Electromagnetic properties of neutrinos

Jarek Nowak

University of Minnesota

High Energy seminar, University of Virginia

Outline

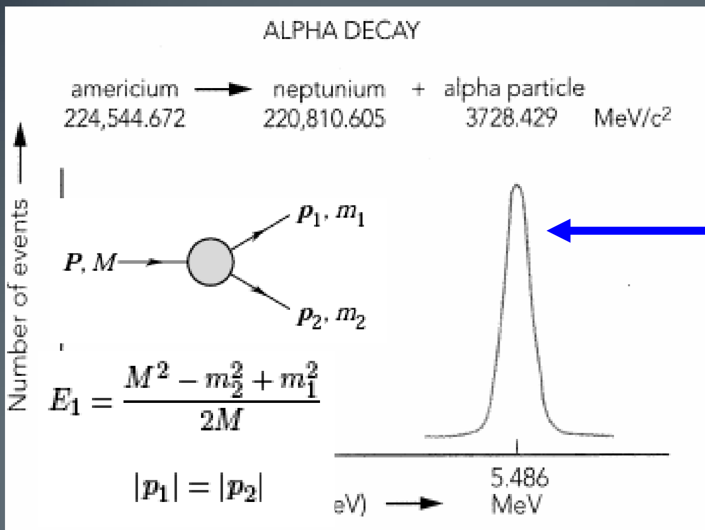
- Properties of massive neutrinos in the Standard Model.
- Electromagnetic properties of neutrinos.
- Neutrino magnetic moment.
- Results from neutrino experiments.
- Constrains from astrophysical observations.

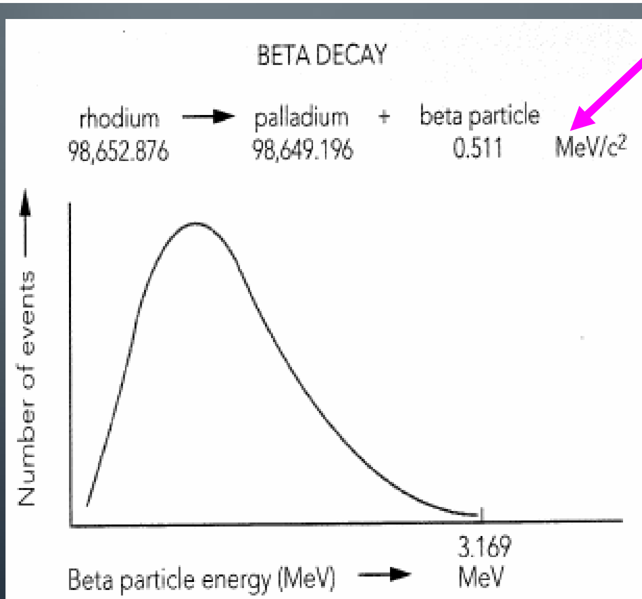
I had to reschedule this seminar twice

November: Stuck in Brazil

March: Stuck in Minnesota

Why Neutrinos?

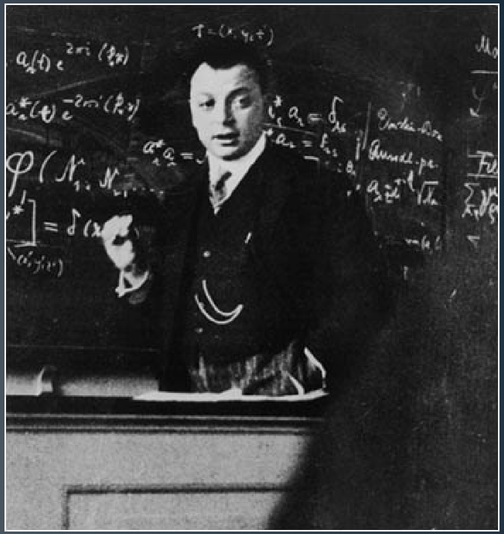


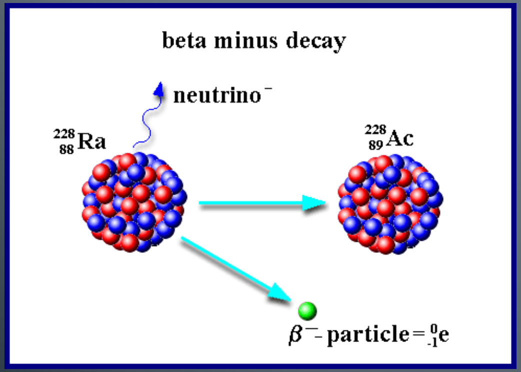


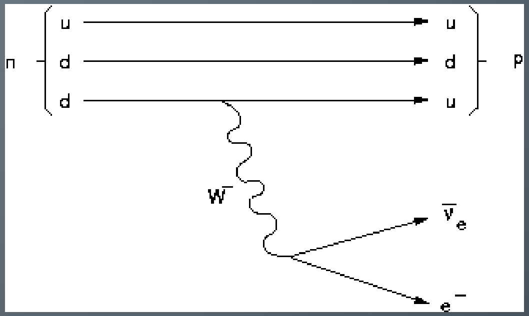
- 2 body alpha decay, E of decay products always the same
- 1913 - 1930 : beta decay = continuous spectrum of E
  - E not conserved?
  - P not conserved?
- "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." (Pauli, 1930)

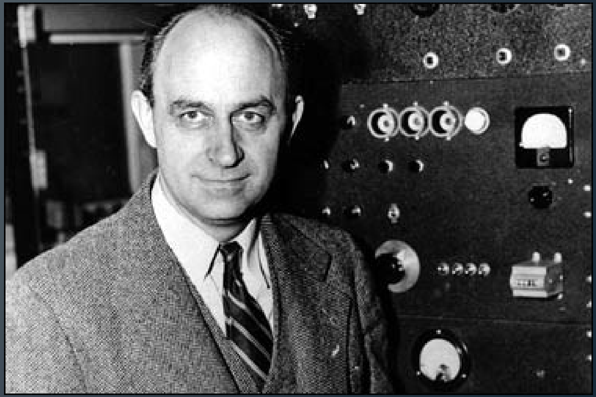
About Neutrino

- Wolfgang Pauli postulated existence of neutrino ("little neutral ones") in order to explain the missing energy in nuclear β^{-} decay in 1930.
- Enrico Fermi presented theory of beta decay in 1934.



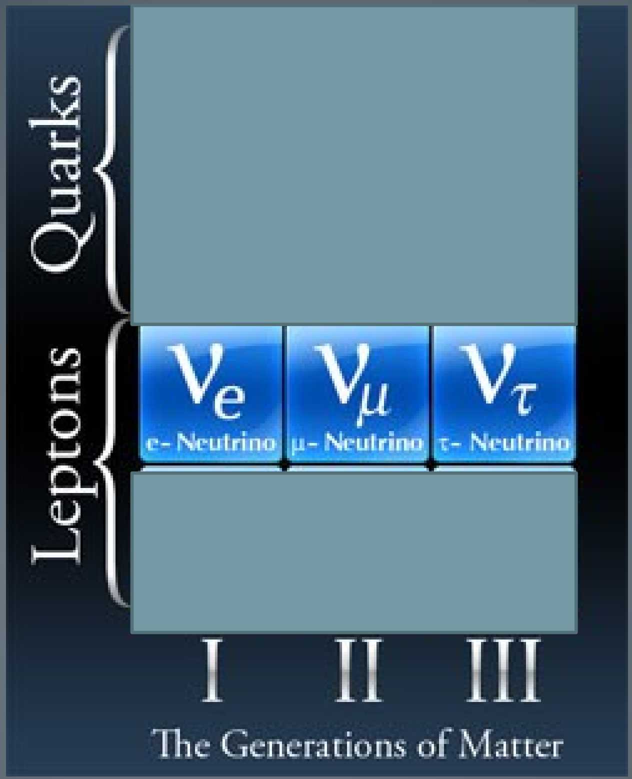






$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$

Neutrinos in the Standard Model

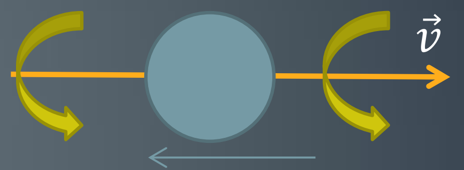


- Force Carriers: Bosons
  - EM: Photon
  - Strong Force: Gluon (8)
  - Weak Forces: W^+, W^-, Z^0

Neutrinos are massless

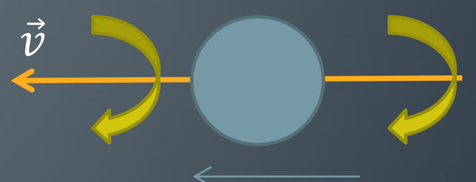
Neutrinos only interact via the Weak force

Neutrinos are left-handed (anti clock-wise)



spin

anti-neutrinos are right-handed



Neutrinos are electrically neutral

Neutrinos have three flavors

electron, muon, tau

Pontecorvo hypothesis

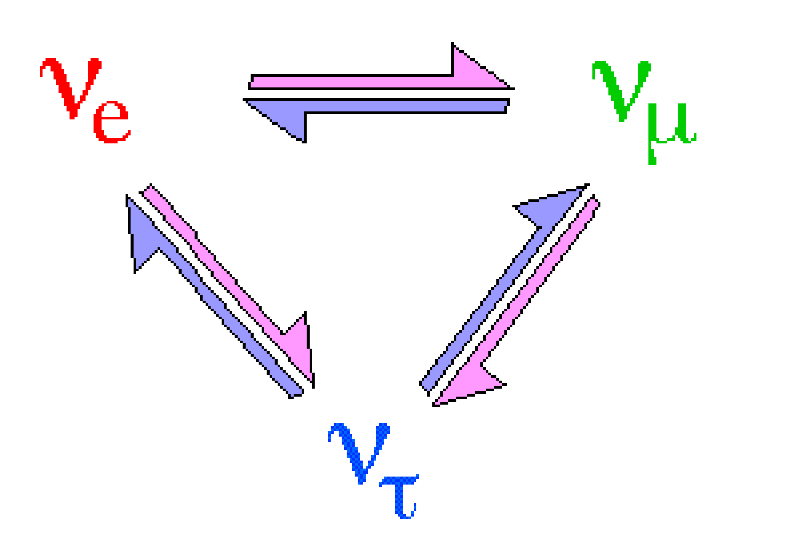
- Back in 1957, Pontecorvo pointed out that if ν's have mass, then it could be the case that the mass eigenstates were not identical to the weak

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Bruno Pontecorvo

- Similar to kaon mixing where it was already known that the weak and strong (mass) eigenstates differed

Given type of neutrino is always produced in one of the charged leptons flavor e, μ and τ.



