BSM physics in neutrino scattering[1]

Xun-Jie Xu[a]

[a]Max-Planck-Institut für Kernphysik, Heidelberg

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[1]Based on 1612.04150, 1702.05721, in collaboration with Manfred Lindner, Werner Rodejohann and Carlos Yaguna.

Outline

1. Introduction to neutrino scattering
   - What
   - Why
   - How
2. Coherent ν-nucleus scattering
   - Concept
   - Constraints on NSI and SPVAT
3. Dirac/Majorana neutrinos with new interactions
   - Distinguish Dirac/Majorana in ν scattering
   - Experimental constraints

What is neutrino scattering?

$$\nu + X \to \cdots + \text{(observable final states)}$$

- $X = e^-$, proton, neutron, nucleus (e.g. Ge, Xe, O, ...).
- Intensive neutrino sources and large detectors.

Why do we study neutrino scattering?

- neutrinos: portal of new physics
  - ν Osc. $\Rightarrow m_\nu \sim \mathcal{O}(10^{-2})\,\mathrm{eV} \Rightarrow$ BSM model building $\Rightarrow$ new interactions
- in ν scattering: very weak SM int. + new int.
  in collider: stronger SM int. + new int.
  - very low SM background $\Rightarrow$ very clean for BSM physics

How to detect?

Elastic

$$\nu + X \to \nu + X$$

e.g. $X = e^-$, $^{76}\mathrm{Ge}$. Only recoil observable. CHARM II, TEXONO

Quasi-elastic

$$\nu + X \to \ell + Y$$

e.g. $\overline{\nu}_e + p \to e^+ + n$ (IBD, reactor), $\nu_\mu + ^{18}\mathrm{O} \to \mu^- + ^{18}\mathrm{F}$ (CCQE, T2K)

Deep inelastic

$$\nu + X \to \cdots (\text{dirty final states!!})$$

e.g. IceCube. using μ track to identify ν_μ.

Elastic scattering

I will focus on elastic scattering:

Elastic

$$\nu + X \to \nu + X$$

- $X = e^-$, elastic ν-electron scattering.
  - CHARM II, TEXNON, LSND...
  - contributes to EW precision test
    - e.g. $\sin^2\theta_W = 0.2324 \pm 0.0083$ (CHARM II, 1994)
- $X =$ nucleus, **Coherent** ν-nucleus scattering.
  - recently observed by COHERENT (6.7σ, **Aug. 2017**), CONUS is running, results coming soon.

Coherent ν-nucleus scattering

What is "Coherent" neutrino-nucleus scattering?

Without Coherency: neutrino wavelength $\ll$ nucleus radius

Sum over cross sections

$$\sigma_{\text{tot}} = \sigma_p + \sigma_p + \cdots + \sigma_n + \sigma_n + \cdots$$

With Coherency: neutrino wavelength $\gg$ nucleus radius

Sum over amplitude, then square

$$i\mathcal{M} = i\mathcal{M}_p + i\mathcal{M}_p + \cdots + i\mathcal{M}_n + i\mathcal{M}_n + \cdots$$

$$\sigma_{\text{tot}} = |i\mathcal{M}_p + i\mathcal{M}_p + \cdots + i\mathcal{M}_n + i\mathcal{M}_n + \cdots|^2$$

Coherent ν-nucleus scattering

Cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 \left[N - (1 - 4s_W^2)Z\right]^2 M_{\text{nucleus}}}{4\pi} \left(1 - \frac{T}{T_{\max}}\right)$$

T: recoil energy, N&Z: neutron&proton numbers

- Large cross section for large N
  - because $1 - 4s_W^2 \approx 0$, $\frac{d\sigma}{dT} \propto N^3$.
- Although large, difficult to detect, T too low,
  - $T_{\max}$ determined by kinetics, 1 MeV neutrino $\Rightarrow$ $T_{\max} \approx$0.1 keV
- Modern tech: ultra-low threshold detection
  - thanks to dark matter experiments

