Search for new physics with the RICOCHET experiment

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Sommaire

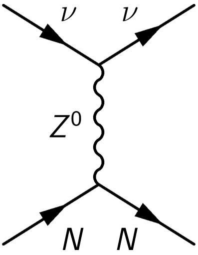
CEνNS phenomenology

What is Coherent Elastic Neutrino Nucleus Scattering (CEνNS) ?

Neutral current interaction between a neutrino and a nucleus as a whole (low-energy process). Blind to the flavour of the incident/scattered neutrino.

Predicted in 1974 by Daniel Z. Freedman, discovered in 2017 by the COHERENT experiment

Is the process constituting the "neutrino floor" known in dark matter direct detection experiments.



State of the art in CEνNS experiments

Many experiments ongoing or in preparation, to improve our knowledge of this process. Only COHERENT have measured CEνNS process.

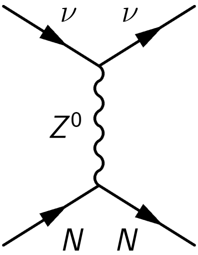
- Ongoing experiments : COHERENT, CONNIE, CONUS, Dresden-II, RED-100
- In preparation : RICOCHET, νCLEUS, MINER, νGeN, TEXONO,...

Standard CEνNS

Cross section of SM CEνNS :

$$\frac{d\sigma_{SM}}{dE_R} = (\mu)\frac{G_F^2}{4\pi}Q_W^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

with $Q_W = (A - Z) - (1 - 4sin^2\theta_W)Z$



$\rightarrow$ scales with number of neutrons in the nucleus.

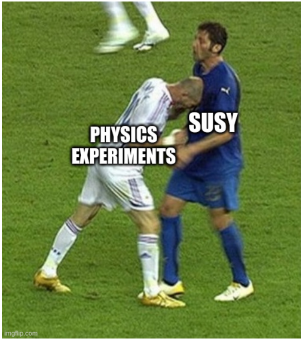
New physics ?

The phenomenology of CEνNS process is very rich in possible new physics. Few examples (in this work) :

- Neutrino magnetic moment (NMM)
- Neutrino generalised interactions (NGI) with new light bosons

Other existing models (will not be discussed) :

- Other electromagnetic properties of the neutrino (millicharge, charge radius)
- Non-standard interactions
- Mogette neutrinos (also known as sterile neutrinos)
- (Not SUSY, nor Mars Attack)



CEνNS with NMM

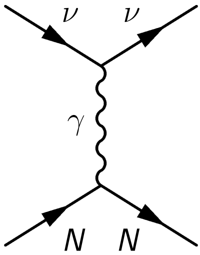
Massive neutrinos have non-zero magnetic moment.

For Dirac neutrinos : $\mu_\nu \sim 10^{-19}\mu_B$

For Majorana neutrinos : $\mu_\nu \sim 10^{-14}\mu_B$

If measured at $\mu_\nu \sim 10^{-12}\mu_B \rightarrow$ hint for new physics + Majorana nature of the neutrino !

$$\frac{d\sigma_{NMM}}{dE_R} = \frac{\pi\alpha^2{\mu_\nu}^2 Z^2}{m_e^2}\left(\frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2}\right) F^2(E_R)$$



CEνNS with NGI

NGIs adds a new light boson that can be of any Lorentz-invariant structure. Lagrangian definition (below EW symmetry breaking scale) :

$$\mathcal{L}_{NGI} = \frac{G_F}{\sqrt{2}} C^{q,P}_{\alpha,\alpha} [\bar{\nu}_\alpha \Gamma^X L \nu_\alpha][\bar{q} \Gamma_X P q]$$

with $X = \{S, P, V, A, T\}$; $\Gamma_X = \{\mathbb{1}, i\gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$; $\alpha = e, \mu, \tau$ and $q = u, d$

Couplings can be universal or defined with a $U(1)$ symmetry, often related to baryon and lepton numbers (ex : $U(1)_{B-L}$).

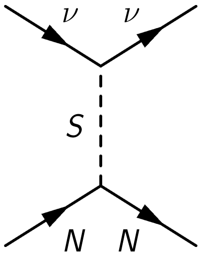
Introducting new bosons can explain the $(g-2)_\mu$ discrepancy.

