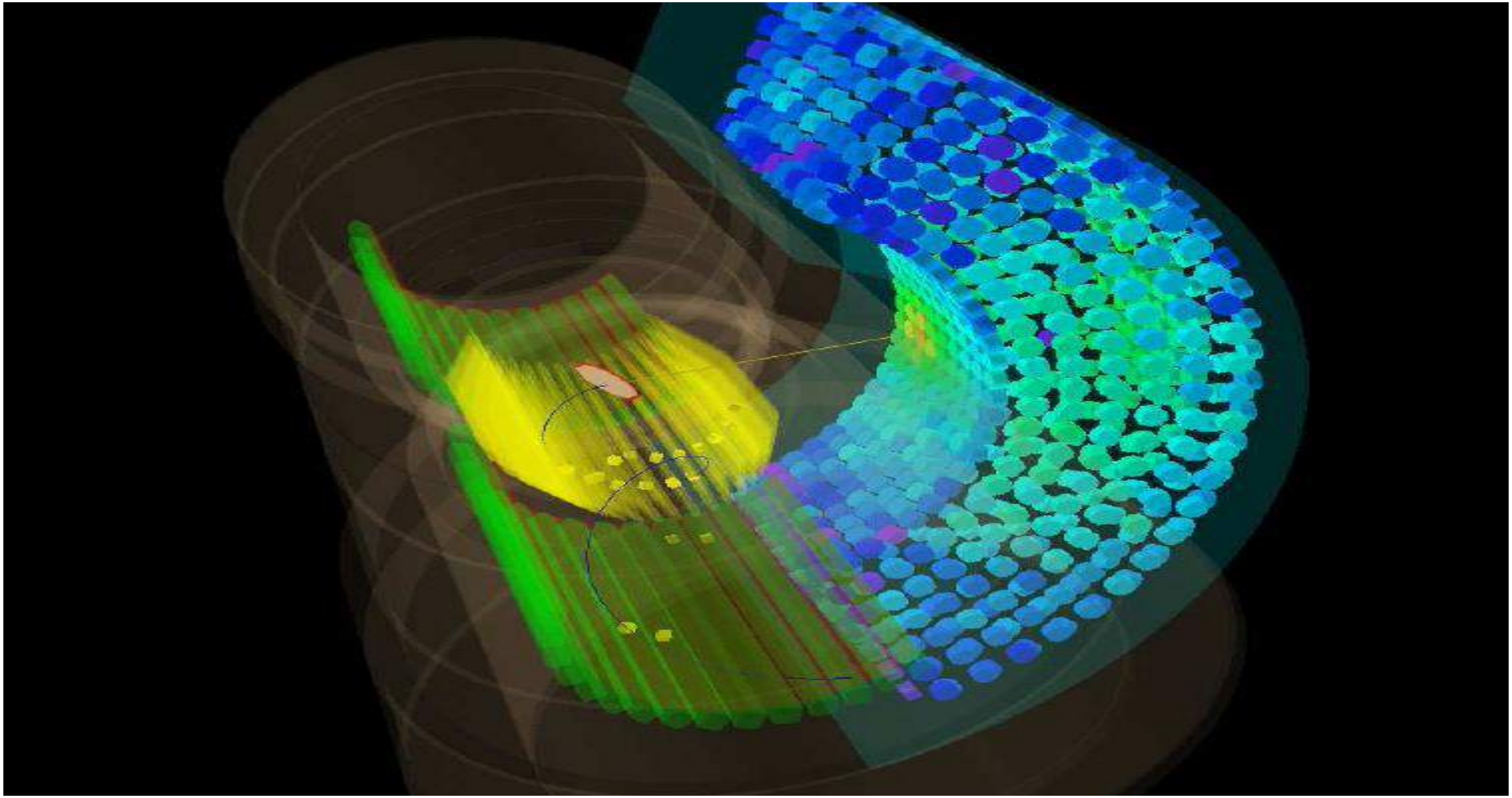
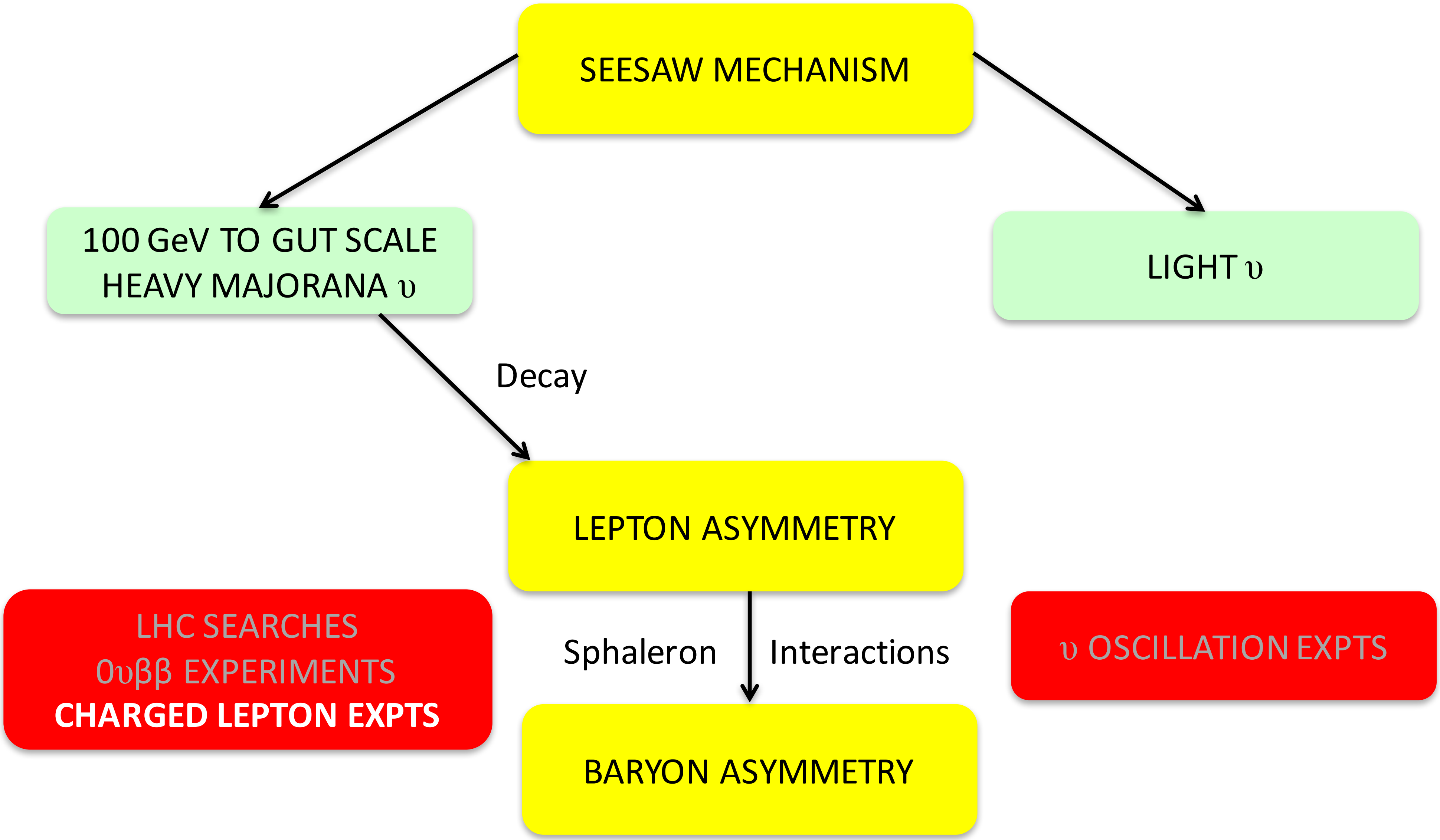
Charged Lepton Flavour Experiments



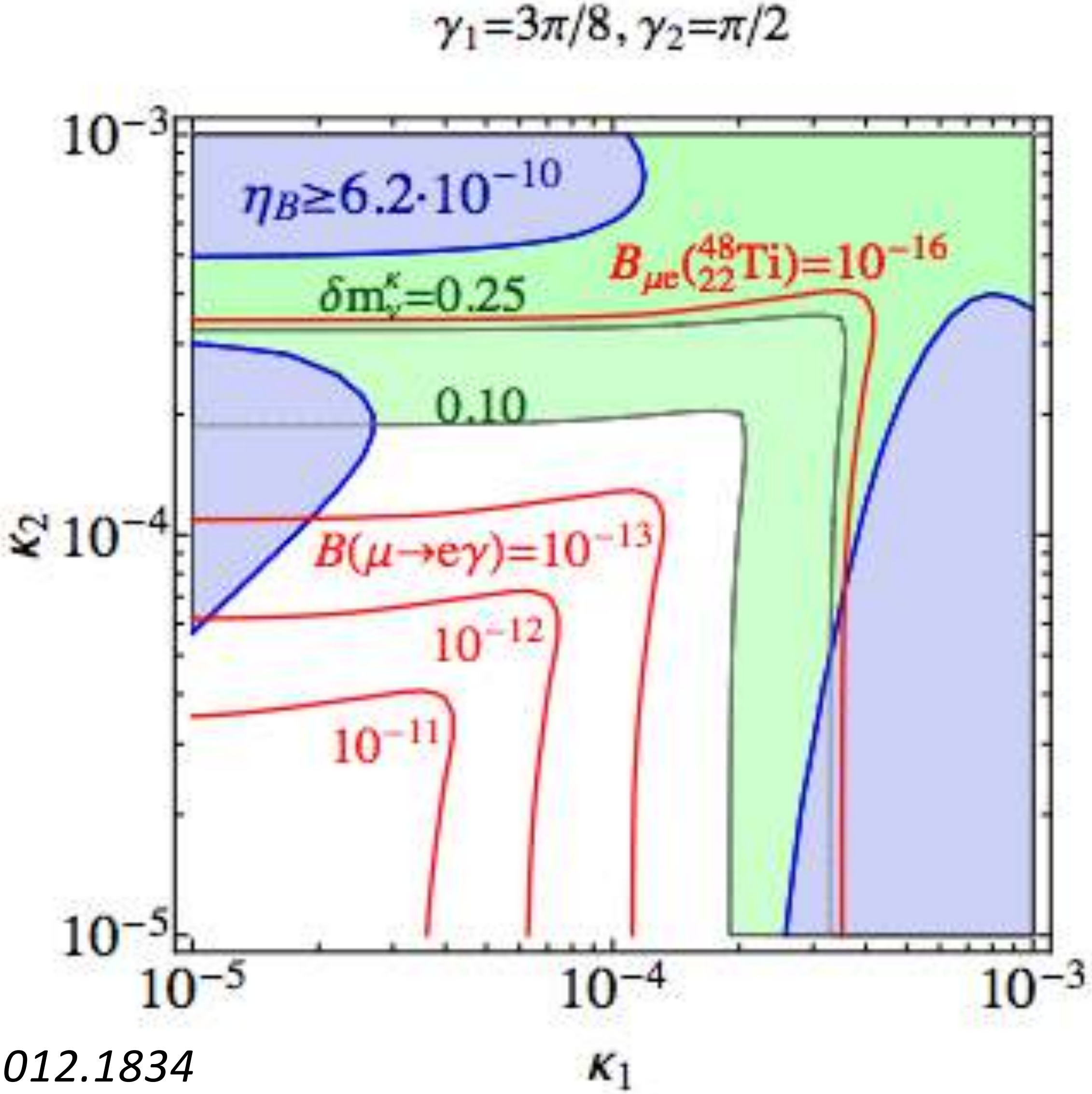
Mark Lancaster
UCL


LHCb
CMS
theorists
ATLAS
Muon Expts

Motivation



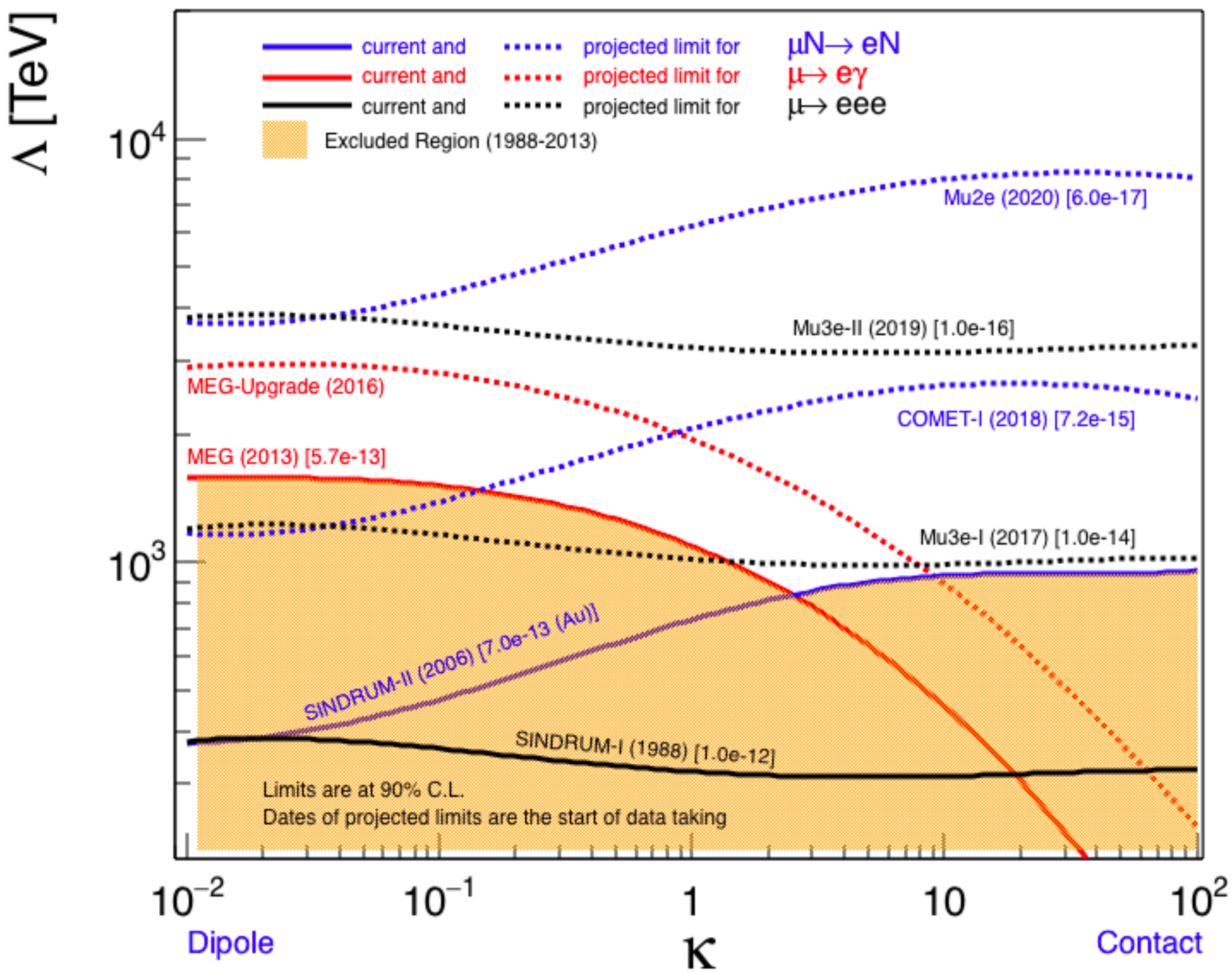
Need all 4 types of experiment



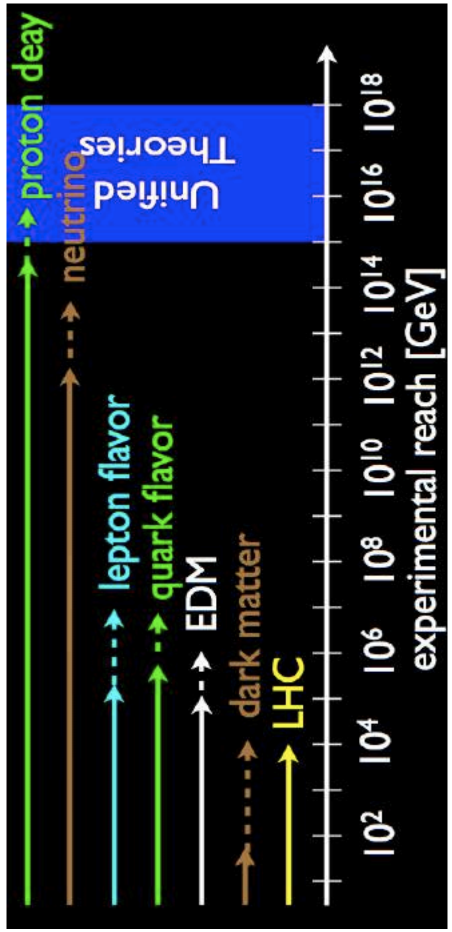
arxiV:1012.1834

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

Motivation



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



Observations

Principal observations being sought are:

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

Muon Expts

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

LHCb/BaBar/Belle

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

Kaon/Pion Expts

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

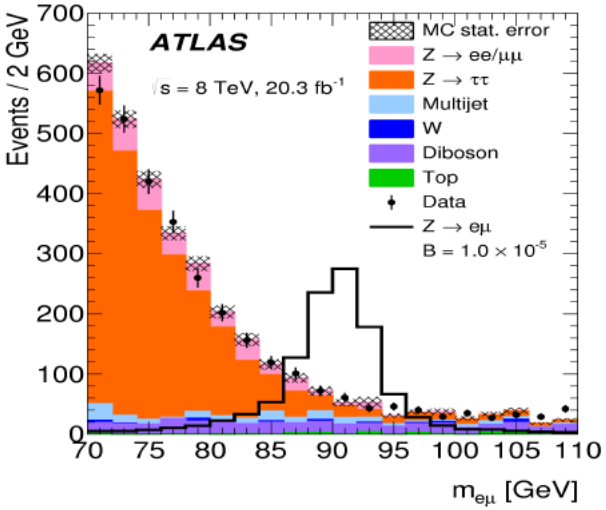
LHC GPD Expts

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

0νββ Expts

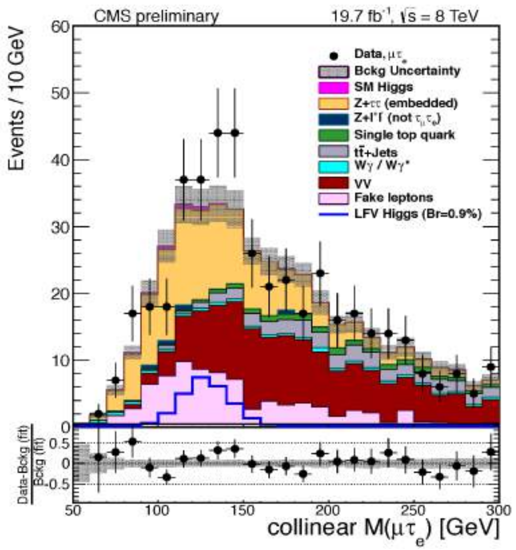
$$N \to ee$$

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



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

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

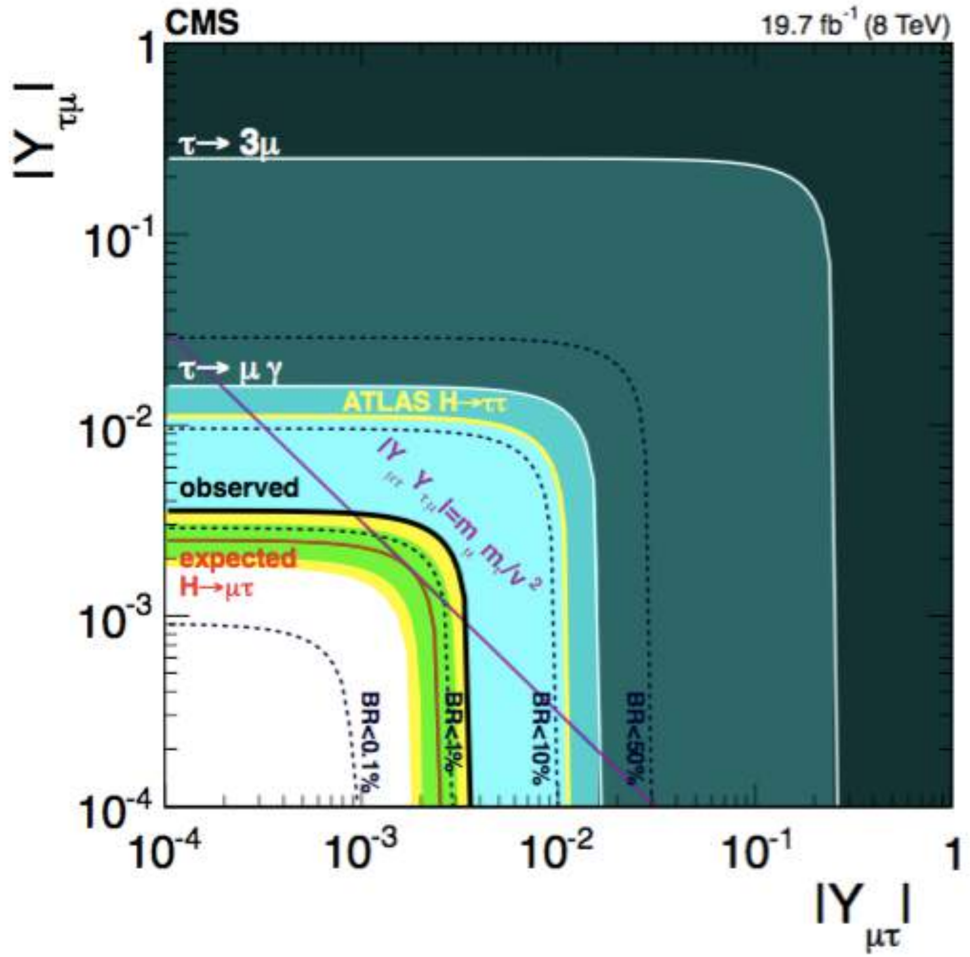


$h \to \mu e$ implied < 1 x 10^{-8} by MEG $\mu \to e\gamma$

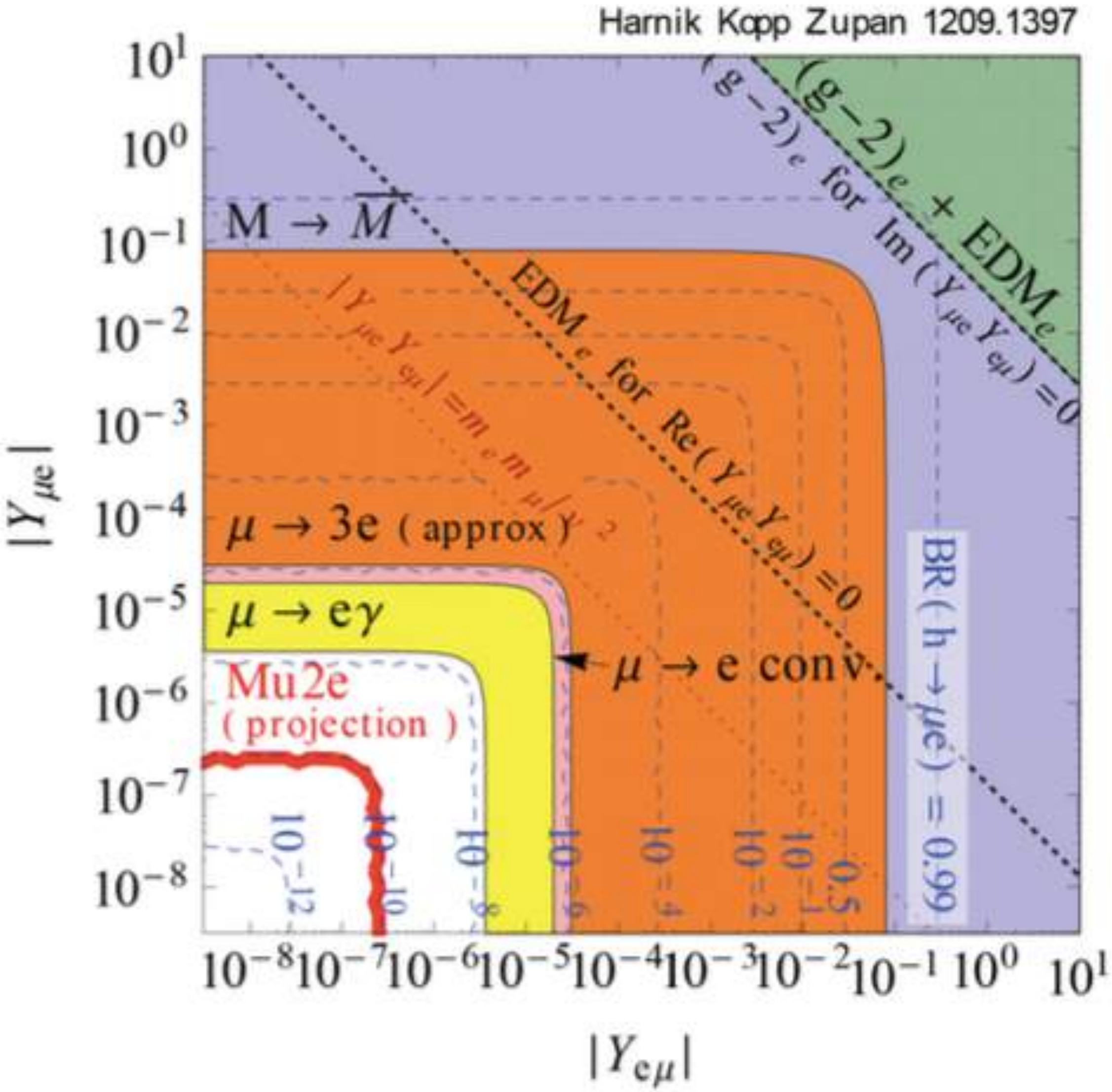
$h \to \mu\tau$ < 1.51 (1.43) x 10^{-2} : CMS (ATLAS)

0.84 +/- 0.4% : CMS

0.53 +/- 0.51% : ATLAS



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



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

e.g. Mu2e will be sensitive to BR ($h \to \mu e$) of 10^{-10} (vs $O(10^{-2})$ at LHC)

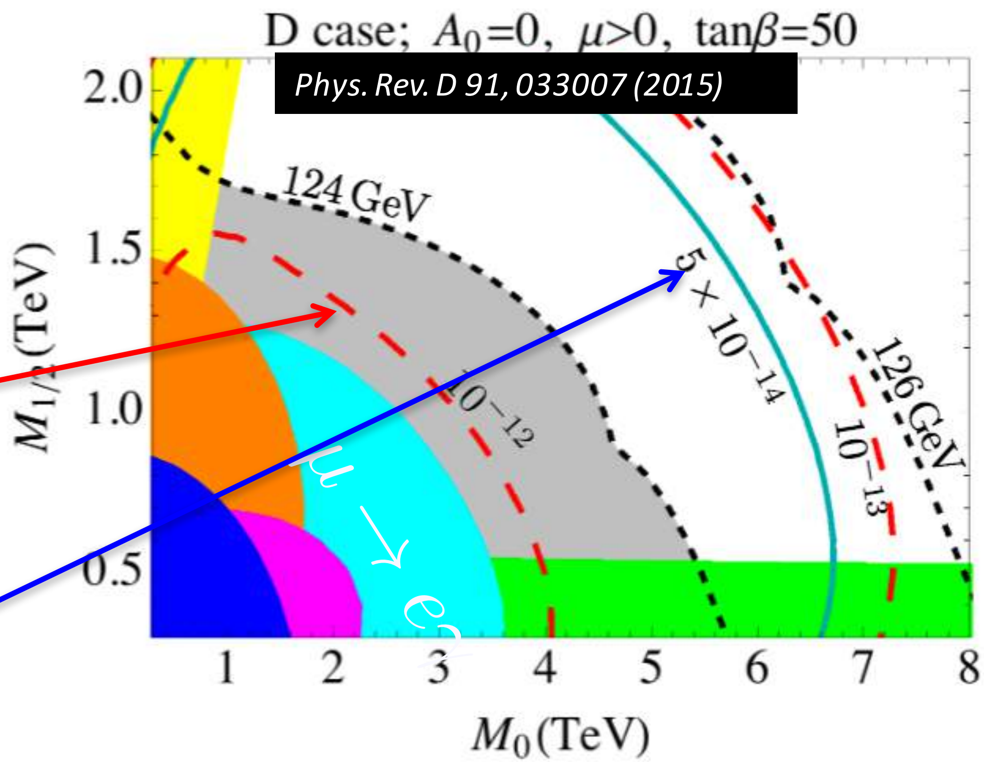
Why Muons ?

