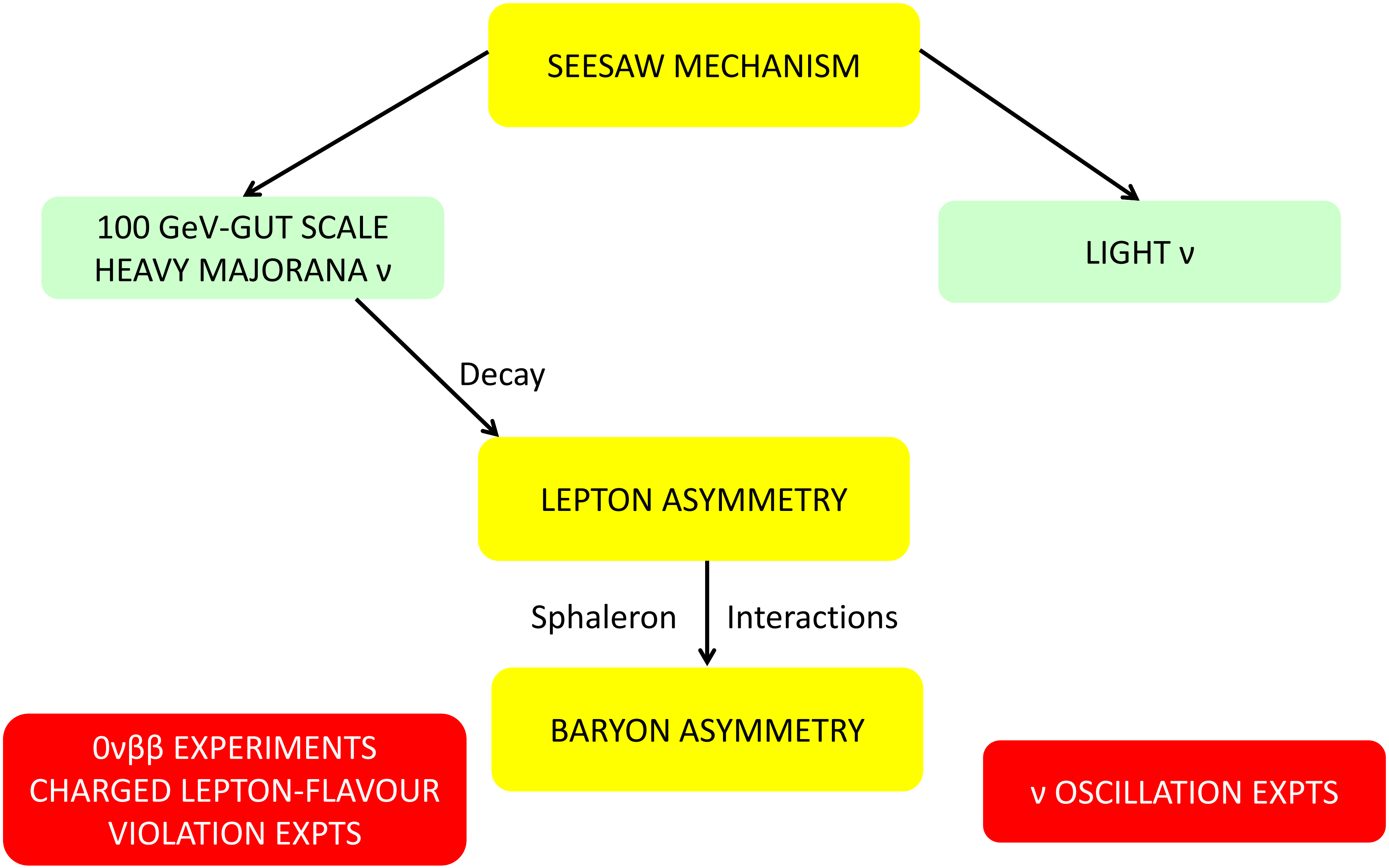
Precision Muon Experiments

Mark Lancaster

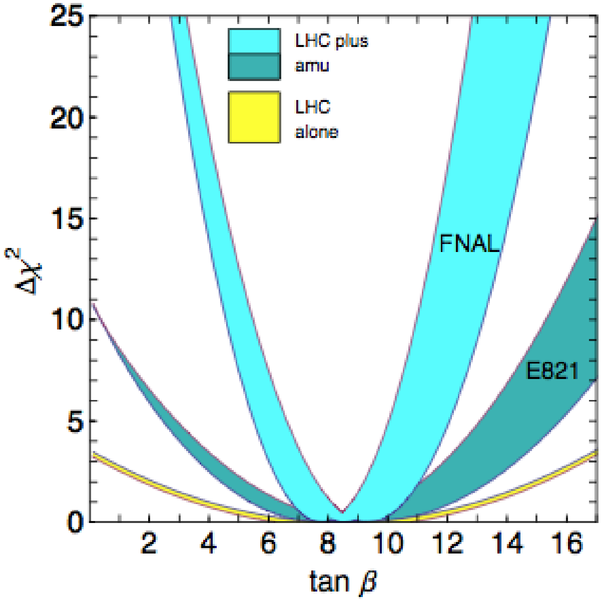
Motivation

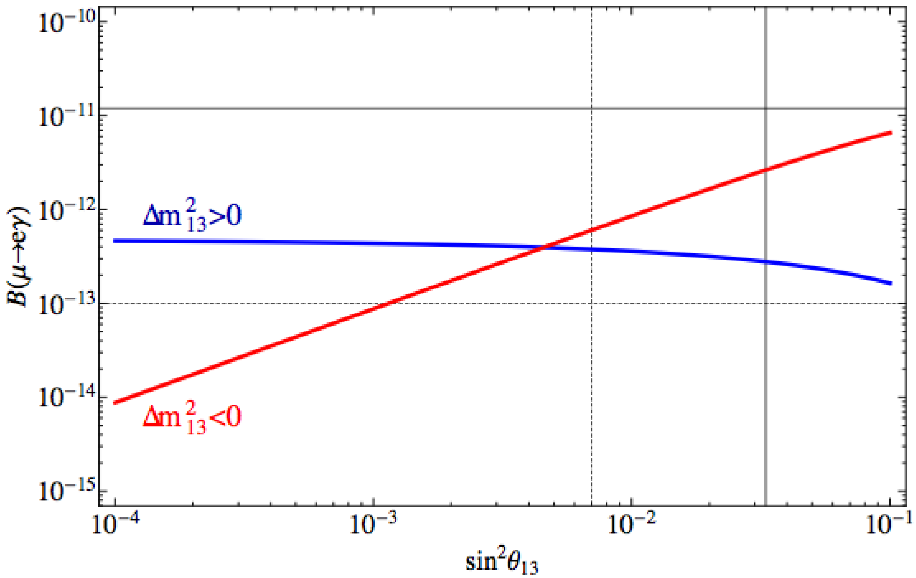

SEESAW MECHANISM
100 GeV-GUT SCALE
HEAVY MAJORANA ν
LIGHT ν
Decay
LEPTON ASYMMETRY
Sphaleron
Interactions
BARYON ASYMMETRY
0νββ EXPERIMENTS
CHARGED LEPTON-FLAVOUR
VIOLATION EXPTS
ν OSCILLATION EXPTS

Motivation

Precision studies of the lepton sector provide insights on new physics to complement LHC and in general are probing physics at a higher scale.

The phenomenology of the universe's matter anti-matter asymmetry will not be understood without neutrino **AND** charged lepton violation measurements.





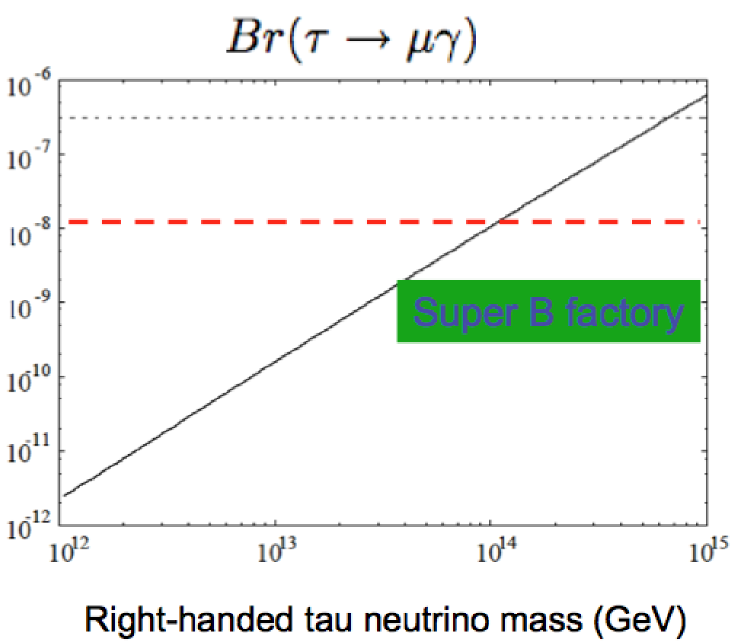
17 of the top 25 hep-ex most cited papers for 2010 are in the neutrino and cLFV area

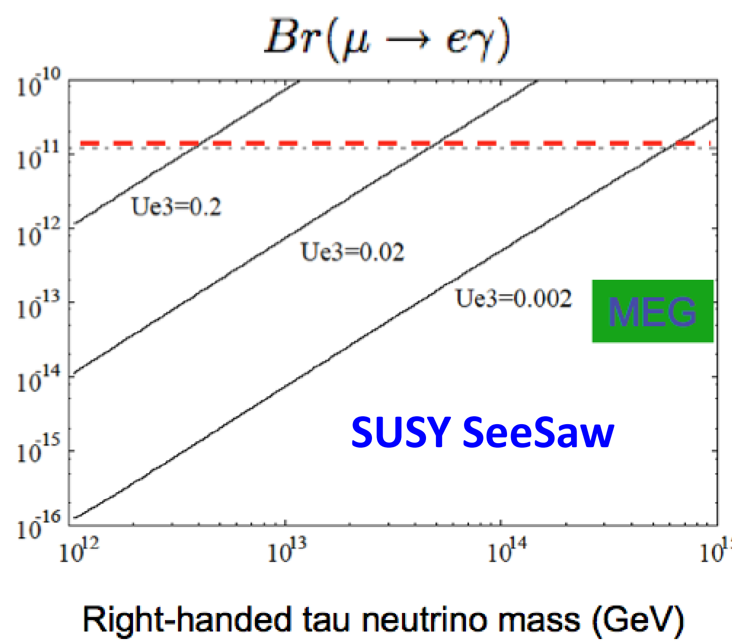
Why Muons ?

Present tau limits are at $O(10^{-8})$ and Super-B $O(10^{-9})$.

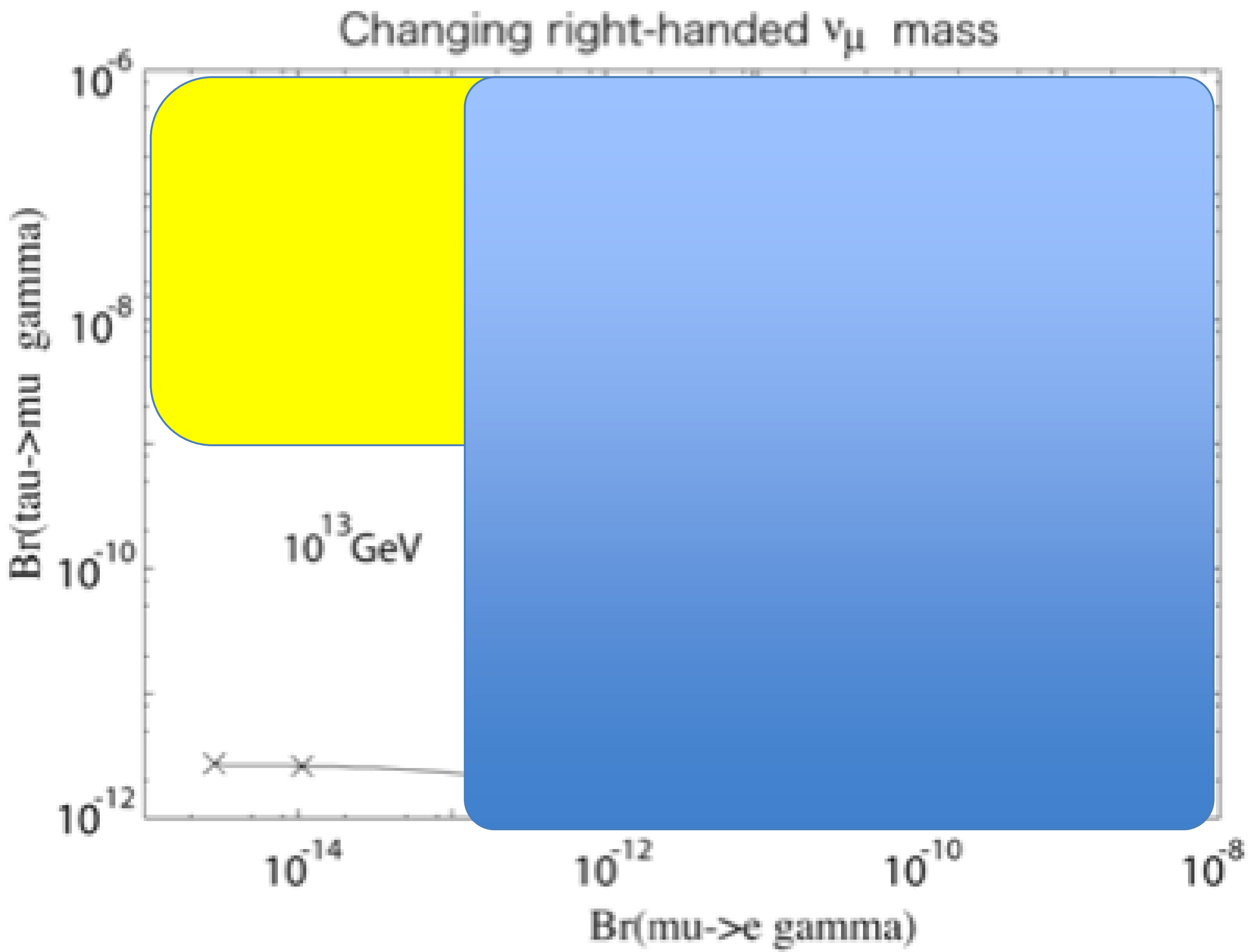
Model dependent but $O(10^{-9})$ in τ has similar sensitivity as $O(10^{-12})$ in μ and this muon sensitivity **will** be achieved in the next year or so.

