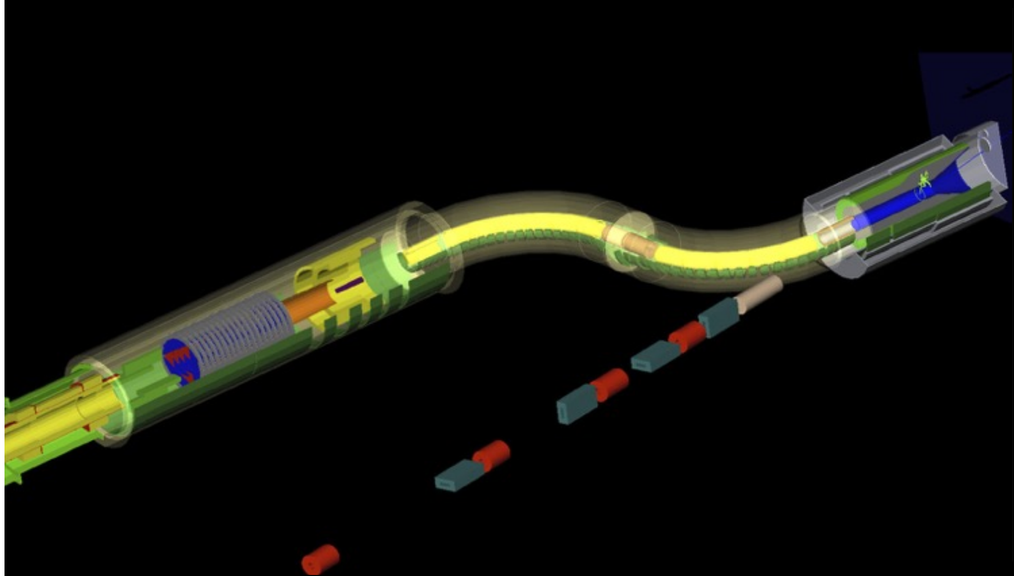
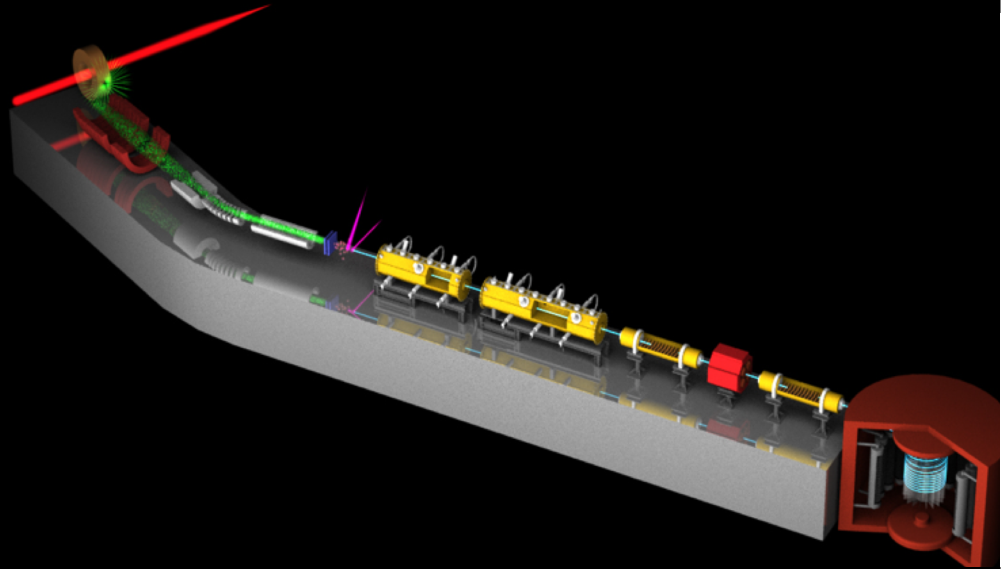
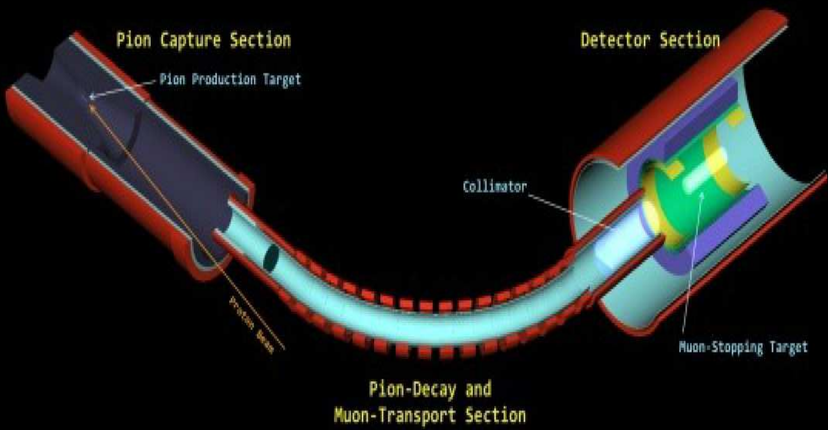
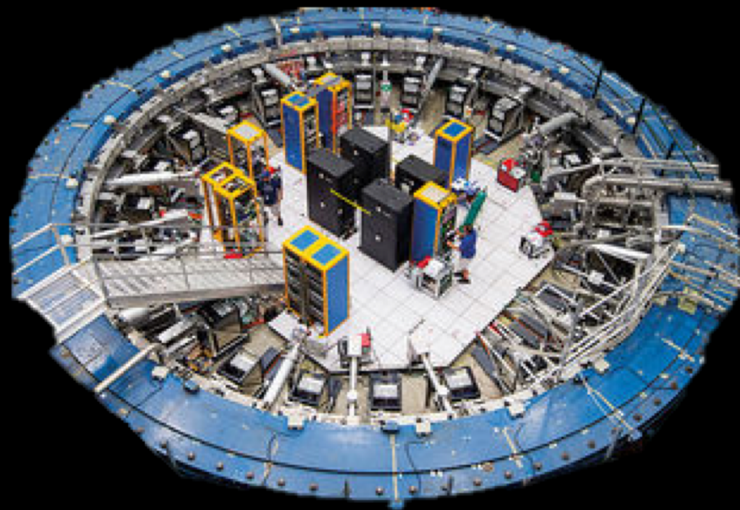
Pulsed Muon Beam Physics





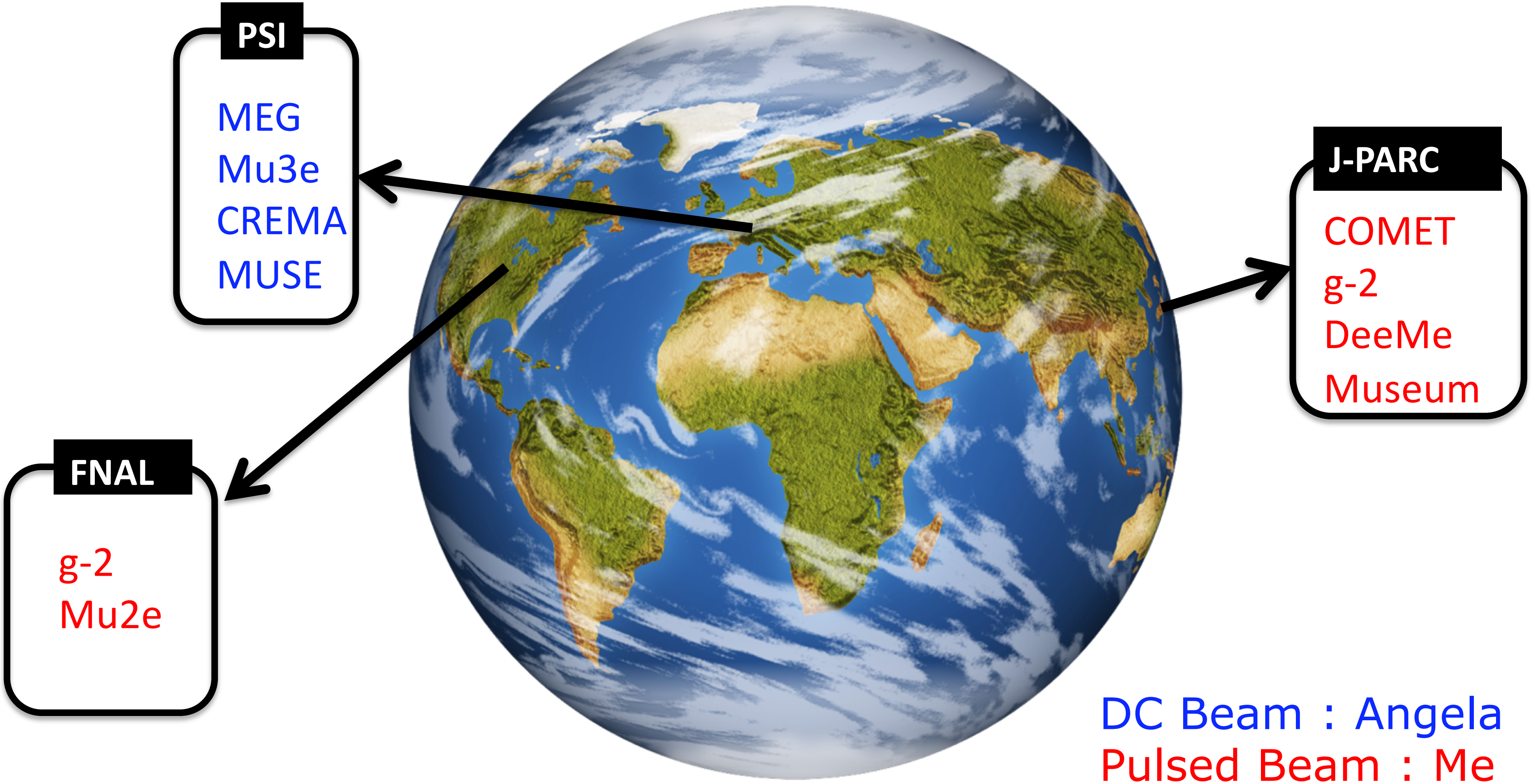




Mark Lancaster
UCL

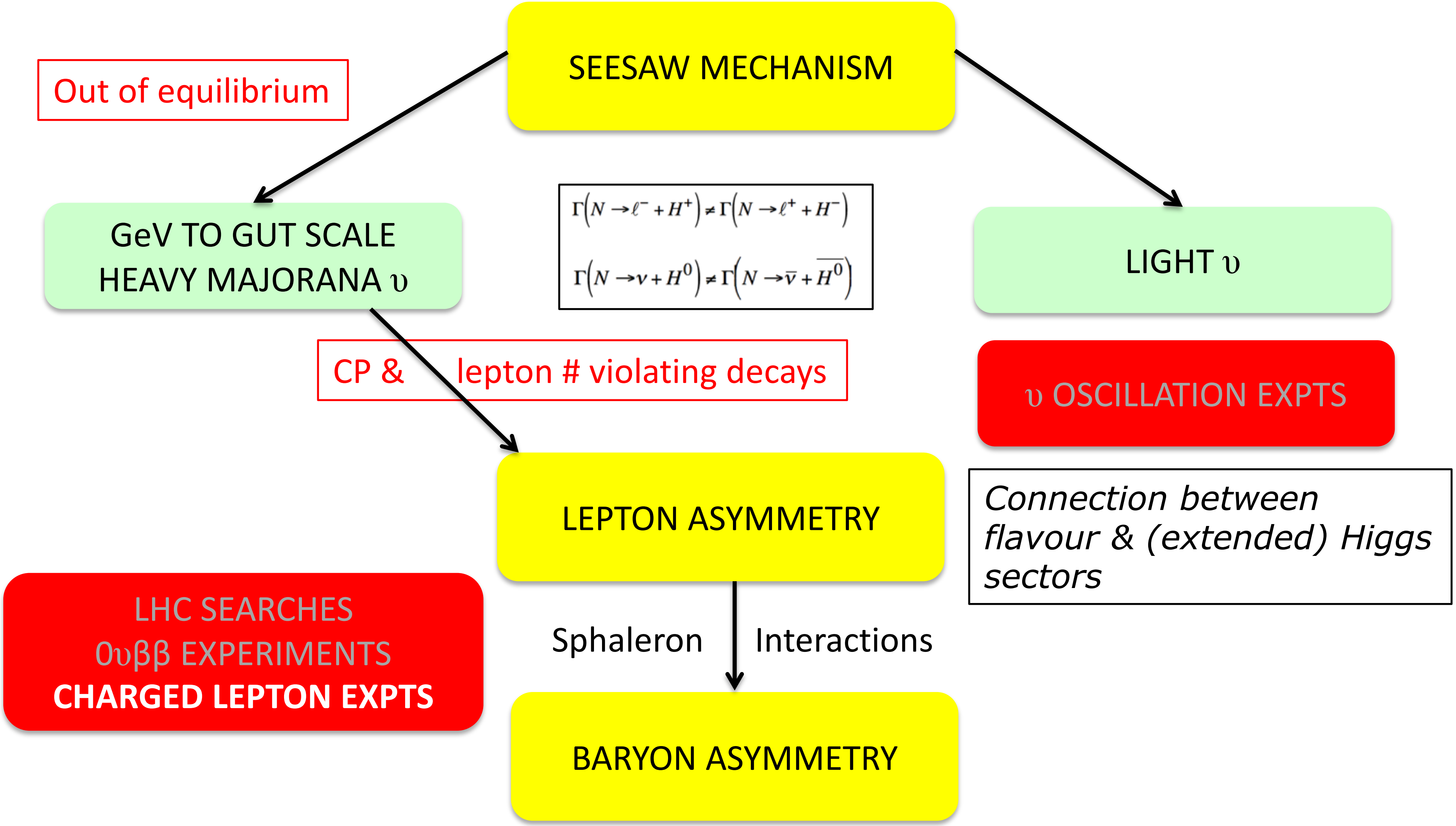

Long Baseline ν
SBN
Theorists
ν Scattering
Muon Expts

$0.5-1B of Muon Experiments



DC Beam : Angela
Pulsed Beam : Me

Motivation: Leptogenesis

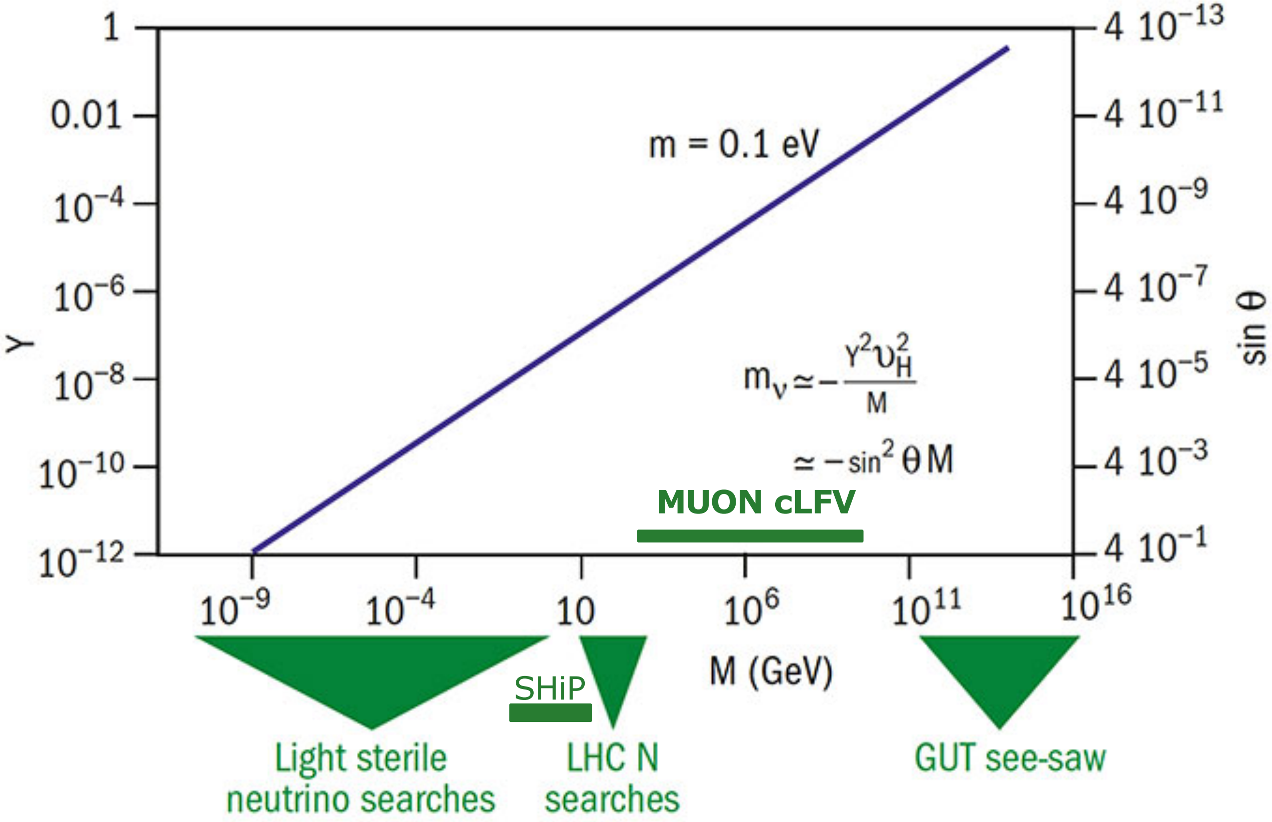


Motivation: Origin of neutrino mass

Requires new degrees of freedom and new interactions

Avoid fine-tuning in Yukawa coupling by:

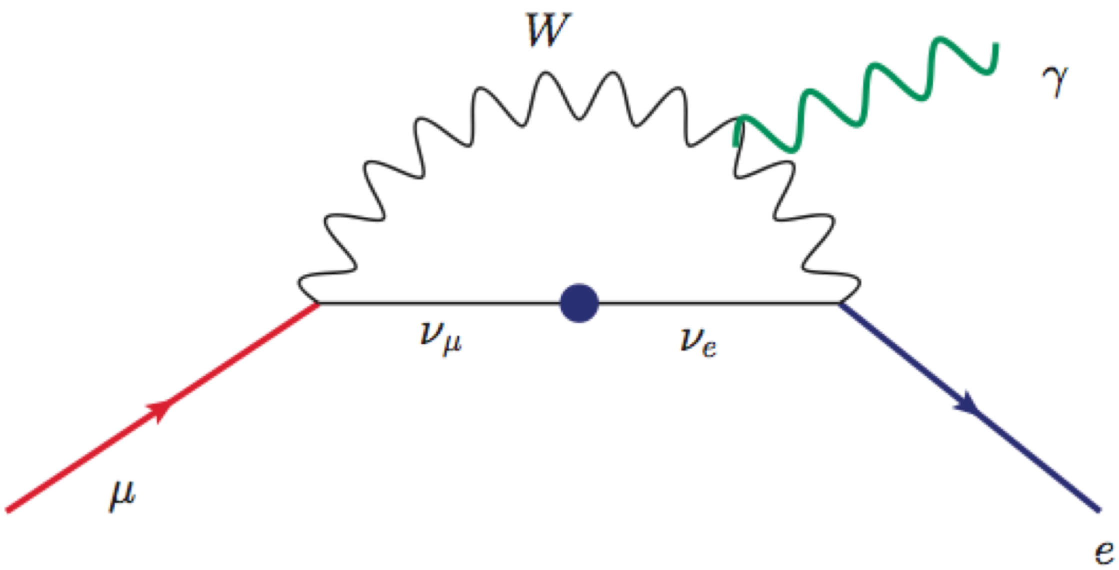
- adding heavy RH Majorana neutrinos, fermion/scalar triplets & Seesaw mechanisms
- radiative & R-parity violating SUSY interactions



Very wide range in possible RH neutrino masses

Enter charged lepton flavour violation

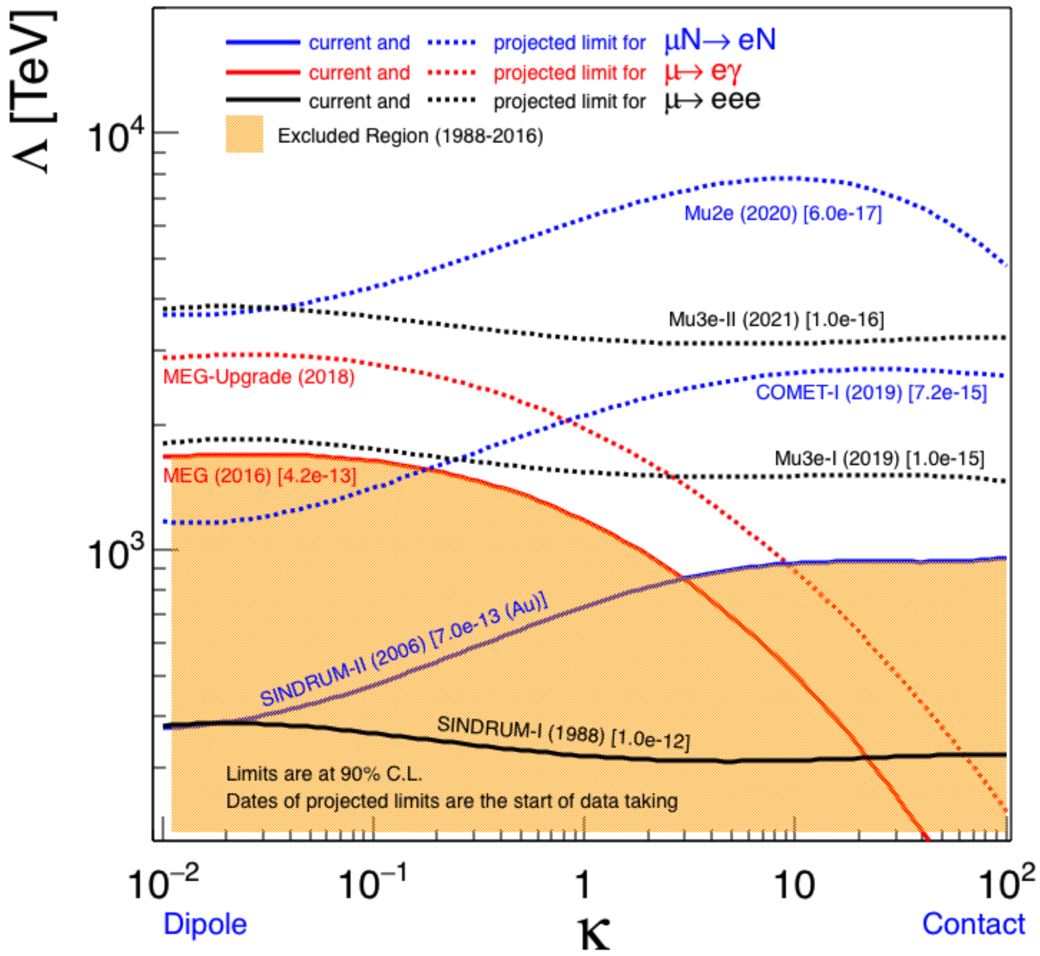
In SM: neutrino oscillations (masses) are intimately connected with charged lepton flavour violation



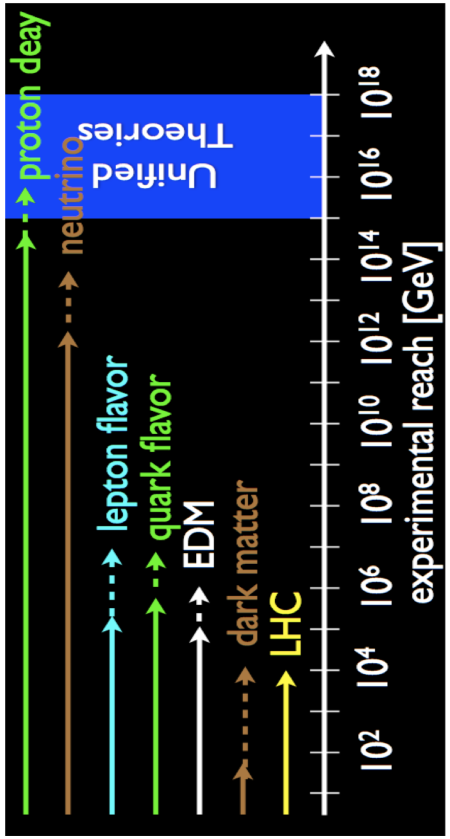
and also in BSM: $\nu_{RH} \to l^- H^+$

And thus to **extensions to the Higgs sector.**

Access to mass scales beyond that probed by ATLAS/CMS



Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097



Scales of upto 8000 TeV for unity coupling

Observations

Principal observations being sought are:

- lepton flavour violation (LFV)
- lepton number violation (LNV)
- lepton universality violation

Muon Expts

$$\mu \to e\gamma$$
$$\mu N \to eN$$
$$\mu \to 3e$$
$$R_p \; (\mu \text{ vs } e)$$
$$(g-2)_\mu$$

HFS

LHCb/BaBar/Belle

$$\tau \to e\gamma, \mu\gamma, 3\mu, \ldots$$
$$D \to \tau\nu / D \to \mu\nu$$

Kaon/Pion Expts

$$K \to \pi\mu e,\ \pi ee,\ \pi\mu\mu$$
$$\pi/K \to e\nu/\mu\nu$$

LHC GPD Expts

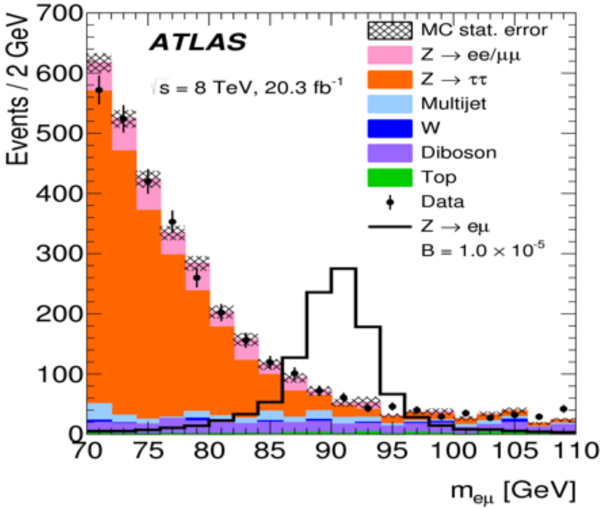
$$h \to \mu\tau, e\tau$$
$$Z \to e\mu, \mu\tau, e\tau$$
$$pp \to lljj$$

0νββ Expts

$$N \to ee$$

At FNAL, J-PARC, KEK, CERN, PSI, TRIUMF

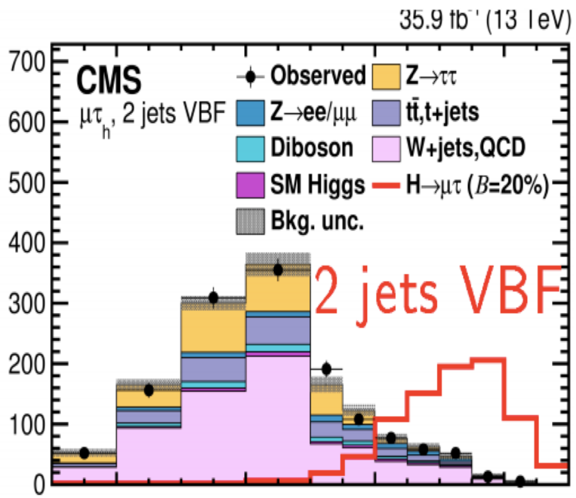
ATLAS/CMS : LFV



$Z \to \mu e$ < 7.5 (7.3) x 10^{-7} : ATLAS (CMS)

Now surpasses LEP but implied limit from SINDRUM is 5 x 10^{-13} from $\mu \to 3e$

Wing Sheung Chan (WG4)
Diego Beghin (WG4)