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

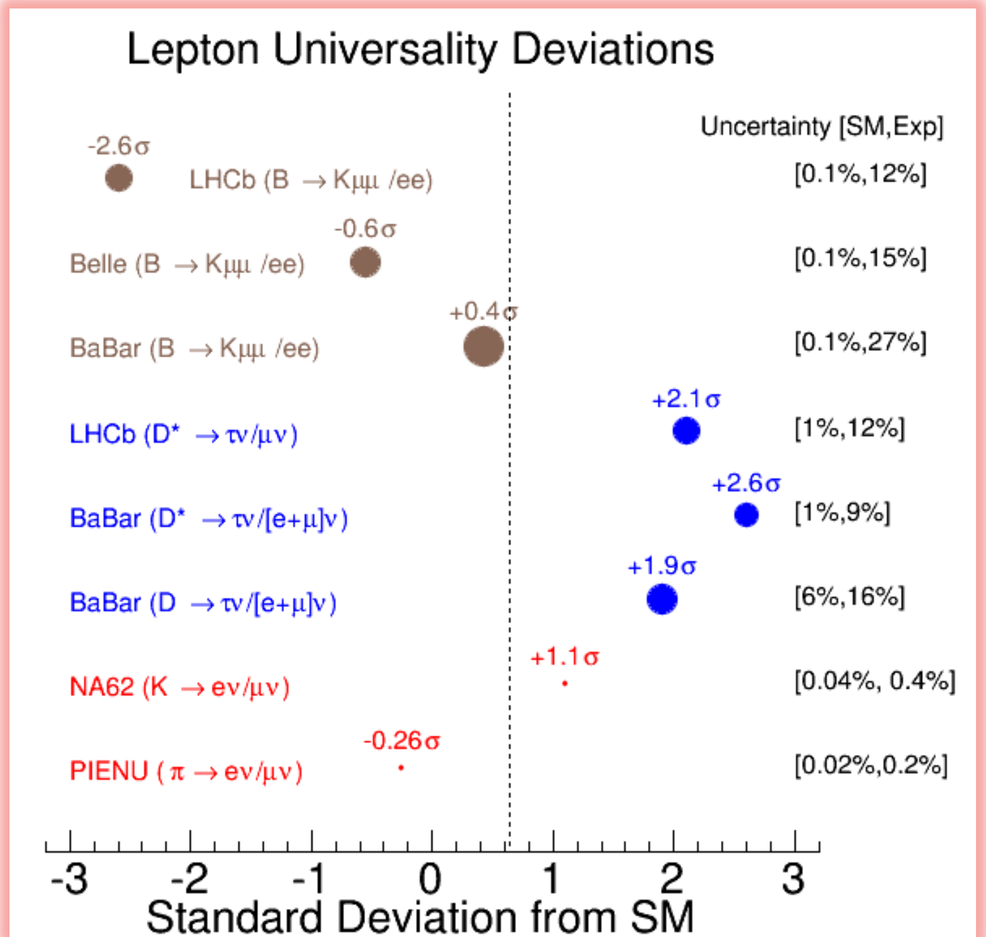
$\tau \to e\gamma$ at 10^{-12}

$\mu \to e\gamma$ reach



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

We need all measurements !!



Combined significance > 3σ for the D/τ measurements

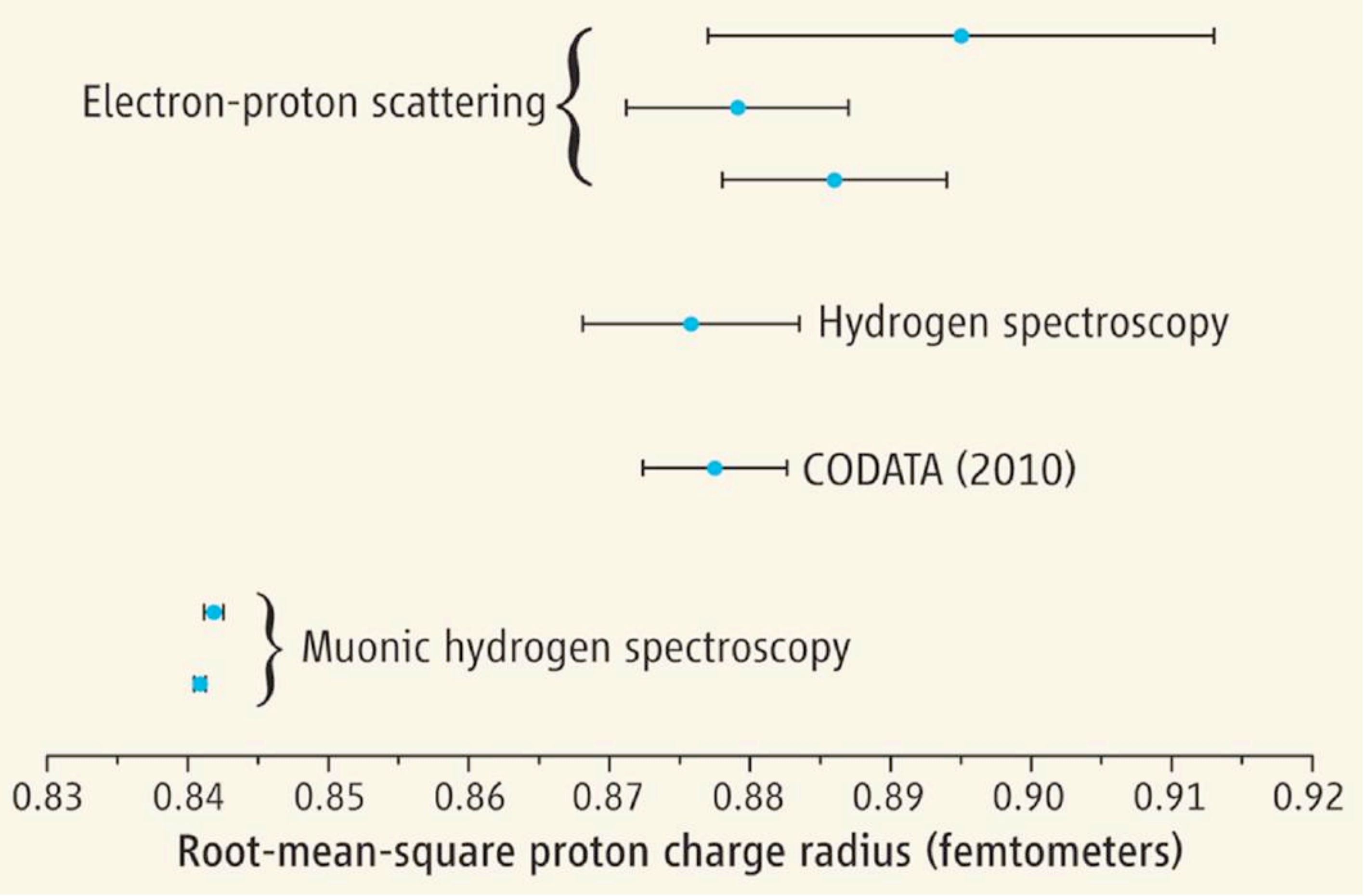
No deviation in e:μ comparison in π/K measurements.


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

The quiet anomaly

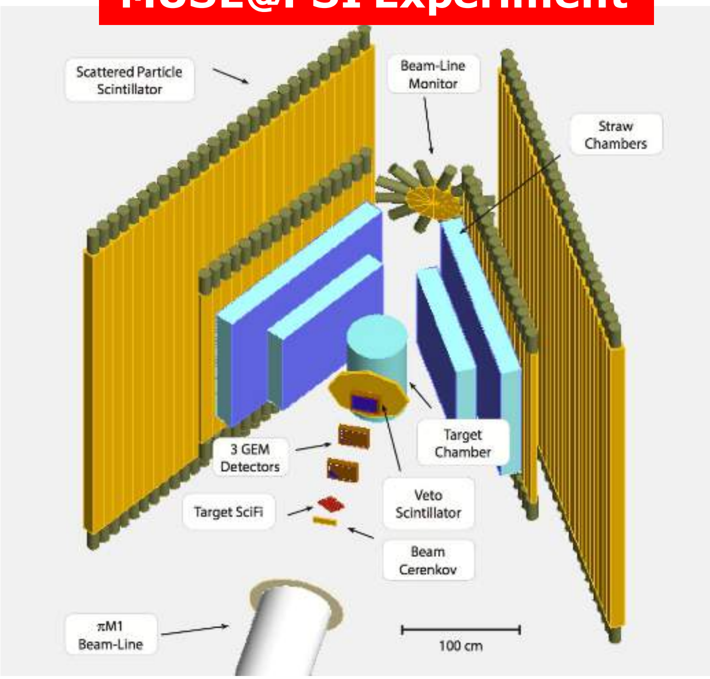


A 7.9σ discrepancy in proton radius measured from "ep" scattering +hydrogen spectroscopy vs muonic hydrogen spectroscopy by CREMA

Possible explanations

- unexpected QCD corrections in muonic-H (2γ, polarisation)
- error in determination of radius from atomic-H (Q^2, model dep.)
- new physics (not changing muon g-2)

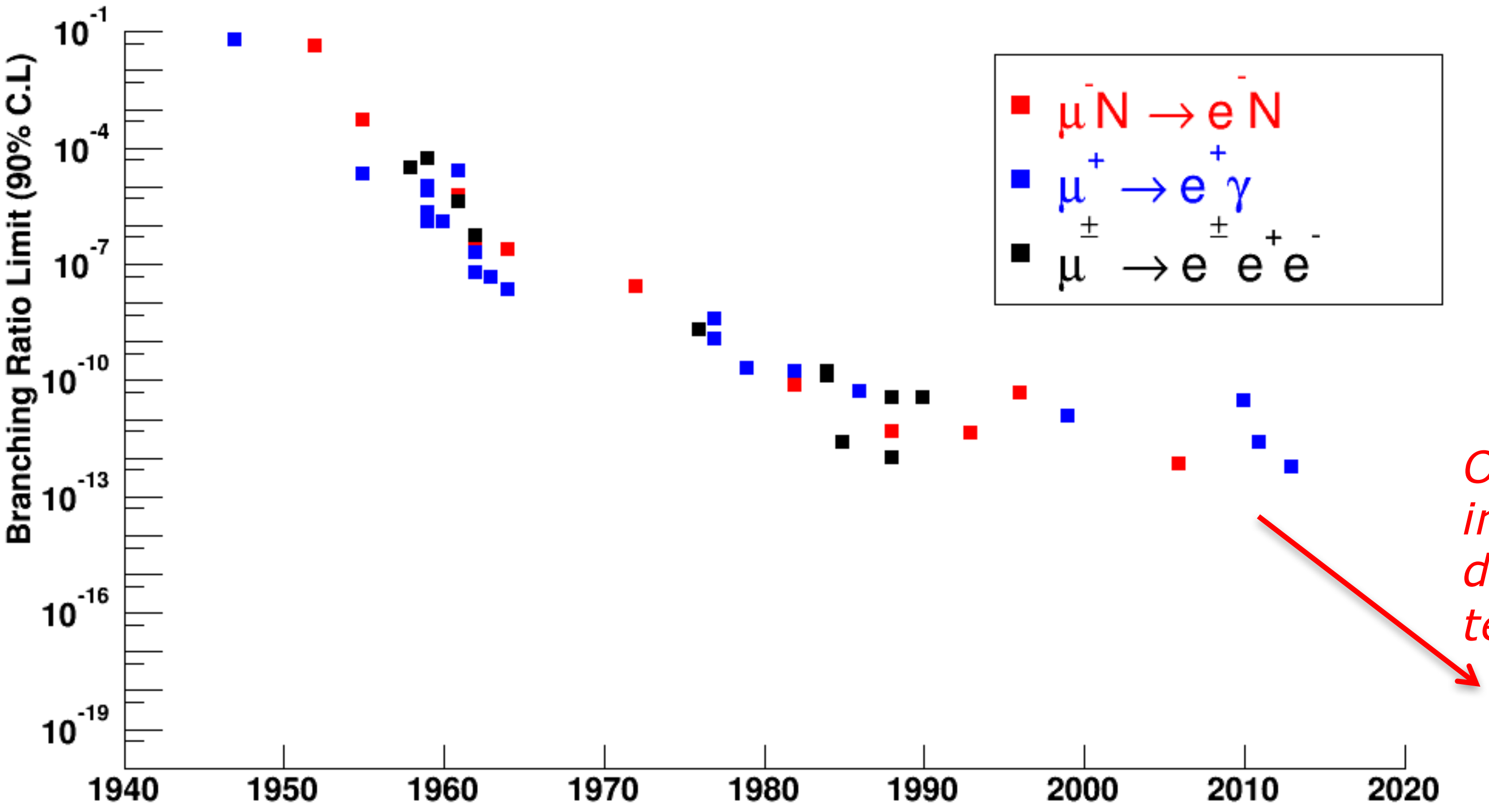
MUSE@PSI Experiment



New data (see arxiv 1509.03235) in next 1-3 years.

- CREMA measurements of muonic-D being analysed now.
- μp vs ep in same experiment (MUSE)
- very low Q^2 ep (PRAD@JLAB)
- new atomic-H spectroscopy from MPI (2s-4p) and LKB (1s-3s)
- low Q^2 form factors from ISR MAMI data

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



O(10^4) improvement driven by new technology

PSI

MEG
Mu3e

J-PARC

COMET
(g-2)
DeeMe

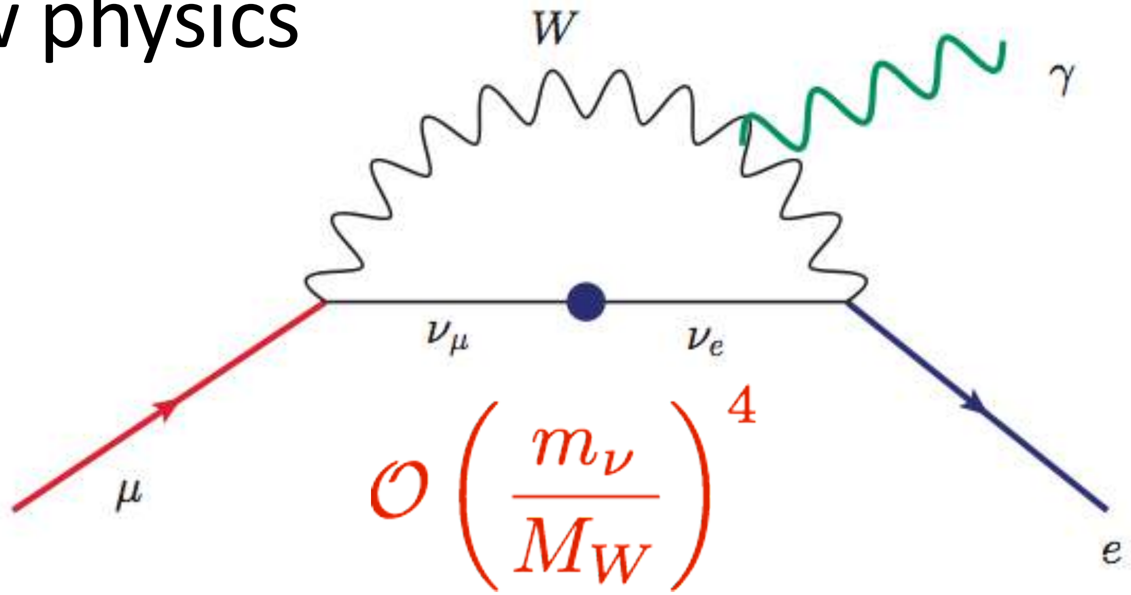
FNAL

(g-2)
Mu2e

Why CLFV ?

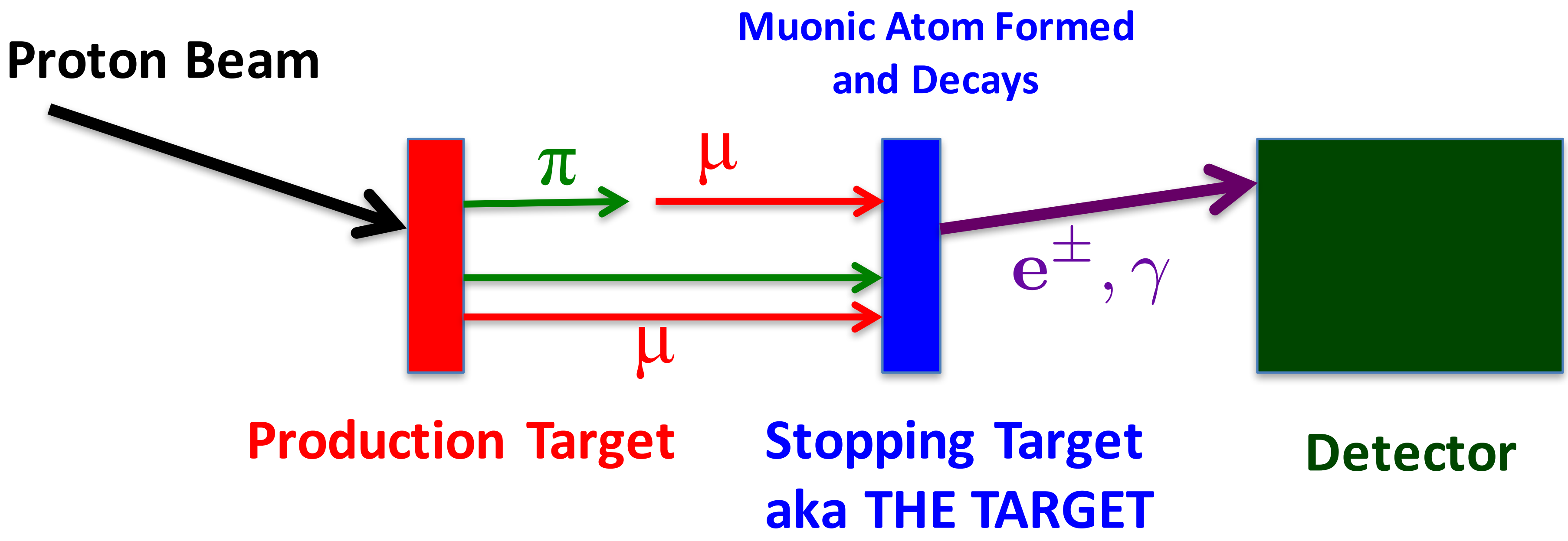
SM is O(10^{-50})

Observation **IS** new physics



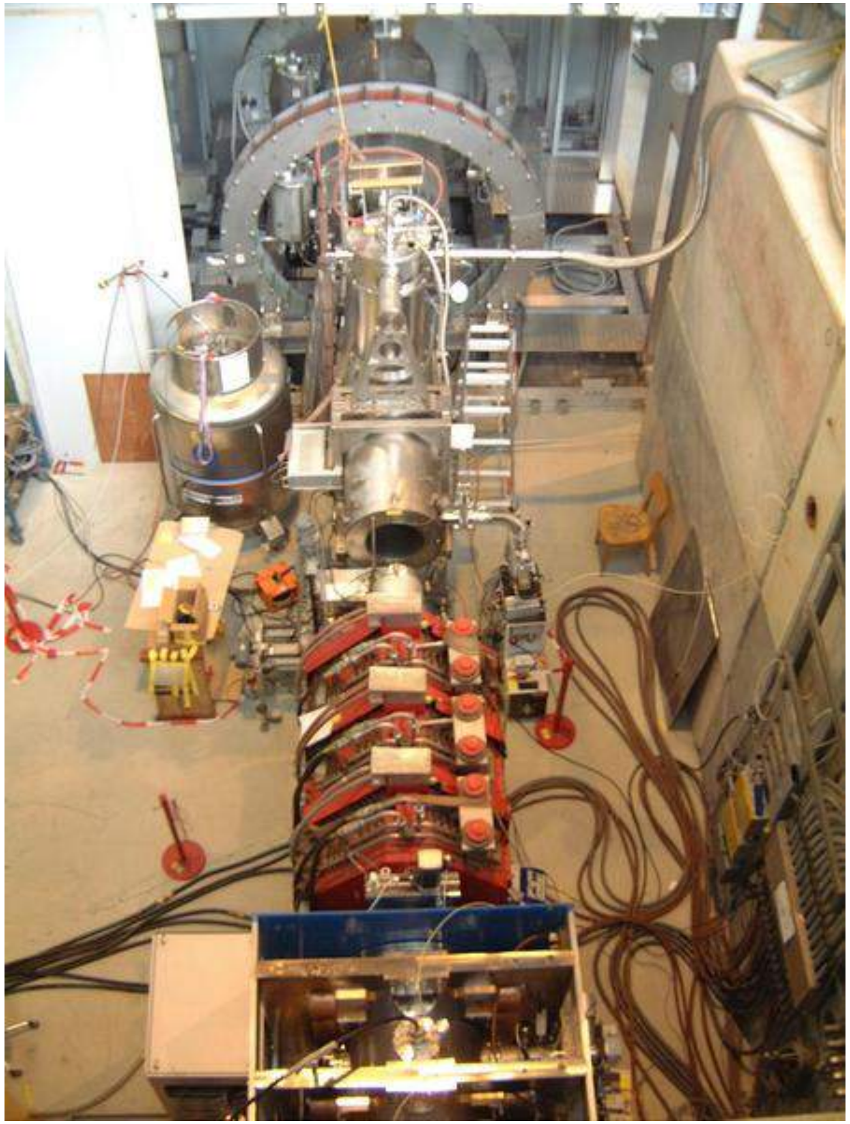
No SM theory systematic

How far we can probe is limited by experiment



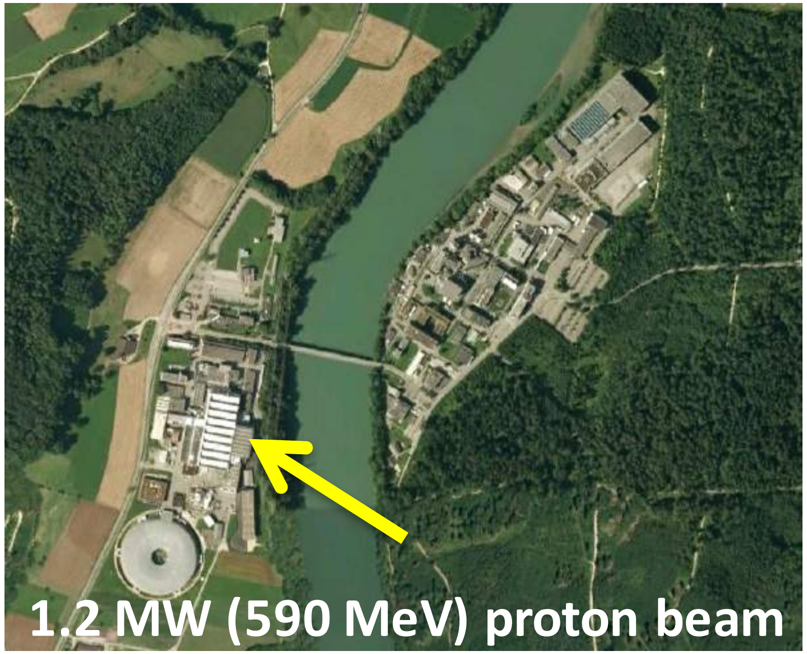
Apply symmetries, translations, rotations, ...

