

# COMET Experiment

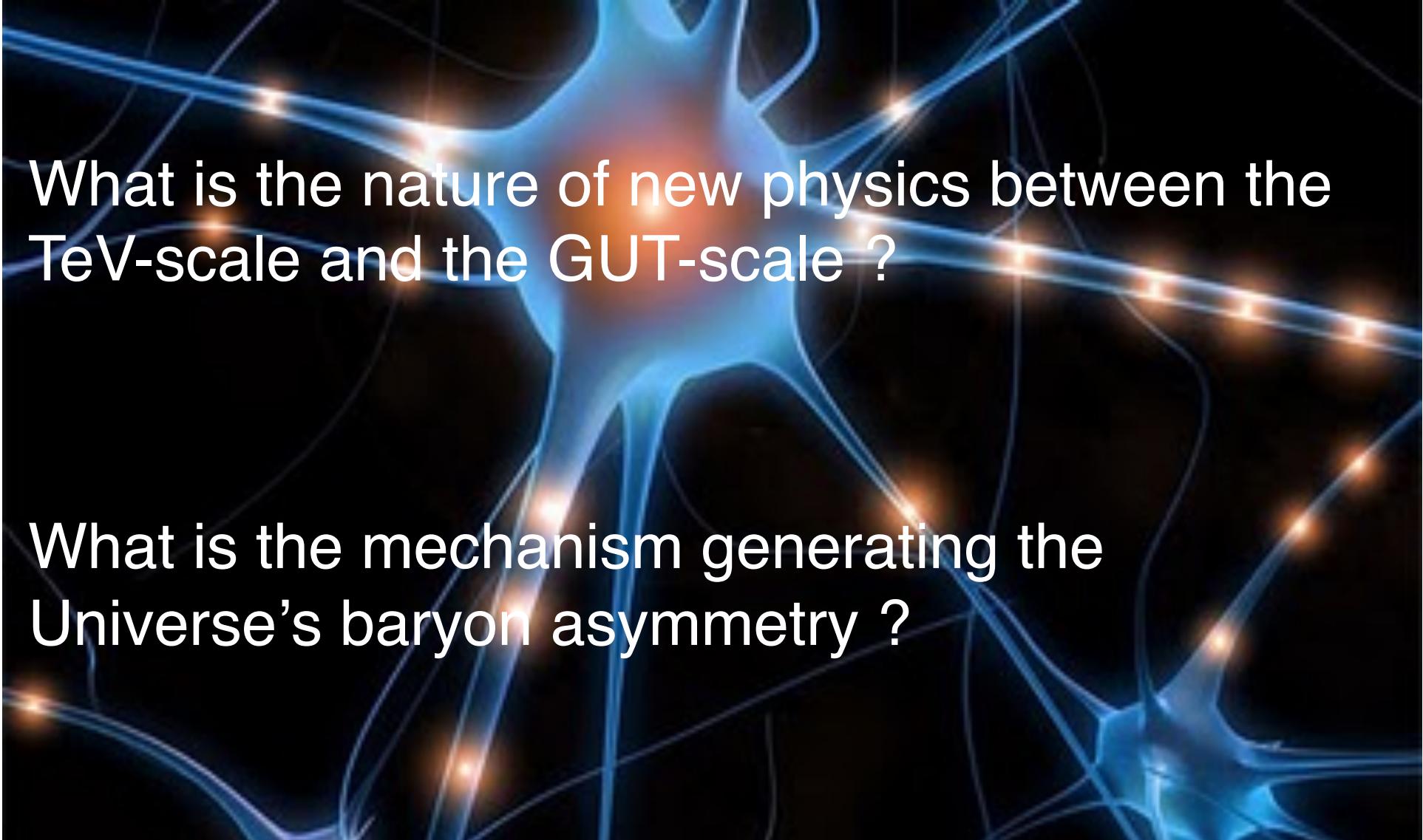
## Muon Conversion @ $10^{-16}$

Mark

JCL

Lancaster

FNAL



What is the nature of new physics between the TeV-scale and the GUT-scale ?

What is the mechanism generating the Universe's baryon asymmetry ?

# Motivation



LHC has much to say on TeV-scale and CP effects in quark sector

**BUT**

We need experiments probing lepton-# violation:

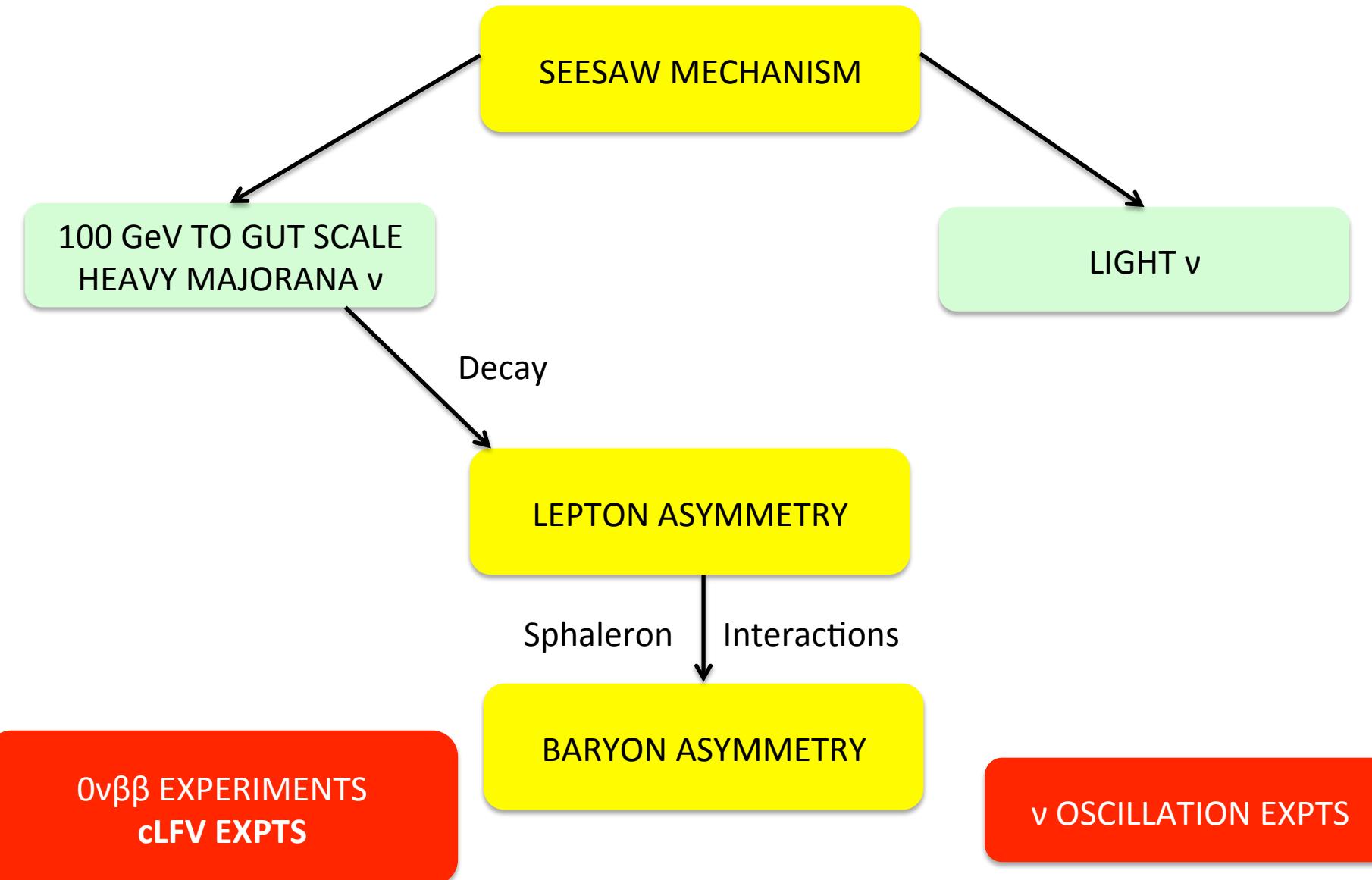
- neutrino oscillation experiments
- neutrinoless double beta decay
- charged lepton flavour violation (cLFV)**

to further our understanding at & beyond the TeV-scale



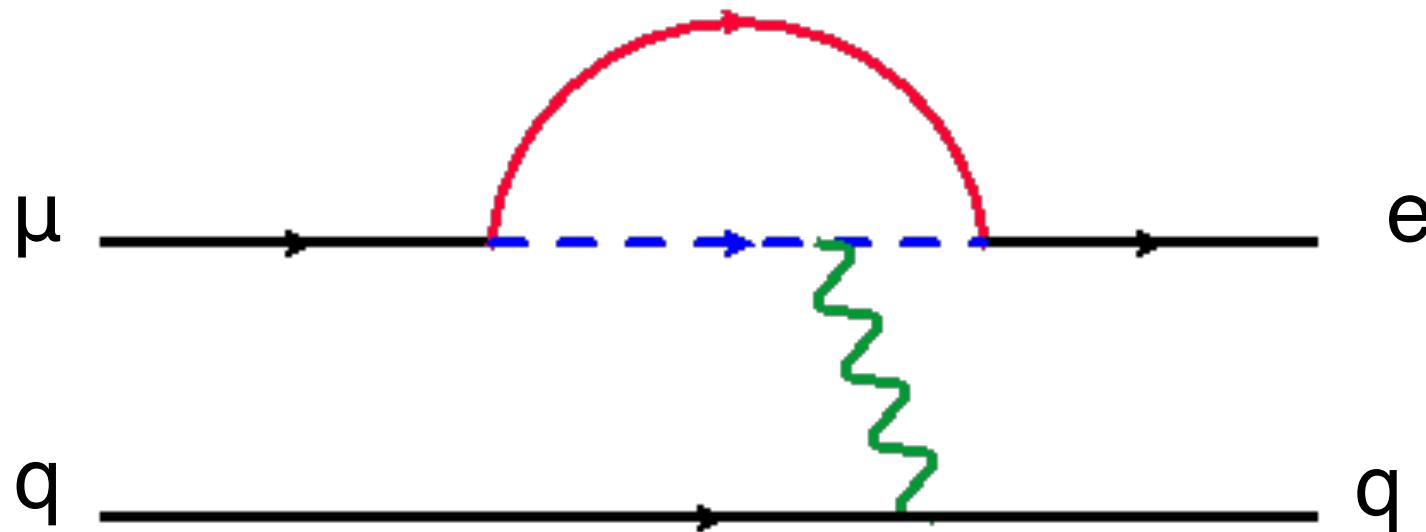
We need **all THREE** types of experiment.

# Motivation





cLFV typically occurs through loop diagrams



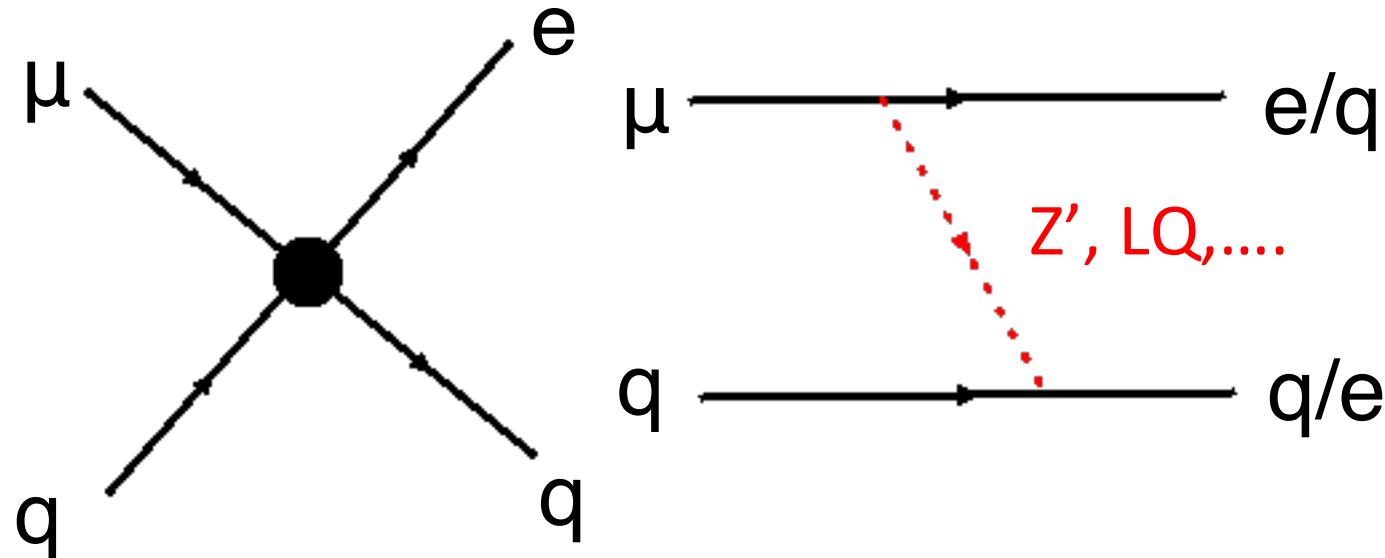
In SM : W loop and oscillating neutrinos : rate is  $O(10^{-50})$