Example

100 kg Ge

Threshold: 0.1 keV

1GW nuclear reactor

Distance: 10m

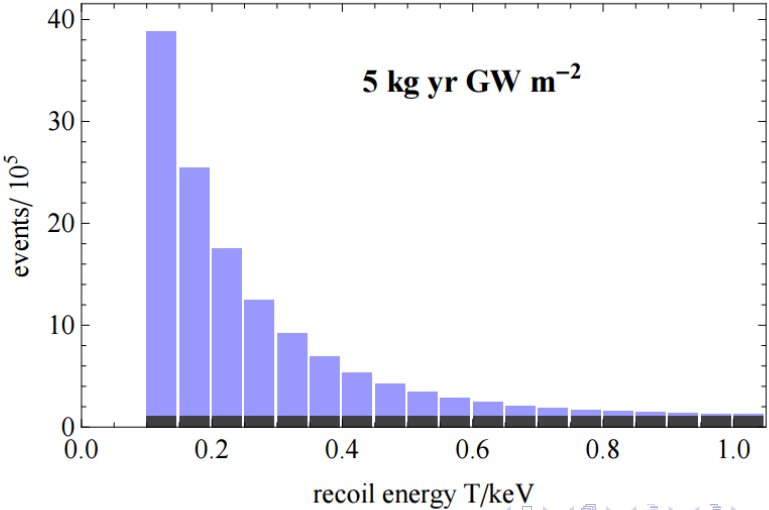
→

Event number:

$7.6 \times 10^6/\mathrm{yr}$

Distribution

Reactor neutrino flux taken from:
V. I. Kopeikin, 2012



Coherent ν-nucleus scattering

Large event number

1. Small, portable detector

2. Precise measurement of neutrino interactions and EW parameters

$$\text{E.g. } \sin^2\theta_W = 0.238 \pm 0.0022$$

(Optimistic estimation in 1612.04150)

3. Finding new physics

$$\text{E.g. NSI, sterile neutrinos, } Z',\ \mu_\nu \ldots$$

new interactions

- If the mediator is heavy, integrated out
  - new gauge bosons (e.g. Z') $\Rightarrow$ NSI (in this talk)
  - any kinds of mediators $\Rightarrow$ SPVAT (in this talk)
- If the mediator is light (WARNING: astrophysical constraints!)
  - interesting case: mediator = photon
    - neutrino magnetic moment μ_ν (cf. 1510.01684, 1706.02555...)
  - or other light mediator
    - cf. 1612.06350, 1711.04531, 1703.00054, 1710.10889...

new interactions

If mediated by a new gauge boson (e.g. Z'), integrated out $\Rightarrow$ NSI

NSI (Non-Standard Interaction)

$$\mathscr{L} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta \left[\overline{q} \gamma^\mu (\varepsilon^{qV}_{\alpha\beta} + \varepsilon^{qA}_{\alpha\beta} \gamma^5) q \right],$$

- Lepton Flavor Violation (LFV)
- Still V-A in $\overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta$, because only left-handed ν
- the only change in $d\sigma/dT$, $Q^2 : Q^2_{\rm SM} \to Q^2_{\rm NSI}$

$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M_{\rm nucleus}}{4\pi} \left(1 - \frac{T}{T_{\rm max}}\right)$$

new interactions

If mediated by any kinds of forces, integrated out $\Rightarrow$ SPVAT

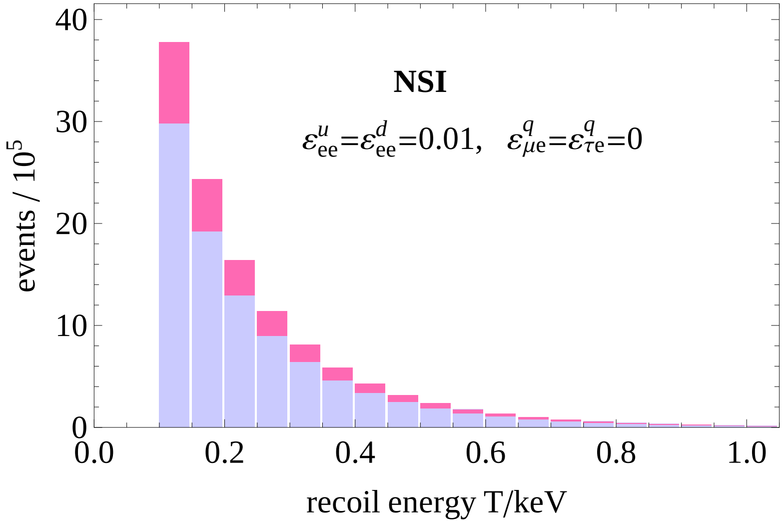
SPVAT (Scalar, Pseudo-S, Vector, Axial-V, Tensor)

$$\mathscr{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a \nu \left[\overline{\psi}\Gamma^a (C_a + D_a i\gamma^5)\psi\right],$$