BDT variable

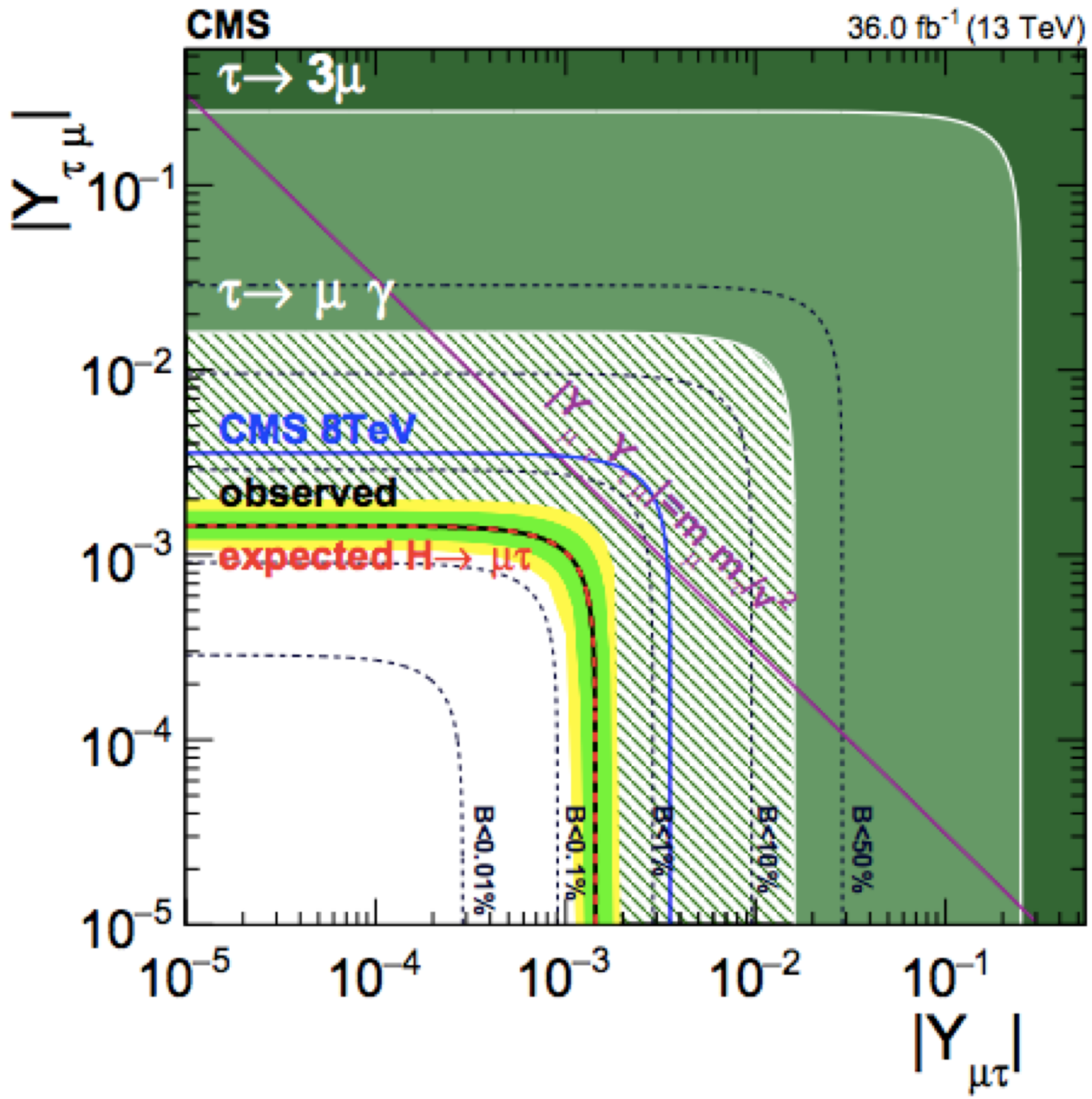
$h \to \mu e$ implied < 1 x 10^{-8} by MEG $\mu \to e\gamma$
CMS : 3.5 x10^{-4}

$h \to \mu\tau$ < 0.25 (1.43) x 10^{-2} : CMS (ATLAS)

Run-1 2.4 sigma CMS "excess" has disappeared…

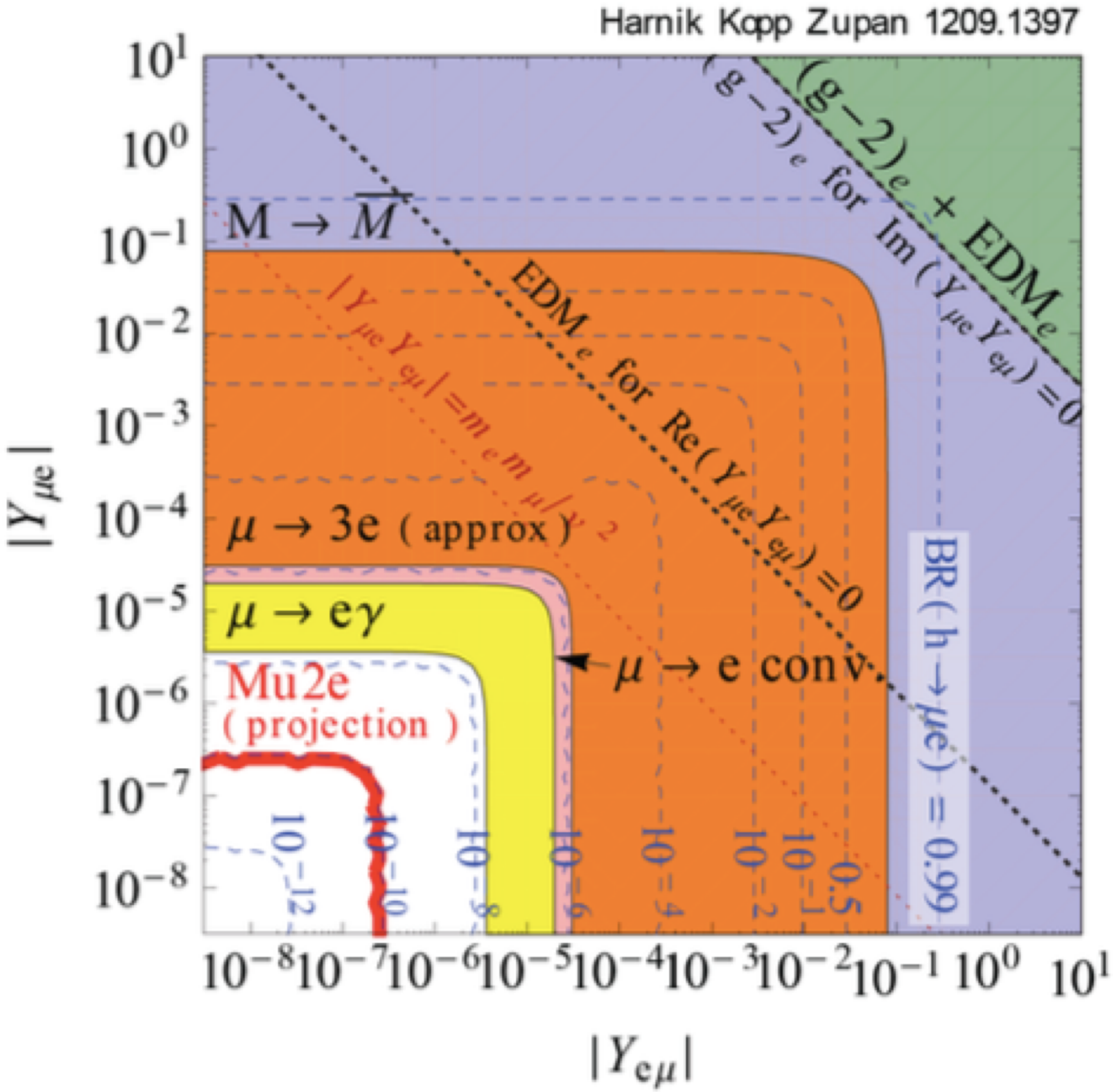
$h \to e\tau$ < 0.61 (1.04) x 10^{-2} : CMS (ATLAS)

ATLAS/CMS : LFV



In H($\mu\tau$) these FV Yukawa coupling limits are stronger than from dedicated LFV τ decay searches.

Why Muons ?



Not the case for H(μe) where muon LFV experiments have much stronger limits.

Mu2e/COMET sensitive to BR ($h \to \mu e$) of 10^{-10} (vs O(10^{-4}) at LHC)

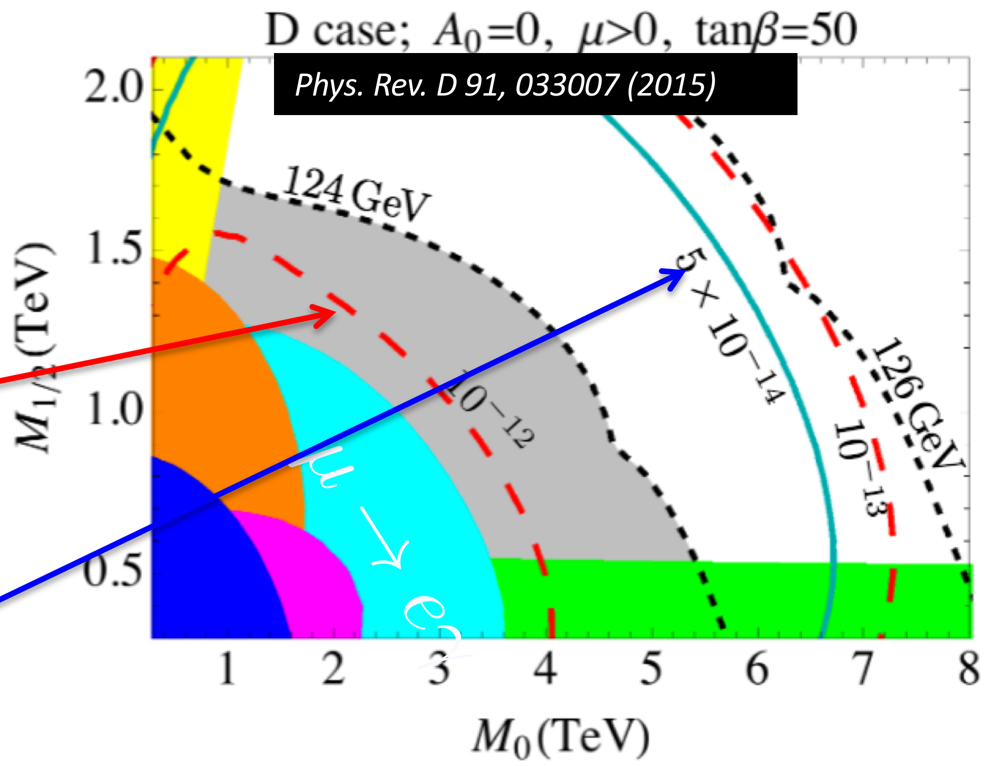
Why Muons ?

Current $\tau \to e\gamma$ limit is 3.3 x 10^{-8} and expected to reach 10^{-9} at Belle-2/LHCb. Similarly for $\tau \to 3\mu$

Mass scaling of $\mu \to e\gamma$ implies < O(10^{-11}) for τ

$\tau \to e\gamma$ at 10^{-12}

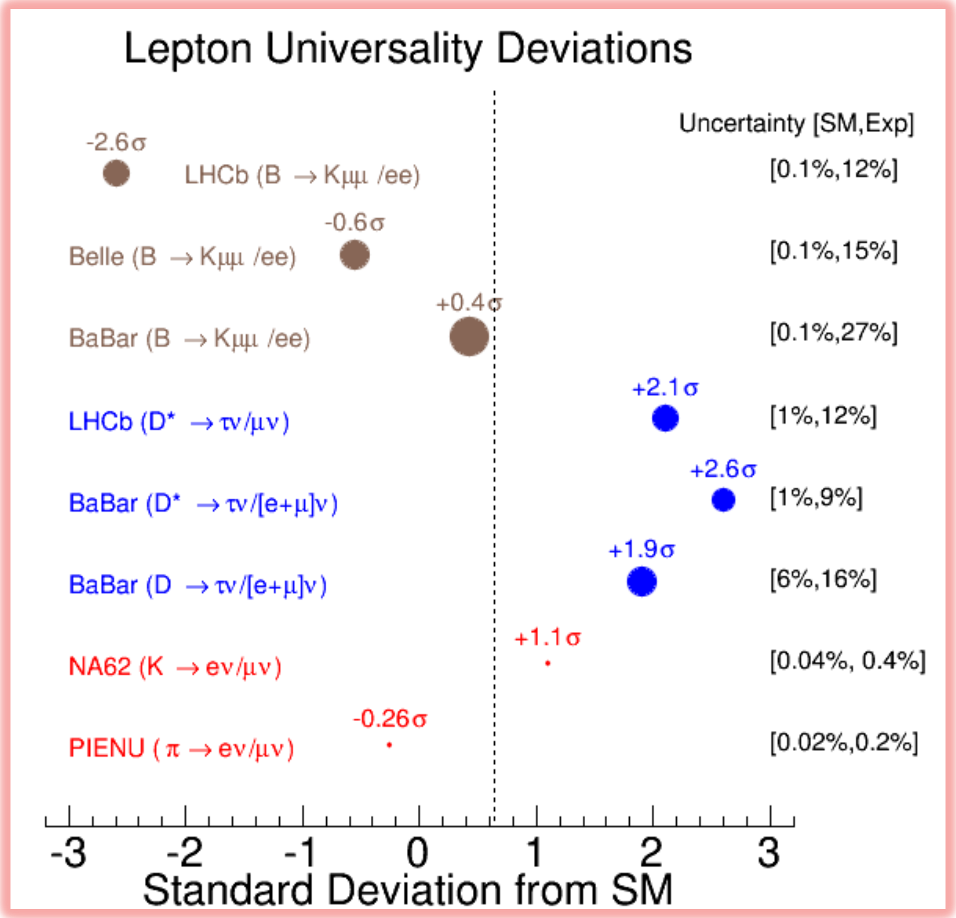
$\mu \to e\gamma$ reach



Taus though probe the "13" mixing : Is the 3rd generation peculiar ?

We need all measurements !!

Francesca Dordei (WG4)



Combined significance > 3σ for the D/τ measurements

No deviation in e:μ comparison in π/K measurements.

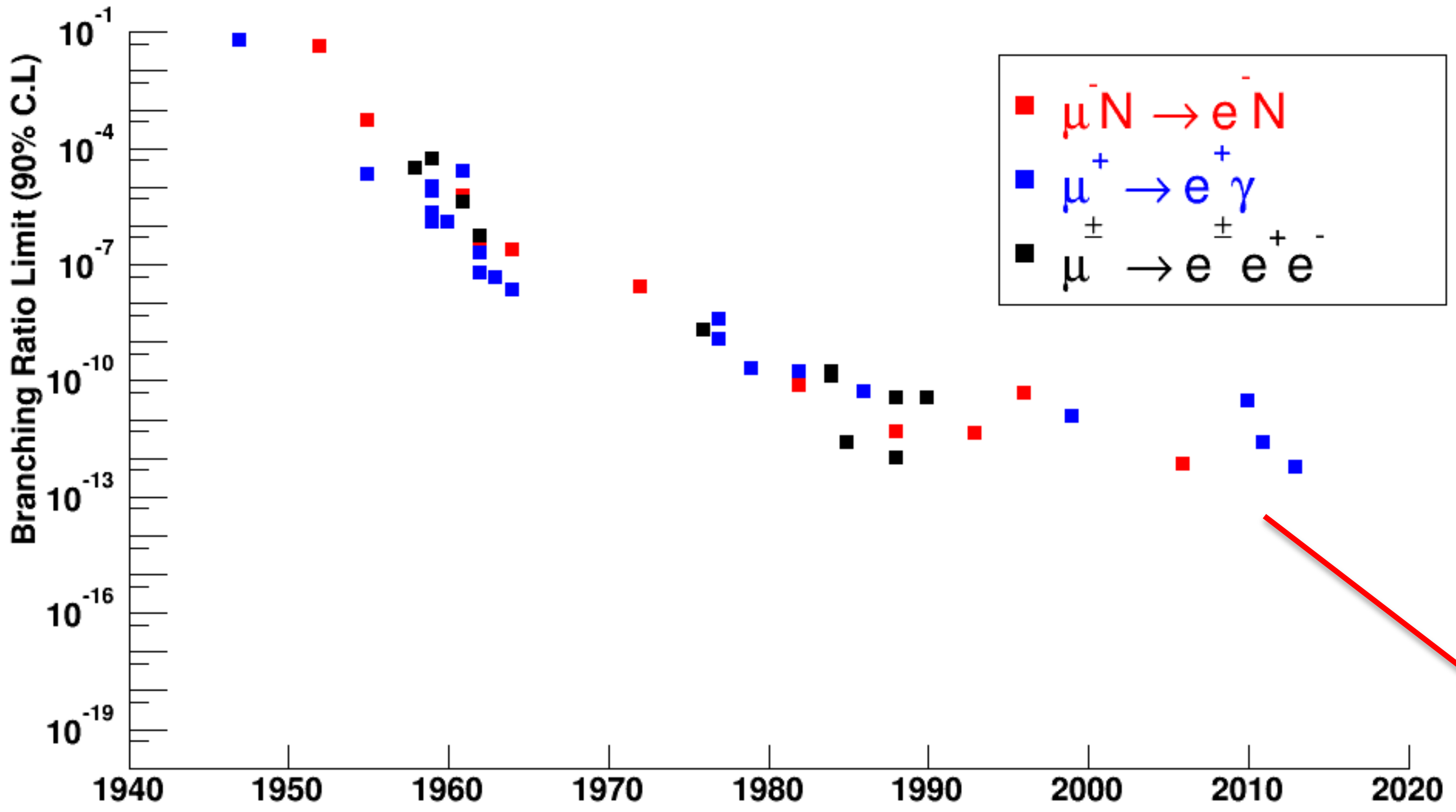
arXiv.org > hep-ph > arXiv:1409.0882

High Energy Physics – Phenomenology

Explaining the Lepton Non-universality at the LHCb and CMS from a Unified Framework

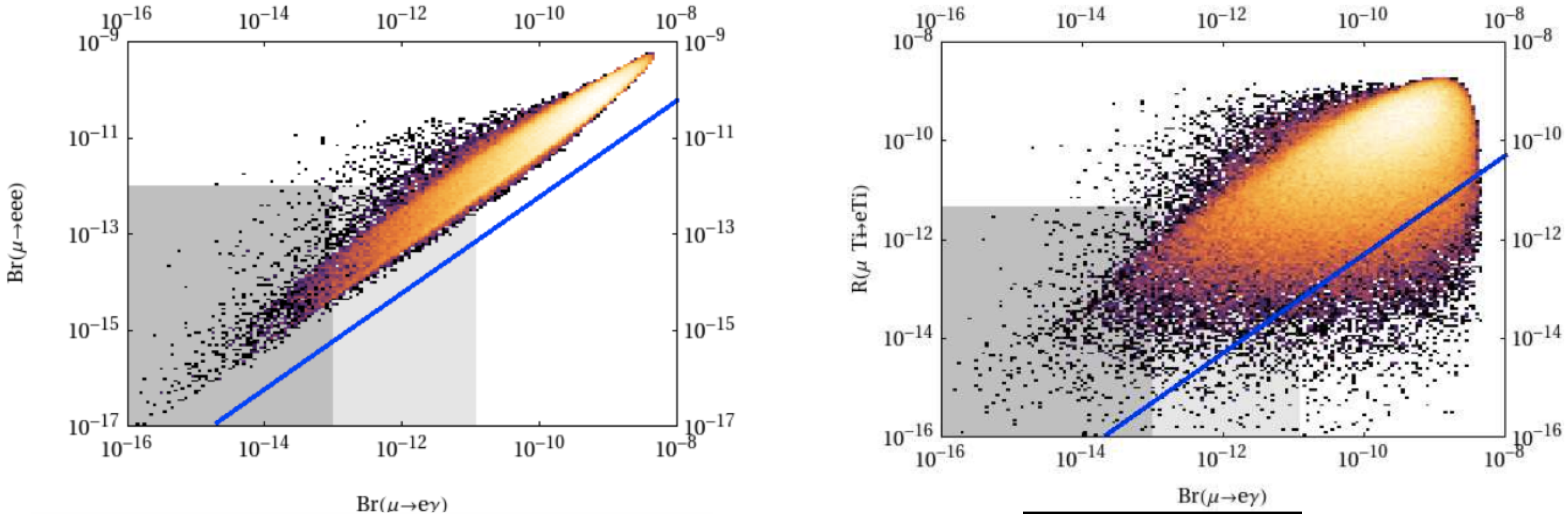
Muon LFV Experiments

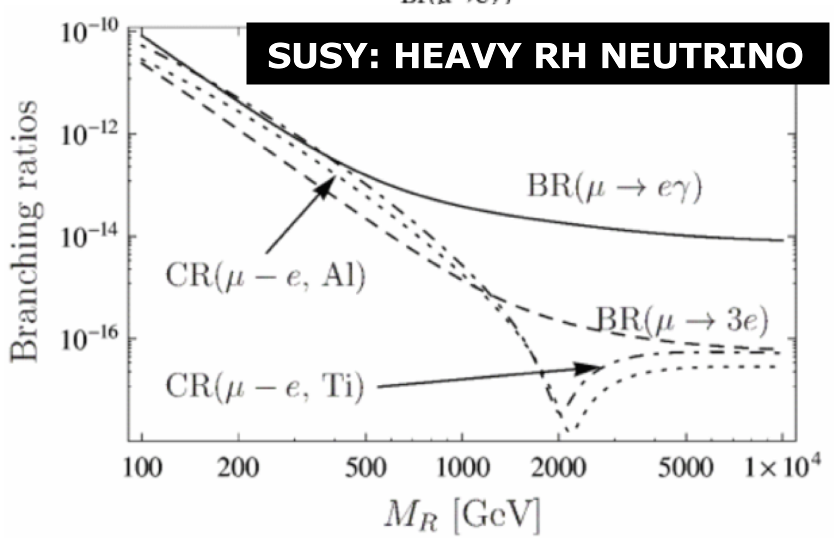
Statistics far exceeds that from τ & LFV Z/h decays at LHC

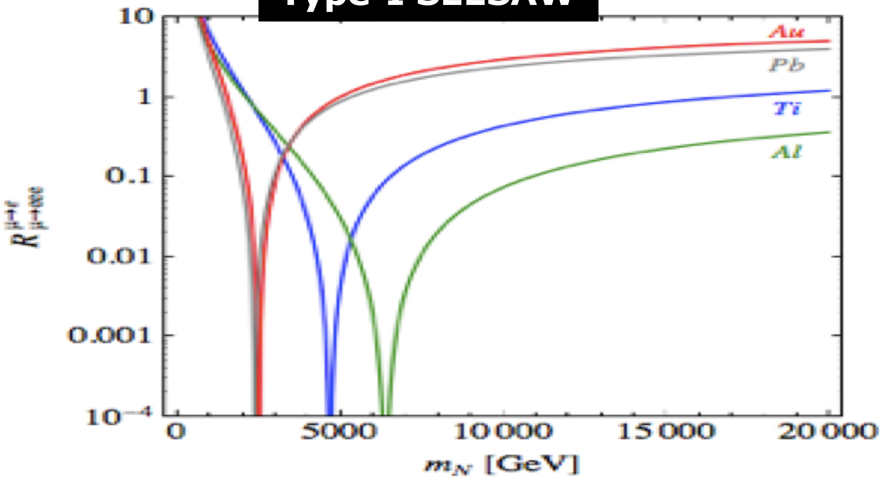


O(10⁴) improvement driven by new technology

Model Dependence



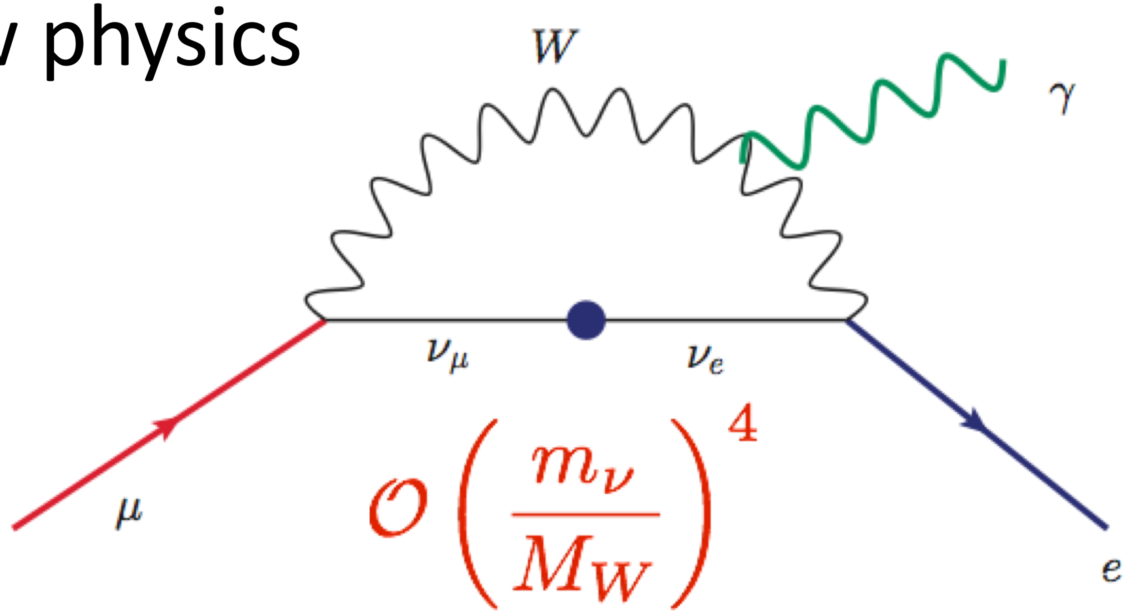




Why CLFV ?

SM is O(10^{-50})

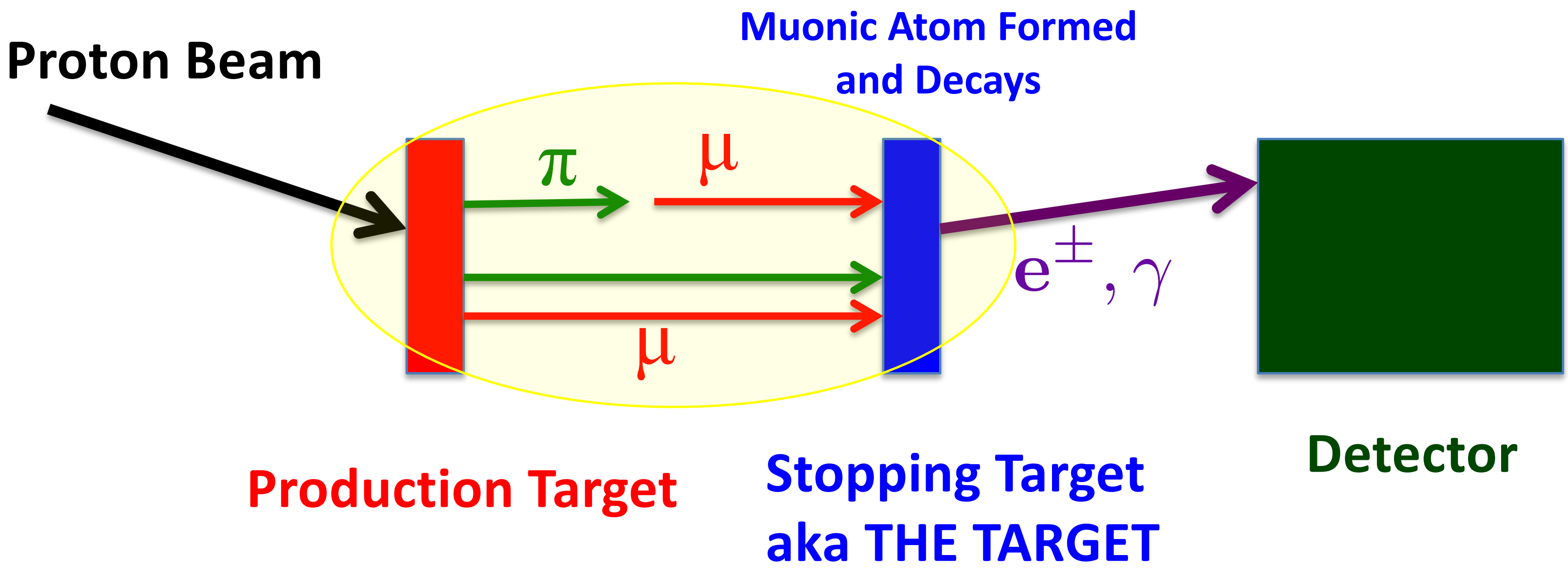
Observation **IS** new physics



No SM theory systematic

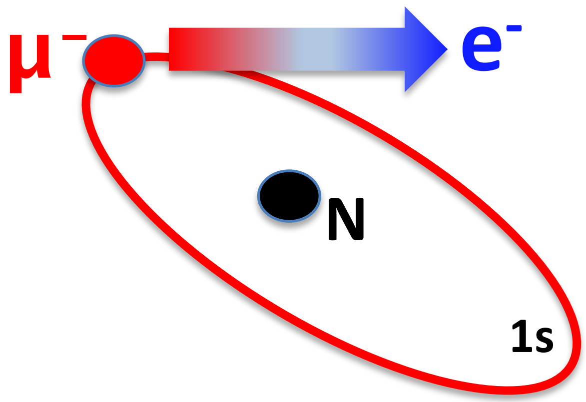
How far we can probe is limited by experiment

Experimental Technique

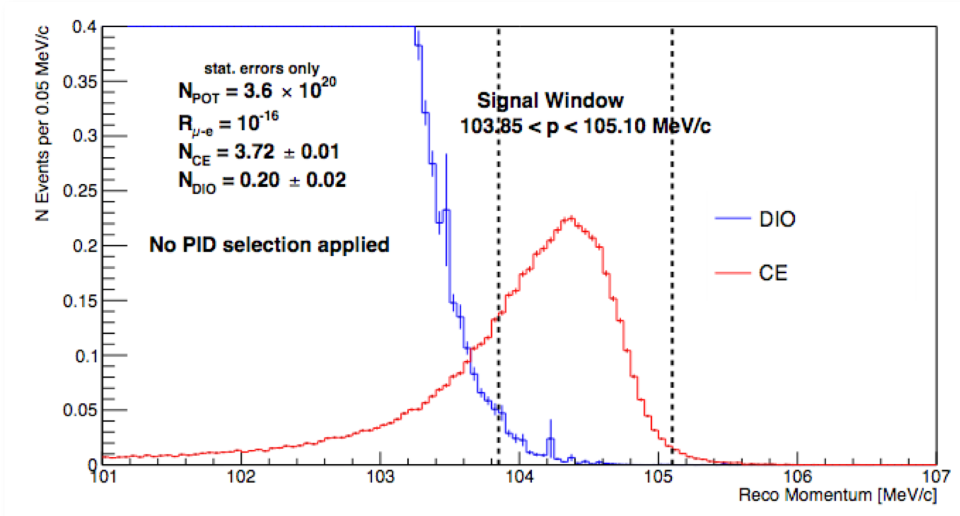


Apply symmetries, translations, rotations, …..

