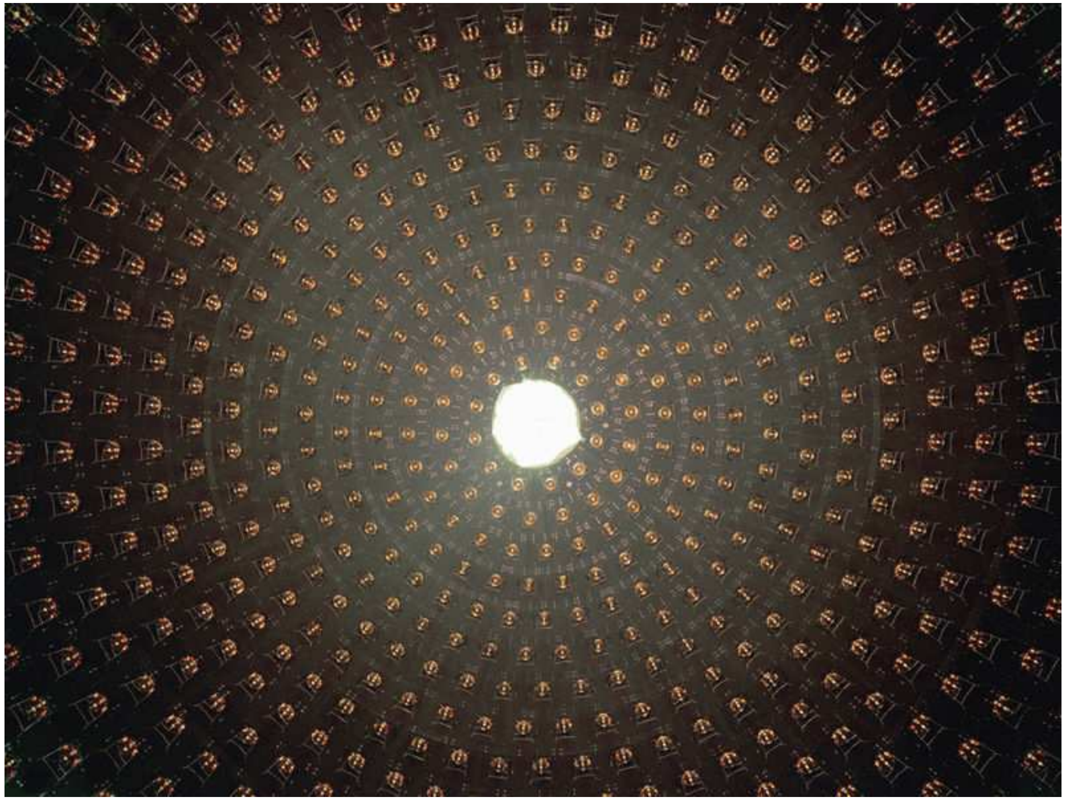
Searching for Sterile Neutrinos from π/K Decays



Louis Lello; Daniel Boyanovsky
Department of Physics and Astronomy
University of Pittsburgh
arXiv:1208.5559

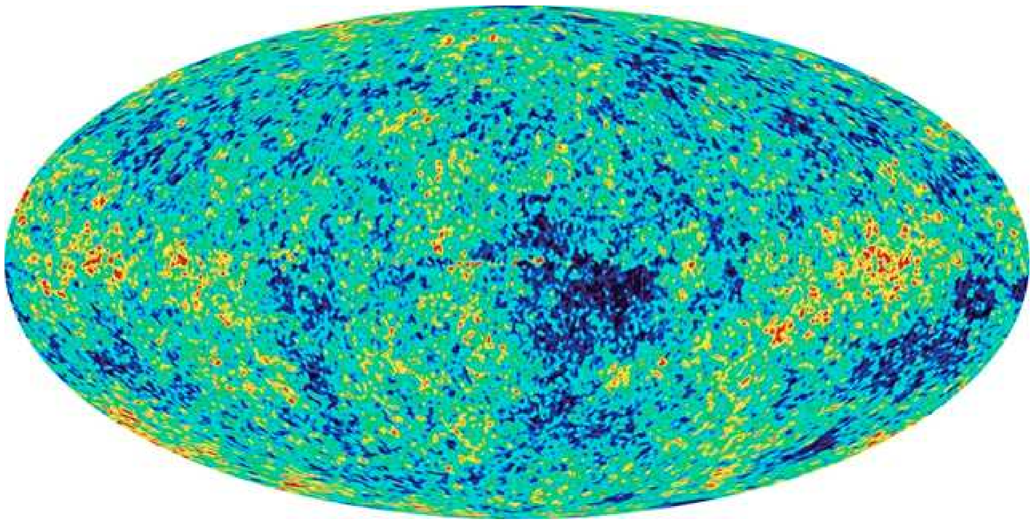
Hints of "sterile" neutrinos

- Possibly more than 3 mass eigenstates.