$$\Gamma^a = \{1, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]\}.$$

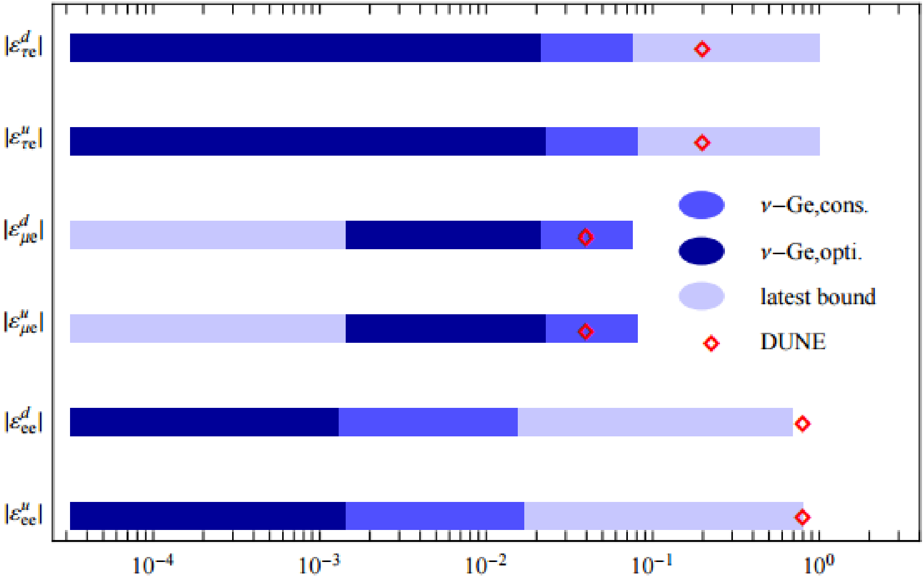
- Scalar (Pseudo-S) mediator $\Rightarrow$ 1 ($i\gamma^5$)
- Charged scalar (Pseudo-S) mediator $\Rightarrow$ 1 ($i\gamma^5$)+$\sigma^{\mu\nu}$
- Vector (Axial-V) mediator $\Rightarrow$ $\gamma^\mu, \gamma^\mu\gamma^5$
- contains all possible Lorentz-invariant interactions

NSI signal



NSI
$\varepsilon^u_{ee}=\varepsilon^d_{ee}=0.01, \quad \varepsilon^q_{\mu e}=\varepsilon^q_{\tau e}=0$
events / 10^5
recoil energy T/keV
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0

Constraint on NSI



NSI review: Davidson et al, hep-ph/0302093

SPVAT

SM cross section:

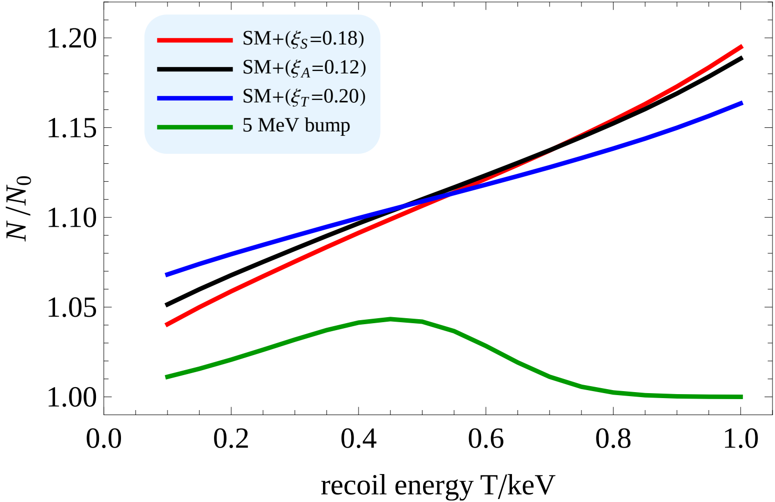
$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M}{4\pi}\left(1 - \frac{T}{T_{\max}}\right)$$

SPVAT cross section:

$$\frac{d\sigma}{dT} = \frac{{G_F}^2 Q^2 M}{4\pi}\left(\boxed{\cdots} \times 1 - \boxed{\cdots} \times \frac{T}{T_{\max}} + \boxed{\cdots} \times \frac{MT}{4E_\nu^2}\right)$$

