Probing New Physics with Muon Beams

Mark Lancaster
University College London

Despair

"As you undoubtedly know, theoretical physics – what with the haunting ghosts of neutrinos, the Copenhagen conviction,

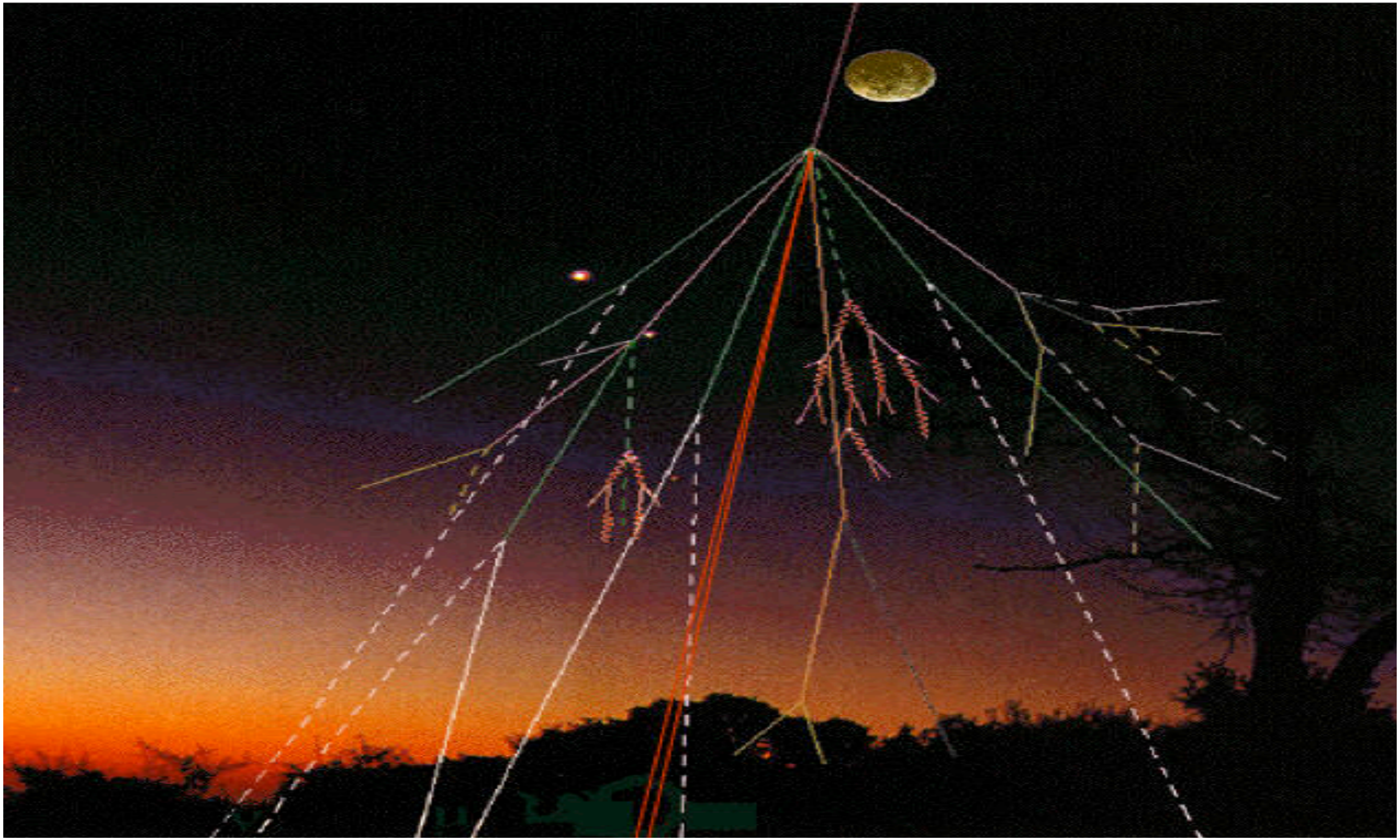
against all evidence, that cosmic rays are protons

Born's absolutely unquantizable field theory, the divergence difficulties with the positron and the utter impossibility of making a rigorous calculation at all

– is in a hell of a way"

June 1934

The problem



Nutters

Late 1920s developed a theory: the "Birth Cry of Atoms"

- Religion inspired fusion model forming atoms that also emitted photons.
- Primary cosmic rays were photons of discrete energies

With a dodgy theory and dubious fits to the ionisation data of cosmic rays – he claimed he could explain all the data !

Millikan ignored warnings from Oppenheimer and got his PhD student to make more measurements to prove "The Birth Cry"

Robert Millikan

Nobel Prize 1923

Fisticuffs

Milikan ignored the fact that if primary cosmic rays were **not** photons then there would be a "lattitude effect" due to the earth's magnetic field.

Millkan failed to measure the "lattitude effect" Compton did and the two Nobel Prize winners had several public spats.

Millikan and Anderson continued to ignore QM and believed e^- and e^+ existed in the nucleus and were knocked out by the "Birth-Cry" cosmic ray photons.

They rejected the Dirac theory of "pair creation" since more e^- were observed than e^+

It was in the Cavendish (Blackett, Rossi, Occhialini) where e^-e^+ pair-creation coincidence measurements were made and which vindicated Dirac.

Soon after Anderson distanced himself from Millikan and continued his work solo…

Form

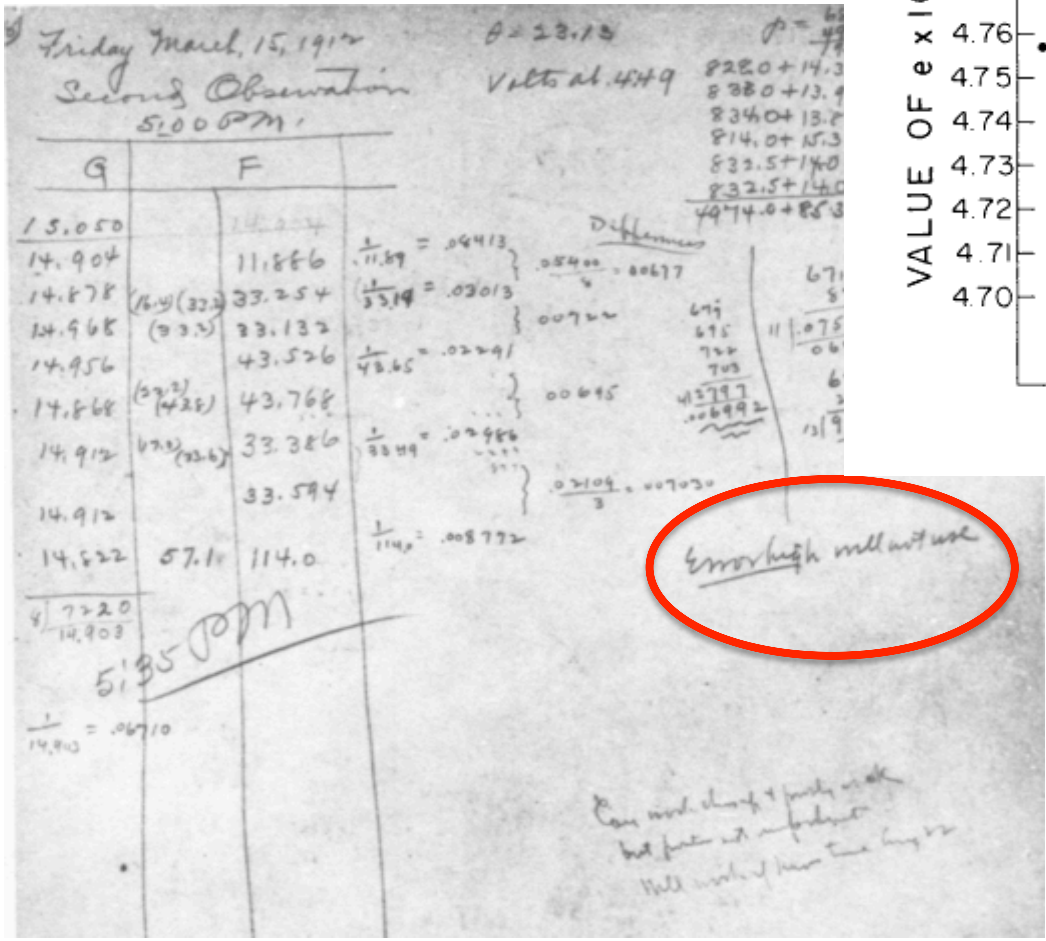
Millikan's notebook for the oil-drop measurements determining "e"

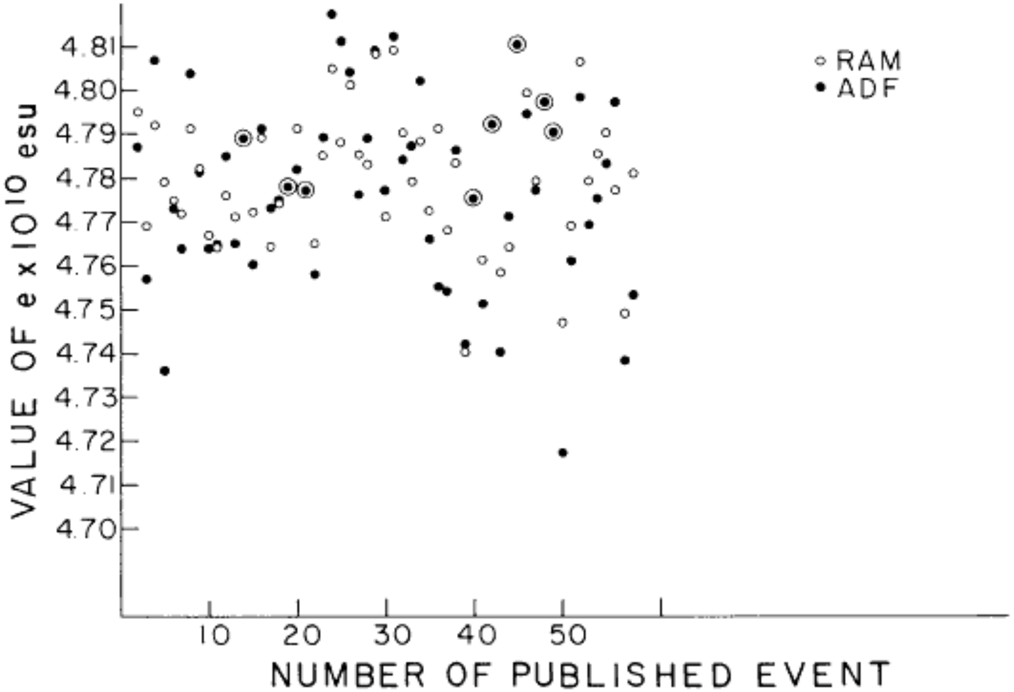
This is almost exactly right & the best one I ever had!!! [20 December 1911]
Exactly right [3 February 1912]
Publish this Beautiful one [24 February 1912]
Publish this surely / Beautiful !! [15 March 1912, #1]
Error high will not use [15 March 1912, #2]
Perfect Publish [11 April 1912]
Won't work [16 April 1912, #2]
Too high by 1½% [16 April 1912, #3]
1% low
Too high e by 1¼%

The published paper only had 58 "selected" measurements from 175.

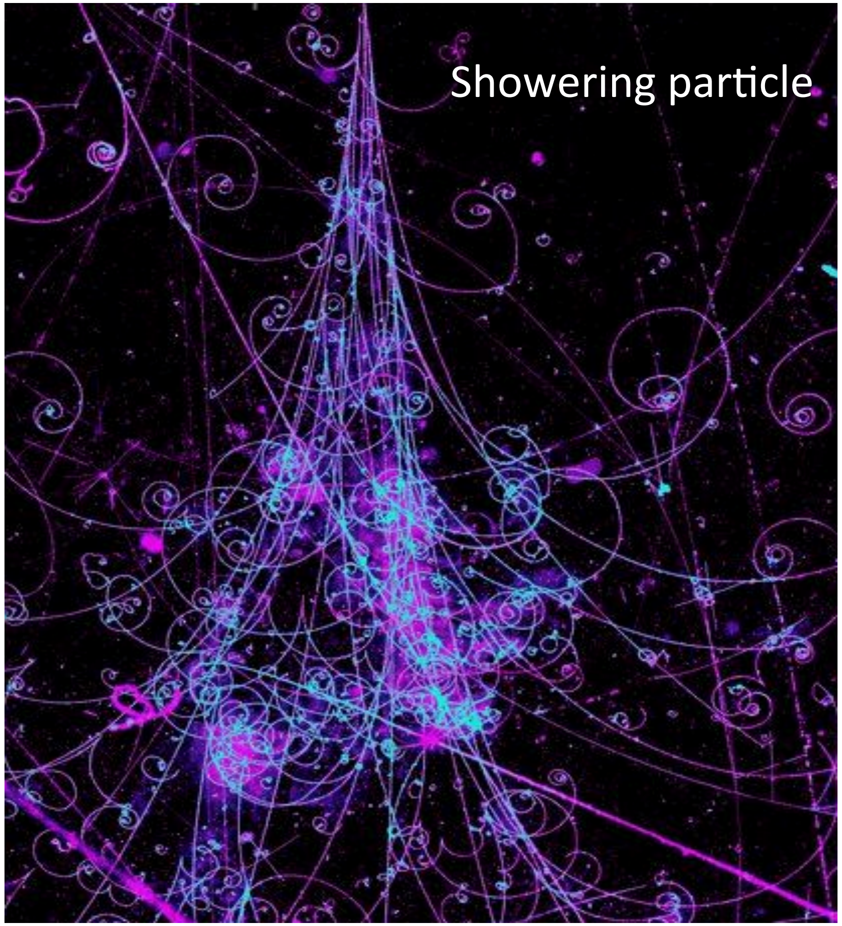
"These drops represent all of those studied for 60 consecutive days, no single drop being omitted."

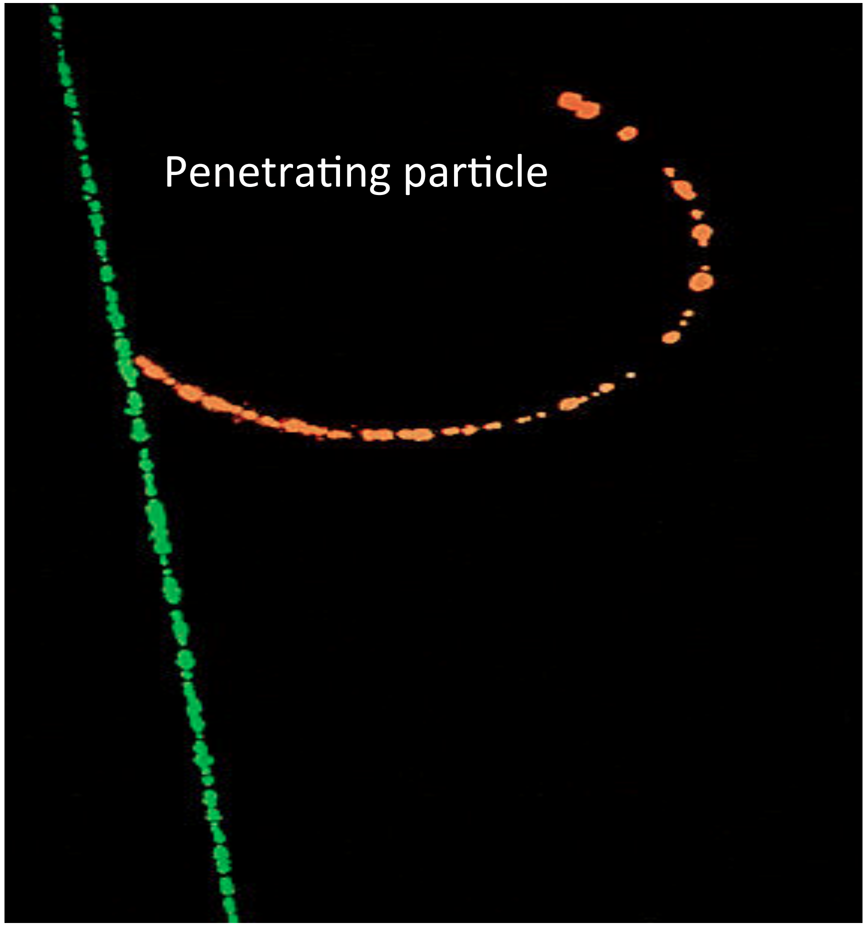
Form


Friday March 15, 1912
Second Observation
5.00 PM
G
F
Differences
5:35 PM
Error high will not use


VALUE OF e x 10^10 esu
NUMBER OF PUBLISHED EVENT
4.81
4.80
4.79
4.78
4.77
4.76
4.75
4.74
4.73
4.72
4.71
4.70
10
20
30
40
50
RAM
ADF

Two types of particle seen





Showering particles believed to be electrons but only after a lot of theoretical work by Bethe, Heitler, Oppenheimer, Carlsson in developing QED of e^+e^- pair creation

Red and Blue Electrons !

But no tweaks to the theory could explain why e^- would be penetrating.

For a time the theorists toyed with the idea of the cosmic-ray particles being protons.

They then rejected that in favour of a model of "red" and "blue" electrons : one type showering and one type penetrating !

These rather embarrassing conjectures were quickly swept under the theorist's carpet when the experimentalists started measuring masses and charges of the penetrating particles.

Chronology

1935 : Yukawa proposes a "mesotron" to explain the finite range of the nuclear force. A particle with mass between e^- and p

March 1937 : Anderson, Neddermeyer (CalTech)
± particles with mass between e and p

April 1937 : Street, Stevenson (Harvard)
mass (+) = $(130 \pm 30)\ m_e$

August 1937 : Nishina, Takeuchi, Ichimiya (Tokyo)
mass(+) = $(220 \pm 40)\ m_e$

June 1938 : Anderson, Neddermeyer
mass (+) ~ $240 \times m_e$

Jan 1939 : Nishina, Takeuchi, Ichimiya
mass(-) = $(170 \pm 10)\ m_e$; mass(+) = $(180 \pm 20)\ m_e$

Everybody goes off to Los Alamos to build a bomb

The 1947 Consensus : Muon and Pion

After the war it was still believed that what had been observed was Yukawa's mesotron.

1947 : Conversi, Pancini and Piccioni showed that interactions of the negative mesotron with the nucleus were not "strong" but "weak".

1947 : Weisskopf, Teller and Fermi noted that the decay time of mesotrons in matter was 10^{12} longer than for the "Yukaka mesotron".

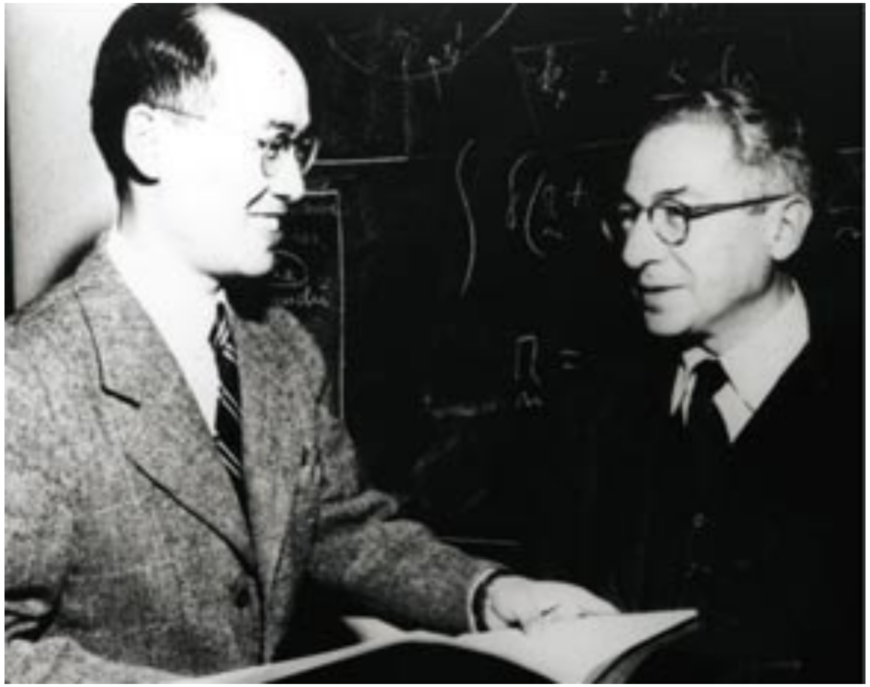
The negative mesotron was then given the symbol : μ.

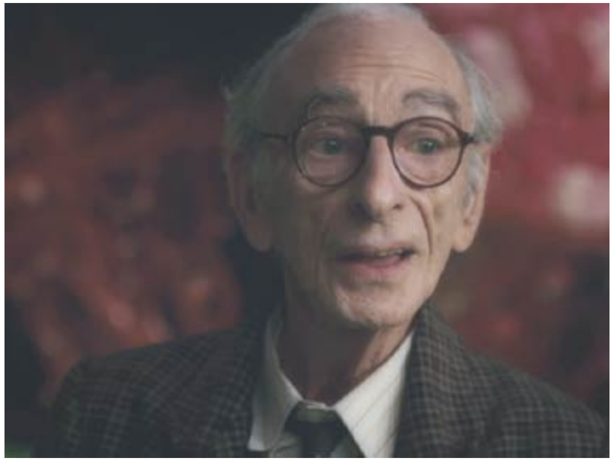
1947 : Lattes, Muirhead, Occhialini and Powell find μ^- arise from decay products of another cosmic ray mesotron that they give the symbol π.

It was finally realised the μ wasn't a meson but the name "mu-meson" persisted for many years with "muon" only being widely adopted in the 1960s.

Yukawa's mesotron was christened the pi-meson and latterly the pion.

Who ordered that ?





Rabi : instrumental in setting up CERN.

One of first CERN experiments was Lederman's "g-2" using the 600 MeV accelerator

Nobel Problems

Muon was "discovered" by 3 sets of experimentalists and cogent interpretation wouldn't have been possible without the theory input.

Arguably the Japanese had the most incisive measurement.

The data and its interpretation took 15 years to be accepted.

Solution – no Nobel Prize for the Muon Discovery !

- Keep the Japanese happy : Yukawa (1949) gets a prize for the pion theory
- Keep the USA happy : Anderson already got the prize for e^+ (1936) and gets the credit for the muon but not a second prize
- Keep the Brits happy : Powell (1950) for the experimental discovery of the pion and Blackett (1948) for cloud chamber.
- Italians not happy….

CDF, D0, ATLAS, CMS, Englert, Guralnik, Hagen, Higgs, Kibble, ….

Nobel Problems

Title:	**Science is measurement: muons, money and the Nobel Prize**
Author:	Jeffrey David Turk ✉
Address:	Scientific Research Centre of the Slovenian Academy of Sciences and Arts, Chemin des Deux Maisons 67/28, 1200 Brussels, Belgium
Journal:	*International Journal of Pluralism and Economics Education 2011 - Vol. 2, No.3 pp. 291 - 305*
Abstract:	This article investigates the difference in measurement methods between contemporary particle physics and economics. The book Measurement in Economics: A Handbook, (Boumans, 2007), is used to present the current state of measurement technique in economics. These views are compared with the measurement of the anomalous magnetic moment of the muon. Particle physics is realist in measurement while economics is not. The reality check on theory that measurement provides in particle physics is conspicuously absent in economics. However, the nature of the social world precludes the use of the same measurement approach.

"Particle Physics is realist in measurement while economics is not"

Physics is in a "hell of a way"

Need new physics to:

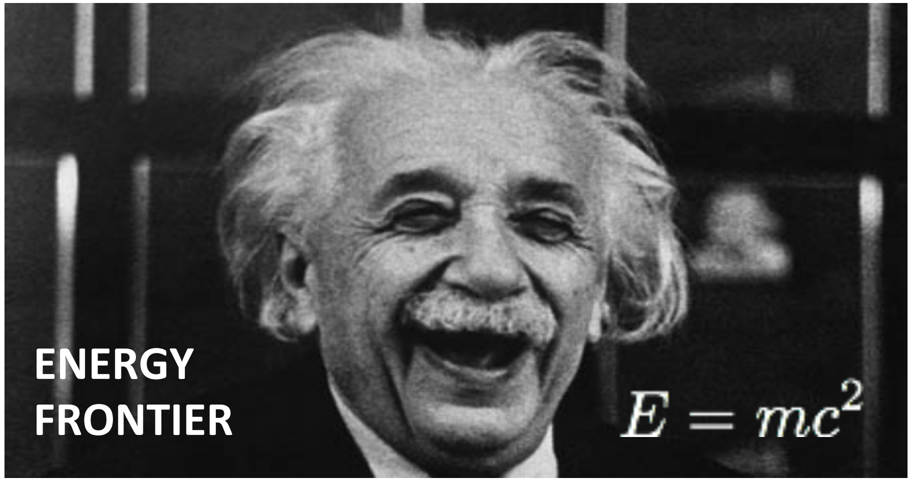
1. Give mass to W/Z and neutrino and explain why $m_\nu/m_t = 10^{-12}$
2. Give significant CP violation to explain matter anti-matter asymmetry but also to explain why there is zero CP in QCD : axion !!!
3. Explain dark matter
4. Develop a quantum theory of gravity

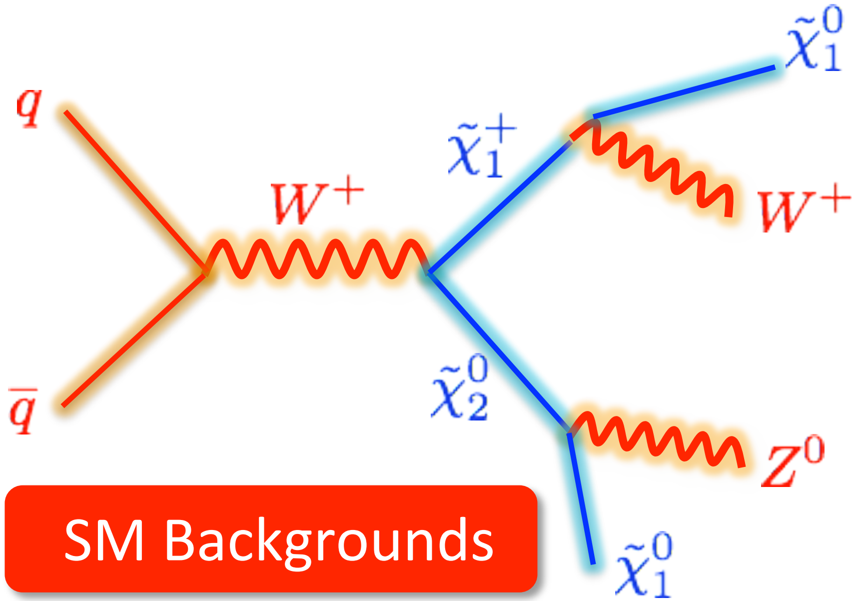
One hopes the LHC will help explain some of this but ……

Current sightings of the death of the SM

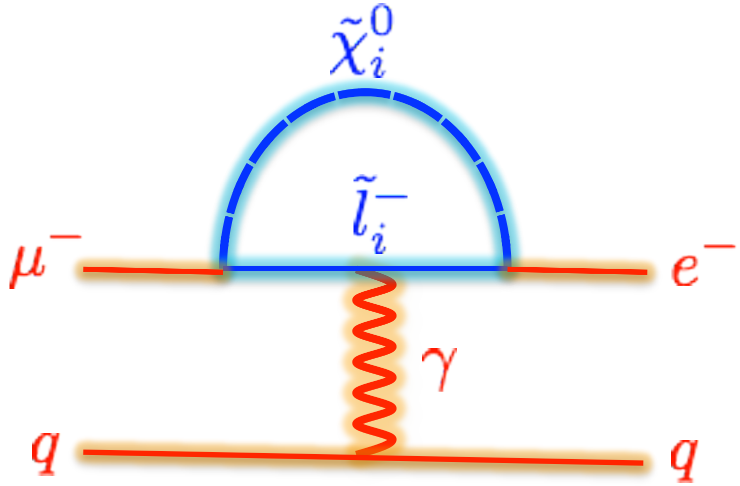
1. Neutrino oscillations : >> 5σ
2. (g-2) of muon : 3.6σ
3. D0 like-sign dimuon asymmetry : 3.9σ
4. DAMA/COGENT/CRESST : 10 GeV dark matter
5. CDF/D0 top asymmetry : 2.4σ (was 3.4σ)
6. LHCb/CDF CP violation in D mesons : 3.8σ
7. CDF W+dijets : 4.1σ
8. ALEPH 4 jet events : 12σ
9. ……

Intensity vs Energy Frontier



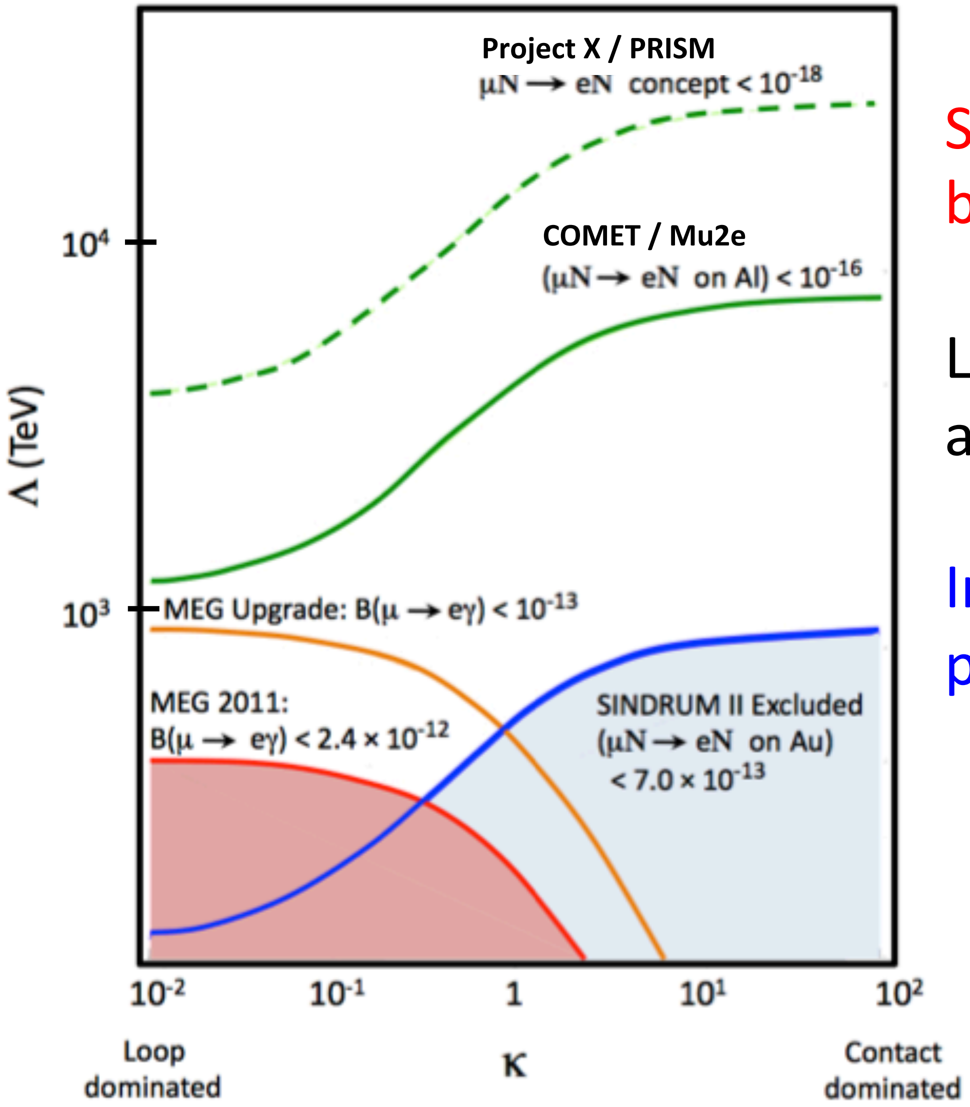


SM Backgrounds



$\mathcal{O}(10^{-50})$ in SM

Why Intensity ?