CEνNS with NGI

Scalar boson :

$$\frac{d\sigma_S}{dE_R} = \frac{{Q_S}^2}{4\pi}\frac{m_N^2 E_R}{E_\nu^2(q^2 + {m_S}^2)^2}F^2(E_R)$$

with $Q_S = g_{\nu,S} g_{q,S}(15.1Z + 14N)$



CEνNS with NGI

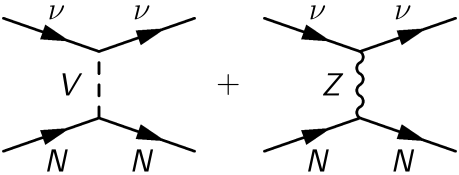
Vector boson :

$$\frac{d\sigma_V}{dE_R} \propto \frac{d\sigma_{SM}}{dE_R} \text{ with } Q_W \to Q_{tot}$$

$$Q_{tot} = Q_W - \frac{\sqrt{2}}{G_F} \frac{Q_V}{q^2 + m_V^2} \, ;$$

$$Q_V = g_{\nu,V}((2g_{u,V} + g_{d,V})Z + (g_{u,V} + 2g_{d,V})N)$$

Interference :

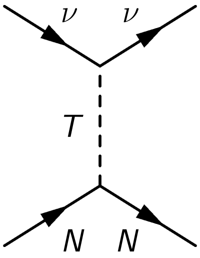


CEνNS with NGI

Tensor boson :

$$\frac{d\sigma_S}{dE_R} = \frac{{Q_T}^2}{2\pi}\frac{m_N(4E_\nu^2 - m_N E_R)}{E_\nu^2(q^2 + {m_T}^2)^2}F^2(E_R)$$

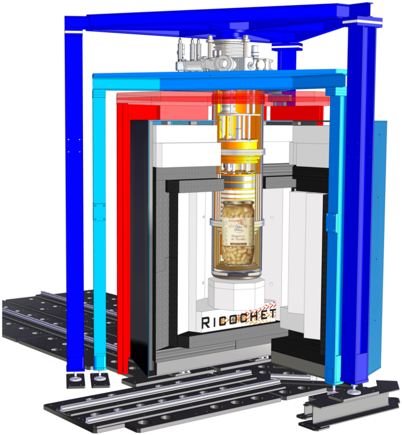
with $Q_T = g_{\nu,T}\, g_{q,T}(0.85Z - 0.08N)$



The RICOCHET experiment

The best mogette fridge ?

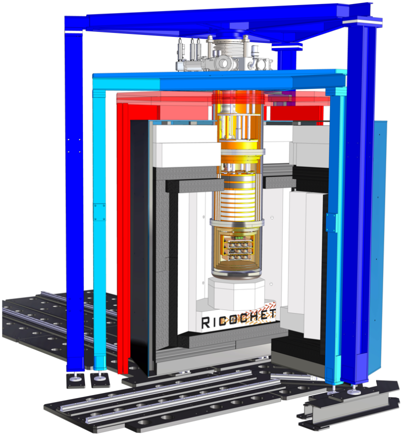
- Is not a 'real' neutrino experiment
- Is actually a fridge prototype (10mK temperature) for storing mogettes in challenging radioactive environment : the Institut Laue-Langevin (ILL) nuclear reactor
- No mogettes should be harmed by energetic particles $\rightarrow$ enjoy your meal !



Detector and shielding

Main detectors : cryogenic bolometers (ROI : [50eV,1keV])

- Two arrays of detectors : CryoCube (Ge, similar to EDELWEISS) and Q-Array (Zn)
- Ability to discriminate nuclear recoils (NR) from electronic recoils (ER) ; 10^3 rejection factor
- β, γ induce ER ; ν,n induce NR $\rightarrow$ neutrons are irreducible background

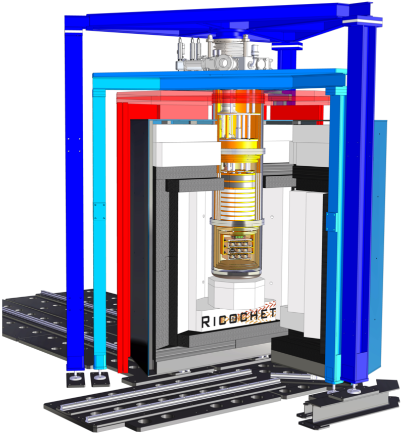


Detector and shielding

About shieldings :