But they change their identity while traveling

Neutrino Oscillations (2 flavors)

(For 3 ν flavors mixing, it needs 3×3 unitary matrix with CP-violating phase.)

Flavor eigenstates **Mass eigenstates**

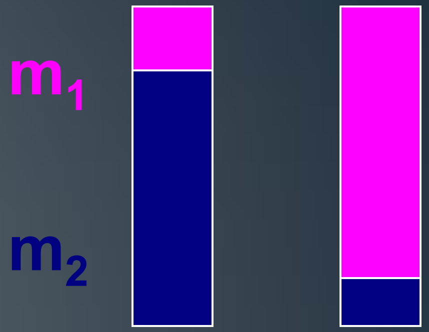
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

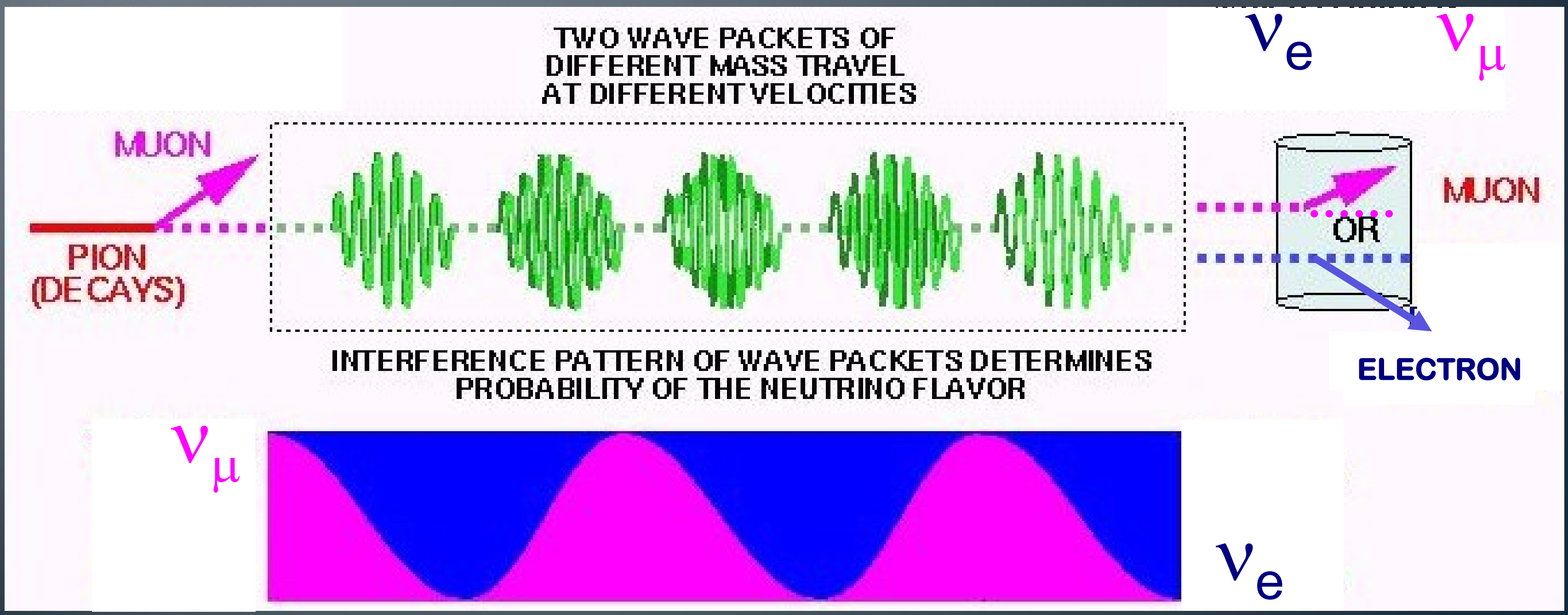
$$|\nu_\mu(t)\rangle = -\sin\theta\, |\nu_1\rangle + \cos\theta\, |\nu_2\rangle$$

e^{-iE1t} e^{-iE2t}

Neutrino Oscillations (2 flavors)

Neutrino flavor states are comprised of mass states





Neutrino Oscillations (2 flavors)

Δm^2 is the difference of the squared masses of the two neutrino states (eV^2)

Distance from neutrino beam creation point to detection point (m,km)

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

θ is the mixing angle

E is the energy of the neutrino (MeV,GeV)

Neutrino Sources

- **Solar : ~ 0.1 - 15 MeV (10^6 eV)**
  - from fusion inside of stars
  - 85% from p+p -> $^2H + e^+ + \nu_e$
- **Man-Made : ~few MeV**
  - Nuclear reactors - byproduct
- **Man-Made : ~ 0.5 MeV - 1 GeV (10^9 eV)**
  - Accelerators - DAR, DIF
- **Atmospheric : ~1 - 10 GeV**
  - cosmic rays = proton from outer space + atm = showers, creates atmospheric neutrinos
  - Same as accelerator

Ray Davis' experiment

- Ray Davis set out to measure solar ν's
- Used a large vat of dry cleaning solution
- Looking for inverse beta decay (CC) with Chlorine converting to Argon
- Deep underground at Homestake gold mine to get away from cosmic ray background

- First oscillation evidence came in 1968 from Davis' solar ν_e experiment
- found 1/3 of the expected ν_e from sun disappearance $\nu_e \rightarrow \nu_x$
- $\Delta m_{12}^2 \sim 8\text{x}10^{-5}$ eV^2, $\sin^2(2\theta) \sim 0.8$
- Controversial result, do we understand fusion, is the experiment correct, could it be due to neutrino oscillation?

The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Still unknown

- (12) Sector: Reactor + Solar, L/E~15,000 km/GeV

$$^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2 \qquad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \qquad ^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \text{C.L.})$$

- (13) Sector mixing observed

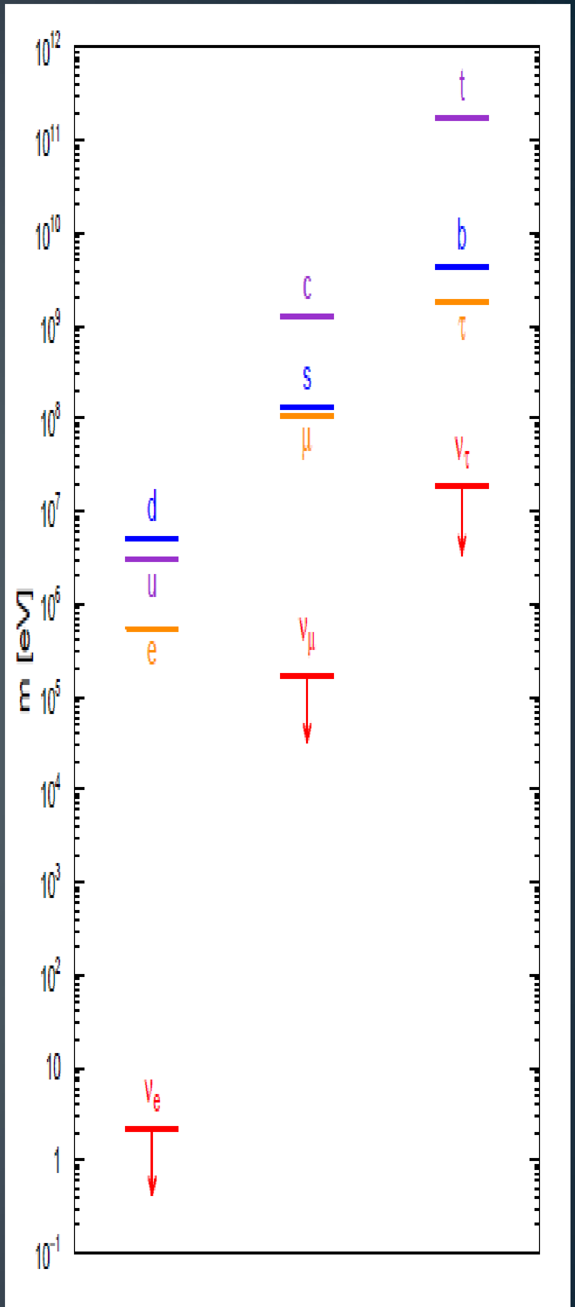
$$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$$

†PRD 83.052002(2011)
††PRL 106. 181801(2011)
*SuperK Preliminary, Nu2010
** Eur.Phys. C27:331-374,2003

Nature of neutrinos

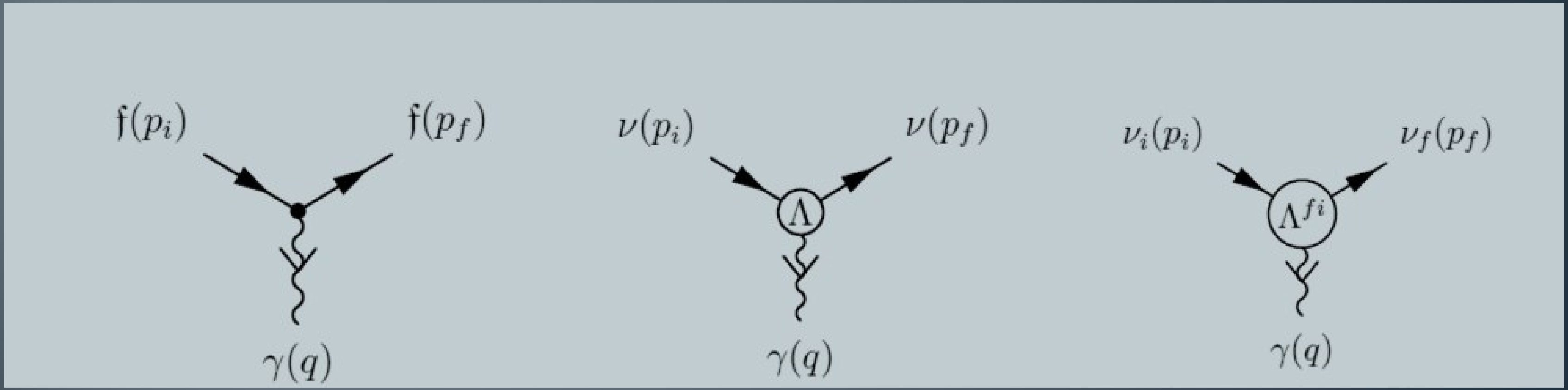
- Neutrinos are not massless, but their mass is very small.
- If neutrinos have mass they travel with $v < c$

- Neutrinos as neutral fermions can be Dirac or Majorana particles.
  - Dirac neutrinos: particle and antiparticle are different
  - Majorana neutrinos are the same particle as antineutrinos.