$$\Psi_{\nu_\alpha} = \sum_j U_{\alpha j} \Psi_{\nu_j}$$

- SBL Oscillation experiments:
  - LSND(1), MiniBooNE(2), reactor anomalies. (W. Louis' talk)
  - Suggests 4th mass ~ O(eV). Not without tension.

- Cosmology:
  - Planck/WMAP N_{eff} >3? Details of sterile thermalization needed. (C. Lunardini's talk)
  - Small scale structure: Warm dark matter. A ~1keV WDM candidate is a potential solution for small scale problem (CDM produces too many substructures)(3)



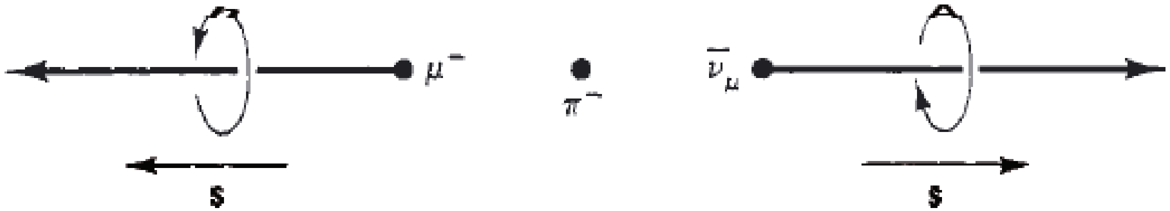
1) Aguilar et. al. (LSND) Phys. Rev. D64, 112007 (2001)
2) MiniBooNE collaboration, Phys. Rev. Lett. 105,181801 (2010)
3) Abazajian et al. arXiv:1204.5379

Decay at Rest – Detecting Heavy Steriles

$$q^* = \frac{1}{2m_M}\left[\left(m_M^2 - (m_l + m_s)^2\right)\left(m_M^2 - (m_l - m_s)^2\right)\right]^{\frac{1}{2}} \quad ; \quad m_s \leq m_M - m_l$$

- Presence of sterile neutrinos implies monochromatic peaks in lepton spectrum (Schrock 1980). Difficult to resolve peaks.

- Massless neutrinos have fixed helicity, cannot boost ahead.



Pion decay at rest with resulting helicity. (Griffiths: Particle Phys)

- Only mention of wrong helicity proposed search requires searching from already identified peaks. Partial decay widths obtained by standard techniques.

$$\Gamma^{++}_{\pi/K \to l\overline{\nu_s}} = \frac{G_F^2}{4\pi}|U_{ls}|^2|V_{ud/us}|^2\, f_{\pi/K}^2\, q^*\, m_l^2 \left[\frac{E_{\nu_s}(q^*)+q^*}{E_l(q^*)+q^*}\right]$$

$$\Gamma^{--}_{\pi/K \to l\overline{\nu_s}} = \frac{G_F^2}{4\pi}|U_{ls}|^2|V_{ud/us}|^2\, f_{\pi/K}^2\, q^*\, m_{\nu_s}^2 \left[\frac{E_l(q^*)+q^*}{E_{\nu_s}(q^*)+q^*}\right]$$