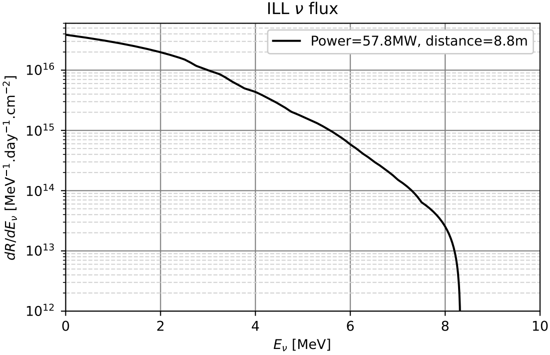
- Lead & borated polyethylene shield to mitigate γ, n fluxes
- Muon veto to cut NR events induced by neutrons coming from Pb spallation by muons
- Thin layers of μ-metal to mitigate magnetic field from neighbour experiment (IN20)

NR background level : 9 evts/d/kg in ROI.



Source : the ILL nuclear reactor

Functions in cycles of 50 days ON → possiibility of ON/OFF data taking. Planned total ON duration : 300d.
Electronic antineutrino spectrum (from STEREO measurement) :

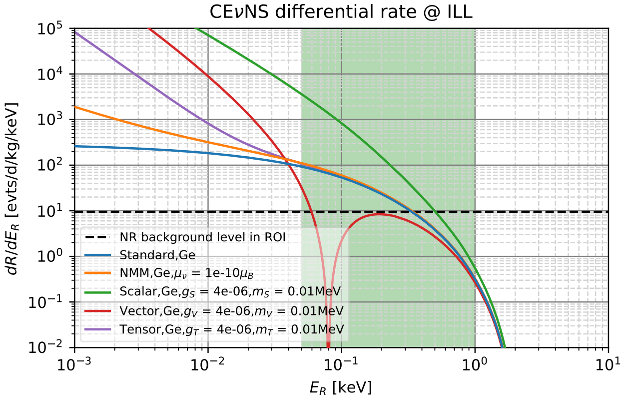


Estimated total event rate : 10.8 evts/day/kg in ROI.

Recoil spectra

Differential recoil rate calculation :

$$\frac{dR}{dE_R} = \frac{1}{m_N} \int_{E_\nu > E_{\nu,\mathbf{min}}} \Phi(E_\nu) \frac{d\sigma_{\nu-N}}{dE_R} dE_\nu$$



Analysis and results

Statistic analysis

Based on a likelihood function :

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\theta}) = \mathcal{L}(\boldsymbol{\theta}) \times \prod_{i}^{N_{\text{bins}}} P\left(N_{i,\text{obs}} | N_{i,\text{sig}}(\boldsymbol{\mu}, \boldsymbol{\theta}) + N_{i,\text{bg}}(\boldsymbol{\theta}) + \Delta N_{i,\text{sig}}^{\text{cal}}(\boldsymbol{\mu}, \theta_{\text{cal}})\right)$$

Nuisance parameters and uncertainties :

- θ_{bg} : background normalisation ; $\sigma_{bg} = 4.7\%$ (50j) or $\sigma_{bg} = 1.9\%$ (300j).
- θ_{sig} : signal normalisation ; $\sigma_{sig} = 3\%$
- θ_{cal} : energy calibration error ; $\sigma_{cal} = 2\%$

Statistic analysis

Profiled likelihood ratio :

$$\lambda(\boldsymbol{\mu}) = \frac{\mathcal{L}(\boldsymbol{\mu}, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\theta}})}$$

Test used for detection sensitivity q_0 :