EM properties of neutrinos

- Neutrino electromagnetic properties can be used to distinguish Dirac and Majorana neutrinos
- Probes of new physics that might exist beyond the Standard Model



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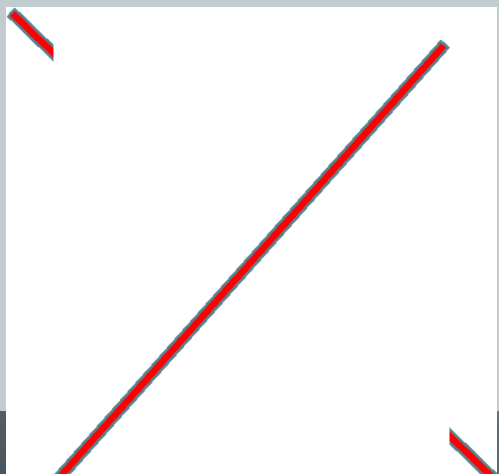

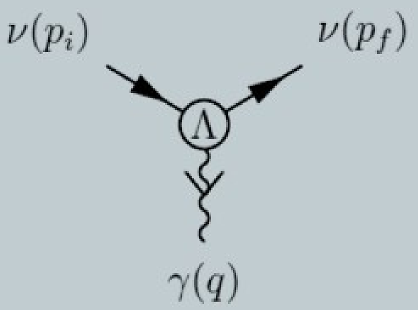

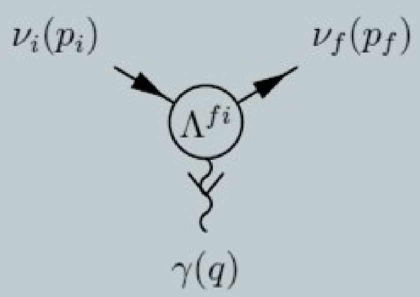

Because neutrino electric charge is zero

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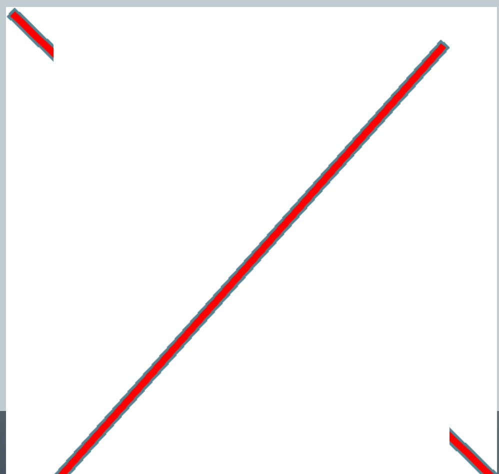
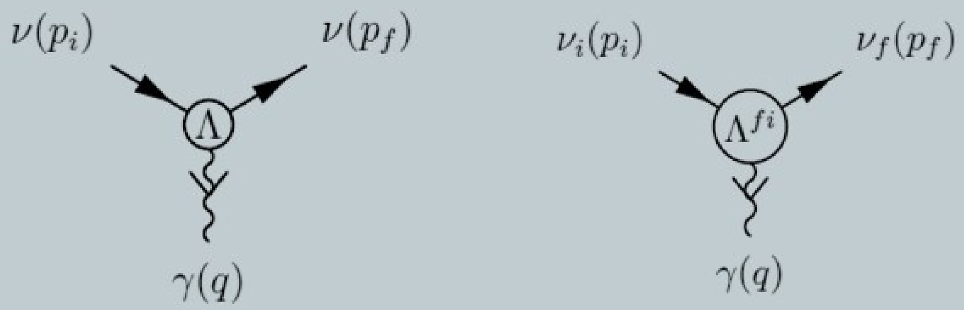




Because neutrino electric charge is zero

Neutrino interaction due to EM moments can occur at the loop level.

Helicity flip (left-handed to right-handed)

Magnetic moment in minimal extended SM

- For Dirac neutrinos

$$\left.\begin{matrix}\mu_{ij}^{\mathrm{D}}\\ \epsilon_{ij}^{\mathrm{D}}\end{matrix}\right\} = \frac{eG_F}{8\sqrt{2}\pi^2}(m_i \pm m_j)\sum_{l=e,\mu,\tau} f(a_l)U_{li}^{*}U_{lj},$$

$$a_l = m_l^2/m_W^2$$

- For small $a_l << 1$

$$f(a_l) \simeq \frac{3}{2}\left(1 - \frac{a_l}{2}\right)$$

- The diagonal magnetic moments are

$$\mu_{ii}^{\mathrm{D}} \simeq \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=e,\mu,\tau} a_l |U_{li}|^2\right)$$

Proportional to neutrino mass

For the leading order it is independent on mixing matrix element

$$\mu_{ii}^{\mathrm{D}} \simeq 3.2 \times 10^{-19}\left(\frac{m_i}{\mathrm{eV}}\right)\mu_B$$

Diagonal elements

- In the extended Standard Model with right-handed neutrinos

$$\left.\begin{array}{c}\mu_{ij}^{\mathrm{D}}\\ \epsilon_{ij}^{\mathrm{D}}\end{array}\right\} = \frac{eG_F}{8\sqrt{2}\pi^2}(m_i \pm m_j)\sum_{l=e,\mu,\tau} f(a_l)U_{li}^{*}U_{lj},$$

- The diagonal dipole electric moment for Dirac neutrinos vanishes

$$\epsilon_{ii}^{\mathrm{D}} = 0$$

- For the Majorana neutrinos both electric and magnetic diagonal moments vanish (matrix is anti-symmetric, CPT invariance)

$$\mu_{ii}^{\mathrm{M}} = \epsilon_{ii}^{\mathrm{M}} = 0$$

Neutrino transition moments

- Neutrino transition moments are off-diagonal element of

$$\left.\begin{array}{c}\mu_{ij}^{\mathrm{D}}\\ \epsilon_{ij}^{\mathrm{D}}\end{array}\right\} = \frac{eG_F}{8\sqrt{2}\pi^2}(m_i \pm m_j)\sum_{l=e,\mu,\tau} f(a_l)U_{li}^* U_{lj},$$

- First non-vanishing elements come from the second term in expansion of $f(al)$ with $a_l = m_l^2/m_W^2$

$$\left.\begin{array}{c}\mu_{ij}^{\mathrm{D}}\\ \epsilon_{ij}^{\mathrm{D}}\end{array}\right\} \simeq -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j)\sum_{l=e,\mu,\tau}\left(\frac{m_l}{m_W}\right)^2 U_{li}^* U_{lj}, \qquad \text{for } i \neq j$$

- The transition moments are suppressed wrt diagonal moments

$$\left.\begin{array}{c}\mu_{ij}^{\mathrm{D}}\\ \epsilon_{ij}^{\mathrm{D}}\end{array}\right\} \simeq -4\times 10^{-23}\left(\frac{m_i \pm m_j}{\mathrm{eV}}\right) f_{ij}\,\mu_B, \qquad f_{ij} = \sum_{l=e,\mu,\tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{li}^* U_{lj}.$$

Transition moment for Majorana neutrinos

- For Majorana neutrinos the transition moments may be non-vanishing.
- Assuming CP conservation, if ν_i and ν_j have the same CP phase

$$\mu_{ij}^{\mathrm{M}} = 0 \qquad \text{and} \qquad \epsilon_{ij}^{\mathrm{M}} = 2\epsilon_{ij}^{\mathrm{D}},$$

- And when ν_i and ν_j have opposite CP phase

$$\mu_{ij}^{\mathrm{M}} = 2\mu_{ij}^{\mathrm{D}} \qquad \text{and} \qquad \epsilon_{ij}^{\mathrm{D}} = 0,$$

- Those moments are still suppressed wrt. diagonal moments.

Effective magnetic moment

- Magnetic moment that is measured in experiment is not that of a massive neutrino, but it is an effective magnetic moment which takes into account neutrino mixing during the propagation between source and detector

$$\mu_\nu^2(\nu_\alpha, L, E) = \sum_j \left| \sum_k U_{\alpha k}^* e^{-i m_k^2 L/2E} \left(\mu_{jk} - i\epsilon_{jk}\right) \right|^2$$

- Only for the magnetic moment

$$\mu_\nu^2(\nu_\alpha, L, E) = \sum_j \sum_{kk'} U_{\alpha k}^* U_{\alpha k'} e^{-i\Delta m_{kk'}^2 L/2E} \mu_{jk} \mu_{jk'}.$$

- And in the case of Dirac neutrino with only diagonal moment it simplifies to

$$\mu_\nu^2(\nu_\alpha, L, E) \to (\mu_\alpha^{\mathrm{D}})^2 = \sum_i |U_{\alpha i}|^2 \mu_i^2.$$

Neutrino Magnetic moment models

- If the neutrino magnetic moment is greater than

$$\mu_\nu \approx 3 \times 10^{-19} \left(\frac{m_\nu}{1\text{eV}}\right) \mu_B.$$

it implies non-trivial extension to the Standard Model

- There are many different models with high value of the magnetic moments but as an example
  - SUSY models
    - $\mu_{\nu e} \cong 10^{-15} - 10^{-16} \mu_B$
    - $\mu_{\nu\mu} \cong 10^{-12} - 10^{-13} \mu_B$
    - $\mu_{\nu\tau} \cong 10^{-12} \mu_B$
- Neutrino magnetic moment not in all models is proportional to neutrino mass.