$\Rightarrow$ distortion of the recoil spectrum

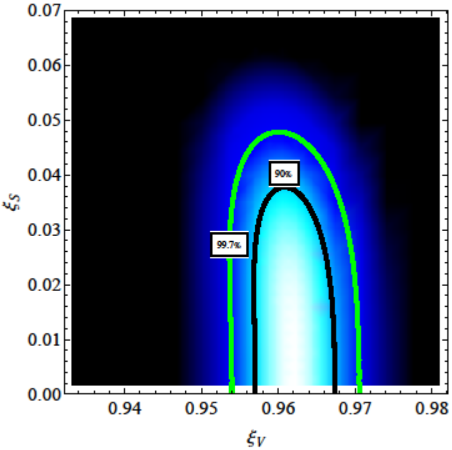
Spectrum distortion by SPVAT



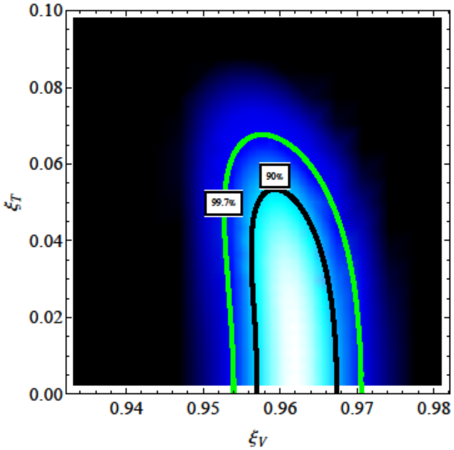
$$\xi_S^2 = \frac{1}{N^2}(C_S^2 + D_P^2),\ \xi_T^2 = \frac{8}{N^2}\left(C_T^2 + D_T^2\right),\ \xi_V = \frac{1}{N}(C_V - D_A),\ \xi_A = \frac{1}{N}(C_A - D_V)$$

Constraint on SPVAT

Constraint on Scalar



Constraint on Tensor



$$\xi_S^2 = \frac{1}{N^2}(C_S^2 + D_P^2),\ \xi_T^2 = \frac{8}{N^2}\left(C_T^2 + D_T^2\right),\ \xi_V = \frac{1}{N}(C_V - D_A),\ \xi_A = \frac{1}{N}(C_A - D_V)$$

A long standing problem....
Are neutrinos Dirac or Majorana particles?

A better way to ask:
Are their masses Dirac or Majorana?

$$\mathscr{L}_D = m_\nu \overline{\nu}\nu, \ \mathscr{L}_M = \frac{1}{2} m_\nu \overline{\nu}^c \nu$$

$m_\nu = \mathscr{O}(10^{-2})$ eV measured by oscillation

Dirac or Majorana?

Most promising approach

neutrinoless double beta decay ($0\nu\beta\beta$)

Alternative

Could be solved by neutrino scattering, if new interactions exist.

The difference between D & M

Only SM interactions:

difference suppressed by mass

$$D - M \propto m_\nu$$

e.g.

$$0\nu\beta\beta \propto |M_{ee}|$$

also applies to any process other (ν scattering, Z decay)

Because:

$$\lim_{m_\nu \to 0} = \mathrm{SM}$$

with new interactions:

difference not suppressed

$$D - M \propto \mathrm{new\ int.}$$

An early (1982) work by Rosen

VOLUME 48, NUMBER 13 PHYSICAL REVIEW LETTERS 29 MARCH 1982

Analog of the Michel Parameter for Neutrino-Electron Scattering: A Test for Majorana Neutrinos

S. P. Rosen

Physics Department, Purdue University, West Lafayette, Indiana 47907, and Physics Division, National Science Foundation, Washington, D. C. 20550[(a)]

(Received 23 December 1981)

- Assume most general 4-fermion interactions (SPVAT)
- Proposed Rosen's ratio R_ρ
  - Define:

$$R_\rho \equiv \frac{\text{forward cro. sec.}}{\text{backward cro. sec.}}$$

  - in SM

$$R_\rho = 2$$

  - with new int.

$$0 \leq R_\rho \leq 2 \text{ (Majorana)}$$
$$0 \leq R_\rho \leq 4 \text{ (Dirac)}$$

Dirac neutrinos have larger parameter space

Most general interactions (SPVAT)

$$\mathscr{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a \nu \left[\overline{\ell}\Gamma^a (C_a + D_a i\gamma^5)\ell\right]$$

$\Gamma^a = \{1, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]\}$

Dirac neutrinos

$2 \times 5 = 10$ coupling constants: C_a, D_a, $(a = S,\ P,\ V,\ A,\ T)$

Majorana neutrinos

$10 - 4 = 6$ coupling constants:

$$C_V = D_V = C_T = D_T = 0$$

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a \nu \left[\overline{\ell}\Gamma^a (C_a + D_a i\gamma^5)\ell\right]$$

$$\frac{d\sigma}{dT}(\nu + \ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2\right]$$

T: Recoil energy, $(A,\, B,\, C)$ = functions of $(C_a,\, D_a)$.

