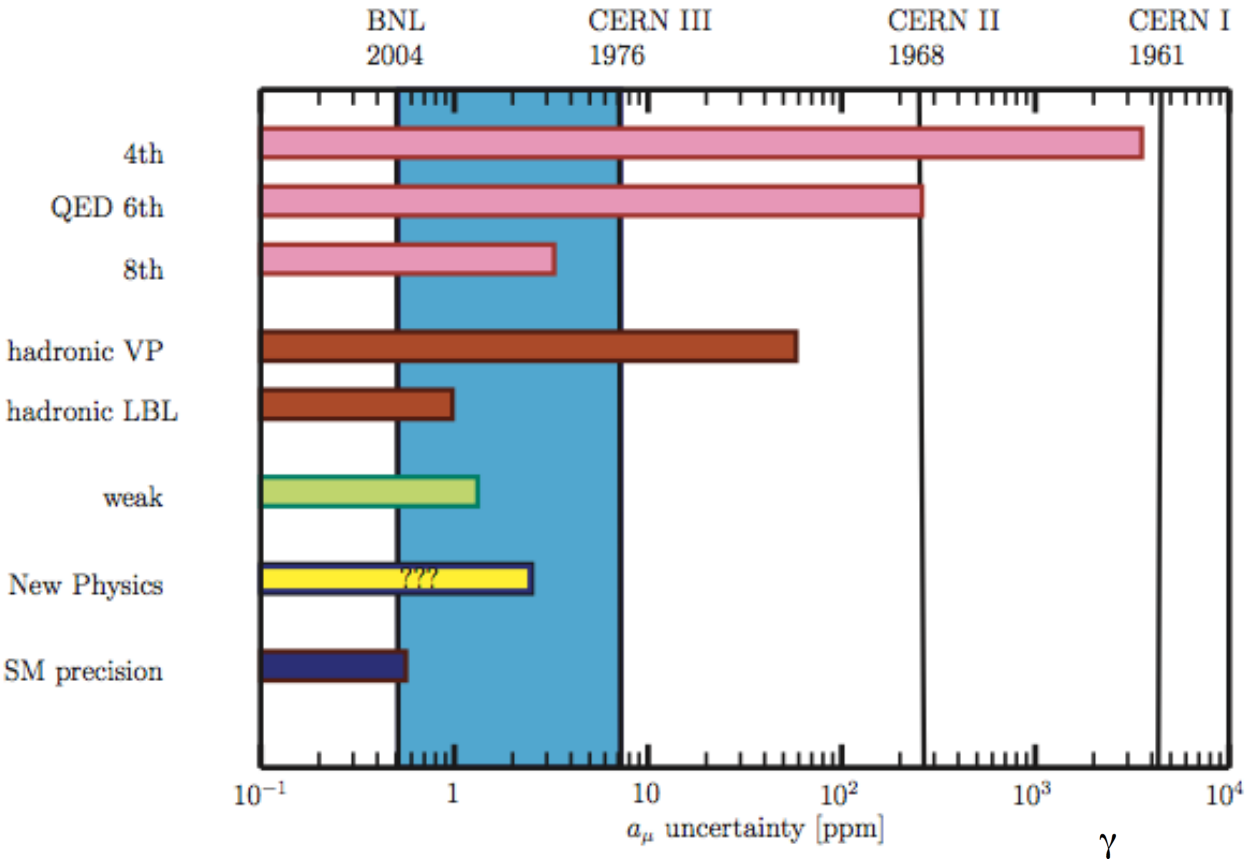
$$\vec{\mu} = g \frac{e\hbar}{2m} \hat{\sigma} \qquad \vec{d} = \eta \frac{e\hbar}{2m} \hat{\sigma}$$

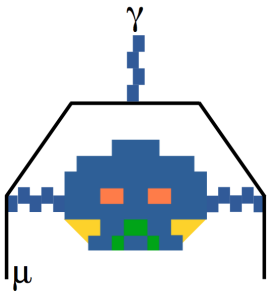
$$g = 2(a+1) \qquad \eta = 0$$

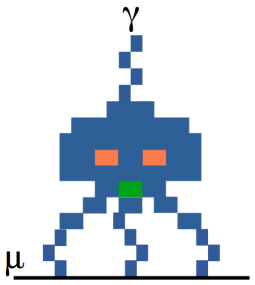
a_μ = ½ (g-2) : has SM (strong, weak, EM) contribution + BSM.
η = 0 : any deviation from this is new physics (CP-violating)

Muon dipole moments (cf neutron) are single-particle and so potentially "cleaner" probes of any BSM physics.
eEDM molecular corrections

g-2 contributions







g-2 methods

$$\vec{\omega}_a = \omega_S - \omega_C$$

average over muons

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

0

$\gamma_{magic} = 29.3$

Traditional approach : use magic p = 3.09 GeV muons.

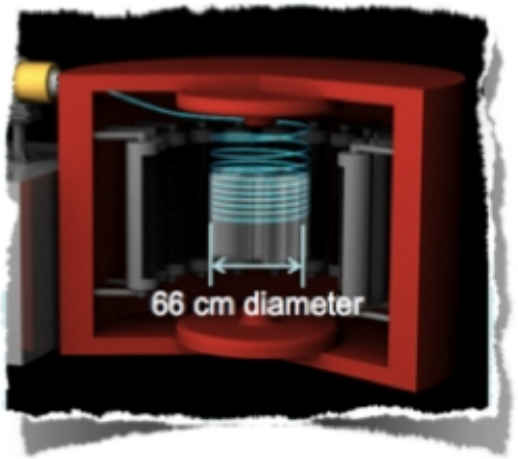
- BNL measurement and proposed FNAL g-2 measurement

Use smaller storage ring with higher (more uniform) B with E=0 & ultra-cold muons

- **J-PARC proposal**

New Approach being pursued at J-PARC (and PSI)

Basic R&D



N. Saito

Give up on the magic momentum and use a smaller device

Industry

	BNL	MRI
Field Strength	1.45 T	7 T
Local Uniformity	100 ppm	1 ppm

g-2 using MRI magnets

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\underbrace{\frac{\vec{\beta}\times\vec{E}}{c}}_{=0}\right]$$

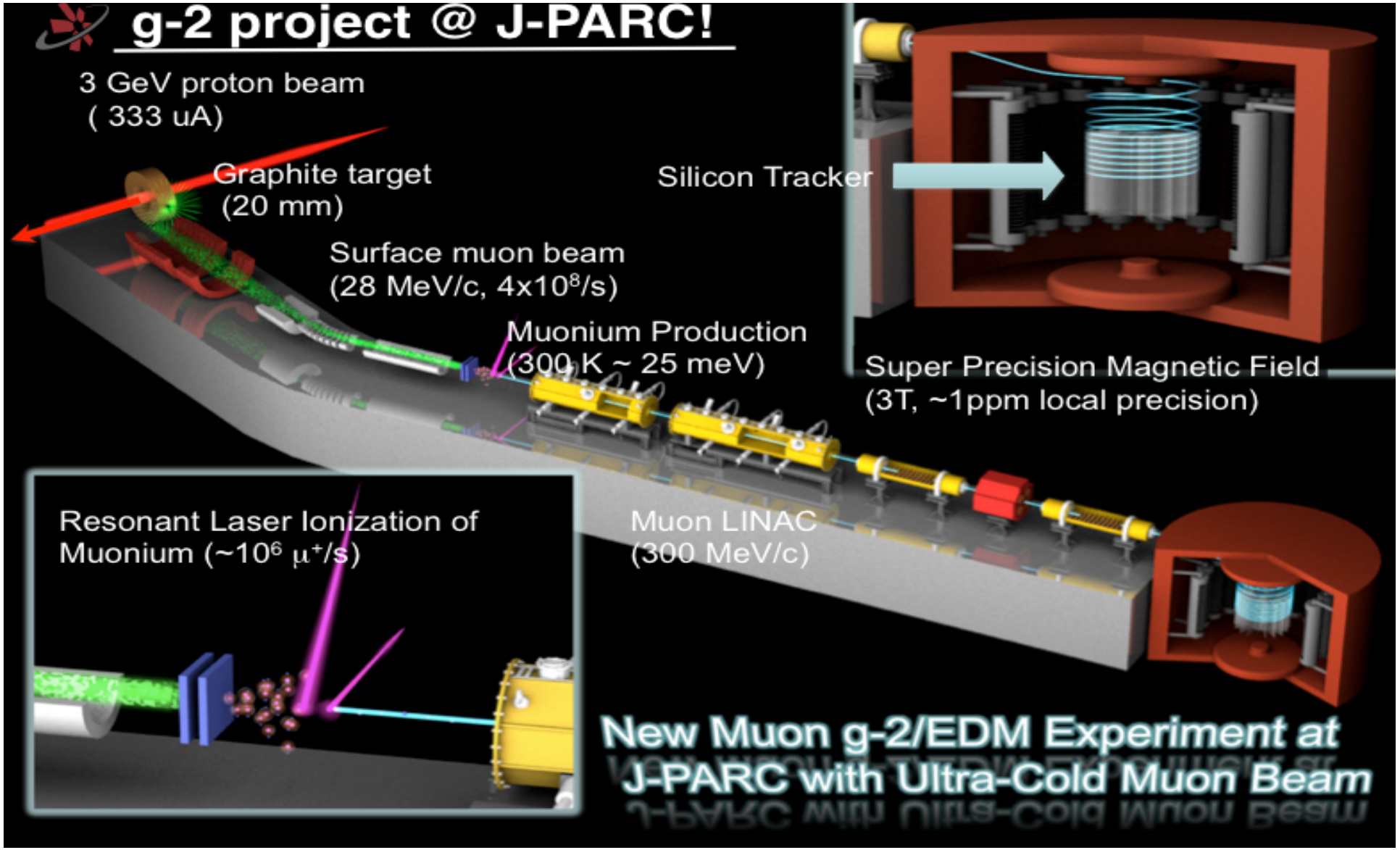
No vertical focussing E-field and larger (& uniform) B-field (MRI)

Requires v.small vertical beam divergence : $\Delta p_T/p_T = 10^{-5}$

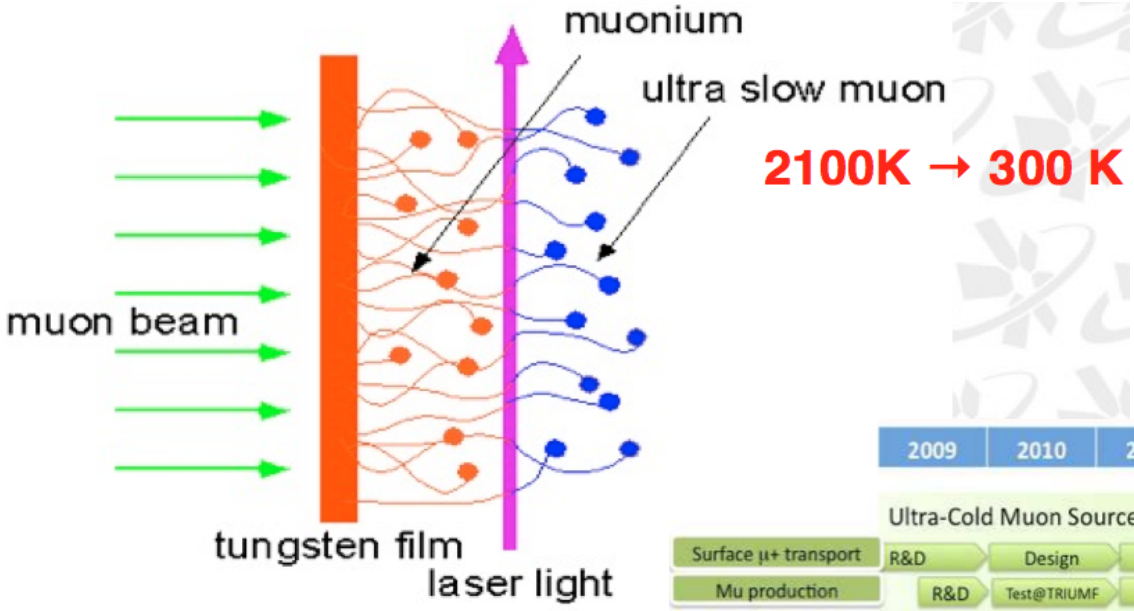
Requires advances in "muonium" production

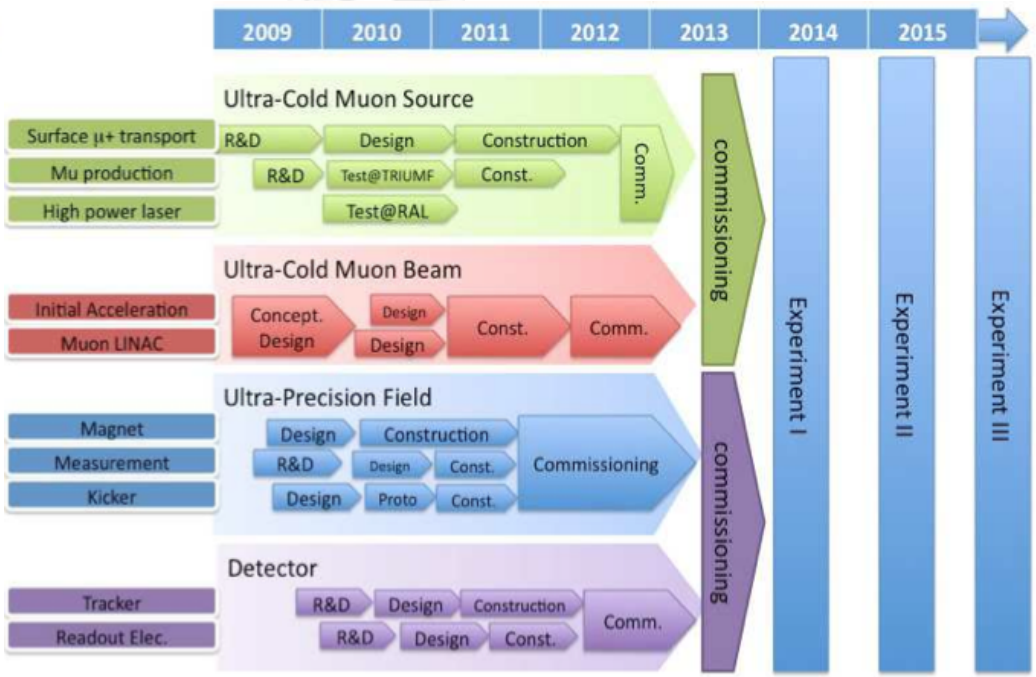
- target materials e.g. nano-structured SiO_2
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)

In dedicated “H” beamline at J-PARC



JPARC g-2


muonium
ultra slow muon
2100K → 300 K
muon beam
tungsten film
laser light


2009
2010
2011
2012
2013
2014
2015
Ultra-Cold Muon Source
Surface μ+ transport
Mu production
High power laser
R&D
Design
Construction
Comm.
R&D
Test@TRIUMF
Const.
Test@RAL
Ultra-Cold Muon Beam
Initial Acceleration
Muon LINAC
Concept. Design
Design
Design
Const.
Comm.
Ultra-Precision Field
Magnet
Measurement
Kicker
Design
Construction
R&D
Design
Const.
Design
Proto
Const.
Commissioning
Detector
Tracker
Readout Elec.
R&D
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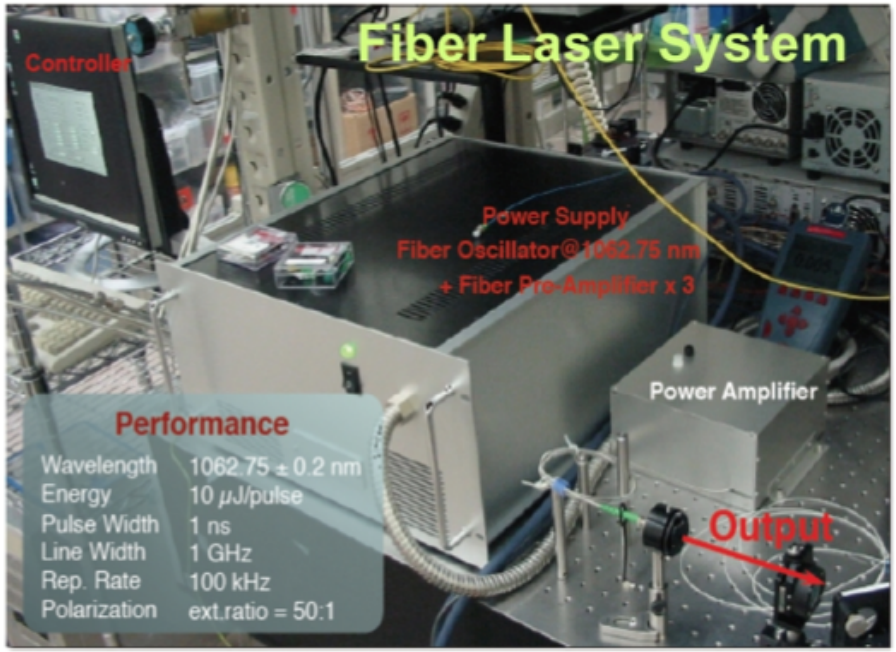
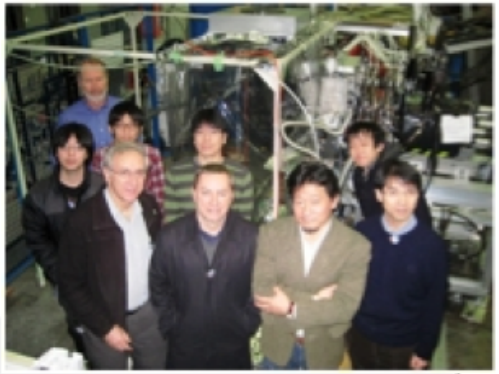
Const.
Comm.
commissioning
commissioning
Experiment I
Experiment II
Experiment III

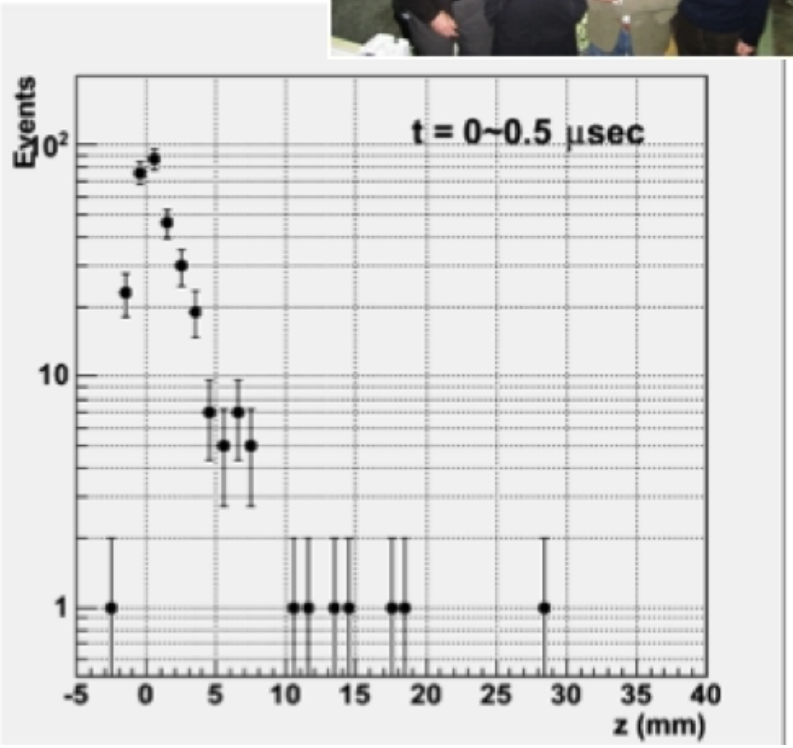
Active R&D on laser / target



Upcoming laser ionization test at RAL

S-1249 TRIUMF muon production on aerogel





An area of fruitful cross-disciplinary collaboration both within HEP
e.g. SiLC readout, BELLE sensors and outside : material scientists, laser chemists etc

Comparison with FNAL g-2

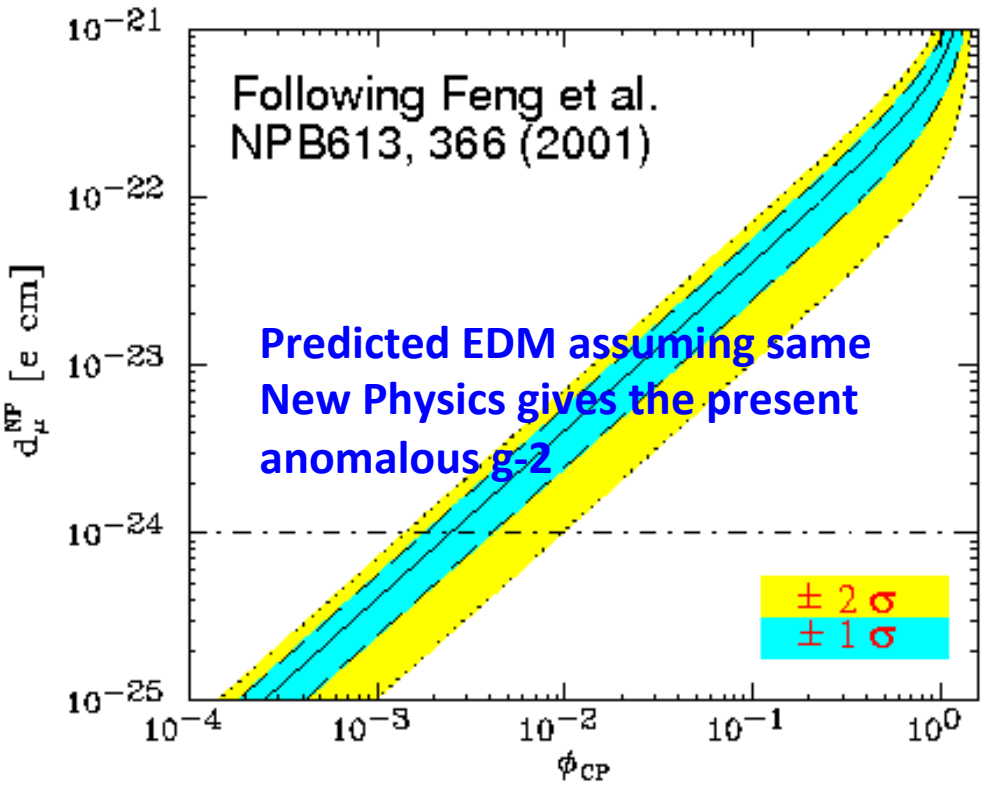
	BNL-E821	Fermilab	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		none/very weak
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

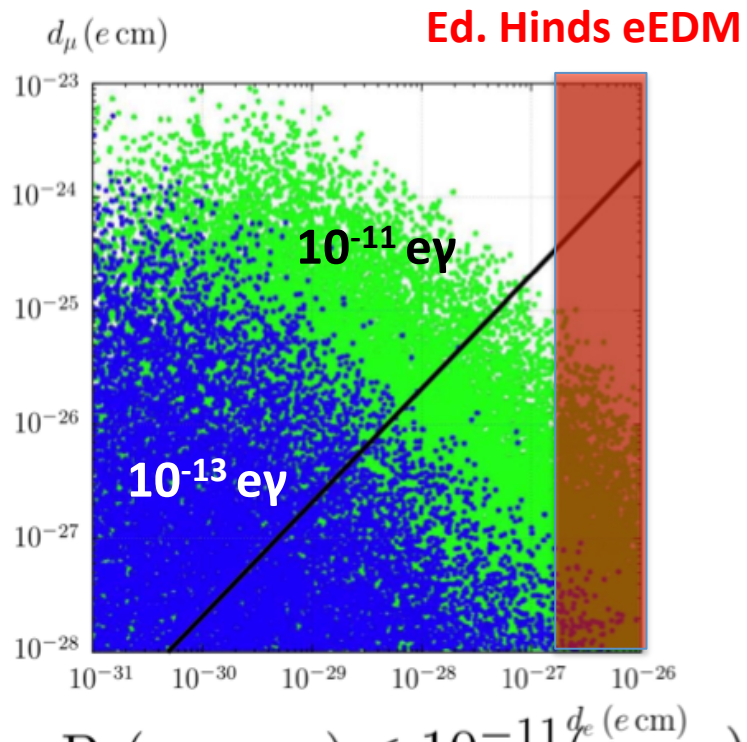
Clearly Pros and Cons of two approaches:

Cold muons : no pion contamination, no coherent betatron oscillations
BUT : π^+ only and as yet unproven method

"Hot" muons : proven technology, utilising existing accelerator etc

Muon EDM





$$\mathrm{Br}(\mu \to e\gamma) < 10^{-11}(\text{green})$$
$$< 10^{-13}(\text{blue})$$

$$d_\mu^{\mathrm{NP}} \simeq 3 \times 10^{-22} \left(\frac{a_\mu^{\mathrm{NP}}}{3 \times 10^{-9}} \right) \tan \phi_{CP} \quad \mathrm{e \cdot cm}$$

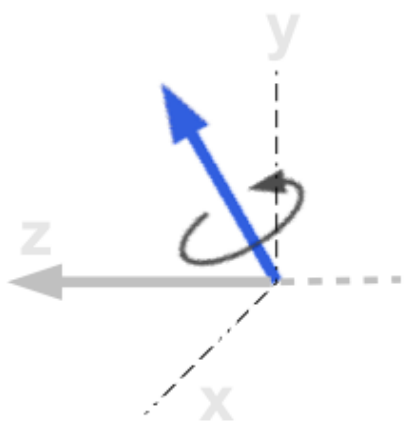
where ϕ_{CP} is a *CP* violating phase.