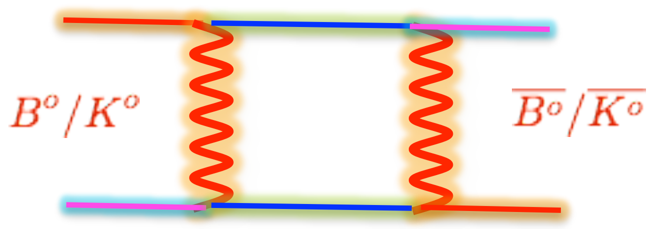
Sensitivity to physics at scales beyond the LHC.

Likely that not all BSM physics is at the LHC TeV-scale.

Interpretation of any LHC BSM physics will require other inputs.

Historically small deviations have been as insightful as new particles in developing a self-consistent (Standard) model.

1. Precise measurement of Kaon-mixing : **prediction of charm quark.**



2. Rare Kaon decays : **first observation of CP-violation**
   : **requirement of CKM and a 3rd generation of quarks**
   - *first input into explaining universe's baryon asymmetry.*

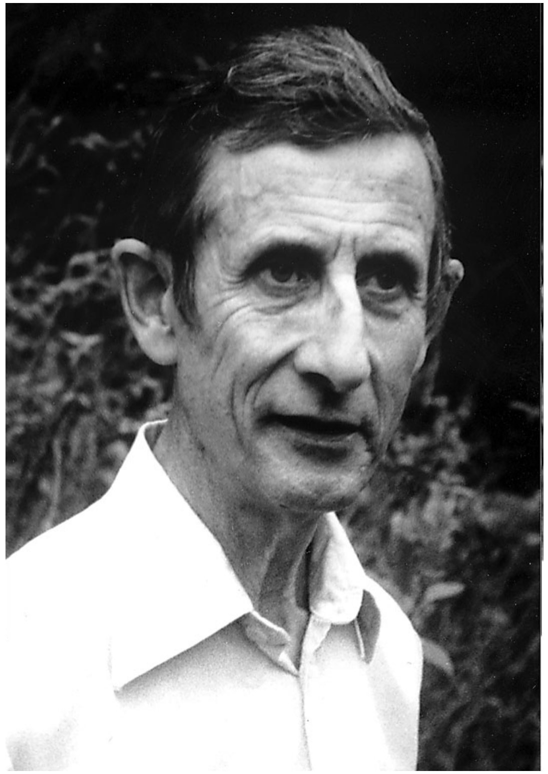
3. Precise measurement of B-mixing **: prediction of large top mass.**

Outside of HEP : tiny deviations in Mercury's orbit : vindication of General Relativity.

Why Rarity Frontier ?

"The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. *Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier*. For making important discoveries, high accuracy was more useful than high energy."

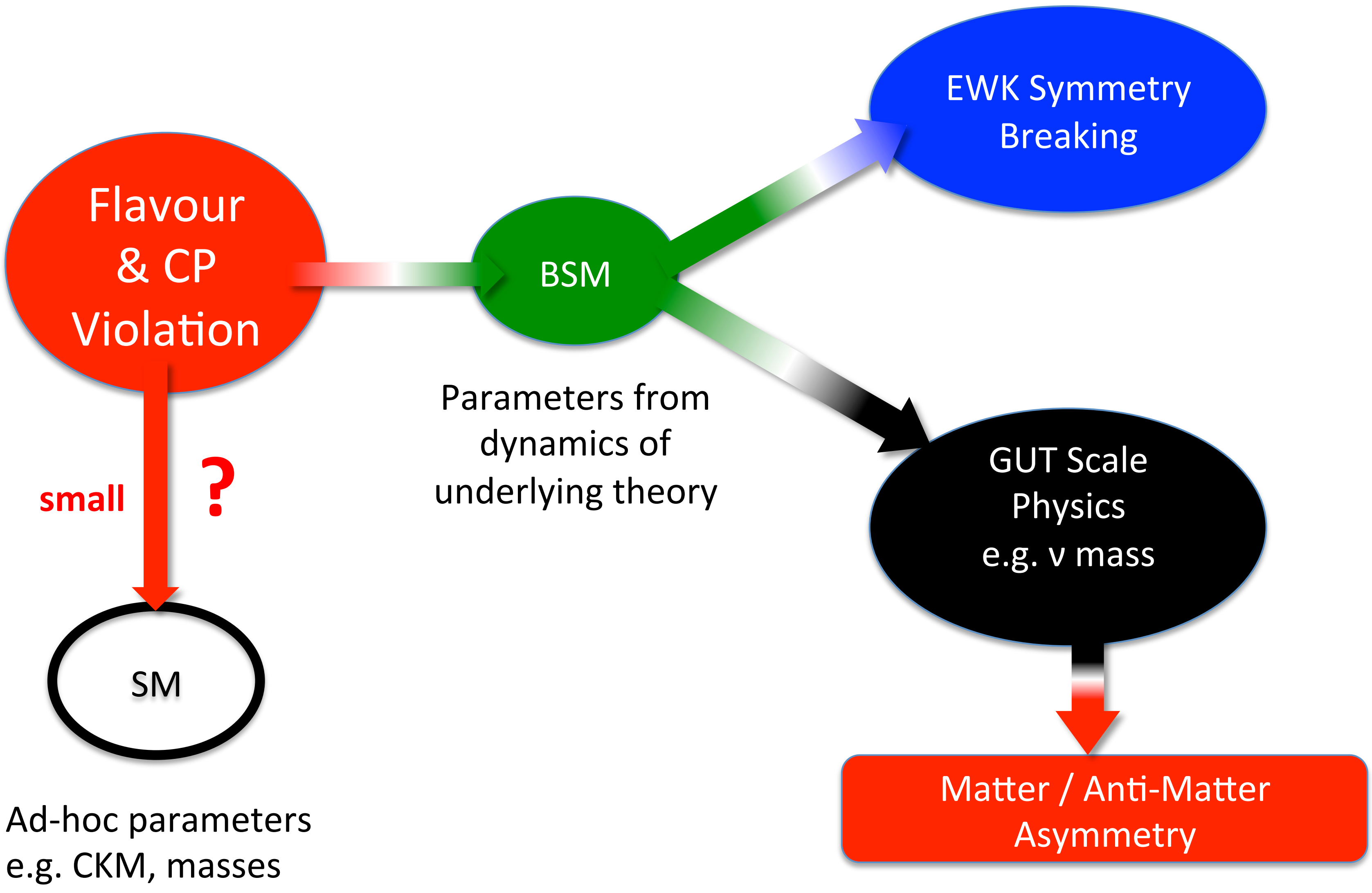
Freeman Dyson



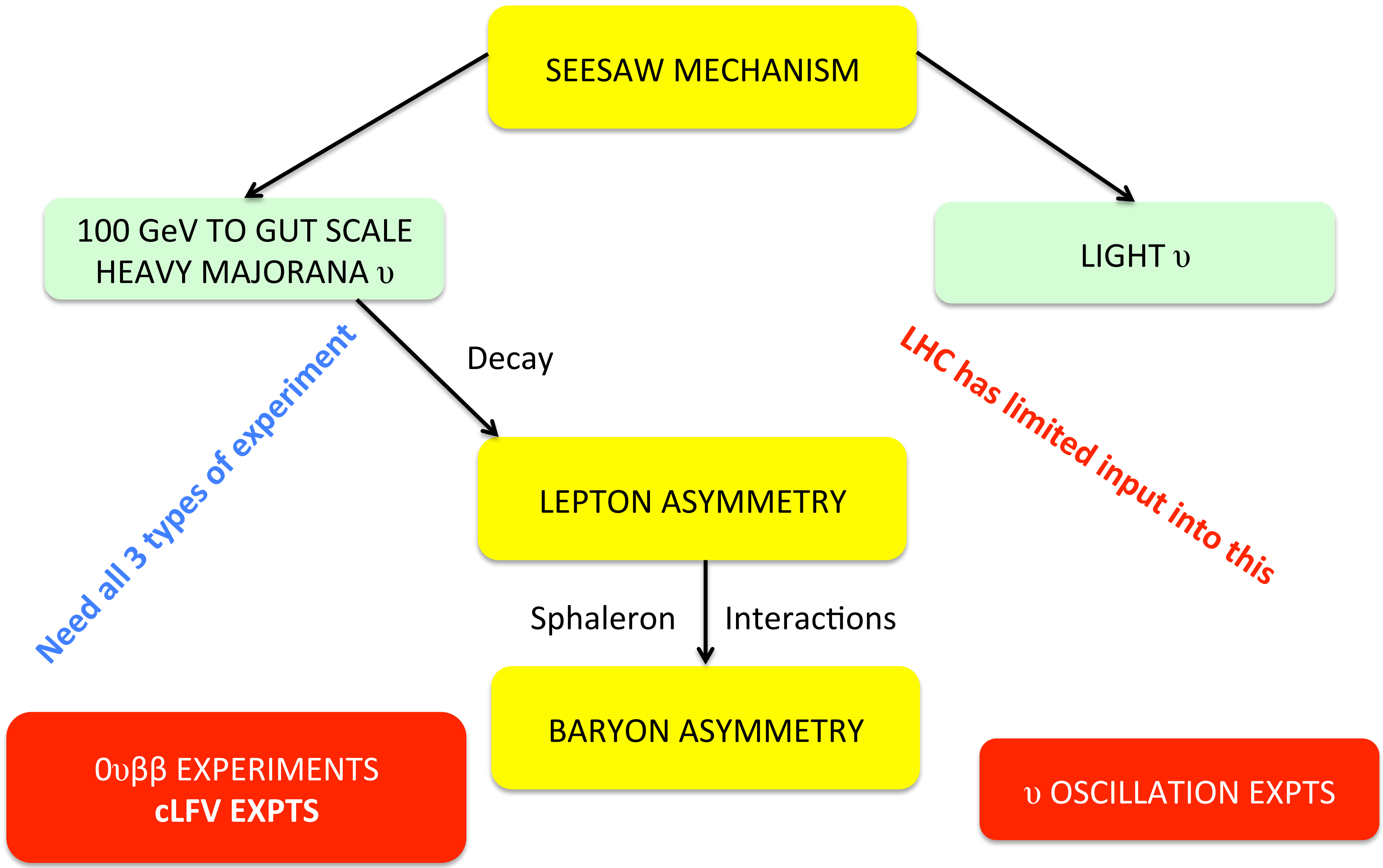
"Limits on the neutron EDM have killed more theories than any other measurement"

Mike Pendlebury

The path to new physics

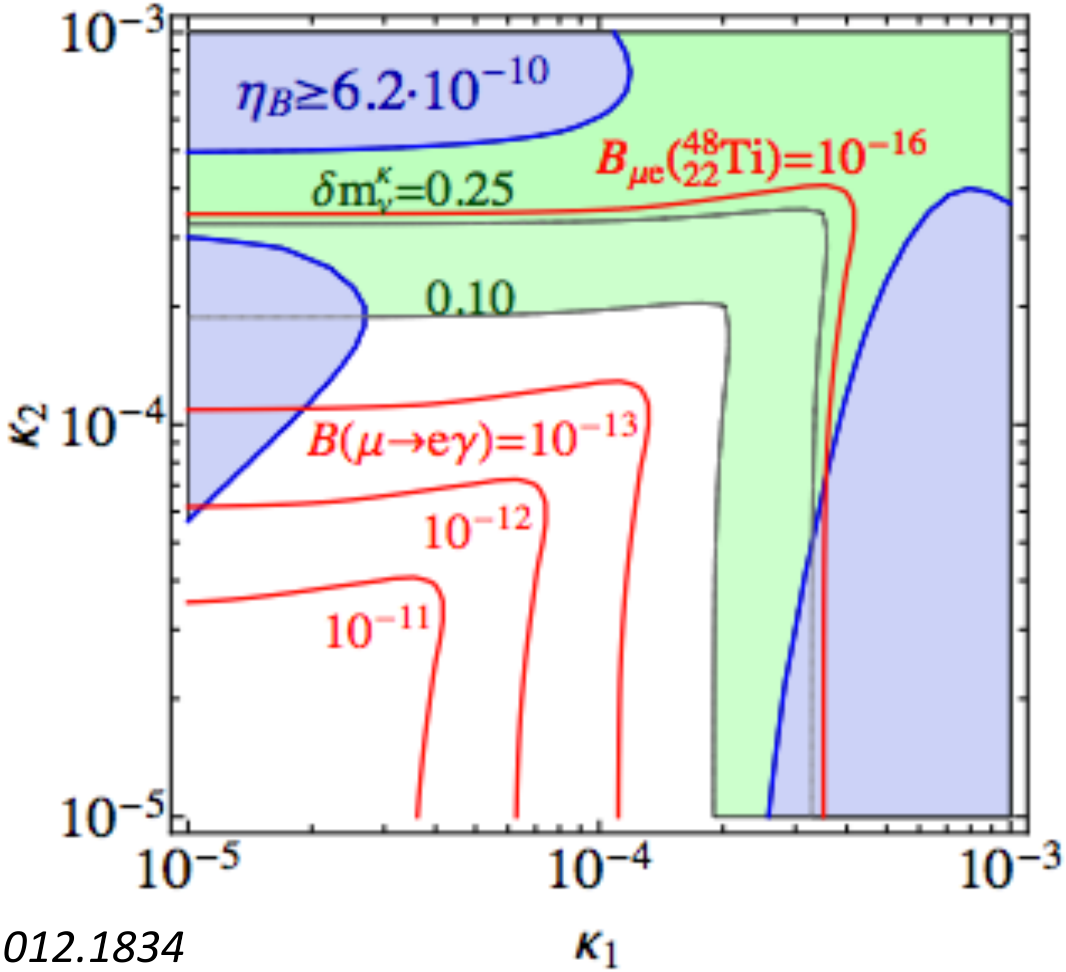


Matter Anti-Matter / Neutrino Synergy



Lepton Flavour Violation / Baryongenesis

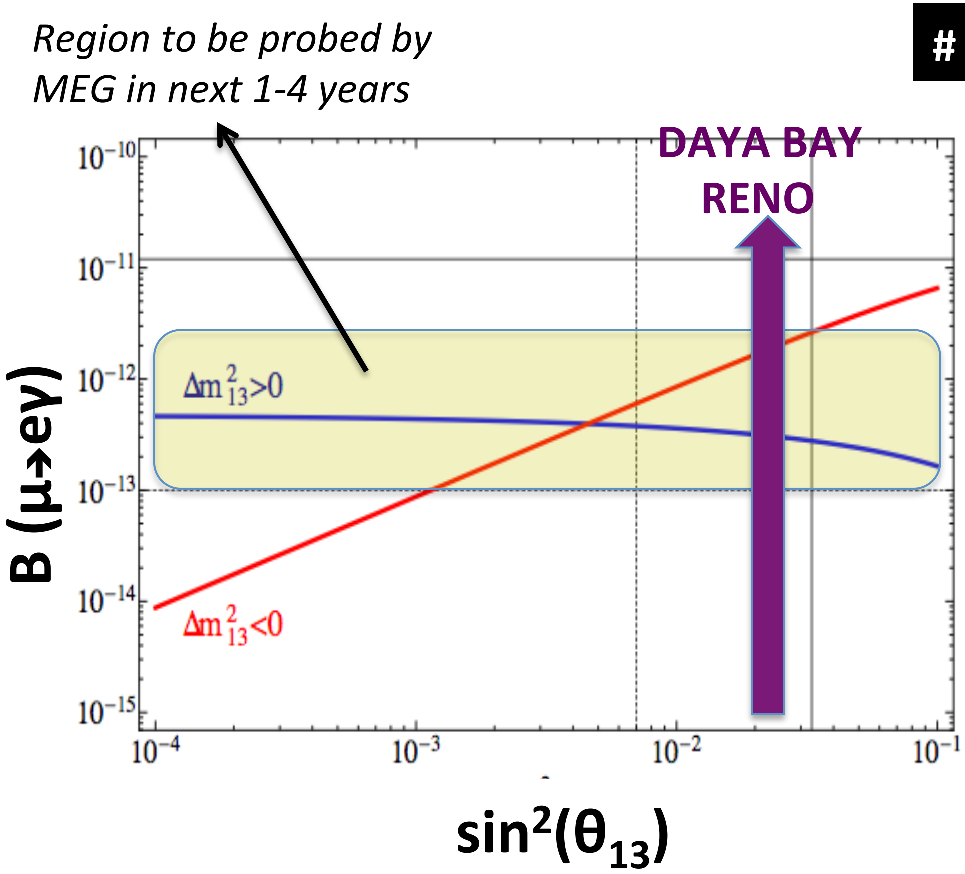
$\gamma_1=3\pi/8, \gamma_2=\pi/2$



arxiV:1012.1834

$\kappa_1, \kappa_2, \gamma_1, \gamma_2$ symmetry breaking parameters

To neutrino & LHC programme



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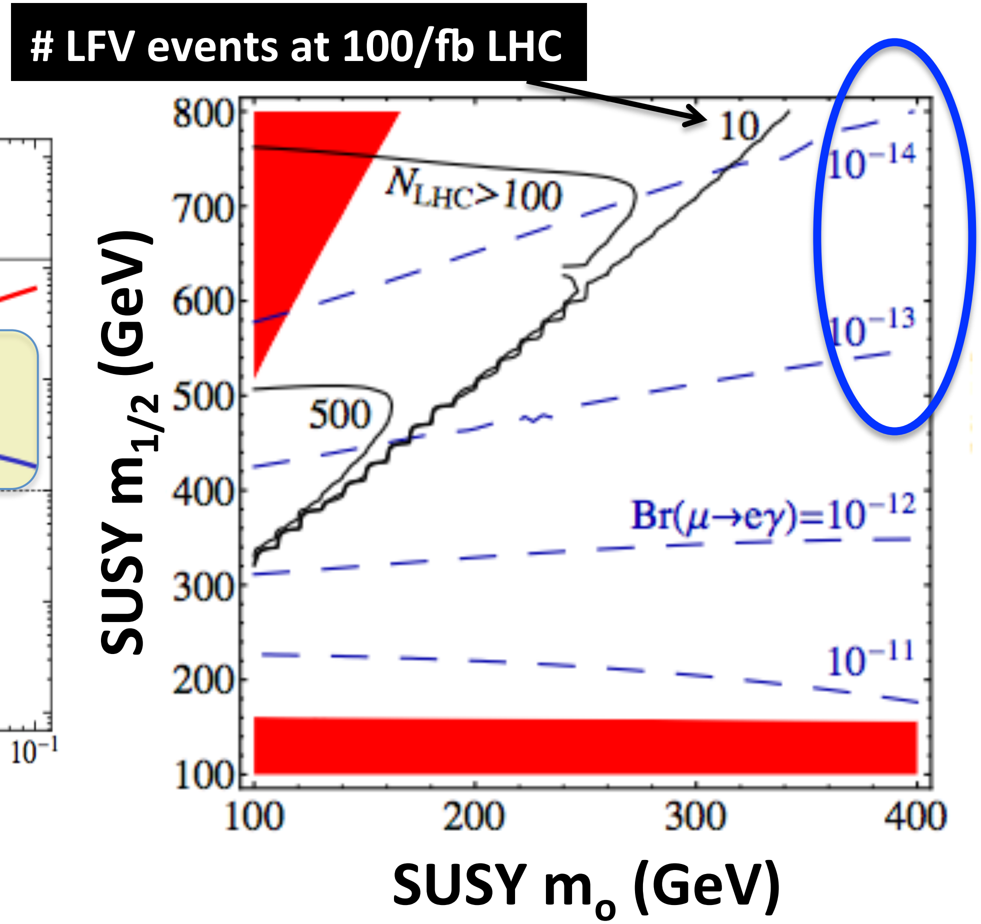
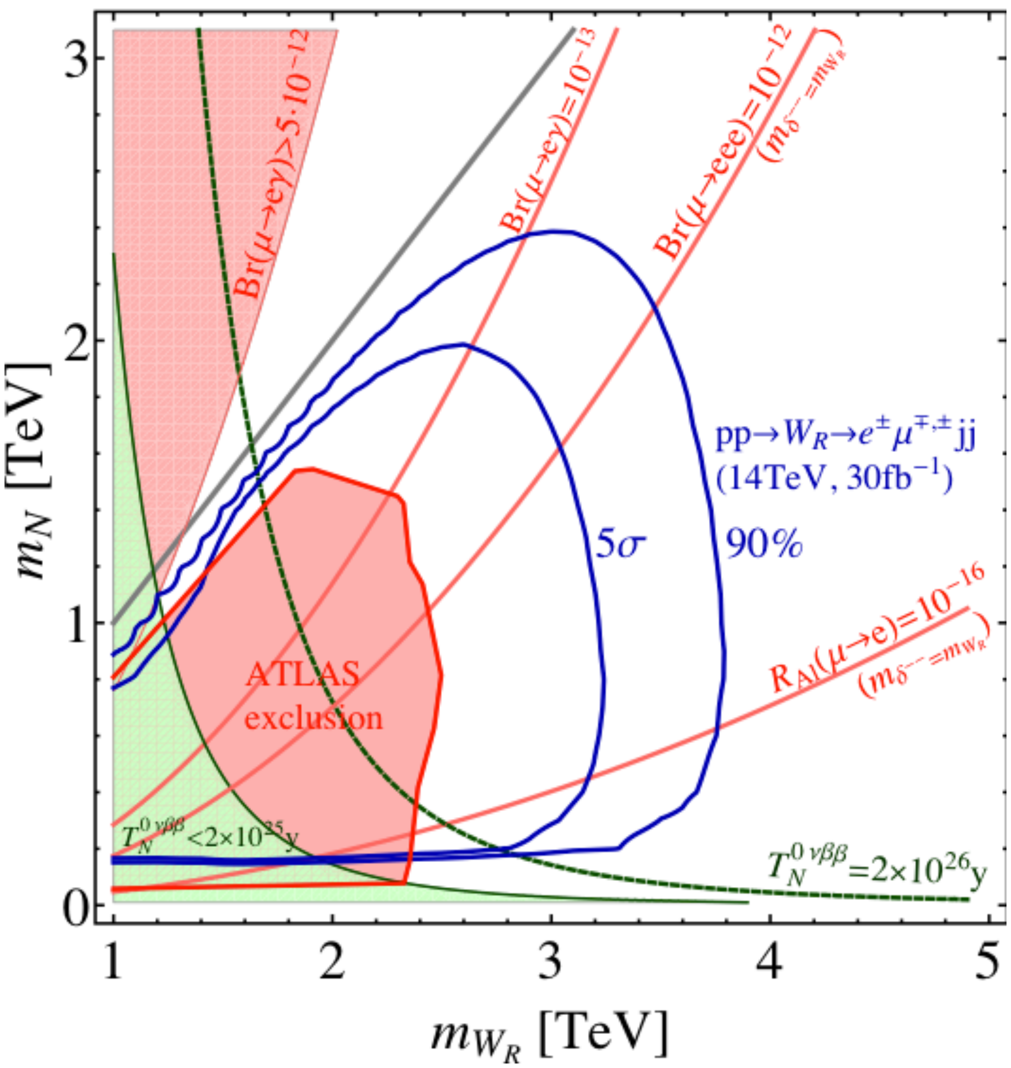
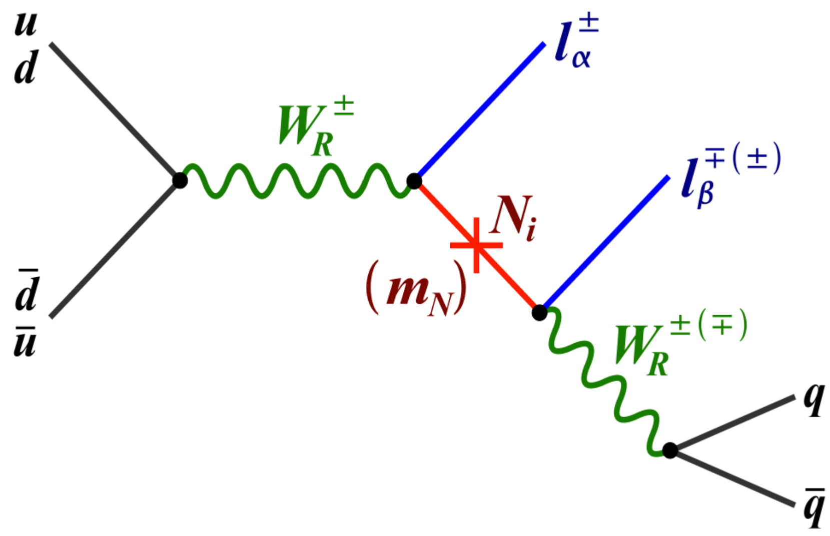