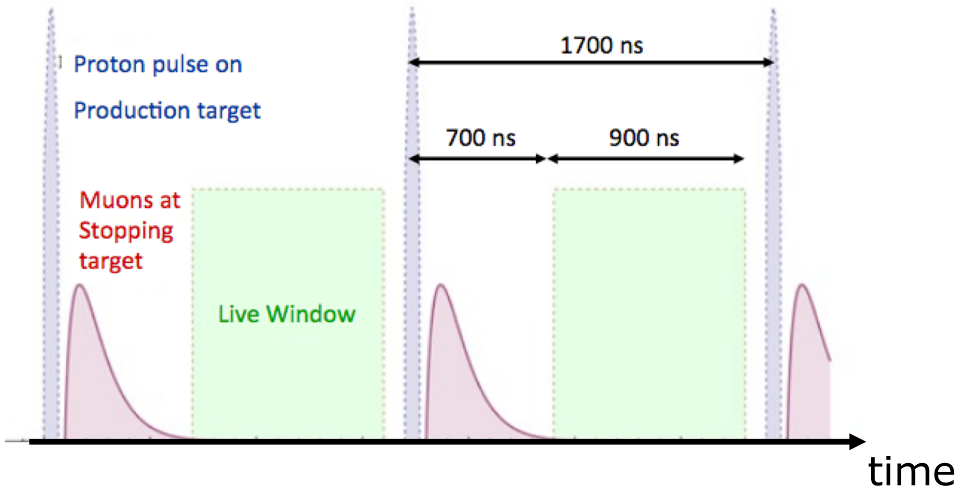
Methodology



Neutrinoless conversion of muon to electron



Al nucleus : 864ns lifetime

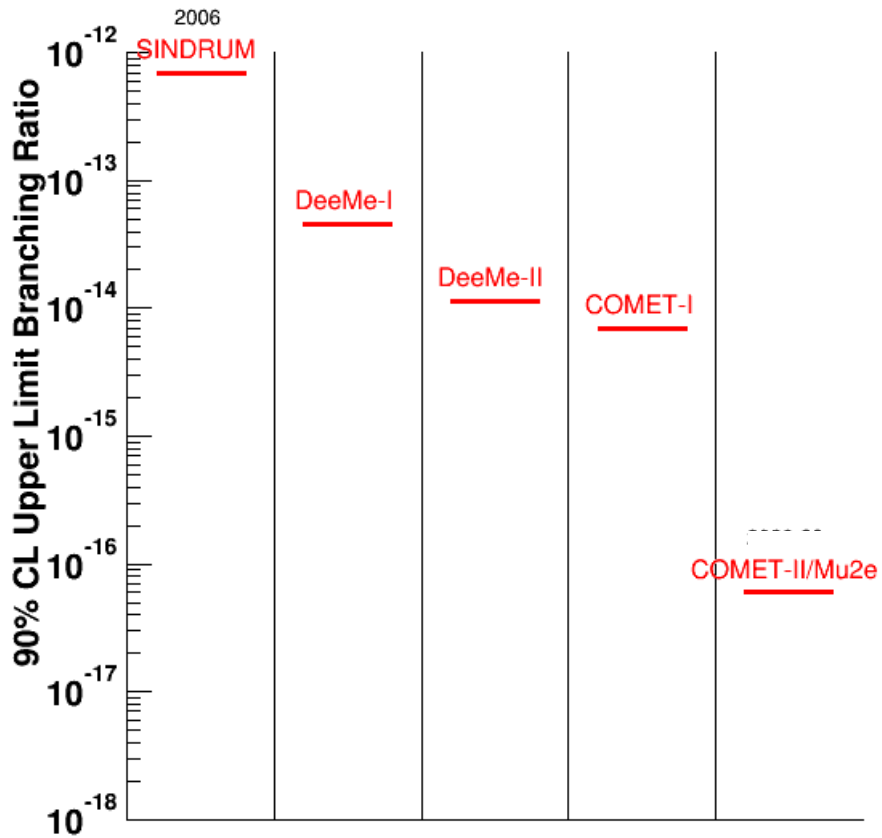


Background Rejection

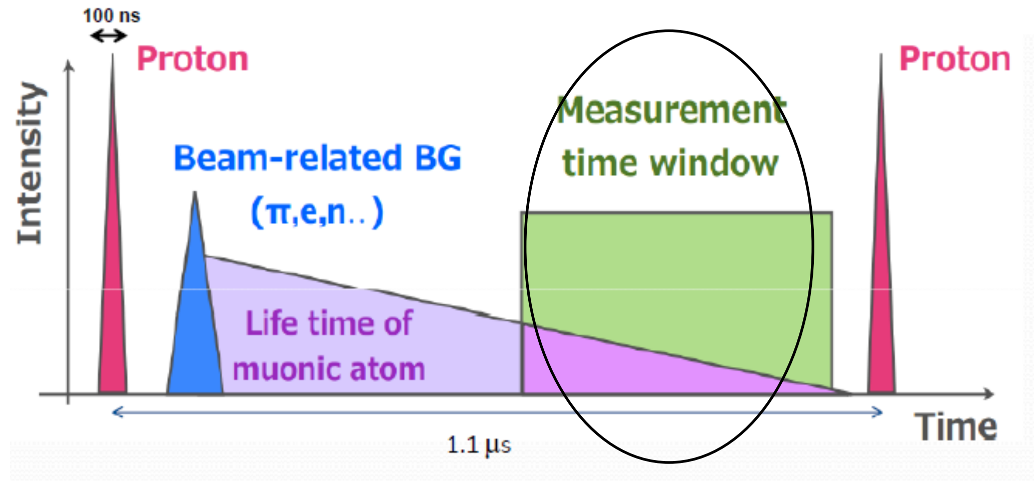
Pulsed proton beam (timing)

High resolution detectors

DeeMe, COMET & Mu2e



"extinction"



Significant improvements made possible by:

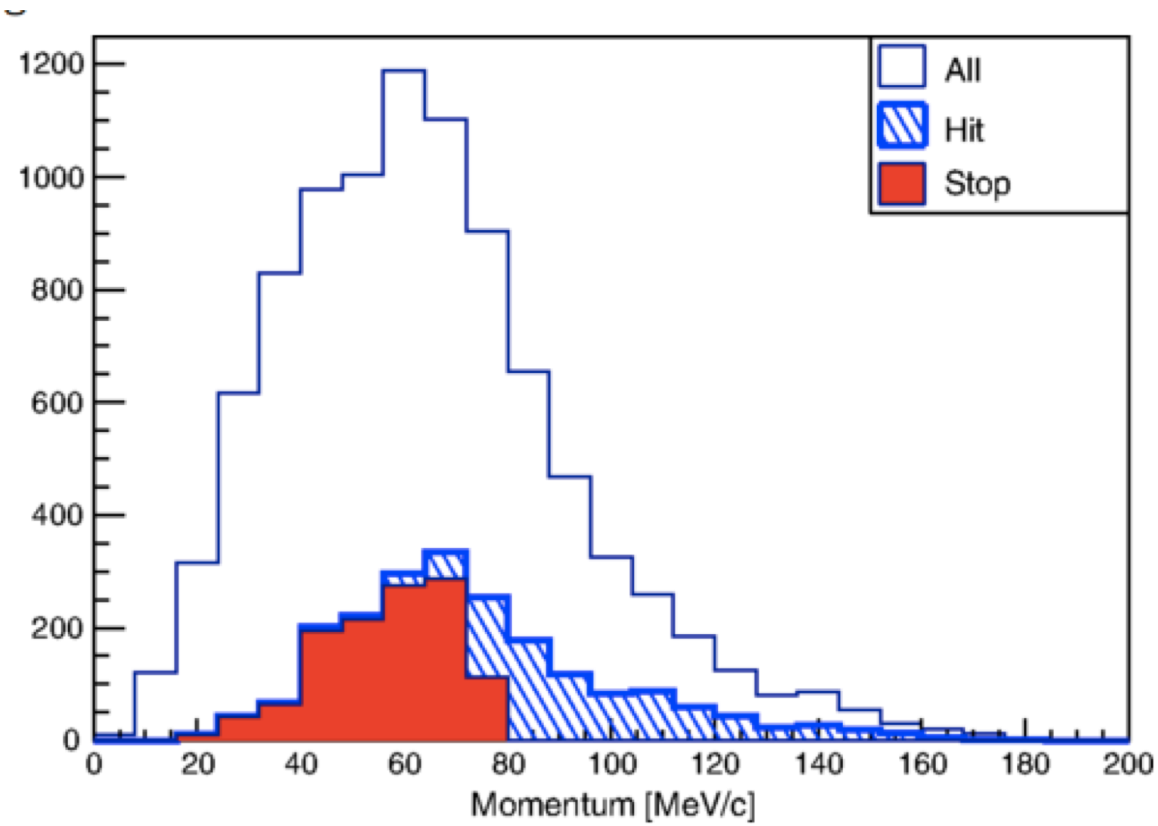
- pulsed proton beams
- advances in s/c magnets & detector resolution

Verification of muon yield

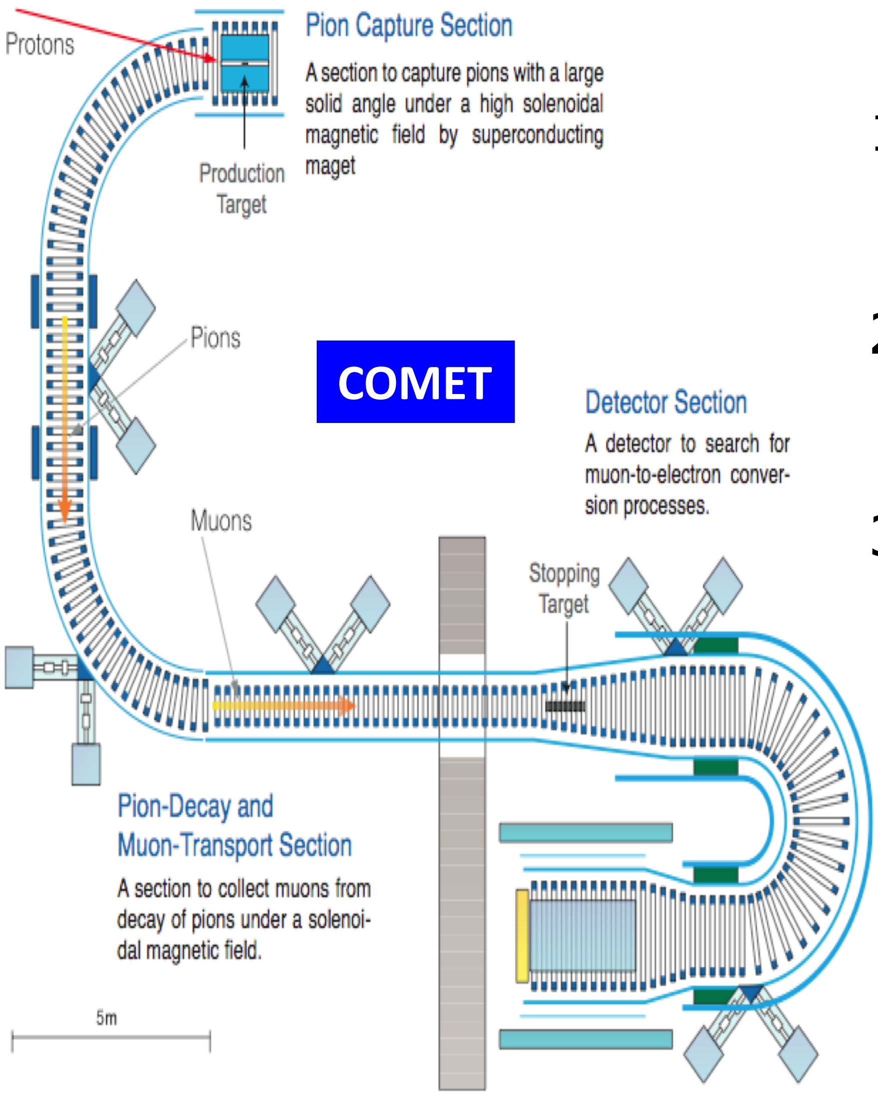
Delivering the world's most intense muon beam

S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017



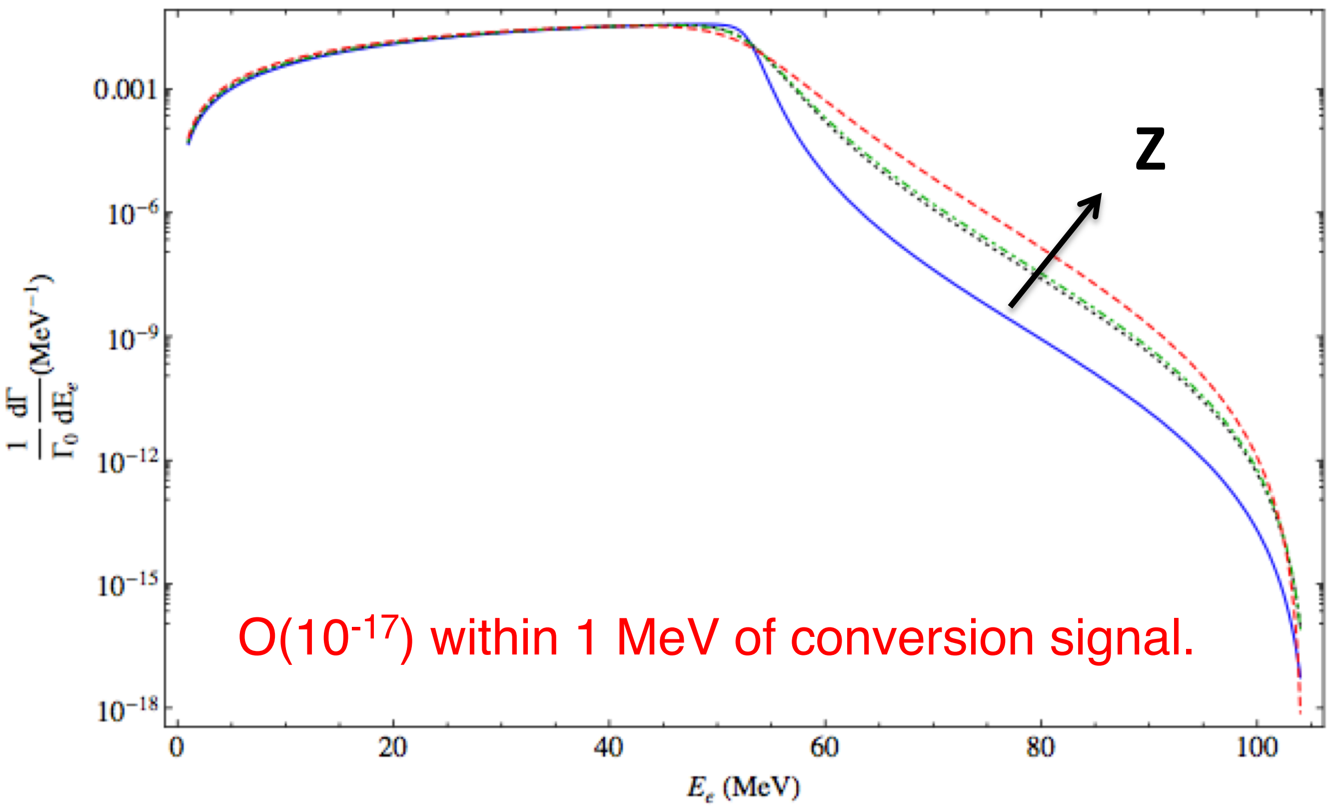
3 components



1. Muon production via intense pulsed, proton beam
2. Momentum selection of low-p negative muons
3. Momentum selection of high-p electrons

Backgrounds

Largest background is **D**ecay **I**n **O**rbit (**DIO**) of stopped muon.
In atom gives electrons beyond the free-muon 53 MeV end-point.

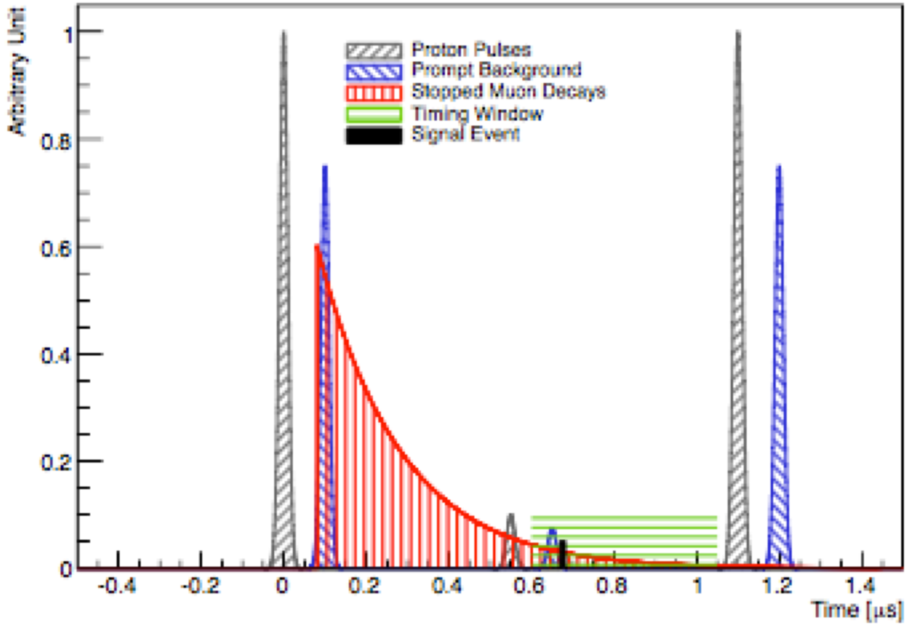


Controlled by detector resolution AND energy loss prior to detector.

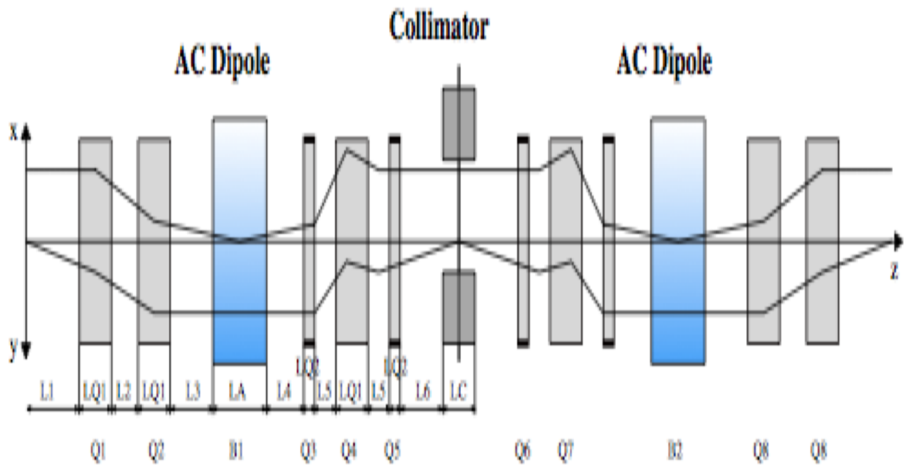
Need FWHM < 1 MeV

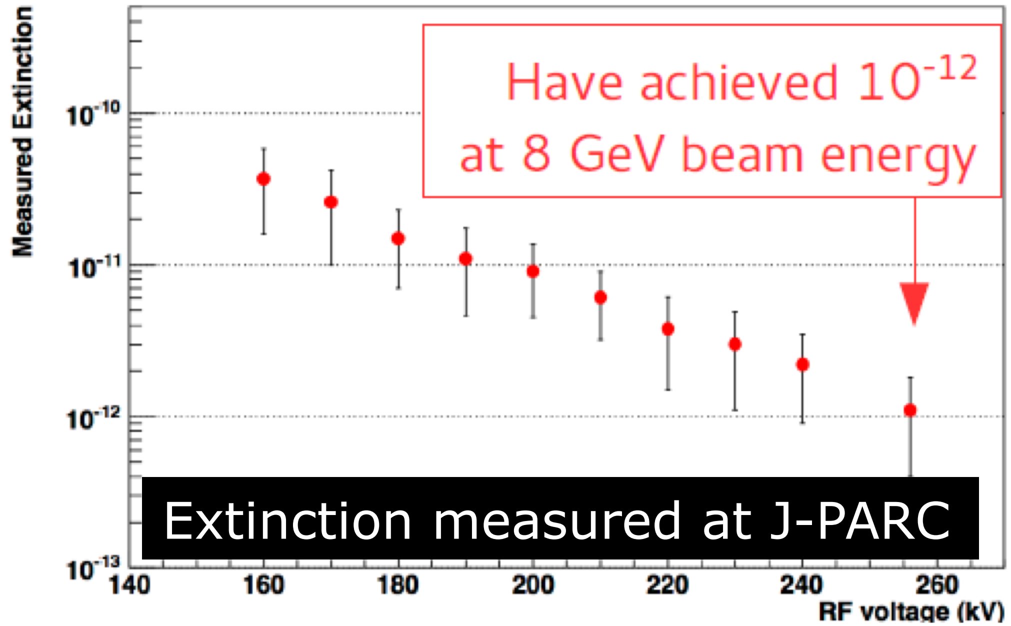
- also backgrounds from anti-p, cosmics, radiative pion capture (γ)

Extinction



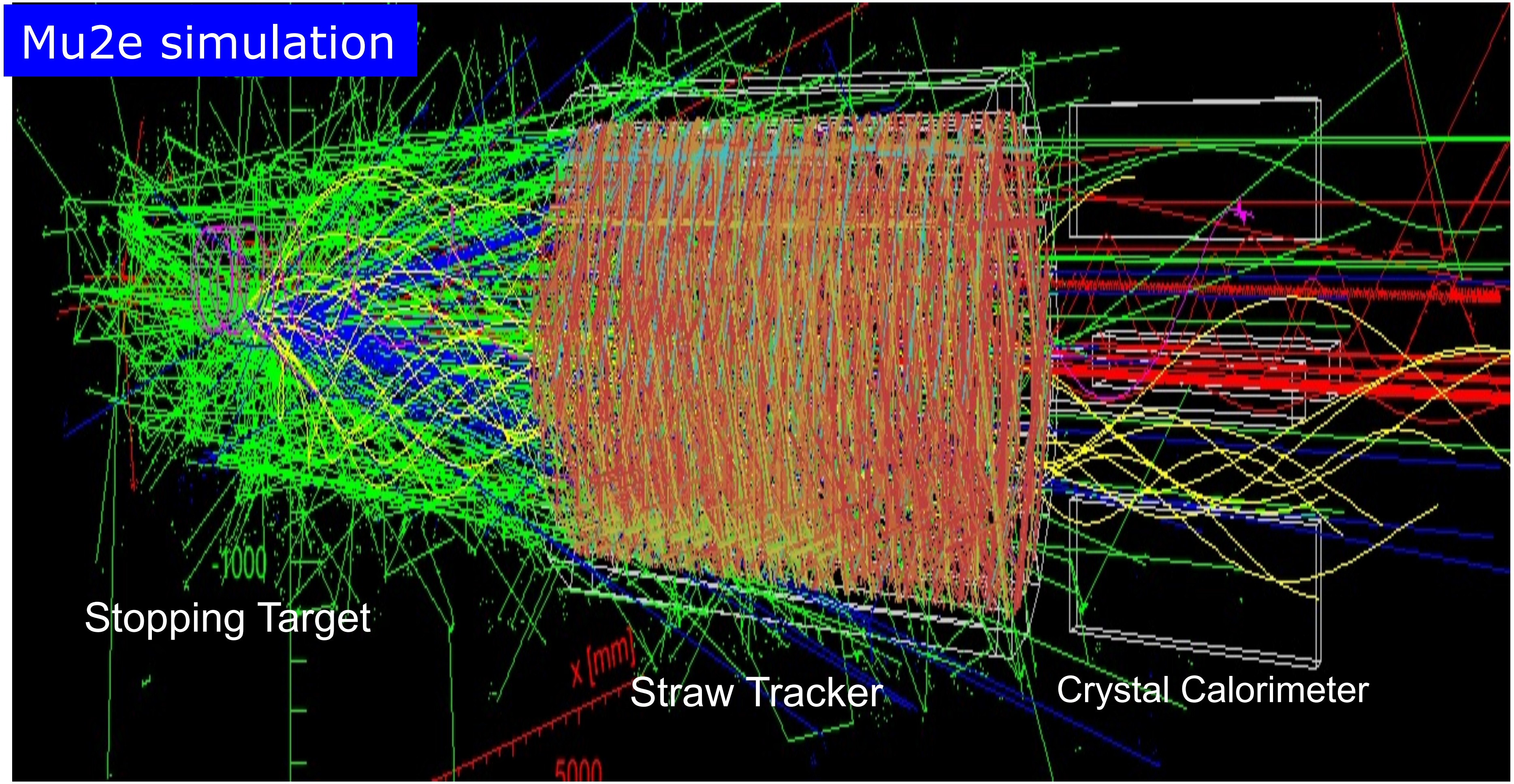
Background from secondary proton pulses in measurement time window