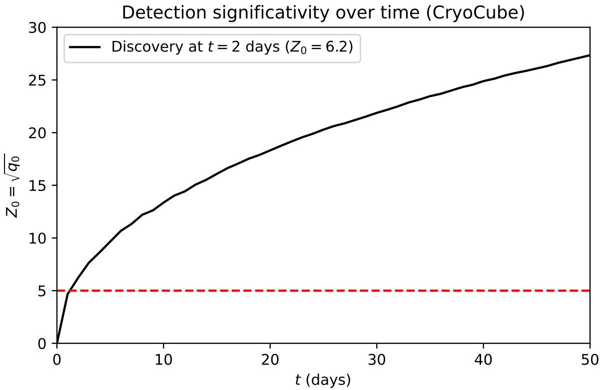
$$q_0 = \begin{cases} -2\ln\lambda(0) & \text{if } \hat{\mu} \geq 0 \\ 0 & \text{else} \end{cases}$$

Test used for calculating upper limits q_μ :

$$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \text{if } \hat{\mu} \leq \mu \\ 0 & \text{else} \end{cases}$$

Analysis done with Asimov data and corresponding asymptotic formulae (see arxiv :1007.1727).

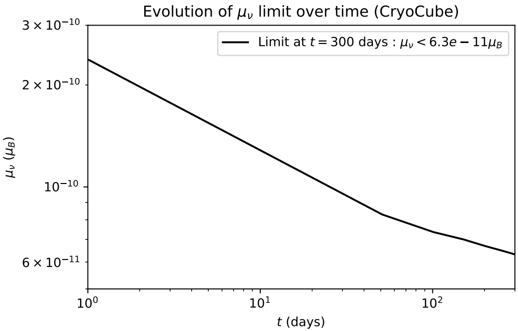
Results (SM CENNS)



Discovery of CEνNS within few days !

50 days precision : $\sim 3\%$; 300 days precision $\sim 1.2\%$

Results (NMM)



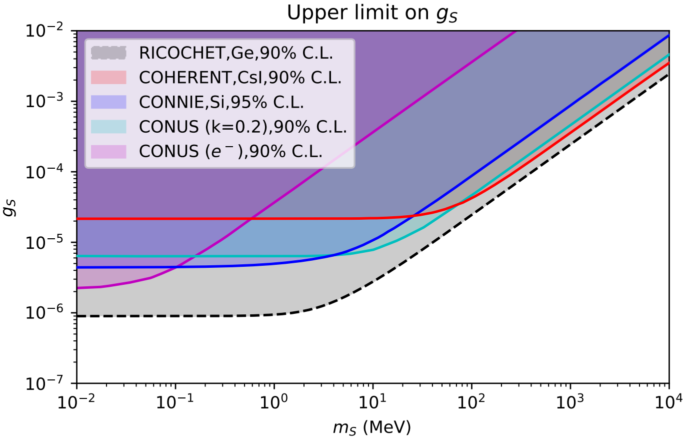
300d limit : $\mu_\nu < 6.3 \times 10^{-11}\mu_B$ (90% C.L.)

Limits from other experiments :

- BOREXINO : $\mu_\nu < 2.8 \times 10^{-11}\mu_B$ (90% C.L.)
- COHERENT : $\mu_\nu < 4.3 \times 10^{-10}\mu_B$ (90% C.L.)

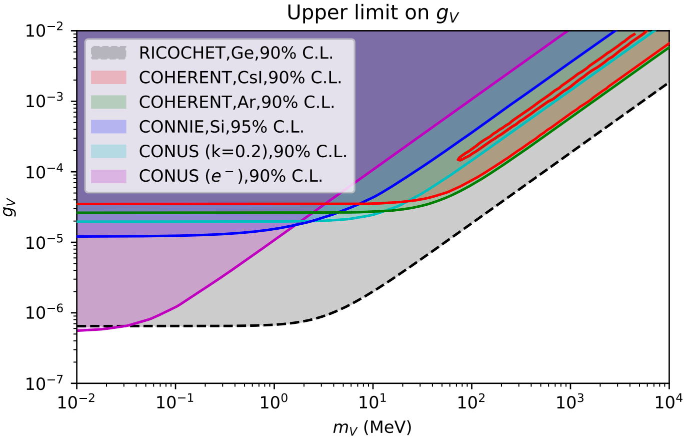
Results (NGI)

Exclusion plot in phase spcace (m_S, g_S) with universal coupling $(Q_{\nu,S} = Q_{q,S} = 1$ i.e. $g_{\nu,S} = g_{q,S})$ (original plot in arxiv :2110.02174)