Current State Of The Art



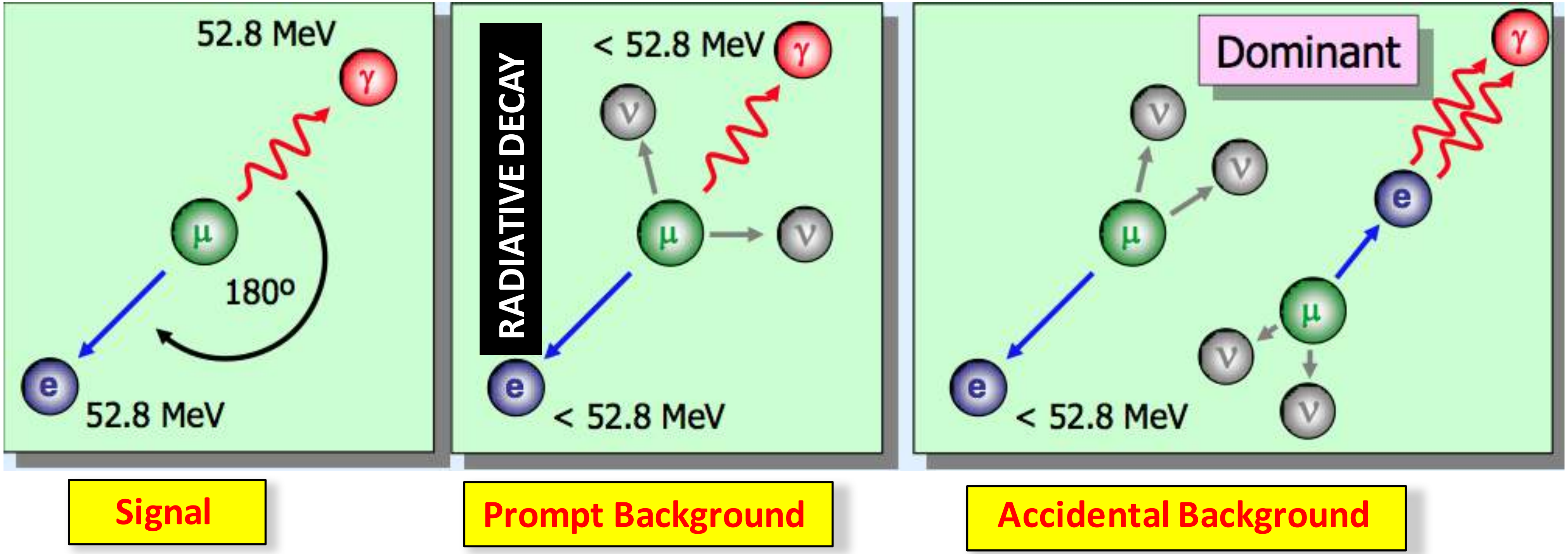
PSI (Zurich/Switzerland) Facility

3x10^{7} "stopped" $\mu+$/sec



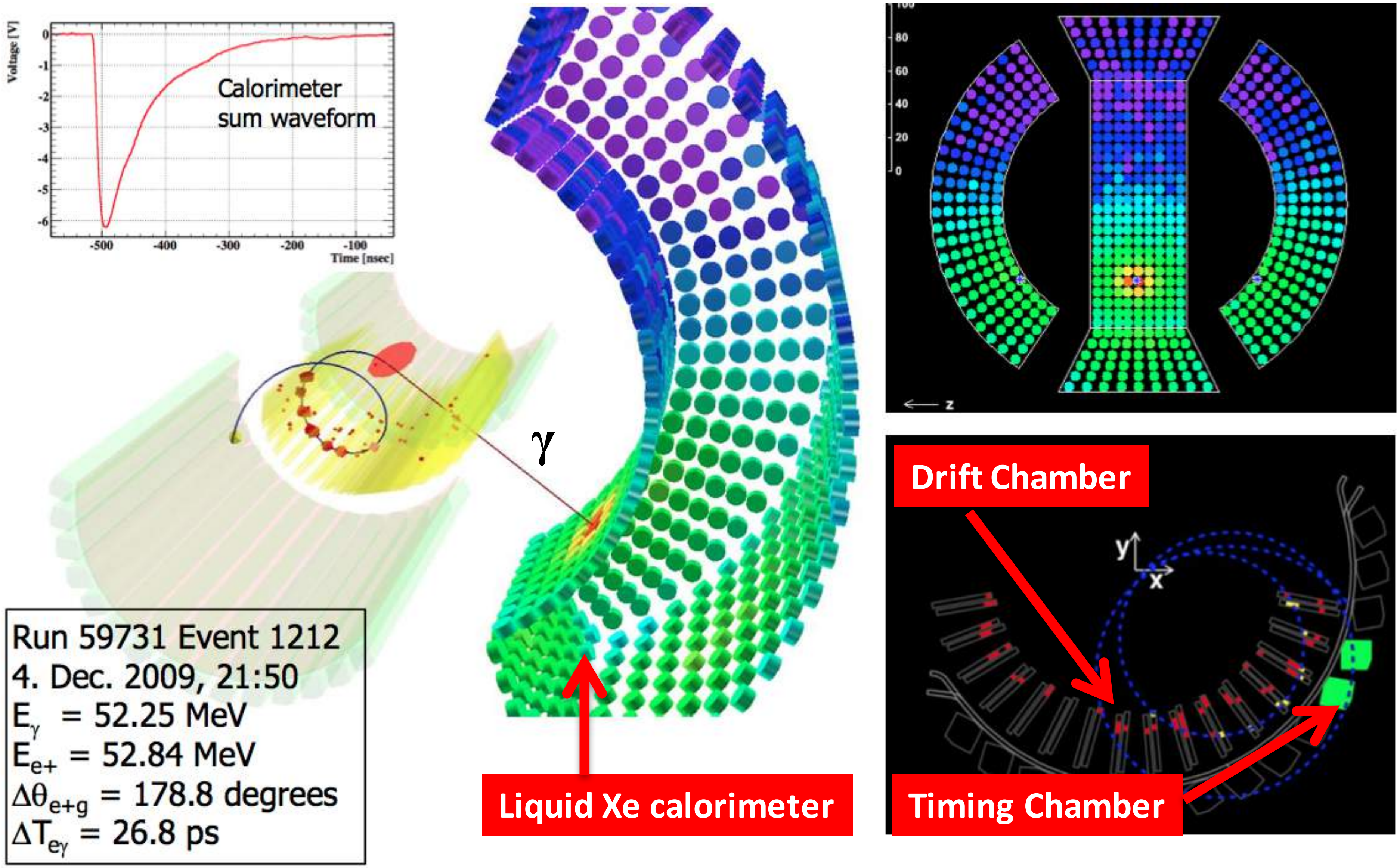
MEG Experiment

MEG present limit on $\mu \to e\gamma$ is 4×10^{-13}. It is aiming to get to 5×10^{-14}



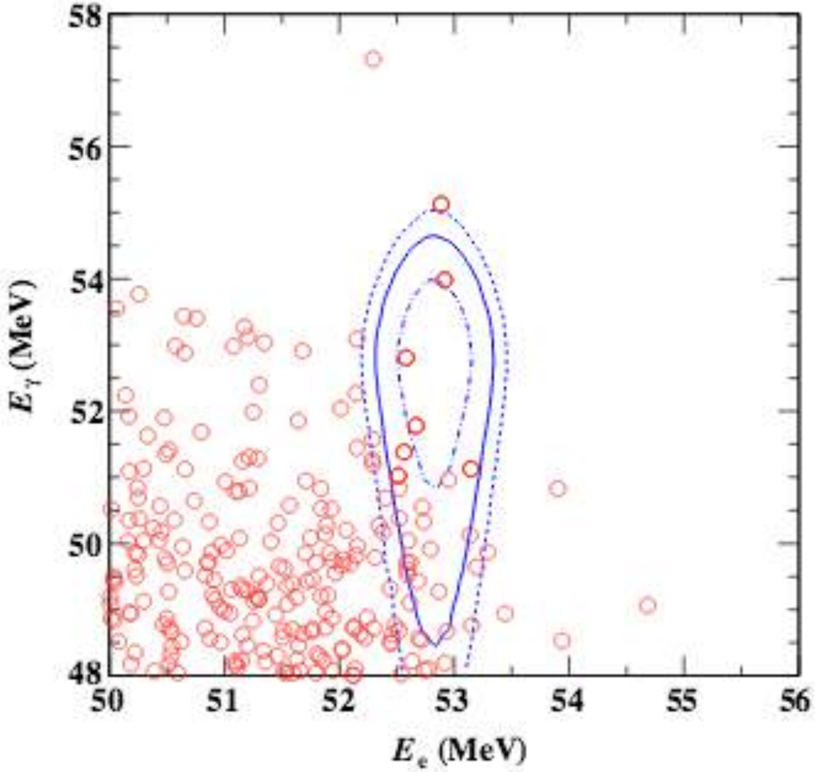
$E_\gamma = E_{e+} = 52.8$ MeV
$\theta_{\gamma e} = 180^0$
γ and e^+ in time

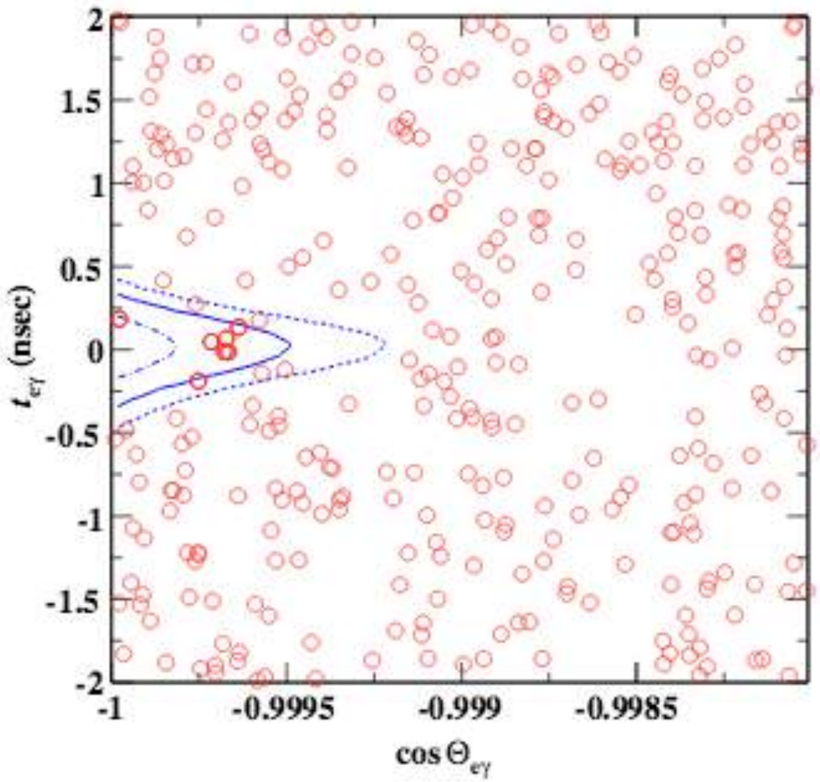
MEG Experiment



MEG Sensitivity determined by

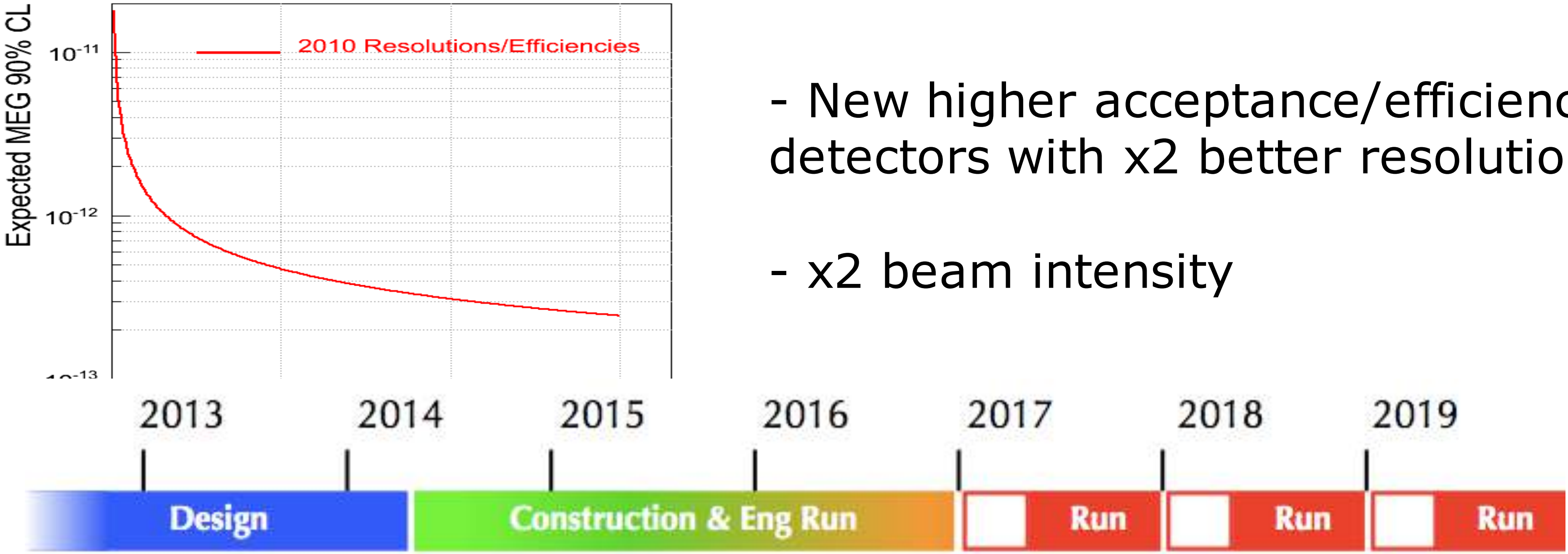
- # of stopped muons : accelerator driven
- Resolution in e^+ and photon energy and angle, time between them





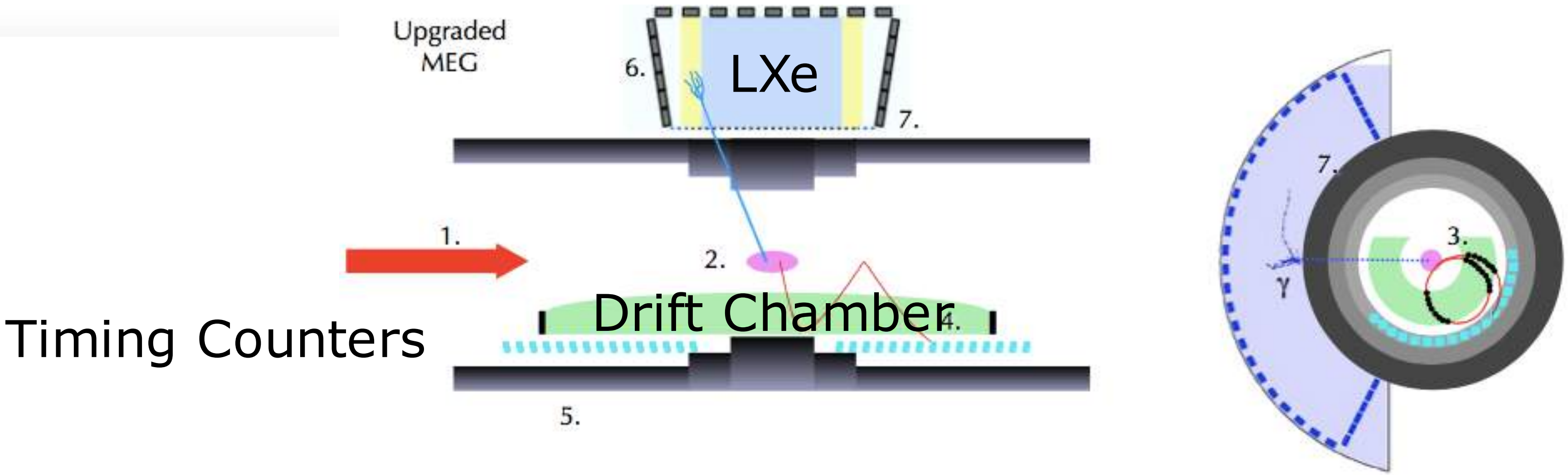
R_μ : Muon stop rate
D : Duty Cycle

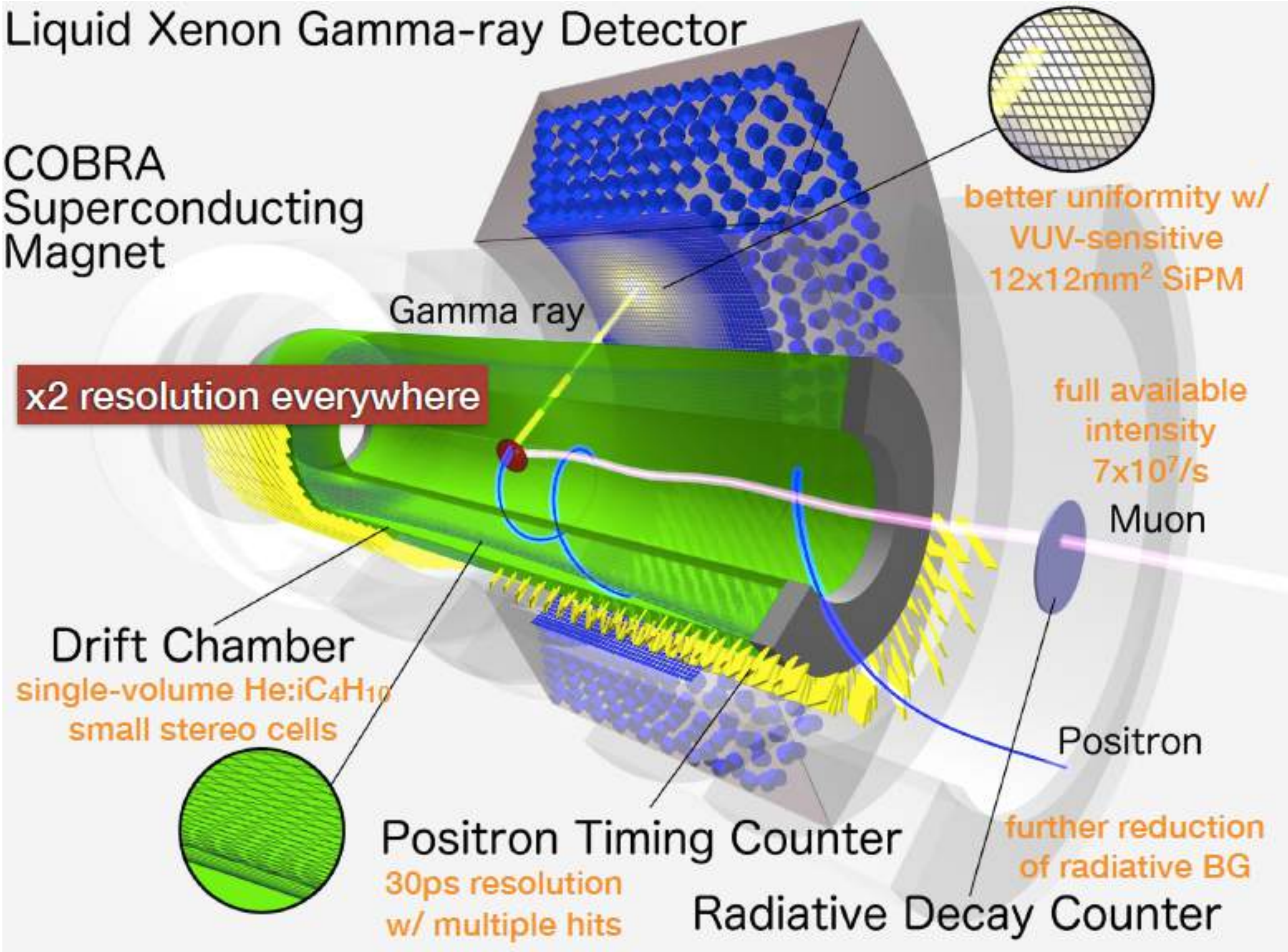
$$N_{\mathrm{BG}} = \left(\frac{R_\mu}{D}\right)^2 \Delta t_{e\gamma} \Delta E_e \left(\Delta E_\gamma\right)^2 \left(\Delta\Theta_{e\gamma}\right)^2$$

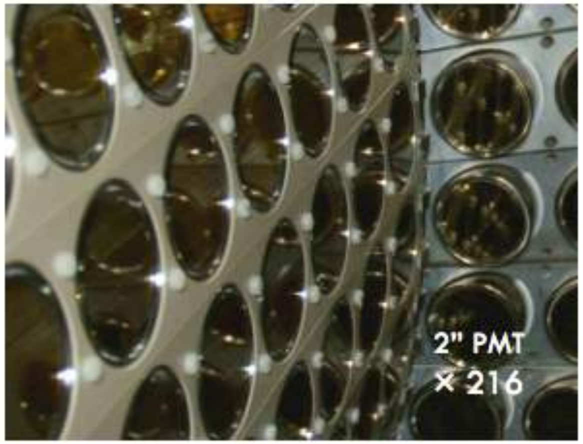


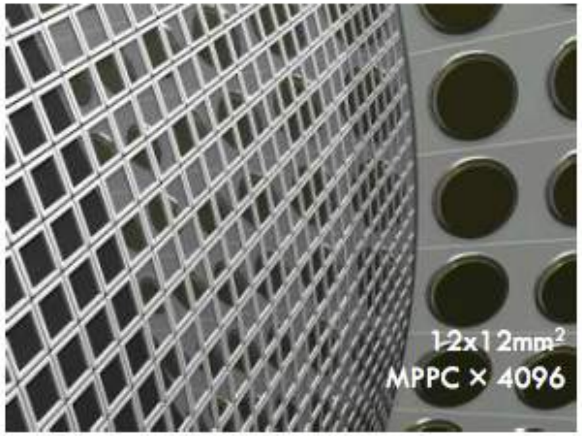
- New higher acceptance/efficiency detectors with x2 better resolution

- x2 beam intensity

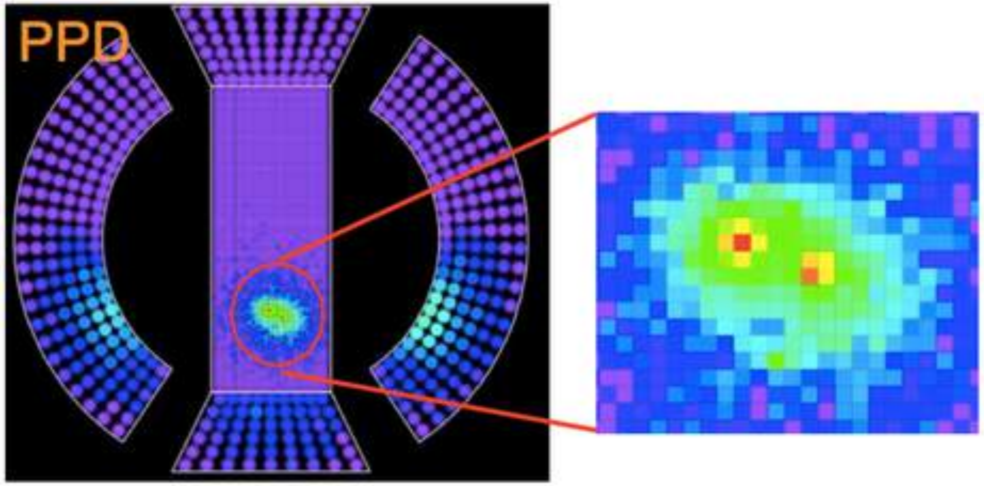



Liquid Xenon Gamma-ray Detector
COBRA Superconducting Magnet
Gamma ray
x2 resolution everywhere
better uniformity w/ VUV-sensitive 12x12mm² SiPM
full available intensity 7x10⁷/s
Muon
Drift Chamber
single-volume He:iC4H10 small stereo cells
Positron
Positron Timing Counter
30ps resolution w/ multiple hits
further reduction of radiative BG
Radiative Decay Counter

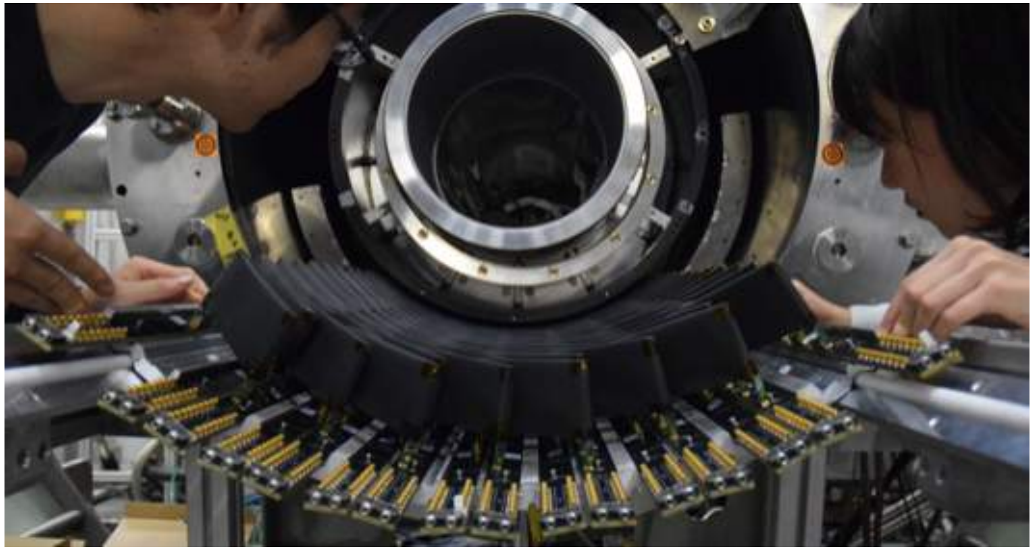




Improved efficiency, acceptance, resolution, uniformity

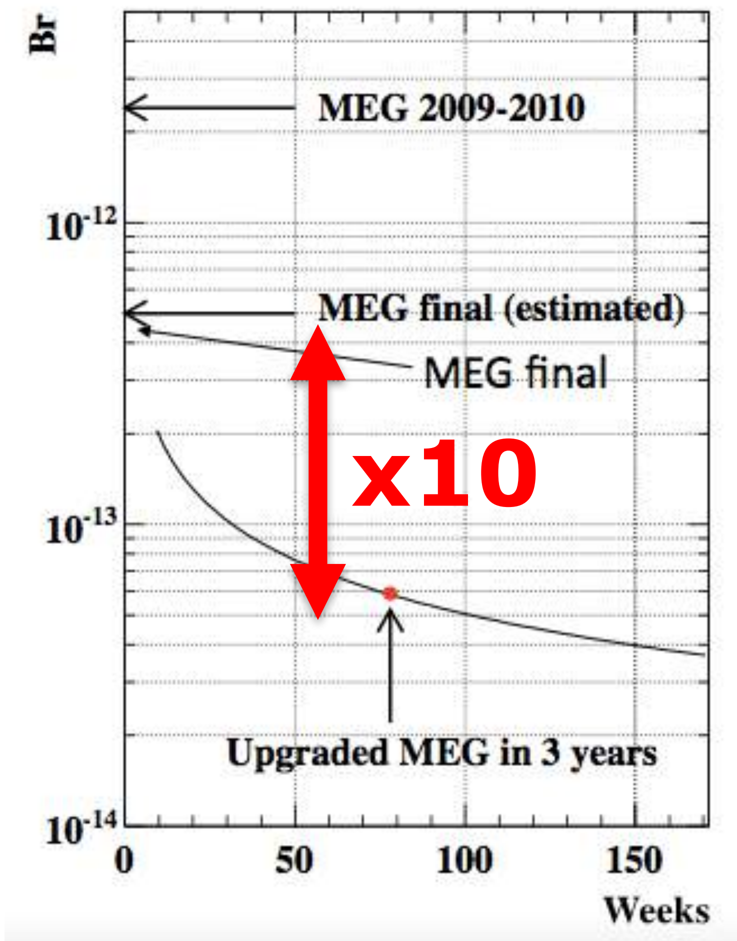


2mm resolution in calorimeter



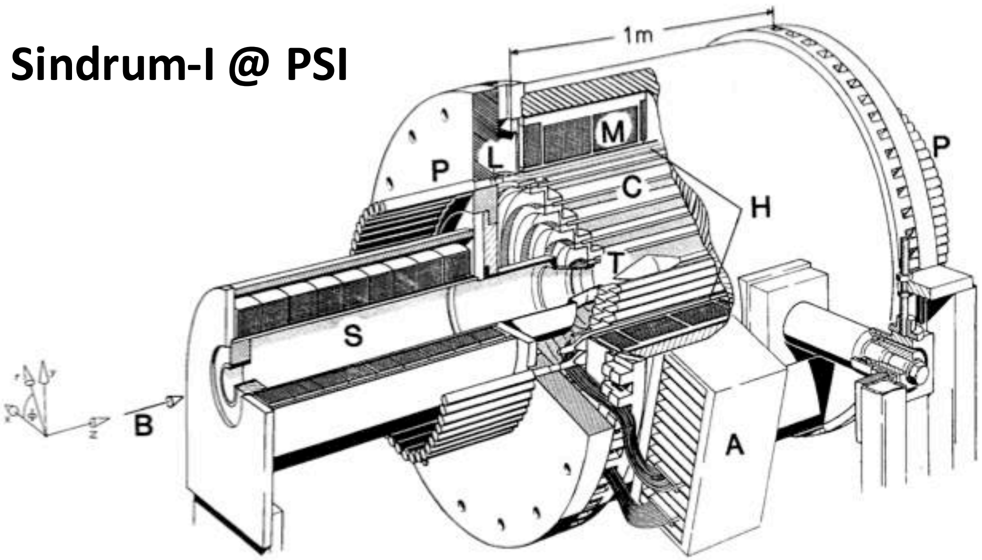
Timing counters : tested already in beam.