Rosen's ratio:

$$R_\rho \equiv \frac{2(A+2B+C)}{A+C}$$

$C_V = D_V = C_T = D_T = 0$ (Majorana)

$0 \leq R_\rho \leq 4$ (Dirac),

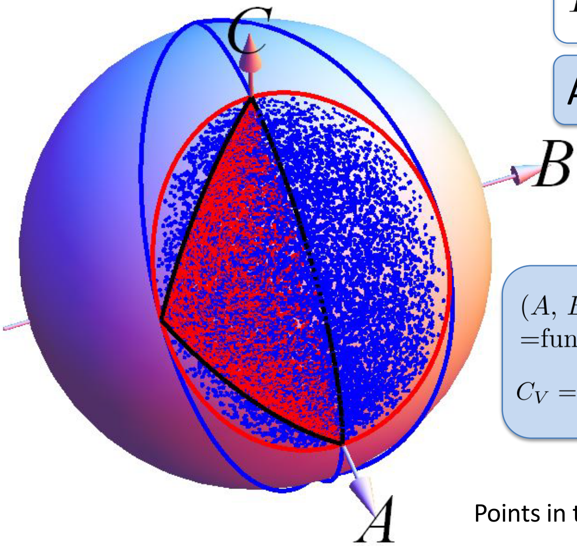
$0 \leq R_\rho \leq 2$ (Majorana).

$$\frac{d\sigma}{dT}(\nu+\ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1-\frac{T}{E_\nu}\right) + C\left(1-\frac{T}{E_\nu}\right)^2\right]$$

$$R_\rho \equiv \frac{2(A+2B+C)}{A+C}$$

Any other ratios?

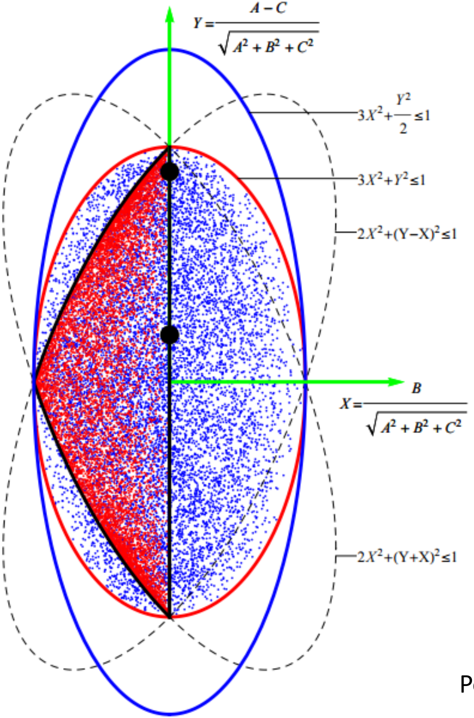
Yes



$(A,\ B,\ C)$
=functions of 10 parameters in $\mathcal{L}$.

$C_V = D_V = C_T = D_T = 0$ (Majorana)

