WIN 2015

3+n sterile neutrino fits.

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Outline

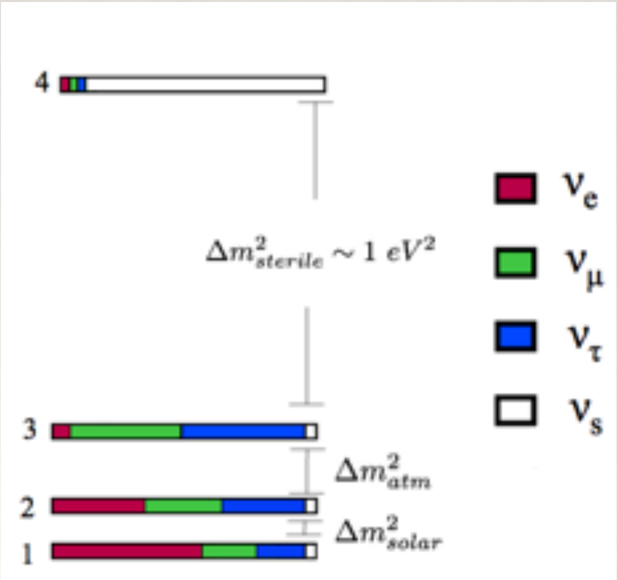
- Introduction to sterile neutrino fits
- Looking at numu disappearance experiments.
- How reliable is the PG test?

Motivation

- Neutrino detectors have to be designed for a limited range of L/E.
- How do we decide how to design the next generation of neutrino experiments?
- Phenomenology provides a guide.

Sterile neutrino models

- We can test many different models.
  - 3 + n: 3 degenerate active neutrinos + n heavier sterile neutrinos.
- 3+1: Has parameters $\Delta m^2_{41}, |U_{e4}|, |U_{\mu 4}|$



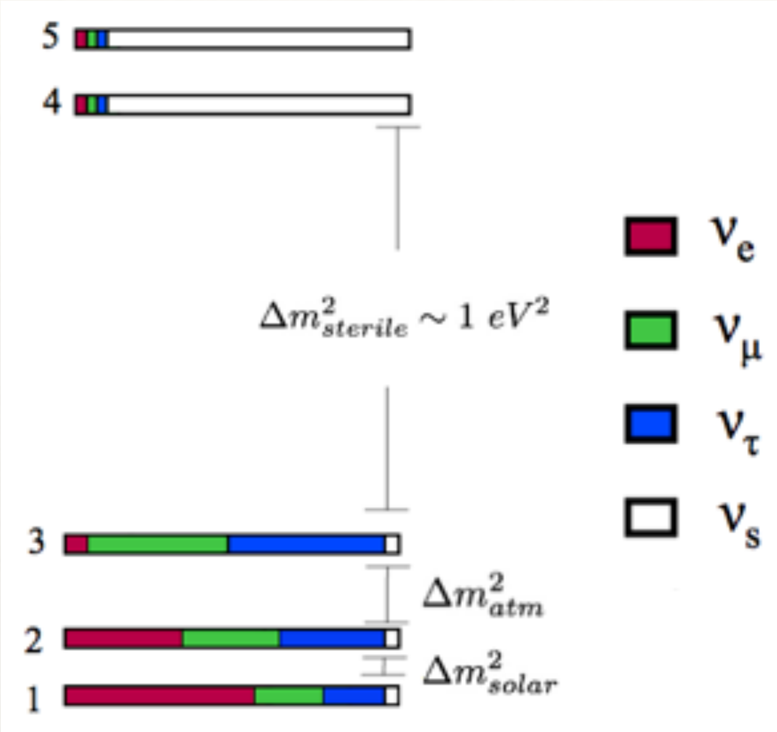
$\sin^2(2\theta_{\mu e})$

$$P(\nu_\alpha \to \nu_\beta) \simeq 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ ,$$

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - 4(1-|U_{\alpha 4}|^2)|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ .$$

Sterile neutrino models

- 3+2: Has parameters $\Delta m^2_{41}, \Delta m^2_{51}, |U_{e4}|, |U_{\mu 4}|, |U_{e5}|, |U_{\mu 5}|, \Phi_{45}$



CP violation: $\nu \neq \bar{\nu}$

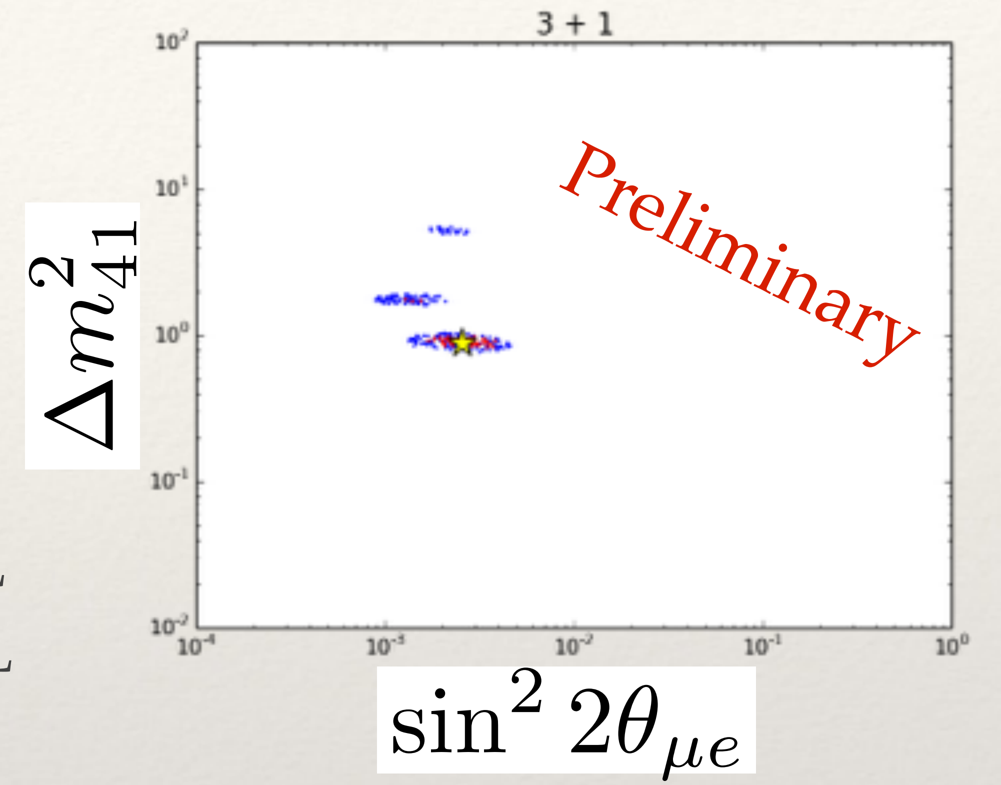
- 3+3: 12 parameters, even more complex.