PDF parameters	Present MEG	Upgrade scenario
$\sigma_{E_{e^+}}$ (keV)	380	110
e^+ σ_θ (mrad)	9	5
e^+ σ_ϕ (mrad)	11	5
e^+ σ_Z / σ_Y(core) (mm)	2.0/1.0	1.2/0.7
$\frac{\sigma_{E_\gamma}}{E_\gamma}$ (%) w>2 cm	1.6	1.0
γ position at LXe $\sigma_{(u,v)}$-σ_w (mm)	4	2
γ-e^+ timing (ps)	120	80
Efficiency (%)		
trigger	≈ 99	≈ 99
γ reconstruction	60	60
e^+ reconstruction	40	95
event selection	80	85



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) and the aim is to get to 10^{-16} with **Mu3e @ PSI**

Same issues as μ→eγ

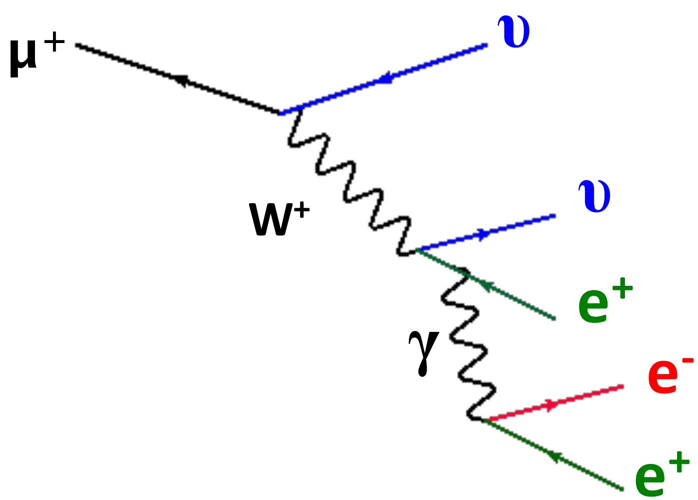
- accidental/pile-up backgrounds : $(R\mu/D)^2$ – so DC beam required.

Issue as go to v. high rates

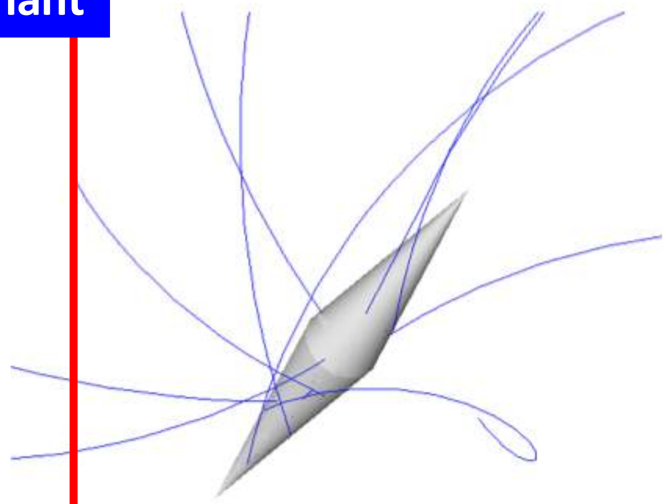
Two μ+ decays and fake e- (Bhaba scattering, γ conversion)

- irreducible background : Rμ

Dominant



BR = 3×10^{-5}



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

Mu3e @ PSI

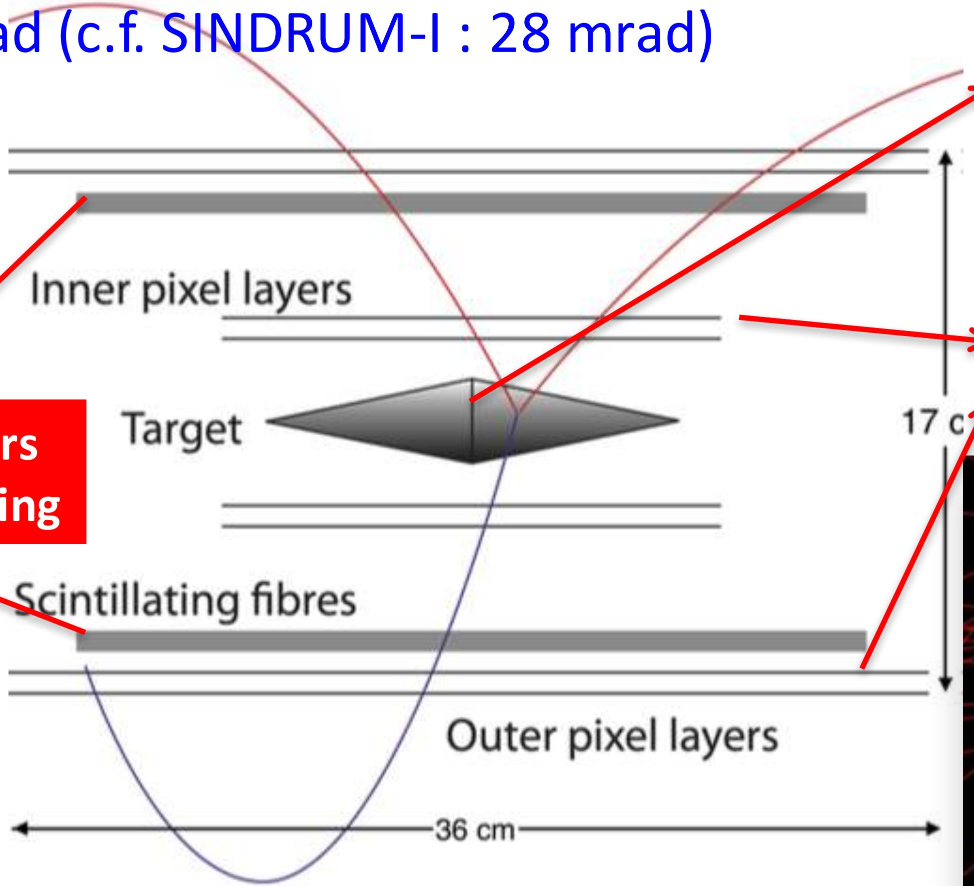
Improve MS-resolution by using v. thin (~ 50µm) HV-MAPS pixel silicon layers

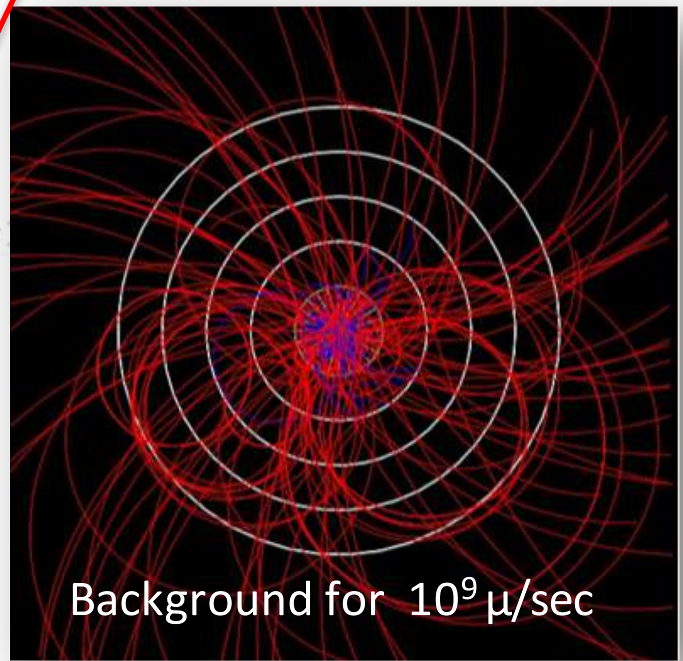
$\sigma(\theta)_{MS}$ = 5 mrad (c.f. SINDRUM-I : 28 mrad)

Hollow double cone target

Very thin silicon sensors for precision momentum and vertexing

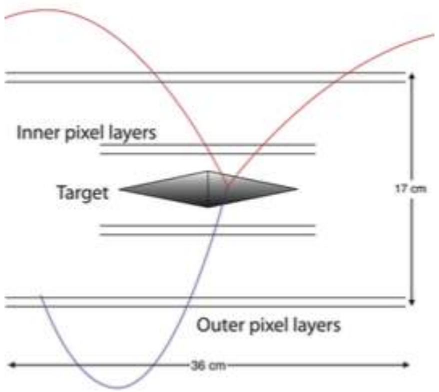
Scintillating Fibers for precision timing



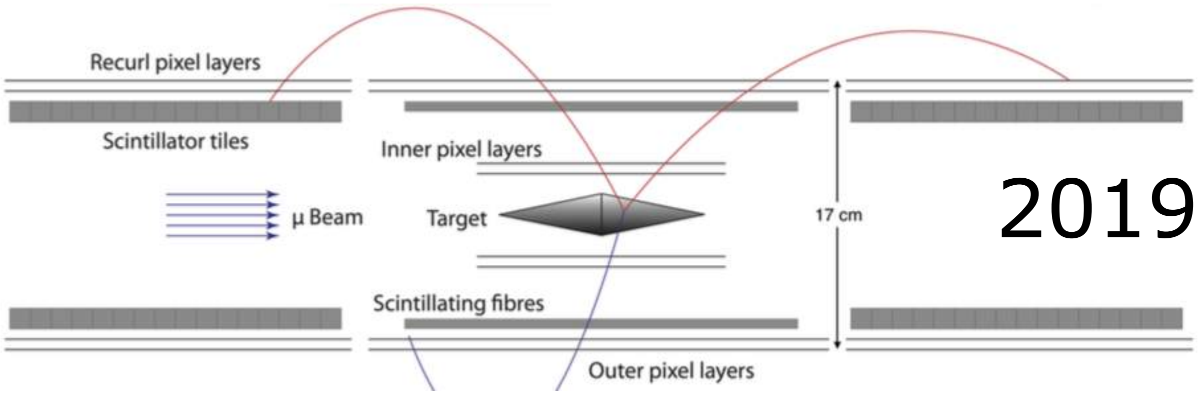


Staged detector : 10^{-14} to 10^{-16} sensitivity

Staged Detector 2017-2023

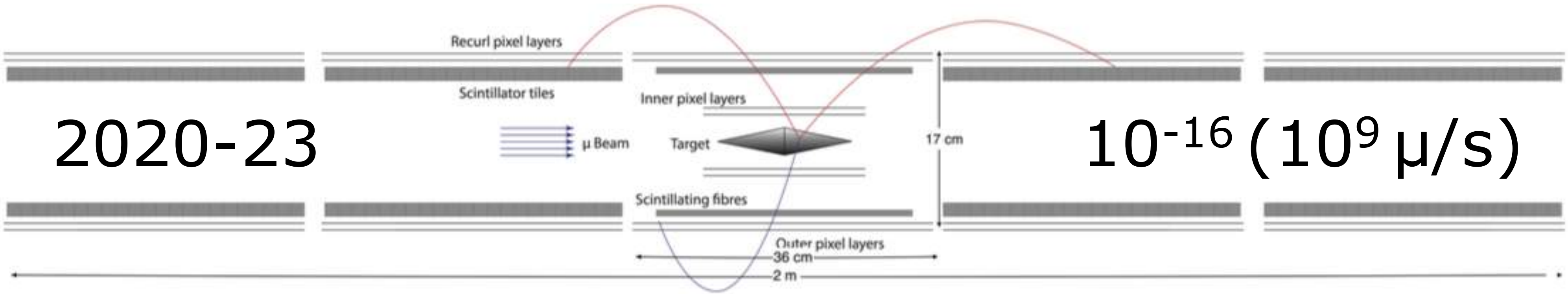


2017-18 : 10^{-14} sensitivity (10^{7} μ/s)



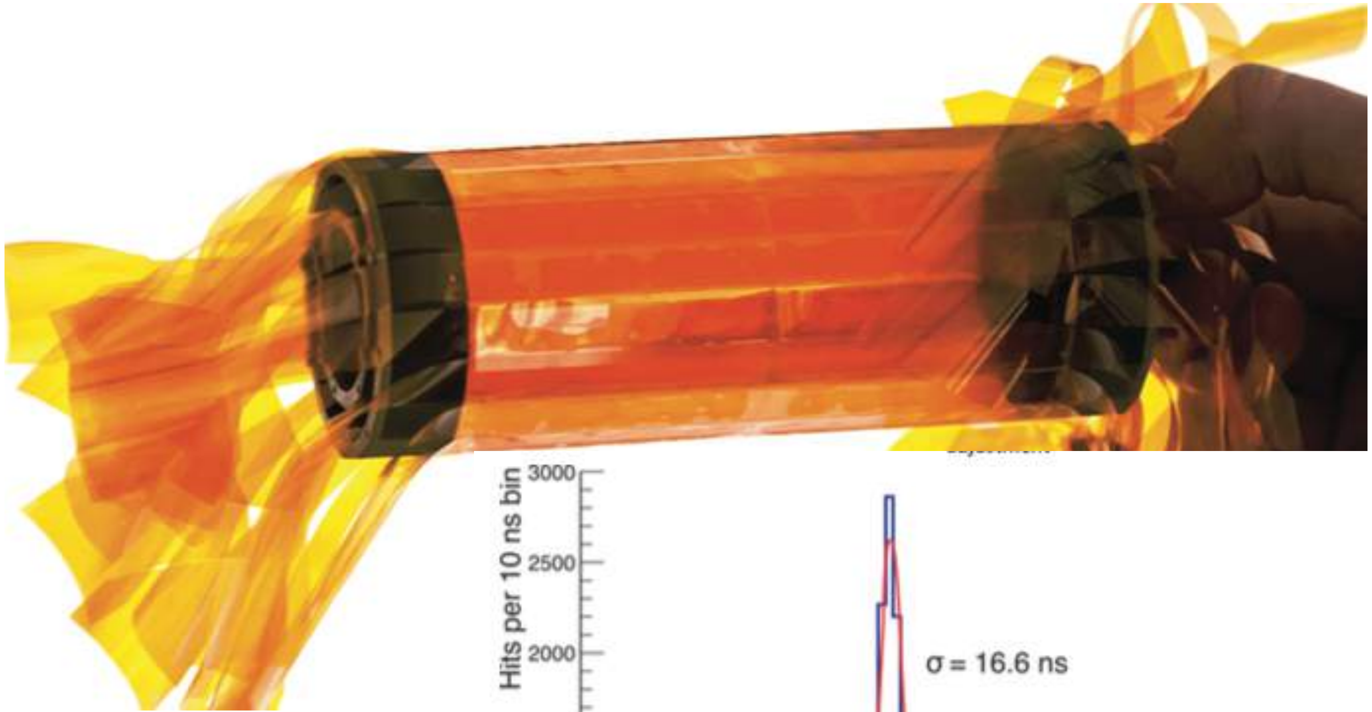
2019-20 : 10^{-15} (10^{8} μ/s)

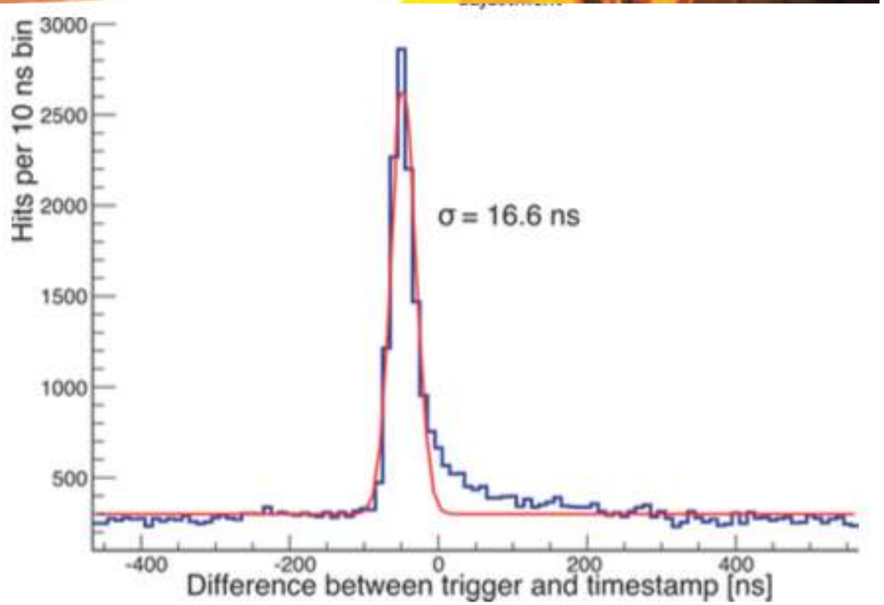
2020-23

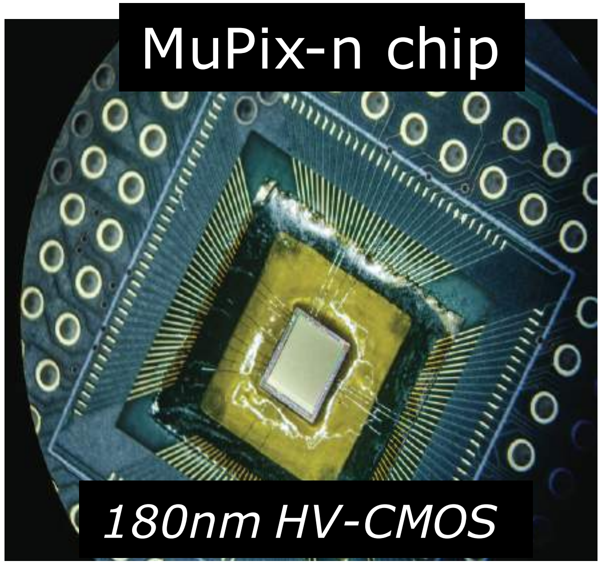


10^{-16} (10^{9} μ/s)

25μm kapton, 50μm silicon : 0.5 MeV, 100μm resolution

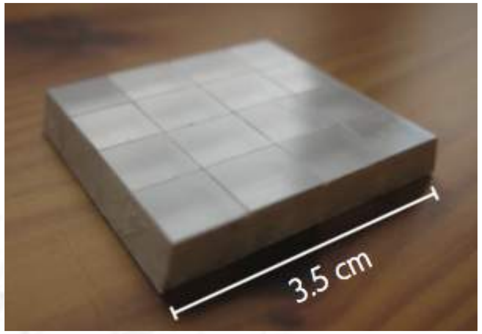


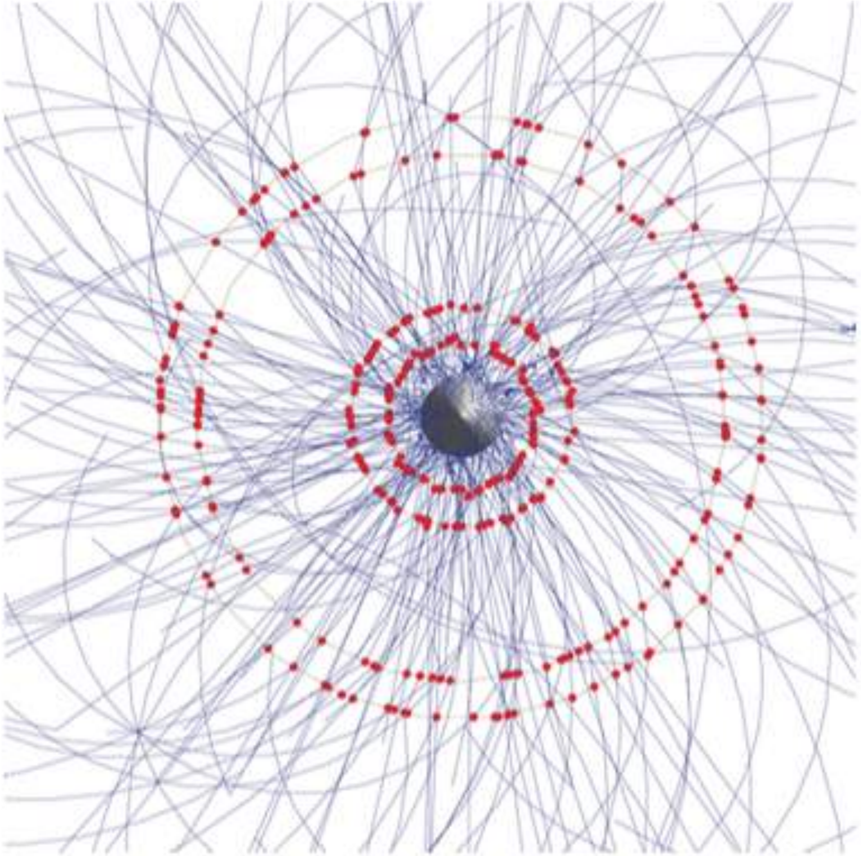




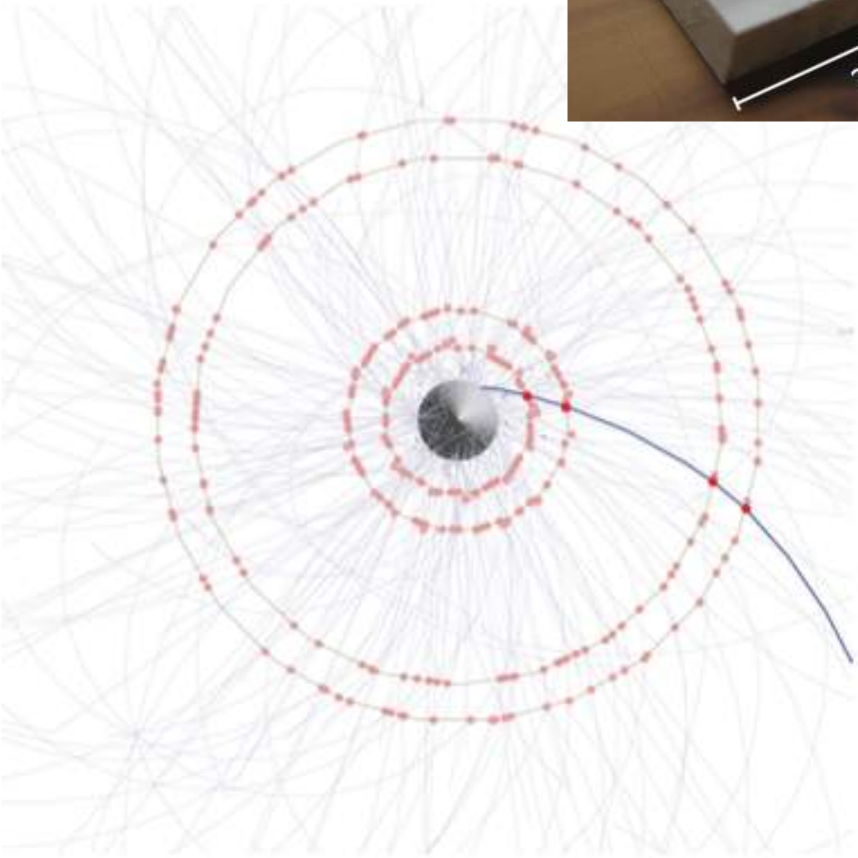
Timing

Scintillating tiles (SiPM) get to 100ps vs 1ns for fibers

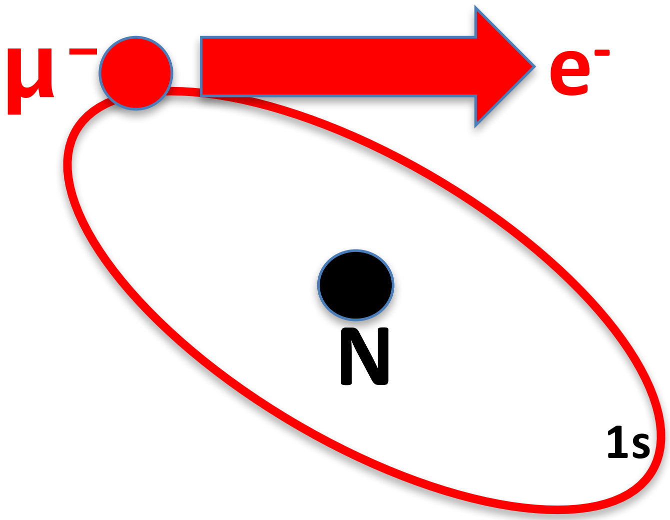




Pixels: O(50 ns)

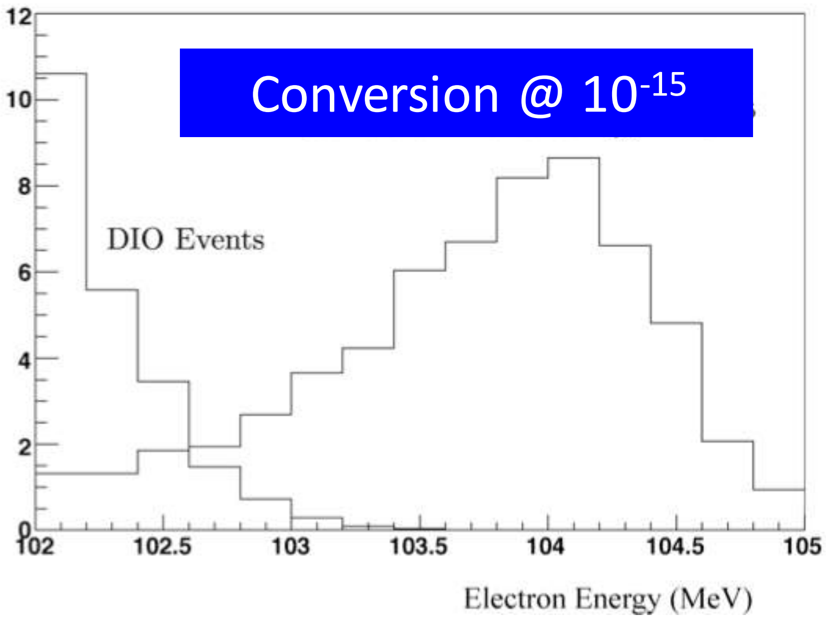


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)