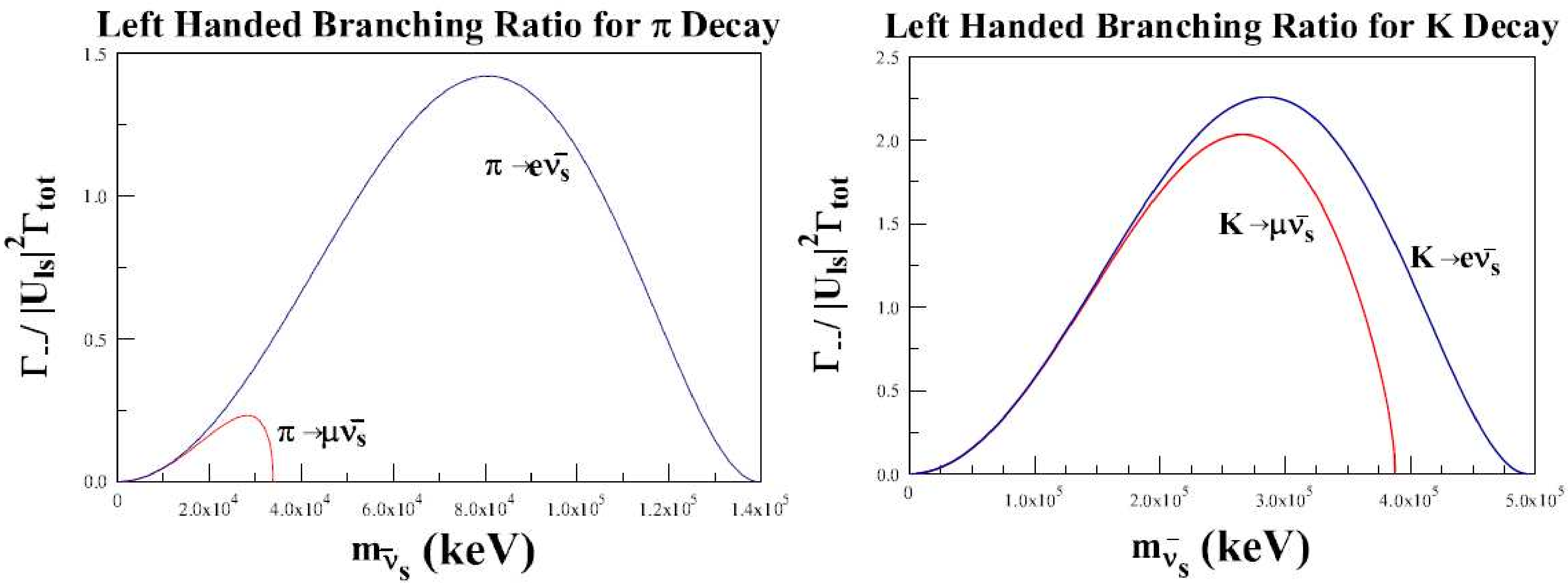
Decay at Rest – Heavy Steriles

$$Br^{--}_{M\to l\bar{\nu}_s} \equiv \frac{\Gamma^{--}_{M\to l\bar{\nu}_s}}{\Gamma^{tot}_M} = |U_{ls}|^2 \frac{2\,Br(M\to\mu\bar{\nu})\, q^*\, m^2_{\nu_s}}{m_\mu^2 m_M \left(1-\frac{m_\mu^2}{m_M^2}\right)^2}\left[\frac{E_l(q^*)+q^*}{E_{\nu_s}(q^*)+q^*}\right]$$

$$Br^{--}_{K\to\mu,e\bar{\nu}_s} \lesssim 10^{-9}-10^{-6} \text{ for } \begin{cases} 4\,\text{MeV} \lesssim m_s \lesssim 360\,\text{MeV} \ (\mu-\text{channel}) \\ 4\,\text{MeV} \lesssim m_s \lesssim 414\,\text{MeV} \ (e-\text{channel}) \end{cases}$$

- Left handed branching ratio unique to massive neutrinos. Helpful for HEAVY sterile
- Spatially separate via Stern Gerlach. Complimentary with searches for monochromatic peaks.
- Bound BR with U bounds*

*Kusenko, Pscoli, Semikov, JHEP 0511, 028 (2005)



Left handed branching ratio for pion/kaon DAR

Standard Treatment Of Neutrino Oscillations

$$\langle \nu_\alpha | e^{-iHt} | \nu_\beta(t) \rangle = \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i \tau_i}$$

$$m_i \tau_i = E_i t - L p_i \cong E(t-L) + \frac{m_i^2}{2E} \mathrm{L}$$

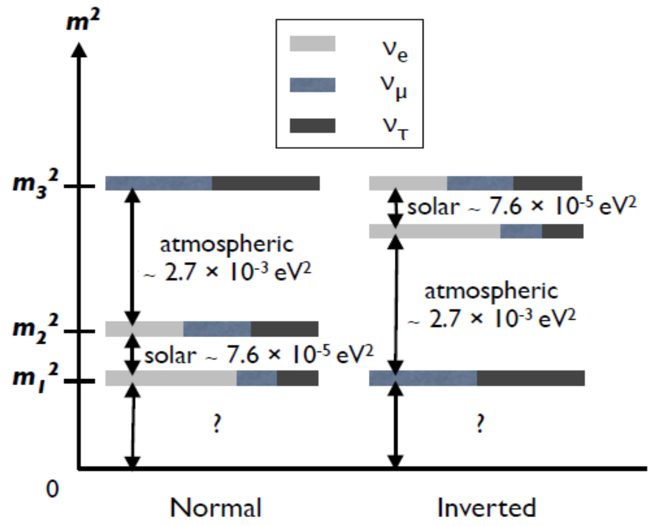
$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m_{ij}^2 L}{2E}}$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} Re[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E} \right)$$