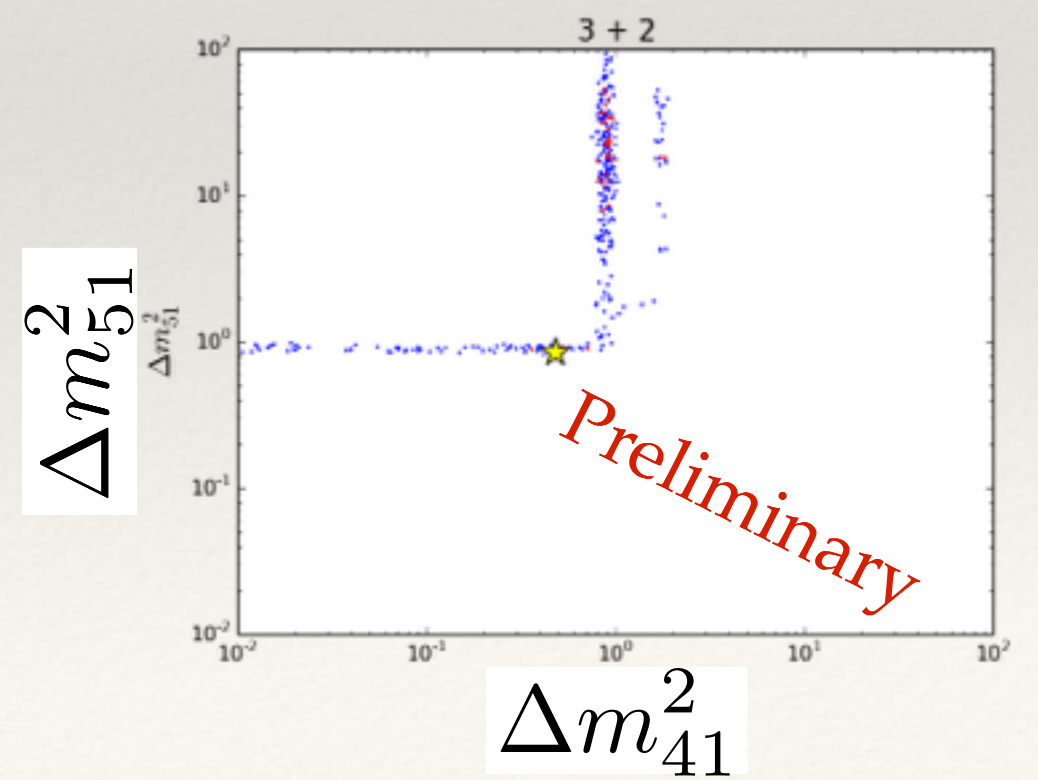
Testing these models

2012 data sets

- Appearance:
  - MiniBooNE-BNB: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$
  - MiniBooNE-NuMI,
  - NOMAD,
  - LSND,
  - KARMEN,
- Disappearance:
  - MiniBooNE-BNB: $\nu_\mu \to \nu_\mu$
  - GALLEX/SAGE,
  - KARMEN/LSND xsec,
  - CCFR84,
  - CDHS,
  - Atmospheric,
  - Bugey,
  - MINOS

Red: 90% CL
Blue: 99% CL





	χ^2_{best}	Pr
Null	290	1.5%
3+1	240	43%
3+2	235	45%

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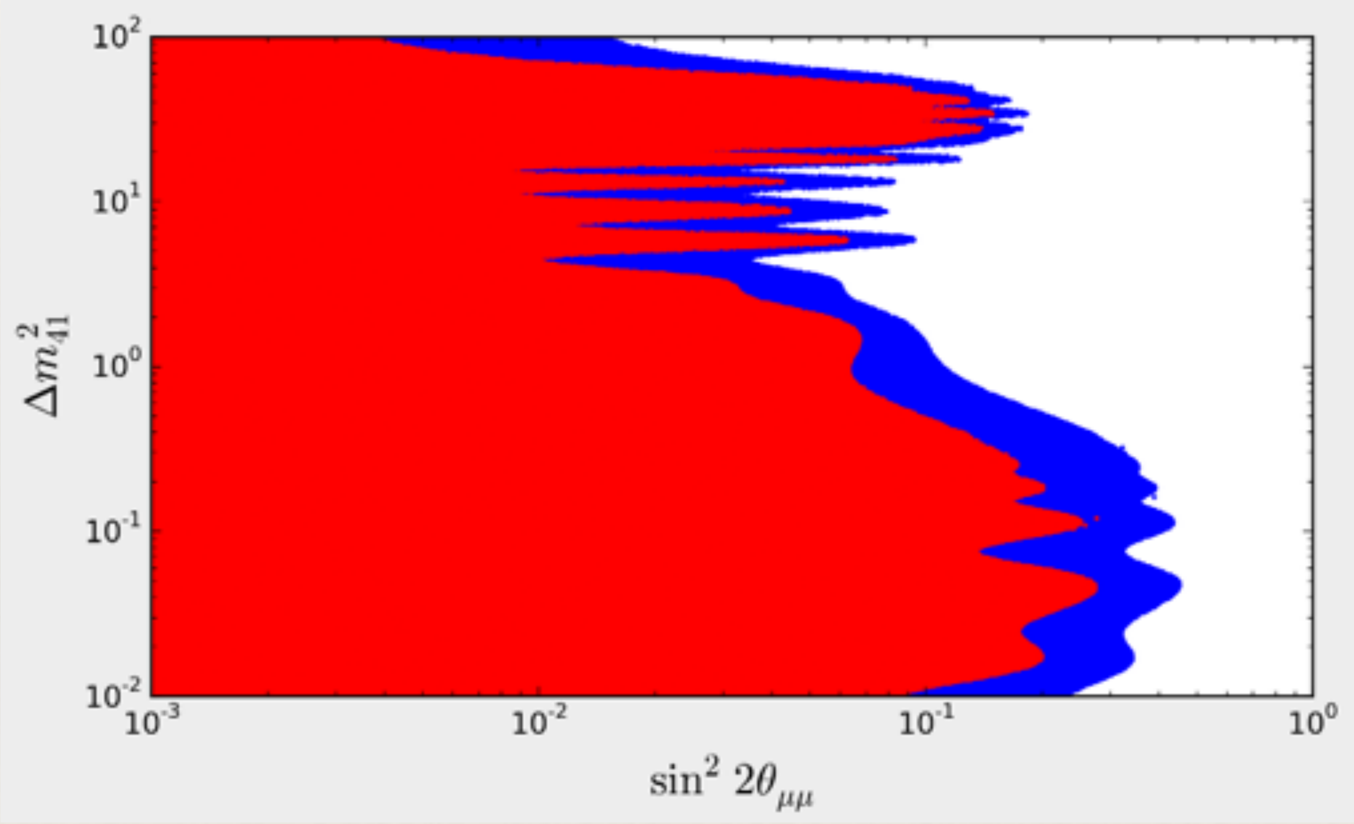
Numu disappearance