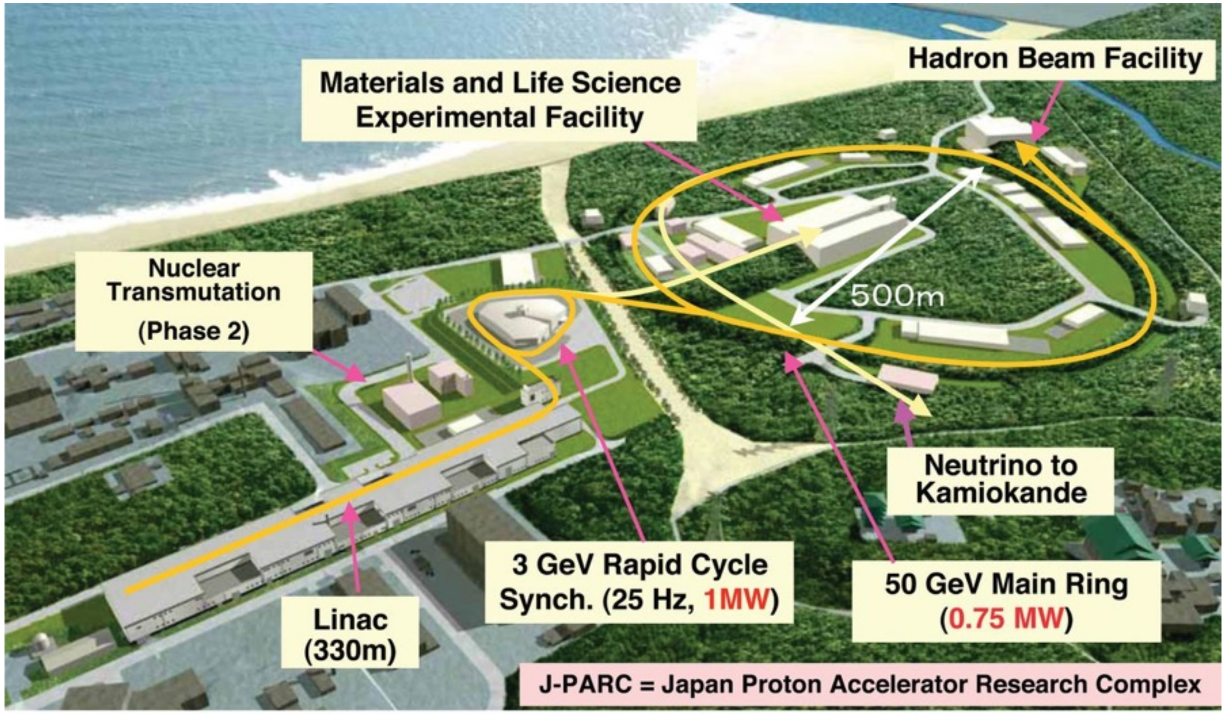
High Rate Environment (>10^{10} μ/s)

Signal identification requires excellent resolution at high-rate

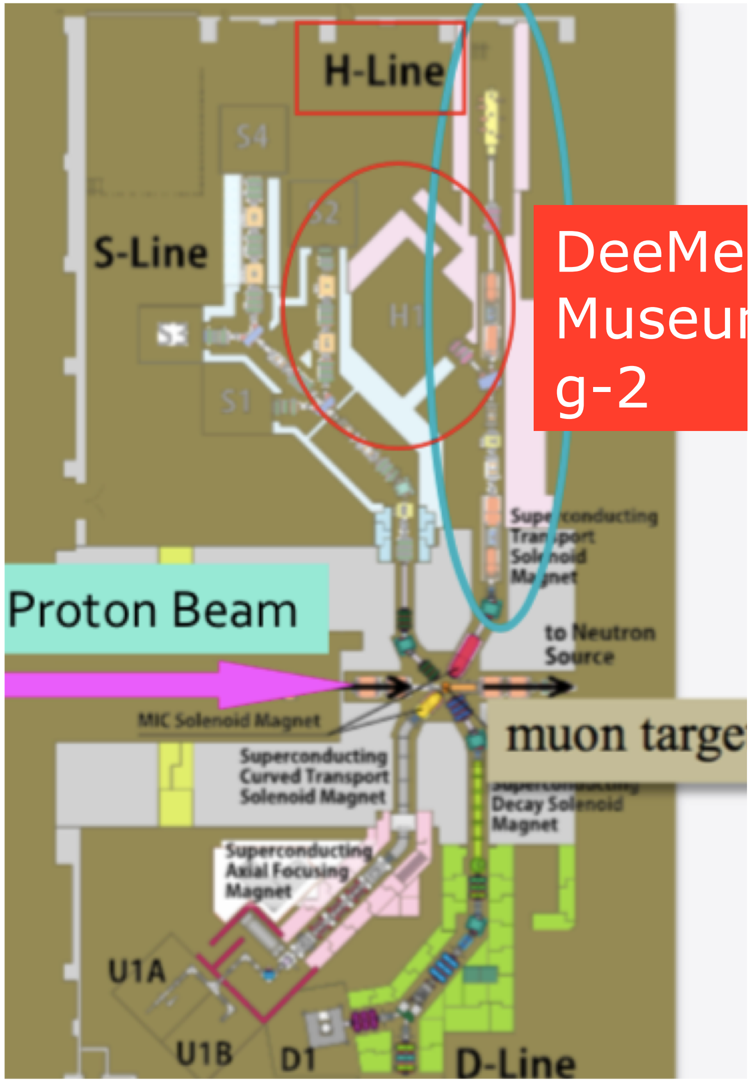


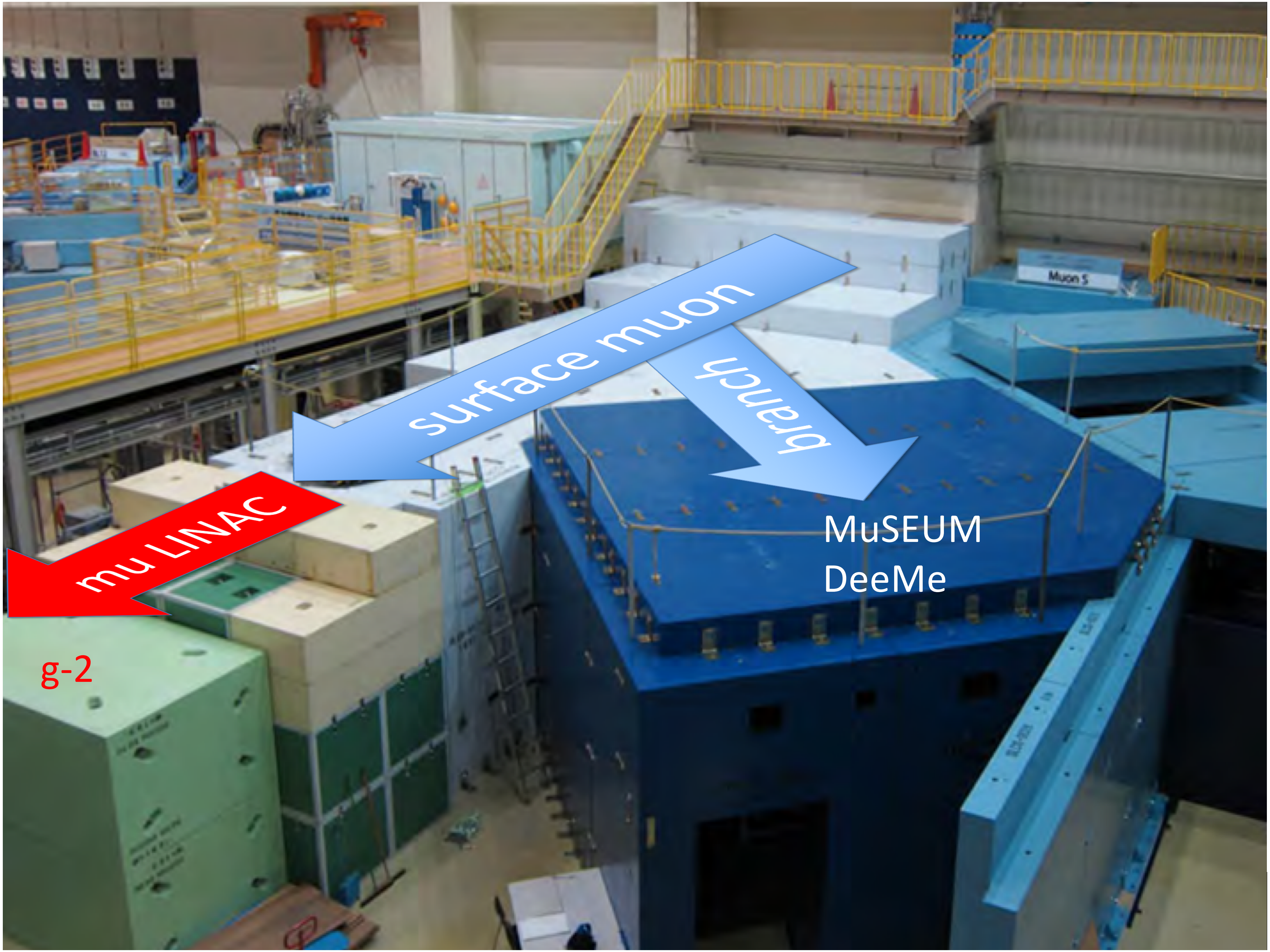
DeeMe @ J-PARC

Daiki Nagao (WG4)

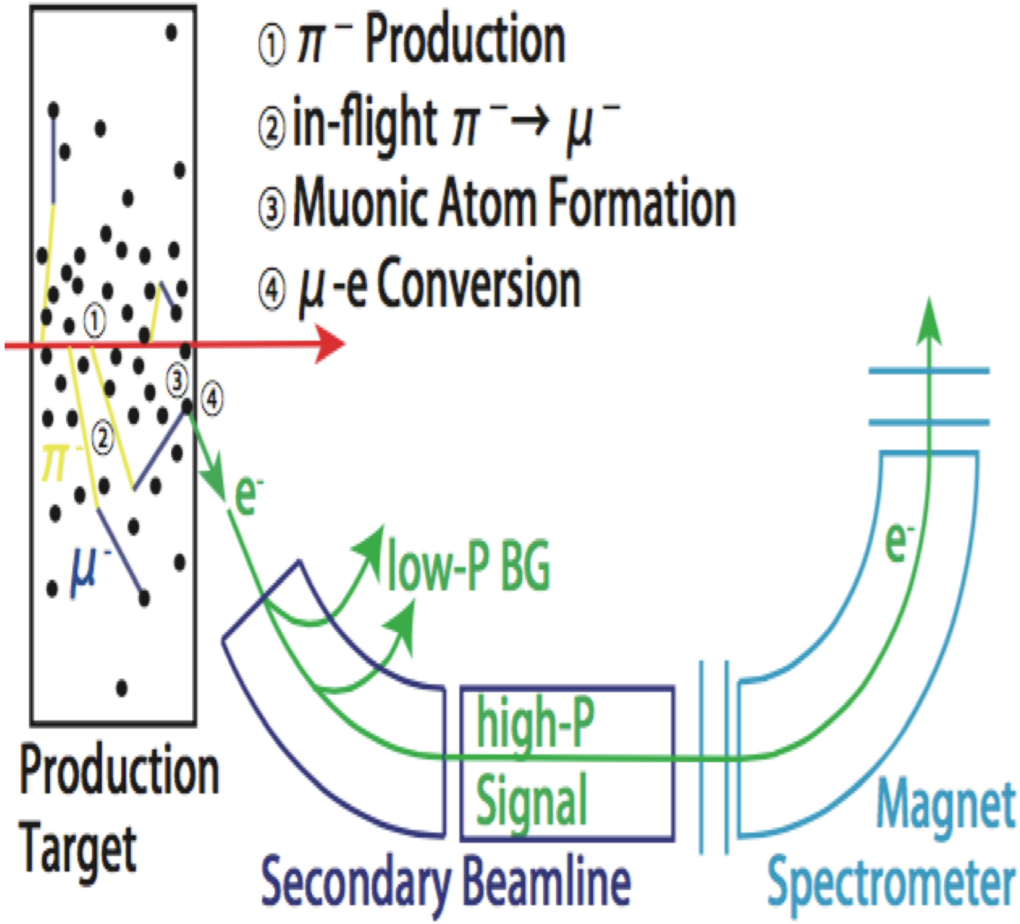


Joint Project between KEK and JAEA

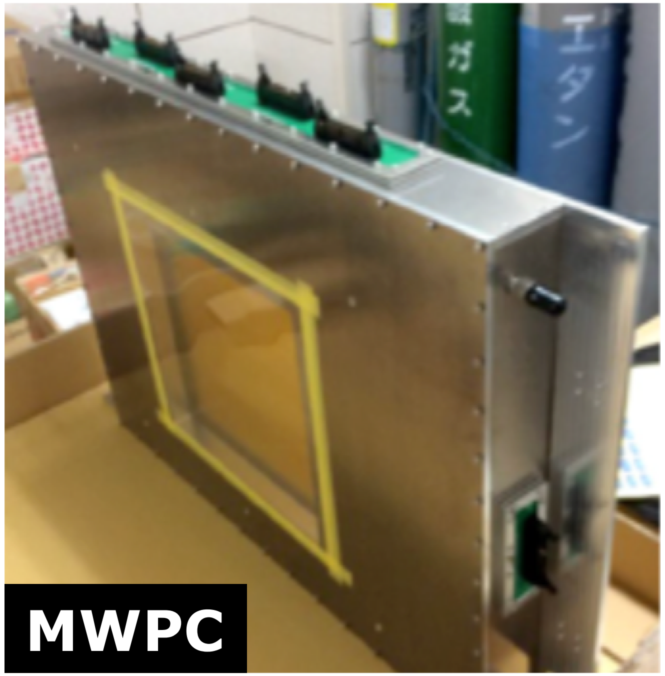



surface muon
branch
MuSEUM
DeeMe
mu LINAC
g-2
Muon 5

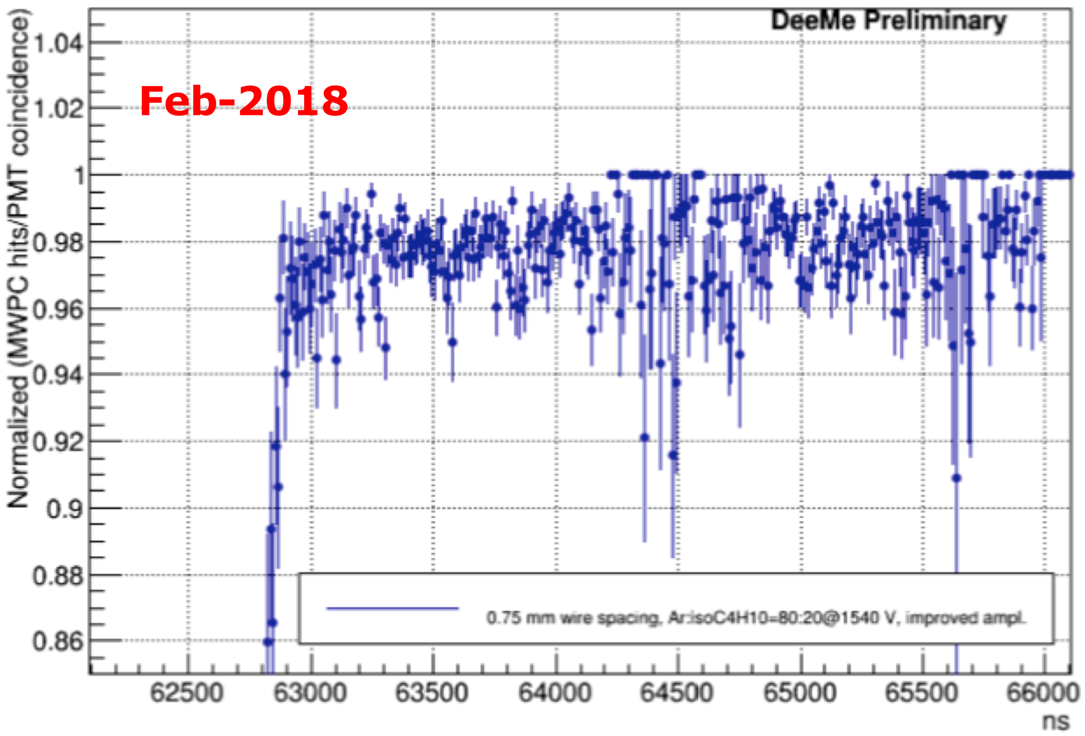
DeeMe @ J-PARC

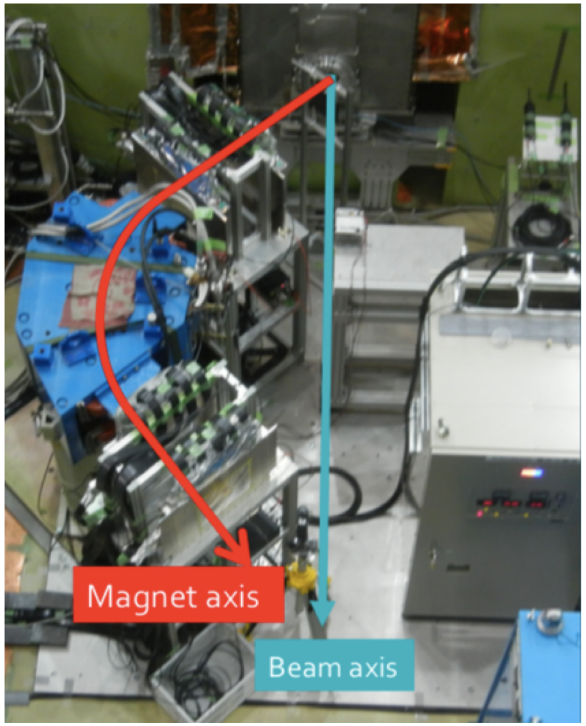


- 3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e-
- 4 MWPCs with Δp=0.5 MeV



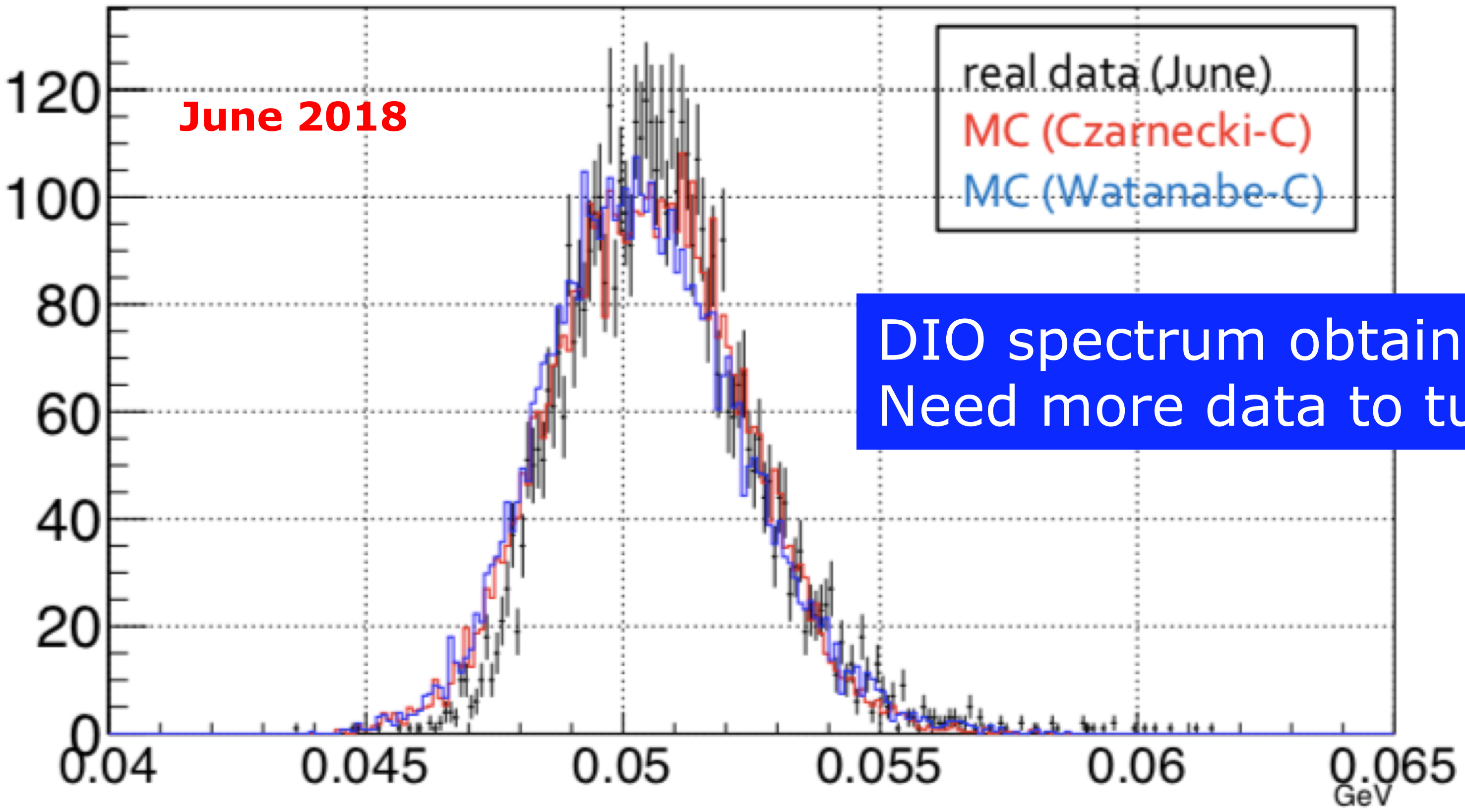
DeeMe @ J-PARC





MWPCs @ 98%
H-line being built : expected to start operating in 2019

DeeMe @ J-PARC



DIO spectrum obtained.
Need more data to tune MC models

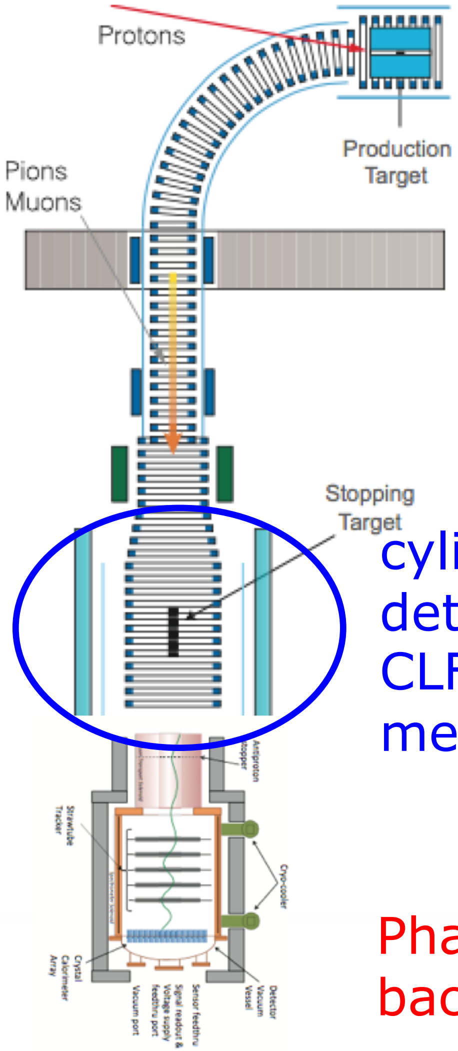
Phase-1 (2019) : C target
Phase-2 : SiC target

COMET @ J-PARC

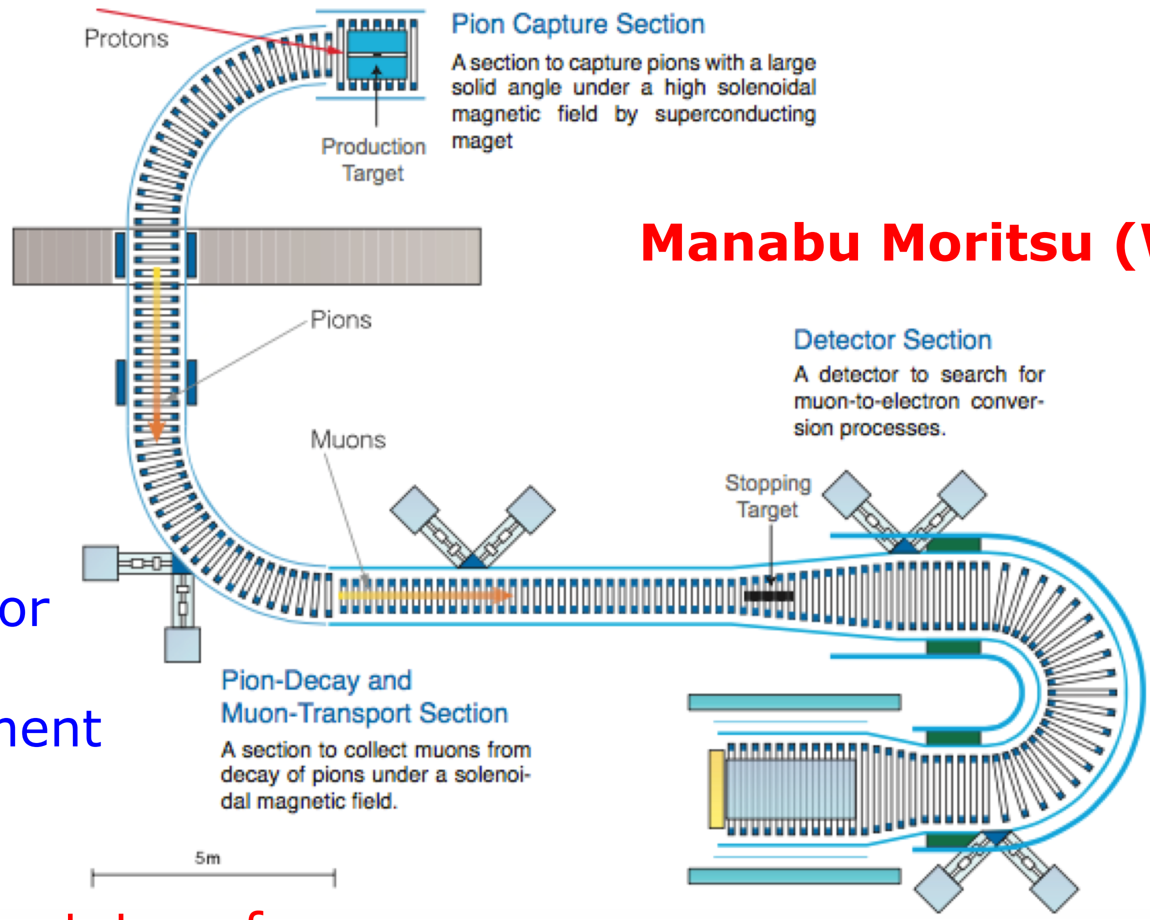
Phase-I

Phase-II

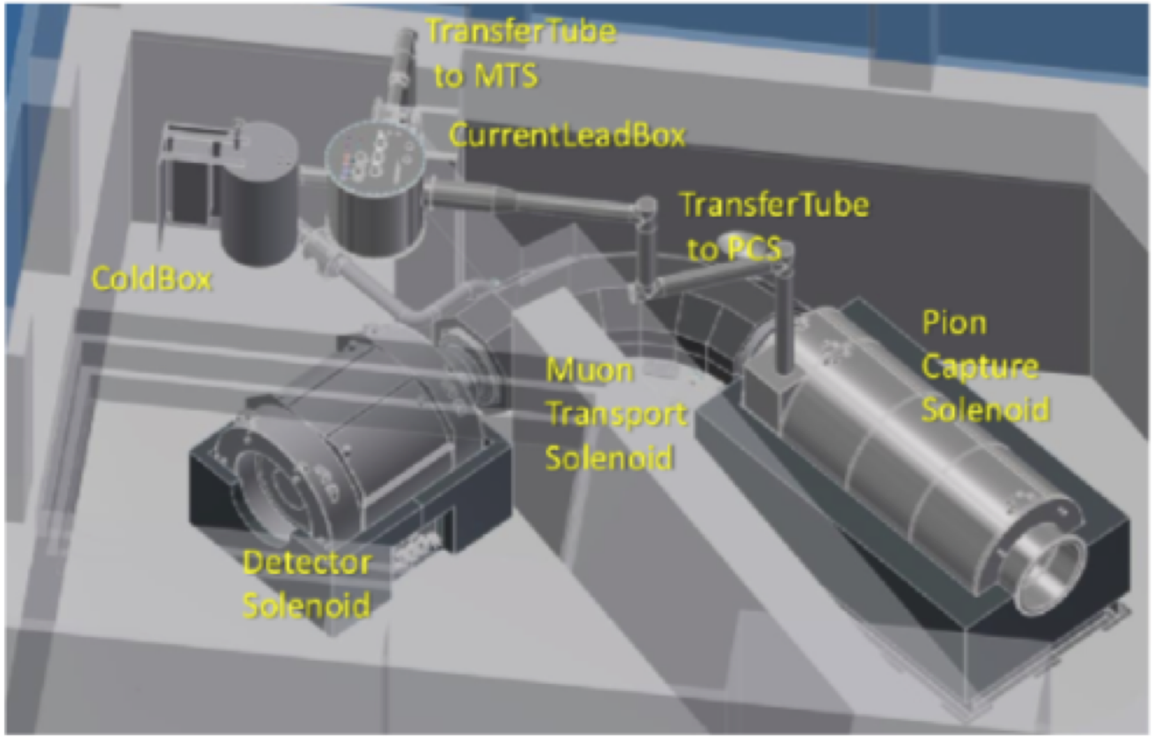
Manabu Moritsu (WG4)