BSM : loop : SUSY particles, heavy neutrinos,...: rate is  $O(10^{-10-20})$



# BSM Physics

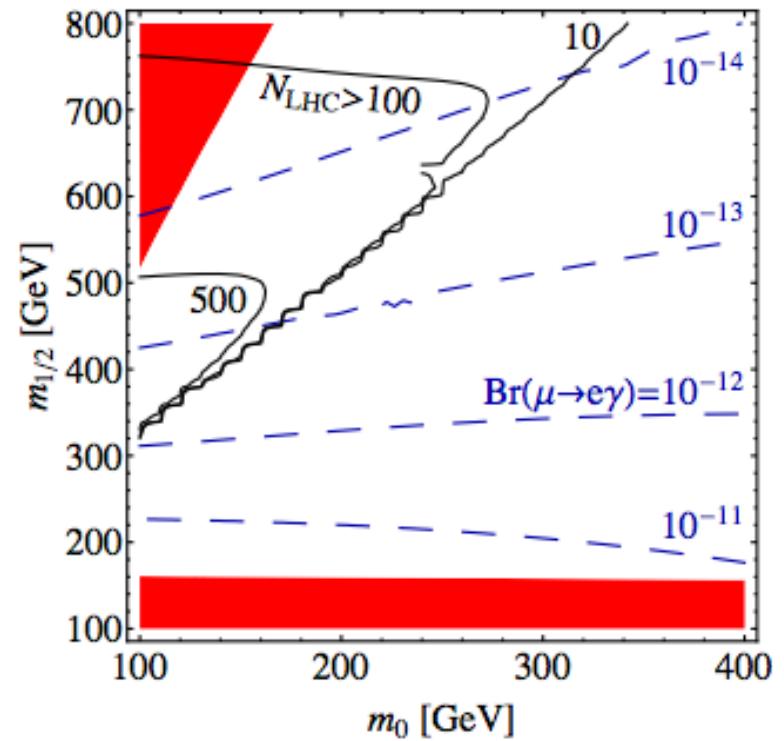
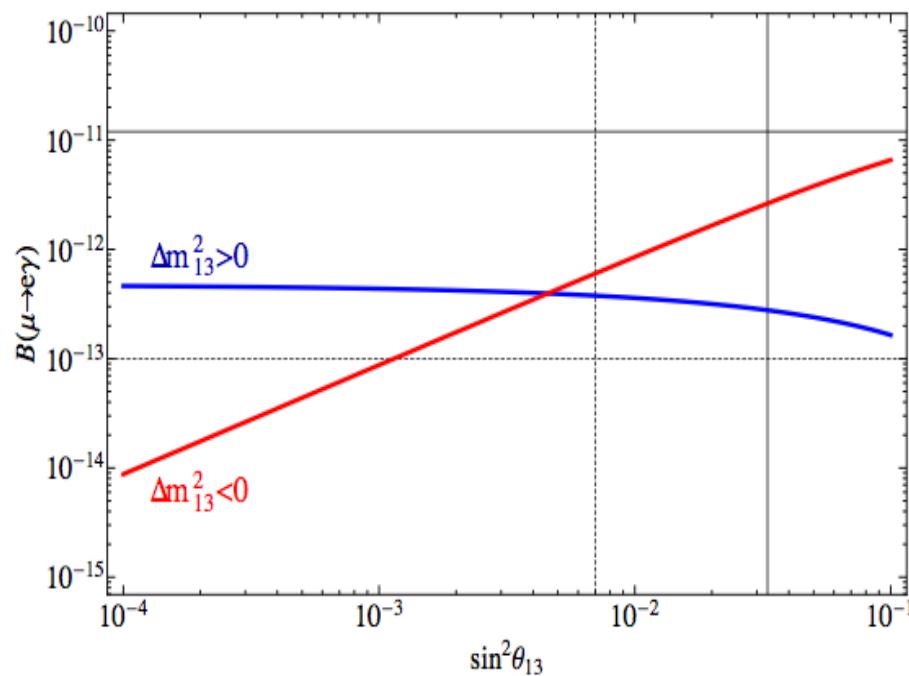
But also e.g. through contact interactions,  $Z'$ , LQ



With sensitivities to scales of  $O(3000 \text{ TeV})$

# Resolving Model Degeneracy

cLFV experiments provide complementary information.



The phenomenology of the universe's matter/anti-matter asymmetry will likely not be understood without neutrino AND CLFV measurements.

# Flavor Physics Observables

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

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

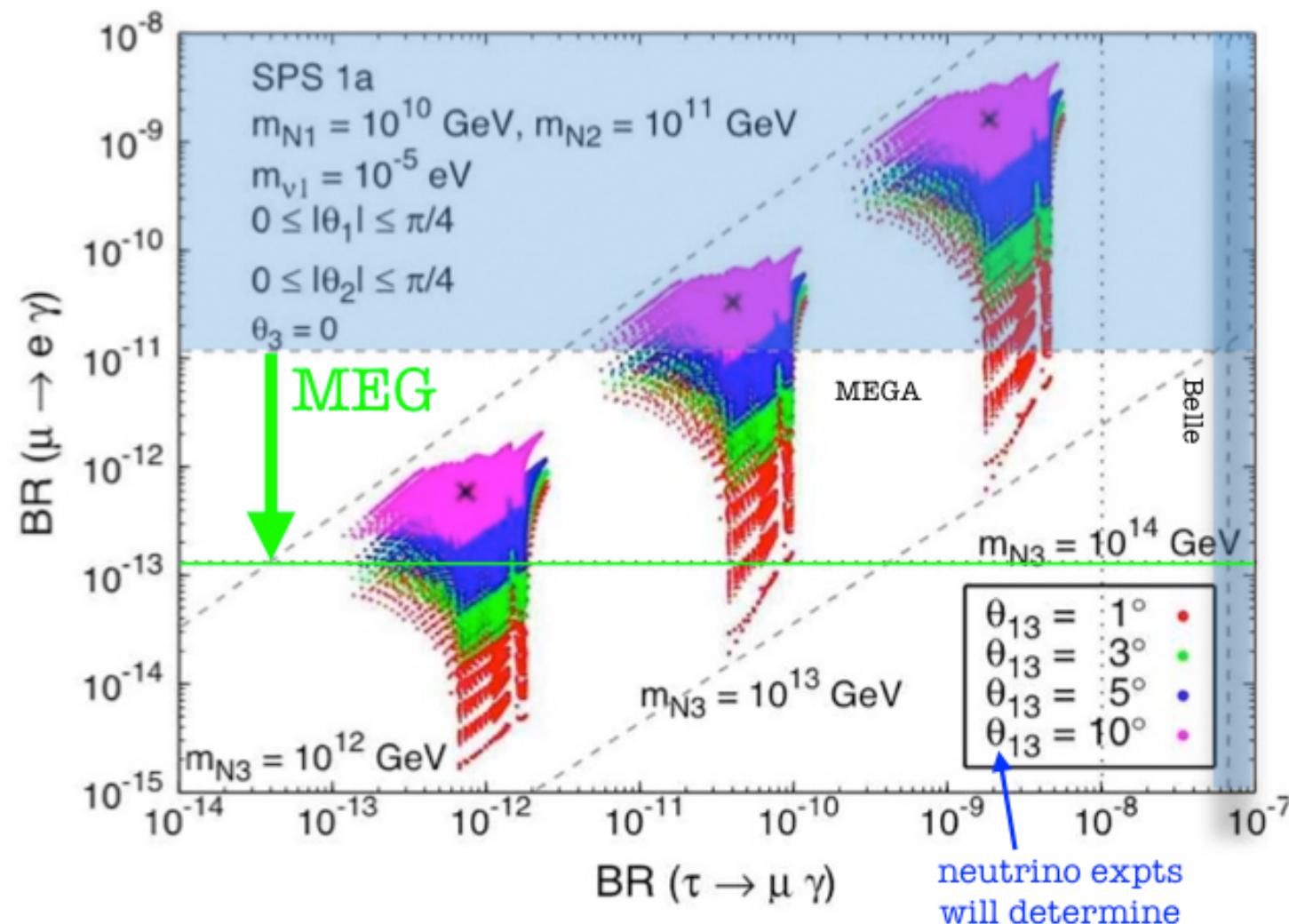


Different SUSY  
and non-SUSY  
BSM models.

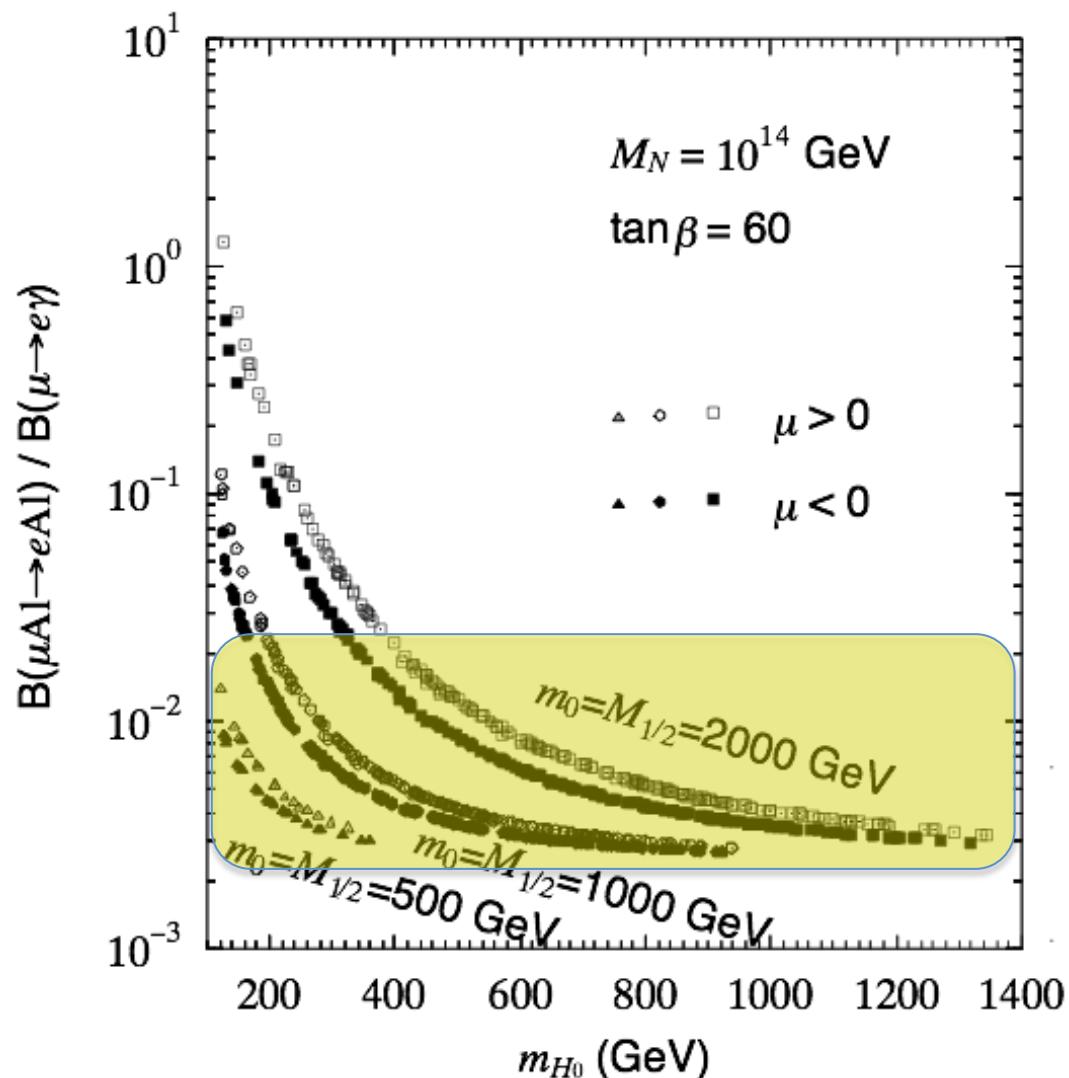
cLFV sensitive to widest  
variety of BSM models