Advances in accelerator/solenoid technology & detectors will increase sensitivity limits by factor of 100 by 2013 ($\mu \rightarrow e\gamma$) & 10^5 ($\mu N \rightarrow eN$) in O(5) years in muon flavour violation.



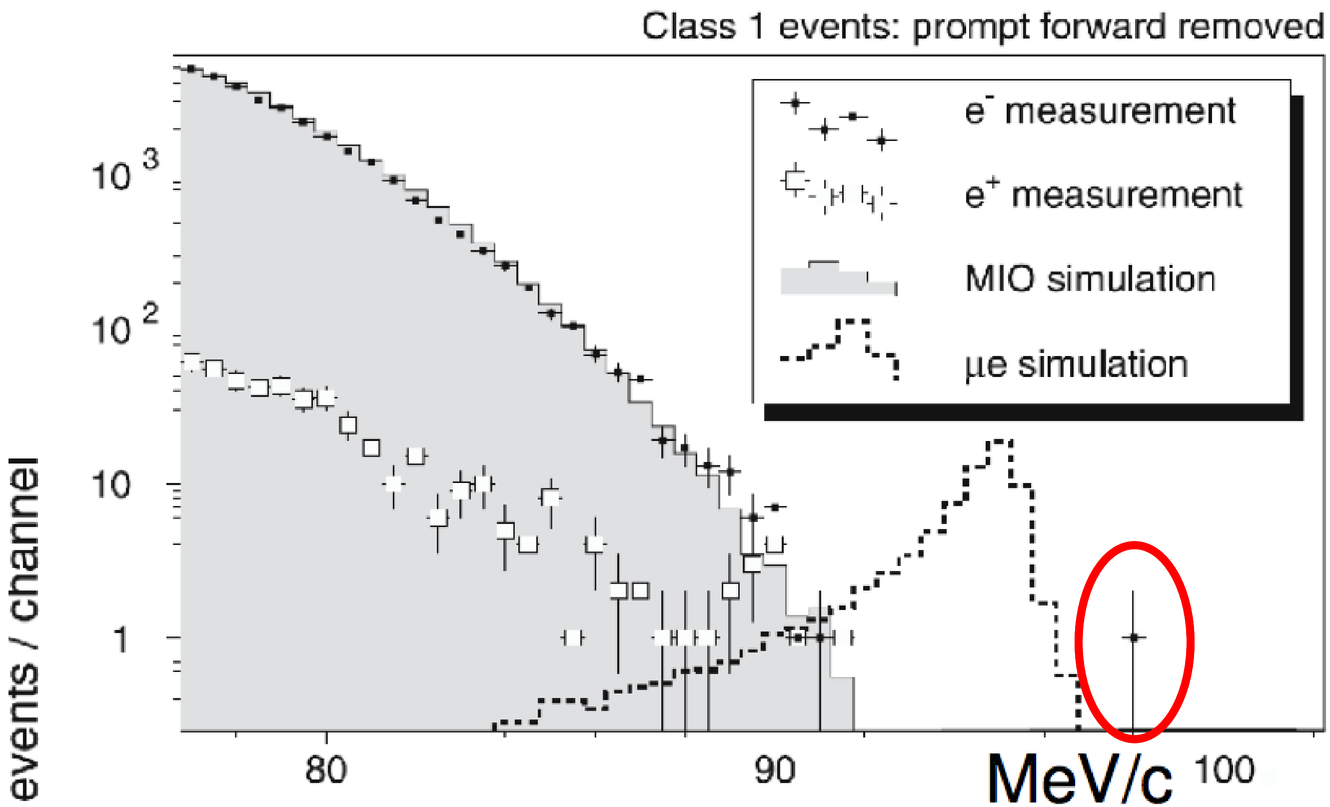


Muons vs Taus



Why Muons ?

In most of the muon measurements we have the situation where the SM rate/value is essentially zero e.g. BR(μ→eγ) is 10^{-53} in SM such that any observation is new physics or …. a systematic error..



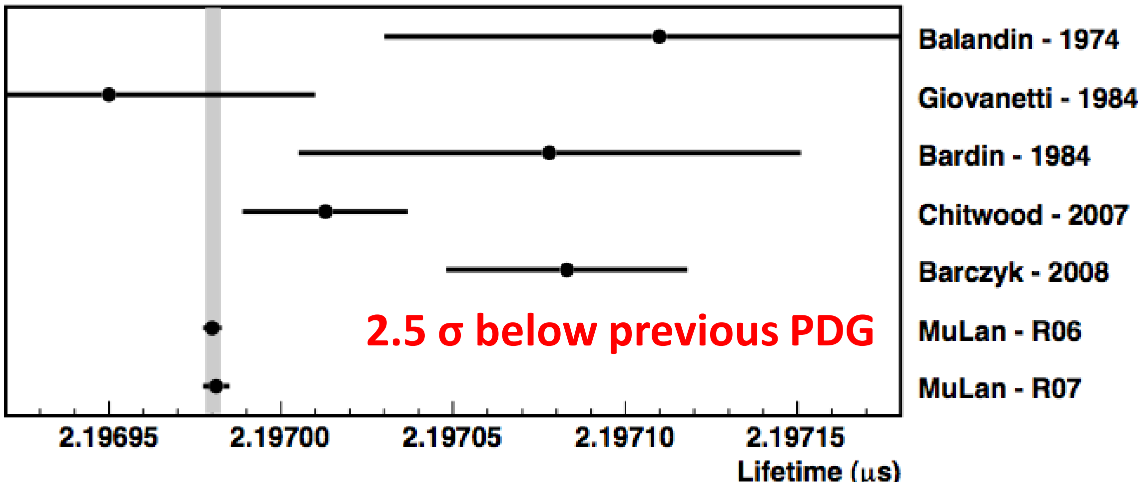
SINDRUM-2 SEARCH FOR cLFV μN-eN

SM is in relatively good shape for muon predictions

e.g. Recent improvement by factor of 10 in muon lifetime and hence G_F

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\delta q)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1+\delta r)$$

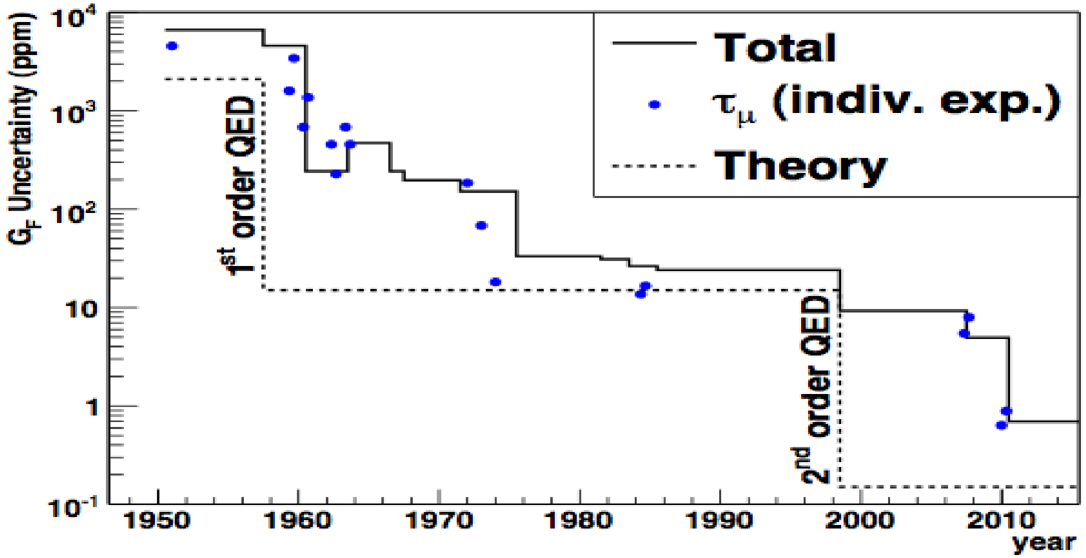


MULAN (@ PSI) : 10^{12} muons

PRL. 106, 041803 (2011)

G_F now know to 1ppm

Theory ~ 0.2 pppm



Measurement Ongoing/Planned

Two classes of measurement

Deviation from precisely known SM value

Magnetic Dipole Moment / “g-2” ~ 0.002 but predicted in SM to 0.42ppm
Present experimental uncertainty : $\Delta(a_\mu) = 63\times10^{-11}$ (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^{-11-12}. SM ~ 10^{-50}

All taking place at PSI, J-PARC/Osaka, FNAL

Muon Dipole Moments

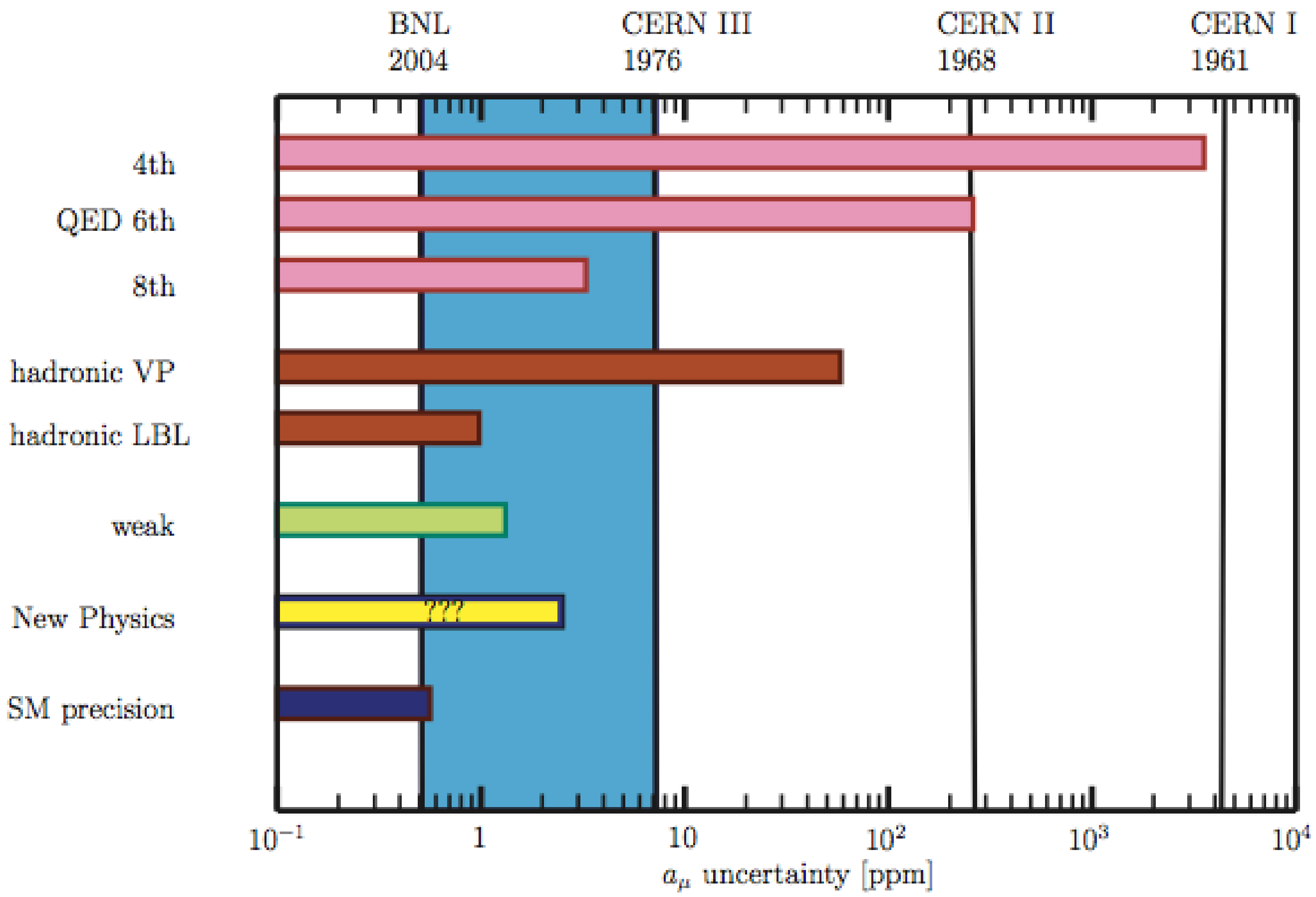
$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

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

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 / a_μ (Magnetic)

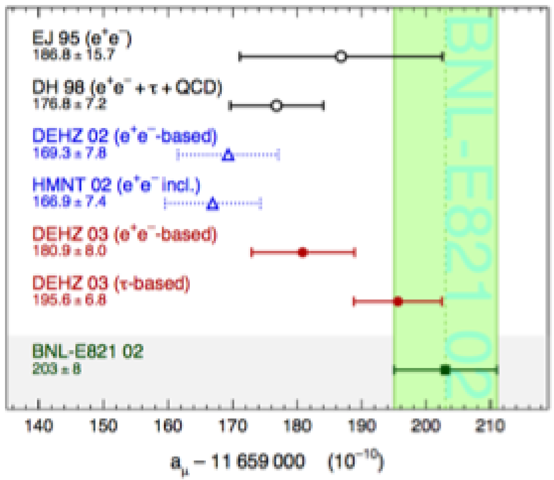


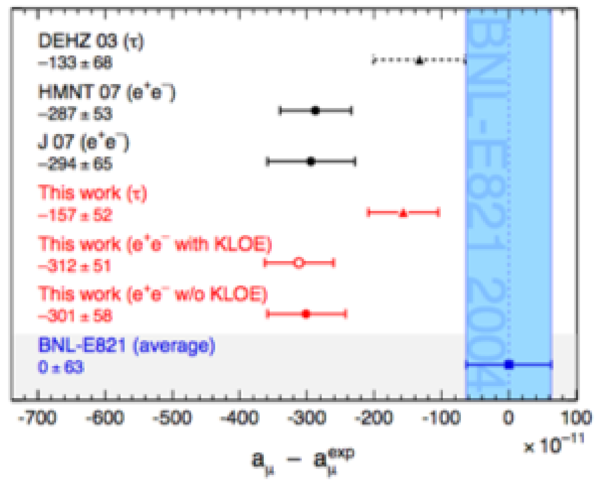
Latest result from BNL E-821 (data 2001, published 2004)

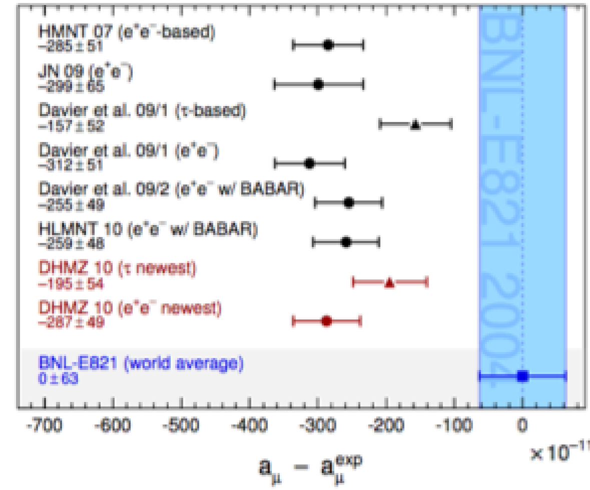
All recent developments have been largely in theory prediction : new techniques & new input low-E e^+e^- / $\gamma\gamma$ data.