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

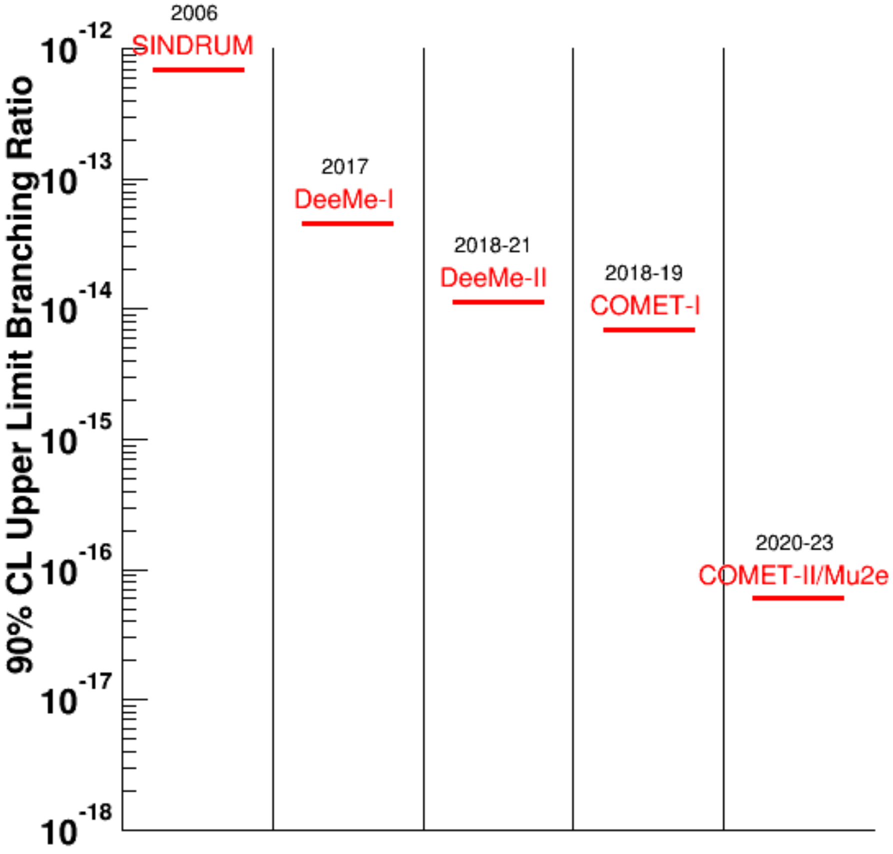
$$\mu^+ \to e^+\gamma$$
$$\mu^+ \to e^+e^-e^+$$



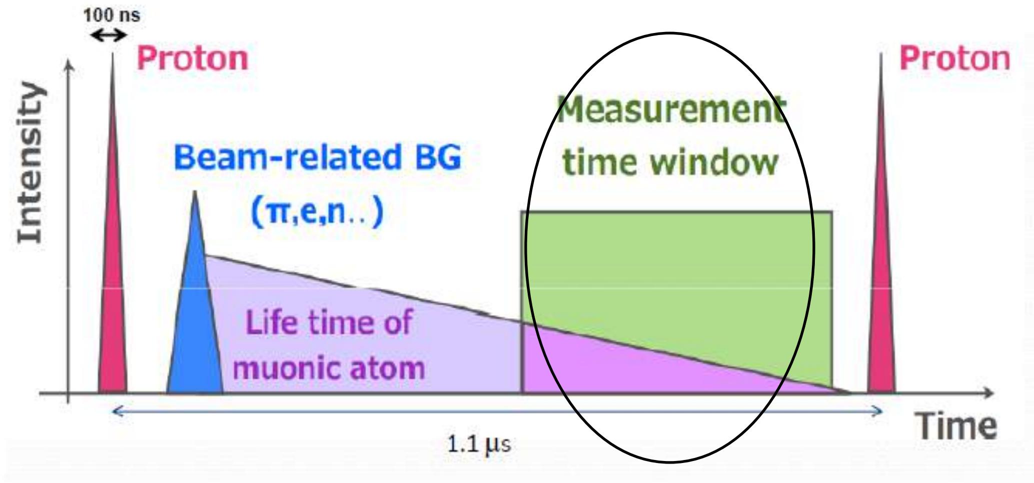
The "conversion process" has a simple one particle signature. $E_e \sim m_\mu$ (>> Ee from free muon decay).

Arguably best route to highest sensitivity at high muon rates.

DeeMe, COMET & Mu2e



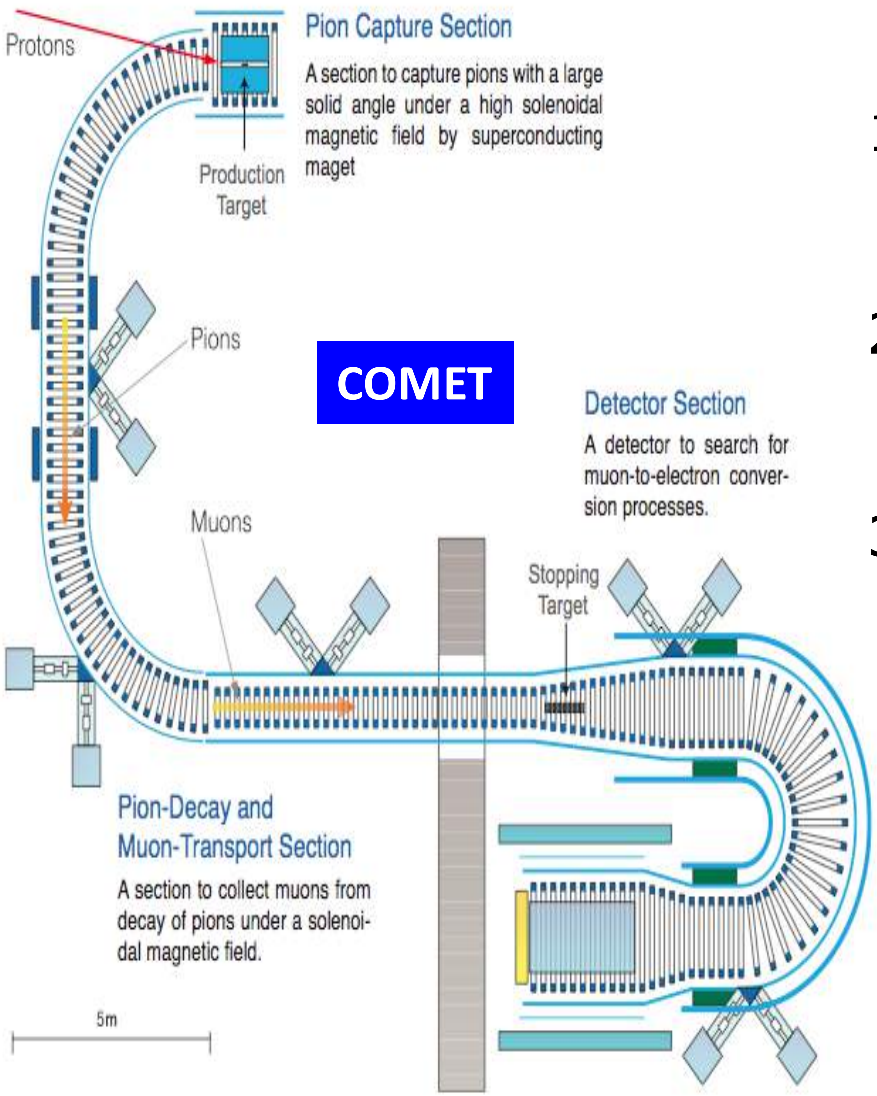
“extinction”



Significant improvements made possible by:

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

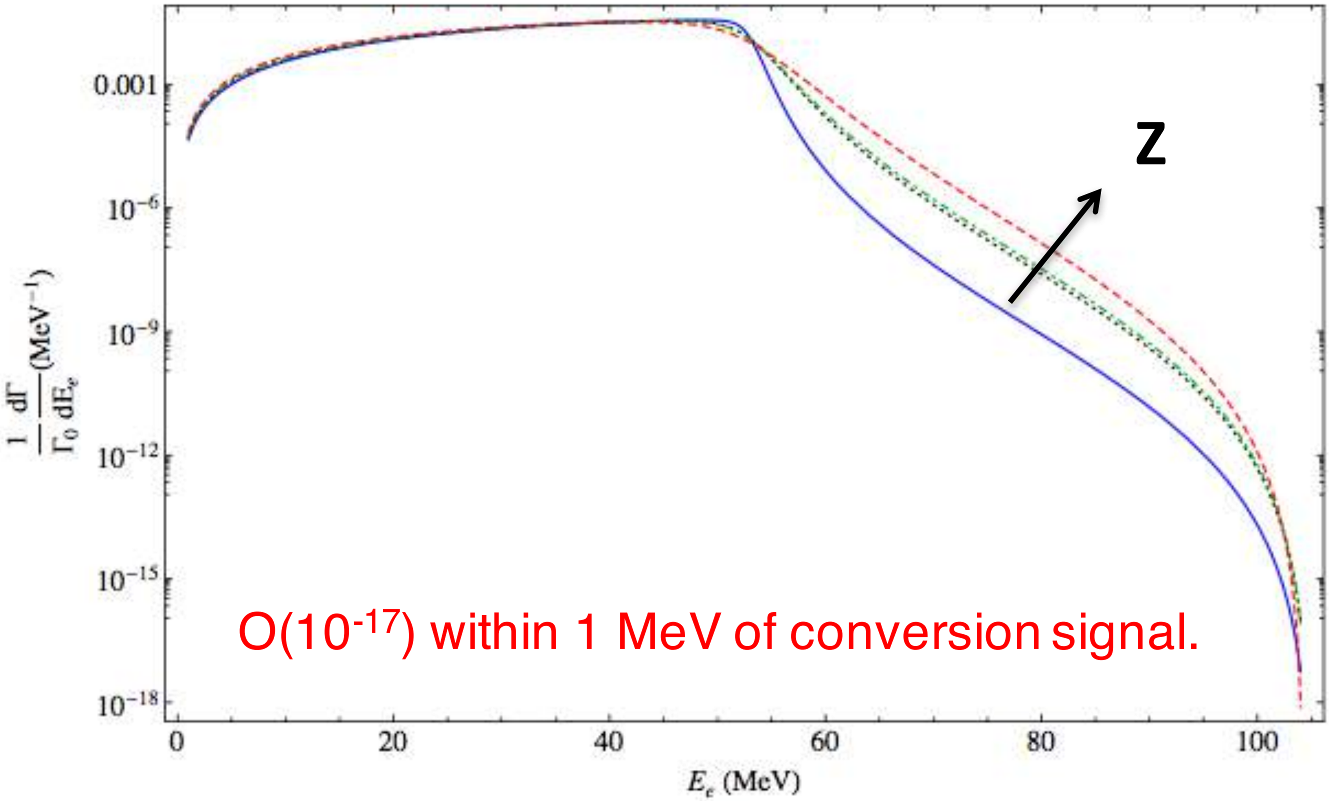
3 components



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

Backgrounds

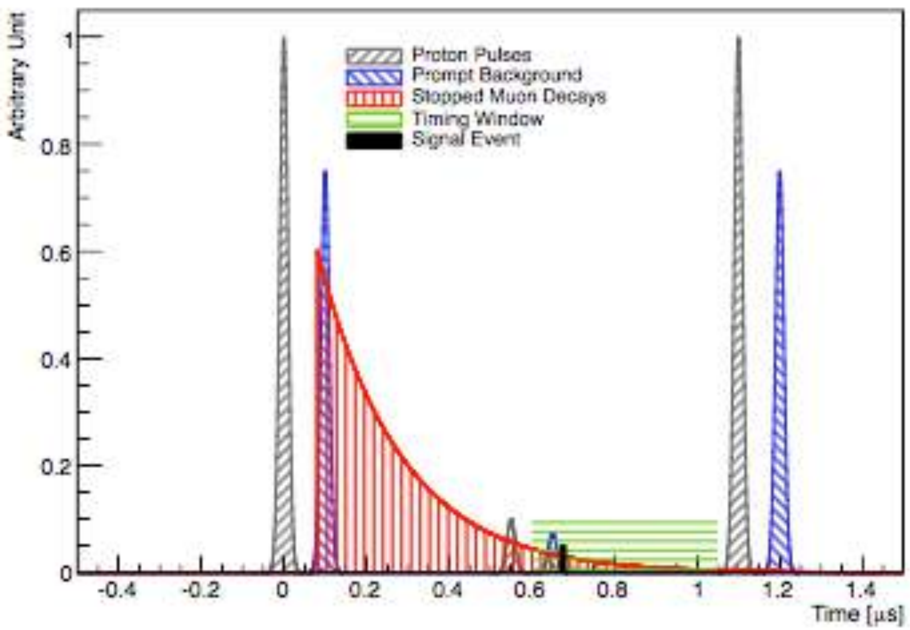
Largest background is **D**ecay **I**n **O**rbit (**DIO**) of stopped muon.
In atom gives electrons beyond the free-muon 53 MeV end-point.



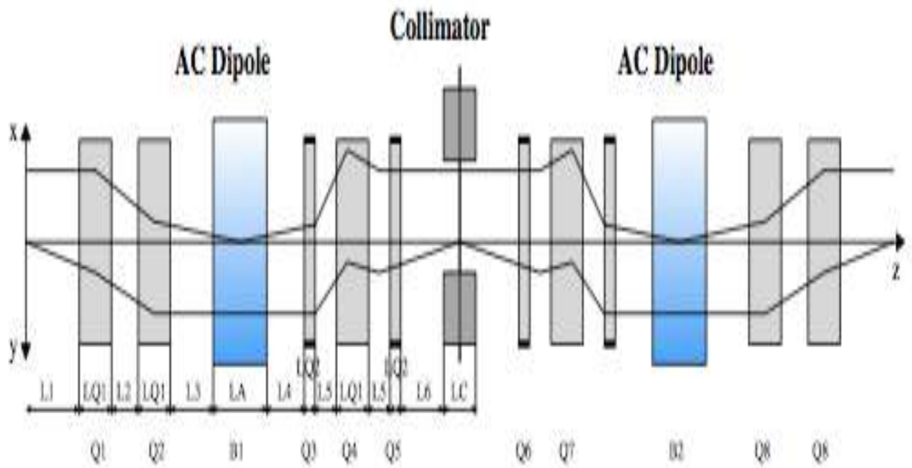
Controlled by detector resolution AND energy loss prior to detector.

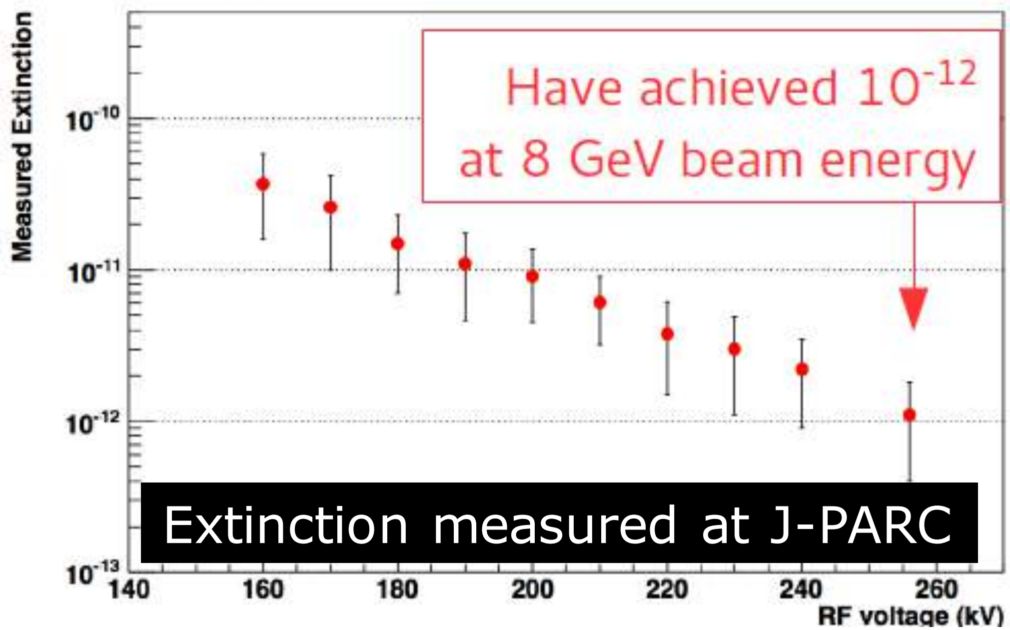
Need FWHM < 1 MeV

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



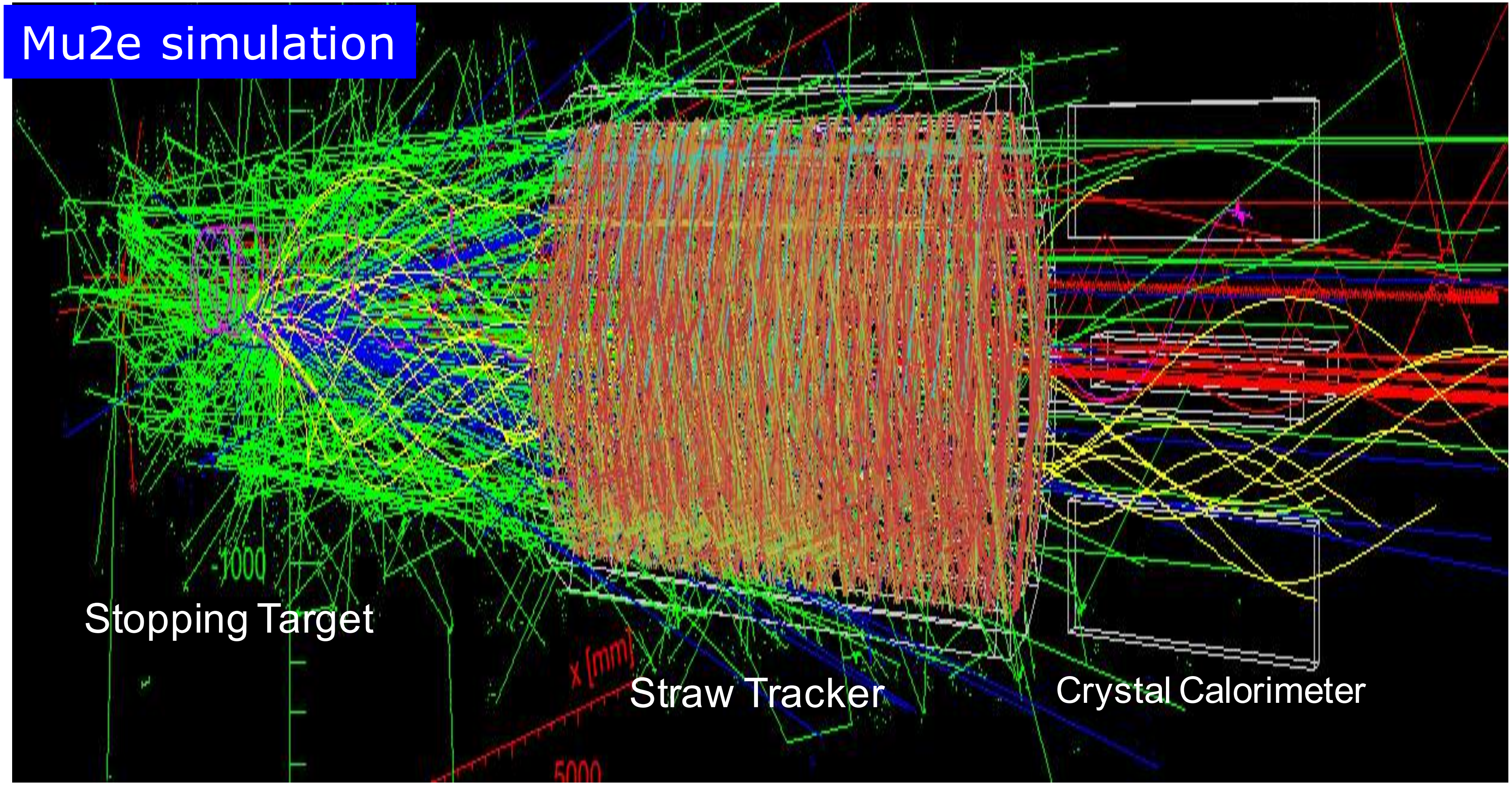
Background from secondary proton pulses in measurement time window





High Rate Environment ($>10^{10}$ μ/s)

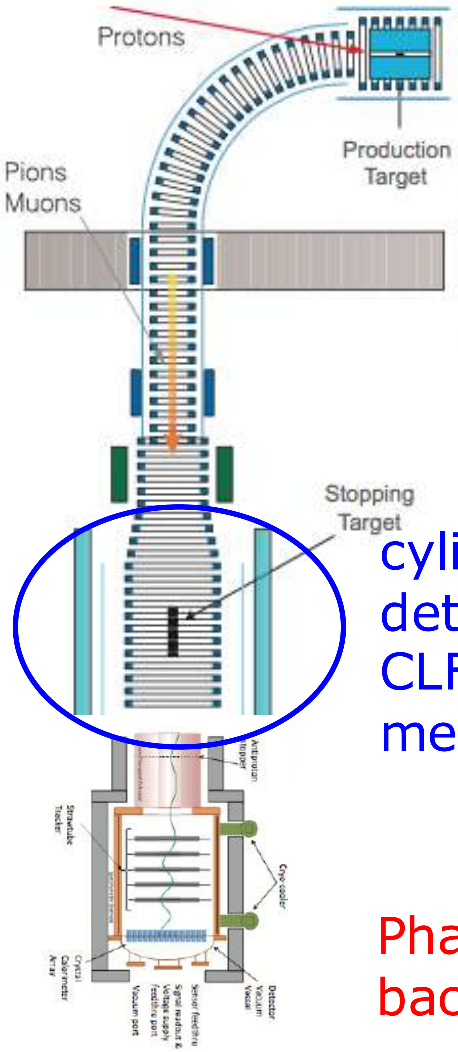
Signal identification requires excellent resolution at high-rate