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

# cLFV in (massive $\nu$ ) SUSY Seesaw

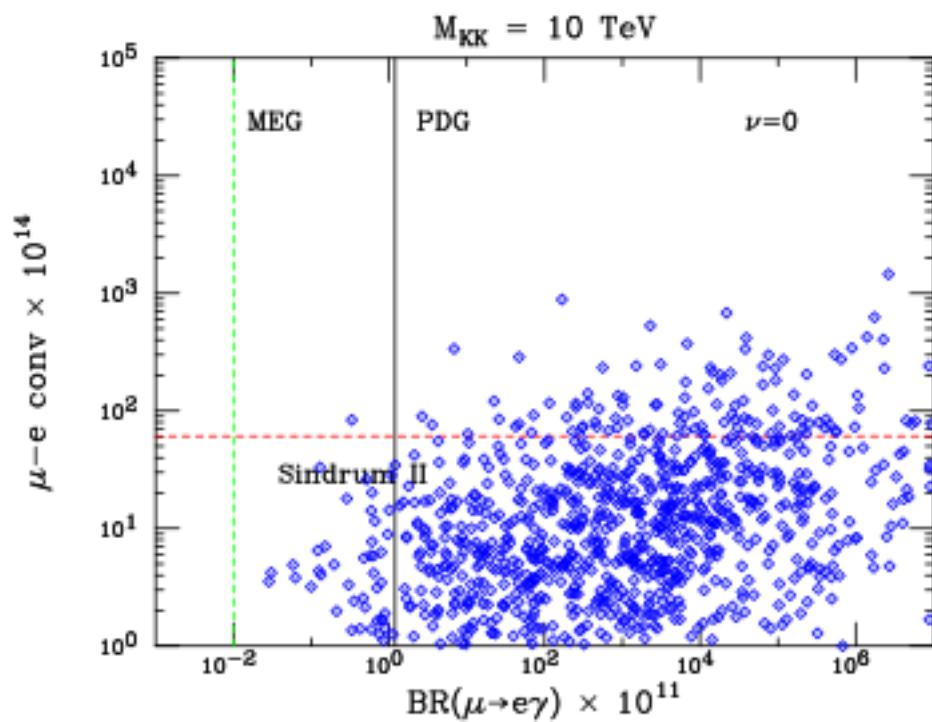
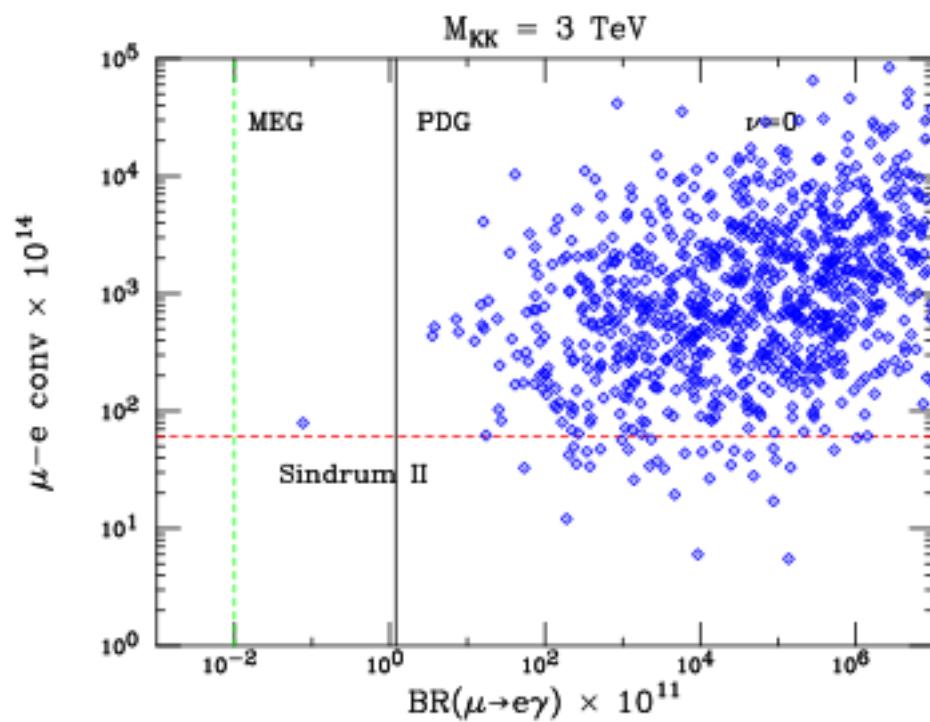


# $\mu N \rightarrow eN$ vs $\mu \rightarrow e\gamma$



O( $10^{-13-15}$ ) in  $\mu N \rightarrow eN$   
required to have similar  
sensitivity as ultimate  
MEG limit of  $10^{-13}$  in  $e\gamma$  for  
typical BSM loops.

# Predictions from Extra Dimensions Model



# cLFV Processes

Many possible cLFV processes and a wide variety of measurements are required to elucidate the BSM physics since rates are process dependent. But....

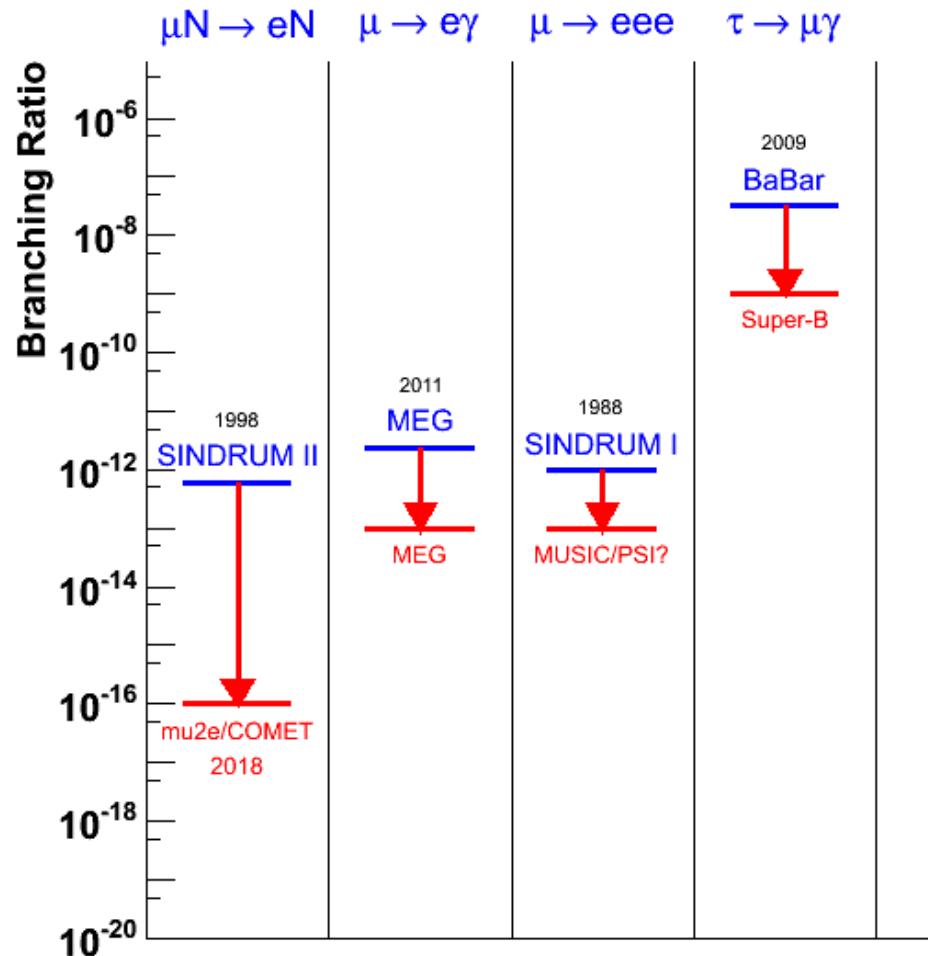
$$\begin{aligned}\mu \rightarrow e\gamma \\ \mu \rightarrow eee\end{aligned}$$

Limited by detector resolutions and accidental coincidences at high  $\mu$  intensity

$$\begin{aligned}\tau \rightarrow e\gamma \\ \tau \rightarrow 3e, 3\mu \\ \tau \rightarrow \mu\gamma \\ \tau \rightarrow 2\mu e \\ \tau \rightarrow 2e \mu\end{aligned}$$

Requires Super-B/KEK-B

# cLFV Processes

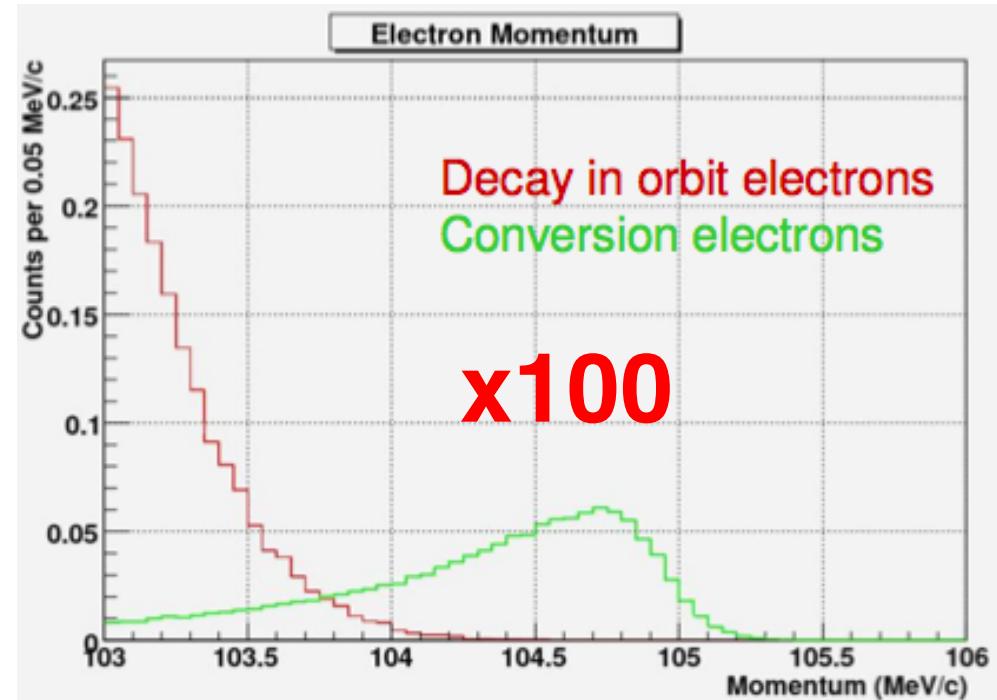
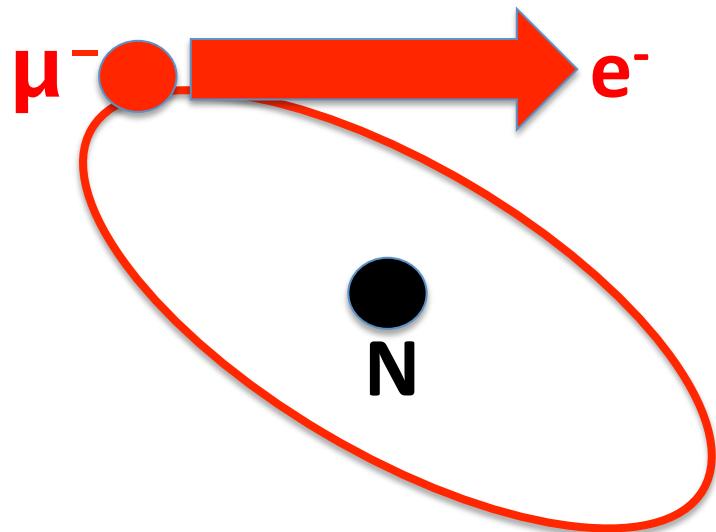


So

$\mu N \rightarrow e N$

Offers best potential in terms  
of BSM reach in near future

# Muon to Electron Conversion



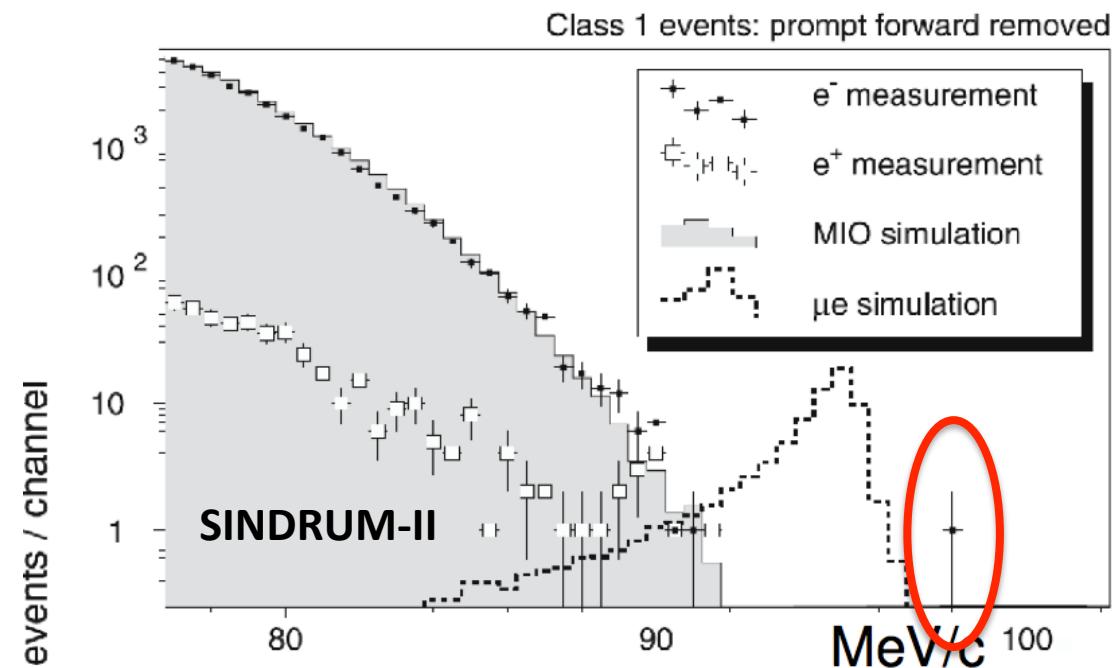
Coherent (all nucleons recoil) neutrinoless transition of  $1s-\mu$  to  $e^-$