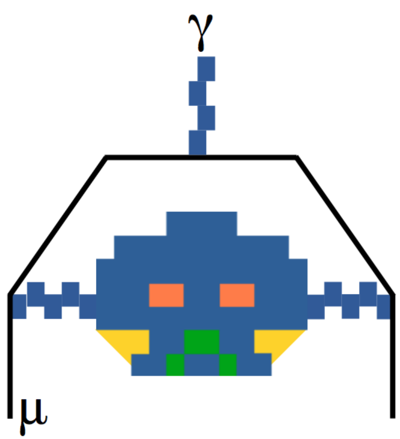
g-2 / a_μ : BNL result

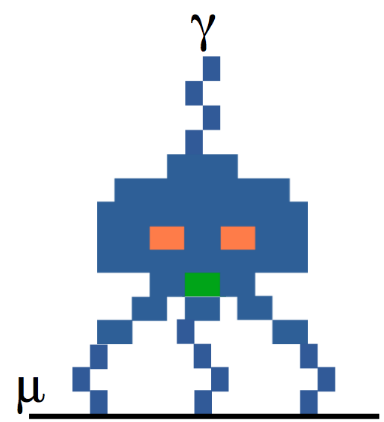
Long-standing discrepancy wrt SM prediction



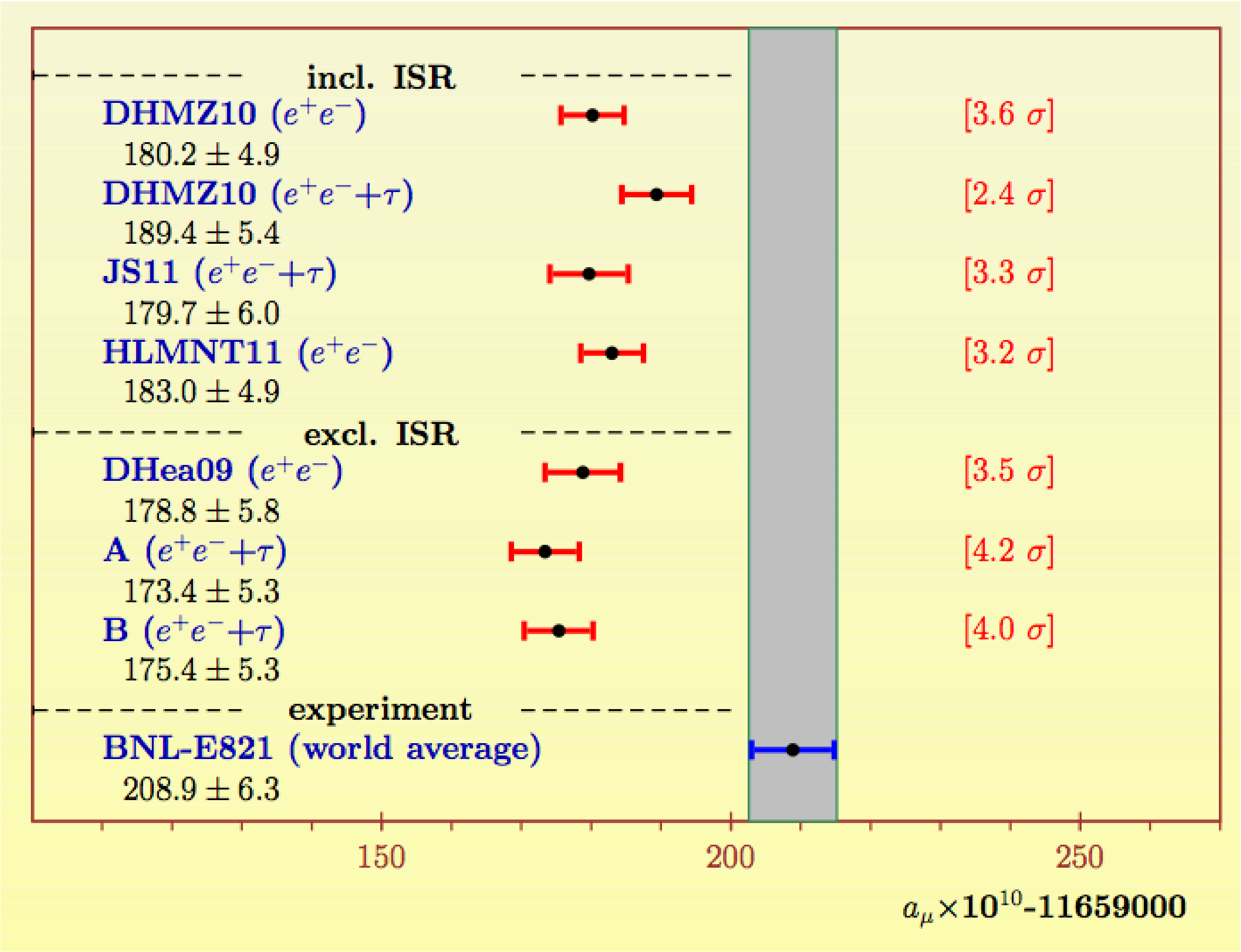








g-2 / a_μ : BNL result



Needs progress on both theory and experiment to establish 5σ significance

g-2 / a_μ : Theory developments/plans

→ Time

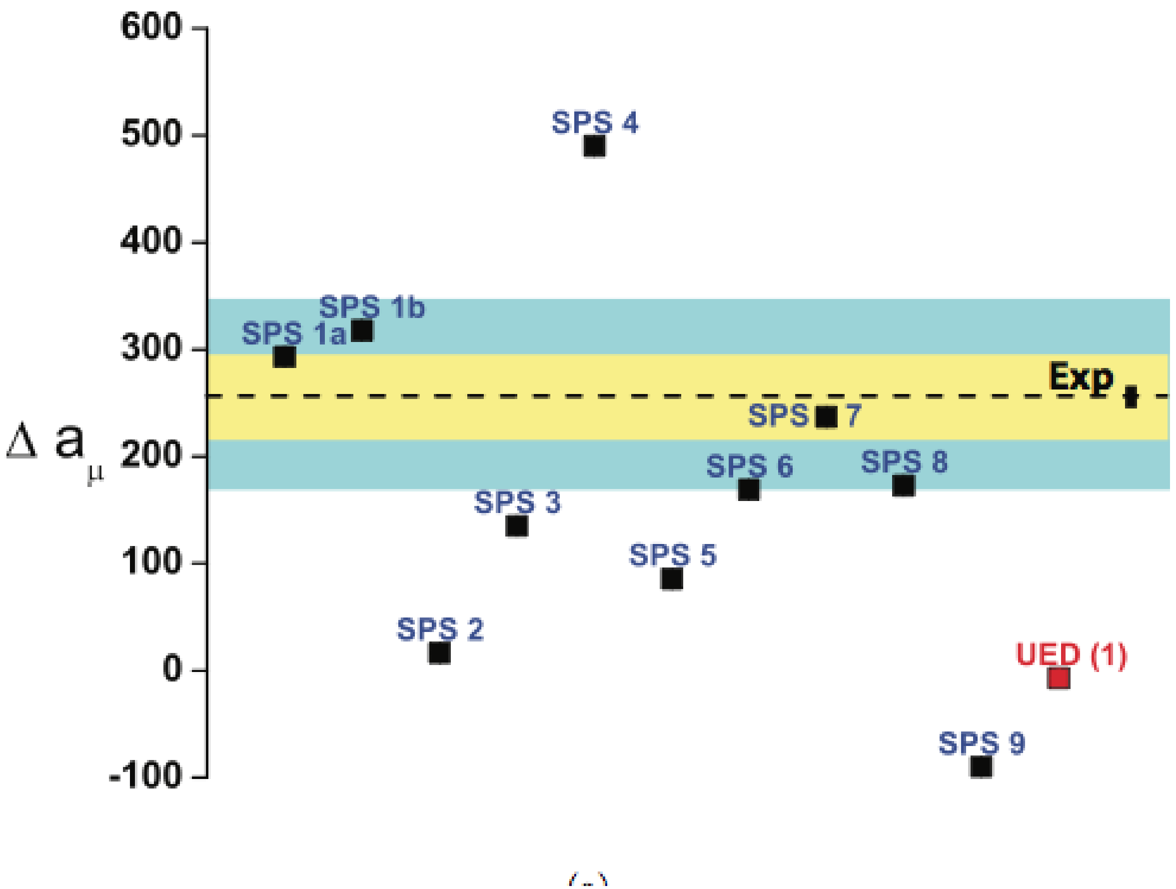
Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops $+$subl. N_C	–	–	–	0 ± 10	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

Several recent workshops in light of new experimental proposals

With better computing power availability **renewed emphasis on lattice calculations**

g-2 / a_μ : Comparison to Snowmass SUSY points



a_μ offers complementary test of BSM to LHC and could potentially help resolve BSM model degeneracies

g-2 / a_μ : Two future experimental proposals

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

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

average over muons

0

$$\gamma_{magic} = 29.3$$

Traditional approach : use magic p = 3.09 GeV muons.

- BNL measurement and proposed FNAL 989 measurement

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

- J-PARC measurement

g-2 / a_μ : FNAL Proposal (E989)

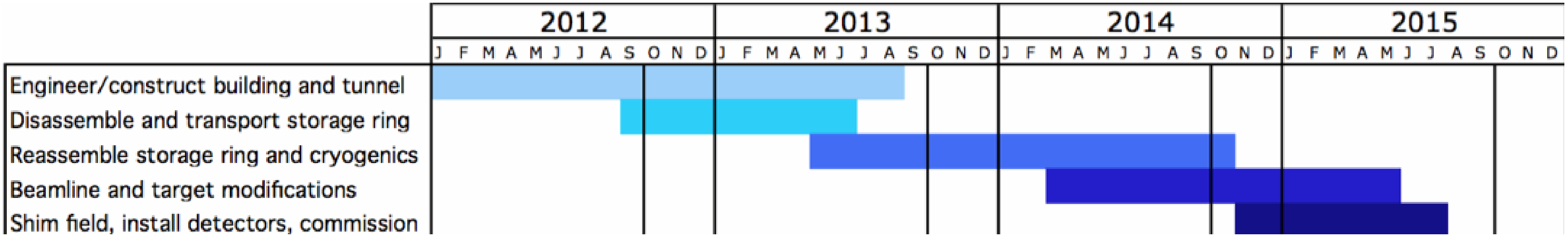
Move existing BNL ring to FNAL and utilise higher intensity FNAL p-beam and 900m π decay line

Aiming for x4 improvement in a_μ uncertainty to be 0.1ppm (16×10^{-11}) measurement

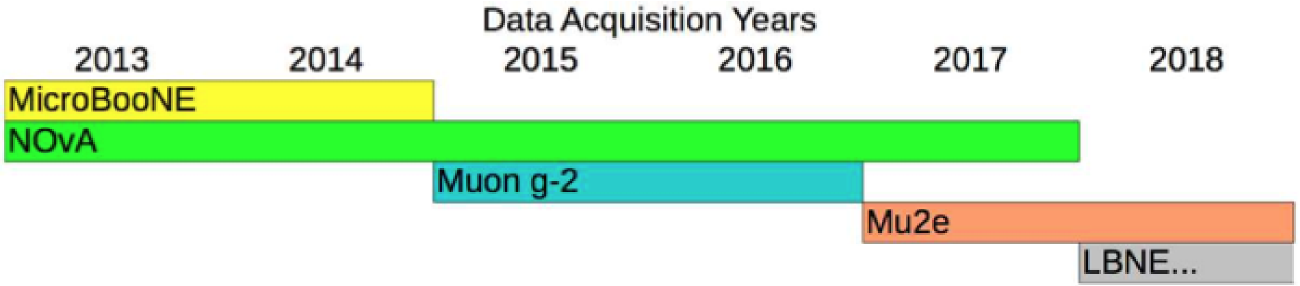
Expecting theory uncertainty to reduce from 49×10^{-11} to 30×10^{-11} such that present ~ 3.5 σ discrepancy would become ~ 7.5σ

FNAL g-2 (E989)

Run in parallel with NOVA : requires $4x10^{20}$ POT : comfortably attainable from 2yrs running ~ 2015-2017.



Can share beam with NOVA/MicroBoone but not with mu2e.
Estimate 2 week turn around to switch between mu2e and (g-2) configuration



Nominally $40M project (with contingency). Some costs shared with mu2e.
CD-1 approval granted in January 2011 and construction begins 2012.