Neutrino-electron elastic scattering

- The most widely used method to determine neutrino magnetic moment is a process

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

$$\left(\frac{d\sigma}{dT}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right]$$

$$\left(\frac{d\sigma}{dT}\right)_{\mu} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

Neutrino-electron elastic scattering

- Cross sections are added incoherently

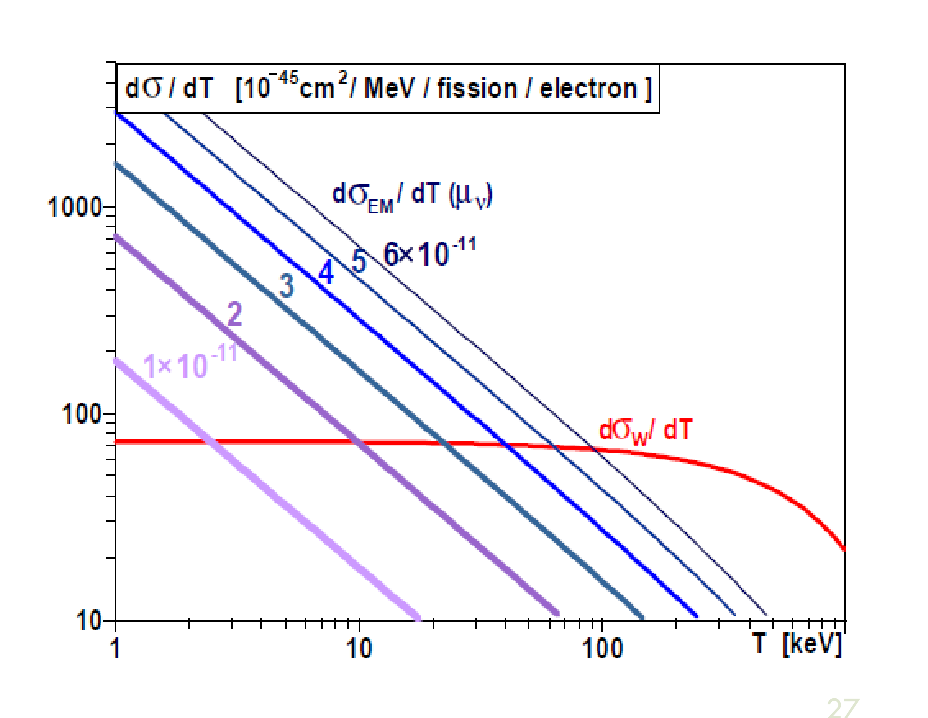
$$\frac{d\sigma}{dT} = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu}.$$

- Two observables
  - Scattering angle

$$\cos\chi = \frac{E_\nu + m_e}{E_\nu}\left[\frac{T}{T+2m_e}\right]^{1/2}$$

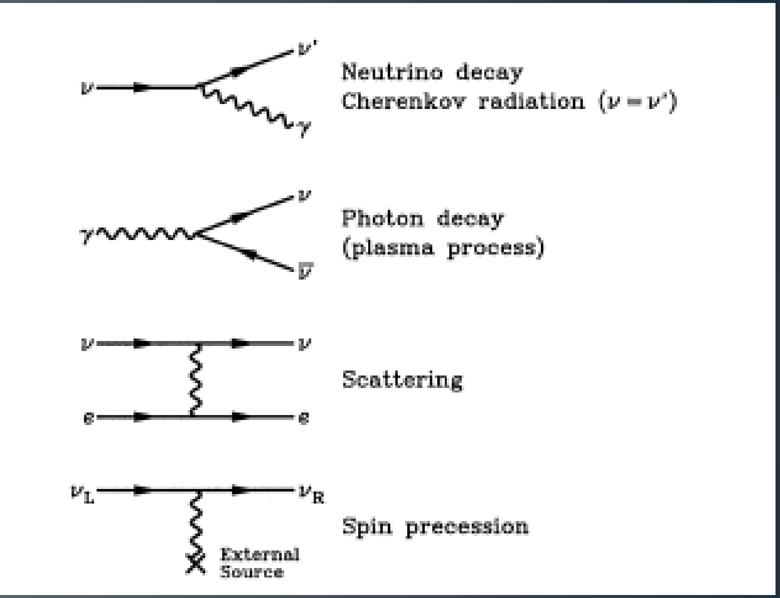
  - Kinetic energy of recoil electron

$$T \leq \frac{2E_\nu^2}{2E_\nu + m_e}.$$



Methods to measure μ_ν

- Direct measurement of neutrinos
  - Solar neutrinos
  - Reactor anti-neutrinos
  - Accelerator base neutrinos
  - SN1987A
- Astronomical observations
  - Evolution of Red Giants (He ignition)
  - Cosmic background



Reactor experiments results

- All reactor experiments measure the neutrino magnetic moment by looking at deviation of the recoil electron spectrum from SM prediction for elastic neutrino-electron scattering.
- Savannah River Laboratory (1976, analysis in 1989) $(2\text{-}4)\times 10^{-10}\,\mu_B$
- Krasnoyarsk experiment (1992) ` $\mu_{\bar{\nu}_e} \leq 2.4 \times 10^{-10}\,\mu_B$
- Rovno experiment (1993) $\mu_{\bar{\nu}_e} \leq 1.9 \times 10^{-10}\,\mu_B$
- TOXONO experiment (2007) $\mu_{\bar{\nu}_e} \leq 7.4 \times 10^{-11}\,\mu_B$
- GEMMA experiment (2012) $\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11}\,\mu_B$

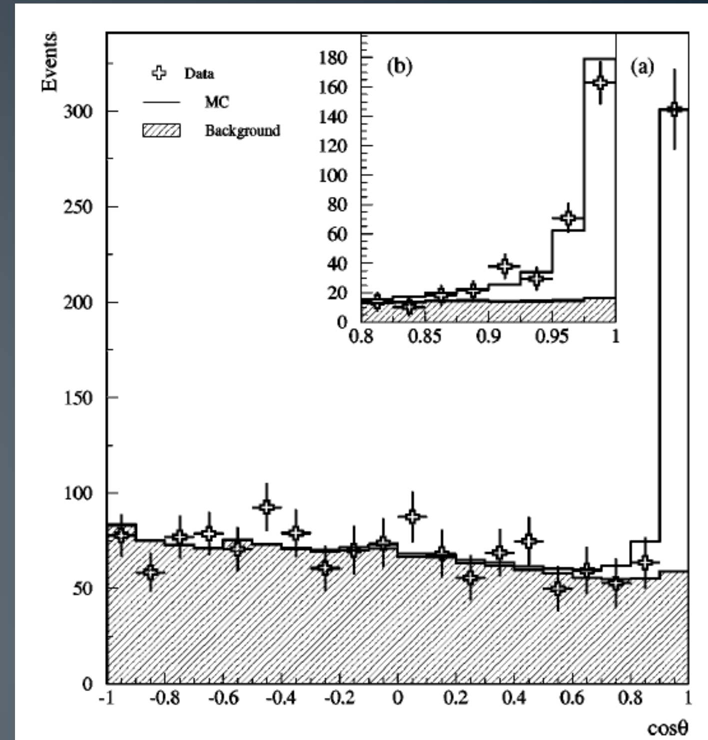
LSND

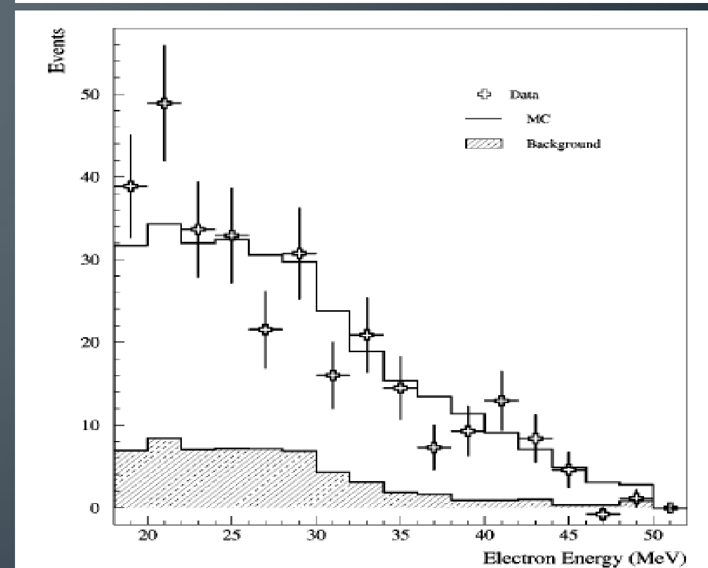
- The limit of the muon-neutrino was obtained in the LSND using ν_μ and $\overline{\nu_\mu}$ fluxes from π^+ an μ^+ decay.

$$\mu_{\nu_\mu} < 6.8\times 10^{-10}\mu_{Bohr}$$

TABLE III. Events, backgrounds and efficiency for cos θ>0.9. The neutrino flux and the flux averaged cross section for the reaction $\nu_e + e^- \rightarrow \nu_e + e^-$ are also shown.