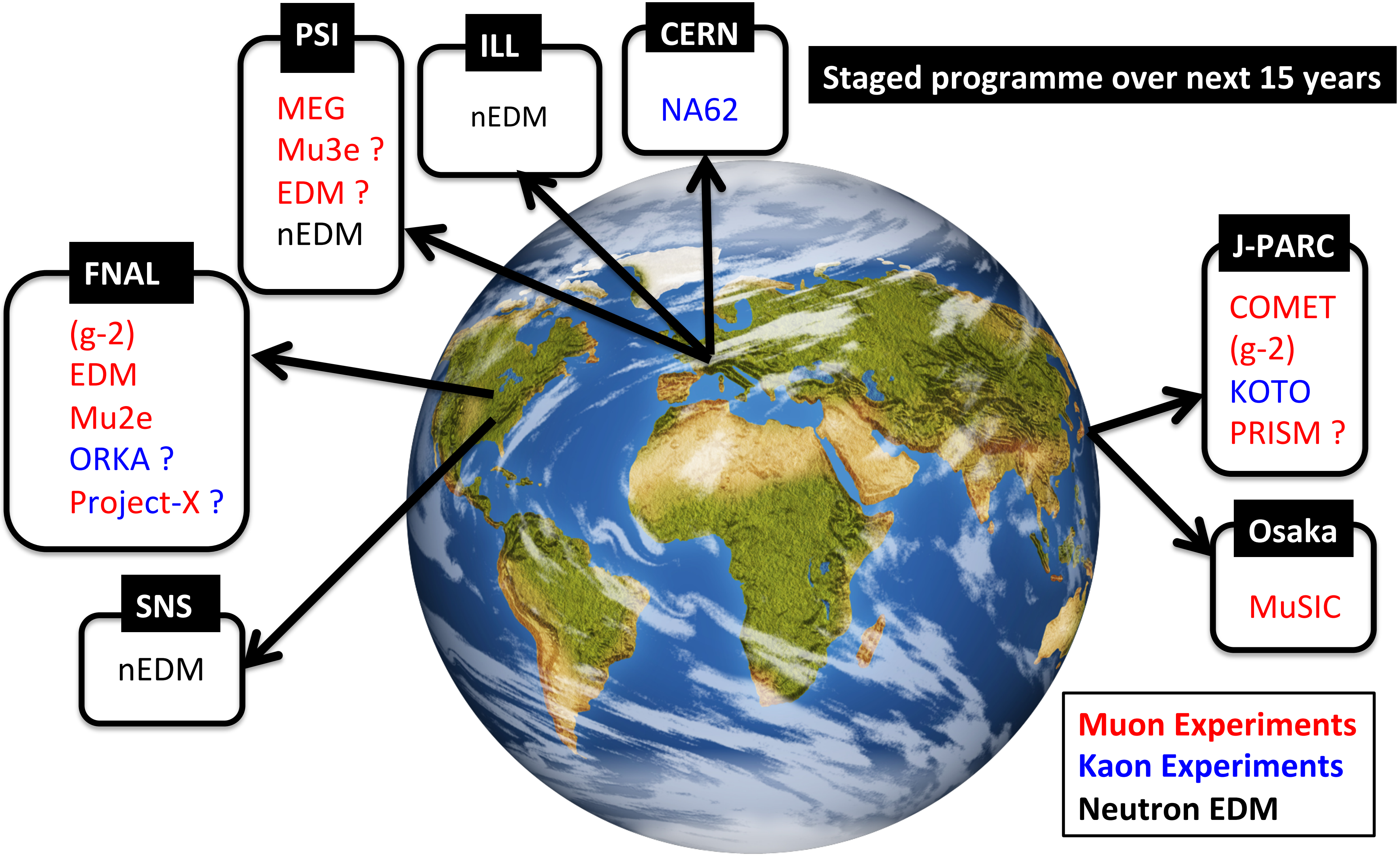
arxiV:1011.1404

Complementary to LHC & higher scales

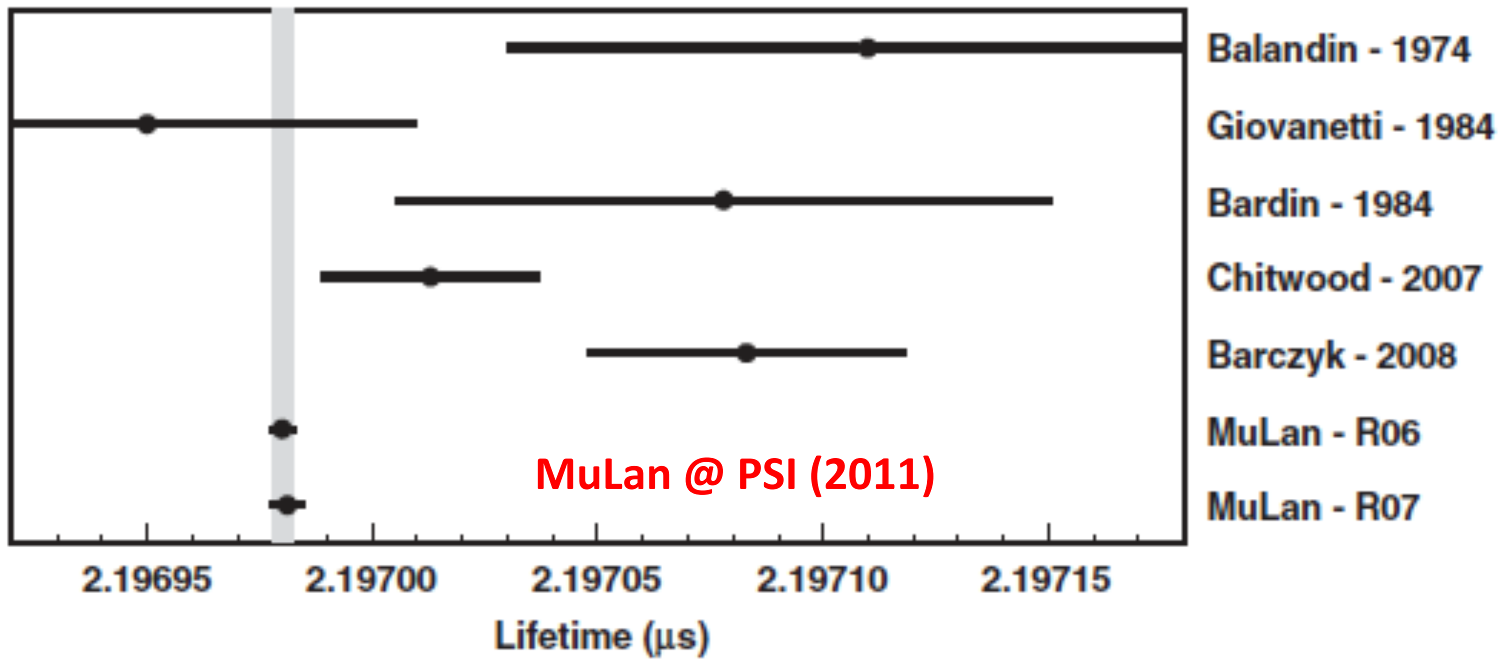




Where ?


PSI
MEG
Mu3e ?
EDM ?
nEDM
ILL
nEDM
CERN
NA62
Staged programme over next 15 years
FNAL
(g-2)
EDM
Mu2e
ORKA ?
Project-X ?
J-PARC
COMET
(g-2)
KOTO
PRISM ?
Osaka
MuSIC
SNS
nEDM
Muon Experiments
Kaon Experiments
Neutron EDM

Bread and Butter Muon Physics



Vital ingredient in establishing consistency (cracks) in SM

Mw (and M_{top}) to M_H uses muon lifetime (G_F)

Bread and Butter Muon Physics

Published online 7 July 2010 | Nature | doi:10.1038/news.2010.337

News

The proton shrinks in size

Tiny change in radius has huge implications.

Geoff Brumfiel

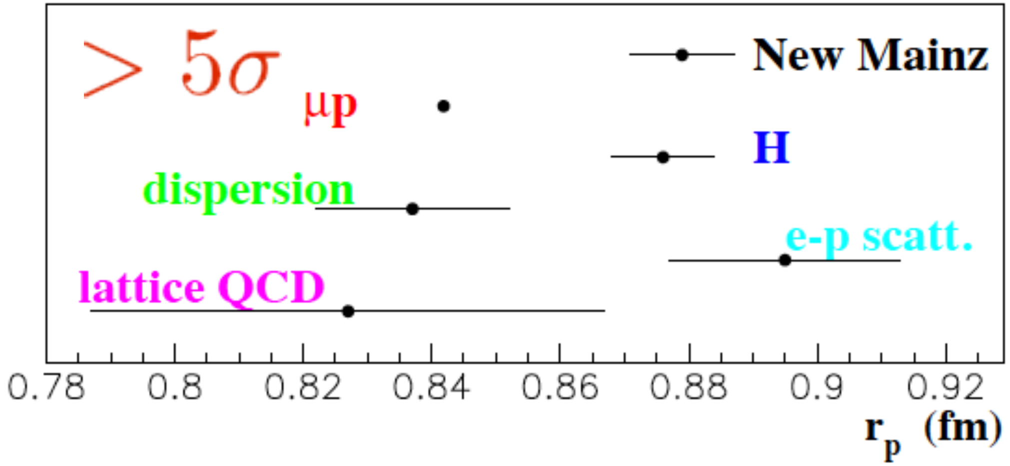
The proton seems to be 0.00000000000003 millimetres smaller than researchers previously thought, according to work published in today's issue of *Nature*[1].

Measurements with lasers revealed that the proton is a touch smaller than predicted by current theories.

PSI / F. Reiser

The difference is so infinitesimal that it might defy belief that anyone, even physicists, would care. But the new measurements could mean that there is a gap in existing theories of quantum mechanics. "It's a very serious discrepancy," says Ingo Sick, a physicist at the University of Basel in Switzerland, who has tried to reconcile the finding with four decades of previous measurements. "There is really something seriously wrong someplace."

Muonic hydrogen
- originally missed it !



Rp = 0.84184 (67) fm (muons)
Rp = 0.8768 (69) fm (electrons)

$$\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0346 r_p^3 \quad \text{meV}$$

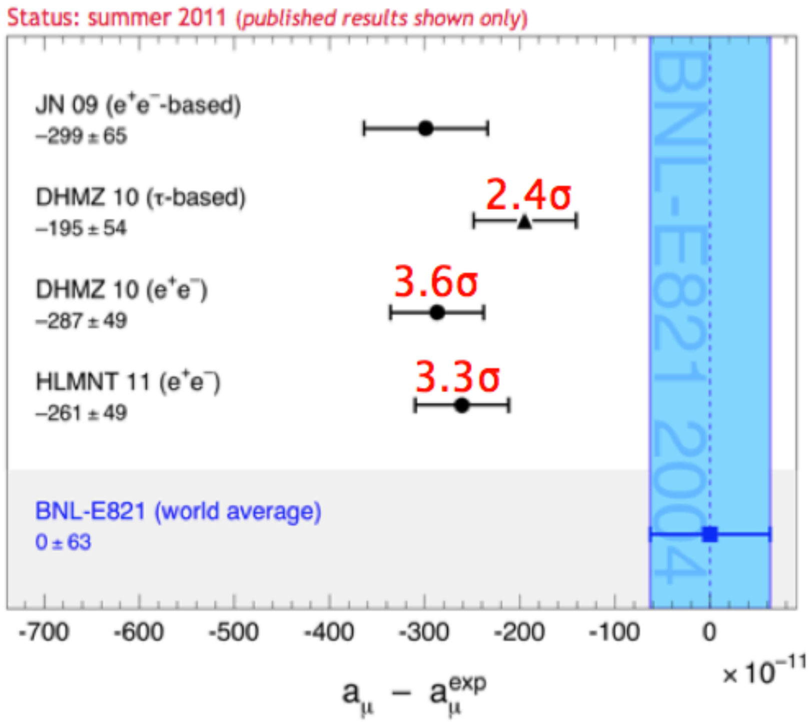
Why Now ?

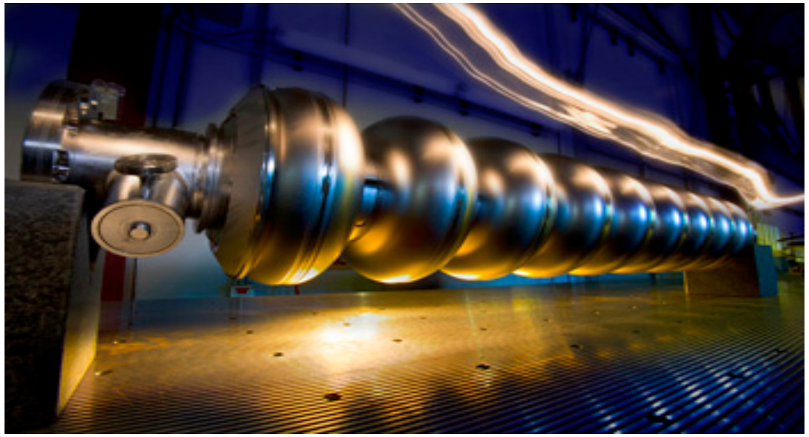
Neutrino oscillations tell us that lepton flavour is not sacrosanct.

Hints of new physics in the muon (g-2) .

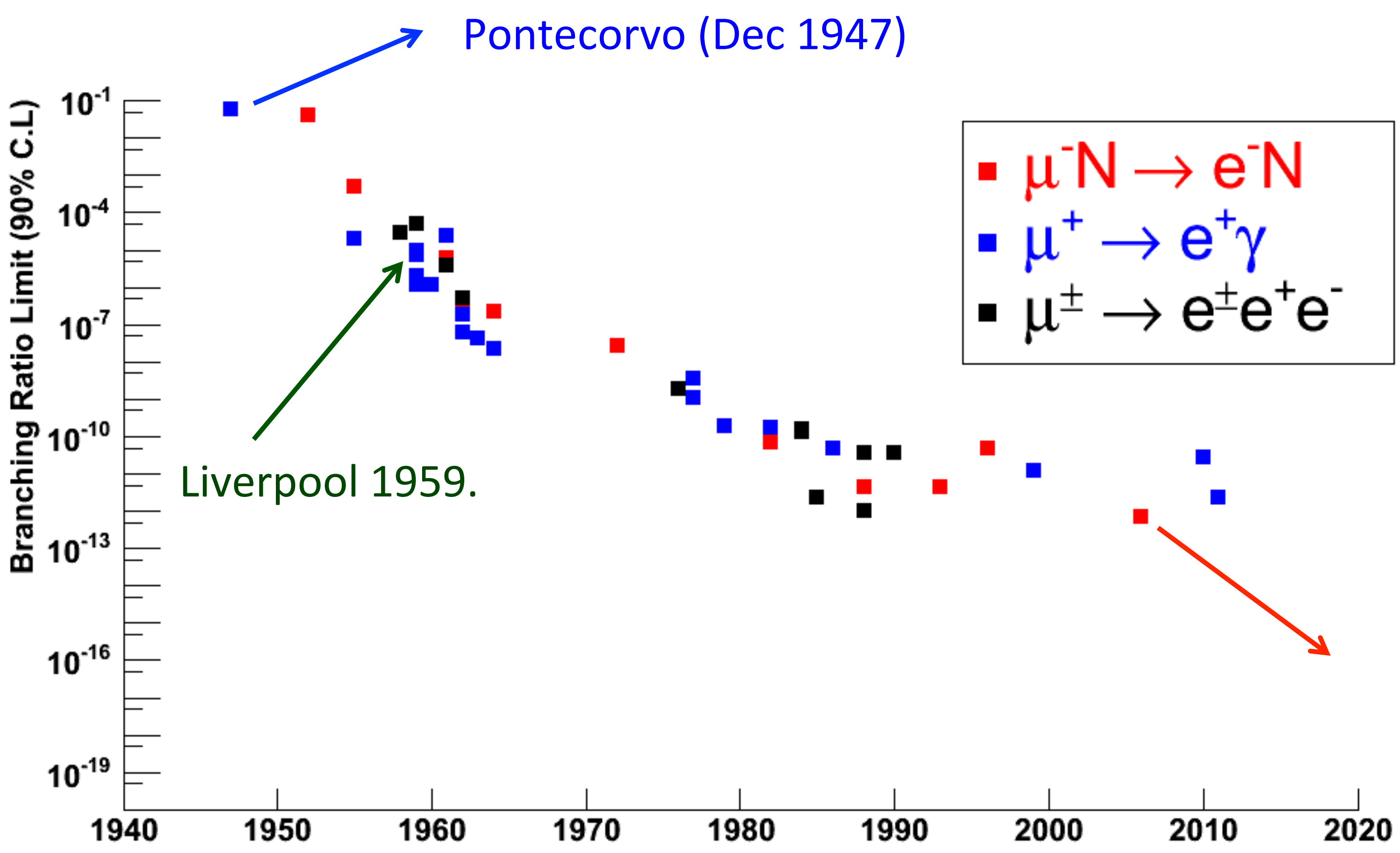
Accelerator advances now allow O(MW) proton beams and for sufficient # μ, K to probe the theoretically interesting regions e.g. that defined by new LHC physics.

Expedited by synergy with neutrino-factory and muon collider R&D.





Why Now ?

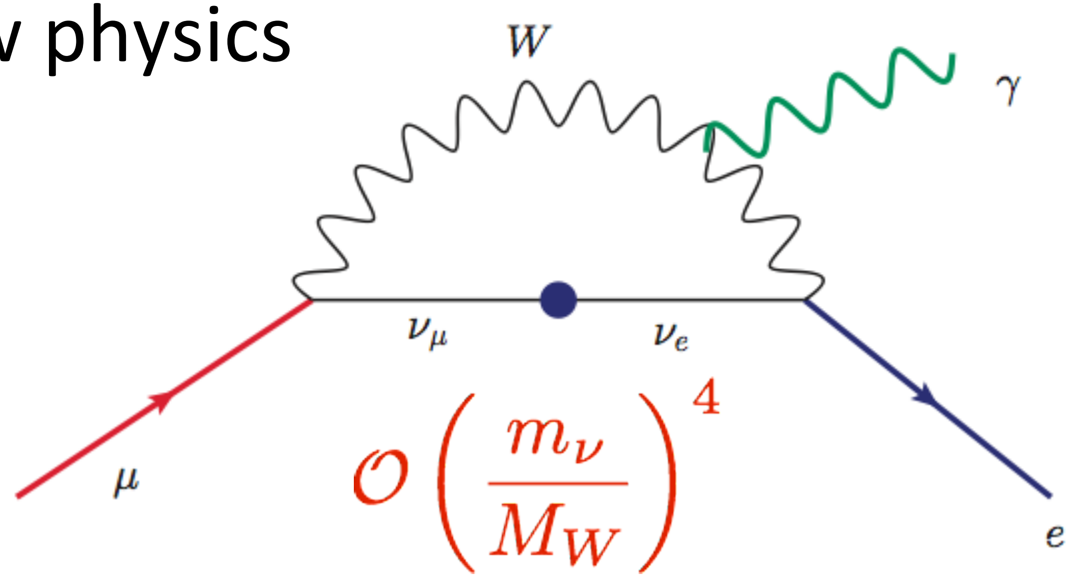


Factor of 10-10,000 improvements in sensitivity in near future.

Muon / Tau LFV

SM is O(10^{-50})

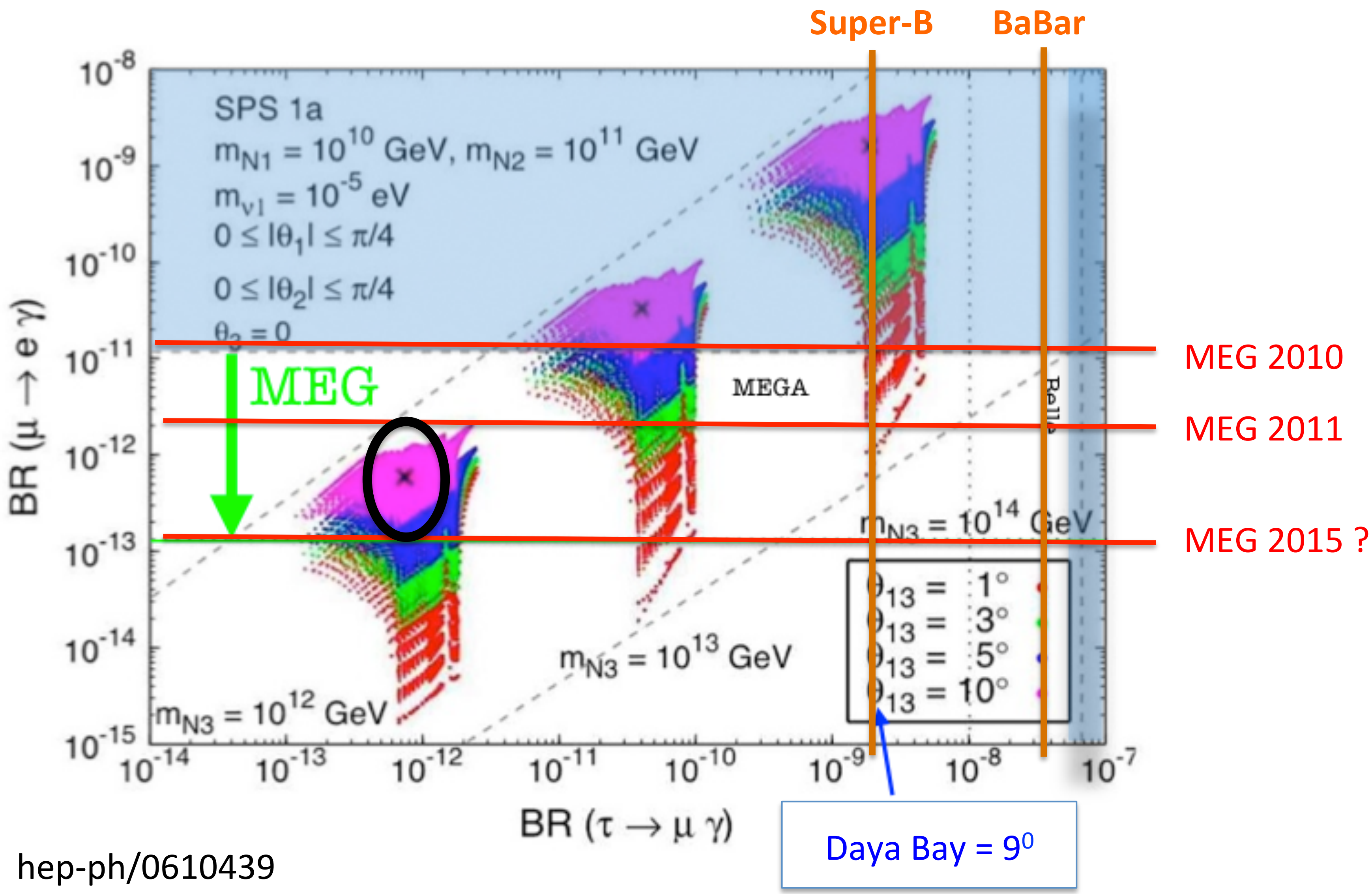
Observation **IS** new physics



No SM theory systematic

How far we can probe is limited by experiment

Sensitive to heavy neutrinos



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.

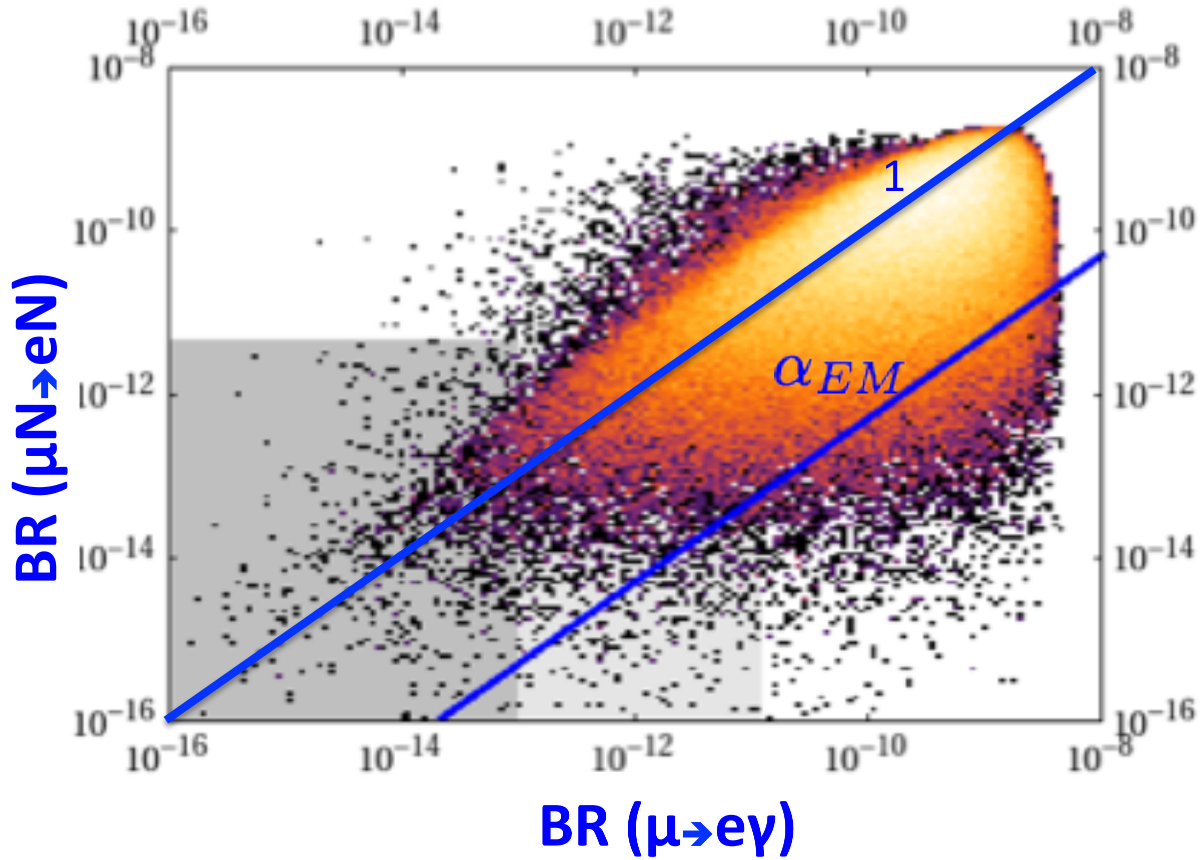
★★★ **Large effects**

★★ **Visible but small**

★ **No sizeable effect**

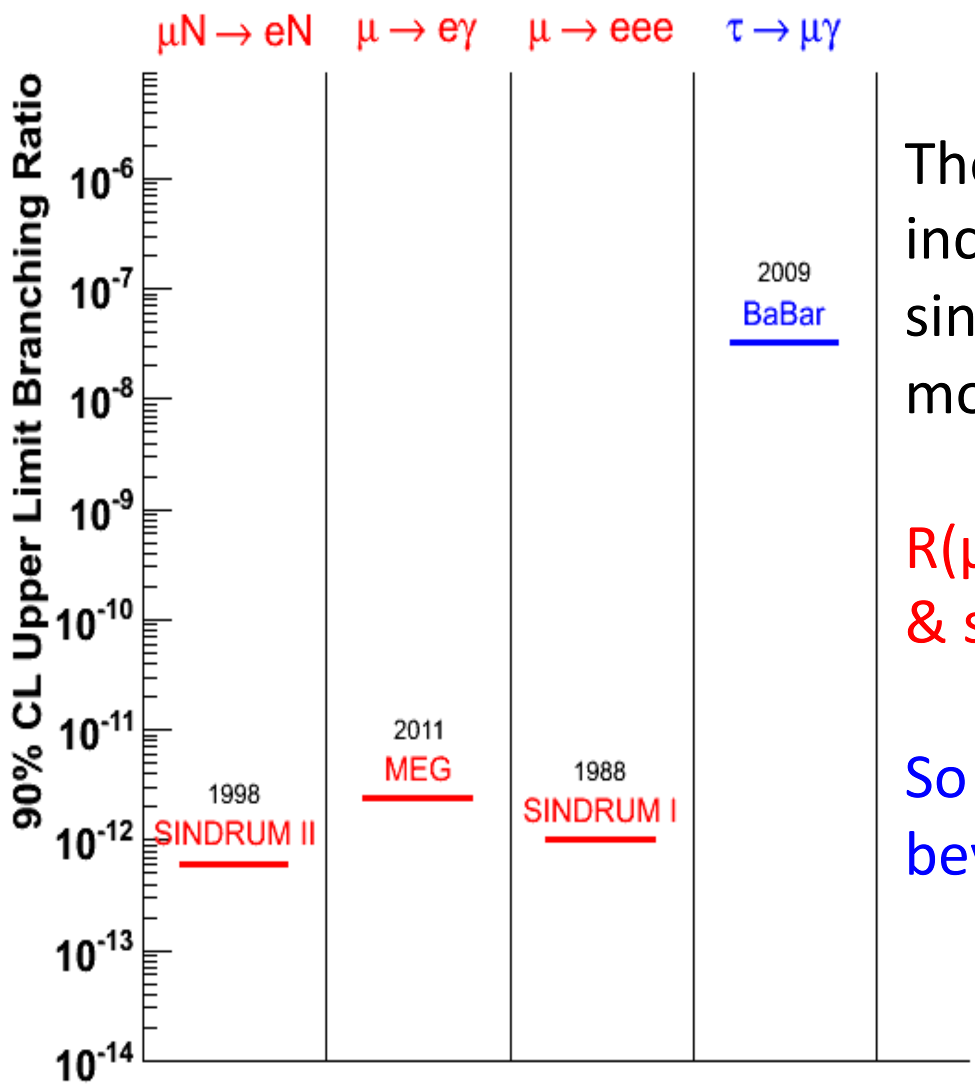
Process Ratios are Model Dependent

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

Where are we now ?