- There is still no evidence of muon neutrino disappearance.



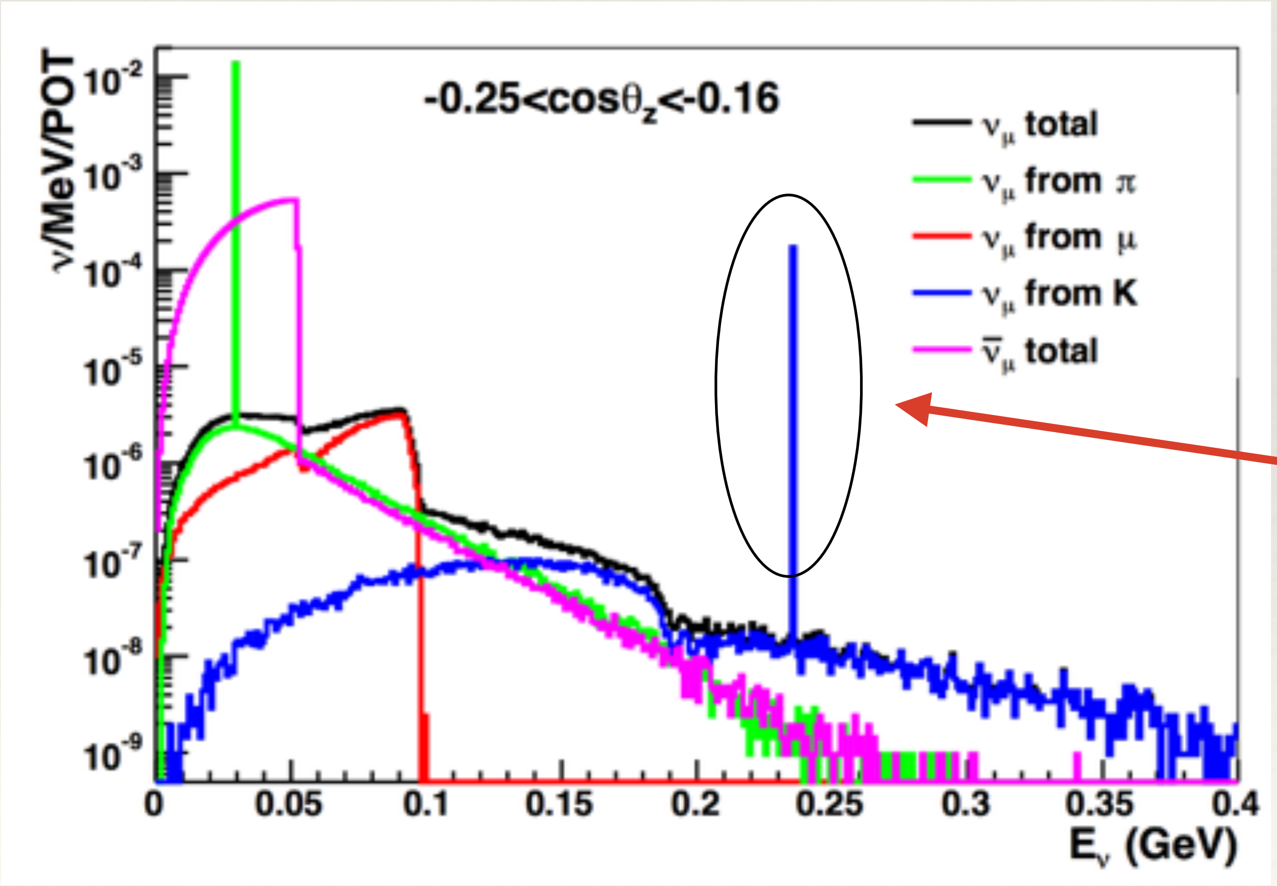
- US DOE challenge: <$10M, decisive in 3 years, autonomous from Fermilab.

A new kind of approach

- Use a mono-energetic, isotropic flux.
  - Energy reconstruction can be poor.
  - Flux is well defined along the detector.
- Use a continuous, long detector.
  - The detector is contiguous and so can be calibrated smoothly along the length.
  - The full oscillation wave is visible.

Kaon decay at rest (KDAR)

- Two body decay at rest is mono-energetic.
- K^+ are produced by protons on a target.
  - These come to rest in the target and surrounding material.