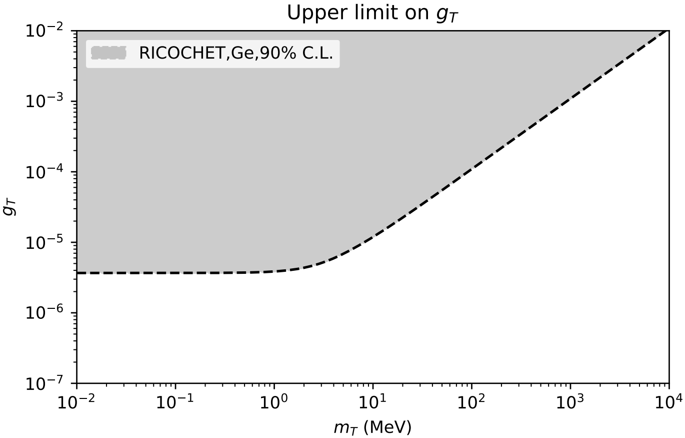
Results (NGI)

Exclusion plot in phase space (m_V, g_V) with universal coupling $(Q_{\nu,V} = Q_{q,V} = 1$ i.e. $g_{\nu,V} = g_{q,V})$ (original plot in arxiv :2110.02174)



Results (NGI)

Exclusion plot in phase space (m_T, g_T) with universal coupling $(Q_{\nu,T} = Q_{q,T} = 1$ i.e. $g_{\nu,T} = g_{q,T})$ (not as popular, poor tensor needs love :( )



Conclusion & perspectives

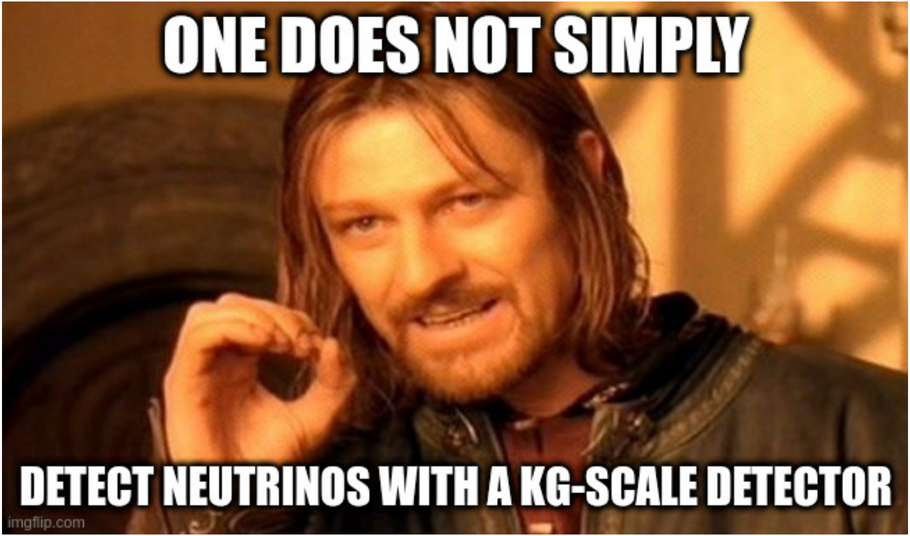
Summary :

- CEνNS measurement is a growing domain in the neutrino/physics community ;
- RICOCHET should detect CEνNS above 5σ discovery threshold within 1 cycle of reactor ON ; it should also improve current limits obtained by other running CEνNS experiments.

Possible improvements of the analysis :

- Take into account ER background and detector efficiencies.
- Better model the background (from GEANT4 simulations for example).
- Support OFF measurements in likelihood function for constraining backgrounds.

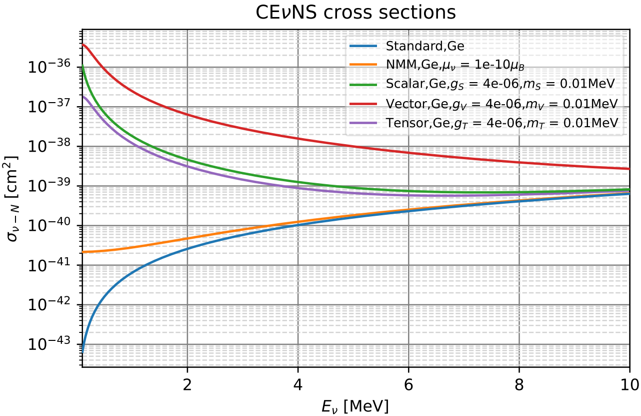
Thank you for your attention !