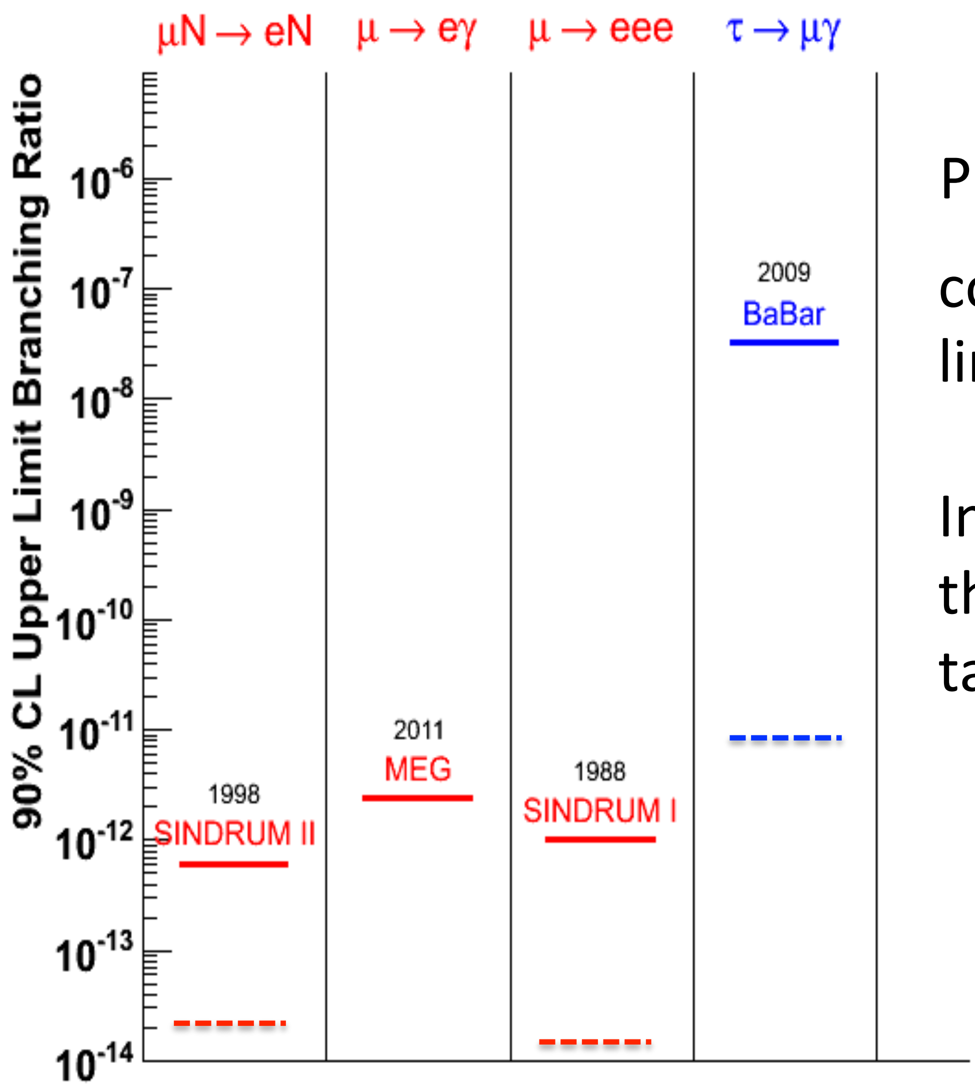


The present eγ limit is the most incisive measurements since typically in BSM models:

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

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

Where are we now ?

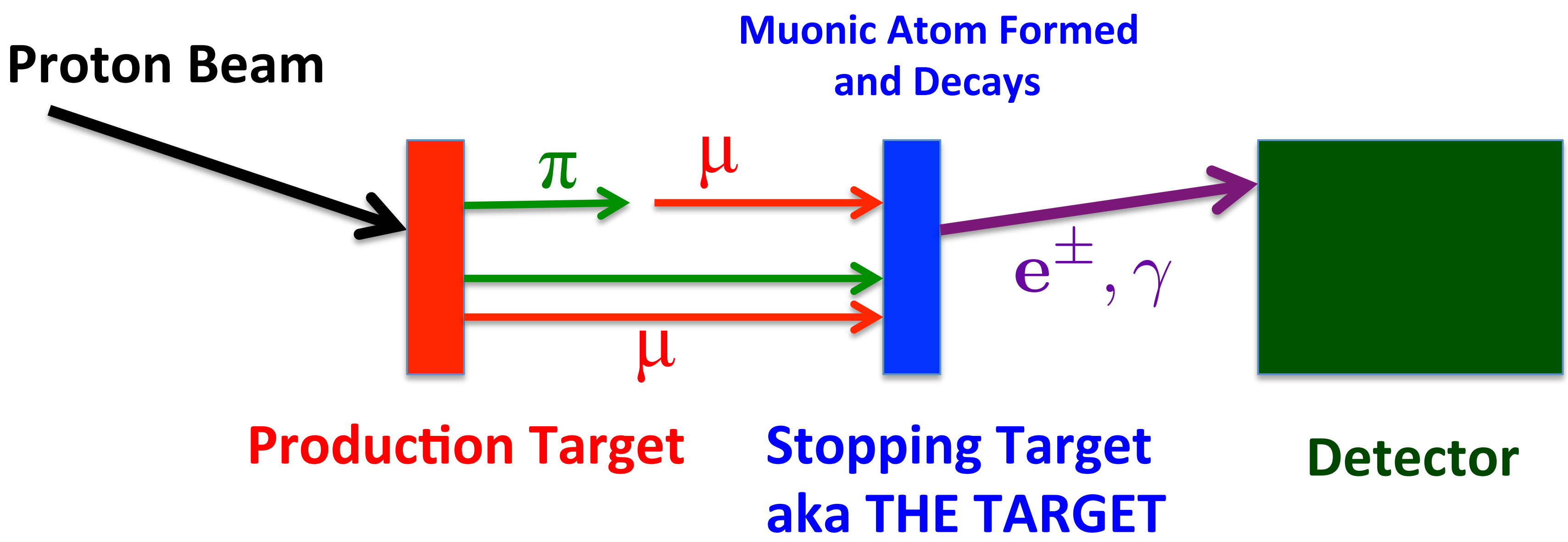


Present MEG $\mu \to e\gamma$

converted to eN and $\tau \to \mu\gamma$ limits shown by -----, ------

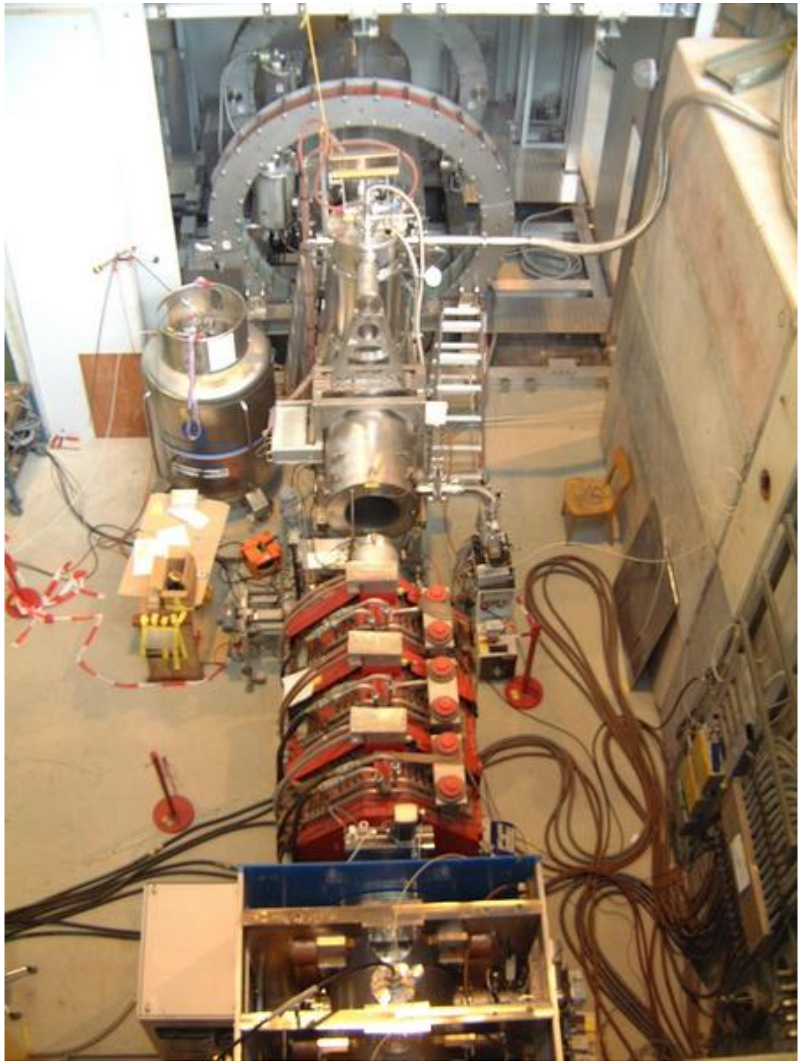
In effect the MEG limit surpasses the eN limits by O(100) and the tau limits by O(1000)

Experimental Technique



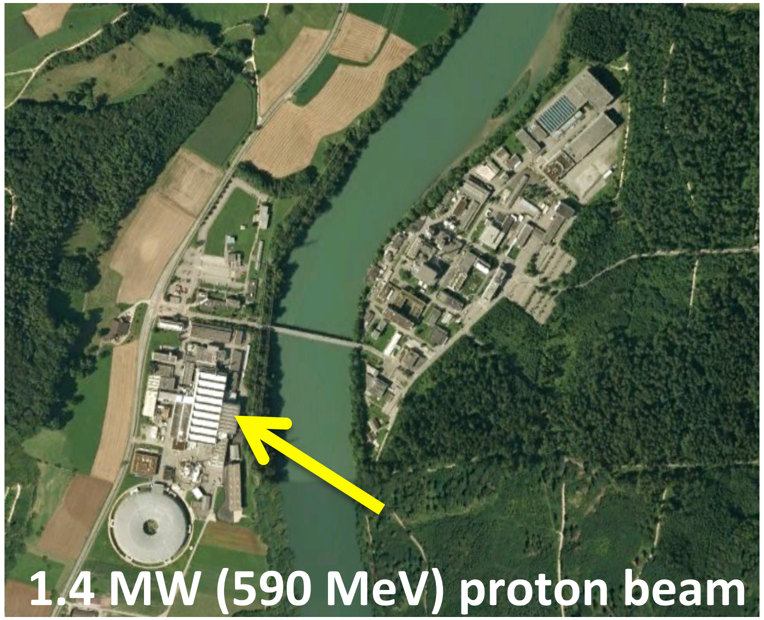
Apply symmetries, translations, rotations, …..

Current State of The Art



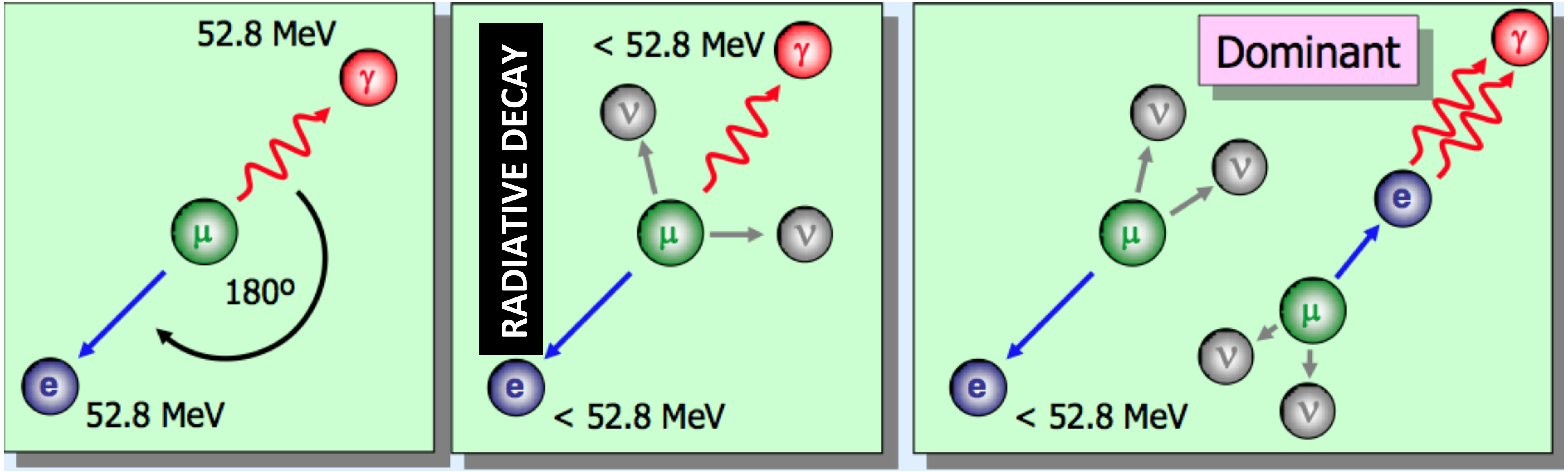
PSI (Zurich/Switzerland) Facility

3×10^{7} "stopped" $\mu+$/sec



MEG Experiment

MEG present limit on $\mu \rightarrow e\gamma$ is 2.4×10^{-12}. It is aiming to get to 1×10^{-13}



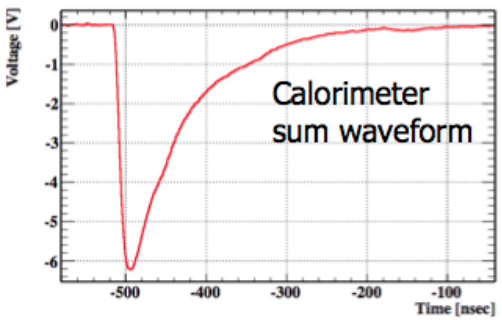
Signal | **Prompt Background** | **Accidental Background**

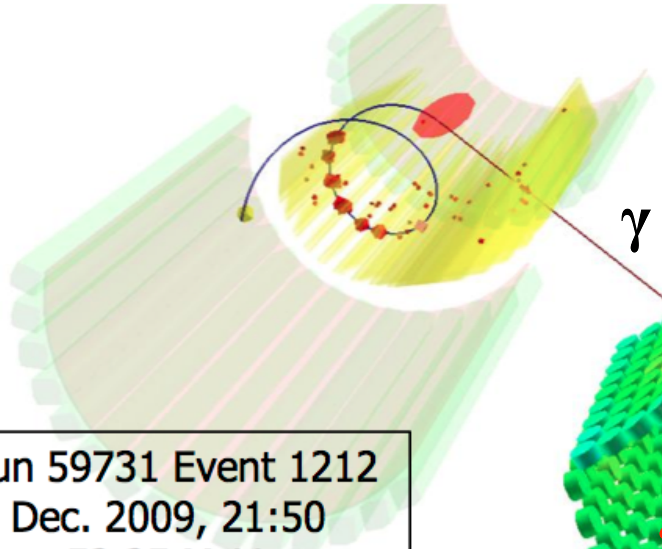
$E_\gamma = E_{e+} = 52.8$ MeV

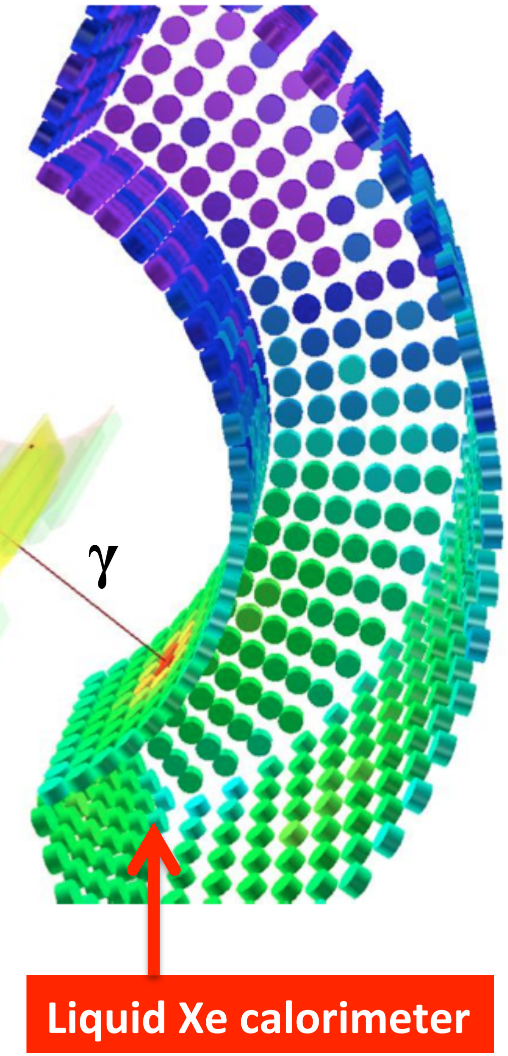
$\theta_{\gamma e} = 180^0$

γ and e^+ in time

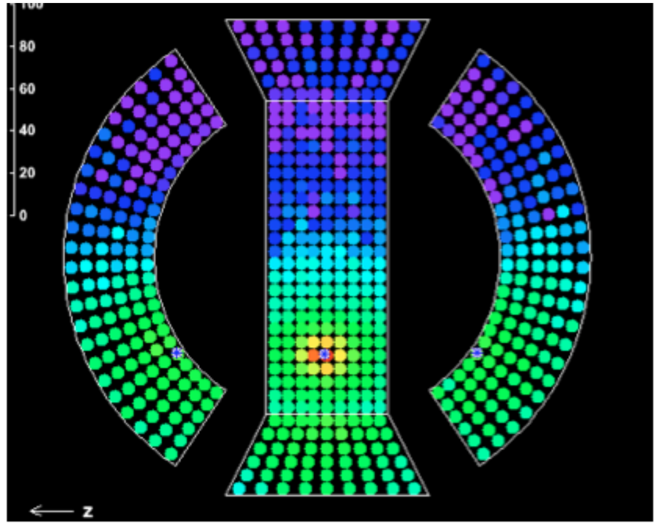
MEG Experiment

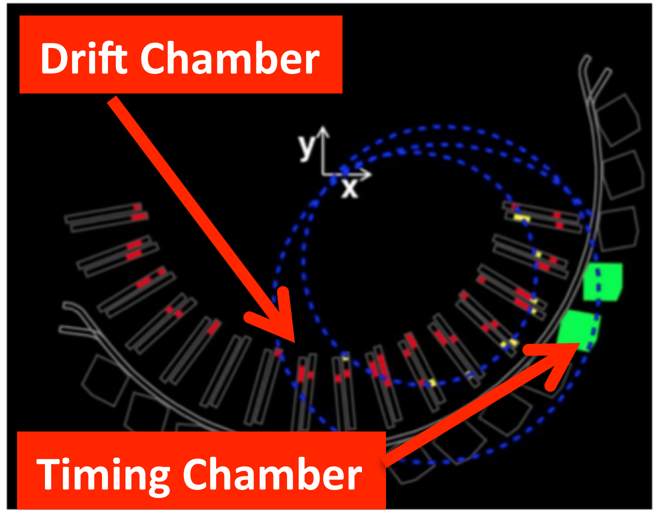






Run 59731 Event 1212
4. Dec. 2009, 21:50
E_γ = 52.25 MeV
E_{e+} = 52.84 MeV
$\Delta\theta_{e+g}$ = 178.8 degrees
$\Delta T_{e\gamma}$ = 26.8 ps

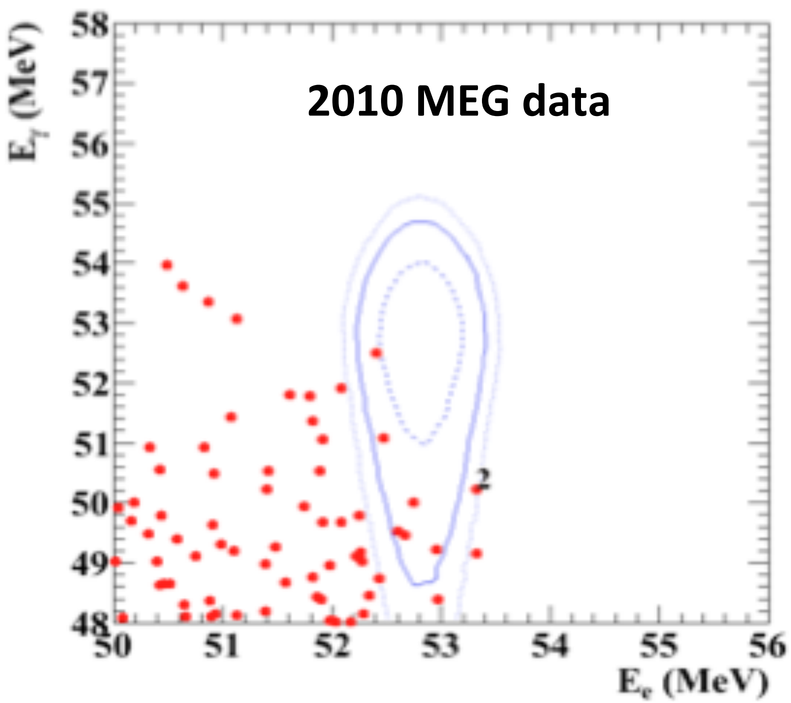


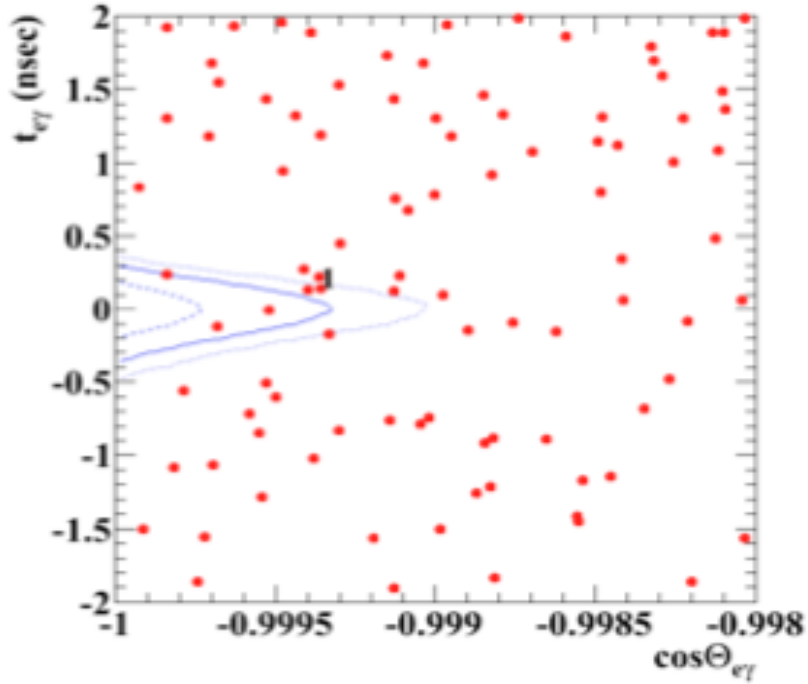


MEG Sensitivity Determined By

- # of stopped muons : accelerator driven (2010 : 2.3 x 10^7/s)

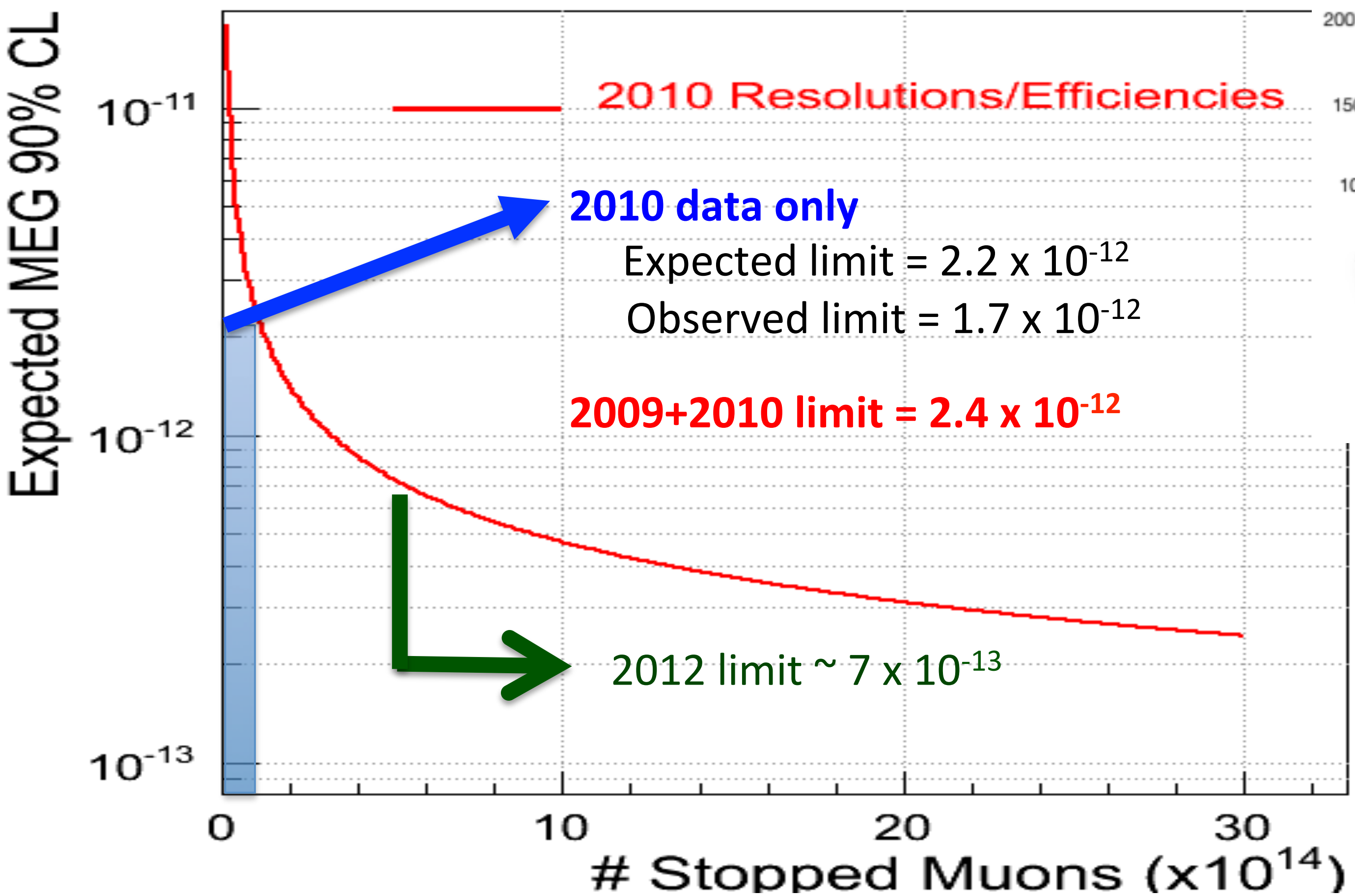
- Resolution in e^+ and photon energy and angle, time between them