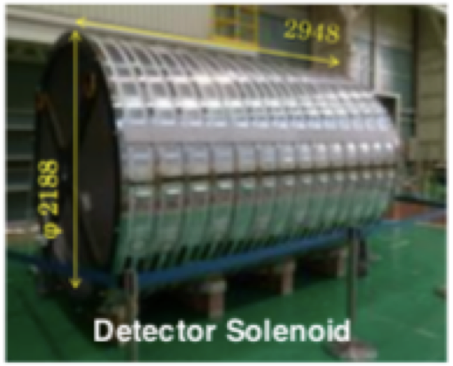


cylindrical detector for CLFV measurement

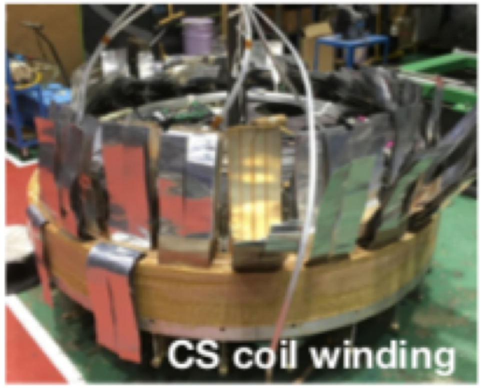


Phase-II prototype for background characterisation



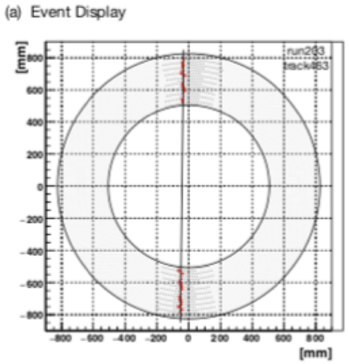


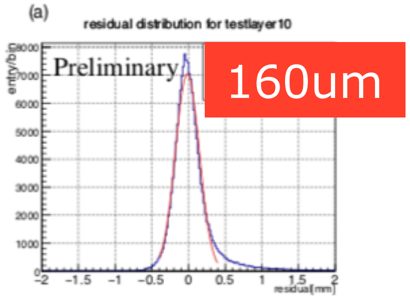
- **Capture solenoid:**
  - Coil winding & cold mass assembly in progress. Cryostat design ongoing.
- **Transport solenoid:**
  - Installed and ready for cryogenic test
- **Bridge & Detector solenoids:**
  - DS coil ready. Cryostat design in progress.
- **Cryogenic System:**
  - Refrigerator test completed. Helium transfer tube in production

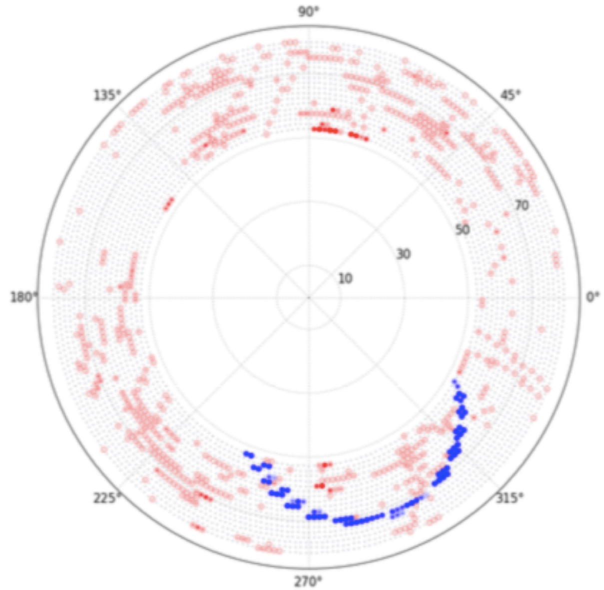


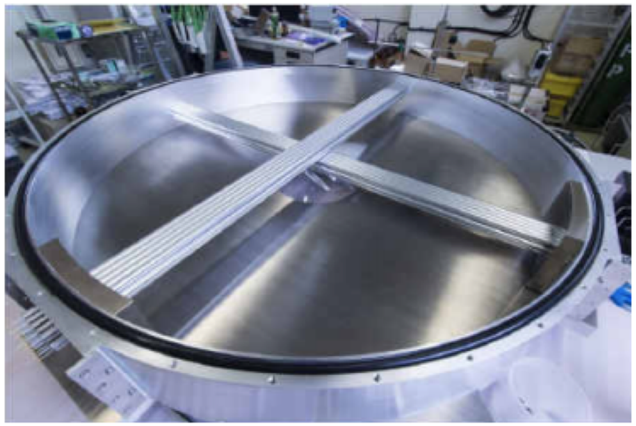
COMET

CDC cosmic-ray test is ongoing in KEK.
Good performance was obtained.

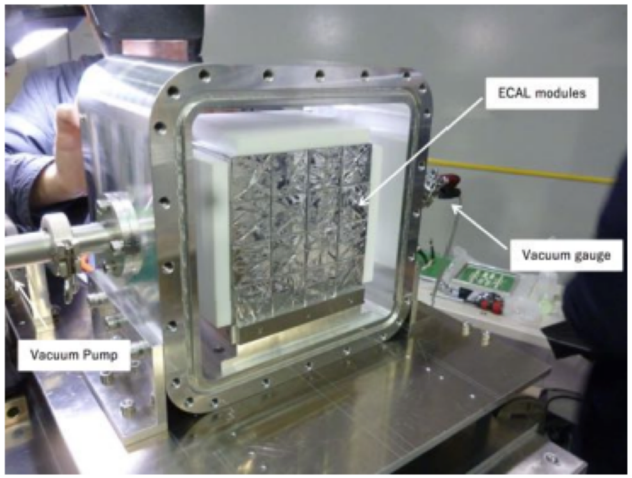








Straw Tracker prototype

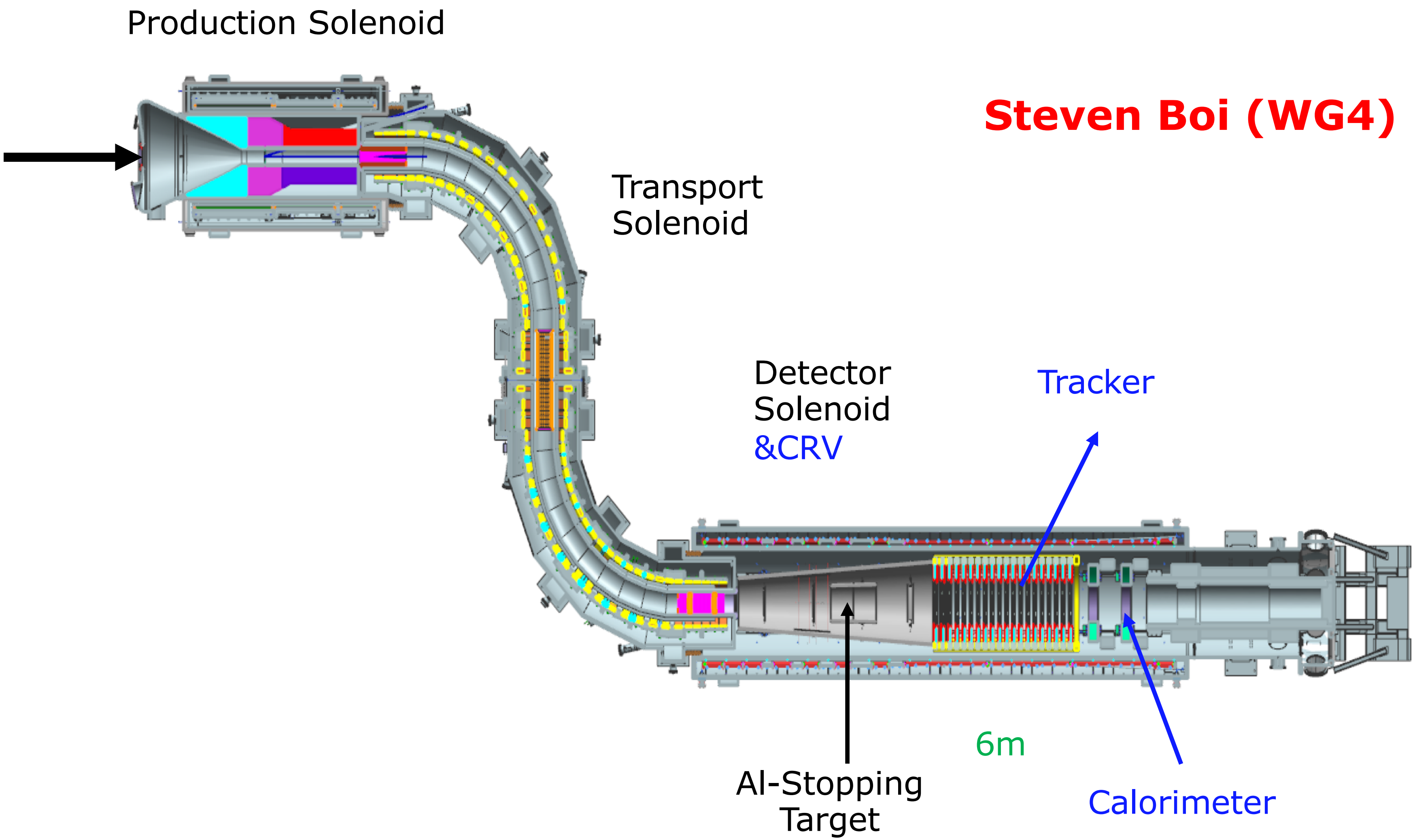


ECAL prototype

COMET

- Detectors completed in 2019
- Beamline construction underway

Mu2e @ FNAL



Steven Boi (WG4)

Mu2e

Mu2e Hall

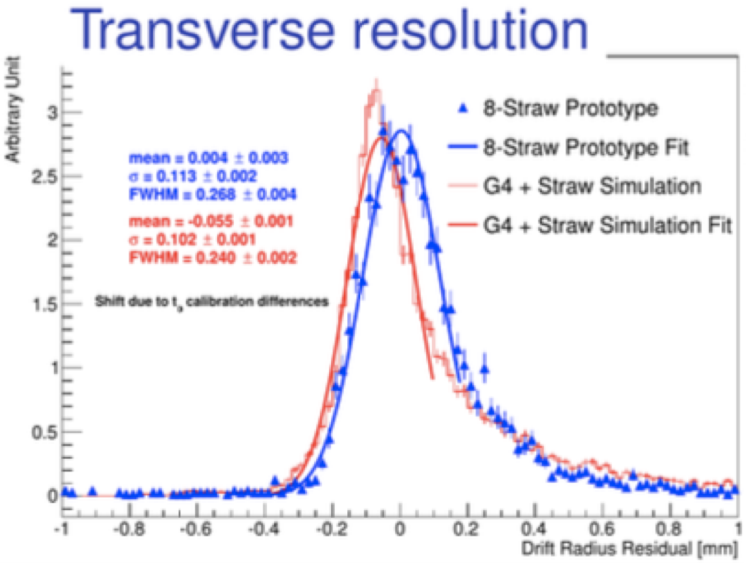
Transport Solenoid Production

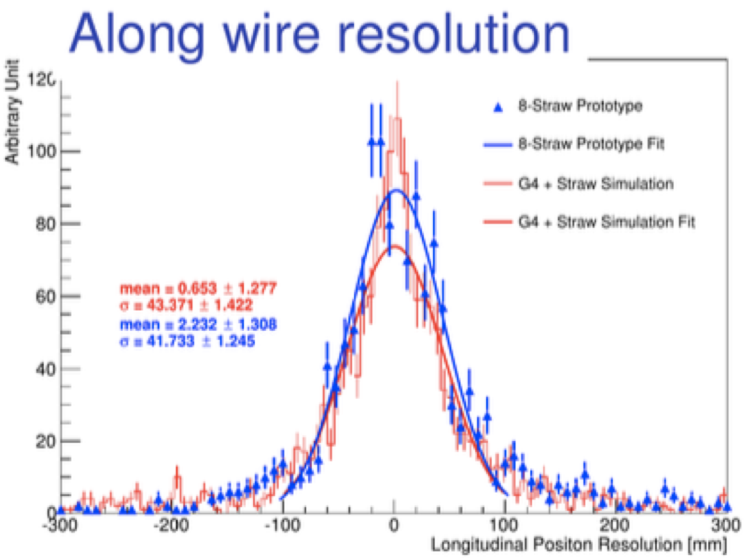
Tracker Production

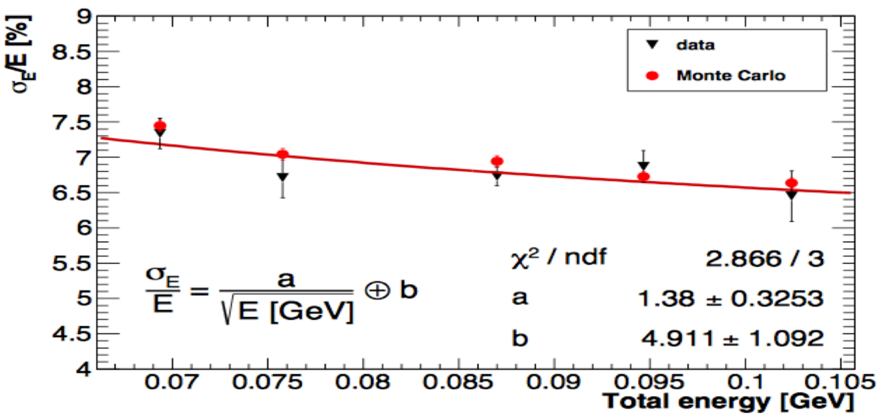
Production Target

Mu2e

- 8 straw prototype giving expected resolutions from LBL p testbeam







Testbeam and simulation agree : 6-7 % resolution at 100 MeV with detector with some leakage.

Expect to achieve design of 5% with full detector.

Most of beamline complete since required for g-2

Commissioning in 2020

CLFV Future

arXiv:1802.02599

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14],
J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12],
F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8],
M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30],
E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5],
A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8],
C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33],
F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18],
G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8],
K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5],
I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2],
S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8],
Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13],
J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21],
M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8],
R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2],
S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

PRISM/PRIME
J. Pasternak (WG4)

Mu2e-II
C. Group (WG4)

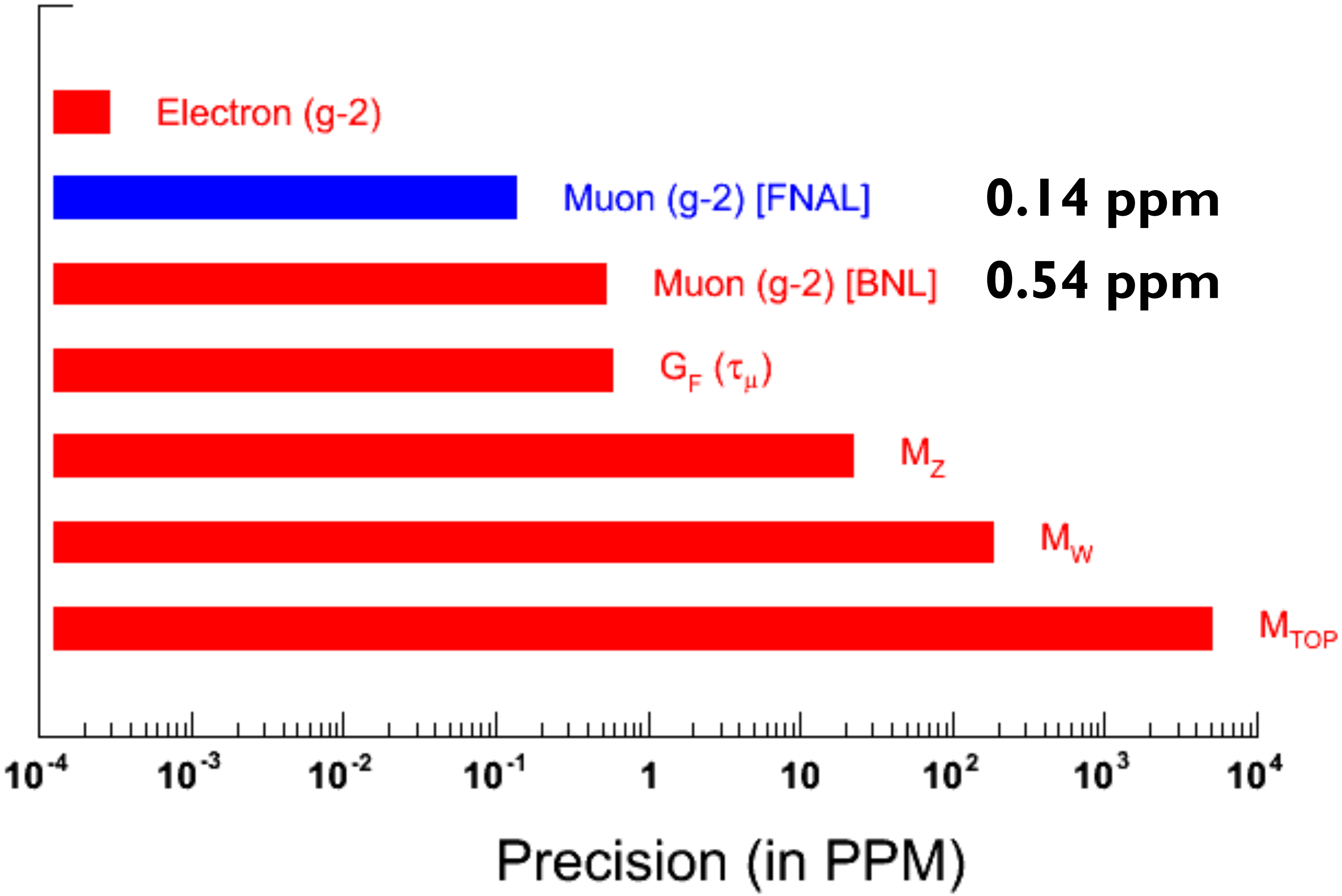
COMET-II

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

$$\mu^- N(A,Z) \rightarrow e^+ N'(A,Z-2)$$

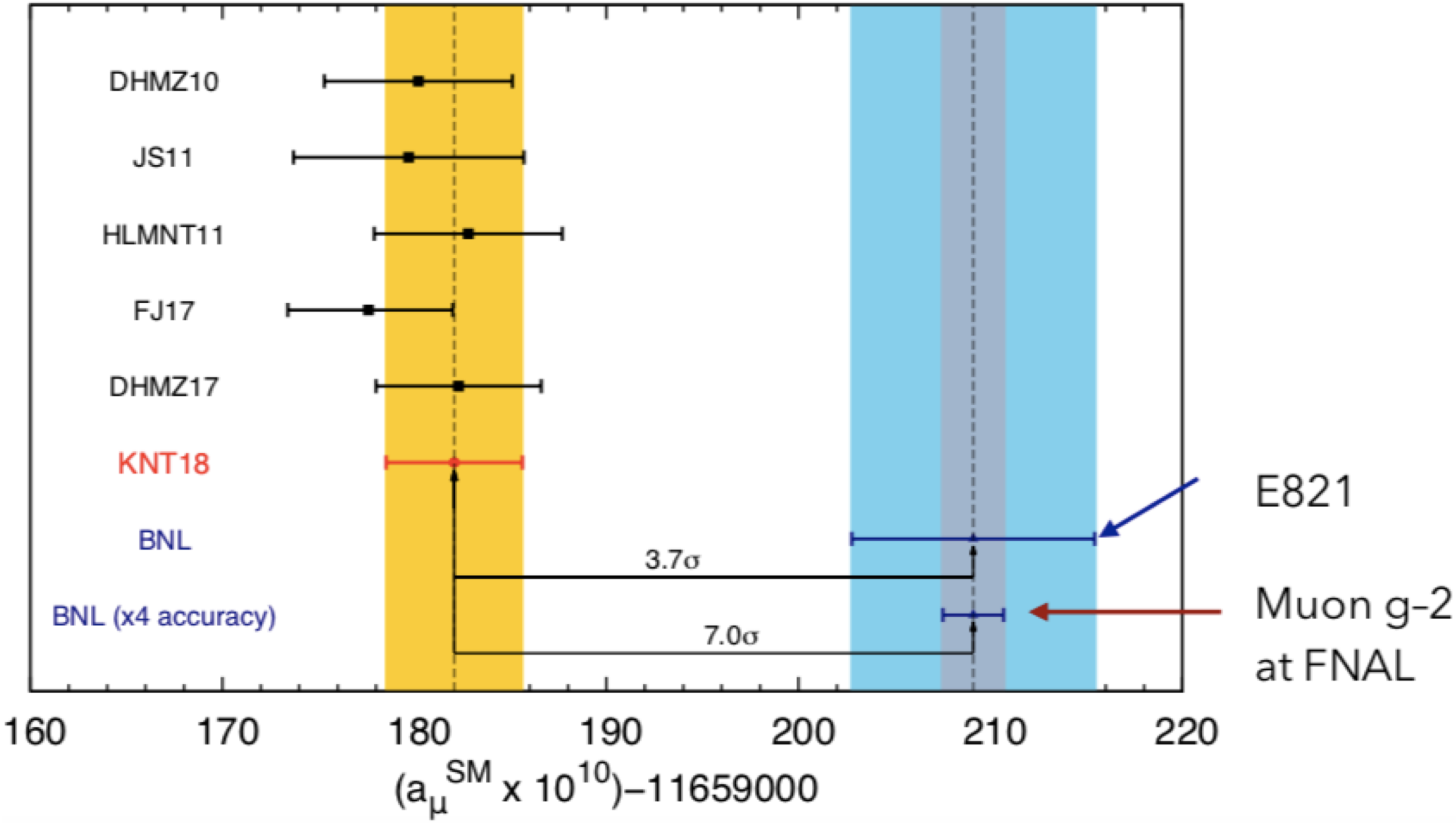
J. Sato : today (WG4)

Make a 0.14 ppm measurement



Current discrepancy with SM

Daisuke Nomura (WG4)



Complements LHC

Measurement probes much of the same TeV-scale BSM landscape as LHC.

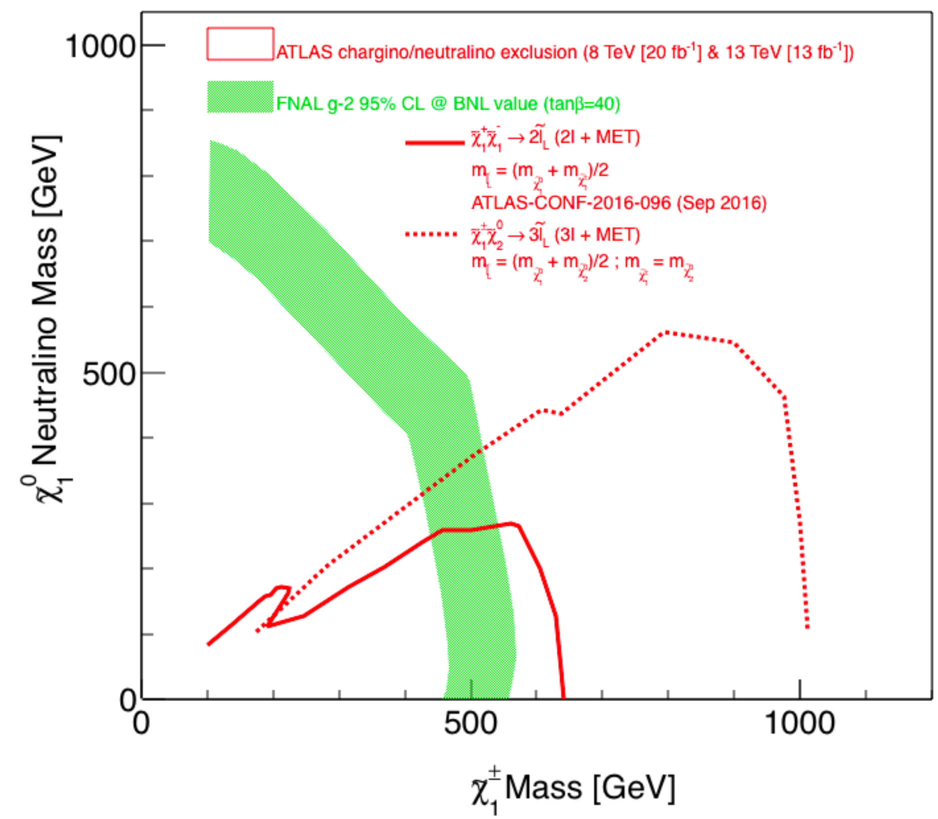
Large +ve anomaly wrt SM

Extended technicolor

SUSY, RS ED
Extra Higgs Doublet

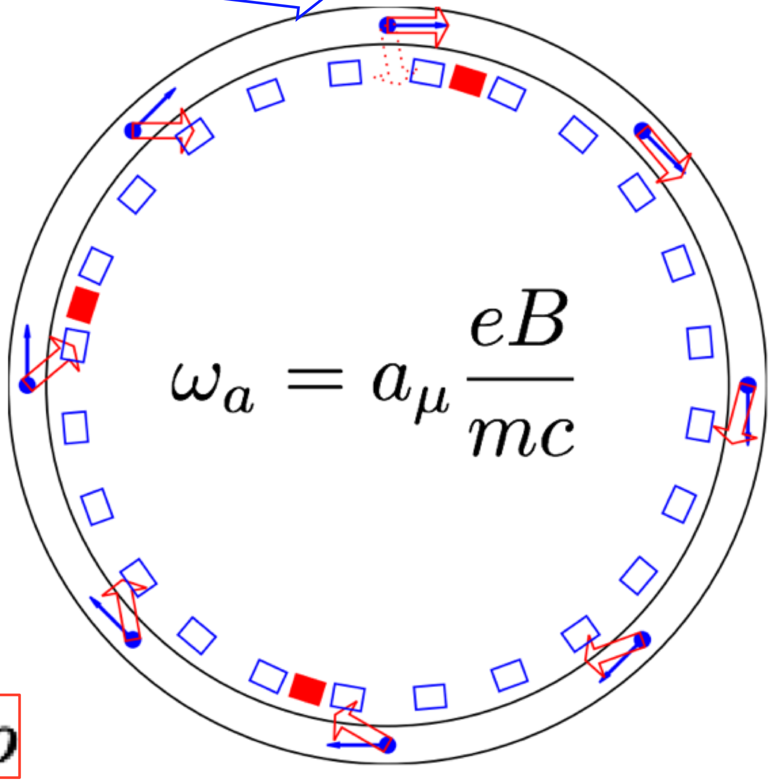
Z', W', Little Higgs,
Universal ED

Value consistent with SM



Methodology

Inject 3.09 GeV muons into a storage ring (B = 1.45 T)



Exploit property that direction of e^+ from μ^+ decay is strongly correlated with μ^+ spin for highest energy e^+

B from Larmor precession frequency of free proton (NMR) ω_p

$$\frac{g-2}{2} = a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

The pieces

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\mathrm{ppt}$$

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\mathrm{ppb}$$

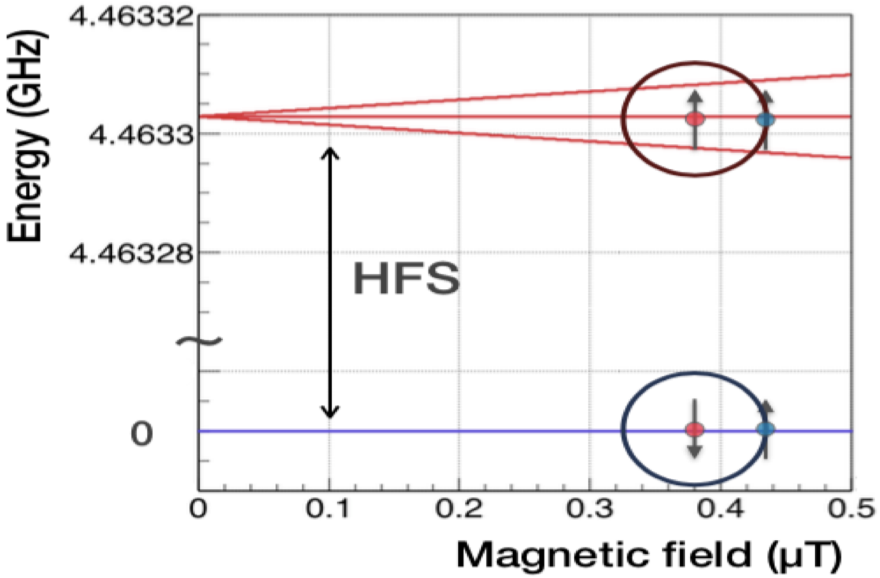
$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\mathrm{ppb}$$

Sohtaro Kando (WG4)

MUSEUM experiment at J-PARC

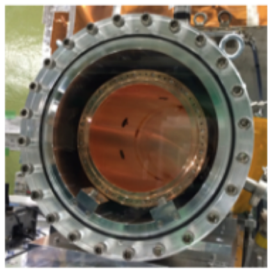
- Test bound state QED
- Reduce mμ/me by factor of 10

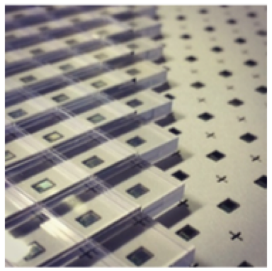
MUSEUM Experiment @ J-PARC



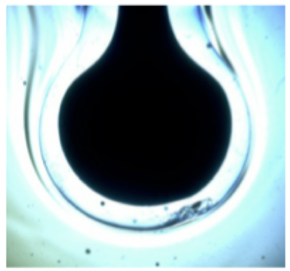
Measure in zero field (ZF) and high field (HF)

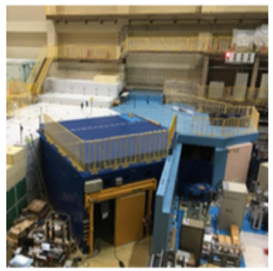
	2011	2013	2015	2017	2019
ZF			R&D	1st ZF, 2nd ZF	3rd ZF, 4th ZF?
HF	Proposal Submitted	R&D	R&D	New Beamline Construction	1st HF?