$$E_e = m_\mu - E_b - E_{\text{rec}}$$

$$E_b \sim Z^2 \alpha^2 m_\mu / 2, \quad E_{\text{rec}} \sim m_\mu^2 / (2m_N)$$

# Muon to Electron Conversion

Previous best measurement used continuous beam with beam veto counters



Significant backgrounds  
Rate limited

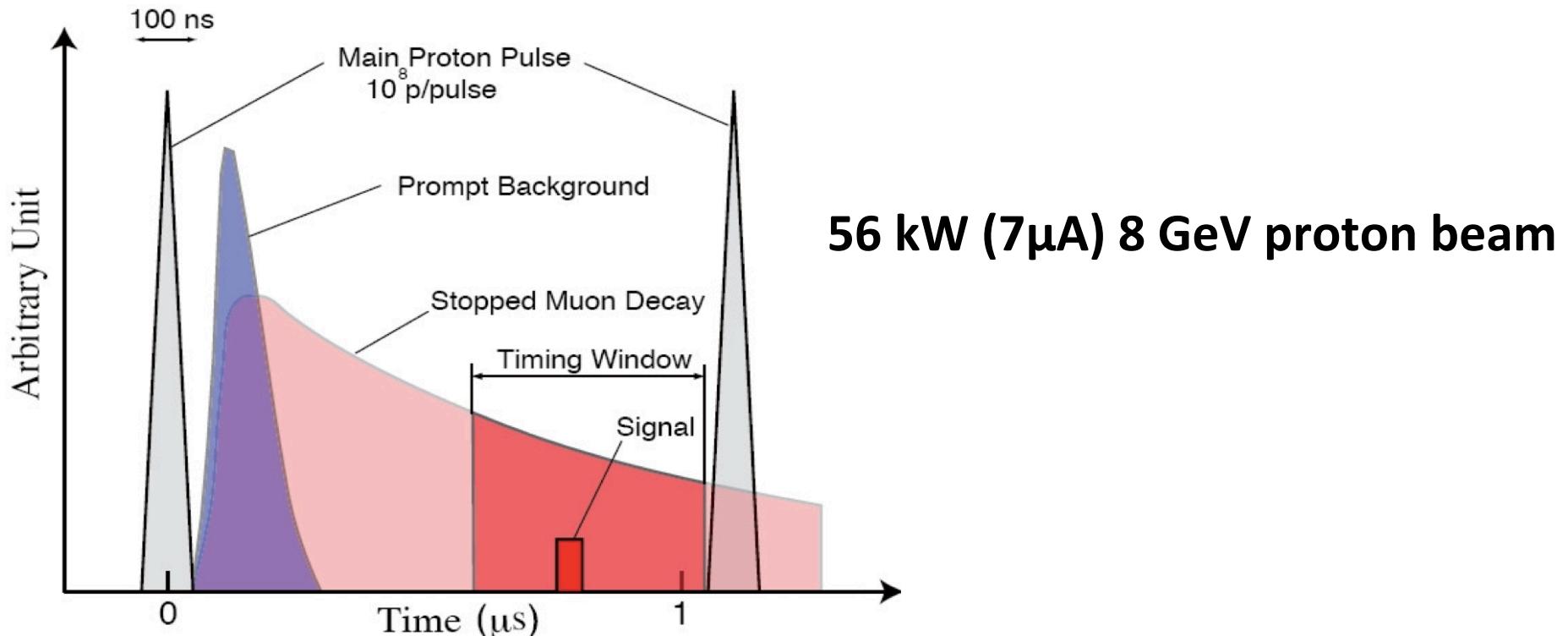
**COMET seeking to improve sensitivity by factor of 10,000**

# How to get $\times 10^4$ improvement

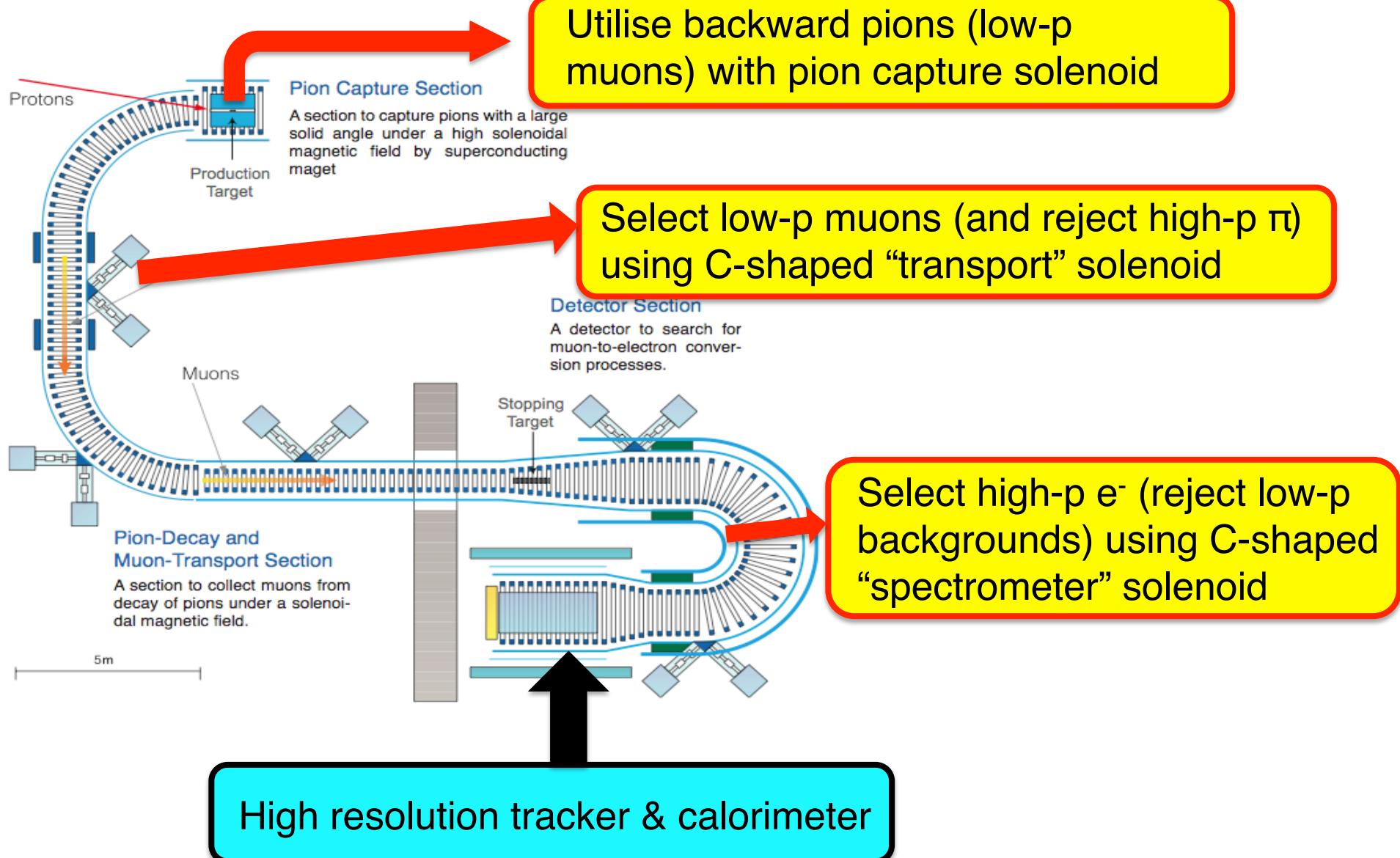
**1. Pulsed Beam** – veto prompt backgrounds via timing cut

## 2. Momentum

**& charge selection** – higher S/B using curved solenoids

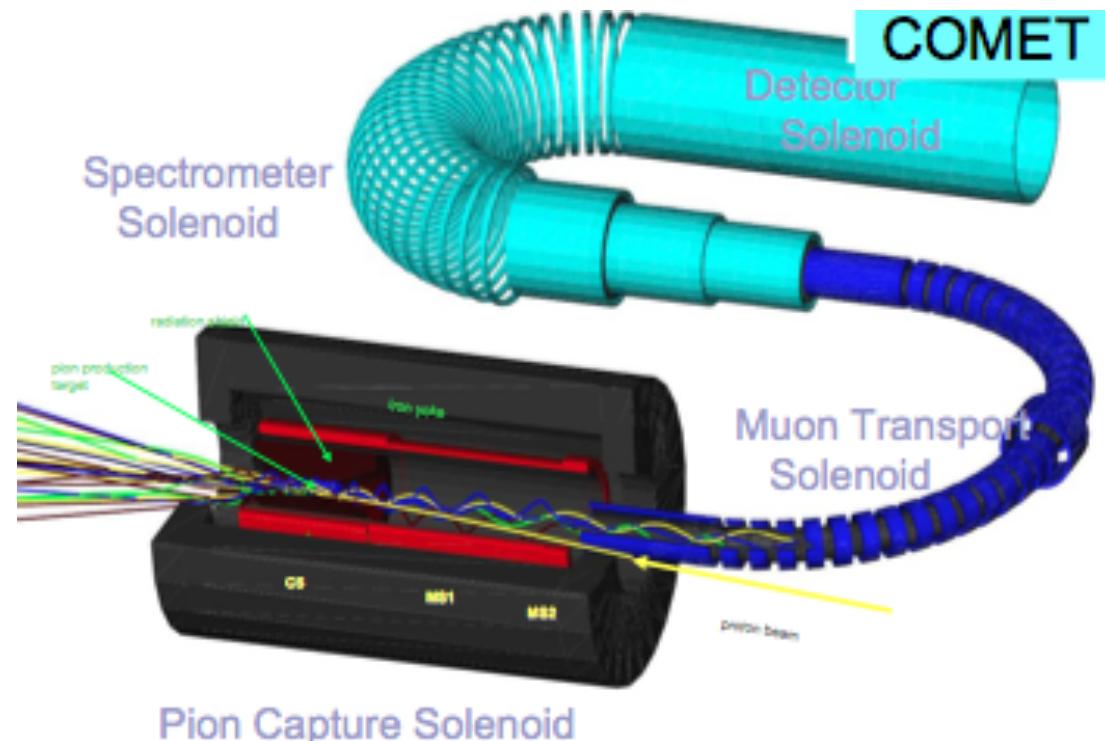


# How to get $\times 10^4$ improvement

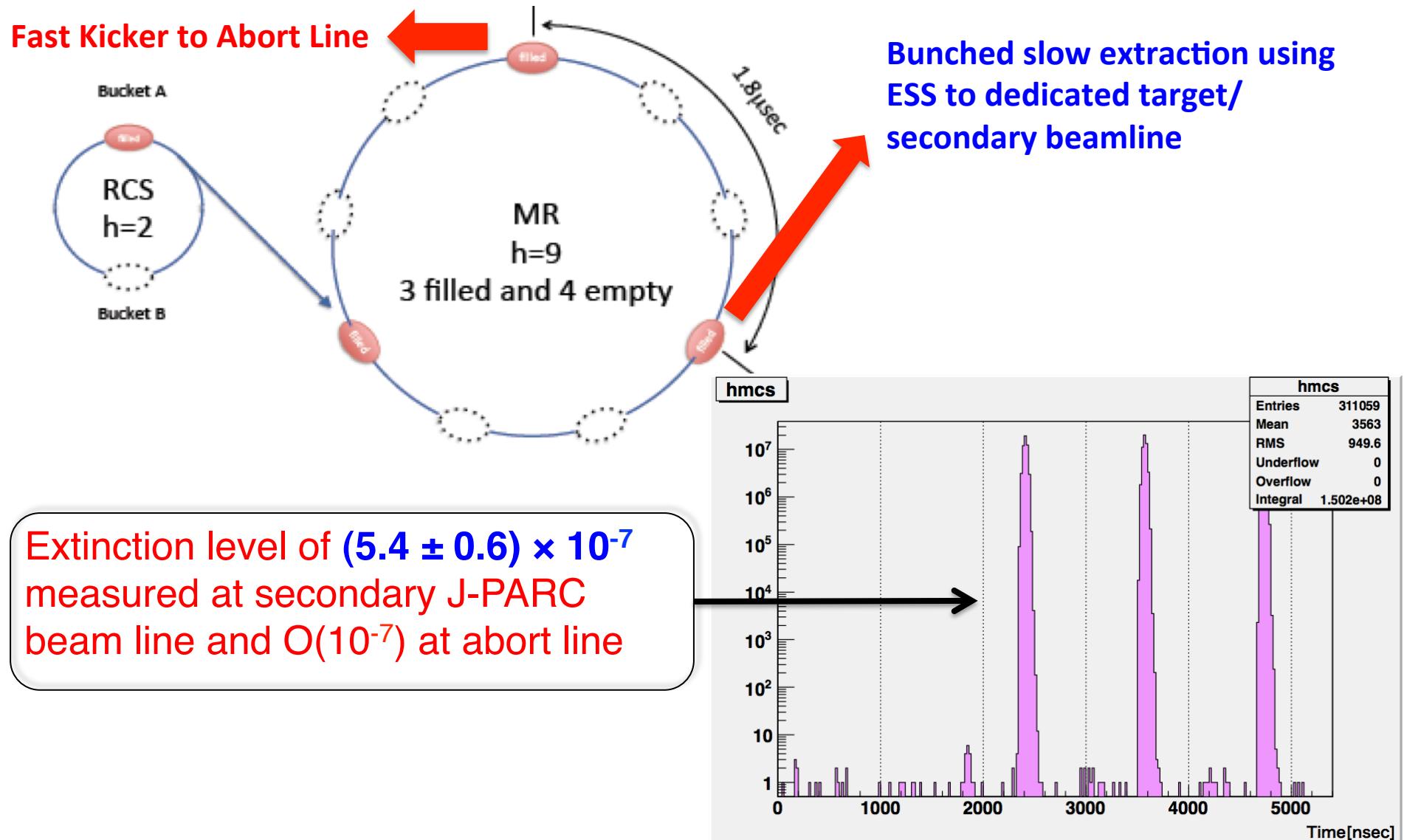


# Key Performance Drivers

1. “**Extinction**” of stray protons between bunches to at least  $10^{-9}$
2. Heat-load/radiation robustness of high-B superconducting solenoids : particularly pion capture solenoid.