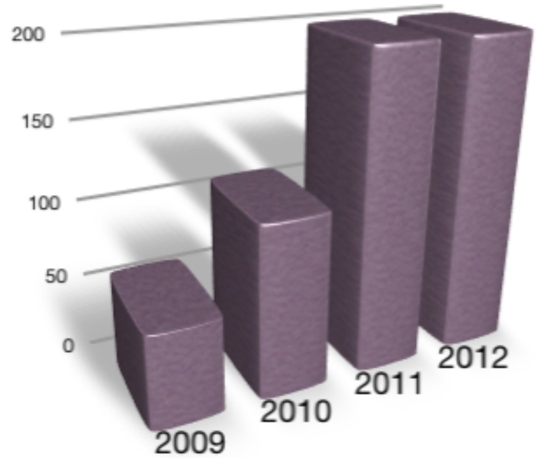




MEG Sensitivity

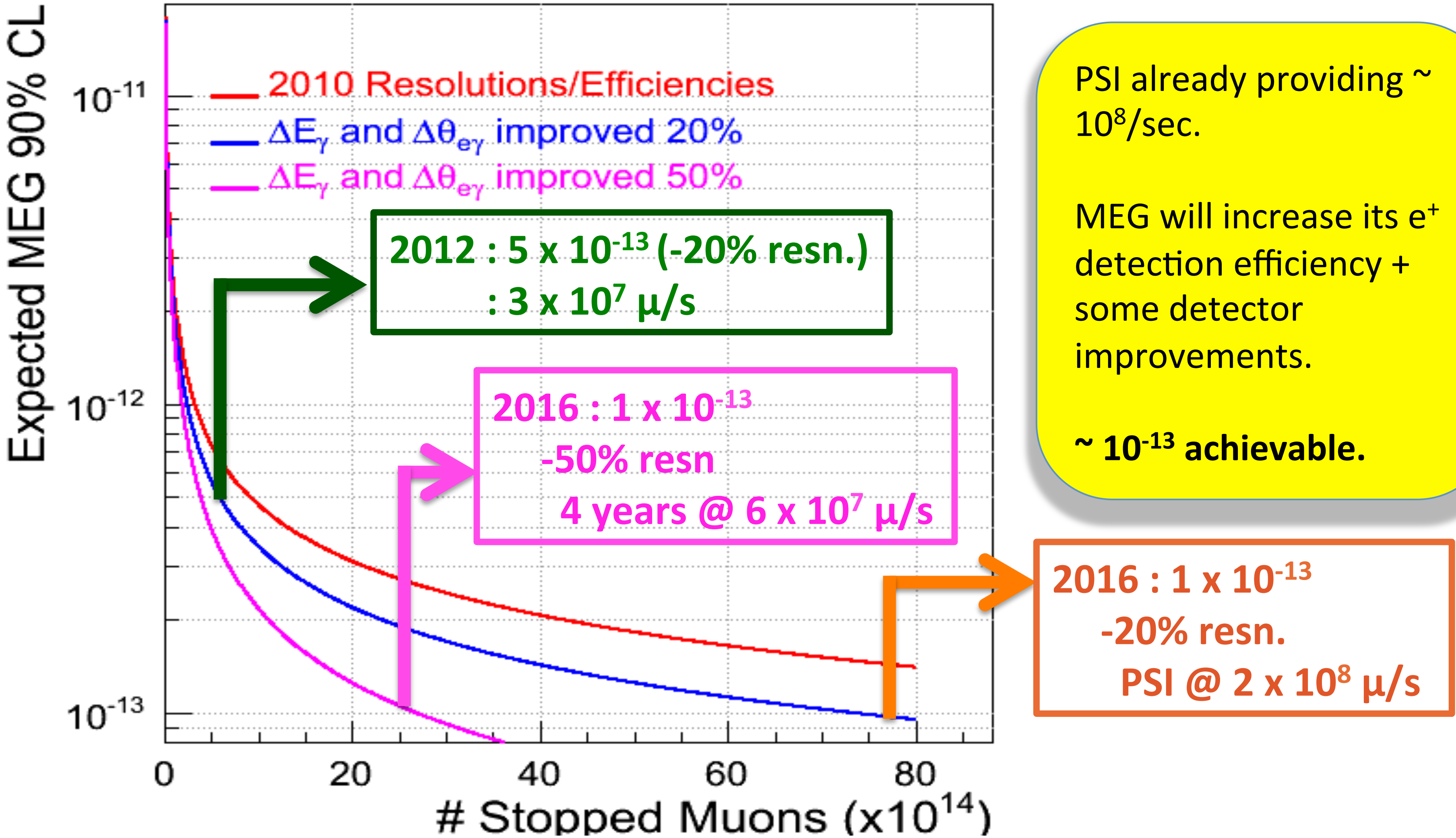
µ on Target x 10^{12}





MEG : 2013-2016

Assume 10^7 sec running per year for 2013-2016.



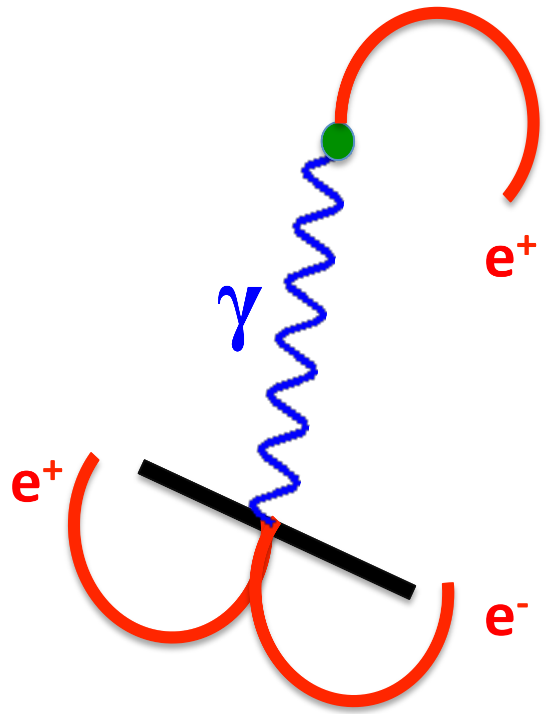
PSI already providing ~ 10^8/sec.

MEG will increase its e^+ detection efficiency + some detector improvements.

~ 10^{-13} achievable.

Below 10^{-13} needs new detector

- E_γ, $\Theta_{e\gamma}$ resolution and pile-up are limiting factors particularly at high μ intensities
- Another option to achieve reduced sensitivity is to have a "track-only" analysis.



Conversion point and event vertex defined by precision tracking.

Optimise material thickness to optimise rate reduction vs resolution degradation.

MEGA (LANL:1990s) used this approach & achieved

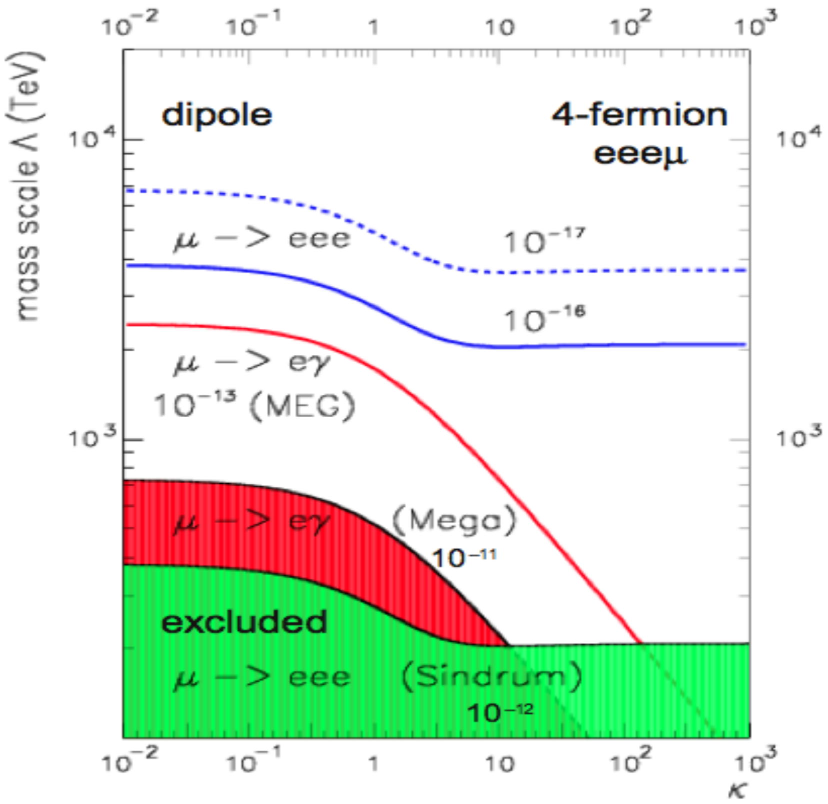
$\Delta\theta_{e\gamma}$ = 33 mrad vs 52 mrad in MEG and

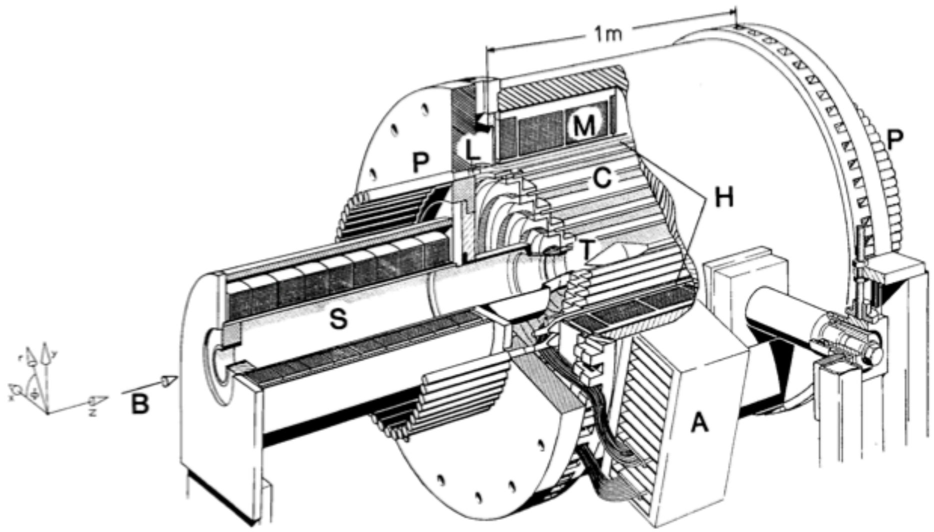
ΔE_γ = 1.7 - 3% vs 4.5 - 5.6% (MEG).

However these resolutions need to be achieved in high pile-up environment.

μ→eee

Current state of the art is 1988 with **limit @ 10^{-12}**





Sindrum-I @ PSI

Given MEG results (@ 10^{-13}) this only begins to get interesting at 10^{-14} (e.g LHT models) BUT ideally would like to get to 10^{-16}

μ→eee

Same issues as μ→eγ

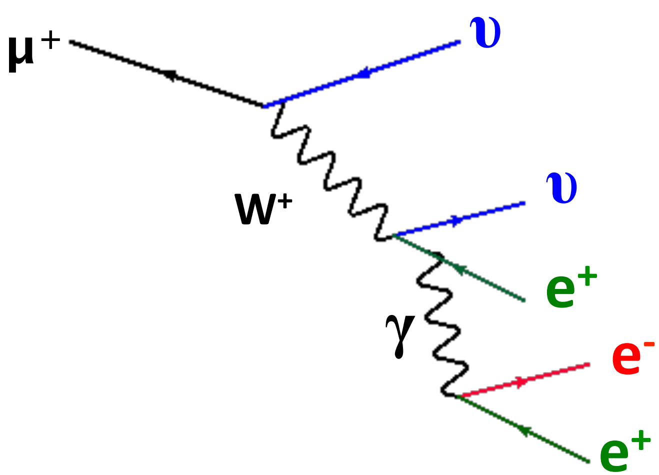
- accidental/pile-up backgrounds : $(R\mu/D)^2$ – so DC beam required.

Issue as go to v. high rates

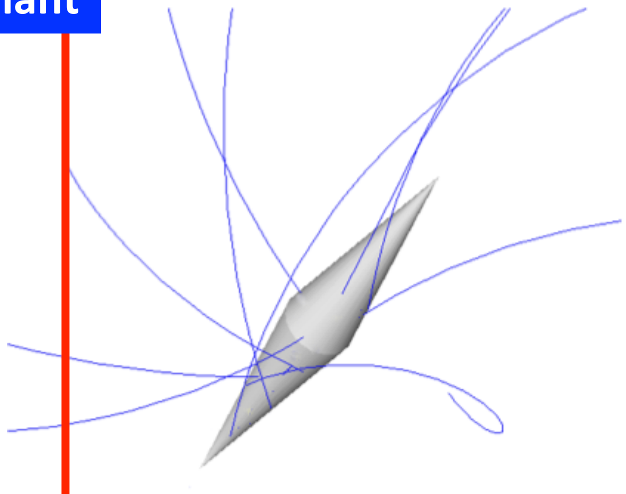
Two μ+ decays and fake e- (Bhaba scattering, γ conversion)

- irreducible background : Rμ

Dominant



BR = $3x10^{-5}$



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

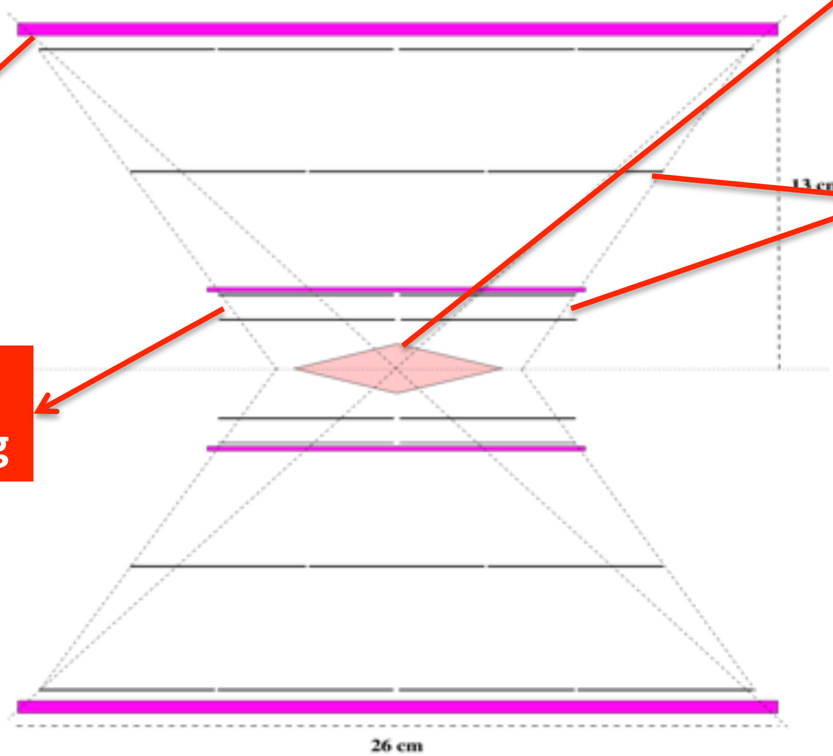
Mu3e Proposal at PSI

Improve MS-resolution by using v. thin (~ 40μm) HV-MAPS pixel silicon layers

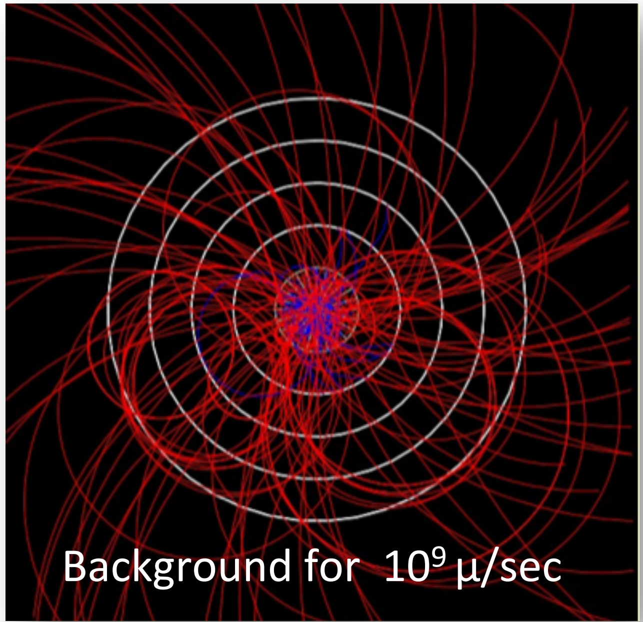
$\sigma(\theta)_{MS}$ = 5 mrad (c.f. SINDRUM-I : 28 mrad)

Hollow double cone target

Very thin silicon sensors for precision momentum and vertexing

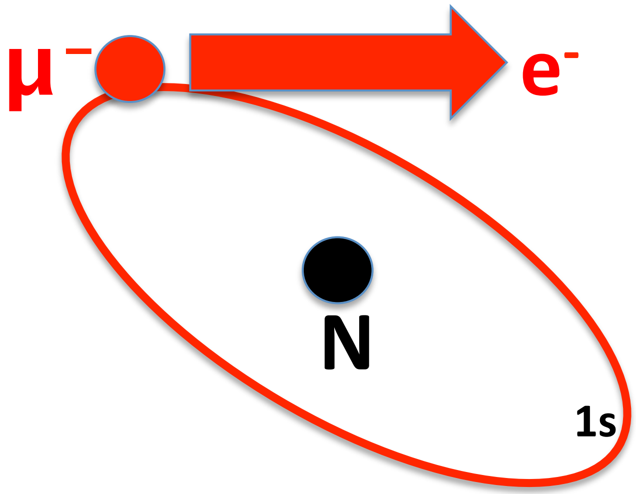


Scintillating Fibers for precision timing



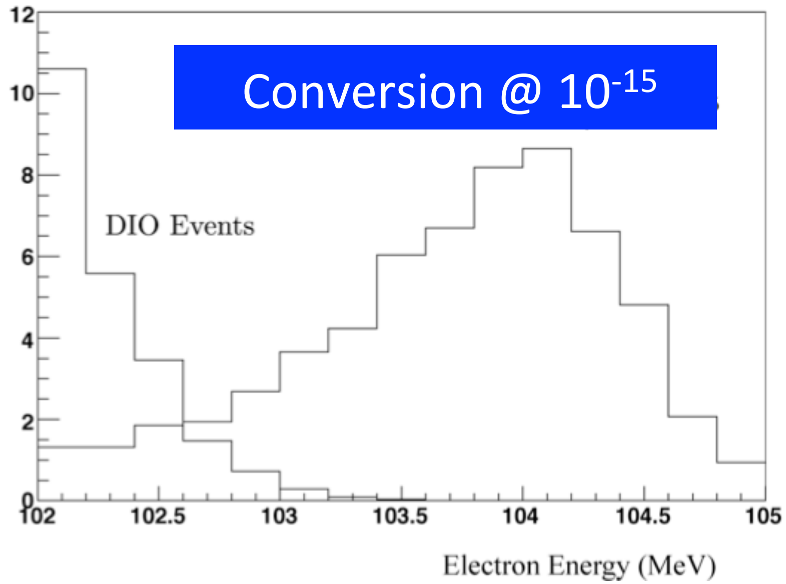
Aiming to achieve 10^{-16}

Muon to Electron Conversion



Processes considered so far suffer, at the highest rates, from accidental backgrounds that scale as $R(\mu)^2$

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



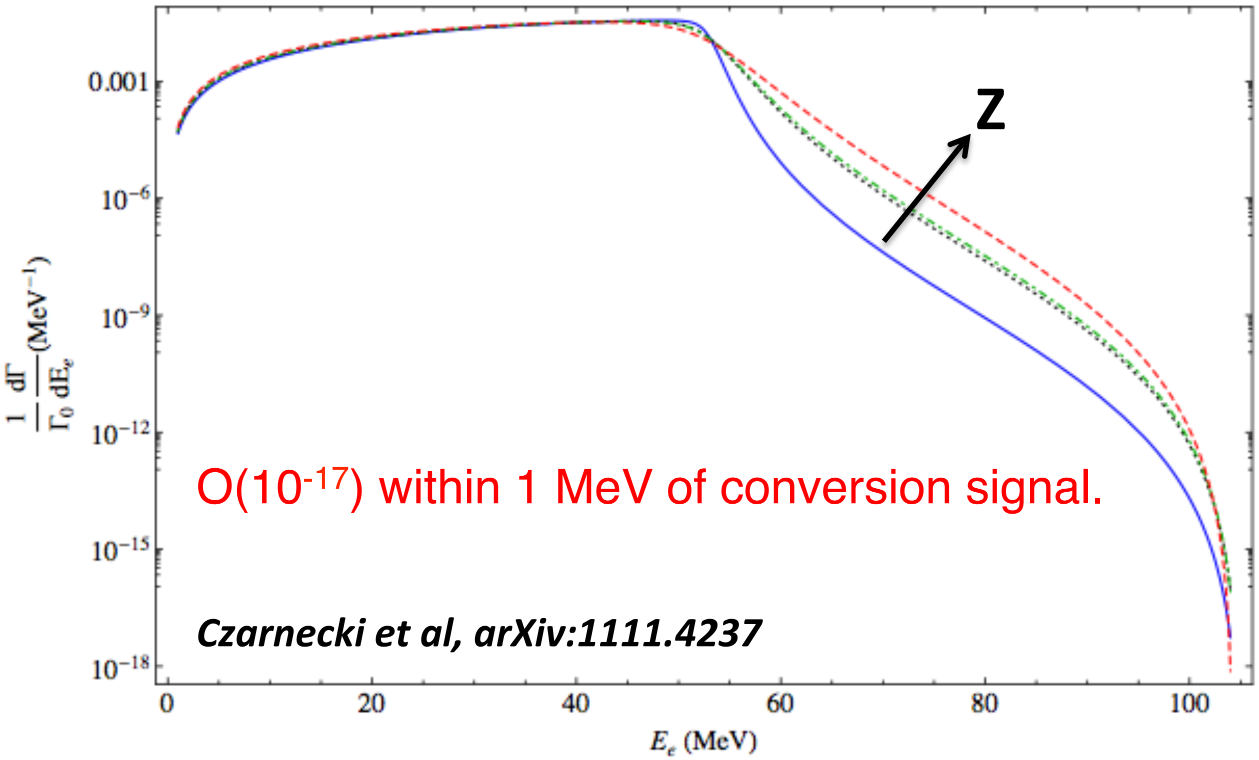
The "conversion process" has a simple one particle signature. Ee ~ m_μ
(>> Ee from free muon decay).

Arguably best route to highest sensitivity at high muon rates.

μN→eN Backgrounds

Two pertinent backgrounds

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



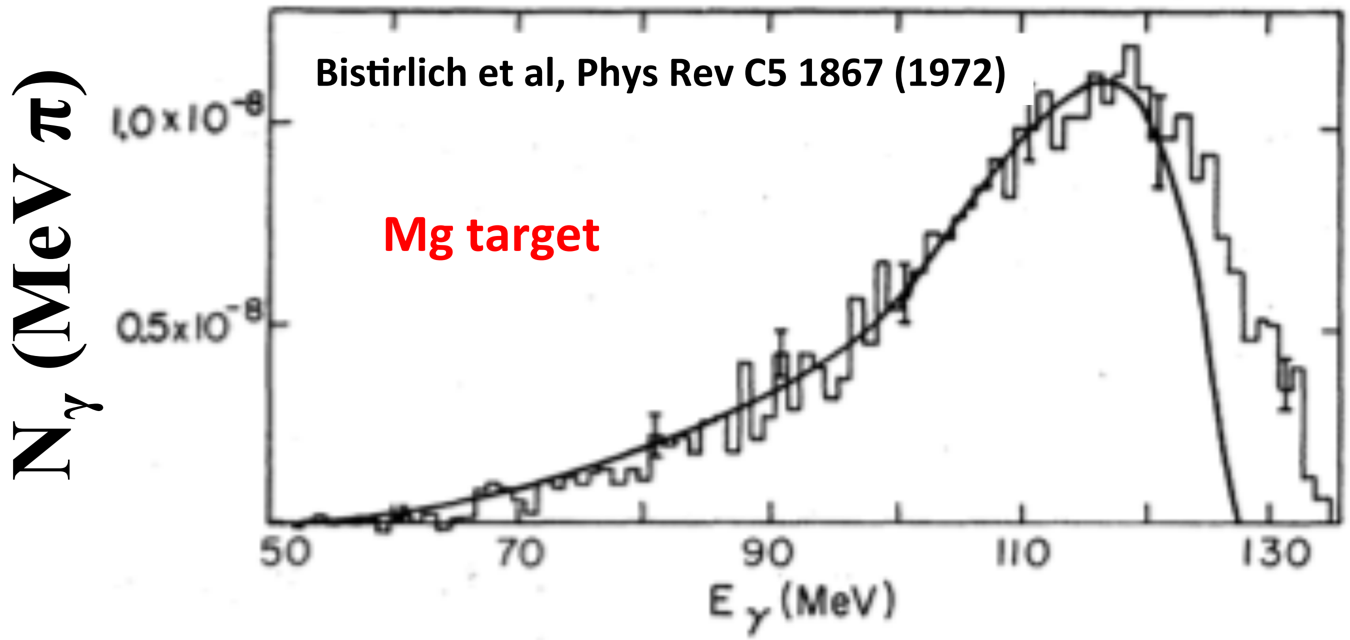
Controlled by detector resolution AND energy loss prior to detector.