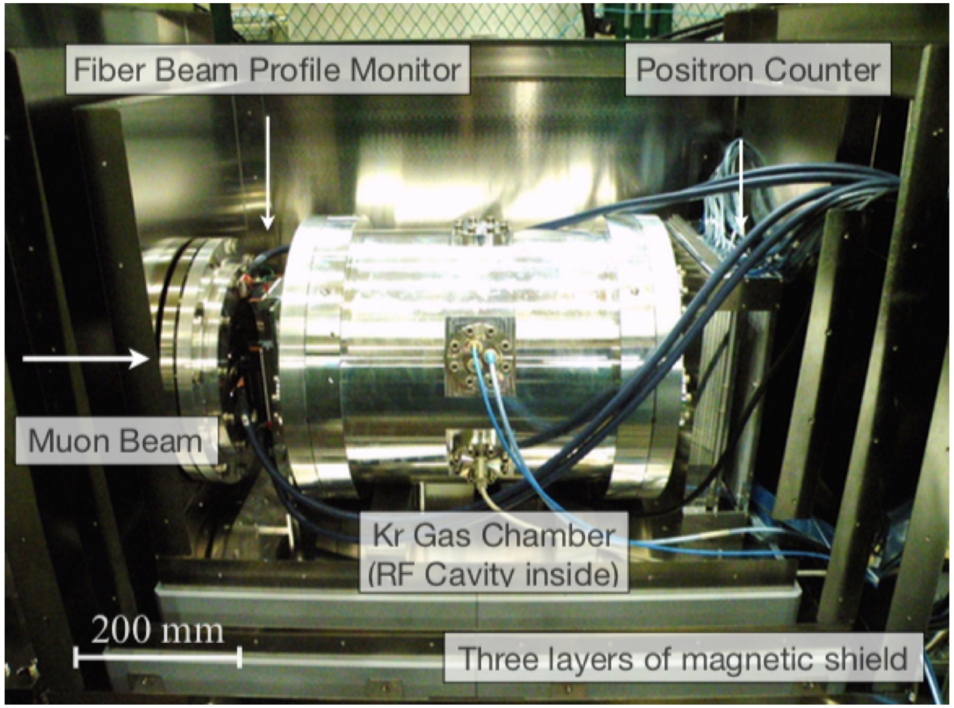

RF Cavity

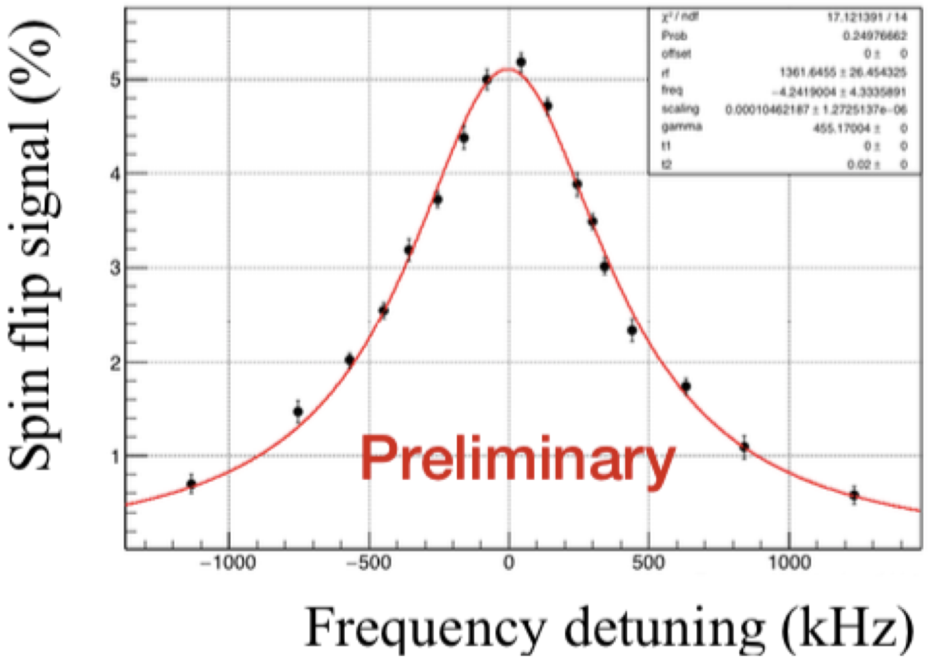

Detector


Magnet


Field probe

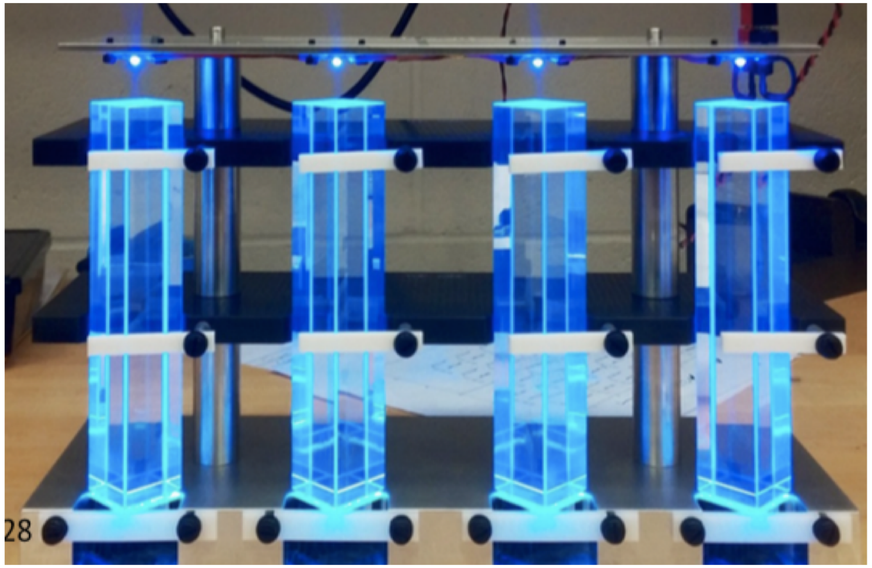

New beamline

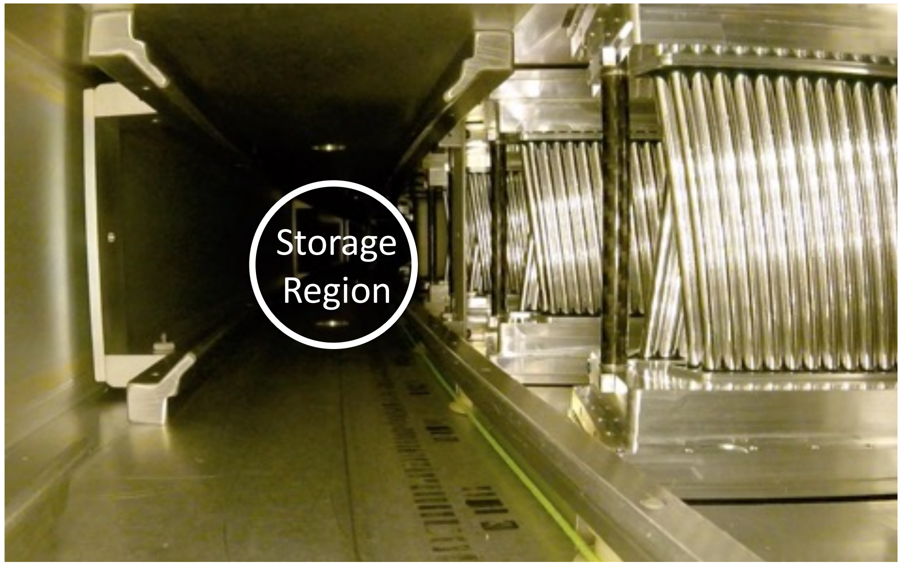




From 2017 data already have a measurement matching previous precision.
With new H-line (2019) huge improvement in stats

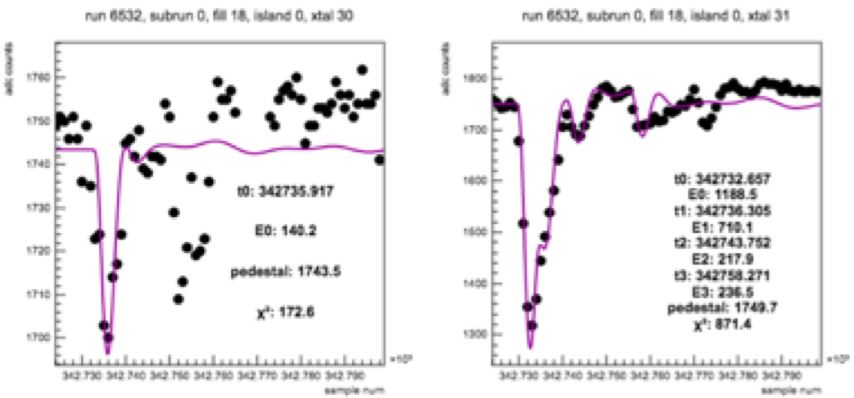
FNAL Muon g-2

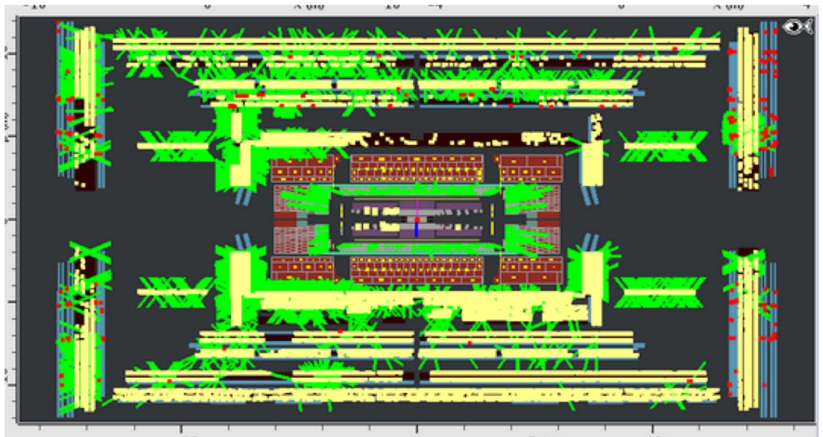




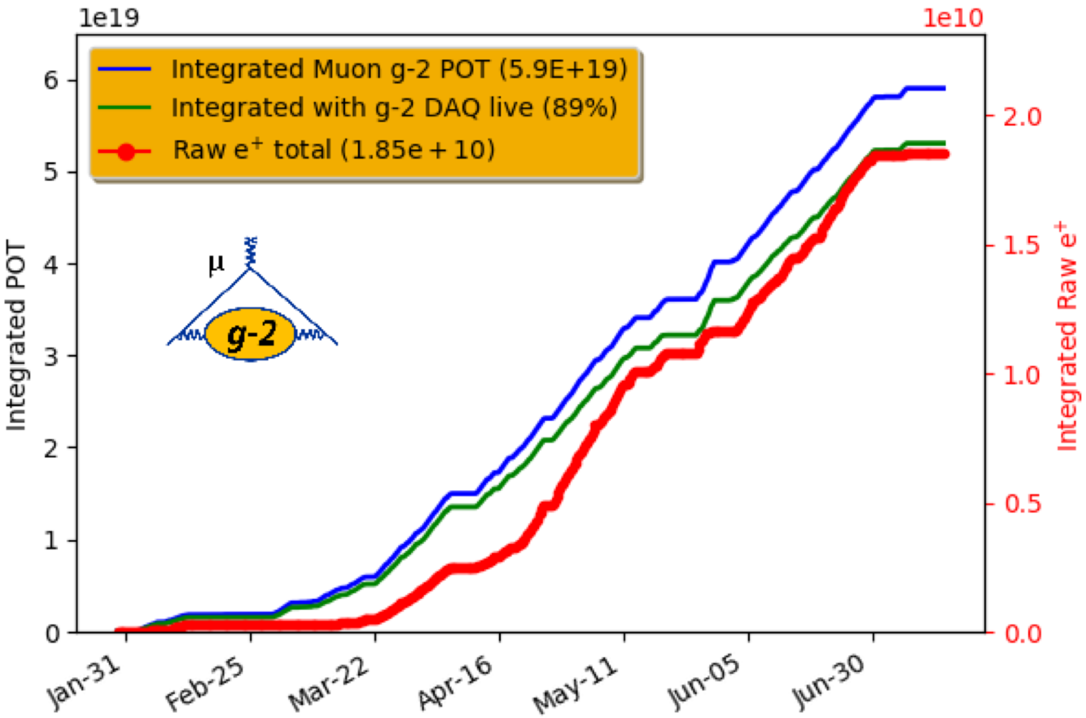
Jarek Kaspar (WG4)

First beam summer 2017





More stats than BNL



BNL recorded 9B e^+/e^- in 5 years

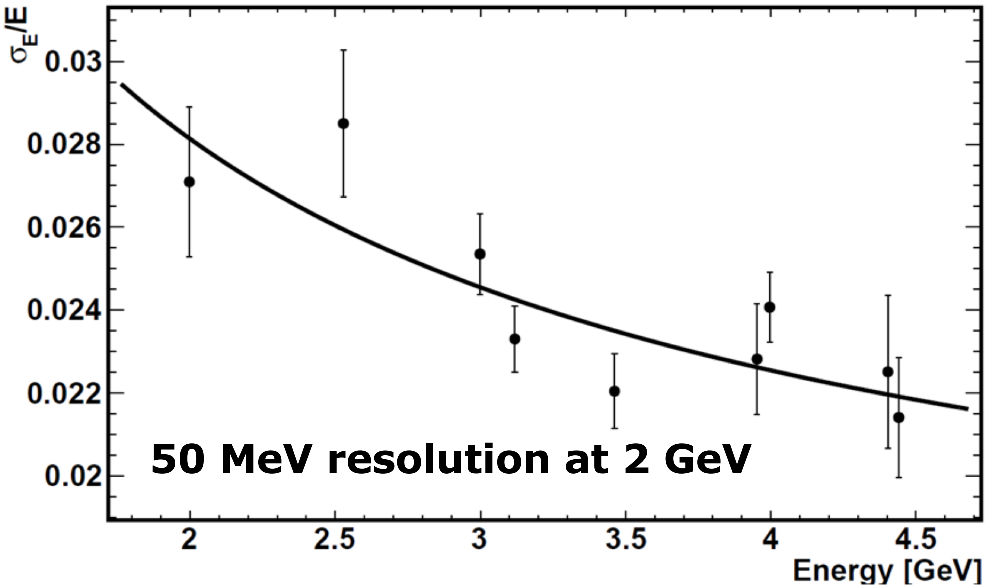
FNAL has recorded 18.5B e^+ in 5 months.

Aiming to record x20 BNL in next 2 years

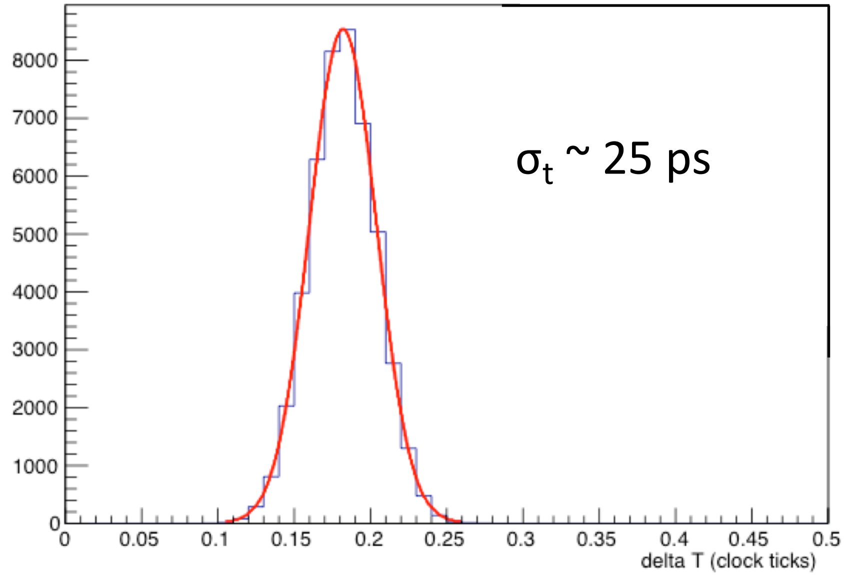
Calorimeter

NIM A 783 (2015),

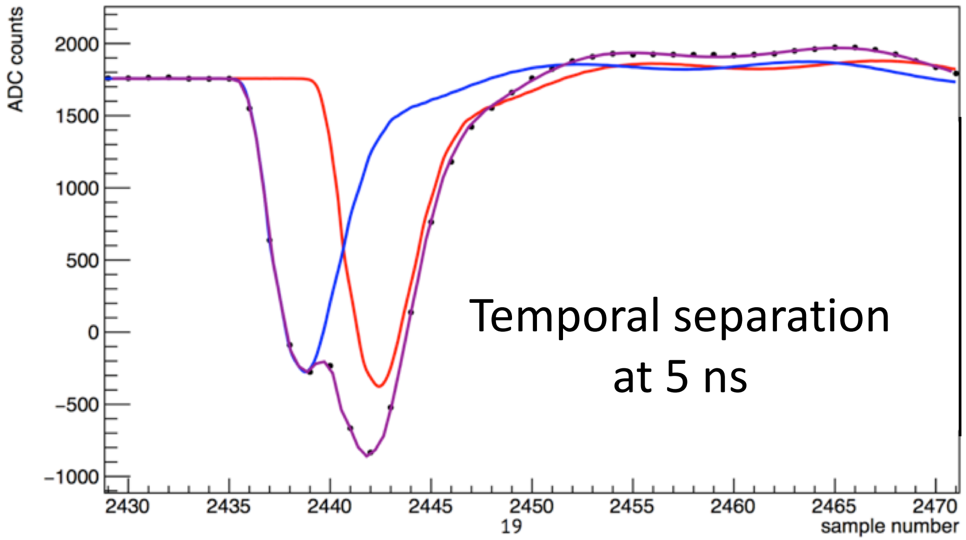
Energy Resolution



Timing Resolution

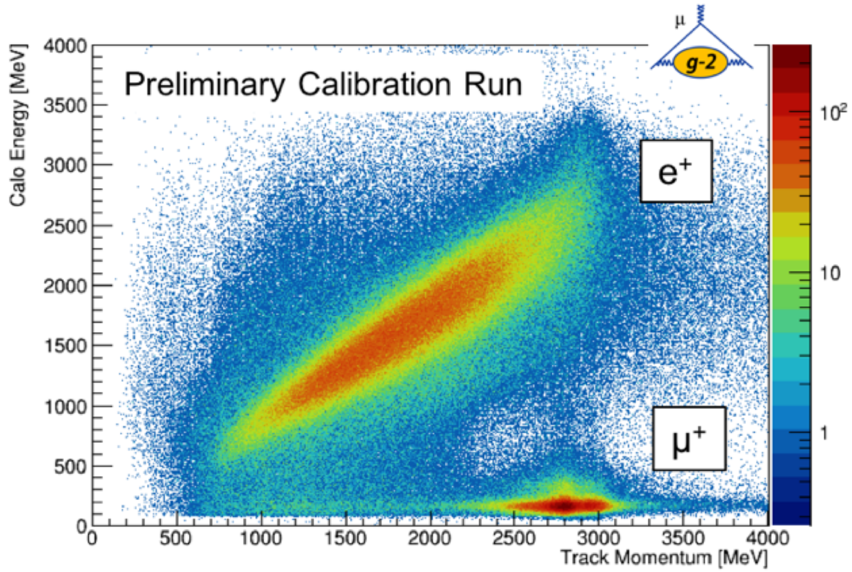


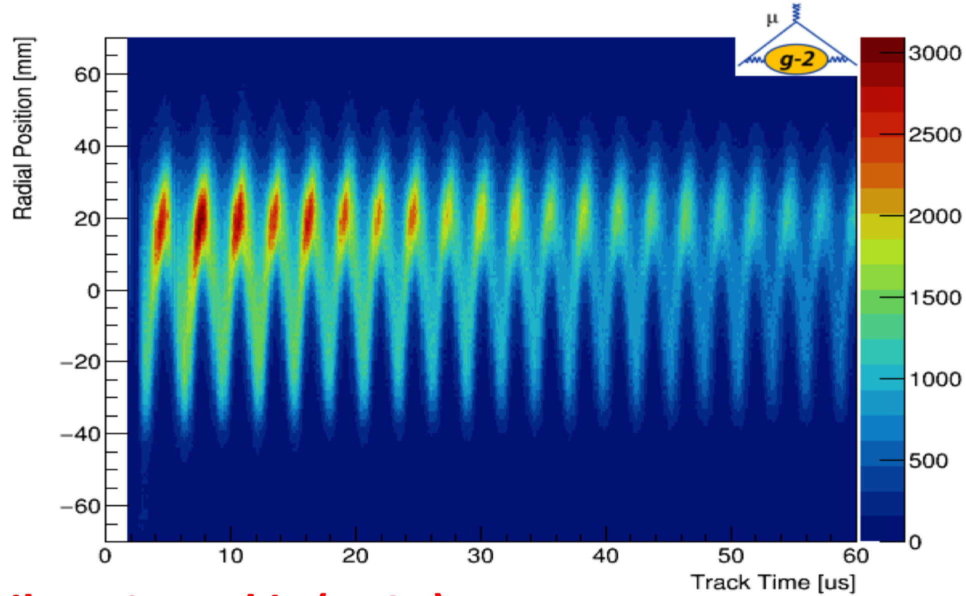
Electron pile-up



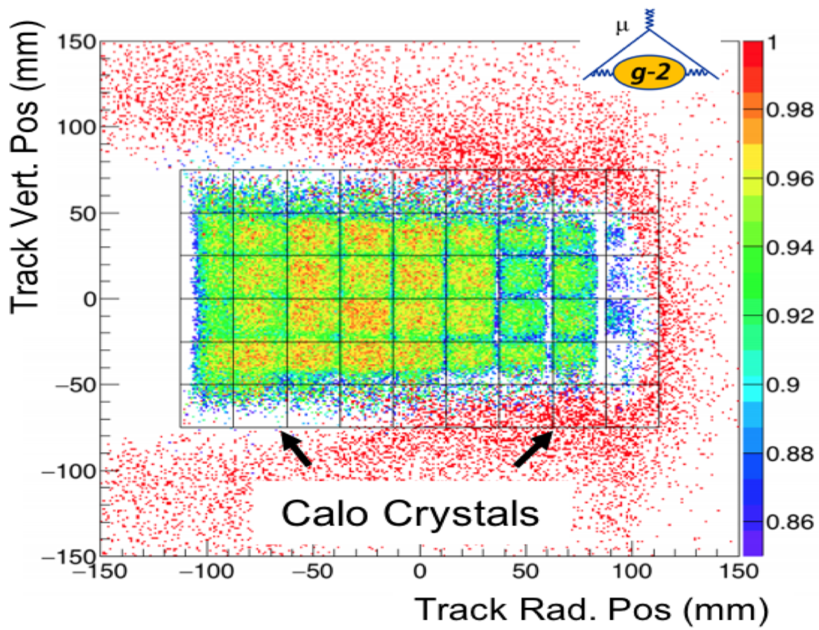
Laser Calibration System

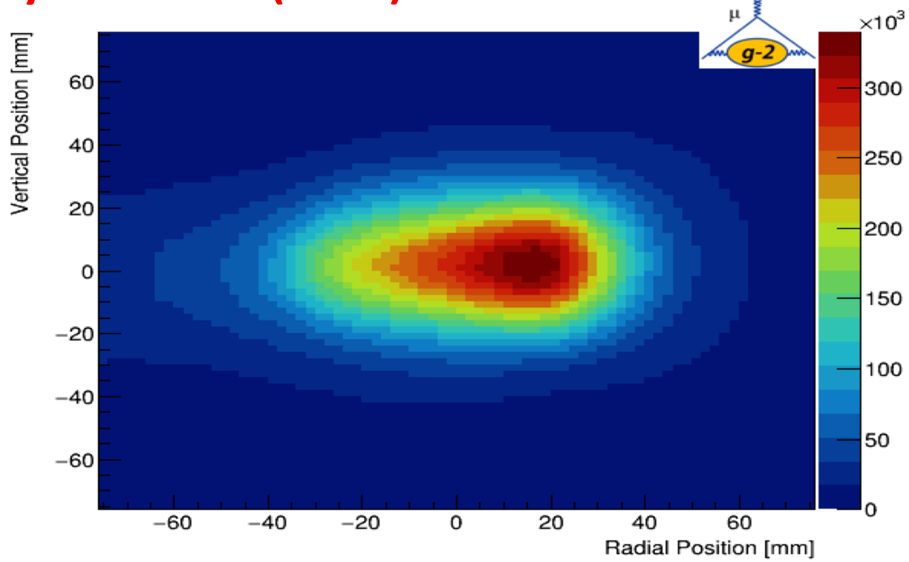
Trackers



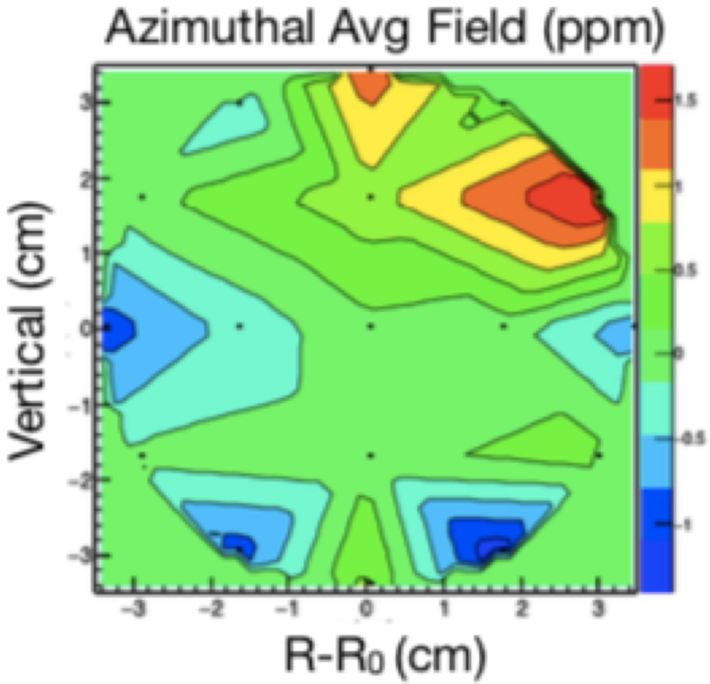


Diktys Stratakis (WG4)