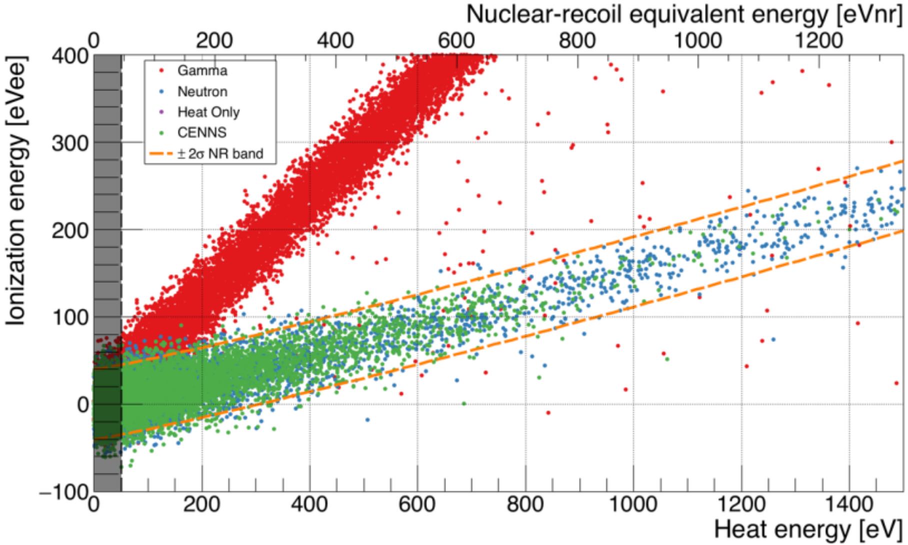
Backup

Total cross sections

CEνNS is the dominant process at reactor neutrino energies (at 10 MeV : 100 times greater CS than IBD)

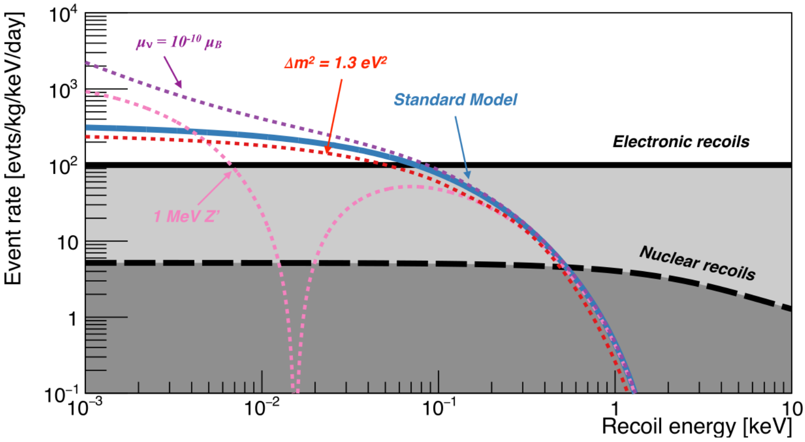


ER/NR discrimination



More precise background curves

From last RICOCHET status paper (arxiv.org :2111.06745)



Nuclear weak charge degeneracy (new vector boson model)

The degeneracy band $Q_{tot} = -Q_W$ does exist but is very thin and hard to compute numerically.

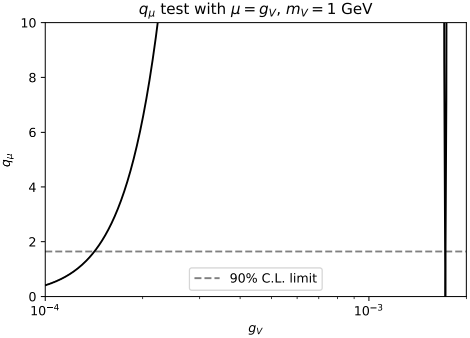


Figure 2 – $q_\mu(g_V)$ with 401 test values of g_V