Need FWHM < 1 MeV

2. Radiative Pion Capture (RPC)

$\pi^- N \to \gamma N^*$ and $\gamma \to e^+ e^-$ External conversion

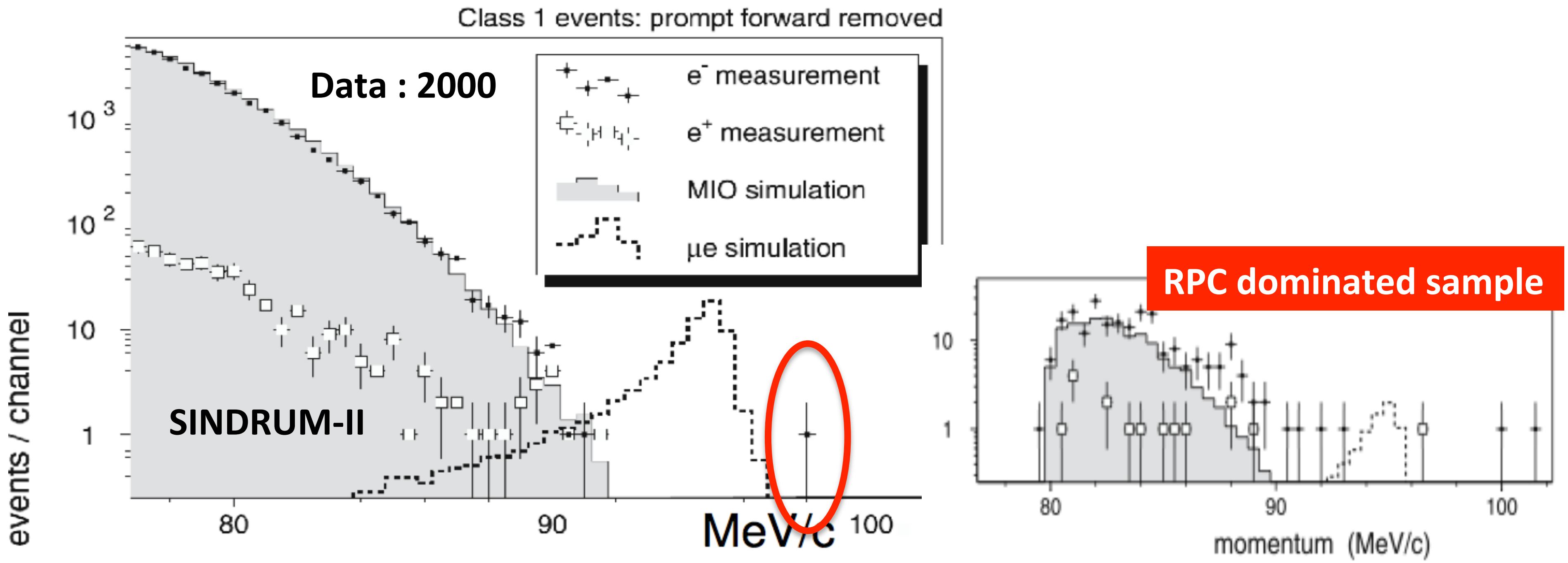
$\pi^- \mathrm{N} \to e^+ e^- N$ Internal conversion



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

Muon to Electron Conversion

Current best measurement (SINDRUM-II @ PSI) used 8mm of CH_2 to reduce pion (RPC) contamination to 1 in 10^9 π reaching target



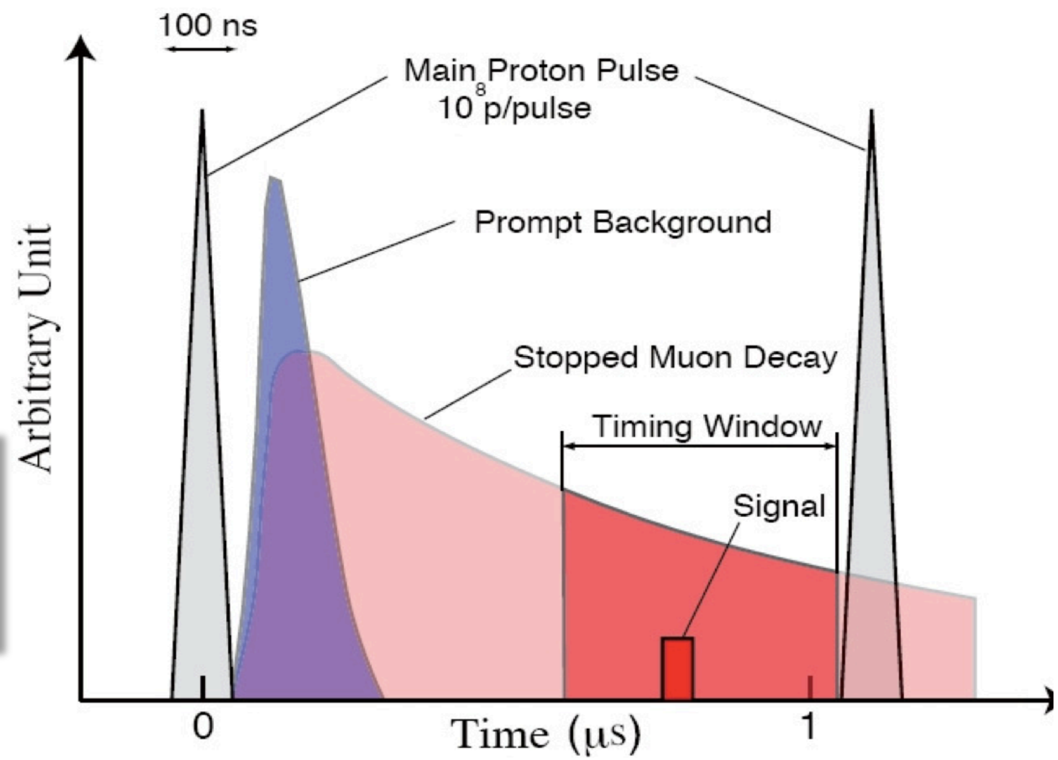
Limit : 7 x 10^{-13} (Gold target).

Next Generation

Going beyond SINDRUM requires

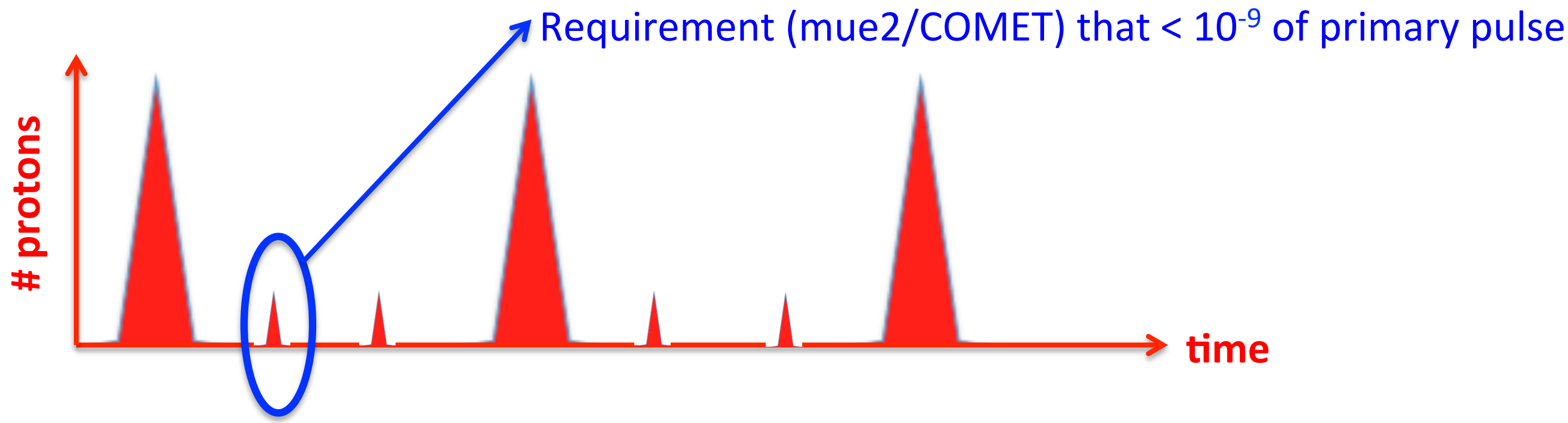
- Rate of stopped muons to be ~ O(5x10^{10})/s
- High resolution (< 1 MeV) e- momentum measurement to control DIO.
- Control of energy loss/straggling in stopping target
- Mechanism to reduce # pions at target and veto prompt backgrounds.

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

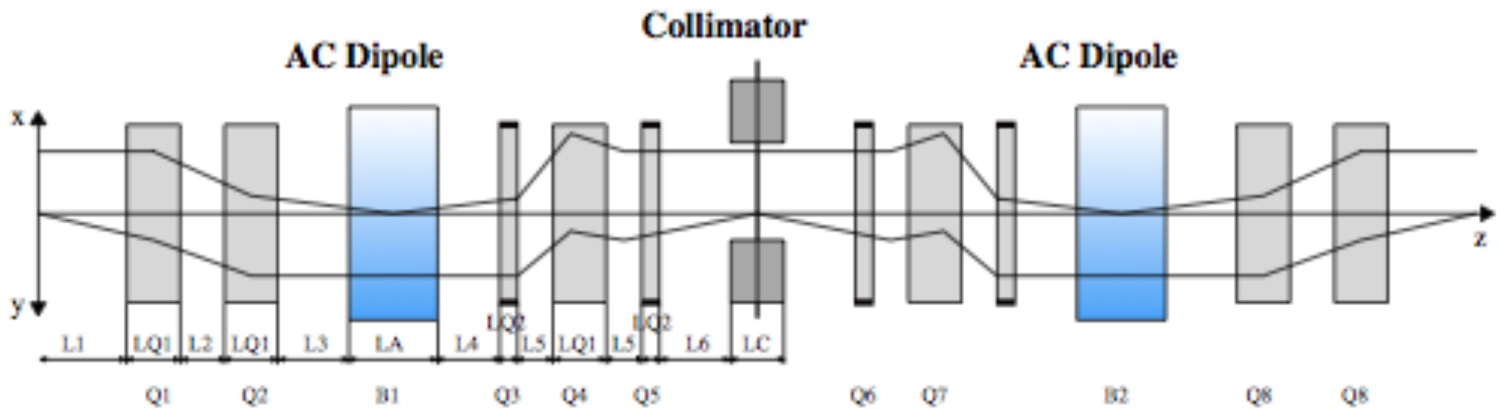


Challenges : Proton Extinction / "After protons"

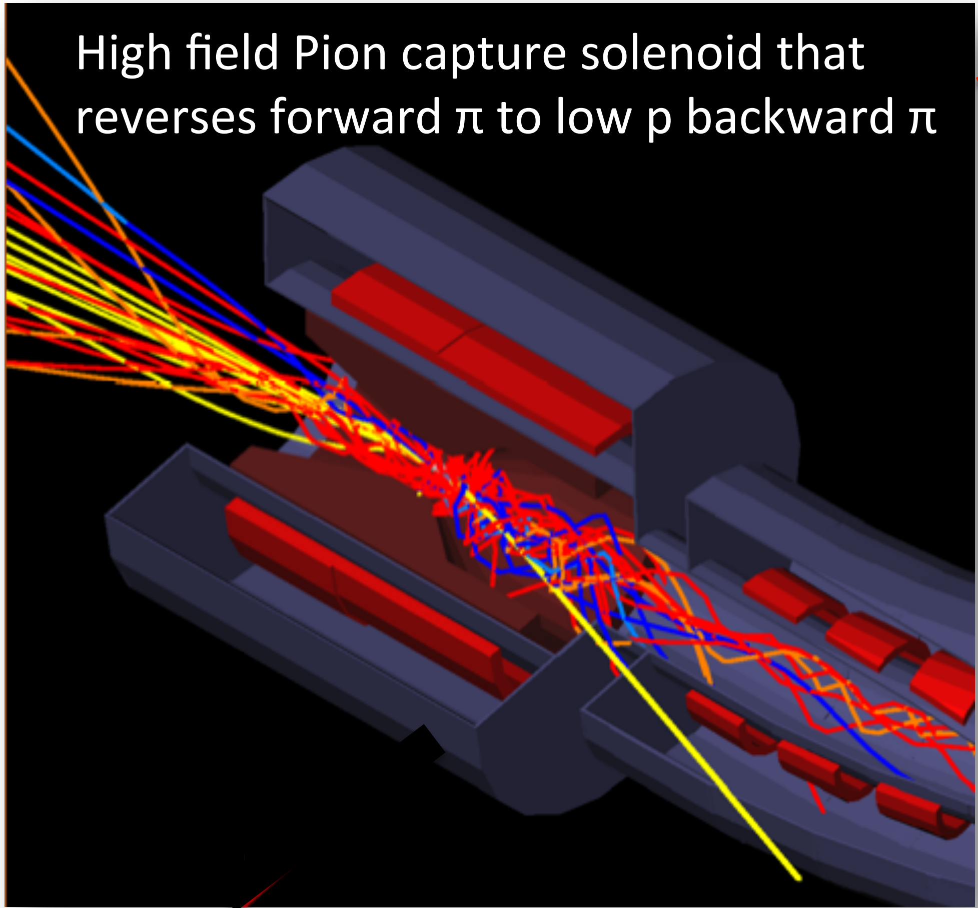
Require that between proton pulses there are no rogue proton pules that could produce a "prompt" background e.g. RPC in the timing window



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



Challenges : Stopped Muon Yield

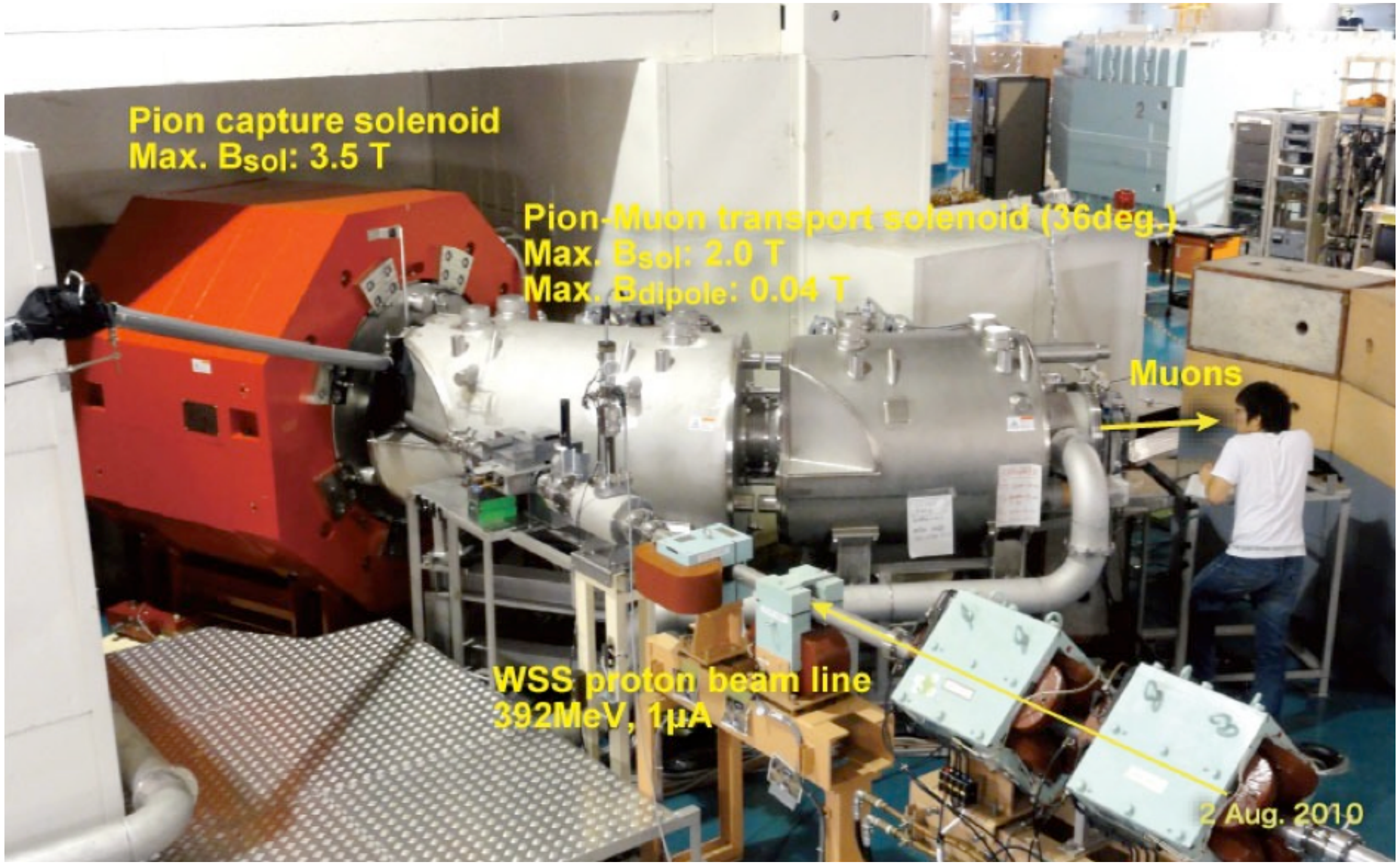


Increases yield by O(1000) - method successfully demonstrated at MUSIC in Osaka in 2010

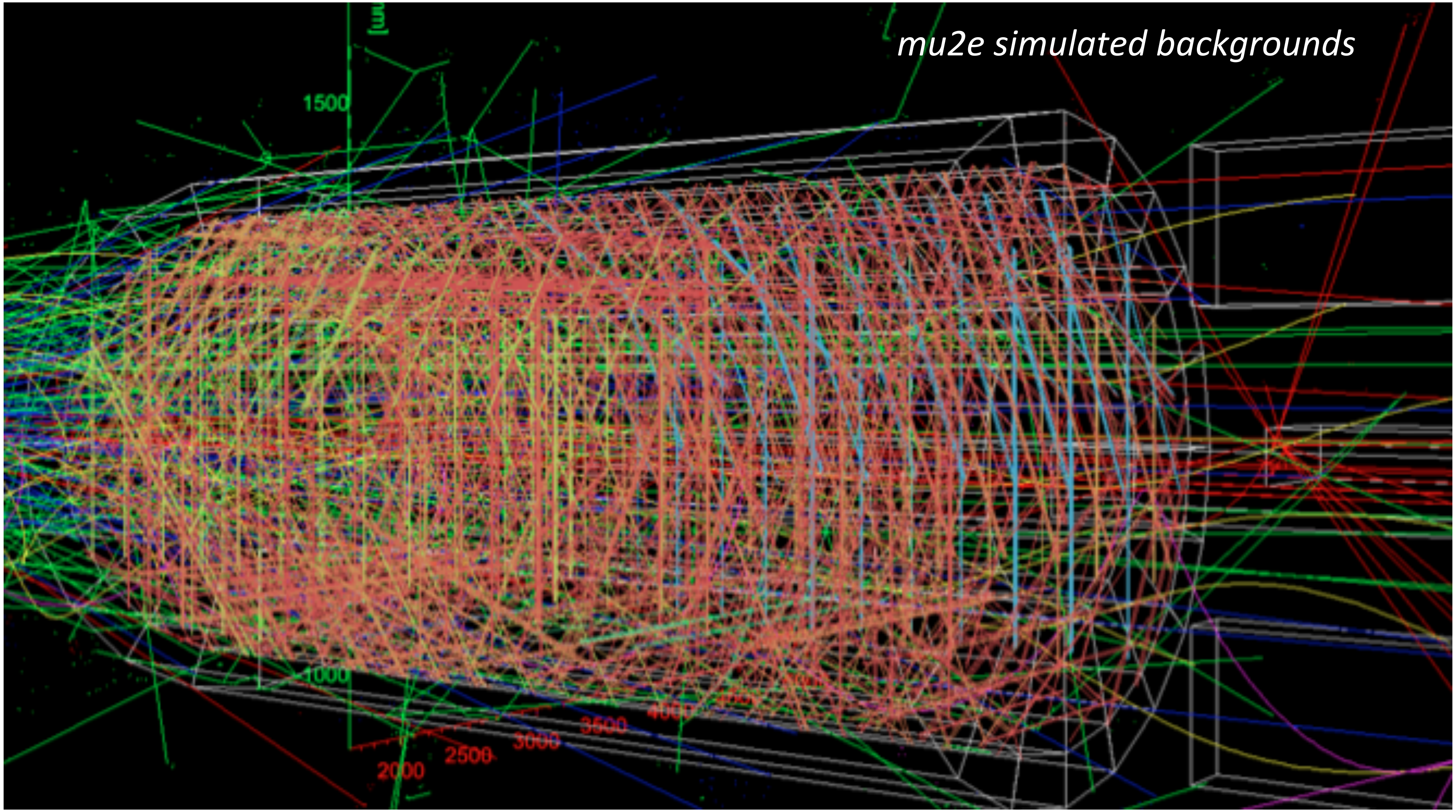
Transport solenoids that select low p (< 50 MeV) muons and reject high p particles **before** the stopping target.

MUSIC @ Osaka

Utilising prototype pion production environment for COMET

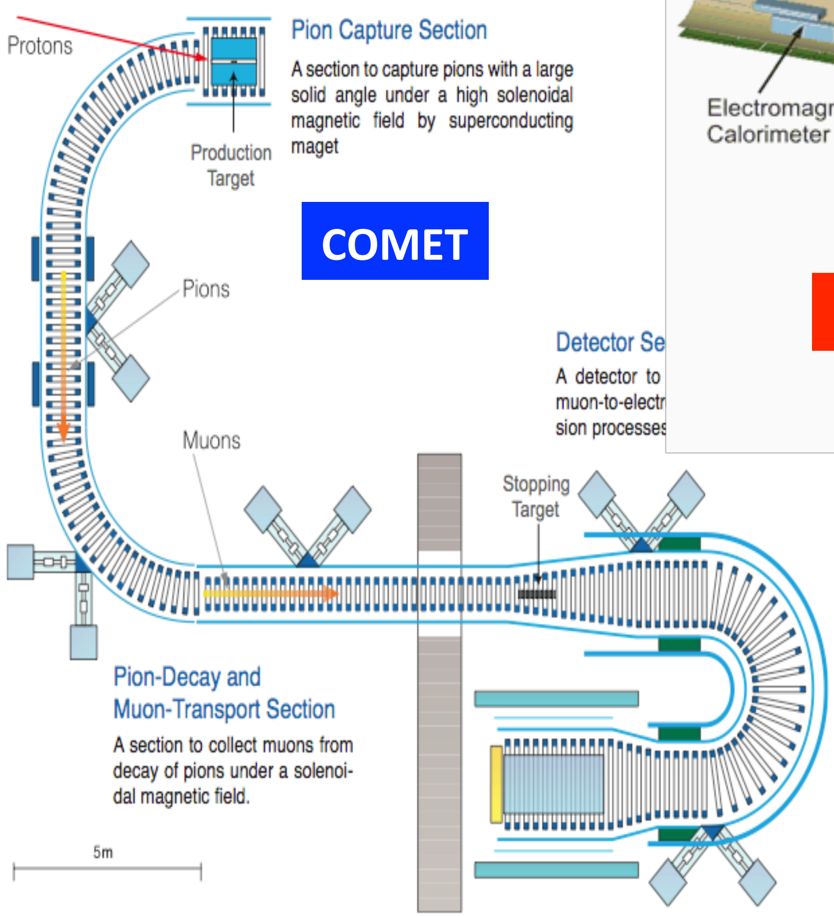


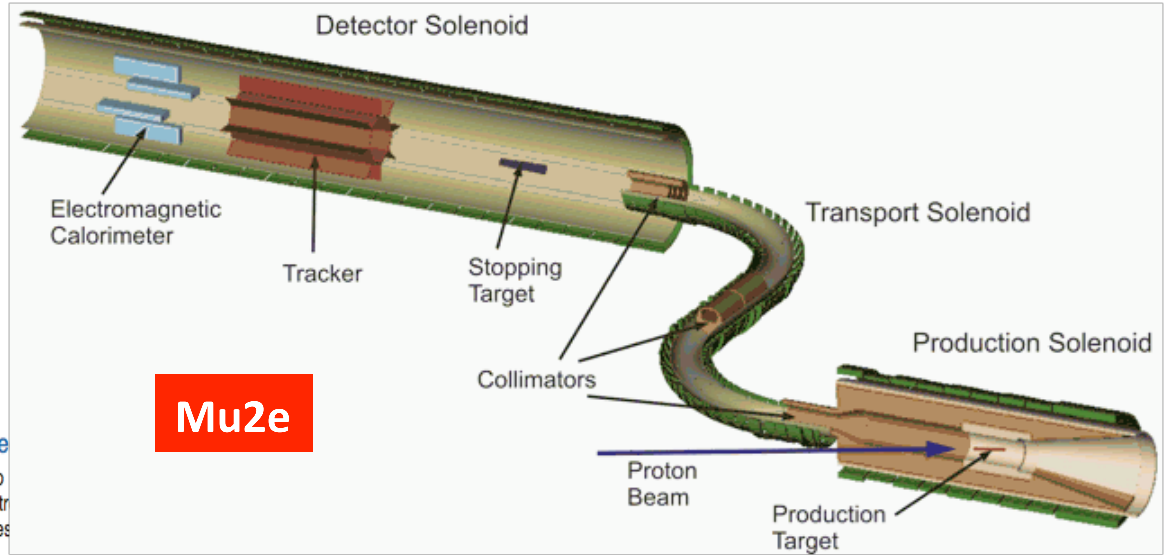
Challenges : High Rates in Detector



COMET/Mu2e : 6×10^{-17}

Sensitivity reach physics wise is at least x10 that of upgraded MEG.



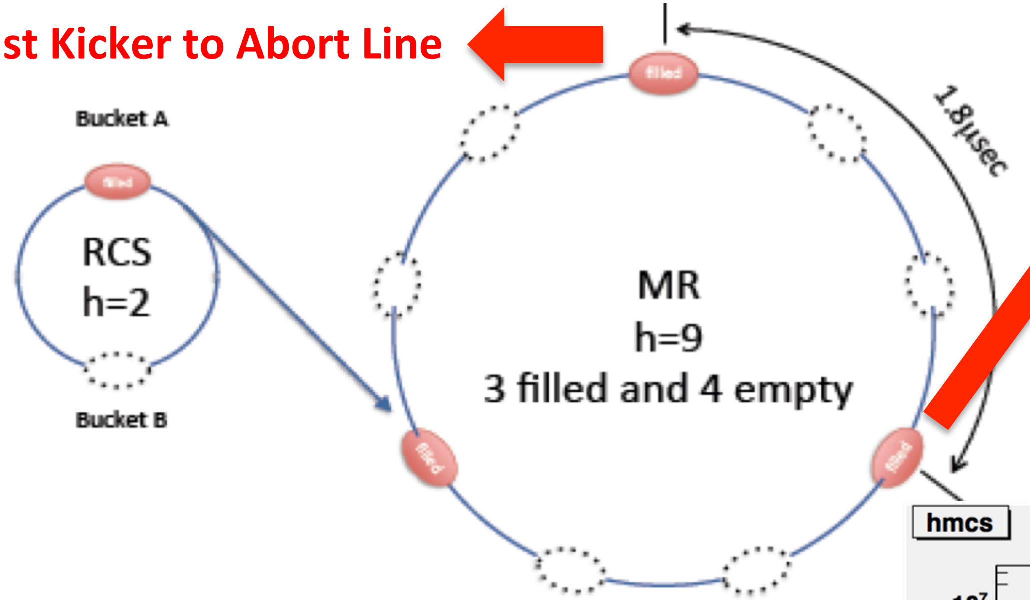


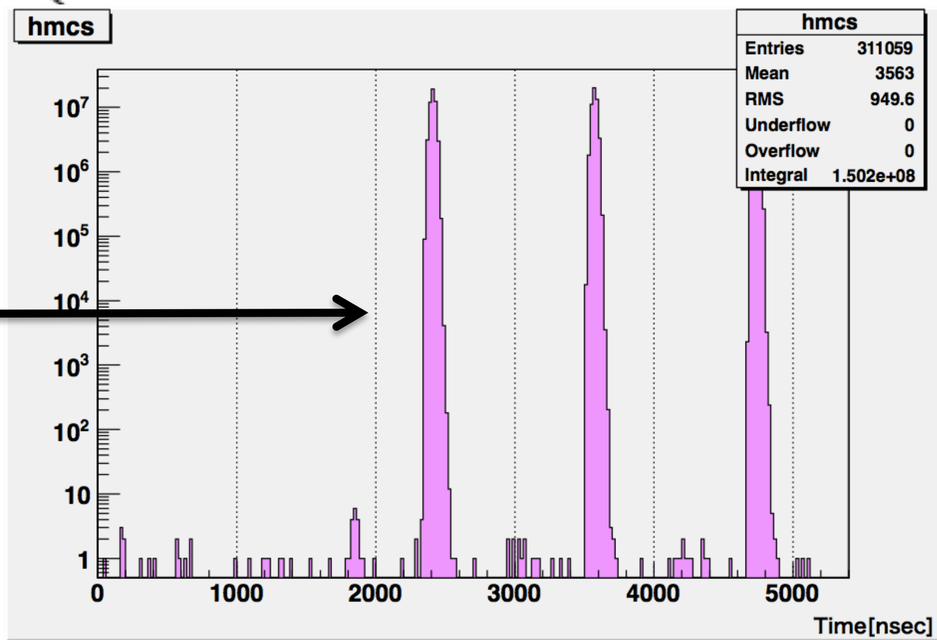
COMET : 10^{18} μ/yr (CDR) with lower acceptance & requirement of dedicated running vs Mu2e 4.5 x 10^{17} μ/yr (CD0) and concurrent Noυa running

COMET : Extinction Studies

Fast Kicker to Abort Line

Bunched slow extraction using ESS to dedicated target/ secondary beamline





Extinction level of **$(5.4 \pm 0.6) \times 10^{-7}$** 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

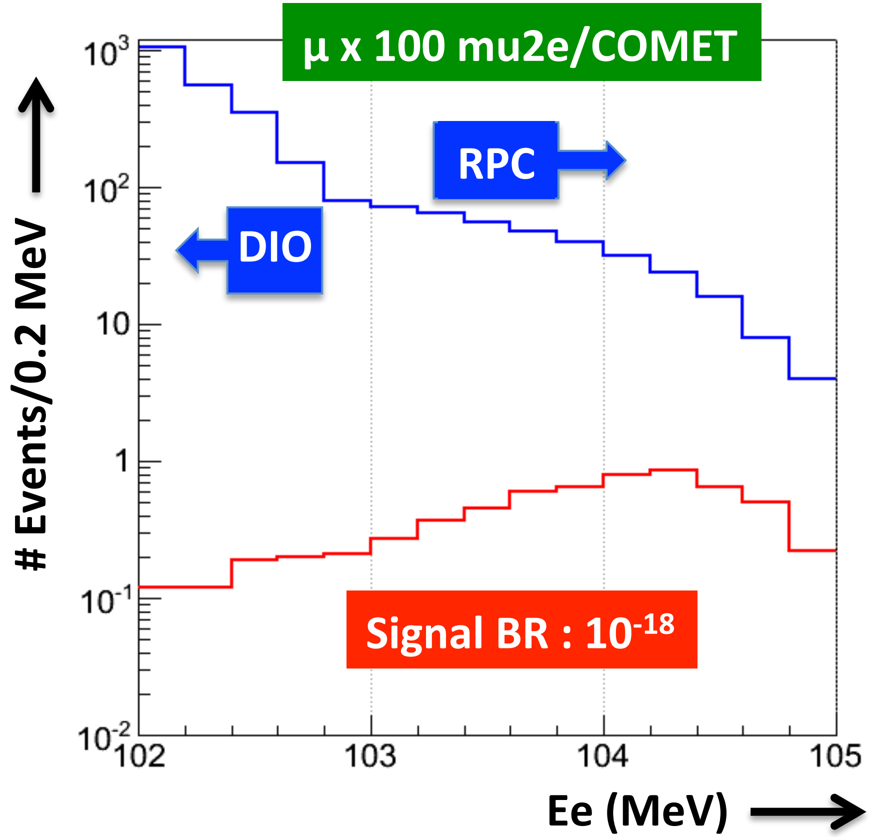
Strategy depends somewhat on whether signal is seen or not.