"Expect" **muon EDM of 10^{-22}** or CP violating phase is strongly suppressed.

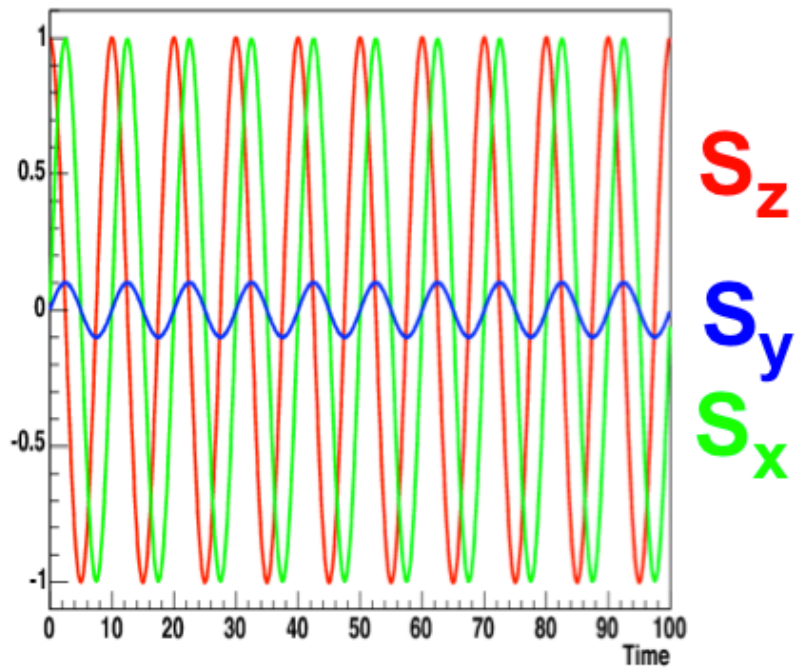
Muon EDM from parasitic g-2 running

magnetic moment anomaly EDM

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

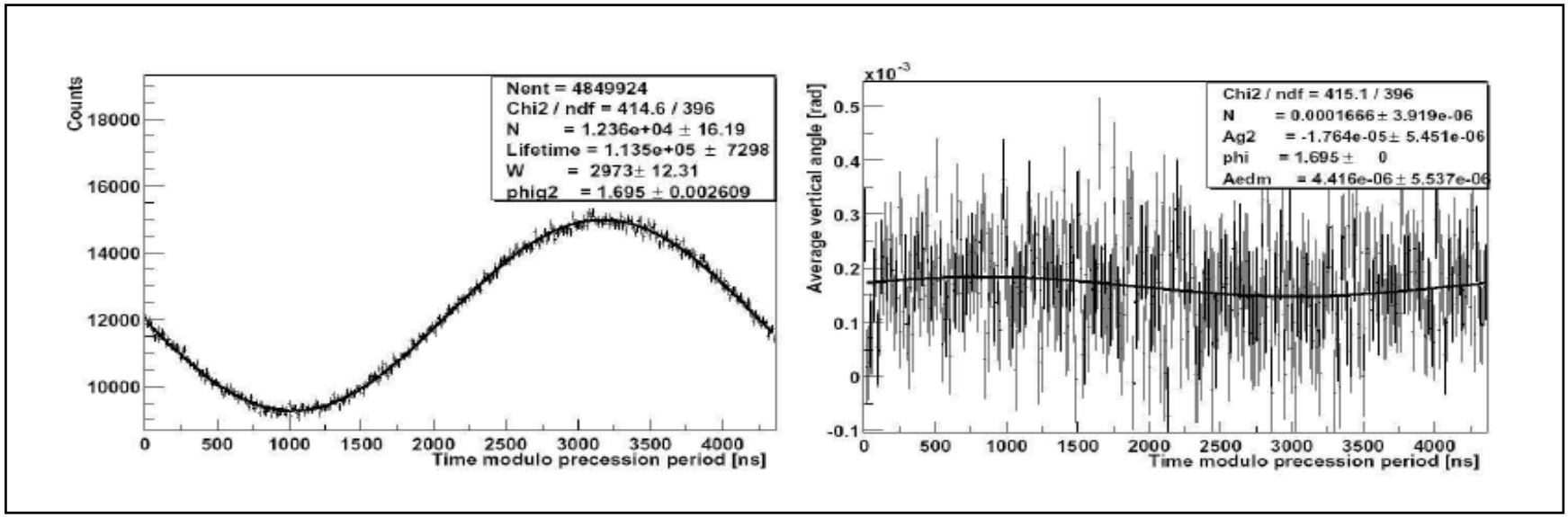


$$S_y = \frac{\eta\beta}{2a}\sin(\omega t)$$



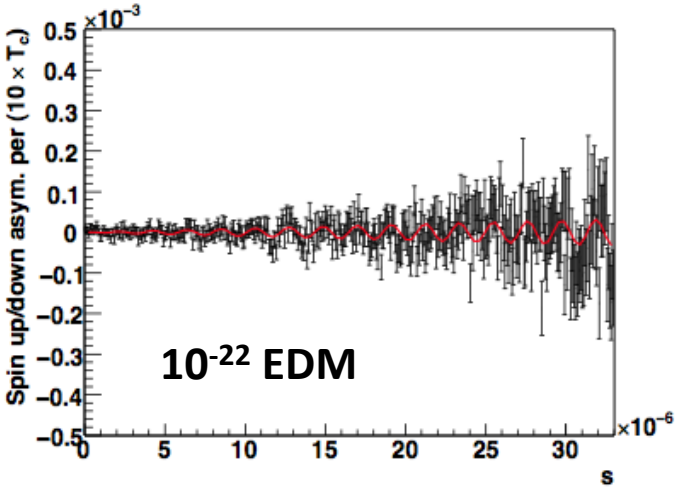
x1,000,000

Muon EDM from parasitic g-2 running



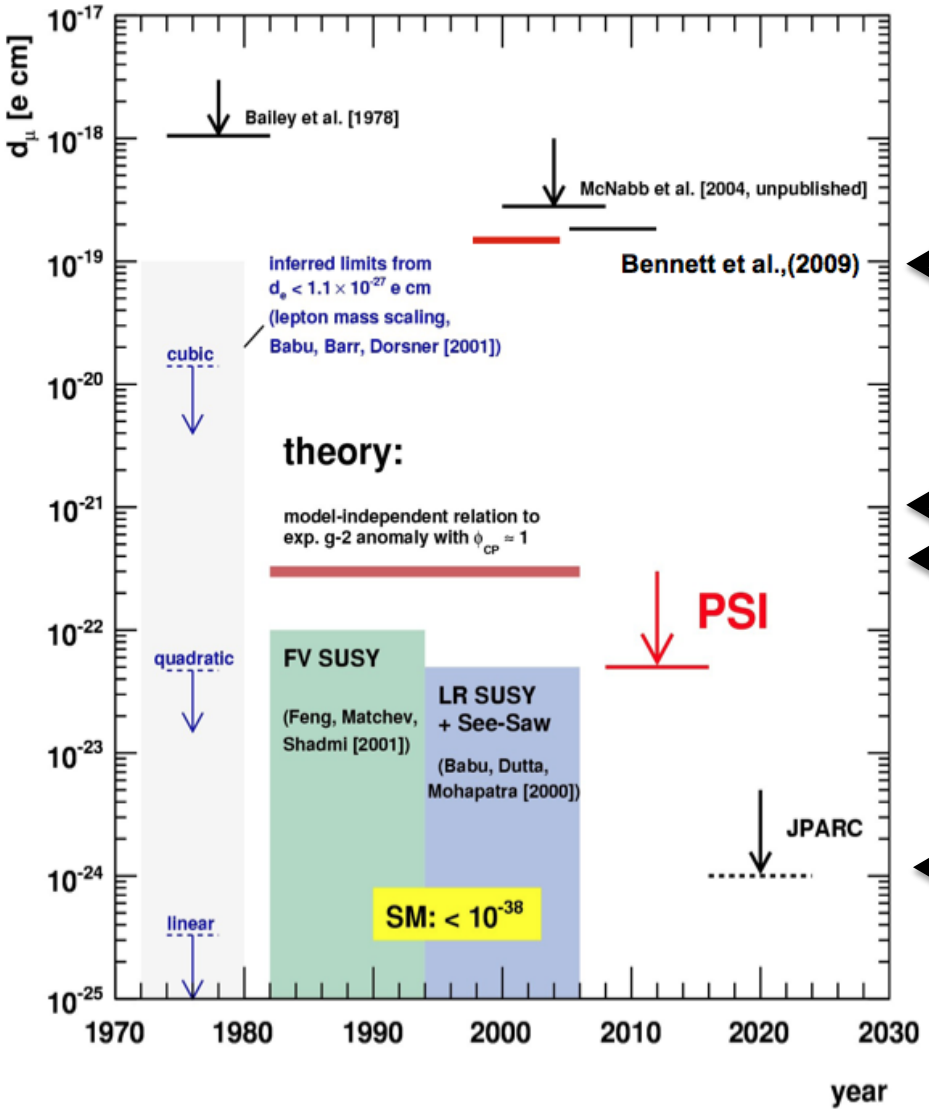
(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

EDM Signal: Average vertical angle modulo g-2 period. 90^0 degree out-of-from g-2



BNL achieved : 1.8×10^{-19}
FNAL g-2 should get to 10^{-21}

Muon EDM from parasitic g-2 running



BNL measurement

FNAL E989 parasitic g-2 (2017)

JPARC parasitic g-2 (2017)

Dedicated Project-X measurement

Dedicated JPARC measurement

Muon EDM beyond 10^{-21}

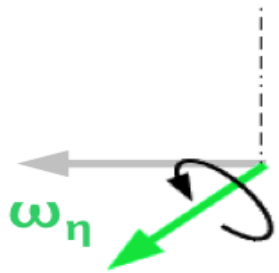
Parasitic EDM has intrinsic limitation at ~ 10^{-21}

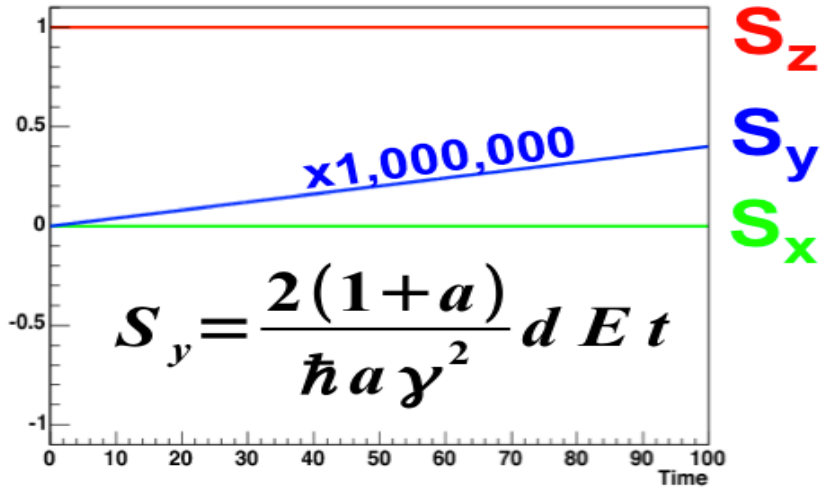
To go below this : use so-called **"Frozen Spin" technique**

- judicious E and B to cancel magnetic moment contribution

magnetic moment anomaly EDM

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





$$S_y = \frac{2(1+a)}{\hbar a \gamma^2} d\, E\, t$$

$$E = \frac{aB\beta}{1-(1+a)\beta^2} \simeq aB\beta\gamma^2$$

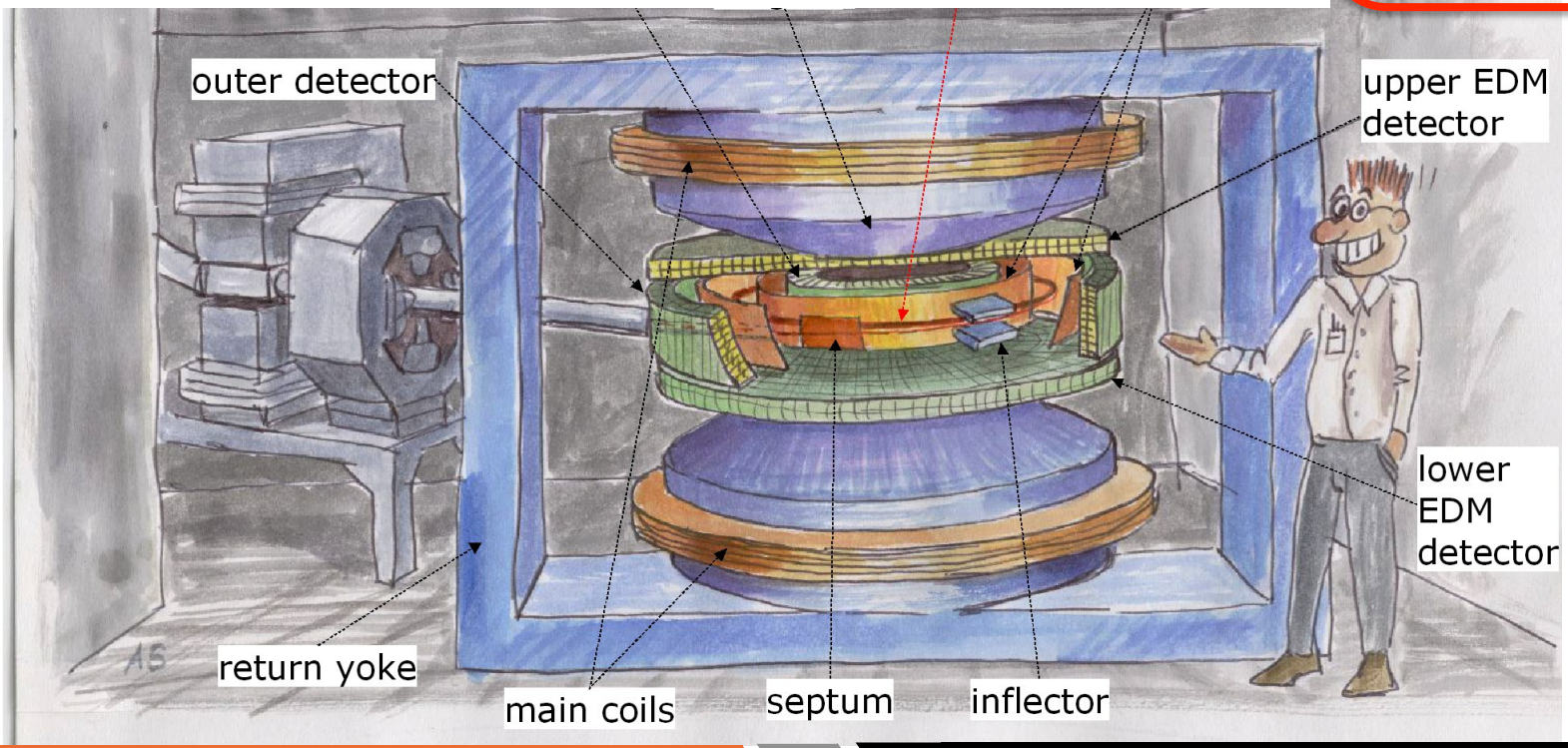
Muon EDM: Frozen Spin

PSI is proof-of-principle experiment for the "frozen spin" technique.
Low momentum (p=125 MeV) and relatively high B-field (1 T)

Ring parameters

B = 1T ← normal conducting; for syst. err. control
↳ E = 0.64 MV/m ← fixed because of momentum
↳ R = 42cm ← **table top**
↳ T = 11ns → **hard to get muons into the ring**

Needs new injection scheme
e.g. 3ns ILC kicker or resonant injection & sacrifice beam Intensity for beam quality



Frozen Spin

J-PARC PROPOSAL : dedicated 11m ring.

J-PARC proposal: $\gamma\tau$ = 11 μs, β = 0.978, P = 50%, B = 0.25 T

⇨ $\sigma_\eta = 4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{16}$ $\sigma_\eta = 2 \times 10^{-11}$

$d_\mu < 10^{-24}$ e cm

PSI proposal: $\gamma\tau$ = 3.4 μs, β = 0.76, P = 90%, B = 1.0 T

⇨ **$\sigma_\eta = 2.4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{12}$ $\sigma_\eta = 10^{-9}$**

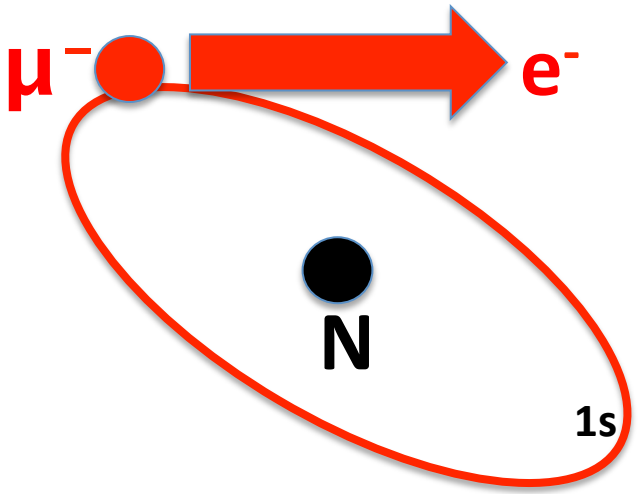
$$\sigma_\eta = \frac{\sqrt{2}ac\gamma}{\tau(e/m)EAP\sqrt{N}}$$

$d_\mu < 5 \times 10^{-23}$ e cm

Muon statistics is the dominant factor!

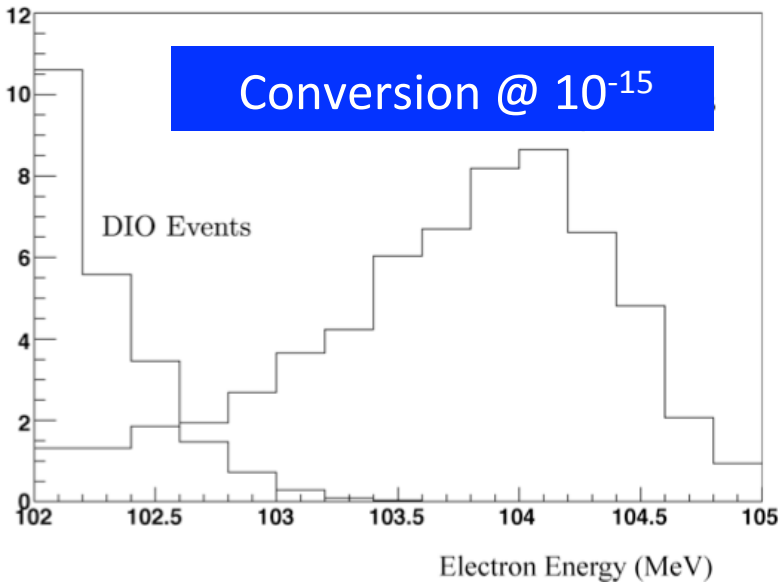
Technique systematically capable of reaching 10^{-27}

Muon to Electron Conversion



$$\mu^+ \to e^+ e^- e^+$$
$$\mu^+ \to e^+ \gamma$$

Suffer at the highest rates,
from accidental backgrounds that scale as $R(\mu)^2$



The "conversion process" has a simple one particle signature. Ee ~ m_μ
(>> Ee from free muon decay).

Arguably best route to highest sensitivity at high muon rates.

Three Japanese Proposals

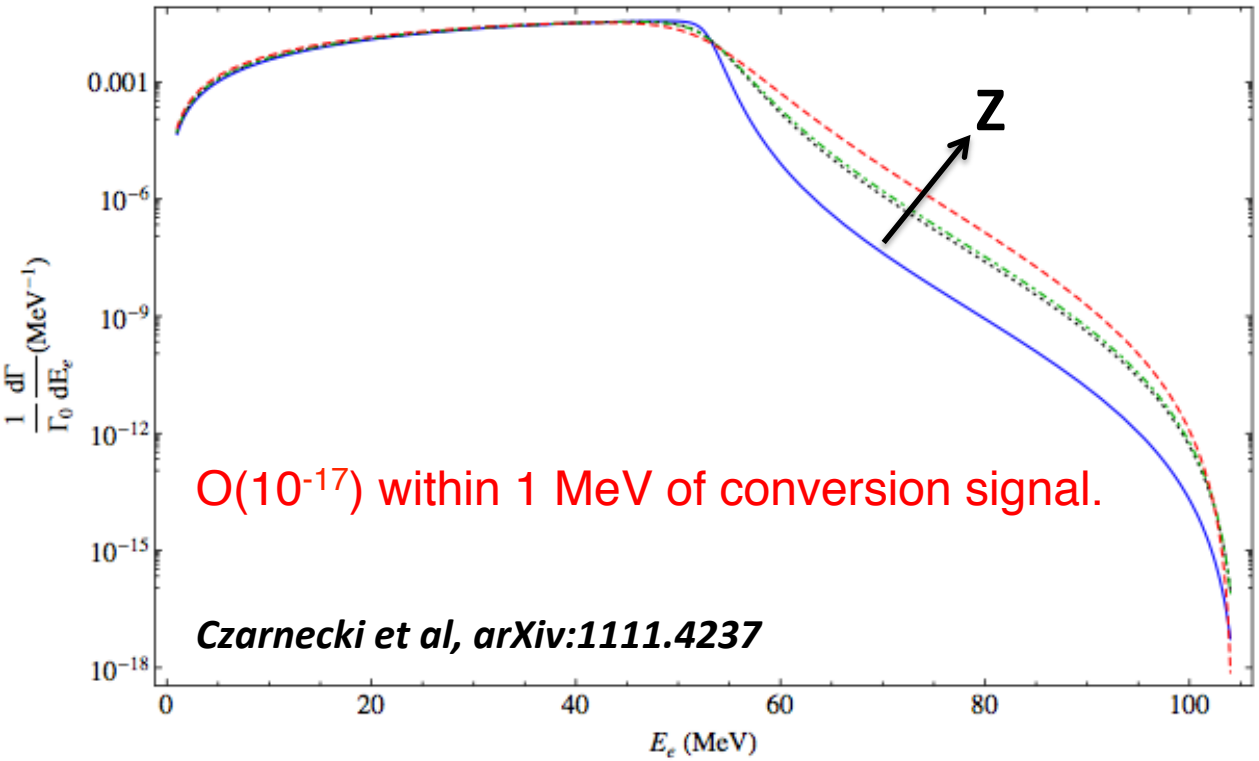
Three proposals

- **DeeMe** at J-PARC : 5×10^{-14} in 2015 to 10^{-14} in2019/20.
  - KEK Muon PAC has granted stage-1 approval
  - JPARC PAC recognises scientific merit and is encouraging further R&D
  - significant synergy with JPARC g-2, particularly new H- beamline.
- **COMET** at J-PARC : 6×10^{-17} in 2022.
  - JPARC stage-1 (of 2 stage) approval based on 2009 CDR.
  - TDR in 2012.
- **PRISM**
  - using FFAG : 10-18 in 202x

μN→eN Backgrounds

Three pertinent backgrounds

1. Decay in orbit (**DIO**) of stopped muon. In atom gives electrons beyond the free-muon 53 MeV end-point.



Controlled by detector resolution AND energy loss prior to detector.