James Bay
Lake Nipigon
Newfoundland and Labrador
N
Thunder Bay
Minn.
Ontario
CANADA
To Burnt Creek 400 miles from Sept-Îles
Duluth
Lake Superior
Superior
Clarke City
Port Cartier
Sept-Îles
Jacques Cartier Passage
Quebec
Baie-Comeau
Rimouski
Saguenay
Sault Ste. Marie
Soo Canal and Locks
Escanaba
Sault Ste
Wisconsin
Georgian Bay
Ottawa
ST. LAWRENCE SEAWAY PROJECT
International Section
Canadian Section
Quebec
Trois-Rivières
St. Lawrence
Montreal
Green Bay
Straits of Mackinac
Lake Huron
New Brunswick
Prince Edward Island
Milwaukee
Muskegon
Michigan
Lake Michigan
Cornwall
Iroquois
Massena
Maine
St. John
Nova Scotia
Halifax
Port Huron
Sarnia
Toronto
Kingston
Ogdensburg
Cape Vincent
Lake Champlain
Chicago
Gary
Lake St. Clair
Detroit
Hamilton
Welland Canal
Niagara Falls
Lake Ontario
Oswego
Vt.
N.H.
Portland
Illinois Waterway
Buffalo
Rochester
N.Y. State Barge Canal (Erie Canal)
Toledo
Lake Erie
Erie
Moses Power Plant
Mohawk
Ill.
Sandusky
Lorain
Conneaut
Ashtabula
Cleveland
New York
Albany
Mass.
Boston
Hudson
Indiana
Ohio
Pennsylvania
Conn.
UNITED STATES
N.J.
New York
R.I.

Alternative technique : ultra-cold muons

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

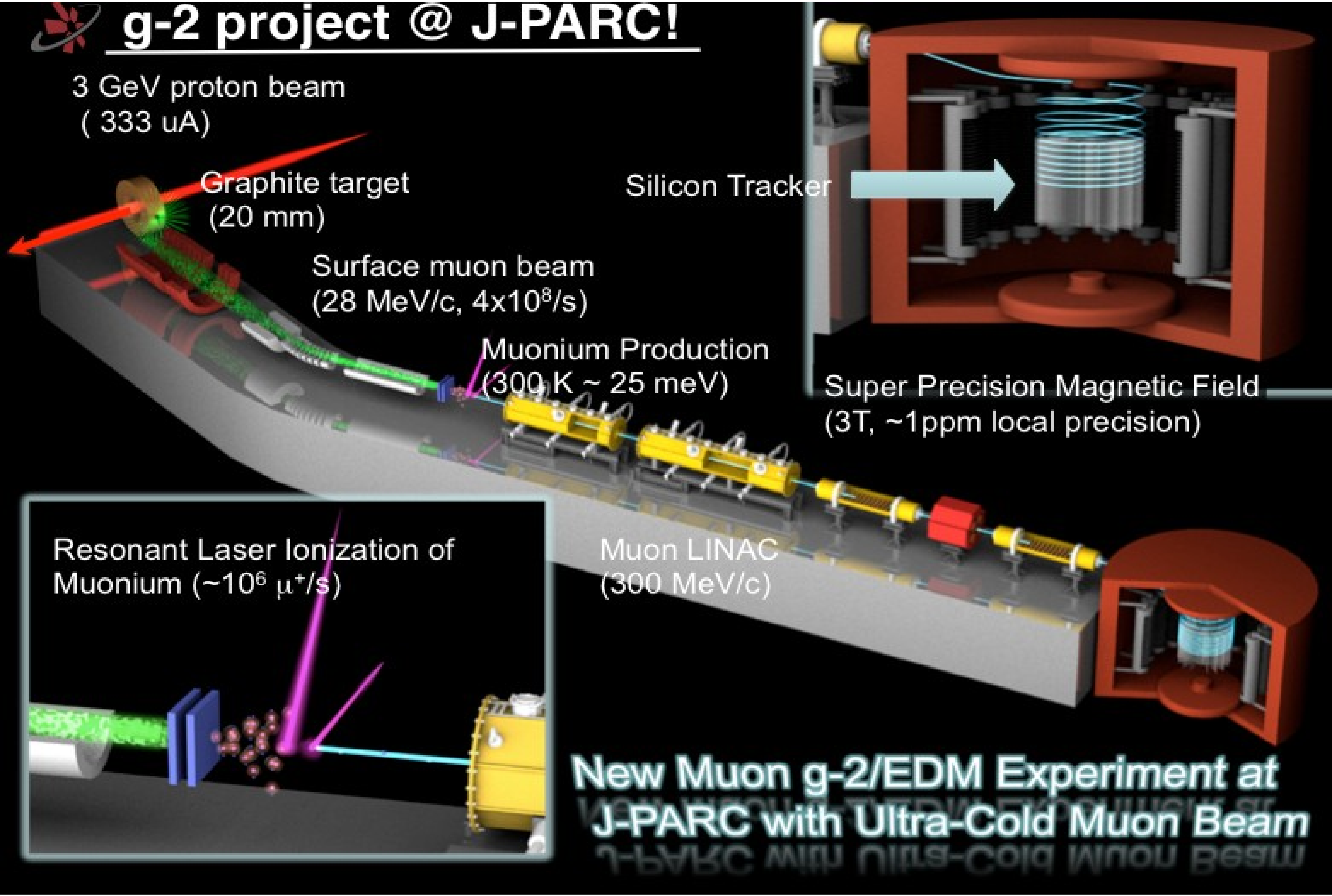
No vertical focussing E-field and larger (and uniform) B-field using MRI advances

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

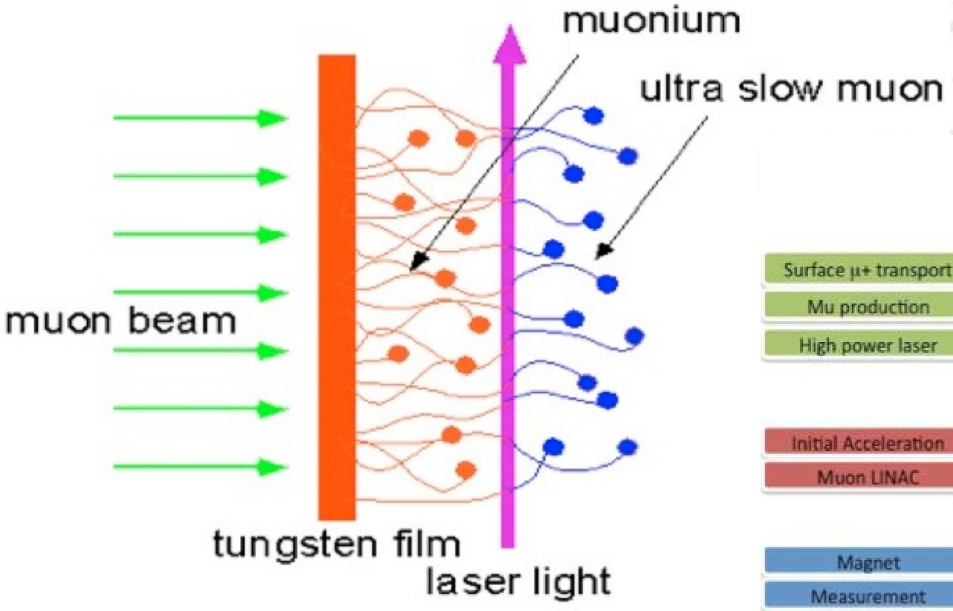
Requires advances in "muonium" production

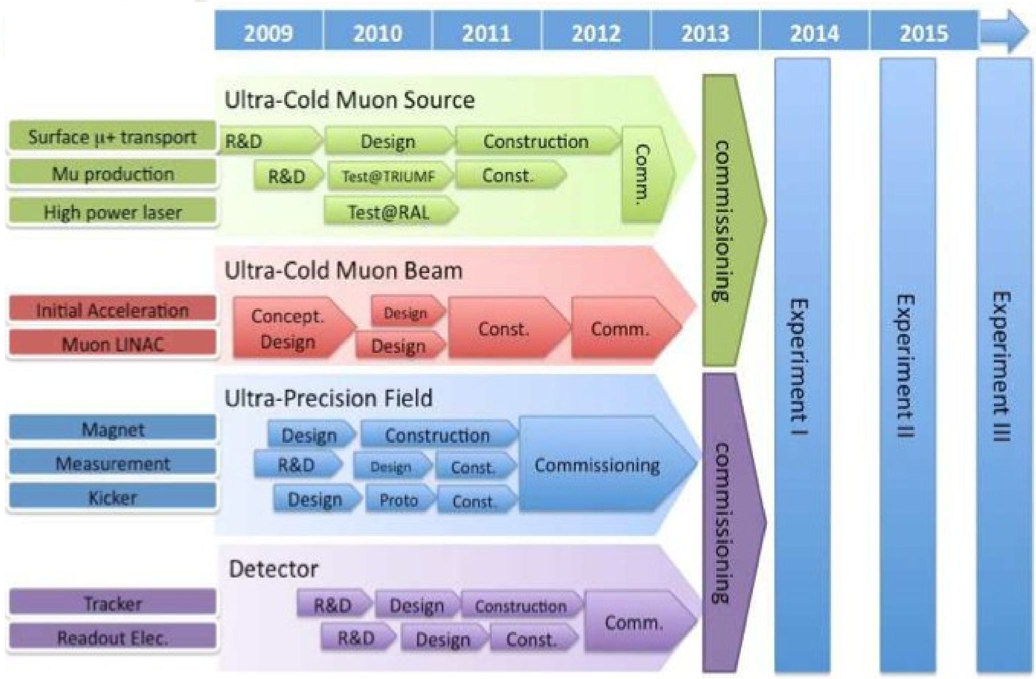
- target materials e.g. nano-structured SiO_2
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)

Techniques being pursued at PSI for EDM measurement and JPARC for g-2


g-2 project @ J-PARC!
3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV)
Silicon Tracker
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

Muons from 2100K to 300K





Active R&D at TRIUMF (different target materials) and RAL/RIKEN

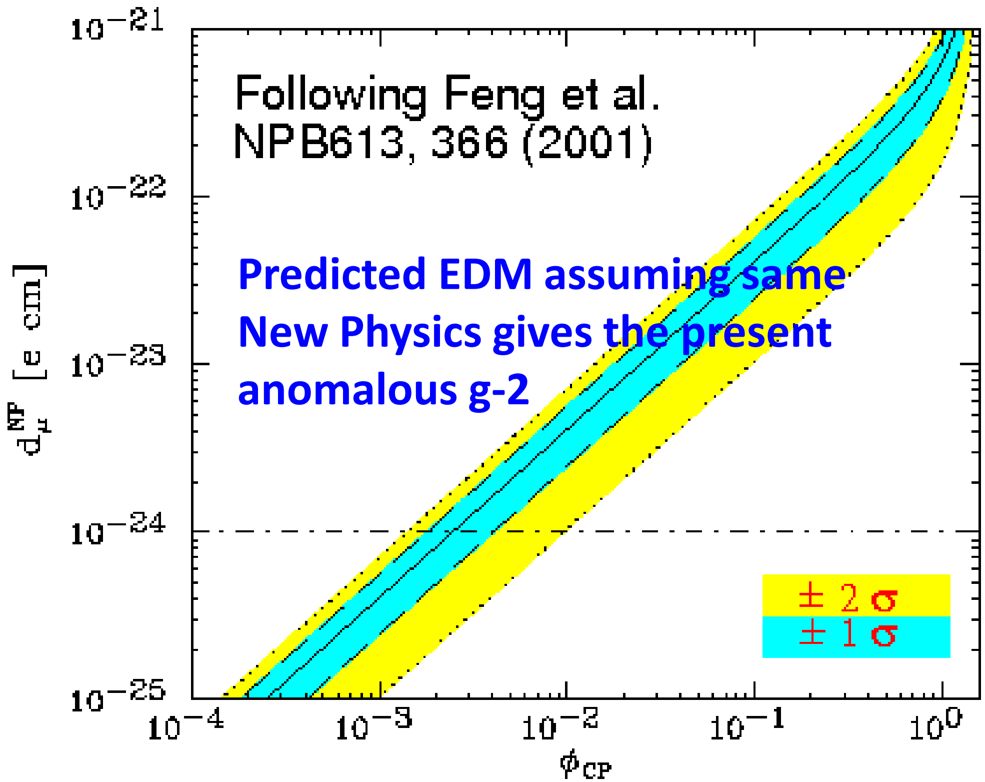
An area of fruitful cross-disciplinary collaboration both within HEP
e.g. SiLC readout, BELLE sensors and outside : material scientists, laser chemists etc

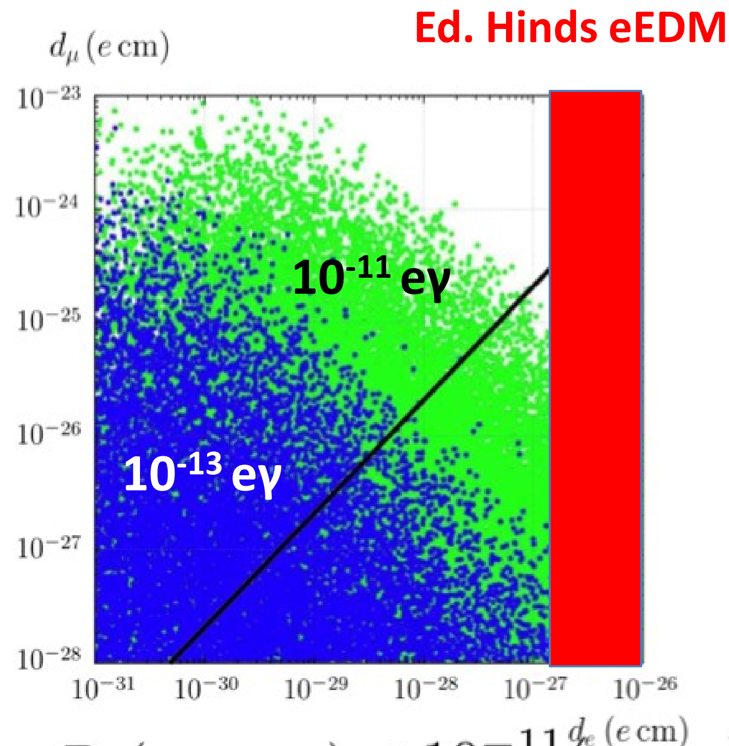
	BNL E821/ FNAL E989		J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		none/very weak
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

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





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

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

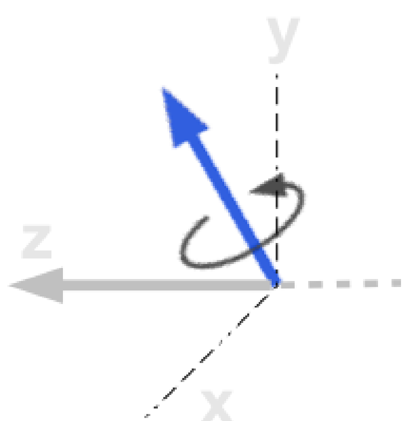
where ϕ_{CP} is a CP violating phase.