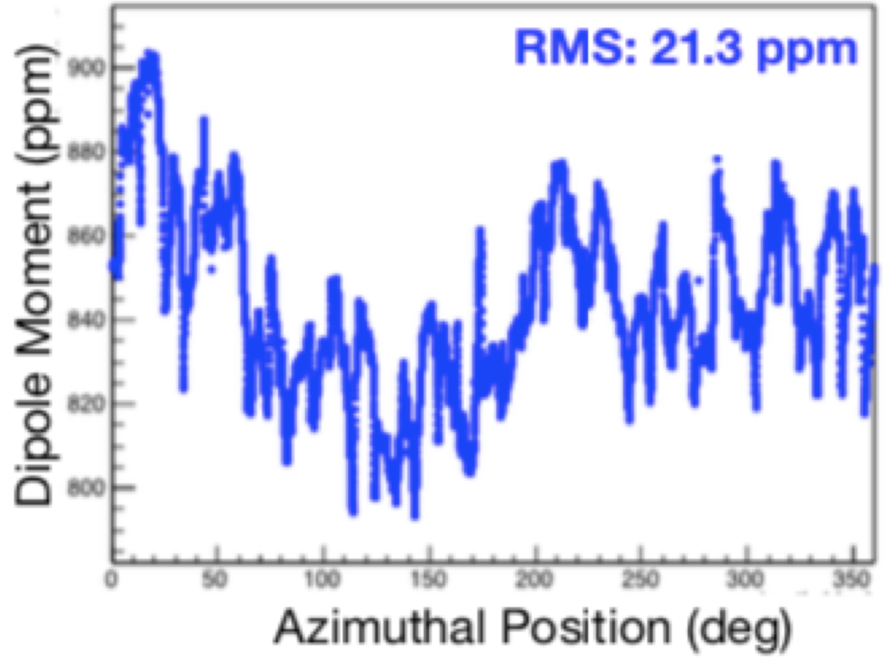


B-field uniformity

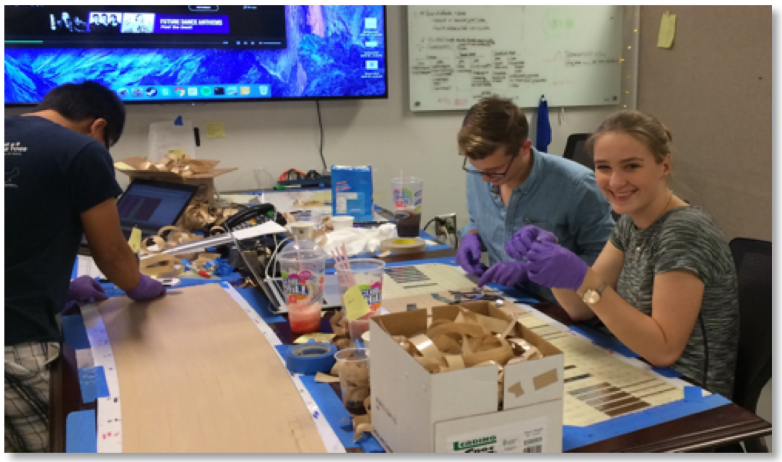


	Norm	Skew
Quad	0.50	0.76
Sext	-0.43	0.63
Octu	-0.07	0.35
Decu	0.23	0.08
Dipole	-0.0	

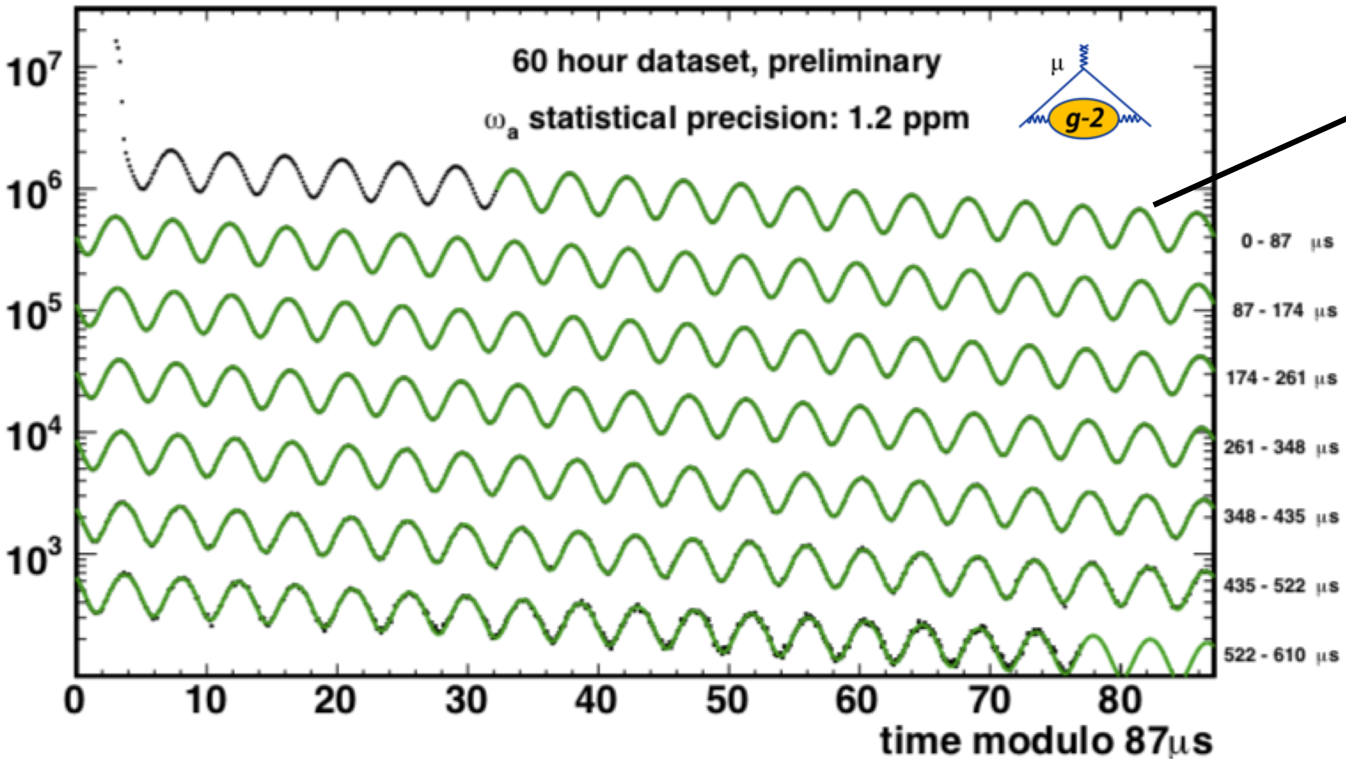
Preliminary



A B-field uniformity 3x better than BNL (x2 was goal)



Analysis of 2018 data well underway



$$\omega_a = a_\mu \frac{eB}{mc}$$

60hr dataset has similar precision to a one year (BNL 1999) dataset

Expect to publish the 2018 data before end of 2019.

Summary

Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC with a significant synergy with the neutrino programme.

Many projects will have their first results/start data taking in the next 2-3 years.

- g-2 : continue running in 2018/19/20
- MUSEUM : running and move to higher stats in 2019
- DeeMe : start run in 2019
- COMET-I : ready for beam in 2019
- Mu2e : commission in 2020.

Good times for pulsed muons !

Backup

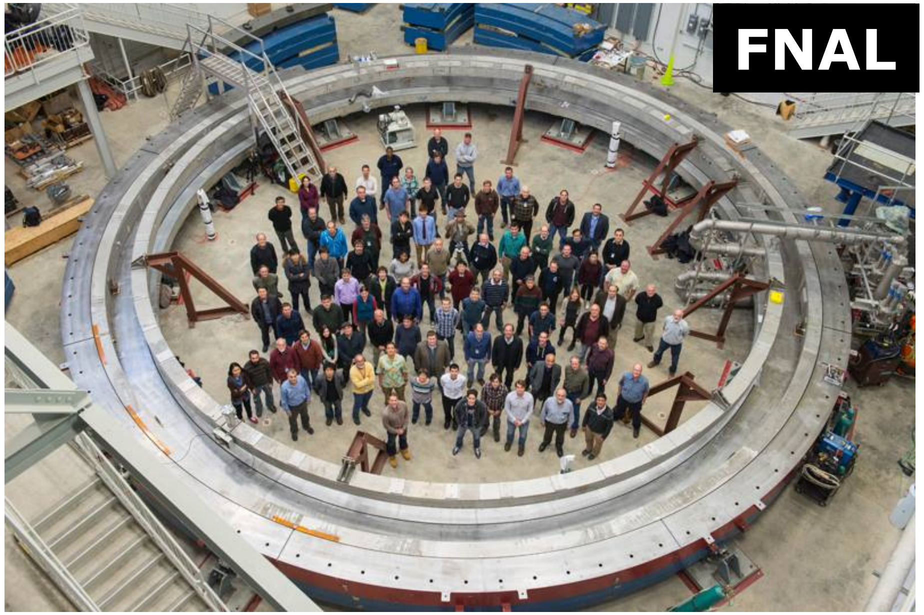
B-field / ω_p systematics

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

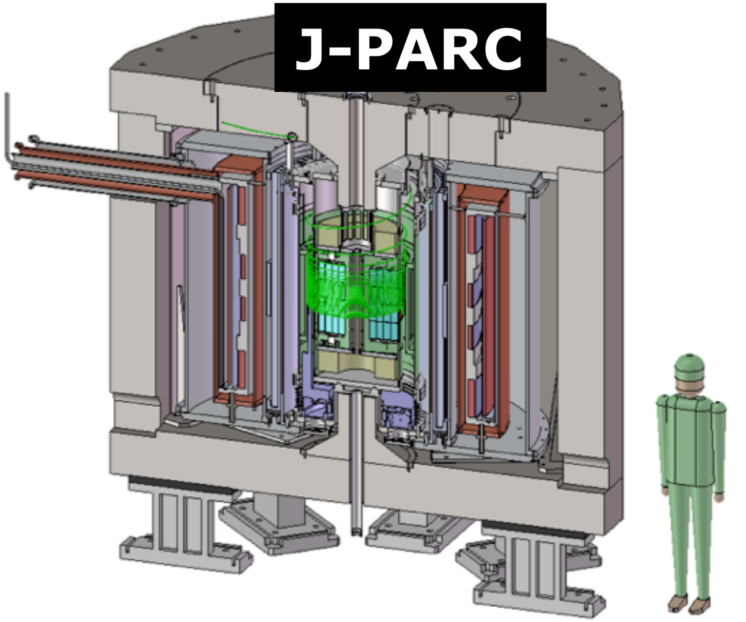
ω_a systematics

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

JPARC vs FNAL



3.094 GeV muons
1.45 T, 14m bespoke magnet
Focussing quadrupoles
Kicker magnets
Emittance: 1000pimm



0.3 GeV muons
3T, 66cm MRI magnet
$\Delta p_T/p_T$ = 1e-5

Apparatus and hence systematics are very different

J-PARC Muon g-2

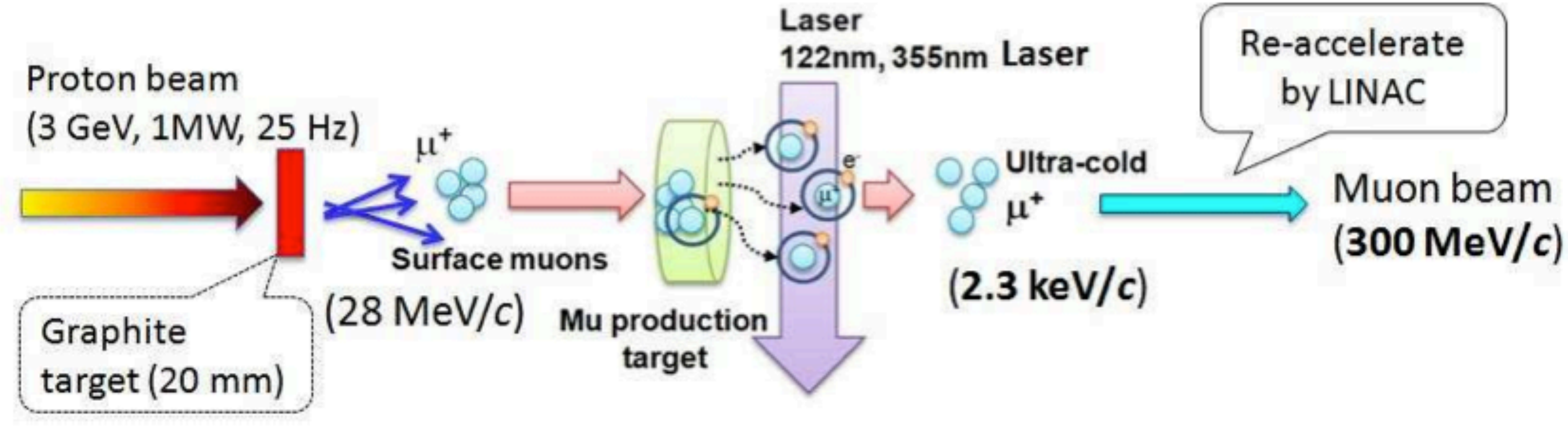
$$\omega_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

FNAL/BNL approach : use magic γ (29.3), p = 3.09 GeV muons.

J-PARC proposal : use E ~ 0
: ultra-cold muons (low β)
: larger (and more uniform) B (3T MRI magnet)

Unlike FNAL/BNL approach. This technique **has yet to be proven to work**

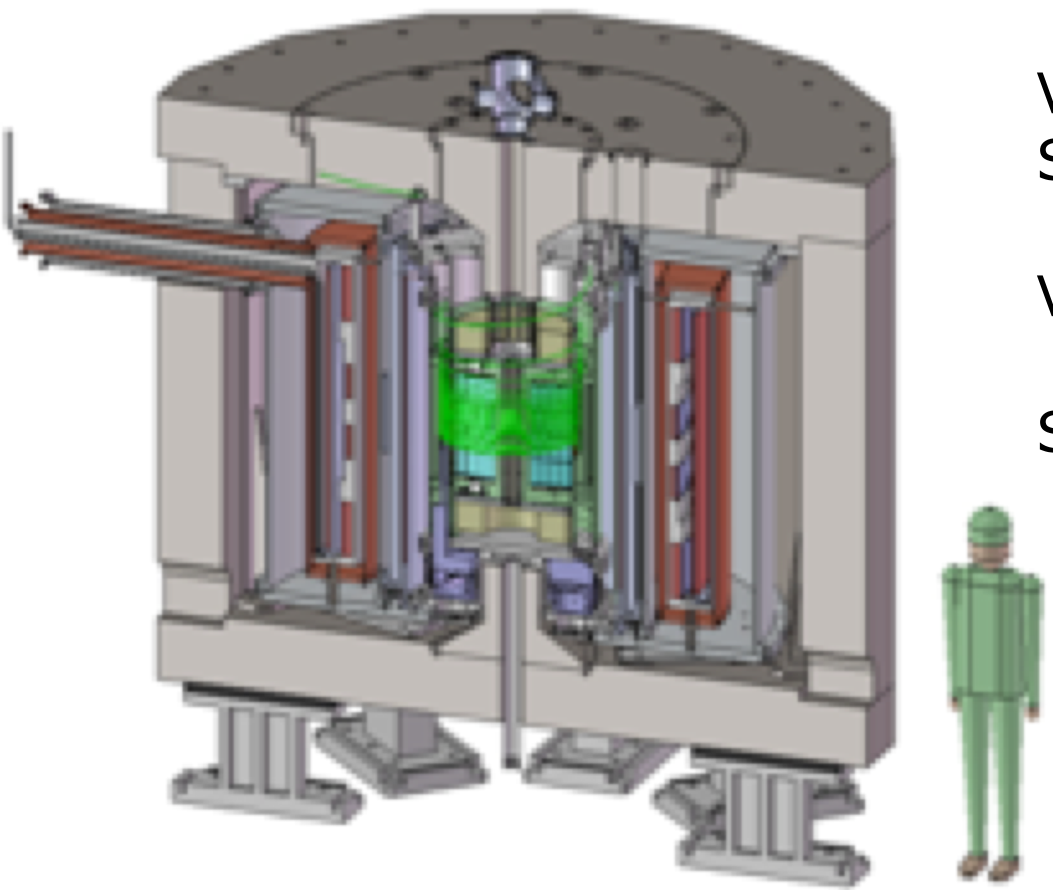
J-PARC g-2 Experiment



Requires several innovations to achieve 10^6 muons/sec

- production of sufficient muonium using special materials
- pulsed 100 μJ VUV lasers to ionise muonium
- muon linac keeping $\Delta p_T/p_T < 1e\text{-}5$: world's 1st muon accelerator !

J-PARC : MRI magnet and Si detectors



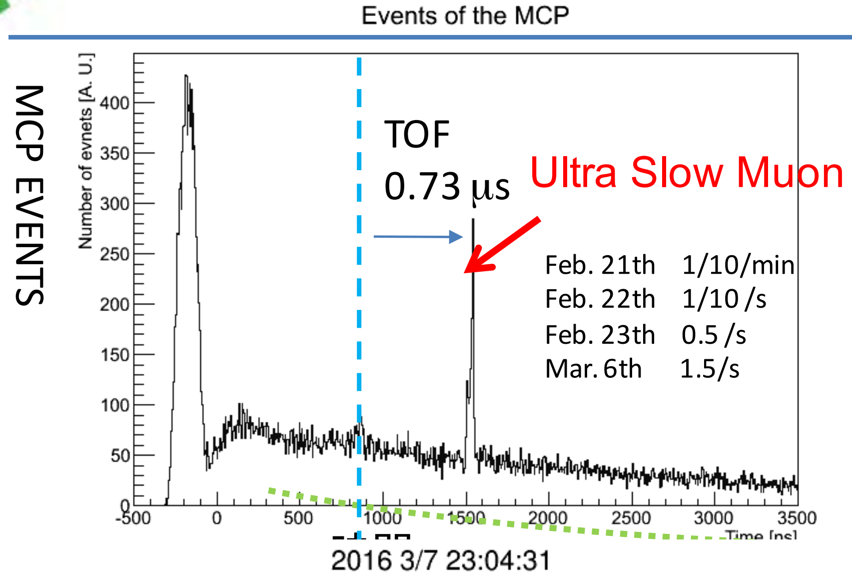
Very precise tracking using
Si detectors

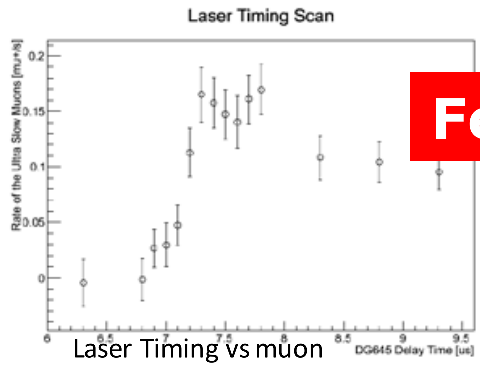
Very uniform field (MRI magnet)

Spiral 3D beam injection !

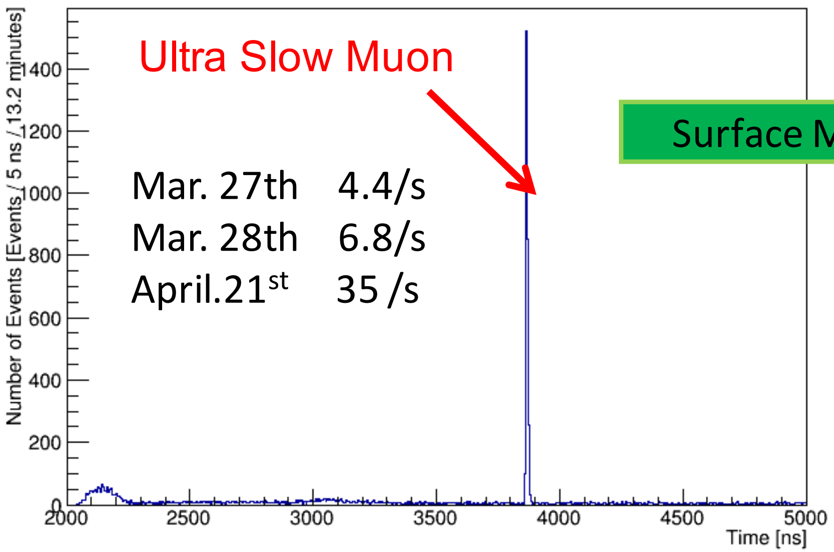
Observation of Ultra Slow Muons @U-Line

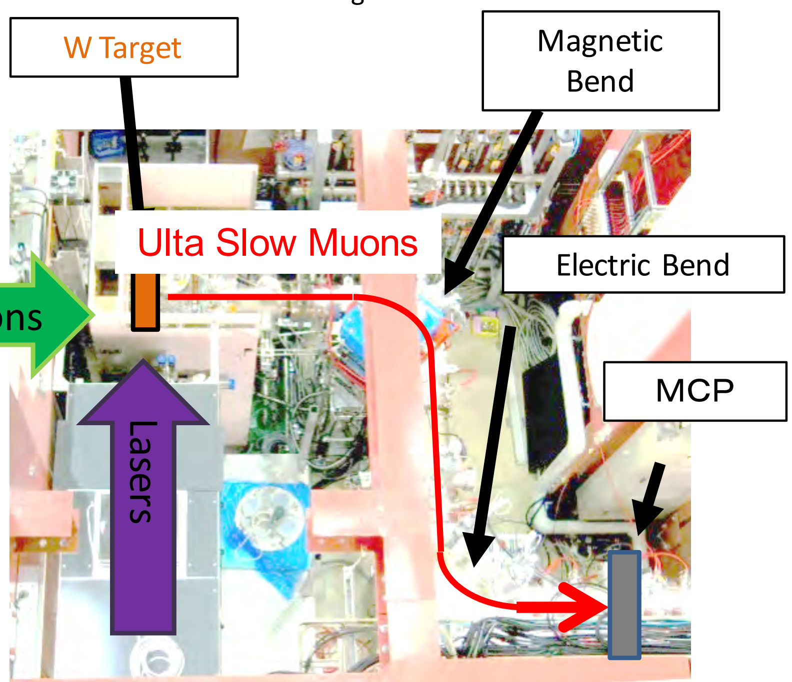
ULTRASLOW MUON MICROSCOPE





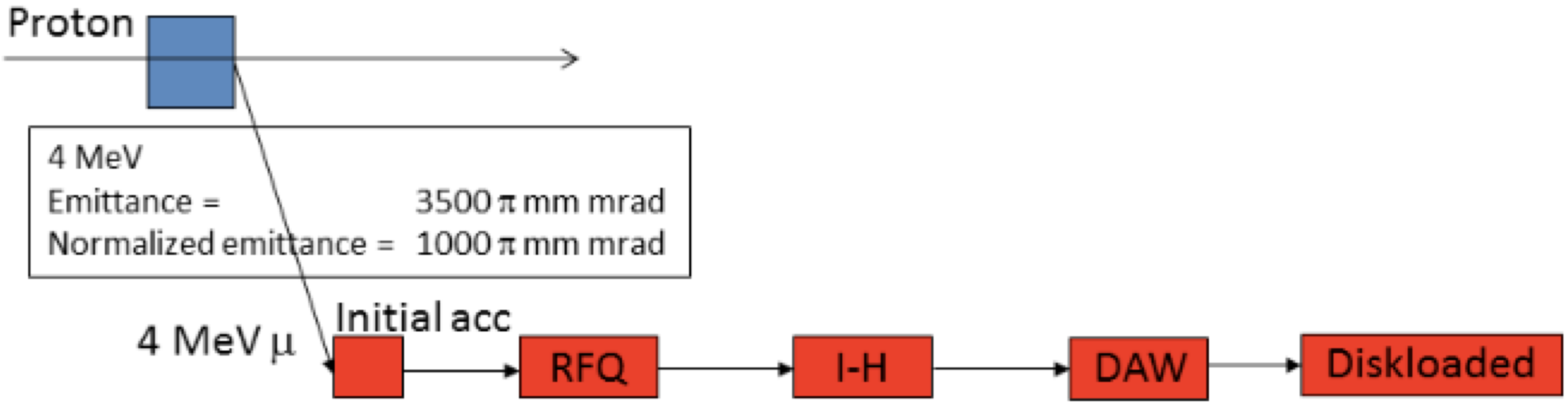
Feb 2016





Topview of U-Line

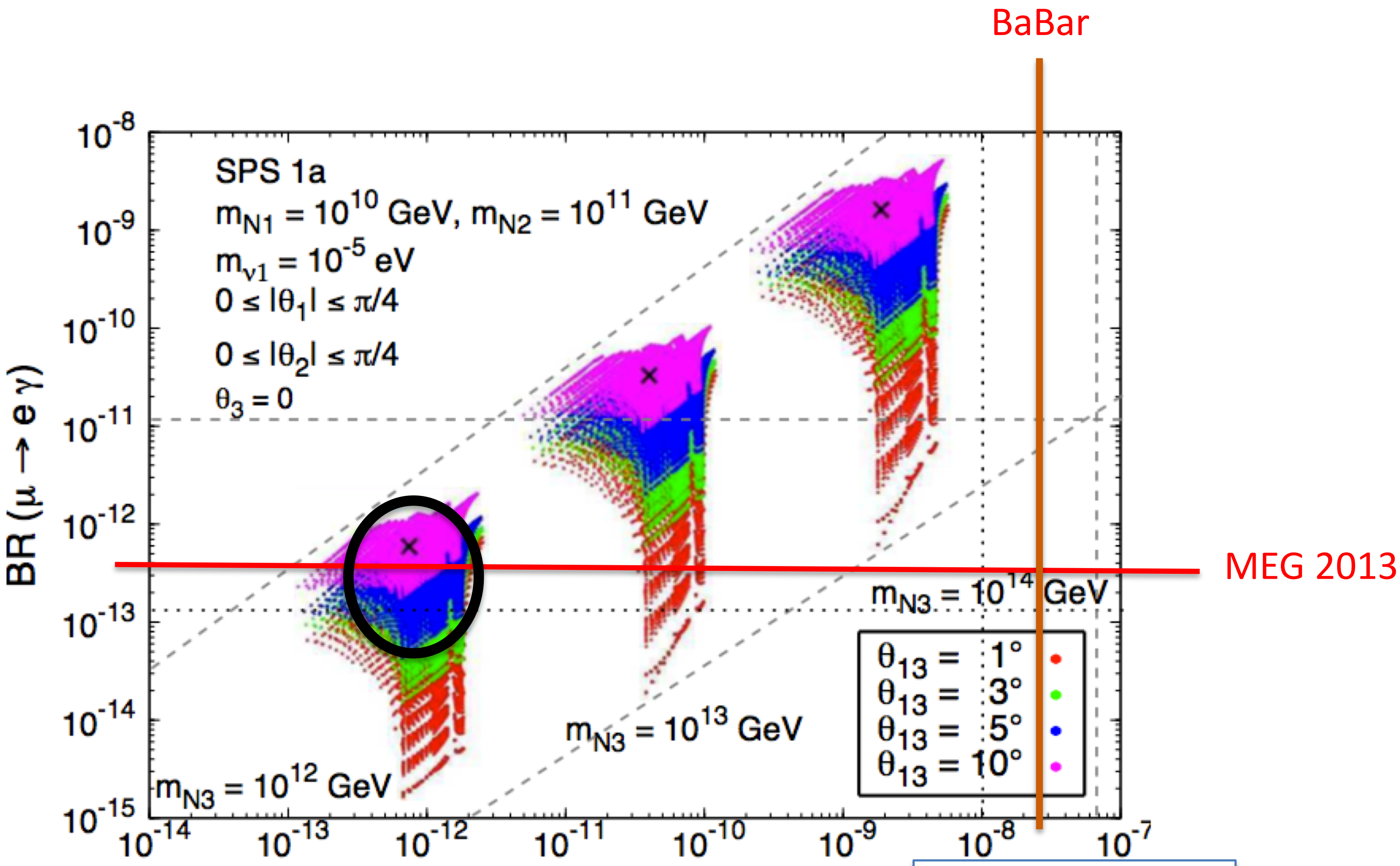
J-PARC: Acceleration progress



	5.7keV	340 keV	4 MeV	50MeV	200 MeV
$\beta\gamma$	0.01	0.08	0.278	0.98	2.71
Emittance(mm mrad)	150	19	5.4	1.5	0.55
Normalized emittance	1.5	1.5	1.5	1.5	1.5

Tests of 1st two acceleration stages completed.

Sensitivity to heavy neutrinos



Daya Bay = 9^0

hep-ph/0610439

Muon LFV

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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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

Different SUSY and non-SUSY BSM models.