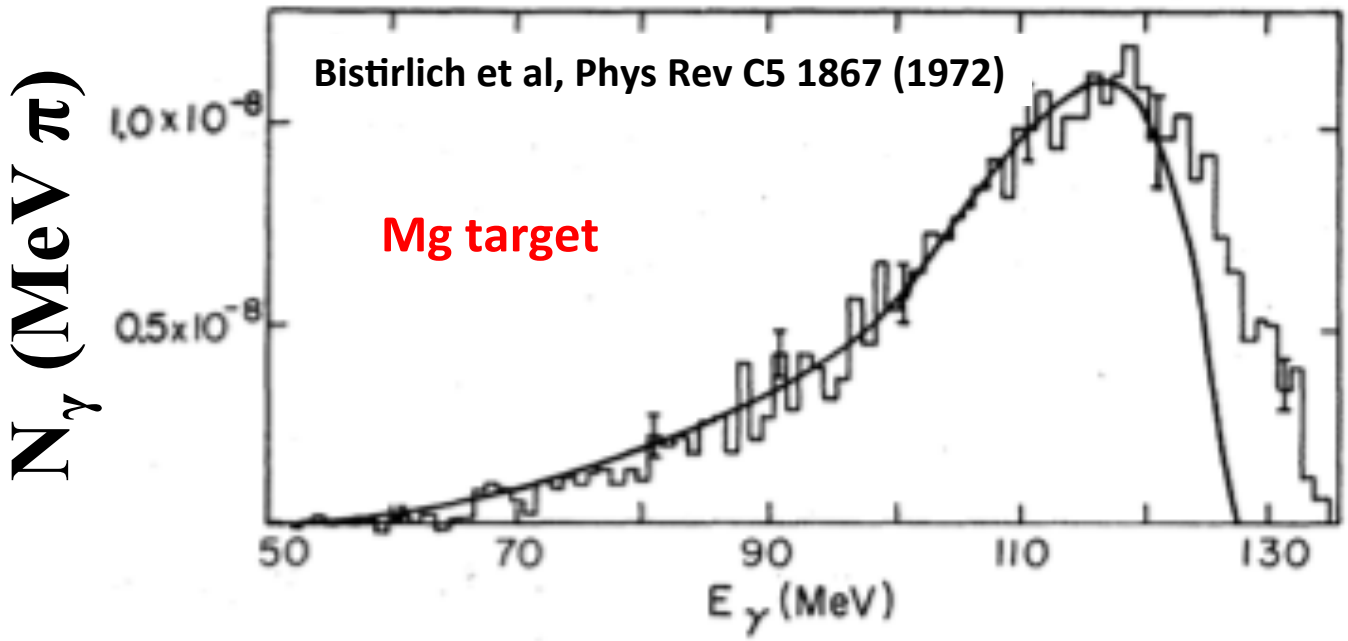
Need FWHM < 1 MeV

μN→eN Backgrounds

2. Radiative Pion Capture (RPC)

$$\pi^- N \rightarrow \gamma N^* \text{ and } \gamma \rightarrow e^+ e^-$$ External conversion

$$\pi^- \mathrm{N} \rightarrow e^+ e^- N$$ Internal conversion



Suppress by reducing # pions on target : wait, stop them, veto them
- beamline and accelerator are the constraint.

Muon to Electron Conversion

3. Instrumental Backgrounds / Devil-In-The-Detail Issues

- Cosmics that radiate electrons in muon stopping-target region

- Muons captured by nucleus result in
  - low energy neutrons that can stop in cosmic ray veto scintillator, produce gamma and veto event.
  - protons (heavily ionising) that can “deaden” a detector region.

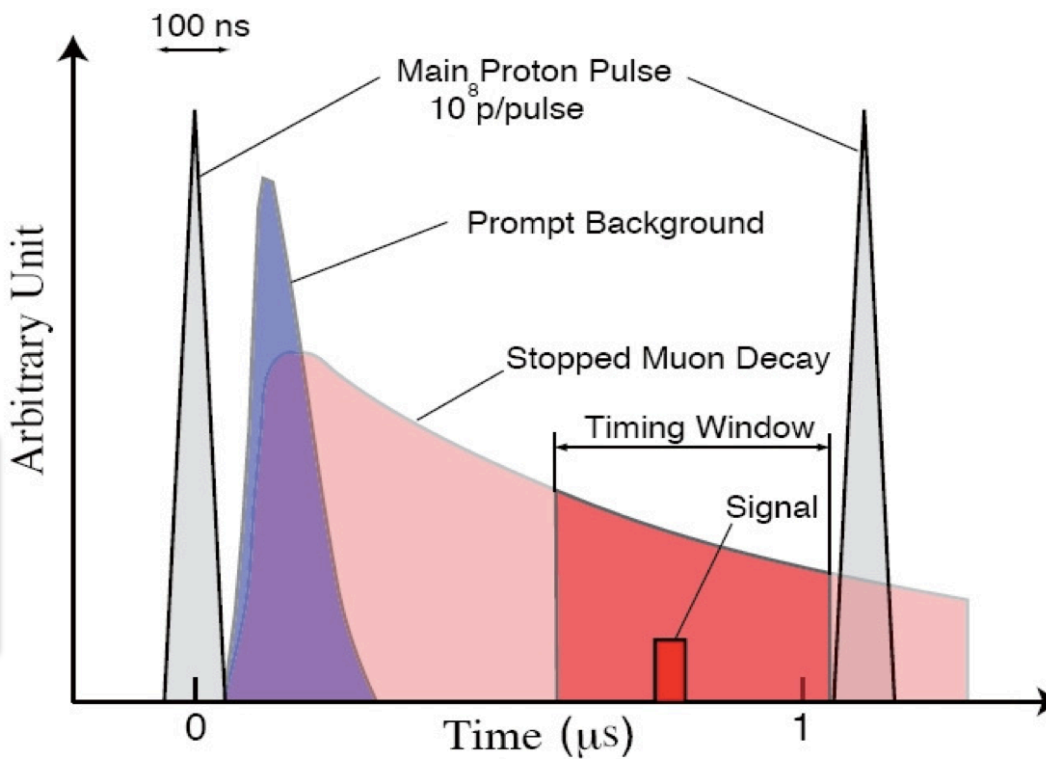
- …..

Challenges

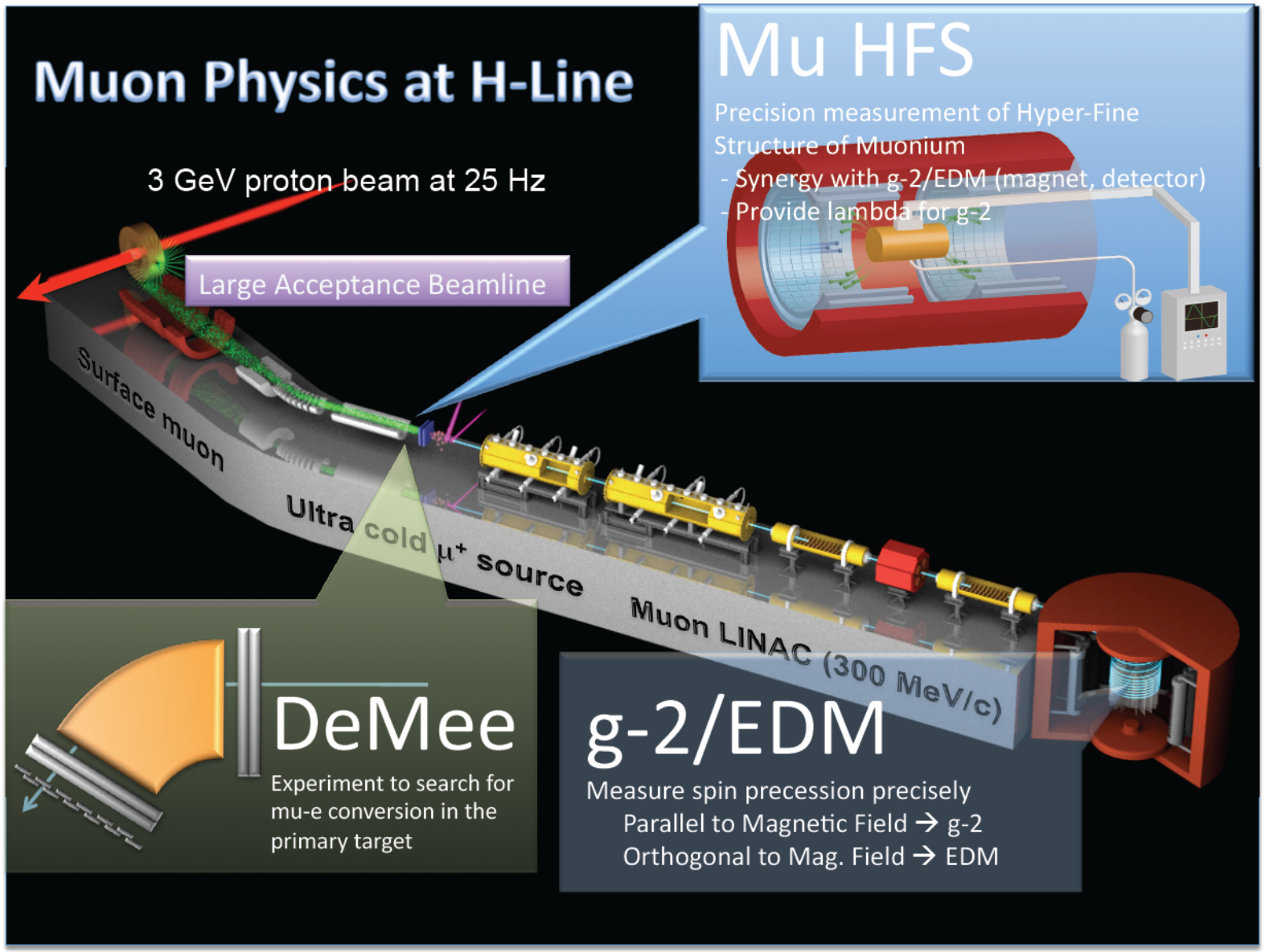
Going beyond SINDRUM requires

- Rate of stopped muons to be ~ O(5×10^{10})/s
- High resolution (< 1 MeV) e- momentum measurement to control DIO.
- Control of energy loss/straggling in stopping target
- Mechanism to reduce # pions at target and veto prompt backgrounds.

All proposed experiments use pulsed beam & only "measure" after prompt background subsided

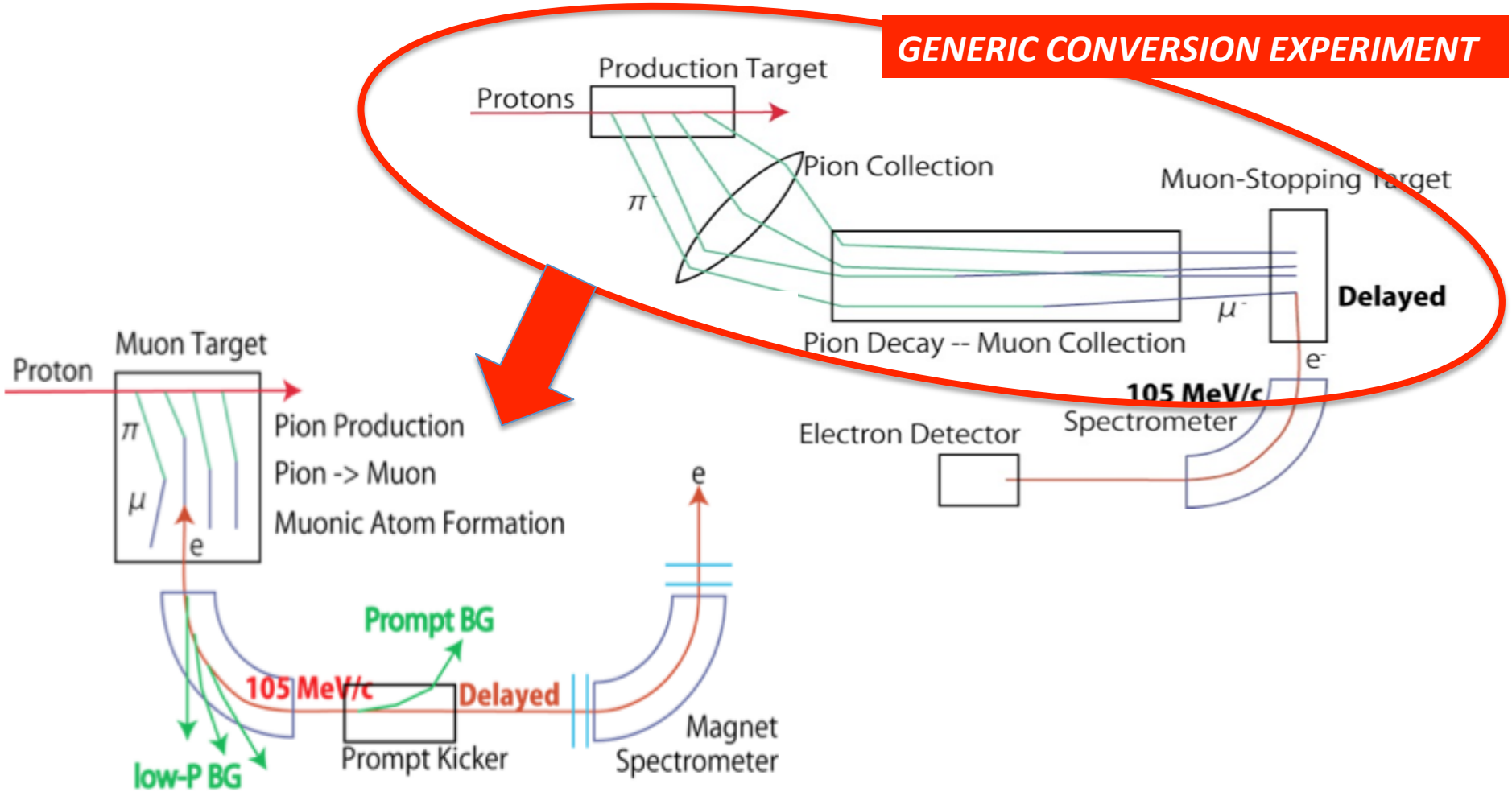


J-PARC H-Line (DeeMe)



DeeMe @ JPARC : O(10^{-14})

Simpler experiment than COMET/mu2e



DeeMe @ JPARC : O(10^{-14})

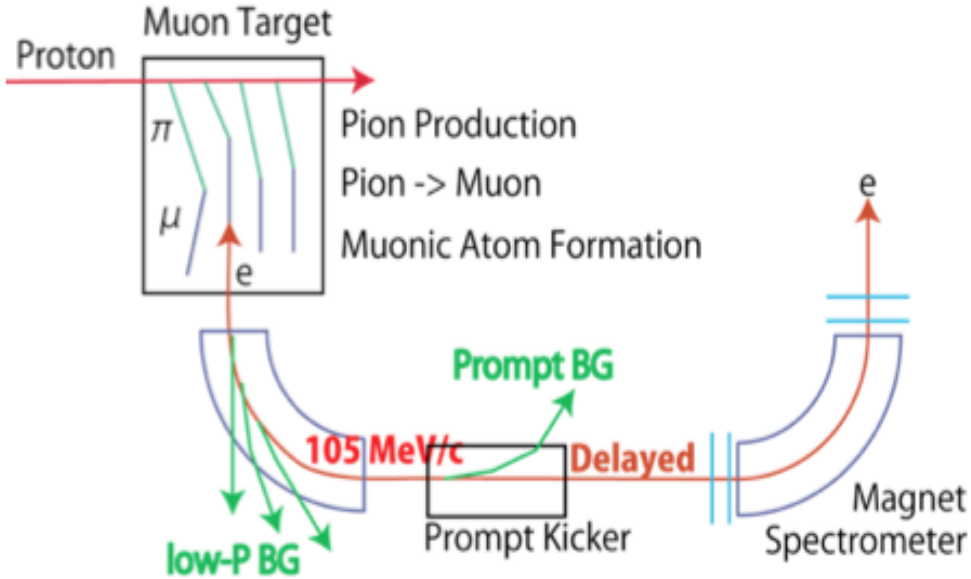
3 GeV "fast extracted" beam (cf ~ 8 GeV at COMET/mu2e)

Production & stopping target are combined : "surface muons" –> μ-atom in target

Spectrometer selects only ~ 105 MeV particles.

Prompt background reduced by delay and fast kicker magnet.

Requirement of extinction is : O(10^{-17})



25Hz rep rate, 300 ns fall time, 385 G

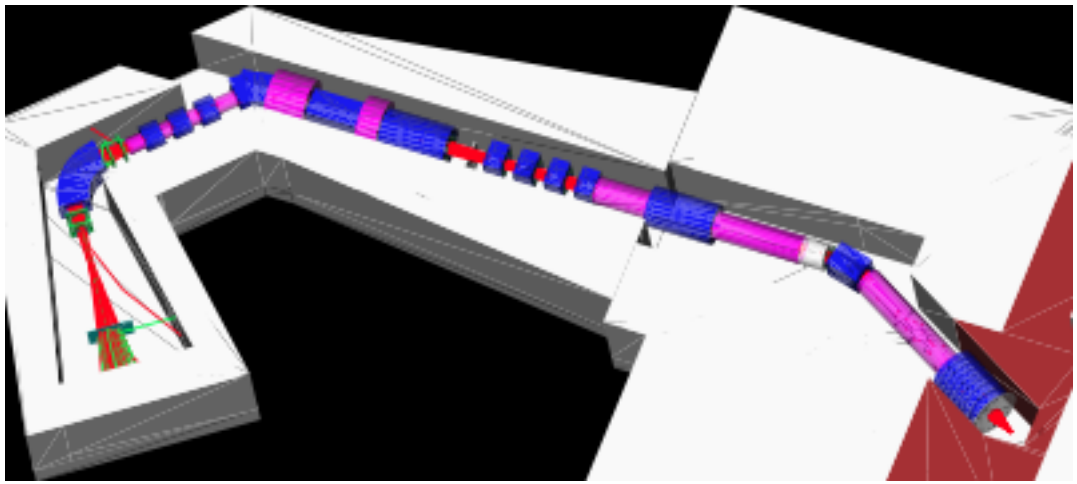
Reduce prompt burst (50 M particles) by factor of 1000.

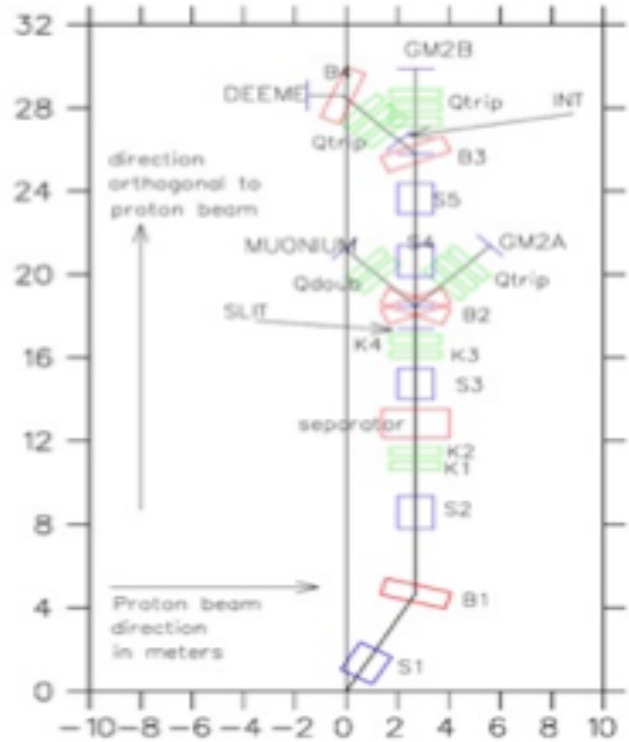
DeeMe @ JPARC : O(10^{-14})

In 2015 : JPARC RCS will provide 1MW @ 3 GeV.

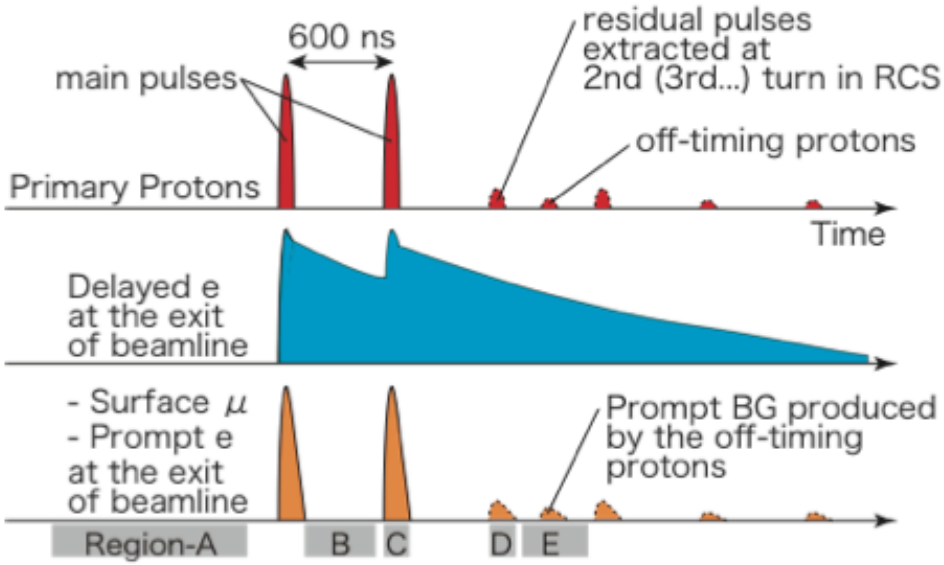
Existing low acceptance (D) beamline and graphite target : 90% BR @ 7×10^{-13}
New high acceptance (H) beamline and SiC target : 90% BR @ 5×10^{-14} for 2×10^{7} s run

Particle yield ($e^{+/-}$ from μ) has already been measured using gated-PMT and agrees well with simulation : **5×10^{9} μ/s/MW (x2 for SiC).**





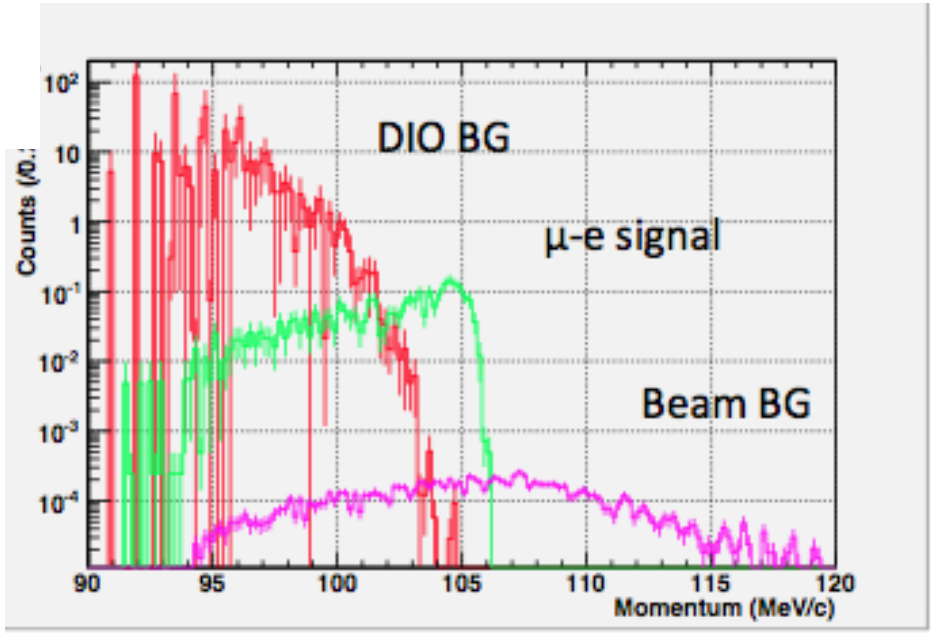
DeeMe @ JPARC : O(10^{-14})



1st extinction measurements performed: no signal recorded from 10^{20} p (258 hrs)

Due to limited momentum acceptance of beamline
DeeMe aims to measure DIO and high-p prompt background in situ

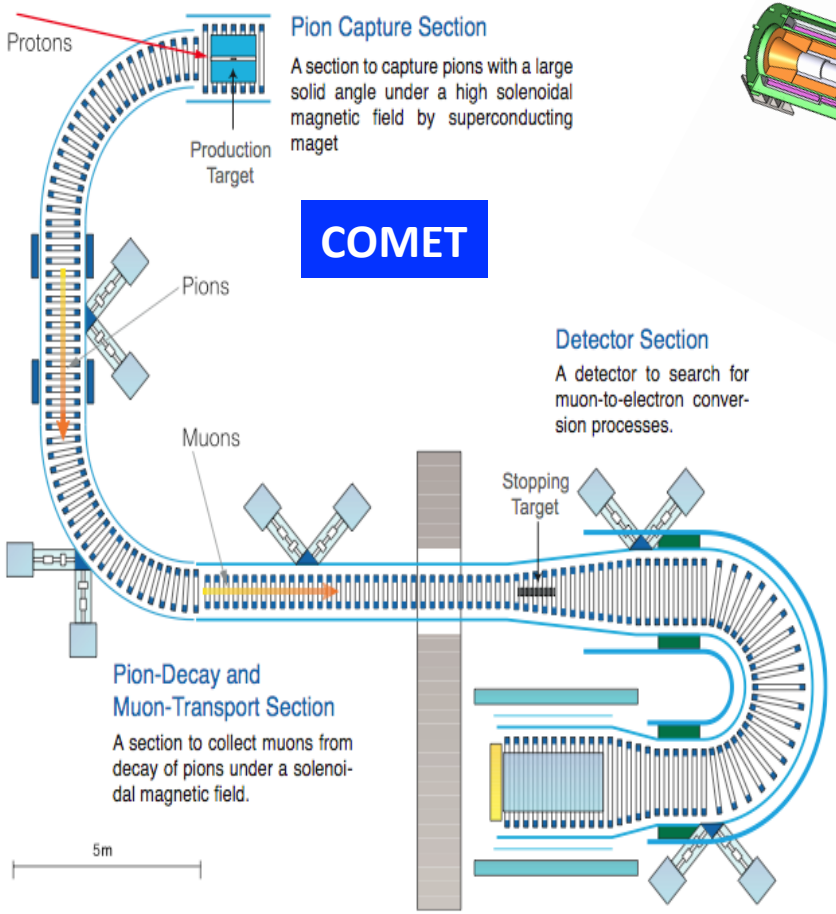
σ(p) < 0.5 MeV (wire chambers)