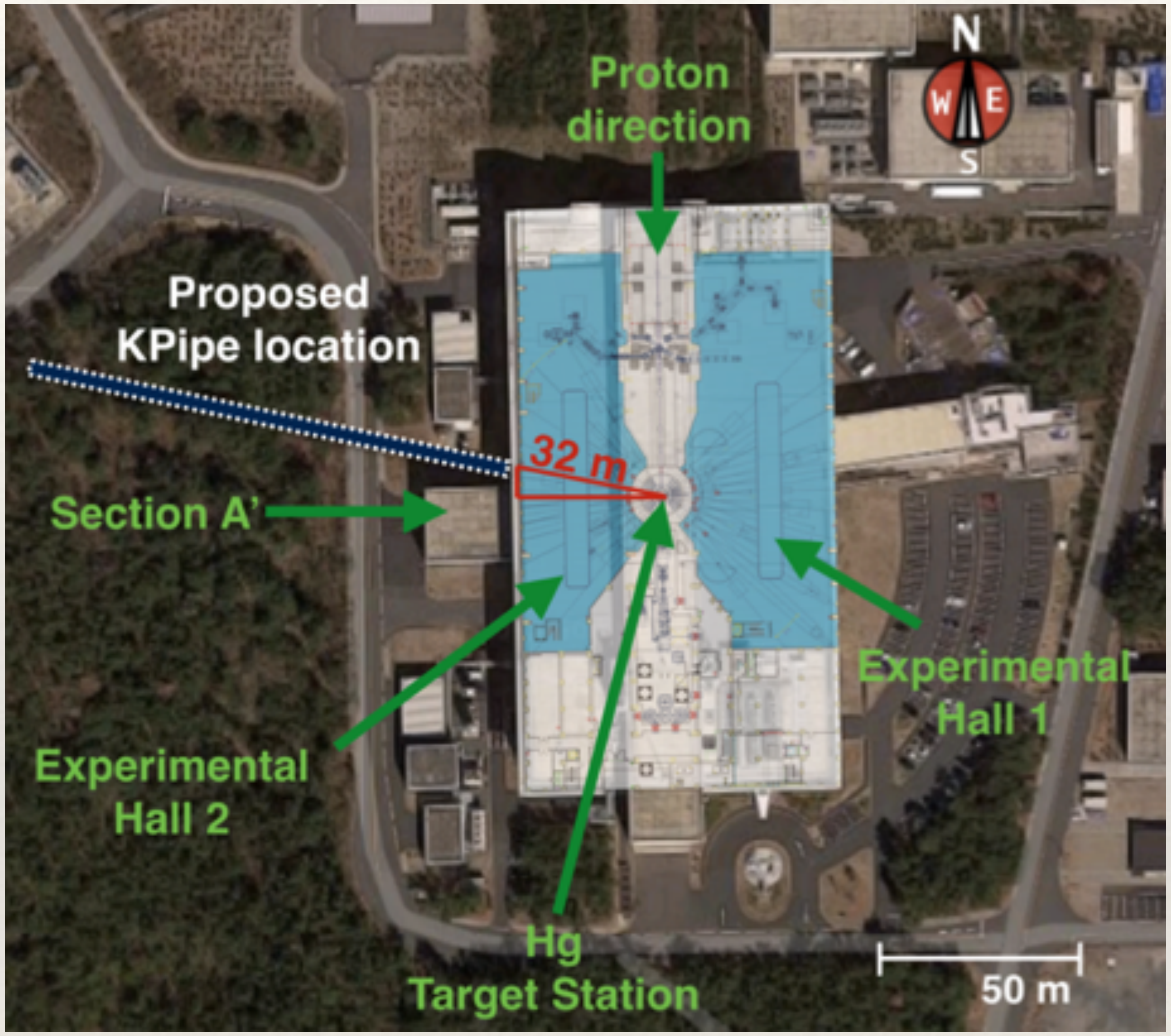


$$K^+ \rightarrow \mu^+ + \nu_\mu$$

KDAR neutrinos are energetic enough to have CC interactions.

KPIPE

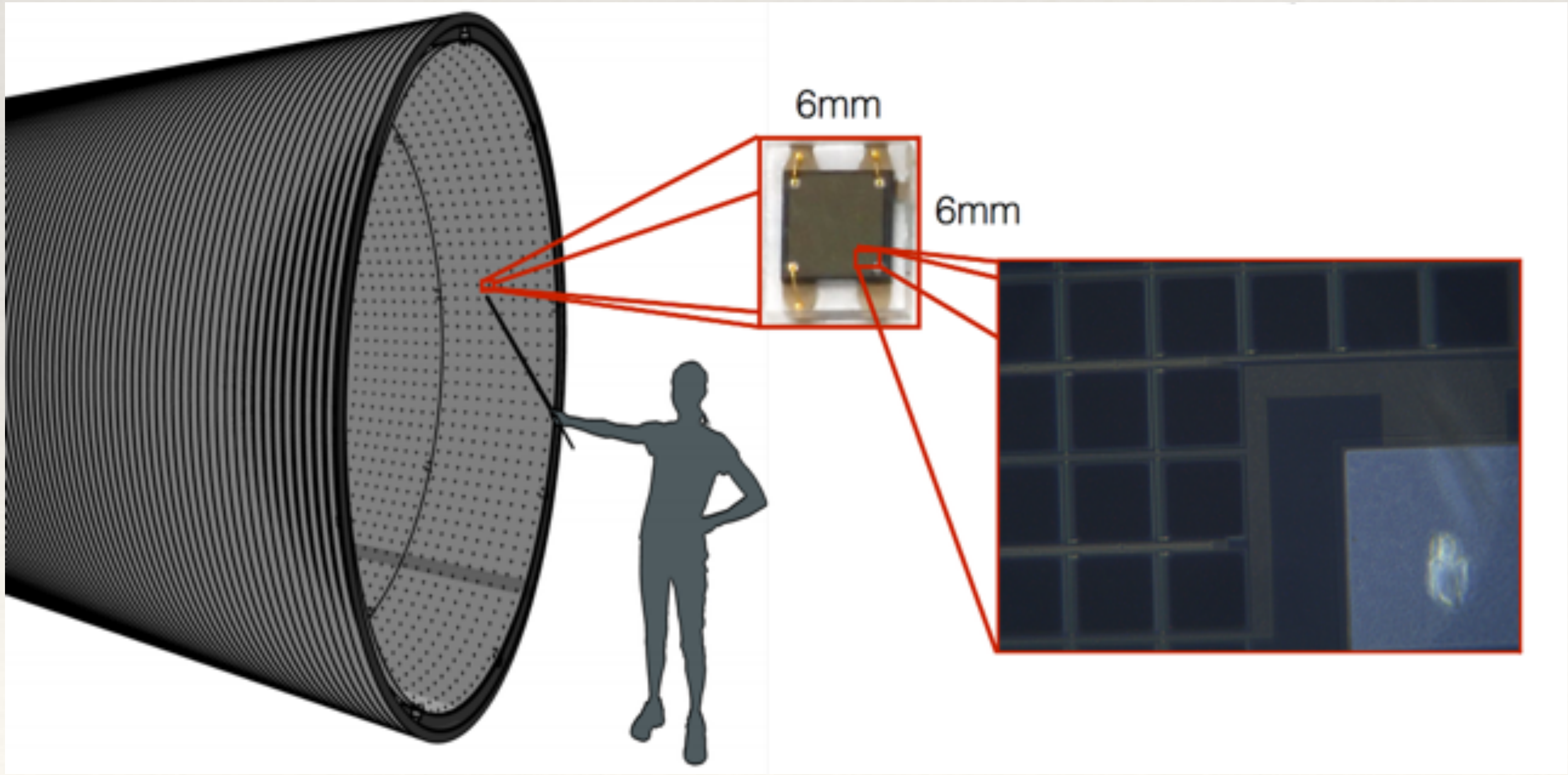
- Hypothetical experiment at the Materials and Life science experimental Facility at J-PARC.
    - Worlds most intense KDAR flux.
- Long detector measures an oscillation in L.
- KDAR is isotropic, so the detector can be placed behind the beam.