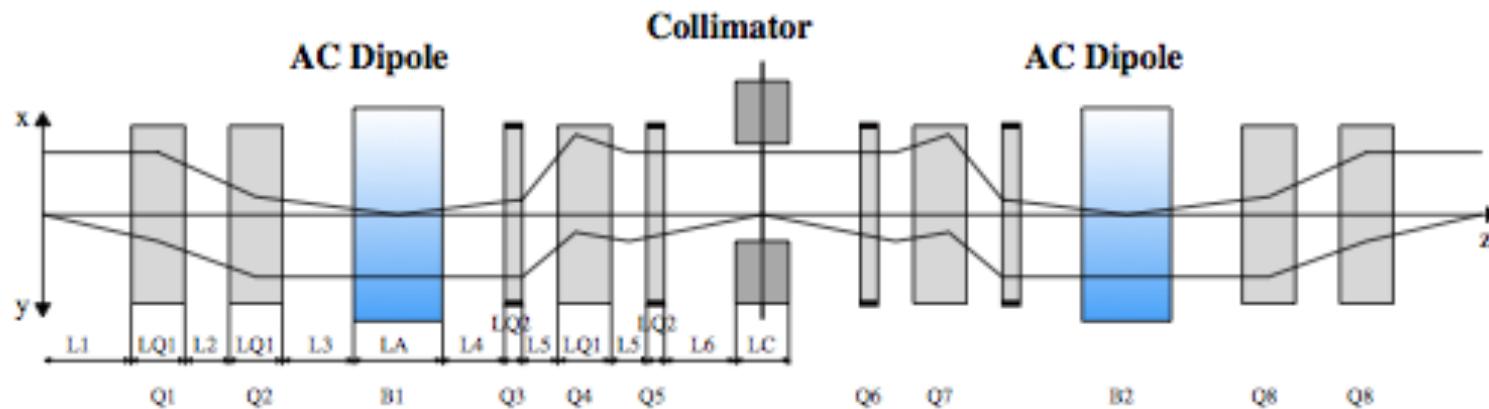


# Proton Beam Extinction Studies



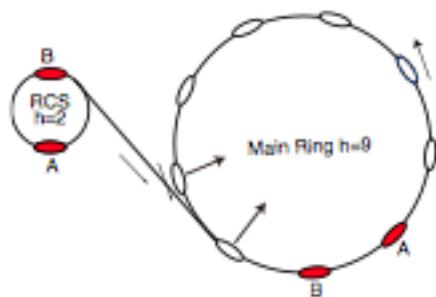
# Getting to extinction beyond $10^{-9}$

1. Improve the beam chopping in LINAC before RCS injection
2. External extinction (AC-dipole) devices before proton target
  - MC (G4BI) studies show  $O(10^{-3})$  added extinction

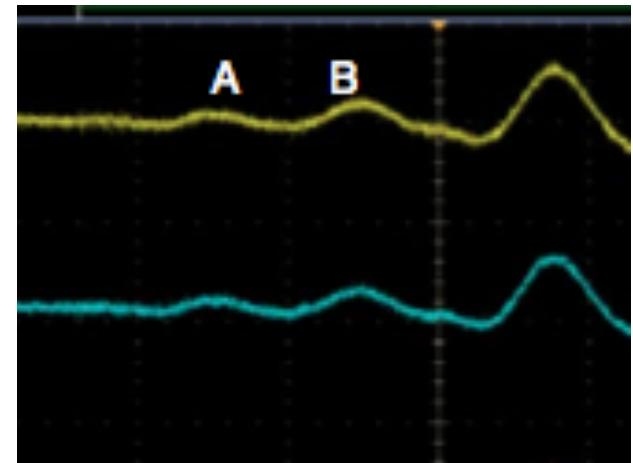
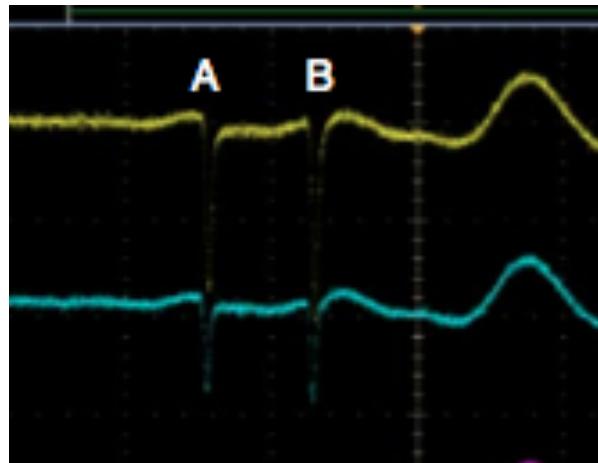


# Getting to extinction beyond $10^{-9}$

## 3. “Double Kicking” injection into the MR

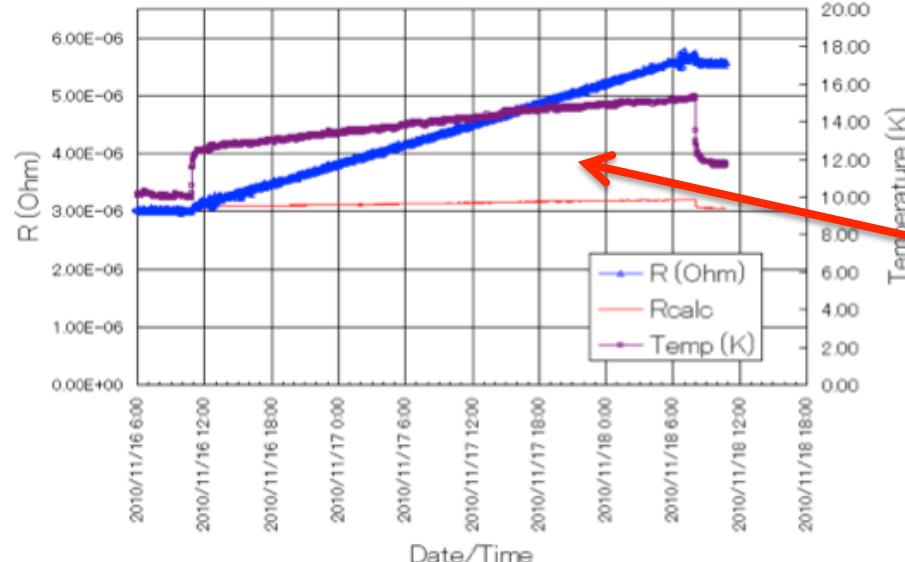


1st measurements  
show  $O(10^{-6})$   
additional extinction  
can be achieved



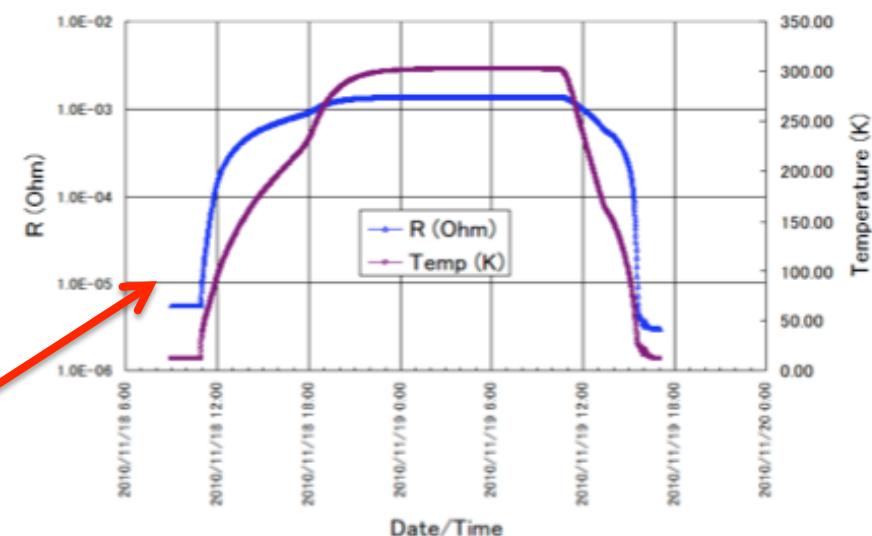
# Superconducting solenoid R&D

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



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

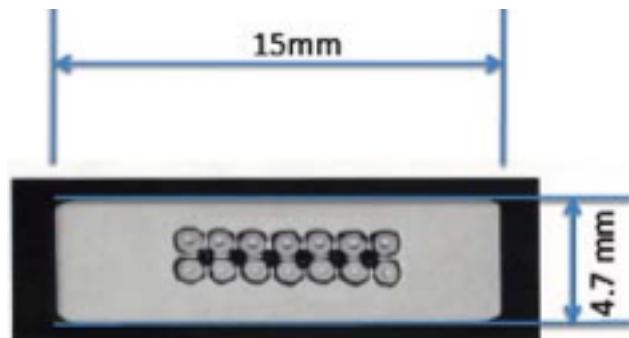
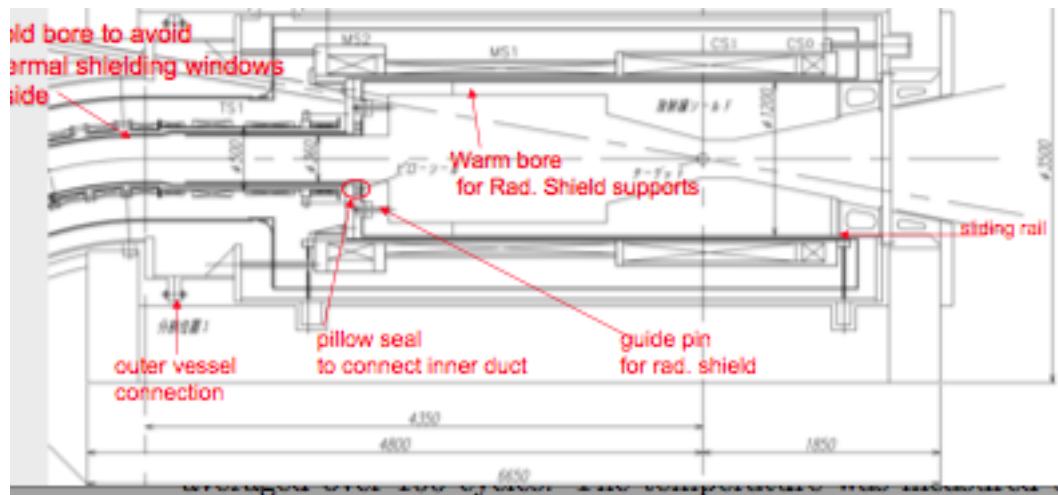
Resistance increased by  $\sim 2.5 \mu\Omega$



½ day thermal cycling returns resistance to pre-radiated value

# Superconducting solenoid R&D

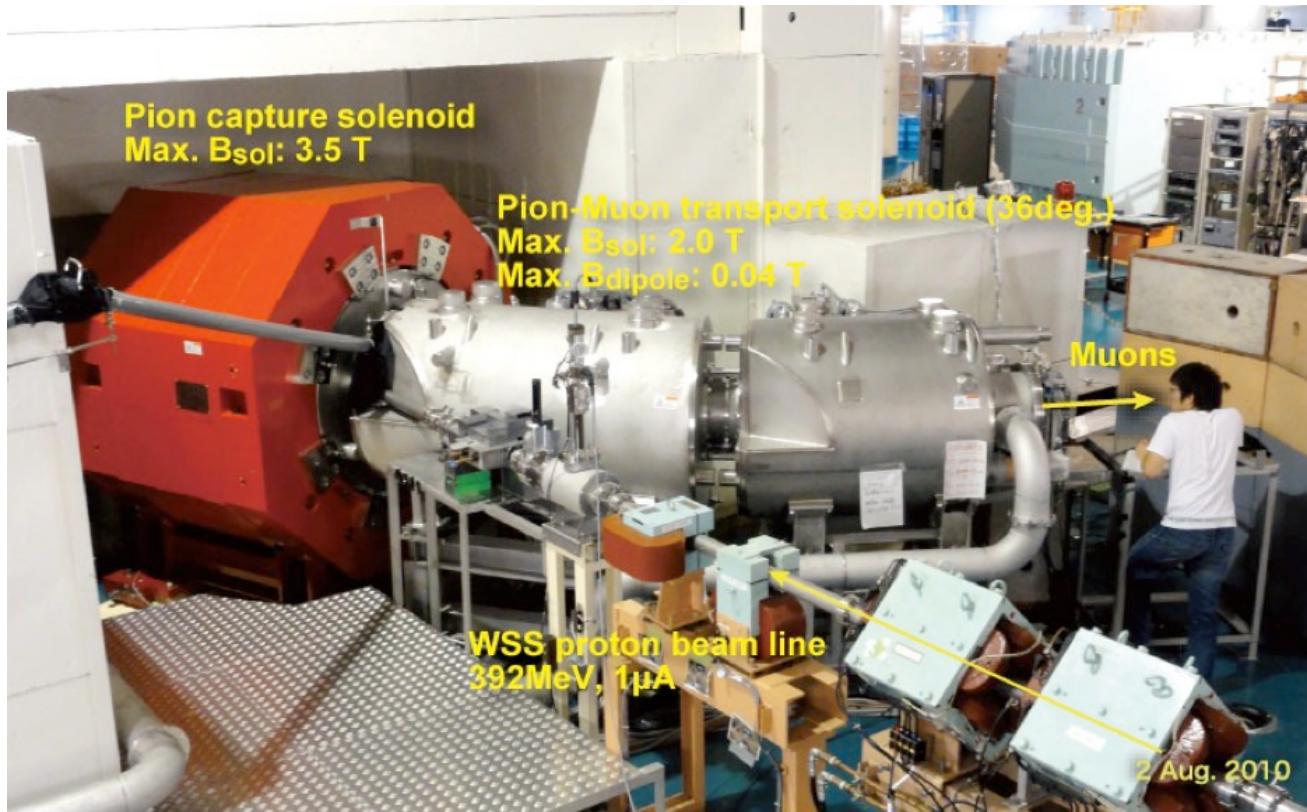
Design work ongoing (in collaboration with FNAL & vendors)



COMET conductor (2009):  
• Size: 4.7x15mm  
• Offset yield point of Al@4K: >85MPa  
• RRR@0T: >450  
• AlCuSC: 7.30.9/1  
• 14 SC strands: 1.15mm dia.