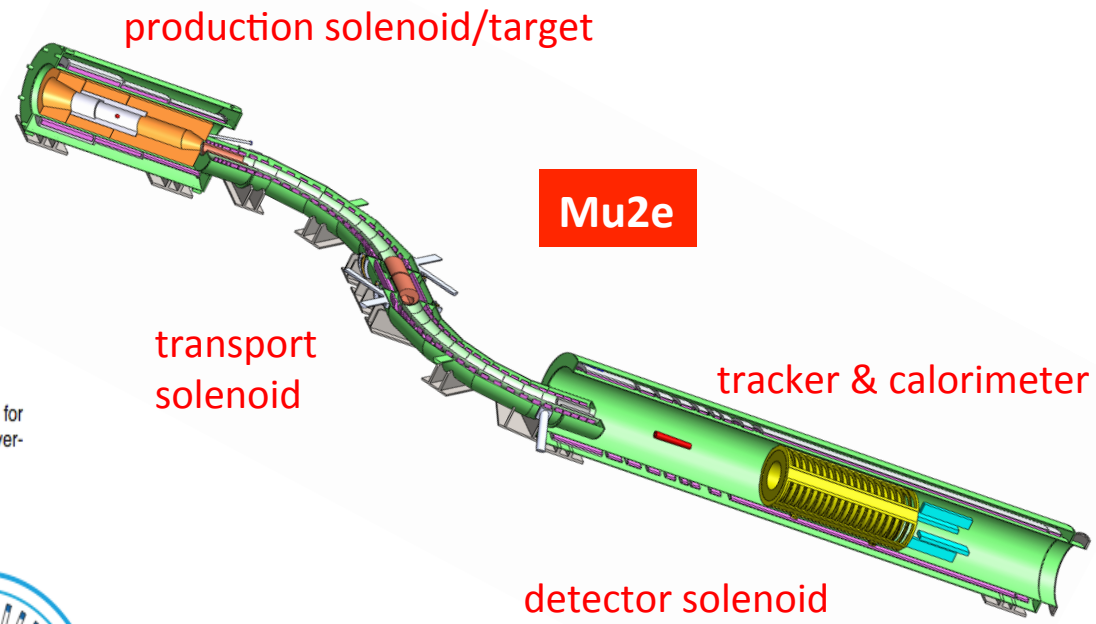


Signal Region: 102.0 -- 105.6 MeV/*c*

COMET : 6×10^{-17}

Design sensitivity is > 1000 MEG (10^{-13}) limit, so x10 with α_{EM}

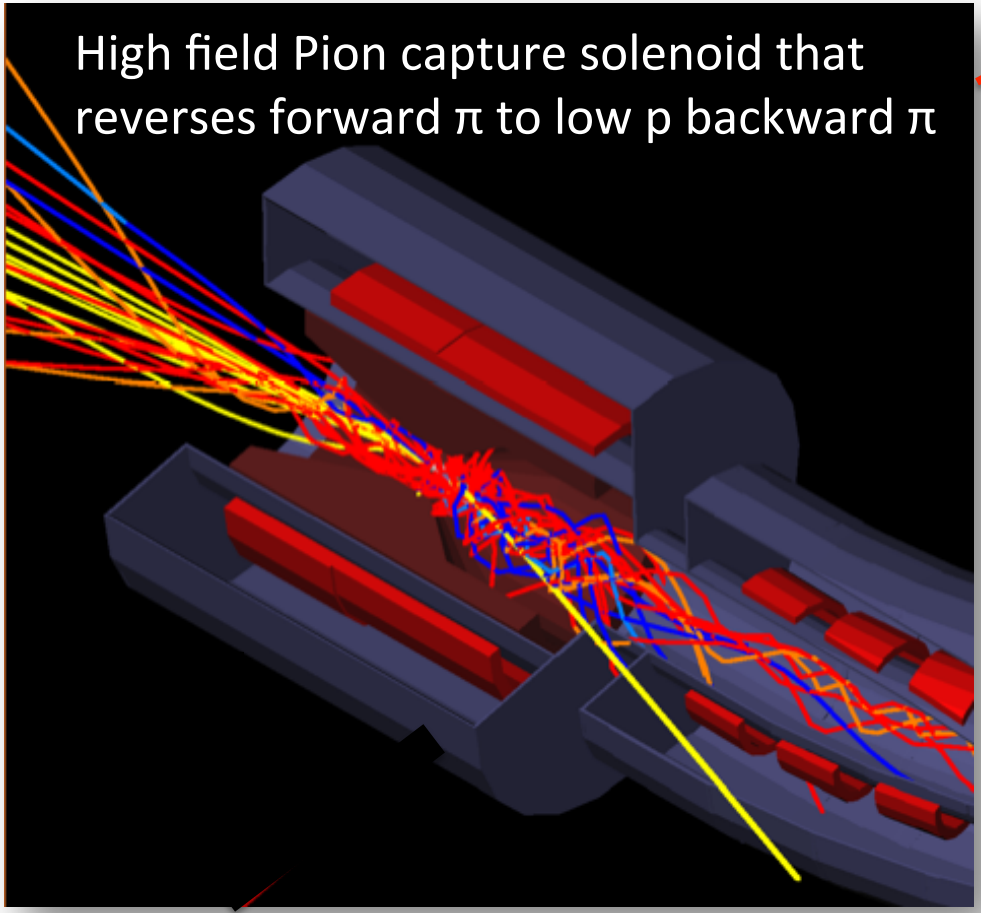




COMET : 10^{18} μ/yr (CDR) with lower acceptance & requirement of dedicated running vs Mu2e 4.5 x 10^{17} μ/yr (CD0) and concurrent Nova running

COMET Collaboration

Challenges : Stopped Muon Yield

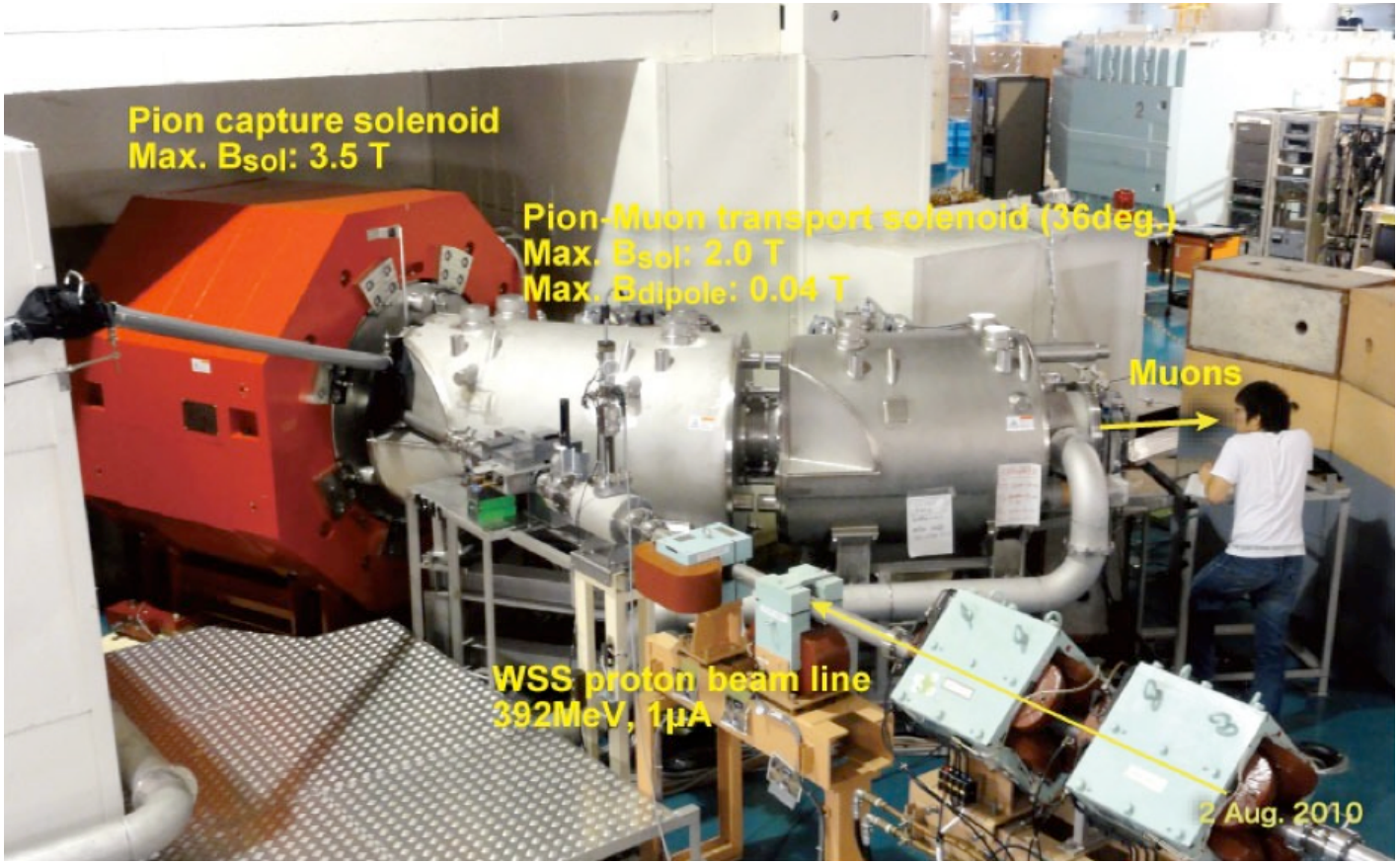


Increases yield by O(1000) - method successfully demonstrated at MUSIC in Osaka in 2010

Transport solenoids that select low p (< 50 MeV) muons and reject high p particles **before** the stopping target.

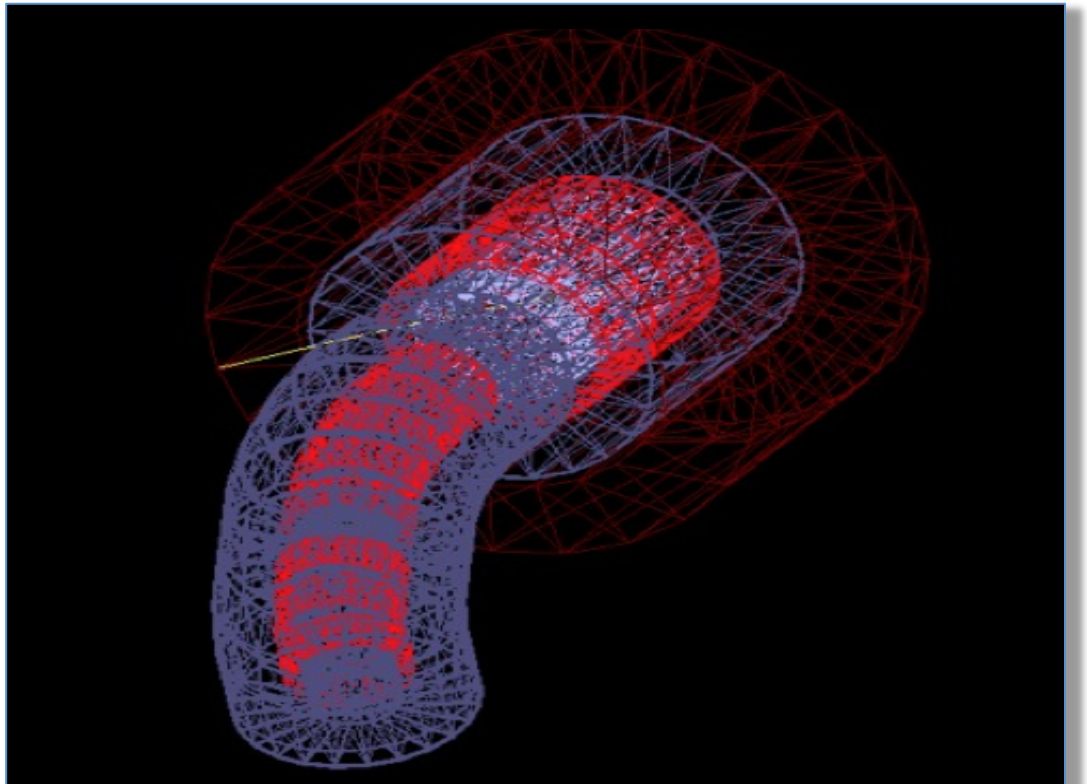
MUSIC @ Osaka

Utilising prototype pion production environment for COMET



MUSIC @ Osaka

Three commissioning runs in 2010/11 with reduced beam I (6pA [2.4mW]) with Cu and Mg targets for muon beam



Due to pion capture solenoid. Muon yield per W of beam power is ~ O(1000) PSI.

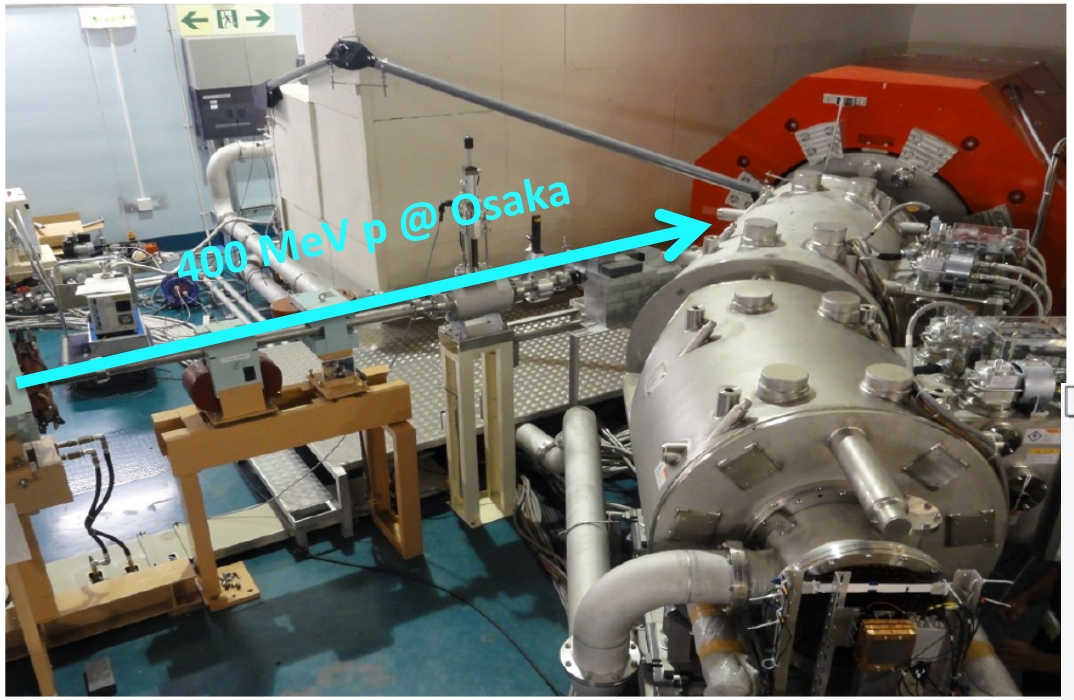
Pion production solenoid

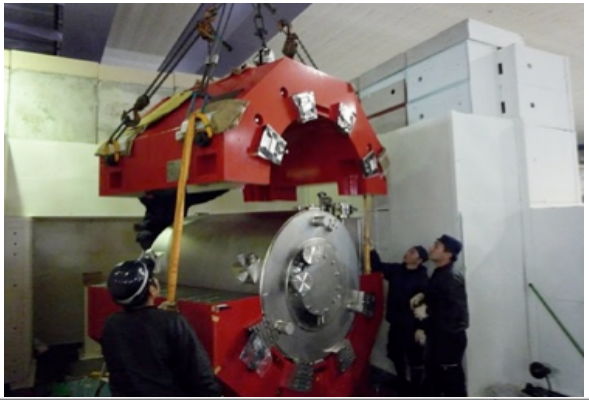
Possibly a mu->3e measurement using a TPC.

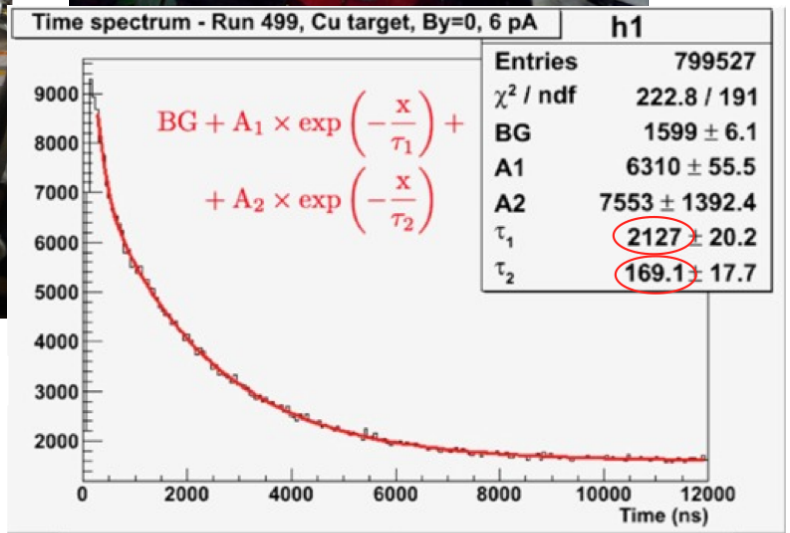
If funded "3e" physics run in 2016.

COMET : Pion Production

Using 56 kW (10^{11} μ/sec) slow extracted 7.1 GeV (KE) from JPARC Main Ring.
Unlike Mu2E requires dedicated beam without neutrino (T2K) running.





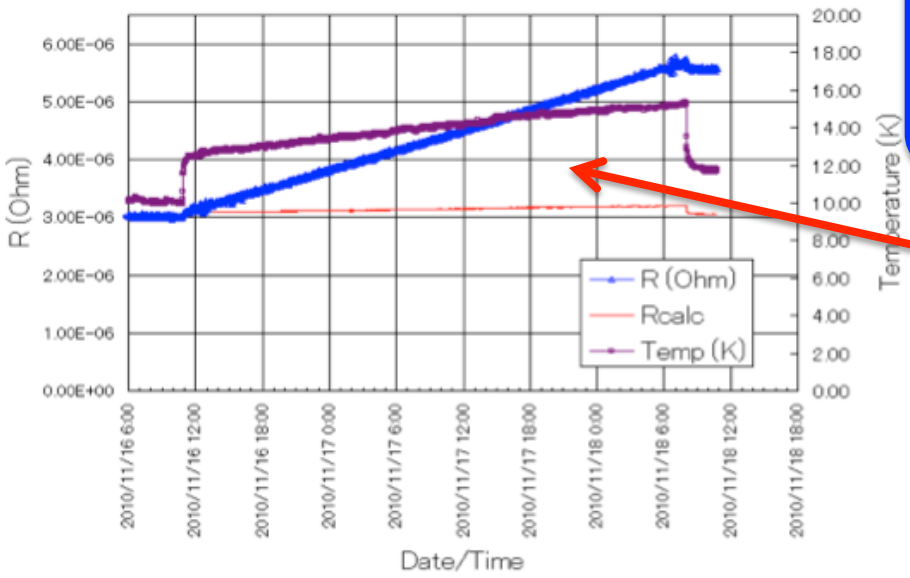


	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5

Observed muons at rate O(1000) x PSI per W of beam power.

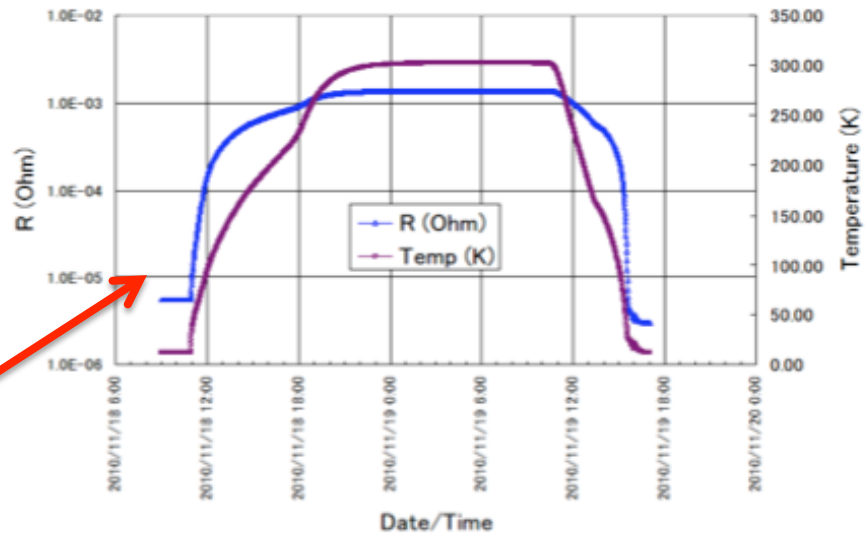
COMET : Irradiation Tests

Pion production solenoid is 1.3m diameter 5T solenoid subject to to 10^{21} n/m^2



Neutron irradiation tests of Superconductor and Al stabiliser at Kyoto nuclear reactor using 10^{20} n/m^2

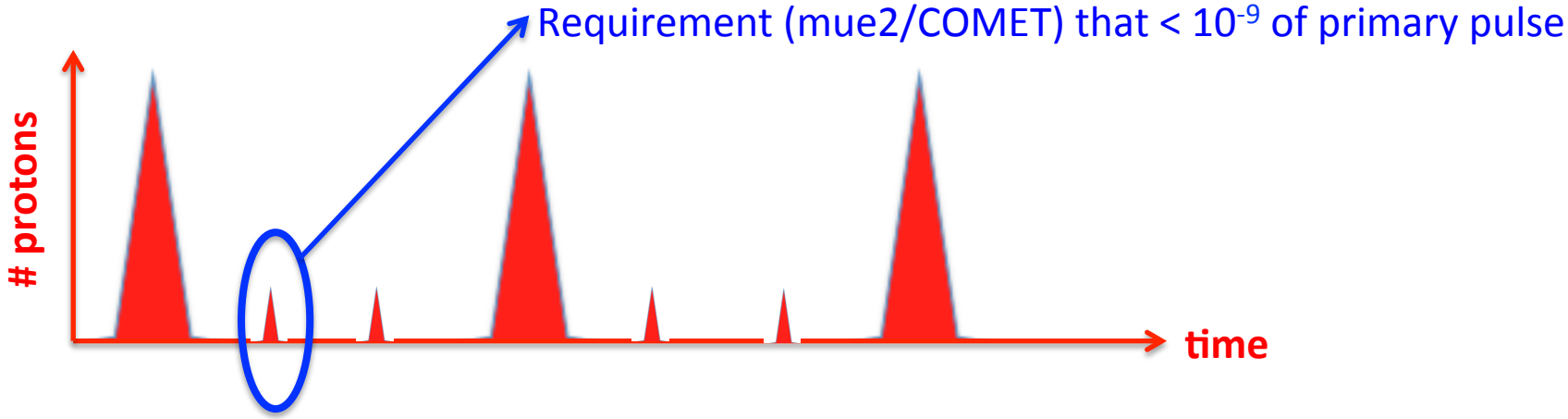
Resistance increased by ~ 2.5μΩ



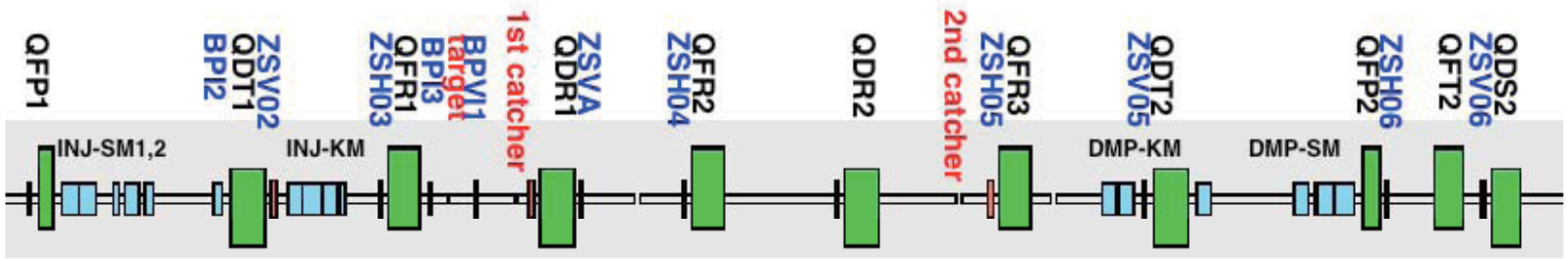
½ day thermal cycling returns resistance to pre-radiated value

Challenges : Proton Extinction / ”After protons”