KPIPE @ MLF @ J-PARC

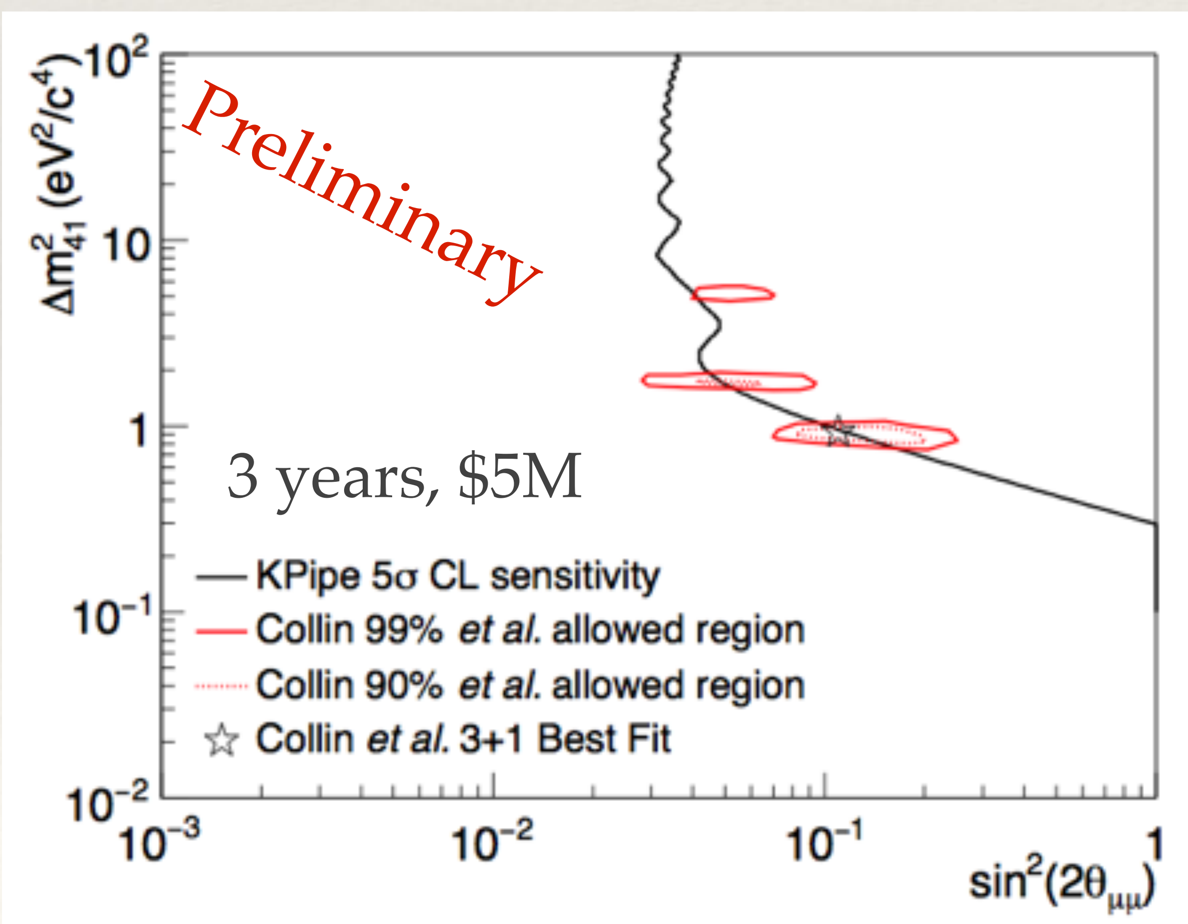
KPIPE

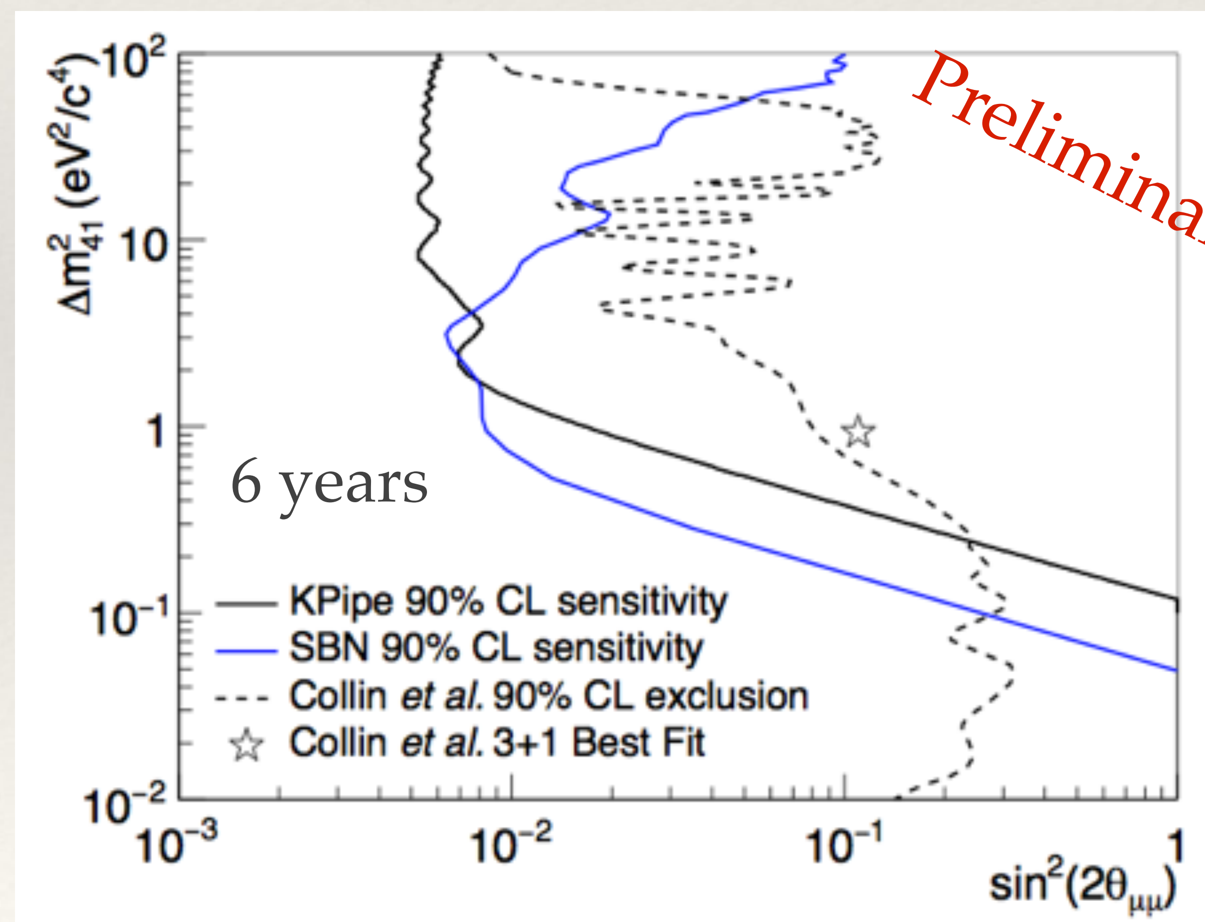
- Detector is a 3m diameter 120m long polyethylene tube.
- Filled with a liquid scintillator.
- With hoops of SiPMs placed 10cm apart.



KPIPE sensitivity

- Projected sensitivity covers 3+1 global best fit at 5 sigma.
- Would drastically improve limits in the high Δm^2 range.





KPIPE

- Watch for our paper on the arXiv this week.

A Decisive Disappearance Search at High-Δm^2 with Monoenergetic Muon Neutrinos

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"KPipe" is a proposed experiment which will study muon neutrino disappearance for a sensitive test of the $\Delta m^2 \sim 1$ eV^2 anomalies, possibly indicative of one or more sterile neutrinos. The experiment will be located at the J-PARC Materials and Life Science Facility's spallation neutron

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Motivation for the parameter goodness-of-fit test