Beam-on events	434 events
Beam-off events×duty ratio	133 events
Beam-excess events	301 events
νC background	59 events
$\nu_\mu e$ background	24 events
$\bar{\nu}_\mu e$ background	27 events
$\nu_e e$ elastic	191 events
Efficiency	0.187
ν_e flux	$11.76\times 10^{13}/\mathrm{cm}^2$
$\langle\sigma\rangle$	$(3.19\pm 0.35\pm 0.33)$ $\times 10^{-43}$ cm^2





DONUT Experiment

- The first and only limit of the tau-neutrino magnetic moment was set by the DONUT experiment.
- 1 event was observed with 2.3 predicted background.

$$\mu_{\nu_\tau} < 3.5 \times 10^{-7} \mu_B .$$

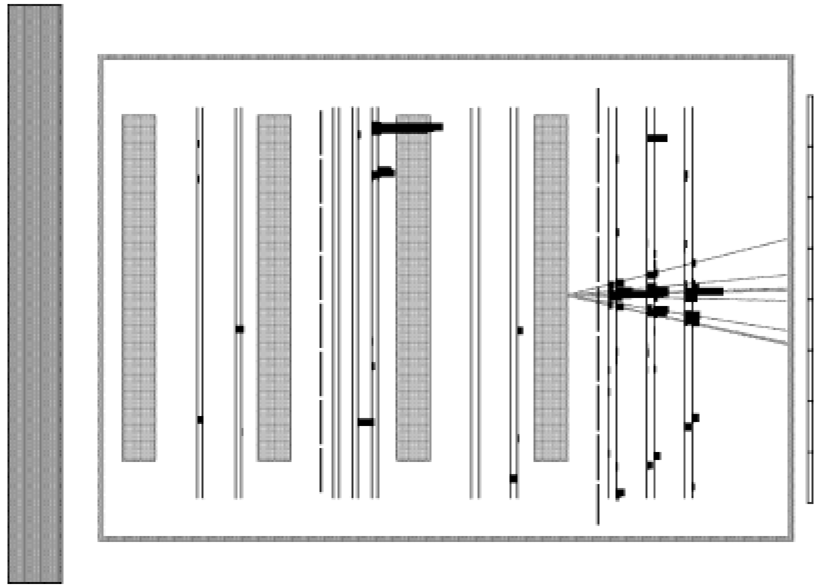
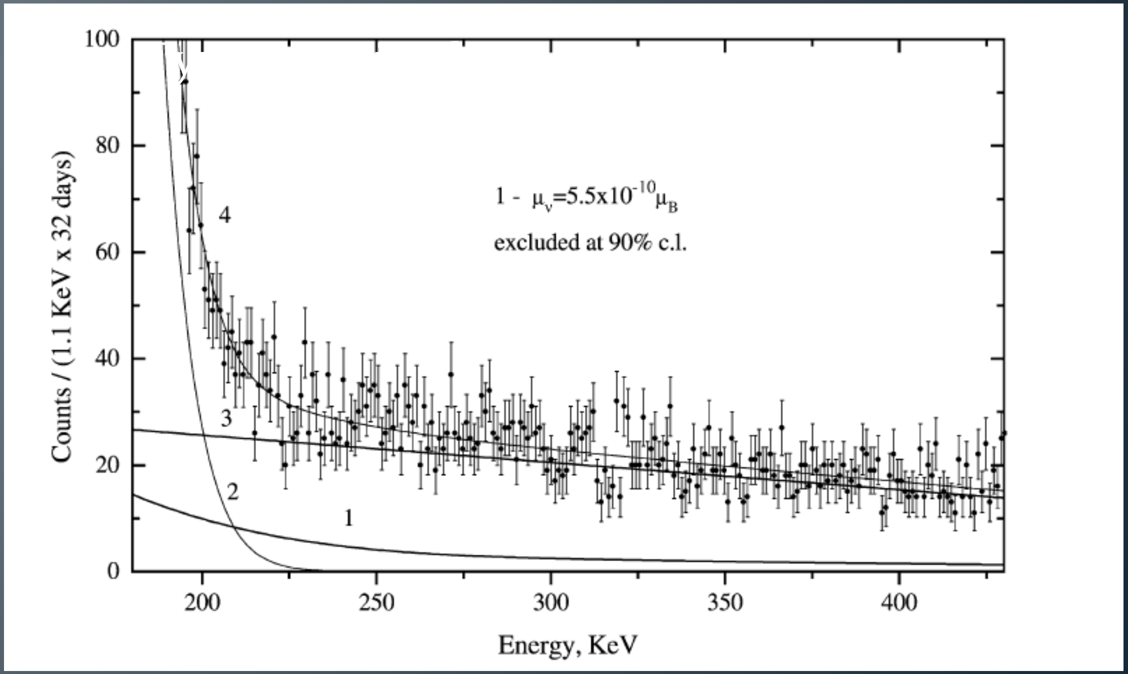


Fig. 4. Target region view of the selected magnetic moment candidate event. Shown are the hits in the scintillating fibers and the reconstructed tracks associated with the neutrino interaction.

Solar neutrinos

- The best results for solar neutrinos were obtained by the BOREXINO collaboration.
- The new upper limit for μ_ν from *pp* and ^{7}Be solar neutrinos.

$$5.4 \times 10^{-11} \mu_B \ \ (90\% \ \ \text{C.L.})$$

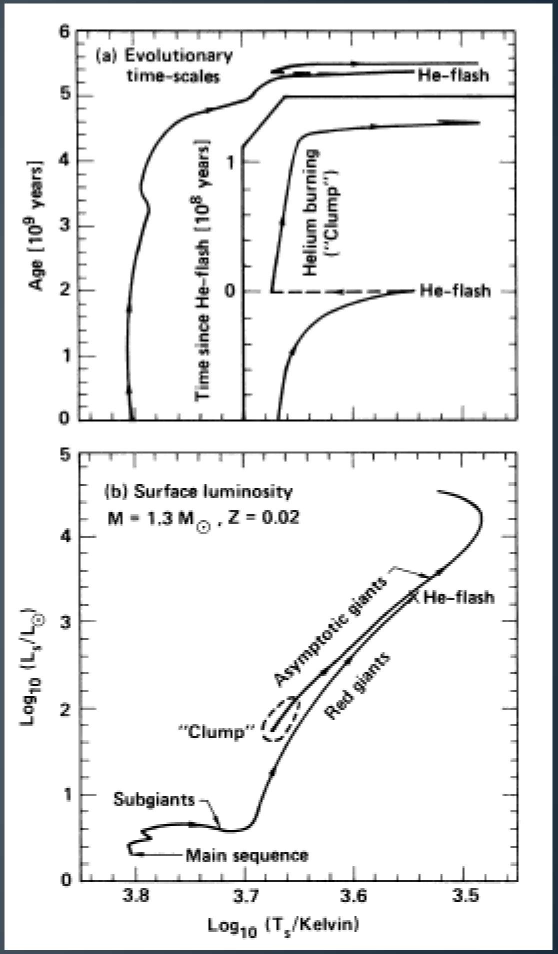


(1) the spectrum of recoil electrons due to magnetic scattering;
(2) 14C β spectrum;
(3) linear background;
(4) total fit.

He Ignition of Red Giants

- Prior to the helium ash, the degenerate He core radiates energy largely by neutrino pair emission.
- Plasmons couple to an electron-hole pair an decays to $Z_0 \rightarrow \nu\bar{\nu}$.
- The neutrino magnetic moment would enhance cooling and will leave the star with bigger He core (and alter its evolution).
- Looking at the ratio of red giants to horizontal branch the unacceptable modification will be caused by

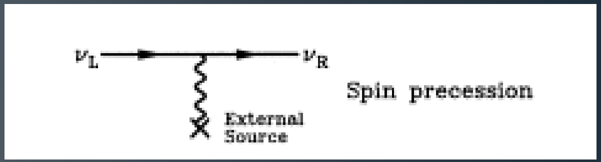
$$\mu_{ij} \leq 3 \times 10^{-12} \mu_B$$



PhysRevD.37.549

Supernova limit (SN1987A)

- If neutrino has a nonzero magnetic moment, then the scattering due to the photon exchange between a neutrino and a charged particle in plasma leads to the neutrino spin flip.

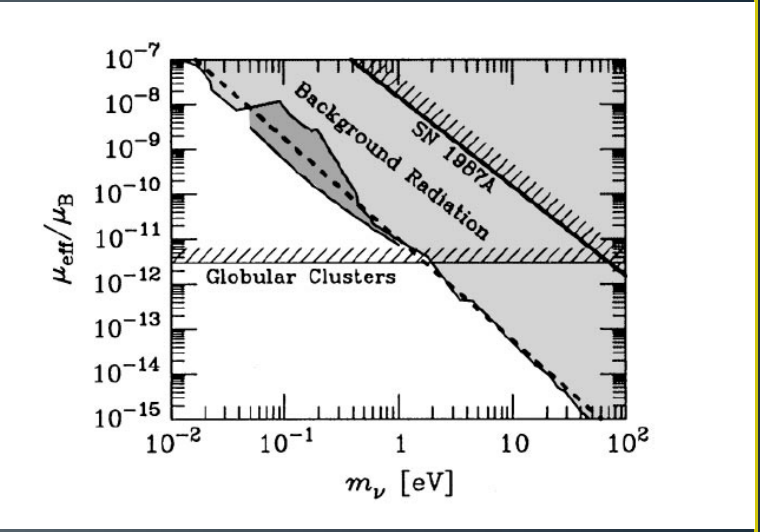


- If a produced particle is a right-handed neutrino (sterile), it leaves SN without further interactions.
- This pattern contradicts to the observed neutrino signal of SN 1987A. The energy released in SN implosion is taken away by sterile neutrinos. Due to this no energy is left for the envelope explosion.

$$\mu_\nu^{SN} \lesssim\sim 10^{-12} \mu_B$$

Radioactive decay and Cherenkov effect

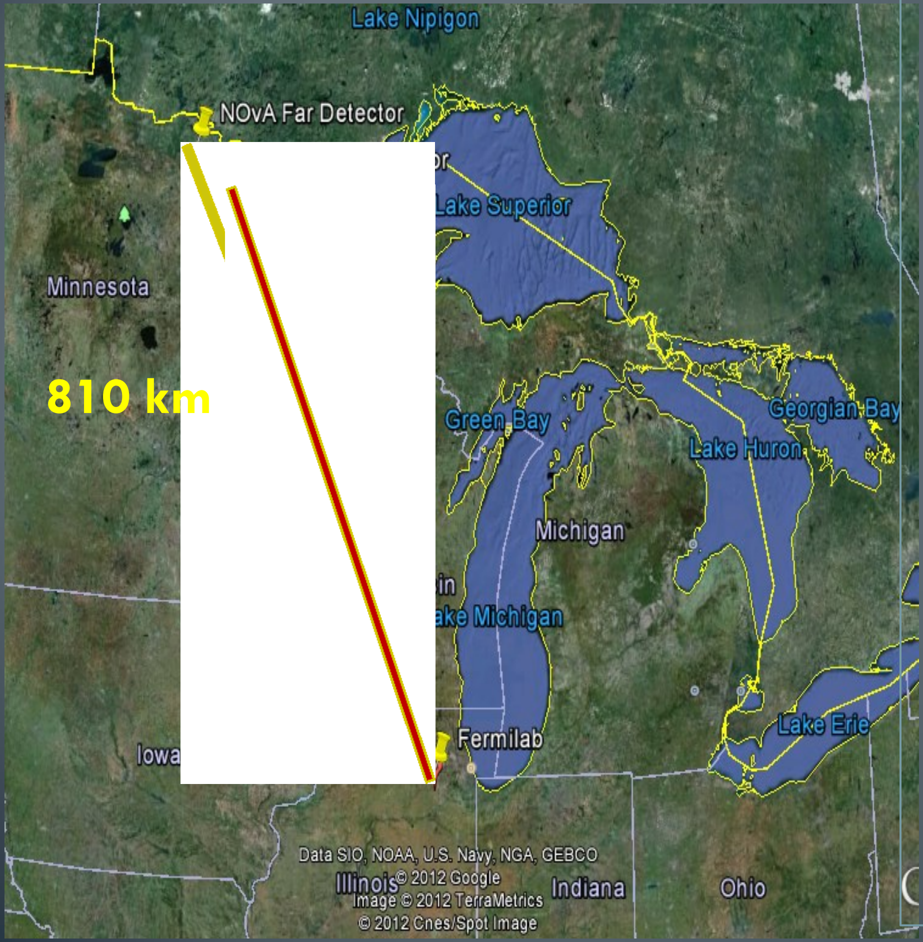
- A neutrino mass eigenstate may decay to another one by the emission of a photon, where the only contributing form factors are the magnetic and electric transition moments.