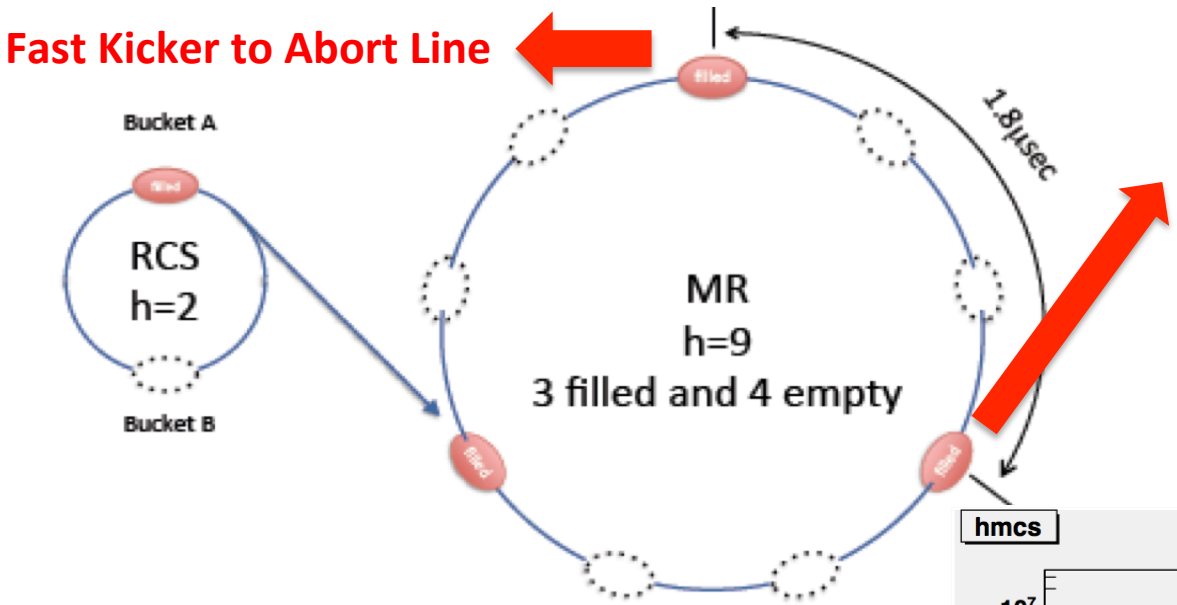
Require that between proton pulses there are no rogue proton pules that could produce a “prompt” background e.g. RPC in the timing window



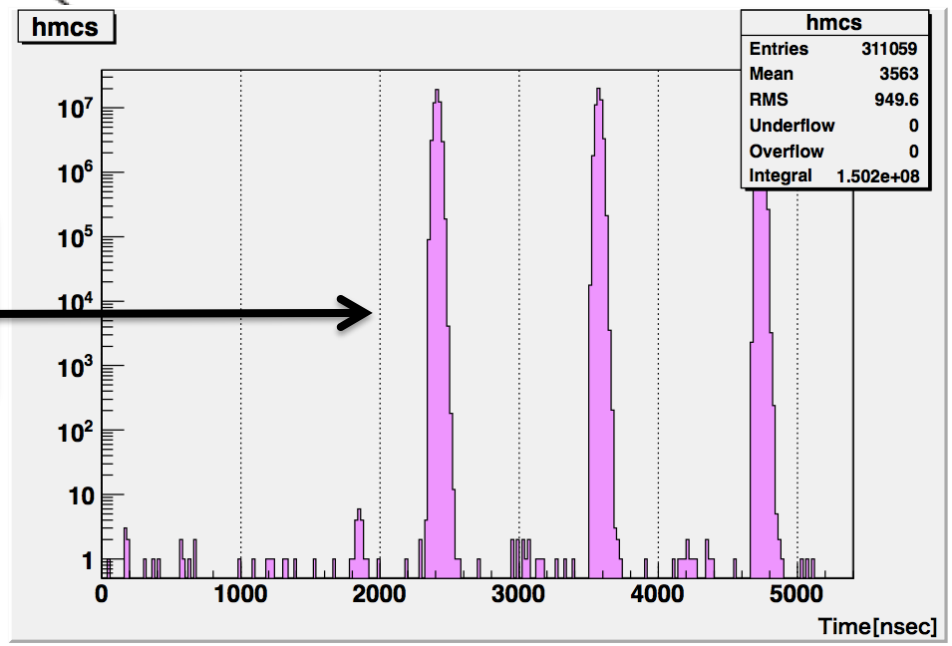
AC dipole/collimator system kicks out the out-of-time particles



COMET : Extinction Studies



Bunched slow extraction using ESS to dedicated target/ secondary beamline



Extinction level of **(5.4 ± 0.6) × 10^{-7}** measured at secondary J-PARC beam line and O(10^{-7}) at abort line

And additional O(10^{-6}) from double kick injection into MR

Beyond COMET/Mu2E

Strategy depends somewhat on whether signal is seen or not.

If signal is seen

- run with high-Z target to elucidate the underlying physics

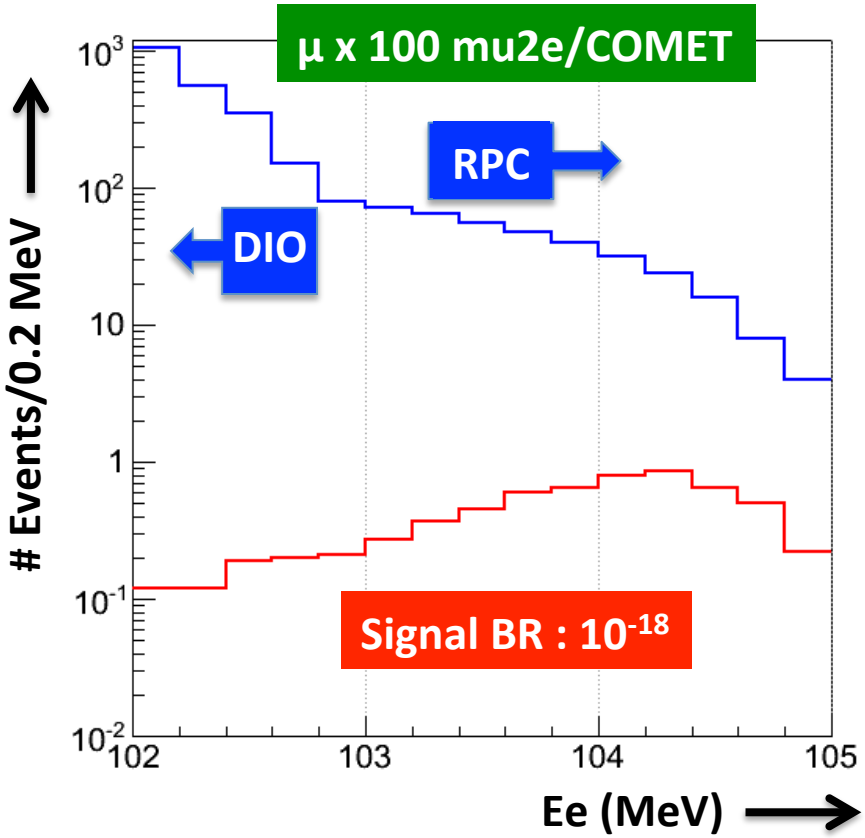
If no signal seen

- push sensitivity down to O(10^{-18})

10^{-18} and beyond is difficult with current methodology/detectors since DIO & RPC backgrounds dominate.

Requires:

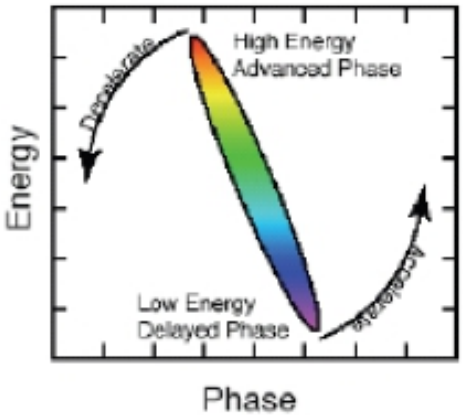
- reduction in # pions at target by O(100)
- better event localisation (t,pos) at target
- reduced E-loss in target (now ~ 1 MeV)

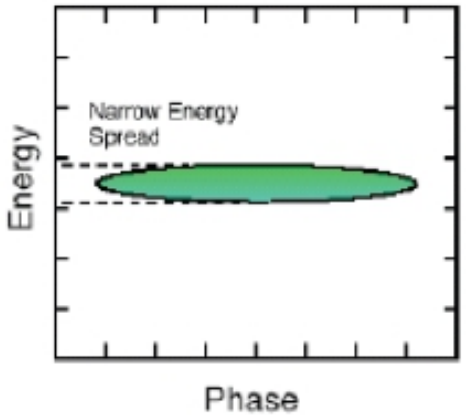


PRISM / PRIME FFAG

Low duty cycle scheme unlike e.g. Project-X

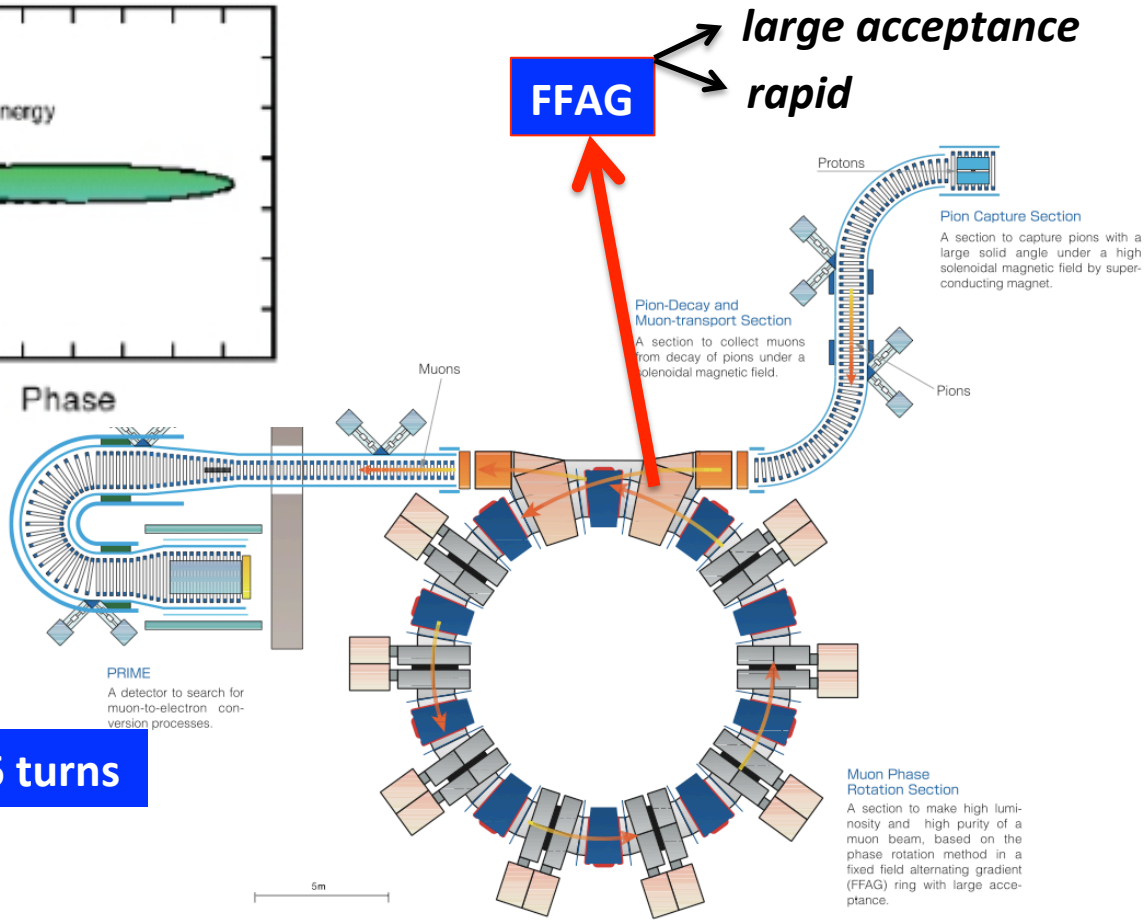
Use initial beam with short pulses (10 ns) and **use phase rotation** to achieve narrow momentum spread at Liouville's expense of longer (220 ns pulse)





Reduce p-spread : 20% to 2% in 6 turns (~1.5 μs).

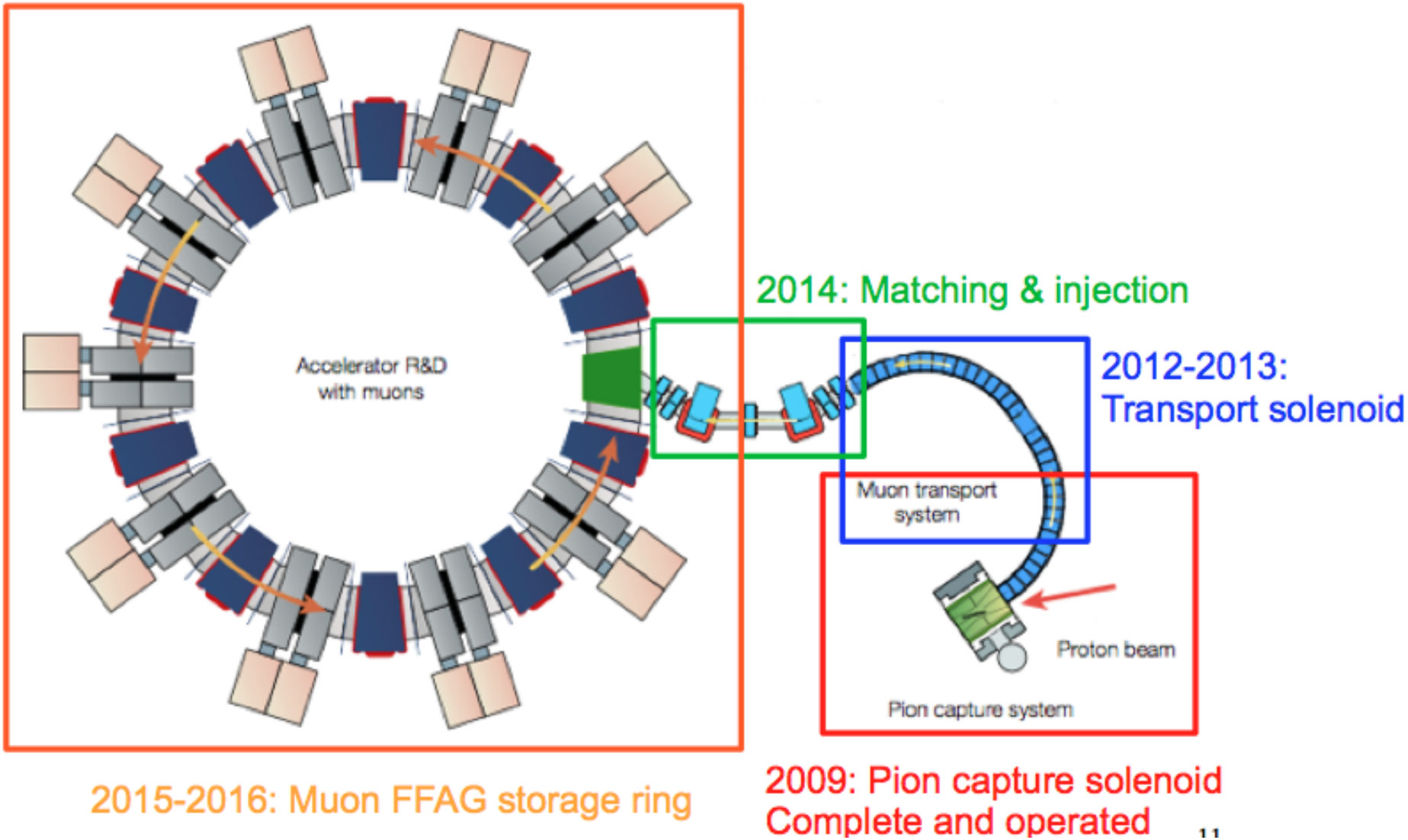
Pions extinguished below 10^{-20} in 6 turns



PRISM / PRIME FFAG

Phase Rotation demonstrated with FFAG at Osaka using α -particles

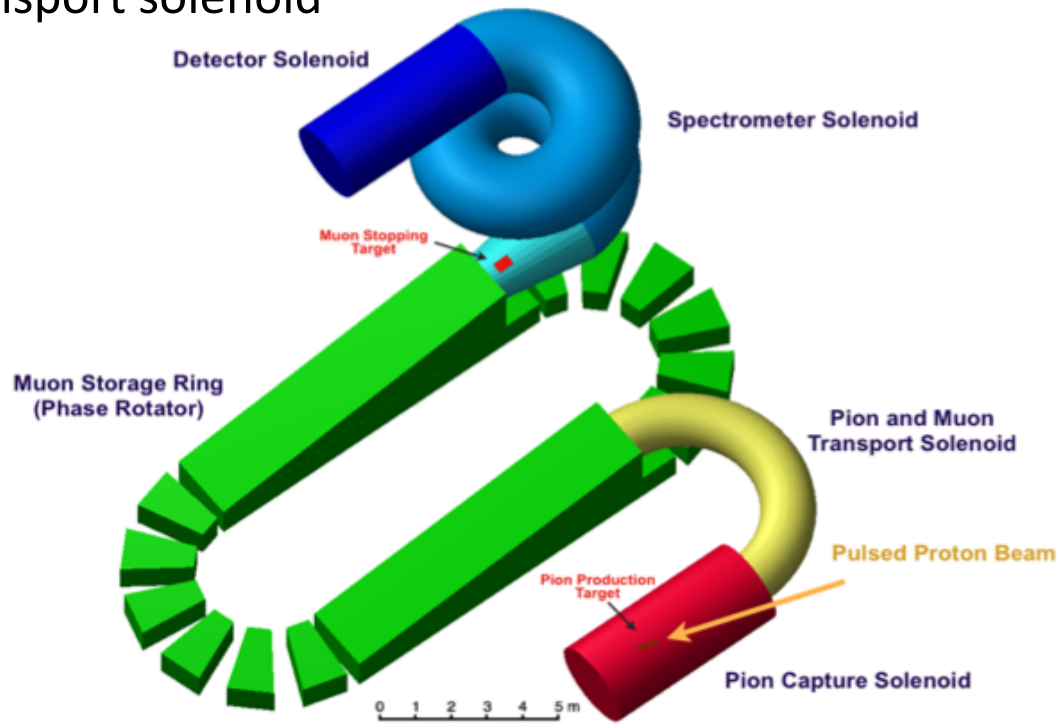
MUSIC Plan (Budget Permitting)



PRISM / PRIME FFAG

Many issues being worked on:
- injection and extraction (80 ns rise time kicker magnets)
- beamline matching

PRIME is detector concept – employs "Guggenheim" electron (p ~ 105 MeV) transport solenoid



CDR in 2012

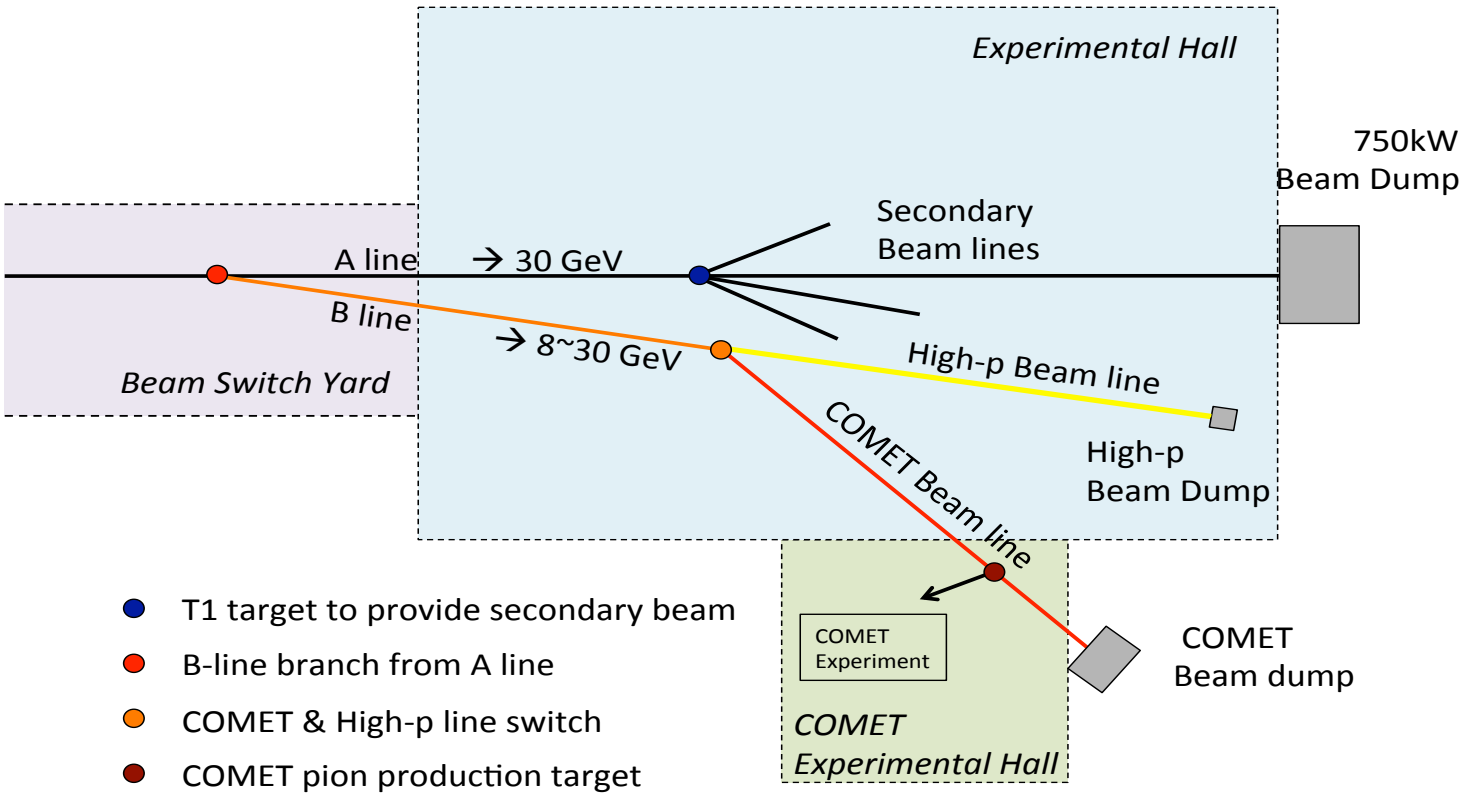
Project-X : Cooling

Much synergy with work on muon collider and many cooling ideas being discussed.