If signal is seen
- **run with high-Z target** to elucidate the underlying physics

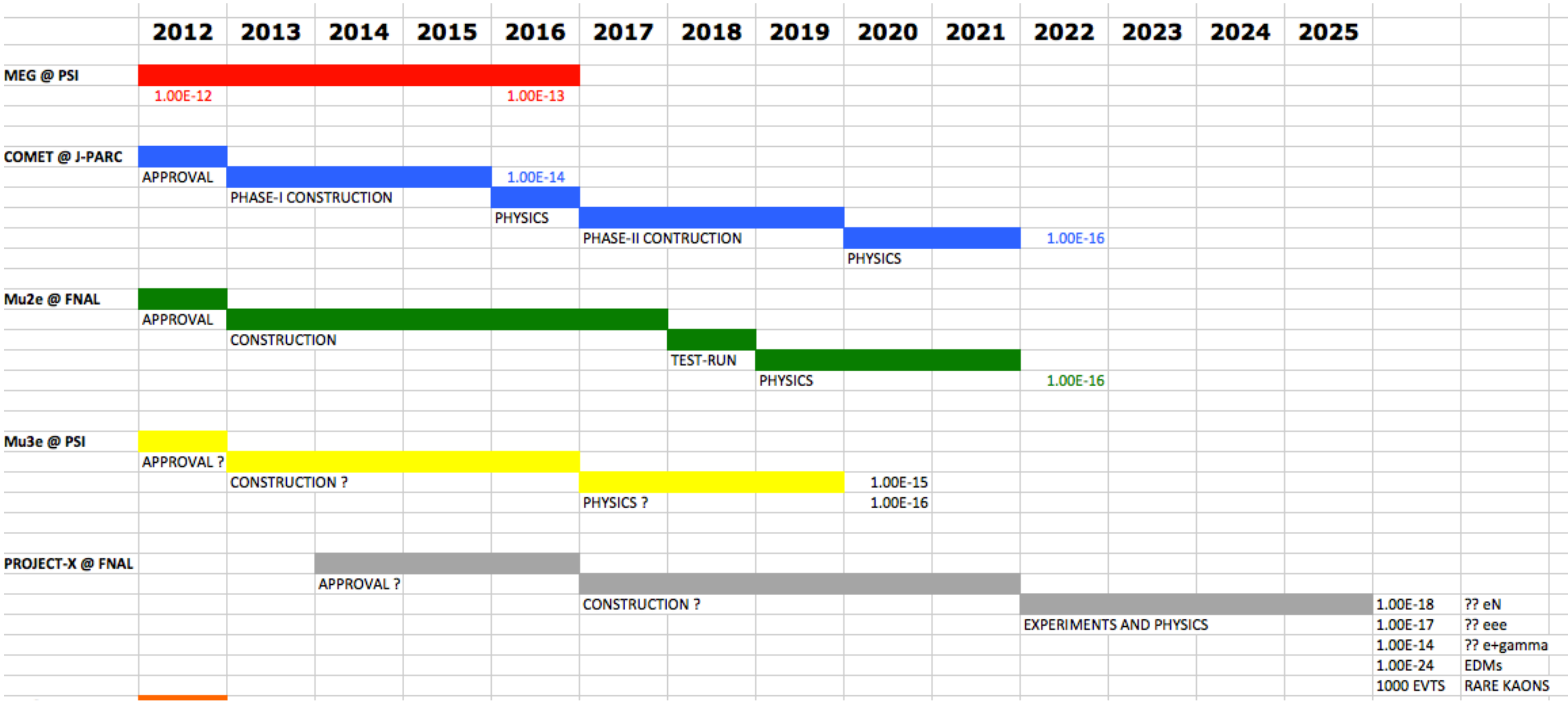
If no signal seen
- push sensitivity down to $O(10^{-18})$

Very challenging requires many of the ideas being explored for NF/muon collider.

- muon momentum selection
- muon cooling (FFAG/helical channel)



Where are we now / timescales ?



COMET unlike Mu2e will be constructed in two phases with 1st data in 2016/17.

COMET Phase-I

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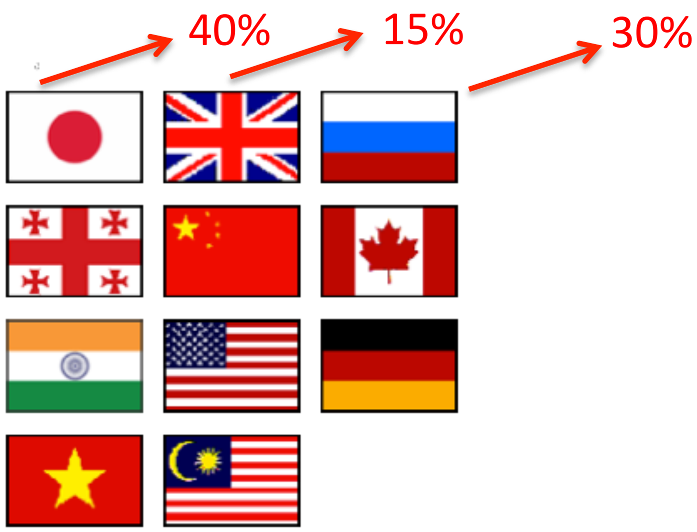
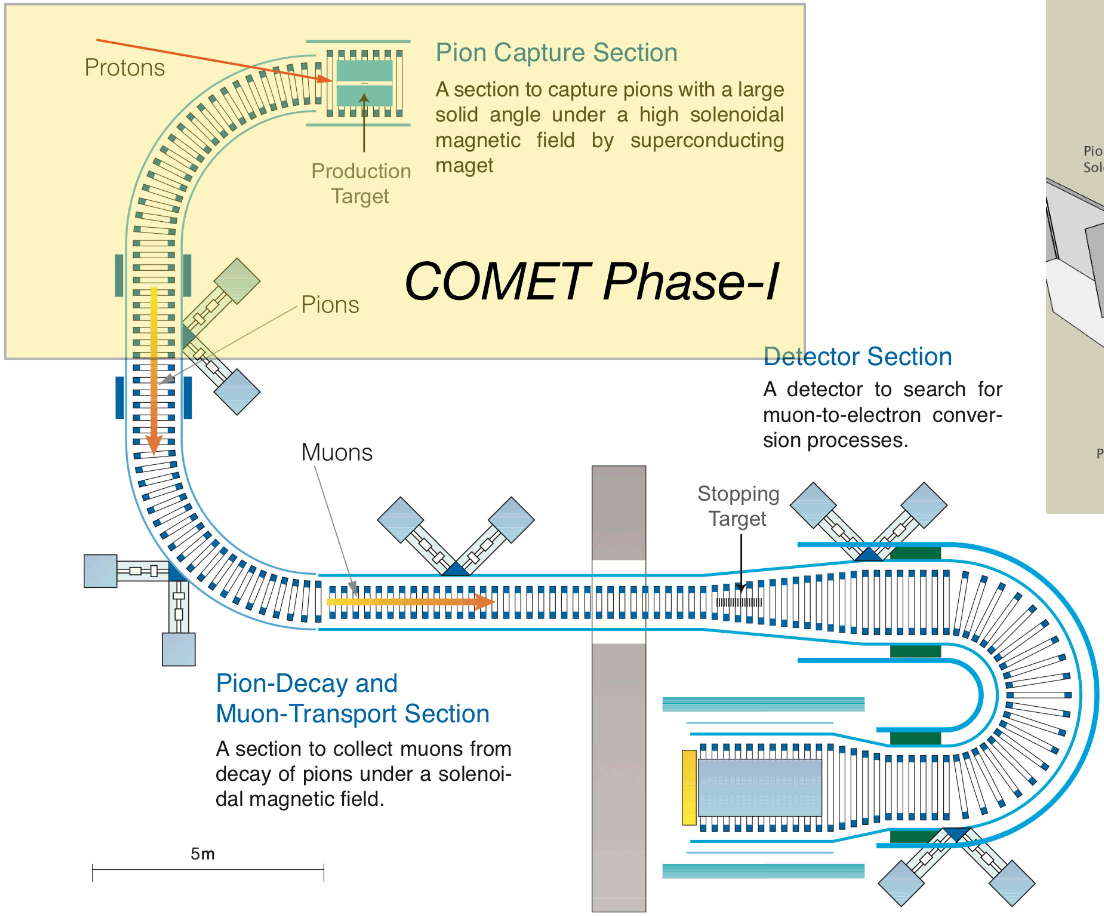
TRIUMF, Canada

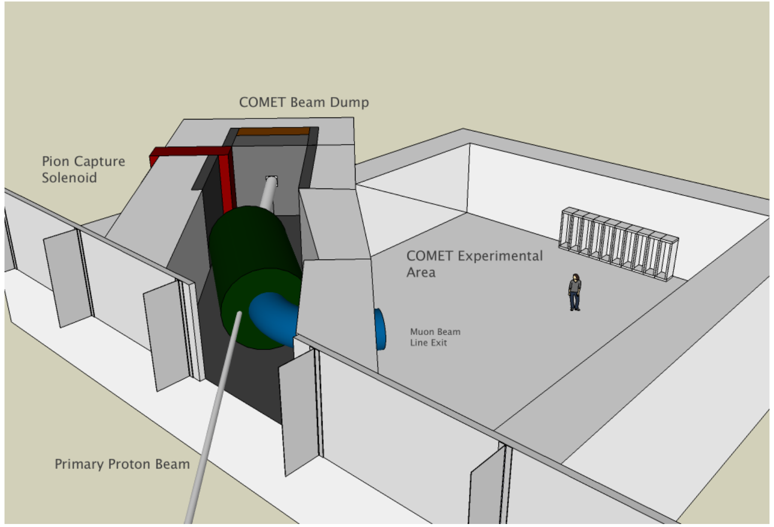


- 107 collaborators
- 25 institutes
- 11 countries

Imperial, UCL and v. recently Manchester, Oxford

COMET Phase-I



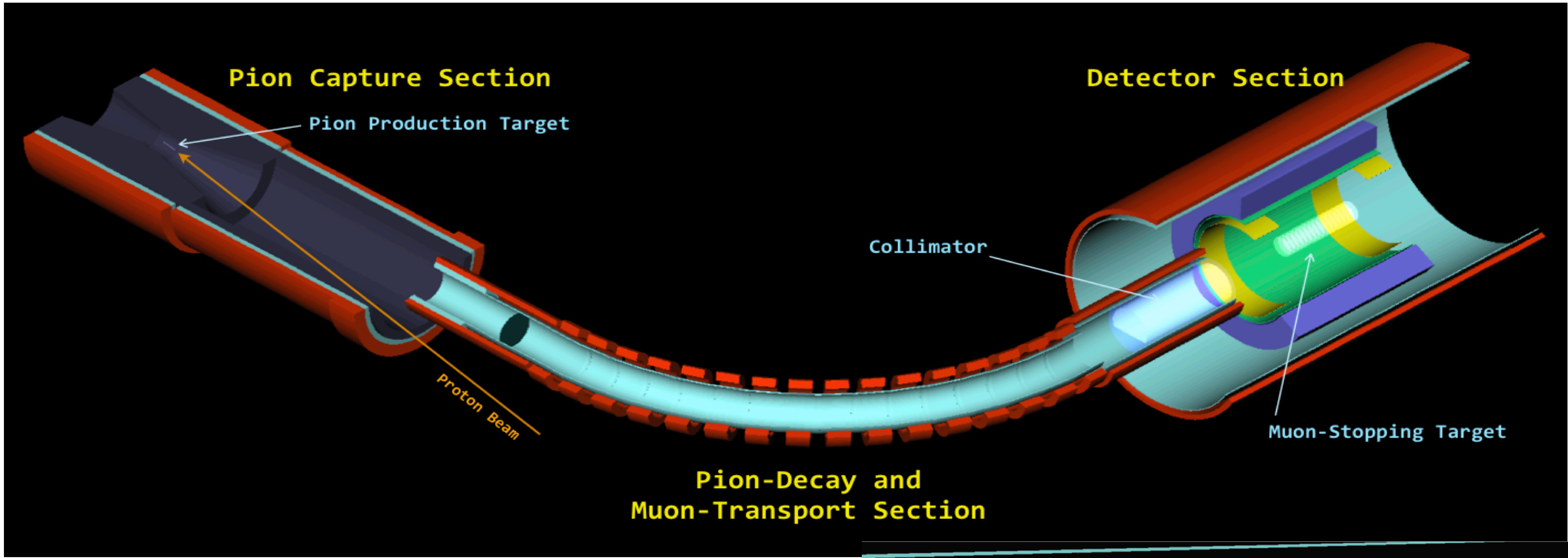


Phase-1
$30M : beamline
$15M : detector/DAQ etc

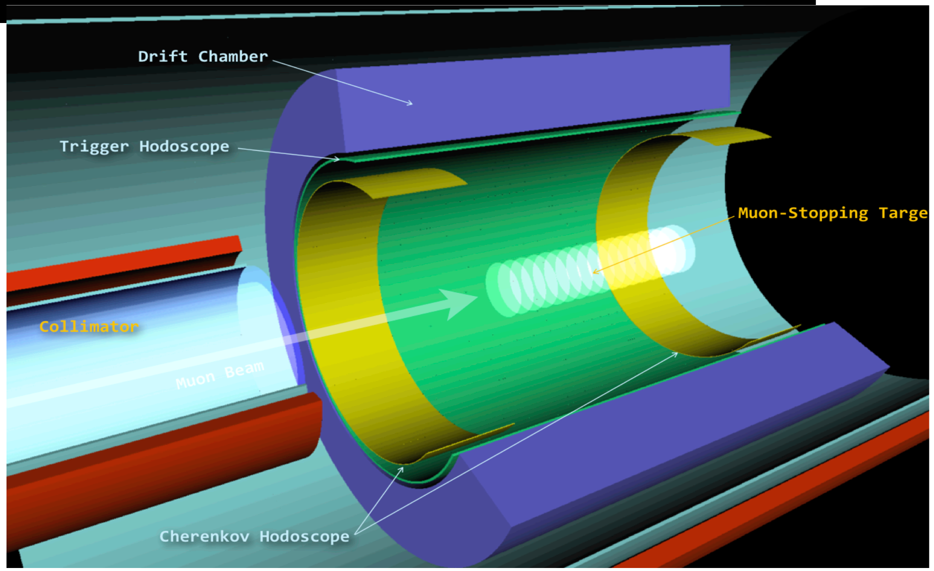
Phase-2
$45M

c.f. Mu2e : $240M

COMET Phase-I



Cylindrical detector (AMY solenoid) has higher acceptance but poorer resolution compared to transverse/phase-II detector



COMET Phase-I : Aims

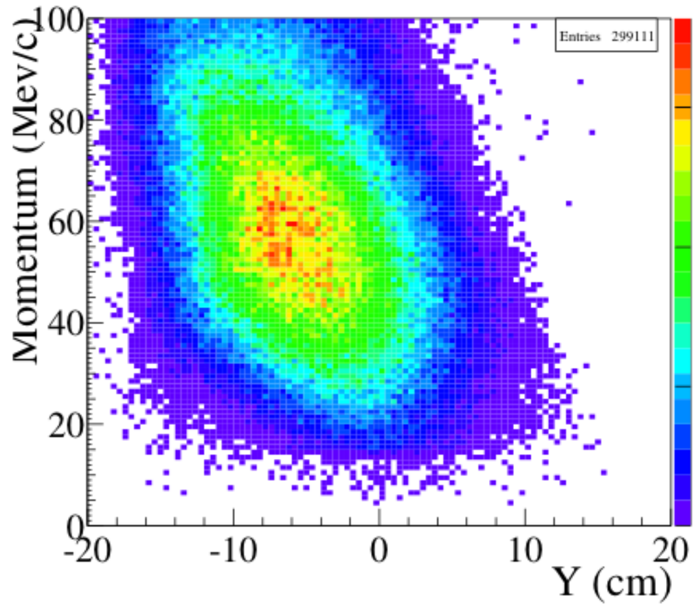
Current Mu2e/COMET sensitivity estimates of BR < 10^{-16} extrapolate current background knowledge over 4 orders of magnitude…

1. Demonstrate that beam extinction of 10^{-9} can be achieved

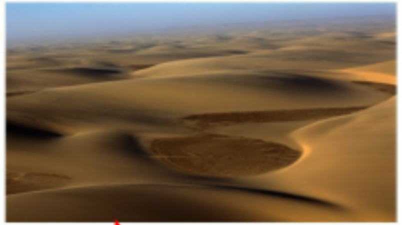
2. Measure in-situ backgrounds : neutrons, anti-p, nuclear capture products and so refine/optimise the simulation.

3. Test final/prototype detectors

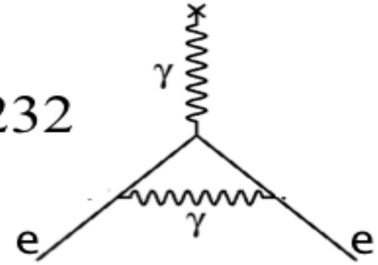
4. Measure conversion process with sensitivity **x100 that of SINDRUM-II** ie go below 10^{-14} :
physics-wise comparable to the MEG (2013) limit.



Muon Magnetic Moment ("g-2")

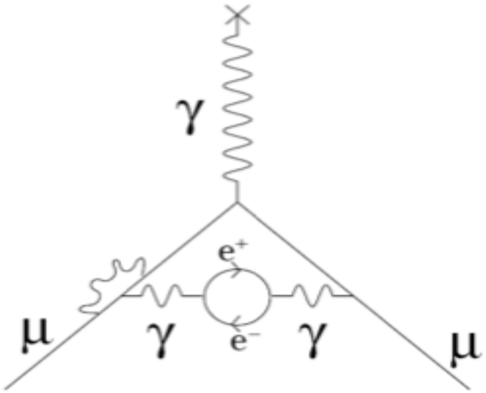


$$\frac{\alpha}{2\pi} = 0.00232$$



$$g_\mu^{exp} = 2.002\ 331\ 841\ 78\ (126)$$

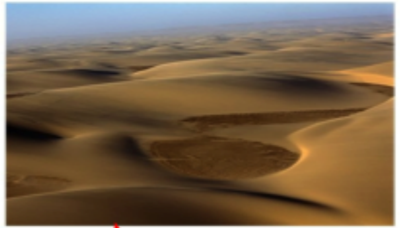
$$2\ 331\ 694\ 36\ (0)$$



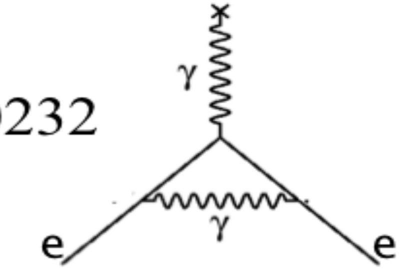
QED

* QED calculation for electron now out to 10th order (12672 diagrams)

Muon Magnetic Moment ("g-2")



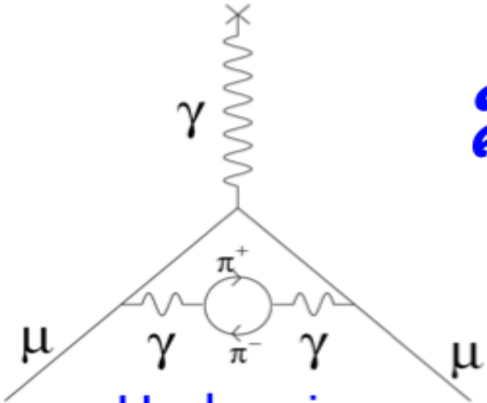
$$\frac{\alpha}{2\pi} = 0.00232$$



$$g_\mu^{exp} = 2.002\ 331\ 841\ 78\ (126)$$

$$2\ 331\ 694\ 36\ (0)$$

$$138\ 60\ (98)$$

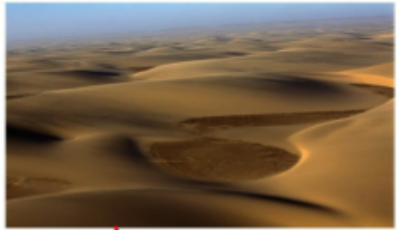


Hadronic

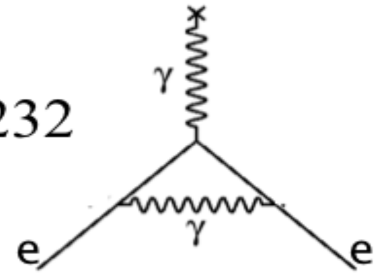
$$\lambda_{sens} \propto \left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$$

* Hadronic corrections for the electron g-2 don't show up until the 12th decimal

Muon Magnetic Moment ("g-2")



$$\frac{\alpha}{2\pi} = 0.00232$$

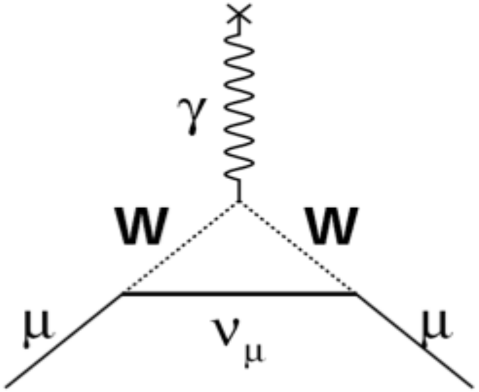


$$g_\mu^{exp} = 2.002\ 331\ 841\ 78\ (126)$$

$$2\ 331\ 694\ 36\ (0)$$

$$1\ 38\ 60\ (98)$$

$$3\ 08\ (4)$$



Electroweak

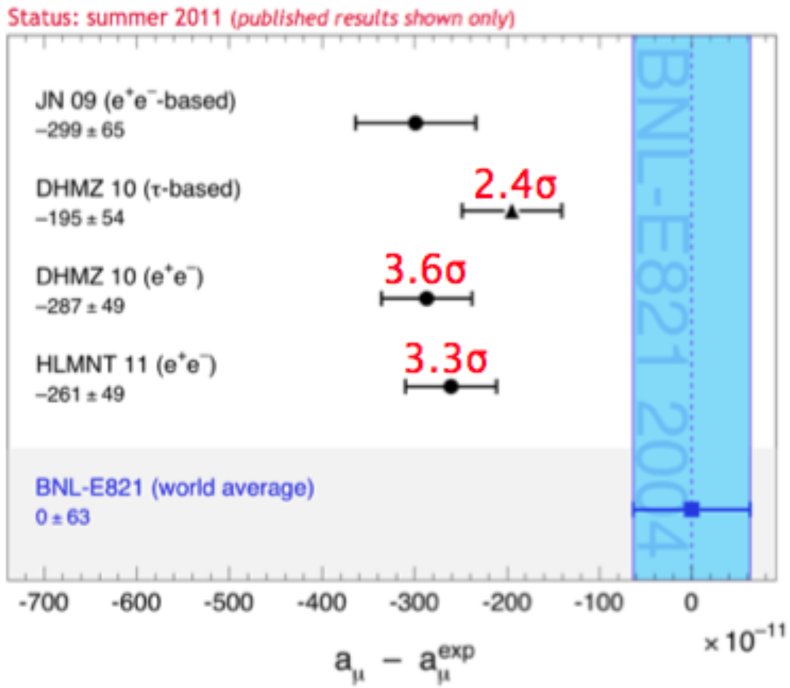
Muon Magnetic Dipole Moment ("g-2")

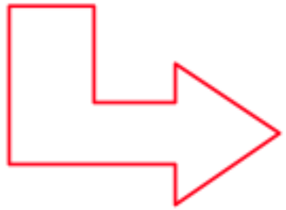
$a_\mu^{exp} = 116\ 592\ 089\ (63) \times 10^{-11}$

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

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

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





3.6σ

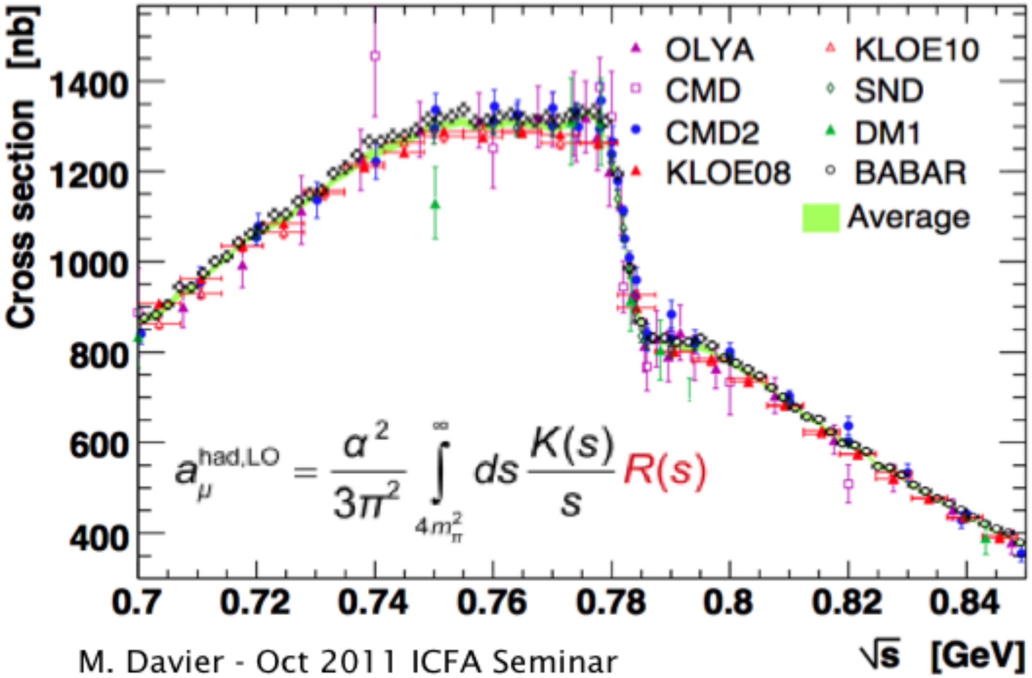
BNL measurement : statistics limited

Muon Magnetic Dipole Moment ("g-2")