arXiv.org > hep-ph > arXiv:hep-ph/0304176

High Energy Physics – Phenomenology

Testing the statistical compatibility of independent data sets

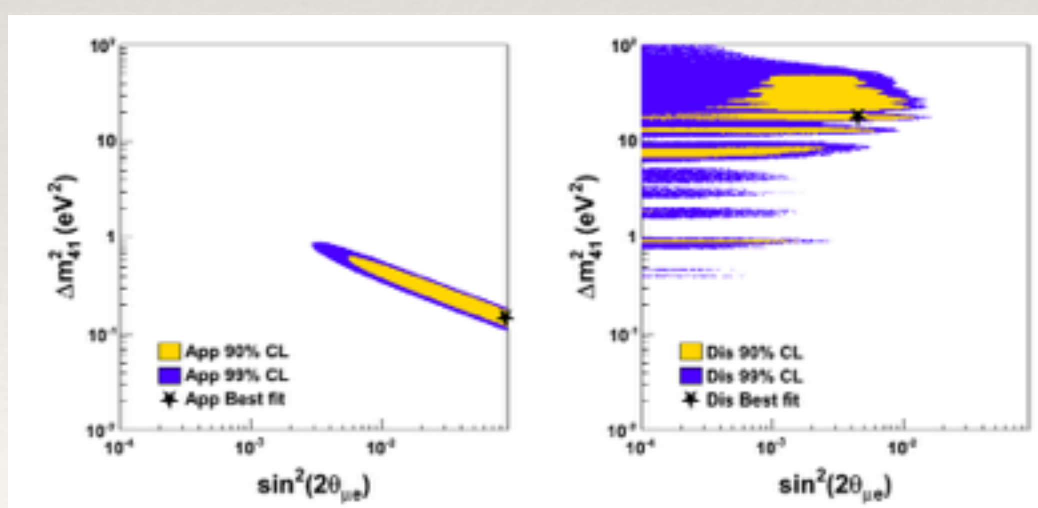
M. Maltoni, T. Schwetz

- Created to address the insensitive bins issue.
- Is interpreted as a test of the compatibility of two data-sets to the predictions of a neutrino oscillation model.

Based on PG, tensions have been observed.

		χ^2_{PG} (dof)	PG(%)
3+1	ν vs. $\bar{\nu}$	15.6 (3)	0.14%
	App vs. Dis	17.8 (2)	0.013%
3+2	ν vs. $\bar{\nu}$	13.9 (7)	5.3%
	App vs. Dis	23.9 (4)	0.0082%
3+3	ν vs. $\bar{\nu}$	10.9 (12)	53%
	App vs. Dis	27.1 (6)	0.014%

arXiv:1207.4765



Parameter goodness-of-fit (PG)

$$\chi^2_{PG} = \chi^2_{glob} - (\chi^2_{app} + \chi^2_{dis})$$

$$N_{PG} = (N_{app} + N_{dis}) - N_{glob}$$
$$= 2 \qquad \text{(for 3+1)}$$

- No. of degrees of freedom is set by the model being tested.
- What is the effect of nuisance parameters on the PG test?