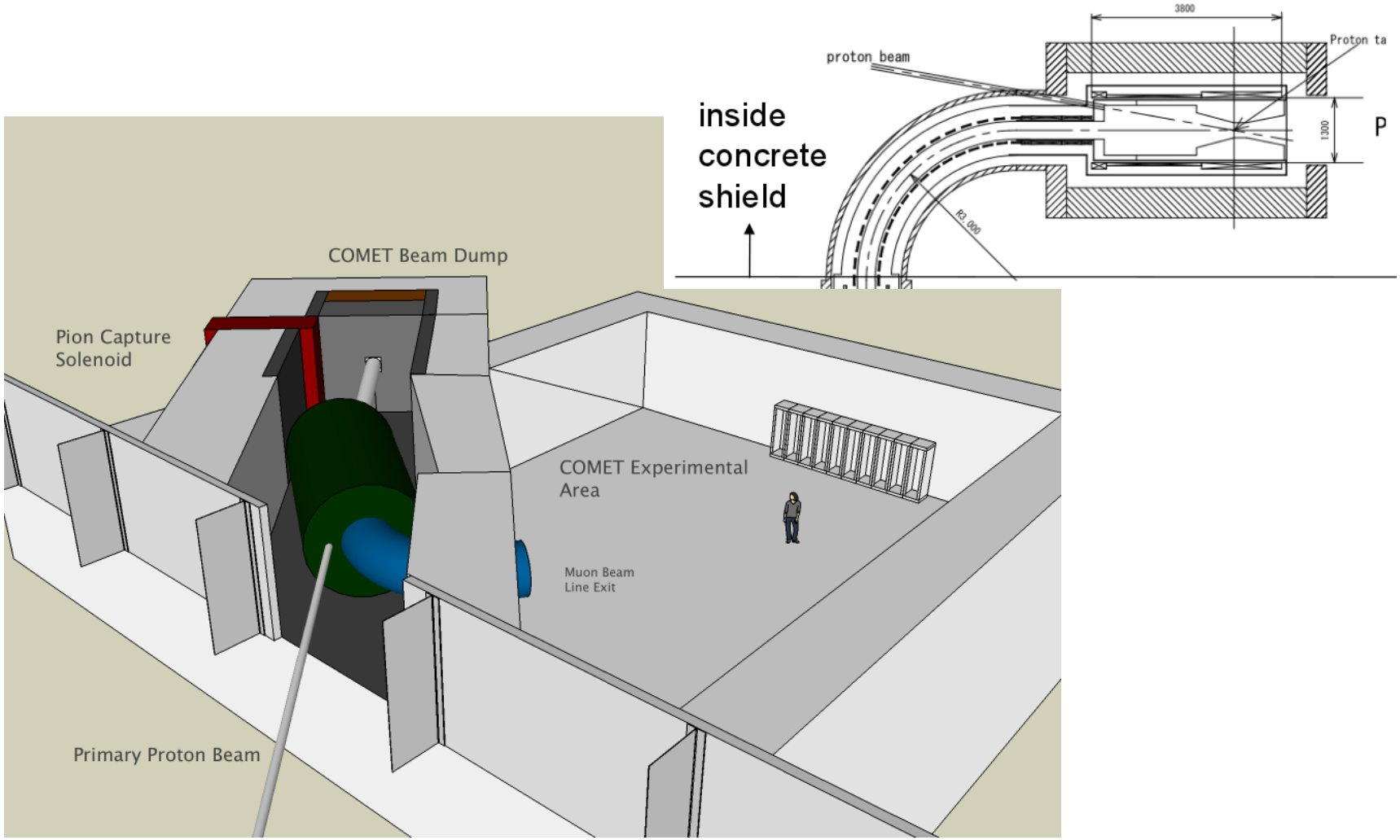
Comparison	**Muon collider**	**P-X Muon beam**
Protons		
Beam energy	8 GeV	3 GeV
Beam power	4 MW	1 MW
Bunches/second	15	10^6
Duty factor	low	high
rms bunch length	3 nsec	20 psec
Muons		
muon/proton ratio	0.1	~0.001
required cooling	extreme	moderate

COMET Phase-I

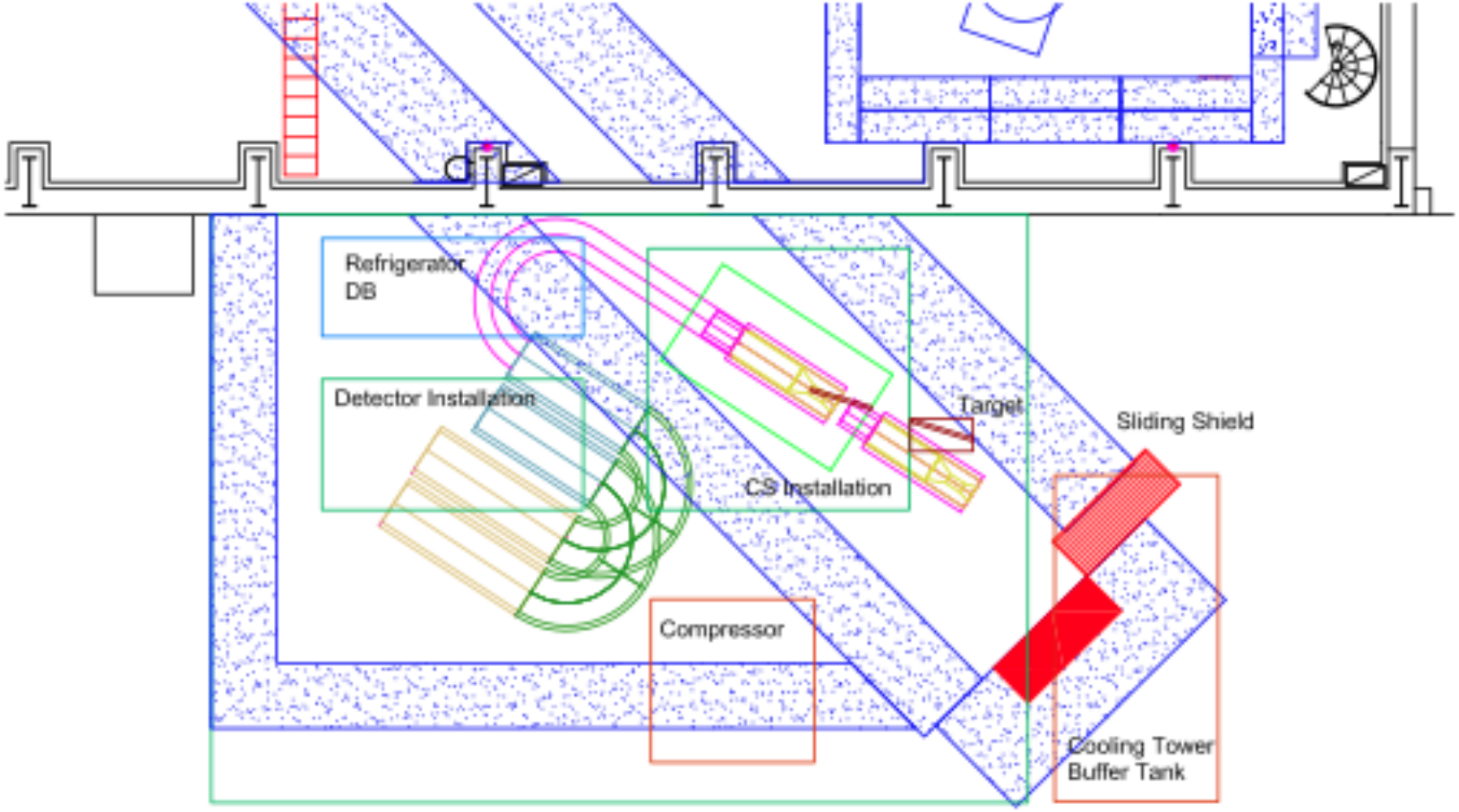
KEK has invited proposals to use a new J-PARC beamline in 2016/17.



COMET Phase-1



COMET Phase-I

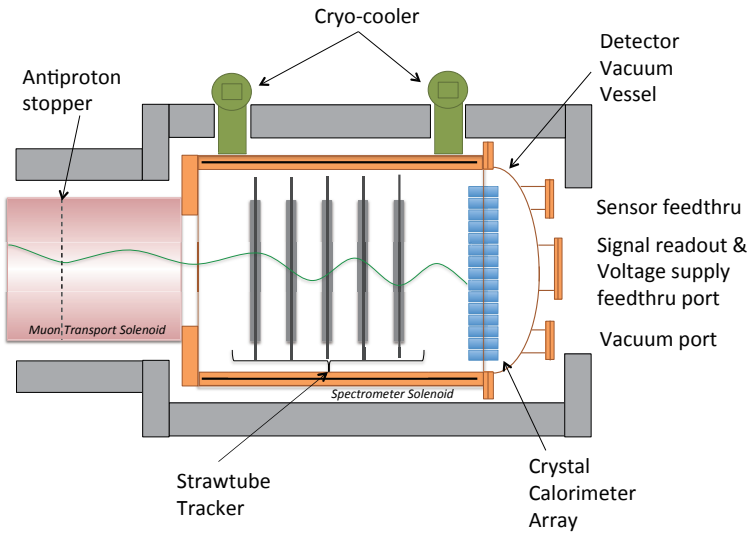


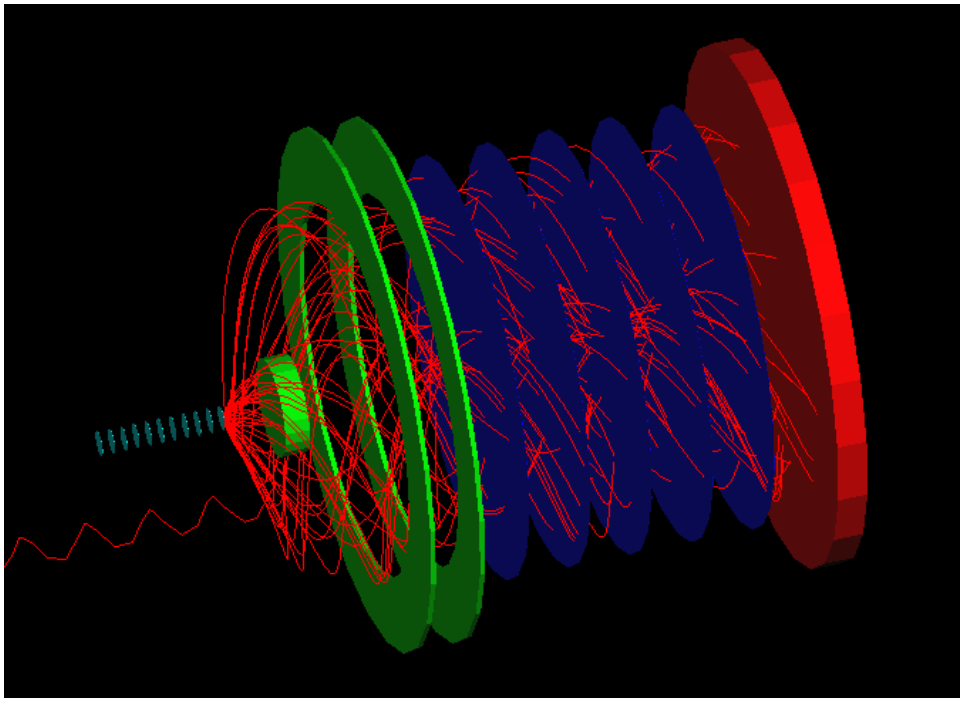
COMET Phase-I

Proposal to be submitted to J-PARC on Friday and will be reviewed in March

Aim is to

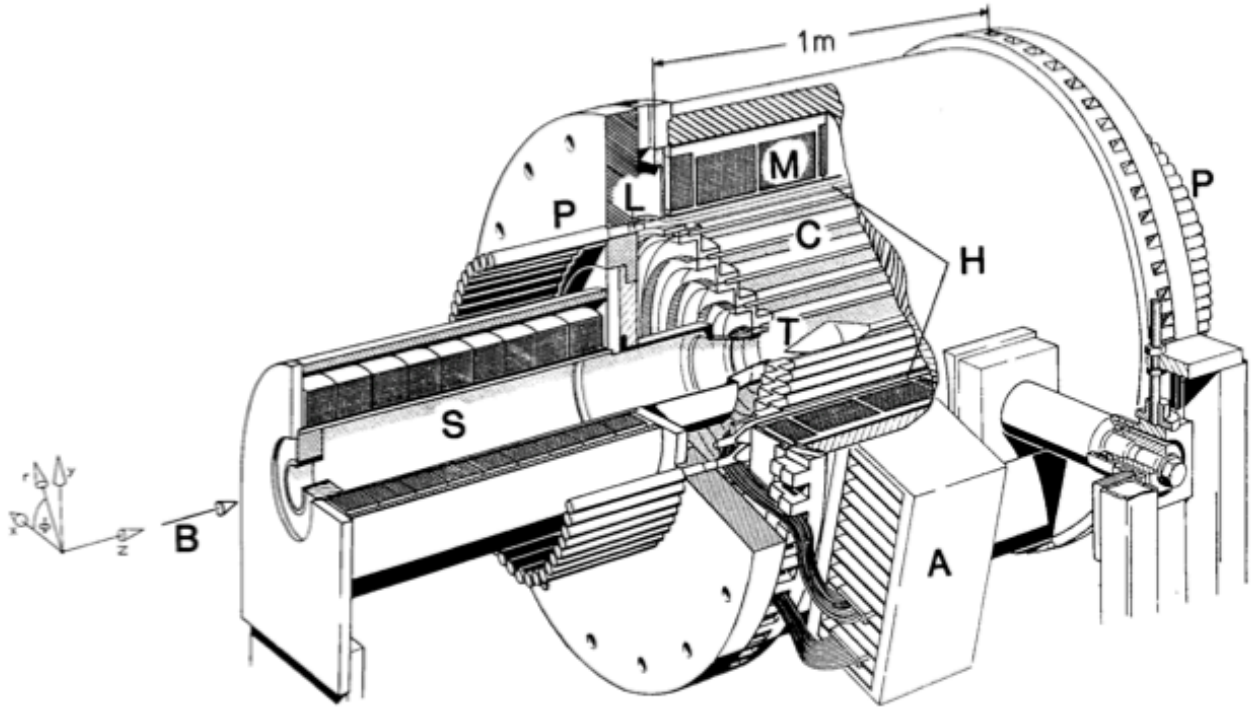
1. Measure in-situ the COMET backgrounds
2. Verify beam extinction.
3. Make conversion measurement with sensitivity intermediate between SINDRUM and COMET/mu2e.
   on the timescale of 2017.





COMET Phase-I

May also use “cylindrical” spectrometer a la SINDRUM to increase acceptance



Summary

There is a vibrant muon programme complementing that at PSI and FNAL.

- Cold muon "g-2" with similar precision as FNAL g-2.
  Potentially an independent 5-sigma observation of (g-2) anomaly.

- Muon EDM using parasitic g-2 technique to reach 10^{-21}

- Muon EDM using frozen spin technique to reach 10^{-24}

- MUSIC @ OSAKA demonstrating the COMET/mu2e muon production technique and FFAGs for phase rotation.

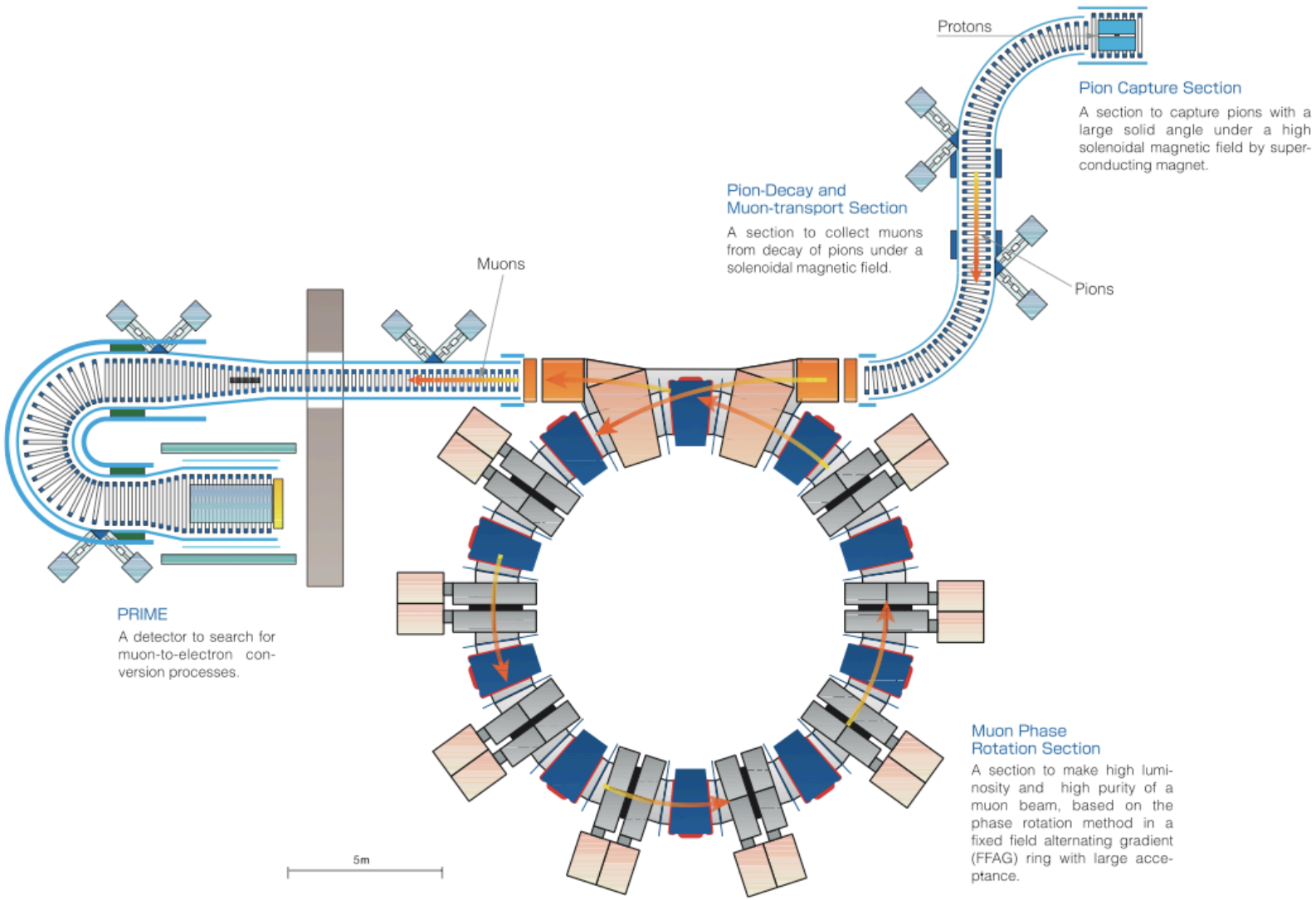
- COMET Phase-I on 2016/17 to make in-situ background & extinction measurements and move beyond the SINDRUM limit

- COMET Phase-I in 202x to reach 6×10^{-17} sensitivity

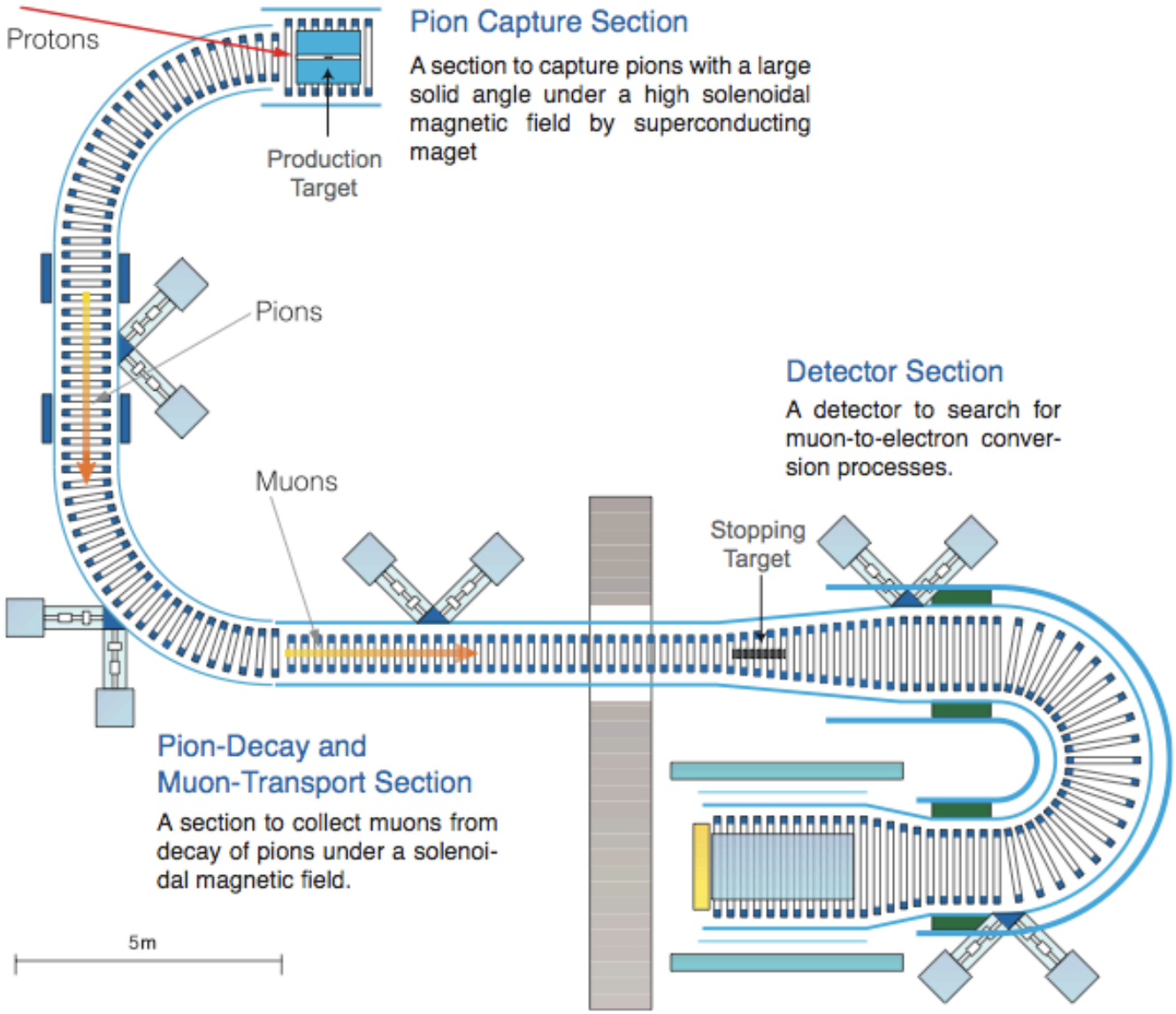
- PRISM/PRIME in 20xx to improve sensitivity by further factor of 100.

BACKUP

Muon EDM: Frozen Spin



COMET


Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
Pions
Detector Section
A detector to search for muon-to-electron conversion processes.
Muons
Stopping Target
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.
5m

μ→eee

Same issues as μ→eγ

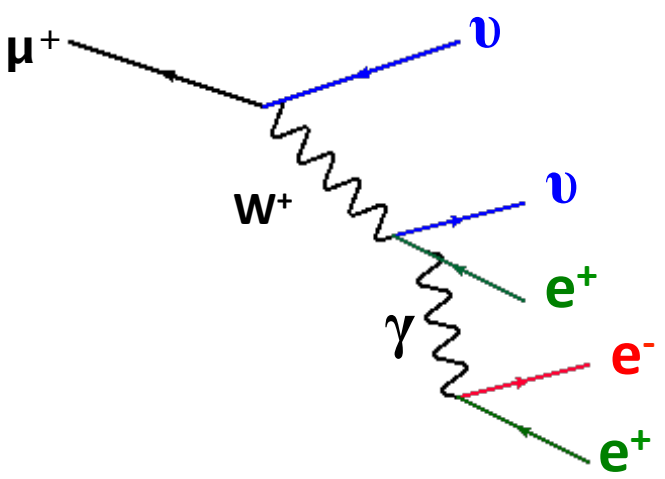
- accidental/pile-up backgrounds : $(R\mu/D)^2$ – so DC beam required.

Issue as go to v. high rates

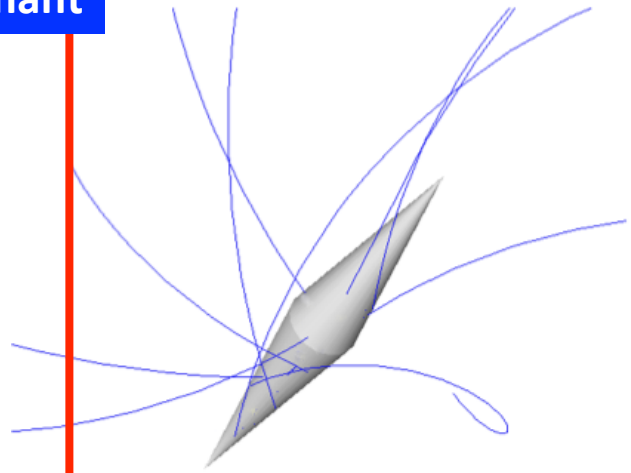
Two μ+ decays and fake e- (Bhaba scattering, γ conversion)

- irreducible background : Rμ

Dominant



BR = 3×10^{-5}



As with μ→eγ the solution is resolution, resolution, resolution…

g-2

Have to contend with higher rate in smaller device

$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

	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	0.1 ppm

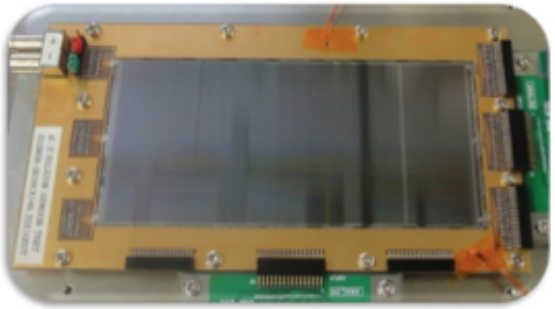
N. Saito NuFact 2011

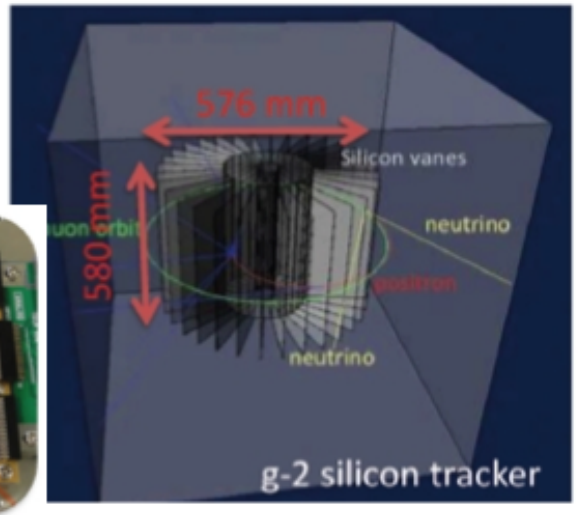
$$\Rightarrow \quad \sigma_\omega = \frac{\sqrt{2}}{A\gamma\tau_\mu\sqrt{N}}$$