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

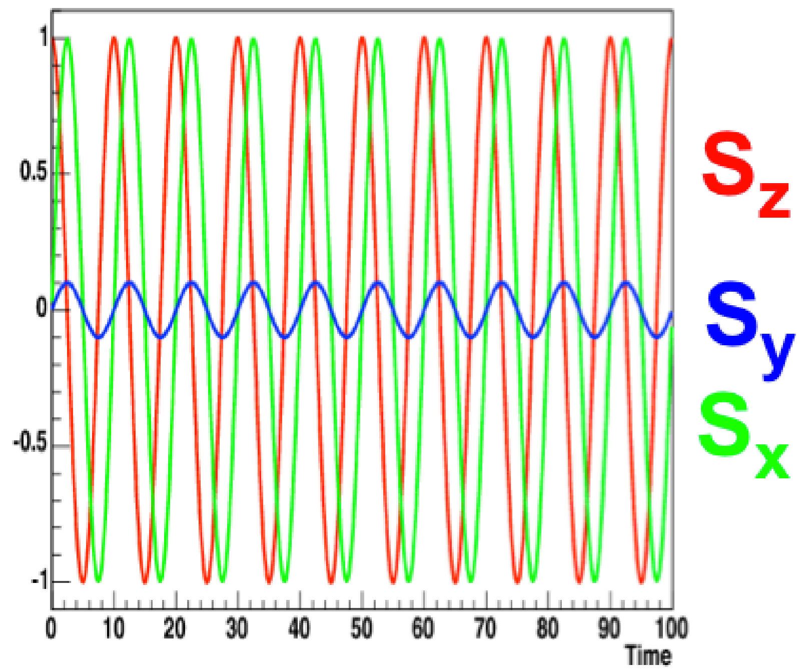
Muon EDM from parasitic g-2 running

magnetic moment anomaly **EDM**

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

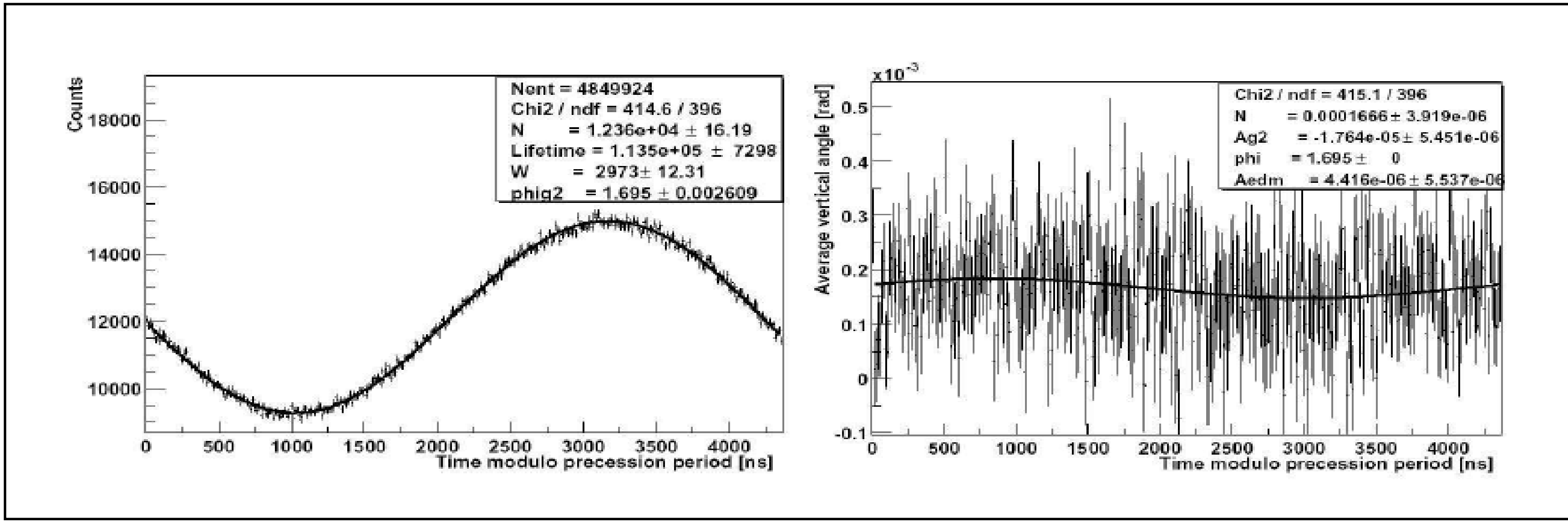


$$S_y = \frac{\eta\beta}{2a}\sin(\omega t)$$



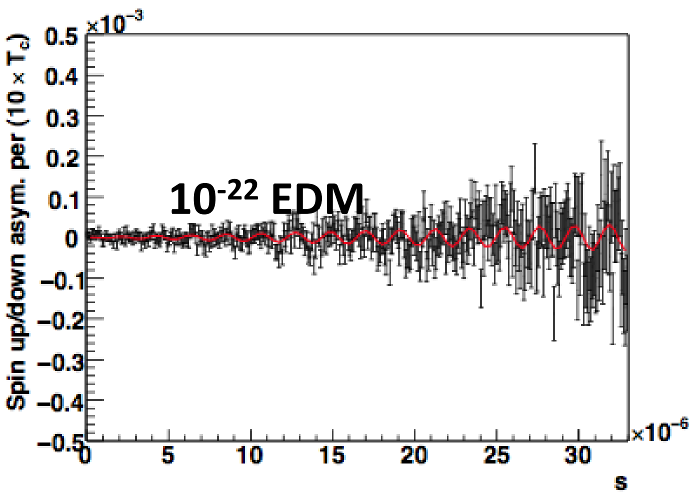
x1,000,000

Parasitic Measurements concurrent with g-2

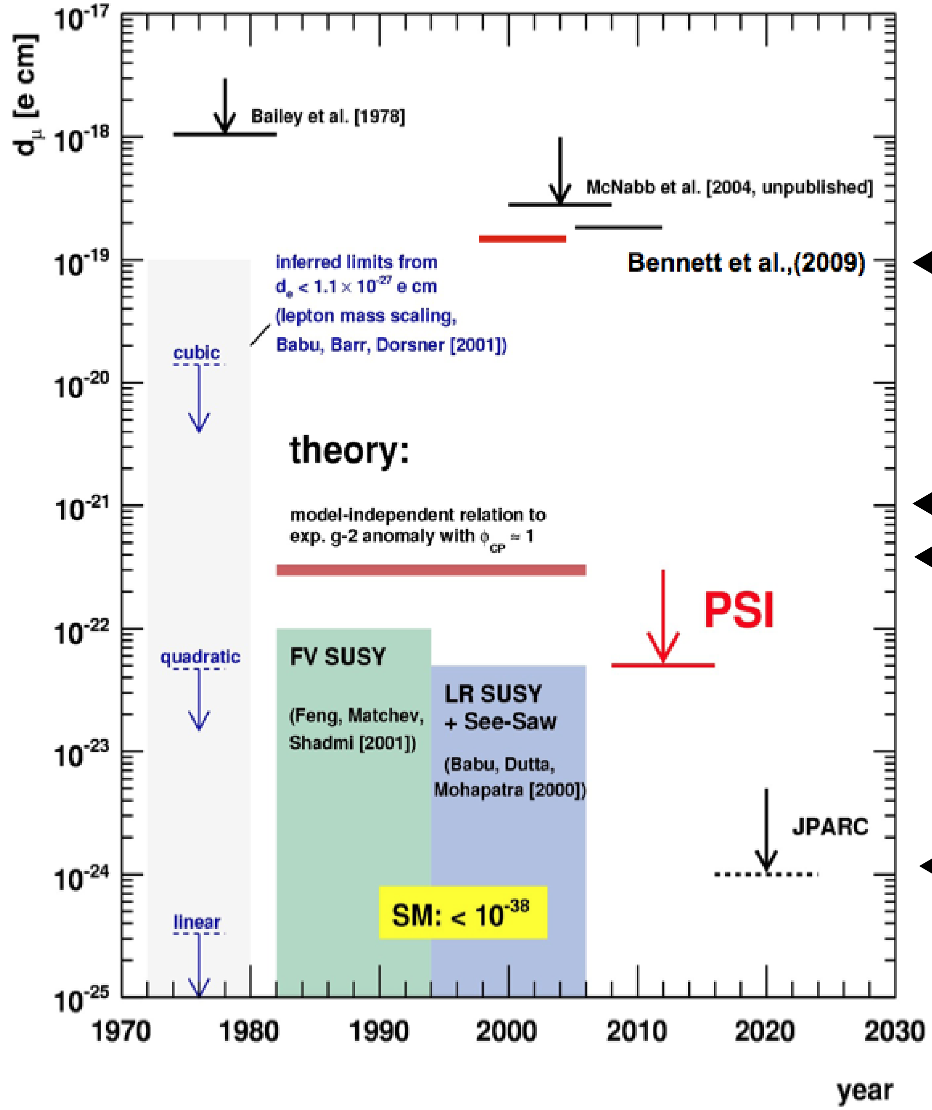


(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

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



Require measurements below 10^{-21}



BNL measurement

FNAL E989 parasitic g-2 (2017)

JPARC parasitic g-2 (2017)

Dedicated Project-X measurement

Dedicated JPARC measurement

EDM Below 10^{-21} : Frozen Spin

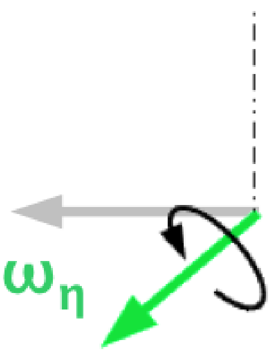
Parasitic EDM has intrinsic limitation at ~ 10^{-21}

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

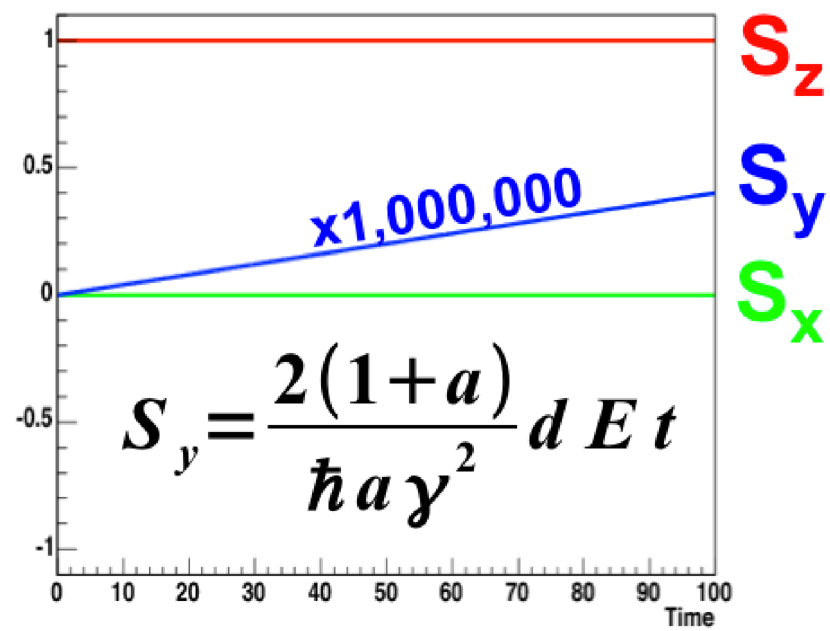
- judicious E and B to cancel magnetic moment contribution

magnetic moment anomaly EDM

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

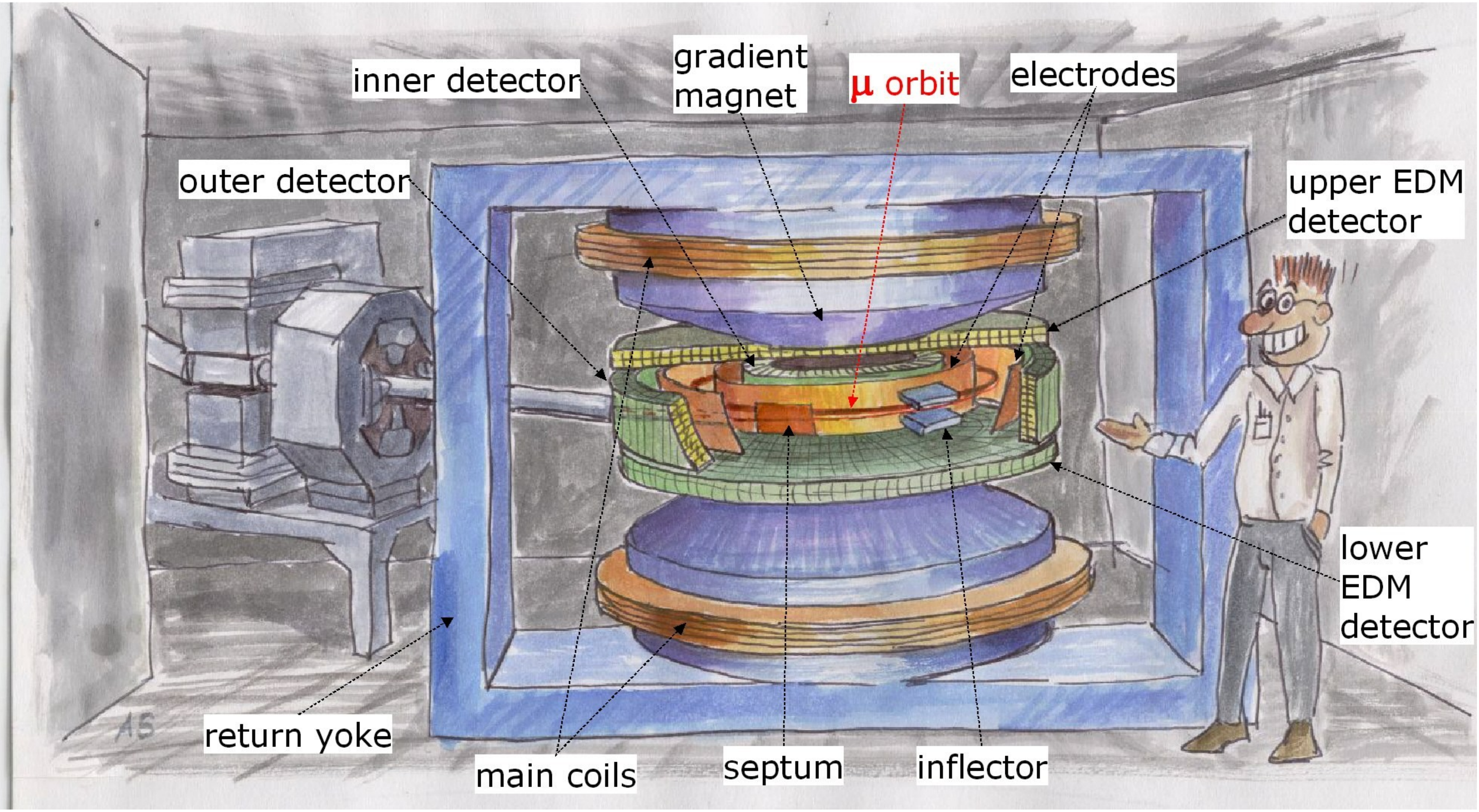


$$E = \frac{aB\beta}{1-(1+a)\beta^2} \simeq aB\beta\gamma^2$$



PSI "Frozen Spin" EDM Proposal

PSI proposal (hep-ex/0606034v3)