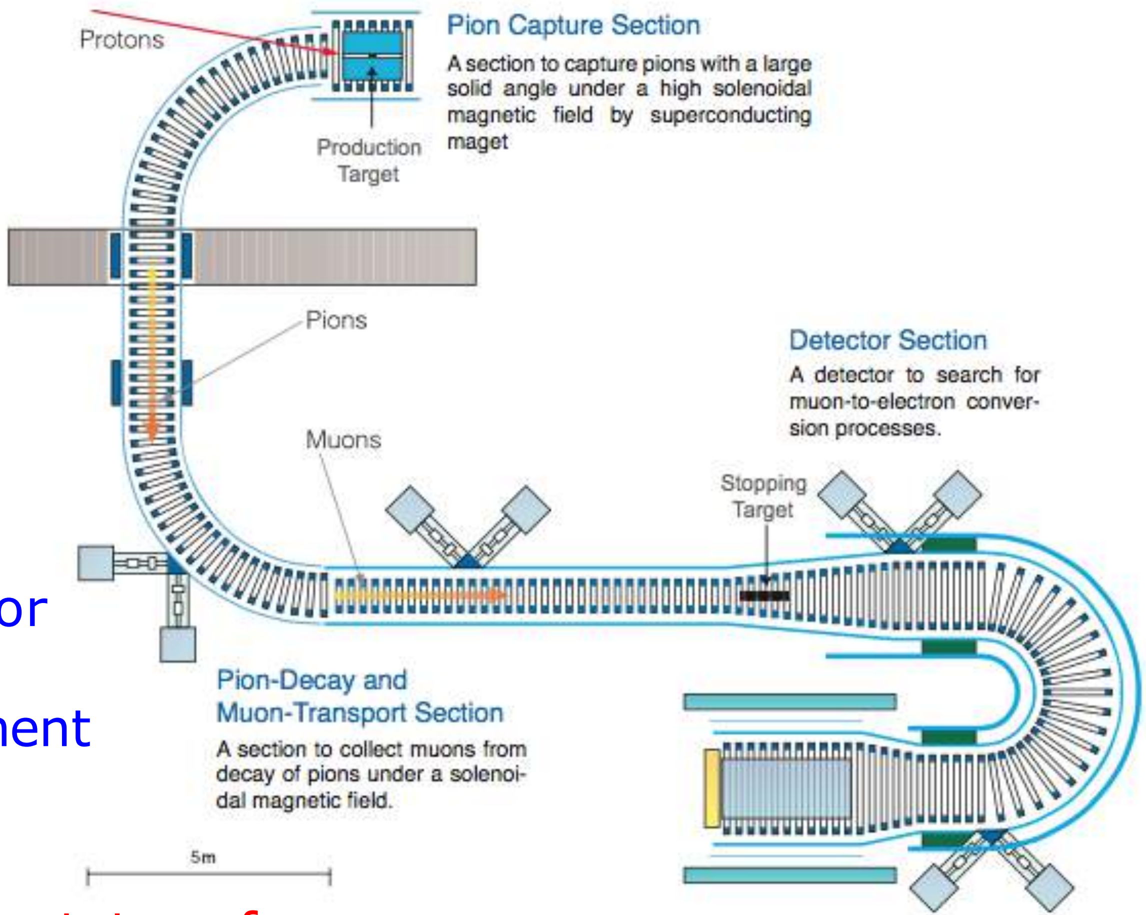
COMET @ J-PARC

Phase-I

Phase-II

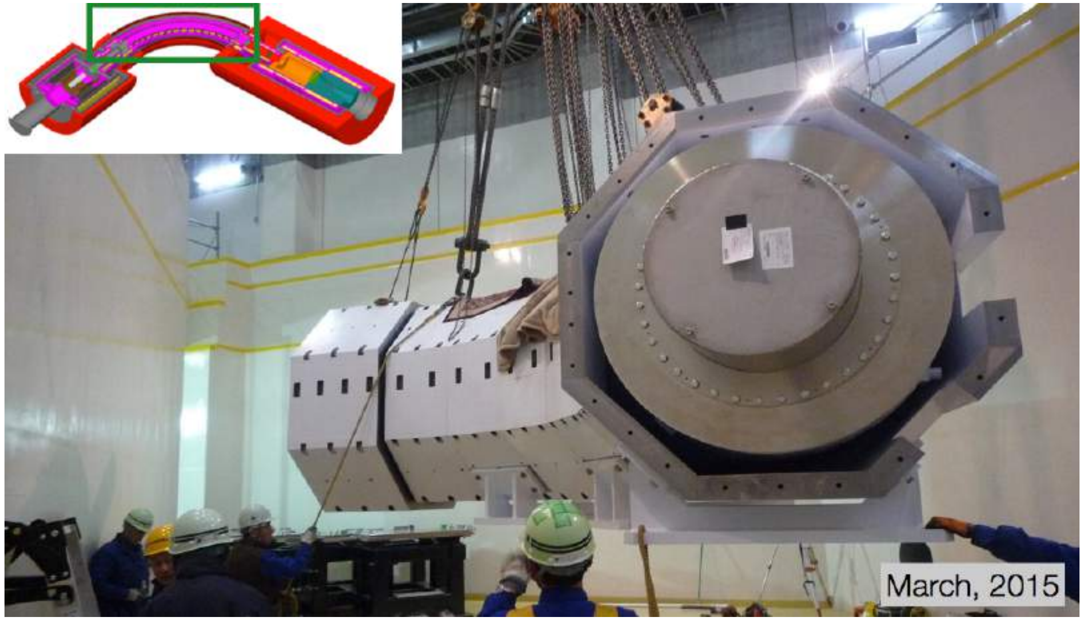


cylindrical detector for CLFV measurement

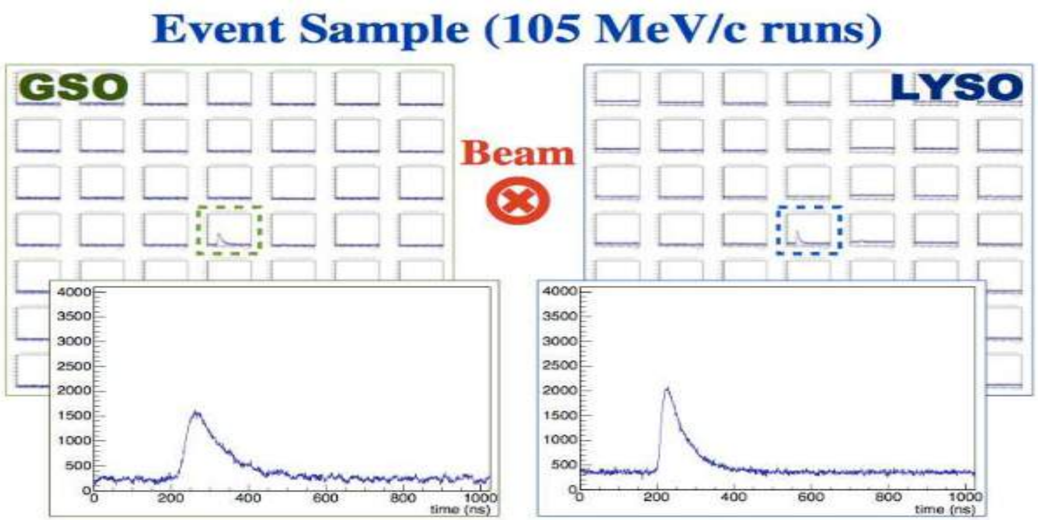


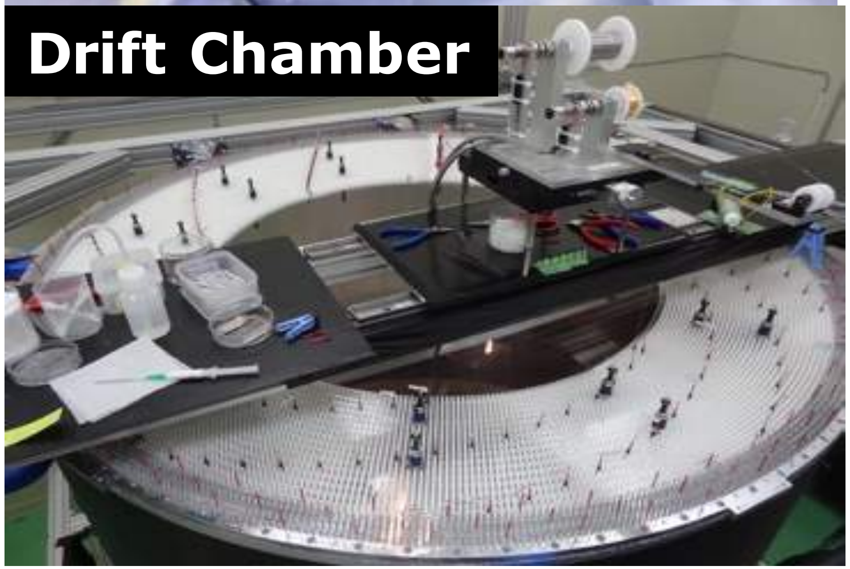
Phase-II prototype for background characterisation

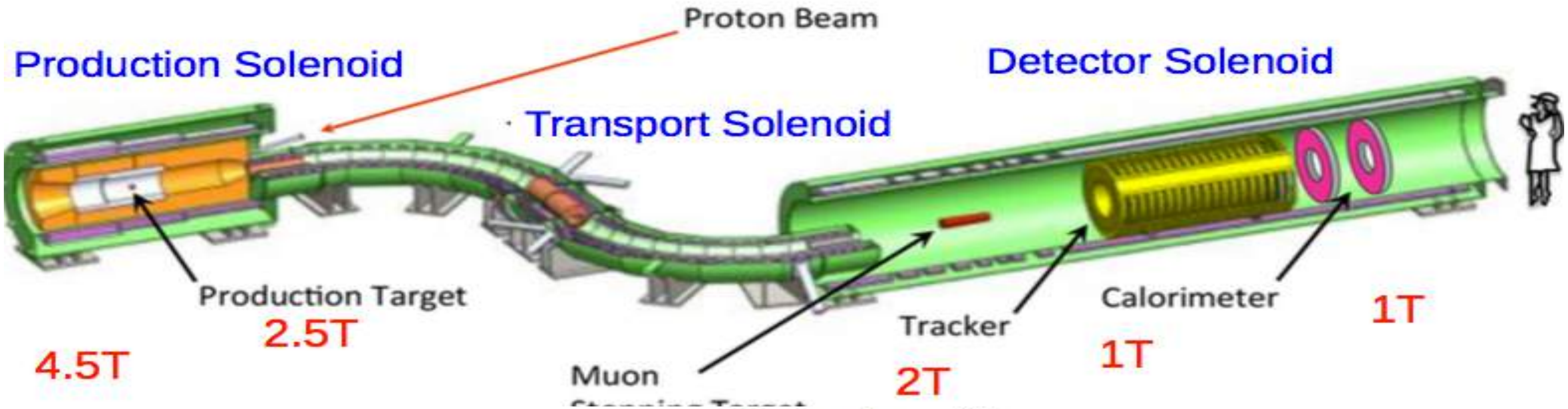
COMET

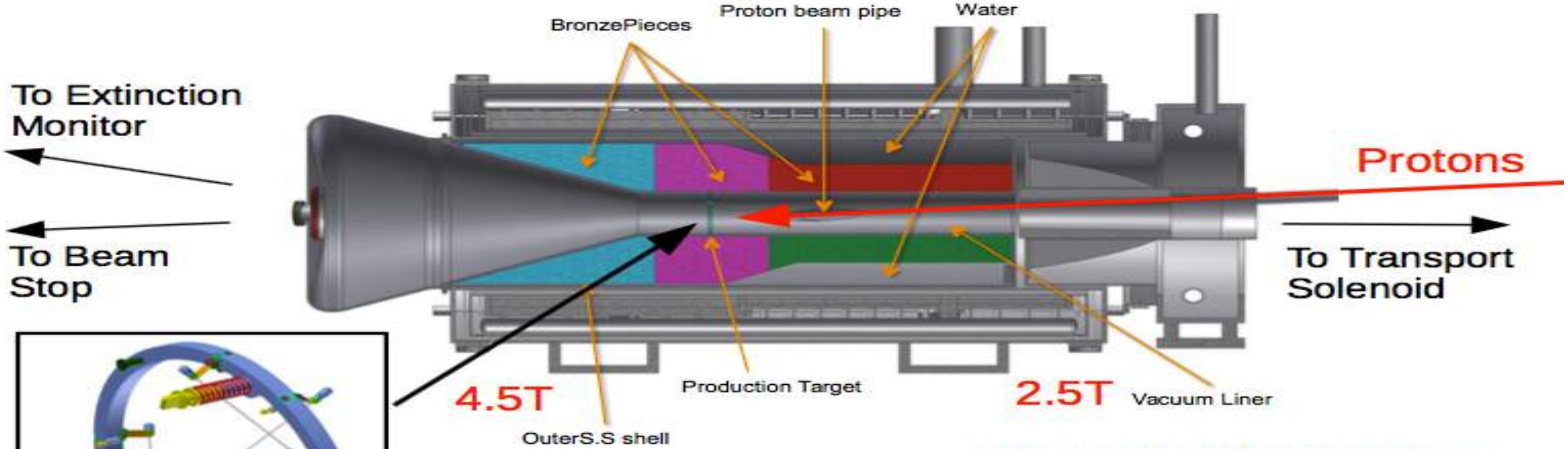

March, 2015

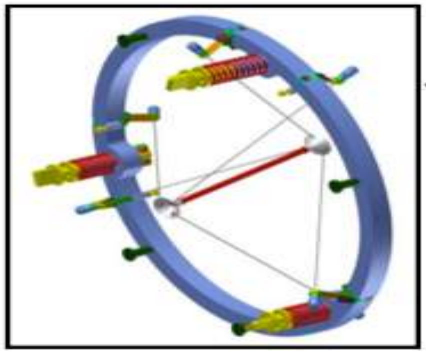

Straw Tracker


Event Sample (105 MeV/c runs)
GSO
LYSO
Beam
time (ns)


Drift Chamber



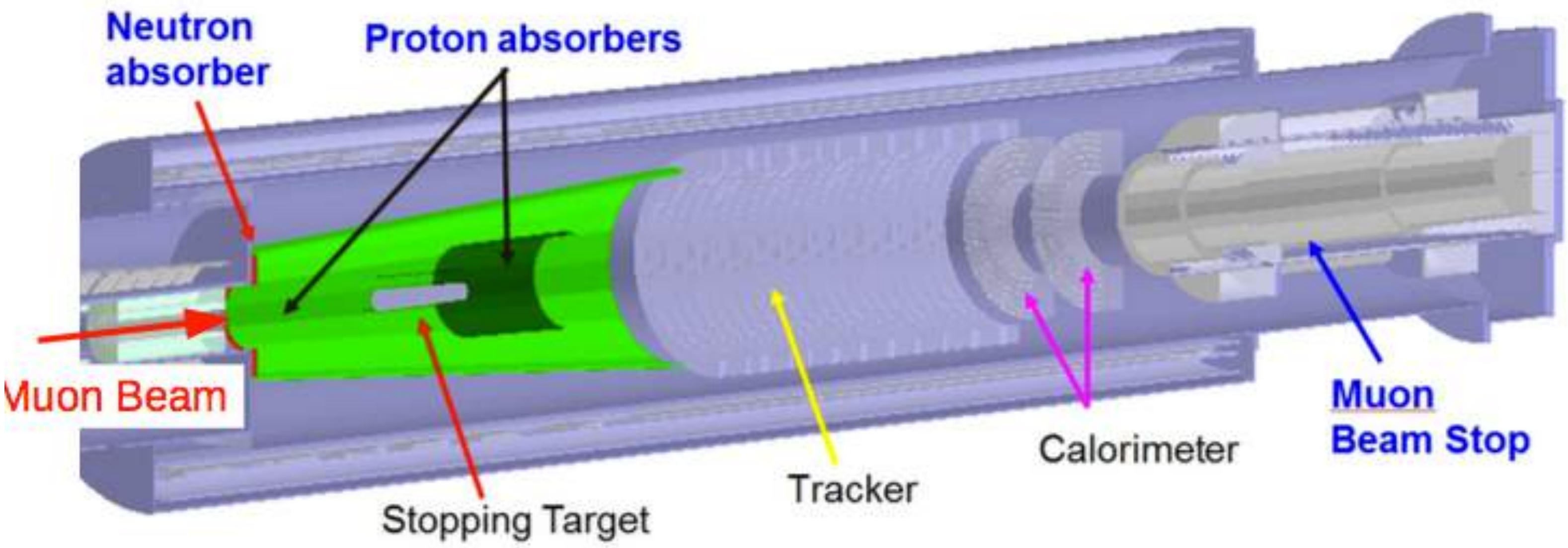




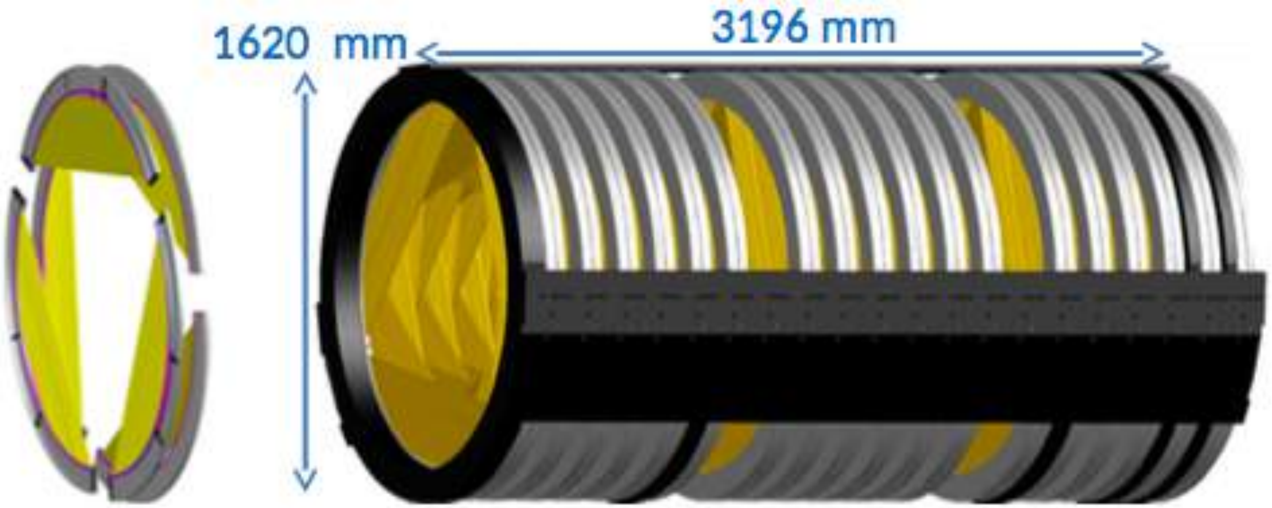
The tungsten production target is about the size of a pencil

The graded field acts as a "mirror" for charged particles, increasing the flux of muons into the TS

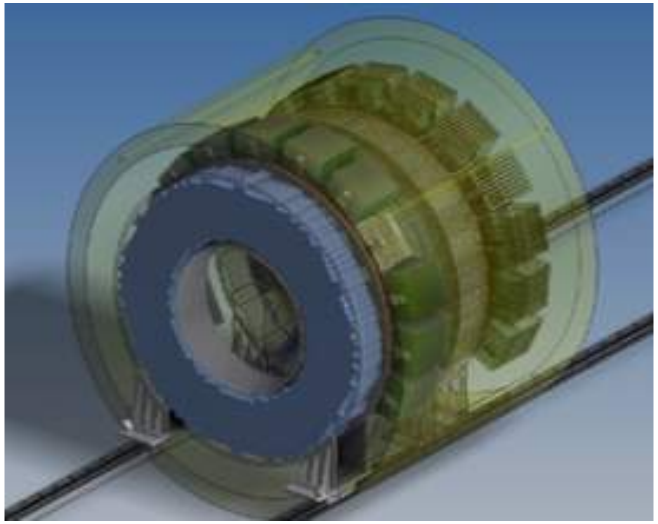
Mu2e



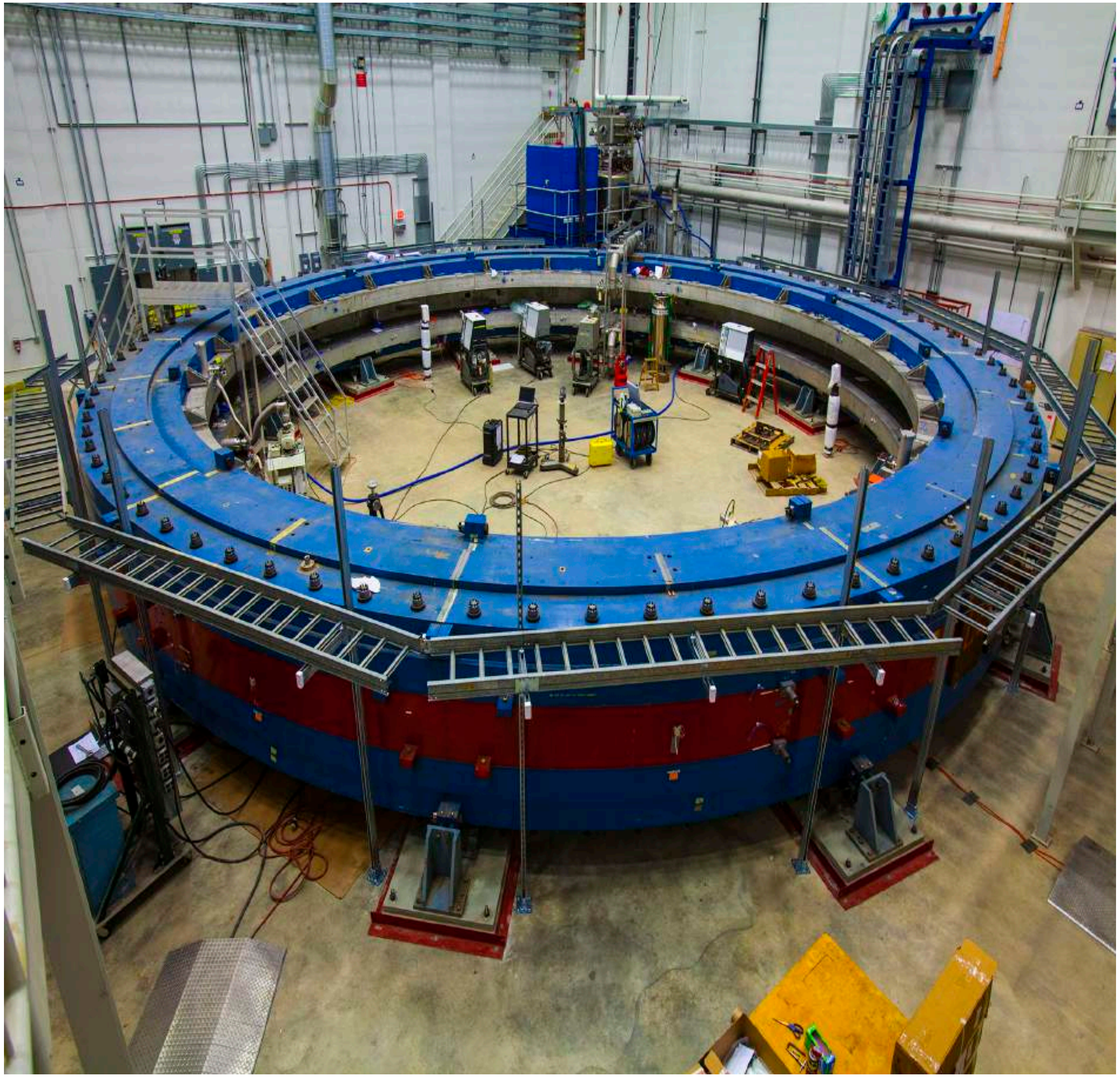
Neutron absorber
Proton absorbers
Muon Beam
Stopping Target
Tracker
Calorimeter
Muon Beam Stop



1620 mm
3196 mm



Both g-2 and Mu2e beamlines from delivery ring to experimental halls are complete

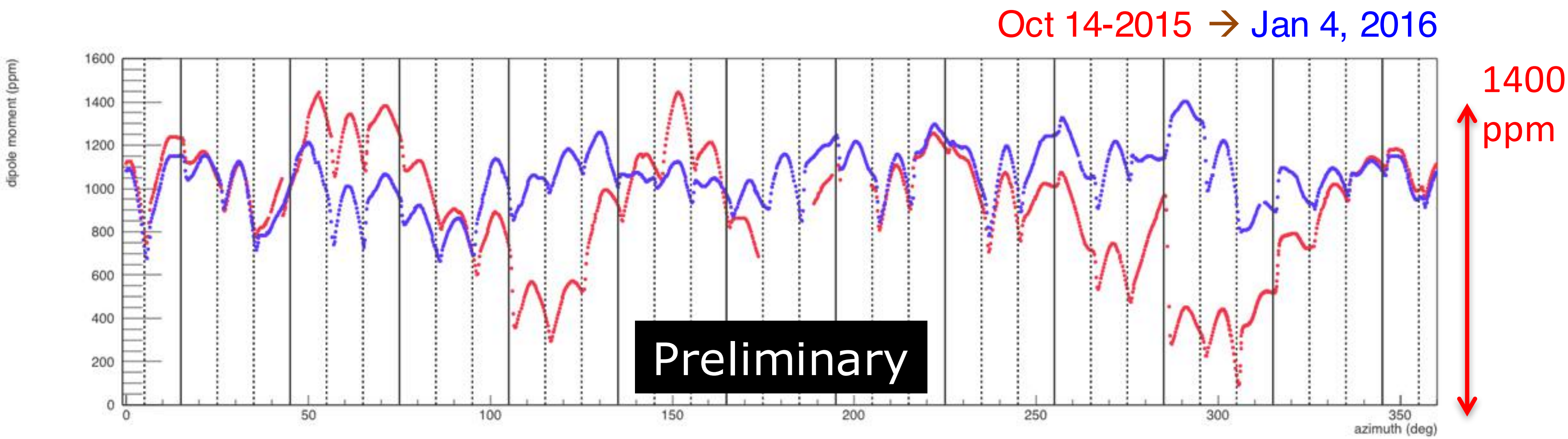


Muon g-2

Field established.
Shimming will be completed in summer

Detectors installed

Data : 2017.

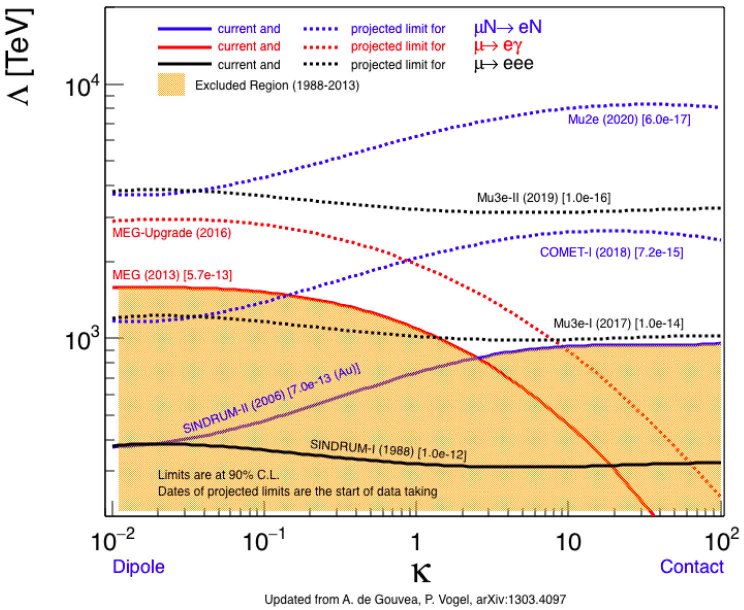


Summary

Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC.