# Pion/Muon Production Prototype : MuSIC

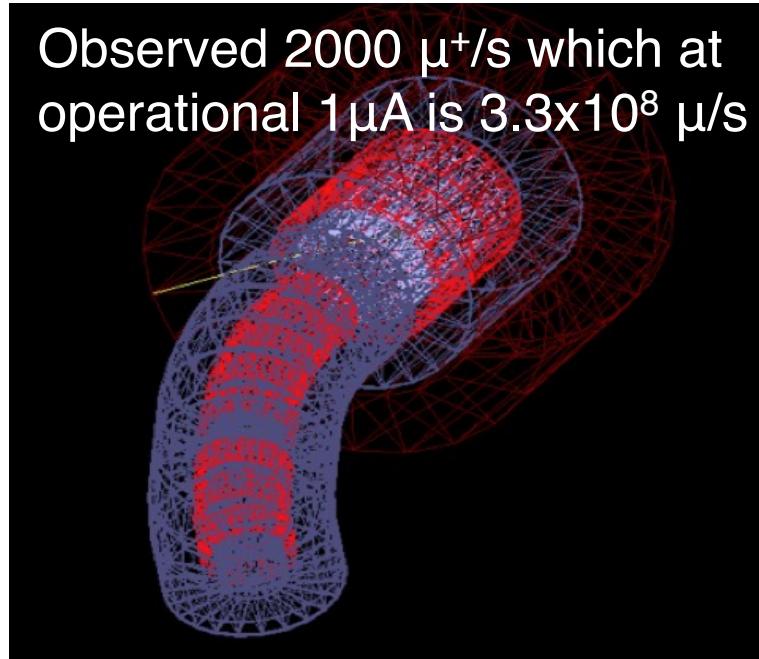
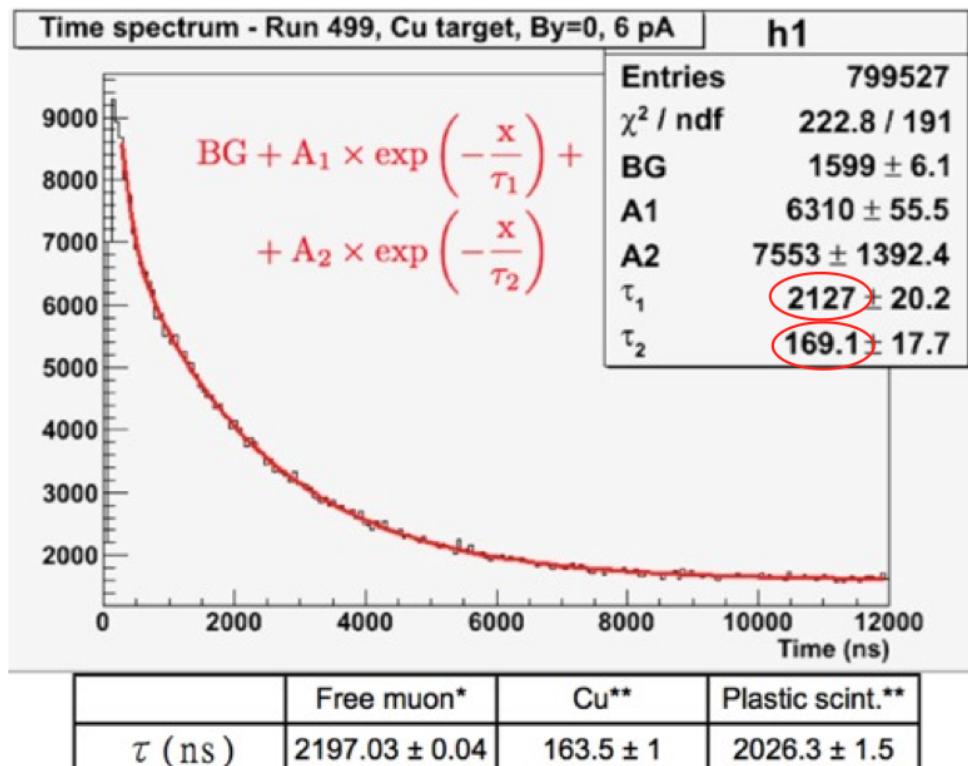
400 MeV 1 $\mu$ A continuous proton beam at Osaka RCNP facility  
using 3.5T pion capture solenoid and graphite target



Aim is to exceed the  
PSI muon rate of  
 $3.5 \times 10^8 \mu/\text{s}$

# Pion/Muon Production Prototype : MuSIC

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

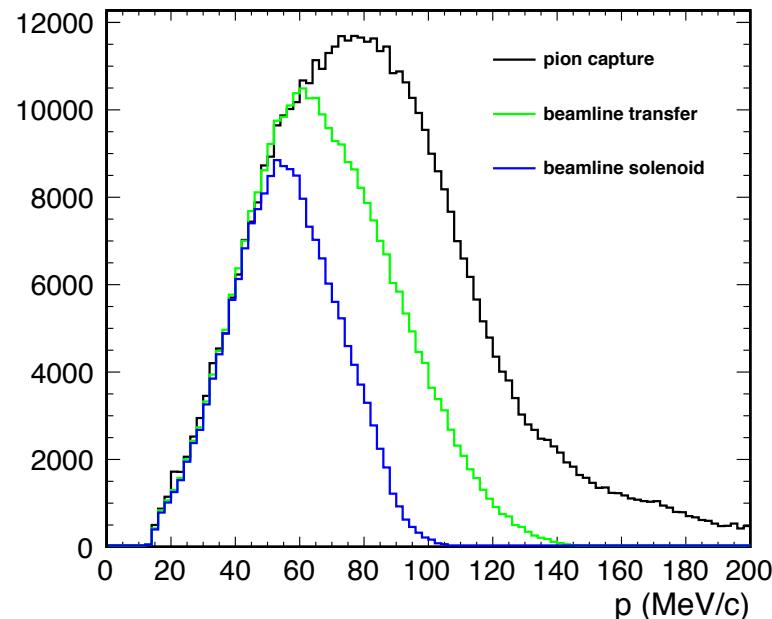


Per Watt of proton power  
MuSIC is producing  
3000x more  $\mu\text{/s}$  than PSI

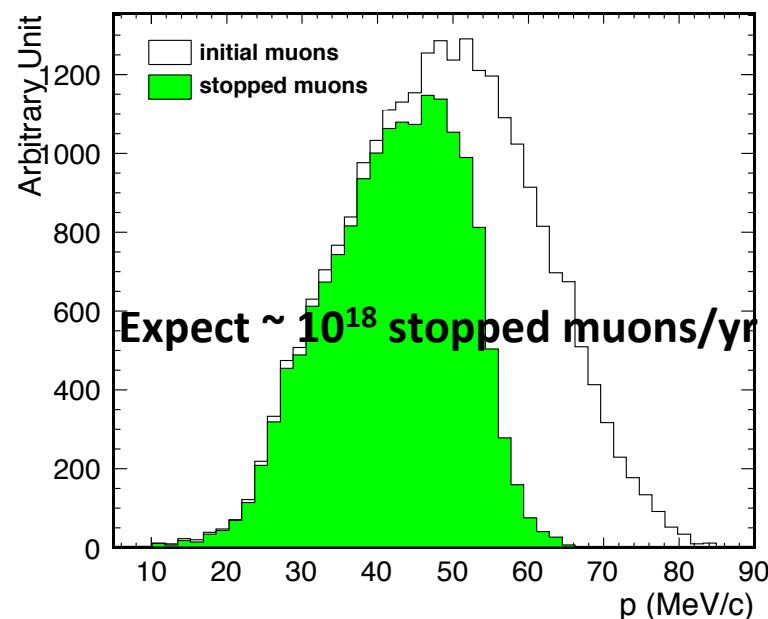
# COMET Sensitivity Studies

Using MARS / G4Beamline and GEANT4.

Still much to do in terms of optimising collimators/beam blockers/target etc



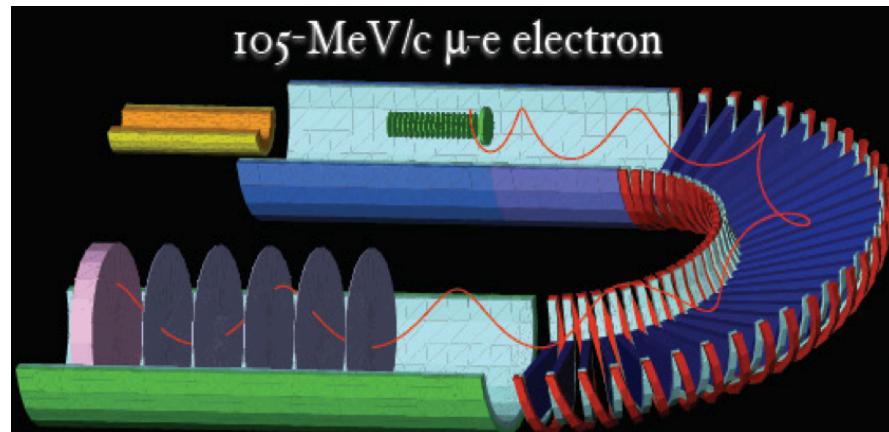
Momentum selection of  $\mu$  as passes down transport beamline



Momentum distributions of muons stopped in Al target



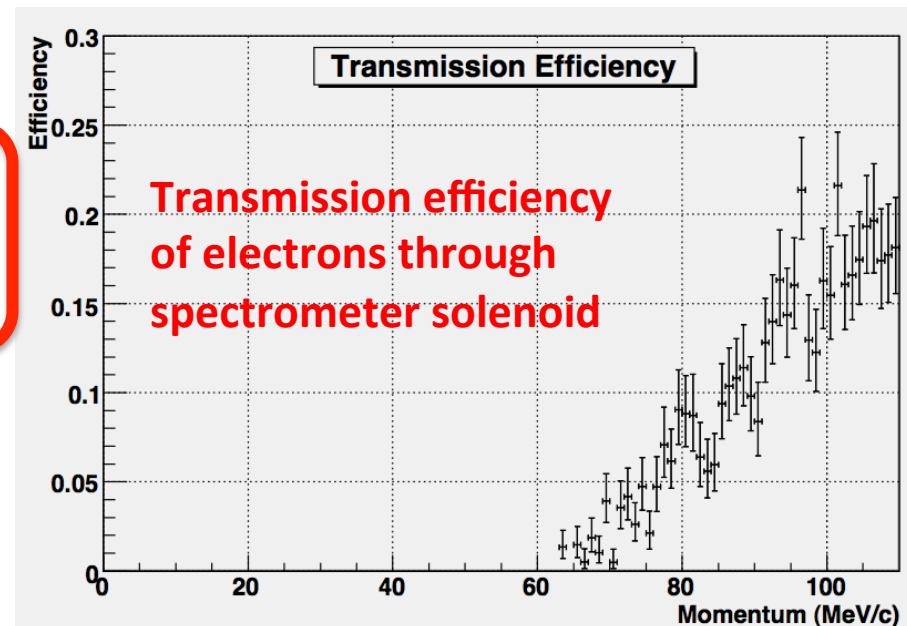
# COMET Sensitivity Studies



Low-p particles have low efficiency for reaching detector ensuring detector rates of 1-10 kHz.

Largest backgrounds from:

- $e^-$  from Decay in Orbit (DIO)  $\mu$
- $e^+e^-$  from  $\gamma$  from  $\pi$  capture



# Muon to Electron Conversion

Single event sensitivity = $(N_p \cdot N_{\mu/p}^{stop} \cdot f_{cap} \cdot A_{\mu-e})^{-1}$	$2.6 \times 10^{-17}$
90% confidence level upper limit	$6.0 \times 10^{-17}$
Events per $1 \times 10^{-16}$ BR	3.8

CDR

Radiative Pion Capture	0.05
Beam Electrons	< 0.1 <sup>‡</sup>
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
$\mu^-$ Capt. w/ n Emission	< 0.001
$\mu^-$ Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

CDR

Estimates being revised for TDR  
as simulation becomes more refined.

DIO uses Shanker calculation.

# COMET Status

CDR completed in 2009 and secured stage-1 (of 2 stages) approval from J-PARC PAC.  
Expect to complete TDR in coming months in readiness of 2<sup>nd</sup> stage of approval process

	2012	2013	2014	2015	2016	2017	2018	2019
MR studies	studies							
Proton beamline				construction				
Pion capture				construction		installation		
Muon transport				construction		installation		
Detector				construction		installation		
infrastructure				construction		installation		
data taking							engineering	physics run

Latest costing ~ \$80M

84 people from 20 institutes : 50% non-Japanese.





# Summary

Neutrino oscillations have shown lepton flavour is not sacrosanct and requires BSM physics.

While the LHC will (hopefully) say much about the TeV-scale the elucidation of leptogenesis and physics beyond the TeV-scale will require lepton flavour experiments.

Charged Lepton Flavour violation processes have no observable SM rate and notwithstanding backgrounds etc are excellent probes of BSM physics.

Beyond MEG, muon to electron conversion experiments promise the best reach into BSM physics in the next 10 years.