$$\frac{\mu_{\mathrm{eff}}}{\mu_{\mathrm{B}}} \lesssim \begin{cases} 0.9\times 10^{-1}\ (\mathrm{eV}/m_\nu)^2 & \text{Reactor } (\bar{\nu}_e)\ , \\ 0.5\times 10^{-5}\ (\mathrm{eV}/m_\nu)^2 & \text{Sun } (\nu_e)\ , \\ 1.5\times 10^{-8}\ (\mathrm{eV}/m_\nu)^2 & \text{SN 1987A (all flavors)}\ , \\ 1.0\times 10^{-11}\ (\mathrm{eV}/m_\nu)^{9/4} & \text{Cosmic background (all flavors)}\ . \end{cases}$$

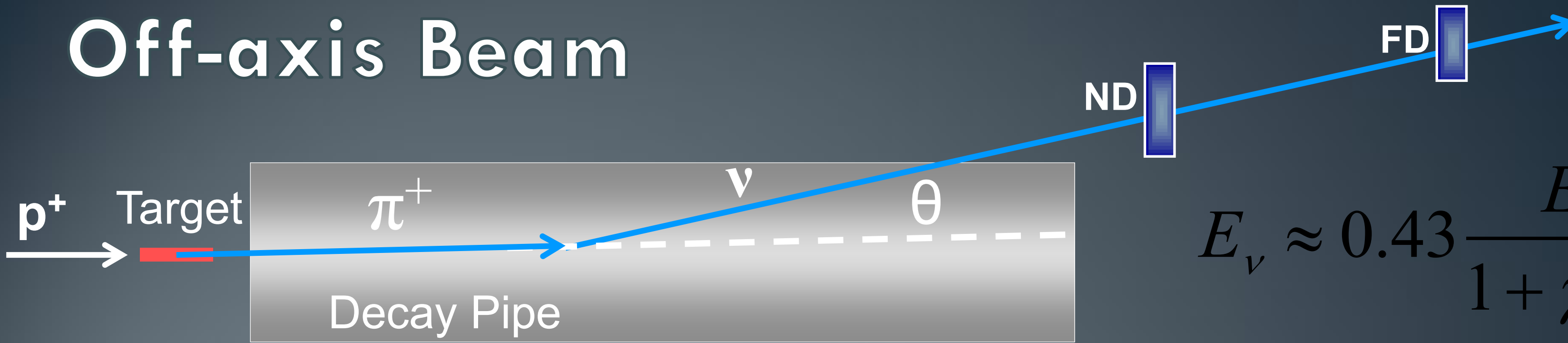
where μ_{ij} and ε_{ij} are the transition moments while $|\mu_{\mathrm{eff}}|^2 \equiv |\mu_{ij}|^2 + |\varepsilon_{ij}|^2$.

NOvA Experiment



- Use the upgraded NuMI beam at Fermilab.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
  - Far detector is 14 mrad off- axis and on the surface (14kton).
  - Near detector is also 14 mrad off-axis but underground(330ton).
  - Location reduces background.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.