Many new and exciting projects will take data in the next 10 years

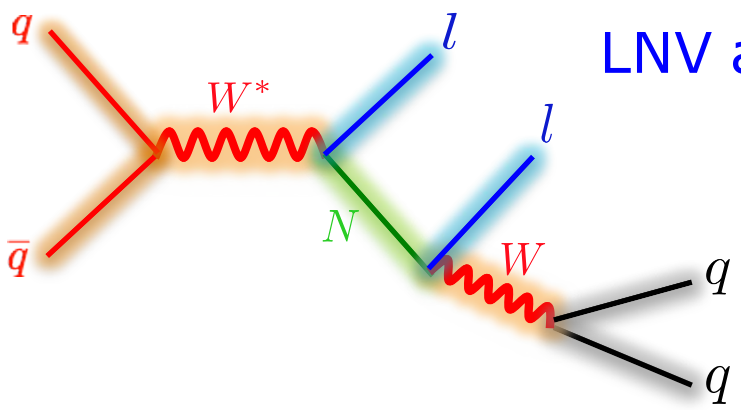
- MEG-II : 2017-2019
- g-2 : 2017-2019
- Mu3e : 2017-2023
- DeeMe : 2017-21
- COMET-I : 2018-19
- Mu2e/COMET-II : 2020-23

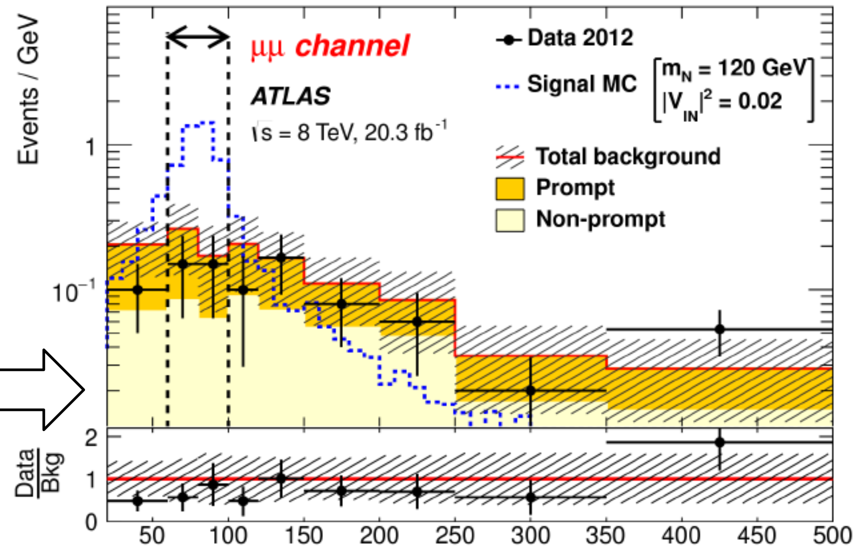


that extend the search for CLFV by 1-4 orders of magnitude

Backup

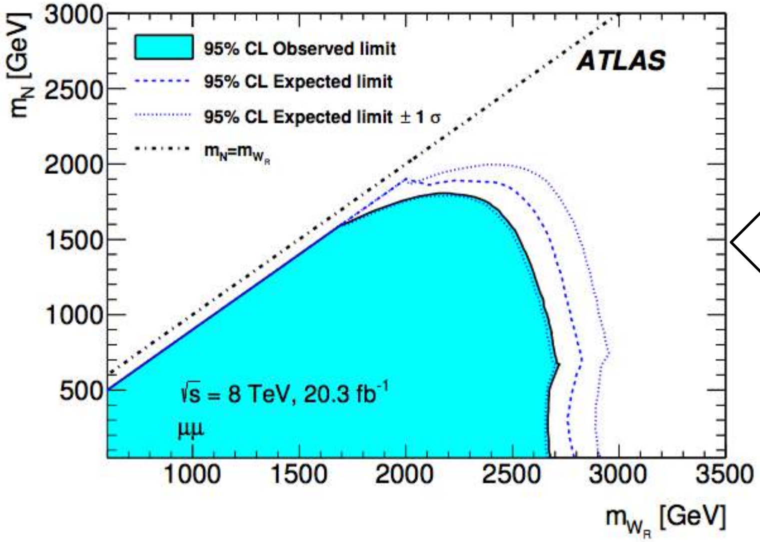
LNV and LFV violating



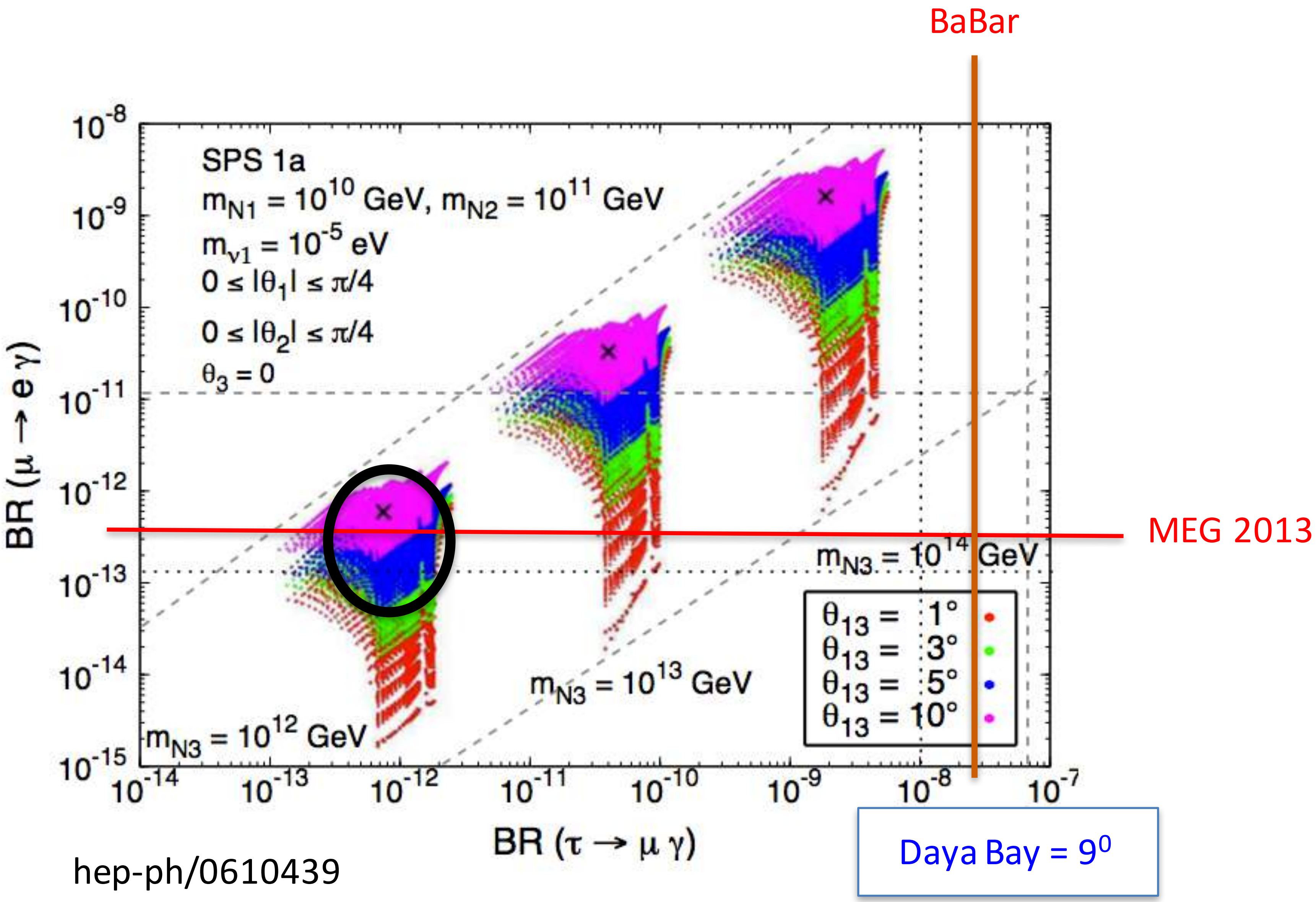


M_{JJ} [GeV]

SM + N_R : "mTISM" :
Limits : O(200) GeV



SM + $SU(2)_R$: "LRSM model"
Limits : O(2-3) TeV



hep-ph/0610439

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)

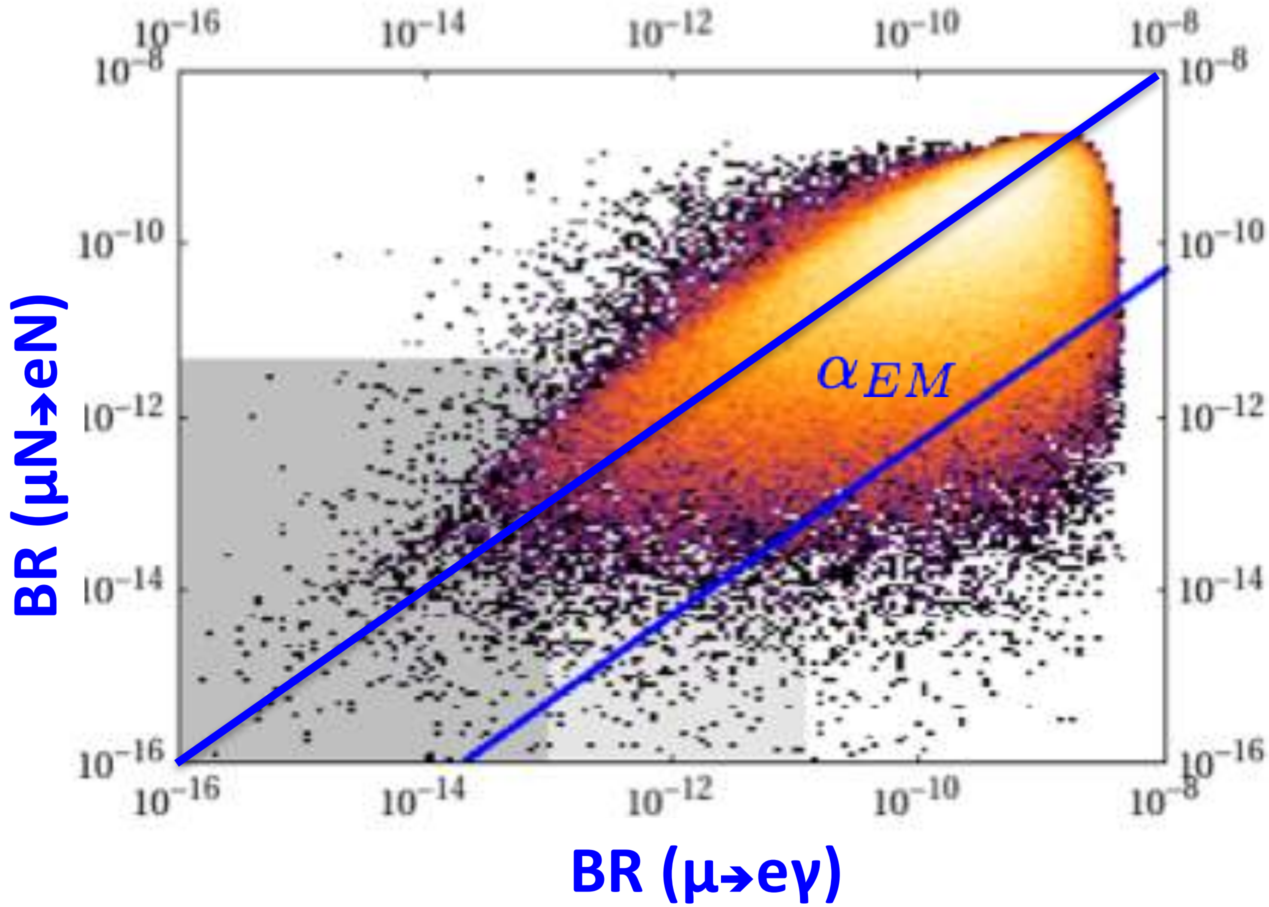
Different **SUSY** and **non-SUSY** BSM models.

★★★ Large effects

★★ Visible but small

★ No sizeable effect

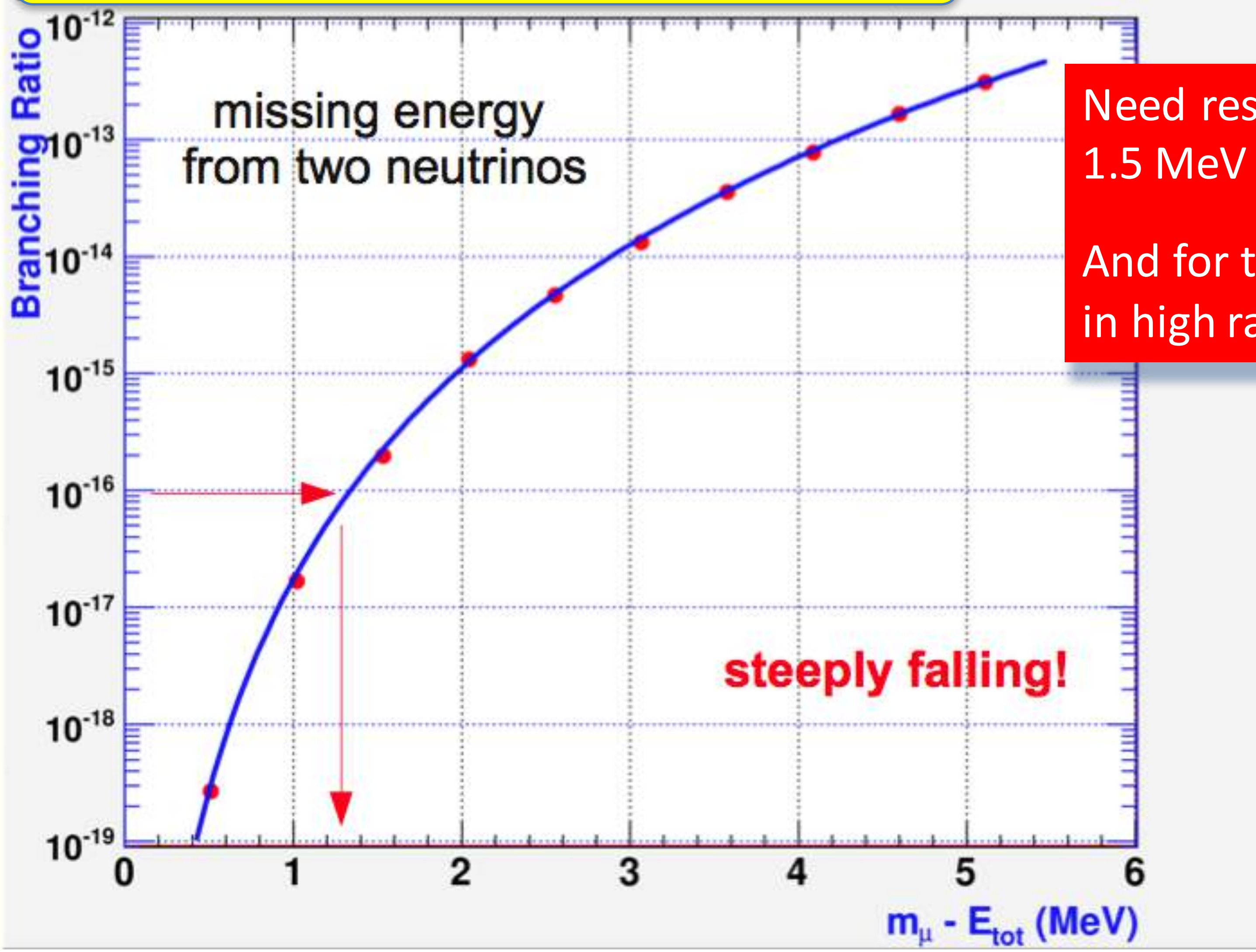
In general in BSM models $\frac{BR(\mu N \to eN)}{BR(\mu \to e\gamma)} = \mathcal{O}(\alpha_{EM})$ but not always…



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

Mu3e: Momentum Resolution

Limit achievable vs cut on mμ - E_{TOT}

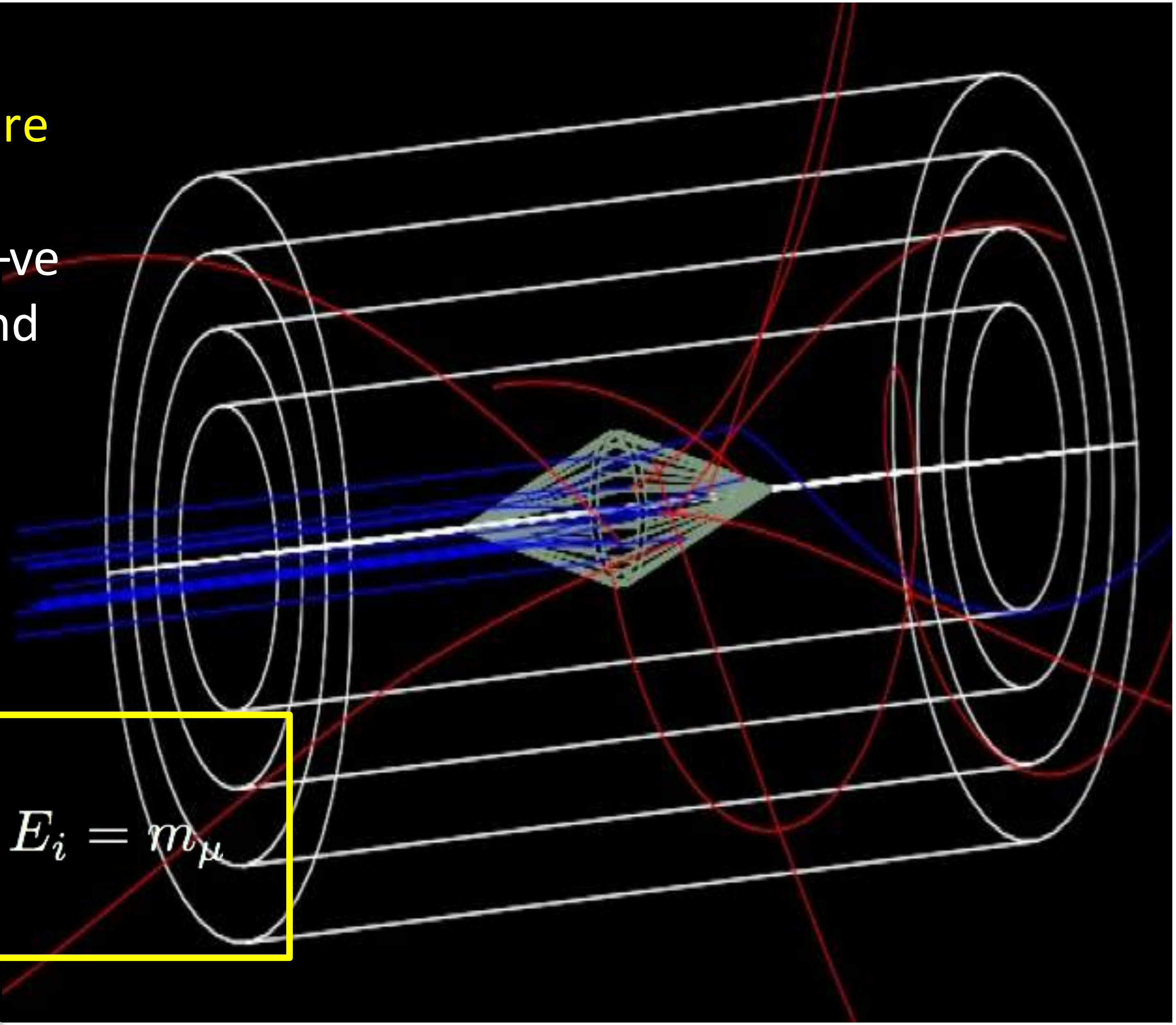


Need resolution on ΣE to 1.5 MeV to reach 10^{-16}

And for this to be achieved in high rate environment

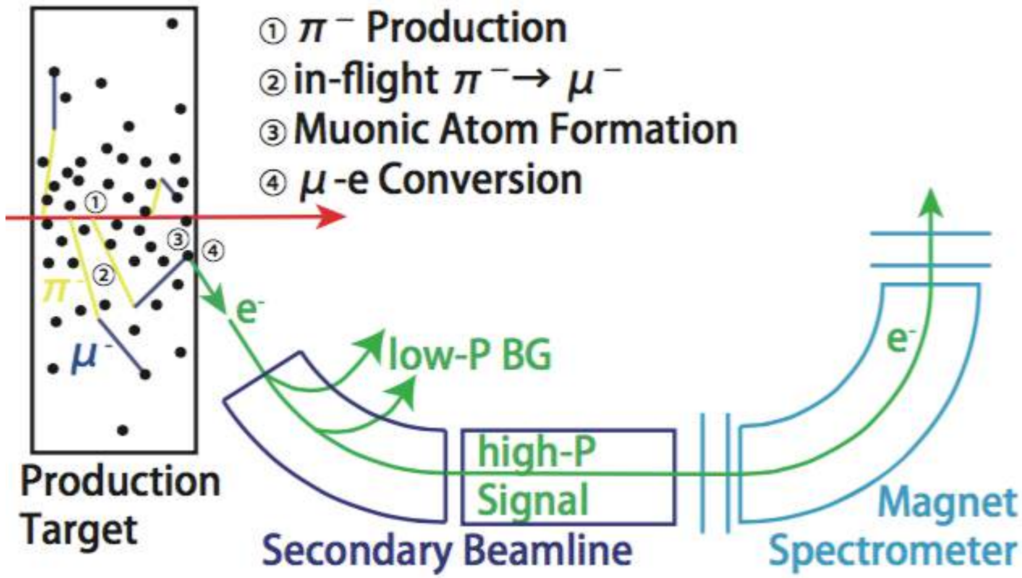
Experimental signature

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

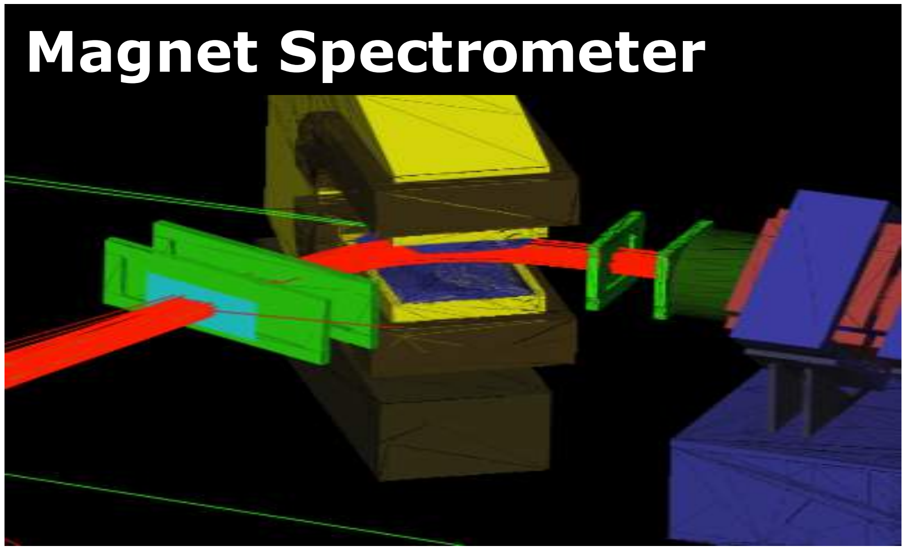


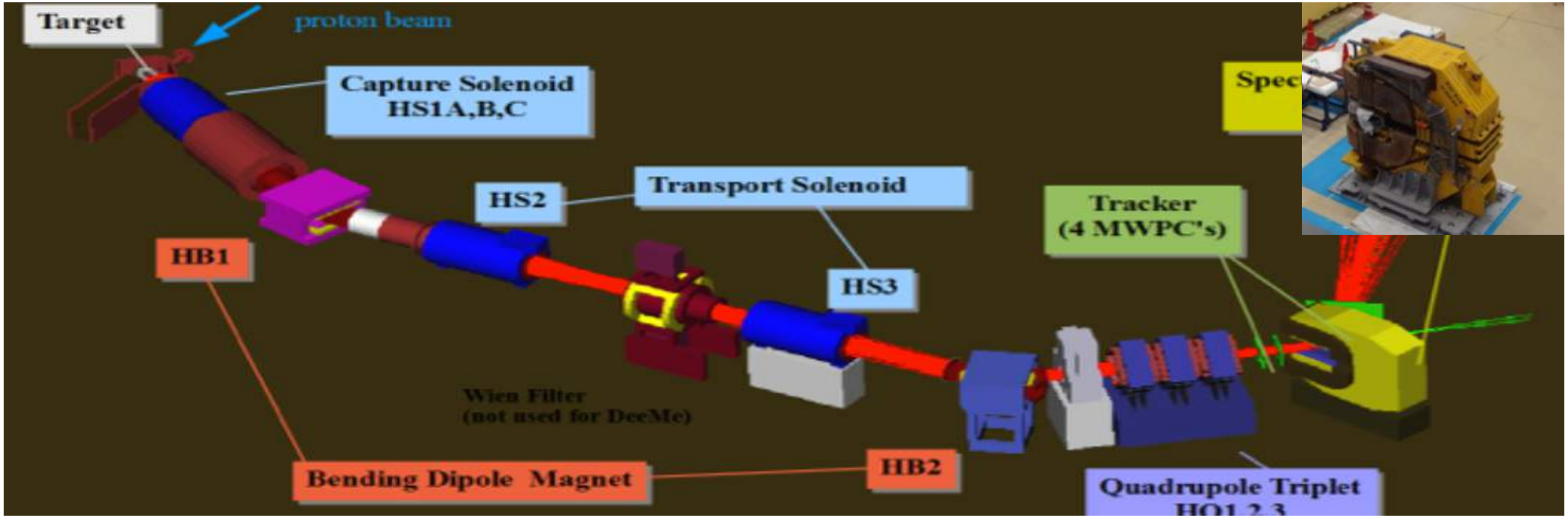
$$\left|\sum_i p_i\right| = 0, \quad \sum_i E_i = m_\mu$$

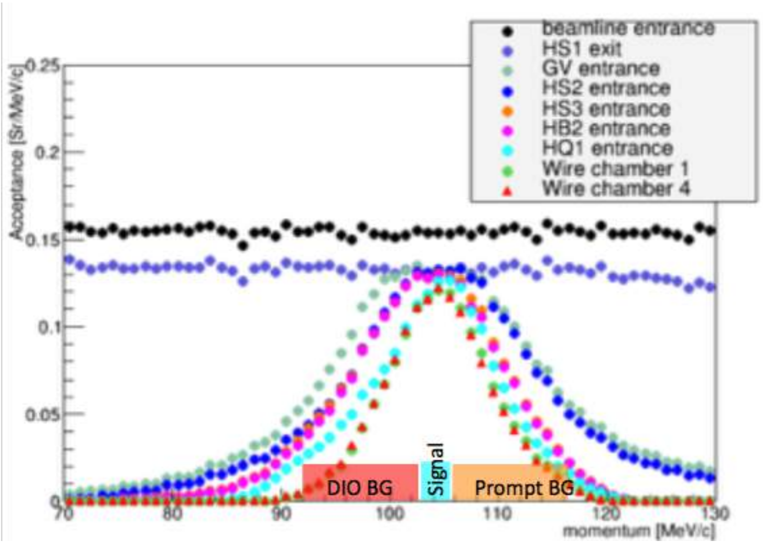
DeeMe @ J-PARC

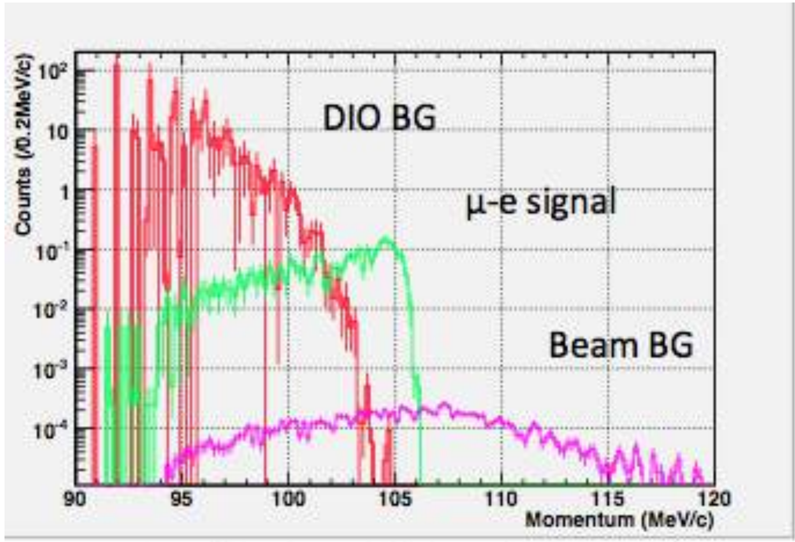


- 3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e-
- 4 MWPCs with Δp=0.5 MeV