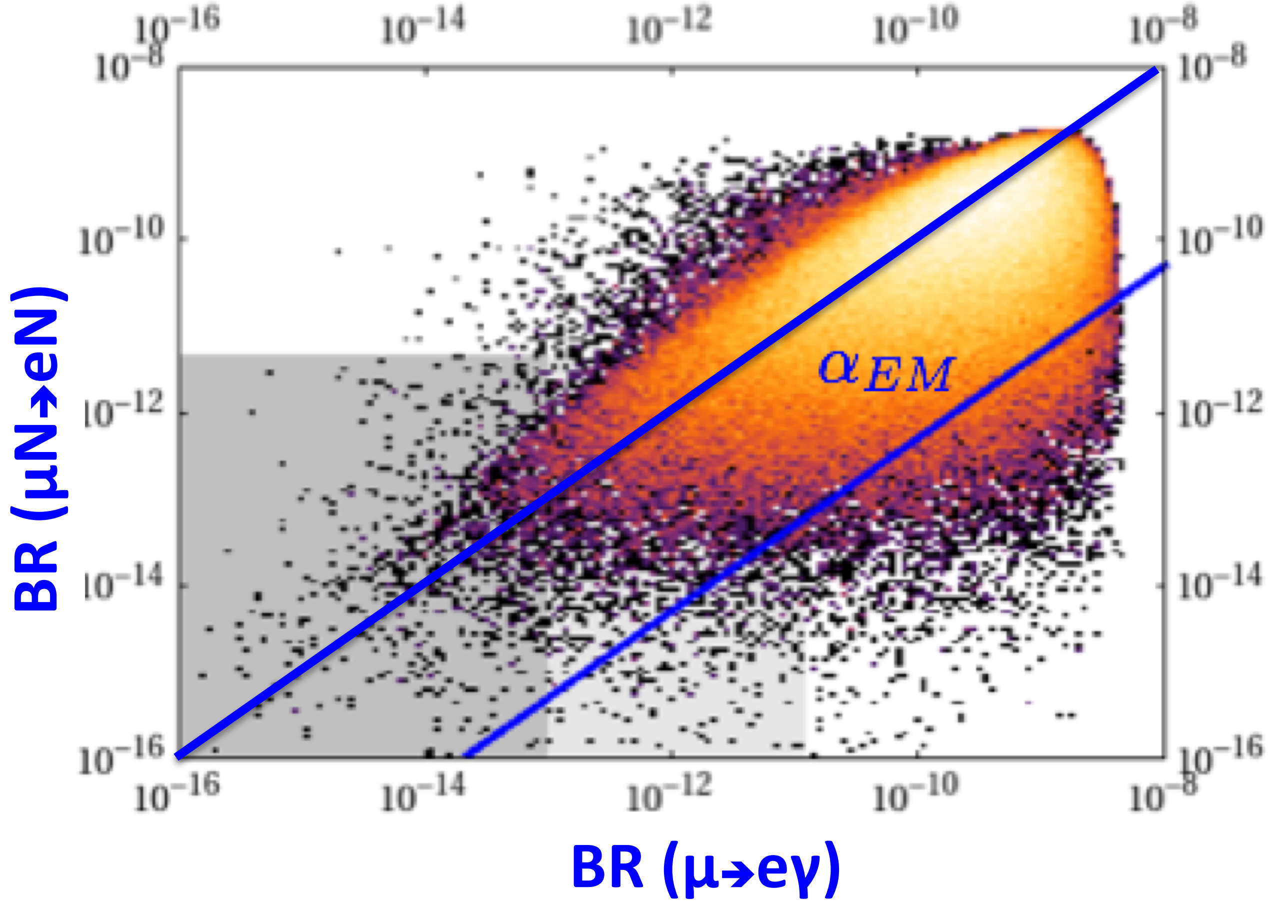
★★★ Large effects

★★ Visible but small

★ No sizeable effect

Process Ratios are Model Dependent

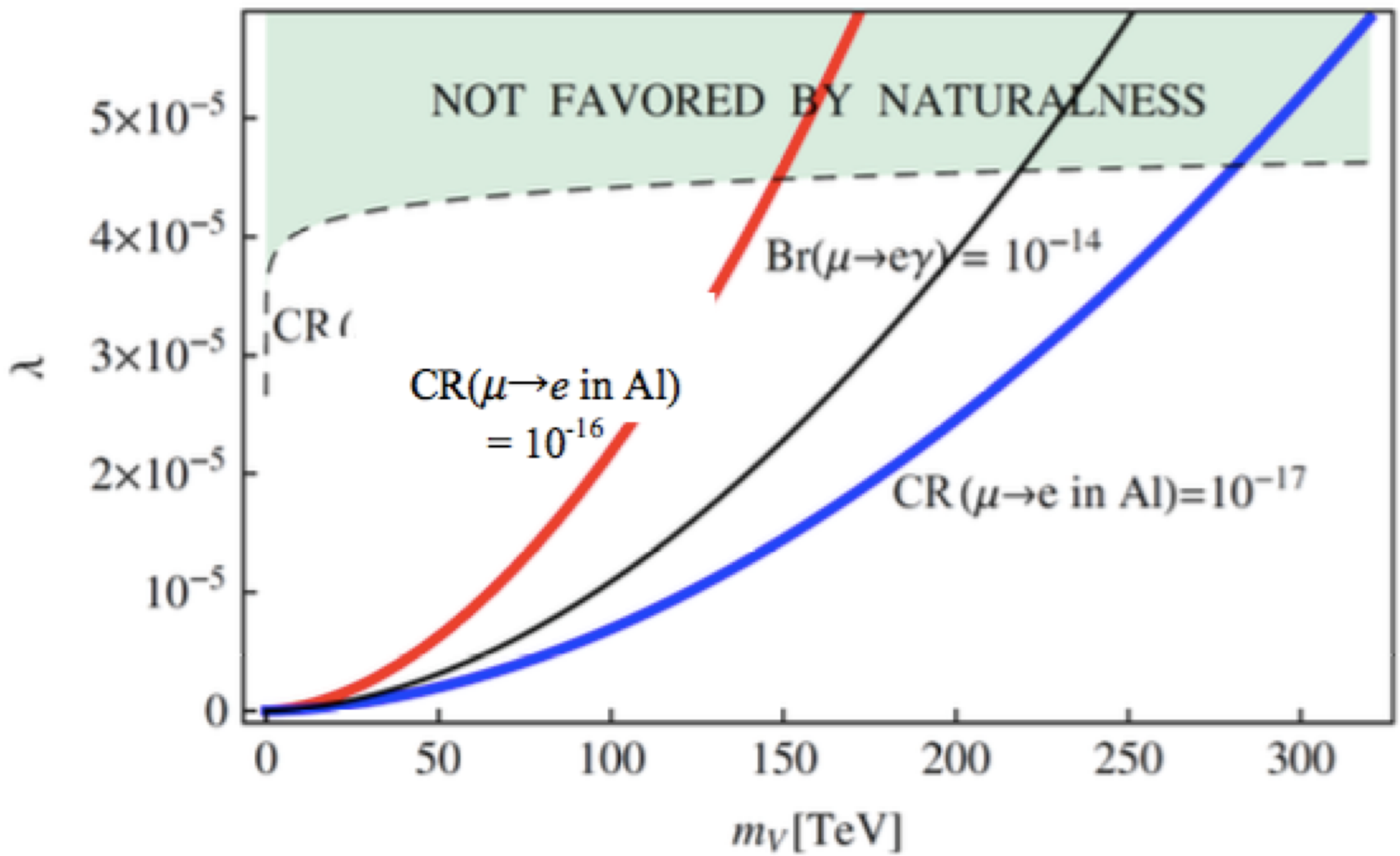
In general in BSM models $\frac{BR(\mu N \rightarrow eN)}{BR(\mu \rightarrow e\gamma)} = \mathcal{O}(\alpha_{EM})$ but not always…



e.g. “Littlest Higgs model” with T-parity (LHT)

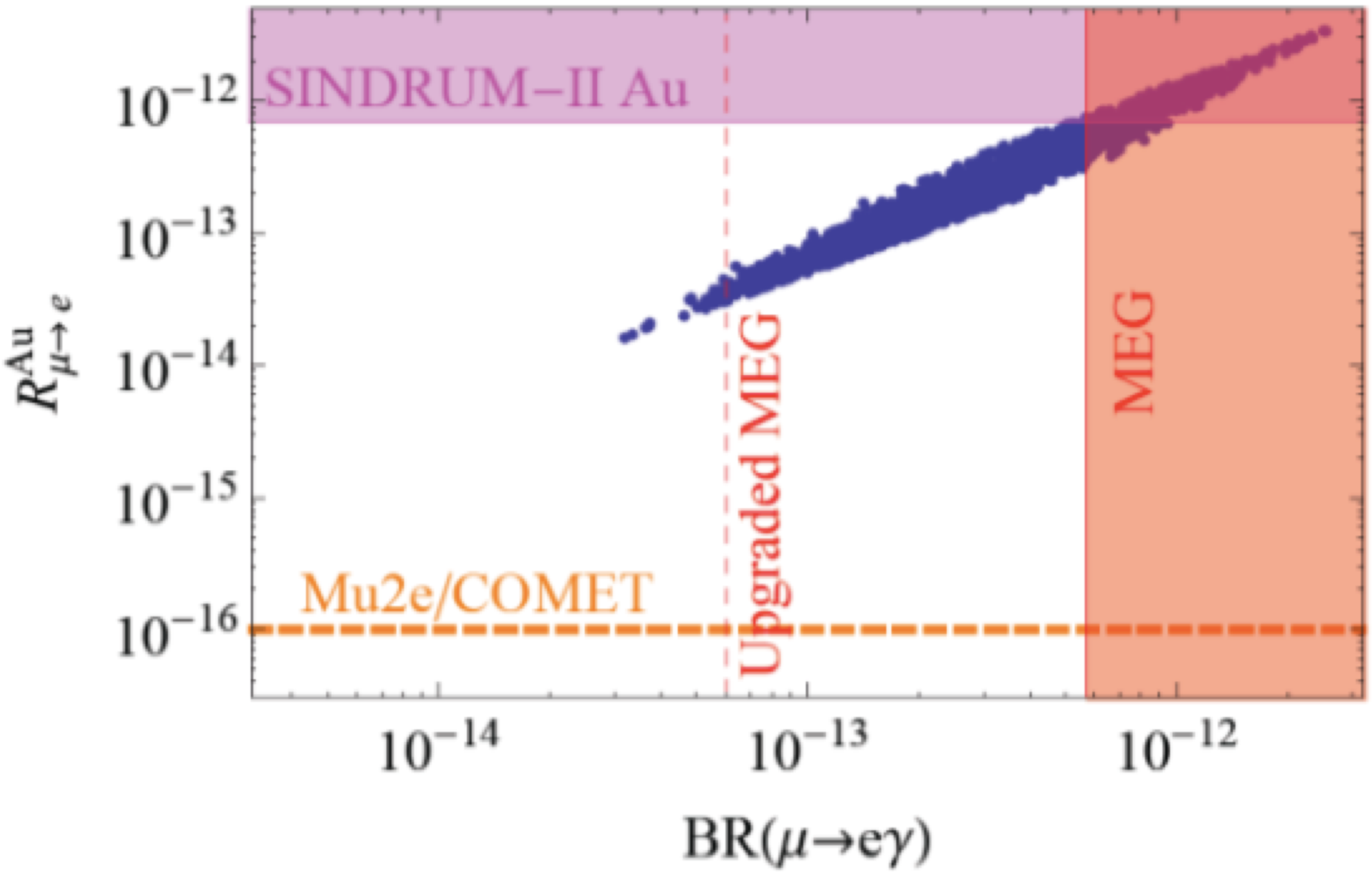
Mu2e/COMET Reach ~ 100 TeV for LQ

Sensitivity to high mass phenomena e.g. scalar leptoquarks not excluded by LHC



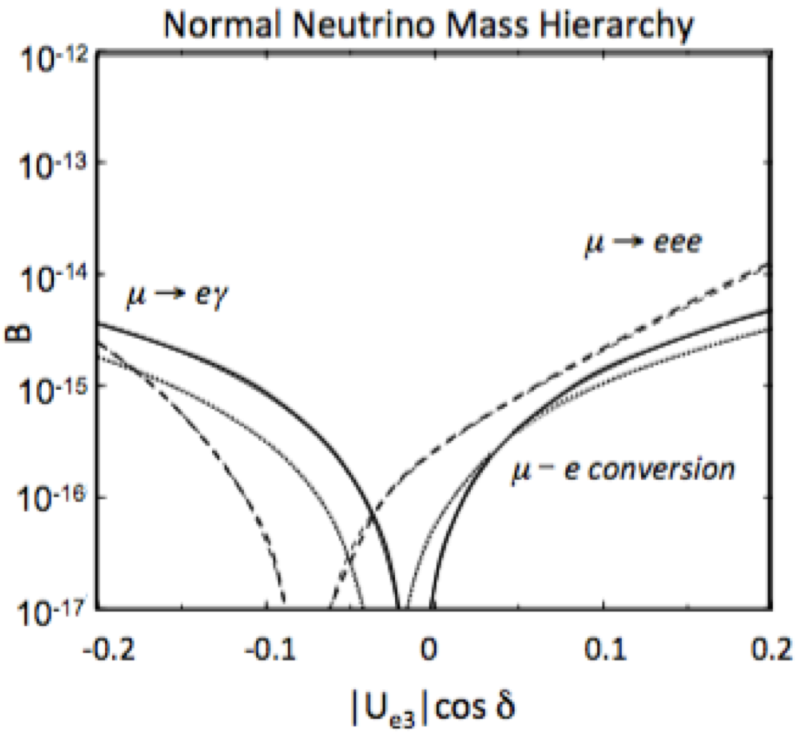
Connection with neutrino mass physics

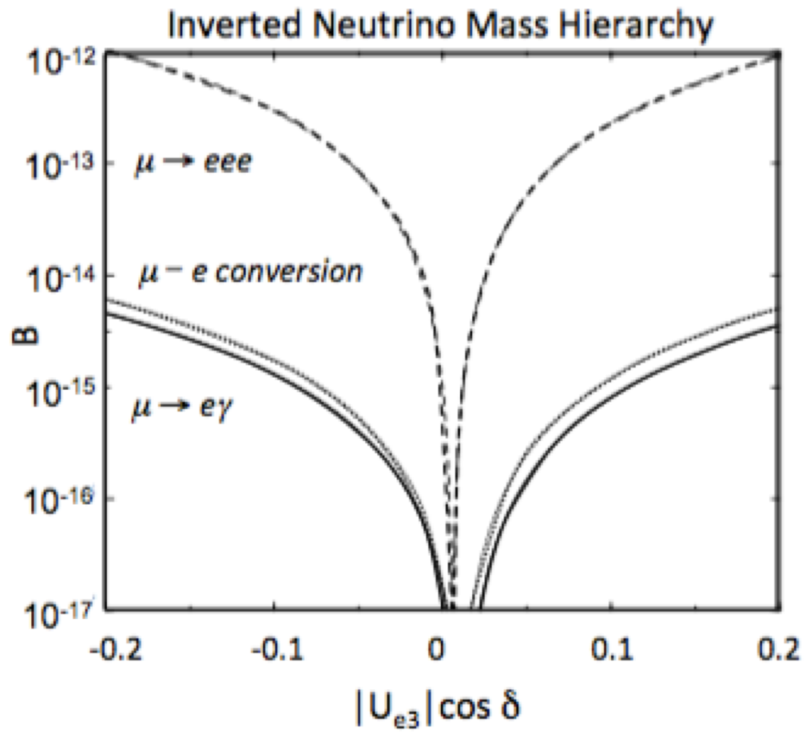
e.g. TeV-scale Left-right seesaw model



Neutrino mass hierarchy

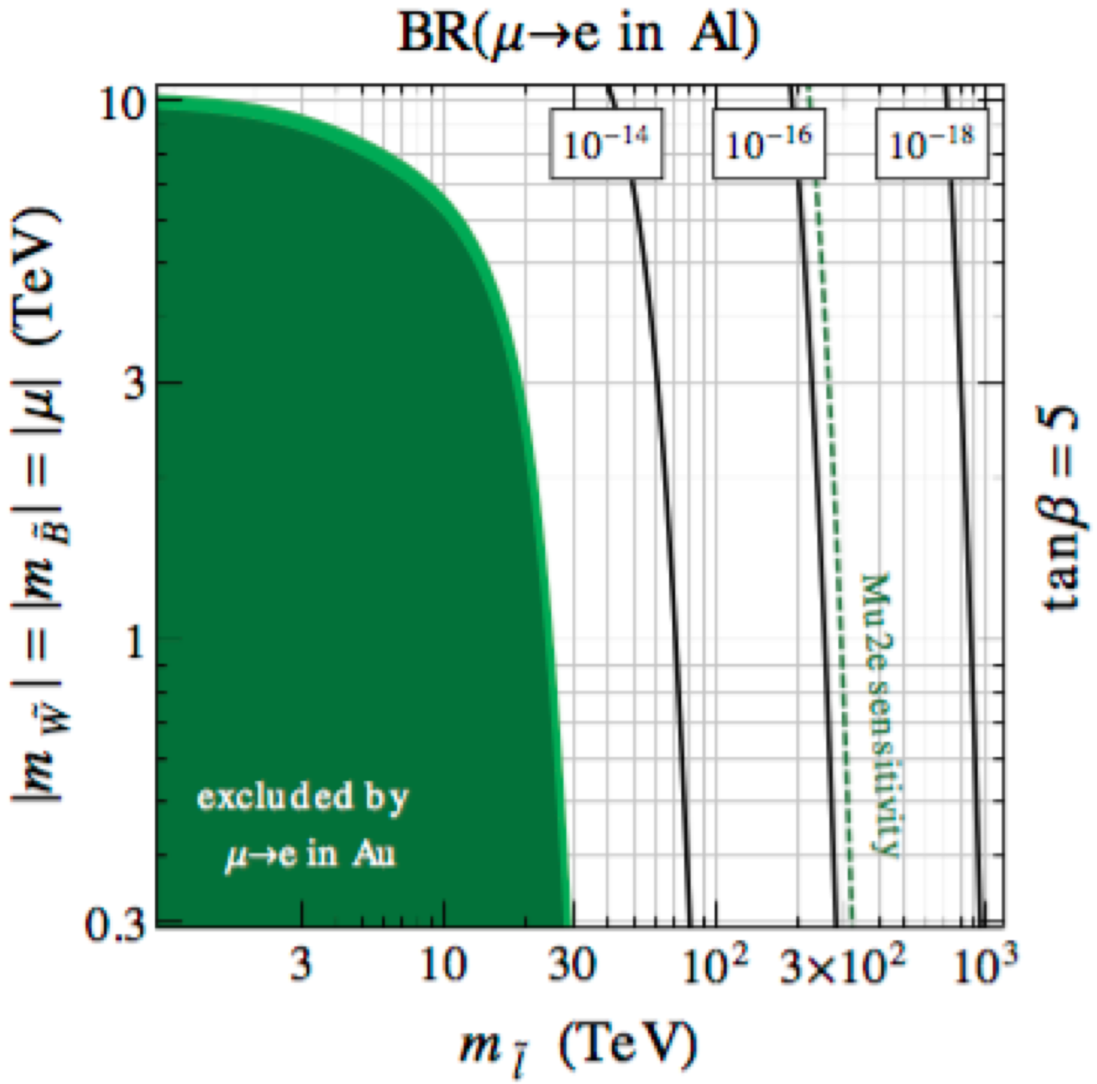
e.g. Majorana neutrino mass from a SU(2) triplet Higgs field





M. Kakizaki, et al, Phys. Lett. **B566**, 210 (2003)

An example: split SUSY



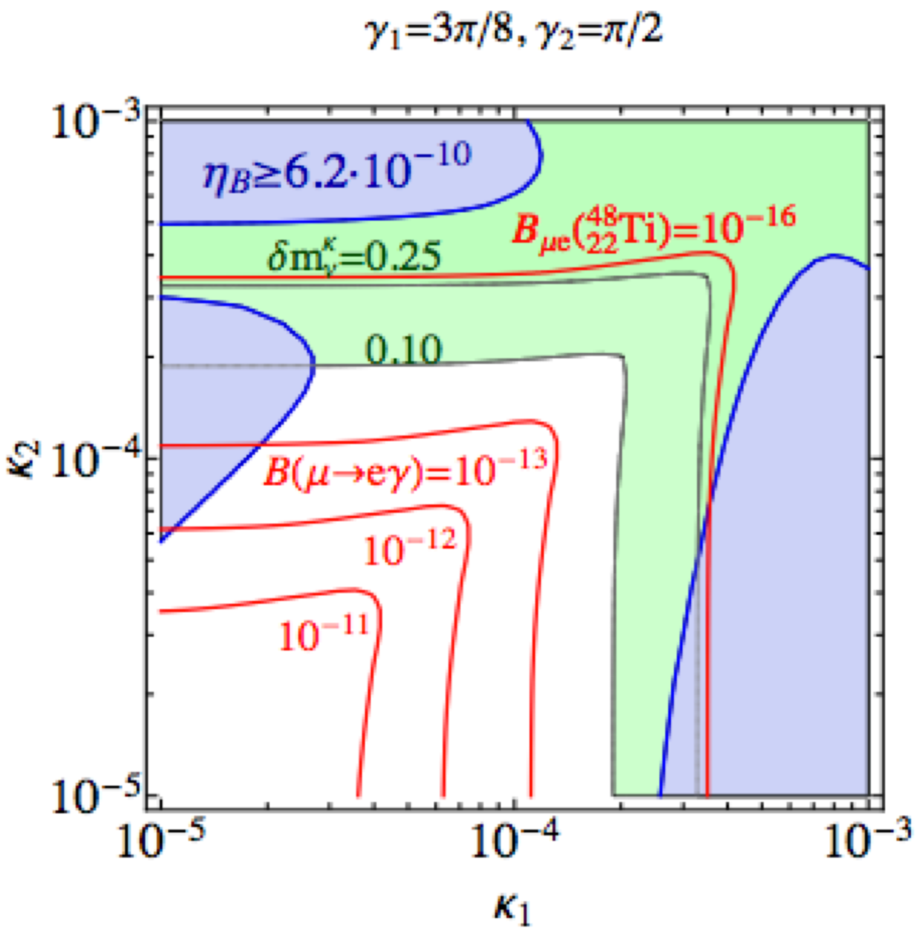
Slepton masses of 300 TeV probed in "Split-SUSY" model.

Present ATLAS direct search limit is 0.6 TeV

Why cLFV ?

No new physics observed coupling to quarks at LHC

In light of ν-oscillations: is the lepton sector different ?

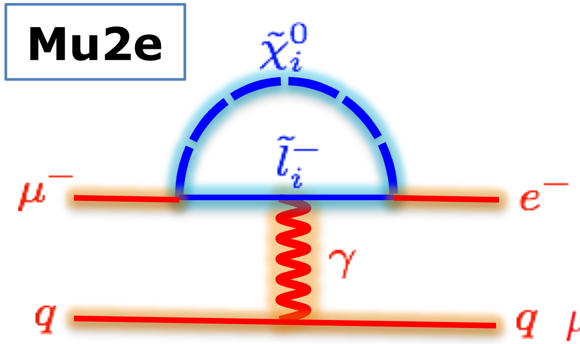


Gives a portal to the physics potentially explaining anti-matter asymmetry through leptogenesis

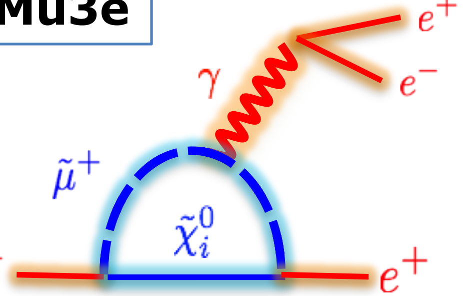
Complements LHC at higher scale

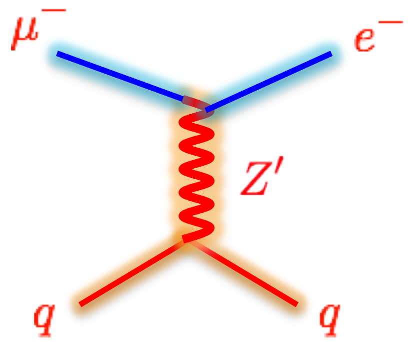
Probing similar range of BSM interactions as LHC

Mu2e



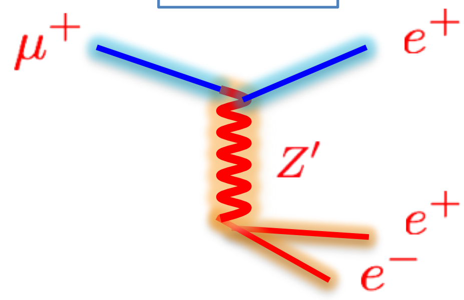
Mu3e

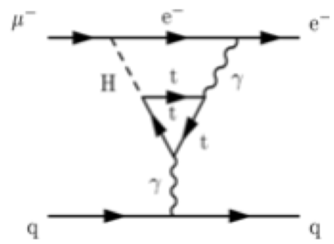




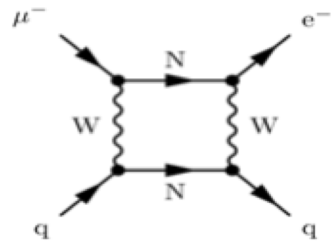
Mu2e

Mu3e



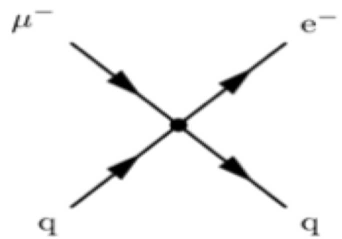


Second Higgs Doublet

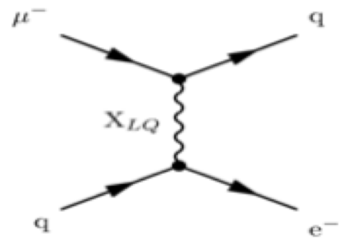


Heavy Neutrinos

Probe LQ masses upto 300 TeV
cf 1 (120) TeV at HL-LHC (LHCb)



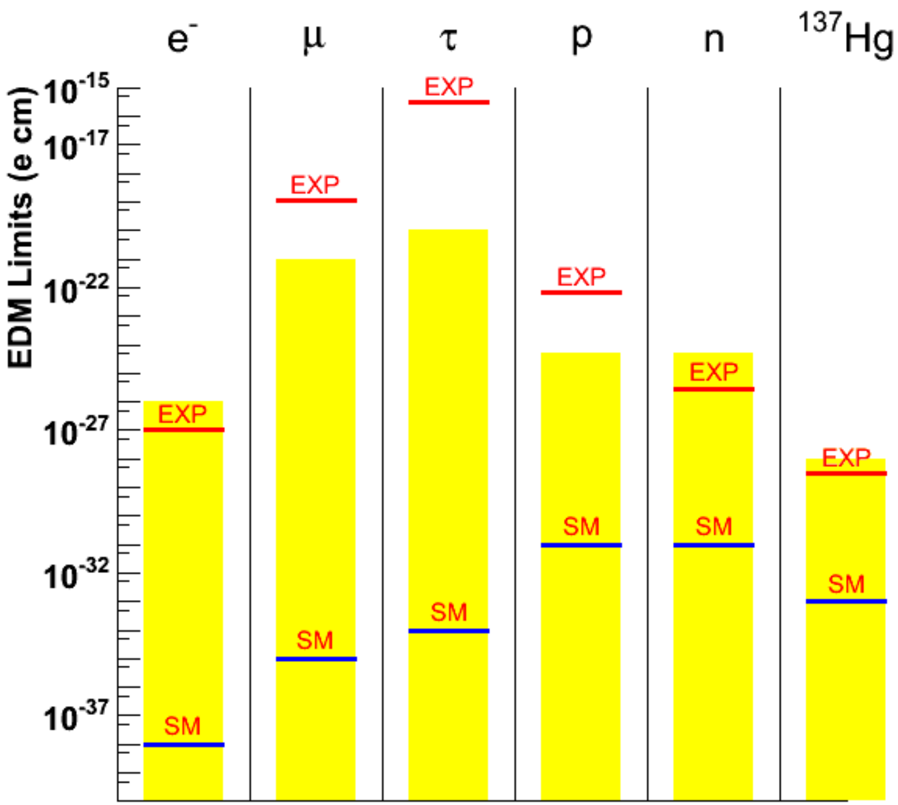
Compositeness



Leptoquarks

Muon EDM

Essentially zero in SM : any observation is new physics



Muon is the only 2nd flav. gen. measurement. and it's free of nuclear / molecular effects

BNL limit is 1.8 x 10^{-19}

Can quickly be improved by x10 and ultimately x100 to 10^{-21}

Needs non mass-scaling BSM effects to see anything given e^- EDM limit