$$+ 2 \sum_{i>j} Im[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin\left(\Delta m_{ij}^2 \frac{L}{2E} \right)$$

- Evolve initial state and boost to lab frame, assume E>>m. Use unitarity for probability.

- Obtain neutrino composition through experiment

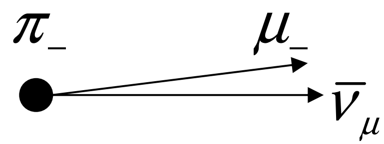


Mixing and mass compositions.

B. Kayser arXiv:hep-ph/0506165

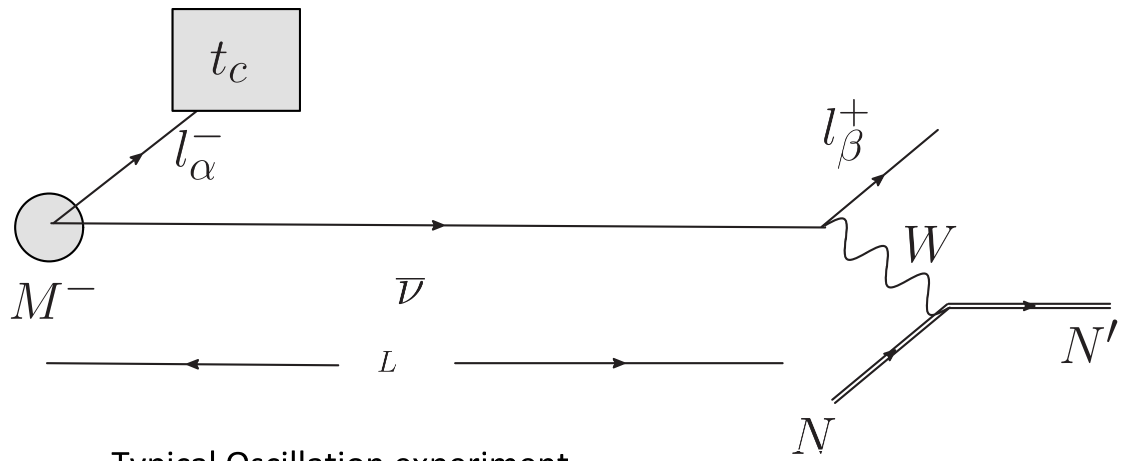
Shortcomings of standard treatment

• Doesn't account for production. Would expect lifetime and entanglement effects (however small they may be).



• Borrow the Wigner Weisskopf method ubiquitous in quantum optics (also used for K/bar{K} mixing).

• Typical accelerator experiment – muon (or e) is stopped at end of decay pipe.



Typical Oscillation experiment

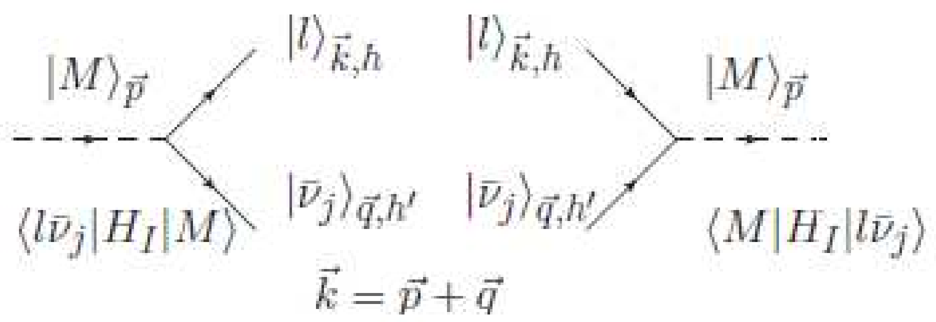
• Note: Will only discuss Dirac neutrinos. Majorana case is similar.