PSI EDM Proposal

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

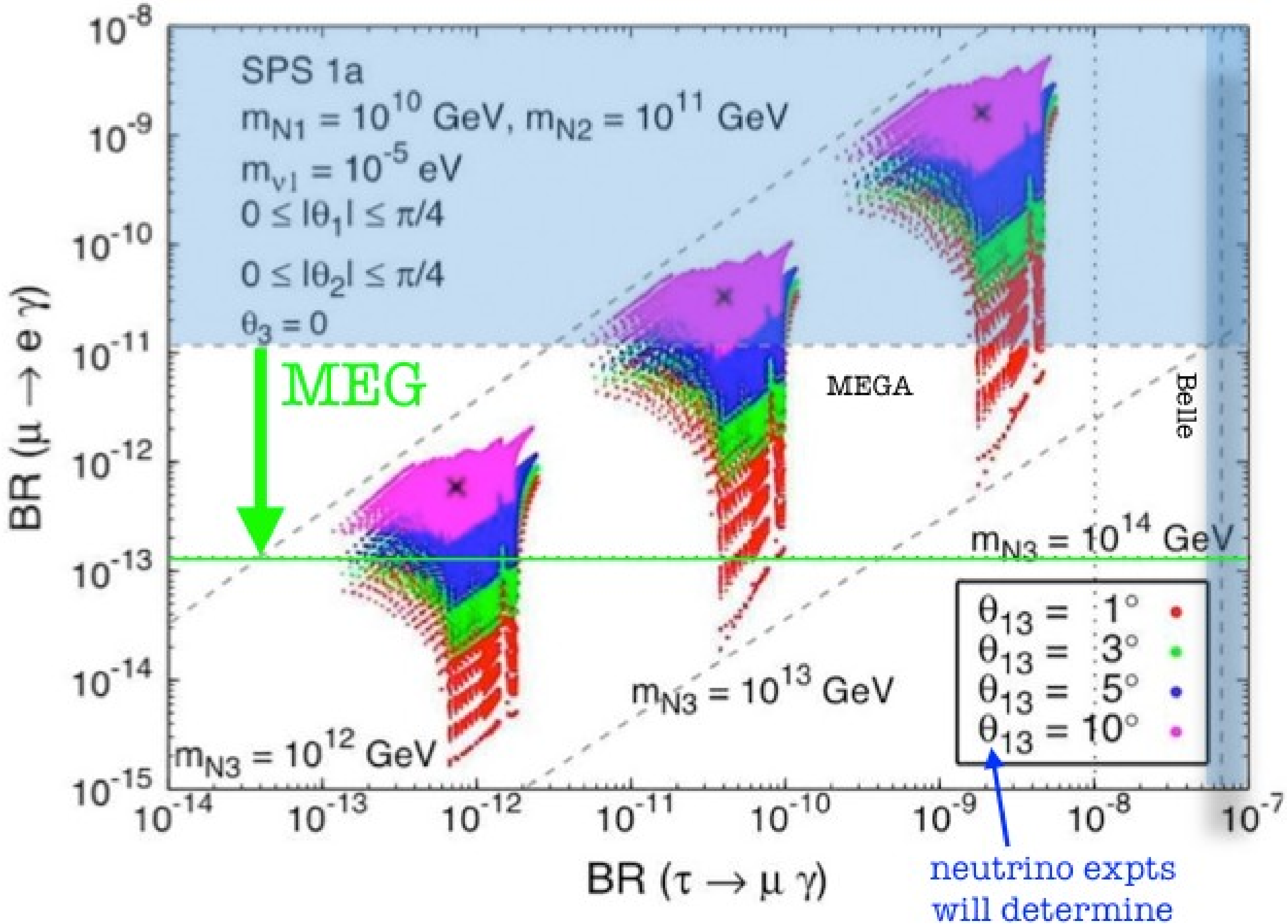
Ring parameters

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

Both JPARC & FNAL have proposals (timescale ~ 2020) to improve this by x50 to 10^{-24}

LFV observed in neutrino sector and in SM predicted to be $O(10^{-50})$ in charged sector
In SM extensions : 10^{-10} to 10^{-20} level

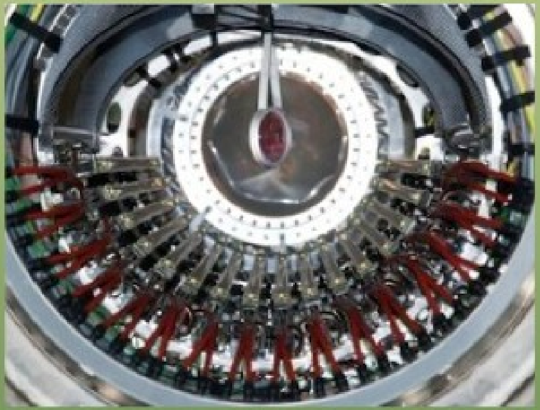


Compared to g-2 / EDMs cLFV tends to have sensitivity beyond EWK scale

MEG Experiment

World Most Intense DC Muon Beam at PSI
10^8 muon / sec

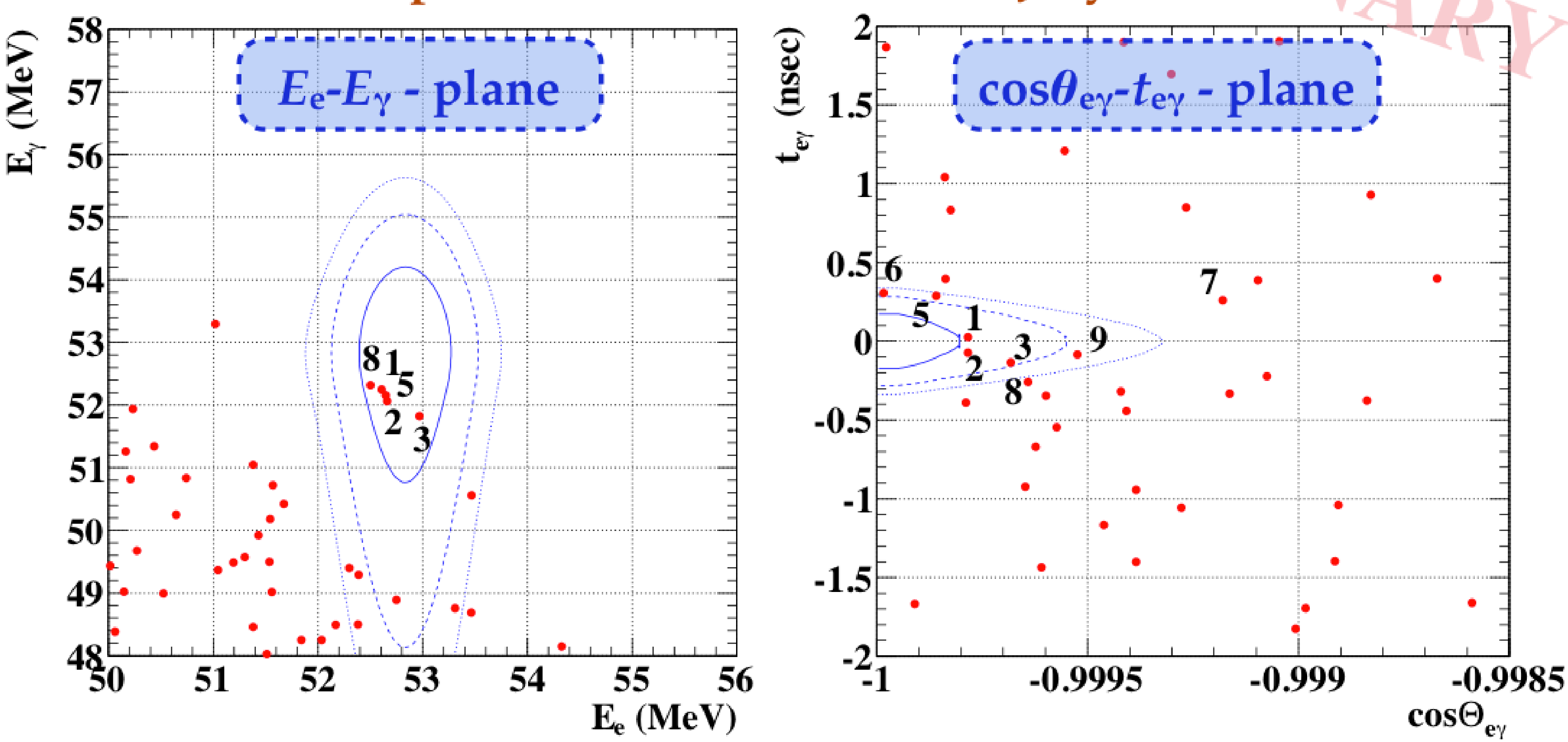
Liquid Xenon Scintillation Detector (gamma)



COBRA Spectrometer (positron)

So far 3 physics runs : 2008, 2009, 2010 and now taking data in 2011

MEG Experiment



Preliminary analysis of 2009 data (July 2010)

Limit < 1.5×10^{-11} @ 90% CL

Final 2009 analysis + 2010 data released for ICHEP-2011 : expected limit < 1.5×10^{-12}

2011 data should get to the intrinsic sensitivity of eγ of 10^{-13}

cLFV beyond 10^{-13}

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

Only candidate is coherent muon to electron transition in muonic atom

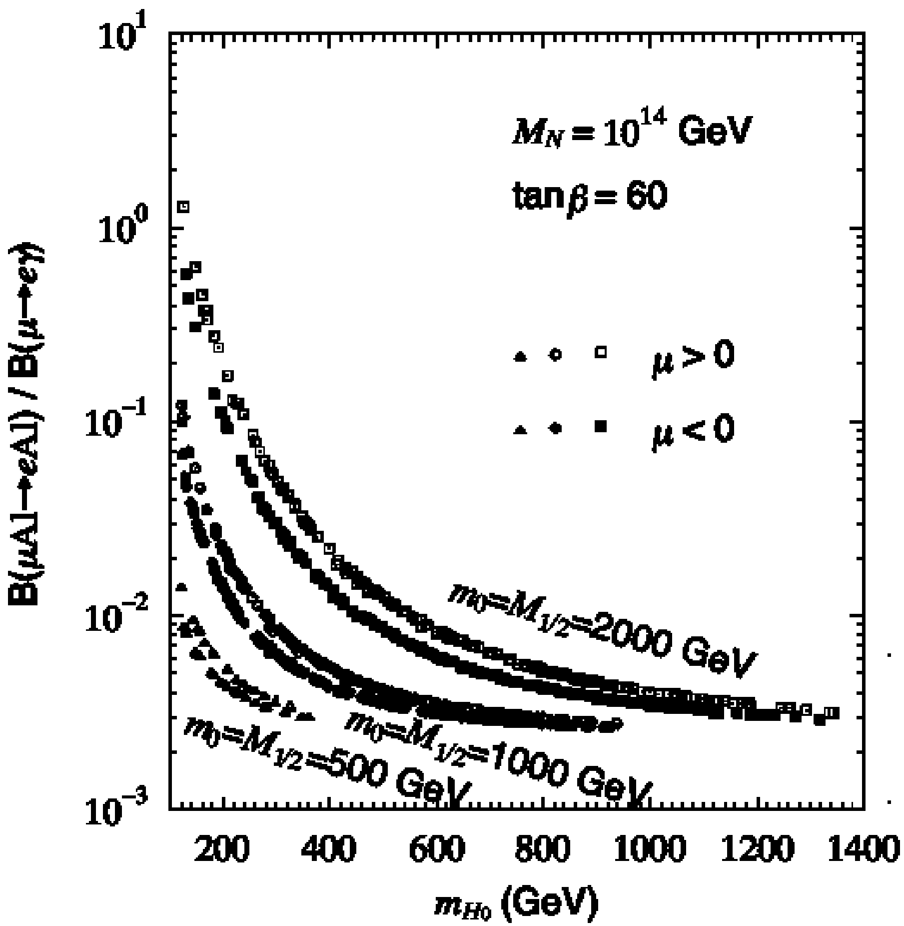
Two proposals:

- COMET (J-PARC)
- Mu2e (FNAL)

With similar timelines (“funding” + 5 ~ 2017), cost ($150M) and sensitivity.