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

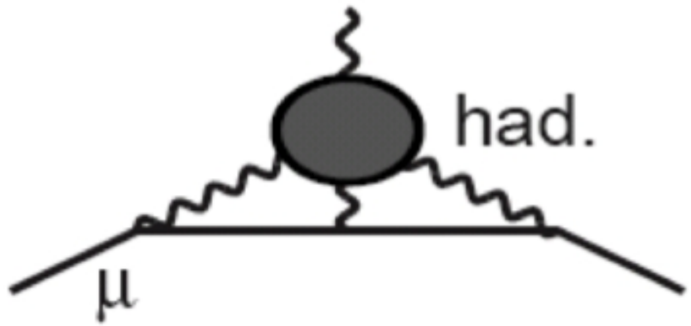
$a_\mu^{LOHVP} = 6\ 903\ \ (42) \times 10^{-11}$

3.6 σ



M. Davier - Oct 2011 ICFA Seminar

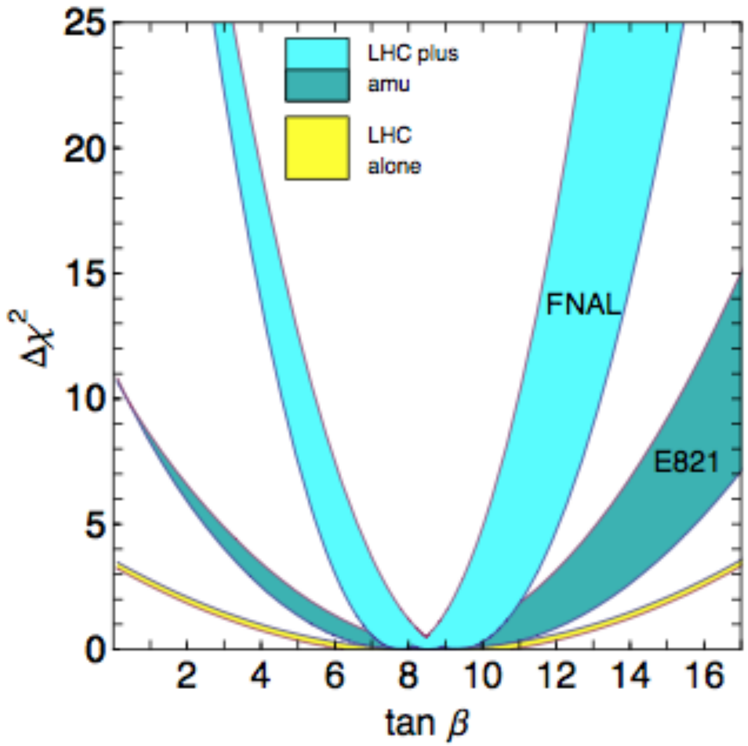
$a_\mu^{HLBL} = 105\ \ (26) \times 10^{-11}$

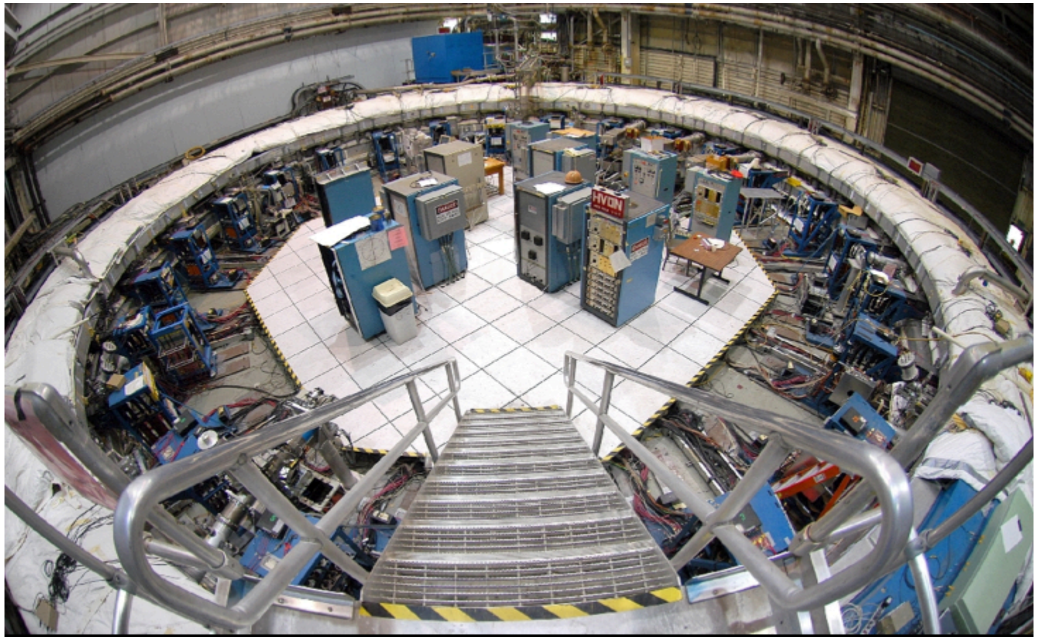


Expect theory error to be further reduced in next 5-years (e.g. lattice QCD)

FNAL Muon g-2

New FNAL experiment will re-use BNL magnets but with x20 stats and reduced systematics.





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

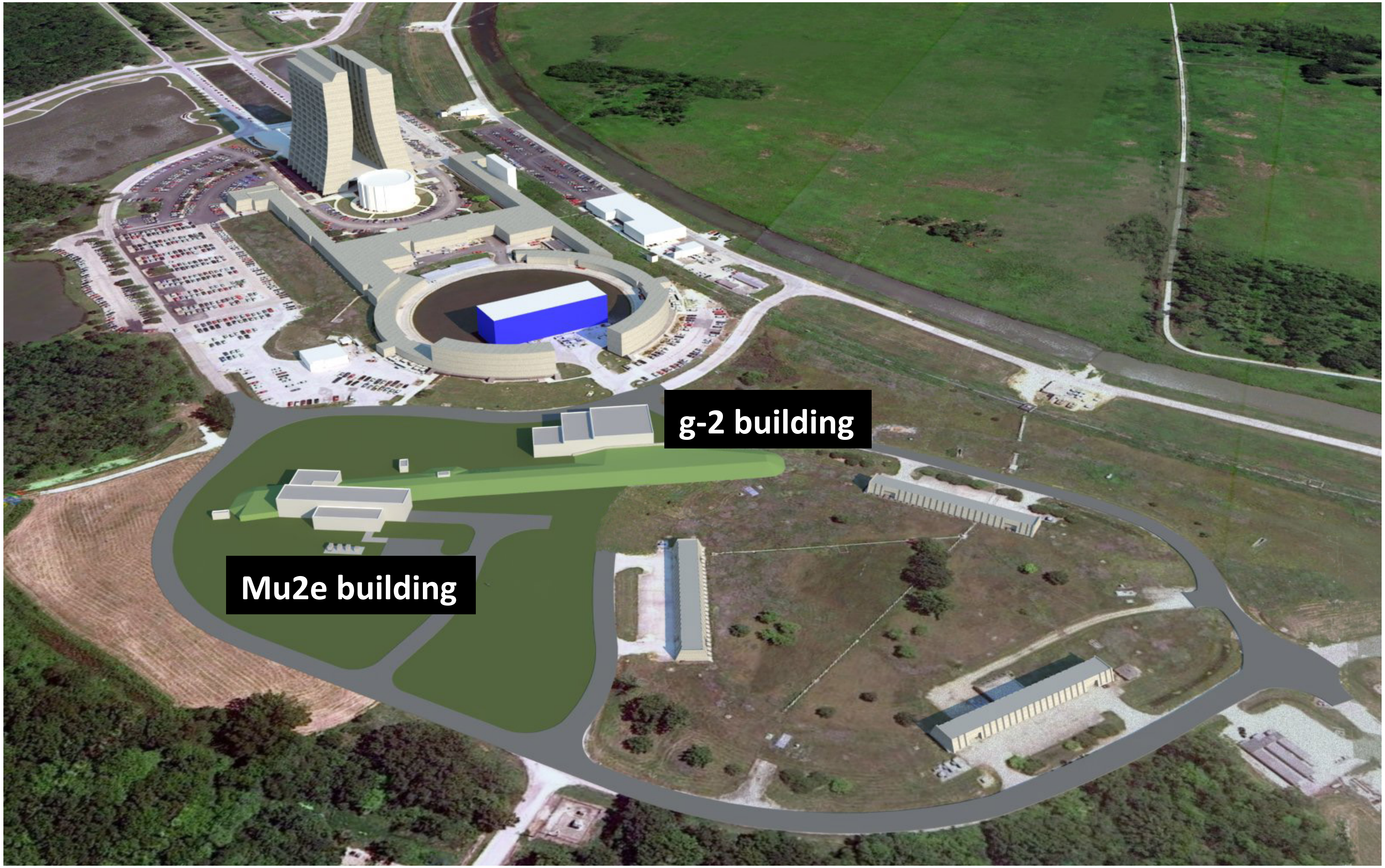
Without theory improvement : 3.6 σ → 5 σ, with theory : 7.5 σ.

Expect CD1 DOE approval ~ one year from now.
Next year FNAL spending \$20M.

Will share much of the Mu2e infrastructure.

Data in 2016/17. **Putting together a UK team to get involved**

FNAL Muon Campus



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

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

average over muons

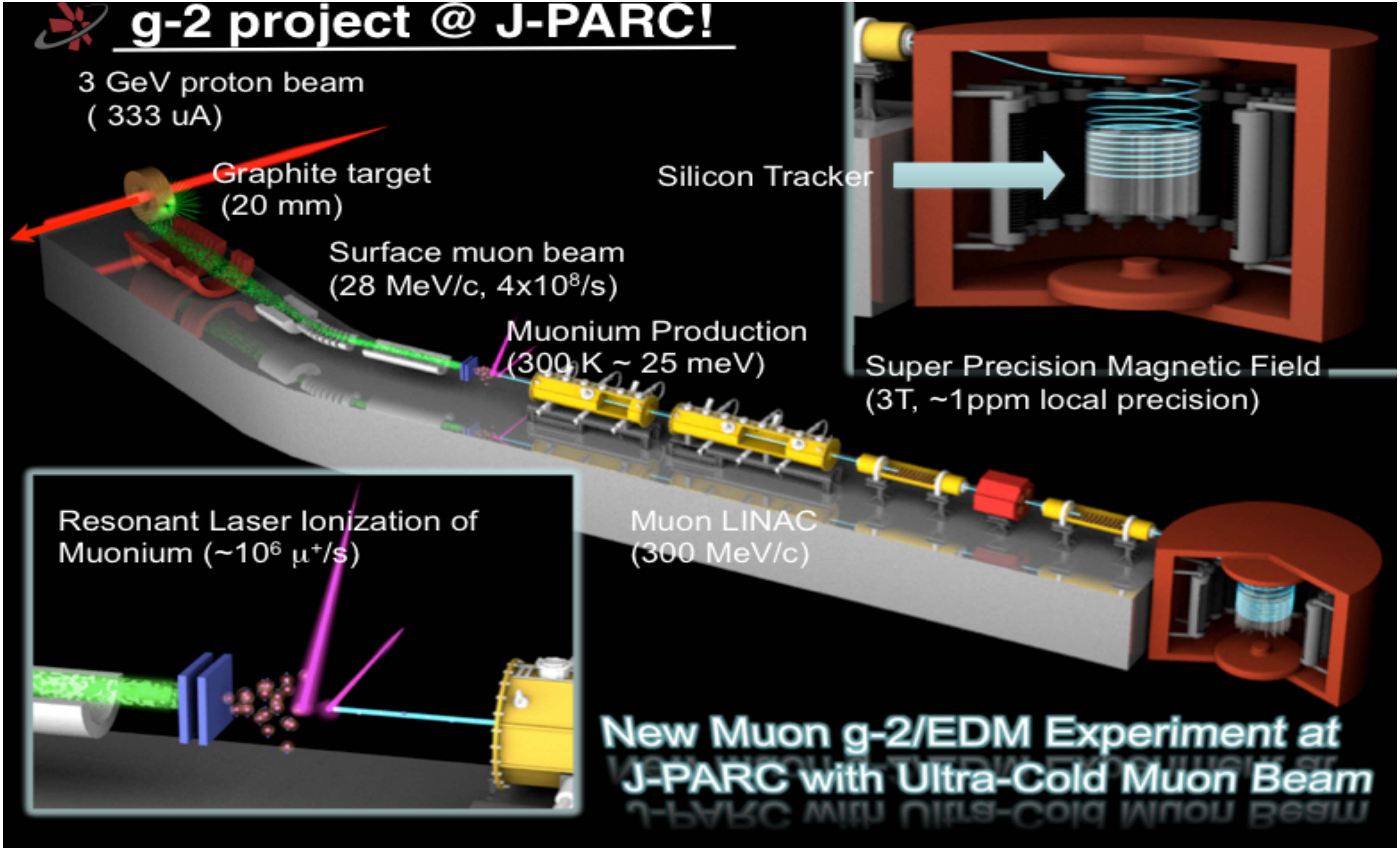
0

$$\gamma_{magic} = 29.3$$

Or

1. No vertical E focussing E field and v. small vertical beam divergence ($\Delta p_T/p_T = 10^{-5}$)
2. $\beta \sim 0$ by using ultra cold muons
3. Very large and uniform B (using MRI magnets)

J-PARC Muon g-2



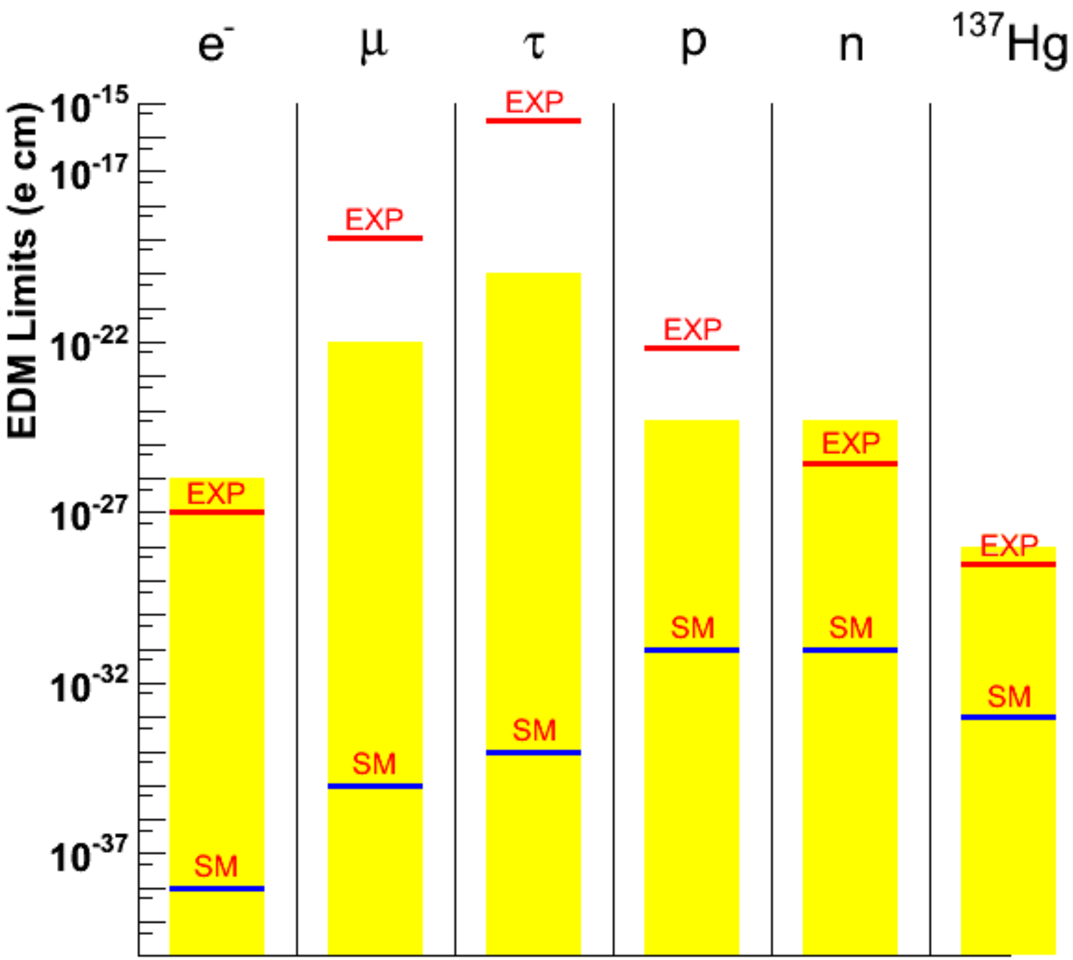
J-PARC Muon g-2

	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

EDMs



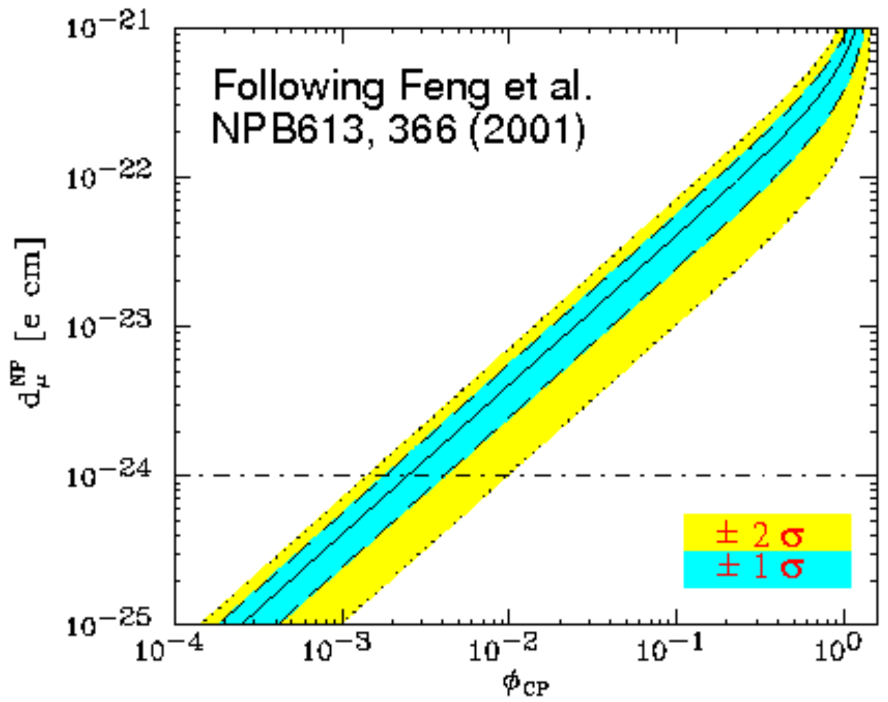
BSM

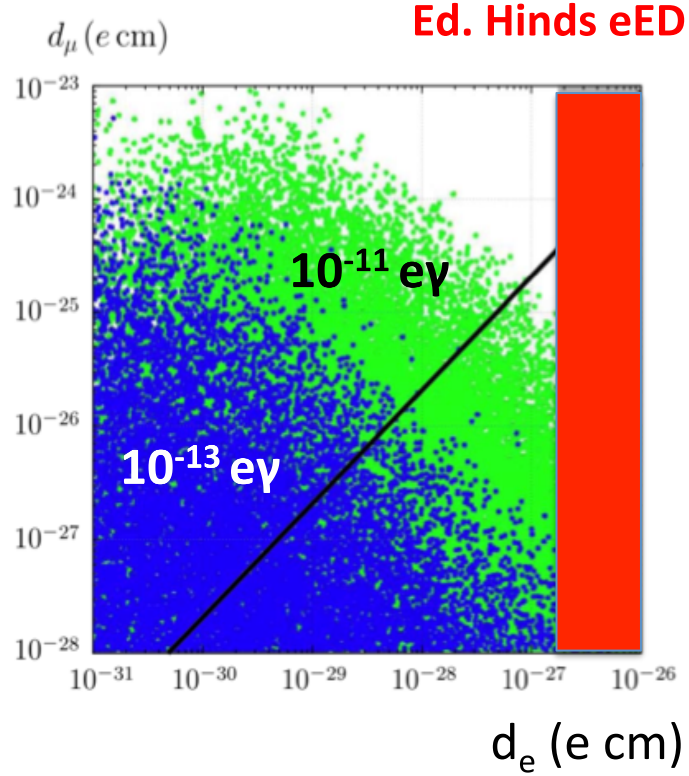
Neutron EDM is one nearest to reaching SM prediction while also being in the "BSM" region.

Muon EDM is 2nd generation and free of nuclear/molecular complications.

Like flavour violation, since SM is heavily suppressed any observation is new physics.

Muon EDM





Expect muon EDM below 10^{-22} and likely below 10^{-24} (SM = 0)

Present limit (BNL) is 1.8 x 10^{-19}.

FNAL (g-2) should reach 10^{-21} looking at vertical angle, 90^0 out of phase with g-2 modulation

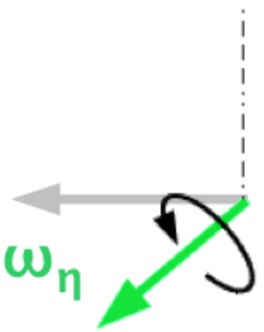
Muon unique since 2nd generation & it's a single particle measurement unlike e/n EDM.

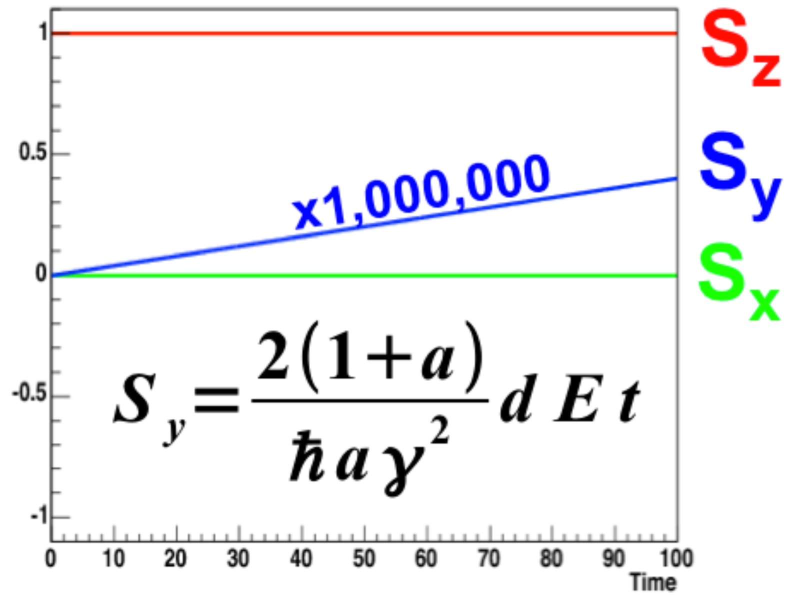
Muon EDM beyond 10^{-21} : Frozen Spin

Judicious choice of E and B to cancel magnetic moment contribution

magnetic moment anomaly — **EDM**

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

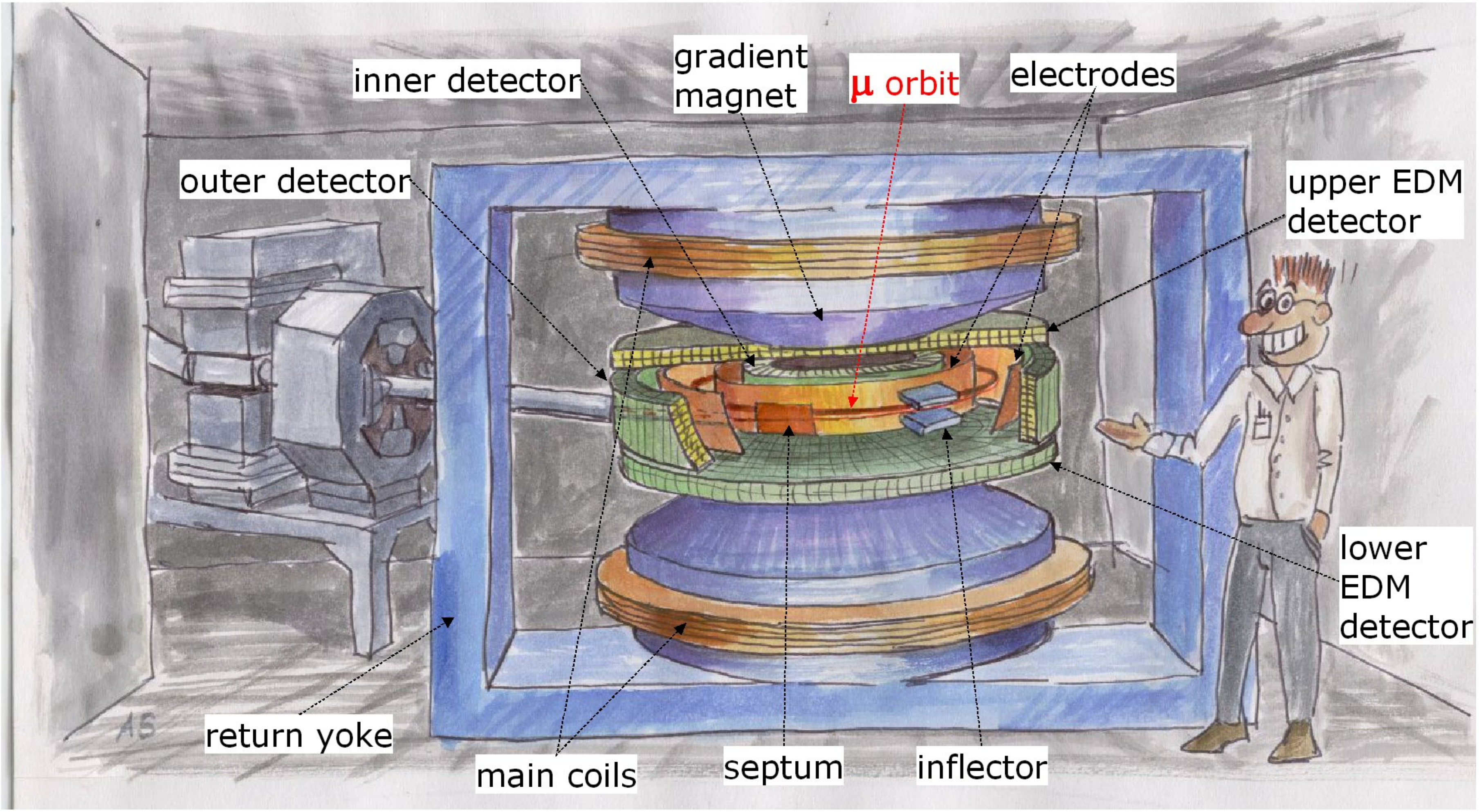




$$E = \frac{aB\beta}{1-(1+a)\beta^2} \simeq aB\beta\gamma^2$$

Muon EDM beyond 10^{-21} : Frozen Spin

PSI proposal (hep-ex/0606034v3)



Summary

There is life outside the LHC !

Muon programme has a host of experiments in next 2-20 years.

Provide a clean and complementary probe of BSM physics to the LHC to energy scales beyond LHC direct searches.

Win-Win

✓ If the LHC throws up nothing – this is the best game in town.

✓ If the LHC discovers new physics then this will elucidate the theory.