Lower γ means higher statistics required

Also need to repolarize muon source or compensate lower A

Highly granular Si tracker, Belle II DSSD under evaluation

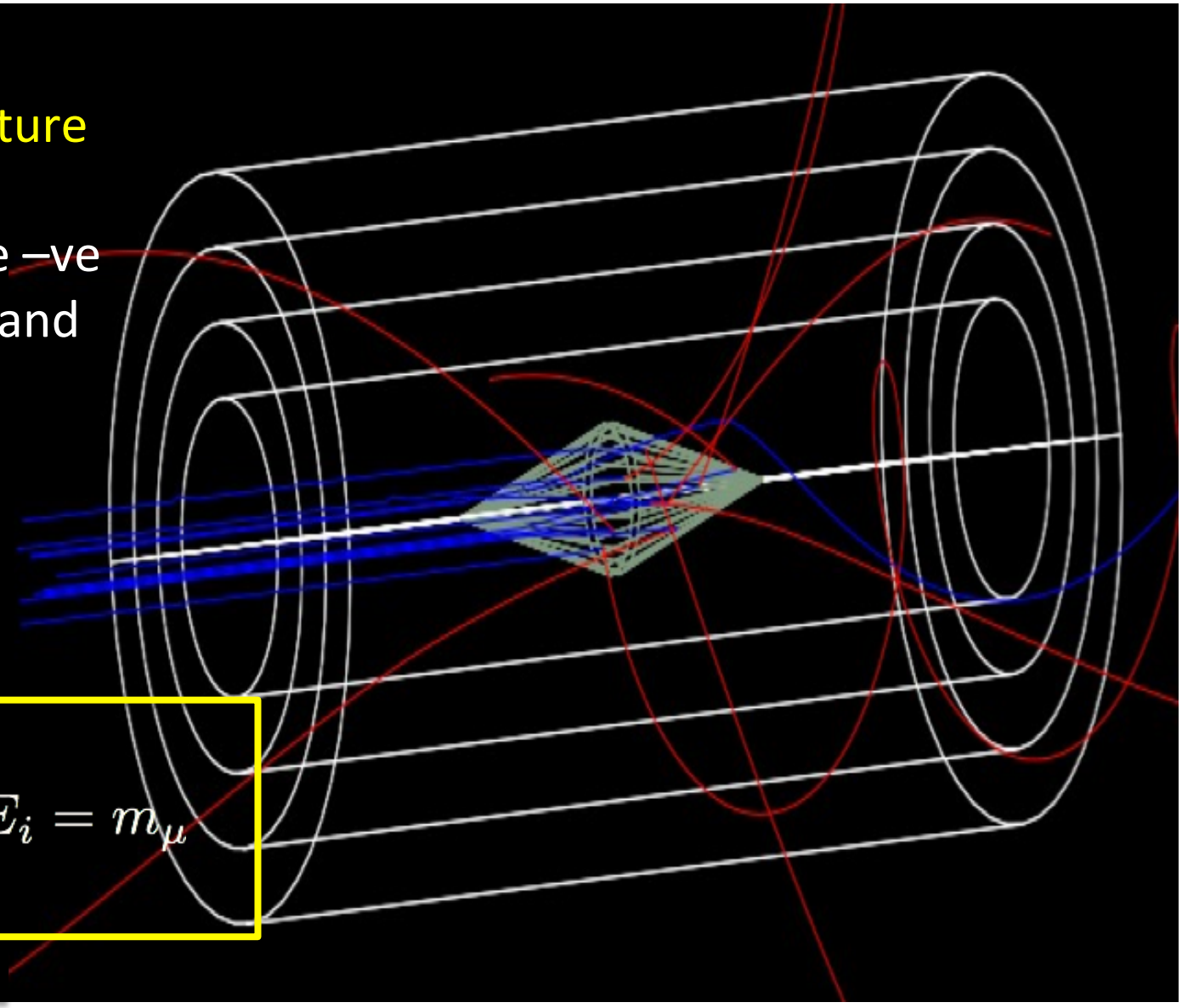




μ→eee

Experimental signature

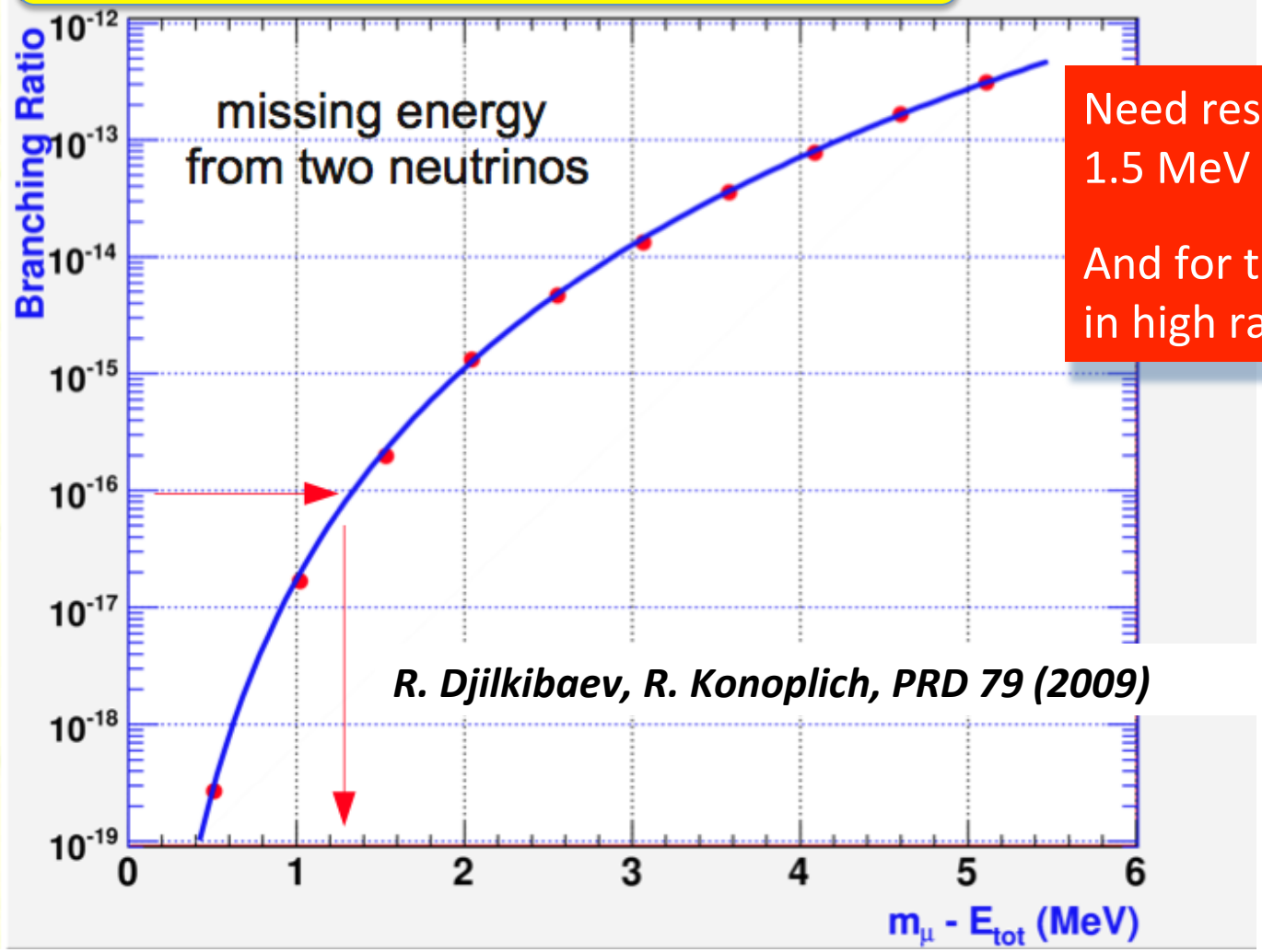
- 2 +ve tracks, one –ve
- common vertex and event time



$$\left|\sum_i p_i\right| = 0, \quad \sum_i E_i = m_\mu$$

μ→eee

Limit achievable vs cut on mμ - E_{TOT}



R. Djilkibaev, R. Konoplich, PRD 79 (2009)

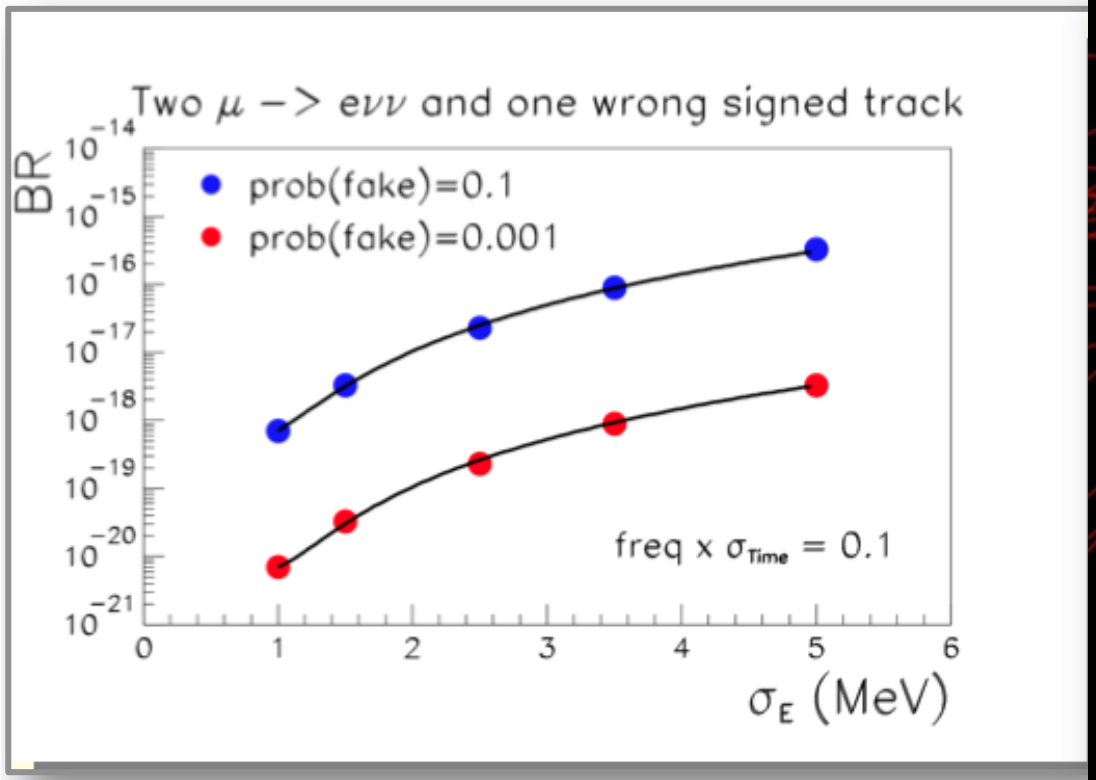
Need resolution on ΣE to 1.5 MeV to reach 10^{-16}

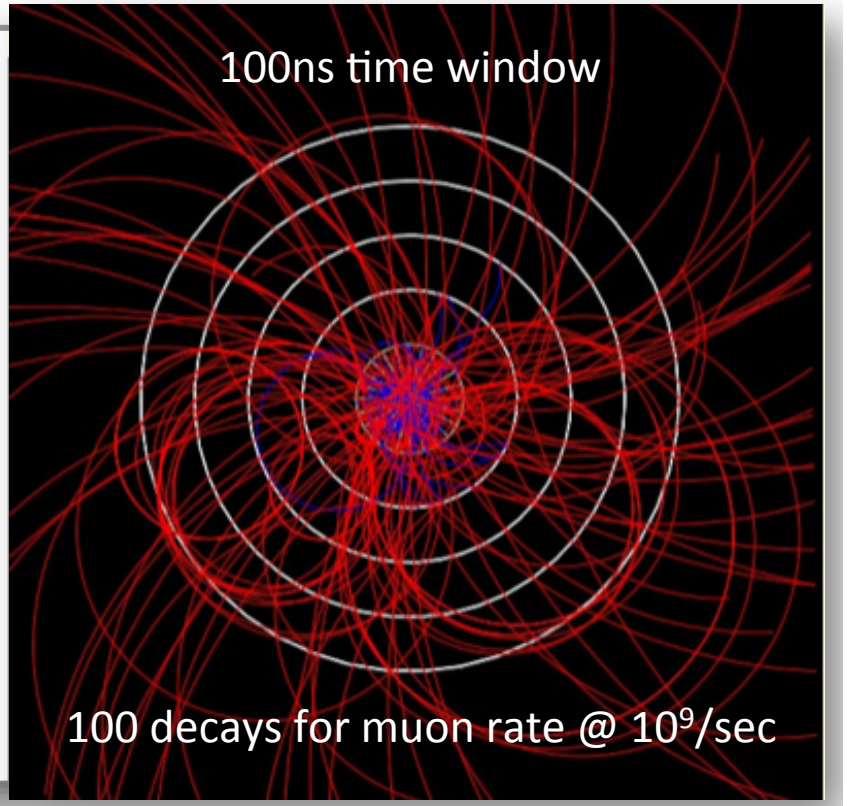
And for this to be achieved in high rate environment

μ→eee : Accidental Background

Accidental background depends on tracking resolution at high muon rates.
Seems tracking OK down to 10^{-17} even at 10^{10} muon stops.

Limiting factor is the irreducible radiative background





Future μ→eee experiments

Two proposals to go beyond current 10^{-12} limit

- MUSIC @ Osaka : 10^{-15} from $3x10^{8}$ μ/s at 400W (E_P = 392 MeV)
  - budget request presently being considered

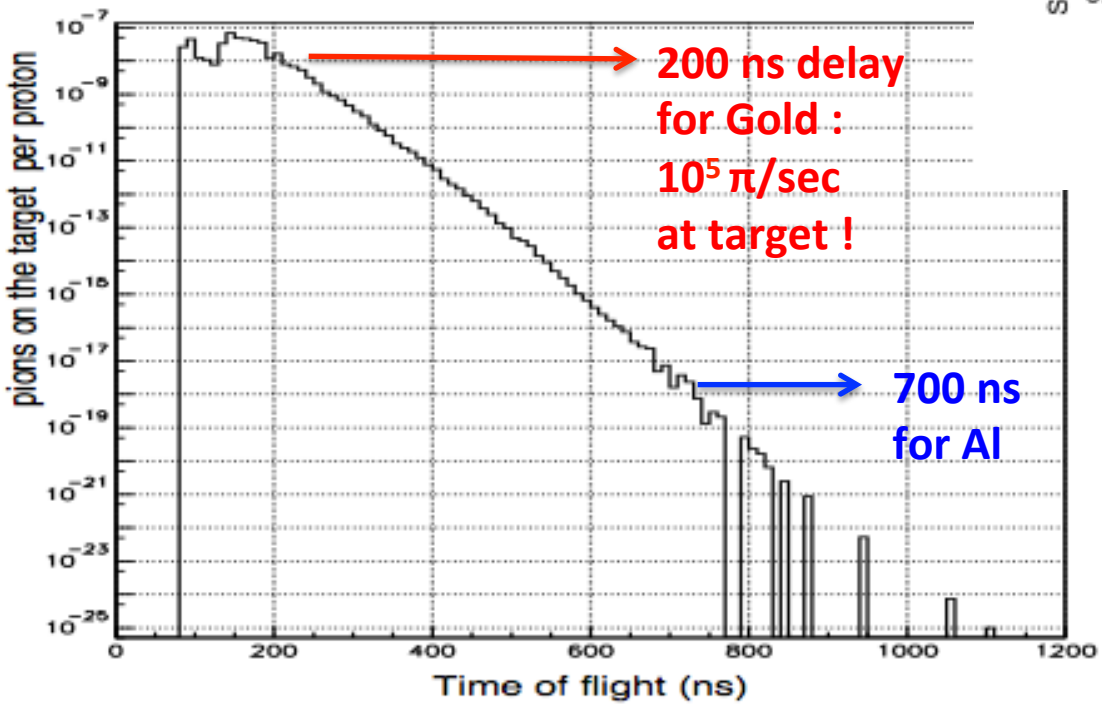
- mu3e @ PSI : < 10^{-16} from > 10^{9} μ/s at 1.4 MW (E_P = 530 MeV)
  - LOI to be submitted early 2012

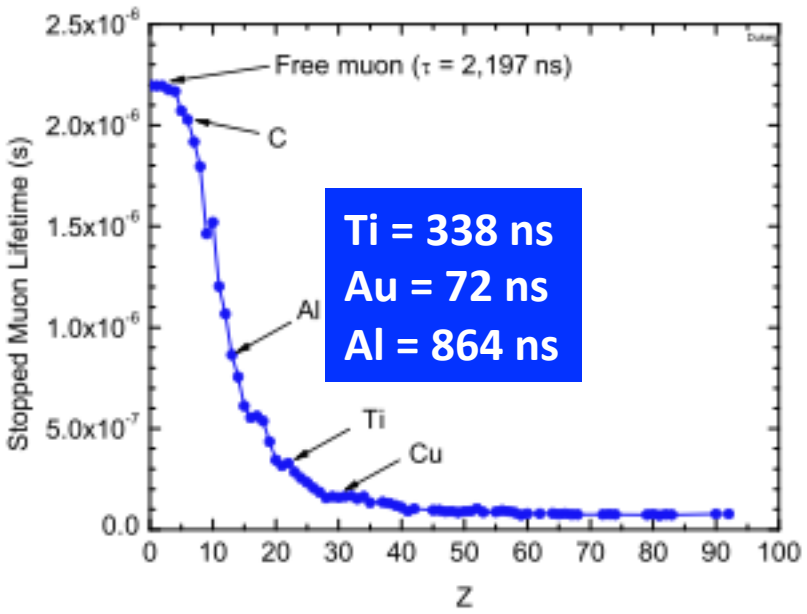
Beyond COMET/Mu2E : High Z Run

Which High-Z

Gold has best discrimination against BSM models but short τ is problematic

- Prompt beam-flash : O(100 ns)
- Delay O(200 ns) still has huge RPC bgrd.





Need facility that can provide beams pulses with configurable time gap and small Δt.

Ti is best bet for higher-Z study

Beyond COMET/Mu2E : O(10^{-18})

Need facility providing O(100) more muons ie ~ O(10^{20}/yr [10^{13}/s]) compared to COMET/Mu2e **AND** significant changes to experiment/beamlines to beat down backgrounds.

J-PARC

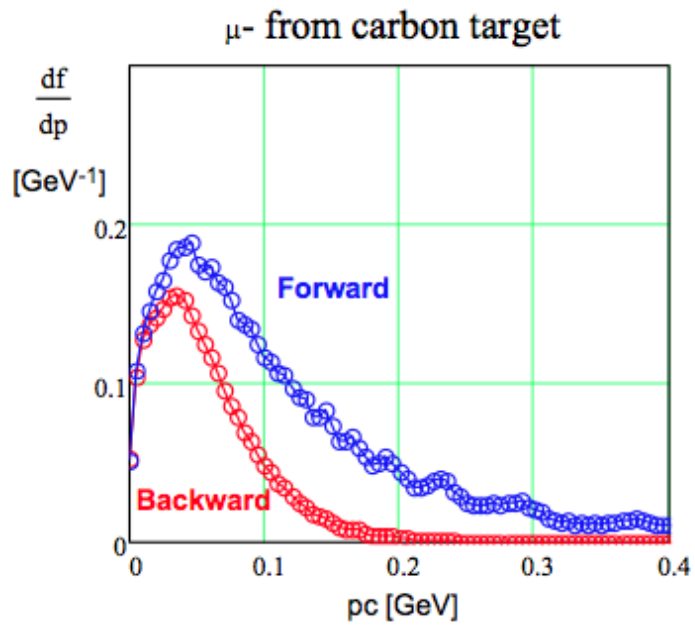
- Will provide 56 kW @ 7.1 GeV (KE) to COMET
- In 2020 MR capable of 300 kW @ 7.1 GeV [1.7 MW @ 3 GeV from RCS]

FNAL (Project-X)

- In 2022 : 2.9 MW @ 3 GeV or 190 kW @ 8 GeV
- Variable beam time-structure within few μs period

Initial PX studies

Muon yield depends linearly on Ep
Run (CW pulses) at 3 GeV (no pbars)
Cylindrical rotating graphite target (1 MW)
Yield into transport solenoid ~ 0.003 μ/p @ 3 GeV



Beyond COMET/Mu2E : $O(10^{-18})$

Two key requirements of next-generation-facilities in addition to muon yield are:

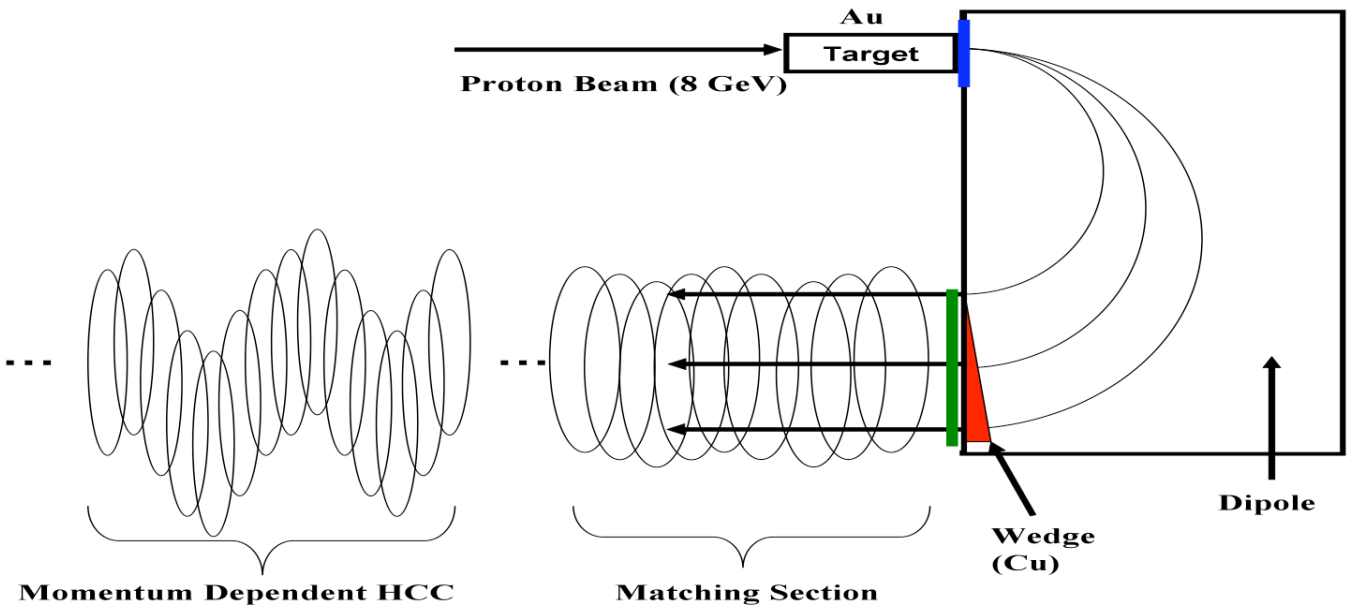
- production of μ with low KE (ie p < 20 MeV) & beam to have a small momentum and time spread.

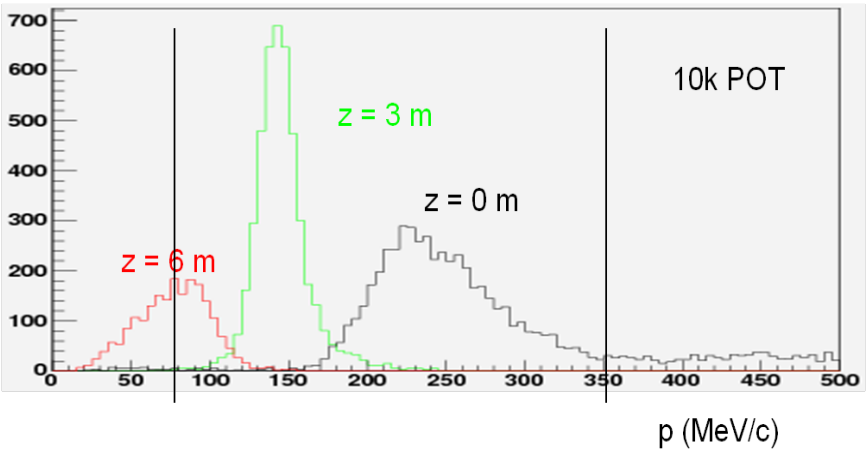
This maximises stopping, ensures stopping is localised such that a single stopping foil could be used which reduces dE/dx of signal-electrons considerably.

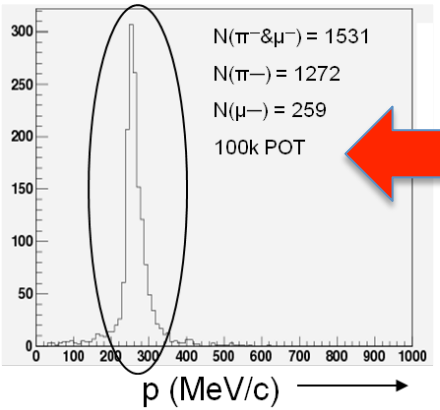
- a large extinction of pions of $O(10^{-14})$ e.g. by having 90m of decay beamline.

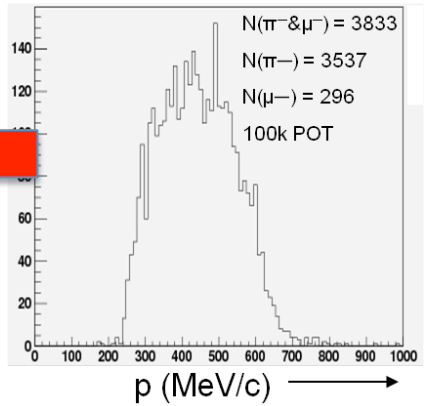
Ideas to achieving this include "beam cooling" / FFAGs but difficult to balance yield with low-p requirement.