cLFV beyond 10^{-13}

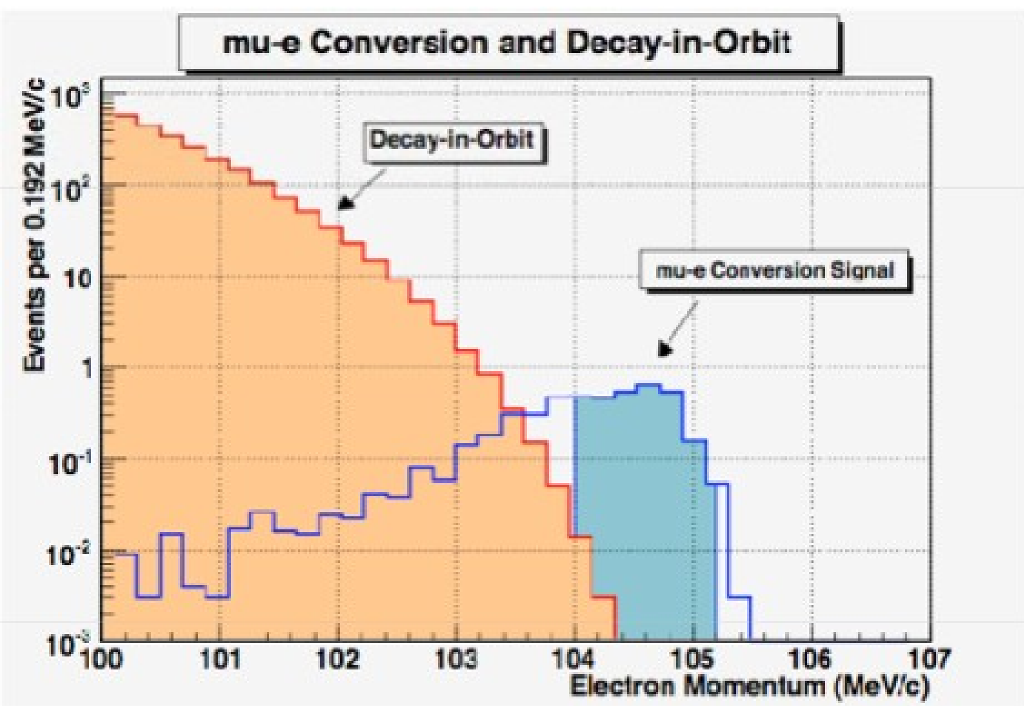
O(10^{-13-15}) in μN-eN is required to have similar sensitivity as MEG limit of 10^{-13} in eγ

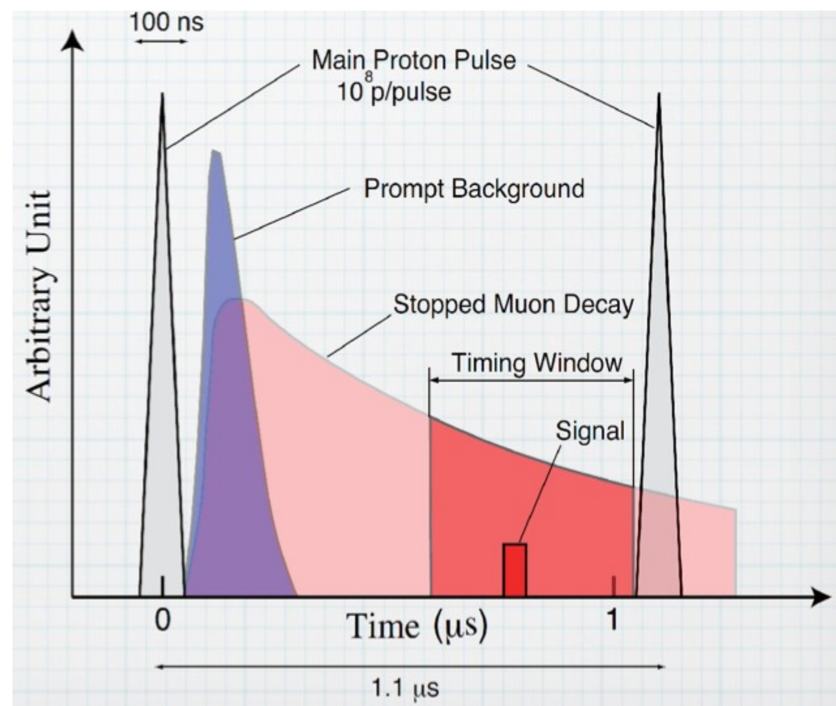


COMET / mu2e are aiming for sensitivity of 10^{-16} with upgrade options to go to 10^{-18}
Factor of ~ 10,000 improvement on previous (SINDRUM-II) limit of 6×10^{-13}

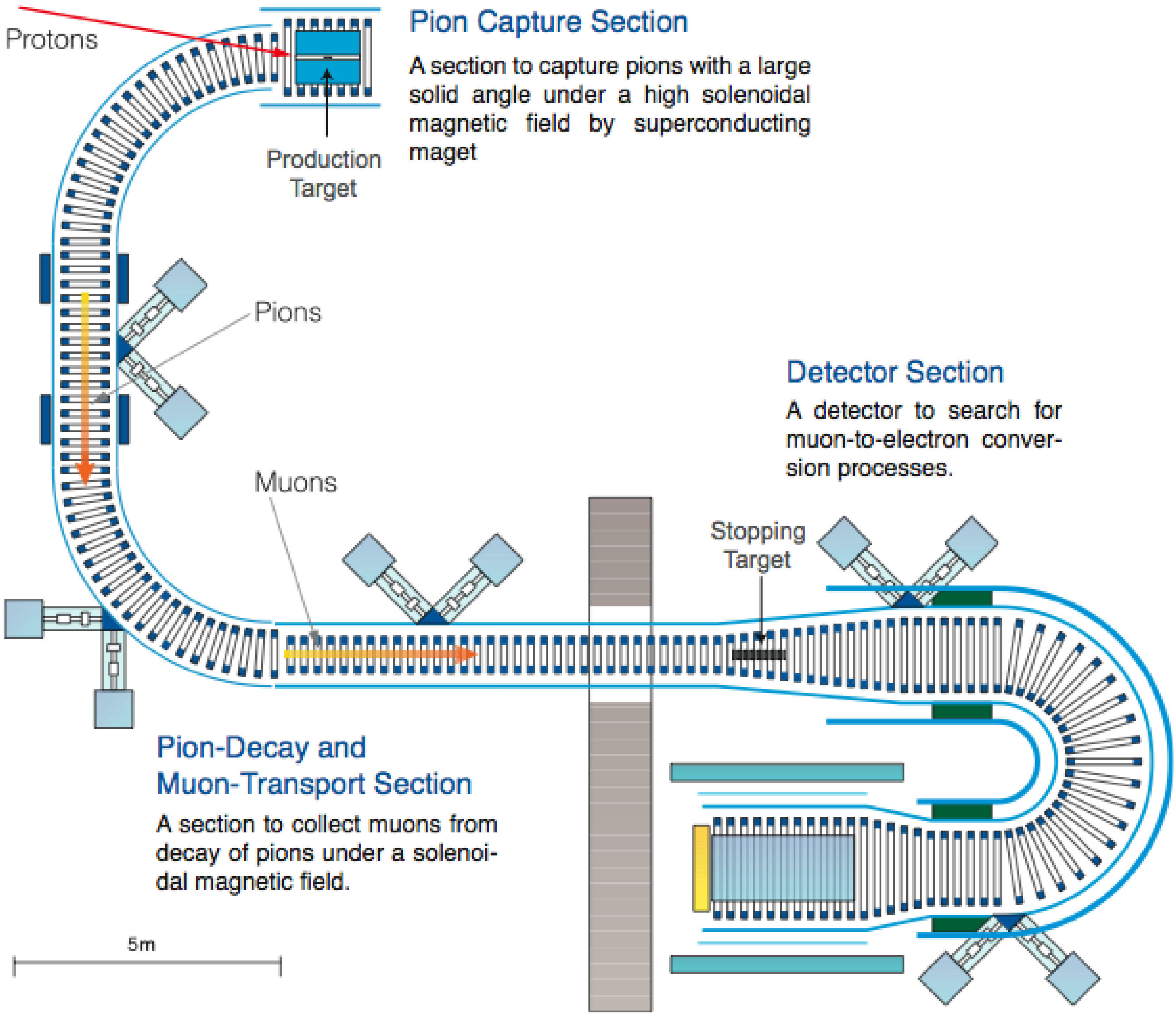
Muon to Electron Conversion

- Pulsed proton beam to reduce prompt backgrounds.
- Measure signal after O(700 ns) delay to reduce standard muon background
- Radiation tolerant superconducting solenoids
    - Improve low momentum backward pion yield around target
    - Momentum select low momentum pions/muons
    - Momentum select high energy (105 MeV) electrons
- High resolution/occupancy straw trackers
- High resolution 100 MeV electron calorimetry

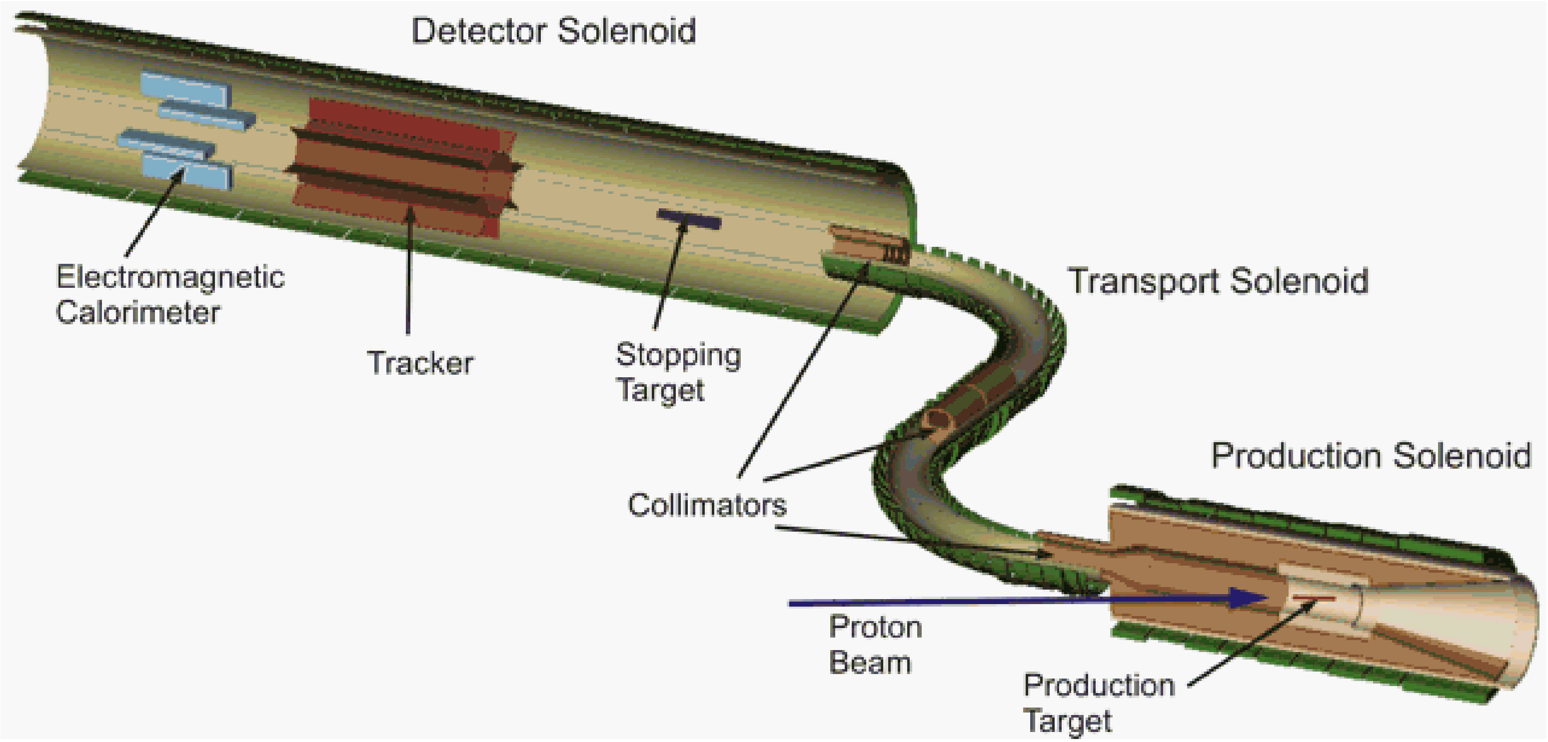




COMET Experiment



Mu2e Experiment



COMET Experiment

UCL

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UK : UCL, Imperial.

Experiment Status

Both experiments at a similar stage:

- COMET received stage-1 of 2 stages of approval from KEK PAC in 2009 based on a CDR.
  Expecting to submit TDR at end of the year.

- mu2e has CD0 in FNAL and similarly is bidding for CD-1 approval before end of year

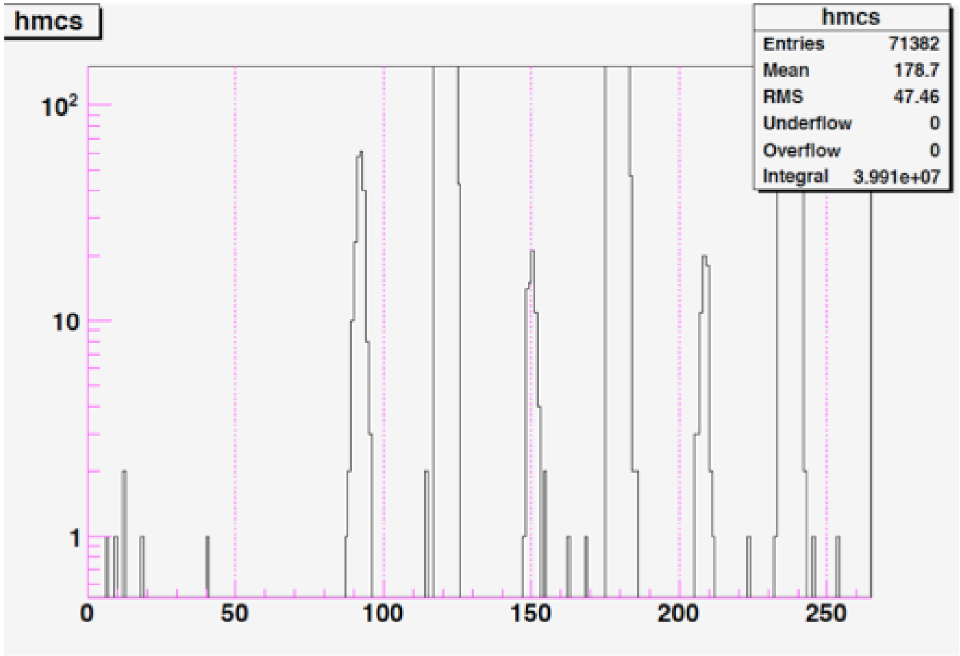
Detector design and some aspects of the simulation are more mature in mu2e.