Wigner Weisskopf Theory (Sketch)

- Treat as initial value problem (pi/K at t=0).
- Expand state in eigenstates of free H, obtain eq for coeff.

$$\frac{d}{dt}C_n(t) = -i\sum_m \langle n | H_I(t) | m \rangle C_m(t)$$

- Infinite hierarchy in principle. Cut hierarchy at 2 particle states.



- Derivative expansion in self energy. Keep up to leading order.
- Time dependent coefficients are obtained! (See paper for gory details)

Full Quantum State

• Full quantum state obtained using Wigner Weisskopf approx. Technical details: Lello, Boyanovsky **arXiv:1208.5559**

• Includes decay width of parent particle and entanglement. Decay width a la Fermi's Golden rule and one loop self energy are reproduced

Exact Entangled Quantum State

$$|M^-_{\vec{p}}(t)\rangle = e^{-iE_M(p)t} e^{-\Gamma_M(p)\frac{t}{2}} |M^-_{\vec{p}}(0)\rangle - F_M \sum_{\vec{q},\alpha j,h,h'} U_{\alpha j} \frac{\overline{\mathcal{U}}_{\alpha,h}(\vec{k})\gamma^\mu \hat{L} \mathcal{V}_{j,h'}(\vec{q}) p_\mu}{\sqrt{8VE_M(p)E_\alpha(k)E_j(q)}} \times$$

$$\left[\frac{1-e^{-i(E^r_M(p)-E_\alpha(k)-E_j(q)-i\frac{\Gamma_M}{2})t}}{E^r_M(p)-E_\alpha(k)-E_j(q)-i\frac{\Gamma_M}{2}} \right] e^{-i(E_\alpha(k)+E_j(q))t} |l^-_\alpha(h,\vec{k})\rangle |\overline{\nu}_j(h',-\vec{q})\rangle$$

$$\lim_{\epsilon\to 0^+} i \frac{\sum_\kappa |\langle M | \hat{H}_I(0) | \kappa\rangle|^2}{E_M - E_\kappa + i\epsilon} = i\Delta E_M + \frac{\Gamma_M}{2}$$

Propagating State

- Measure muon (or e) leaves true propagating neutrino state

- Recover original state when prefactors independent of mass

Propagating state

$$|\tilde{\bar{\nu}}(\vec{q},h_i)\rangle \equiv \langle l_\alpha^-(h_i,\vec{k})|M_{\vec{p}}^-(t_c)\rangle$$

$$|\tilde{\bar{\nu}}(\vec{q};h_i)\rangle = -e^{-iE_\alpha(k)t_c}\sum_{j,h'} U_{\alpha j}\,\Pi_{\alpha j}^P\,\mathcal{M}_{\alpha j}^P(\vec{k},\vec{q},h_i,h')\,\mathcal{F}_{\alpha j}[\vec{k},\vec{q};t_c]\,e^{-iE_j(q)t_c}\,|\bar{\nu}_j(h',-\vec{q})\rangle$$

- Definitions obvious from full state. F is the important quantity.

- As expected, dependence on disentanglement scale, decay width

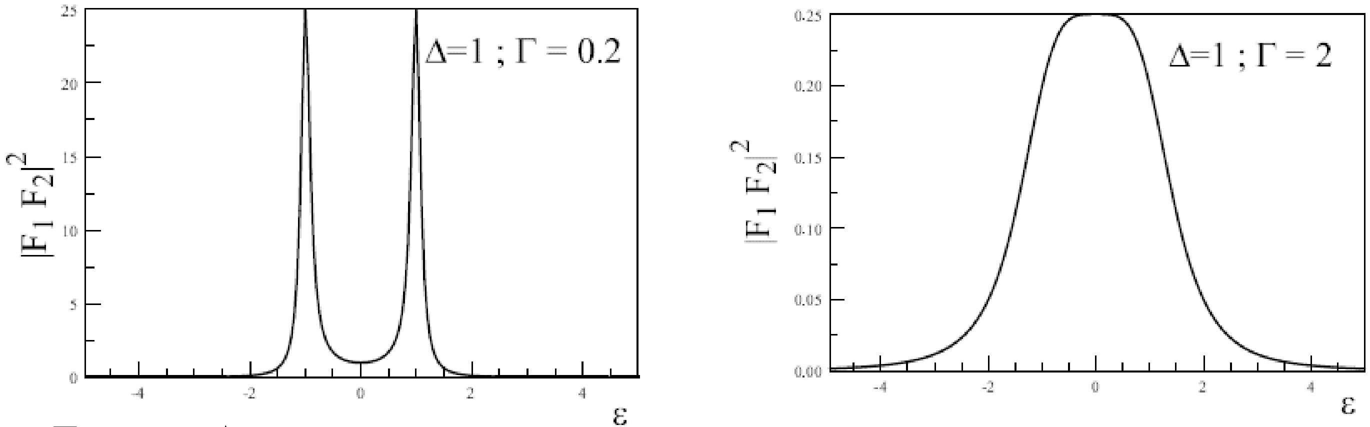
- Transition rate easily obtained from here. Interference contained in “F” terms