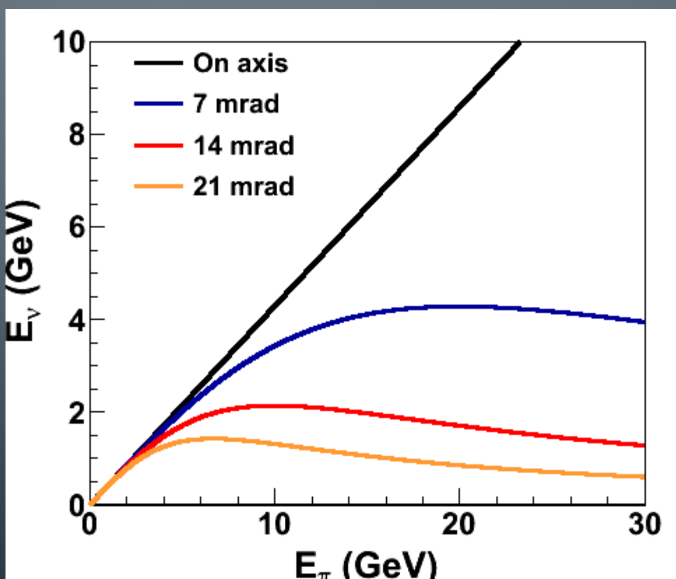
Off-axis Beam

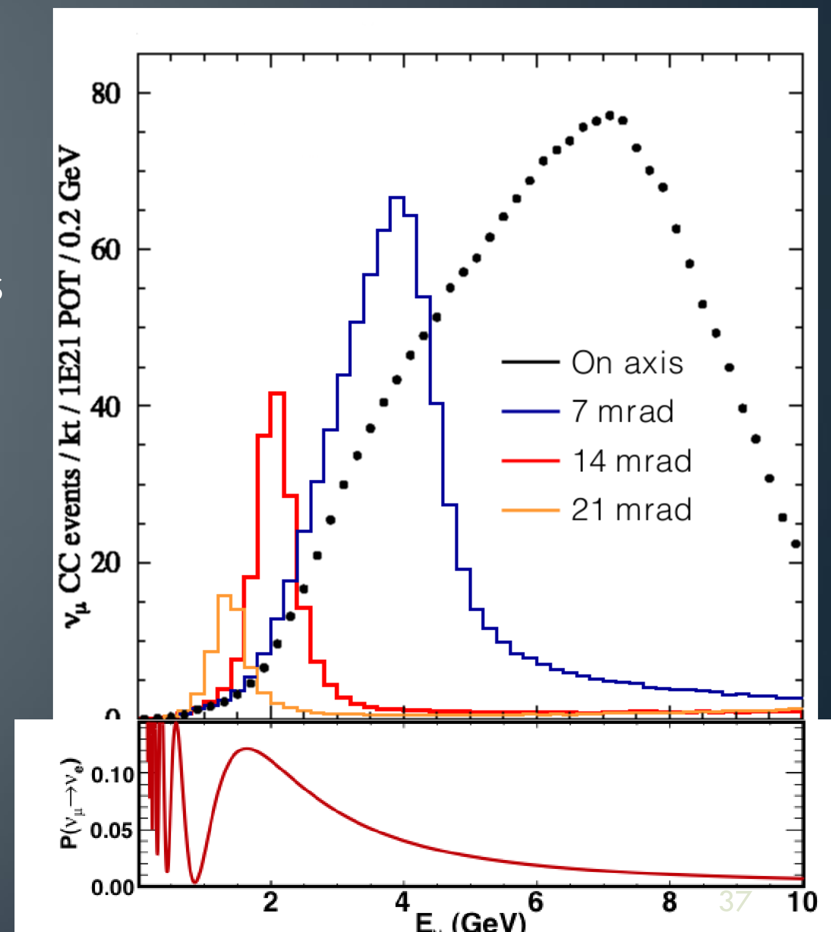


$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

At 14 mrad off-axis, narrow band beam peaked at 2 GeV

- Near oscillation maximum
- Few high energy NC background events

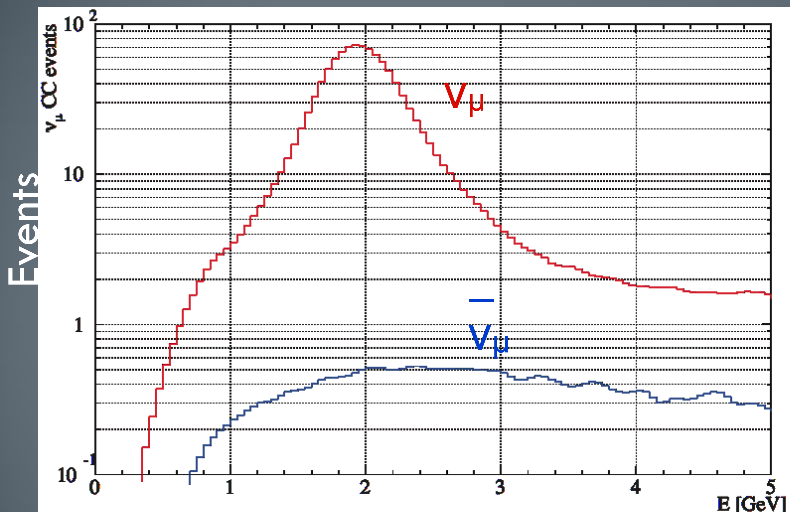


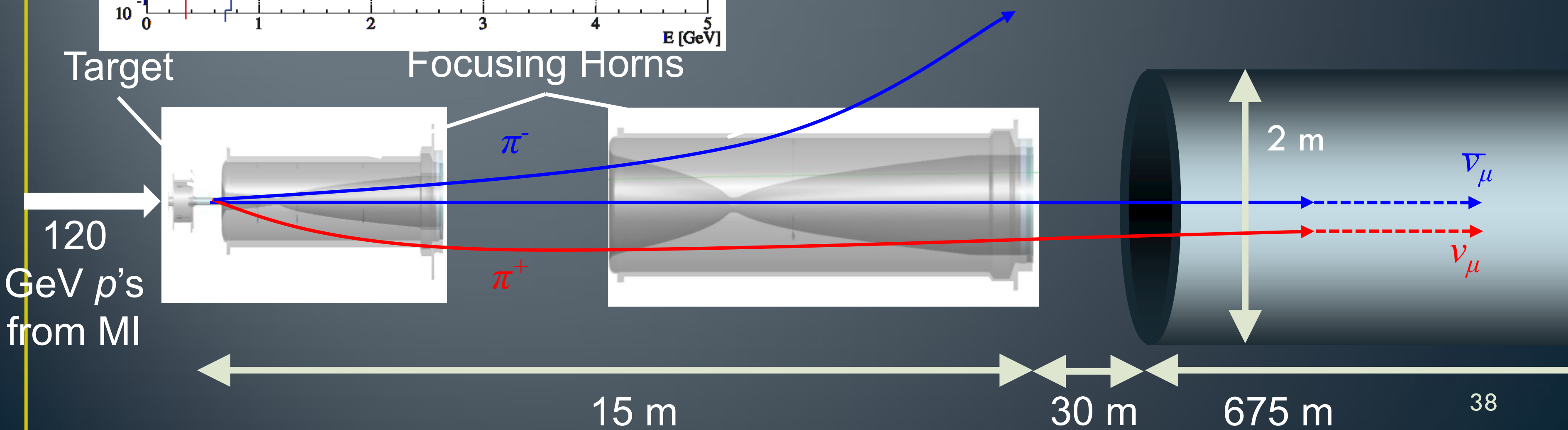


Making a Neutrino Beam@NOvA

Neutrino mode

Horns focus π^+, K^+

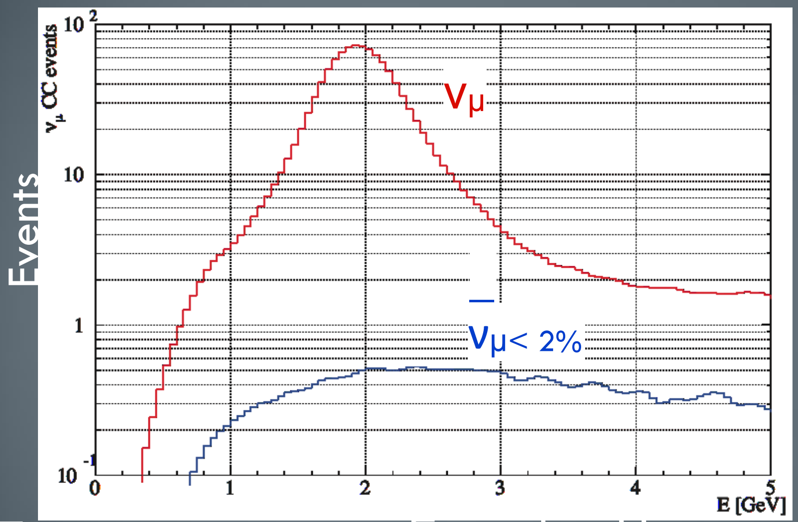




Making a Neutrino Beam@NOvA

Neutrino mode

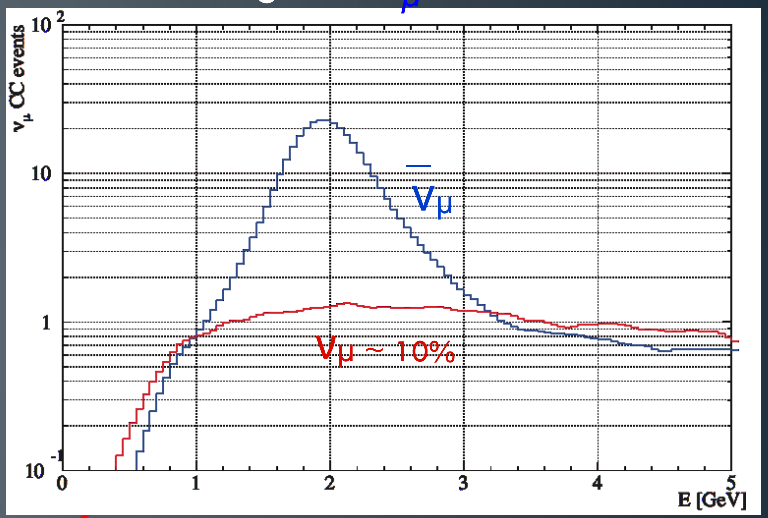
Horns focus π^+, K^+

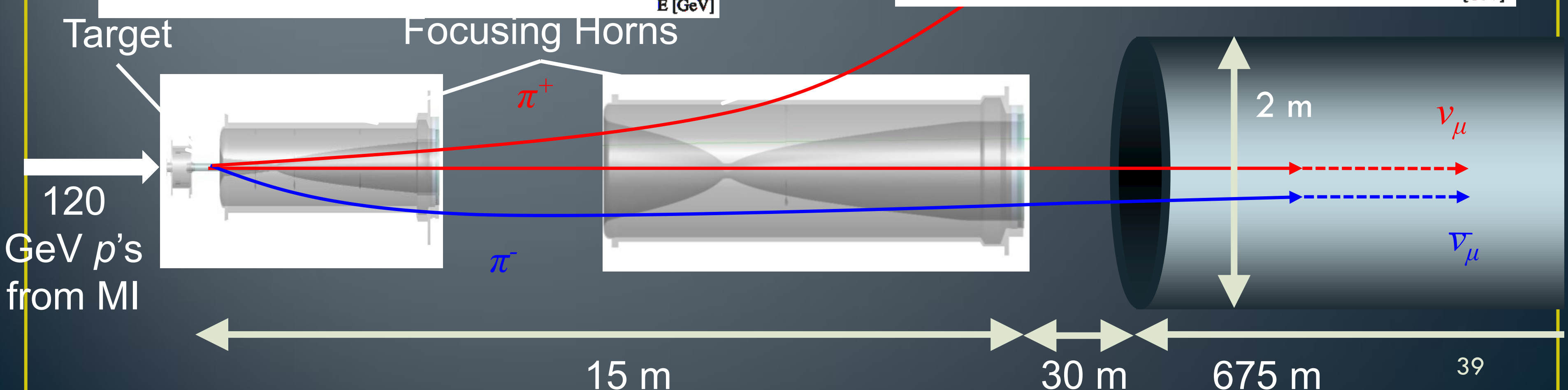


Anti-neutrino Mode

Horns focus π^-, K^-

enhancing the $\bar{\nu}_\mu$ flux

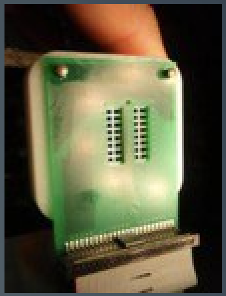




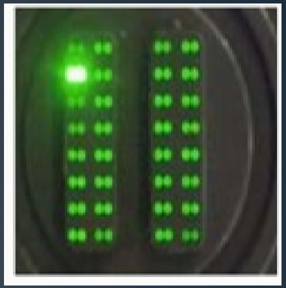
The NOvA detectors

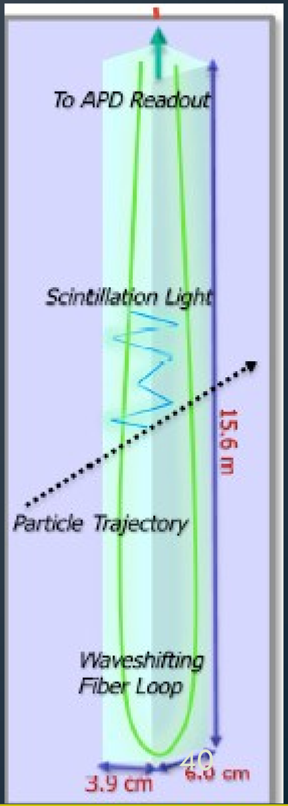
- 14 kton Far Detector
  - 64 % active detector.
  - 344,064 detector cells read by APDs.
- 0.3 kton Near Detector
  - 19,104 cells (channels).
- Each plane just 0.15 X_0. Great for e^- vs. π^0 .