Points in the plot: **Dirac** / **Majorana**



2D Projection

$$X \equiv \frac{B}{R}, \; Y \equiv \frac{A-C}{R},$$

$$R \equiv \sqrt{A^2 + B^2 + C^2}$$

Dirac bound

$$3X^2 + Y^2 \le 1$$

Proof: see 1702.05721

Majorana bound

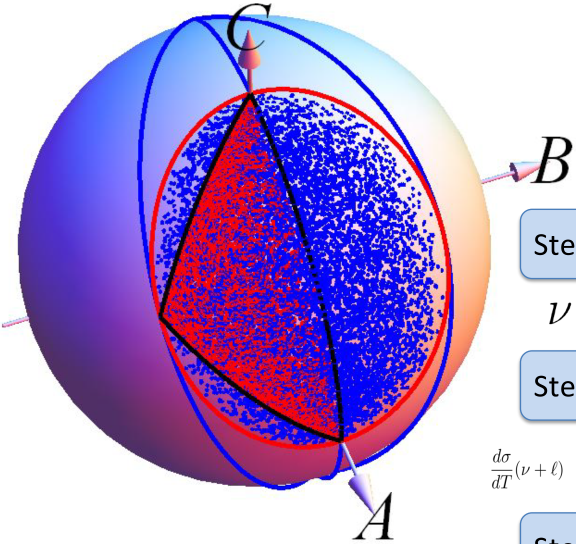
$$2X^2 + (Y \pm X)^2 \le 1$$

$$\text{and} \quad X \le 0$$

Proof: see 1702.05721

Points in the plot: **Dirac** / **Majorana**

D/M? How to Distinguish?



Step 1: neutrino scattering

$$\nu + e^- \to \nu + e^-$$

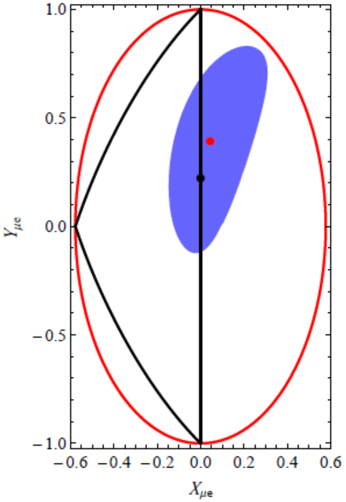
Step 2: measure A B C

$$\frac{d\sigma}{dT}(\nu+\ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1-\frac{T}{E_\nu}\right) + C\left(1-\frac{T}{E_\nu}\right)^2\right]$$

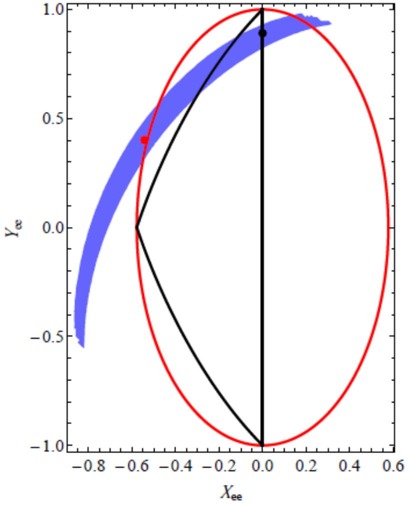
Step 3: look at this ball

Current experiments

CHARM-II

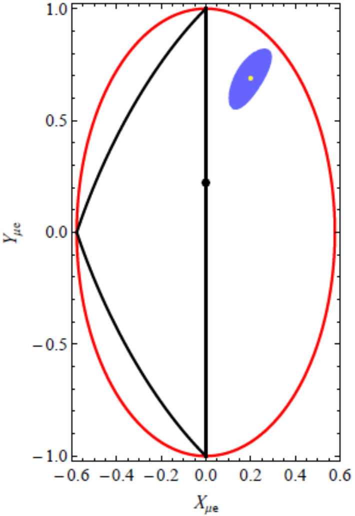


TEXONO

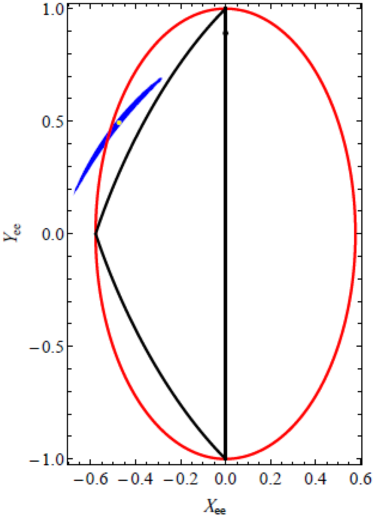


Future, ¼ uncertainties

CHARM-II



TEXONO



Can coherent be used?

$$\frac{d\sigma}{dT}(\nu + \ell) = \frac{{G_F}^2 M}{2\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{MT}{4E_\nu^2}\right],$$

$$\frac{d\sigma}{dT}(\overline{\nu} + \ell) = \frac{{G_F}^2 M}{2\pi}\left[C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{MT}{4E_\nu^2}\right],$$

Conclusion: No

Summary

- Coherent ν-nucleus scattering would be very powerful in searching for BSM physics
  - NSI, SPVAT, ...
- Dirac/Maojarana could be solved by neutrino scattering (if new interactions exist).