- Factorizes into production, propagation, detection

Qualitative Interpretation

• Intrinsic uncertainty in energy. Γ>>Δ yields overlapping Lorentzians, reduces to usual Pontecorvo state. Large uncertainty blurs states together.

• Width of Lorentzian versus energy separation. Energy conservation in short width limit



$$E_\nu = \varepsilon \pm \Delta$$

Product of Lorentzians when peak separation is greater(lesser) than decay width

• This is relevant for short baseline experiments. Long baseline focuses on much smaller mass differences.

• Corrections due to decay width and entanglement length scale are present as expected

• As ΓL <<1, recover original coherent picture.

Modifying Quantities

- Two important dimensionless quantities

- Bring about amplitude suppressions and phase shifts.

Important Scales:

$$\mathcal{R}_{ij} = \frac{\Delta_{ij}}{\Gamma_M(p)} = \frac{\delta m_{ij}^2}{2\Gamma_M M_M} \frac{E_M(p)}{E(q)}$$

Suppression and phase shift

$$e^{-\Gamma_M(p) L_c}$$

Suppression

- Both are miniscule for reactors (L~0, long lifetimes). Unchanged!

Modifying Oscillation Formula

- Main difference: Amplitude modification and phase shift

- Similar results in literature through different analysis*

Modified version in full glory:

$$\mathcal{P}_{\alpha\to\beta} = \delta_{\alpha,\beta} - 2\sum_{j>i} \mathrm{Re}\left[U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i}\right] \mathrm{Re}\left[1 - I_{ij}\right] - 2\sum_{j>i} \mathrm{Im}\left[U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i}\right] \mathrm{Im}\left[I_{ij}\right]$$

$$\mathrm{Re}[I_{ji}] = \frac{1}{\sqrt{1+\mathcal{R}_{ji}^2}} \frac{1}{1-e^{-\Gamma_M(p)L_c}} \left\{ \cos\left[\frac{\delta m_{ji}^2}{2E} L - \theta_{ji}(E)\right] - e^{-\Gamma_M(p)L_c} \cos\left[\frac{\delta m_{ji}^2}{2E}(L - L_c) - \theta_{ji}(E)\right] \right\}$$

$$\mathrm{Im}[I_{ji}] = \frac{1}{\sqrt{1+\mathcal{R}_{ji}^2}} \frac{1}{1-e^{-\Gamma_M(p)L_c}} \left\{ \sin\left[\frac{\delta m_{ji}^2}{2E} L - \theta_{ji}(E)\right] - e^{-\Gamma_M(p)L_c} \sin\left[\frac{\delta m_{ji}^2}{2E}(L - L_c) - \theta_{ji}(E)\right] \right\}$$

$$\cos[\theta_{ji}(E)] = \frac{1}{\sqrt{1+\mathcal{R}_{ji}^2}} \;;\; \sin[\theta_{ji}(E)] = \frac{\mathcal{R}_{ji}}{\sqrt{1+\mathcal{R}_{ji}^2}}$$