32-pixel APD



Both ends of a fiber to one pixel

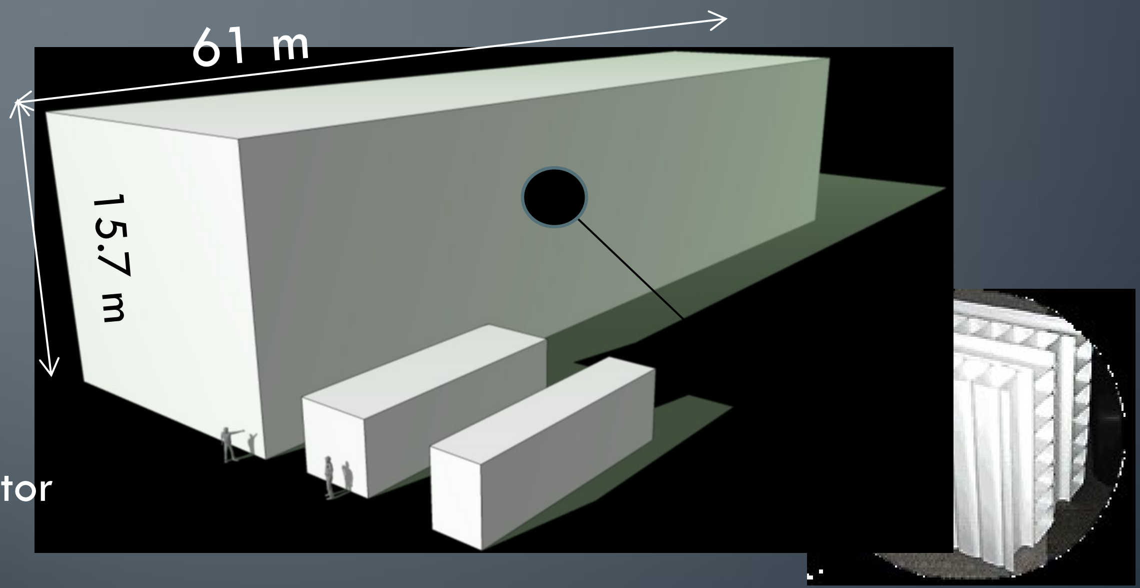




Far detector
14 kton
986 planes

Near detector
0.3 kton

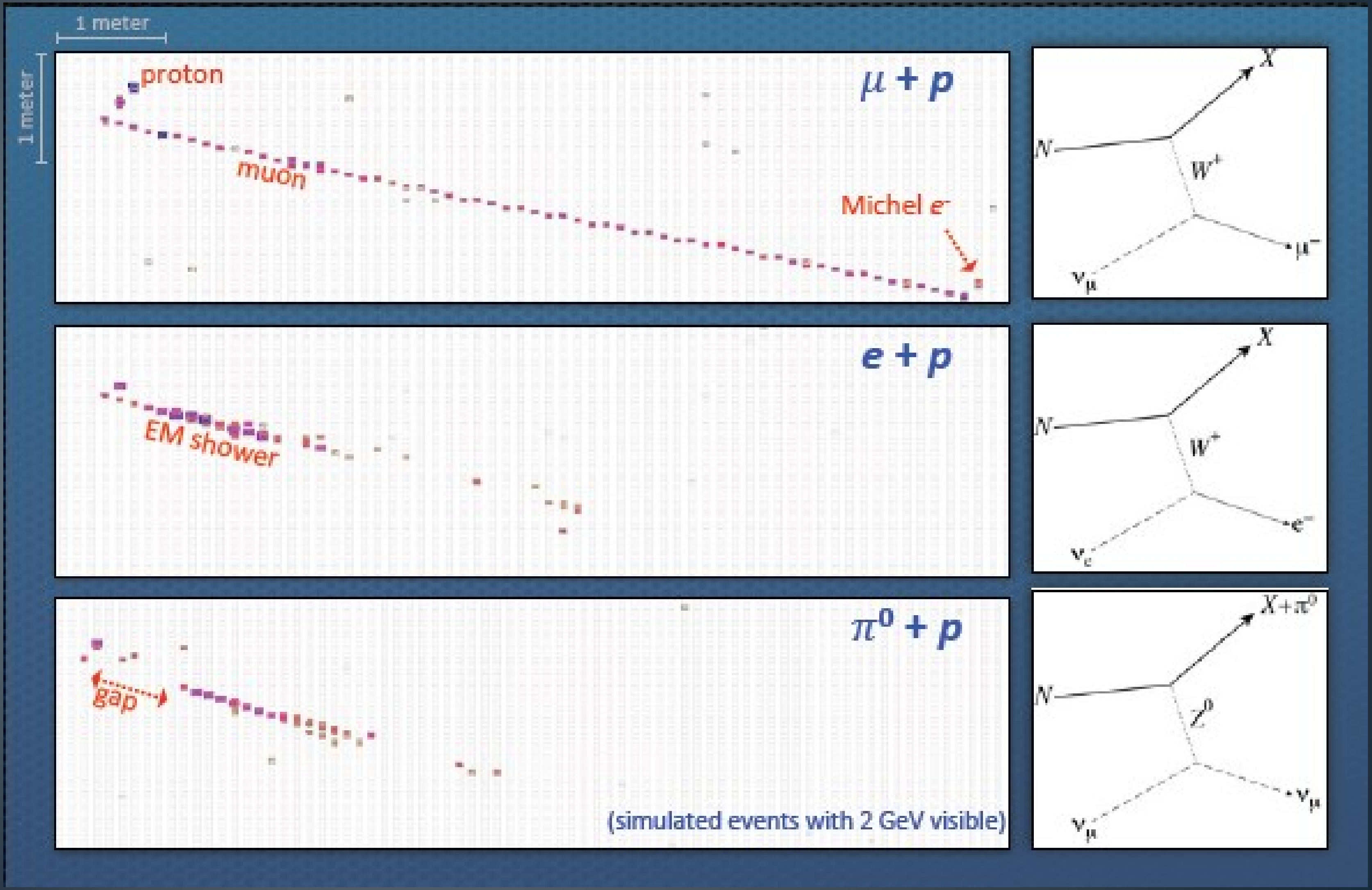
Prototype detector
0.2 kton



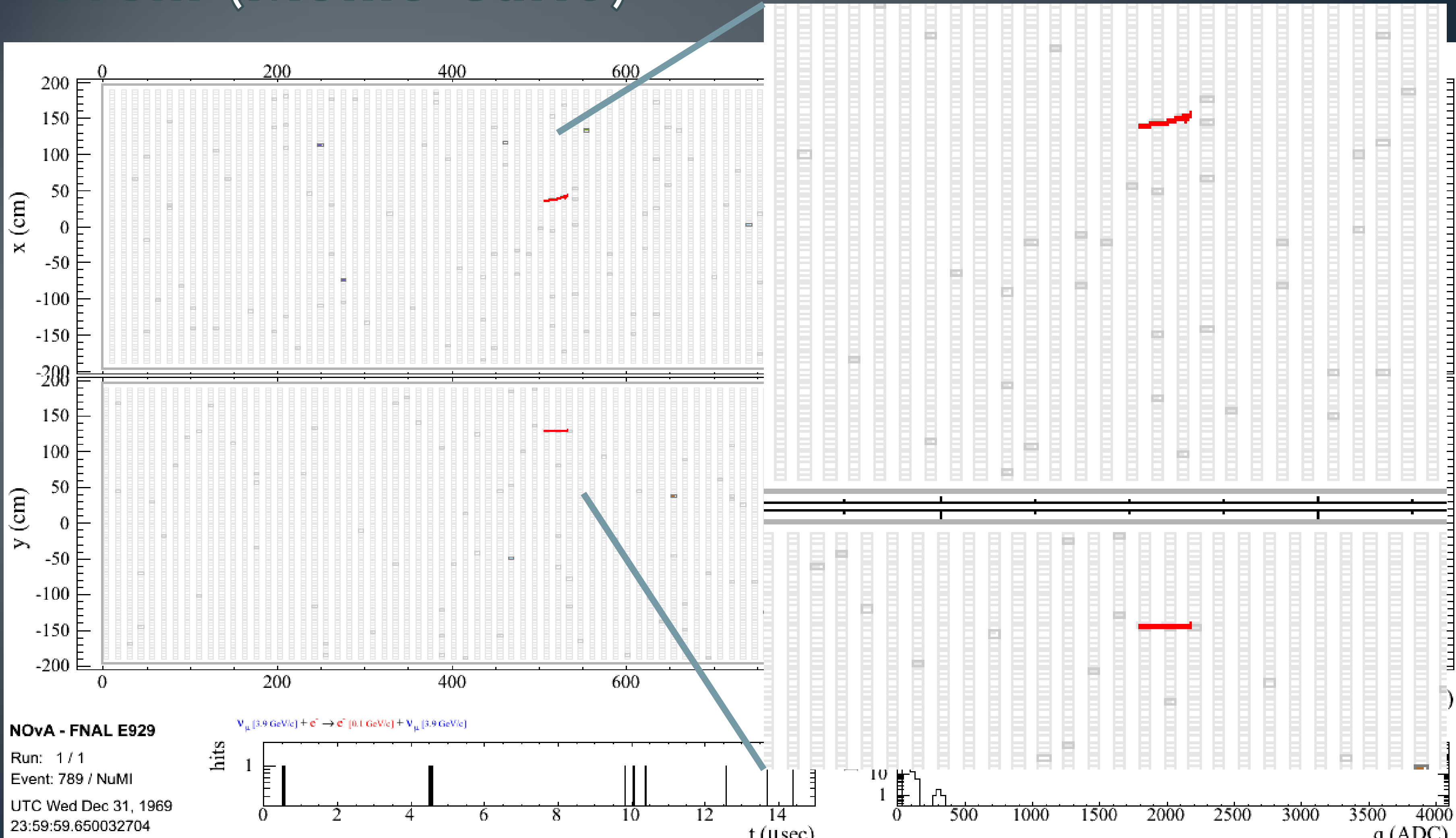
MC Events in NOvA

Excellent granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



Example to neutrino magnetic moment signal event (Monte Carlo)

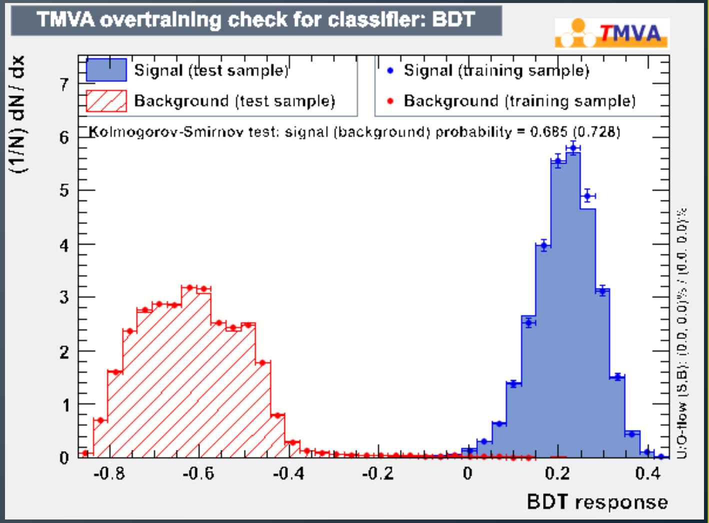


Neutrino Magnetic moment at NOvA

- The upgraded NuMI beam will provide with very intense beam of ν_μ and $\bar{\nu}_{\mu}$.
- The cross section for the elastic $\nu_\mu + e \rightarrow \nu_\mu + e$ is expressed in term of the recoil energy of the outgoing electron.
- Signal signature in the NOvA near detector
  - Only e produces low energy electron with significant $\cos\theta$ variations for $\cos\theta > 0.90$.
  - The kinetic energy cut: $15\text{MeV} < T < 100\text{MeV}$.
  - $15\text{MeV} < T$: μ^- capture produce boron nuclei which beta decay $^{12}B \rightarrow {}^{12}C$ with energy endpoint 13.4 MeV.
  - For $T > 100\text{MeV}$ the weak interaction dominates @LSND limit.

Neutrino Magnetic moment at NOvA

- With our best reconstruction algorithms at this moment we expect about 150 reconstructed events of $\nu_\mu + e \rightarrow \nu\mu + e$ with true T_e<100 MeV in three years of running in the neutrino mode.
- This analysis requires removal of enormous number of events from neutrino scattering on nucleus.
  - About 4 in-detector and 15in surrounding rock neutrino interactions.
- With pre-selection cuts the Boosted Decision Tree classifier gives background events only a few times higher than signal events.



Summary

- Electromagnetic properties are still unknown.
- Limits on magnetic moments from astrophysical sources are lower by a few orders of magnitude that from terrestrial experiments.
- The new neutrino experiments can set new limits due to their high intensity (assuming background can be removed).