PX – Dipole + Wedge









Summary

The future is extremely bright for muon LFV. Limits will be pushed down by 10^{-6} in next 5-15 years.

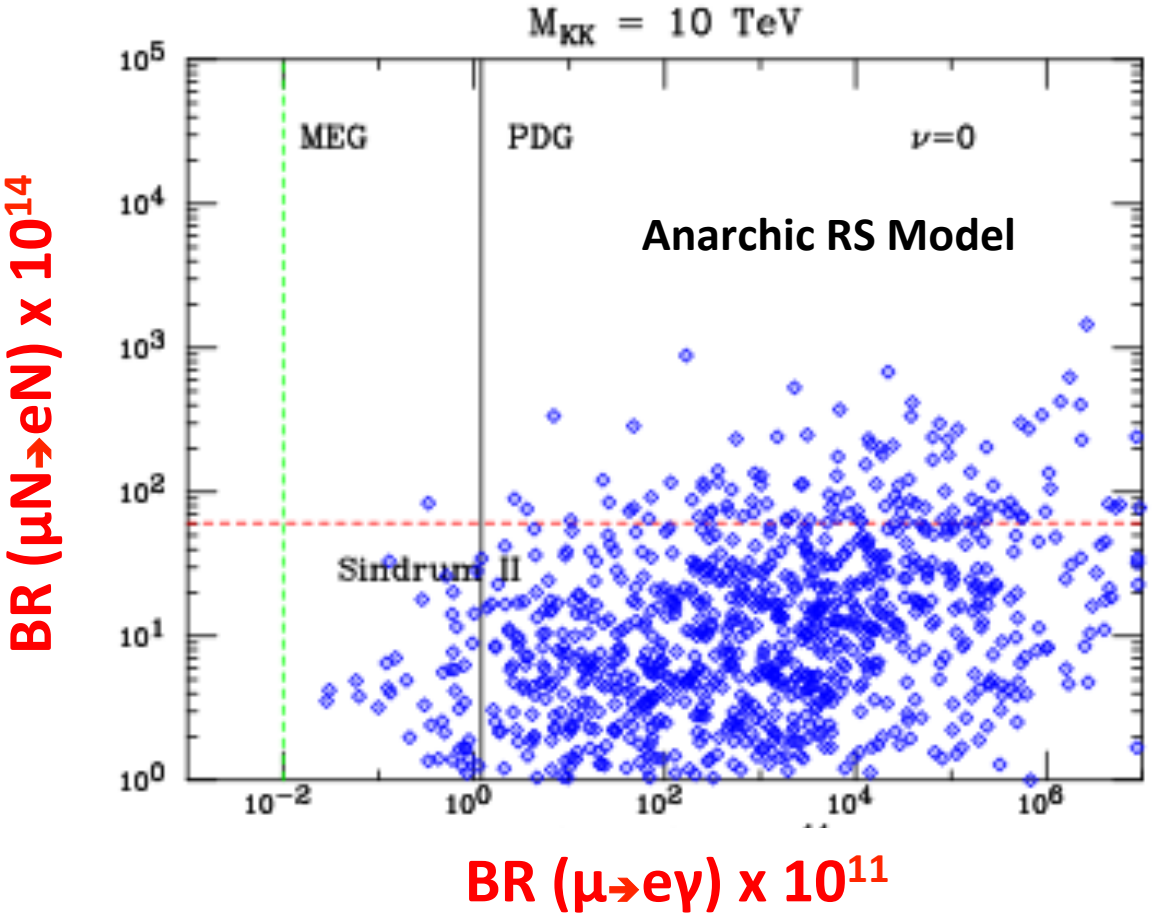
It offers a complementary sensitivity to BSM physics to the LHC and a reach to some phenomena beyond the LHC particularly those pertaining to leptogenesis.

Measurements are not limited by theory but technical innovation.

As an experimentalist this is a wonderful place to be and in which the next generation can receive hands-on and analysis skills.

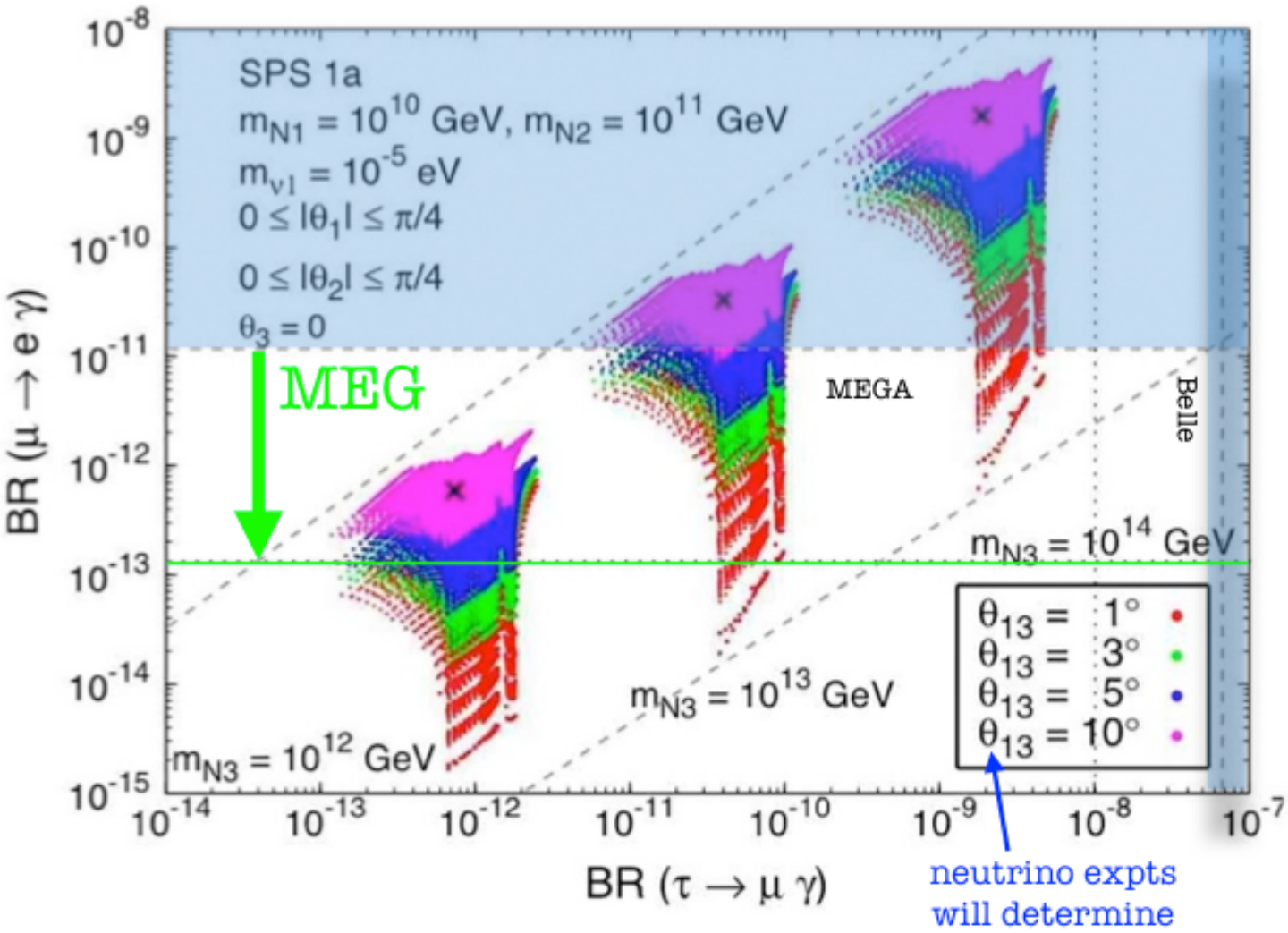
But it needs investment in facilities and accelerator and detector R&D.

Process Ratios are Model Dependent

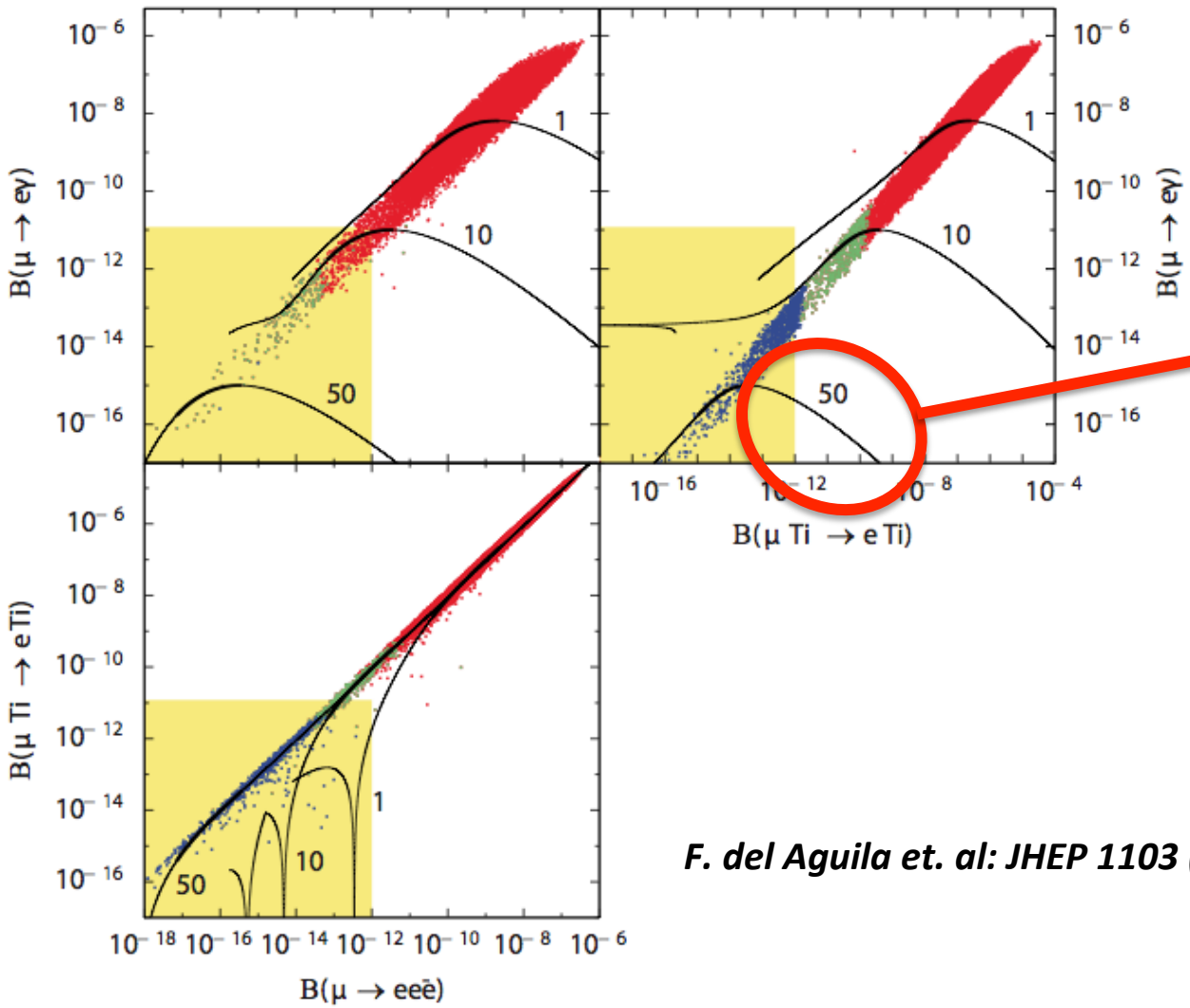


Agashe et al, Phys.Rev.D74:053011,2006

cLFV in (massive ν) SUSY Seesaw



Little Higgs Model

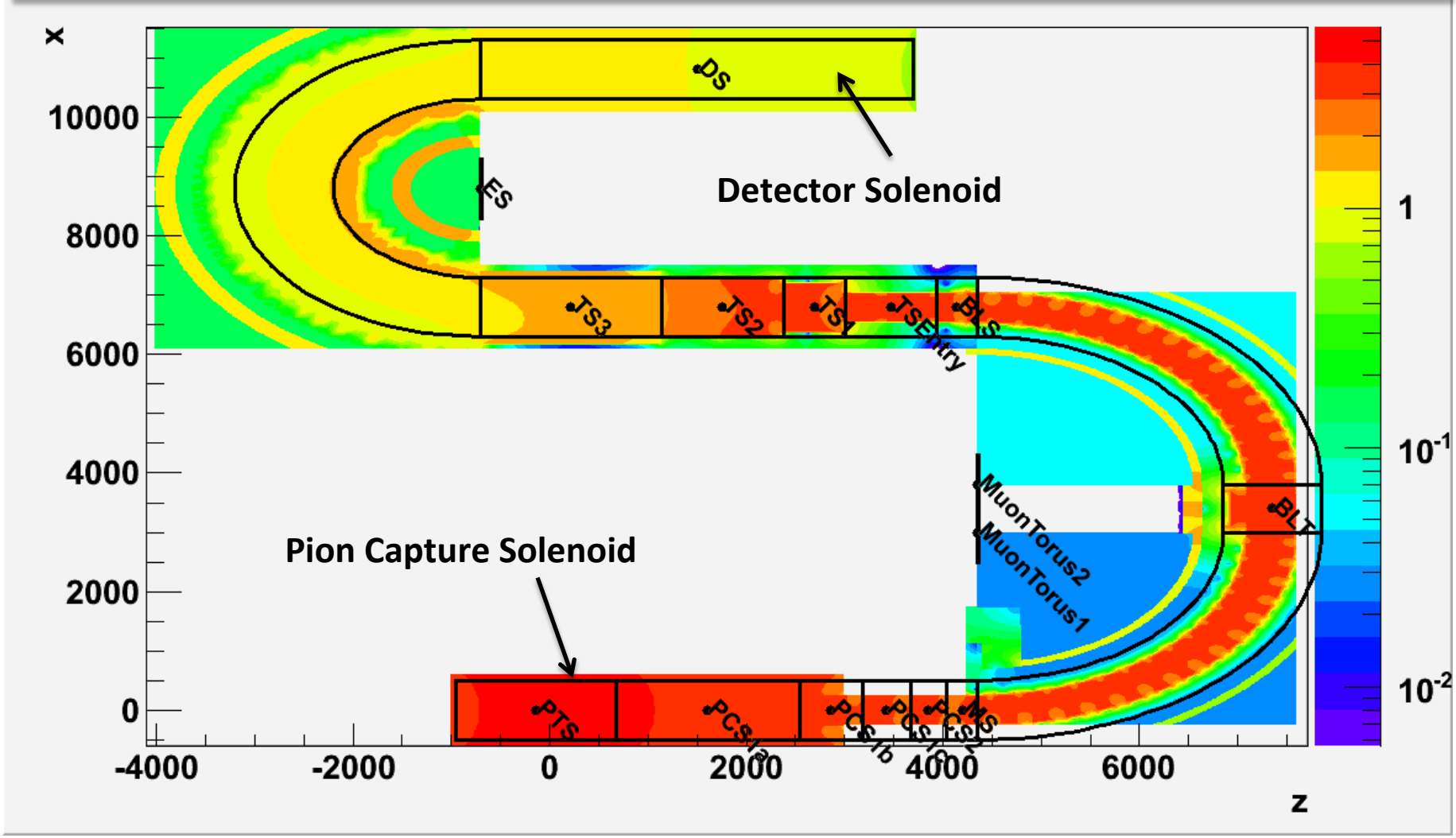


50 TeV scale

F. del Aguila et. al: JHEP 1103 (2011)

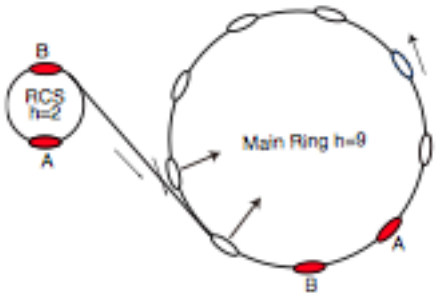
Graded Fields

Magnetic Fields in COMET (in Tesla)

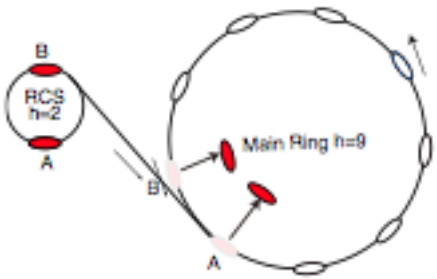


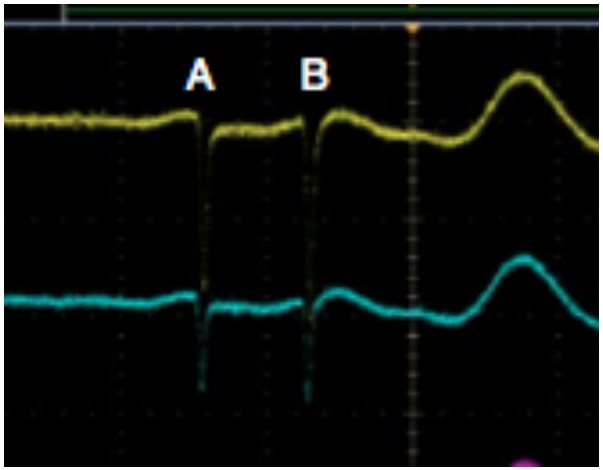
COMET Extinction

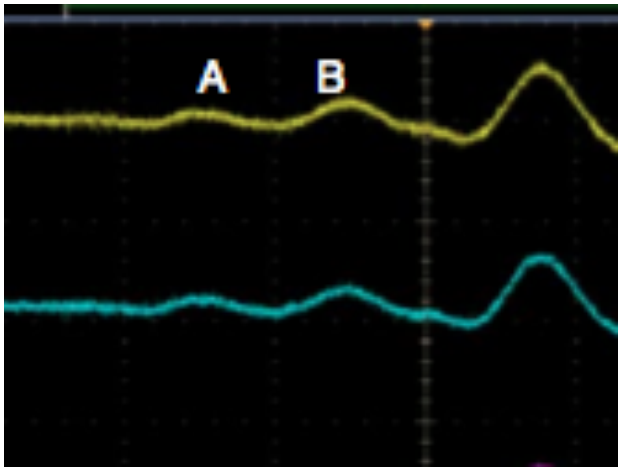
"Double Kicking" injection into the MR



1st measurements show O(10^{-6}) additional extinction can be achieved







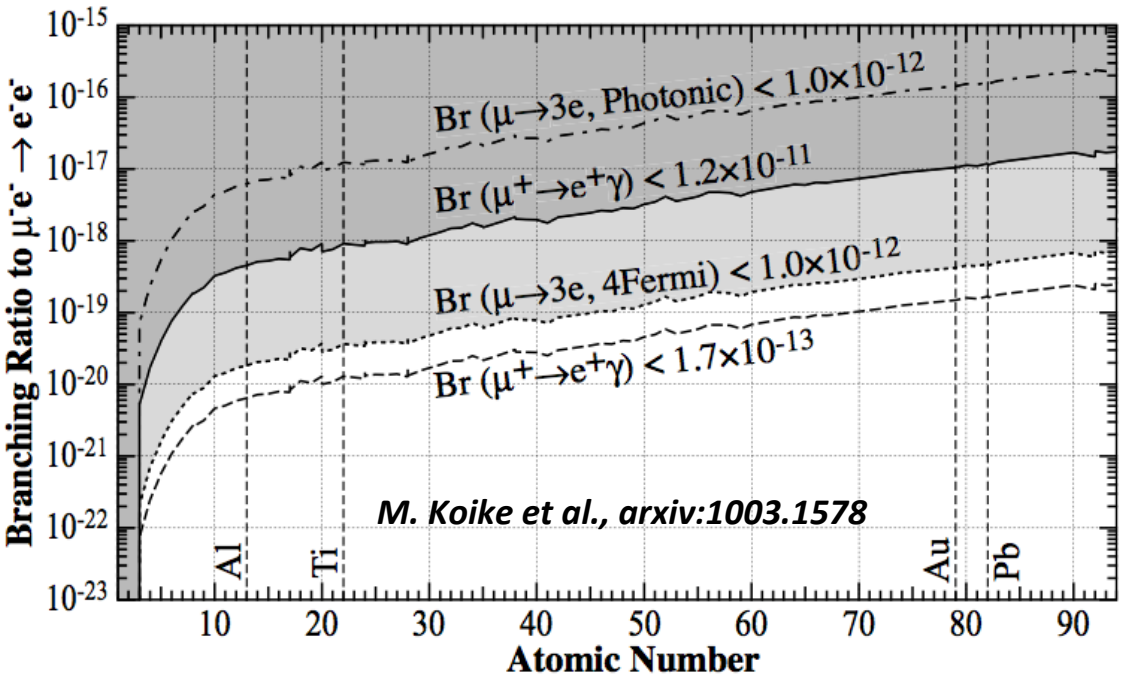
cLFV in Muonic Atoms

In high-Z muonic atom : e^- attracted to nucleus and hence μ^-

And cLFV decay:

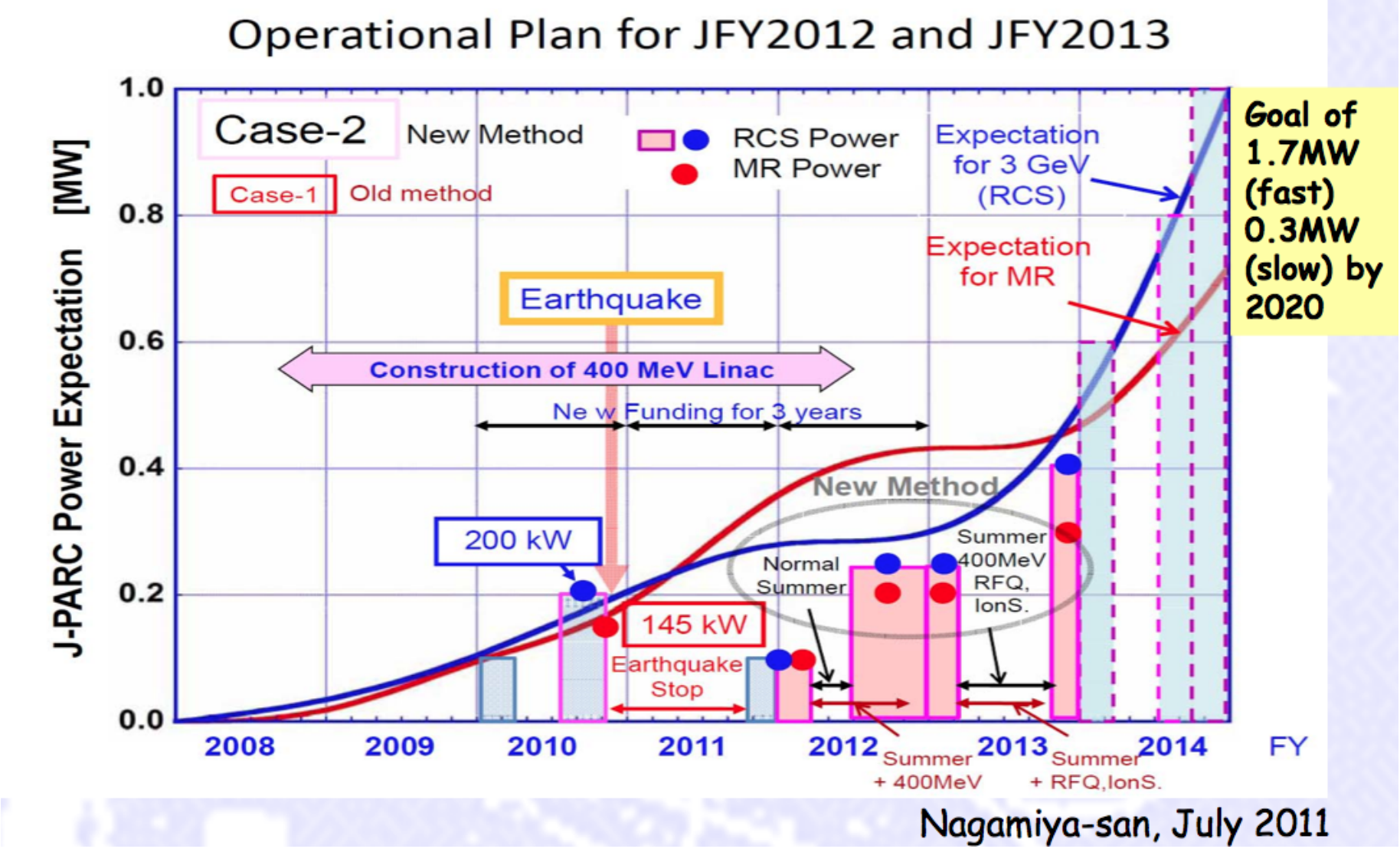
$$\mu^- e^- \rightarrow e^- e^-$$

is $(Z-1)^3$ enhanced (offset somewhat by increased nuclear capture)



MEG/SINDRUM-I limits mean expected BR < 10^{-19}

Requires $O(10^{20})$ stopped μ ie 100 x Mu2e/COMET.

Next generation experiment.

J-PARC Timeline