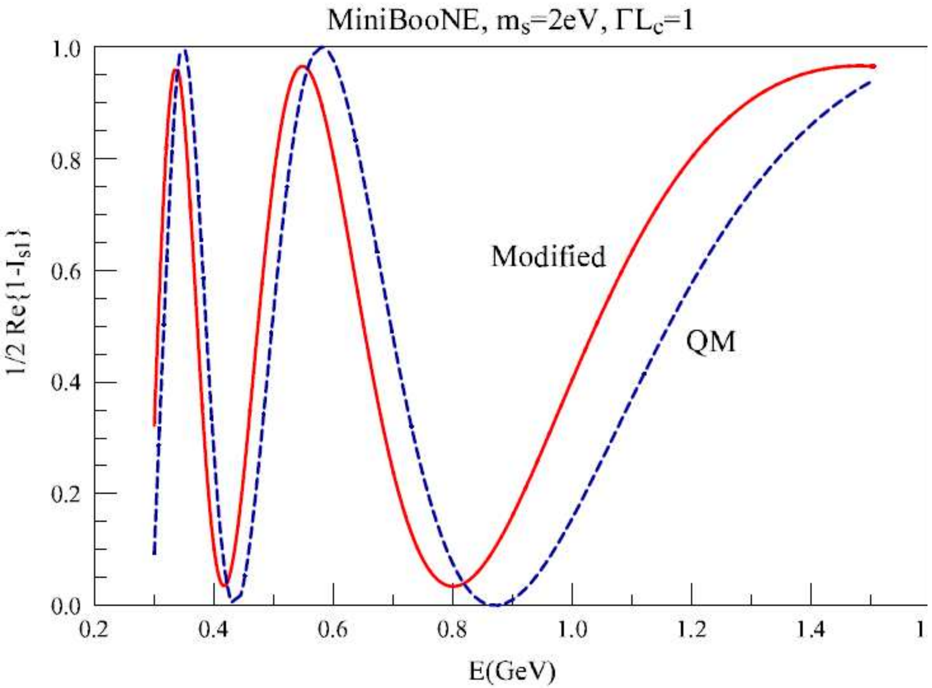
* D. Hernandez, A. Yu. Smirnov, Phys.Lett. B706, 360 (2012)
* E. Kh. Akhmedov, D. Hernandez, A. Yu. Smirnov, JHEP 1204, 052 (2012).

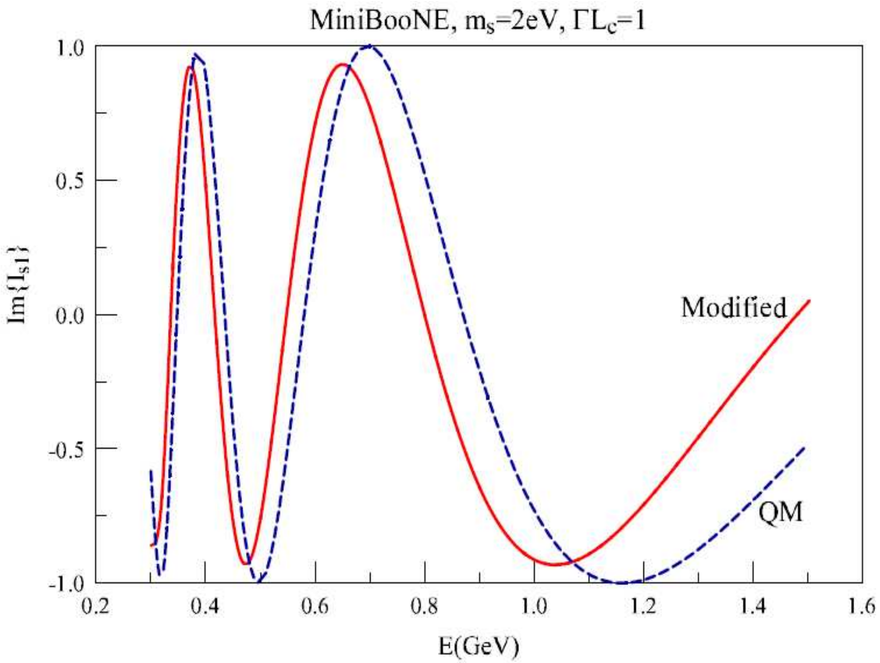
Present Accelerator Experiments: MiniBooNE

• Depending on sterile mass and *experimental parameters*, data may need further analysis.

• MiniBooNE: Baseline ~ 540m, E~1GeV, ΓL~1. Sensitive to 1eV.

• ~10-15% modification to mass and angle. (3+1)