**COMET has 1 of 2 stage J-PARC approval and significant milestones have already been reached in proton extinction, s/c magnet design and pion capture @ MuSIC.**

# BACKUP

# Curved Solenoids

In a curved solenoid the centre of the helical trajectory of a charged particle drifts towards the perpendicular direction to the curved solenoid plane.

$$D = \frac{p}{qB} \theta_{bend} \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right)$$

*D : drift distance*

*B : Solenoid field*

*$\theta_{bend}$  : Bending angle of the solenoid channel*

*p : Momentum of the particle*

*q : Charge of the particle*

*$\theta$  :  $\text{atan}(P_T/P_L)$*

$$B_{comp} = \frac{p}{qr} \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right)$$

*p : Momentum of the particle*

*q : Charge of the particle*

*r : Major radius of the solenoid*

*$\theta$  :  $\text{atan}(P_T/P_L)$*

# MUSIC vs COMET vs PSI

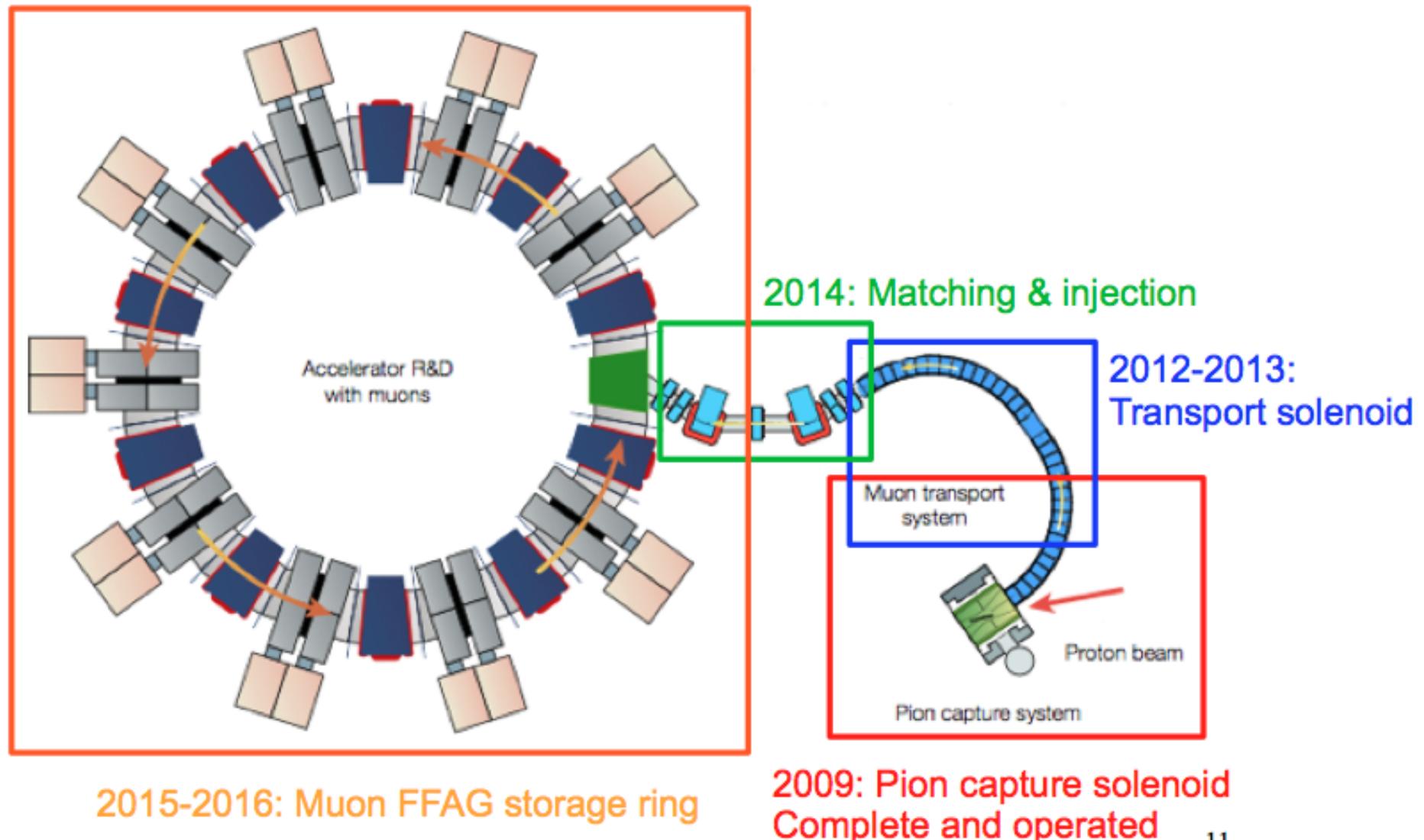
	PSI <sup>(1)</sup> ( $\mu$ E4)	MuSIC	COMET <sup>(2)</sup>	NuFACT <sup>(3)</sup>
Muon intensity (/sec)	$3.5 \times 10^8$	$10^{8-9}$	$10^{11}$	$10^{12-13}$
Muon momentum (MeV/c)	85-125 (total range)	20-70	20-70	170-500
Time structure	Continuous	Continuous	Pulsed	Pulsed
Proton beam power/energy (W/GeV)	1.2M / 0.590	400 / 0.4	56k / 8	4M / 8
Beam current ( $\mu$ A)	1.8	1	7	Not given
Production target	Graphite	Graphite	Tungsten	Mercury jet
Capture Solenoid Max Field Strength (T)	5.0	3.5	5.0	20

(1) Based on: "A New High-intensity, Low-momentum Muon Beam for the Generation of Low-energy Muons at PSI", Prokscha, T.; Morenzoni, E. et al. (Hyperfine Interactions, Volume 159, Issue 1-4, pp. 385-388)

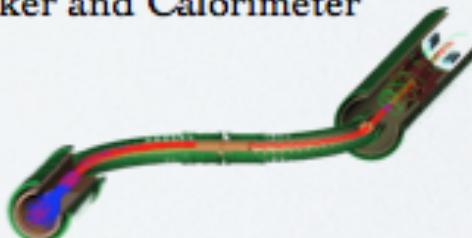
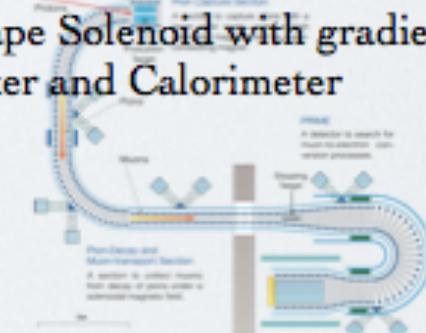
(2) COMET CDR

(3) Based on The Muon Collider/Neutrino Factory Target System, H.Kirk and K.McDonald (Aug.14,2010) and Study-II report

# MUSIC Plan (Budget Permitting)

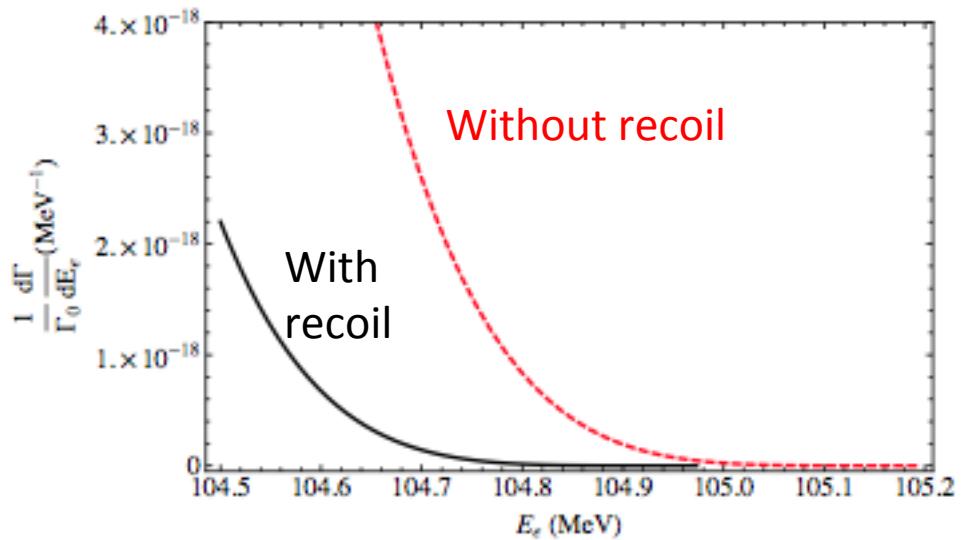
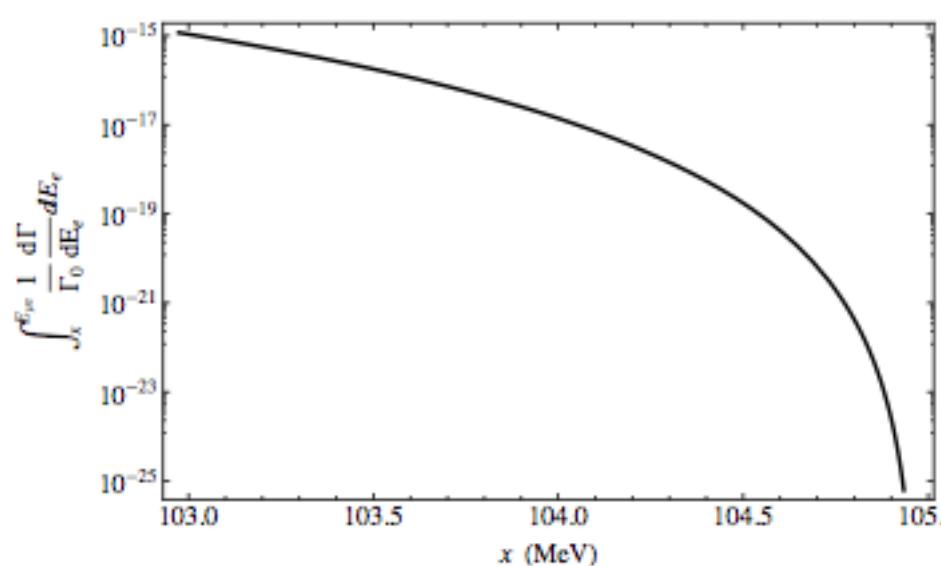


# Mu2e vs COMET

	<b>Mu2e</b>	<b>COMET</b>
<b>Proton Beam</b>	8GeV, 20kW bunch-bunch spacing 1.69 $\mu$ sec rebunching Extinction: $< 10^{-10}$	8GeV, 50kW bunch-bunch spacing 1.18-1.76 $\mu$ sec empty buckets Extinction: $< 10^{-9}$
<b>Muon Transport</b>	S-shape Solenoid	C-shape solenoid
<b>Detector</b>	Straight Solenoid with gradient field Tracker and Calorimeter 	C-shape Solenoid with gradient field Tracker and Calorimeter 
<b>Sensitivity</b>	SES: $2 \times 10^{-17}$ 90% CL UL: $6 \times 10^{-17}$	SES: $2.6 \times 10^{-17}$ 90% CL UL: $6 \times 10^{-17}$

# DIO Spectrum

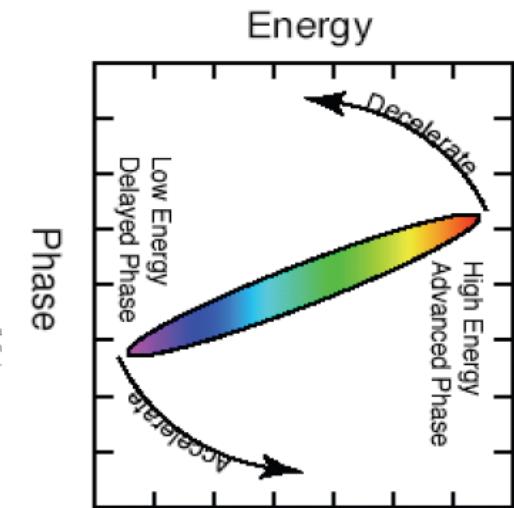
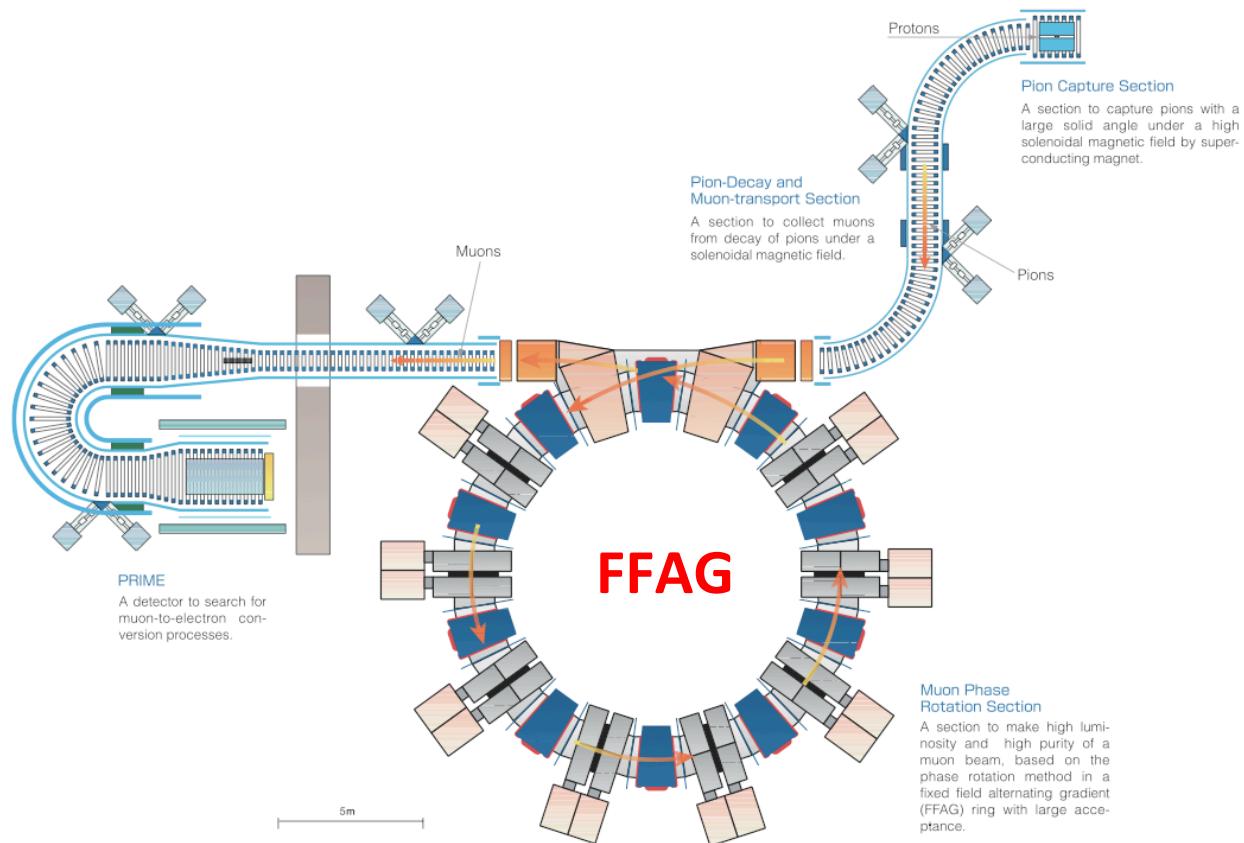
A. Czarnecki, X. Tormo, W. Marciano : Phys. Rev. D 84, 013006 (2011)