2

Parameters:

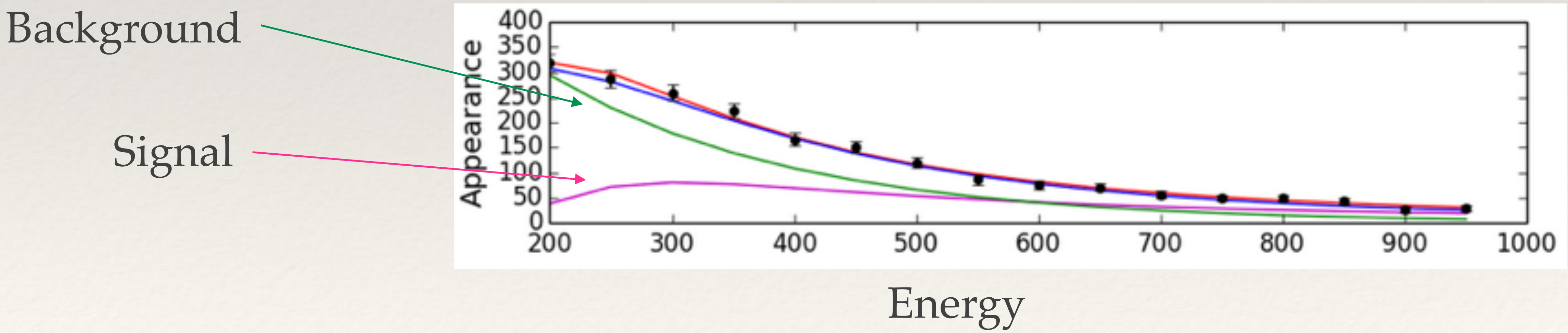
$$P(\nu_\mu \to \nu_e) \simeq 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

$$P(\nu_e \to \nu_e) \simeq 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

3

Study nuisance parameter in a toy model

- 3+1 toy model is composed of:
  - Disappearance,
  - Appearance
    - With and without an unexpected background.



Toy model

- Throw many experiments
  - Data points are selected based on random distributions
  - Background is added to data points.
  - Chi^2 fit is performed for Appearance, Disappearance, and Global, with pull parameter (A) for background normalization.
    - For the case of background, $A_{\text{true}} = 0.4, A_{\text{expected}} = 0.0 \pm 0.15 \quad \rightarrow \quad \text{find } A_{\text{fit}}$
  - Calculate the PG
- χ^2 PG for many throws is histogrammed

$$\chi^2_{\nu_e app} = \sum_{i=1}^{16} \frac{(d_i^{\nu_e app} - (osc_i^{\nu_e app} + b_i^{\nu_e app}(A_{fit})))^2}{(\sigma_i^{\nu_e app})^2} + \frac{(A_{fit} - A_{exp})^2}{\sigma^2_{A_{exp}}}$$

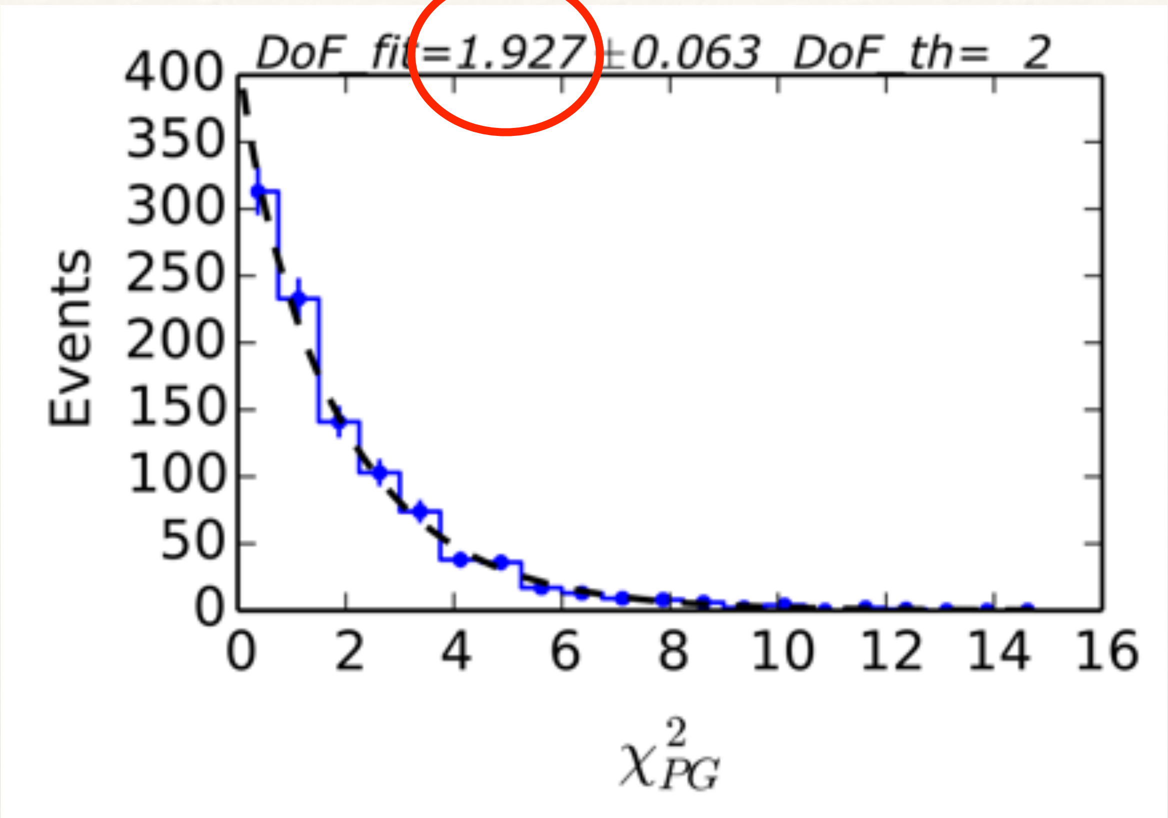
$$\chi^2_{disapp} = \sum_{i=1}^{16} \frac{\left(d_i^{\nu_\mu disapp} - osc_i^{\nu_\mu disapp}\right)^2}{\left(\sigma_i^{\nu_\mu disapp}\right)^2} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e disapp} - osc_i^{\nu_e disapp}\right)^2}{\left(\sigma_i^{\nu_e disapp}\right)^2}$$