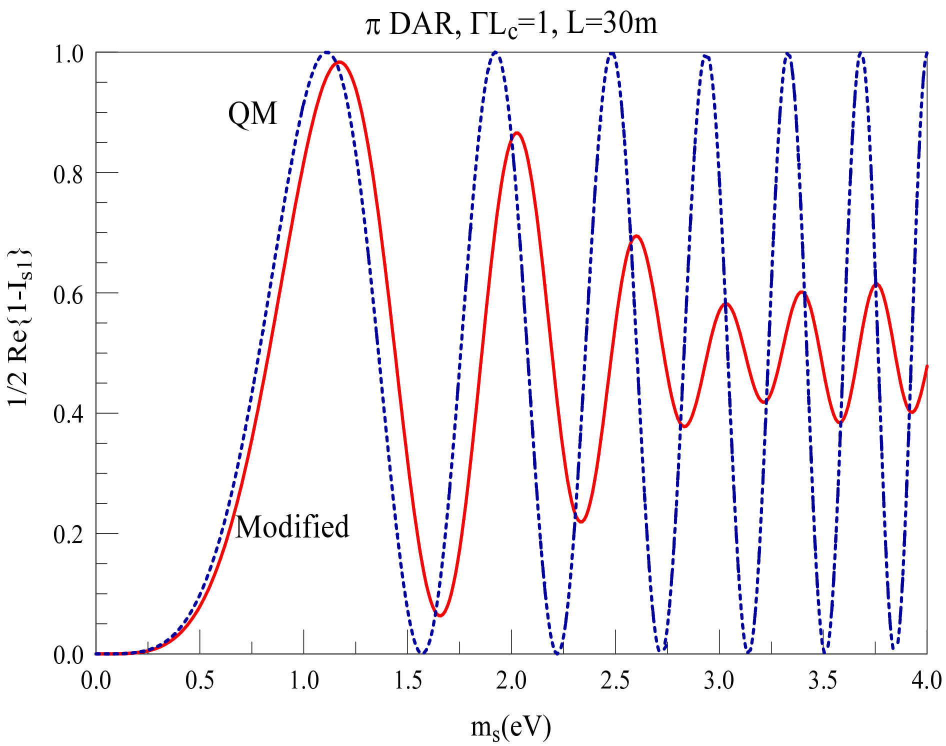


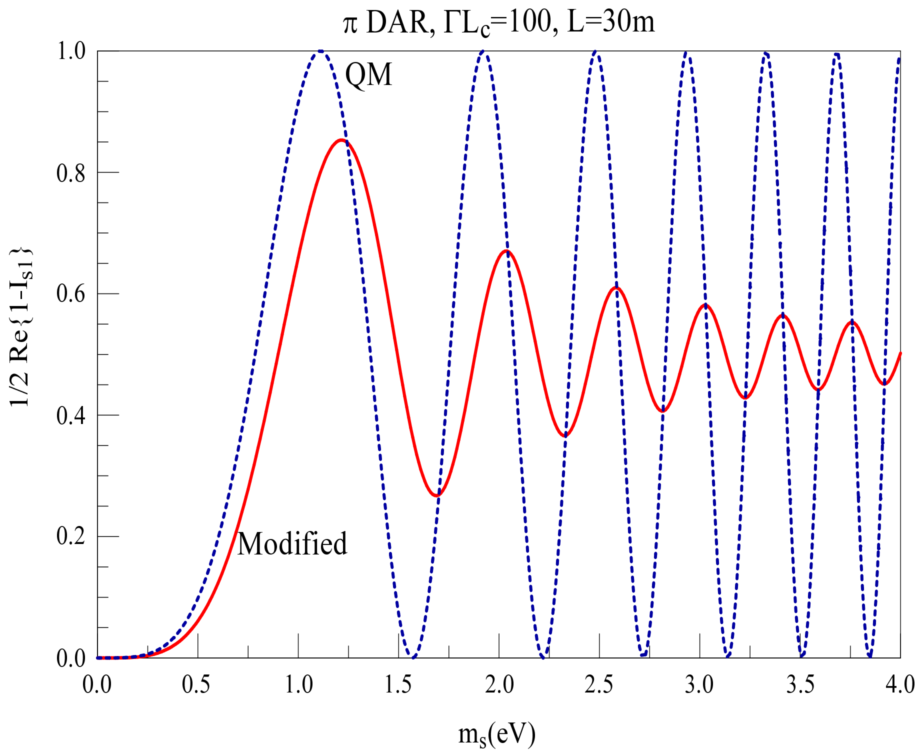


Decay at rest experiments

- Future proposed experiments seek to study decay at rest, potentially able to glean hints of sterile neutrinos

- Modifications to simple quantum mechanical picture are clear (for various ΓL)





Summary

- Heavy steriles might be found with combined searches for monochromatic lines and Stern-Gerlach experiment.

- Neutrino oscillations may decohere. Must control decay width and stopping distance to use (naive) QM formulae.

- Irrelevant for reactor experiments

- MiniBooNE would miss by ~15% for 3+1 with 1 eV sterile

- Keep in mind for next gen experiments.

Questions?? Comments??