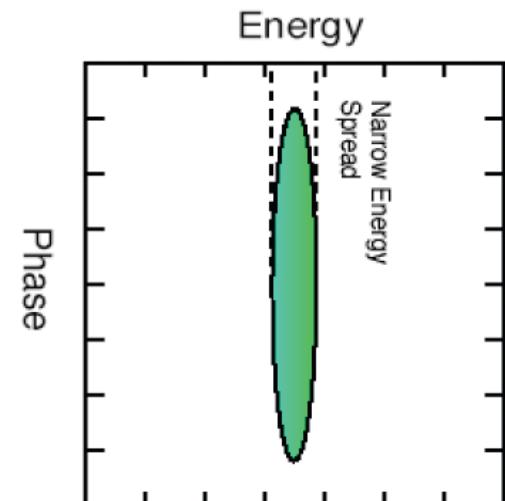
**Total rate of decay-in-orbit events, for aluminum, with electron energy larger than  $x$ , normalized to the free muon decay rate  $\Gamma_0$ .**

# Getting to $10^{-18}$ : PRISM

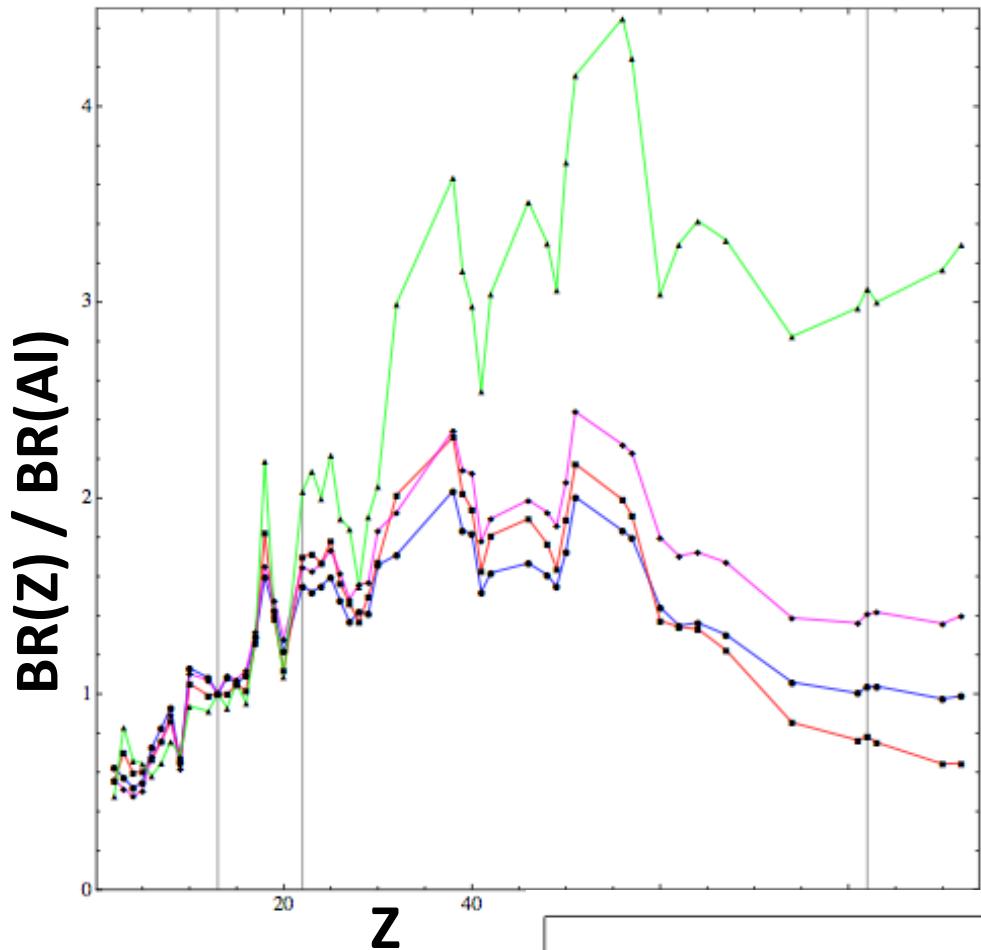
Use FFAG to create narrow energy-spread muon beam and reduce  $\pi$  background.



## PHASE ROTATION



# Z dependence of BSM physics



## Dipole / Scalar / Vector Interactions

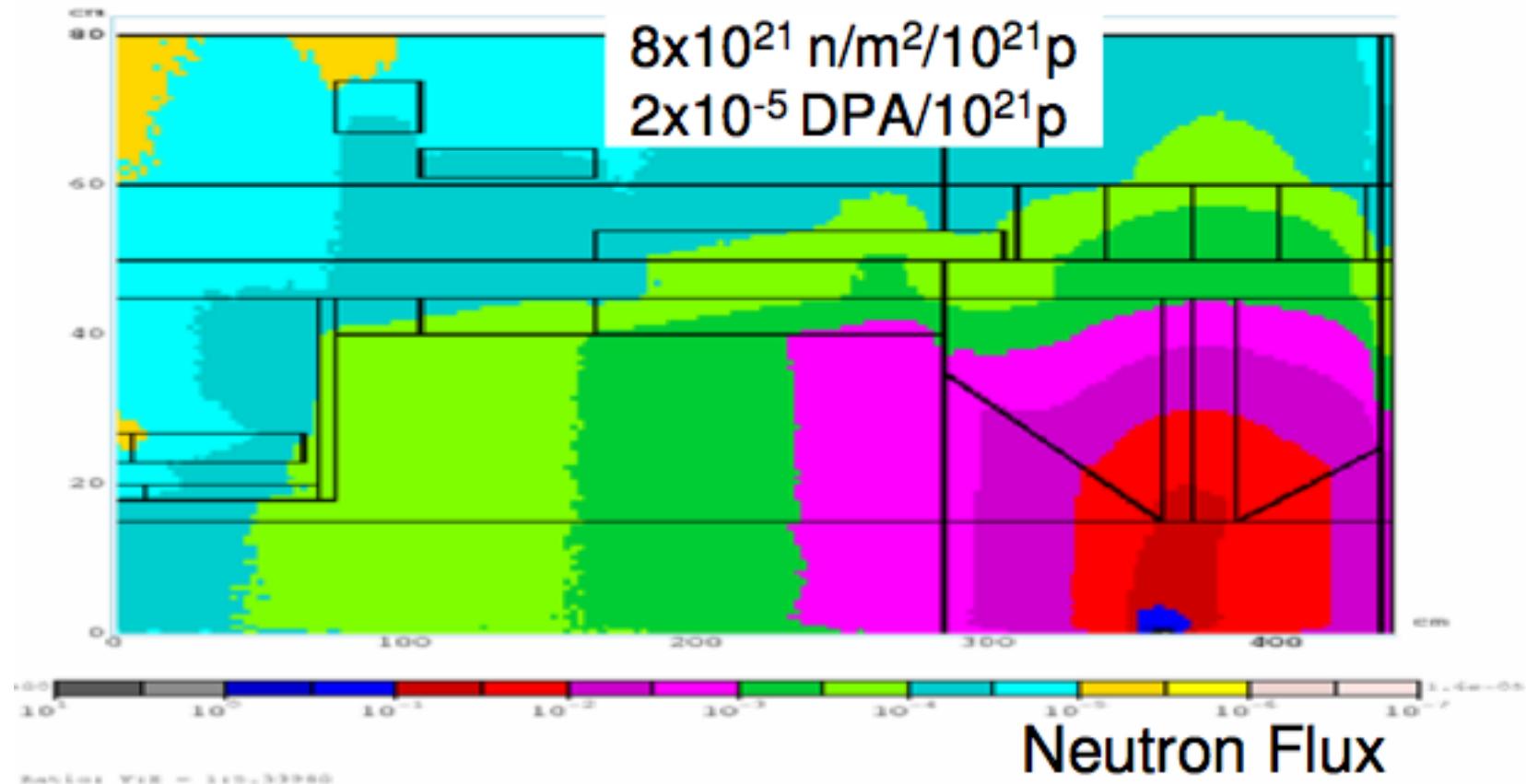
PRISM would use Ti  
vs Al in COMET

Would like to  
measure at high and  
low-Z but high-Z  
difficult due to  
smaller muonic atom  
lifetime

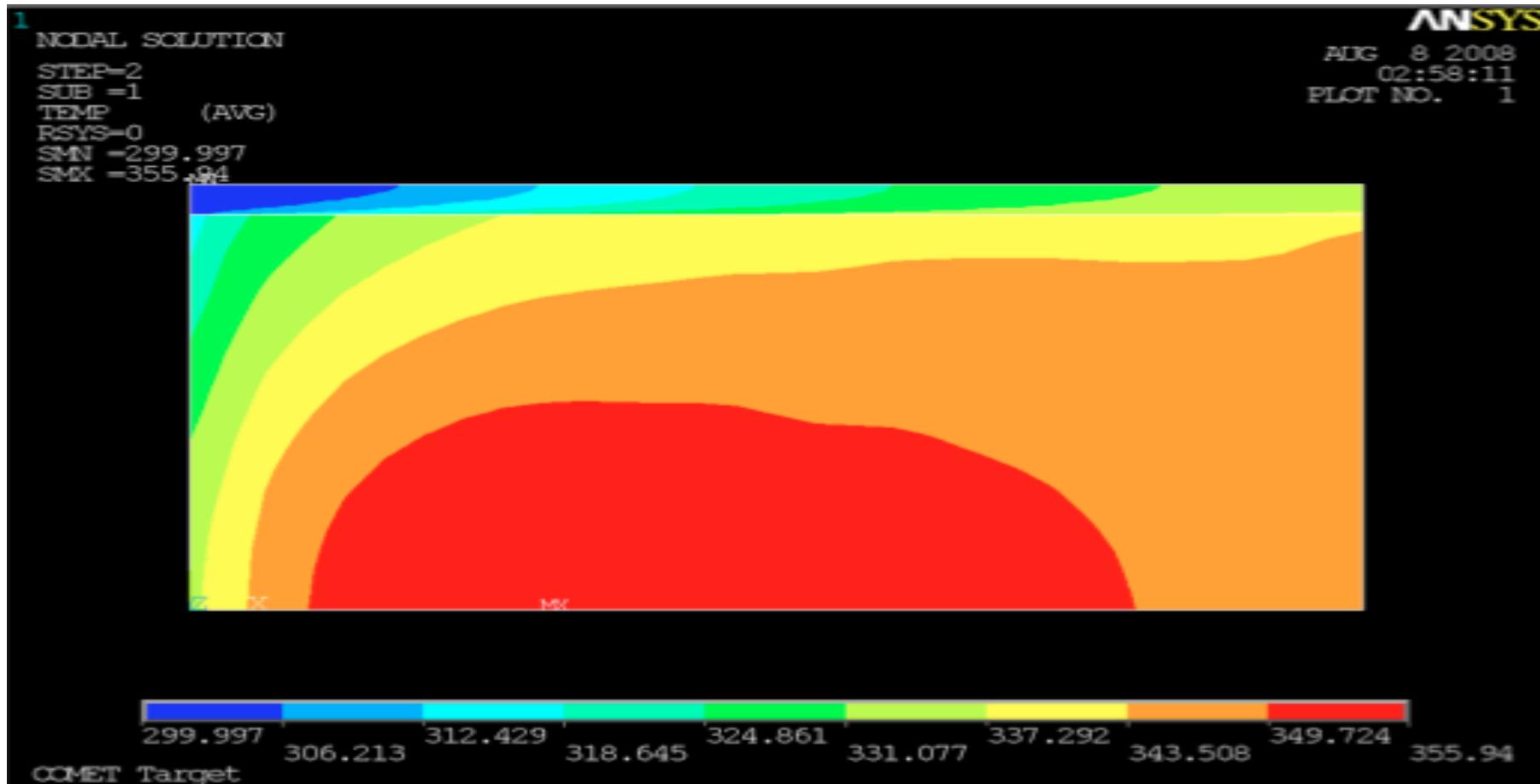
	aluminum	titanium	lead
Atomic number	13	22	82
Lifetime of muonic atoms ( $\mu$ sec)	0.88	0.33	0.082
Relative $\mu^- - e^-$ conversion branching ratio	1	1.7	1.15



# Neutron Flux



# Neutron Flux



Tungsten target cooling by water. Color indicates temperature from 300 K (Blue) to 356 K (Red). Water with initial temperature of 300 K flows in a thin layer surrounding the target rod from the left to the right.