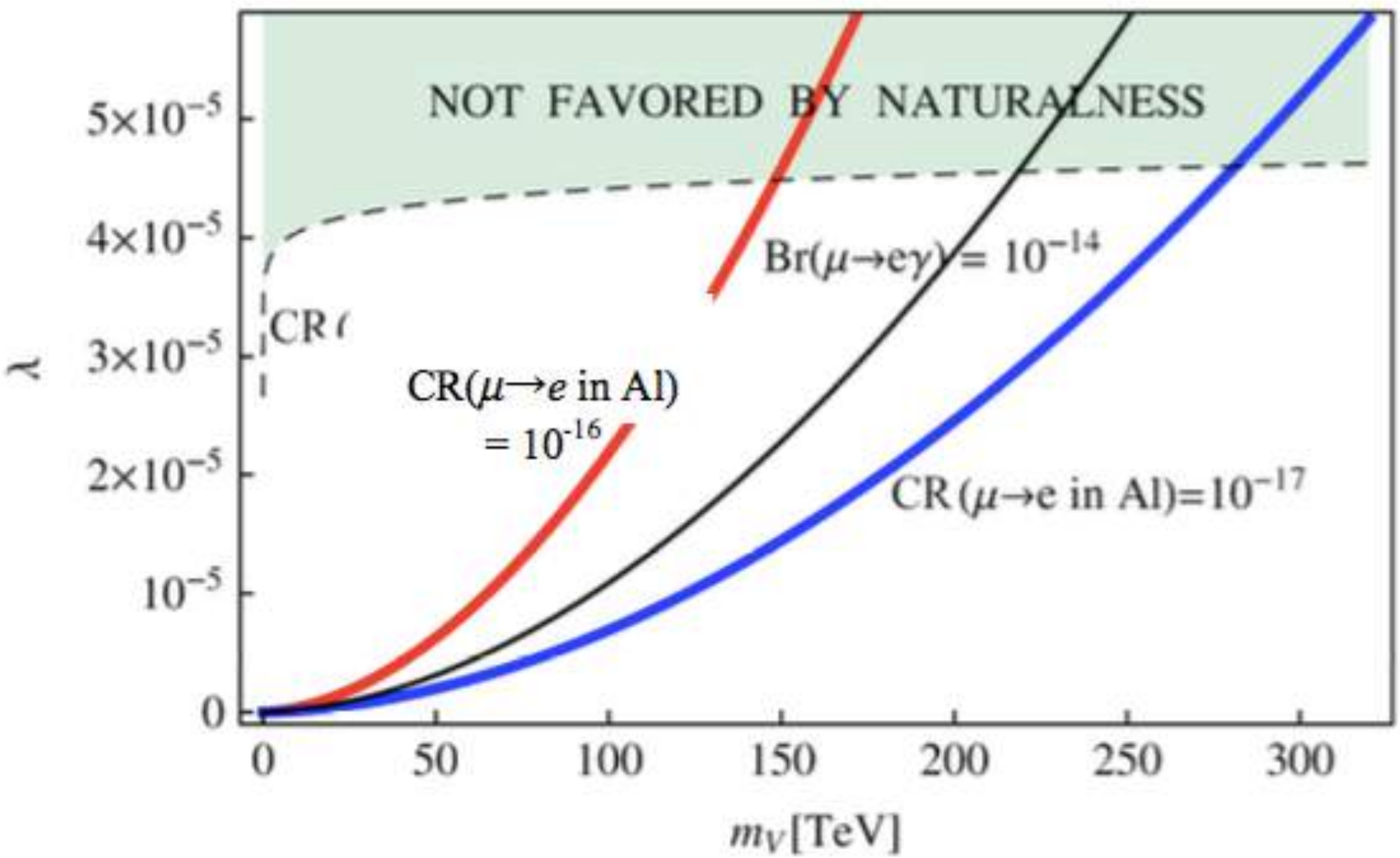


Signal Region: 102.0 -- 105.6 MeV/c

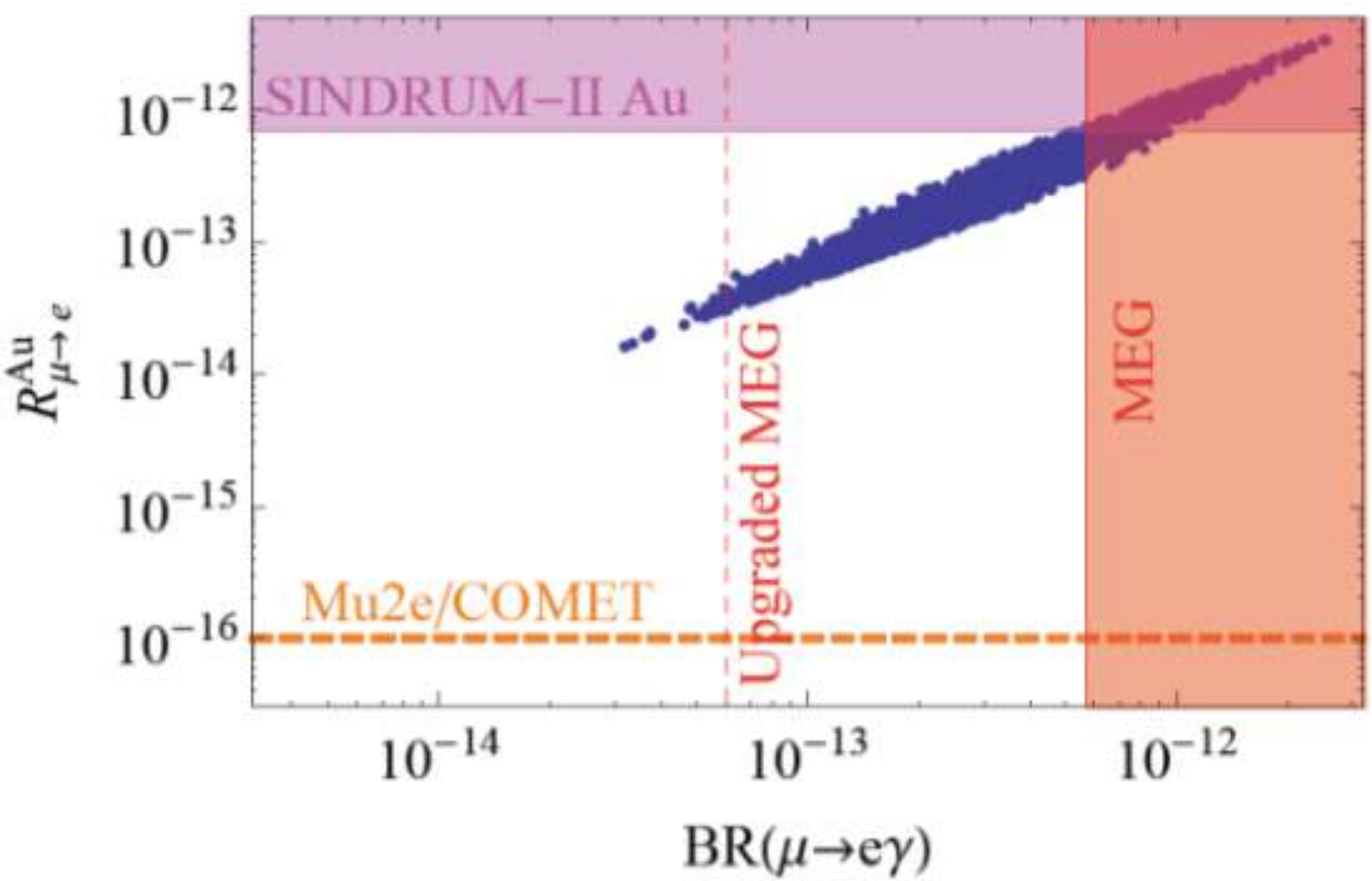
Extinction to 10^{-18} achieved in 2014

Mu2e/COMET Reach ~ 100 TeV for LQ

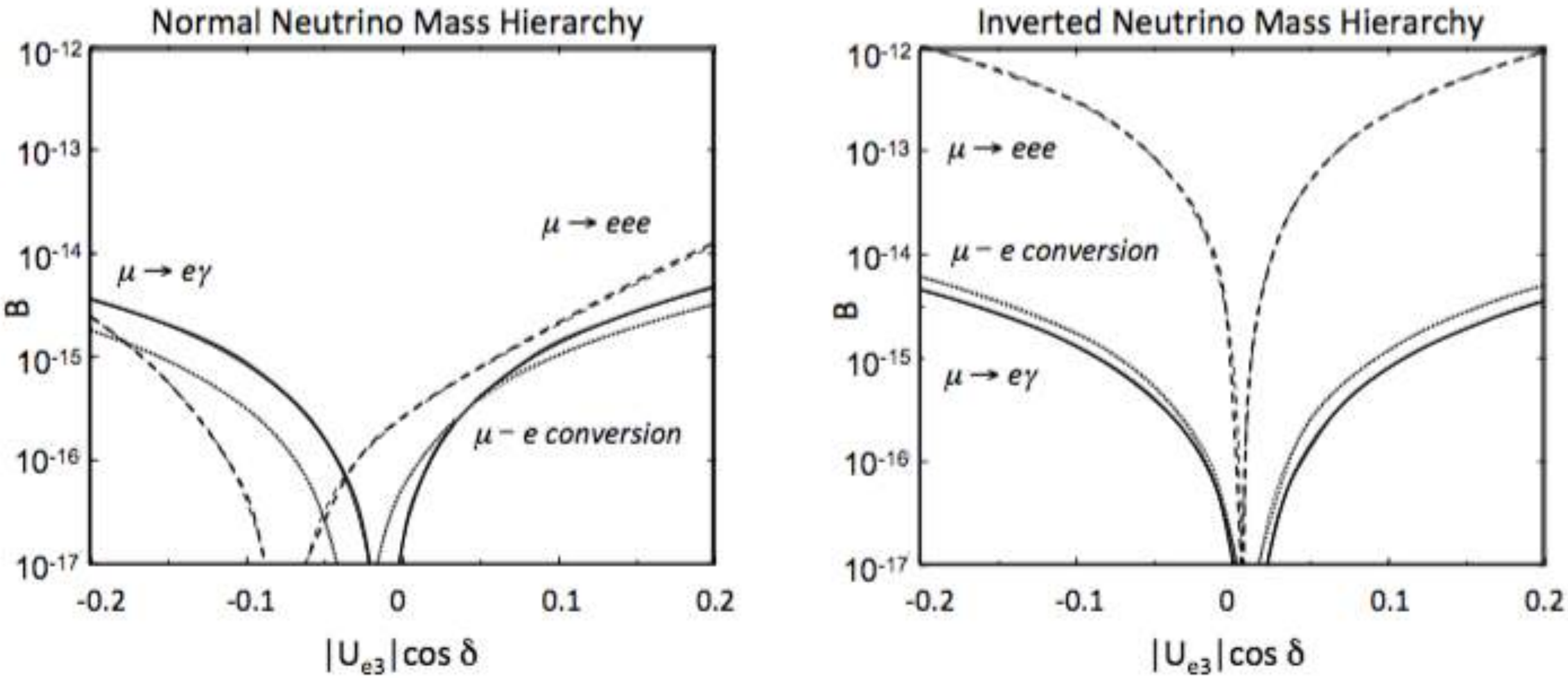
Sensitivity to high mass phenomena e.g. scalar leptoquarks not excluded by LHC



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



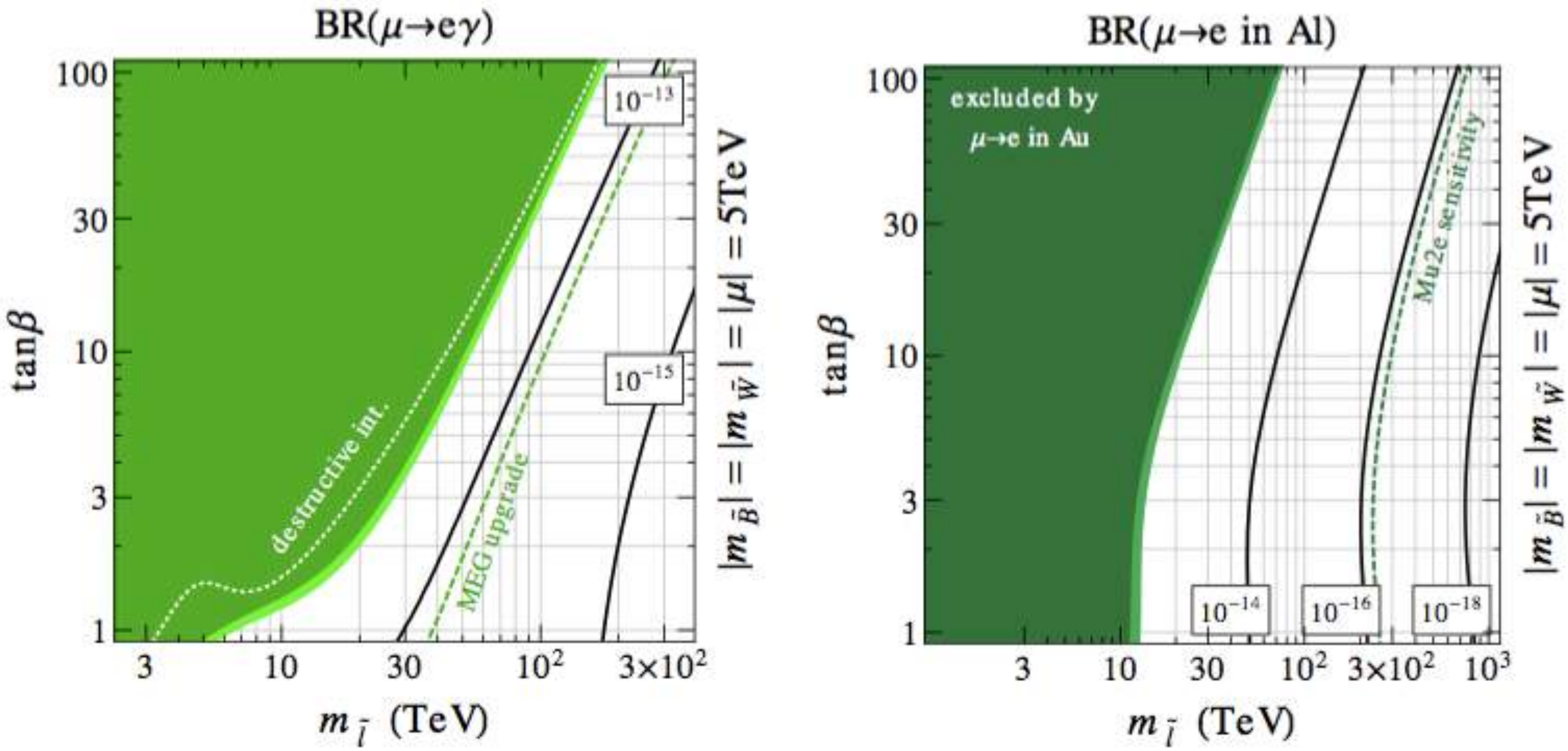
e.g. Majorana neutrino mass from a SU(2) triplet Higgs field



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

Motivated by Higgs mass

Sfermions not at TeV scale but: 100 – 1000 TeV with gauginos at a few TeV



Muon g-2 Interest….

arXiv.org > hep-ph > arXiv:1512.06715

High Energy Physics – Phenomenology

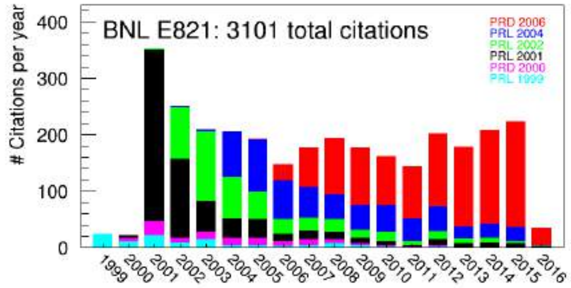
750 GeV Diphoton Resonance, 125 GeV Higgs and Muon g-2 Anomaly in Deflected Anomaly Mediation SUSY Breaking Scenario

Fei Wang, Lei Wu, Jin Min Yang, Mengchao Zhang

(Submitted on 21 Dec 2015)

We propose to interpret the 750 GeV diphoton excess in deflected anomaly mediation supersymmetry breaking scenarios, which can naturally predict the coupling between a singlet field and the vector-like messengers. The scalar component (S) of the singlet field can serve as the 750 GeV resonance. The messenger fields, whose masses are of order the gravitino scale, can be as light as F_\phi \sim {\cal O}(10) TeV when the messenger species N_F and the deflection parameter 'd' are moderately large. Such light messengers can induce the large loop decay process S \to \gamma\gamma. Our results show that such a scenario can successfully accommodate the 125 GeV Higgs boson, 750 GeV diphoton excess and the muon g-2 without conflicting with the LHC constraints. We also comment on the possible explanations in the gauge mediation supersymmetry breaking scenario.

Comments: 15 pages,1 figure
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Cite as: arXiv:1512.06715 [hep-ph]



arXiv.org > hep-ph > arXiv:1511.07447

High Energy Physics – Phenomenology

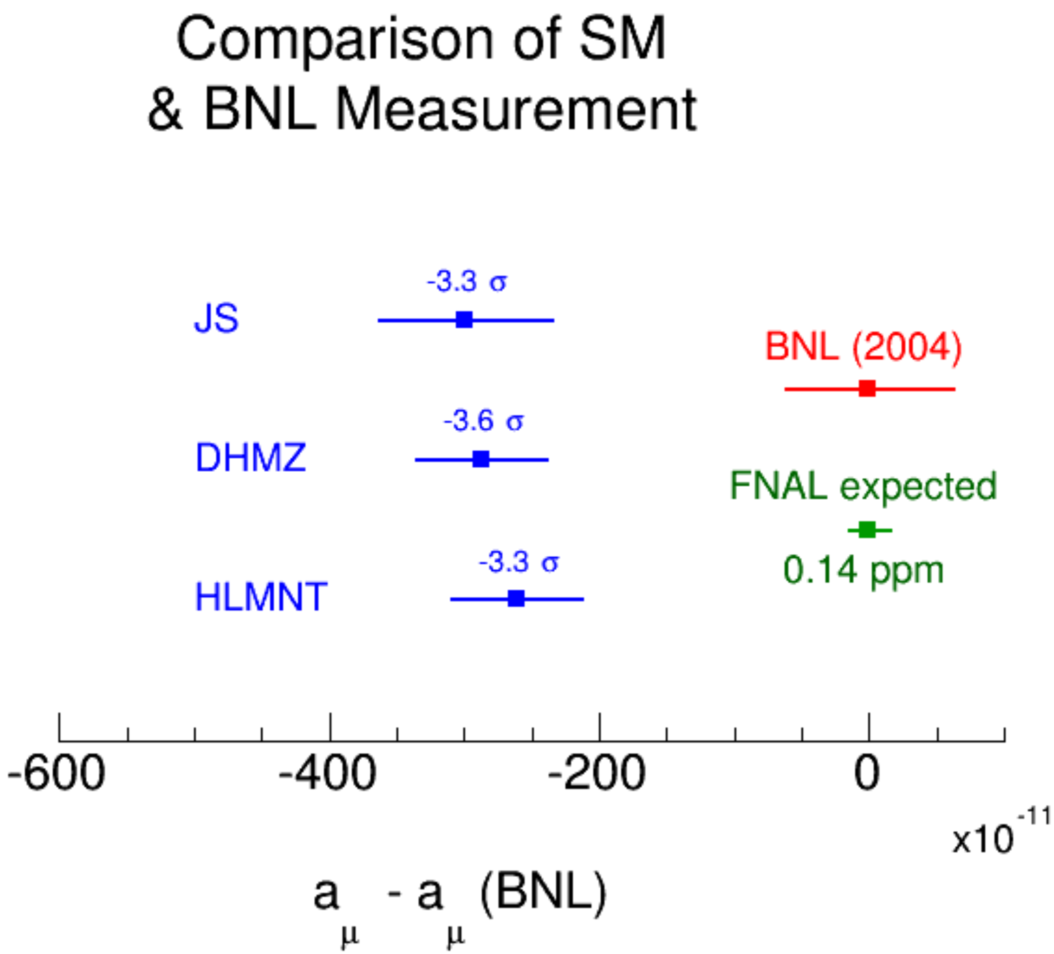
Z' models for the LHCb and g-2 muon anomalies

Ben Allanach, Farinaldo S. Queiroz, Alessandro Strumia, Sichun Sun

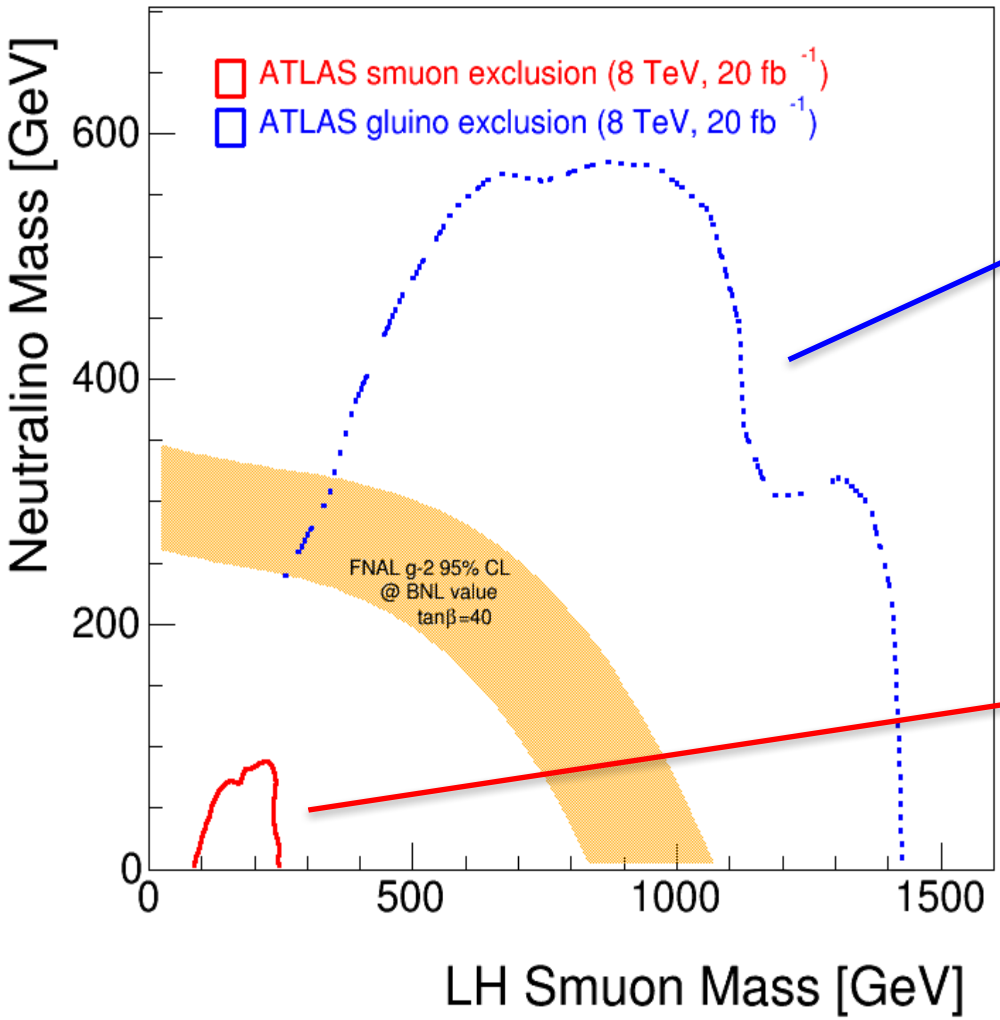
(Submitted on 23 Nov 2015)

We revisit a class of Z' explanations of the anomalies found by the LHCb collaboration in B decays, and show that the scenario is tightly constrained by a combination of constraints: (i) LHC searches for di-muon resonances, (ii) pertubativity of the Z' couplings; (iii) the B_s mass difference, and (iv) and electro-weak precision data. Solutions are found by suppressing the Z' coupling to electrons and to light quarks and/or by allowing for a Z' decay width into dark matter. We also present a simplified framework where a TeV-scale Z' gauge boson that couples to standard leptons as well as to new heavy vector-like leptons, can simultaneously accommodate the LHCb anomalies and the muon g-2 anomaly.

Comments: 10 pages, 11 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Report number: CETUP2015-028
Cite as: arXiv:1511.07447 [hep-ph]


Comparison of SM
& BNL Measurement
-3.3 σ
JS
BNL (2004)
-3.6 σ
DHMZ
FNAL expected
0.14 ppm
-3.3 σ
HLMNT
-600
-400
-200
0
x10^-11
aμ - aμ (BNL)

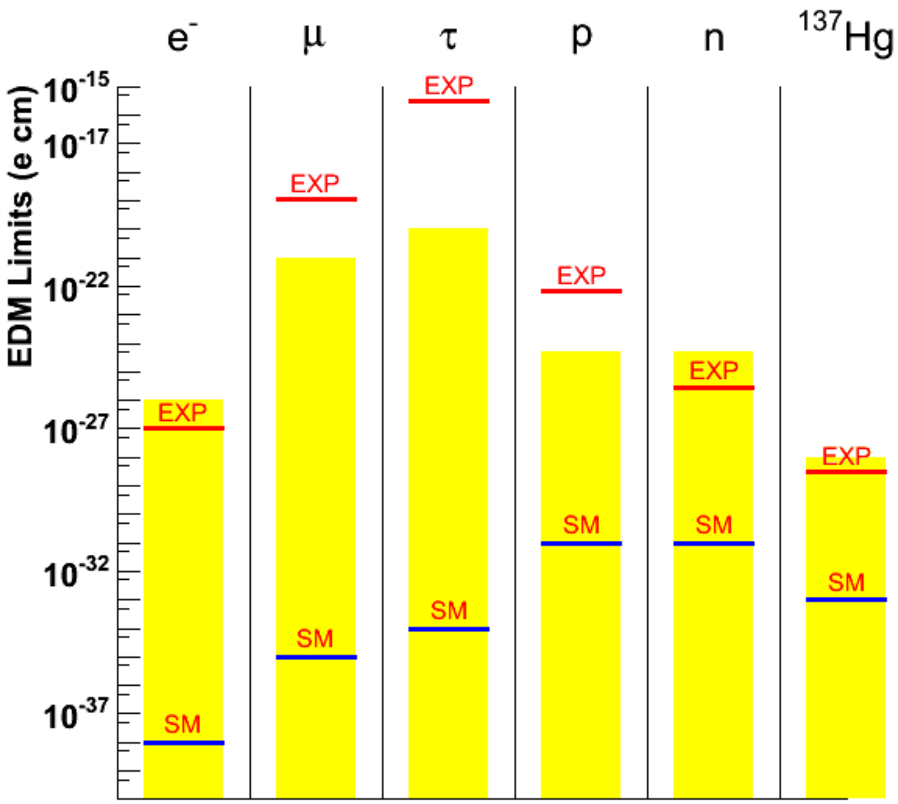
Muon g-2 SUSY sensitivity



Strongly interacting (colour) new physics (SUSY)

Weakly interacting (non-coloured) new physics

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 1.8×10^{-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