$$\chi^2_{global} = \sum_{i=1}^{16} \frac{(d_i^{\nu_e app} - (osc_i^{\nu_e app} + b_i^{\nu_e app}(A_{fit})))^2}{(\sigma_i^{\nu_e app})^2} + \frac{(A_{fit} - A_{exp})^2}{\sigma^2_{A_{exp}}} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_\mu disapp} - osc_i^{\nu_\mu disapp}\right)^2}{\left(\sigma_i^{\nu_\mu disapp}\right)^2} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e disapp} - osc_i^{\nu_e disapp}\right)^2}{\left(\sigma_i^{\nu_e disapp}\right)^2}$$

Toy model, no background

- Background normalization (A_{true}) is set to zero.

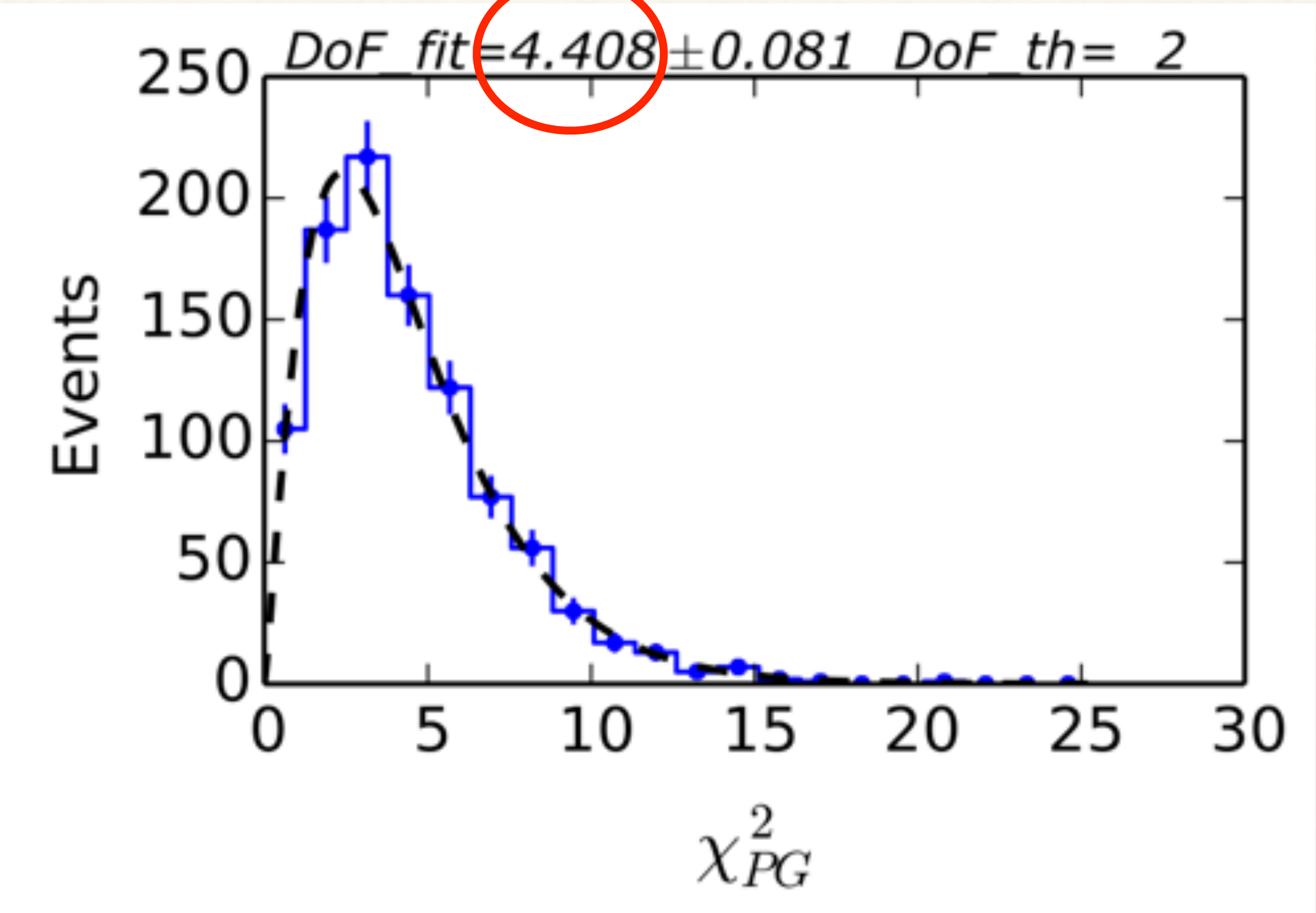
- χ^2 PG distribution comes out with expected No. of degrees of freedom.
  - For 3+1, we expected 2.



PG test works in this case

Toy model, with background

- Now,
  - $A_{\text{true}} = 0.4$
  - $A_{\text{expected}} = 0.0 \pm 0.15$
- χ^2 PG distribution now has an incorrect No. of degrees of freedom.



PG test fails in this case

Summary of PG test

- Changing the scaling of the background model changes the d.o.f of the underlying χ^2_{PG} distribution.
- Some experiments (eg: MiniBooNE) have backgrounds that can look like a signal.

Conclusion

- Introduction to sterile neutrino fits
  - We are in the process of updating our 3+n fits.
- KPIPE is a proposed numu disappearance experiment using Kaon decay at rest.
  - Projected to covers 3+1 global best fit at 5 sigma.
- How reliable is the PG test?
  - Under certain circumstance there is a problem.
  - We welcome ideas on how to solve this.

Backup

Challenges of numu disappearance

- There are two approaches:
  - A wide band decay-in-flight beam.
    - Requires excellent energy reconstruction.
  - A near and far detector.
    - The fluxes seen by the near and far detector are usually not identical.
    - The detectors need to be cross calibrated very well.

Compare Allowed Regions for Nu/Nubar and Appearance/Disappearance