Aspects of the accelerator/solenoid design more mature in COMET
- COMET has prototype pion production environment (MUSIC @ OSAKA)

Formal collaboration between the two experiments at KEK-FNAL level – particularly in area of radiation tolerance of superconducting solenoids.

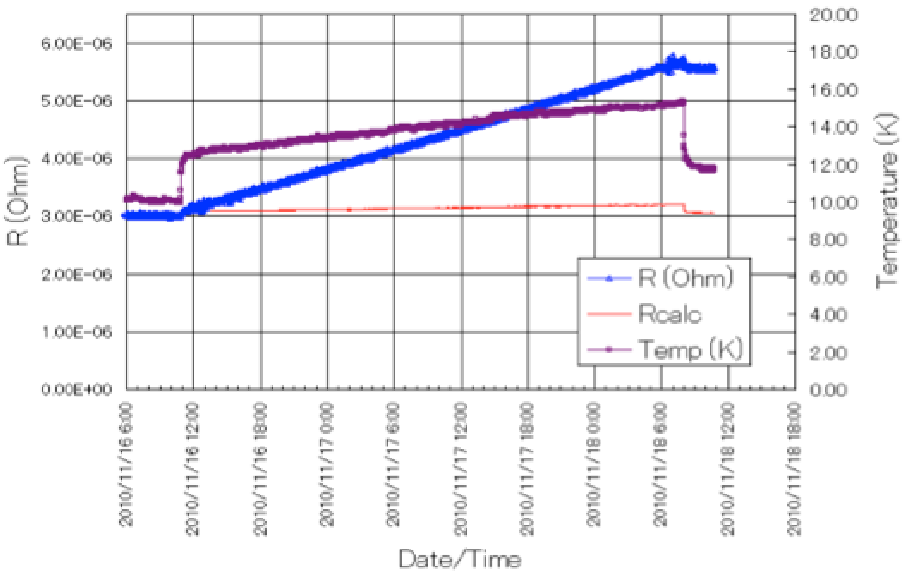
It's certainly an area (cf Dark Matter) where independent verification of a signal across 2 experiments would be welcome.

Proton Extinction / Magnet Irradiation



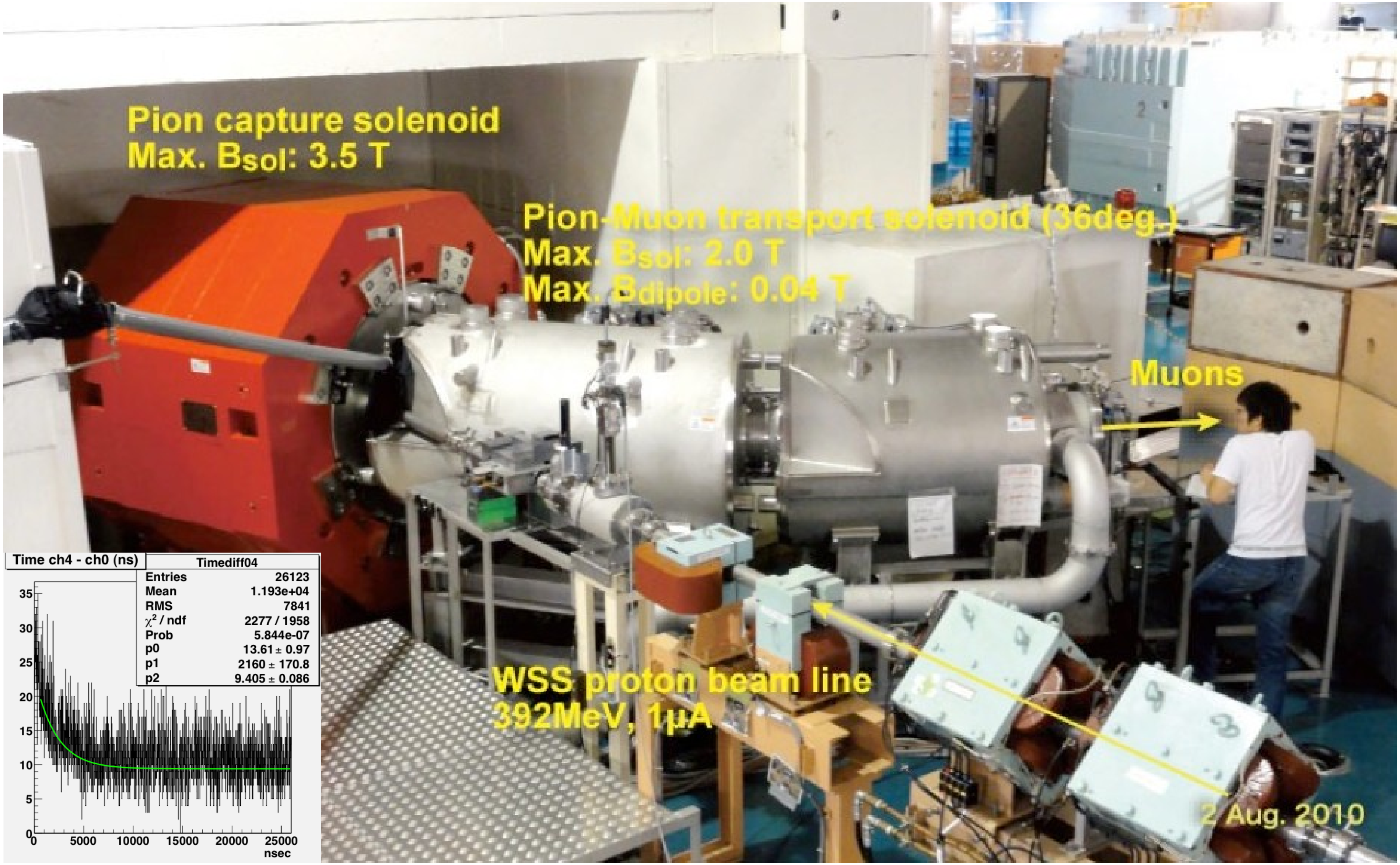
Require absence of spill-over protons between pulses at level of 10^{-9}

Already proven at 10^{-7}



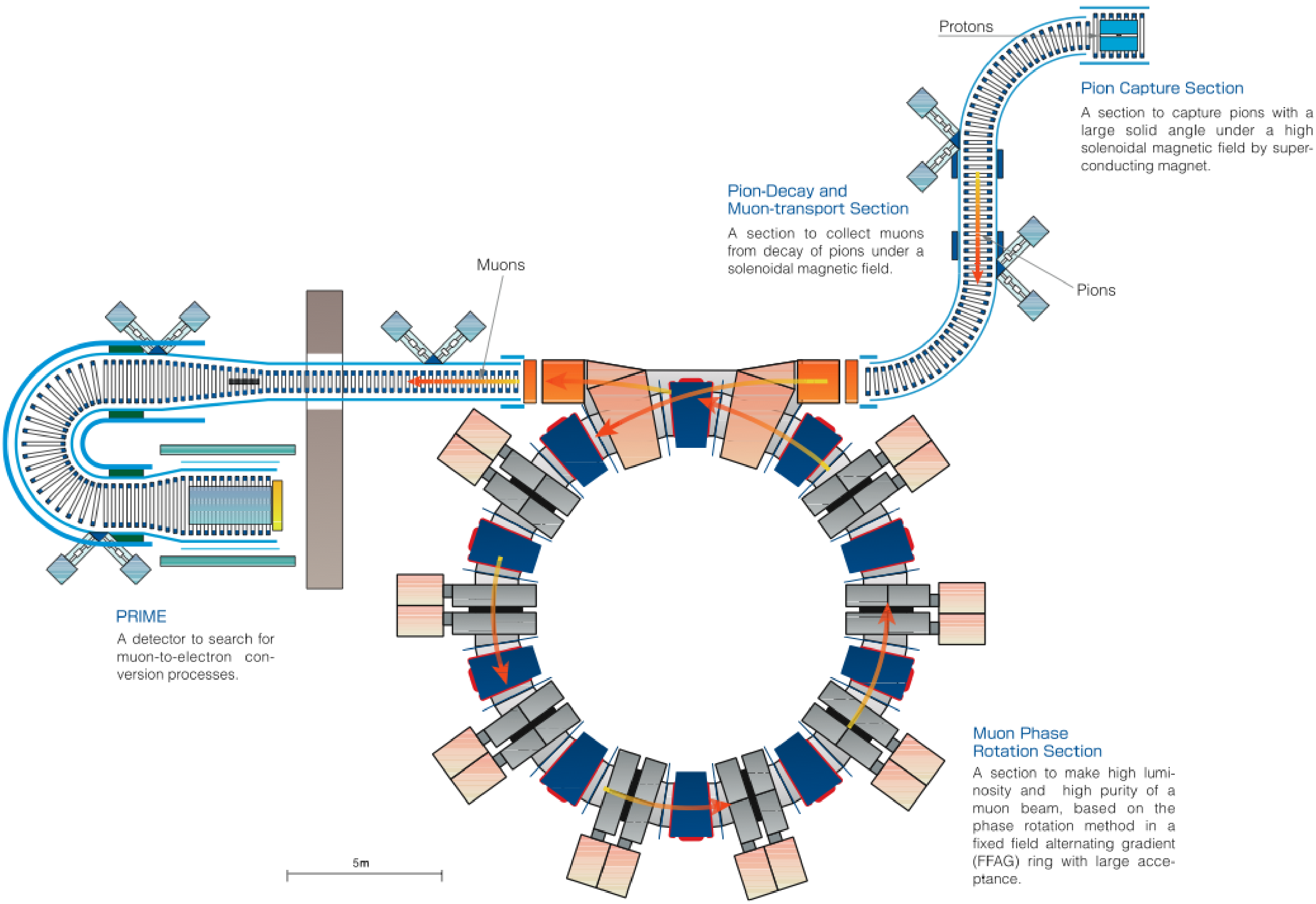
Irradiation of Al-stablised NbTi super conducting material using Kyoto reactor

MUSIC experiment at Osaka

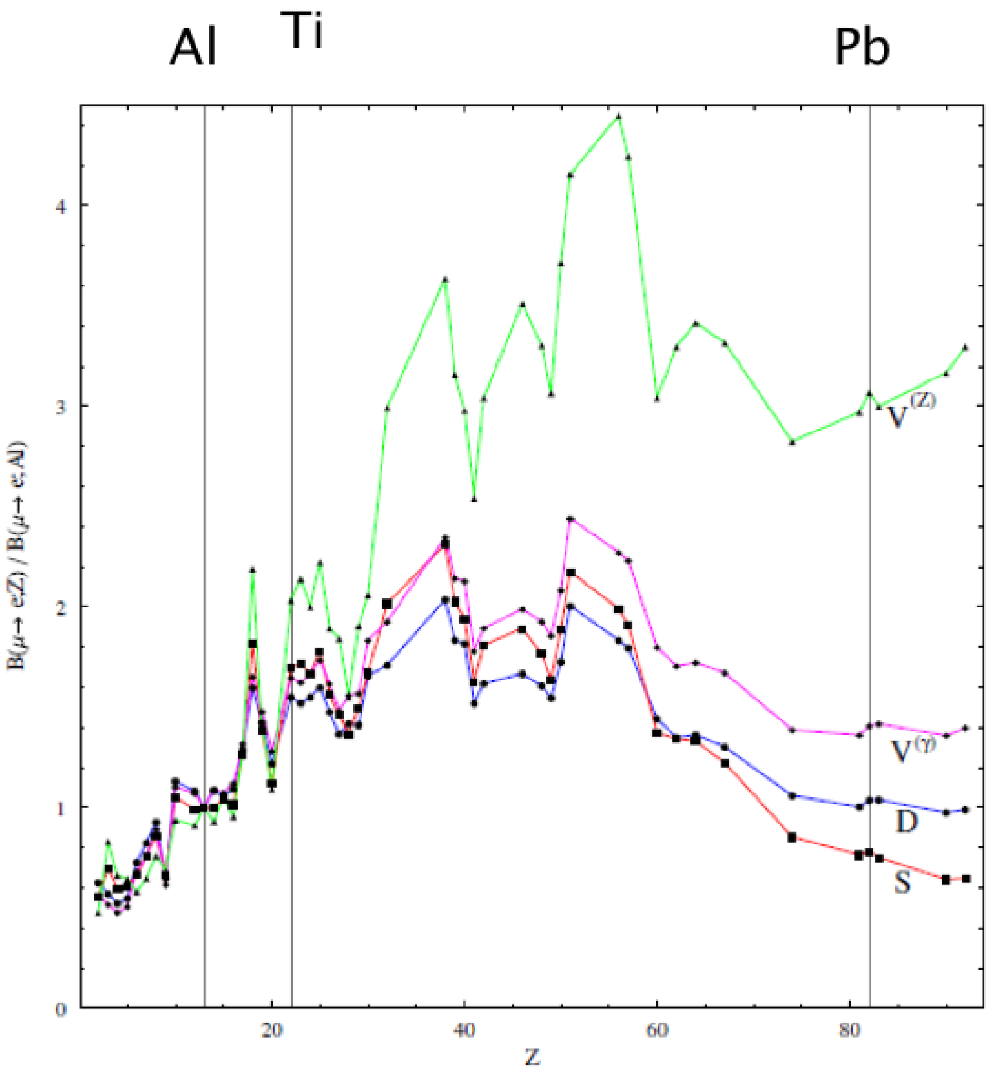


Beyond 10^{-16} : COMET to PRISM

Addition of an FFAG – reduces pion background & provides higher quality muon beam



PRISM would also introduce a variety of targets



Vector (Z–like coupling)

Vector(γ–like coupling)

Photonic dipole

Scalar coupling

Conclusions

There is life outside the LHC

Precision muons : well defined 10+ year programme with cross-disciplinary appeal

- Next generation (g-2) will reach 0.1ppm level and would move BNL 3σ to 7.5σ
- Muon EDMs will reach sensitivity @ 10^{-24} level
- Lepton flavour violation limits will improve by 100-10,000 in next 2-8 years particularly with mu2e/COMET.

Muon experiments provide a clean and complementary probe of BSM physics and particularly at high energy scales with a connection to leptogenesis.